The Center for BRIGHTBEAMS
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Optical Stochastic Cooling in CESR with an Arc-bypass

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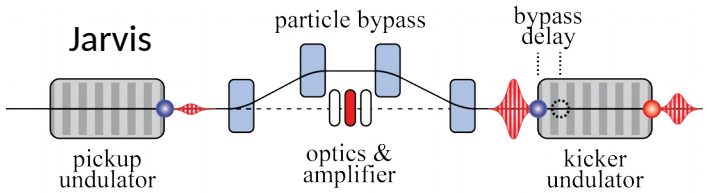
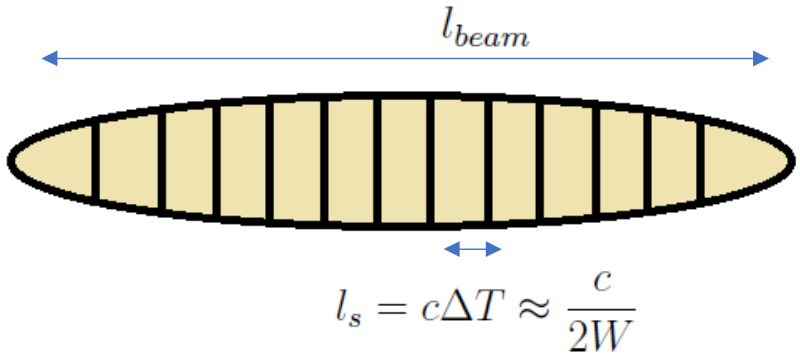
Basics of Optical Stochastic Cooling (OSC)

First proposed in mid 1990's as an improvement over well-known microwave based stochastic cooling[1,2].

Transition to optical frequencies brings an increase of system bandwidth, W of ≈10^4 which allows for a finer 'slicing' of the beam reducing the number of particles in a sample.





- A magnetic chicane creates a longitudinal displacement between each particle and its own wave-packet:
  $$\Delta s = M_{51}x + M_{52}x' + M_{56}\Delta P/P$$
- A resonant interaction between the particle and its wave-packet occurs in the kicker.
- **Results in a change in the particles energy:** $\delta u = \Delta\mathcal{E}\sin(k_l\Delta s)$

A.A.Mikhailichkenko, M.S. Zolotorev, Optical stochastic cooling Phys. Rev. Lett. 71, 4146 (1993).
M. S. Zolotorev, A. A. Zholents, Transit-time method of optical stochastic cooling, Phys. Rev. E 50, 3087 (1994)

Longitudinal Cooling with OSC for Small Amplitudes

Consider the equations of motion in the longitudinal plane (θ,u) for a particle with a small energy deviation

$$\dot{\theta} = h\omega_s \eta \frac{u}{U_s}$$

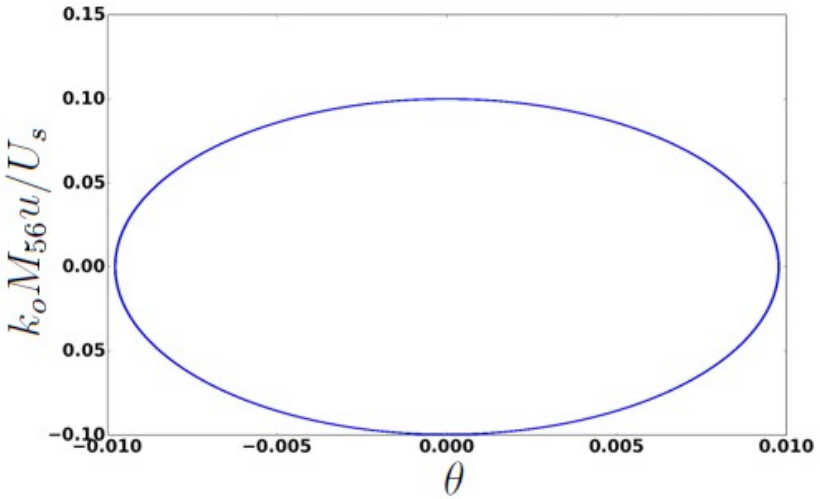
$$\dot{u} = \frac{qV\omega_s}{2\pi}\left(\sin(\phi) - \sin(\phi_s)\right) \approx -\frac{qV\omega_s}{2\pi}\cos(\phi_s)\theta$$

Where $\theta = \phi - \phi_s$ Relative RF phase

$u = U - U_s$ Relative energy

Combing the two above equations yields:

$$\ddot{u} + \Omega^2 u = 0 \qquad \Omega = \omega_s \sqrt{\frac{h\eta\cos(\phi_s)qV}{2\pi\gamma mc^2}}$$



And so the particle oscillates in the longitudinal phase space at the synchrotron frequency.

Longitudinal Cooling with OSC for Small Amplitudes

The kick for OSC is described using $\delta u = \Delta\mathcal{E}\sin(k_o s)$ where $s = M_{56}u/U_s$ $k_o \equiv \frac{2\pi}{\lambda_o}$

The Equations of motion become

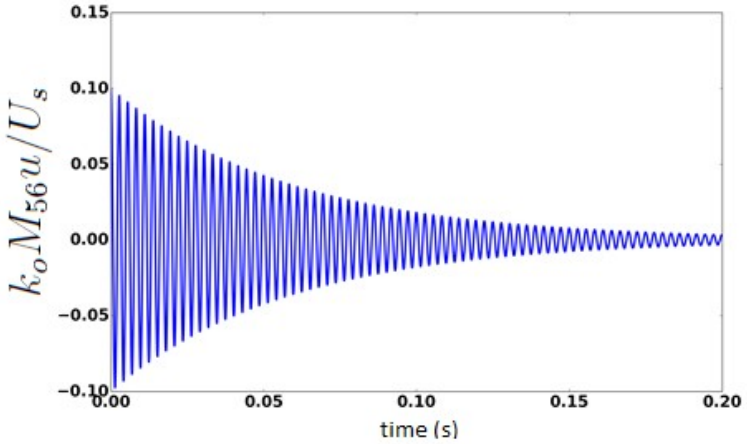
$$\dot{\theta} = h\omega_s\eta\frac{u}{U_s} \qquad \dot{u} = -\frac{\omega_s}{2\pi}qV\cos(\phi)\theta - \frac{\omega_s k_o M_{56}\Delta\mathcal{E}}{2\pi}\frac{u}{U_s}$$

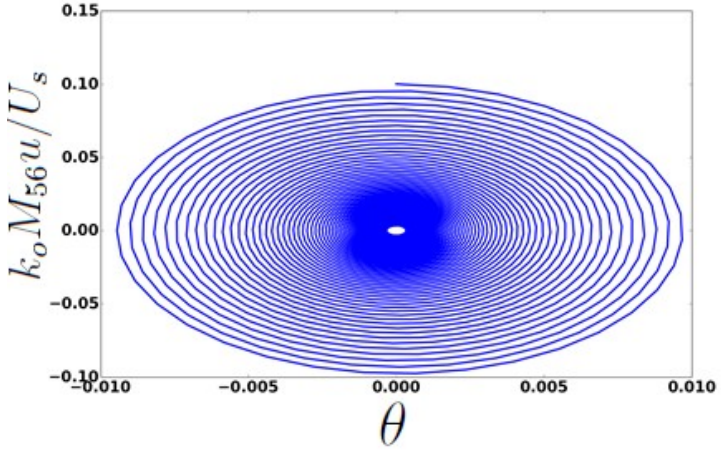
Which combines to give a DE equivalent to that of a damped-harmonic oscillator $\ddot{u} + 2\lambda_u\dot{u} + \omega_s u = 0$

Where $\boxed{\lambda_u = \frac{k_o M_{56}}{2\tau_s}\frac{\Delta\mathcal{E}}{U_s}}$ is the longitudinal damping rate in amplitude.

Compare this to the damping rate from SR $\lambda_{SR} \approx \frac{1}{2\tau_s}\frac{\Delta\mathcal{E}_{SR}}{U_s}$

- SR loss in the ring is much larger than the OSC kick amplitude.
- The OSC works by modulating the particles energy loss, w.r.t energy; not by significantly altering the total energy loss.
- Typically $k_o M_{56} \approx 10^4$ thus the OSC is still effective even though radiative losses from the undulators are small.





