Application of Optical Stochastic Cooling Mechanism to Beam Shaping

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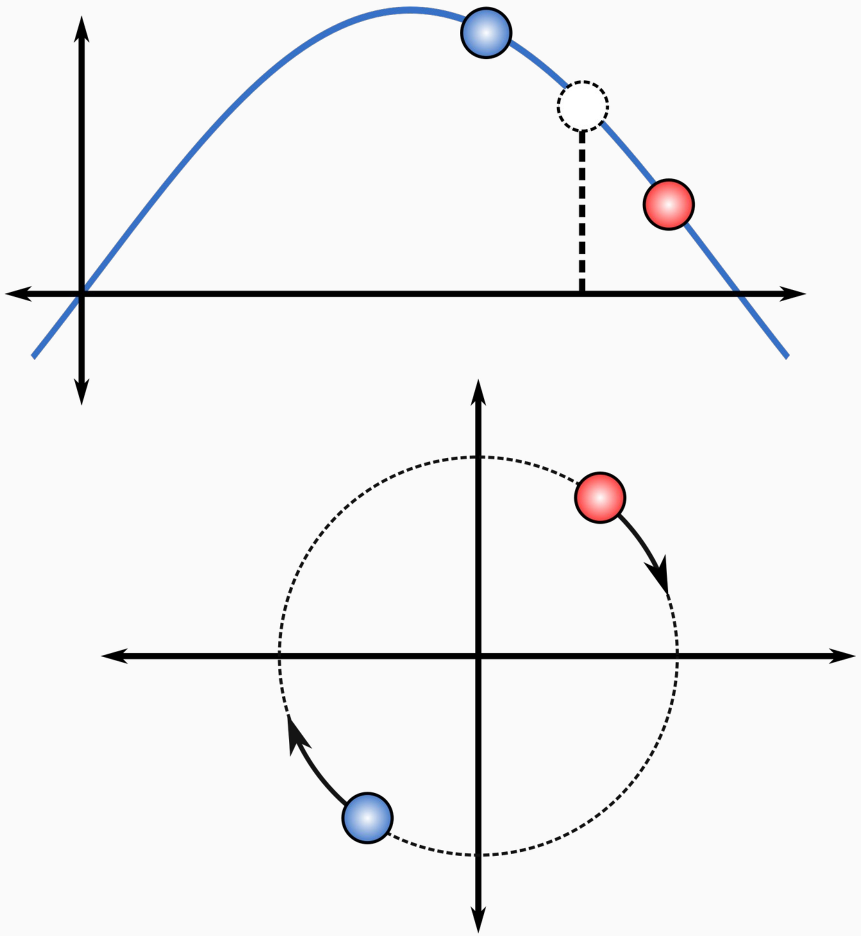
Overview

Theory	Techniques	Simulation	Shaping	Conclusion
Longitudinal Dynamics	Multi-Turn Shaping	IOTA Lattice	Momentum Reduction	Additional Distributions
OSC Mechanism	Intra-Turn Shaping	Toy Model	Micro-bunch Formation	Physical Limits
Optical Line/ Amplification		ELEGANT		Experimental Limits

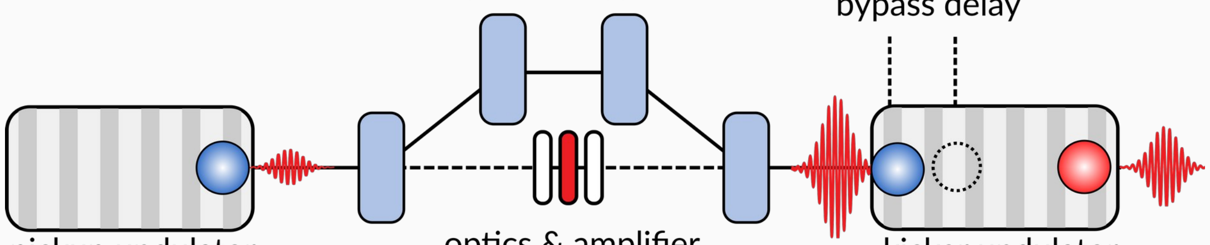
Longitudinal Motion in Rings

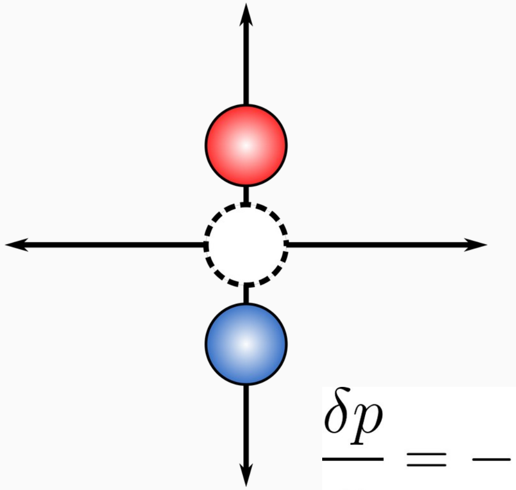
- Storage rings trap bunches of particles
  - Momentum spread usually causes smearing
- The RF system is responsible for holding the bunch together and restoring energy lost to radiation
- Particles orbit the reference point in longitudinal phase space with a constant frequency

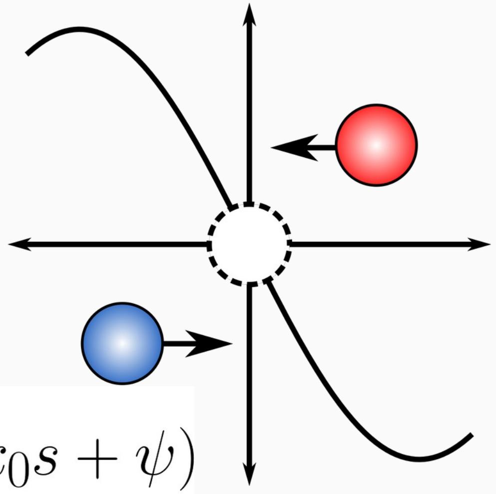


Optical Stochastic Cooling

- OSC has 4 main components
  - The pickup and kicker undulators
  - p dependent particle bypass
  - Optical Line
- Radiation produced in the pickup applies a force in the kicker
- The strength of the force depends on the momentum deviation of each particle



