# Experimental Demonstration of Optical Stochastic Cooling

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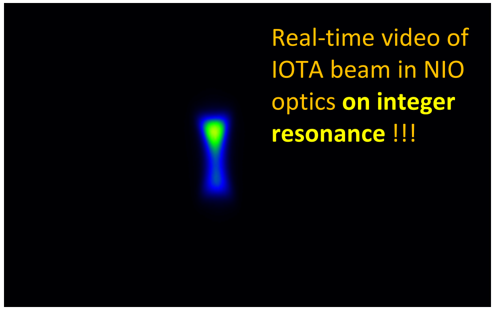
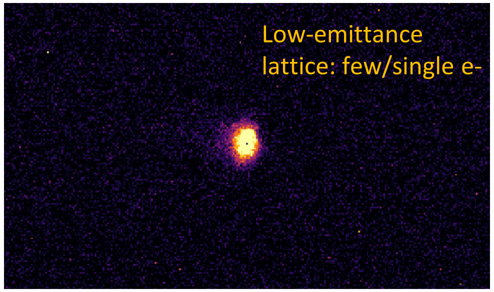
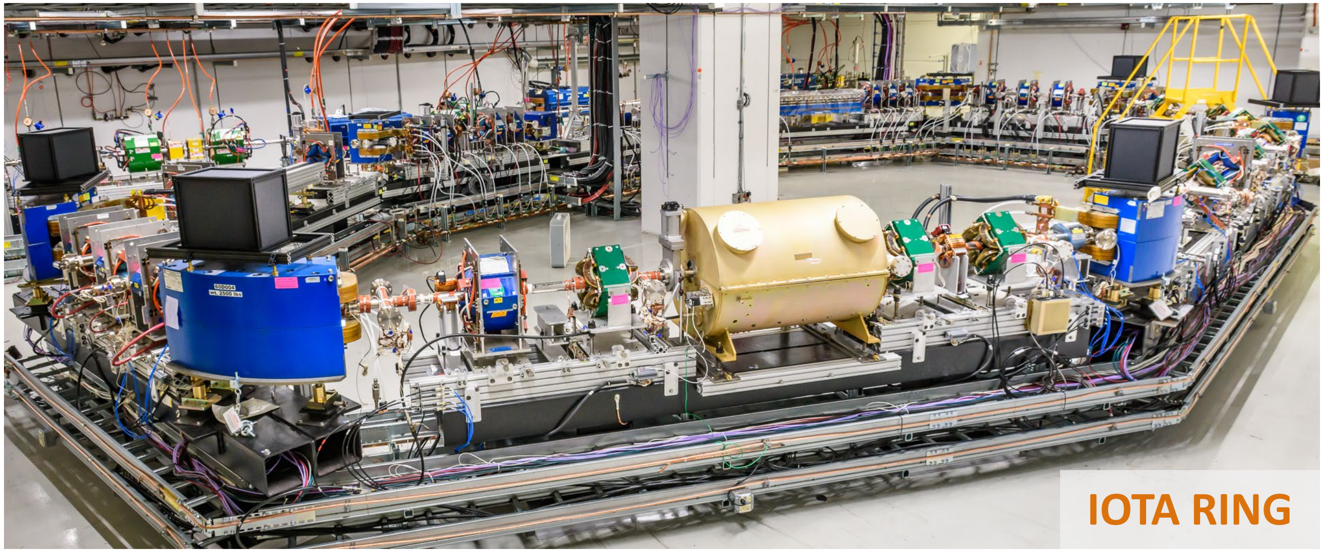
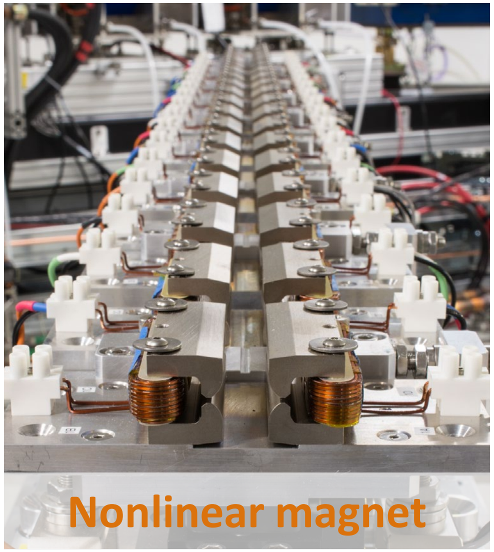
# IOTA/FAST: a center for Acc. and Beam Physics

- 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
- …



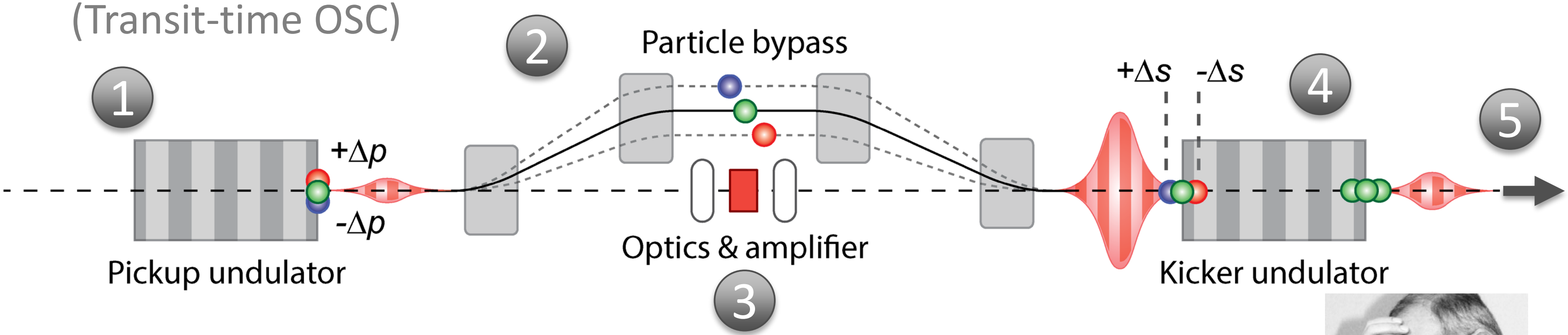



# OSC extends the SC principle to optical bandwidth

(Transit-time OSC)

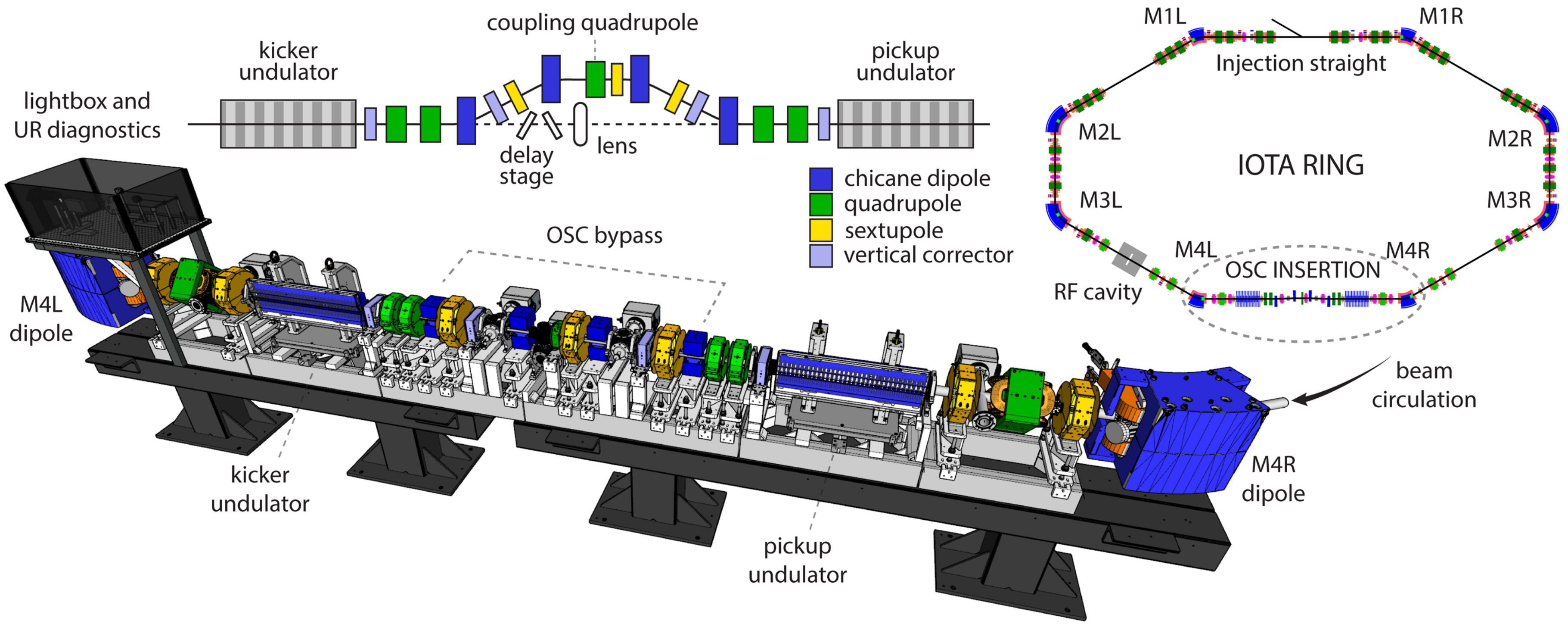



1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates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

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


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

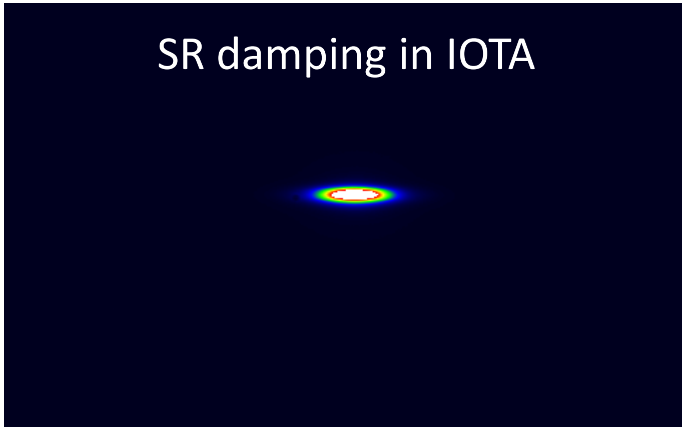
# A staged approach for OSC at IOTA

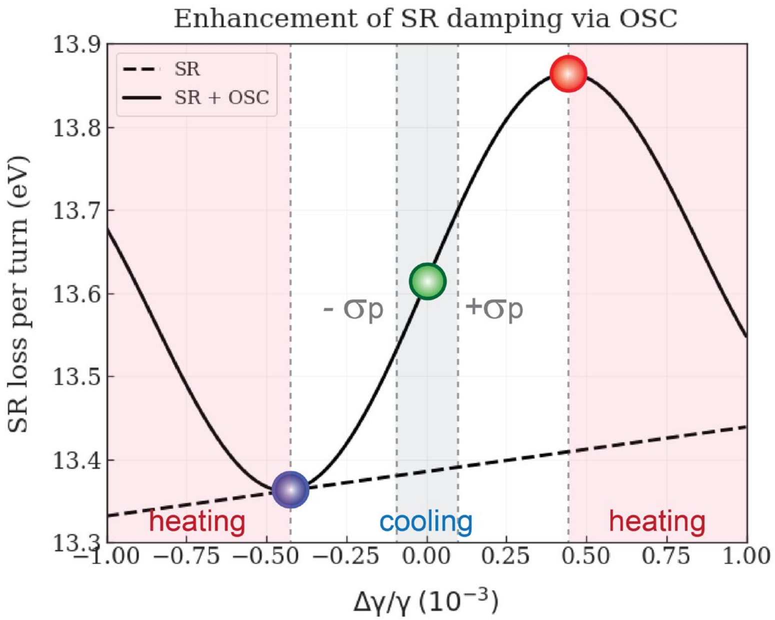


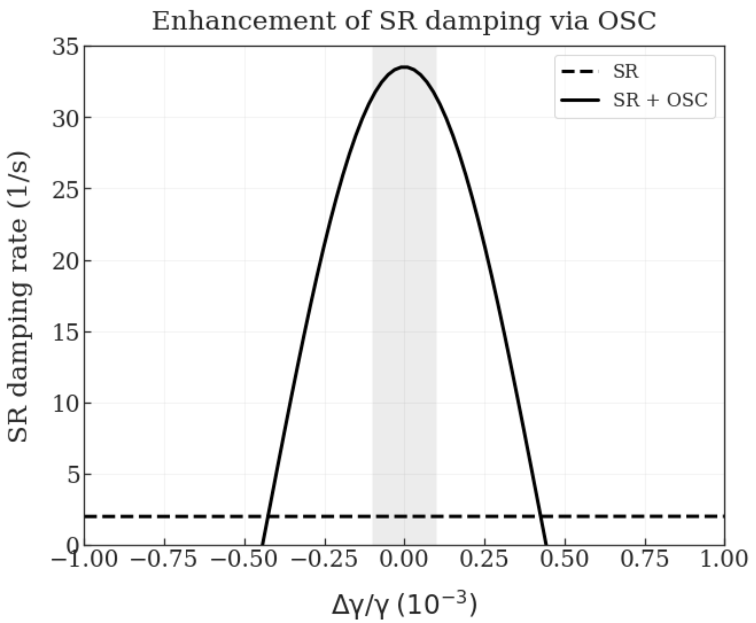

- **Non-amplified OSC (~1-μm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-μm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification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

