Towards a Muon Collider

International
MUON Collider
Collaboration

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Science & Technology Facilities Council
ISIS

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CERN - plans

2040

- HL LHC upgrade to LHC complex under construction
  - Order of magnitude improvement in luminosity
  - First data 2029
- Strong future hides a growing challenge
  - Need to decide on next generation project
  - Options look costly, in money and electricity consumption
- Lead time is 25 years for next collider – must start now

DUNE – plans (potential)

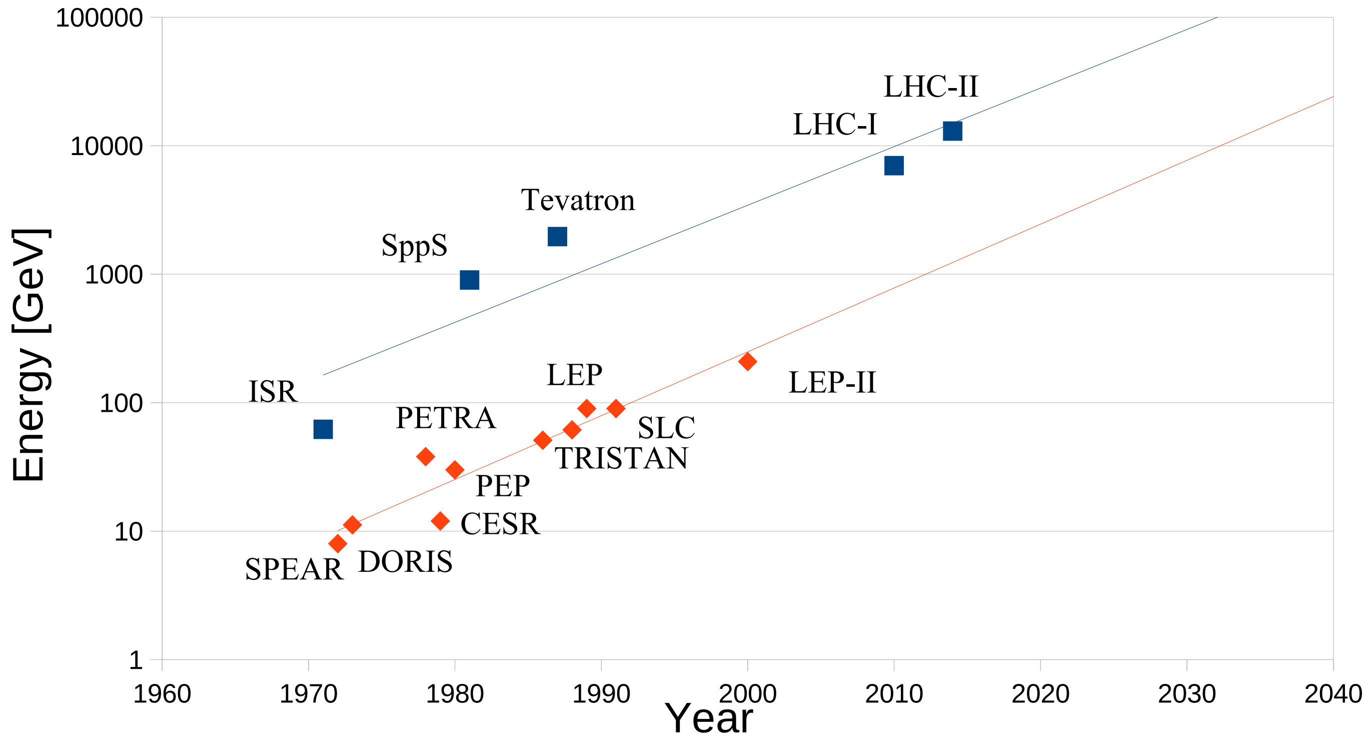
Experiment Stage	Physics Milestone	Exposure (kt-MW-years)	Years (Staged)
Phase I	5σ MO ($\delta_{\mathrm{CP}} = -\pi/2$)	16	1-2
	5σ MO (100% of δ_{CP} values)	66	3-5
	3σ CPV ($\delta_{\mathrm{CP}} = -\pi/2$)	100	4-6
Phase II	5σ CPV ($\delta_{\mathrm{CP}} = -\pi/2$)	334	7-8
	δ_{CP} resolution of 10 degrees ($\delta_{\mathrm{CP}} = 0$)	400	8-9
	5σ CPV (50% of δ_{CP} values)	646	11
	3σ CPV (75% of δ_{CP} values)	936	14
	$\sin^2 2\theta_{13}$ resolution of 0.004	1079	16

Neutrino beam available in 2032

Snowmass Neutrino Frontier: DUNE Physics Summary, Dune Collaboration, https://arxiv.org/abs/2203.06100

- US → DUNE
  - Slightly longer timeline
  - Still finding out eventual plan following P5

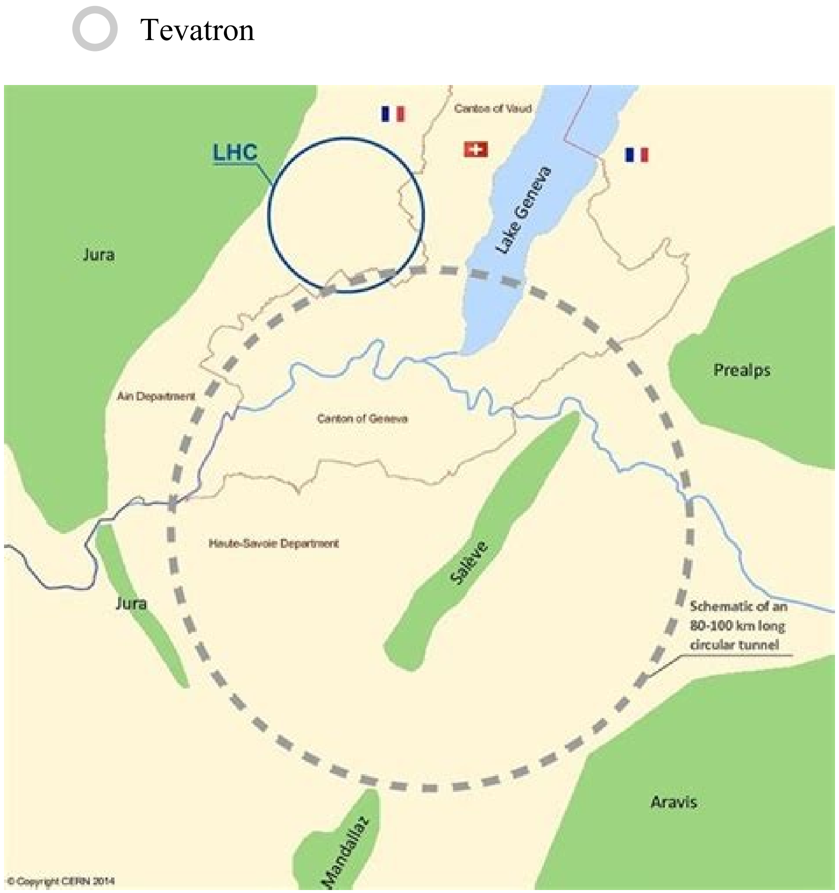
Back to the Future...



