



Optical Stochastic Cooling Program @ FAST/IOTA

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Accelerator Research Division

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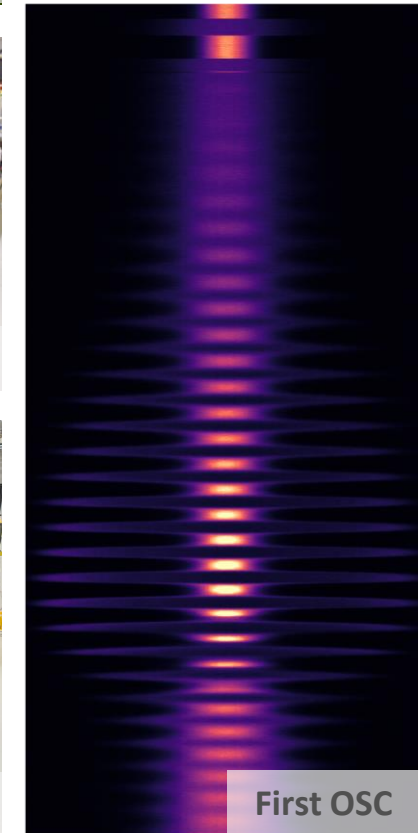
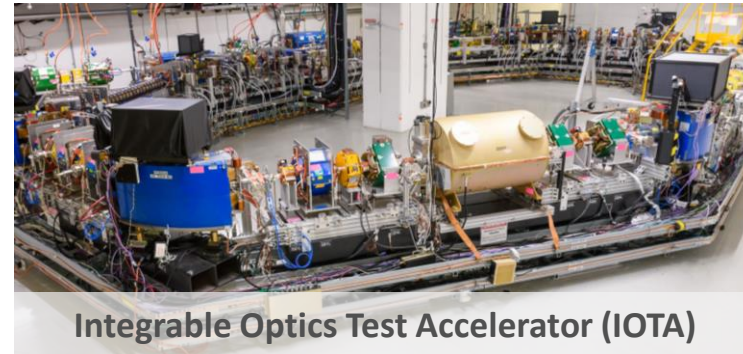
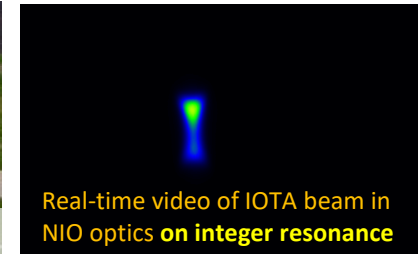
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Thanks to the outstanding group of people at FAST/IOTA

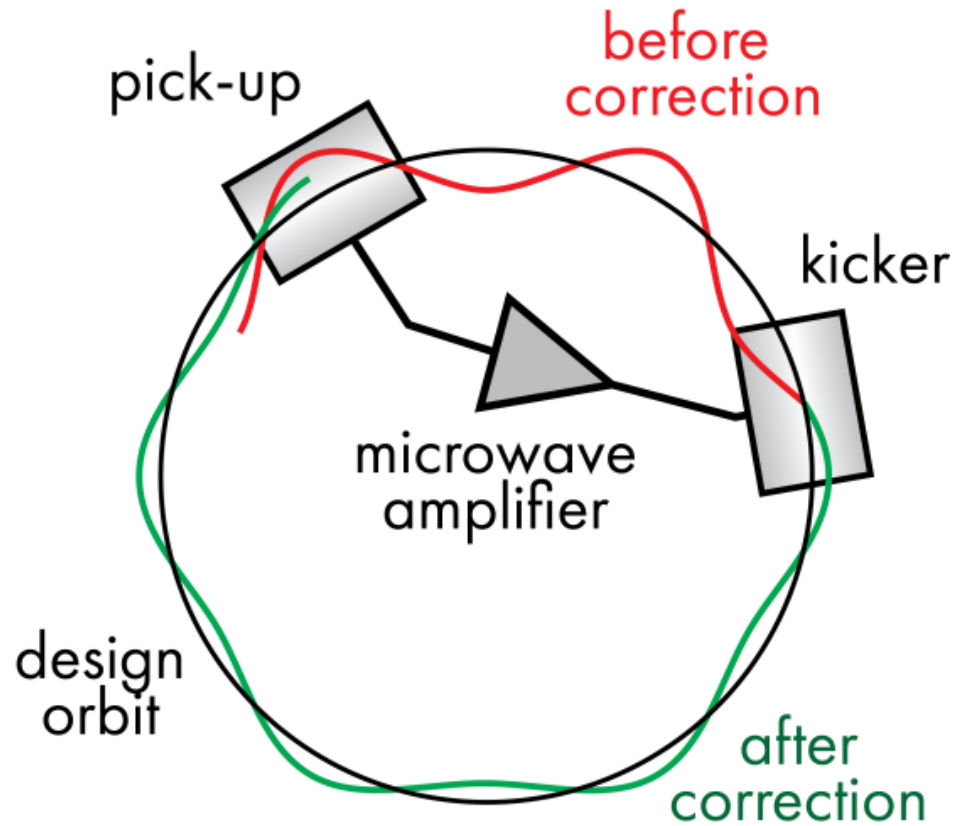


FAST/IOTA: a center for Accelerator Science and Technology R&D

- **Dedicated AST R&D facility with intensity-frontier focus**: take novel AST from concept, to demonstration, to practice for HEP
- Also, high-impact, cross-office (DOE) R&D and collaborator-driven programs; strong education and training element
- **First demonstration of ILC cryomodule beam-accelerating-gradient spec**; 31.5 MeV/m (2017)
- **First demonstration of Nonlinear Integrable Optics** (2020); operation on integer resonance
- **First demonstration of Optical Stochastic Cooling** (2021); ~7000x increase in state-of-the-art frequency bandwidth



Stochastic Cooling: an enabling technology for colliders and beyond



1984 Nobel:
van der Meer &
Rubbia

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

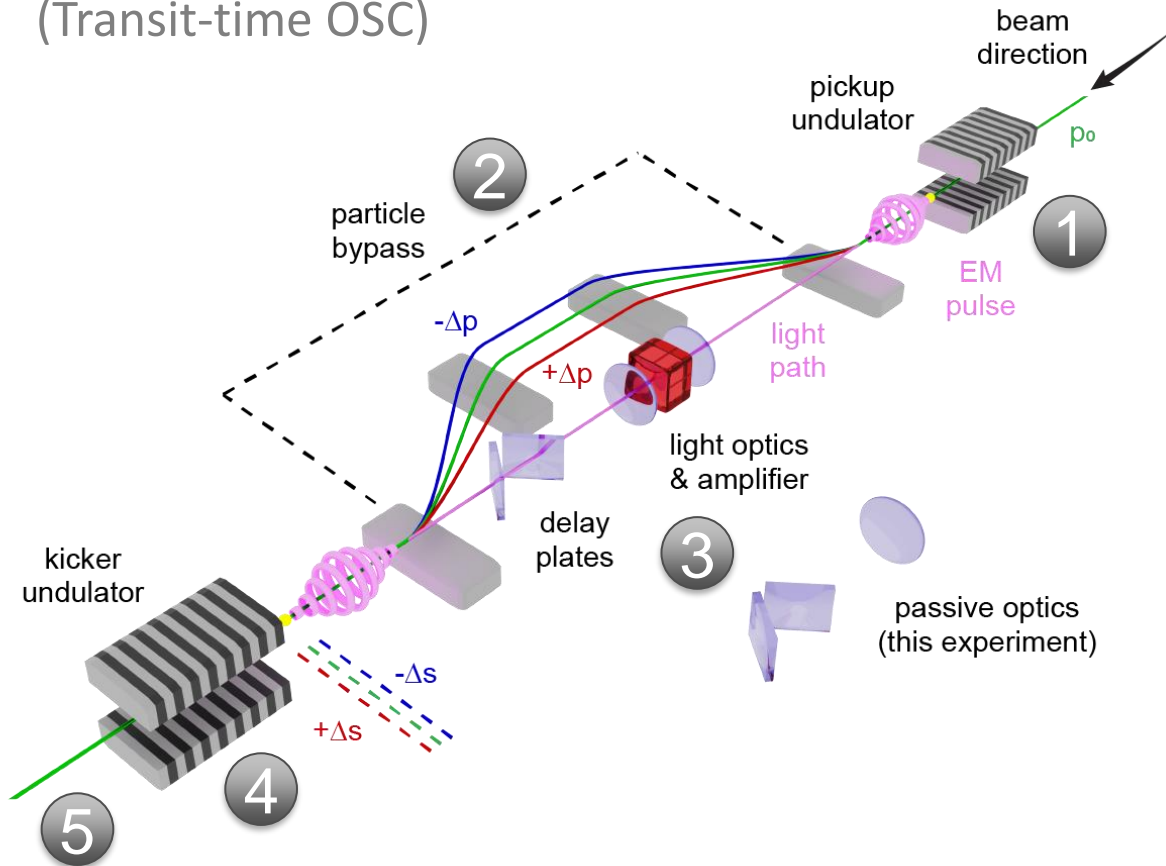
“How then can cooling work? It must necessarily be through deformation of phase space, such that particles move to the center of the distribution and (to satisfy Liouville) the empty phase space between the particles moves outwards. Clearly, the fields that do this must have a very particular shape,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

(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)**

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 @ IOTA: a new state-of-the-art in particle-beam cooling

- **Optical Stochastic Cooling**: first successful realization of stochastic cooling in the optical regime; *Nature* 08/11/22
- 100-MeV electrons in IOTA with an optical wavelength of 950 nm
- Demonstrated system bandwidth of ~ 30 THz; **>7000x higher** than microwave SC
- Demonstrated flexible, strong cooling for **1D, 2D and 3D**; Cooling **~ 10 x stronger** than synchrotron-radiation damping with no amplification!
- manuscript in preparation with other “beam” results

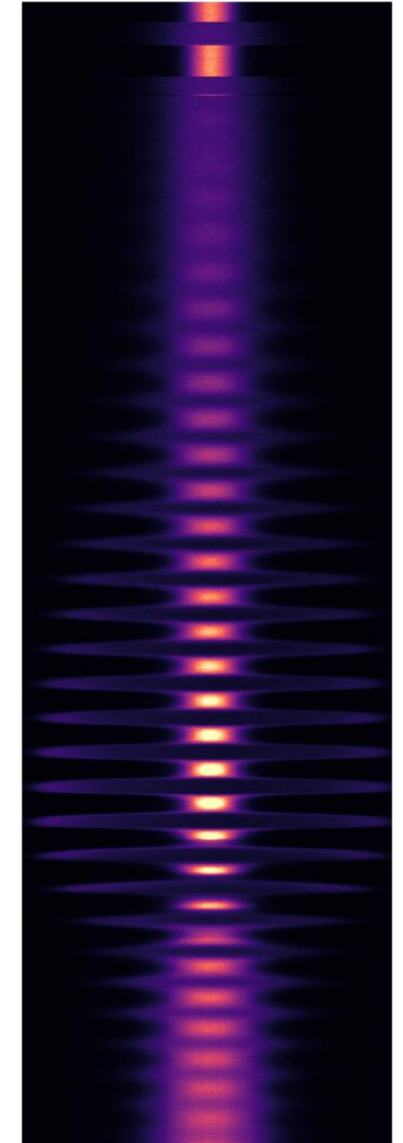
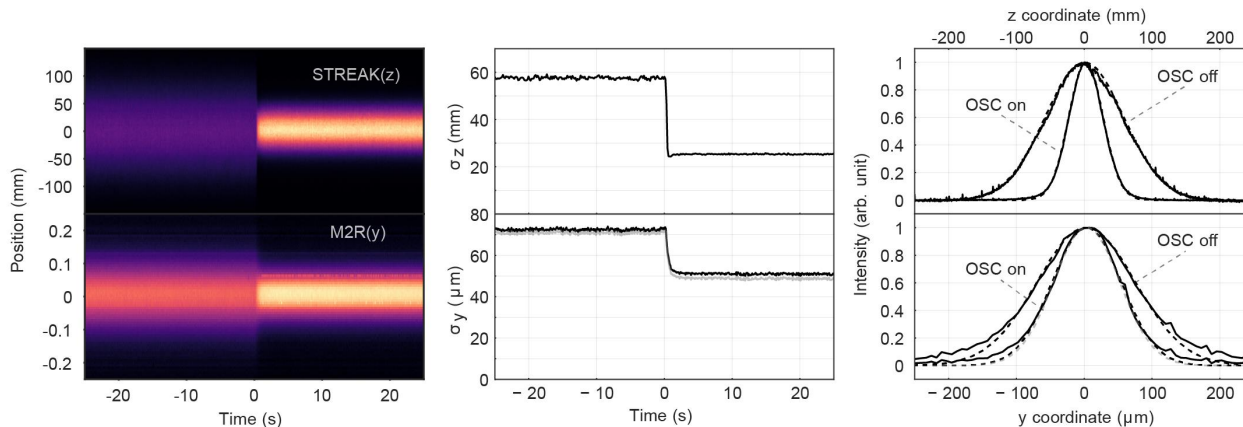
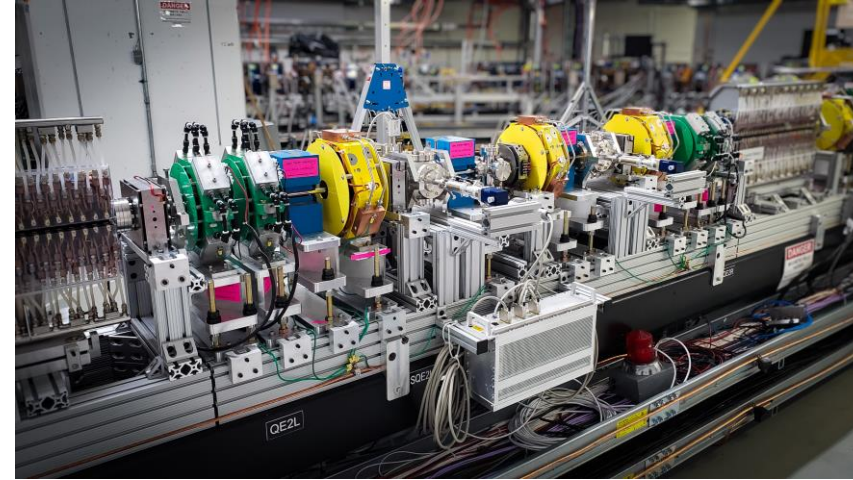
Experimental demonstration of optical stochastic cooling

<https://doi.org/10.1038/s41586-022-04969-7>

Received: 16 March 2022

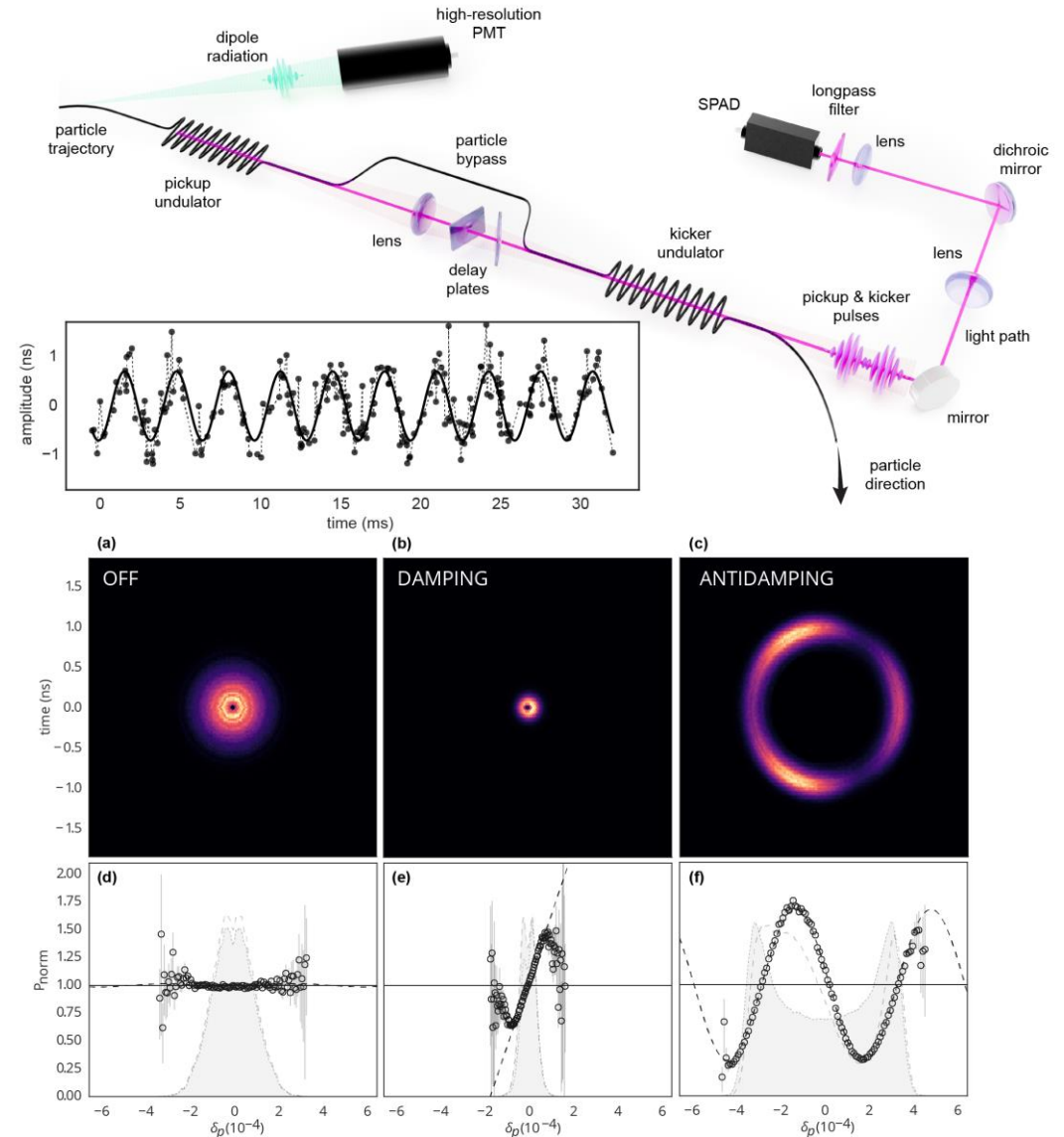
Accepted: 13 June 2022

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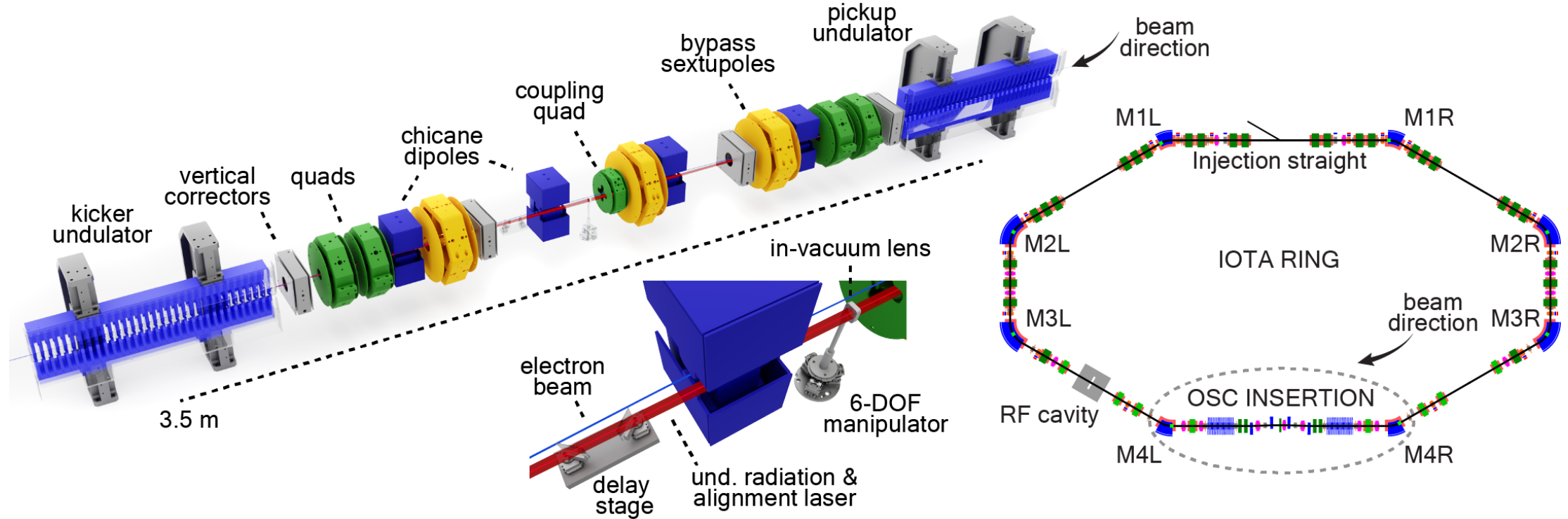


