Challenges for the Muon Collider

International MUON Collider Collaboration

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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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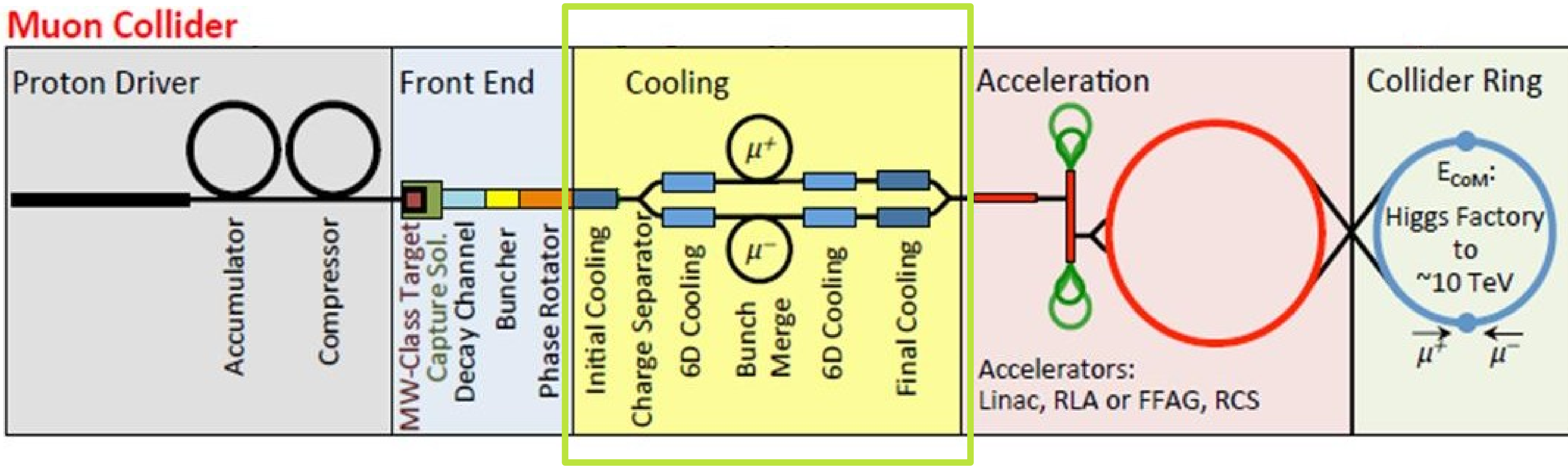

How to realise cooling?

- 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

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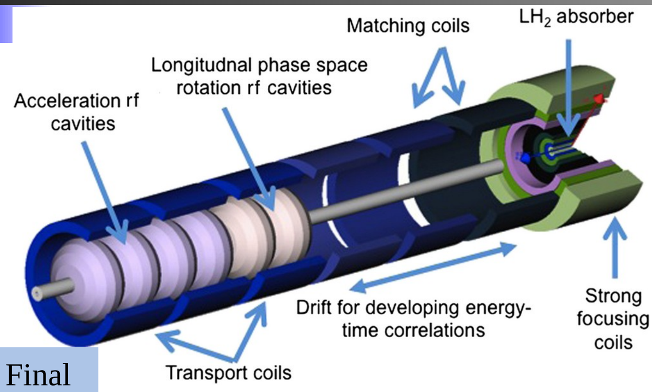
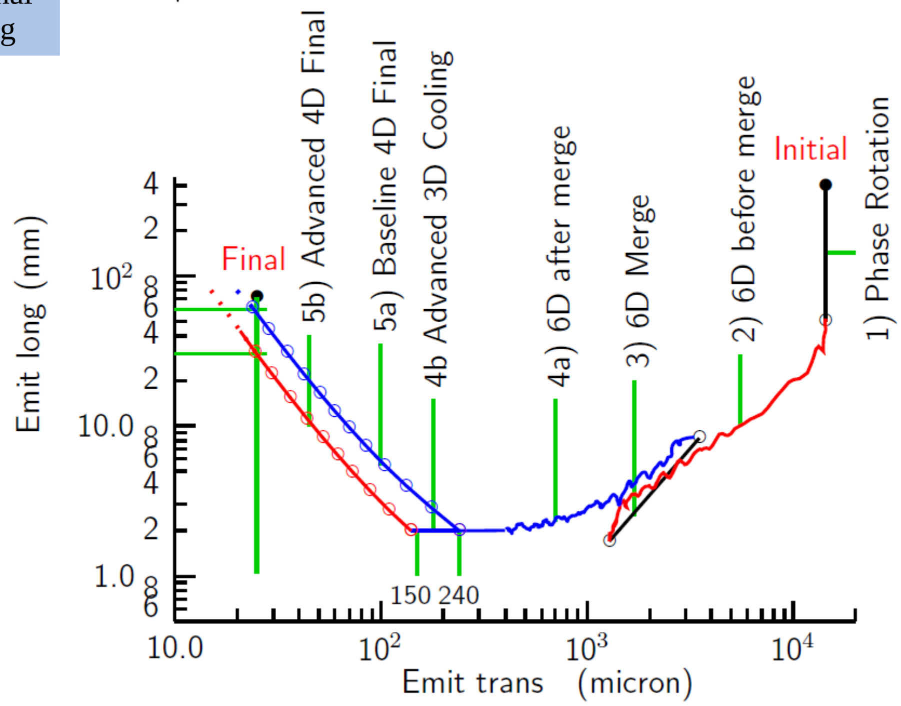
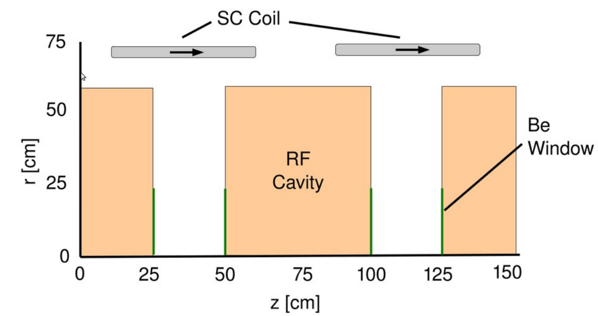


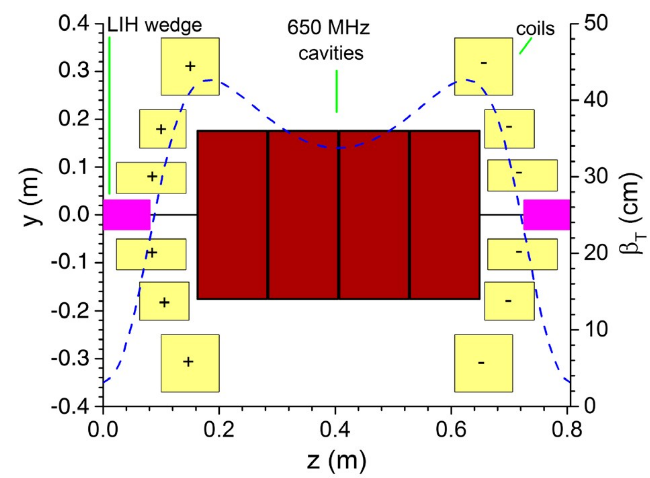
4D Final cooling



Phase rotation



6D cooling



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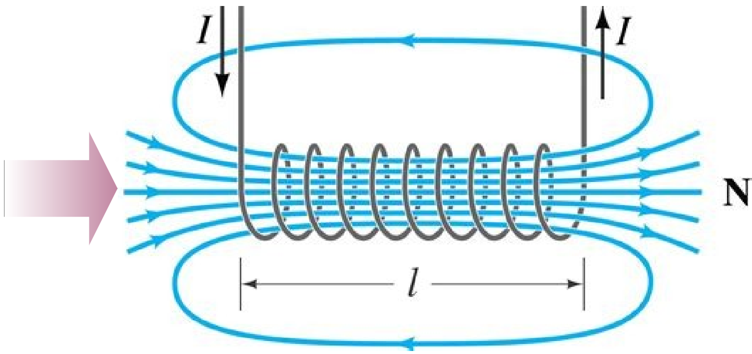
Solenoid optics

- 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

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

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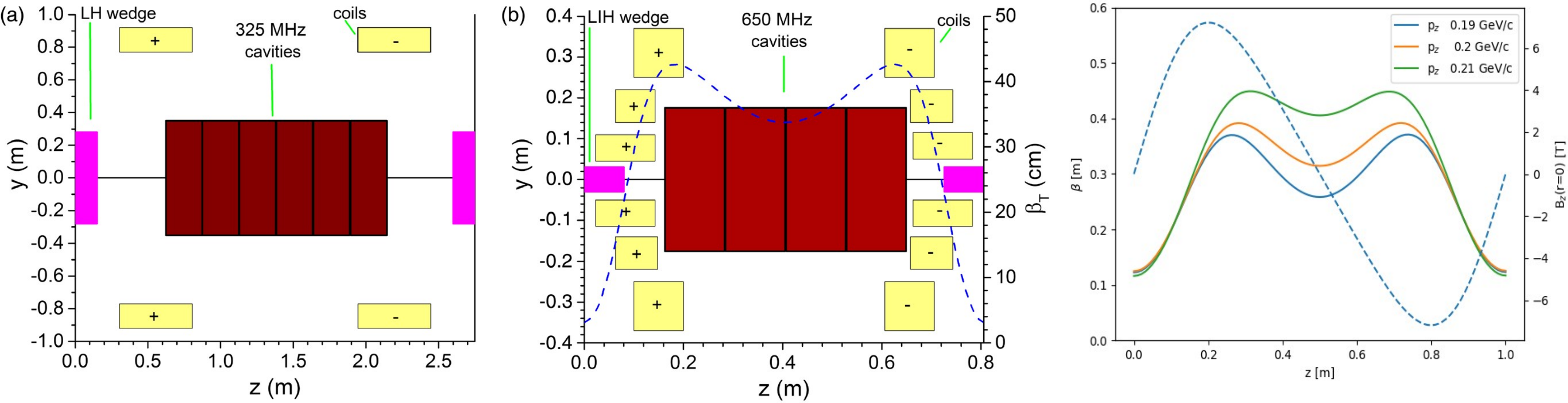
Rectilinear Cooling

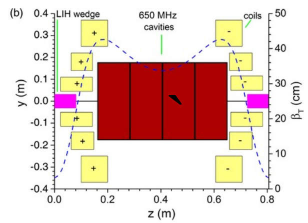


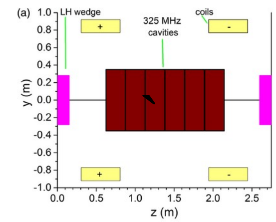
D. Stratakis and R. Palmer, Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study, Phys. Rev. ST Accel. Beams 18, 2015

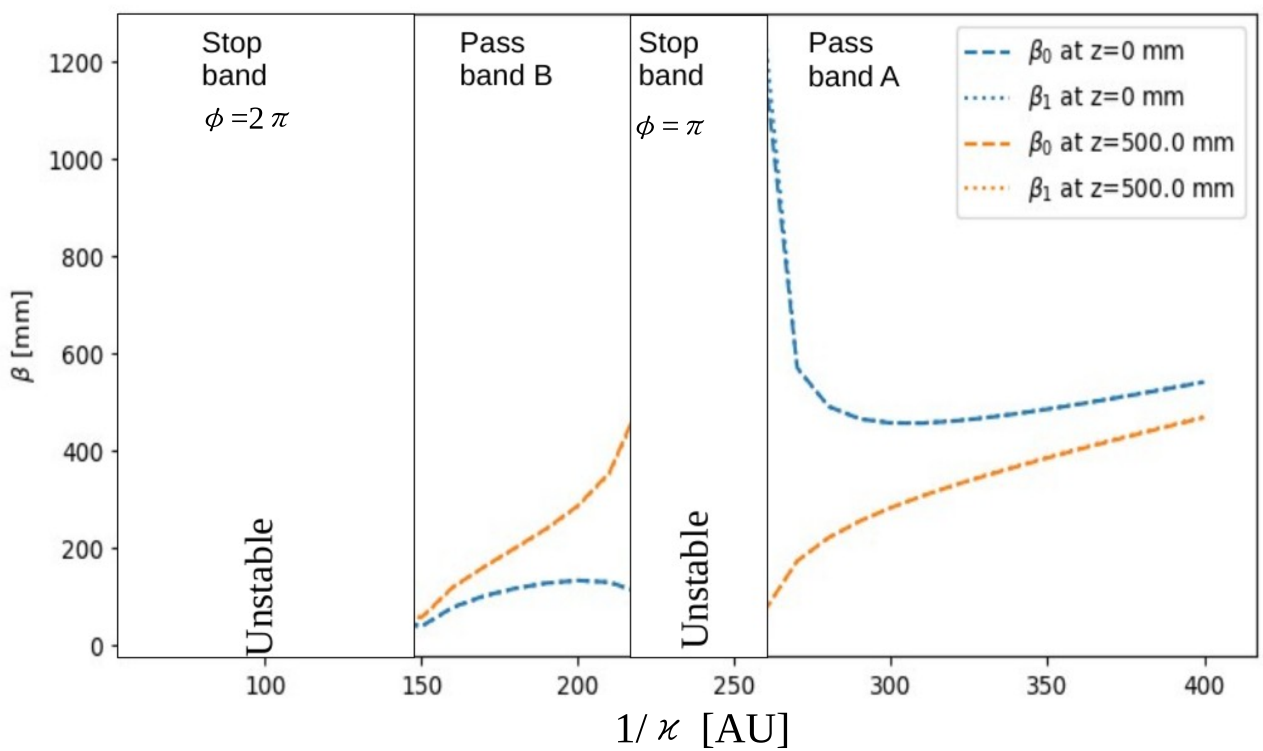
- 6D Cooling
  - Combined function dipole-solenoid magnets
    - Weak dipole field is a perturbation
    - Focus at the asborber with alternating solenoid polarity
  - Compact lattice – RF integrated into magnet cryostat
  - Lithium Hydride or lH2 absorbers
  - Careful field shaping to control position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