- Effort to explore phenomena at higher and higher energies
- Corresponds to smaller scales
- Higher energy → bigger, more expensive, more power hungry

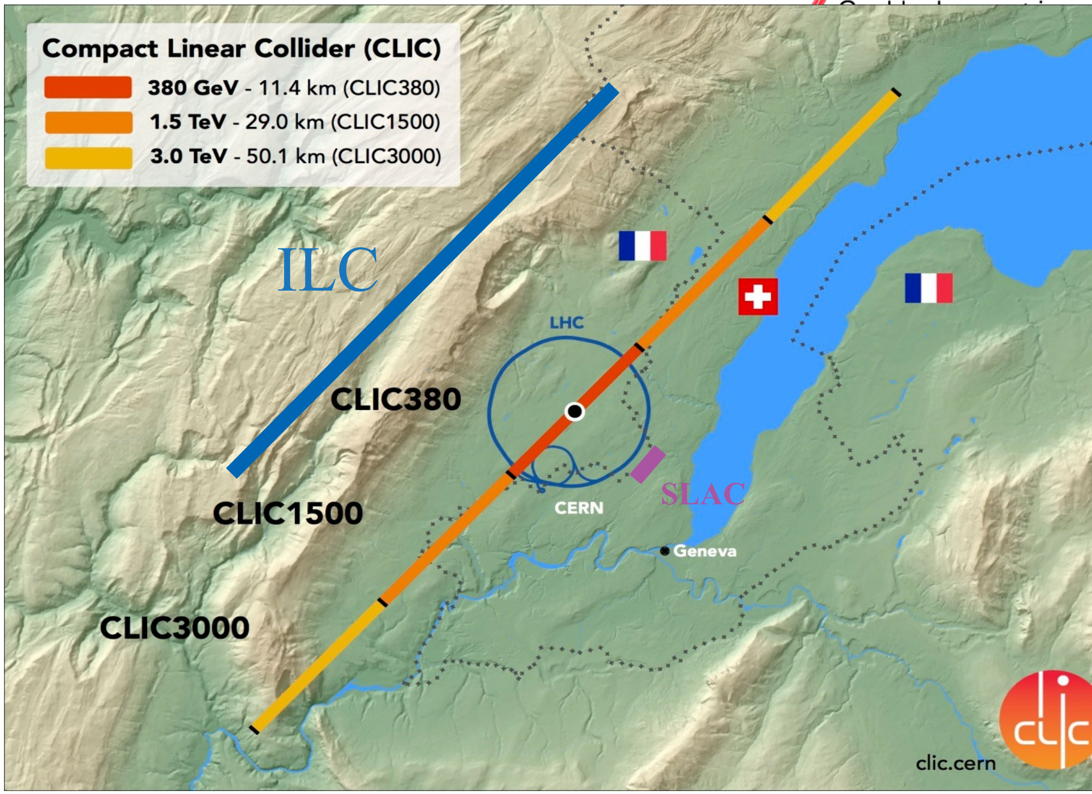
E.g. circular colliders

- Tevatron
  - 1.96 TeV proton - antiproton
  - 6.2 km circumference
- LEP/LHC
  - 14 TeV proton proton (LHC)
  - 209 GeV e^+e^- (LEP)
  - 27 km circumference
- FCC (proposed)
  - 90 – 350 GeV e^+e^-
  - 100 TeV proton-proton
  - 90-100 km circumference



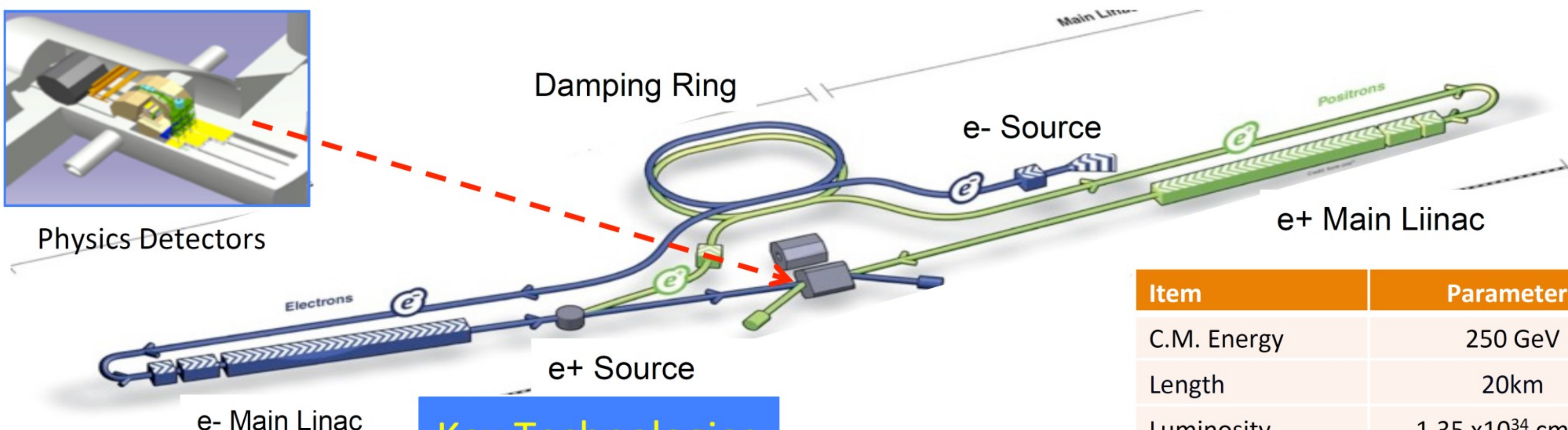
E.g. linear colliders

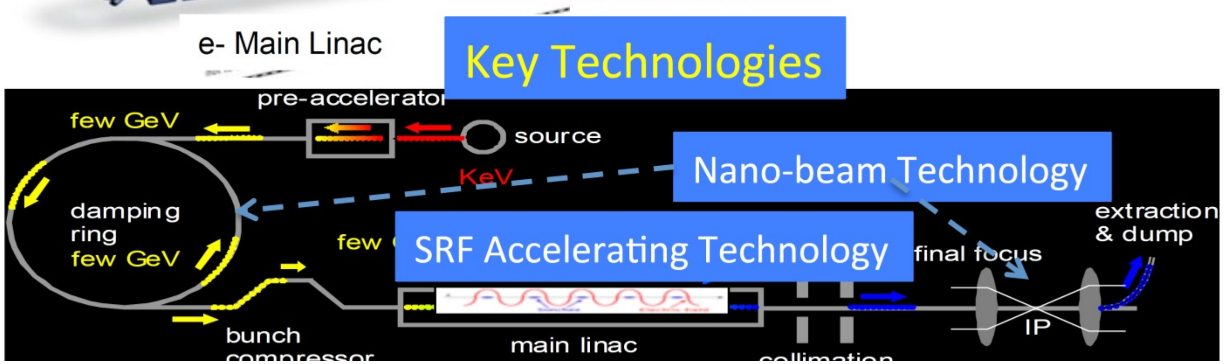
- SLAC (California)
  - 3 km length
  - 90 GeV e^+e^-
- ILC (proposed)
  - 31 km
  - 500 GeV e^+e^-
- CLIC (proposed)
  - 380 GeV e^+e^-
  - 11 km



Electron-positron colliders

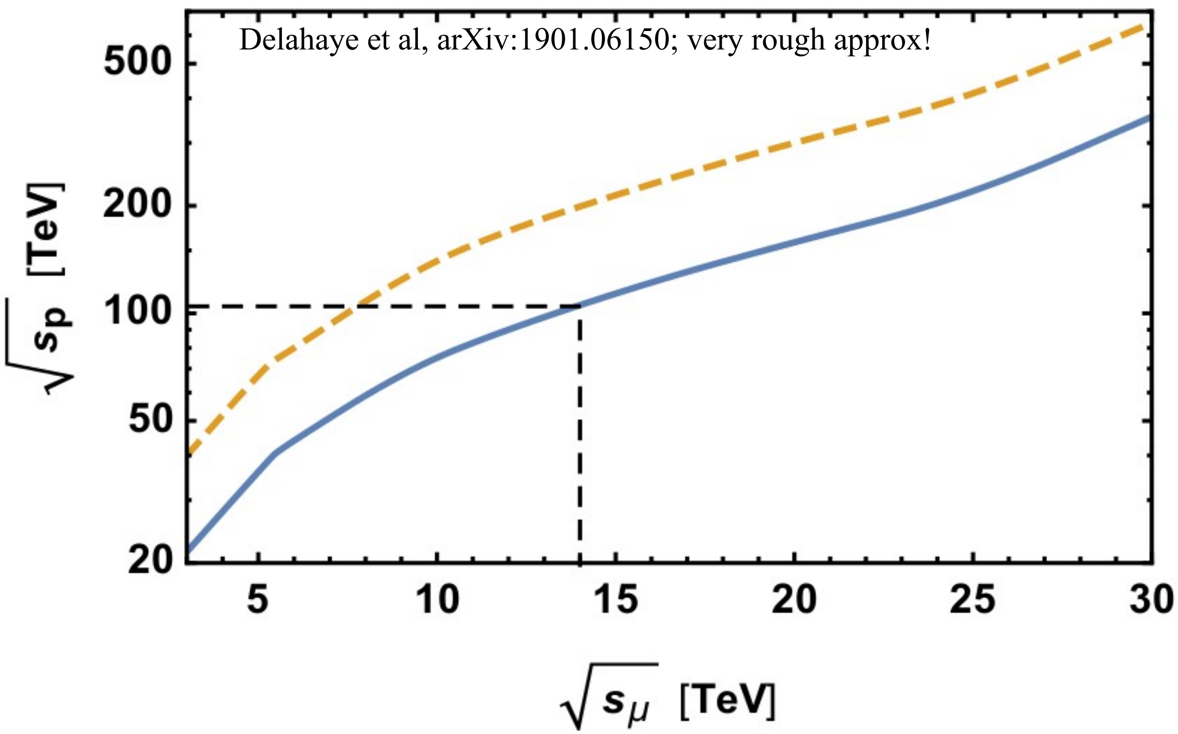
- Circular machines limited by synchrotron radiation
  - Power emitted ~ E^4/m^4
  - Practically limits centre-of-mass energy to ~ 150 GeV
- Linear machines limited by available RF acceleration
  - Practically limits centre-of-mass energy to ~ 100s GeV





Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	**7.7** nm@250GeV
SRF Cavity G.	**31.5** MV/m

What about protons?



