Challenges for the Muon Collider

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MUON Collider
Collaboration

C. T. Rogers
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Recap

- Last time
  - Discussed the advantages of the muon collider
  - Discussed luminosity drivers
  - Presented issues surrounding muon capture
  - Described ionisation cooling – physics
- This time
  - Describe implementation of ionisation cooling
  - Talk about the acceleration
  - Talk about collision
  - Discuss the path to the muon collider – how to make it happen

The Facility – Ionisation Cooling

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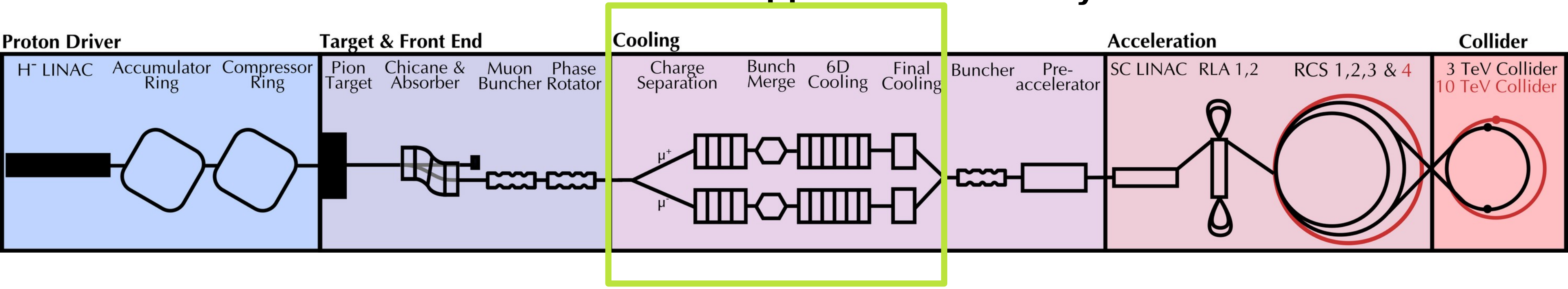


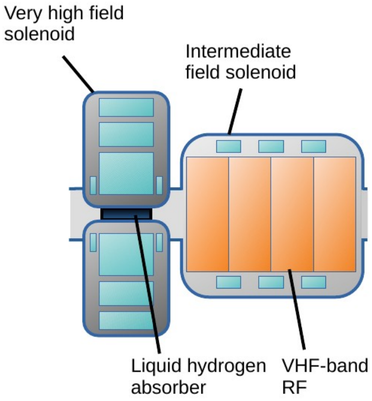
How to realise cooling?

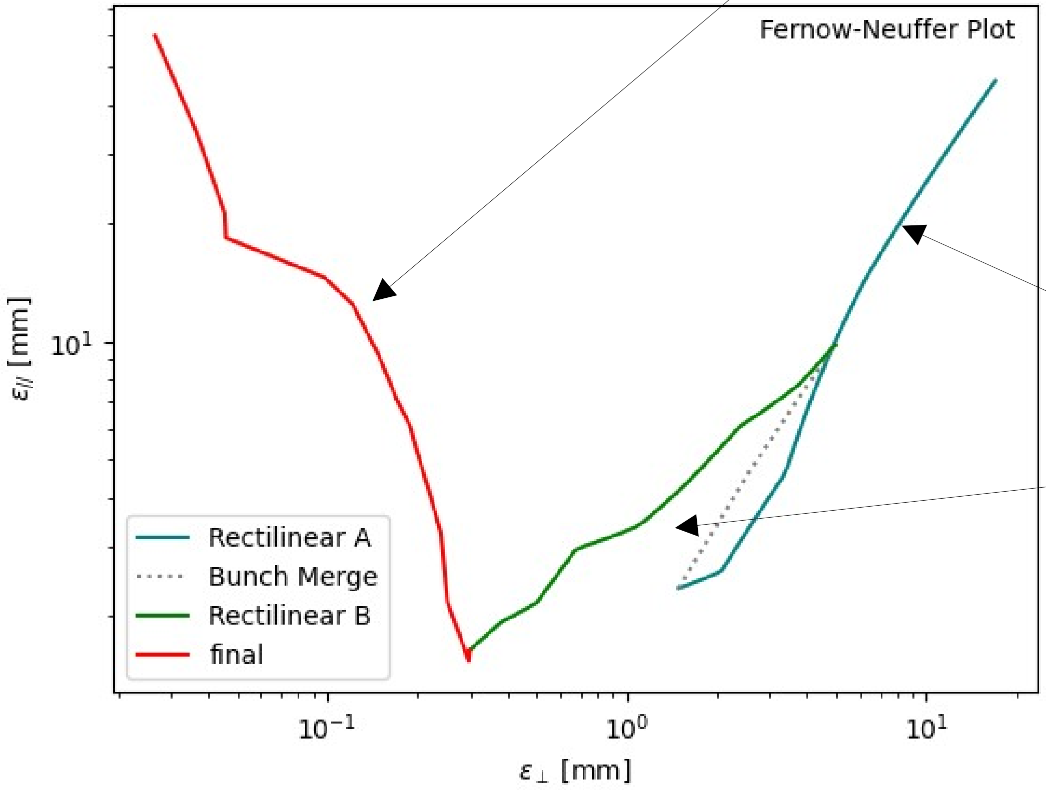
- To realise ionisation cooling:
- Need to focus strongly in transverse space
  - Both horizontal and vertical focusing to cool in both planes
- Need to maintain sufficient transverse acceptance
- Need to reaccelerate to keep cooling quick
- Need to focus strongly in longitudinal space
  - Short bunch → bigger energy spread
  - Reduce the relative effect of the heating
- Solenoids
  - Initially weaker, for more acceptance
  - Finally strong → strongest(!) for more focusing
- Lots of RF
  - Maintain both bunching and reacceleration

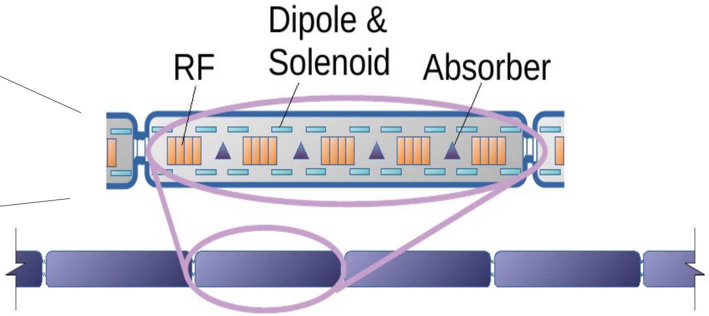
Muon Cooling

Sayed et al, PRSTAB 18, 2015
Fol et al, IPAC22

4D Final cooling







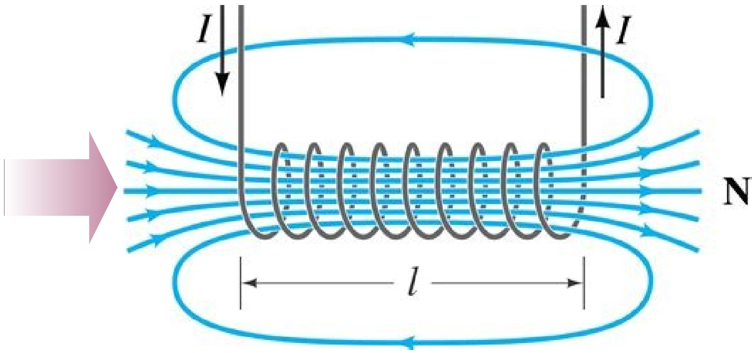
Stratakis et al, PRSTAB 18, 2015
Zhu et al, arxiv 2409.02613

Rectilinear cooling

es Council

Solenoid optics

- Solenoids behave as a focusing system
- Fringe field generates kinetic angular momentum
- Angular momentum → focusing
- Assuming cylindrical symmetry



$$2\beta_\perp\beta_\perp'' - (\beta_\perp')^2 + 4\beta_\perp^2\kappa^2 - 4(1+\mathcal{L}^2) = 0,$$

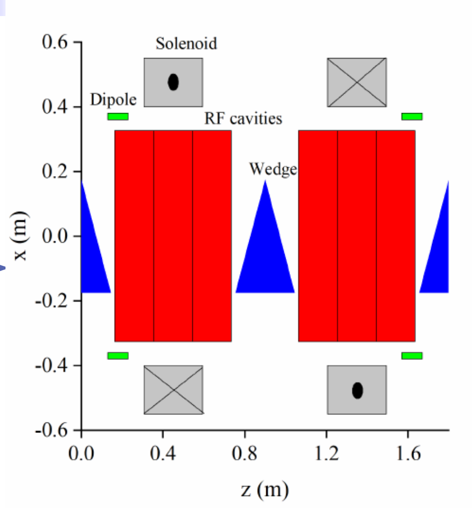
$$\kappa(z) \simeq \frac{qB_z(r=0,z)}{2P_z} \simeq 0.15\frac{B[\mathrm{T}]}{P_z[\mathrm{GeV/c}]}\mathrm{m}^{-1}.$$

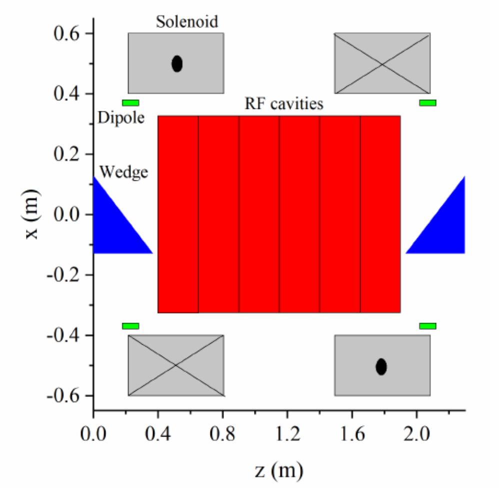
$$\mathcal{L} \simeq \frac{\langle L_{\mathrm{canon}}\rangle}{2mc\epsilon_N}.$$

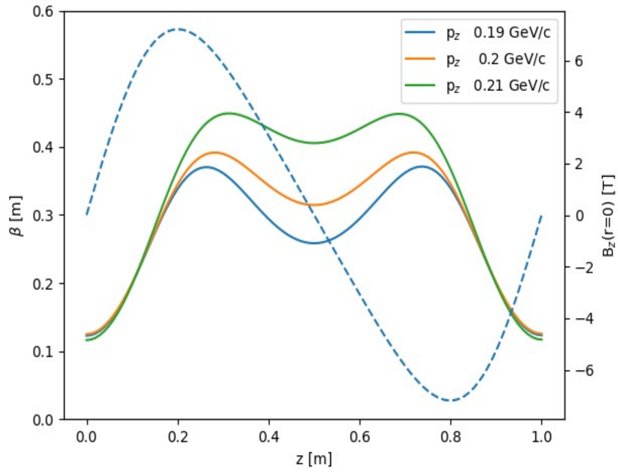
G. Penn, Beam Envelope Equations for Cooling of Muons in Solenoid Fields, PRL 85, 2000

$$\phi = \int_0^{z_0} \frac{1}{\beta_\perp} dz$$

Rectilinear Cooling





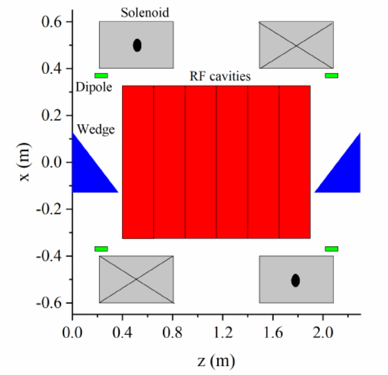


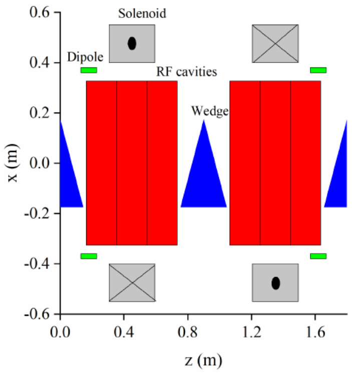
D. Stratakis and R. Palmer, Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study, Phys. Rev. ST Accel. Beams 18, 2015

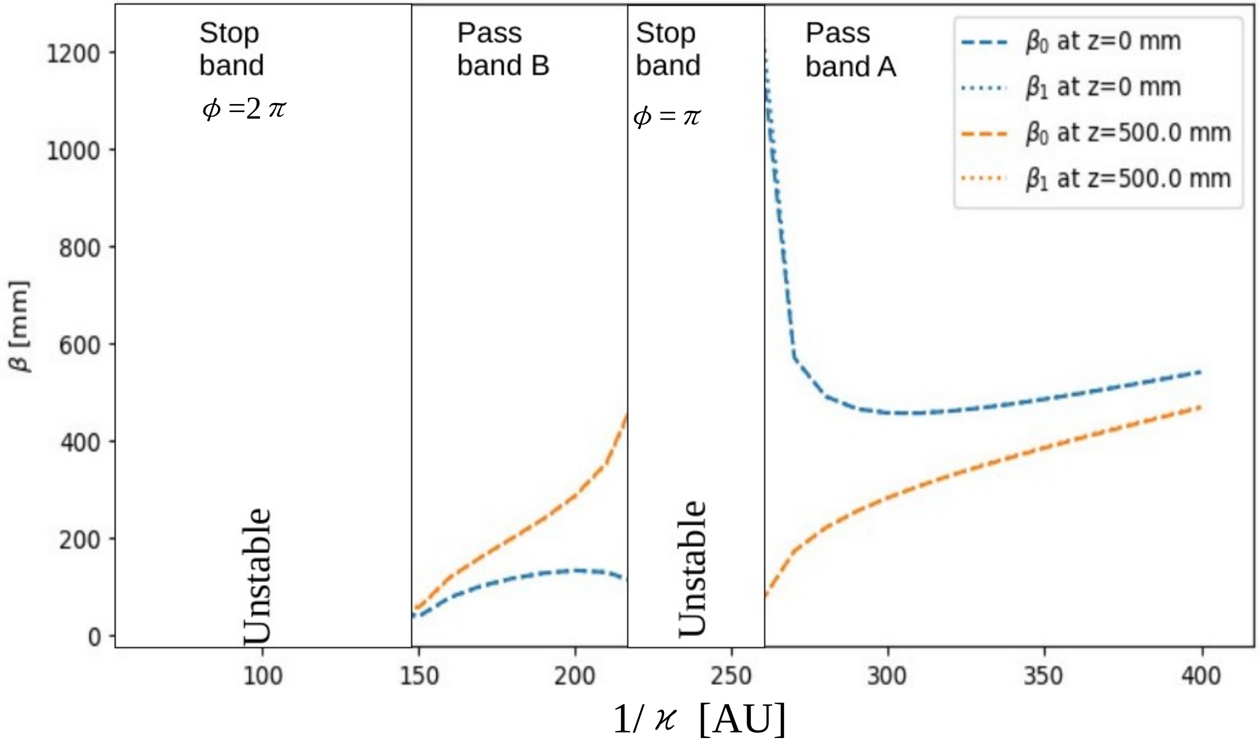
- 6D Cooling
  - Combined function dipole-solenoid magnets
    - Weak dipole field is a perturbation
    - Focus at the asborber with alternating solenoid polarity
  - Compact lattice – RF integrated into magnet cryostat
  - Lithium Hydride or lH2 absorbers
  - Careful field shaping to control position of stop-bands

