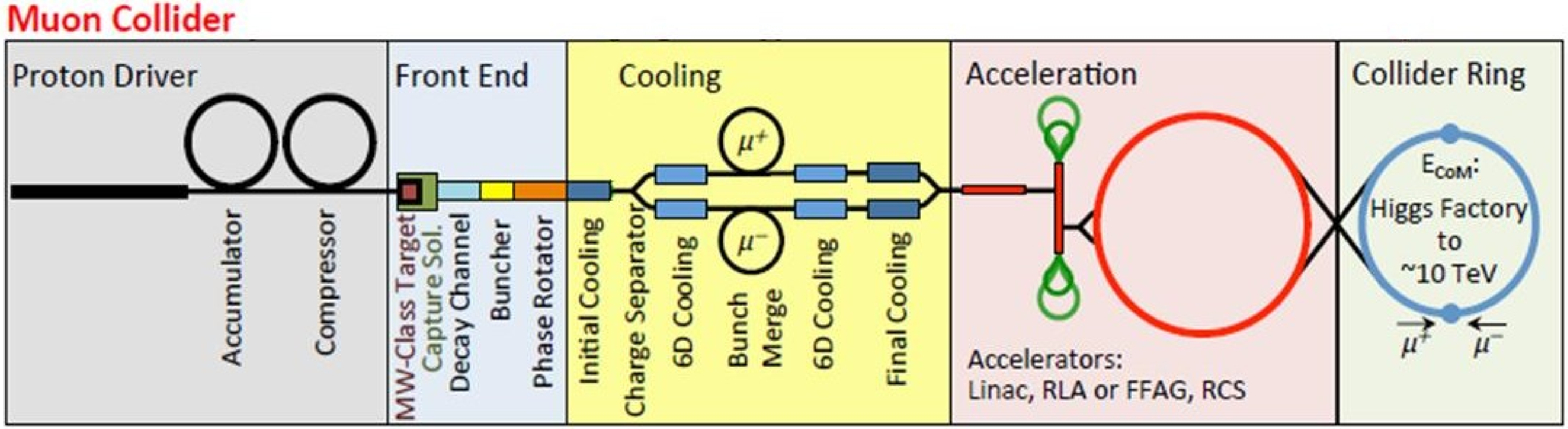
Muon Beam Generation and Fast Cooling

International
MUON Collider
Collaboration

C. T. Rogers
Rutherford Appleton Laboratory

With thanks to International Muon Collider Collaboration and Muon Accelerator Programme

Muon Collider



- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Designed for high energy while maximising luminosity

Recap

$$\mathfrak{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L} \frac{f_{hg}\sigma_\delta \overset{\boxed{2}}{\bar{B}}}{\underset{\boxed{4}}{\varepsilon_\perp \varepsilon_L} n_b \underset{\boxed{3}}{f_r}} \underbrace{\overset{\boxed{4}}{\eta_+\eta_-}(\overset{\boxed{5}}{\eta_\tau P_p} \overset{\boxed{1}}{\gamma m_\mu c^2})^2}_{P_+P_-}$$

1) Luminosity increases with the square of muon energy/power
    - Number of collisions per bunch increases as muon lifetime increases
    - Beam size decreases as energy increases (geometric emittance)
2) High field, low circumference collider ring → more luminosity
    - Shorter path length, more collisions before muon decay
3) Low repetition rate, few bunches is best
    - Assume that the bottleneck is in the number of protons
    - Fewer collisions, but each collision is more intense
4) High quality muon source is essential
    - Low emittance, good capture efficiency
5) Good efficiency acceleration is essential
    - High voltage systems

- The whole muon collider is designed to maximise luminosity!

The Facility – From protons to muons

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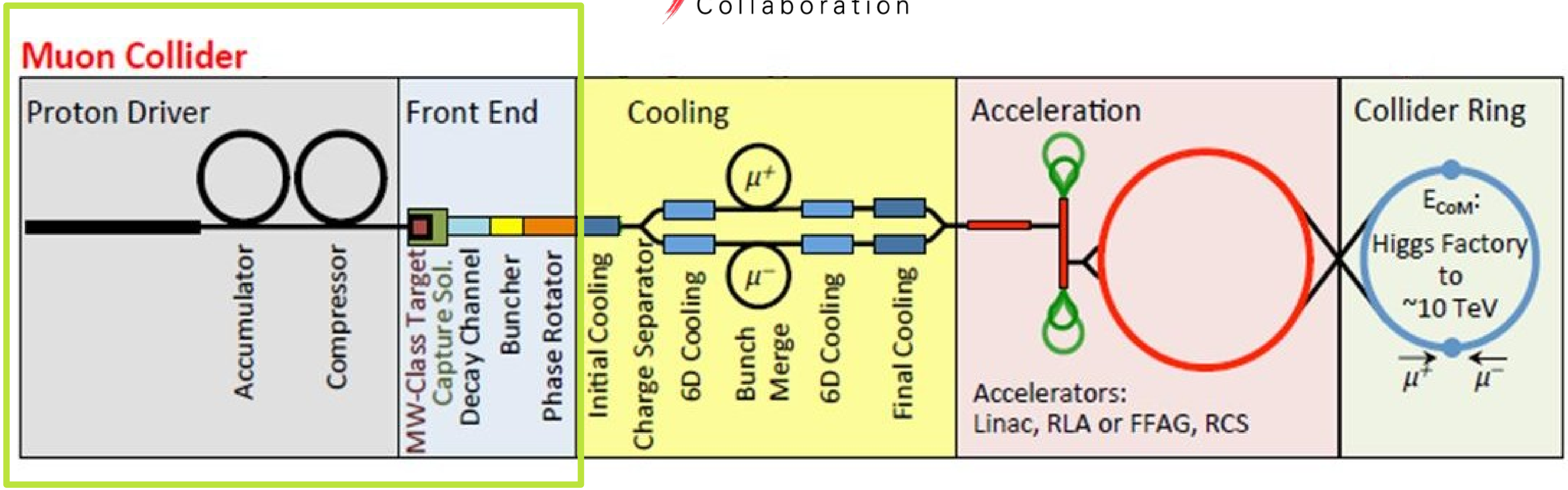
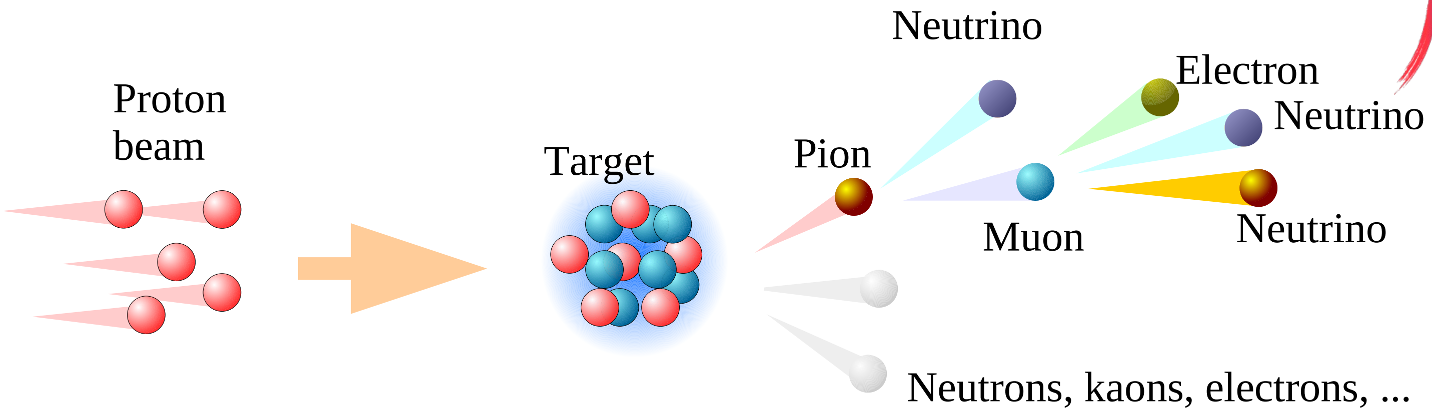


Artificial Muons



- Muons produced by putting protons onto target
- Pions come out
- Pions decay radioactively to muons
- Enables an intense muon source

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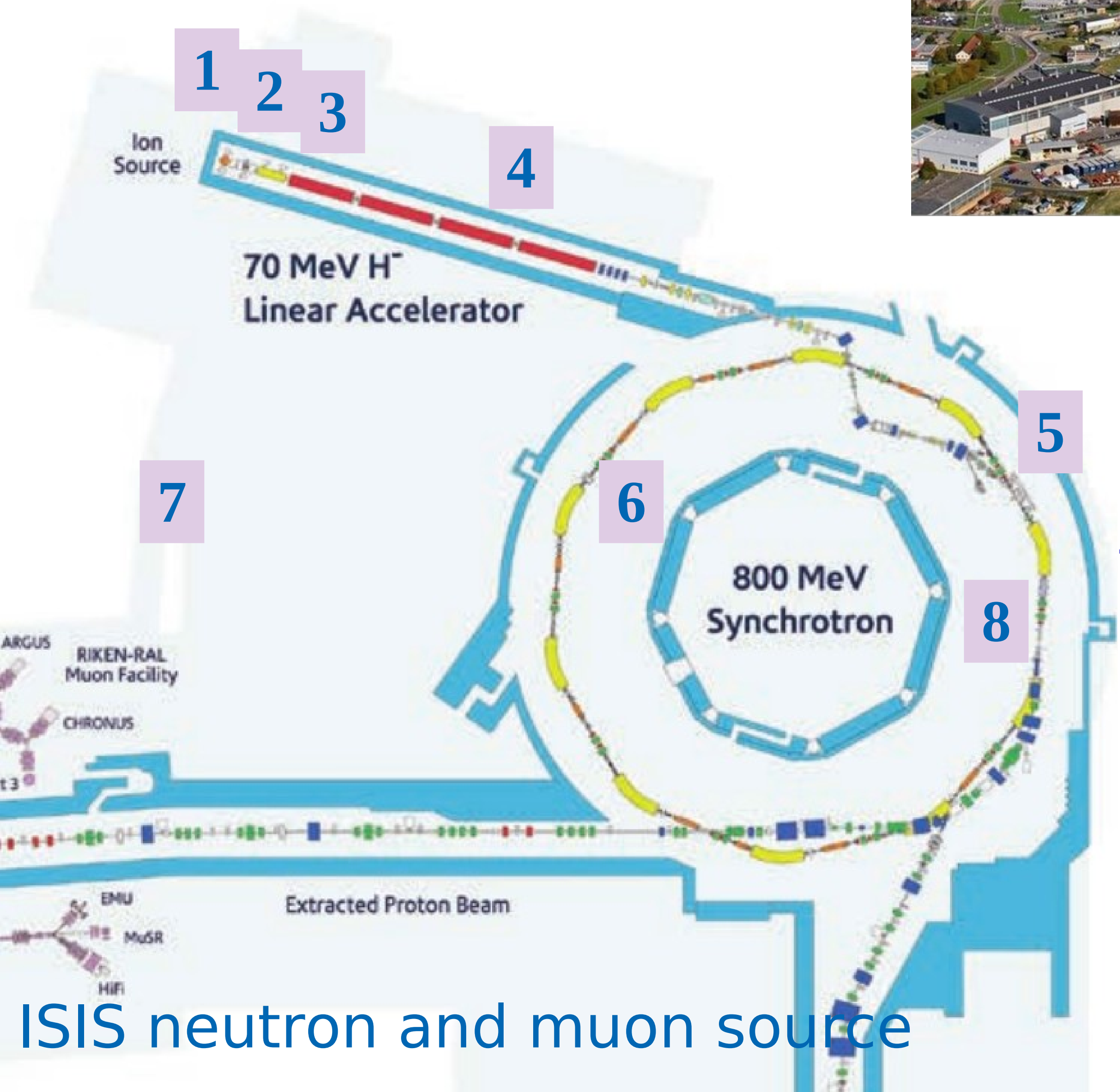
Proton Source



1) Ion source: spark across H gas to make H^- ions
2) Accelerate and focus in Radiofrequency Quadrupole
3) Chop into pulsed beam using fast/slow kicker
4) Accelerate in linac
5) Inject into a ring through a foil
6) Accelerate some more (maybe)
7) Compress the proton bunch to very short length
8) Extract and bring onto a target

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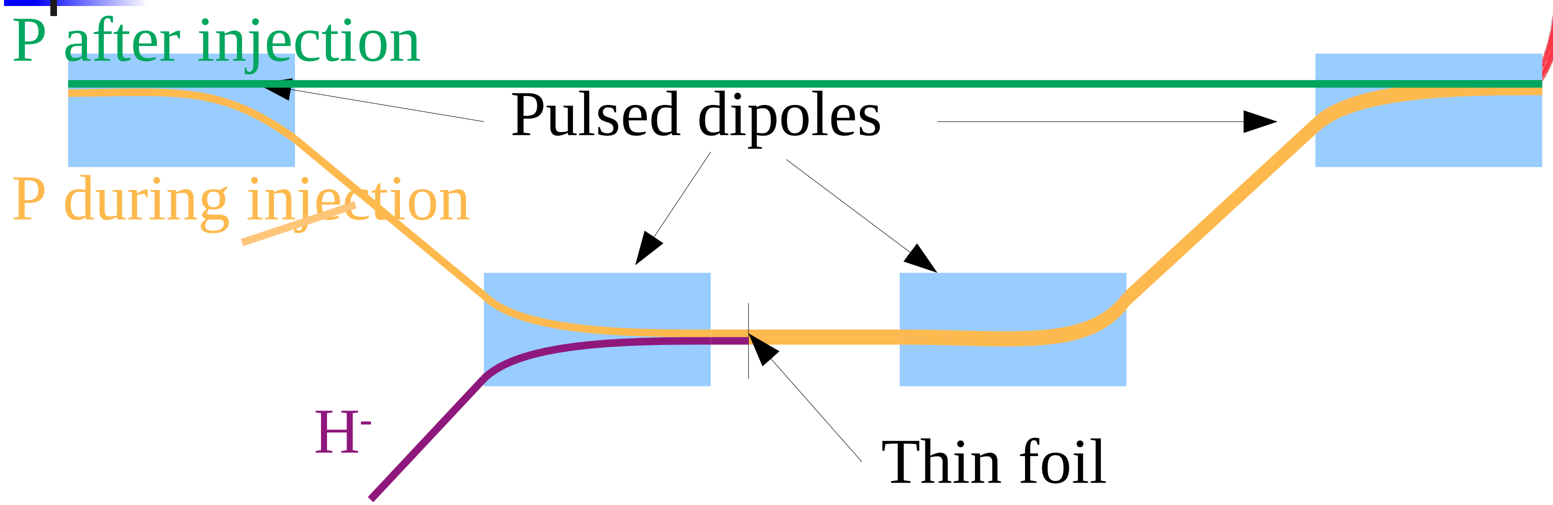
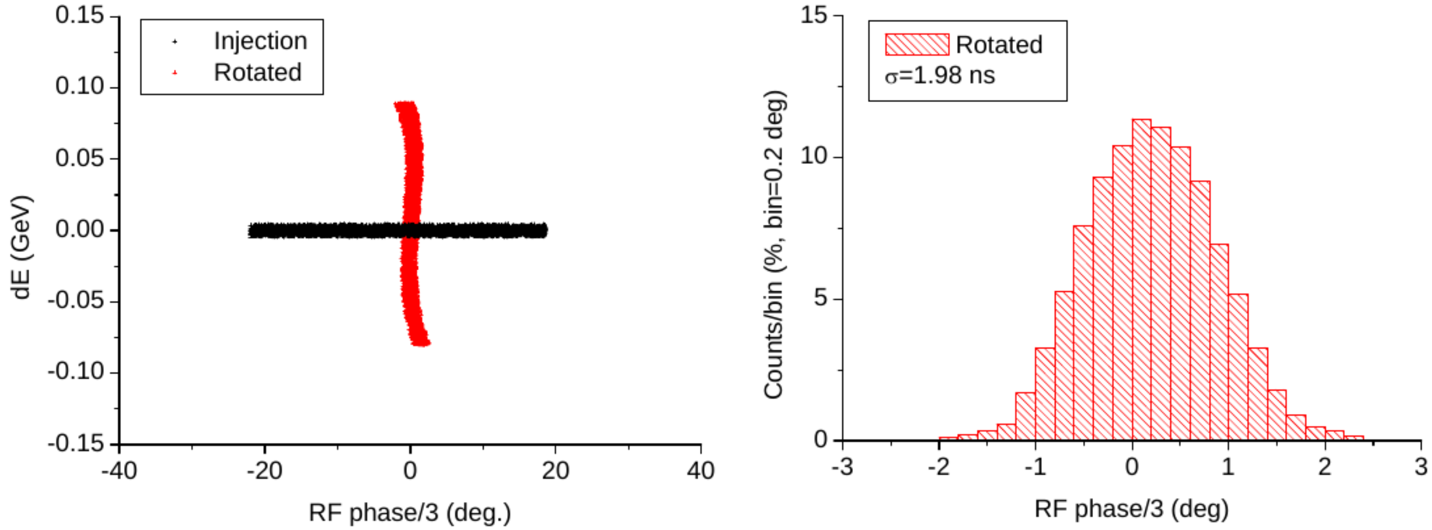
Charge Exchange Injection