Energy at which cross-section is equal

Assuming equal Feynman amplitude (EW)

Assuming factor 10 enhancement in pp (EW+QCD)

- Proton collision energy is shared between quarks
  - Effective energy significantly reduced
- Seek a particle which
  - Is not so low mass as an electron
  - Is a fundamental particle
- **Muons!**

Muons

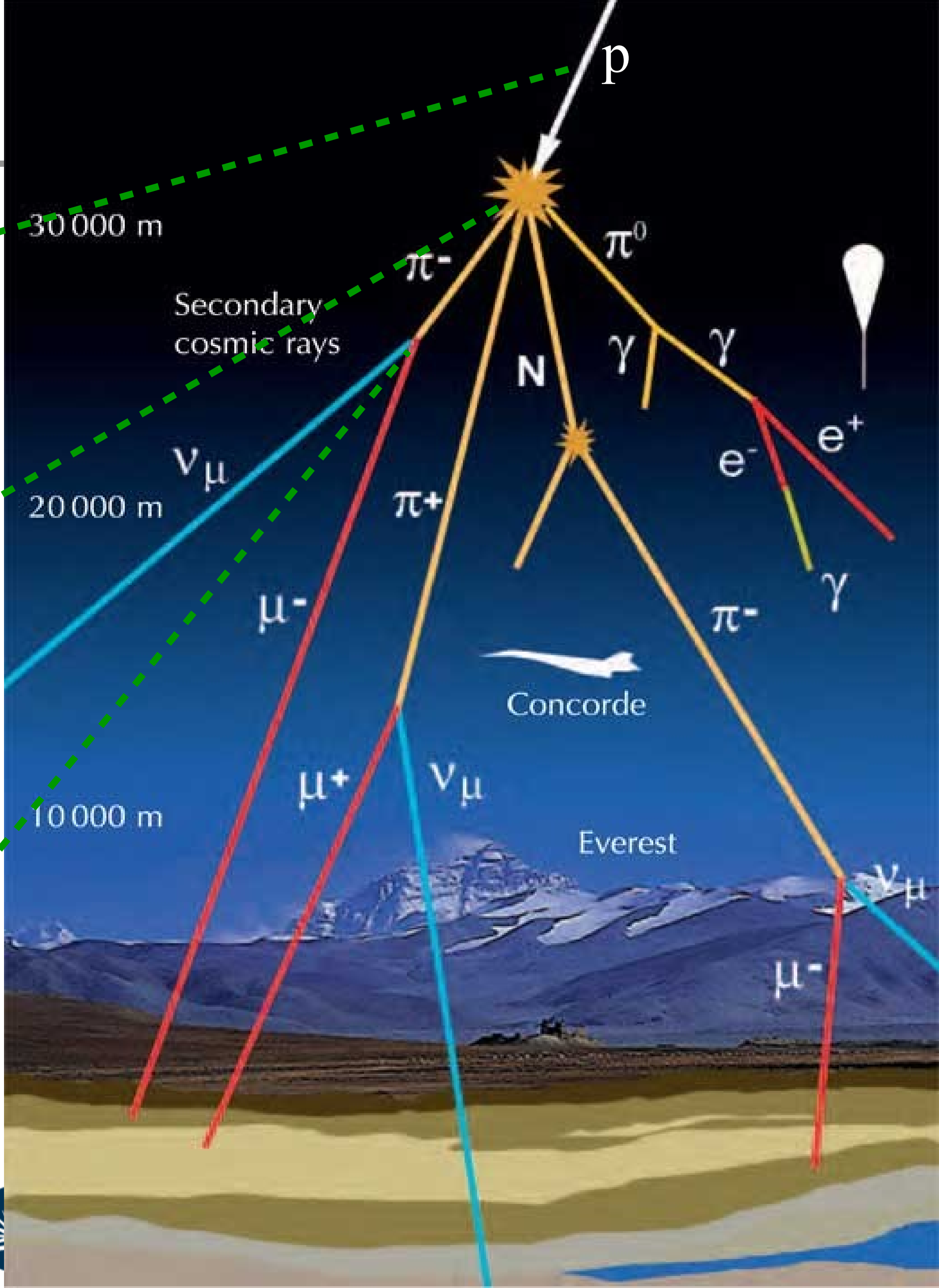
- Muon
  - Half-life 2.2 μs
  - Mass 105.658 MeV/c
  - 207 times electron mass

Muons are Common

Proton or ion strikes atmosphere

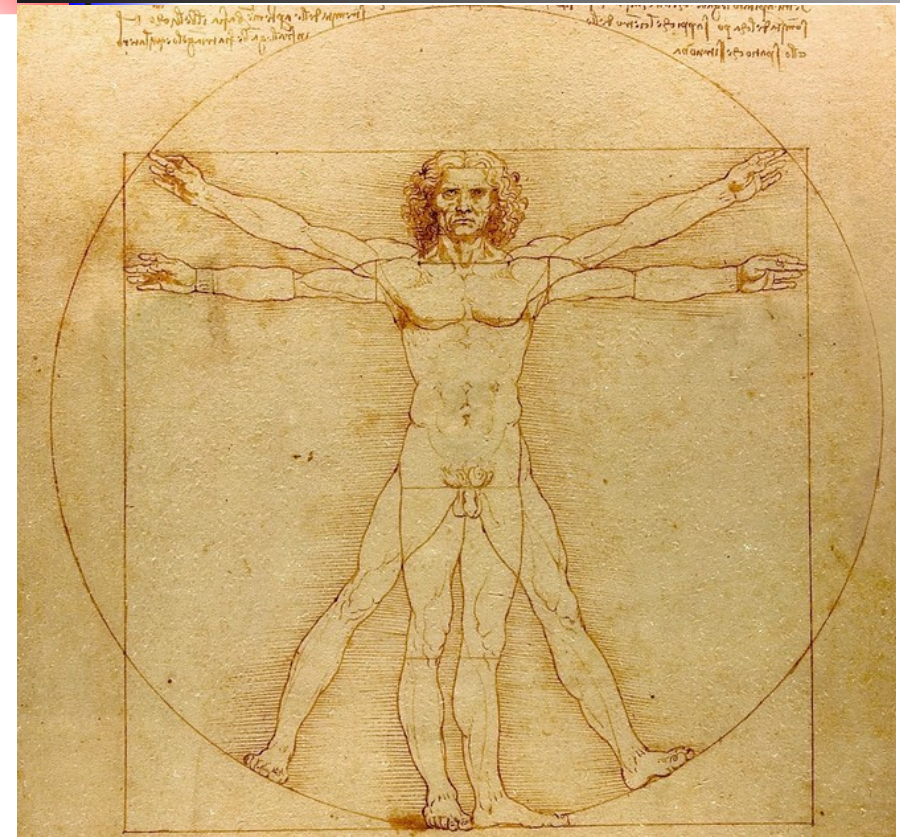
Proton breaks up nucleus in air atom, making a pion

Pion decays radioactively to make a muon



About 1 muon per second crosses your body

Muons are Rare!



