Methods of Beam Conditioning for FELs

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September 23, 2003

Conclusions

- Conditioning without growth of effective emittance is possible in a symplectic system.
- Maxwell's Equations impose some challenging restrictions on conditioning systems but…
- …it is possible to construct some theoretical designs that work in principle.
- It appears to be difficult (but maybe not impossible) to achieve the amount of conditioning likely to be required by real FELs.
- Non-conventional (laser, laser-plasma) conditioning holds promise.
  - See talk by A. Sessler

The Hamiltonian for an ideal conditioner is straightforward

$$\boxed{H = \frac{\mu}{L} J + \frac{\kappa}{L} z J}$$

J and z are conserved

$$\Delta\phi = \mu + \kappa z$$

$$\boxed{\Delta\delta = \kappa J}$$

- Since J is conserved, the effective emittance of the bunch is preserved
- Since z is conserved, the bunch length is preserved
- There is a phase advance that depends upon z
- κ is the conditioning parameter:

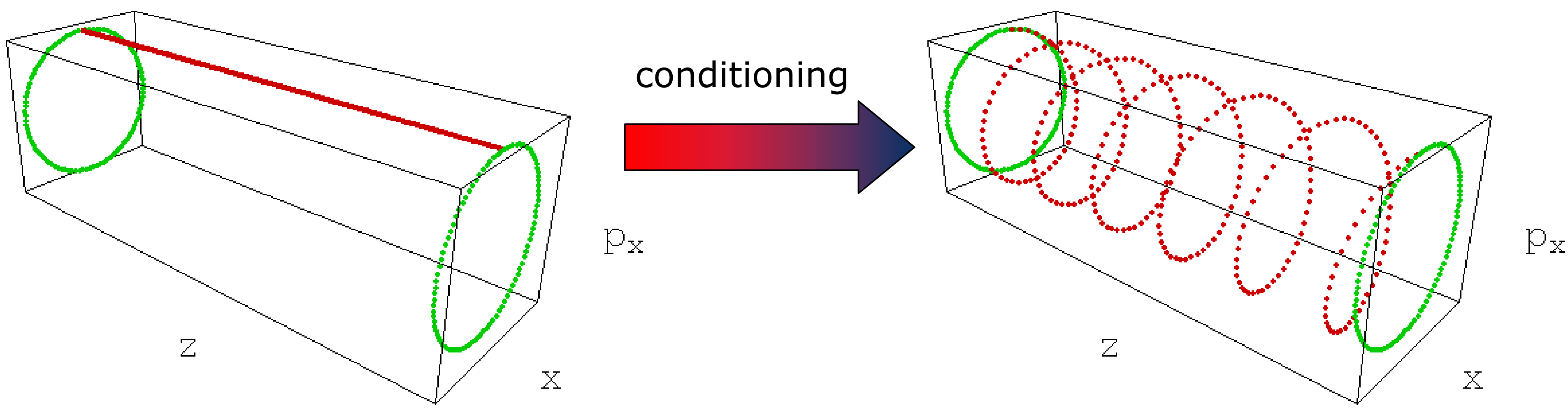
$$\boxed{\frac{\Delta\gamma}{\gamma J} = \kappa = \frac{1}{2\beta_u} \frac{\lambda_u}{\lambda_r}}$$

There are extreme effects in transverse phase space

- $\Delta\phi = \mu + \kappa z$

- For LCLS, $\kappa \approx 5\ \mu m^{-1}$

  So for $\sigma_z \approx 20\ \mu m$, there is a *variation* in phase advance of order **100 radians** along the length of the bunch!



Effect of conditioning on transverse phase-space distribution

How do we construct a conditioning beamline?

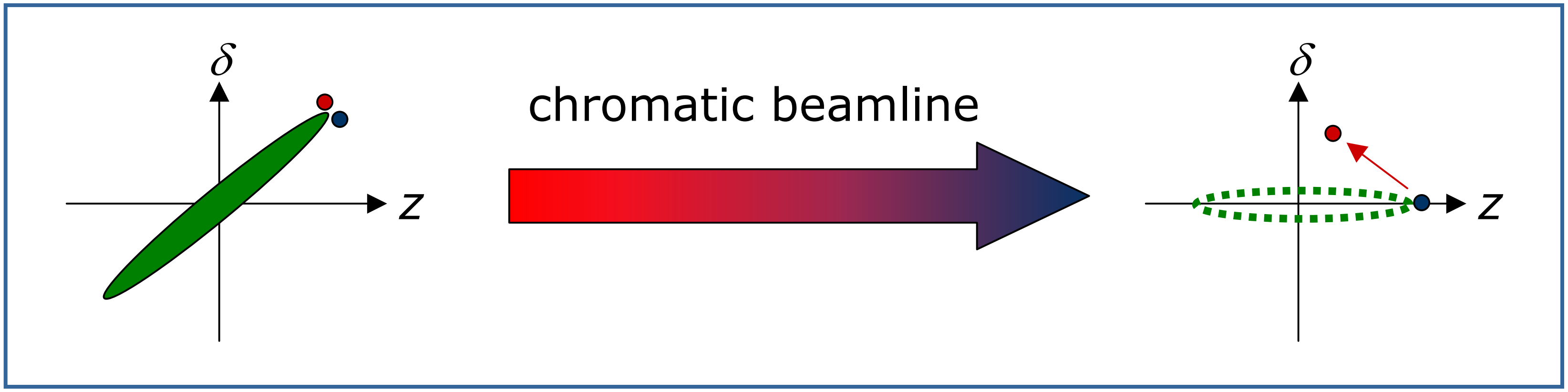
- The Hamiltonian for a linear, “smoothly focusing” beamline may be written:

$$H = \frac{\mu}{L} J + 2\pi \frac{\xi}{L} \delta J$$

phase advance (per unit length)

chromaticity (per unit length)

- This gives us $\Delta z = 2\pi\xi J$
- Two RF cavities may be used at either end of the beamline to convert Δz to $\Delta\delta$ as follows:

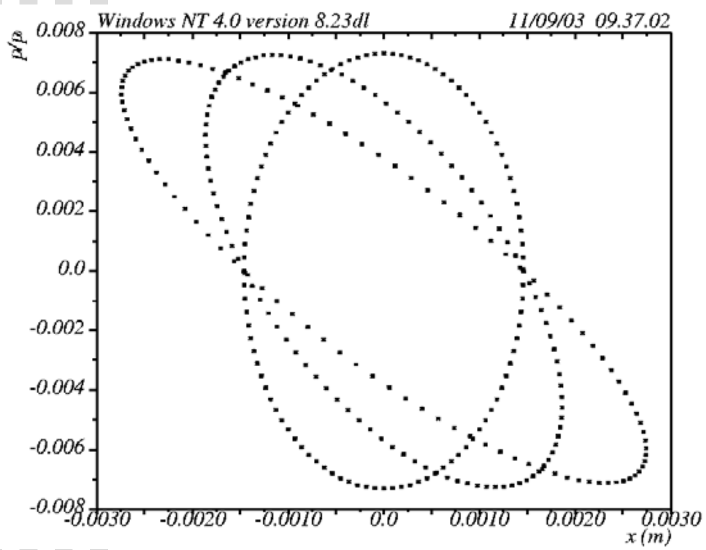


- *Note that the bunch length is no longer preserved!*

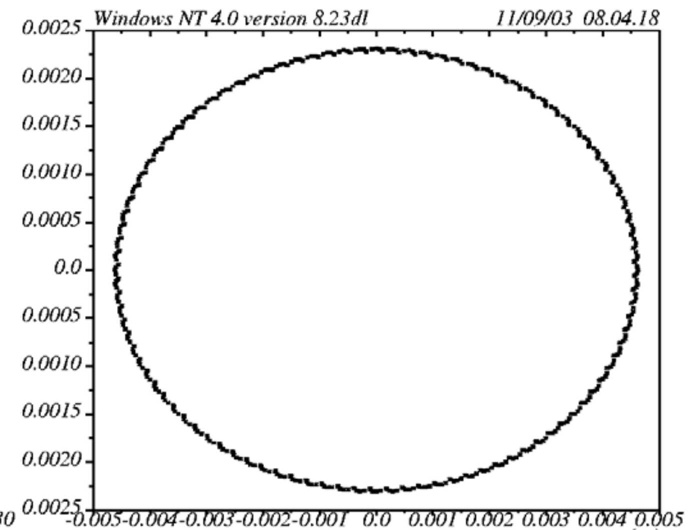
The beta function can change with energy