Cooling along two degrees of freedom, small amplitude

Longitudinal displacement now given by

$$s = M_{51}x_\beta + M_{52}x'_\beta + M_{56}\frac{u}{U_s}$$

Which leads to damping rates given as:

$$\lambda_u = k_o\frac{M_{51}D + M_{52}D' + M_{56}}{2\tau_s}\frac{\Delta\mathcal{E}}{U_s}$$

$$\lambda_x = -k_o\frac{M_{51}D + M_{52}D'}{2\tau_s}\frac{\Delta\mathcal{E}}{U_s}$$

Summing the damping rates returns (on the RHS) the expression obtained when damping is only done in the longitudinal plane

$$\lambda_u + \lambda_x = \frac{k_o M_{56}}{2\tau_s}\frac{\Delta\mathcal{E}}{U_s}$$

We therefore see horizontal damping is done by redistributing the total damping rate into the horizontal plane via the presence of dispersion in the pickups and kicker

$$\frac{\lambda_x}{\lambda_u} = \frac{M_{56}}{M_{56} + DM_{51} + D'M_{52}} - 1$$

V. Lebedev, “OPTICAL STOCHASTIC COOLING” in Beam Dynamics Newsletter, No. 65, Issue Editor: Y. Zhang, Editor in Chief: W. Chou, pp. 97-112, (2014); http://icfa-usa.jlab.org/archive/newsletter.shtml

Large amplitude particles and the cooling range

- Large amplitude particles can be longitudinally displaced by more than $\lambda_l/2$ and therefore the OSC kick switches signs
- Averaging over betatron/synchrotron oscillations yields the amplitude dependent damping rates[1]:

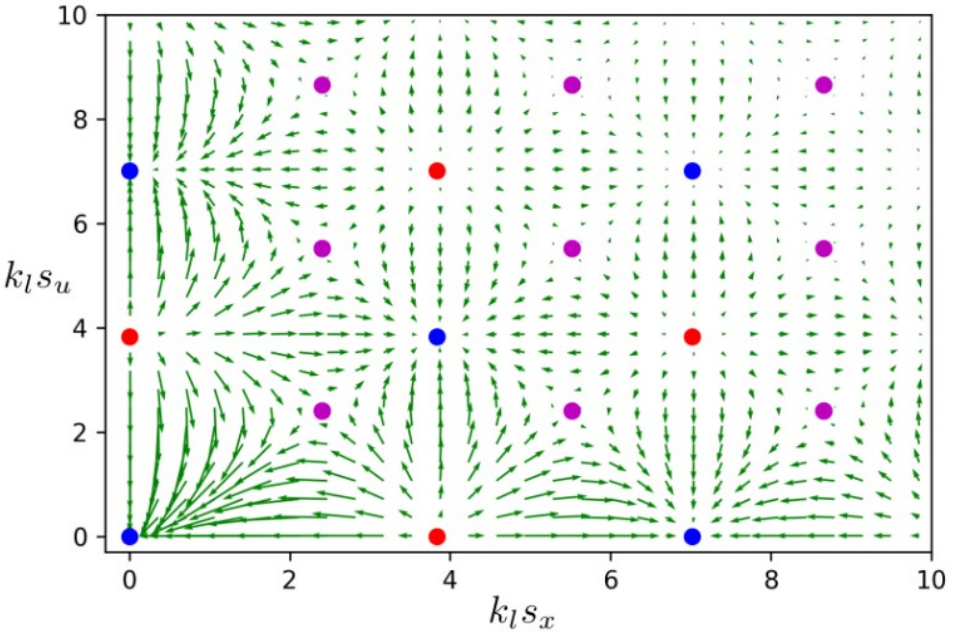
$$\lambda_x = 2\lambda_{xo}\frac{J_0(k_l s_u)J_1(k_l s_x)}{k_l s_x} \qquad \lambda_u = 2\lambda_{uo}\frac{J_0(k_l s_x)J_1(k_l s_u)}{k_l s_u}$$

(s_x,s_u are the amplitudes of a particle's longitudinal displacement)

- For 1-D cooling $k_l s_x$ **or** $k_l s_u < \mu_{1,1}$=3 .83 and for 2-D cooling $k_l s_x$ **and** $k_l s_u < \mu_{1,0}$=2.41.
- The cooling acceptances are:

$$\epsilon_{max} = \frac{\mu_{0,1}^2}{k_l^2(\beta M_{51}^2 - 2\alpha M_{51}M_{52} + \gamma M_{52}^2)}$$

$$\left(\frac{\Delta P}{P}\right)_{max} = \frac{\mu_{0,1}}{k(M_{51}D + M_{52}D' + M_{56})}$$



[1]V.A. Lebdev "Optical Stochastic Cooling" ICFA Beam Dyn. Newsletter **65** (2014)

Cooling ranges for the dog-leg chicane

Define the cooling ranges as:

$$\eta_x = \sqrt{\frac{\epsilon_{max}}{\epsilon_o}} \qquad \eta_p = \frac{1}{\sigma_p}\left(\frac{\Delta P}{P}\right)_{max}$$

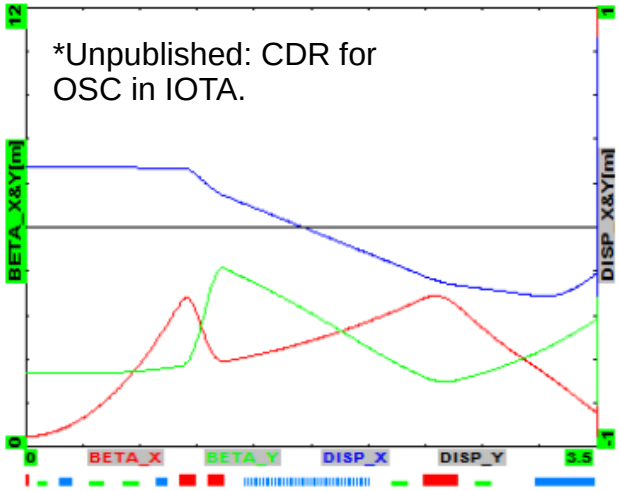
- The linear optics dog-leg chicane (planned for IOTA) consist of 4 dipoles and a single center quad needed for horizontal cooling.

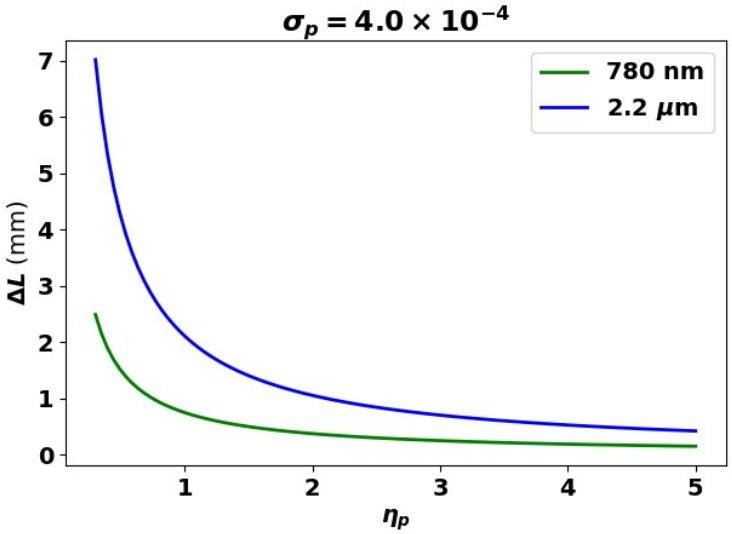
- In the case of equal horizontal and longitudinal damping the cooling ranges can be written as:

$$\eta_x = \frac{\mu_{0,1}}{2k_l\Delta L}\sqrt{\frac{D^{2*}}{\epsilon_o\beta^*}} \qquad \eta_p = \frac{1}{\sigma_p}\frac{\mu_{0,1}}{k_l\Delta L}$$

- Typically results in ΔL of a few mm

- **This short delay seriously constrains the design of the OA resulting in limited gain**