Pass bands

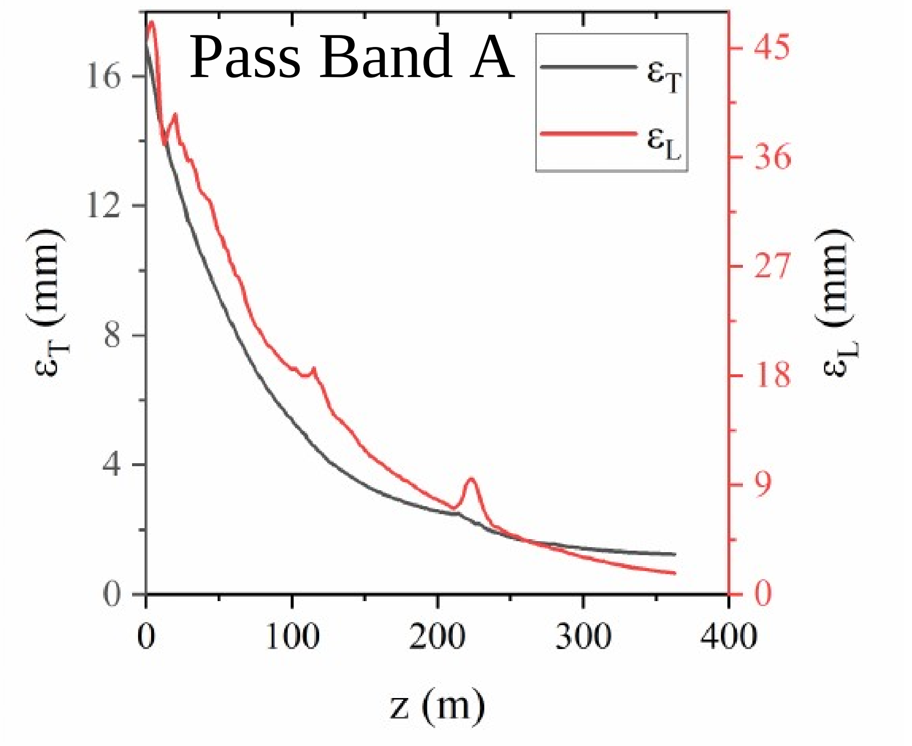
- Pass Band A
  - Less focusing
  - Better acceptance
- Pass Band B
  - More focusing
  - Worse acceptance

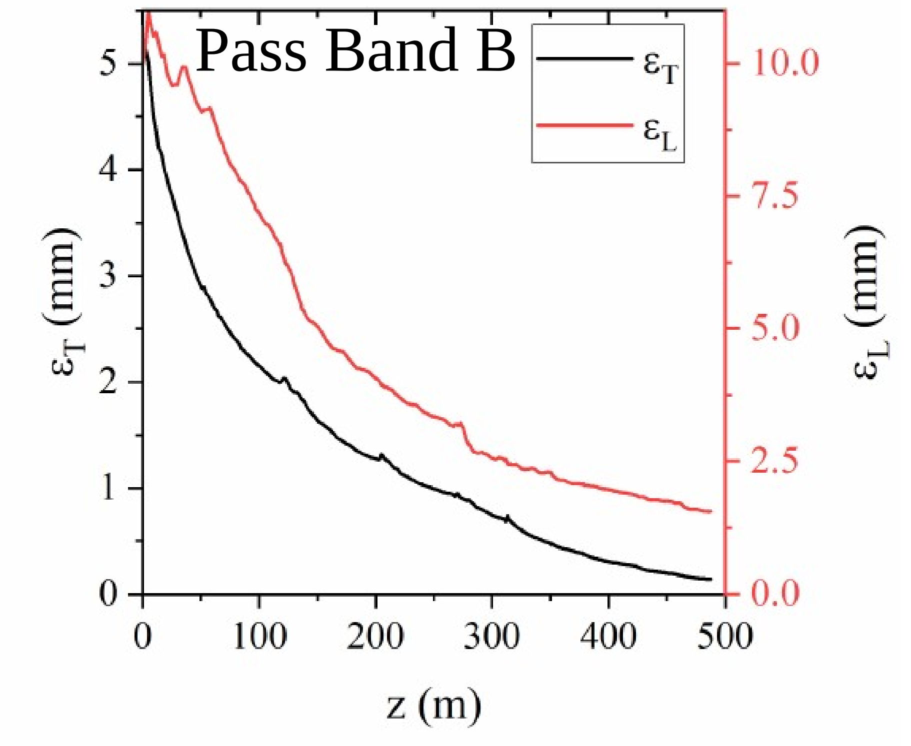






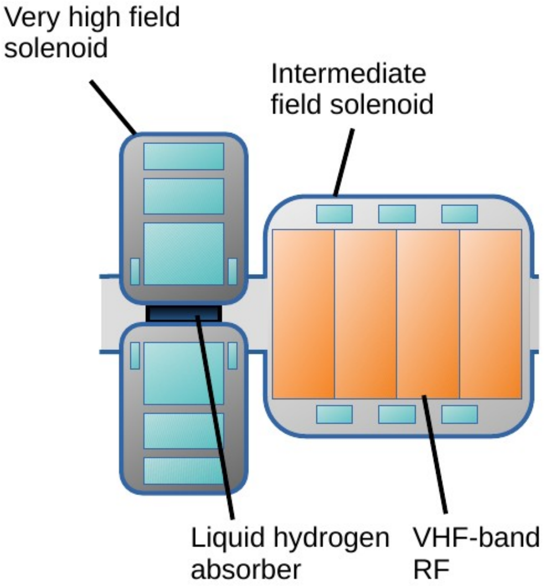
Rectilinear cooling performance





- As the beam nears equilibrium emittance cooling slows
- New lattice, shorter and stronger fields
  - Smaller DA
  - More focusing
- Repeat until the limit on magnet is reached ($\beta \sim$ few cm)
  - Physical limits of solenoid construction

Final cooling



H. Sayed et al., High field – low energy muon ionization cooling channel, Phys. Rev. ST Accel. Beams 18, 2015
Fol et al, IPAC22

- Challenge is to get very tight focussing
- Go to high fields (~30 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

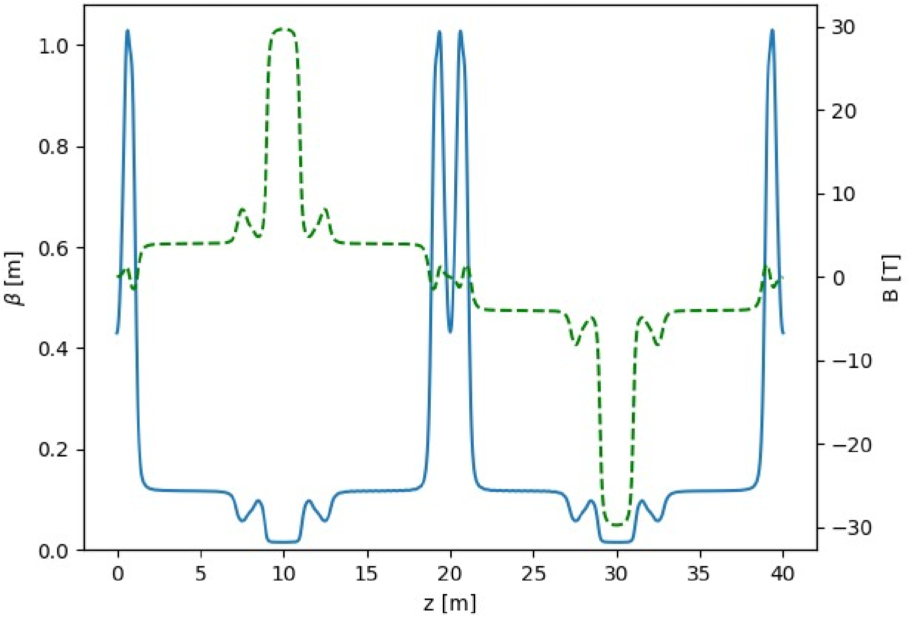
Final cooling

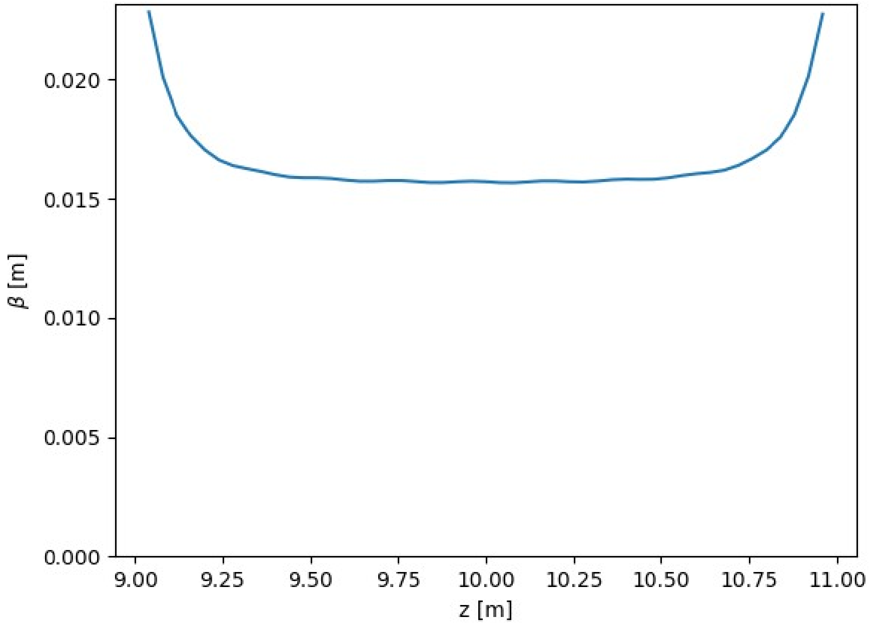
- In uniform field

$$2\beta_\perp \cancelto{0}{\beta''_\perp} - \left(\cancelto{0}{\beta'_\perp}\right)^2 + 4\beta_\perp^2\kappa^2 - 4(1+\mathcal{L}^2) = 0,$$

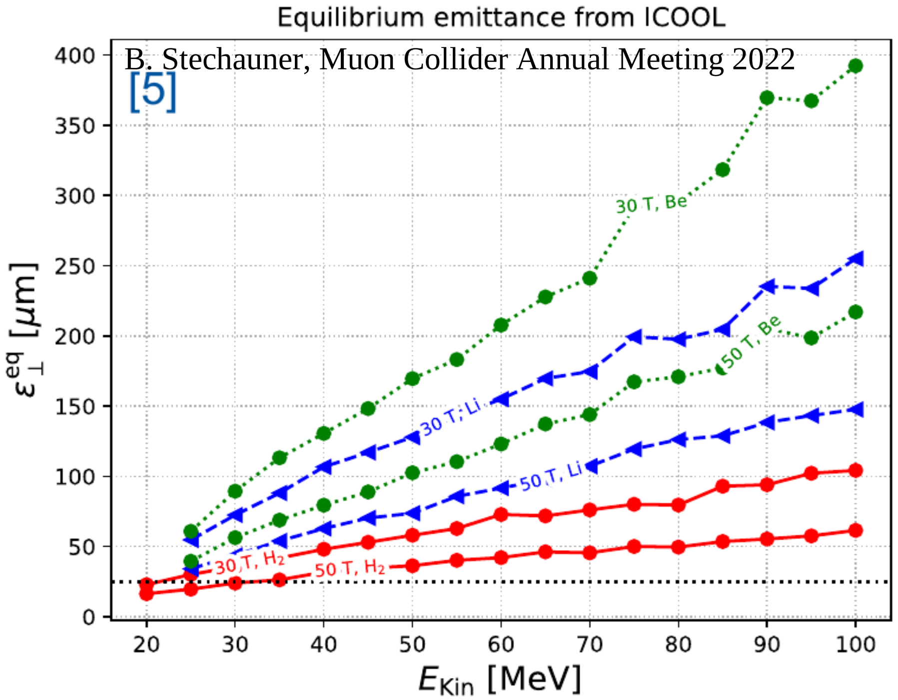
$$\beta_\perp = \frac{\sqrt{1+\mathcal{L}^2}}{\kappa}$$

- Reach $\beta \sim$ 1 cm – but not practical to introduce dispersion



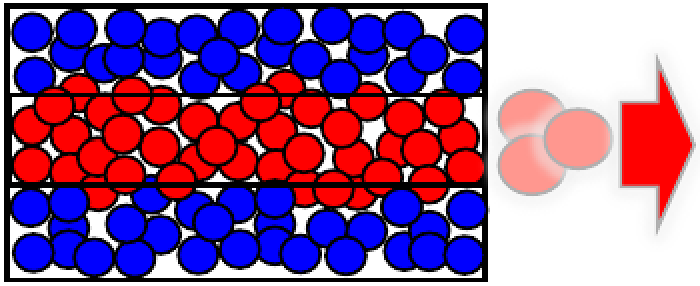


Final cooling - absorber


Equilibrium emittance from ICOOL

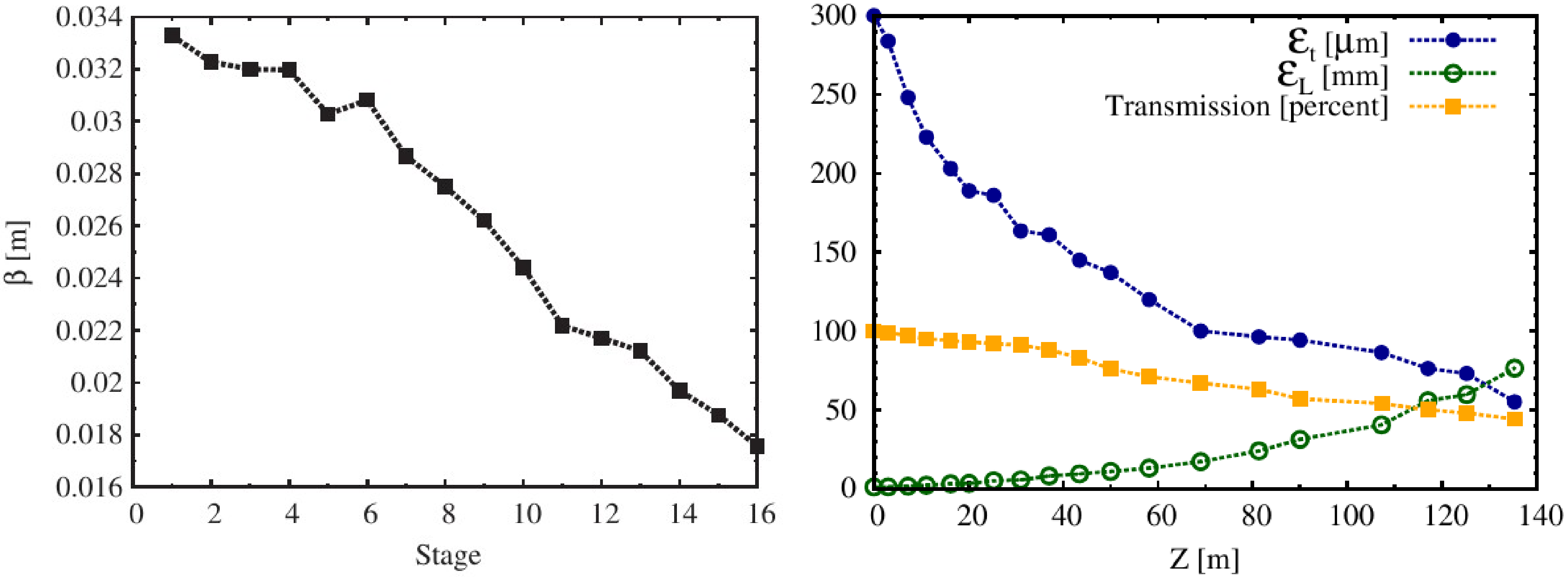
B. Stechauner, Muon Collider Annual Meeting 2022

[5]



- Significant benefit to use Hydrogen absorber
  - Much less energy loss per scatter
- Narrow, intense beam is enough to boil H_2
  - Next to very thin windows
- Can cause damage to windows → burst
- Requires care!

