The Center for BRIGHTBEAMS
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An Optical Stochastic Cooling (OSC) Path-Length Stability Experiment at the Cornell Electron Storage Ring (CESR)

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March 17, 2022

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Outline

- Acknowledgements
- Introduction to beam cooling/stochastic cooling
- Optical stochastic cooling (OSC) overview
- Experimental efforts/goals at Cornell
- Lattice Development
- OSC Feedback
- Conclusion

Acknowledgements

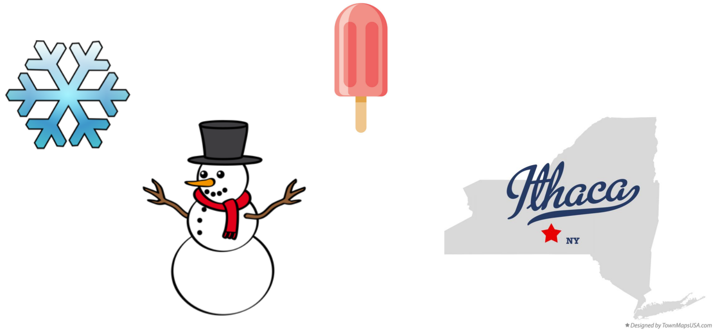
- This work is supported by the U.S. National Science Foundation under Award No. PHY-1549132, the Center for Bright Beams, NSF-1734189
- M.B. Andorf, I.V. Bazarov, D.C. Burke, J.M. Maxson, V. Khachatryan, D.L. Rubin, S.T. Wang

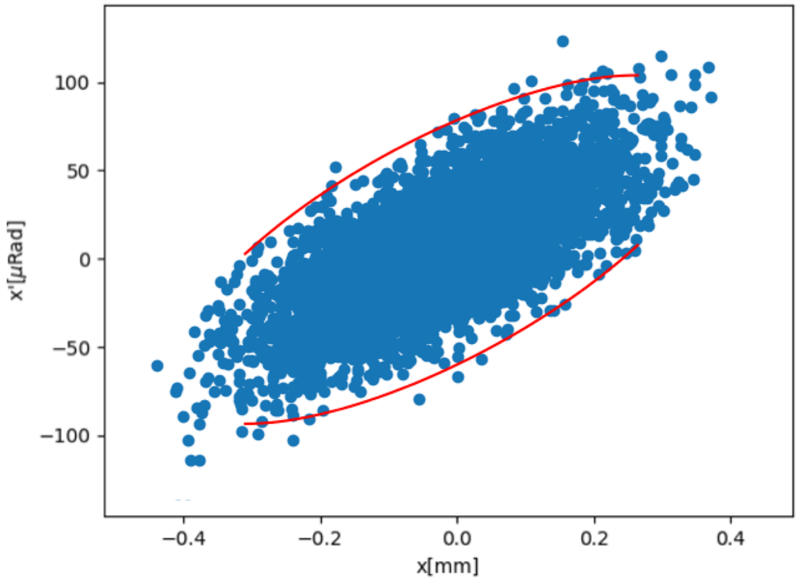
CBB

- **Title**: Light Path and Accelerator Optics Design for Optical Stochastic Cooling Stability Experiments in CESR
- **CBB Objective** - “Objective 2 (Cool): Develop methods for cooling beams using optical stochastic cooling to increase beam luminosity in next-generation colliders.“
  - First deliverable: “Proof of principle demonstrations of key elements of optical stochastic cooling at IOTA and CESR.“

What is beam cooling?

- Temperature → Phase space volume
- Emittance growth in an accelerator due to intrabeam scattering (IBS), beam-beam effects
- Beam cooling aims to reduce the emittance and create a brighter beam
- Beam cooling → non-Liouvillean processes (violate assumption of conservative force – interactions with electrons, photons, etc.)
- Electron cooling and stochastic cooling developed for hadron and heavy-ion colliders
  - IBS growth rates exceed synchrotron damping rates



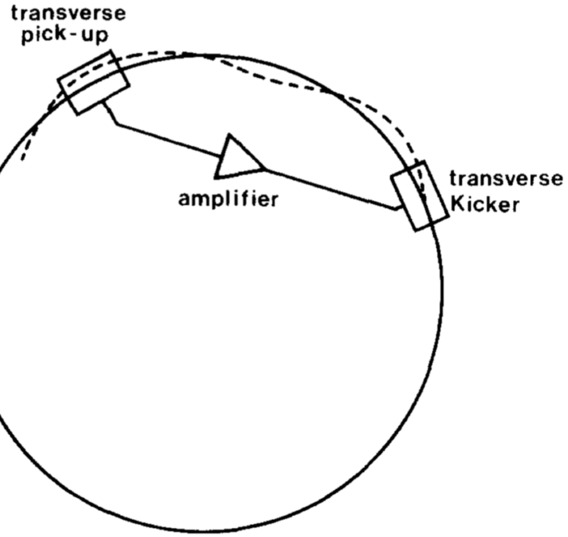


M. Steck, CAS Warsaw (2015)

Stochastic Cooling

- Invented in 1968 by Simon van der Meer (1984 Nobel Prize in Physics)
- Cooled antiprotons at CERN, discovery of the Z and W bosons in 1983
- The process involves:
  - Detection of a signal in the pickup revealing a particle’s transverse displacement
  - Transporting, manipulating and amplifying this signal
  - Using the signal to apply a transverse momentum kick to the same particle in the kicker
- After one turn, the displacement is: $x_c = x - \lambda x$
- Betatron motion phase advance (pick-up to kicker): $(n + 1/2)\pi$
- For a bunch of particles, system is resolved to resolution of $\mathrm{T} = \frac{1}{2W}$
  - Corrective kick to test particle also kicks other particles within time frame of $\pm \mathrm{T}/2$
  - Change of RMS spread of beam:

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



M. Steck, CAS Warsaw (2015)
D. Mo˙hl, G. Petrucci, L. Thorndahl and S. van der Meer, Phys Rep 58 (2), pp. 73-119 (1980)

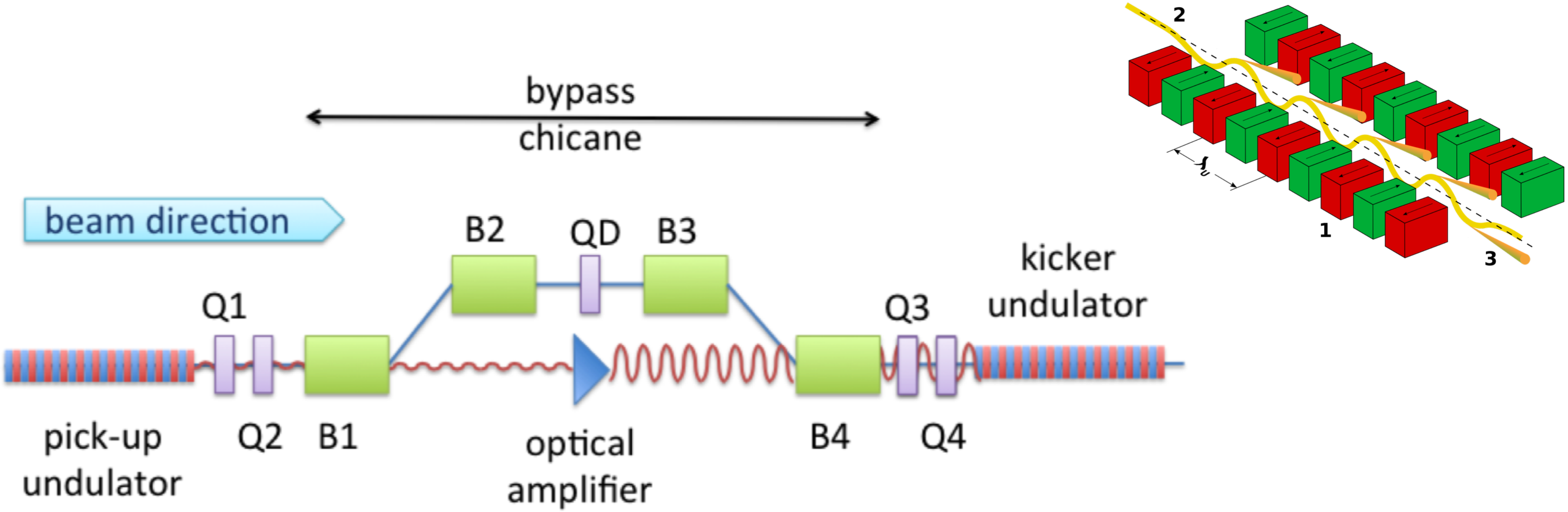
OSC Introduction

- First proposed in 1993 by Mikhailichenko and Zolotorev
- Transit time version developed in 1994 by Zholents and Zolotorev
- Same idea as microwave stochastic cooling, but now have much larger bandwidth of optical amplifiers (compare GHz scale to hundreds of THz)
- Thus, OSC can produce damping rates 4 orders of magnitude larger than those of microwave stochastic cooling
- Currently two ongoing OSC programs:
  - At IOTA (Fermilab):
    - Passive OSC with 100 MeV electrons
  - At CESR (Cornell):
    - Path stability and lattice testing first
    - Eventually active OSC demonstration on 1 GeV electrons

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)

How does OSC work?

- Particle radiates a EM wave-packet in the pickup undulator
- Particle trajectory sent through chicane, separating it from the optical radiation
  - Path length depends on deviations from reference particle
- Optical radiation from pickup sent through an optical transport (active has optical amplifier)

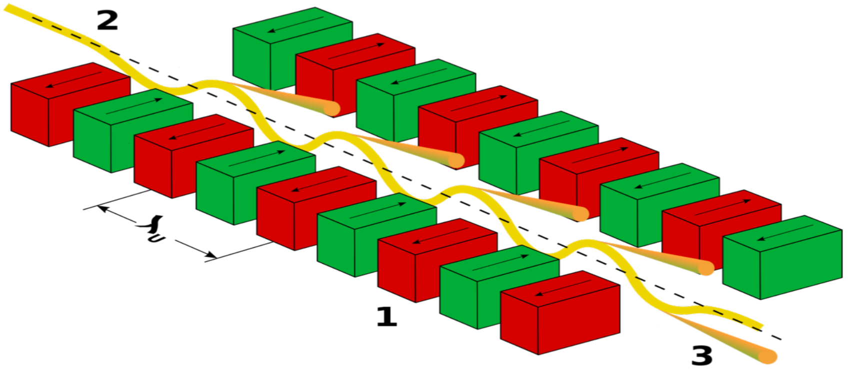


OSC Introduction

- Chicane and optical path each tuned so reference particle arrives at the kicker undulator in phase with its radiation (no net energy exchange)
- For many revolutions, the arrival time of a non-reference particle will oscillate between early/late relative to the reference particle
- Particles experience an energy exchange and thus a corrective kick
  - This works because we couple the arrival time with the momentum
- The path length difference between a particle and the reference particle

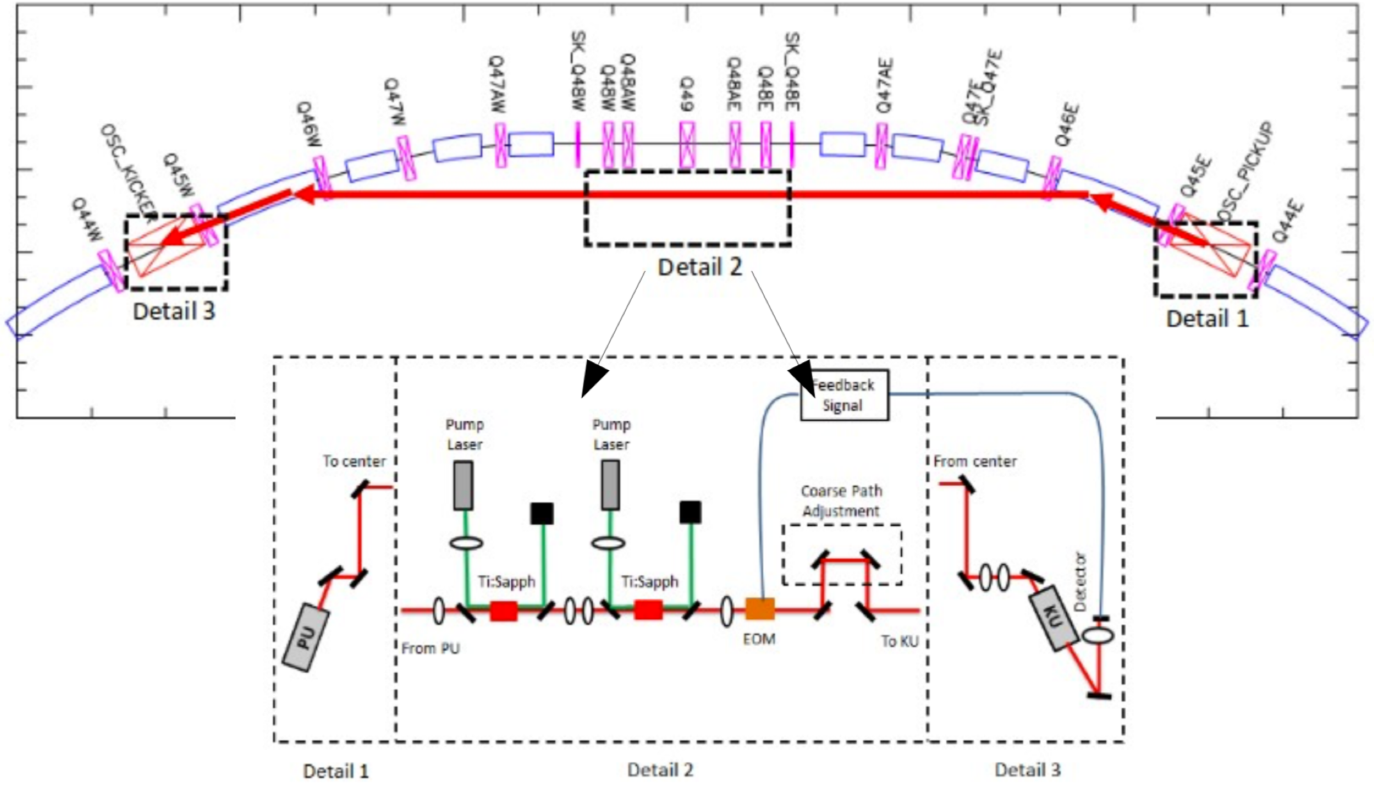
$$\Delta s = M_{56} \Delta P / P$$

- The particle will get an energy kick in the kicker like $\delta u = \Delta \mathcal{E} \sin(k_l \Delta s)$



Active Test in CESR

- Eventual OSC demonstration at 1 GeV in CESR
- Light path will go through northern arc of CESR
- Amplifier (Ti:Sapphire) and path length control (feedback system) contained
- Arc bypass
  - Recent paper by M. B. Andorf et al
  - Different from typical dog leg bypass
  - Relative delay of light and particle beam is independent of cooling



M. B. Andorf et al. Physical Review Accelerators and Beams 23 (2020) 102801

Stability

- Relative arrival times between transit times of particle and wave-packet must be known to about 300 attoseconds – not possible
- However, can indirectly measure it through the total radiated energy of the PU and KU - modulates with the path-length error
- If we know our path-length error, we can stabilize the path-length through feedback
- So, before a full, active OSC demonstration at CESR, we are working on a demonstration of the necessary stabilization/synchronization between the light and particle paths

