The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

Optical Stochastic Cooling in CESR

M. Andorf,on the behalf of the OSC team.

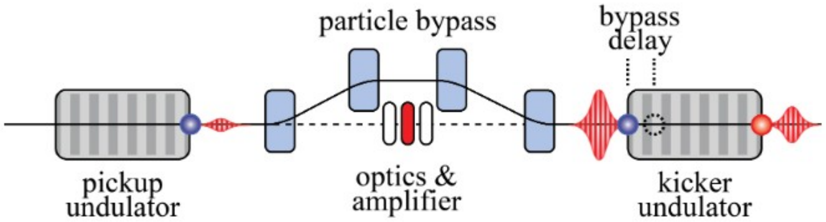
12/8/2020

Accelerator Physics and Technology Seminar

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

What is OSC?

Optical Stochastic Cooling (OSC) is a particle beam cooling technique that can potentially increase damping rates by 4-orders of magnitude over ordinary stochastic cooling enabling cooling of the bright hadron/heavy-ion beams found in modern particle colliders.



There are currently two complimentary PoP OSC experiments:

In the IOTA ring at Fermilab:

- Will demonstrate “passive” OSC with 100 MeV electrons. Very fast damping relative to SR rates.
- Additional plan to test “active” OSC with a low gain (~7dB) amplifier based on Cr:ZnSe

In CESR:

- **Active OSC demonstration on 1 GeV electrons.**
- **Based on a “arc” bypass that allows for an amplifier with straightforward scaling to gains needed for hadron/heavy ion cooling.**

Why is cooling needed?

In a storage ring competing phenomenon grow or reduce the emittance:

- Synchrotron radiation primarily emitted in bend magnets and the restoration of that lost energy from RF cavities results in a reduction of emittance—for hadrons this damping is usually negligible except at very high energies.
- Intrabeam scattering (IBS) and beam-beam effects (in colliders) increases the emittance.

In a collider small emittance is desirable to increase the luminosity

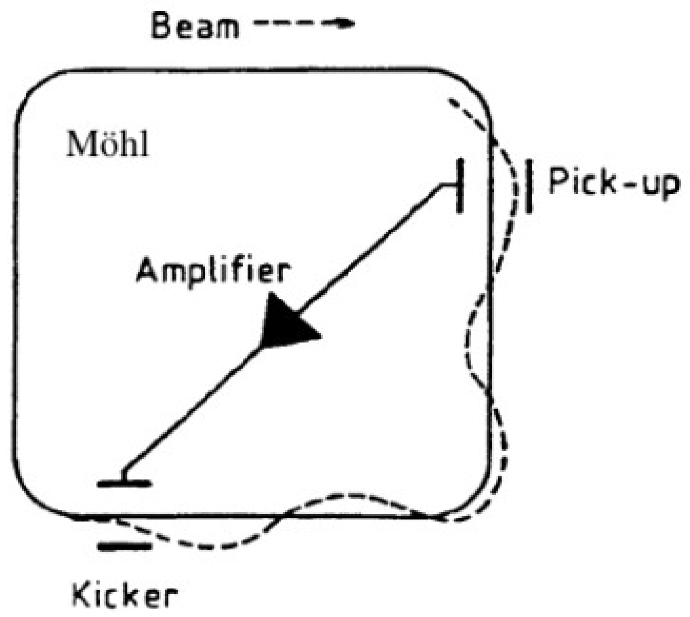
$$\mathcal{L} = f_o N_b \frac{N_1 N_2}{4\pi \beta_x \beta_y \epsilon_x \epsilon_y}$$

Specific to hadron and heavy-ion colliders IBS growth rates exceed synchrotron damping rates and so external **cooling techniques** have been developed, namely **electron cooling** and **stochastic cooling**.

Neither technique can cool a stored beam at the densities and energies used in modern colliders and so there is a lot of interest in developing advanced cooling techniques like OSC, CeC and MBEC.

Stochastic Cooling

To understand the motivation for OSC, let's consider ordinary stochastic cooling and its limitations—specifically transverse cooling and let's start with a single particle.



The system consist of:

- a **pickup** that detects a particle's position.
- an **amplifier** to relay and amplify the pickup signal
- a **kicker** which applies a transverse momentum kick to the particle with an amplitude proportional to the pickup signal.

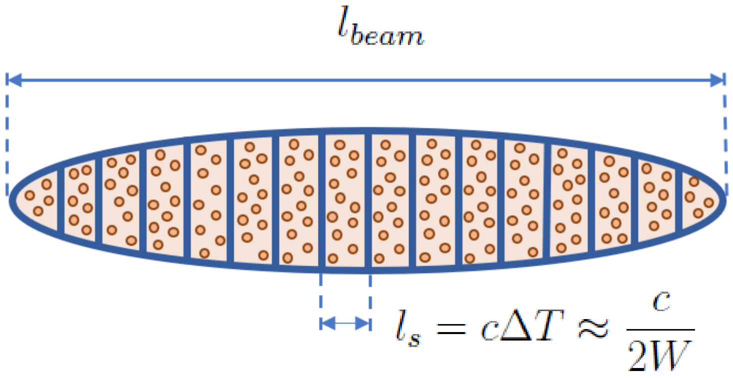
  Optimally the phase-advance between pickup and kicker is an odd-integer multiple of π/2.

After one turn the corrected position is $\mathbf{x_c=x-\lambda x}$ and the entire processes is repeated

Thus, when considering a single particle we expect exponential damping with a damping constant **λ**. The optimal setting is **λ=1** and the oscillation is damped in one turn.

Stochastic Cooling

Now consider a particle bunch. There is a finite time resolution of the pickup and kicker ΔT in which many particles will overlap. In addition to a **coherent kick** the particle will also receive **incoherent kicks** from $\mathbf{N_s}$ neighboring particles that are within the system's time resolution.

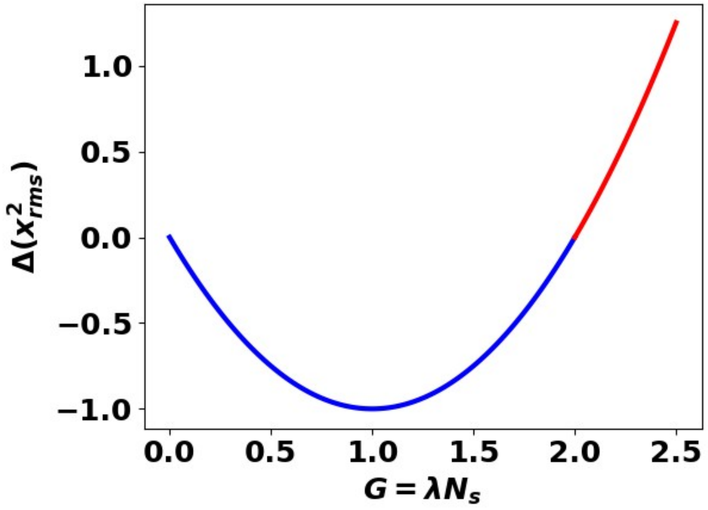


Let $\mathbf{g=\lambda N_s}$, then after one pass some particular particle's position is changed as:

$$\Delta x = -\frac{g}{N_s}x - g\langle x\rangle_{s'}$$

And the change in the RMS spread of the beam (per turn) is

$$\Delta(x^2_{rms}) = -\frac{(2g-g^2)}{N_s}x^2_{rms}$$

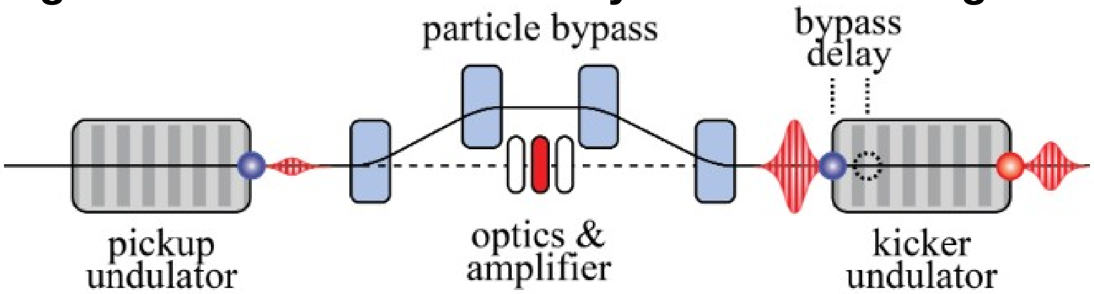


The maximum decrease in $\mathbf{x_{rms}^2}$ is when **g=1.** Thus, the maximum damping rate scales as $\mathbf{\lambda=1/N_s}$.