Final cooling - performance



- $\beta \sim$ cm
- Significant longitudinal emittance growth
- Transmission losses
- Final transverse emittance <~ 50 micron

Luminosity formula

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

- We have taken a beam that is ~ 100 mm wide and made a beam that is ~ few mm wide
- Need to accelerate it on a short time scale << muon lifetime
  - Time dilation is on our side!
- Need to bring it to collision

The Facility – Acceleration

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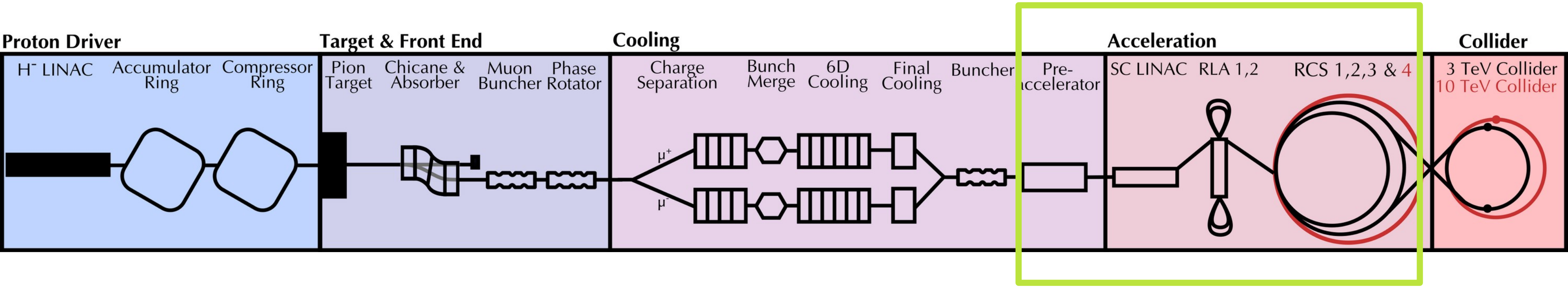


Acceleration efficiency

- During acceleration, muon lifetime is constantly increasing due to Lorentz time dilation.
- Starting from time dilated radioactive decay:

$$\frac{dN}{dt} = -\frac{1}{\gamma\tau_\mu}N = -\frac{m_\mu c^2}{E\tau_\mu}N$$

- Chain rule:

$$\frac{dN}{dE} = \frac{dN}{dt}\frac{dt}{dE}$$

$$\frac{dN}{dE} = -\frac{N}{\delta_\tau E}$$

Change in γ in muon lifetime:

$$\delta_\tau = q\bar{V}\tau_\mu/mc$$

- Integrate

$$N_\pm = N_{0\pm}\left(\frac{E}{E_0}\right)^{-1/\delta_\tau}$$

Acceleration efficiency

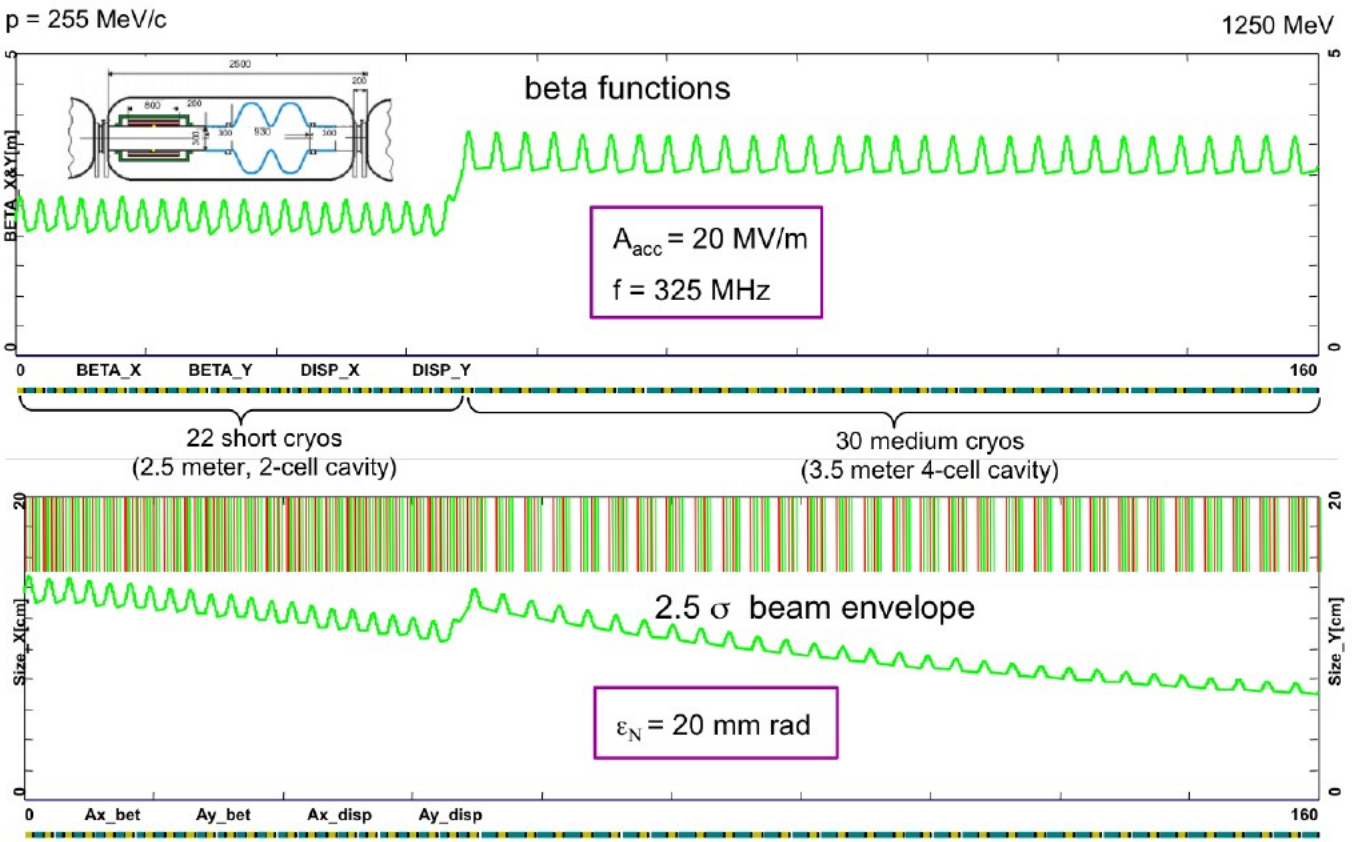
- Chaining multiple acceleration stages

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$

- Seek to accelerate from 0.2 GeV to 5e3 GeV
- E_f/E_i=2.5e4
- Average gradient ~ 10 MV/m → 84 % survival rate
- Average gradient ~ 1 MV/m → 19 % survival rate
- Compare with ILC → 11 km @ 250 GeV → 23 MV/m
  - But we don’t want to use a linac all the way!

Linac to start

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$

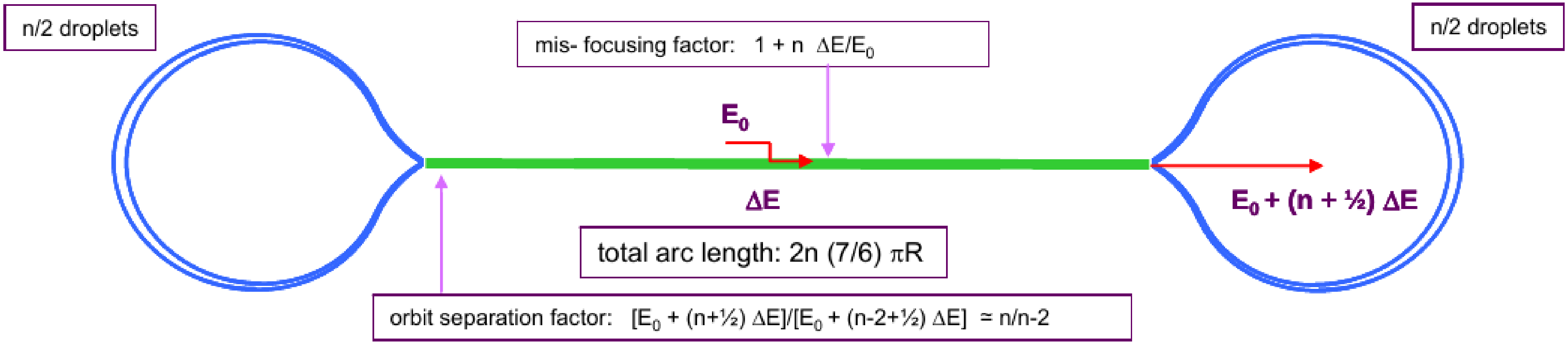


Kurup et al, The Muon Linac for the International Design Study for the Neutrino Factory, Proc. IPAC11

- At low energy (up to ~ few GeV) linac is cost effective
  - Non-relativistic → RF synchronisation is slow, expensive in a ring
  - Not much linac makes large E_f/E_i

Recirculating Linac

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$



n/2 droplets

mis- focusing factor: 1 + n $\Delta E/E_0$

n/2 droplets

E_0

ΔE

$E_0 + (n + ½)\ \Delta E$

total arc length: 2n (7/6) πR

orbit separation factor: $[E_0 + (n+½)\ \Delta E]/[E_0 + (n-2+½)\ \Delta E] \approx n/n-2$

Bogacz, Muon Acceleration Concepts for NuMax, JINST 13 (2018)

- At higher energy can recirculate through the linac
  - Less focusing required → geometric emittance
  - Real estate gradient in the linac is higher
- Can’t ramp magnets quickly enough
  - Use recirculators to bring the beam back into the linac
  - Worry about mis-focusing in the linac
  - Worry about time of flight in the return arcs & phasing RF correctly
  - “ERL-like”

Pulsed Synchrotrons

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$

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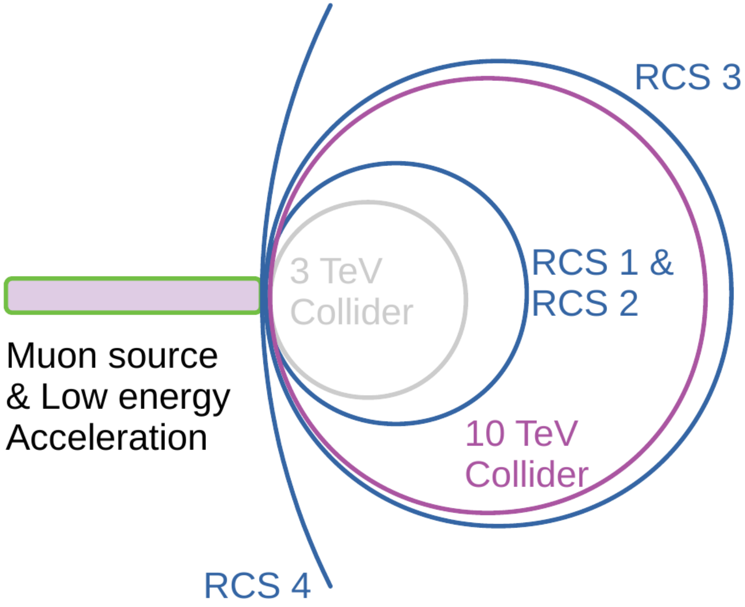

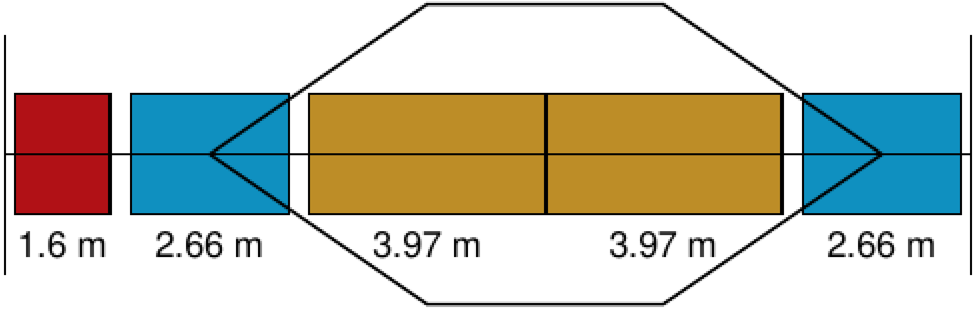

- At highest energy, can use synchrotrons
  - Ramp magnets in synchronisation with increasing beam energy
  - Need extremely fast ramp < few ms
  - To keep ring compact, use combination of
    - Fixed superconducting and
    - Pulsed normal conducting magnets
  - Shielding components from decay losses

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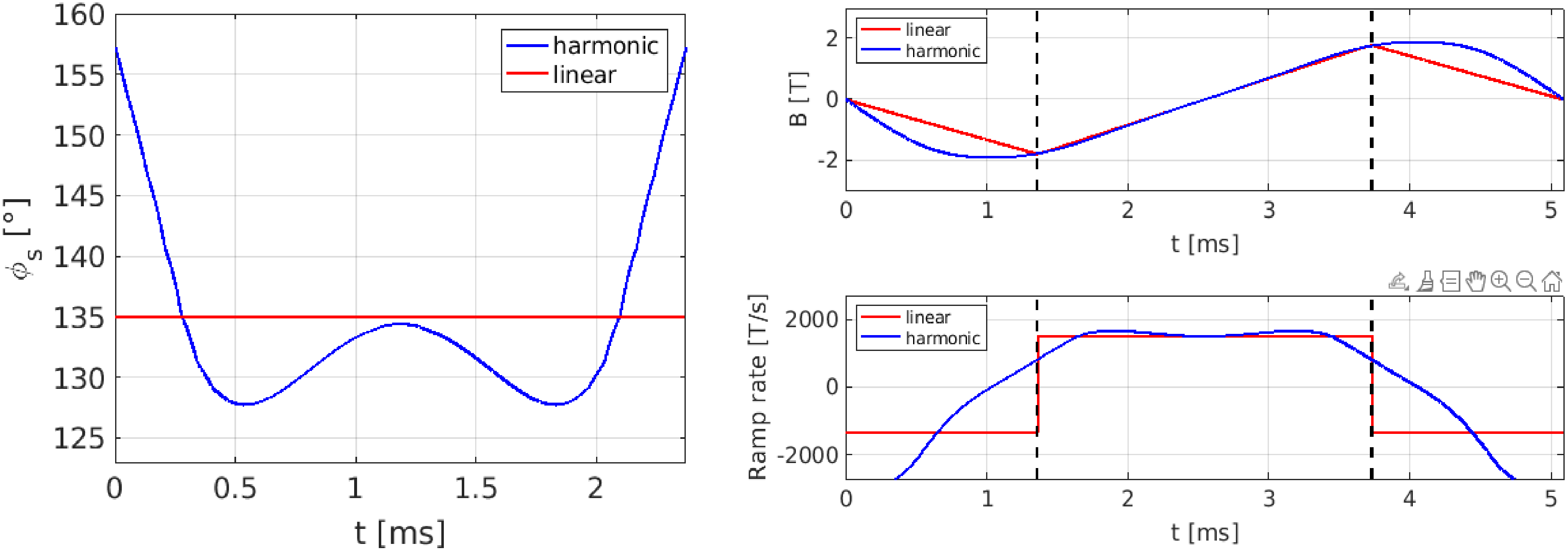
Synchronisation