Geometry of Path Test

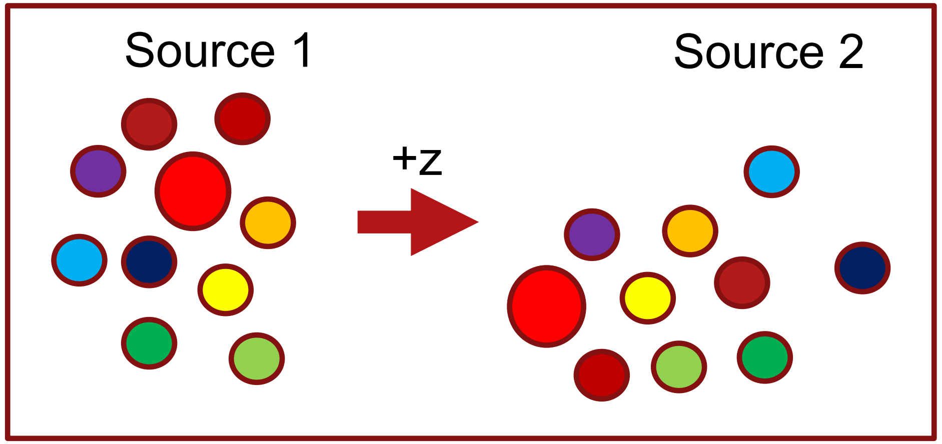
- Light from two dipoles (44W & 46E in CESR) is interfered in interferometer
- The same feedback system envisioned for full OSC will be used to stabilize the optical path (interference pattern)
- We can answer two main questions:
  1. Can we stabilize and synchronize the light and particle paths over distances about the same as planned for OSC?
  2. Can we properly set our lattice (longitudinal mixing) to maximize our interference visibility?

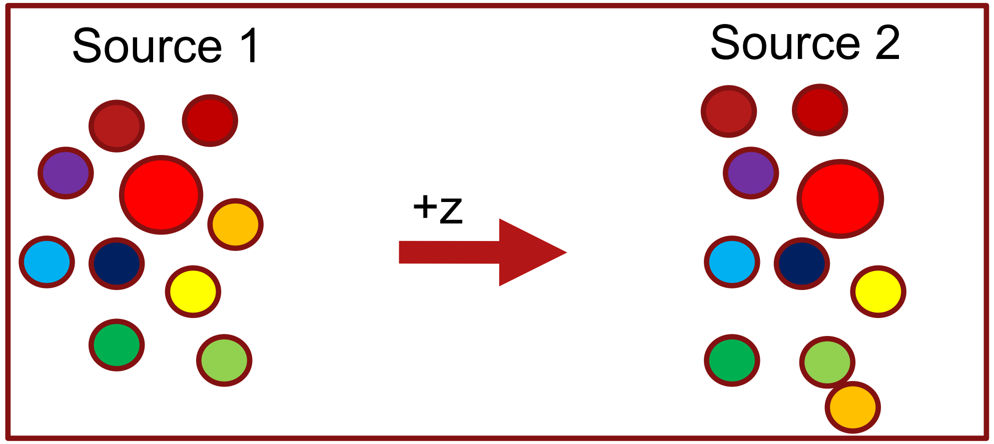
Requirements for Interference

- The two radiation fields must be strongly correlated (good interference visibility)
- This is achieved by minimizing the longitudinal mixing of the particles between the two radiation source points
  - For two points in an accelerator, longitudinal mixing is defined as the RMS deviation from the reference particle's path length between the two source points in the ring
- **Must have RMS mixing less than wavelength used in experiment (750 nm)**

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

A. Zholents, M. Zolotorev. Nuclear Instruments and Methods in Physics Research A 394 (1997) 316-320


Bad Longitudinal mixing


Better Longitudinal mixing

Longitudinal Mixing

- Can derive the RMS longitudinal mixing between two points in the ring
  - M_{ij} and T_{ijk} are the first and second order transfer matrices between the two points
- Third order terms insignificant for our purposes
- Need to create a lattice that minimizes the equation/maximizes interference visibility

$$\left.\sigma_{\Delta s}^2 = \epsilon_x\left[\beta M_{51}^2 - 2\alpha M_{51}M_{52} + \gamma M_{52}^2\right]\right\}\text{Linear Betatron}$$

$$\left.\begin{aligned}&+\epsilon_x^2\left[2\left(T_{511}\beta - T_{521}\alpha + T_{522}\gamma\right)^2\right.\\ &\left.+\left(T_{521}^2 - 4T_{511}T_{522}\right)\right]\end{aligned}\right\}\text{2nd Order Betatron}$$

$$\left.+\sigma_\delta^2\left(\eta M_{51} + \eta' M_{52} + M_{56}\right)^2\right\}\text{Linear Synchrotron}$$

$$\left.\begin{aligned}&+2\sigma_\delta^4\left(T_{511}\eta^2 + T_{512}\eta\eta' + T_{522}\eta'^2\right.\\ &\left.+T_{516}\eta + T_{526}\eta' + T_{566}\right)^2\end{aligned}\right\}\text{2nd Order Synchrotron}$$

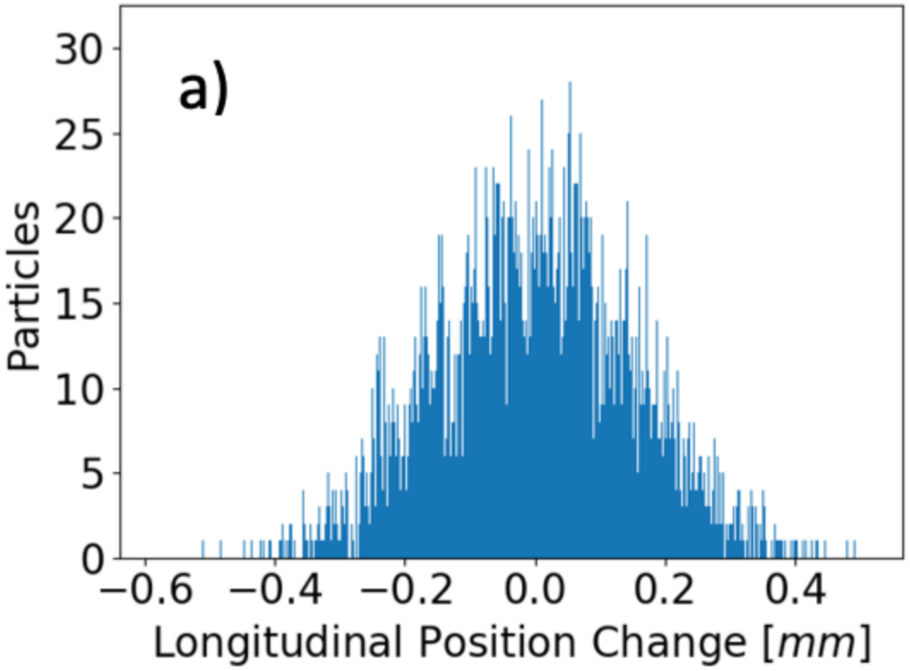
$$\left.+\epsilon_x\sigma_\delta^2\left(\beta\xi_1^2 - 2\alpha\xi_1\xi_2 + \gamma\xi_2^2\right)\right\}\text{Cross Terms}$$

