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Laser applications for accelerators:

Beam manipulation using lasers

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- Laser slicer (IFEL)
  - The problem
  - The solution
  - Examples
- Laser heater (IFEL)
  - The problem
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- Optical stochastic cooling
  - Stochastic cooling: the Nobel prize
  - Invention and application
  - Optical stochastic cooling
- Ion accelerators
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Storage ring short pulse x-ray source and bunch slicing

- The need for short pulse, short wavelength light sources
  - High resolution dynamics in solids
- Existing laser based light source
  - Atomic radiation from short pulse laser irradiated solids (ps, KeV)
  - High order harmonics (as, 100 eV)
  - Thomson scattering
- Ways to generated short pulse radiation from beam based sources
  - Free electron lasers
  - a storage ring
    - *One pass machine, such as an ERL*
    - *Deflecting a beam*
    - *Slicing the beam*
    - *Thomson scattering*

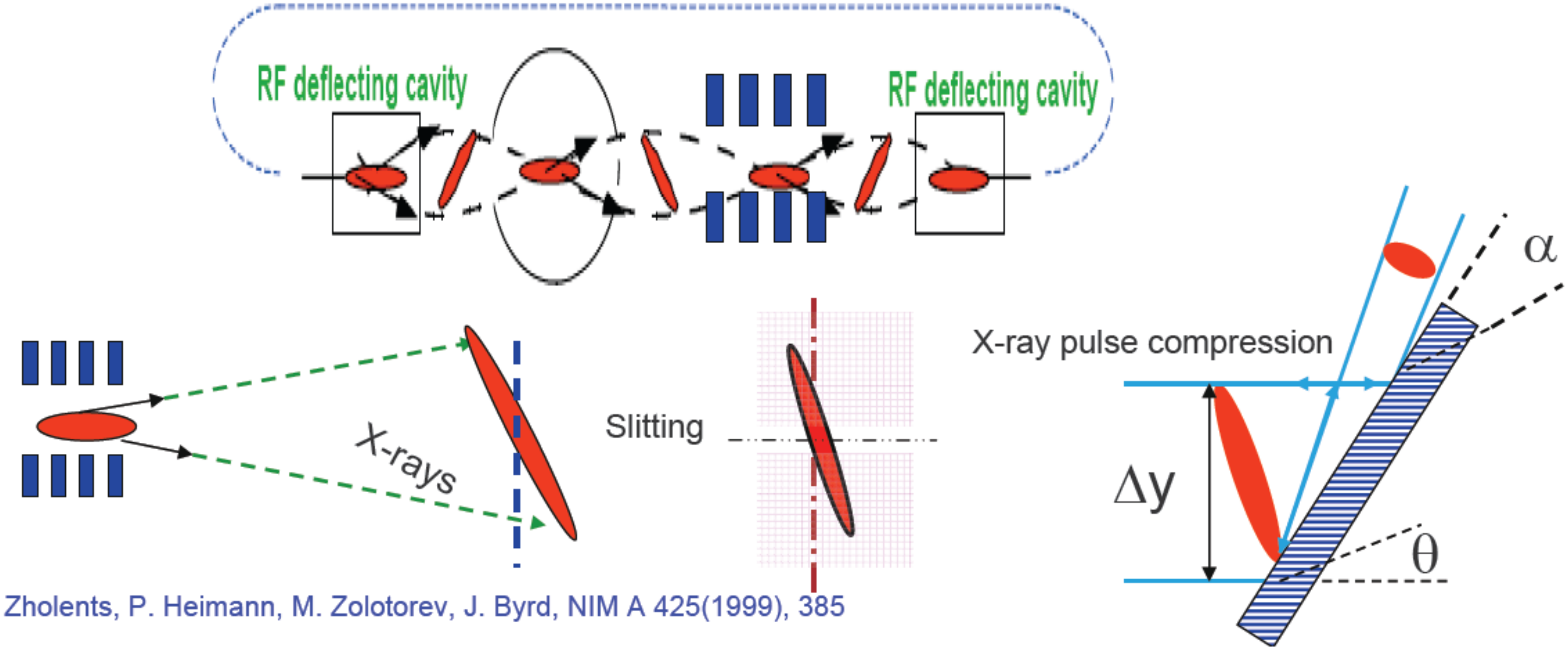
Bunch length in a storage ring

- Limited by many factors for about 100 ps
  - Energy spread thus dispersion
  - Intra beam scattering
  - RF noise
  - Beam instability
- Scientists want short x-ray for ultrafast science, ~100 fs
  - Deflecting cavity (to be demonstrated)
  - Low momentum compaction factor operation (play with the dispersion of the optics in the ring, operational at BESSY, 0.7 ps, and BESSY II, 3.5 ps)
  - Laser pulse slicing

Short pulse radiation in a storage ring: deflecting cavity

Concept

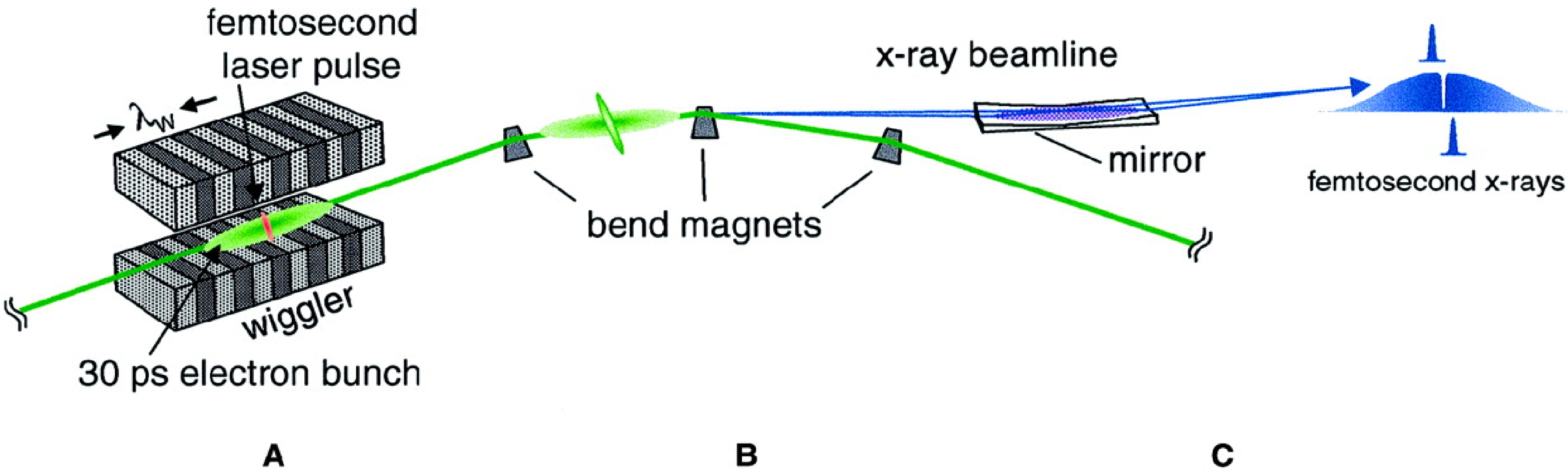
- Use transverse-deflecting rf cavities to impose a correlation ("chirp" between the longitudinal position of a particle within the bunch and the vertical momentum.
- The second cavity is placed at a vertical betatron phase advance of $n\pi$ downstream of the first cavity, so as to cancel the chirp.
- With an undulator or bending magnet placed between the cavities, the emitted photons will have a strong correlation among time and vertical slope.
- This can be used for either pulse slicing or pulse compression.



A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425(1999), 385

The idea of bunch slicing

- Schematic of the laser slicing method for generating femtosecond synchrotron pulses.



(A) Laser interaction with electron bunch in a resonantly tuned wiggler.
(B) Transverse separation of modulated electrons in dispersive bend of the storage ring.
(C) Separation of femtosecond synchrotron radiation at the beamline image plane.

A. A. Zholents and M. S. Zolotorev, *Phys. Rev. Lett.* 76, 912 (1996)
R. W. Schoenlein et al., Science 287, 2237 (2000)

Bunch slicing

- Energy gain or loss of an IFEL

$$\frac{\Delta\gamma}{\gamma} \propto \frac{AKL_U}{\gamma^2}\sin\left[(k+k_U)z - kct\right]$$

$A = \dfrac{e}{mc^2}\dfrac{\sqrt{\pi W Z_0}}{R}$	Laser field amplitude (if the laser fill the wave guide)
$K = \dfrac{eB_U\lambda_U}{2\pi mc},\ L_U$	Undulator parameter and undulator length
$k_U,\ \lambda_U$	Undulator wave number and wavelength
$k,\ \lambda$	Laser wave number and wavelength
W	Laser power
$Z_0 = 377\Omega$	Vacuum impedance
R	Wave guide radius

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

A. van Steenbergen et al., Phys. Rev. Lett. 77, 2690 (1996).

Bunch slicing: Energy gain and loss

$$\frac{\Delta\gamma}{\gamma} \propto \frac{AKL_U}{\gamma^2}\sin\left[(k+k_U)z - kct\right]$$

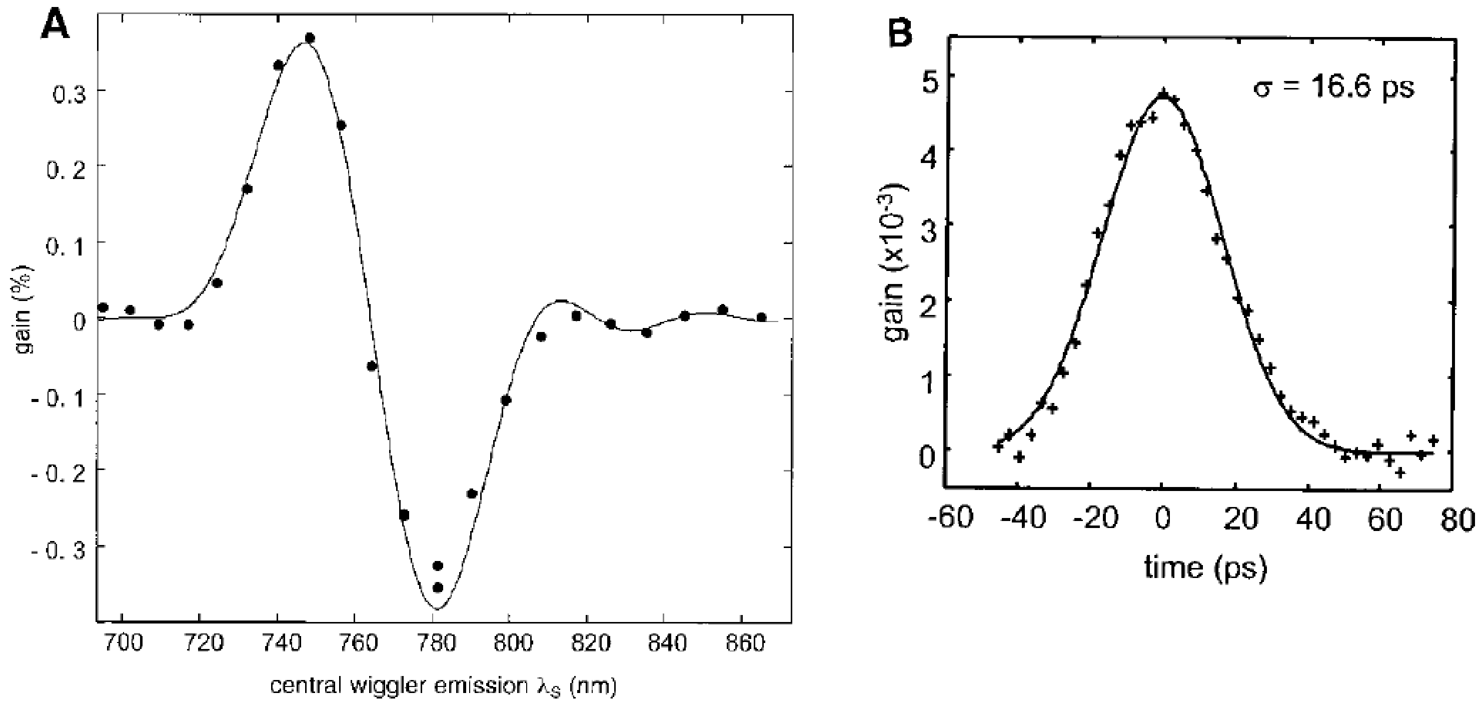


Fig. 2. (**A**) Measured and predicted (solid line) gain in the laser oscillator pulse energy as a function of wiggler tuning λ_S, with λ_L = 780 nm. (**B**) Measured gain in the amplified laser pulse energy as a function of time delay between the laser pulse and the electron bunch (solid line is a Gaussian fit with σ = 16.6 ps).

A. A. Zholents and M. S. Zolotorev, *Phys. Rev. Lett.* 76, 912 (1996)

General transform matrix in accelerators

$$\begin{pmatrix} u \\ u' \\ \delta \end{pmatrix} = \begin{pmatrix} I_C & I_S & I_D \\ I'_C & I'_S & I'_D \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u_0 \\ u'_0 \\ \delta_0 \end{pmatrix}$$

$$I_U = \int_L \frac{U(s)}{\rho(s)} ds, \quad I_V = \int_L \frac{V(s)}{\rho(s)} ds, \quad I_D = \int_L \frac{D(s)}{\rho(s)} ds.$$

- *U* and *V* are independent cosinelike and sinelike solution of the motion;
- ρ: bending radius;
- *L* is the distance between the two undulators
- *D* is the dispersion from the bypass.
- δ_i: momentum deviation at the cooling undulator
- u can be x,y, or z

H. Wiedemann, Pharticle Accelerator Physics, 3rd edition, Springer Verlag, p. 920

Bunch slicing: pulse duration and dispersion

- Clearly the minimum pulse duration is determined by the laser pulse duration plus total slippage length between the beam and the laser
- The pulse duration is further characterized by the path difference between the particles

$$\Delta l = \sqrt{\sigma_x^2 I_U^2 + \sigma'^2_x I_V^2 - \sigma_e^2 I_D^2}$$

$$I_U = \int_L \frac{U(s)}{\rho(s)} ds, \quad I_V = \int_L \frac{V(s)}{\rho(s)} ds, \quad I_D = \int_L \frac{D(s)}{\rho(s)} ds.$$

  - *U* and *V* are independent cosinelike and sinelike solution of the motion;
  - ρ: bending radius;
  - *l* is the distance undulators and the radiation device
  - *D* is the dispersion function.
  - $\sigma_{x,}$ σ'_x : beam size and divergence
  - σ_e : energy spread