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$

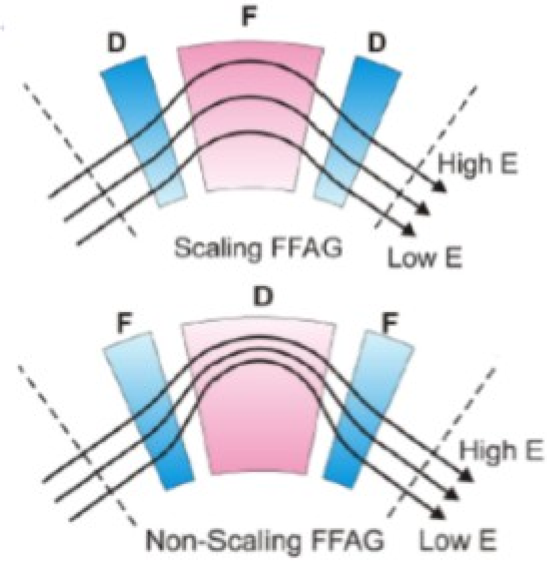


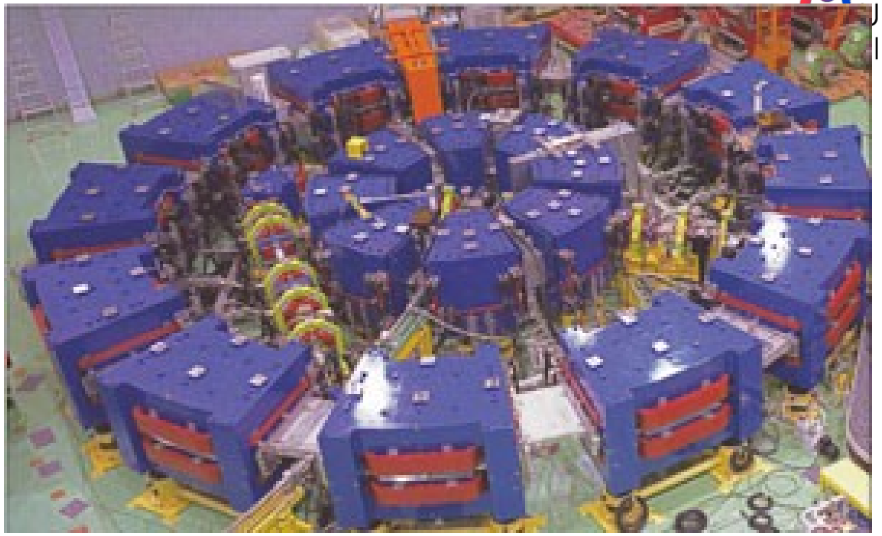
F. Batsch, Muon Collider workshop 2022

- For cost/efficiency, magnets must ramp on a resonant circuit
- Use sum of two harmonics to make a pseudo-linear ramp
- Synchronous phase of RF cavities adjusts to accelerate beam

Alternative - FFAs

$$\eta_\tau = \frac{N_\pm}{N_{0\pm}} = \prod_i \left(\frac{E_{i+1}}{E_i}\right)^{-1/\delta_{\tau,i}}$$





- Alternative to get fast acceleration – use Fixed Field Accelerators
  - Beam moves across aperture of combined function magnets
  - Sample stronger dipole fields at higher momenta
  - **Either:** move fast enough that optical resonances are not a problem
  - **Or:** add in sextupole+ to correct chromaticity
    - (There exists a “scaling FFA” field that perfectly corrects chromaticity)

The Facility – Collider

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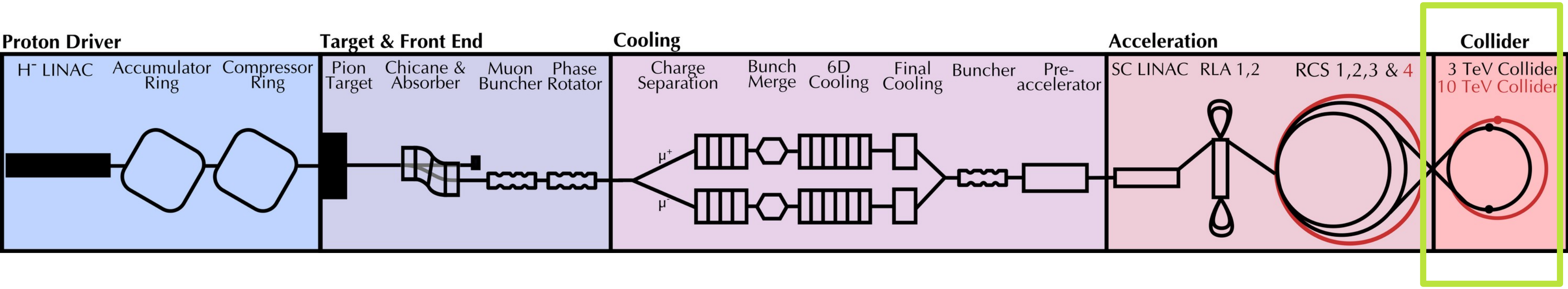
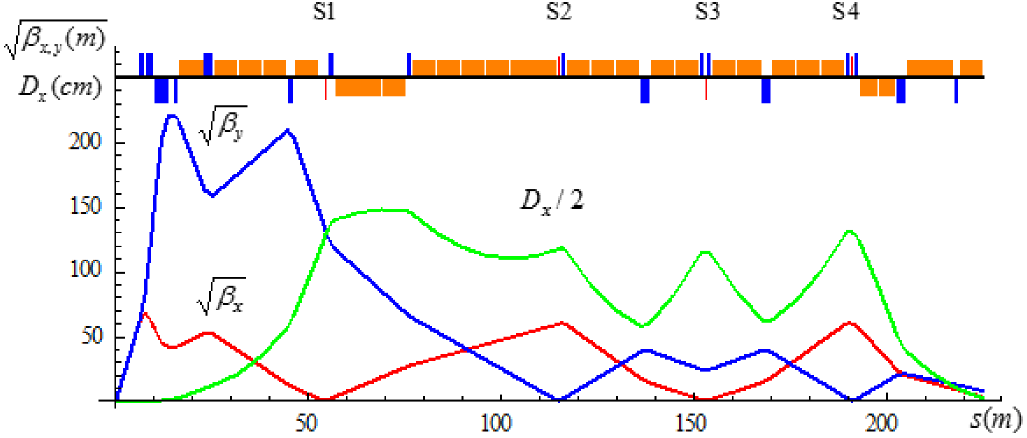


MC Accelerator/Collider Ring

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

- We’ve seen how to get very rapid acceleration
- Now look at the collider ring
  - High field → short ring → many collisions
  - Tight focusing at IP
  - Hourglass effect → Short bunch

Chromaticity Correction



$$\kappa = \frac{q}{p}\frac{dB}{dx}$$

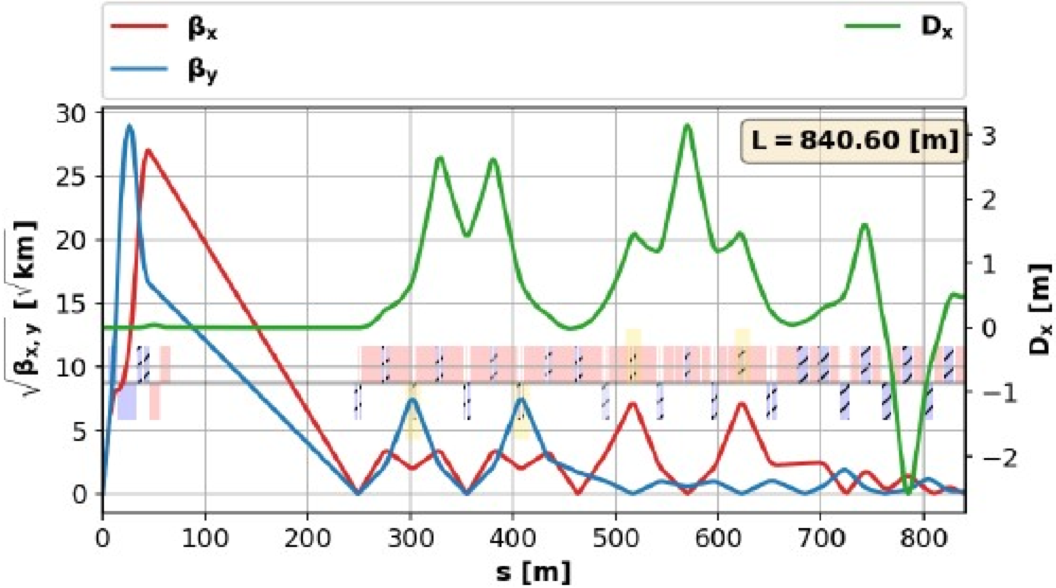
- Short bunch → large momentum spread ~ 1e-3
  - Off-momentum particles are not focused correctly
- Chromaticity correction
  - Sextupoles very close to interaction point
  - Sextupole focusing strength varies with transverse position
  - Introduce correlation between momentum and position
    - Dispersion
  - Correct the mis-focusing of the quadrupoles

Short bunch

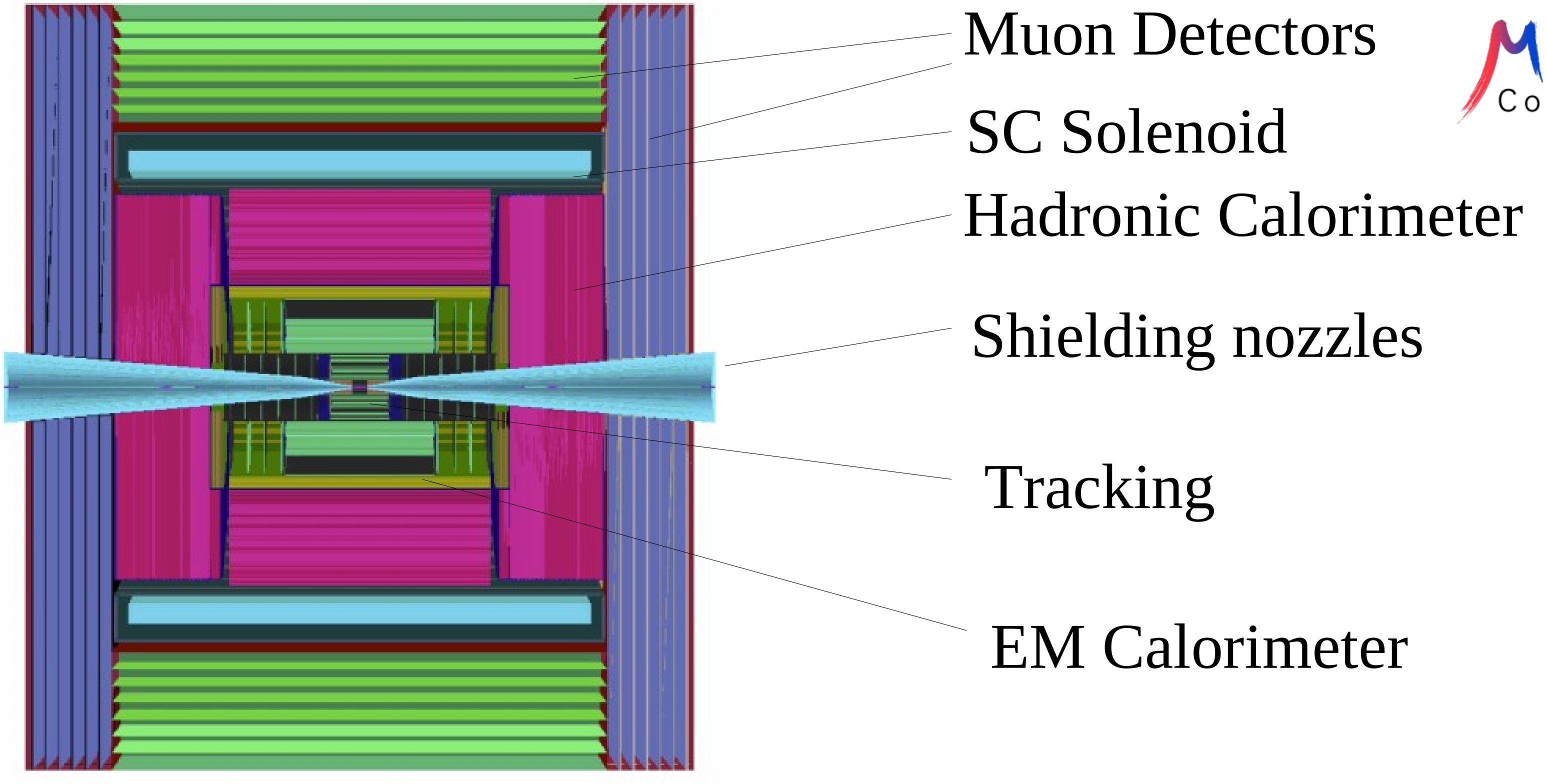
- Bunch length maintained by RF
- Driven by Momentum Compaction Factor
  - Path length (time-of-flight) variation with energy

$$\alpha_p = \frac{\mathrm{d}L/L}{\mathrm{d}p/p} = \frac{p}{L}\frac{\mathrm{d}L}{\mathrm{d}p} = \frac{1}{L}\oint \frac{D_x(s)}{\rho(s)}\mathrm{d}s.$$