Pass bands

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







Rectilinear cooling performance

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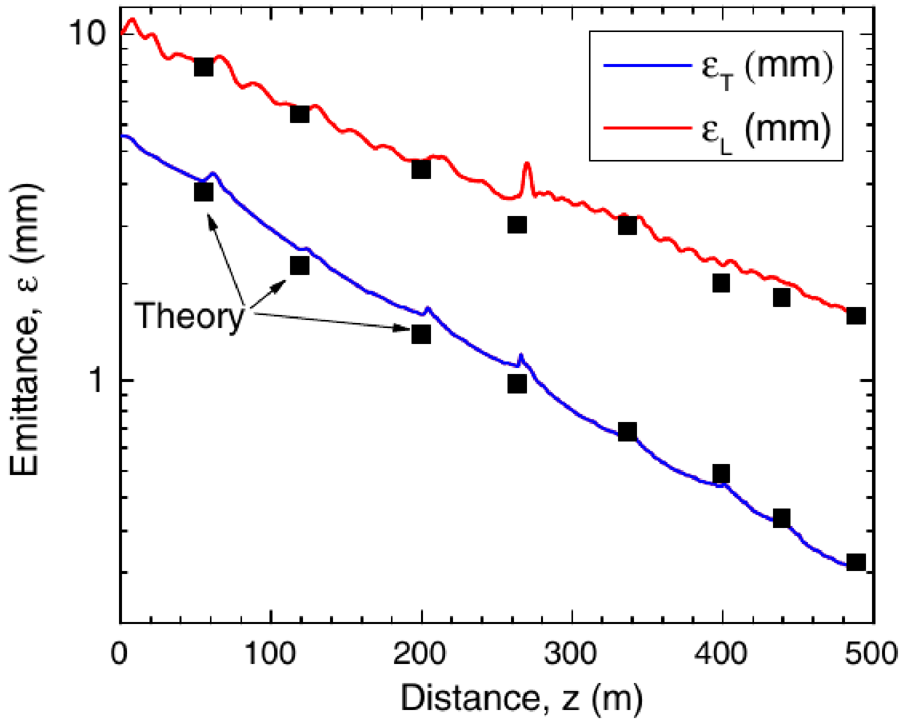
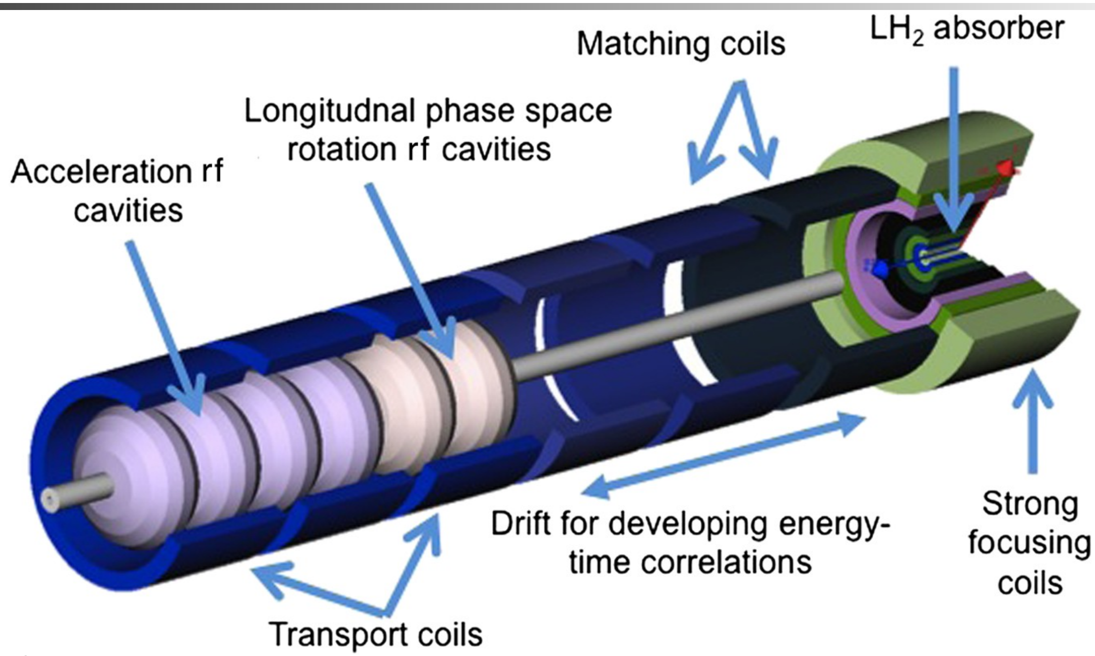


- As the beam nears equilibrium emittance cooling slows
- New lattice, shorter and stronger fields
  - Smaller DA
  - More focusing
- Repeat until the limit on magnet is reached ($\beta \sim$ few cm)
  - Hoop stress

Final cooling



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

- 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

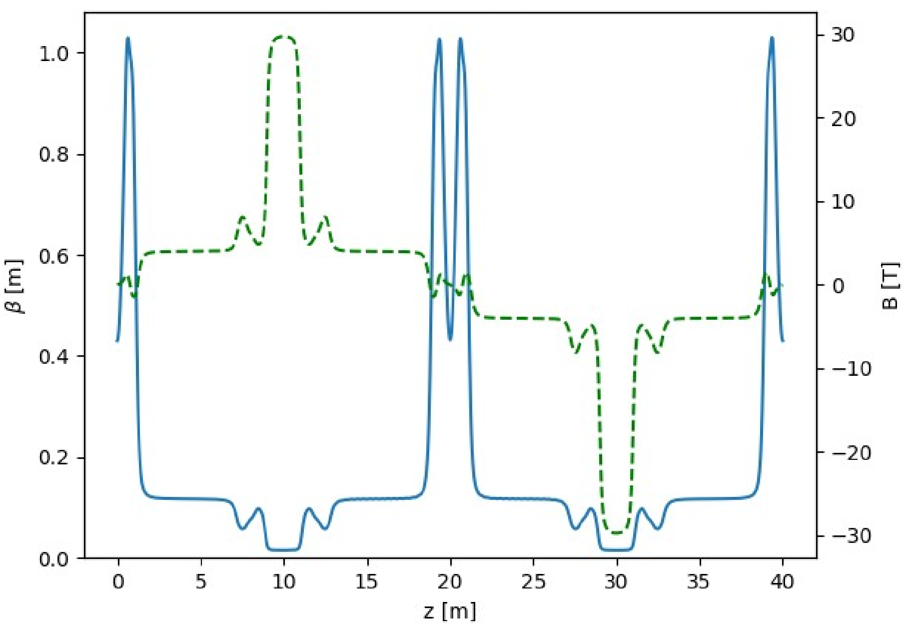
- In uniform field

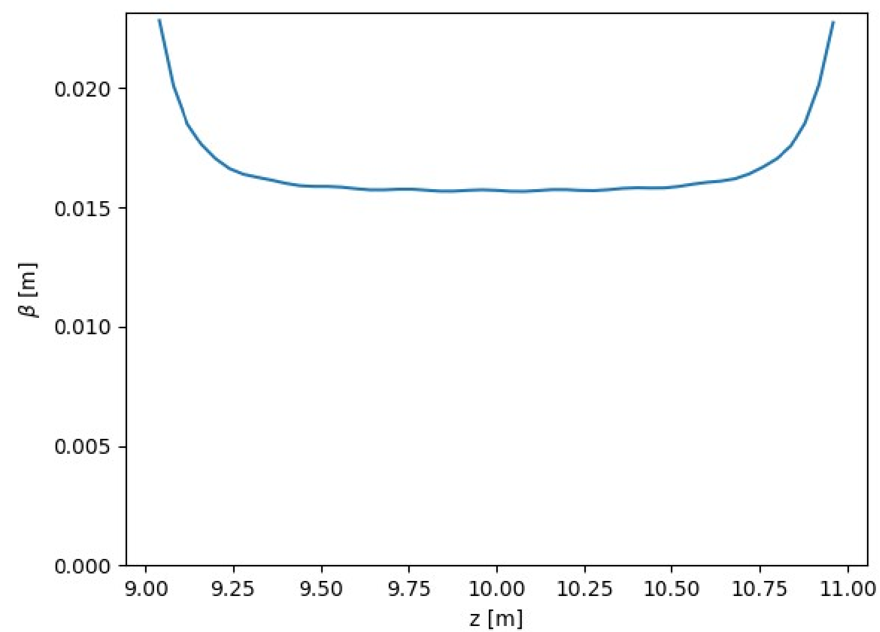
0 0

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

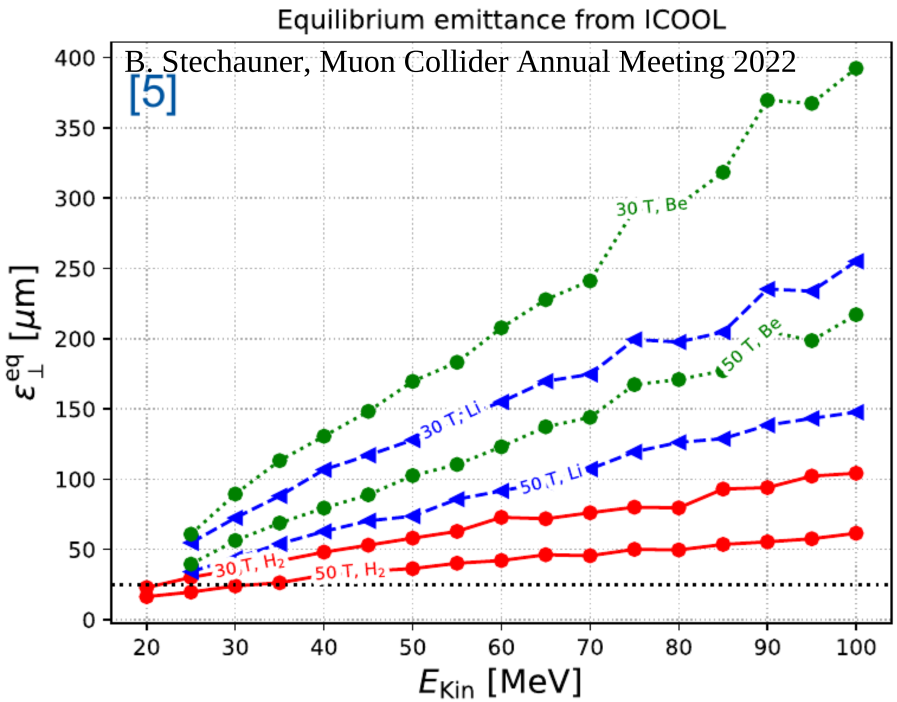
$$\beta_\perp = \frac{\sqrt{1+\mathcal{L}^2}}{\kappa}$$

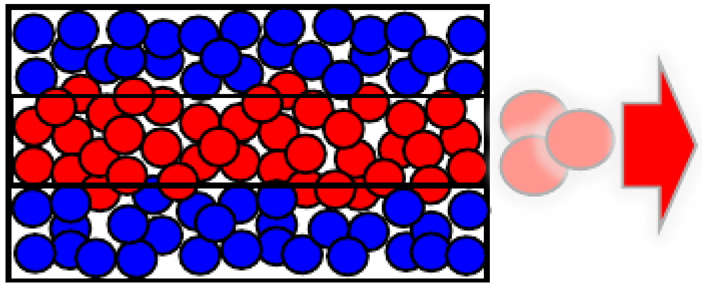
- Reach $\beta \sim$ 1 cm – but not practical to introduce dispersion