- And

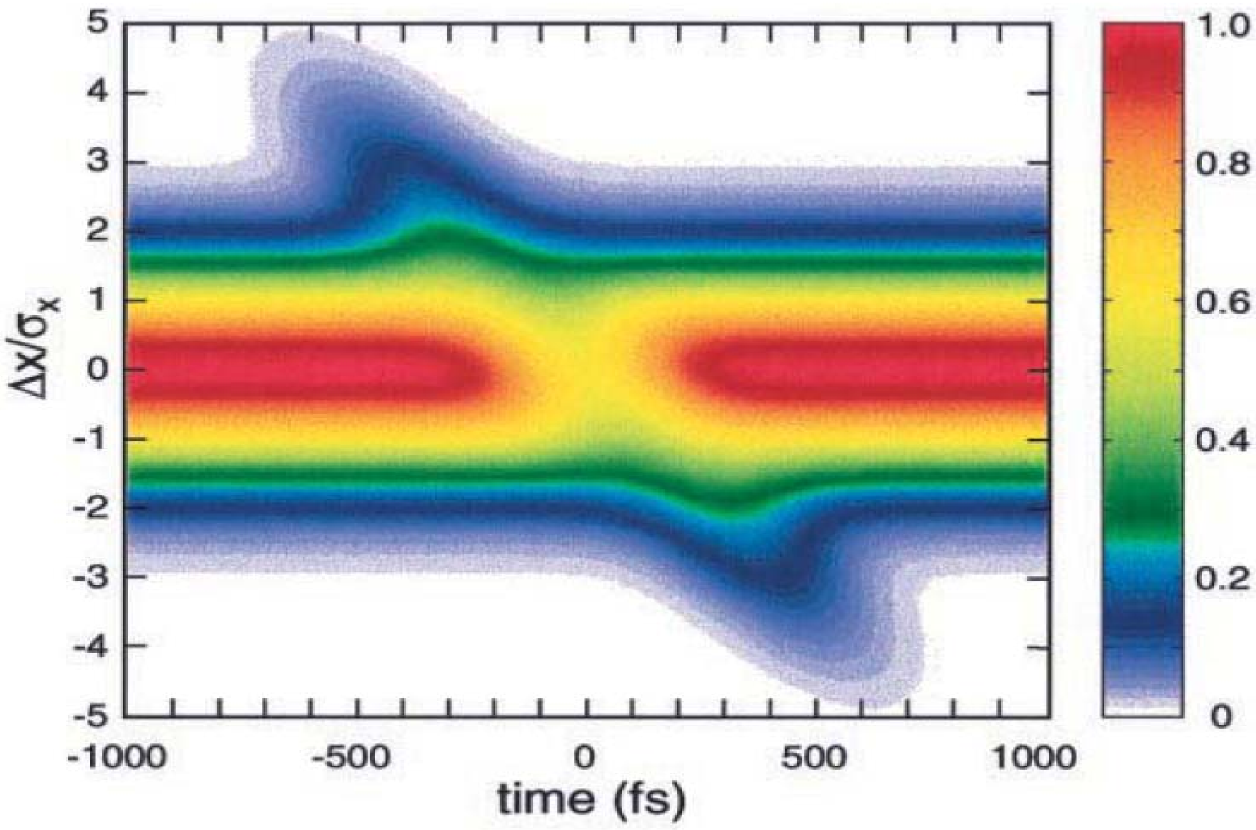
$$\Delta t = \sqrt{\tau_L^2 + l_s^2 / c^2 + \Delta l^2 / c^2}$$

A. A. Zholents and M. S. Zolotorev, *Phys. Rev. Lett.* 76, 912 (1996)

Dispersion and path length difference

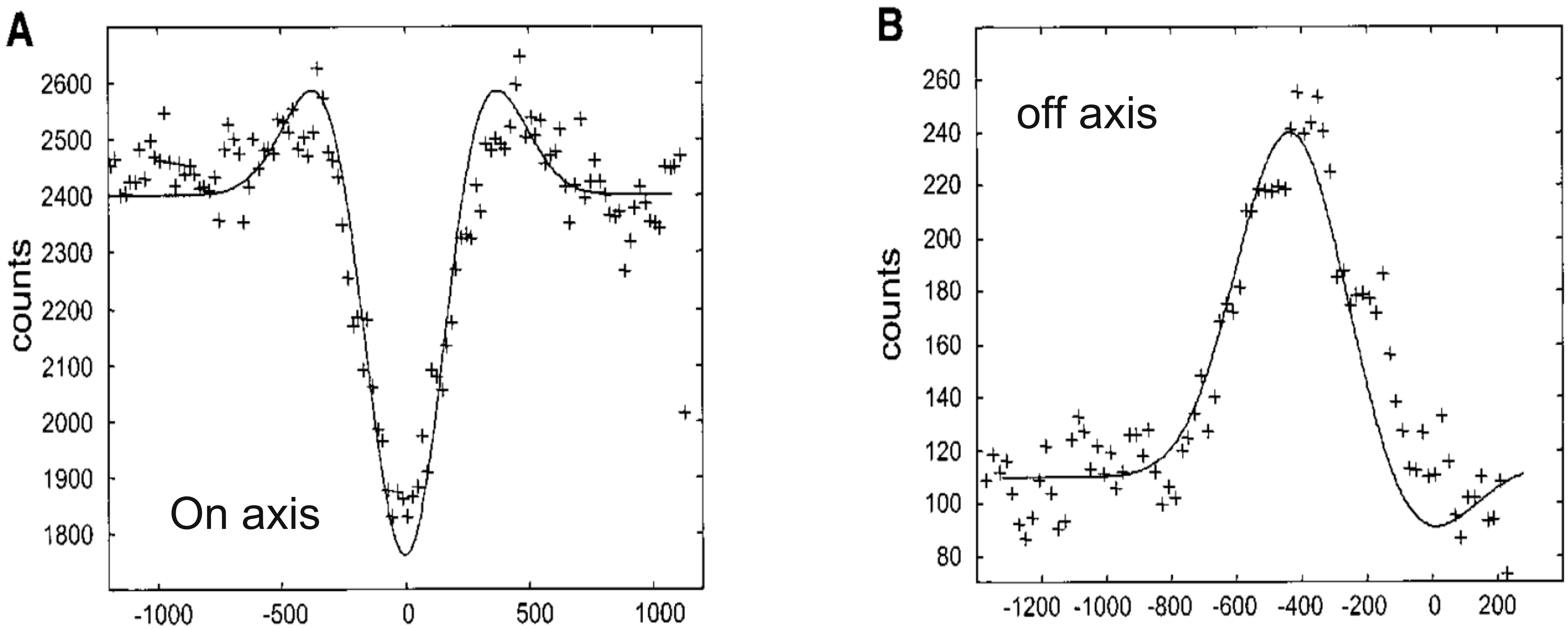
$$\Delta l = \sqrt{\sigma_x^2 I_U^2 + \sigma'^2_x I_V^2 - \sigma_e^2 I_D^2}$$

Fig. 3. Model calculation of the electron bunch distribution (as a function of horizontal displacement Δx and time) at the radiating bend magnet, following interaction with the laser pulse in the wiggler, and propagation through 1.5 arc sectors of the storage ring.



Demonstration experiment

- ALS Storage ring
  - E=1.5 GeV, σ_E=1.2 MeV,
  - Udulator: L_U=3 m, K=13, λ_U=16 cm
  - Laser: λ=800 nm, τ_L=100 fs, power W=4 GW (0.4 mJ per pulse), 1 kHz
  - Expected energy modulation ΔE=9 MeV, measured 6 MeV



R. W. Schoenlein et al., Science 287, 2237 (2000)

Summary

- Practical issues
  - Difficult for higher energy rings
    - *For APS at E=7 GeV, σ_E=6.7 MeV,*
      - laser energy ($\propto\Delta E^2$) will be 30 time higher, 12 mJ, doable
      - Wiggler period ($\propto\gamma^2$) will be 65 m, difficult
  - Pulse duration limitation: slippage, dispersion
  - photon flux limitation: reduction factor $0.5\eta\tau_L/l_b$, η<1.

- Light sources implemented femto slicing
  - Advance Light Source, LBL
    - *10^5 photons/s, 2-10 keV, beam energy 1.5 GeV*
  - BESSY II, Berlin,
    - *10^4 ph /s /0.1% BW, 100 fs, 0.3-1.4 keV, beam energy 1.7 GeV*
    - *S.Khan et al., PRL 97, 074801 (2006).*
  - Swiss Light Source, in progress
  - SOLEIL, in progress

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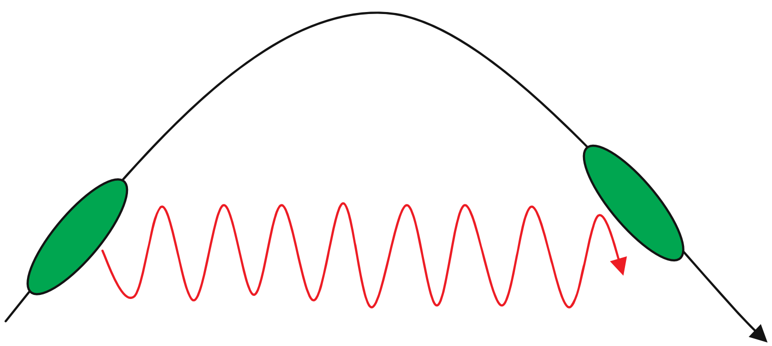
Suppressing micro bunching using: laser heater

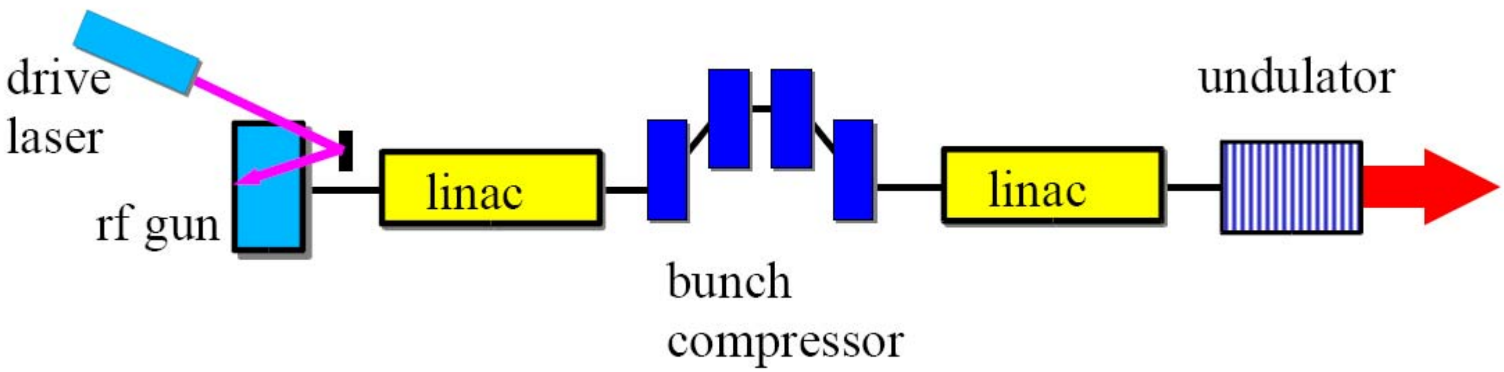
- XFEL needs high peak current, thus bunch compression
  - LCLS: 10 ps ->200 fs
- Compression cause micro-bunching instability
  - Seeded by small longitudinal density modulation (drive laser?)
  - Driven by CSR and wake field
  - In a bend, the radiation from the tail catches the head, cause additional density modulation (10-20 micron level)
  - Accompanied by growth in energy spread and
  - Destroys the emittance
- To fight with the instability
  - Increase the uncorrelated energy spread can in crease the Landau damping
  - Wiggler
  - Plus a Laser heater



Simulation results for LCLS

Table 2: Core-slice-averaged median values and quartile half-ranges for nominal and jitter results from `elegant`, and slice-averaged FEL results from GENESIS (last two columns). Δt_{80} is the total length of the core slices, σ_δ is the rms energy spread, $\epsilon_{n,x}$ is the normalized rms horizontal emittance, λ is the light wavelength, L_g is the gain length, and P_{out} is the output radiation power.

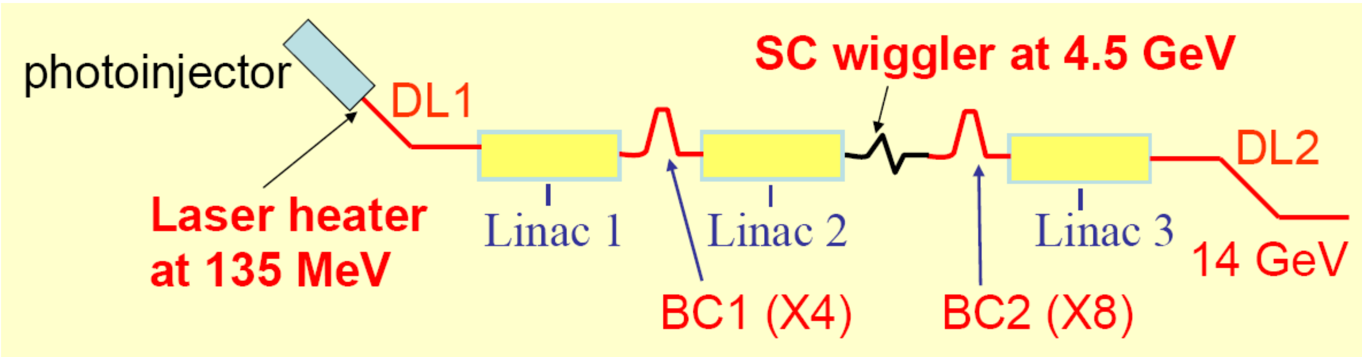
jitter	CSR	Current	Δt_{80}	σ_δ	$\epsilon_{n,x}$	λ	L_g	P_{out}
?	?	kA	ps	10^{-4}	μm	A	m	GW
no	no	3.9	0.20	0.9	0.68	1.500	3.1	12.2
yes	no	3.8 ± 0.6	0.21 ± 0.04	0.9 ± 0.3	0.68 ± 0.01	1.499 ± 0.003	3.2 ± 0.2	11.4 ± 2.6
no	yes	4.0	0.20	3.0	3.13	1.502	9.7	0.7
yes	yes	4.3 ± 1.0	0.19 ± 0.05	3.1 ± 1.0	3.16 ± 0.50	1.502 ± 0.004	9.5 ± 0.8	1.1 ± 0.4



Borland, Proc. PAC 03, p2707

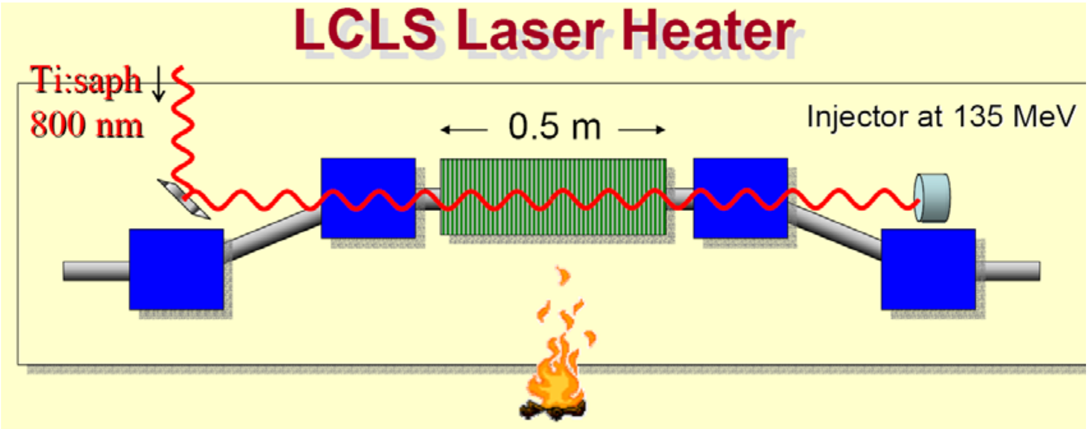
Laser heater and some details

- The energy spread from the PC gun is too small to matter for the FEL but good for CSR micro-bunching growth
- Need to increase the uncorrelated spread:
  - laser heater (inverse free electron laser)
  - and a wiggler



