Accelerator Injection and Extraction

Course given at the US Particle Accelerator School

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Rev. 2

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Accelerator and Storage Rings Basics

$$\begin{bmatrix} \cos\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right) & \frac{\sin\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)\rho}{\sqrt{k\rho^2+1}} & \frac{\cos\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)\rho}{k\rho^2+1} - \frac{\rho}{k\rho^2+1} \\ -\frac{\sqrt{k\rho^2+1}\sin\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)}{\rho} & \cos\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right) & -\frac{\sin\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)}{\sqrt{k\rho^2+1}} \\ 0 & 0 & 1 \end{bmatrix}$$

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Circular Machine Basics

- Lorentz Force:

$$\vec{F} = q\left(\vec{E} + \vec{\beta} \times \vec{B}\right)$$

- Momentum:

$$\vec{p} = \frac{m_0 \gamma \vec{\beta}}{c}$$

- Equation of motion:

$$\frac{d\vec{p}}{dt} = \vec{F}$$

Note: cp: momentum [eV], m_0 rest energy [eV], q charge [e_0]

Equation of Motion

- Typically, E is 0 (except in accelerating cavities)
  B is B_3 vertical guide field (except in focusing elements)
- Then the eq of motion becomes

$$q\left(\beta_2(s)B_3\hat{i}-\beta_1(s)B_3\hat{j}\right)=\frac{m_0\gamma\left(\left(\frac{\mathrm{d}}{\mathrm{d}s}\beta_1(s)\right)\hat{i}+\left(\frac{\mathrm{d}}{\mathrm{d}s}\beta_2(s)\right)\hat{j}+\left(\frac{\mathrm{d}}{\mathrm{d}s}\beta_3(s)\right)\hat{k}\right)}{c}$$

- Integrate this twice and get:

$$\vec{x}=-\frac{\beta_{2,0}m_0\gamma\left(\cos\left(\frac{B_3qcs}{\gamma m0}\right)\hat{i}-\sin\left(\frac{B_3qcs}{\gamma m0}\right)\hat{j}\right)}{B_3qc}$$

-

- This describes a circle with radius

$$\rho=\frac{\beta_{2,0}m_0\gamma}{B_3qc}=\frac{pc}{B_3qc}$$

- The “B-rho” value is then a property of the beam:

$$B\rho=\frac{pc}{qc}=3.33564\,pc,\;\; pc\;[\mathrm{GeV}];\, q=1$$

- The circle thus defined is used as *reference orbit*. All beam dynamics can be expressed relative to this orbit.
  - Series expansion about the reference orbit.

Frenet-Serret Coordinates

- To do this we transform into a beam-following coordinate system called Frenet-Serret or TNB (tangent-normal-binormal) coordinates.

tangent (longitudinal)
normal (horizontal)
binormal (vertical)

$$\begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = \begin{bmatrix} \sin\left(\frac{s}{\rho}\right) & \cos\left(\frac{s}{\rho}\right) & 0 \\ \cos\left(\frac{s}{\rho}\right) & -\sin\left(\frac{s}{\rho}\right) & 0 \\ 0 & 0 & -1 \end{bmatrix} \circ \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

- and the Lorentz equation becomes

$$\left[\frac{d^2}{ds^2} X_1(s) = \frac{\frac{d}{ds} X_2(s)}{\rho}, \frac{d^2}{ds^2} X_2(s) = -\frac{\frac{d}{ds} X_1(s)}{\rho}, \frac{d^2}{ds^2} X_3(s) = 0 \right]$$

Hill's Equation

- Modern accelerators are built from discrete bending and focusing magnets. ρ and focusing k are functions of s.

$$\frac{d^2}{ds^2} X_2(s) = -\frac{X_2(s)}{\rho(s)^2} - k(s) X_2(s) \text{ and } \frac{d^2}{ds^2} X_3(s) = k(s) X_3(s)$$

- Mr. Hill found that solutions have the form

$$\xi_1(s) = a' \cdot w(s) \cdot \cos(\psi(s))$$

$$\xi_2(s) = a \cdot w(s) \cdot \sin(\psi(s))$$

- with w(s) being given by the *envelope equation*

$$-\frac{1}{w(s)^3} - w(s)k(s) + \frac{d^2}{ds^2} w(s) = 0$$ amplitude

- and $$\frac{d}{ds}\psi(s) = \frac{1}{w(s)^2}$$ phase

Matrix Optics

- Solutions like Mr. Hill's can be expressed by a matrix algorithm:

$$\begin{bmatrix} x(L) \\ \frac{\mathrm{d}}{\mathrm{d}L}x(L) \end{bmatrix} = R \circ \begin{bmatrix} x(0) \\ \left(\frac{\mathrm{d}}{\mathrm{d}s}x(s)\right)\Big|_{s=0} \end{bmatrix}, \quad R = \begin{bmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{bmatrix}$$

- Change notation to that commonly used in accelerator work:

$$w(s) = \sqrt{\beta(s)}, \quad \frac{\mathrm{d}}{\mathrm{d}s}w(s) = -\frac{\alpha(s)}{w(s)}, \quad \gamma(s) = \frac{1+\alpha(s)^2}{\beta(s)}$$

- and it can be shown that (1-turn matrix)

$$R_p = \begin{bmatrix} \alpha(0)\sin(\mu(L)) + \cos(\mu(L)) & \sin(\mu(L))\beta(0) \\ \left(-\frac{\alpha(0)^2}{\beta(0)} - \frac{1}{\beta(0)}\right)\sin(\mu(L)) & -\alpha(0)\sin(\mu(L)) + \cos(\mu(L)) \end{bmatrix}$$

Matrix from 0 to *s*

- Without derivation we give the R matrix between two points of unequal β(*s*) and α(*s*):

$$\begin{bmatrix} \frac{\sqrt{\beta(s)}\left(\sin(\mu(s))\alpha(0) + \cos(\mu(s))\right)}{\sqrt{\beta(0)}} & \sqrt{\beta(s)}\sin(\mu(s))\sqrt{\beta(0)} \\ \frac{(-\alpha(0)\alpha(s)-1)\sin(\mu(s)) + (\alpha(0)-\alpha(s))\cos(\mu(s))}{\sqrt{\beta(0)}\sqrt{\beta(s)}} & \frac{\left(-\sin(\mu(s))\alpha(s) + \cos(\mu(s))\right)\sqrt{\beta(0)}}{\sqrt{\beta(s)}} \end{bmatrix}$$

- The connection between *k*(*s*) and β(*s*) and α(*s*) is:

$$k(s) = \frac{\alpha(s)^2 + \left(\frac{\mathrm{d}}{\mathrm{d}s}\alpha(s)\right)\beta(s) + 1}{\beta(s)^2}$$

Floquet Coordinates

- The one-turn matrix R_p looks a bit like a rotation matrix. Lets make this more explicit:
  - define a matrix

$$F = \begin{bmatrix} \frac{1}{\sqrt{\beta(s)}} & 0 \\ \frac{\alpha(s)}{\sqrt{\beta(s)}} & \sqrt{\beta(s)} \end{bmatrix}$$

  - transform an arbitrary phase-space vector:

$$Q = \begin{bmatrix} q \\ p \end{bmatrix} = F \circ \begin{bmatrix} x \\ xp \end{bmatrix} = \begin{bmatrix} \frac{x}{\sqrt{\beta(s)}} \\ \frac{\alpha(s)x}{\sqrt{\beta(s)}} + \sqrt{\beta(s)}xp \end{bmatrix}$$

- Transform R_p:

$$R_n = F \circ R_p \circ F^{-1} = \begin{bmatrix} \cos(\mu(L)) & \sin(\mu(L)) \\ -\sin(\mu(L)) & \cos(\mu(L)) \end{bmatrix}$$

- Apply R_n on Q:

$$R_n \circ Q = \begin{bmatrix} \frac{\cos(\mu(L))x}{\sqrt{\beta(s)}} + \sin(\mu(L))\left(\frac{\alpha(s)x}{\sqrt{\beta(s)}} + \sqrt{\beta(s)}xp\right) \\ -\frac{\sin(\mu(L))x}{\sqrt{\beta(s)}} + \cos(\mu(L))\left(\frac{\alpha(s)x}{\sqrt{\beta(s)}} + \sqrt{\beta(s)}xp\right) \end{bmatrix}$$

- The length of the result is

$$a^2 = \frac{\beta(s)^2 xp^2 + 2\alpha(s)\beta(s)x \cdot xp + \beta(s)^2 x^2 + x^2}{\beta(s)}$$

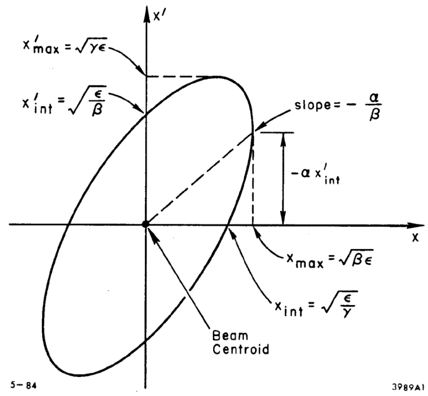
Machine Ellipse

$$\gamma(s) = \frac{1+\alpha(s)^2}{\beta}$$

- or, using the Twiss $\gamma(s)$:

$$a^2 = xp^2\beta(s) + 2x \cdot xp \cdot \alpha(s) + x^2\gamma(s)$$

- This is known as the *Courant-Snyder Invariant*. It describes an ellipse in x-xp (phase-) space.
  - a^2 is the area of the ellipse.
  - $\varepsilon = a^2/\pi$ is called the *emittance*

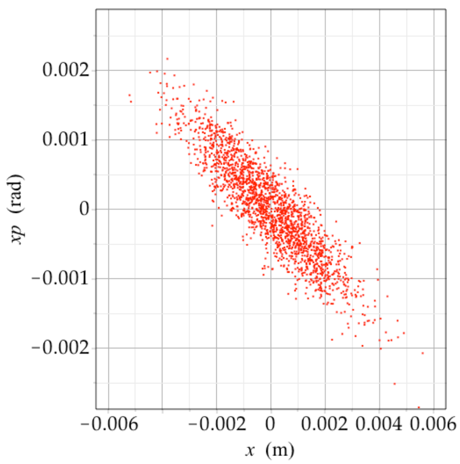


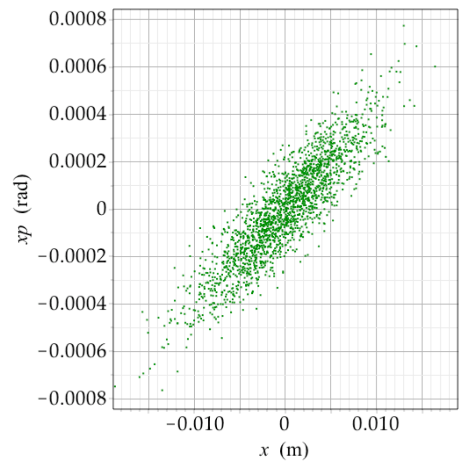
Liouville's Theorem

- A conservative system (like a beam line) does not change phase-space volume (emittance).
  - in practise, phase-space volume *can* grow due to nonlinearity & filamentation
- Once emittance has grown, there is *no way* to make it small again.
  - unless cooling techniques are used or radiation damping applies.
- Beam transfer is a significant source of emittance growth
  - (not a theorem by Liouville!)
- You cannot "merge" phase space using (static) magnets.

Machine *vs* Beam Ellipse

- The ellipse thus defined is a property of a closed ring (except for the area).
- Each particle given by (x,xp) is moving on such an ellipse.
- a *dynamic* equilibrium



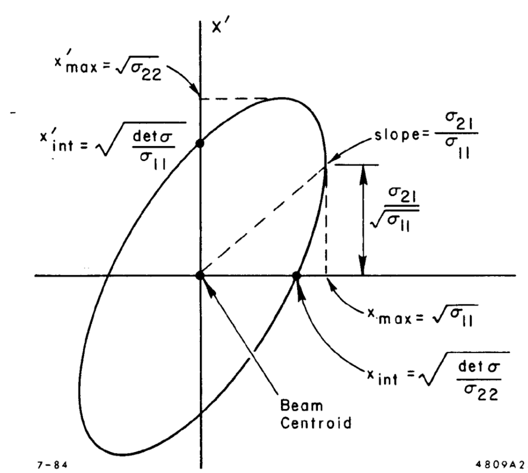


- We need to describe a *beam ellipse* as well: Σ matrix

$$\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix}, \qquad \sigma_{21} = \sigma_{12}$$

$$\sigma_{11} = \overline{x^2}, \qquad \sigma_{12} = \sigma_{21} = \overline{x \cdot xp},$$

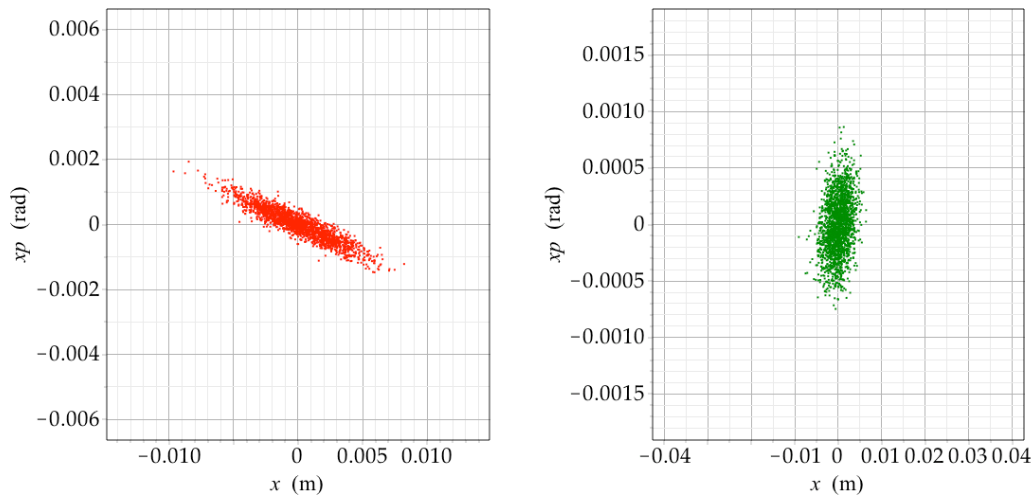
$$\sigma_{22} = \overline{xp^2}$$



- Compare to the previous figure

$$\begin{bmatrix} \sigma 11 & \sigma 12 \\ \sigma 21 & \sigma 22 \end{bmatrix} = \begin{bmatrix} \varepsilon\beta(s) & -\varepsilon\alpha(s) \\ -\varepsilon\alpha(s) & \varepsilon\gamma(s) \end{bmatrix}$$

- What about a beam injected *off-axis* or one that has a different aspect ratio??
- A *mismatched* beam, no equilibrium



Element-Wise Description

- Drift section

$$\frac{d^2}{ds^2}X_2(s)=0 \Rightarrow R_D=\begin{bmatrix} 1 & s \\ 0 & 1 \end{bmatrix}$$

- Quadrupole (watch out: cosh etc. for k<0 i.e. defocusing!)

$$\frac{d^2}{ds^2}X_2(s)=-kX_2(s) \Rightarrow R_Q=\begin{bmatrix} \cos\left(\sqrt{k}s\right) & \frac{\sin\left(\sqrt{k}s\right)}{\sqrt{k}} \\ -\sqrt{k}\sin\left(\sqrt{k}s\right) & \cos\left(\sqrt{k}s\right) \end{bmatrix}$$

- Dipole (wedge bending magnet, δ=δp/p)

$$\frac{d^2}{ds^2}X_2(s)=-\frac{X_2(s)}{\rho^2}-kX_2(s)-\frac{\delta}{\rho} \Rightarrow ?$$

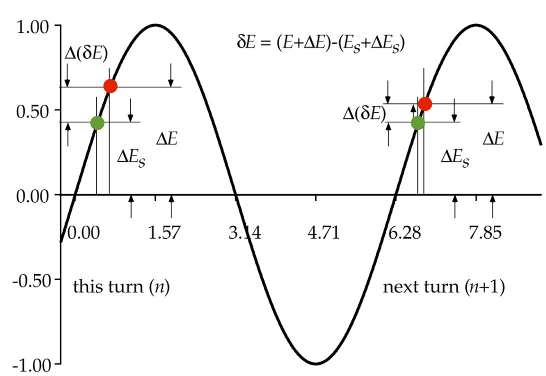
- Turns out we need a third coordinate: δ=δp/p

$$R_B = \begin{bmatrix} \cos\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right) & \frac{\sin\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)\rho}{\sqrt{k\rho^2+1}} & \frac{\cos\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)\rho}{k\rho^2+1} - \frac{\rho}{k\rho^2+1} \\ -\frac{\sqrt{k\rho^2+1}\sin\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)}{\rho} & \cos\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right) & -\frac{\sin\left(\frac{\sqrt{k\rho^2+1}\cdot s}{\rho}\right)}{\sqrt{k\rho^2+1}} \\ 0 & 0 & 1 \end{bmatrix}$$

Note: the quantity $-k\rho^2$ is also known as field index n

Synchrotron Motion

- Acceleration in a synchrotron requires an rf system.
- The rf frequency is synchronous with the revolution time in the synchrotron.
- Beam particles oscillate in time and energy about the reference phase and energy
  - phase stability (Vecksler & MacMillan)



- oscillating particle
- reference particle

Equation of Motion

- The equations of motion can be written as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}\Phi(t)=\frac{\omega_{rf}^2\eta W(t)}{\beta^2 E_s} \qquad W(t)=-\delta E(t)/\omega_{rf}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}W(t)=\frac{1}{2}\frac{qV\left(\sin(\Phi_s)-\sin(\Phi(t))\right)}{h\pi} \qquad \eta=\left(\frac{1}{\gamma^2}-\frac{1}{\gamma_t^2}\right),\ \text{the } \textit{slip factor}$$

- This can be solved for $\Phi(t) = \Phi_s + \phi(t)$ and $\phi(t)$ small. If we use initial conditions $\Phi(0) = 0$ and $W(0) = W_0$, we get

$$W(t)=W_0\cos\left(\frac{1}{2}\frac{\sqrt{2}\omega_{rf}\sqrt{\eta}\sqrt{q}\sqrt{V}\sqrt{\cos(\Phi_s)}t}{\beta\sqrt{\pi}\sqrt{h}\sqrt{E_s}}\right),\quad \phi(t)=\frac{\sqrt{2}\omega_{rf}\sqrt{\eta}\sin\left(\frac{1}{2}\frac{\sqrt{2}\omega_{rf}\sqrt{\eta}\sqrt{q}\sqrt{V}\sqrt{\cos(\Phi_s)}t}{\beta\sqrt{\pi}\sqrt{h}\sqrt{E_s}}\right)W_0\sqrt{h}\sqrt{\pi}}{\beta\sqrt{E_s}\sqrt{q}\sqrt{V}\sqrt{\cos(\Phi_s)}}$$

- This describes harmonic motion
  - and an ellipse in phase space.

Rf Bucket

- Small-amplitude synchrotron oscillations have a frequency

$$\Omega_s=\sqrt{\frac{h\omega_s^2\eta qV\cos(\Phi_s)}{2\beta^2\pi E_s}}$$

η: slip factor
h: harmonic of rf
ω_s: rf frequency
V: peak rf voltage
β: relativistic velocity
E_s: beam energy
Φ_s: synchronous phase

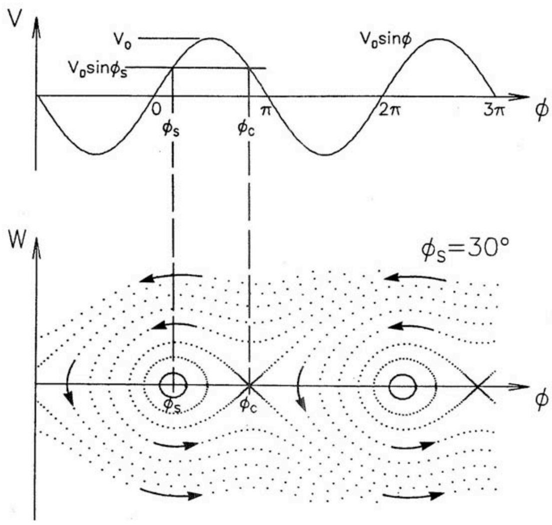
- The amplitude is limited: “bucket height”:

$$\frac{\widehat{\delta(E)}}{E_s}=\frac{\sqrt{-\pi\eta hVqE_s\left(\sin(\Phi_s)\pi-2\sin(\Phi_s)\Phi_s-2\cos(\Phi_s)\right)}\beta}{E_s\pi\eta h}$$

- and a max. phase width not subject to simple analytic expression

- There are h “rf buckets” in a synchrotron.
- Energy (W in the figure below) and phase ϕ are the direct longitudinal equivalents to xp and x

M. Craddock



“Thin” Elements

- Thin quads are a useful approximation to make algebra simple

$$R_Q = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -kf & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & kf & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

  – a series of these converges to a regular quadrupole
- “Thin dipoles” can be defined in an ad-hoc fashion (Brown & Servranckx)

$$R_D := \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -\dfrac{\sin(\theta)}{\rho} & 1 & 0 & 0 & 0 & \sin(\theta) \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\sin(\theta) & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

References

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- H. Wiedemann, Particle Accelerator Physics, Vol. 4, Springer, 2015, esp. Part III Chap. 7.
- K.L. Brown and R.V. Servranckx, SLAC-PUB-3381, 1984.
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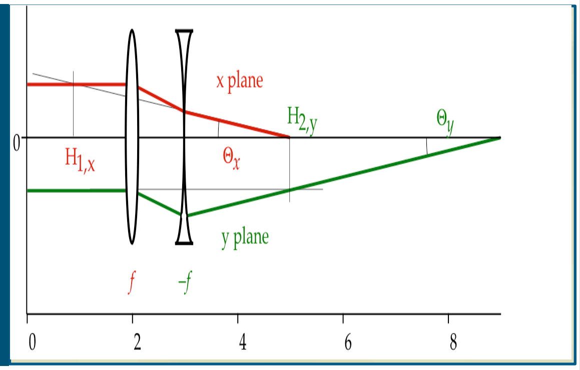
Matching Sections



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Matching Fundamentals

- Match injecting beam-properties to ring Twiss functions
  - $\beta_x, \alpha_x, \beta_y, \alpha_y$ match => at least 4 quadrupoles needed
  - if dispersion is involved, need at least one dipole & more quads
  - if rotation (coupling) is involved, need skew quads.
  - a workable solution is not guaranteed for any sequence of elements.
- Optical building blocks make this easier:
  - Doublet: parallel to point
  - Quarter-wave transformer: match FODOs with different parameters
  - Telescope, to magnify or demagnify a beam
- Analytic evaluation using thin-lens optics can guide the initial layout.

Insertions

- Often, the machine design can accommodate injection with an insertion
  - Dispersion suppressors
  - high-β sections
  - symmetry points with $\alpha = 0$
  - 180° sections to facilitate closed kicker bumps with 2 kickers.
- Such sections are inserted using two techniques
  - $R = I$ sections; these are transparent (often $R = -I \bullet -I$)
  - $R \neq I$ sections; but $\beta_x, \alpha_x, \beta_y, \alpha_y$ matched (changes machine tune)

Some Building Blocks

- Doublet
- Transformers
- Dispersion suppressor
- Propagation of Twiss functions:

$$T_2 = R_{12} \cdot T_1 \cdot R_{12}{}' , \quad T_1 = \begin{bmatrix} \beta(0) & -\alpha(0) \\ -\alpha(0) & \gamma(0) \end{bmatrix}$$

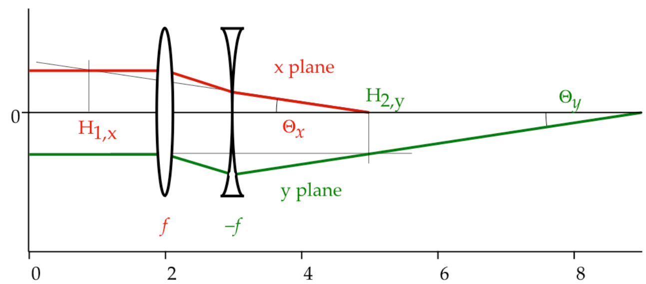
- explicit:

$$\begin{bmatrix} \beta(s) \\ \alpha(s) \\ \gamma(s) \end{bmatrix} = \begin{bmatrix} r_{11}^2 & -r_{11}r_{12} - r_{11}r_{21} & r_{12}^2 \\ -r_{21}r_{11} & r_{11}r_{22} + r_{12}r_{12} & -r_{22}r_{12} \\ r_{21}^2 & -2r_{21}r_{22} & +r_{22}^2 \end{bmatrix} \circ \begin{bmatrix} \beta(0) \\ \alpha(0) \\ \gamma(0) \end{bmatrix}$$

Doublet Lens

- A doublet lens focuses in both planes, but with different properties:

$$R = \begin{bmatrix} -L_d k_f + 1 & L_d & 0 & 0 & 0 & 0 \\ L_d k_d k_f - k_d - k_f & -L_d k_d + 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & L_d k_f + 1 & L_d & 0 & 0 \\ 0 & 0 & L_d k_d k_f + k_d + k_f & L_d k_d + 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$



- Two doublets spaced by more than their focal length make a beta transformer, with a transformation ratio roughly

$$\frac{\beta_2}{\beta_1} \approx \frac{L_2^2}{L_D^2}$$

L_D = spacing between the doublets
L_2 = space to downstream waist, β_2
β_1 = incoming β

  – (if the β in x and y are similar one may need triplets)
- The focal length of each doublet is then

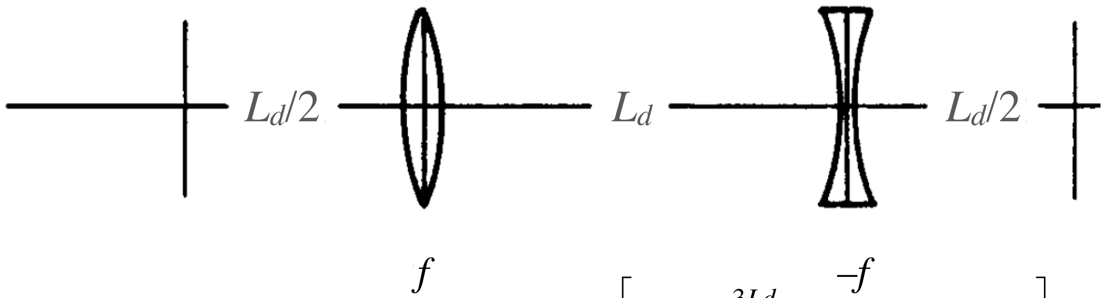
$$f_u \approx \frac{L_D^2}{L_D + L_2}, \quad f_d \approx \frac{L_D L_2}{L_D + L_2}$$

subscript u is upstream, d is downstream

- and the phase advance $\mu = \pi$.
- These are starting points for numerical fitting (e.g. Mad-X)
- For small β at the injection point need to move the matching quads closer else the whole array gets too long.

Quarter-Wave Transformer

- A q-w-t is a FODO cell arranged like this:

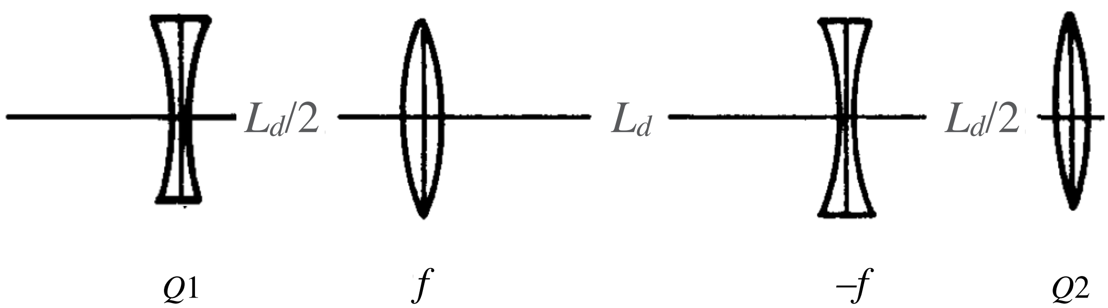


- for $f = 1/k = \sqrt{2}/L_d$,
  its R-Matrix looks like this:

$$\begin{bmatrix} -\sqrt{2} & \frac{3Ld}{2} & 0 & 0 & 0 & 0 \\ -\frac{2}{Ld} & \sqrt{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sqrt{2} & \frac{3Ld}{2} & 0 & 0 \\ 0 & 0 & -\frac{2}{Ld} & -\sqrt{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- its phase advance is $\pi/2$
  - how can you tell?

- To make a matching section, we add 2 quads:



$$\begin{bmatrix} -\sqrt{2}-\frac{3LdkQ1}{2} & \frac{3Ld}{2} & 0 & 0 & 0 & 0 \\ \frac{2Ld(KQ2-kQ1)\sqrt{2}+3KQ2Ld^2kQ1-4}{2Ld} & -\frac{3KQ2Ld}{2}+\sqrt{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sqrt{2}+\frac{3LdkQ1}{2} & \frac{3Ld}{2} & 0 & 0 \\ 0 & 0 & \frac{2Ld(KQ2-kQ1)\sqrt{2}+3KQ2Ld^2kQ1-4}{2Ld} & \frac{3KQ2Ld}{2}-\sqrt{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- This section propagates the beta functions as follows:

$$\beta_{x2} = \left(-\sqrt{2} - \frac{3L_d k_{Q1}}{2}\right)^2 \beta_{x1} - 3\left(-\sqrt{2} - \frac{3L_d k_{Q1}}{2}\right) Ld\alpha_{x1} + \frac{9L_d^2}{4}\gamma_{x1}$$

k_{Q1} & L_d set β_2

$$\beta_{y2} = \left(+\sqrt{2} + \frac{3L_d k_{Q1}}{2}\right)^2 \beta_{y1} + 3\left(-\sqrt{2} - \frac{3L_d k_{Q1}}{2}\right) Ld\alpha_{y1} + \frac{9L_d^2}{4}\gamma_{y1}$$

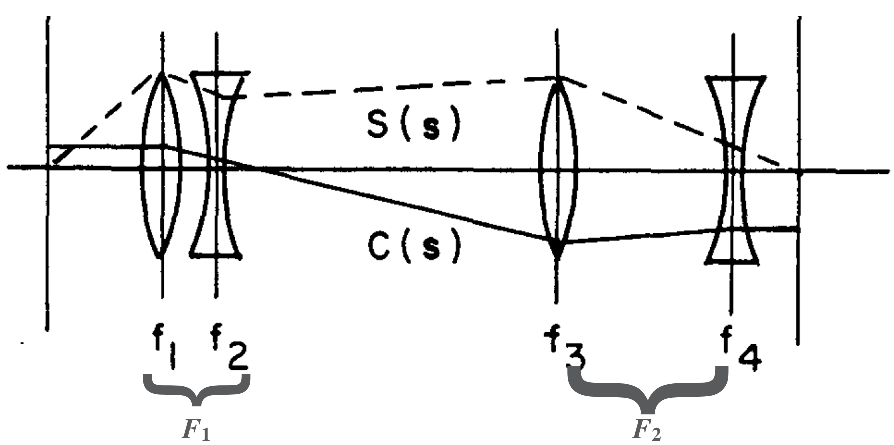
- Matching procedure:
  - set L_d, $Q1$ to achieve β_{x2}, β_{y2} as desired
  - set $Q2$ to achieve desired α_{x2}, α_{y2}.
  - for $\beta_{x1} = \beta_{y1}$ and $\alpha_{x1} =-\alpha_{y1}$ we get $\beta_{x2} = \beta_{y2}$ and $\alpha_{x2} =-\alpha_{y2}$
  - Putting this at the symmetry point of a FODO matches one FODO to another one with different parameters
- Analytic expressions for L_d, k_{Q1} as $f(\beta_{x2}, \beta_{y2})$ can be found but are not insightful.

Half-Wave Transformer

- A Half-wave transformer is characterized by a Matrix

$$R = \begin{bmatrix} -R_{11} & 0 \\ 0 & -1/R_{11} \end{bmatrix}$$

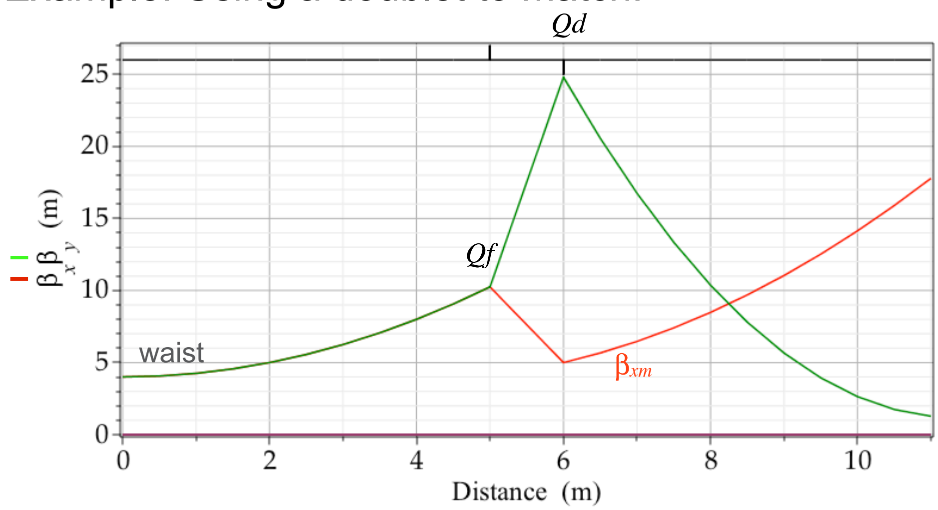
R_{11} is the magnification $F_2/F_1 = \sqrt{(\beta_2/\beta_1)}$
F_1, F_2 is the effective focal length of each doublet
Phase advance is $\mu=\pi$
R_{33} may differ from R_{11}



- The distance to the waist is about the focal length of the 2nd doublet.
- The distance between the doublets is the sum of the focal lengths of each doublet, and the magnification, the ratio of the two.
- Such transformers work well between points with $\alpha_x = \alpha_y = 0$.
- As before, these considerations help getting starting values for the numerical fitting.

Match of a FODO to a Waist

- Consider a ring where an insertion has been provided with a double-waist, which we want to match to. The incoming beam has FODO-like parameters.
- Example: Using a doublet to match:



- R matrix for the matching section:

$$\begin{bmatrix} -Ld2kQf+1 & -Ld1Ld2kQf+Ld1+Ld2 & 0 & 0 & 0 & 0 \\ Ld2kQdkQf-kQd-kQf & (Ld2kQdkQf-kQd-kQf)Ld1-Ld2kQd+1 & 0 & 0 & 0 & 0 \\ 0 & 0 & Ld2kQf+1 & Ld1Ld2kQf+Ld1+Ld2 & 0 & 0 \\ 0 & 0 & Ld2kQdkQf+kQd+kQf & (Ld2kQdkQf+kQd+kQf)Ld1+Ld2kQd+1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- β_x at the 2nd quadrupole (Q_d) is

$$\beta_{xm} = \left(-L_{d2}k_{Qf}+1\right)^2 \beta_{xw} + \frac{\left(L_{d1}+L_{d2}\left(-L_{d1}k_{Qf}+1\right)\right)^2}{\beta_{xw}}$$

- we can find the value for the 1st matching quad:

$$k_{Qf} = \frac{L_{d1}{}^2 + L_{d1}L_{d2} + \beta_{xw}{}^2 - \sqrt{L_{d1}{}^2\beta_{xm}{}^2\beta_{xw}{}^2 - L_{d2}{}^2\beta_{xw}{}^2 + \beta_{xm}{}^2\beta_{xw}{}^3}}{\left(L_{d1}{}^2 + \beta_{xw}{}^2\right)L_{d2}}$$

- not very instructive in itself, but we use this result to look at α_{xm} after Qd:

$$\alpha_{xm} = \frac{\sqrt{L_{d1}{}^2\beta_{xm}\beta_{xw} - L_{d2}{}^2\beta_{xw}{}^2 + \beta_{xm}\beta_{xw}{}^3} + \beta_{xm}\beta_{xw}\left(L_{d2}k_{Qd}-1\right)}{L_{d2}\beta_{xw}}$$

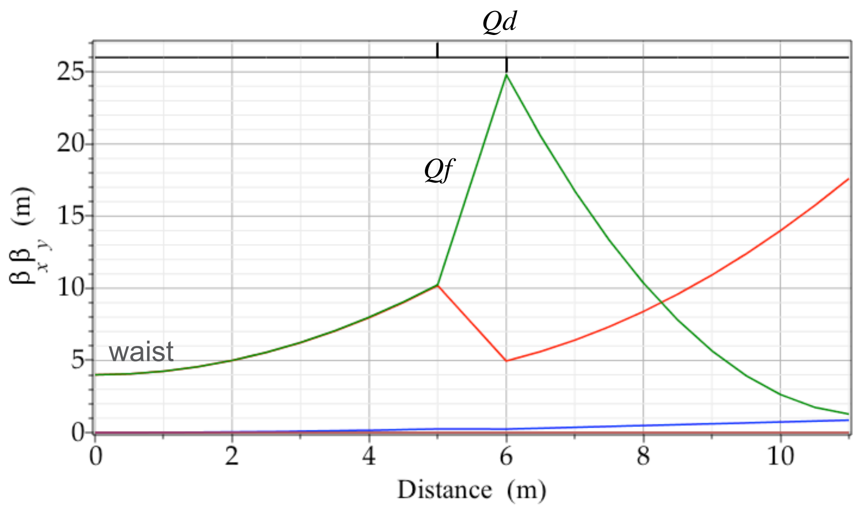
- We (usually) want α_x to be ≤0 after Qd, so we can solve:

$$k_{Qd} < \frac{\beta_{xm}\beta_{xw} - \sqrt{L_{d1}{}^2\beta_{xm}\beta_{xw} - L_{d2}{}^2\beta_{xw}{}^2 + \beta_{xm}\beta_{xw}{}^3}}{\beta_{xm}\beta_{xw}L_{d2}}$$

- At which point we have expressions for the two quadrupoles & need to put in numbers.
- If we use $L_{d1} = 5$ m, $L_{d2} = 1$ m, $\beta_{xm} = \beta_{ym} = 4$ m, we get $k_{Qf} = 0.43/$m and $k_{Qd} < -0.42/\mathrm{m}$. The previous figure was calculated using $k_{Qd} = -0.54/\mathrm{m}$.
- The following cells will be the FODO array we match into, with the first cell likely needing slight adjustments.
- This exercise shows that even simple matching problems have complex algebra unless we restrict the parameter space

Dispersion Matching

- Injection regions may have 0 or finite dispersion that we need to match to. The situation is made more complicated by septa that create dispersion of their own.



Dispersion Suppressors

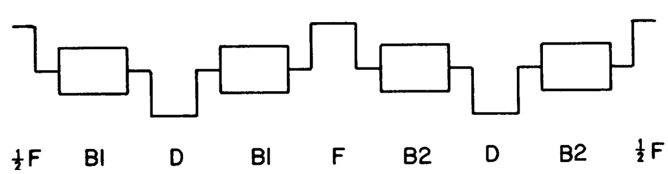
- We demonstrate dispersion matching by introducing dispersion suppressors. Techniques to match to finite dispersion are similar.
- A FODO cell has dispersion given by

$$\eta_{Qf} = \frac{L\theta}{4} \frac{1+\frac{1}{2}\sin\left(\frac{\mu}{2}\right)}{\sin\left(\frac{\mu}{2}\right)^2}$$

θ = bending angle of cell

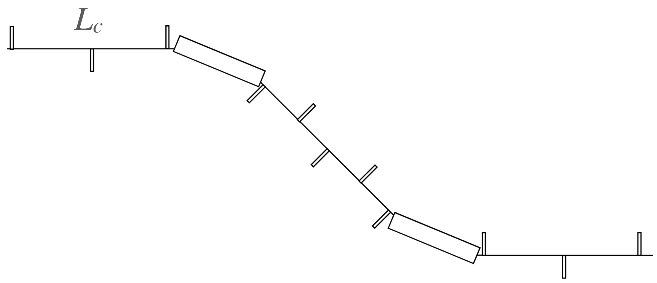
- It can be shown that such a cell transforms 0 dispersion to twice its matched value.
  - a cell with half bending angle can match dispersion to 0 (!)
- In more detail:

$$\theta_1 = \theta_D\left(1-\frac{1}{4\sin\left(\frac{\mu}{2}\right)^2}\right),\ \theta_2 = \theta_D\left(\frac{1}{4\sin\left(\frac{\mu}{2}\right)^2}\right)$$



A Dispersion-Matched DogLeg

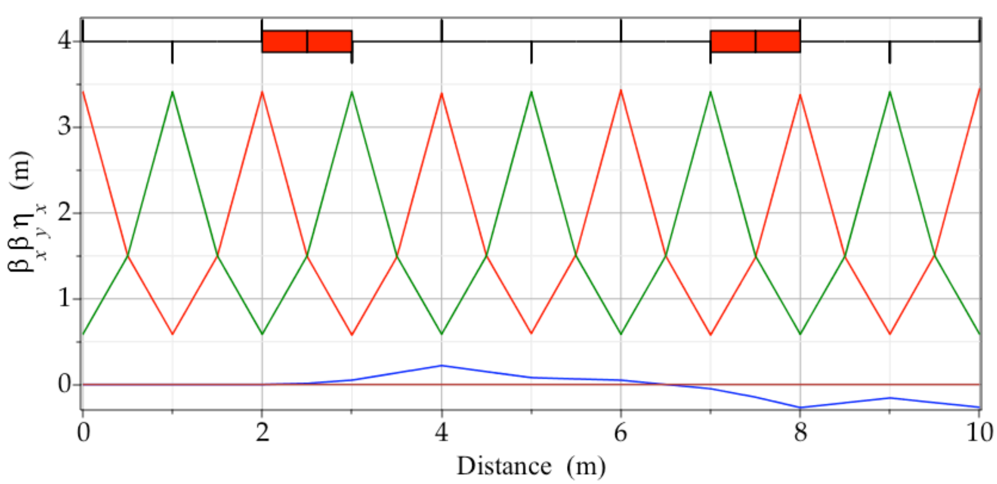
- Consider a (horizontal) offset in the geometry of a beam line
- without the optics: large dispersion at end.
  - roughly $\theta * 2.5 * L_c$
  - How can optics make this 0 to 1st order ??



- A 180° section in between the dipoles should flip dispersion in sign
  - the 2nd dipole then makes it 0.
  - by symmetry dispersion should be 0 at the center but *not* the slope of dispersion, which is <0!
  - This works when d' = 0 only!

Thin-Quad Model of DogLeg

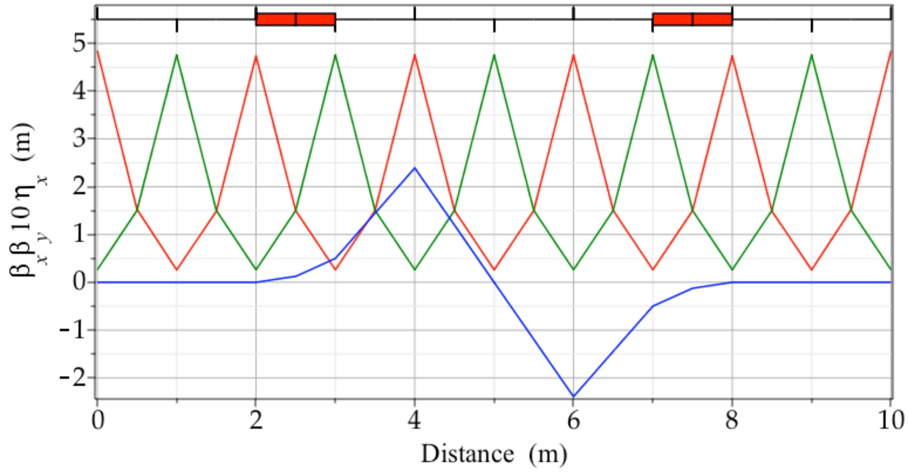
- One approach is to make the FODO cells 90° & see how far we get with this:
  - for a symmetric (QD = –QF) cell, $kQ = \frac{2\sqrt{2}}{L_c}$
- Result (for θ_{bend} = 0.1 mrad and L_c = 2 m):



- So this did not work

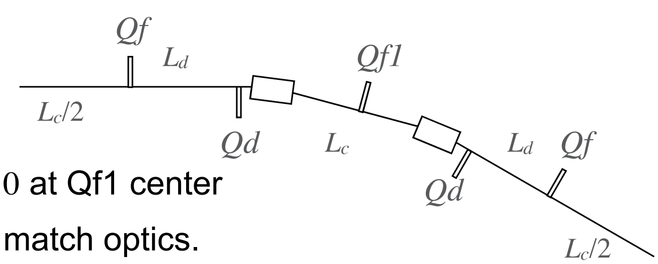
- In this case, it is easy to find an analytic solution to make dispersion 0 at the symmetry point:
- the phase advance/cell is just over 127°.

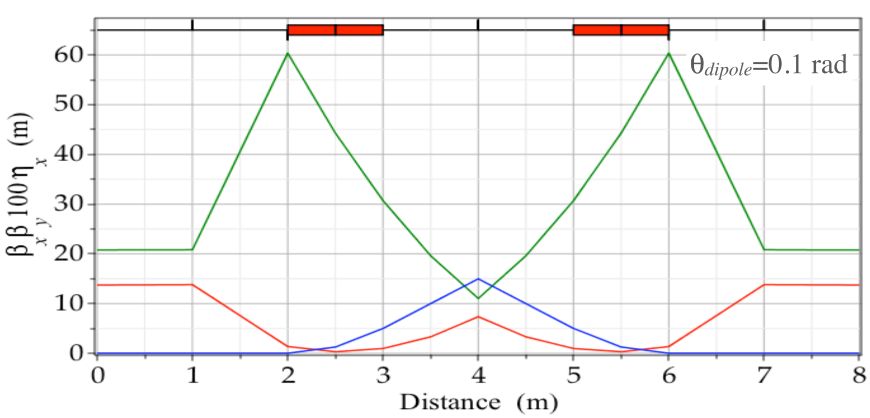
$$kQ = \frac{3.582}{L_c}$$



Bending Section

- For a bending section, achromat cells are a good starting point:
- Example: DBA cell:
  - use Ld=1 m, Lc= 4 m:
  - k_{Qf1} = 1.33 m^{-1} to make η' = 0 at Qf1 center
  - Qf, Qd to adjust focusing & match optics.

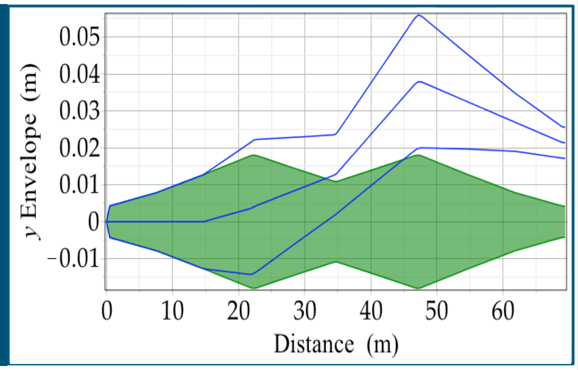




References

- K.L. Brown and R.V. Servranckx, SLAC-PUB-3381, 1984.

Single-turn Injection



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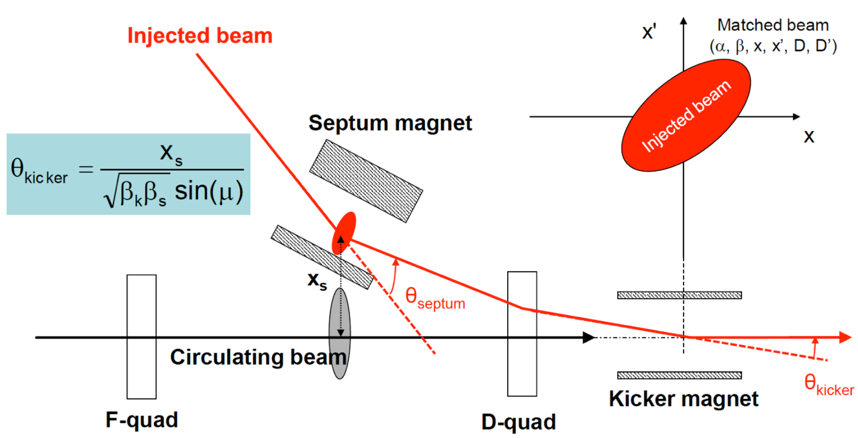
ANL

July 2024
USPAS, Rohnert Park

Fundamental Approach

- Bring incoming beam as close to the closed-orbit as feasible
- Use a time-varying field to deflect incoming bunch onto orbit
  - why a time-varying field??
  - On what time scale?
- Septum magnet is a dipole narrow on the ring side.

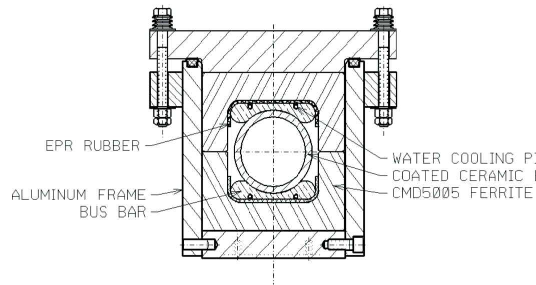
C. Bracco, CERN



"Real-World" Limitations

- Ferrite Kicker Parameters

vertical kicker, H<–>h



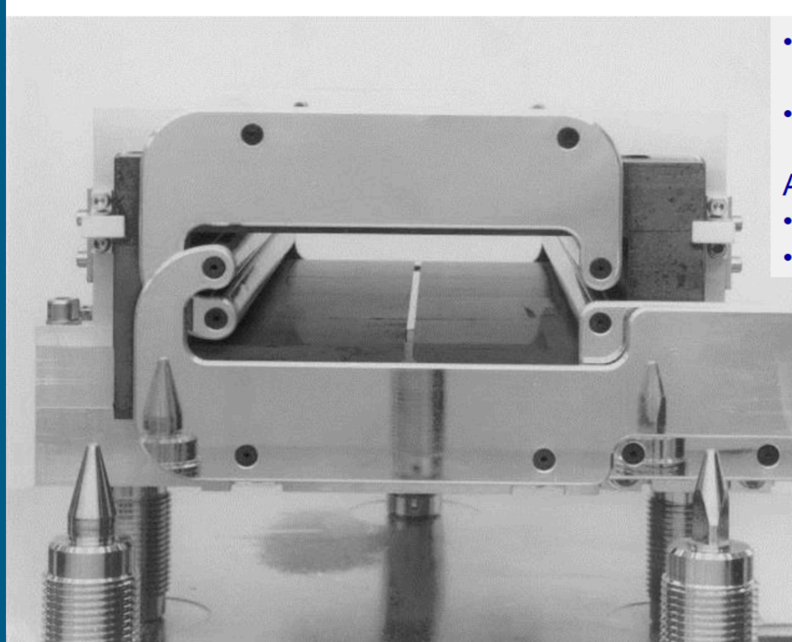
- Field: $$B \approx \mu_0 \frac{N \cdot I}{h}$$
- Inductance $$L \approx \mu_0 \frac{N^2 H}{h} l$$

h: full gap height
H: full gap width
l: length

- It turns out that for any reasonably fast rise/fall time the voltage requirement is prohibitive if $N > 1$
- 10 to 30 kA pulses not uncommon, ≥ 100 ns.