10^{27} atoms
1 muon per second

- 10^{27} metres → size of the observable universe
- 10^{27} kg → mass of Jupiter
- 10^{27} Joules → energy to evaporate all water on earth
- How can we make a collider?

The Muon Collider

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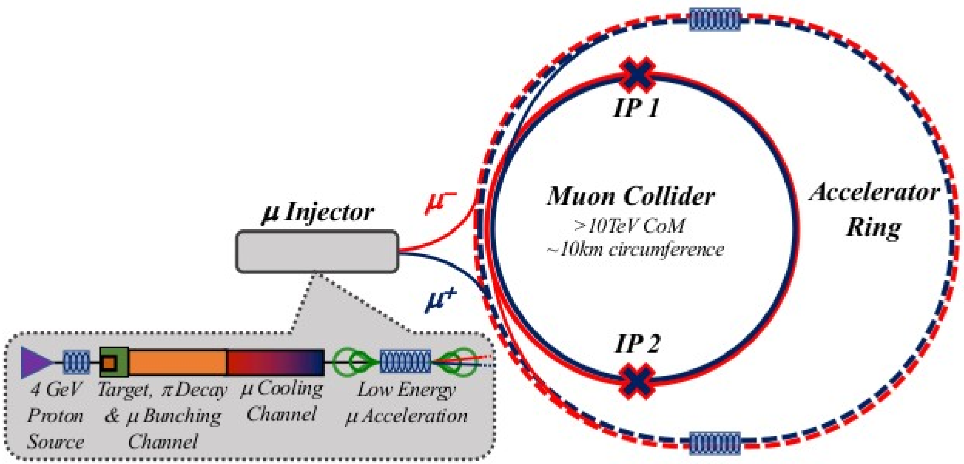
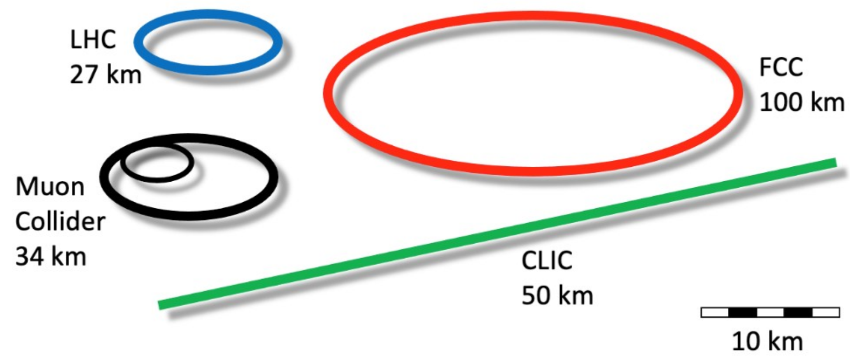
Muon Collider





- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Critical Issues:
  - High initial beam emittance
  - Short muon lifetime
  - Neutrino radiation
  - Detector Beam induced Background

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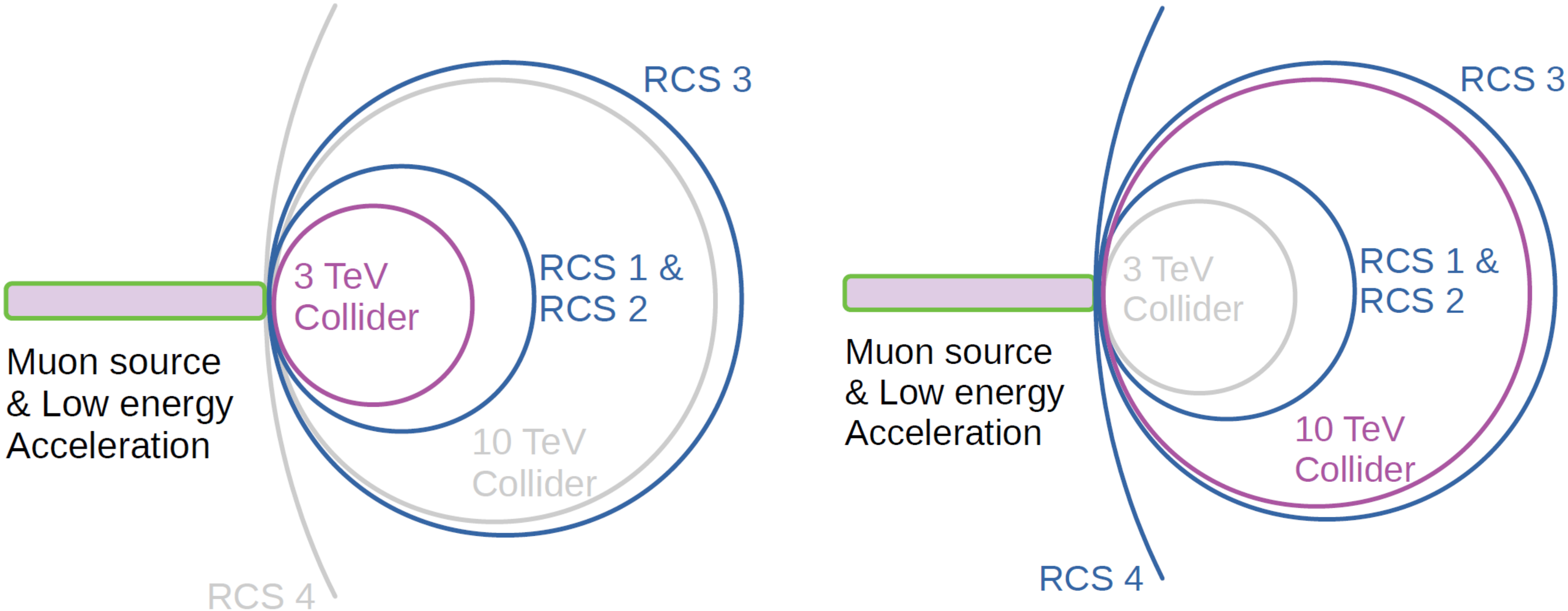
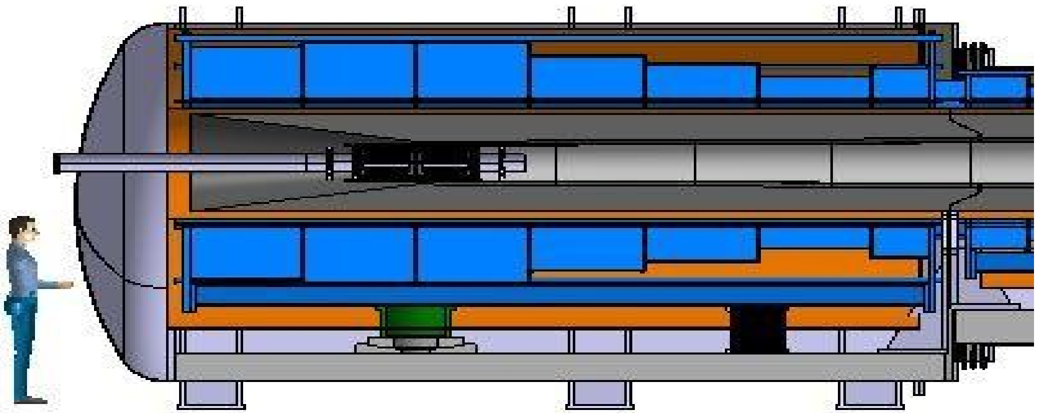
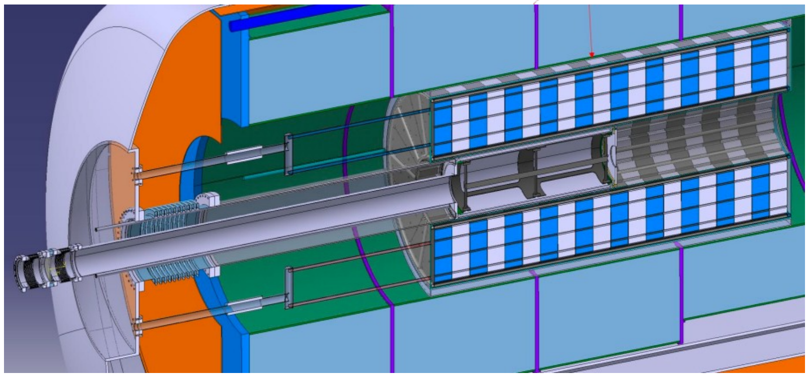
Muon Collider - Staging