$$2J = \gamma x^2 + 2\alpha x p_x + \beta p_x^2$$

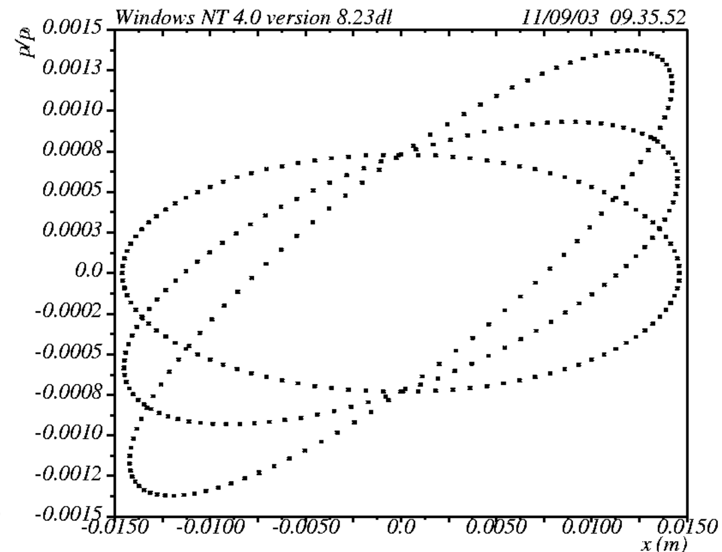
- If β varies with energy, then chirping the bunch introduces a phase space mismatch along the bunch.
- The action J of each slice of the bunch is preserved, but…
- …the effective emittance of the whole bunch is blown up.