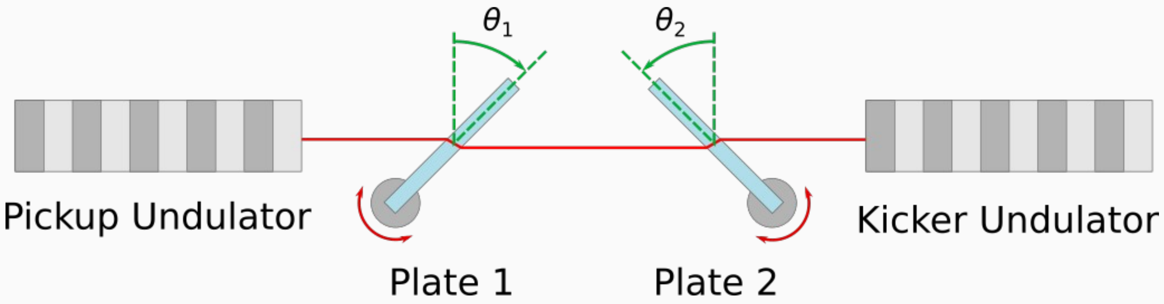


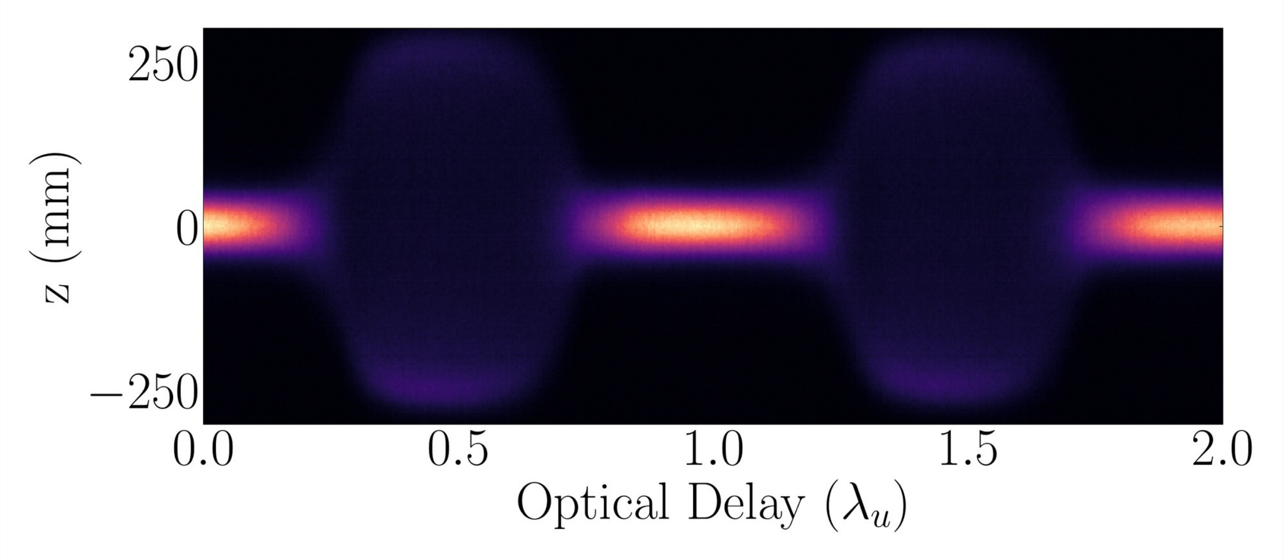


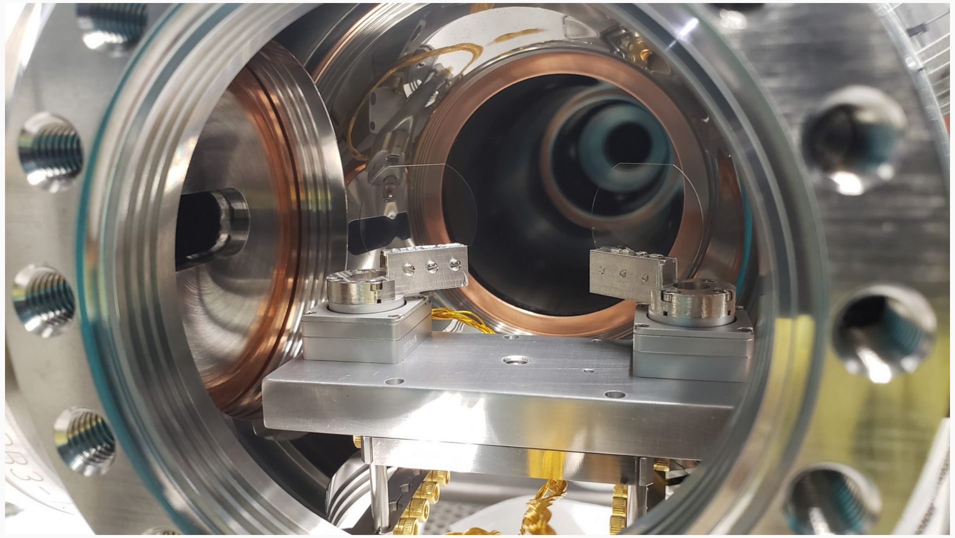
$$\frac{\delta p}{p} = -\kappa \sin(k_0 s + \psi)$$

Optical Delay Line

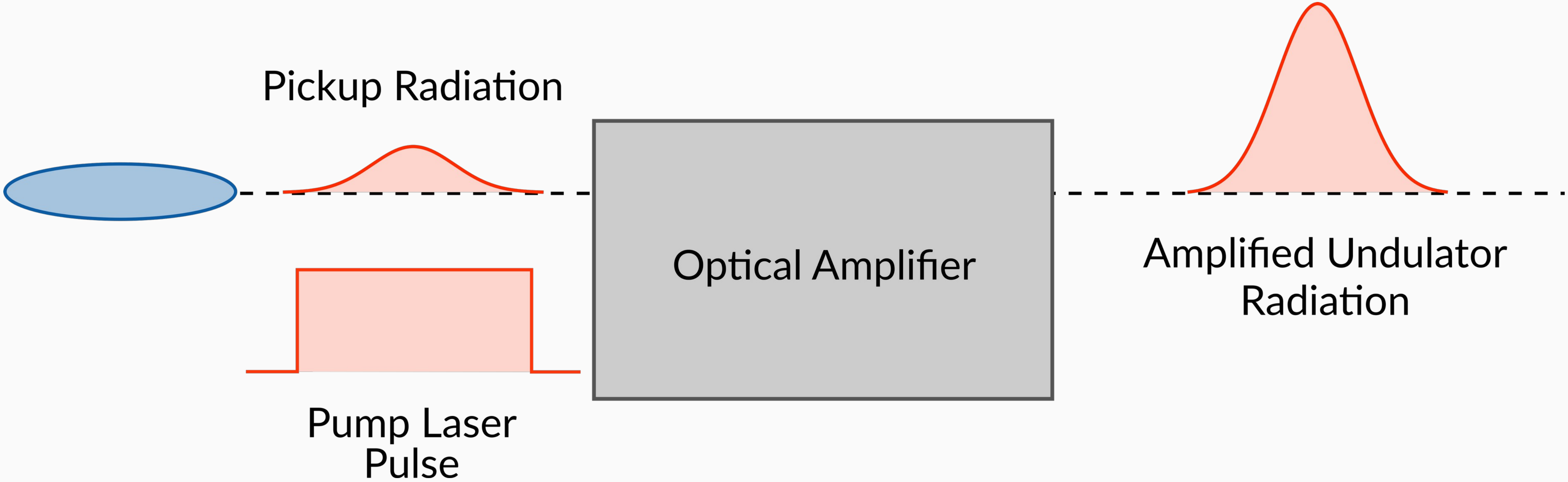
- The delay system controls the arrival of the radiation in the kicker
  - The reference particle receives no net energy change





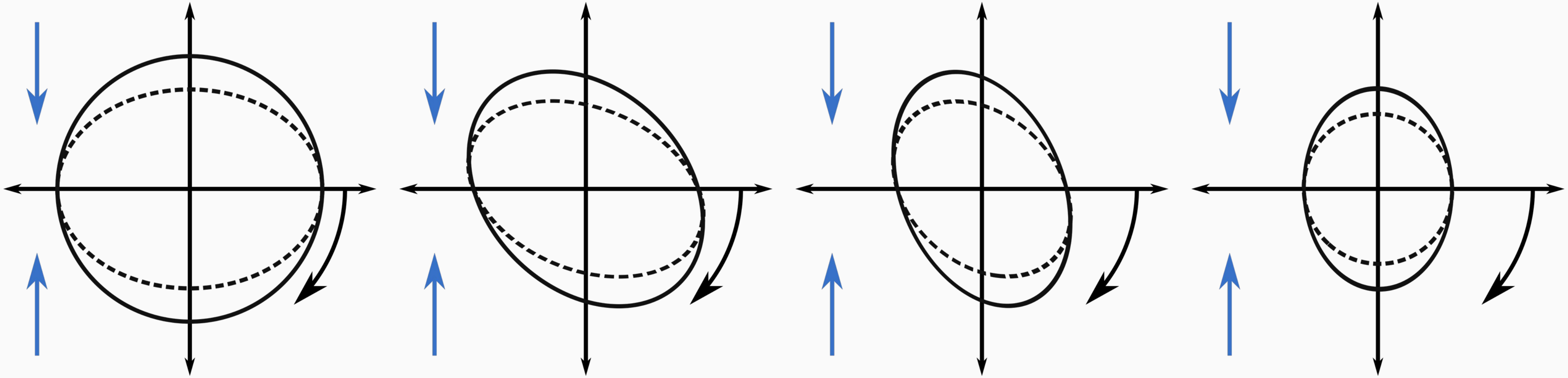


Optical Amplifier



- An optical amplifier can be inserted in the optical line to increase the cooling rate using a CW drive laser

