Optical Stochastic Cooling @ Fermilab's IOTA Ring

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MSU/FRIB APES

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On behalf of an excellent team:

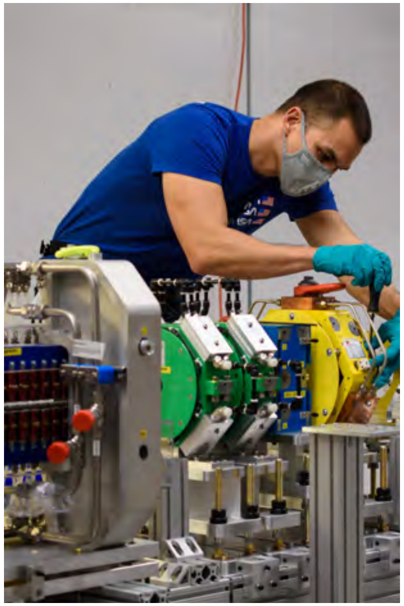
- **OSC team:** V. Lebedev, A. Romanov, J. Ruan, H. Peikarz, P. Piot, A.J. Dick, S. Chattopadhyay,

- **Supported at IOTA/FAST by:** K. Carlson, N. Eddy, D. Edstrom, R. Espinoza, D. Franck, S. Nagaitsev, L. Nobrega, M. Obrycki, J. Santucci, A. Valishev, S. Wesseln

- **OSC Collaborators:** (UC Berkeley) A. Charman, G. Penn, J. Wurtele

Biographical Sketch

- Associate Scientist / Peoples Fellow in the Fermilab Accelerator Division from Aug. 2017
- Ph.D. in Physics from Vanderbilt ('09); Advisor: Charles Brau
- Academia (VU), Industry (AES) & Nat. Lab (FNAL)
- PI for Optical Stochastic Cooling experiment at the IOTA ring @ FNAL
- PI for a new DOE/HEP ECA on amplified OSC, advanced beam control and sensing

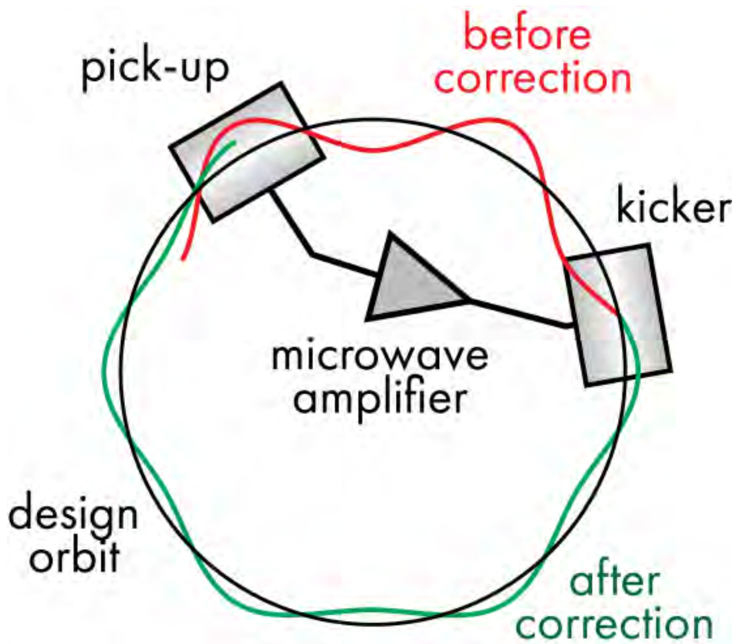


Cooling is a vital element of many modern accelerators

- Synchrotron-radiation damping
  - Replacement of energy lost to SR with longitudinal acc. in RF; occurs naturally but requires significant amounts of SR
- Electron cooling
  - Thermalization of hot beam with cold bath of copropagating electrons; very unfavorable energy scaling ($\gamma^{5/2}$)
- Stochastic cooling
  - Direct measurement and correction of incoherent particle motions via random-sampling process
- “Advanced Beam cooling”
  - High-bandwidth variants of SC; coherent electron cooling (CeC), optical stochastic cooling (OSC)

SC: a powerful technique but limited to GHz BW

Simplified stochastic cooling system



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

cooling heating

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

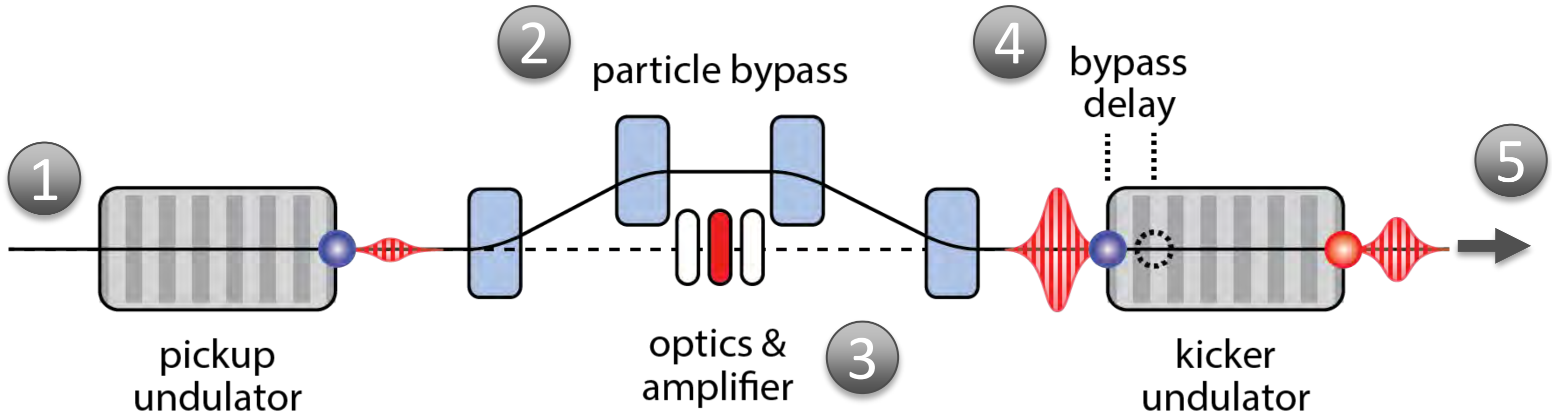
1984 Nobel: van der Meer/Rubbia

1) We can increase beam brightness if we have granular information about particle ensemble.

2) Bandwidth (time resolution) of feedback system controls cooling rate

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)

OSC extends the SC principle to optical bandwidth

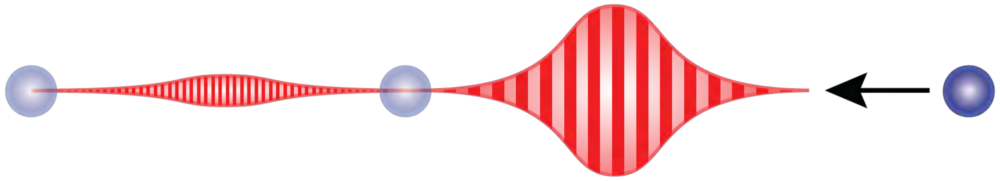


1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates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

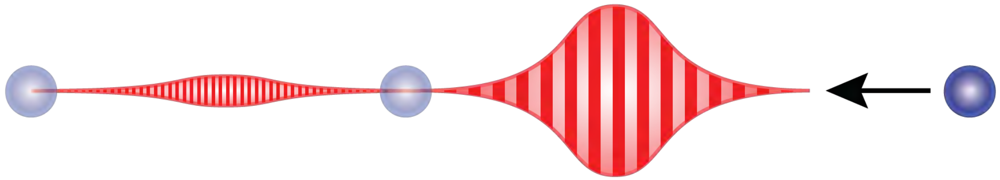
10^3 – 10^4 increase in cooling rate over SC
(~10s of THz BW vs few GHz)

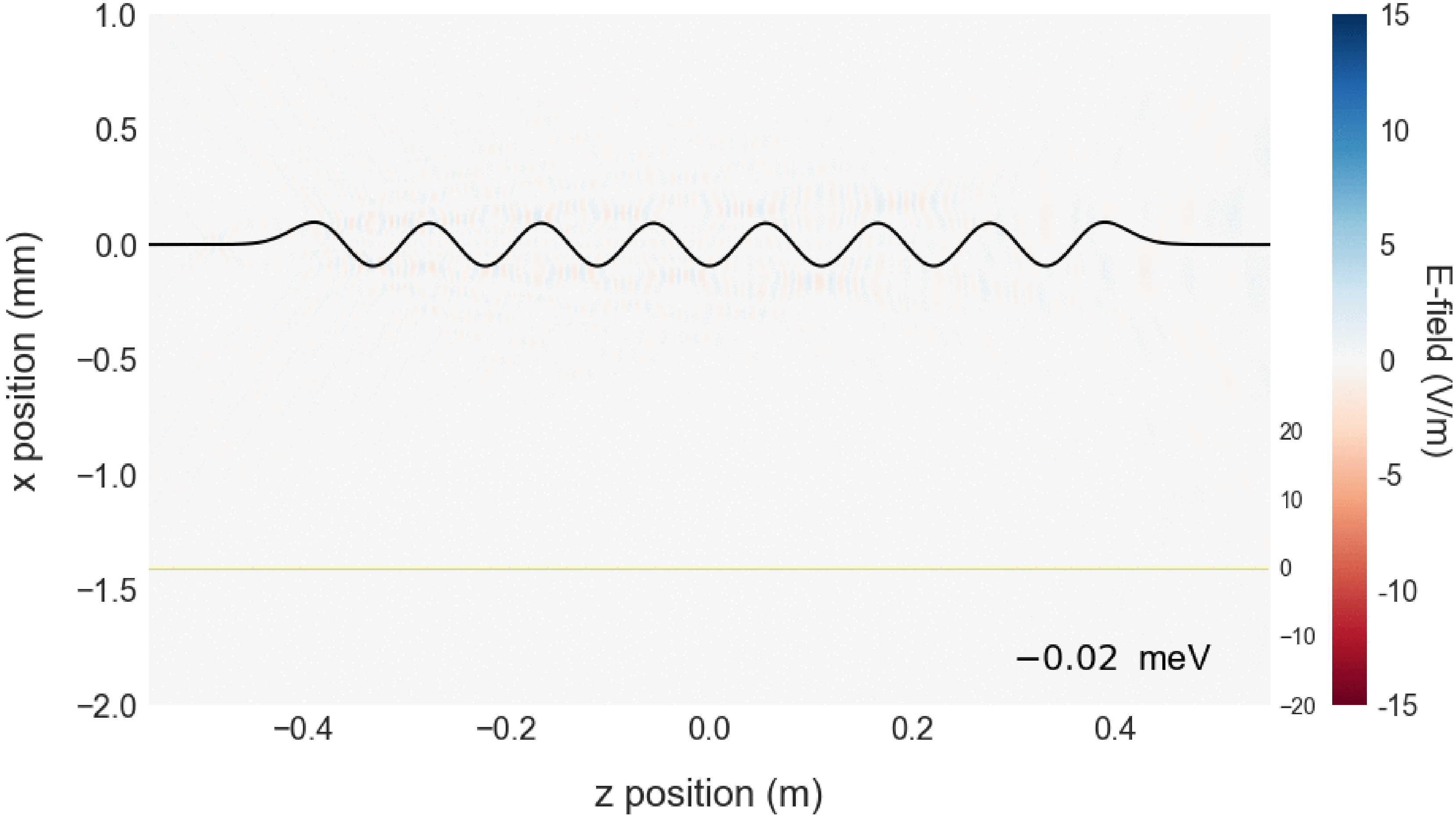
[1] A.A.Mikhailichkenko, M.S. Zolotorev, "*Optical stochastic cooling*," Phys. Rev. Lett. 71 (25), p. 4146 (1993)
[2] M. S. Zolotorev, A. A. Zholents, "*Transit-time method of optical stochastic cooling*," Phys. Rev. E 50 (4), p. 3087 (1994)

Energy exchange depends on particle deviation…

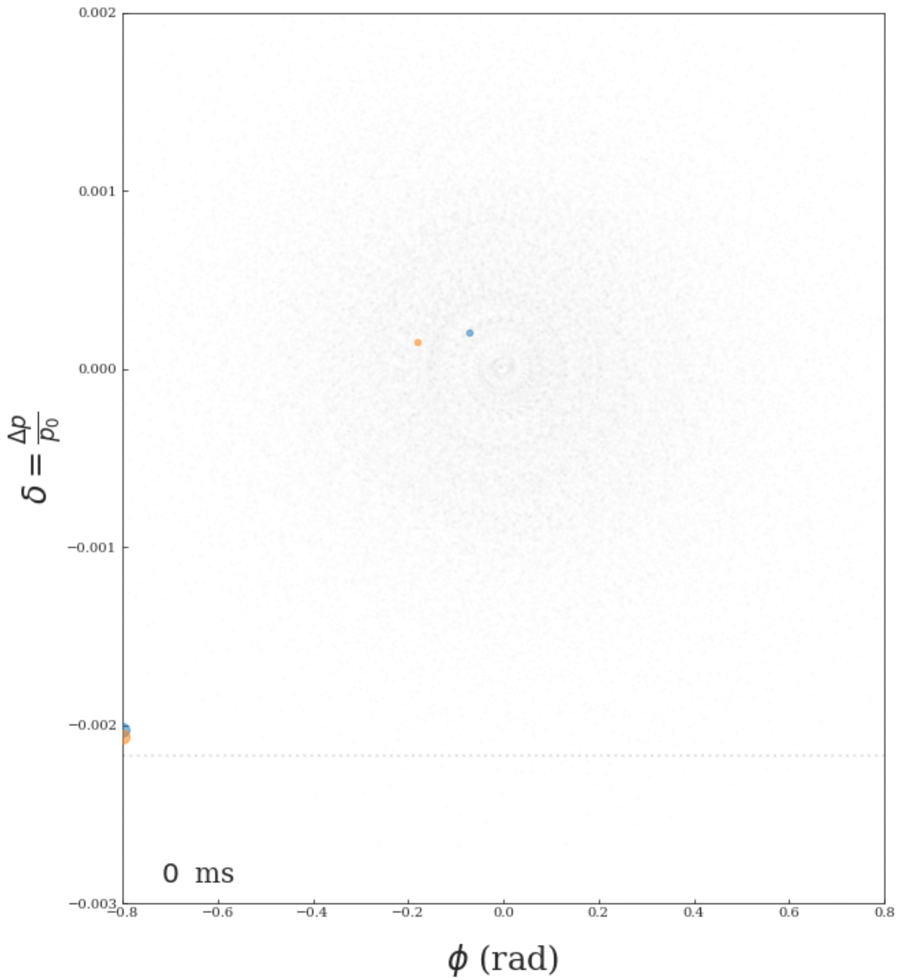


Energy exchange depends on particle deviation…





… but only "cools" particles within a certain range

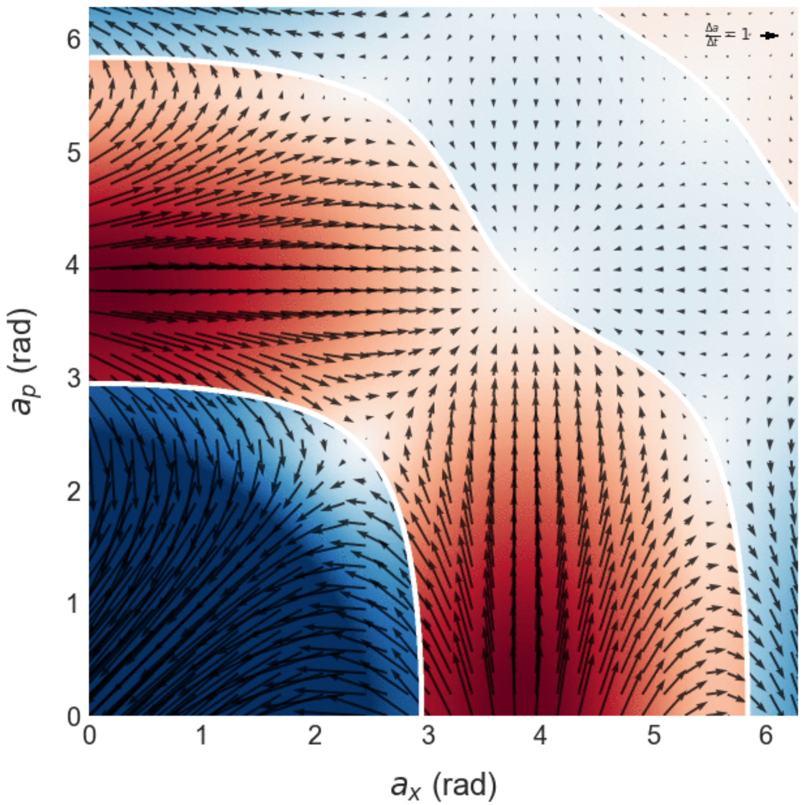


$$\frac{\delta p}{p} = -\kappa \sin(k_0 s)$$

OSC creates a cooling/heating surface in phase space

- The cooling force has an effective aperture in phase space
- An OSC experiment/system requires a balance of cooling rate against this cooling range
- Many cooling and heating zones; tuning bypass delay modifies their strength and polarity
- Hints at possibilities for advanced phase-space control and specialized SR-damping systems

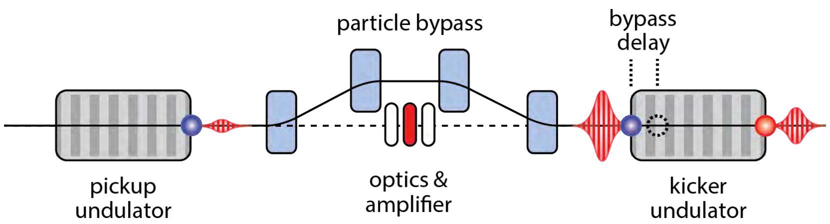
$$\frac{\delta p}{p} = -\kappa \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right)$$

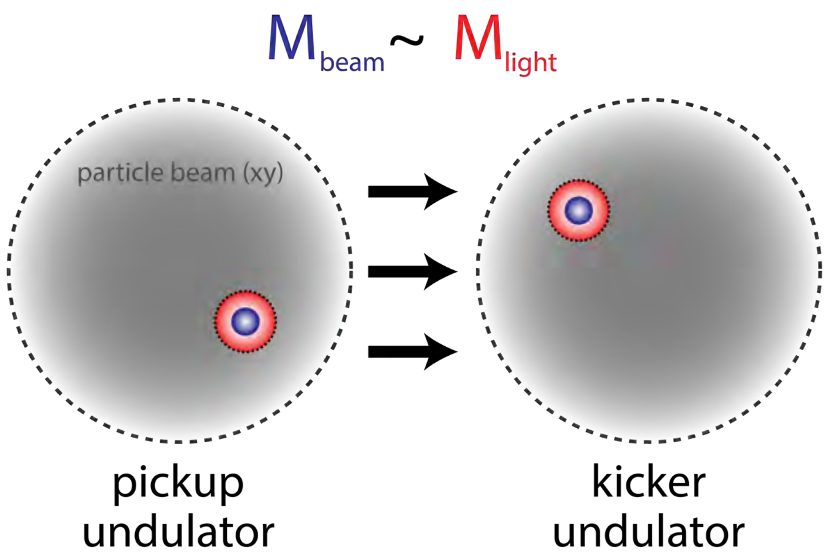


Cooling map integrated over betatron and synchrotron oscillations; arrows show mag. and dir. of net cooling force

Also possible to sample the beam transversely in OSC

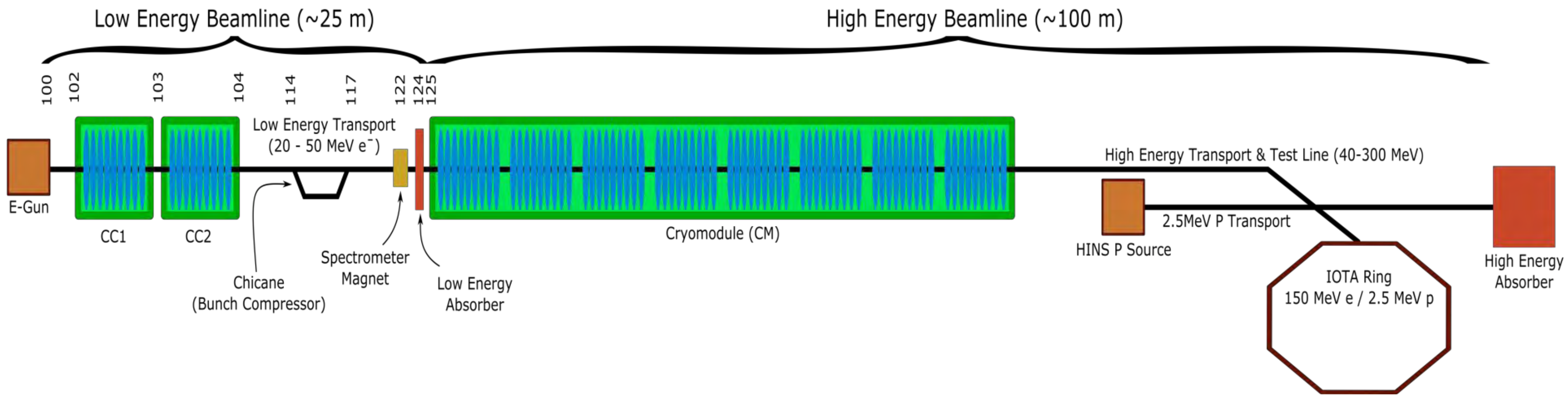
- Due to short wavelength, coherent-mode size of the undulator radiation can be smaller than the particle beam
- “Transverse optical sampling” can provide a dramatic reduction in the number of particles per “sample”
- Transport matrices for the light and the beam should be matched
- Of potential interest for longitudinal cooling of high-intensity beams in ring-based electron coolers





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

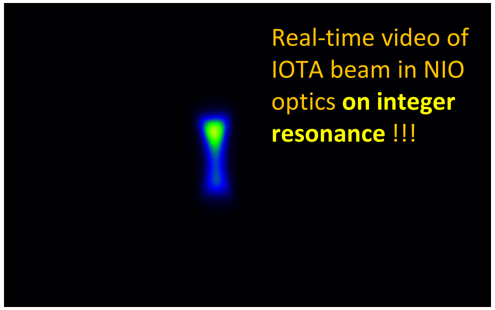
- IOTA/FAST establishes a unique capability at FNAL to address frontier topics in Accelerator and Beam Physics
- Dedicated facility for intensity-frontier accelerator R&D