β = 0.2 m



β = 2 m



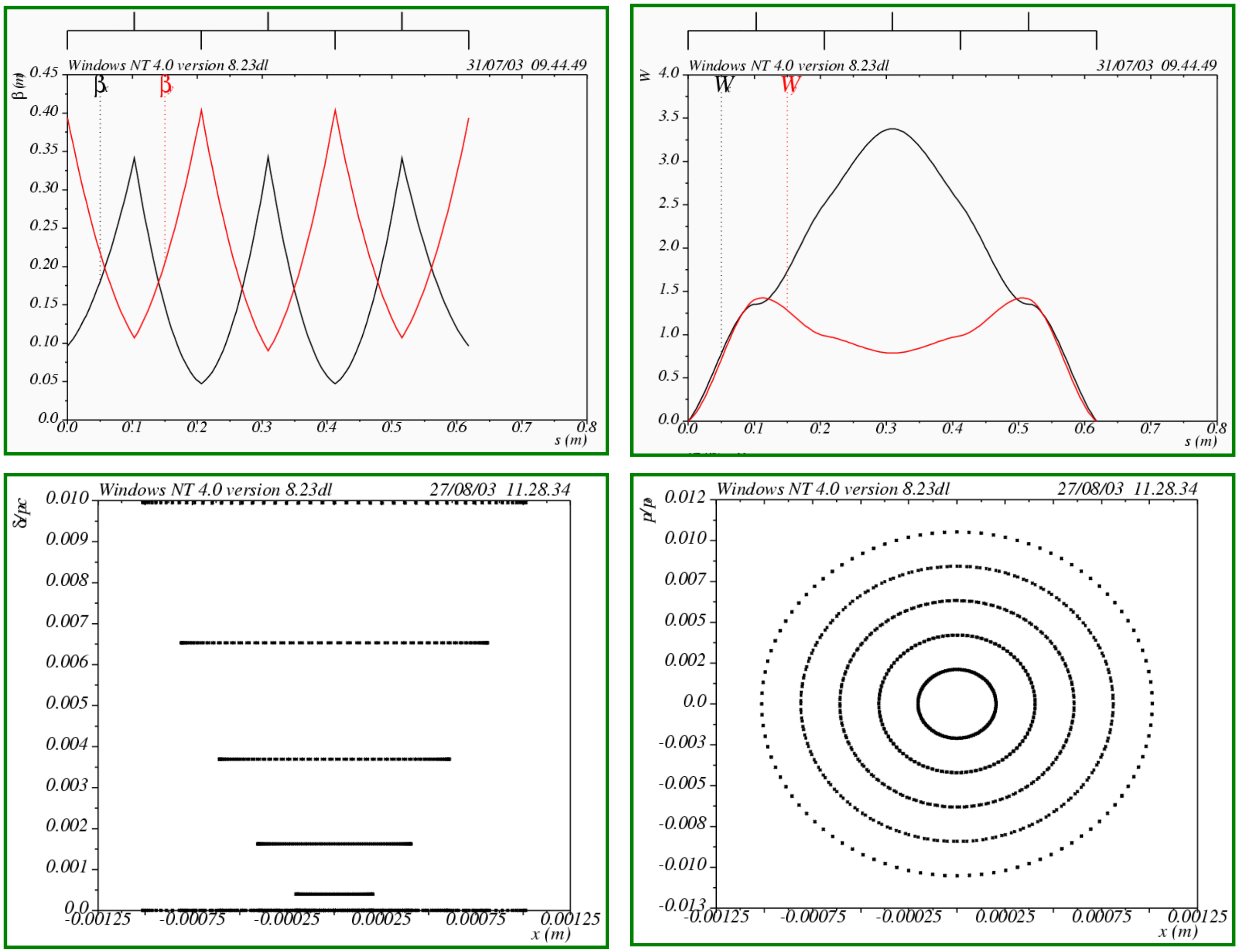
β = 20 m

Tracking through solenoid: k_s=1 m^{-1}; k_sL=2π; δ =0, +2.5%, +5.0%

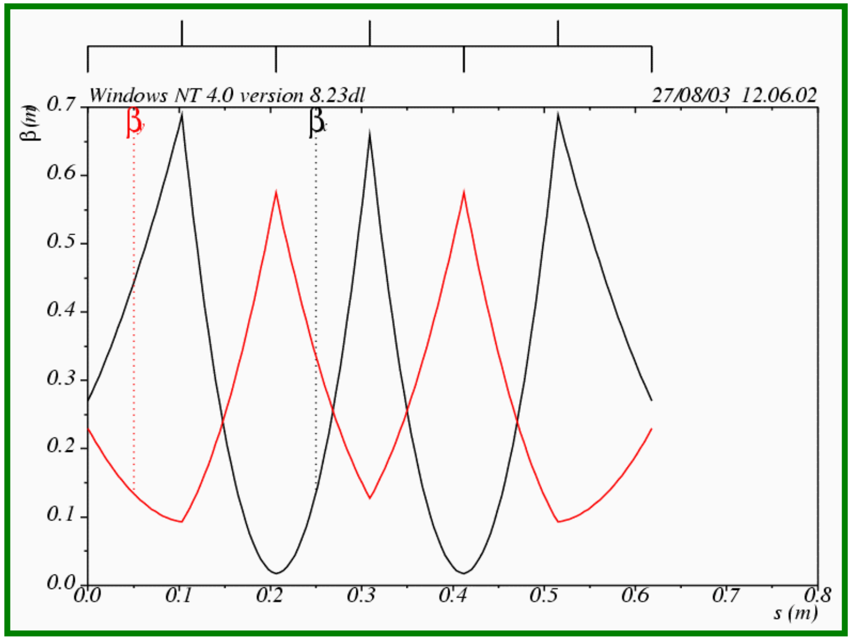
Thanks to Kwang-Je Kim!

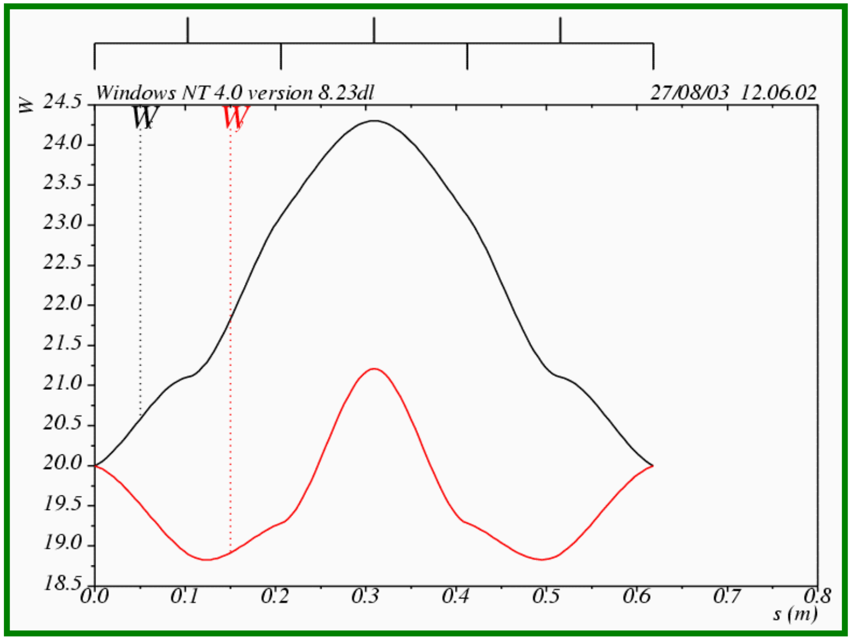
A FODO lattice can be tuned to achieve matching

