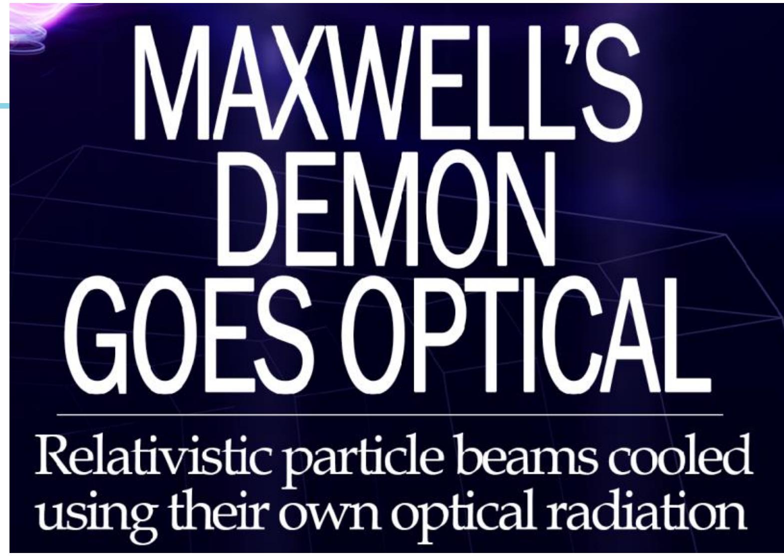
First Experimental Demonstration of Optical Stochastic Cooling

Sergei NAGAITSEV (Fermilab/U.Chicago) on behalf of the OSC collaboration

July 7, 2022



First Experimental Demonstration of Optical Stochastic Cooling, J. Jarvis, V. Lebedev, A. Romanov, D. Broemmelsiek, K. Carlson, S. Chattopadhyay, A. Dick, D. Edstrom, I. Lobach, S. Nagaitsev, H. Piekarz, P. Piot, J. Ruan, J. Santucci, G. Stancari, and A. Valishev

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What is beam cooling?

- Cooling is a reduction in the phase space occupied by the beam (for the same number of particles).
  - It’s not about the beam temperature
- Equivalently, cooling is a reduction in the random motion of the beam.

- Examples of non-cooling:
  - Beam scraping (removing particles with higher amplitudes) is NOT cooling;
  - “Cooling” due to beam acceleration;
  - Expanding the beam transversely lowers its transverse temperature. This is NOT cooling;
  - Coupling between degrees of freedom may lead to a reduction in the phase-space projection area. This is NOT cooling.

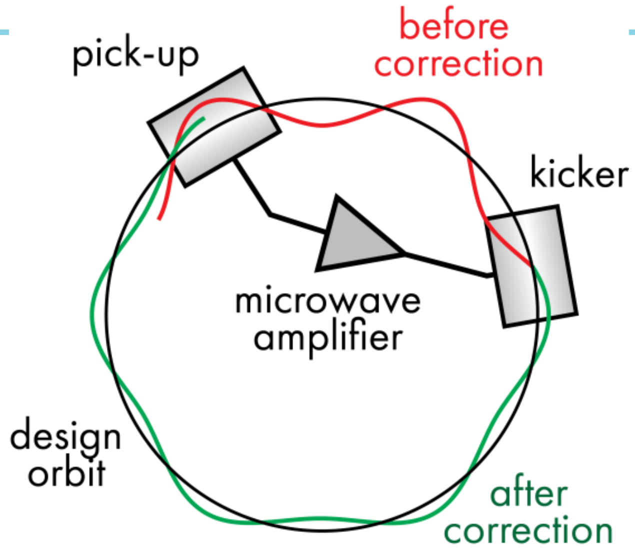
Why cool beams?

- Particle accelerators create a beam with a virtually limitless reservoir of energy in one (longitudinal) degree of freedom. This energy can couple (randomly and coherently) to other degrees of freedom by various processes, such as:
  - Scattering (intra-beam, beam-beam, residual gas, internal target, foil @ injection);
  - Improper bending and focusing;
  - Interaction with beam's environment (e.g. wake fields);
  - Space-charge effects;
  - Secondary and tertiary beams;
- Normally, it is necessary to keep momentum spreads in the transverse degrees of freedom at ~10^{-4} of the average longitudinal momentum.

Beam cooling methods

- Two basic methods employed for hadron beam cooling today:
  - Stochastic cooling (1984 Nobel Prize in Physics)
  - Electron cooling
- Stochastic Cooling
  - Tested experimentally at CERN in ICE ring, 1977-78
  - Employed in the past for pbar accumulation at CERN & Fermilab (also planned at FAIR)
  - Successfully employed for ion bunched-beam cooling at the top energy in RHIC;
  - Various variations of stochastic cooling were proposed for the EIC: coherent electron cooling, micro-bunching cooling, optical stochastic cooling.
    - Present baseline is based on the CEC-MB concept

Stochastic Cooling: an enabling technology for colliders



(simplified stochastic cooling system)

$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi \sigma_x{}^* \sigma_y{}^*}$$

1984 Nobel: van der Meer/Rubbia

Simon van der Meer (COOL 1993 workshop, Montreux):