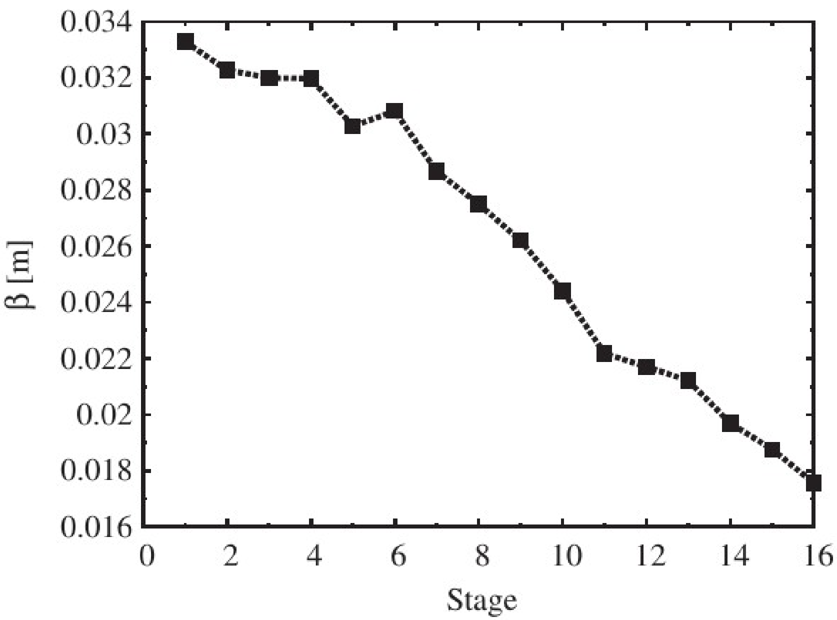
Final cooling - absorber

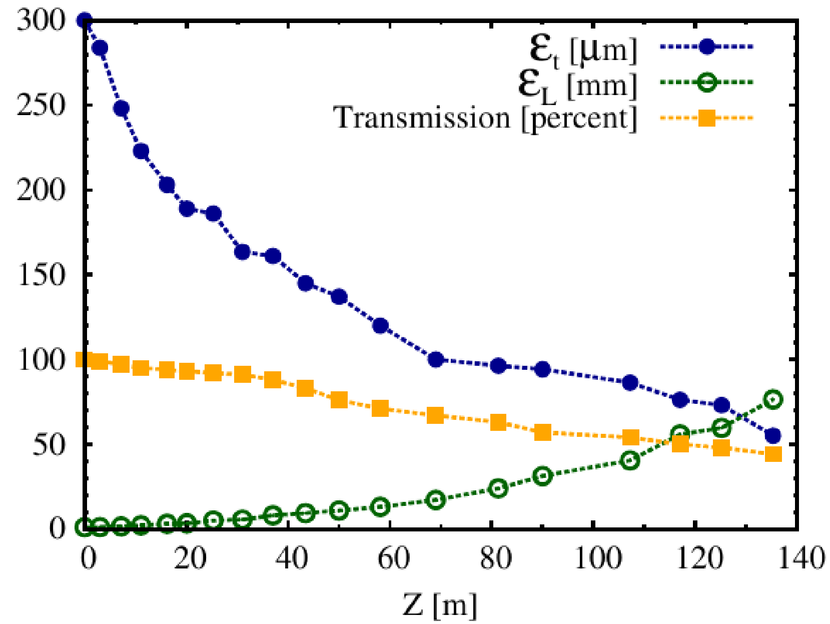




- Significant benefit to use Hydrogen absorber
  - Much less energy loss per scatter
- Narrow, intense beam is enough to boil H_2
  - Next to very thin windows
- Can cause damage to windows → burst
- Requires care!

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

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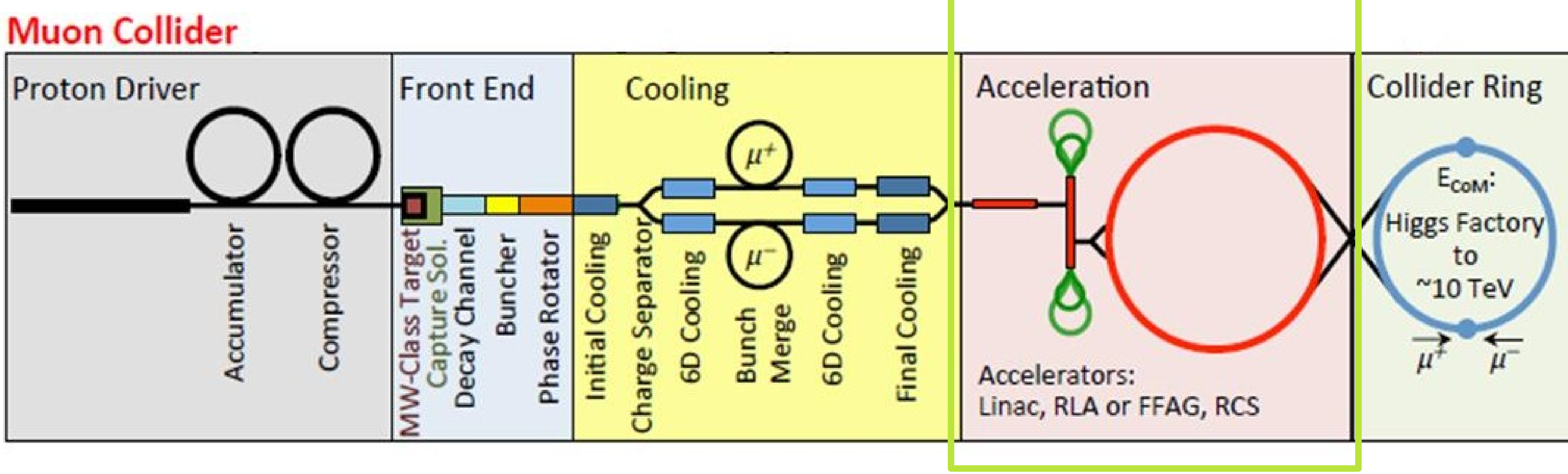
The Facility – Acceleration



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

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

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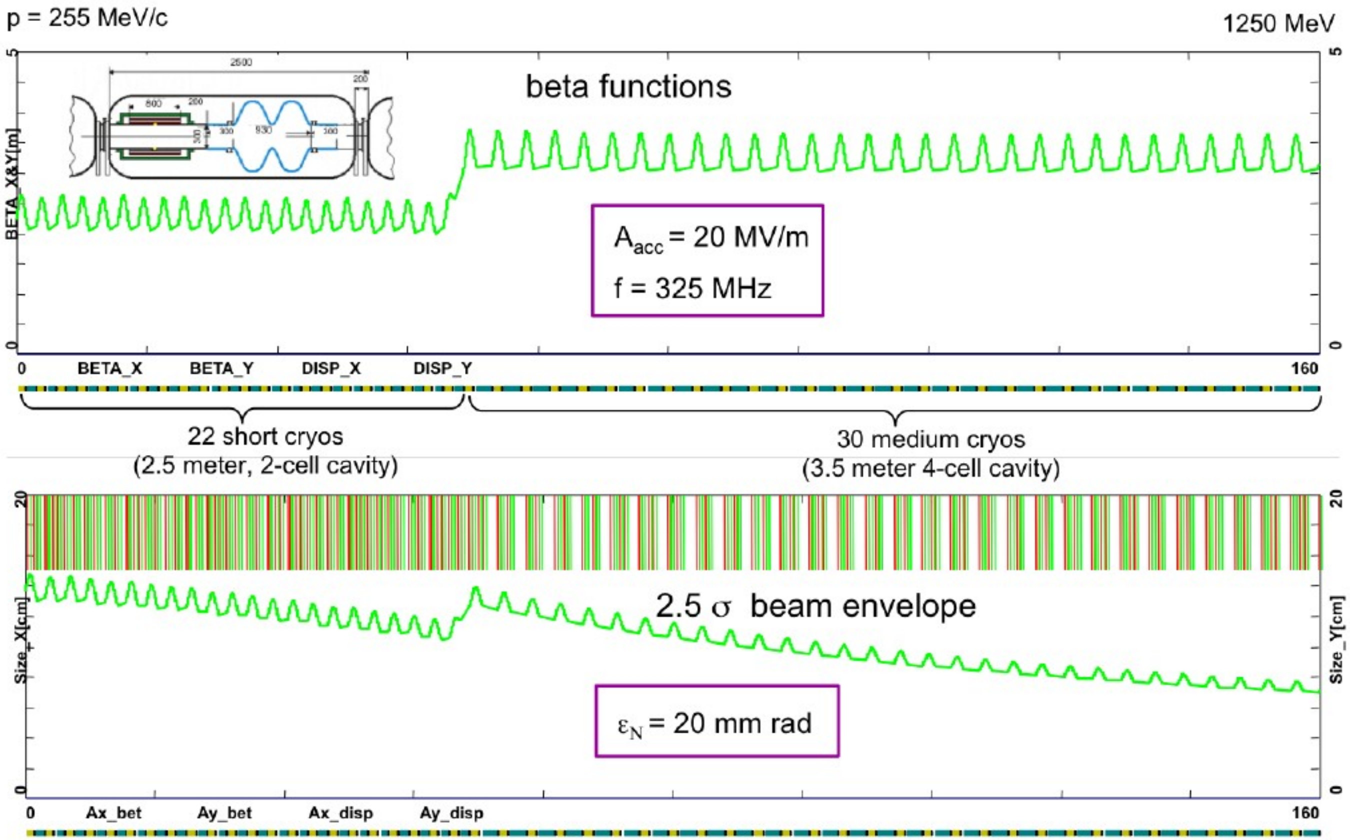

Kurup et al, The Muon Linac for the International Design Study for the Neutrino Factory, Proc. IPAC11

- 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

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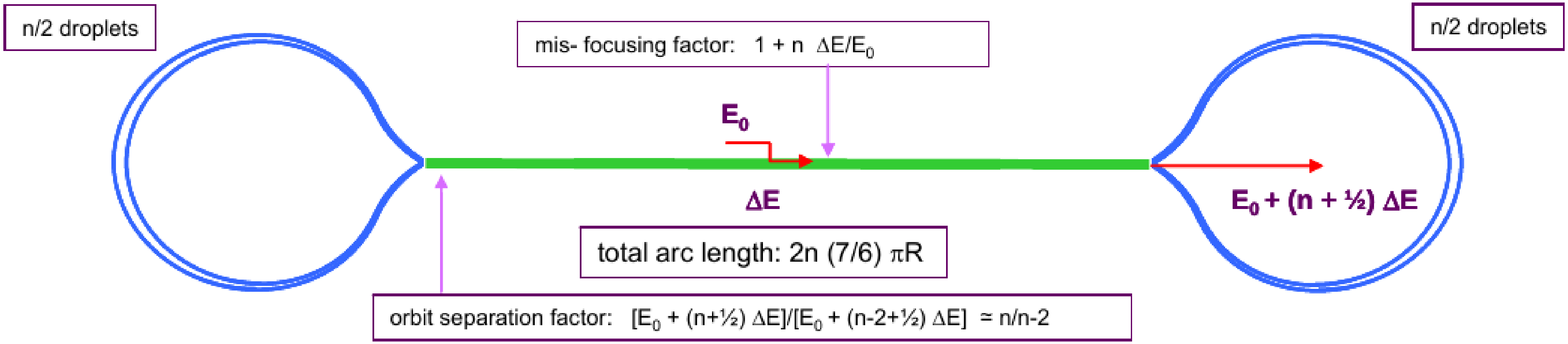
Recirculating Linac

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



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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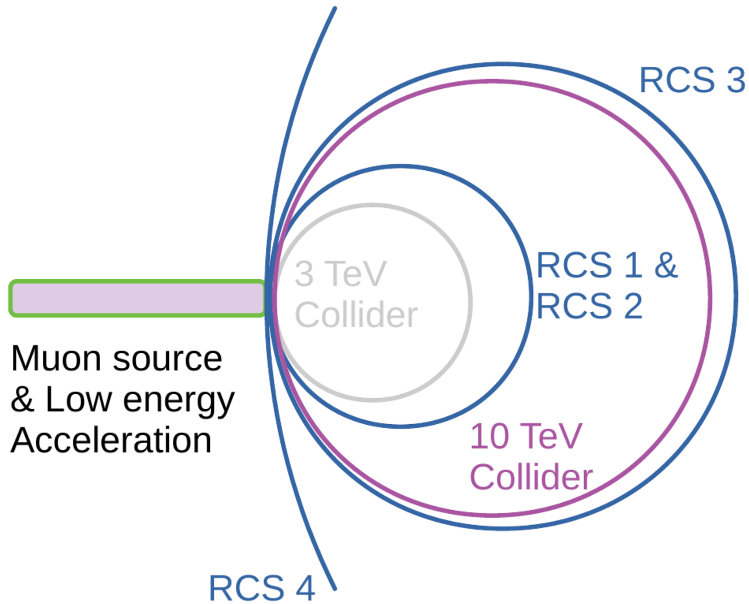

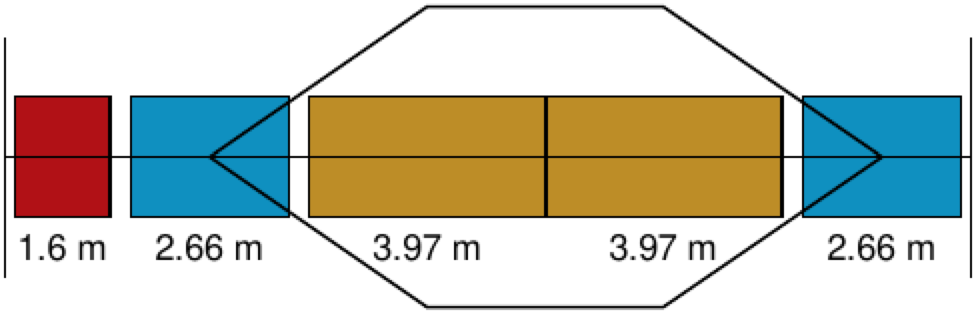

- At highest energy, can use synchrotrons
  - Ramp magnets in synchronisation with increasing beam energy
  - Need extremely fast ramp < few ms
  - To keep ring compact, use combination of
    - Fixed superconducting and
    - Pulsed normal conducting magnets
  - Shielding components from decay losses