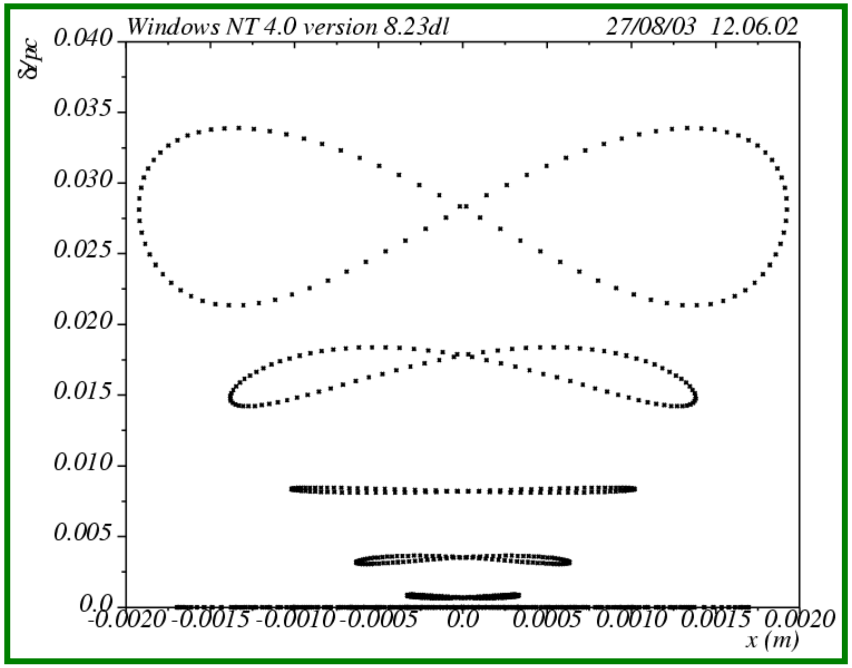
- 6 quadrupoles in 4 families, with RF cavities at either end.
- Track particles with different values of action up to 5 μm, and different *z* positions, from -2 mm to +2 mm.
- Initial energy deviation 0; final energy deviation proportional to action.

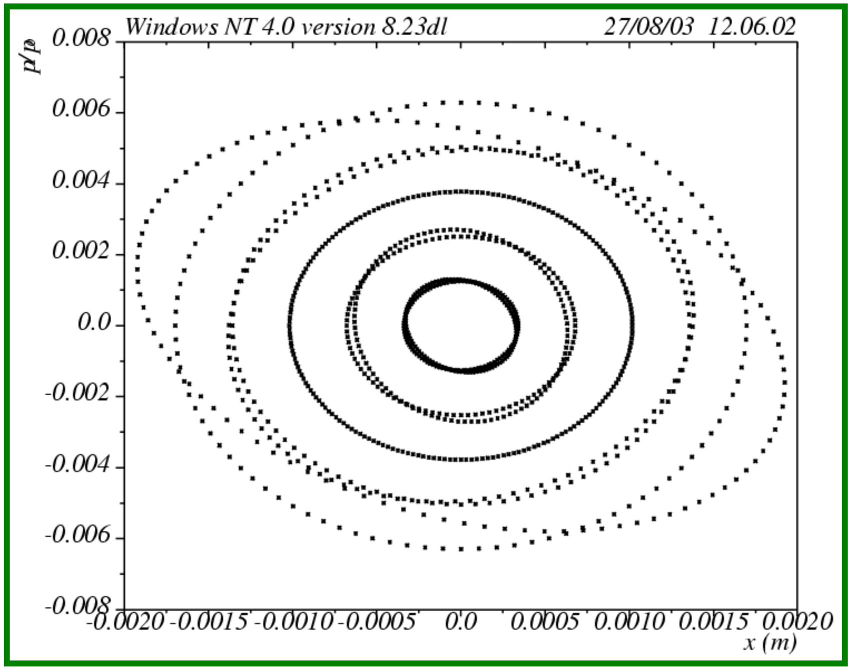


Detuning the lattice creates a mismatch









Conditioning can be provided in different ways

- Our beamline analysis shows us how (in principle) to avoid growth of the effective emittance while conditioning
- Different types of conditioner can be used in a properly "matched" beamline, to provide conditioning without growth of effective emittance
  - RF cavities + chromatic "FODO" beamline
  - RF cavities + solenoid
  - TM_{210} mode cavity
  - TM_{110} mode cavity + sextupoles
  - Laser or laser-plasma approaches
- We now consider the amount of conditioning that may be provided by the first four approaches
- A. Sessler will consider conditioning using lasers and plasmas

Simple schemes provide small amounts of conditioning

- For a chromatic conditioner:

$$\frac{\Delta\gamma}{\gamma J} = -2\pi\xi \frac{eV_{RF}}{E}\frac{\omega_{RF}}{c}$$

example

$$\xi = -1$$
$$eV_{RF}/E = 0.01$$
$$f_{RF} = 4.8\ \mathrm{GHz}$$
$$\frac{\Delta\gamma}{\gamma J} = 6\times 10^{-6}\ \mu\mathrm{m}^{-1}$$

- For a solenoid conditioner:

$$\frac{\Delta\gamma}{\gamma J} = \frac{BL}{(B\rho)}\frac{eV_{RF}}{E}\frac{\omega_{RF}}{c}$$

example

$$BL = 100\ \mathrm{Tm}$$
$$eV_{RF}/E = 0.01$$
$$f_{RF} = 4.8\ \mathrm{GHz}$$
$$\frac{\Delta\gamma}{\gamma J} = 30\times 10^{-6}\ \mu\mathrm{m}^{-1}$$

