Final Cooling with Thick Wedges for a Muon Collider

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Fermilab

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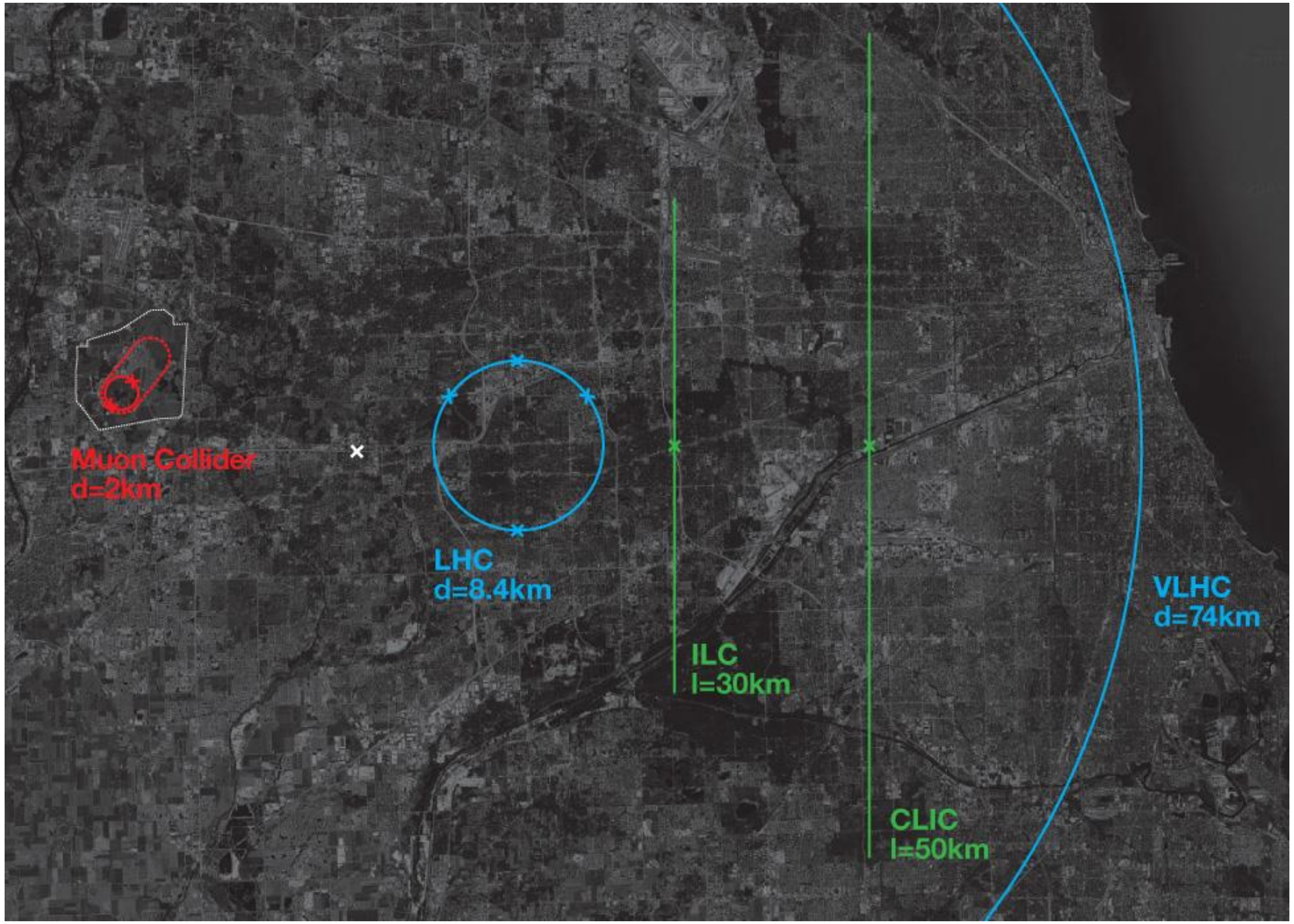
What is a Muon Collider?

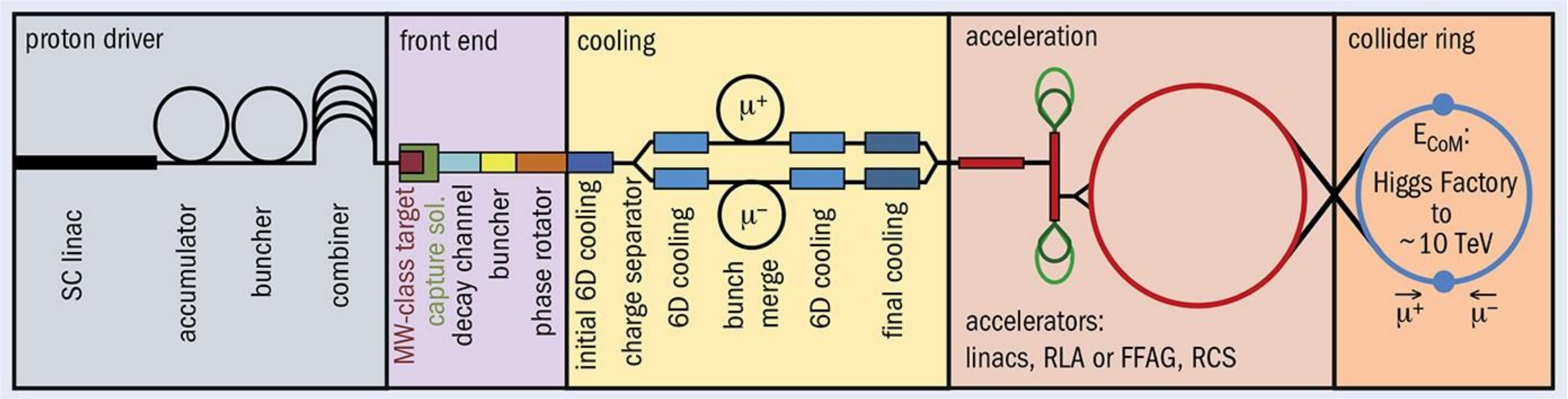
- Proposed particle accelerator colliding muons and antimuons
- Current particle accelerators use protons or electrons
  - Electrons lose energy to radiation – harder to reach high energy
  - Protons are composite particles – collisions more complex
- Muons are high mass, elementary particles – best of both worlds
- Potential to reach new energy scale (10 TeV) with smaller footprint

What is a Muon Collider?