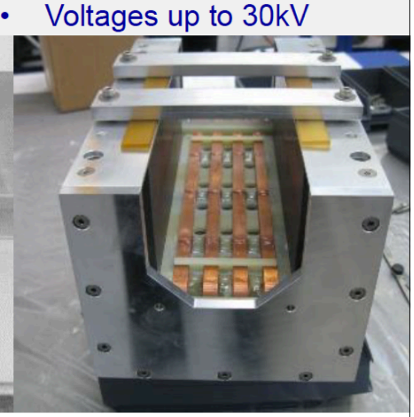
Lumped Inductance Kicker (p)

M. Barnes, CERN



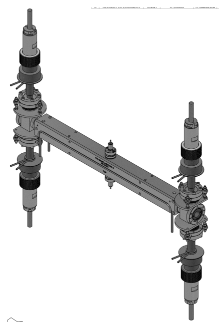
- Used for "slower" systems (typically > ~1μs rise/fall).
- "Simple" and "robust".

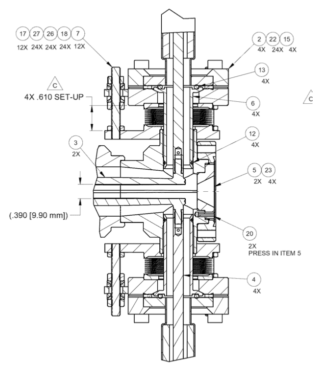
At CERN:
- Currents up to 18.5 kA
- Voltages up to 30kV

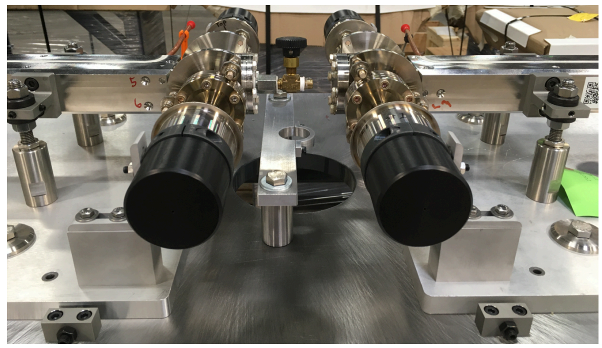


Strip-line kicker (e⁻)

- Fastest kickers use strip-line technology
- e-m wave in *opposite* direction to beam travel
- Weaker kick but can be down to a few ns
- Ex: APS-U injection kicker 27 kV, 0.7 m, 1 mr @ 6 GeV
  - pulsers with ≈ 8.5 ns fwhm.

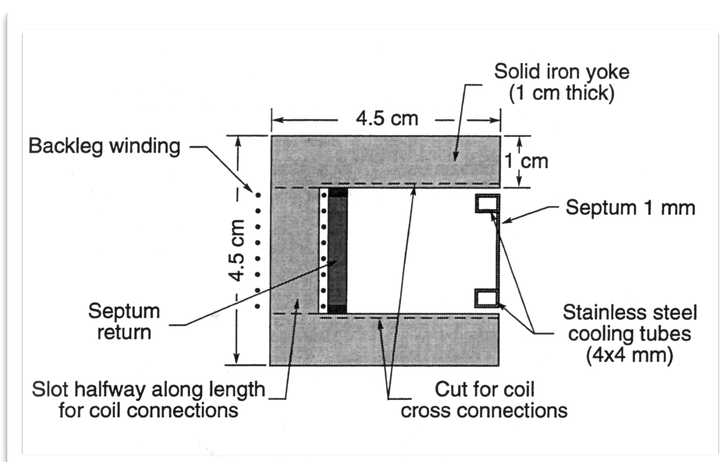






Septum Magnets

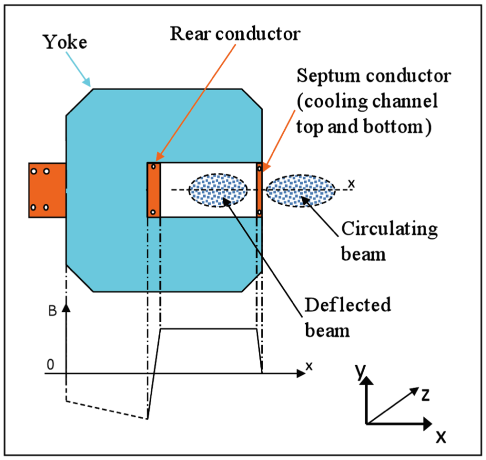
- With the limited kicker angle we only have a small gap between the injecting and circulating beam.
- => use (one or more) septum magnet(s) to line up the incoming beam.

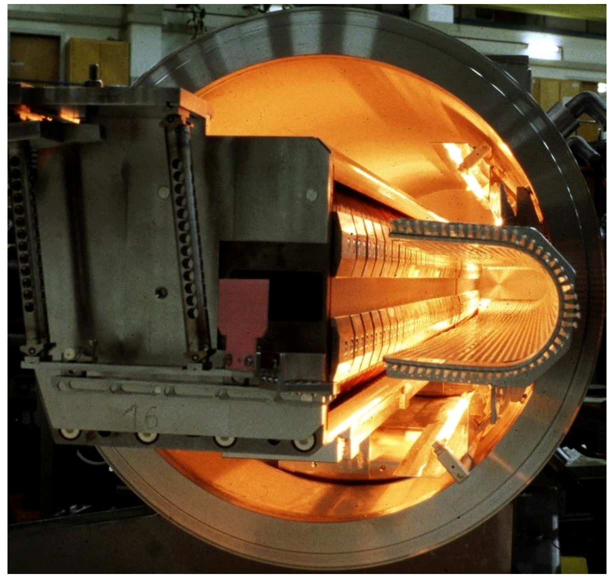


Pulsed Septum Magnet (*p*)

- Pulsing septum reduces power dissipation => higher fields
  - more difficult and expensive.

M. Barnes, CERN

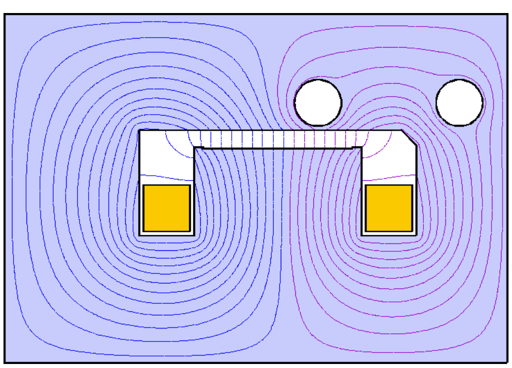


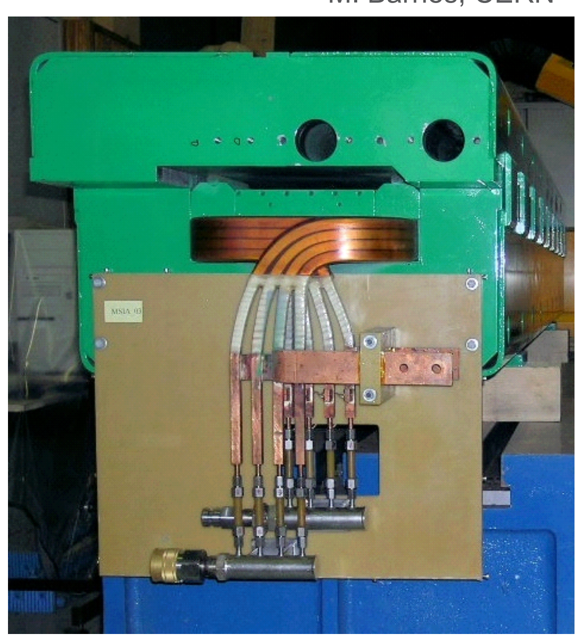


Lambertson Septum (LHC)

- No current sheet near the beams => robust.
- Deflection orthogonal to beam separation.

M. Barnes, CERN





Optimizing a Machine for Injection

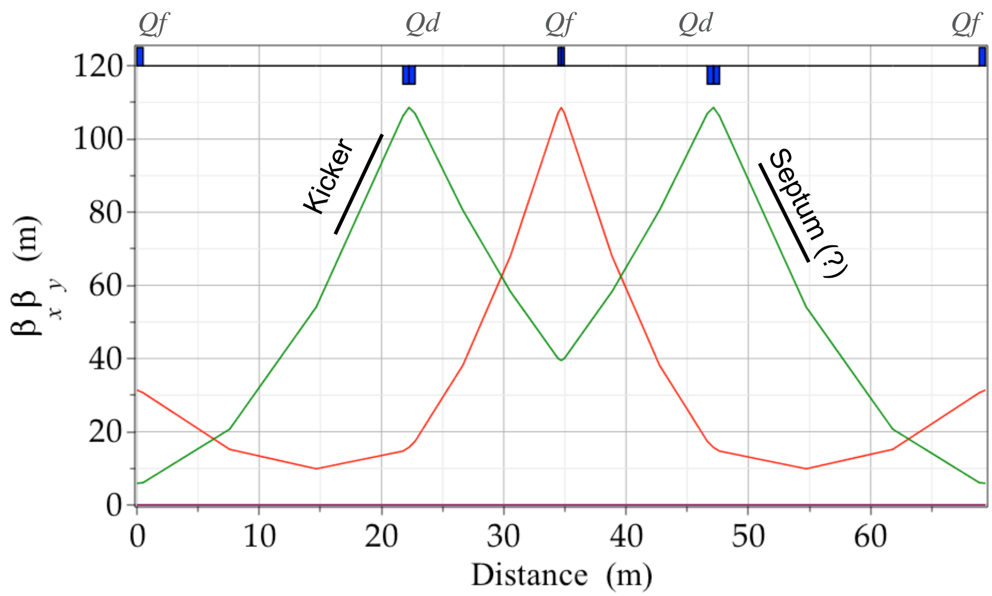
- Want maximum effect from the limited kicker angle: R_{12}
  - kicker @ high β, most parallel beam
- Want maximum clearance for the septum
- Partial transformation through a kicker followed piece of ring:

$$\begin{pmatrix} x \\ xp \end{pmatrix}_2 = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}\left(\sin(\mu_{12})\alpha_1 + \cos(\mu_{12})\right) & \sqrt{\beta_1\beta_2}\sin(\mu) \\ \frac{(-\alpha_1\alpha_2 - 1)\sin(\mu_{12}) + (\alpha_1 - \alpha_2)\cos(\mu_{12})}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}\left(\cos(\mu_{12}) - \alpha_2\sin(\mu_{12})\right) \end{pmatrix} \bullet \begin{pmatrix} x \\ xp + \delta xp \end{pmatrix}_1$$

- => high β at kicker & septum; 90° phase advance
- Insertions help, if the lattice allows it

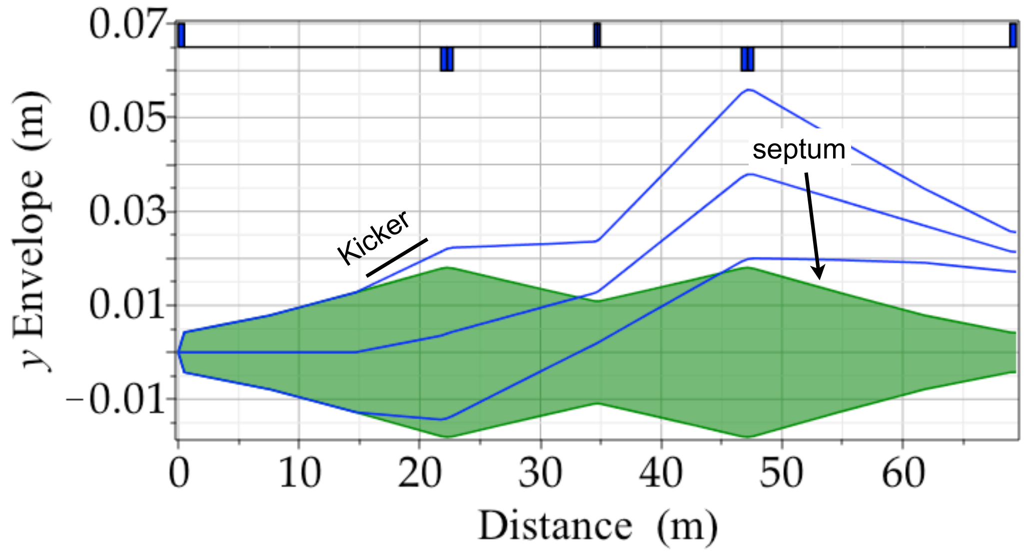
Simple Insertion

- A matched insertion transforming β from its ring value to a higher value
  - typically have η=0 in straight.

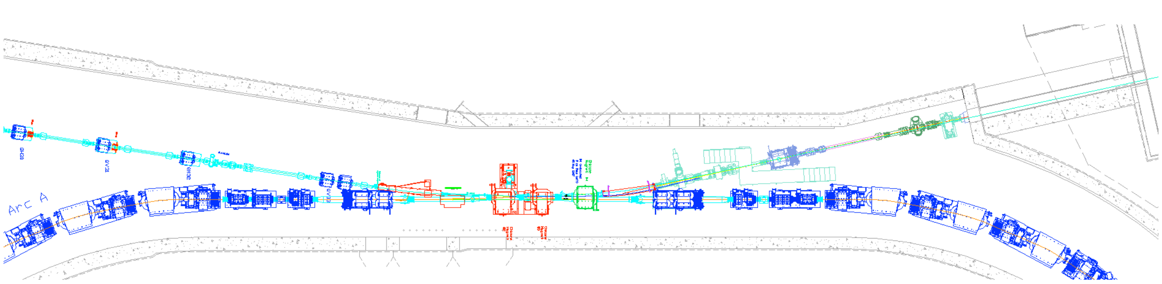


Envelope plot

- It is often better to sacrifice β for phase angle
  - beam envelope shrinks with √β
  - necessary clearance: 3-5 σ for protons, 10 σ or more for electrons.

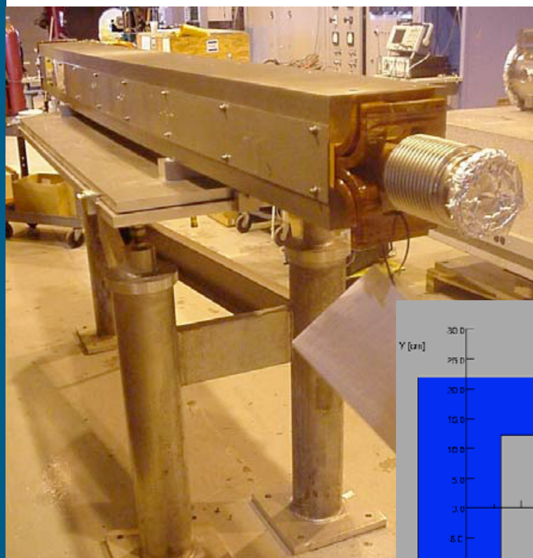


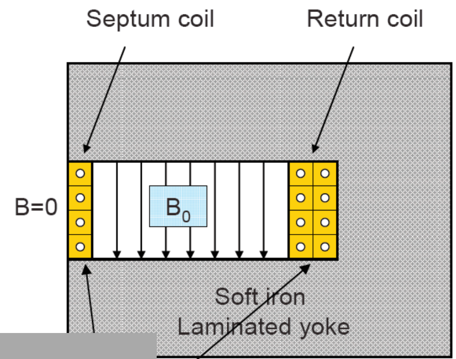
Example: SNS Ring Injection System

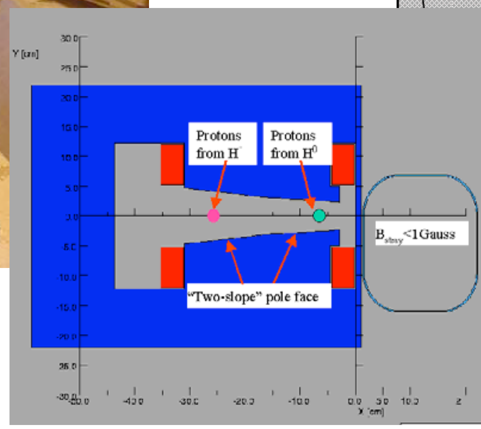


Septum Magnets (SNS)

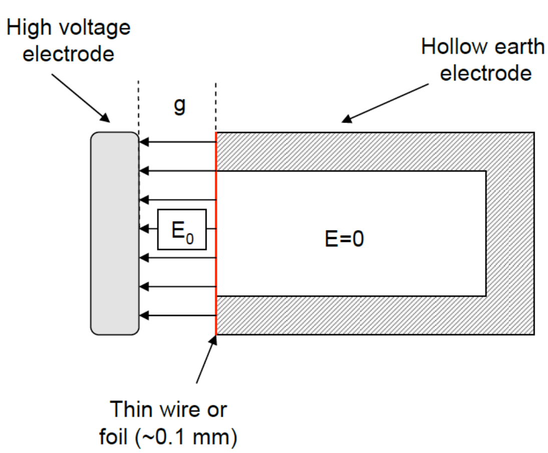
M. Plum, ORNL





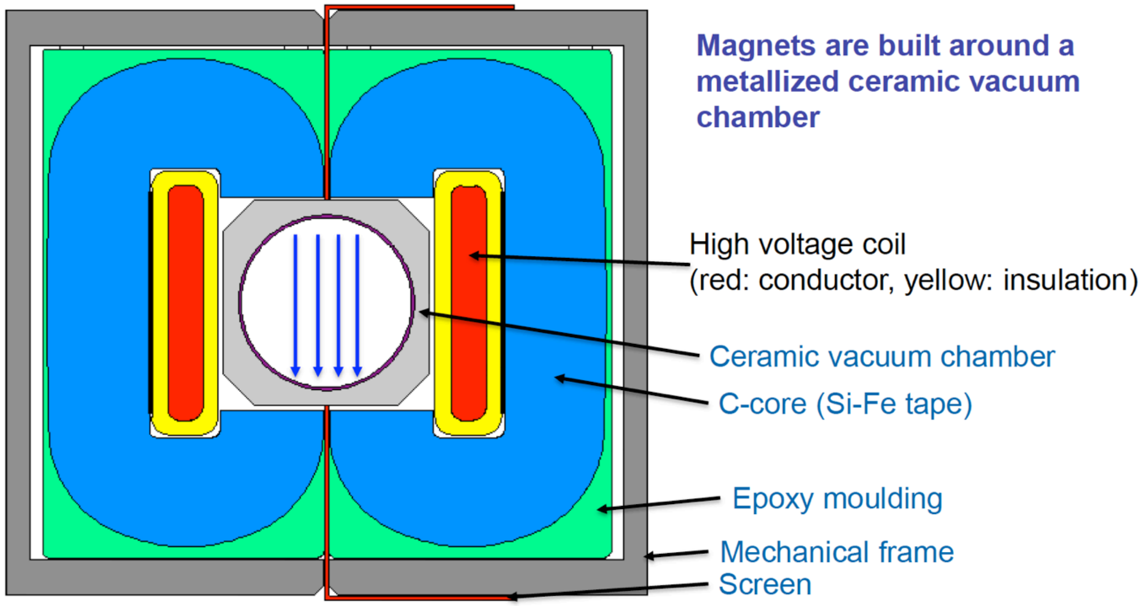


Electrostatic Wire Septum



Kicker Magnet (LHC MKD)

Magnets are built around a metallized ceramic vacuum chamber



Variations on the Theme

- In many cases the kicker angle is limiting
  - Use a slower but stronger closed bump to assist.
- How to make a “closed bump”?
- Use Matrix optics ($\beta_1=\beta_2$):

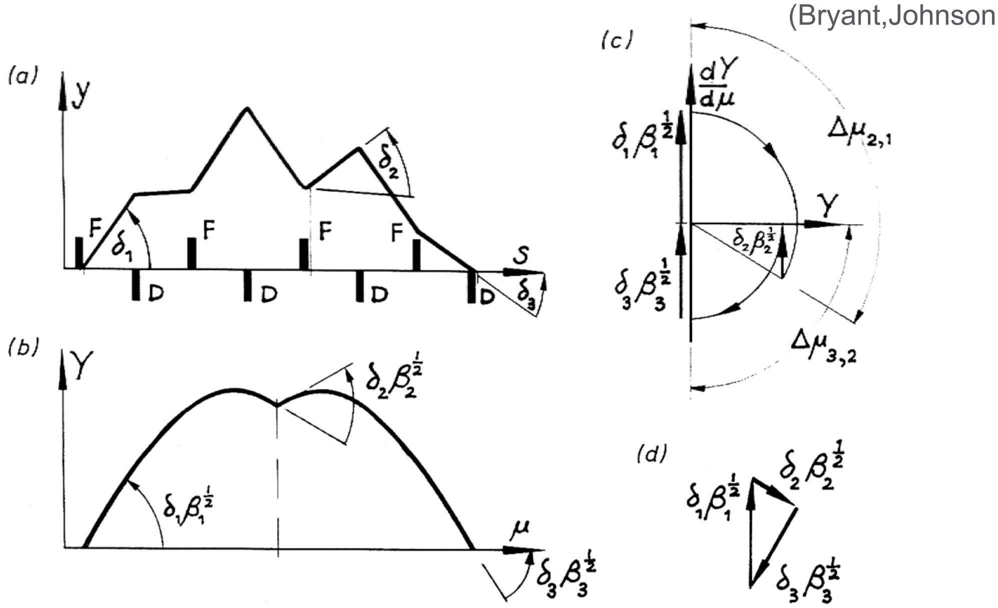
$$\begin{bmatrix} x \\ xp \end{bmatrix}_2 + \begin{bmatrix} 0 \\ \delta xp_2 \end{bmatrix} = \begin{bmatrix} \sin(\mu)\alpha(0)+\cos(\mu) & \beta(0)\sin(\mu) \\ \left(-\frac{\alpha(0)^2}{\beta(0)}-\frac{1}{\beta(0)}\right)\sin(\mu) & -\sin(\mu)\alpha(0)+\cos(\mu) \end{bmatrix} \circ \left(\begin{bmatrix} 0 \\ \delta xp_1 \end{bmatrix} + \begin{bmatrix} x \\ xp \end{bmatrix} \right)$$

- (if β or α are unequal, need to use the full matrix from the “Basics” talk, slide 8 in the book)
- need $[x,xp]_2$ to be equal to $[0,0]$ (for $[x,xp]_2=[0,0]$) to close the bump

Three-Bump

- 3-Bump allows freedom in phase advance.

(Bryant,Johnson)



Specific Injection Issues for Accelerators

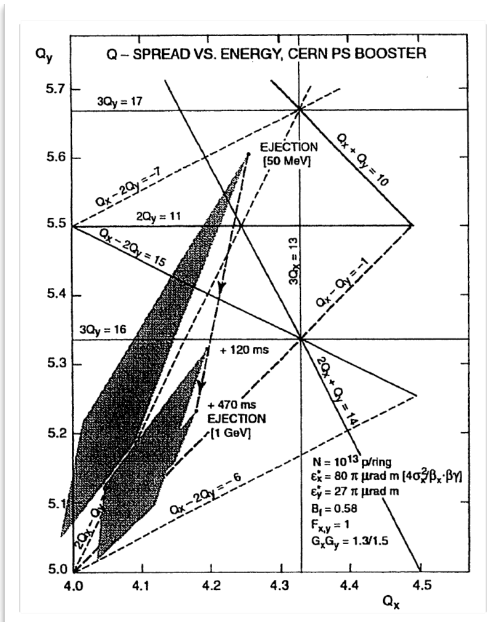
- Beams are larger in size
  - geometric emittance is $\propto 1/\gamma$
- Space-charge forces are stronger (esp. for hadrons)
  - biggest effect is tune spread covering larger part of working area.
  - tune spread can lead to distorted distributions: mismatch
  - sign is usually reduced injection efficiency
  - effect is difficult to assess => tracking needed
- Beam loss at beginning of acceleration
  - longitudinal acceptance shrinks, sometimes dramatically.
- Transient beam loading causes longitudinal mismatch
  - Rf voltage changes upon a slug of beam entering machine.

Space Charge

- Non-relativistic charges repel each other
  - a defocusing force, reduces betatron tune

$$\delta Q_{sc} = -\frac{R^2 n_0 r_0}{2Q\beta^2\gamma^3\sigma^2 l_b}$$

  - amplitude-dependent
    => becomes a tune spread
  - also can modulate the Twiss functions:
    => amplitude-dependent mismatch
- Mitigation:
  - better correction may help
  - increase injection energy

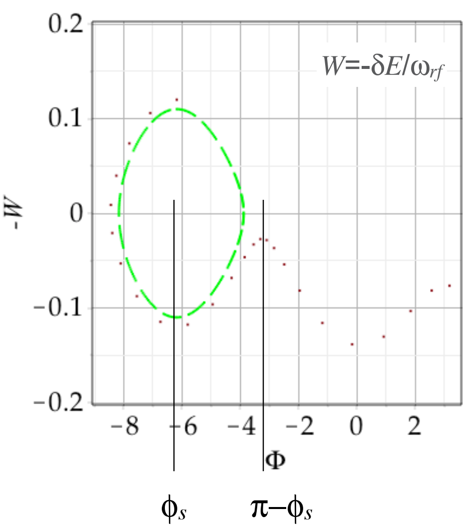


Rf Acceptance

- longitudinal match similar to transverse match
  - bucket height (max. $\delta E/E$):

$$\frac{\delta E}{E} < \frac{\beta\sqrt{V\cdot q}}{\sqrt{\pi h E_s \eta}}\sqrt{-(\pi-2\phi_s)\sin(\phi_s)+2\cos(\phi_s)}$$

  - bucket length: no closed soln; fixed points are ϕ_s and $\pi-\phi_s$, “left side” found numerically.

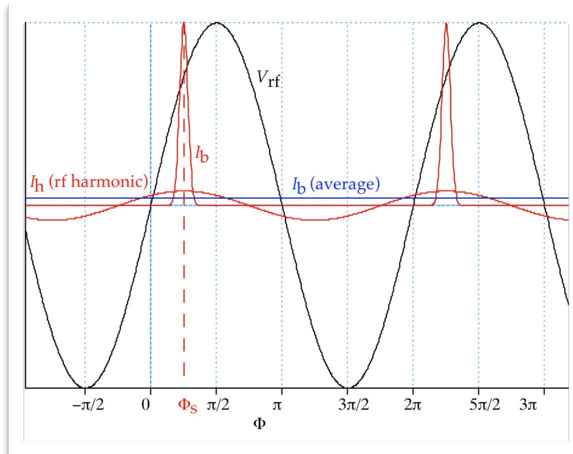


Transient Beam Loading

- Beam current induces voltage in cavity
  - > not in phase with rf voltage

$$V_b = \frac{2 i_b R_s \cos(\Psi)\, e^{\frac{I}{2}(\pi - 2\Phi_s + 2\Psi)}}{1+\beta}$$

  - ψ: detuning angle
    β: coupling factor
    ϕ_s: synchronous angle
    R_s: shunt resistance
    i_b: beam current
- The sum voltage is different in magnitude and phase
- compensate by feed-forward



Steering Error (Offset)

(see V. Kain, CERN lectures)

- Work in normalized coordinates

$$q_{new} := q_0 + \delta \cos(\theta)$$

$$p_{new} := p_0 + \delta \sin(\theta)$$

$$J := \frac{1}{2}\bar{p}^2 + \frac{1}{2}\bar{q}^2$$

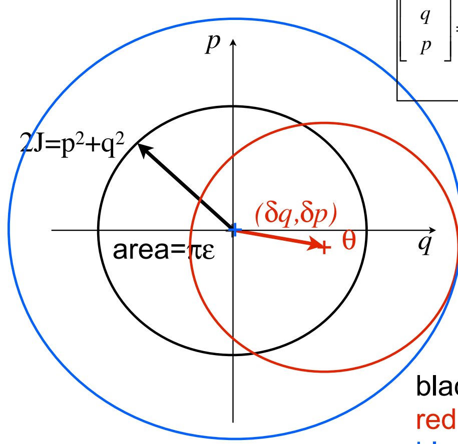
$$J = \frac{1}{2}\delta^2 + \left(\sout{p_0 \sin(\theta) + q_0 \cos(\theta)}\right)\delta$$

=0 on average

$$+\frac{1}{2}p_0^2 + \frac{1}{2}q_0^2$$

$$= \varepsilon_0 + \frac{1}{2}\delta^2$$

$$\begin{bmatrix} q \\ p \end{bmatrix} = \begin{bmatrix} \frac{x}{\sqrt{\beta(s)}} \\ \frac{\alpha(s)x}{\sqrt{\beta(s)}} + \sqrt{\beta(s)}xp \end{bmatrix}$$



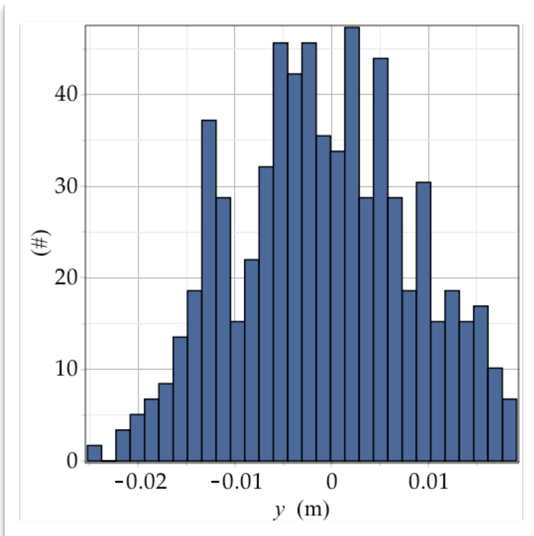
black: ring
red: injected
blue: ring, enlarged

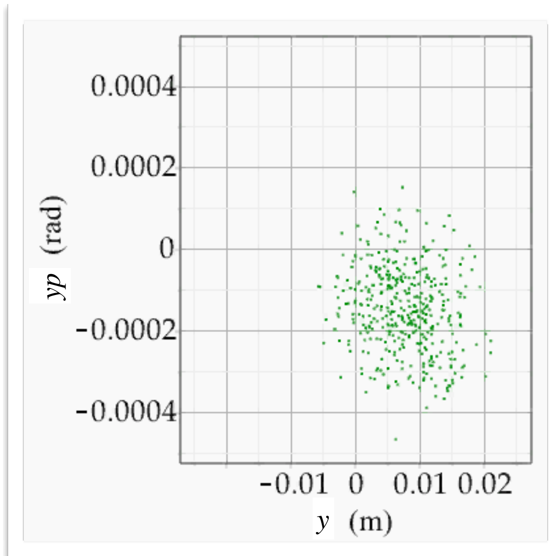
$$\delta^2 = \frac{1}{2}\left(\frac{\alpha\delta_x}{\sqrt{\beta}} + \sqrt{\beta}\delta_{xp}\right)^2 + \frac{1}{2}\frac{\delta_x^2}{\beta}$$

$$\frac{\varepsilon_{new}}{\varepsilon_0} := 1 + \frac{1}{2}\frac{\delta_x^2 + \left(\alpha\delta_x + \beta\delta_{xp}\right)^2}{\beta\varepsilon_0}$$

small β: sensitive to x
large β: sensitive to xp

Injection Offset





Phase-Space Mismatch

- Ring: $\alpha_1,\beta_1,\gamma_1$
- injected: $\alpha_2,\beta_2,\gamma_2$
- start from betatron oscillation:

$$x_2 = \sqrt{2\beta_2 J_2}\cos(\phi)$$

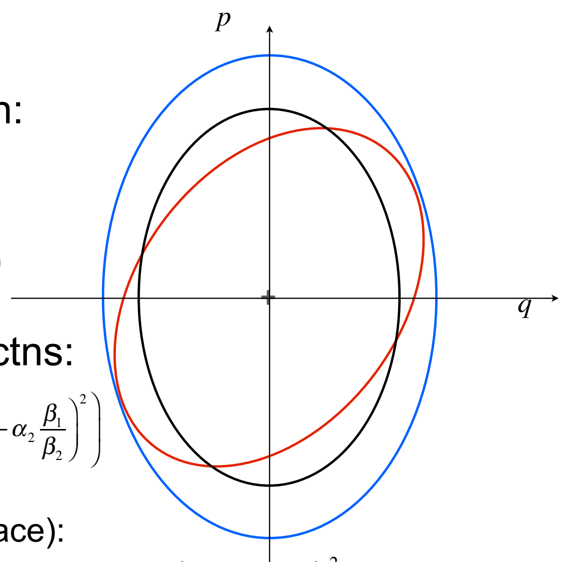
$$xp_2 = -\sqrt{\frac{2J_2}{b_2}}\left(\sin(\phi)+\alpha_2\cos(\phi)\right)$$

- normalize using *ring* Twiss fctns:

$$J_x = \bar{q}_2^2\left(\frac{\beta_1}{\beta_2}+\frac{\beta_2}{\beta_1}\left(\alpha_1-\alpha_2\frac{\beta_1}{\beta_2}\right)^2\right)+\bar{p}_2^2\frac{\beta_2}{\beta_1}-2\bar{q}_2\bar{p}_2\left(\frac{\beta_2}{\beta_1}\left(\alpha_1-\alpha_2\frac{\beta_1}{\beta_2}\right)^2\right)$$

  – new “Twiss functions” (in q-p space):

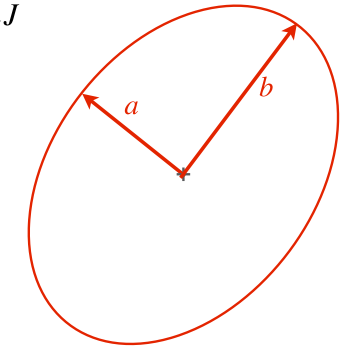
$$\alpha_{new} = -\frac{\beta_2}{\beta_1}\left(\alpha_1-\alpha_2\frac{\beta_1}{\beta_2}\right), \quad \beta_{new} = \frac{\beta_2}{\beta_1}, \quad \gamma_{new} = \frac{\beta_1}{\beta_2}+\frac{\beta_2}{\beta_1}\left(\alpha_1-\alpha_2\frac{\beta_1}{\beta_2}\right)^2$$



- Define H such that

$$a=\frac{A}{\sqrt{2}}\left(\sqrt{H+1}+\sqrt{H-1}\right),\ \ b=\frac{A}{\sqrt{2}}\left(\sqrt{H+1}-\sqrt{H-1}\right),\ \ A=\sqrt{2J}$$

$$H=\frac{1}{2}\left(\gamma_{new}+\beta_{new}\right)=\frac{1}{2}\left(\frac{\beta_1}{\beta_2}+\frac{\beta_2}{\beta_1}+\frac{\beta_2}{\beta_1}\left(\alpha_1-\alpha_2\frac{\beta_1}{\beta_2}\right)^2\right)$$



- Then define λ

$$\lambda=\frac{1}{\sqrt{2}}\left(\sqrt{H+1}+\sqrt{H-1}\right),\ \ \frac{1}{\lambda}=\frac{1}{\sqrt{2}}\left(\sqrt{H+1}-\sqrt{H-1}\right)$$

- and get

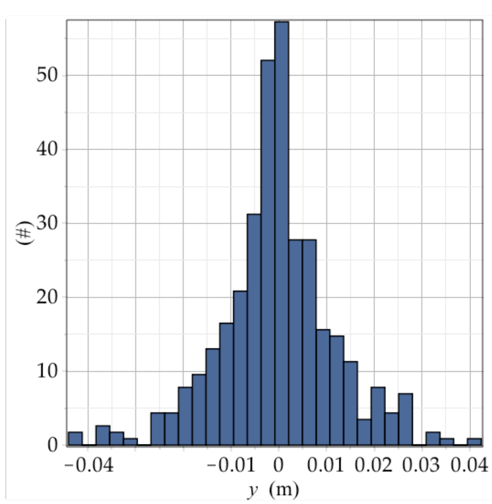
$$x_{new}=\lambda\cdot A\sin\left(\phi+\phi_1\right),\ \ xp_{new}=\frac{1}{\lambda}\cdot A\cos\left(\phi+\phi_1\right)$$

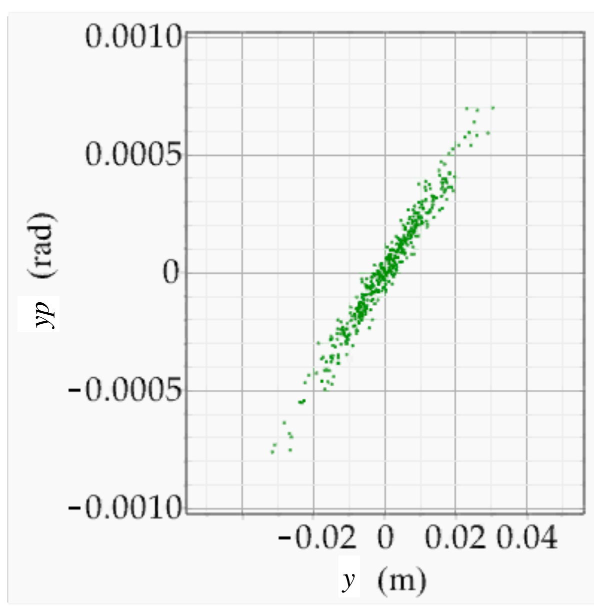
- and finally

$$\varepsilon_{new}=\frac{1}{2}\varepsilon_0\left(\lambda^2+\frac{1}{\lambda^2}\right)=\frac{1}{2}\varepsilon_0\left(\frac{\beta_1}{\beta_2}+\frac{\beta_2}{\beta_1}+\frac{\beta_2}{\beta_1}\left(\alpha_1-\alpha_2\frac{\beta_1}{\beta_2}\right)^2\right)$$

Matching issues

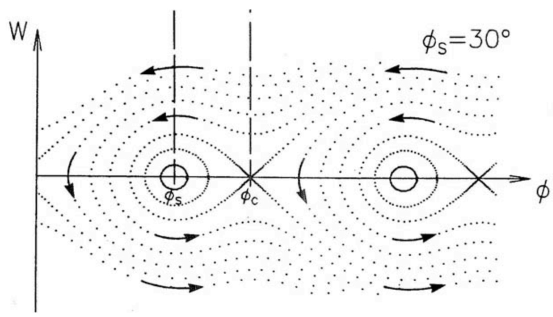
- Here is what happens when we inject a mismatched beam into a machine with some nonlinearity:





Longitudinal Plane

- The same matching issues exist in the longitudinal plane:
  - position –> phase (=time)
  - angle –> energy (=dϕ/dt)



- If rf frequencies are the same or a multiple of each other; phase the systems wrt. each other.
- Bunch aspect ratio should match bucket aspect ratio
  - this can be tricky for injection from a linac

Longitudinal Matching

- Usually, the injectee ring is larger than the injector ring.
  - It is also not uncommon that f_{rf}(injectee) ≠ f_{rf}(injector)
- Match the aspect ratio of bunch & bucket to prevent emittance growth.
- Since the bunch usually only fills the linear part of the bucket, his can be done analytically:
  - from the solution to the small-amplitude motion we define the aspect ratio as the ratio of the extreme energy and phase deviations:

$$A = \frac{\widehat{W}}{\hat{\phi}} = \frac{1}{2}\frac{\sqrt{2}\sqrt{\omega_{rev}}\beta\sqrt{E_s}\sqrt{q}\sqrt{V}\sqrt{\cos(\Phi_s)}}{\omega_{rf}^{(3/2)}\sqrt{\eta}\sqrt{\pi}}$$

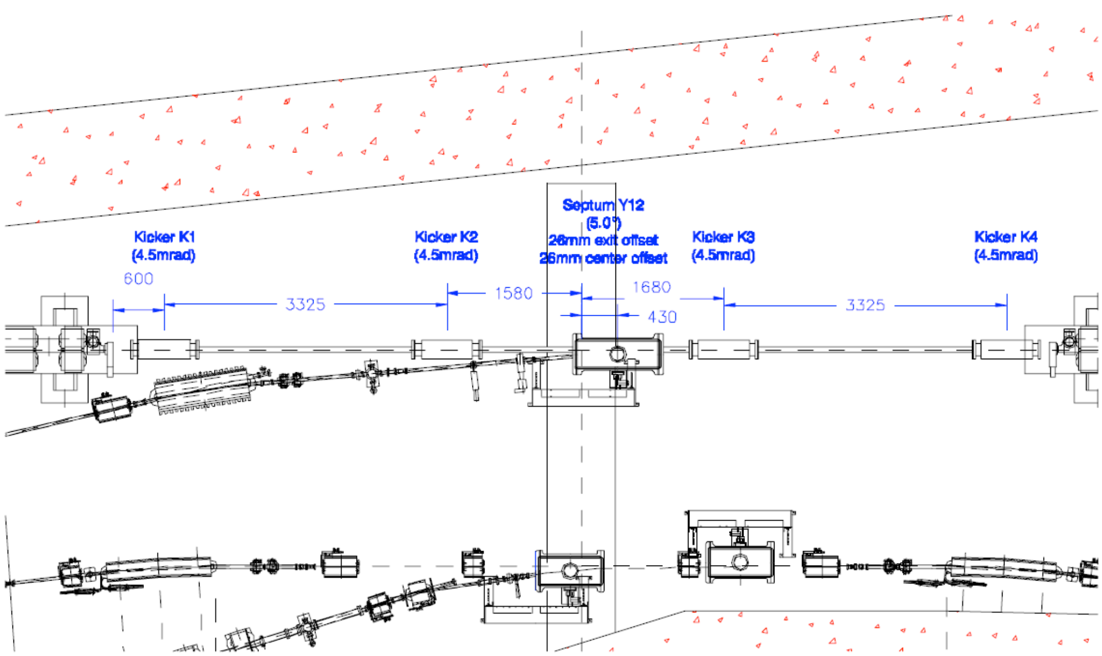
- We can now find the ratio for two different rings (1 and 2) of the aspect ratios, for the same rf frequency in both rings:

$$\frac{A_2}{A_1} = \frac{\sqrt{\omega_{rev2}}\sqrt{V_2}\sqrt{\eta_1}}{\sqrt{\eta_2}\sqrt{\omega_{rev1}}\sqrt{V_1}}$$

ω_{rev}: revolution frequency
η: slip factor
V; rf voltage

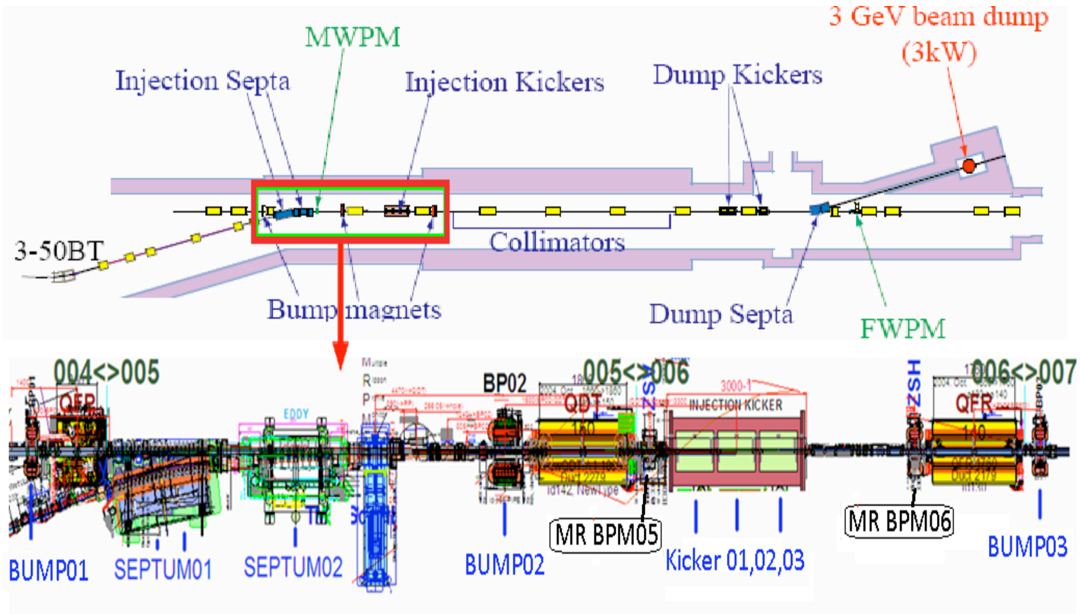
- unless one or both rings are close to transition, or one or both rings have lattice that manipulate the transition energy, this ratio is near unity for equal rf voltages.
  – since then $\eta \approx 1/\gamma_t^2 = \alpha_p \approx 1/\nu_x^2 \approx 1/R$
- If the frequencies differ, the frequency ratio becomes another parameter in the equation.

SLS Injection Section

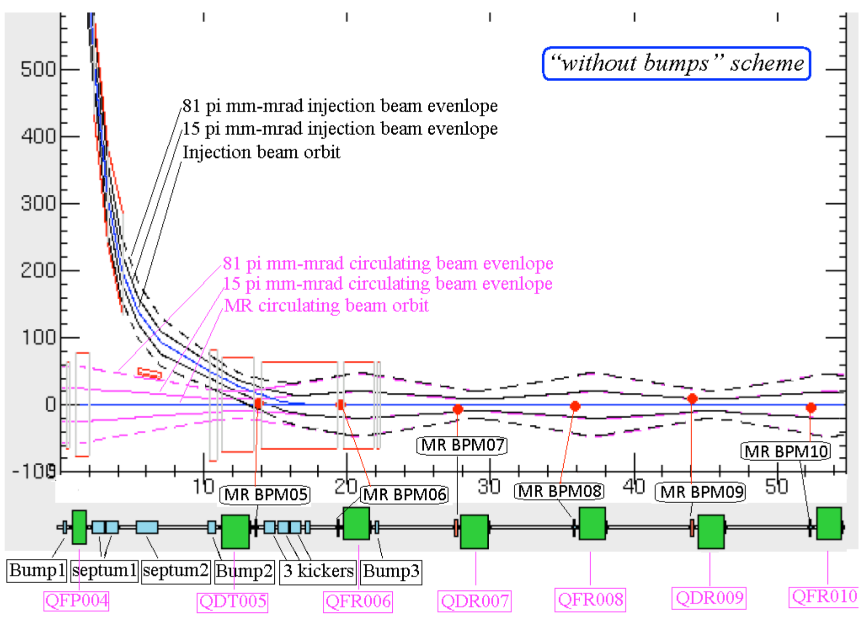


Some *real-life* Injection Systems

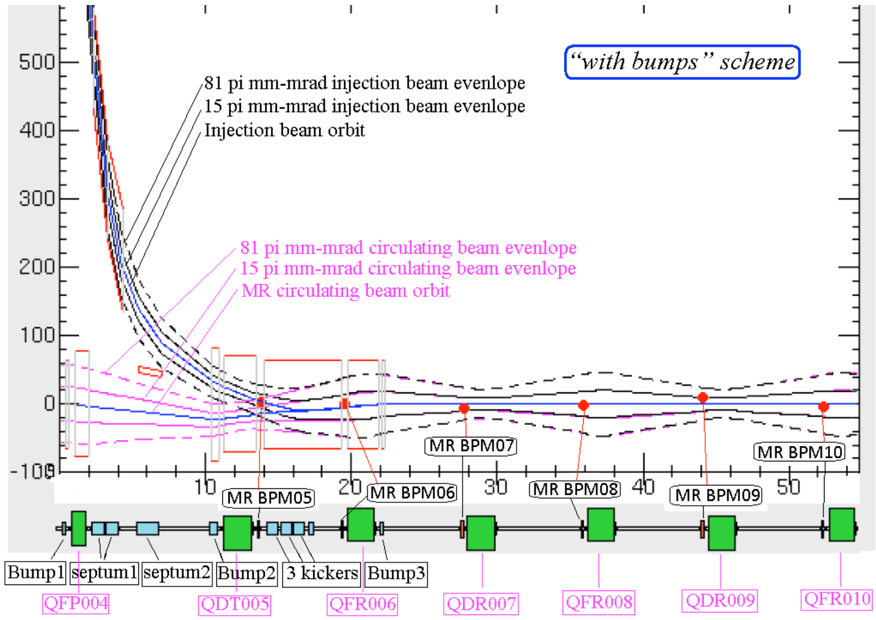
- JPARC Main ring (3 GeV protons -> 50 GeV)



- Only fast kicker, no slow bumps used



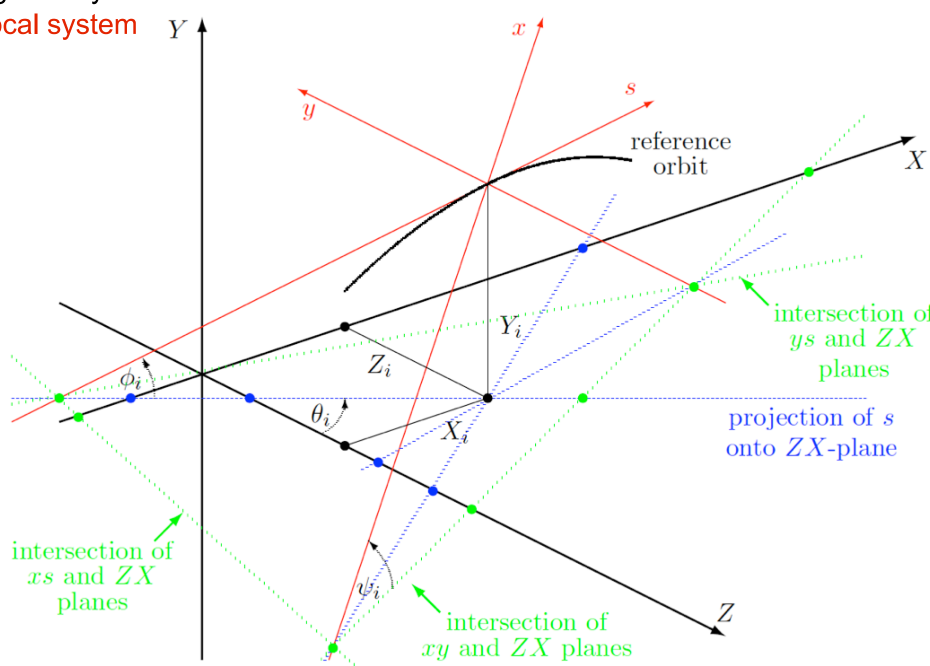
- Slow bumps make room for low-energy circulating beam
  - during acceleration the beam shrinks -> bump is collapsed)



Local & Global Coordinate System

X,Y,Z: global system

x,y,s: local system



Local-Global Transformations

- At each point, the displacement of the ref. orbit is given by a vector V and a matrix W:

$$V = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \qquad W = \Theta \quad \Phi \quad \Psi$$

$$\Theta = \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}, \quad \Phi = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}, \quad \Psi = \begin{pmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- θ, ϕ and ψ are often called "pitch, yaw and roll"
- Roll will lead to coupling that needs to be compensated for a complete match
  - operationally difficult: best to avoid in final matching section
  - Mad-X SROTATION handles beam matrix properly.