As a beam becomes brighter the best achievable damping rate from stochastic cooling decreases. For very bright beams the damping rate is significantly less than IBS growth rates making ordinary stochastic cooling ineffectual.

Optical Stochastic Cooling (OSC)

Ordinary stochastic cooling is done with microwaves and state-of-the-art systems have about 8 GHz of bandwidth. By contrast, broadband optical amplifiers boast bandwidths as high as 100 THz. If stochastic cooling techniques can be implemented at optical wavelengths **optimal damping rates can be increased by 4-orders of magnitude.**



$$\frac{1}{\tau_{opt}} \approx \frac{W\sigma_l}{NC}$$

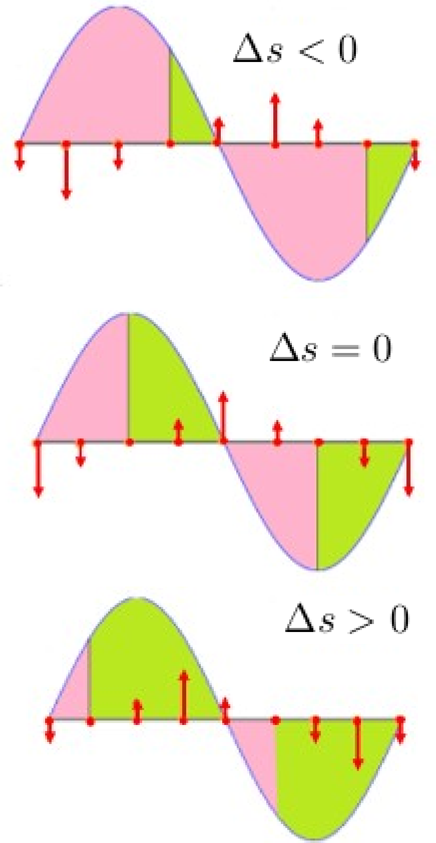
OSC was first proposed by Mikhailichenko and later refined into the ‘transit-time’ version by Zolotorev and Zholents.

In transit time OSC:

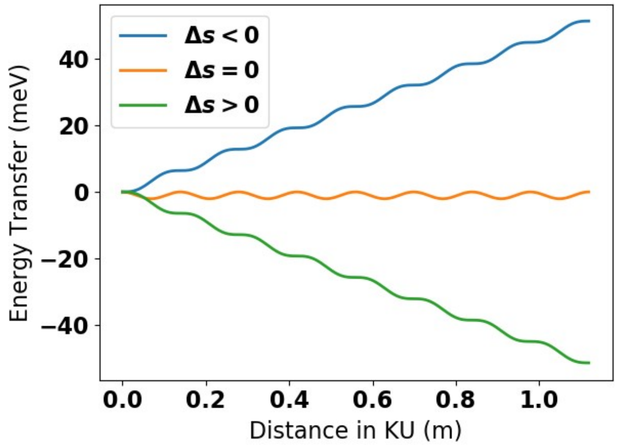
- All particles radiate short identical wave-packets in the Pickup Undulator (PU)
- A magnetic bypass creates a unique longitudinal displacement between each particle and its own wave-packet, Δs between the **(PU)** and kicker undulator **(KU)**
- A resonant interaction between the particle wave-packet occurs in the KU.
- **Result is a change in the particles energy**

$$\delta u = -\Delta\mathcal{E}\sin(k_l \Delta s)$$

Particle/wave interaction in the KU



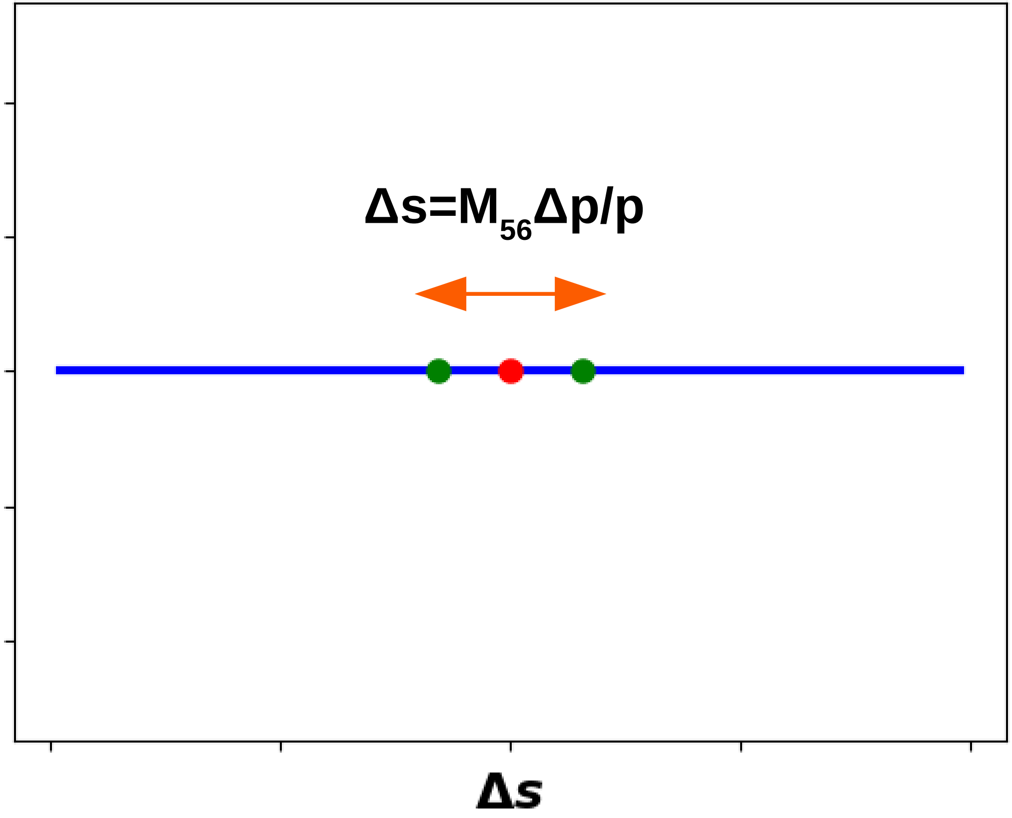
$$\frac{d\mathcal{E}}{dt} = q\boldsymbol{v} \cdot \boldsymbol{E}$$



Consider a particle light wave co-propagating in an undulator at ‘resonance’

- Inside an undulator a particle is made to oscillate transversely
- The PU radiation is polarized in the same direction as the particles *transverse* motion in the KU and so an energy exchange takes place
- **The sign and magnitude of the energy exchange is determined by the relative phase between the light and particle motion**
- At resonance this transverse motion causes the particle to ‘slip’ behind the light one wavelength per every undulator period. **The energy coherently grows along the length of the undulator**