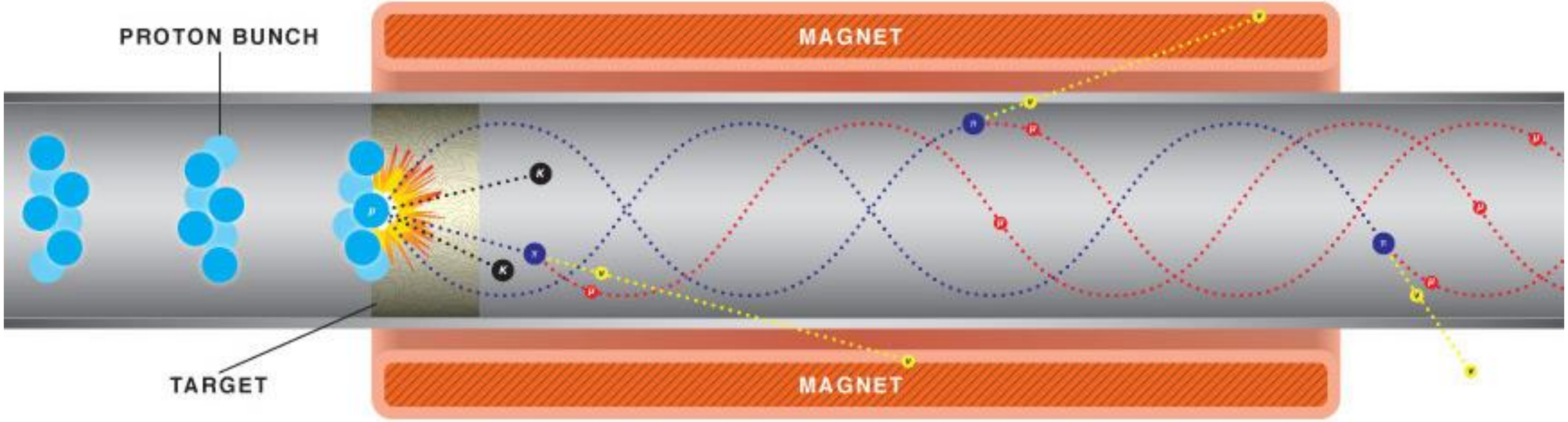


Muon production

- Muons are unstable, must produce, accelerate, and collide them before they decay
- Proton-target collisions produce pions, which decay into muons



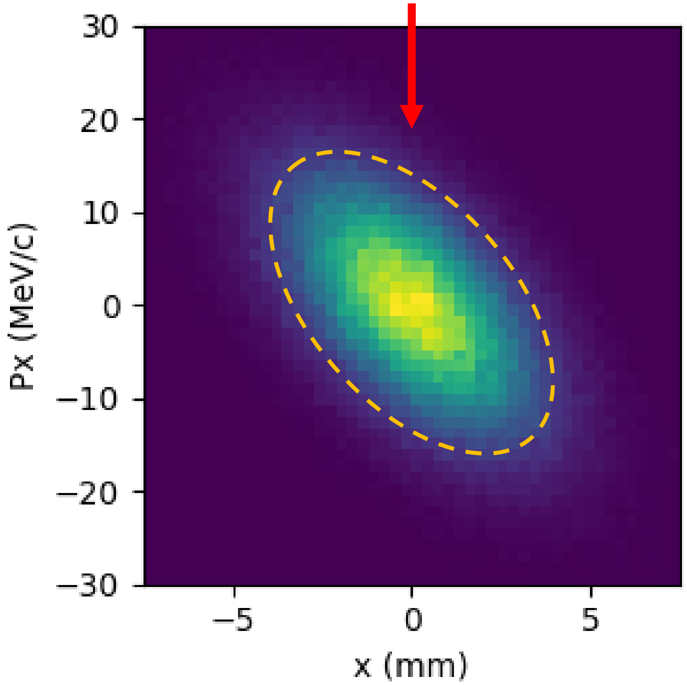
Muon production



Emittance and Cooling

- Initially high variance in muon position and momentum – measured by *emittance*
- Emittance measured in longitudinal (parallel to beam) and transverse (perpendicular to beam) axes
- Reducing emittance is important for maximizing luminosity; this process is known as *cooling*

Emittance = area of distribution in phase-space

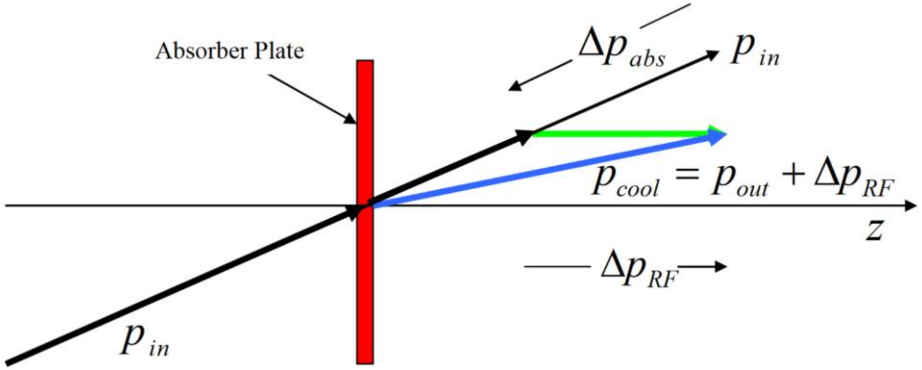


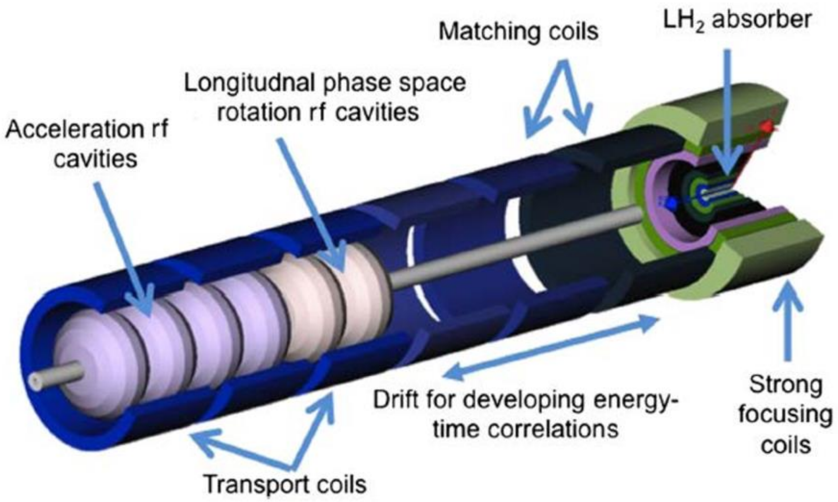
$$\langle \mathcal{L} \rangle = \frac{N_1 N_2 n_b f_r}{4\pi \sigma_x \sigma_y}$$

