Phase-space Tailoring using Optical Stochastic Cooling

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Overview

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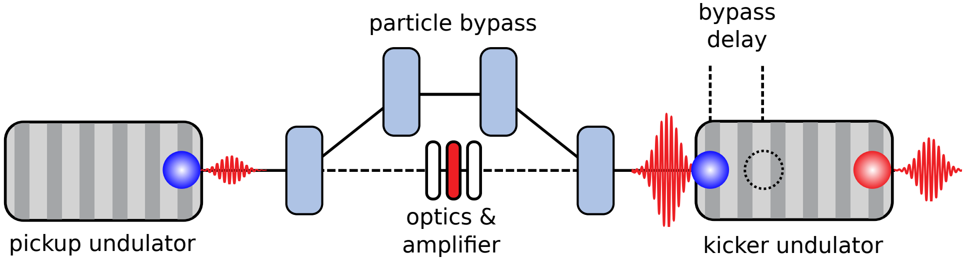
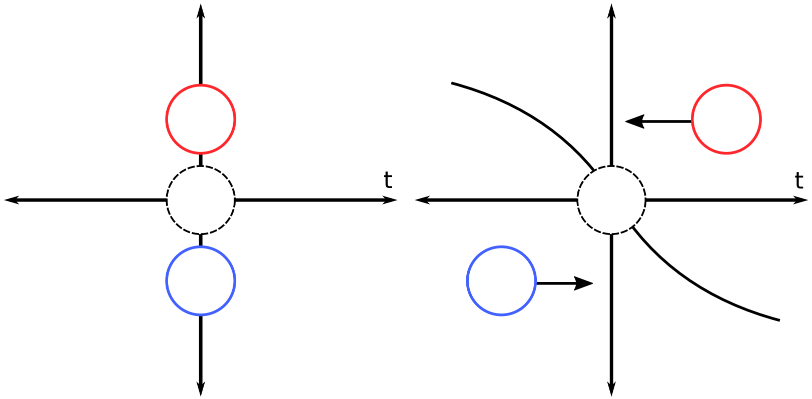
- Description of the OSC Mechanism and storage ring dynamics
- Amplified OSC and two shaping methods
- Simulation Methods and a new storage ring design
- Complications, nonlinear effects, and scattering
- Simulated Results
- Characterization of radiation and light source applications

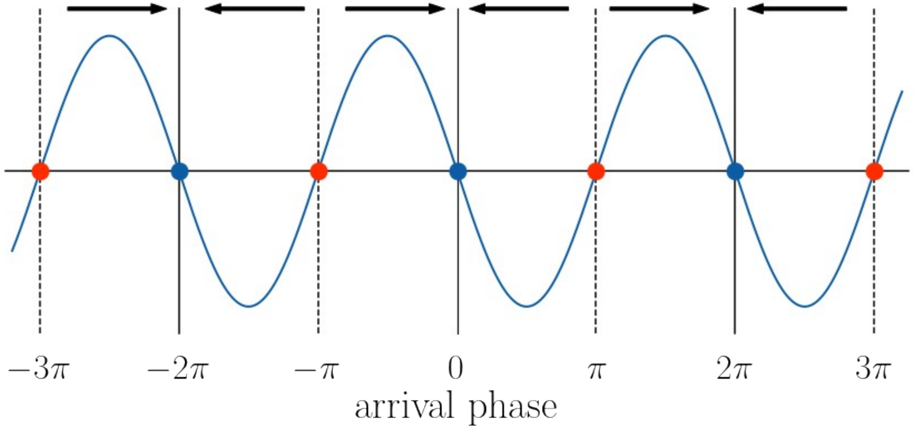
Optical Stochastic Cooling

- OSC uses a particle's own radiation to correct momentum deviation



- The chicane bypass introduces a momentum dependence to the path length between undulators
- The arrival phase between the particle and its radiation determines the strength and direction of the kick





OSC Heating and Optical Delay

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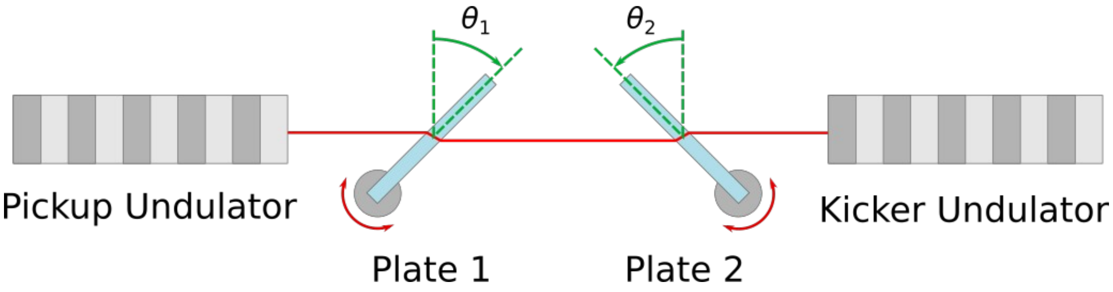
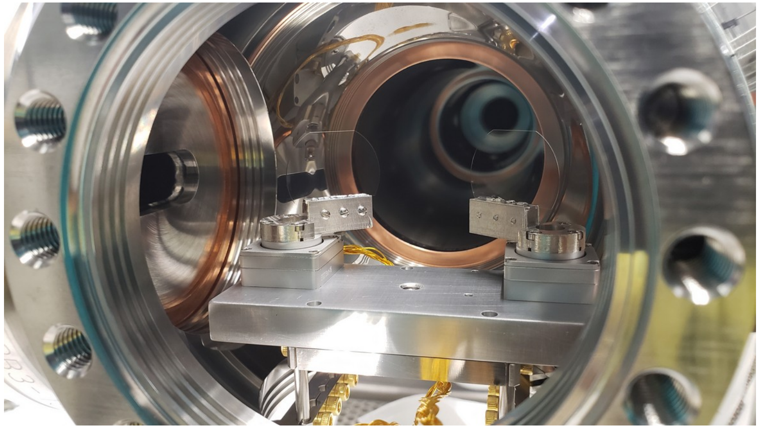
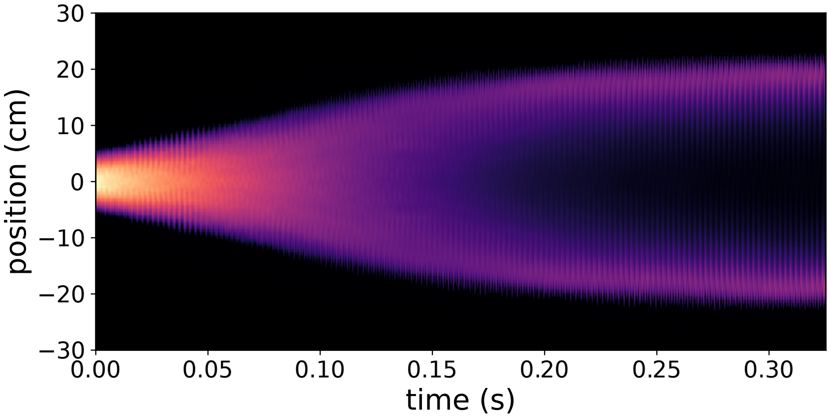
- The OSC experiment uses a pair of glass plates to control the optical delay



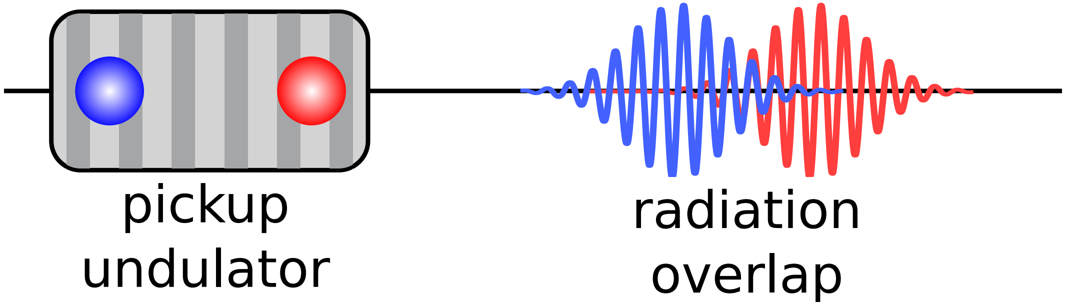
- By setting the optical delay to half of the radiation wavelength, particles are heated away from the design momentun

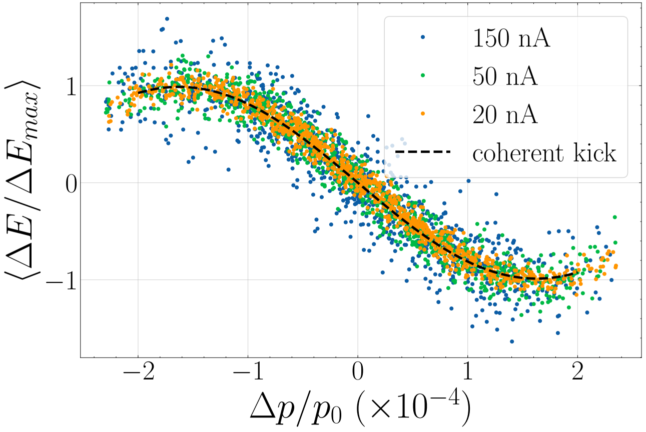


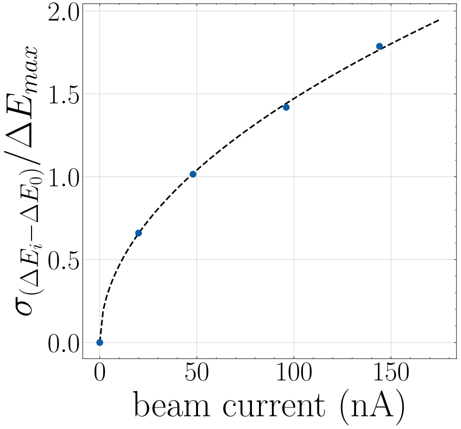


Incoherent Effects

- An individual particle will interact with the fields of its neighboring particles as well
- As the particle density increases, more particles will be in each slice and the incoherent contribution to cooling will grow
- This is the ultimate limit of stochastic cooling and the primary motivation for using optical wavelength