- Introduce section of ring having tunable dispersion to enable control of α_p

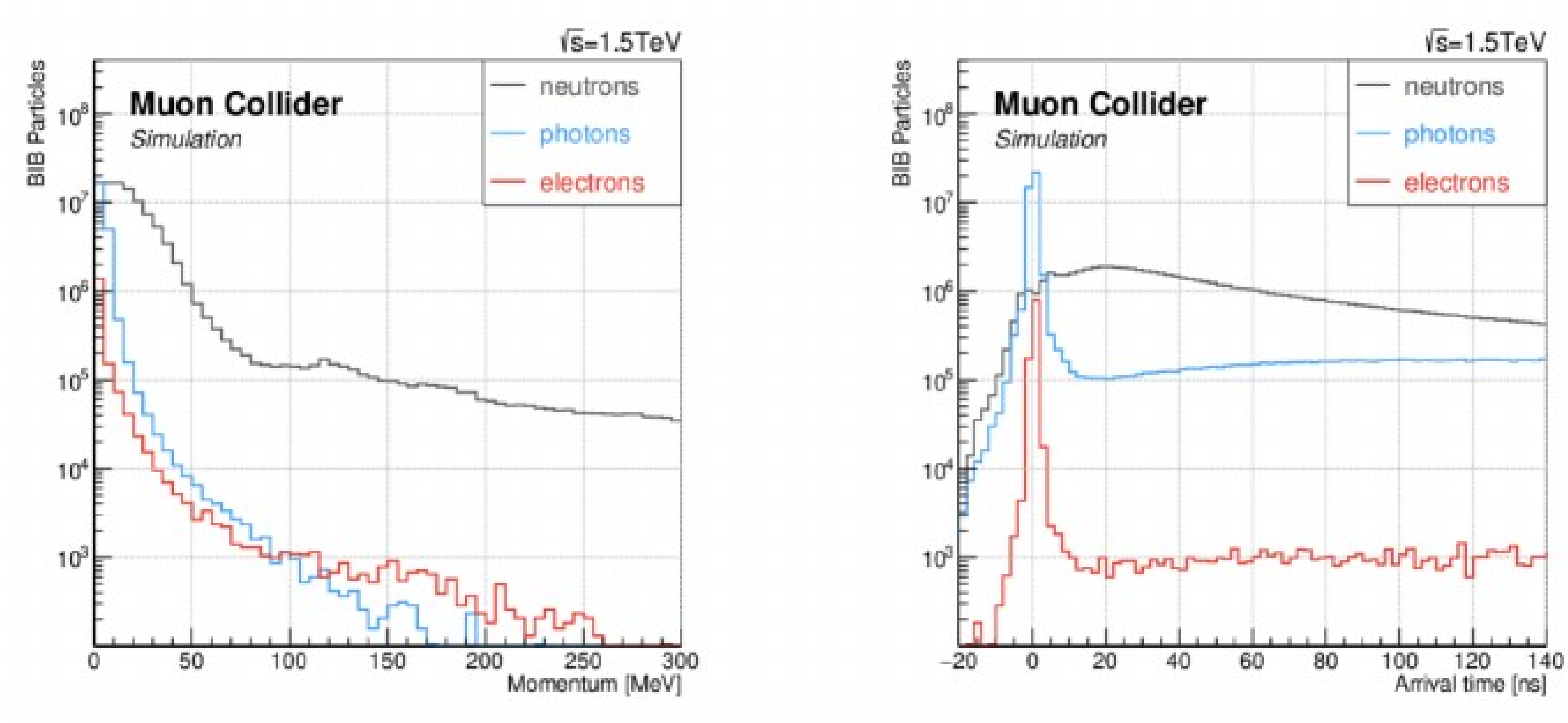


Muon Collider Detector



- Muon collider
  - Rather standard detector arrangement
  - Based on e^+e^- detector
  - Shielding masks is crucial component to block decay products

BIB Characteristics

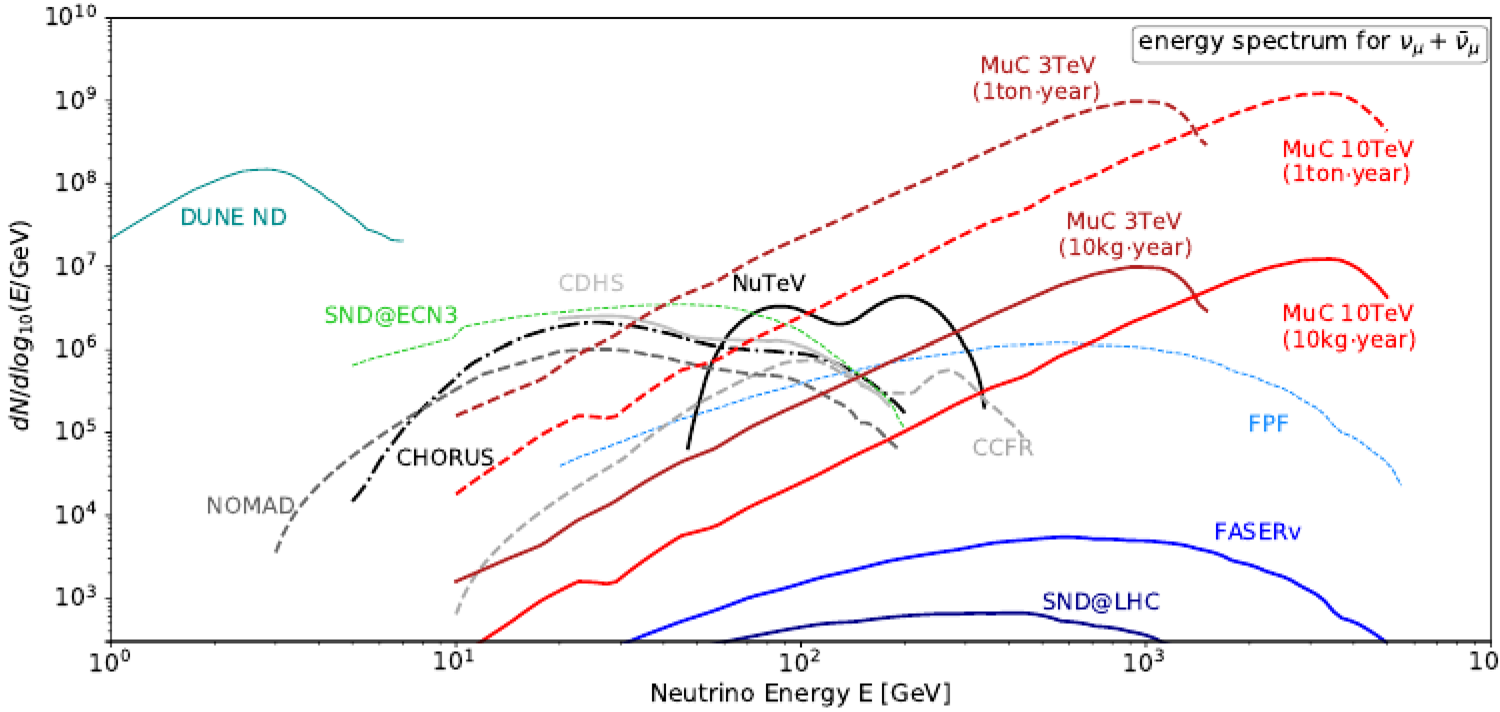


- Beam induced background (BIB) arising due to muon decays

Neutrino beams – blessing and curse

- Muon decays yield high intensity neutrino beams
  - Neutrino beam from IP straight O(1) metre across
    - Significant fraction of the muons in the collider ring decay here
  - Can be used for experiments
  - Create very weak neutron shower where they emerge
  - Must stay below off-site limits for neutron flux over 1 year average
  - Must apply ALARP (As Low As Reasonably Possible) principle
- Either (likely all 3)
  - Periodically move beam elements
  - Add small deviations to the beam in the beam pipe
  - Use land near surface for neutrino experiments
- Expect to be able to mitigate to negligible level
  - i.e. consistent with existing facilities

Neutrino beams



- Huge neutrino flux many orders of magnitude greater than other experiments

The Muon Collider – Hardware R&D

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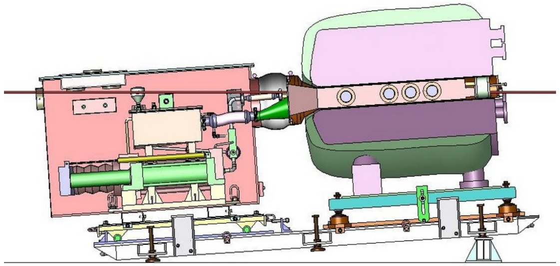
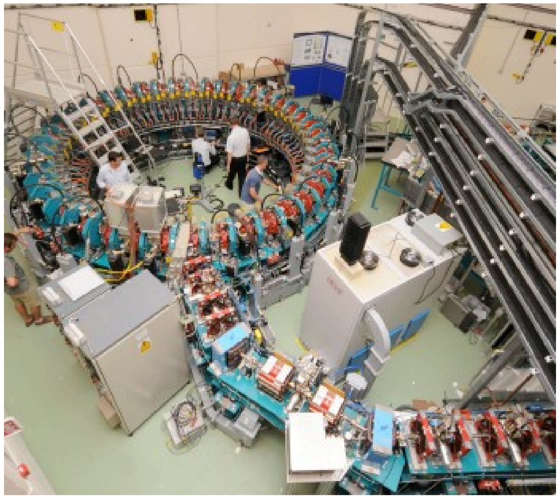
Muon Accelerator R&D

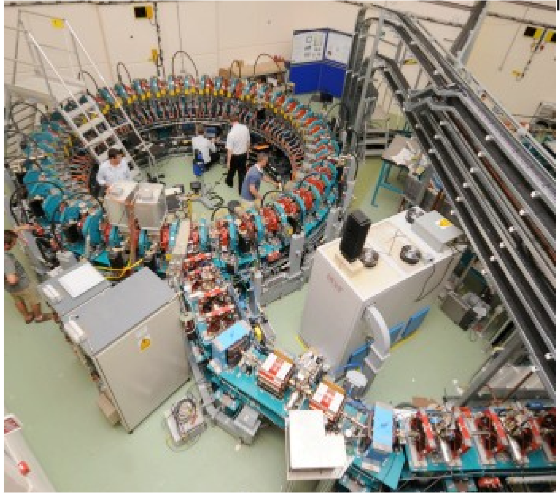
- MERIT
  - Demonstrated principles of muon accelerator proton targetry/pion production
- EMMA
  - Demonstrated fast acceleration in FFAGs
- CBETA
  - Demonstrated RLAs using FFA arcs
- MUCOOL
  - Cavity R&D for ionisation cooling
  - Demonstrated operation of cavities at high voltage in magnetic field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

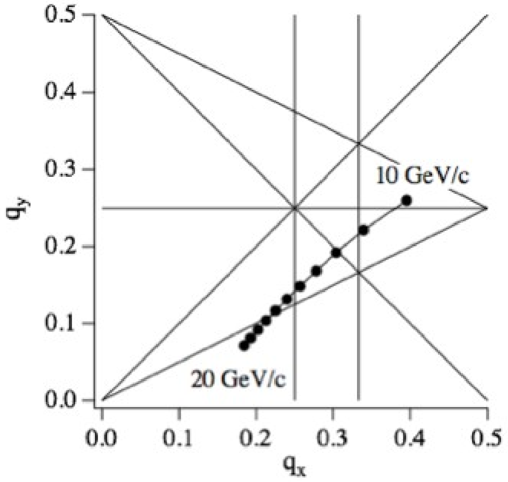




EMMA

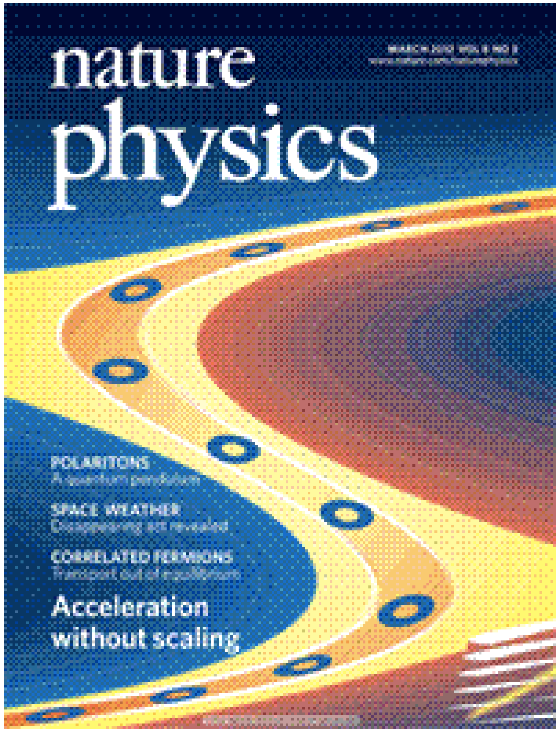
- EMMA demonstrated rapid acceleration of electrons at ~ MeV energy
  - Prove “non-scaling” FFA principle
  - Scales to muons at ~ GeV scale
- Non-scaling FFA
  - Accelerate rapidly through resonances
  - Normally the beam would be destroyed
  - If resonance is weak and acceleration fast beam can survive
- Need a beam test to be convinced
  - Electron model





EMMA

- Beam moves across aperture during acceleration
- Tune reduces
  - Crossing resonances
- Beam size stays ~ same
- Non-scaling FFA principle works