Single-electron OSC also produced excellent results

- First closed-loop interaction of a single relativistic particle with its own radiation field
- Successfully resolved the underlying OSC physics using a single electron as the probe
- Observe expected modulation of photon-emission probability due to the OSC system
- Used the OSC force to freely manipulate the single-particle action
- Excellent agreement between system performance with single particle and with beam
- Manuscript in preparation



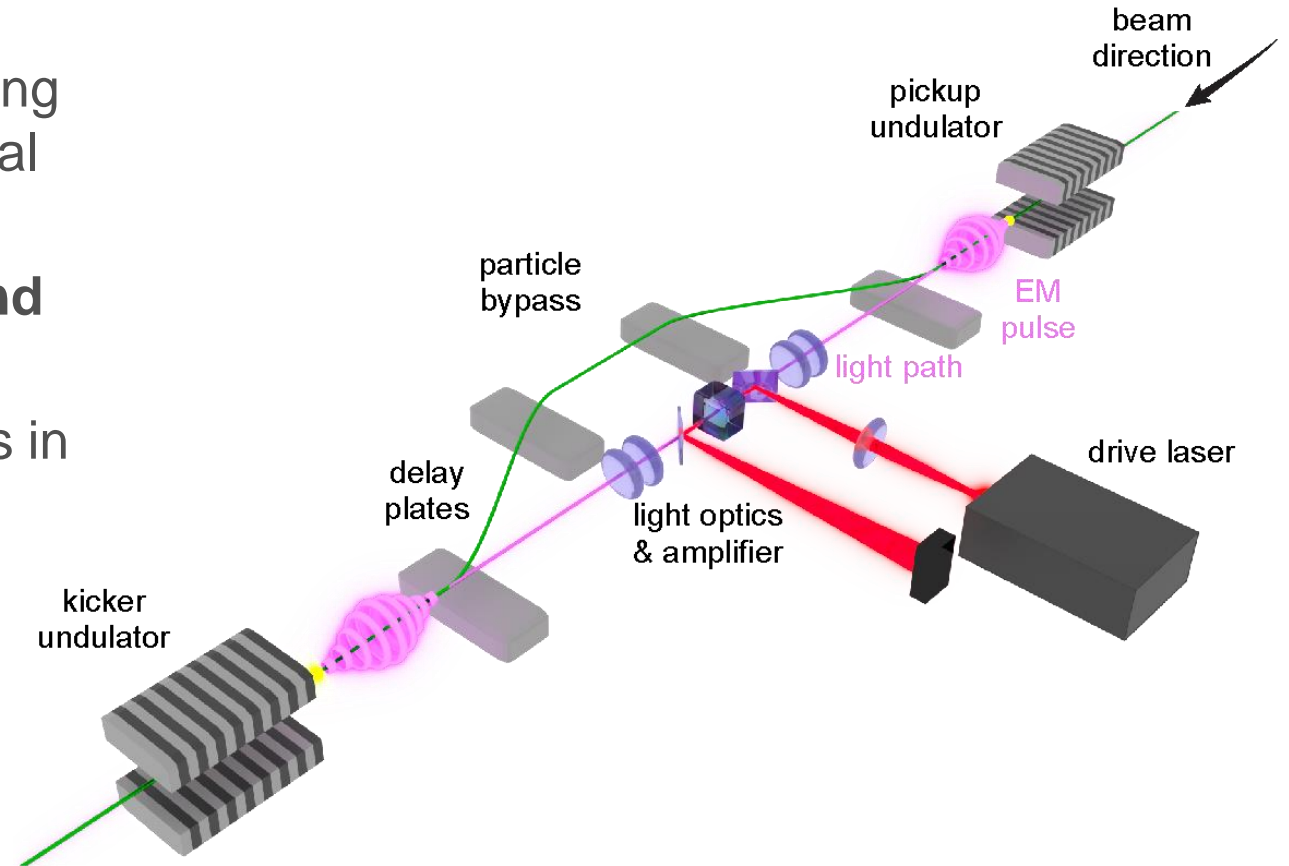
A staged approach for OSC at IOTA



- **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, advanced phase-space control, QM noise in amplification + effect on cooling, diffusion/heating, etc...

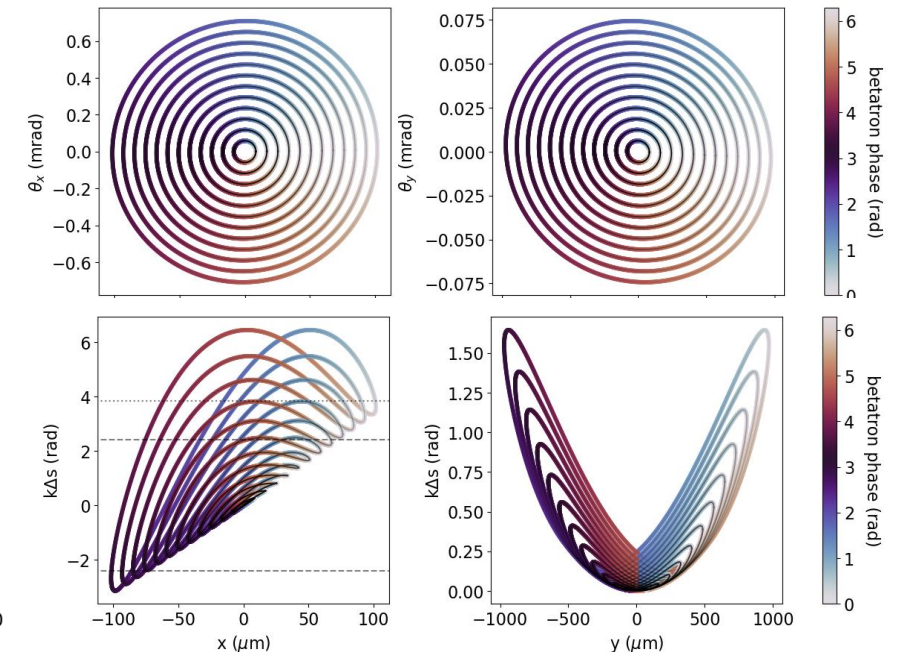
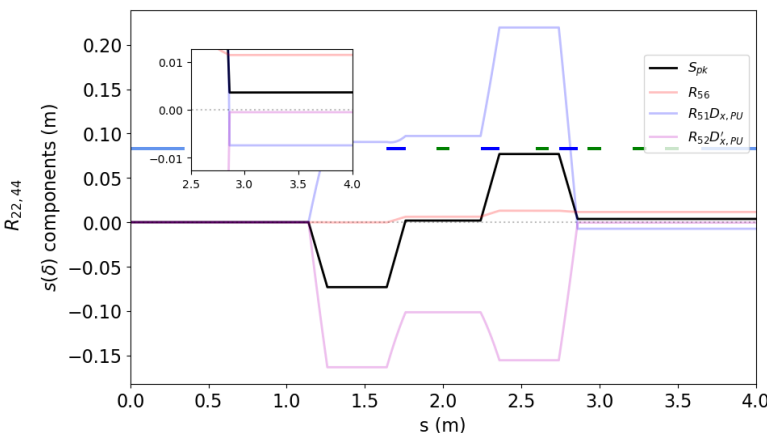
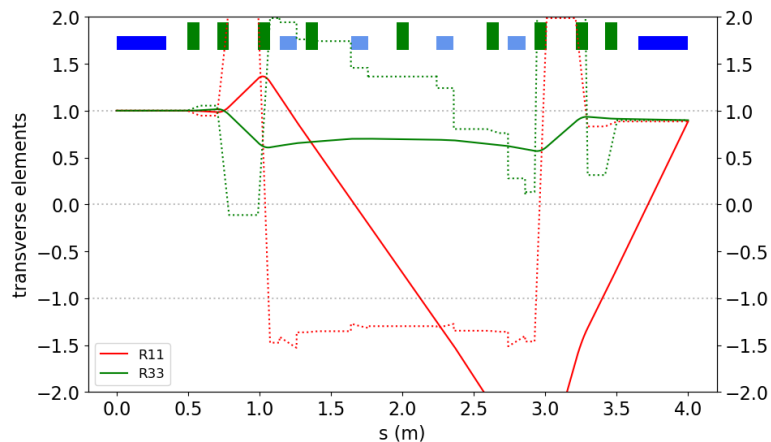
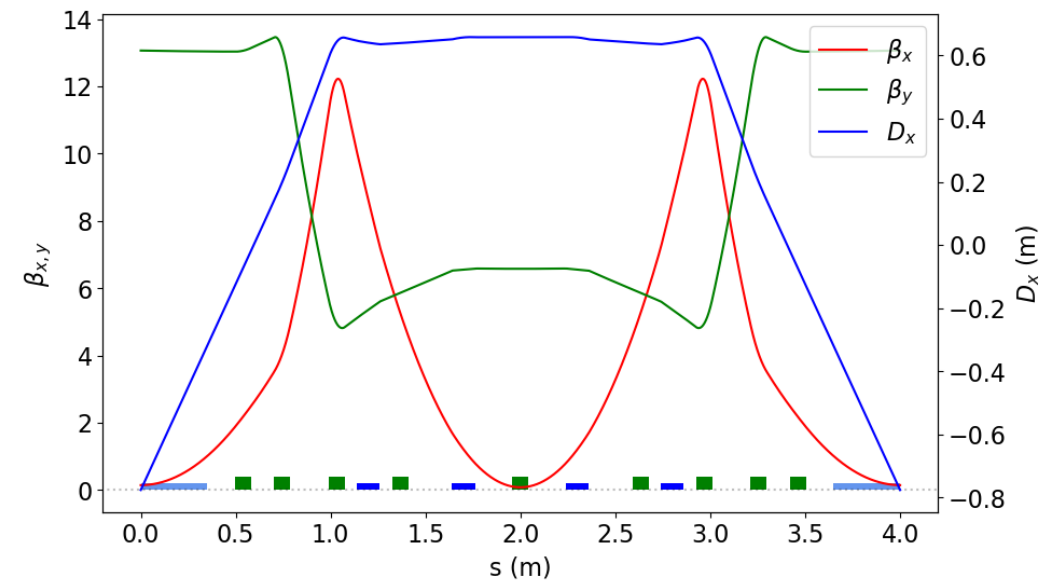
Amplified-OSC experiment is now under conceptual development

- **Higher-delay system:** 6mm vs 0.6mm – provides optics budget and stronger cooling
- **More complex bypass** for balancing competing requirements and enabling different operational modes
- **Good matching between electron optics and light optics** (i.e. matched transfer matrices)
- **Telescopic in-vacuum optics** with tight focus in amplifier and DOF suppression in undulators
- **Longer wavelength** for 1) amplifier compatibility; 2) cooling range: partial compensation of higher delay; 3) reduced requirements on bypass stability
- **Power gain ranging from 0dB to ~40dB;** corresponding to cooling times of $O[1\text{ms}]$
- Will have CDR exploring all critical systems



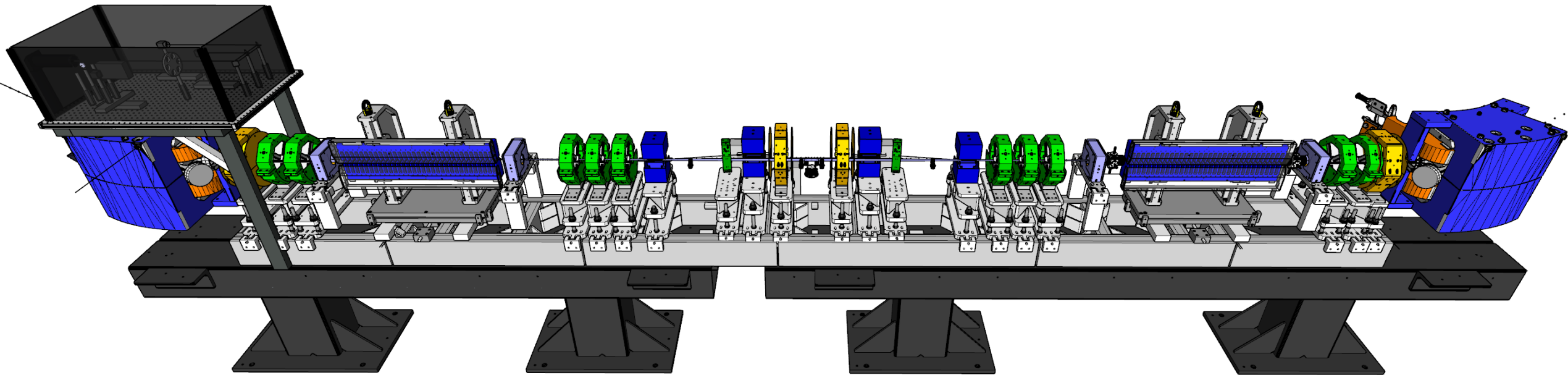
Extensive bypass optimization effort

- Physical bypass configuration should be complex enough to meet needs of all operational modes while still being physically realizable
- Extensive multi-objective optimization campaign using cymad (i.e. MADX) with genetic algorithms (CNSGA) in Xopt and Pymoo
- Optimization on critical performance parameters for OSC (mappings, rates, ranges, etc...)
- Solutions will determine required bypass layout/contents



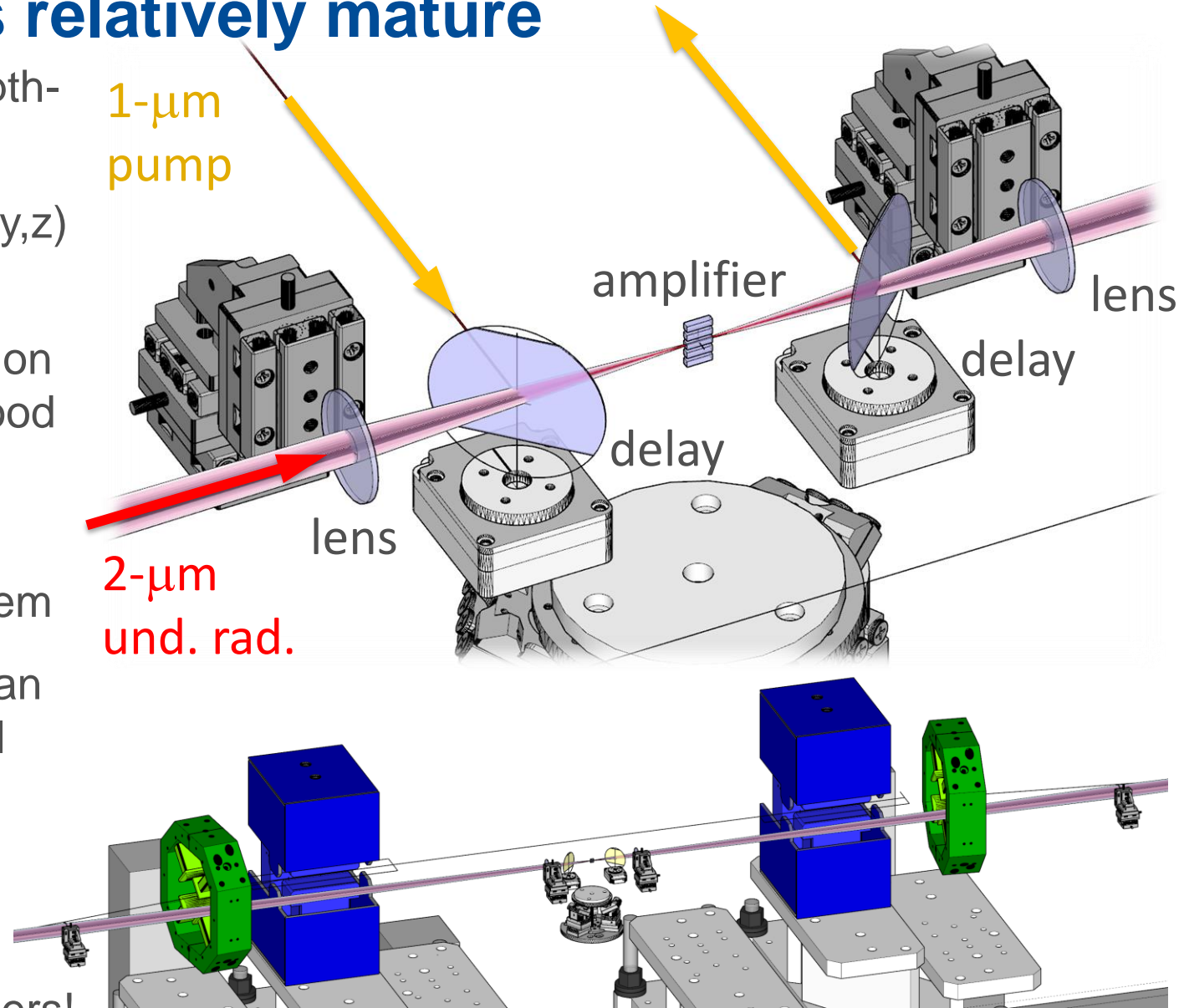
Iterative design process for integrated system is underway

- Beginning to iterate between solid-model considerations and bypass optimization
- **Will most likely need:** 1) new undulators, 2) additional outer quads, 3) new bypass quads (small), 3) additional multifunction correctors, 4) new bypass sextupoles.
- **Will definitely need:** 1) new vacuum envelope
- **Might need:** 1) new chicane dipoles (permanent-magnet based w/trim?)