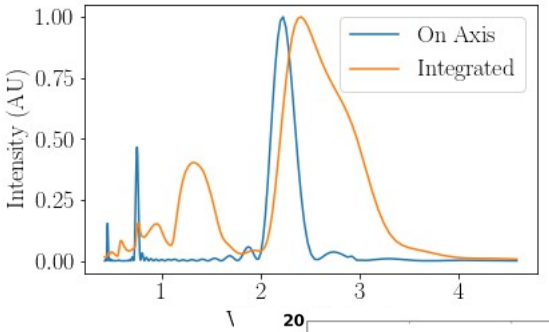
Cr:ZnSe for active OSC in IOTA

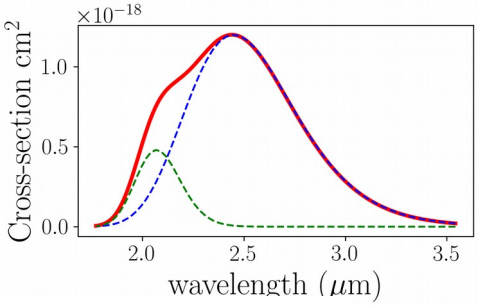
Looked for mid-IR amplifiers after original 800 nm (Ti:Sapph) plan abandoned. Settled on Cr:ZnSe due to:

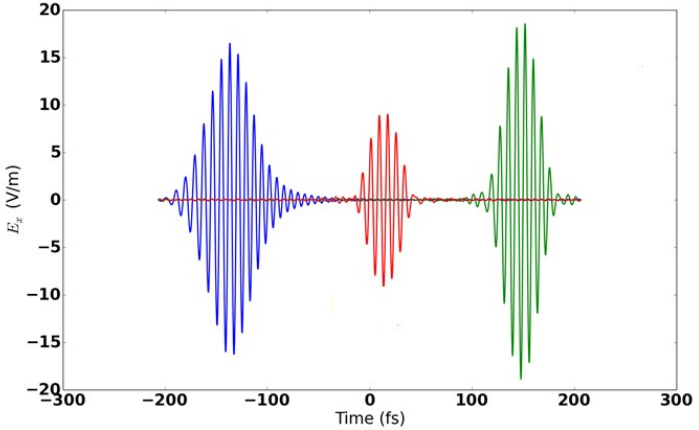
- 2.2 μm wavelength for increased optical delay
- Large amplification BW comparable to Ti:Sapph.
- Results in very little pulse distortion during amplification and host dispersion.

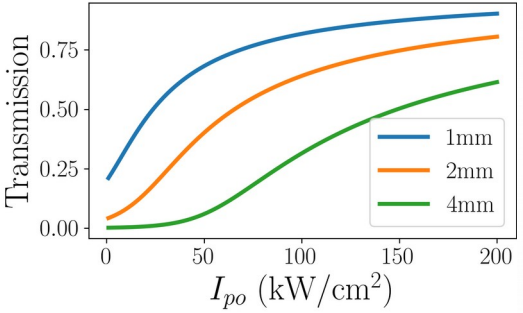
Even with transition to mid-IR, can still only budget 1-mm thick crystal

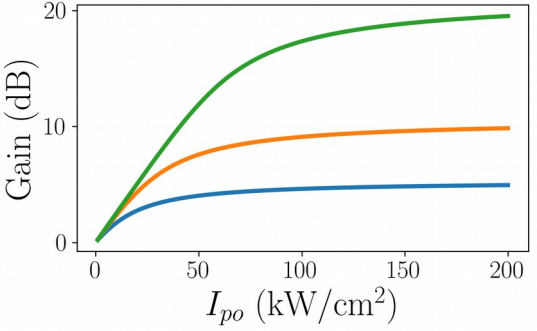
- Amplifier gain is set by absorption of pump laser (thulium) intensity.
- Intensity absorption saturates and crystal becomes transparent.
- **Expect 7 dB of gain emission peak (2.45) results in a factor of 1.7 increase in damping rates.**



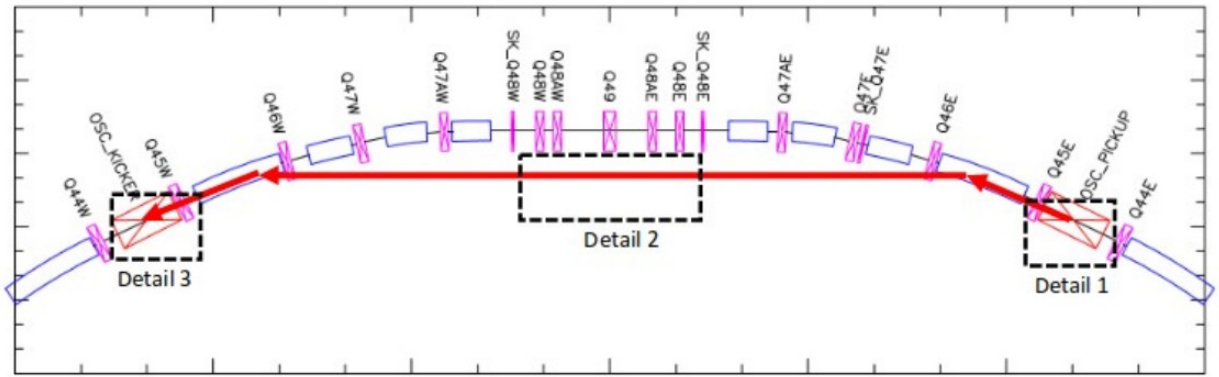








Arc-bypass in CESR



- Gives a significant increase in the optical delay, **ΔL=63.3 cm**, while still preserving cooling ranges.
- Allows for obtaining a high-gain amplifier either from
  (i) staging
  (ii) multi-pass schemes

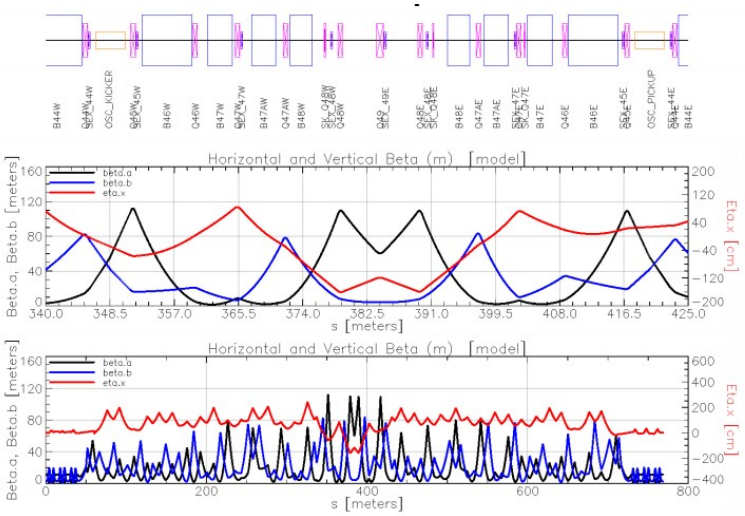
initial demonstrations will concentrate damping power into horizontal plane, however simultaneous cooling is possible with this layout.

Parameter	Value
Beam Energy (GeV)	1.0
λ_l, (nm)	780
Undulator Parameter, K	4.5
Period (cm)	28
$\Delta\mathcal{E}$ (meV)	420*
$\gamma\theta_m$	3.5
Geometry	Helical

Parameter	Horizontal Cooling	Mixed Cooling
$\epsilon(nm)$	1.41	1.41
σ_u	3.7×10^{-4}	3.7×10^{-4}
η_x	1.73	2.66
η_p	11.8	2.1
λ_{xo} (s^{-1})	0.82	0.5
$\lambda_{x,SR}$,(s^{-1})	0.79	0.73
λ_{po} (s^{-1})	0.05	0.25
$\lambda_{p,SR}$ (s^{-1})	1.38	1.38

*passive w/ ideal imaging

Arc-bypass optimizations



Optimization routines in TAO were used to set the linear/nonlinear optics.