- High current → accumulate beam over many turns
  - Charge exchange injection of H^- ions through a thin foil
  - Foil removes electrons
  - Issues: Scattering and energy loss of protons in foil
- Painting of beam into synchtron acceptance using fast “bumper” magnets
  - Move recirculating/injected beam phase space
- Foil lifetime is critical limit
- Space charge at injection is critical limit

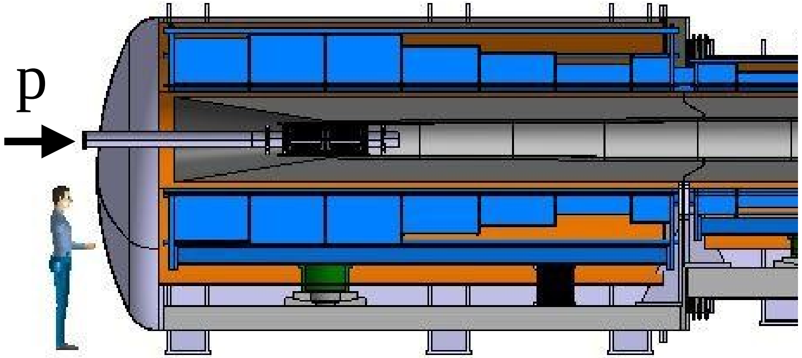
Bunch Compression

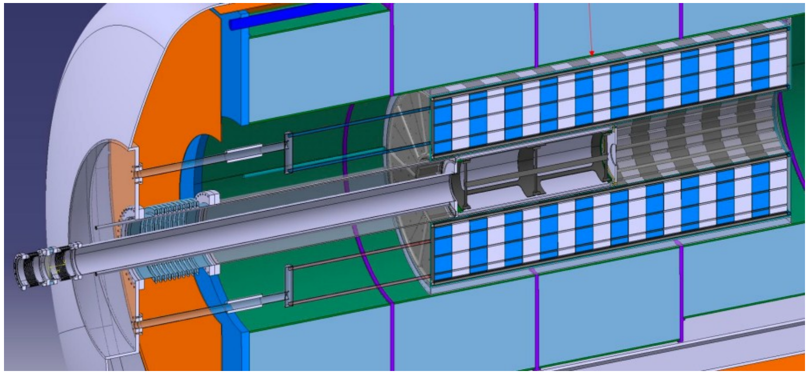


M. Aiba, CERN-AB-2008-060 BI (2008)

- Aim is to rotate the beam in longitudinal phase space
  - Short proton bunch → short muon bunch
  - Reduce longitudinal emittance of the muons
- Achieve bunch compression by rotation in the RF bucket
- Limitations:
  - Space charge → higher energy

MC Target



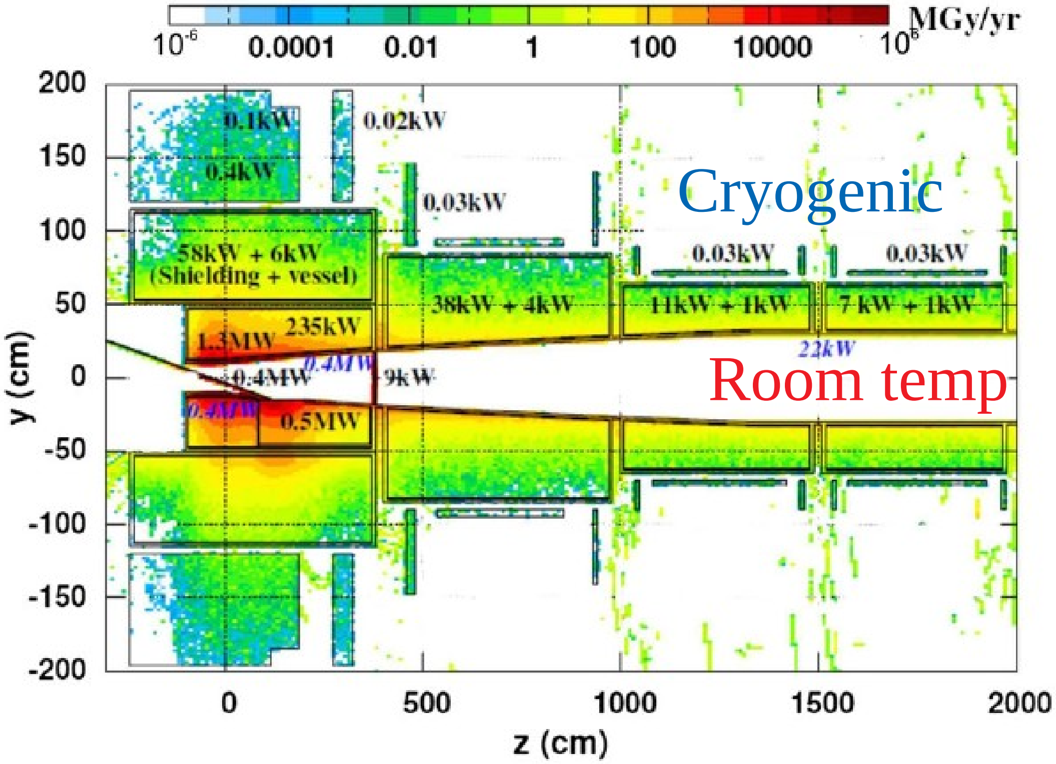


- Protons on target → pions → muons
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Challenge: Energy deposition on solenoid
- Challenge: Solid target lifetime

Radiation issues (magnet)

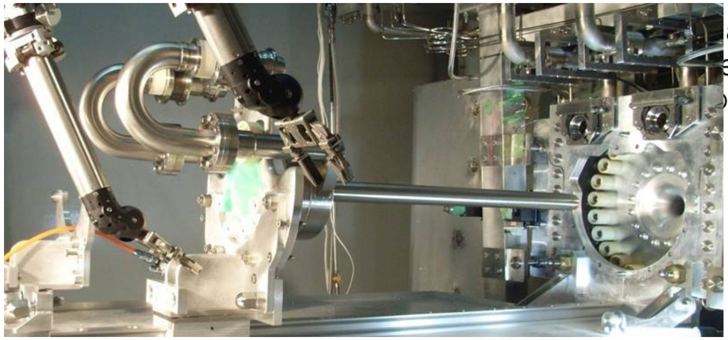
- Radiation load significant issue
  - Degrades insulation/glue
  - Requires more cooling
    - 1 kW heat → O(200) kW electricity
- Shield at room temperature
- Magnet at superconducting temperature
  - HTS → warmer, more efficient

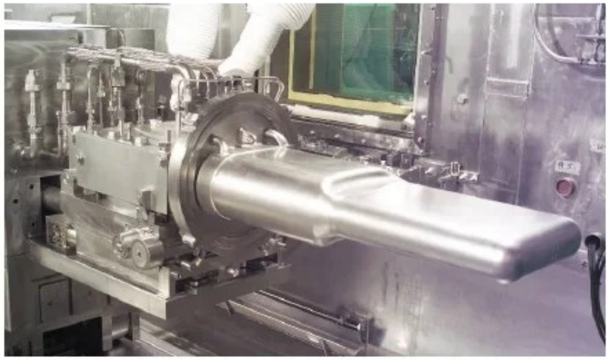
Neutrino factory, Bogomilov et al, PRSTAB 17 (2014)

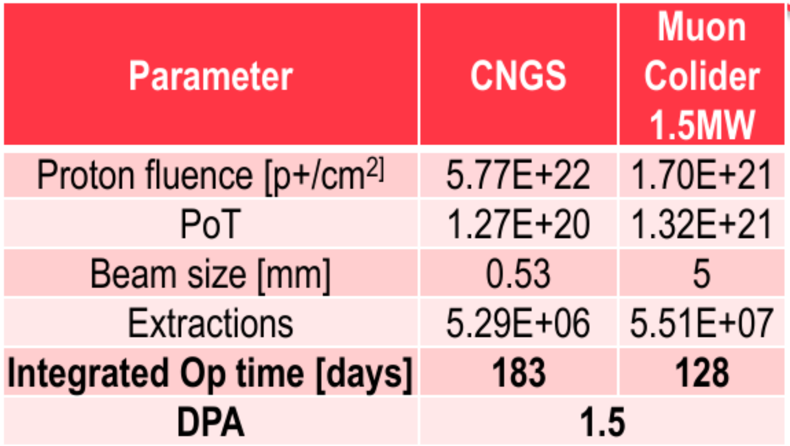


Radiation issues (target)

- Radiation on target can make an issue
  - Instantaneous shock
  - Long term radiation damage
- Liquid metal targets (Pb)
  - Cavitation issues
  - Specific issues around Hg
- Flowing/moving solid targets
  - Geometry issues
  - Target wheels – e.g. PSI
  - Fluidised powder







Parameter	CNGS	Muon Collider 1.5MW
Proton fluence [p+/cm^2]	5.77E+22	1.70E+21
PoT	1.27E+20	1.32E+21
Beam size [mm]	0.53	5
Extractions	5.29E+06	5.51E+07
Integrated Op time [days]	**183**	**128**
DPA	**1.5**	

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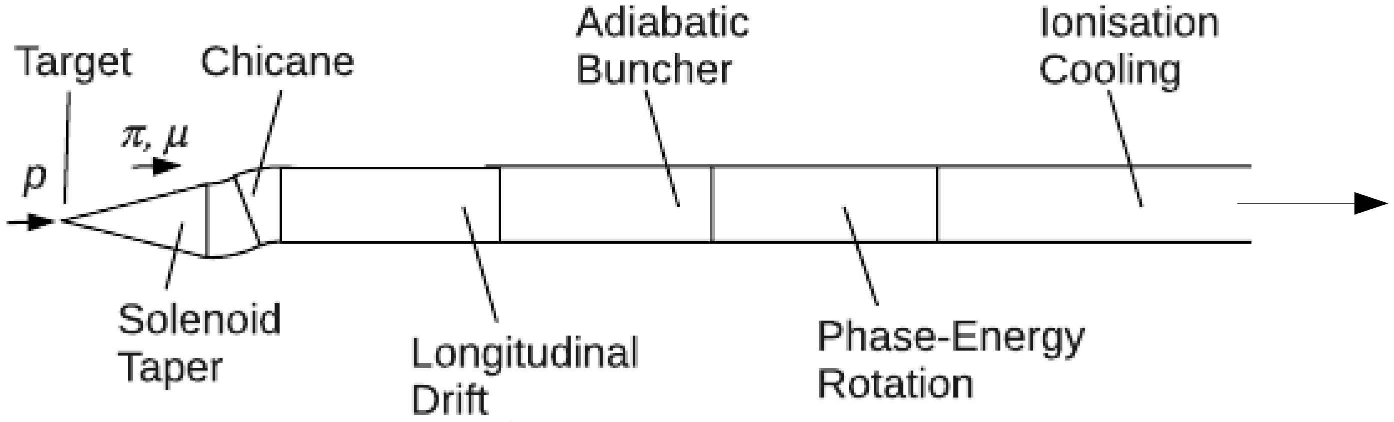
Muon front end



- Muon front-end to capture muon beam
- Solenoid taper
- Solenoid chicane removes high momentum particles
- Beryllium plug removes low momentum impurities
- Longitudinal capture system
  - Adiabatically bunch beam
  - Phase rotate

