Lecture 9: Diagnostics

High Brightness Electron Injectors for Light Sources

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Outline

- Standard Diagnostics
  - Charge
  - Energy and Energy Spread
  - Bunch Length
  - Profile Measurements
- Phase Space Measurements
  - Space Charge vs Emittance Dominated
  - Transverse
    - Pepper Pot
    - Single Shot
    - 3 Screen
    - Quadrupole Scan
    - Temporal Slice
  - Longitudinal
    - RF Phase
    - Transverse Kicker
  - Tomographic

Charge

- Faraday Cup
  - Destructive
  - Must contain secondary emission
- Toroid
  - Non-destructive
  - Must break the vacuum pipe to prevent the return current cancelling the beam current
- BPMs
  - Non-destructive
  - Sum signal proportional to current

Energy and Energy Spread

- Spectrometer Magnet
  - Introduces energy vs position correlation
  - Minimize transverse beam size at spectrometer entrance
  - Need consistent position and angle at spectrometer entrance
  - Collimator at entrance solves both problems
  - Resolution commonly limited by beam size at entrance
- Solenoid Magnet
  - Introduces energy vs angle correlation
  - Poor resolution so difficult to determine energy spread

Bunch Length Measurement

- Streak Camera
  - Generate light pulse proportional to current pulse
  - Photons converted to low energy electrons at front end of streak camera
  - Voltage ramp applied to transverse plates to produce position correlated to time
  - Resolution determined by photon beam size usually set by input collimator
- RF Deflector
  - Very simlar to streak camera but eliminates photon pulse
  - RF field with transverse component used to produce position correlated to time
  - At 0° phase setting the head and tail are deflected opposite directions
  - Minimize transverse beam size at input for optimum resolution
- Electro-Optic Crystal
  - Optical pulse polarization modulated by electric field from electron beam passing a birefringent crystal
  - Resolution limited by electric field pulse length which is determined by beam energy and distance between electron beam and crystal
  - Use optical pulse measurement techniques to measure pulse length
  - Wakefields can make results difficult to interpret

Profile measurement

- Destructive Measurement
- Measure current density as function of transverse coordinates
- Must verify screen and detector not saturated
- Common Screen Materials
  - Phosphor
  - YAG
  - OTR
- Wire Scanner
  - Produces signal proportional to total charge at fixed position of one coordinate
  - Wire scanned through beam to measure 1D distribution
  - Signal detected on photomultiplier/scintillator downstream of wire scanner
  - Resolution limited by wire size

Screen Comparison

Screen	Resolution	Dynamic Range	Time Response
Phosphor	≈ 50 μm	small	ms
YAG	≈ 20 μm	medium	< ms
OTR	≈ 10 μm	large	fs
Wire	≈ 10 μm	large	ns

Phase Space Diagnostics

- No diagnostic discussed so far can measure the phase space distribution
- Thus phase space correlations will not be detected (except x-y correlations)
- Preference is to measure phase space for optimizing injector performance

Space Charge or Emittance Dominated Regime

$$\ddot{\sigma}_x + k_x \sigma_x = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^3} + \frac{I}{\gamma^3 I_0 \left(\sigma_x + \sigma_y \right)}$$

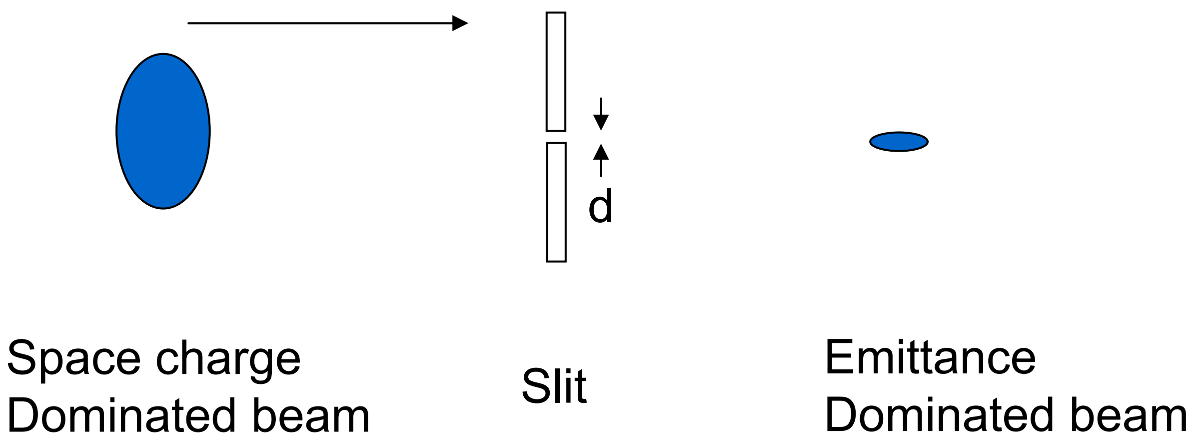
$$R = \frac{I \sigma_x^3}{\gamma I_0 \varepsilon_n^2 \left(\sigma_x + \sigma_y \right)}$$

$R >> 1$ Space Charge Dominated

$R << 1$ Emittance Dominated

Reduction of Space Charge

- To measure emittance requires emittance dominated beam
- Space charge dominated beam must be converted to emittance dominated



Reduction of Space Charge

$$R_i = \frac{I\sigma_x^3}{\gamma I_0 \varepsilon_n^2 \left(\sigma_x + \sigma_y\right)}$$

$$R_f = \frac{I\dfrac{d}{\sigma_x}d^3}{2\gamma I_0 \varepsilon_n^2 \left(\dfrac{d}{\sigma_x}\right)^2 \sigma_y} \qquad \text{where } d << \sigma_x$$

$$\frac{R_f}{R_i} = 2\left(\frac{d}{\sigma_x}\right)^2 \qquad \text{where } \sigma_x \approx \sigma_y$$

Pepper Pot

- Measure angle and spread downstream of slit on a screen as a function of slit position
- Reconstruct transverse phase space

$$\langle x^2 \rangle = \frac{\sum_{n=1}^{N} Q_n x_n^2}{\sum_{n=1}^{N} Q_n}$$

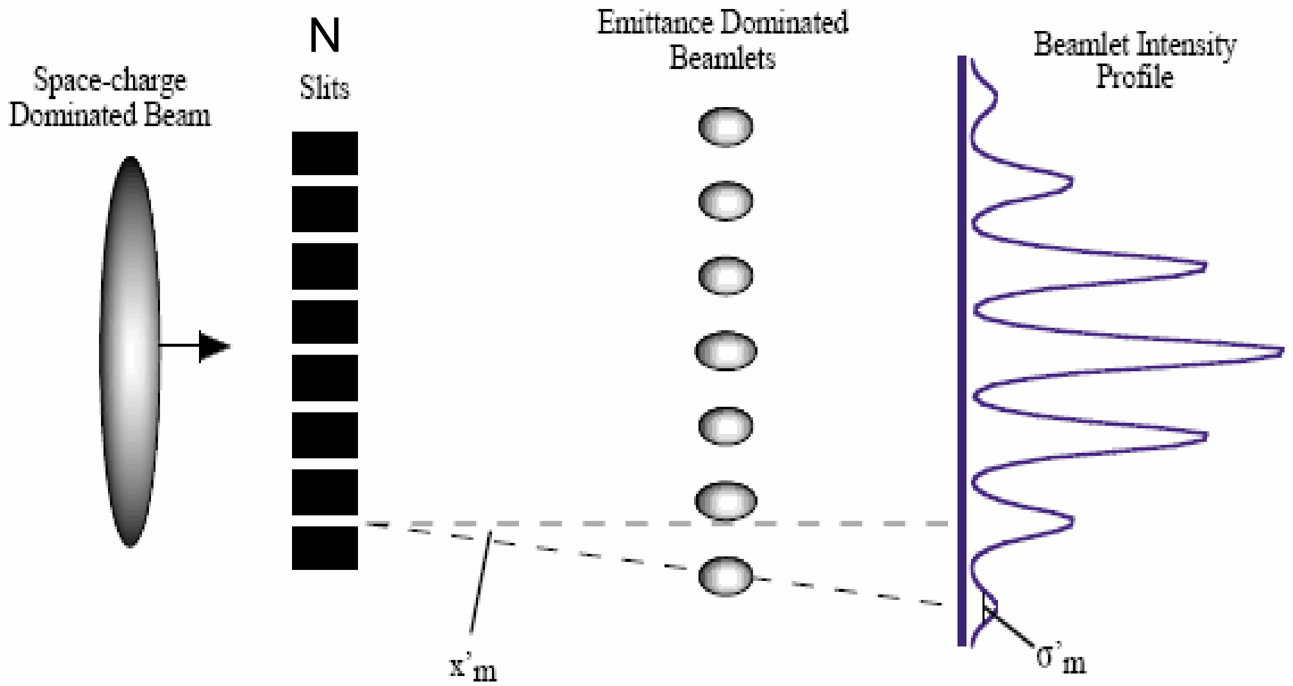
$$\langle x'^2 \rangle = \frac{\sum_{n=1}^{N} Q_n \left(x_n'^2 + \sigma_n'^2 \right)}{\sum_{n=1}^{N} Q_n}$$

$$\langle x x' \rangle = \frac{\sum_{n=1}^{N} Q_n x_n x_n'}{\sum_{n=1}^{N} Q_n}$$