- Staging → active discussion
- Energy staging
  - 3 TeV initial stage (2040s) @ ~10 T collider ring
  - 10 TeV second stage (2050s) @ ~16 T collider ring
- Luminosity staging
  - 10 TeV initial stage (2040s) @ ~10 T collider ring
  - Luminosity upgrade misses target luminosity by ~ 30 %

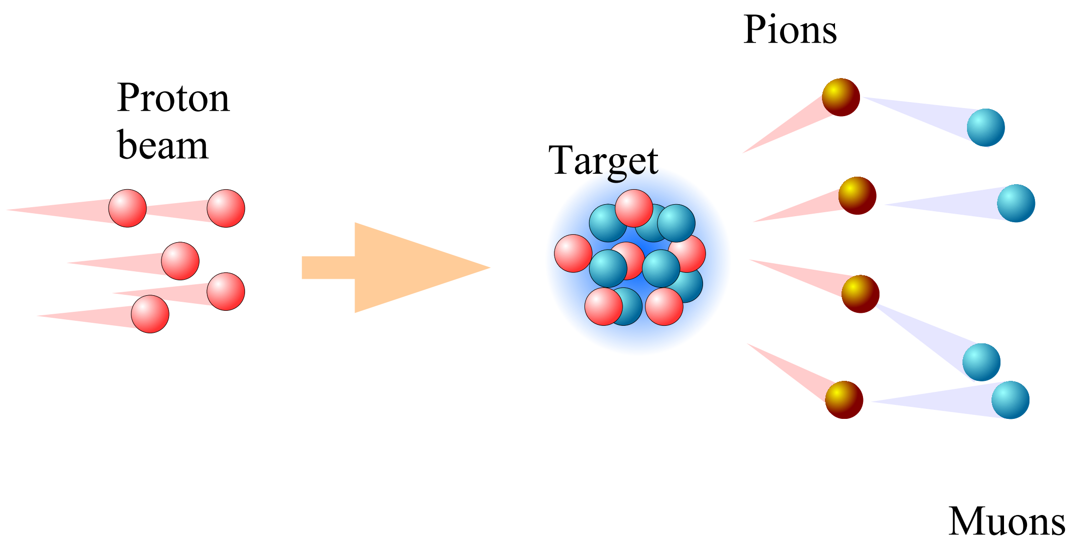
MuC Target





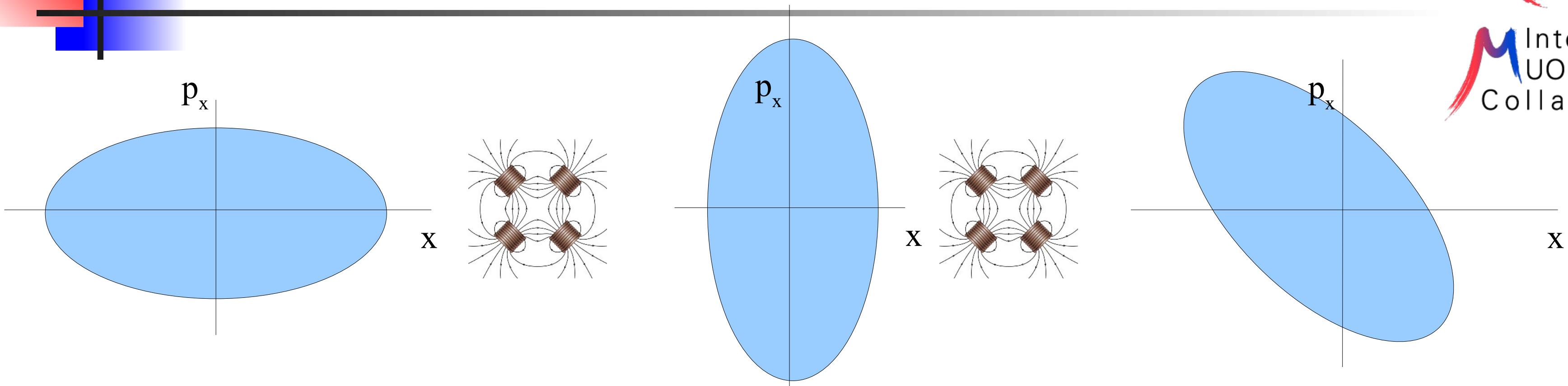
- Protons on target → pions → muons
  - Graphite target takes proton beam to produce pions
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Target similar to T2HK/Dune Phase 2
- Solenoid comparable to spherical tokamak solenoids

Beam brightness



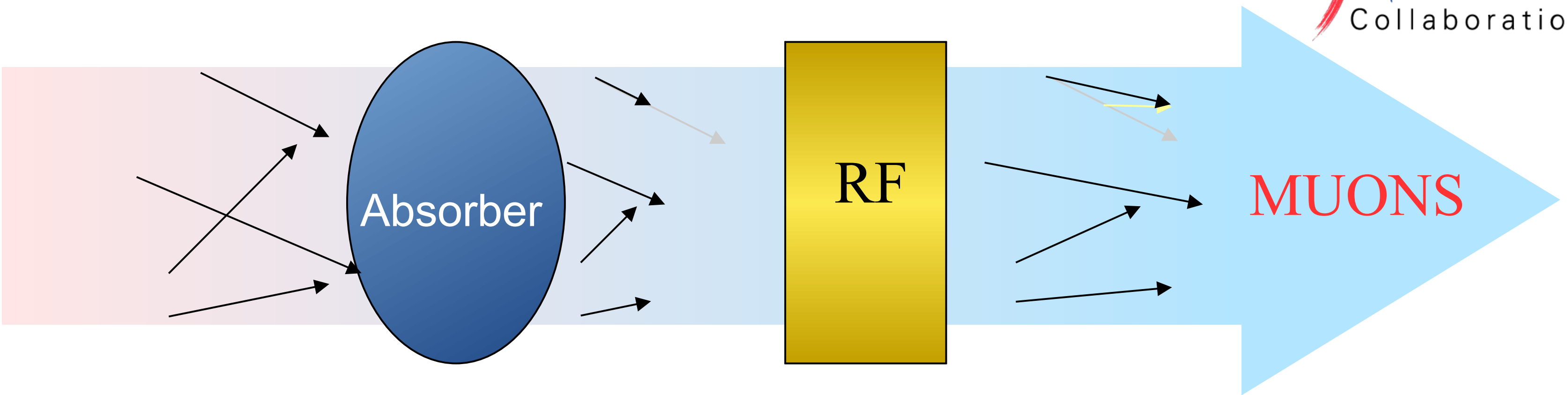
- Orderly beam of protons
- Pions leave the target in many directions
- Pions decay in many different positions
- Low brightness beam
- High emittance beam

Beam Emittance



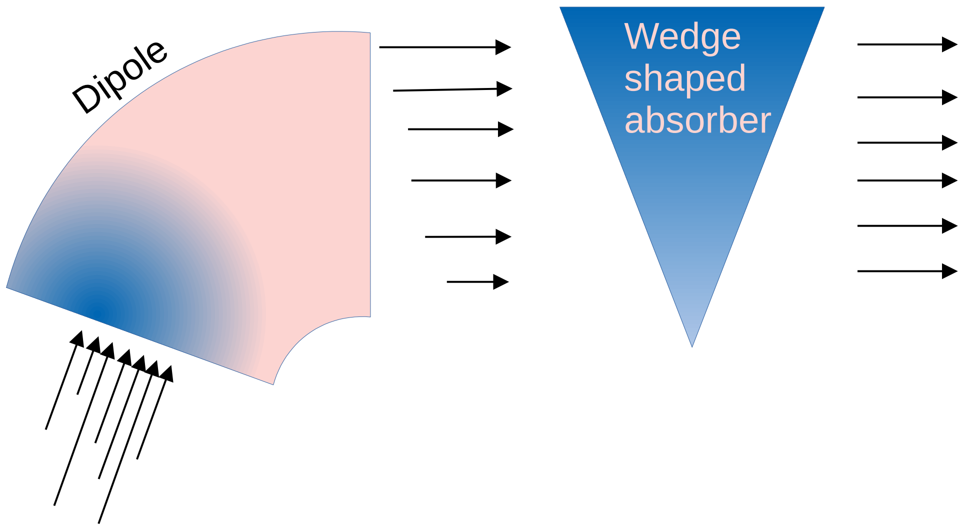
- Consider a beam traversing some quadrupole focussing
  - Beam width is reduced
  - Transverse momentum spread is increased
- Or quadrupole defocussing
  - Beam width is increased
  - Transverse momentum spread is reduced
- Area (emittance ε) in (x, p_x) phase space is conserved
- Volume in (x, p_x, y, p_y, t, E) space is in general conserved by accelerator focussing systems
  - Consequence of Liouville's theorem
- Initial muon beam has very large emittance → capture and 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