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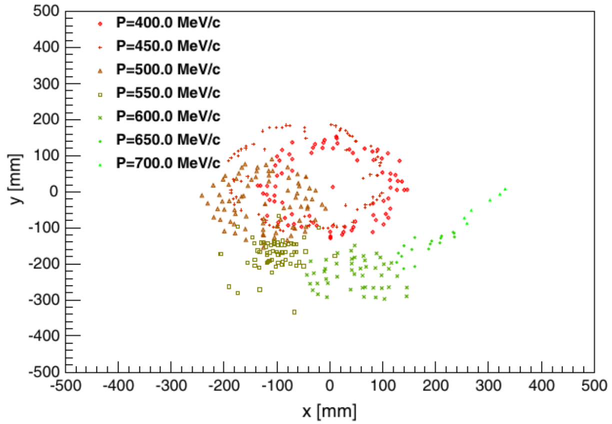
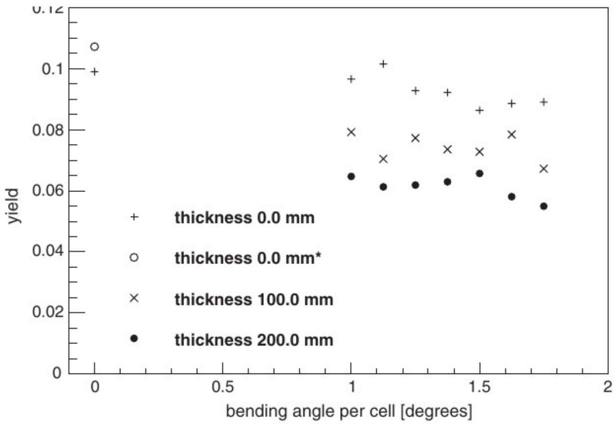
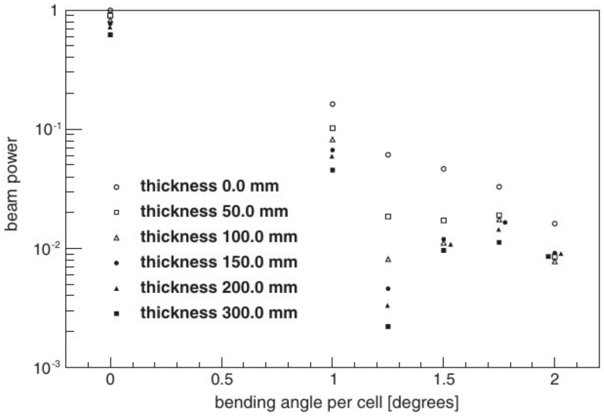
Chicane/proton absorber

- Solenoid chicane
  - No dipoles!
  - Vertical dispersion → low pass filter
  - Excellent transport properties within acceptance
- Beryllium plug
  - Protons stop more quickly than muons/pions
  - Removes low momentum protons







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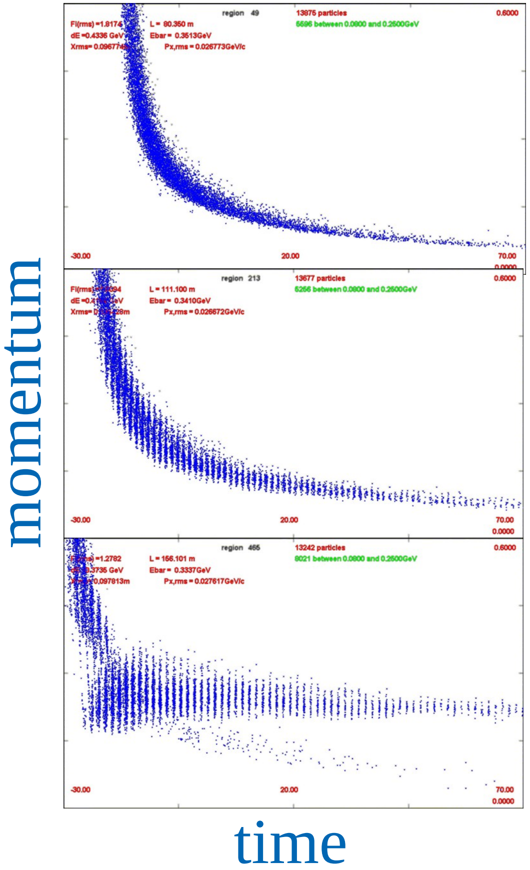
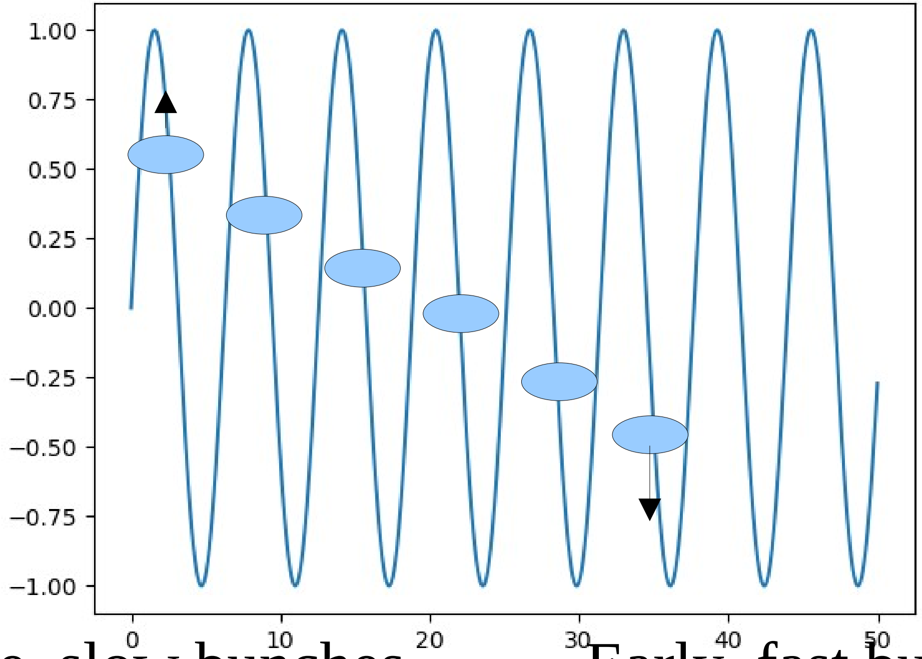
Buncher/Phase Rotator

- Drift to develop energy-time relation
- Buncher adiabatically ramp RF voltages
- Phase rotator → misphase RF
  - High energy bunches decelerated
  - Low energy bunches accelerated

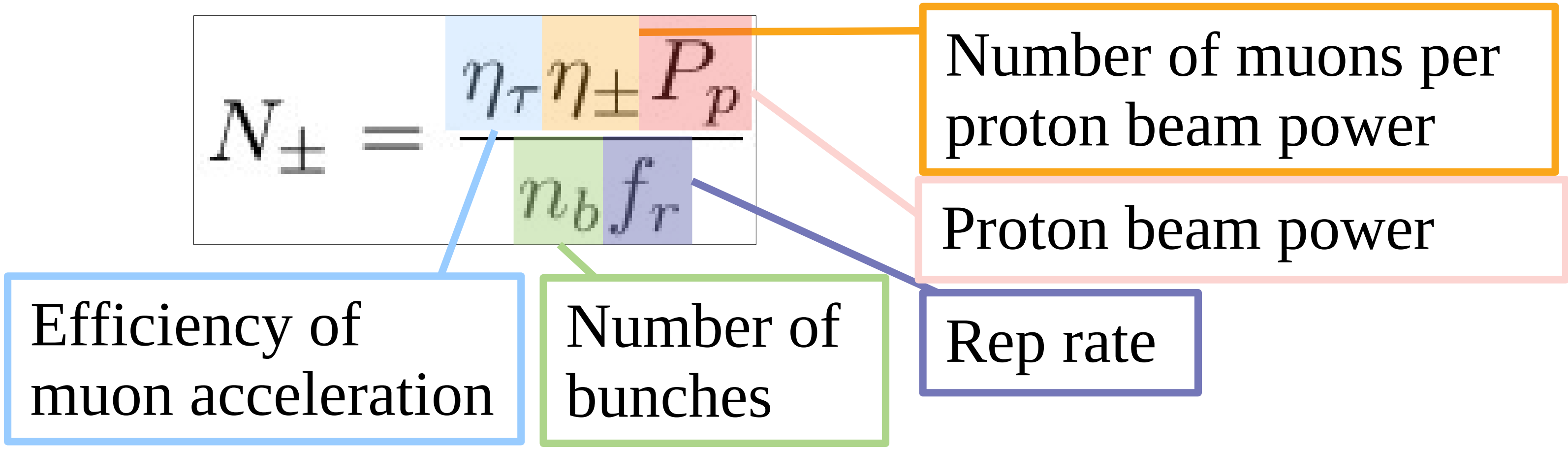




Late, slow bunches Early, fast bunches decelerated

Luminosity consideration

$$\mathfrak{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L \;=\; 4.4\text{e}36 \text{ MeV MW}^{-2}\text{ T}^{-1}\text{ s}^{-2}} \frac{f_{hg}\sigma_\delta \bar{B}}{\varepsilon_\perp \varepsilon_L n_b f_r} \underbrace{\eta_+\eta_-(\eta_\tau P_p \gamma m_\mu c^2)^2}_{P_+P_-}$$



$$N_\pm = \frac{\eta_\tau \eta_\pm P_p}{n_b f_r}$$

Number of muons per proton beam power

Proton beam power

Efficiency of muon acceleration

Number of bunches

Rep rate

- Proton beam power ~ 1-2 MW → (FNAL, JPARC, SNS)
- Approx 0.1 $\mu^{+/-}$ per 8 GeV proton → O(1e14) muons per MW
- BUT: muon front end produces multiple bunches (about 20)
- Rep rate is between 60 Hz (SNS) and 0.1 Hz (JPARC)
- Emittance is huge

The Facility – Ionisation Cooling

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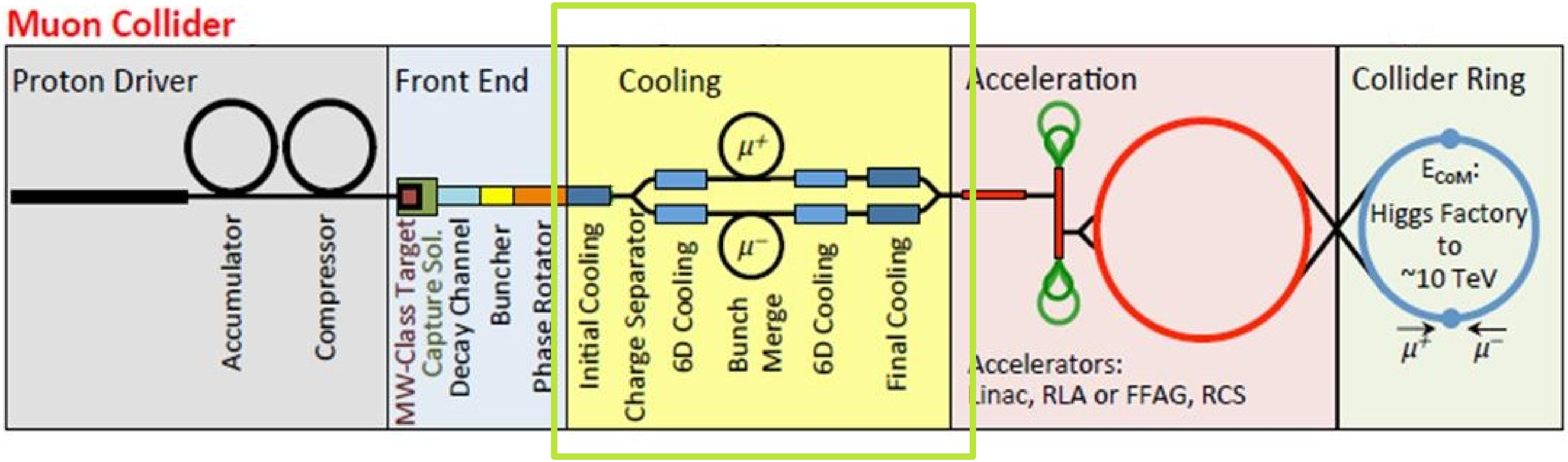

Ionisation Cooling - intro

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- Muon front end produces huge flux of muons
- Muons have too large emittance at the source
- How can we reduce beam emittance? COOLING!
    - Laser cooling
    - Stochastic cooling
    - Electron cooling
    - **Too slow**
- Ionisation cooling (and Frictional cooling)

Ionisation Cooling

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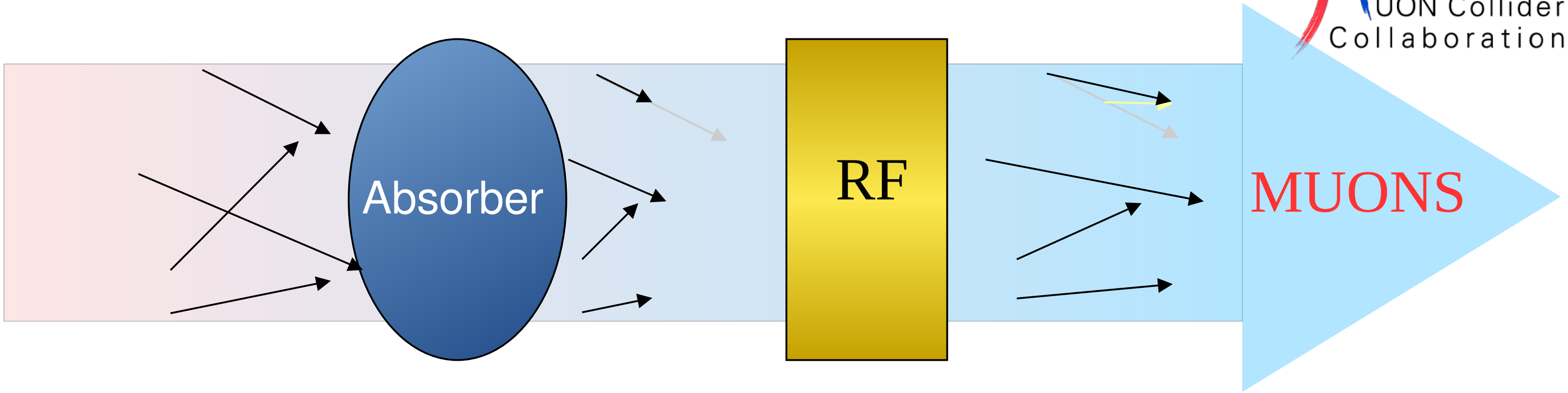

- Beam loses energy in absorbing material
  - Absorber removes momentum in all directions
  - RF cavity replaces momentum only in longitudinal direction
  - End up with beam that is more straight
- Multiple Coulomb scattering from nucleus ruins the effect
  - Mitigate with tight focussing
  - Mitigate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

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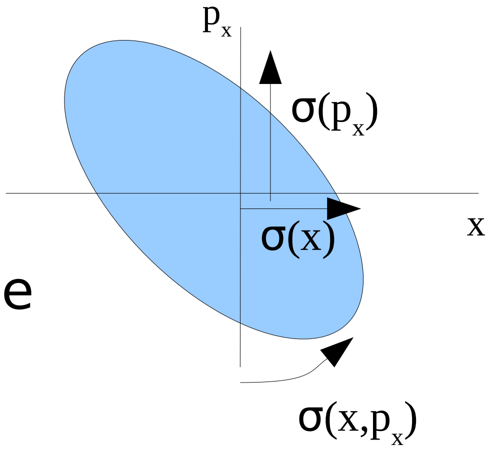
Beam emittance in 4D



- Normalised RMS beam emittance in 2D
  - area of ellipse aligned with beam

$$\varepsilon_{2d} = \frac{1}{m}\sqrt{\sigma^2(x)\sigma^2(p_x) - \sigma^2(x,p_x)}$$