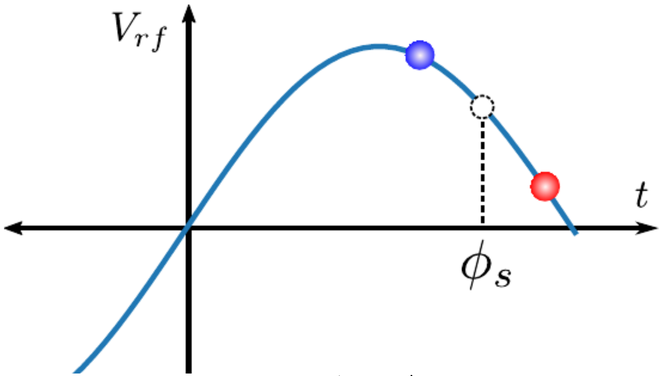


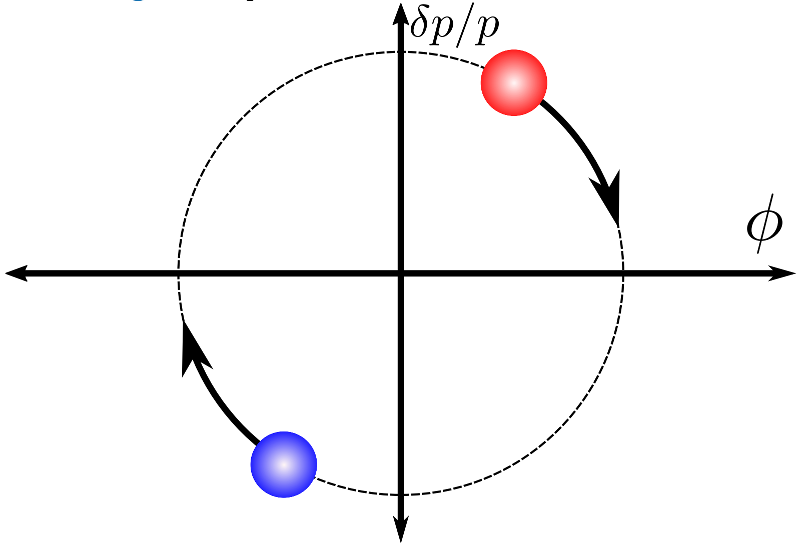




Longitudinal Motion in Rings

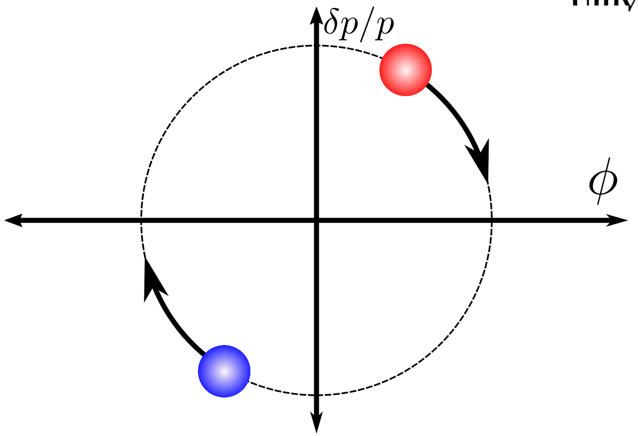
- The RF system in a storage ring is responsible for keeping the beam together as it naturally spreads out
- It applies a force depending on the position in the bunch causing slow particles to speed up and fast particles to slow down
- Particles orbit the design momentum in LPS with a predictable frequency

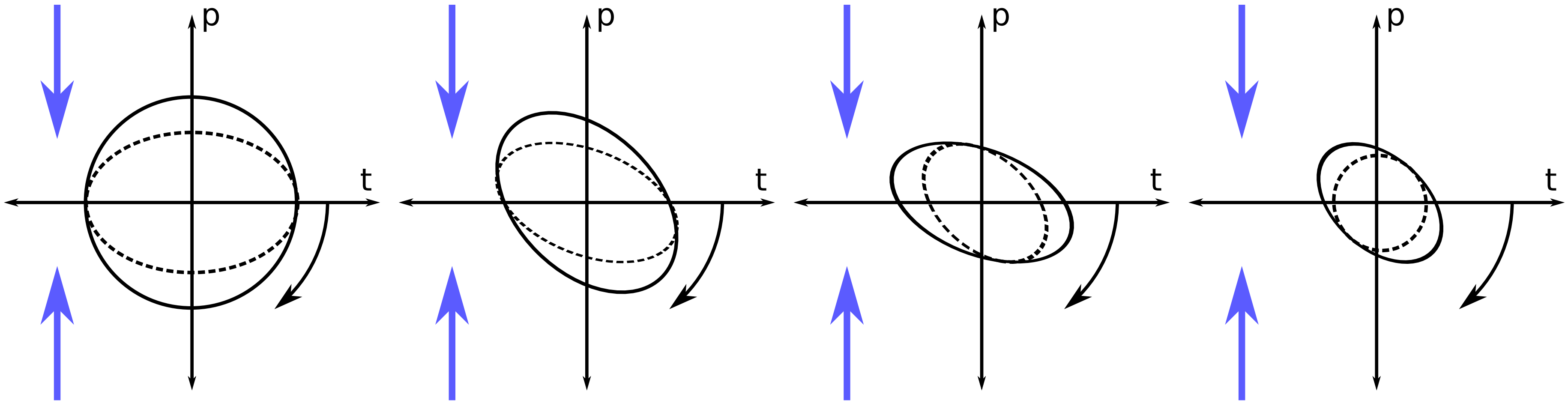




OSC in Phase Space

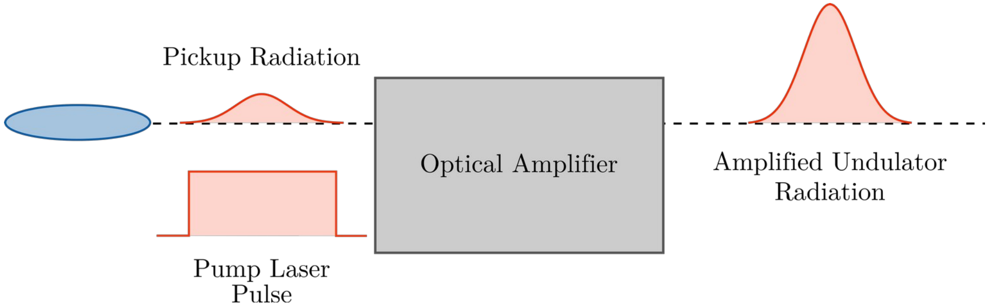
- The OSC kick only affects the momentum of the particle
- As the beam orbits due to synchrotron motion, the LPS area is reduced

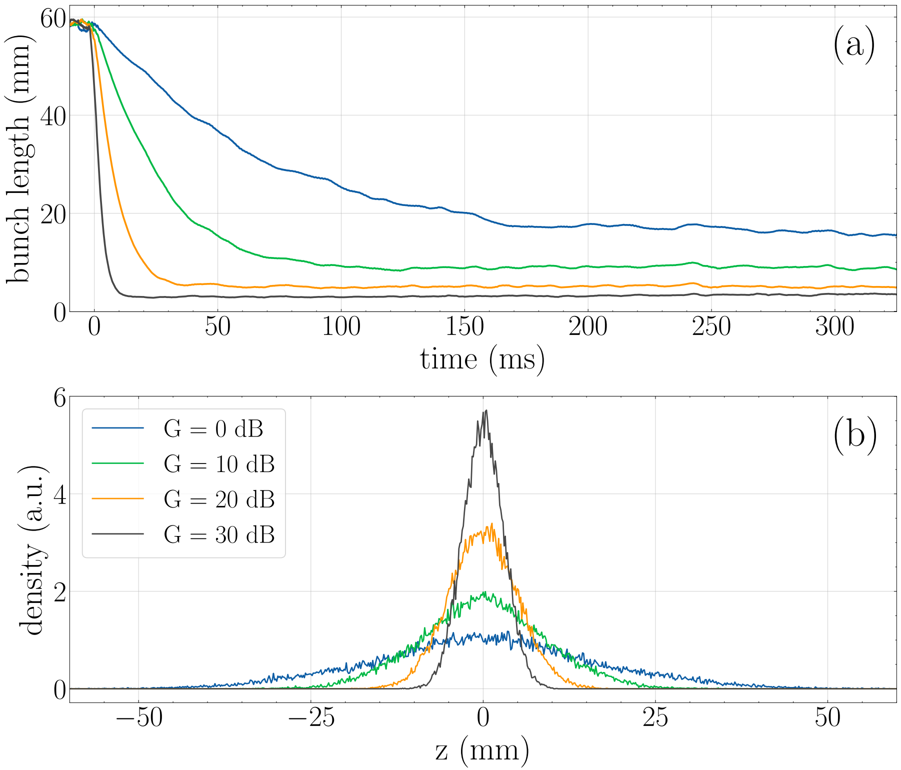




Amplified OSC

- The undulator radiation can be amplified using an optical amplifier



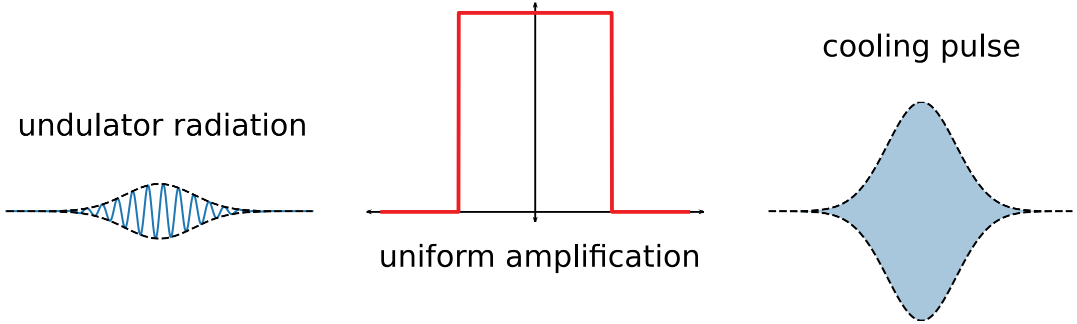


- The amplified radiation produces a larger kick, speeding up the OSC process
- We can use the pump laser to control the phase space of the beam