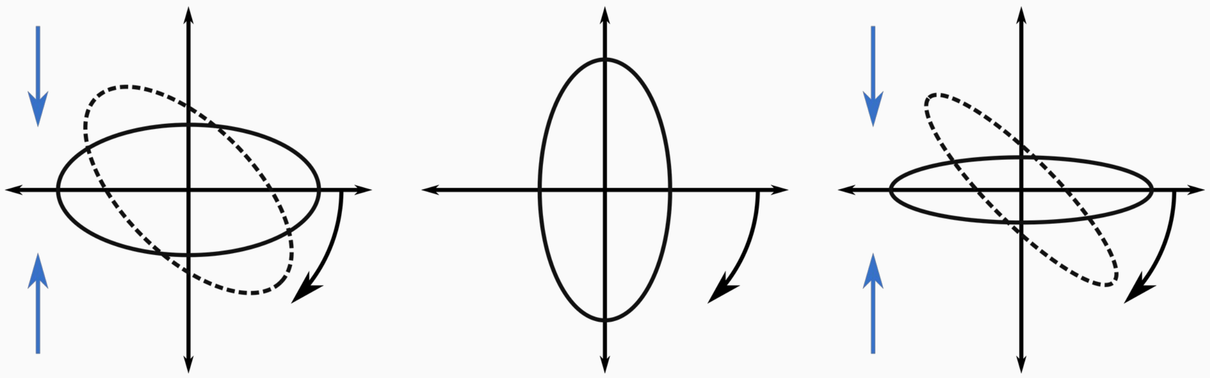
OSC in Phase Space

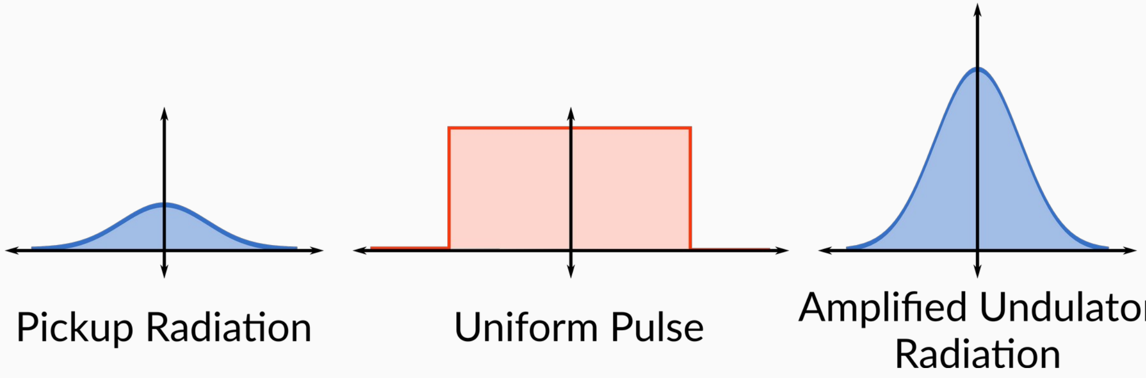


- The OSC mechanism provides a corrective kick in momentum
- This *squeezes* the beam in one direction, but as the beam orbits in LPS, it shrinks uniformly

Turn-Dependent Shaping

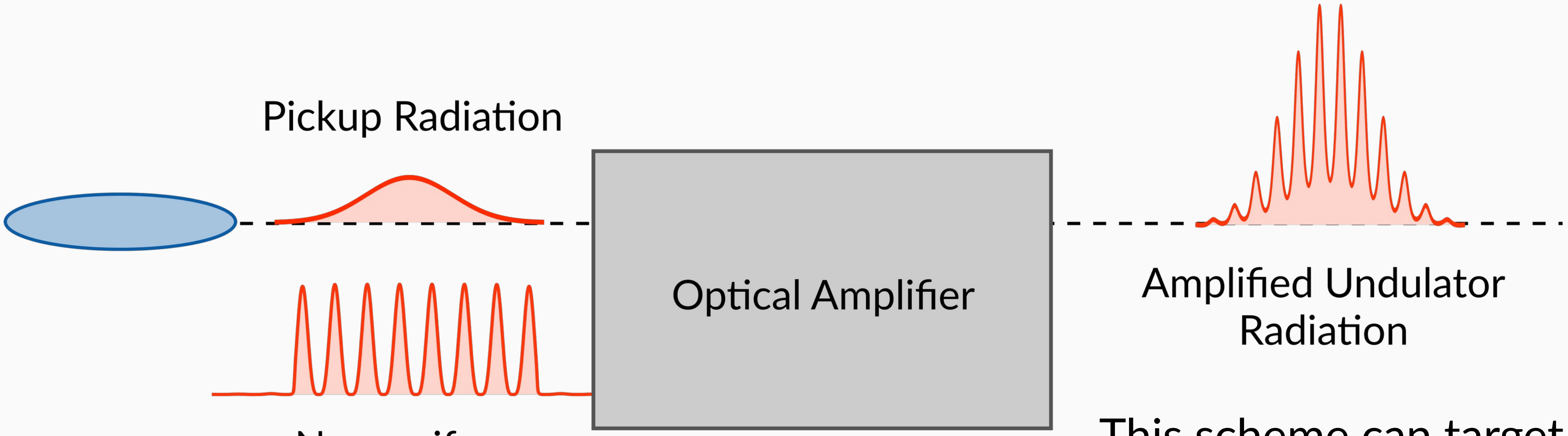
- In normal operation, the undulator radiation is always amplified but this is not necessarily required
- The amplification can be modulated on a turn-by-turn basis
- By timing the amplification with the synchrotron motion, the beam is squeezed in only one direction





Intra-turn Shaping

- The amplification pulse can be a function of time within a single turn

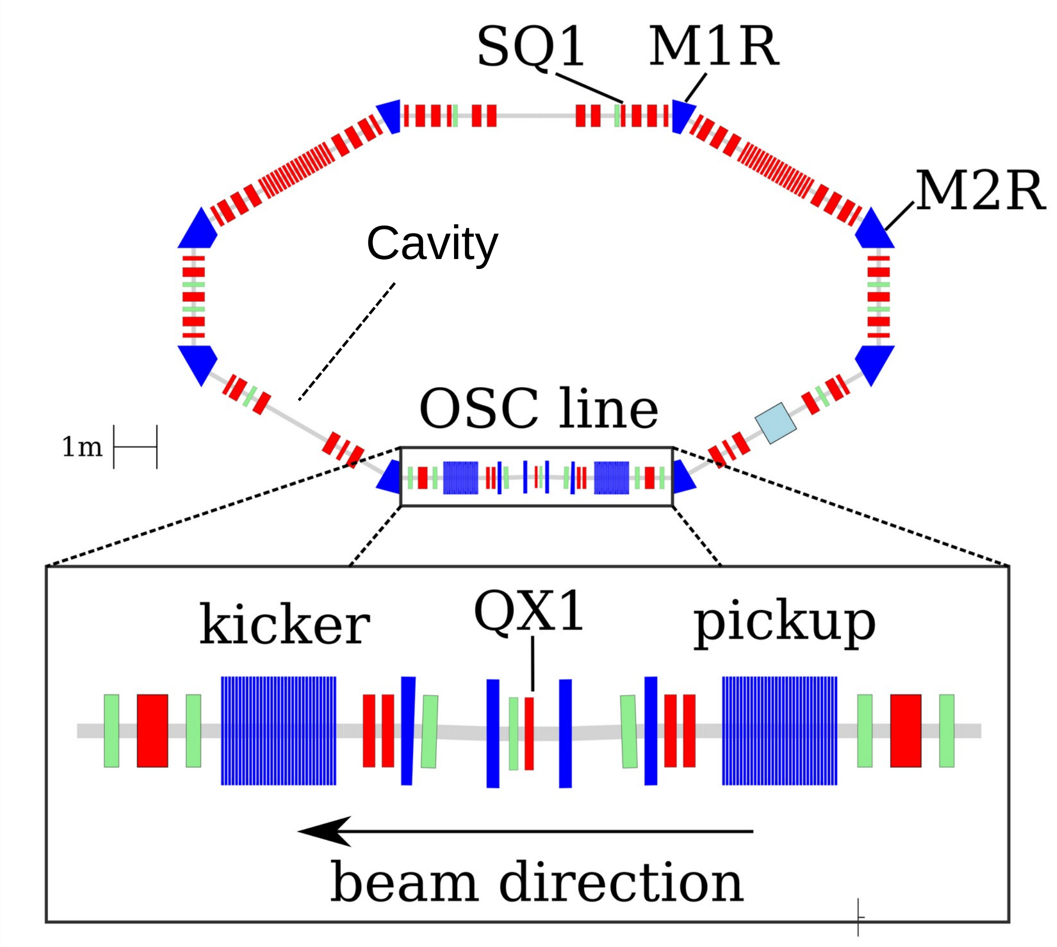


* more work is needed to identify laser shaping methods

This scheme can target cooling to specific region and may be combined with optical delay

Modeling of OSC at IOTA

- OSC was demonstrated at IOTA in 2021
  - This lattice is used to simulate the shaping since it is well studied
- A simple toy model was used for quick simulations of various shaping methods
  - Based on transfer matrices
  - Pickup → Kicker
  - Kicker → RF Cavity
  - RF Cavity → Pickup