- $\sigma^2(u_i)$ and $\sigma^2(u_i, u_j)$ are variance and covariance
  - Also written as $<u_iu_j>$
- Can be written as

$$\varepsilon_{2d} = \frac{1}{m}\sqrt{|\mathbf{V_{2d}}|}$$

- In higher dimensions the definition generalises

$$\varepsilon_{2nd} = \frac{1}{m_\mu}\sqrt[n]{|\mathbf{V}|}$$

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Transverse cooling (1)

- Say we pass through some material at a focus
  - P decreases due to ionisation
  - Multiple Coulomb Scattering increases angular spread
- For a cylindrically symmetric beam with angular divergence Θ_x

$$\begin{aligned}\sqrt{|\mathbf{V}_\perp|} &= (<x^2><p_x^2> - <xp_x>^2 - <xp_y>^2) \\ &\approx p_z^2(<x^2><\Theta_x^2> - <x\Theta_x>^2 - <x\Theta_y>^2)\end{aligned}$$

The change in emittance is given by

$$\frac{d\epsilon_n}{dz} = \frac{1}{2m^2\epsilon_n}\frac{d\sqrt{|\mathbf{V}_\perp|}}{dz}$$

$$\boxed{\varepsilon_{2nd} = \frac{1}{m_\mu}\sqrt[n]{|\mathbf{V}|}}$$

Transverse cooling (2)

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$$\frac{d\epsilon_n}{dz} = \frac{1}{2m^2\epsilon_n}\frac{d\sqrt{|\mathbf{V}_\perp|}}{dz}$$

- Only p$_z$ and $< \Theta_i^2 >$ change; applying product rule

$$\frac{d\epsilon_n}{dz} \approx \frac{1}{2m^2\epsilon_n}(2\frac{dp_z}{dz}\frac{\sqrt{|\mathbf{V}_\perp|}}{p_z} + < x^2 > p_z^2\frac{d < \Theta_x^2 >}{dz})$$

- Use (from $E^2 + p^2 = m^2$) $E\,dE/dz \approx p_z\,dp_z/dz$
- Use standard formula $\beta_\perp = \frac{< x^2 > p}{m\epsilon_n}$
- Use scattering (from atomic physics) $\frac{d < \Theta_x^2 >}{dz} \approx \frac{13.6^2}{(p\beta_{rel})^2 L_R}.$
- Gives $\frac{d\epsilon_n}{dz} \approx \frac{1}{\beta_{rel}^2 E}\left\langle\frac{dE}{dz}\right\rangle\epsilon_n + \frac{1}{2m^2\epsilon_n} < x^2 > \frac{13.6^2}{(\beta_{rel})^2 L_R}.$

Transverse cooling (3)

- Rearranging $$\frac{d\epsilon_n}{dz} \approx \frac{1}{E}\left\langle\frac{dE}{dz}\right\rangle\epsilon_n + \frac{1}{2m}\frac{13.6^2}{L_R}\frac{\beta_\perp}{\beta_{rel}^3 E}.$$

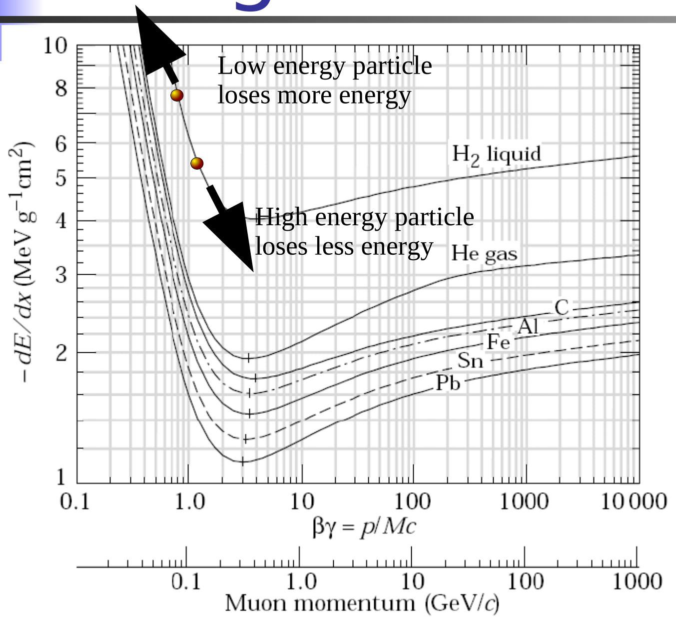
dE/dz is negative!
Cooling

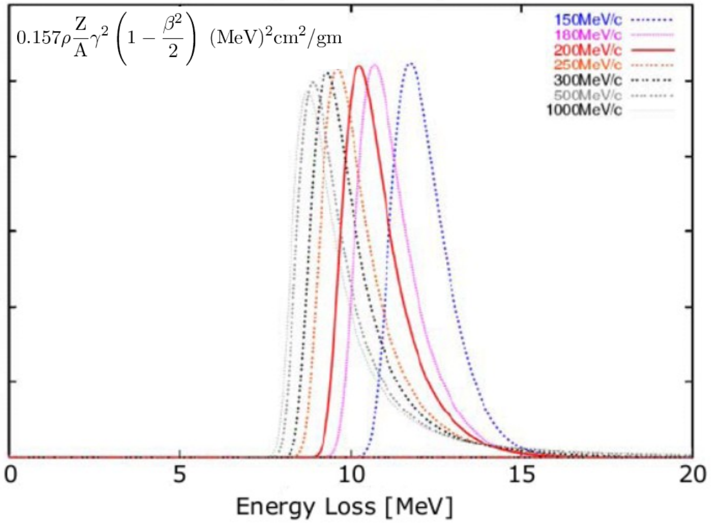
Heating

- There exists an equilibrium emittance where the two terms balance (no emittance change)

$$\epsilon_n(equilibrium) = \frac{1}{2m}\frac{13.6^2}{L_R}\frac{\beta_\perp}{\beta_{rel} < \frac{dE}{dz} >}$$

Longitudinal Heating





- In longitudinal phase space, the beam is usually heated
  - Heating due to random noise in the energy loss I.e. “straggling”
  - Heating due to curvature in energy loss (heating or weak cooling)

$$\frac{d<E^2>}{dz} = \left(2\frac{d}{dE}\frac{dE}{dz}\right) < E^2 > + \left(\frac{d<E^2>}{dz}\right)_{Vlasov}$$

- Mitigate using emittance exchange
  - Move emittance from longitudinal to transverse phase space

Emittance exchange

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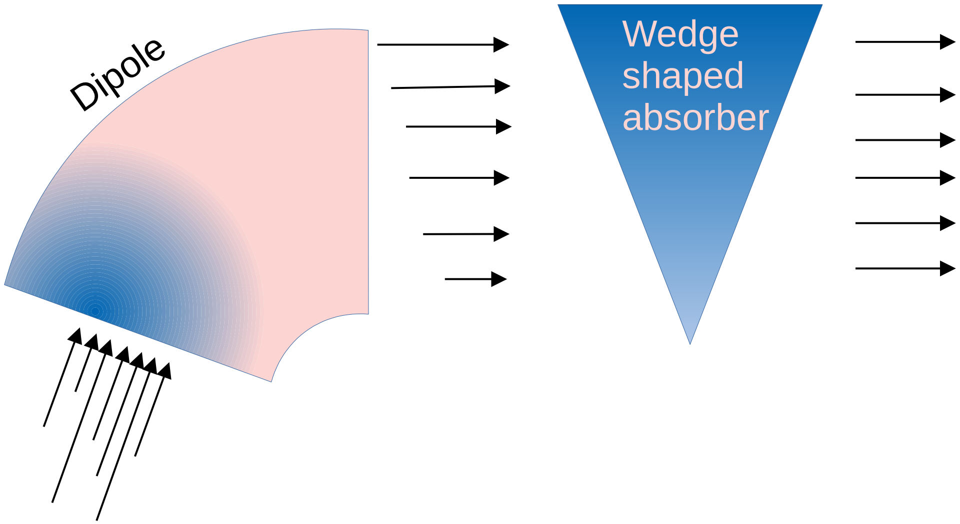

- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves dipole wider with energy-position correlation
- Beam goes through wedge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

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Emittance exchange

- Longitudinal emittance change becomes

$$\frac{d<E^2>}{dz} = \left(2\frac{d}{dE}\frac{dE}{dz}\right)<E^2> + \left(\frac{d<E^2>}{dz}\right)_{Vlasov}$$

$$\frac{\partial \frac{\mathrm{dE}}{\mathrm{ds}}}{\partial \mathrm{E}} \Rightarrow \left.\frac{\partial \frac{\mathrm{dE}}{\mathrm{ds}}}{\partial \mathrm{E}}\right|_0 + \frac{\mathrm{dE}}{\mathrm{ds}}\frac{\eta\rho'}{\beta \mathrm{cp}\rho_0}$$

dispersion

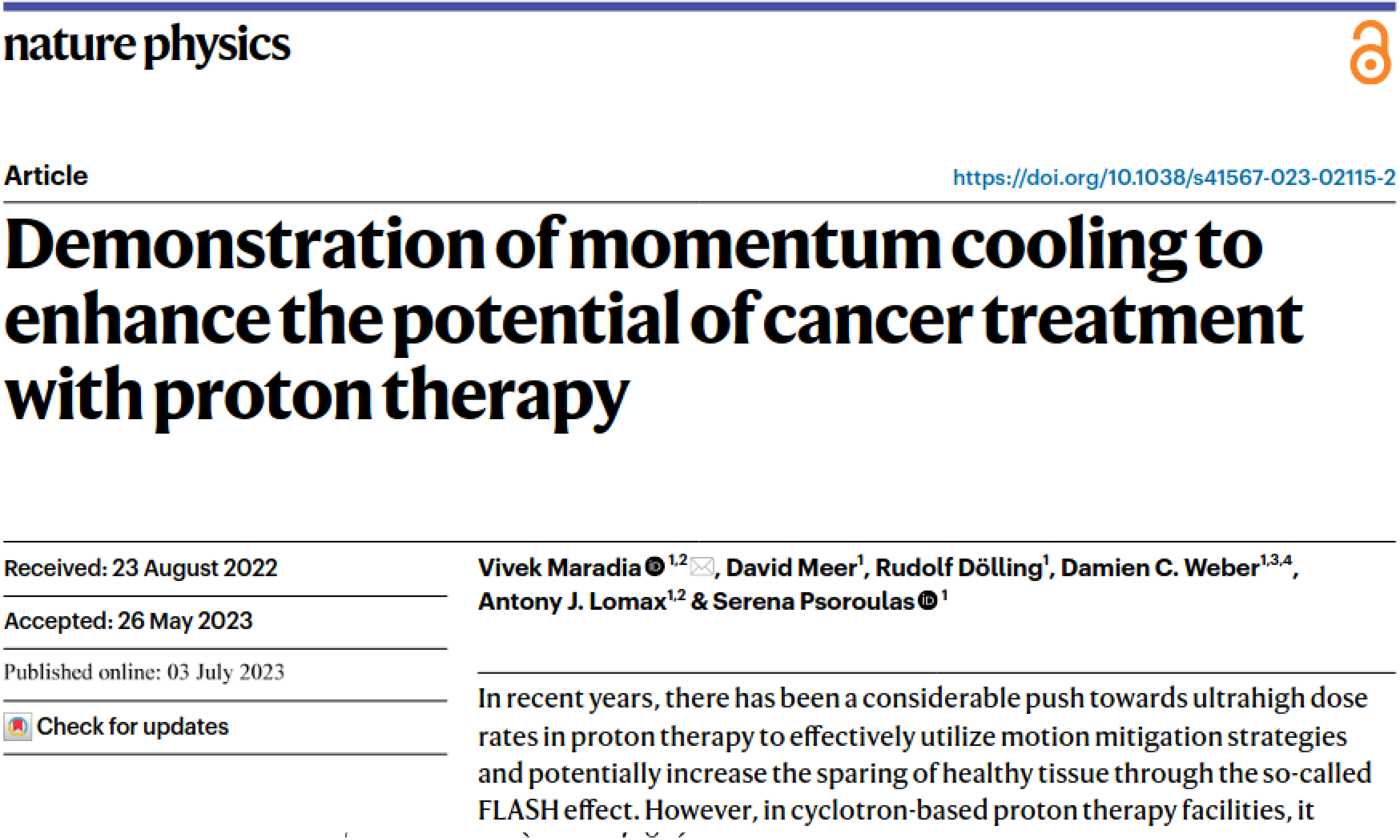
Effective density
Variation with position

- Transverse emittance change becomes

$$\frac{d\epsilon_n}{dz} \approx \frac{1}{\beta_{rel}^2 E}\left\langle\frac{dE}{dz}\right\rangle\epsilon_n + \frac{1}{2m^2\epsilon_n}<x^2>\frac{13.6^2}{(\beta_{rel})^2 L_R}.$$

$$\frac{1}{\beta^2\mathrm{E}}\frac{\mathrm{dE}}{\mathrm{ds}}\left(1-\frac{\eta\rho'}{\rho_0}\right)\epsilon_{\mathrm{N}}$$

Hadron therapy application



nature physics

Article

https://doi.org/10.1038/s41567-023-02115-2

Demonstration of momentum cooling to enhance the potential of cancer treatment with proton therapy

Received: 23 August 2022

Accepted: 26 May 2023

Vivek Maradia[1,2], **David Meer**[1], **Rudolf Dölling**[1], **Damien C. Weber**[1,3,4], **Antony J. Lomax**[1,2] & **Serena Psoroulas**[1]

In recent years, there has been a considerable push towards ultrahigh dose rates in proton therapy to effectively utilize motion mitigation strategies and potentially increase the sparing of healthy tissue through the so-called FLASH effect. However, in cyclotron-based proton therapy facilities, it

Muon Cooling R&D

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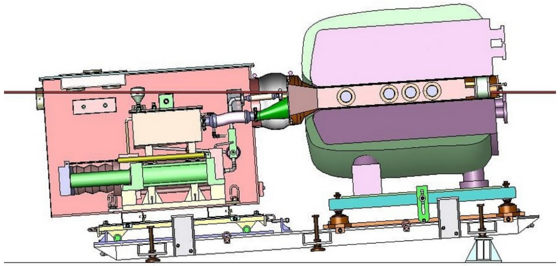
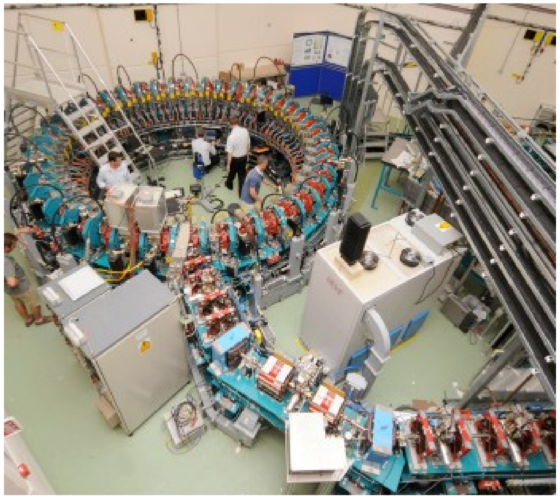
Muon Accelerator R&D