$$\xi_1 = T_{511}\eta + 2T_{512}\eta' + T_{516}$$

$$\xi_2 = T_{512}\eta + 2T_{522}\eta' + T_{526}$$

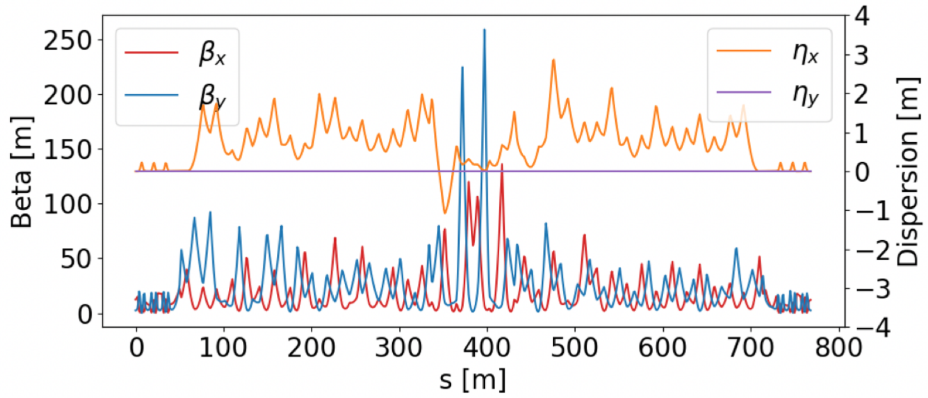
The CHESS Lattice is Insufficient

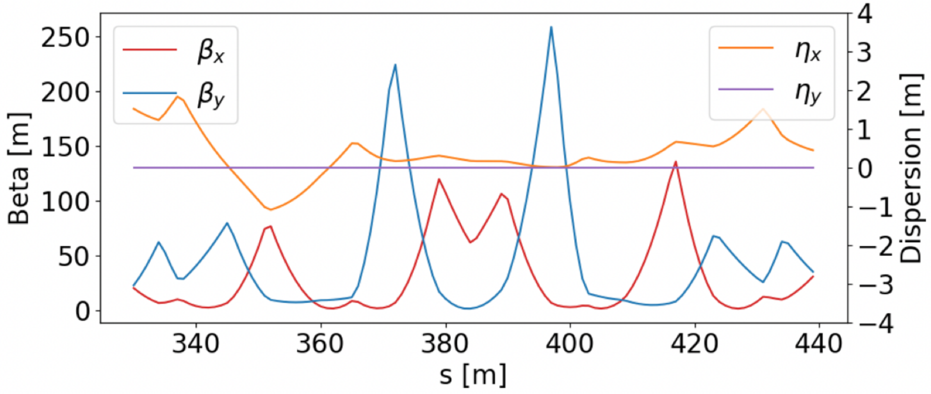
- CESR's usual operating conditions are optimized for the Cornell High Energy Synchrotron Source (CHESS) X-ray user facility
  - 6 GeV CHESS lattice
- The longitudinal mixing between source points in the CHESS lattice is about 300x too great to see visible light interference
- Plot: 10000 particles tracked through ring, difference in longitudinal position relative to reference particle at source points plotted

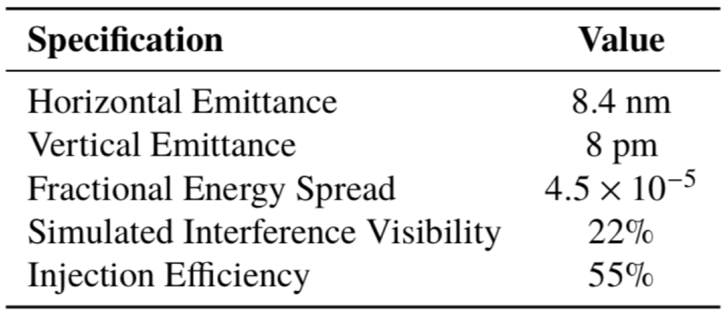


We need our own lattice

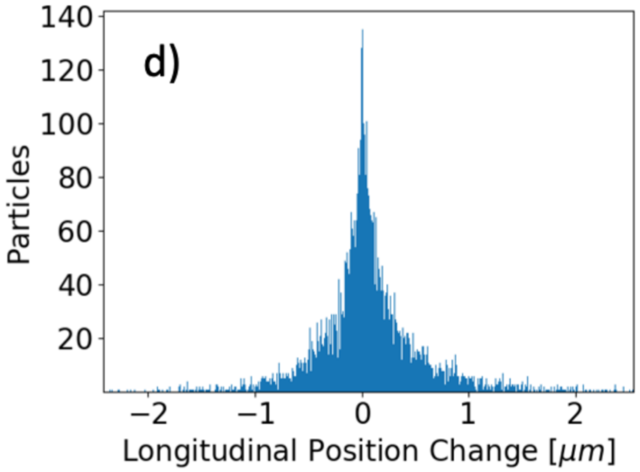
- Tune magnet (quadrupoles and sextupoles) strengths to minimize the longitudinal mixing between the source points
  - Optimizations done using BMAD/Tao built-in optimizers
- 21% interference visibility seen in 10,000 particle tracking code
- However, this lattice has many challenges to overcome





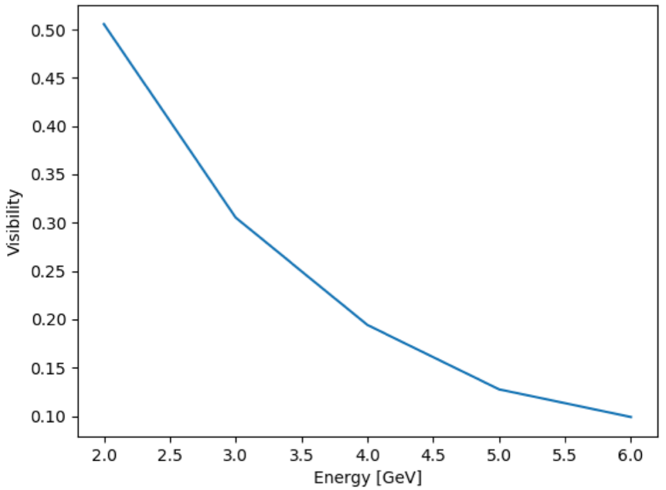


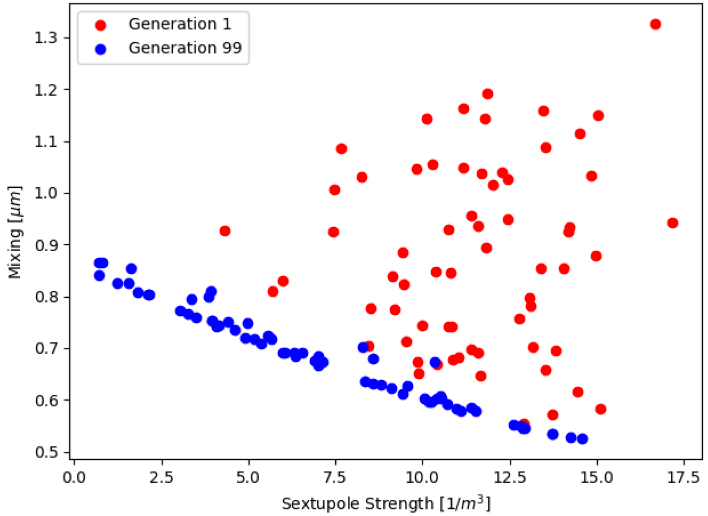
Specification	Value
Horizontal Emittance	8.4 nm
Vertical Emittance	8 pm
Fractional Energy Spread	4.5×10^{-5}
Simulated Interference Visibility	22%
Injection Efficiency	55%



Lattice Issues

- The lattice cannot be implemented at CESR at the usual 6 GeV
  - The lattice requires Q47W and Q47E to have very strong fields, running at 3.4 GeV would be the highest energy possible
  - Mixing/visibility scales with energy
  - 3 GeV was chosen
    - CESR has run at this energy before
- Correcting the second order terms require strong sextupole strengths, and there are only four of them in bypass
  - Dynamic aperture and injection efficiency significantly degraded
- Other CESR-specific considerations

