



# Demonstration of Optical Stochastic Cooling in an Electron Storage Ring

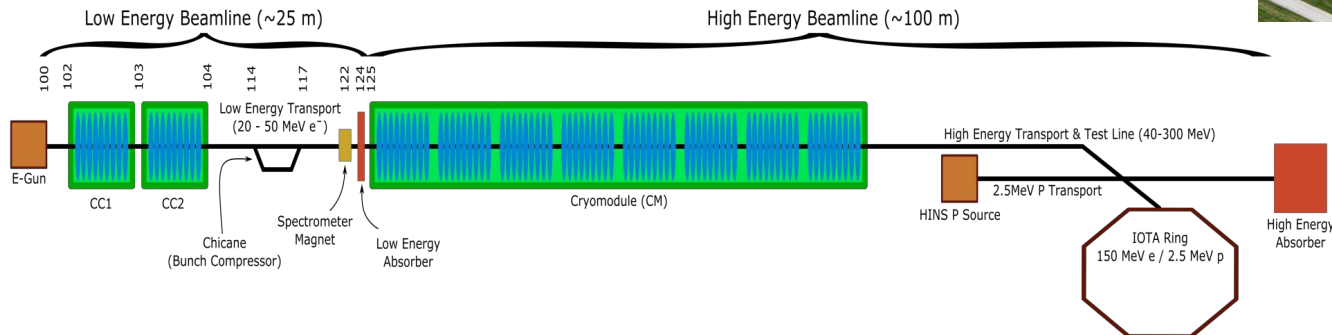
Jonathan Jarvis (on behalf of the IOTA/FAST team)

Scientist @ FNAL Accelerator Division: Accelerator Research Dept.

August 12, 2022

# IOTA/FAST Facility: a leading center for Acc. and Beam Physics

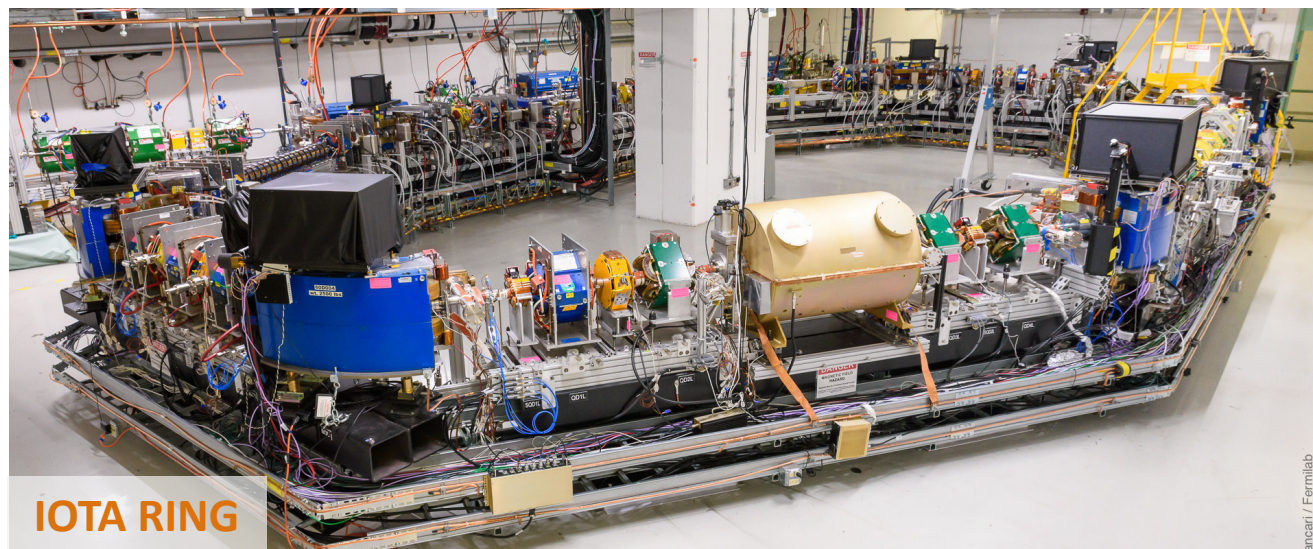
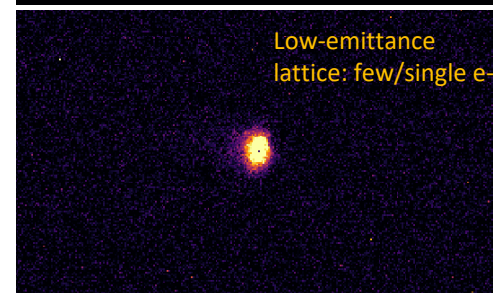
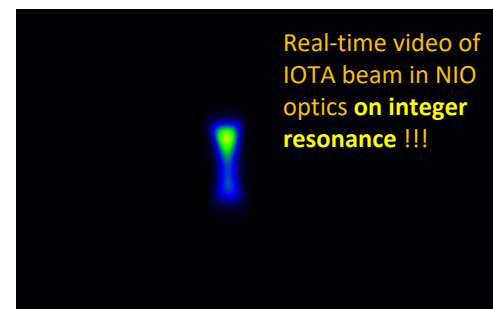
- **IOTA/FAST establishes a unique capability at FNAL to address frontier topics in ABP**
- Dedicated facility for intensity-frontier accelerator R&D
- 2.5 MeV Proton injector currently under construction for R&D with high-intensity beams
- Integrated SRF testing with high-intensity beams (historical 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)



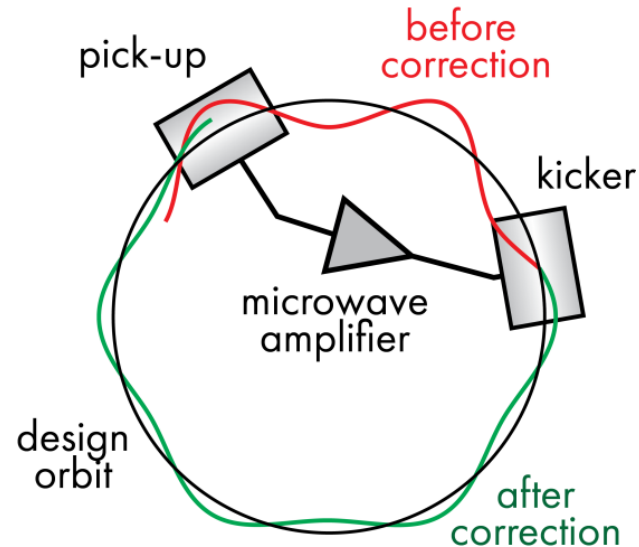


# IOTA/FAST: a center for Acc. and Beam Physics

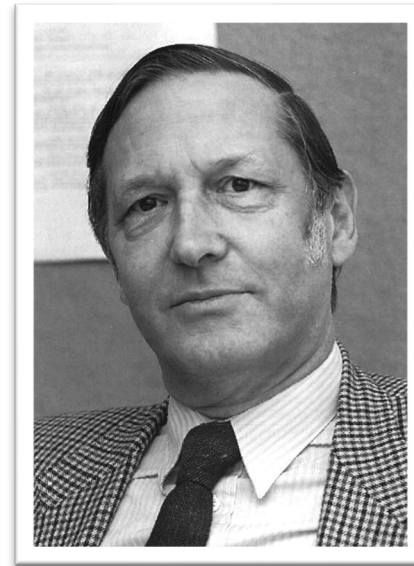
- Suppression of coherent instabilities via Landau damping (NIO, E-lenses)
- Mitigation of space-charge effects (NIO, E-lenses)
- **Advanced beam cooling; Optical Stochastic Cooling**
- Photon and Quantum Science with a single electron
- Development of novel instrumentation and methods
- ...



# Stochastic Cooling: an enabling technology for colliders



(simplified stochastic cooling system)



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:

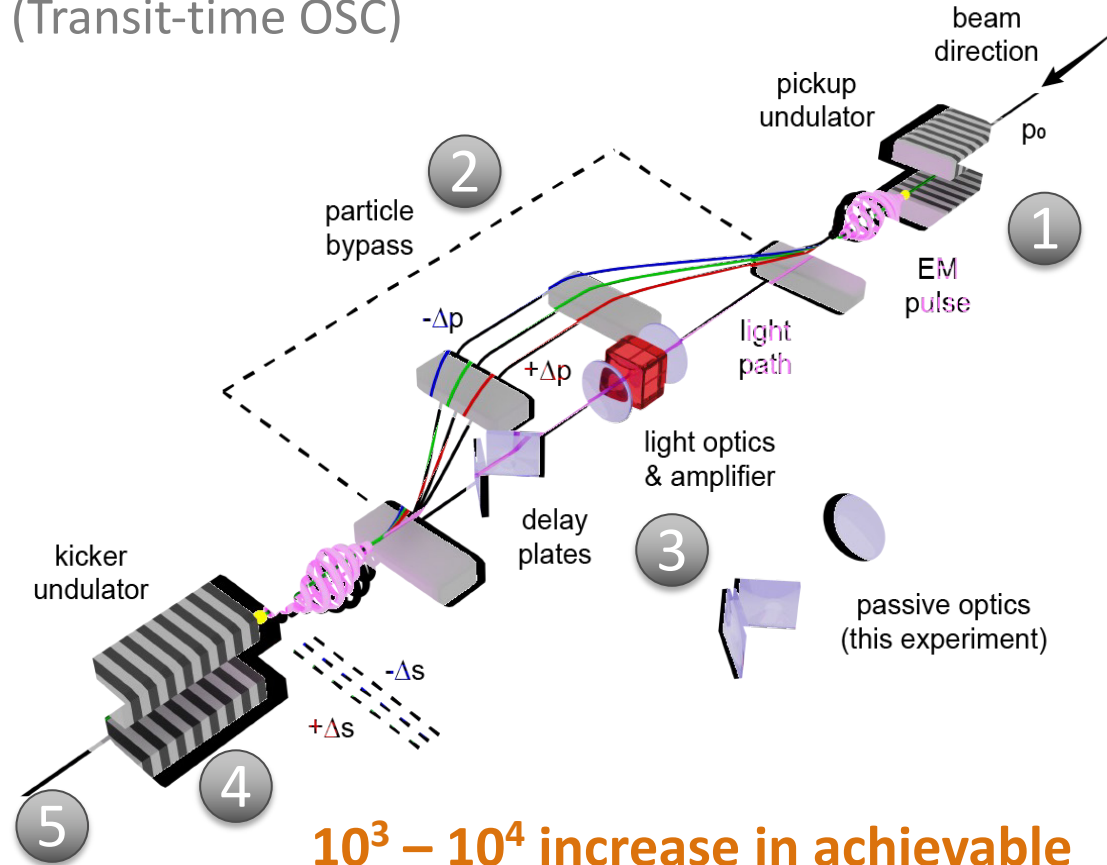
1. The field that cools a particular particle must be correlated with the particle's phase-space position. **In short, the field must know where each particle is.**
2. The field that pushes a particular particle towards the centre should preferably push the empty phase-space around it outwards. **It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



# OSC extends the SC principle to optical bandwidth

(Transit-time OSC)



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

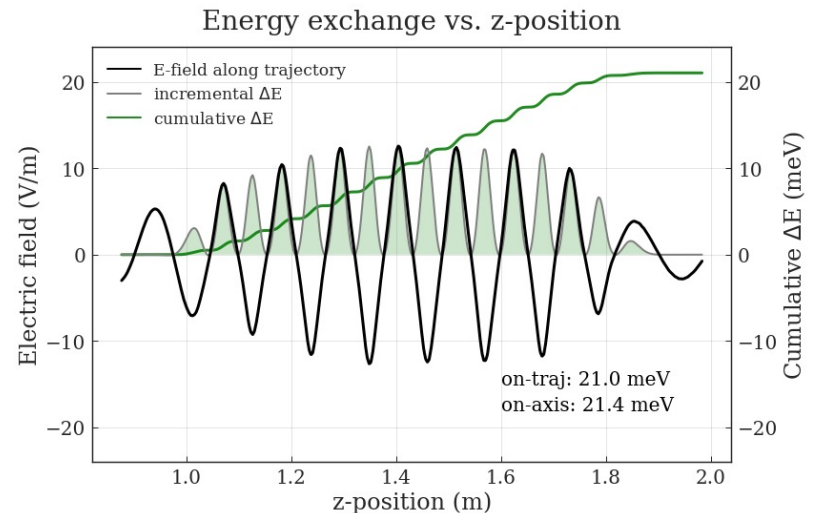
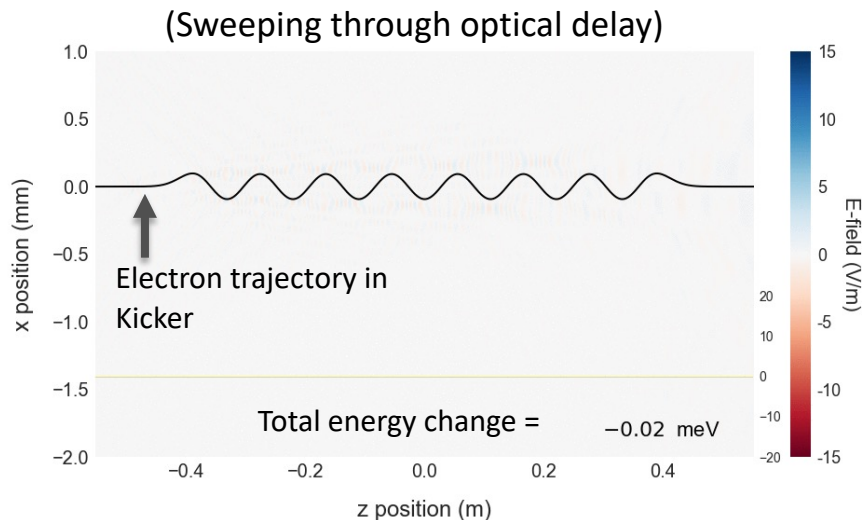
1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates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

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



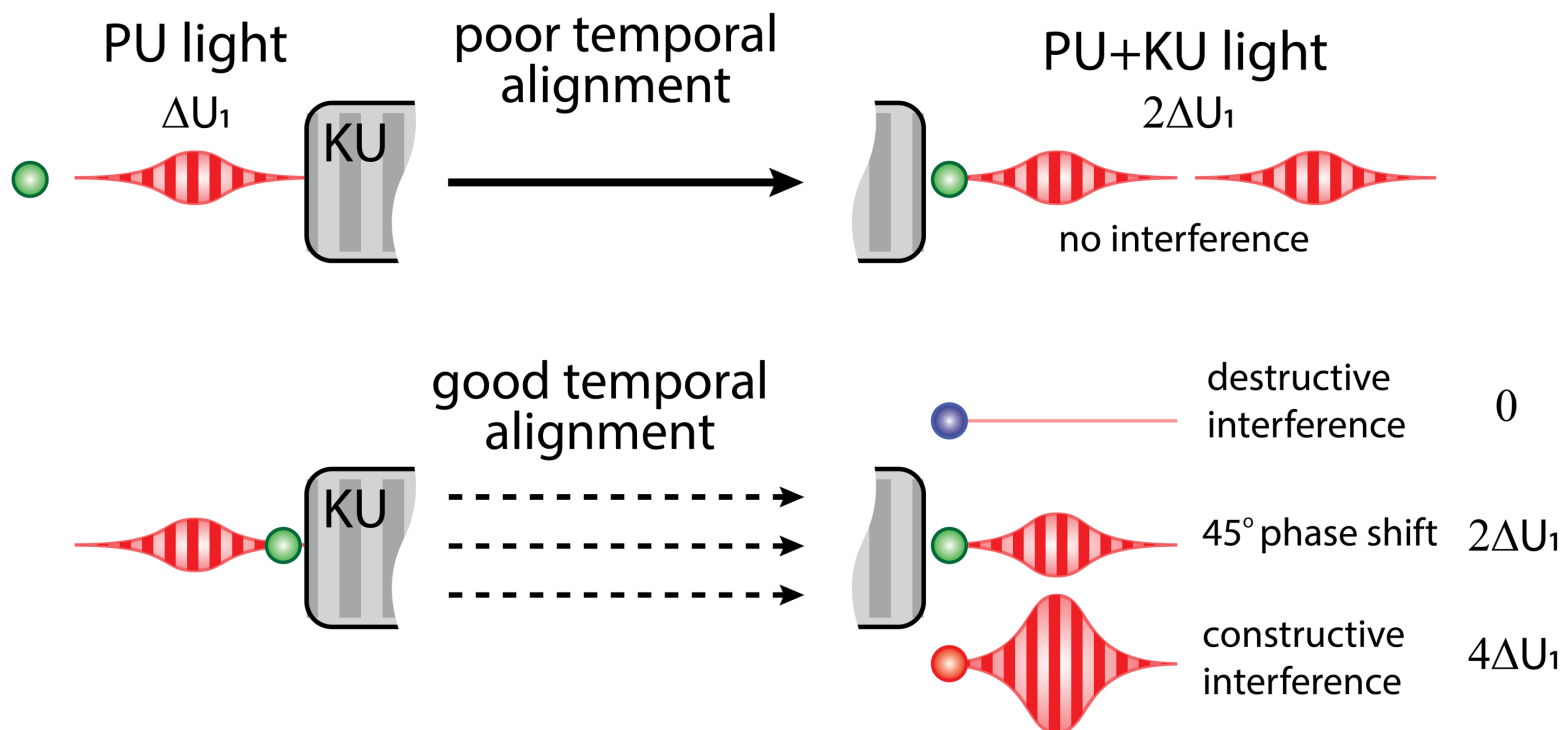
# OSC principle: corrective kick based on a particle's error