- 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





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Muon Ionisation Cooling Experiment (MICE)

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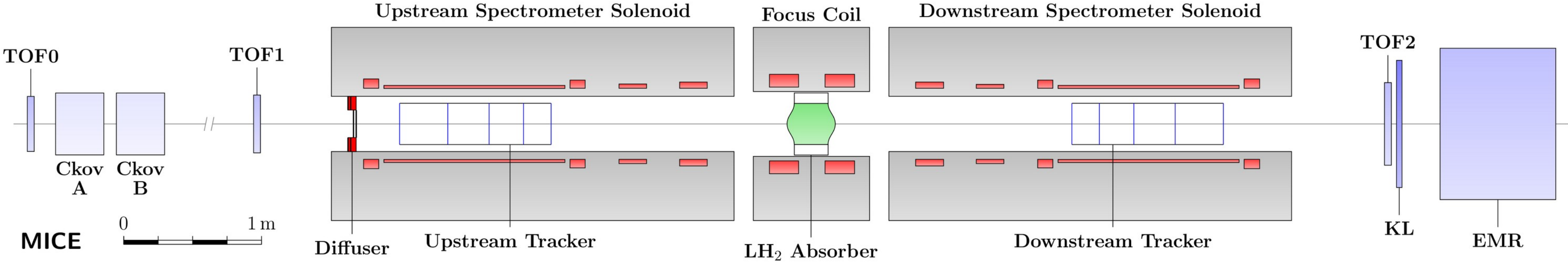

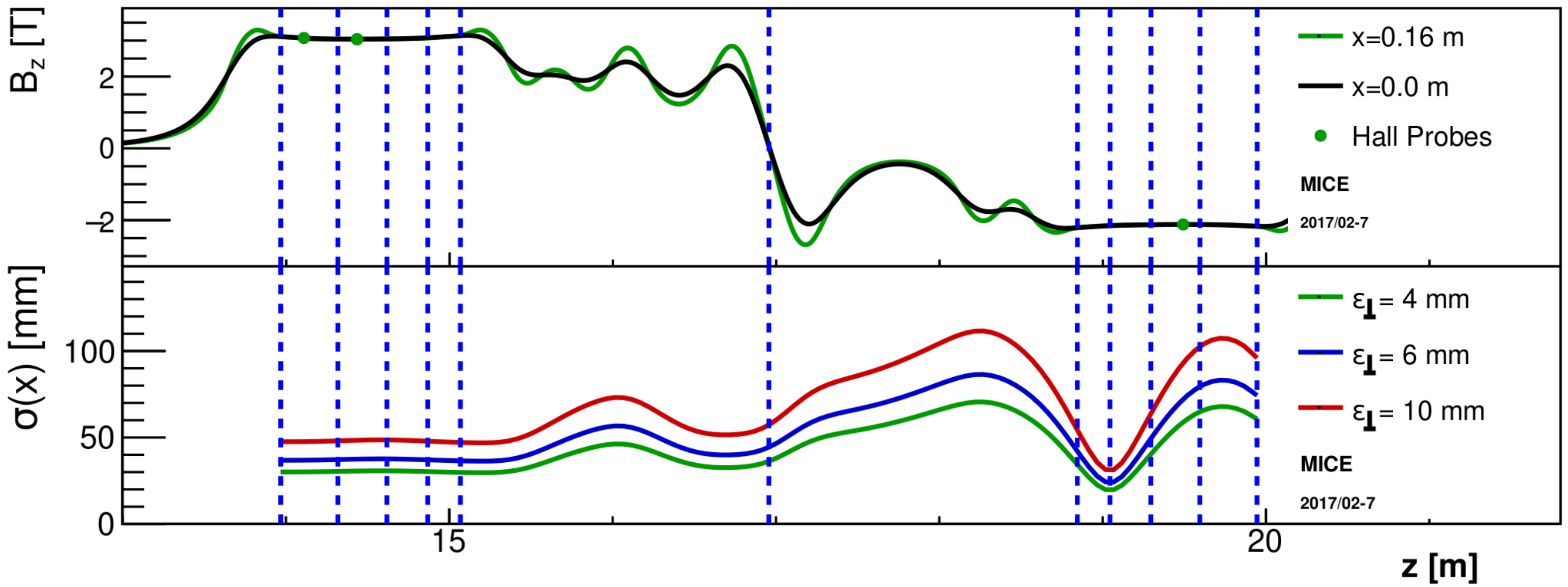

Experimental set up

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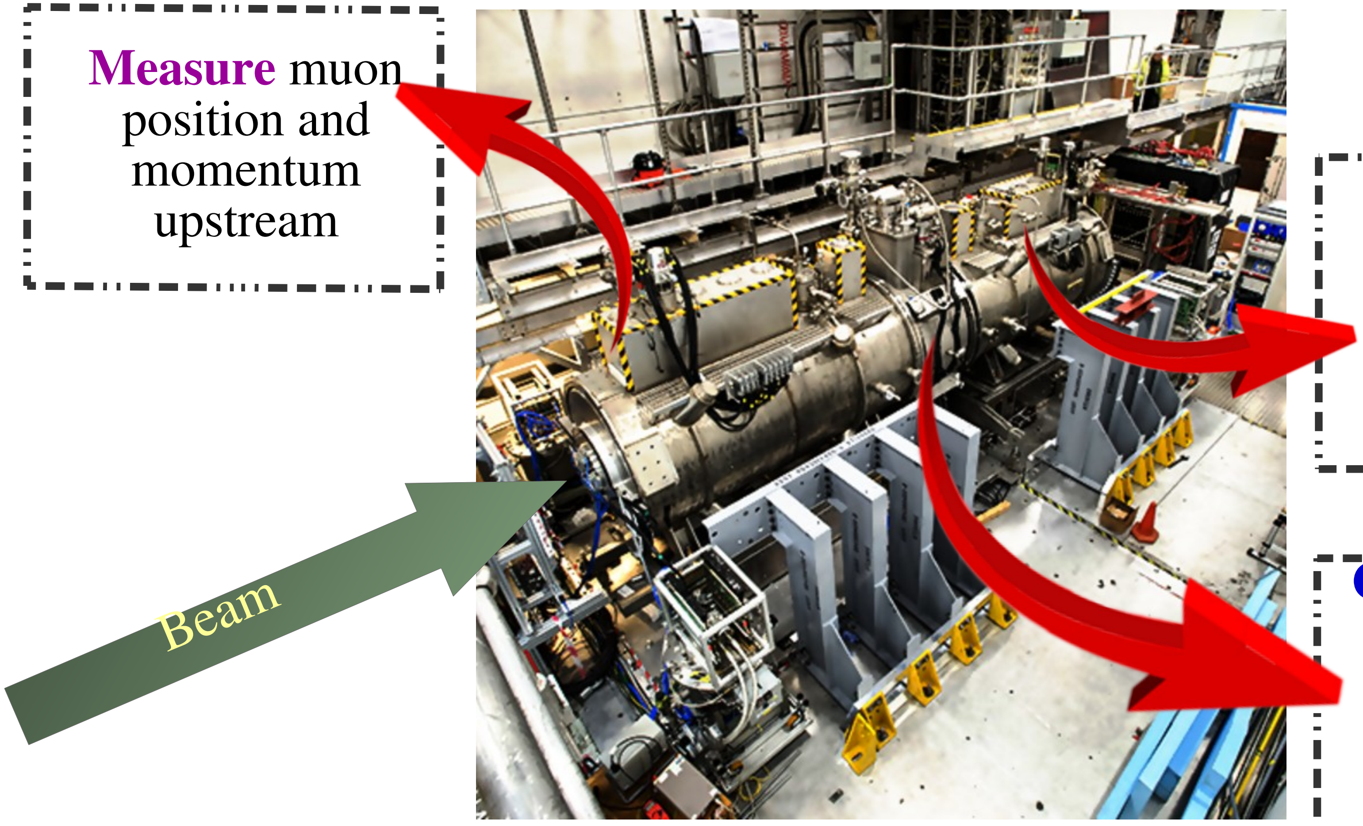
Measure muon position and momentum upstream



Measure muon position and momentum downstream

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

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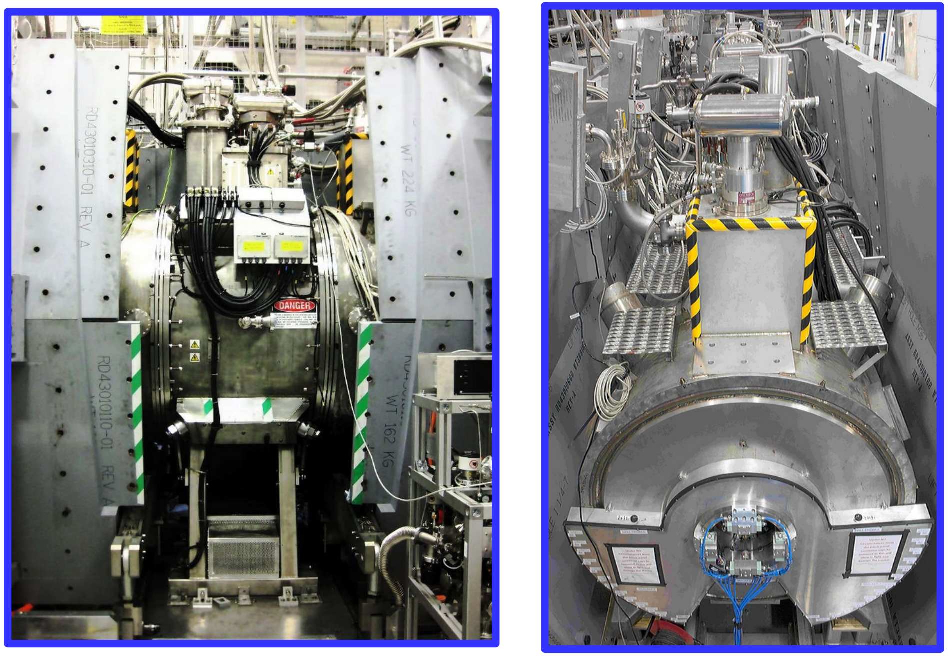
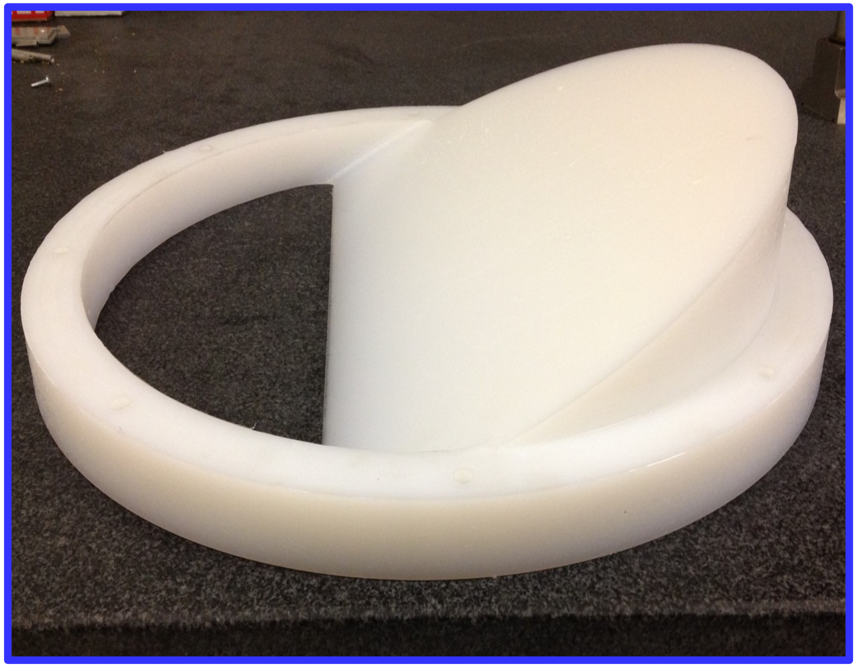
Superconducting Magnets



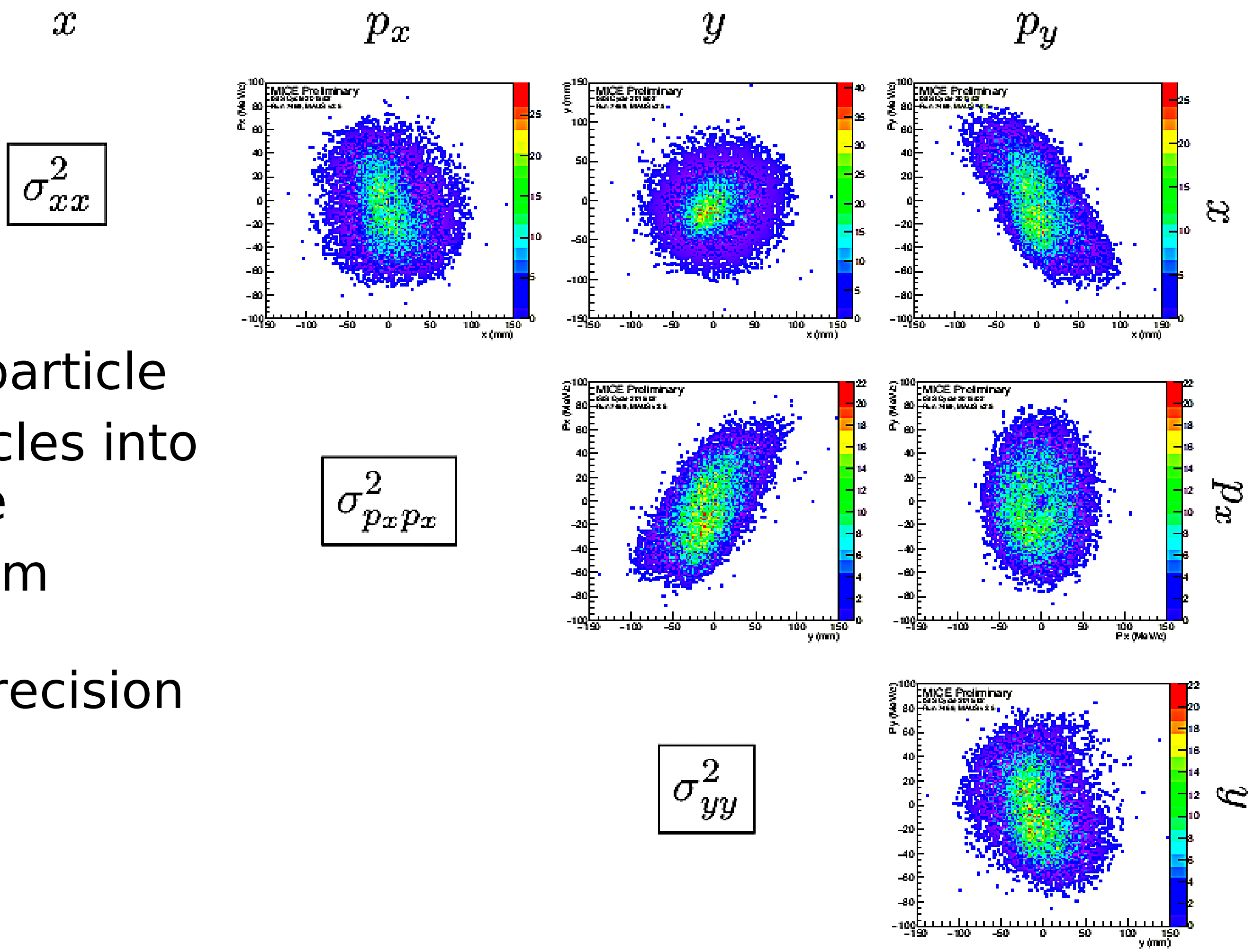
- Spectrometer solenoids upstream and downstream
  - 400 mm diameter bore, 5 coil assembly
  - Provide uniform 2-4 T solenoid field for detector systems
  - Match coils enable choice of beam focus
- Focus coil module provides final focus on absorber
  - Dual coil assembly - possible to flip polarity