$$\varepsilon_{nx} = \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

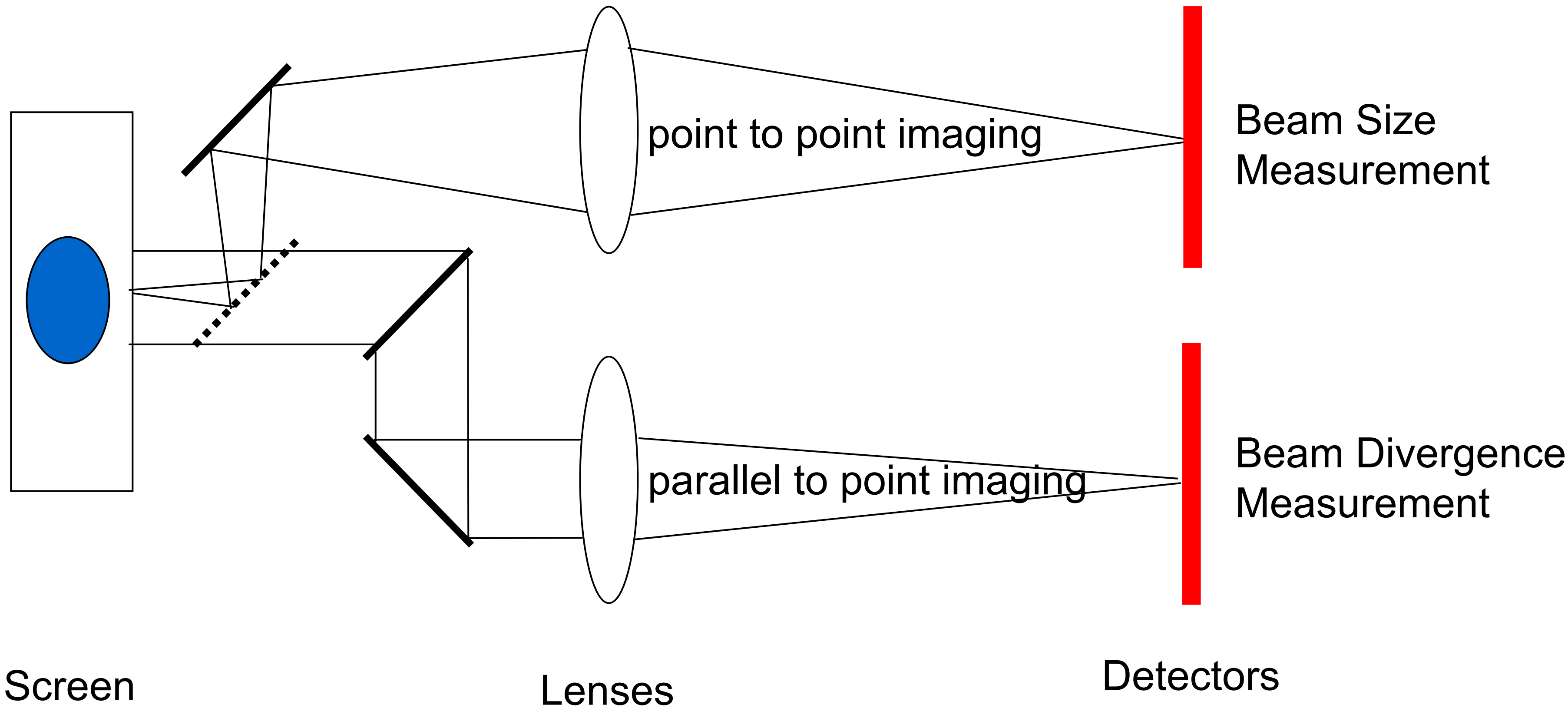
MultiSlit Pepper Pot

- N measurements made simultaneously



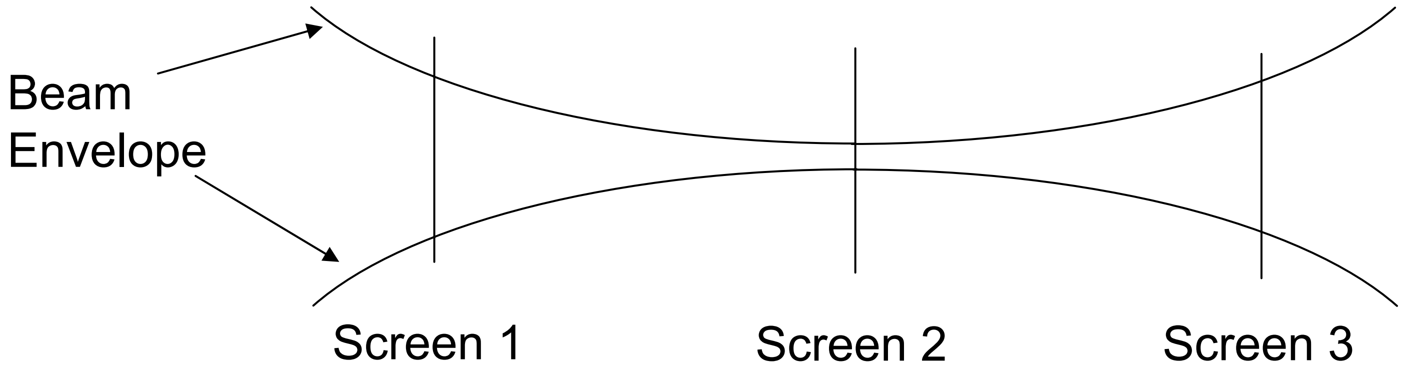
S.G. Anderson, PRST AB, vol 5, p 14201, 2002.

Single Shot


point to point imaging
Beam Size
Measurement
parallel to point imaging
Beam Divergence
Measurement
Screen
Lenses
Detectors

3 Screen

- Measure Transverse Beam Size at 3 z positions
  - Fit results to parabola
  - Ideally beam converging at screen 1 and diverging at screen 3 with screen 2 near the waist
- Can measure x and y emittance simultaneously

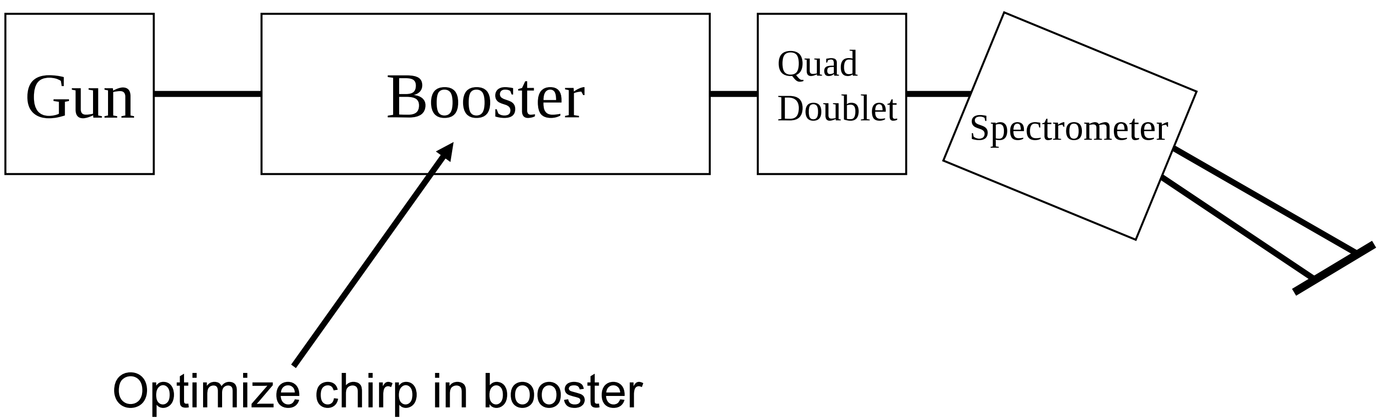


Quad Scan

- Measure beam size at fixed position as a function of quadrupole strength located upstream of screen
- Quadrupole varied to move the waist from downstream to upstream of the screen
- Minimum 3 beam size measurements required but generally more measurements are used
- As described measures the projected emittance only

Quad Scan Slice Emittance

- Impart linear energy chirp on electron beam typically by accelerating in a linac off crest
- Measure beam size in a dispersive section
- Slice energy or time axis in software and analyze each slice independently



Slice Emittance Analysis

- Measure beam size as a function of quad current in a dominantly dispersive section with linearly chirped beam