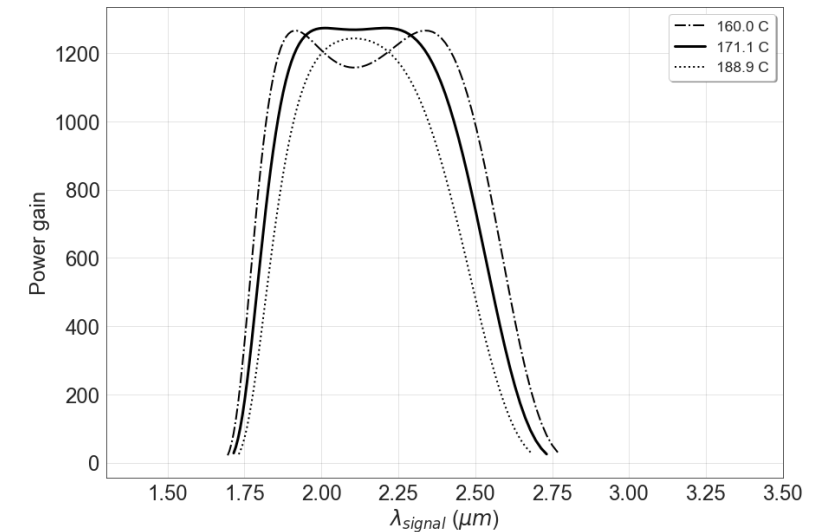
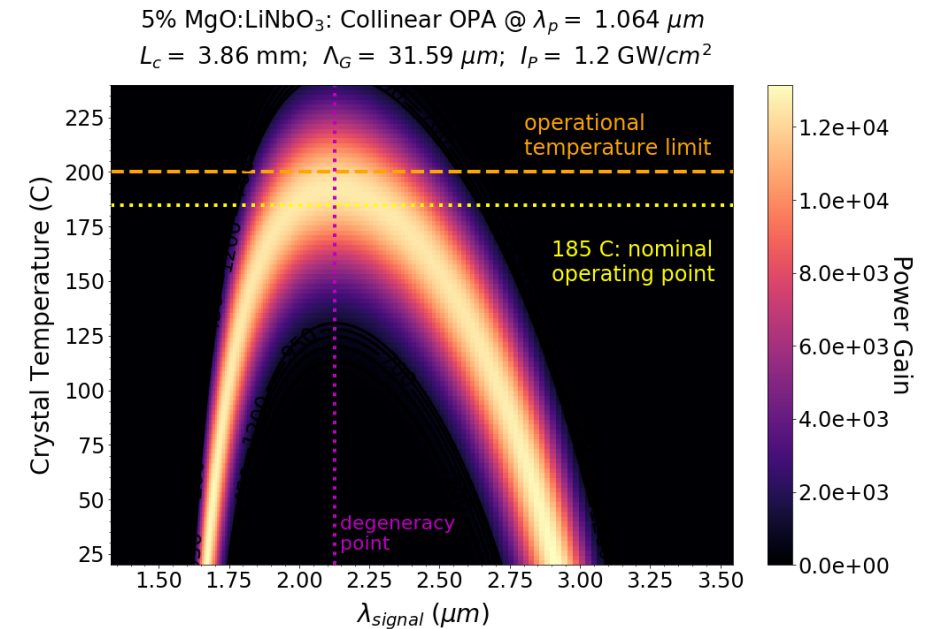
Overall light-optics design is relatively mature

- Positive-identity, telescopic optics with depth-of-field suppression; four lenses
- All lenses independently controllable in (x,y,z) dimensions
- MgF_2 optics for low group-velocity dispersion @ $2\mu\text{m}$ (minimize pulse spreading) and good manufacturability
- Delay plates are also dichroic mirrors for coupling pump laser in and out of the system
- Upstream plate fixed after alignment but can be paired with external mirrors if additional delay range is required
- “Bandolier” of amplifier crystals on 6-DoF hexapod (in case of damage)
- *maintain compatibility with various amplifiers!



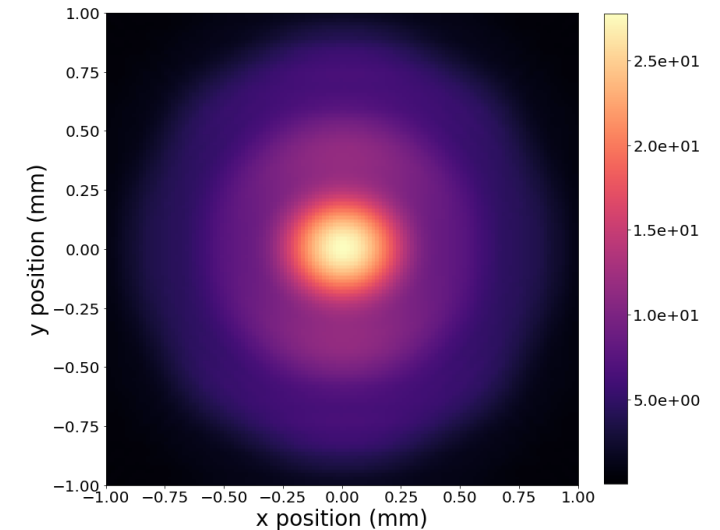
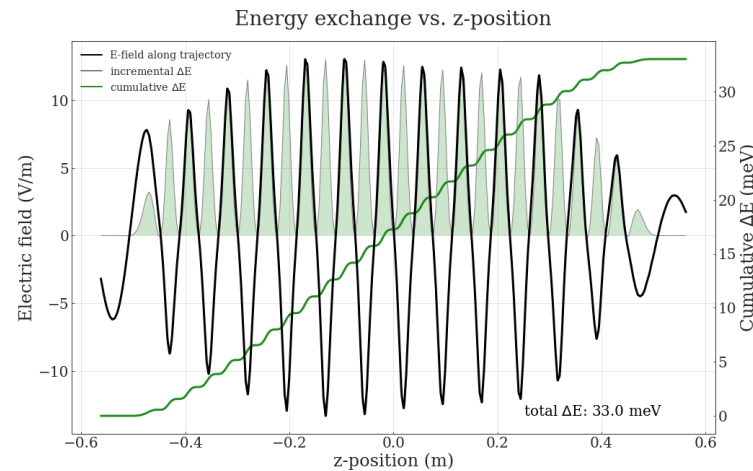
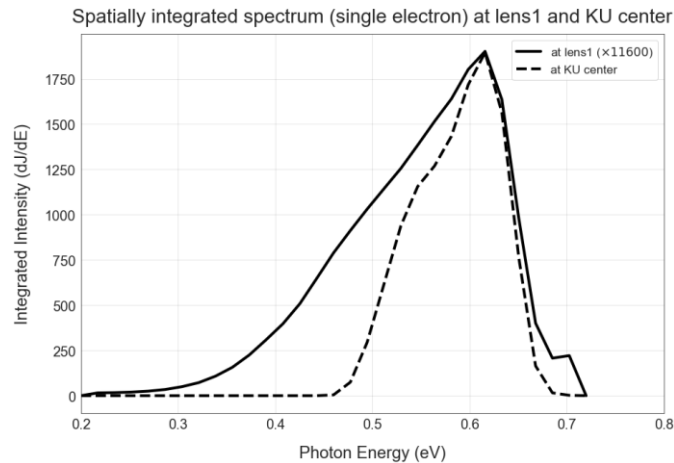
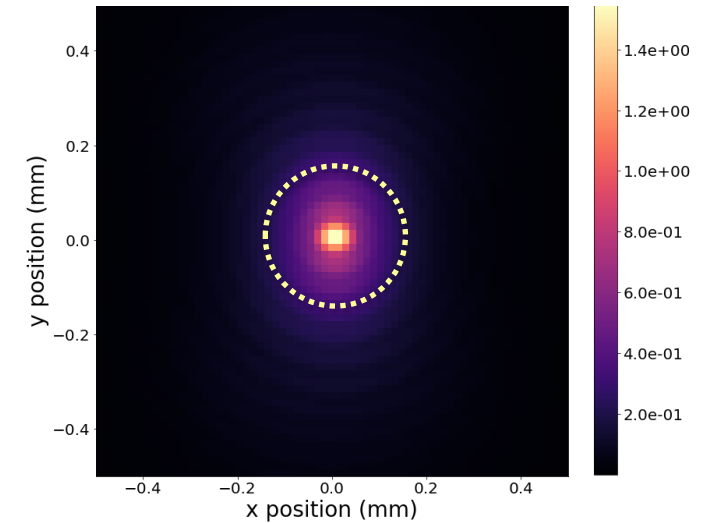
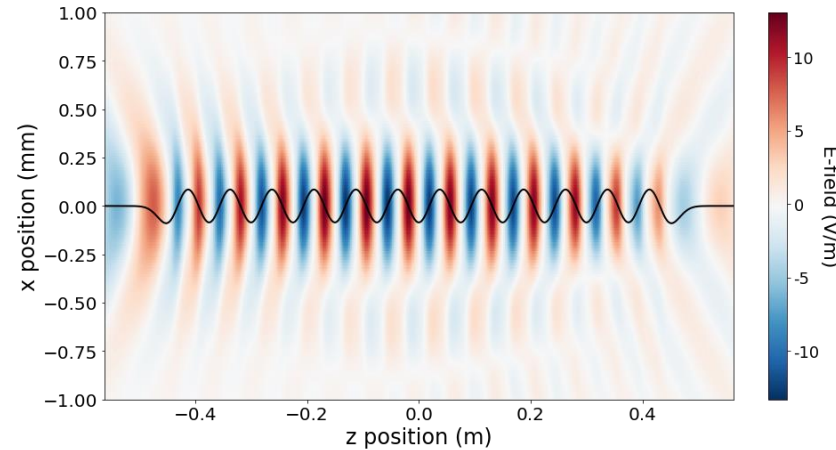
OSC amplifier based on MgO:PPLN

- Amplifier must be “single pass” (low delay)
- Also needs low group-velocity dispersion and widest gain bandwidth possible; should be well matched to undulator fundamental
- A PPLN OPA operating near “degeneracy” should meet all requirements
- Type-0 interaction (eee) in 5%MgO:PPLN
- Operation at max temperature possible to reduce photorefractive effect (damage mechanism); ~185 C
- Accounting for all delay needs, a 3.86-mm crystal length is possible: **~40dB of gain for expected pump intensities.**

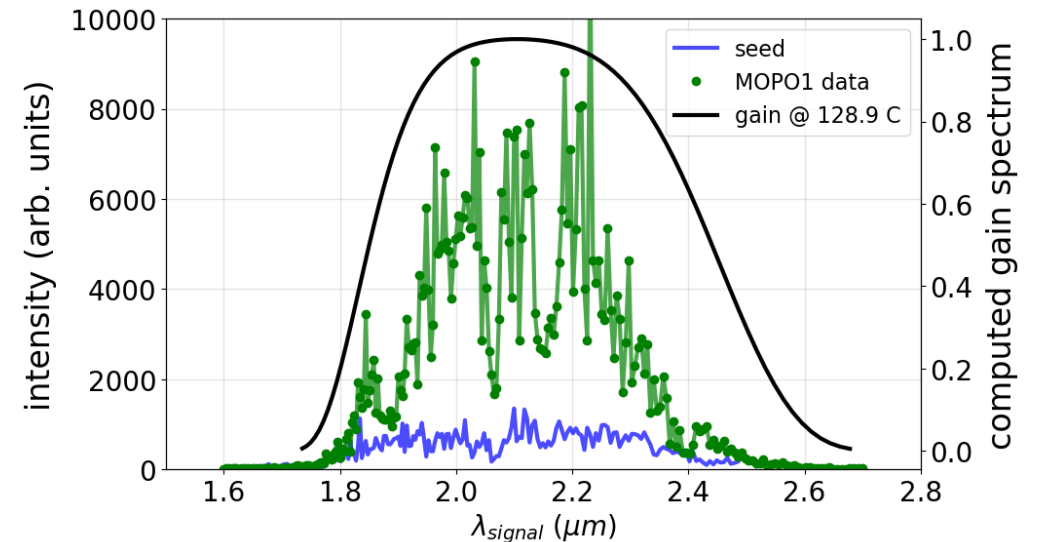
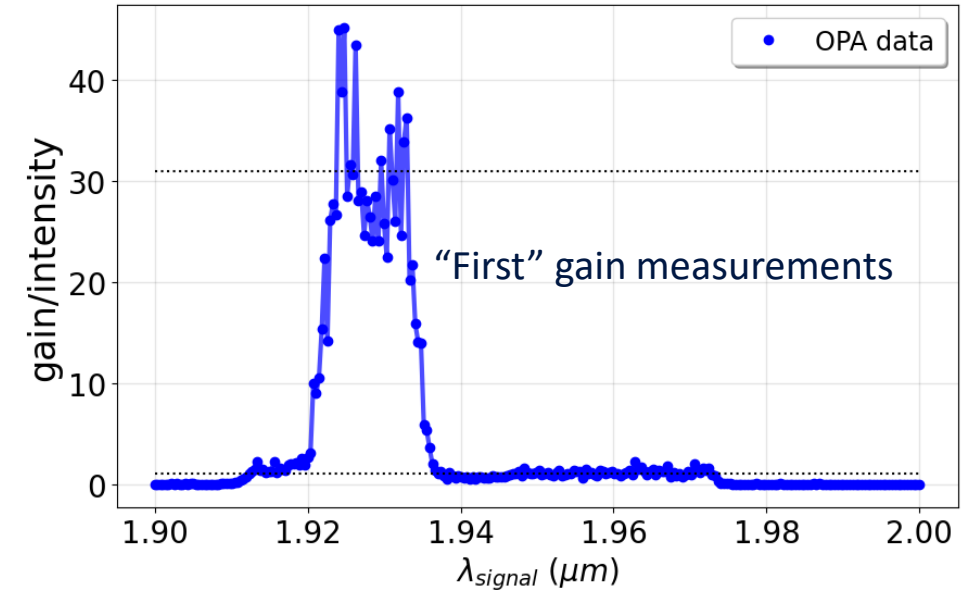
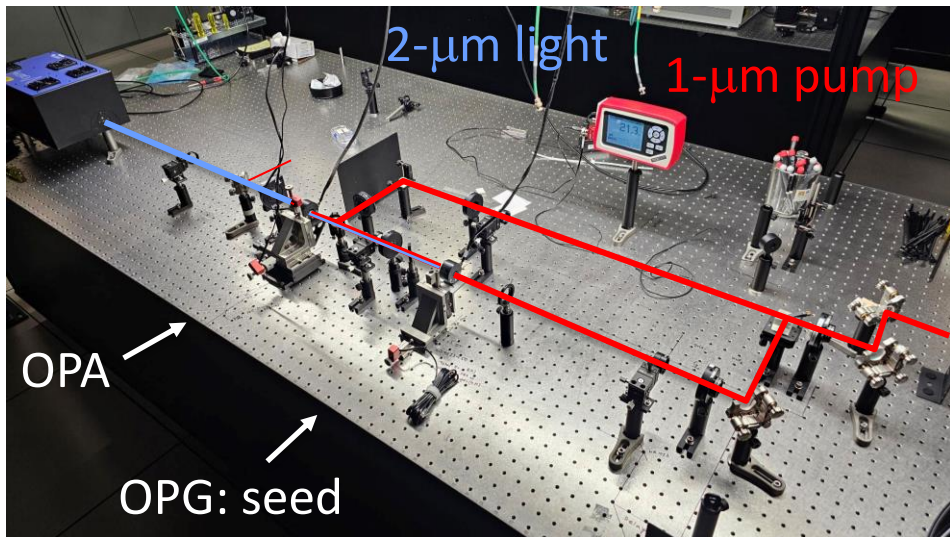
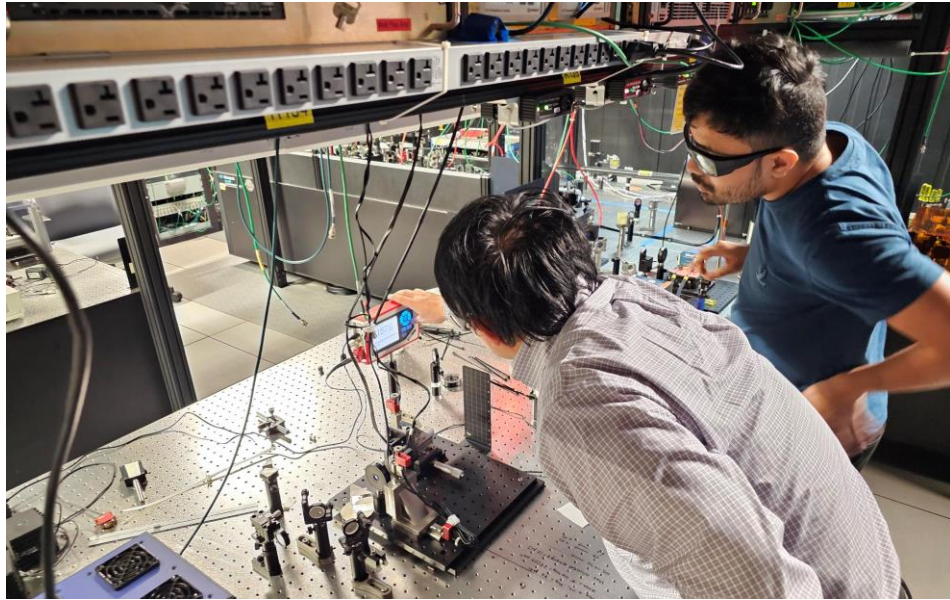


OSC simulations underway for integrated optical system

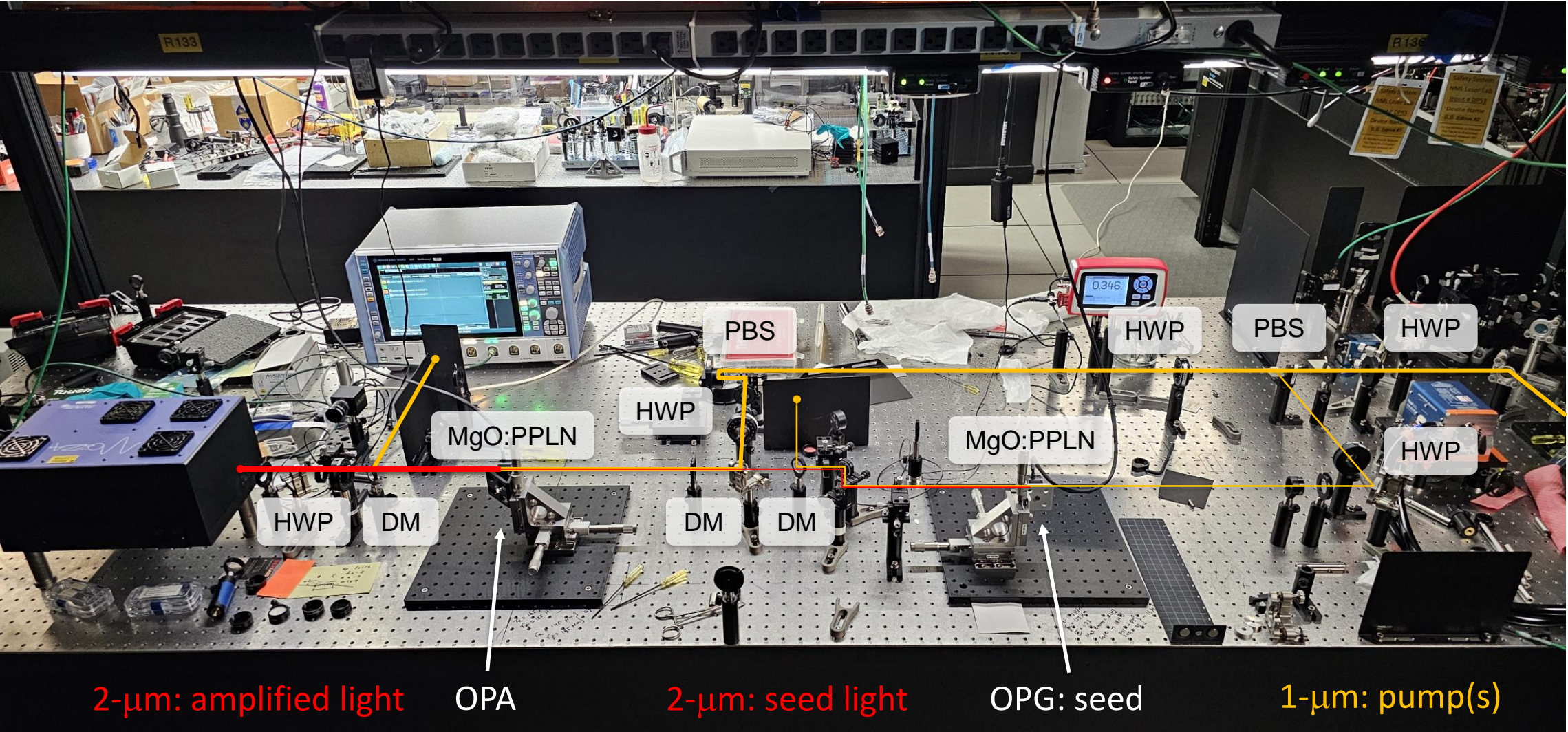
- SRW simulations of full optical system including PPLN and computed gain
- ***Does not yet include any frequency-dependent phase shifts vs gain; will use measurements once available