OSC Shaping Methods

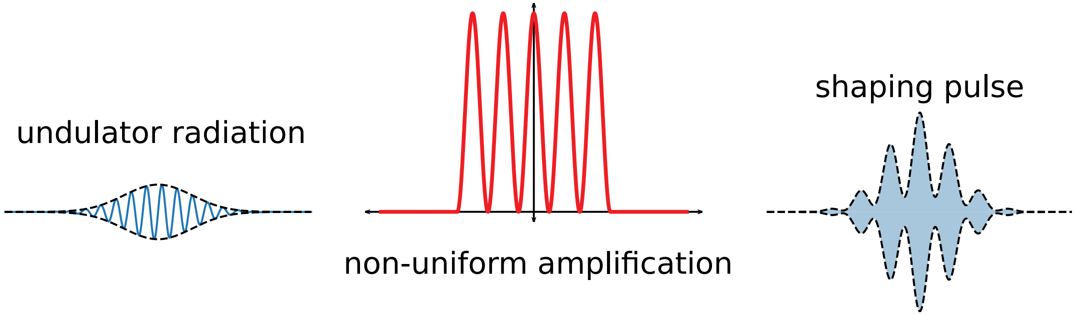
Slow-Modulation

- The amplification is uniform but may vary from turn to turn
- Usually as a function of the synchrotron phase



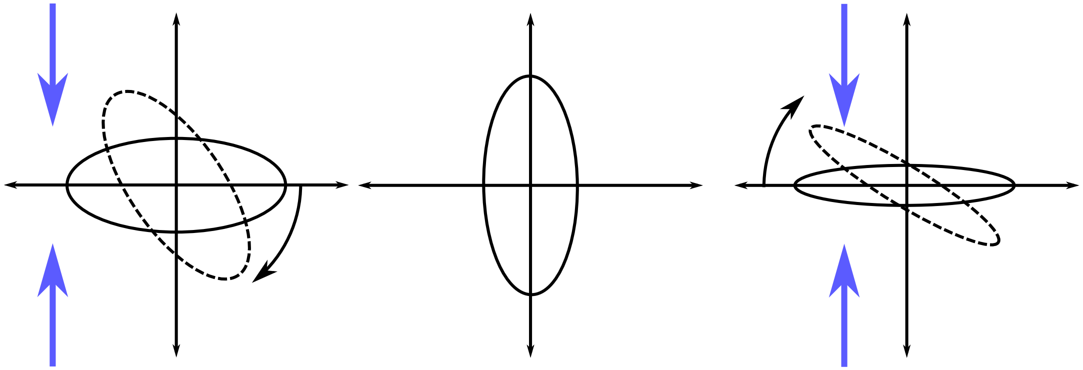
Fast Modulation

- The shape of the pump laser pulse is modulated
- This targets cooling to specific longitudinal regions of the beam

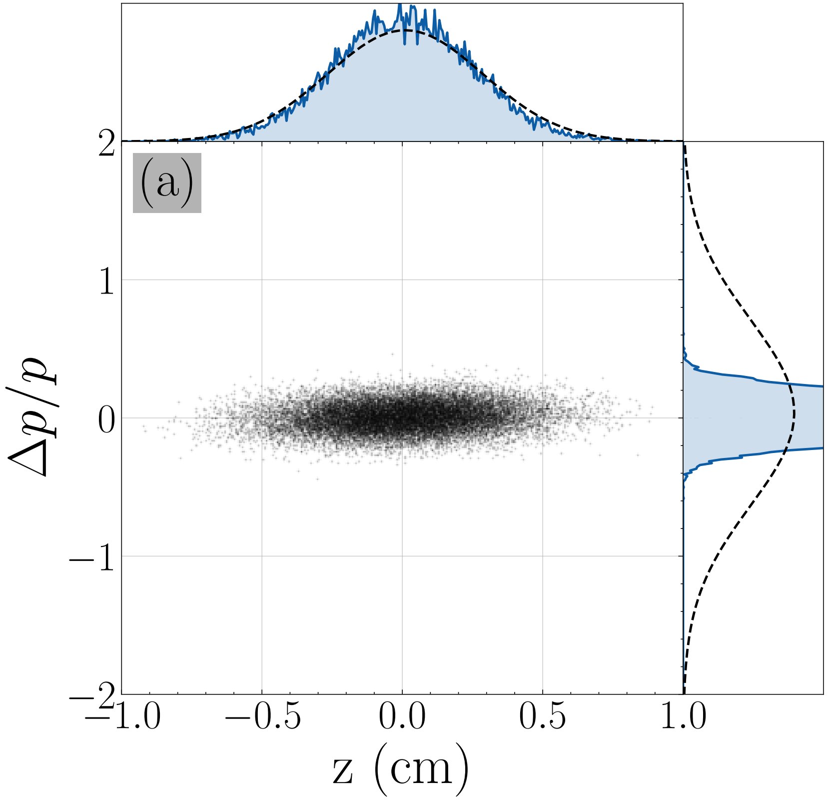


Momentum Spread Reduction

- Slow-modulation can be used for reducing a single degree-of-freedom

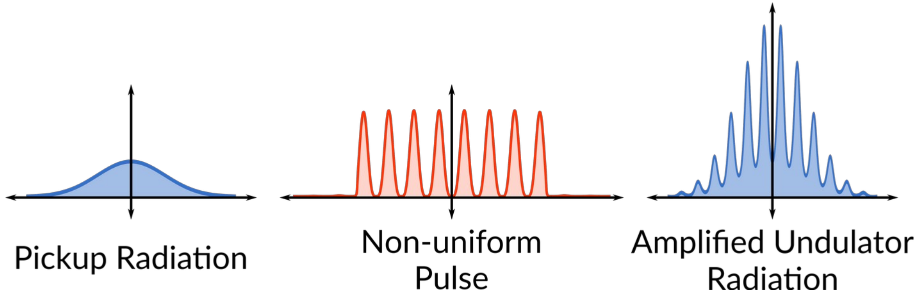


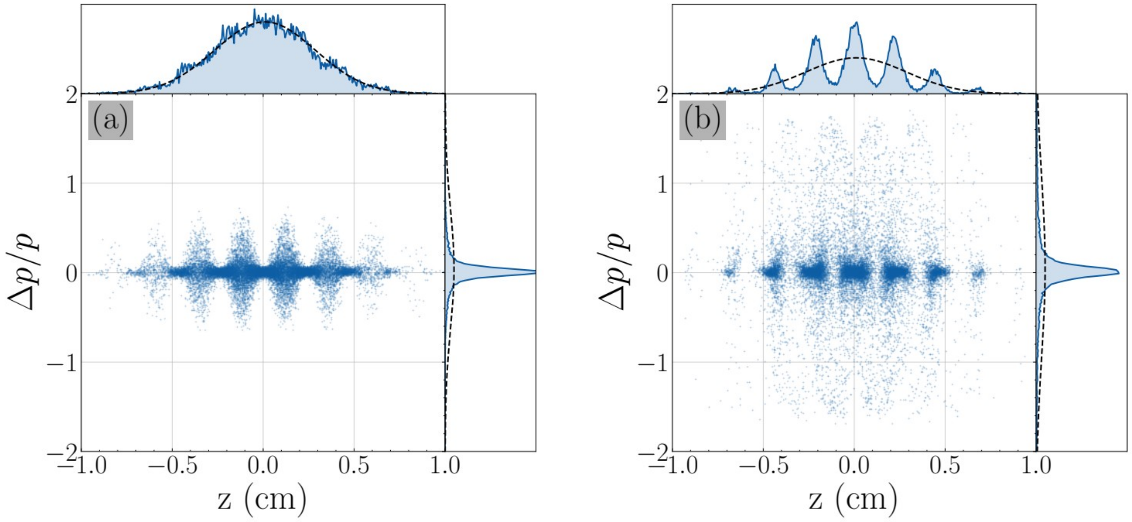
- Here the kick is amplified only at the top of every synchrotron period

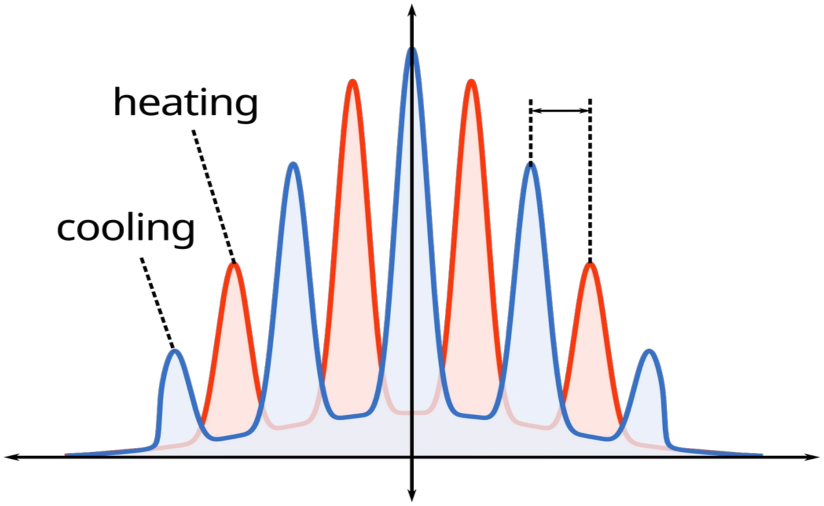


Targeted Cooling and Heating

- Fast-modulated shaping is used to target cooling to specific regions of the beam
- It can also be used to target heating