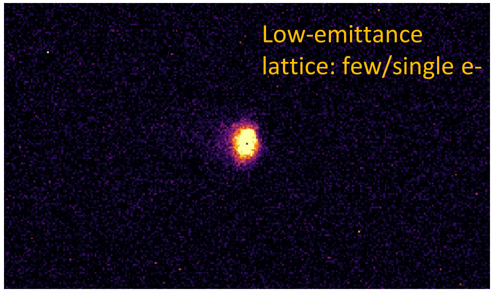


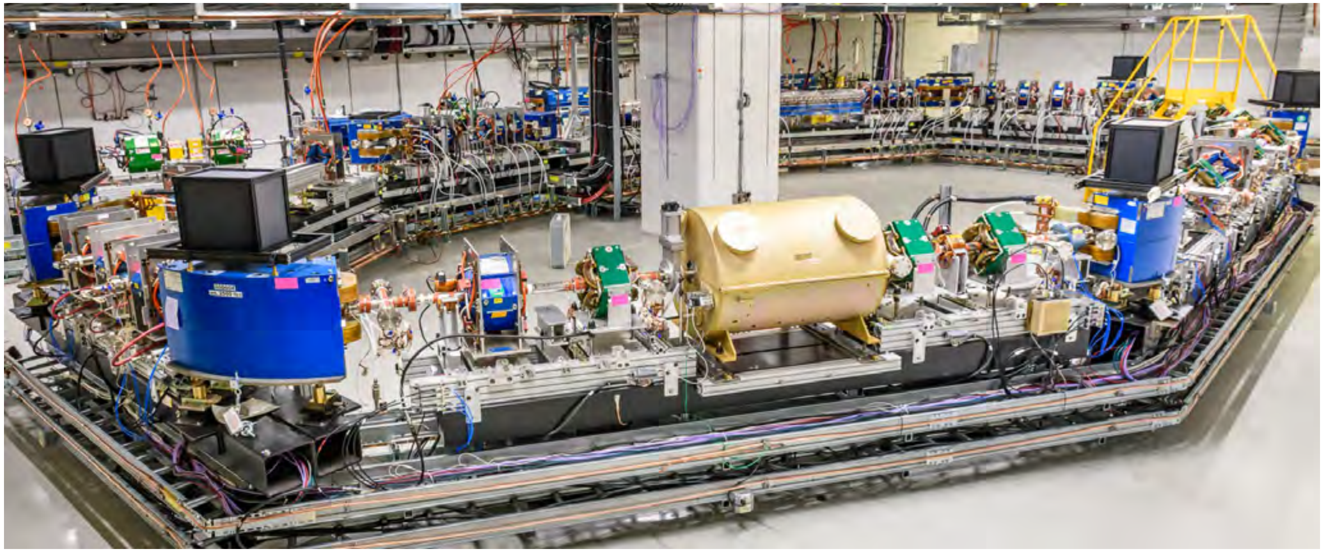
- IOTA's 2.5 MeV Proton injector currently under construction for R&D with space-charge-dominated beams
- Electron beams are supplied to IOTA from FAST, a 1.3 GHz Superconducting RF electron linear accelerator
  - o Beam energy: 40-300 MeV
  - o Bunch charge: 1e- to 3 nC (160 pC nominal)
  - o Pulse frequency: up to 5 Hz (83 MHz train)

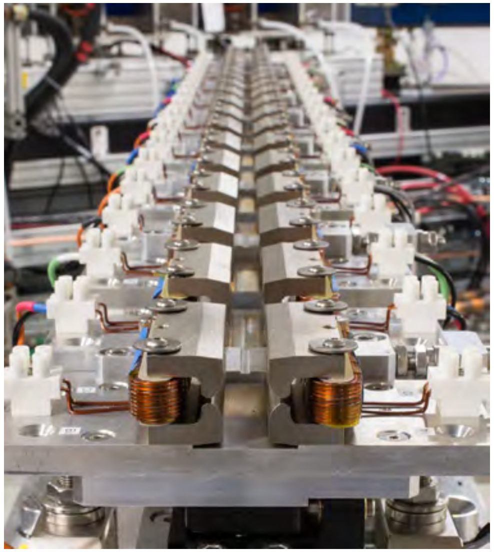
A growing portfolio of R&D at IOTA:

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

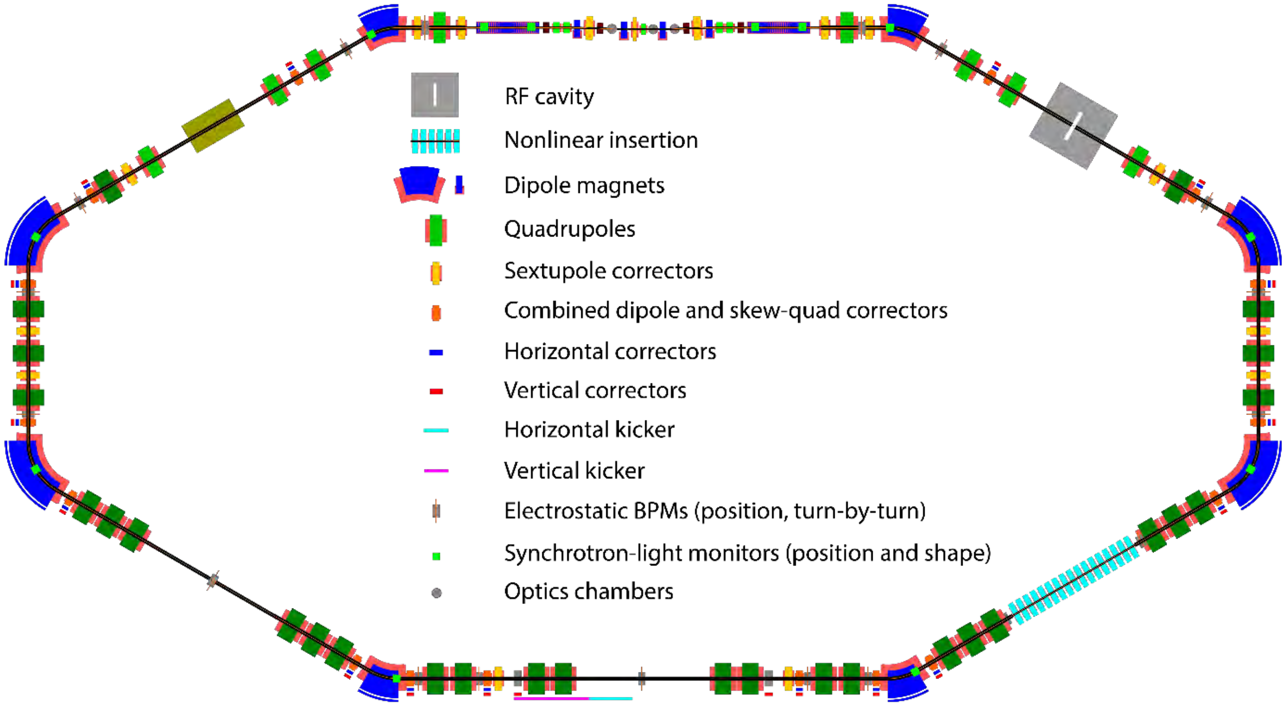






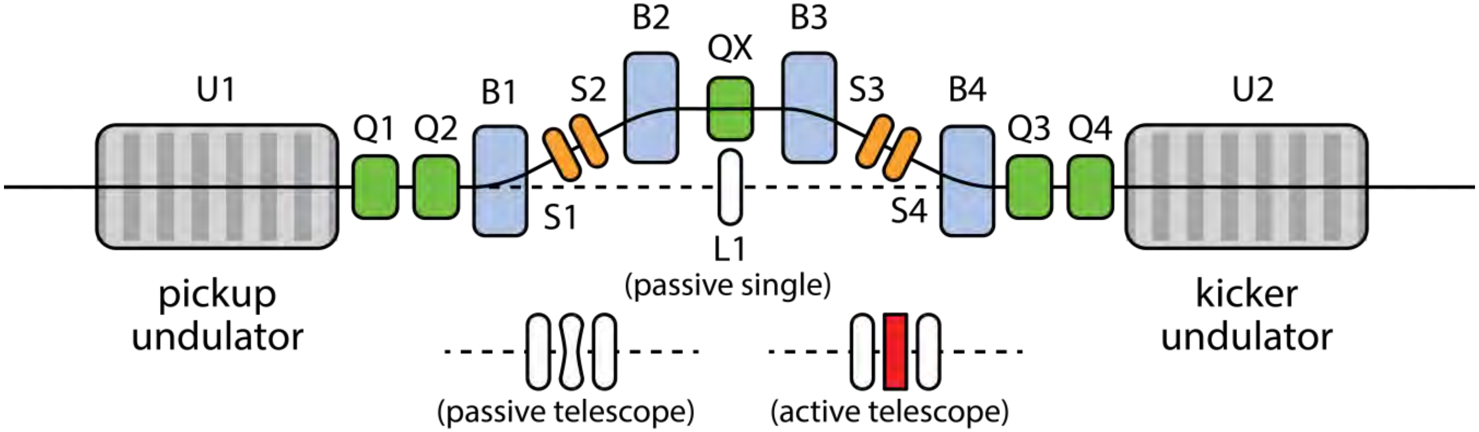


IOTA was designed with OSC as a key requirement



- Highly reconfigurable, R&D facility; supports dedicated OSC runs
- Low energy (100 MeV) reduces equilibrium emittance, energy spread and increases synchrotron radiation damping time ($\tau_{\varepsilon x}$~1 sec, $\tau_{\varepsilon s}$~0.5 sec)
- … improves cooling ranges and the relative strength of OSC
- Observation/exploration of the fundamental OSC physics decoupled from technological challenges related to high optical gain

An effective program includes two configurations

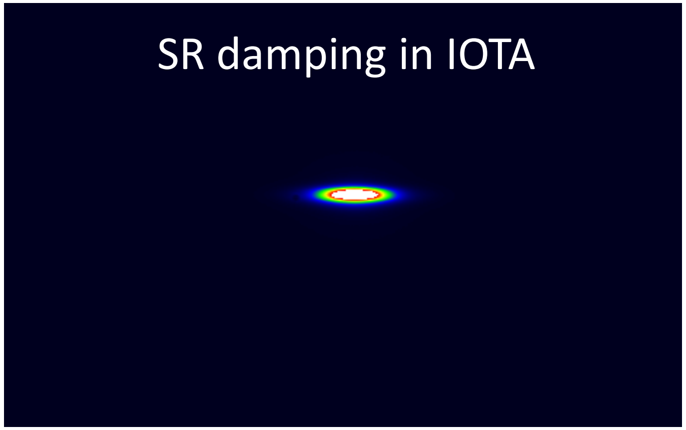


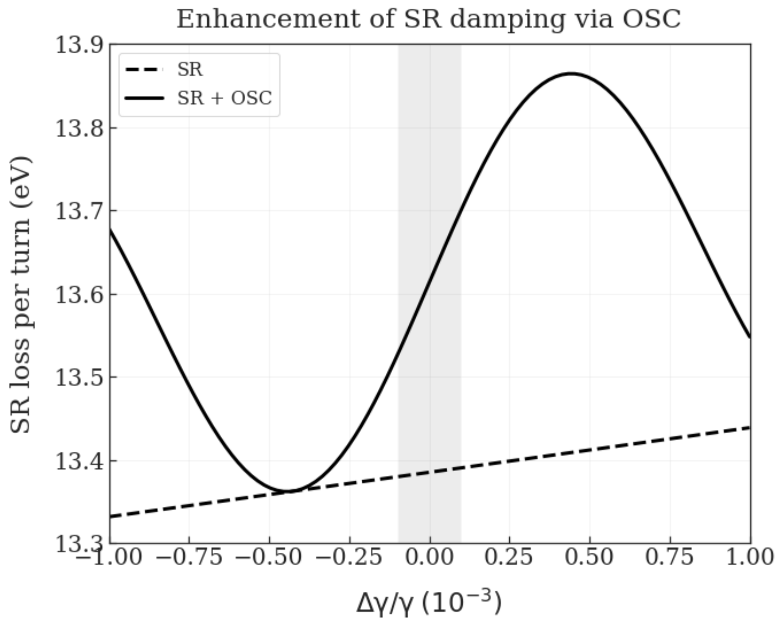
- **Non-amplified OSC (~1-µm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-µm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification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

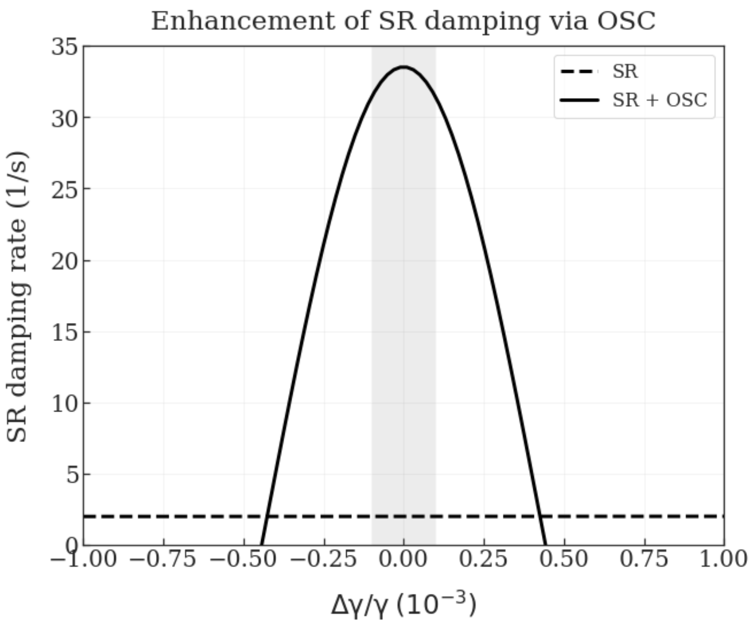
- **Strategy: focus on investigating fundamental physics and use as guidance for development of operational systems and subsystems**

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 dominates sync. rad. damping by ~10-20x without any optical amplification ($\tau_{\varepsilon s}$~50 ms, $\tau_{\varepsilon x}$~50 ms; uncoupled in xy)**



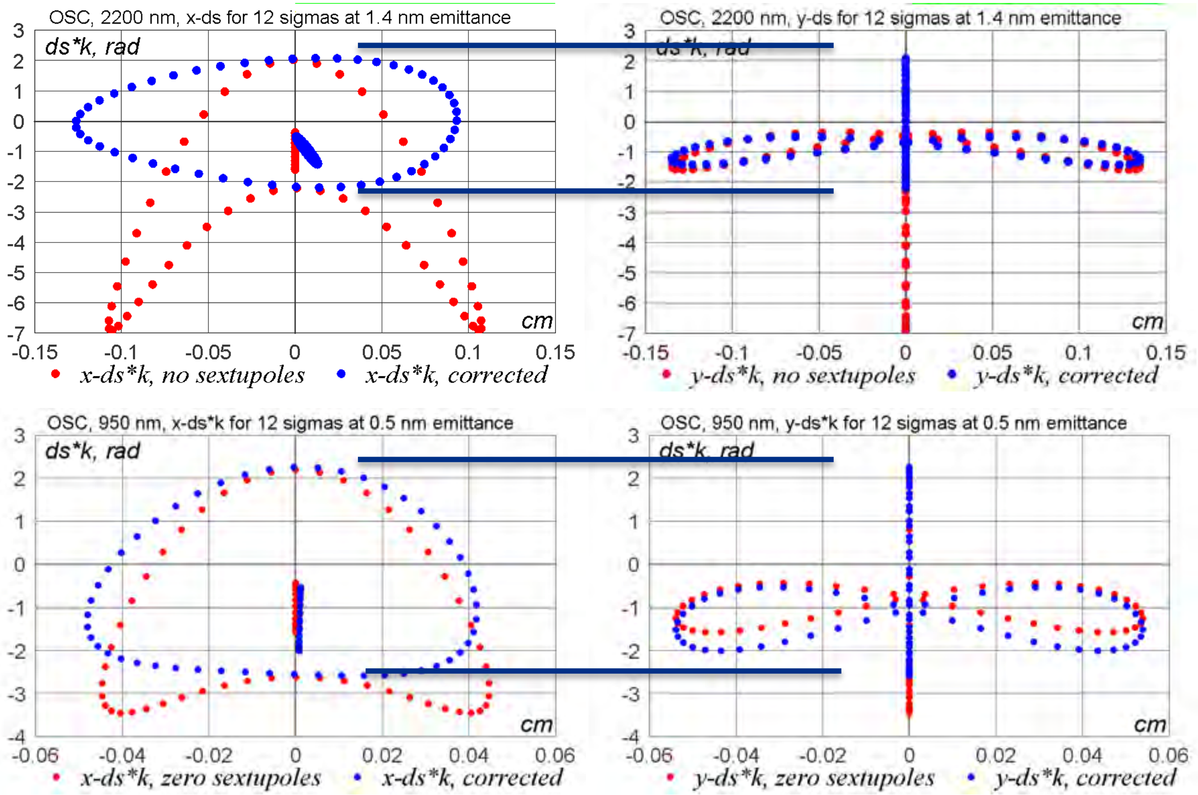




Nonlinear path lengthening compensated by sextupoles

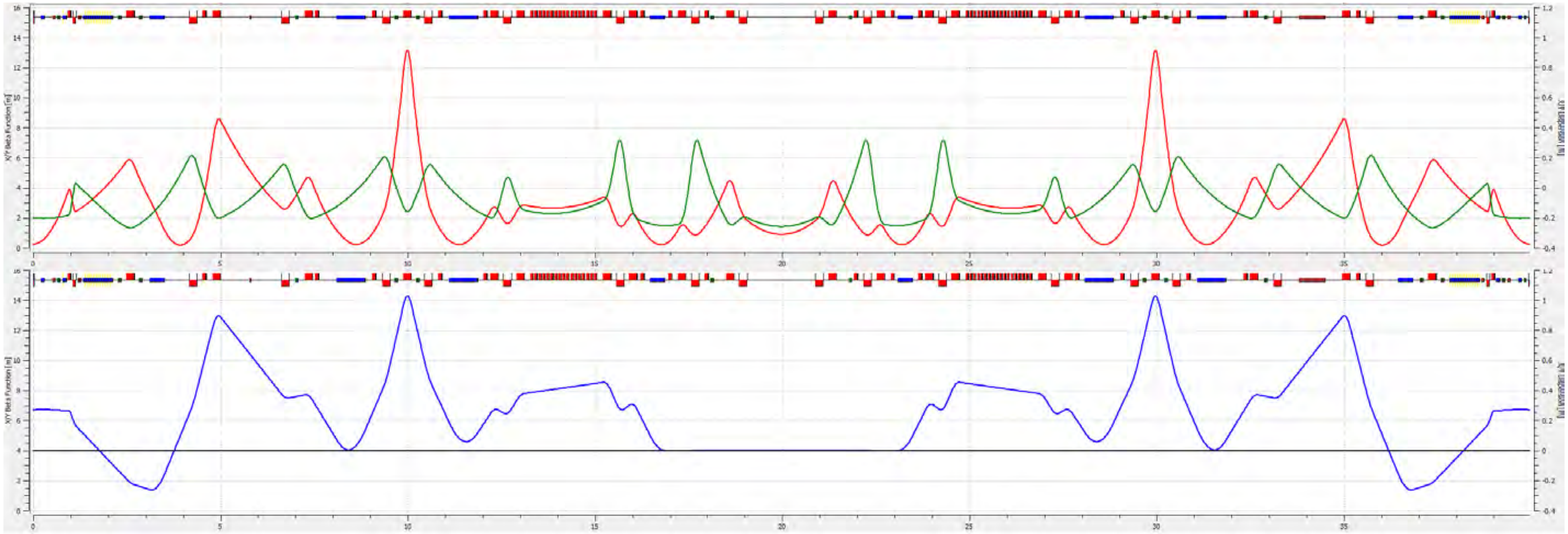
- Large amplitude particles deviate from linear mapping
- Nonlinearity dominated by angular deviations
- Correction creates large chromaticity that must be corrected by IOTA sextupoles
- Nonlinearity less critical in non-amplified experiment due to larger lattice functions in the bypass (i.e. smaller angles)

$$\Delta s_2 = \frac{1}{2}\int \left(\theta_x(s)^2 + \theta_y(s)^2\right) ds$$



(A. Romanov)