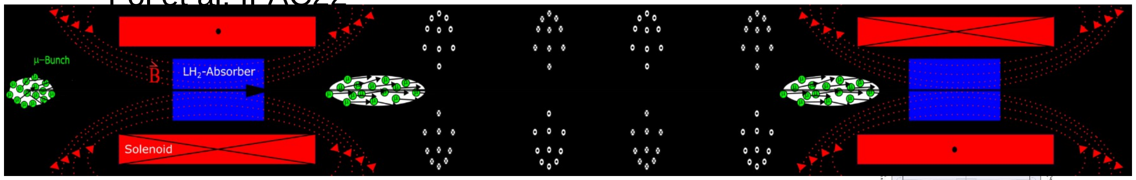
Emittance exchange

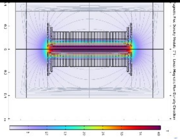


- Initial beam is narrow with some momentum spread
  - Low transverse emittance and high longitudinal emittance
- Beam follows curved trajectory in dipole
  - Higher momentum particles have higher radius trajectory
  - Beam leaves dipole wider with energy-position correlation
- Beam goes through wedge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

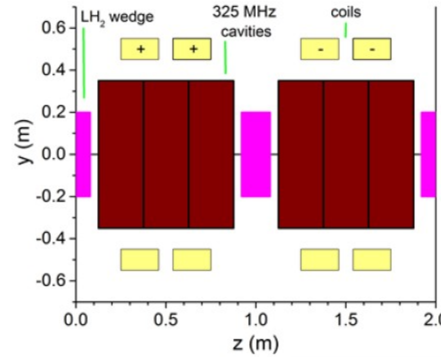
Muon Cooling

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





4D Final cooling



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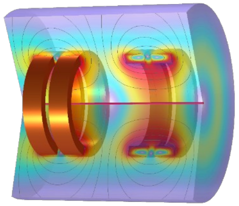
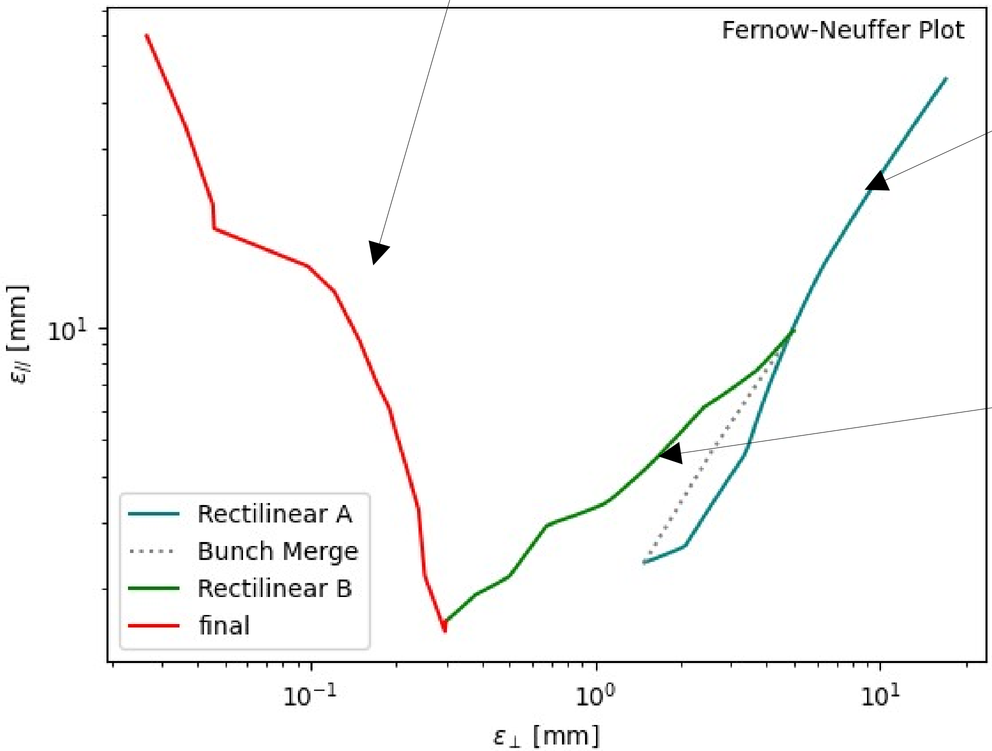
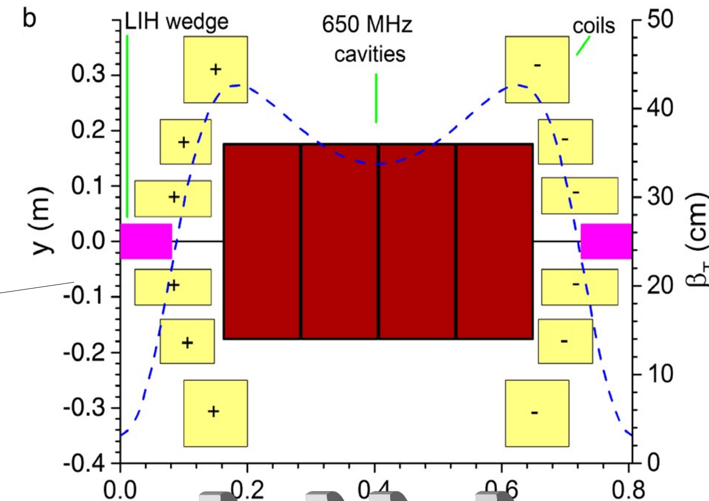


Rectilinear cooling



Stratakis et al, PRSTAB 18, 2015
Zhu et al, COOL23



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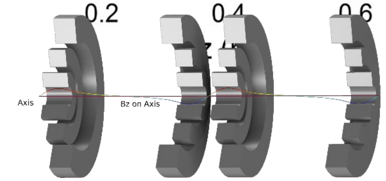
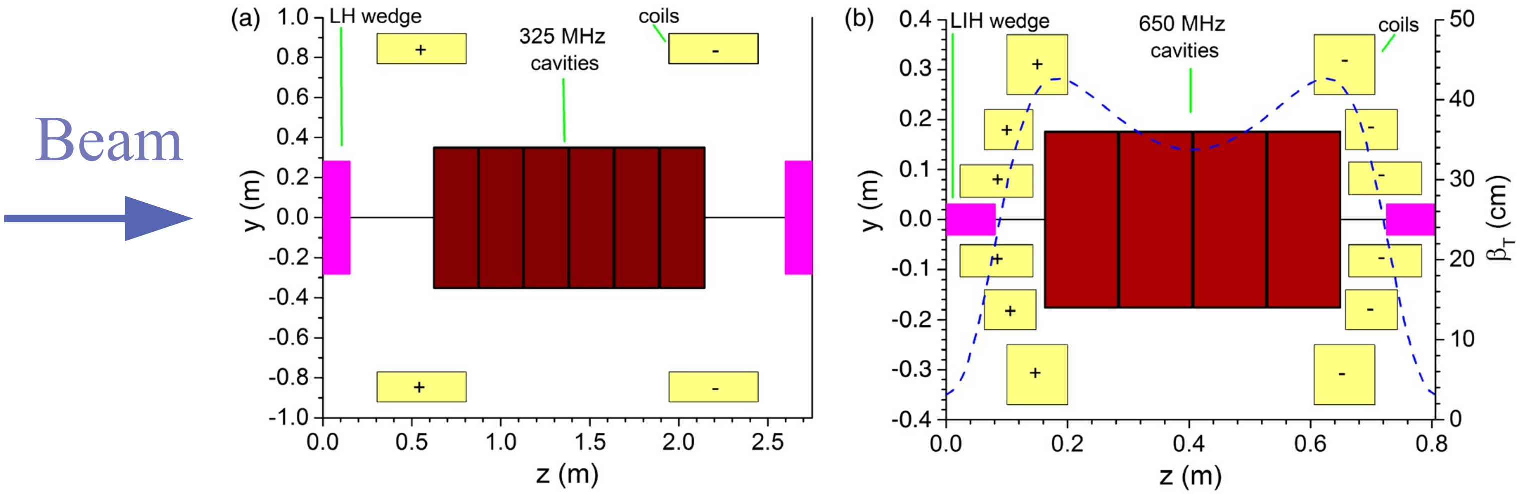