- 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
- IOTA's OSC design naturally produces **3D cooling...**
- Transit-time OSC produces longitudinal (energy) cooling, but:
  - A single coupling quad in the bypass can share cooling between the longitudinal and horizontal planes
  - Operation of the storage ring on a transverse coupling resonance shares the horizontal cooling with the vertical plane





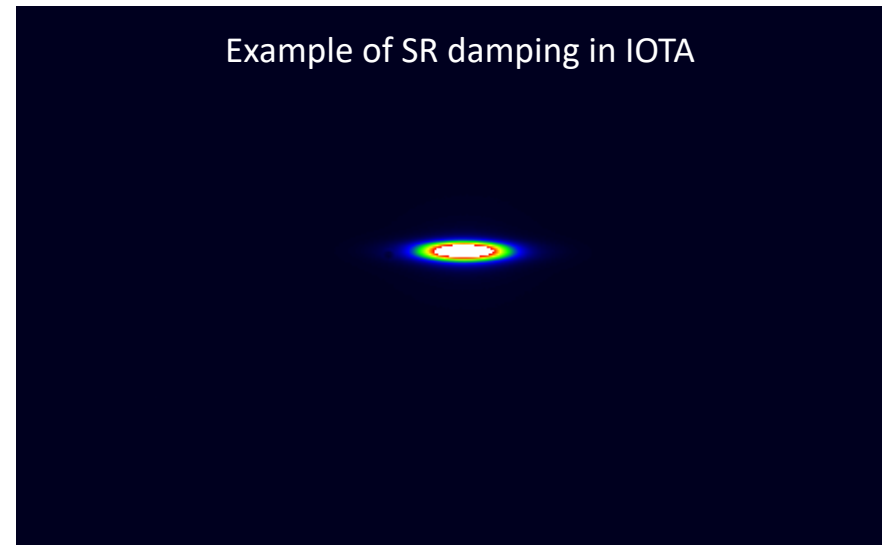
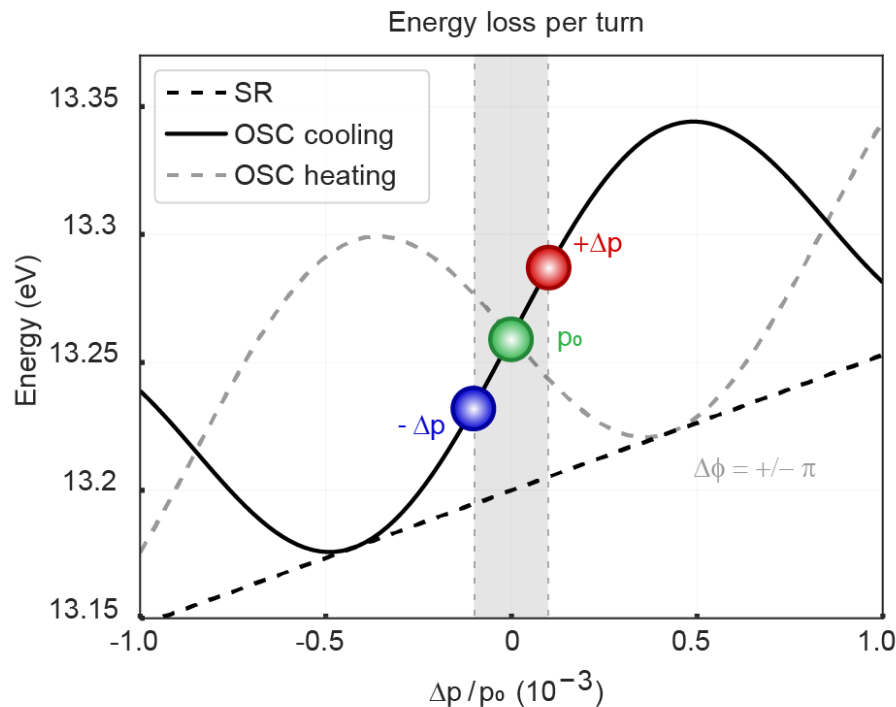
# OSC energy exchange has the character of interference



- 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  $\sim 10\times$  without any optical amplification ( $\tau_{\text{eS}} \sim 50$  ms,  $\tau_{\text{ex/y}} \sim 100$  ms)

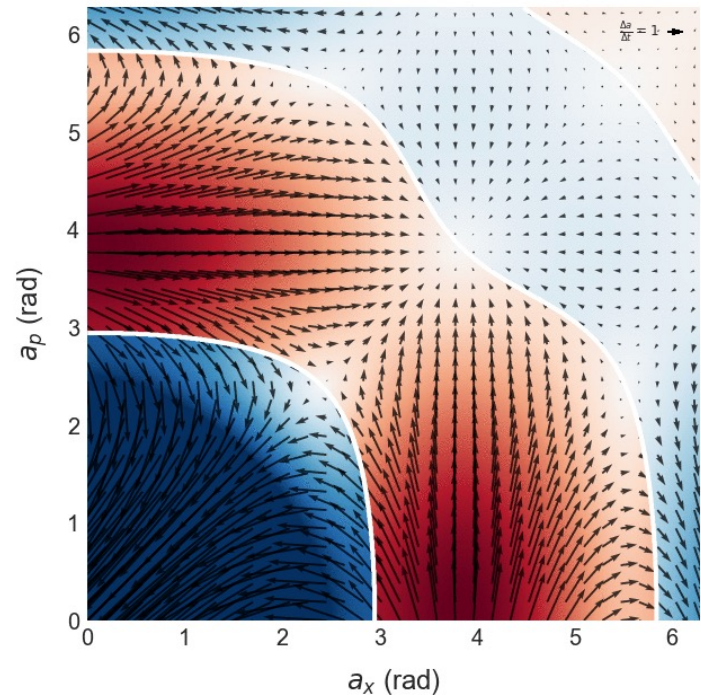




# Short wavelength results in finite range of the OSC force

- 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

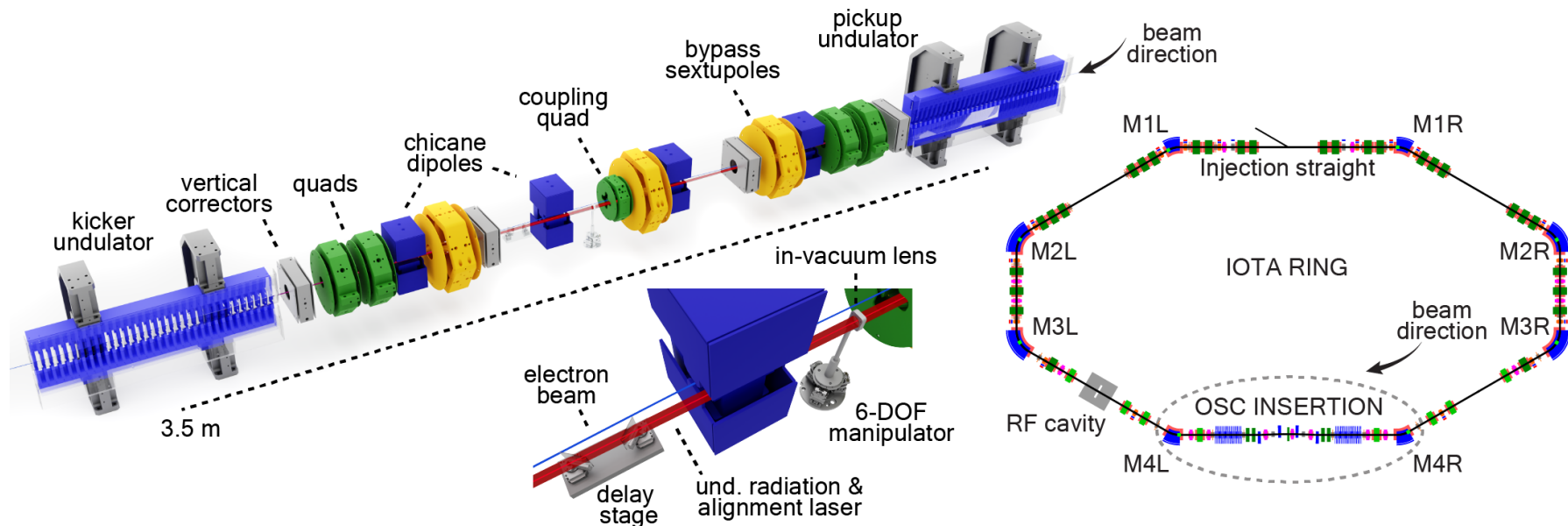
(Sweeping through optical delay)



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

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

# A staged approach for OSC at IOTA

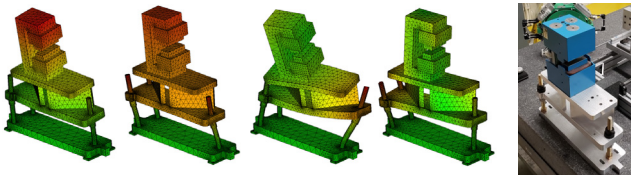
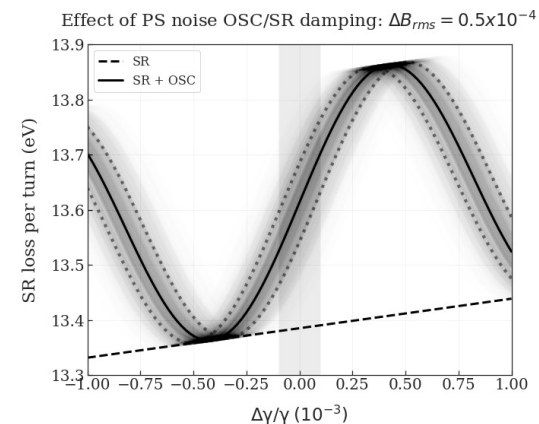
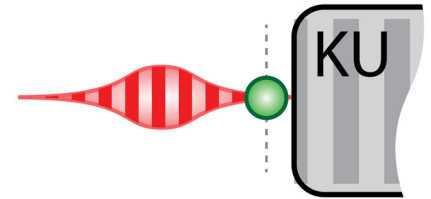
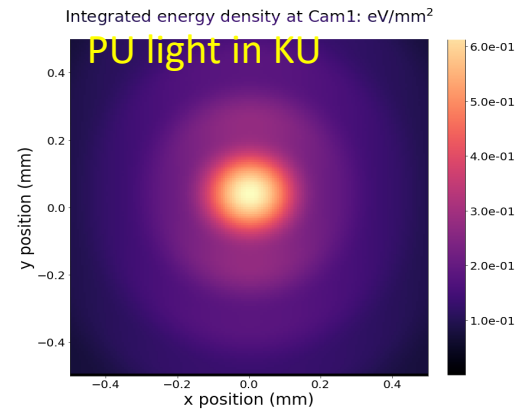


- **Non-amplified OSC ( $\sim 1\text{-}\mu\text{m}$ ):** simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC ( $\sim 2\text{-}\mu\text{m}$ ):** OSC amplifier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



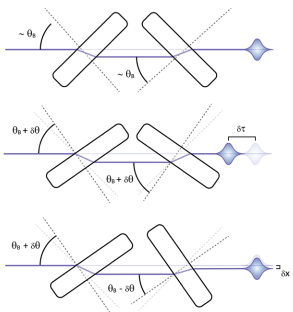
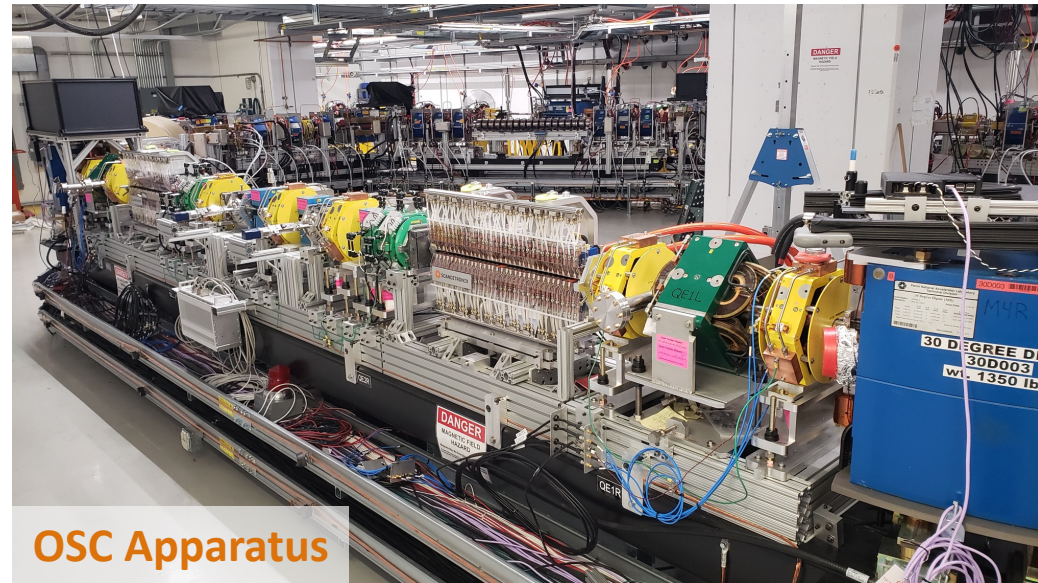
# What makes (“simple”) OSC challenging?

1. Beam and PU light must overlap through the KU
  - The undulator light is  **$\sim 200\ \mu\text{m}$**  wide
  - Want angle between light and beam at  **$< \sim 0.1\ \text{mrad}$**
2. Beam and PU light must arrive  **$\sim$ simultaneously** for maximum effect
  - Absolute timing should be better than  **$\sim 0.3\ \text{fs}$**
  - The entire delay system corresponds to  $\sim 2000\ \text{fs}$
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  **$\sim 0.3\ \text{fs}$**
  - This means total ripple+noise in chicane field must be at the  **$\sim \text{mid } 10^{-5}$**  level
4. Practical considerations of design and integration!

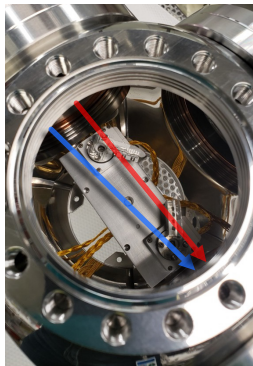


# OSC apparatus successfully integrated in IOTA

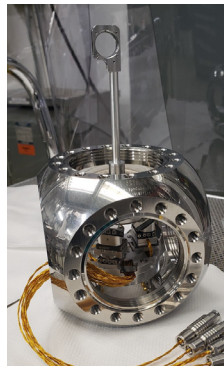
- Established and corrected OSC lattice to desired precision
- Achieved  $\sim 80\%$  of theoretical max aperture and  $\sim 20$ -min lifetime; sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully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