For LCLS, we need 5 μm^{-1}

Specialized cavities also provide "small" conditioning

- For example, TM_{210} mode cavity

  *A. Sessler, D. Whittum, L-H. Yu, PRL **68** 3, p.309 (1992)*

$$E_z = \frac{1}{4}\left(\frac{j_{21}}{R}\right)^2 E_0 \boxed{\left(x^2 - y^2\right)} \cos\left(\omega t + \delta\right)$$

$$P = \frac{m^2 c^5}{e^2} \frac{J_3\left(j_{21}\right)^2}{16Q} \left(\frac{eE_0}{mc^2}\right)^2 \frac{\omega L}{c} R^2$$

$$\frac{\Delta\gamma}{\gamma J} = \frac{1}{\gamma} \frac{eE_0}{mc^2} \frac{\omega}{c} \beta$$

$P = 1\,\mathrm{MW}$ $\quad eE_0/mc^2 = 11\,\mathrm{m}^{-1}$

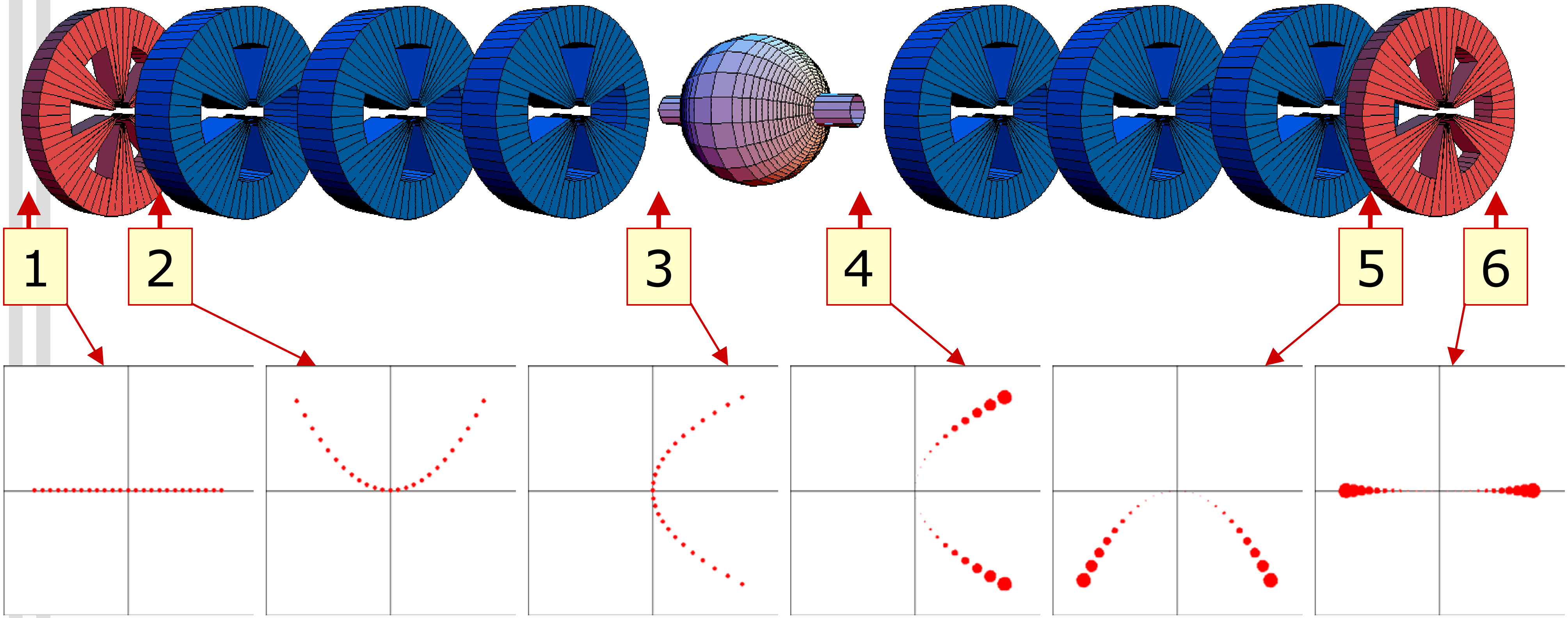
$\gamma = 4000$

$f_{RF} = 5\,\mathrm{GHz}$

$\beta = 20\,\mathrm{m}$

$$\frac{\Delta\gamma}{\gamma J} = 6 \times 10^{-6}\,\mu\mathrm{m}^{-1}$$

We can condition with sextupoles and a TM_{110} cavity



- A "matched" beam enters the conditioner.
- The first sextupole distorts the horizontal phase space.
- The phase space is rotated through $\pi/2$.
- The cavity gives a correlation between x and δ.
- The phase space is rotated through a further $\pi/2$.
- The final sextupole removes the phase space distortion.