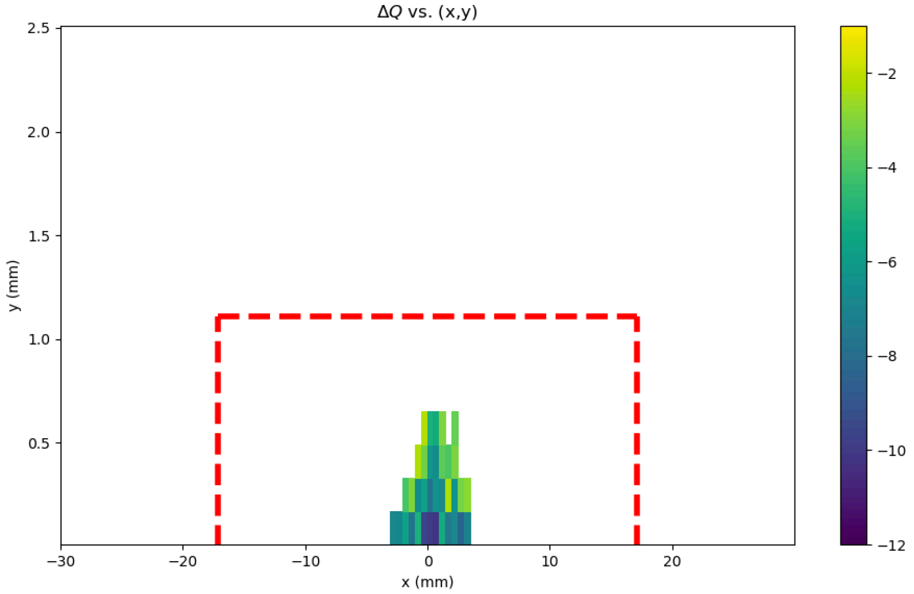




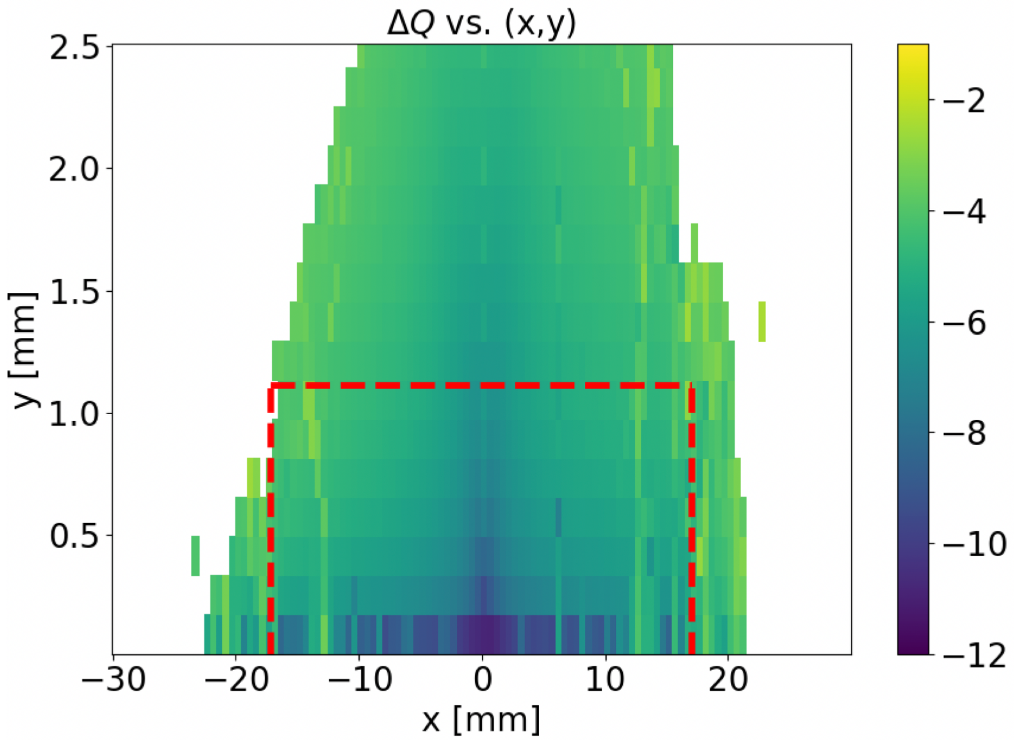
Dynamic Aperture

- To correct for this, the 71 sextupoles outside of the bypass were optimized using a genetic algorithm
  - Genetic algorithm utilizes “particle survival limits” found with BMAD particle tracking
- Plots shown use frequency map analysis (FMA) method