(1) Increase the energy spread by a factor of 10

(2) Do it at a location with minimum emittance effect



Huang, FEL 04

Energy modulation in an IFEL

- Energy gain or loss of an IFEL

$$\frac{\Delta\gamma}{\gamma} = \frac{AKf(K)L_U}{\gamma^2}\sin\left[(k+k_U)z - kct\right]$$

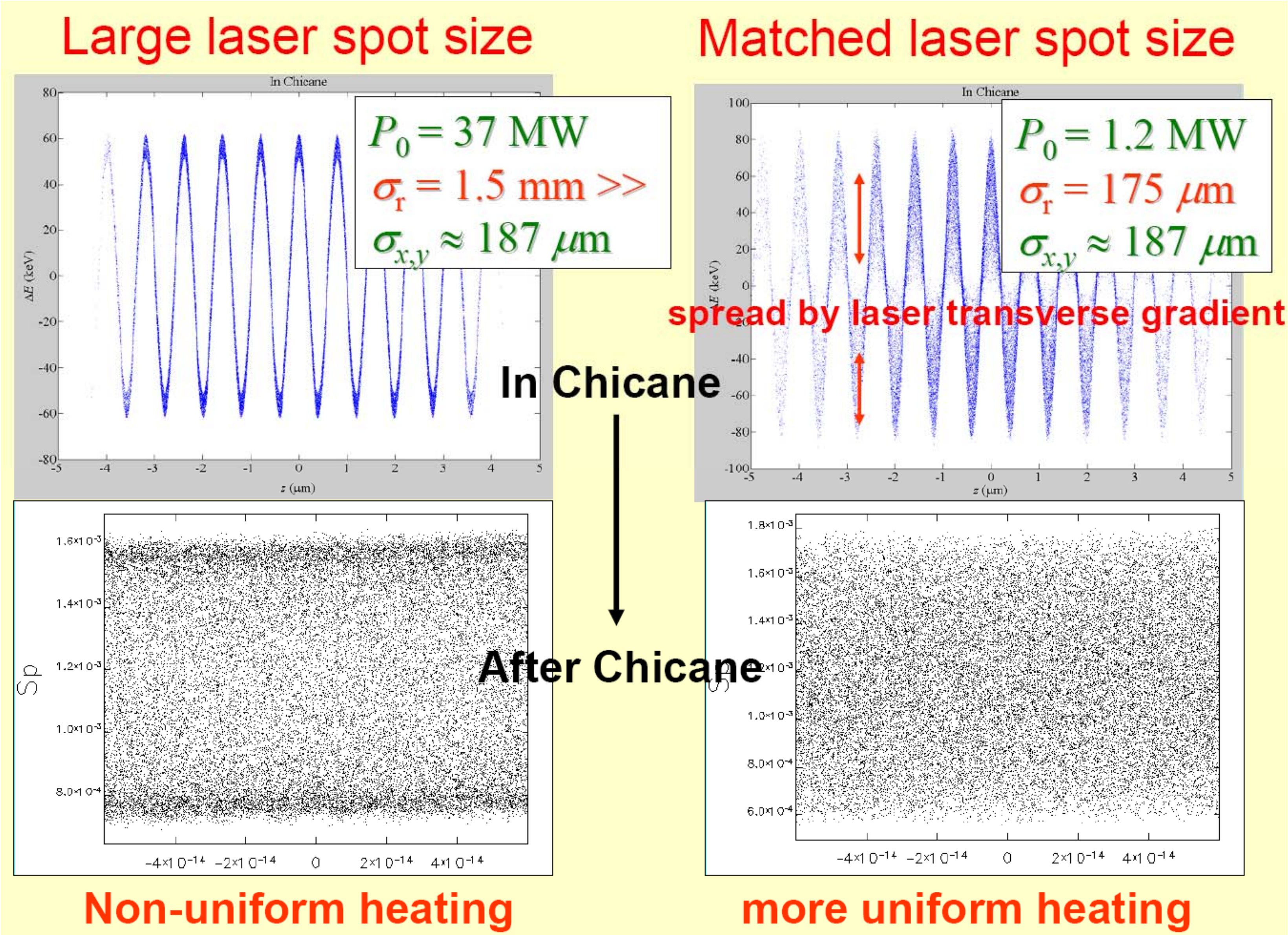
$A = \frac{e}{mc^2}\frac{\sqrt{\pi W Z_0}}{R}$	Laser field amplitude, R: laser beam radius
$K = \frac{eB_U\lambda_U}{2\pi mc}$, L_U	Undulator parameter and undulator length
k_U, λ_U	Undulator wave number and wavelength
k, λ	Laser wave number and wavelength
W	Laser power
$Z_0 = 377\Omega$	Vacuum impedance

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- Energy per pulse for the laser: 100 micro-joules

A. van Steenbergen et al., Phys. Rev. Lett. 77, 2690 (1996).

Effect of beam matching in an undulator



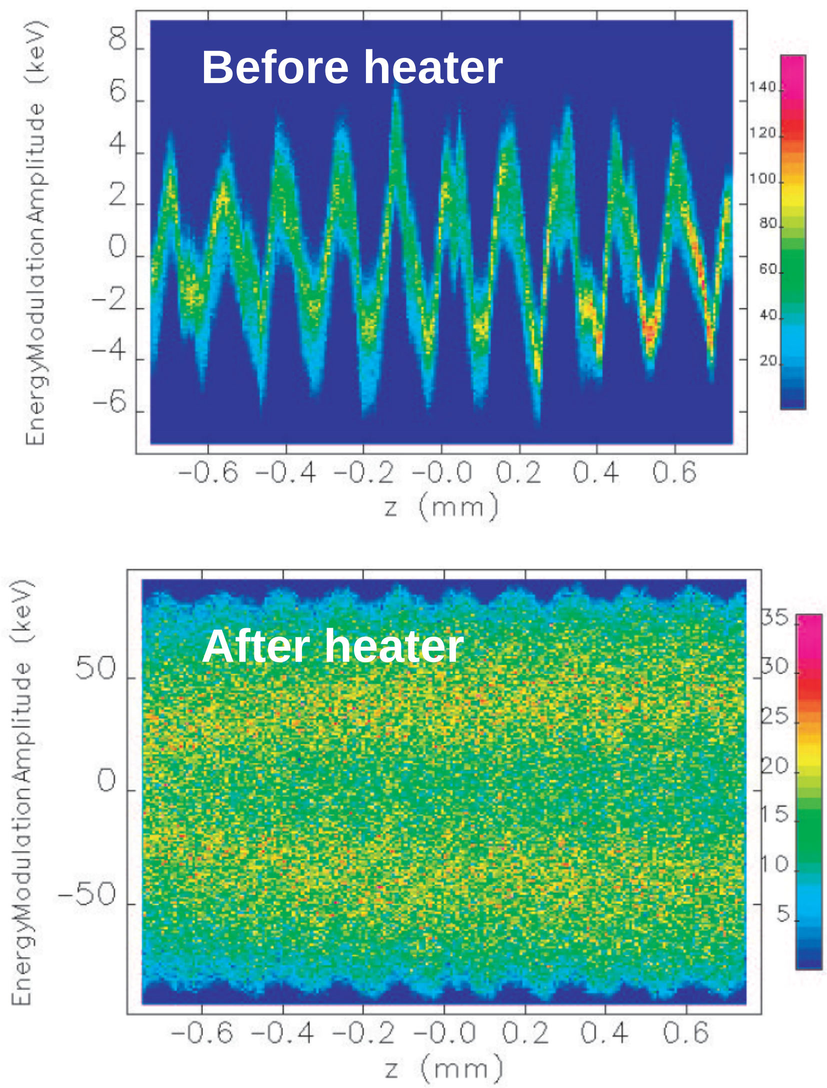
Huang et al., FEL 04; Phys. Rev. ST Accel. Beams 7, 074401 (2004)

Simulation Result for LCLS

TABLE II: Main parameters for the LCLS laser-heater.

Parameter	Symbol	Value
electron energy	$\gamma_0 mc^2$	135 MeV
average beta function	$\beta_{x,y}$	10 m
transverse rms beam size	$\sigma_{x,y}$	190 μm
undulator period	λ_u	0.05 m
undulator field	B	0.33 T
undulator parameter	K	1.56
undulator length	L_u	0.5 m
laser wavelength	λ_L	800 nm
laser rms spot size	σ_r	175 μm
laser peak power	P_L	1.2 MW
Rayleigh range	Z_R	0.6 m
maximum energy modulation	$\Delta\gamma_L(0)mc^2$	80 keV
rms local energy spread	$\sigma_{\gamma_L} mc^2$	40 keV

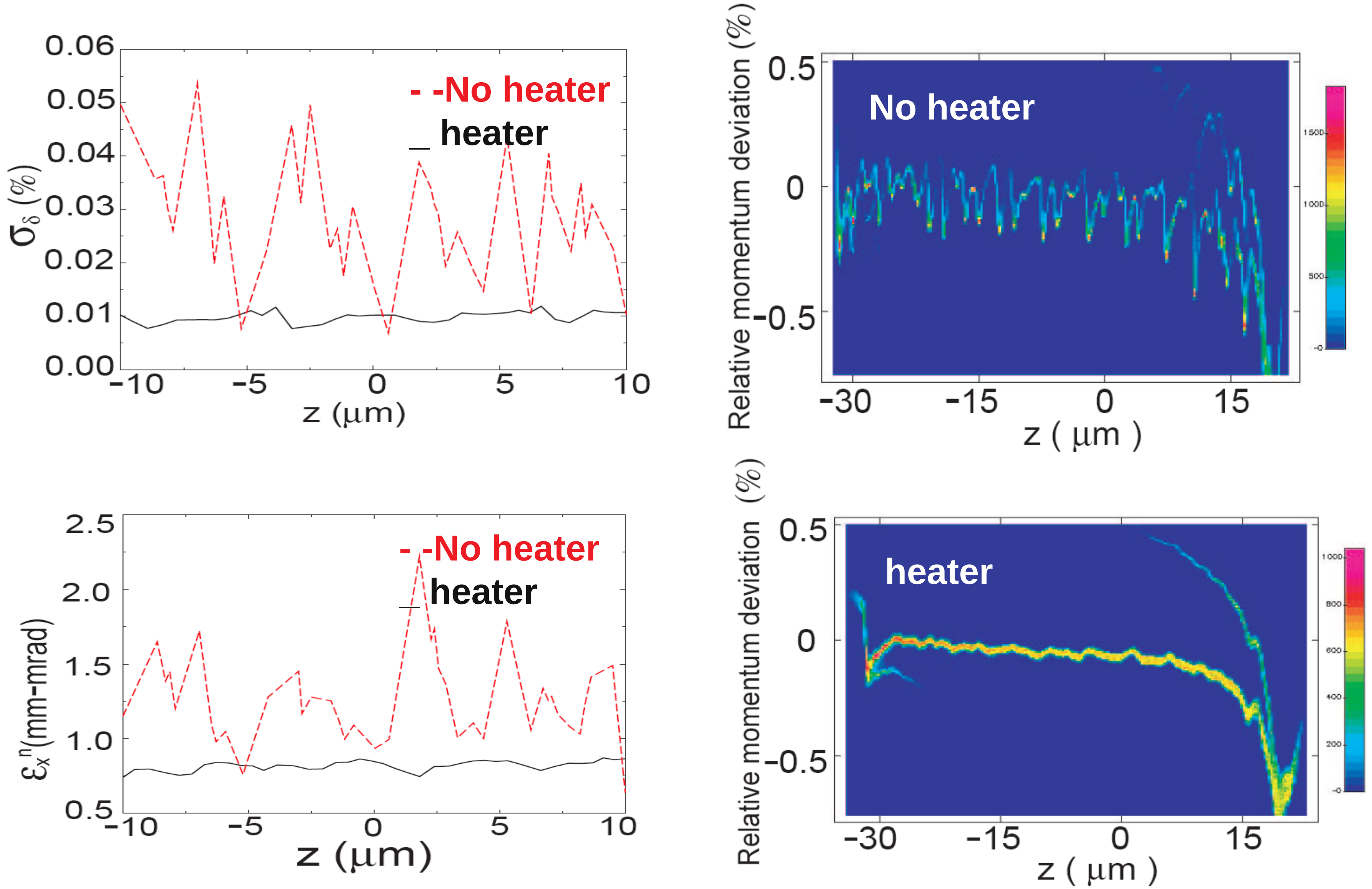
Energy modulation



Simulation for 8% laser modulation at 150 microns

Wu et al, SLAC-PUB-10430

Simulation Result: undulator entrance



Wu et al, SLAC-PUB-10430

Laser beam heater: summary

- In simulation, it does seem to suppress the effect of micro-bunching effect
- Need to match the beam for best heating effect
- Problems
  - Will the heater seed bunching at certain frequency?
  - What is needed to be done to see this?