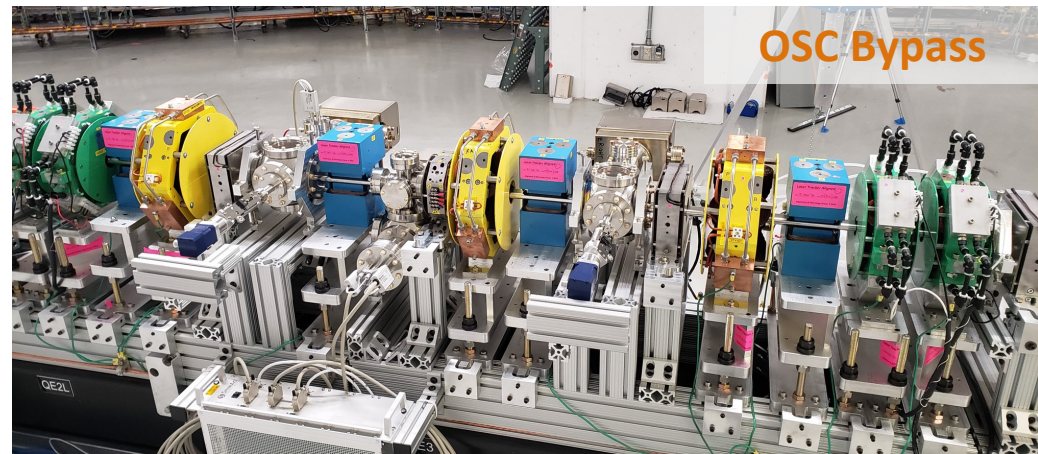
Delay stage



Delay stage

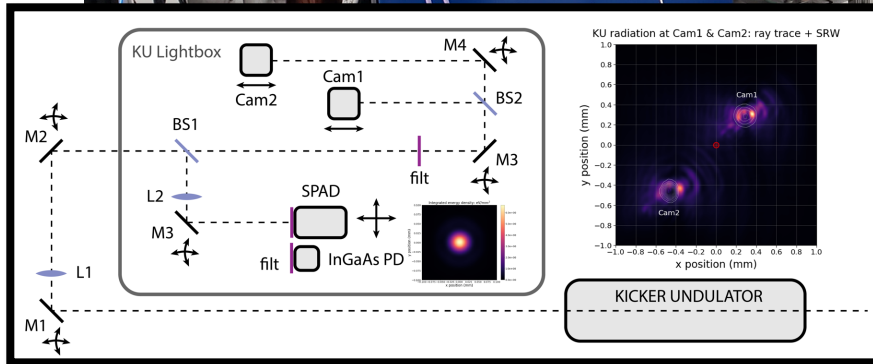
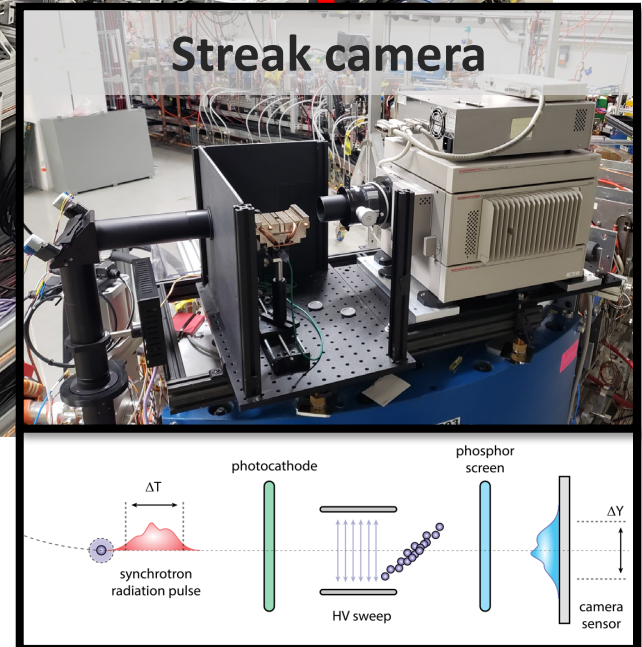
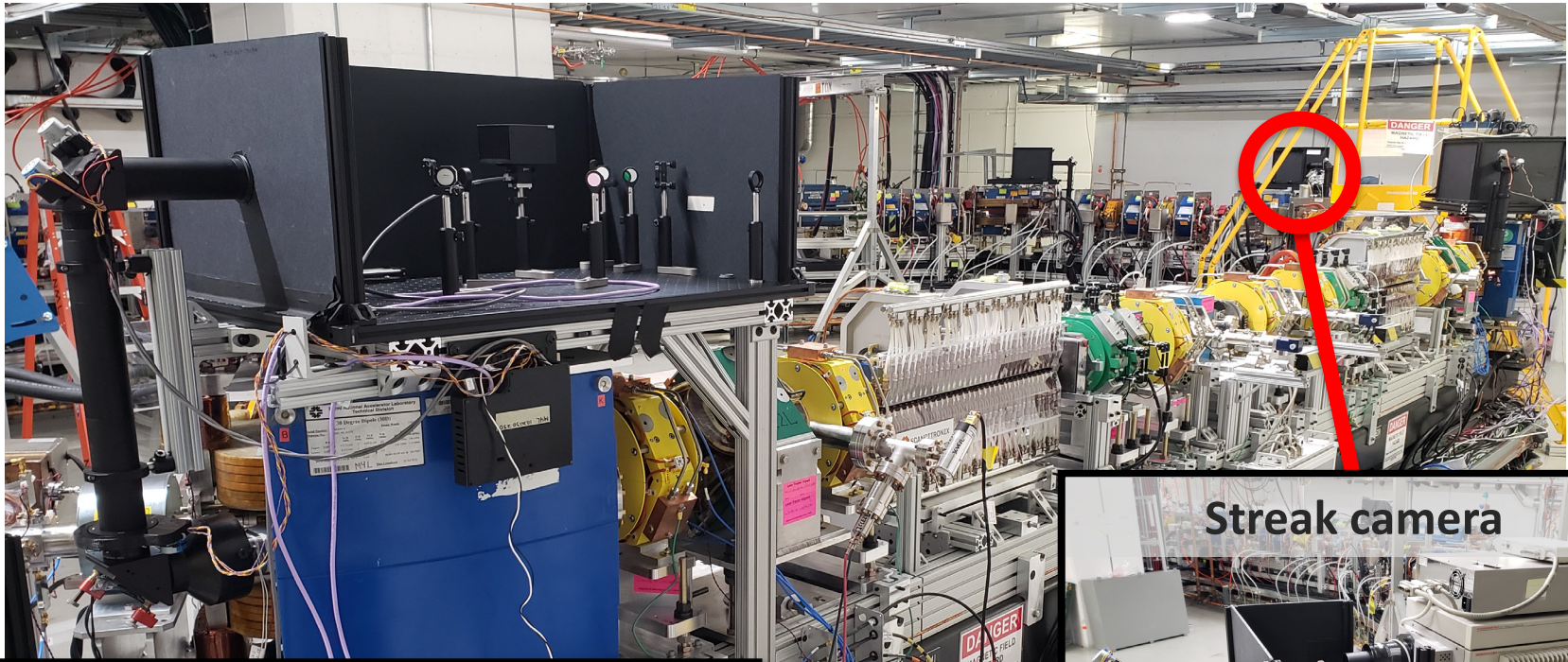


lens stage





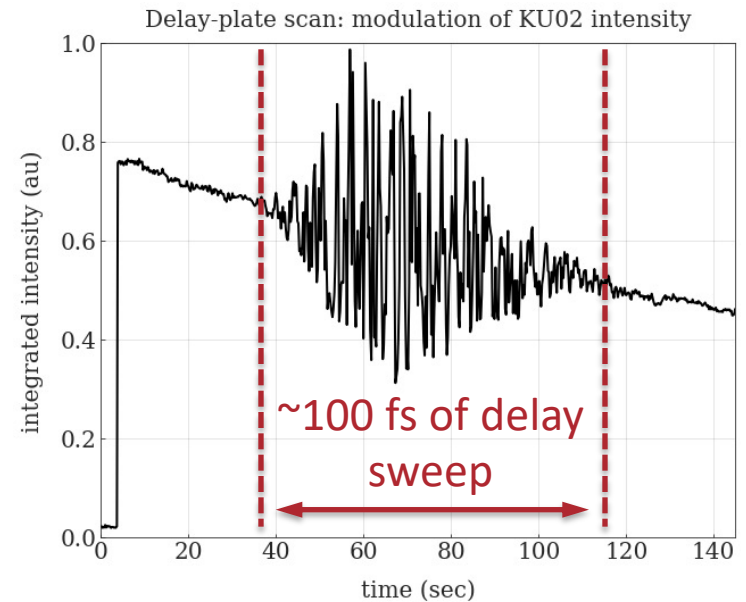
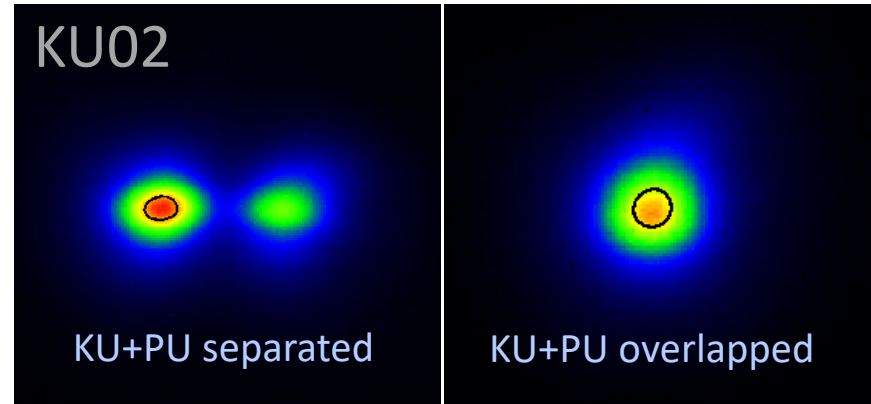
# OSC is monitored via synchrotron-rad. stations



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

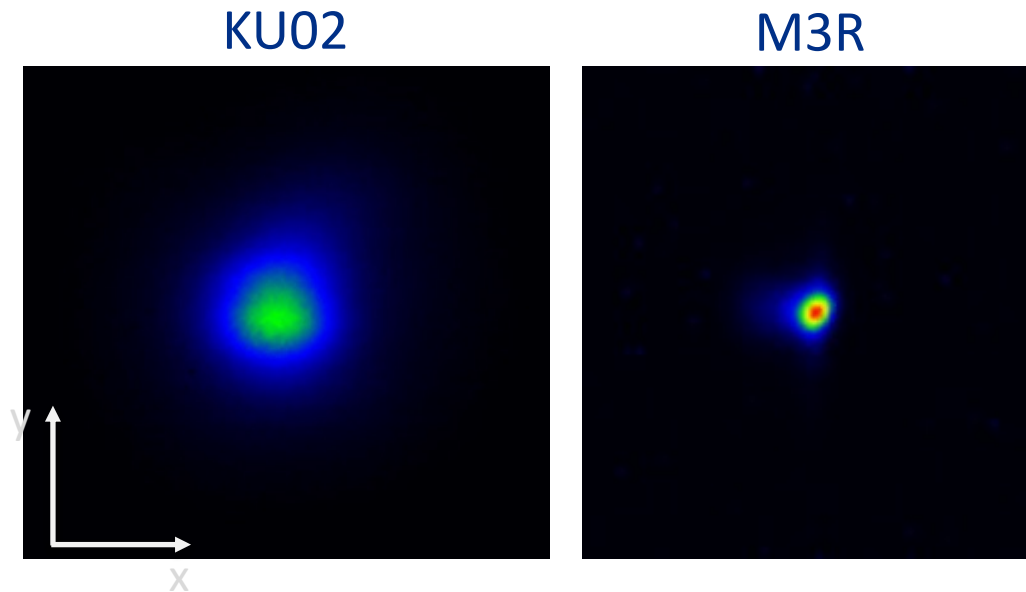
# On 04/20/21, interference was observed at full undulator power

- 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

# Observed strong UR modulation and cooling/heating on 4/20



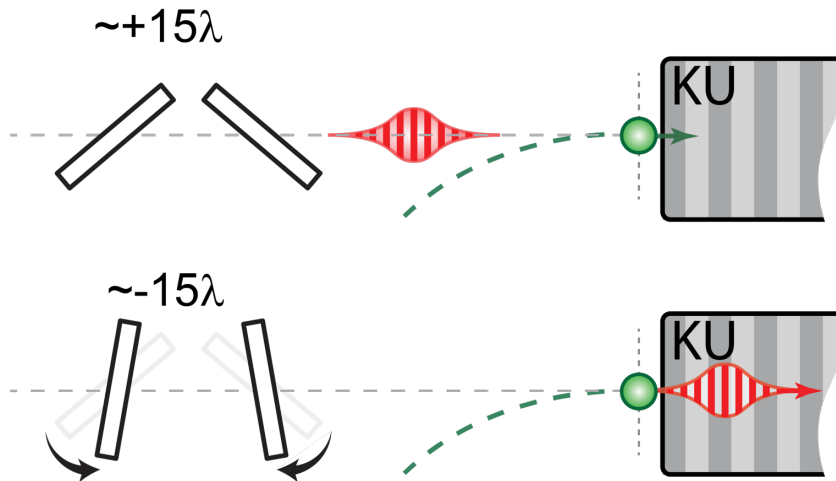
(movies not taken simultaneously but are representative)

- Bypass and optical delay are fixed in the movies above
- **FNAL Main Injector ramp was sweeping beam across OSC zones**
- Regulation upgrades resulted in excellent stability of OSC (~10s-100s nm?)

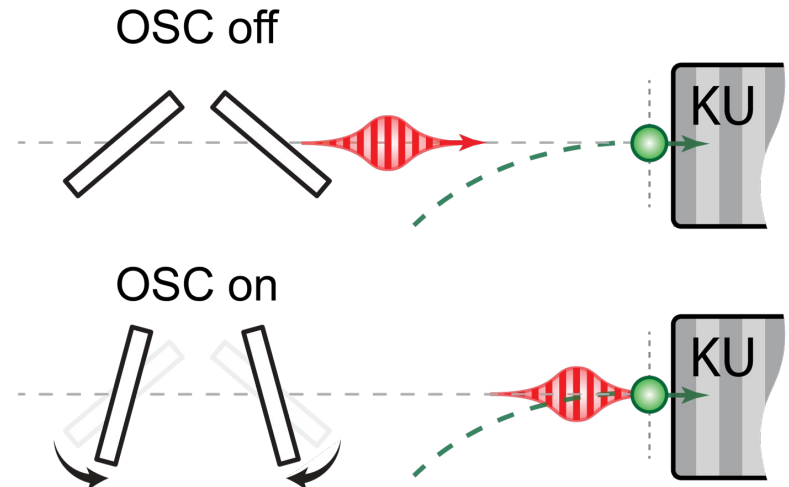
# After much work... OSC was strong and stable

- **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
- Two primary measurements:

## SLOW DELAY SCANS ( $\sim 0.03 \lambda/\text{sec}$ )



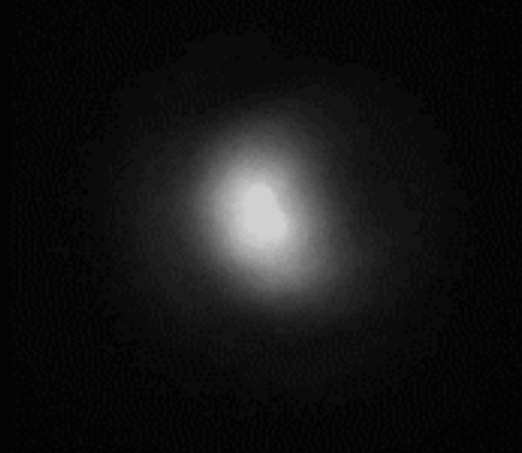
## FAST TOGGLES ( $\sim 15 \lambda/\text{sec}$ )





