Final Cooling Technique with Thick Wedges

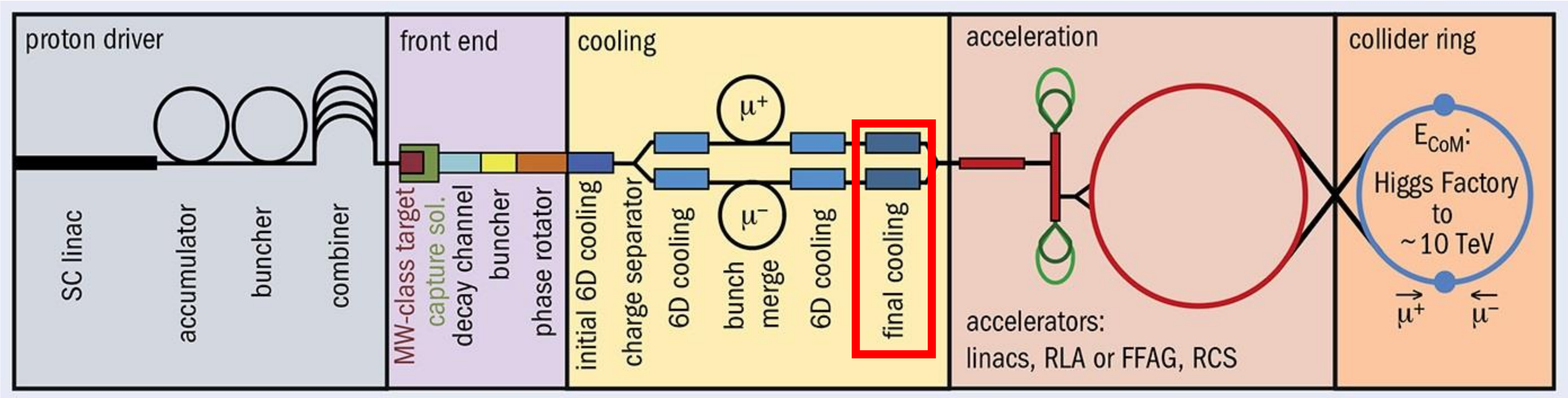
Daniel Fu, University of Chicago

Diktys Stratakis and David Neuffer, Fermilab

11/30/2023

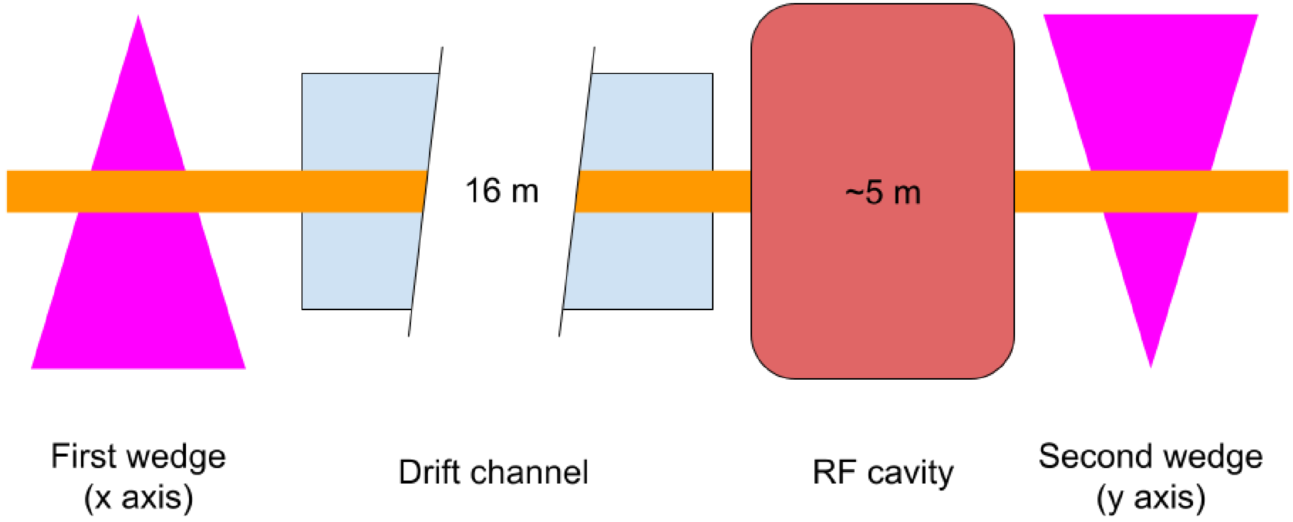
Introduction

- Final cooling is a major problem for development of a muon collider
- Conceptual method for final cooling proposed by Neuffer in 1612.08960
- We demonstrated feasibility and optimized design using simulation