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Cooling of a particle beam

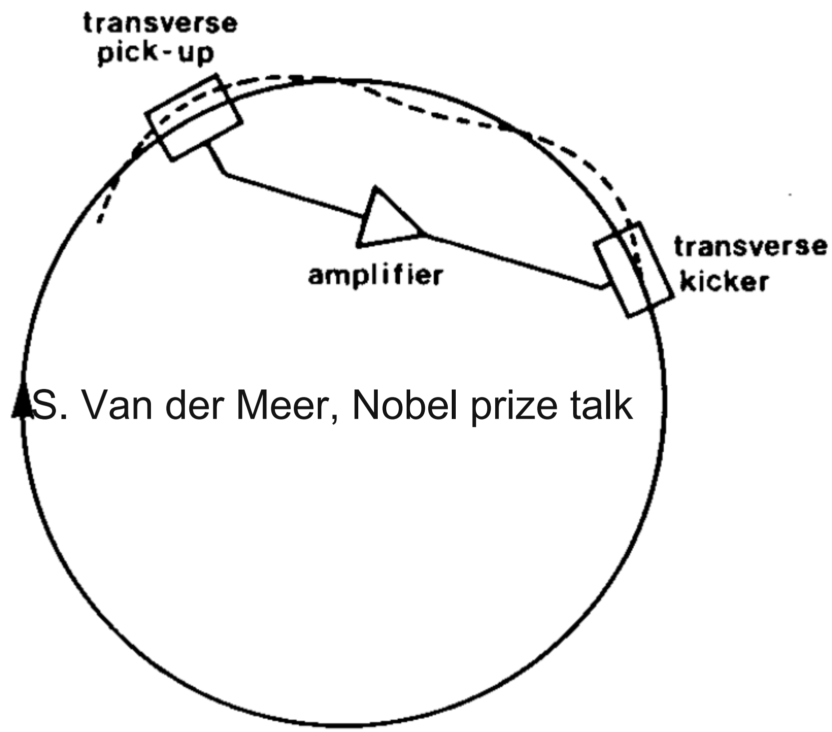
- Needs for better beam emittance
  - High brightness for beam based light sources
  - High luminescence for colliders
  - Cost saving for FELs
- Beam cooling methods
  - Ionization cooling: muon, ions
  - Electron cooling: ions
  - Radiation cooling: electrons
  - Emittance exchange
  - Stochastic cooling: ions
  - Optical stochastic cooling: electrons

Stochastic cooling: history

- 1968, invented by S. van der Meer
- 1975, demonstration at ISR
- 1977-83, tested at CERN, FNAL, Novosibirsk, INS-Yokyo
- 1984, Nobel prize to van der Meer, shared with C. Rubbia, for finding of W and Z bosons
- 1993, extended to optical stochastic cooling by A. A. Mikhailichenko and M. S. Zolotorev

How does it work

- A bunch is a mix of particles and empty space
- One can squeeze the empty space out
- To do so
  - The information of the particle position is needed
  - The information is feed back to the particle
- For a one particle betatron cooling
  - Particle position pick up
  - Info amplified
  - Info fed back to the particle
  - Amplitude reduced over time
- For many particles
  - Each particle feels its own kick
  - Kick of other particles average to zero
  - Assuming adequate mixing



S. Van der Meer, Nobel prize talk

Stochastic cooling explained

- Think N particles as a set of harmonic oscillators

$$x_i(t) = A_i \cos(\omega_i t + \phi_i), \quad i = 1,2,\dots,N$$

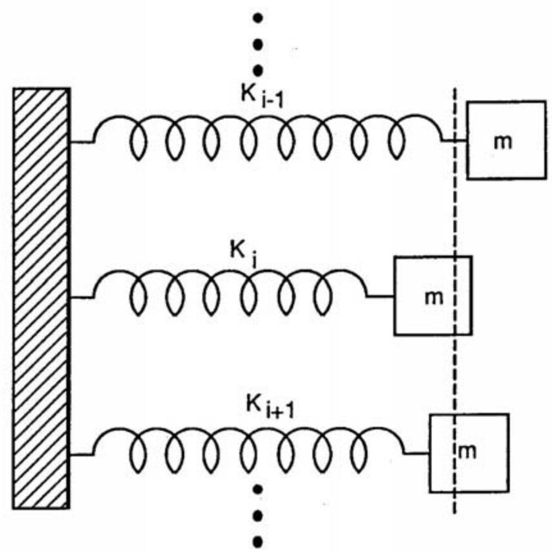
- At certain time *t*, the average position

$$\overline{x}(t) = \frac{1}{N}\sum_{i=1}^{N} x_i(t), \quad \overline{x^2}(t) = \frac{1}{N}\sum_{i=1}^{N} x_i^2(t)$$

- And the time average

$$\langle \overline{x}(t) \rangle = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} \frac{1}{N}\sum_{i=1}^{N} x_i(t)dt = 0$$

$$\langle \overline{x^2}(t) \rangle = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} \frac{1}{N}\sum_{i=1}^{N} x_i^2(t)dt = \frac{1}{2N}\sum_{i=1}^{N} A_i^2$$



$$\lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} \cos(\omega t + \phi)dt = \begin{cases} \cos\phi, \omega = 0 \\ 0, \omega \neq 0 \end{cases}$$

$$\int_0^{2\pi} \cos^2(\omega t + \phi)dt = \pi$$

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

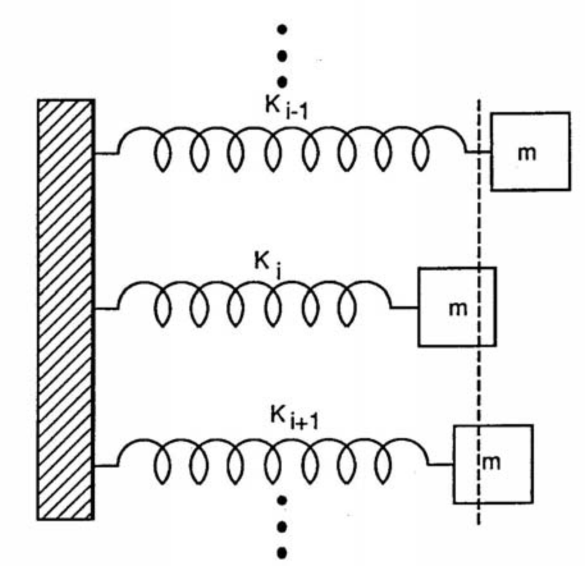
Stochastic cooling explained

- Suppose at some time when $\bar{x}(t) \neq 0,$ a kick of $\Delta x(t) = -g\bar{x}(t)$ is applied, without changing the speed of the oscillators. The new position is

$$x_{ic}(t) = x_i(t) - \frac{g}{N} x_i(t) - g\,\frac{1}{N}\sum_{k \neq i}^{N} x_k(t)$$

- So the amplitude of each oscillator becomes a function of time and the rms amplitude is

$$\sigma^2(t) = \left\langle \overline{x^2}(t) \right\rangle = \frac{1}{2N}\sum_{i=1}^{N} A_i^2(t)$$



- Now the question is
  - Can we reduce the amplitude over time?
  - If yes, how quickly can we do it?

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Stochastic cooling explained

- With the kick, the change in amplitude is

$$\Delta x(t) = -g\bar{x}(t) = -\frac{g}{N}\sum_{i=1}^{N} x_i(t)$$

$$\begin{aligned}\Delta A_i^2(t) &= \left[x_i(t) + \Delta x(t)\right]^2 - x_i^2(t) \\ &= -2gx_i(t)\bar{x}(t) + g^2\bar{x}(t)^2 \\ &= -2gx_i(t)\frac{1}{N}\sum_{j=1}^{N} x_j(t) + \frac{g^2}{N^2}\sum_{j=1}^{N}\sum_{k=1}^{N} x_j(t)x_k(t).\end{aligned}$$

- Averaging over time

$$\left\langle \Delta A_i^2(t,\tau)\right\rangle = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}\left[-2g\underline{x_i(t+\tau)}\frac{1}{N}\sum_{j=1}^{N}\underline{x_j(t+\tau)} + \frac{g^2}{N^2}\sum_{j=1}^{N}\sum_{k=1}^{N}\underline{x_j(t+\tau)}\,\underline{x_k(t+\tau)}\right]d\tau$$

$$x_i(t+\tau) = A_i(t)\cos[\omega_i(t+\tau) + \phi_i]$$

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Stochastic cooling explained

$$\left\langle \Delta A_i^2(t,\tau) \right\rangle = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} \left[-2g x_i(t+\tau) \frac{1}{N} \sum_{j=1}^{N} x_j(t+\tau) + \frac{g^2}{N^2} \sum_{j=1}^{N} \sum_{k=1}^{N} x_j(t+\tau) x_k(t+\tau) \right] d\tau$$

- Both terms on the right have

$$\frac{1}{2T}\int_{-T}^{T} x_i(t) x_j(t) dt = \frac{1}{2T}\int_{-T}^{T} A_i \cos(\omega_i t + \phi_i) A_j \cos[\omega_j(t+\tau) + \phi_j] dt$$

$$= \frac{1}{2T} \frac{A_i A_j}{2} \int_{-T}^{T} \cancel{\cos[(\omega_i + \omega_j)t + \phi_i + \phi_j]} + \cos[(\omega_i - \omega_j)t + \phi_i - \phi_j] dt$$

$$= \begin{cases} A_i^2/2, \; i = j \\ 0, \; i \neq j \end{cases}$$

- Therefore

Kick by self signal

$$\boxed{\left\langle \Delta A_i^2(t,\tau) \right\rangle} = -\boxed{\frac{2g}{N} \frac{A_i^2(t)}{2}} + \boxed{\frac{g^2}{N^2} \sum_{j=1}^{N} \frac{A_j^2(t)}{2}}$$

Amplitude change as a function of time

Kick by other signals other particles

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Stochastic cooling explained

$$\left\langle \Delta A_i^2(t,\tau) \right\rangle = -\frac{2g}{N}\frac{A_i^2(t)}{2} + \frac{g^2}{N^2}\sum_{j=1}^{N}\frac{A_j^2(t)}{2}$$

- Use $\sigma^2(t) = \left\langle \overline{x^2}(t) \right\rangle = \frac{1}{2N}\sum_{i=1}^{N} A_i^2(t),\ \Delta\sigma^2(t) = \frac{1}{2N}\sum_{i=1}^{N}\left\langle \Delta A_i^2(t,\tau) \right\rangle,$ and summing over i, we have

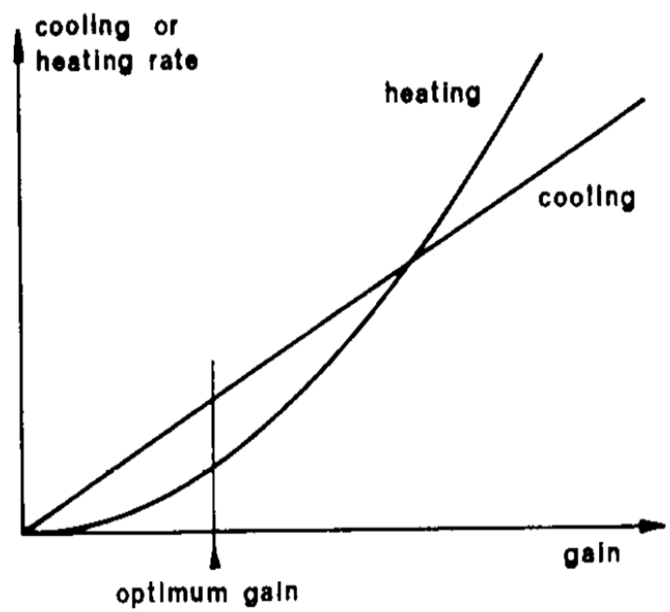
$$\sum_{i=1}^{N}\left\langle \Delta A_i^2(t,\tau) \right\rangle = -\frac{2g}{N}\sum_{i=1}^{N}\frac{A_i^2(t)}{2} + \frac{g^2}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{A_j^2(t)}{2}$$

$$\Delta\sigma^2(t) = \frac{-2g + g^2}{N}\sigma^2(t)$$

- That is, the average amplitude changes over time!
- Can be cooling or heating! At optimum gain $g_0=1$,

$$\Delta\sigma^2(t) = -\frac{1}{N}\sigma^2(t)$$

- This is the change per correction.
- That favors smaller particle numbers!



S. Van der Meer, Nobel prize talk

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Stochastic cooling:
How to measure the signal and the bandwidth limitation

Perform a Fourier transform over an arbitrary period of time 2T

$$\bar{x}(t) = \sum_{n=-\infty}^{\infty} a_n e^{-in\omega t}$$ **Schottky signal in time**

$$a_n = \frac{1}{2\mathrm{T}} \int_{-\mathrm{T}}^{\mathrm{T}} \bar{x}(t) e^{in\omega t} dt, \ \omega = \frac{\pi}{\mathrm{T}}$$

All measurements system have errors thus, with a response function G

$$\bar{x}'(t) = \int_0^t G(t-t')\bar{x}(t')dt'$$

$$\bar{x}'(t) = \sum_{n=-\infty}^{\infty} g_n a_n e^{-in\omega t}, \quad g_n = \frac{1}{2\mathrm{T}} \int_{-\mathrm{T}}^{\mathrm{T}} G(t) e^{in\omega t} dt$$

For a finite bandwidth Δf, the total samples the system can have per second is Δf. Thus the cooling rate is the change in δ^2 per correction and the number of measurement per second, and at optimum gain g_0=1,

$$\boxed{\frac{d}{dt}\sigma^2(t) = \frac{\Delta f}{N}\sigma^2(t)}$$

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Stochastic cooling: cooling time

The above will work only when the phases are always random, therefore there is always enough of deviation to drive the cooling. With a mixing rate of M (=1 for perfect mixing, >1 for less than perfect), meaning the time needed for the system to randomize, cooling time is now

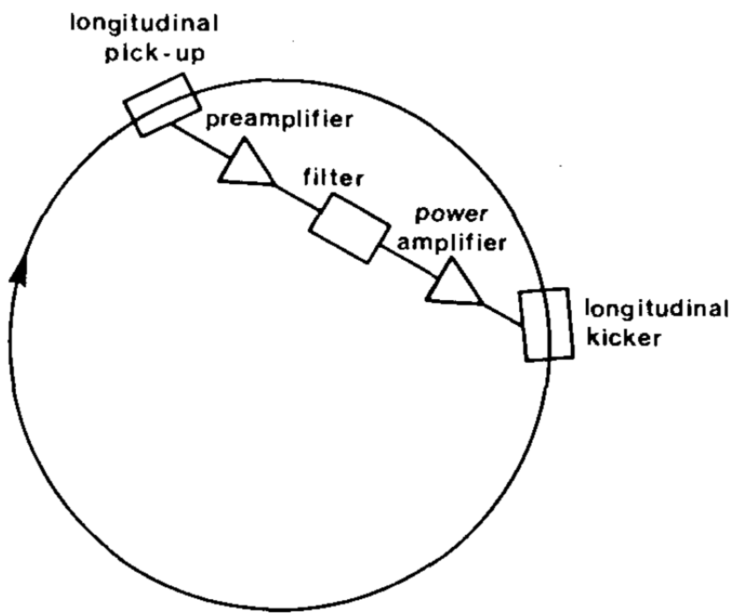
$$\frac{1}{\tau} = \frac{\Delta f}{MN}$$ instead of $$\frac{1}{\tau} = \frac{\Delta f}{N}$$

It also works for energy correction, etc.

J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Stochastic cooling: cooling time and results

Pickup-amplifier-kicker, in microwave.



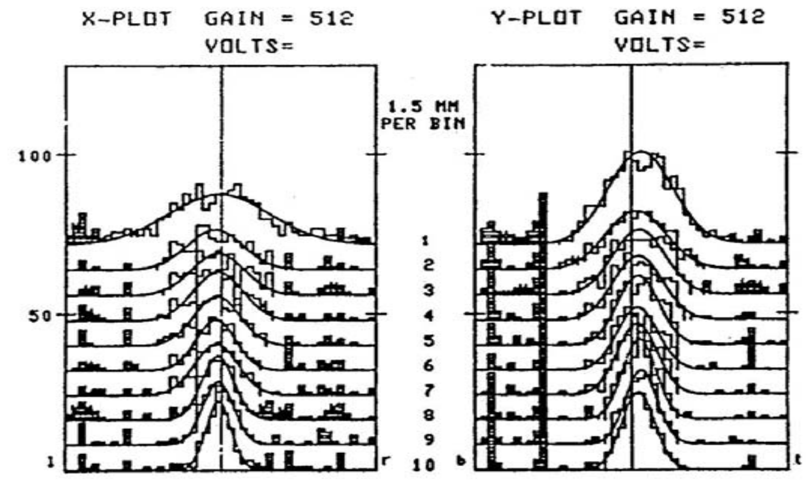


Fig. 10.7. Beam profiles in the FNAL Debuncher ring. The profiles were obtained at 0.22-sec intervals. The earliest time is at the top of the plot; the latest, at the bottom.