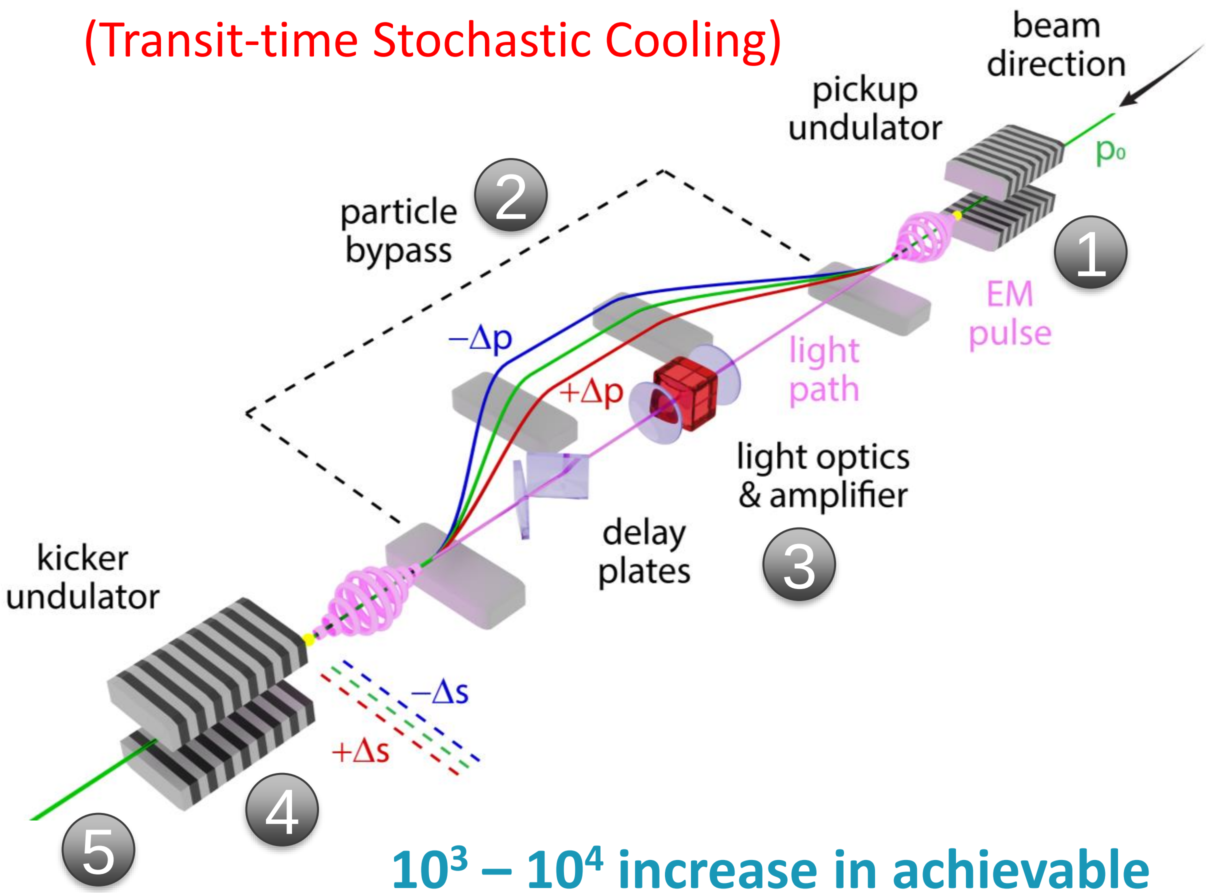
“How then can cooling work? It must necessarily be through deformation of phase space, such that particles move to the center of the distribution and (to satisfy Liouville) the empty phase space between the particles moves outwards. Clearly, the fields that do this must have a very particular shape, strongly correlated with particle position. In fact, at least two conditions must be satisfied:

1. The field that cools a particular particle must be correlated with the particle’s phase-space position. **In short, the field must know where each particle is.**
2. The field that pushes a particular particle towards the centre should preferably push the empty phase-space around it outwards. **It should therefore treat each particle separately.**

With stochastic cooling, these two conditions are clearly corresponding to the function of the pickup and kicker. **Both must be wide-band in order to see individual particles as much as possible**.”

Optical stochastic cooling

(Transit-time Stochastic Cooling)



1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates over many turns

10^3 – 10^4 increase in achievable stochastic cooling rate (~10s of THz BW vs few GHz)

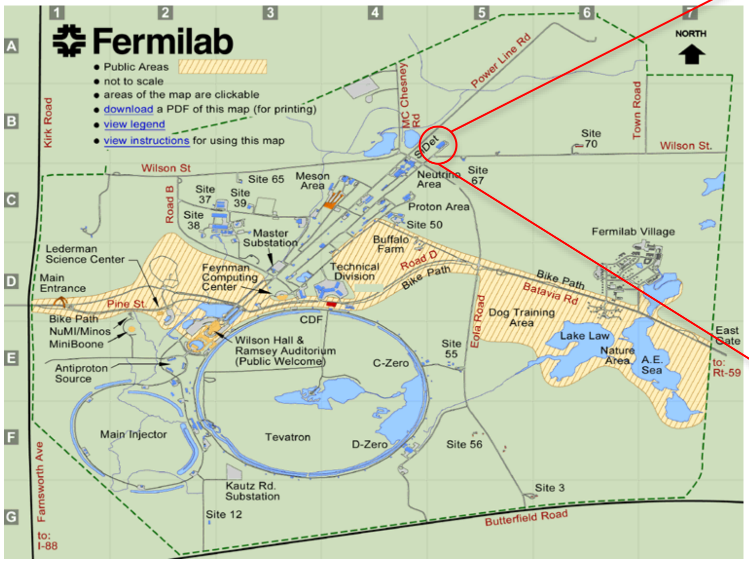
A.A.Mikhailichkenko, M.S. Zolotorev, "*Optical stochastic cooling*," Phys. Rev. Lett. 71 (25), p. 4146 (1993)

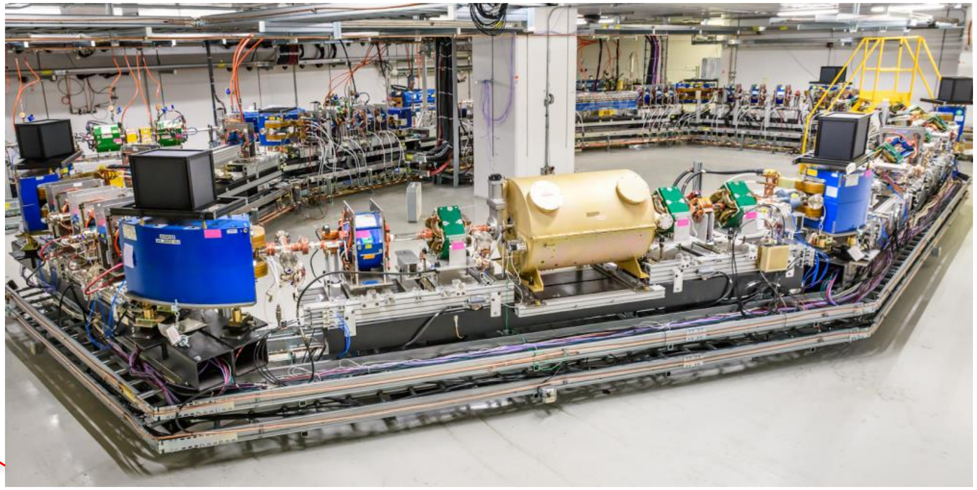
M. S. Zolotorev, A. A. Zholents, "*Transit-time method of optical stochastic cooling*," Phys. Rev. E 50 (4), p. 3087 (1994)

Optical Stochastic Cooling demonstration at Fermilab

Fermilab's Integrable Optics Test Accelerator (IOTA)

