Maximising luminosity at the Muon Collider

International
MUON Collider
Collaboration

C. T. Rogers
Rutherford Appleton Laboratory
On behalf of the International Muon Collider Collaboration

Science & Technology Facilities Council
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Muon Collider

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- Muon collider is capable of **awesome physics**
  - Excellent discovery reach
  - Precision measurement
- Need to ensure that the beam has the highest luminosity possible
  - High quality beam while retaining the high current

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y}$$

Number of particles Per bunch

Rate of bunch crossings

RMS bunch size

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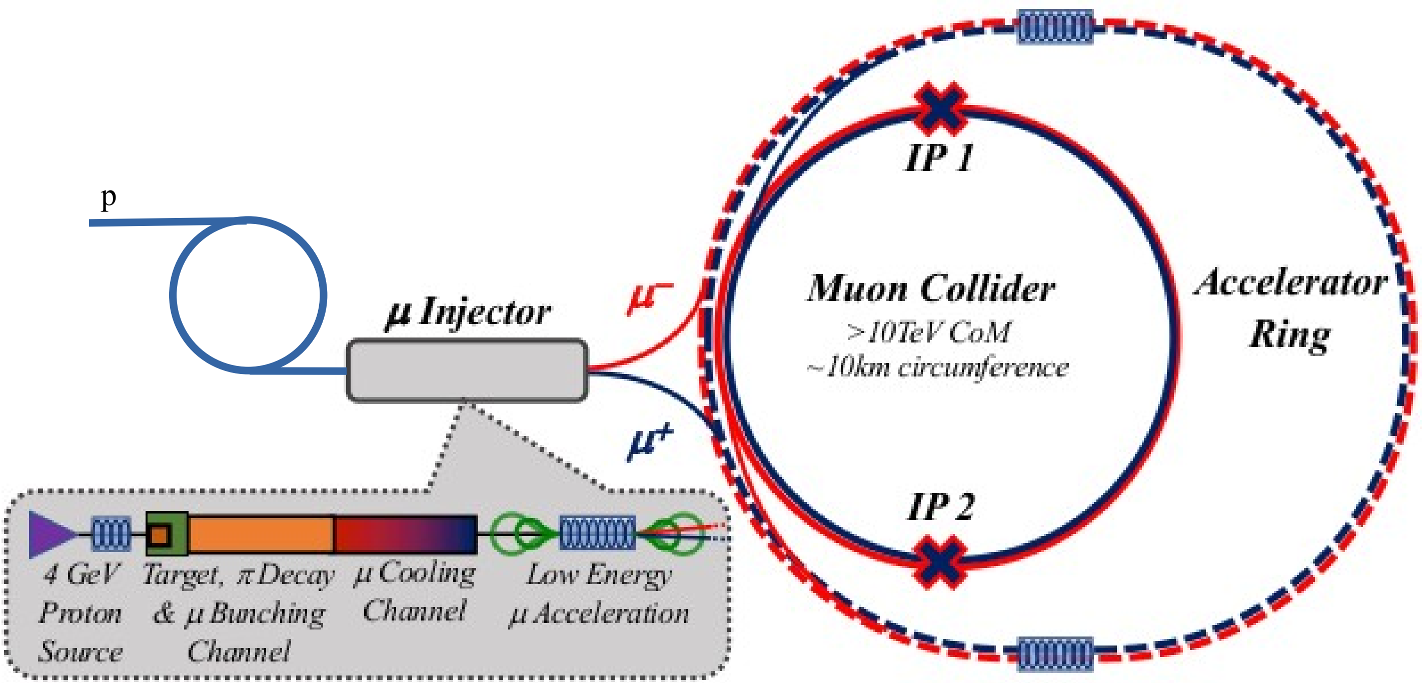
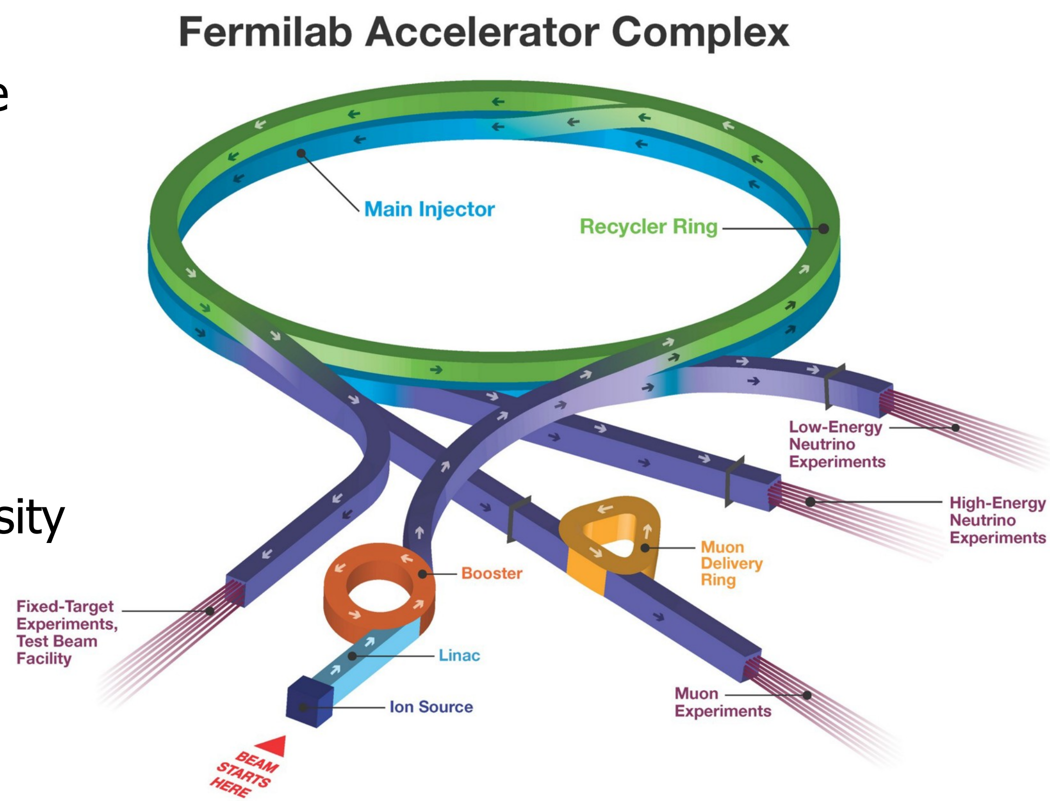
Muon Collider Facility