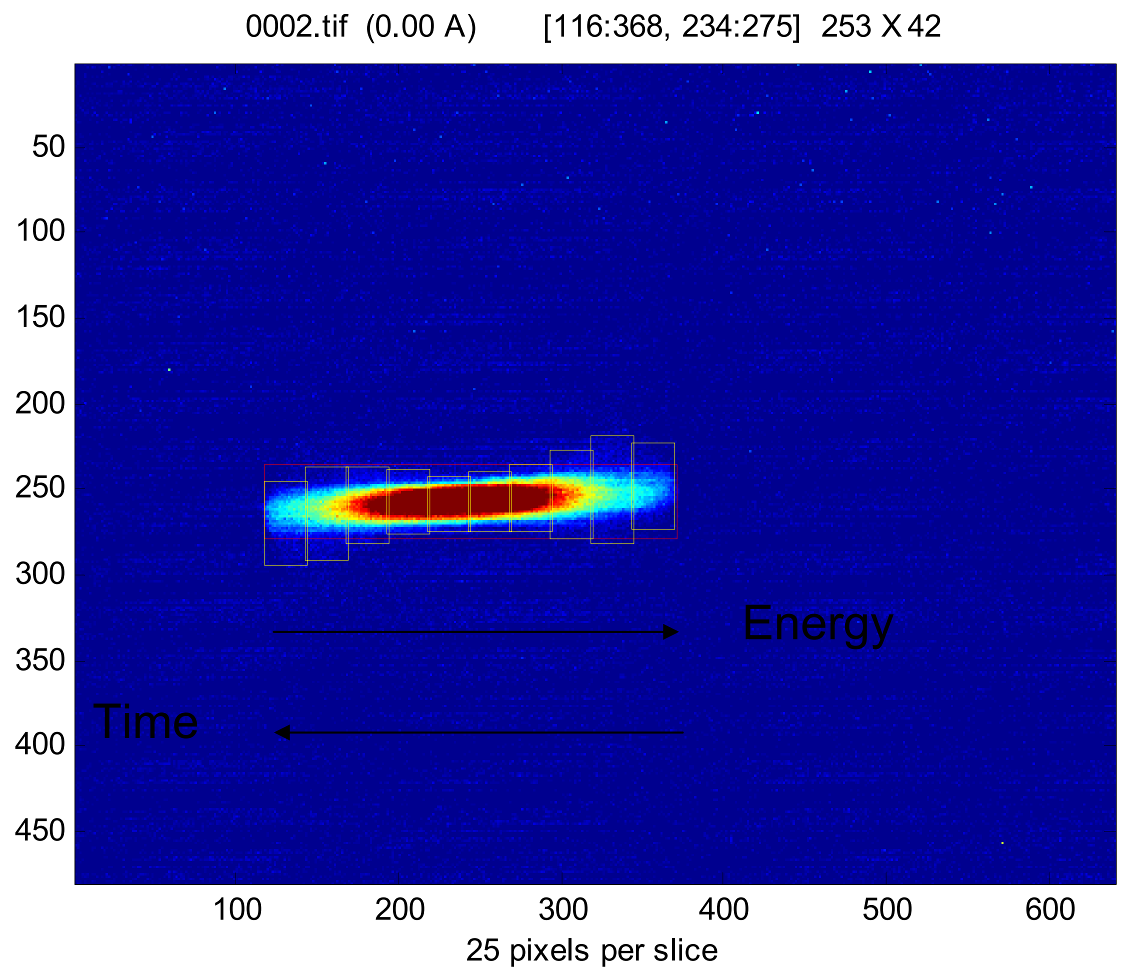
$$\Delta x_n = \iint \left(x - x_{1n} \right)^2 \, f_n(x,y)\, dx\, dy$$

- Fit σ_{11}, σ_{12}, σ_{22}
- Also measure slice centroids with respect to the projected centroid

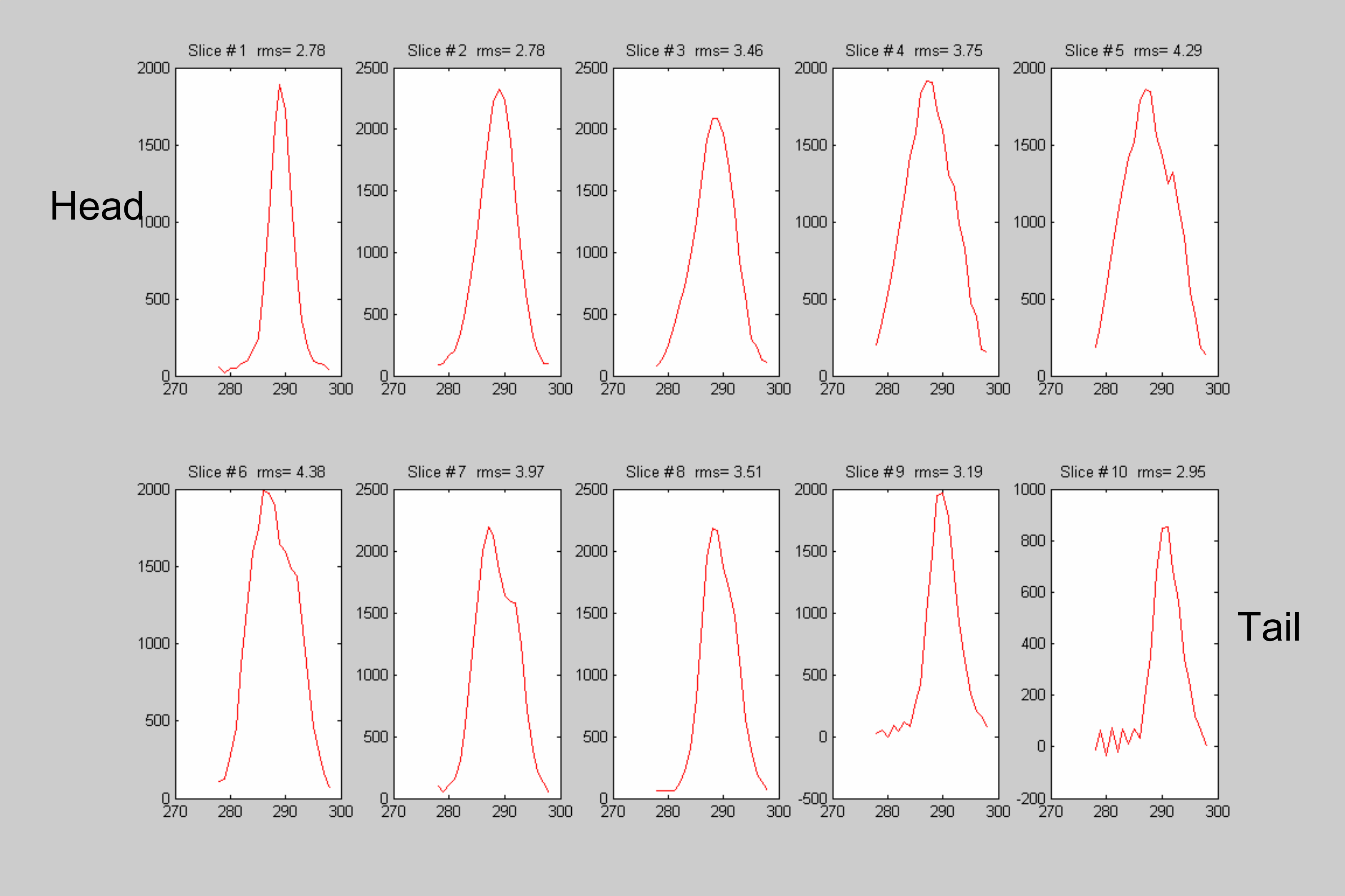
$$x_n = \iint x \, f_n(x,y)\, dx\, dy - \iint x \, f_{projected}(x,y)\, dx\, dy = x_{1n} - x_{0n}$$

- Fit x_0, x_0' (centroid position and angle)
- Actually 5 parameters to describe the slice ellipse not just 3 Twiss parameters