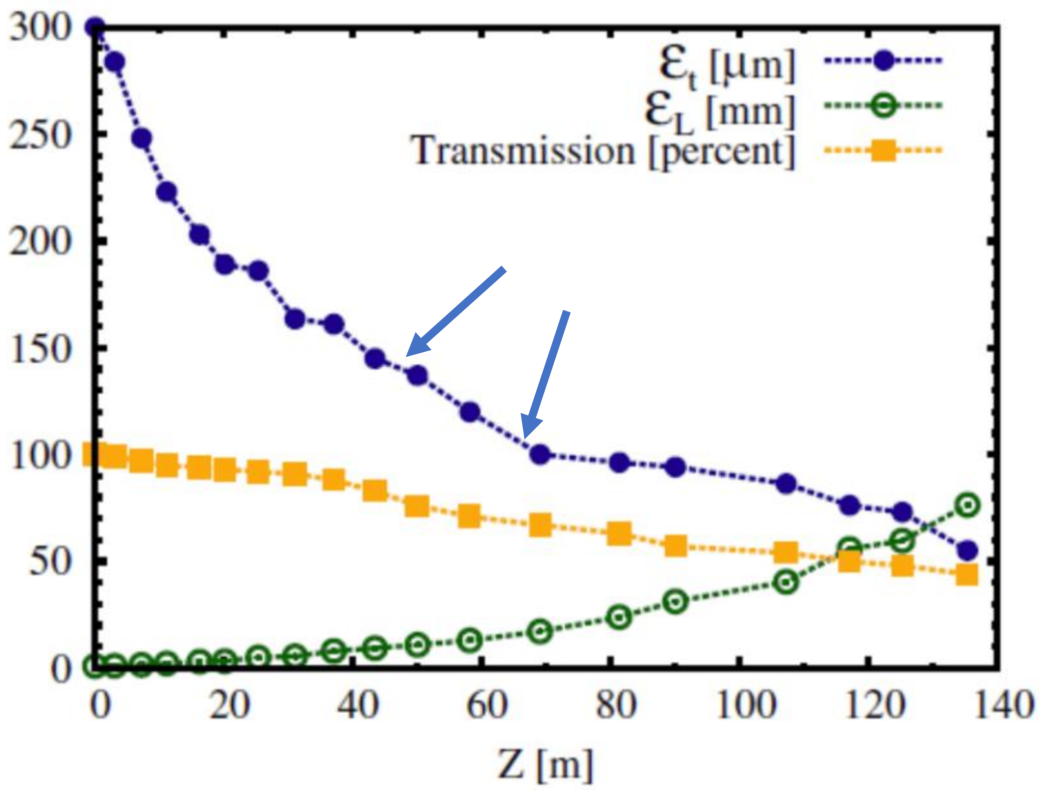
Proposed Final Cooling Concept

- Beam passed through a thick wedge, which cools beam in one transverse axis through emittance exchange
- Drift channel to build up correlation between time and momentum
- RF cavity reduces momentum spread through phase rotation
- Beam passed through second wedge to cool in second transverse axis



Simulation Methods

- Input distributions based on intermediate stages of high-field solenoid cooling channel
- Considered two initial transverse emittances
- G4Beamline used to simulate wedge and phase rotation process



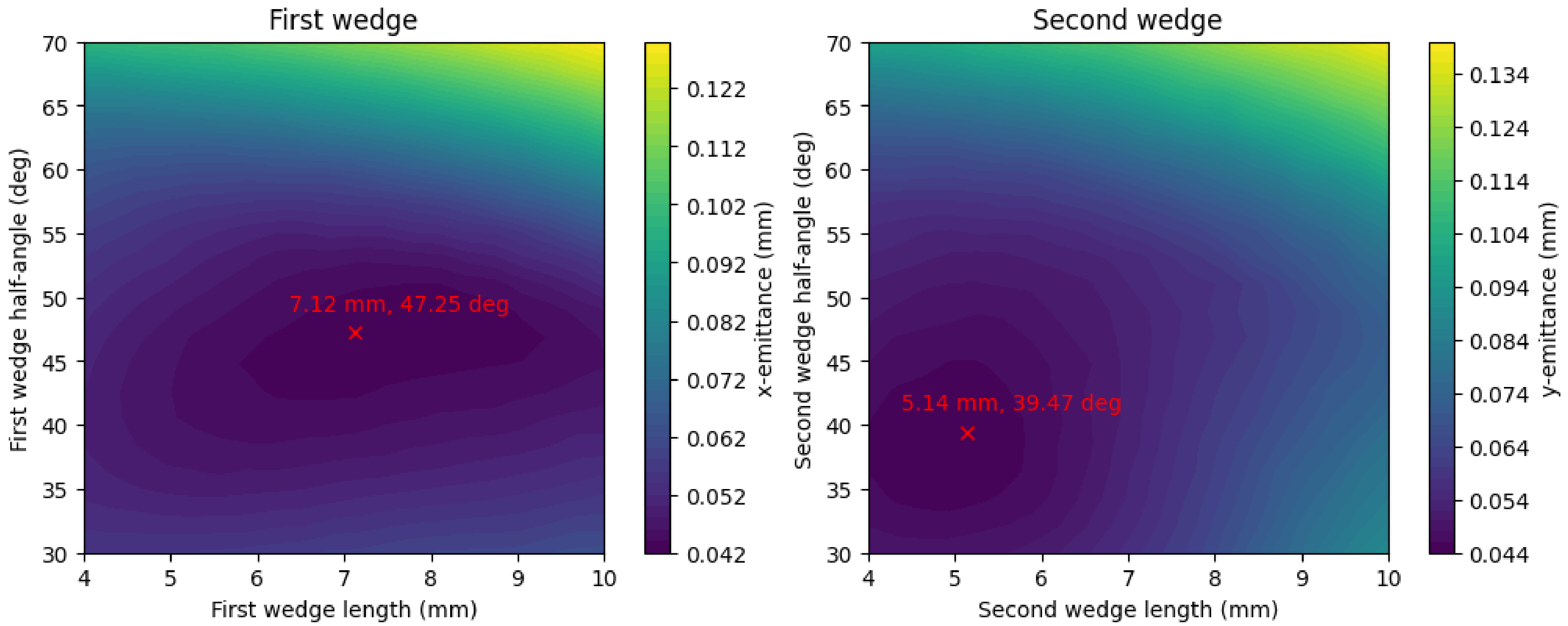
Source: [1612.08960](https://arxiv.org/abs/1612.08960)

