Experimental Demonstration of Optical Stochastic Cooling: Single-Particle Feedback in the Optical Regime

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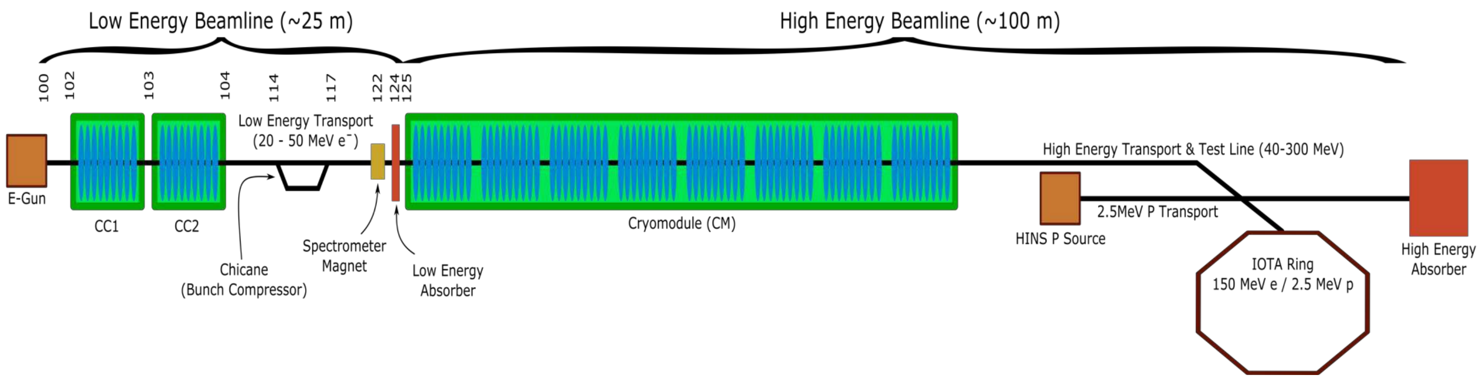
Sept 15, 2022

IOTA/FAST Facility: a center for Accelerator and Beam Physics

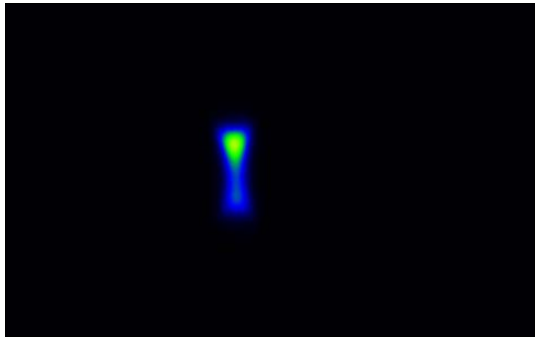
- **IOTA/FAST establishes a unique capability at FNAL to address frontier topics in ABP**
- Dedicated facility for intensity-frontier accelerator R&D
- 2.5 MeV Proton injector currently under construction for R&D with high-intensity beams
- Integrated SRF testing with high-intensity beams (historical roots as ILC test facility; maintain capability to bring ILC-related testing back online if needed)
- ~30 Collaborating institutions
- Nat. Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Many opportunities for R&D with cross-office benefit in DOE/SC (HEP, NP, BES)



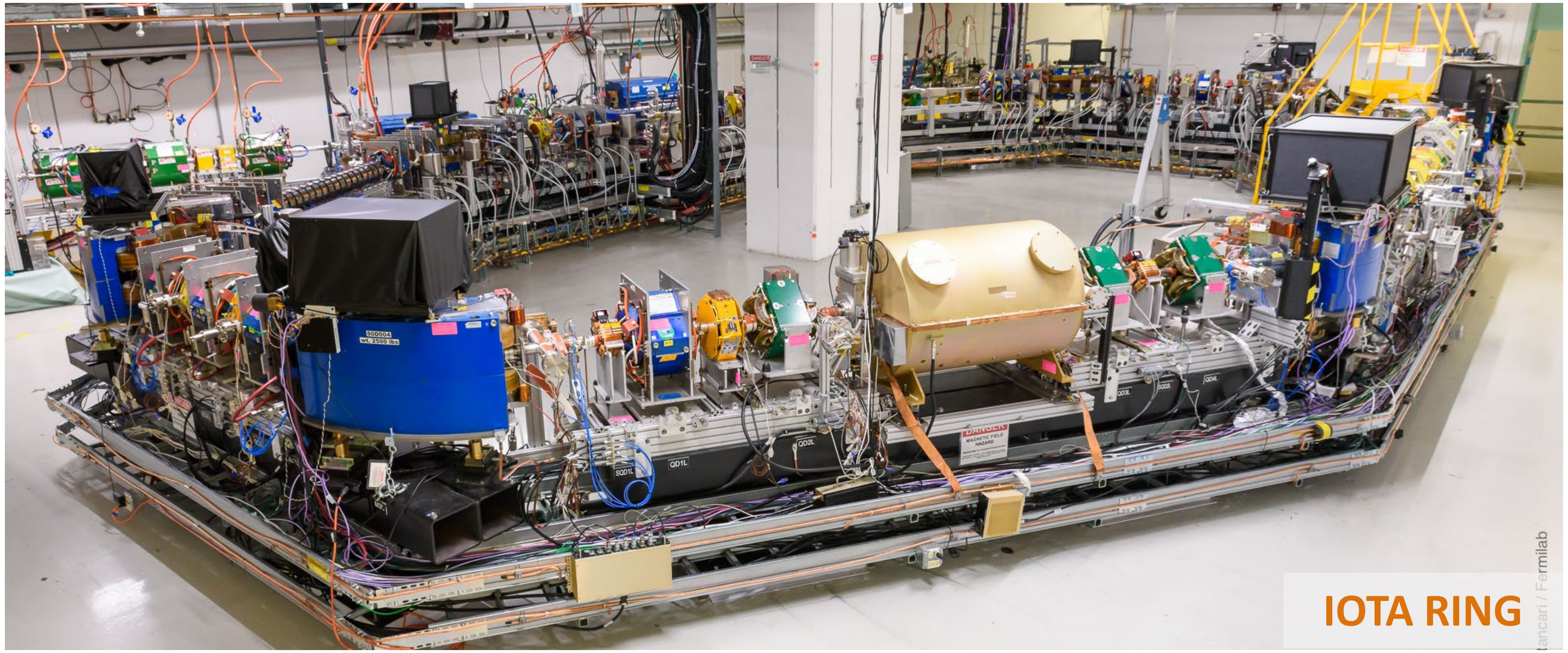
A broad and expanding R&D program @ IOTA

- Suppression of coherent instabilities via Landau damping (NIO, E-lenses)
- Mitigation of space-charge effects (NIO, E-lenses)
- **Advanced beam cooling; Optical Stochastic Cooling**
- Photon and Quantum Science with a single electron
- Development of novel instrumentation and methods

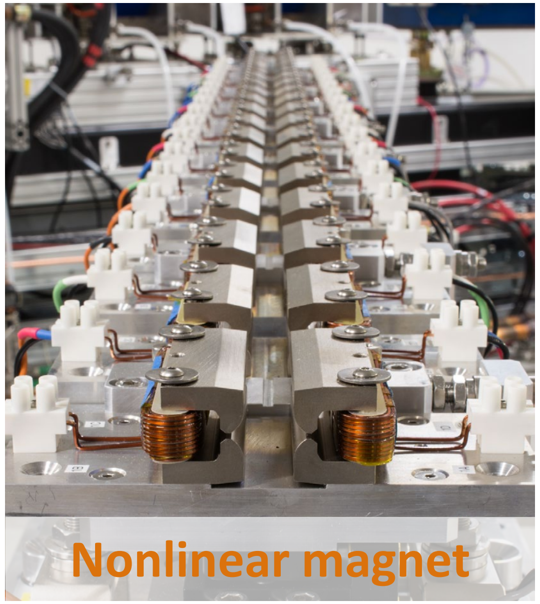
Real-time video of IOTA beam in NIO optics **on integer resonance** !!!



Low-emittance lattice: few/single e-

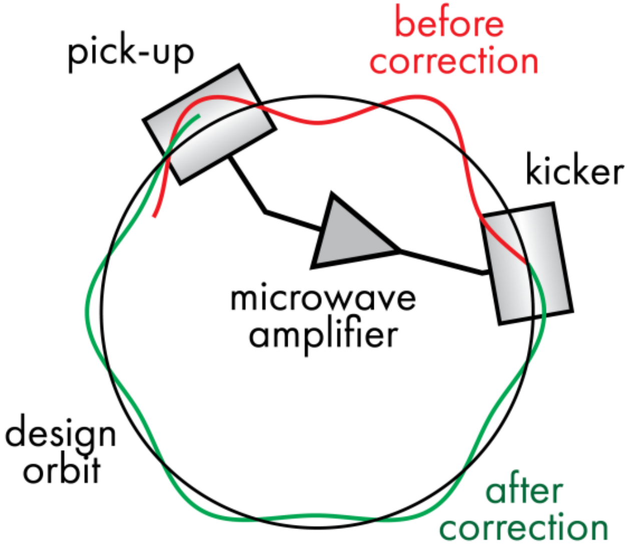


IOTA RING



Nonlinear magnet

Stochastic Cooling: an enabling technology for colliders



(simplified stochastic cooling system)

1984 Nobel: van der Meer & Rubbia

$$\frac{1}{\tau} = \frac{2W}{N}\left(2g - g^2\right)$$

cooling heating

g : fraction of total sample error corrected per pass
N: total # of particles in ensemble
W: bandwidth of feedback system (Hz)
τ : cooling time for variance (seconds)

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.

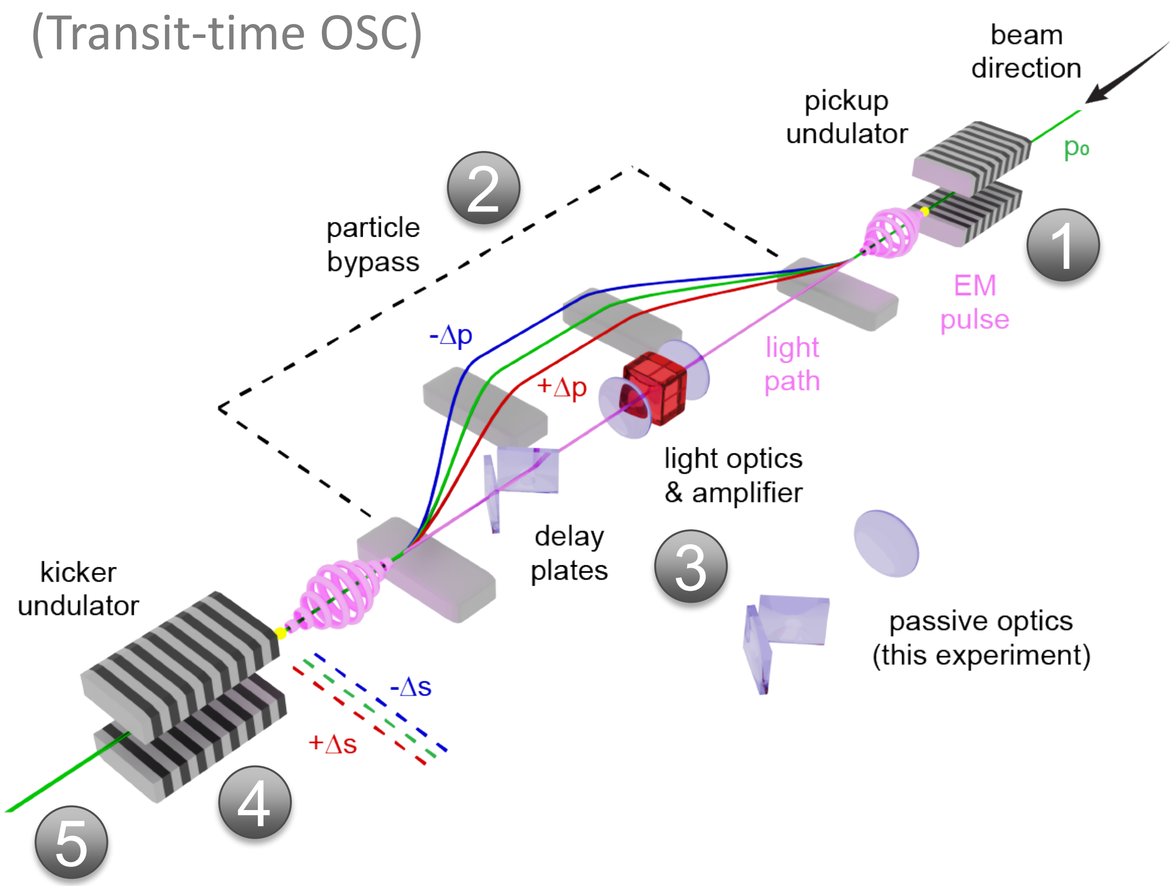
In short, the field must know where each particle is.

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."

OSC extends the SC principle to optical bandwidth



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)

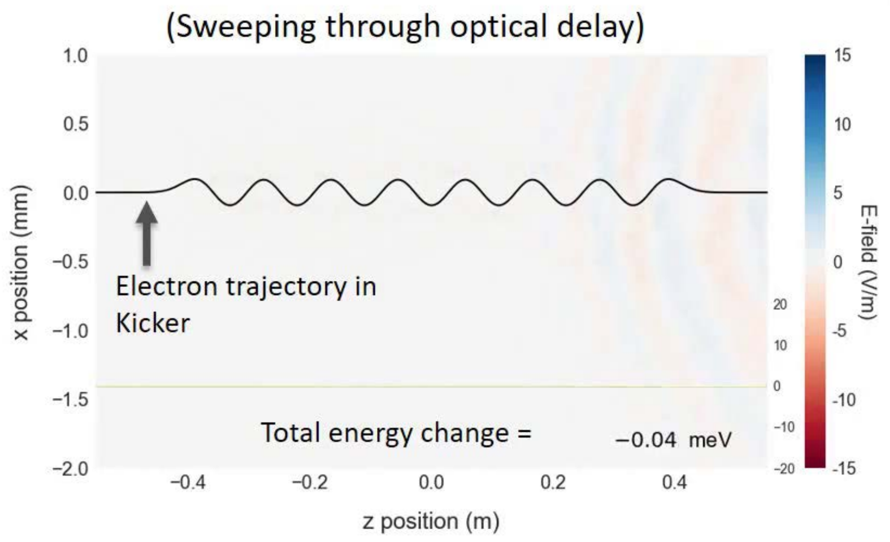
A.A.Mikhailichkenko, M.S. Zolotorev, "*Optical stochastic cooling*," Phys. Rev. Lett. 71 (25), p. 4146 (1993)
M. S. Zolotorev, A. A. Zholents, "*Transit-time method of optical stochastic cooling*," Phys. Rev. E 50 (4), p. 3087 (1994)

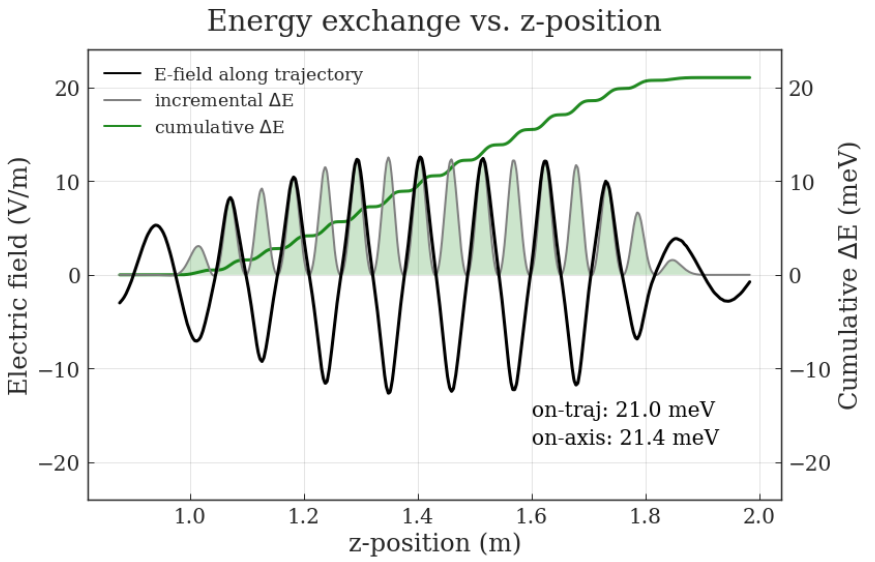
OSC principle: corrective kick based on a particle's error