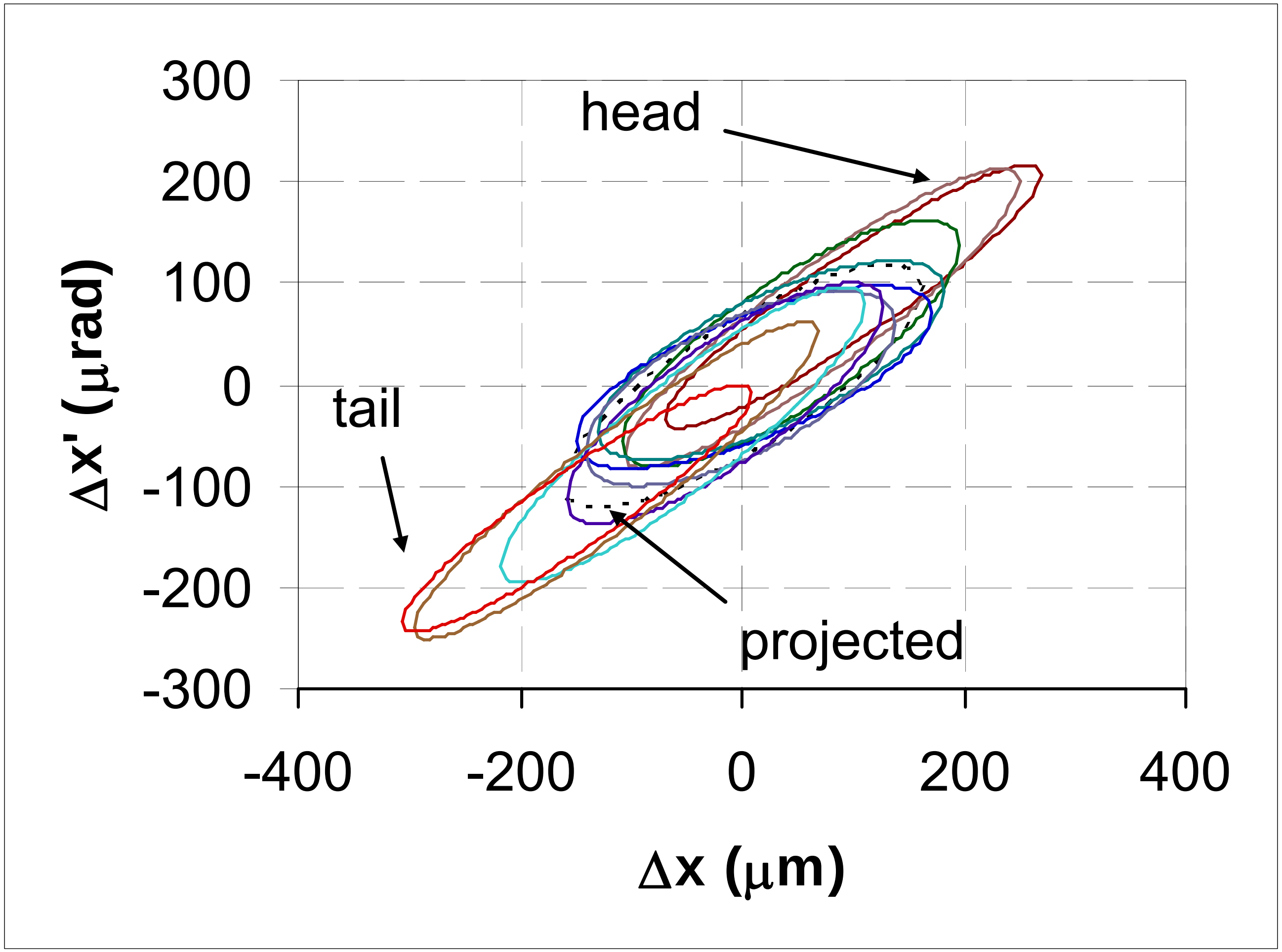
Typical Beam Measurement



Slice Projections

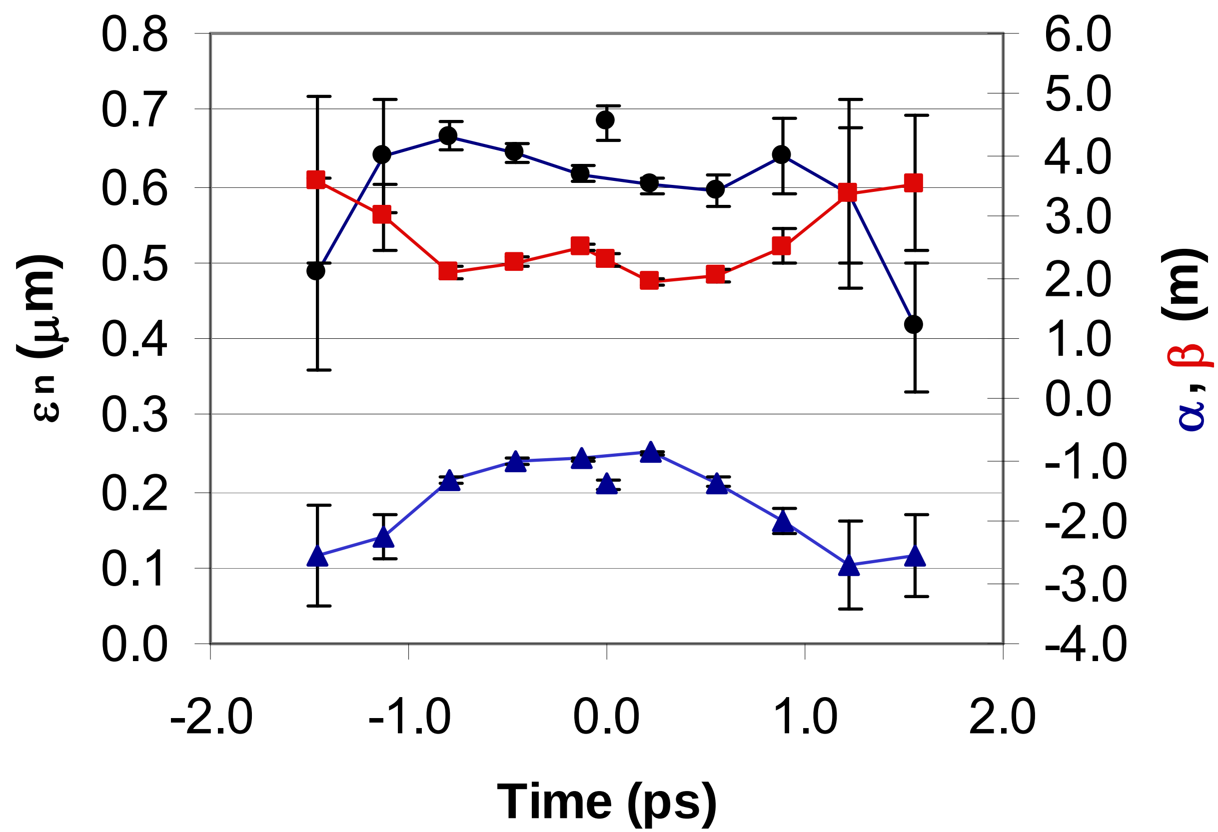


Phase Space



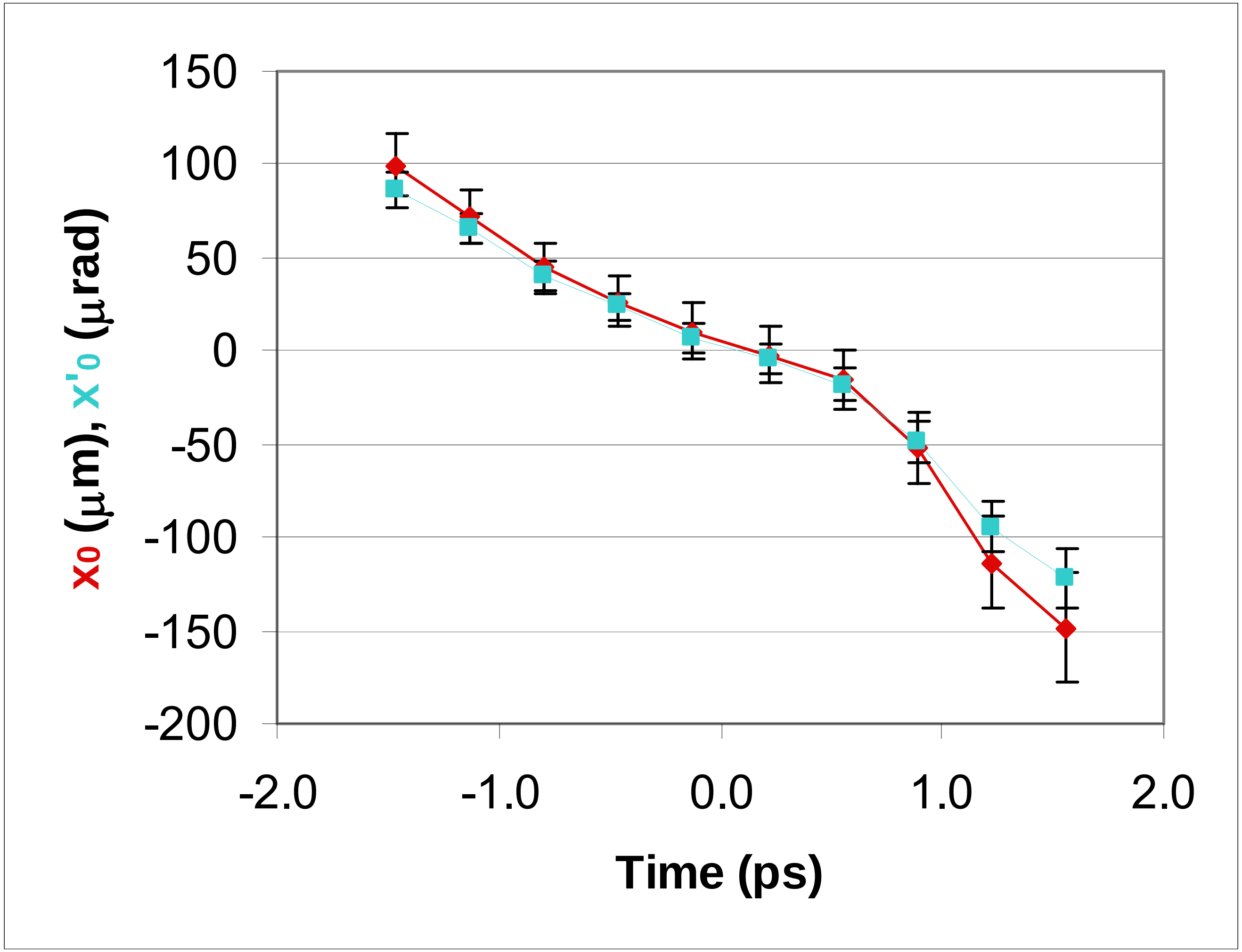
300
200
100
0
-100
-200
-300
-400
-200
0
200
400
head
tail
projected
Δx' (μrad)
Δx (μm)