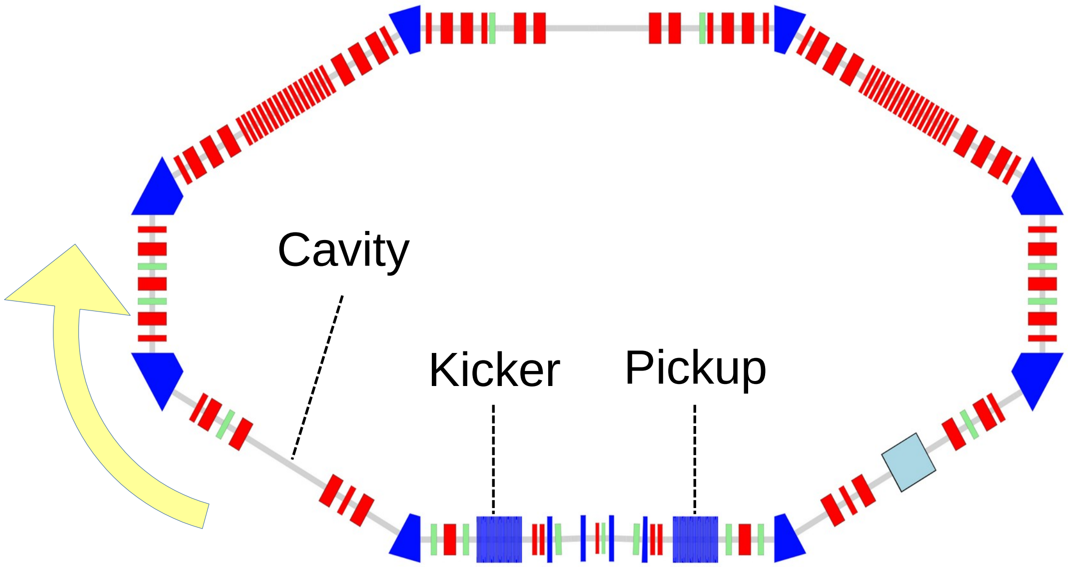


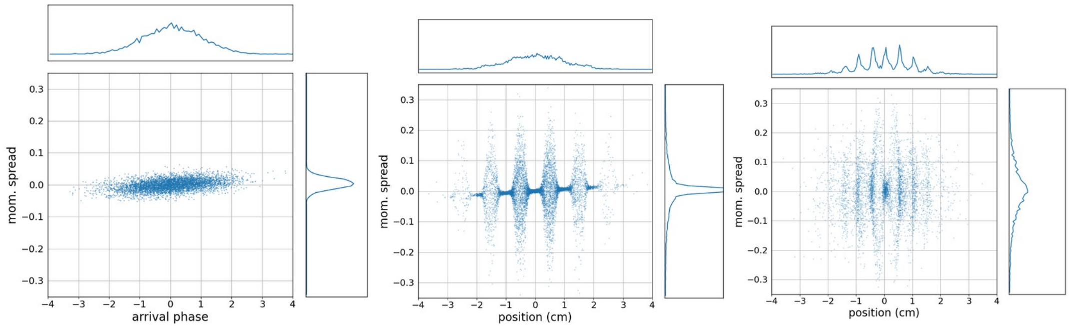




Simulation Methods

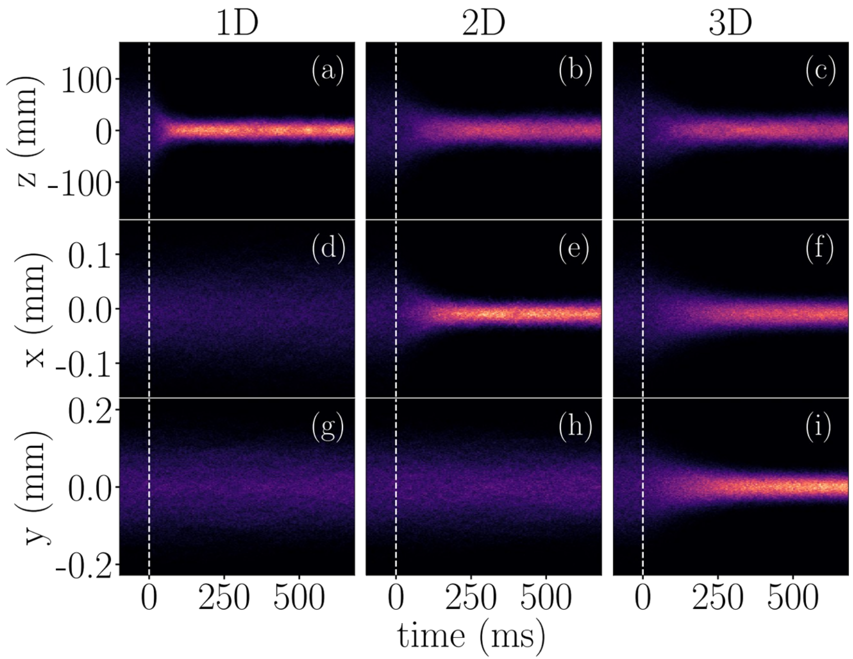
- A simple toy-model is made up of t transfer matrices between 3 points
  - Pickup to Kicker
  - Kicker to RF Cavity
  - RF Cavity to Pickup
- At each location a kick is applied corresponding to the OSC kick, RF Cavity restoring force, and diffusive effects
- This model is quick but lacks more complex effects

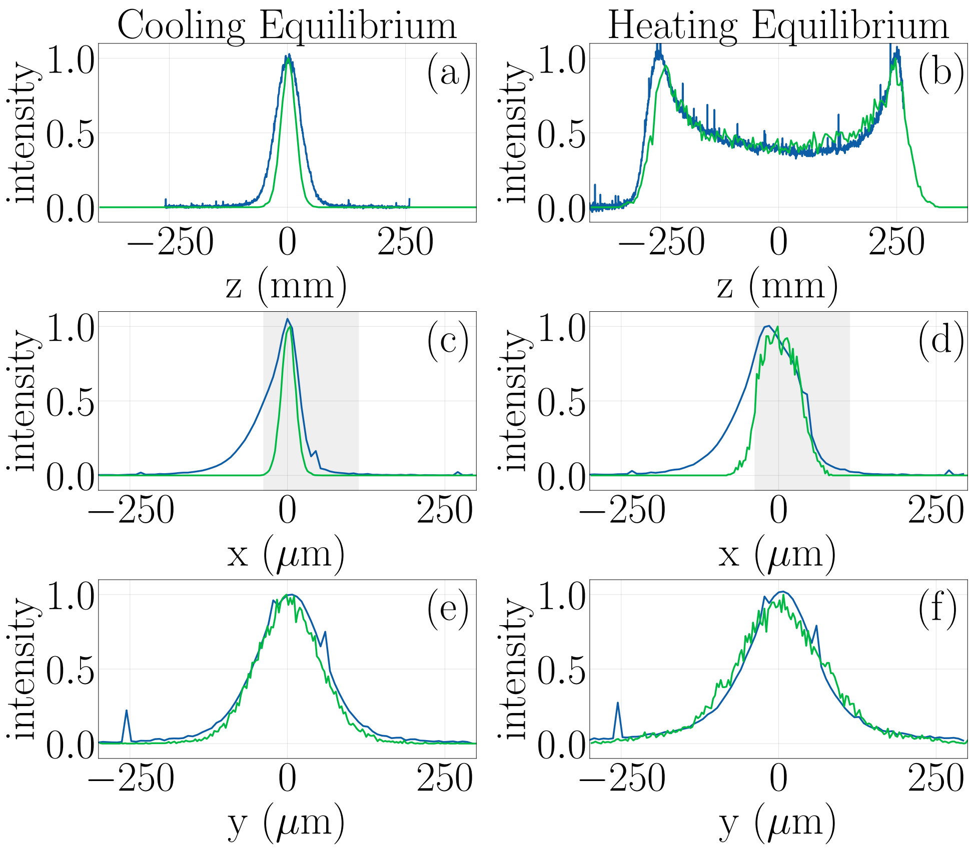




ELEGANT Model of OSC

- We developed a computational model of OSC in the particle tracking code ELEGANT