# "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)

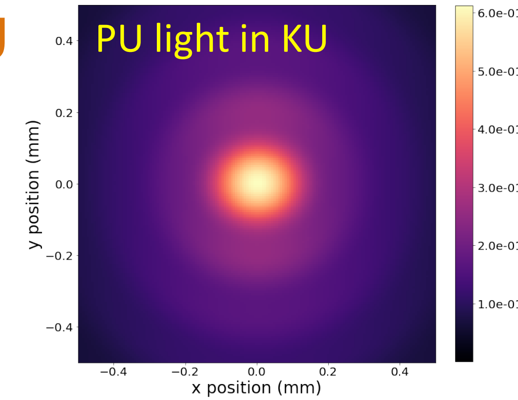


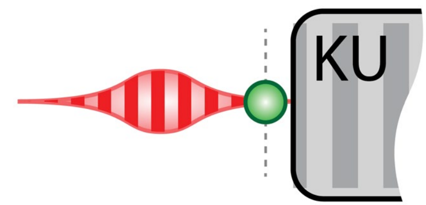



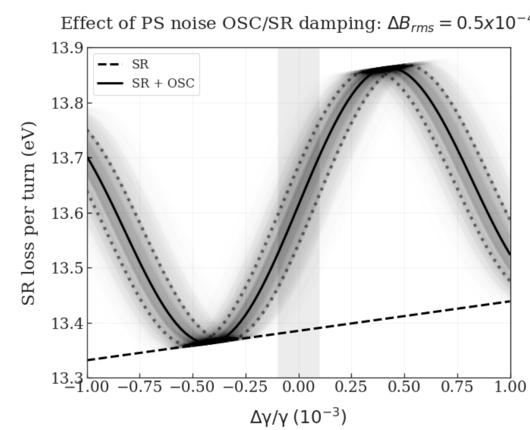



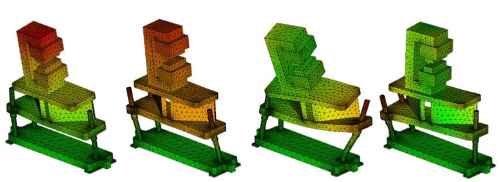
# What makes ("simple") OSC challenging?

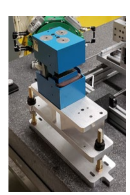
1. Beam and PU light must overlap through the KU
   - The undulator light is **~200 μm** wide
   - Want angle between light and beam at < **~0.1 mrad**
2. Beam and PU light must arrive ~simultaneously for maximum effect
   - Absolute timing should be better than **~0.3 fs**
   - The entire delay system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

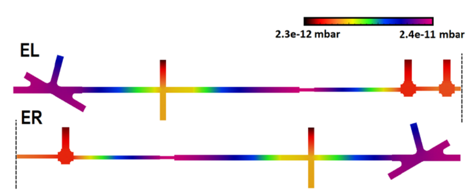


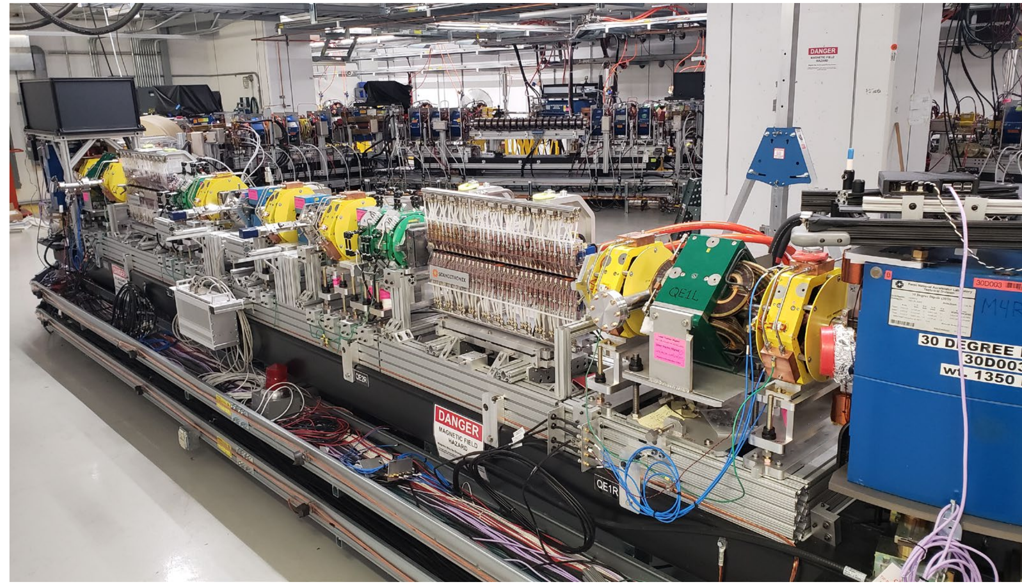



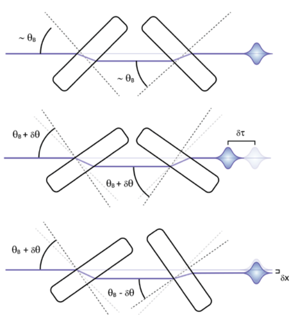




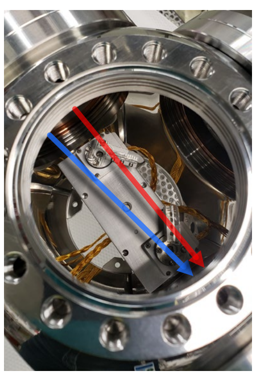
# OSC apparatus successfully integrated in IOTA

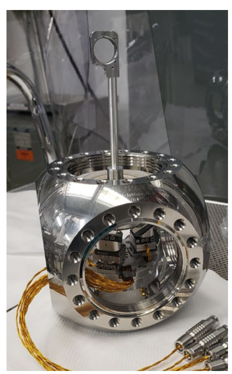
- Established and corrected OSC lattice to desired precision
- Achieved ~80% of theoretical max aperture and ~20-min lifetime; sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully validated all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

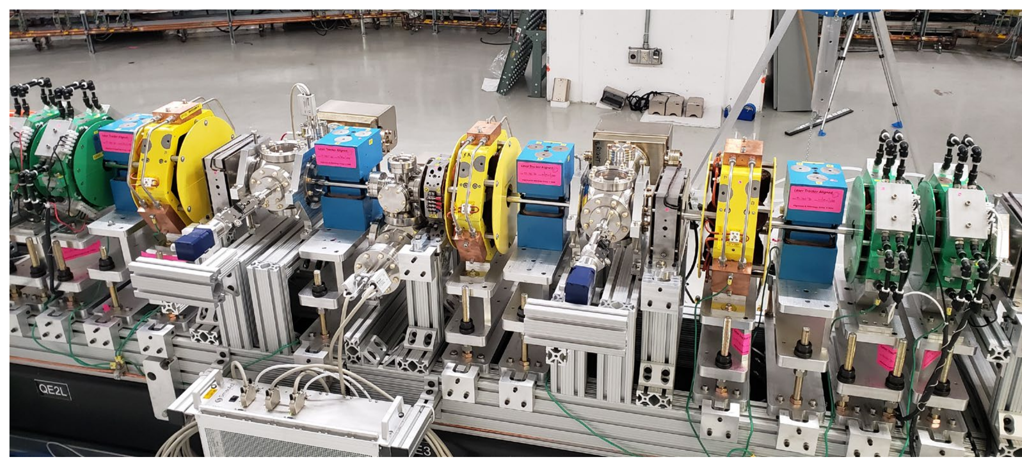


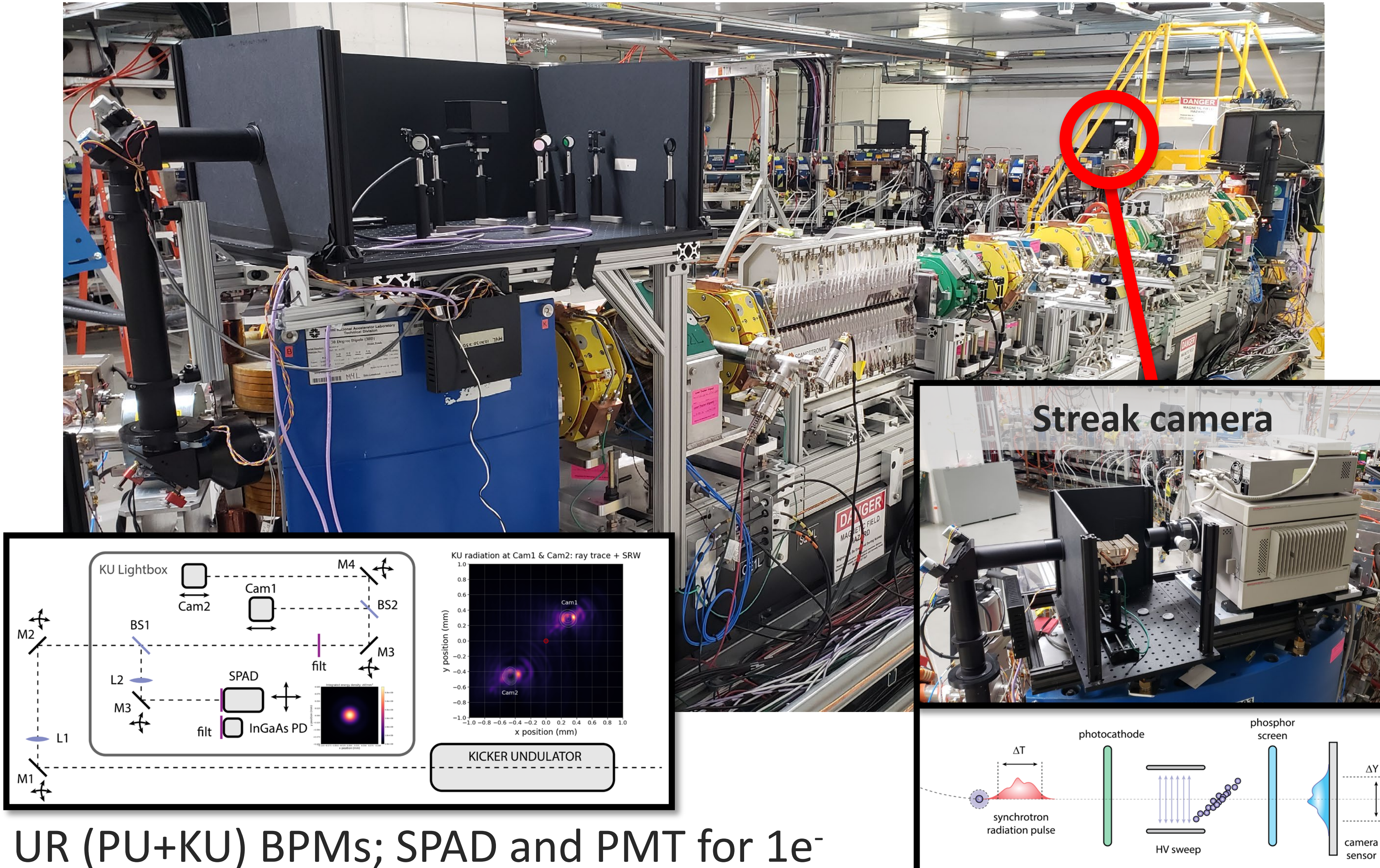
Delay stage







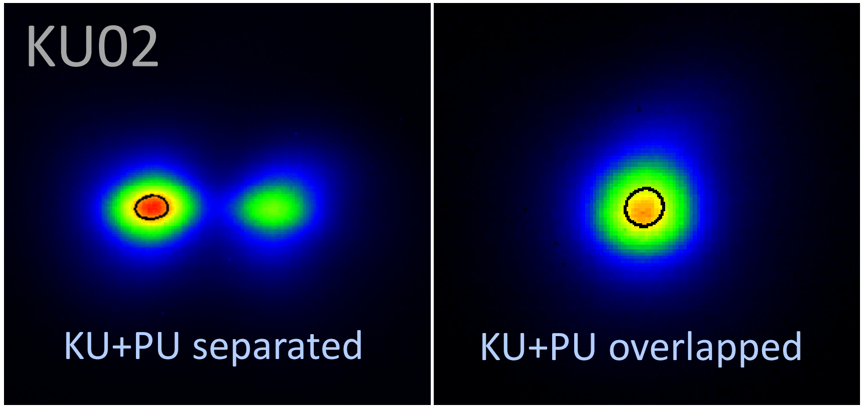
# OSC is monitored via synchrotron-rad. stations