To get an initial starting place a phase advance of 3π is assumed to simplify formulas for the acceptances and cooling rates:

An optimization was run with the objectives of :

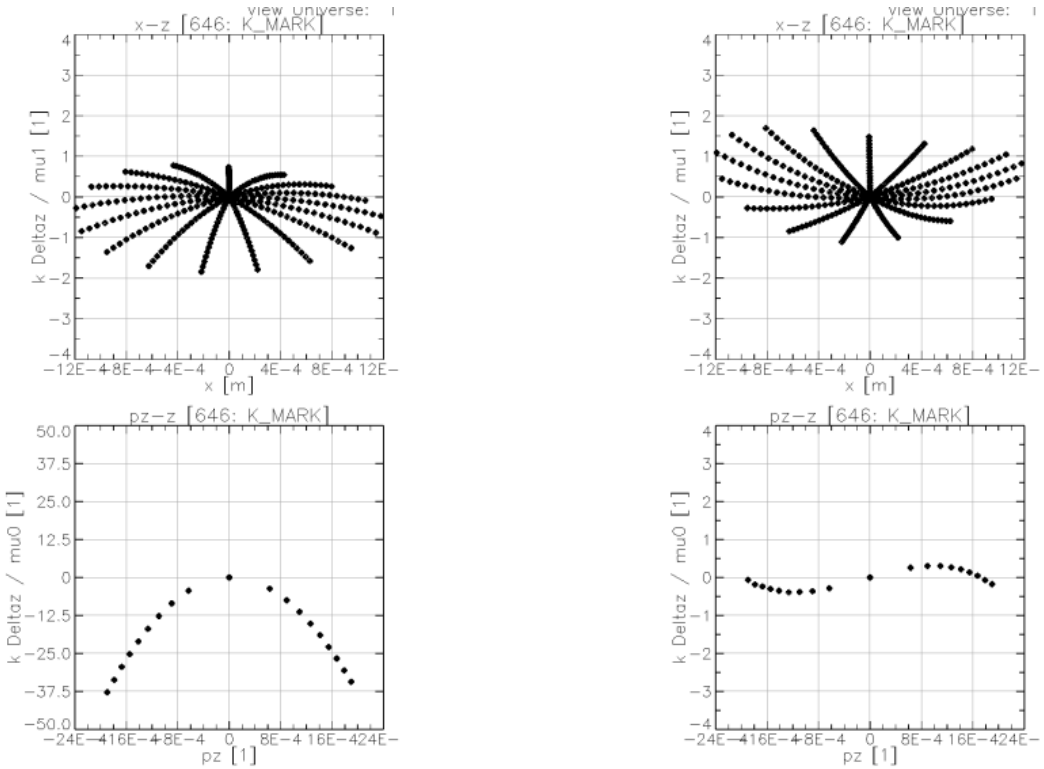
1) Minimizing dispersion in the undulators → $\epsilon_{max} = \frac{\mu_{0,1}^2 \beta}{k_l^2 4D^2}$
2) Maximizing dispersion derivatives → $\lambda_x = \frac{\Delta E}{2\tau_s U_s}(-2\alpha D^2/\beta - 2DD')$
3) Setting $M_{56} \approx 2DD'$ → $(\frac{\Delta P}{P})_{max} = \frac{\mu_{0,1}}{k_l(M_{56} - 2\alpha D^2/\beta - 2DD')}$

After this we found we could directly optimize the cooling rates/acceptances using standard OSC formulas

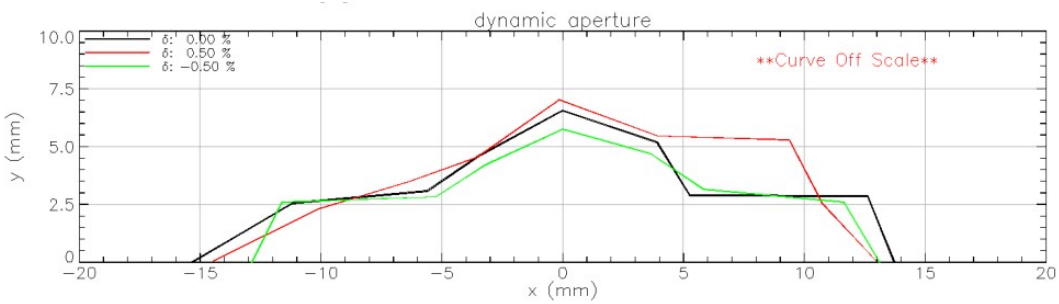
This technique was originally done to get purely horizontal cooling, however we were also able to obtain a bypass with equal longitudinal and horizontal cooling rates.

Arc-bypass non-linearity

- Sextupoles are used to correct nonlinear path lengthening through the chicane.
- Requires strength an order of magnitude larger than existing sextupoles used for chromaticity corrections in CESR
- Required re-optimization to get an acceptable DA



Note change in scale for momentum acceptance!



Dipole stability and path length change

A single-dipole change, anywhere in the ring, results in a displacement of the reference orbit at the PU and consequently introduces an orbit error: $\Delta s = -M_{51}x_{err} - M_{52}x'_{err}$

Additionally if the dipole is in the chicane there are two additional (**and dominant!**) contributions to the path length change

1) A change in the horizontal orbit through the dipole:

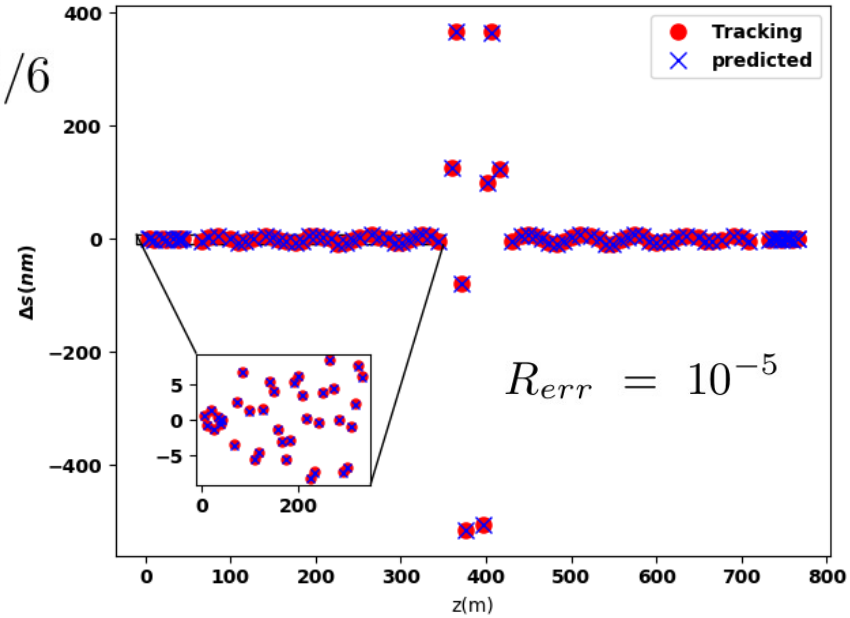
$$\Delta x = R_{err}\theta z_{dip}/2 \longrightarrow \Delta s = \int \Delta x/\rho dz = R_{err}L\theta^2/6$$

2) At the exit of the dipole the particle has been displaced in the horizontal phase-space as:

$$(\Delta x, \Delta x') = R_{err}(\theta L/2, \theta)$$

Resulting in a displacement

$$\Delta s = R_{err}(M_{51,dip}\theta L/2 + M_{52,dip}\theta)$$



Path-length stability requirements

- A constant path-length error between the reference particle and its PU-wavepacket results in a reduction of the damping rate as: $\lambda_x = cos(k_l s_{err})\lambda_{xo}$

- If there is a random jitter in the path-length much faster than the damping time, the error must be averaged over:

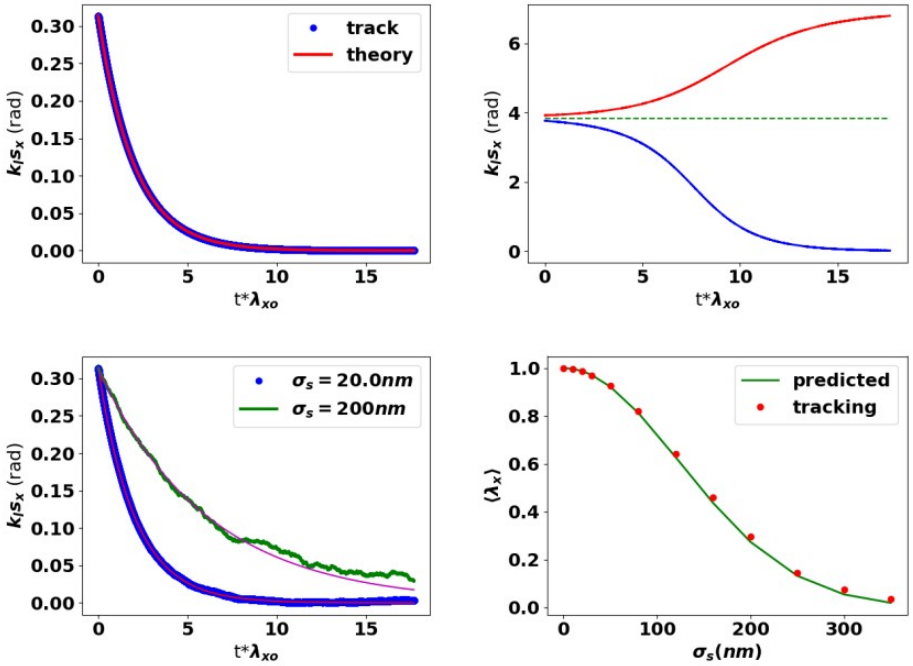
$$\langle \lambda_{x,u} \rangle = \lambda_{x,u} \int_{-\infty}^{\infty} \cos(k_l \Delta s_{err}) \frac{\exp(-\Delta s_{err}^2/2\sigma_s^2)}{\sigma_s\sqrt{2\pi}} d\Delta s_{err}$$
$$= \lambda_{x,u} \exp(-k_l^2 \sigma_s^2/2)$$

To verify a fast-tracking routine based on transfer matrices was used to see horizontal dynamics. Particle is initiated in PU, propagated and kicked in the KU:

$$\Delta x_\beta = -\frac{\Delta\mathcal{E}}{U_s} D \sin(k_l(M_{51}x_{\beta,PU} + M_{52}x'_{\beta,PU}))$$

$$\Delta x'_\beta = -\frac{\Delta\mathcal{E}}{U_s} D' \sin(k_l(M_{51}x_{\beta,PU} + M_{52}x'_{\beta,PU}))$$

and then propagated back to PU.



First damping rates/bifurcations from OSC theory were confirmed. Then gaussian jitter is applied to path length and a best fit is performed to get the damping rate.

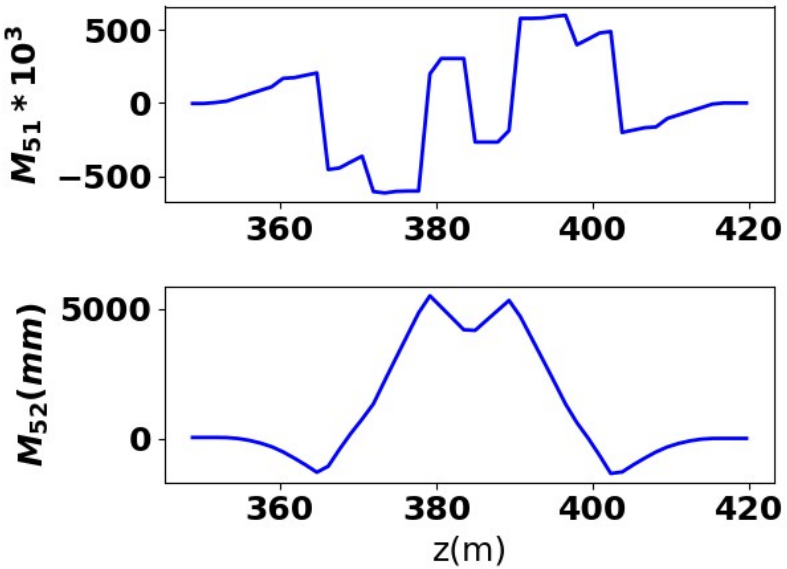
Dipole stability requirements

- For dipoles outside the bypass a relative error of $R_{err}=1x10^{-5}$ results in an RMS-path jitter of 40 nm and reduces the damping rate by 5%

- For dipoles inside the chicane this same relative error results in an RMS-path jitter of 910 nm and consequently there is no cooling.

- **For bypass dipoles, $R_{err}=5x10^{-7}$ is required for the damping rate to be reduced by no more than 5%**

- Machine studies in CESR will be done this fall to quantify orbit stability.



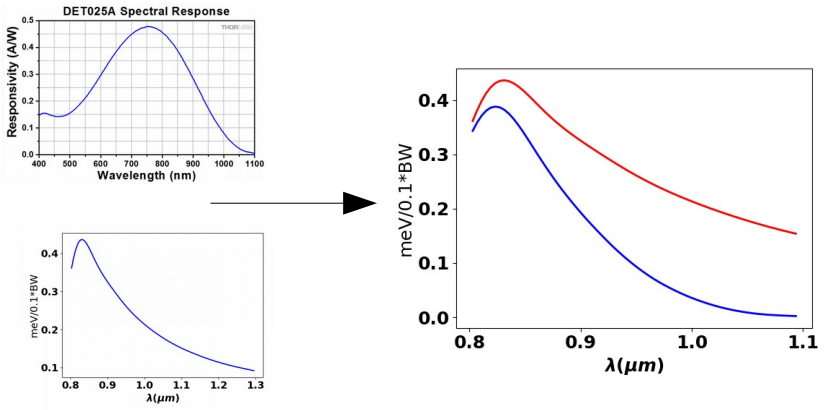
Sensitivity is the result of

1) The arc bypass consist of dipoles with fairly large bend angles (in comparison to a chicane-style bypass)
2) Large M_{51} and M_{52} in the bypass. Difficult to constrain while maintaining acceptable OSC parameters. On going work.

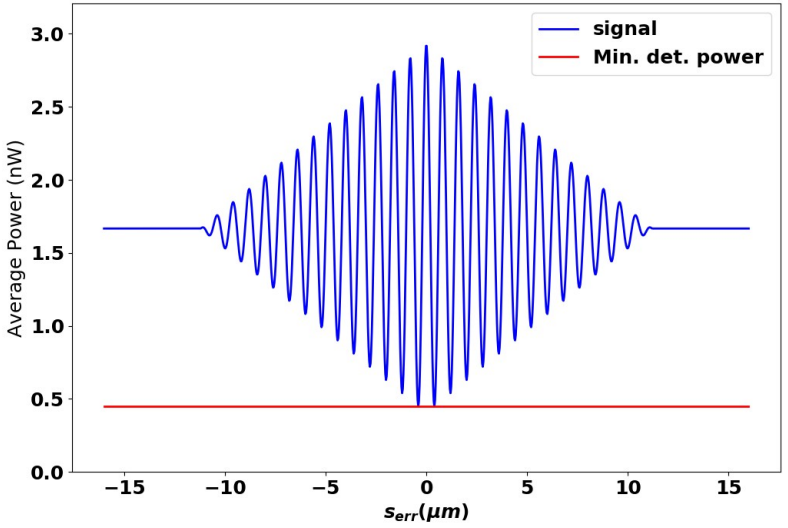
Feedback for path length stabilization

Total radiation coming from the PU and KU modulates with the path-length error as:

$$\Delta E_{beam} = -N\Delta\mathcal{E}\left[1 + \frac{s_{pulse-|s_{err}|}}{s_{pulse}}\sin(k_l s_{err}) \times \exp\left(-\frac{\mu_{0,1}^2}{2}\left(\frac{1}{\eta_x^2} + \frac{1}{\eta_u^2}\right)\right)\right]$$