OSC-lattice design for 950nm

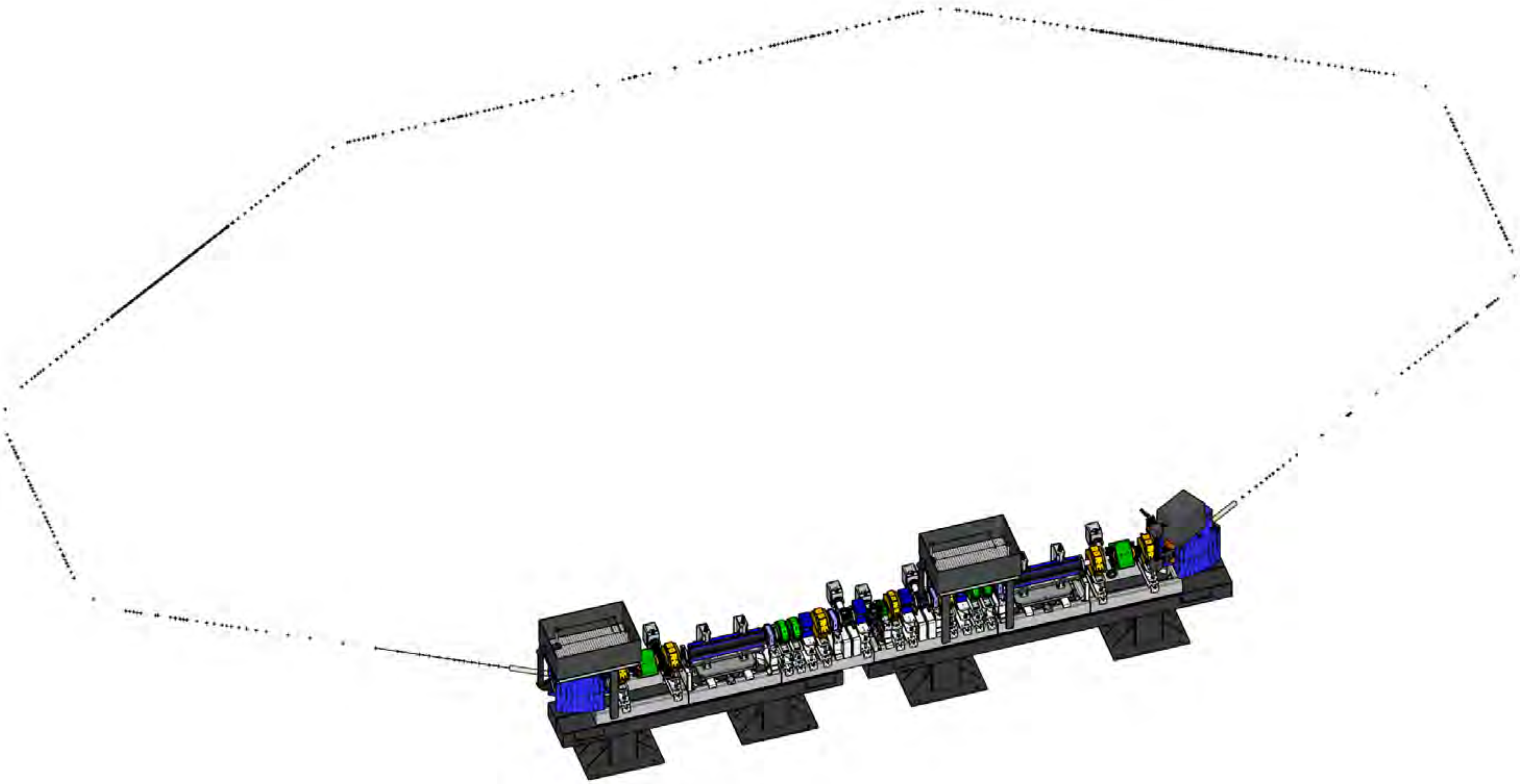


Betas start, x,y	25, 200 cm
D_x start	27 cm
Tunes, x,y	5.42, 2.42
Mom. compaction factor	0.00172
Mode emittances	0.426 / 0.423 nm
Natural chromaticity (x,y)	-10.2 / -8.1

Energy drop	12.7 eV
Bunch length @70V	3.9 cm
Energy spread	0.99 E-4
Sync. Tune/freq. @70V	2.72 E-5 / 204 Hz
Emitt. damp. times (x,y,s)	(1.056,1.056,0.519) s
Chrom. from OSC sextupoles	29.2 / -20.9

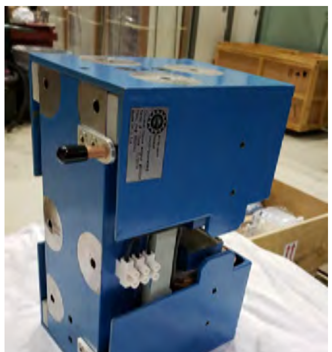
OSC at IOTA

Hardware, diagnostics, procedures, operations

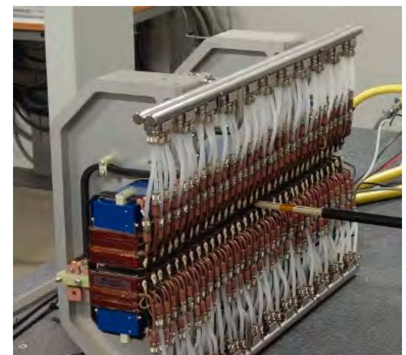


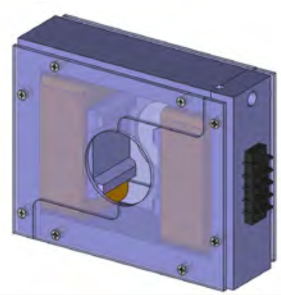
High density of compact magnets for IOTA OSC

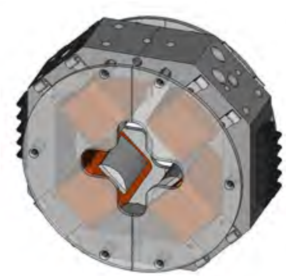
- Chicane dipoles (4x), quads (4x), undulators (2x), sextupoles (7x), coupling quad (1x), vertical correctors (4x)
- Design/performance balanced between integrated-field requirements, beam aperture/vacuum envelope, space available, thermal considerations; field screens to reduce cross-talk;


OSC Dipoles


OSC Quads


OSC Undulators

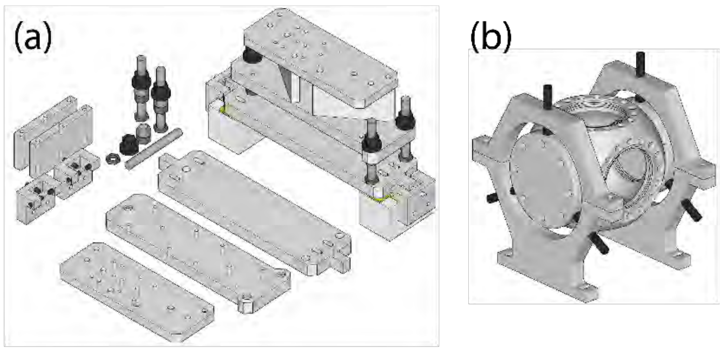

Y Correctors

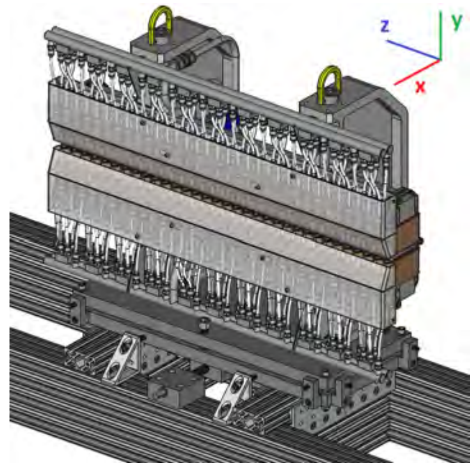

Coupling Quad

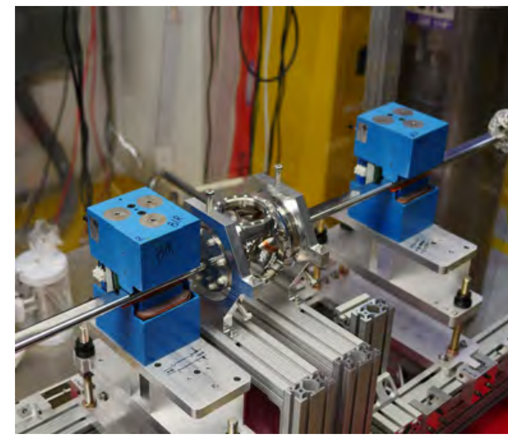

IOTA Sextupoles

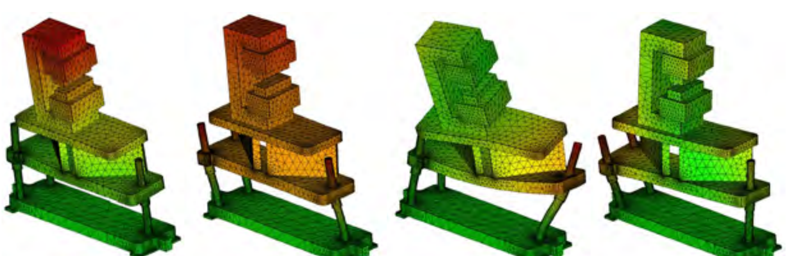
Flexible elements for magnet and chamber positioning

- Universal 6-DOF support stands with high rigidity, precision and reliability
- 6-DOF supports for undulators; includes long-range horizontal motion
- Low-profile, concentric mounts for additional chamber support & positioning
- Emphasis on stability of critical elements

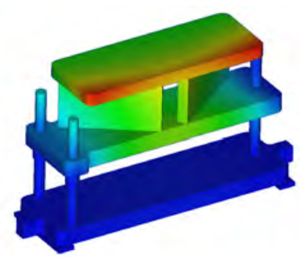


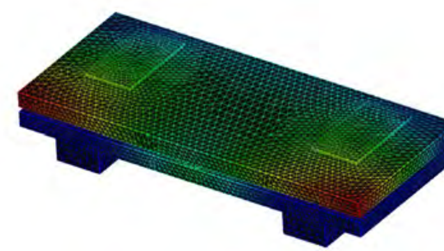






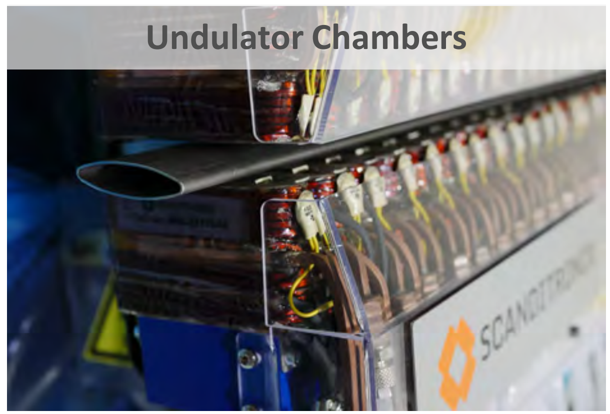
f_1=55 Hz f_2=119 Hz f_3=224 Hz f_4=275 Hz

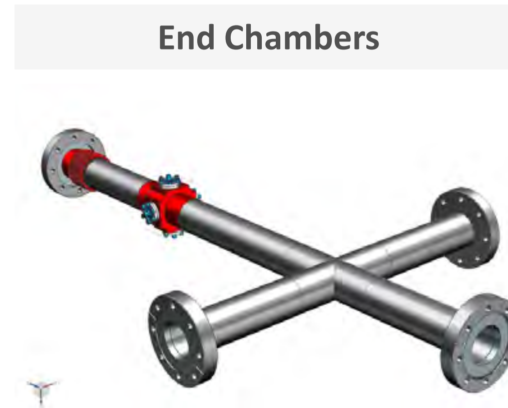


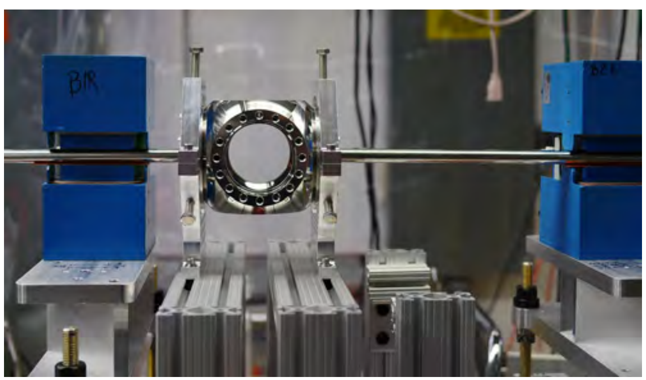


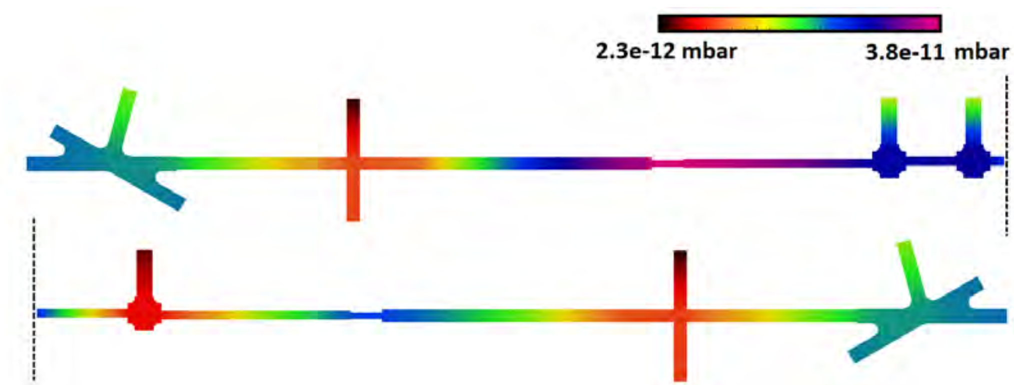
Efforts to minimize mag. errors and achieve hard UHV

- Bypass, diagnostic and optics chambers are all seamless 316L construction with 316LN flanges; all elements checked with μ meter
- All tubing vacuum fired at 950 ºC for reduced H_2 outgassing rate
- Molflow simulations of full vacuum envelope for H_2 look OK



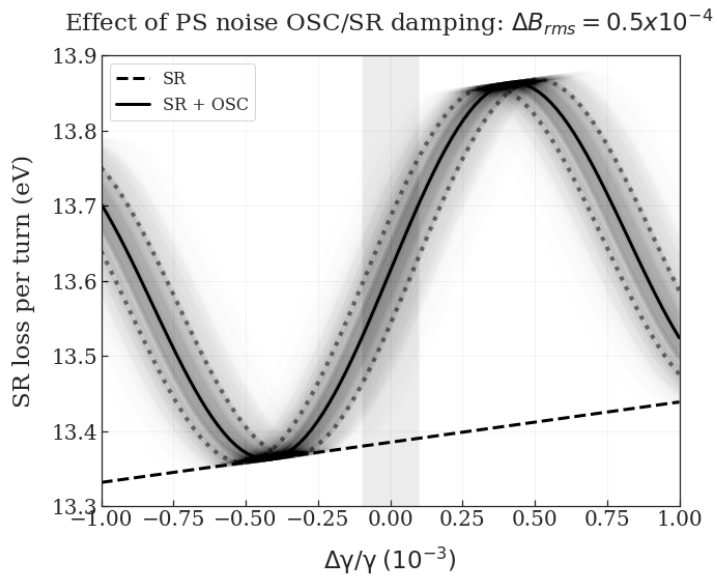


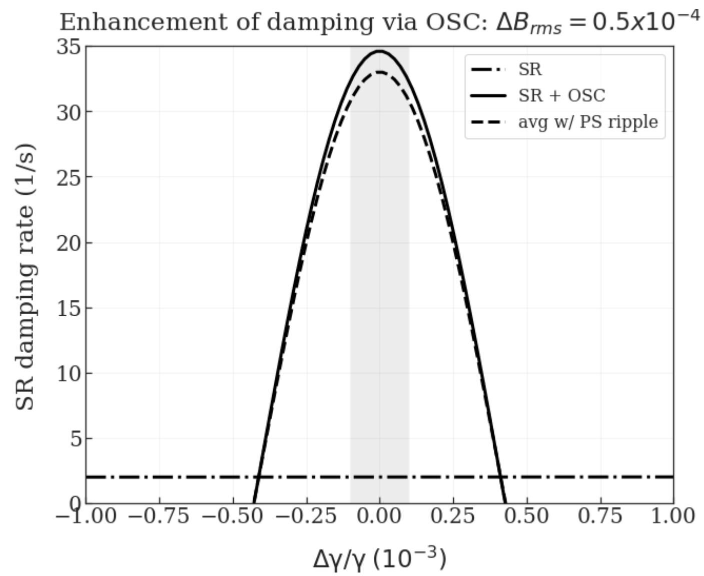




Power-supply stability at ~ 10^{-4} is acceptable

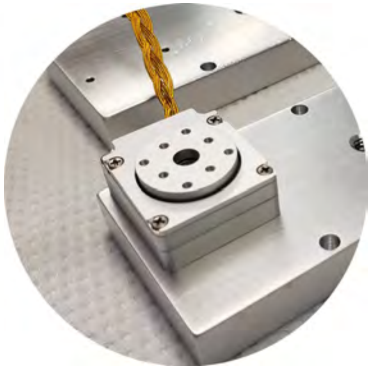
- Ripple in field will produce ripple in chicane delay and therefore relative arrival phase for entire beam
- For slow variations ($>\tau_{osc}$), beam centroid may cool rapidly to off-design momentum values
- For fast variations, the beam samples many curves and cools with a slightly reduced rate
- 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

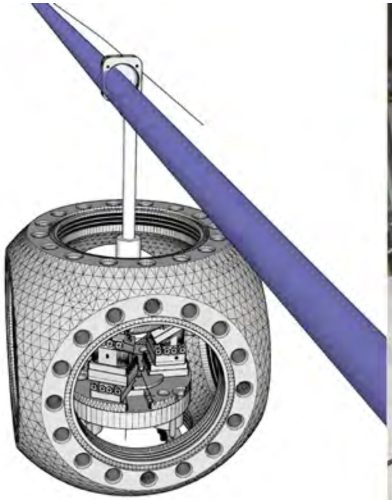


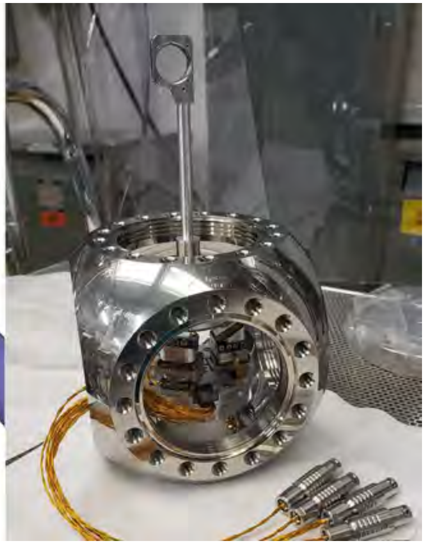


Integrated commercial motion solutions for OSC

- “Smarpod” from SmarAct; hexapod like with 0.5-kg normal load, 0.25-kg transverse
- Provides full 6-DOF motion with sufficient throw; ~10^{-11} Torr; bakeable up to ~130 °C
- Critical system for alignment of optics in the OSC experiments, especially amplified OSC
- SmarAct rotary stages for precision delay/shift stage: non-magnetic, ~10^{-11} Torr; bakeable up to ~130 °C

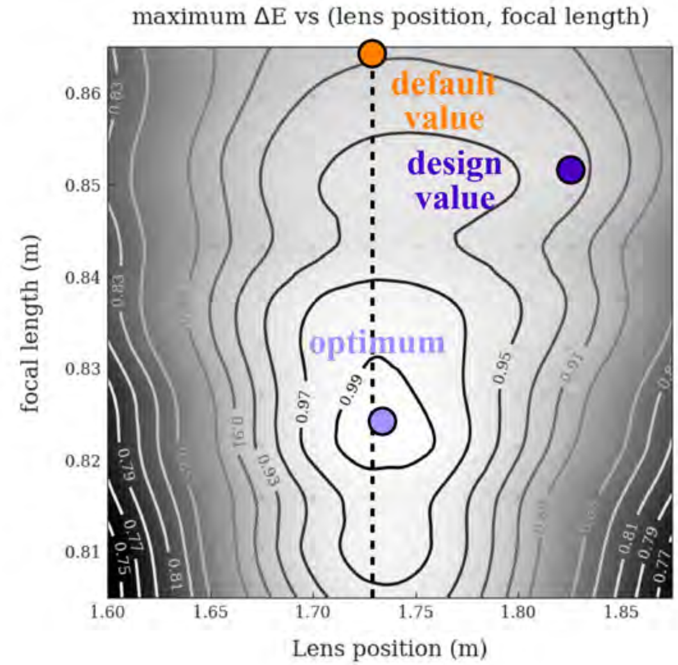


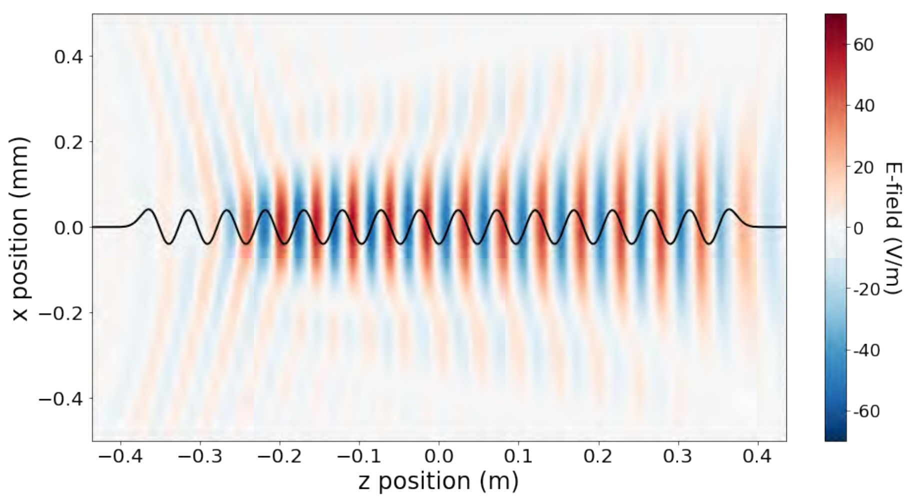


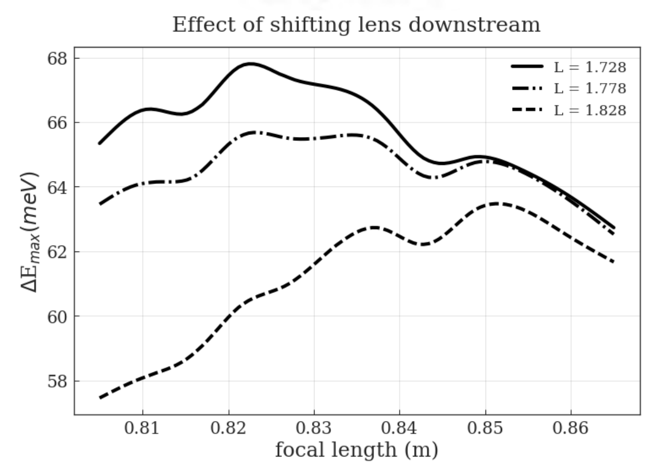


Lens parameters optimized for maximum OSC kick

- To avoid mechanical interference with coupling quad, lens position must be shifted longitudinally
- Focal length can be adjusted to compensate somewhat while simultaneously reducing the steepness of the local ΔE “surface”