First beam Aug 21, 2018



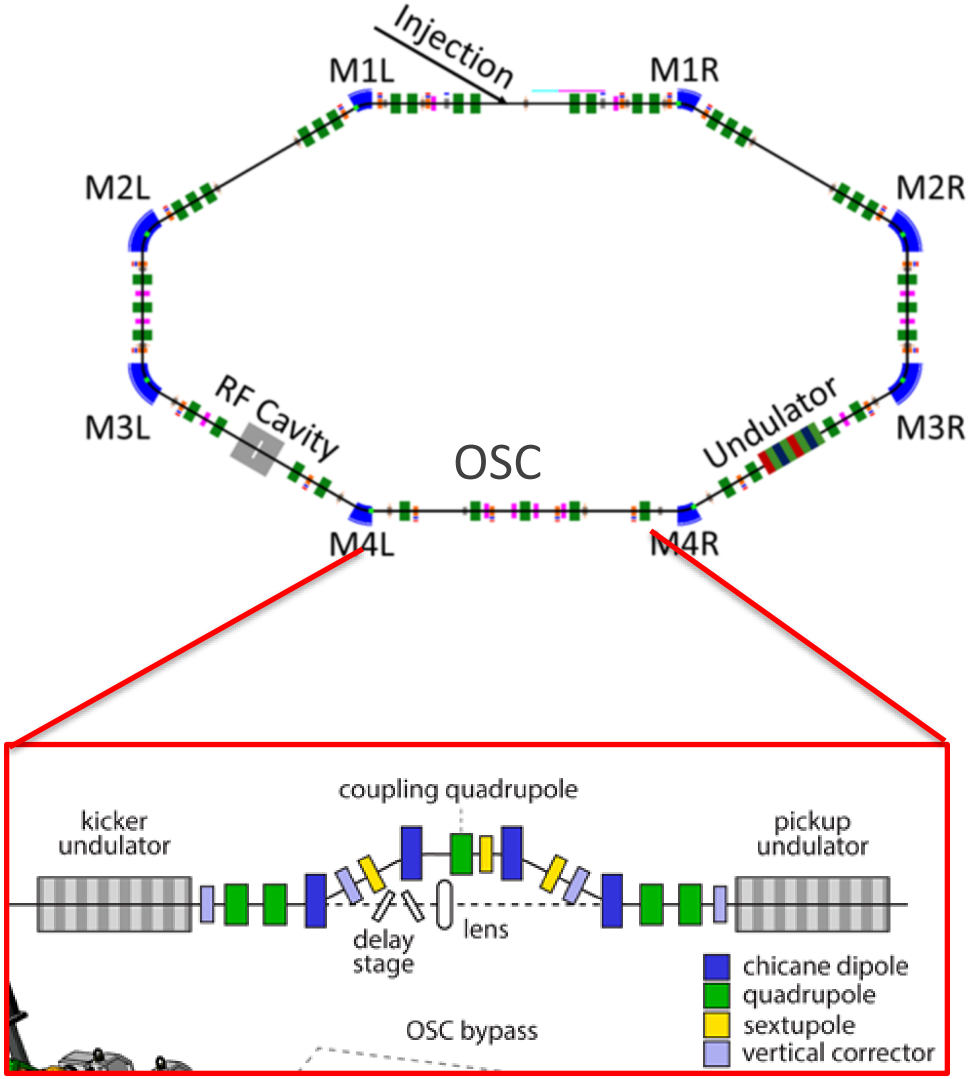


Circumference: 40 m (133 ns)

Electron energy: 100-150 MeV

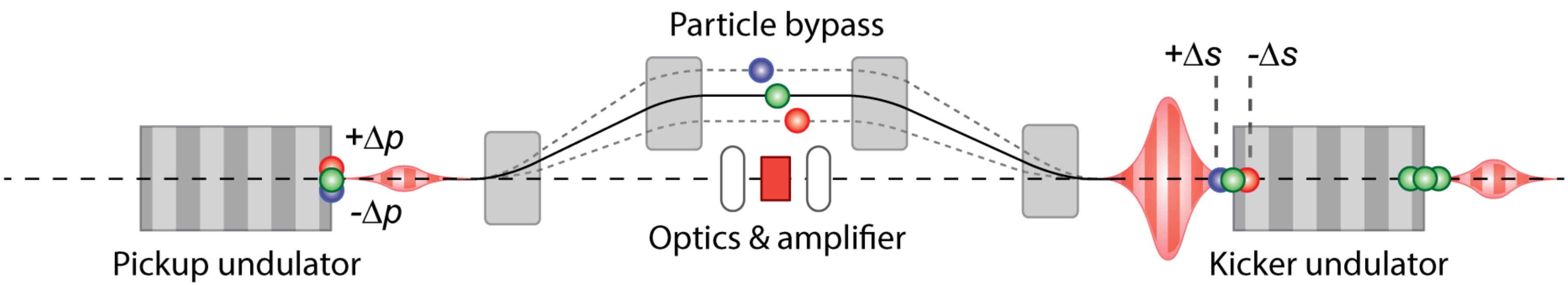
Primary purpose of IOTA: accelerator science and technology research