# Delay scan with OSC in the 3D configuration

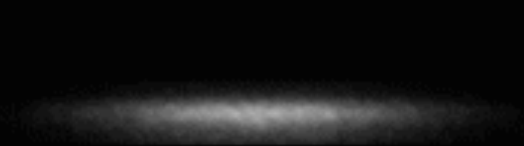
Interfering UR



Transverse beam distribution



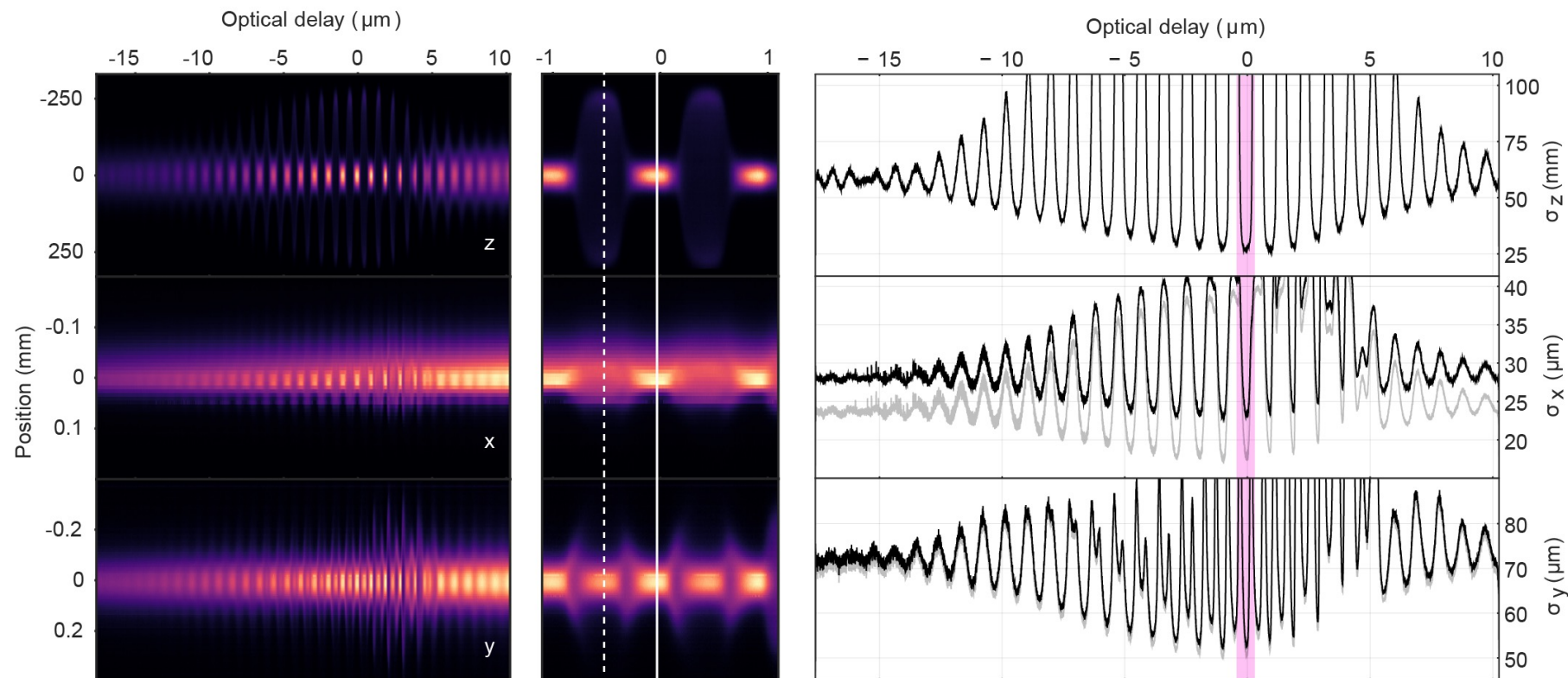
Longitudinal beam distribution



Video @ ~15x realtime

Delay-scan rate  $\sim 0.03\lambda/s$

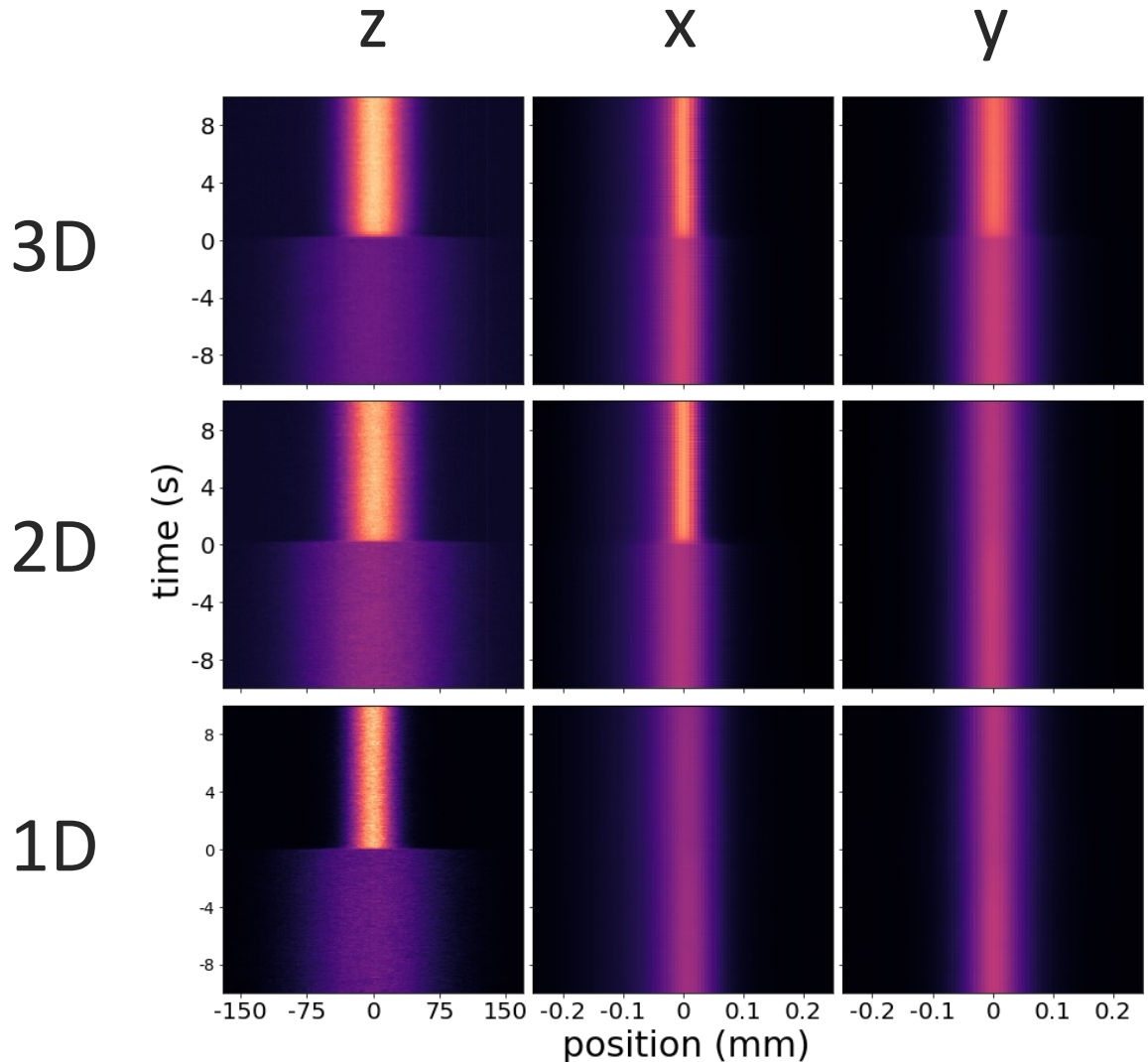
# Delay scans show expected OSC structure



- Delay scan over entire OSC overlap region ( $\sim 30\lambda$ )
- OSC alternates between cooling and heating modes
- Strong simultaneous cooling is observed for all three planes
- Envelope corresponds to  $\sim 20$ -THz bandwidth ( **$\sim 2000\times$  greater than conventional stochastic cooling**)

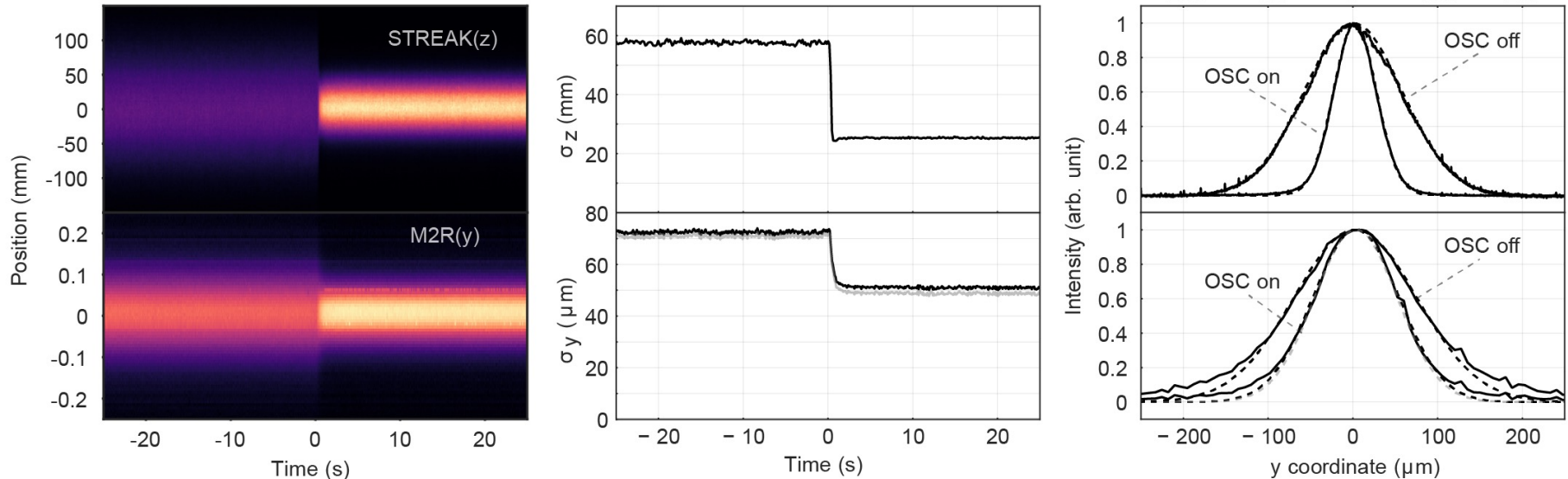
# OSC Cooling configurations at a glance...

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



# Equilibrium sizes used to estimate the OSC force

(3D OSC toggle)

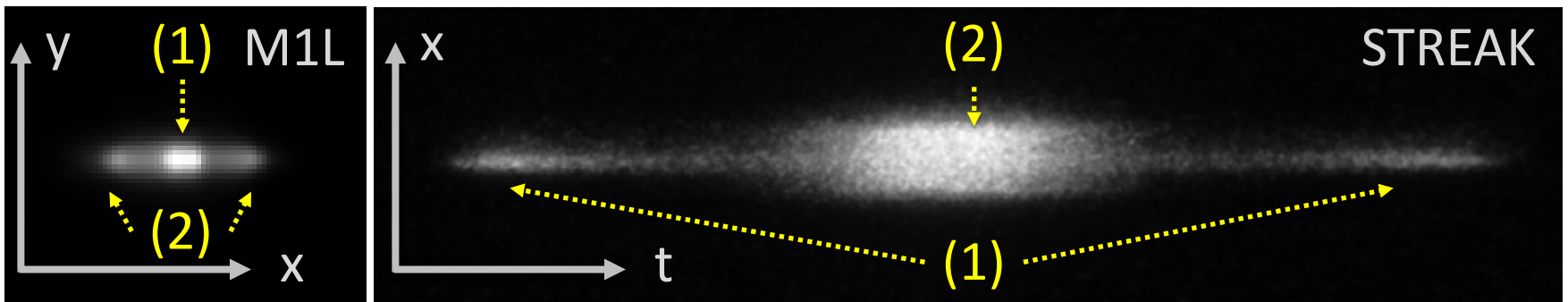
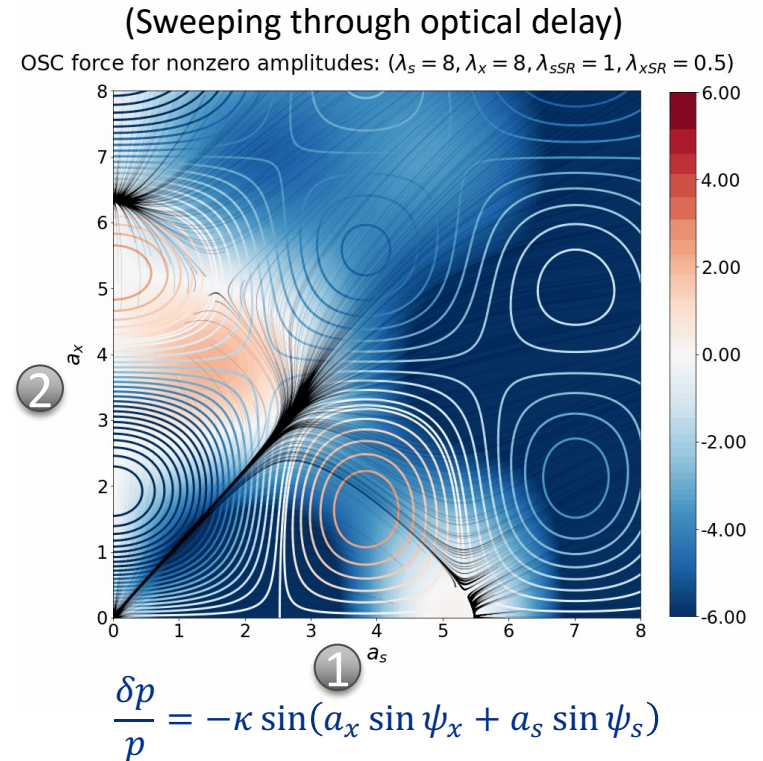


- Accounting for intrabeam scattering, total OSC force is  $\sim 9\times$  stronger than the longitudinal SR damping
- $\sim 60\%$  of the expected value from detailed simulations of the undulator radiation (accounting for known losses)
- Similar strength for 2D and 1D configurations, but full analysis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



# Clear observation of expected OSC zone structure

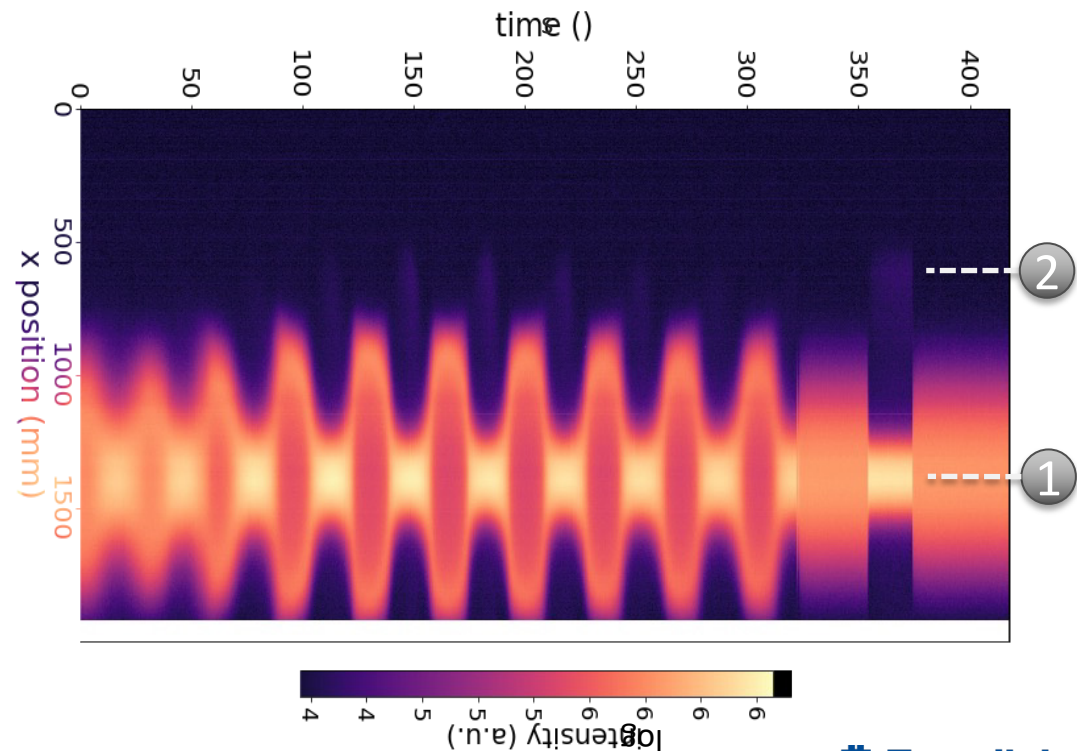
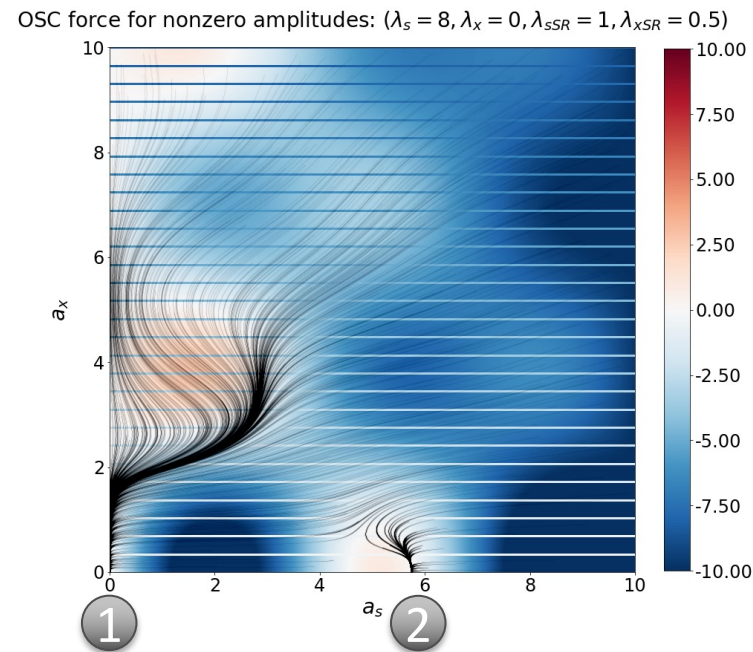
- (e.g) OSC in the 2D (z,x) configuration
- In “heating” mode, expect two high-amplitude attractors
- (1): high synchrotron amplitude, low betatron amplitude
- (2): high betatron amplitude, low synchrotron amplitude



Transverse and longitudinal projections for heating mode of 2D OSC

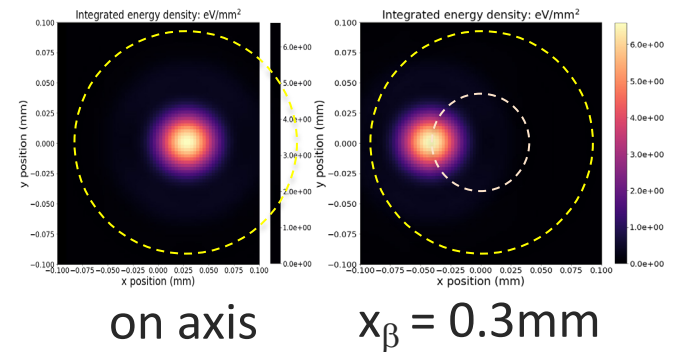
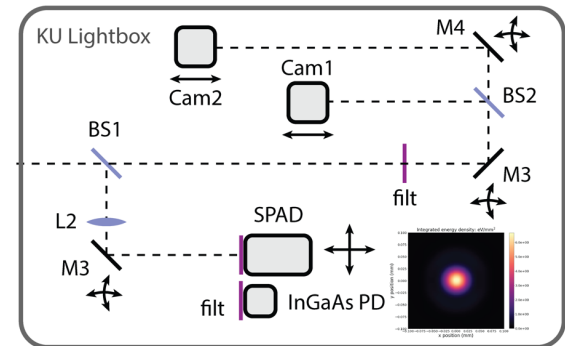
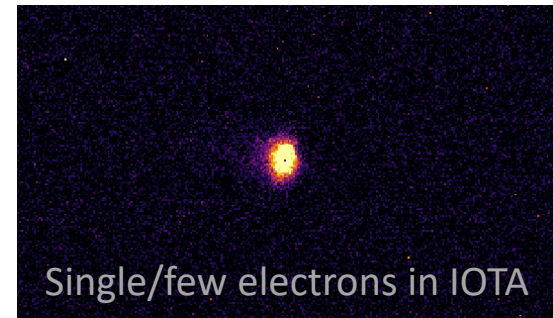
# Clear observation of expected OSC zone structure