Twiss Parameters



Projected values displayed at t=0

Offsets

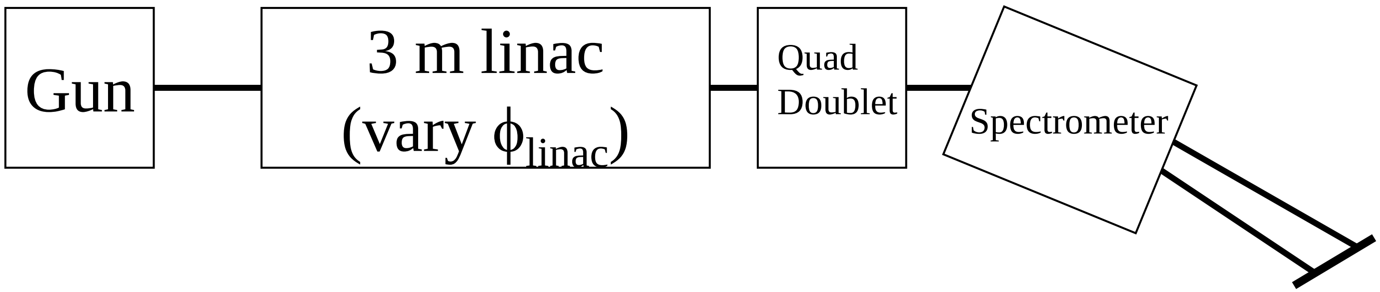


Longitudinal Emittance

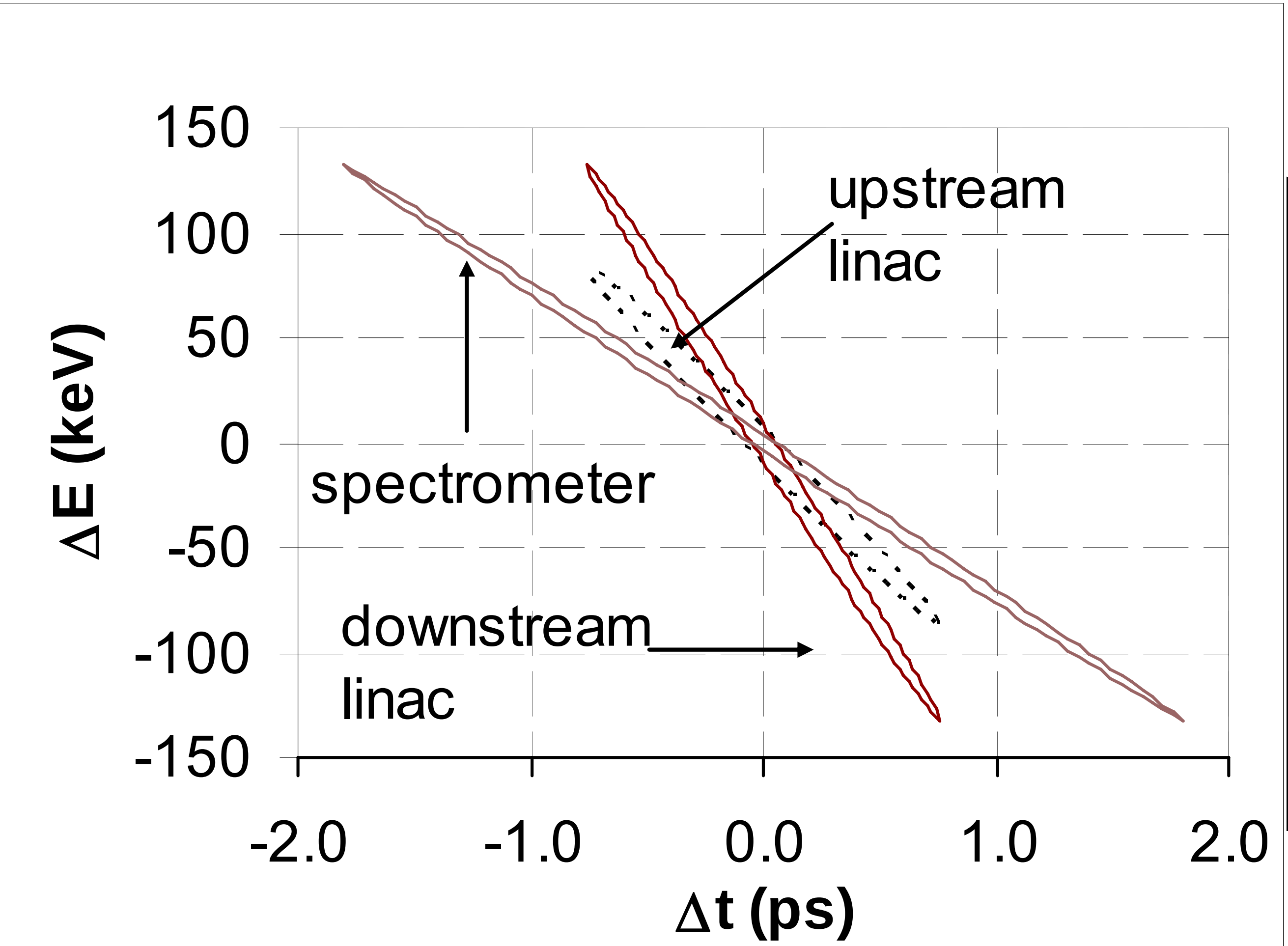
- Techniques to measure distribution in energy and time
  - Introduce energy chirp by accelerating off crest and measure energy distribution as a function of rf phase
  - Introduce correlation between time and position and correlate energy with the other transverse position

RF Phase Technique

- Measure Energy Spectra as a function of accelerator phase
- Technique analogous to Quad scan transverse emittance measurement