Modeling of OSC

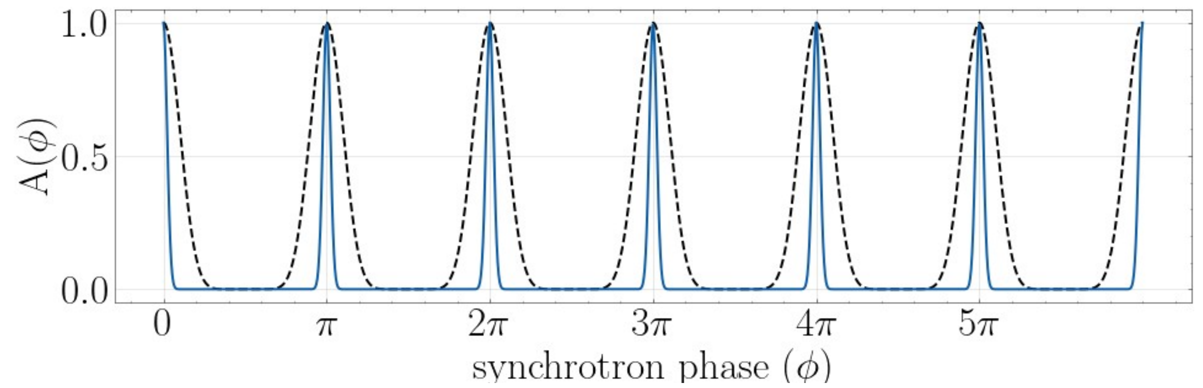
- **For more accurate simulations, we used a model of we developed OSC in ELEGANT**
  - Synchrotron radiation, intra-beam & residual gas scattering
  - Full particle tracking (400,000 km)

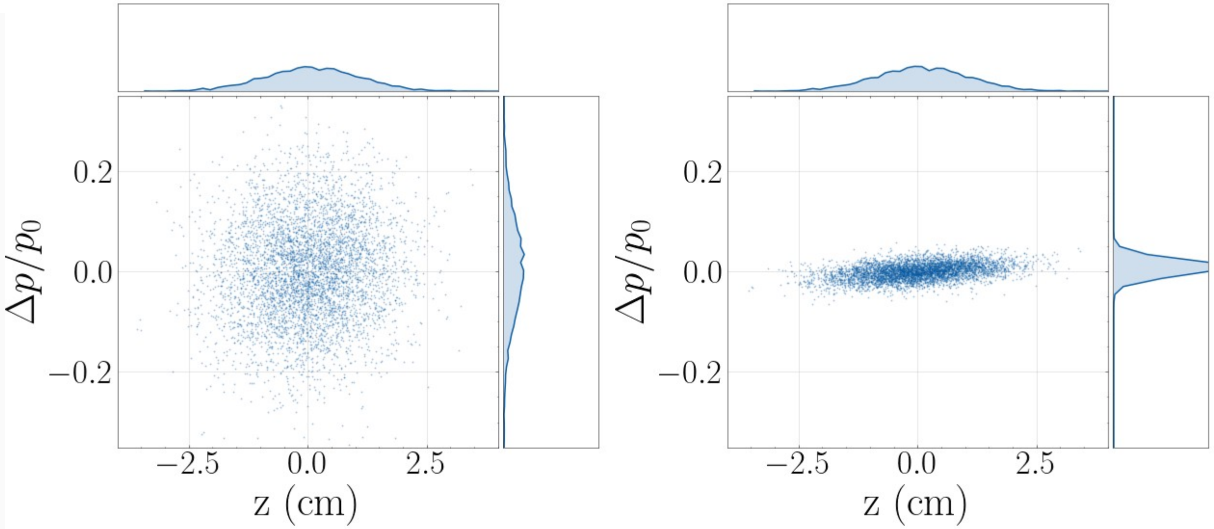
- **This model was benchmarked against the data collected during the OSC experiment**
  - Excellent agreement with cooling rates and equilibrium distributions

Energy Spread Reduction

- Amplify the OSC radiation as a function of the synchrotron phase
- Ideally, use periodic delta functions
  - 0, π, 2π, 3π, ...
- Increase the rate of cooling by using wider envelopes