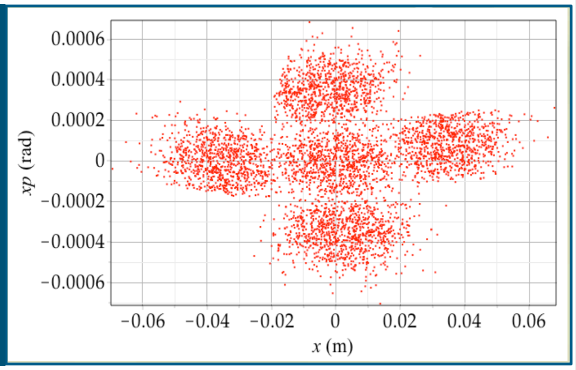
Some Practical Considerations

- "Treaty Point": hand-off from the beam-line designer to the machine designer.
  - often a symmetry point in the ring, or the downstream end of the injection septum.
- Coordinate matching:
  - Programs like Mad allow arbitrary starting point.
  - Difficulty: if injection line and ring are not in the same plane.

References

- USPAS Course Materials, “Injection and Extraction of Beams” by Michael Plum and H.-Ulrich (Uli) Wienands, Nashville, Jun-2009.
- B. Goddard, “Overview of Injection & Extraction Techniques” in CERN Accelerator School on Beam Injection, Extraction and Transfer, Erice, IT, Mar-2017, https://indico.cern.ch/event/451905/timetable/
- C. Bracco, “Injection: Hadron Beams”, ibid.
- M. Barnes, “Kicker Magnets”, ibid.
- V. Kain, “Emittance Preservation”, ibid.
- P.J. Bryant and K. Johnsen, “The Principles of Circular Accelerators and Storage Rings”, Cambridge University Press, U.K., 1993.
- M. Tomizawa et al., “Injection and Extraction Orbit of the J-PARC Main Ring”, Proc. EPAC2006 Edinburgh, GB, 1987.
- The MAD-X Program User’s Reference Manual, CERN May-2017.

Multi-turn Injection



U. WIENANDS, J. CALVEY, O. MOHSEN
ANL

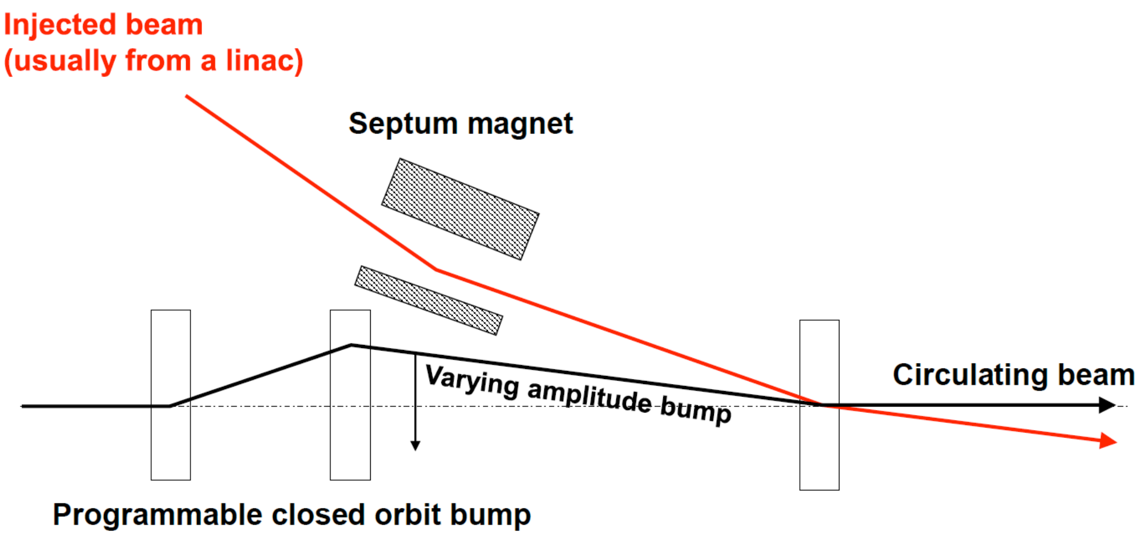
July 2024
USPAS, Rohnert Park

Why and when Multi-turn Injection?

- Injector is short
  - Inject subsequent bunches, box-car fashion
  - mostly an issue of kicker rise/fall times.
- Injector does not have enough intensity
  - accumulate more particles
  - How to do that?
    - Liouville limits what can be done, no "merging" of phase space!
    - new beam has to occupy different region in phase space, longitudinal or transverse (transverse stacking, slip-stacking)
    - Charge-exchange injection is one way around this (common for protons)
    - Damping makes this easy for electrons

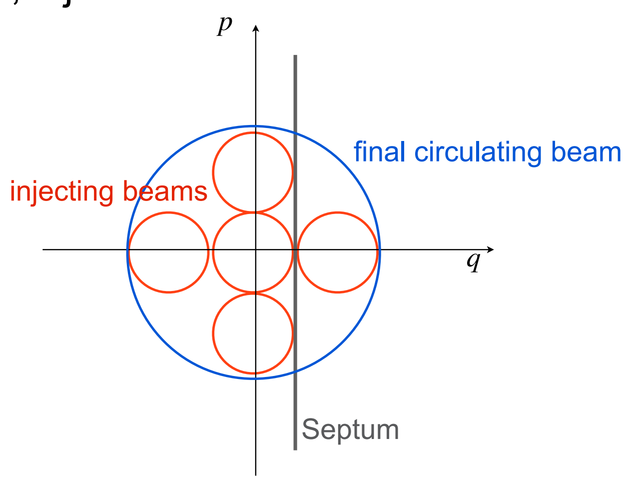
Transverse Multi-turn Injection

- Simplest implementation (CERN PS Booster)



Basic Scheme

- Inject off axis, let betatron oscillation pull the injected beam off the septum
- The simplest case: Q = 0.25, inject centered beam and 4 turns around it.
- For simplicity assume $\beta_1 = \beta_2$ and $\alpha = 0$, angle offset $= 0$
  - usually the case.



Analysis of 5-turn injection

- Assume Gaussian beam:

$$I(x) = \frac{I_0}{2}\frac{\sqrt{2}e^{-\frac{1}{2}\frac{(x)^2}{\sigma^2}}}{\sigma\sqrt{\pi}}$$

this is the spatial distribution

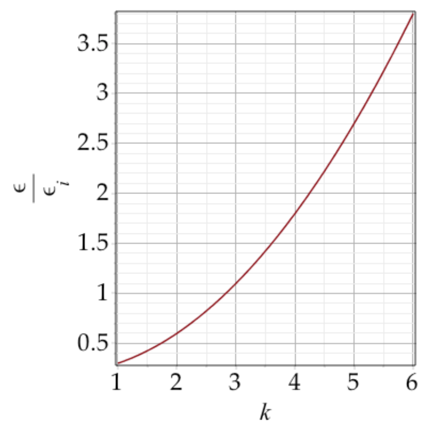
- cutting off at $k\sigma/2$ due to the septum:

$$\frac{I}{I_0} = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{1}{4}k\sqrt{2}\right)$$

- We can write the final emittance using the formula from the previous lecture:

$$\frac{\varepsilon}{\varepsilon_i} = 1 + \frac{1}{2}\frac{\delta_x^{\ 2}}{\beta\varepsilon_i} = 1 + \frac{1}{2}k^2$$

$\alpha = 0$, $\delta xp = 0$ and $\delta x = k\sigma_x$



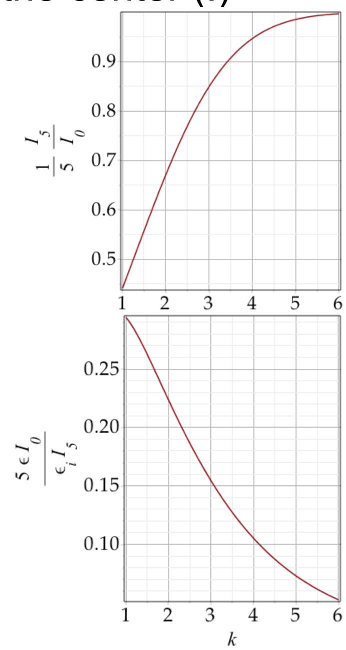
Injection Efficiency

- We lose a fraction x each time the beam passes the septum
  - but not if it is “on the other side”!

turn	C	1	2	3	4
0	1				
1	(1-x)	(1-x)			
2	(1-x)	(1-x)	(1-x)		
3	(1-x)	1	(1-x)	(1-x)	
4	(1-x)	(1-x)	1	(1-x)	(1-x)
Total	$(1-x)^4$	$(1-x)^3$	$(1-x)^2$	$(1-x)^2$	(1-x)

- The total beam loss involves 4 time scraping the injecting beam & 4 times the circulating beam at the center (!)

$$\frac{I_5}{5 \cdot I_0} = \left(1 - \frac{I}{I_0}\right)^{4*2}$$

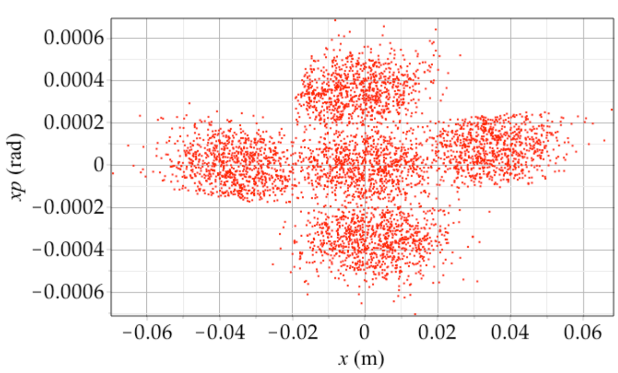


- Often beam, brightness (int/emittance) is what counts

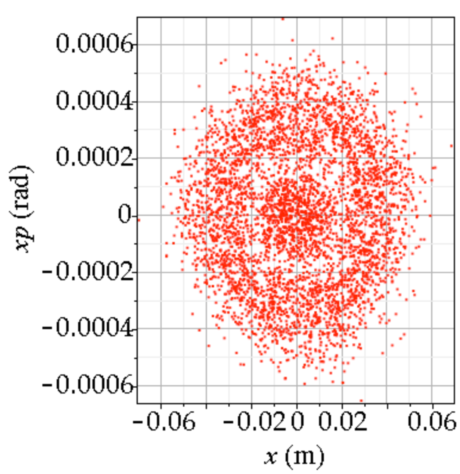
- beam loss has a knee near $k = 3.5$;
  - ≈ 90% efficiency
  - brightness favors $k \approx 1$ but >50% loss ☹

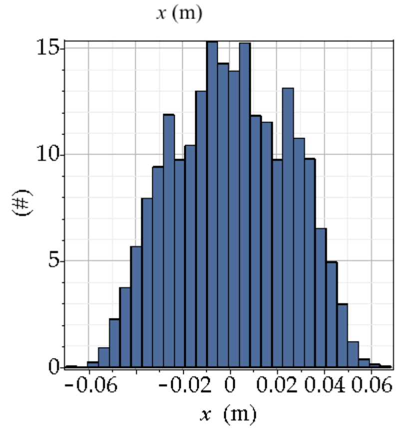
Result of a tracking run

Turn 5



Turn 2000





Histogram of x turn 2000

emittance growth 1.25 (rms)
to 1.5 (FWHM)

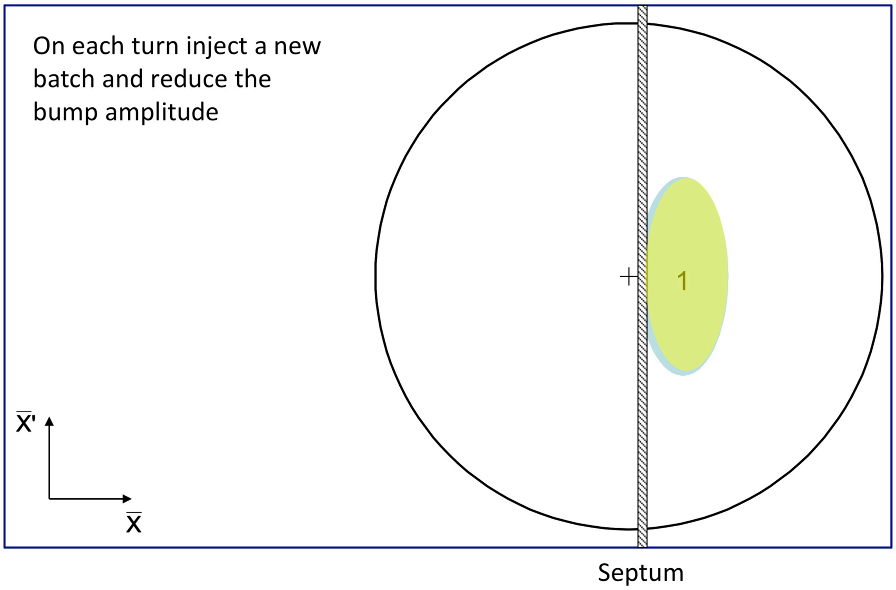
Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$

Beam rotates π/2 per turn in phase space

C. Bracco

Turn 1



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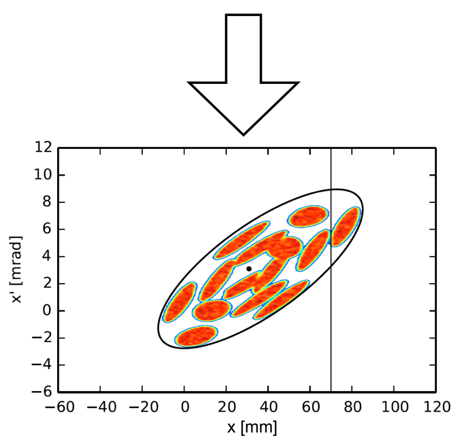
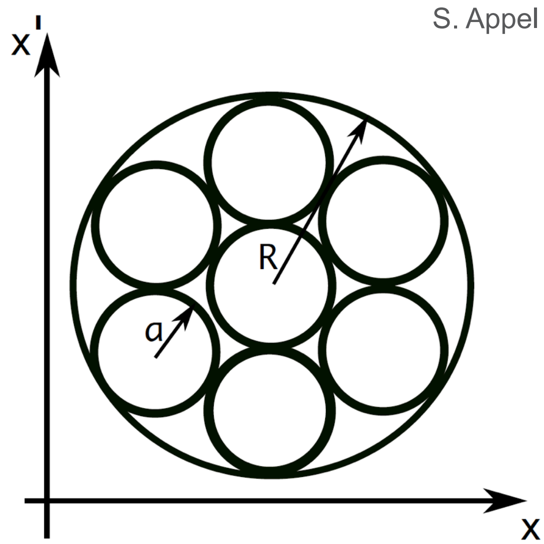
SIS 18 Injection (GSI)

- Hexagonal dense packing of 7 beam-pulses
  - tune = 1/6; match as on-axis
- Optimization using g.a.



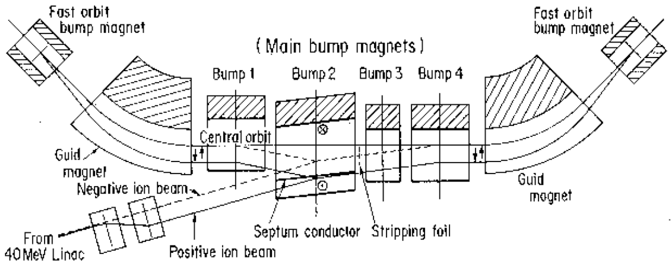
S. Appel



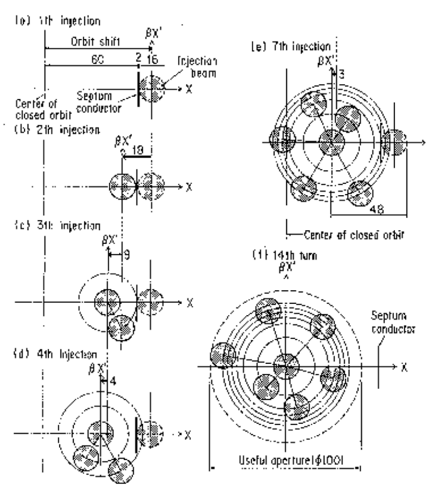
Requires relatively large gaps to make work

KEK PS Injection

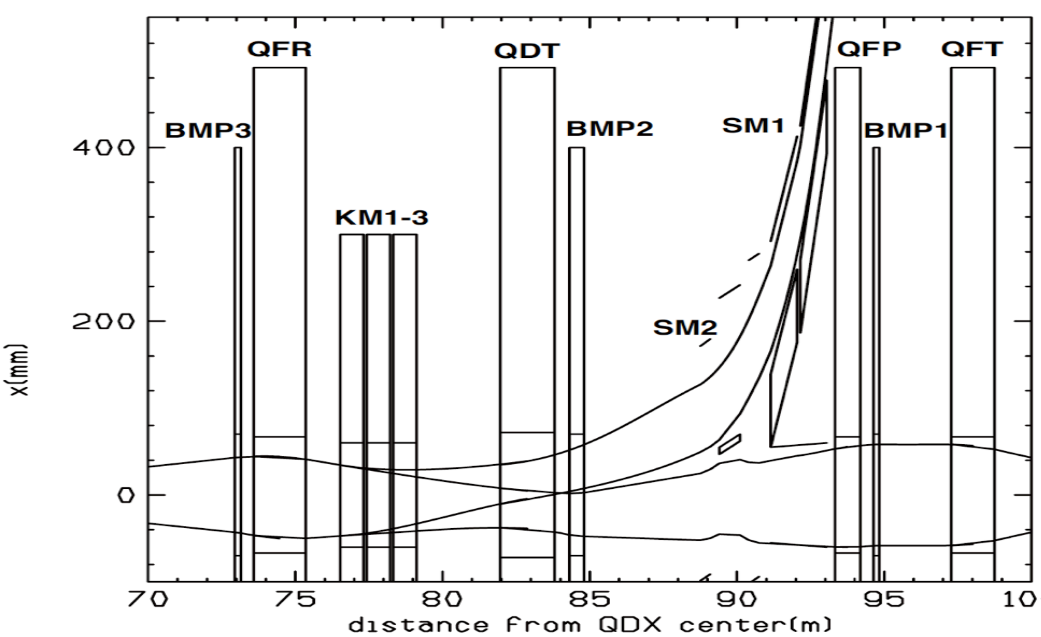
- Double-bump system (fast-slow)



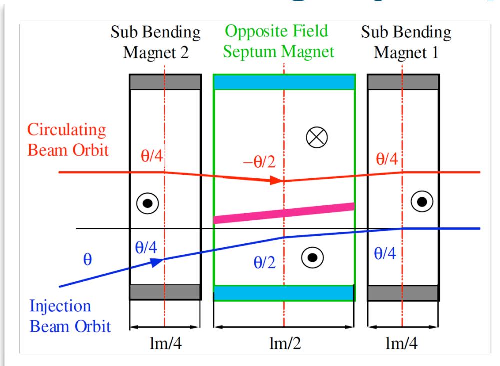
14-turn injection

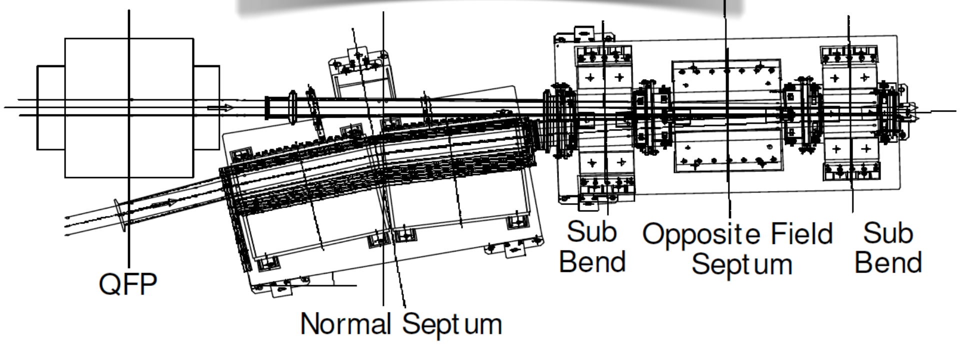


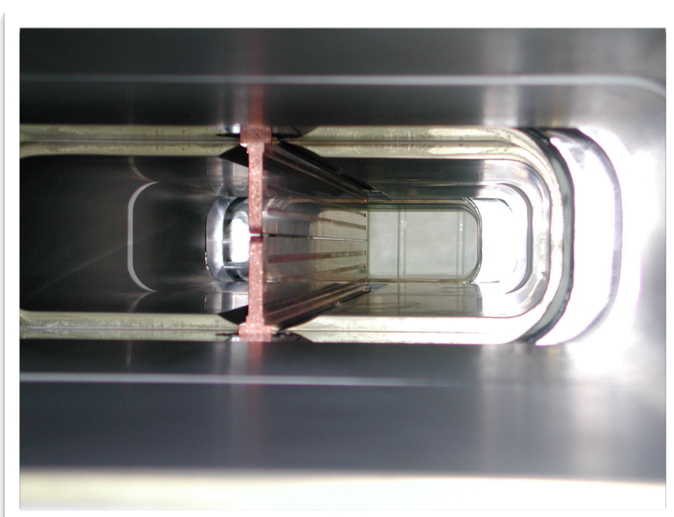
JPARC Main Ring Injection



JPARC Main-Ring Inj. Septum







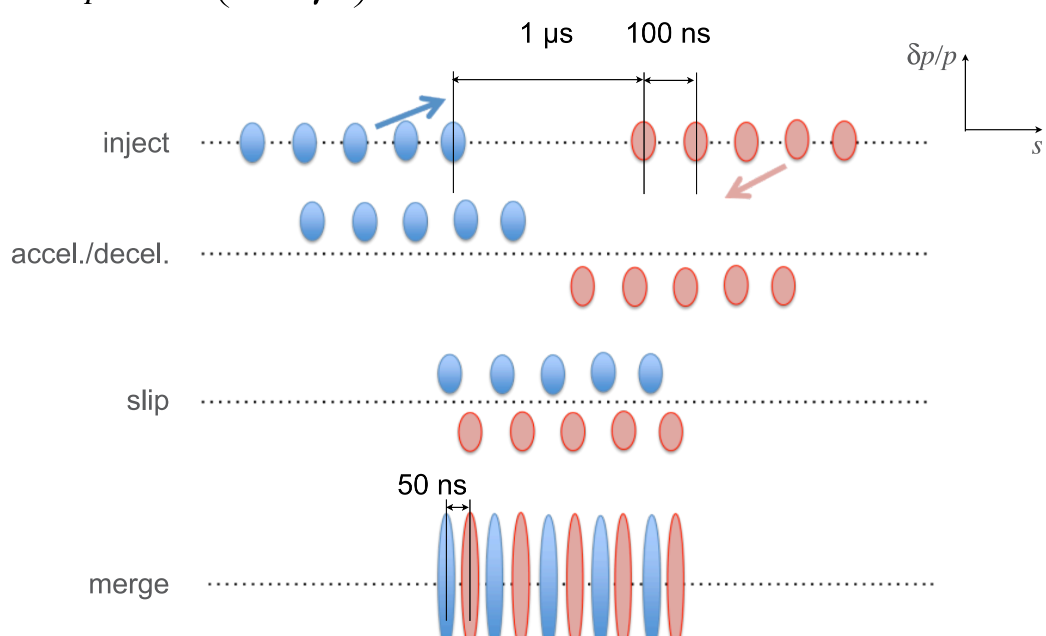
Slip Stacking

- Inject batches in box-car fashion
- "slip" the second batch in azimuth to overlap with the first one using a 2nd rf frequency
- "merge" the two batches using the rf.
- Requires the slip factor h to be large enough and momentum acceptance.
- May involve debunching of the stack

Example: CERN SPS (LHC ions, proposed)

$$\frac{\Delta t}{t} = \eta \frac{\Delta p}{p}, \quad \eta = \left(\alpha_p - \frac{1}{\gamma^2} \right)$$

T. Argyropoulos, CERN

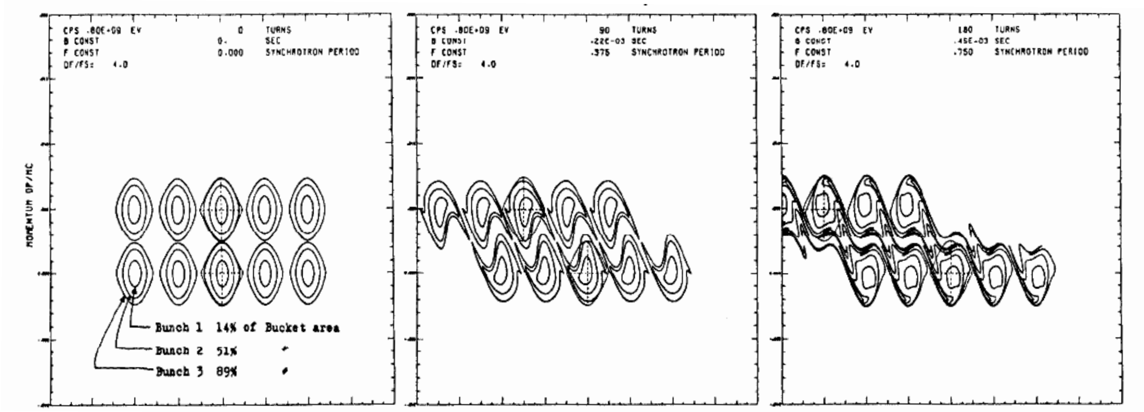


here: frequency doubling

Longitudinal phase space

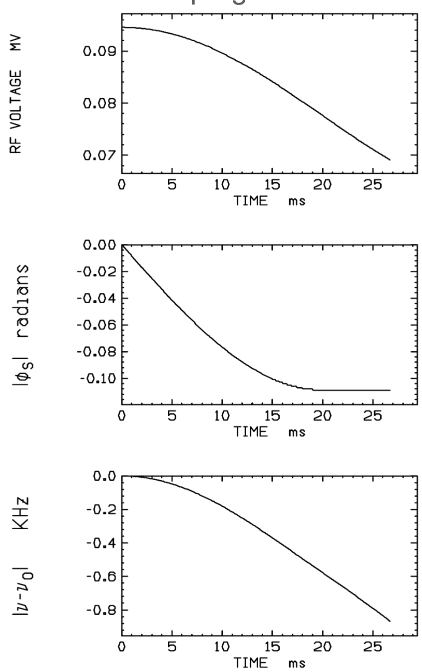
- modelling for CERN SPS (for p-bar production)
  - $\alpha = \Delta f / f_s > 4.$
- note existence of two series of rf buckets, offset in $\delta p/p$

turn 0 turn 90 turn 180

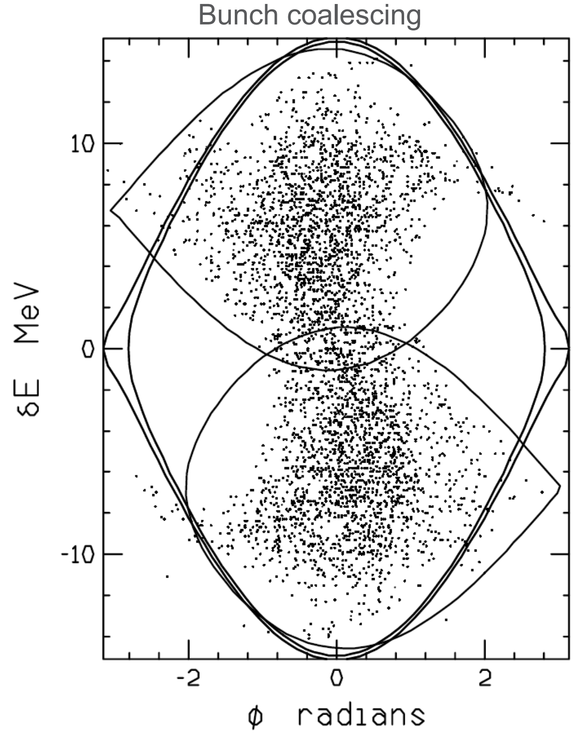


FNAL Main Injector

Rf program



Bunch coalescing



Multi-turn Parameters

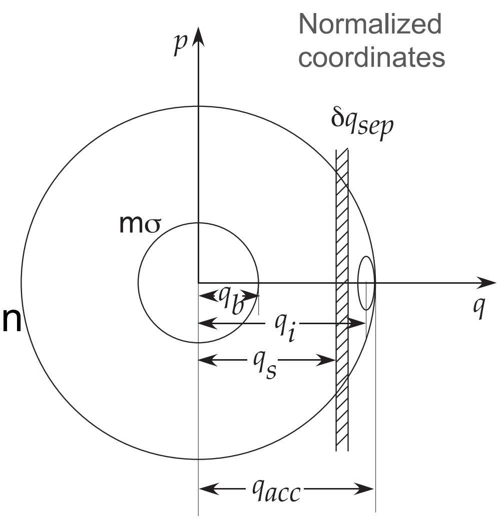
- Tune of the ring
  - each turn, the injected beam is displaced by 2Pi/n in phase space.
  - needs to be enough to move beam off the septum.

- Betatron match of offset beam:

$$\frac{\beta_i}{\beta_r} = \left(\frac{\varepsilon_i}{\varepsilon_r}\right)^{\frac{1}{3}} \qquad \frac{\alpha_i}{\alpha_r} = \frac{\beta_i}{\beta_r}$$

- The minimum phase rotation is then

$$\mu_{\min} = \frac{\pi}{\arccos\left(\frac{q_s}{q_{acc}}\right)}$$



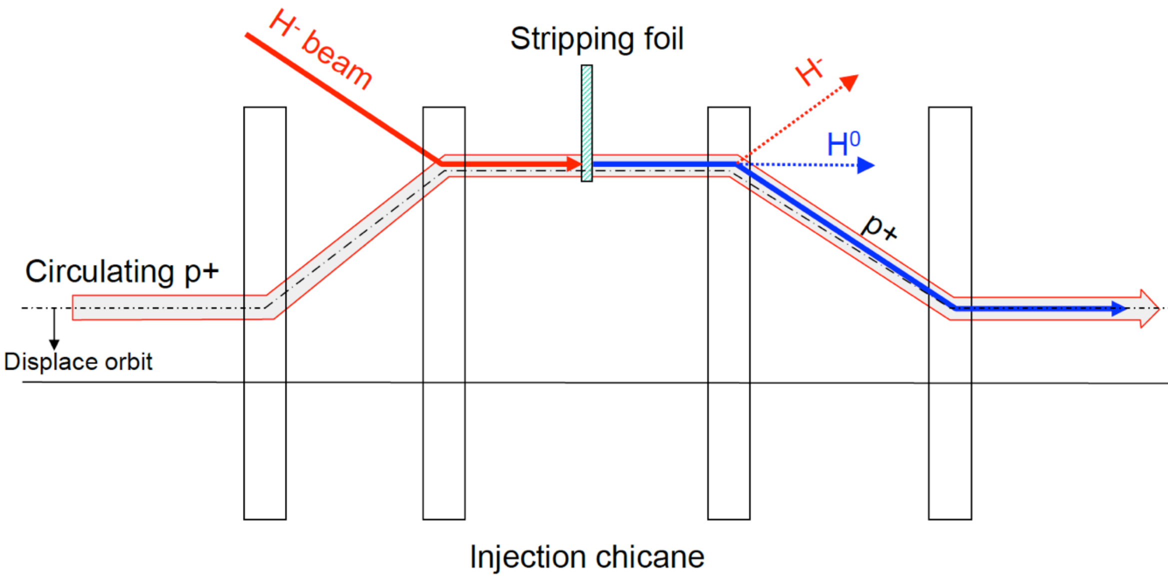
Charge-Exchange Injection

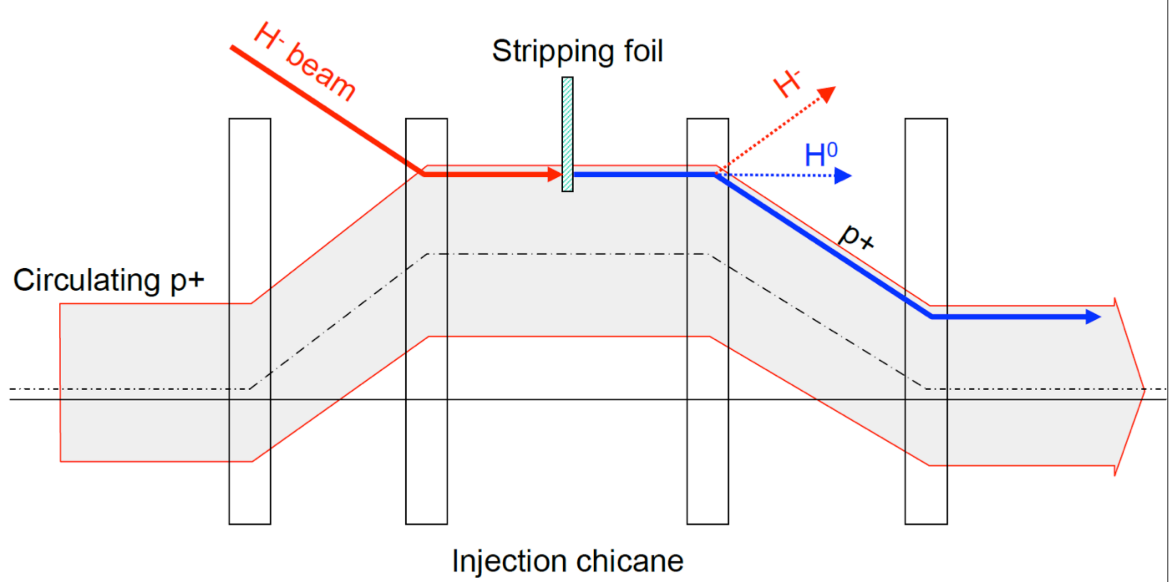
- Accelerate H^- ions up to a moderately high energy
  - 10s…1000 MeV, typically
  - upper limit set by Lorentz stripping
  - lower limit set by stripper efficiency

- Send them through a stripper foil
  - both weakly-bound electrons will get striped off, H^- -> H^+
  - stripper foil is thin => protons can pass through with minimal scattering
    - 50 µg/cm^2 @ 50 MeV to 200 µg/cm^2 @ 800 MeV.
  - ability to merge phase space; charge exchange is non-Liouvillian.

- This works with heavier ions as well
  - often use a multi-stage approach to fully strip ions for efficiency

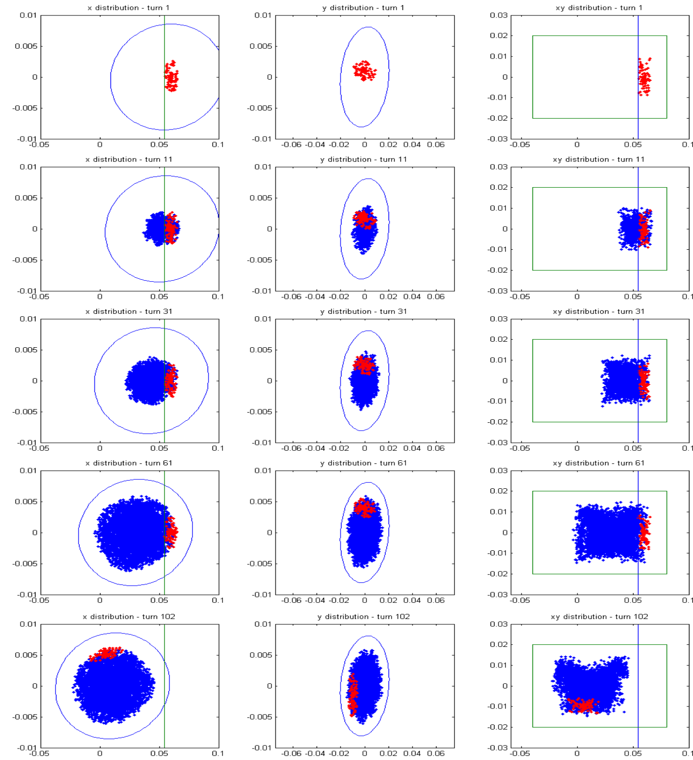
H– injection Schematic





Charge exchange H- injection painting

Time

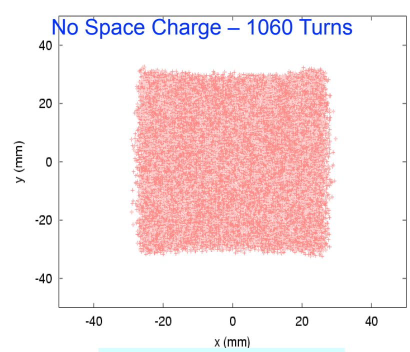


M. Plum, ORNL

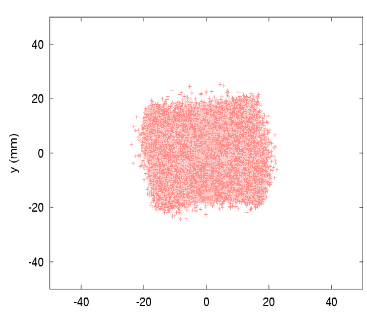
SNS Painting with Space-Charge

M. Plum, ORNL

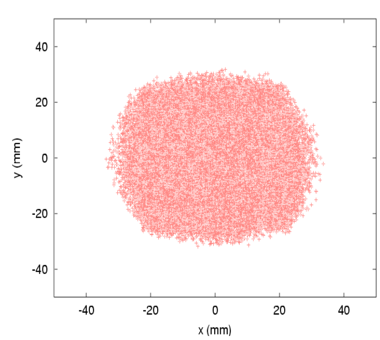
- Injection painting scheme optimized to minimize space charge and beam loss: Paint with hole in the center to help create uniform density.
- Also try to keep circulating beam foil intercepts to a minimum (~7-10 foil hits per proton).
- Footprint suits stringent target requirements.



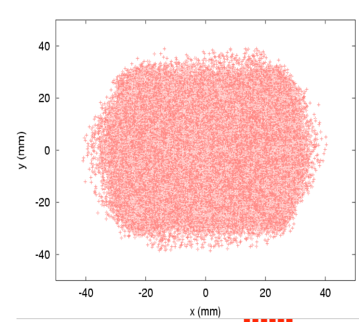
200 Turns



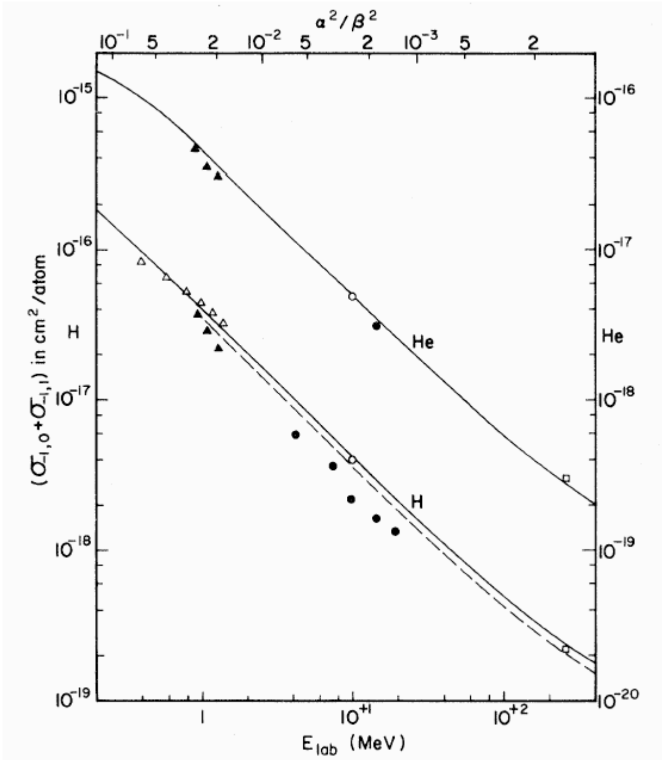
600 Turns



1060 Turns



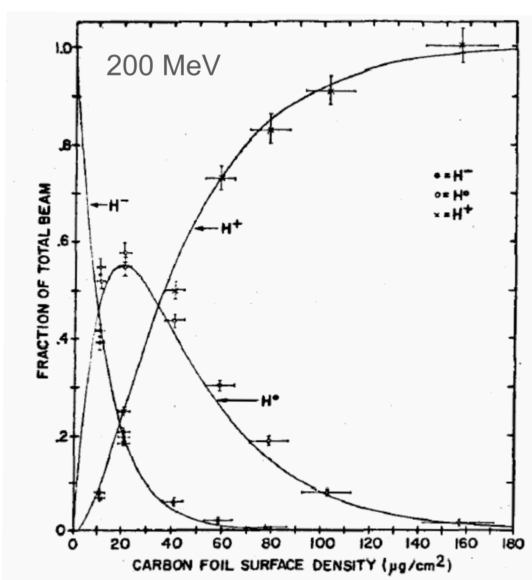
Stripping Cross Section *vs* Energy

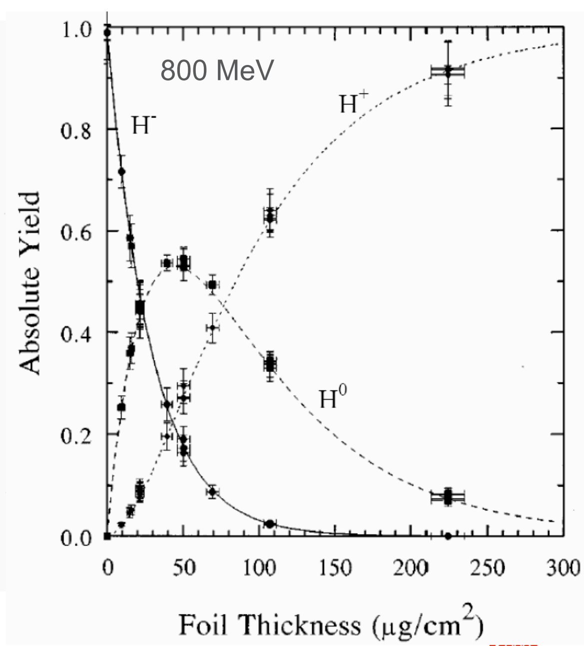


Chou et al., NIMA, 2008

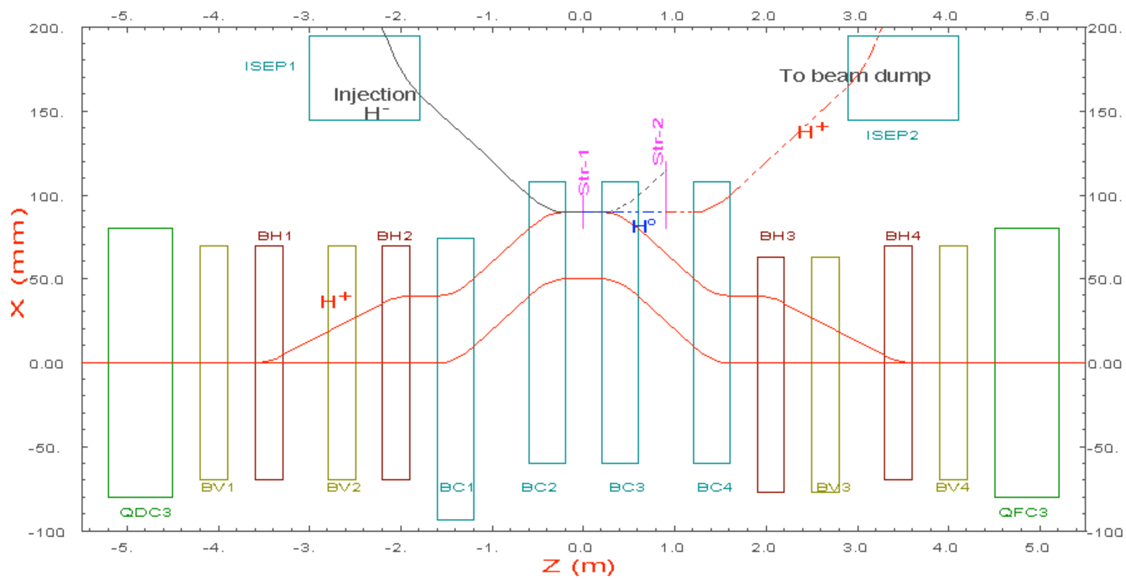
Stripping Efficiency @ 200 MeV and 800 MeV

Chou et al.

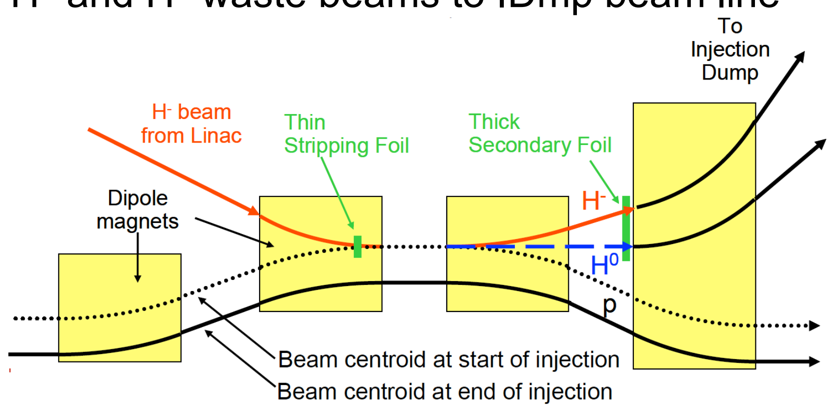




H– Injection Layout (SNS)



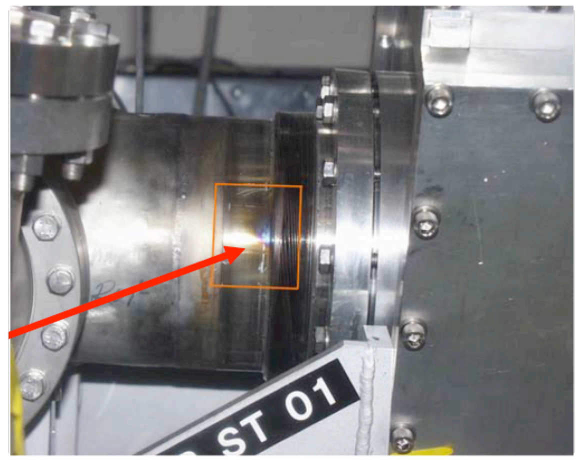
- Closed orbit bump of about 100 mm
- Merge H^- and circulating beams with zero relative angle
- Place foil in 2.5 kG field and keep chicane #3 peak field <2.4 kG for H^0 excited states
- Field tilt [arctan(By/Bz)] >65 mrad to keep electrons off foil
- Funnel stripped electrons down to electron catcher
- Direct H^- and H^0 waste beams to IDmp beam line



Where do the Stripped e⁻ go??

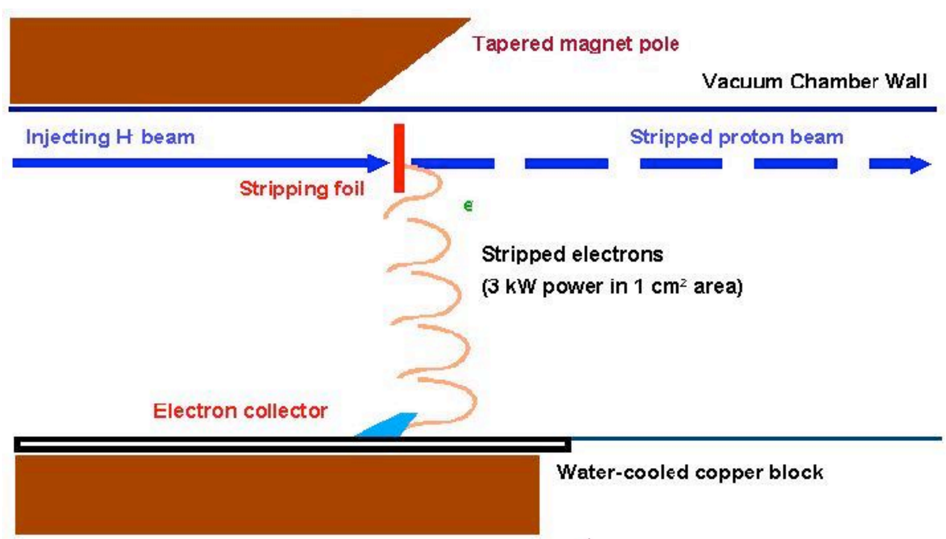
- 2 e^- per stripped proton @ incident beam energy
  - 1/938 time the total energy of the proton beam: ≈ 1.5 MeV*100 mA
  - At SNS: P_{e-} up to 1.5 kW… not negligible!