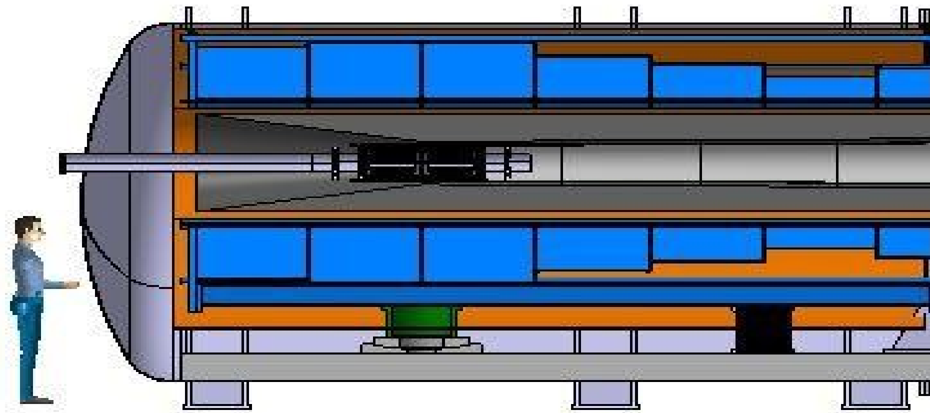
- MW-class proton driver → high proton flux
  - Fermilab proton facility may be compatible
- Target & solenoid capture → large acceptance for pions
- Muon cooling → laser-like muon beam
- Rapid acceleration & tight focusing at the interaction point
- **Luminosity is key to muon collider design**

Proton driver

- MW-class proton driver → high proton flux
  - Fermilab proton facility can be compatible
- Low number of bunches
  - But each bunch ultra intense
  - Fermilab ideal
- Short bunches
  - Maximise instantaneous intensity



MuC Target

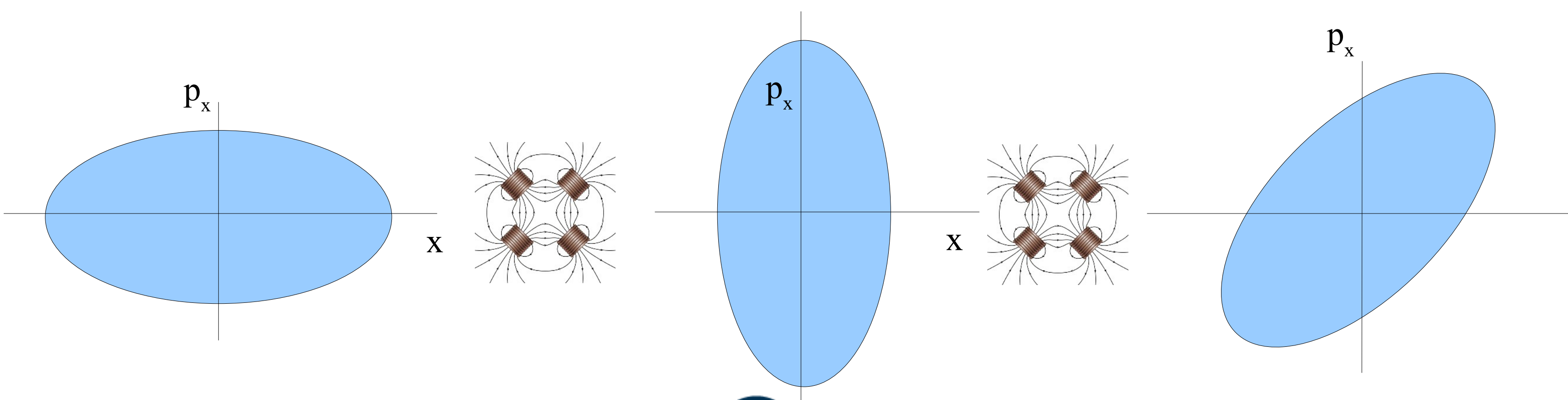


- Protons on target → pions → muons
  - Graphite target takes proton beam to produce pions
  - Heavily shielded, very high field solenoid captures π^+ and π^-
  - Taking best bits of LBNF/μ2e target concepts
- Investigating force-flow cooled High Temperature Superconductor
  - Operation at 20 K → more efficient cryo plant
  - Smaller footprint and stored energy than LTS
- Also strong synergy with
  - Fusion
  - UHF Magnets for science