Absorber



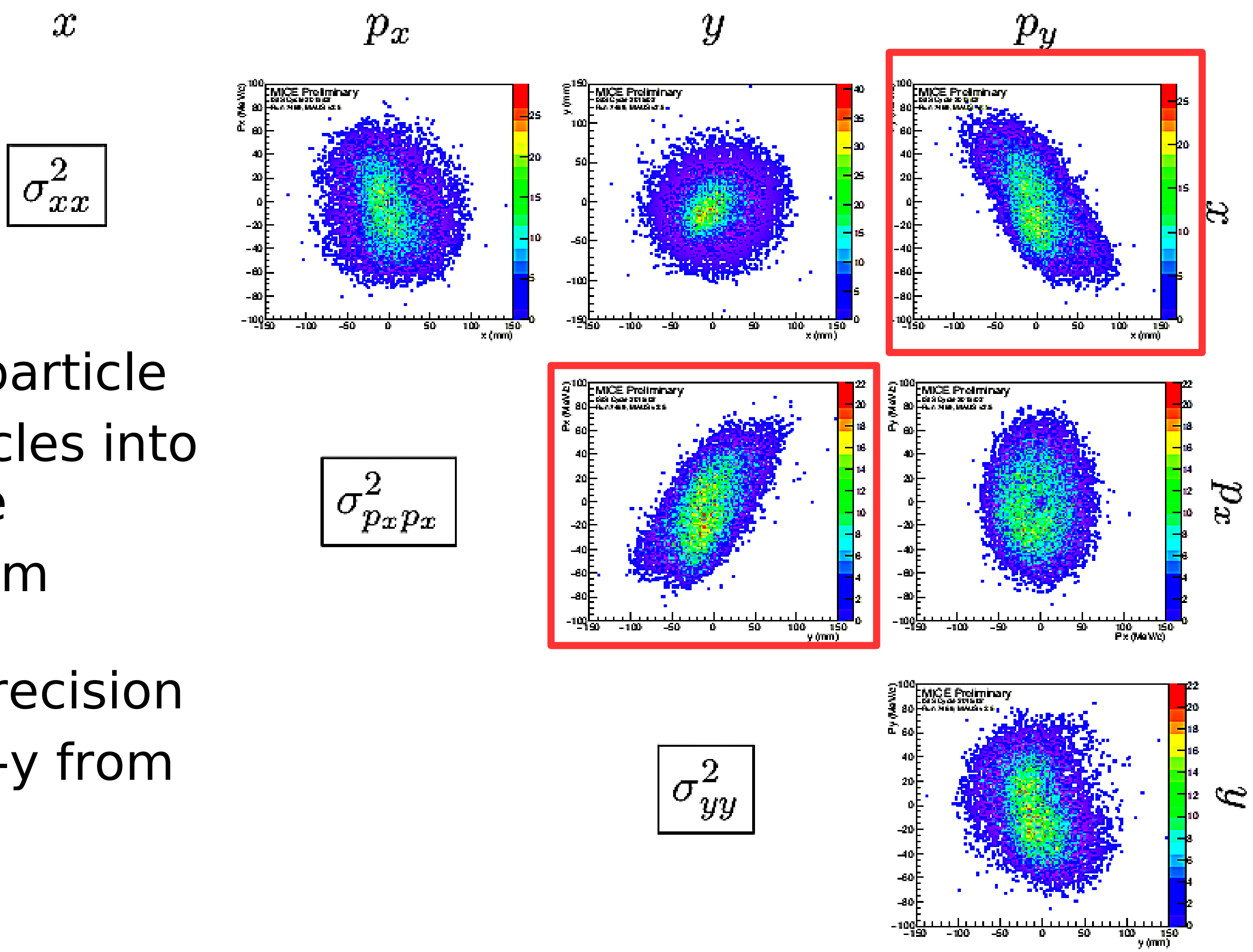
- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45° polythene wedge absorber for longitudinal emittance studies

Phase space reconstruction



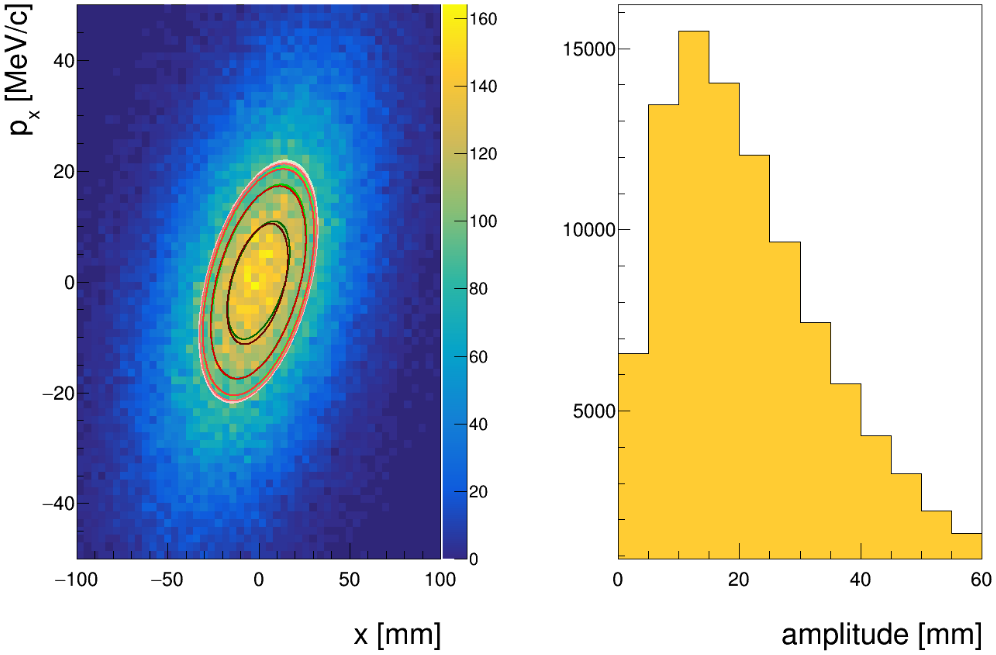
- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision

Phase space reconstruction



- MICE individually measures every particle
- Accumulate particles into a beam ensemble
- Can measure beam properties with unprecedented precision
- E.g. coupling of x-y from solenoid fields

Amplitude reconstruction



- Phase space (x, p_x, y, p_y)
- Normalise phase space to RMS beam ellipse
  - Clean up tails
- Amplitude is distance of muon from beam core
  - Conserved quantity in normal accelerators
- Ionization cooling reduces transverse momentum spread
  - Reduces amplitude
- Mean amplitude ~ “RMS emittance”

Increase in core density

- Muon ionisation cooling has been demonstrated by MICE
  - Muons @ ~140 MeV/c
  - Transverse cooling only
  - No re-acceleration
  - No intensity effects

nature

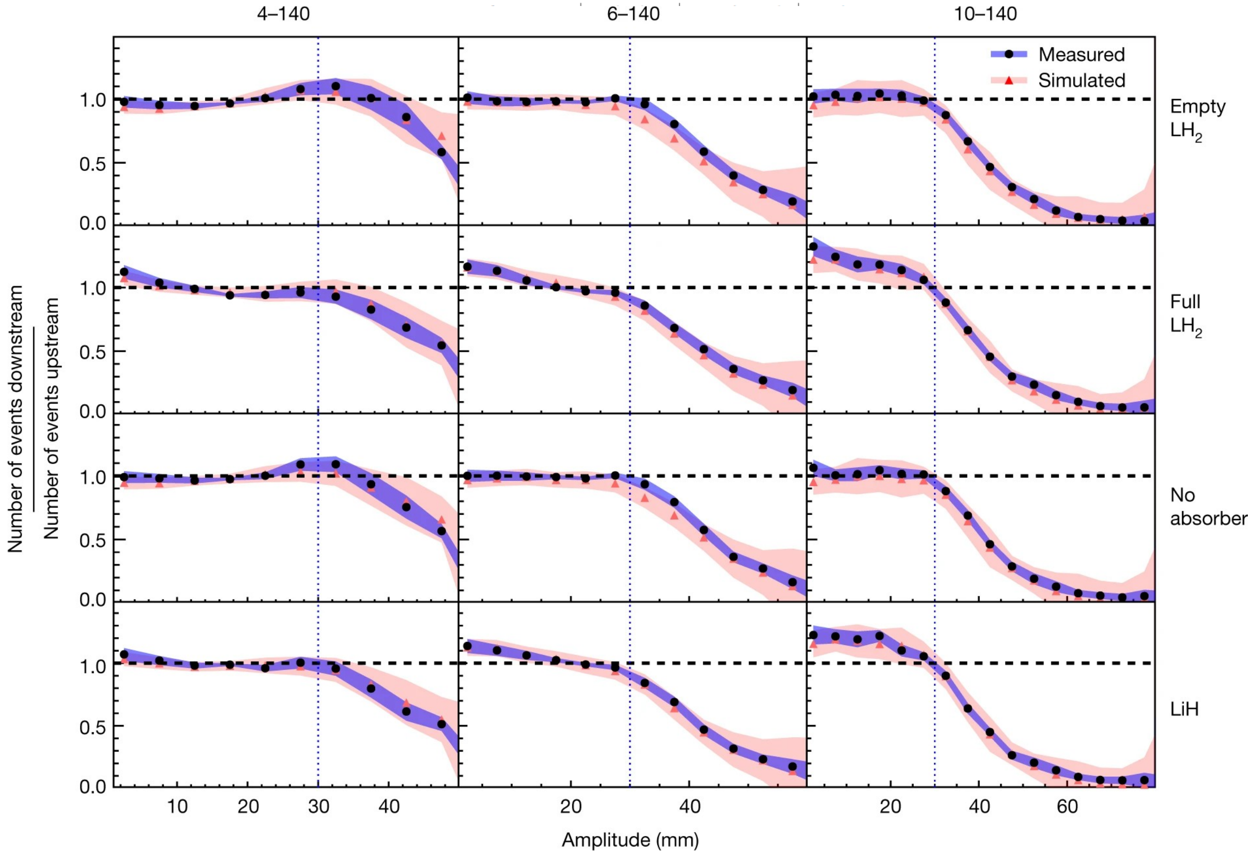
nature > articles > article

Article | Open Access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

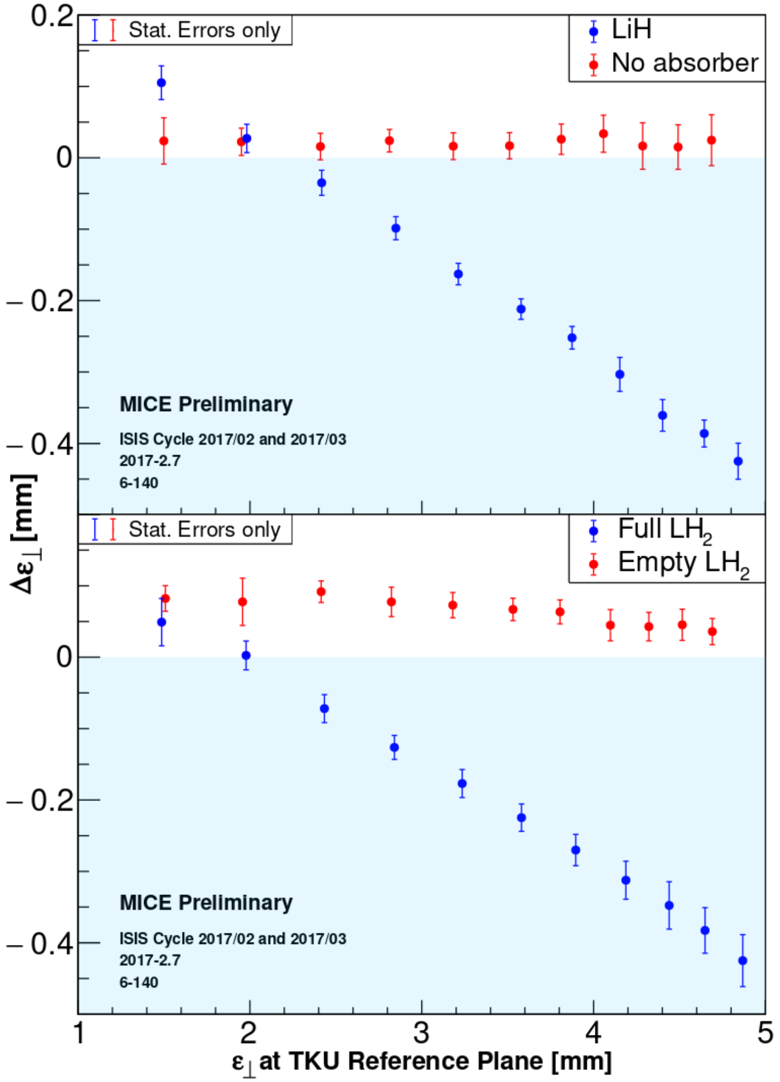
Nature **578**, 53–59(2020) | Cite this article



Emittance reduction

International
UON Collider

- 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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ISIS Neutron and
Muon Source