$$A(\phi) = cos(\phi)^n \qquad n = (2, 4, 6, \dots)$$

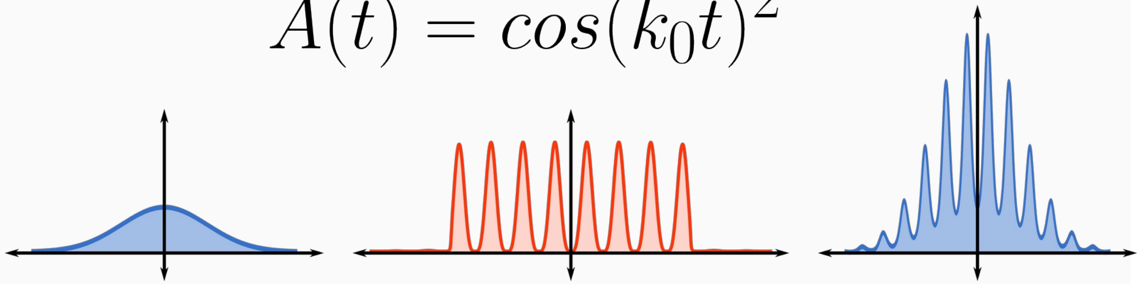




Micro-bunch Formation

- Target temporal slices of the beam using a "*comb*" distribution

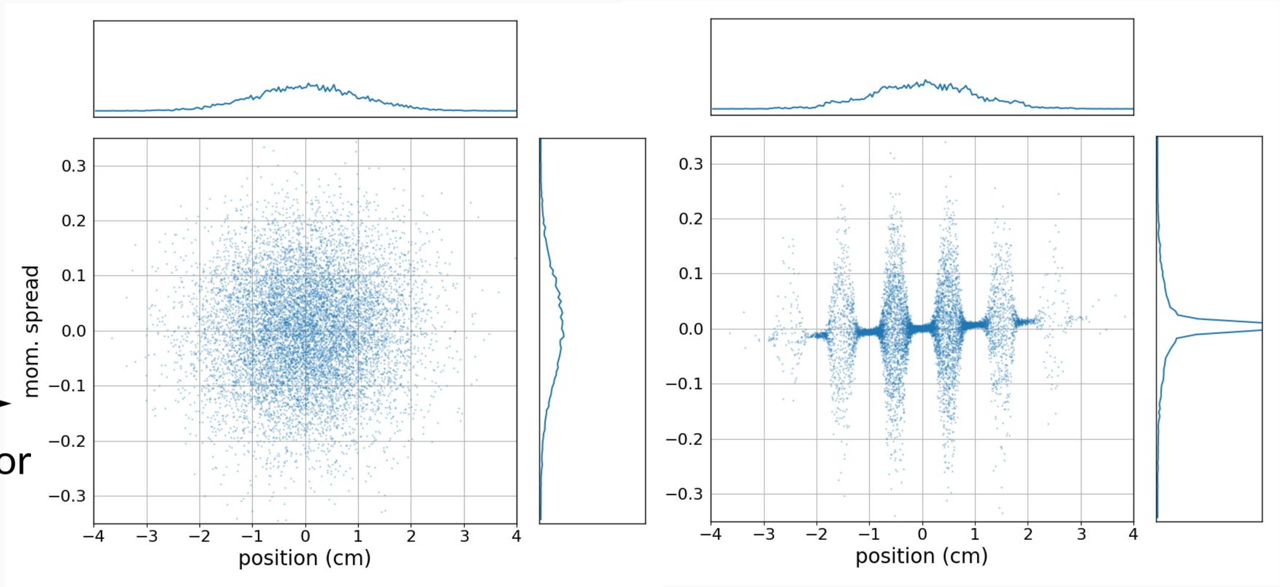
$$A(t) = cos(k_0 t)^2$$



Pickup Radiation | Non-uniform Pulse | Amplified Undulator Radiation

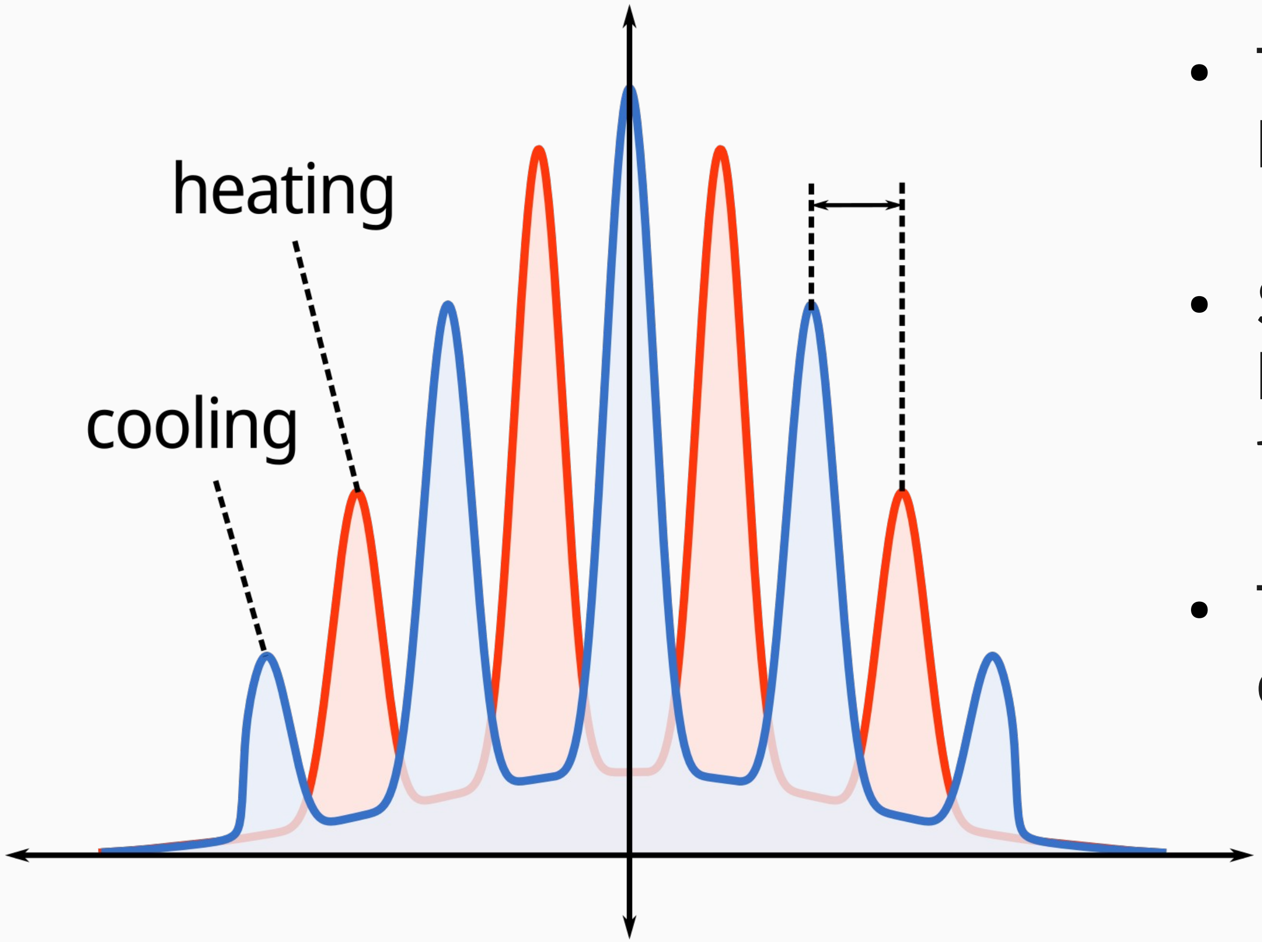
- Combine with flattening term

$$A(\phi, t) = cos(\phi)^n cos(k_0 t)^2$$



Unfortunately, this just pinches the beam at points k_0 apart!