Start

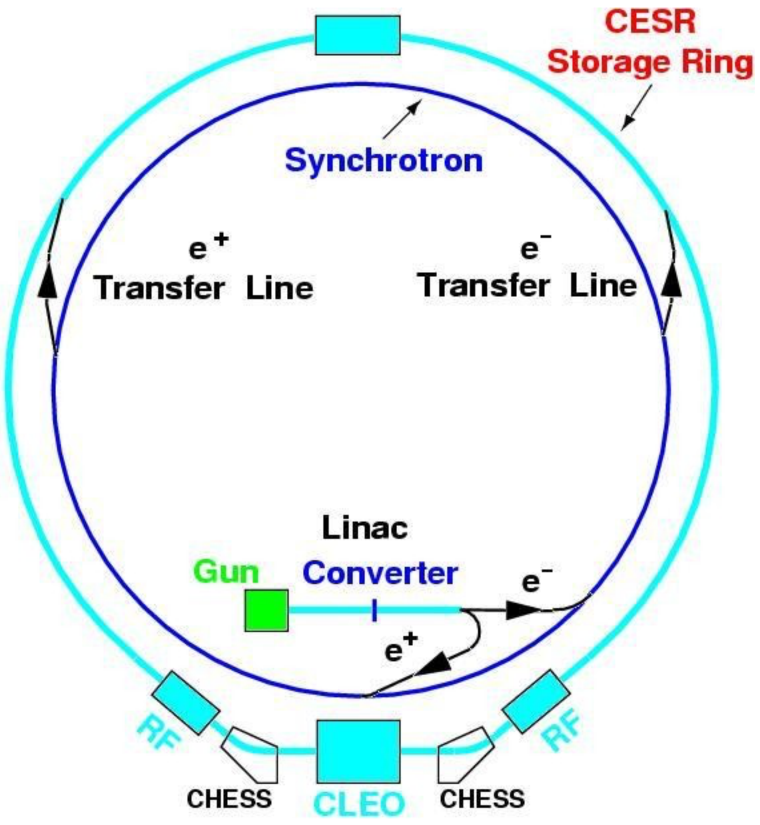


Finish



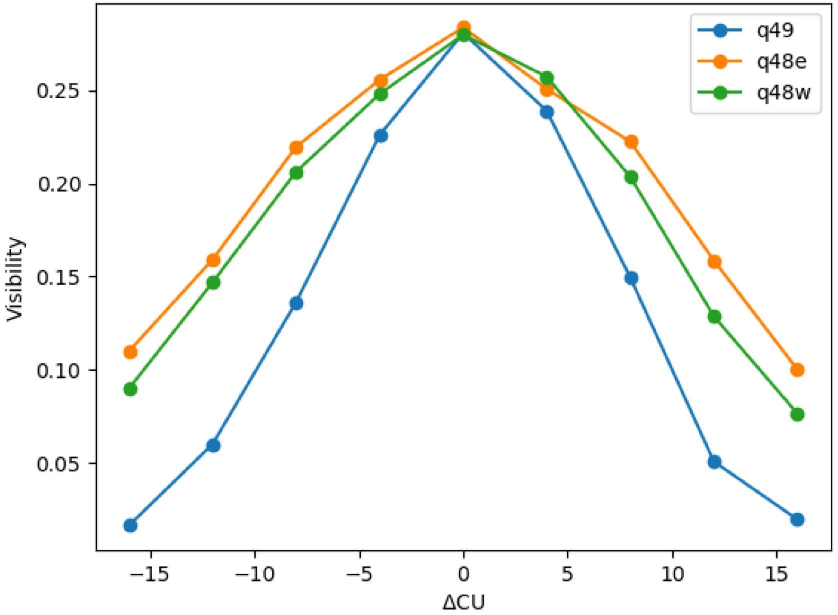
Injection

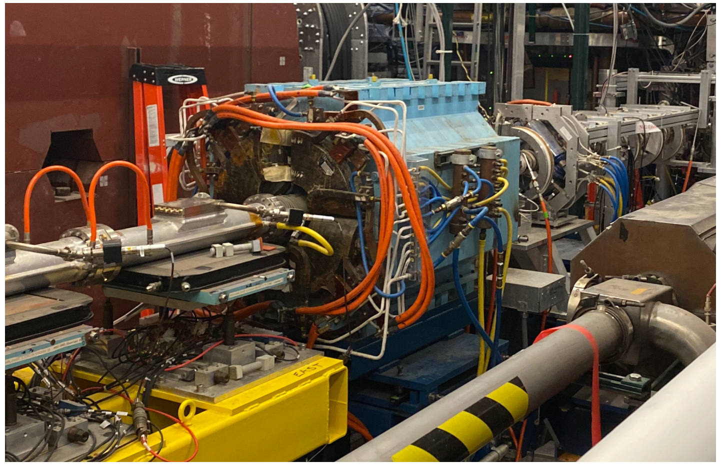
- At CESR, particles are injected from the inner synchrotron to the outer storage ring
- Injection efficiency calculated by simulating injection and tracking around the ring (S. Wang)
  - Simulate the location of particle loss
- Before optimizations, less than 5% of particles survived injection, 61% died along the south arc
  - Particles cannot be lost in the south arc, permanent magnet undulators located there
- DA and injection optimized with genetic algorithm
- After this optimization, the injection efficiency was brought up to 55%, with no particles lost in the south arc



Sensitivity

- Less than a 0.02% error/fluctuation in the fields of 3 bypass quadrupoles (Q49, Q48E, Q48W) would destroy the interference in simulation
- Fortunately, the field strengths of each were monitored during CHESS operations and the fields were shown to be stable enough for this experiment



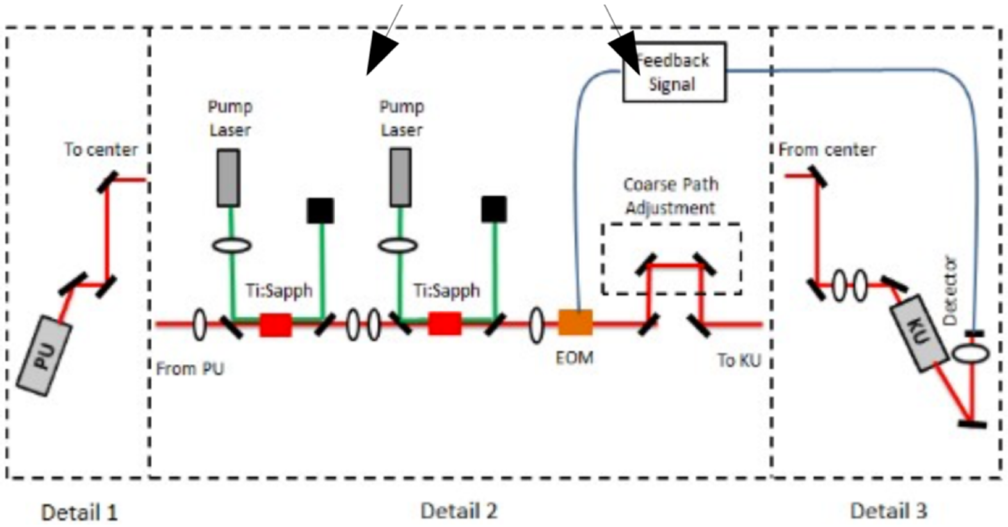


Lattice Summary/Outlook

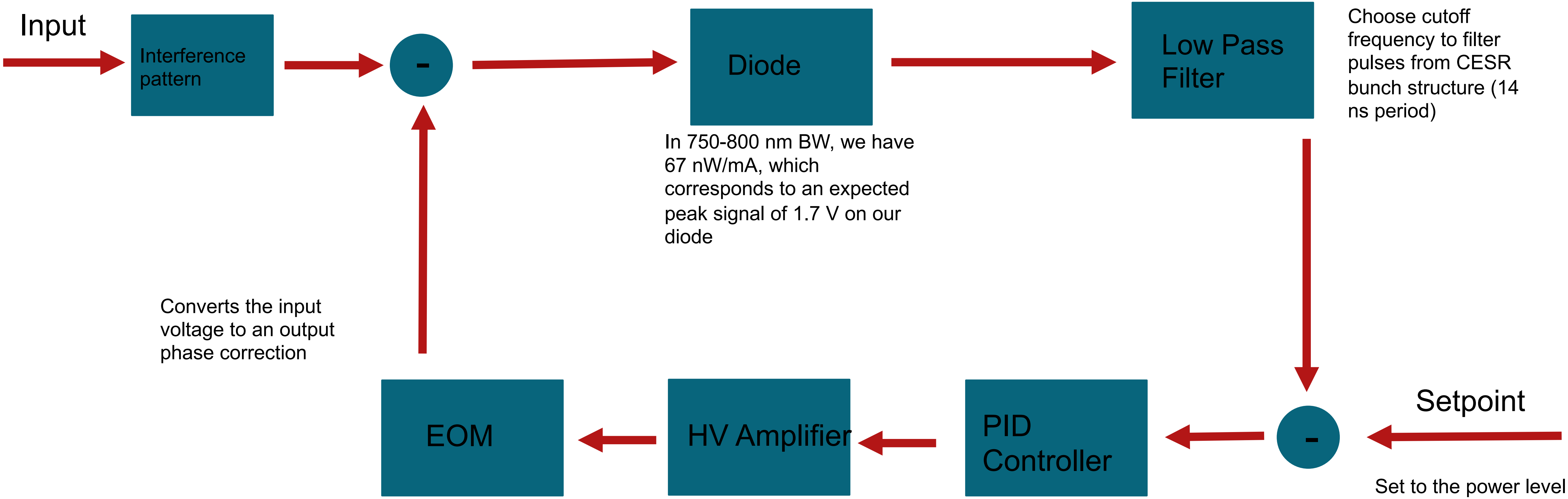
- Have designed a lattice that provides 21% visibility at 750 nm
- Meets all of CESR requirements for 3 GeV
- Had machine time last spring
  - Successfully implemented a similar lattice at 6 GeV
- Steps to implement the 3 GeV lattice
  - First must demonstrate successful ability to switch back and forth between 6 and 3 GeV (synchrotron)
  - Store a beam with the CHESS lattice at 3 GeV
  - Implement the OSC lattice incrementally

Feedback

- So we know how to get interference, how to we stabilize it?
- We are going to use a feedback system that emulates that of the full OSC
  - Electro-optic modulator (EOM) based: crystal’s index of refraction changes with applied voltage, hence delaying the light
- The EOM will be driven by a PID controller
  - An EOM-based system can increase the path-length stabilization requirement by a factor of about 30
- The EOM will be adjusting the light from the west dipole just before it meets the light from the east.