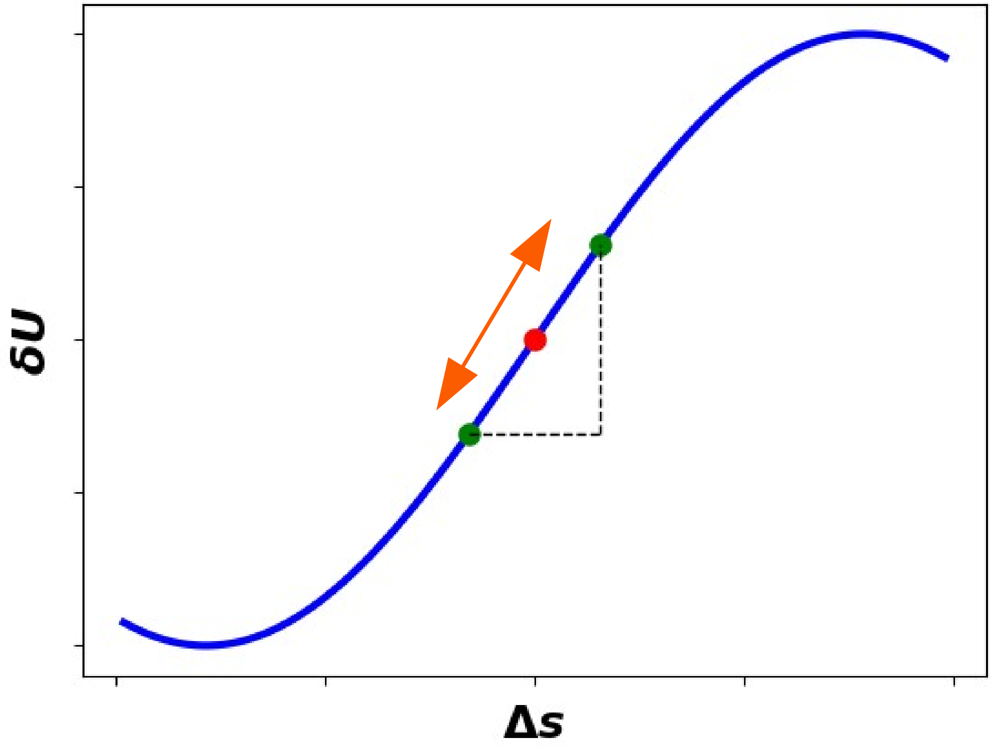
Transit-Time Method of Cooling



To understand the transit-time method we will look at momentum/energy cooling:

- Consider two points in the ring, the PU and KU locations.
- The path length between PU and KU, relative to the reference orbit and ignoring betatron motion, is determined by the particle's momentum: $\mathbf{\Delta s = M_{56} \Delta p/p}$
- If a particular particle is observed over many turns in the ring, it's arrival will oscillate in front/behind the reference particle at the synchrotron frequency.

Transit Time Method of Cooling



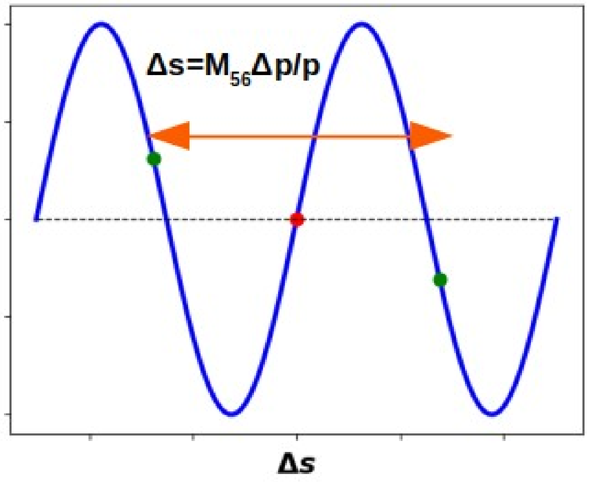
- In the context of OSC, **Δs** is also a particle's displacement in the KU with respect to the wave-packet it radiated in the PU. Thus, during a single pass each particle in the bunch receives a small momentum kick determined by the particle's (instantaneous) momentum error:

$$\begin{aligned}\delta u &= -\Delta\mathcal{E}\sin(k_l\Delta s)\\ &= -\Delta\mathcal{E}\sin(k_l M_{56}\Delta p/p)\\ &\approx -(\Delta\mathcal{E}M_{56}k_l)\Delta p/p\end{aligned}$$

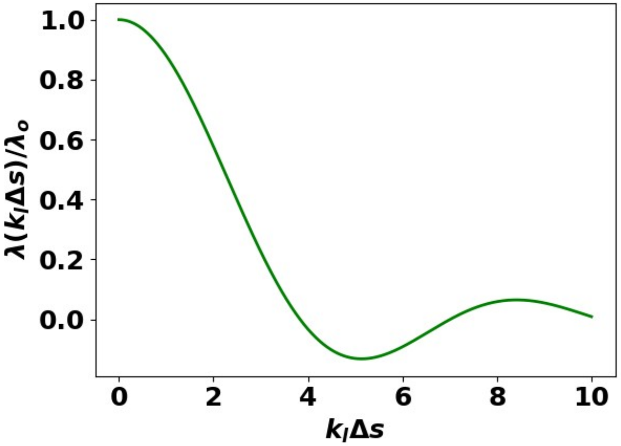
- A typical kick value is on the order of **100 meV** while a typical energy error may be on the order of **100 keV**. Thus, a particle is damped over millions of turns in the ring.
- The *slope* of the kick w.r.t momentum determines the damping rate:

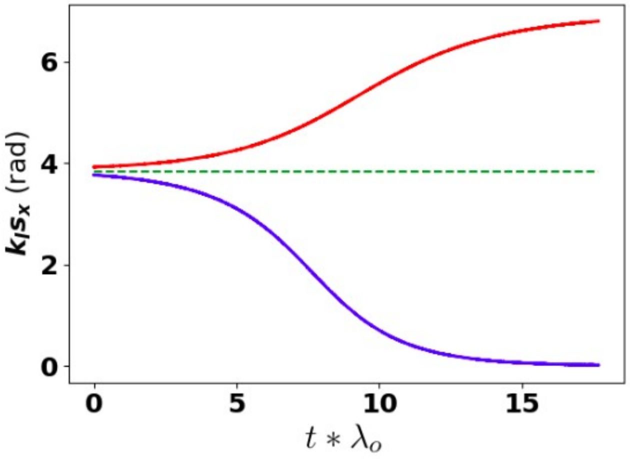
$$\lambda_p = \frac{k_l M_{56}}{2\tau_s}\frac{\Delta\mathcal{E}}{U_s}$$

Cooling Boundary



- As the longitudinal displacement of the particle gets larger the kick becomes nonlinear. For a large enough displacement the kick the sign switches.
- Therefore, there is a **cooling range** or acceptance. Particles inside the range are damped and particles outside are anti-damped.
- To find the range, the instantaneous damping rate is averaged over a synchrotron period.