IOTA vs. OSC-SR

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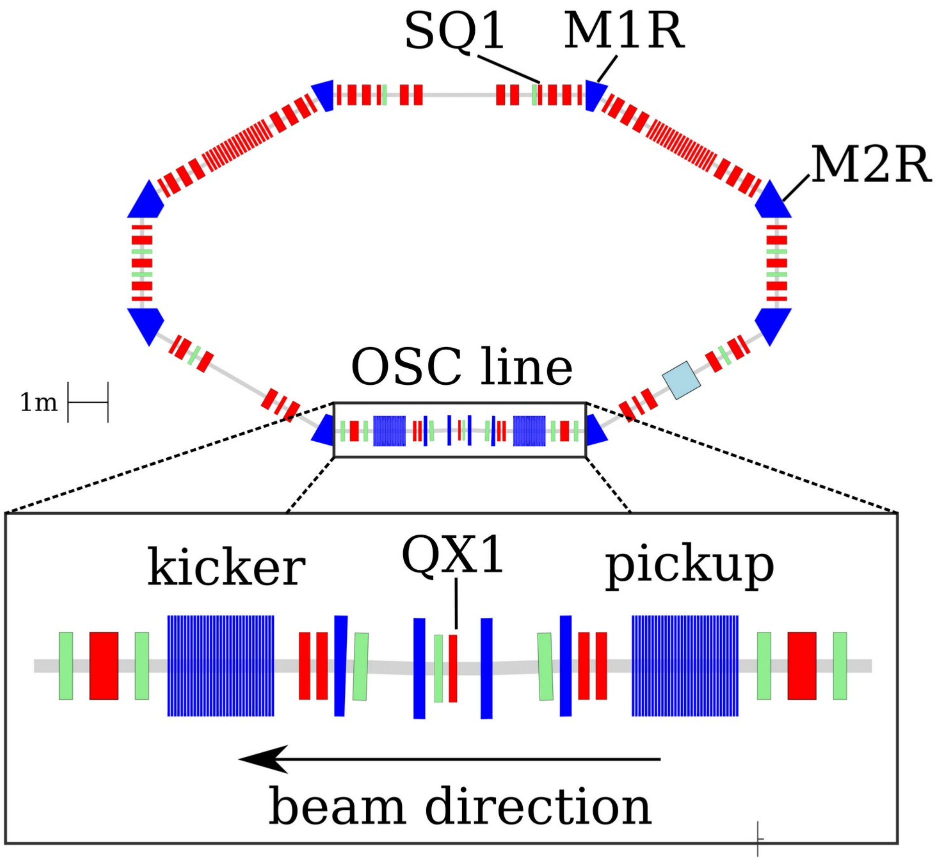
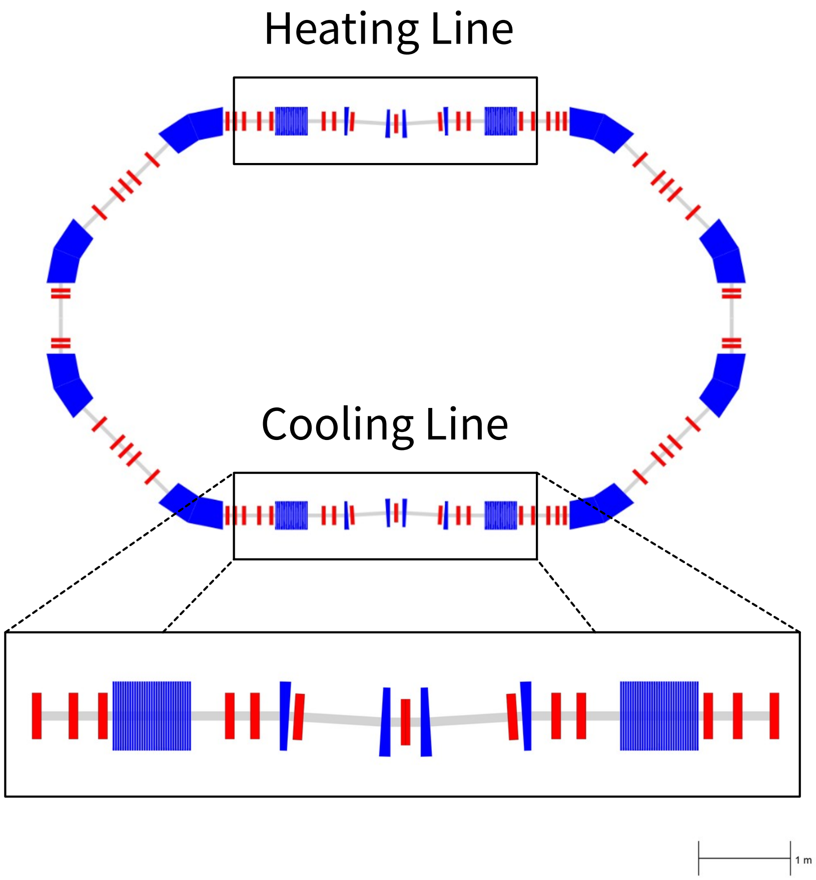
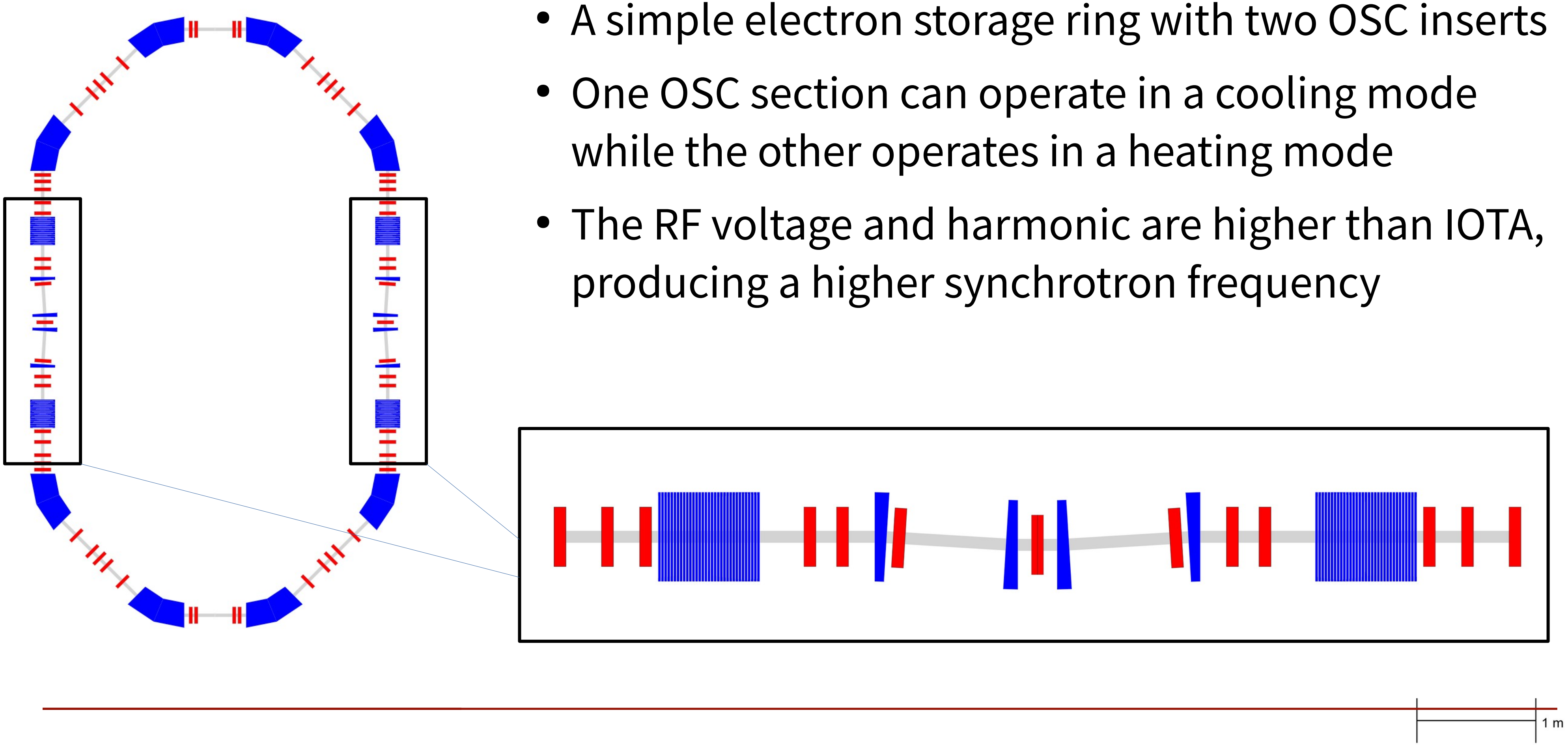




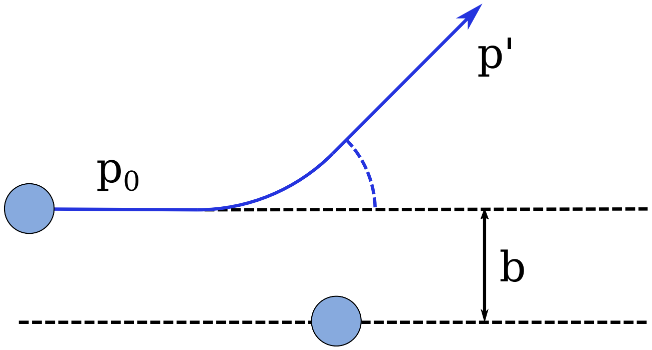
Simple OSC Storage Ring

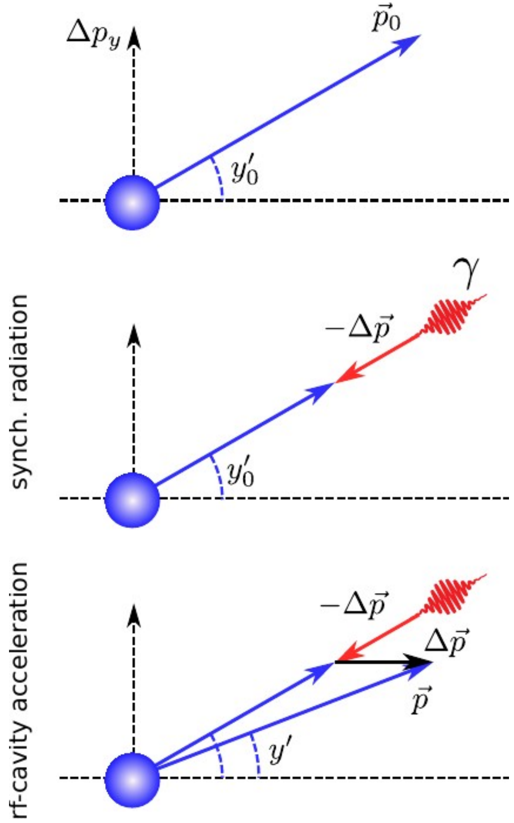
- A simple electron storage ring with two OSC inserts
- One OSC section can operate in a cooling mode while the other operates in a heating mode
- The RF voltage and harmonic are higher than IOTA, producing a higher synchrotron frequency



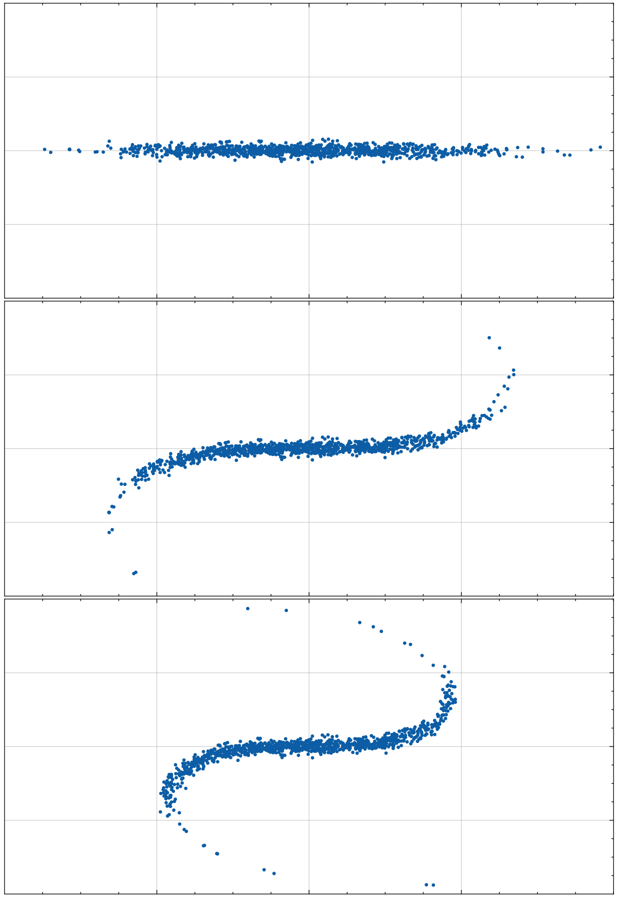
Diffusive Effects

- There are several diffusive mechanisms in storage rings that affect the OSC shaping processes
  - Quantum excitation from synchrotron radiation
  - Scattering with residual gas molecules
  - Space-charge and intra-beam scattering
- These will partially limit the resolution of the shaping methods