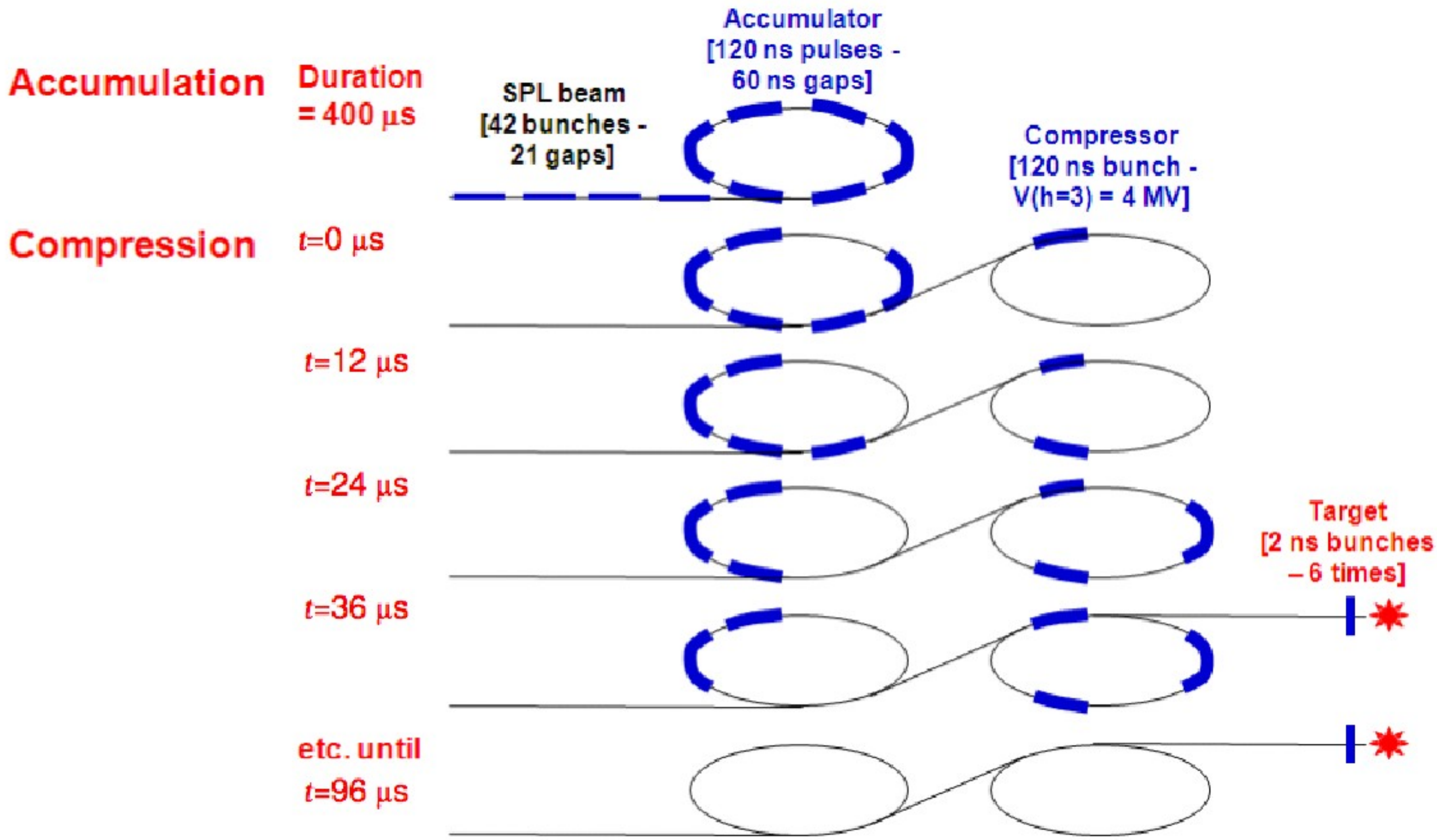
Capturing the Beam

- Even with a strong magnet, capturing the pions is hard
  - Large spread in angles
  - Large spread in momenta
  - → Large **emittance**
- Emittance is a conserved quantity
  - Size of the beam in position-momentum phase space
  - No amount of focusing can reduce it
    - **Liouville's theorem**
- What can we do?

Joseph Liouville
1809 - 1882

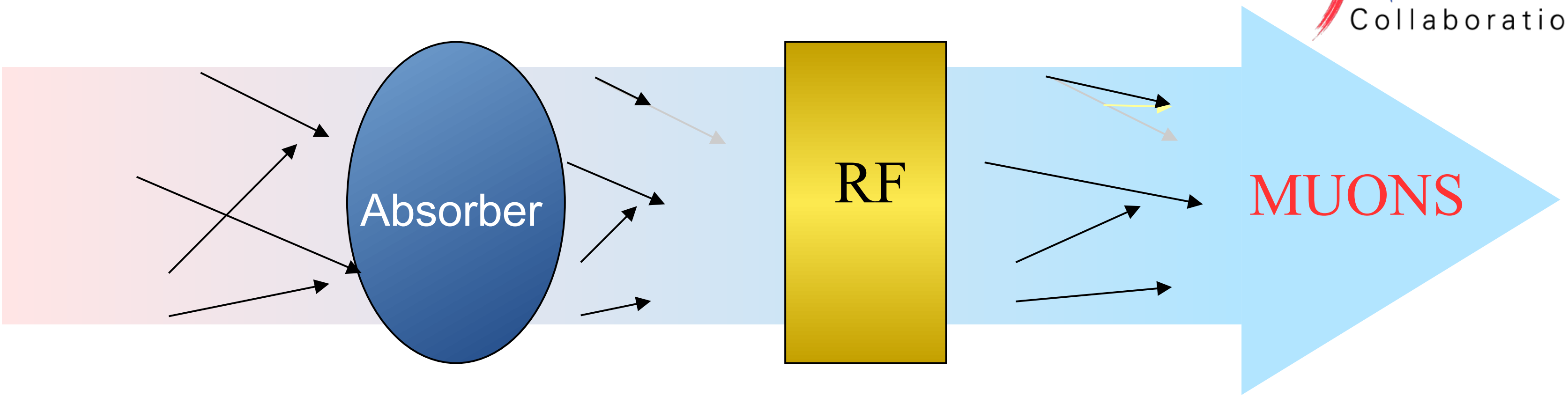


Example – short proton bunch



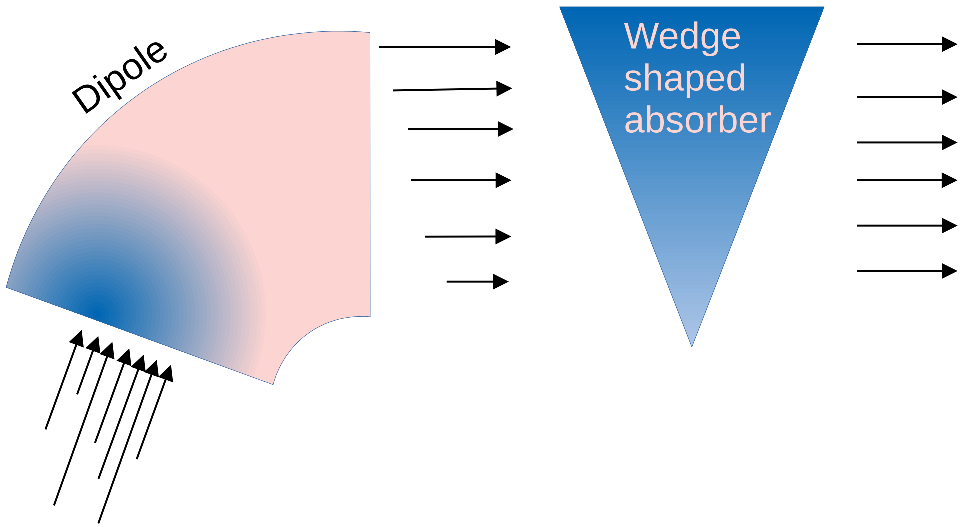
- Energy spread from pion production is irreducible
- Time spread follows from the proton bunch length
- Short proton bunch → short pion bunch → short muon bunch
- We can go one step better - **cooling**