- OSC is based on energy exchange between a particle and its undulator-radiation field
- Sign and magnitude of correction depends on particle's momentum error (1D cooling)
- Neighboring particles add a random contribution that produces diffusion
- IOTA's OSC design naturally produces 3D cooling…

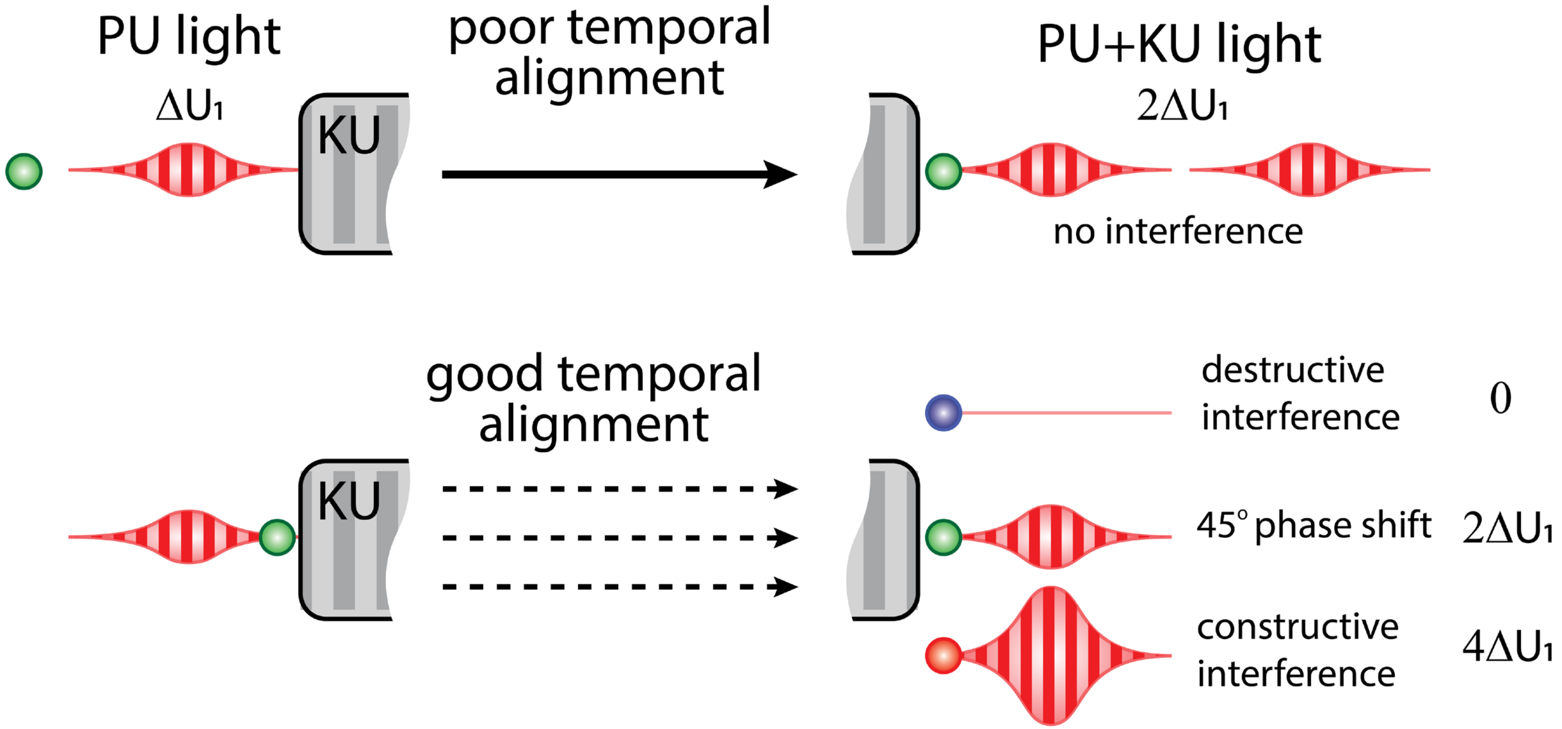
  - Coupling in the bypass shares cooling between the longitudinal and horizontal planes (2D)

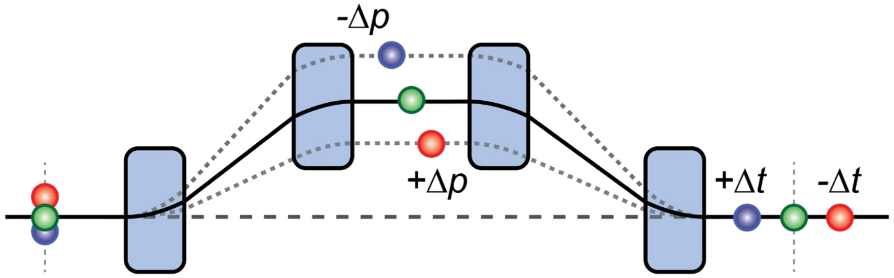
  - Operation of the storage ring on a transverse coupling resonance shares the horizontal cooling with the vertical plane (3D)





OSC energy exchange has the character of interference





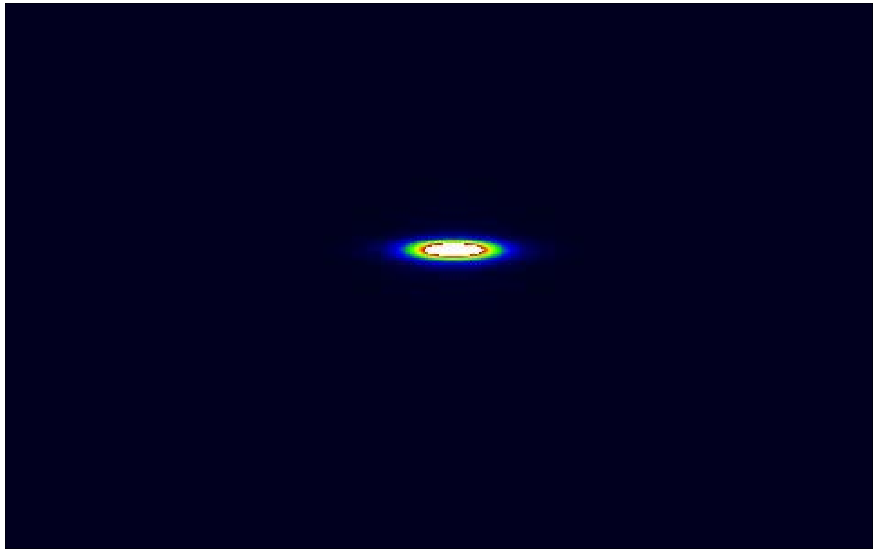
$$c\Delta t \sim \underbrace{(M_{51}D + M_{52}D'}_{\text{transverse}} + \underbrace{M_{56})}_{\text{longitudinal}}\frac{\Delta p}{p}$$

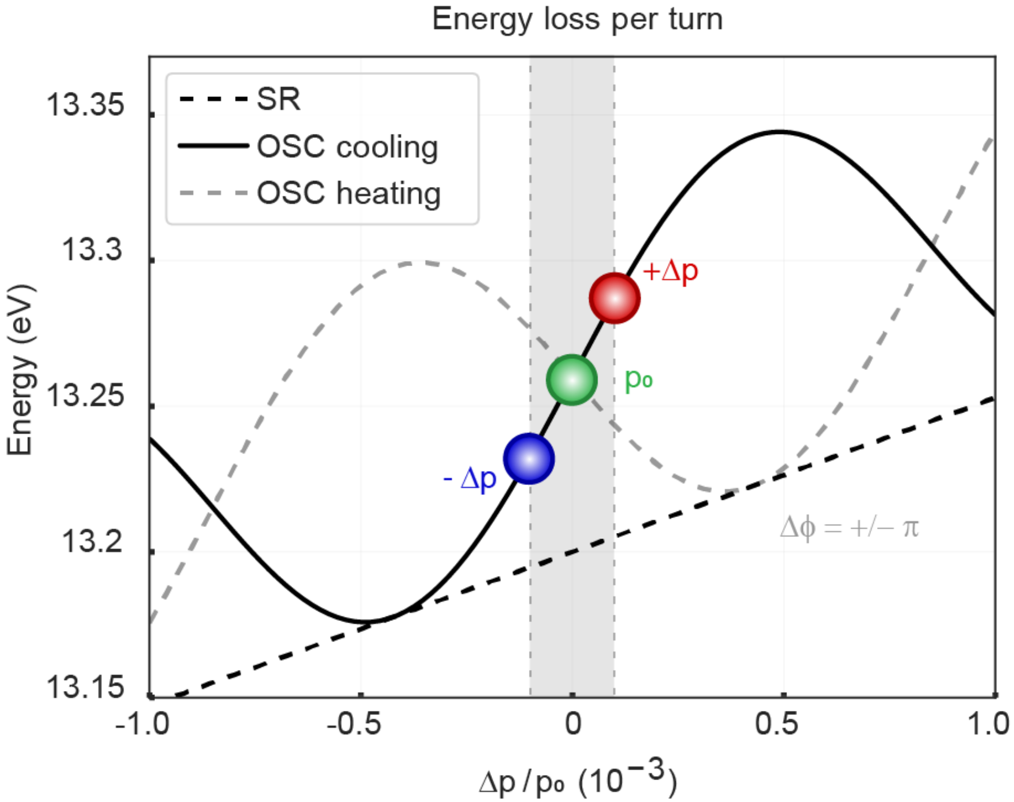
- Matching optical delay and particle-bypass delay will produce interference between the PU and KU radiation
- Amount of light emitted then depends strongly on the delay change due to the particle's momentum (and trajectory) error

Fermilab

Interference of UR greatly amplifies SR damping

Example of SR damping in IOTA



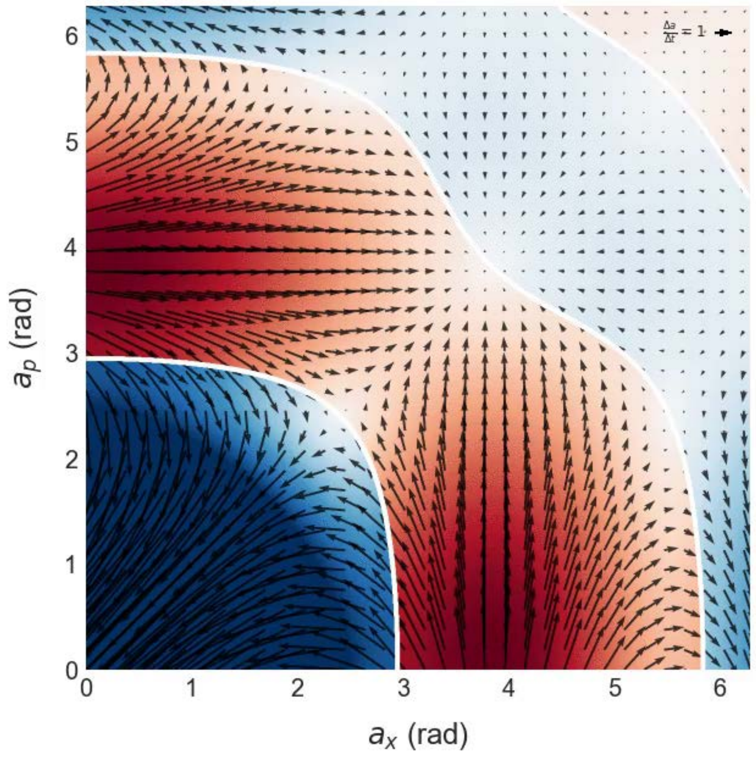


- SR-damping rate goes as ***dU/dE***
- UR interference produces large ***dU/dE*** for small deviations in ***E***
- IOTA's OSC was designed to dominate SR damping by ~10x without any optical amplification ($\tau_{\varepsilon s}$~50 ms, $\tau_{\varepsilon x/y}$~100 ms)

Short wavelength results in finite range of the OSC force

- Due to short wavelength of radiation, OSC force can be reduced or even inverted at large amplitudes
- OSC must be averaged over betatron and synchrotron motions
- "Cooling range" is the fundamental zone where all particles are cooled towards zero amplitude
- Other attractors can exist at high amplitudes
- Shifting delay by half a wavelength inverts cooling and heating zones

(Sweeping through optical delay)

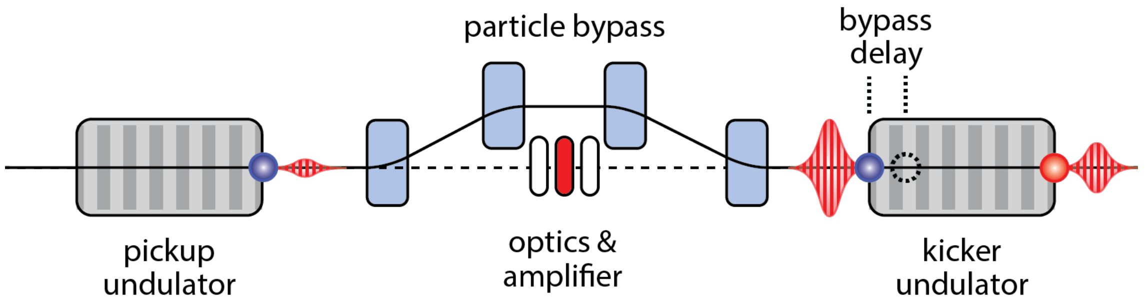


$$\frac{\delta p}{p} = -\kappa \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right)$$

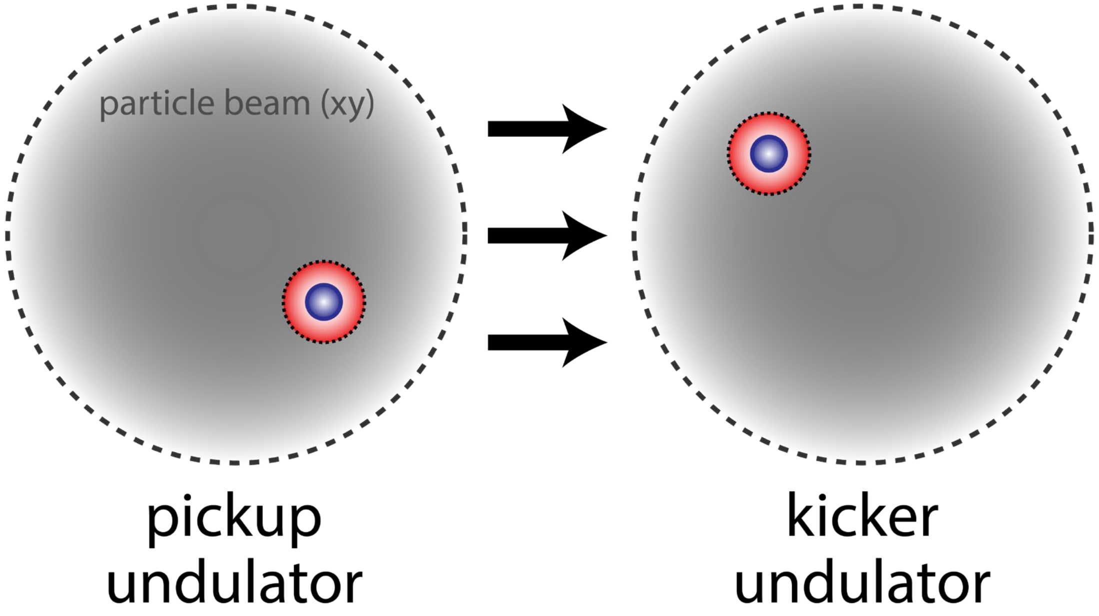
Cooling map integrated over betatron and synchrotron oscillations; arrows show mag. and dir. of net force