Elements of the Feedback System



Input

Interference pattern

-

Diode

In 750-800 nm BW, we have 67 nW/mA, which corresponds to an expected peak signal of 1.7 V on our diode

Low Pass Filter

Choose cutoff frequency to filter pulses from CESR bunch structure (14 ns period)

Setpoint

-

Set to the power level of an un-interfered pulse (1.7 V), π/2 error

PID Controller

HV Amplifier

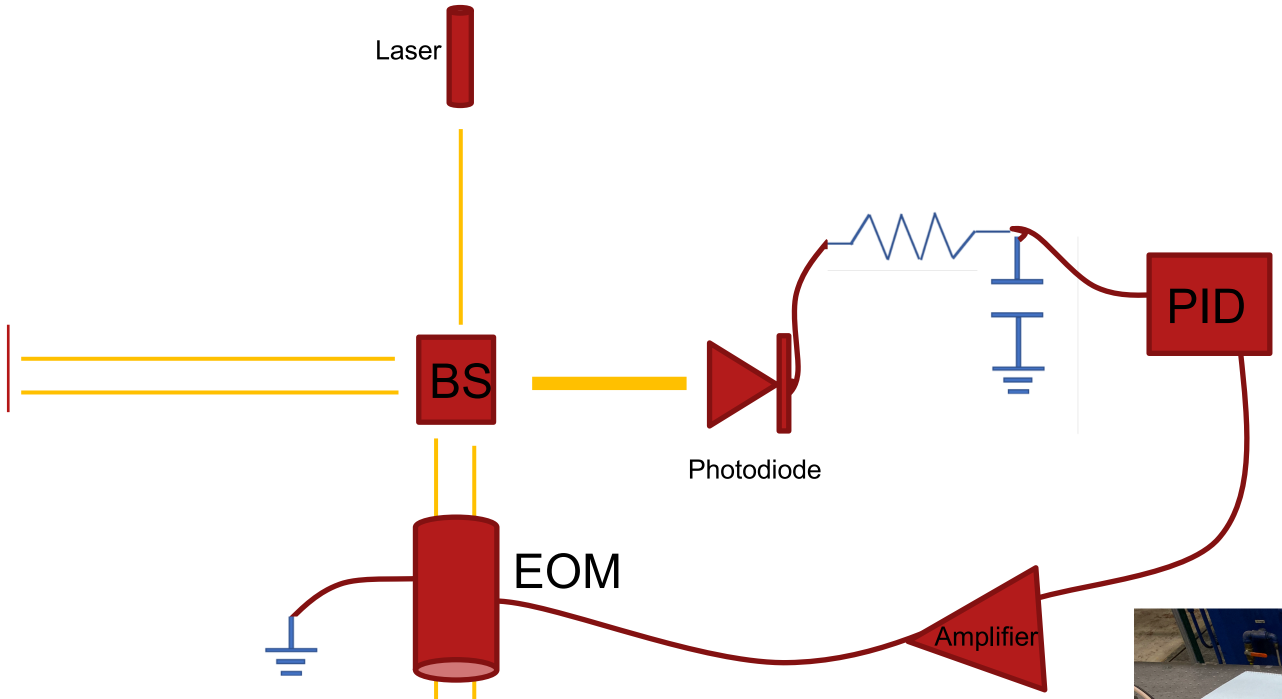
EOM

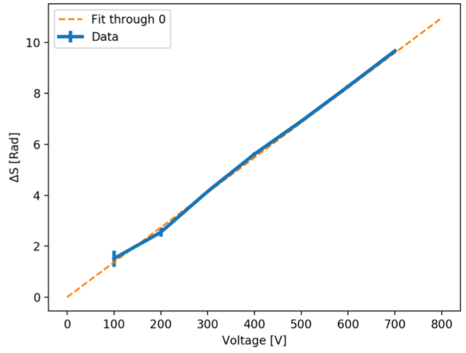
Converts the input voltage to an output phase correction

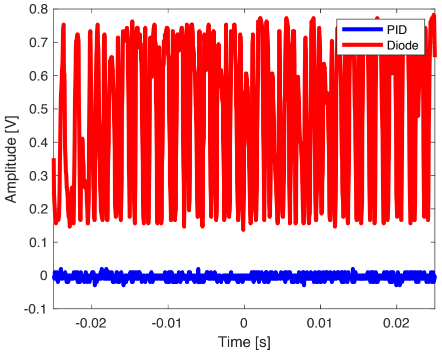
Our EOM can correct for ~2.5 μm at 750 nm

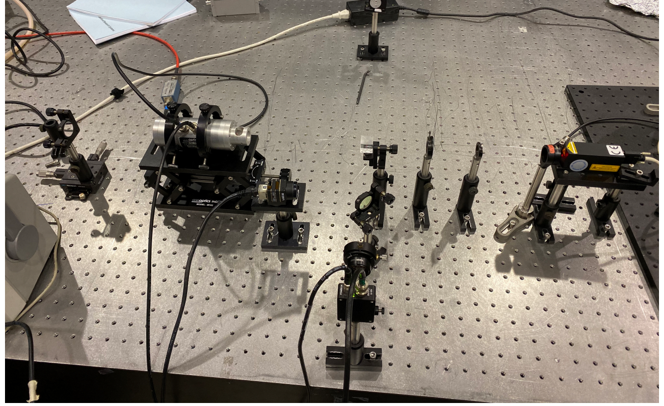
Set-up

- Tabletop Michelson demonstration
- Path jitter in Wilson Lab’s L0E measured and stabilized
- When light is interfered, the voltage reading on the photodiode will modulate according to the modulation of the path length error
  - In this case, it is the noisy environment of L0E
  - For instance, banging on the optics table will oscillate the path length by more than a wavelength, causing the voltage reading to “fold over itself”