Averaging yields **the amplitude dependent damping rate:**

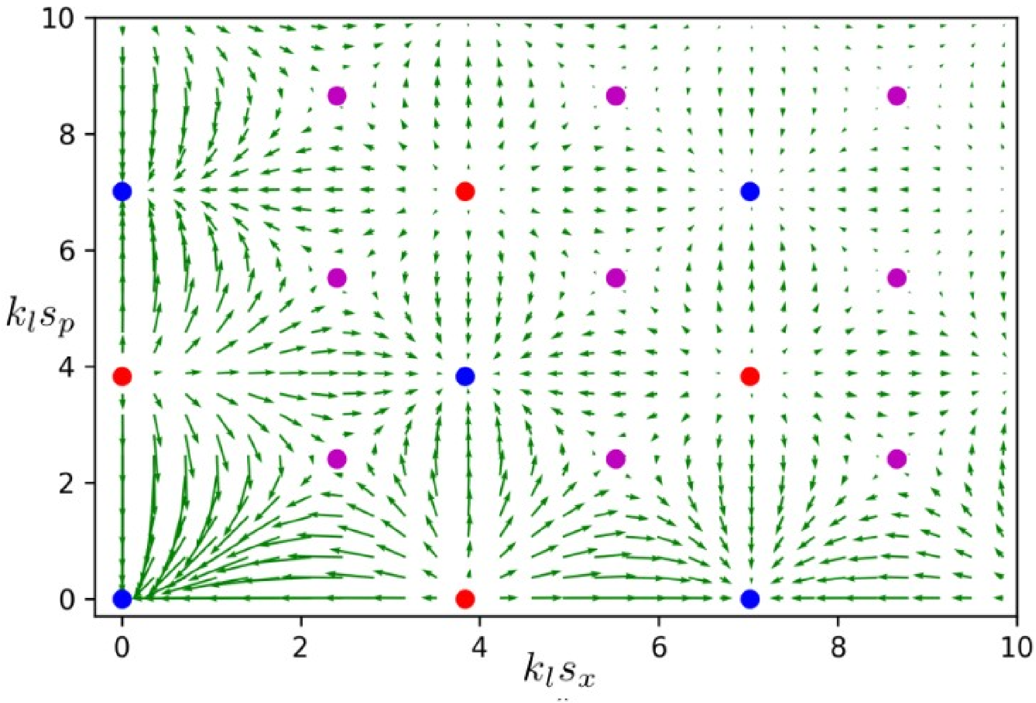
$$\lambda(k_l \Delta s) = 2\lambda_o \frac{J_1(k_l \Delta s)}{k_l \Delta s}$$

Cooling Ranges for 2 plane damping

See: V. Lebedev "*Optical Stochastic Cooling*" *ICFA Beam Dynamics Newsletter, issue 65.*

- So far we've considered longitudinal damping. Lattice dispersion couples the longitudinal and horizontal plane, and can be used to achieve damping in both planes.
- Dispersion merely *redistributes* the damping decrements (i.e. for a fixed kick amplitude, including horizontal dispersion will reduce the longitudinal damping rate):

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



- A conservative estimate of the cooling ranges are:

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

where

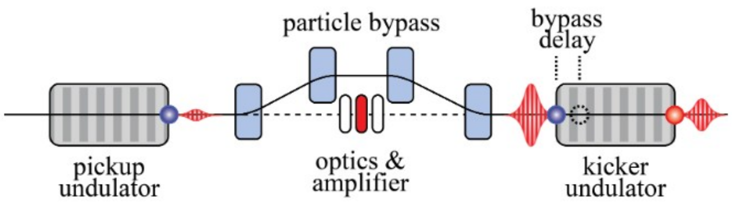
$$k_l s_x(\epsilon_o = \epsilon_{max}) = \mu_{0,1}$$

$$k_l s_p(\Delta p = \Delta p_{max}) = \mu_{0,1}$$

$$\mu_{0,1} \approx 2.405$$

The Challenge of Active OSC

- The dog-leg style bypass used in IOTA and originally considered for the CESR test works great for passive-OSC, but seriously constrains an amplifier that can be used for active OSC.

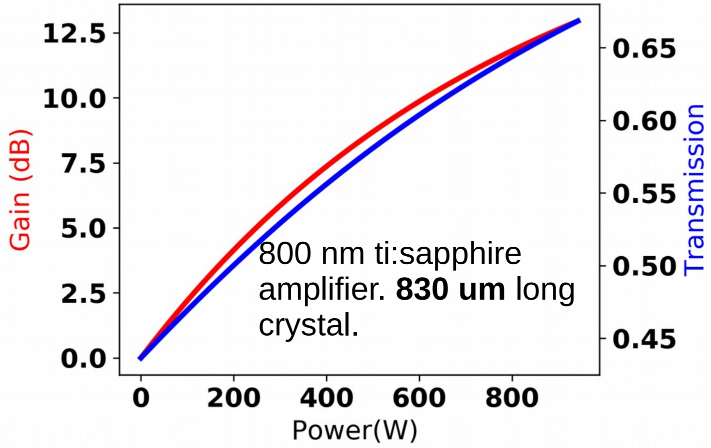


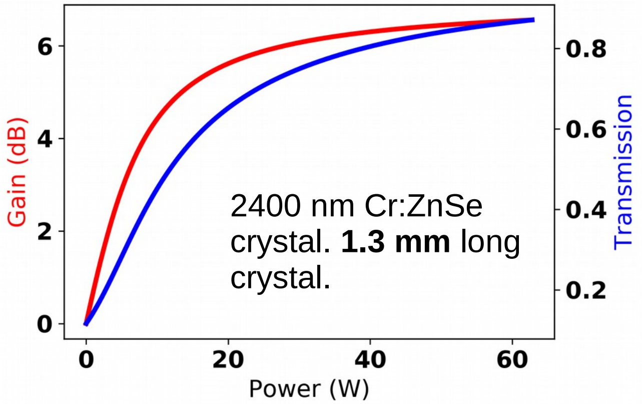
$$\sigma_p M_{56} \ll \lambda_l$$

$$2M_{56} \approx \Delta z_{total}$$

- To damp particles with a large momentum error, a small M_{56} is needed.
- A small M_{56} implies a short crystal length.
- A short crystal length makes high gain amplification difficult or impossible.
- **High gain amplification is a must for heavy-ion or hadron cooling.**