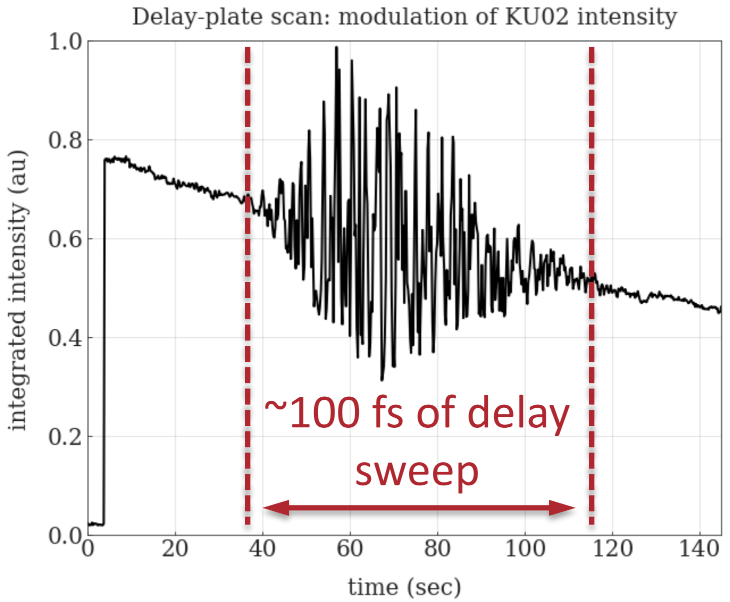



UR (PU+KU) BPMs; SPAD and PMT for $1e^-$

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

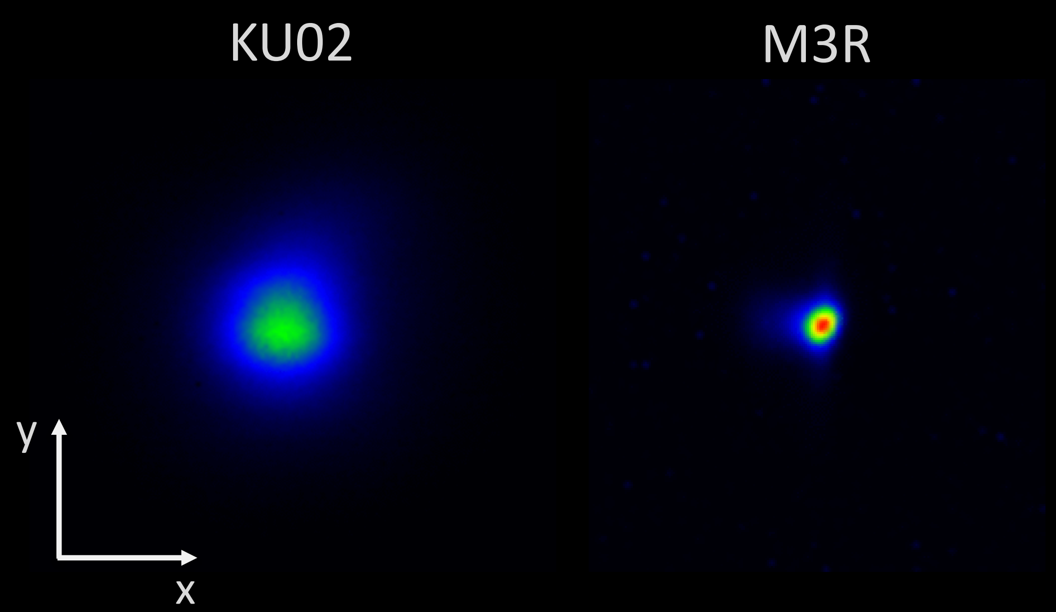
- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- In-vacuum light optics and closed-orbit bumps were used to maximally overlap the coherent modes of the undulators, first on the detectors and then inside the kicker undulator
- This coherent-mode overlap, in both 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

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

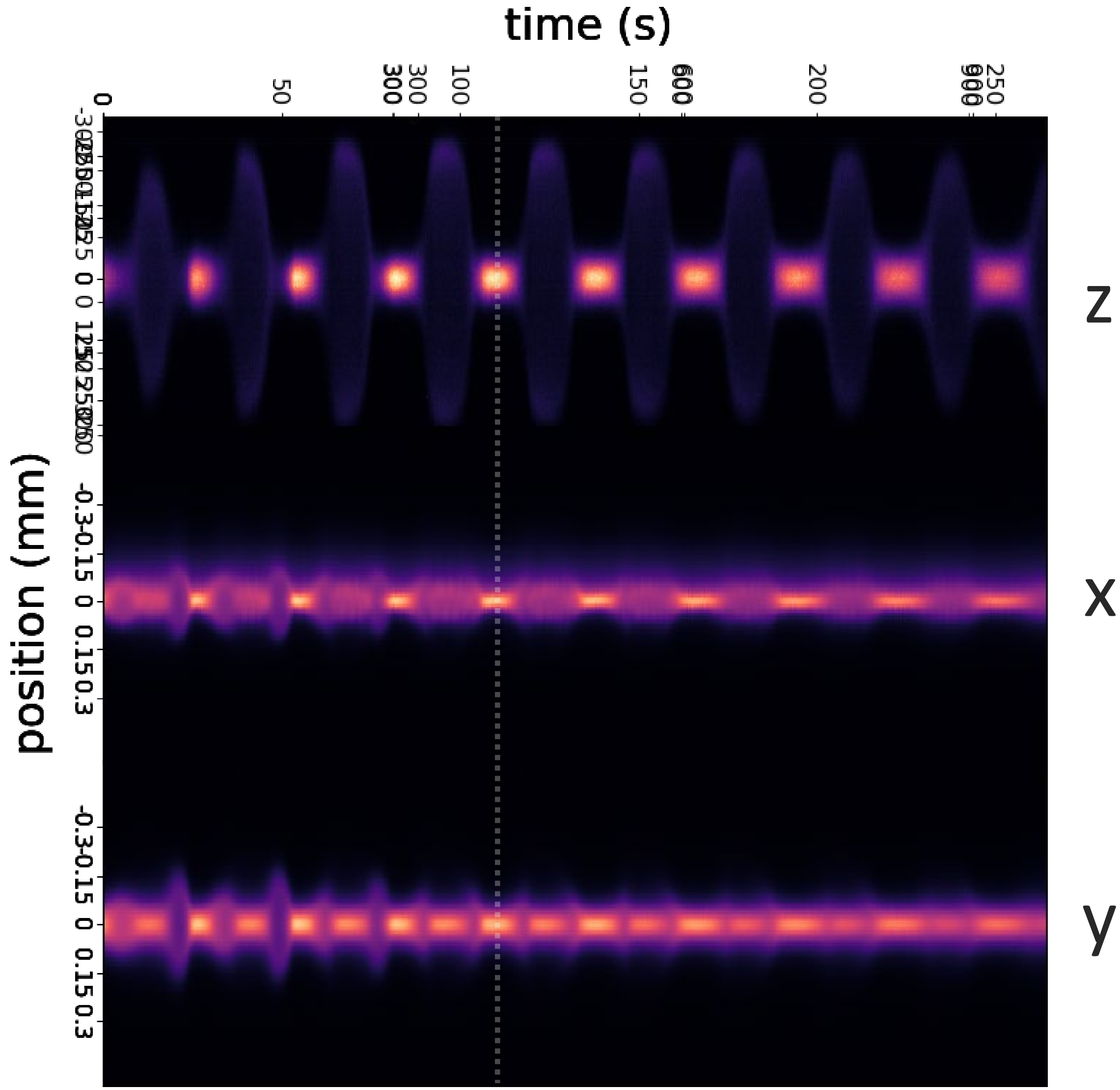



(movies not taken simultaneously but are representative)

- 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 nm?)

# After much work… OSC was strong and stable

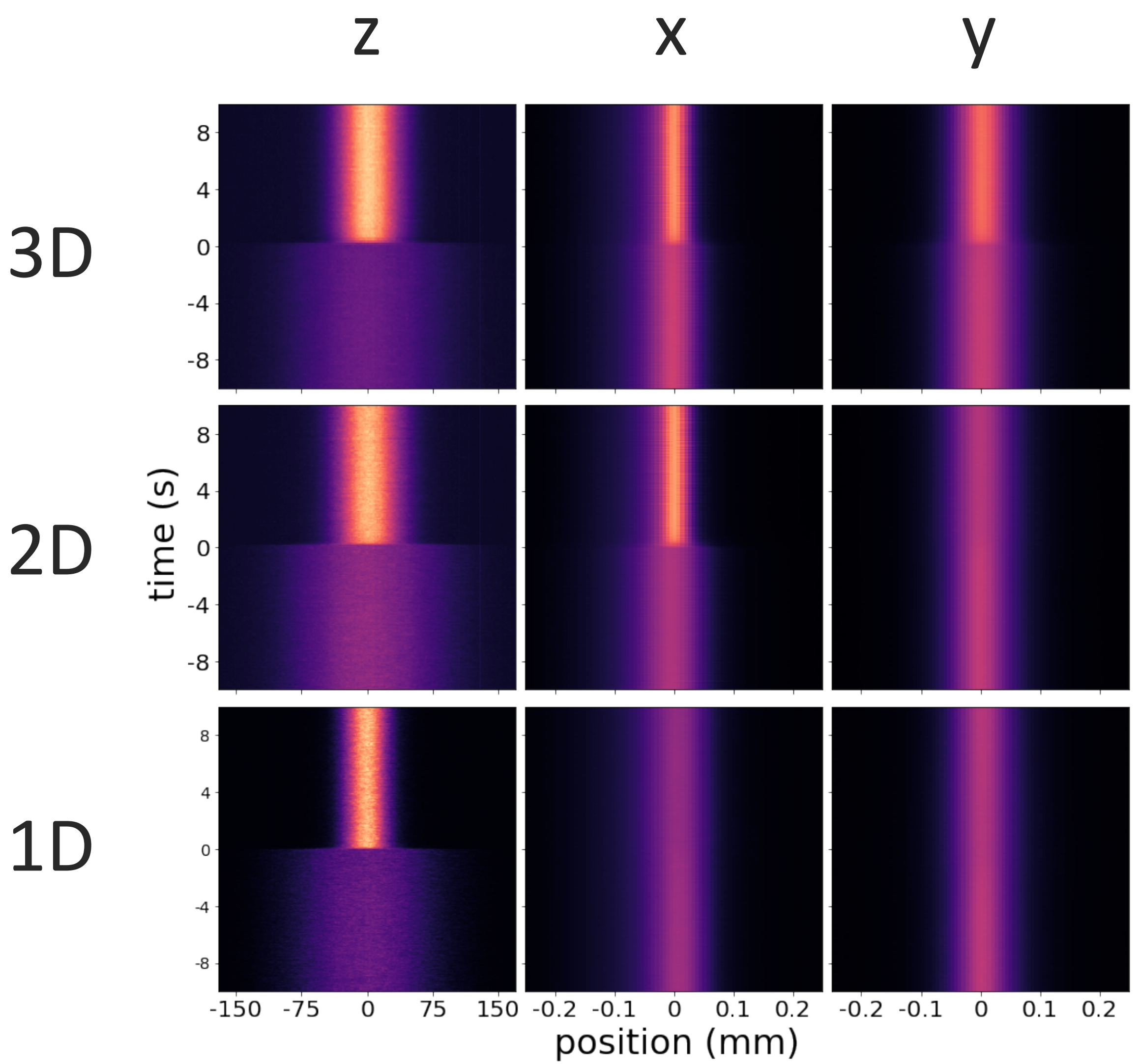
- 1D: lattice decoupled and bypass quad set to null transverse response to OSC; some residual due to dispersion @ SR BPM
- 2D: lattice decoupled and bypass coupling to nominal
- 3D: lattice coupled and bypass to nominal
- OSC system is reoptimized for each configuration
- Delay system is scanned at a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