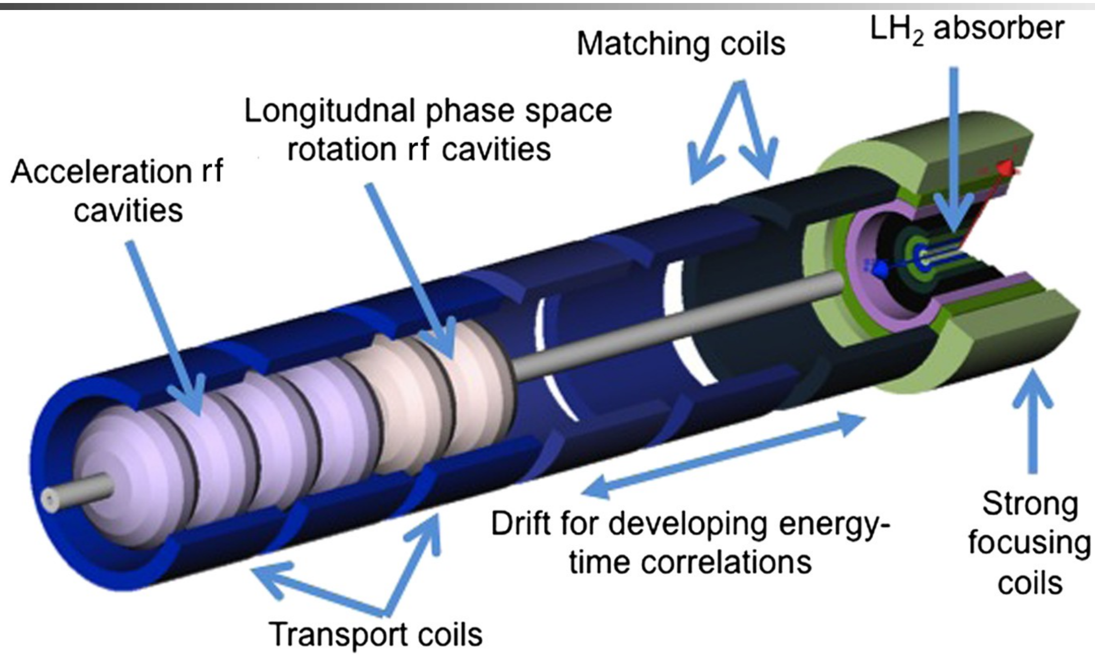
Rectilinear Cooling



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
  - Compact lattice – RF integrated into magnet cryostat
  - Lithium Hydride or lH2 absorbers
  - Careful field shaping to control position of stop-bands

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

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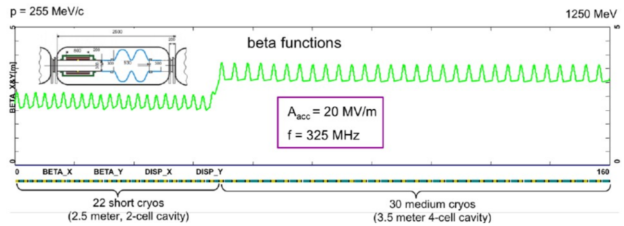
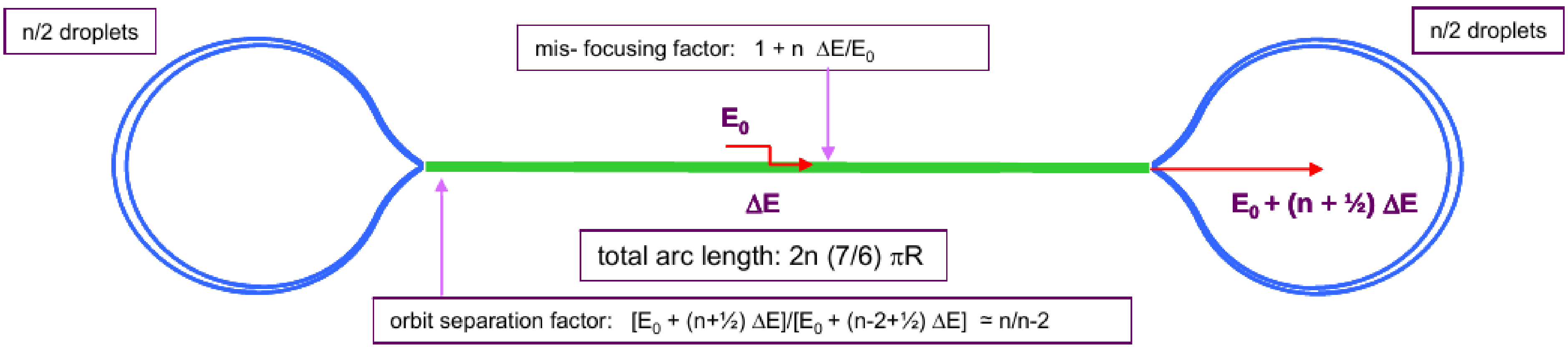
Acceleration – Linac and RLA





- First acceleration – use linac
  - Get highest real-estate gradient
- At higher energies – recirculate through the linac
  - More efficient use of equipment
  - Need to pay attention to (mis)focusing effects and timing with RF

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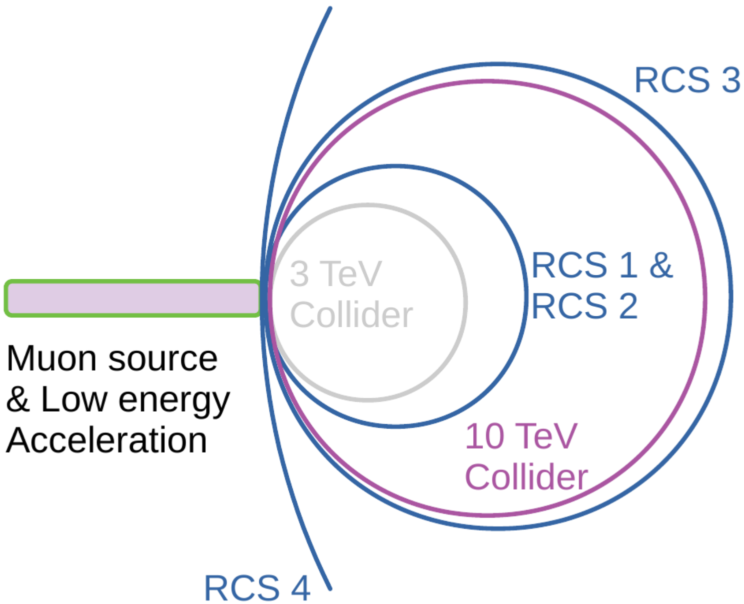
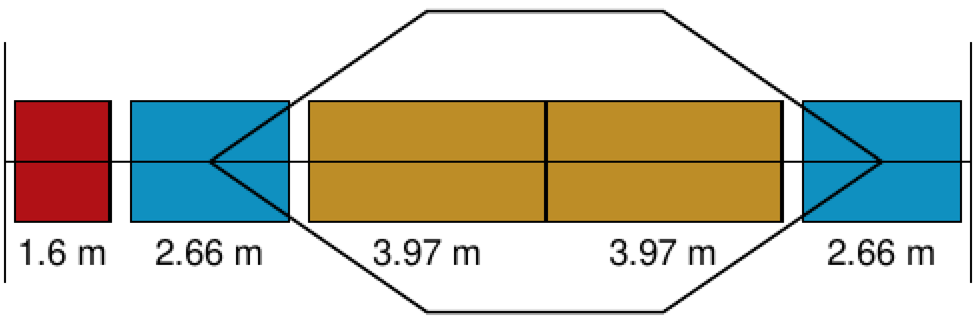
Pulsed Synchrotrons