Layout of the OSC section in IOTA

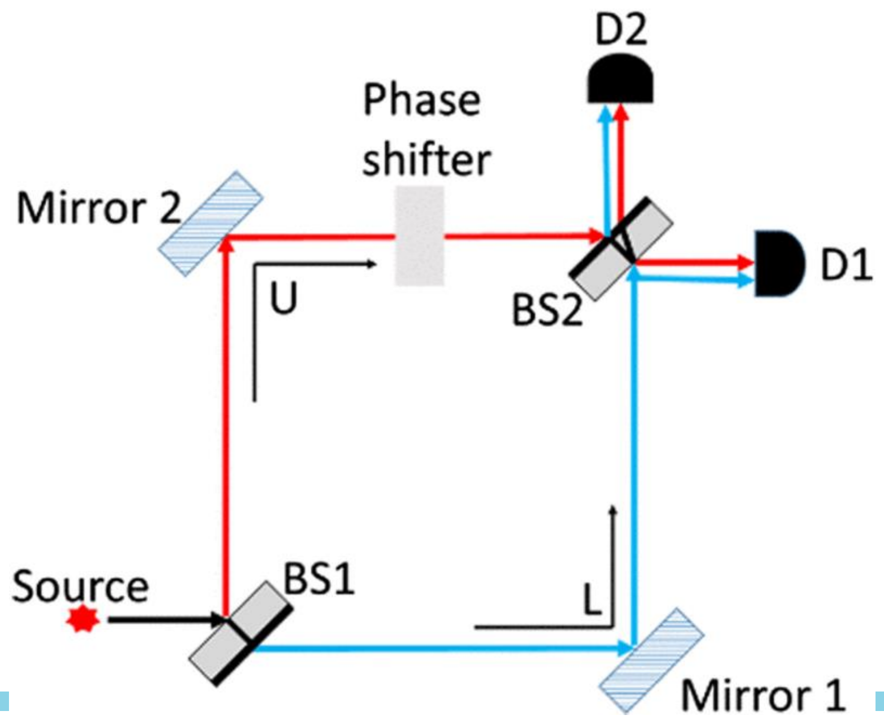


Fermilab

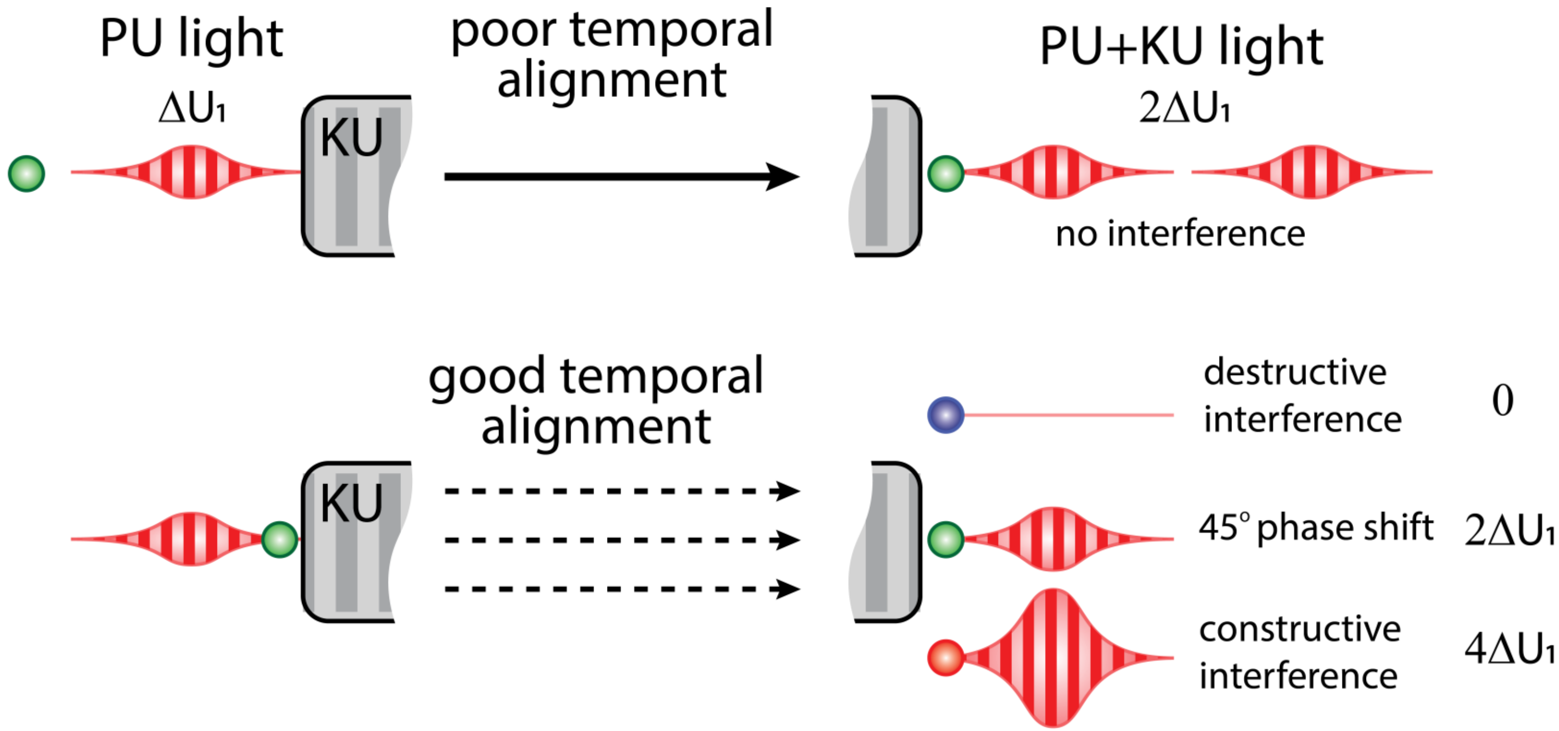
OSC: electron and photon interference



Mach-Zehnder Interferometer



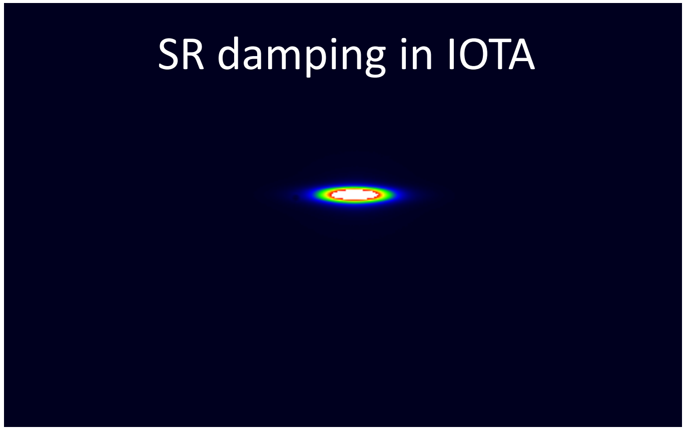
OSC energy exchange has the character of interference