# Delay scan with OSC in the 3D configuration

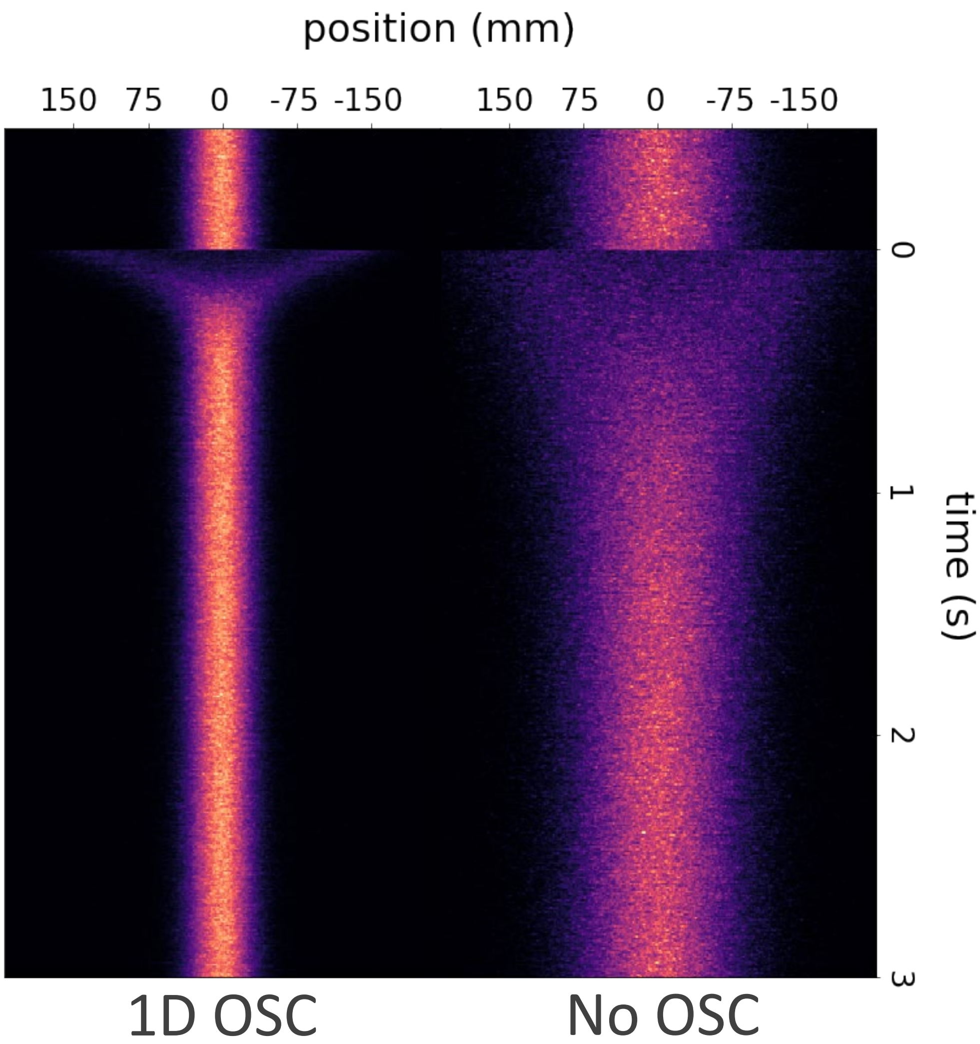
# OSC Cooling configurations at a glance…

- 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.



# Total OSC ~8x stronger than longitudinal SR damping

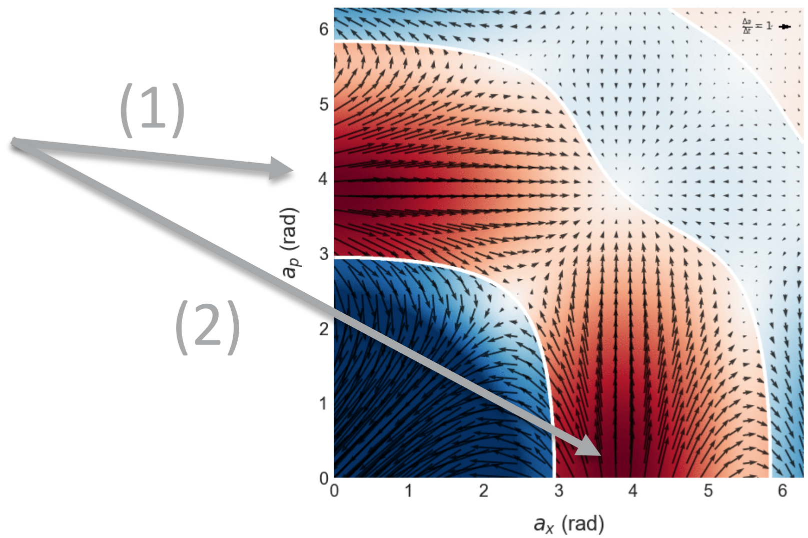
- Can estimate OSC strength relative to synchrotron-radiation damping via:
  - **Equilibrium sizes**
  - **Direct "fast" measurements of damping after a kick**
- Sizes: full takes all relevant effects into consideration (e.g. IBS, gas scattering, cooling range, etc…)
- Direct/fast: Placed system in the 1D cooling mode and "kicked" beam longitudinally with RF phase jumps
- Initial analysis gives total emittance cooling rate of **~8x** SR damping (z) for both methods



(Streak camera projections)

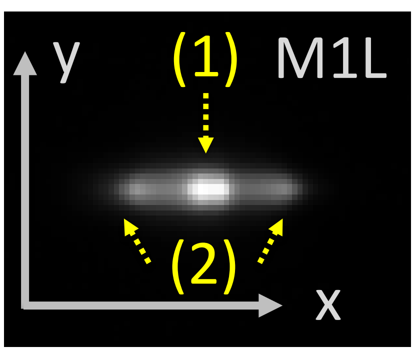
# Clear observation of expected OSC zone structure

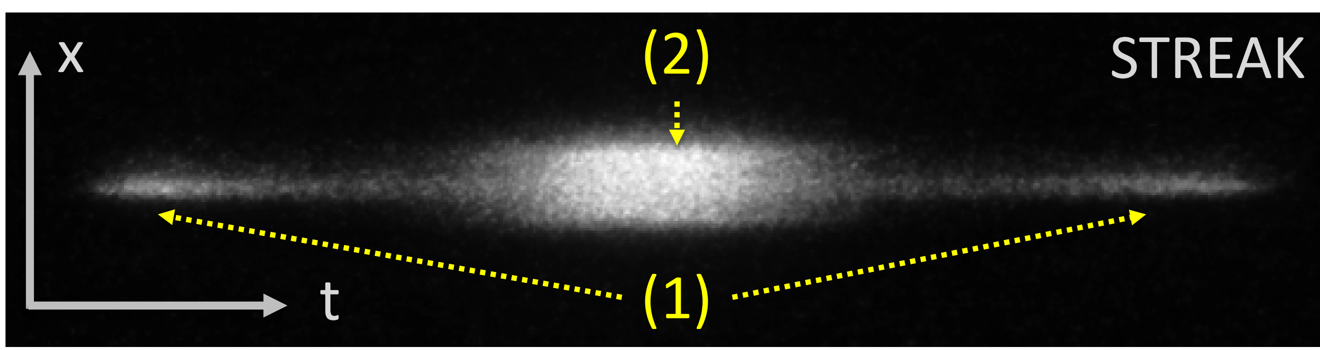
- (e.g) OSC in the 2D (z,x) configuration
- In “heating” mode, expect two high-amplitude attractors
- (1): high synchrotron amplitude, low betatron amplitude
- (2): high betatron amplitude, low synchrotron amplitude




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

2D Cooling map integrated over betatron and synchrotron oscillations; arrows show mag. and dir. of net force

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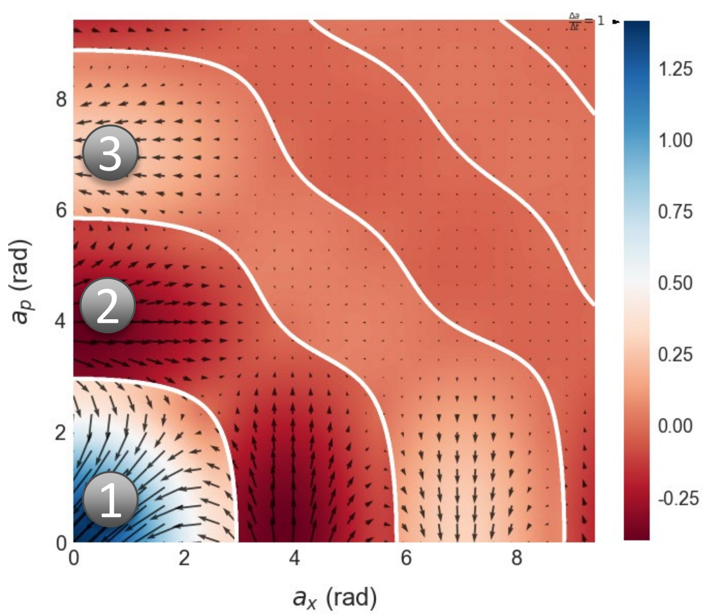
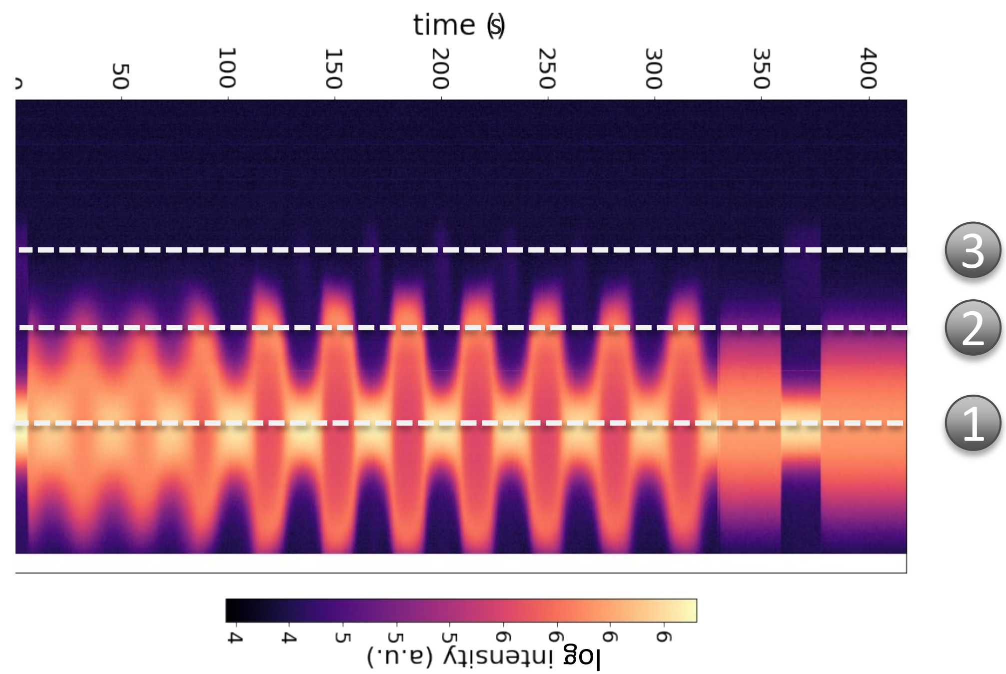
# Observe expected OSC zone structure

- For cooling mode with a high-intensity beam, appear to observe the much weaker 2nd-order zone; requires full analysis + corrections
- ① : fundamental cooling zone
- ② : fundamental heating zone
- ③ : 2nd-order cooling zone



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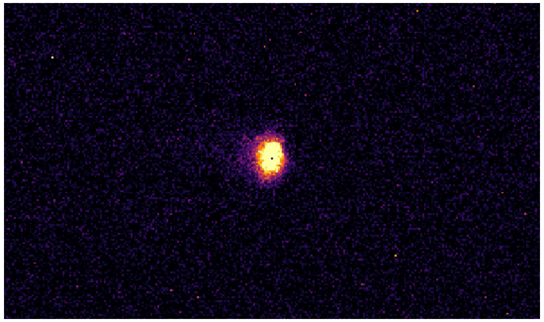
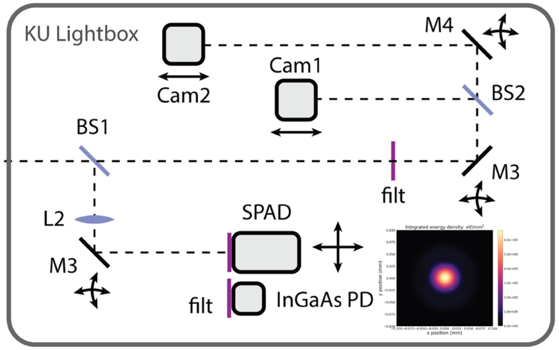
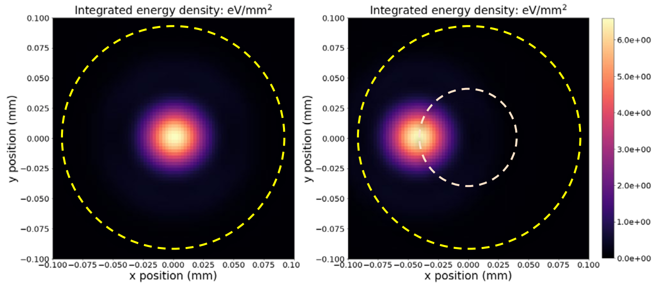
# IOTA enables single-electron OSC studies