Transverse sampling can further increase effective BW of OSC

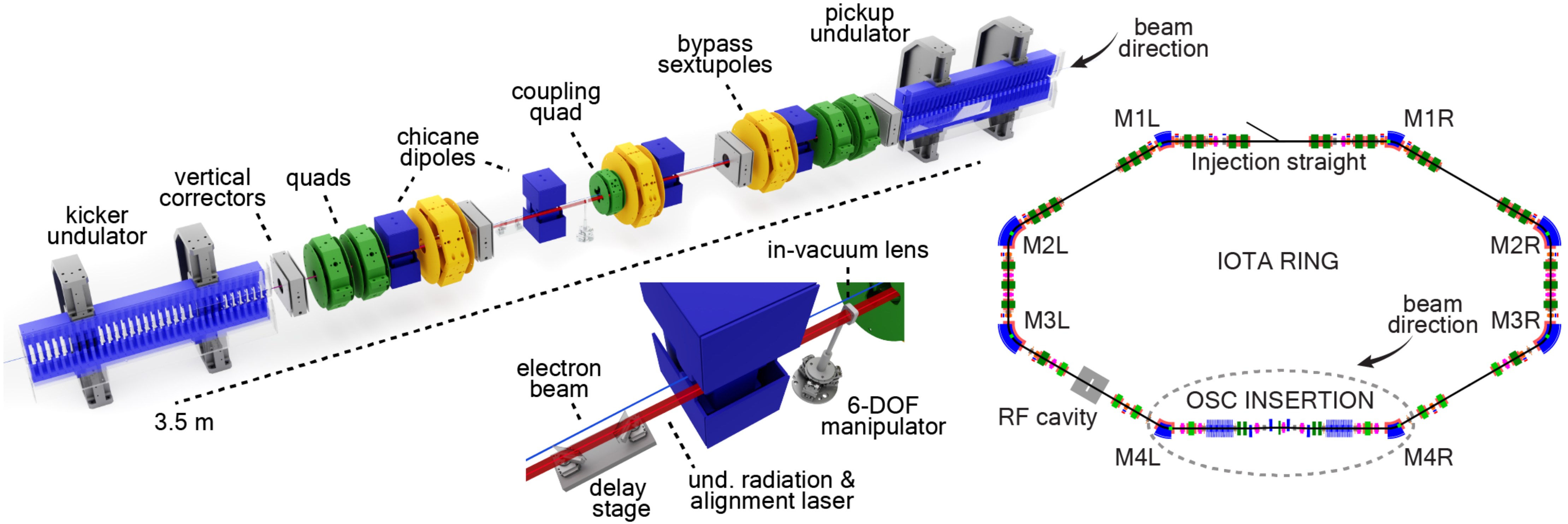
- Due to short wavelength, coherent-mode size of the undulator radiation can be smaller than the particle beam
- "Transverse optical sampling" can provide a dramatic reduction in the number of particles per "sample"
- Transport matrices for the light and the beam should be matched
- Potential for further increase of the achievable cooling rate (optimum gain)



$M_{beam} \sim M_{light}$



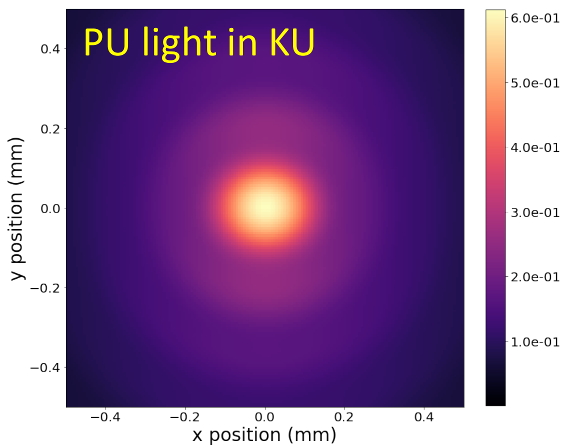
A staged approach for OSC at IOTA

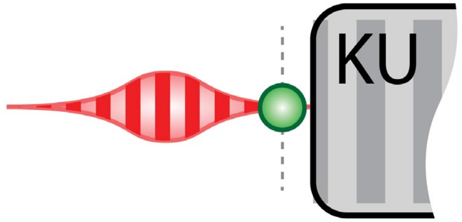


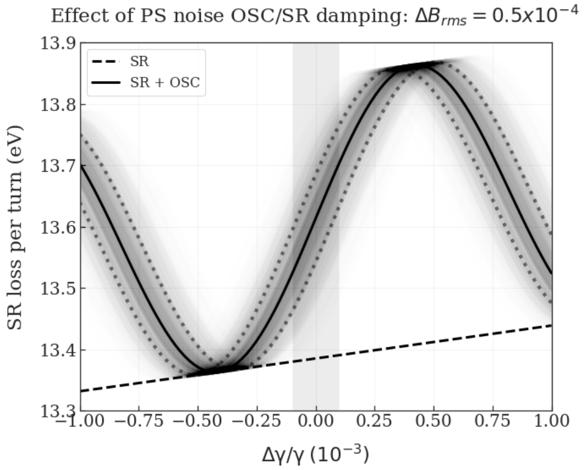
- **Non-amplified OSC (~1-µm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-µm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification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

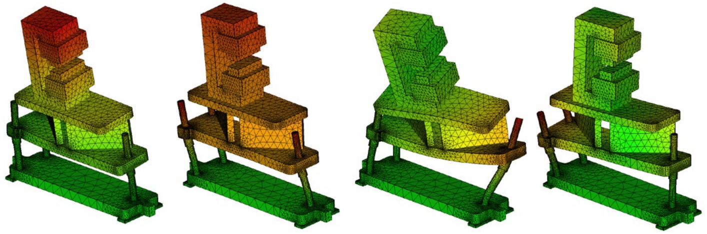
What makes (“simple”) OSC challenging?

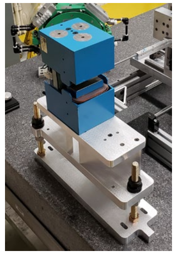
1. Beam and PU light must overlap through the KU
   The undulator light is **~200 μm** wide
   Want angle between light and beam at < **~0.1 mrad**
2. Beam and PU light must arrive ~simultaneously for maximum effect
   Absolute timing should be better than **~0.3 fs**
   The entire delay system corresponds 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

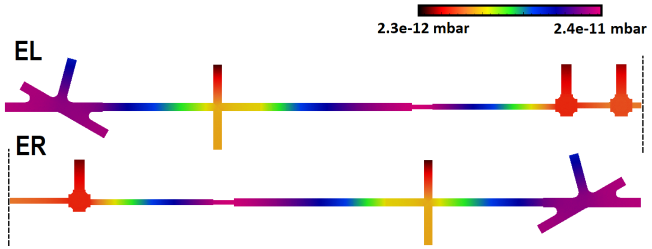






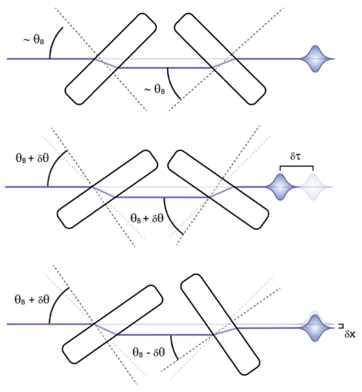




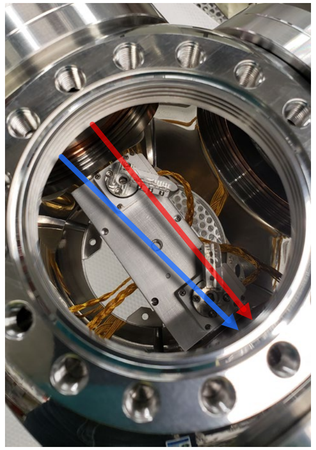


OSC apparatus successfully integrated in IOTA

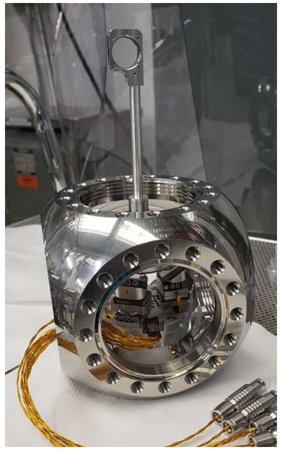
- Established and corrected OSC lattice to desired precision
- Achieved ~80% of theoretical max aperture and ~20-min lifetime; sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully validated all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



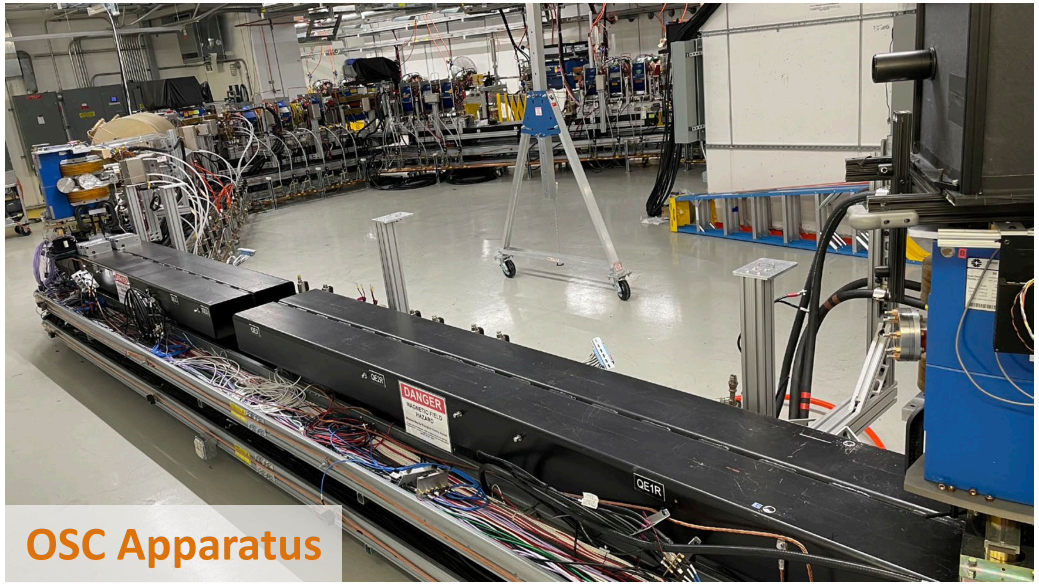
Delay stage

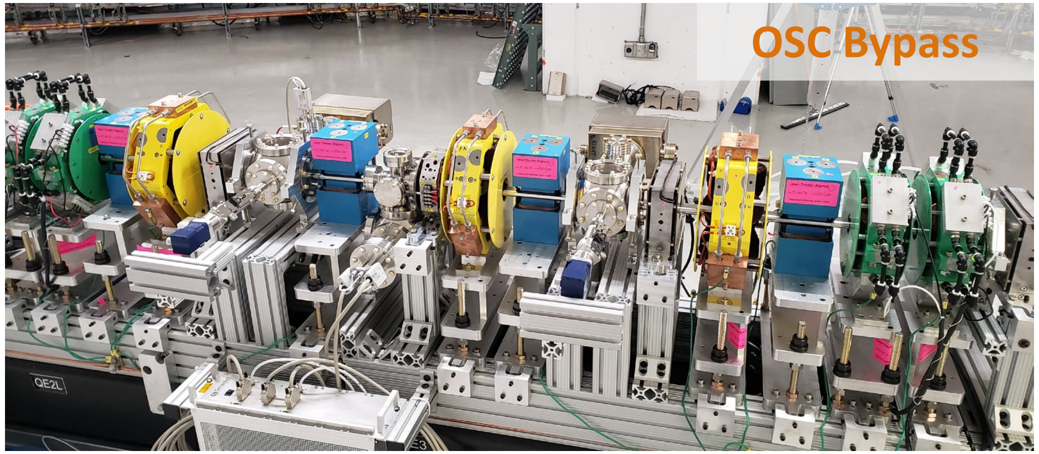


Delay stage



lens stage





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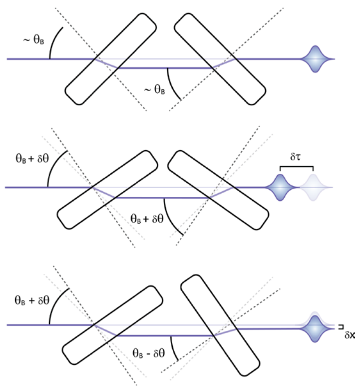
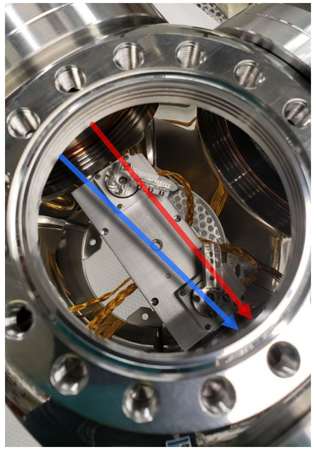
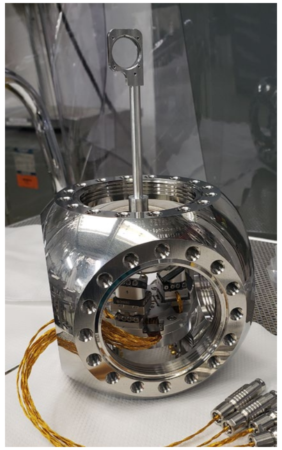