Variances in position related to transverse emittance

Ionization Cooling

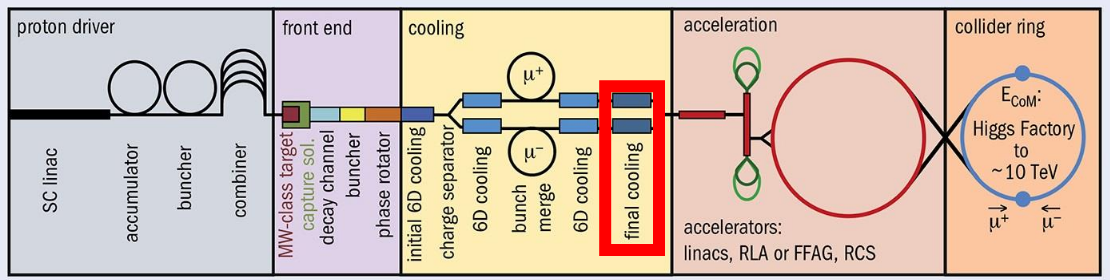
- Used because of short lifetime of muon
- Beam passed through matter, loses energy through ionization
- Momentum reduced in all axes (transverse and longitudinal)
- Beam is then reaccelerated with RF cavity
- Ends with greater proportion of momentum in longitudinal direction, achieving cooling

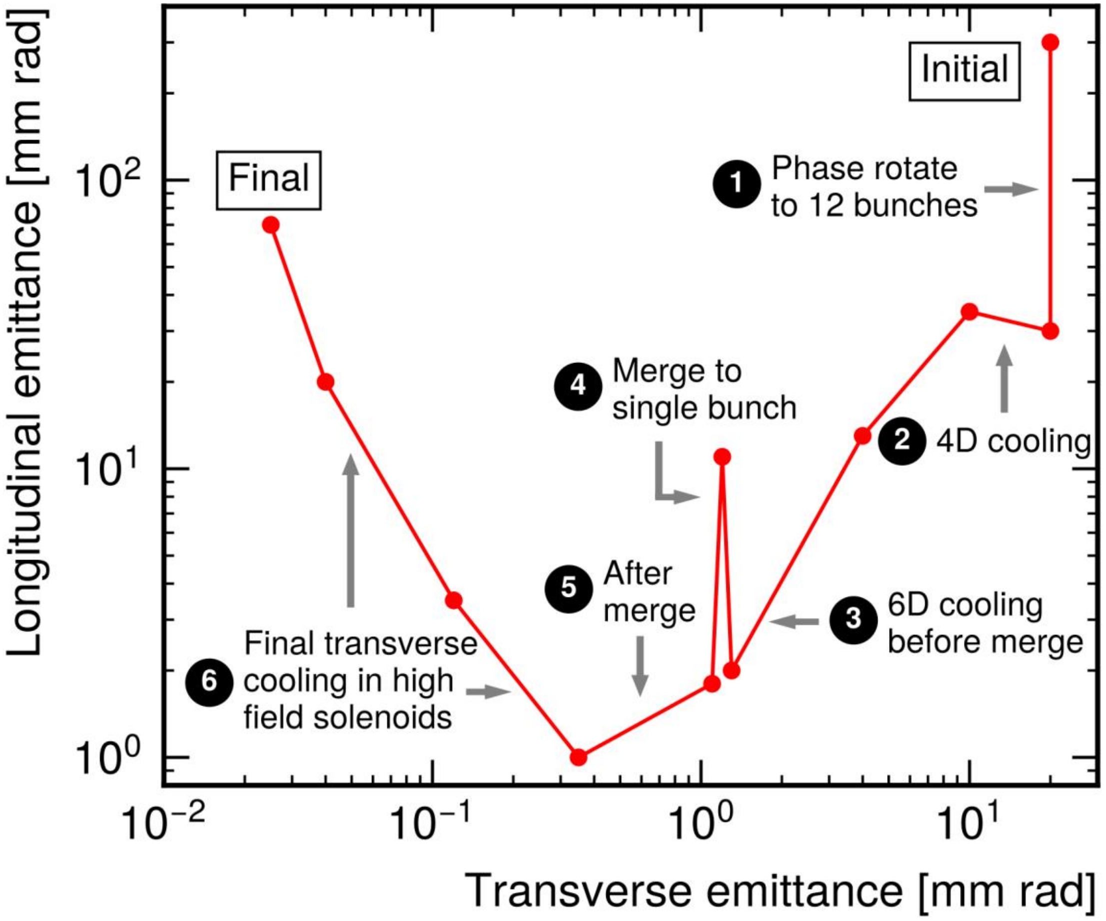




Final Cooling

- Cooling occurs in several stages
- Initial stages reduce emittance in all axes (6D cooling)
- Final cooling reduces transverse emittance, longitudinal emittance allowed to grow (4D cooling)
- Target emittance around 30 μm transverse, 100 mm longitudinal