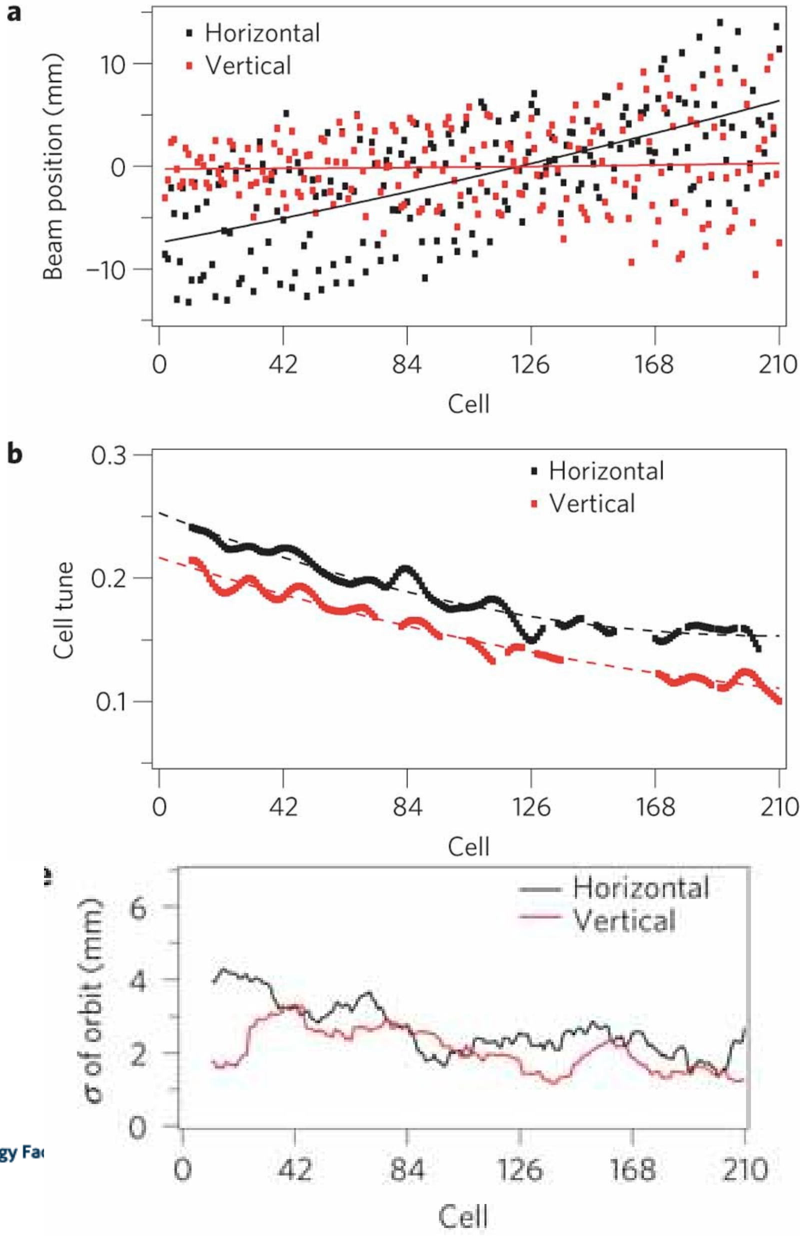
nature physics

POLARITONS
A quantum pendulum

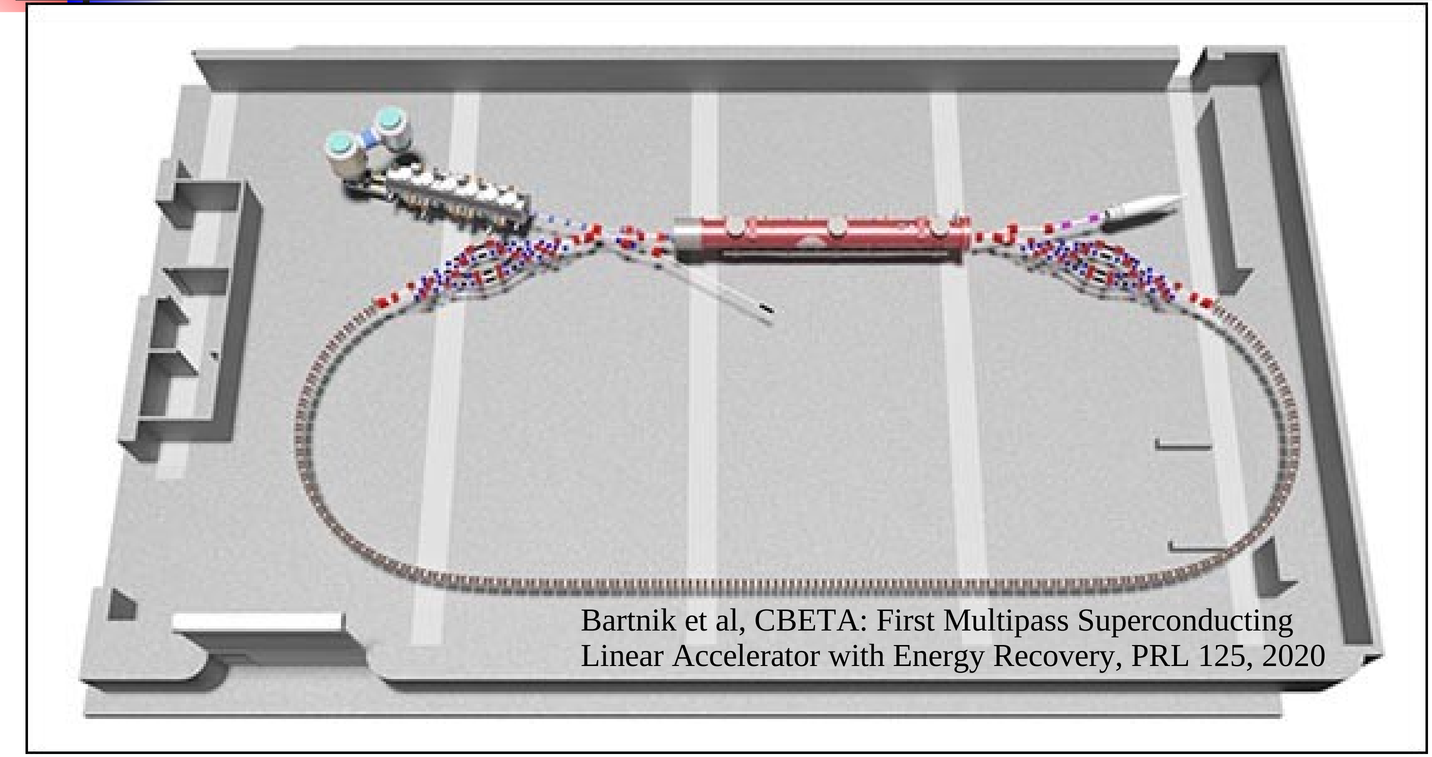
SPACE WEATHER
Disappearing act revealed

CORRELATED FERMIONS
Transport out of equilibrium

Acceleration without scaling



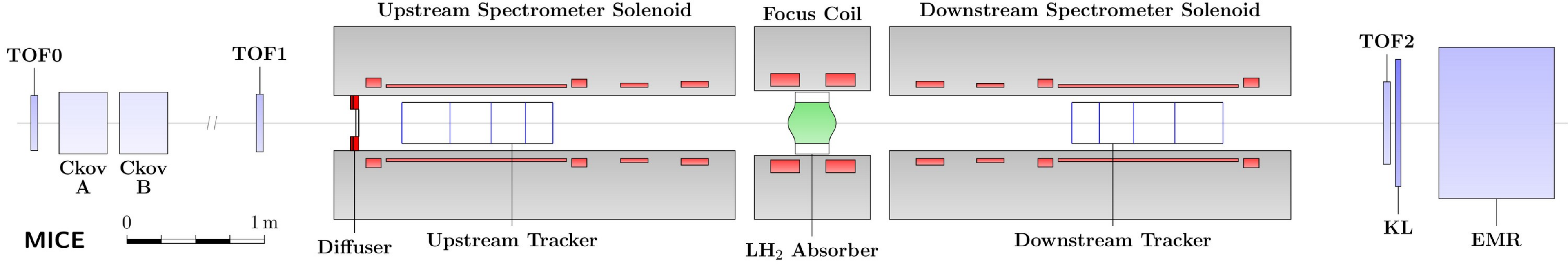
CBETA

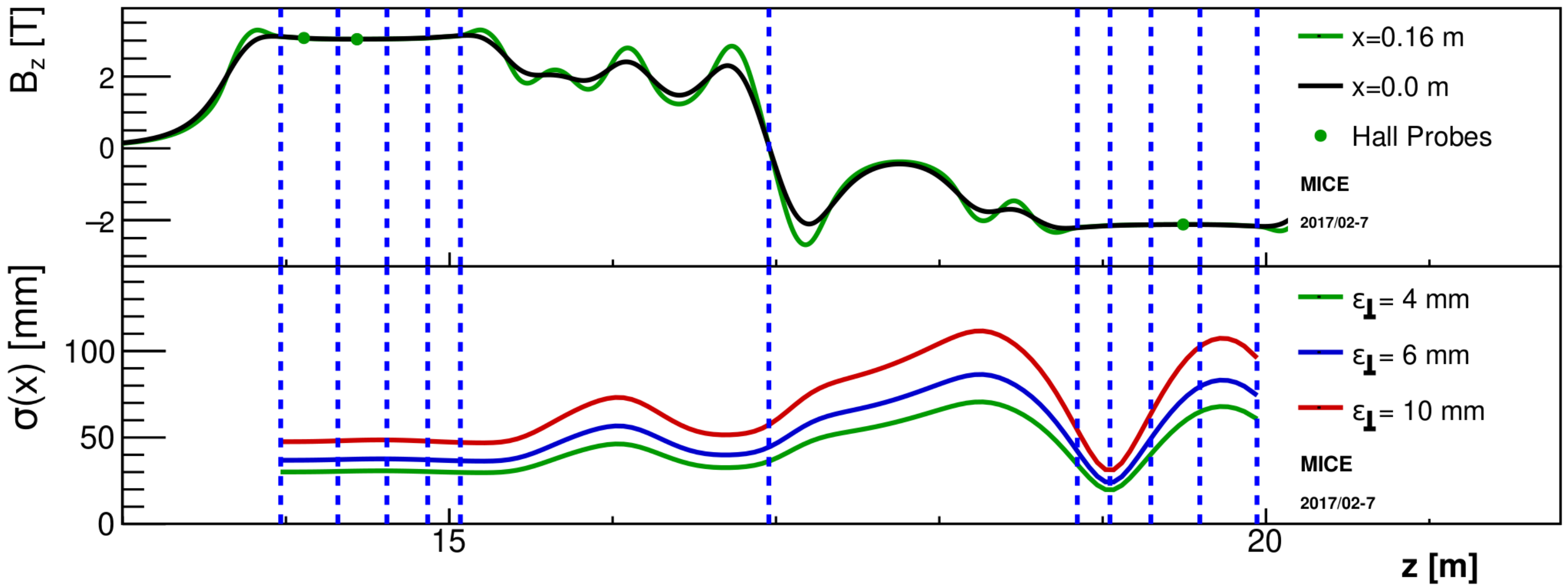


Bartnik et al, CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery, PRL 125, 2020

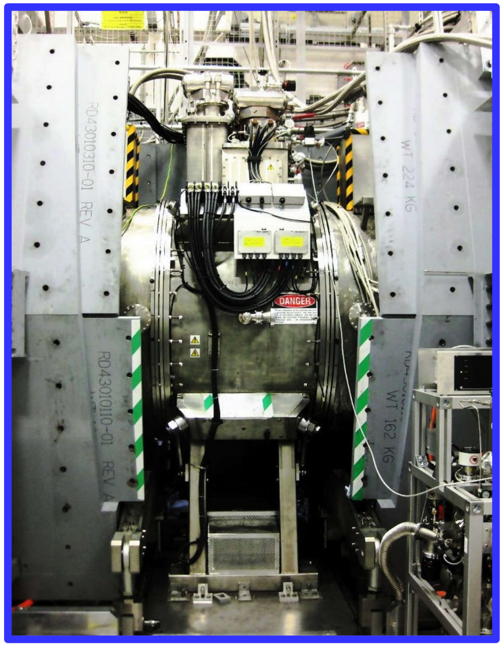
- Energy Recovery Linac that used single FFA arc – 5 turns:
  - Beam goes through linac
  - Time delay line
  - FFA arc – same ring for all different energies
  - Back into RF
- Beam is subsequently decelerated in a further 5 turns

Muon Ionisation Cooling Experiment (MICE)



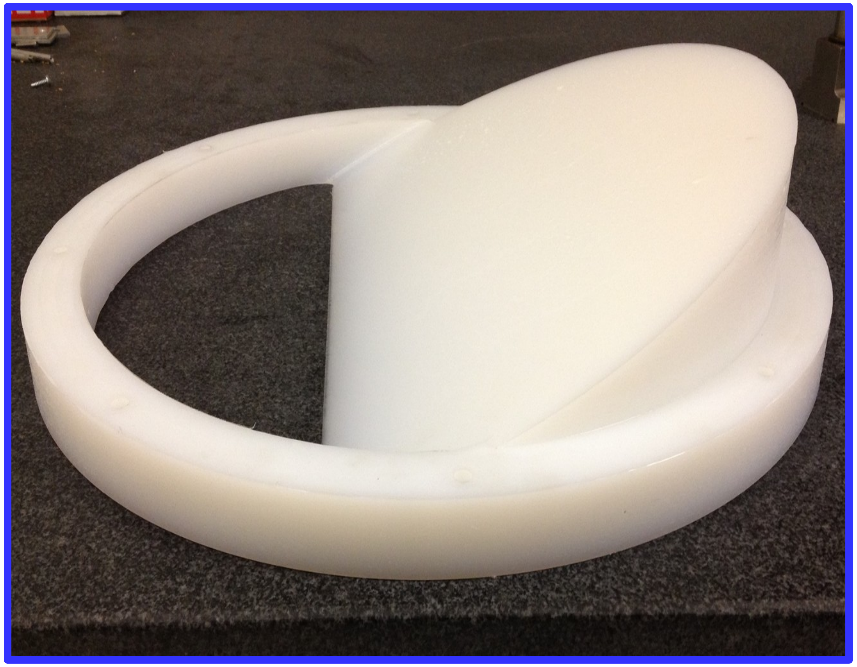


Superconducting Magnets



- 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

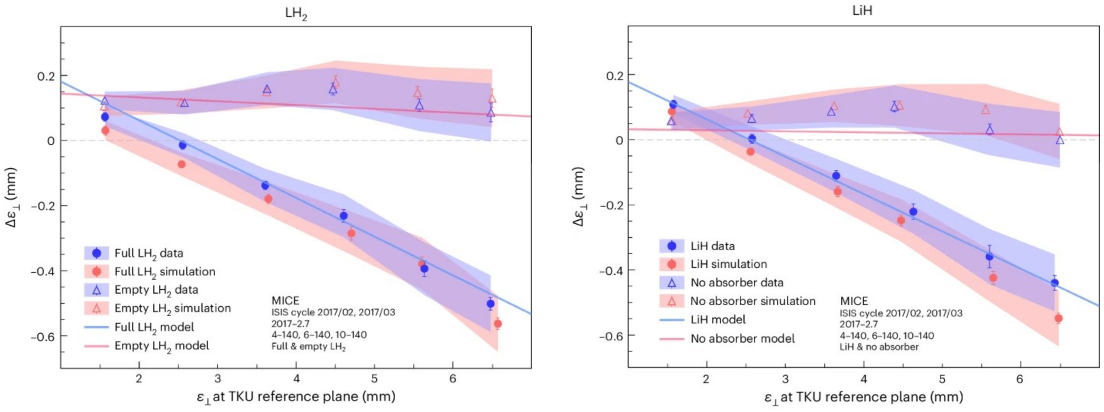
Absorber

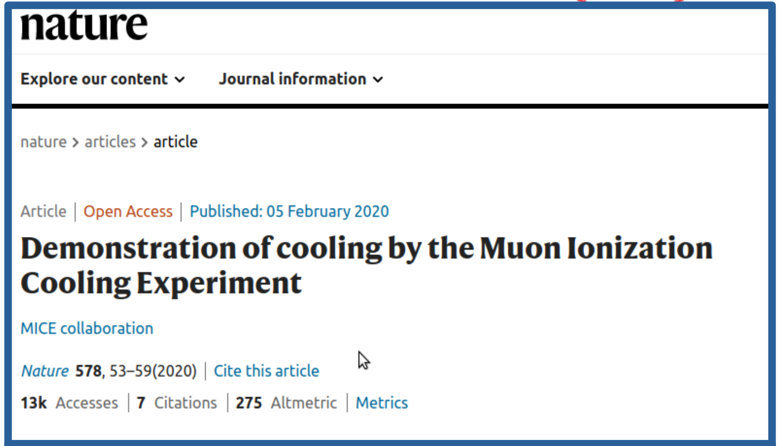


- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45^{o} polythene wedge absorber for longitudinal emittance studies

MICE

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





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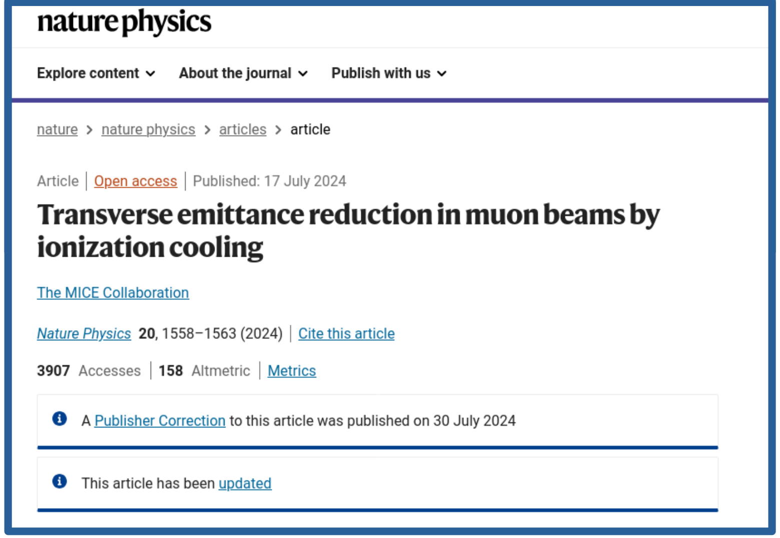
Article | Open Access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