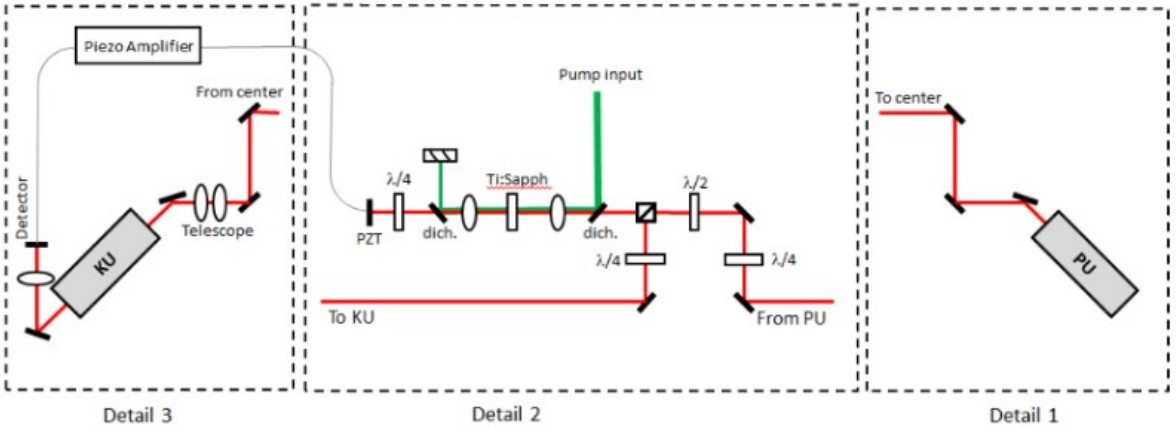
Accounting photo-diode spectral bandwidth, NEP, response time and including noise gating yields for a S/N ratio of 10 at maximum interference we require 3×10^6 particles (will do OSC with closer to 10^7 particles)



Energy modulation can be used for feedback provided noise levels do not result in path jitter greater than λ/2 within the response time of the feedback system

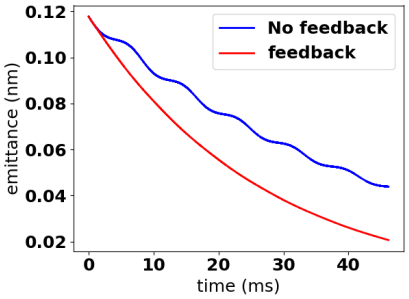
Feedback for path length stabilization

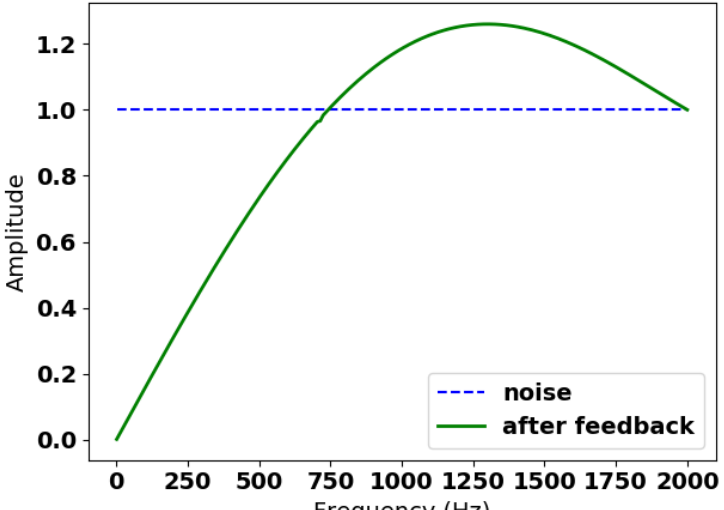
- Piezoelectric actuator moves a mirror to adjust the path length
- Photo-diode registers turn-by-turn intensity measurement (~390 kHz) but is averaged over response time of the actuator (~500 μs)
- Response time of actuator limits cancellation to noise with frequencies of a few hundred Hz



$$F(t) = \frac{1}{t_{int}} \int_{t-t_{int}}^{t_{int}} \sin(\omega t')dt' = 2\frac{\sin\phi/2}{\phi}\sin(\omega t - \phi/2) \qquad \phi = \omega t_{int}$$

- Preliminary machine studies shows noise around 3rd harmonic of 60 Hz
- Broadband EOM can replace actuator if high frequency noise cancellation is required
- Laser test of feedback system is planned

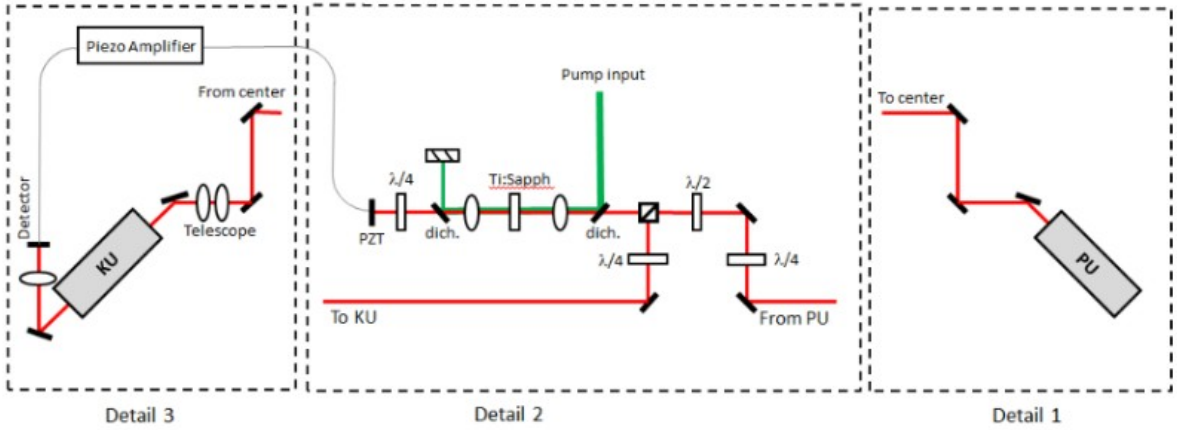




Double-pass amplification scheme

Super-Achromatic wave-plates cover the bandwidth of PU radiation. Waveplates are required to:

- Circular to linear polarization conversion for insertion into amplifier arm
- 90 degree linear rotation to extract from amplifier arm



3-mm thick Ti:Sapph crystal

CW pumping at 532 nm, 95% of pump energy is absorbed. 1 MW/cm^2 intensity yields:

- **P-Polarization 12 dB**
- **S-Polarization 5 dB**

30 µm spot-size results in 30 W for pump laser. Rayleigh range 3.5 mm exceeds crystal length. Chirped mirrors compensate dispersion from lenses/crystal.

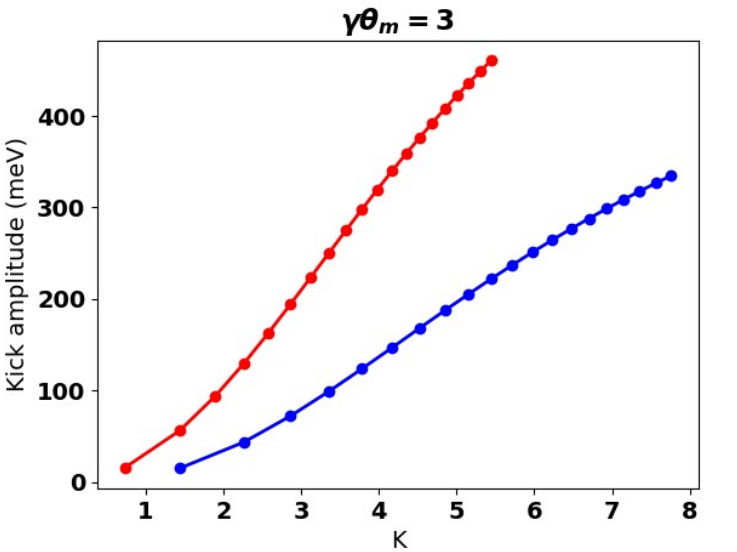
Staging yields higher gains but requires multiple-pump lasers

Why Helical Undulators?

$$\Delta\mathcal{E} = \frac{2\pi}{3} e^2 k_o N_u F_T(K, \gamma\theta_m)$$

Semi-analytic formulas[1] used to compute the on-axis electric field in PU assuming perfect imaging:

- K is varied while keeping undulator length and wavelength fixed.
- **Helical undulator results in a higher kick for a smaller K**



Dispersion in the PU and KU is needed for horizontal cooling:

- Eq. emittance (prior to cooling) is dominated by contributions coming from the PU and KU
- Small emittance is desired for cooling range considerations. **This ruled out planar undulators.**