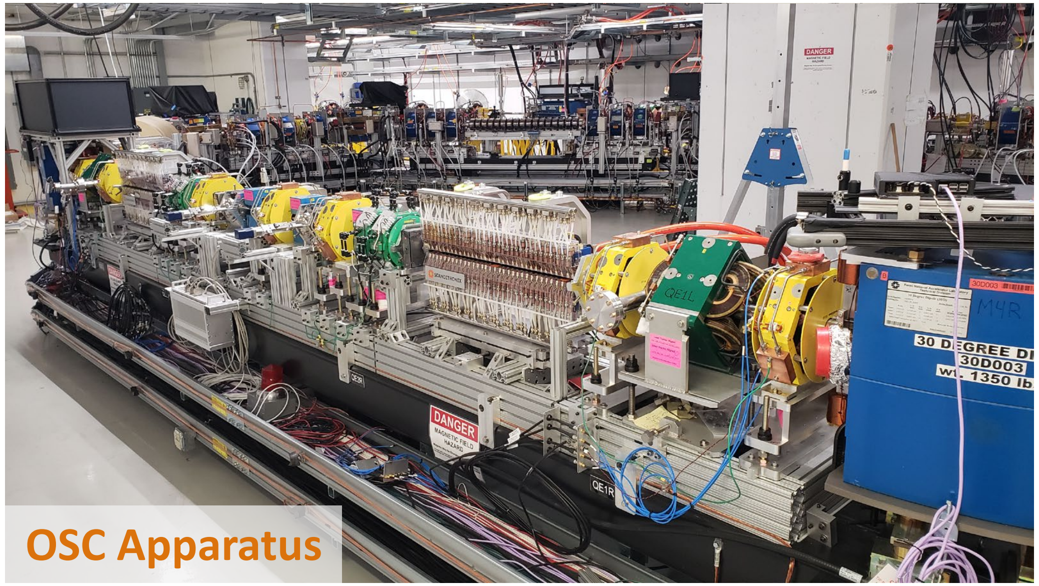
Delay stage

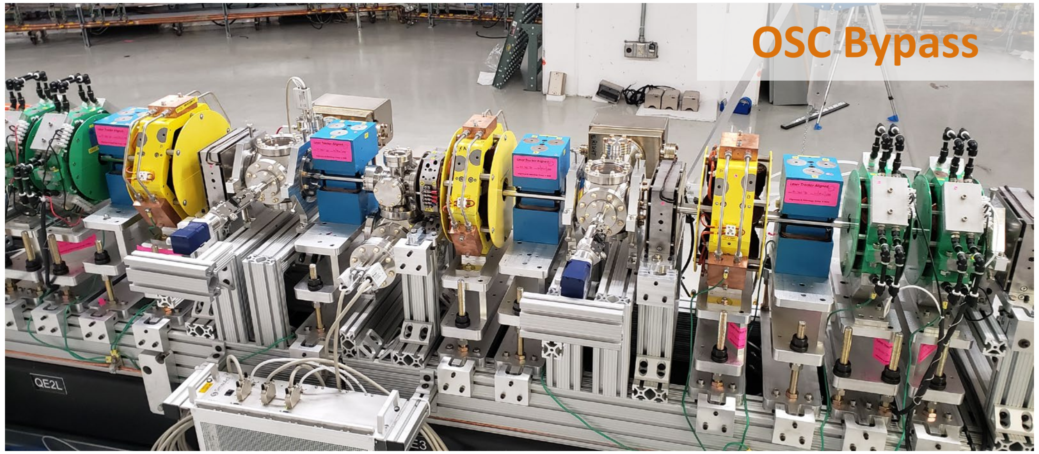


Delay stage

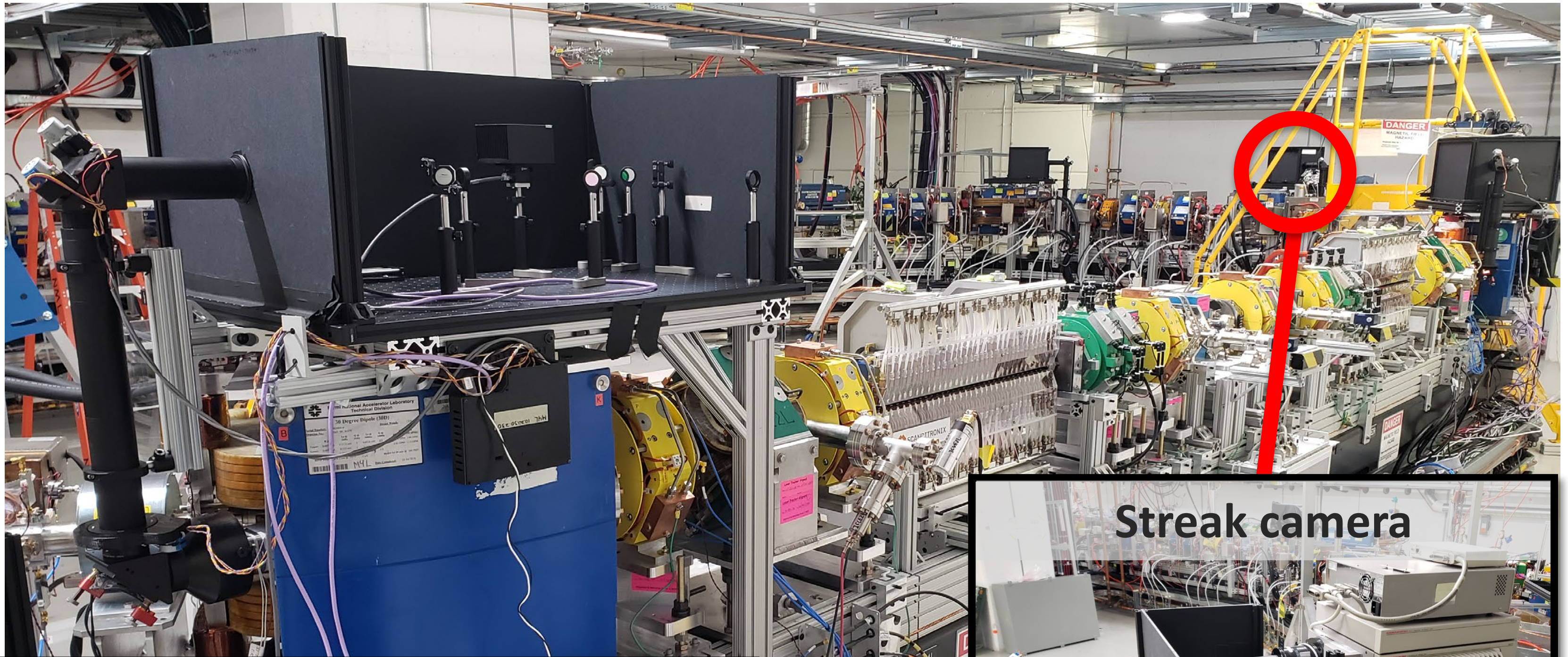


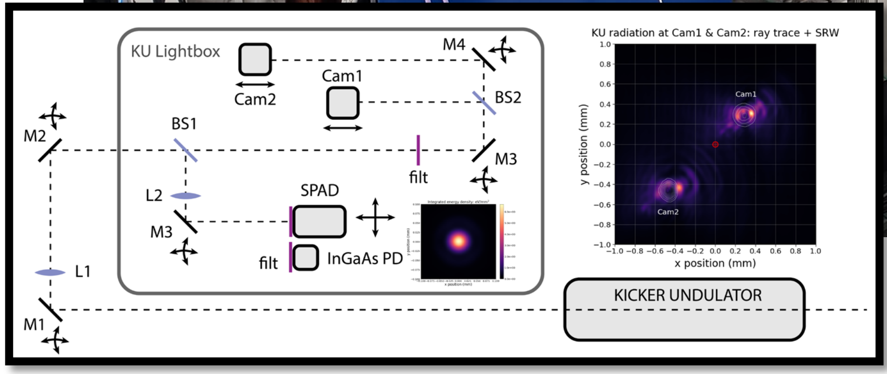
lens stage



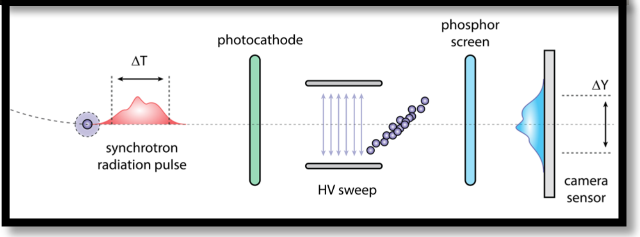


OSC is monitored via synchrotron-radiation stations

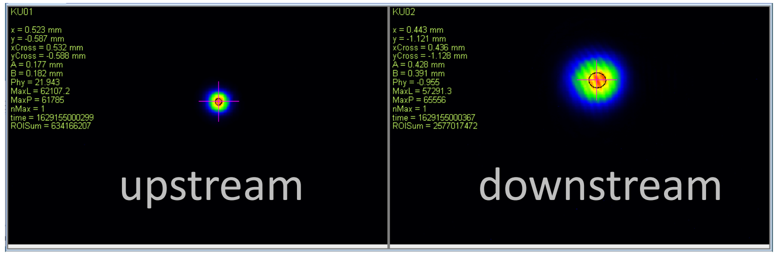




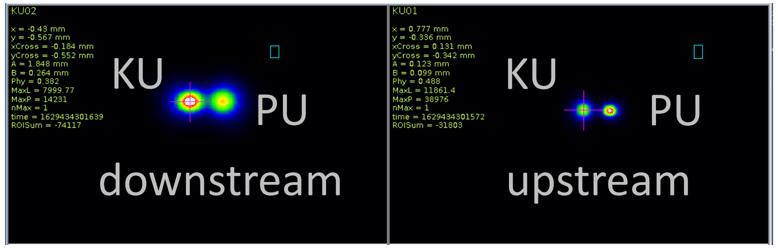
UR (PU+KU) BPMs; SPAD and PMT for 1e^{-}

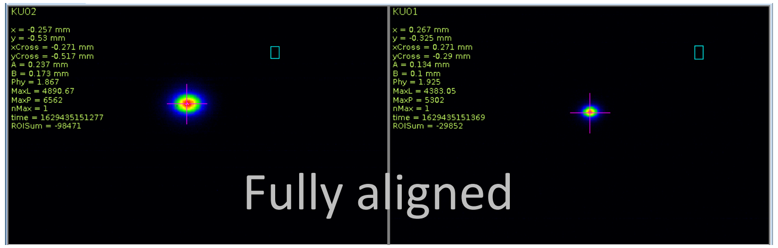


Alignment laser



Undulator-rad. BPMs



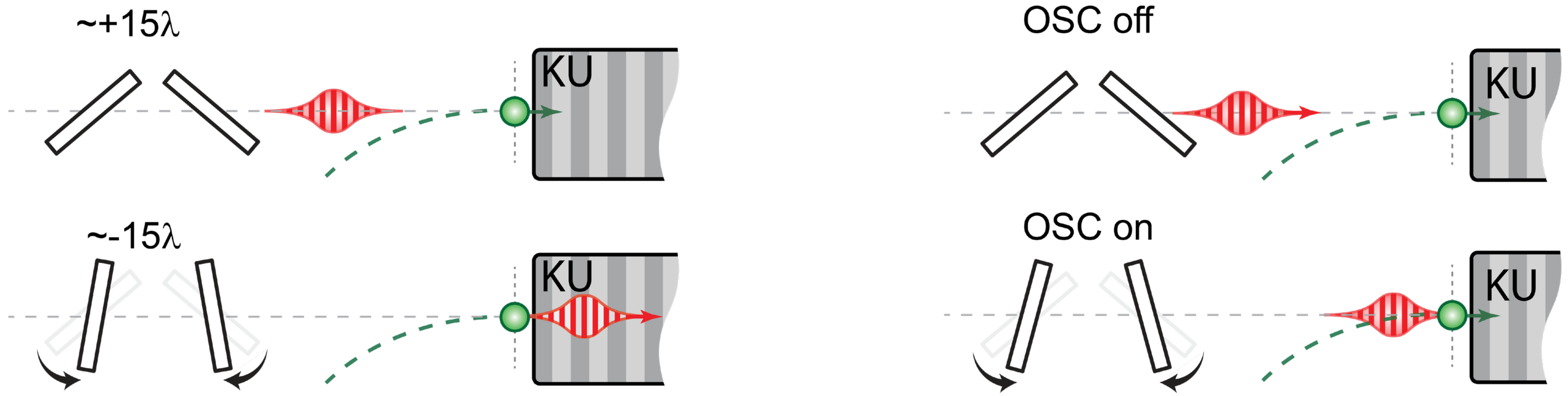


After much work… OSC was strong and stable

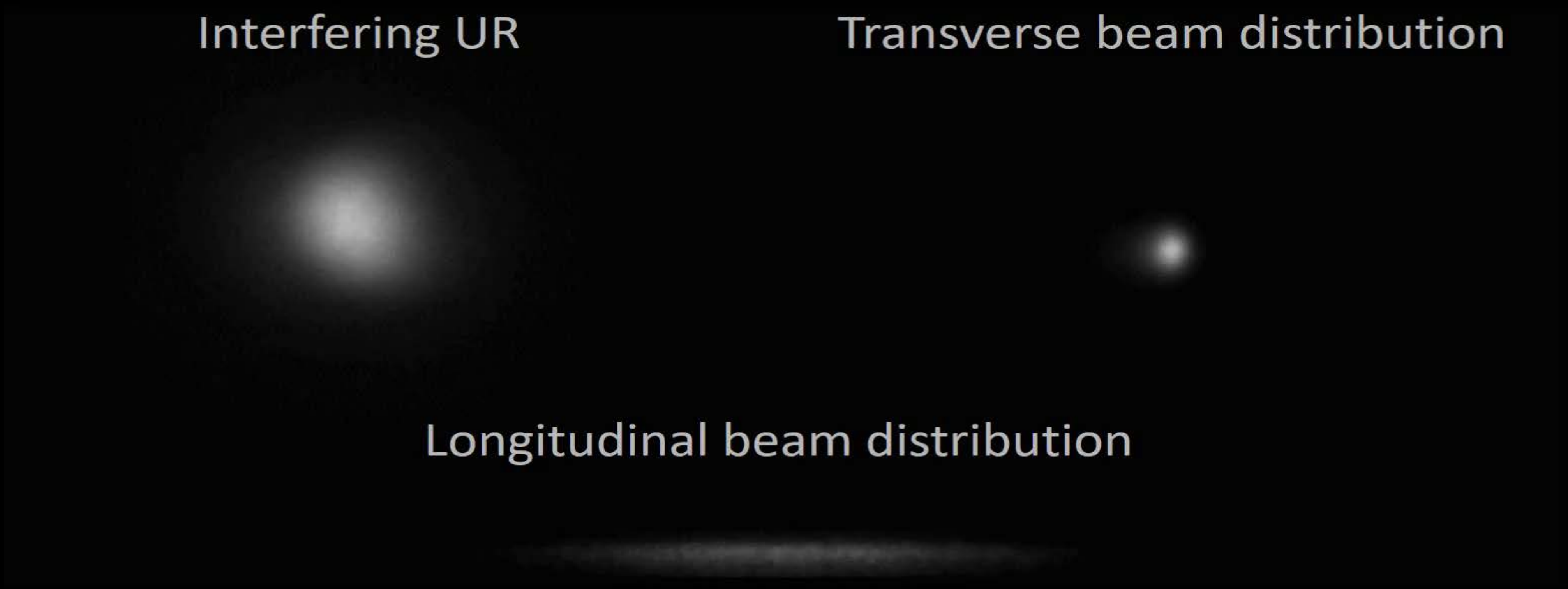
- **OSC was achieved and characterized in 1D, 2D and 3D configurations**
  - 1D: lattice decoupled and bypass quad set to null transverse response to OSC (some residual due to dispersion @ SR BPM)
  - 2D: lattice decoupled and bypass coupling to nominal
  - 3D: lattice coupled and bypass to nominal
- OSC system is reoptimized for each configuration

SLOW DELAY SCANS (~0.03 λ/sec)

FAST TOGGLES (~15 λ/sec)