Ionisation Cooling



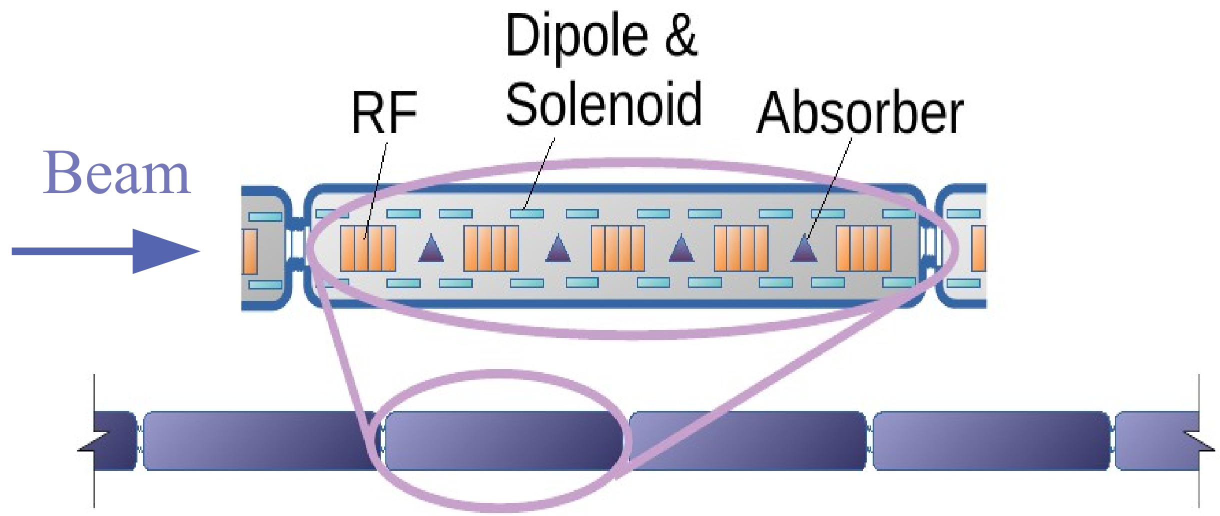
- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate with low-Z materials
  - Equilibrium emittance where MCS completely cancels the cooling
- Reduce transverse emittance in this way

Emittance exchange



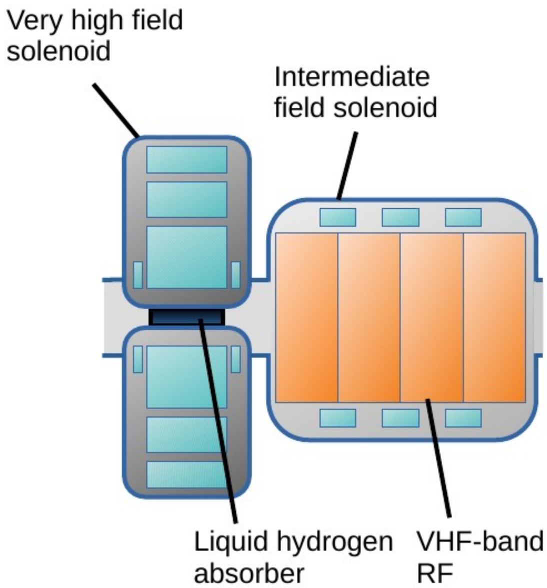
- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves dipole wider with energy-position correlation
- Beam goes through wedge shaped absorber
  - Beam leaves wider without energy-position correlation
  - High transverse emittance and low longitudinal emittance

Rectilinear Cooling



- 6D Cooling
  - Combined function dipole-solenoid magnets
  - Compact lattice – RF integrated into magnet cryostat
  - Lithium Hydride or lH2 absorbers
  - Careful field shaping to control position of stop-bands