Burn mark from stripped electrons in LANL PSR



Control of Electrons

- The SNS primary stripper foil is in a tapered magnetic field, which directs the electrons down to a watercooled catcher.



Effect of Foil on the Beam

Particle Data Group

- Any matter in the beam path will scatter:

$$\theta_{rms} = \frac{0.0136\sqrt{\frac{X_0}{x}}\left(1+0.038\ln\left(\frac{X_0}{x}\right)\right)}{\beta cp}$$

cp=momentum in GeV
X_0=radiation length
x = thickness
$\beta = v/c$

  - Note: the above is optimistic for thin foils as large-angle scatters are underestimated => "plural" scattering

- This increases the beam emittance:

$$\varepsilon = \sigma_{xp}^2 \beta_{Twiss} = \varepsilon_0 + \beta_{Twiss}\theta_{ms}^2 n_{foil}$$

- Also, particles lose energy in the foil

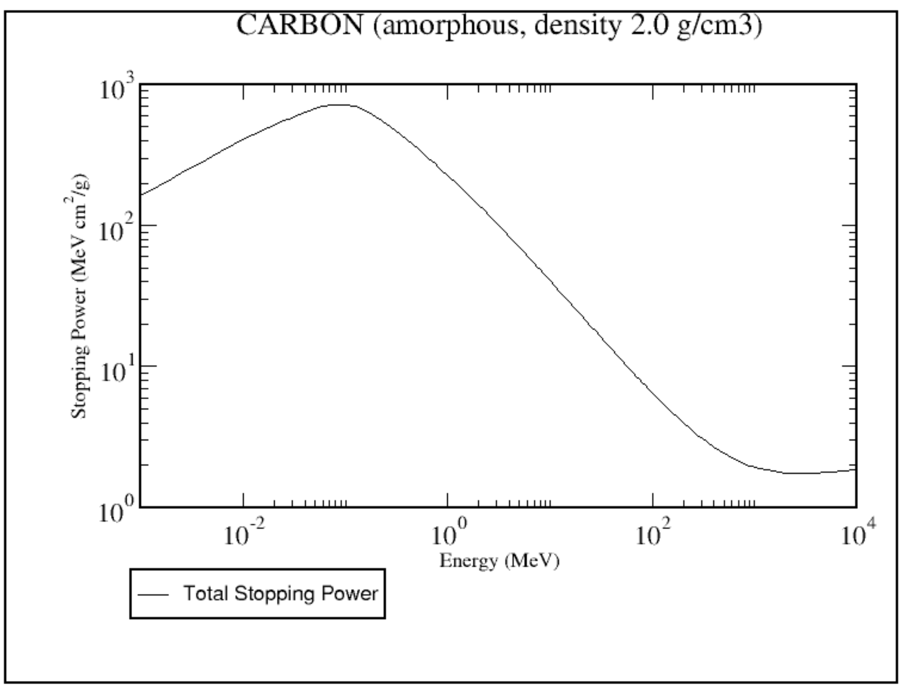
$$\left\langle -\frac{dE}{dx}\right\rangle = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right] . \quad \text{[MeV/(g/cm}^2\text{)]}$$

$$K = 0.307 \text{ [MeV/(mol/cm}^2\text{)]} \quad W_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1+2\gamma m_e/M + (m_e/M)^2} .$$ for a particle of mass M

  - This generates significant power that has to be dissipated (radiation)

dE/dx for ^{12}C

NIST PSTAR



0^{th}-Order Design of H⁻ injection

- Decide on the number of turns needed (intensity, emittance)
- Decide on stripper foil thickness needed
  - mostly depends on minimum efficiency desired
- Decide on the final emittance
  - space-charge consideration
- Evaluate the scattering for the # of turns needed
  - in general, scattering should not dominate the final emittance
- Evaluate foil heating
- iterate and hopefully converge
- Modelling (ACCSIM or other codes)
  - many labs write their own tailored to their specific needs

Foil Heating

C.J. Liaw et al.

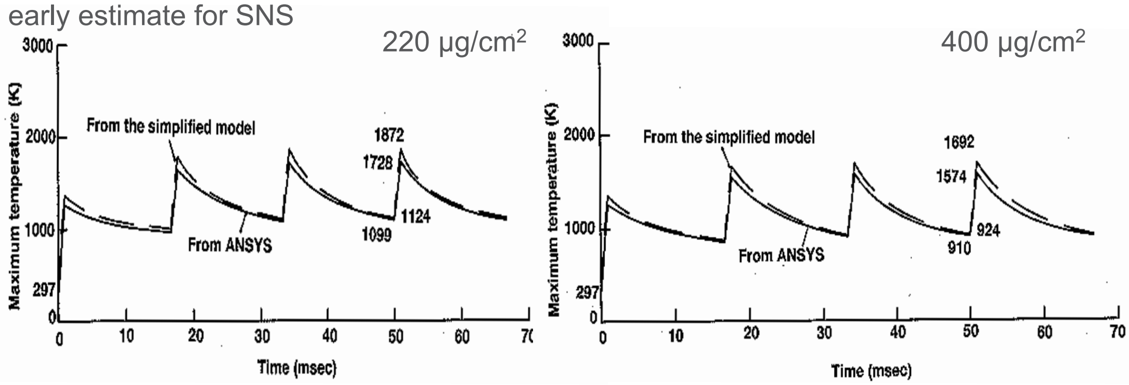
- Foil heating due to a pulsed beam

$$\rho_c V_c c_c \, dT_c/d\tau = -2\sigma \, f\varepsilon_c A_c (T_c^4 - T_0^4) + PA_c$$

  - T-rise due to specific heat of foil, T-fall due to radiative cooling

P: Power, T: abs temp
A: area, V: volume
ε: emissivity, ρ: density
σ: Stefan-Boltzmann
c: spec. heat capacity
$_c$: carbon foil, $_0$: ambient

early estimate for SNS



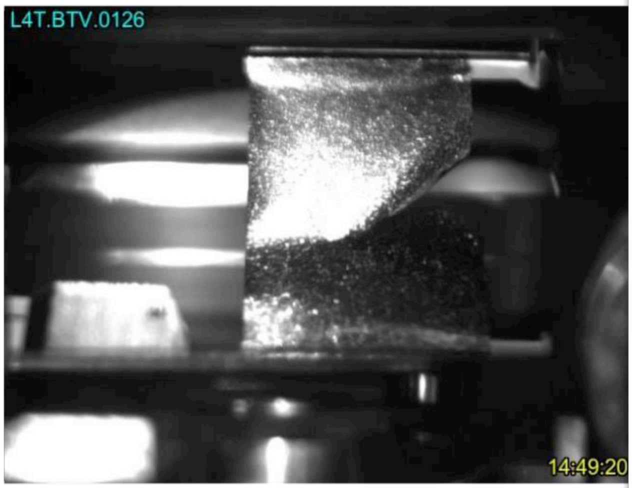
Liaw et al., proc. PAC 1999, New York

Stripper Foils

- Stripper foil damage

B. Goddard

CERN PS Booster



SNS

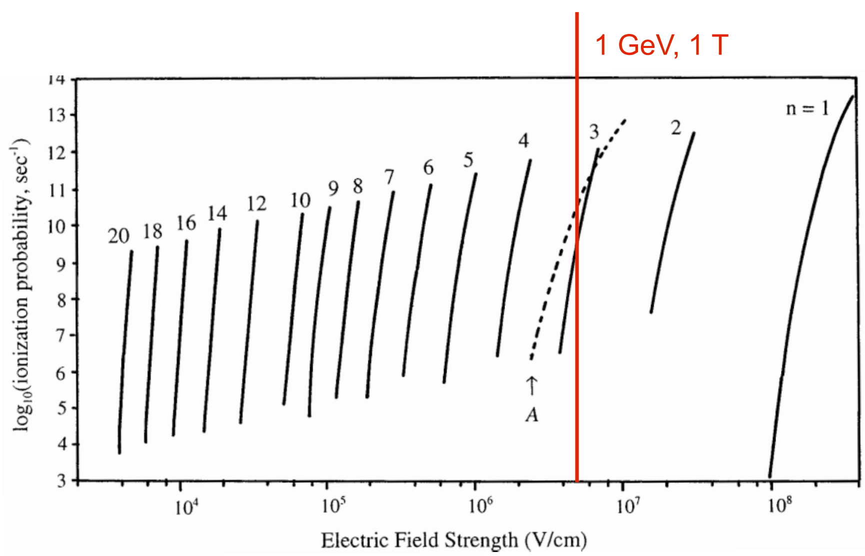
- is there a way to strip without a foil??

Alternatives to Stripper Foils

- Lorentz stripping in a strong magnetic field

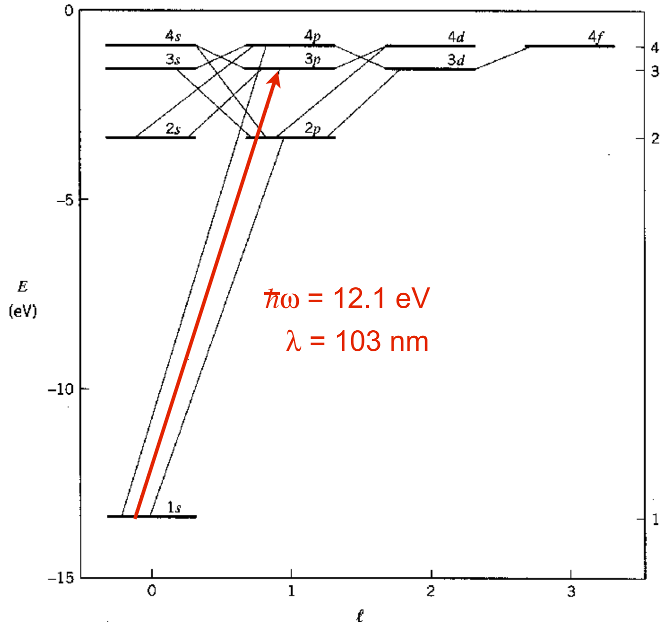
B. Goddard

  – works at high energy, but only H^- –>H^0
  – H^0 not amenable to Lorentz stripping as is; however, excited H^0 atoms are



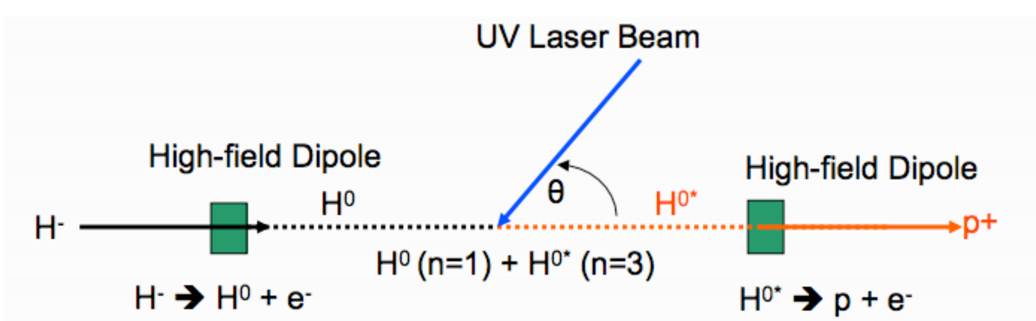
Laser Stripping

- H^0 can be excited by a laser of suitable wavelength
- lifetime $10^{-9}\ldots10^{-10}$s
  - long enough to travel a foot or so
- then strip in a 2nd strong dipole



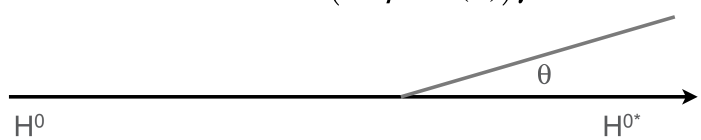
Laser Stripping

- Strip H^- to H^0 in a strong B-field
- Excite H^0 with a laser of the right (Lorentz-shifted!) wavelength
- Strip excited H^0 to H^+ in another strong B-field



- Doppler shift shortens the laser wavelength
- use angle θ to “tune” the laser on resonance

$$h\omega \rightarrow h\omega\left(1+\beta\cos(\theta)\right)\gamma$$



Details

- Fundamentally, the resonance is narrow,
  - the laser line width is narrow as well
  - particles have different γ and angle so low probability of excitation
  - > would need enormous laser power to make this work efficiently

- The key to success is to tailor the laser beam divergence and to dispersion-match the angle θ.

- SNS has shown this can actually work, 90% efficiency, 7 ns
  - working on 10 μs system
  - will need an optical cavity to get to cw.

References

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- T. Argyropoulos et al., “Slip stacking in the SPS”, CERN LIU Day Apr-2014.
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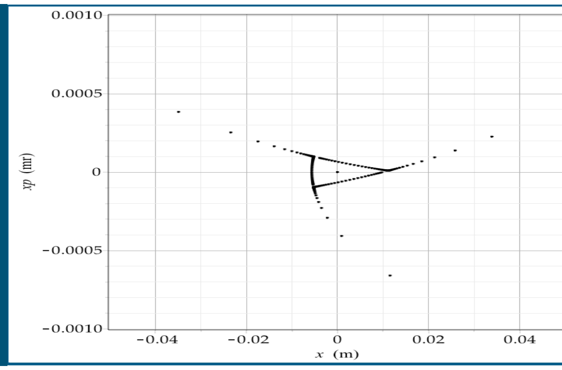
- W. Chou et al.,”Stripping Efficiency and Lifetime of Carbon Foils“, arXiv:physics/0611157
- C.J. Liaw et al., “Calculation of the Maximum Temperature on the Carbon Stripping Foil of the Spallation Neutron Source”, Proc. PAC99, New York, NY 3300(1999).

Slow Extraction



U. WIENANDS, J. CALVEY, O. MOHSEN
ANL

July 2024
USPAS, Rohnert Park

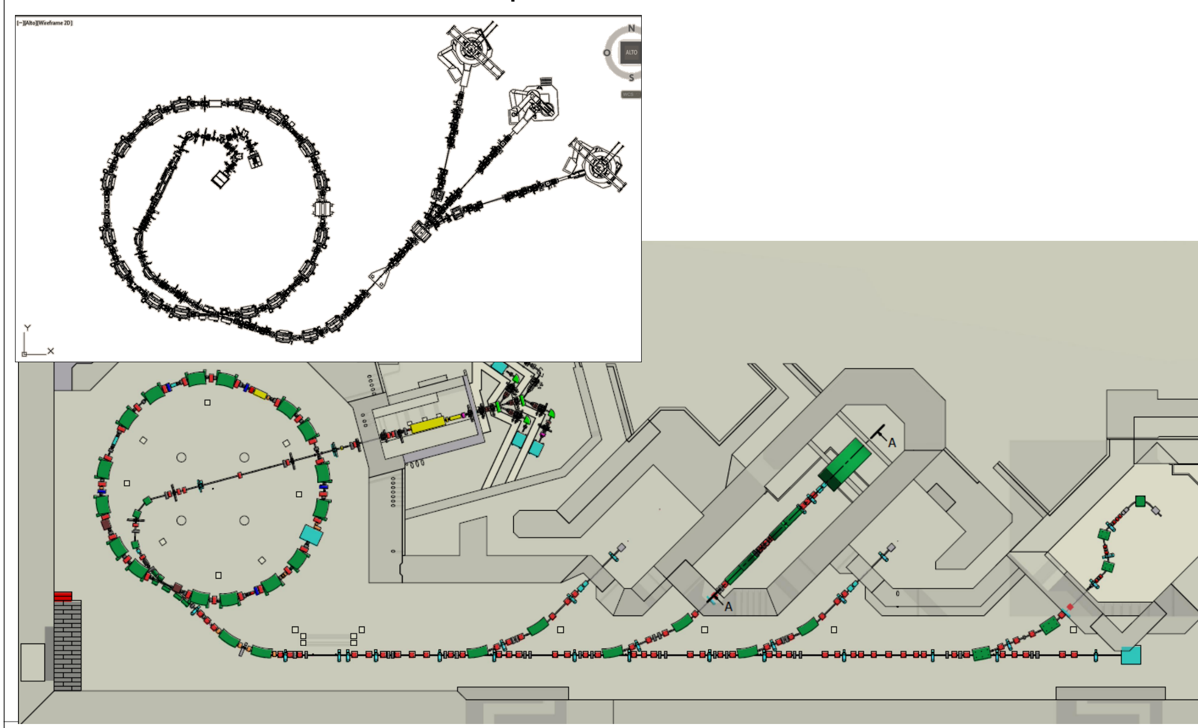
Slow Extraction

- Single turn extraction from a ring => very small duty factor
  - t_{rev}/t_{cycle}: 1E-5 or similar
- This can be an issue for coincidence experiments
  - random coincidences increase with peak rate, actual coincidences with the average rate.
- Need a method to “peel off” the beam slowly, ms to seconds.
- General idea: run beam onto a resonance & peel off the unstable particles.
  - on an isolated resonance, the phase space topology is easily understood and controlled.

Slow Extraction: What for?

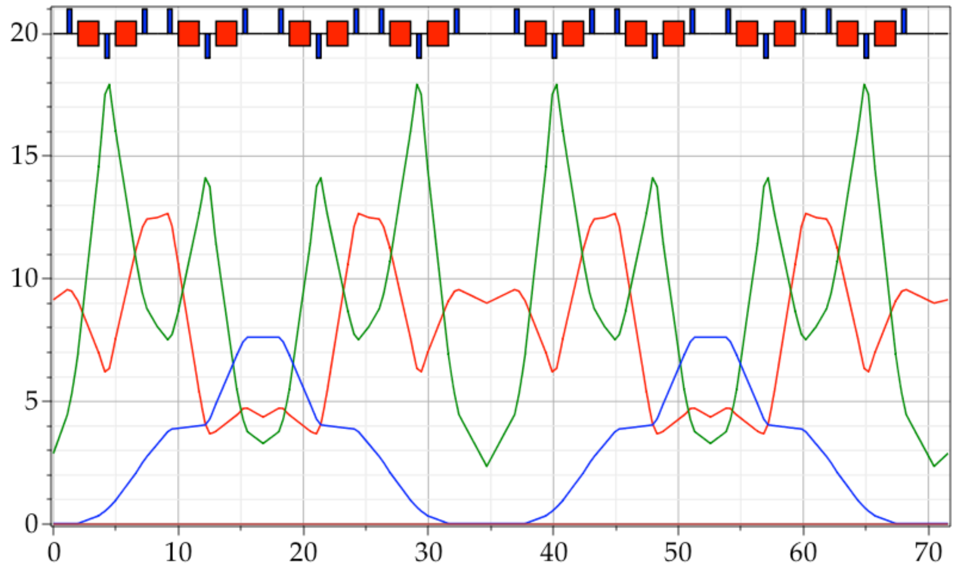
- Single turn extraction from a ring => very small duty factor
  - t_{rev}/t_{cycle}: 1E-5 or similar
- This can be an issue for coincidence experiments
  - random coincidences increase with peak rate, actual coincidences with the average rate.
- Medical therapy applications also use it
  - MedAustron (Vienna, AU), CNAO (Pavia, IT), MGH (Boston, MA)
- General idea: run beam onto a resonance & peel off the unstable particles.
  - on an isolated resonance, the phase space topology can be understood and controlled.

CNAO and MedAustron: 2 implementations of PIMMS

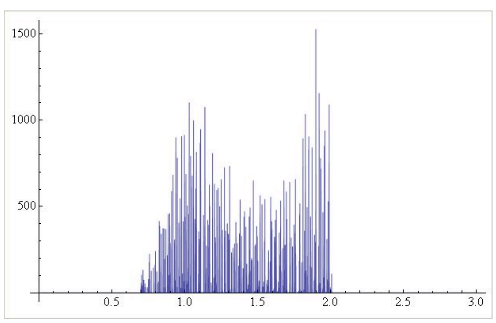


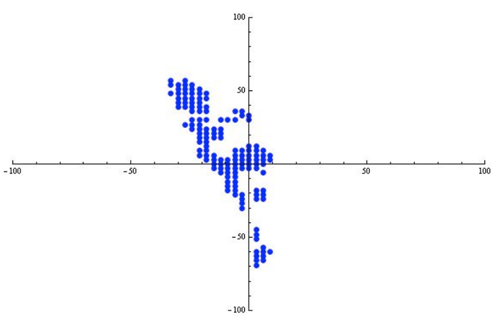
"PIMMS-like" lattice

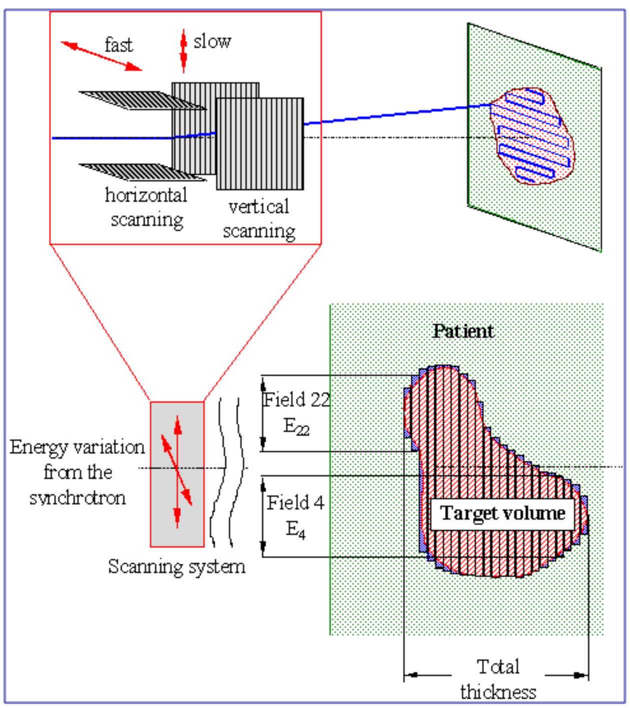
- FODO with inserts for various systems



Active systems

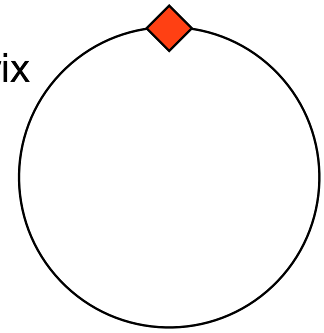






1/3-Integer Extraction

- 1/3-integer and 1/2-integer resonances are being used for extraction. We will discuss the 1/3 integer extraction in some detail.
- Consider a ring with a single (thin) sextupole:



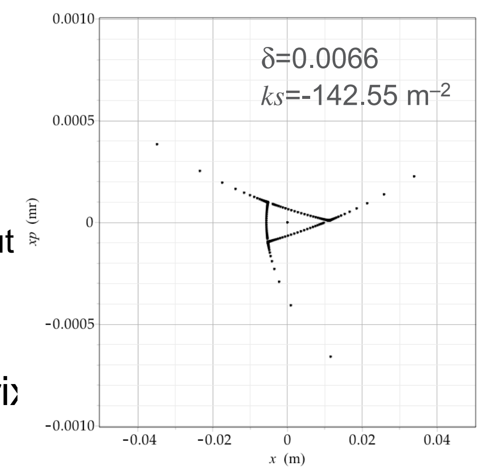
- The ring is described by its 1st-order matrix M, the sextupole by its transfer function:

$$\begin{bmatrix} x \\ xp \end{bmatrix} = \begin{bmatrix} x \\ -ks \cdot x^2 + xp \end{bmatrix}$$

- The quadratic term distorts the phase-space topology and separates stable & unstable particles

Fixed Points

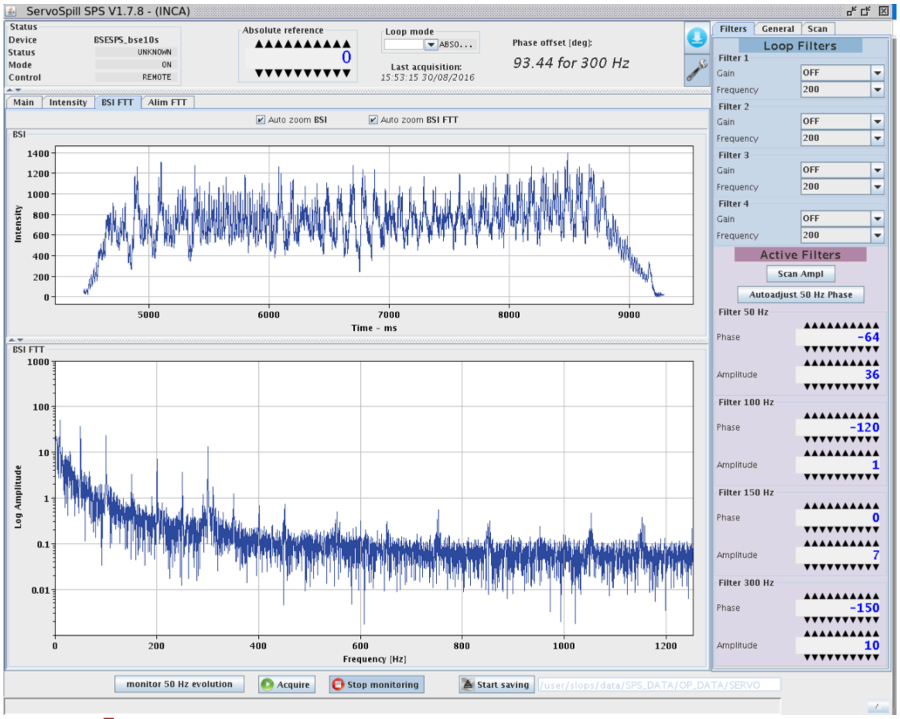
- We can look at the phase space for this system:
  - [0,0] is stationary
  - small (x,xp) is nearly ellipsoidal
  - there are three fixed points that repeat every 3 turns.
    - Qx = 1/3 exactly
  - at larger amplitude, particles stream out
  - separation lines from bounded to un-bounded motion: “separatrices”



- A septum to intercept the separatrix extracts the beam
- change the tune to shrink stable area => slow extraction

SPS Slow Extraction Spill

M. Fraser



Note the oscillations in the intensity.

The FFT reveals power lines (50 Hz*n) but also others

Third-Integer Resonance Analysis

- Consider a ring with a tune ($Q_r+\delta$) and a sextupole with integrated strength ks.
- The ring has a horizontal 1-turn R-matrix that defines its tune and lattice functions:

$$R_p = \begin{bmatrix} \alpha(0)\sin\left(2\pi(Q_r+\delta)\right)+\cos\left(2\pi(Q_r+\delta)\right) & \sin\left(2\pi(Q_r+\delta)\right)\beta(0) \\ \left(-\frac{\alpha(0)^2}{\beta(0)}-\frac{1}{\beta(0)}\right)\sin\left(2\pi(Q_r+\delta)\right) & -\alpha(0)\sin\left(2\pi(Q_r+\delta)\right)+\cos\left(2\pi(Q_r+\delta)\right) \end{bmatrix}$$

  – Sextupole is given on slide 4.
- We find the fixed points by applying this map 3 times to (x,xp)
- The result is too messy to use directly, but we can taylor-expand and keep only up to 2nd order

- The truncated three-turn map is then

$$\frac{5x\beta kl_{SR}(\alpha x+xp\beta)}{4} - \frac{kl_{SR}\left(-\frac{\left(xp^2\beta^2+2x\,xp\,\beta\alpha+x^2(\alpha^2-1)\right)\sqrt{3}}{2}+x^2\alpha+x\,xp\,\beta\right)\beta}{4} - \frac{kl_{SR}(xp\beta+x(\alpha+1))(xp\beta+x(\alpha-1))\beta\sqrt{3}}{8} + \frac{\beta^2 kl_{SR}\,x\,xp}{2} - \frac{(12\alpha kl_{SR}x^2+24\pi\delta xp)\beta}{8} - \frac{(24\pi\alpha\delta+4)x}{8} - \frac{\left(4\beta^3 kl_{SR}xp^2+8\alpha\beta^2 kl_{SR}\,x\,xp+\left((4\alpha^2-4)x^2 kl_{SR}+4xp\right)\beta-24x\left(\delta\pi-\frac{\alpha}{6}\right)\right)\sqrt{3}}{8} + \frac{\beta kl_{SR}(\alpha x+xp\beta)^2\sqrt{3}}{2} - \frac{(-4\alpha kl_{SR}x^2-18\pi\delta xp)\beta}{2} - \frac{(-18\pi\alpha\delta-3)x}{2} - \frac{\sqrt{3}\left((kl_{SR}x^2-xp)\beta+6x\left(\delta\pi-\frac{\alpha}{6}\right)\right)}{2} = x$$

x

$$\frac{1}{\beta}\left(-\frac{kl_{SR}(xp\beta+x(\alpha+1))(xp\beta+x(\alpha-1))\beta}{4} - kl_{SR}\left(-\frac{(x^2\alpha+x\,xp\,\beta)\sqrt{3}}{2}-\frac{xp^2\beta^2}{8}+\frac{x^2(\alpha^2+1)}{8}\right)\beta + \frac{kl_{SR}\left(-\frac{\left(xp^2\beta^2\alpha+2x\,xp(\alpha^2+1)\beta+x^2\alpha(\alpha^2+1)\right)\sqrt{3}}{2}+\frac{11xp^2\beta^2}{2}+12x\,xp\,\beta\alpha+\frac{13x^2\left(\alpha^2-\frac{11}{13}\right)}{2}\right)\beta}{4} + \frac{kl_{SR}\left(xp^2\beta^2\alpha+2x\,xp(\alpha^2-7)\beta+x^2\alpha(\alpha^2-15)\right)\beta\sqrt{3}}{8} - \frac{\beta^3 kl_{SR}xp^2}{2} - \frac{3\alpha\beta^2 kl_{SR}\,x\,xp}{2} - \frac{\left((-8\alpha^2-4)x^2 kl_{SR}-24\pi xp\alpha\delta+4xp\right)\beta}{8} - 6x\pi\delta(\alpha^2+1) - \frac{\left(-4\alpha\beta^3 kl_{SR}xp^2-8x\,kl_{SR}xp\left(\alpha^2+\frac{1}{2}\right)\beta^2+\left(-4\alpha^3 kl_{SR}x^2-24xp\left(\delta\pi+\frac{\alpha}{6}\right)\right)\beta+(-4\alpha^2-4)x\right)\sqrt{3}}{8} - \frac{5kl_{SR}\left(\frac{3xp^2\beta^2}{5}+\frac{8x\,xp\,\beta\alpha}{5}+x^2\left(\alpha^2-\frac{4}{5}\right)\right)\beta}{2} - \frac{kl_{SR}(\alpha\beta xp+x(\alpha^2-2))(\alpha x+xp\beta)\beta\sqrt{3}}{2} - \frac{\left(x^2(4\alpha^2+1)kl_{SR}+18\pi xp\alpha\delta-3xp\right)\beta}{2} + \frac{\sqrt{3}\left(\left(\alpha kl_{SR}x^2-6xp\left(\delta\pi+\frac{\alpha}{6}\right)\right)\beta+(-\alpha^2-1)x\right)}{2}\right) = xp$$

xp

where a resonant tune of n+2/3 has been used.

- still messy, but Maple can solve for the fixed points:

$$x_{fp} = -\frac{8\delta\pi}{\beta_x ks}, \quad xp = \frac{8\alpha\delta\pi}{ks\beta_x^{\,2}}; \quad x_{fp} = \frac{4\delta\pi}{\beta_x ks}, \quad xp = \frac{4\pi\left(-\alpha\pm\sqrt{3}\right)\delta}{ks\beta_x^{\,2}}$$

- The first one is a single point, the 2nd one is a conjugate pair.
  - defining parameter is $\dfrac{\delta}{ks}$

d/ks has two signs, which can cancel.
Are these equivalent?

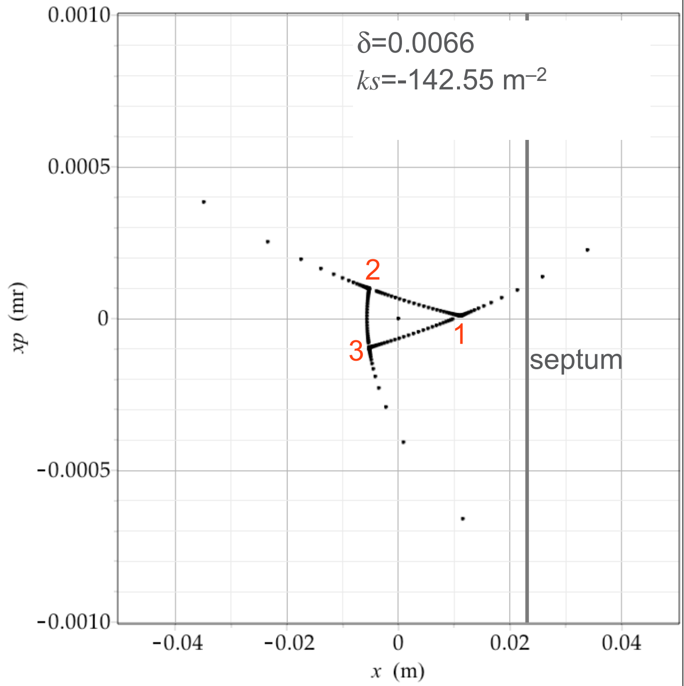
- These define a triangle in phase space with an area of

$$\frac{48\pi^2\delta^2\sqrt{3}}{\beta^3 ks^2}$$

Resonance Triangle

- Putting some numbers in we indeed get the three fixed points.
- The area of the triangle is:

$$\pi\varepsilon = \frac{820.544\delta^2}{ks^2\beta_x^3}$$



Stepsize

- Extraction efficiency is directly calculated from the stepsize:

$$\varepsilon = 1 - \frac{w}{\Delta x}$$ w: septum thickness

- With the stepsize

$$\Delta x = \frac{\left(2\alpha + \sqrt{3}\right)\left(-x_i \beta k l_{SR} + 12\pi\delta\right) x_i}{2}$$

  - This can be varied for fixed δ/ks, so independent degree of freedom.

- These formulae give us starting values for the design.

Emittance

- Liouville tells us that the minimum extracted emittance is

$$\frac{\varepsilon_r}{n}$$

- but to get this we need a programmed bump in x and xp.
  - follow the movement of the UFP, i.e.

$$\delta x(\delta) = -\frac{25.133(\delta - \delta_0)}{ks\beta_x}$$

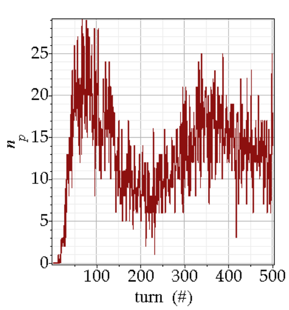
- the rate of change in δ in turn controls the intensity of the extracted beam
  - for maximum duty factor, δ is a function of the beam distribution.

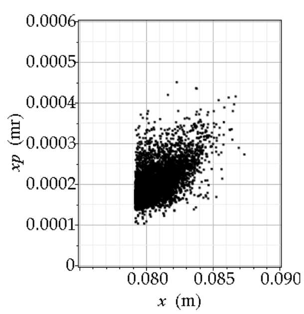
Modelling of a Slow-Extraction Cycle

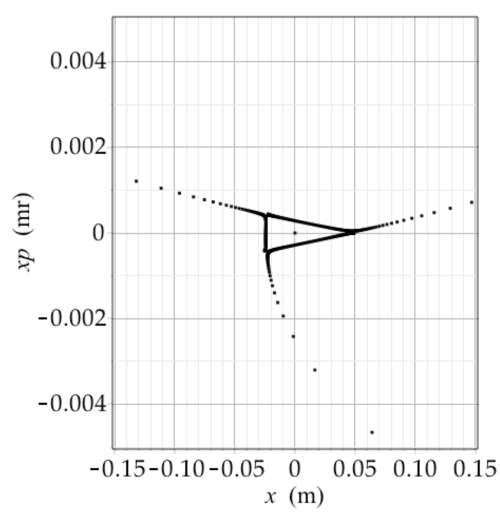
- Assume β_x=100 m, ε=10^{-5}. Chose a stepsize of 2 mm and put the septum 3 cm away from the fixed point.
- Solve for the stepsize and the triangle area to find

$$\delta = 0.002735, ks = -0.01398$$

- The UFP is then at $x_{fp} = 0.049$
- A first spill plot:

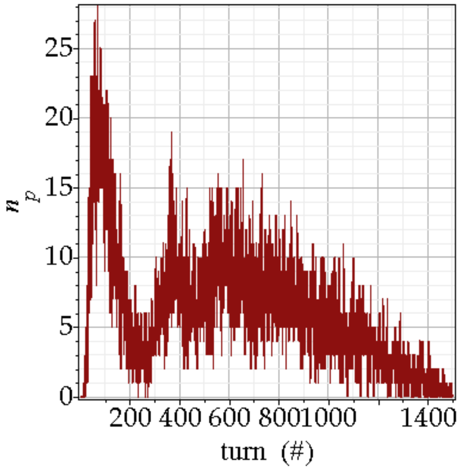


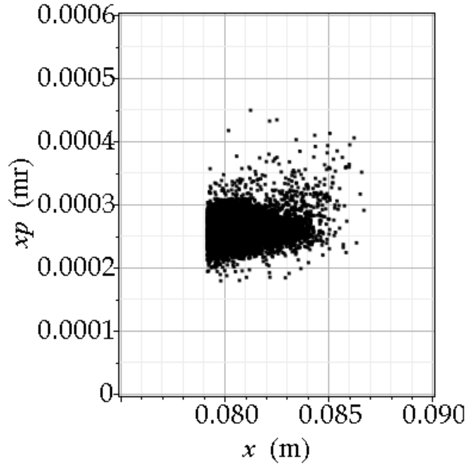




Another demo run

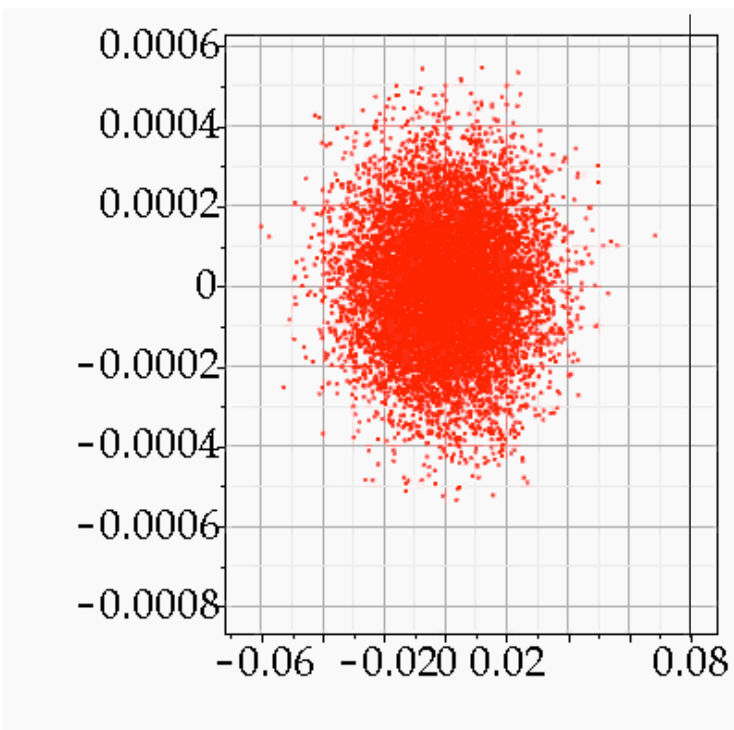
- “Overrun the resonant tune to reduce residual beam”





Movie

- Moving the centroid to keep extracted beam stationary.
  - not quite in this example

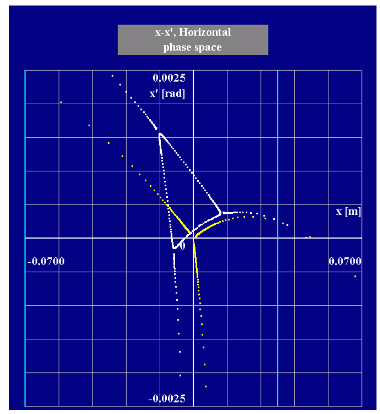


Chromatic Slow Extraction

- If the chromaticity of the machine is not 0, δ and the momentum of the particles are correlated.
  - Beam-lets get extracted according to their momentum.
- If the chromaticity and the dispersion fulfill the *Hardt condition* [1], the longitudinal emittance of the extracted beam can be reduced in addition to the transverse.

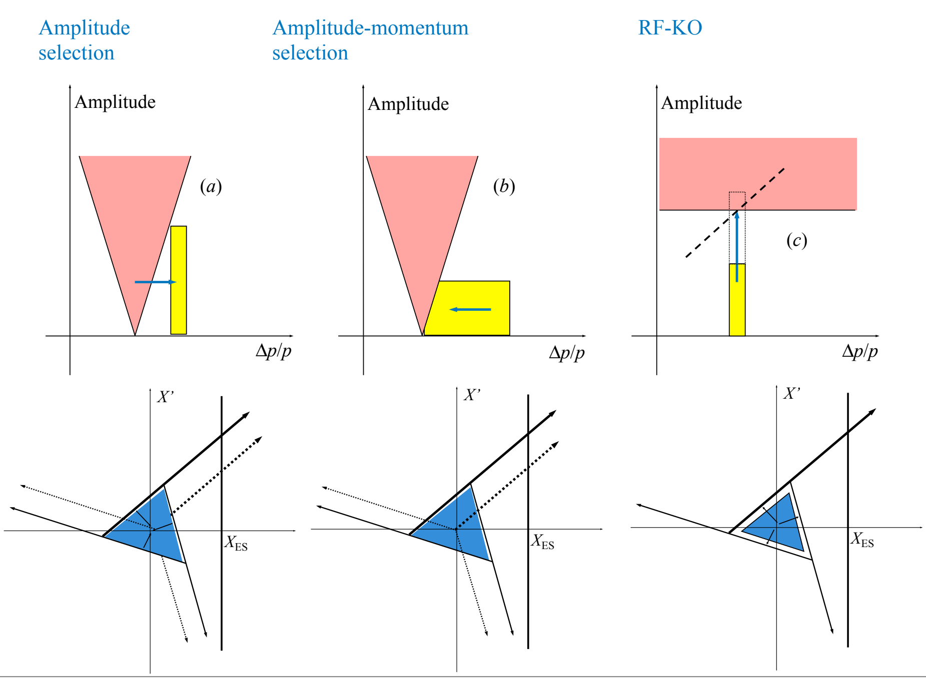
$$\xi = \frac{ks}{4\pi\nu}\left(\eta_s^{'}\cos\left(\phi_s\right) - \eta_s\sin\left(\phi_s\right)\right)$$

ϕ_s = septum phase



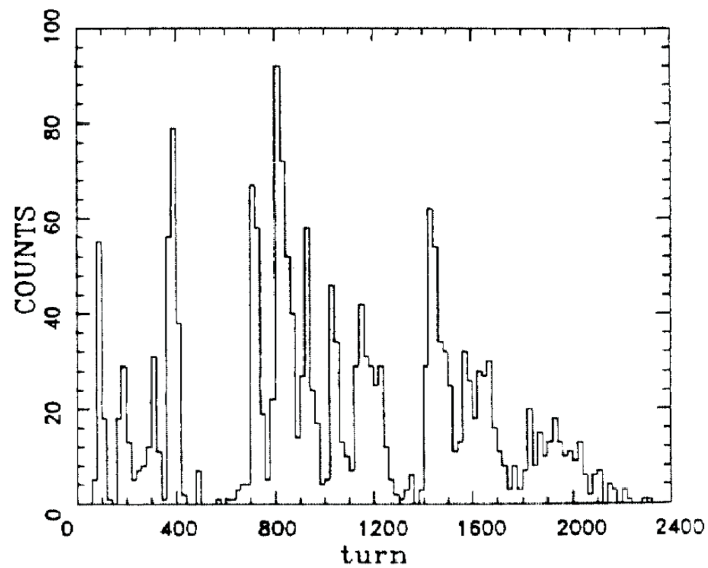
[1] W. Hardt, *Ultraslow extraction out of LEAR (transverse aspects)*, CERN Internal Note PS/DL/LEAR Note 81-6, (1981).