- 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 ~0.3mm (~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





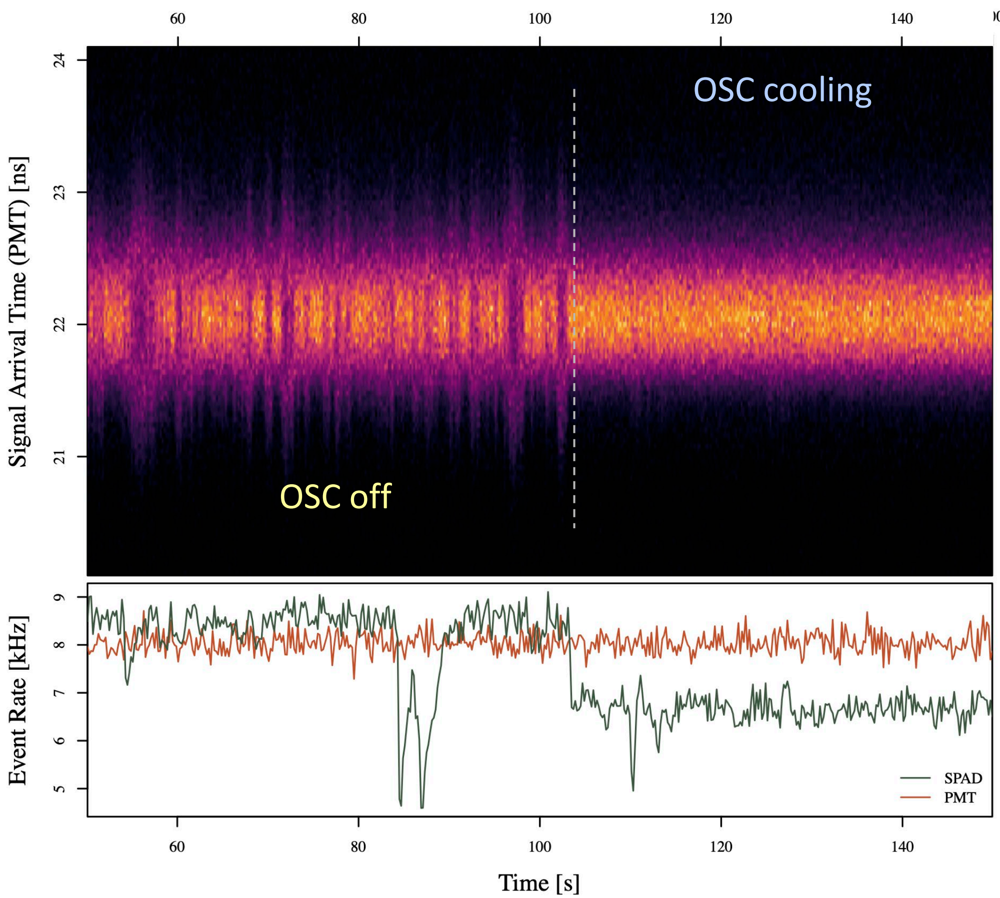




on axis $x_\beta = 0.3\text{mm}$

# 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; amplitude corresponds to ~5 sigma (no OSC)

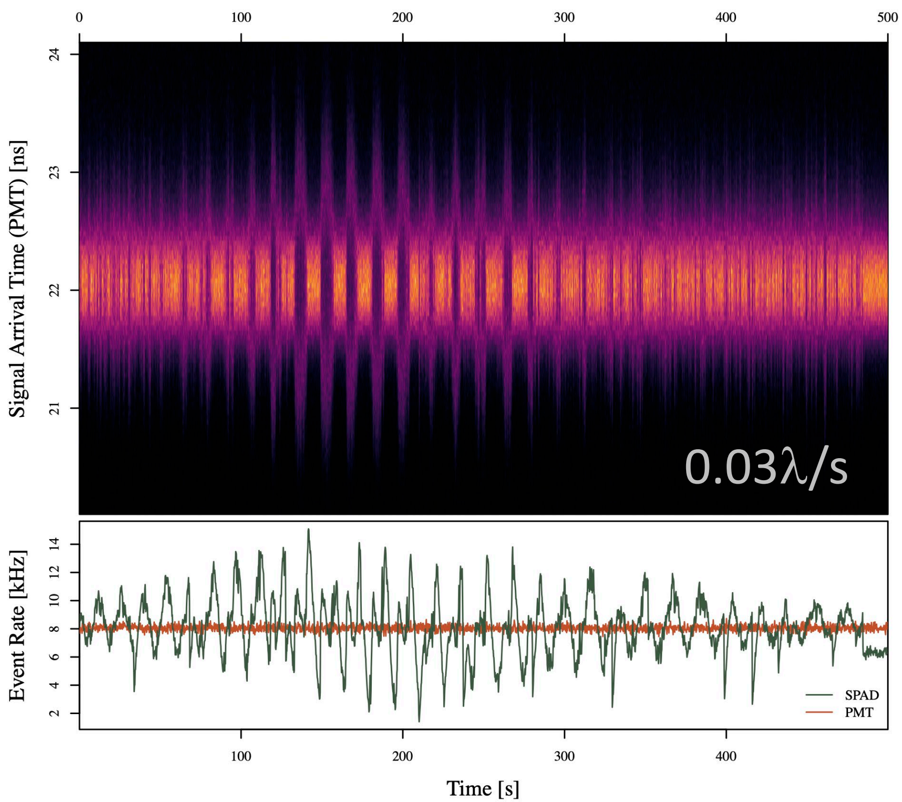
## 1D OSC configuration

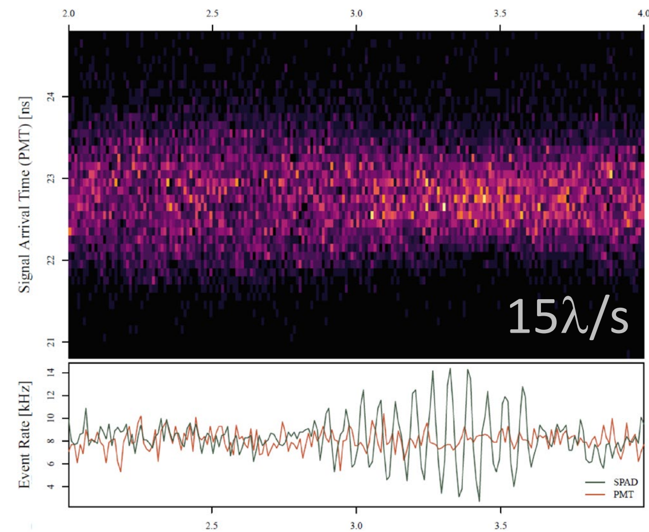


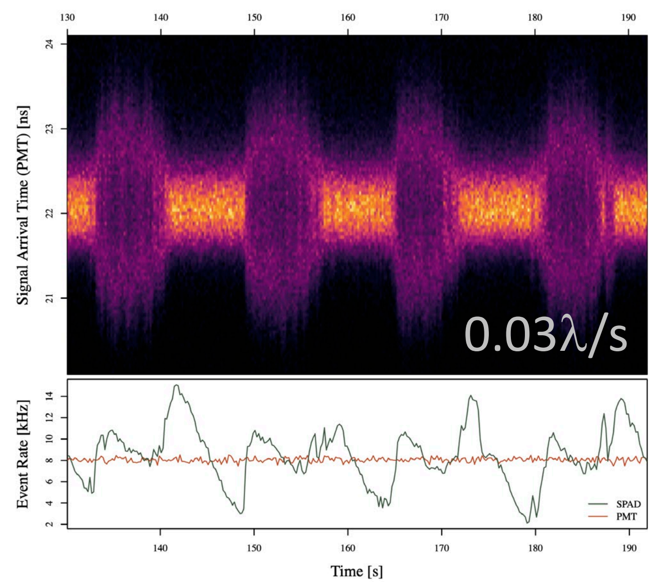

(Plots by G. Stancari)

# 1e⁻ 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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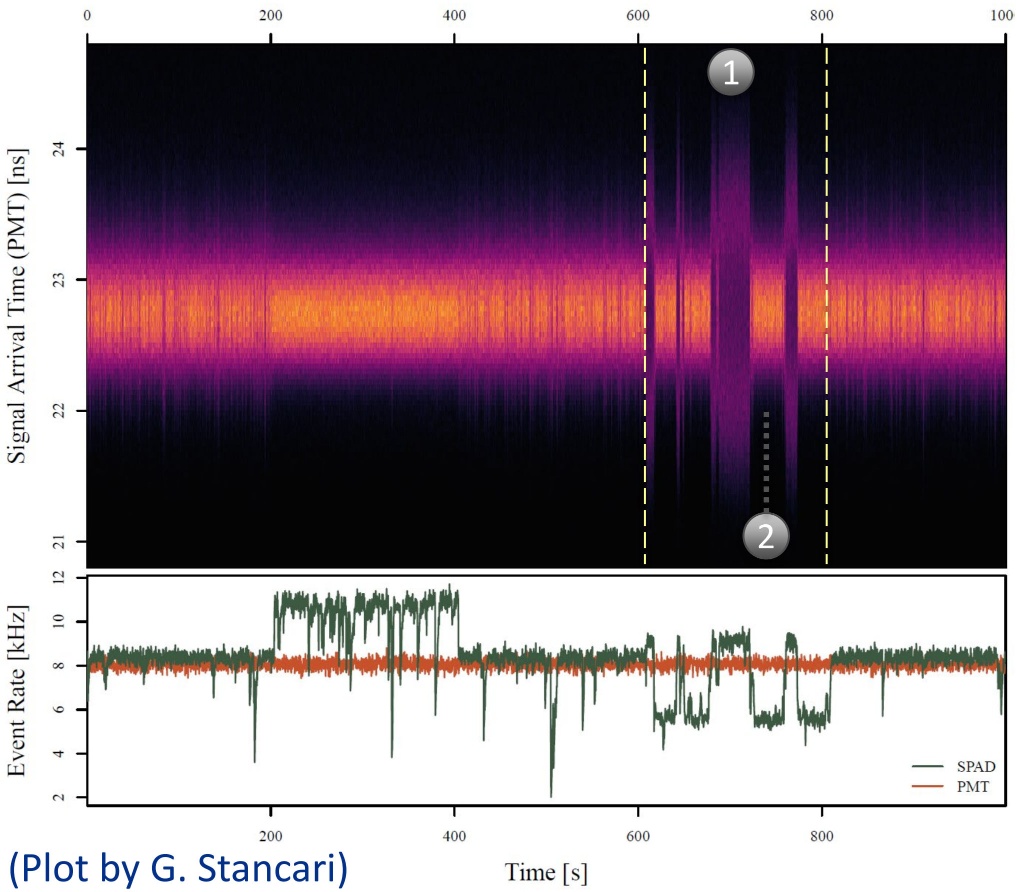
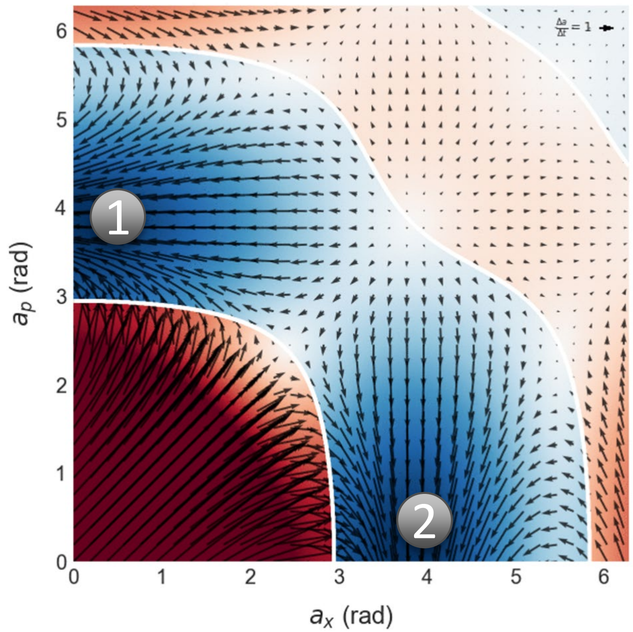
# Observe bistable transitions between OSC attractors