Parameters Considered

- Wedge geometry
  - Half-angle
  - Length
- Initial beam parameters
  - Momentum
  - Momentum spread
  - Emittances
  - Twiss parameters (beta, alpha)
- RF cavity parameters
  - Drift channel length
  - Frequency
  - Gradient
  - Phase

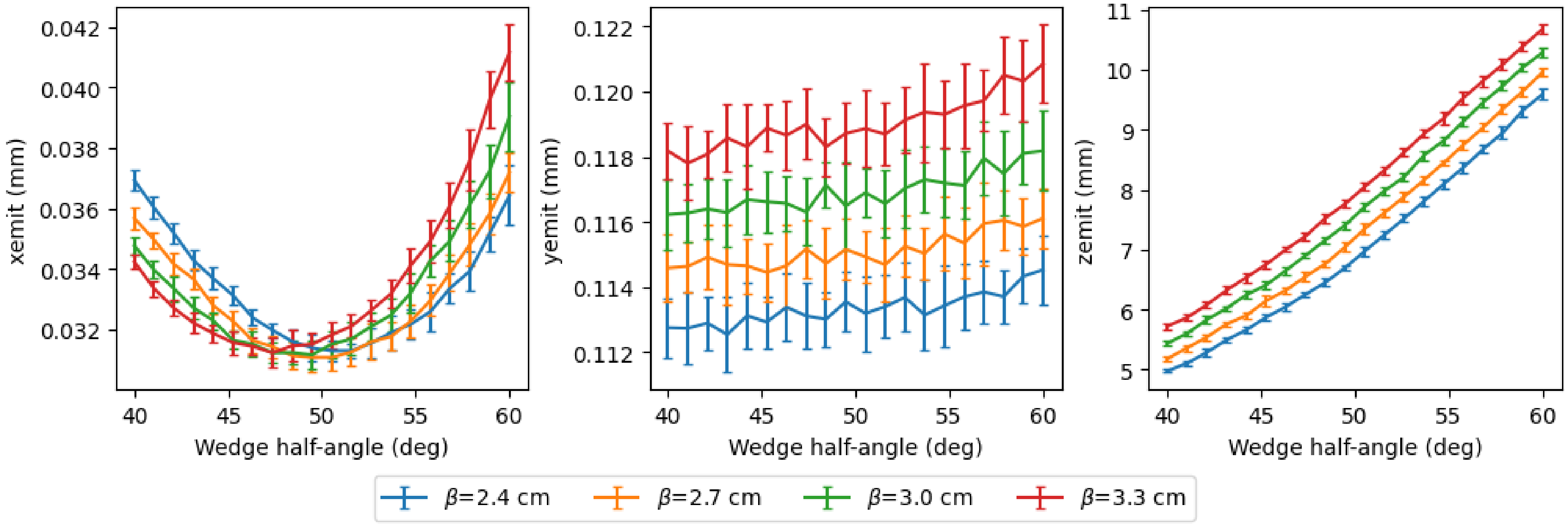
Optimal geometries for wedges

- Determined optimal length and half-angle of first and second wedges to minimize output transverse emittance