Extraction methods



Noise sensitivity

- High sensitivity to tune makes system sensitive.
- Ex: Simulation with $\delta=0.011$, 2×10^{-4} noise & ac ripple on quadrupoles:

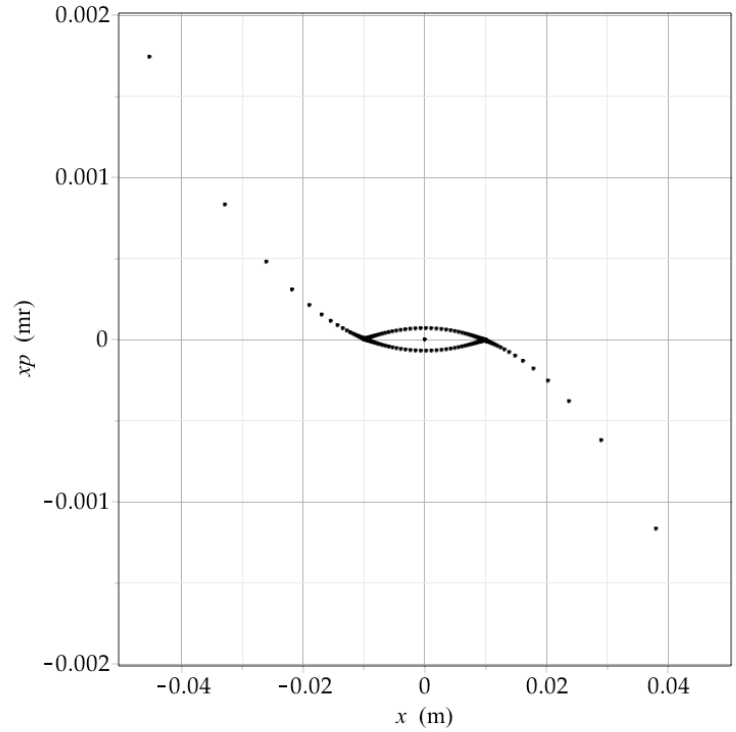


1/2-Integer Extraction

- It is also possible to extract on a 1/2 integer resonance
  - stronger resonance => easier to avoid residual beam left in ring.
- But it is a linear resonance => no separatrices
- This is overcome by using an octupole to drive the resonance & provide nonlinearity.
- 1/2-integer is a stop band: easier to completely empty the ring

Half Integer Resonance

- Driven by an octupole

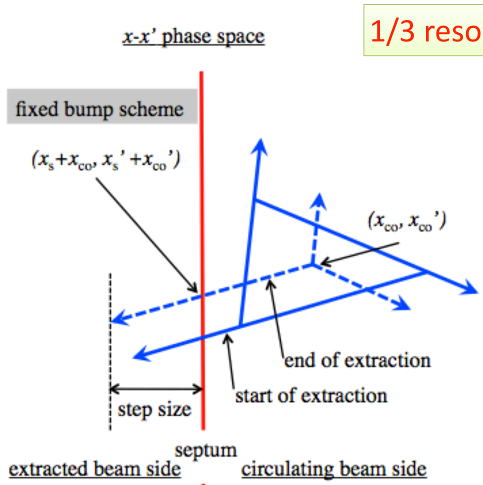


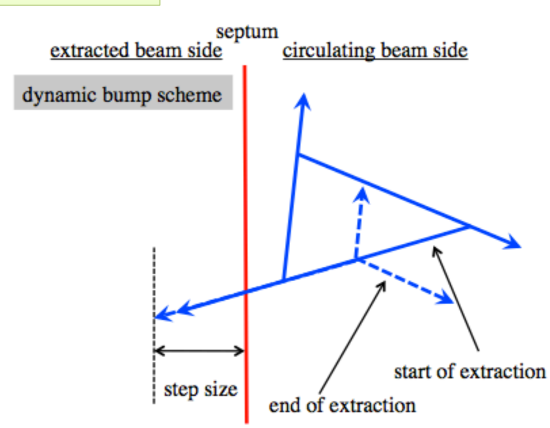
Schemes for Very High Extraction Efficiency (low beam loss)

(Masahito Tomizawa)

- Electrostatic Septum (ESS) QF-QF high β (small α) 40m
  -> large step size (20mm)
- dispersion free at ESS + low horizontal chromaticity
  -> Separatrix is independent of $\Delta p/p$
  depends on tune (constant resonant sextupole)

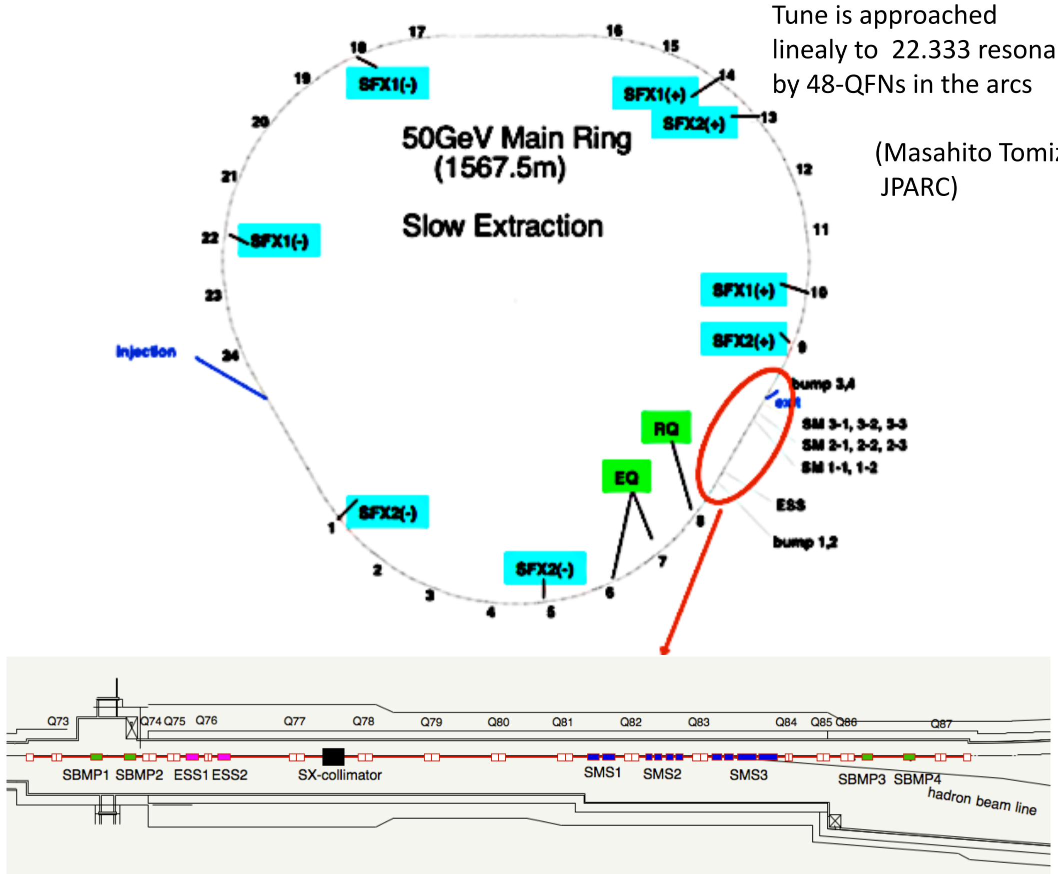
1/3 resonant extraction





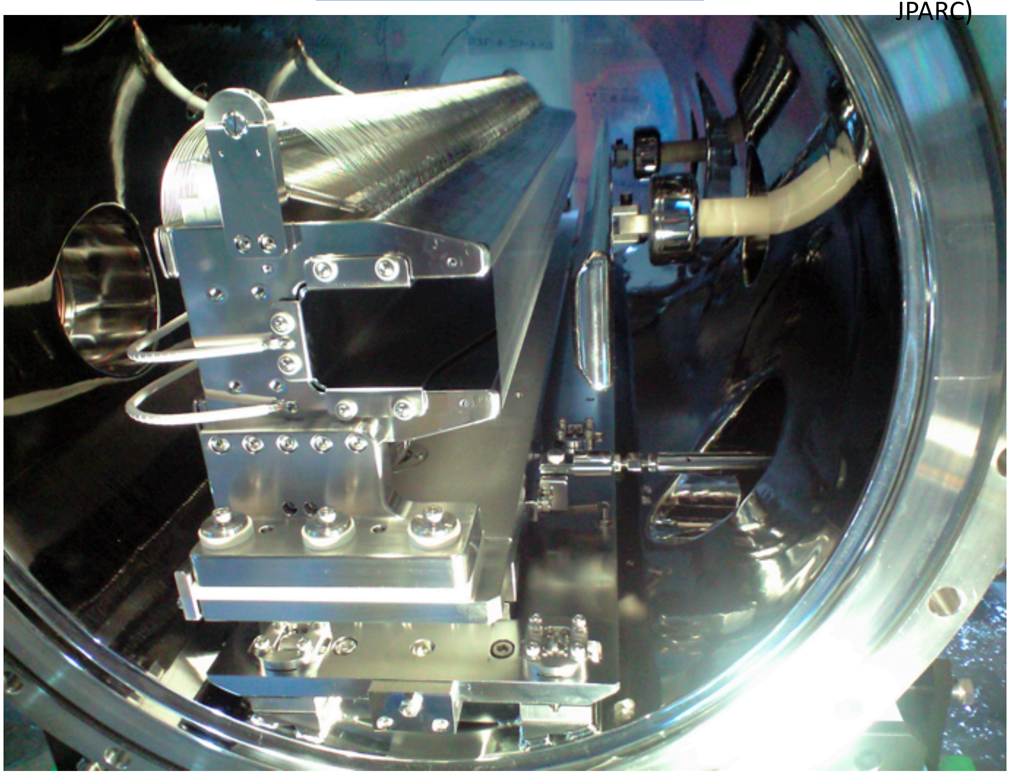
Tune is approached
linealy to 22.333 resonance
by 48-QFNs in the arcs

(Masahito Tomizawa
JPARC)

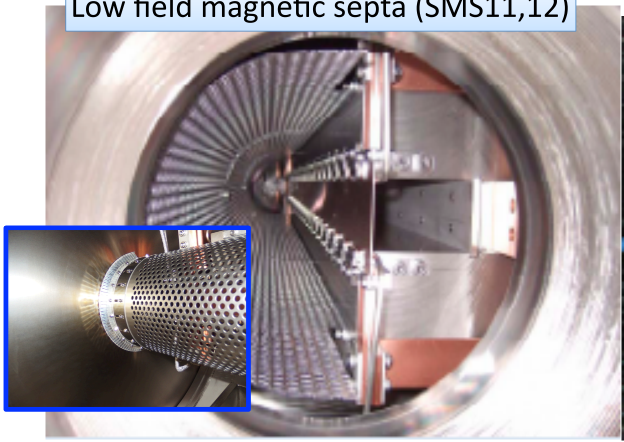


Electro Static Septa (ESS1,2)

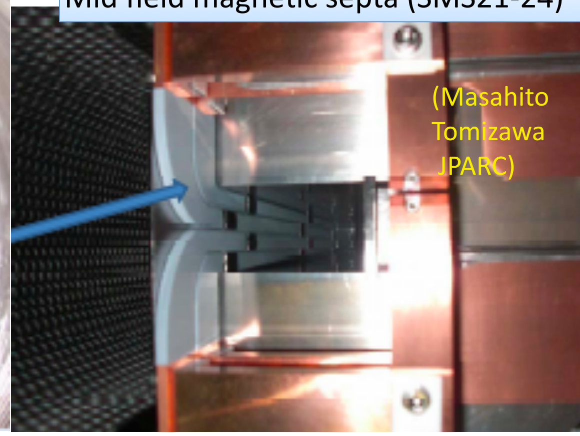
(Masahito
Tomizawa
JPARC)



Low field magnetic septa (SMS11,12)

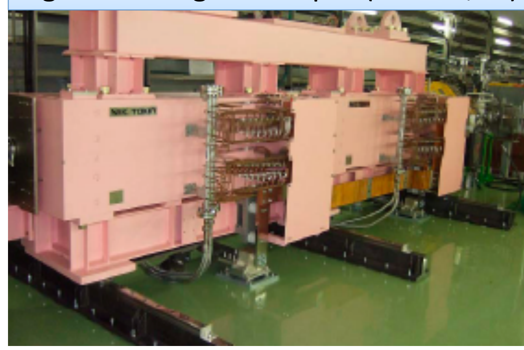


Mid field magnetic septa (SMS21-24)



High field magnetic septa (SMS31,32)

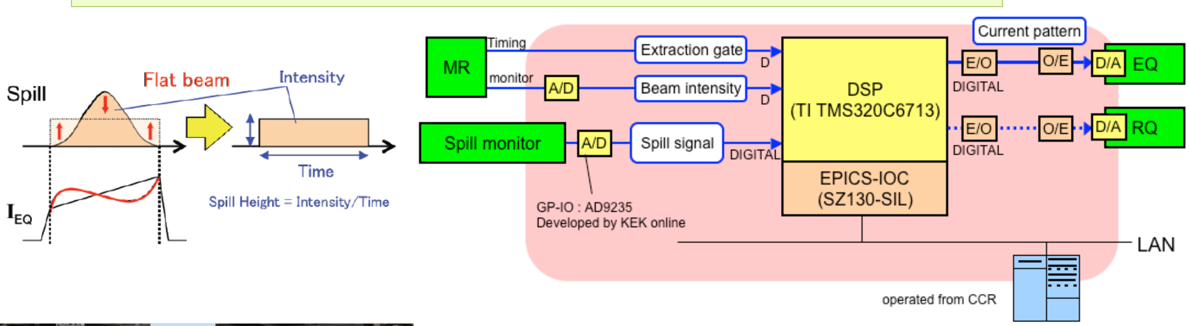
High field magnetic septa (SMS33,34)

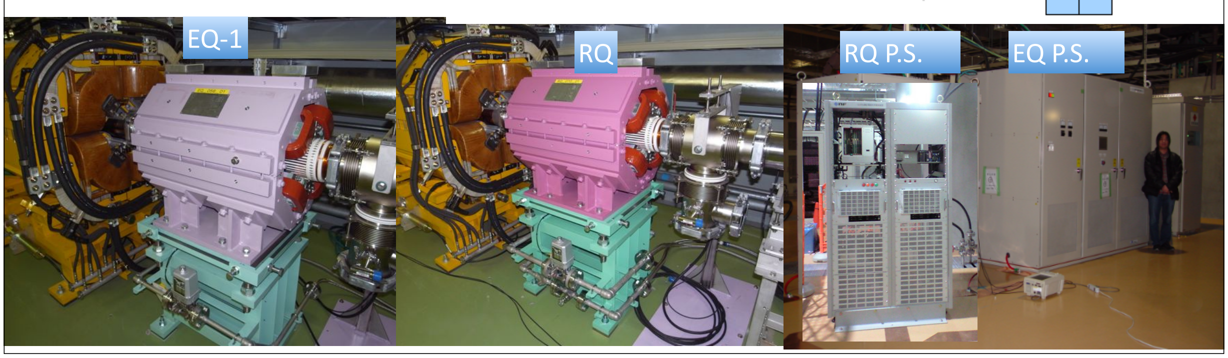


Beam Spill Feedback System

(Masahito Tomizawa JPARC)

A beam intensity monitor is placed in external beam line.
Uniform beam spill shape is obtained from tune modulation by quadrupoles EQ
Tune ripples are compensated by quadrupole RQ (and EQ)
A DSP processes EQ and RQ current values from the monitor signal





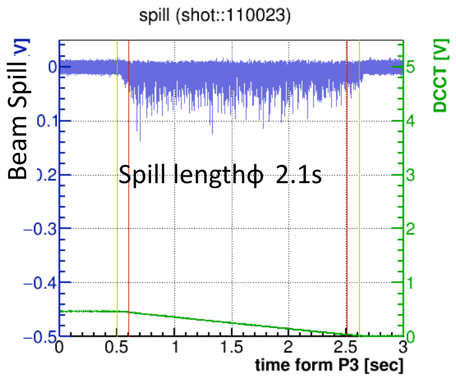
41.6kW User Operation Performances

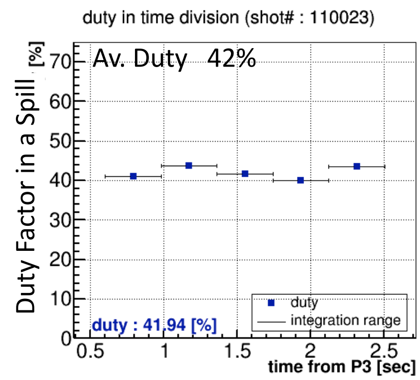
(Masahito Tomizawa JPARC)

I(t): PM signal sampled at 100KHz through 10KHz LPF

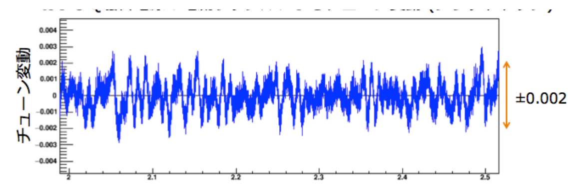
$$Spill\,Duty\,Factor = \left[\int_0^T I(t)dt\right]^2 \Big/ \left[\int_0^T dt \cdot \int_0^T I^2(t)dt\right]$$

ideal spill -> 100%





Large tune ripple produced by BM and Q current ripple



New Result 5/29 Study Duty 58%

Multi-Turn Extraction (CERN PS)

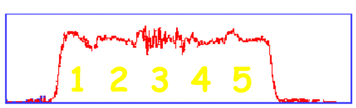
- CERN SPS is 11 times as long as PS.
  - 10 PS batches & one batch gap

PS PS $C_{SPS} = 11\ C_{PS}$

SPS circumference

(M. Giovannozzi) CERN

First PS batch Second PS batch Gap for kicker



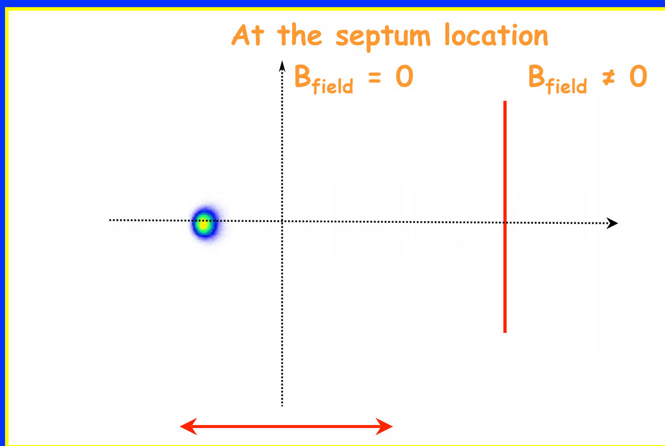
Beam current transformer in the PS/SPS transfer line

(total spill duration 10.5 μs)

- How to extract over 5 turns?
  - slice the bunches, or
  - split the beam into 4+1 beamlets using 4th order resonance.
- Splitting in principle allows loss-less extraction of 5 turns
- Proven to work @ the SPS

Novel CERN multi-turn extraction

Final stage after 20000 turns (about 42 ms for CERN PS)

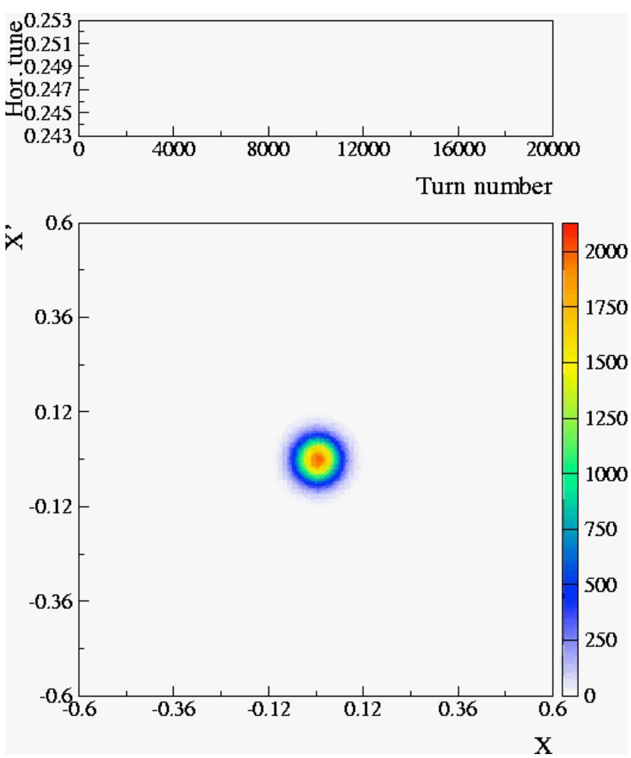


About 6 cm in physical space

Slow (few thousand turns) bump first (closed distortion of the periodic orbit)

Fast (less than one turn) bump afterwards (closed distortion of periodic orbit)

MTE Demo

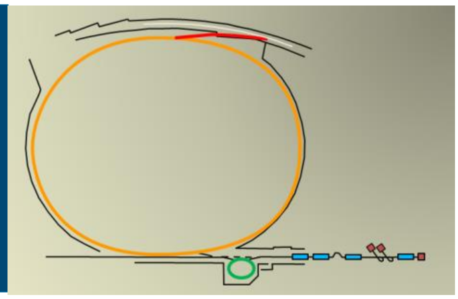


M. Giovanozzi et al., CERN

References

- M. Fraser & B. Goddard, “SPS slow-extraction: Challenges and possibilities for improvement”, Physics Beyond Colliders Kick-off Workshop, CERN, Sep-2016.
- M. Tomizawa, “J-PARC Slow Extraction”, Slow-Extraction Workshop, Darmstadt, DE, Jun-2016.
- M. Giovannozzi, “Resonant extraction: review of principles and experimental results”, ibid.

Electron Injection: Synchrotron Radiation and Injection Schemes



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Argonne National Laboratory

US Particle Accelerator School
Rohnert Park, CA
July 2024

1

Outline

- **Introduction**
- **Synchrotron radiation**
- **Electron beam injection schemes:**
  - **On-axis**
  - **Off-axis (betatron)**
  - **Synchrotron**
- Multipole kickers
- Top-up operation
- Swap-out injection
- Electron beam extraction
- Diagnostics

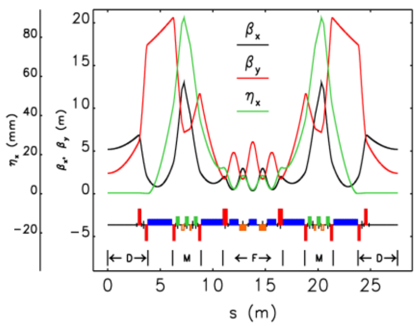
2

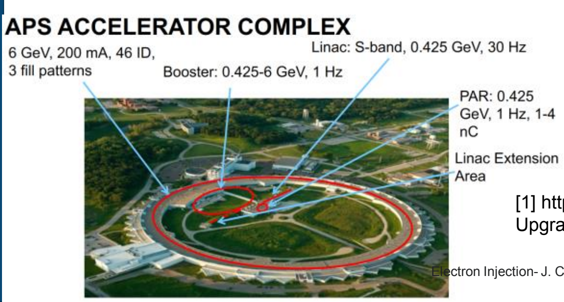
Introduction

- Previously we discussed hadrons (composite particle with mass > 900 MeV)
- Now we'll talk about electrons (fundamental particles with mass ~= 0.5 MeV)
  - Same applies to positrons, with some minus signs
- Most key concepts still apply (optics, phase space, matching, etc.)
- Big difference is synchrotron radiation
  - Radiation power ~$1/m^3$
  - Electrons radiate ~6e9 times as much as protons
  - Electron motion is damped
  - Space charge effects less severe in $e-$ as they become relativistic at lower E ($\gamma = \frac{E}{mc^2}$)
- Damping radiation allows for:
  - Different injection schemes and techniques
  - Relaxed tolerances on injection precision and matching
- Electron injection used in light sources and colliders

Example: Advanced Photon Source Upgrade[1] (APS-U)

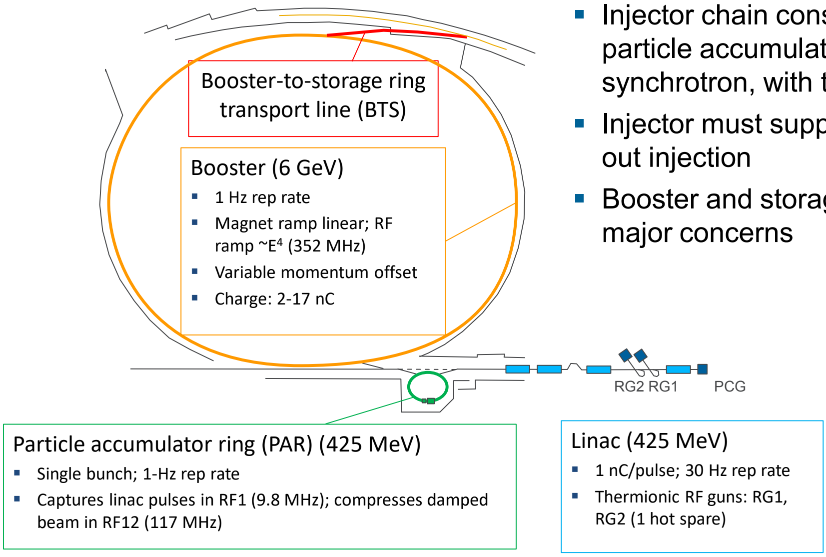
- Light source: circulating electron beam is used to produce focused and intense x-ray beams
- New storage ring: 42-pm emittance @ 6 GeV, 200 mA
- X-rays produced by "insertion devices", which shake the beam in a certain way to produce the desired x-ray beam
- Challenging lattice with small dynamic aperture
- **Uses swap-out injection: full bunch replacement**



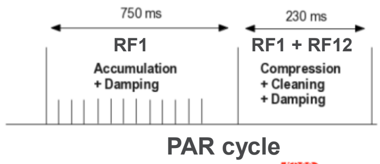


[1] https://aps.anl.gov/APS-Upgrade/Documents

APS-U injector chain



- Injector chain consists of a linear accelerator, particle accumulator ring, and booster synchrotron, with transfer lines between them
- Injector must supply full charge bunch for swap-out injection
- Booster and storage ring injection efficiencies are major concerns

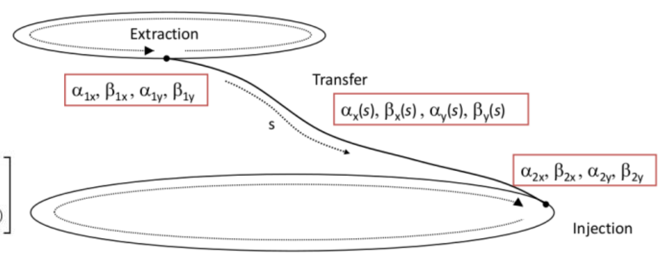


Transfer line

- A transfer line (TL) transports the beam from extraction of one machine to injection of the next one
- Trajectories must be matched ($\beta_{x,y}$, $\alpha_{x,y}$, $\eta_{x,y}$ and $\eta'_{x,y}$)
- Additional constraints as minimum bend radius, maximum quadrupole gradient, magnet aperture, cost, etc.
- Each element can be expressed as a matrix, thus the TL can be represented by the product of n matrices

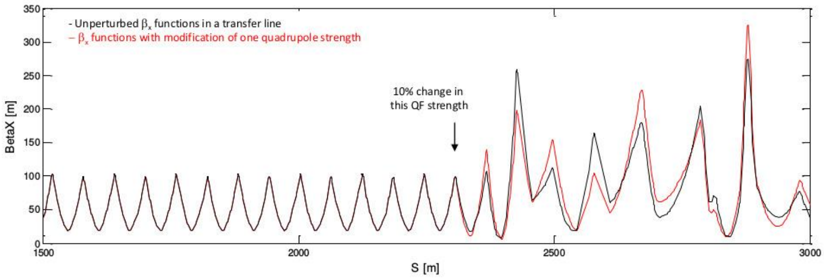
$$\begin{bmatrix} x_2 \\ x_2' \end{bmatrix} = \bar{M} \begin{bmatrix} x_1 \\ x_1' \end{bmatrix} = \prod_{i=1}^{n} M_i \begin{bmatrix} x_1 \\ x_1' \end{bmatrix}$$

$$\bar{M} = \begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(cos(\Delta\mu) + \alpha_1 sin(\Delta\mu)) & \sqrt{\beta_2\beta_1} sin(\Delta\mu) \\ \sqrt{\frac{1}{\beta_2\beta_1}}((\alpha_1 - \alpha_2)cos(\Delta\mu) - (1 + \alpha_1\alpha_2) sin(\Delta\mu)) & \sqrt{\frac{\beta_1}{\beta_2}}(cos(\Delta\mu) - \alpha_2 sin(\Delta\mu)) \end{bmatrix}$$



Twiss and Dispersion Propagation

- Transfer lines are single pass machines -> no periodic solution exists
- Twiss parameters $\beta_{x,y}$, $\alpha_{x,y}$, $\eta_{x,y}$ and $\eta'_{x,y}$ are propagated through $\overline{M}$
- Twiss and dispersion values at any point depend on
  - Machine elements
  - Initial coordinates
- A change of an element only affects the downstream Twiss and dispersion values



Synchrotron Radiation

Radiation power

A point-like particle travelling under acceleration radiates a total power as:

$$P_\gamma = \frac{2 r_c m_0 \gamma^6 \left(\vec{\dot{\beta}}^2 - \left(\vec{\beta} \times \vec{\dot{\beta}} \right)^2 \right)}{3c}$$

first derived by Lienhard in 1898

Transverse and longitudinal radiated power can be expressed as:

$$P_\gamma = \frac{2\ r_c\ c\ \gamma^2 \dot{p_\perp}^2}{3\ m_0}$$

$$P_\gamma = \frac{2\ r_c\ \dot{p_{||}}^2}{3\ m_0\ c}$$

The transverse power is a factor γ^2 more severe than the longitudinal

Power emitted

The variation of $p_\perp$ is related to the bending radius (ρ) as:

$$\frac{\partial}{\partial t} p_\perp = \frac{m\ \gamma\ \beta^2}{\rho}$$

Assuming β≈1, this gives:

$$P_\gamma = \frac{E^4\ C_\gamma\ c}{2\ \pi\ \rho^2} \qquad C_\gamma = \frac{4\ \pi\ r_c}{3\ m_0^3}$$

What is the ratio between C_γ(e−) and C_γ (p+)? Just look at the following table....

Machine	Particle	Circum. [km]	Energy [GeV]	Synch.Rad Critical Energy [eV]	Total Power emitted SR [kW]
LEP	e^+e^-	26.7	100	$7 \cdot 10^5$	$1.7 \cdot 10^4$
LHC	p	26.7	7000	44	7.5

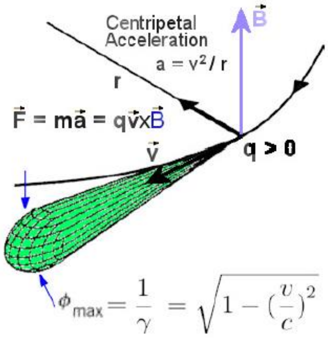
Energy loss

The energy loss due to radiation over 1 turn is obtained by integrating this over 2π

$$U_\gamma = \frac{E^4\ C_\gamma\ c}{\rho}$$

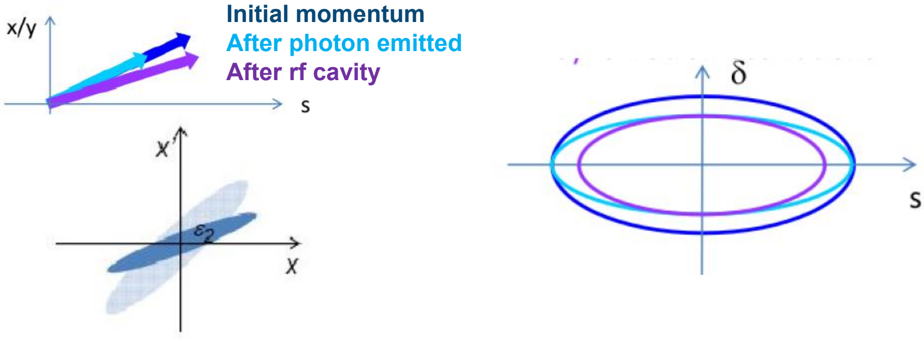
The light emitted by particles on a bend trajectory is within a forward cone of angle θ_{SR}

$$\theta_{\rm SR} = \frac{1}{\gamma}$$



Radiation damping

- This effect takes place on circular machines at energies where synchrotron radiation is emitted (e.g. synchrotron light source).
- The beam energy is kept *constant* thanks to the accelerating cavities, which provide the exact energy lost by SR per turn
- The angle of a particle against the reference orbit is the ratio of transverse over longitudinal momentum $yp_0 = p_\perp/p$



Radiation damping

However when the particle changes its momentum by Δp

$$yp = yp_0 \frac{p_\perp}{p + \Delta p} \approx yp_0 \left(\frac{p_\perp}{p} - \frac{p_\perp}{p^2} \Delta p \right) = \left(1 - \frac{\Delta p}{p} \right) yp_0 \quad (1)$$

The position (y) and angle (yp) at a given position can be expressed in terms of $A = \sqrt{\epsilon}$, β and ϕ as;

$$y = A\sqrt{\beta} cos(\phi) \quad (2)$$

$$yp = -\frac{A(sin(\phi) + cos(\phi))}{\sqrt{\beta}} \quad (3)$$

(if one neglects the contribution equal or higher than $O(\Delta p^3)$)

Emittance reduction

The Courant-Snyder invariant reads as;

$$A^2 = \beta \, yp^2 + 2\alpha \, y \, yp + \gamma \, y^2 \quad (4)$$

When crossing the cavity, the invariant is modified by $(A + \Delta(A))^2 - A^2$ which is equal to taking the total derivative of Eq. (4) , this leads to

$$2A\Delta(A) = 2\alpha \, y\Delta(yp)yp^2 + 2\beta yp + \Delta(yp) \quad (5)$$

It has been assumed $\Delta y = 0$ at the cavity, in fact

$$\Delta yp = -\frac{U_\gamma}{E_s} yp \quad (6)$$

Plug Eqs. (6, 2, 3) into Eq. (5) and integrating over all phases ($\phi = 0..2\pi$) leads to

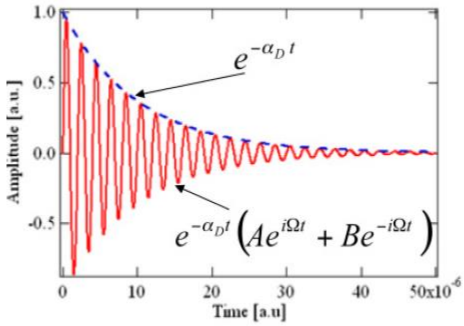
$$2\Delta(A) = -\frac{A \, U_\gamma}{E_s} \xrightarrow{\text{Diff.Eq.}} 2\frac{d}{dt}A(t) = -\frac{A(t)U_\gamma}{\tau_s \, E_s} \quad (7)$$

where τ_s is the revolution time of the synchronous particle

Synchroton Radiation: Damping Time

Solving Eq (7) and assuming $A(t=0) = A_0$

$$A(t) = A_0 \cdot e^{t \cdot D_y} \qquad (8)$$



We define the vertical damping rate (D_y) as,

$$D_y = -\frac{U_\gamma}{2\tau_s E_s} = \frac{J_y}{2\tau_s} \quad (9)$$

The resulting betatron motion is damped in time

Synchroton Radiation: Damping Time

Motion in the horizontal and longitudinal planes are also damped

However the derivation is more complex, as dispersion links both plans (see Ref [1], Ch 8)

$$D_x = \frac{(1-D)U_\gamma}{2\tau_s E_s} = \frac{J_x}{2\tau_s} \qquad (10)$$

$$D_z = \frac{(2+D)U_\gamma}{2\tau_s E_s} = \frac{J_z}{2\tau_s} \qquad (11)$$

Where D depends on the dispersion (η(s)), bending radius (ρ(s)) and the focusing elements (k(s)) of the ring as,

$$D = \frac{\int \frac{\eta(s)(1+2\rho(s)^2)k(s)}{\rho(s)^3} ds}{\int \frac{1}{\rho(s)^2} ds} \qquad (12)$$

D_x, D_y and D_z are related by Robinson's damping criterion:

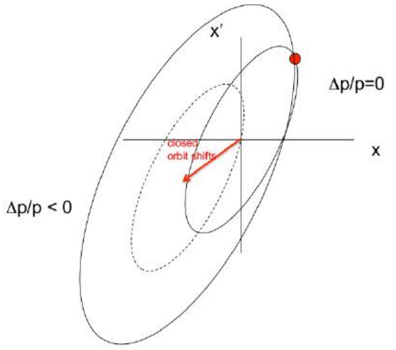
$$J_x + J_y + J_z = 4 \qquad (13)$$

Synchroton Radiation: Quantum Excitation

Eq. (8) tells us that emittance ⇒ 0 for sufficient time

In reality there is a competing process between radiation damping and quantum excitation that determines the equilibrium $\in_x$, $\in_y$ and $\in_z$

When an e^- emits a photon with energy (μ_γ) on a dispersive region there are 2 effects



- x changes as $\frac{\eta(s)u_\gamma}{E_s}$
- xp changes and so $\frac{\eta'(s)u_\gamma}{E_s}$ due to $\frac{1}{\gamma}$

Synchroton Radiation: Quantum Excitation

Following the same strategy as used to solve Eq. (4) (but now for the horizontal plane), we arrive at

$$\Delta(A^2) = \frac{(\beta\eta'^2 + 2\alpha\eta\eta' + \gamma\eta^2)u_\gamma^2}{E_s^2} \qquad (14)$$

The final emittance depends on the Twiss and dispersion functions. For convenience we define

$$\mathcal{H}(s) = \beta\eta'^2 + 2\alpha\eta\eta' + \gamma\eta^2 \qquad (15)$$

Integrating Eq.(14) and weighting over the number of emitted photons $(N_\gamma(u_\gamma(s)))$ we arrive at the following equation

$$\frac{\Delta(A^2)}{\tau_s} = \frac{\int \frac{\mathcal{H}u_\gamma(s)^2 N_\gamma(u_\gamma(s))}{E_s^2} ds}{c\tau_s} \qquad (16)$$

Synchroton Radiation: Equilibrium Emittance

After converting Eq.(16) into a differential equation and adding the damping contribution Eq.(7) we arrive at,

$$2\frac{d}{dt}A(t)\;A(t) = -\frac{A(t)^2 U_\gamma}{\tau_s\;E_s} + \frac{\int \frac{\mathcal{H} u_\gamma(s)^2 N_\gamma(u_\gamma(s))}{E_s^2} ds}{c\tau_s} \qquad (17)$$

After solving this differential equation,

$$A(t)^2 = A_0\; e^{-\frac{U_\gamma\; t}{\tau_s\; E_s}} + \frac{\int \mathcal{H} u_\gamma(s)^2 N_\gamma(u_\gamma(s)) ds}{c\tau_s\; E_s^2} \qquad (18)$$

It is now clear that $A^2(t) = \in(t) \neq 0$ when $t \;\rightarrow \infty$

Synchrotron Radiation: Equilibrium Emittance

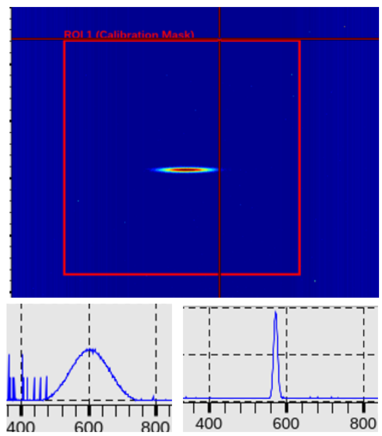
The competition between radiation damping and excitation produces an equilibrium beam which is Gaussian in both planes

The equilibrium horizontal emittance is $\epsilon_{x0} = C_q \frac{\gamma^2}{J_x}\frac{I_{5x}}{I_2}$ (19)

$$I_{5x} = \oint \frac{H}{\rho} \mathrm{ds} \qquad I_2 = \oint \frac{1}{\rho^2} \mathrm{ds} \qquad C_q \approx 3.8 \times 10^{-13}$$

Ideally, there is no vertical dispersion, and the equilibrium vertical emittance is determined by the photon emission angle ~ 1/γ. In practice there is always some coupling between the x and y planes. The emittances obey the rule $\epsilon_x + \epsilon_y = \epsilon_{x0}$

Beam extracted from APS booster

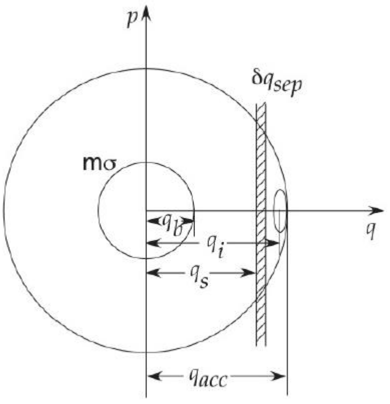


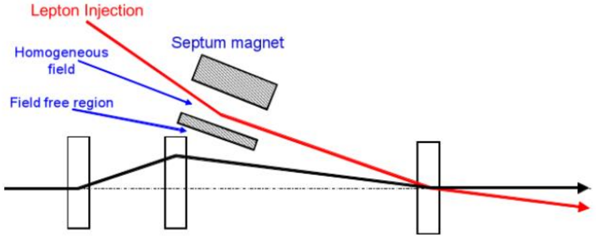
X profile Y profile

Electron Injection Schemes

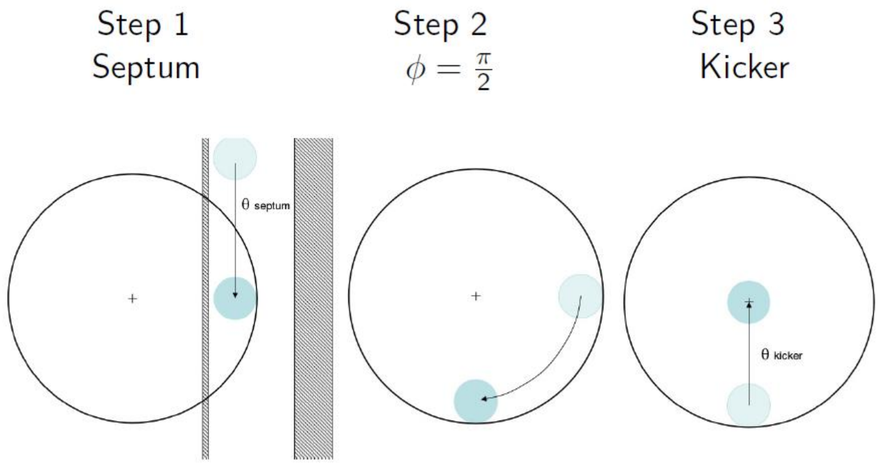
Injection scheme

- Bring injected beam as close as possible to reference orbit, by:
  - Septum (either DC or pulsed)
  - Kicker (pulsed, low field, fast rise/fall times)
- Bumped circulating beam to relax septum/kicker requirements
- Inject beam into machine acceptance





Injection steps



Beam losses

- Injection process should minimize beam losses for both injected or circulating beams to avoid irradiation, activation or even direct damage of machine components
- A thin septum is desirable to align the incoming beam to the current beam onto the orbit bump
- Orbit bump is usually constructed by 3 (or 4) correctors to bring stored beam close to septum (and as parallel as possible)
- Injected beam should fit into the acceptance of the machine (e.g. storage rings >10 σ of stored damped beam)
- Acceptance of injection system should at least stay above a few σ except for very brief moments to minimize beam losses

Quantum lifetime

- The equilibrium emittance obtained in Eq. (18) determines the distribution of the electrons which will be Gaussian (Central Limit Theorem)
- There is a constant exchange of particles in the core of the beam and in the tail
- e− stored beams are inevitably Gaussian beams. If beam's tail is, it will be replenished at expenses of intensity
- The Quantum Lifetime (τ_q) is found to be [2]: $$\frac{1}{\tau_q} = \frac{A_0^2}{D_x \sigma_x^2} e^{-\frac{A_0^2}{2\sigma_x^2}}$$

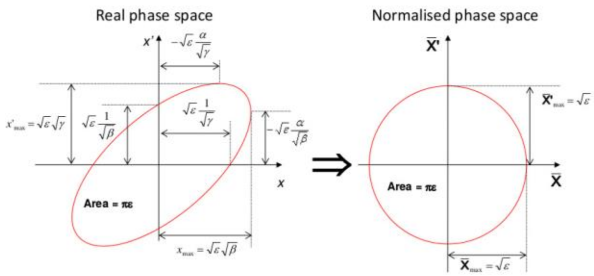
In absence of resonance, with D_x the horizontal damping time, Eq. (10) and A_0 the physical aperture of the machine:

A_0/σ_x	5	5.5	6	6.5	7
τ_q	1.8 min	20.4 min	5.1 h	98.3 h	103 days

Normalized Coordinates

- Normalized coordinates are frequently used to analyze injection and extraction schemes

$$x, x' \xrightarrow{N} X, X' \quad \begin{pmatrix} X \\ X' \end{pmatrix} = N \begin{pmatrix} x \\ x' \end{pmatrix} = \frac{1}{\sqrt{\beta_s}} \begin{pmatrix} 1 & 0 \\ \alpha_s & \beta_s \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$

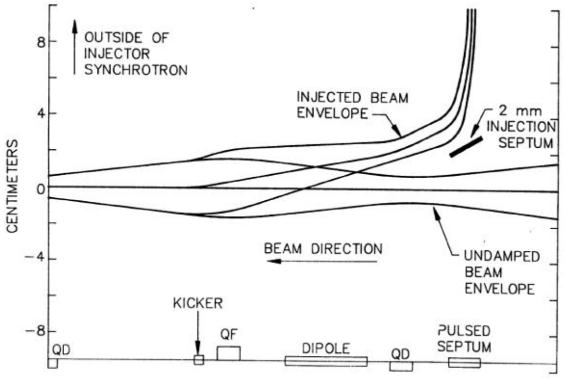


$$X = \frac{x}{\sqrt{\beta}} \qquad X' = \frac{\alpha x + \beta x'}{\sqrt{\beta}}$$

$$\varepsilon = \gamma \cdot x^2 + 2\alpha \cdot x \cdot x' + \beta \cdot x'^2 \qquad \varepsilon = \bar{X}^2 + \bar{X}'^2$$

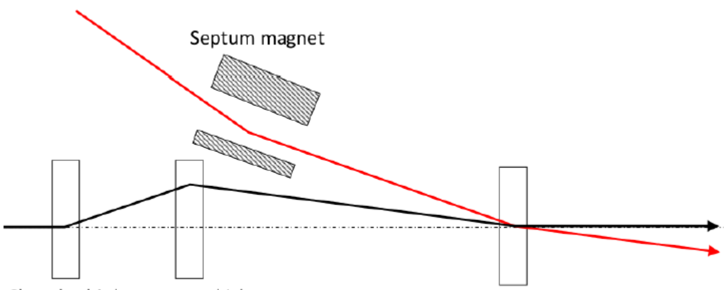
On axis injection

- Simplest idea- use septum and kickers to bring injected beam onto closed orbit
- Don't need an orbit bump
- Will kick out / disrupt other bunches
- Works for:
  - Single bunch machines (e.g. APS booster)
  - Swap-out injection (more on this later)



Betatron injection

- Injected beam is offset at the septum with its own Twiss, dispersion and emittance
- Injected beam is injected with an angle with respect to the closed orbit
- Injected beam performs damped betatron oscillations about the closed orbit

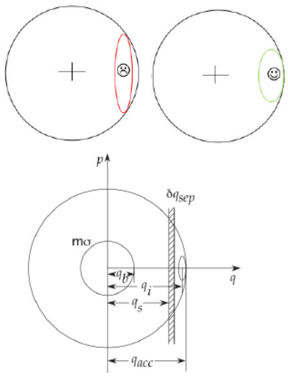


Betatron Injection: Optimum Injection

There exists an optimum injection where the mis-matched at the septum is minimized

Optimum conditions:

- Circle curvature (circulating) = Ellipse curvature (injected)
- Upright ellipse



circulating: $\epsilon_{acc} = q_{acc}^2 + p_{acc}^2$

injected: $\epsilon_i = b_i p_i^2 + \frac{q_i^2}{b_i}$

where b_i represents the beta function into norm. phase space $b_i = \frac{\beta_i}{\beta_r}$

Optimum condition is expressed as:

$$\frac{d^2 q_{acc}}{dp_{acc}^2}|_{p=0} = \frac{d^2 q_i}{dp_i^2}|_{p_i=0}$$

Betatron injection: optimum injection

$$\frac{d^2 q_{acc}}{dp_{acc}^2}|_{p_{acc}=0} = -\frac{1}{\sqrt{\epsilon_{acc}}}$$

$$\frac{d^2 q_i}{dp_i^2}|_{p_i=0} = -\frac{b_i^{3/2}}{\sqrt{\epsilon_i}}$$

Which leads to

$$\frac{\beta_i}{\beta_{acc}} = \left(\frac{\epsilon_i}{\epsilon_{acc}}\right)^{1/3}$$

if injection happens at a point where $\alpha_r \neq 0$:

$$a_i = \alpha_{acc} - \alpha_i \frac{\beta_i}{\beta_{acc}}$$

The optimum is when ellipse is not tilted ($a_i = 0$), therefore

$$\frac{\alpha_i}{\alpha_{acc}} = \frac{\beta_i}{\beta_{acc}}$$

- These equations solve the matching problem for off-axis injection
- General rules are:
  - Injection (as extraction) are located on straight sections
  - Septum is placed at a high beta point to reduce the phase space taken by the width of the septum

Betatron Injection: Injection Parameters

Machine acceptance ($\sqrt{\epsilon_{acc}}$) should exceed the injection septum (q_s) in order to inject the beam into the closed orbit

This condition is assured by shifting the closed orbit towards the septum by means of 180° - bump (upstream and downstream kickers are located at phase advanced $\pm 90°$) w.r.t. septum

At the septum we need a displacement of

$$\delta q_s = q_s - q_b$$

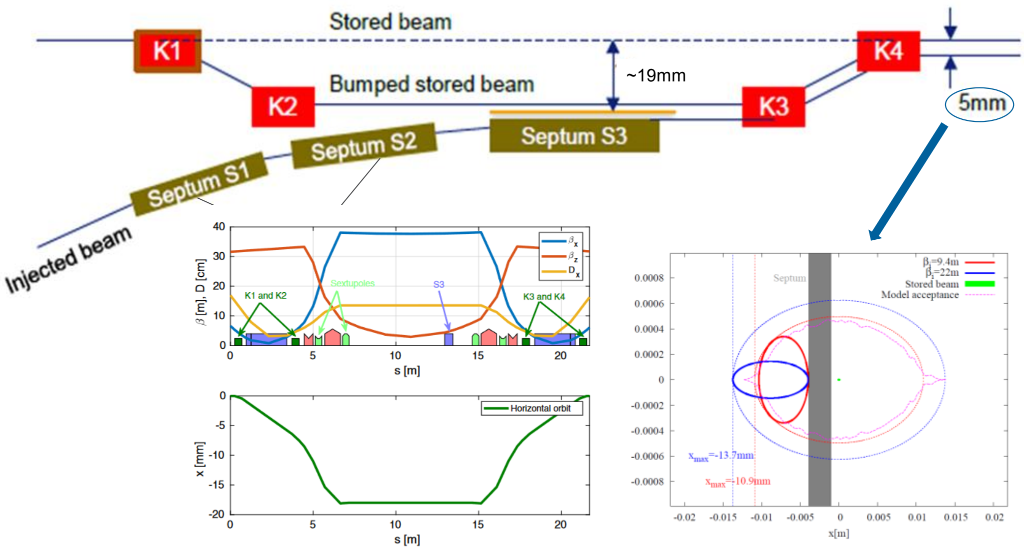
The angle required by the upstream kicker is

$$\delta x'_k = \frac{\delta p_k}{\sqrt{\beta_k}} = \frac{\delta q_s}{\sqrt{\beta_k}} = \frac{q_s - q_b}{\sqrt{\beta_k}}$$

as they are 90° apart. Taking into account that $q_s = \frac{x_s}{\sqrt{\beta_r}}$ and $q_b = \mathrm{m}\sqrt{\epsilon_b}$, we arrive at

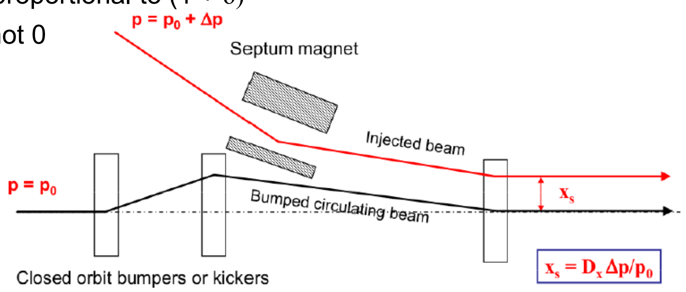
$$\delta x'_k = \frac{x_s}{\sqrt{\beta_k \beta_r}} - \frac{\mathrm{m}\sqrt{\epsilon_b}}{\sqrt{\beta_k}}$$

Example: ESRF EBS (S. White) [3]



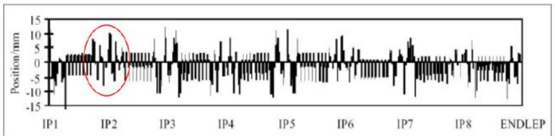
Synchrotron injection scheme

- An alternative injection scheme that avoids off-axis injection in the transverse plane is the synchrotron or longitudinal injection. In this case the beam is centered in x/y but off-energy
  - Beam injected parallel to circulating beam
  - Synchrotron oscillations at Qs
  - Beam does not perform betatron oscillations
  - Energy loss due to SR is proportional to $(1 + \delta)^3$
  - Dispersion at injection is not 0

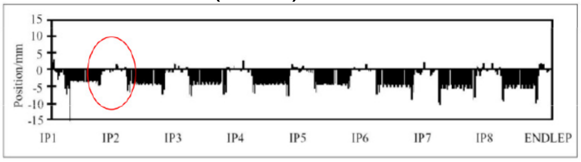


Example: LEP

- Both schemes were implemented in LEP [4], [5] at 20 GeV
- Betatron Injection : 6000 turns (0.6 s)



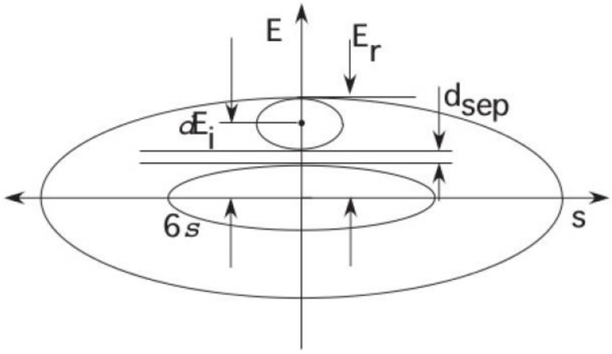
- Synchrotron Injection: 3000 turns (0.3 s)



- Synchrotron Injection in LEP gave improved background for experiments due to small orbit offsets in zero dispersion straight sections

Phase space

- In this scenario the phase space (z, E) looks like:



- The septum appears as a horizontal line of a thickness given by d_{sep} = ths/η, where ths the physical thickness of the septum and η the dispersion at the septum location

Energy offset

- The horizontal offset required is: $\delta x = \sqrt{(m\sigma_E \eta)^2 + m^2 \epsilon_x \beta_x} + n\sigma_{E_{inj}}\eta$
- In terms of the energy offset: $\delta_E = m\sqrt{\sigma_E^2 + \frac{\epsilon_x}{\mathcal{H}}} + n\frac{\sigma_E}{\mathcal{H}}$
  - *m* is the number of minimum acceptance during injection, in terms of stored beam σ
  - *n* is the number of σ accepted of the injected beam
- This equation shows the importance of $\mathcal{H}$
- Colliders are suitable for synchrotron injection (as η(IP) = 0)
- Circular light sources are not as well suited since the value of $\mathcal{H}$ is dictated by the low emittance requirements

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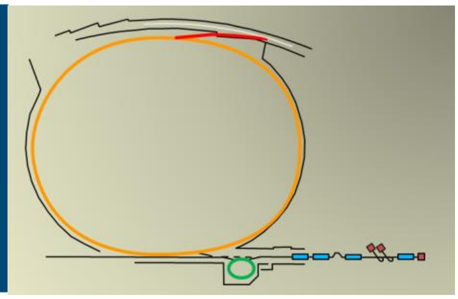
Electron Injection: Multipole Kickers, Top-Up Operation



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Rohnert Park, CA
July 2024

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Outline

- Introduction
- Synchrotron radiation
- Electron beam injection schemes
- **Multipole kickers**
  - **Quadrupole**
  - **Sextupole**
- **Top-up operation**
- Swap-out injection
- Electron beam extraction
- Diagnostics

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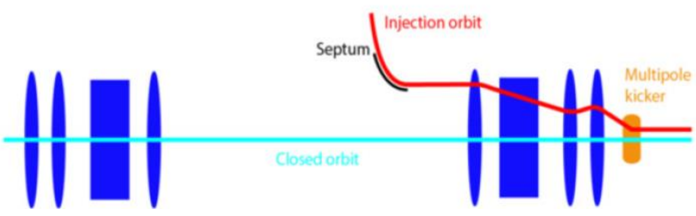
Multipole kickers

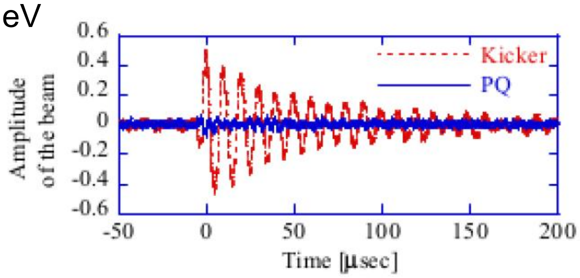
Quadrupole kicker

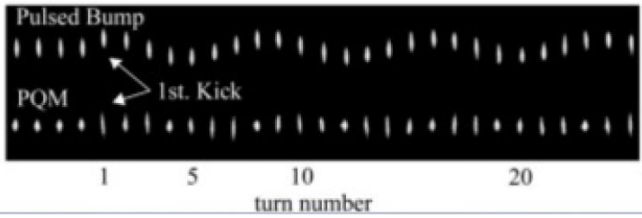
- The hardware implemented is a septum plus a pulsed quadrupole
- Pros:
  - Stored beam is unperturbed, since the multipole magnet has 0 field on axis
  - Betatron or synchrotron injection schemes could be implemented
  - Reduced space
- Cons:
  - Alignment of the pulsed magnet (distortion of stored beam)
  - Beam profile modulation
  - Transient emittance growth



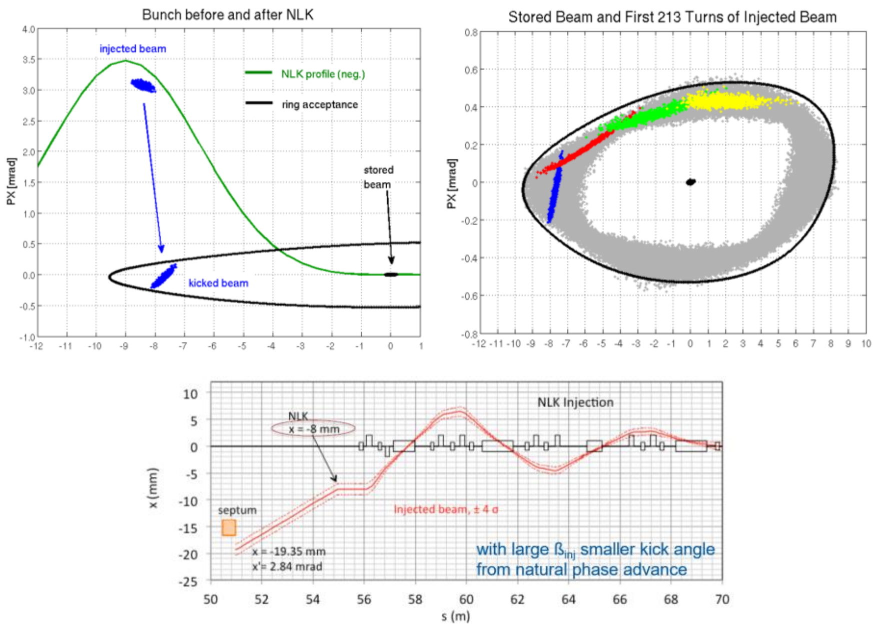
Example: Photon Factory Advanced Ring (PF-AR) 2007

- This scheme was experimentally tested at PF-AR in KEK, Japan [1]
- Beam injection at 3 GeV





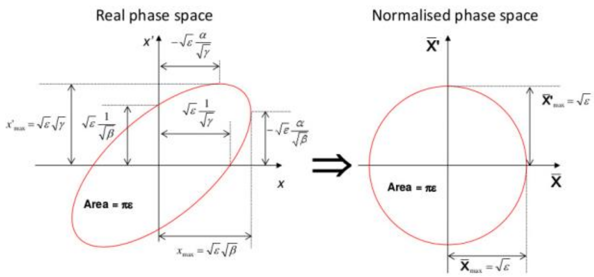
Sirius injection scheme [2]



Normalized Coordinates

- Normalized coordinates are frequently used to analyze injection and extraction schemes

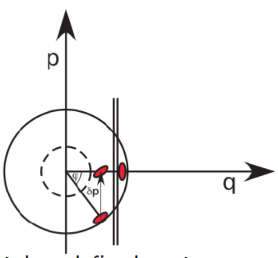
$$x, x' \xrightarrow{N} X, X' \quad \begin{pmatrix} X \\ X' \end{pmatrix} = N \begin{pmatrix} x \\ x' \end{pmatrix} = \frac{1}{\sqrt{\beta_s}} \begin{pmatrix} 1 & 0 \\ \alpha_s & \beta_s \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}$$



$\varepsilon = \gamma \cdot x^2 + 2\alpha \cdot x \cdot x' + \beta \cdot x'^2$ $\qquad$ $\varepsilon = \bar{X}^2 + \bar{X}'^2$

Phase space

Injected beam usually enters at $q = q_i, p = 0$
After rotating ϕ the quadrupole kicks the beam closer to closed orbit
It also focuses/defocuses the injected beam $\Rightarrow$ changing its matching condition



$$q = q_i \qquad p = p_i$$

$$q_{i,1} = q_i cos(\phi) + p_i sin\phi$$
$$p_{i,1} = p_i cos(\phi) + q_i sin\phi$$

$$q_{i,2} = q_{i,1}$$
$$p_{2,1} = p_{i,1} + k_q q_{i,1}$$

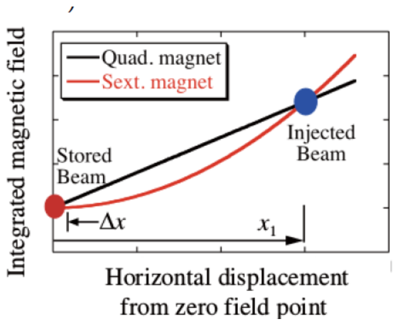
Initial and final emittances

$$\epsilon_0 = q^2 + p^2$$
$$\epsilon_2 = q_{i,2}^2 + p_{i,2}^2 = (1 + k_q^2)q^2 + 2k_q pq + p^2$$

Although the beam is miss-matched it will be damped!