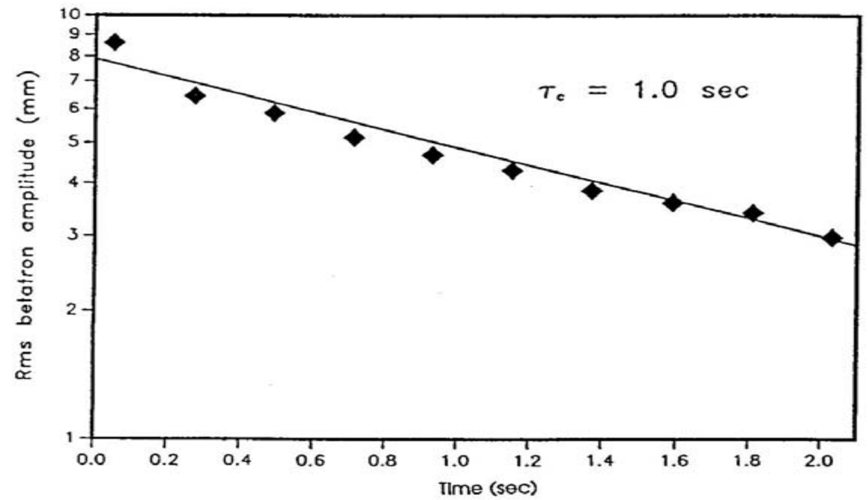


Fig. 10.8. Plot of the horizontal beam size versus time derived from the measurements shown in Fig. 10.7.

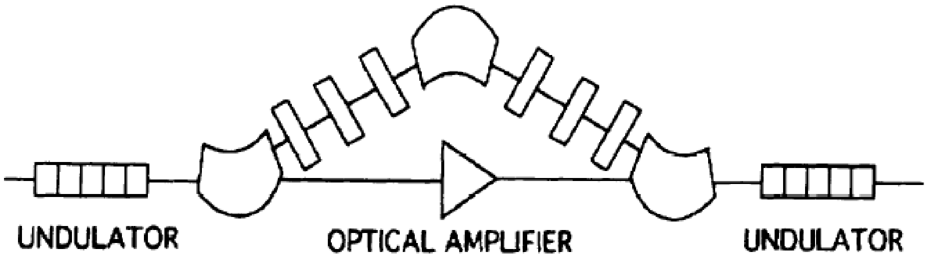
J. Marriner and D. McGinnis, AIP 249, 693 (1992)

Optical stochastic cooling: transient time method

- Why optical? Higher bandwidth
  - Conventional system with waveguide has limited bandwidth of about 1 GHz
  - Optical system easily goes up to THz. A 10% bandwidth at 800 μm gives 40 THz of bandwidth.
- Thus allowing more particles to be cooled in a shorter time
- Better for electron and proton systems
- Transient time method: allows adjustment of mixing
- Implementation
  - An undulator as signal pick up
  - Optically amplified
  - Another undulator as a kicker

$$\frac{1}{\tau} = \frac{\Delta f}{MN}$$

The radiation from U1 is amplified and brought together with the beam in U2 where the particle energy is changed. The change is determined by the relative phase between the particle and the transient time of the radiation.

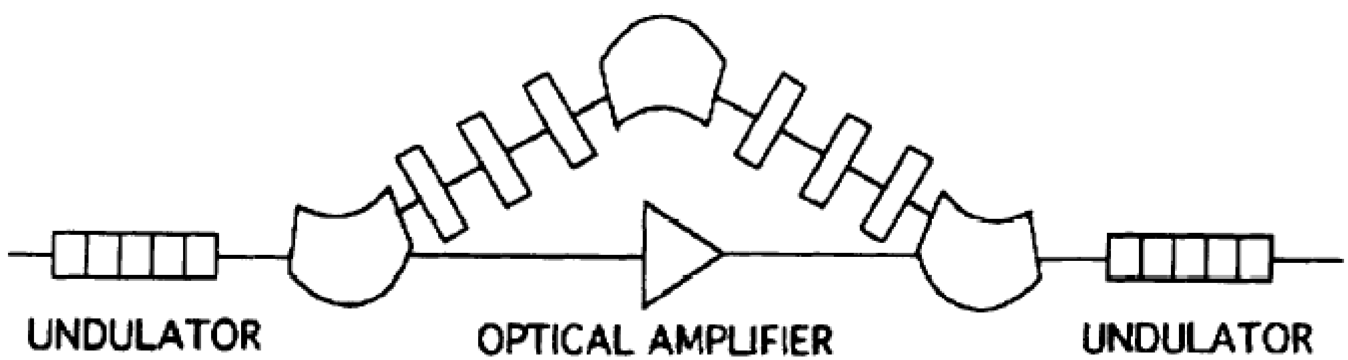


A. Mikhailichenko and M. S. Zolotorev, PRL 71, 4146 (1993).
M. S. Zolotorev and A. A. Zholents, PRE 50, 3087 (1994)

Optical stochastic cooling: things to follow

Using longitudinal effect as an example

- Formulating the kick correction
- Calculating the cooling decrement
- Obtain the optimum relative kick
- Obtain the optical gain
- Numerical examples



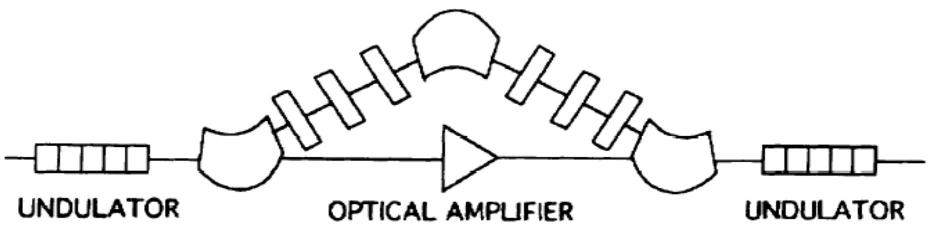
A. Mikhailichenko and M. S. Zolotorev, PRL 71, 4146 (1993).
M. S. Zolotorev and A. A. Zholents, PRE 50, 3087 (1994)

Optical stochastic cooling: the kick

- In the first undulator, an electron radiates

$$E_i = E_0 \sin(kz - \omega t + \phi_i)$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



  – E_0: amplitude, $k=2\pi/\lambda$, $\omega=kc$, ϕ is the phase; λ_u, K: undulator period and parameter; γ: beam energy.

- In the second undulator, the particle feels the kick from its own radiation, and other particles

$$\Delta\delta_i = \frac{\delta P_i}{P} = -[sign(I_D)]G\sin(\Delta\phi_i)$$

$$\Delta x_i = -D_2\Delta\delta_i$$

$$\Delta x_i' = -D_2'\Delta\delta_i$$

$$\Delta\phi_i = k(l_i - l_0)$$

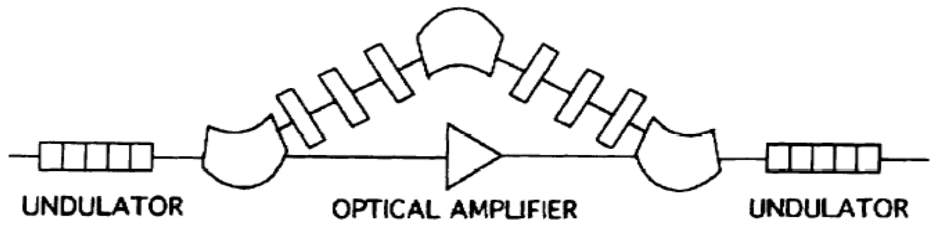
$$G = g\frac{qE_0 N_u \lambda_u K[JJ]}{2c\gamma}\Big/P$$

- δP: relative momentum deviation after the kick
- $\Delta\phi$, phase shift between the radiation and the particle
  – l_i,l_0, path length through the bypass
  – N_u : number of undulator periods
  – g: amplification factor of the optical
  – D_2, D'_2 are the dispersion and derivative in the second undulator
- Δx, $\Delta x'$, changes in betatron coordinate and angle
  – G is the fractional kick in momentum
- γ, E_0, relativistic factor of particle and radiation field of the a particle

S. Y. Lee, ‘Beam Damping in OSC’, http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

General transform matrix in accelerators

$$\begin{pmatrix} u \\ u' \\ \delta \end{pmatrix} = \begin{pmatrix} I_C & I_S & I_D \\ I'_C & I'_S & I'_D \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u_0 \\ u'_0 \\ \delta_0 \end{pmatrix}$$



$$I_U = \int_L \frac{U(s)}{\rho(s)} ds, \quad I_V = \int_L \frac{V(s)}{\rho(s)} ds, \quad I_D = \int_L \frac{D(s)}{\rho(s)} ds.$$

- *U* and *V* are independent cosinelike and sinelike solution of the motion;
- ρ: bending radius;
- *L* is the distance between the two undulators
- *D* is the dispersion from the bypass.
- δ_i: momentum deviation at the cooling undulator
- u can be x,y, or z

- The path length, which defines the transient time, is as following

$$l_i = l_0 + x_i I_U + x_i' I_V + \delta_i I_D$$

l_0: reference path length for particles with zero momentum deviation

H. Wiedemann, Pharticle Accelerator Physics, 3rd edition, Springer Verlag, p. 920

Optical stochastic cooling: cooling rates

- A particle will feel the radiation from all other particles, thus the change of momentum is (for $I_D>0$)

$$\delta_{ic} = \delta_i - G\sin(\Delta\phi_i) - G\sum_{k\neq i}^{Ns}\sin(\Delta\phi_i + \psi_{ik})$$

  - $\psi_{ik} = \phi_k - \phi_i$ is the phase difference between particles.
  - δ_i: momentum deviation from the average at the cooling undulator
  - δ_{ic}: momentum after the kick
  - $N_s=0.5N_bN_u\lambda/l_b$ is the number of interaction particle

$$\phi_i = kl_i$$

$$x_{ic} = x_i + D_2\sin(\Delta\phi_i) + D_2\sum_{k\neq i}^{Ns}\sin(\Delta\phi_i + \psi_{ik}),$$

$$x_{ic}' = x_i' + D_2'\sin(\Delta\phi_i) + D_2'\sum_{k\neq i}^{Ns}\sin(\Delta\phi_i + \psi_{ik}),$$

Same Eqs as before, except the kick depends on the phase difference

- From here, the average of the following change due to the kick can be calculated, using the same technique used before, and the distribution function of the beam.

$$\left\langle\Delta\delta^2\right\rangle = \left\langle\delta_{ic}^2 - \delta_i^2\right\rangle,\quad \left\langle\Delta x^2\right\rangle = \left\langle x_{ic}^2 - x_i^2\right\rangle,\quad \left\langle\Delta x'^2\right\rangle = \left\langle x'^2_{ic} - x'^2_i\right\rangle$$

S. Y. Lee, ‘Beam Damping in OSC’, http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Optical stochastic cooling: cooling rates

- For the momentum change

$$\Delta\delta^2 = \delta_{ic}{}^2 - \delta_i{}^2 = \delta_i{}^2 - 2\delta_i G\sum_{k=1}^{Ns}\sin(\Delta\phi_i + \psi_{ik}) + G^2\sum_{k=1}^{N_s}\sum_{j=1}^{N_s}\sin(\Delta\phi_i + \psi_{ij})\sin(\Delta\phi_i + \psi_{ik}) - \delta_i{}^2$$

$$= \underline{-2\delta_i G\sum_{k=1}^{Ns}\sin(\Delta\phi_i + \psi_{ik})} + \underline{G^2\sum_{k=1}^{N_s}\sum_{j=1}^{N_s}\sin(\Delta\phi_i + \psi_{ij})\sin(\Delta\phi_i + \psi_{ik})}$$

- Average over the ensemble and time, note that

$$\boxed{\left\langle \sum_{k=1}^{N_s}\sum_{j=1}^{N_s}\sin(\Delta\phi_i + \psi_{ij})\sin(\Delta\phi_i + \psi_{ik})\right\rangle = \sum_{j=1}^{N_s}\sin^2(\Delta\phi_i + \psi_{ij}) = \frac{N_s}{2}}$$

$$\boxed{\left\langle 2\delta_i G\sum_{k=1}^{Ns}\sin(\Delta\phi_i + \psi_{ik})\right\rangle \approx \left\langle 2\delta_i G\sum_{k=1}^{Ns}\sin(\Delta\phi_i)\right\rangle = \mathrm{Im}\left[2G\int \delta\exp(ik\delta l)f(x,P_x,\delta)\,dx\,dP_x\,d\delta\right]}$$

- Where the particle distribution function, path length and transverse momentum are

$$f(x,p_x,\delta) = \frac{1}{(2\pi)^{3/2}\sigma_x^2\sigma_\delta}\exp\left[-\frac{x^2+P_x{}^2}{2\sigma_x^2} - \frac{\delta^2}{2\sigma_\delta^2}\right]$$

$$p_x = \beta x' + \alpha x \quad \Rightarrow x' = \frac{p_x - \alpha x}{\beta}$$

***α, β* are the Twiss parameters, *p* is the normalized betatron phase space coordinate in the first undulator**

$$\delta l = l - l_0 = xI_U + x' I_V + \delta I_D = xI_U + \frac{p_x - \alpha x}{\beta}I_V + \delta I_D = x\left(I_U - \frac{\alpha}{\beta}I_V\right) + p_x\frac{I_V}{\beta} + \delta I_D$$

Optical stochastic cooling: cooling rates

$$\left\langle 2\delta_i G \sum_{k=1}^{Ns} \sin(\Delta\phi_i + \psi_{ik}) \right\rangle$$

$$= \mathrm{Im}\left[2G \int \delta \exp[ik\delta l] f(x,P,\delta)\, dx dP d\delta \right]$$

$$= \mathrm{Im}\left\{ \frac{2G}{(2\pi)^{3/2}\sigma_x^2\sigma_\delta} \int \delta \exp\left[ik\left(x\left(I_U - \frac{\alpha}{\beta} I_V \right) + P\frac{I_V}{\beta} + \delta I_D \right)\right] \exp\left[-\frac{x^2+P^2}{2\sigma_x^2} - \frac{\delta^2}{2\sigma_\delta^2} \right] dx dP d\delta \right\}$$

$$\begin{cases} \int \exp\left[ikx\left(I_U - \frac{\alpha}{\beta} I_V \right) - \frac{x^2}{2\sigma_x^2} \right] dx = \sqrt{2\pi}\sigma_x \exp\left[-\frac{1}{2} k^2 \left(I_U - \frac{\alpha}{\beta} I_V \right)^2 \sigma_x^2 \right] \\ \int \exp\left[ikP\frac{I_V}{\beta} - \frac{P^2}{2\sigma_x^2} \right] = \sqrt{2\pi}\sigma_x \exp\left[-\frac{1}{2} k^2 \left(\frac{I_V}{\beta} \right)^2 \sigma_x^2 \right] \\ \int \delta \exp\left[ik\delta I_D - \frac{\delta^2}{2\sigma_\delta^2} \right] = i\sqrt{2\pi} k I_D \sigma_\delta{}^3 \exp\left[-\frac{1}{2} k^2 I_D{}^2 \sigma_\delta^2 \right] \end{cases}$$

$$= 2GkI_D\sigma_\delta^2 e^{-\frac{1}{2}k^2\left(\left(I_U - \frac{\alpha}{\beta} I_V \right)^2 \sigma_x^2 + \left(\frac{I_V}{\beta} \right)^2 \sigma_x^2 + I_D{}^2\sigma_\delta^2 \right)} = 2GkI_D\sigma_\delta^2 e^{-u}$$