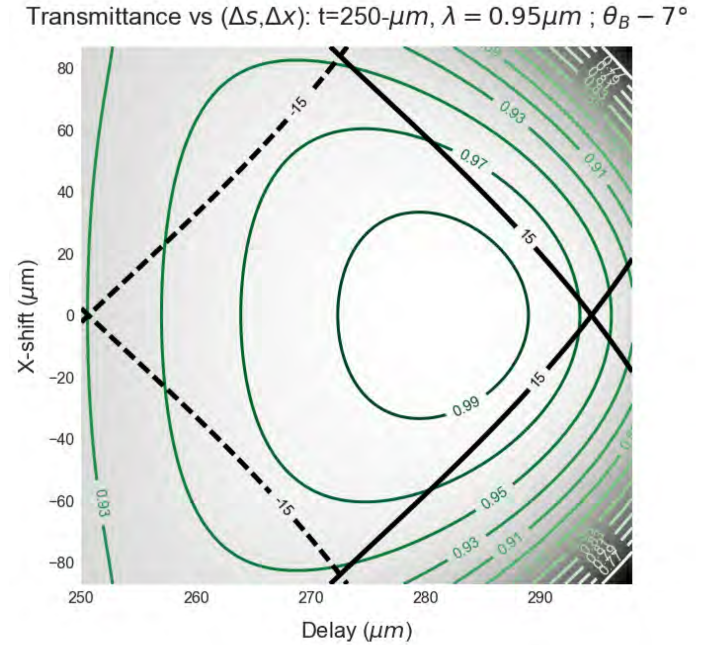


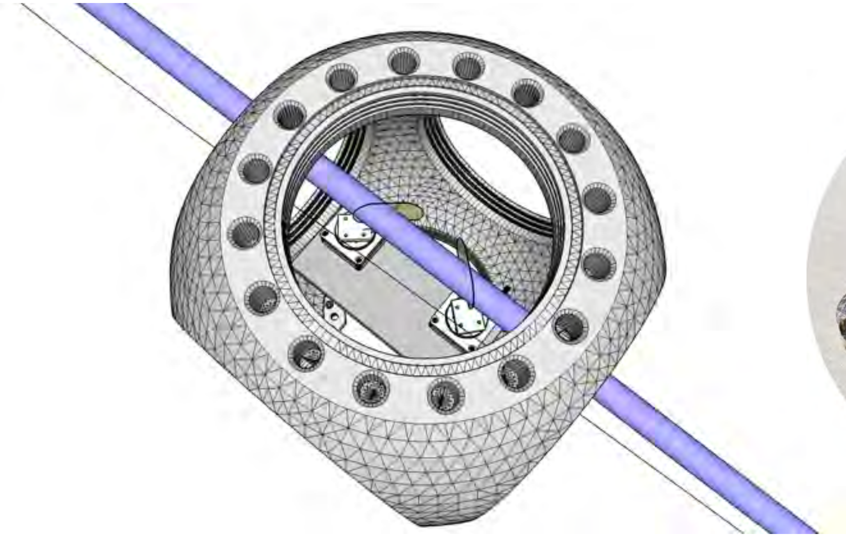


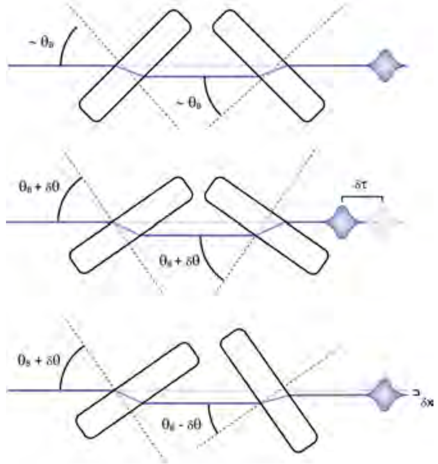


Fine tune alignment and delay with a single stage:

- Precision slabs centered near the Brewster angle; >95% transmission over +/- 20°
- Coordinated adjustment lets us independently select longitudinal delay and horizontal shift
- Delay resolution ~λ_r/250
- Invert cooling zones (0.5 μm) in ~8 ms
- Precision mapping of thickness profile indicates acceptable flatness

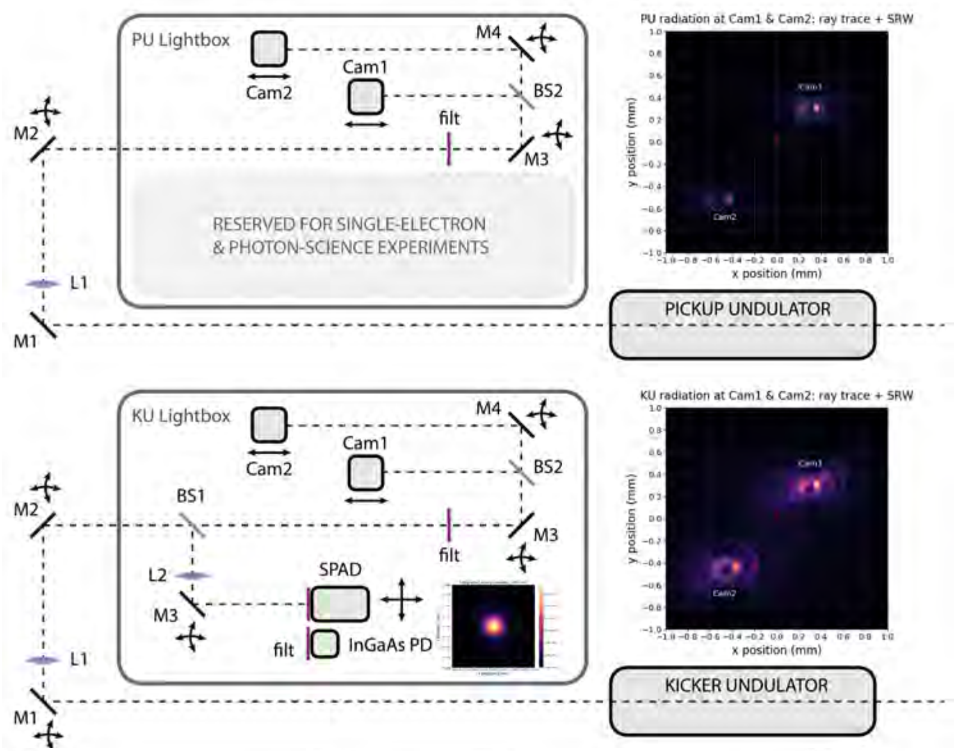


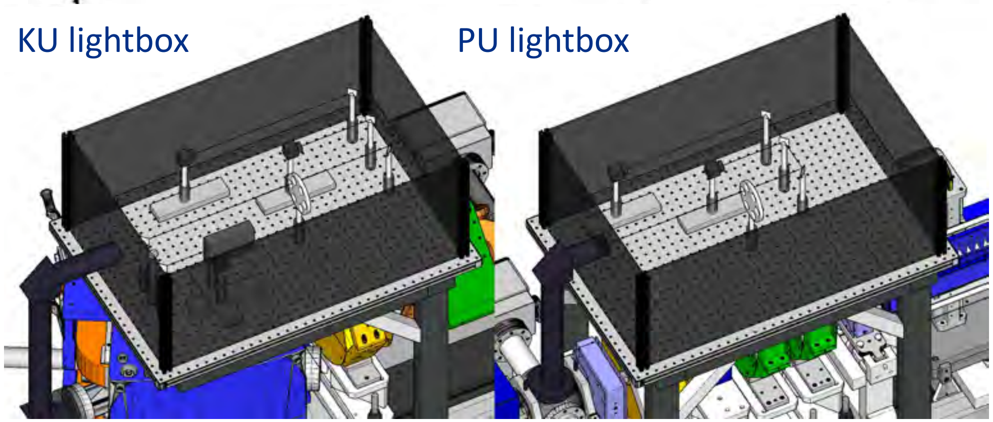




Flexible lightboxes/diagnostics for Both PU and KU

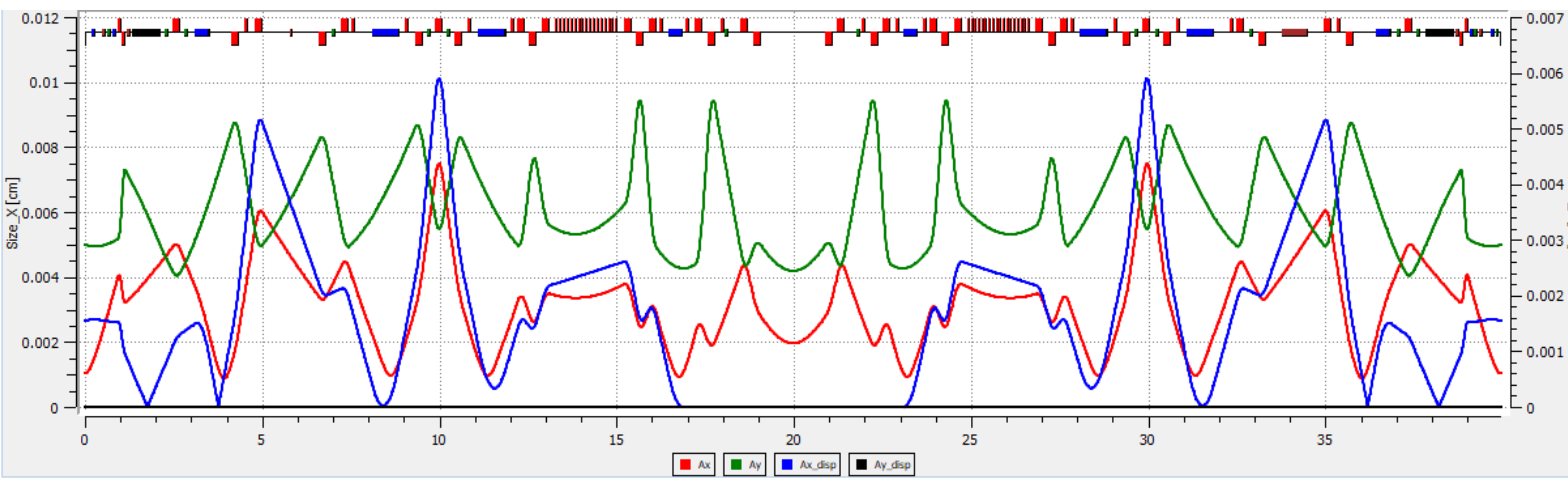
- UR BPMs, PIN PD, SPADs, single-electron diagnostics
- Want spatial alignment of **<100 μm**, and angular alignment of **<100 μrad**
- HeNe through surveyed pinholes defines nominal optical axis, ~+/- 50 μm
- Image the UR from two locations (upstream & downstream); variable positioning allows arbitrary 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





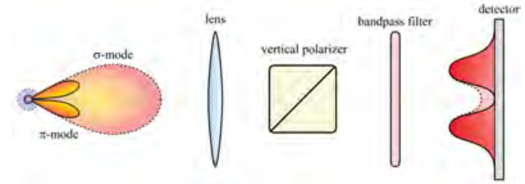
Small beam sizes present measurement challenges

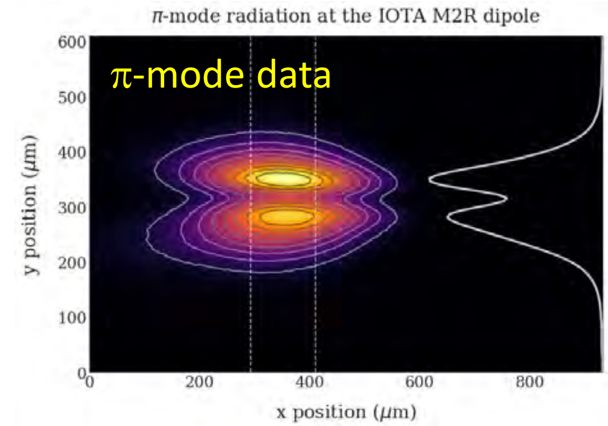
- A small equilibrium emittance increases the cooling range for OSC, which is otherwise fixed by wavelength and bypass delay
- Necessarily means small lattice functions in main dipoles where we can most easily monitor the beam size via SR
- Interested in equilibrium sizes as well as dynamics

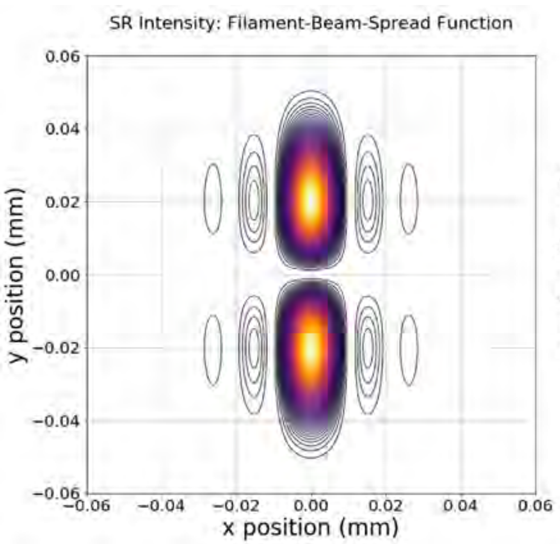


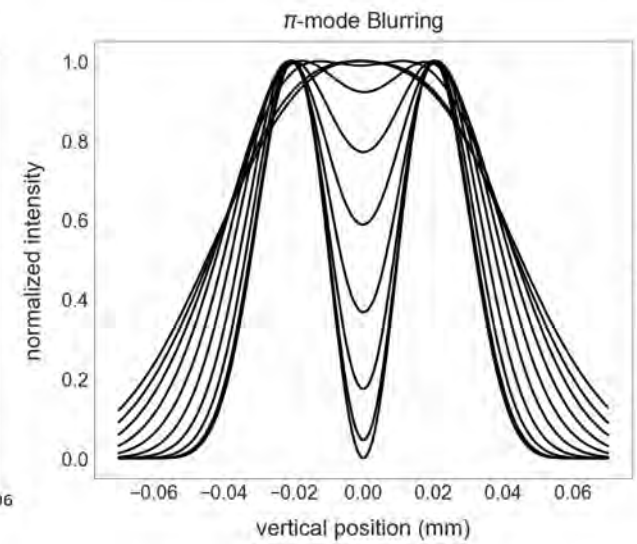
Expanding IOTA's diagnostics for OSC

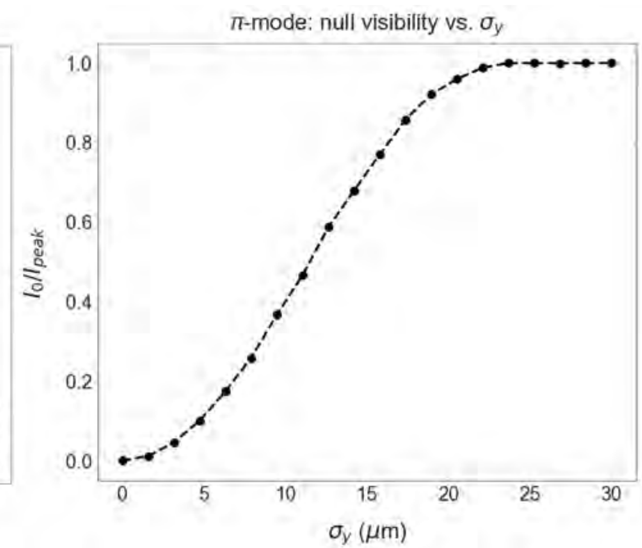
- Want several ways to measure small beam sizes (~10 μm) /emittances (~0.5 nm)
  - Direct imaging >20 μm)
  - π-mode imaging (~5-μm to ~50 μm)
  - sync-rad. interferometry (~10-100's μm)
- Tested a π-mode prototype in IOTA run #1
- Installing a streak camera in IOTA for precision bunch-length measurements







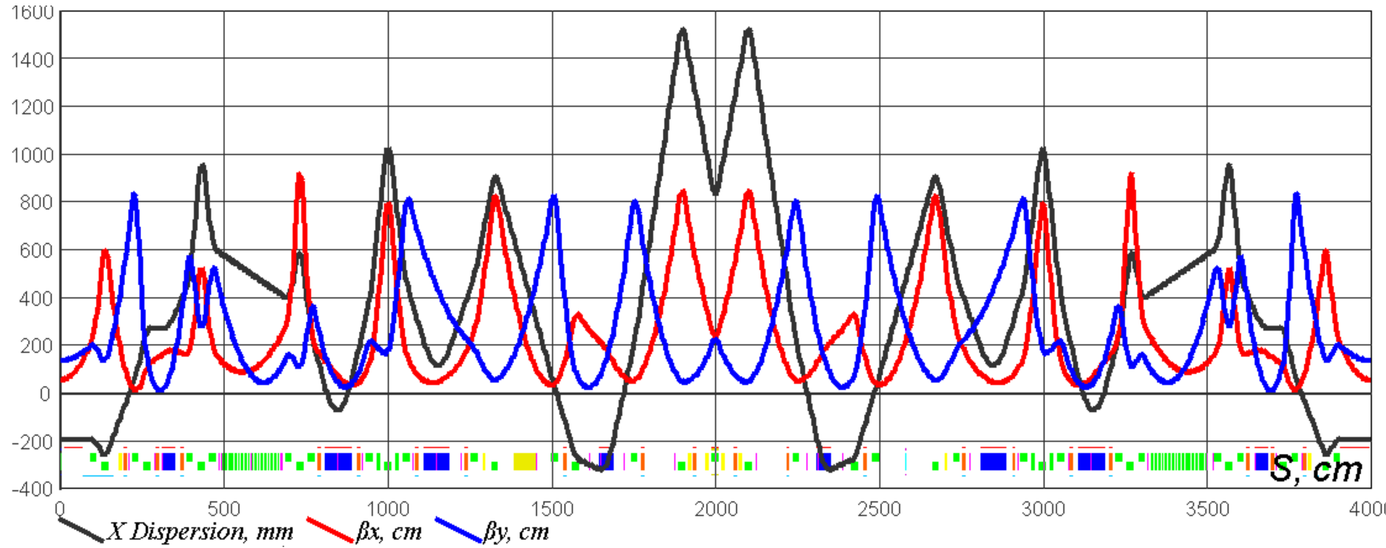




Designed a low-emittance lattice similar to OSC

1. Demonstrate and characterize a LE lattice in IOTA (~1 nm)
2. Develop and exercise diagnostics for measurement of small beam size (~10 μm)
3. **Gain relevant, high-fidelity operations experience**

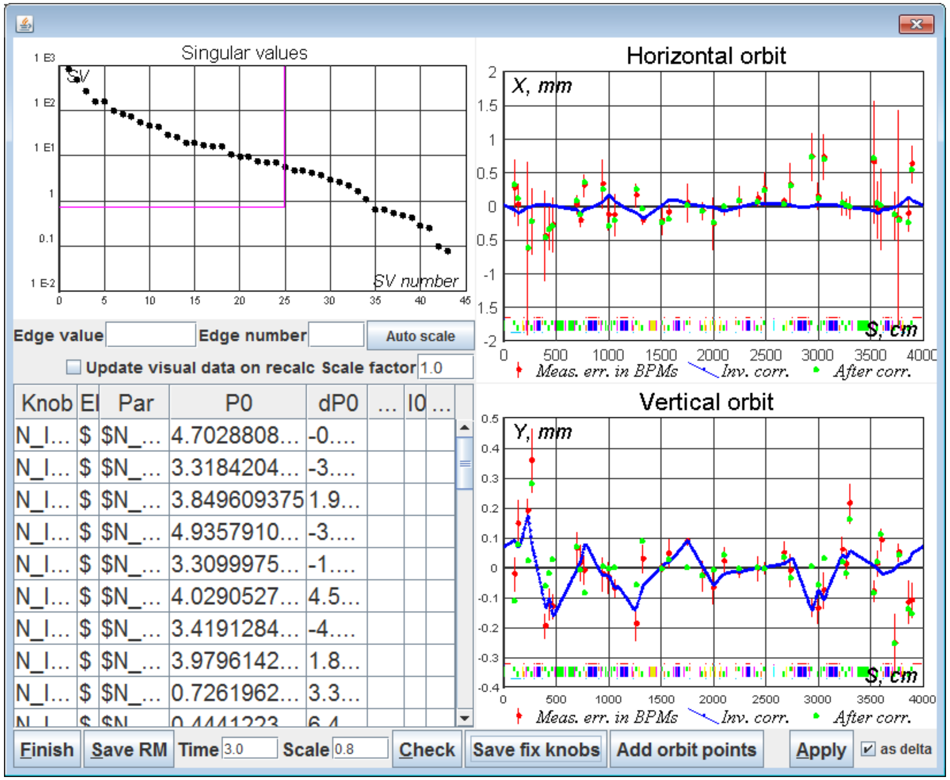
- Emulates many properties of OSC lattice (avg. lattice functions, beam sizes, emittance, on x-y coupling resonance, momentum spread, IBS regimes, lifetime, etc…)



LE lattice successfully implemented during IOTA Run #1

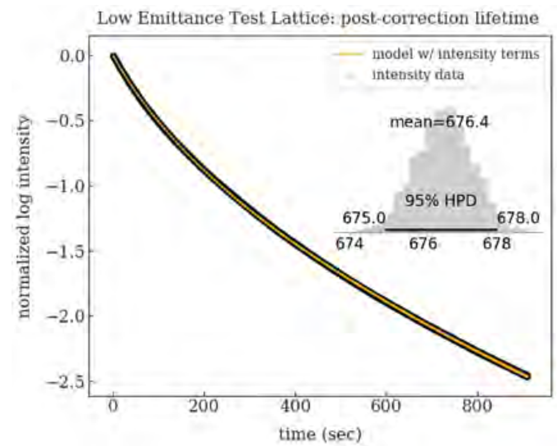
- Optimized injection energy and steering to get detectable signal on BPMs and SL cameras
- Used manual bumps and random tuning to establish betatron capture
- Had to tune RF-frequency by ~1 kHz to achieve synchrotron capture
- Used LOCO to build:

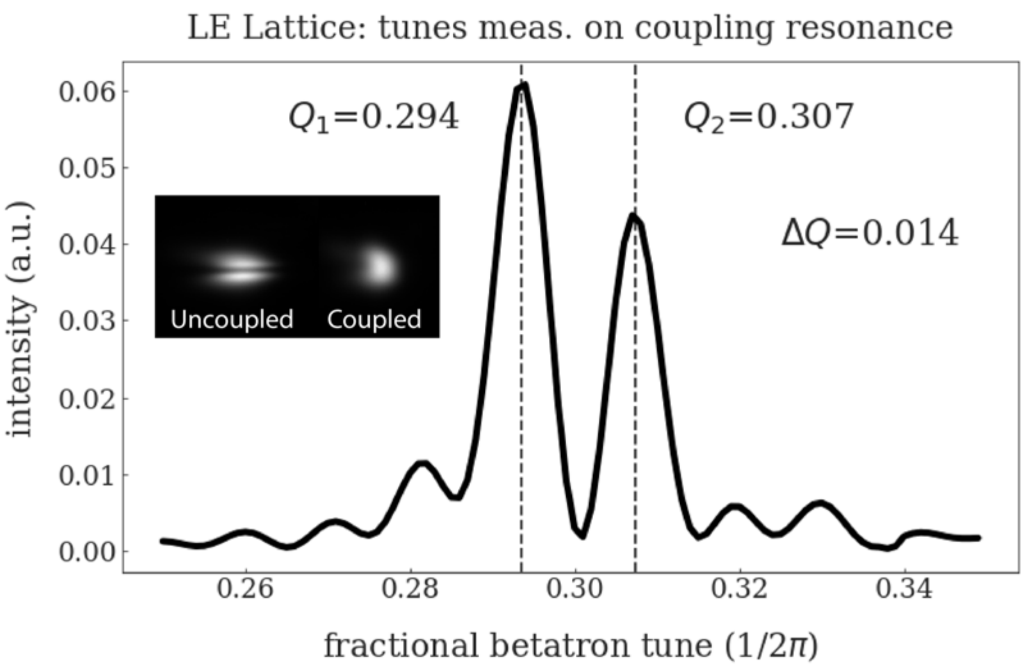
1. Optimized injection config.
2. Flat-orbit config.
3. Coupling corr. & tune knobs

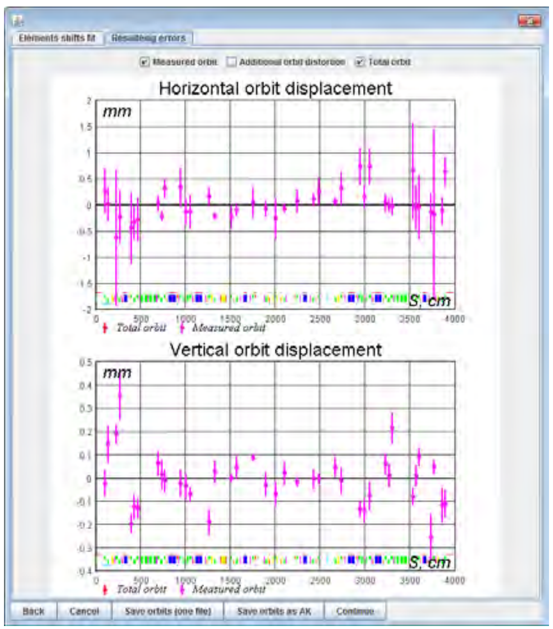


Corrected orbit & lattice to extent allowed by # of BPMs

- In Run #1, IOTA BPMs had insufficient sensitivity for OSC particle #s; $<10^7$
- Restricted to 7 sync.-light BPMs for orbit/lattice correction
- LOCO correction of orbit to few-hundred microns
- PS limitations on skew quads/correctors were an issue

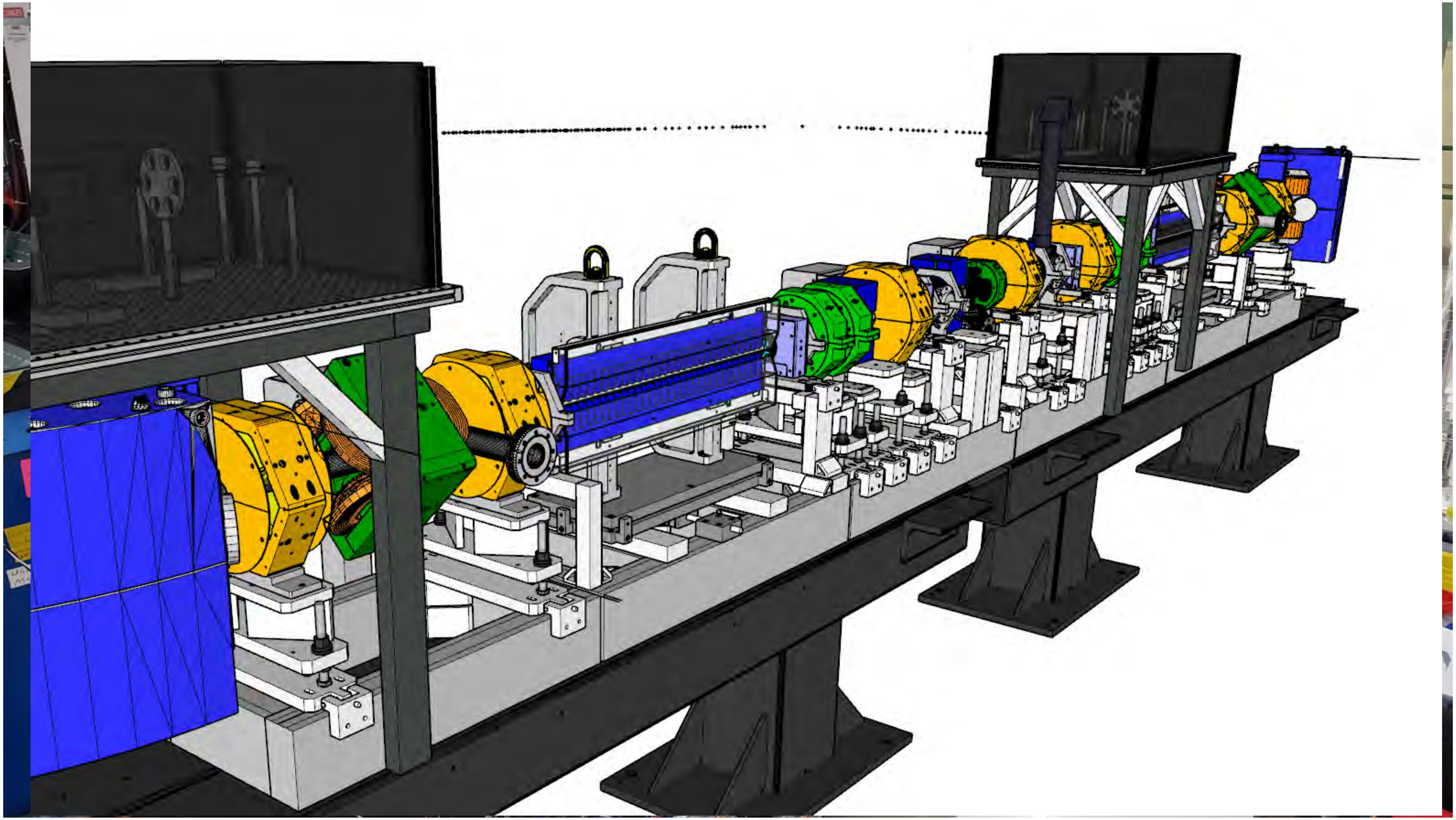




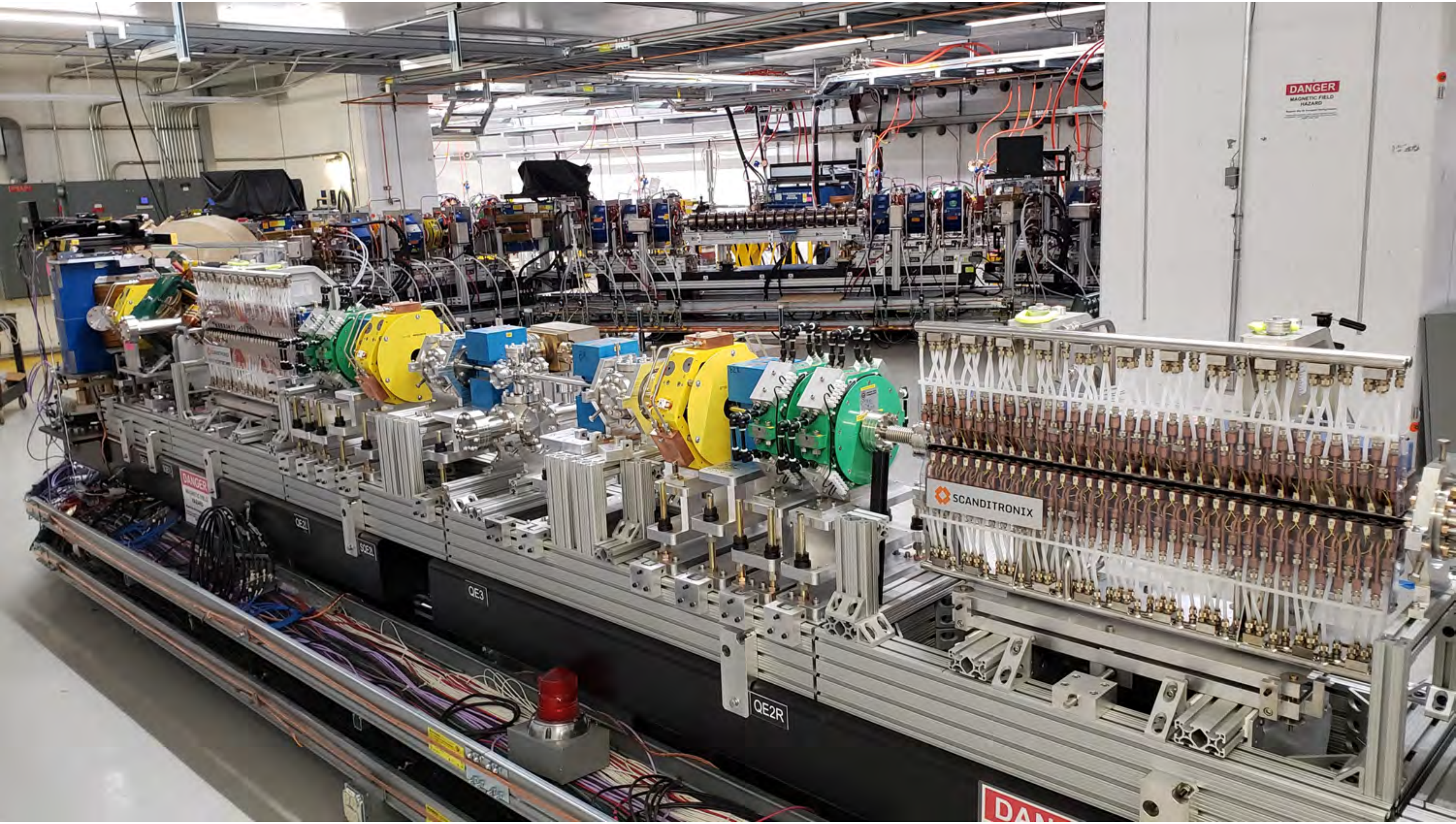


Fermilab

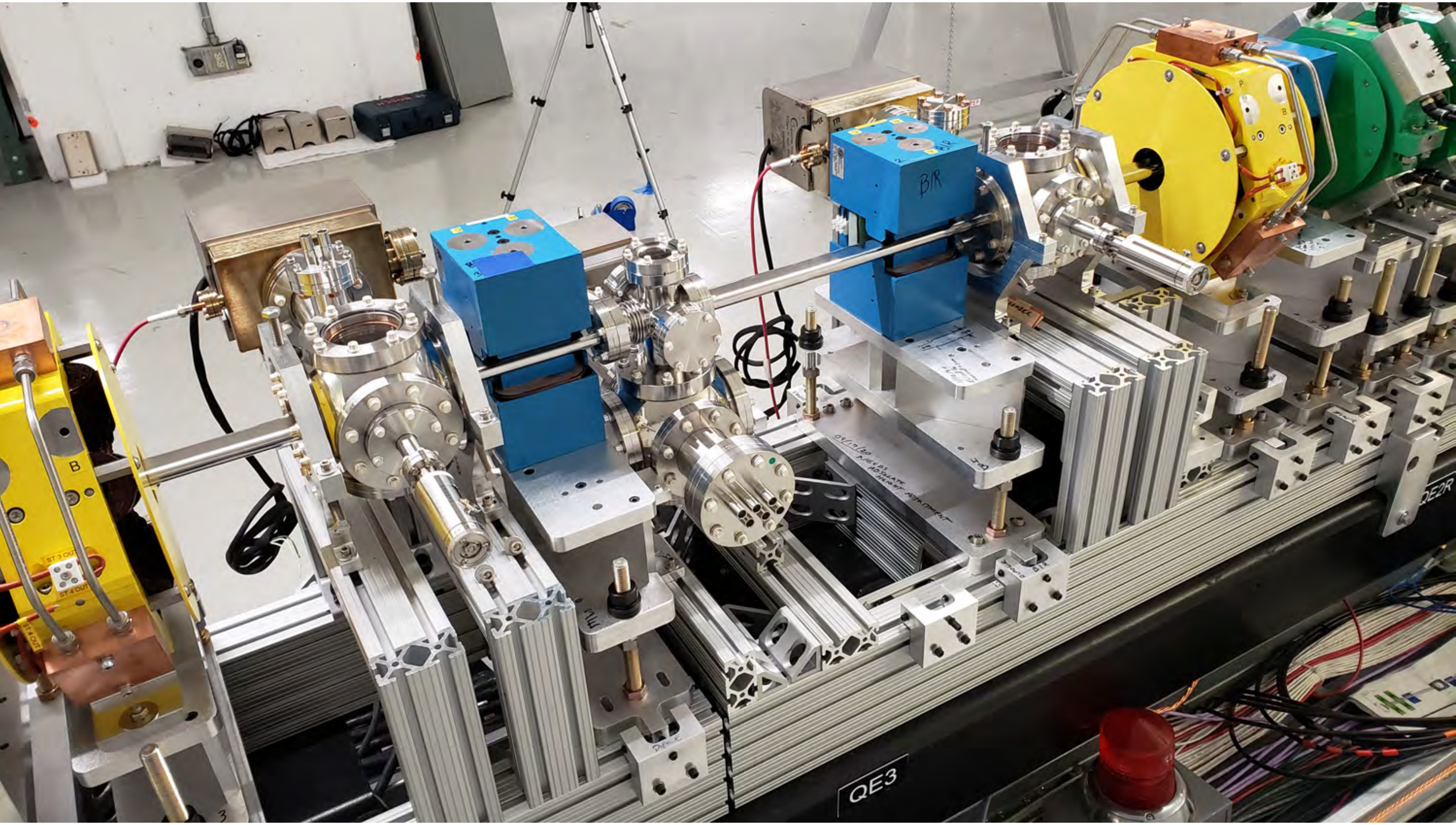
OSC installation in IOTA is nearly completed



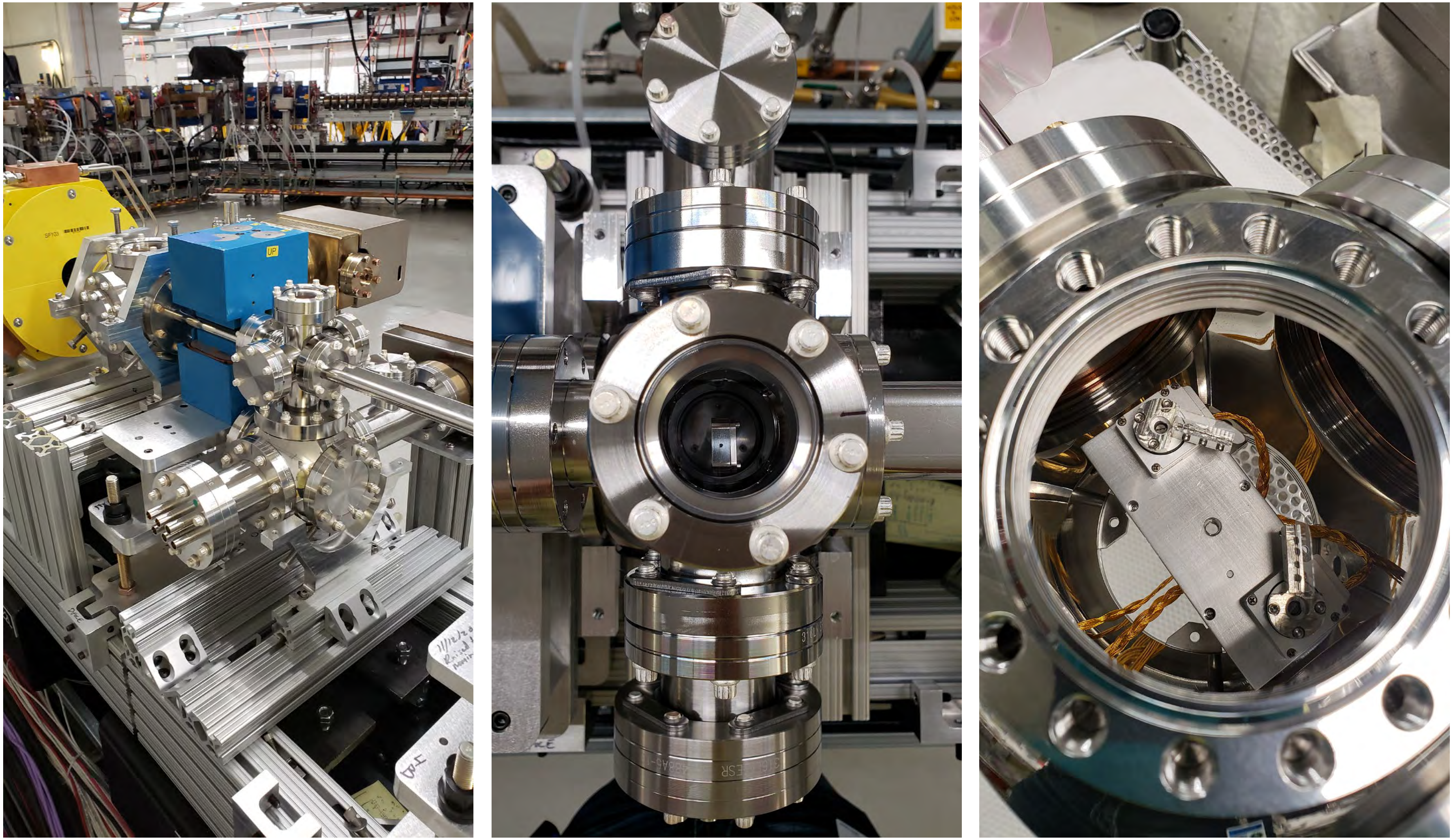
OSC apparatus in IOTA (~90% complete):



OSC diagnostics and optics chambers

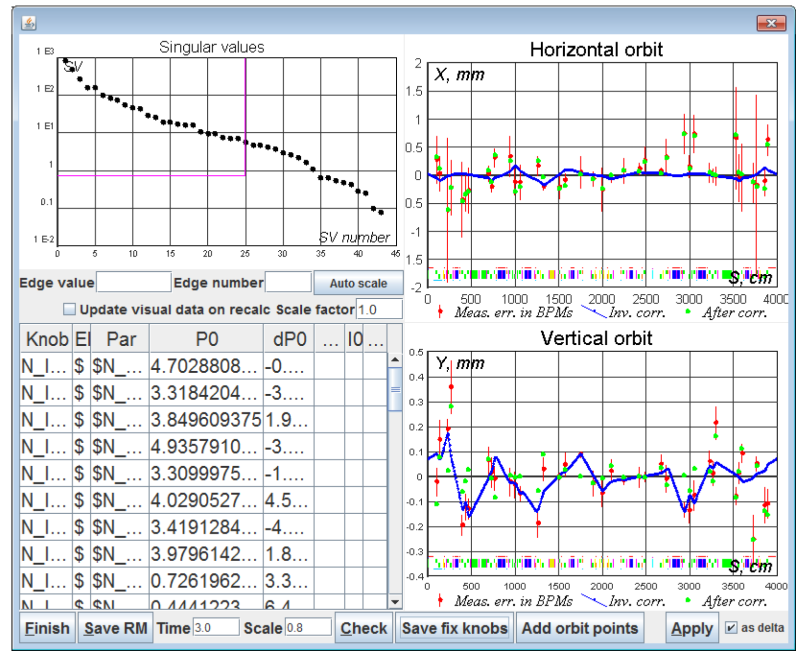


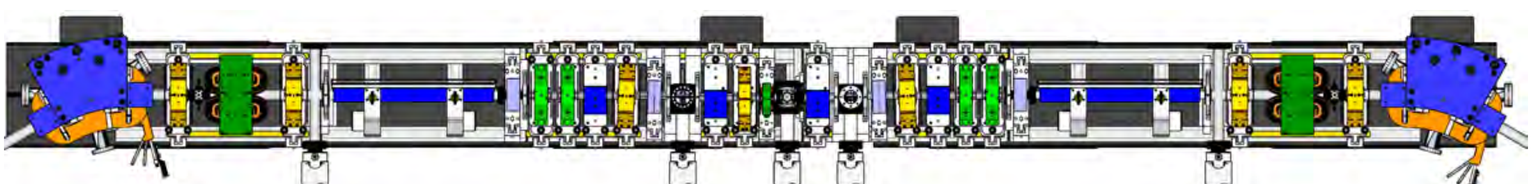
OSC lens and delay stage with in-vac motion:



Commission OSC lattice and systems beginning ~DEC. ’20

- Anticipate ~1 month of commissioning activities
- Injection, tuning, capture, LOCO + manual adjustments until good agreement with model
- Exercise all diagnostics and control systems w/o OSC
- Characterize non-OSC beam dynamics w/ OSC lattice across all regimes