The Sextupole/TM_{110} provides stronger conditioning

$$E_z = \frac{j_{11}}{R} B_0 x \sin(\omega t + \delta)$$

$$P = \frac{m^2 c^5}{e^2} \frac{J_2(j_{11})^2}{4Q} \left(\frac{eB_0}{mc^2}\right)^2 \frac{\omega L}{c} R^2$$

$$\frac{\Delta\gamma}{\gamma J} = \frac{1}{\gamma} \frac{eB_0}{mc^2} k_2 l \beta^2$$

We assume multiple passes through the conditioner, with a different betatron phase on each pass

$P = 1\,\mathrm{MW}$ $\quad eB_0/mc^2 = 12\,\mathrm{m}^{-1}$

$\gamma = 4000$

$f_{RF} = 5\,\mathrm{GHz}$

$\beta = 20\,\mathrm{m}$

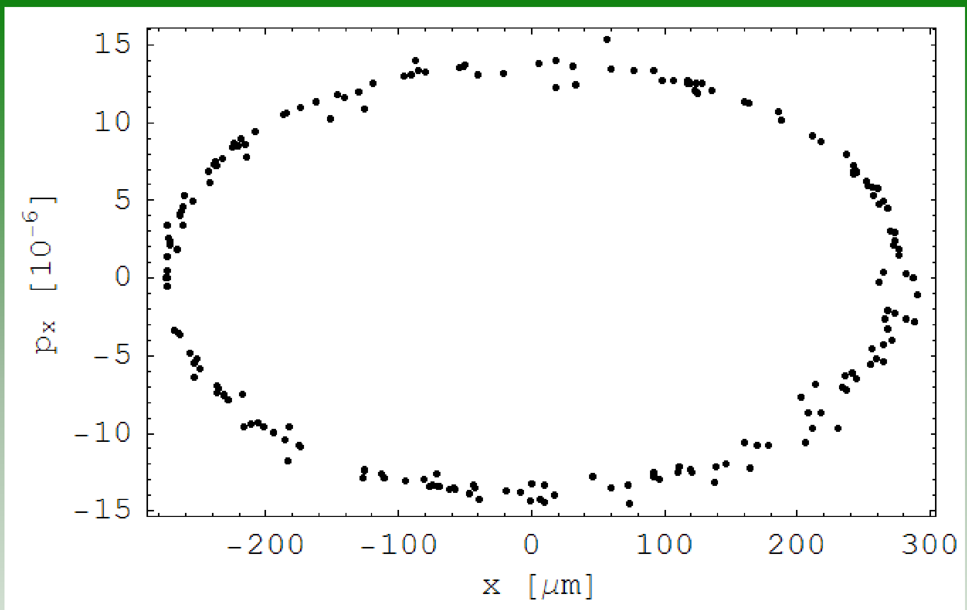
$k_2 l = 300\,\mathrm{m}^{-2}$

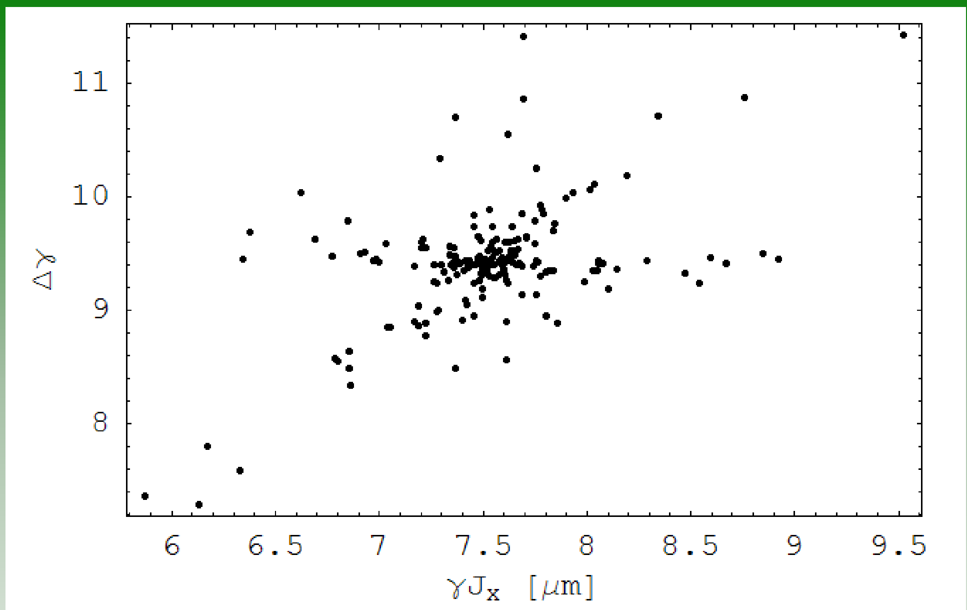
$$\frac{\Delta\gamma}{\gamma J} = 360 \times 10^{-6}\,\mu\mathrm{m}^{-1}$$