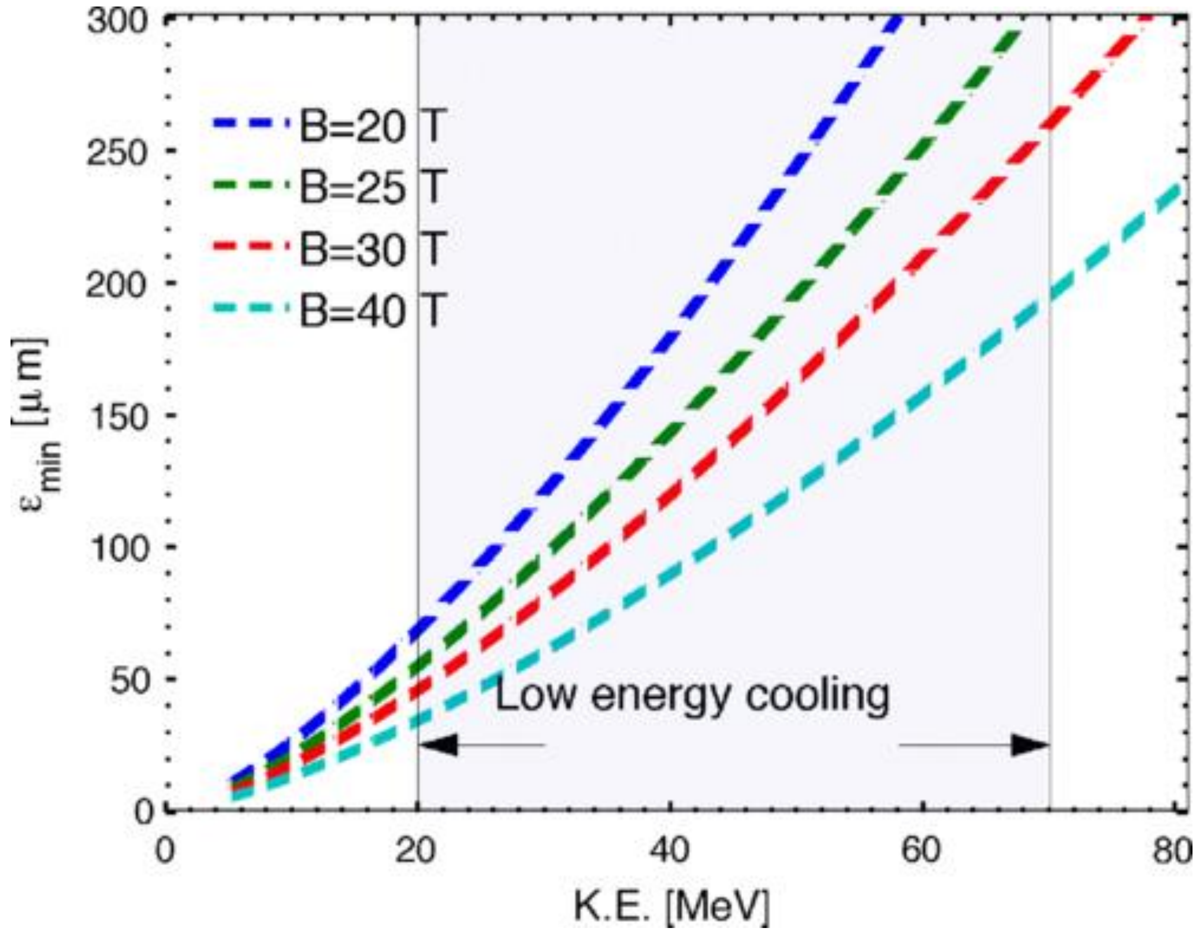
Problems with Baseline Final Cooling

- Multiple scattering limits emittance reduction – equilibrium point dependent on momentum and beam width (β_t)
- High field (40-50 T) solenoids required to focus beam – impractical to construct and operate
- Low momentum required – drastically increases longitudinal emittance
- Motivates alternate final cooling methods

$$\varepsilon_{N,\mathrm{eq}} \cong \frac{\beta_t E_s^2}{2\beta mc^2 L_R (dE/ds)}$$

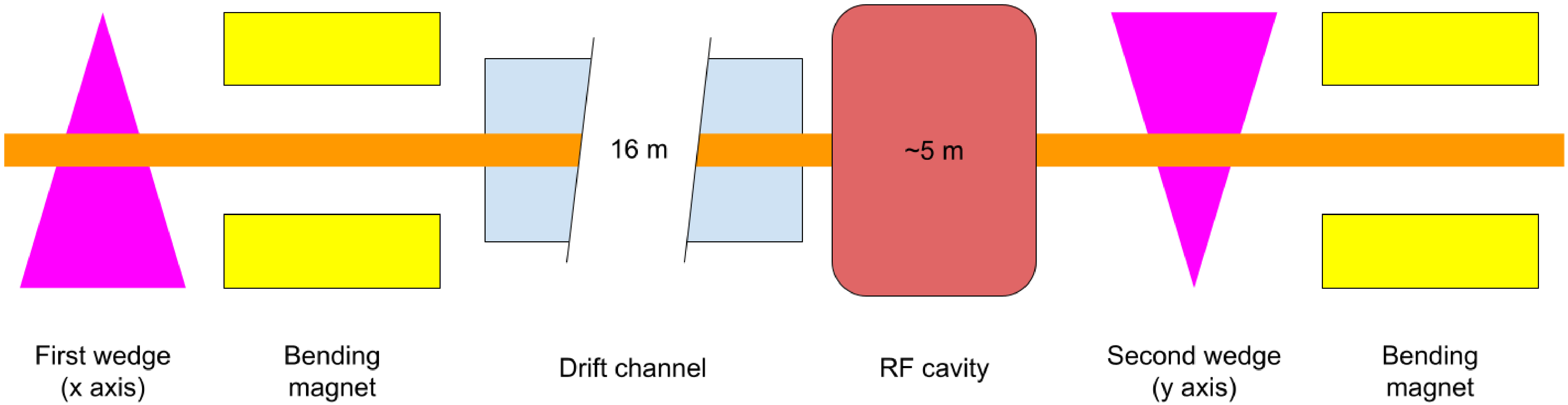
$$\beta_t(m) \cong \frac{2P_\mu(GeV/c)}{0.3B(T)}$$