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Synchronisation

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

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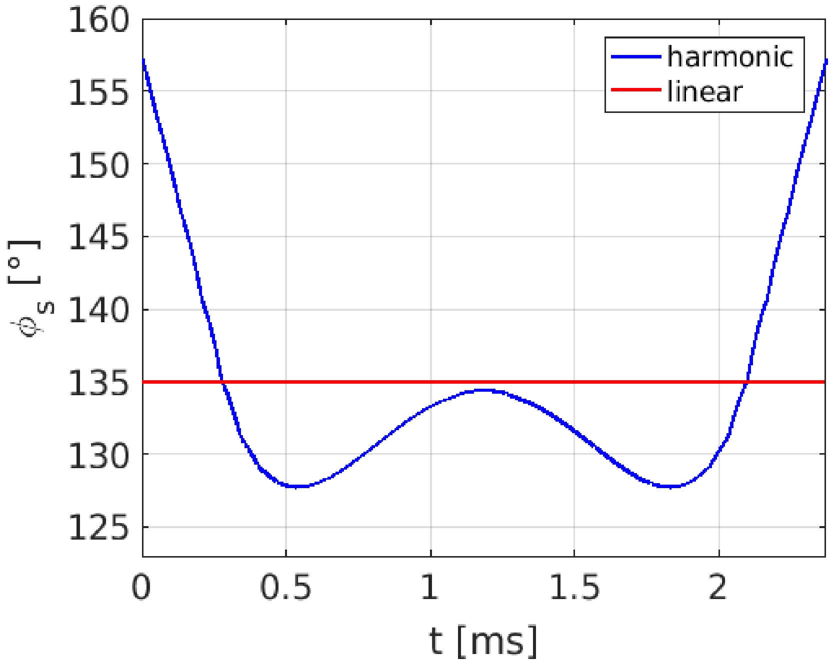

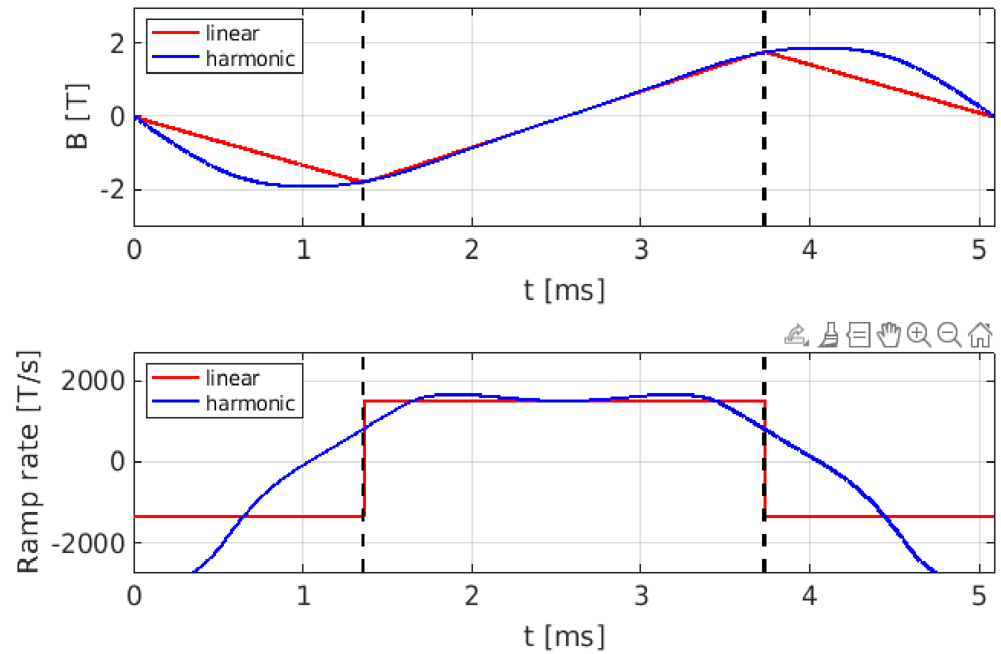

F. Batsch, Muon Collider workshop 2022

- 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

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Alternative - FFAs

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

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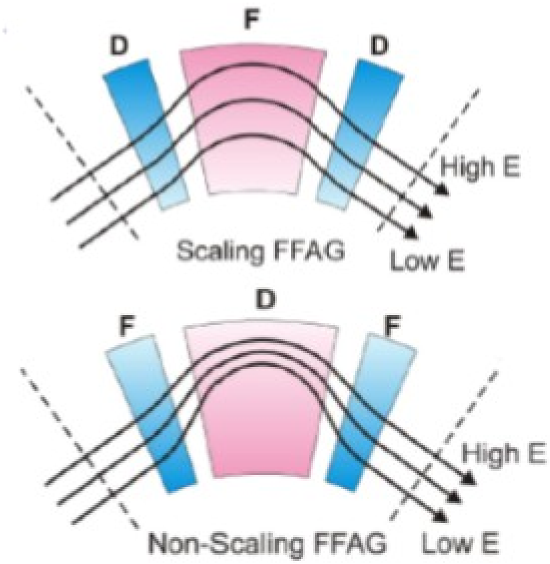

- Alternative to get fast acceleration – use Fixed Field Accelerators
  - Beam moves across aperture of combined function magnets
  - Sample stronger dipole fields at higher momenta
  - **Either:** move fast enough that optical resonances are not a problem
  - **Or:** add in sextupole+ to correct chromaticity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

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The Facility – Collider

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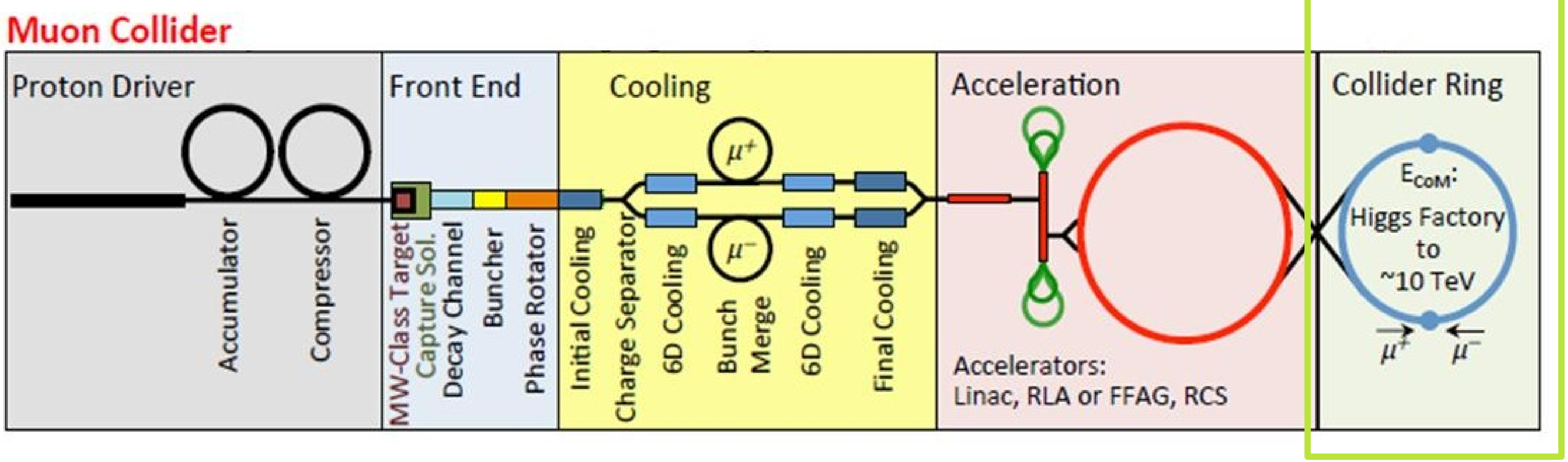
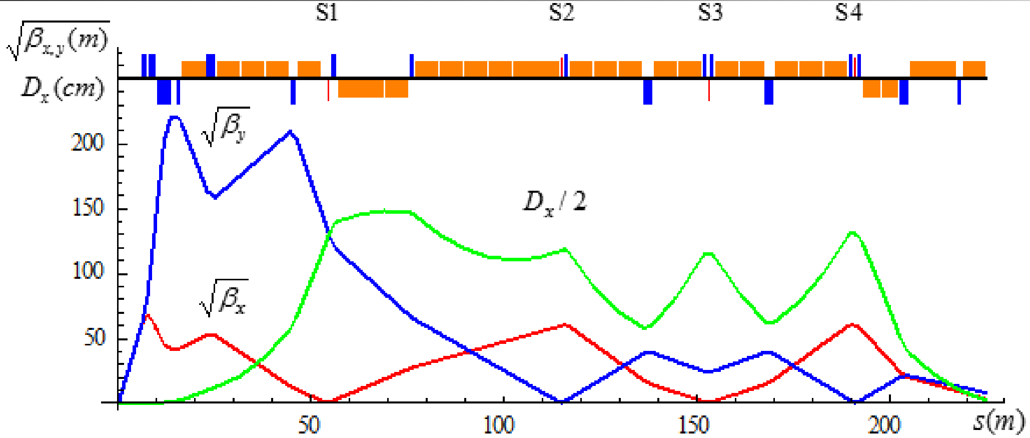


MC Accelerator/Collider Ring

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

- 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

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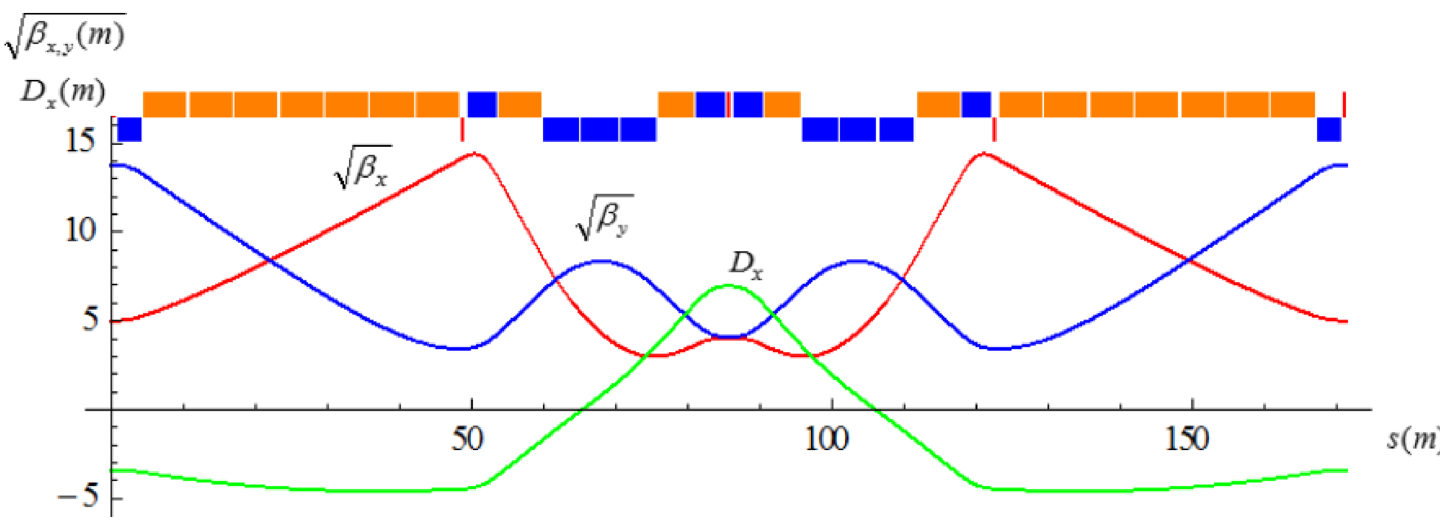
Short bunch

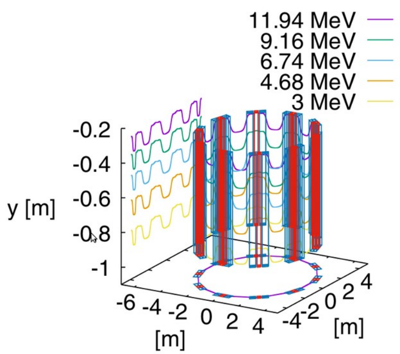
- Bunch length maintained by RF
- Driven by Momentum Compaction Factor
  - Path length (time-of-flight) variation with energy

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

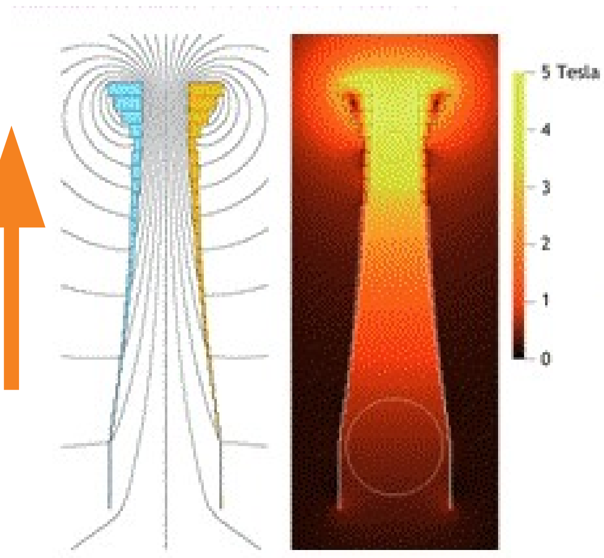
- Introduce section of ring having tunable dispersion to enable control of α_p