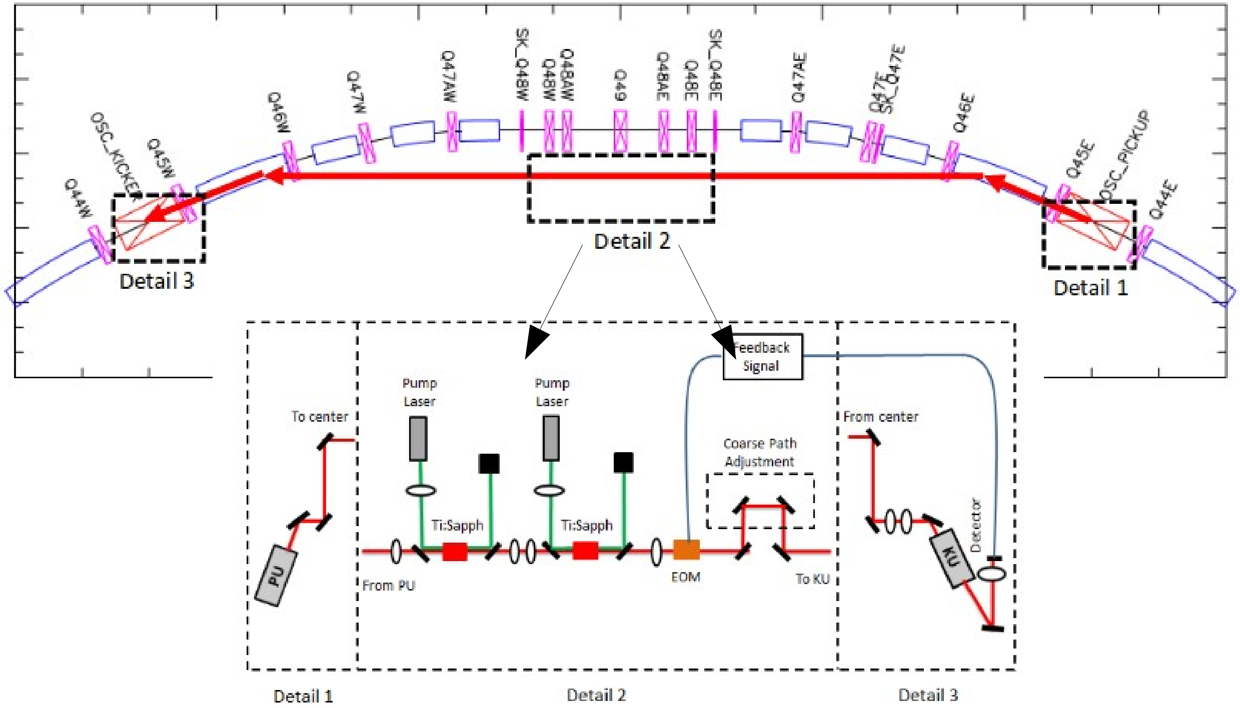
Parameter	value
σ_p	1.0×10^{-4}
η_p	5





Active demonstration of OSC in CESR

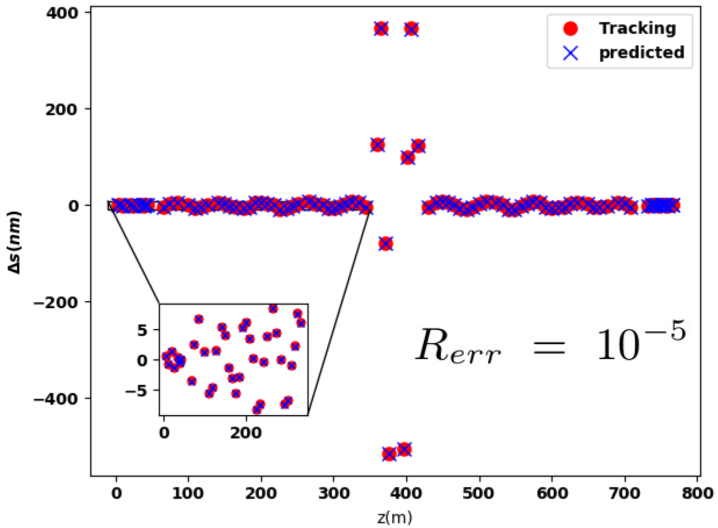
- Light path takes a short cut along a chord of between B46E/ W dipoles.
- **Total delay of 20+ cm** while still being able to cool large-amplitude particles. Allows for straight-forward staging of amplifier.
- Increased path-length and introduction of mirrors implies higher sensitivity to noise.

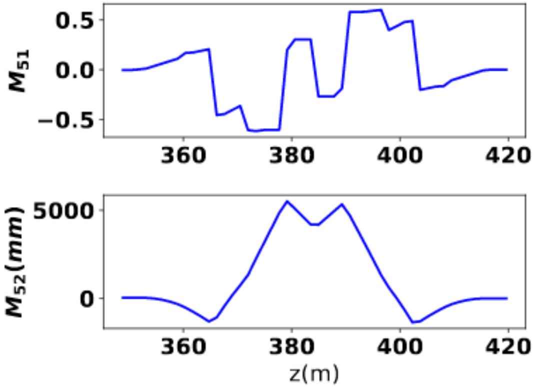


Parameter	Horizontal Cooling	Simultaneous Cooling
$\epsilon_o(nm)$	0.73	0.73
σ_p	3.7×10^{-4}	3.7×10^{-4}
η_x	2.8	3.11
η_p	31.3	2.1
$\lambda_{xo}\ (\mathrm{s}^{-1})$	0.91	0.77
$\lambda_{x,SR}\ (\mathrm{s}^{-1})$	0.73	0.73
$\lambda_{po}\ (\mathrm{s}^{-1})$	0.01	0.24
$\lambda_{p,SR}\ (\mathrm{s}^{-1})$	1.27	1.27

Dipole stability requirement

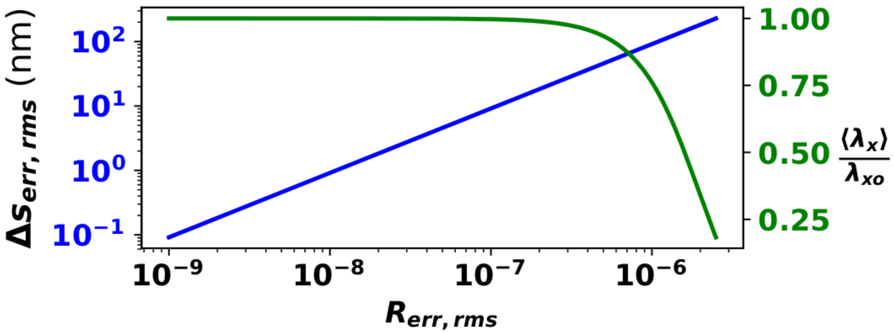
- Small changes in dipole strengths (i.e. from power supply fluctuations) cause path-length errors between particle and wave-packet.
- Dipoles outside the bypass shift the equilibrium orbit at the PU causing a path-length change.



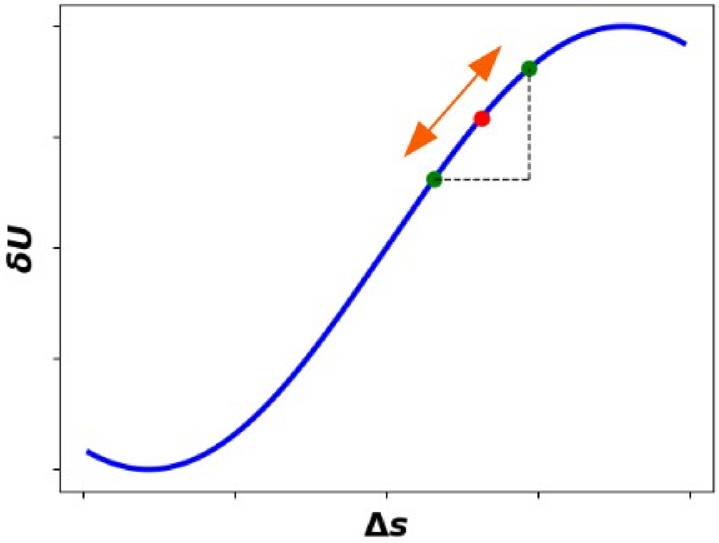


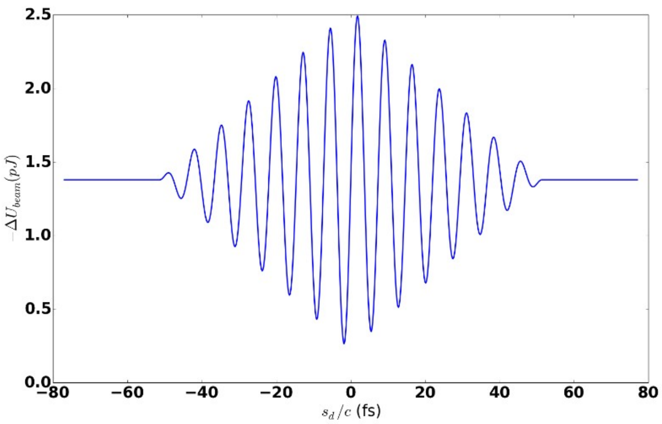
- Path length is much more sensitive to fluctuations from dipoles inside the bypass
  1) arc-length through the dipole changes
  2) At the exit of the dipole, the displacement of the reference orbit results in an additional path-length change

- For the arc bypass sensitivity is increased compared to the dog-leg approach because:
  1) Dipoles are fairly strong (6.4 degree bends)
  2) M_{51} and M_{52} can grow quite large over the long distance separating PU and KU
- Also sensitive to quad transverse motion.