Nonlinear Synchrotron Motion



- The synchrotron frequency depends on the phase-space amplitude of the particle
- A "flattened" beam will lose coherence over time
  - The basic momentum spread reduction technique relies on a constant frequency
  - The LPS will be reduced in both dimensions

Slow-modulation Shaping

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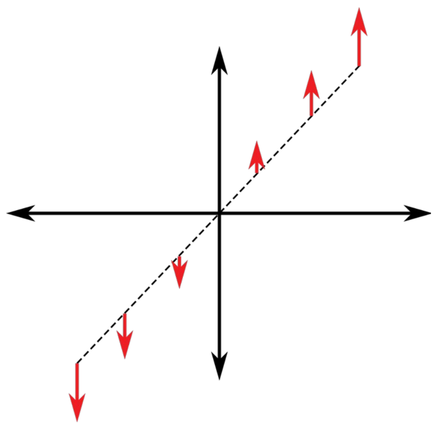
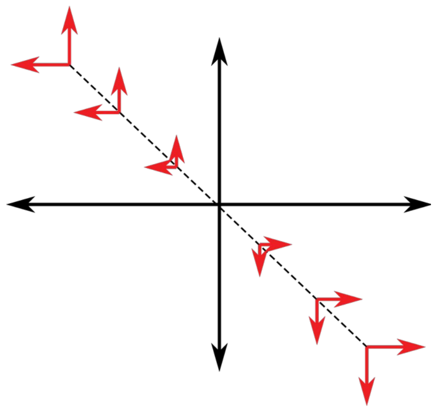
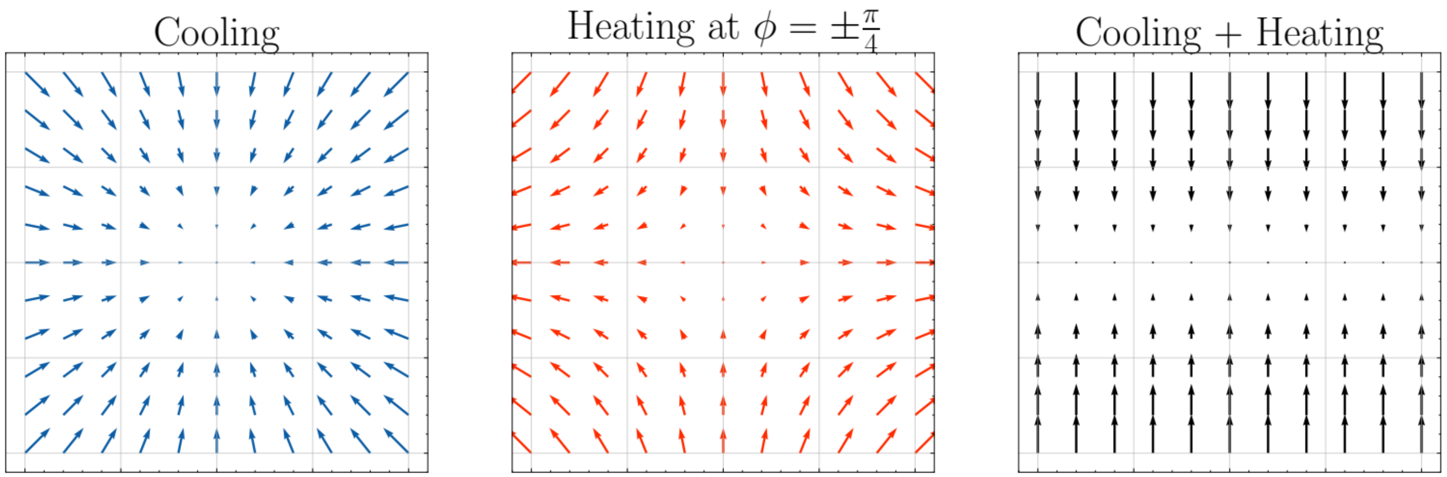


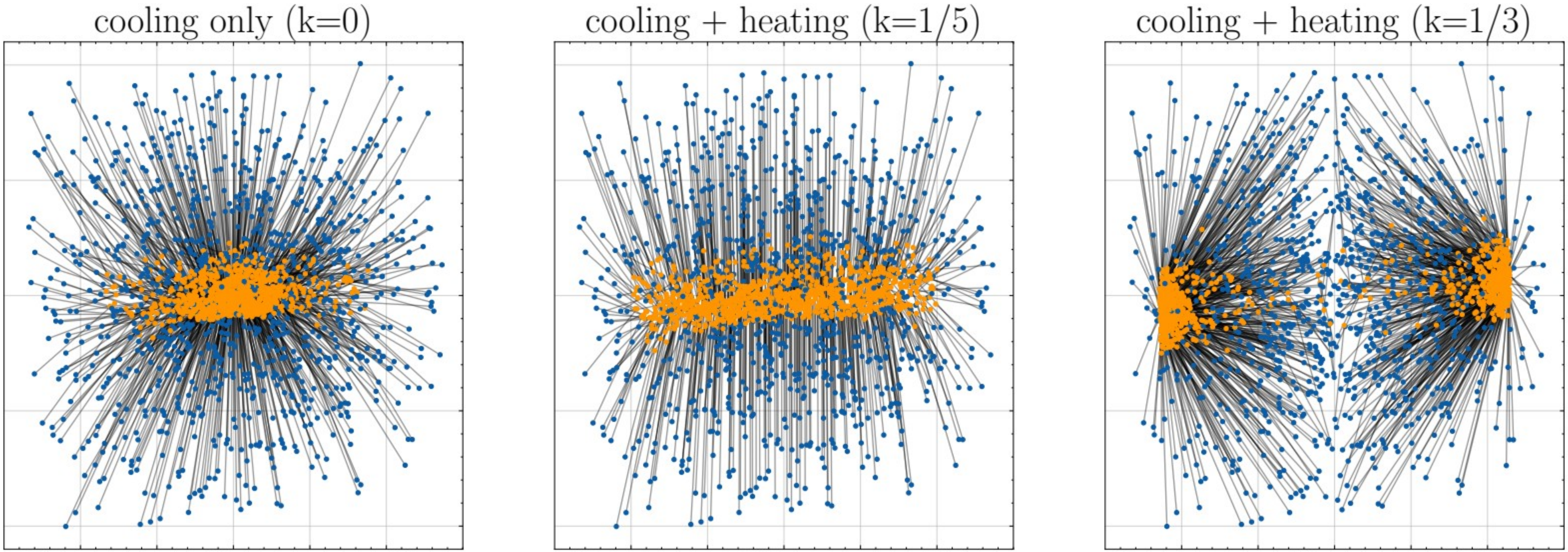


- Apply a heating kick at +/- 45 deg.
  - Creates a quadrupole-like focusing/defocusing kick
- The strength of the heating kick can be set to counteract the nonlinear synchrotron frequency



Simulated Results

- We simulated the momentum spread reduction + heating at 45 deg. using the high-fidelity model of OSC in ELEGANT, including diffusive effects



Simulated Results (Cont.)

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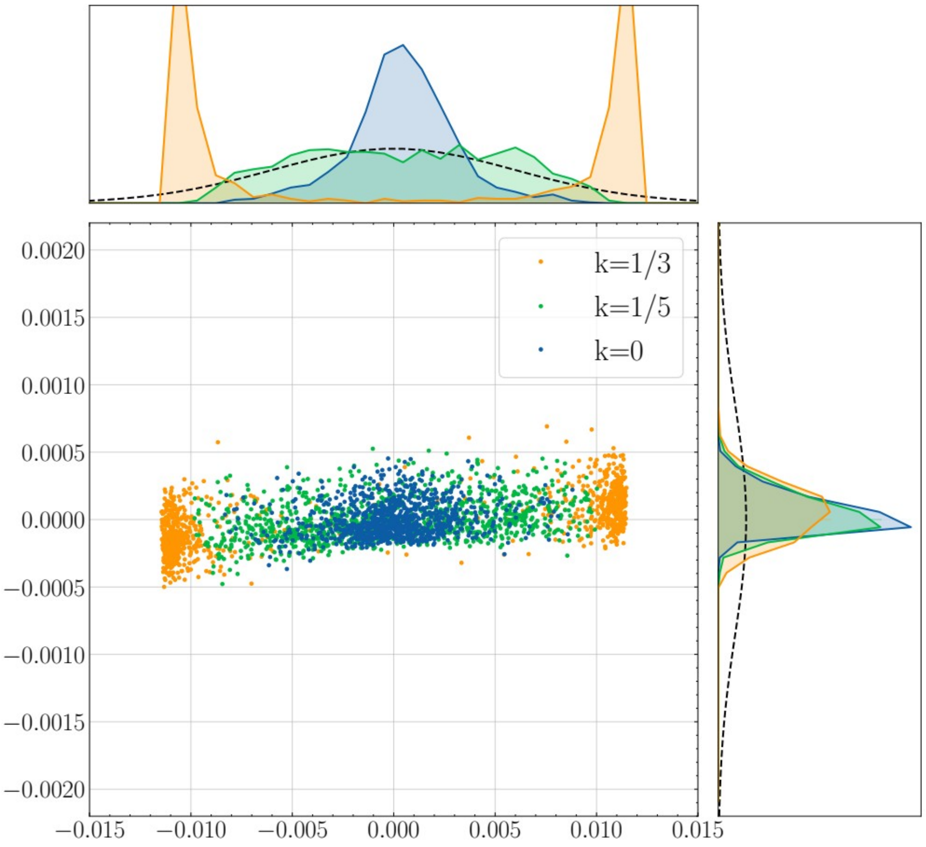
- The momentum spread is reduced more than the bunch length even in the basic case
- The strength of the heating kick is a fraction of the cooling kick
- As the strength of the heating kick increases, so does the equilibrium bunch length
- The beam eventually splits into two beamlets when