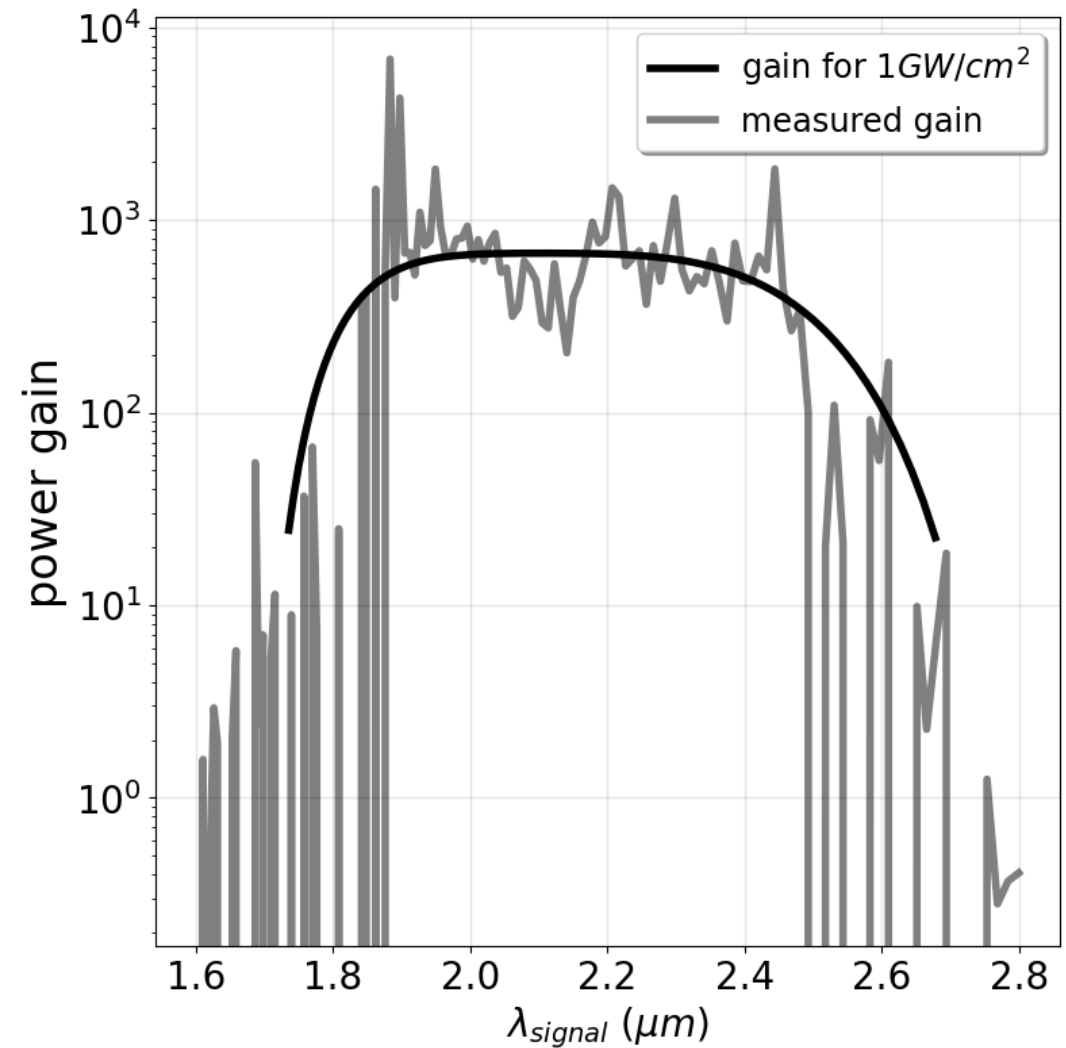
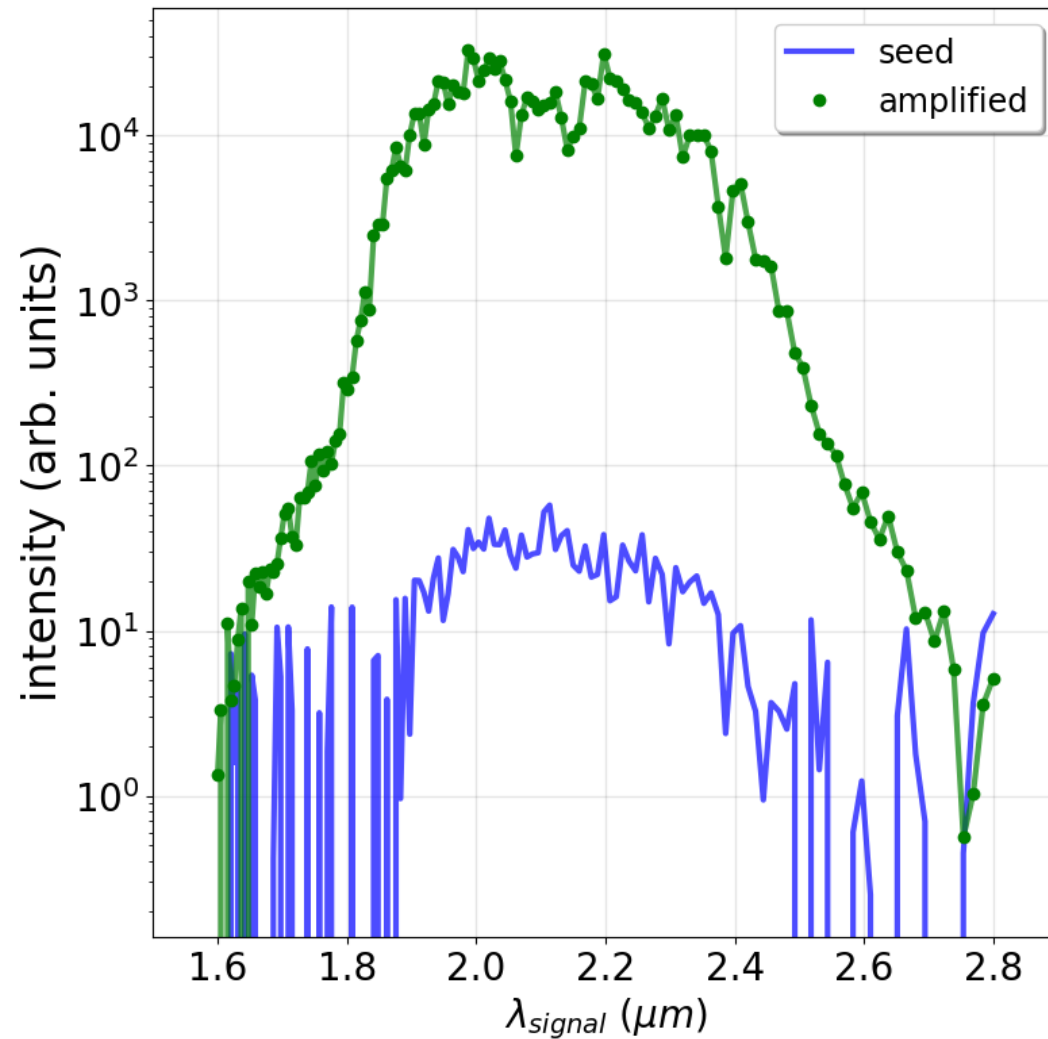
Developing amplifier and full optical system in the FAST laser lab



Amplifier has been successfully prototyped and characterized

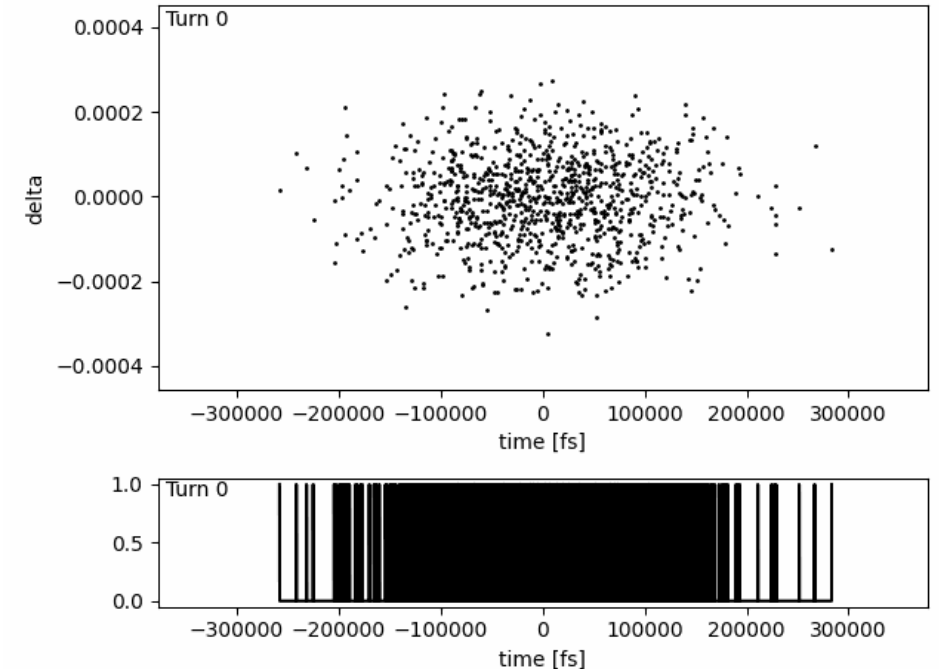
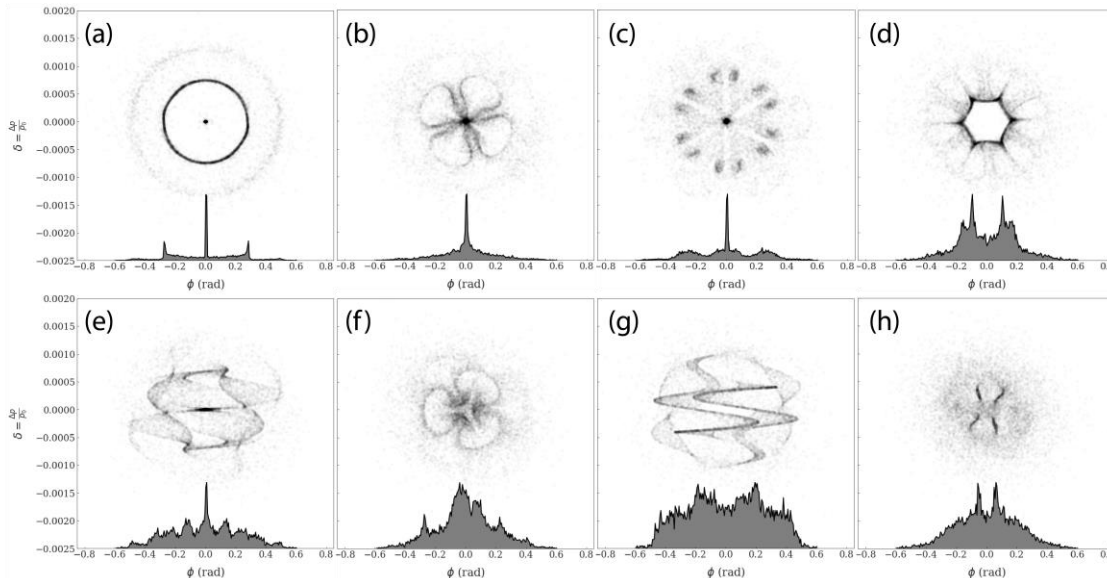
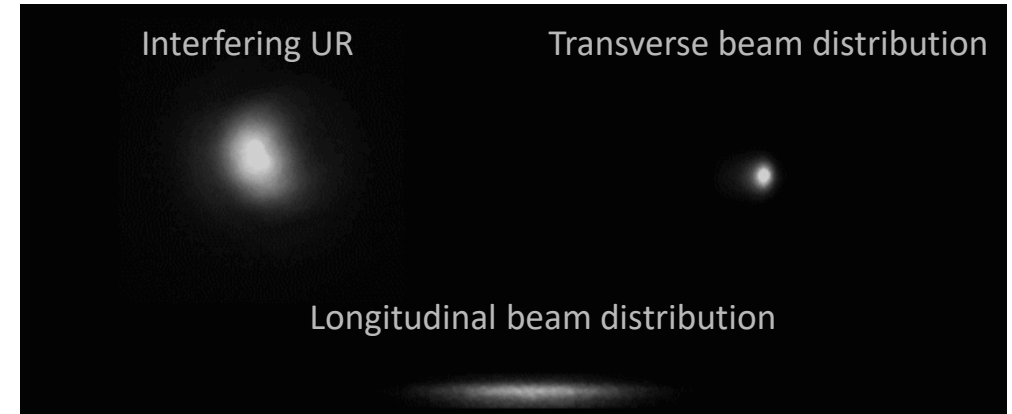


Low delay (~4mm) high-gain (~30dB) amplification achieved



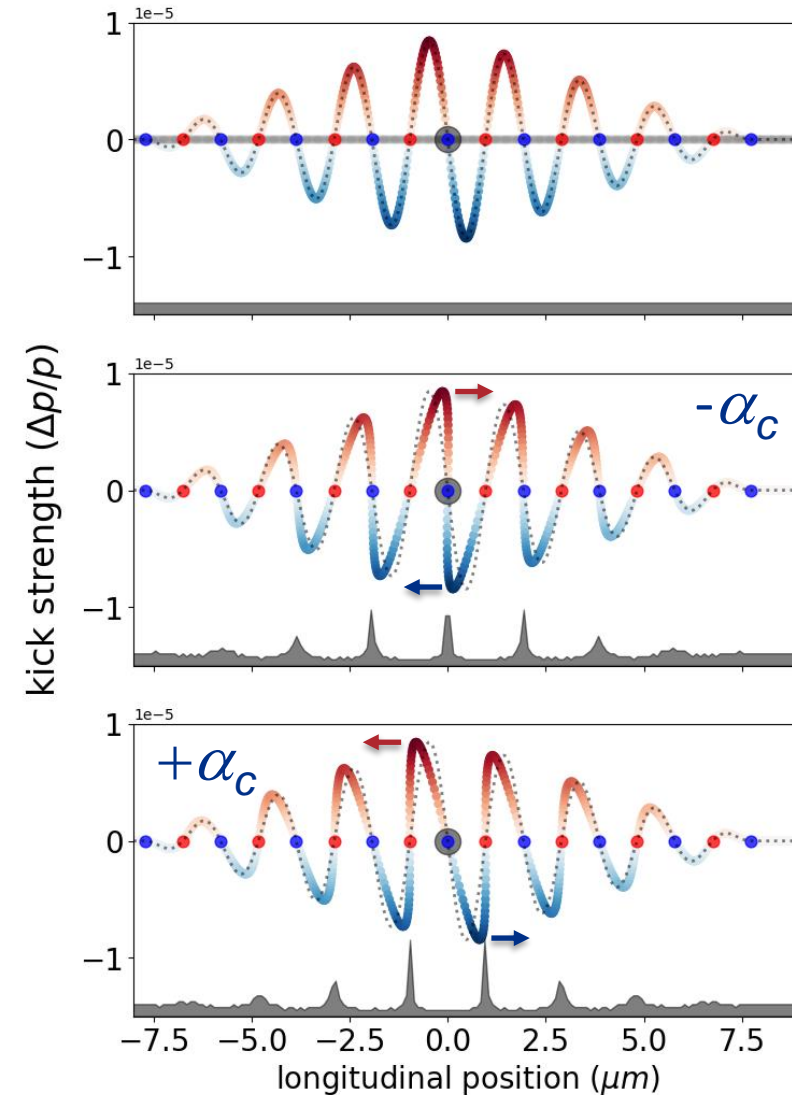
OSC systems as a flexible tool for advanced beam manipulation

- The OSC force is very powerful and can be structured in space and time with great freedom (delay, gain, optics, mapping, etc...).
- The amplified-OSC system is being designed to enable a robust program in exploring “distributions on demand”
- Will develop and test advanced control policies using Reinforcement Learning + surrogate models




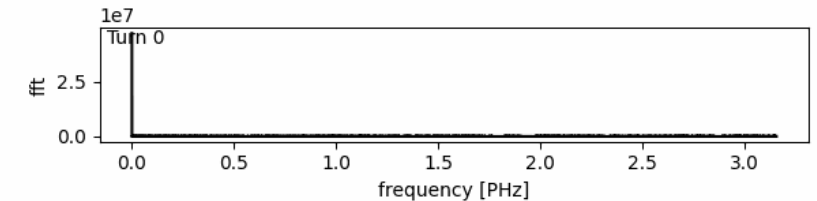
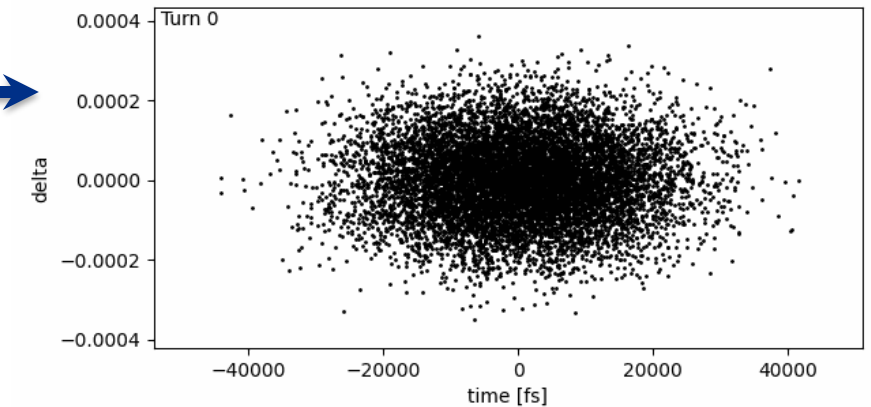
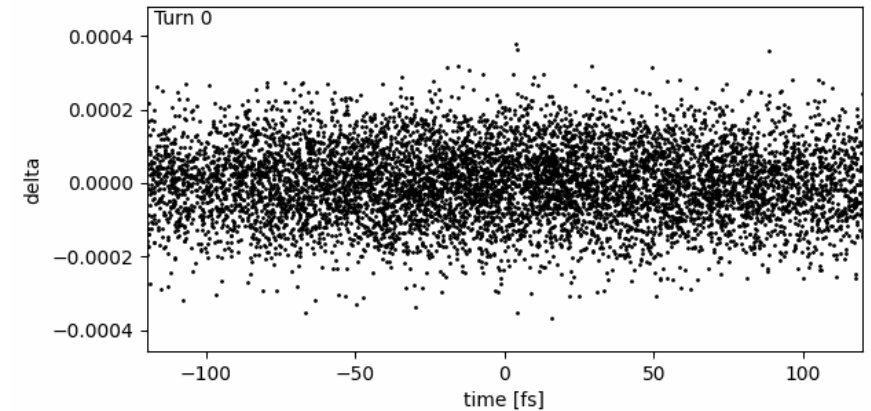
Optical Stochastic Crystallization: Targeting a demonstration of SSMB

- **Standard OSC** maps particles' energy deviations onto appropriate energy corrections; **creates attractors in momentum**
- “**OSX**” **creates attractors in both momentum and longitudinal position simultaneously**; these are **naturally locked to the beam structure itself**
- The strength of the OSX attractors increases dramatically as they are populated... further populating and cooling the attractors
- Cooling may also extend to transverse planes if system is properly designed
- Transverse cooling would also receive enhanced gain