Path length error and feedback stabilization





OSC requires extreme precision between transit times of particle and wave-packet

- Relative arrival times must be known to better than **300 as**

Direct detection is not possible, nor is it required

- The total radiated energy of the PU and KU modulates with the path-length error and so provides an indirect measure of it

With path-length error detectable, feedback stabilization is possible. Anything that can modify the light or particle path-length can be used

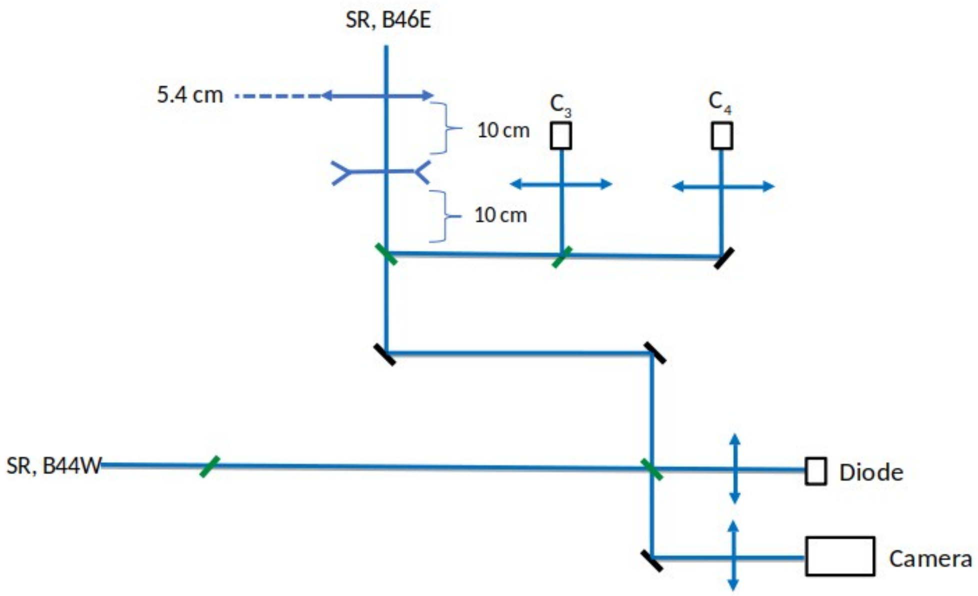
- Want to have a fast response and also large correction range
- **Present design will use an Electric-Optic Modulator (EOM) for corrector**

Path-length Stabilization Test with Dipole Radiation

- Before going for a high-gain OSC demonstration, we are pursuing a reduced test to demonstrate the light and particle paths can be stabilized to the required precision.
- Light from two dipoles, separated by roughly the same distance as the PU and KU will be for OSC, are interfered.
- The same EOM based feedback system envisioned for OSC is used to stabilize interference signal and therefore path-length jitter.

This reduced test has several advantages:

- No need to build and install undulators.
- Allows us to leverage existing Be mirrors.
- Simpler modifications to the CESR vacuum chamber—mirrors do not sit inside dipoles.
- Test can be done at the nominal CESR energy of 6 GeV.



Longitudinal mixing and fringe visibility

Correlation technique for measurements of beam emittance and energy spread[1]

Alexander Zholents*, Max Zolotorev

The time domain radiation field is the superposition of single particle wave-packets off-set by the particles arrival time in the bend

$$E_{1,2}(t) = \sum_{i=1}^{N} e(t - \tau_i^{(1,2)}),$$

Interfering the field of a single particle gives a signal:

$$\langle I(\tau)\rangle = \left\langle \Big(E_1(t) + E_2(t+\tau) \Big)^2 \right\rangle = \langle I_1\rangle + \langle I_2\rangle - 2\langle E_1(t)E_2^*(t+\tau)\rangle$$

The last term is proportional to the correlation function

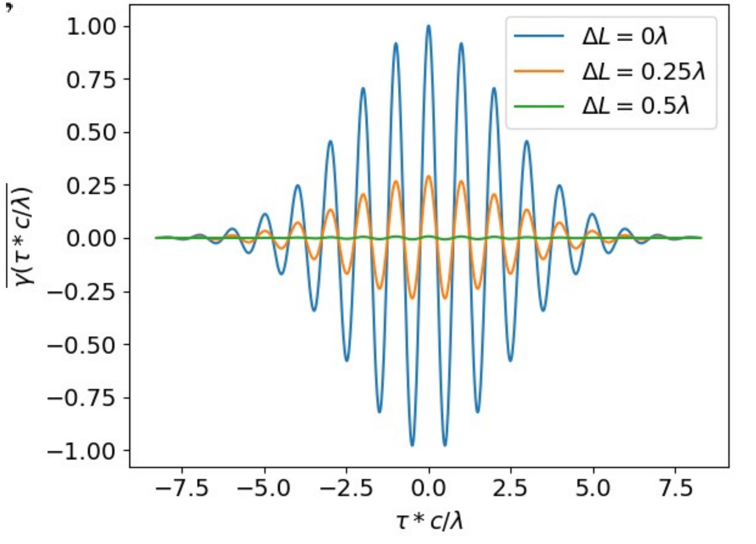
$$\gamma_{12}(\tau) = \frac{\langle E_1(t)E_2^*(t+\tau)\rangle}{[\langle |E_1(t)|^2\rangle\langle |E_2(t)|^2\rangle]^{1/2}},$$

For a Gaussian beam the correlation function is proportional to:

$$\overline{\gamma_{1,2}(\tau)} \propto \exp\left(- \frac{(k^2\sigma_s^2}{2} \right) \exp\left(- \Delta\frac{\omega^2\tau}{2} \right) \exp\left(i\omega_o\tau \right)$$

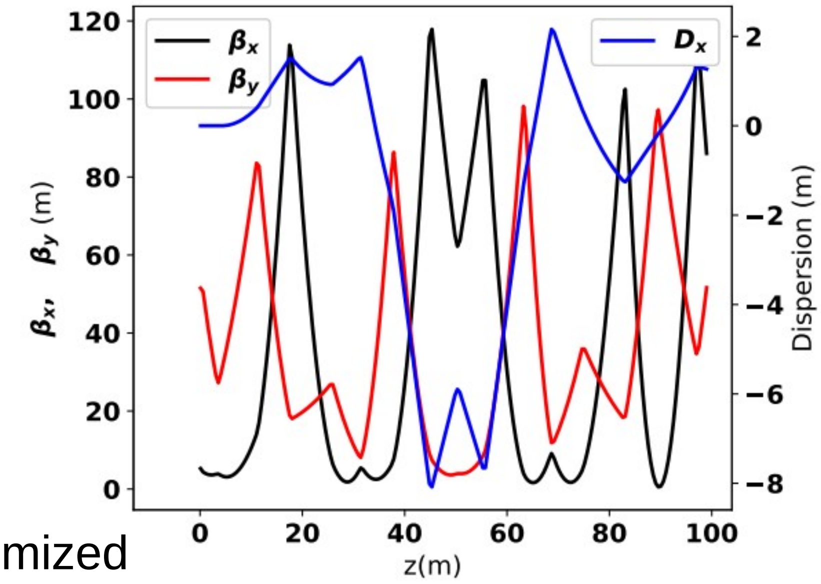
Where: $\sigma_s = \sqrt{\sigma_{x,s}^2 + \sigma_{p,s}^2}$

is the amount of longitudinal mixing of the beam between the two dipoles



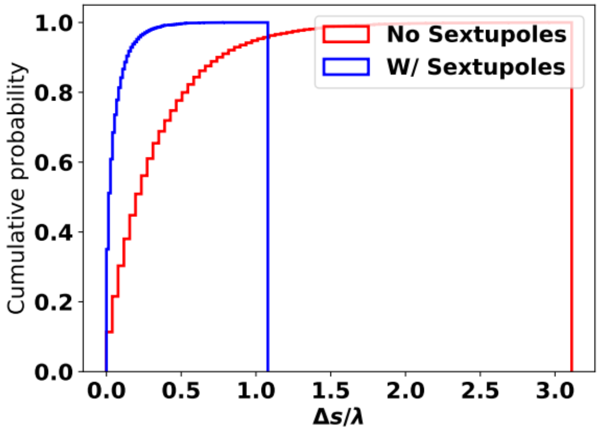
Isochronous bypass

Parameter	value
$\epsilon(nm)$	35 nm
σ_p	7.8×10^{-4}
s_x	5 nm
s_p	14 nm
Visibility (@ 780 nm)	99 %