Sextupole kicker

- The hardware implemented is a septum plus a pulsed sextupole [3]
- Pros:
  - Stored beam is unperturbed, since the multipole magnet has 0 field on axis
  - Betatron or synchrotron injection schemes could be implemented
  - Extended field-free region on-axis (less distortion of stored beam)



Comparison field gradient (k) and the field strength (kl) on the stored beam

$$k_2 l = 0.05 k_1 l$$
$$k_2 = 0.1 k_1$$

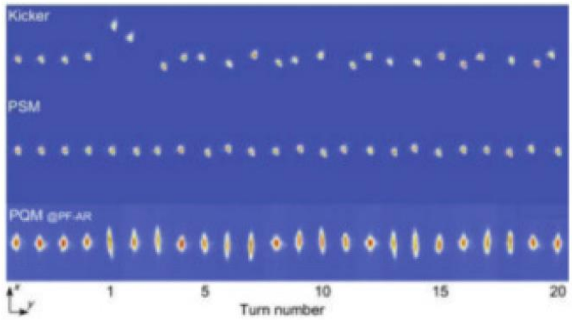
Example: Photon Factory Advanced Ring (PF-AR)

- Installation of pulse sextupole magnet at the Photon Factory in 2008

4-kicker

PSM

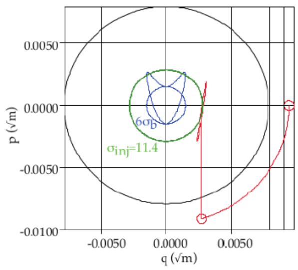
PQM



- Coherent dipole oscillations of the stored beam in both planes are much smaller
- Top-up injection 0.02% in peak to peak during two hours
- Amplitude of the stored beam oscillation in the injection was much reduced

Phase space

Analysis is very similar to the PQM scheme



$$q = q_i \qquad p = p_i$$

$$q_{i,1} = q_i cos(\phi) + p_i sin\phi$$
$$p_{i,1} = p_i cos(\phi) + q_i sin\phi$$

$$q_{i,2} = q_{i,1}$$
$$p_{2,1} = p_{i,1} + k_s q_{i,1}^2$$

Initial and final emittances

$$\epsilon_0 = q^2 + p^2$$

$$\epsilon_2 = q_{i,2}^2 + p_{i,2}^2 = (1 + k_s^2 q_b^2) q_b^2$$

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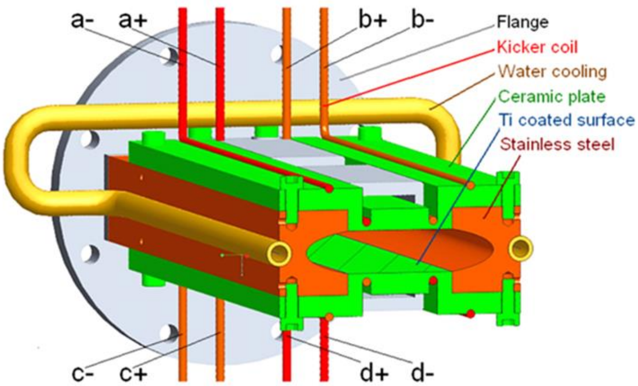
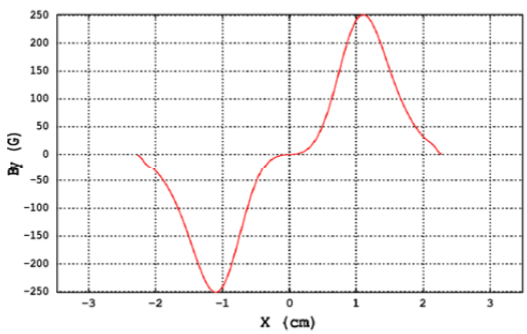
Nonlinear kicker- BESSY II Design [4]





- Design challenges: eddy currents in the metallic frame and the connection of the eight wires in series
- There will always be a sweet spot with vanishing horizontal and vertical fields somewhere in the center of the magnet. Not necessarily where the gradient is zero, even with better designs.
- Building the NLK is non-trivial.
- Nice recent results from MAX IV [5]

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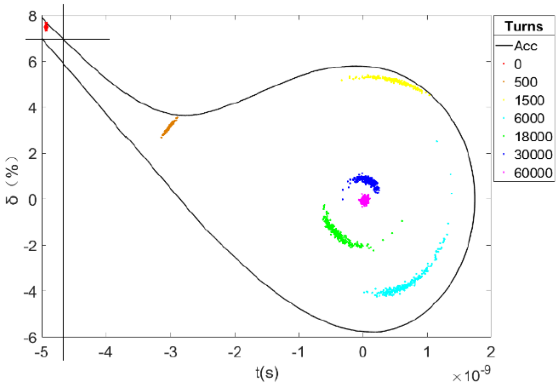
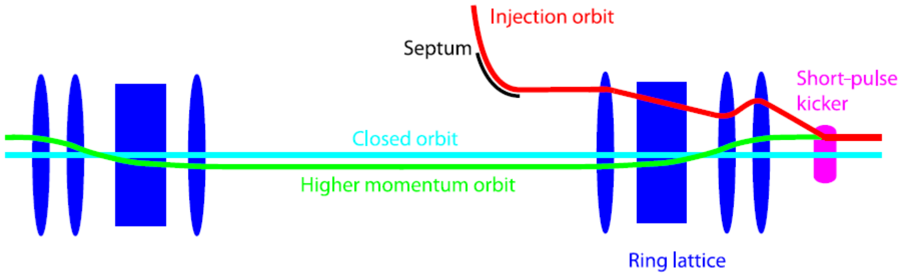
Longitudinal injection [6]

- With radiation damping, rf bucket takes on a “golf club” shape- particles with a (negative) time and (positive) energy offset can be accepted
- Does not require an orbit bump
- No disturbance of stored beam
- Requires very fast injection kicker (< 10 ns) to kick injected but not stored beam





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Top-up Injection

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Fill & Coast Cycles

- In the old days, machines operated in two modes:
  - Fill: beam current is replenished with new bunches from the injector. Experiments are paused.
  - Coast: stored beam, no injection.
- The rate of beam loss for a ring with current I and beam lifetime τ_b is:

$$\frac{dI}{dt} = \frac{I}{\tau_b}$$

- Each injection pulse increases the circulating current:

$$\Delta i_{inj} = \frac{Q_{inj}}{\tau_{rev}}$$

- The total fill time is then $t_f = \frac{I}{\Delta i_{inj} f_{inj}} = \frac{I}{Q_{inj}} \frac{\tau_{rev}}{f_{inj}}$

Q_{inj}: charge per injector pulse
Δi_{inj}: change in stored-beam current

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- Fill-and-coast average intensity

$$\int_0^T I dt = \frac{T}{t_c + t_f} \int_0^{t_c} I_0 \exp\left(-\frac{t}{\tau_b}\right) dt$$

t_c: coast time
t_f: fill time
T: averaging time

- t_c is optimal when average over peak intensity is maximized

$$\frac{1}{I_0 T} \int_0^T I dt = \frac{\tau_b}{t_f + t_c} \left(1 - \exp\left(-\frac{t_c}{\tau_b}\right)\right)$$

- This is the case when $\frac{t_f + t_c}{\tau_b} = \exp\left(\frac{t_c}{\tau_b}\right) - 1$

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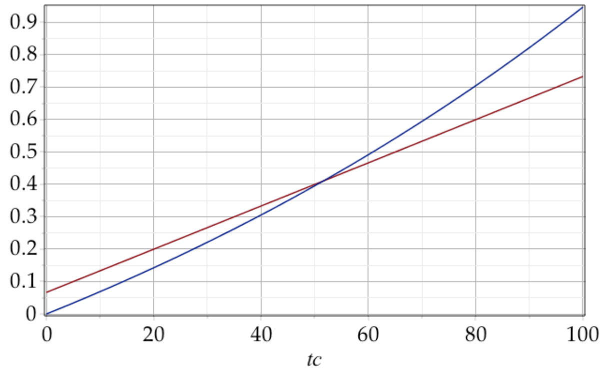
Optimum Condition

- Ex: τ_b =150 [min], t_f=10 [min]
- Optimum t_c = 50 min



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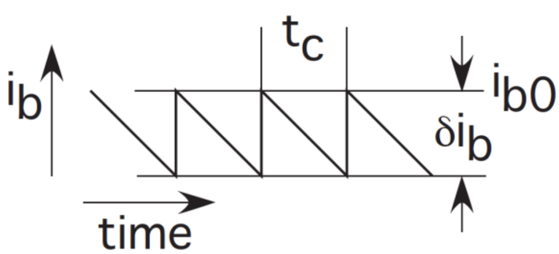
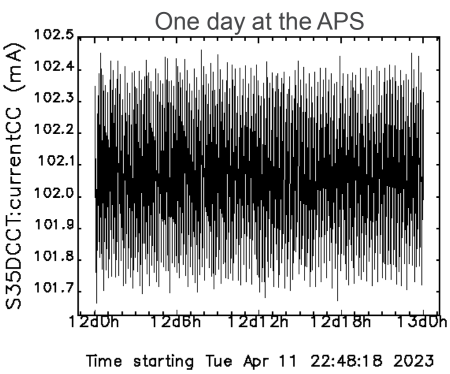
Top-up injection

- Rather than having separate fill and coast modes, maintain total current by frequent single shot injections to "top up" the lowest charge bunch
  - Allows for very stable current- good for experiments
  - No downtime for filling
  - Injection transient is relatively small
- Pioneered at the APS in the late 90's [7]
- Now standard for light sources





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Top-up injection

- The injector is running (almost) all the time. Intensity of a bunch varies exponentially: $Q_b = Q_0 \exp(-t_i / \tau_b)$
- For a given injector charge, each bunch needs the average injection rate:

$$Q_{inj} = Q_0\left(1-\exp\left(-\frac{t_c}{\tau_b}\right)\right) \Rightarrow t_c = \frac{1}{f_{i,b}} = -\ln\left(1-\frac{Q_{inj}}{Q_0}\right)\tau_b$$

- Therefore the average injection rate needed for n_b bunches is

$$f_{inj} = \Sigma f_{i,b} = \sum_b \frac{1}{-\ln\left(1-\frac{Q_{inj}}{Q_0}\right)\tau_b}$$

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Injector and Control Requirements

- The injector has to be programmable to inject into any rf bucket.
- A bunch-current monitor is needed to monitor charge in every bunch to select the next candidate for refill.
- Light sources have special safety requirements:
  - Block top-up if magnet currents are out of spec.
  - Block top-up if there is no beam in the ring
  - Clearing magnets in photon beam lines, if possible.
  - Avoidance of possibility to get injecting beam into the expt. hutches
- In colliders, a state machine allows top-up only when it is safe to do so.

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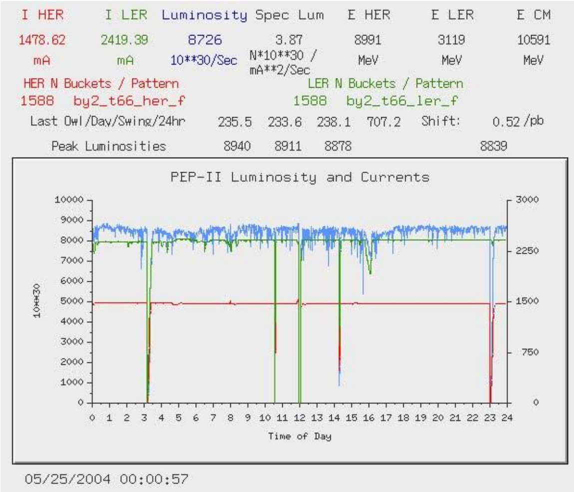
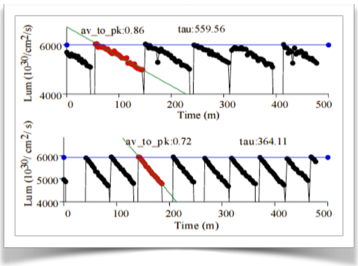
PEP-II "Trickle Charge" [8]





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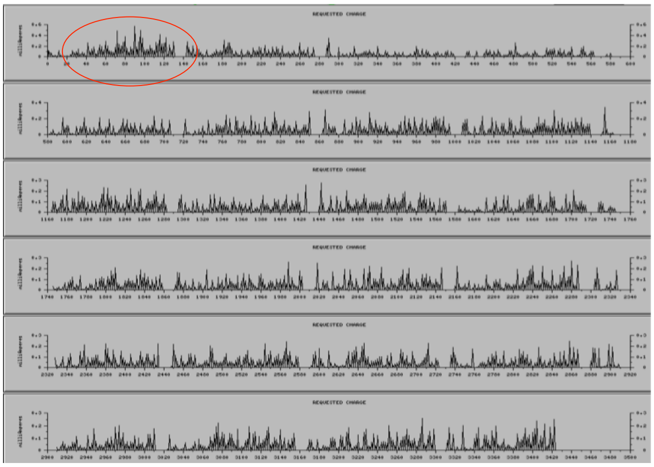
Top-up rate as a Diagnostic

- Top-up rate indicates bunch lifetime. Can show when bunches "hog" the injector



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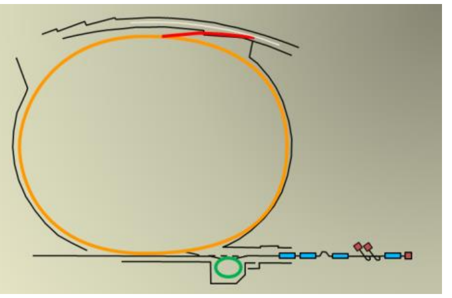
Electron Injection: Swap-Out Injection, Beam Extraction



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Rohnert Park, CA
July 2024

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Outline

- Introduction
- Synchrotron radiation
- Electron beam injection schemes
- Multipole kickers
- Top-up operation
- **Swap-out injection**
  - **Vertical vs horizontal injection**
  - **Emittance exchange**
  - **High charge injectors**
- **Electron beam extraction**
  - **Dealing with a high energy density beam**
- Diagnostics

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Swap-out Injection

Swap-out Injection [1]

- Swap-out injection technique enables to inject bunches into very small aperture rings where acceptance is very limited
  - Replace depleted stored bunch with fresh bunch from the injector
  - No disturbance of stored beam
  - Allows pushing to lower emittance

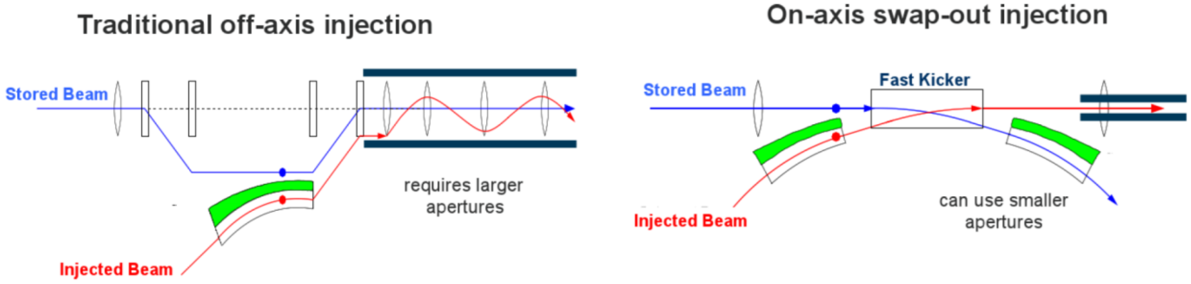
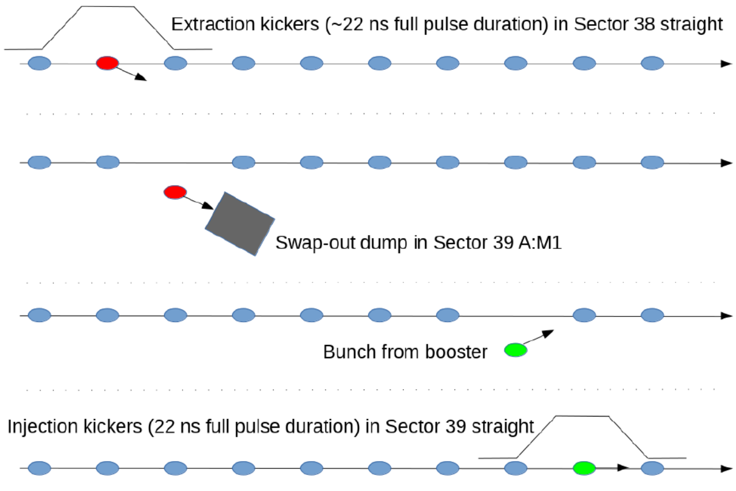
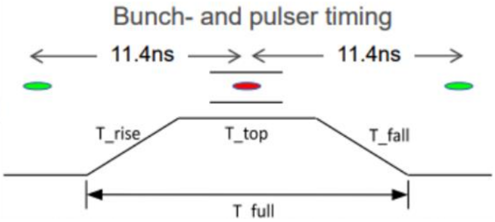


Diagram courtesy C. Steier (ALS).

Challenges of swap-out injection at APS-U

- Injecting large booster beam into small dynamic aperture
- Requires very fast injection kickers (rise and fall in ~22ns)
- Injector must provide full charge bunch (up to 16nC)





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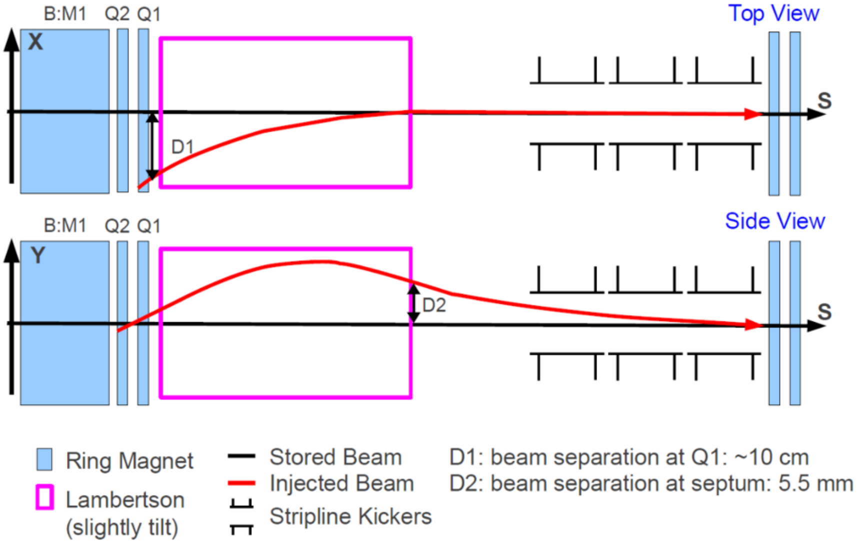
Initial idea: vertical injection

- Smaller vertical beam size → more room for kickers → less required kicker strength



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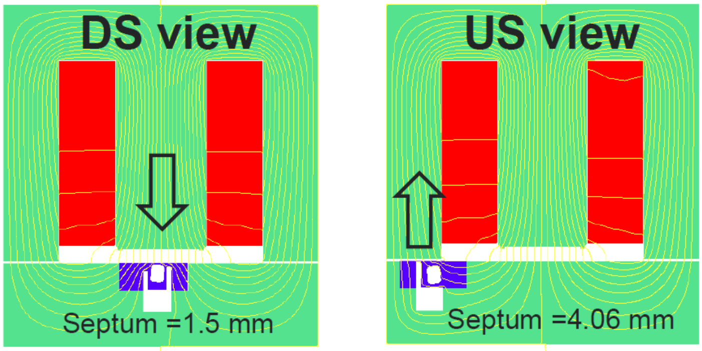
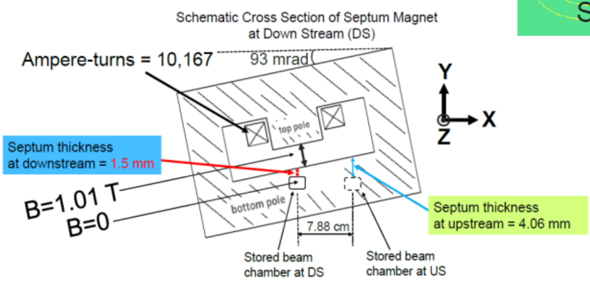
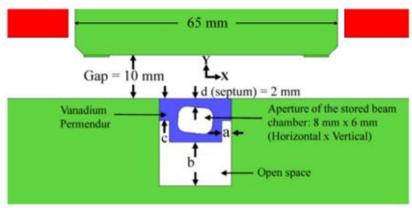
DC Lambertson Septum Design

- Required complicated septum design, tilted in all 3 dimensions
- Extremely difficult to build with required tolerances
- Ultimately abandoned







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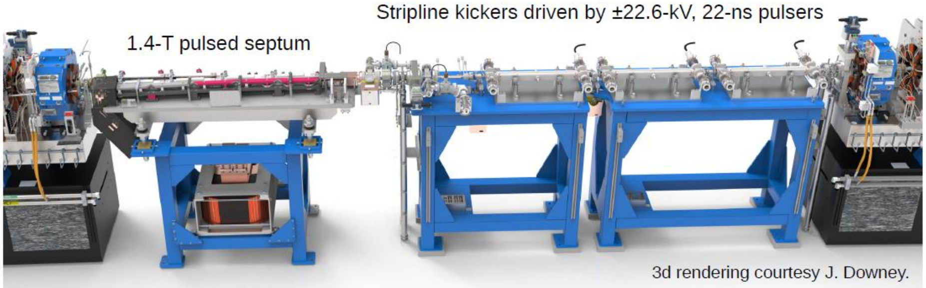
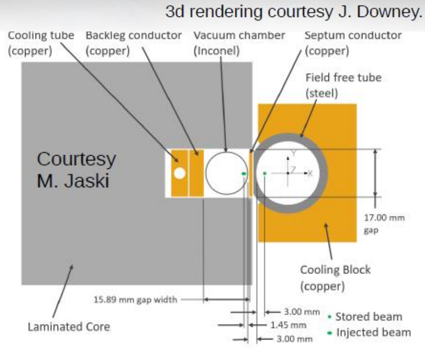
New idea: horizontal injection with emittance exchange



- Exchange x-y emittances in BTS, so horizontal beam size is small
- Septum kicks horizontally- design is simpler (but still difficult)
- Kickers also horizontal



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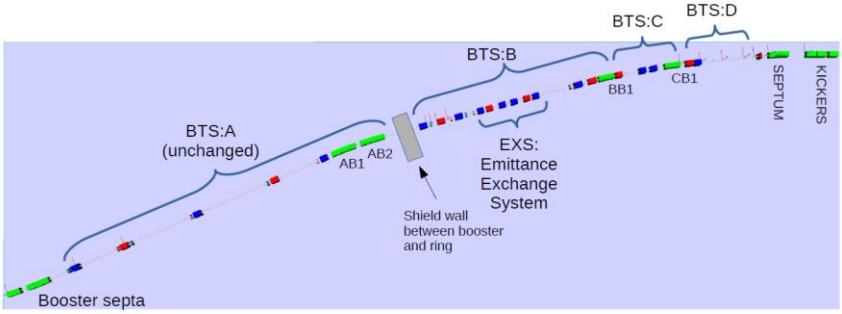
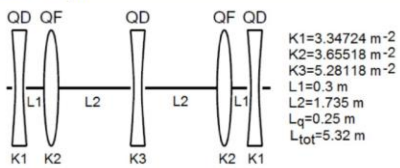
Emittance exchange in the BTS [2,3]

- Exchange x and y emittances via a series of skew quadrupoles





From P. Kuske et al.

$$R = \begin{pmatrix} 0 & D \\ D & 0 \end{pmatrix}$$

Where D is the 2x2 drift space matrix for the total length of the system!

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Emittance exchange in the BTS

- A skew quad is just a quad rotated by π/4 $\quad \mathrm{M_{sq}}(K) = \mathbf{R}(-\frac{\pi}{4})\mathrm{M_q}(K)\mathbf{R}(\frac{\pi}{4})$
  - $\mathbf{M_q}$(K) is the transfer matrix of a normal quadrupole ($K \equiv kL_q$)
  - **R**(ψ) is the transfer matrix for a rotation about the s-axis by angle ψ

$$\mathrm{M_q} = \begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix} \qquad \mathrm{A} = \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \qquad \mathrm{B} = \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix}$$

$$\mathbf{R}(\mp\frac{\pi}{4}) = \frac{1}{\sqrt{2}}\begin{pmatrix} \mathbf{I} & \mp\mathbf{I} \\ \pm\mathbf{I} & \mathbf{I} \end{pmatrix}$$

$$\mathrm{M_{sq}} = \frac{1}{2}\begin{pmatrix} \mathbf{A}+\mathbf{B} & -\mathbf{A}+\mathbf{B} \\ -\mathbf{A}+\mathbf{B} & \mathbf{A}+\mathbf{B} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & K & 0 \\ 0 & 0 & 1 & 0 \\ K & 0 & 0 & 1 \end{pmatrix}$$

- Note $\mathbf{M_q}$, $\mathbf{M_{sq}}$, and **R** are 4x4 matrices

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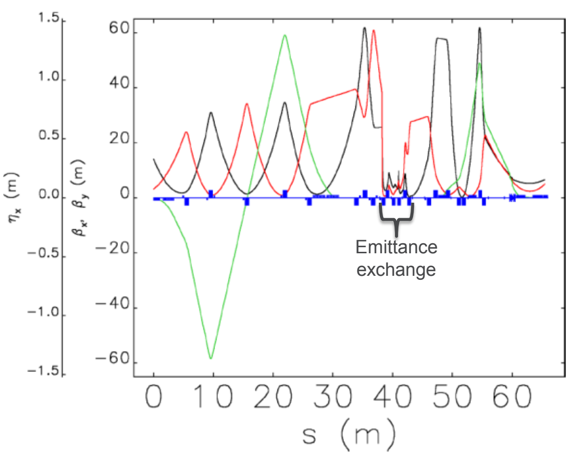
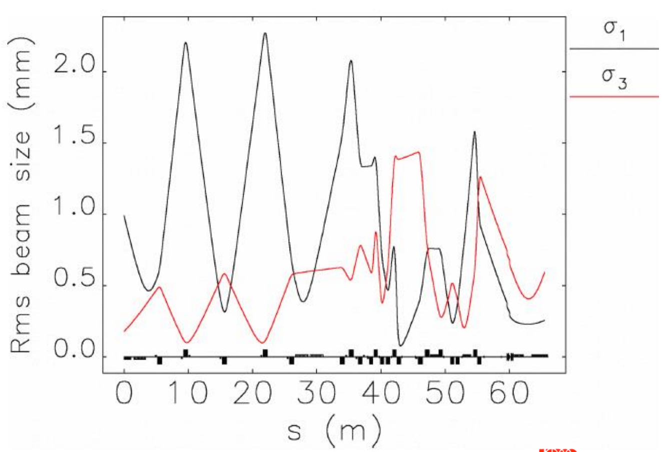
Emittance exchange

- For a drift space $$\mathbf{M}_d(L) = \begin{pmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{D} \end{pmatrix}, \text{ with } \mathbf{D} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$
- The full emittance exchange matrix $\mathbf{M}_{\mathbf{ex}}$ is a product of skew quad and drift matrices: $\mathbf{M}_{\mathbf{ex}}$ **= Q1 D1 Q2 D2 Q3 D2 Q2 D1 Q1**
- We want $\mathbf{M}_{\mathbf{ex}}$ = **R** $$R = \begin{pmatrix} 0 & D \\ D & 0 \end{pmatrix}$$
- This gives a series of equations, from which we can determine quad strengths and drift lengths

Lattice functions and beam sizes

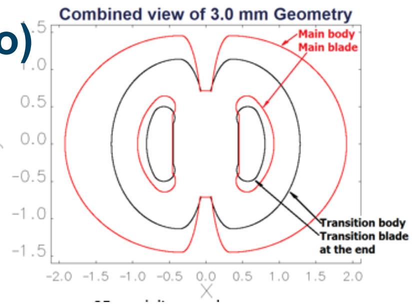
- A solution with reasonable quad strengths was found for the APS-U BTS
- Dispersion must be 0 in emittance exchange section

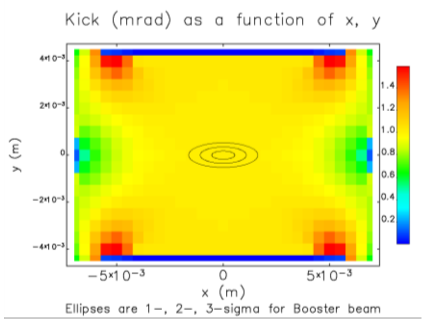


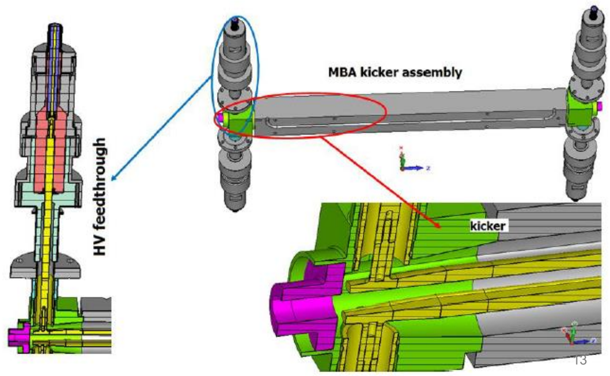


Stripline kicker design (X. Sun, CY. Yao)

- 3D design of kicker blades and feedthrough optimized using CST Microwave Studio to minimize impedance mismatches
- Calculated kickmap used in injection simulations







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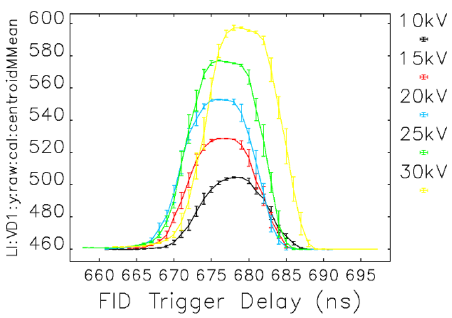
Stripline kicker testing

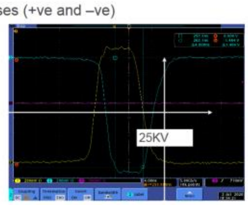
Prototype kicker built and tested in BTX line (vertically), deflection observed in flag

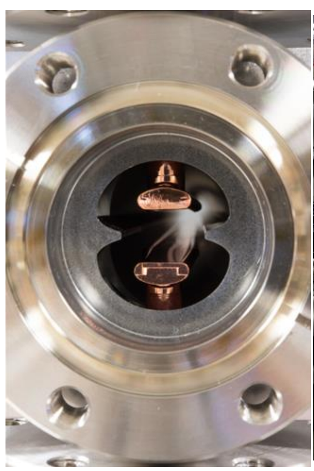
Connected to the 30-kV FID pulser, ran at 20-kV for more than 6 months



Output pulses (+ve and –ve)

40ns





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Frequency of injection

- Typically we want to regulate the stored current to C~0.1%
- Inject bunch with charge ~5% higher than nominal, extract when 5% lower
- Increase lifetime by running with high x-y coupling
  - Increases Touschek lifetime
  - Reduces intrabeam scattering
- Lifetime also depends on lattice errors
- For round beam and reasonable errors, need to inject every 18 – 30 seconds

N_b	Charge nC	κ	ϵ_x pm	ϵ_y pm	σ_δ %	$\tau_{10^{th}}$ h	ΔT_{inj} s	$\tau_{50^{th}}$ h	ΔT_{inj} s
48	15.34	0.99	31.9	31.6	0.145	3.7	28.0	4.0	30.3
324	2.27	0.99	29.8	29.5	0.136	15.0	16.7	16.1	17.9
324	2.27	0.13	41.7	5.6	0.138	7.3	8.1	9.1	10.1

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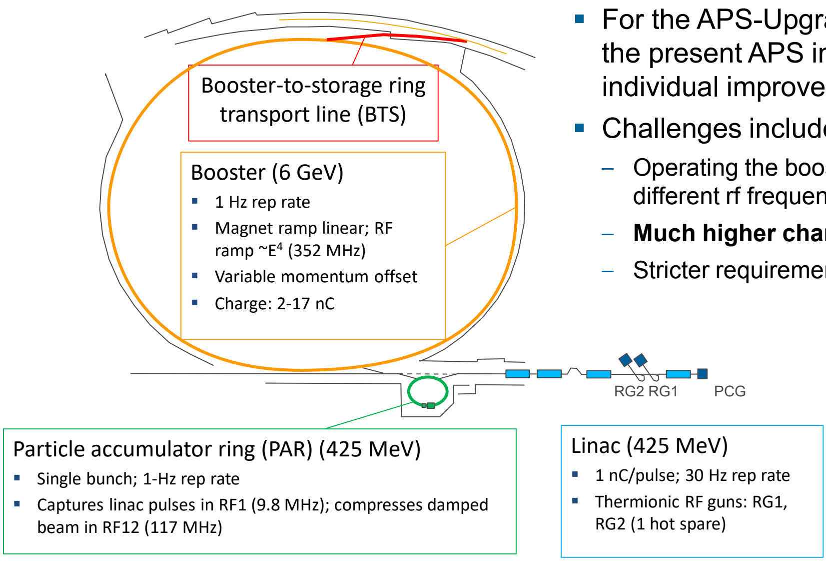
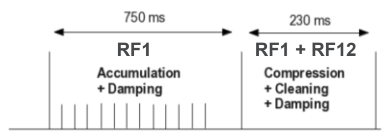
APS-U injector chain [4,5]



- For the APS-Upgrade, it was decided to leave the present APS injector chain in place and make individual improvements where needed.
- Challenges include:
  - Operating the booster synchrotron and storage ring at different rf frequencies
  - **Much higher charge per bunch (up to 17 nC)**
  - Stricter requirement for charge stability (±5% rms)



PAR cycle

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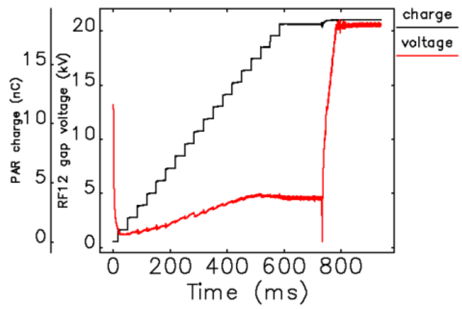
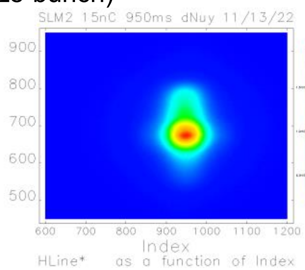
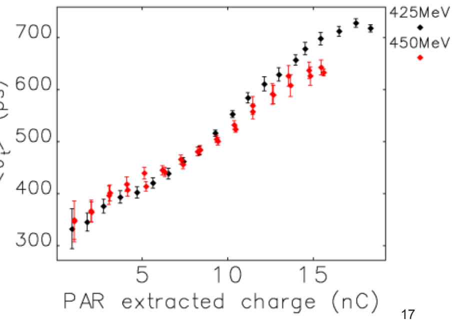
High charge in the PAR[1,2]

- Achieved high-charge goal of 20 nC extraction in 1-Hz operations.
- PAR bunch length more than doubles from 1 – 20 nC.
  - Large reduction in booster injection efficiency.
- Plan to mitigate:
  - High power 12th harmonic amplifier (compress bunch)
  - Higher energy from linac (stabilize bunch)
- Also observe ion-induced vertical beam size blowup[3]







[1] K. Harkay et al., MOPLM21, NAPAC19.
[2] K. Harkay et al., THYYPLM3, IPAC19.
[3] J. Calvey et al., THPOA14, NAPAC16.

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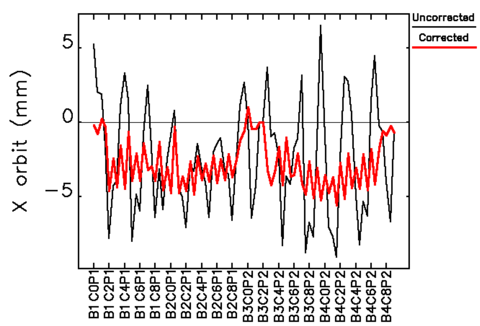
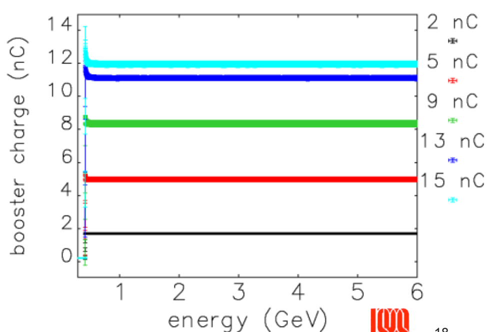
High charge in the booster

- Achieved 12 nC booster charge
- Progress and improvements:
  - Switching from a “low emittance” lattice to one with zero dispersion in the straight sections[1]
  - Orbit correction over the booster ramp.
  - Current-controlled sextupole power supplies
  - New and re-commissioned diagnostics: synchrotron light monitors (SLMs)[2], photodiode bunch duration monitor (BDM)[3] and turn-by-turn BPMs.
  - Improvements to control of injection trajectory[4]
  - Optimizing RF cavity voltage at injection vs charge
- Efficiency drops above 10 nC injected charge[5].
- Good short-term charge stability (<5% rms)





[1] J. Calvey et al., NAPAC16, pp. 647-650.
[2] K. Wootton et al., proc. IBIC23.
[3] J. Dooling et al., IPAC18, pp. 1819-1822.
[4] C-Y. Yao et al., IPAC21, pp. 419-421.
[5] J. Calvey et al., IPAC21, pp. 197-199.

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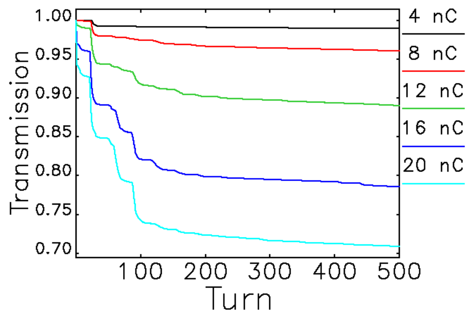
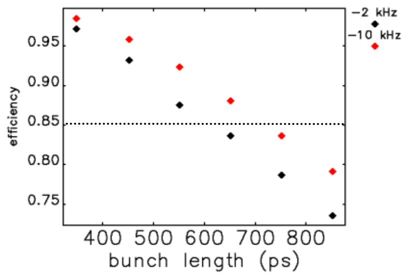
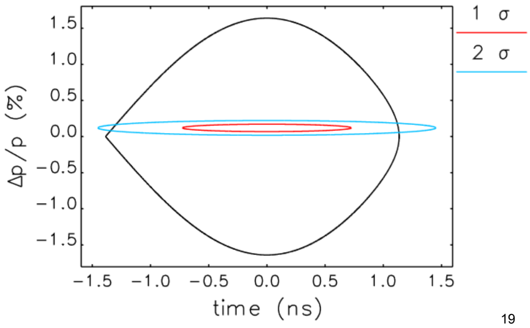
Simulating booster injection

- Using elegant [1], tracked 3000 booster turns (3.5 ms), where most losses occur.
- Model includes momentum offset (-0.6%), transverse and longitudinal impedance [2], beam loading in rf cavities, and incoming beam parameters (e.g., beam size and bunch length vs charge) derived from measurements.
- Good agreement with measured efficiency.
- Main source of losses: PAR bunch length, beam loading.
- Efficiency can be improved with shorter bunch length (PAR improvements) and detuning cavities[3].