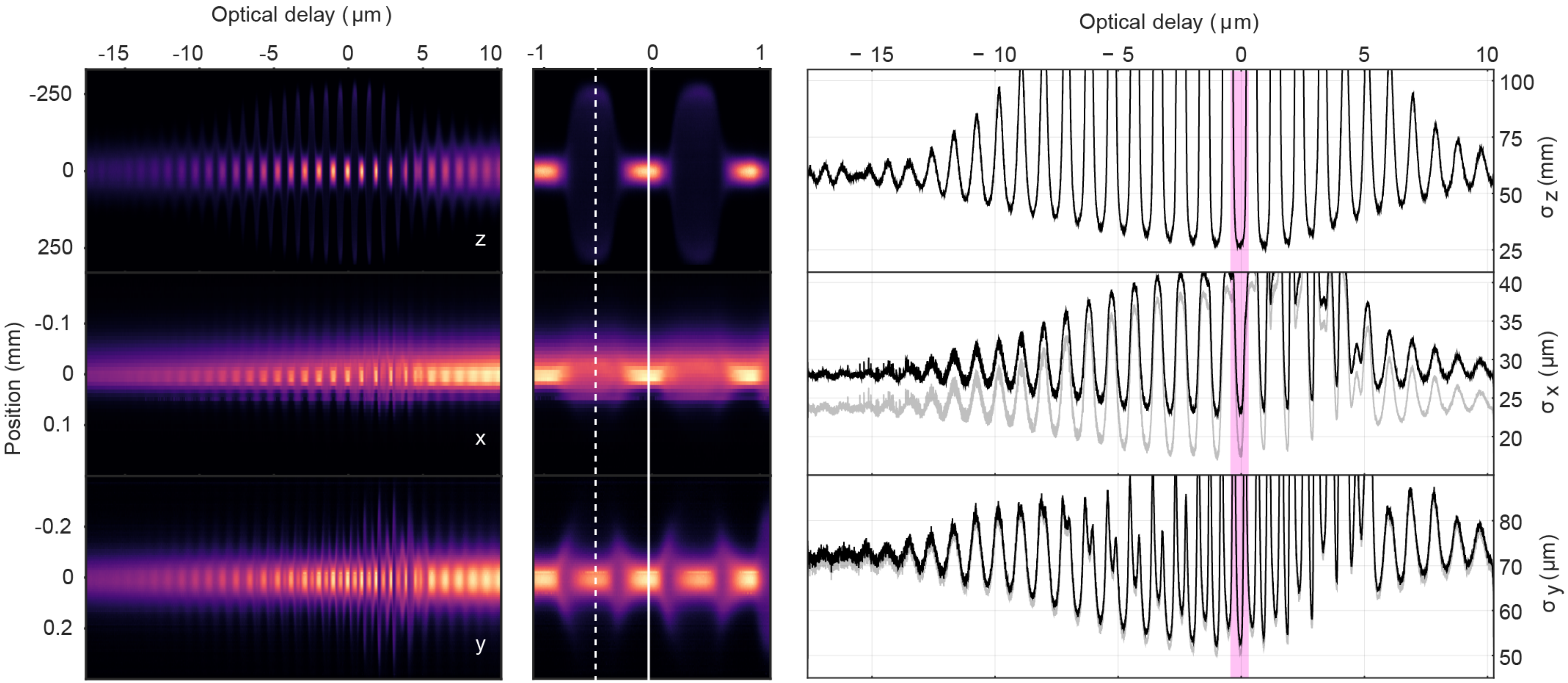
Delay scan with OSC in the 3D configuration



Video @ ~15x realtime

Delay-scan rate ~0.03λ/s

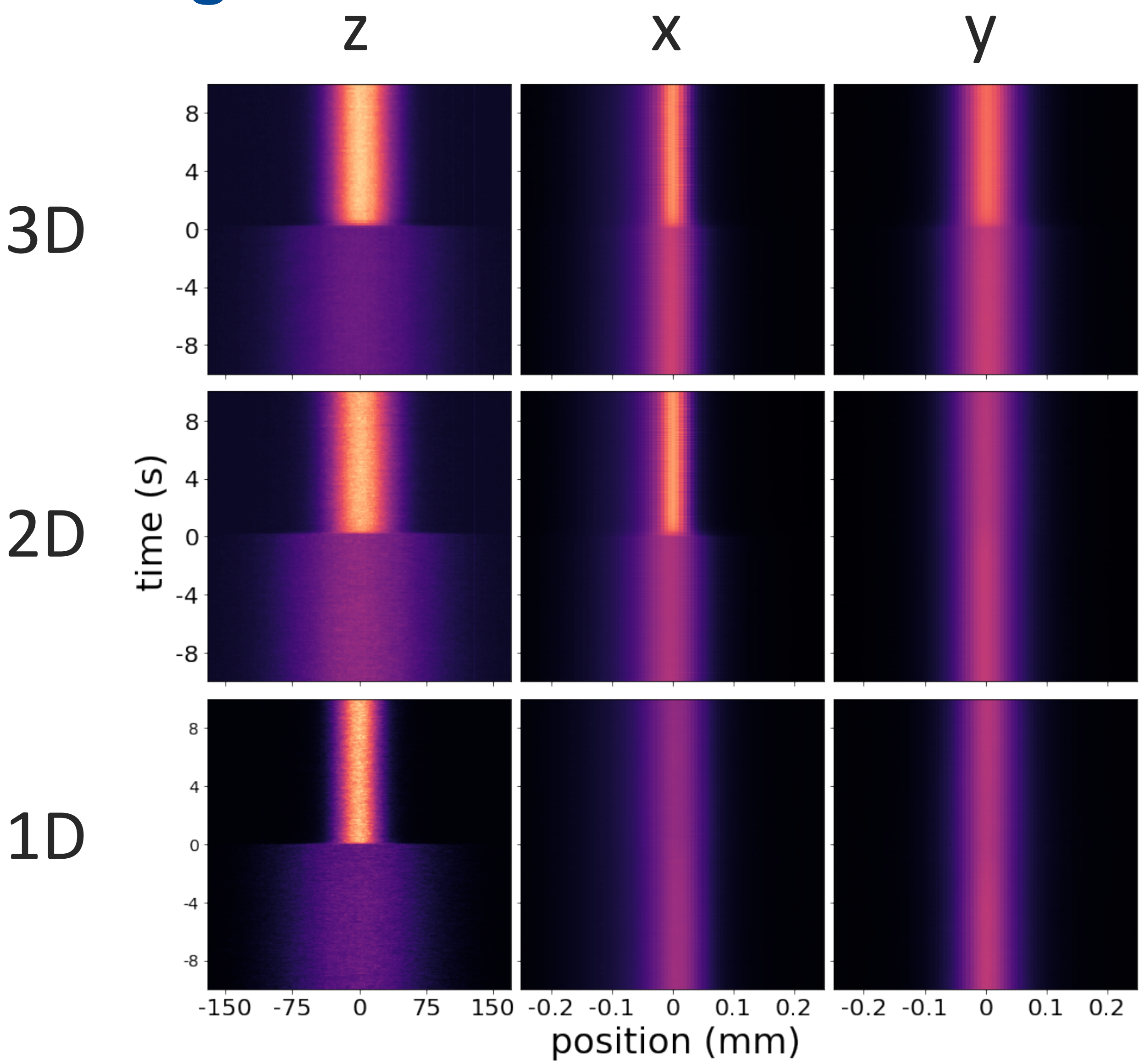
Delay scans show expected OSC structure and bandwidth



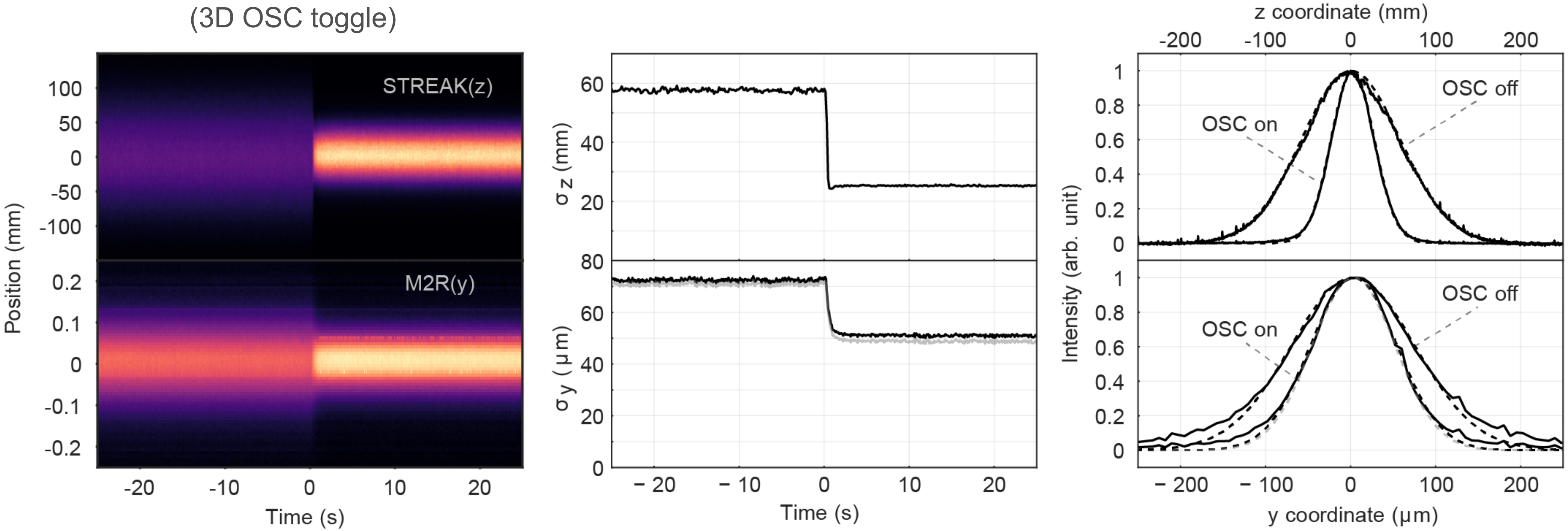
- Delay scan over entire OSC overlap region (~30λ)
- OSC alternates between cooling and heating modes
- Strong simultaneous cooling is observed for all three planes
- Envelope corresponds to >20-THz BW **(~2000x greater than conventional stochastic cooling)**

OSC Cooling configurations at a glance…

- OSC toggles "quickly" place the system in a cooling or heating mode
- OSC system initially detuned longitudinally by ~30 wavelengths; i.e. OSC off
- Delay plates are then snapped at max speed (15λ/s) to the orientation for optimal cooling
- OSC system would remain stable over the beam lifetime.



Equilibrium sizes used to estimate the OSC force

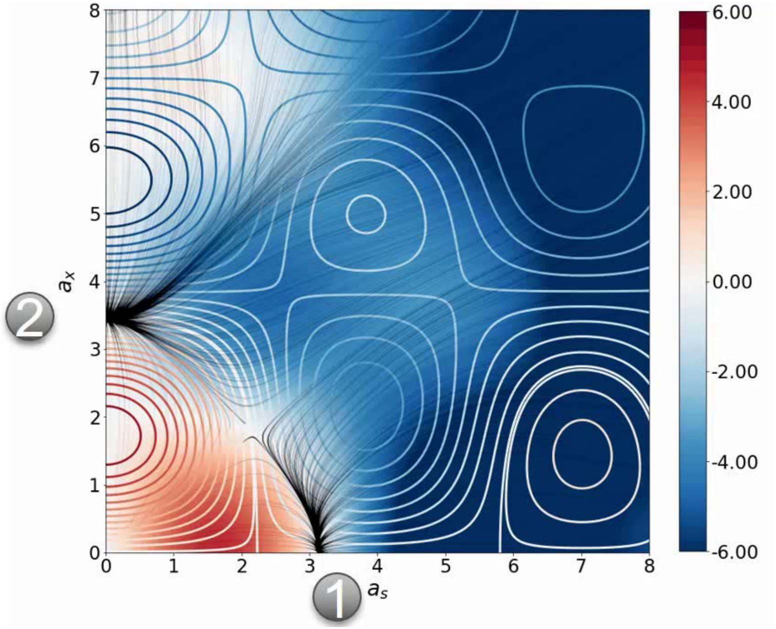


- Accounting for intrabeam scattering, total OSC force is ~9x stronger than the longitudinal SR damping
- ~60% of the expected value from detailed simulations of the undulator radiation (accounting for known losses)
- Similar strength for 2D and 1D configurations, but full analysis ongoing

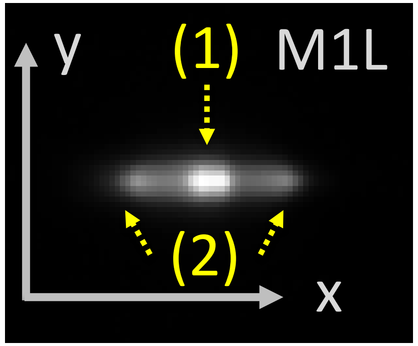
Clear observation of expected OSC zone structure

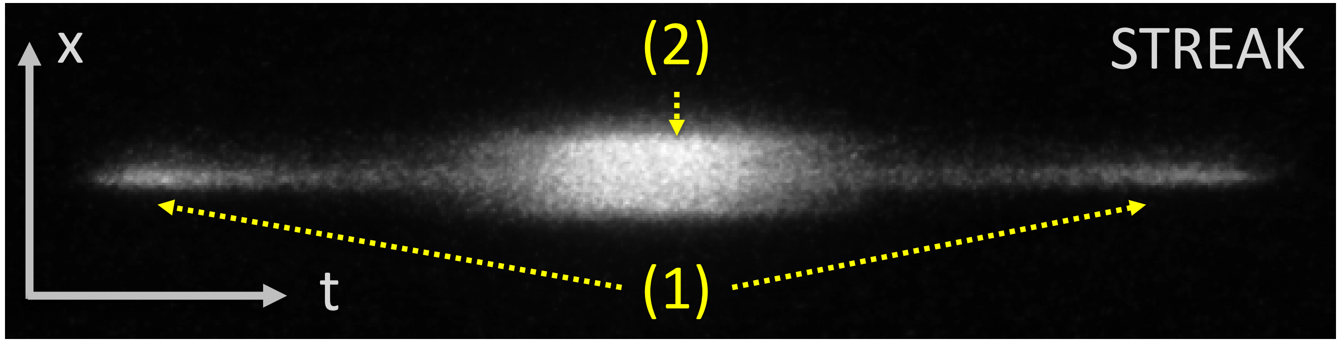
- (e.g) OSC in the 2D (z,x) configuration
- In “heating” mode, expect two high-amplitude attractors
- (1): high synchrotron amplitude, low betatron amplitude
- (2): high betatron amplitude, low synchrotron amplitude

(Sweeping through optical delay)



$$\frac{\delta p}{p} = -\kappa \sin(a_x \sin\psi_x + a_s \sin\psi_s)$$





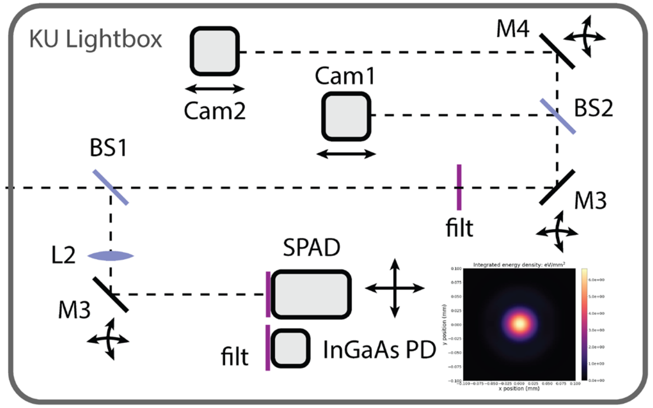
Transverse and longitudinal projections for heating mode of 2D OSC

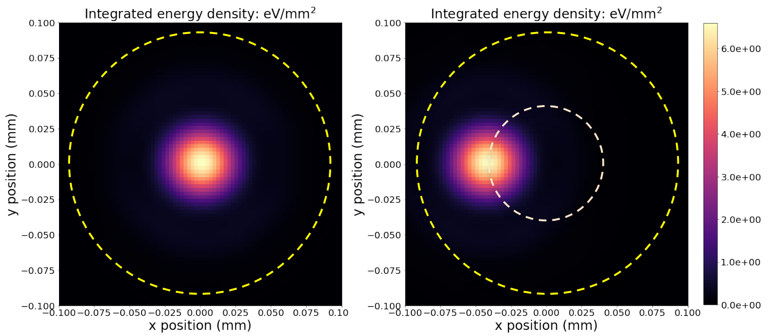
Fermilab

IOTA enables single-electron OSC studies

- Can reliably inject and store a single electron in IOTA; **OSC system/physics changes probability of photon detection in fundamental band of UR**
- Fundamental (KU+PU) UR was focused on the active element of a SPAD (KU lightbox); demagnified so that betatron excitations up to ~0.3mm (~10 sigma) remain on SPAD's active element
- HydraHarp event timer records all detected photons for both the SPAD and PMT (M3L lightbox) over many minutes
- Performed full OSC delay scans and toggles of cooling/heating for 1D and 2D OSC configuration