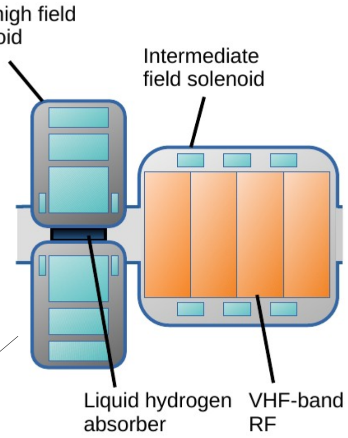
Final cooling

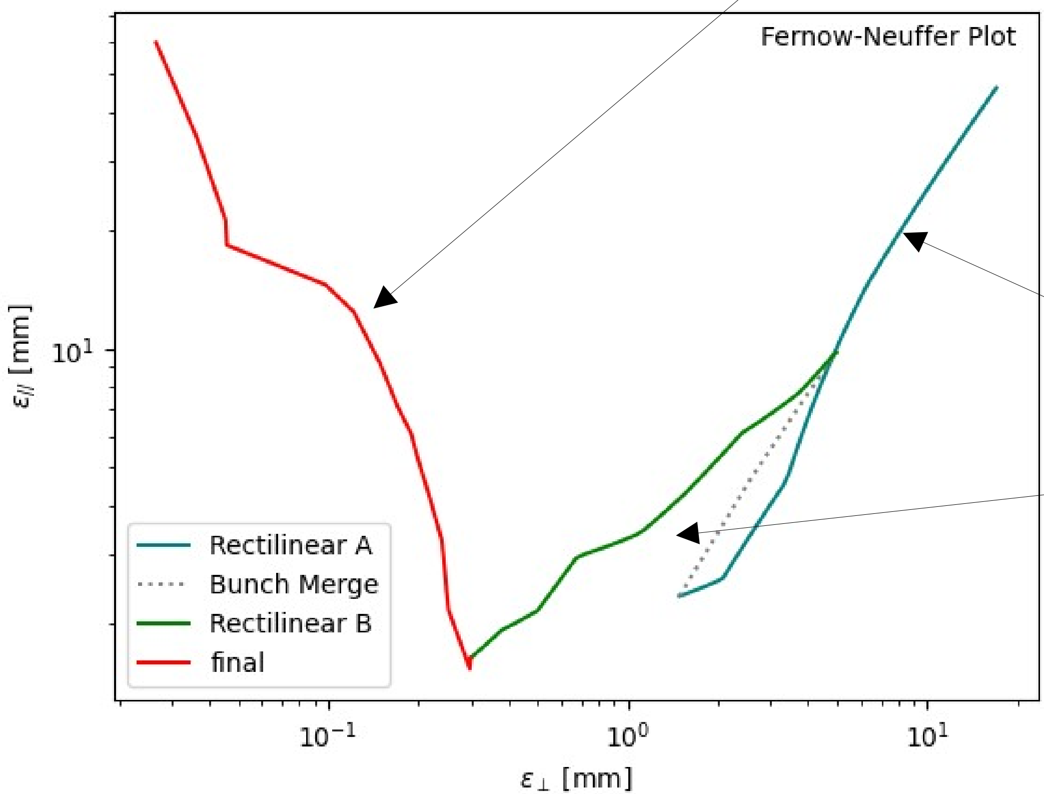


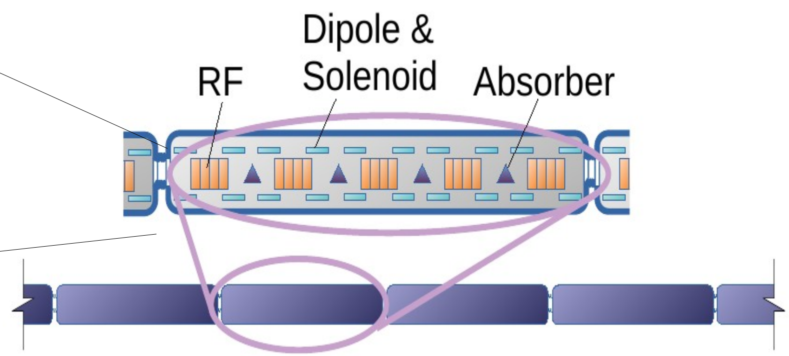
- Challenge is to get very tight focussing
- Go to very high fields (~30 - 40 T) and lower momenta
  - Causes longitudinal emittance growth
  - Chromatic aberrations introduce challenges
    - Elaborate phase rotation required to keep energy spread small
    - Move to low RF frequency to manage time spread

Muon Cooling

4D Final cooling







Rectilinear cooling

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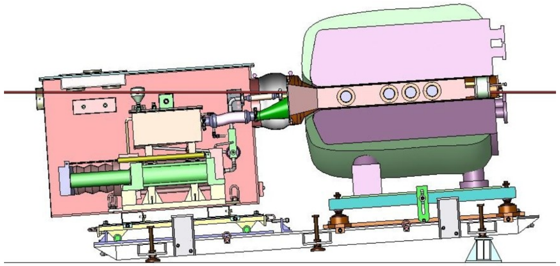
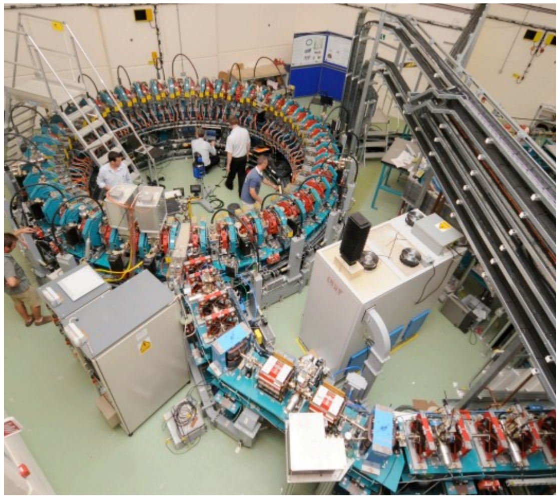
Muon Accelerator R&D

- MERIT
  - Demonstrated principles of muon accelerator proton targetry/pion production
- EMMA
  - Demonstrated fast acceleration in FFAGs
- MUCOOL
  - Cavity R&D for ionisation cooling
  - Demonstrated operation of cavities at high voltage in magnetic field
    - Breakdown suppression using high pressure gas
    - Careful RF coupler design and cleaning in vacuum
- MICE
  - Ionisation cooling demonstration