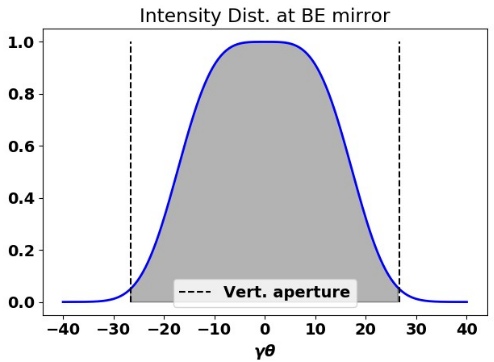
- Starting from the OSC design, the bypass was re-optimized to be isochronous. The changes were relatively small because
  1) OSC requires small but nonzero mixing between PU and KU
  2) Dipoles used for interference are in the proximity of where the PU and KU will be.

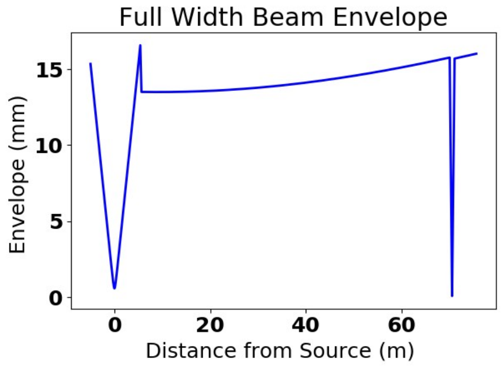
- Sextupoles are needed to correct nonlinear path-lengthening.



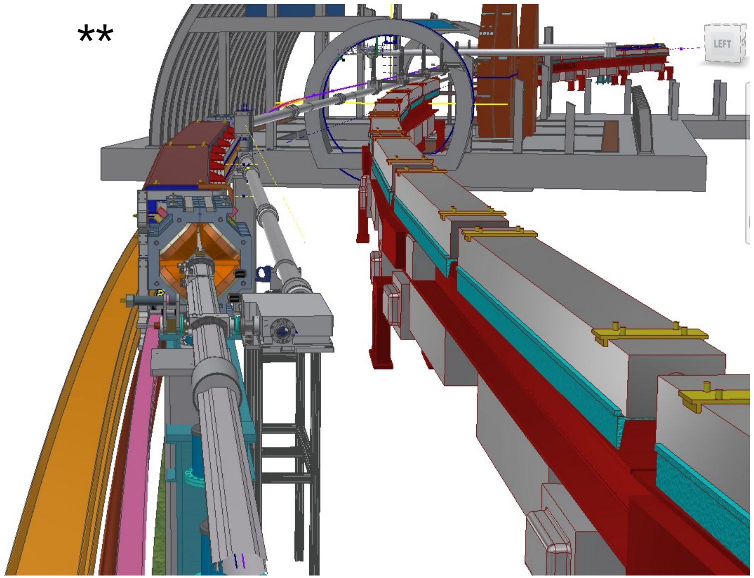
Light path

- 1/2’’x1/2’’ Beryllium mirror picks off a portion of dipole light. Vertical aperture accepts>99% of light.
- West path consist of a set of collimating lenses and focusing lenses for EOM aperture.
- Entire path is in rough vacuum, isolated from CESR vacuum.
- **Installation in December 2020**





**



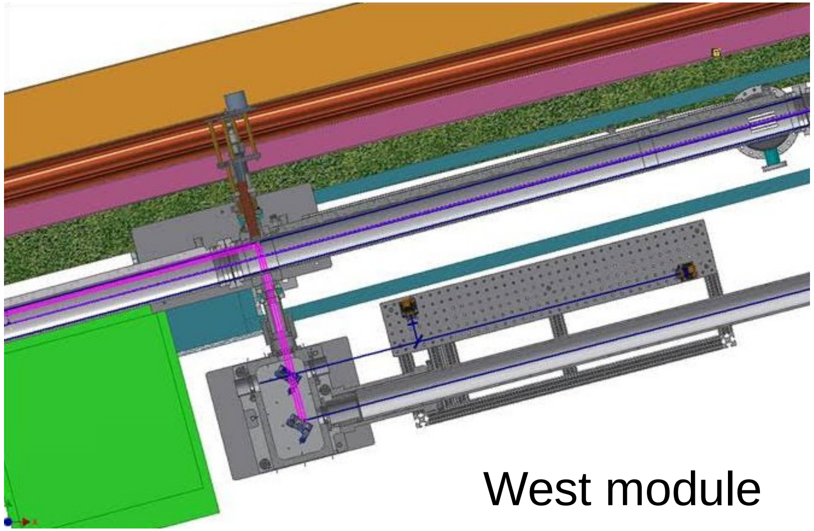
Parameter	value
Beam Energy	6 GeV
Bend Radius	58.6 m
Critical wavelength	0.15 nm
Mirror Dimensions	12.7X12.7 mm
Average power on mirror*	0.8 uW/mA