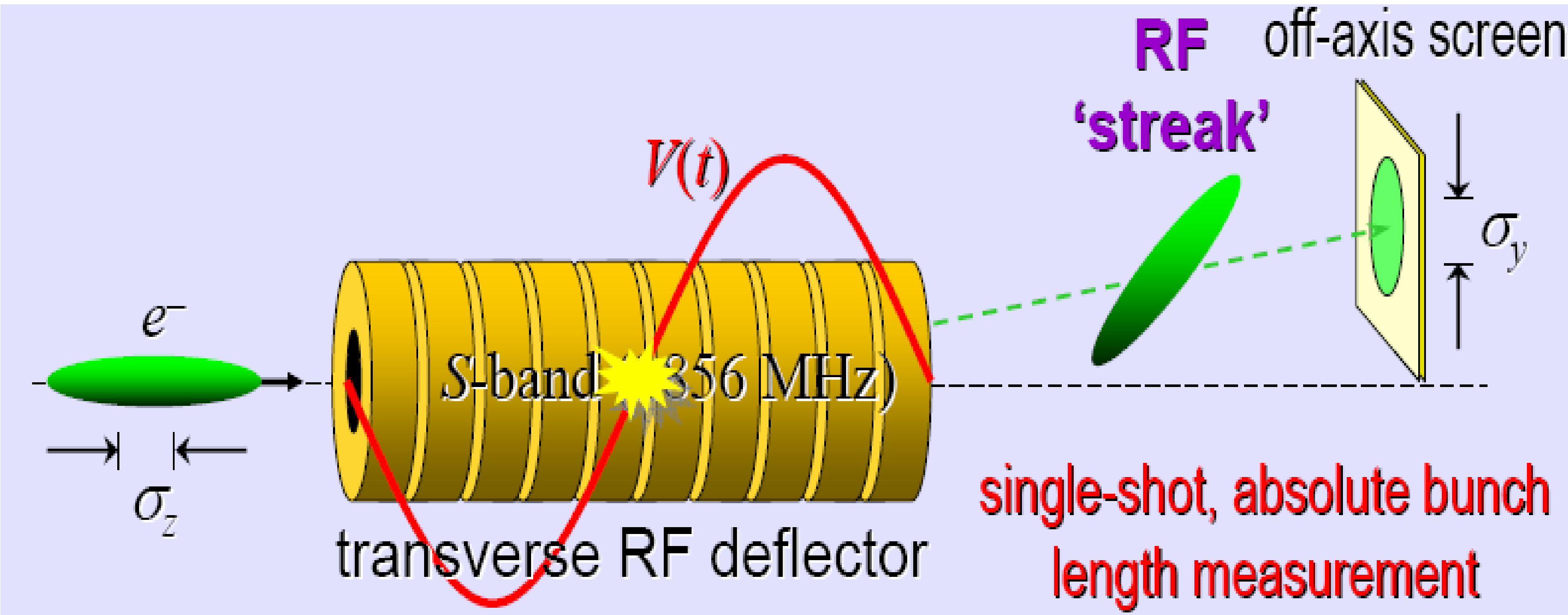
Results



Twiss Parameters
Downstream Linac

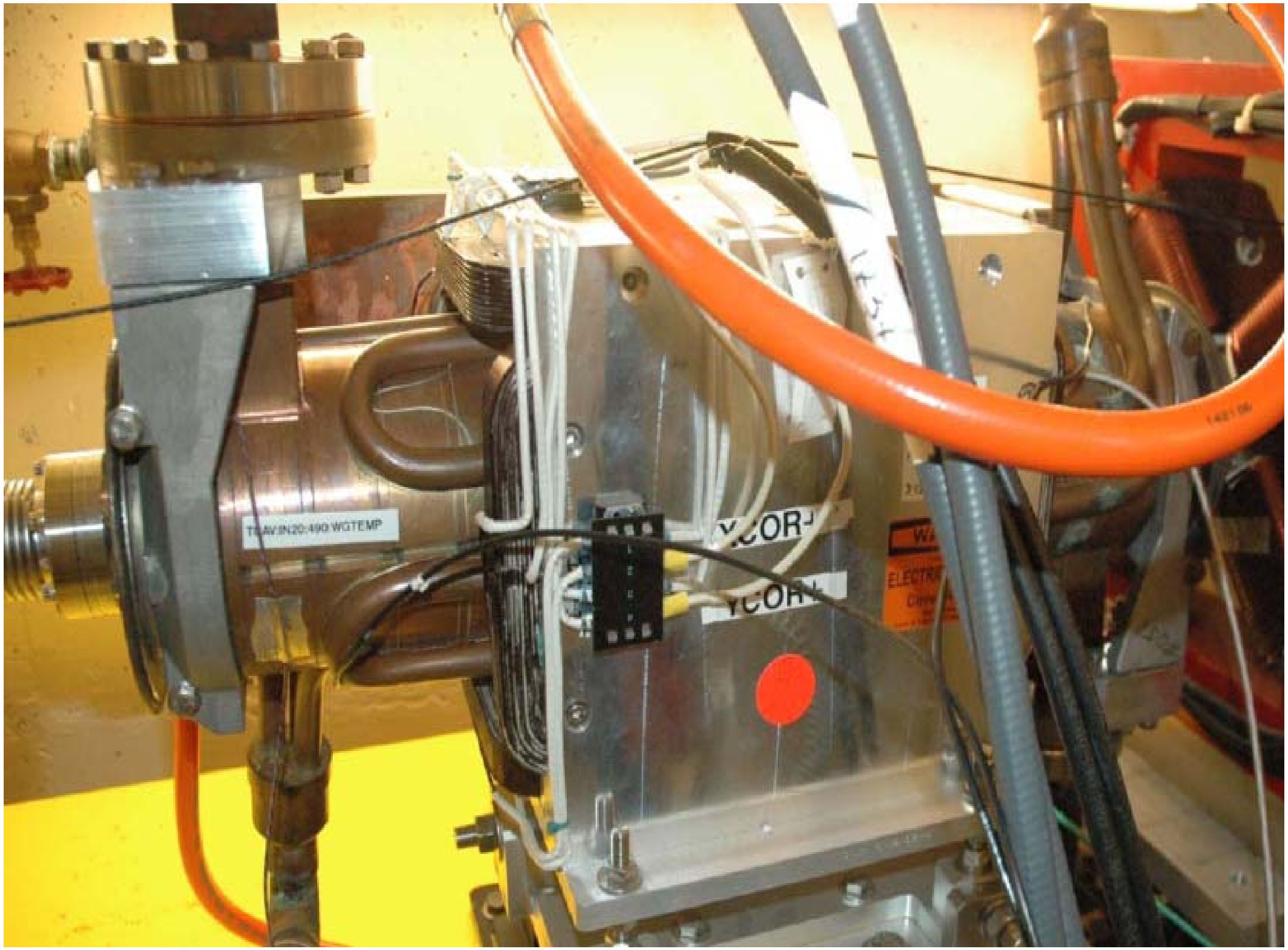
	RMS	Units
τ_{11}	0.575	ps^2
τ_{12}	-100	keV ps
τ_{22}	17629	keV^2
ε_l	6.8	keV ps
σ_E	133	keV
$\sigma_{E\ uncorr}$	9.02	keV
σ_t	0.76	ps
slope	-175	keV/ps