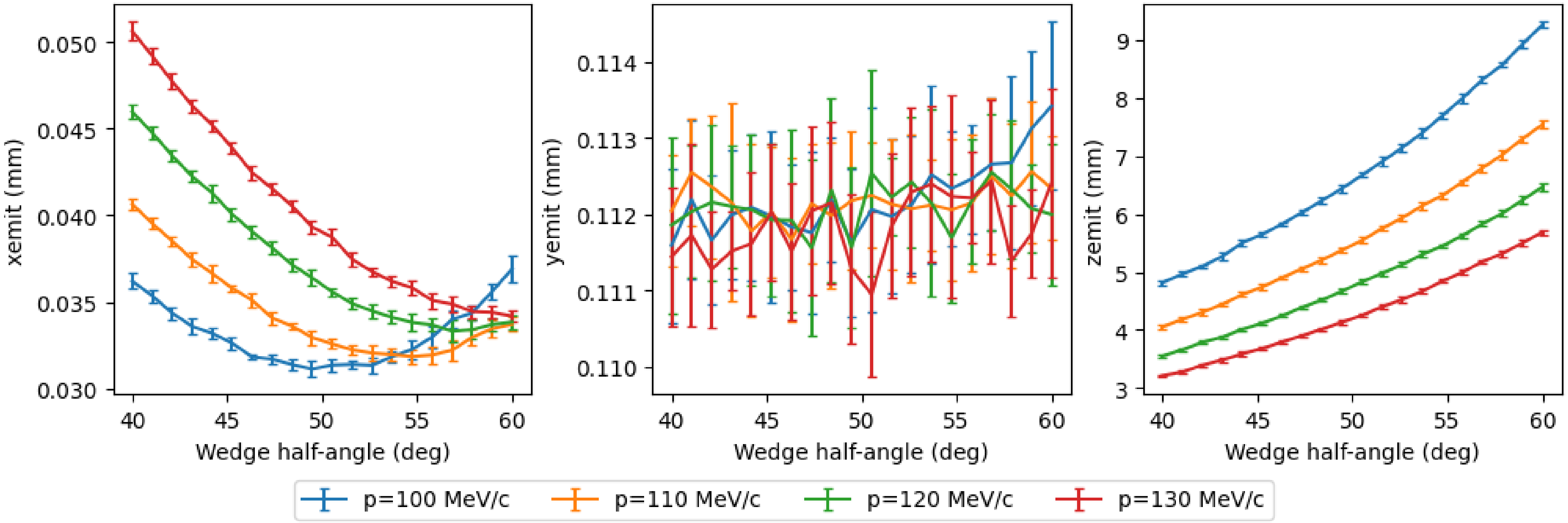
Effects of β

- Decreasing β (stronger focusing) reduces emittance growth in longitudinal and non-cooling transverse axes
- Does not significantly affect emittance in cooling axis



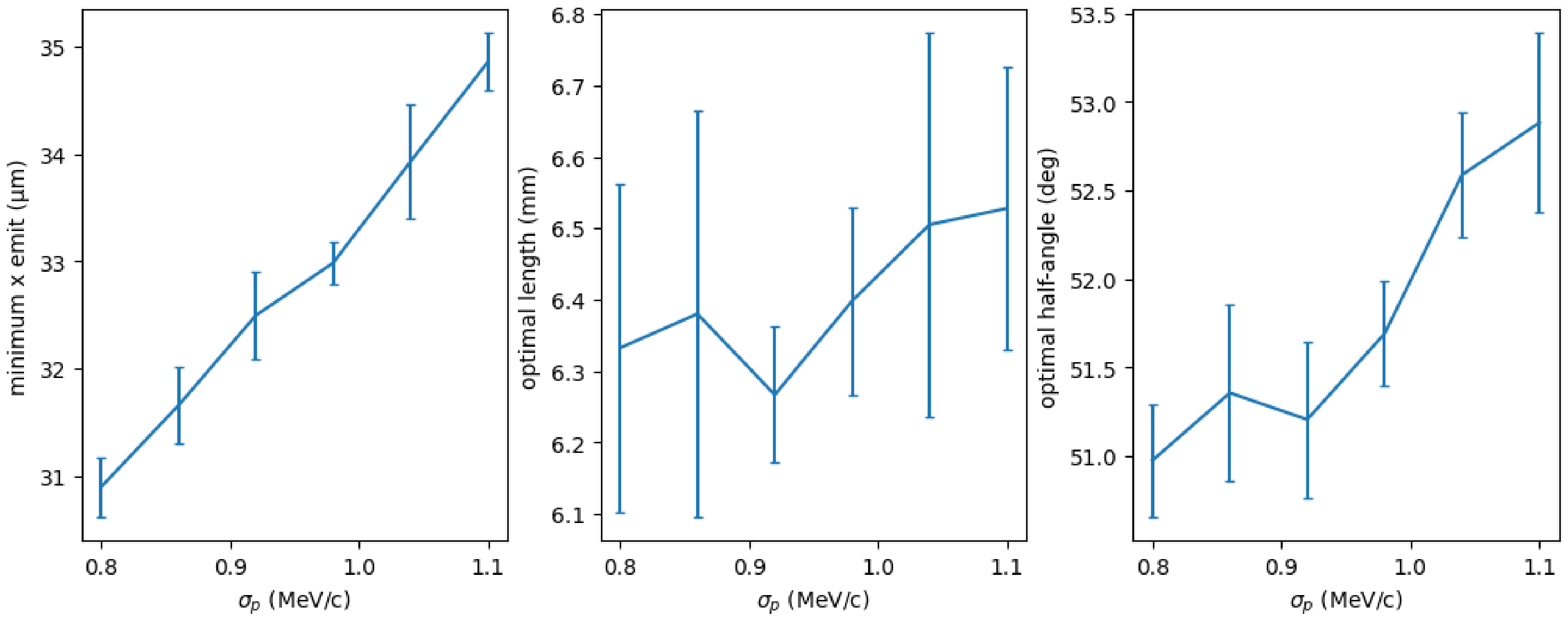
Effect of Momentum

- Reducing momentum improves cooling
- Does not affect emittance in non-cooling axis