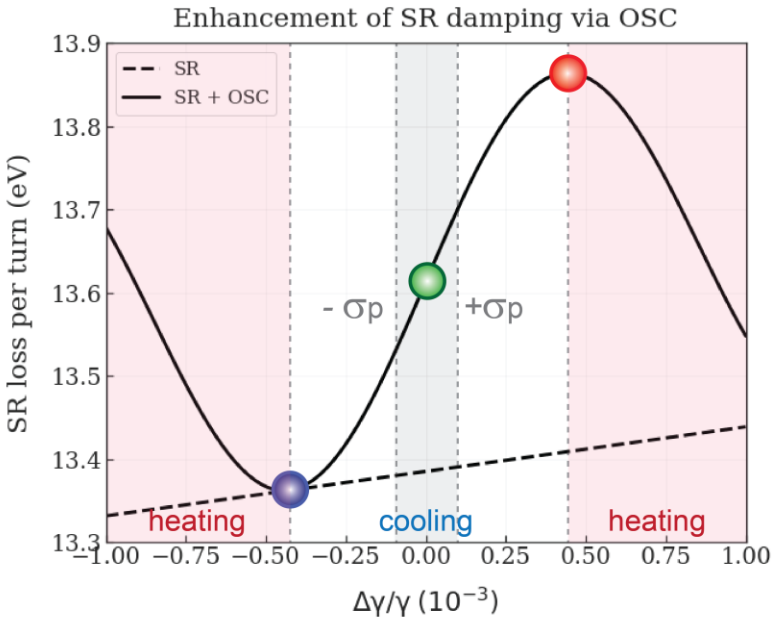


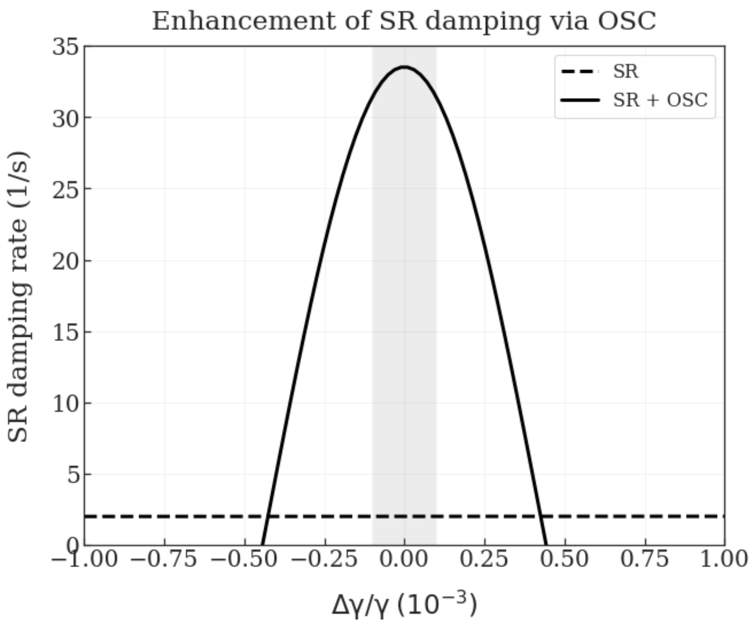
- Matching optical delay and particle-bypass delay will produce interference between the PU and KU radiation
- Amount of light emitted then depends strongly on the delay change due to the particle's momentum (and trajectory) error
- Neighboring particles add a random contribution that produces diffusion

"Interference" of UR greatly amplifies SR damping

- SR-damping rate goes as ***dU/dE***
- UR interference produces large ***dU/dE*** for small deviations in ***E***
- IOTA's OSC was designed to dominate SR damping by ~10x without any optical amplification ($\tau_{\varepsilon s}$~50 ms, $\tau_{\varepsilon x/y}$~100 ms)

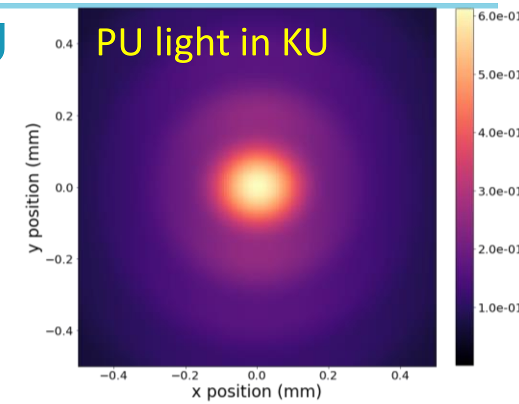


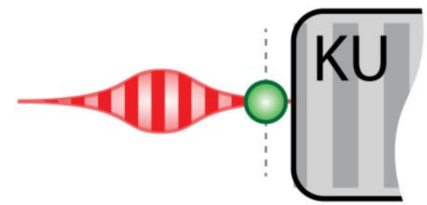


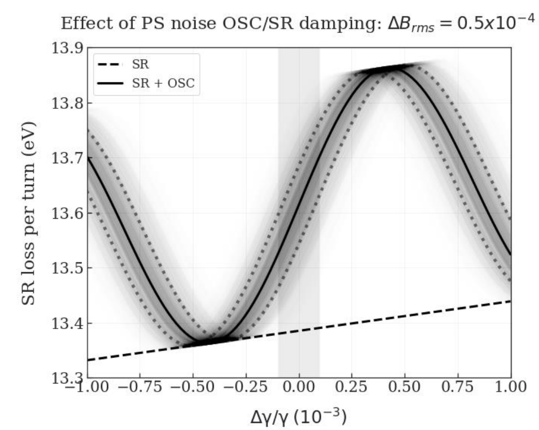


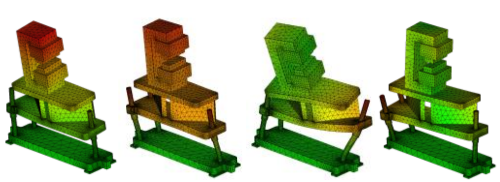
What makes ("simple") OSC challenging?

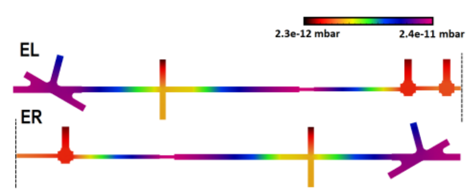
1. Beam and PU light must overlap through the KU
   - The undulator light is **~200 μm** wide
   - Want angle between light and beam at < **~0.1 mrad**
2. Beam and PU light must arrive ~simultaneously for maximum effect
   - Absolute timing should be better than **~0.3 fs**
   - The entire delay system corresponds to ~2000 fs
3. The electron bypass and the light path must be stable to much smaller than the wavelength
   - Arrival jitter at the KU should be better than **~0.3 fs**
   - This means total ripple+noise in chicane field must be at the **~mid 10^{-5}** level
4. Practical considerations of design and integration!