- For 1D **cooling mode** with a high-intensity beam, we can also observe the much weaker 2<sup>nd</sup>-order cooling zone
- Increased intrabeam scattering to high amplitudes populates this zone
- ① : fundamental cooling zone
- ② : 2<sup>nd</sup>-order cooling zone



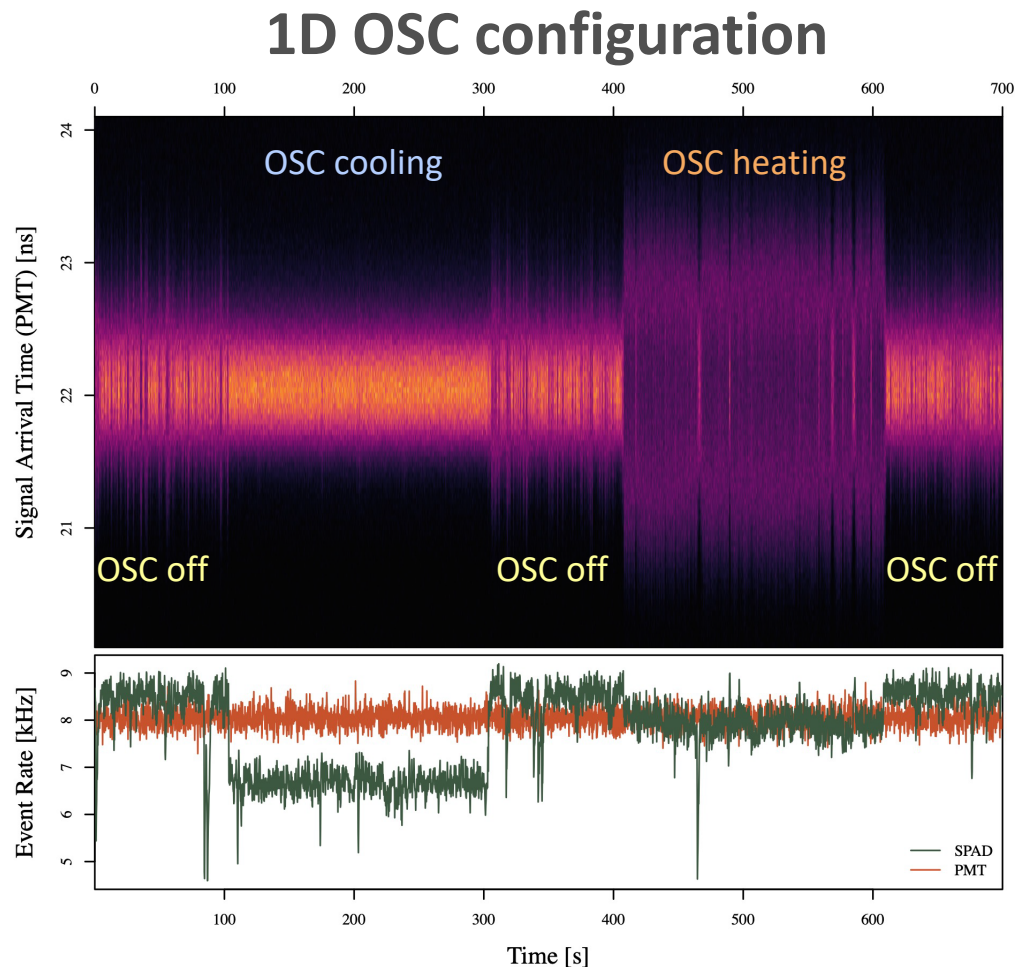
# IOTA enables single-electron OSC studies

- Can reliably inject and store a single electron in IOTA; **OSC system changes probability of photon detection in fundamental band**
- Fundamental (KU+PU) was focused on the active element of a SPAD (KU lightbox); demagnified so that betatron excitations up to  $\sim 0.3\text{mm}$  ( $\sim 10$  sigma) remain on SPAD's active element
- HydraHarp event timer captures every detected photon for both the SPAD and PMT (M3L lightbox) over many minutes; referenced to IOTA revolution marker with resolution of a few hundred ps, which is sufficient to observe OSC phenomena
- Performed full OSC delay scans and toggles of cooling/heating for 1D and 2D OSC configuration



# 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 ( $\sim 170$  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

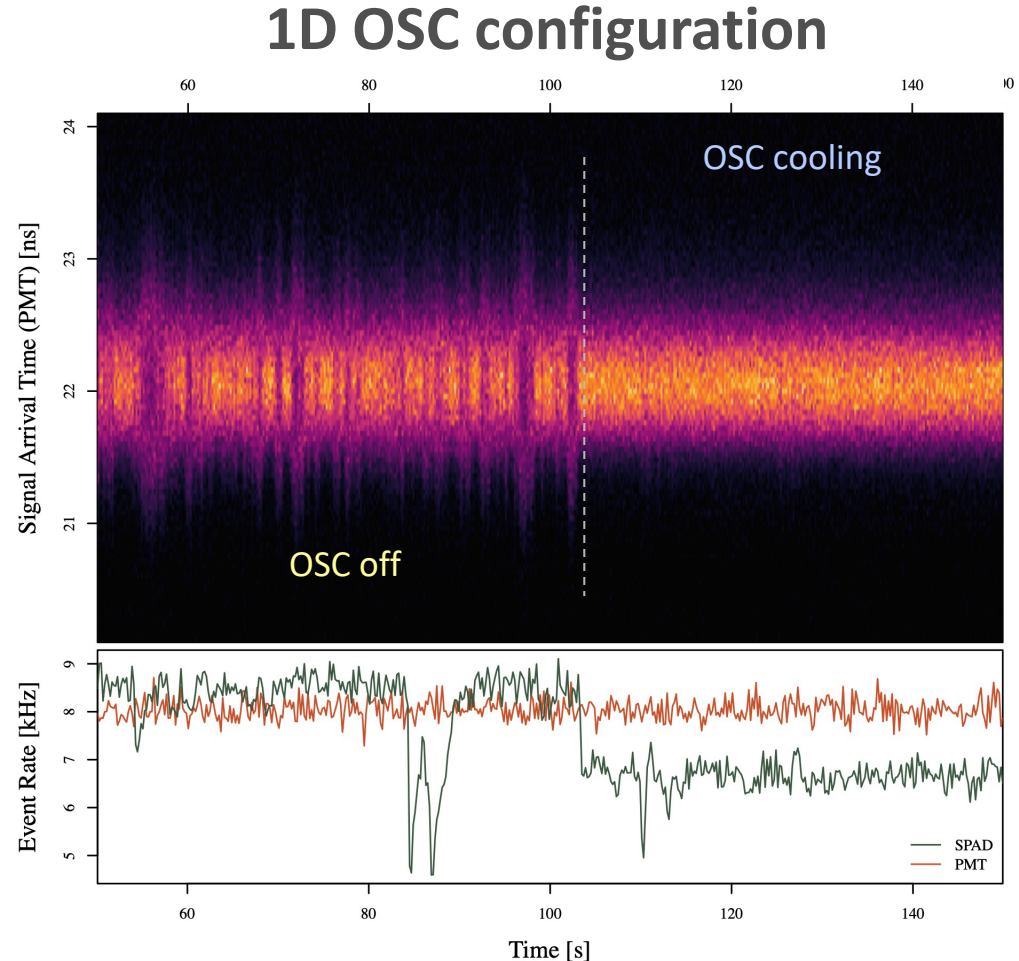


(Plots by G. Stancari)



# OSC for single electron is visible in photon timing

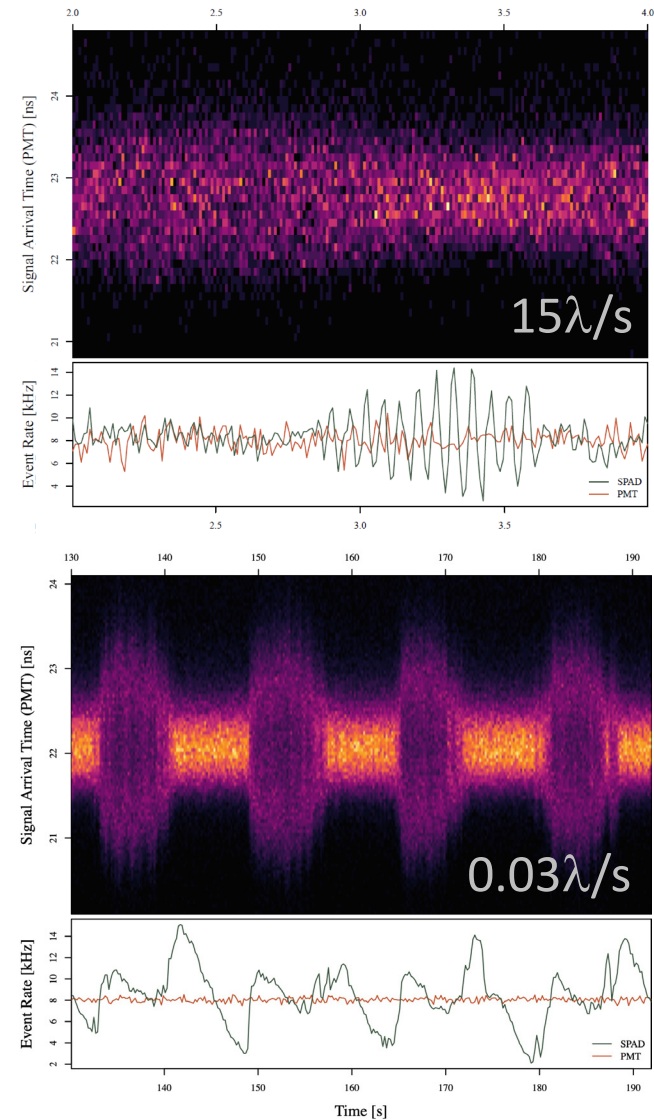
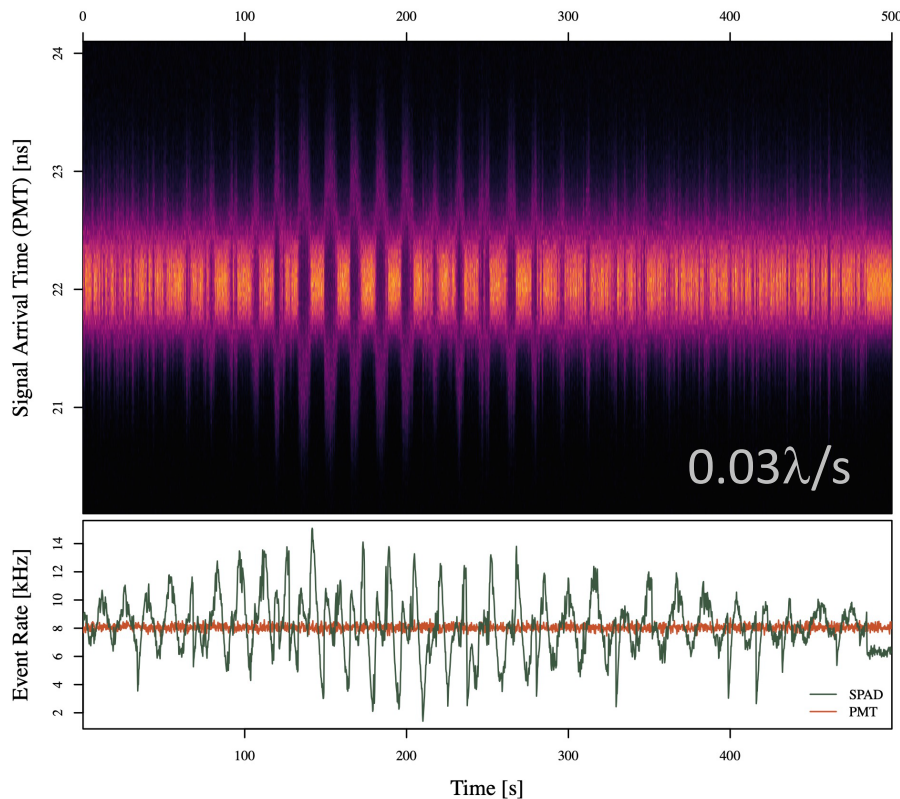
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(Plots by G. Stancari)

# $1e^-$ delay scans have same structure as with beam

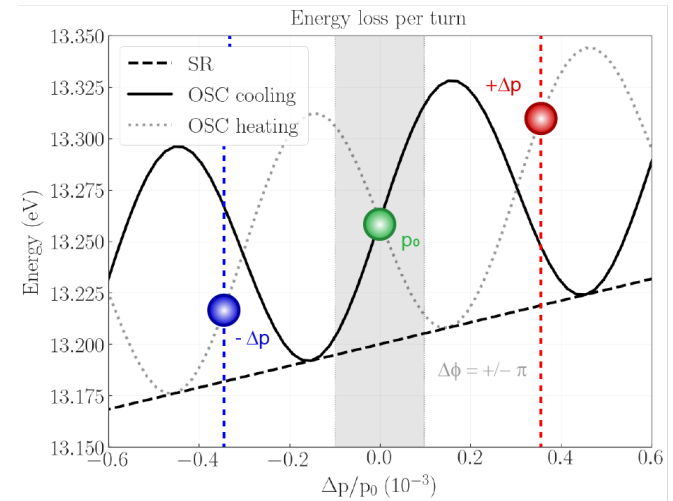
- “Fast” delay scans ( $\sim 0.5\lambda$  in  $\sim 30\text{ms}$ ) show modulated emission probability with minimal disturbance of the beam



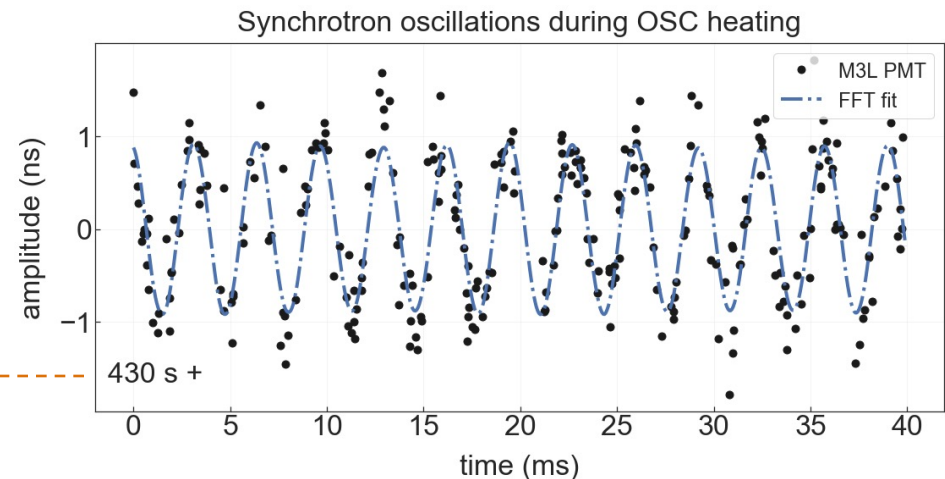
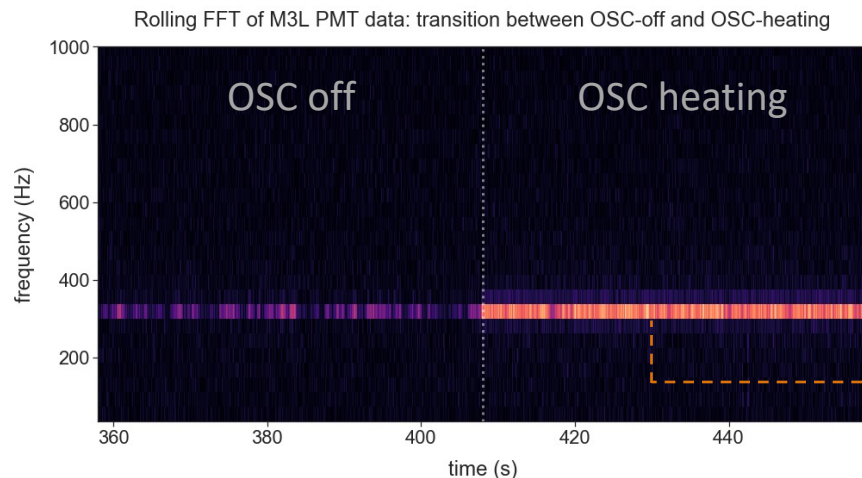
(Plots by G. Stancari)