Experimental set up

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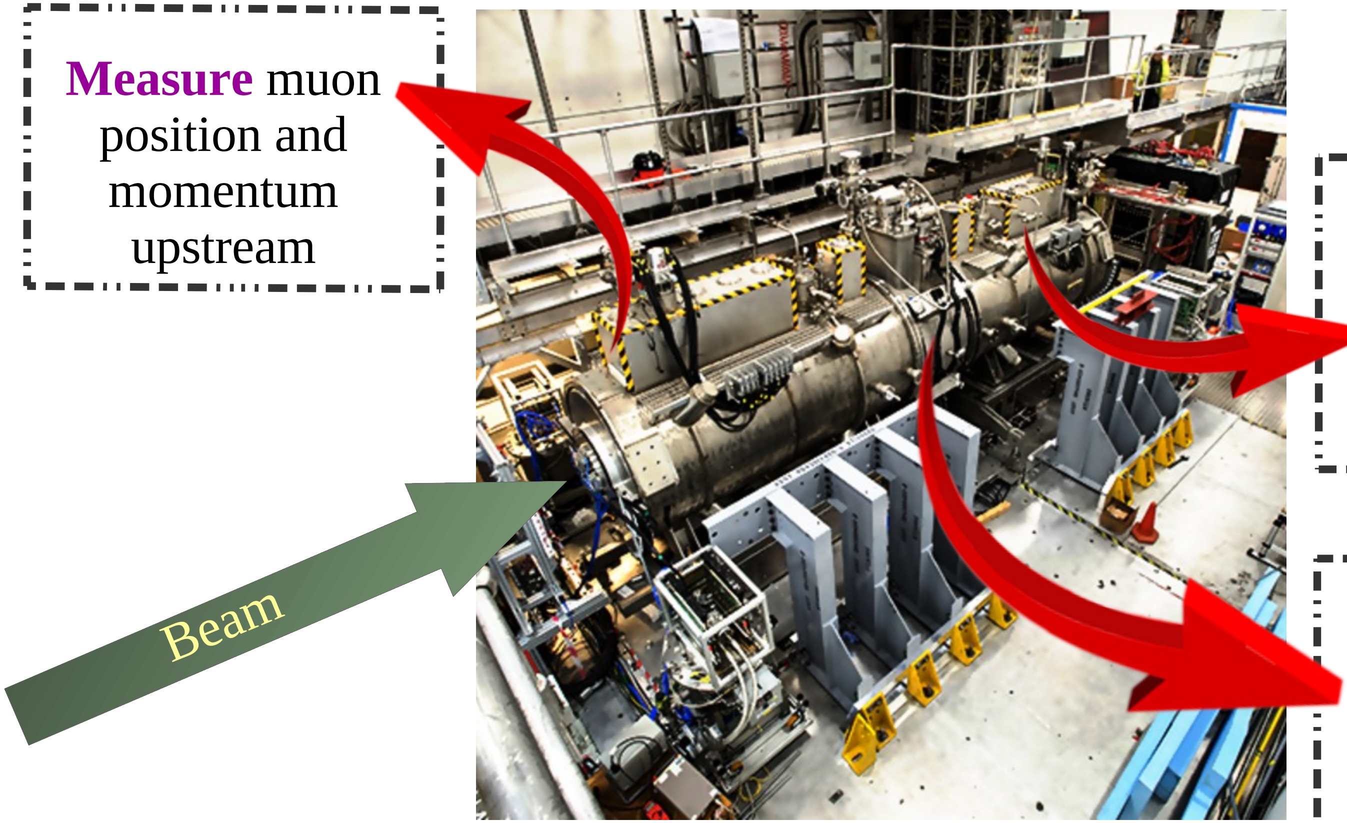
Measure muon position and momentum upstream



Measure muon position and momentum downstream

Cool the muon beam using LiH, LH_2, or polyethylene wedge absorbers

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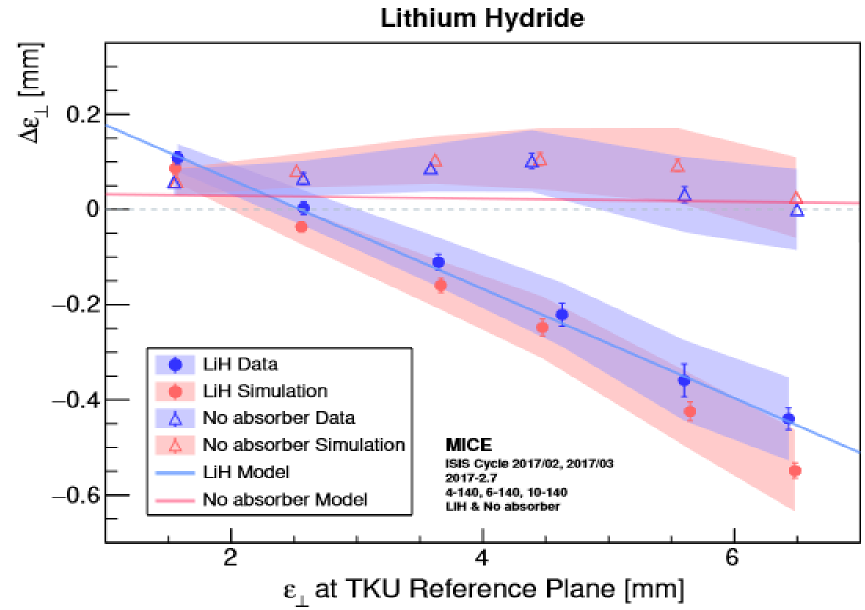
Emittance reduction

- When absorber installed:
  - Cooling above equilibrium emittance
  - Heating below equilibrium emittance
- When no absorber installed
  - Optical heating
  - Clear heating from Al window



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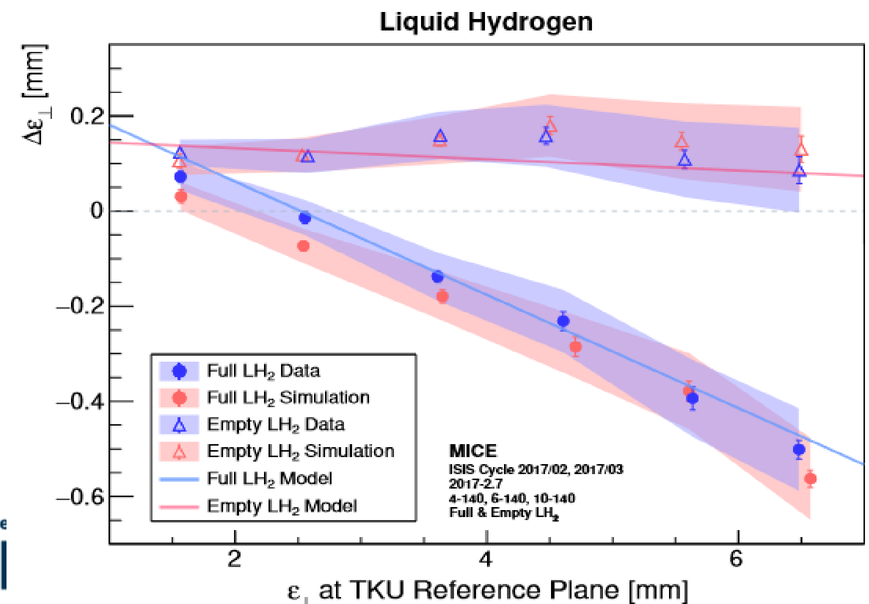