Comments on Momentum Spread Reduction

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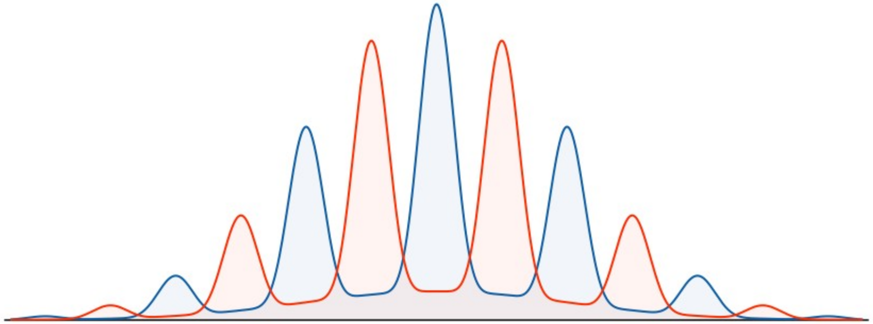
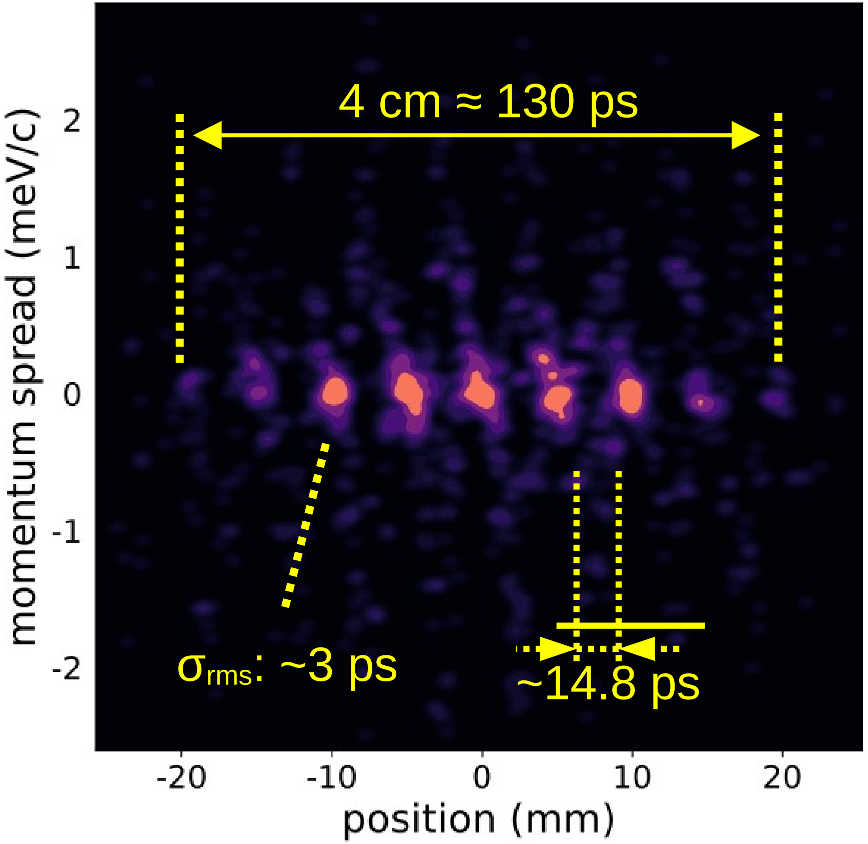
- The primary motivation behind reducing the momentum spread is to produce short duration beams
- OSC already reduces the size of a beam in a storage ring but it is limited by incoherent effects
- When the momentum spread is reduced in this way, the longitudinal density remains the same so **the incoherent effects do not get stronger**
- **This can produce shorter bunches than standard OSC but for a shorter duration**
- All mixing is due to diffusive and scattering effects

Micro-bunch Formation

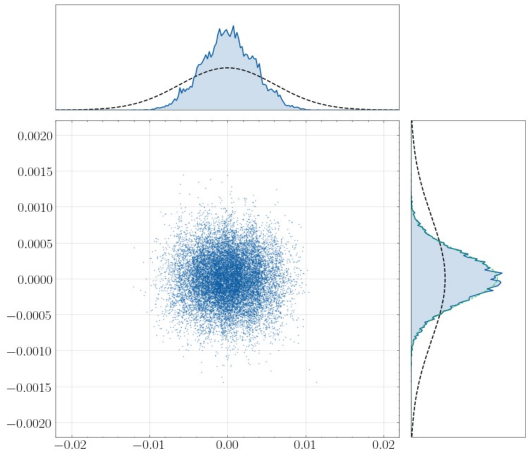
- The OSC mechanism can be used to form tunable micro-bunches
- This requires two OSC inserts to be operating simultaneously

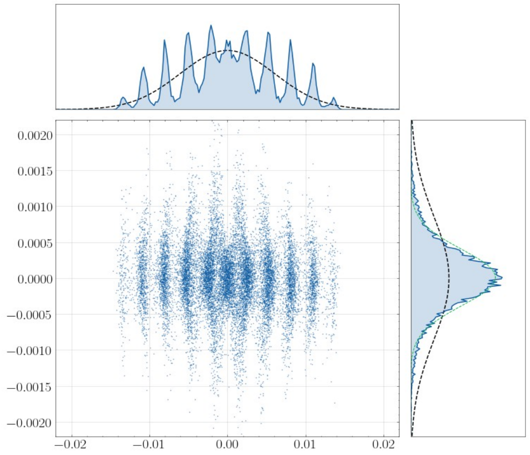


- The same problem exists with maintaining coherence



Micro-bunching Shaping





- Standard Micro-bunching
  - The beam starts to form micro-bunches but they quickly move towards the design momentum
  - This can be fixed by increasing the gain and working quickly
- Micro-bunching + heating @ phi = 45 deg.
  - Micro-bunches maintain the desired separation and form sharp peaks
  - Central peak suffers most from diffusive effects

Radially Symmetric Distributions

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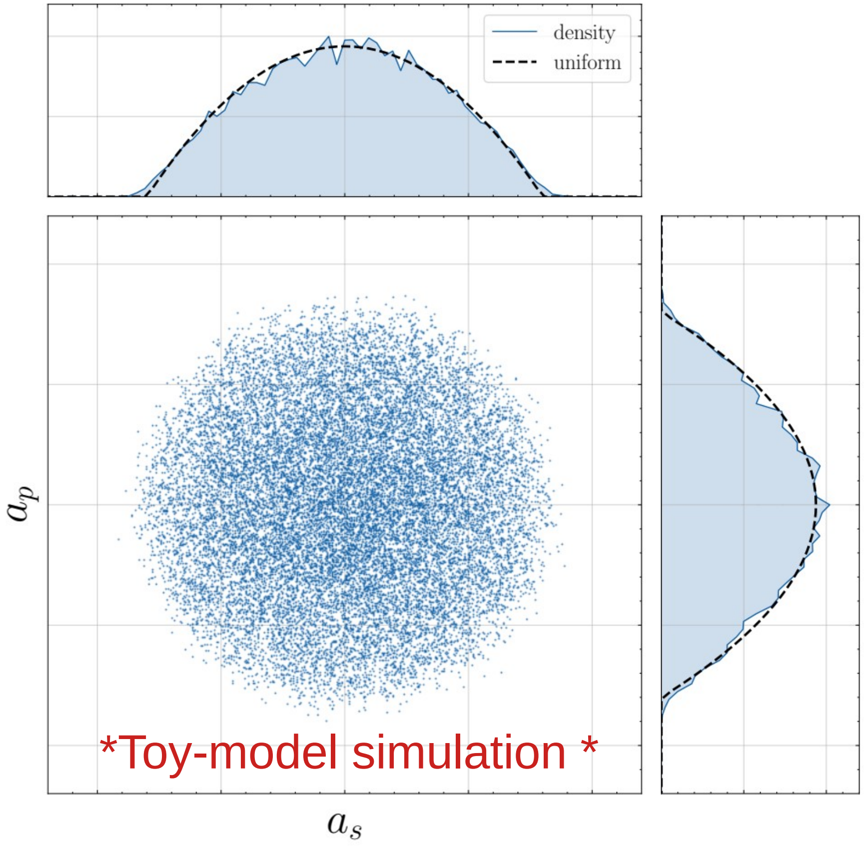
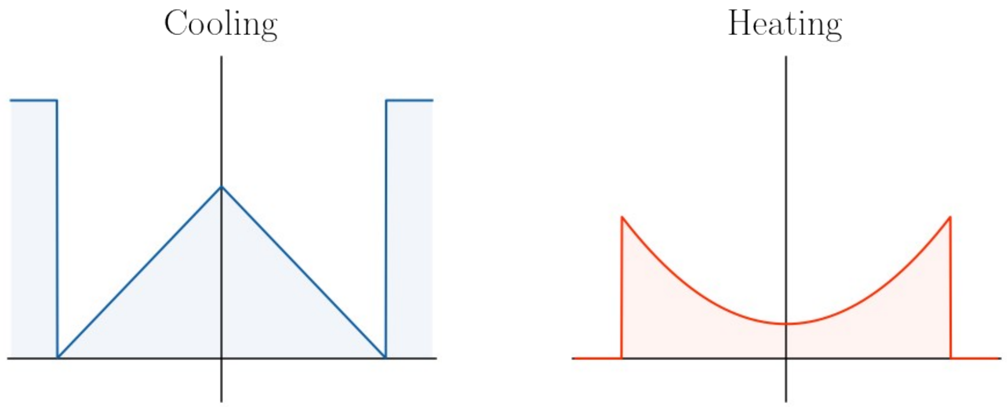


- The fast-modulated shaping method can be used to form radially symmetric distributions
- The heating and cooling lines operate separately with different shaping pulses