Problems with Baseline Final Cooling

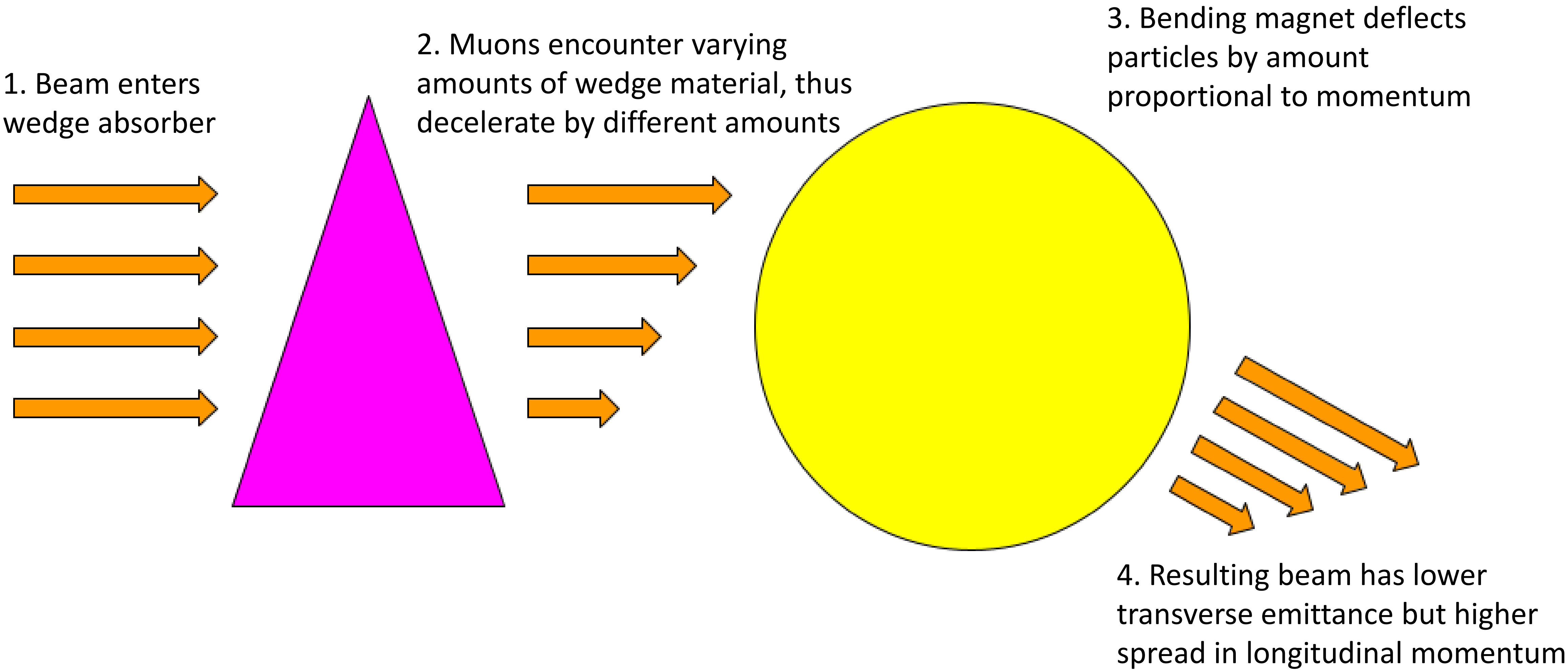


Final Cooling with Thick Wedges

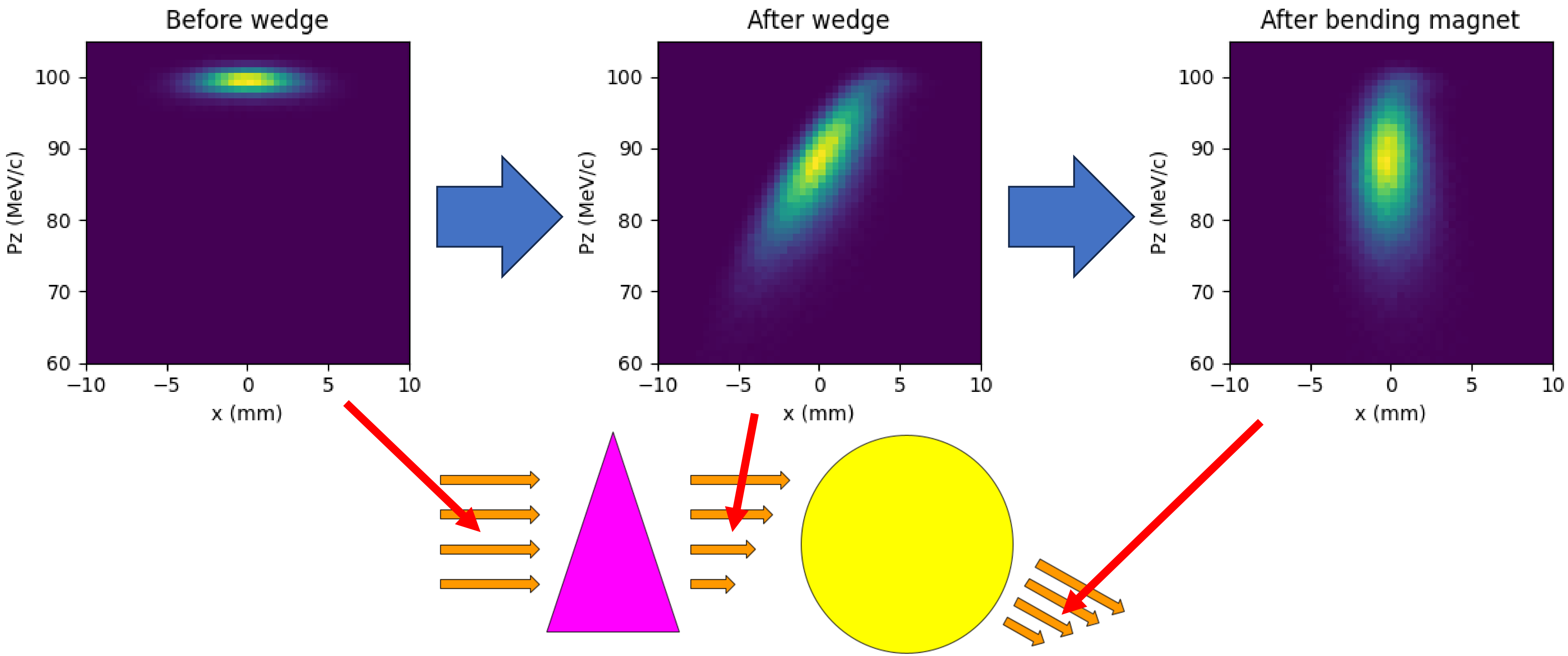
- Conceptual final cooling design proposed by Neuffer in 1612.08960
- Utilizes wedge-shaped absorbers to achieve emittance exchange
- Alternative means of emittance exchange – lower field requirements