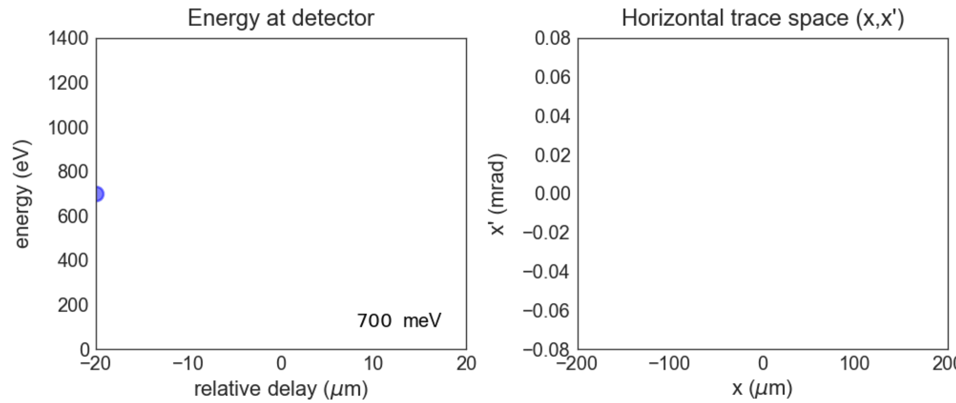




Experimental program executed in several phases

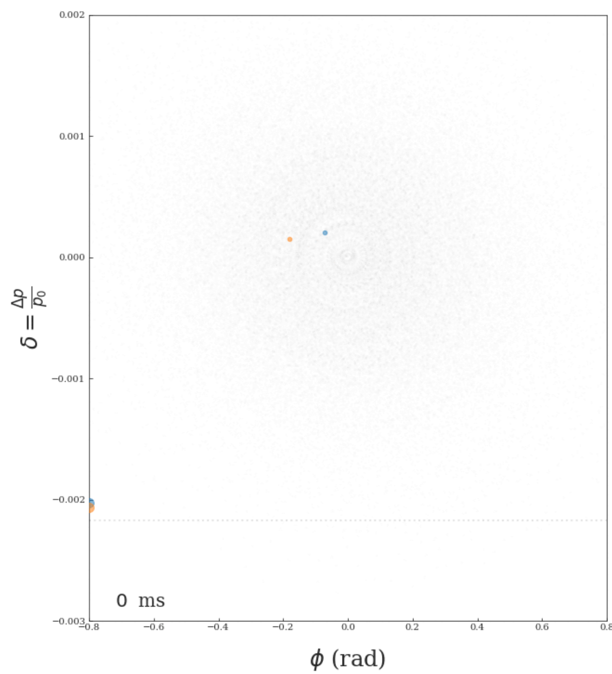
Ph1: Demonstration Experiment

- ~1e3 to ~1e5 particles
- fine alignment of PU/KU radiation
- delay scan + UR interference on diode detector
- beam image in SR diagnostics



Ph2: Systematic Studies

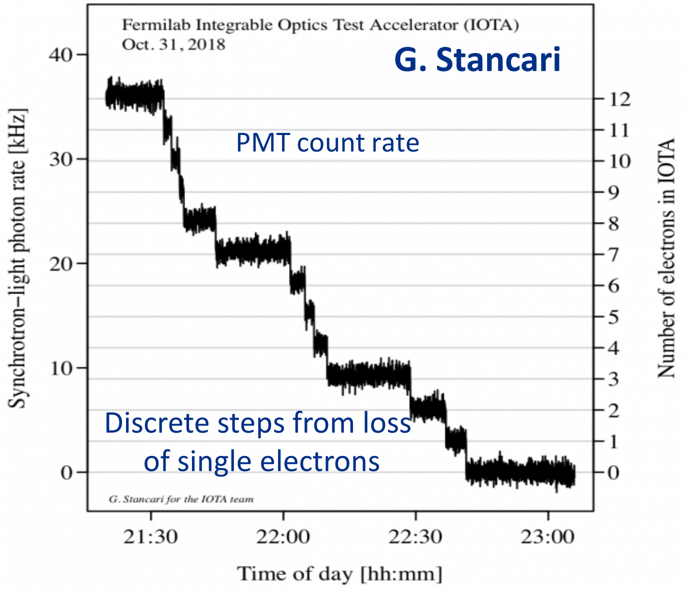
- Systematic examination of rates, ranges, coupling, nonlinearities, etc…
- All regimes: $N_e = [1,\sim 10^6]$
- Basic "phase-space control"

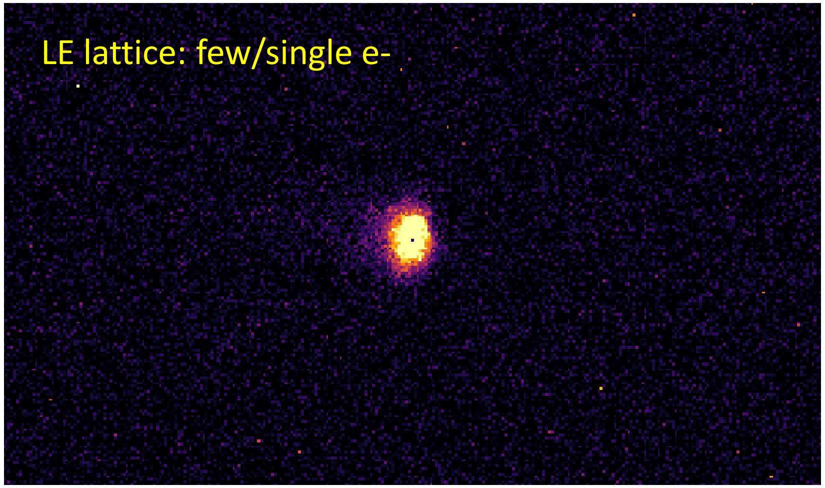


Experimental program executed in several phases

Ph3: Single/few Electron OSC and Advanced Concepts

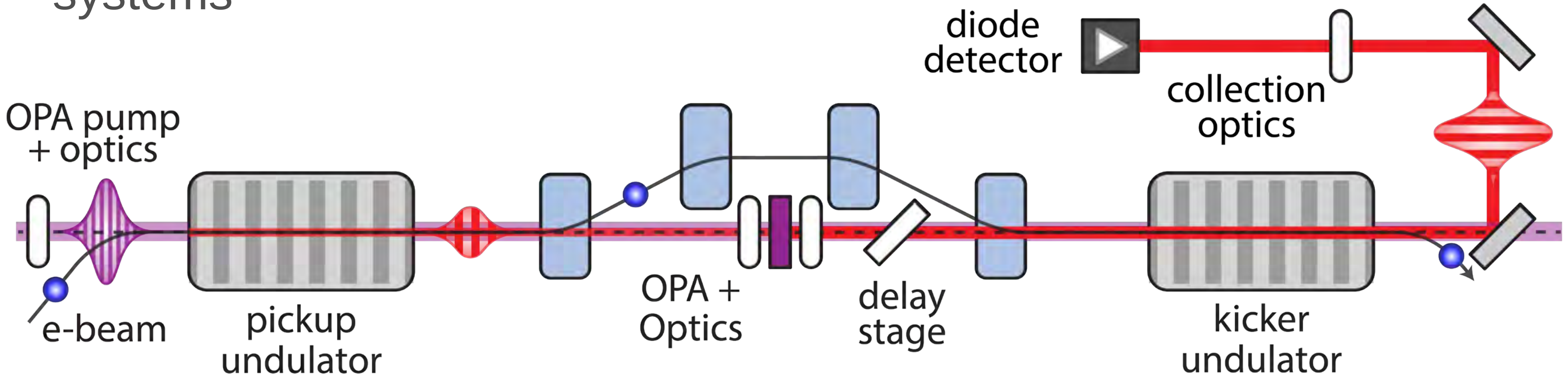
- Installation of improved imaging diagnostics
- Controlled modulation of emission probability due to UR interference
- Manipulation of single electron; transfer between different OSC cooling zones
- Active modulation of optical, RF, magnetic systems to manipulate beam structure using OSC





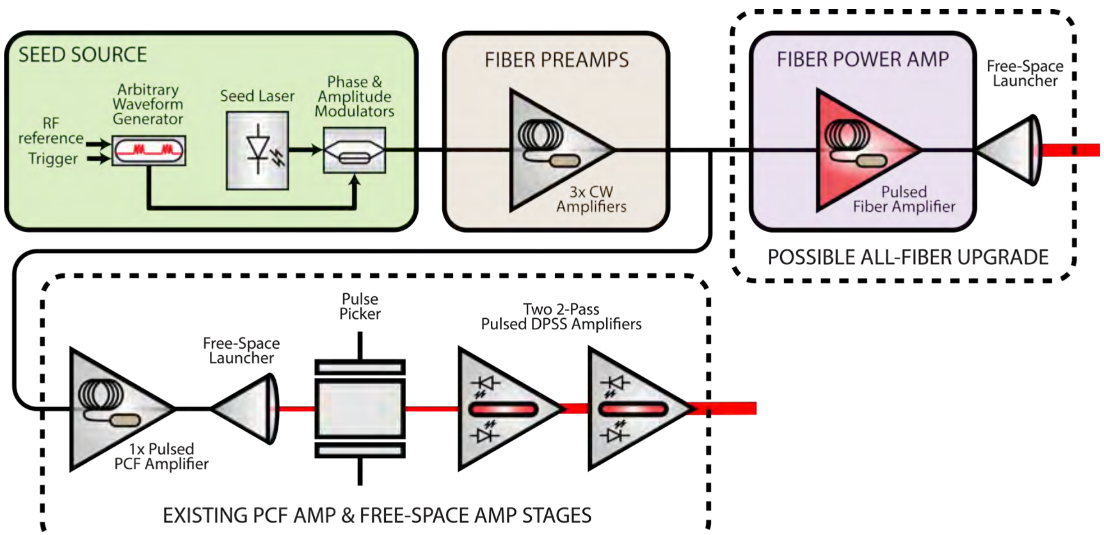
New program in amplified OSC at IOTA in underway

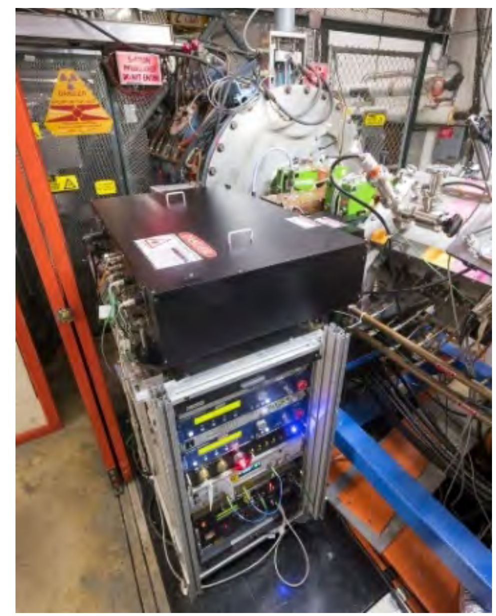
- 5-year DOE/HEP ECA program to develop OSC concepts and technology for applications in beam cooling, control and sensing
- Includes a complete high-gain OSC experiment at IOTA (30-dB power gain)
- Reinforcement learning + turn-by-turn OSC modulation for advanced beam control
- Development of specialized diffractive optics for OSC applications
- Emphasize conceptual and technological paths towards operational systems



Specialized drive laser for amplified-OSC program

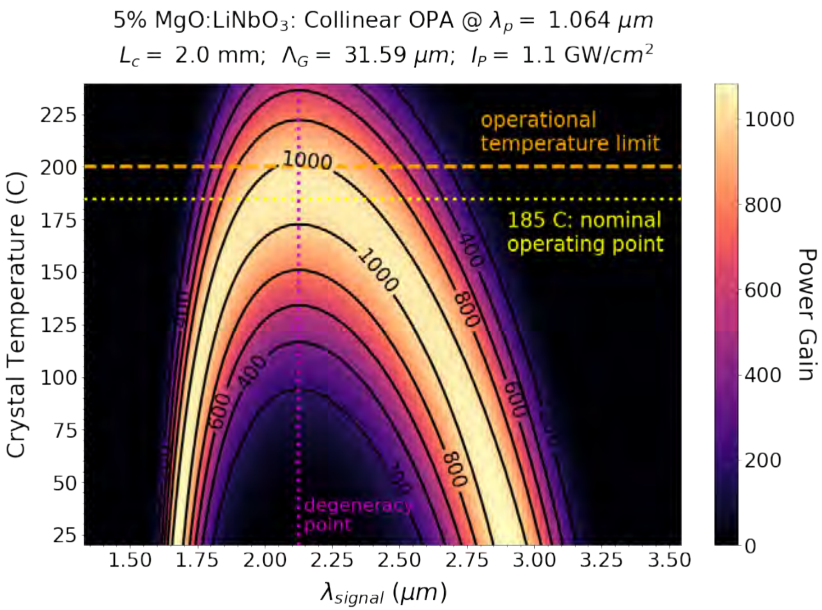
- Linac-Laser Notcher (LLN); an operational component of the FNAL acc. complex with years of drive-laser R&D
- LLN laser matches the needs of a high-gain OPA for OSC in IOTA at 2128 nm; plan to replicate system with mods for OSC
- Seed source includes arbitrary pulse-by-pulse programmability; excellent platform for RL-based control with OSC

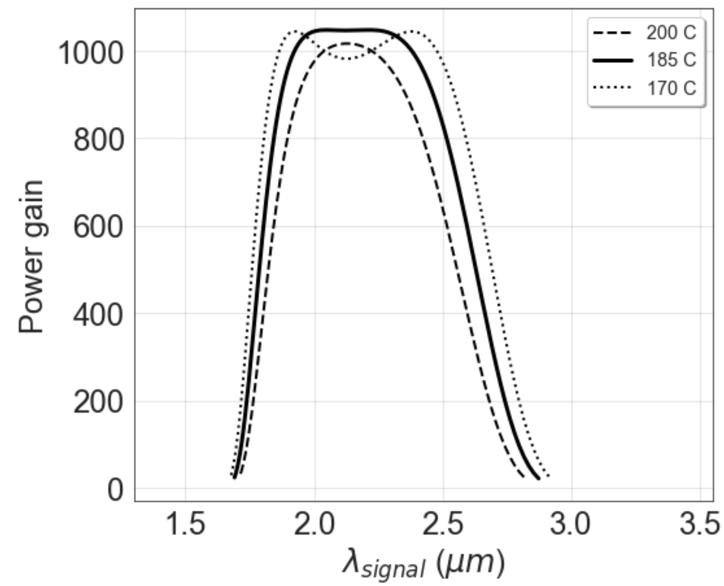




Estimated power gain and BW for planned OPA

- Amplified-OSC design will target ~4 mm of optical delay with 2.5 mm of delay budgeted for a 2-mm-thick periodically poled MgO:LiNbO3 (PPLN) crystal; BaF_2 optics elsewhere (~3.3-mm total thickness)
- Pumped at 1064 nm with intensities of ~1 GW/cm2 and operated at the degeneracy point (2128nm)
- Operate near temperature limit to suppress photorefractive effect
- May require filtering of und-rad harmonics to prevent BLIIRA and GLIIRA





Conclusions:

- OSC is at an intersection of fundamental beam-physics studies and pathfinding for operational cooling systems; IOTA is an excellent platform for a broad research program in this area
- Installation of the non-amplified OSC apparatus in IOTA is nearly complete
- **Commissioning and non-amplified OSC experiments will begin in DEC ’20**
- **Amplified OSC experiments beginning in ~FY’22/23**; staged program with the FAST linac and IOTA ring; amplifier development and testing at FAST, then amplified-OSC demonstration and experiments in IOTA; broader program including advanced beam control and sensing
- **Interested in collaborations on advanced topics using OSC physics and hardware; this is an excellent time to get involved as we begin the amplified-OSC program; Posting for a postdoc expected soon**

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EXTRAS

Scattering dynamics in the OSC lattice

(V. Lebedev)

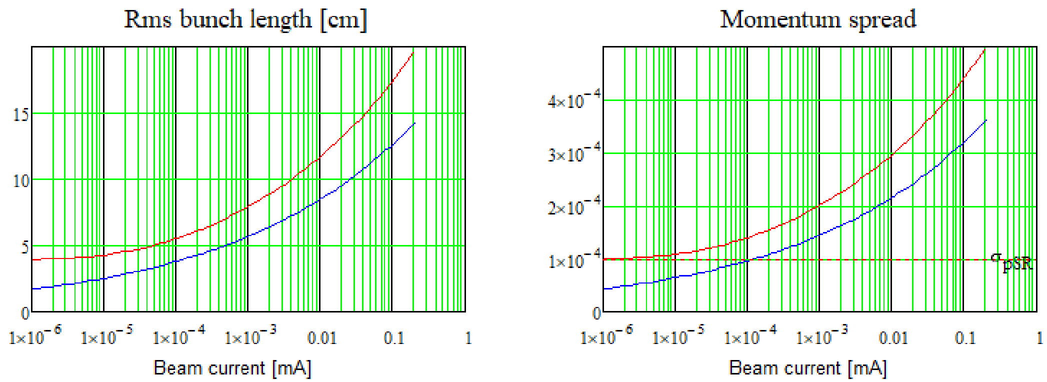


Figure 50: Dependences of rms bunch length (left) and rms momentum spread (right) on the beam current with (blue) and without (red) OSC. The horizontal dashed line shows momentum spread set by SR cooling in the absence of OSC.

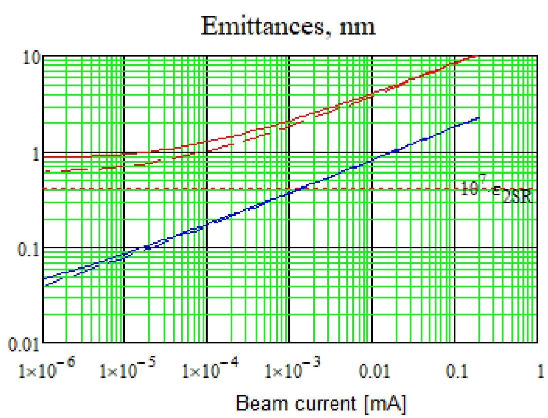


Figure 51: Dependences of the mode emittances on the beam current with (blue) and without (red) OSC. Horizontal dashed line shows equilibrium emittance set by SR in the absence of IBS, gas scattering and OSC. Dashed lines show the emittances of the second mode.

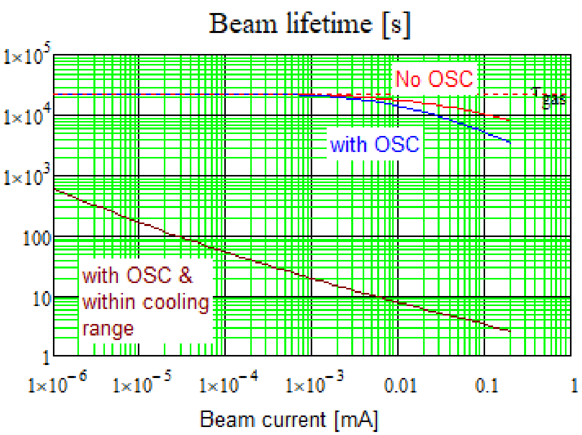
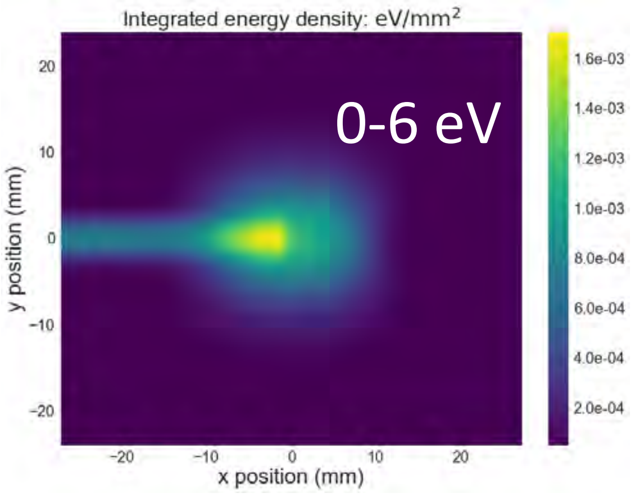
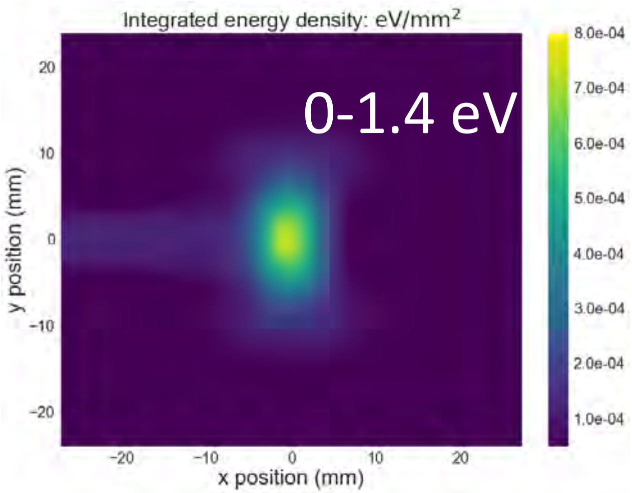
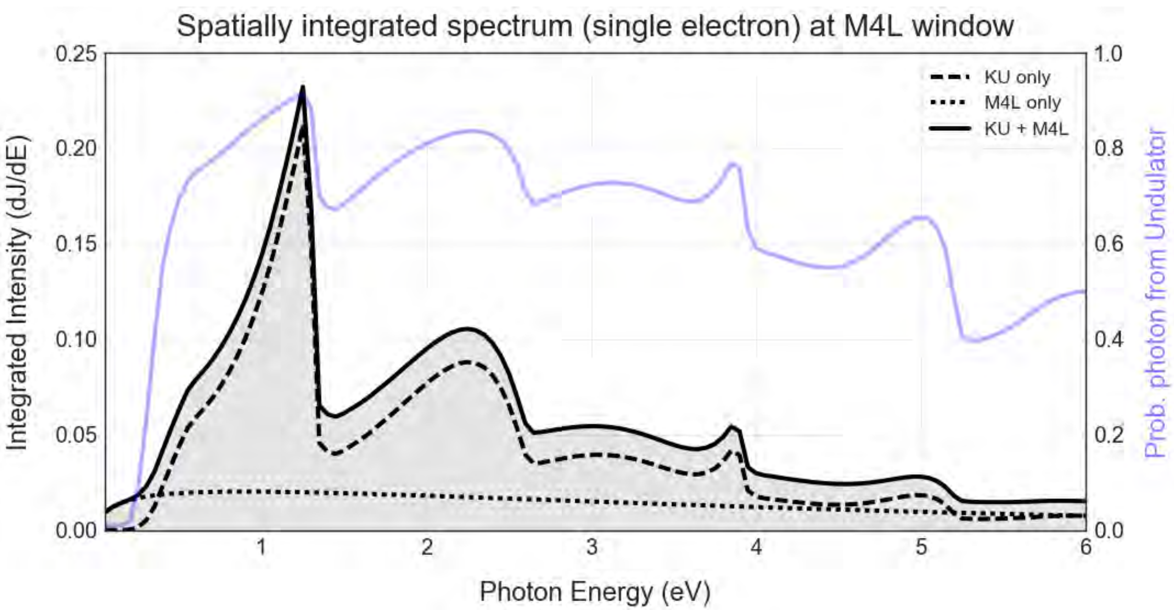