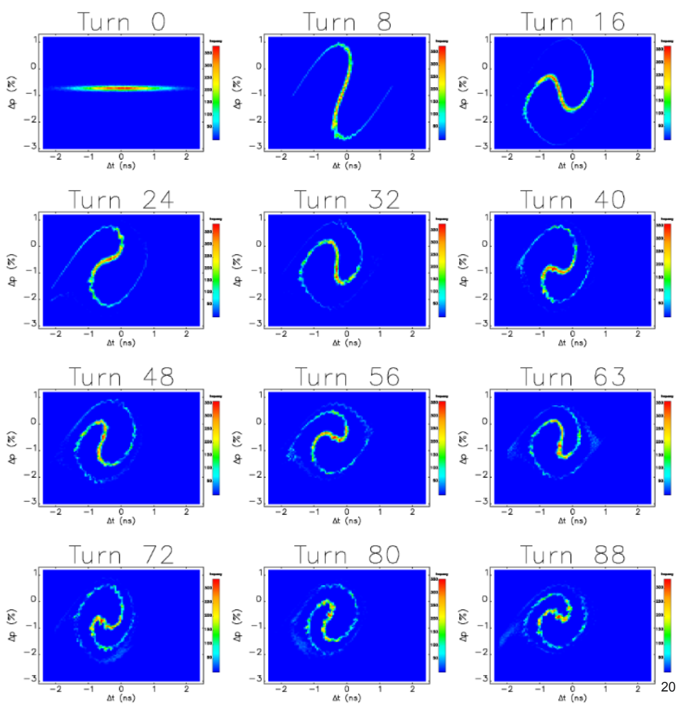
[1] M. Borland. ANL/APS LS-287, (2000). Y. Wang et al. *Proc. of PAC 2007*, 3444–3446 (2007).
[2] R. R. Lindberg et al. *Proc. IPAC 2015*. TUPJE078.
[3] J. Calvey et al., *Proc. IPAC21*, pp. 197-199





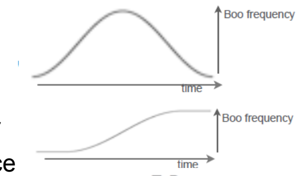
Longitudinal phase space

- Losses around turns 24, 63, and 88



Injection/extraction timing & synchronization (IETS)

- APS-U storage ring (SR) will have higher frequency than old one
- SR, booster, and PAR rf frequencies will be decoupled
- Booster frequency can be adjusted along the energy ramp
  - Bucket targeting with frequency bump- changes time beam spends in the booster
  - Overall frequency ramp - optimize both injection efficiency and extracted emittance



T. Berenc

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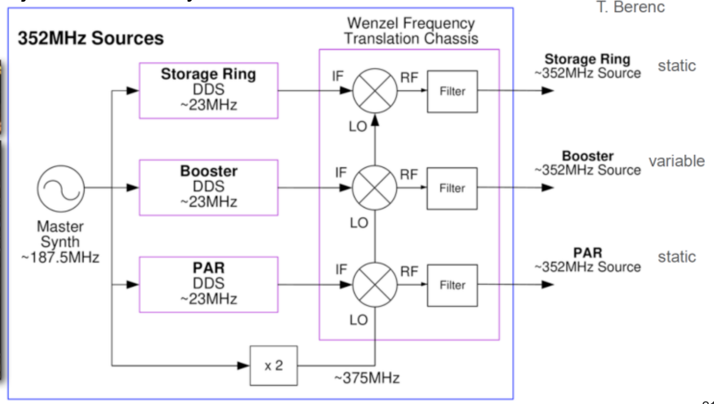

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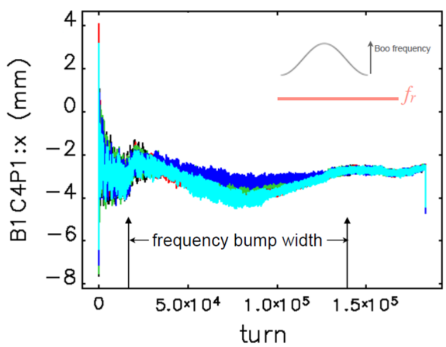
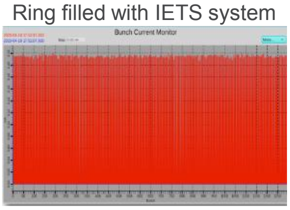
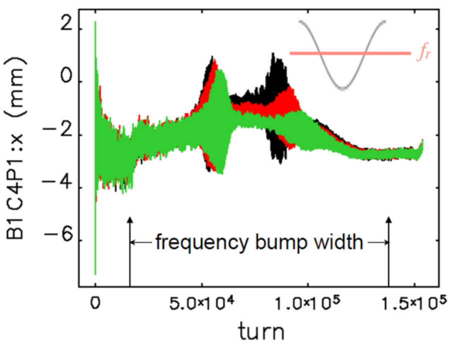
Targeting bumps

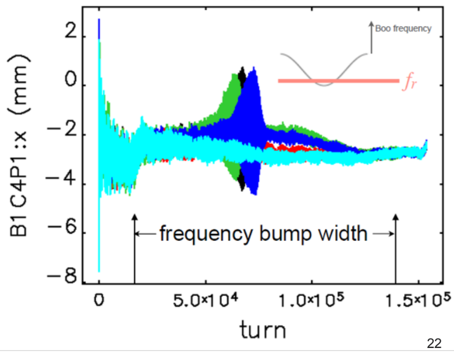
- X position in dispersive BPM
- Positive frequency bump -> negative X bump
- Bump height different for each shot
- Instability seen for negative frequency bump from crossing cavity resonance
- Confirmed that bumps put the beam in the right SR bucket



Ring filled with IETS system







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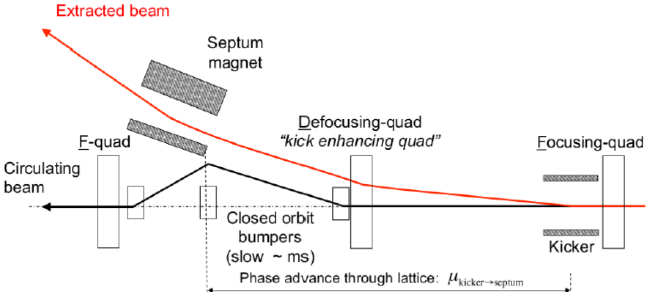
Electron Beam Extraction

Introduction

- In essence extraction is the reverse process of injection (although there's no need to close the bump)
- For a ramping machine, it takes place at higher energies
  - Stronger elements are required, orbit bump might be needed
  - Less space charge effect (usually not a concern for e^-)
- Power density issues due to small emittances
- Single-turn (Fast extraction) is typically used for e^- machines



Kick Optimization

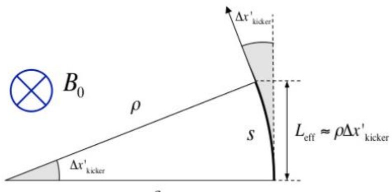
- To minimize the kicker deflection required:

$$\Delta x'_{kicker} = \frac{x_{extr} - x_{bump}}{\sqrt{\beta_{kicker}\beta_{septum}} sin\mu_{kicker,septum}}$$

  - Optimum phase advanced between kicker and septum ($\approx \pi/2$)
  - Defocusing quad in between to contribute to extraction
  - Large β at the kicker (small divergence) and septum

The kicker integrated strength is (small angles approximation)

$$\Delta x'_{kicker} = \frac{s}{\rho} \approx \frac{B_0 \int_0^s dl}{B_0 \rho} = \frac{q}{p}\int_0^s B \cdot dl = \frac{q}{p} B_0 L_{eff}$$



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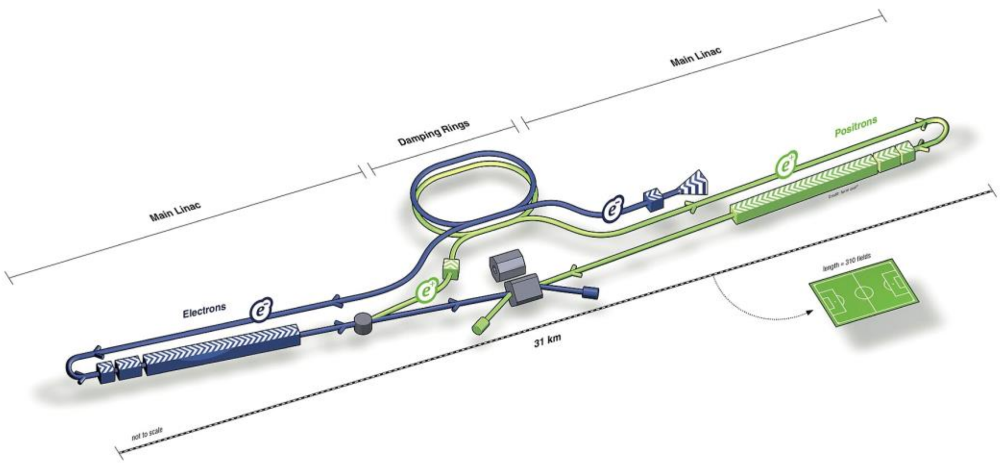
Example: International Linear Collider (ILC)

- Proposed electron-positron collider, 500 GeV collisions
- Electrons and positrons damped to small emittance in “damping rings” (DR)
- Extraction from DR must be clean to preserve emittance



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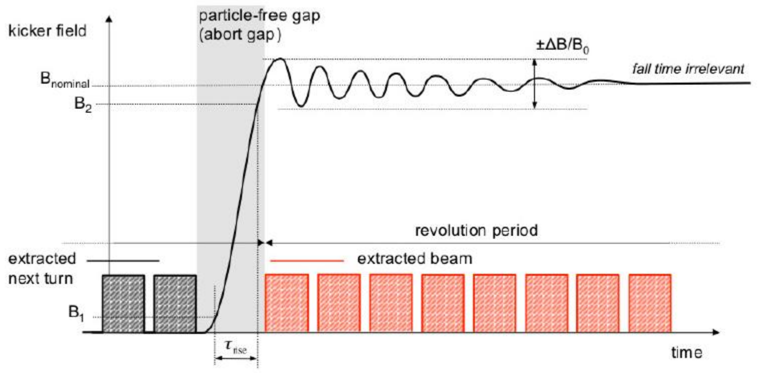
Kick Pulse Shape (full beam extraction)



- Rise-time, τ_{rise} usually defined between given limits [%] of B nominal
- Ripple definitions depends on the tolerable emittance growth
  - Very challenging for damping rings provide since they provide extremely small emittances

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Jitter Tolerances: linear collider damping rings (DR)

- In order to preserve small emittances coming out of DR
  - Kicker jitter $\leq 10\% \; (1 \cdot \sigma)$

$$\frac{\delta x'}{x'} \leq \frac{1}{10}\frac{\sigma}{\delta x} = \frac{1}{10}\frac{\sqrt{\epsilon_{ext}\beta}}{d_s + m\sqrt{\epsilon_{inj}\beta}}$$

where m is the number of σ that the extracted beam has to clear from the injected beam

Damping Rings of linear collider work at a regime where

$$\frac{\epsilon_{ext}}{\epsilon_{inj}} \approx 10^{-3}$$

If we apply the design NLC (aka ILC) DR values [6];

- $\beta = 3$ m
- ϵ_{inj} = 3 mm
- ϵ_{ext} = 3 μm
- m = 7

$$\frac{\delta x'}{x'} = 3 \cdot 10^{-4}$$

Which has not been achieved operationally yet

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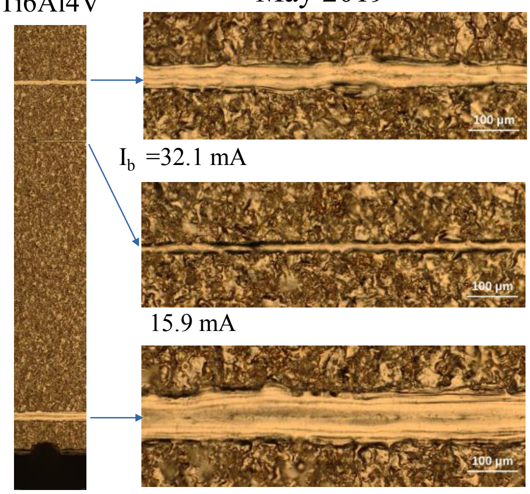
Dumping the extracted beam

- The ultra-low emittance, high-intensity electron beams in Fourth Generation storage ring machines can cause high-energy-density (HED) interactions on technical surfaces such as collimators or vacuum chamber walls.
  - HED is defined as energy densities equal to or above 10^{11} J/m^3[1].
  - In HED regime, can have melting or even vaporization of surface
  - Radiation dose is defined as absorbed energy per unit mass, units are “Gray”. 1 Gy = 1 J/kg
  - HED regime is 37 MGy in aluminum, 11.2 MGy in copper, and 5.2 MGy in tungsten.
  - In APS-U, peak total dose may reach 150 MGy.
- Need to protect hardware from electron beam during whole-beam loss events.

Two experiments were conducted in the APS Storage Ring to approach APS-U conditions in potential collimator material [7]

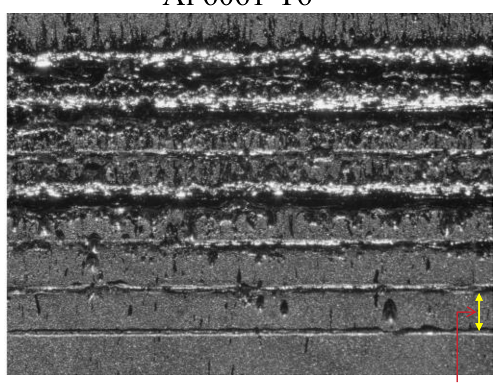
Ti6Al4V

May 2019



January 2020

Al 6061-T6



$$\frac{X_{o,Ti}}{\rho_{Ti}} = 3.56 \text{ cm}$$

$$\frac{X_{o,Al}}{\rho_{Al}} = 8.9 \text{ cm}$$

J. Dooling

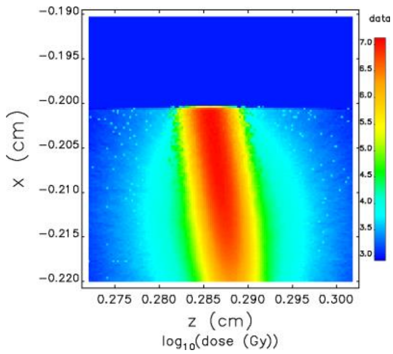
Dose maps in aluminum and copper

$E_a = D\rho$

ρ_{Al} = 2.7 g/cm^3

ρ_{Cu} = 8.92 g/cm^3

Beam striking Al



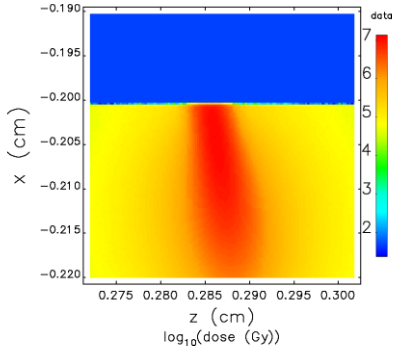
3rd turn (peak) of 5

Maximum Dose

Turn	Al	Cu
	(MGy)	(MGy)
1	3.11	2.96
2	11.09	10.57
3	13.53	13.62
4	9.45	9.28
5	4.81	4.48

Not that different! But E_a varies with density, so ~3.3x higher in Cu!!

Beam striking Cu



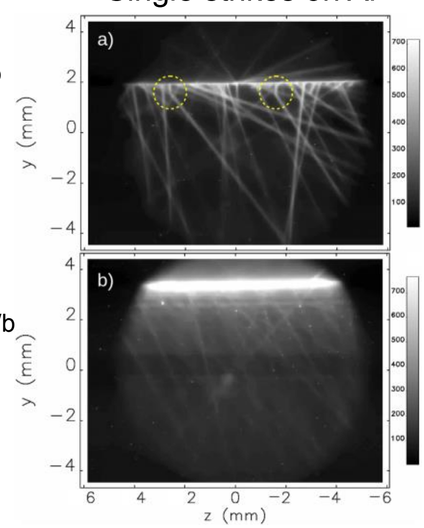
3rd turn (peak) of 5

Optical images of beam strikes

Single strikes on Al

67 mA
2.2 nC/b

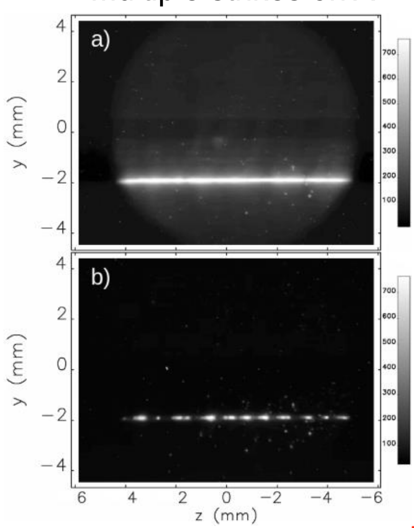
200 mA
0.77 nC/b



Multiple strikes on Al

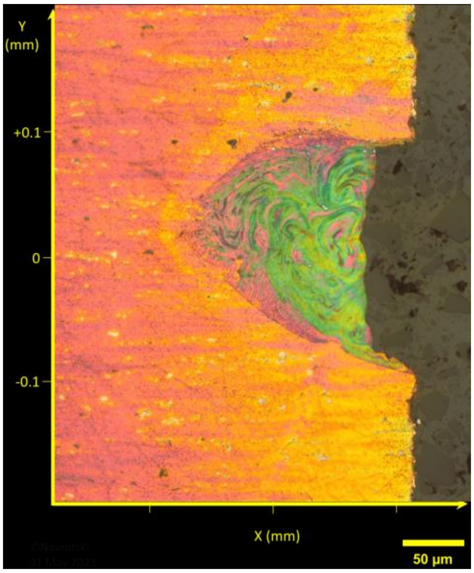
200 mA
1st

200 mA
5th

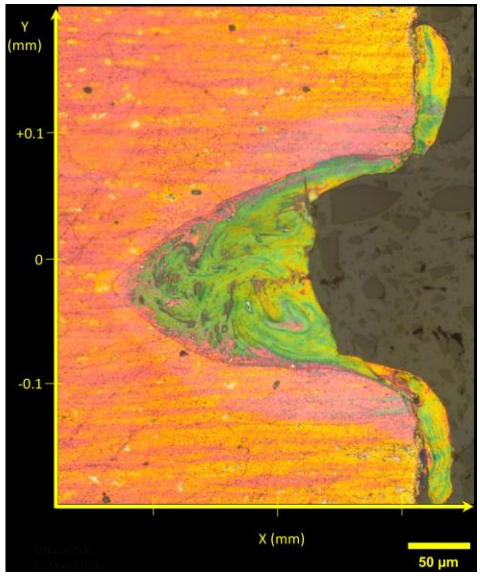


Cross sections of strike regions

Single strike on Al



Multiple strikes on Al



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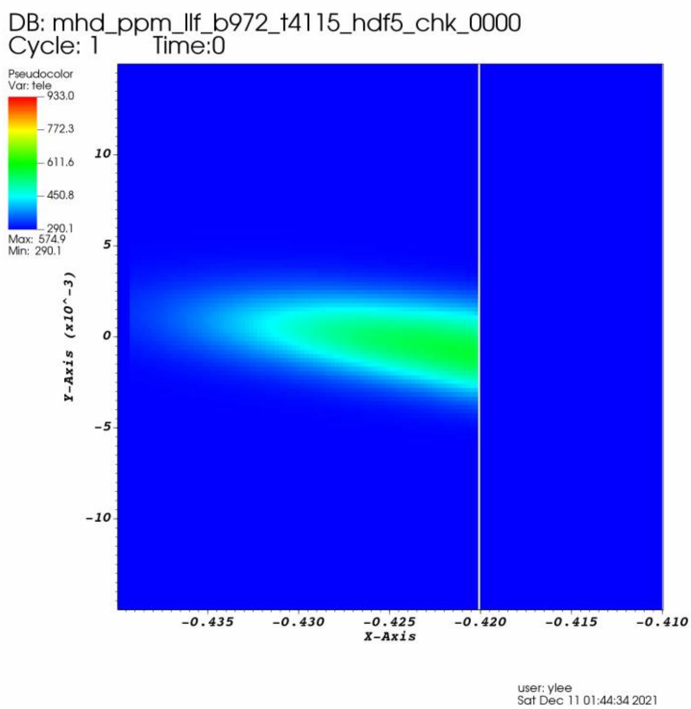
Simulation of beam strike

Color: temperature
Black: above melting temp of Al



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Strategies for protection of APS-U chambers

- Fast abort (unplanned)—Fan-out kicker
  - Vertically spreads the beam on the five collimators to reduce energy density and power density
  - Half sine-wave
  - Necessary above 30 mA
- Slow aborts—Decoherence kicker (DK)
  - The DK weakly kicks the beam causing the transverse beam size to inflate after a number of turns reducing energy and power density
  - Injection kickers then send bunches one-by-one into the swap-out dump

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References

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[2] P. Kuske, F. Kramer, “Transverse emittance exchange for improved injection efficiency”, Proceedings of IPAC'2016, Busan, Korea (2016).
[3] K.-J. Kim and A. Sessler, “Transverse and Longitudinal Phase Space Manipulation and Correlations”, AIP Conf. Proc. 821, 115 (2006).
[4] K. Harkay et al., THYYPLM3, IPAC’19.
[5] J. Calvey et al., THYD4, NAPAC’22.
[6] T. Raubenheimer et al., "Damping Ring Designs for a TeV Linear Collider", SLAC-PUB-4808, 1988.
[7] J. Dooling et al., “Collimator irradiation studies in the Argonne Advanced Photon Source at energy densities expected in next-generation storage ring light sources”, PRAB 25, 043001 (2022).

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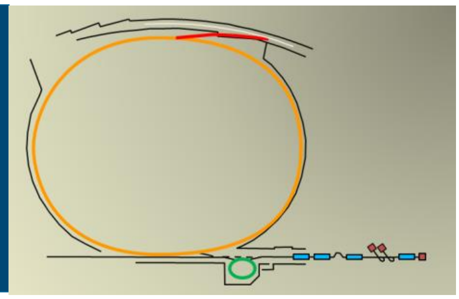
Diagnostics



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Argonne National Laboratory

US Particle Accelerator School
Rohnert Park, CA
July 2024

1

Motivation

- User needs…
  - Final users of the beam always pushing machine performance
  - High-quality, long term stability and flexibility
- So the Accelerator Physicist requires…
  - Instrumentation to diagnose the beam
  - Fast and non-destructive (beam and instrument) methods are preferred
- Most common measurements are:
  - Current
  - Beam position
  - Bunch length
  - Transverse emittance
  - Beam loss
  - Beam profile

2

Emittance

Recap from Monday lecture….

Emittance (ε) is related to the area (a) occupied by the beam in phase space as:

$$\epsilon = a^2\pi$$

Σ matrix was defined as:

$$\Sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} = \epsilon \begin{bmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{bmatrix} \Rightarrow det|\Sigma| = \epsilon$$

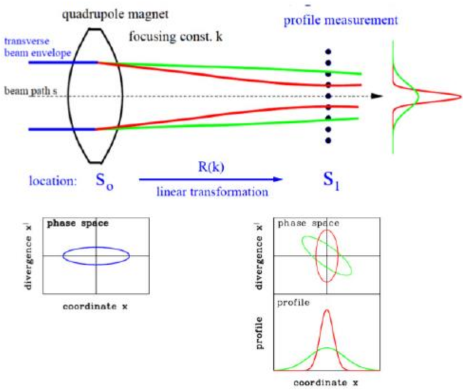
which is a function of s

Here:

$$\sigma_{11} = \overline{x^2} \qquad \sigma_{12} = \sigma_{21} = \overline{x \cdot x'} \qquad \sigma_{22} = \overline{x'^2}$$

Quadrupole Scan

From a profile determination, the emittance can be calculated via linear transformation, if a well known and constant distribution is assumed



- Quadrupole is scanned for different values of *k*
- Beam width σ is changed according to the focusing strength of the quad
- *R* is the transport matrix from s_0 to s_1 $\Rightarrow$ *R(k)*
- ϵ_0 is obtained from the different σ^i measurements

Quadrupole Scan

The beam width (x_{rms}) is measured at s_1, thus σ_{11} = x_{rms}^2
Different values of quadrupole strength are sampled
k_1, k_2, k_3, k_4 ... so the transfer matrix from s_0 to s_1 is,

$$R(k_i) = R_{\text{drift}} \cdot R_{\text{quad}}(k)$$

The Σ matrix transforms as,

$$\Sigma_{s_1} = R(k_1) \cdot \Sigma_{s_0} \cdot R^T(k_1)$$

We can construct a system of equations for all k_n values as

$$\sigma_{11}^{s_1}(k_1) = R_{11}^2(k_1) \cdot \sigma_{11}^{s_0} + 2R_{11}(k_1)R_{12}(k_1) \cdot \sigma_{12}^{s_0} + R_{12}^2(k_1) \cdot \sigma_{22}^{s_0}$$
$$\vdots$$
$$\sigma_{11}^{s_1}(k_n) = R_{11}^2(k_n) \cdot \sigma_{11}^{s_0} + 2R_{11}(k_n)R_{12}(k_n) \cdot \sigma_{12}^{s_0} + R_{12}^2(k_n) \cdot \sigma_{22}^{s_0}$$

Quadrupole Scan

More than 3 values of k_n are needed if we want to estimate the error of our calculation
R(k_n) can be obtained using thin-lens approximation:

$$R(k_n) = R_{\text{drift}} \cdot R_{\text{quad}}(k_n) = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ k_n & 1 \end{bmatrix} = \begin{bmatrix} 1 + k_n L & L \\ k_n & 1 \end{bmatrix}$$

Thus:

$$\sigma_{11}^{s_1} = R_{11}(k_n)(\sigma_{11}^{s_0} R_{11}(k_n) + \sigma_{12}^{s_0} R_{12}(k_n)) + R_{12}(k_n)(\sigma_{21}^{s_0} R_{11}(k_n) + \sigma_{22}^{s_0} R_{12}(k_n))$$

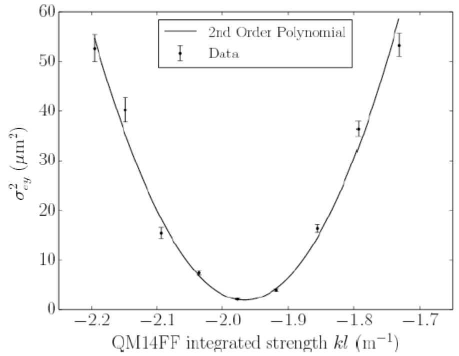
And with the above:

$$\sigma_{11}^{s_1}(k_n) = \sigma_{11}^{s_0} L^2 \cdot k_n^2 + (2L\sigma_{11}^{s_0} + 2L^2 2L\sigma_{12}^{s_0}) \cdot k_n + L^2\sigma_{22}^{s_0} + 2L\sigma_{12}^{s_0} + \sigma_{11}^{s_0}$$

Quadrupole Scan

- Fitting a parabola to the measured sij gives three coefficients: *a*, *b* and *c*

$$\sigma_{11}^{s_1}(k_n) = a(k_n - b)^2 + c = ak_n^2 - 2abk_n + (c + ab^2)$$



which give the Σ matrix at s_0:

$$\sigma_{11}^{s_0} = \frac{a}{L^2}$$

$$\sigma_{12}^{s_0} = -\frac{a}{L^2}\left(\frac{1}{L} + b\right)$$

$$\sigma_{22}^{s_0} = \frac{1}{L^2}\left(ab^2 + c + \frac{2ab}{L} + \frac{a}{L^2}\right)$$

Emittance Measurement

- ε can now be obtained:

$$\epsilon^{s_0} = \sqrt{\sigma_{11}^{s_0}\sigma_{22}^{s_0} - \sigma_{12}^{s_0}\sigma_{12}^{s_0}} = \sqrt{\frac{ac}{L}}$$

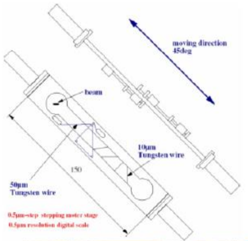
- A similar measurement uses three (or more) screens to do the same measurements without changing quad settings.
- An extension of this method is to measure the full 4x4 matrix (vertical beam size, x-y coupling):

$$\begin{aligned}\Sigma_{11} &= R_{11}^2\hat{\Sigma}_{11} + 2R_{11}R_{12}\hat{\Sigma}_{12} + R_{12}^2\hat{\Sigma}_{22}\\ \Sigma_{33} &= R_{33}^2\hat{\Sigma}_{33} + 2R_{33}R_{34}\hat{\Sigma}_{34} + R_{34}^2\hat{\Sigma}_{44}\\ \Sigma_{13} &= R_{11}R_{33}\hat{\Sigma}_{13} + R_{11}R_{34}\hat{\Sigma}_{14} + R_{12}R_{33}\hat{\Sigma}_{23} + R_{12}R_{34}\hat{\Sigma}_{24}.\end{aligned}$$

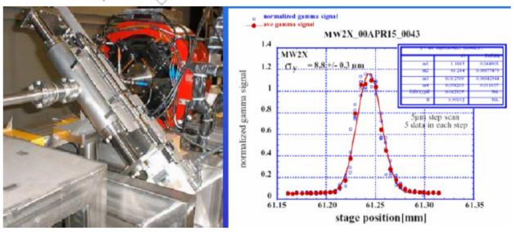
- A full 5x5 matrix (including dispersion) is also possible

Wire Scan

- Change in voltage on wire induced by secondary emission of γ detected by Cerenkov

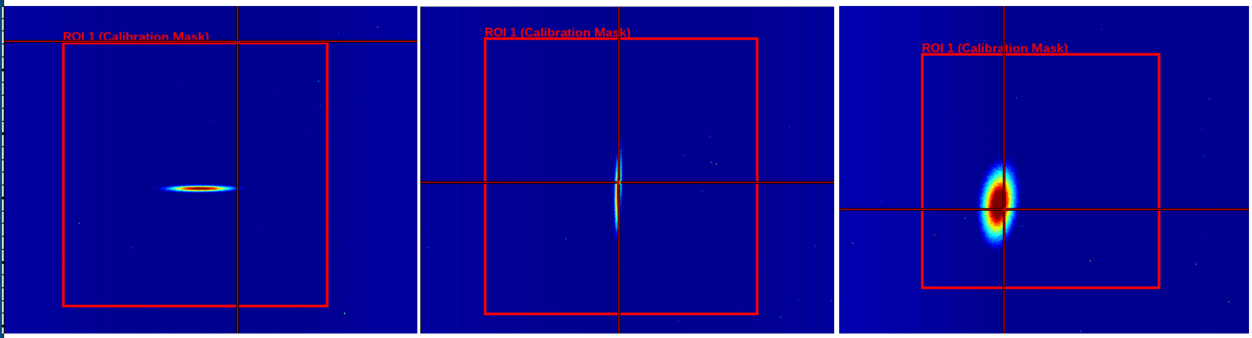


thin W wires and 5 μm precision stepper-motors (courtesy H. Hayano, 2003)



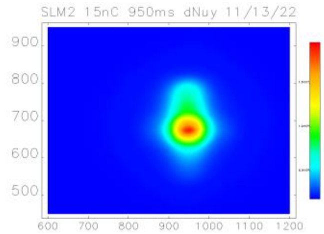
Fluorescent screen

- Insert into beam path, gives beam location and size
- Destructive measurement
- Images from APS-U BTS line showing emittance exchange



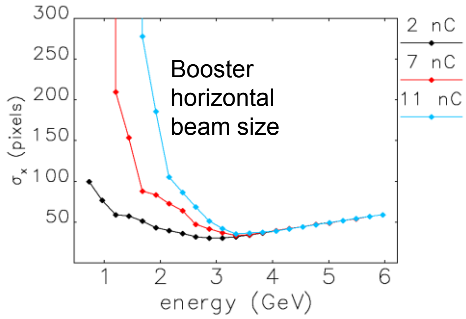
Synchrotron light monitors (SLMs)

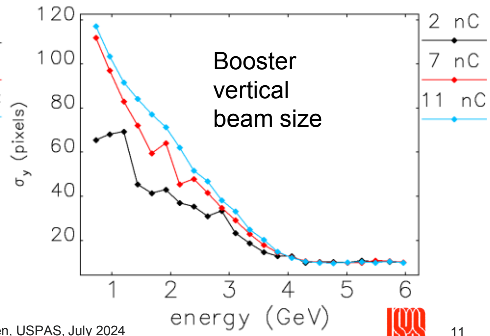
- Measure beam size from emitted synchrotron light
- Can use visible part of spectrum
- Beam size measurements from APS booster
  - Initial beam size blowup damps in first half of ramp
  - Second half shows increase in emittance with energy



Vertical beam size blowup in PAR (from trapped ions)

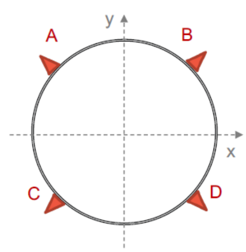
Polished copper mirror





Beam position monitor (BPM)

- Determine beam position my measuring the voltage on four pickups around the chamber
- Sophisticated electronics allow for turn-by-turn, or even bunch-by-bunch measurements
- Sum of pickups gives rough measurement of beam current

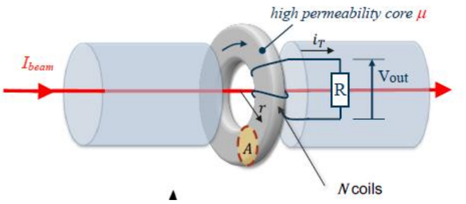


$$x = K_x \frac{v_A+v_C-v_B-v_D}{v_A+v_C+v_B+v_D} + x_0 = K_x \frac{\Delta_x}{\Sigma} + x_0$$

$$y = K_y \frac{v_A+v_B-v_C-v_D}{v_A+v_B+v_C+v_D} + y_0 = K_y \frac{\Delta_y}{\Sigma} + y_0$$

Beam current monitors

- Beam current transformer (BCM)
  - Beam current induces magnetic field in ferrite ring
  - Magnetic field induces current in wire
  - Voltage drop across resistor proportional to beam current (for high enough frequency)
- Fast measurements: bunch charge monitor
  - Processing of fast pickup such as a BPM with high bandwidth ADC
  - Resolution down to 10's of ps



$$v_{out} = i_T R = -N \frac{d\Phi_H}{dt}$$

$$i_{beam} = v_{out} \frac{N}{R}.$$

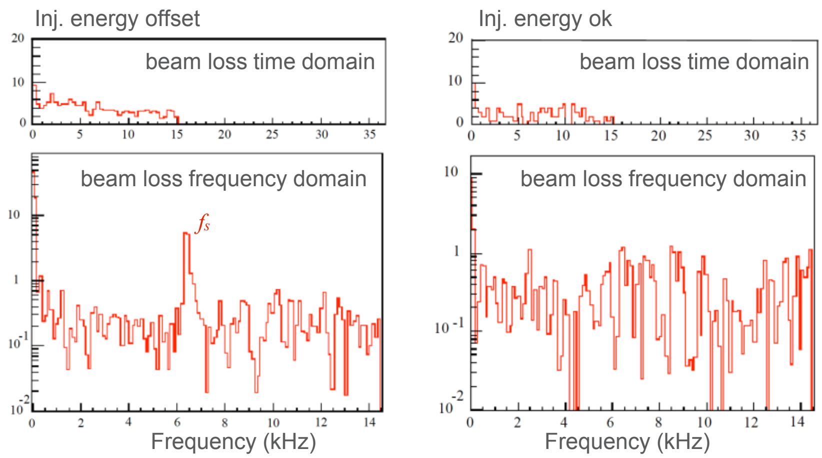
Injection Tuning

- Typically, injection setup follows a straight-forward strategy
  - Put the incoming beam onto its design trajectory.
  - Make sure the kicker(s) are timed correctly wrt. the injecting beam
  - Put the injecting beam on-axis using kicker(s) and bumps
  - If needed, use orbit correctors just upstream of the injection to make the turn-2 orbit like the turn-1 orbit. The injected bunch should now store.
  - With rf on, analyze the motion of the injecting beam for synchrotron oscillations
    - These indicate either a phase or an energy offset
    - Reduce by adjusting either incoming beam or the ring parameters (rf phase, energy).
  - For off-axis injection, collapse the orbit bump until the desired injection orbit (1st turn) is reached; or until injection efficiency is optimized.

Fourier Transform

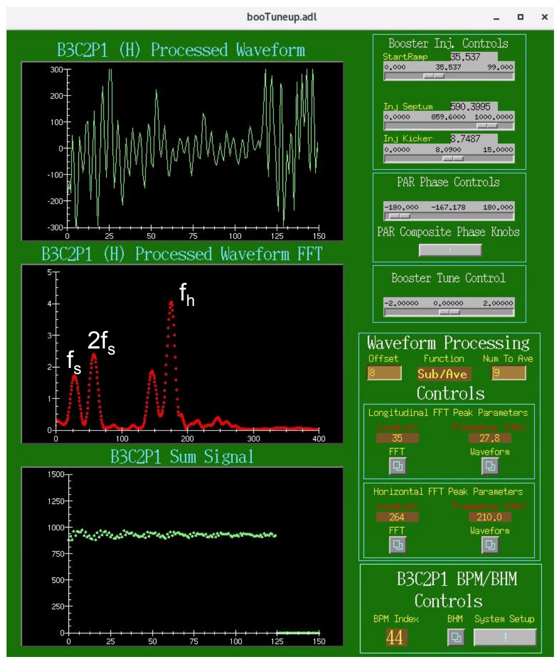
- A powerful way of diagnosing injection trouble is to use FFT of either BPM signals or of beam-loss signals.

PEP-II & BaBar beam-loss data



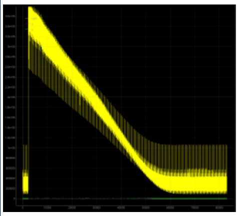
APS booster injection correction

- Take an FFT of BPM position in first 128 turns
- Longitudinal mismatch → synchrotron tune peak(s)
  - Fix with timing and/or rf phase changes
- Horizontal mismatch → horizontal tune peak
  - Fix by adjusting injection kicker and/or septum
- Similar process for vertical

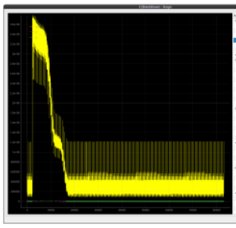


Diagnostics for APS-U commissioning milestones

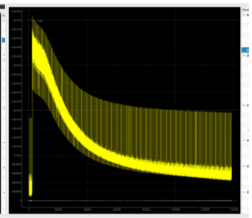
- Beam directed through BTS transfer line (fluorescent screens, BPMs)
- First turn around the ring (BPMs)
- Stored beam with rf (turn-by-turn BPMs)



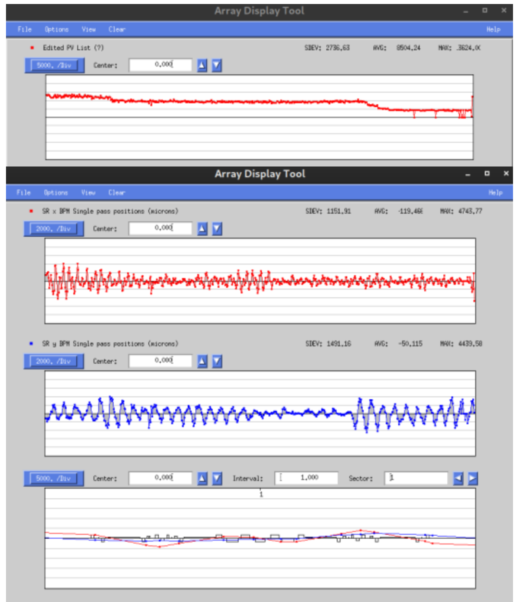
80 turns, no rf



20 turns, rf on



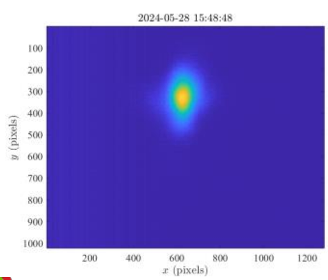
400 turns, after rf tuning



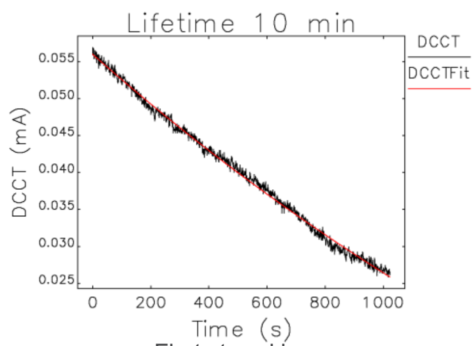
First turn BPM sum signal and trajectory

Diagnostics for APS-U commissioning milestones

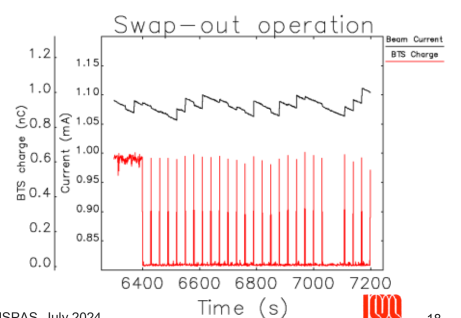
- Stored beam with rf (DC current monitor)
- Multibunch swap-out operation (bunch current monitor)
- 50 mA beam current (DC current monitor)
- Beam size measurement (pinhole camera)
- First light- opening x-ray beamline shutters



Initial beam size measurement



First stored beam



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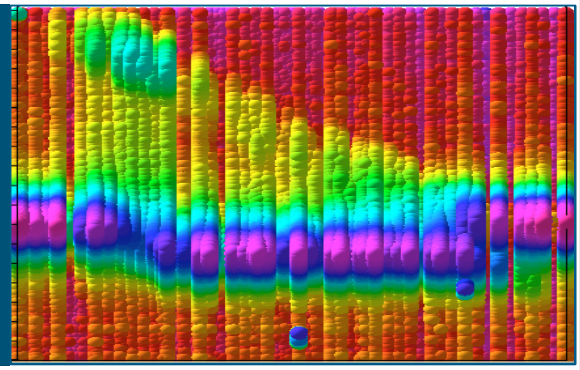
Crystal Extraction



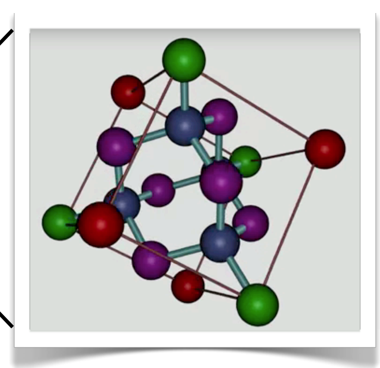
U. WIENANDS, J. CALVEY, O. MOHSEN

July 2024
USPAS, Rohnert Park

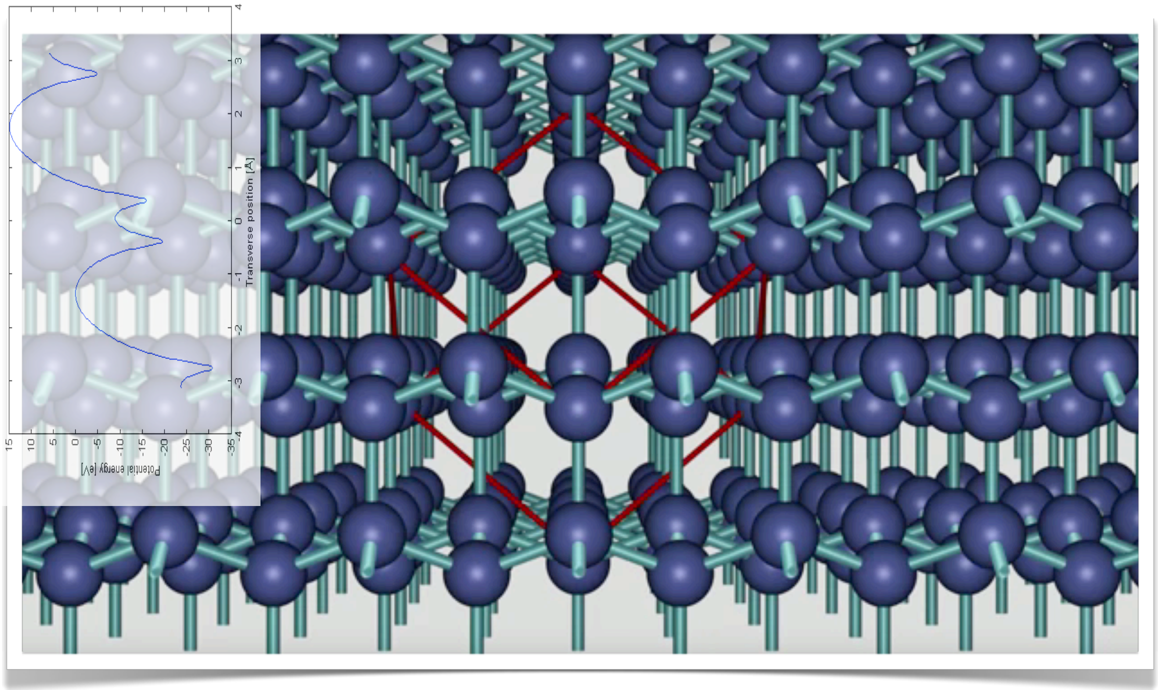
Crystalline Potentials

Si crystals

Si unit cell



Si (111) Planes



- The electric field near a nucleus is

$$E(\vec{r}) = \frac{1}{4\pi\varepsilon_0}\frac{Ze}{r^2}$$

e.g. 2*10^{12} V/cm at 0.1Å

and for a crystalline plane can be approximated by a continuum potential:

$$U(\vec{r}) = \frac{1}{d}\int V(\vec{r},z)dz$$

which is about 20..25 eV for a Si(110) crystal

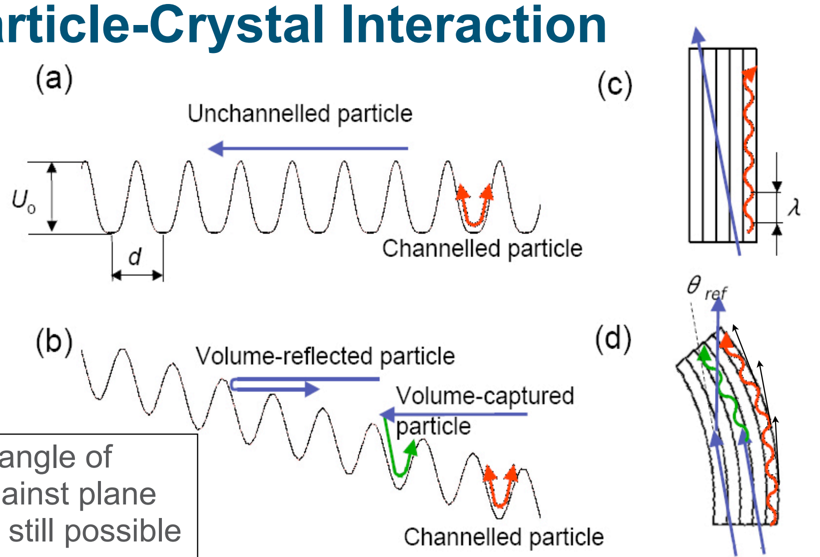
- The transverse energy is then

$$E_\perp = \frac{p_\perp}{2\gamma M} + U\left(\vec{r}_\perp\right) = \frac{1}{2}pv\Theta^2 + U\left(r_\perp^2\right)$$

Particle-Crystal Interaction

Possible processes:

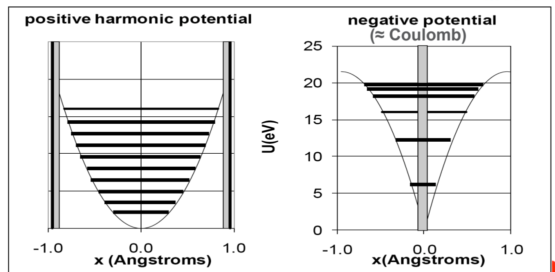
- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection



Critical angle: max. angle of incoming particle against plane where channeling is still possible

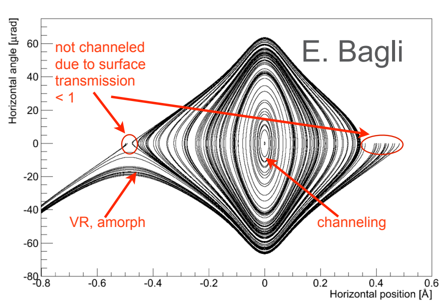
$\theta_{crit} = \sqrt{2U_0/E}$

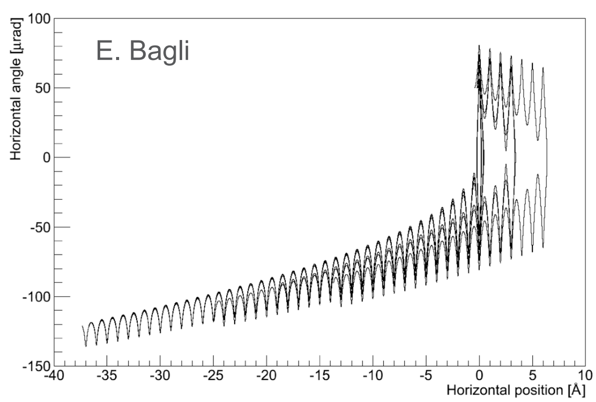
Potential shape differs depending on polarity

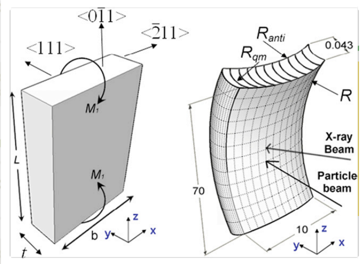


Phase Space (bent crystal)

- Same topology as a (moving) rf bucket



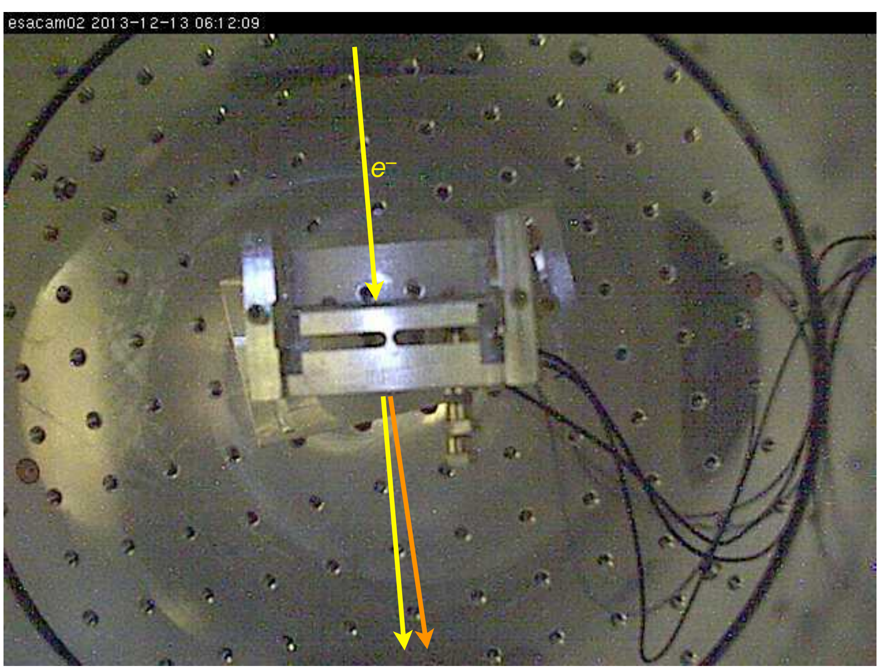




Main crystal features

- **Crystal thickness 60±1 µm**
  Once the crystal will be back in Ferrara we will measure crystal thickness with accuracy of a few nm.
- **(111) bent planes (the best planes for channeling of negative particles).**
- **Bending angle 402±9 µrad (x-ray measured). If needed I can provide a value with lower uncertainty.**