Average value per pass

There are chromatic and other effects to worry about

- Let us track 4100 times through the beamline, including:
  - variation in sextupole strength with energy
  - chromaticity in quadrupole sections
  - *z*-dependent transverse deflections (from *B* field) in cavity
  - rms bunch length 100 μm
  - betatron phase advance ~0.5×2π between passes
  - conditioner parameters as in the example on the previous slide

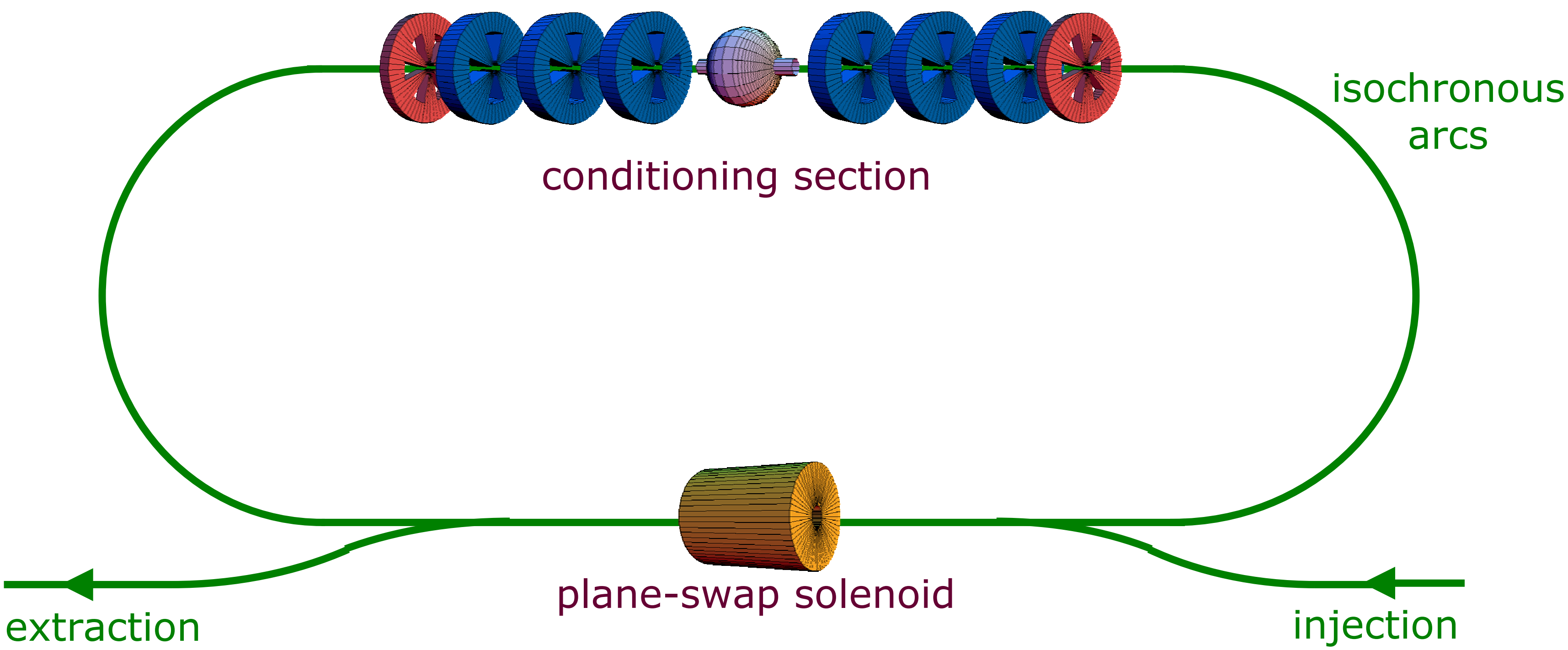




- Initial transverse action J = 7.5 μm
- Conditioning parameter $\kappa = \Delta\gamma/\gamma J$ = 1.25 μm^{-1}
  - *Value from single pass increased 4100 times*

Might this work for LCLS?

- 7.5 μm is five times the nominal emittance
- 1.25 μm^{-1} is a quarter of the required conditioning, but…
- …100 μm is four times the final bunch length
  - bunch compression done properly will amplify the conditioning by the compression factor



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