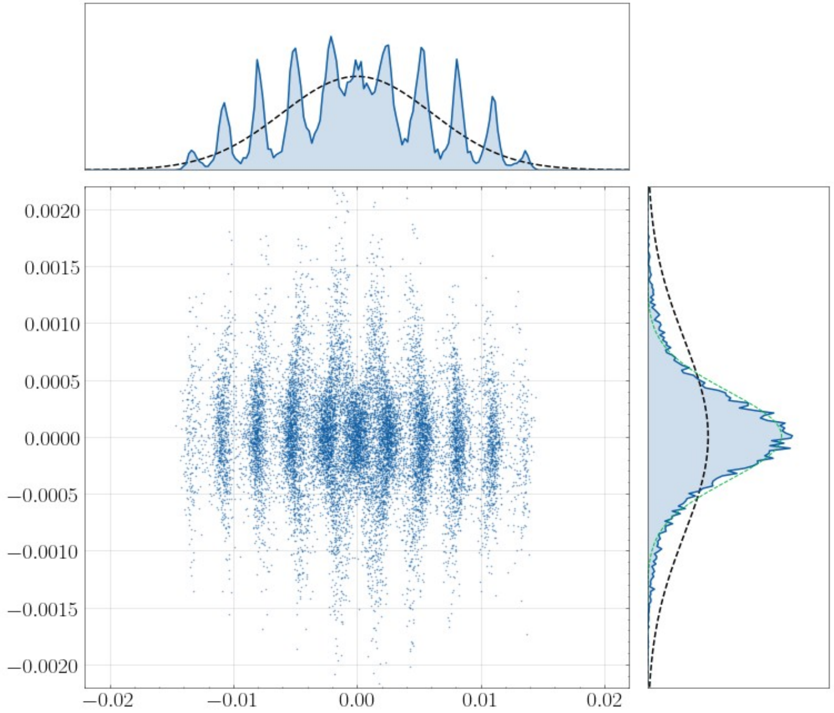


Radiation Production

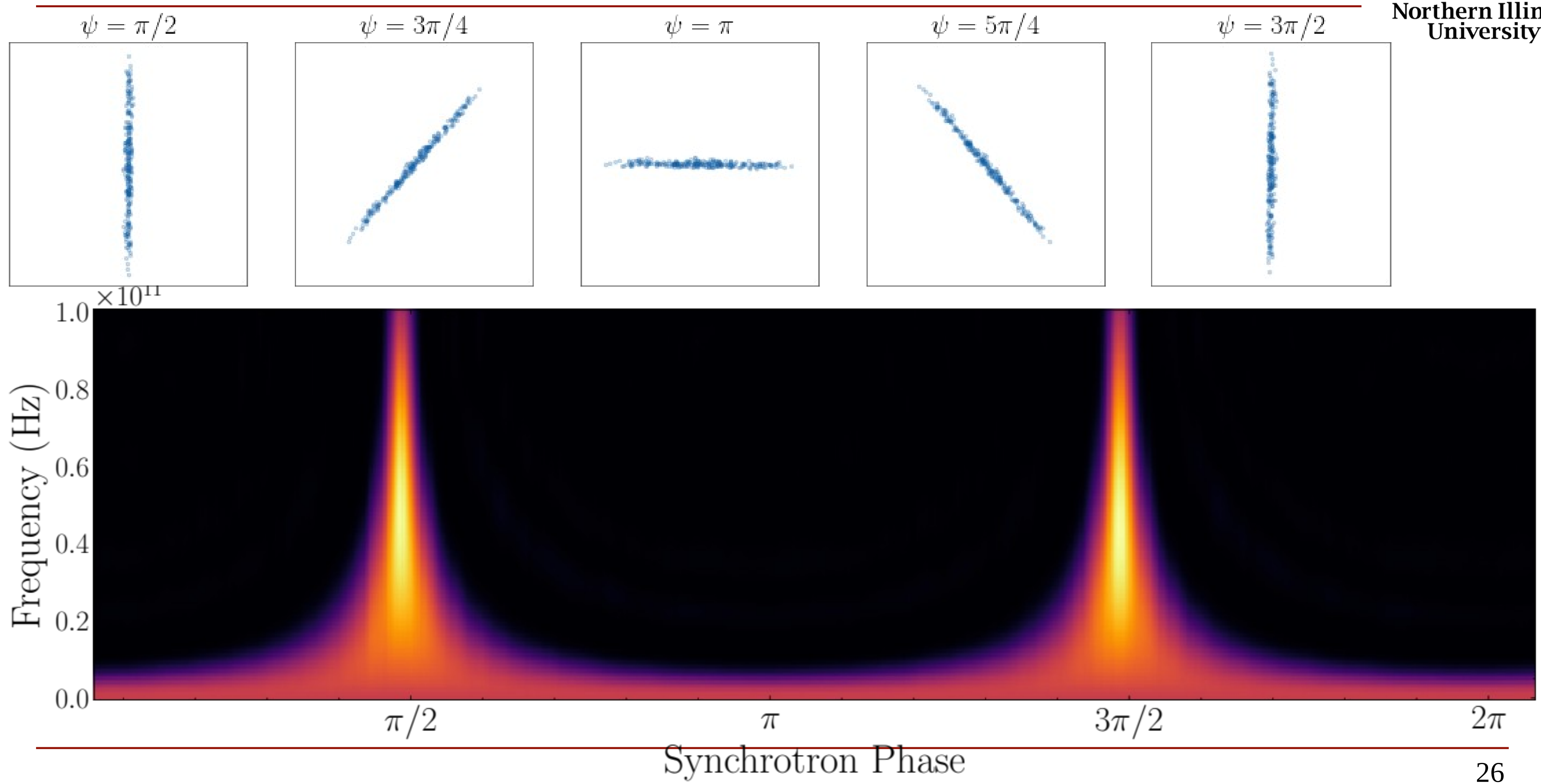
- Both shaping methods produce equilibrium beams which have interesting longitudinal profiles
- The coherent radiation produced by a beam is related to the longitudinal bunch form factor

$$F(\omega) \propto \left| \int_{-\infty}^{\infty} \rho(t) \exp(-i\omega t) dt \right|^2$$

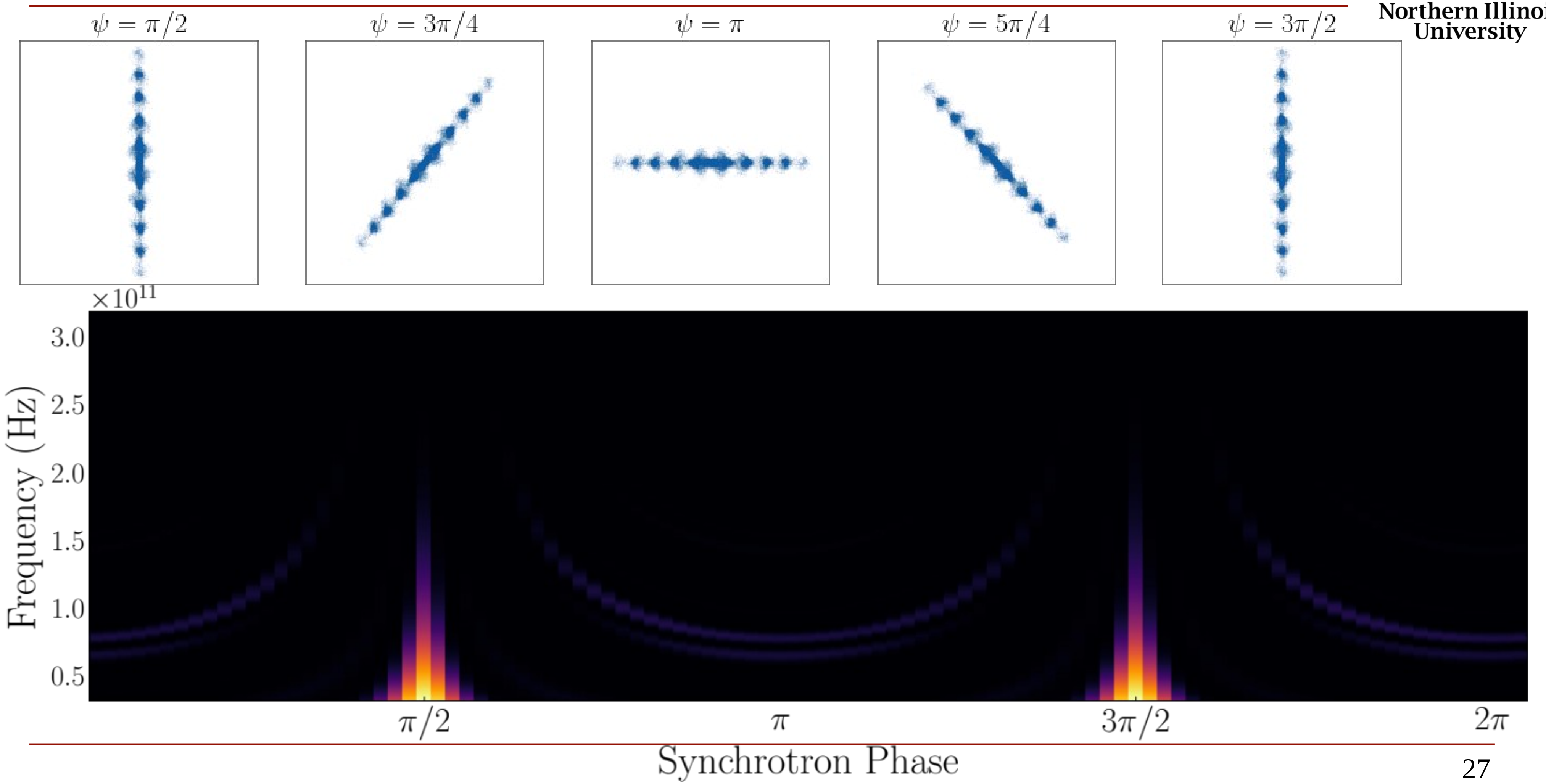
- The beam continues to orbit LPS so the longitudinal distribution changes periodically with the synchrotron frequency



Short Bunch Spectrum



Micro-bunch Spectrum



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Conclusion

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- We have developed two methods of beam shaping using the OSC mechanism which are capable of:
  - Reducing the spread of a single degree-of-freedom in LPS
  - Forming tunable micro-bunches
  - Producing arbitrary radially-symmetric distributions in LPS
- There are several effects that limit these methods and there are ways to fight them
- These shaped electron bunches could be used in light source applications
- More investigation is needed into coupled-OSC and if it could be used for transverse beam shaping

Questions?

Thank you!