# 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



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

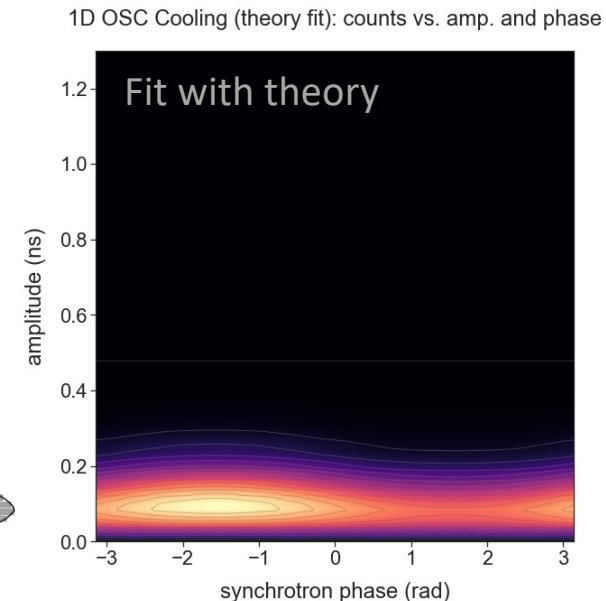
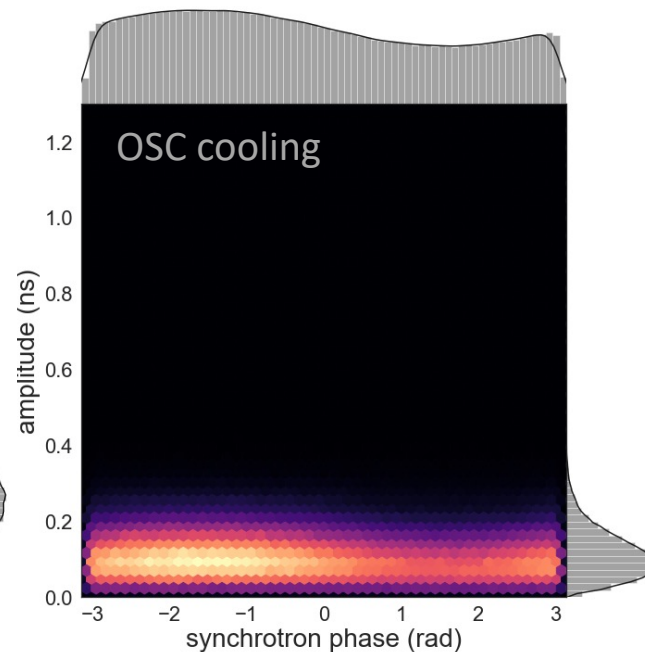
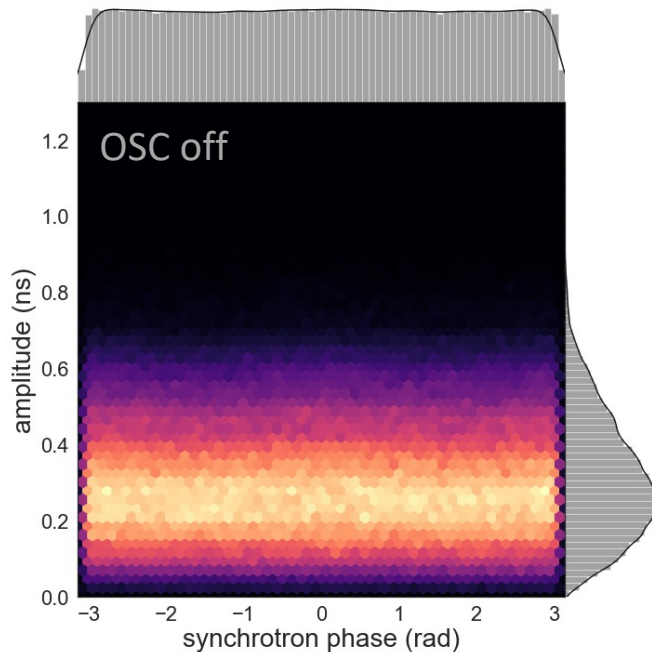
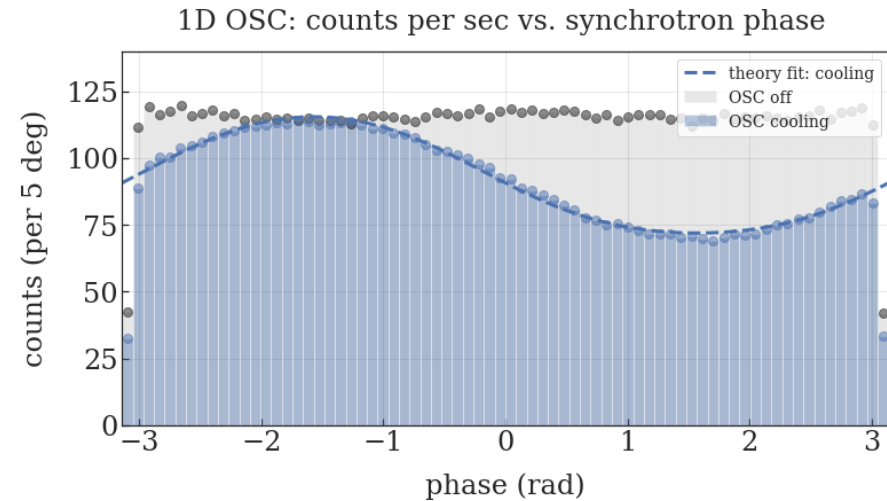




# OSC photon detection oscillates with synchrotron phase

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

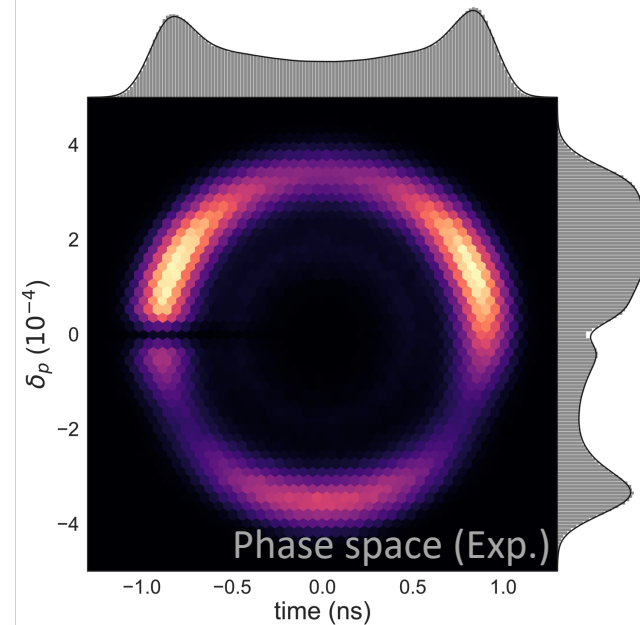
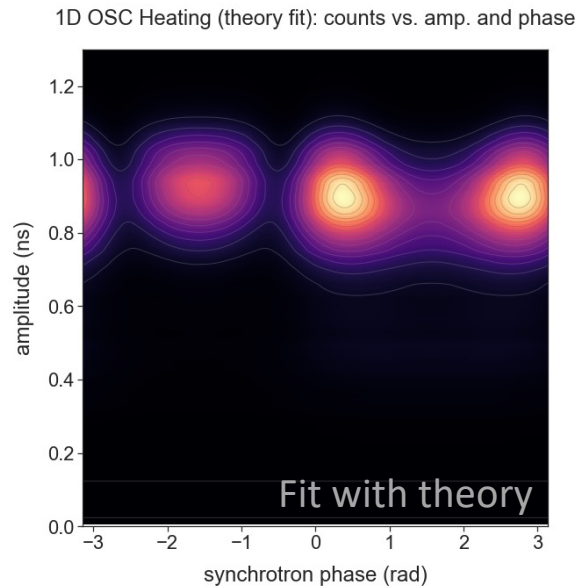
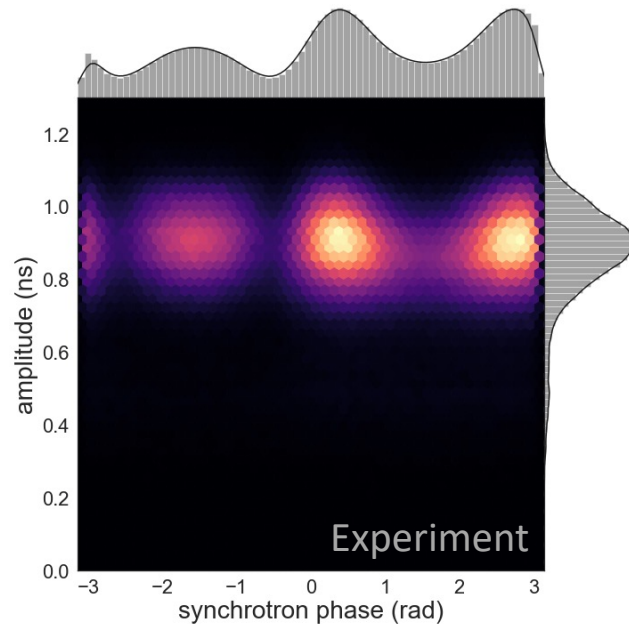
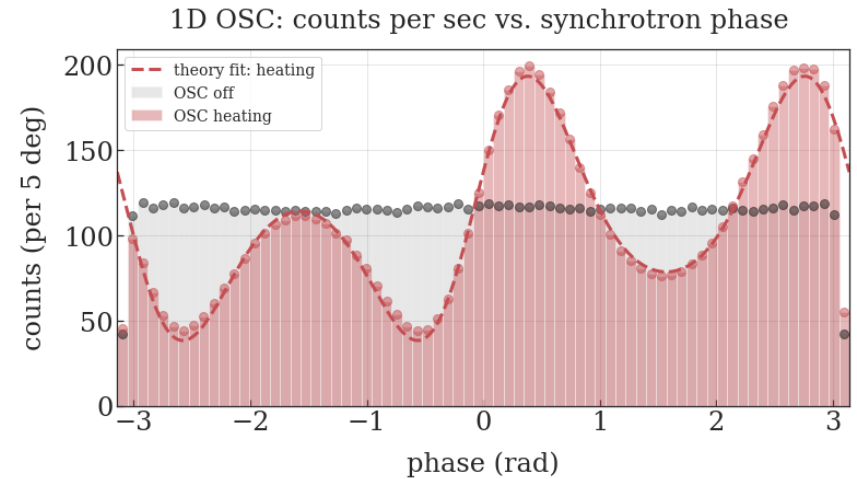
$$\frac{\delta p}{p} = -\kappa \sin(a_s \sin \psi_s + \varphi_0)$$



# OSC photon detection oscillates with synchrotron phase

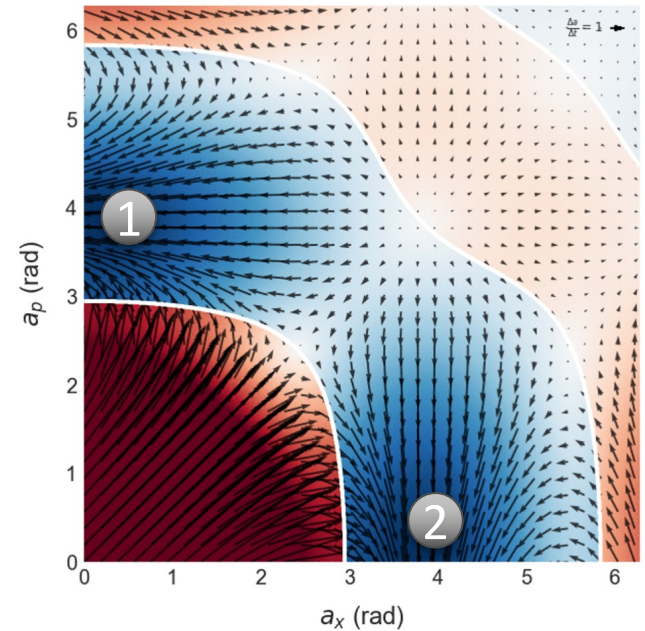
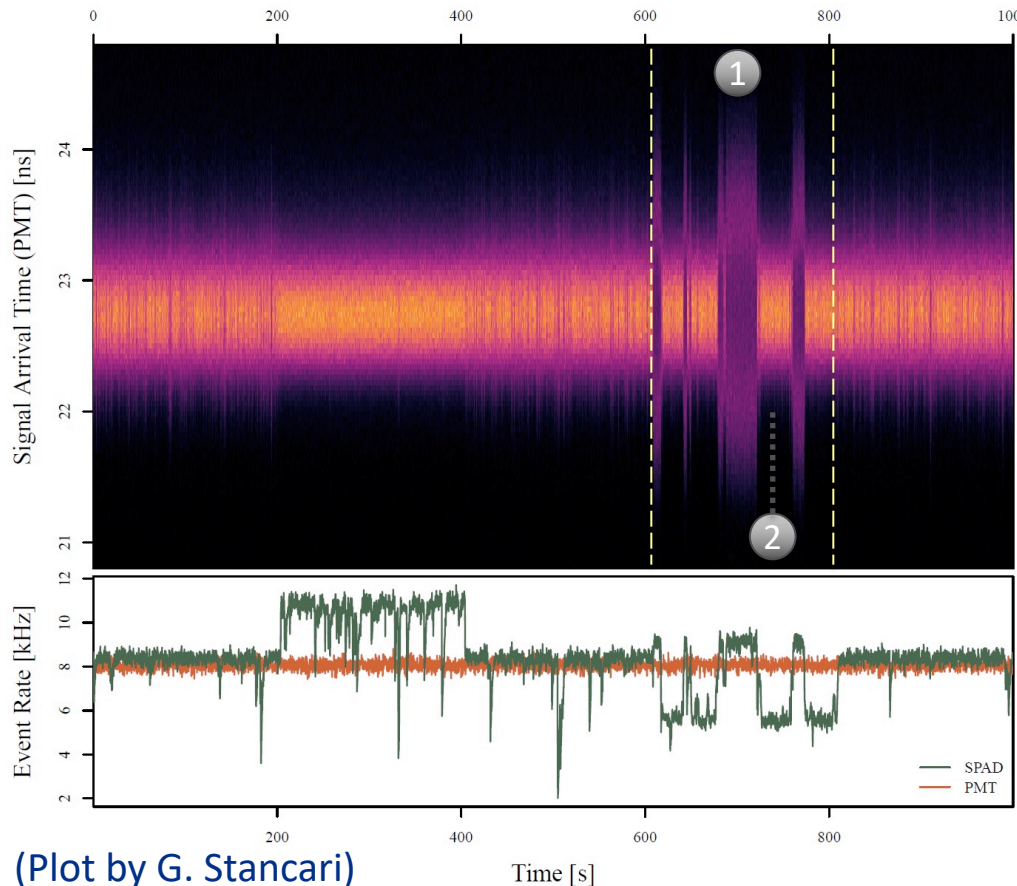
- Very large amplitudes in heating mode produce strong modulation
- Excellent test of theory; complex structure gives strong constraints on various experimental parameters