Optical stochastic cooling: cooling rates

$$u = \frac{1}{2}k^2\left[\left(I_U - \frac{\alpha}{\beta}I_V\right)^2\sigma_x^2 + \left(\frac{I_V}{\beta}\right)^2\sigma_x^2 + I_D{}^2\sigma_\delta^2\right]$$

$$= \frac{1}{2}k^2\left[\left(I_U{}^2 - 2I_U\frac{\alpha}{\beta}I_V + \left(\frac{\alpha}{\beta}I_V\right)^2 + \left(\frac{I_V}{\beta}\right)^2\right)\sigma_x^2 + I_D{}^2\sigma_\delta^2\right]$$

$$\begin{cases} \sigma_x^2 = \beta\varepsilon_x \\ \beta\gamma - \alpha^2 = 1 \quad \Leftrightarrow \dfrac{\alpha^2+1}{\beta} = \gamma \end{cases}$$

$$u = \frac{1}{2}k^2\left[\left(\beta I_U{}^2 - 2\alpha I_U I_V + \gamma I_V{}^2\right)\varepsilon_x + I_D{}^2\sigma_\delta^2\right]$$

α β, γ are the twiss parameters at the first undulator, and ε_x is the emittance

Optical stochastic cooling: cooling rates

- Therefore we have

$$\left\langle \Delta\delta^2 \right\rangle = \left\langle {\delta_{ic}}^2 - {\delta_i}^2 \right\rangle = -2GkI_D\sigma_\delta^2 e^{-u} + \frac{G^2}{2}N_s$$

- And the cooling decrement is

$$\alpha_\delta = -\frac{\left\langle \Delta\delta^2 \right\rangle}{\left\langle \delta^2 \right\rangle} = 2GI_D k e^{-u} - \frac{G^2 N_s}{2}\frac{1}{\sigma_\delta^2}$$

- Where u is the a measure of the total thermal energy of the beam

$$u = \frac{1}{2}k^2\left[\left(\beta {I_U}^2 - 2\alpha I_U I_V + \gamma {I_V}^2\right)\varepsilon_x + {I_D}^2\sigma_\delta^2\right]$$

Optical stochastic cooling: cooling rates

- Optimizing over G, the optimum cooling occurs at

$$G_\delta = \frac{2kI_D\sigma_\delta^2}{N_s}e^{-u}$$

$$\alpha_{\delta,\max} = \frac{2k^2 I_D{}^2\sigma_\delta^2}{N_s}e^{-2u}$$

- Place unulators placed at the betatron waist, so that,

$$\alpha = 0, \gamma = 1/\beta$$

$$u = \frac{1}{2}k^2\left[\left(\beta I_U{}^2 + \frac{1}{\beta}I_V{}^2\right)\varepsilon_x + I_D{}^2\sigma_\delta^2\right]$$

S. Y. Lee, ‘Beam Damping in OSC’, http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Optical stochastic cooling: cooling rates

- Following the same procedure, for the transverse dimension

$$\alpha_x = -\frac{\left\langle \Delta P_x{}^2 + \Delta x^2 \right\rangle}{\left\langle \sigma_x{}^2 \right\rangle} = 2GI_\perp k e^{-u} - \frac{G^2 N_s H_2}{2\varepsilon_x}$$

- Optimizing over G, the optimum transverse cooling occurs at

$$G_x = \frac{2kI_\perp \varepsilon_x}{N_s H_2} e^{-u}$$

$$\alpha_{x,\max} = \frac{2k^2 I_\perp{}^2 \varepsilon_x}{H_2} e^{-2u}$$

- Using mirror symmetry for the by pass insert and have unulators placed at the betatron waist, so that,

$$H_2 = \frac{1}{\beta_2}\left(D_2{}^2 + p_2{}^2\right)$$

$$I_\perp = D_2 I_U, \quad \alpha_2 = D_2' = 0$$

$$u = \frac{1}{2}k^2\left[\left(\beta I_U{}^2 + \frac{1}{\beta} I_V{}^2\right)\varepsilon_x + I_D{}^2 \sigma_\delta^2\right]$$

Sub script 2 denoted the location of the second undulator

Optical stochastic cooling: cooling dynamics

- One has the cooling dynamics is now

$$\frac{d\sigma_\delta^2}{dt} = -\frac{2GI_D k e^{-u}}{T}\sigma_\delta^2 + \frac{G^2 N_s}{2T}$$

$$\frac{d\varepsilon_x}{dt} = -\frac{2GI_\perp k e^{-u}}{T}\varepsilon_x + \frac{G^2 N_s H_2}{2T}$$

T is the revolution period

- For equal optimum cooling, G_x=G_δ, thus

- Equal cooling can only occur at I_D=$I_\perp$

$$\begin{cases} \dfrac{I_\perp \varepsilon_x}{H_2} = I_D \sigma_\delta^2 \\ \dfrac{\alpha_\delta}{\alpha_x} = \dfrac{I_D}{I_\perp} \end{cases} \xrightarrow{I_D = I_\perp} \begin{cases} \varepsilon_x = H_2 \sigma_\delta^2 \\ \alpha_\delta = \alpha_x \end{cases}$$

S. Y. Lee, ‘Beam Damping in OSC’, http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Equal cooling decrement dynamics

- With $\varepsilon_x = H_2\sigma_\delta^2$
- The dynamics becomes

$$\frac{du}{dt} = -\frac{2GI_D k e^{-u}}{T}u + \frac{G^2 N_s}{2T}v$$

$$\begin{cases} v = \frac{1}{2}k^2\left[\left(\beta I_U{}^2 + \frac{1}{\beta}I_V{}^2\right)H_2 + I_D{}^2\right] \\ u = \frac{1}{2}k^2\left[\left(\beta I_U{}^2 + \frac{1}{\beta}I_V{}^2\right)\varepsilon_x + I_D{}^2\sigma_\delta^2\right] = v\sigma_\delta^2 \end{cases}$$

- At optimal Gain

$$G_{opt} = \frac{2kI_D}{N_s}\sigma_\delta^2 e^{-u} = \frac{2kI_D}{vN_s}ue^{-u}$$

$$\Rightarrow \frac{du}{dt} = -\frac{2k^2 I_D{}^2}{vN_s T}u^2 e^{-2u}$$

- The solution is

$$\boxed{\int_u^{u_0}\frac{e^{2u}}{u^2}du = \frac{2k^2 I_D{}^2}{vN_s T}t}$$

S. Y. Lee, 'Beam Damping in OSC', http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Gain for OSC

- During one pass of the undulator, a particle emits *n* photons at energy $h\nu$

$$n \approx \frac{q^2 \xi}{4\varepsilon_0 \hbar c}[JJ]^2$$

$$\begin{cases} \xi = \dfrac{K^2}{2+K^2} \\ [JJ] = J_0\left(\dfrac{1}{2}\xi\right) - J_1\left(\dfrac{1}{2}\xi\right) \end{cases}$$

- The coherence mode area A, and total radiation time Δt_R are

$$A \approx 2\lambda N_u \lambda_u$$

$$\Delta t_R = \frac{N_u \lambda}{c}$$

- Thus the total energy emitted is

$$WA\Delta t_R = \frac{c}{8\pi} E_0{}^2 A\Delta t_R = \frac{1}{4\pi} E_0{}^2 \lambda_u (N_u \lambda)^2 = n\hbar\omega = \frac{q^2 k \xi}{4\varepsilon_0}[JJ]^2$$

M. S. Zolotorev and A. A. Zholents, PRE 50, 3087 (1994)

Gain for OSC

- During one pass of the undulator, a particle emits *n* photons at energy $h\nu$

$$\frac{1}{4\pi}E_0^{\ 2}\lambda_u\left(N_u\lambda\right)^2=\frac{q^2k\xi}{4\varepsilon_0}[JJ]^2$$

$$\Rightarrow E_0^{\ 2}=\frac{2\pi^2q^2\xi}{\varepsilon_0\lambda_uN_u^{\ 2}\lambda^3}[JJ]^2=\frac{\pi^2q^2K^2}{2\varepsilon_0\gamma^2N_u^{\ 2}\lambda^4}[JJ]^2$$

$$\begin{cases}\lambda=\dfrac{\lambda_u}{2\gamma^2}\left(1+\dfrac{K^2}{2}\right)=\dfrac{\lambda_u}{2\gamma^2}\dfrac{K^2}{2\xi}\Rightarrow\lambda_u=\dfrac{4\gamma^2\xi}{K^2}\lambda\\ k=\dfrac{2\pi}{\lambda}\end{cases}$$

$$\Rightarrow E_0=\frac{\pi qK}{\sqrt{2\varepsilon_0\gamma}N_u\lambda^2}[JJ]$$

Gain for OSC

- At optimum gain

$$G_{opt}=\frac{2kI_D}{N_s}\sigma_\delta^2 e^{-u}=g_{opt}\frac{qE_0N_u\lambda_u K[JJ]}{2c\gamma}\Big/P$$

- Use

$$P=\gamma mc,\quad r_0=\frac{q^2}{mc^2},\quad k=\frac{2\pi}{\lambda}$$

$$\Rightarrow \frac{4I_D}{N_s}\sigma_\delta^2 e^{-u}=g_{opt}r_0\frac{\sqrt{2}[JJ]^2}{\sqrt{\varepsilon_0\gamma}}\xi$$

$$\Rightarrow g_{opt}=\frac{4I_D\sqrt{\varepsilon_0\gamma}}{\sqrt{2}N_s r_0\xi[JJ]^2}\sigma_\delta^2 e^{-u}$$

- At high energy, at u=1

$$g_{opt}\approx\frac{I_D\sqrt{\varepsilon_0\gamma}}{N_s r_0}\sigma_\delta^2=\frac{2I_D\sqrt{\varepsilon_0\gamma}l_b\sigma_\delta^2}{N_b N_u\lambda r_0}$$

- Laser peak power

$$P=WAg_{opt}{}^2$$

M. S. Zolotorev and A. A. Zholents, PRE 50, 3087 (1994)

Electron examples: laser power

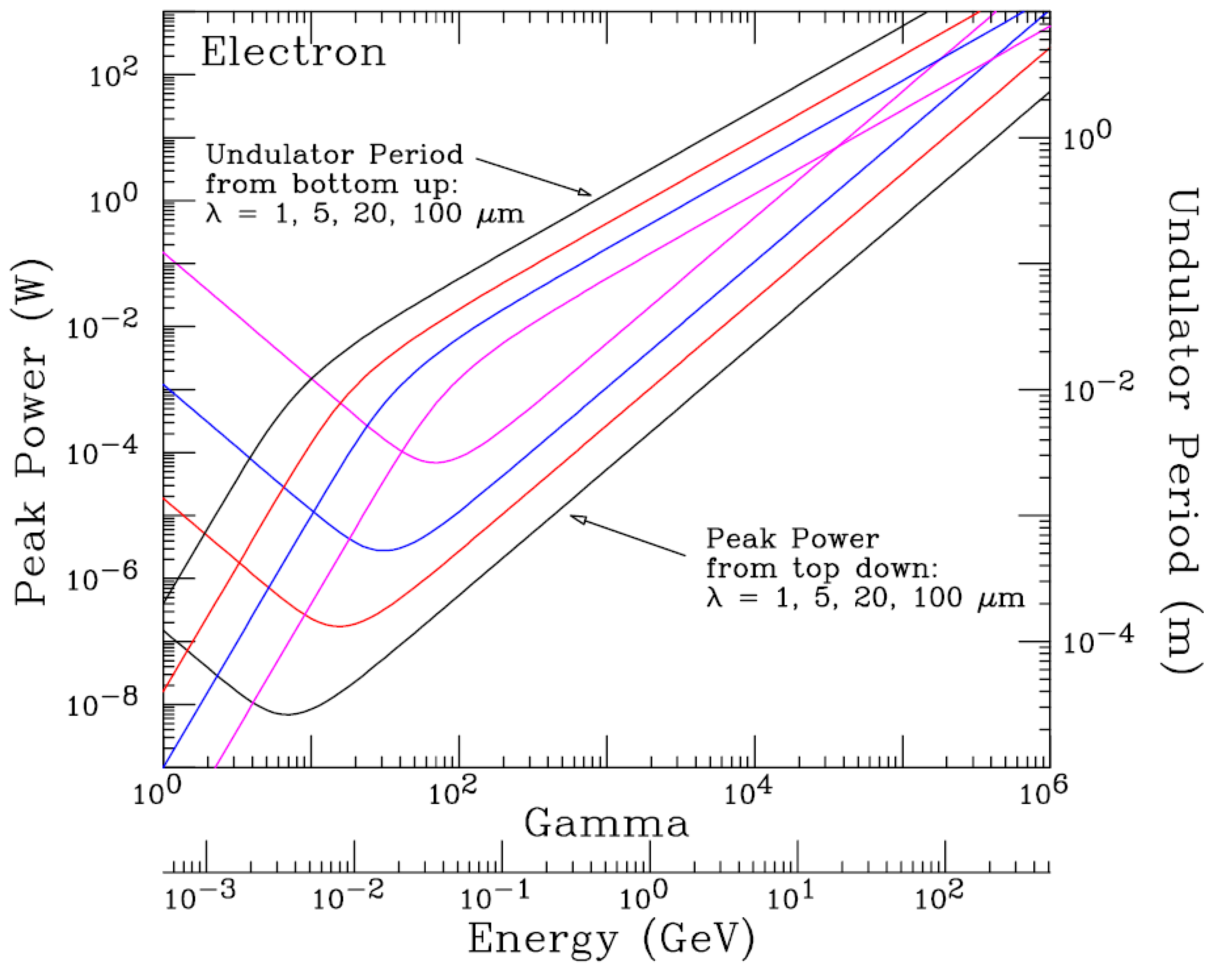


FIG. 4: The peak laser amplifier power vs γ for optimal gain in the optical stochastic cooling for electron storage rings. The parameters for the electron storage ring are $\sigma_\ell = 1$ cm, $\sigma_\delta = 1.3 \times 10^{-4}$, $N_{\rm B} = 1.0 \times 10^{11}$, and $B_{\rm u} = 1.0$ T.