MC Accelerator/Collider Ring

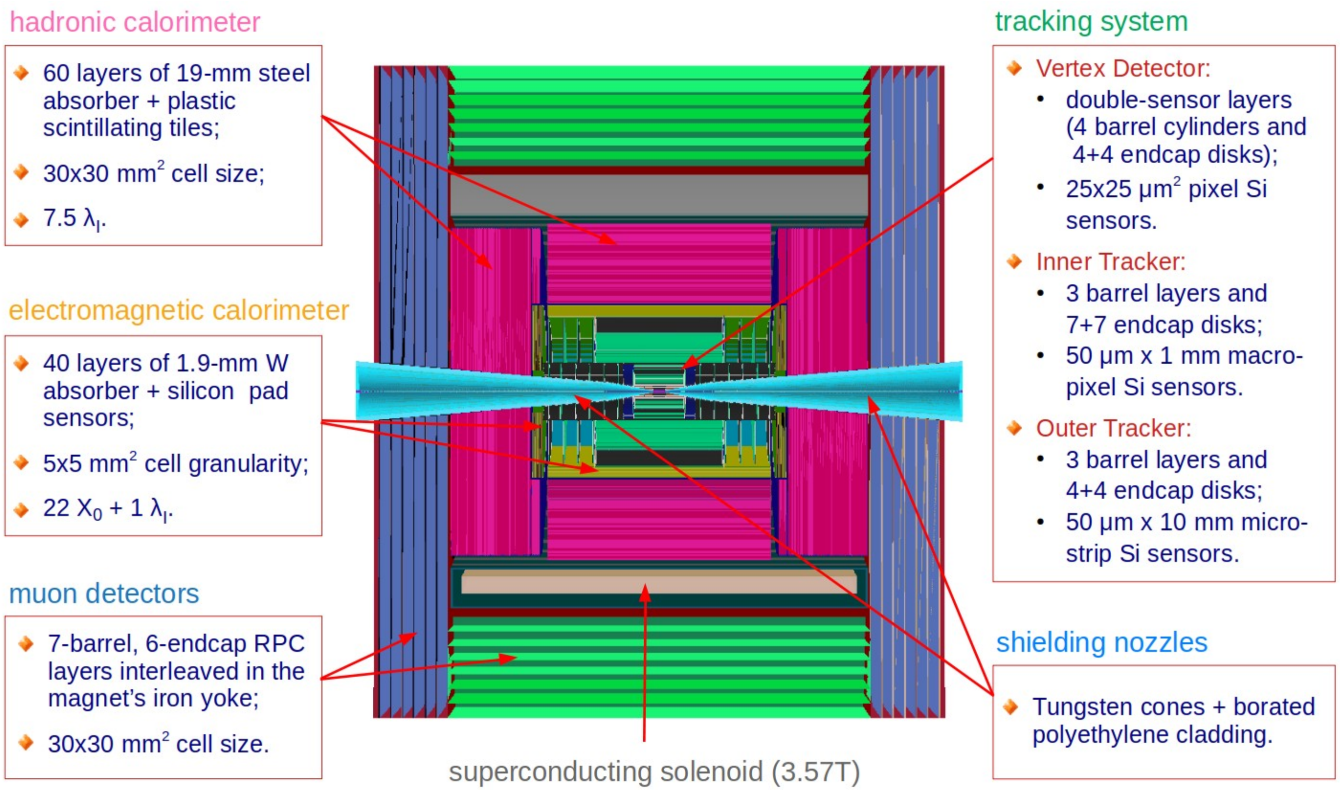


Beam goes up
During
Acceleration



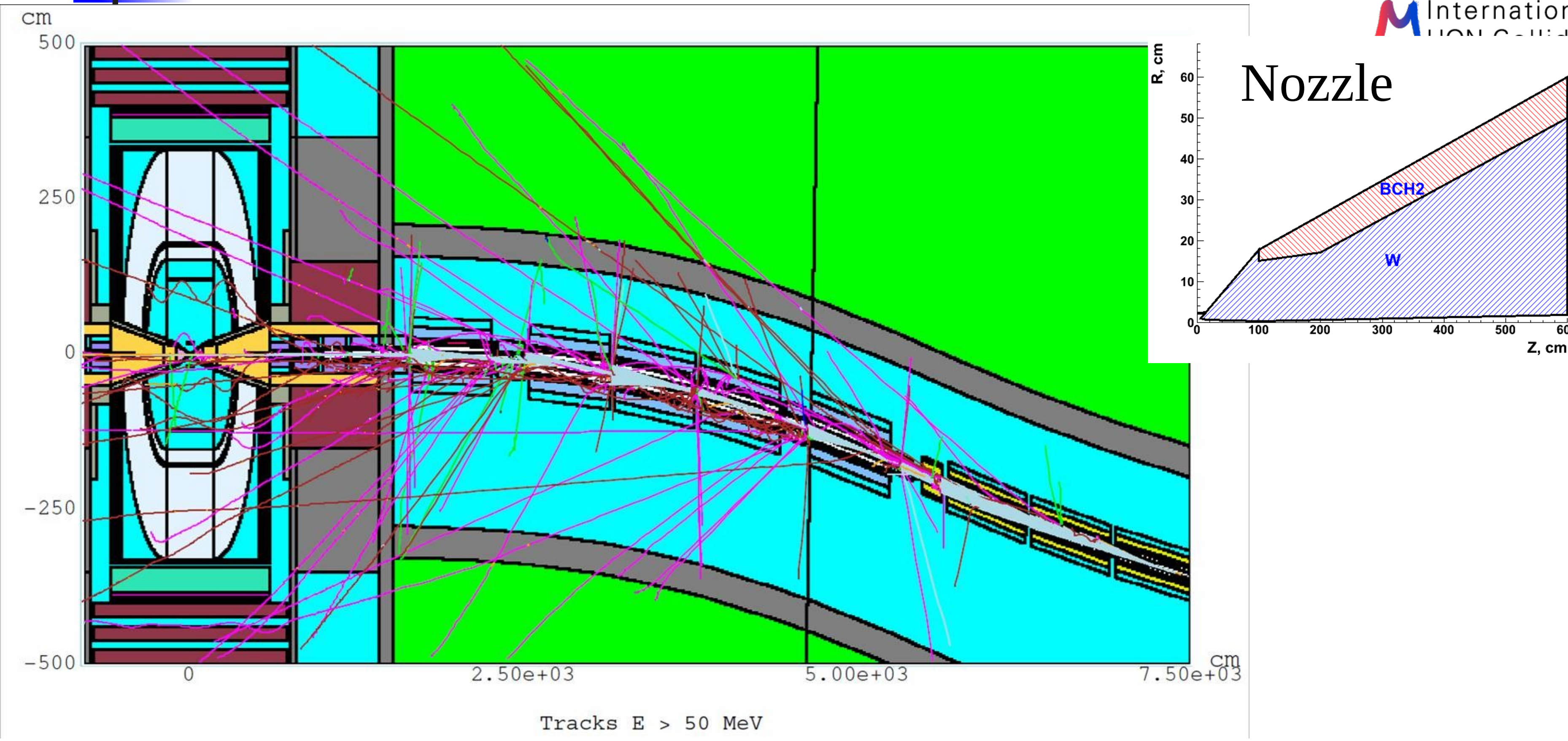
- FFA concept
  - Fixed field accelerator using vertical orbit excursion
    - Constant path length at different energy
    - “Relativistic cyclotron”
  - Enables fixed frequency acceleration
  - Removes the limit on minimum bunch length
  - No need to ramp magnets
  - Challenge: Wide aperture RF cavities

Muon Collider Detector



- Muon collider
  - Rather standard detector arrangement
  - Based on e^+e^- detector

Muon Collider - BIB



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

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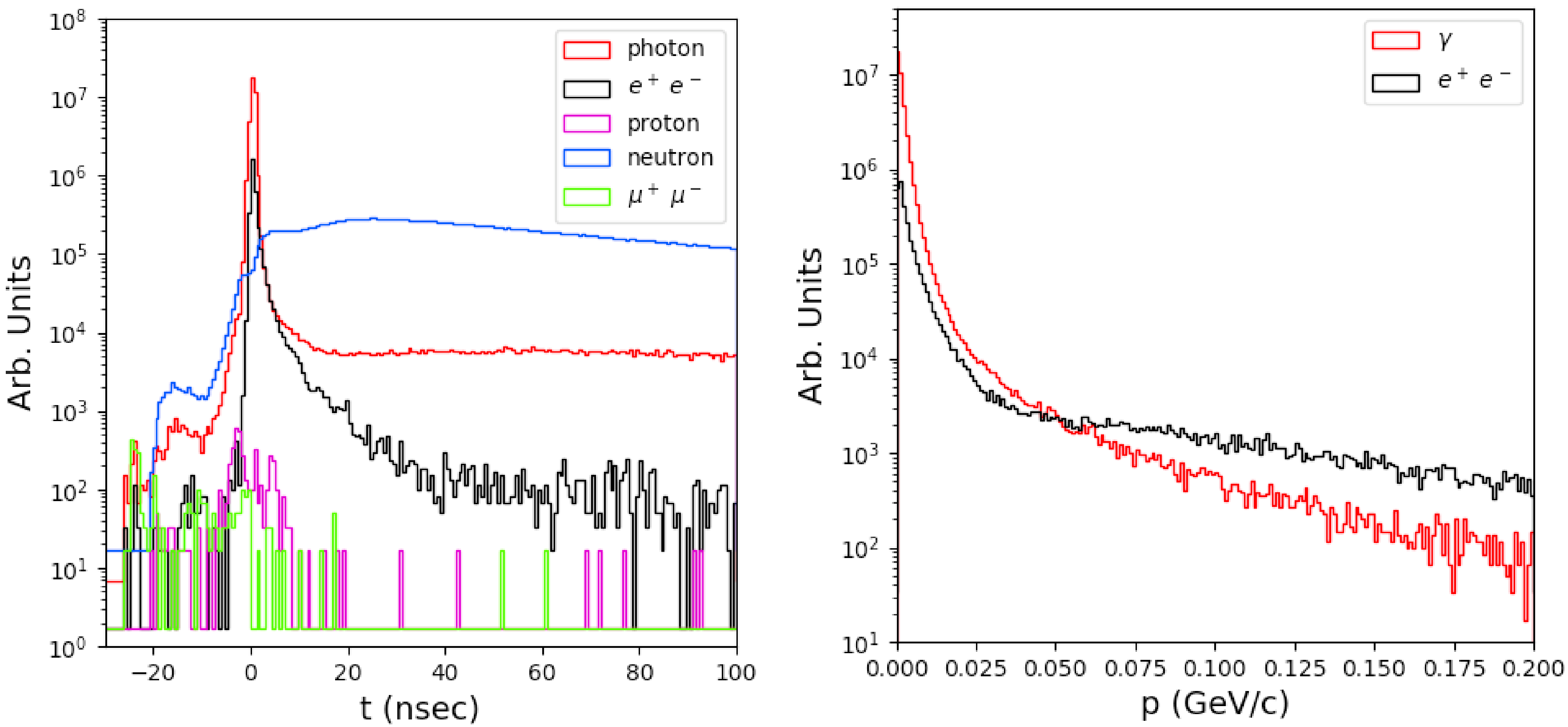
BIB Characteristics



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

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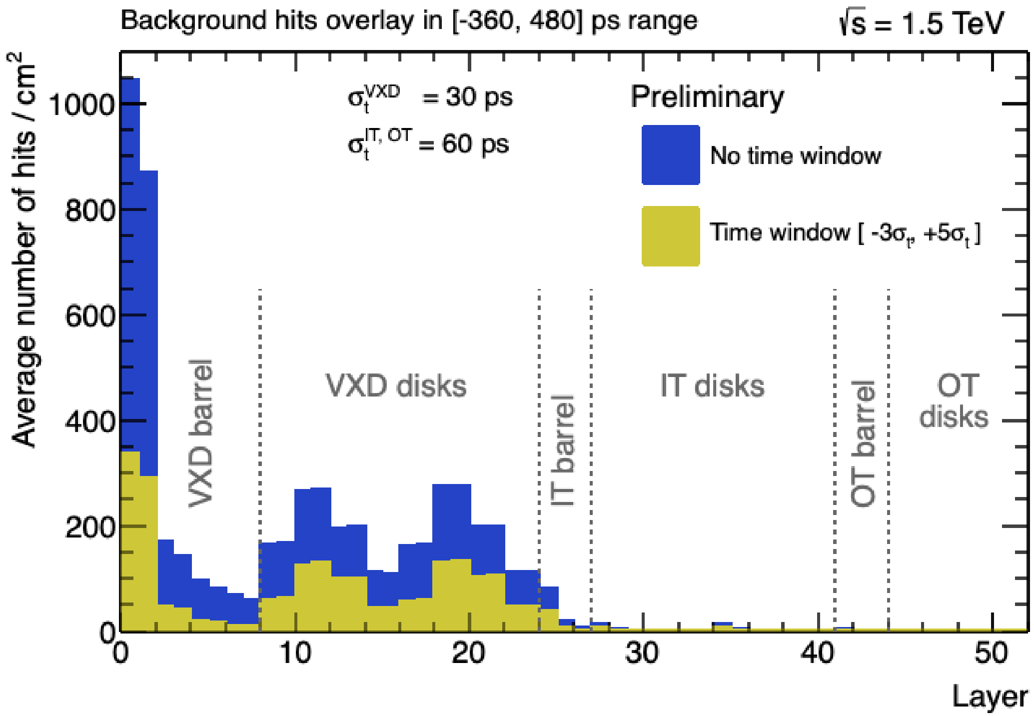
BIB Rejection