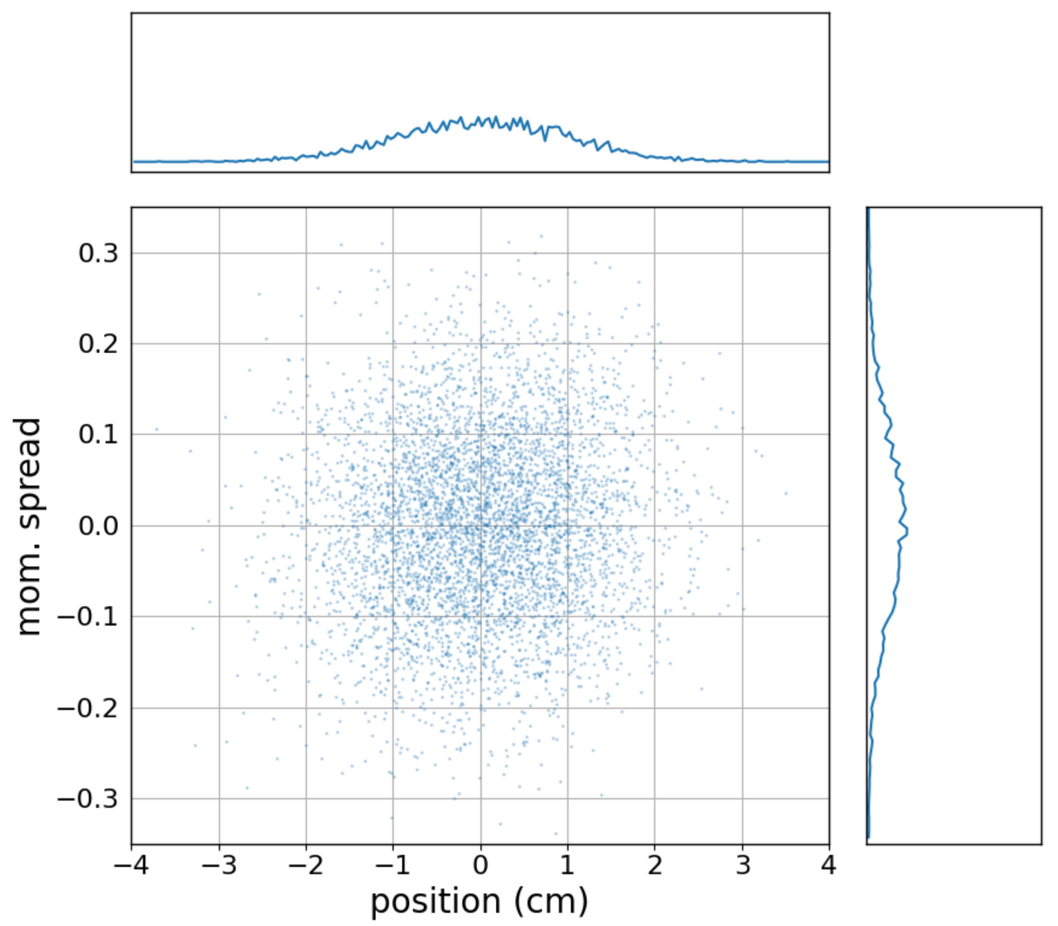
Micro-bunch Formation

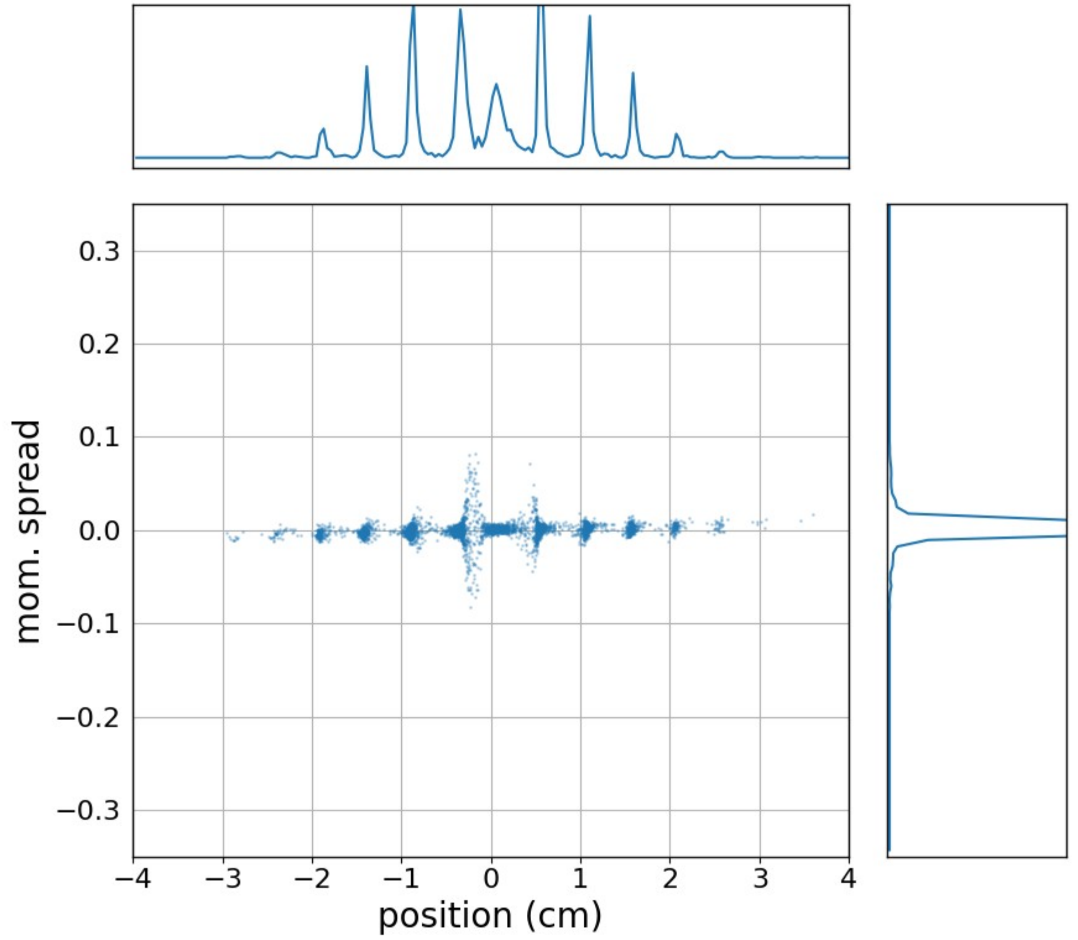


- The solution to this is to introduce heating modes
- Shifting the comb distribution during heating modes will help move particles to the correct spaces
- The delay can be introduced using the delay plates

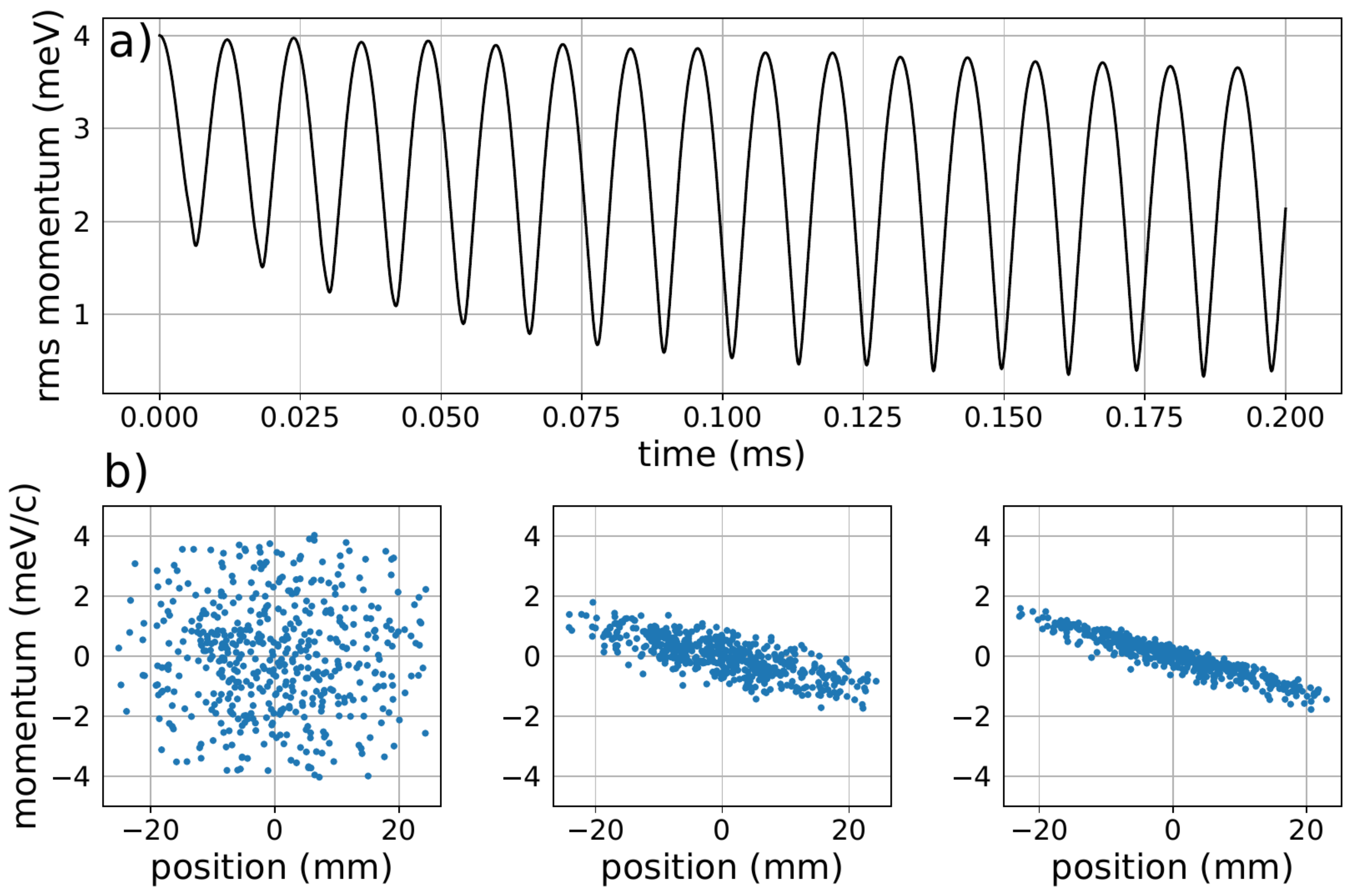
$$A(\phi, t) = cos(\phi)^n cos(k_0(t + \phi/4))^2$$