The Muon Collider – Future R&D

International
MUON Collider
Collaboration

C. T. Rogers
Rutherford Appleton Laboratory

Science & Technology Facilities Council
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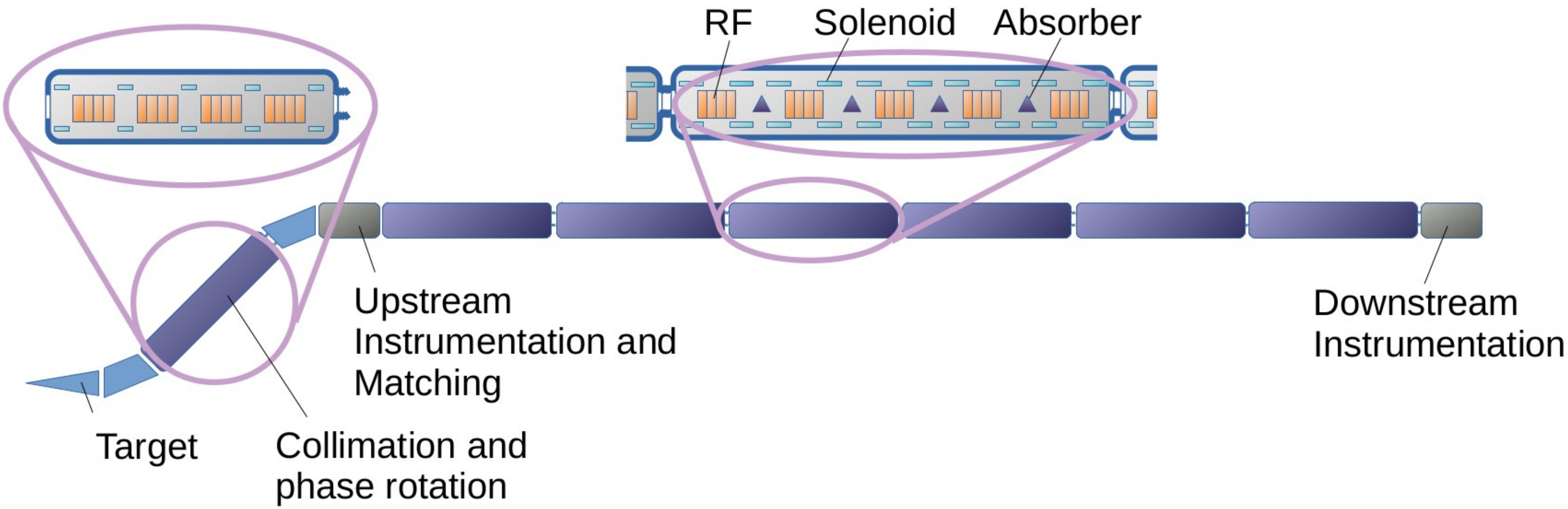
Cooling Demonstrator



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

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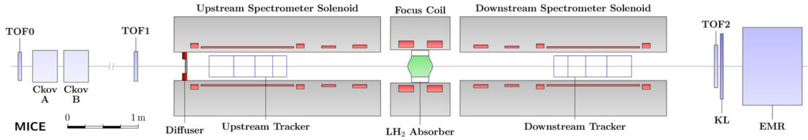
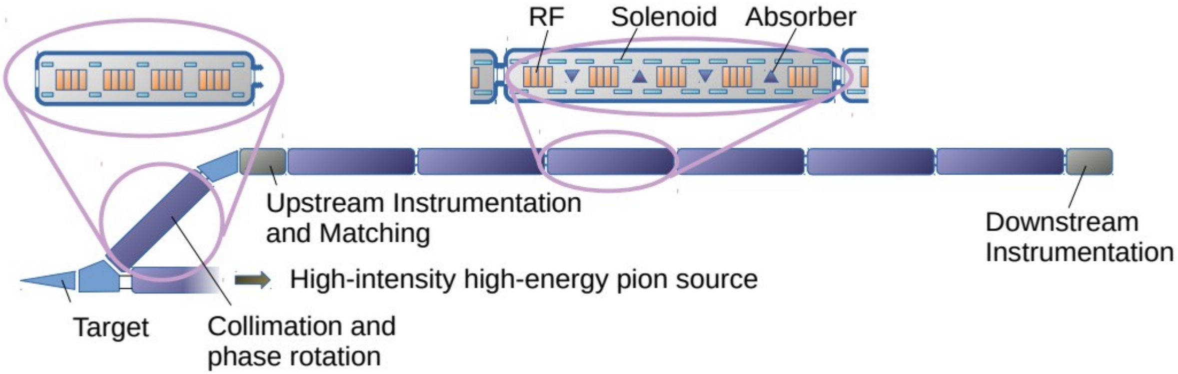
Comparison with MICE





	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

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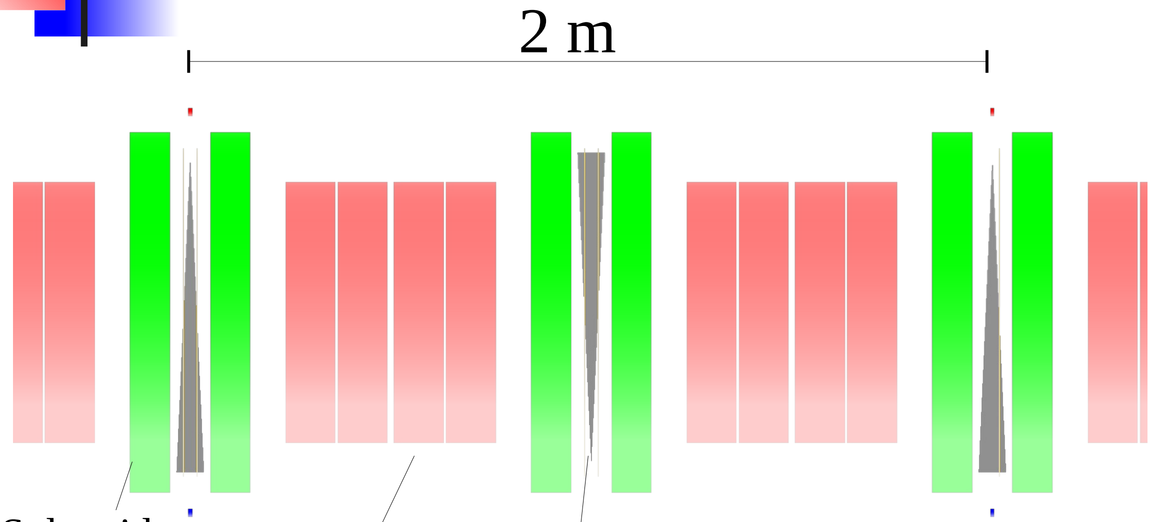
Preliminary Cooling Cell Concept

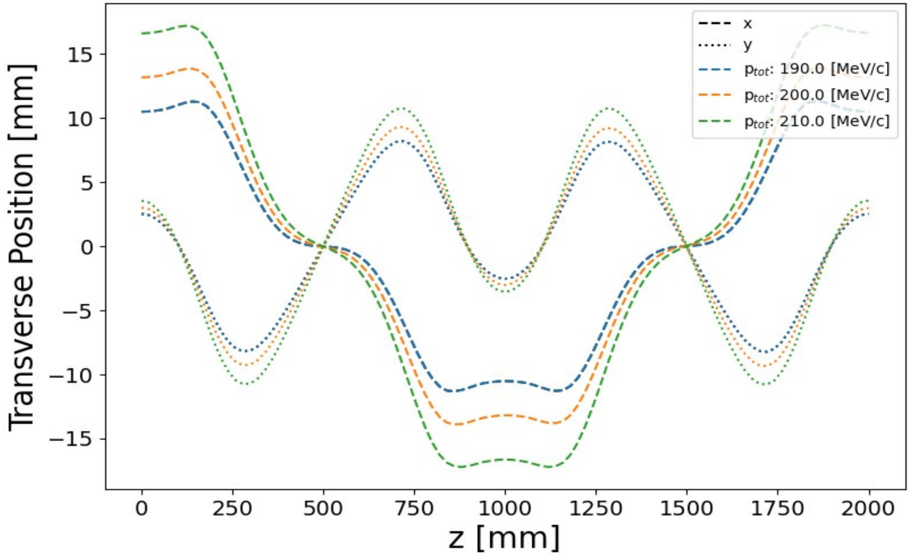

2 m

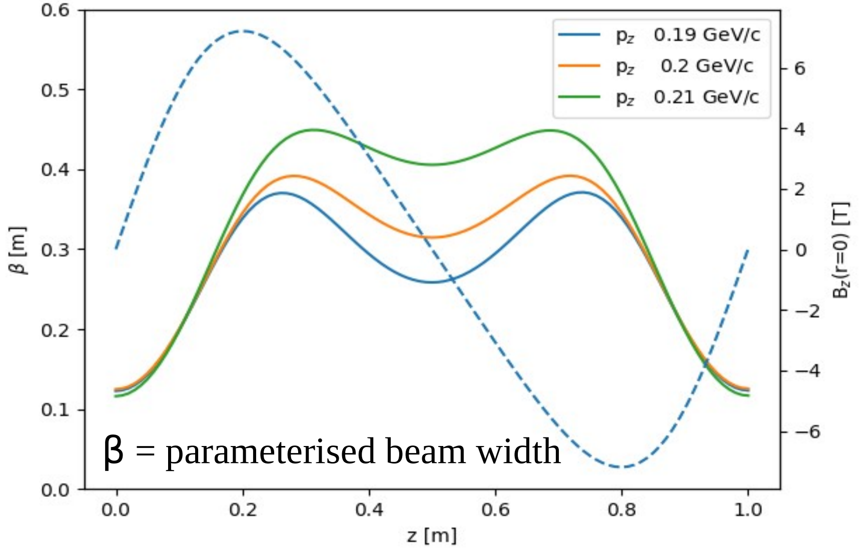
Solenoid + dipole

RF cavity

Absorber

Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

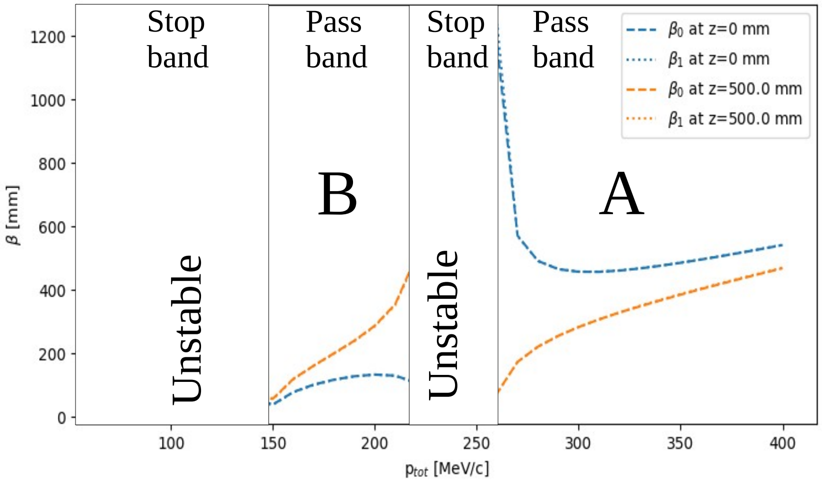


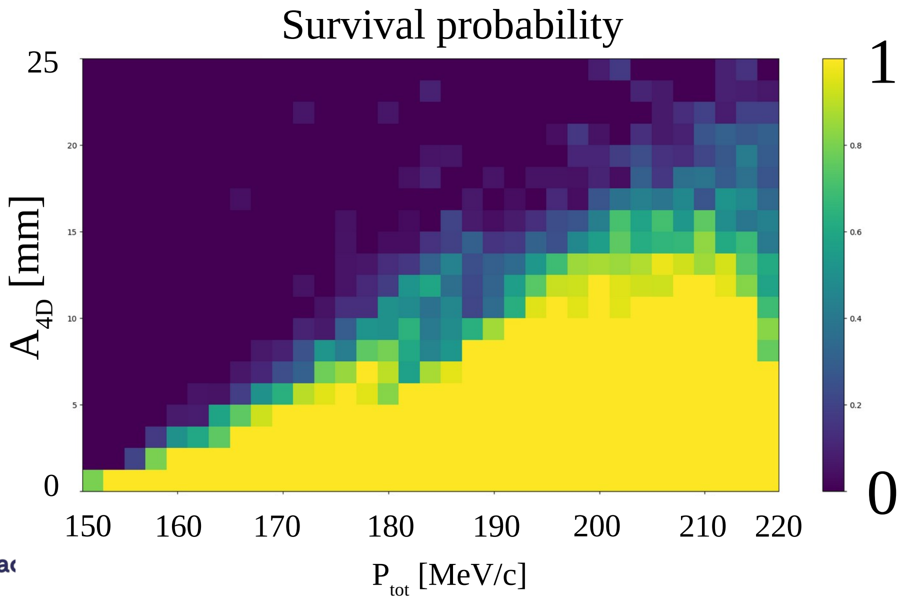


β = parameterised beam width

Optics vs momentum

- Operation in area **A**
  - High dynamic aperture
  - Larger β
  - Larger emittances
- Operation in area **B**
  - Lower dynamic aperture
  - Smaller β
  - Lower emittances
- Lattice operates in area **B**
  - May wish to check out area A also





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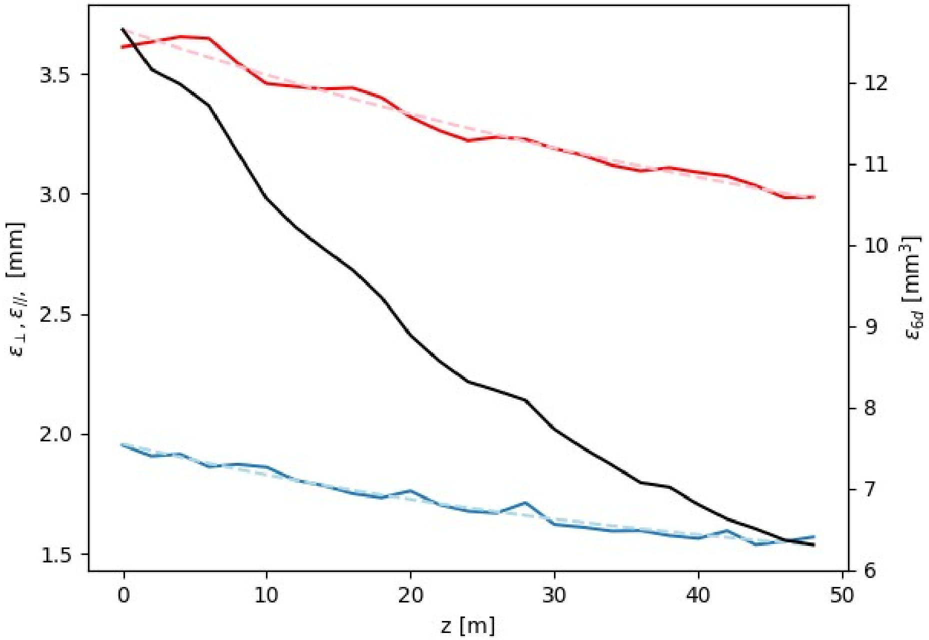
Performance