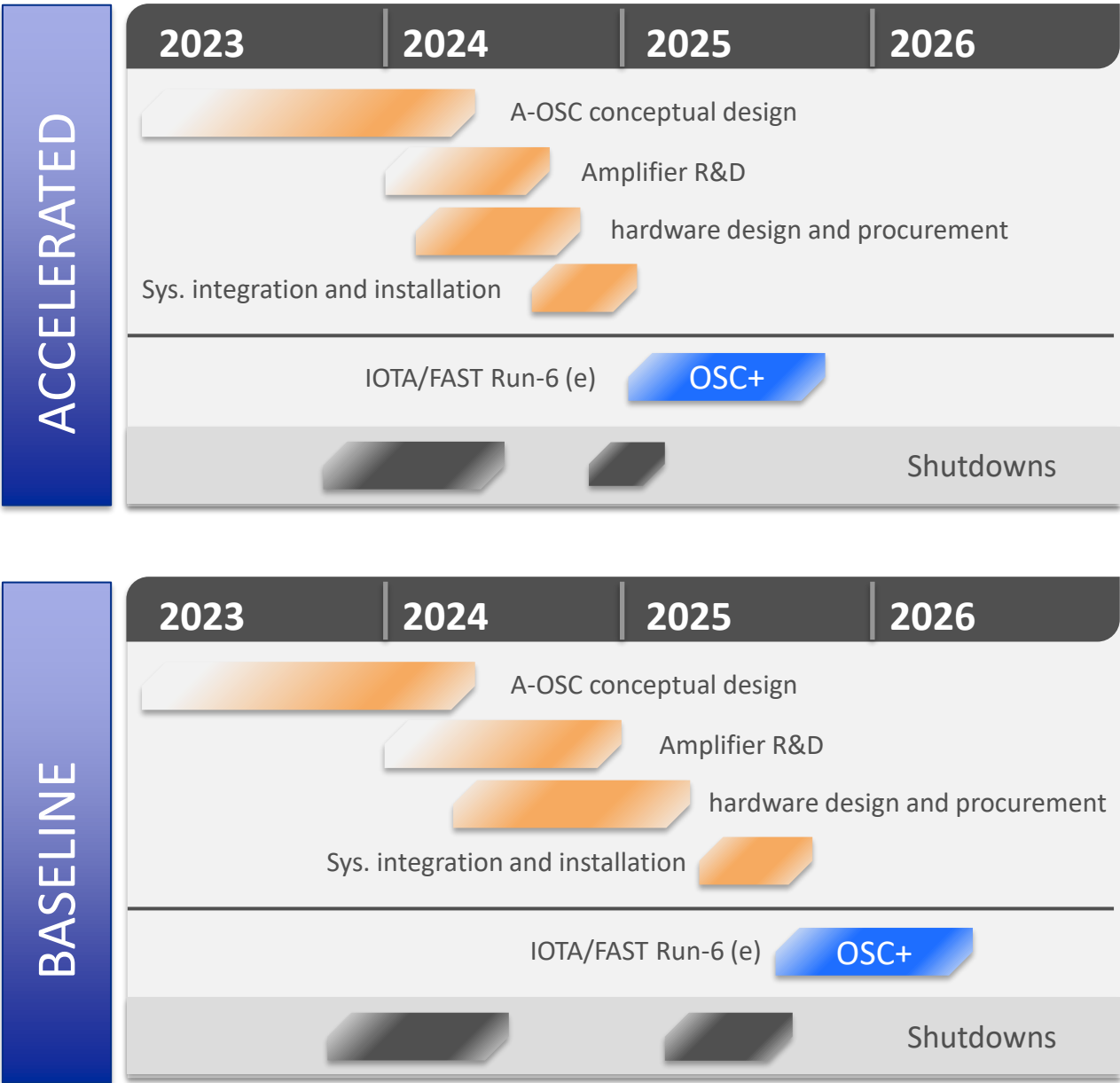
A demonstration of OSX during amplified-OSC run is feasible

- Need to develop simulation tools further and perform systematic studies to understand requirements and limitations; similar issues to other SSMB concepts
- Initial simulations suggest that modest gain and beam densities are sufficient to initiate crystallization
- Beam manipulations (both simple and advanced) may relax requirements further. 
- Once the crystallization starts, a reduced gain may be sufficient to maintain the process
- RL control policies may enable further optimizations through complex, dynamic adjustments of bypass, lattice, RF and light optics

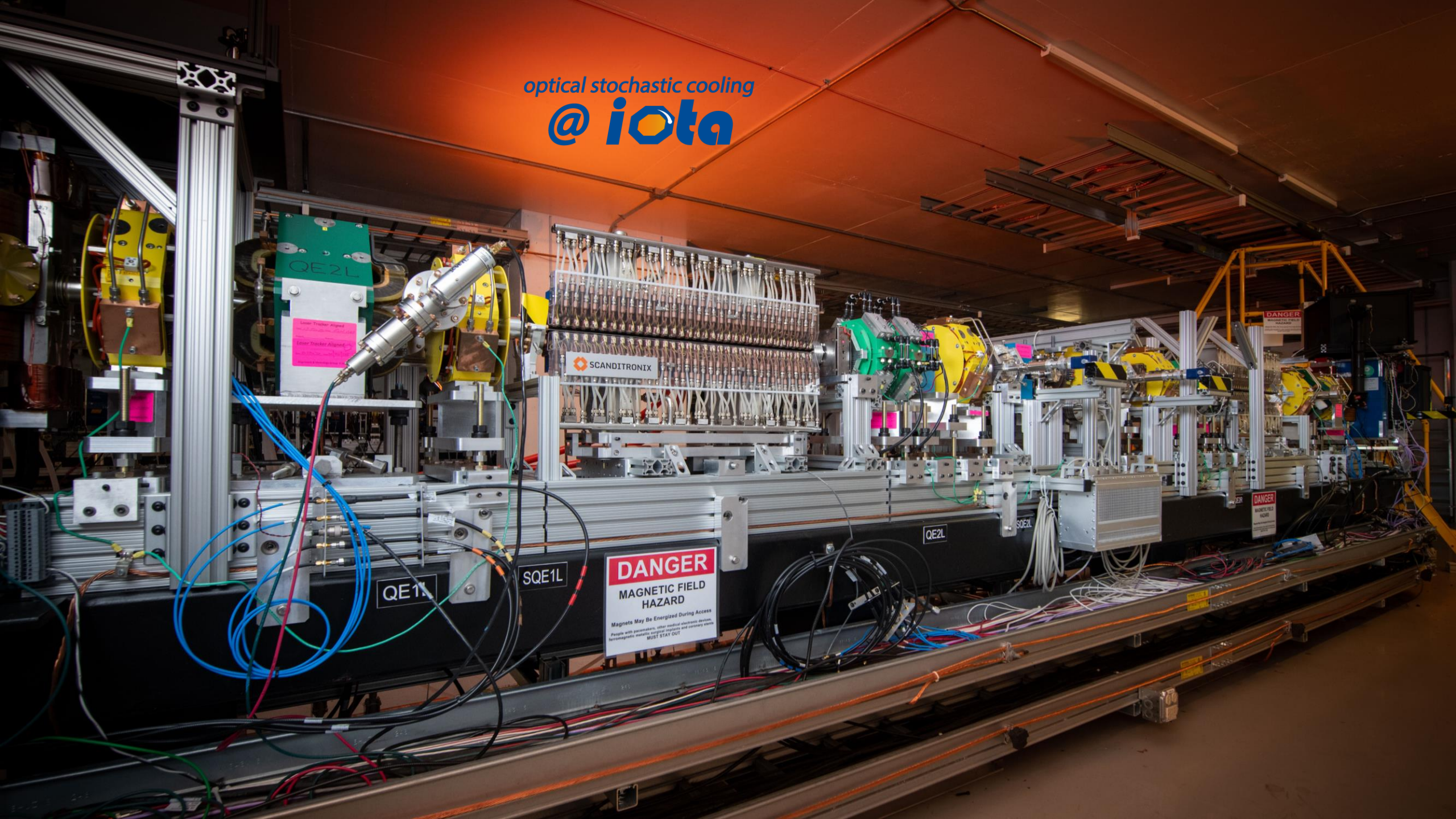


Summary and Timeline

- OSC program has been very successful so far; the underlying physics of the method has been carefully validated, explored and benchmarked
- Amplified OSC is presently in the conceptual and hardware-design phase
- The OSC amplifier is currently under development in the FAST laser lab and high-gain amplification (~1000x) has been successfully achieved in a high-fidelity prototype.
- Methods for OSC-based advanced beam manipulation are under development and will be tested during the amplified-OSC run
- A successful amplified-OSC program opens the way to an immediate experimental attempt at SSMB via the OSX concept.

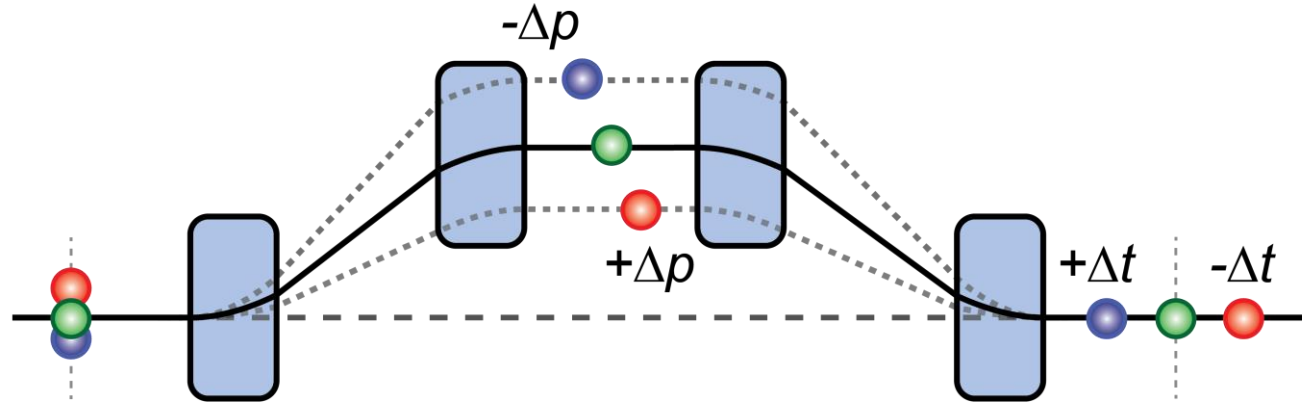


optical stochastic cooling
@ **iota**



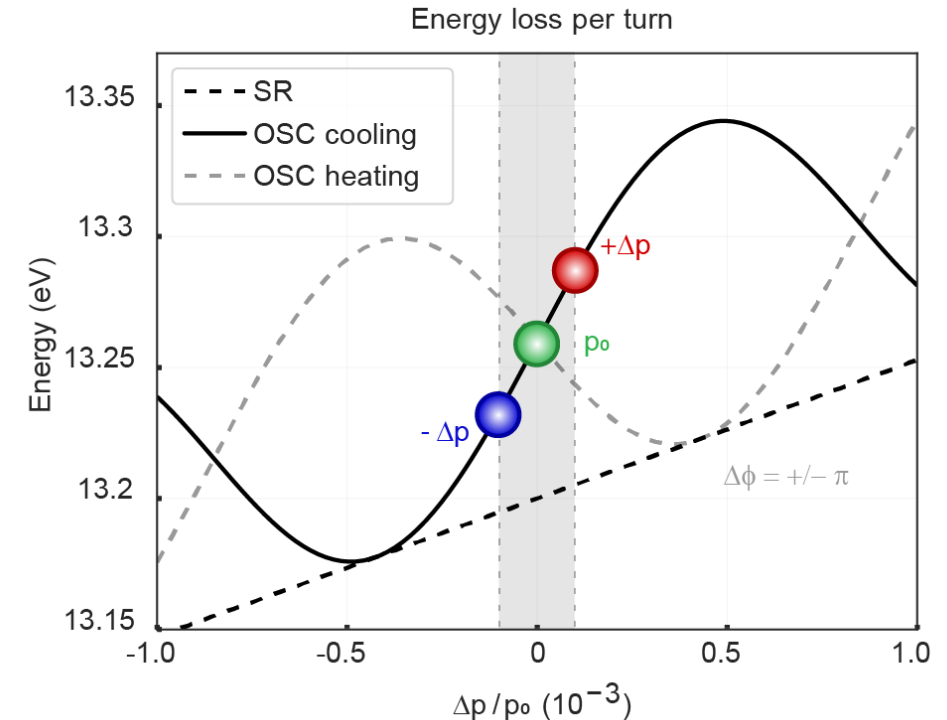
EXTRAS

Reminder: OSC bypass maps momentum errors onto time delay



- Lower (higher) energy particles take a longer (shorter) 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

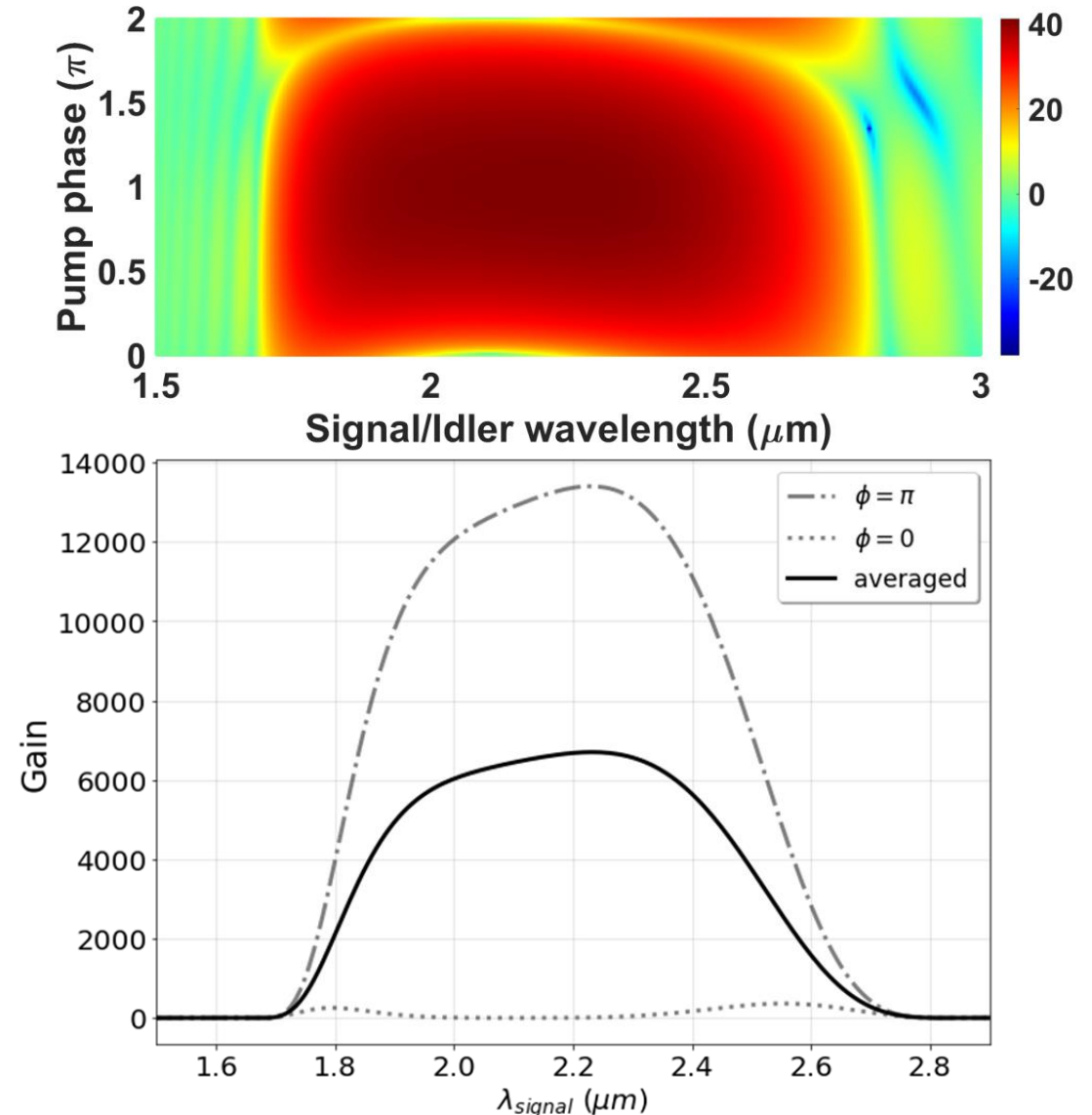
OSC bypass mechanism



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

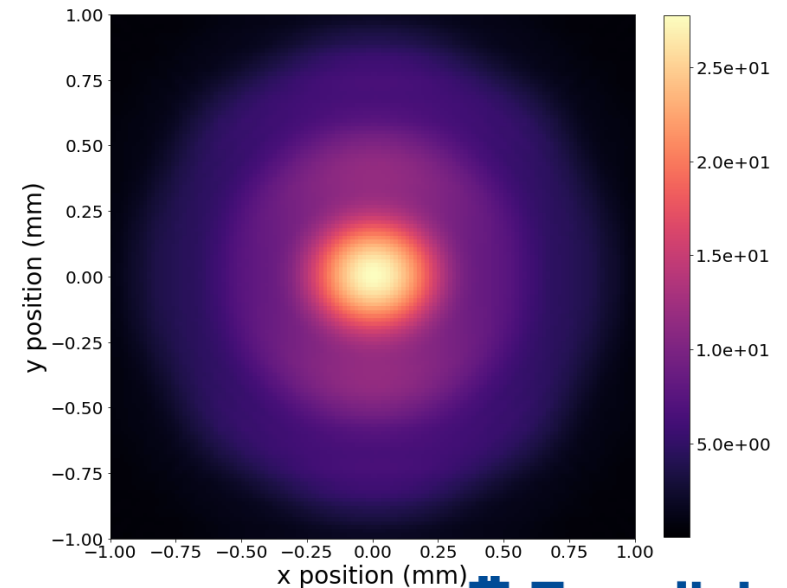
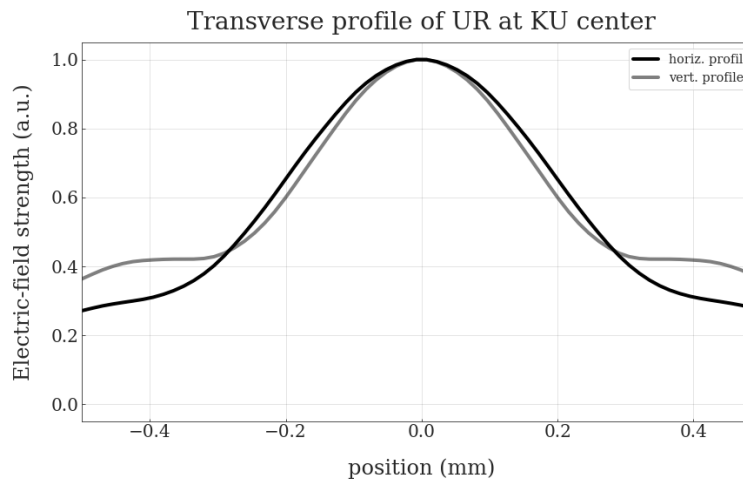
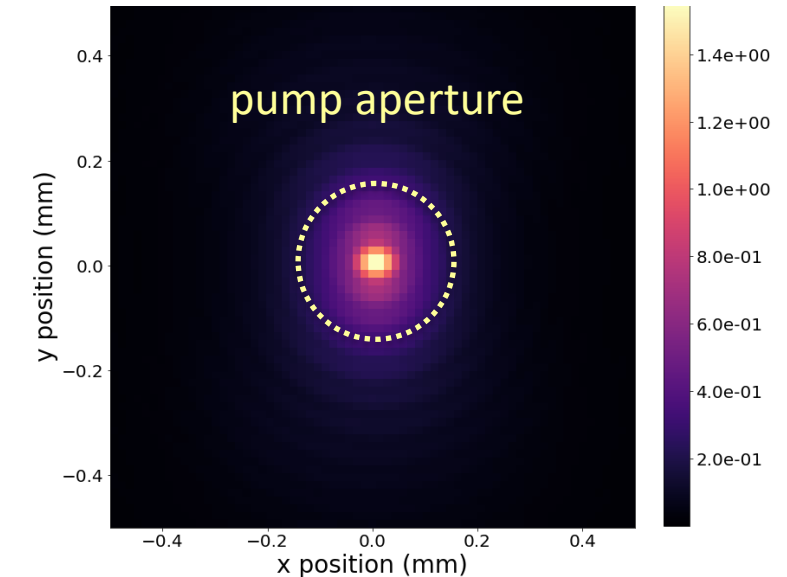
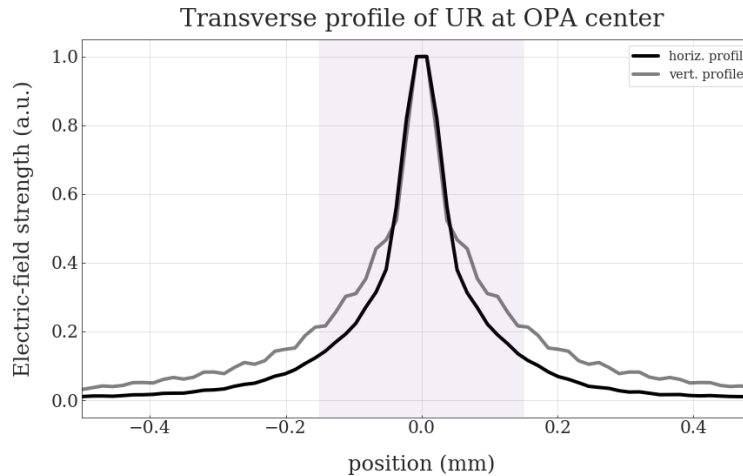
Some issues with an OPA at degeneracy for this application