Micro-bunch Formation



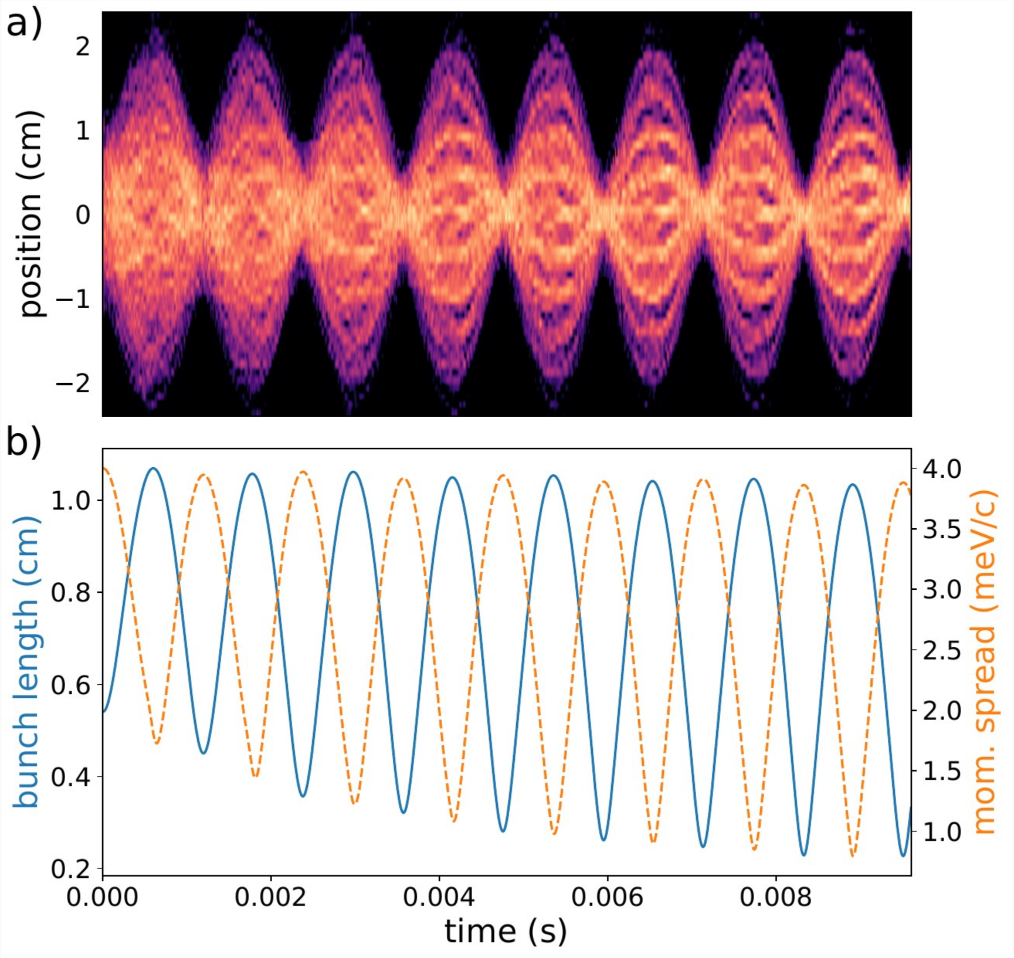


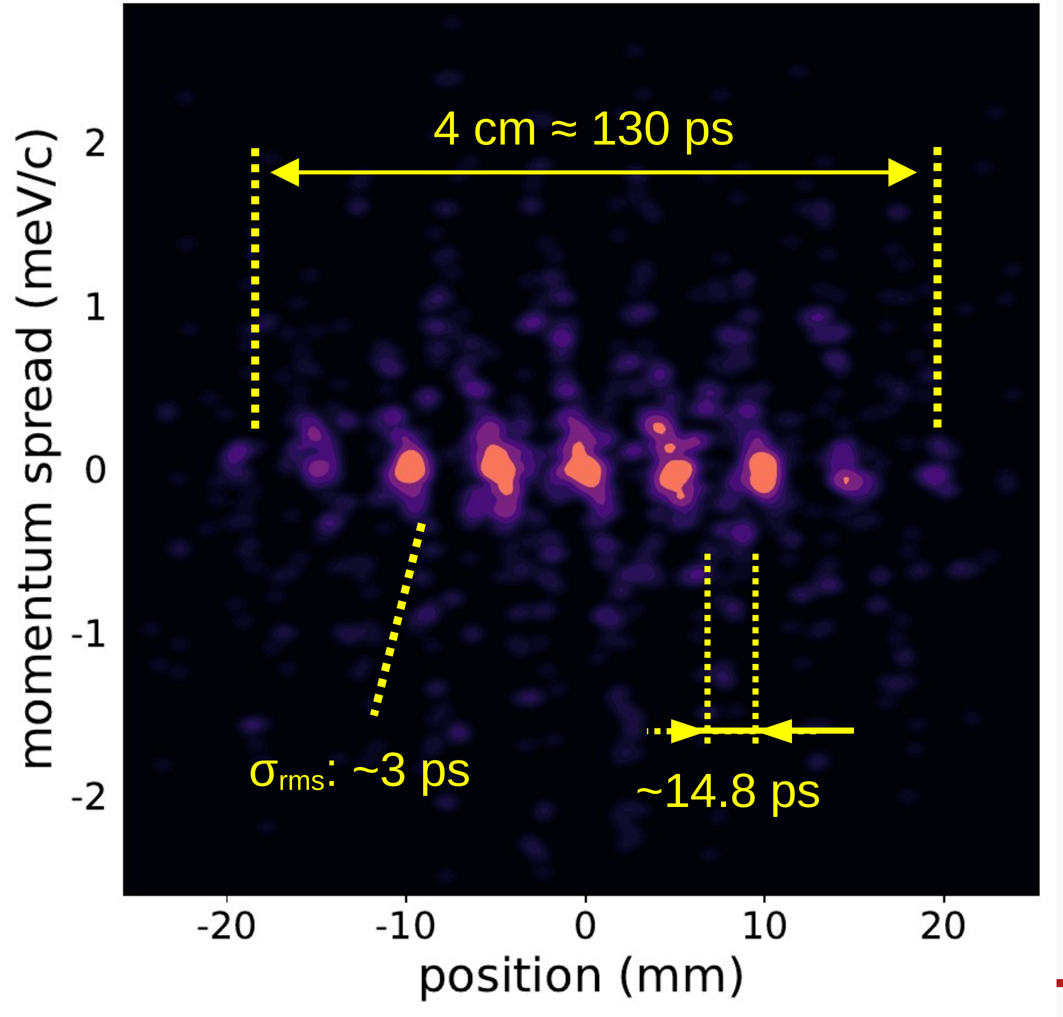
ELEGANT Simulations



- The beam flattening was demonstrated in ~20 synchrotron periods (~0.2 s) for a gain of 30 dB
- ~90% reduction in momentum spread
- Minimal reduction in the non-flattened plane