Figure 52: Dependences of beam lifetime on the beam current with (blue and brown) and without (red) OSC. The brown (bottom) curve shows the beam lifetime inside the cooling acceptance ($\Delta p/p=5.7\cdot10^{-4}$), while red and blue curves show the total beam lifetime in the ring determined by the RF bucket height ($\Delta p/p=6.9\cdot10^{-3}$)

Contamination from IOTA dipole is low

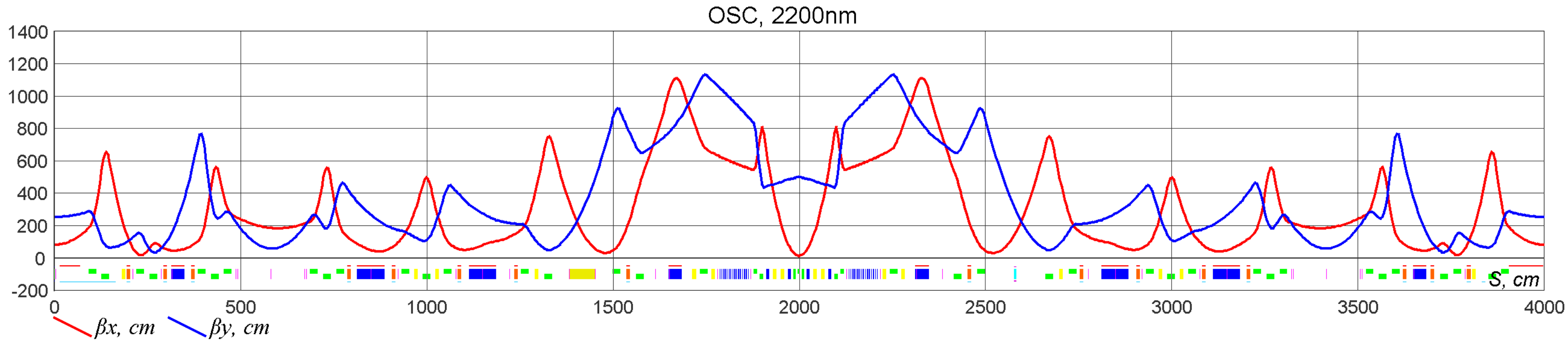


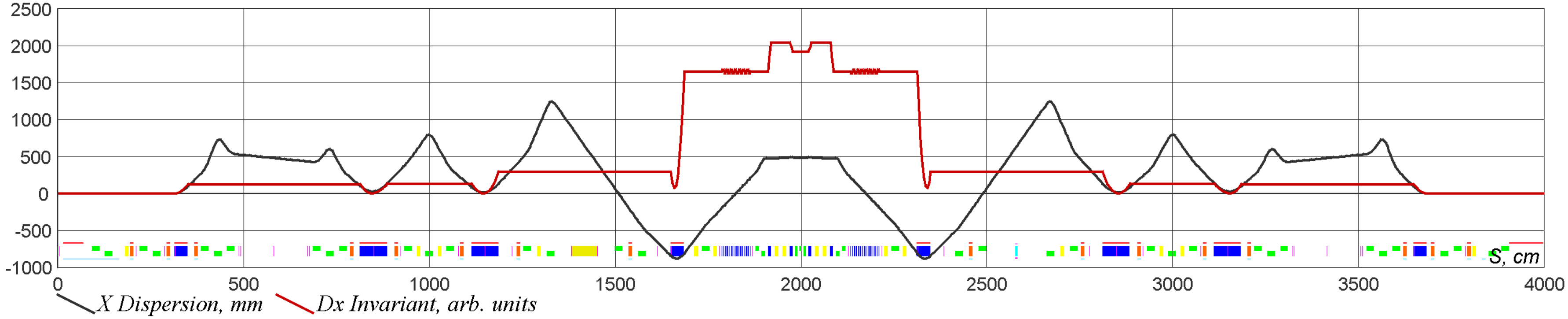




- Radiation from Und. and Dipole not well separated in time (~100 fs)
- ~85% of photons in the fundamental band will be from the undulator
- With aperture on output window: >90%

Linear lattice design for 2200 nm (low-gain version)





Betas start, x, y	12, 500 cm
D_x start	48 cm
Tunes, x, y	5.42, 3.42
Mom. comp.	-0.0165
Emittances, x, y	1.44 E-7 cm

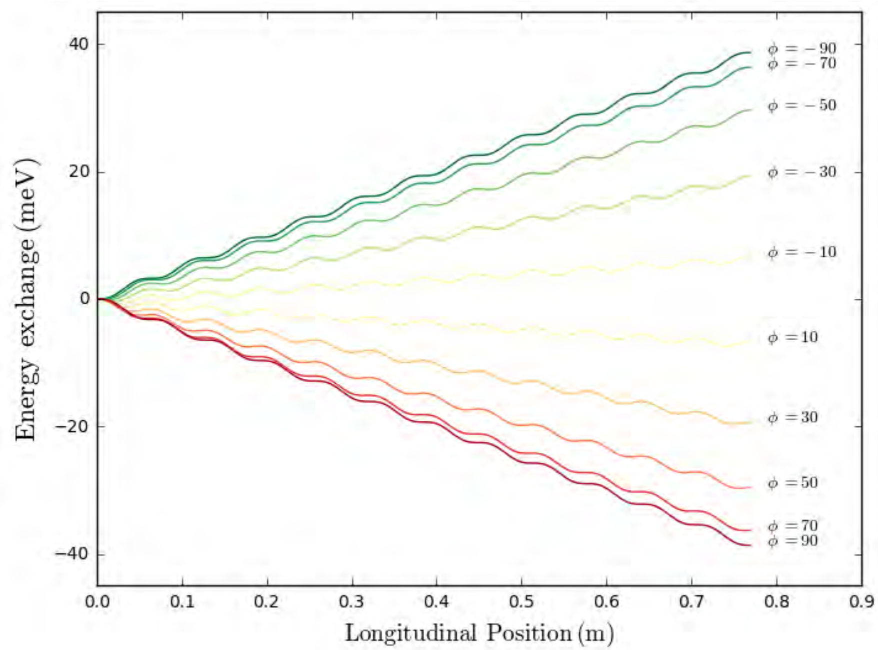
Energy drop	13.25 eV
Bunch length @30V	19.9 cm
Energy spread	1.06 E-4
Sync. Tune @30V	5.6 E-5
Damp. times (x, y, s)	(1.9, 1.9, 1.1) s

Cooling force determined by mapping between undulators

- Reference particle experiences zero net energy change
- Interestingly, max possible kick is twice the energy lost from emission in a single undulator
- For small deviations, cooling force is linear; nonlinear for large deviations
- Cooling force can reverse sign and cause heating/antidamping

$$\frac{\delta p}{p} = -\kappa \sin(k_0 s) = -\frac{\sqrt{G}\,\Delta E}{cp}\sin(k_0 s)$$

$$\lambda_r = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \qquad K = \frac{q_e B \lambda_u}{2\pi m_e c}$$



$$\Delta E \approx \frac{\pi {q_e}^2 N_u}{3\epsilon_0 \lambda_r} K^2 \left(1 + \frac{K^2}{2}\right) f_T(K, \gamma\theta_m)$$

Most critical OSC parameters: cooling rates and ranges

- In the linear approximation, path lengthening is:

$$s = M_{51}x + M_{52}x' + \left(M_{56} - \frac{L_{pk}}{\gamma^2}\right)\frac{\Delta p}{p}$$

$$x = x_\beta + D\frac{\Delta p}{p},$$

$$x' = x'_\beta + D'\frac{\Delta p}{p}$$

- In absence of betatron oscillations:

$$s = \left(M_{51}D + M_{52}D' + M_{56} - \frac{L_{pk}}{\gamma^2}\right)\frac{\Delta p}{p} = S_{pk}\frac{\Delta p}{p}$$

- Can estimate cooling rate (1/s) for longitudinal emittance as:

$$\lambda_s = f_0 \kappa k_0 S_{pk}$$

$$\frac{\delta p}{p} = -\kappa \sin(k_0 s) = -\frac{\sqrt{G}\,\Delta E}{cp}\sin(k_0 s)$$

M_{56} and S_{pk} must be different to have horizontal cooling

- Sum of friction decrements then sets value of horizontal cooling

$$\lambda_x = f_0 \kappa k_0 \left(M_{56} - S_{pk} - \frac{L_{pk}}{\gamma^2} \right)$$

- So for a given setting of the chicane (M_{56}) the cooling ratio is determined by the dispersion and its derivative at the exit of the pickup.

$$s = \left(M_{51} D + M_{52} D' + M_{56} - \frac{L_{pk}}{\gamma^2} \right) \frac{\Delta p}{p} = S_{pk} \frac{\Delta p}{p}$$

- We can then couple the horizontal and vertical DOF elsewhere in the ring to achieve full 6D cooling.

$$\frac{\lambda_x}{\lambda_s} = \frac{M_{56}}{S_{pk}} - 1$$

OSC creates a cooling/heating surface in phase space

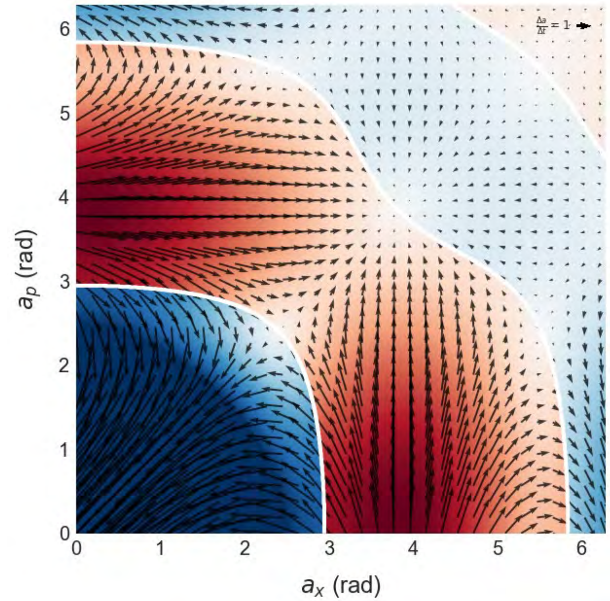
- On successive passes through the cooling insertion, particles will have different betatron and synchrotron coordinates
- Path lengthening depends on these coordinates, and the cooling force on a given pass increases or decreases
- This creates a cooling/heating surface that particles will move along
- Integrating over betatron and synchrotron periods reveals the cooling range for OSC:

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

$$a_p = -k_0(M_{51}D + M_{52}D' + M_{56})\left(\frac{\Delta p}{p}\right)_m$$

$$a_x = -k_0\sqrt{\tilde{\varepsilon}\left(\beta {M_{51}}^2 - 2\alpha M_{51}M_{52} + (1+\alpha^2){M_{52}}^2/\beta\right)}$$

$$\begin{bmatrix} F_x \\ F_s \end{bmatrix} = \begin{bmatrix} \lambda_x(a_x, a_p)/\lambda_x \\ \lambda_s(a_x, a_p)/\lambda_s \end{bmatrix} = 2\cos(k_0 s_0)\begin{bmatrix} J_0(a_p)J_1(a_x)/a_x \\ J_0(a_x)J_1(a_p)/a_p \end{bmatrix}$$



$$\mu_{01} = 2.405$$

Cooling ranges depend on delay and wavelength

$$\varepsilon_{max} = \frac{{\mu_{01}}^2}{{k_0}^2\left(\beta {M_{51}}^2 - 2\alpha M_{51}M_{52} + (1+\alpha^2){M_{52}}^2/\beta\right)}$$

$$n_{\sigma x} = \sqrt{\frac{\varepsilon_{max}}{\varepsilon}}$$

$$\left(\frac{\Delta p}{p}\right)_{max} = \frac{\mu_{01}}{k_0 S_{pk}}$$

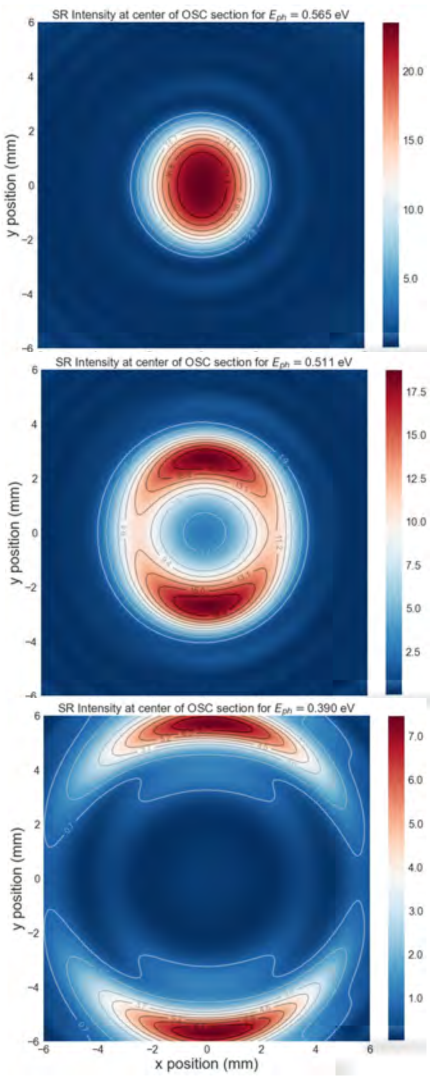
$$n_{\sigma p} = \frac{\left(\frac{\Delta p}{p}\right)_{max}}{\sigma_p}$$

- Designing an effective OSC system means setting a balance between cooling ranges and rates

Simulations performed with Sync. Rad. Workshop

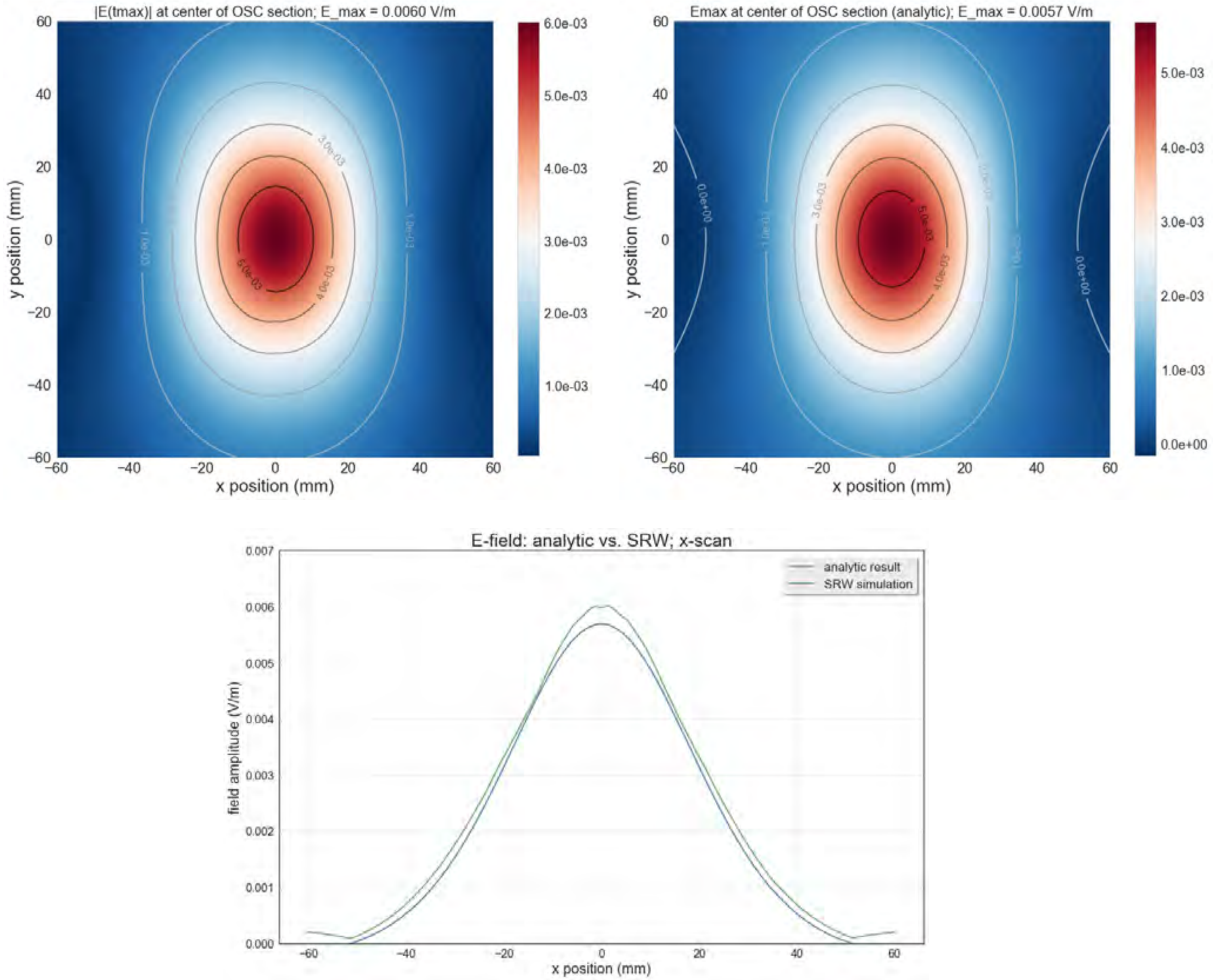
Wave-optics simulation code. Developed in 1990's, primarily for the simulation of beamlines at light sources.

1) Radiation wavefront is generated by particle traversing specified mag. Field
2) Wavefront is propagated through optical system in the spectral domain.
3) Fields are converted into time domain.
4) Compute slippage and determine field experienced by the co-propagating particle (particle does not modify wavefront in KU)



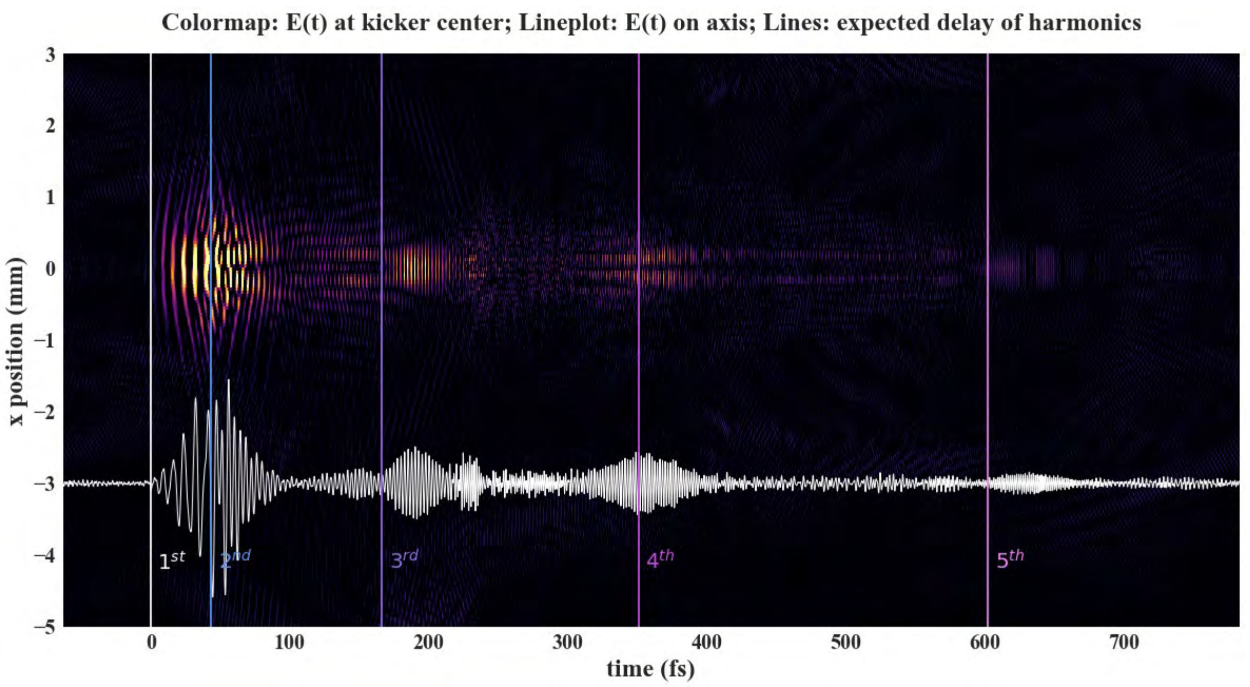
O. Chubar, P. Elleaume, Proc. EPAC98, Stockholm Sweden, p.1177 (1998).