- 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



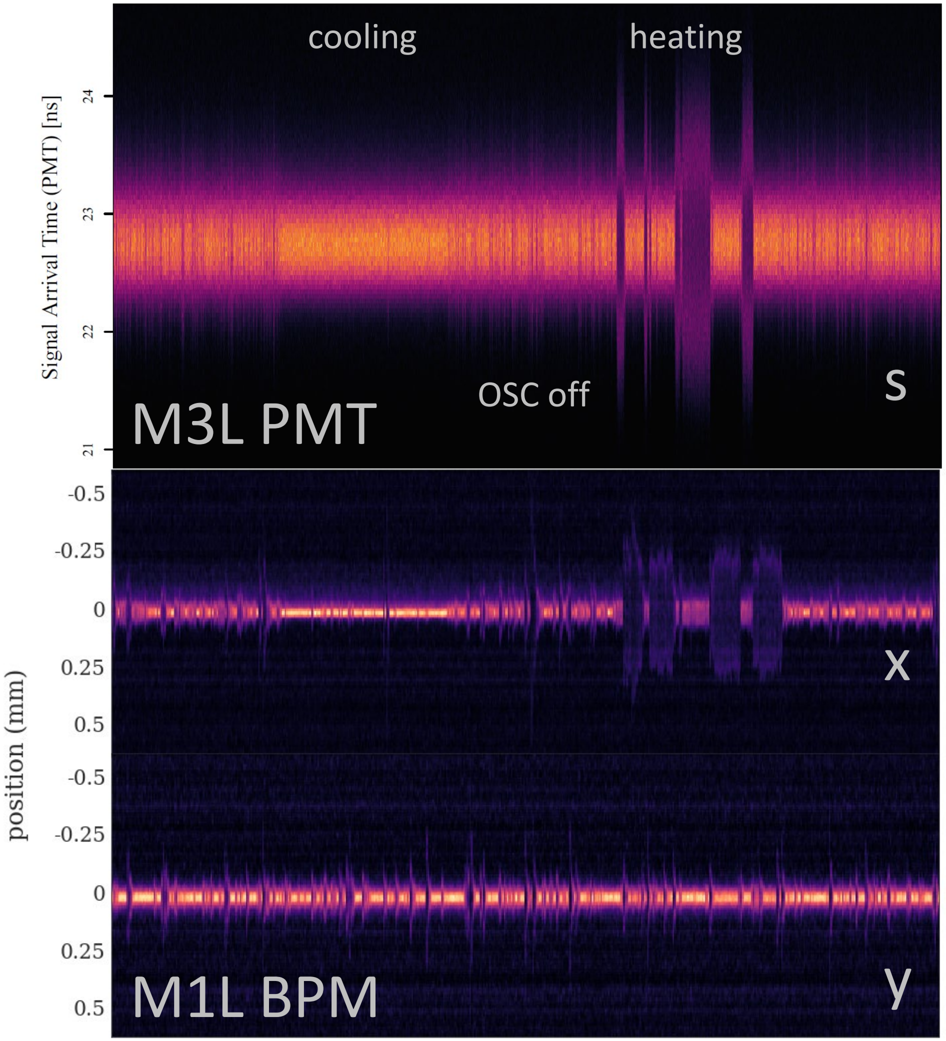

(Plot by G. Stancari)

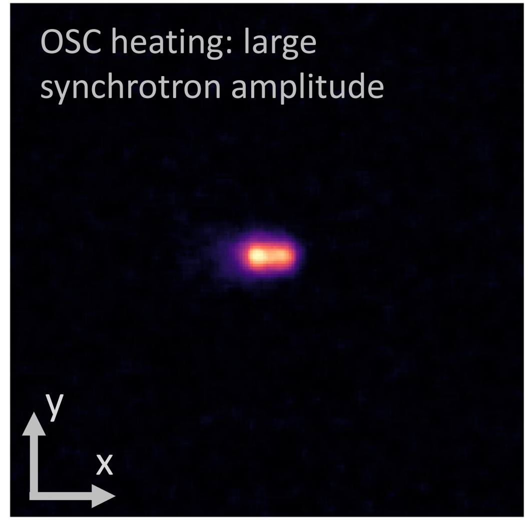


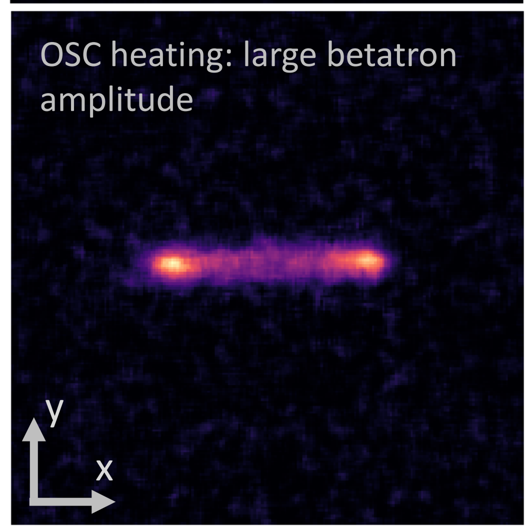

$$\frac{\delta p}{p} = -\kappa \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right)$$

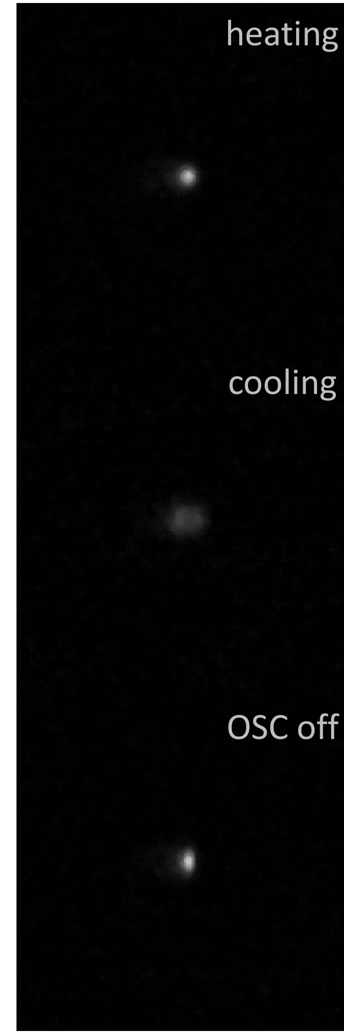
Cooling map integrated over betatron and synchrotron oscillations; arrows show mag. and dir. of net force

# Analysis of SR BPMs confirms the observation



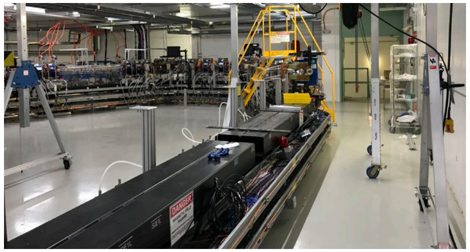
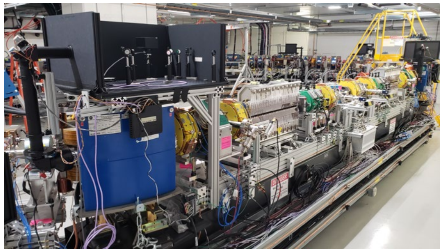

OSC in the **2D configuration** (z,x)

# OSC studies and shift summary

**Phases:**

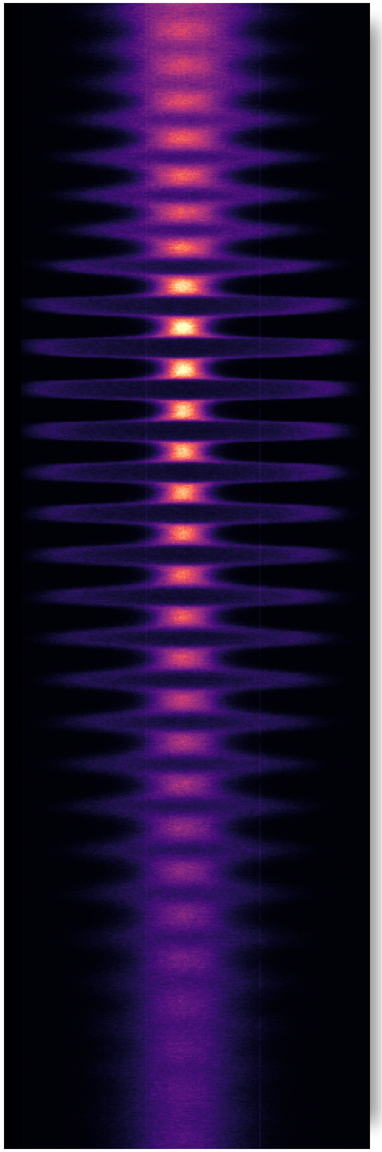
- Ph1: Apparatus Commissioning
  - Installation, injection and lattice correction, validation of all critical diagnostic and control systems
- Ph2: Demonstration Experiment
  - Alignment of OSC systems and observation of effect of OSC; optimization of strength and characterization of essential parameters
- 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**

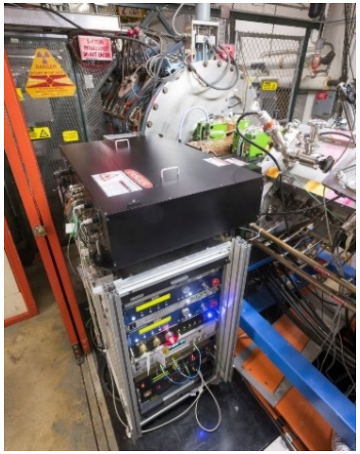
# Conclusions:

- 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; full analysis of the data is underway
- Successfully demonstrated OSC in 1, 2 and 3 dimensions
- "OSC" of a single electron was definitively observed
- Running list of topics for an additional passive-OSC run: improved diagnostics and measurements, exploration of nonlinearities (sextupoles), better vacuum w/bakeout, enhanced control/performance of lattice…
- Established a strong foundation for development of amplified OSC experiment: validated many critical subsystems and concepts; gathered excellent operational experience and learned many valuable lessons

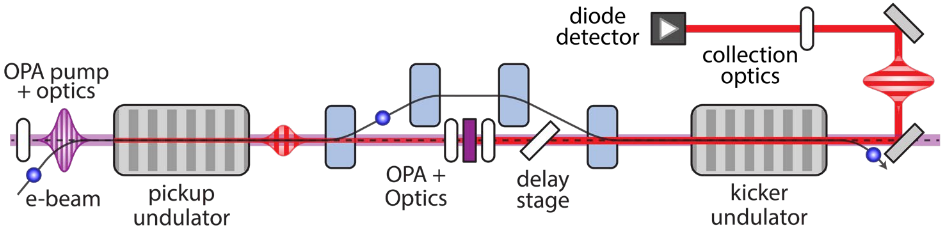


# New program in Amplified OSC + control & sensing

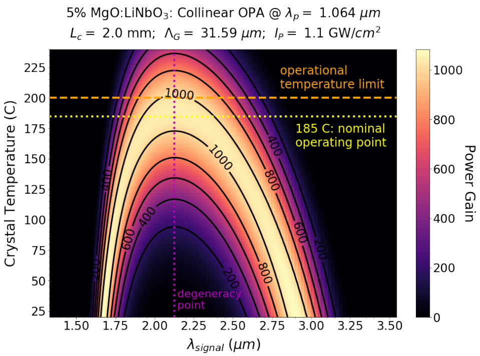
- Now developing a new OSC system at IOTA with high-gain optical amplification (30 dB)
- Combining flexible pump laser with machine/reinforcement learning techniques and specialized optics; goal of establishing new capabilities for beam cooling and control
- Program will emphasize pathfinding for operational systems using physics and technology of OSC
- **New postdoc position for amplified OSC; join us! (academicjobsonline:#18465)**