S. Y. Lee, 'Beam Damping in OSC', http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Electron example: final emittance

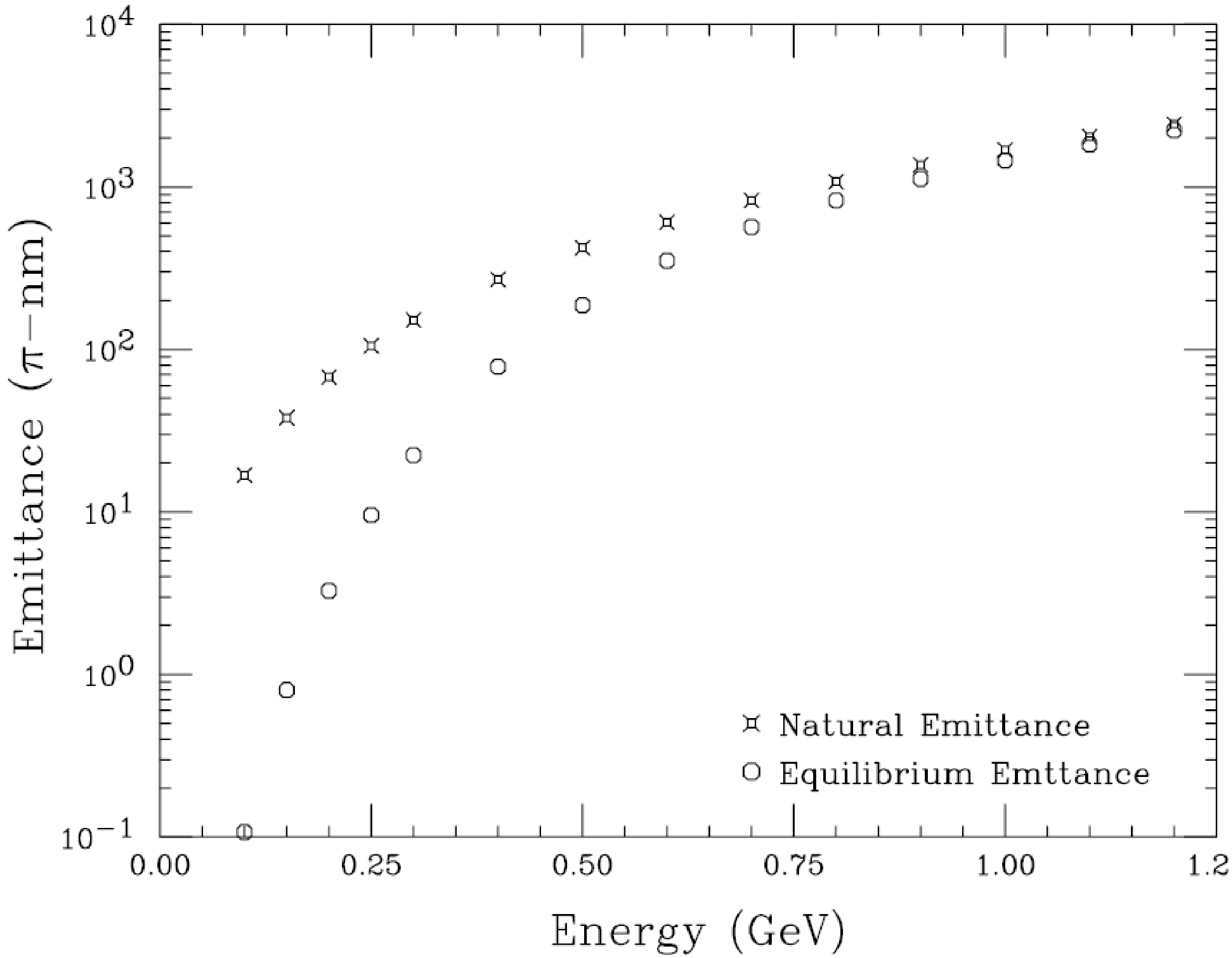


FIG. 5: The equilibrium electron emittance for a cooling time of 0.1 s is shown as a function of the electron beam energy.

S. Y. Lee, ‘Beam Damping in OSC’, http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Proton example: laser power

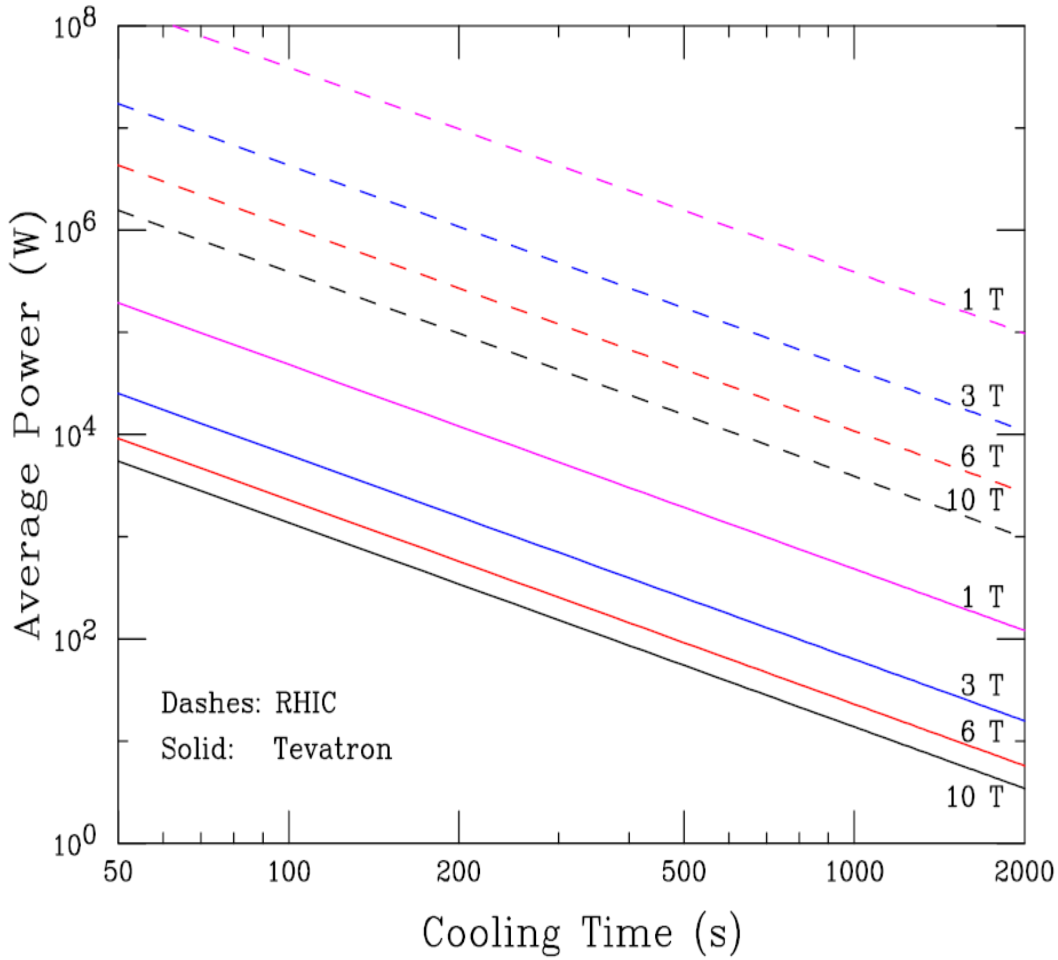


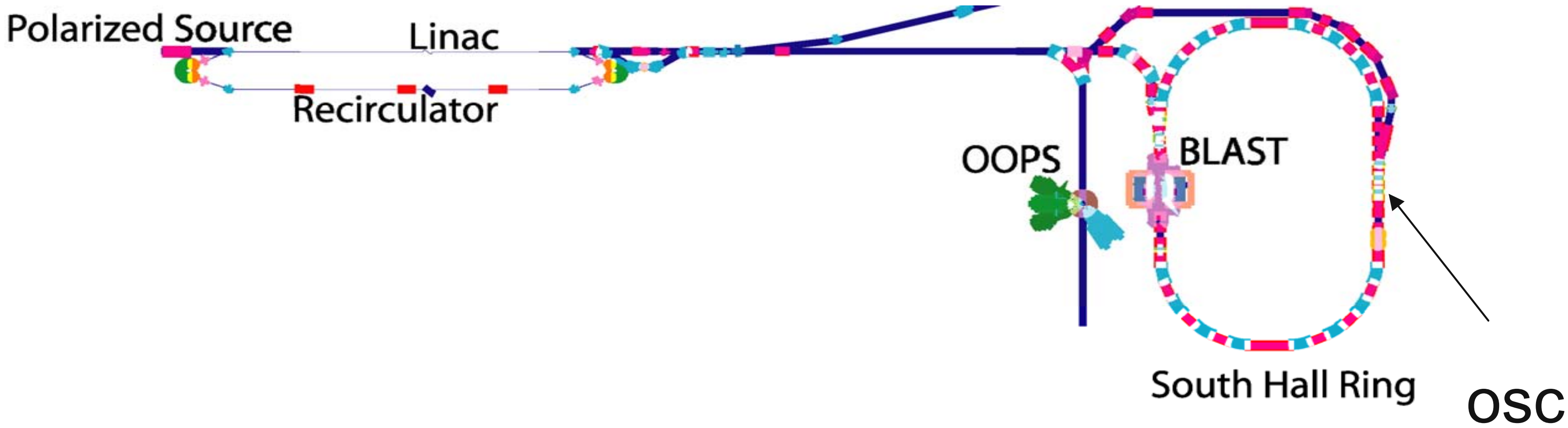
FIG. 6: The laser amplifier power in the low gain regime for Tevatron at 1 TeV and RHIC at 100 GeV/amu. The laser wavelength is $\lambda = 1\mu$, and the undulator parameters are $N_{\rm u} = 10$ with the magnetic field strength $B_{\rm u}$ listed in the graph. The corresponding beam parameters are $\sigma_\ell = 0.37$ m, $\sigma_\delta = 1.3 \times 10^{-4}$, $n_b = 36$ bunches, each containing $N_{\rm B} = 2.7 \times 10^{11}$ particles, at $E_b = 1$ TeV for the TEVATRON; and $\sigma_\tau = 2$ ns, $\sigma_\delta = 1.0 \times 10^{-3}$, $n_b = 60$ bunches, each containing $N_{\rm B} = 1.0 \times 10^{9}$ particles, $E_b = 100$ GeV/nucleon for gold ion, and the circumference of 3833.85 m for RHIC.

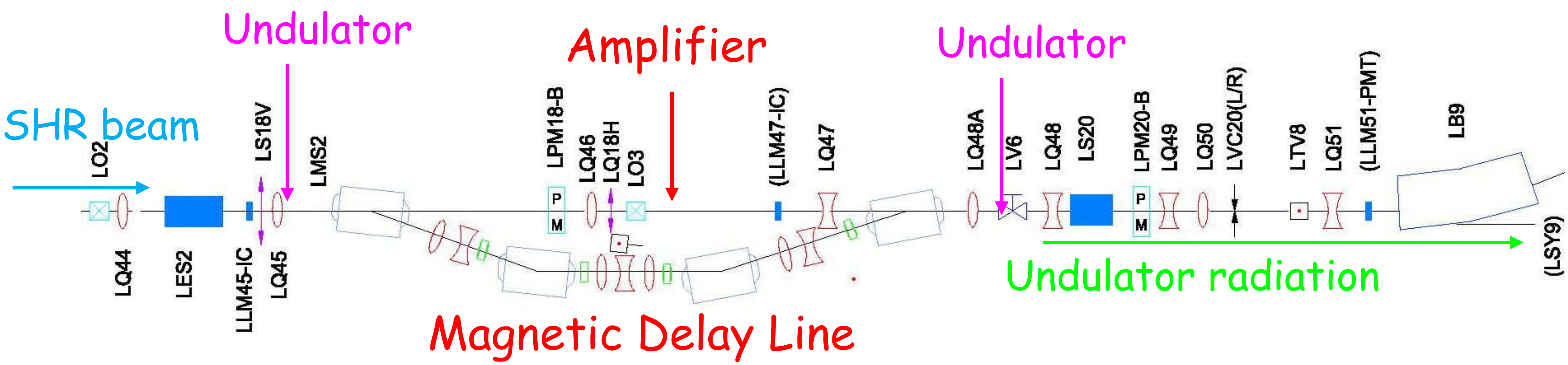
S. Y. Lee, 'Beam Damping in OSC', http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf

Optical stochastic papers

- C. Tschalaer ,'Optical Stochastic Cooling - Beam Bypass Parameters and Optical Gain,' MIT-Bates Internal Report, B/IR#07-02
- S.Y. Lee, 'Optical Stochastic Cooling possibilities at MIT-Bates', http://filburt.lns.mit.edu/accelphy/OSC/Pubs/BATES.ps
- M. Babzien et al., 'Optical stochastic for RHIC using optical parametric amplification,' PRSTAB 7, 012801(2004)
- S.Y. Lee, 'Beam Damping in Optical Stochastic Cooling,' http://filburt.lns.mit.edu/accelphy/OSC/Pubs/IUCF-AP-02-01.pdf
- A. Zholents and M. Zolotorev, 'Optical stochastic cooling of muons,' PRSTAB 4, 031001(2001)
- S. Heifets and M. Zolotorev, 'Quantum theory of Optical Stochastic Cooling,' PRE 65, 016507 (2002).
- A.Zholents, W.Barletta, S.Chattopadhyay, M.Zolotorev, 'Halo Particle Confinement in the VLHC using Optical Stochastic Cooling ,' JACoW Proc. EPAC 2000, 262
- A. Zholents and M. Zolotorev, 'An Amplifier for Optical Stochastic Cooling ,' JACoW Proc. PAC 1997,1804
- Damping Ring for testing the Optical Stochastic Cooling Method
- A.A. Mikhailichenko, BINP, JACoW Proc. EPAC 1994, 1214
- **M. Zolotorev and A. Zholents, 'Transit-time method of optical stochastic cooling,' PRE, 50, No 4 (1994)**
- A.A. Mikhailichenko and M.S. Zolotorev, 'Optical Stochastic Cooling ', PRL 71, 4146(1993).