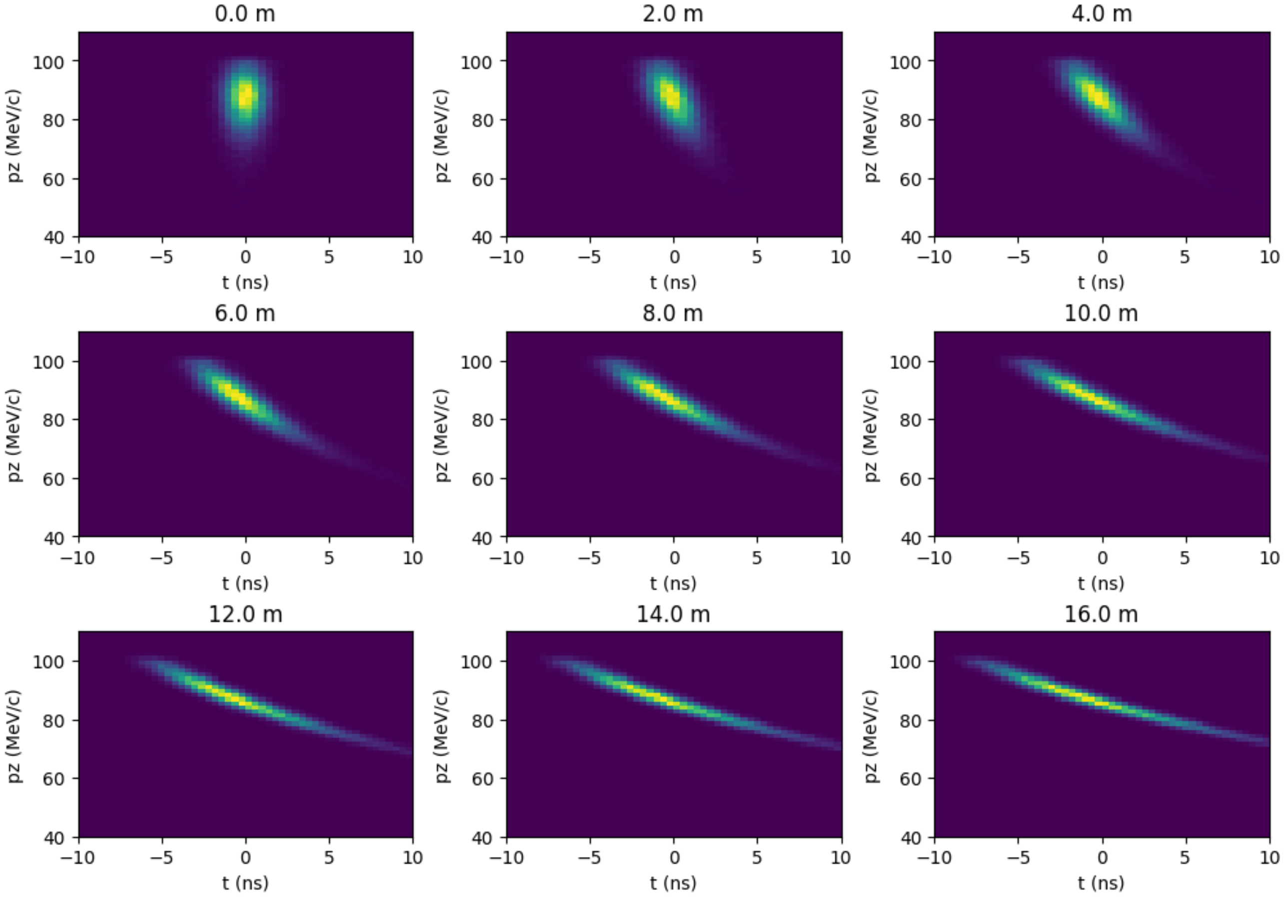


Effect of Momentum Spread

- Decreasing momentum spread increases cooling
- Optimal wedge angle correlated with initial momentum spread
- Optimal wedge length unaffected