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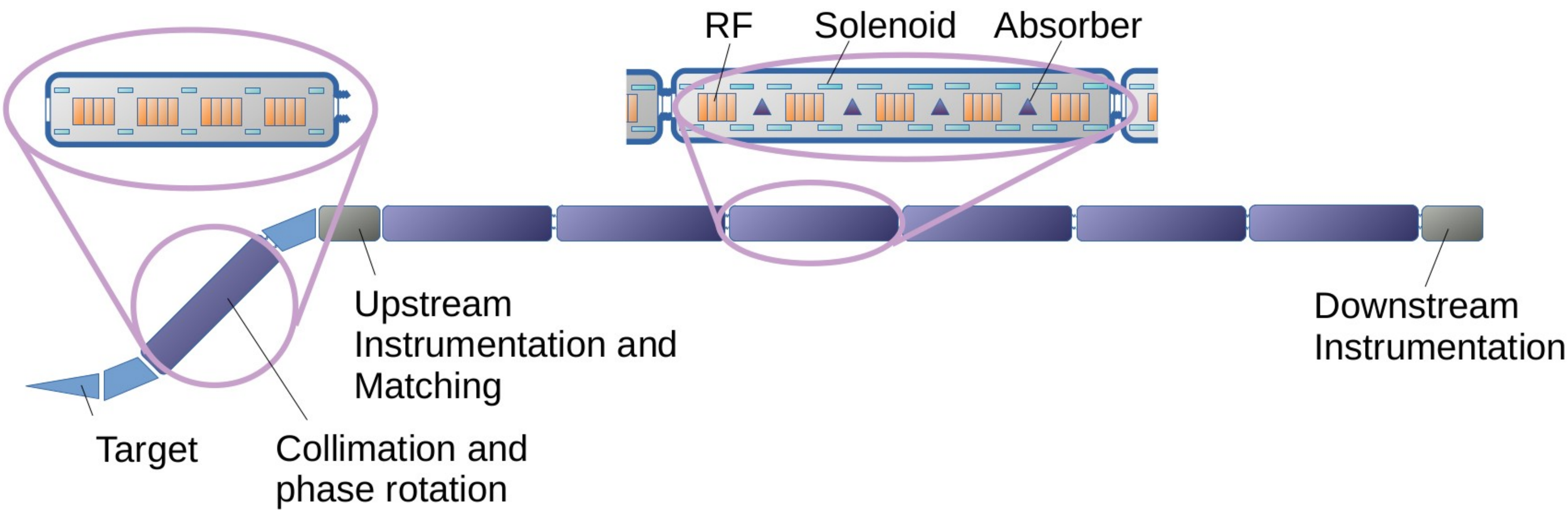
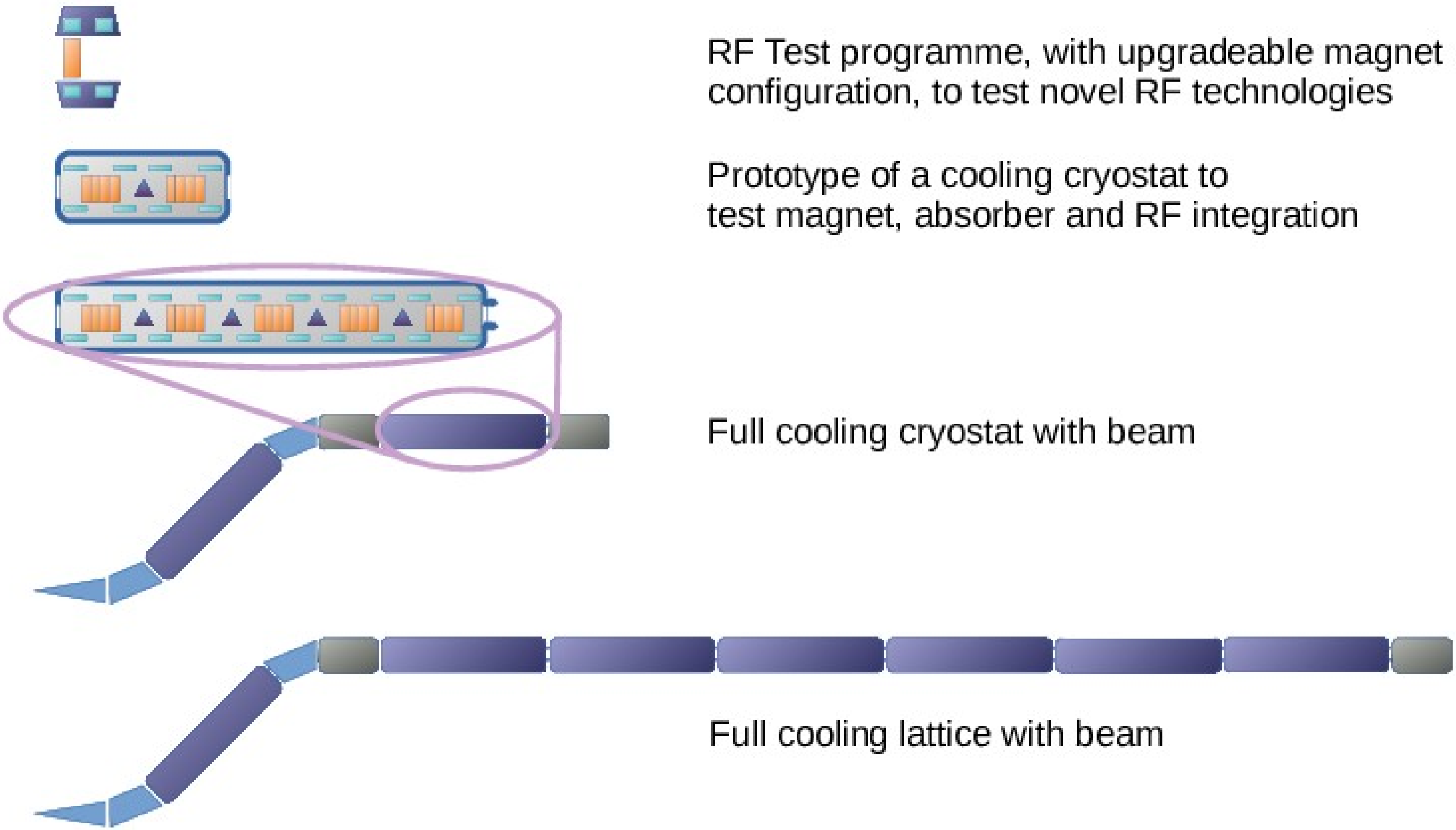
Cooling Demonstrator