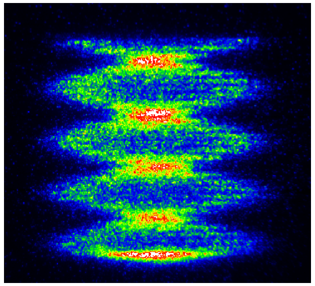
LLN drive laser




Amplified-OSC concept




Calculated amplifier performance



Phase-space control

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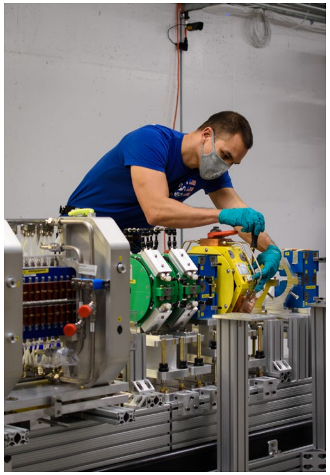
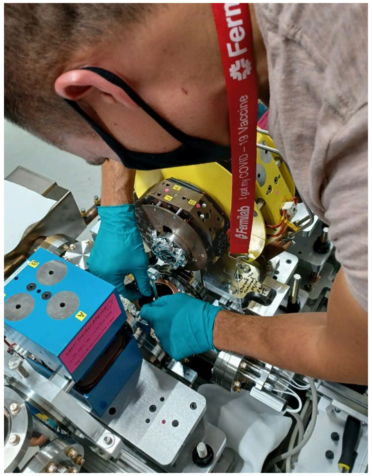
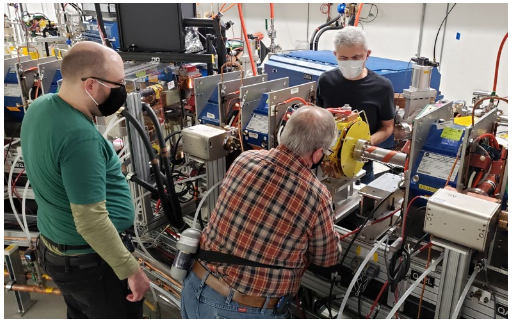
# A huge and ongoing “thank you” to the IOTA team

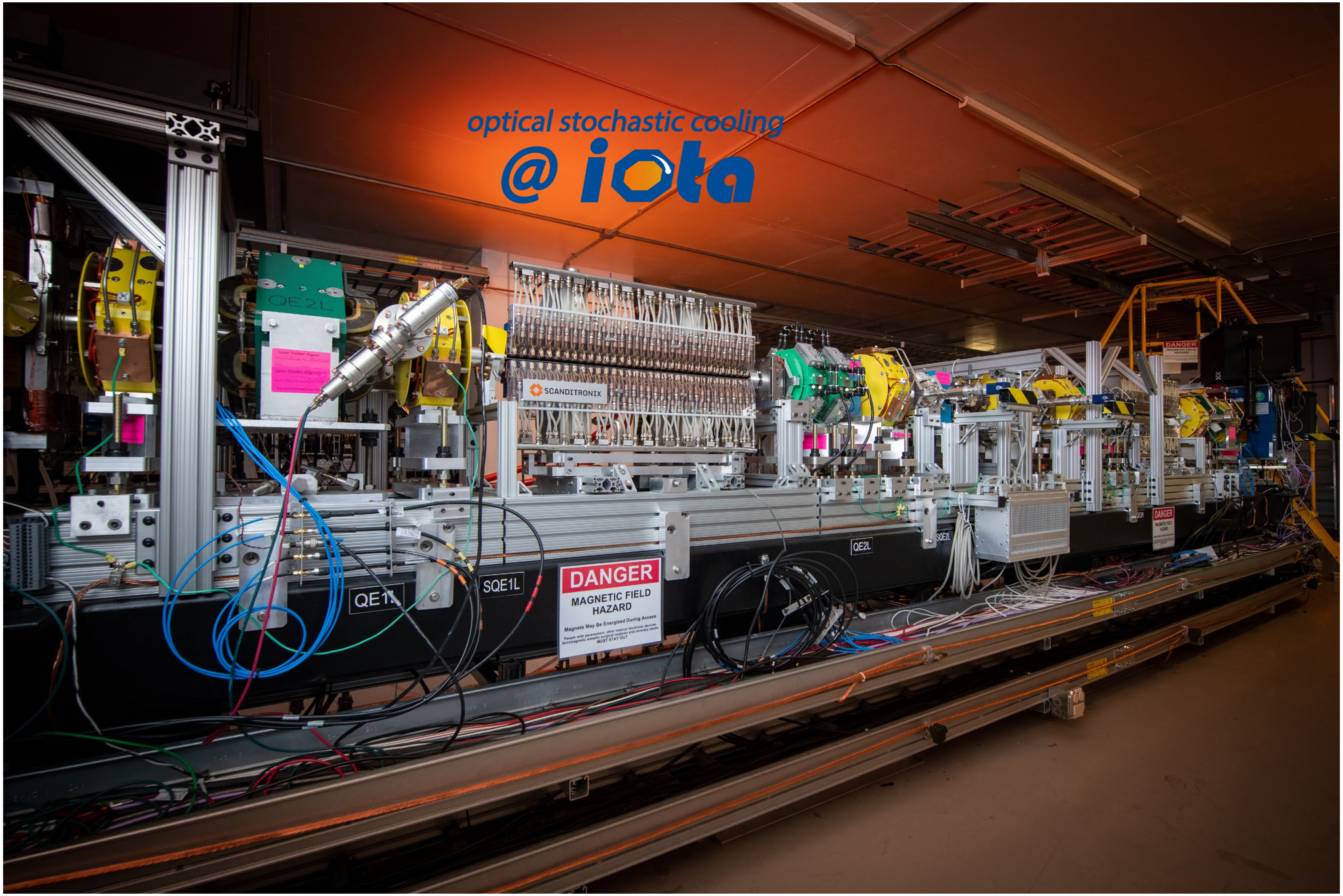







optical stochastic cooling
@ iota

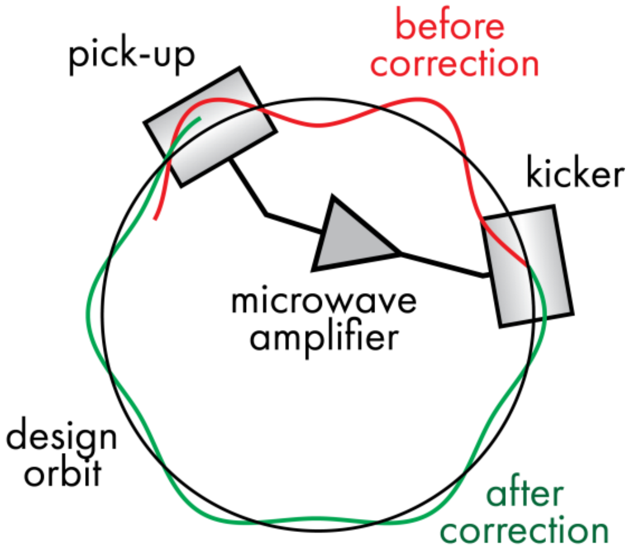

optical stochastic cooling
@ iota
QE2L
SCANDITRONIX
QE1L
SQE1L
DANGER
MAGNETIC FIELD
HAZARD
QE2L

# EXTRAS

# IOTA OSC configurations and measurements:

- From ~$10^8$ electrons down to single electron (nominal ~$10^5$)
- 1D (s), 2D (s,x), 3D (s,x,y) OSC
- Delay scans
- OSC toggles (e.g. off/cooling/off/heating/off)

# 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):

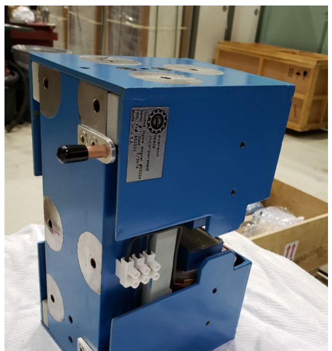
"How then can cooling work? It must necessarily be through deformation of phase space, such that particles move to the center of the distribution and (to satisfy Liouville) the empty phase space between the particles moves outwards. Clearly, the fields that do this must have a very particular shape, 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**."

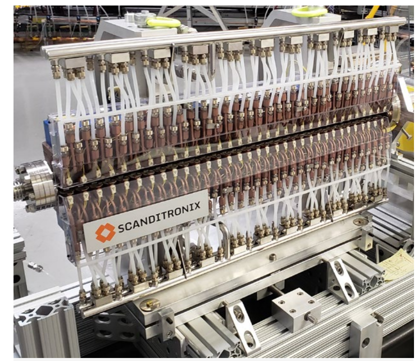
# High density of compact magnets for IOTA OSC

- 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;



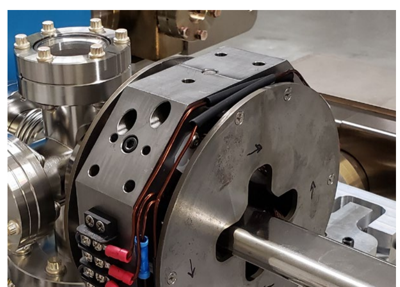
OSC Dipoles


OSC Quads

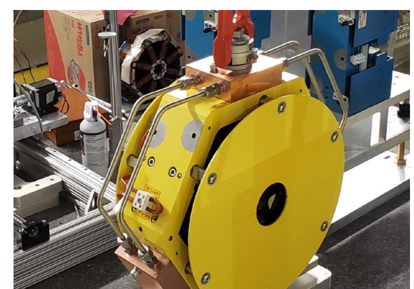



OSC Undulators

Y Correctors



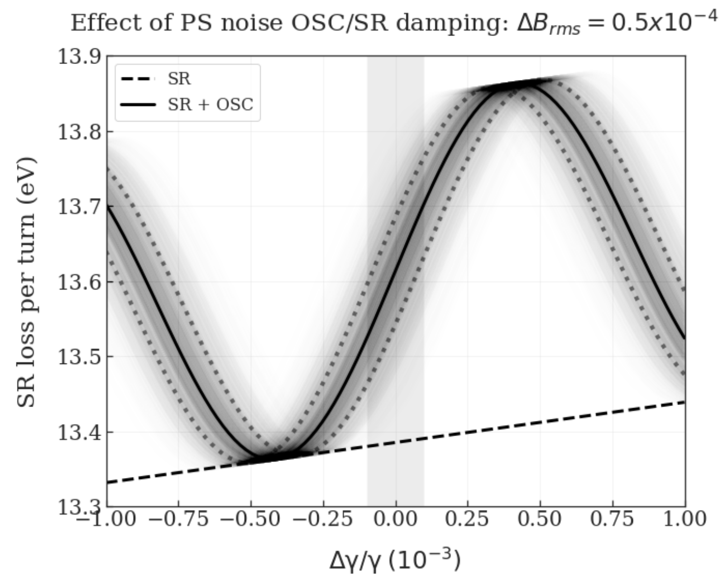
Coupling Quad

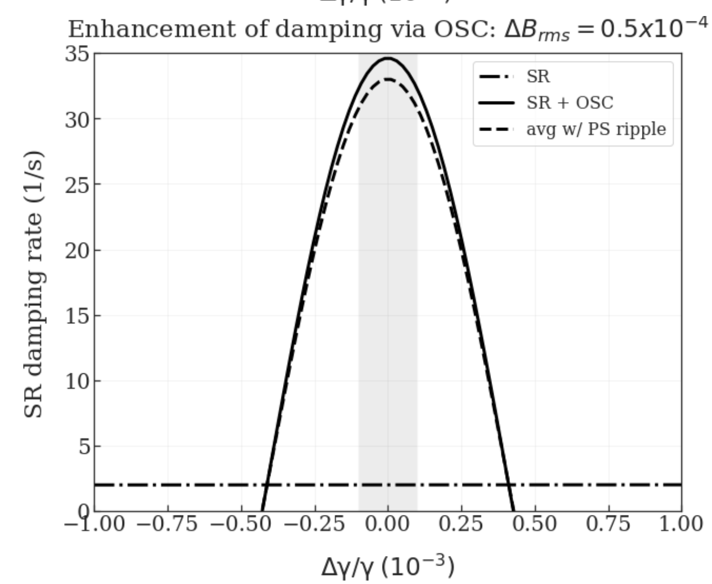


IOTA Sextupoles

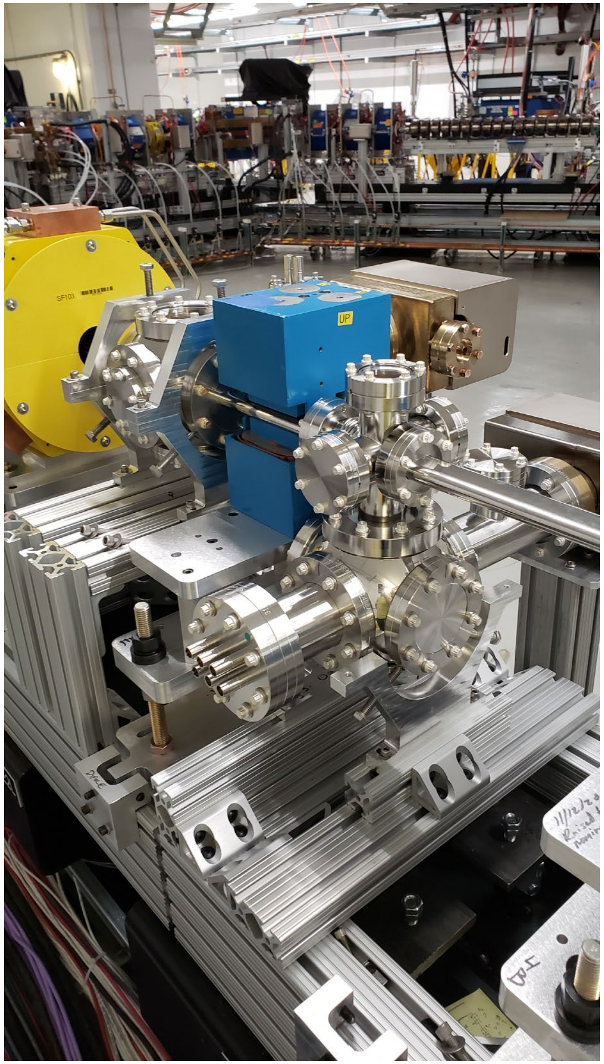
# Power-supply stability at ~ $10^{-4}$ is acceptable