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

Neutrino beams

- Muon decays yield high intensity neutrino beams
  - O(1) metre across
  - 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
  - Seek to 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

The Muon Collider – Hardware R&D

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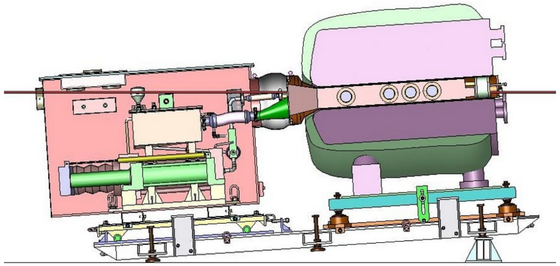
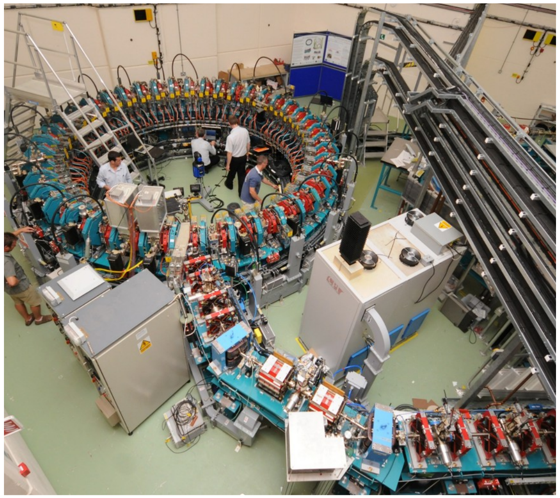
Muon Accelerator R&D

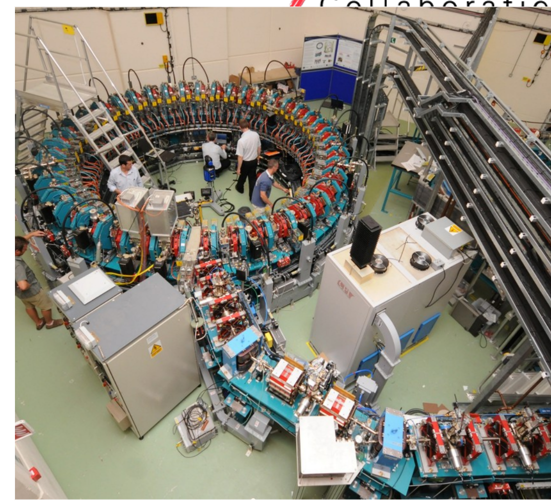
- MERIT
  - Demonstrated principles of muon accelerator proton targetry/pion production
- EMMA
  - Demonstrated fast acceleration in FFAGs
- CBETA
  - Demonstrated RLAs using FFA arcs
- MUCOOL
  - Cavity R&D for ionisation cooling
  - Demonstrated operation of cavities at high voltage in magnetic field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

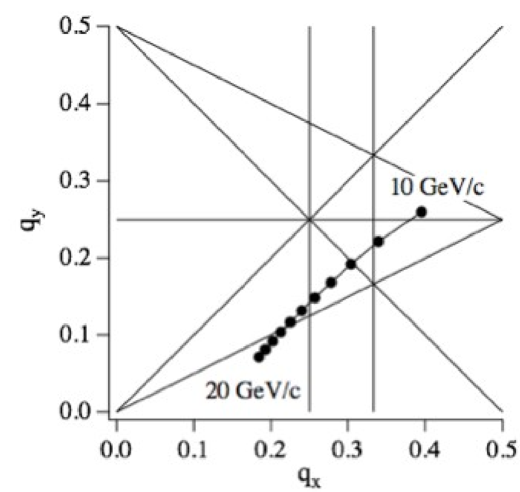




EMMA

- 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





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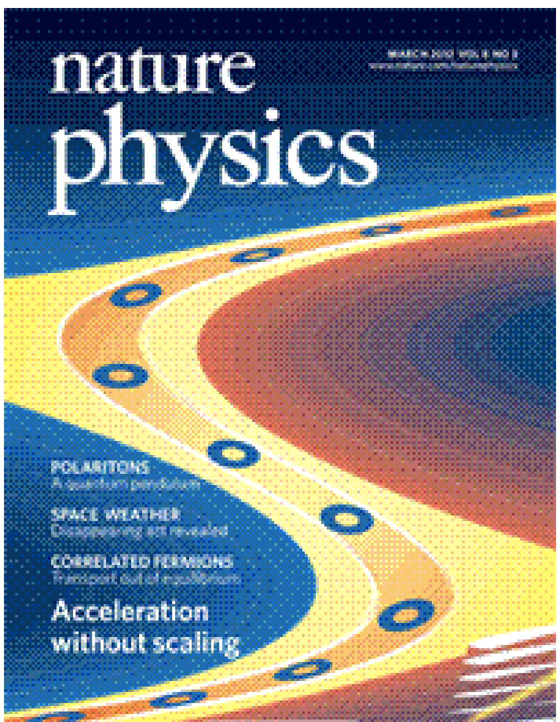
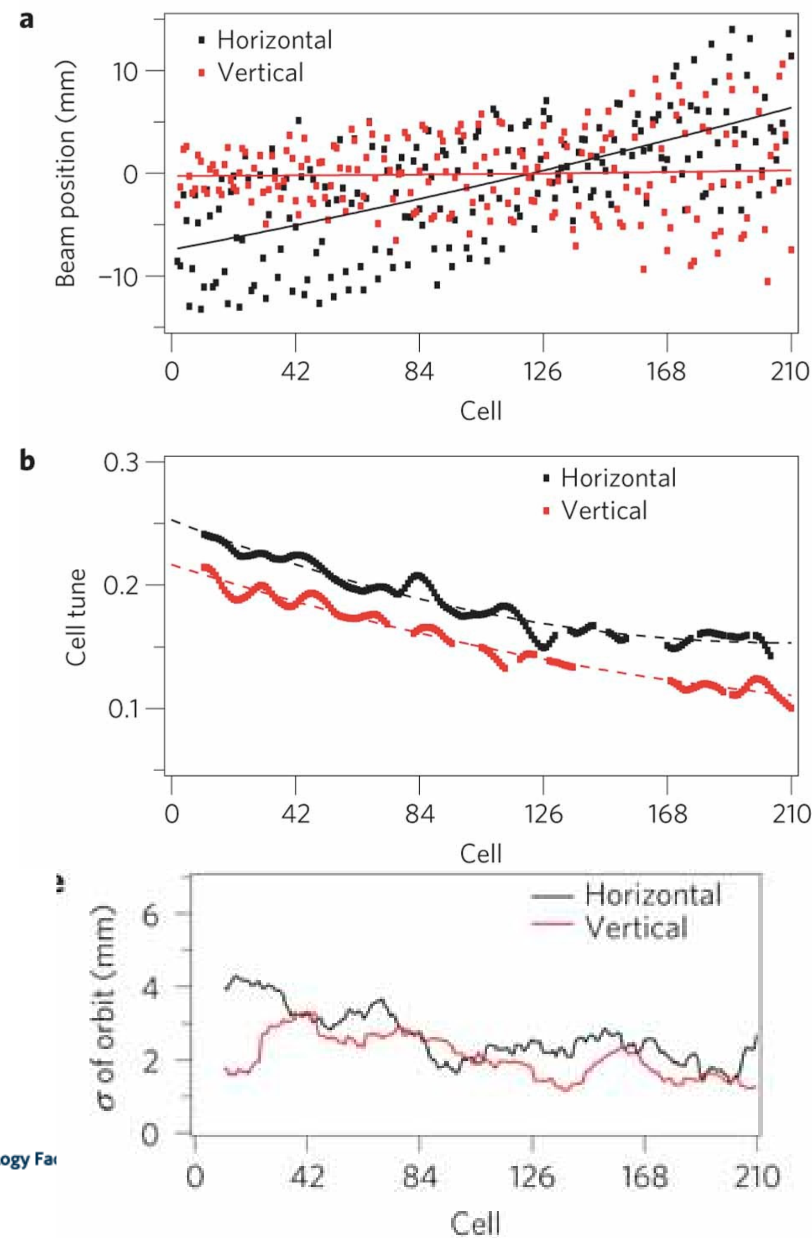
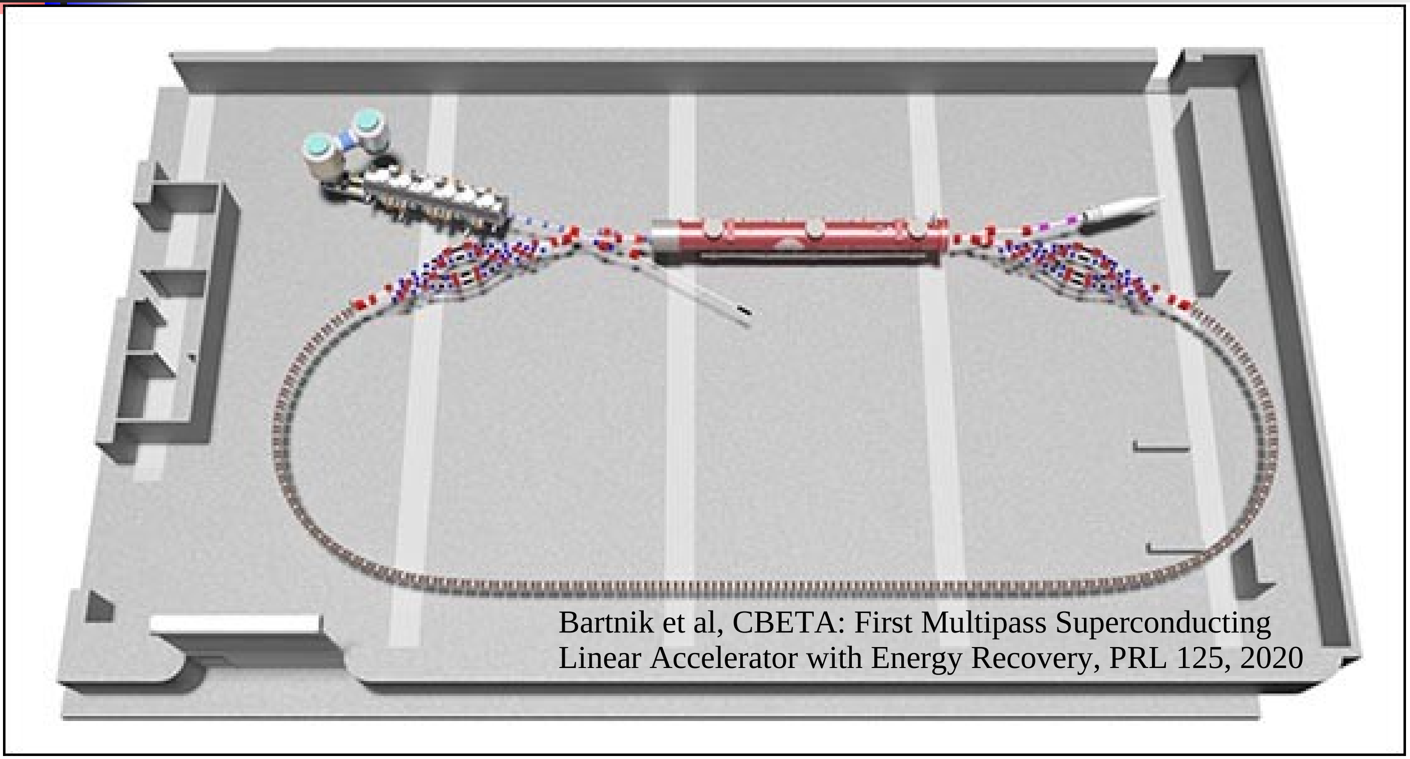
EMMA