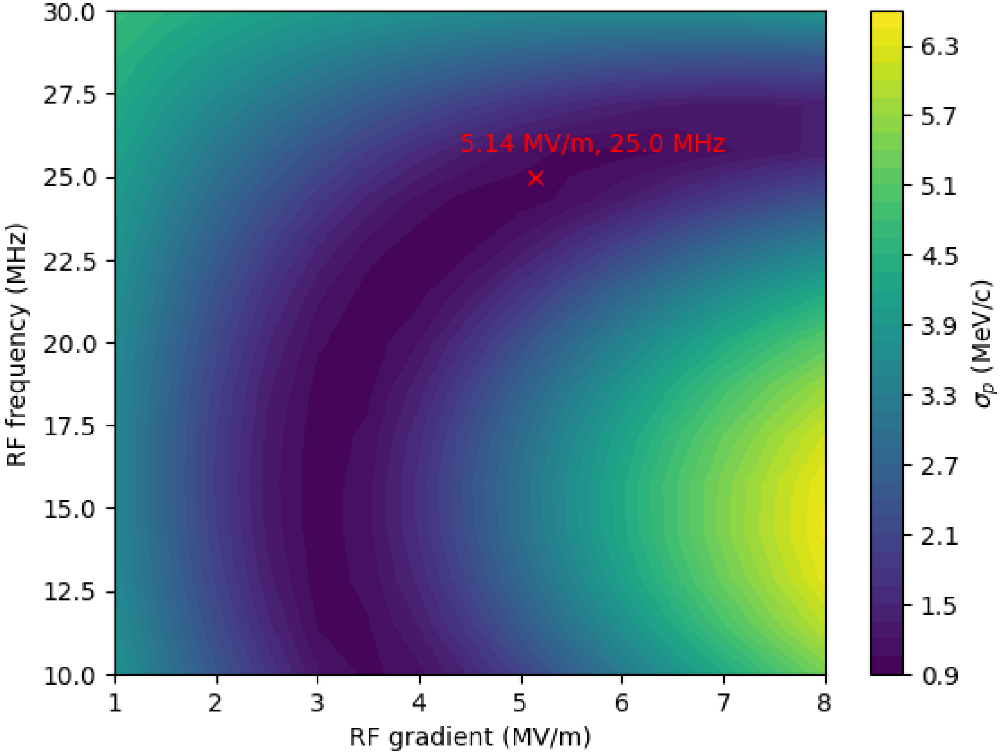
Effect of Drift Length

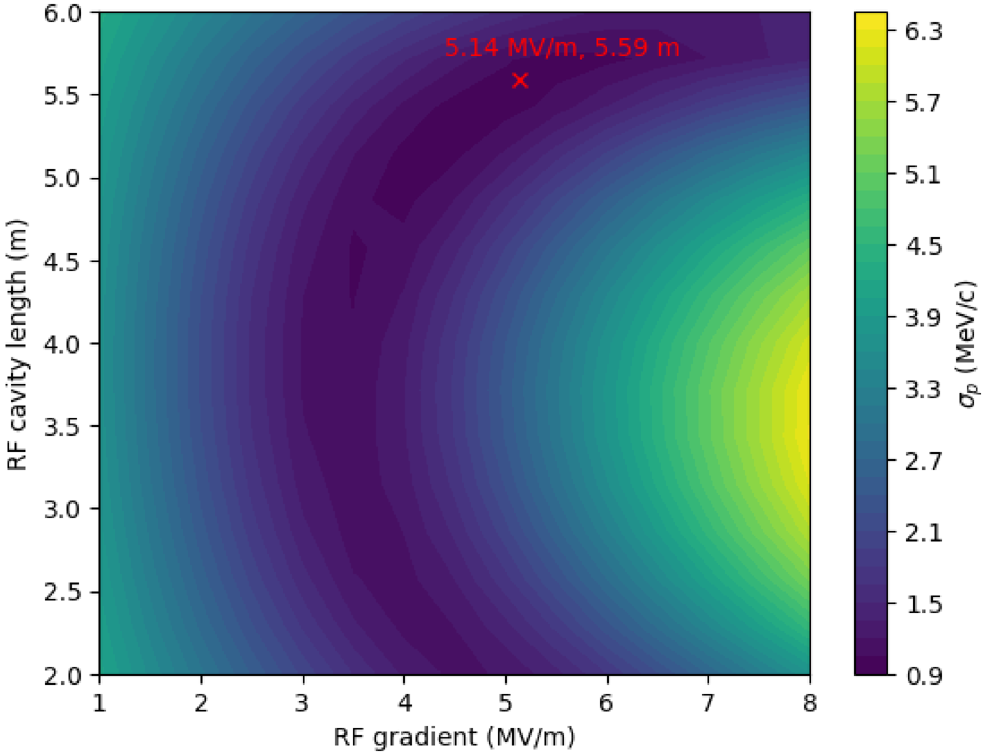


- Higher drift length makes phase rotation more effective
- 16m chosen as longest practical length