- Good cooling performance
  - Transverse and longitudinal emittance reduced by ~ 20 %
  - Approx factor two reduction in 6D emittance
- Optimisation ongoing
- Assumes perfect matching for now



Transmission losses	2.00%
Decay losses	4.00%
Trans ε in	1.95 mm
Trans ε out	1.57 mm
Long ε in	3.61 mm
Long ε out	2.99 mm
6D ε in	12.7 mm^3
6D ε out	6.3 mm^3

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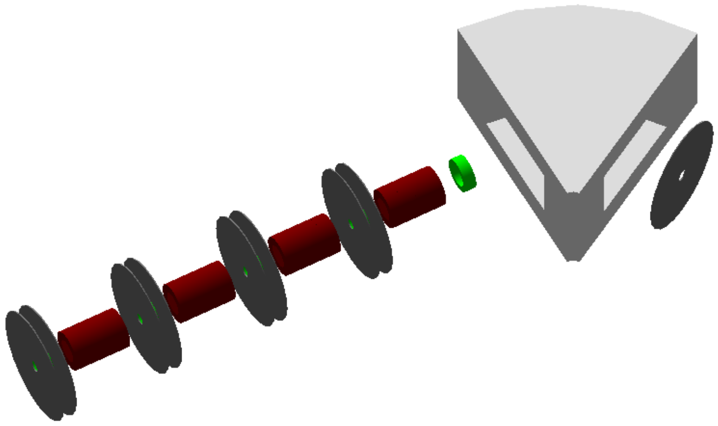
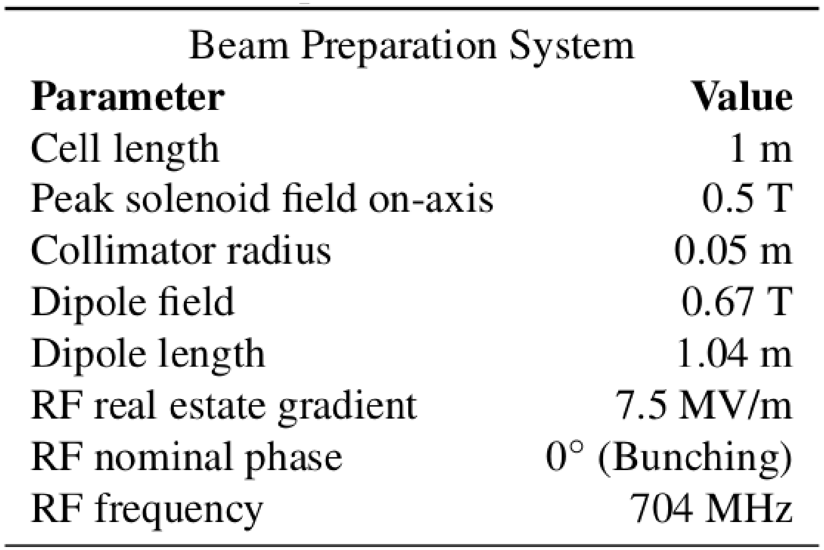
Beam preparation system

- ~ 100 ps pulsed muon beams don’t exist
    - Muons have only rarely been accelerated in conventional RF cavity
    - Low emittance muon beam challenging to achieve
- Need to consider a system to prepare the muon beam
    - Assume momentum collimation in switchyard
    - Transverse collimation
    - Longitudinal phase rotation

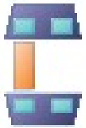




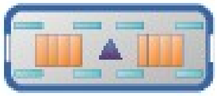
Beam Preparation System

Parameter	**Value**
Cell length	1 m
Peak solenoid field on-axis	0.5 T
Collimator radius	0.05 m
Dipole field	0.67 T
Dipole length	1.04 m
RF real estate gradient	7.5 MV/m
RF nominal phase	0° (Bunching)
RF frequency	704 MHz

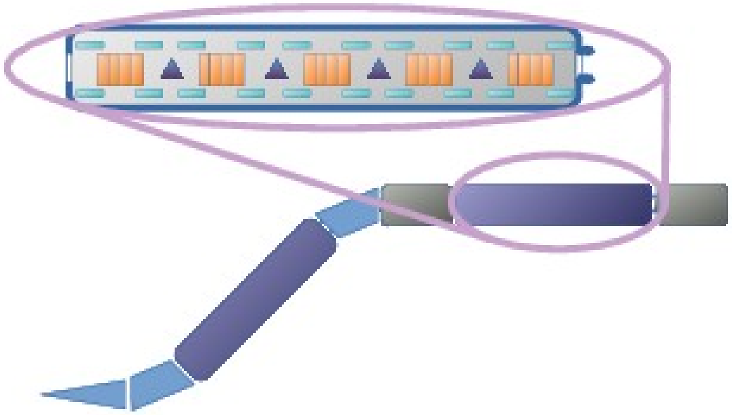
Muon cooling - plan



RF Test programme, with upgradeable magnet configuration, to test novel RF technologies



Prototype of a cooling cryostat to test magnet, absorber and RF integration



Full cooling cryostat with beam

Full cooling lattice with beam

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MUCOOL Cavity R&D

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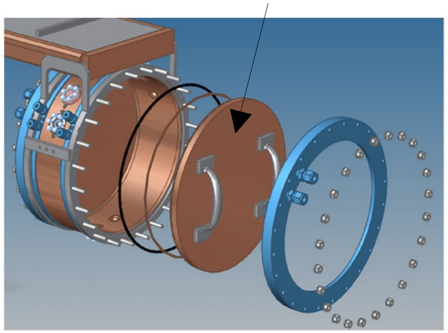
- Cooling requires strong B-field overlapping RF
  - B-field → sparking in RF cavities
- Two technologies have demonstrated mitigation

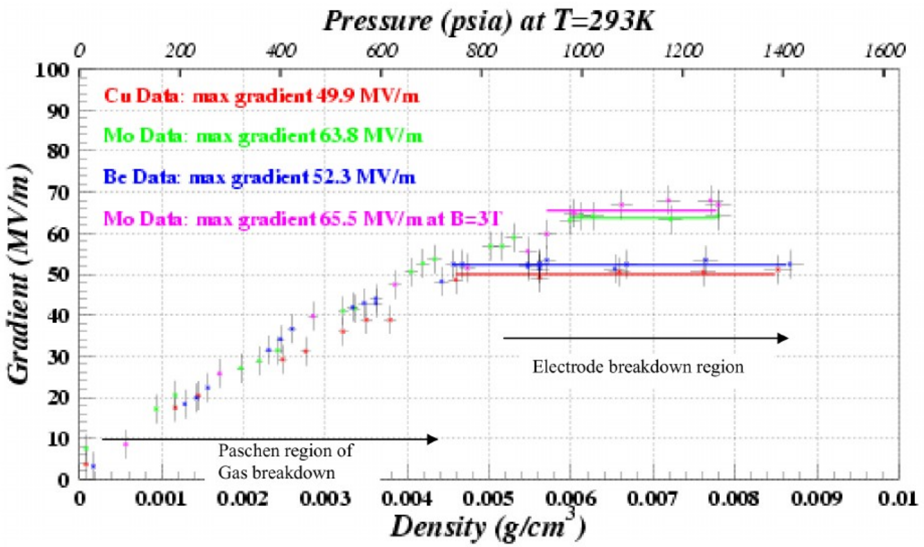
Bowring et al, PRAB 23 072001, 2020

Material	B-field (T)	E-field (MV/m)
Cu	0	24.4 ± 0.7
Cu	3	12.9 ± 0.4
Be	0	41.1 ± 2.1
Be	3	$> 49.8 \pm 2.5$

Double vs Cu cavity in 0 T

Changeable Cu/Be walls





High Pressure gas

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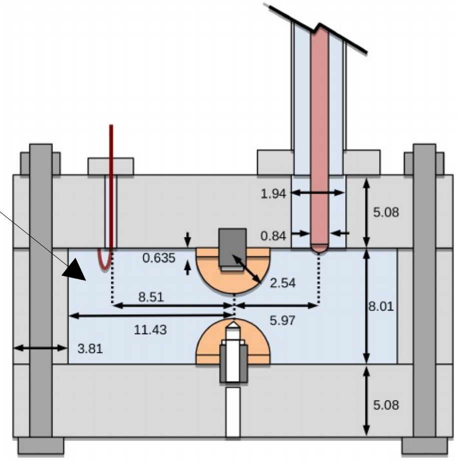
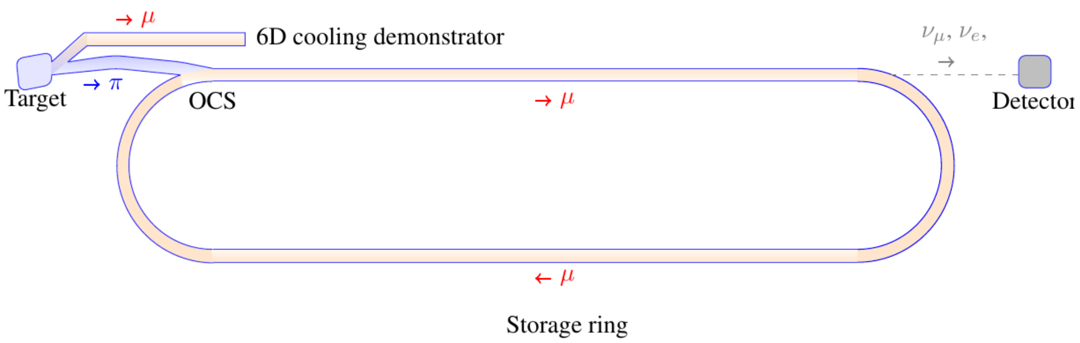
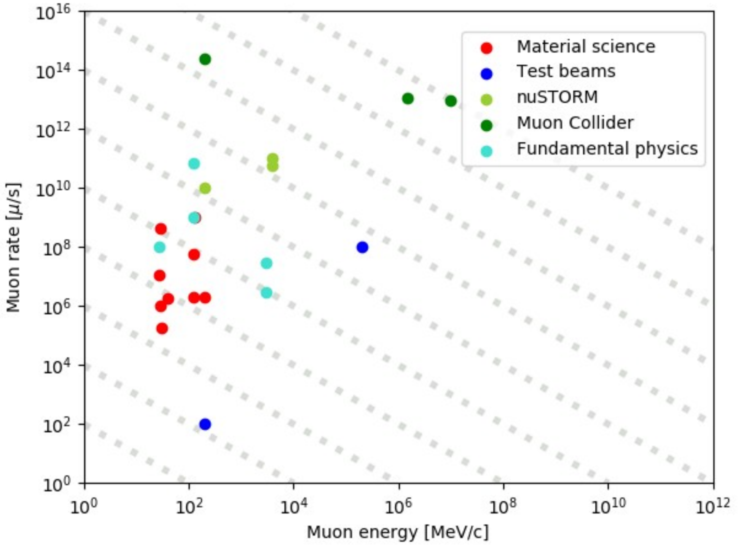


Freemire et al, JINST 13 P01029, 2018

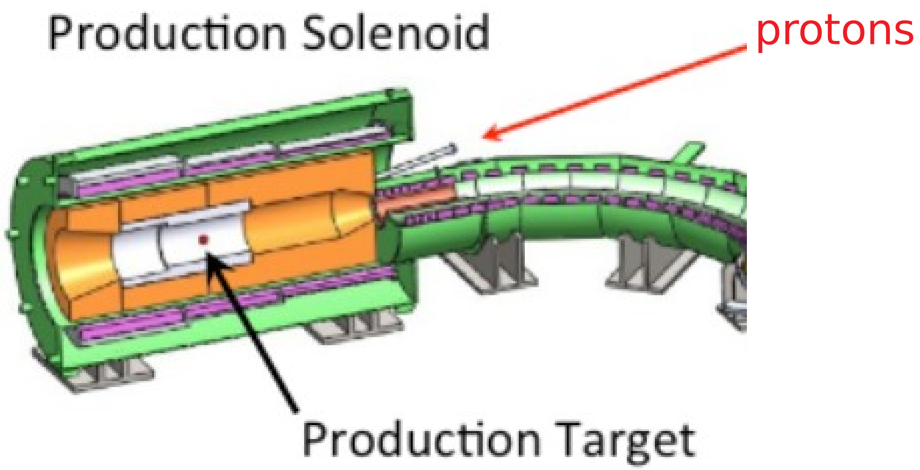
Synergy with nuSTORM

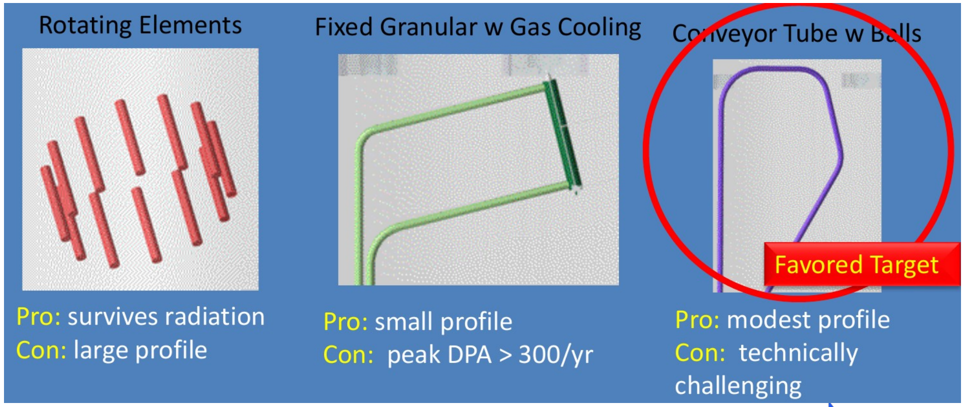




- NuSTORM → “next scale” muon facility
  - FFA-based storage ring (no acceleration)
  - Muon production target and pion handling
  - Possibly shared with cooling demonstrator
- Aim to measure neutrino-nucleus cross-sections
  - E.g. reduce neutrino oscillation experiment resolutions
  - Nuclear physics studies
  - Sensitivity to Beyond Standard Model physics

Synergy with mu2e





Rotating Elements	Fixed Granular w Gas Cooling	Conveyor Tube w Balls
Pro: survives radiation Con: large profile	Pro: small profile Con: peak DPA > 300/yr	Pro: modest profile Con: technically challenging

- Muon-to-electron conversion experiments
  - Look for rare decay processes
- Under construction now
- R&D for phase II in progres
- Target station similar to MC target
  - But lower power, lower fiel
- Excellent opportunity to test ideas on target station
- Build collaboration

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Summary

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Rutherford Appleton Laboratory

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Final Word

- Development of a high brightness muon source is challenging
- Proton driver
  - Foil heating
  - Bunch compression
- Target
  - Radiation load, esp on the magnet
- Cooling
  - RF cavities
  - Novel technique
- Valuable to explore the technology