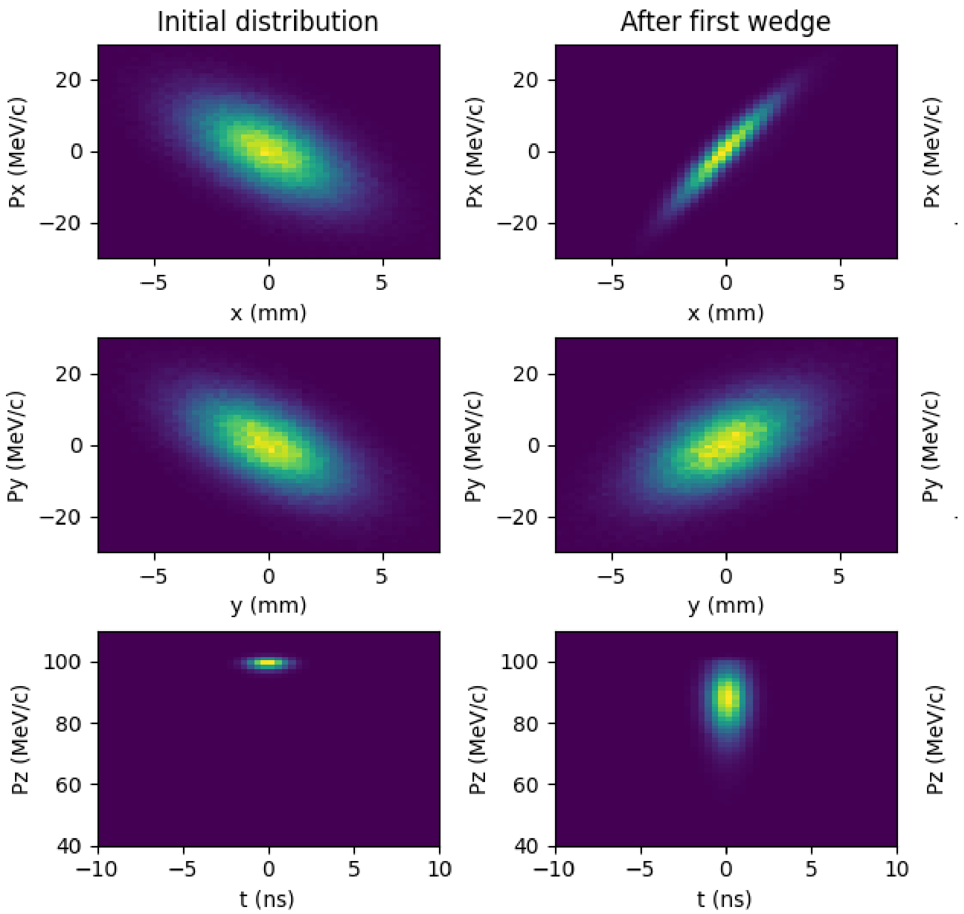
Wedge Cooling Mechanism



Wedge Cooling Mechanism



Wedge Cooling Mechanism



Emittance in axis of wedge (x) decreases

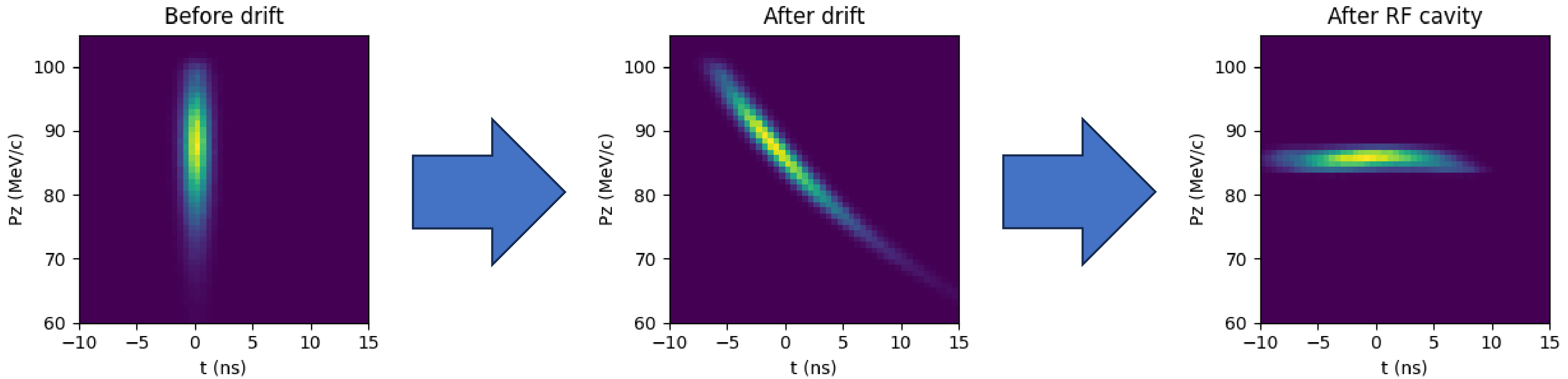
Emittance in second transverse axis (y) unchanged

Emittance in longitudinal (z) axis increases due to increased spread in momentum

Momentum spread must be reduced before second wedge

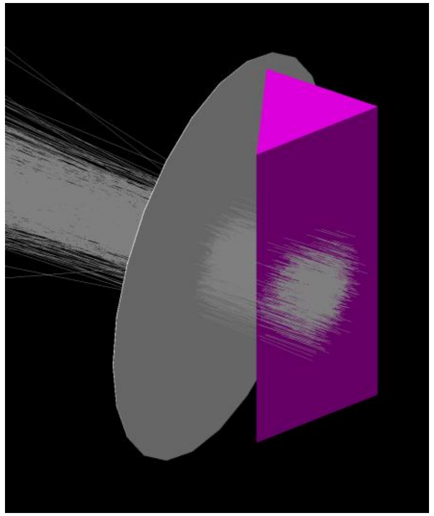
Phase Rotation

- Particles travel through drift channel – correlation between z and Pz
- RF cavity applies time-varying E-field – decelerates faster muons and accelerates slower muons
- Decreases longitudinal momentum spread at the cost of increasing longitudinal position spread (longitudinal emittance unchanged)



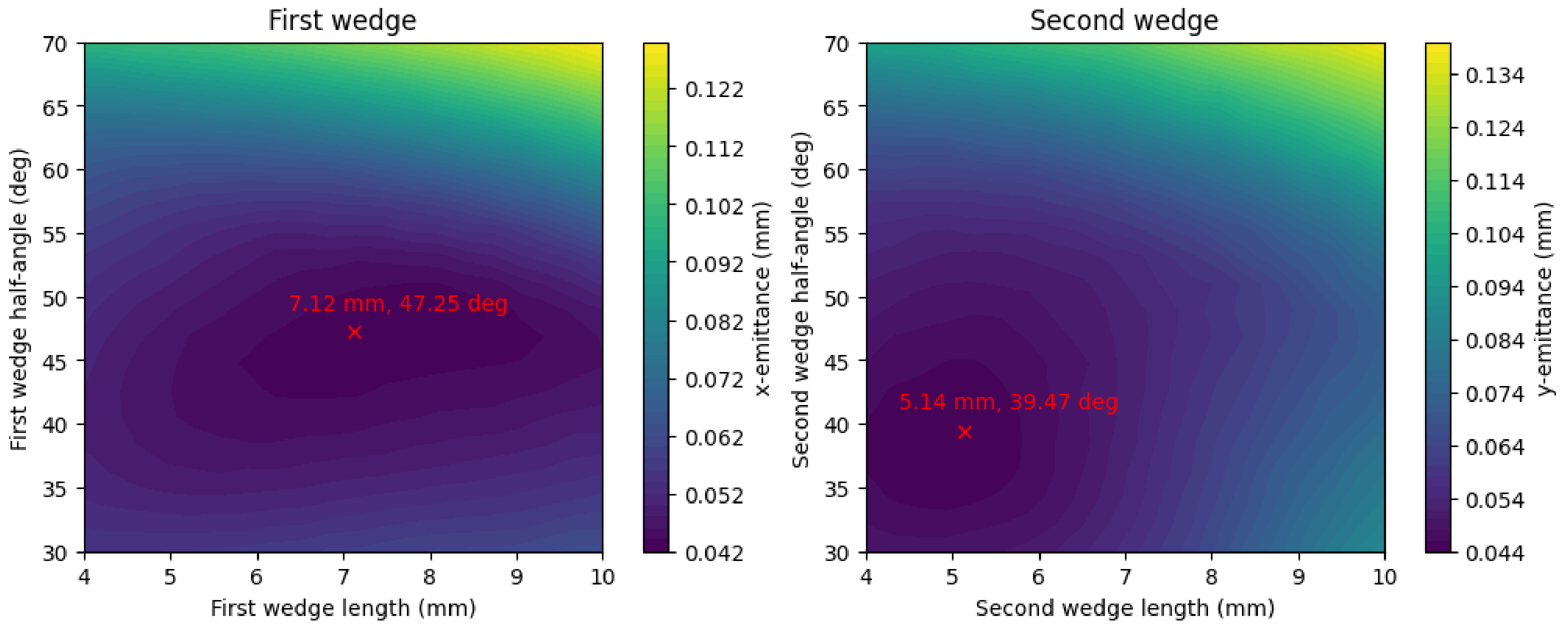
Simulation and Optimization

- Simulated using G4Beamline software
- Optimization conducted using Nelder-Mead method (scipy)
- Optimized 1st wedge, drift length, RF cavity, and 2nd wedge sequentially