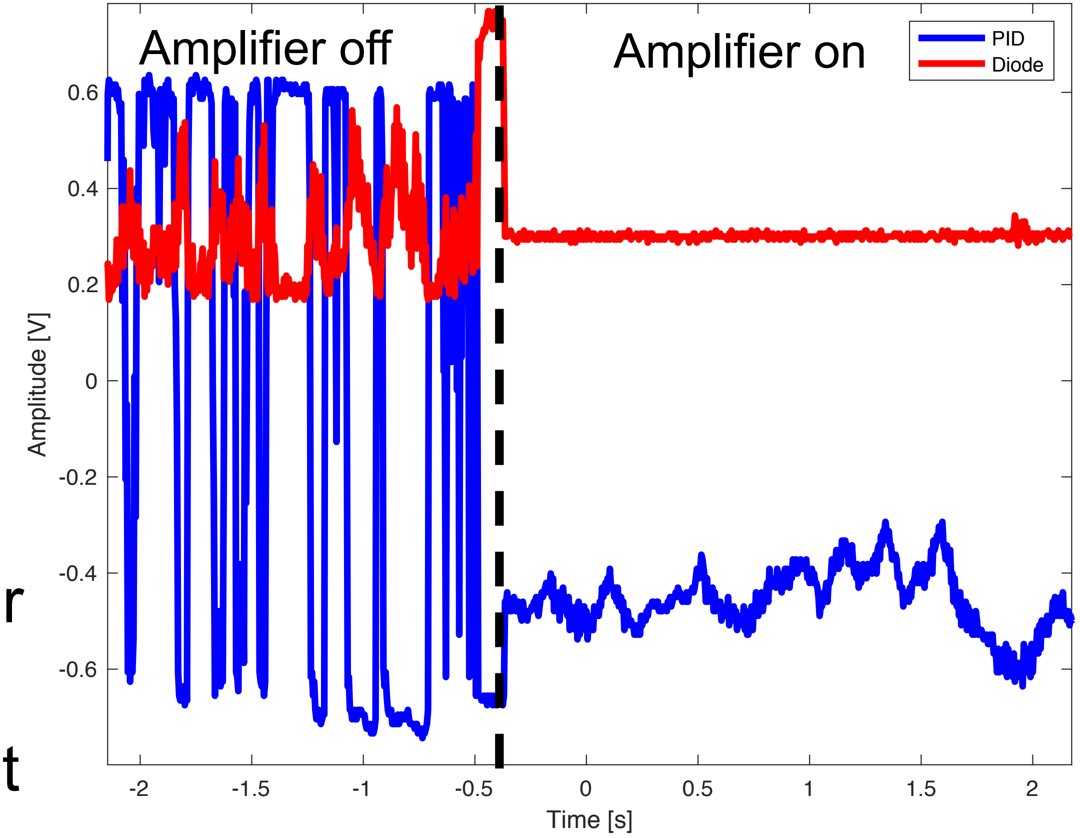






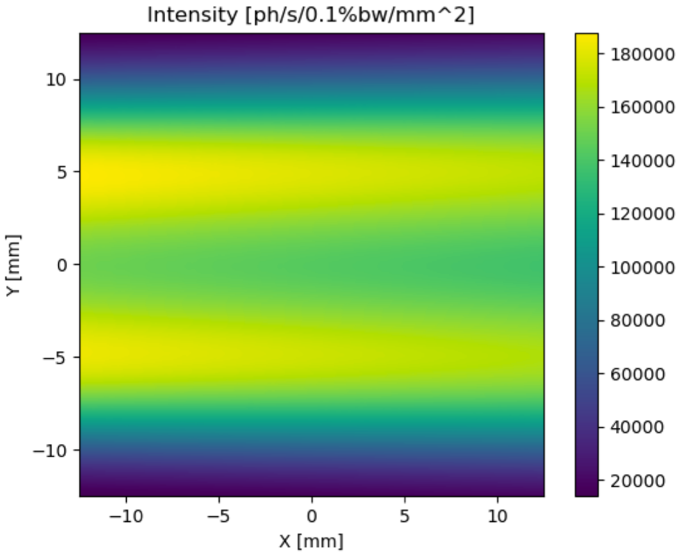
Results

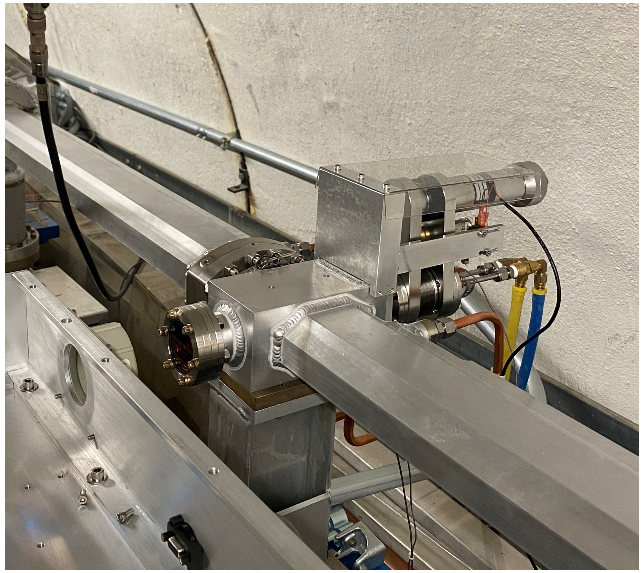
- Elements
  - LPF cutoff at 10 kHz
  - PID
    - 100 kHz BW
    - Optimal coefficient values: 0.4, 10^4, and 0
  - Amplifier: 1000x gain, 10 kHz BW
  - EOM: 272 V half-wave voltage
- 813 nm of peak-to-peak path length jitter observed without feedback
- Feedback on: 4 nm standard deviation error from setpoint
- Meets stabilization requirements for OSC at CESR
- Once interference is established in CESR, the system will be installed



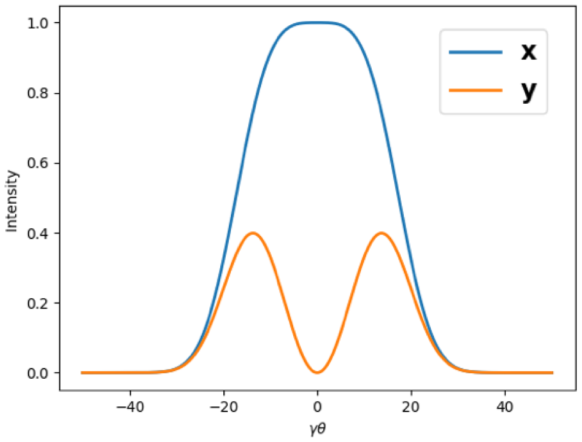
Optics

- 1/2”x1/2” water-cooled Beryllium mirror collects light downstream from each dipole
- Light from west is propagated 80 m across the ring to the EOM in the east
- West path consist of a set of collimating lenses and focusing lenses for EOM aperture
- East path focuses to optics table
- Calculated 67 nW/mA in 50 nm BW



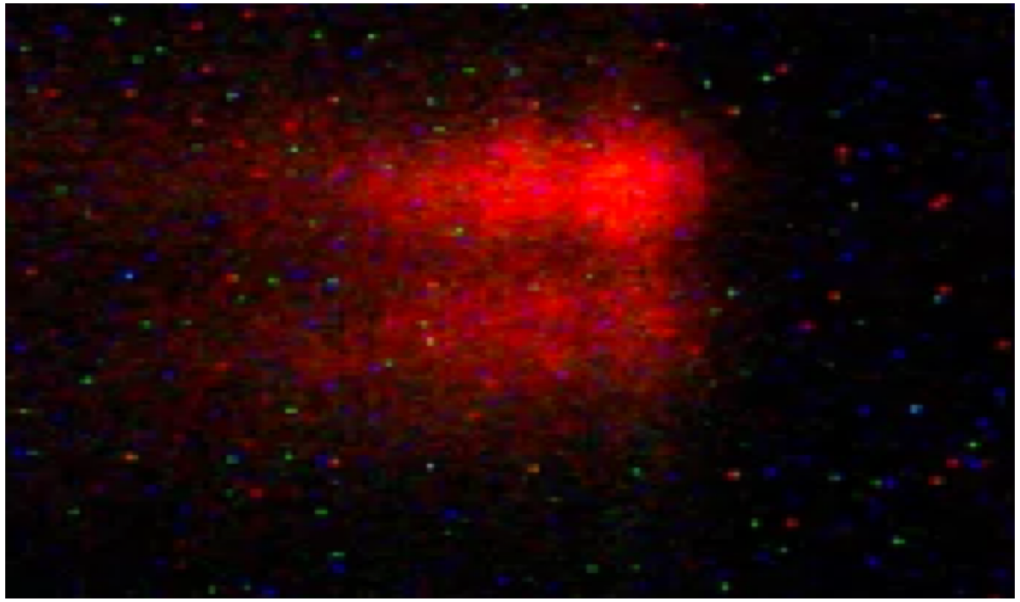


Parameter	Value
Dipole Bend Radius (ρ)	58.6 m
Critical Wavelength (ω_c)	0.15 nm
Particle Energy	3 GeV
Total Power/Particle (P_γ)	99.76 GeV/s



Alignment

- Most difficult/tedious part so far
- Done remotely and parasitic to normal CHESS operations
  - Can only adjust something on Tuesdays
- Cameras/screens placed sequentially downstream throughout the light path
- Many challenges with radiation damage
- Paths eventually aligned, joined at east optics table



Drone Footage

Conclusion/Outlook

- OSC is a promising technique for beam cooling
- Goal for OSC at CESR is the demonstration of active cooling

Currently pursuing a test of path length stability to…

- Show stabilization of light path and time accuracy with particles in bypass
- Demonstrate OSC feedback system
- Properly set our lattice to maximize our interference visibility

- The contents of this presentation will be reported at IPAC22

Thank you!