- For a given pump phase, the signal is amplified and its phase is relatively preserved; however, this requires amplification of the corresponding idler at a specific phase
- Undulator wave packet already has definite amplitude/phase relationships for all “signal-idler pairs”
- Using both sides of degeneracy may scramble the wave packet’s “information;” can still operate on one side of degeneracy at the expense of system bandwidth; ~30% reduction in kick is expected
- Also, random pump phases (effectively due to particle positions) will average total gain down by ~3 dB; kick reduced by $\sim\sqrt{2}$



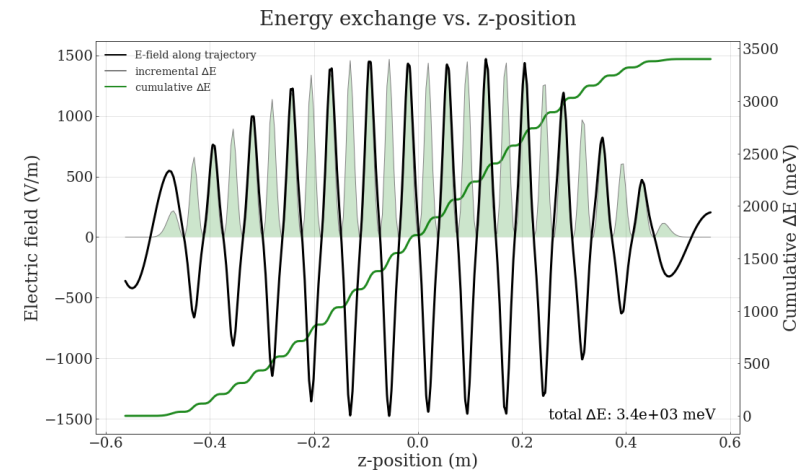
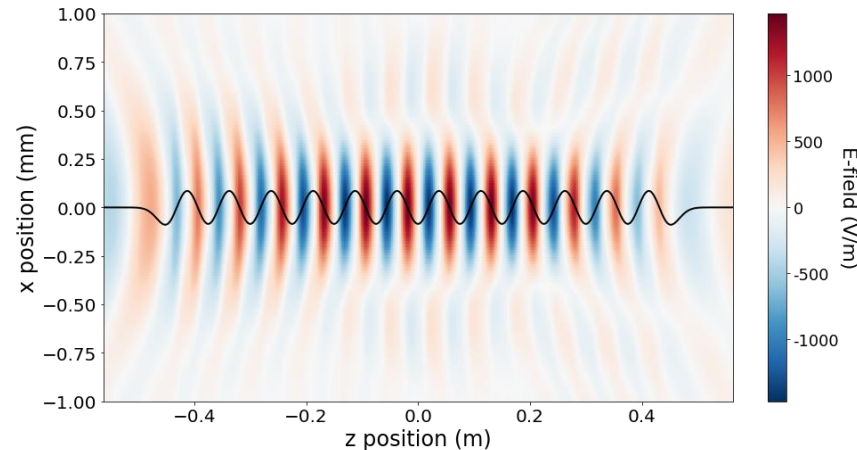
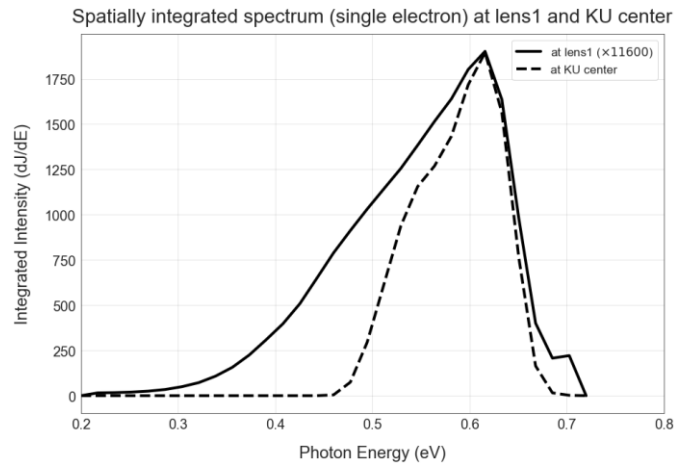
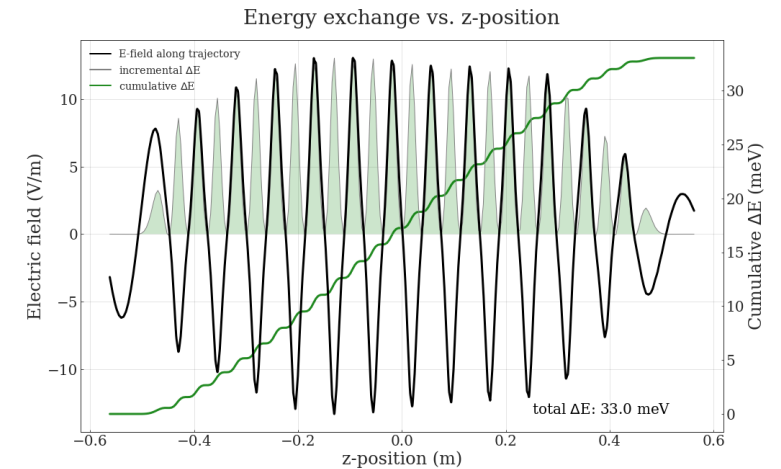
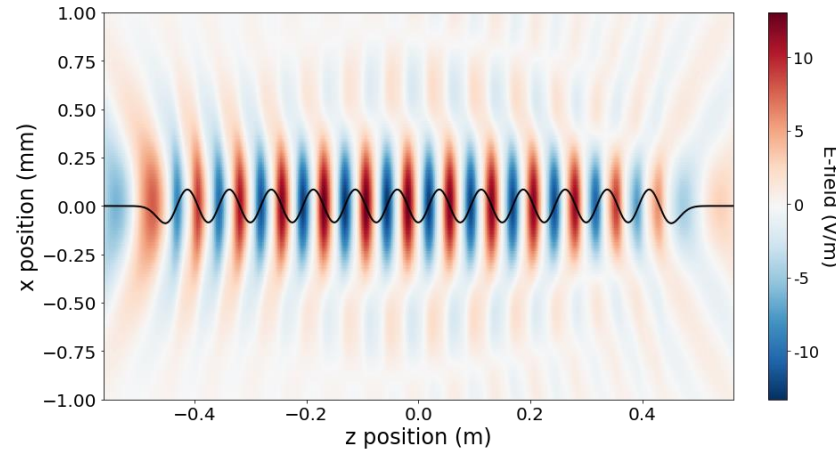
OSC simulations underway for integrated optical system

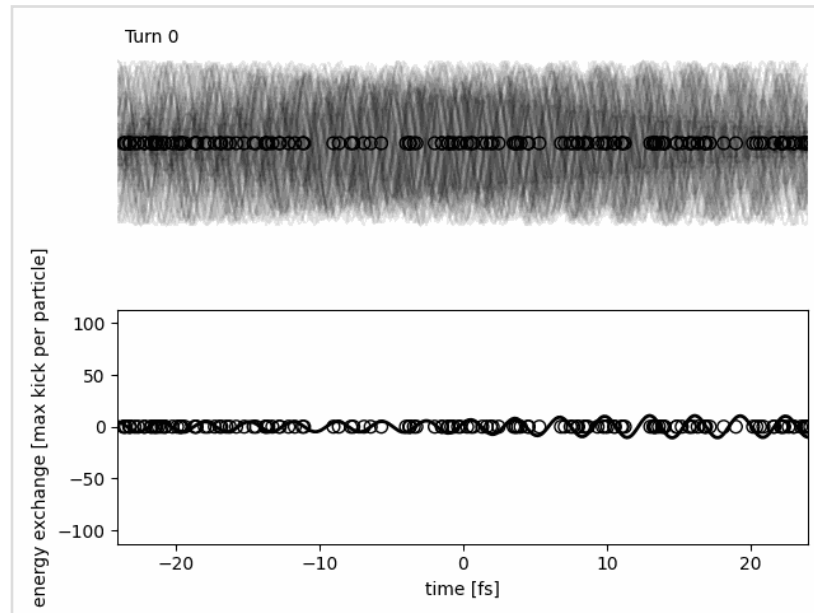
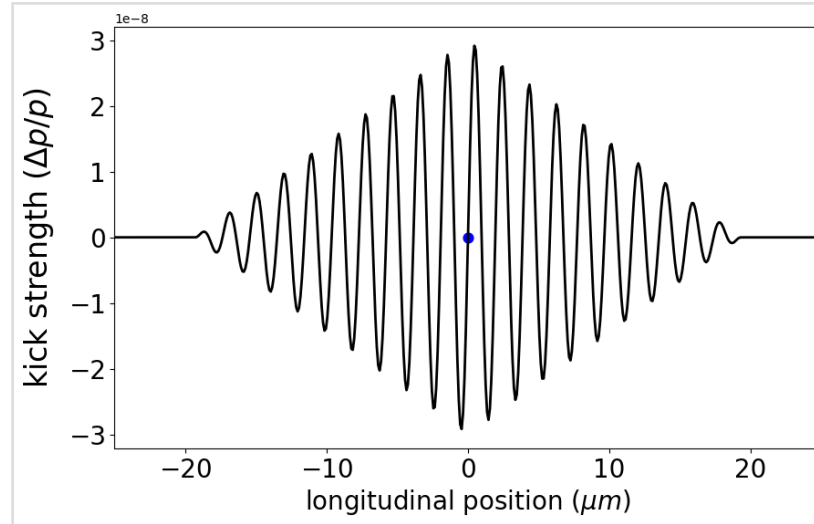
- FWHM of undulator radiation in OPA $\sim 100\text{ }\mu\text{m}$
- For pump with $\sim 30\mu\text{J}$ in 200ps and diameter of $\sim 300\text{ }\mu\text{m}$, should reach $\sim 1\text{GW}/\text{cm}^2$ (required for high gain @ $\sim 30\text{-}40\text{dB}$)
- At the expense of integrated-system bandwidth, pump can be focused further providing up to $\sim 10\text{GW}/\text{cm}^2$
- Damage threshold of PPLN is the primary limitation: $\sim 7\text{GW}/\text{cm}^2$ in the $\sim 10\text{ps}$ regime

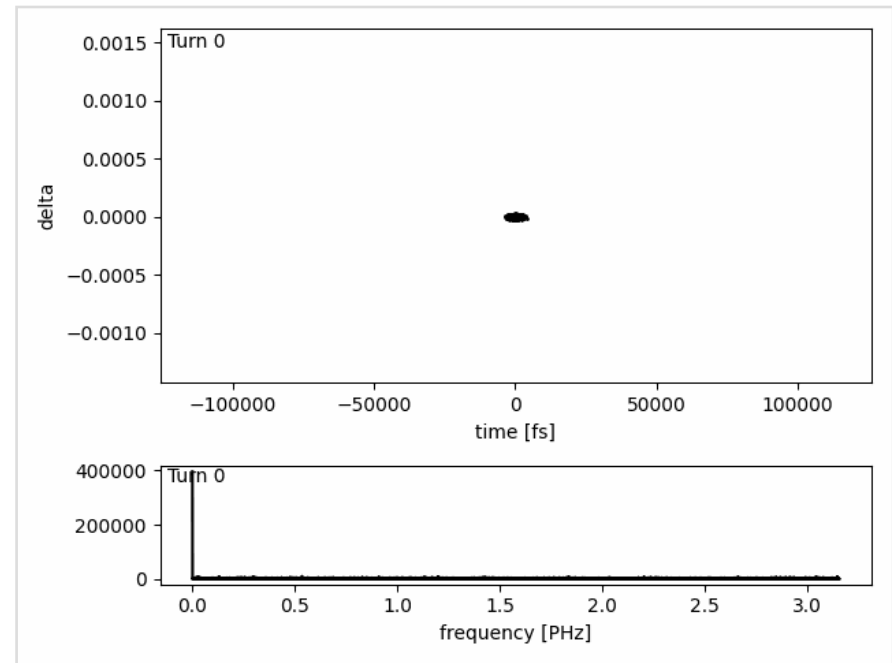
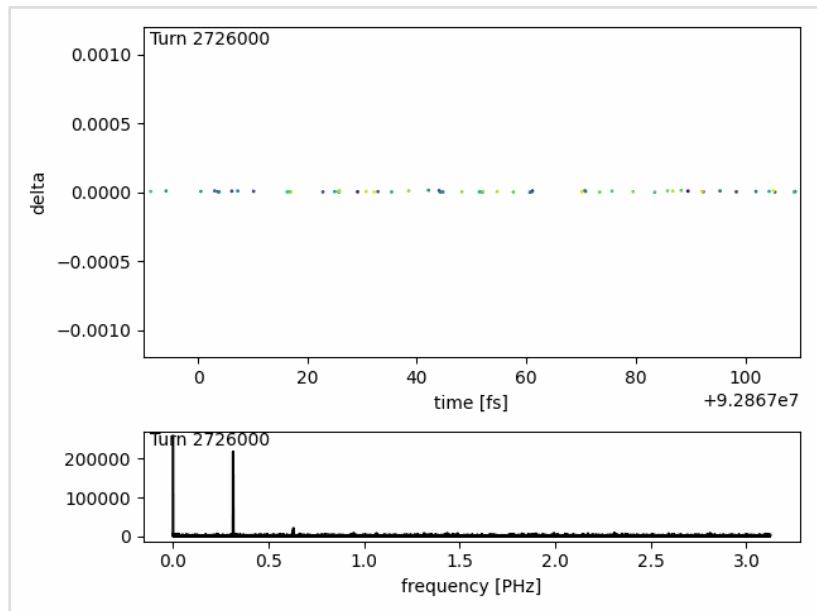
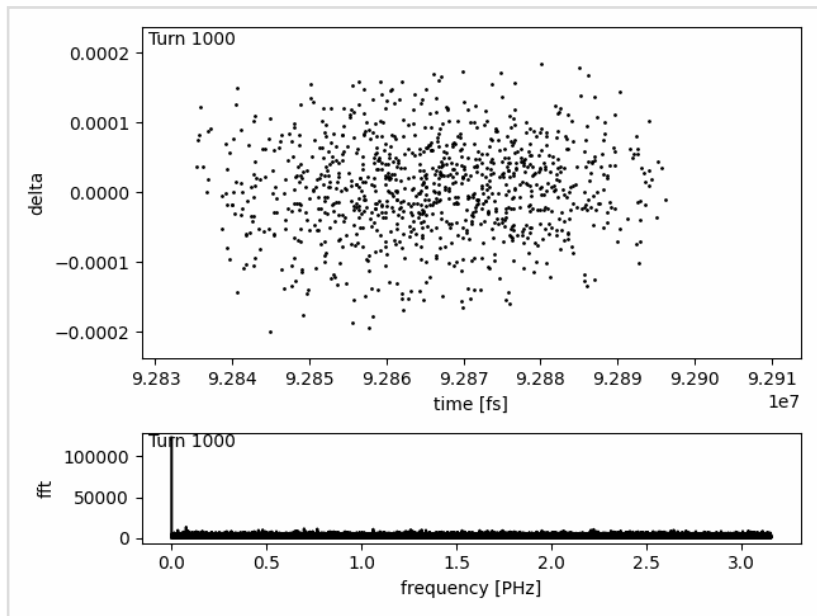


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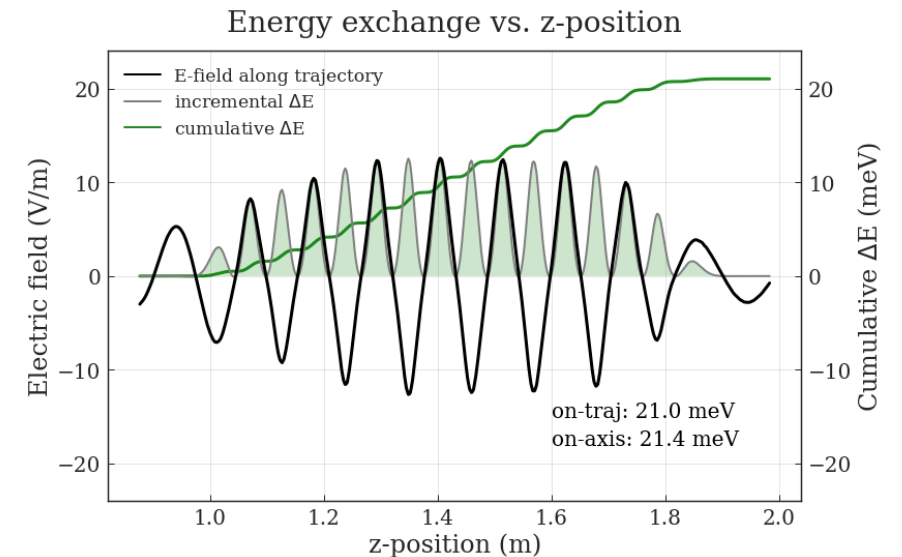
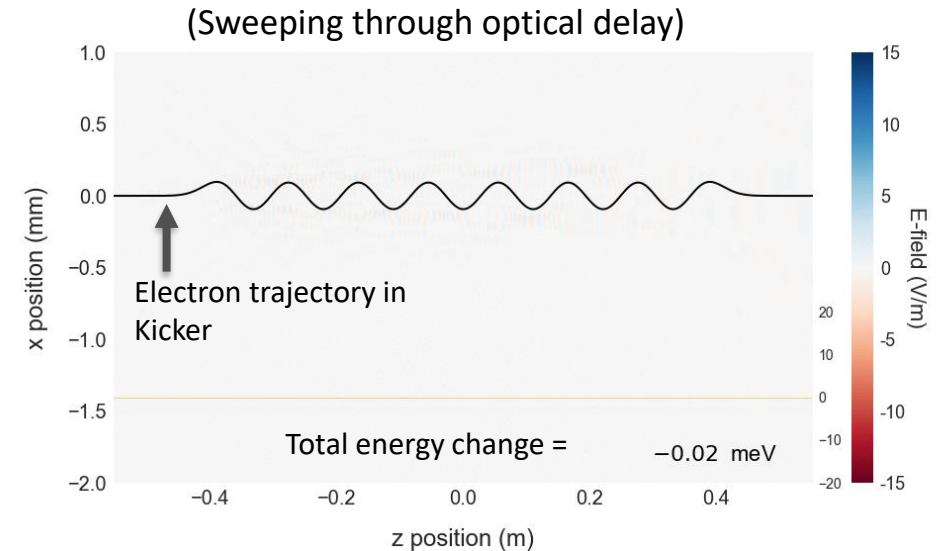






OSC principle: corrective kick based on a particle's error

- 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
- Transit-time OSC produces longitudinal (energy) cooling, but system can be configured for 1D, 2D or 3D cooling:
 - Quads in the bypass can share the 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