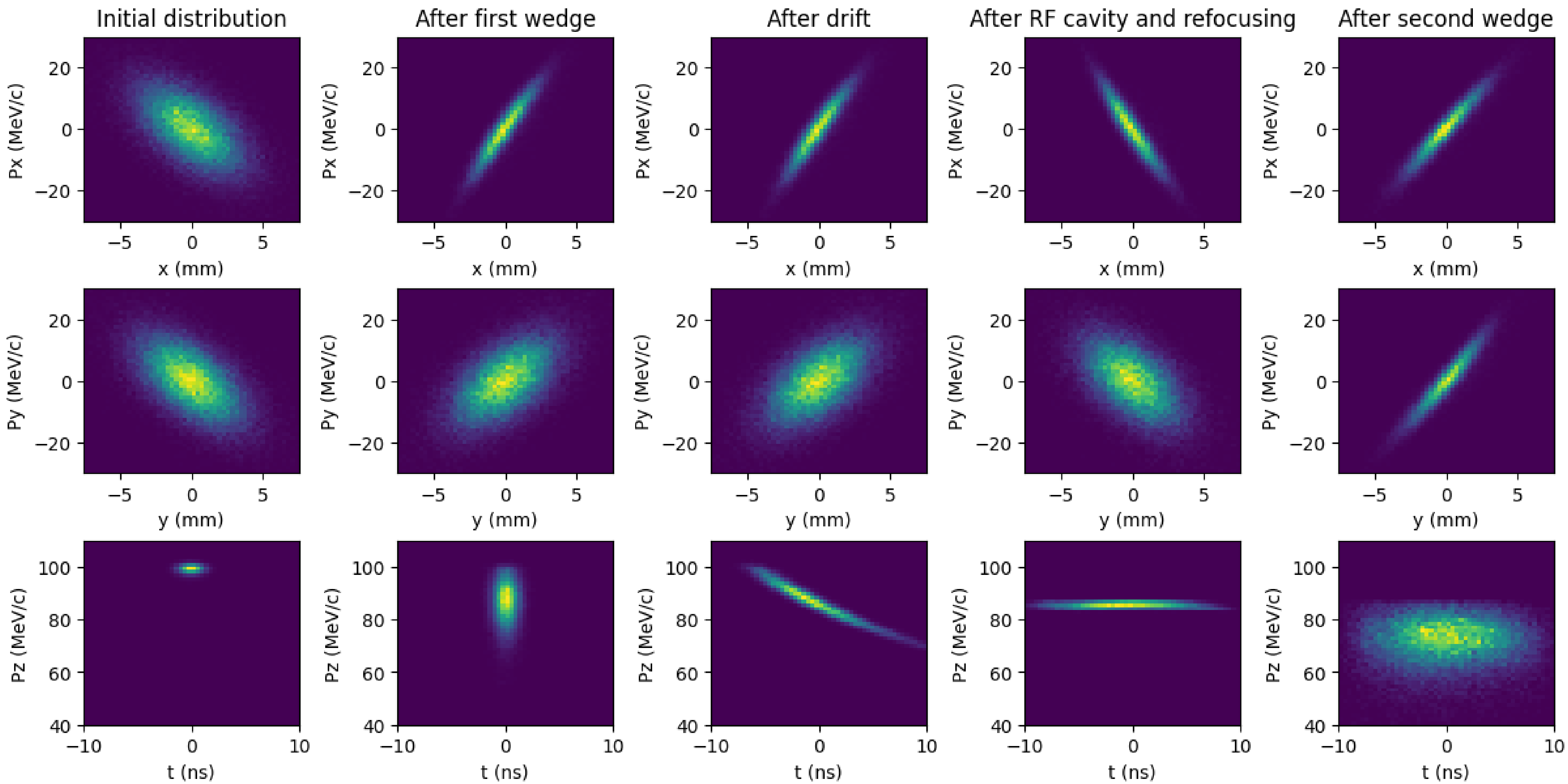
Effect of RF cavity parameters

- Optimal frequency is lower, 25 MHz chosen as lowest practical frequency
- Optimal gradient and cavity length determined