Good agreement with analytic approximations in the appropriate regime (K<<1, R>>L_{und})

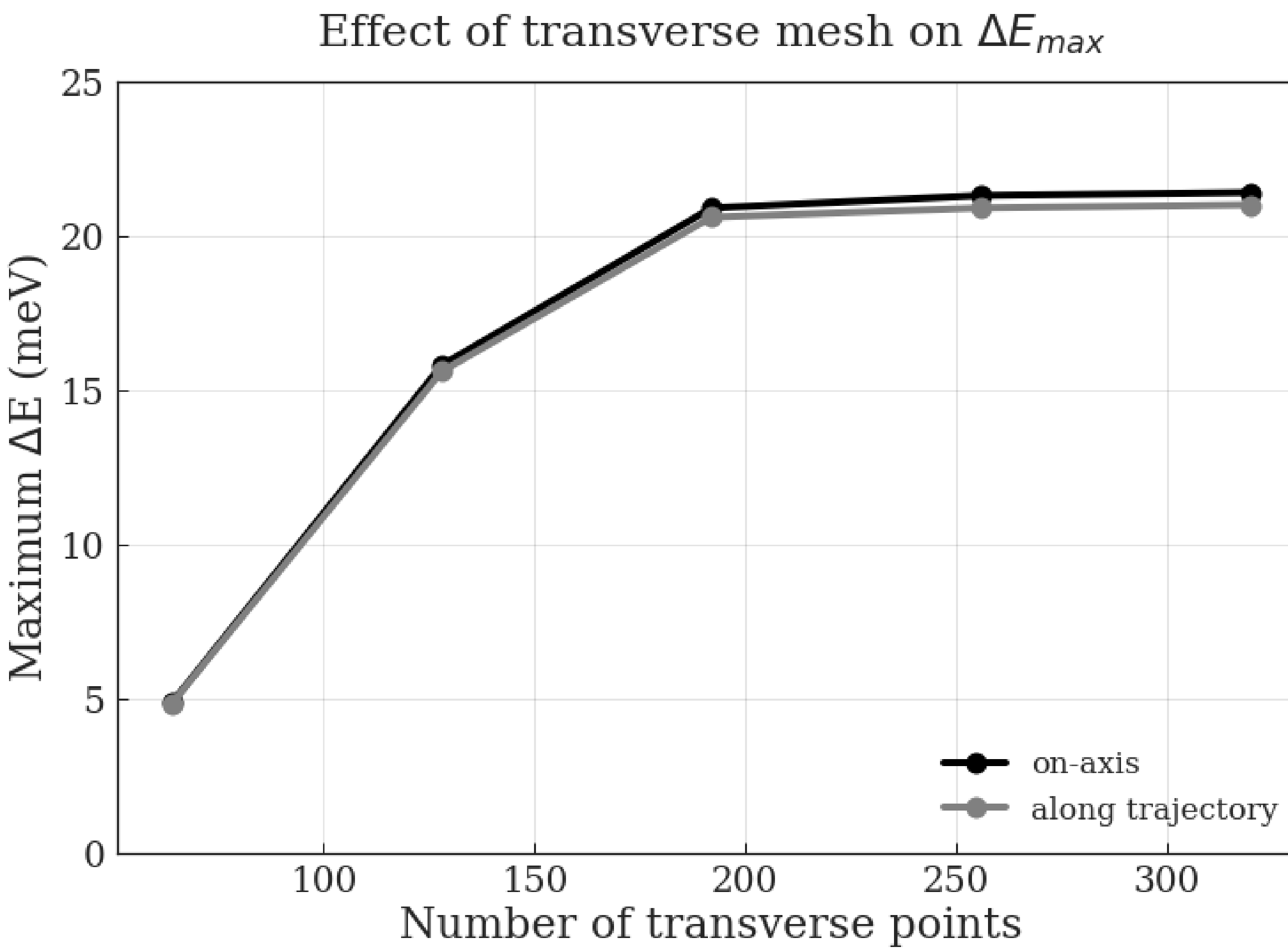


Custom routines for dispersive optics

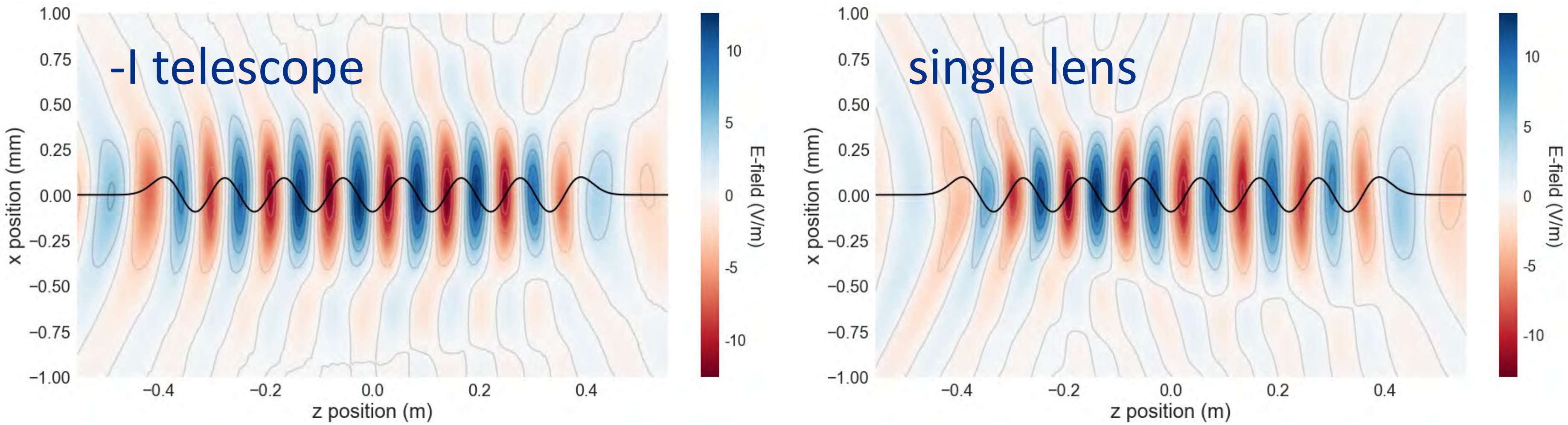
- Index of refraction described w/ the Sellmeier equation
- Custom optics routines based on SRW's transmission element
- Captures "all" orders of dispersion
- Observe appropriate delays and broadening

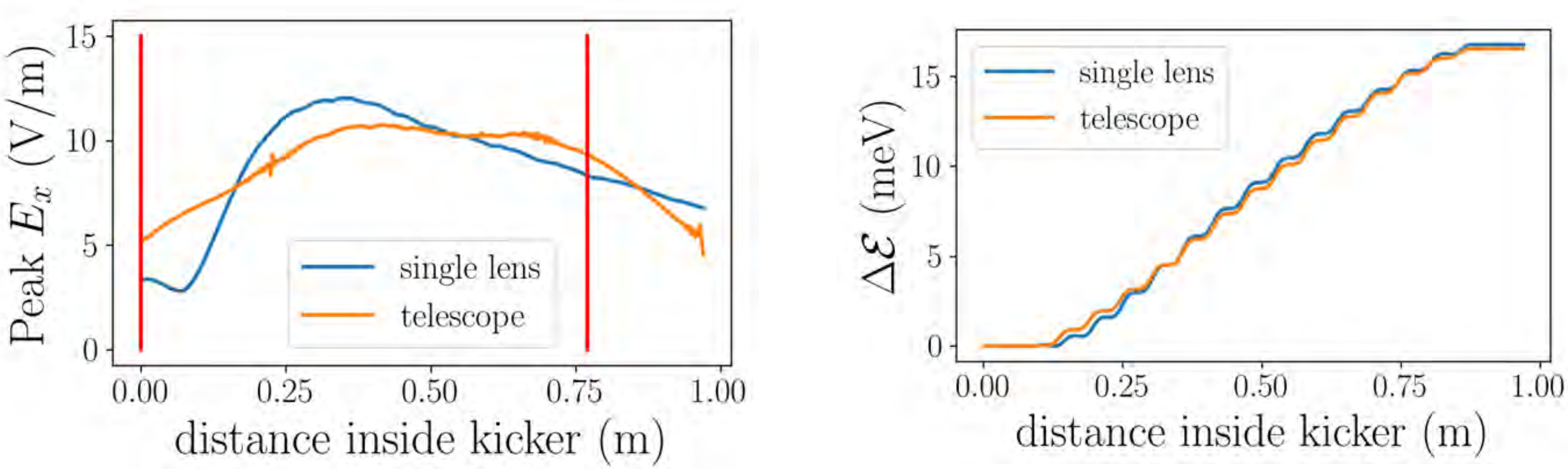


Simulations well converged for Nx/Ny > 200



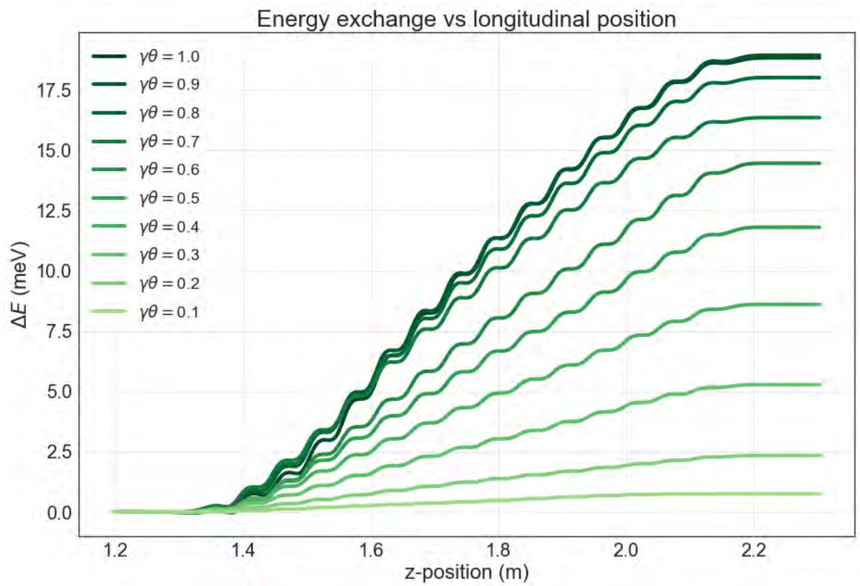
A single lens can give comparable ΔE to telescope

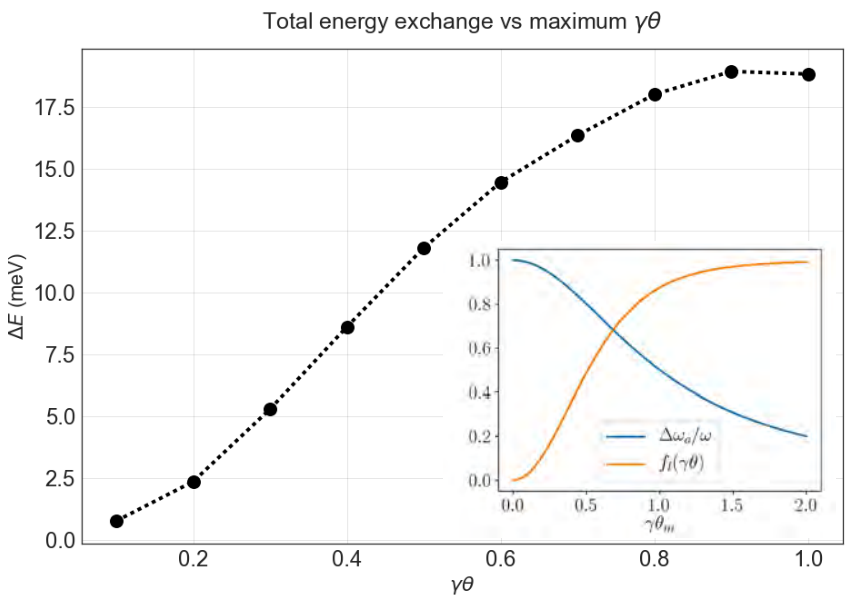


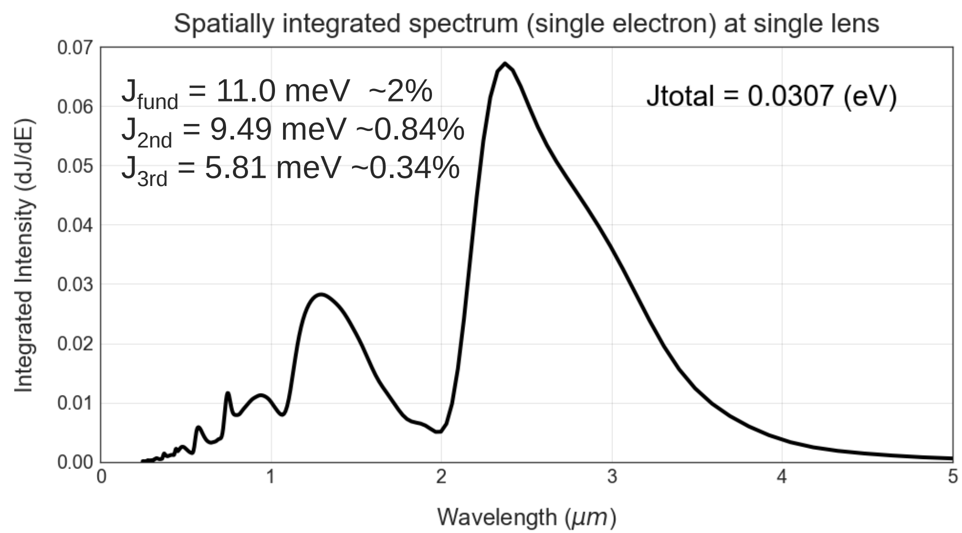


Maximum kick depends on collection angle

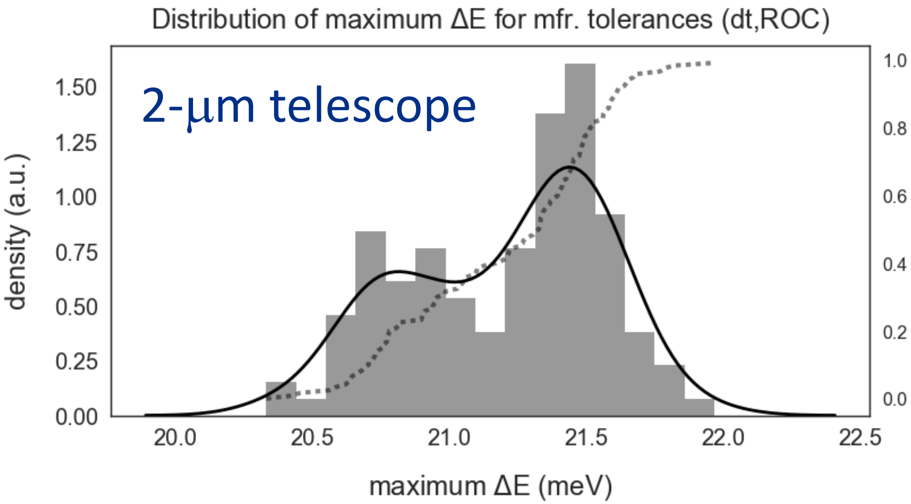
- Collection beyond $\gamma\theta = 0.8$ provides little benefit;
- For single lens, corresponds to ~7-mm radius at center of OSC section
- Matches well with theory

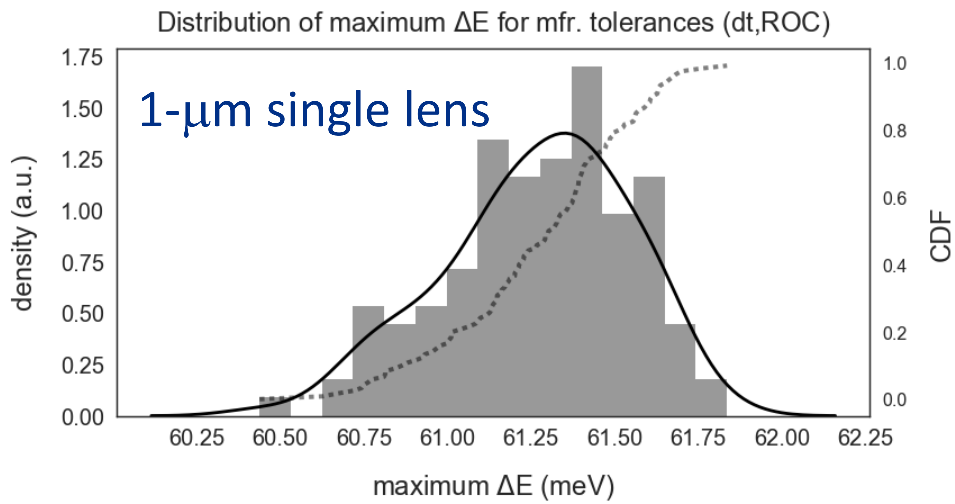






Optics manufacturing spreads acceptable

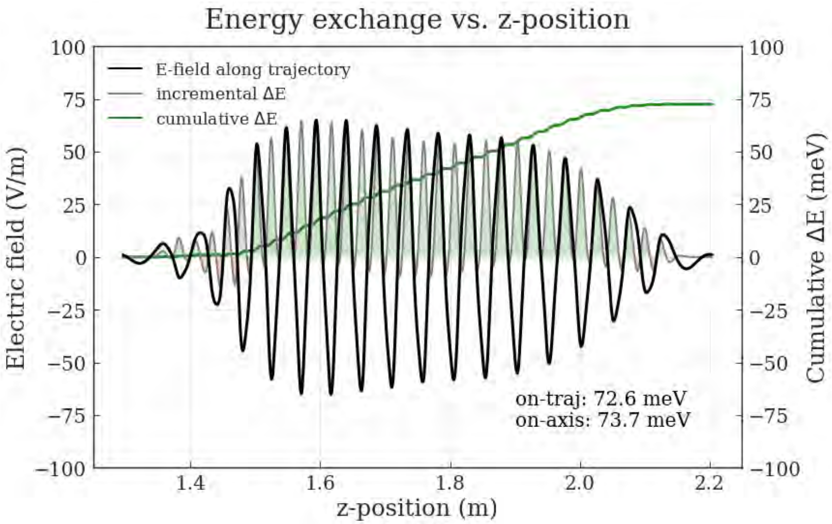


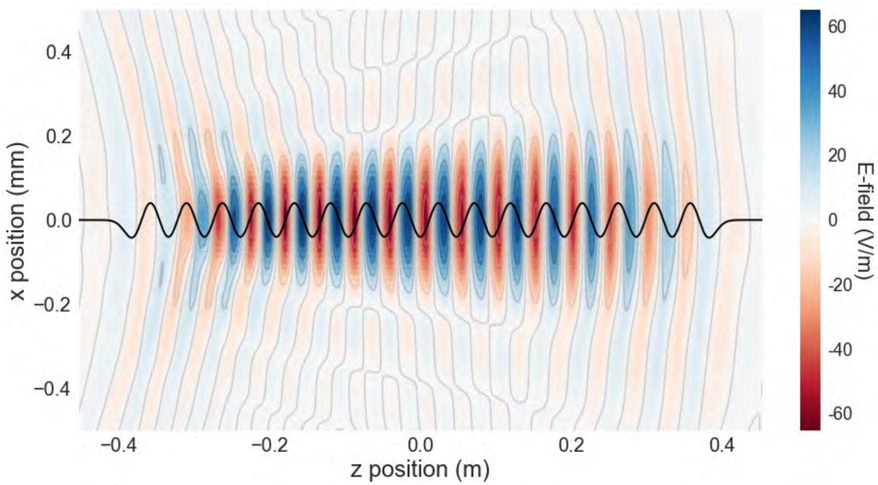


- Monte Carlo simulations using central thickness and ROC spreads from manufacturer
- ~5% (~1%) spread in maximum kick value for 2um (1um)
- Tolerances are primarily set by manufacturing dropout, so to a point, can get higher tolerance for somewhat higher price
- Deviations in central thickness of lenses could be measured and applied to fabrication of delay plates; not needed for 1um case

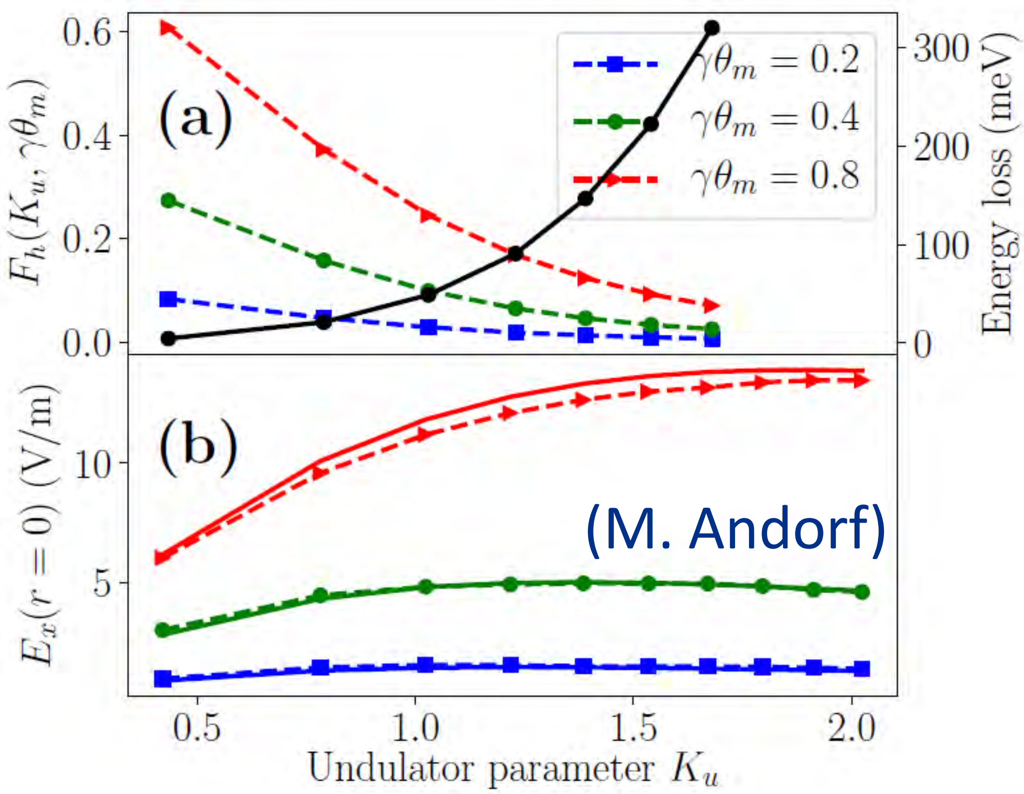
Performance of single lens makes 1-um (passive) possible

- A shorter wavelength requires reduced delay to maintain balance of rates and ranges
- Insufficient delay (<1mm) available for a telescopic optical system at 1μm
- Single lens dramatically reduces complexity of optical system and associated risks
- Detectors in this range are far superior to those available at 2 μm; also improves compatibility with single-electron studies





Correction factor for large K



$$\delta t = \frac{z\left(1-\bar{\beta}\right) + \frac{K^2}{8\gamma^2 k_u}\sin(2k_u z)}{c}$$

Measurement and shimming of magnets underway

- Many new OSC and proton-injector magnets for IOTA
- New field-mapping station at IOTA/FAST for rapid iteration in measurement/shimming process
- Still eliminating systematics, and upgrading user friendliness, but system performance is looking good
- ~2 pts/sec and sensitivity is ~few 10^{-5} (<1 unit) for normalized multipoles at typical R_{ref} and excitation.