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 **$\sim 0.3\ \text{fs}$**

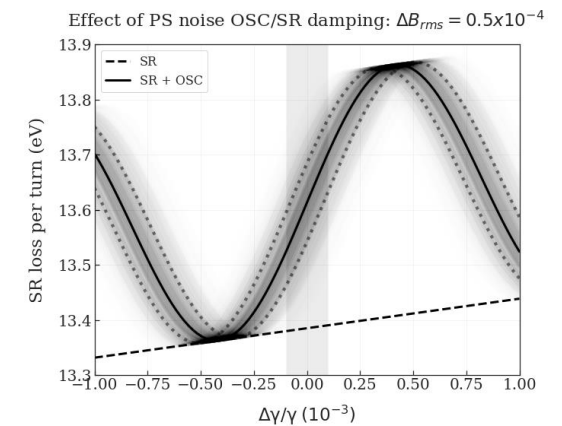
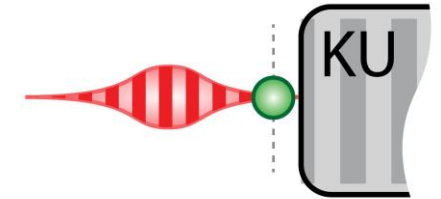
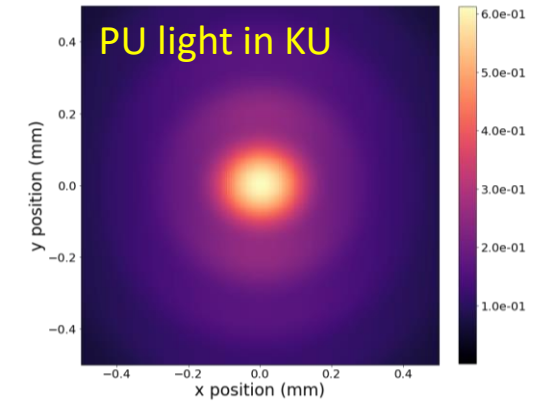
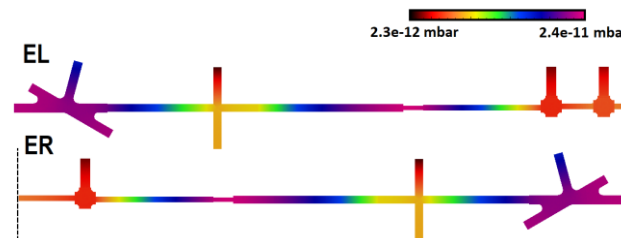
The entire delay system corresponds to $\sim 2000\ \text{fs}$

3. The electron bypass and the light path must be stable to much smaller than the wavelength

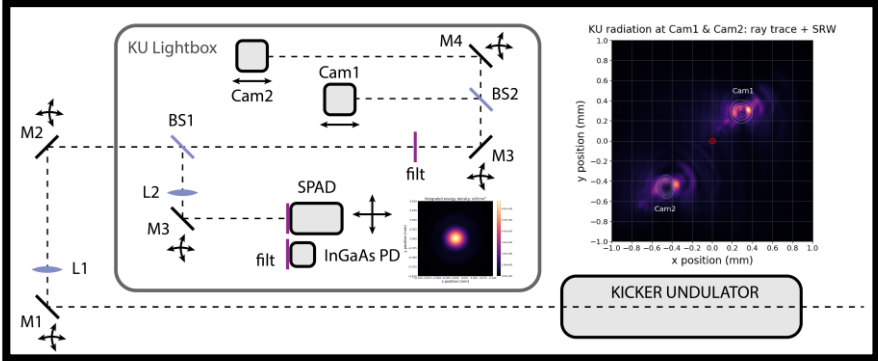
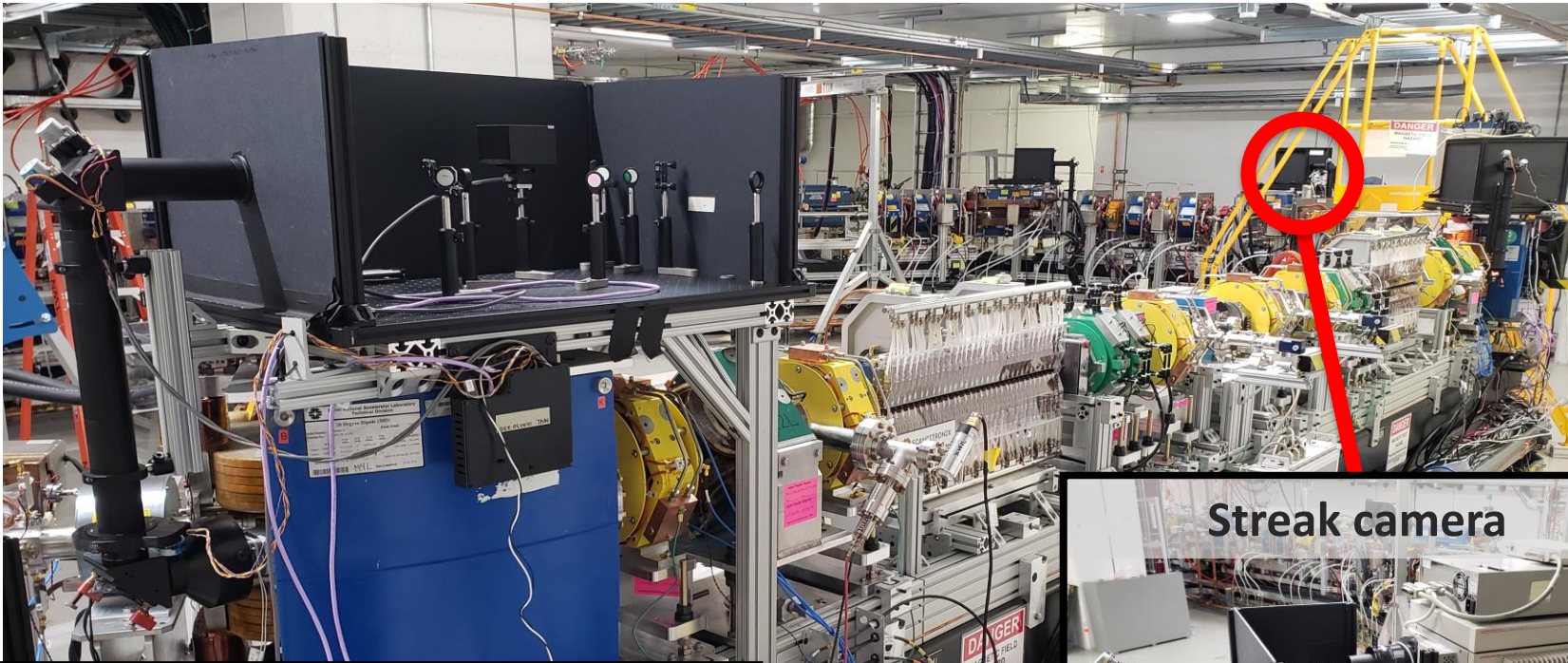
Arrival jitter at the KU should be better than **$\sim 0.3\ \text{fs}$**

This means total ripple+noise in chicane field must be at the **$\sim \text{mid } 10^{-5}$** level

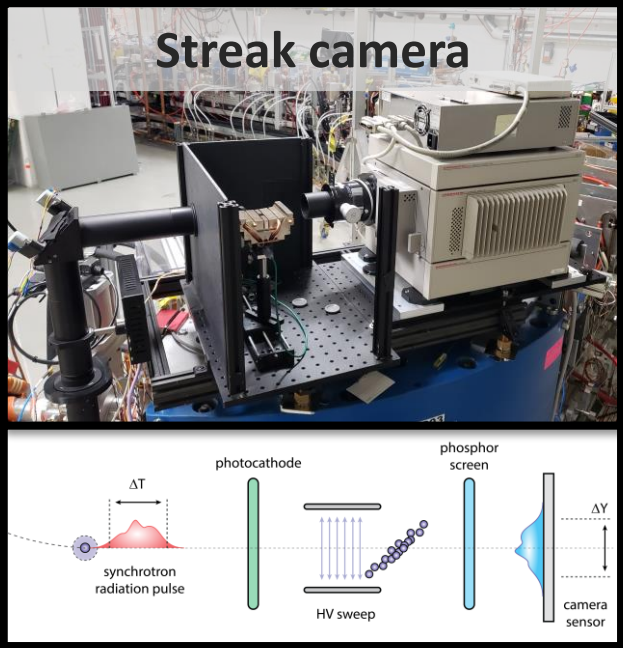
4. Practical considerations of design and integration



OSC is monitored via synchrotron-rad. stations

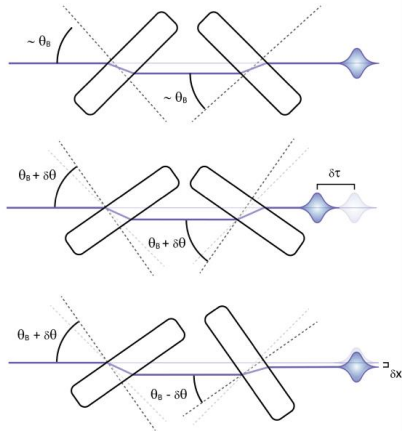


UR (PU+KU) BPMs; SPAD and PMT for $1e^-$

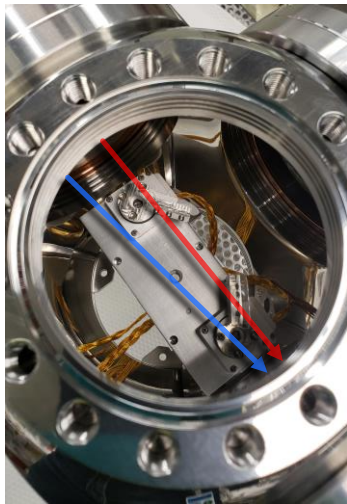


First OSC experiment successfully explored essential physics

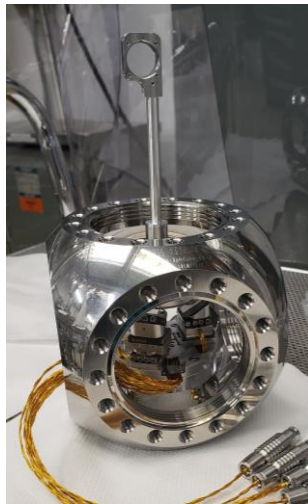
- First OSC: April 20, 2021; End of Run#3: Aug 29, 2021
- Successfully achieved OSC in 1D, 2D and 3D configs
- 100 MeV energy; 10^8 electrons down to a single electron
- 1- μm design wavelength and no optical gain
- ~30-THz Bandwidth for the integrated OSC system
- Simple optical system with single lens, delay plates and a total delay of ~0.65 mm
- Initial results reported in 08/11/22 issue of Nature



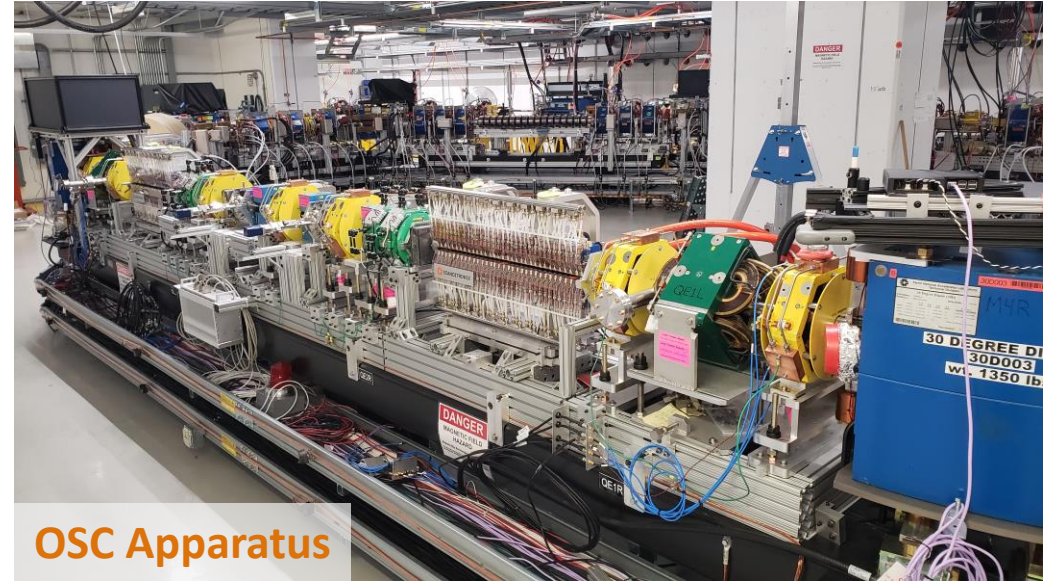
Delay stage



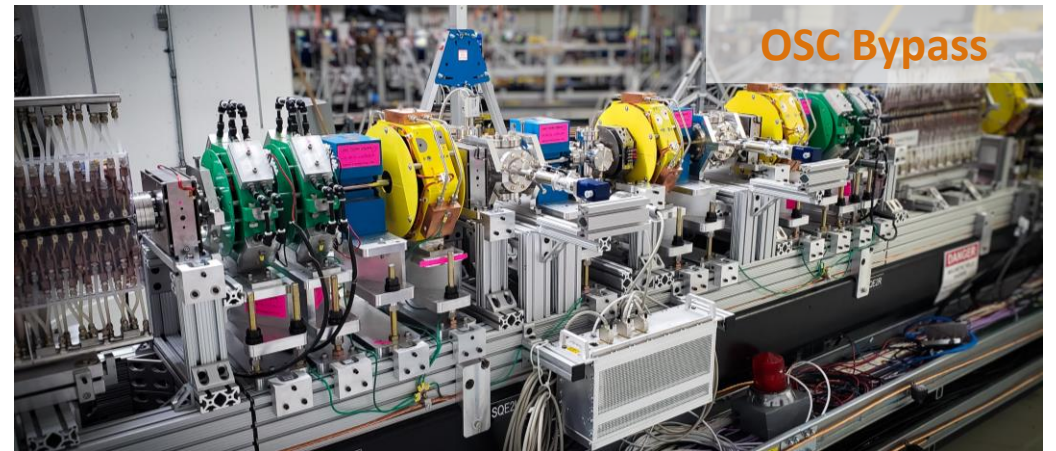
Delay stage



lens stage

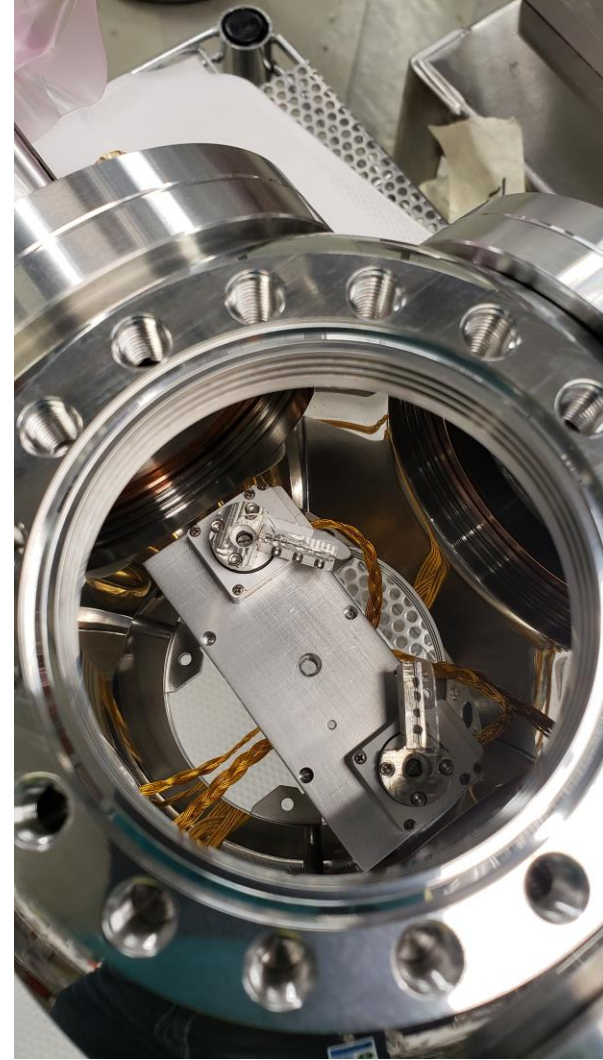
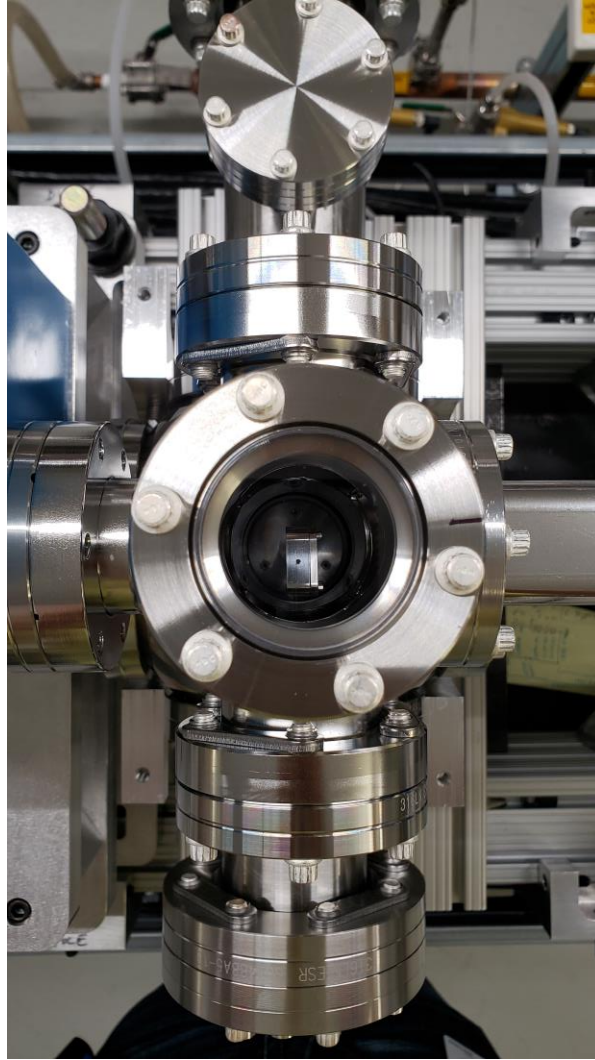
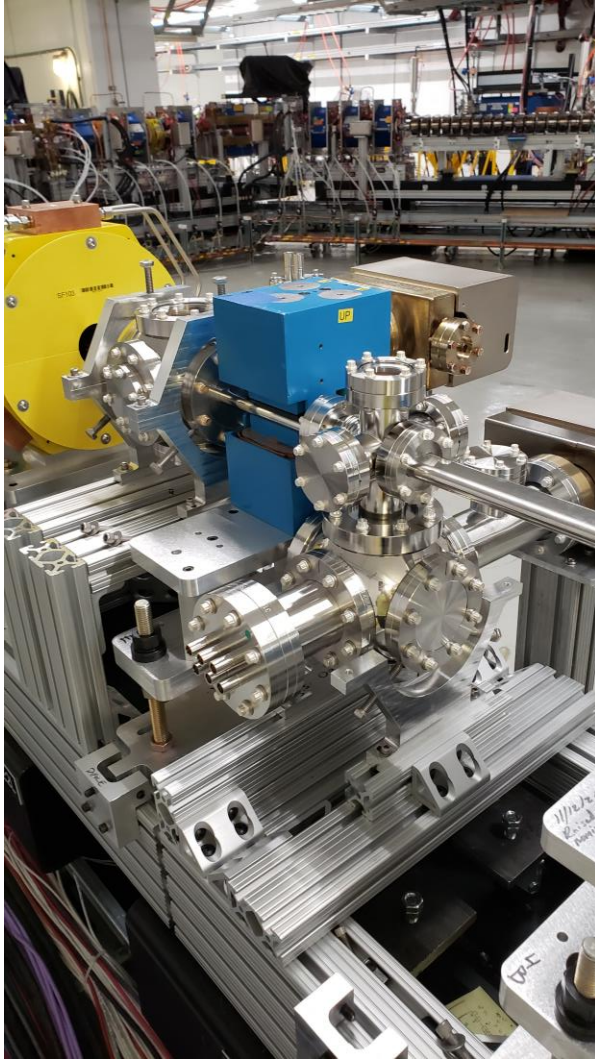