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



# 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

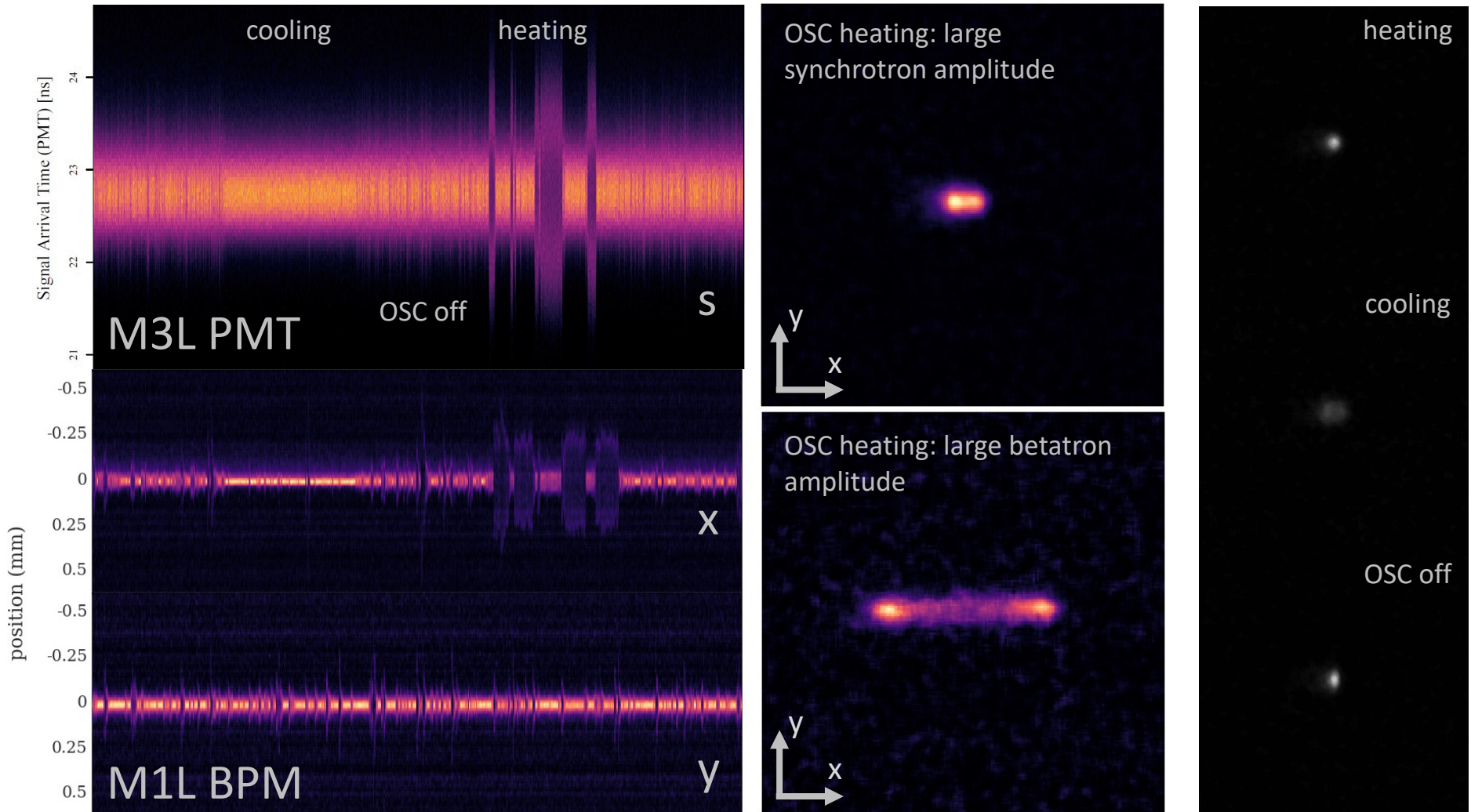


$$\frac{\delta p}{p} = -\kappa \sin(a_x \sin \psi_x + a_p \sin \psi_p)$$

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



# Analysis of SR BPMs confirms the observation



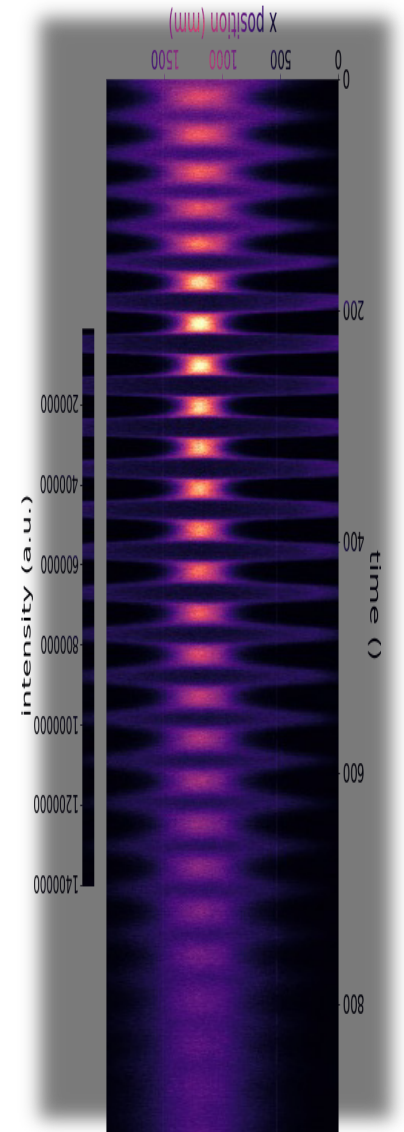
Single electron only present in one attractor at a time



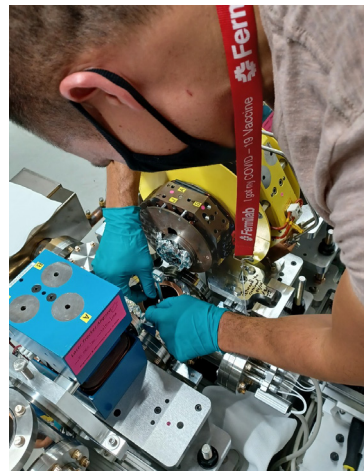
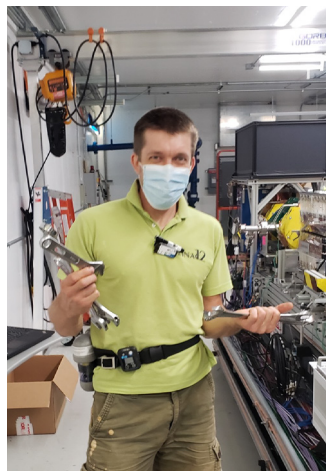
# Conclusions:

- OSC is at an intersection of fundamental beam-physics studies and the development of operational cooling systems
- 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  **$\sim 2000\times$**  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 powerful and unique probe of the OSC physics
- This program established a strong foundation for development of our new amplified OSC experiment (ECA): 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.



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



optical stochastic cooling

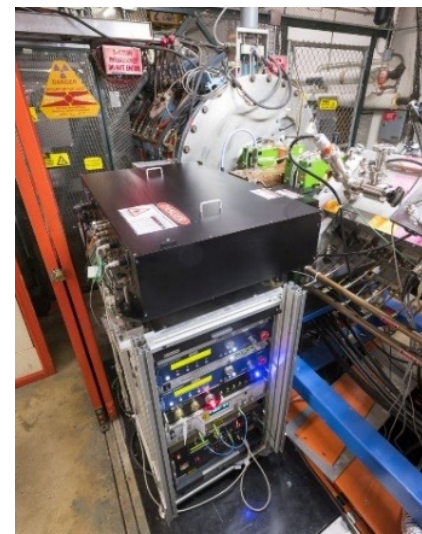
@ iota

Fermilab

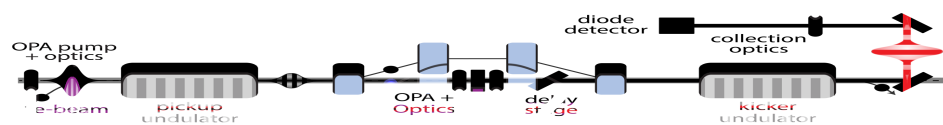


# New program in Amplified OSC + control & sensing

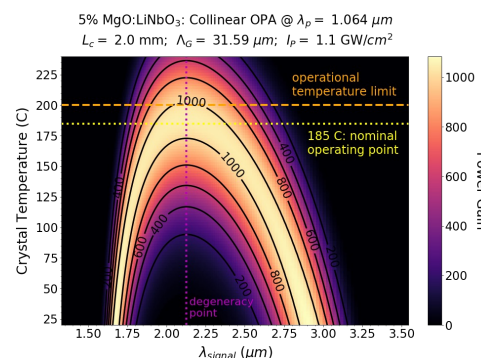
- Now developing a new OSC system at IOTA with high-gain optical amplification (30 dB;  $\sim$ ms cooling times)
- Combining flexible pump laser with reinforcement-learning techniques and specialized optics; goal of establishing new capabilities for beam cooling and control
- Advanced OSC simulation 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!**



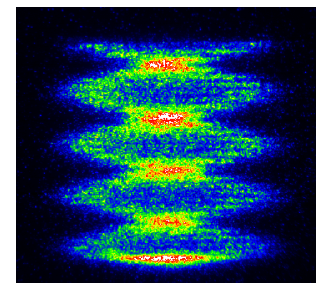
LLN drive laser



Amplified-OSC concept

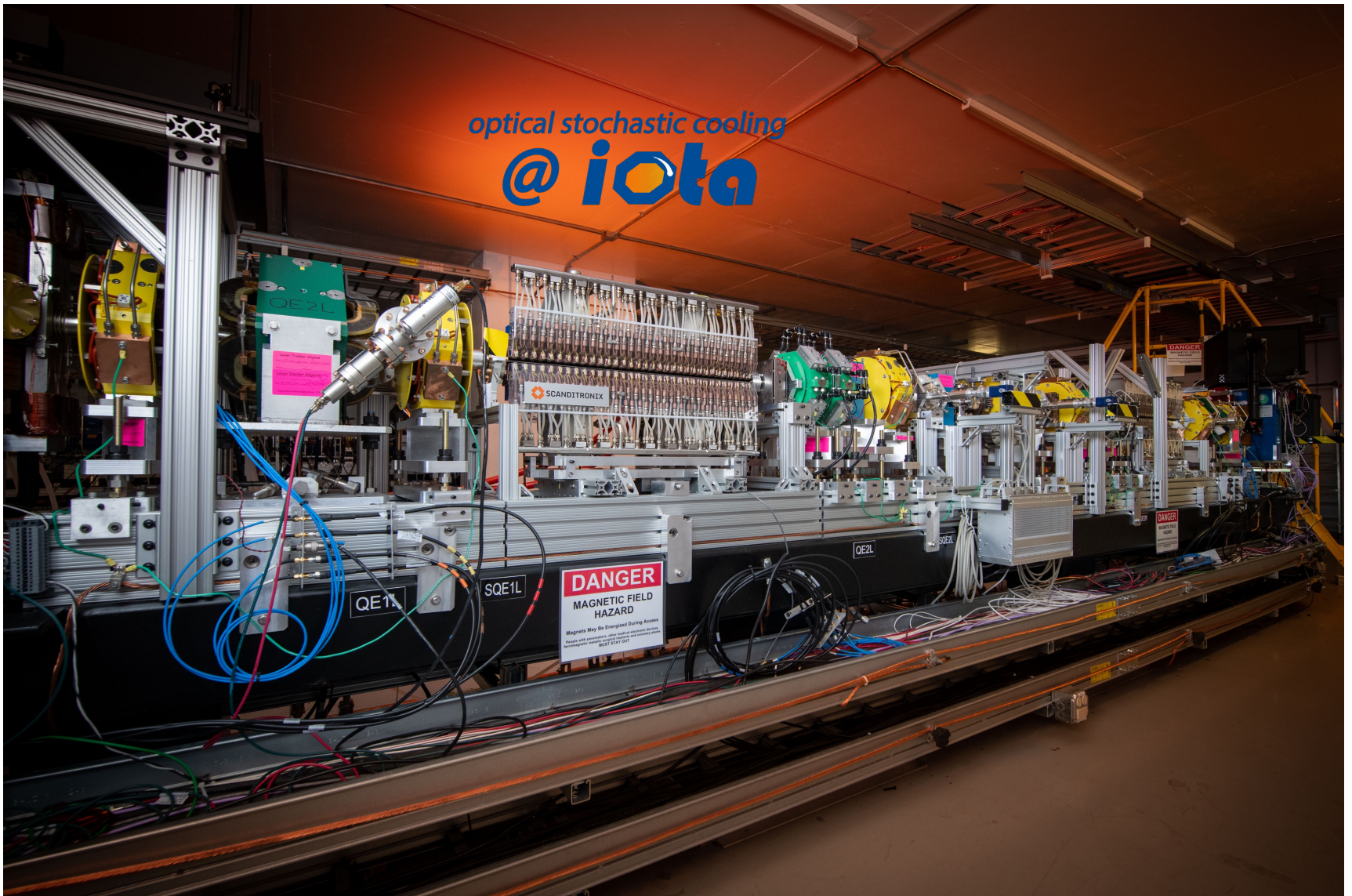


Calculated amplifier performance



Phase-space control

optical stochastic cooling  
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# EXTRAS

# OSC studies and summary

## Phases:

- **Ph1: Apparatus Commissioning**
  - Installation, injection and lattice correction, validation of all critical diagnostic and control systems
- **Ph2: Demonstration Experiment**
  - Alignment of OSC systems and observation of effect of OSC; optimization of strength and characterization of essential parameters
- **Ph3: Systematic Studies of OSC Concepts**
  - Optimized configurations for 1D, 2D and 3D; full characterization of OSC performance (e.g. rates & ranges) in different configurations and regimes

10/09/20: Installation of OSC hardware begins

02/11/21: First turn in IOTA w/OSC hardware

02/15/21: First stored beam

03/10/21: First undulator light (632nm; temporary power to undulators at low current)

~03/31/21: Cables pulled

★ 04/07/21: **First interference signal (@632 nm)**

04/16/21: Undulators at full power for first time

★ 04/20/21: **First light & interference at 950nm; First observation of effects from OSC**

05/17/21: IBEND upgrade results in stable OSC

07/23-08/05: *break*

★ 08/10/21: **Stable 2D cooling**

★ 08/12/21: **Stable 1D cooling**

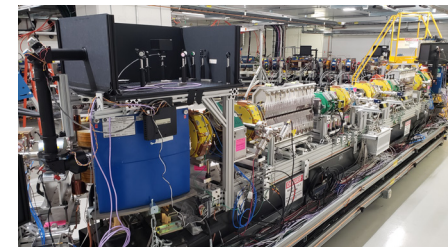
08/13/21: Vacuum intervention and replacement of in-vacuum lens

08/16/21: First OSC with new lens

08/17/21: transition to 101 MeV lattice

★ 08/18/21: **Achieved first 3D cooling**

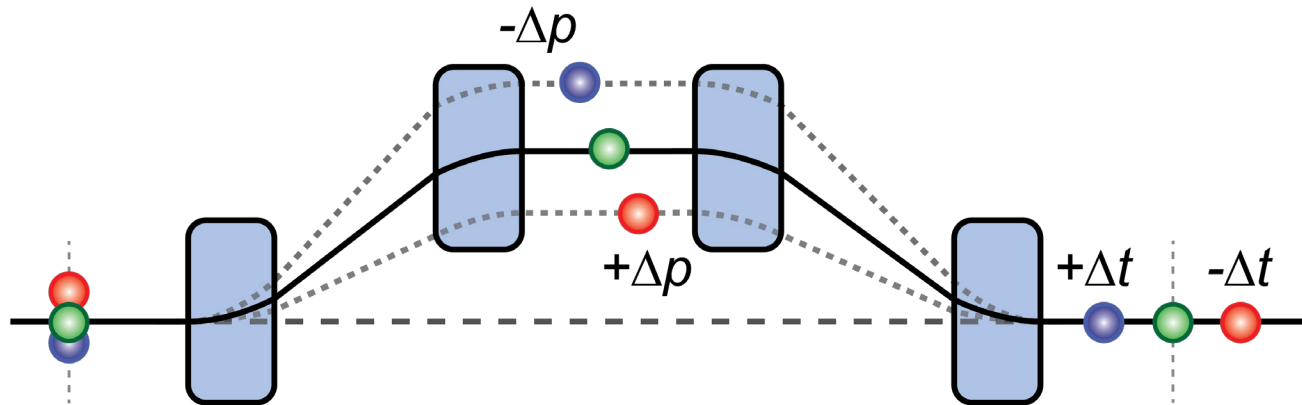
★ 08/27/21: **Achieved (measured) OSC with a single electron**



# IOTA OSC configurations and measurements:

- From  $\sim 10^8$  electrons down to single electron (nominal  $\sim 10^5$ )
- 1D (s), 2D (s,x), 3D (s,x,y) OSC
- Delay scans
- OSC toggles (e.g. off/cooling/off/heating/off)
- PMT and SPAD timing data for single electron