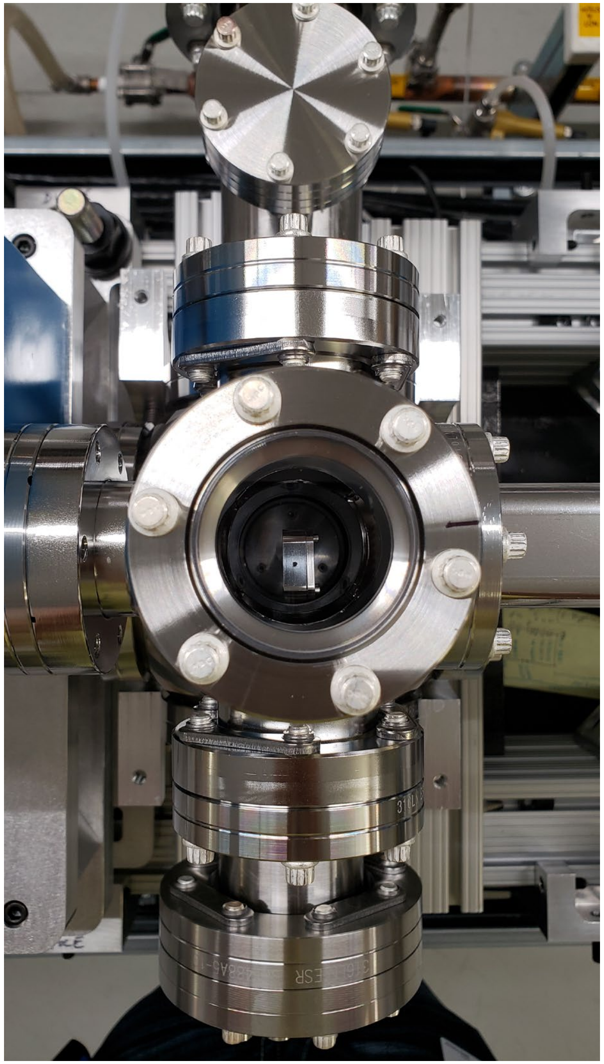
- Ripple in field will produce ripple in chicane delay and therefore relative arrival phase for entire beam
- Slow variations ($>\tau_{osc}$), effectively detune bypass to off-design momentum values
- For fast variations, the beam samples many curves and cools with a reduced rate
- For $\sigma_{\Delta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

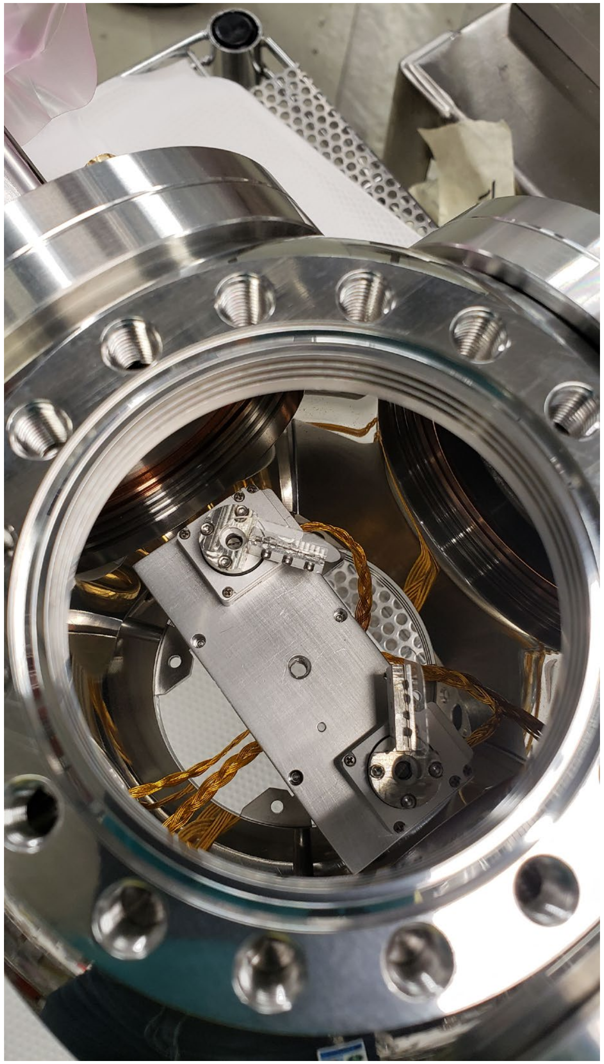



# OSC lens and delay stage with in-vac motion:

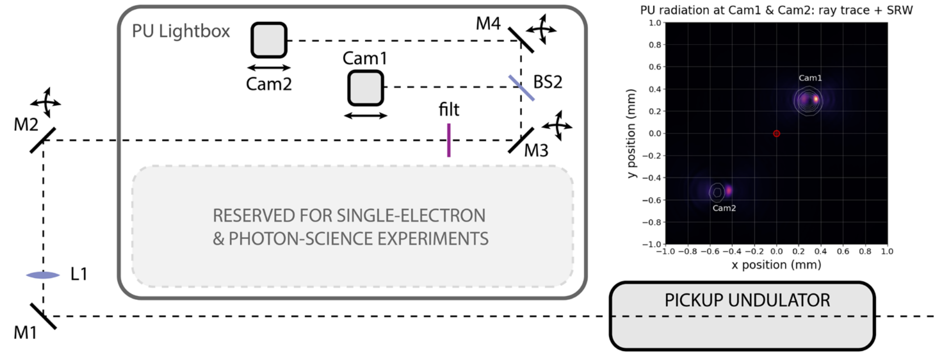


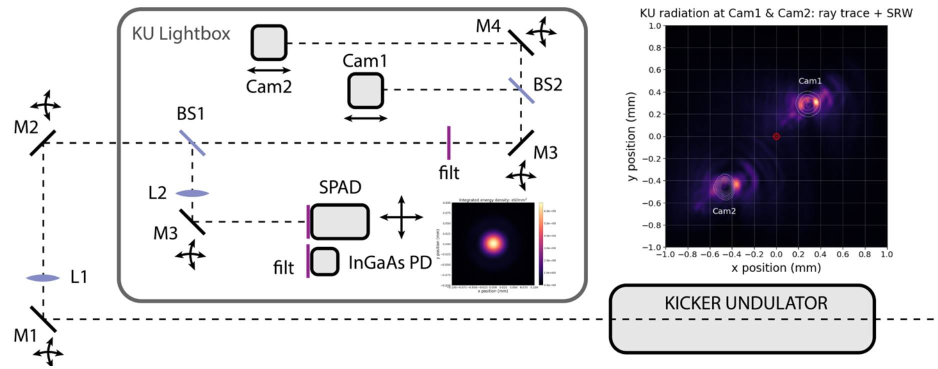



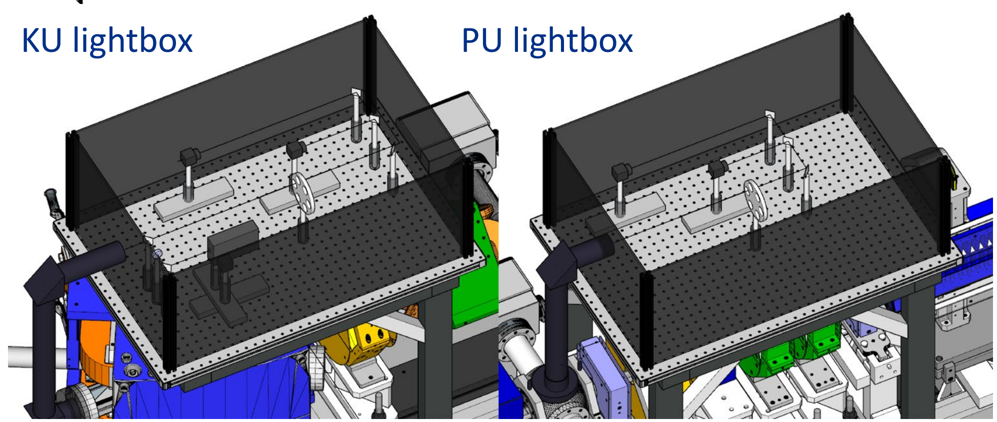


# Flexible lightboxes/diagnostics for Both PU and KU

- UR BPMs, PIN PD, SPADs, single-electron diagnostics
- Want spatial alignment of **<100 μm**, and angular alignment of **<100 μrad**
- HeNe through surveyed pinholes defines nominal optical axis, ~+/- 50 μm
- 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 **~10’s μm & 10’s μrad**, range ~ +/- 5 mm & +/- 5mrad

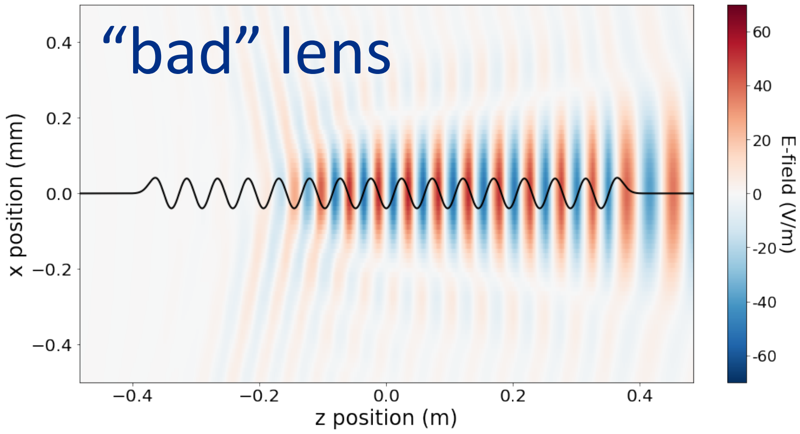


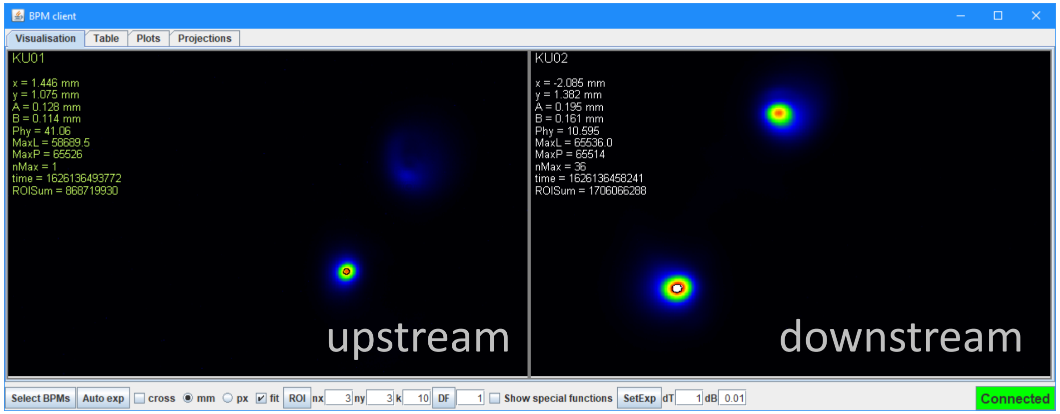



# Good lens, bad lens…

- Manufacturing error resulted in ~5% longer focal length for initial lens; used in initial OSC observations; resulted in weaker cooling and complex behavior with xy-coupling




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