OSC Apparatus

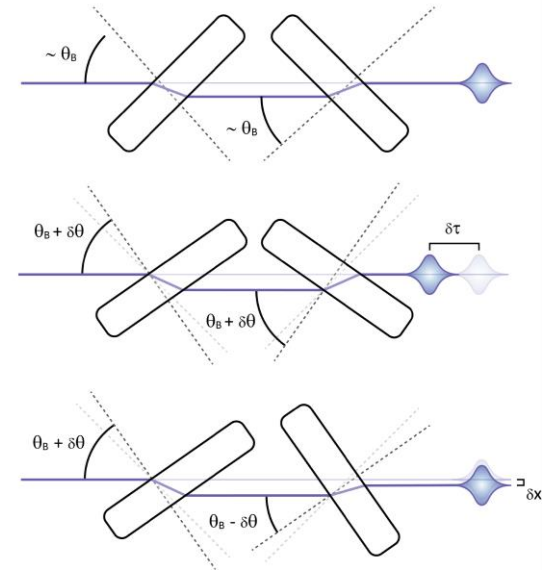
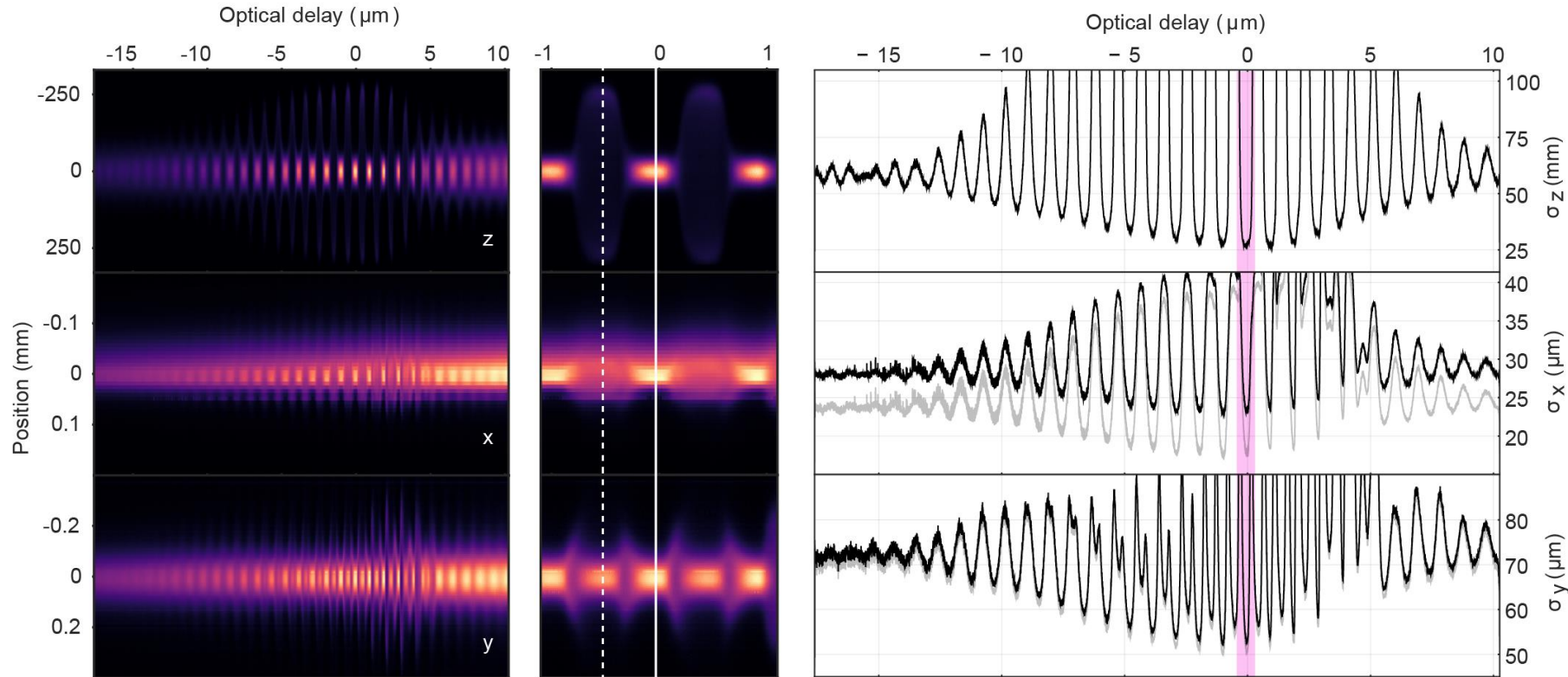


OSC Bypass

Optics and in-vacuum motion for passive OSC

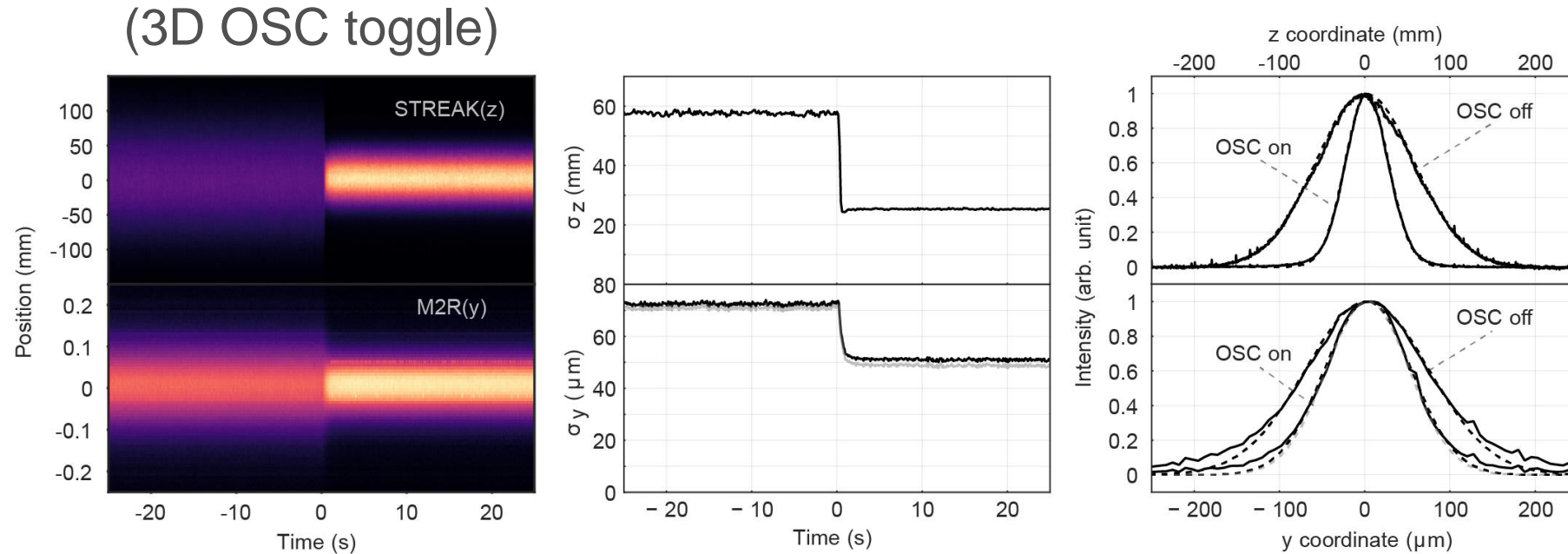


OSC system demonstrated excellent performance and expected structure



- 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 ~ 30 -THz bandwidth (**$\sim 7000\times$ greater than conventional stochastic cooling**)

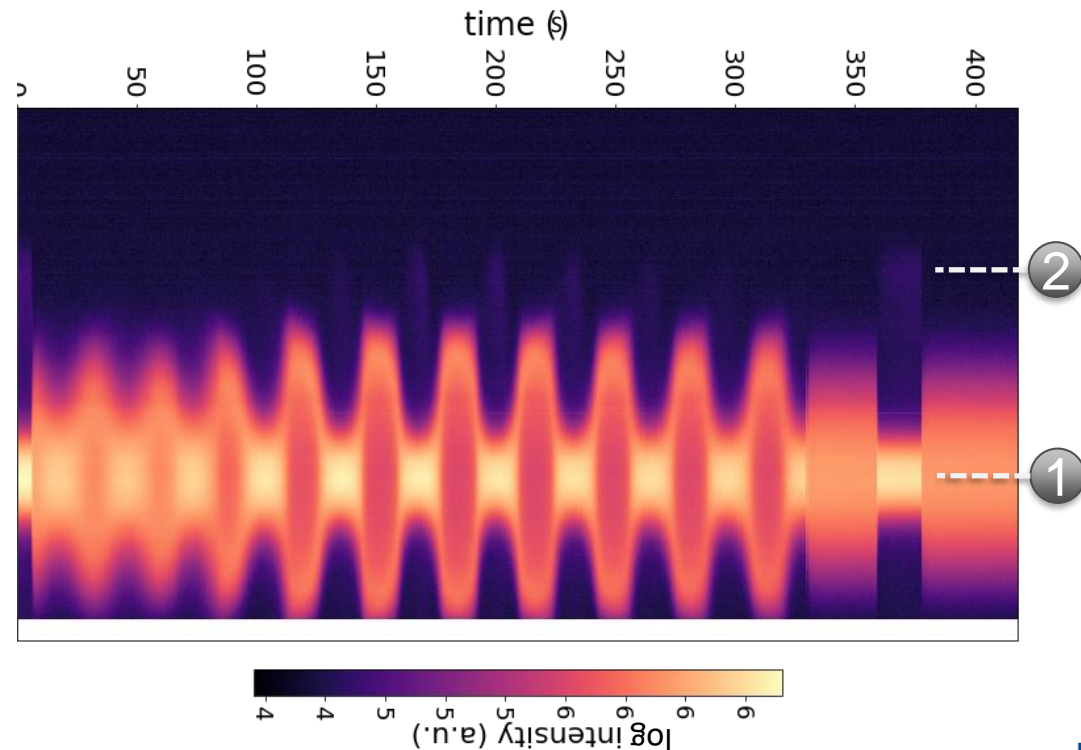
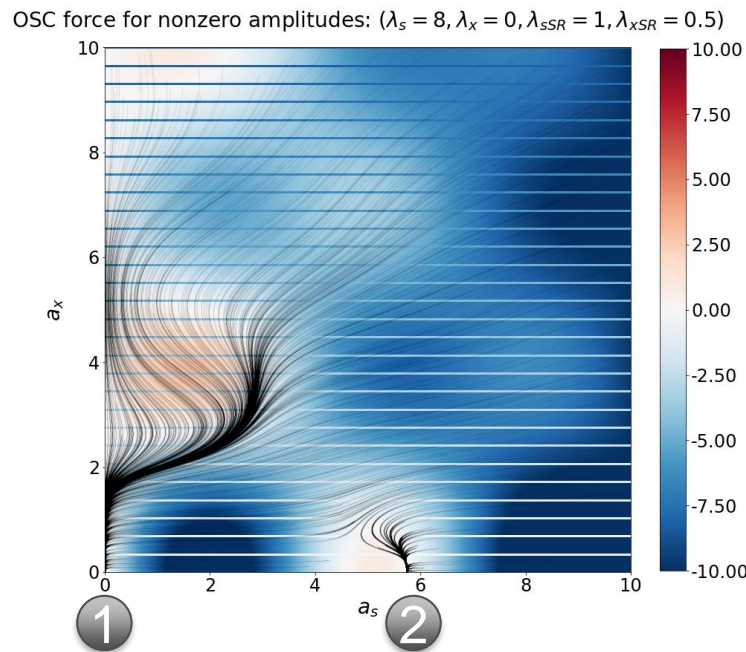
OSC force was an order of magnitude larger than SR damping



- 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); subsequent OSC simulations suggest agreement to $\sim 10\%$
- Similar strength for 2D and 1D configurations

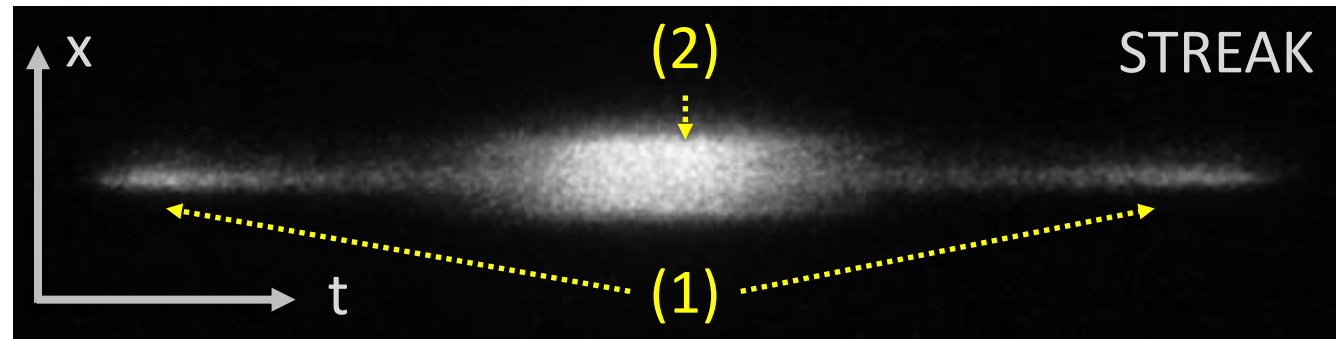
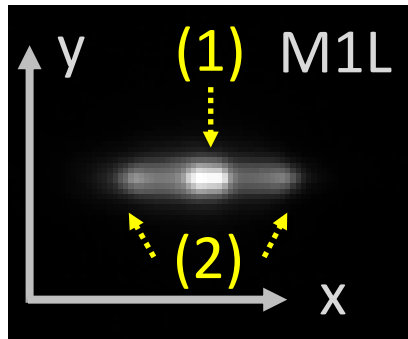
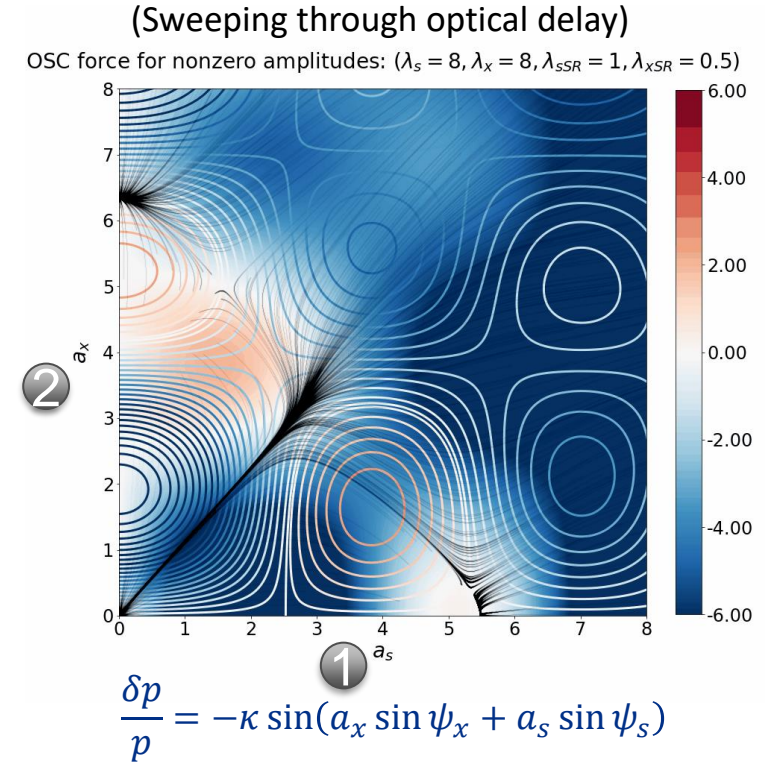
Clear observation of expected OSC zone structure

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



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



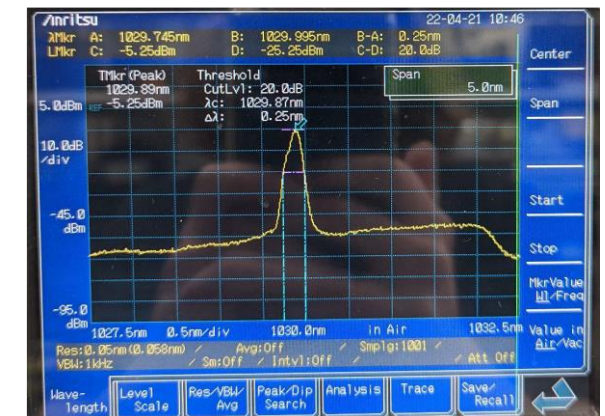
Transverse and longitudinal projections for heating mode of 2D OSC

New, all-fiber pump laser from Optical Engines

- Was originally developed for next-gen laser notcher
- New system was tested at manufacturer under conditions required for amplified OSC experiment
- Demonstrated: ~200-ps pulses @ 7.5 MHz; ~33 uJ/pulse (250-W avg output) – i.e. **can pump every turn**
- Very clean spectrum, $\sigma_\lambda \sim 0.1 \text{ nm}$, under operational conditions
- Performance limited by heating of fiber and mirror
- Some testing also performed at ~1% duty factor; some increase in performance is possible with additional effort
- **Arbitrary turn-by-turn programmability:** enabling capability for advanced beam control experiments

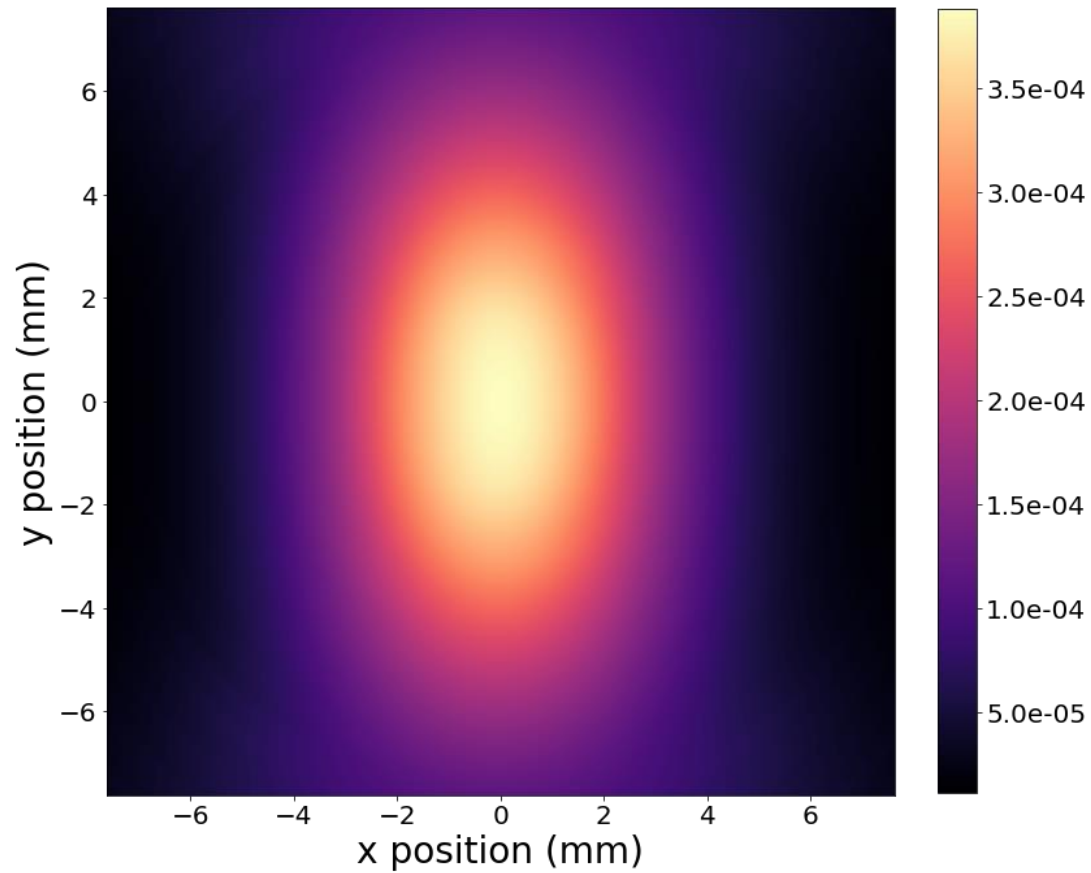


Original laser system for FNAL linac laser notcher



OE spectral measurement @250W

Integrated energy density at first Lens: eV/mm²



Integrated energy density at L2: eV/mm²