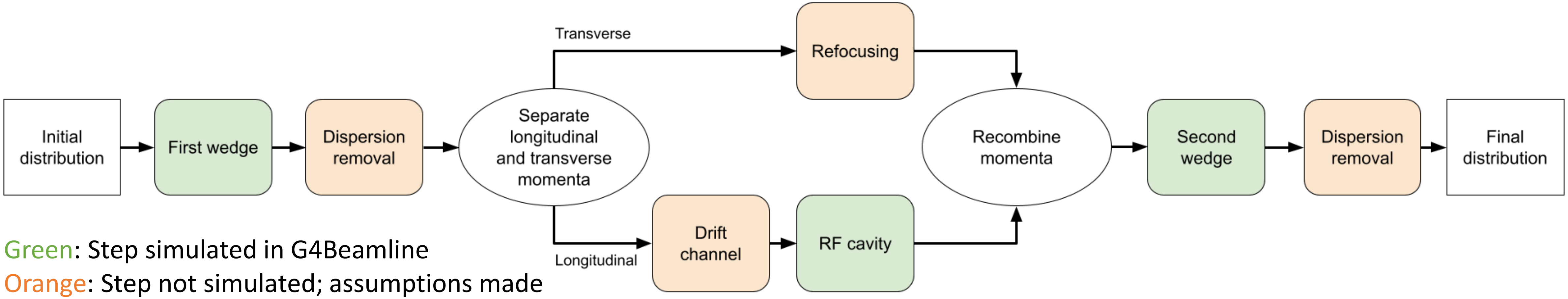
Left: Example G4Beamline simulation

Right: Optimal parameters for the first and second wedges



Caveats and Assumptions

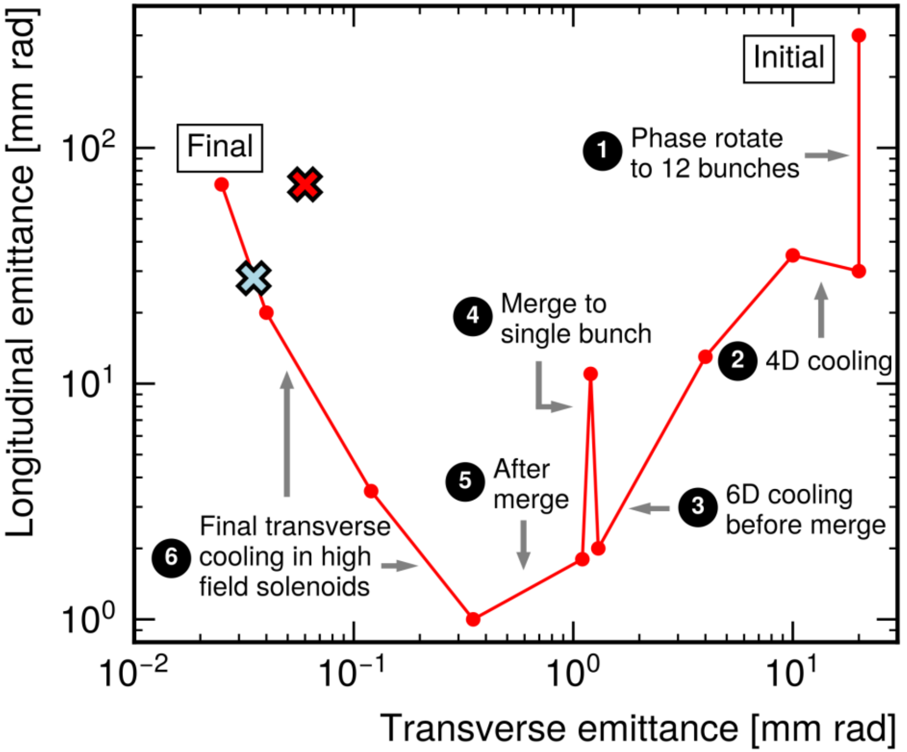
- Magnets for focusing, beam transport, and bending were not designed – idealized versions assumed
  - Required magnet strengths not precisely known
- Only longitudinal behavior was considered in the RF cavity
- Losses from muon decays and inter-particle interactions ignored

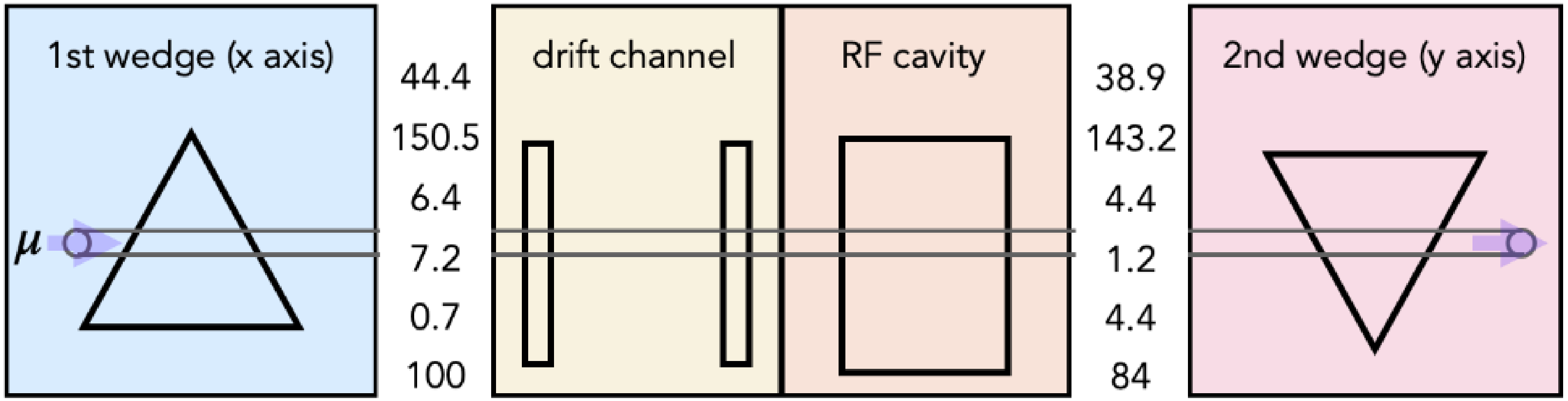


Green: Step simulated in G4Beamline
Orange: Step not simulated; assumptions made

Results

- Optimized conceptual design
- Achieved lower transverse emittance (x) than previous best results (x)
- Demonstrated cooling from first and second wedges