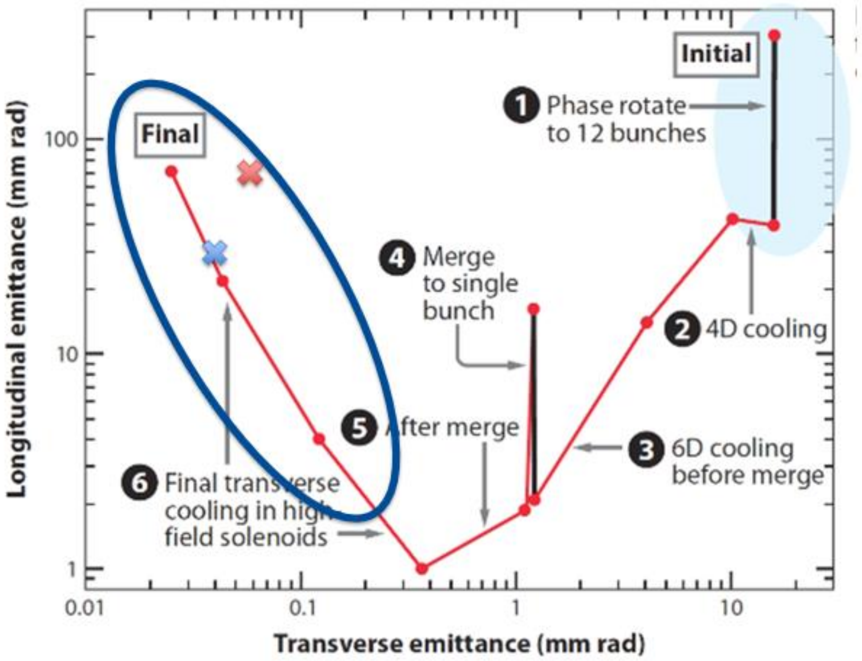


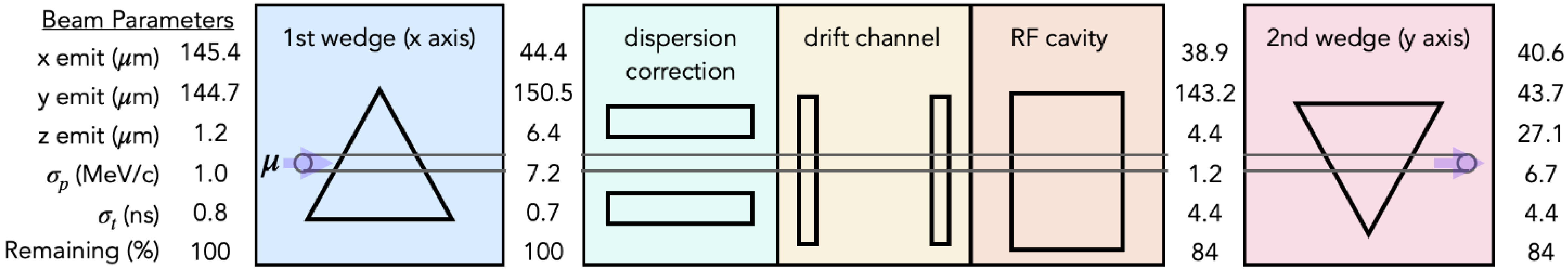
Phase-space diagram of cooling process



Results

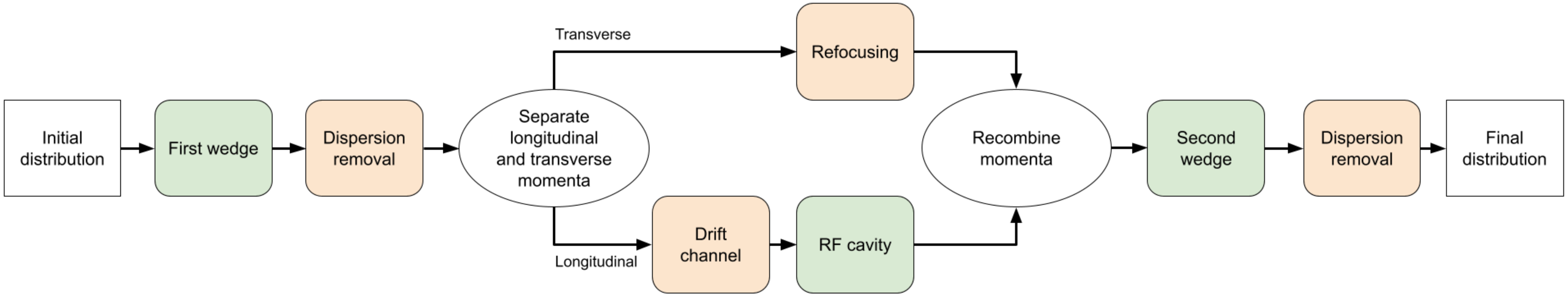
- Achieved lower transverse emittance than previous best results
- Demonstrated cooling from first and second wedges





Assumptions and Caveats

- Dispersion removal, drift channel, and focusing lattice not designed, idealized versions assumed (previous results are best-case)
- Only longitudinal behavior was considered in the RF cavity
- Possibility of refocusing before second wedge (potential for further performance improvement)



Next Steps

- Reduce assumptions described on previous slide, specifically by designing and simulating the magnetic components
- Further optimize design to achieve equal cooling from second wedge
- Characterize effect of changing multiple variables (potentially with high-performance computing)

(additional slides follow)

Optimized Channel Statistics

145 µm initial emittance case						
Stage	x emit (µm)	y emit (µm)	z-emit (mm)	sigma-p (MeV/c)	sigma-t (ns)	Beam remaining
Initial distribution	145.3	144.7	1.256	1.001	0.745	100.0%
After first wedge	44.4	150.5	6.409	7.247	0.745	100.0%
After RF cavity + 15% cut	38.9	143.2	4.436	1.293	4.404	84.0%
After second wedge + 4σ cut	40.6	43.7	27.170	6.693	4.401	83.8%

110 µm initial emittance case						
Stage	x emit (µm)	y emit (µm)	z-emit (mm)	sigma-p (MeV/c)	sigma-t (ns)	Beam remaining
Initial distribution	110.0	109.8	1.385	0.798	0.933	100.0%
After first wedge	33.4	114.9	7.357	6.510	0.933	100.0%
After RF cavity + 15% cut	28.9	113.7	5.039	1.395	4.475	84.0%
After second wedge + 4σ cut	32.2	38.7	28.754	7.120	4.472	83.8%

Summary of Variables Considered

Variable	Status
Wedge geometry (half-angle and length)	Optimal values determined
Initial beta	As low as possible; 3.0 used
Initial alpha	Optimal value estimated at 0.7
Initial momentum	As low as possible; 100 MeV/c used
Initial momentum spread	As low as possible; 0.8-1.0 MeV/c used
Drift length	As long as practical; 16m used
RF frequency	25 MHz used, optimal value is lower
RF gradient and length	Optimal values determined

Effects of α

- Increasing α decreases growth of emittance in longitudinal and second transverse axes (similar to decreasing beta)
- Past around 0.5, increasing α decreases wedge performance (minimum transverse emittance increases)