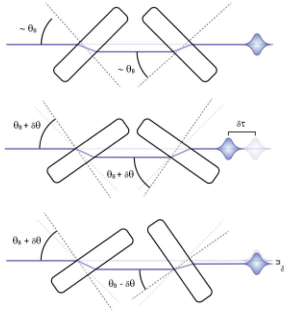




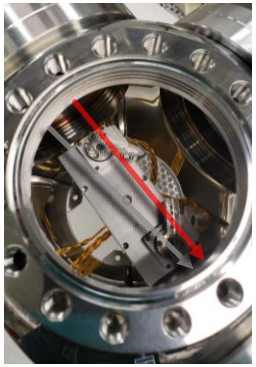


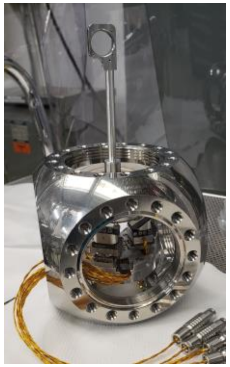
OSC apparatus successfully integrated in IOTA

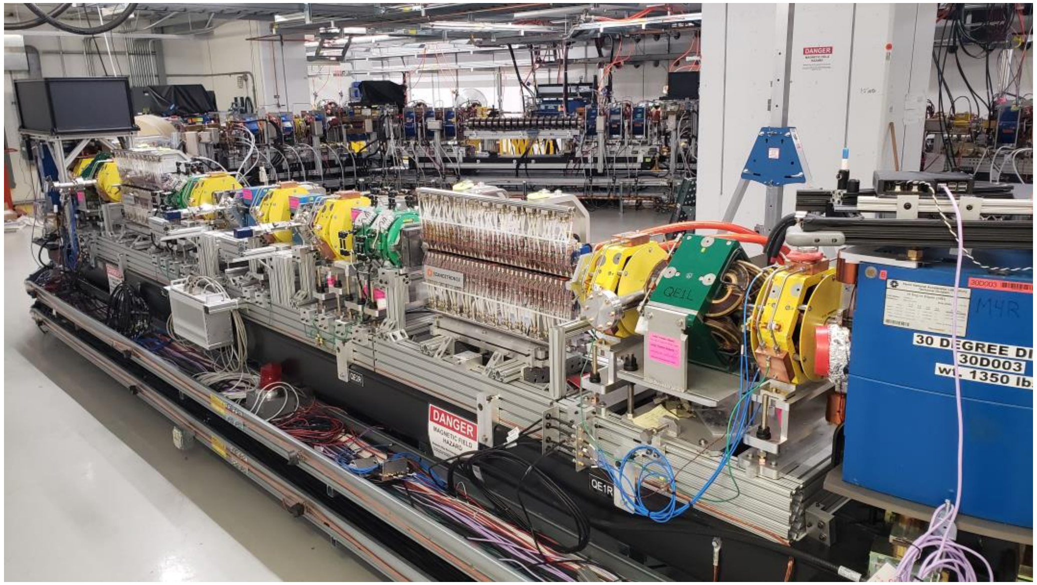
- Established and corrected OSC lattice to desired precision
- Achieved ~80% of theoretical max aperture and ~20-min lifetime; sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully validated all diagnostic and control systems