RF Deflector



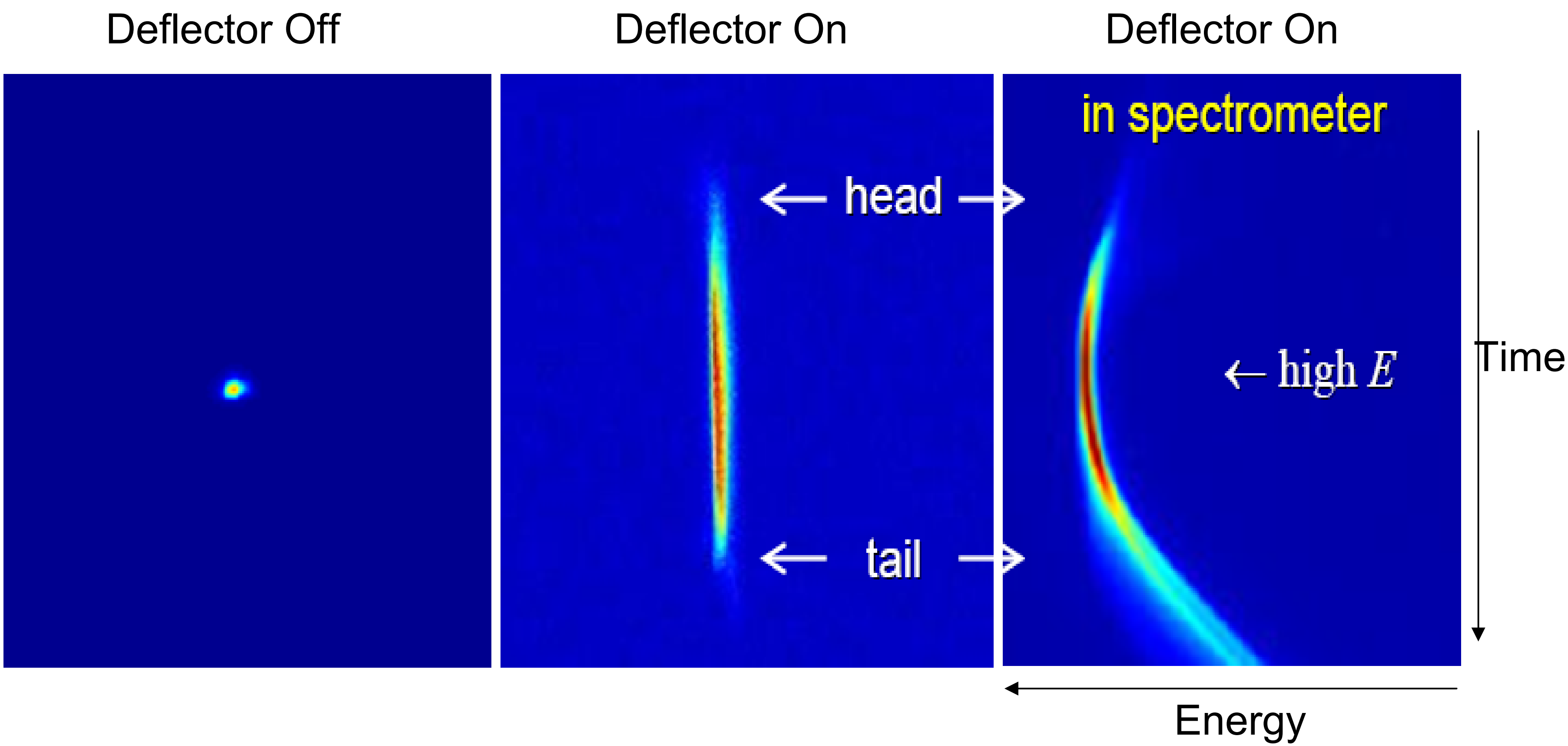
Courtesy P. Emma

Hardware



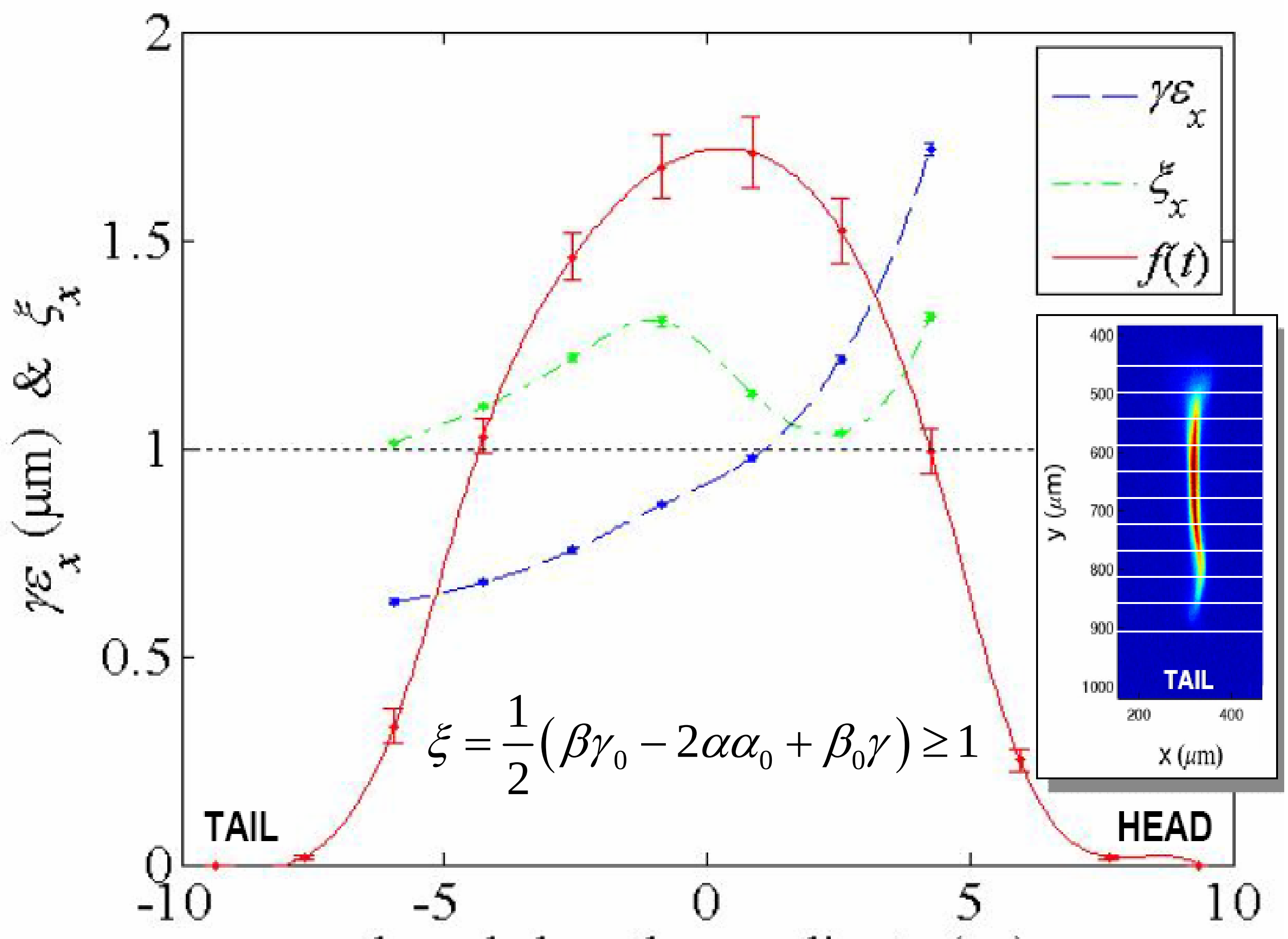
L = 55 cm
V = 1 MV

Time Resolved Measurements



From LCLS

Slice Emittance



1 nC, 135 MeV **100 A**

Courtesy P. Emma

RF Deflector

- Measure bunch length
- Slice Emittance or Energy Spread
- Single Shot Longitudinal Phase Space
- Resolution limited by beam size
  - Energy resolution limited by bend plane beam size at spectrometer entrance
  - Temporal resolution limited by non-bend plane beam size at rf deflector

Tomography

- Measure actual phase space distribution instead of fitting Twiss parameters or ellipse
- Only 3 measurements required to fit Twiss parameters but Tomographic techniques use multiple projections to determine actual phase space distribution
- No new hardware required
- Reconstruct the distribution from the data instead of fitting Twiss parameters
- Can be used for transverse, longitudinal and slice phase spaces

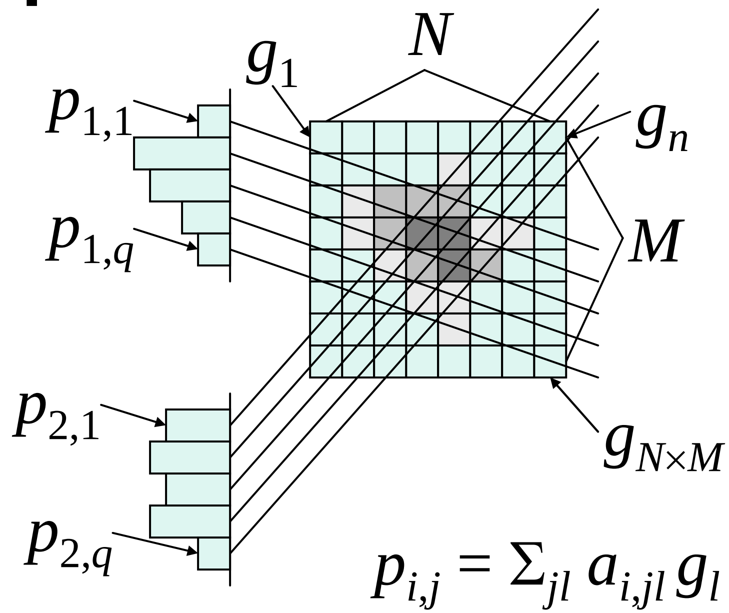
Algebraic Reconstruction Technique

- Many different transformations of an image g generate a set of histograms or projections p_i.
- Find the transport matrix a_i, so that $p_{i,j} = \Sigma_{jl}\, a_{i,jl}\, g_l$.
- The algorithm iterates an initial guess $g^{(0)}$ for each projection i according to

$$g_q^{(k+1)} = g_q^{(k)} + \Sigma_j \left[a_{i,jq}\,(p_{i,j} - \Sigma_l\, a_{i,jl}\, g_l^{(k)}) / \Sigma_{nl}\, a_{i,nl}^2\right]$$

until each projection has been used.

- Repeat until convergence achieved.



Courtesy H. Loos

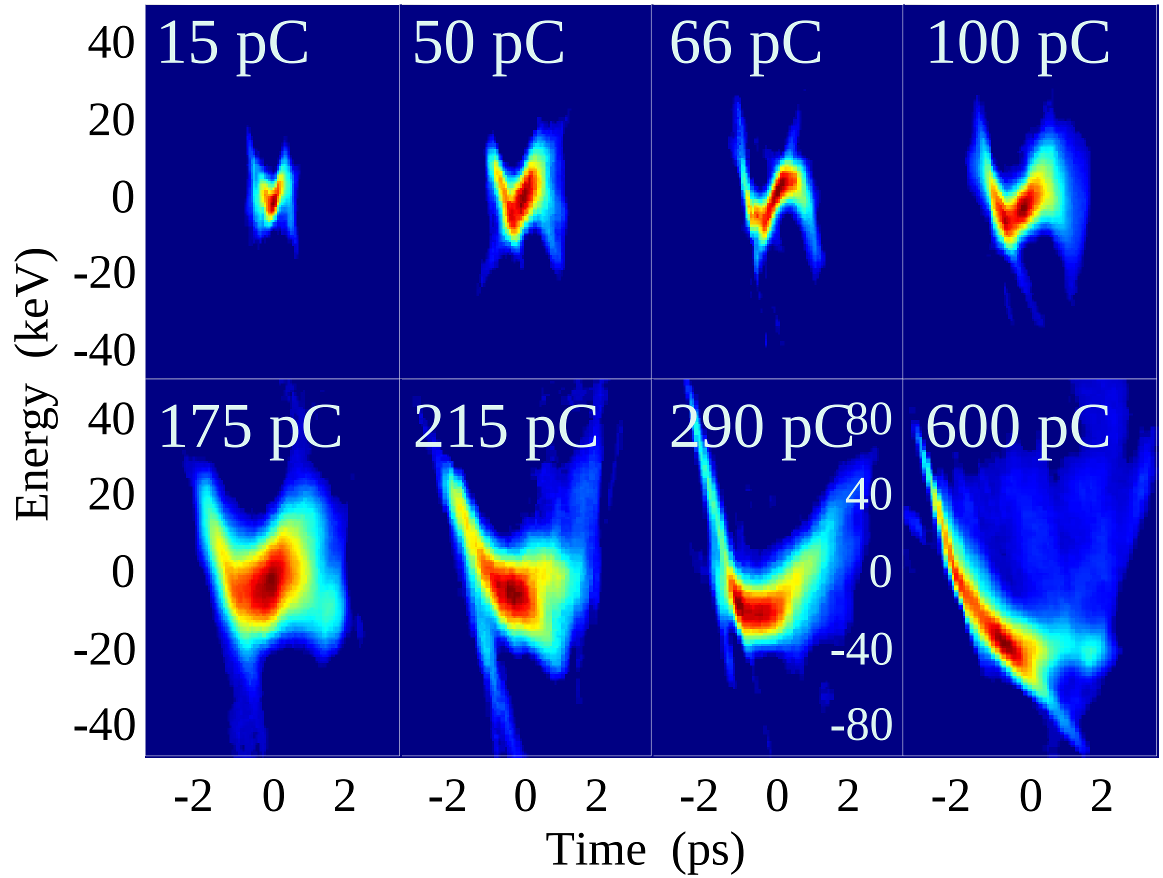
ART and Other Methods

- Filtered Backprojection
  - Developed for rotation of geometric object.
  - No unique definition of angle in phase space.
  - Inter- and extrapolation of projections necessary.
- ART
  - Works for arbitrary set of linear and nonlinear phase space transformations.
  - Constraints on solution can be implemented.
- MENT (Maximum Entropy)
  - Guarantees nonnegative solution.
  - Better suppression of artifacts than ART
  - Not yet implemented here…