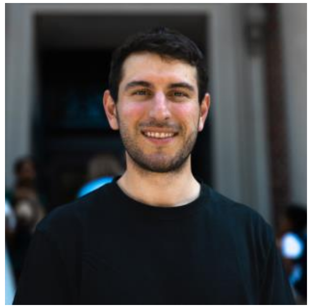


Beam Parameters		After 1st wedge (x axis)	After drift channel, RF cavity	After 2nd wedge (y axis)
x emit (μm)	145.4	44.4	38.9	40.6
y emit (μm)	144.7	150.5	143.2	43.7
z emit (μm)	1.2	6.4	4.4	27.1
σ_p (MeV/c)	1.0	7.2	1.2	6.7
σ_t (ns)	0.8	0.7	4.4	4.4
Remaining (%)	100	100	84	84

Next Steps

- Improve simulation and optimization
  - Include magnets in simulation to reduce assumptions
  - Global optimization using Bayesian methods and surrogate modelling
  - Validate results v.s. particle count and other parameters
- Combine wedges with other cooling methods
- Demonstrators for wedge cooling technology

Dr. Karri DiPetrillo



Anthony Badea

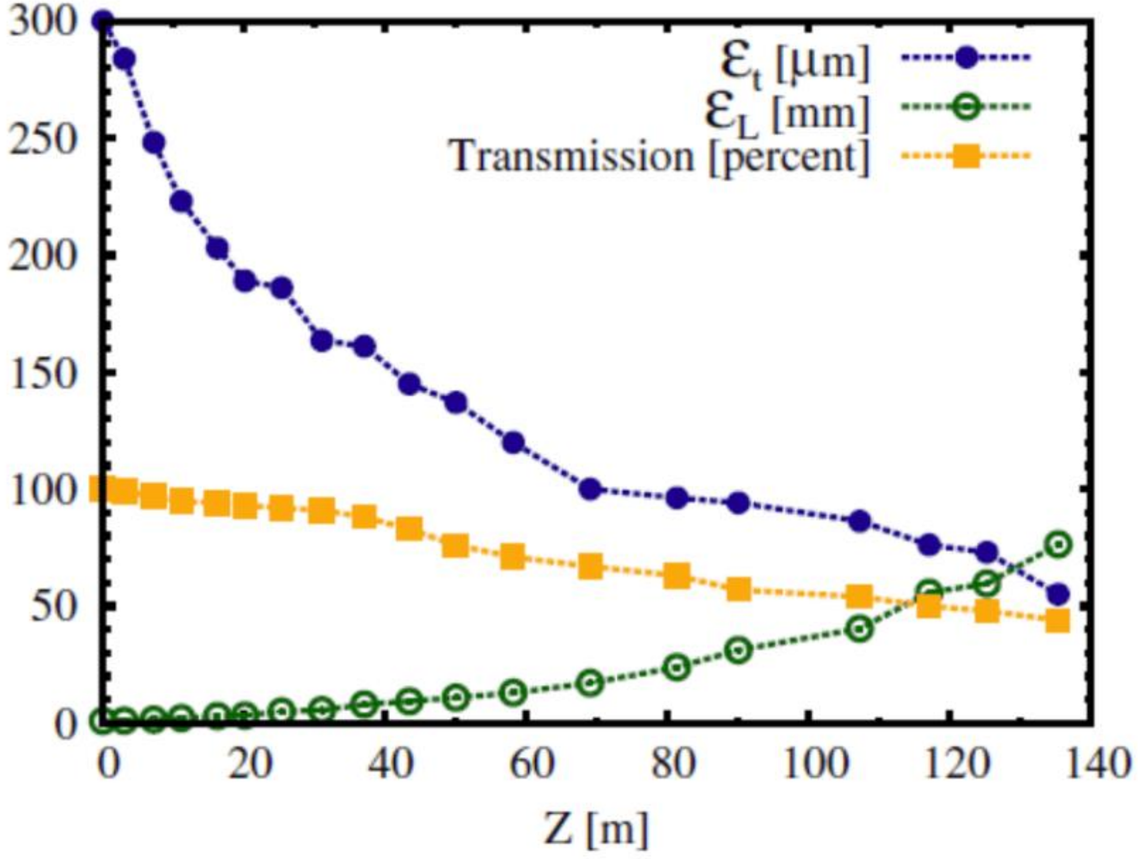
Ryan Michaud

Thank you for listening!

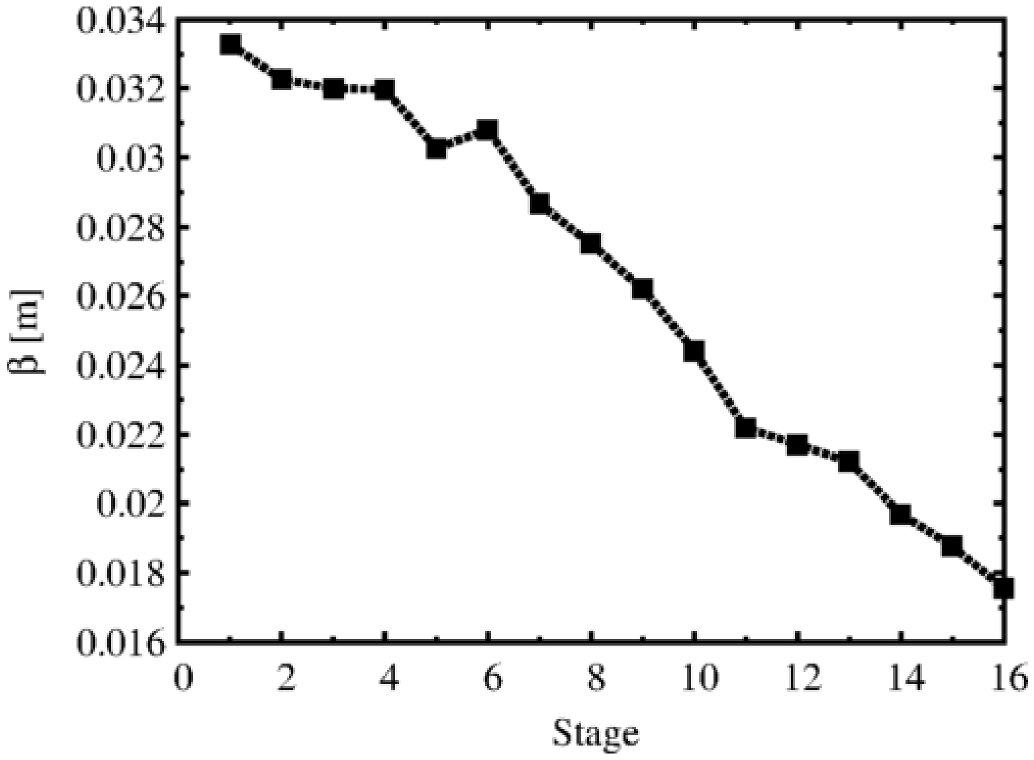
Questions?

Backup slides

Baseline Graphs



Source: 1612.08960



Source: 10.1103