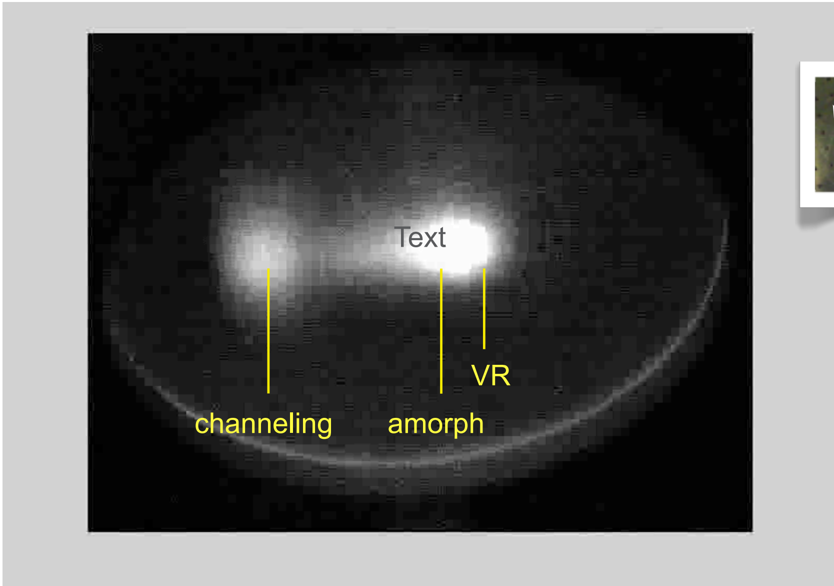
T513 Expt. @ SLAC ESA



Electron Deflection @ 4.2 GeV

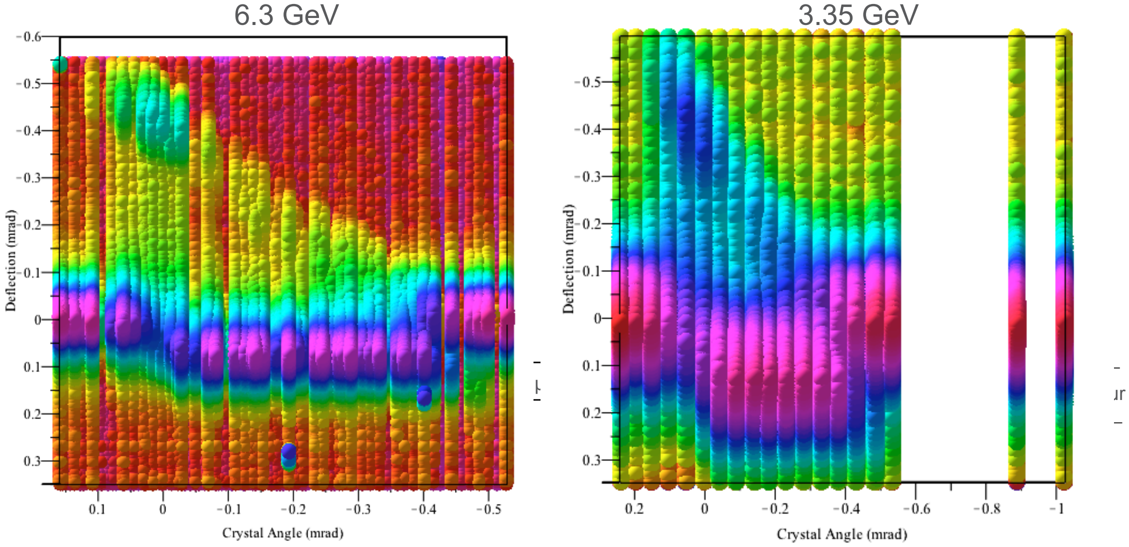
https://www.sciencedaily.com/releases/2015/02/150225132110.htm

(Movie credit: T. Wistisen)

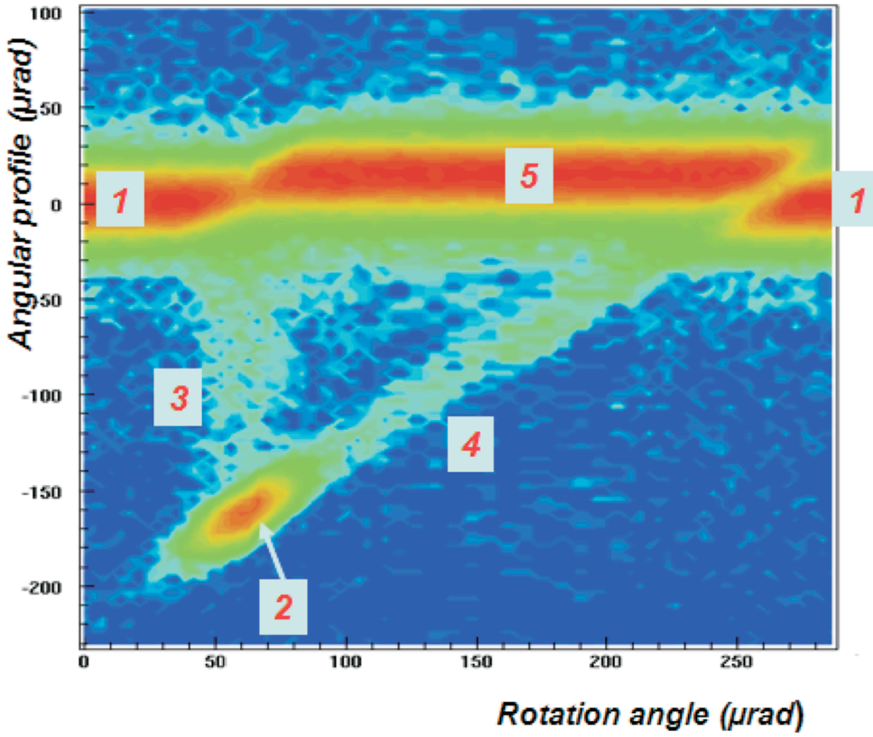


Triangle Plots

Colors rep. log(intensity).
Crystal angles from fit to laser spot (est'd uncertainty 2…5 μrad)



Deflection Triangle (Protons)

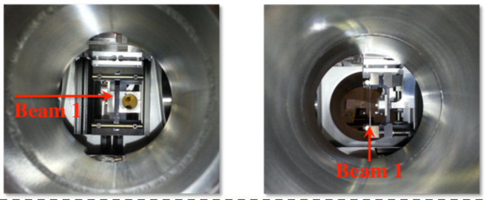


- Protons channel reasonably well channeling has been used to extract from h.e. synchrotrons
  - U70 in Protvino
  - proposed for LHC halo extraction (expt. in place)
    - critical angle 2.4 μrad
    - Tsyganov's radius ≈ 15 m
    - > 10s of μr bending achievable.
- Electron channeling efficiency only ≈ 25%, not enough
  - but volume reflection about 95% albeit at maybe 1/4 the angle
  - extraction using a VR array may be possible
  - this is interesting for beam collimation

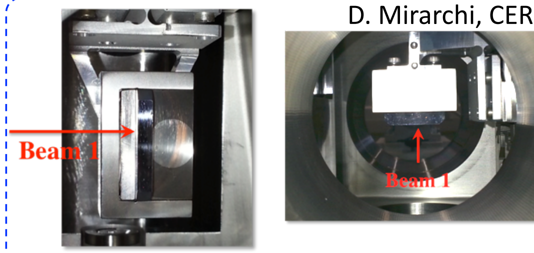
Hardware installed in the LHC

Two crystals** installed in the **IR7 (Beam1)** during **April 2014: (developed in the UA9 framework)

Silicon Strip crystal in the horizontal plane



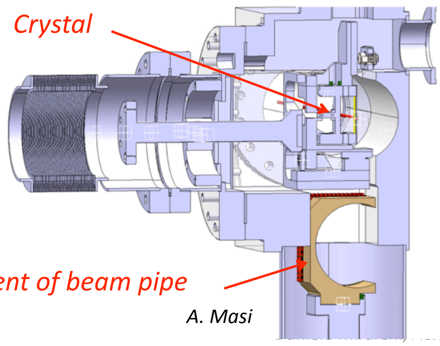
D. Mirarchi, CERN



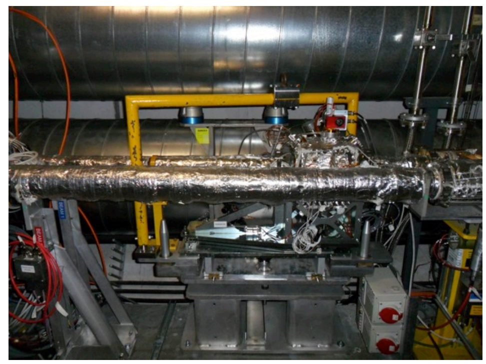
Quasi-mosaic crystal in the vertical plane

And relative goniometers: (UA9 framework)

- ✓ Piezo actuator in closed loop (angular stage)
- ✓ Transparent during normal operation

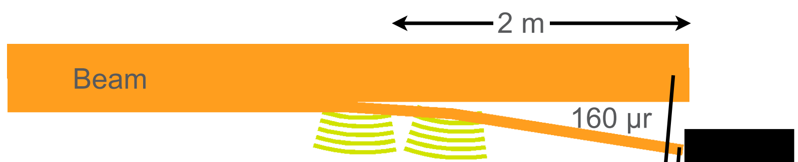


A. Masi

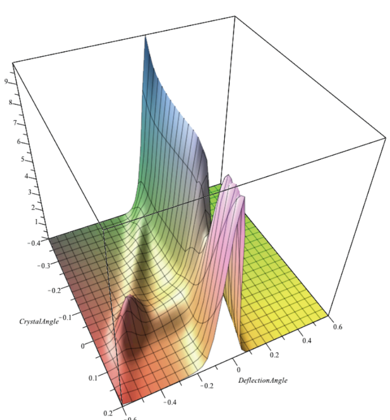


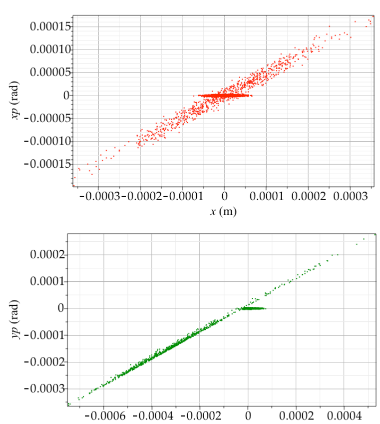
VR Collimator Concept

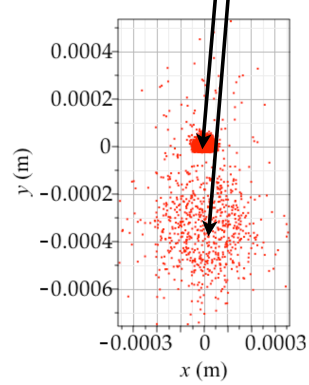
- The T513 data can help designing beam collimation for e^-:



pdf to generate deflections







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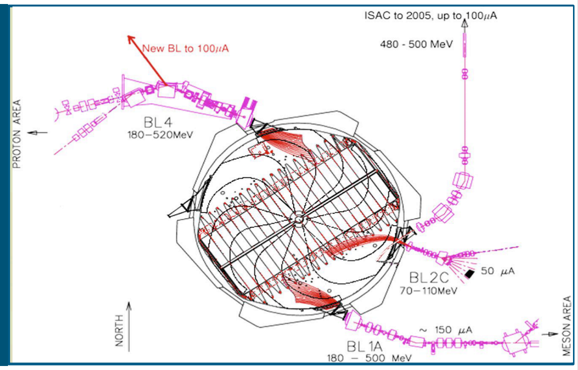
Cyclotron Injection & Extraction



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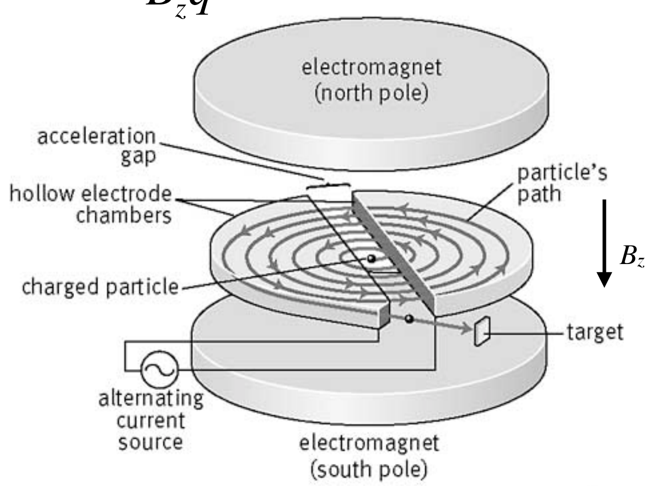
Cyclotron

- Circular accelerator with a spiral beam trajectory
  - this keeps the revolution frequency constant, until relativity kicks in:

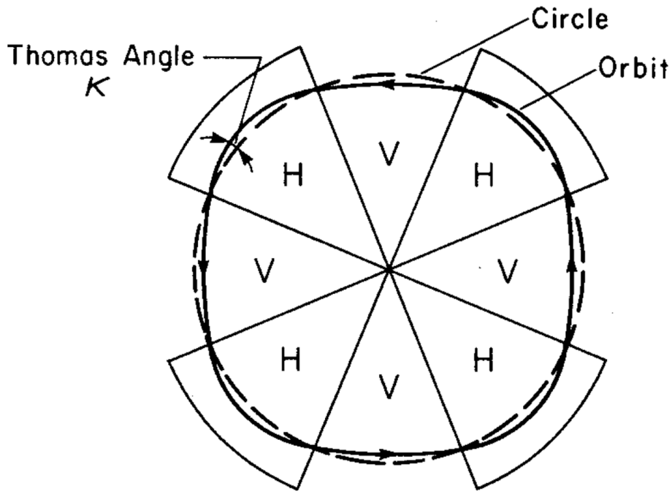
$$\gamma m_0 \omega = qB_z \qquad R = \frac{mv}{B_z q}$$



Precision Graphics

Isochronous Cyclotron

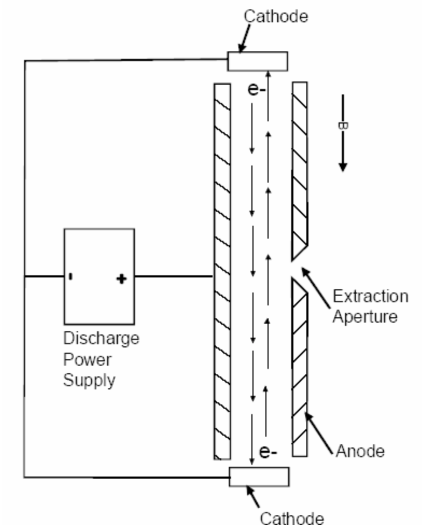
- Alternating field provides for stronger focusing
  - allows for higher beam energy as spiral pitch gets tighter



- For even higher energy need spiral-shaped fields
  - even higher focusing
  - turn separation at large radius is lost

Cyclotron Injection

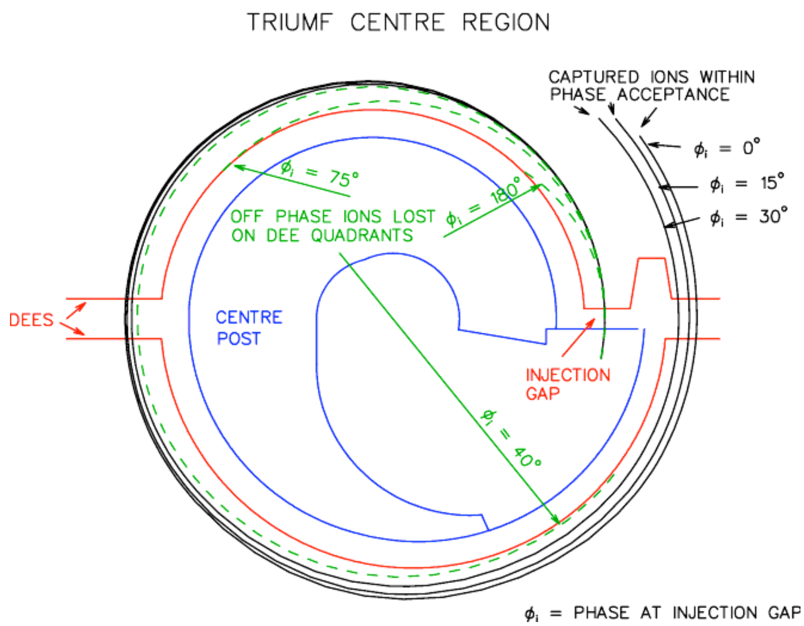
- internal source: simple arrangement; typically protons or light ions



Penning Ion Source (PIG)

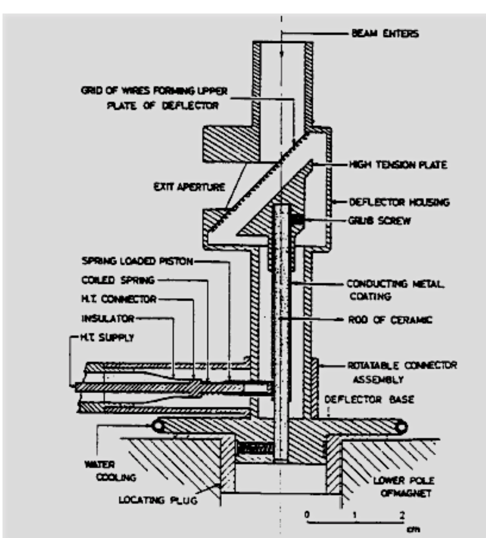
- Center region of an industrial cyclotron (IBA C18/9)

Center Region



Electric Mirror Inflector

- Simple, high fields (≈ beam energy), delicate extraction grid



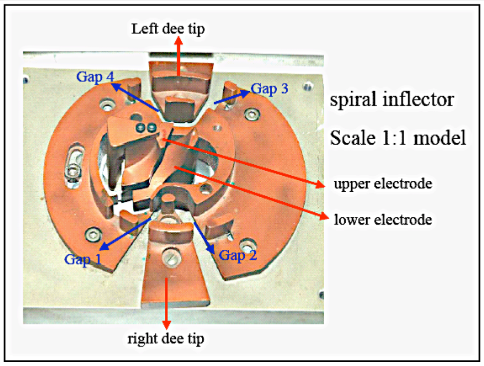
not really used anymore

Spiral Inflector

- A twisted capacitor, following the particle path in the e-m field
  - E-field always normal to particle path
  - Voltage required: $$V = 2\frac{E}{q}\frac{d}{A}$$

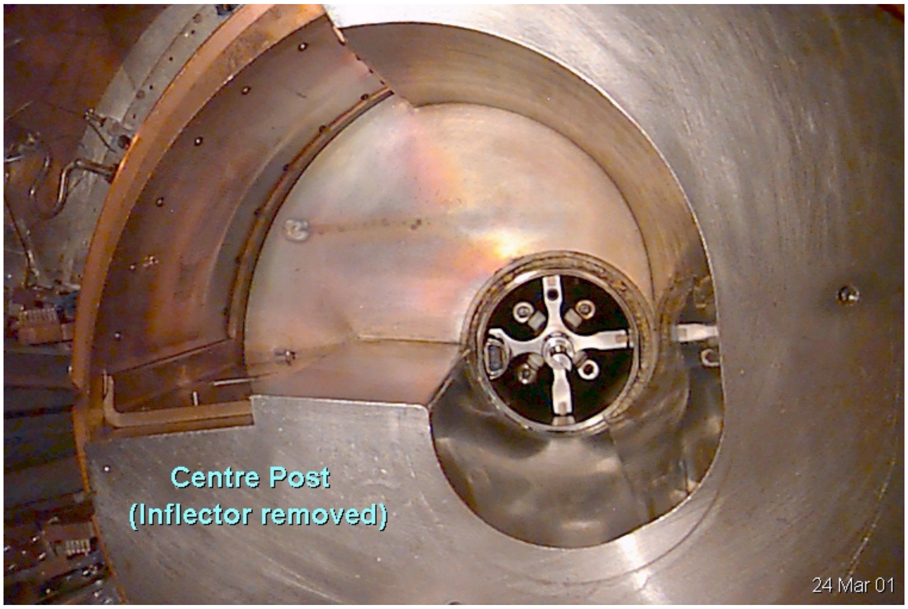
E: particle energy
q: particle charge
d: gap of inflector
A: radius of inflector

  - The field can also tilt around the particle orbit in the inflector to fine-tune the direction (tilt parameter k')
  - A and k' are design parameters.



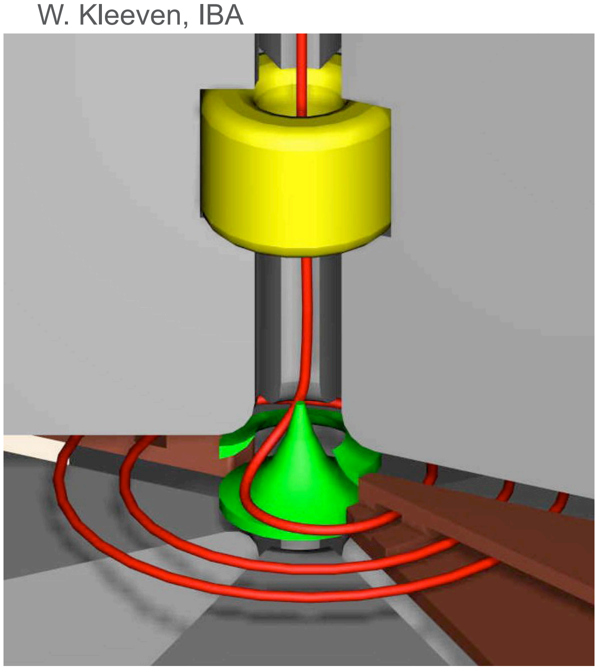
Spiral Inflector

Center Region



Magnetostatic Inflector

W. Kleeven, IBA



- Easier at higher energy
- No high voltage; field by main coils
- under study

Transport of a Beam through the Inflector

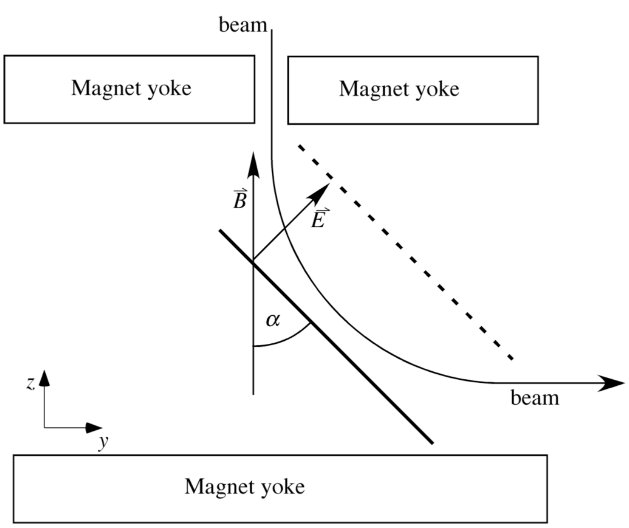
- No R-matrix for a beam through a (spiral) inflector exists
  - > an infinitesimal F matrix is used.

$$F(s) = \frac{R(s+ds,s)-1}{ds}$$

$$\Sigma(s+ds) = R\Sigma(s)R^T \quad \Rightarrow \quad \frac{d\Sigma}{ds} = F(s)\Sigma(s) + \Sigma(s)F(s)$$

  - we can then integrate to transport Σ along the inflector

Mirror Inflector



$$x = E_y / B\omega(\omega t - \sin \omega t)$$

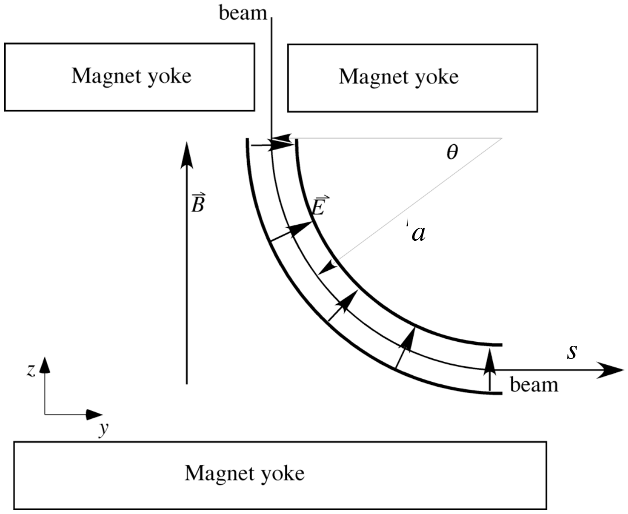
$$y = E_y / B\omega(1 - \cos \omega t)$$

$$z = (\omega / 2B)E_z t^2 - v_0 t + z_0$$

with $\omega = qB/m$

Spiral Inflector

- Motion is circular about B and follows E => spiral



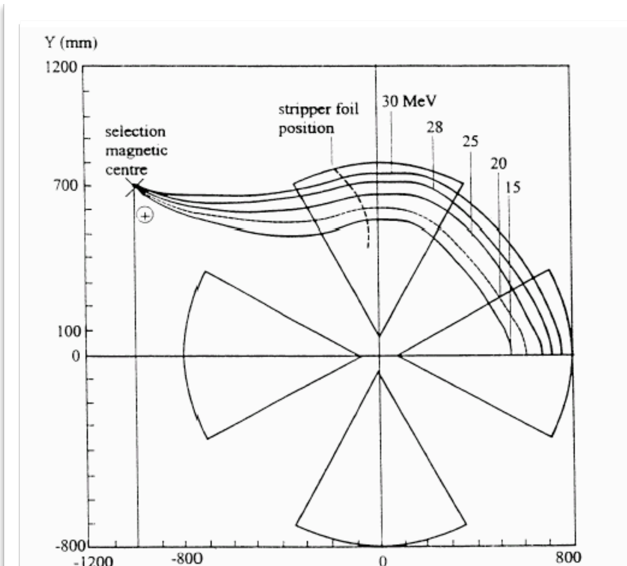
$$F = \begin{bmatrix} 0 & 1 & -Ck & 0 & 0 & 0 \\ -S^2k^2 & 0 & -Sk/a & 0 & 0 & Sk \\ Ck & 0 & 0 & 1 & 0 & 0 \\ -Sk/a & 0 & 0 & 0 & 0 & 2/a \\ -Sk & 0 & -1/a & 0 & 0 & 1 \\ -Ck/a & 0 & 0 & -1/a & 0 & 0 \end{bmatrix}$$

$$C = \cos\frac{s}{a},\ \ S = \sin\frac{s}{a},\ \ k = \frac{1}{\rho}$$

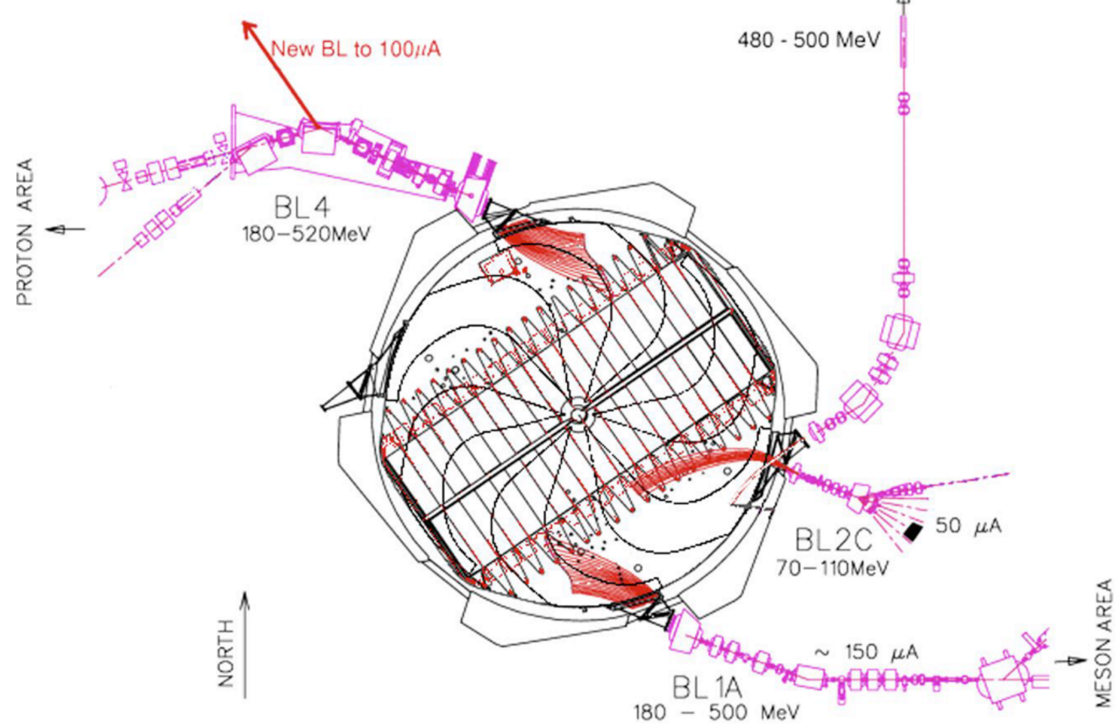
a: electric radius of curvature
ρ: magnetic radius of curvature
s: path length

H– Extraction

- Simplest extraction is by stripping H– ions:
- quite efficient
- no turn separation needed
- can extract several beams
- can select intensity by partial interception of beam
- varian: accelerate H_2^+ and strip to H^+



TRIUMF H– Extraction



Cyclotron Extraction

- For the deflector, *turn separation* is needed to avoid the deflector electrode being hit by beam.

$$\Delta r(\theta_n) = \Delta r_0(\theta_n) + \Delta x \sin\left(2\pi n(\nu_r - 1) + \theta_0\right) + 2\pi(\nu_r - 1) x \cos\left(2\pi n(\nu_r - 1) + \theta_0\right)$$

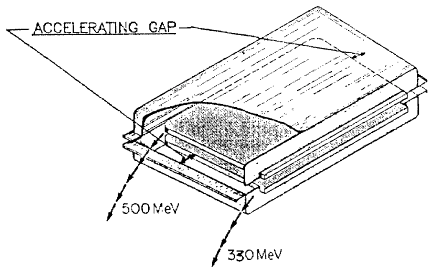
- The acceleration part is given by

$$\Delta r_0 \approx \frac{r}{2}\frac{\Delta E_{turn}}{E}$$

  - in an isochronous cyclotron, r grows slower than E so the turns bunch up towards the top end.
  - The higher V_{rf}, the higher is ΔE and thus turn separation.

TRIUMF AAC

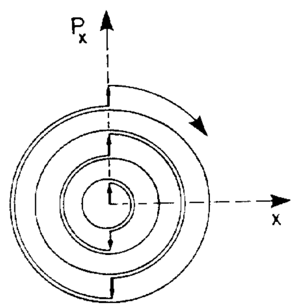
- Increase DE/turn from 320 keV to 620 keV using a 4th harmonic cavity

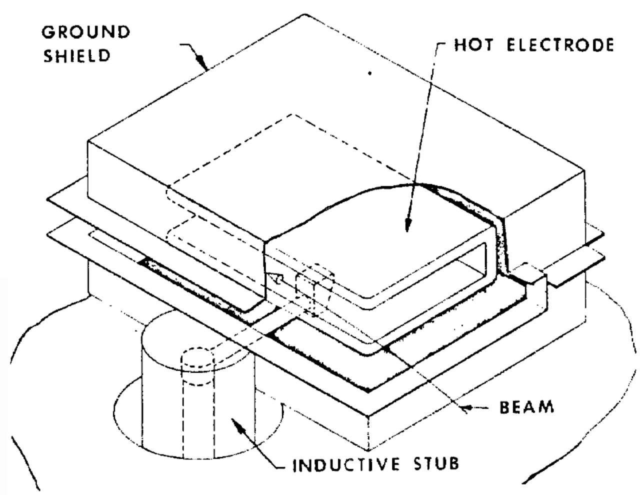


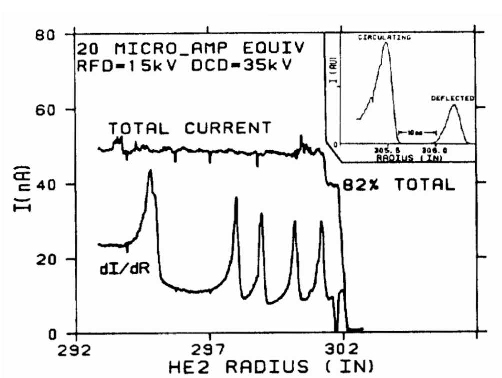
- double turn separation; lower Lorentz stripping.

Excitation of the 3/2 radial Resonance

- 11.5 MHz, 25 kV, Δr from 1.5 mm to 5 mm (at 440 MeV)







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- R. Baartman, “Matching of ions sources to cyclotron inflectors”, EPAC88, Rome, June 6-10, 947(1988).
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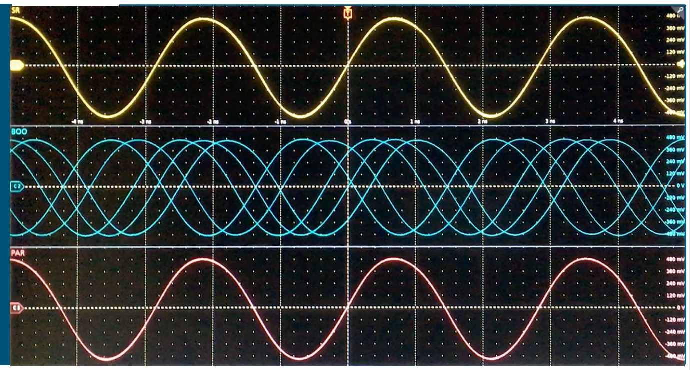
Machine Synchronization



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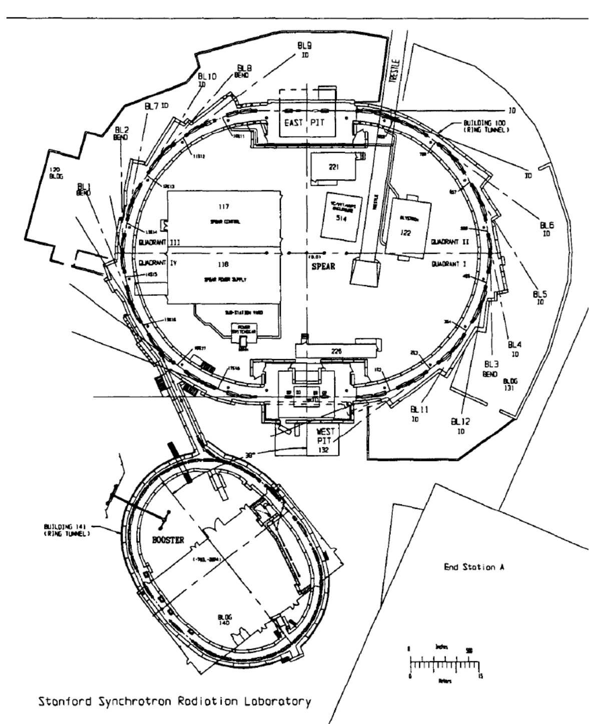
Machine Synchronization and Rf Matching

- When only one rf frequency is used,rf matching is straightforward
  - adjust the rf voltage of the receiving ring so its acceptance matches the one from the extracting ring.
- In hadron machines, rf often needs to ramp commensurately with the speed of the particles. Still, frequencies match at moment of beam transfer.
- Transferring from a smaller to a larger ring may involve bucket-targeting into the larger ring. Typically this is taken into account when designing the overall geometry by making the smaller ring skip or add turns while keeping the rf static.

- When an existing facility gets updated, maintaining the old single-frequency scheme may become too restrictive.
- Examples:
  - SLAC Spear 3: Switch storage-ring rf to 476.3 MHz, maintain 358.5 MHz for Booster synchrotron
  - Argonne APS: Change storage-ring circumference by 40 cm for new lattice to avoid moving all front-ends and experiments. Raise storage-ring rf from 351.94 MHz to 352.05 MHz. Maintain Booster rf (??)

Spear3

- 3 GeV Light source.
  - 234.5 m circumference
  - 476.34 MHz rf, h=372
- 3 GeV Booster
  - 134 m circumference
    - 4/7 * C_{Spear3}
  - 358.53 MHz rf, h=160



Numerology

- With the given circumference ratio (7/4) and the aimed-for harmonic-numbers, the frequency ratio is (exactly)

$$\frac{f_B}{f_{SP}} = \frac{7}{4}\frac{h_B}{h_{SP}} = \frac{7}{4}\frac{160}{372} = \frac{70}{93}$$

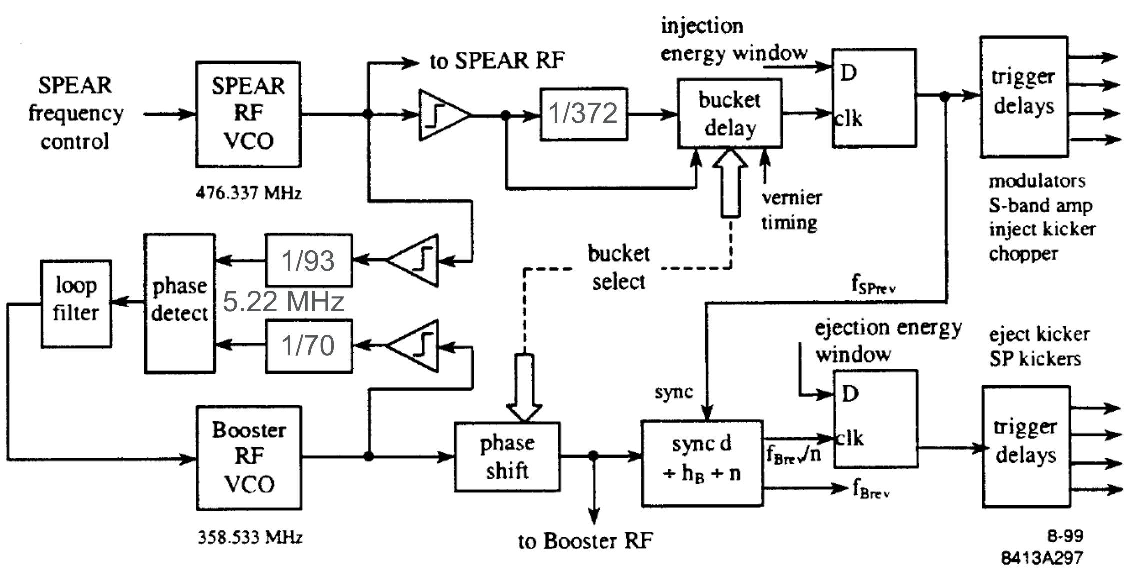
- Then there is a common frequency

$$\frac{f_B}{70} = \frac{f_{SP}}{93} = 5.122 \text{ MHz, or } 1/0.3347\ \mu\text{s or } 4\frac{h_{SP}}{f_{SP}}$$

- IOW, 4 Spear3 rf buckets are directly accessible from the Booster.
- What about the other 368 rf buckets?
  - Time-shift (phase-shift) the Booster rf!
  - Need 93 different phase shifts $\Phi_n = \Phi_0 + n \cdot 2\pi \cdot \frac{70}{93}$

Spear3 Injection Timing

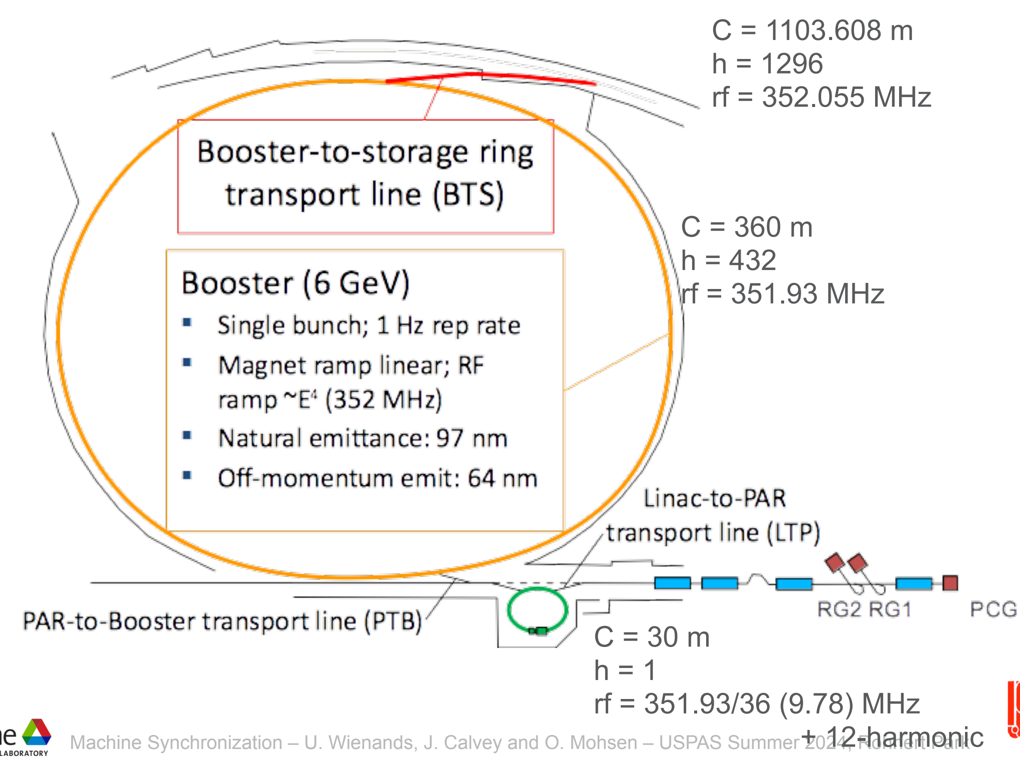
- Hybrid (analog & digital) implementation.



APS-U Injection-Extraction Timing & Synch (IETS)

- The Spear3 scheme has some drawbacks for APS:
  - Frequency difference is small, ≈120 kHz (≈ 8 μs). “Magic ratios” would be very large.
  - APS Booster injects from another ring (PAR) so shifting its phase would impede PAR=> Booster transfer.
  - APS Booster operates at -0.6% momentum offset for emittance reasons, would like to inject closer to on-momentum and ramp momentum further negative.
  - APS synchronizes timing to 60-Hz line frequency, which randomizes injection timing relative to the revolutions of the rings.
- Adopted a frequency slewing-scheme (with beam) to move Booster rf away from its nominal value to target in SR bucket and control momentum offset.

APS & Injectors Layout



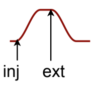
IETS Numerology

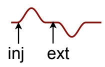
- Booster frequency offset from SR frequency by

$$f_{Boo} = f_{SR}\left(1+\frac{1}{N}\right), \text{ where } N = 2881 \text{ (e.g.)}$$

- Modulate Booster rf during acceleration with a cosine-like function (to avoid sharp transients):

bump frequency

ramp 

bucket targeting 

forward

$$\Delta_{Wramp}\left(\begin{cases} 0 & r \le r_0 \\ \frac{1}{2}-\frac{1}{2}\cos\left(\frac{\pi(-r_0+r)}{r_1-r_0}\right) & r_0 < r \text{ and } r \le r_1 \\ 1 & r_1 < r \end{cases}\right) + \frac{1}{2}\left(\Delta_{Wtgtfwd}+\Delta_{W0fwd}\right)\left(\begin{cases} 0 & r \le r_0 \\ 1-\cos\left(\frac{2\pi(-r_0+r)}{r_1-r_0}\right) & r_0 < r \text{ and } r \le r_1 \\ 0 & r_1 < r \end{cases}\right) + \Delta_{Wramp}$$

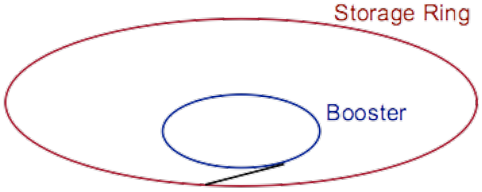
return

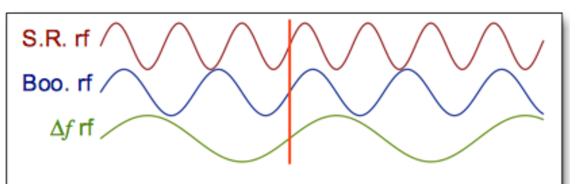
$$\begin{cases} 0 & r \le r_{r0} \\ -\frac{1}{2}+\frac{1}{2}\cos\left(\frac{\pi(-r_{r0}+r)}{r_{r1}-r_{r0}}\right) & r_{r0} < r \text{ and } r \le r_{r1} \\ -1 & r_{r1} < r \end{cases} - \frac{1}{2}\left(\Delta_{Wtgtfwd}+\Delta_{W0fwd}\right)\left(\begin{cases} 0 & r \le r_{r0} \\ 1-\cos\left(\frac{2\pi(-r_{r0}+r)}{r_1-r_0}\right) & r_{r0} < r \text{ and } r \le r_1-r_0+r_{r0} \\ 0 & r_1-r_0+r_{r0} < r \end{cases}\right)$$

- Coefficients calculated before each Booster injection.

Injection timing/RF generation for synchronization

- APS-U storage ring and Booster will use different rf frequencies.
  - Booster (at -0.6% momentum offset): $f_{Boo} = f_{S.R.}(1-\Delta f)$, $f_{S.R.} = 352.055$ MHz, $\Delta f \approx 140$ kHz
  - Booster cannot accommodate this frequency shift (additional -3.5% momentum offset).
  - *Frequency ramp for Booster is desirable to optimize beam injection and extraction.*
- Δf encodes the path-length correction and frequency ramp for bucket-targeting.
  $\Delta f = f_{S.R.}/N$, N an integer; every N storage ring cycles the rf waves line up.
- Counting cycles of Booster and storage ring rf and Δf, bunch-to-bucket transfer is possible at 0-crossing of Δf.





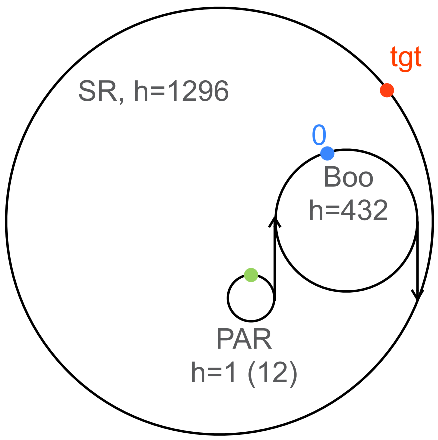
Schematic of rf frequencies (Df exaggerated)

Wienands

U. Wienands, "Booster-APS-U MBA Synchronization," white paper (Oct 2017).
A. Xiao, M. Borland, APS-U Beam Physics Review (May 16-17, 2018).

Bucket Counting

- An *Orientation Counter* counting storage-ring rf modulo 1296*N keeps track of the relative orientation of Booster and storage-ring to facilitate the timing at storage-ring injection



Bunch in PAR • is aimed into Booster bucket 0.
Bunch in Booster • is aimed into specific rf bucket • in the SR.

System has to keep track of these from Booster injection despite frequency differences.

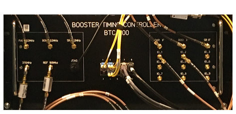
The rational relationship between the frequencies allows that

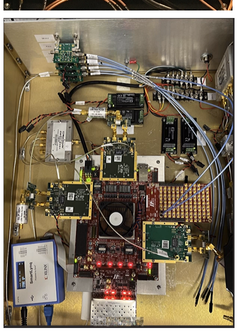
A phase detector measuring beam against SR rf allows to monitor the process

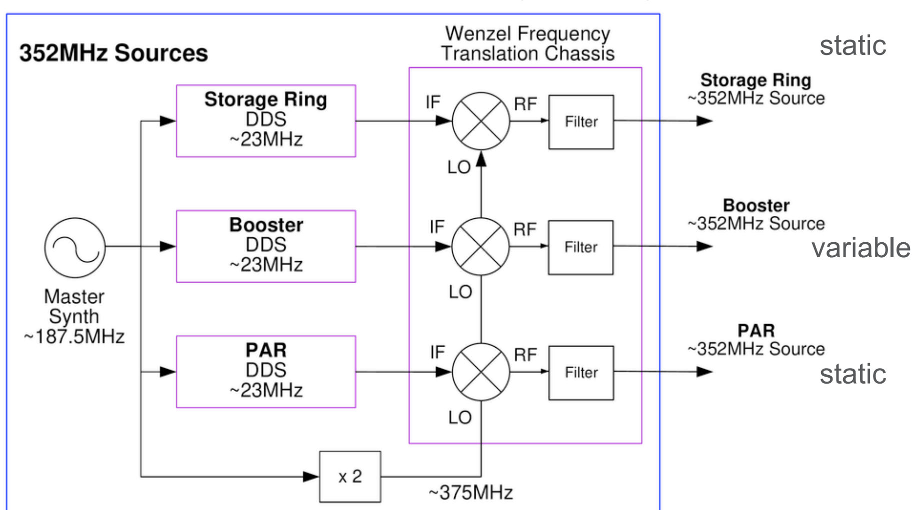
Frequency Sources

- DSSs are being used to generate references for SR, Booster and PAR
- combined with ramp & targeting calculation in BTC200

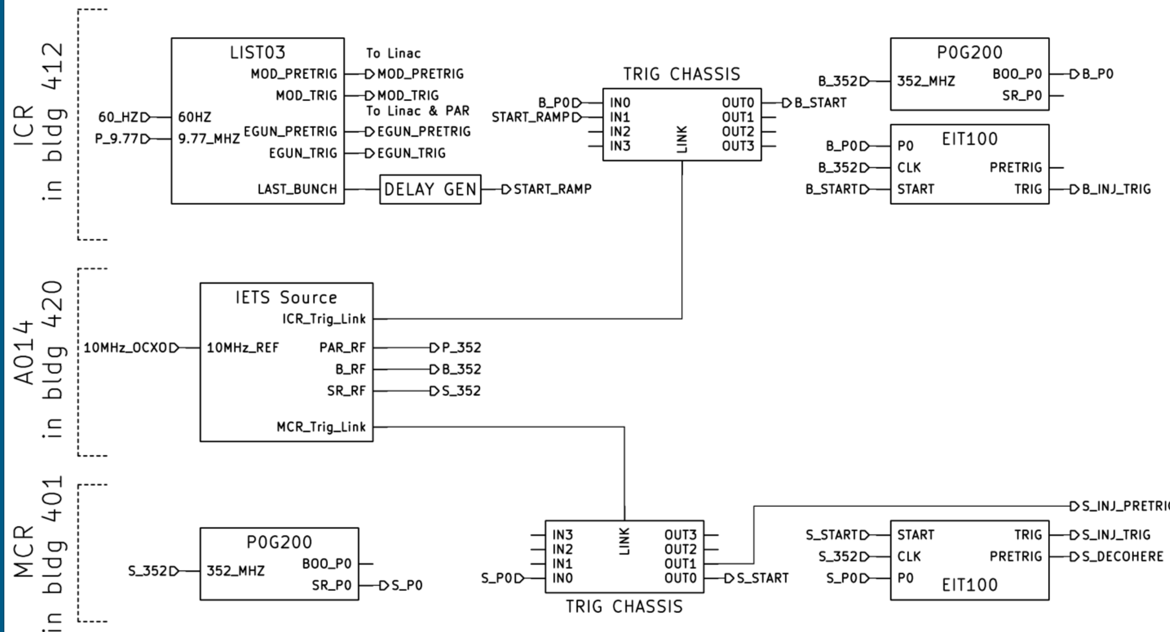
(T. Berenc)







APS-U IETS Block Diagram



IETS First Operation at APS-U

Rf

BTC, Rf

Bunch-Arrival vs time (internal Booster beam)