Single/few electrons in IOTA





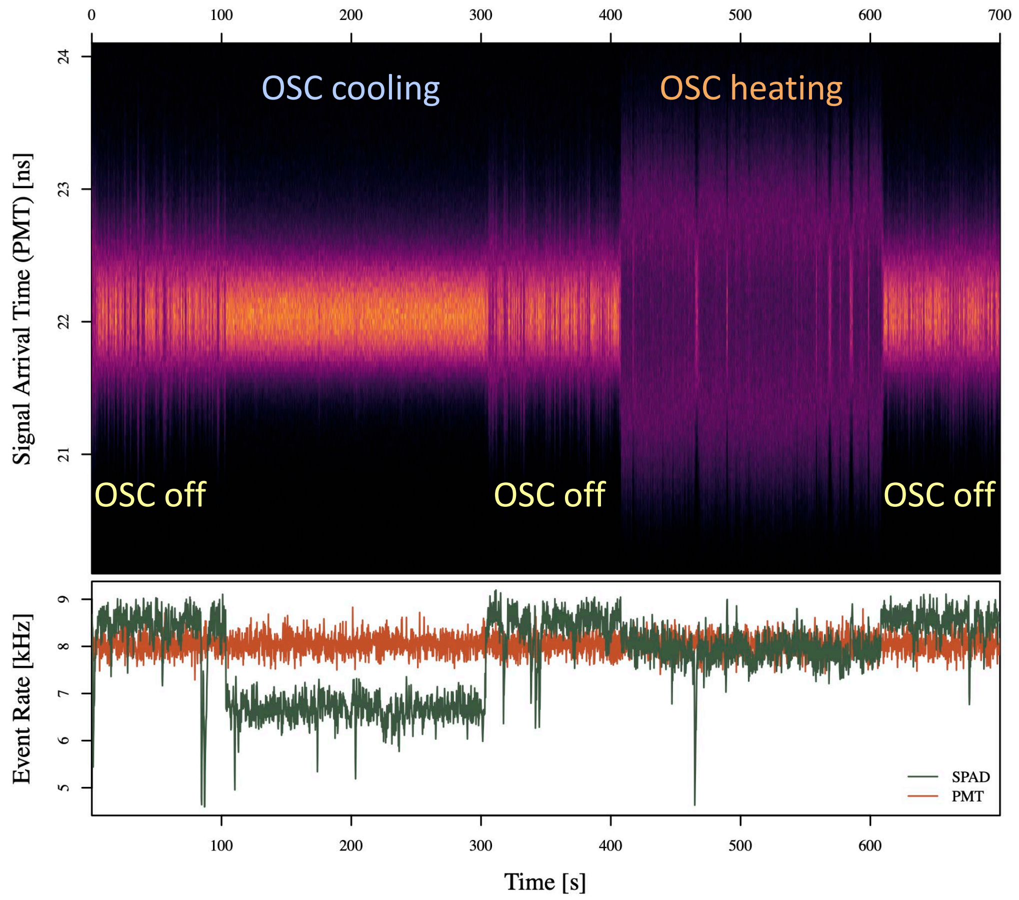
on axis

$x_\beta = 0.3$mm

OSC for single electron is visible in photon timing

- Event data is binned in 40-ps intervals and integrated for 200-ms windows
- *Equilibrium bunch size with OSC off (~170 ps) is smaller than the system resolution
- Large excitations (gas scattering) are commonly observed with OSC off
- Synchrotron excitations are strongly damped with OSC in the cooling mode (1D)
- Observe projected turning points in the heating mode

1D OSC configuration



(Plots by G. Stancari)

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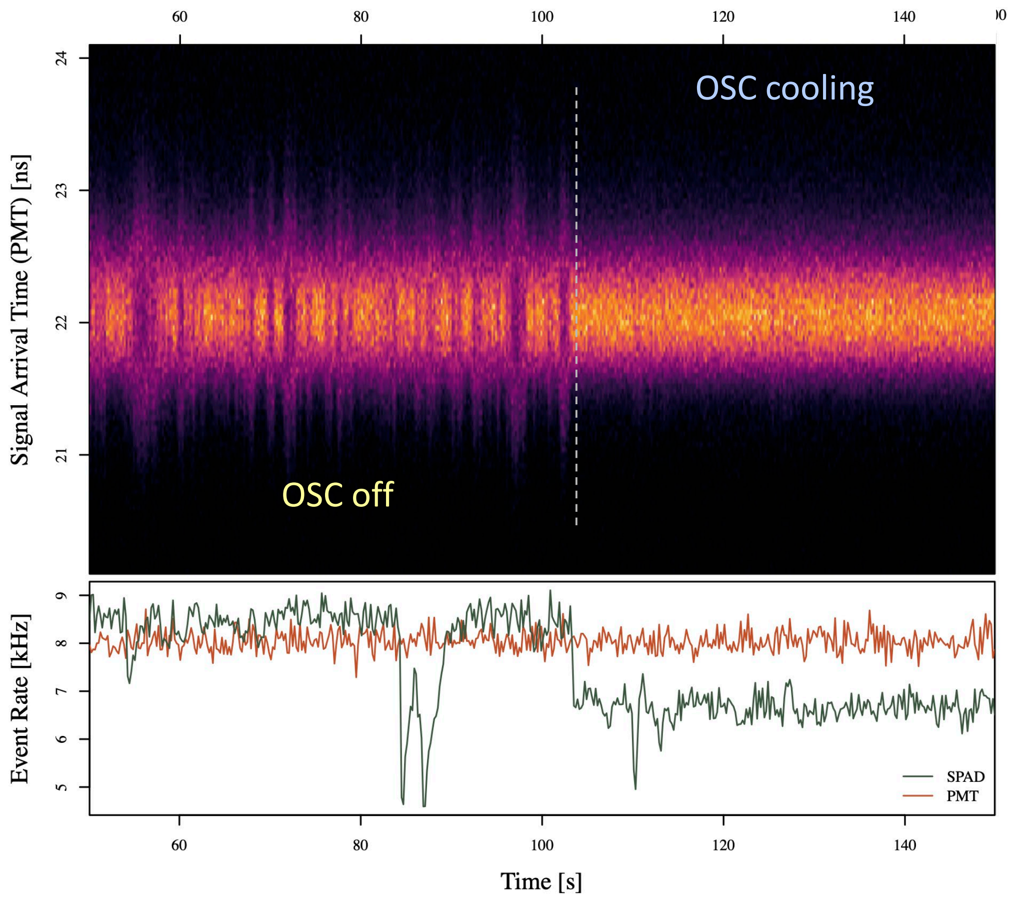
- Observe projected turning points in the heating mode

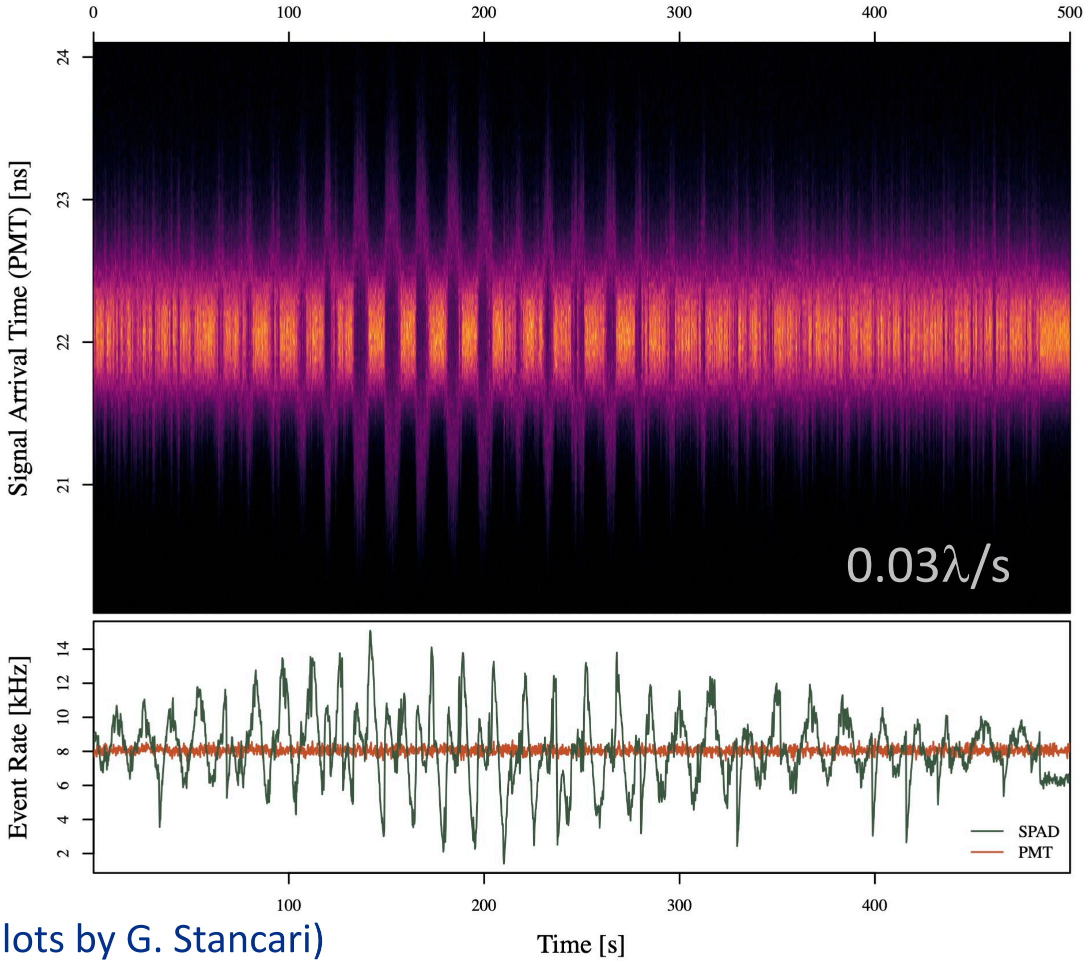
1D OSC configuration

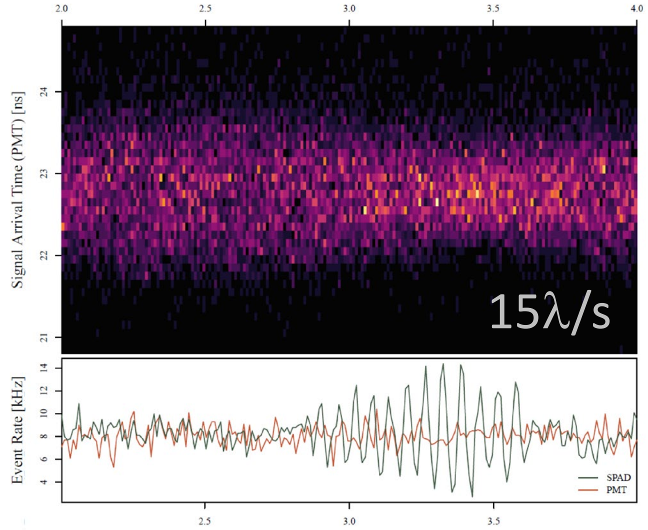


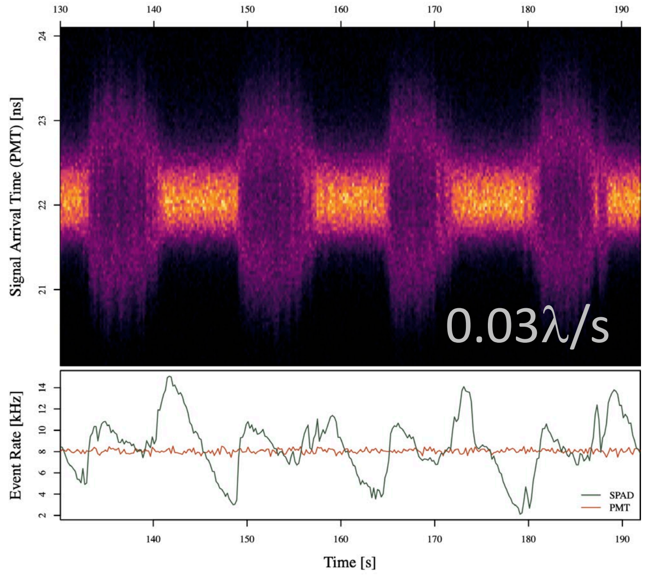
(Plots by G. Stancari)

Single-electron delay scans have same structure as with beam

- “Fast” delay scans (~0.5λ in ~30ms) show modulated emission probability with minimal disturbance of the beam







(Plots by G. Stancari)

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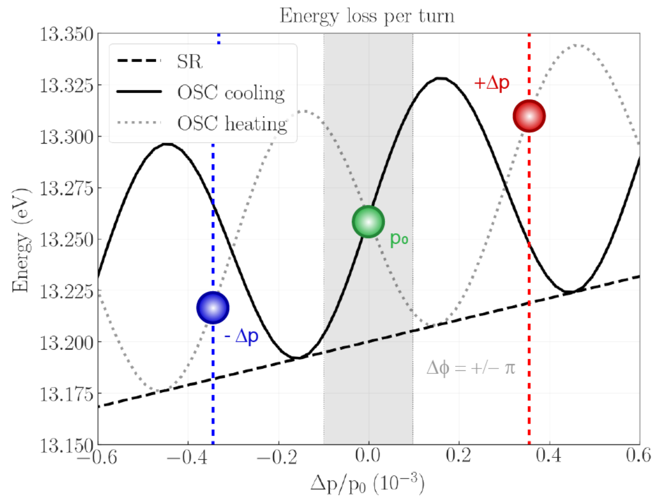
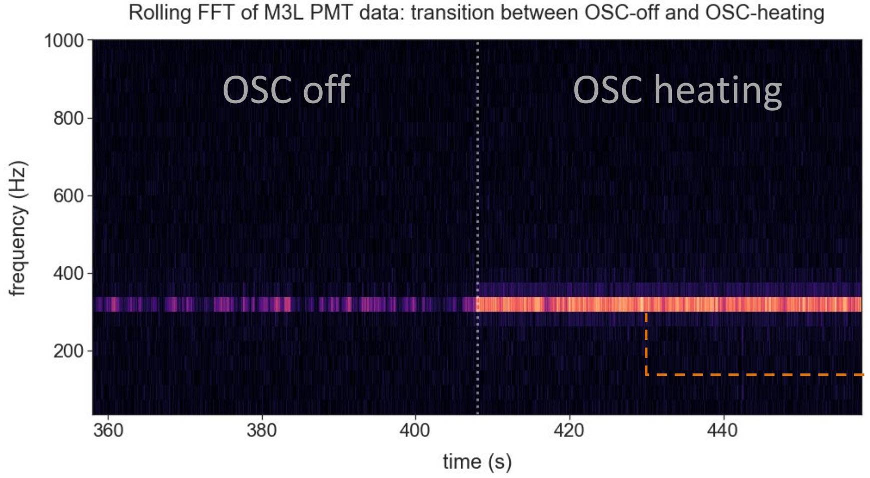
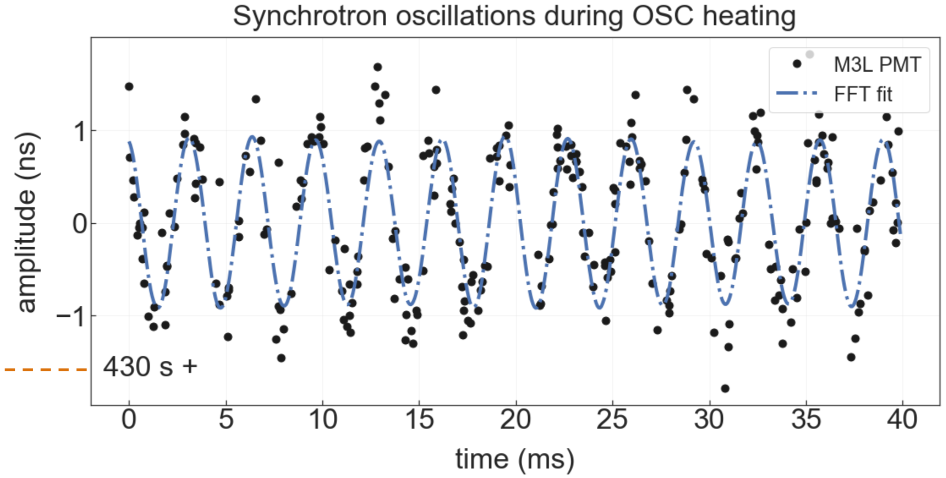
OSC photon detection oscillates with synchrotron phase