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

13k Accesses | **7** Citations | **275** Altmetric | Metrics



nature › nature physics › articles › article

Article | Open access | Published: 17 July 2024

Transverse emittance reduction in muon beams by ionization cooling

The MICE Collaboration

Nature Physics **20**, 1558–1563 (2024) | Cite this article

3907 Accesses | **158** Altmetric | Metrics

A Publisher Correction to this article was published on 30 July 2024

This article has been updated

The Muon Collider – Future R&D

International
MUON Collider
Collaboration

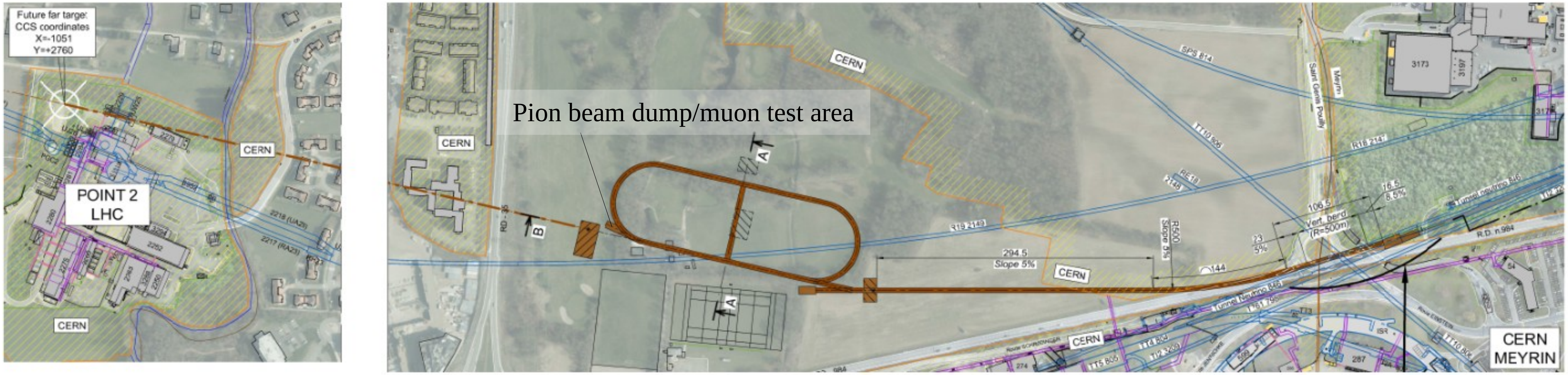
C. T. Rogers
Rutherford Appleton Laboratory

Science & Technology Facilities Council
ISIS

Making the Muon Collider Real

- Proton and electron accelerators have a century of operations
- How can we make a muon collider real?
  - Prototyping of key technology
  - Physics facilities using key technology
  - Staging

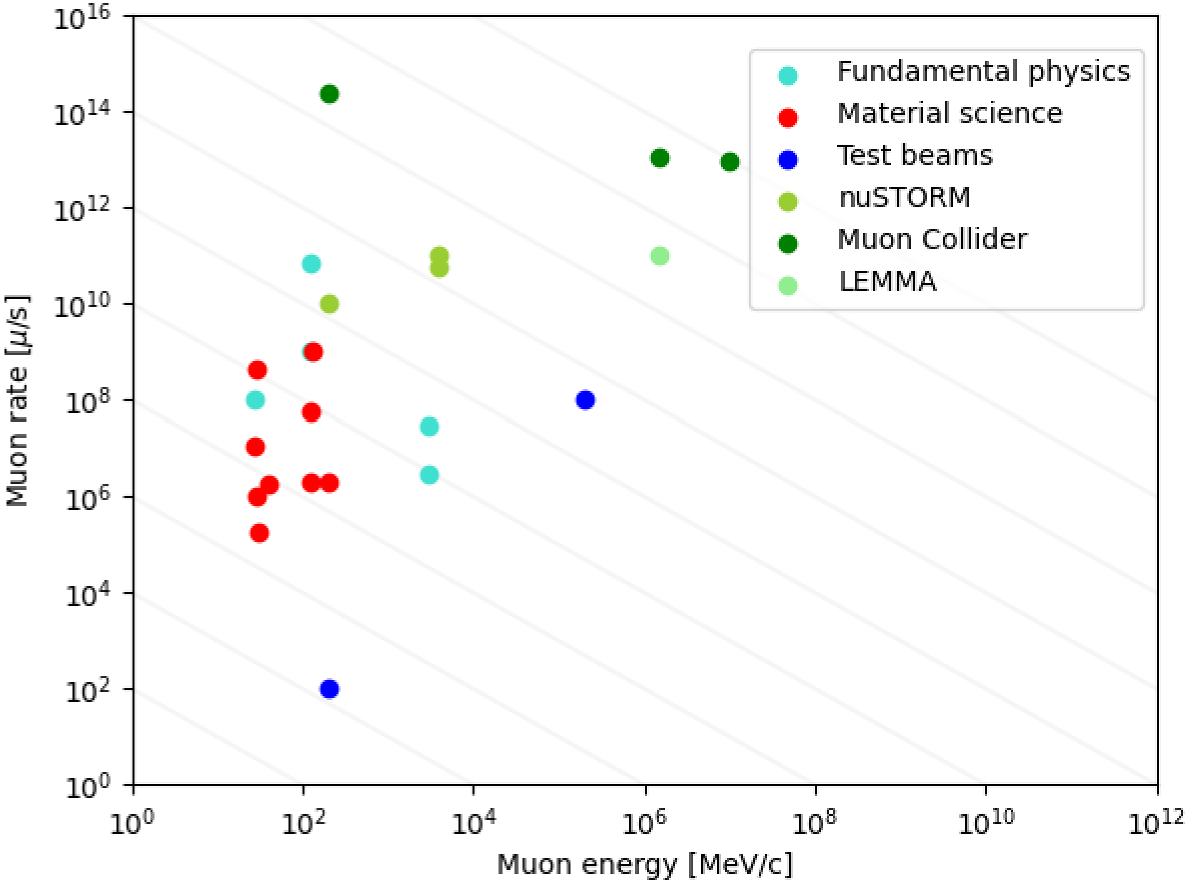
nuSTORM



nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

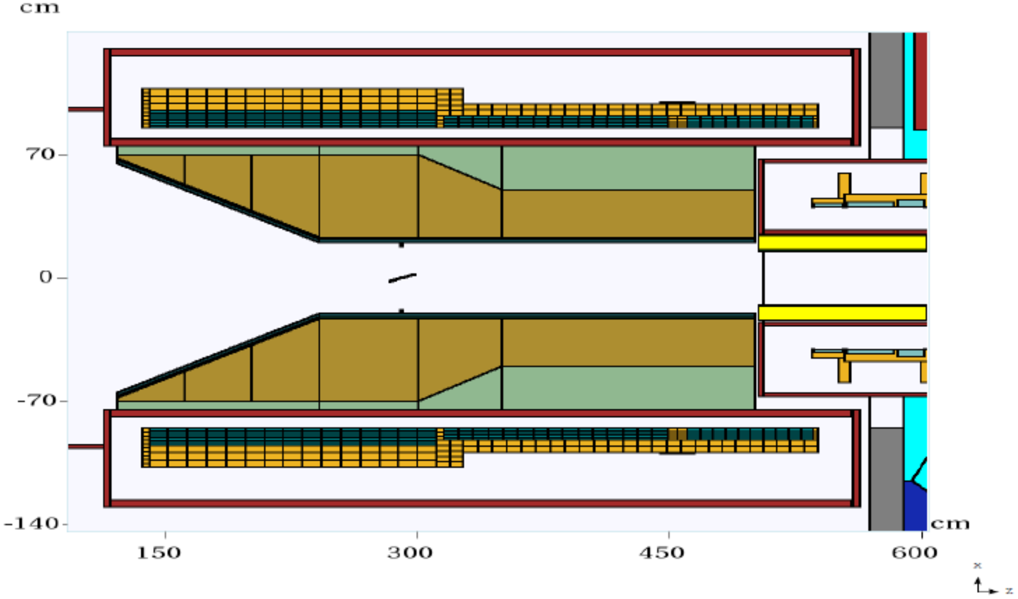
- Neutrinos from stored muons
  - Create ~ GeV pions using conventional pion target
  - Bring the pions to a storage ring
  - Pions decay to muons which are in momentum acceptance of ring
    - Pions are lost
    - Muons are stored
  - Decay to neutrinos

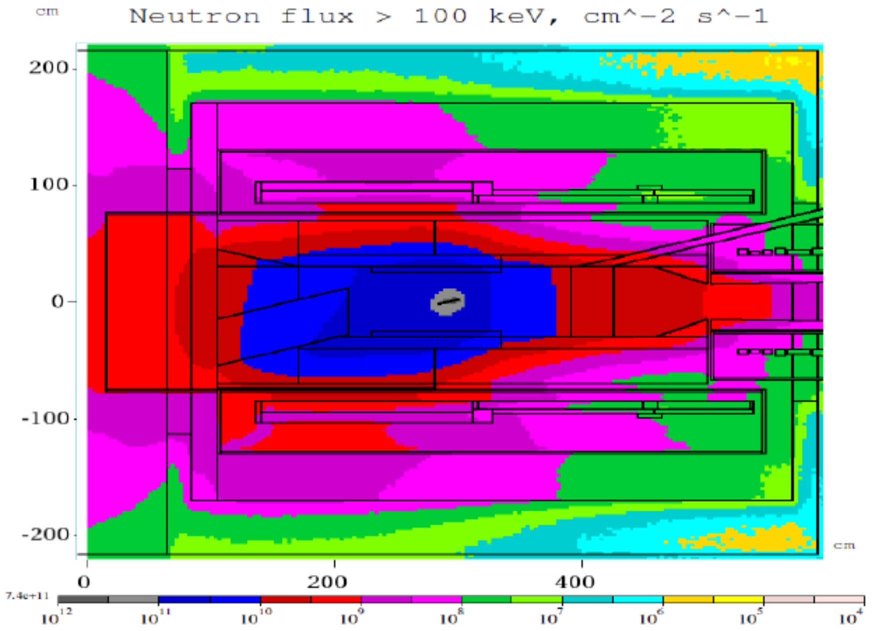
Survey of Muon Beamlines



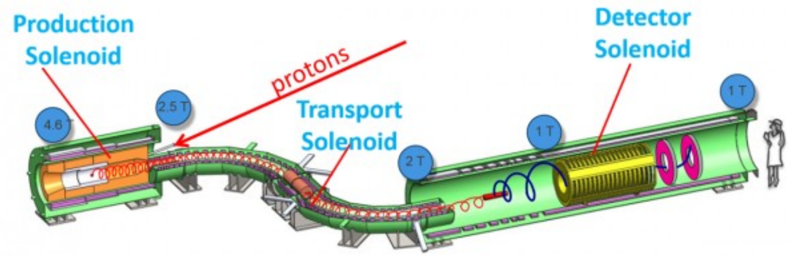
Mu2e

V. Pashikin, Mu2e collaboration

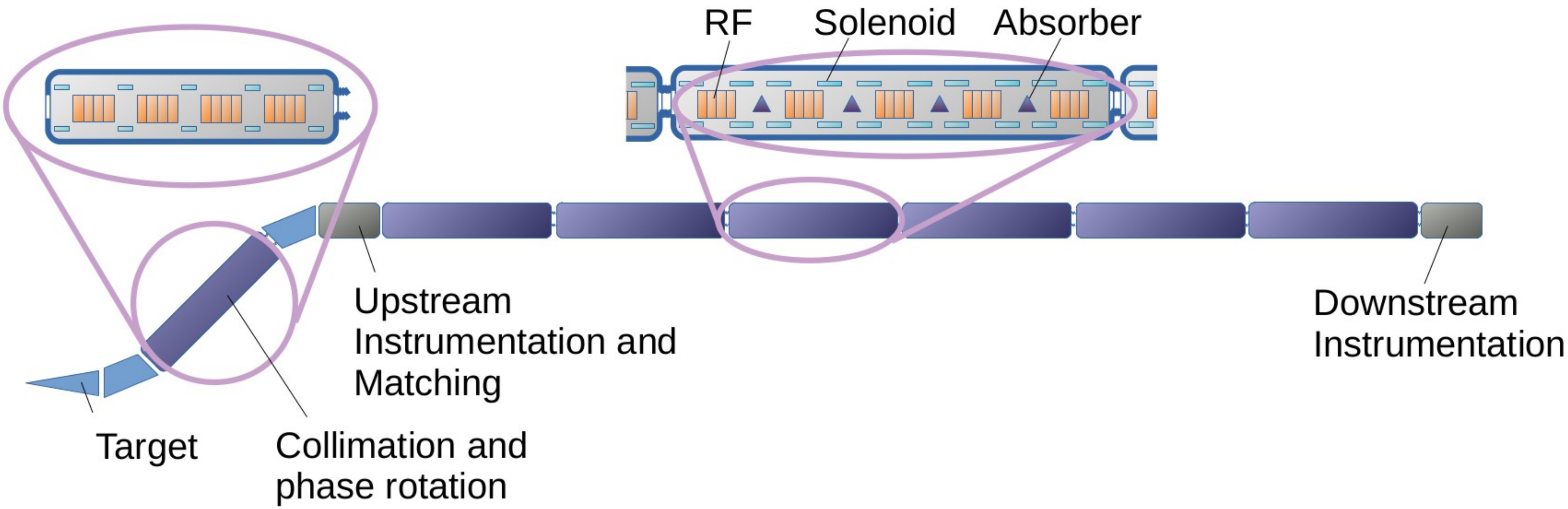



Neutron flux > 100 keV, cm^-2 s^-1

- Mu2e → search for rare muon decay
- Use muons produced by pions on target in solenoid field
  - ~10s kW
  - ~few T
  - Scaled down version of MuC target