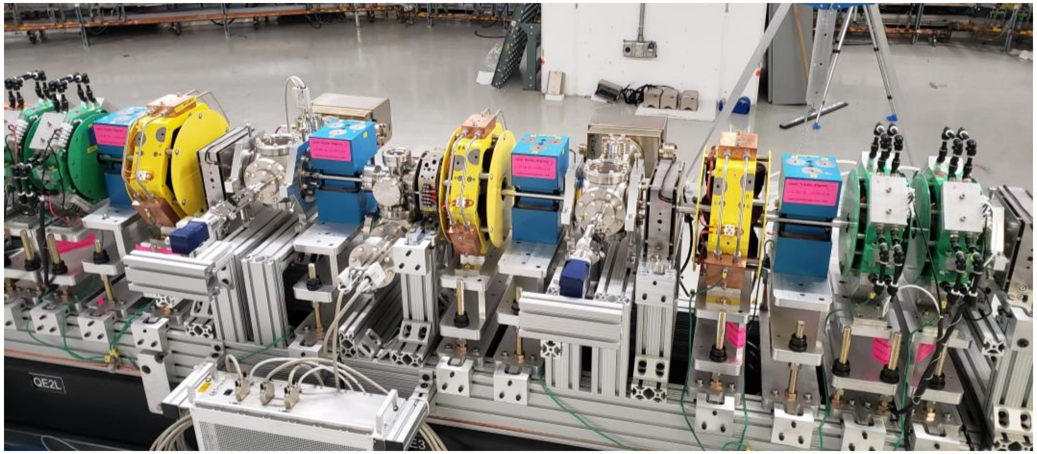


Delay stage

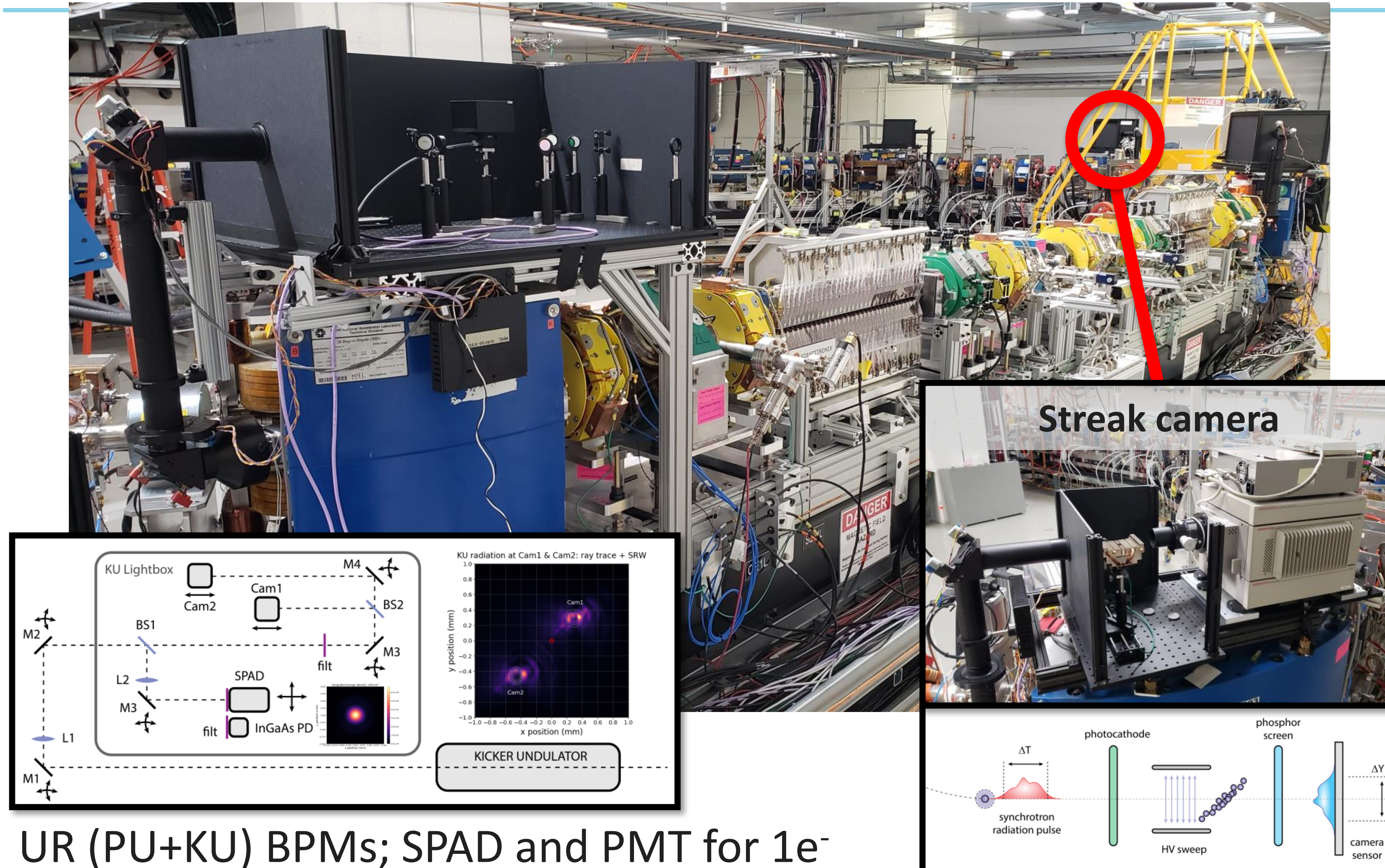








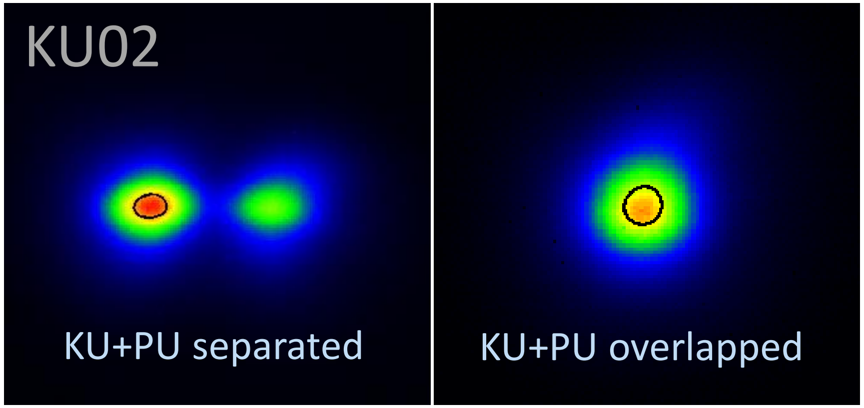
OSC is monitored via synchrotron-rad. stations

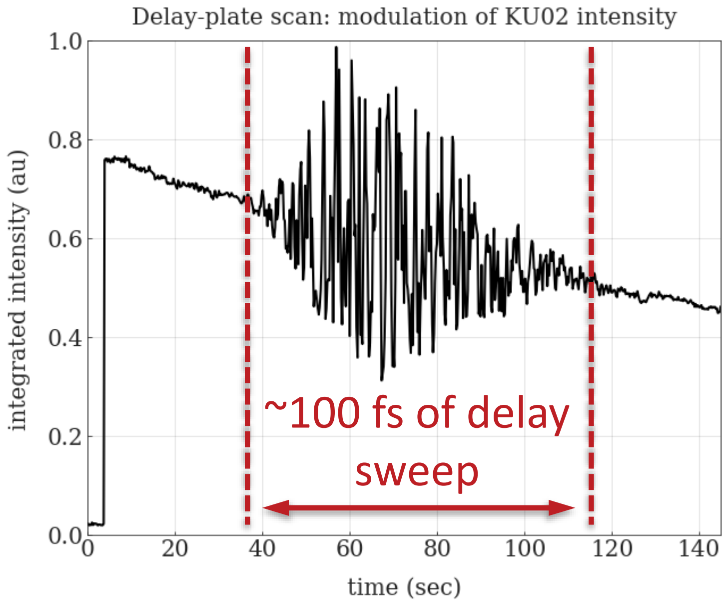


UR (PU+KU) BPMs; SPAD and PMT for 1e$^-$

On 04/20/21, interference was observed at full undulator power

- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- In-vacuum light optics and closed-orbit bumps were used to maximally overlap the coherent modes of the undulators, first on the detectors and then inside the kicker undulator
- This coherent-mode overlap, in both space and time, is the fundamental requirement for producing OSC
- When this condition was met, synchrotron-radiation cameras throughout IOTA were monitored for a definite effect on the beam….