- Similarly, for a fixed delay setting, probability of photon emission/detection oscillates during synchrotron oscillations
- Fourier transform photon-timing data to extract amplitude and phase of synchrotron oscillation during long OSC toggles
- Map undulator-photon detections onto amplitude and phase of the oscillation to see probability oscillations



$$\frac{\delta p}{p} = -\kappa \sin(a_s \sin\psi_s + \varphi_0)$$

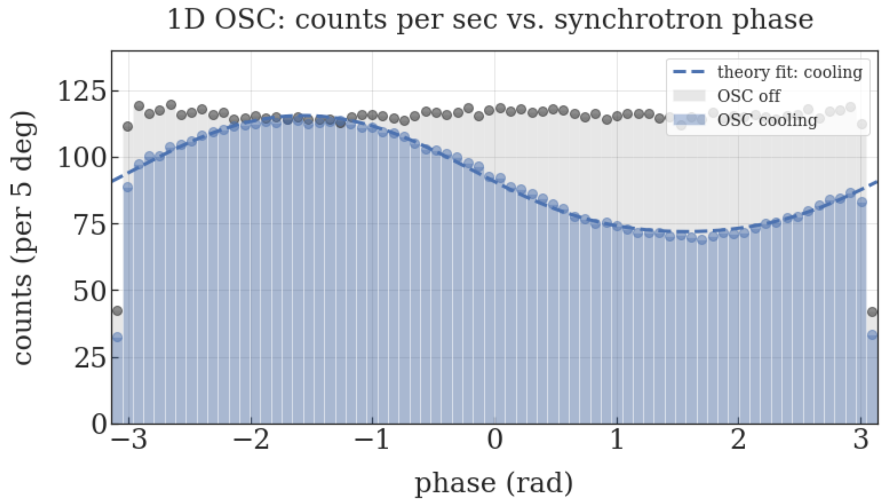


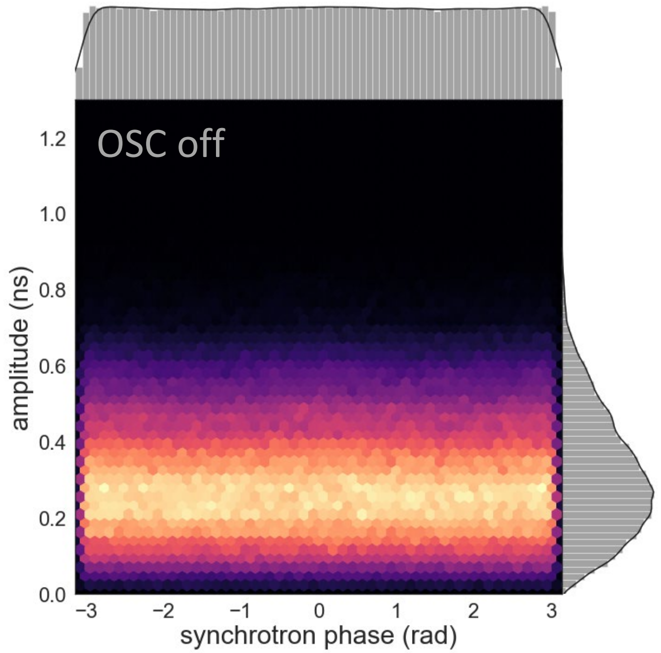


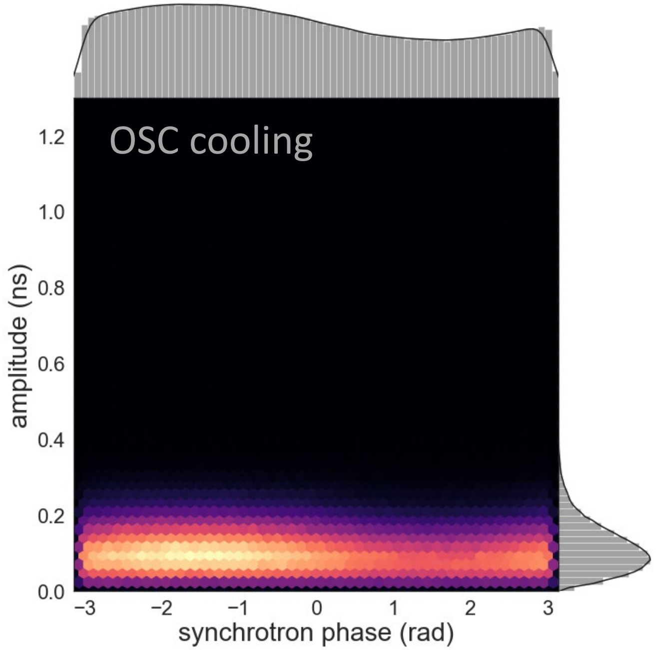
OSC photon detection oscillates with synchrotron phase

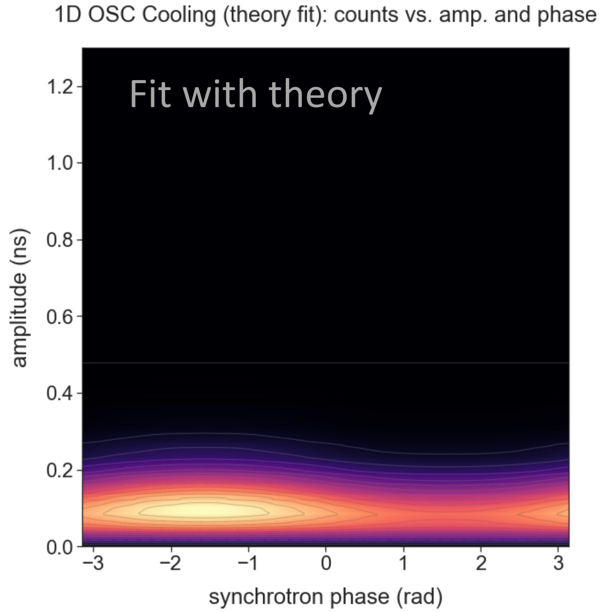
- Confirm no modulation of emission probability in the OSC-off case
- Small amplitudes in the cooling mode produce clear, modest modulation of detection probability

$$\frac{\delta p}{p} = -\kappa \sin(a_s \sin\psi_s + \varphi_0)$$



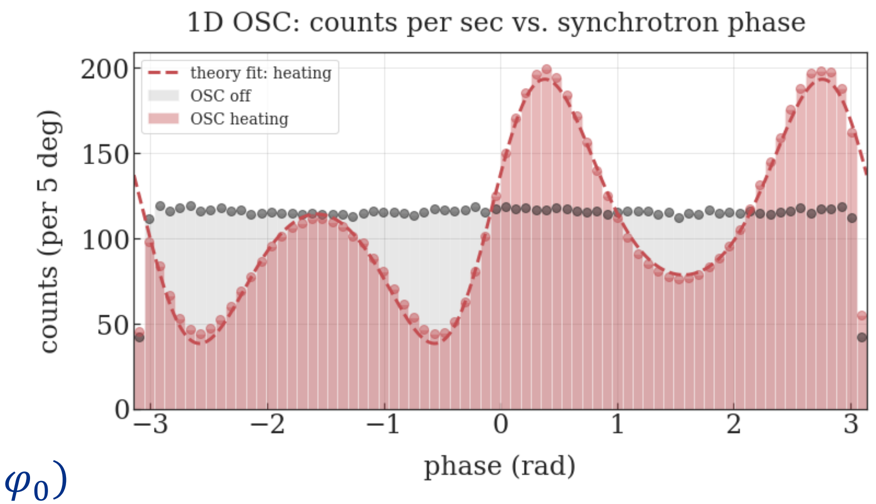




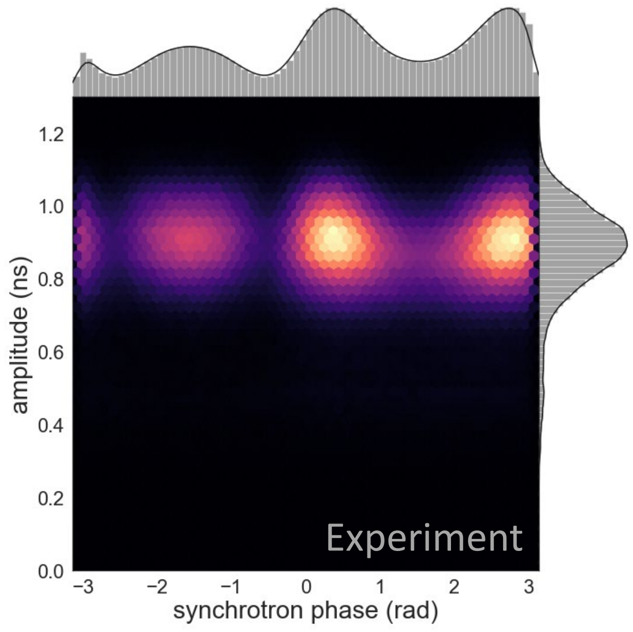


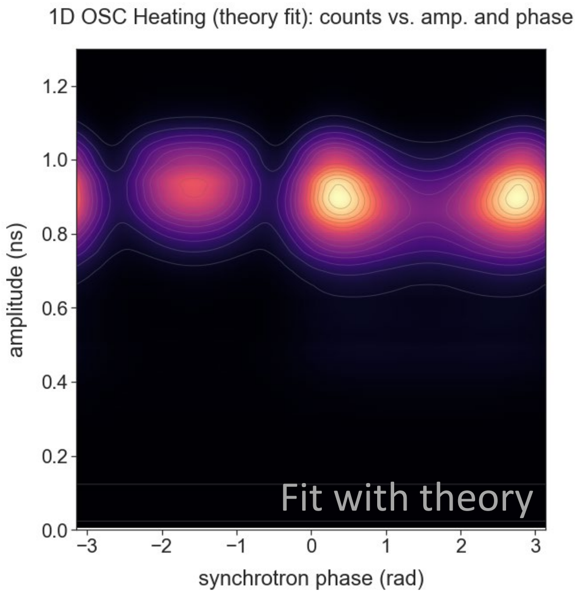
OSC photon detection oscillates with synchrotron phase

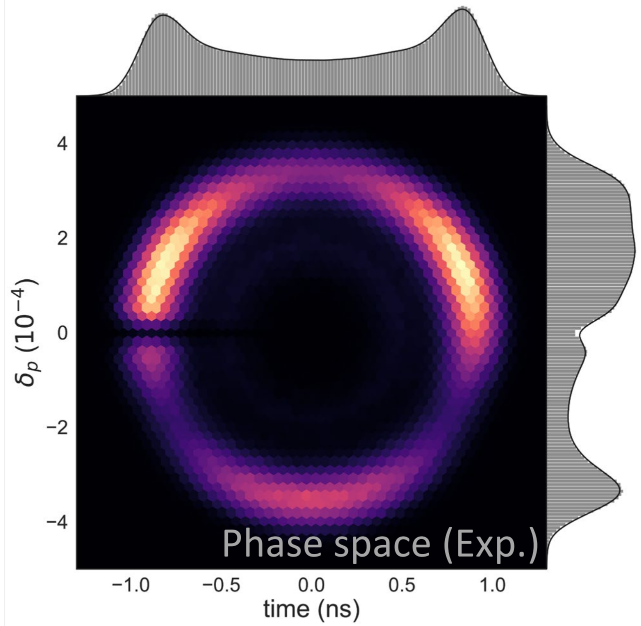
- Very large amplitudes in heating mode produce strong modulation
- Excellent test of theory; complex structure gives strong constraints on various experimental parameters



$$\frac{\delta p}{p} = -\kappa \sin(a_s \sin \psi_s + \varphi_0)$$

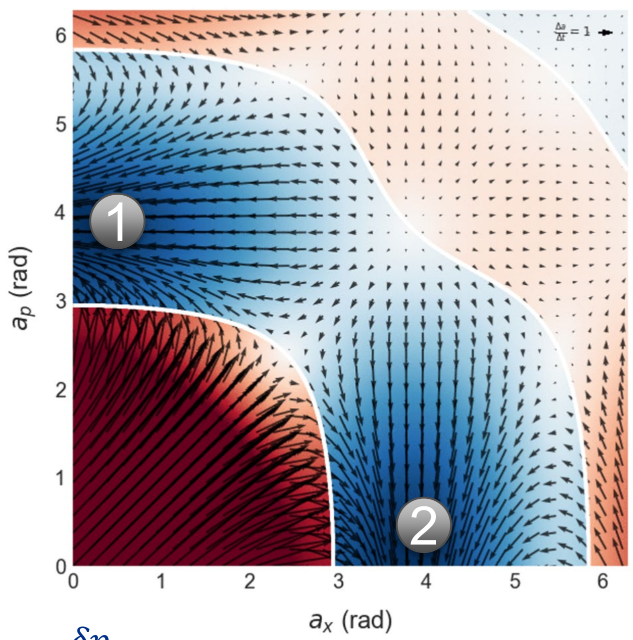




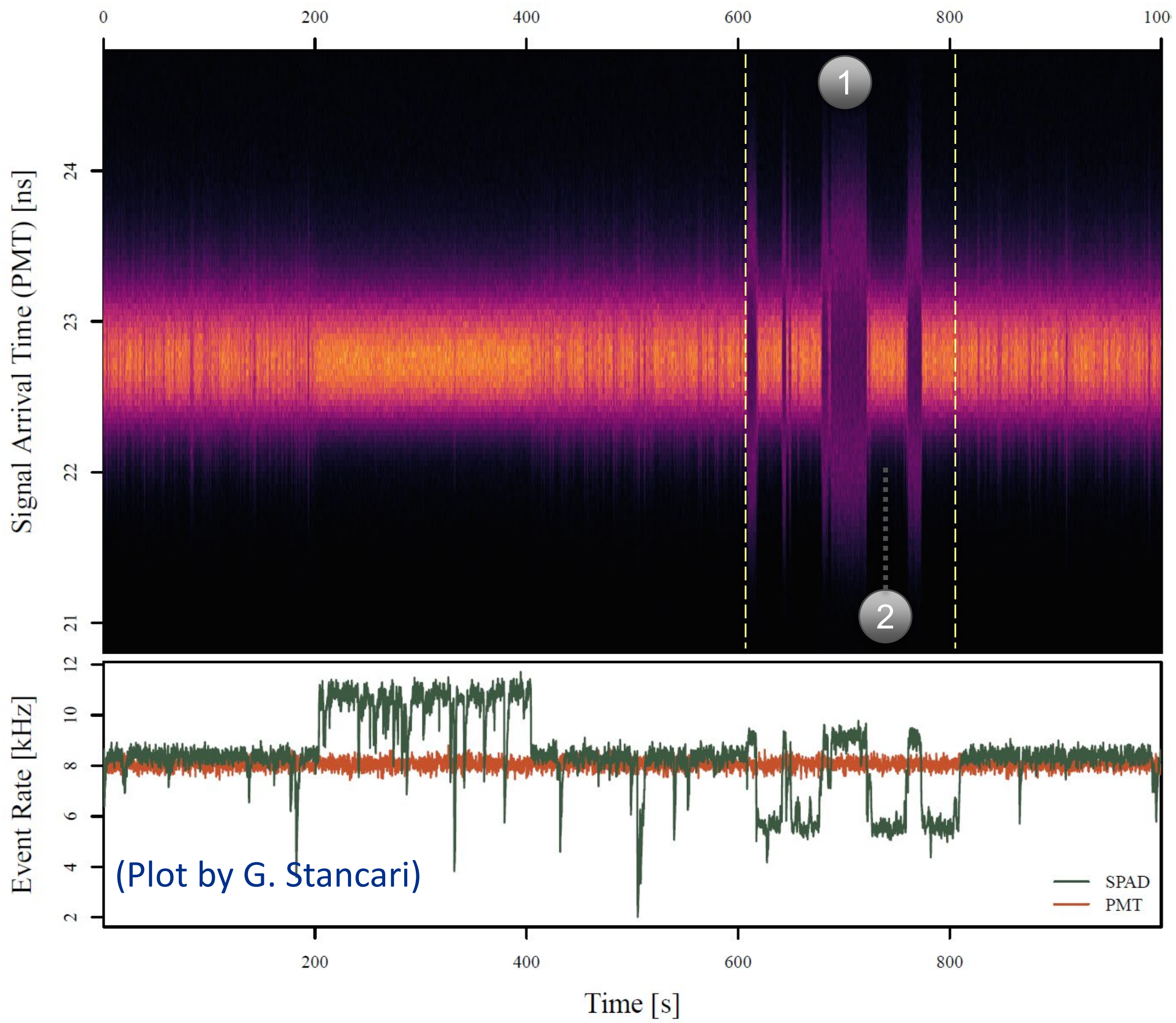


Observe bistable transitions between OSC attractors

- OSC in the **2D configuration** (z,x)
- As with a beam, expect the same two attractors in heating mode…
- …but, single electron can only be in one attractor at a time



$$\frac{\delta p}{p} = -\kappa \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right)$$