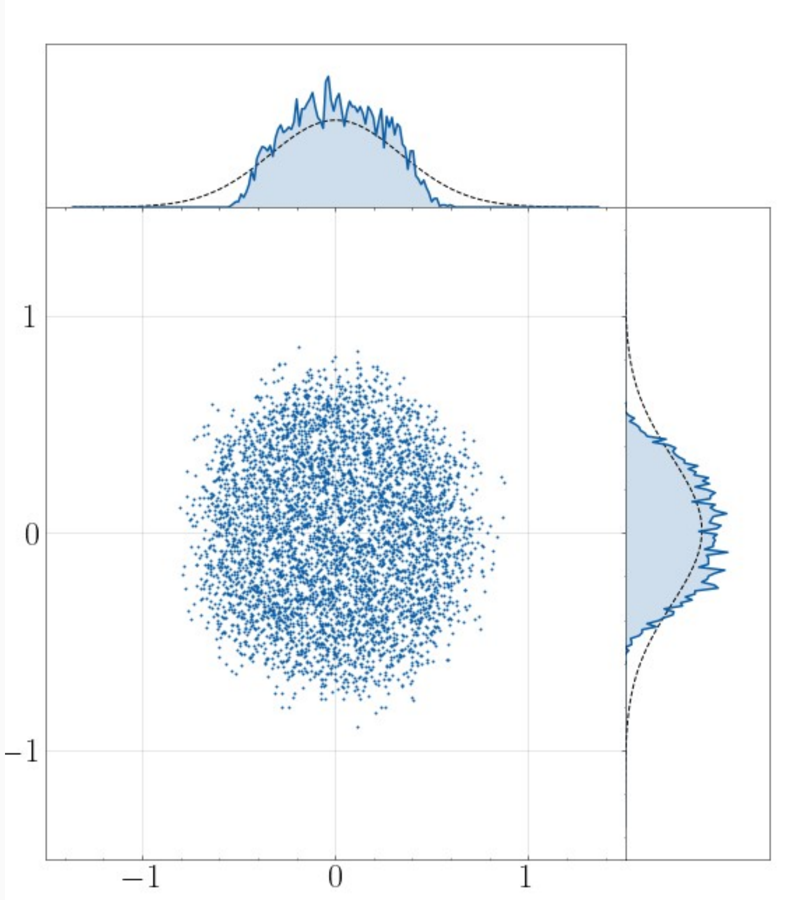
ELEGANT Simulations



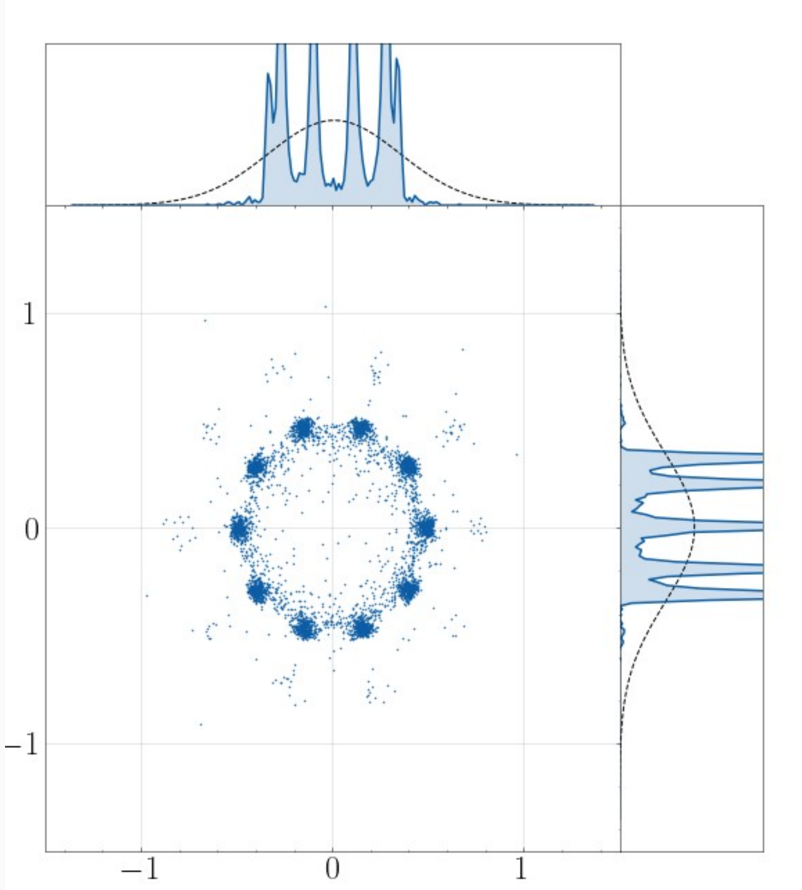


More Distributions

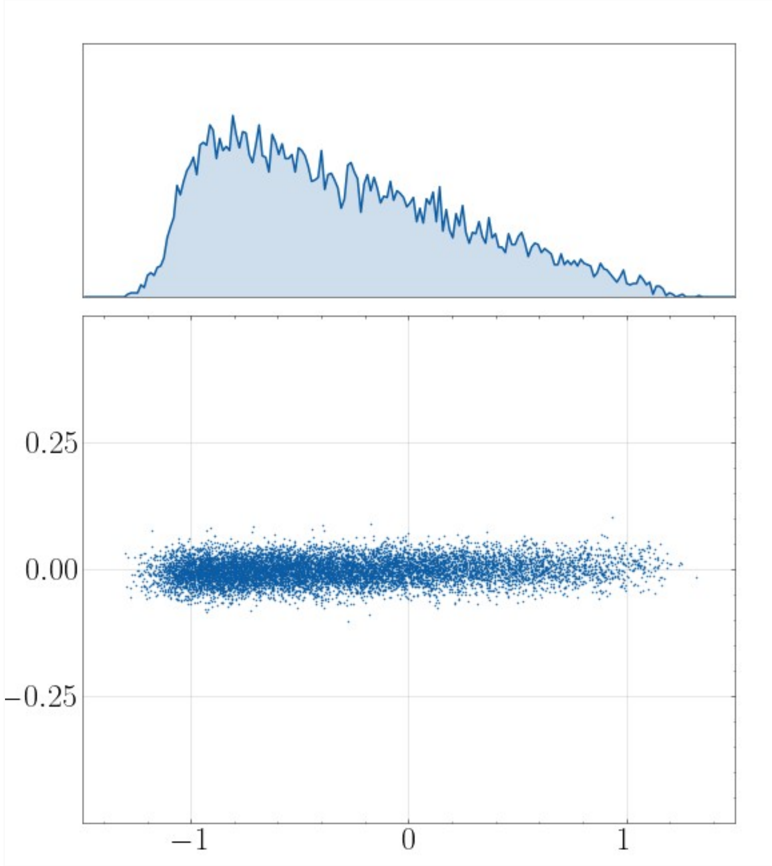
Uniform Distribution



Ring of Beamlets



Wedge Distribution



Conclusion

- Physical Limitations
  - Efficiency of these methods may be limited by scattering, cooling limits of OSC, intra-beam effects, etc.
- Experimental Limitations
  - Amplified OSC has not yet been demonstrated
  - Methods for shaping the drive laser pulse are not yet understood
  - Speed of the delay plates may limit access to heating modes
- Applications
  - Microbunching can be used as a tunable source of coherent THz radiation
  - Shaping the transverse phase space

Acknowledgments

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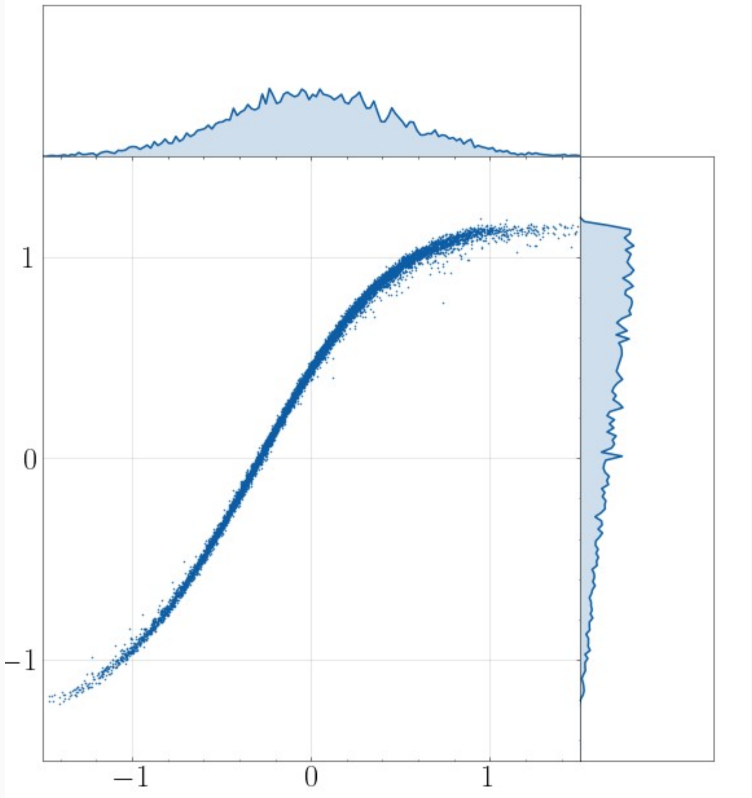
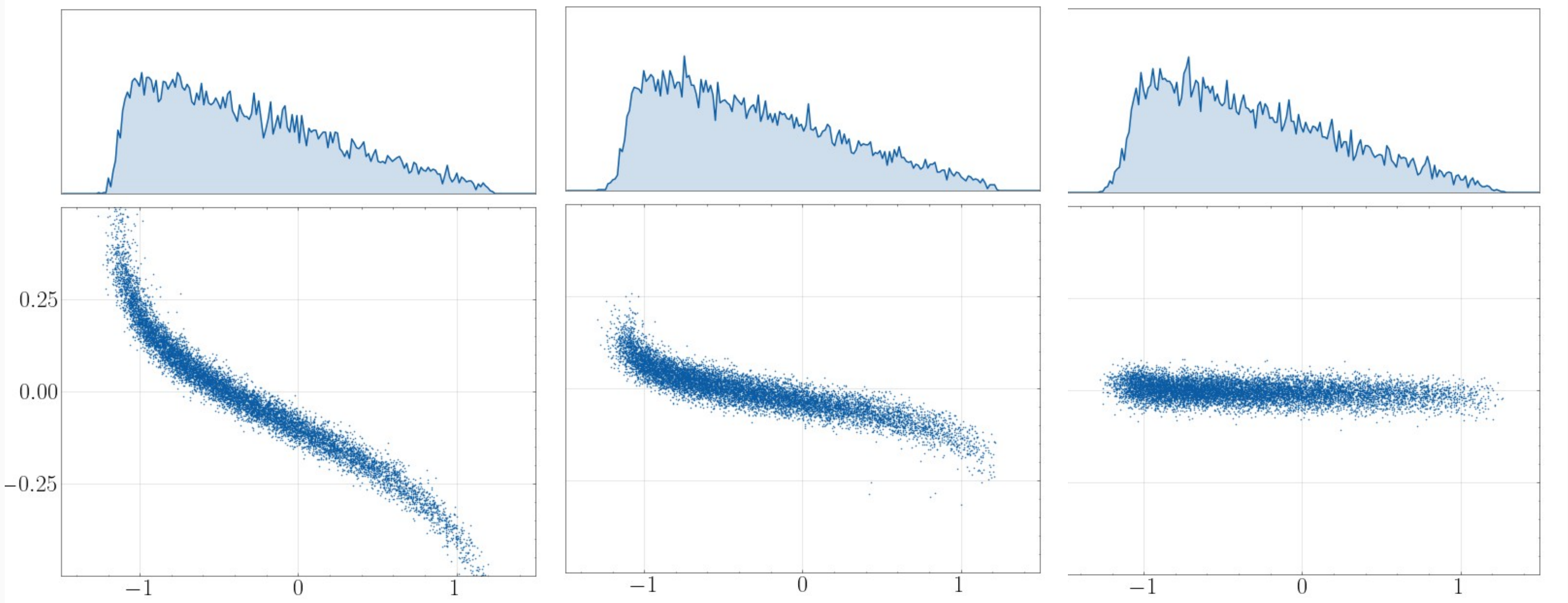
- Thank you to Dr. Michael Borland for his help implementing the ELEGANT model

Longitudinal Shaping

Smear the momentum distribution as you sweep the optical delay



90° later, the momentum spread becomes the longitudinal profile



Reduce the momentum spread