*Bandwidth from 750-800 nm

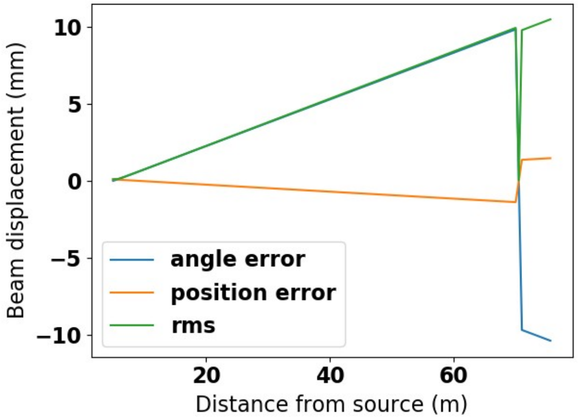
**Drawing by D. Burke

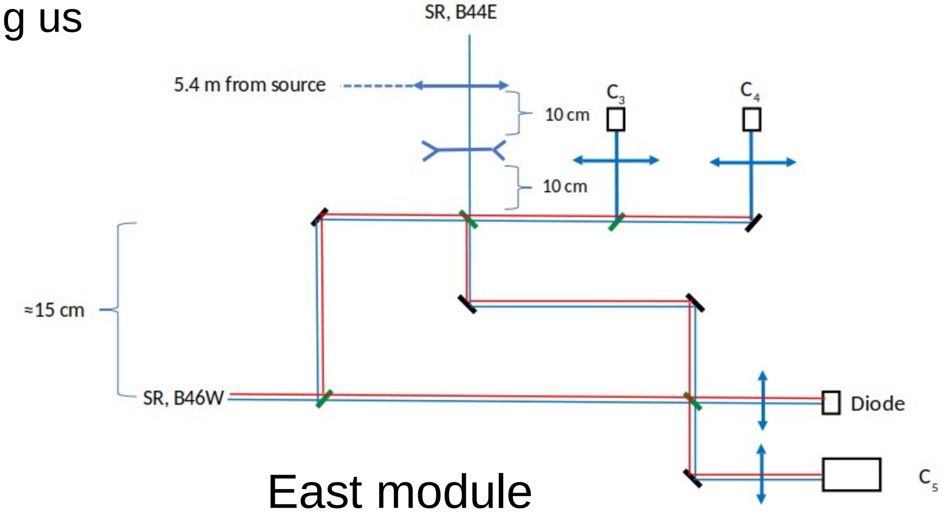
Light path alignment

- A beamsplitter just outside of the first dipole (west) combines the SR light with an alignment laser. The laser is aligned to the SR on two cameras separated by ~75 cm. The remaining downstream optics are aligned to the laser.
- Relative error in position and angle between SR and laser is within 100 µm and 130 µrad at the beamsplitter.
- This error is then propagated along the light path. **Displacement remains small relative to aperture.**
- In the east module a portion of the laser is picked and aligned to light from the second dipole.
- With only the laser an interferometer is formed allowing us to align both SR paths to each other.



West module



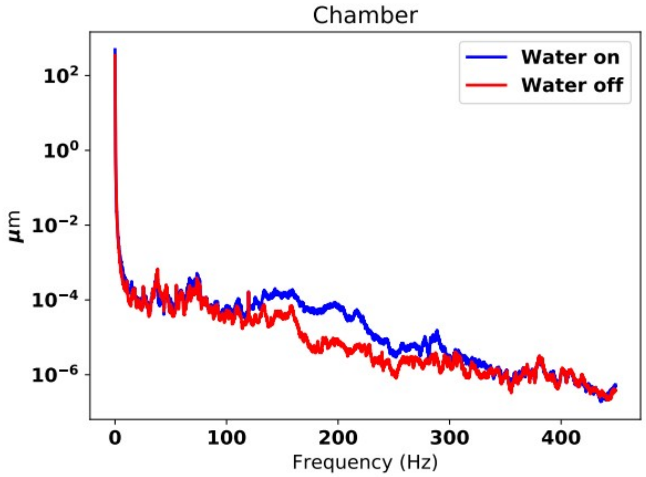


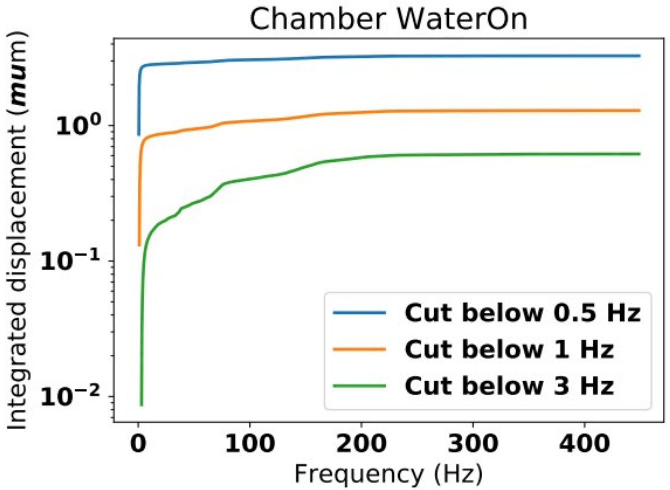
East module

Vibration analysis in the CESR tunnel*

Accelerometer measurements were done at several locations in the CESR tunnel

- Integrated noise above 1 Hz results in displacements <1 μm
- Low frequency noise may need additional slow path-length compensation.
- **No show stoppers found**





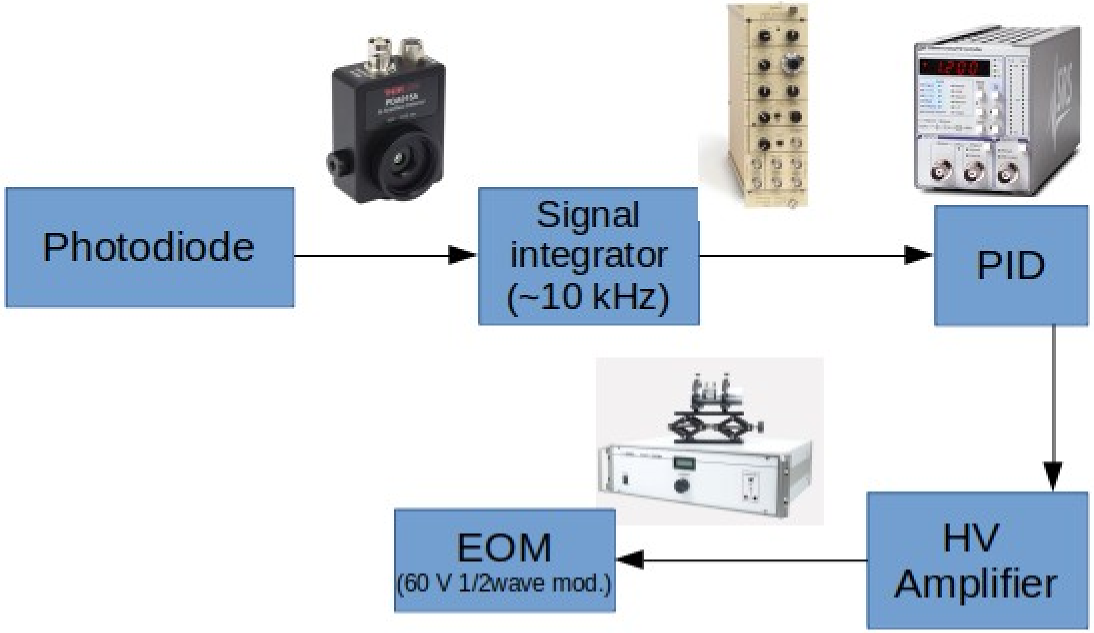
*Measured by A. Lyndaker

Feedback

Photodiode registers pulses at CESR's bunch spacing:
- Nominal spacing is 14 ns. minimum spacing, set by RF, is 2 ns
- Diode saturates at relatively low peak bunch currents—S/N ratio improves with more bunches

Signal integrator smooths over pulse structure. Integration time is set by a compromise between:
1) Short integration time allows for fast noise cancellation.
2) Long integration time decreases minimum detectable power.

EOM selected for low Half-wave voltage:
- Path adjustment +/- 2.4 μm. Exceeds measured vibration noise by a large margin.



Parameter	value
Diode NEP	29.2 pW/Hz$^{1/2}$
Minimal Detecable Power (100 μs integration time)	2.1 nW
Diode Saturation Bunch Current (w/ 50 nm BW)	20 μA
Crystal	Lithium Tantalate
Half-wave Voltage	60 V
Peak amplifier Voltage	750 V
Amplifier bandwidth	0-250 kHz

Summary

- The ultimate goal for OSC in CESR is the demonstration of high gain cooling
- High gain cooling requires a long bypass which increases sensitivity to noise requiring the need for a feedback system
- As an intermediate step we are pursuing a path length stabilization test with dipole radiation. **This is a cost effective test that allows us to demonstrate the highest risk components for OSC using a long bypass**:
  1)Synchronization and stabilization between light and particle paths
  2) Precise tuning of the linear and nonlinear beam optics to set longitudinal mixing
- **Installation begins in Winter 2020/2021 with measurements to follow in Winter/Spring 2021.**