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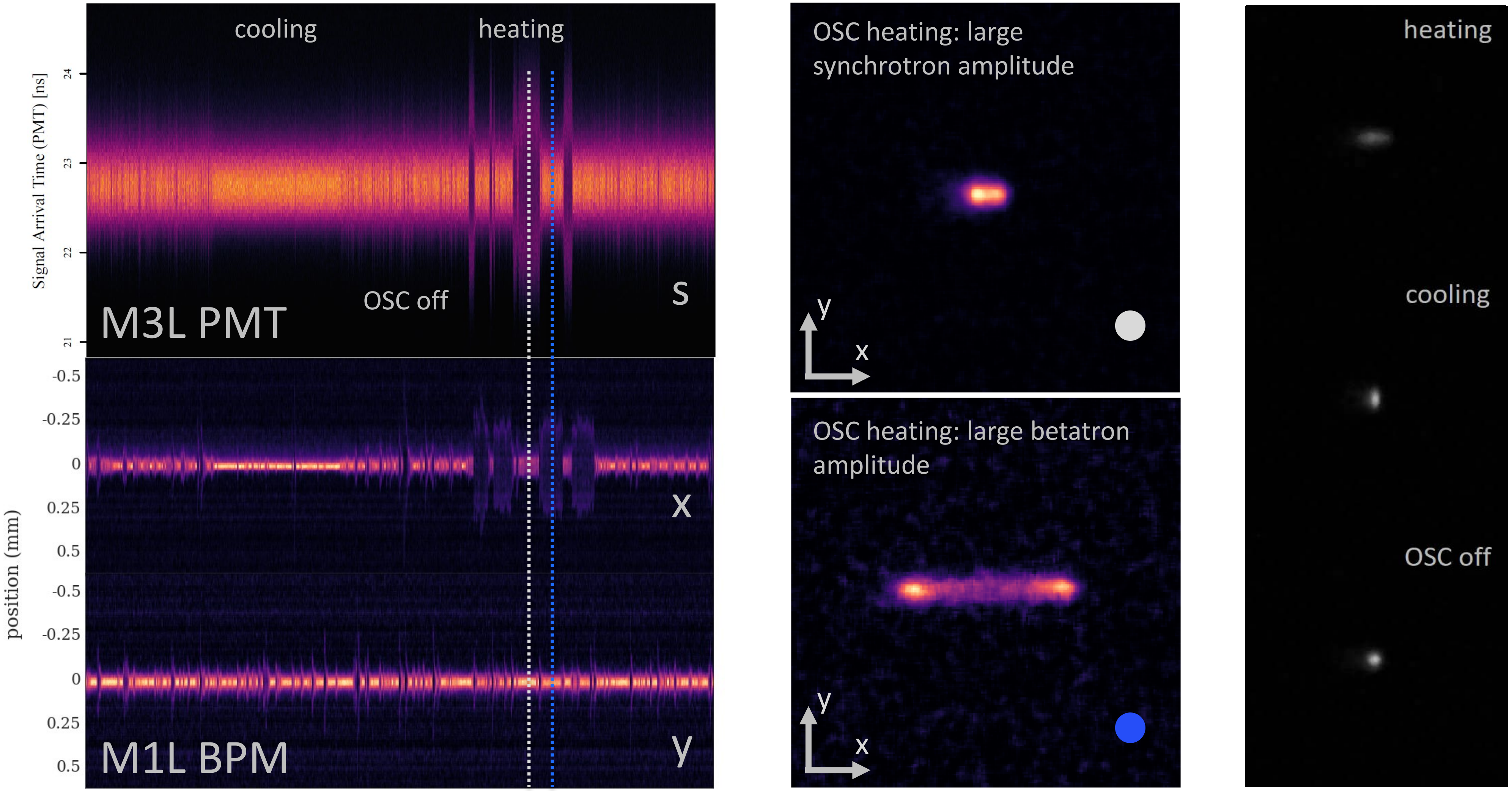
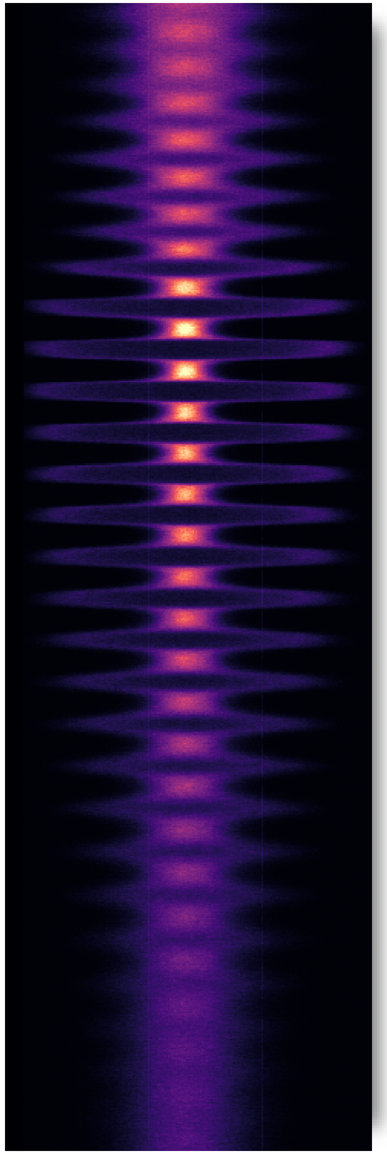
Analysis of SR BPMs confirms the observation



Single electron can only be present in one attractor at a time

Conclusions:

- OSC is at an intersection of fundamental beam-physics studies and the development of operational systems for cooling and phase-space control
- Comprehensive, systematic studies of the non-amplified OSC physics were carried out during IOTA Run #3 with OSC demonstrated in 1,2 and 3 dimensions
- This is the first experimental demonstration of a stochastic cooling technology in the optical regime; achieved system bandwidth is **~2000x** that of conventional SC systems; initial report published in *Nature* (Aug. 10, 2022)
- "OSC" of a single electron was definitively observed; $1e^-$ serves as a fundamental probe of the OSC physics
- This program established a strong foundation for development of our new amplified OSC experiment: validated many critical subsystems and concepts; gathered excellent operational experience and learned many valuable lessons

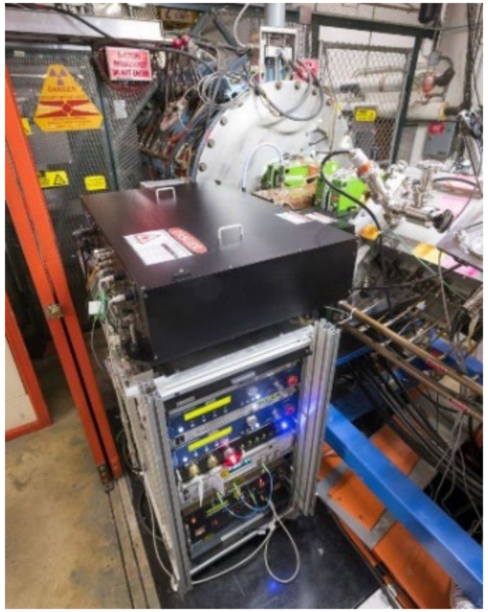


Fermi National Accelerator Laboratory is operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

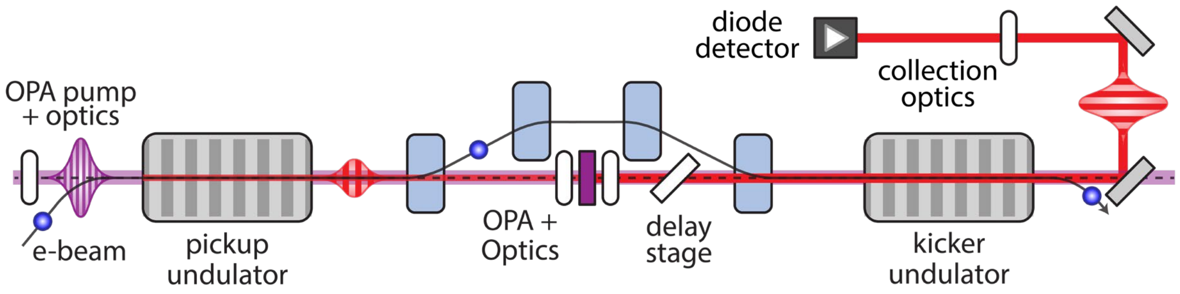
New program in Amplified OSC + control & sensing

- Now developing a new OSC system at IOTA with high-gain optical amplification (30-40 dB; ~ms cooling times)
- Combining flexible pump laser with reinforcement-learning techniques and specialized optics; goal of establishing new capabilities for beam cooling and control
- Advanced OSC simulation tools under development
- Program will emphasize pathfinding for operational systems using physics and technology of OSC
- **New postdoc position for amplified OSC; come join us at Fermilab!**

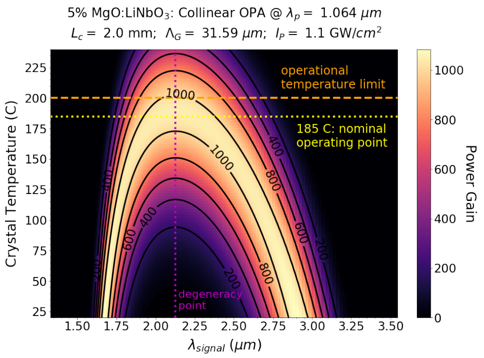
https://academicjobsonline.org/ajo/jobs/22290



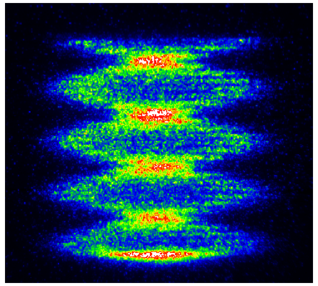
LLN drive laser



Amplified-OSC concept



Calculated amplifier performance



Phase-space control

A huge and ongoing “thank you” to the IOTA team

optical stochastic cooling
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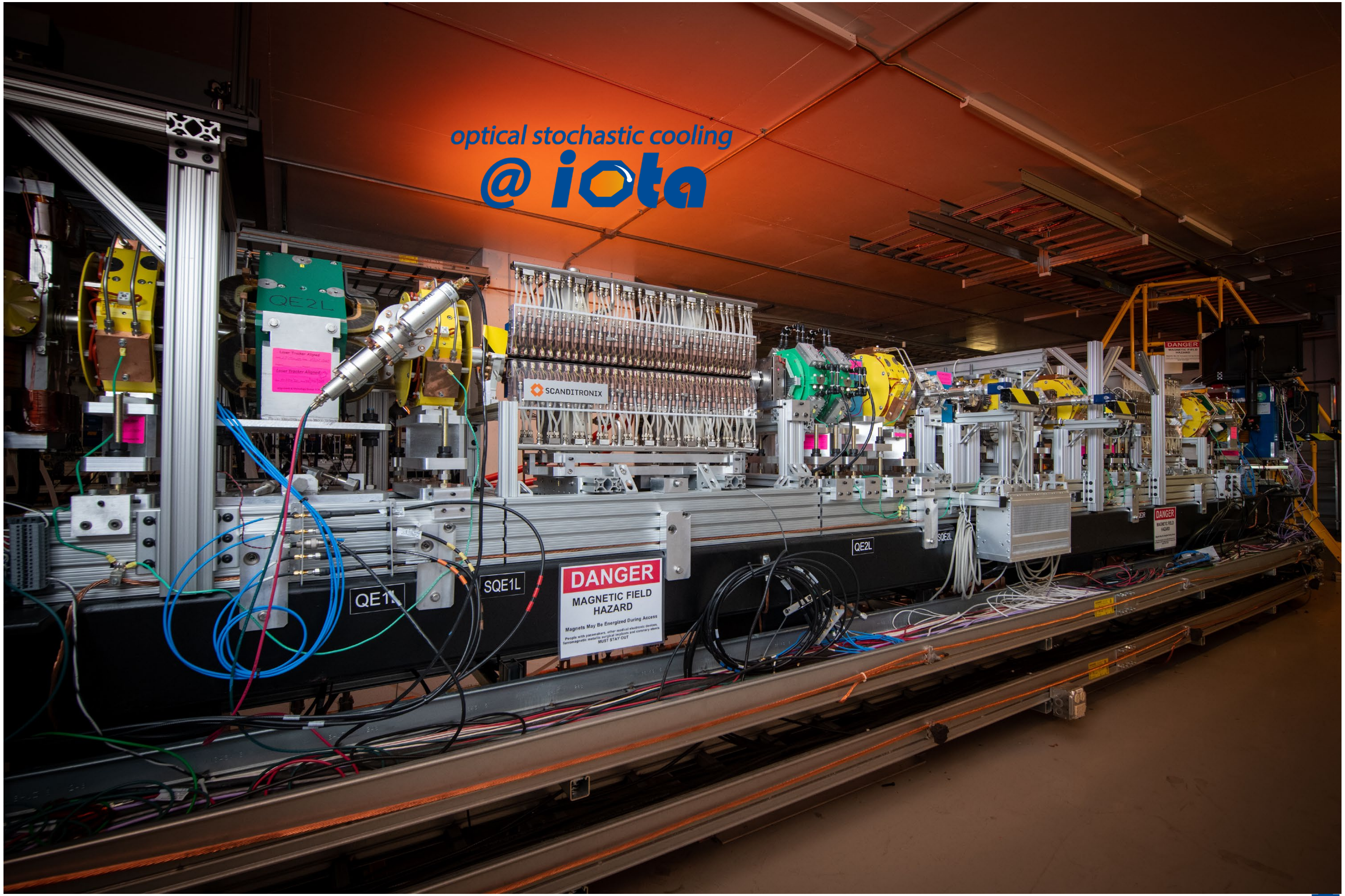
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SCANDITRONIX
DANGER
MAGNETIC FIELD
HAZARD
QE1L
SQE1L
QE2L