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





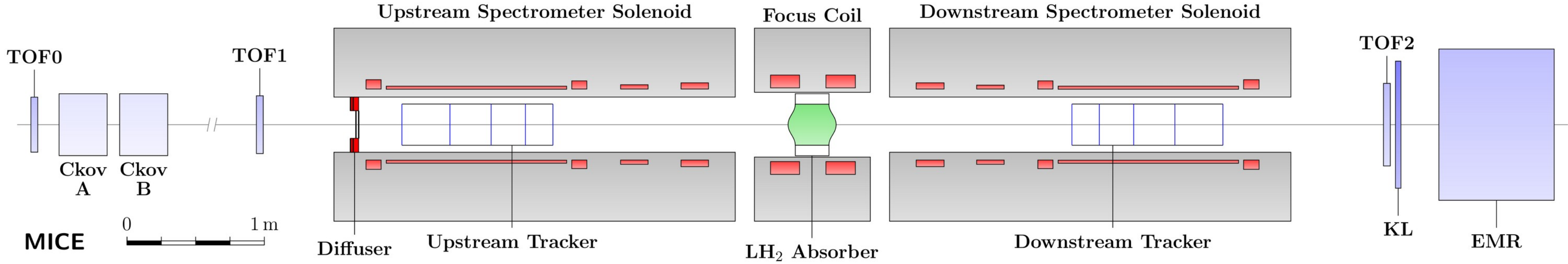
CBETA

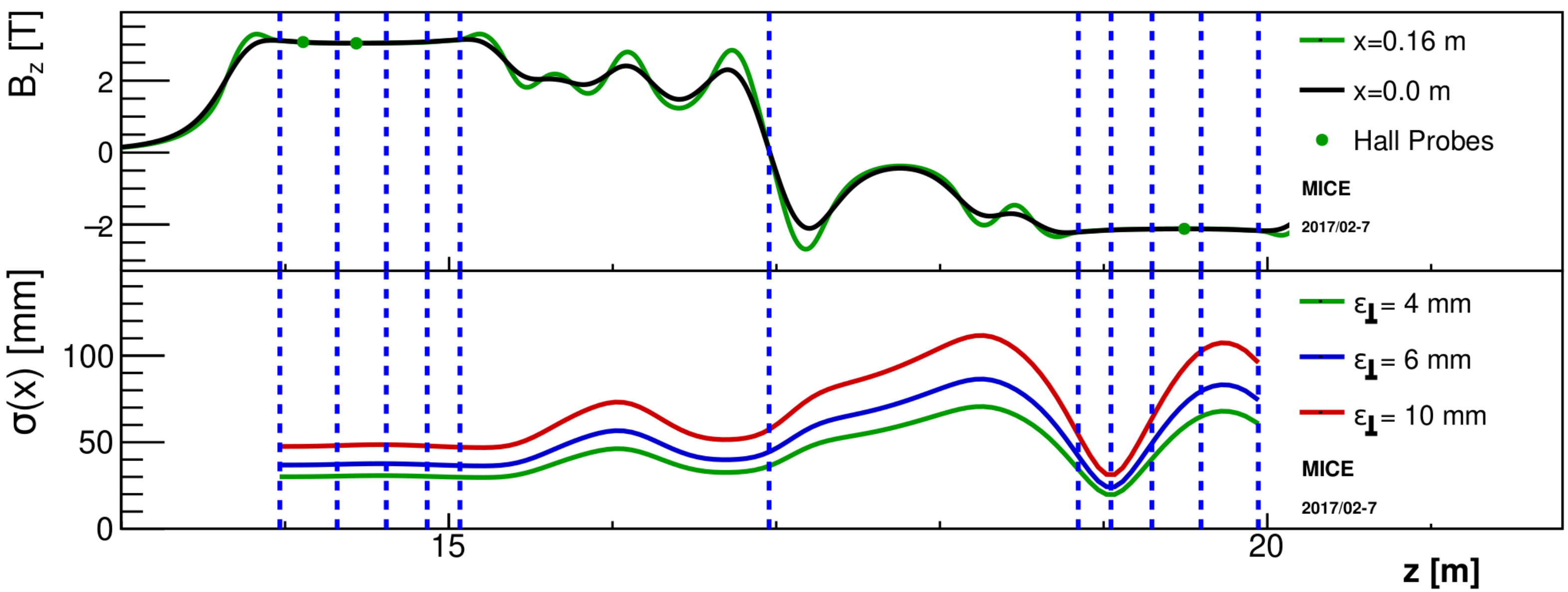


Bartnik et al, CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery, PRL 125, 2020

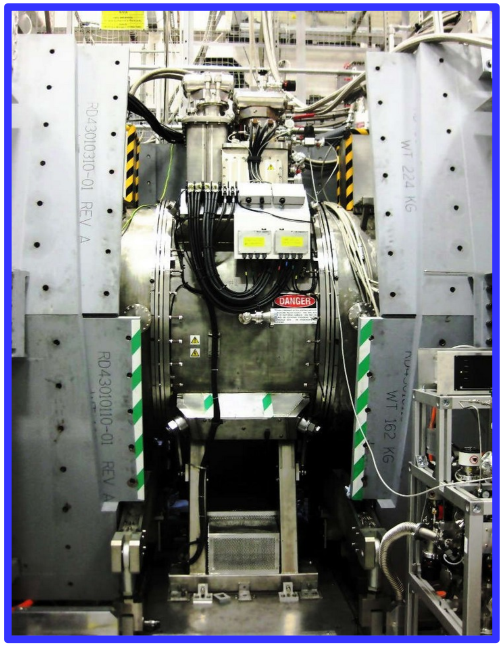
- Energy Recovery Linac that used single FFA arc – 5 turns:
  - Beam goes through linac
  - Time delay line
  - FFA arc – same ring for all different energies
  - Back into RF
- Beam is subsequently decelerated in a further 5 turns

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

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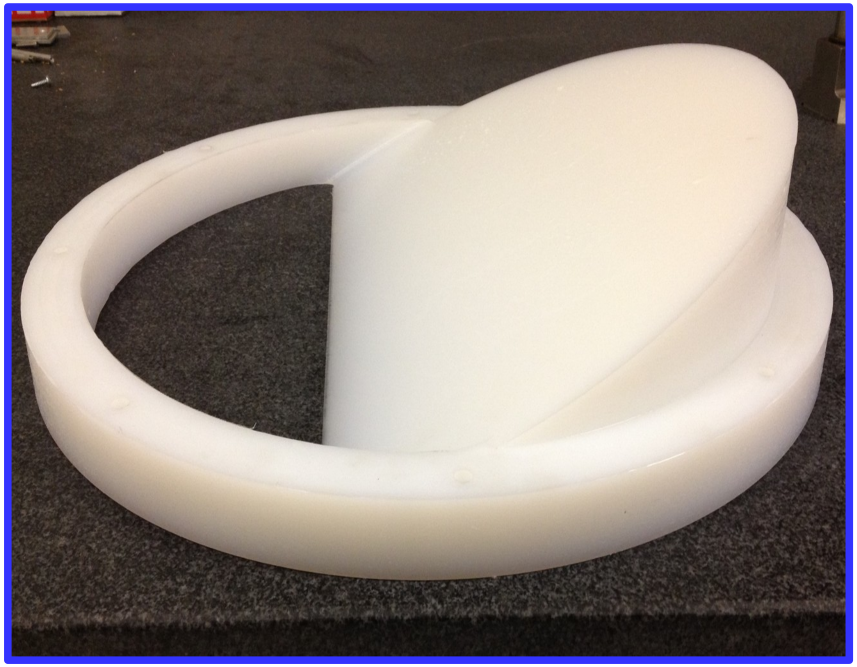
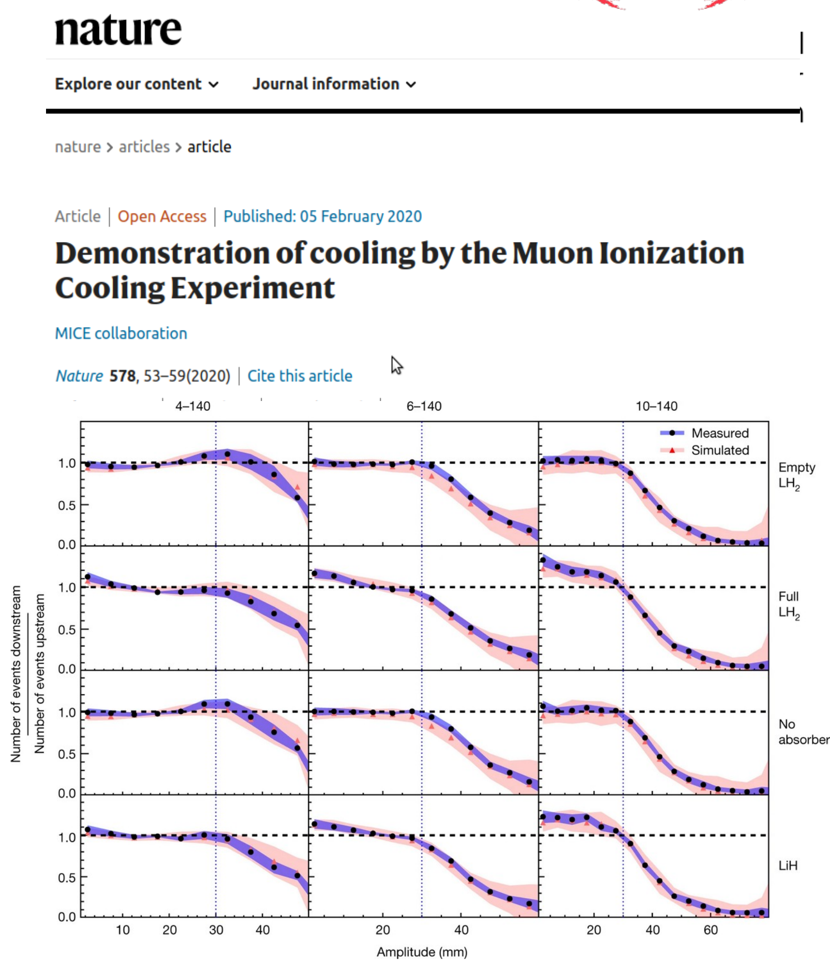
Absorber



- 65 mm thick lithium hydride absorber
- 350 mm thick liquid hydrogen absorber
  - Contained in two pairs of 150-180 micron thick Al windows
- 45º 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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Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

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

The Muon Collider – Future R&D

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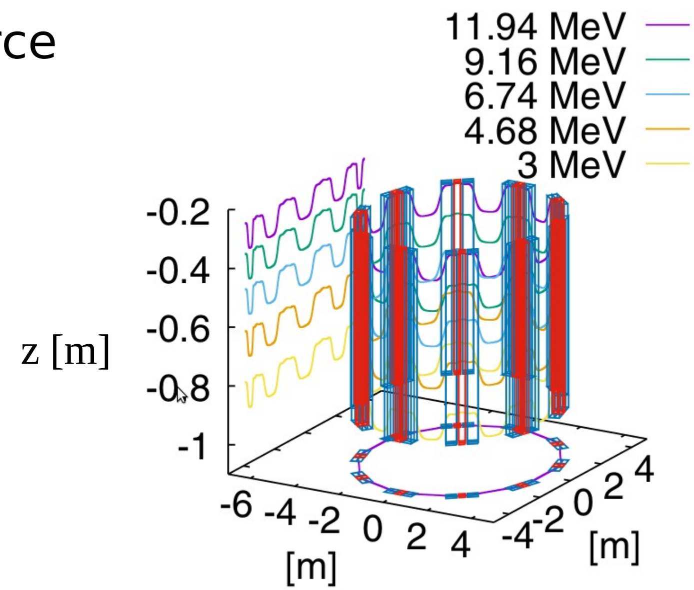
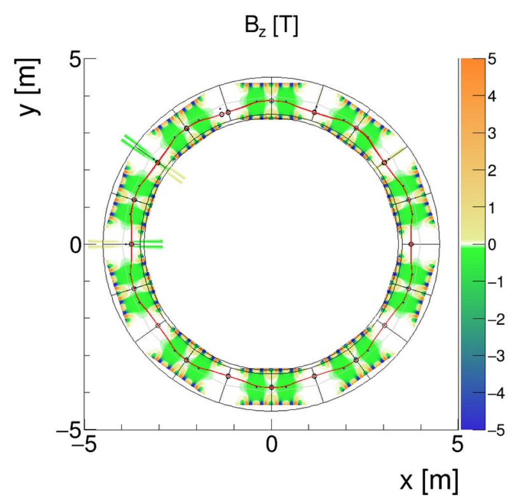
Making the Muon Collider Real

- 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

The future – FETS-Ring?

- FETS ring FFA prototype for ISIS protons
  - Scaled test for a neutron spallation source
  - vFFA?
  - Magnet prototyping in progress
- Questions
  - Can we build the magnet?
  - Can we accelerate to high intensity?
  - Can we control tune?
  - How do we correct for errors?
  - Can we inject/extract?