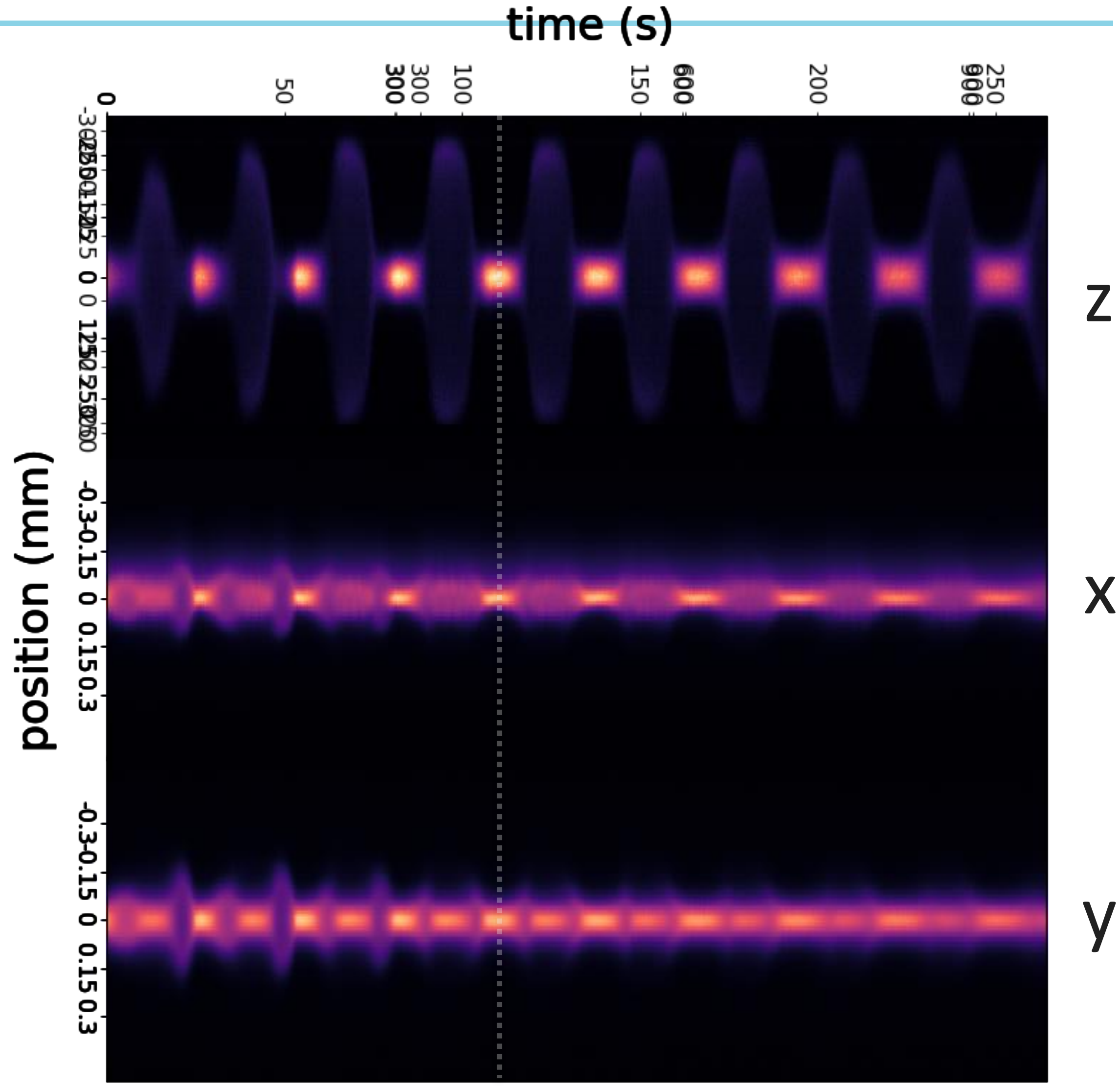




Delay scan through entire wavepacket-overlap region

After much work… OSC was strong and stable

- 1D: lattice decoupled and bypass quad set to null transverse response to OSC; some residual due to dispersion @ SR BPM
- 2D: lattice decoupled and bypass coupling to nominal
- 3D: lattice coupled and bypass to nominal
- OSC system is reoptimized for each configuration
- Delay system is scanned at a constant rate of 0.01deg/sec
- Corresponds to ~one wavelength every 30 sec



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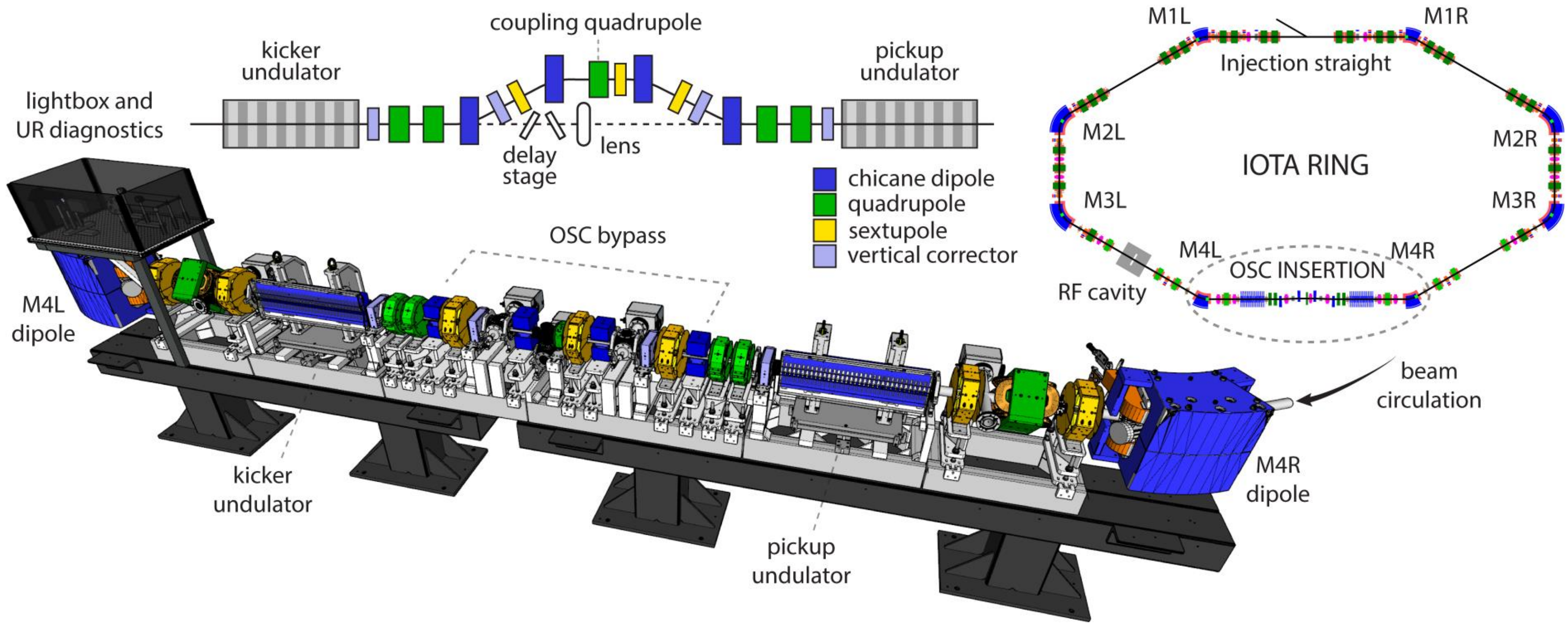
A staged approach for OSC at IOTA



- **Non-amplified OSC (~1-μm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-μm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification + effect on cooling, active phase-space control for improved cooling

Conclusions from our OSC experiments

- Our first ever demonstration of stochastic beam cooling at optical frequencies serves as a foundation for more advanced experiments with high-gain optical amplification and advances opportunities for future operational OSC systems with potential benefit to a broad user community in the accelerator-based sciences.
- Many of the OSC (technical) features are common to the CEC method
- May offer a feasible method for cooling hadrons at energies below ~4 TeV (e.g. at the EIC). May also enhance the existing synch radiation facilities.