Optical stochastic cooling at MIT Bates





http://filburt.lns.mit.edu/accelphy/OSC/osc.html

Optical stochastic cooling: summarizing

- Achievement of highest luminosity in collider experiments requires combination of complementary techniques
- Promising technique for high energy protons, ions to lower cooling time under certain conditions
- Not effective for high energy electrons due to radiation cooling
- Technique has not been experimentally verified
- Significant technical challenges in implementation for proton: laser power
- Can test much of physics with lower energy stored electron beam

Content

- Laser slicer
  - The problem
  - The solution
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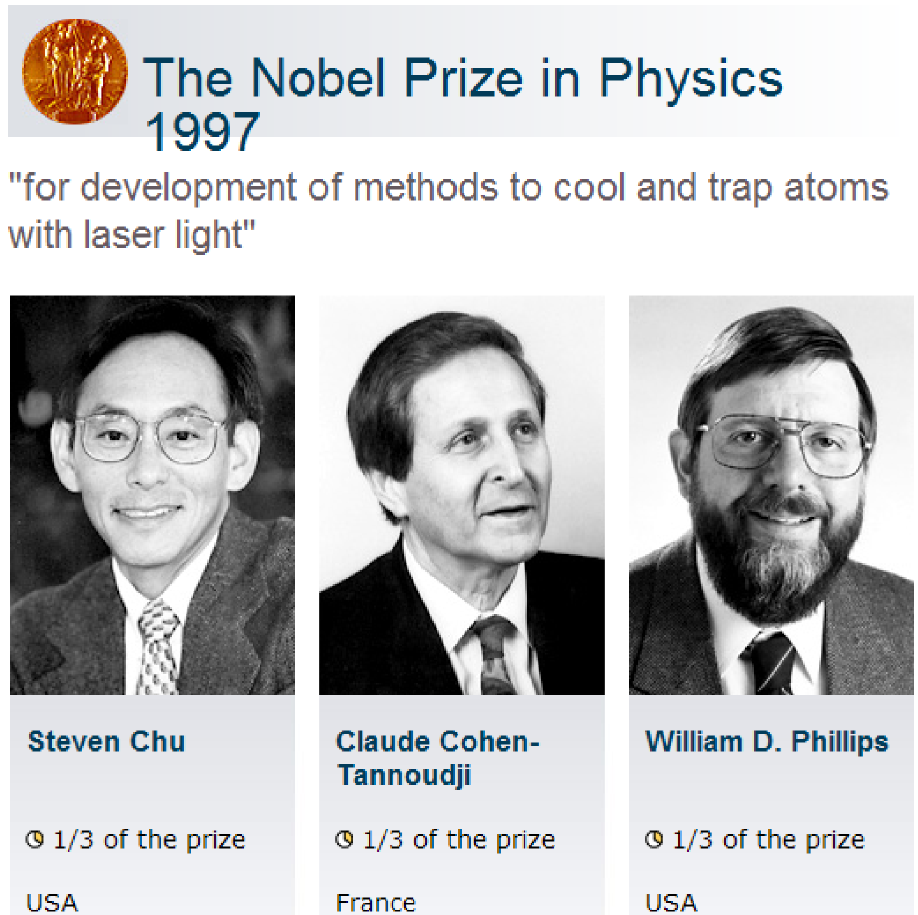
- Laser heater
  - The problem
  - The solution
  - Example
- Optical stochastic cooling
  - Stochastic cooling: the Nobel prize
  - Invention and application
  - Optical stochastic cooling
- Ion accelerators
  - Laser cooling
  - Laser stripping

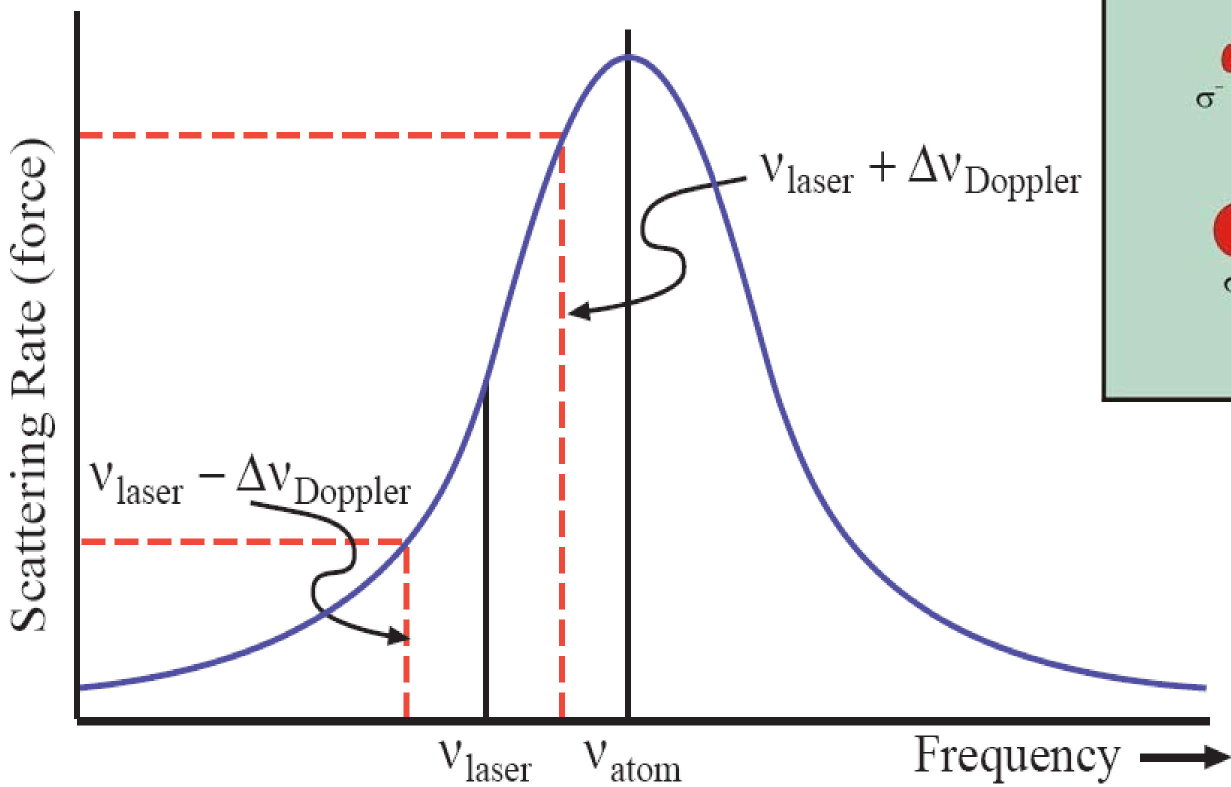
Laser ion cooling

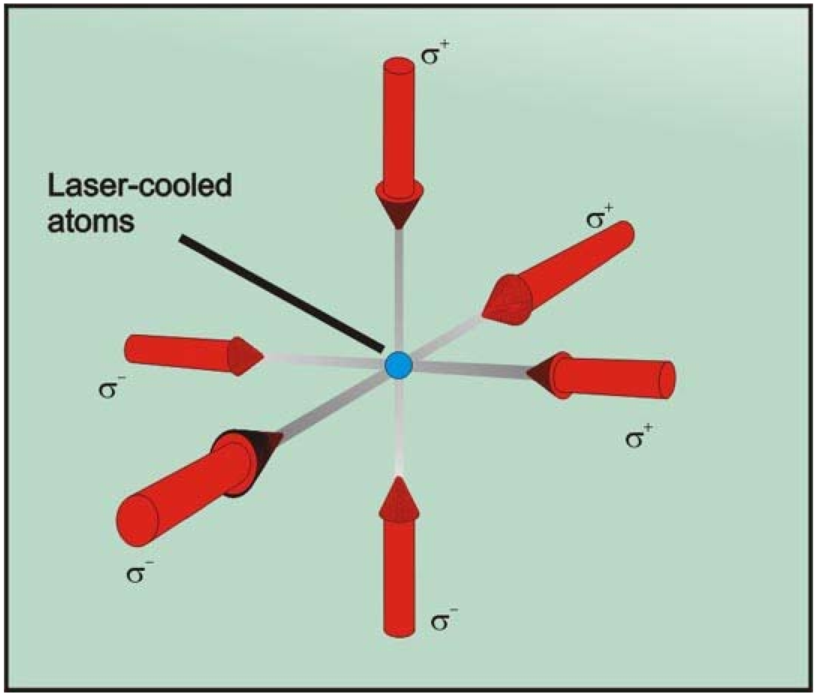
- Laser cooling is a process of transferring laser momentum to atoms/ions
- Then the ions cool down by radiation
- It also applies to ions in a storage ring
- Can generate “crystal beams” (Gilbert, Phys. Rev. Lett. 60, 2022 (1988))



Laser ion cooling

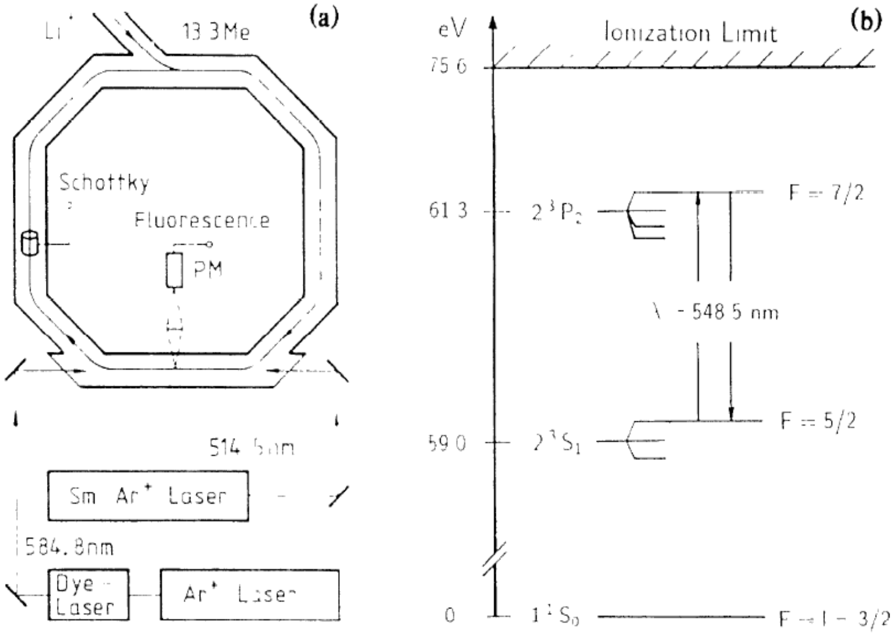
- Mechanism
  - Doppler shift
  - Absorbing less, radiate more



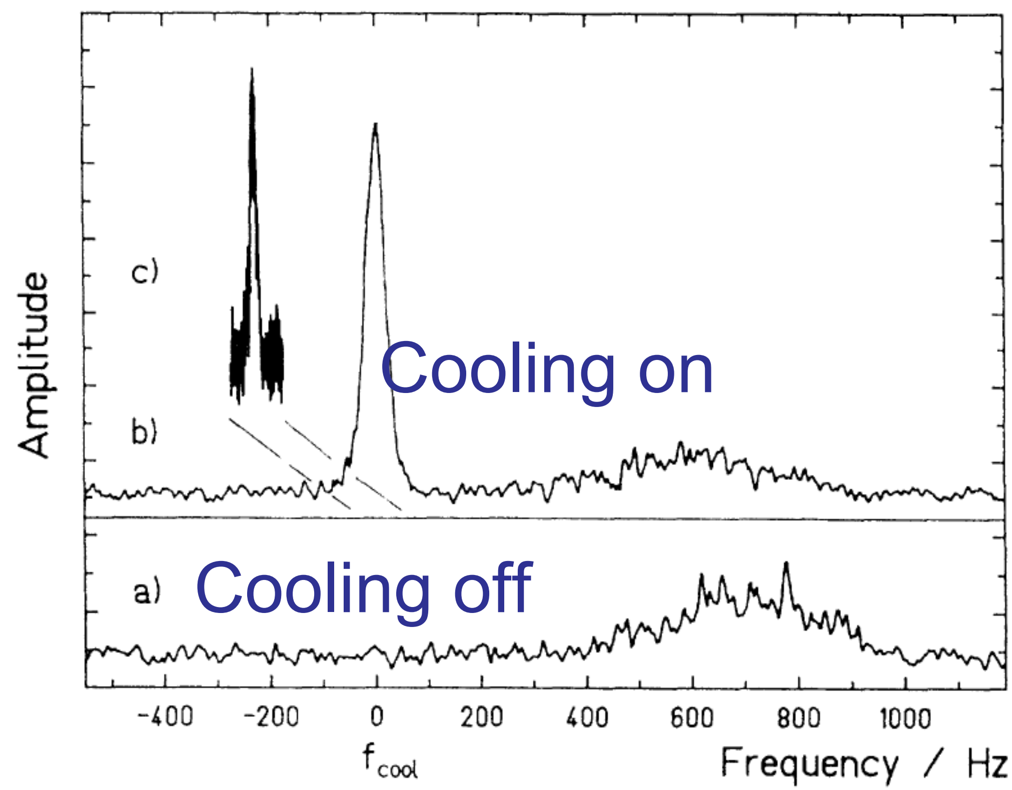


Laser ion cooling in storage ring

- Demonstration



Schottky spectrum

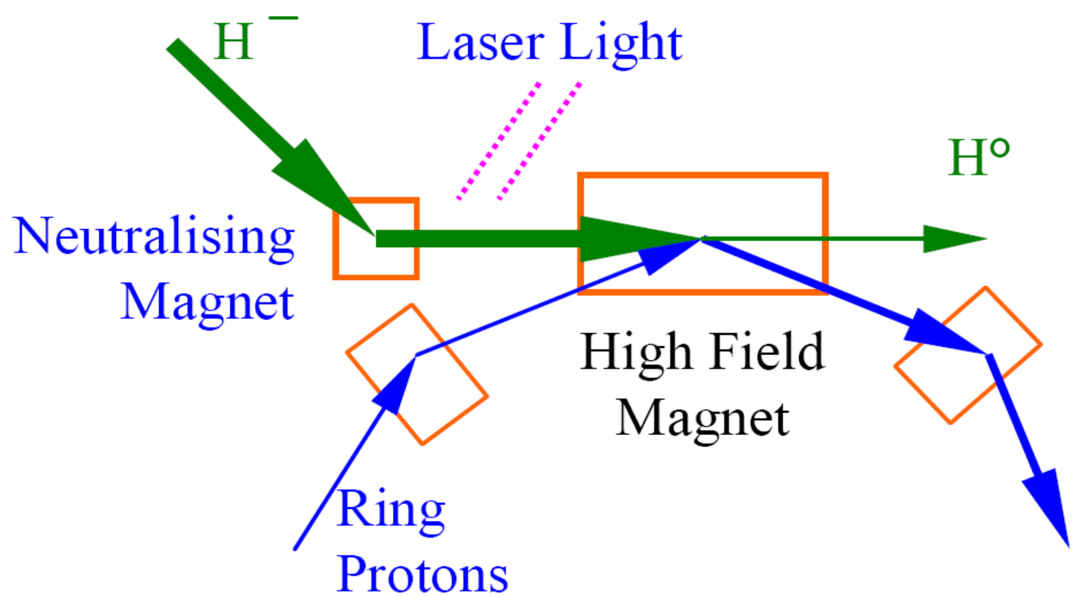


Two lasers:
An Ar ion laser co-propagating with the ions, set at resonance for ions at lower energy side;
A counter propagating dye laser tuning at high energy size swept to higher value.

S. Schroeder, Phys. Rev. Lett. 64, 2901 - 2904 (1990)

Laser stripping

- To purify the ionic states for ion accelerators (proton included)
- For proton machine, needs H^+, but many start with H^-
  - Foil stripping
  - Lorentz + Laser stripping
    - *Any particle travel in a B field will see a E field of* $\boldsymbol{\varepsilon}=\gamma(\mathbf{v}/c)\times\mathbf{B}$,
    - *Thus an electron can be pull from the ion*
- Proof of priciple experiment at SNS: Danilov et al., PRSTAB **10**, 053501 (2007).



P. Drumm et al., Proc. EPAC 2000, 2234 (2000)