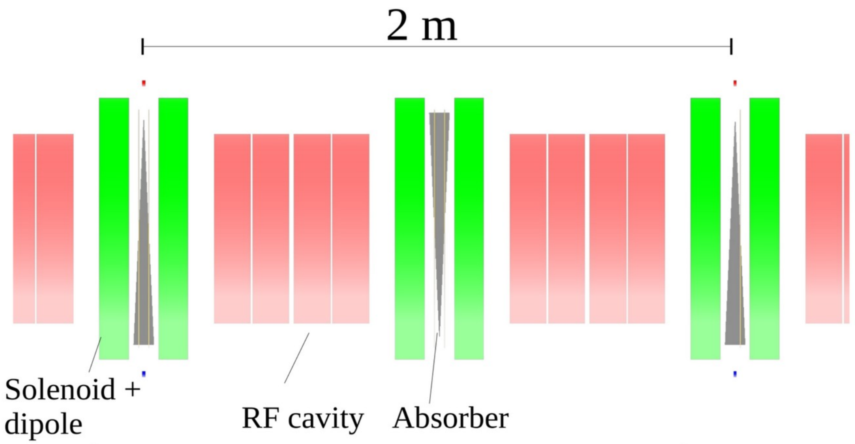


Cooling Demonstrator



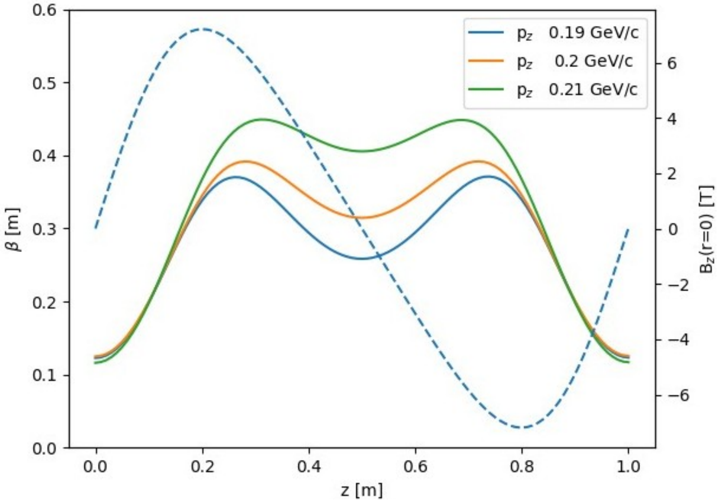
- Build on MICE
  - Longitudinal and transverse cooling
  - Re-acceleration
  - Chaining together multiple cells
  - Routine operation

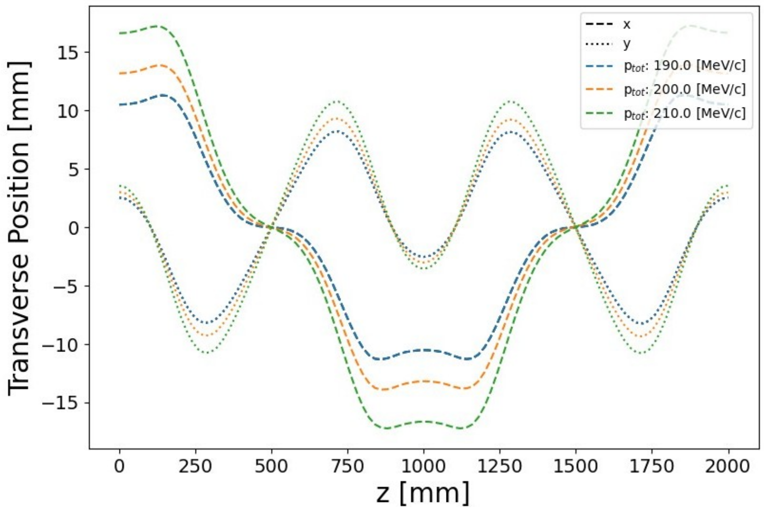
Cooling Demonstrator



Cooling System

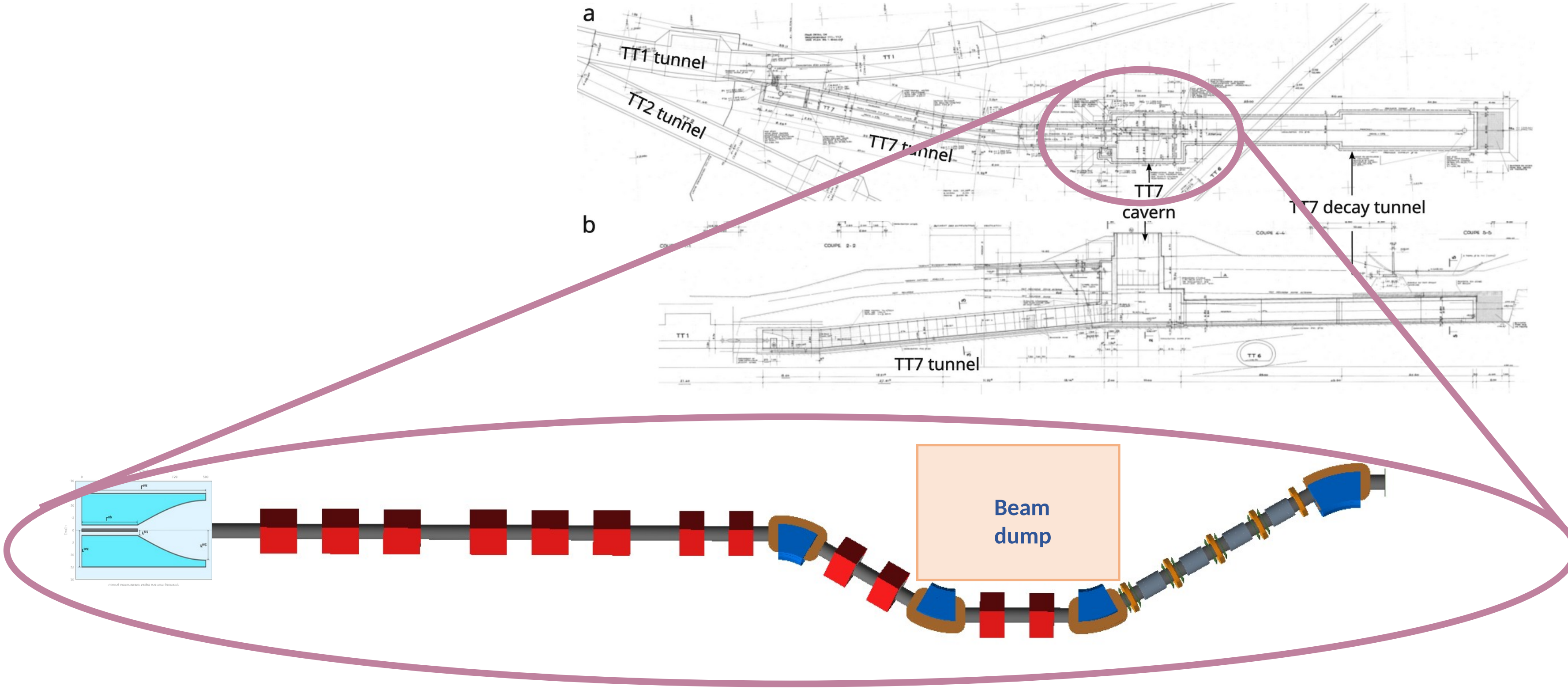
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH





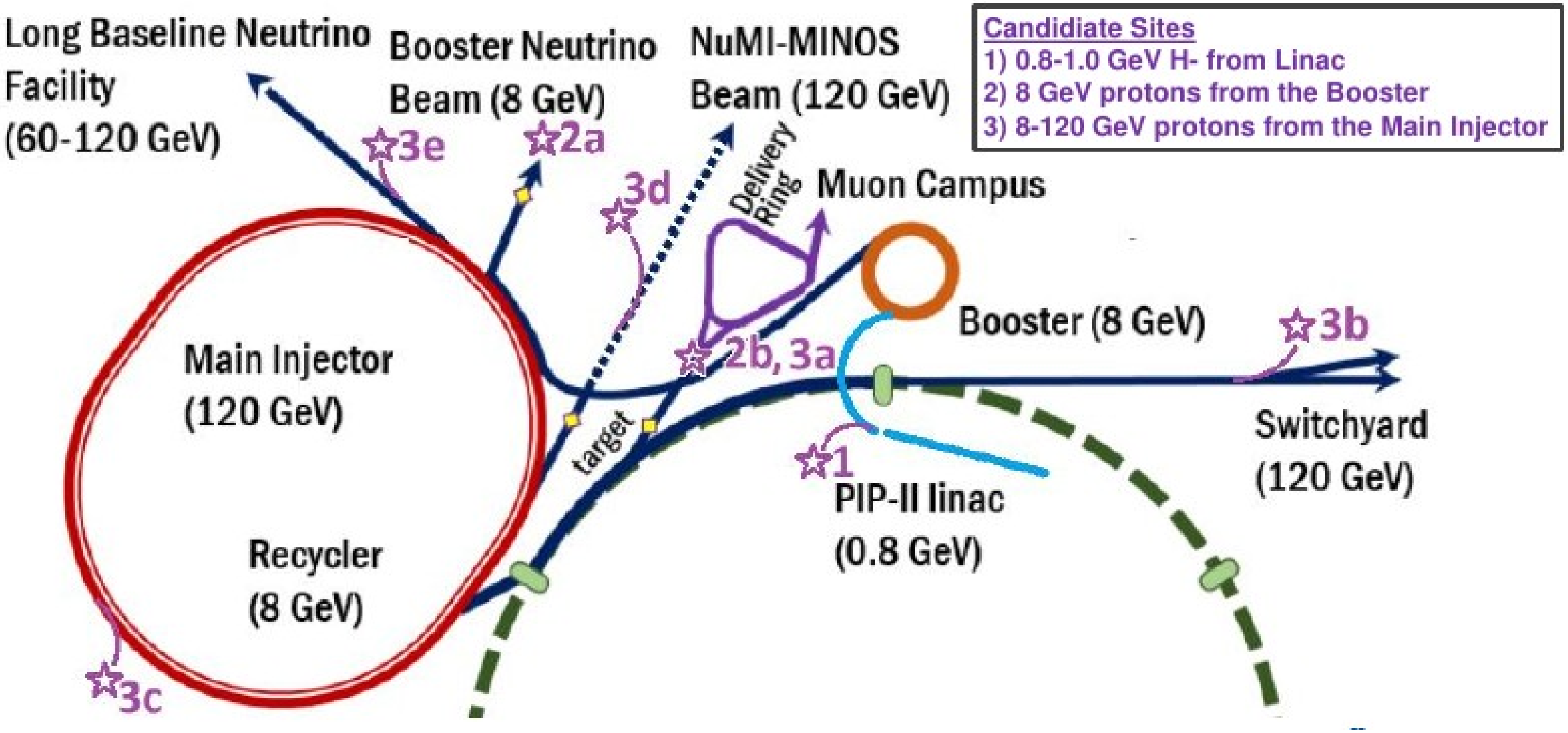
Cooling Demonstrator

- Potential CERN implementation



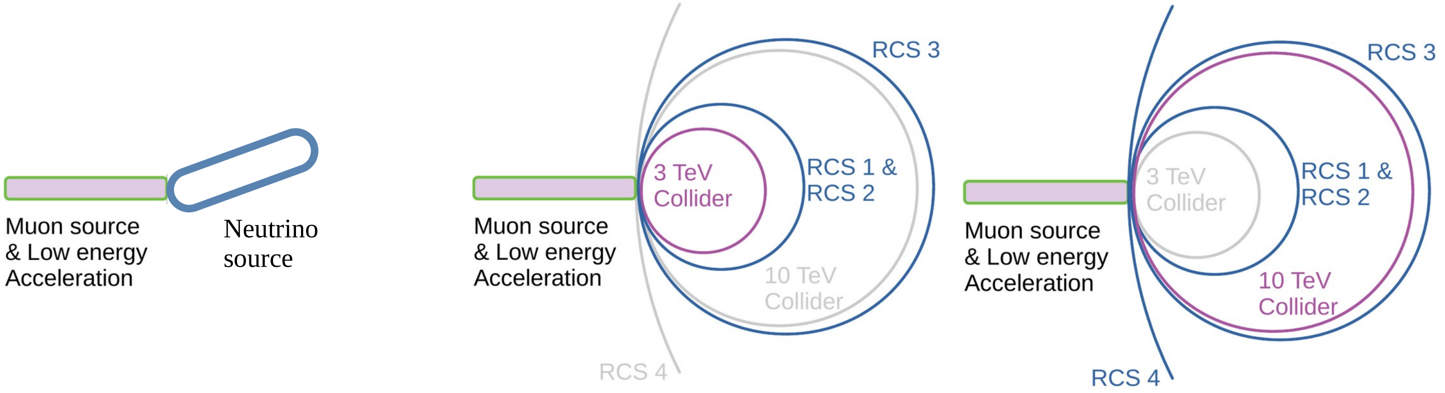
Cooling Demonstrator

- Potential Fermilab implementation



Candidiate Sites
1) 0.8-1.0 GeV H- from Linac
2) 8 GeV protons from the Booster
3) 8-120 GeV protons from the Main Injector

Staging



- Introduce a staged approach to MuC
  - Prototypes **(Present day)**
  - Neutrino sources
  - Muon-based Higgs factory
  - 3 TeV muon collider
  - 10 TeV muon collider
- Each stage within reasonable budget, on reasonable time scale

Summary

International
MUON Collider
Collaboration

C. T. Rogers
Rutherford Appleton Laboratory

Science & Technology Facilities Council
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Summary

- We’ve looked at the major components of the muon collider
  - Proton driver
  - Muon production and capture
  - Ionisation cooling
  - Acceleration
  - Collision
- We’ve looked at the steps that have been made, and continue to be brought to bear, to make it happen
  - Technology demonstrators
  - Physics facilities

Final Word

International
MUON Collider
Collaboration

- The muon collider has the potential to explore physics reach at the highest energies
  - Fraction of the footprint of comparable facilities
  - Expectation of much lower power requirements
  - Advance particle physics by ~ decades
- Many technical challenges
  - All are manageable with current or near-to-current technologies
- This is **your** accelerator
  - The technology is for you to invent
  - The technology is for you to demonstrate
  - Muon collider will be a defining technology for **your** generation

The muons are calling
And we must go

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Further Information

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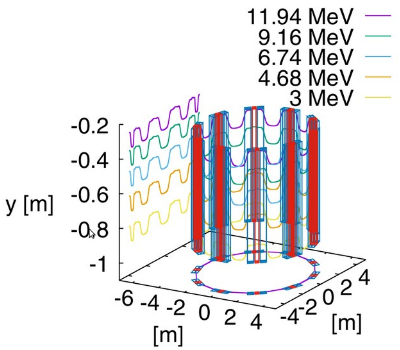
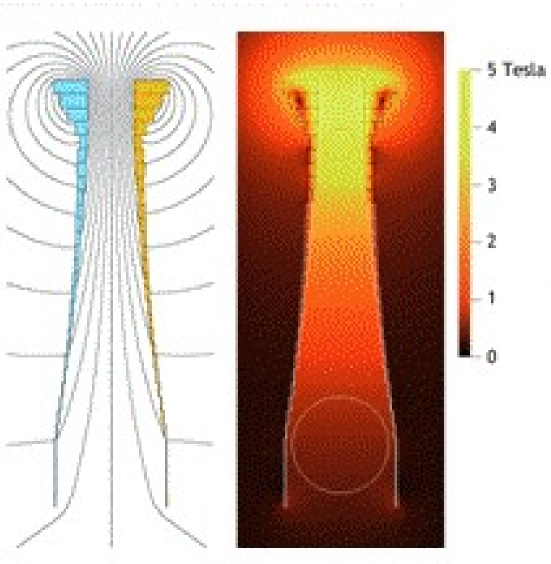
MC Accelerator/Collider Ring



Beam goes up During Acceleration



- FFA concept
  - Fixed field accelerator using vertical orbit excursion
    - Constant path length at different energy
    - “Relativistic cyclotron”
  - Enables fixed frequency acceleration
  - Removes the limit on minimum bunch length
  - No need to ramp magnets
  - Challenge: Wide aperture RF cavities