# A particle's momentum error maps to temporal delay

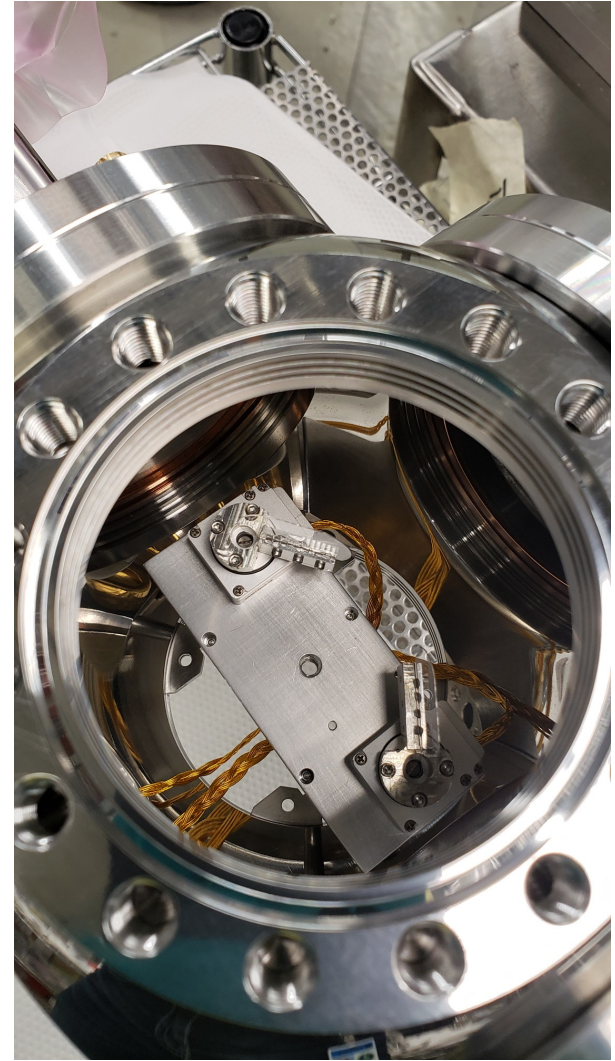
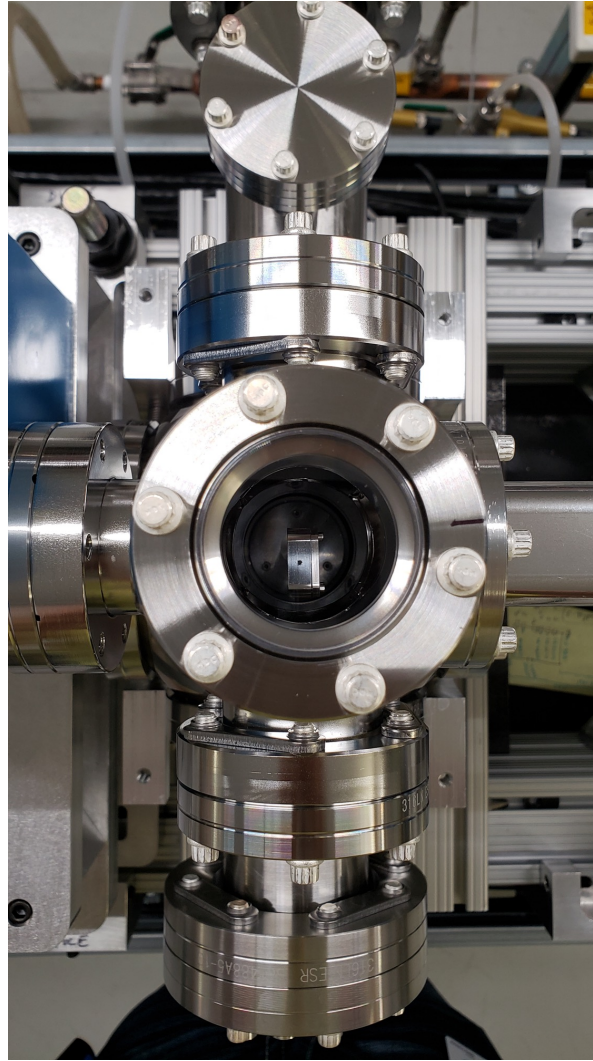
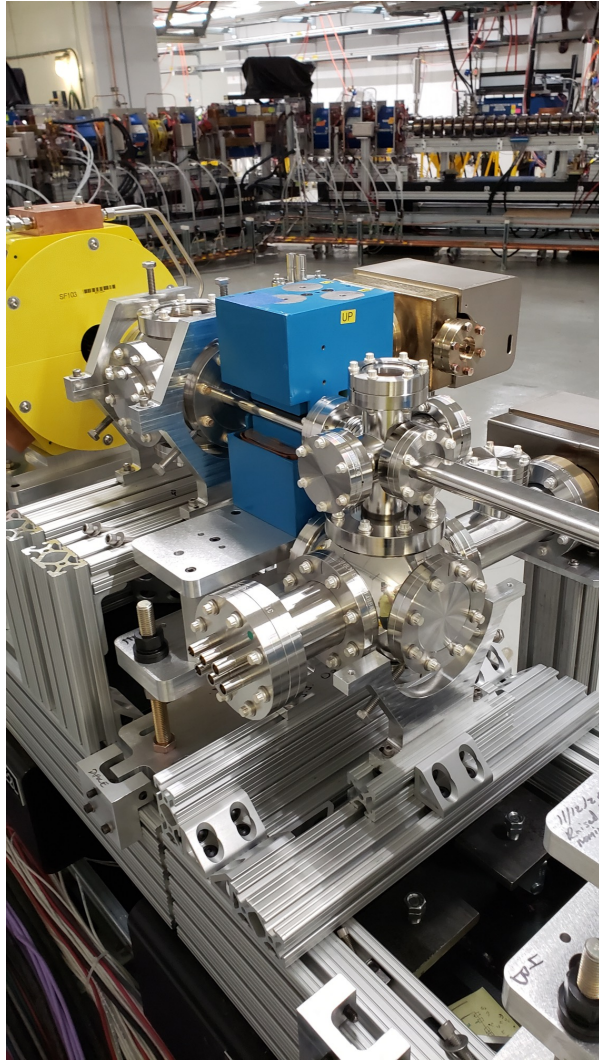


- Lower (higher) energy particles take a longer path through the bypass and thus arrive at the entrance to the KU later (sooner) than the reference particle
- There are also contributions from the transverse elements of the mapping depending on the dispersion at the exit of the PU undulator

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



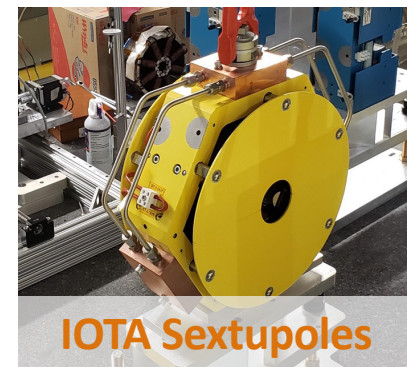
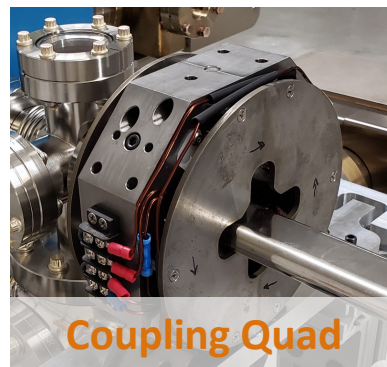
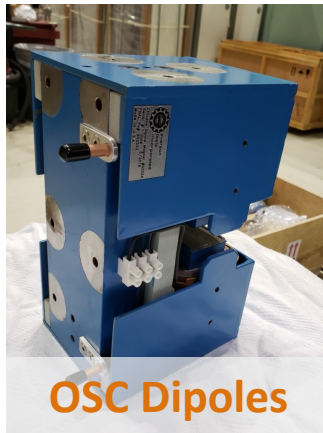
# OSC lens and delay stage with in-vac motion:





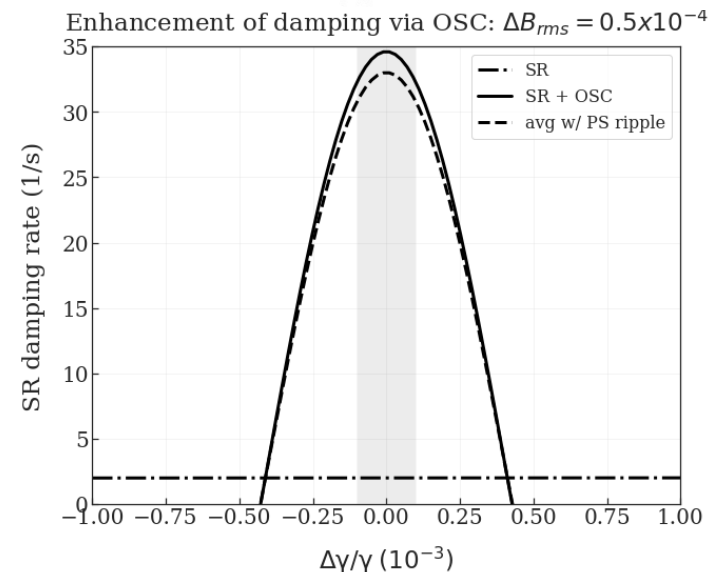
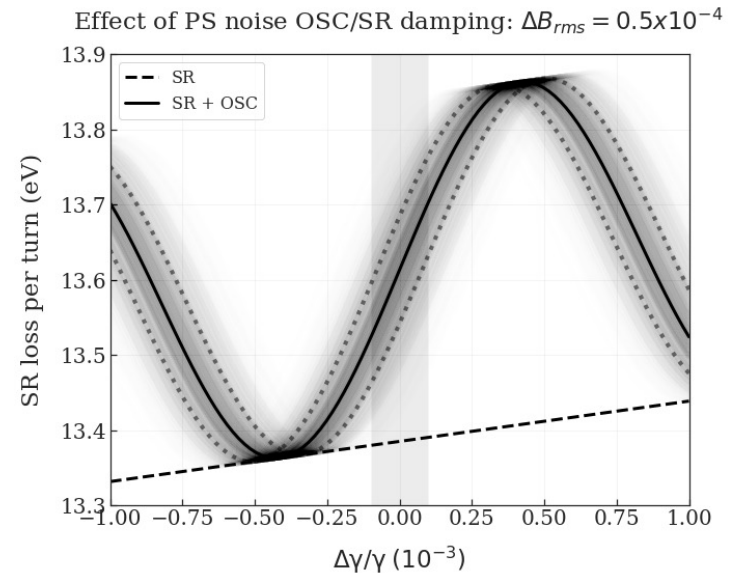
# High density of compact magnets for IOTA OSC

- Chicane dipoles (4x), quads (4x), undulators (2x), sextupoles (7x), coupling quad (1x), vertical correctors (4x)
- Design/performance balanced between integrated-field requirements, beam aperture/vacuum envelope, space available, thermal considerations; field screens to reduce cross-talk;



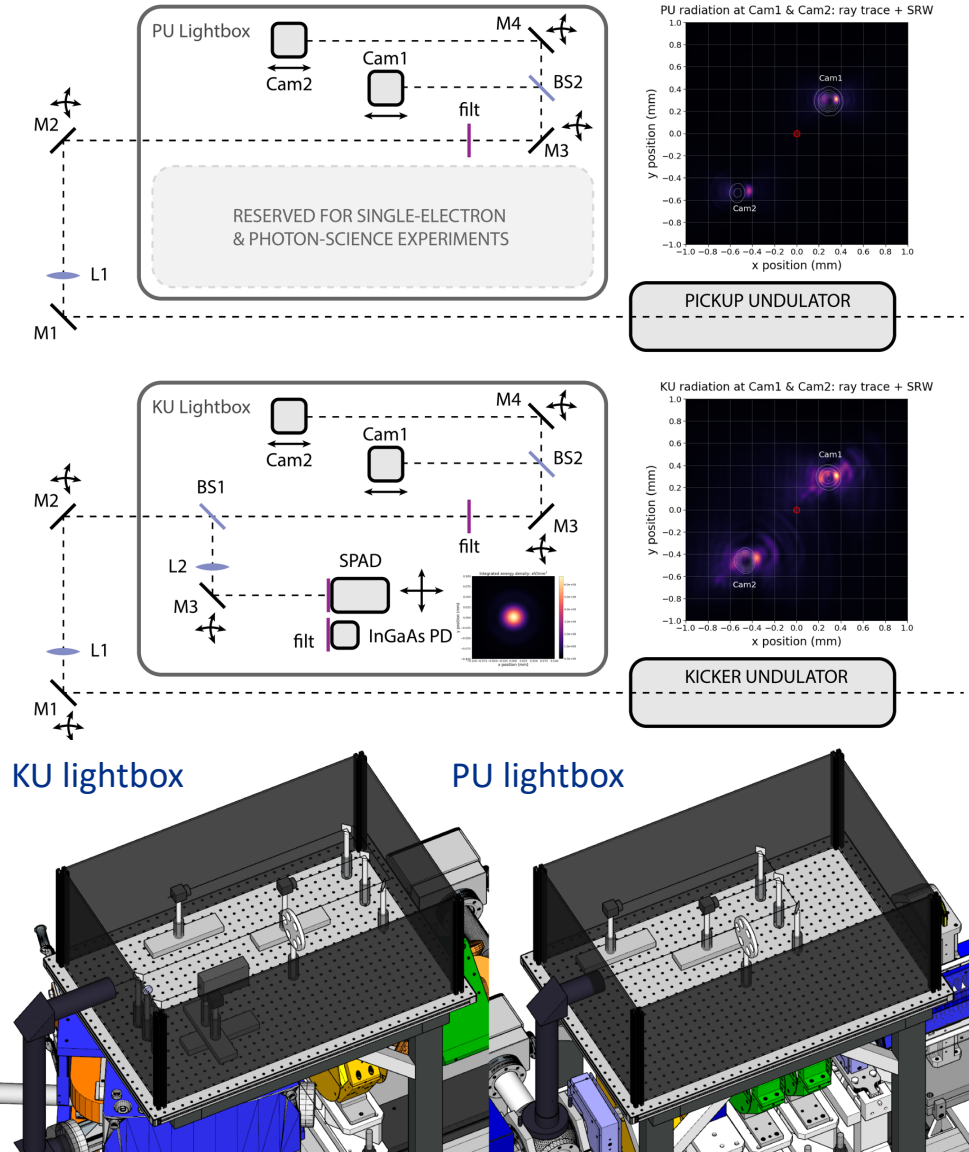
# Power-supply stability at $\sim 10^{-4}$ is acceptable

- Ripple in field will produce ripple in chicane delay and therefore relative arrival phase for entire beam
- Slow variations ( $>\tau_{\text{OSC}}$ ), effectively detune bypass to off-design momentum values
- For fast variations, the beam samples many curves and cools with a reduced rate
- For  $\sigma_{\Delta B} \sim 10^{-4}$ , path change is a small fraction of the cooling range
- BiRa PCRC systems @ ripple+noise of  $10^{-5}$  for dipoles



# Flexible lightboxes/diagnostics for Both PU and KU

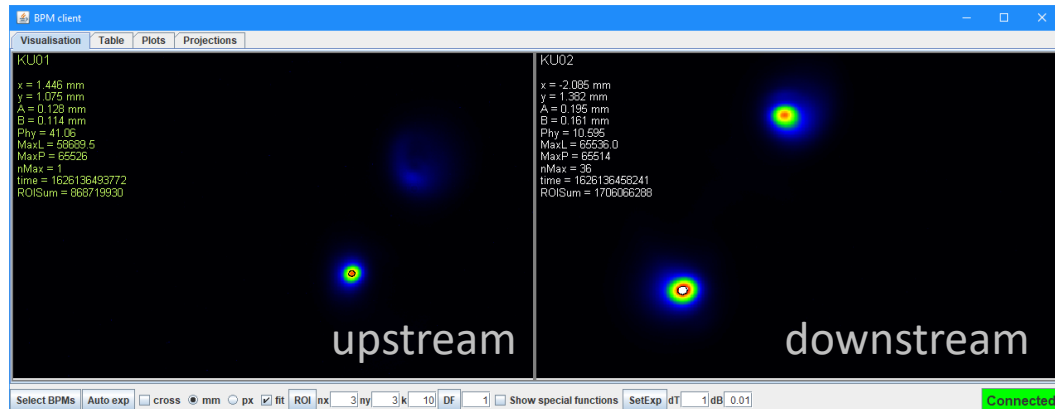
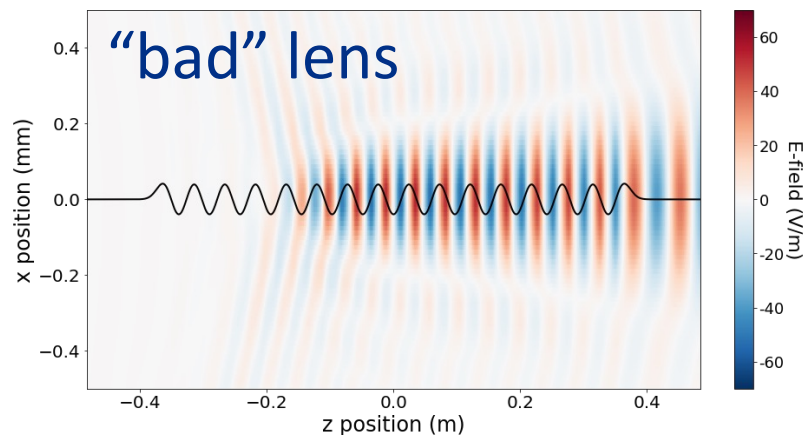
- UR BPMs, PIN PD, SPADs, single-electron diagnostics
- Want spatial alignment of  $<100\ \mu\text{m}$ , and angular alignment of  $<100\ \mu\text{rad}$
- HeNe through surveyed pinholes defines nominal optical axis,  $\sim \pm 50\ \mu\text{m}$
- Image the UR from two locations (upstream & downstream); variable positioning allows arbitrary placement of the UR BPMs
- Infer the error of the closed orbit at the center of the undulator ( $dx, dy, dx', dy'$ ) relative to the nominal optical axis
- When aligned, spots overlap each other and the optical axis; expect resolution of  $\sim 10\text{'s}\ \mu\text{m}$  &  $10\text{'s}\ \mu\text{rad}$ , range  $\sim \pm 5\ \text{mm}$  &  $\pm 5\ \text{mrad}$





# Good lens, bad lens...

- Manufacturing error resulted in  $\sim 5\%$  longer focal length for initial lens; used in initial OSC observations; resulted in weaker cooling and difficult tuning



- Lens was swapped in final month of the run; improved cooling, easier alignment and behavior more aligned with theoretical expectations