What is a reasonable minimum value of the kick amplitude? Consider the ratios of OSC and SR damping:

$$\lambda_x + \lambda_u \approx \lambda_x = \frac{k_l M_{56}}{2\tau_s}\frac{\Delta\mathcal{E}}{U_s}$$

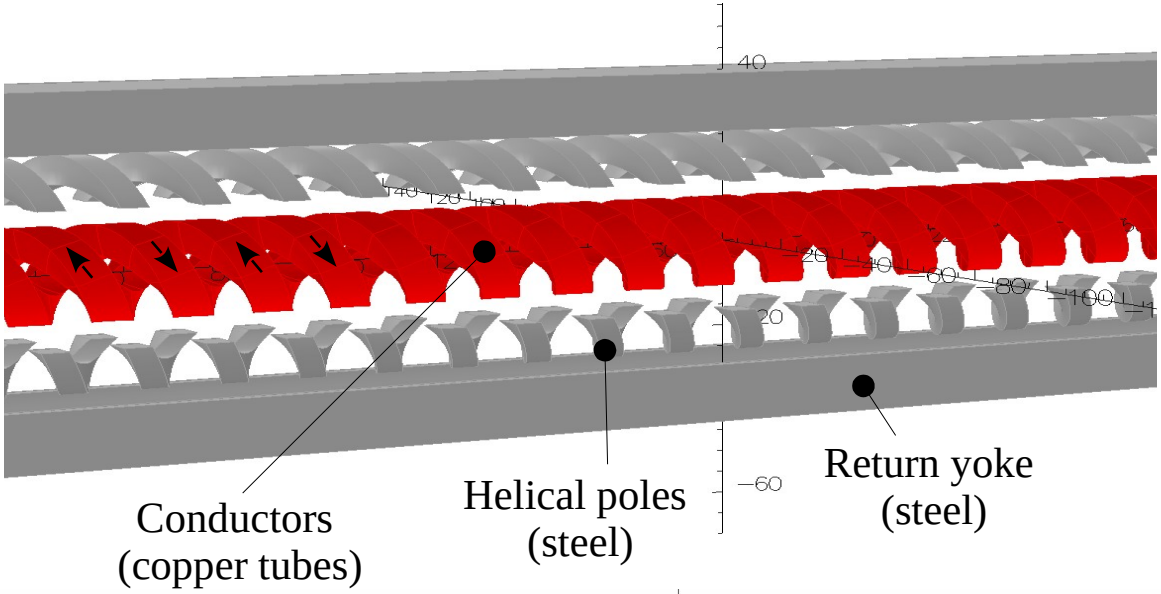
$$\lambda_{x,SR} \approx \frac{1}{2\tau_s}\frac{U_\gamma}{U_s}$$

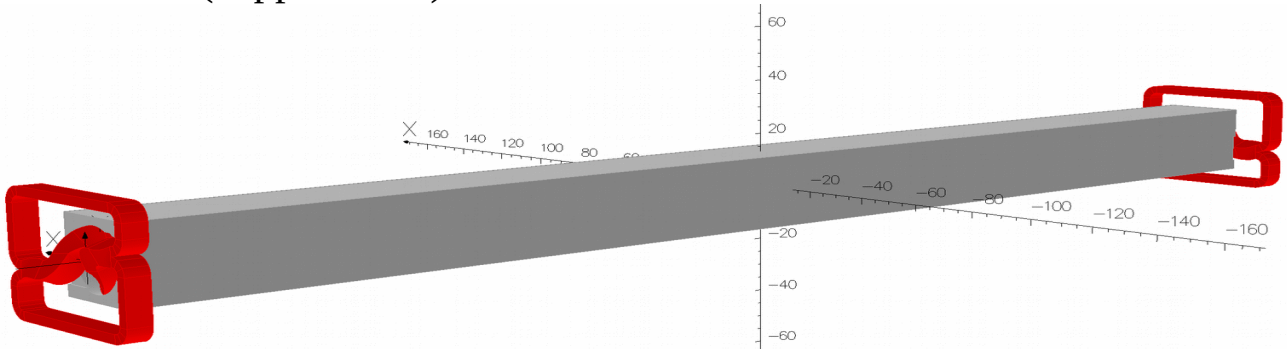
$$\longrightarrow \quad \frac{\lambda_x}{\lambda_{x,SR}} \approx k_l M_{56}\frac{\Delta\mathcal{E}}{U_\gamma}$$

$K_l M_{56}$ is constrained by the cooling range, U_γ set by beam energy. Determines Kick amplitude> 300 meV to exceed SR damping

[1]M. B. Andorf, V. A. Lebedev, J. Jarvis, and P. Piot Phys. Rev. Accel. Beams 21, 100702

Helical undulator design, geometry, parameters





- Total length: 4.2 m
- Period length: 28 cm
- Number of periods: 15
- Inner diameter: 89 mm
- On-axis field amplitude: 1.73 kGs

- Conductor: each helix is 8 columns × 7 rows of round copper tubes with 5/16" OD and 0.065" wall thickness

- Current per wire: 220A
- Total current per helix: 12.3 kA
- Total Voltage: 125 Volts
- Total power: 27.5 kW
- Cooling water pressure drop: 4.7 Bars
- Temperature ΔT: 25^0C
- Number of cooling channels: 14
- Water flow: 4.2 gallons per minute

Each turn is a separate copper tube. Connections are organized at each end.

Magnetic field corrections at ends is controlled by modifying the length of helical poles and return yoke.

Field calculations are performed with Opera3D

Undulator magnetic field

- Undulator model central field is in good (<1Gs) agreement with ideal field profile
- The length for which the model field agrees with the ideal profile within 1% is 385.6 or 13.8 period.
- Possible geometrical errors, construction misalignment effects were studied and determined negligible for the OSC.

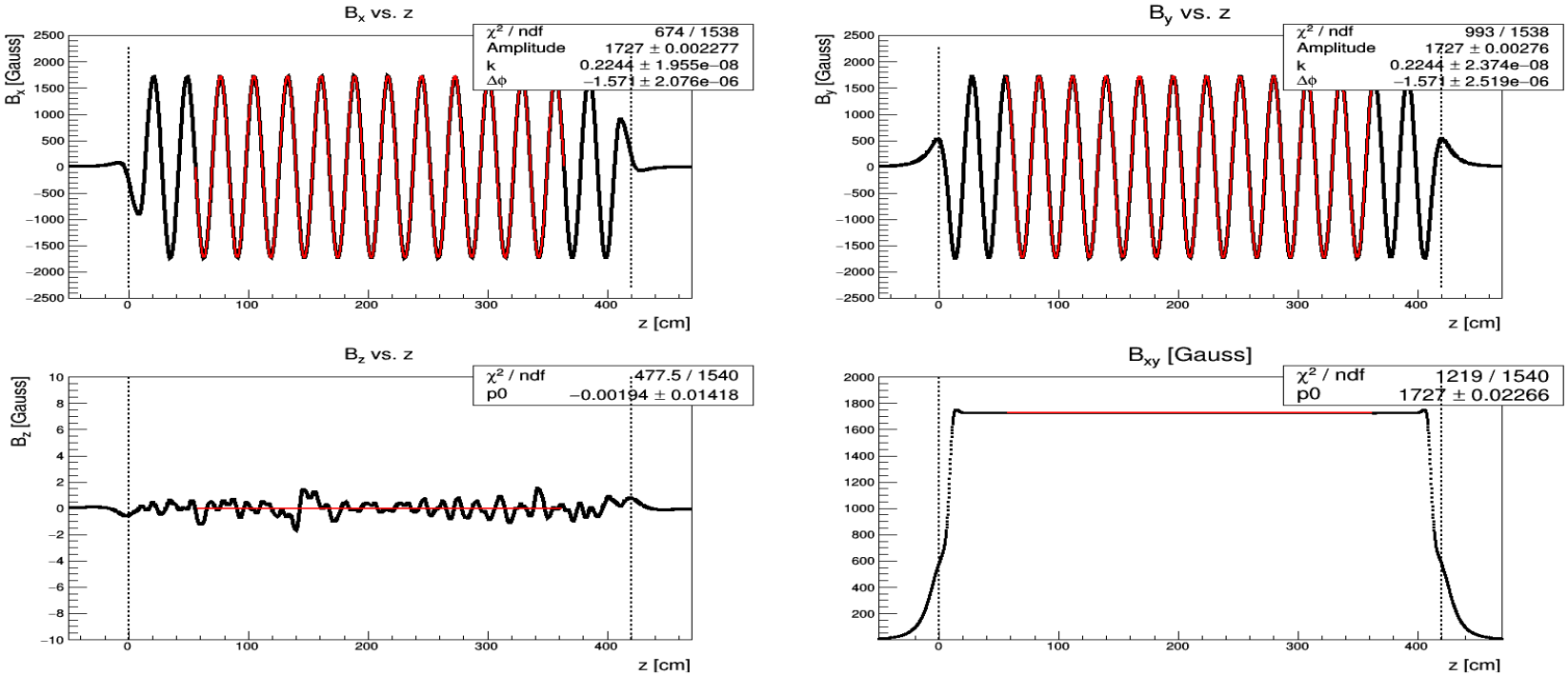
Fit functions are:

B_x fit function is: $Amp \cdot \cos(kz+\Delta\phi)$

B_y fit function is: $Amp \cdot \sin(kz+\Delta\phi)$

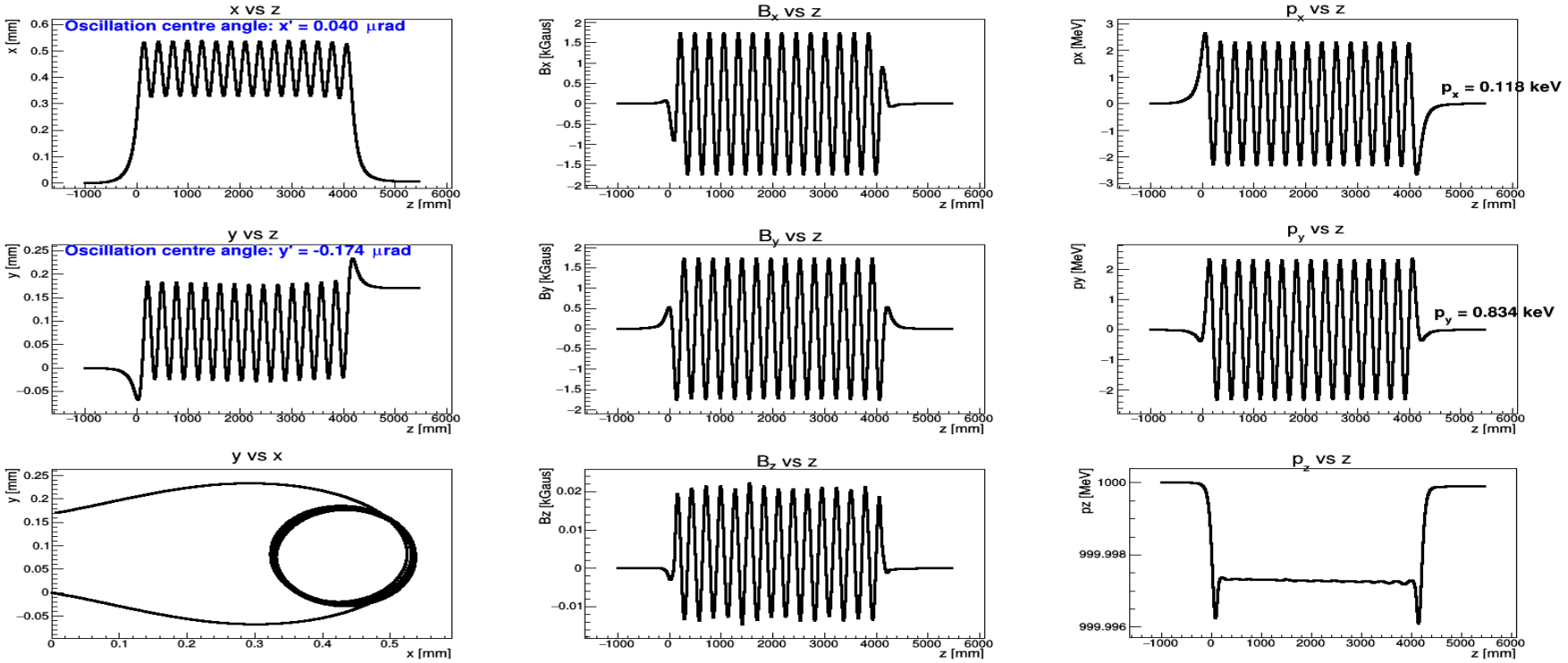
B_{xy} and B_z fit functions are: const

During the fit, field error is considered 1 Gs



Tracking of electrons through OSC undulator field

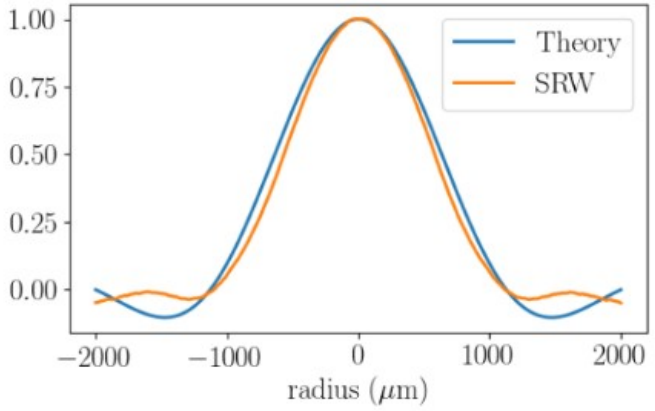
- Beam oscillation center angles (x'=dx/dz and y'=dy/dz) are ~0
- The beam will exit from undulator field with ~0 transverse momentum
- Beam vertical offset after it passes through the undulator field will be corrected using CESR steering magnets

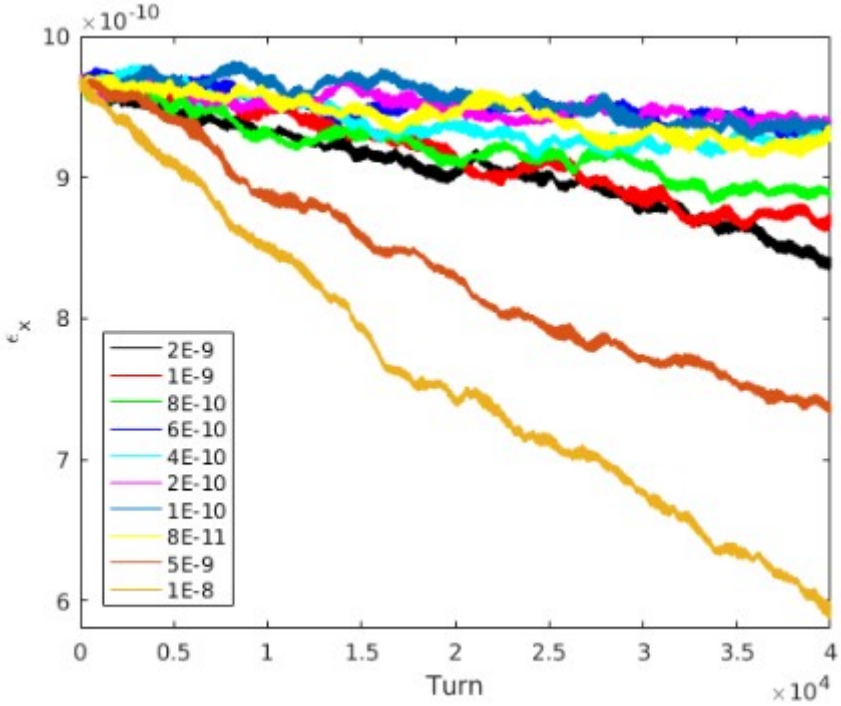


Full OSC simulations with BMAD

Detailed simulations developed that include

- SR emission effects (damping and excitation)
- Incoherent kick contributions based on gaussian statistics
- Longitudinal/Transverse field dependence dependence when accounting kick value
- Path length errors from dipole jitter





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