Courtesy H. Loos

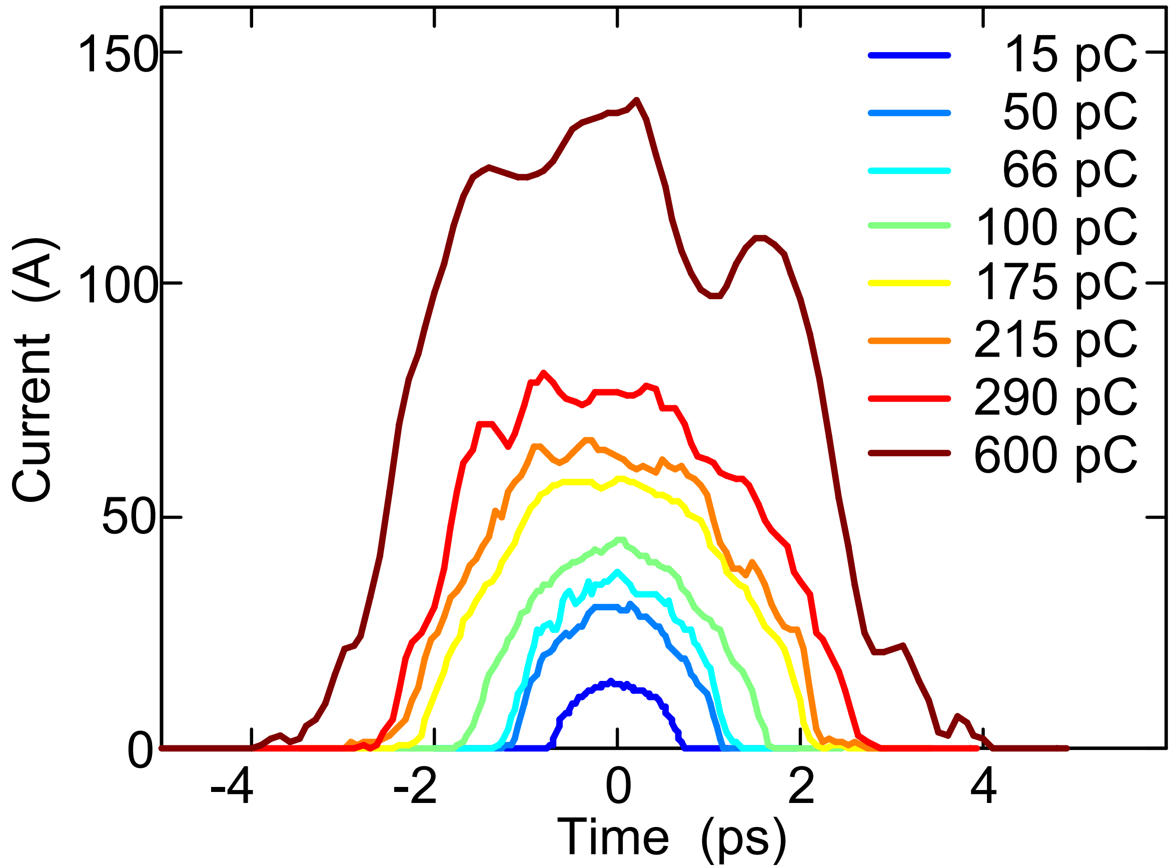
Reconstructed Longitudinal Phase Space

- Artifacts due to linac phase and amplitude drifts.
- Removal of 'streak' artifacts with 7% floor cut.
- Slice energy spread grows with charge
- Energy spread higher in bunch tail for higher charges.



Current

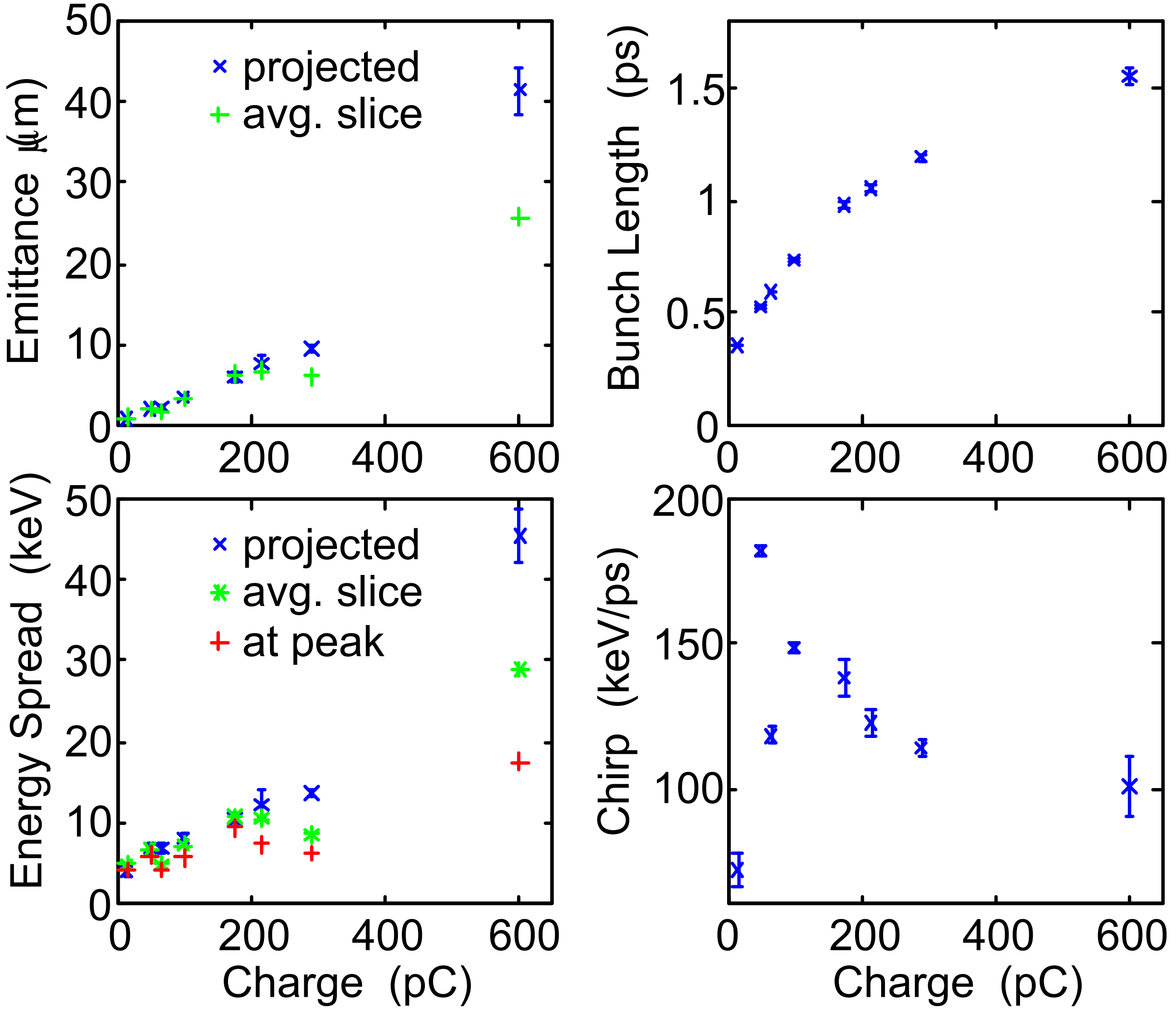
- Compression below 100 pC and elongation above.
- Smooth time distributions showing little structure.
- Structure can be attributed to artifacts.



Longitudinal Emittance

Normalized emittance

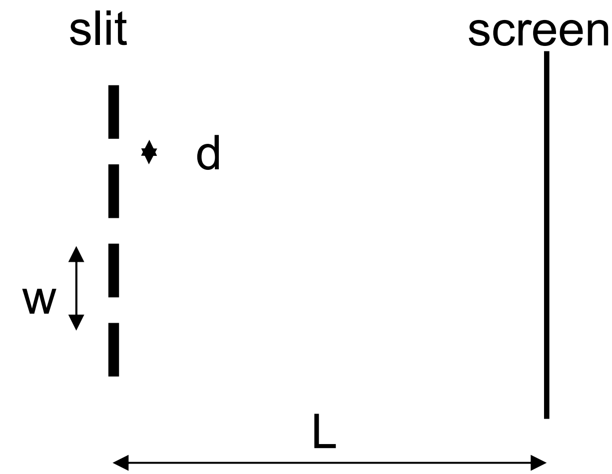
$\varepsilon_n = \varepsilon[\text{keV}]/m_0 c$



Summary

- Phase space techniques most useful for optimizing injector performance
  - Allows one to determine and possibly correct correlations
  - Could be used in feedback systems
- Tomographic reconstructions are the most powerful
  - Measure the actual phase space distribution
- Can extend techniques to measure 4D phase space measurements instead of 2D

Home Work #1



- Multi-Slit Pepper Pot Design
  - Assume Q = 1 nC
  - Δz = 3 mm
  - ε_{nx} = 1.5 μm
  - E = 5 MeV
  - $\sigma_x = \sigma_y$ = 1 mm

1. Is the beam emittance or space charge dominated?
2. What is the maximum slit width, d, necessary to produce an emittance dominated beam?
3. What is the minimum slit spacing, w, to separate the beamlets at a screen a distance L from the slit?

Home Work #2

- Assume the cathode is primarily emitting from two small spots on the cathode with Gaussian distributions as shown below.

$$I(x,y)=\frac{A_1}{2\pi\sigma_1^2}e^{-\frac{(x-x_1)^2+(y-y_1)^2}{2\sigma_1^2}}+\frac{A_2}{2\pi\sigma_2^2}e^{-\frac{(x-x_2)^2+(y-y_2)^2}{2\sigma_2^2}}$$

1. What is the rms width of the beam distribution at the cathode?

$$\sigma_x^2=\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}x^2 f(x,y)\,dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}f(x,y)\,dxdy}\qquad \int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{x^2}{2\sigma^2}}dx=1\qquad \int_{-\infty}^{\infty}\frac{x^2}{\sqrt{2\pi}\sigma}e^{-\frac{x^2}{2\sigma^2}}dx=\sigma^2$$