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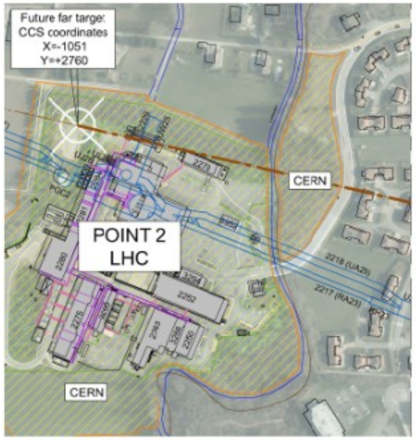
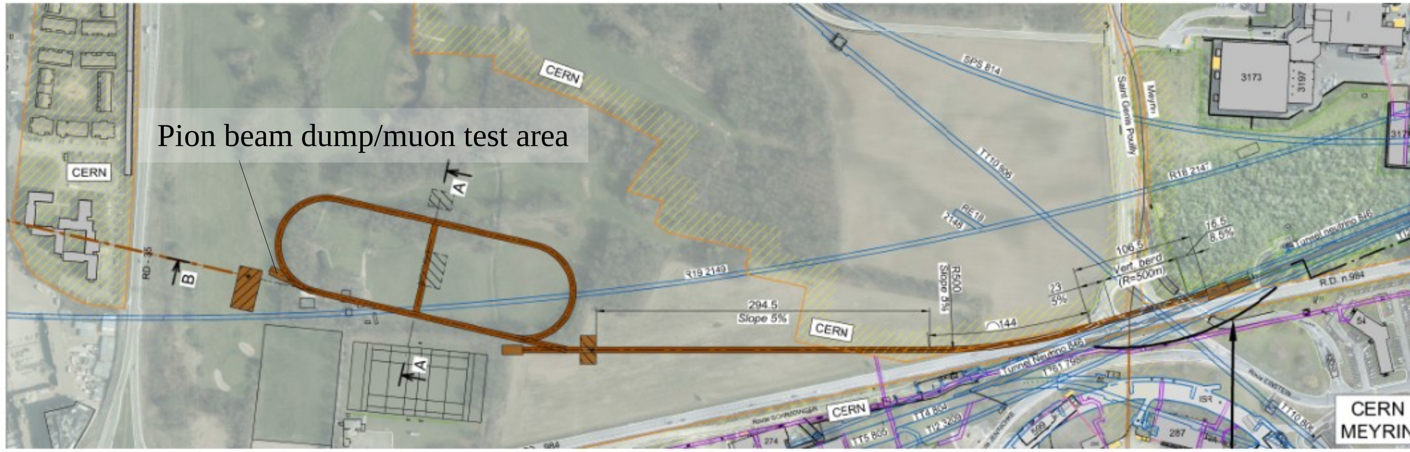
nuSTORM



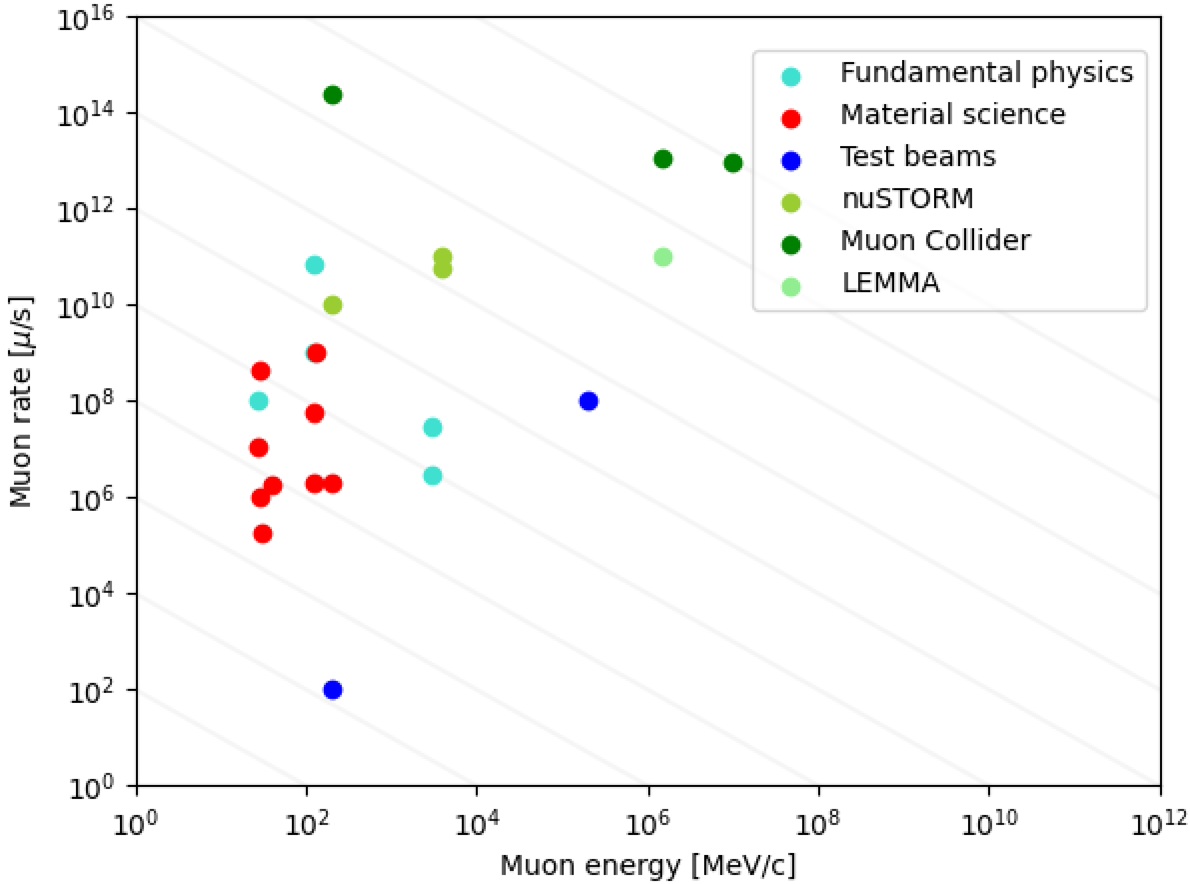


nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

- 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

International MUON Collider Collaboration



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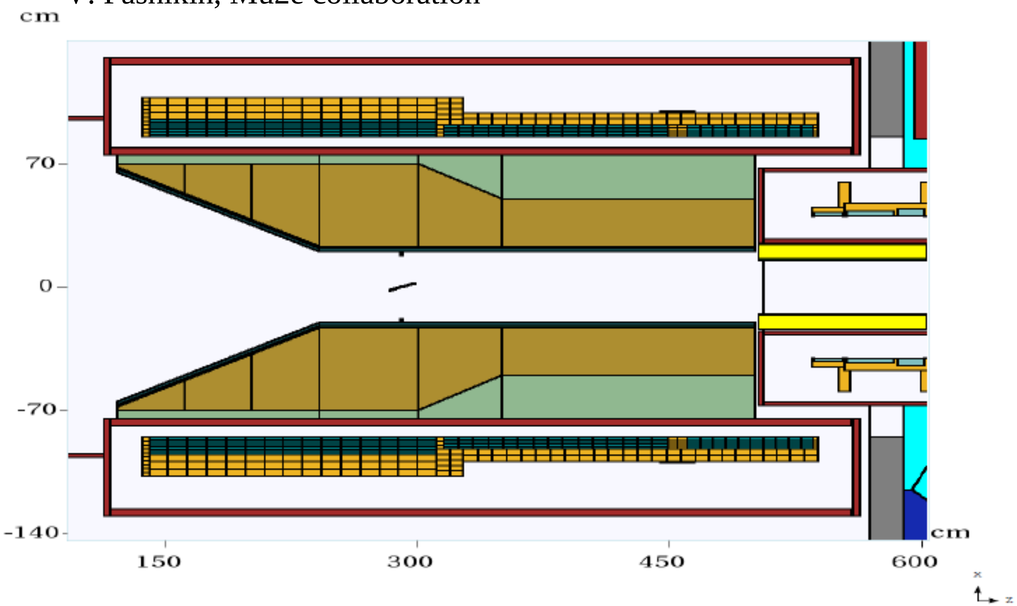
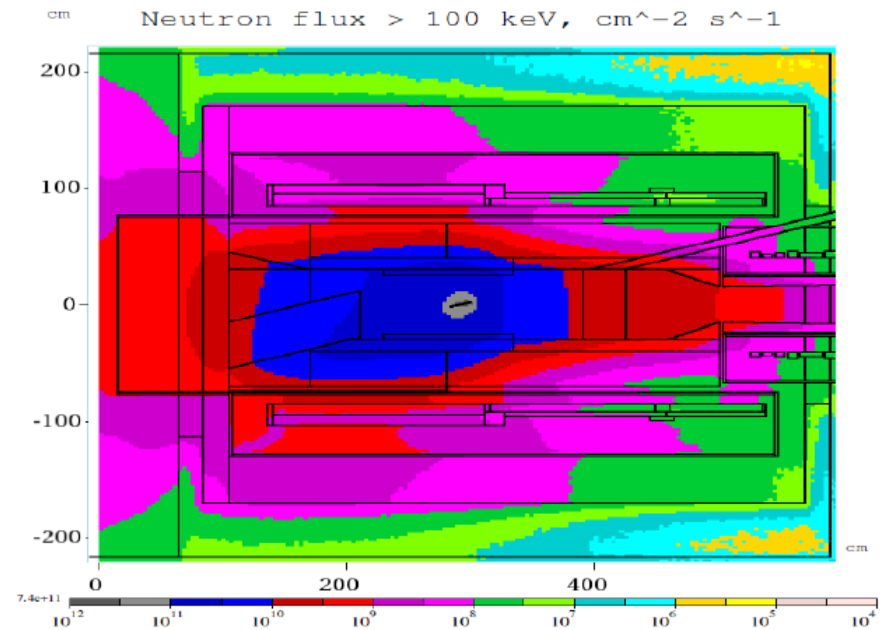
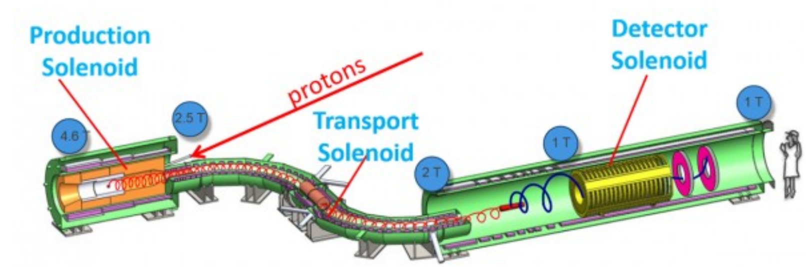
Mu2e

V. Pashikin, Mu2e collaboration





- 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



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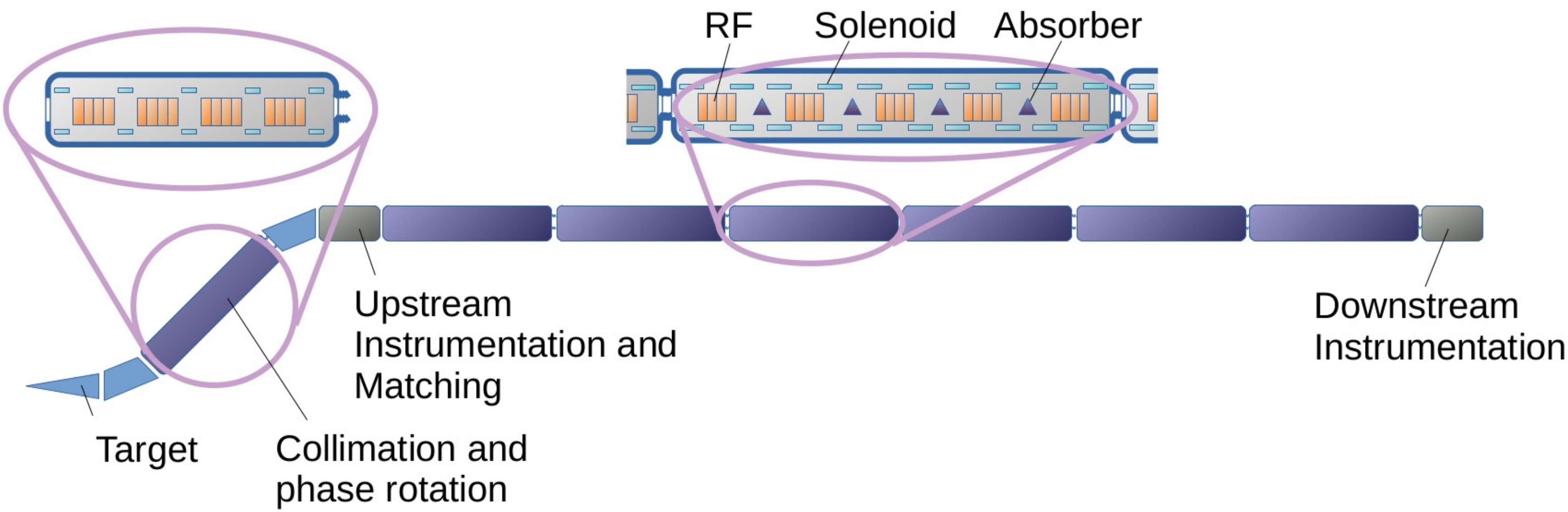
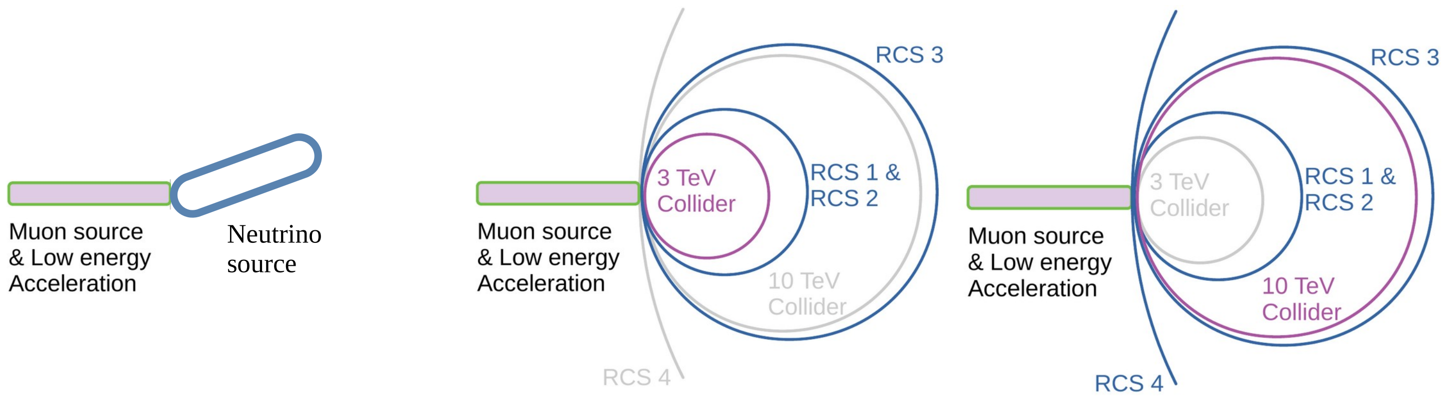
Cooling Demonstrator



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

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

- 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 follow