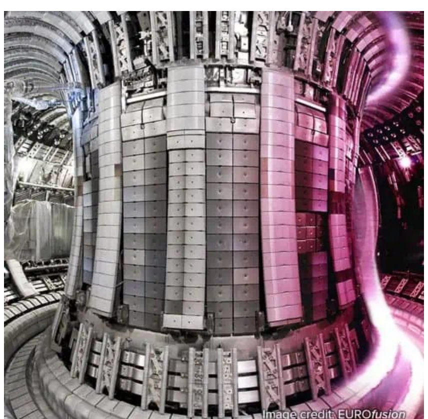
- Build on MICE
  - Longitudinal and transverse cooling
  - Re-acceleration
  - Chaining together multiple cells
  - Routine operation

Muon cooling – R&D Programme



Technology applications

- High field solenoids have many important application
  - Developing collaboration with fusion experts
  - MRI magnets
- Muon beam techniques have application in many other fields
  - Muon spin resonance (muSR)
  - Muon tomography
- Delivery of such a muon beam is a unique achievement
  - Harnessing an entirely “new” form of matter



Final Word

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- The muon collider
  - Far higher energy than e^+e^- colliders
  - Far smaller footprint than equivalent proton colliders
- Many technical challenges
  - All are manageable with current or near-to-current technologies
  - Must demonstrate practical solutions
- Muon collider has potential to advance particle physics by many decades
  - We must now deliver it

Further Information

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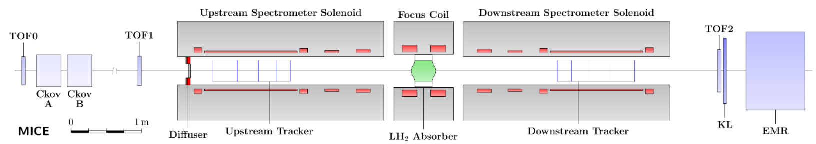
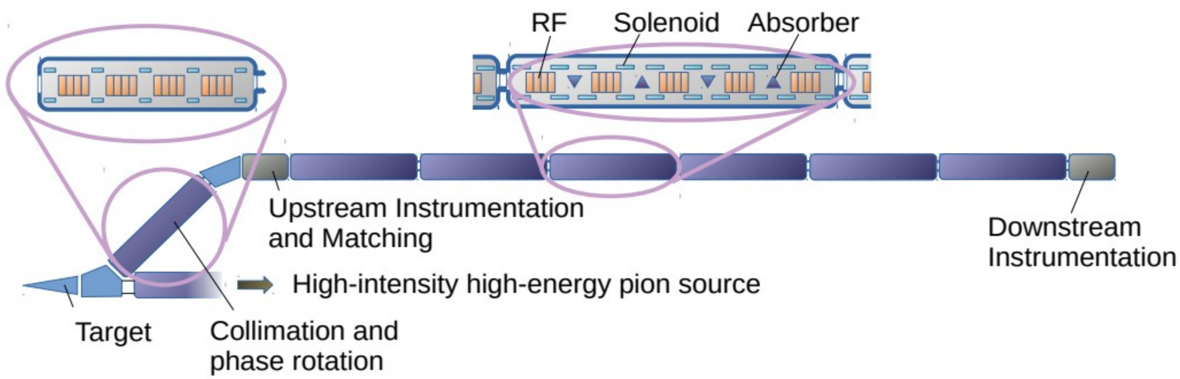
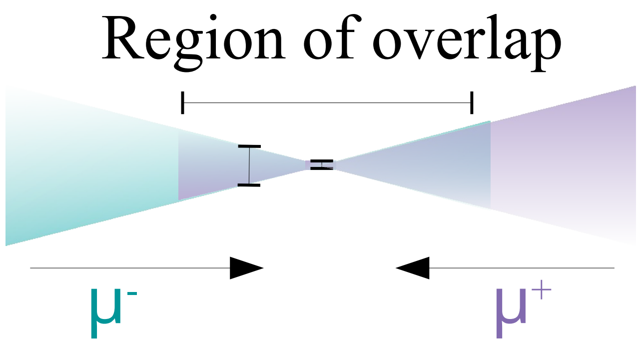
Comparison with MICE

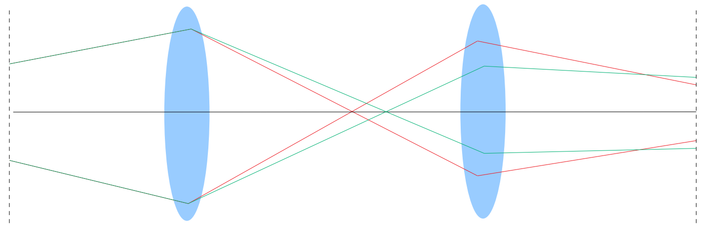




	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

Longitudinal emittance





- Need also to reduce the longitudinal emittance
  - Final focus “telescope” responds differently to different momentum particles
    - Just like chromatic effects in an optical lens
  - Beam size gets smeared if the bunch is long
- Mitigations exist
  - But fundamentally, we want to have a low longitudinal emittance
    - Beam size in time-energy space

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