- At higher 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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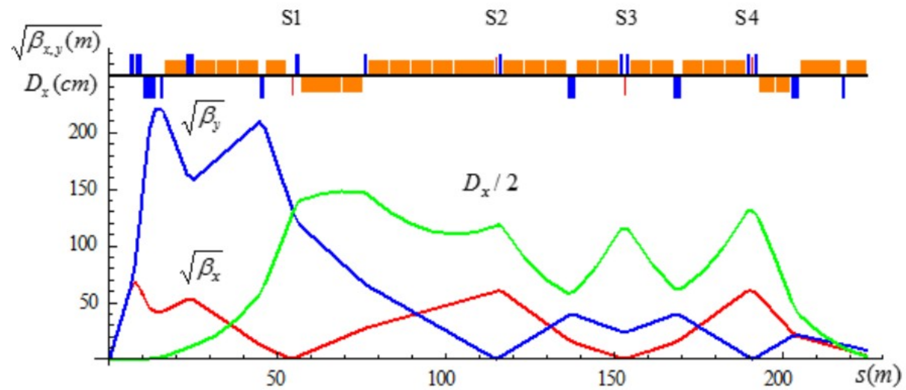
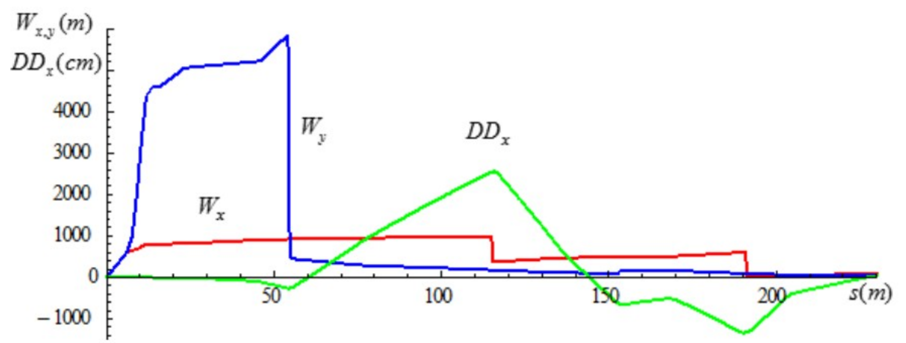
Collider ring

- Luminosity increases for shorter collider ring
  - Seek to achieve highest possible mean dipole field
  - Low radius, many bunch crossings before decay
- Luminosity increases for tight final focusing
  - Correction for chromatic aberrations $\rightarrow$ focusing strength vs energy
  - Require very short bunches $\rightarrow$ whole bunch at the focus at same time





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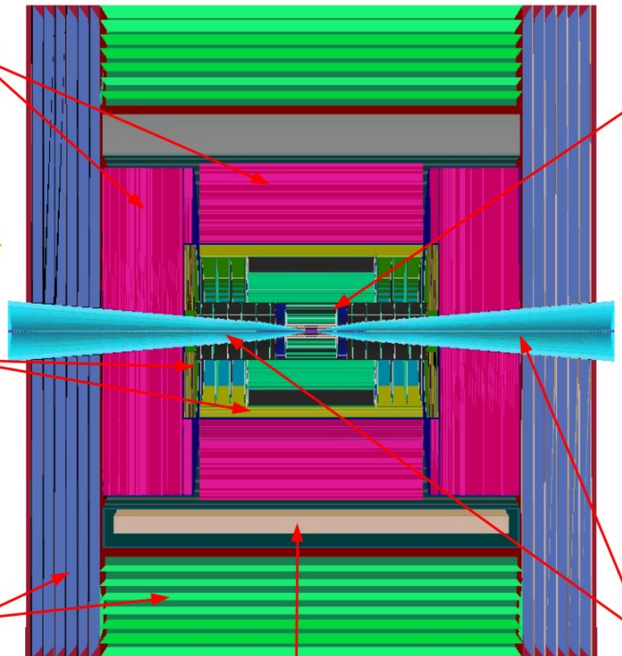
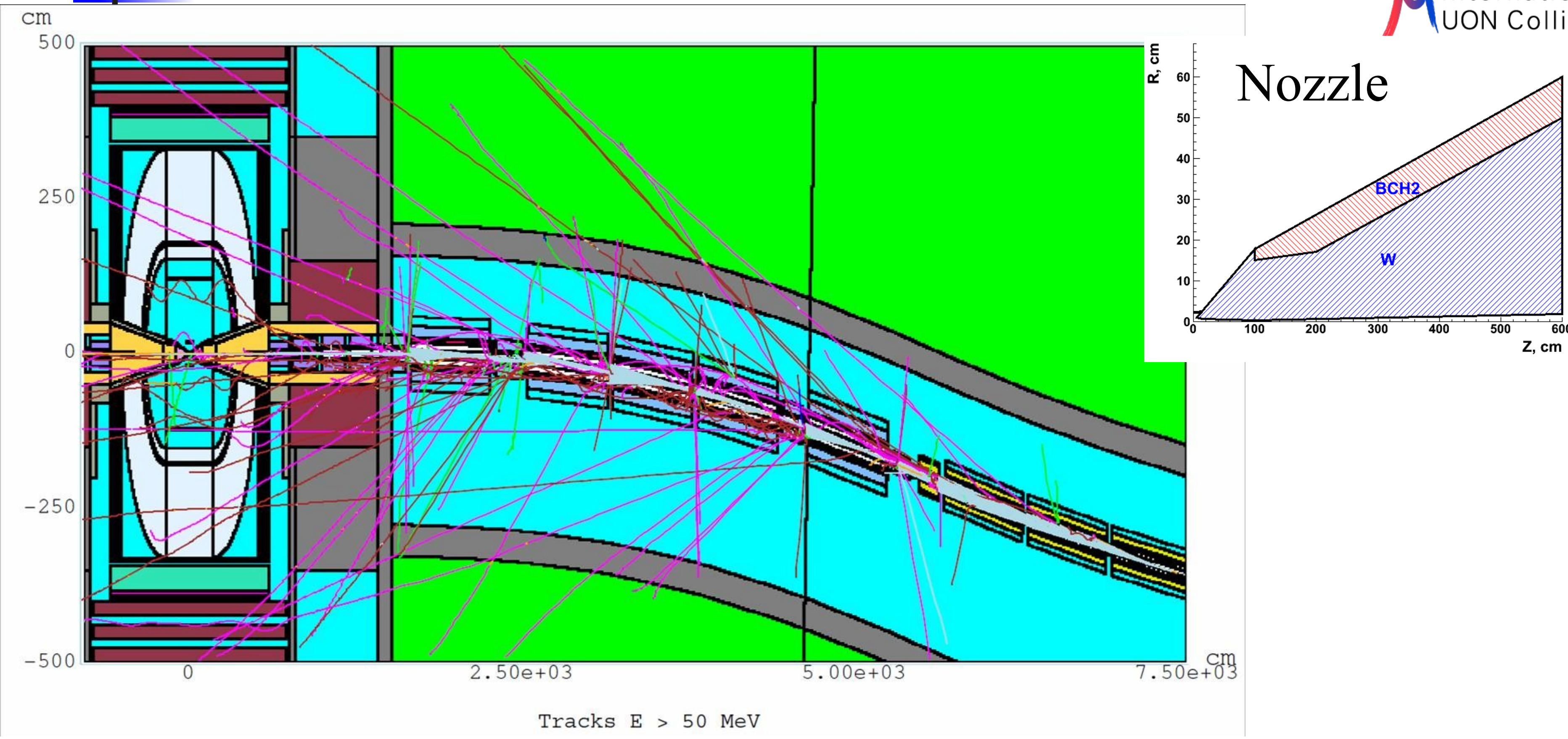
Muon Collider Detector (3 TeV)



- Muon collider
  - Rather standard detector arrangement
  - Based on e^+e^- detector
  - Significant shielding nozzles required

Muon Collider - BIB



- Beam induced background (BIB) arising due to muon decays
- Shield detector from direct radiation
- Timing cut to remove background

Muon Collider – Facility Parameters

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

- Luminosity follows roughly ~ E^2
  - Beam size shrinks as energy increases
- Factor two surplus luminosity *on paper*
  - Compared with e.g. FCC-hh

Muon Collider – Detector Parameters

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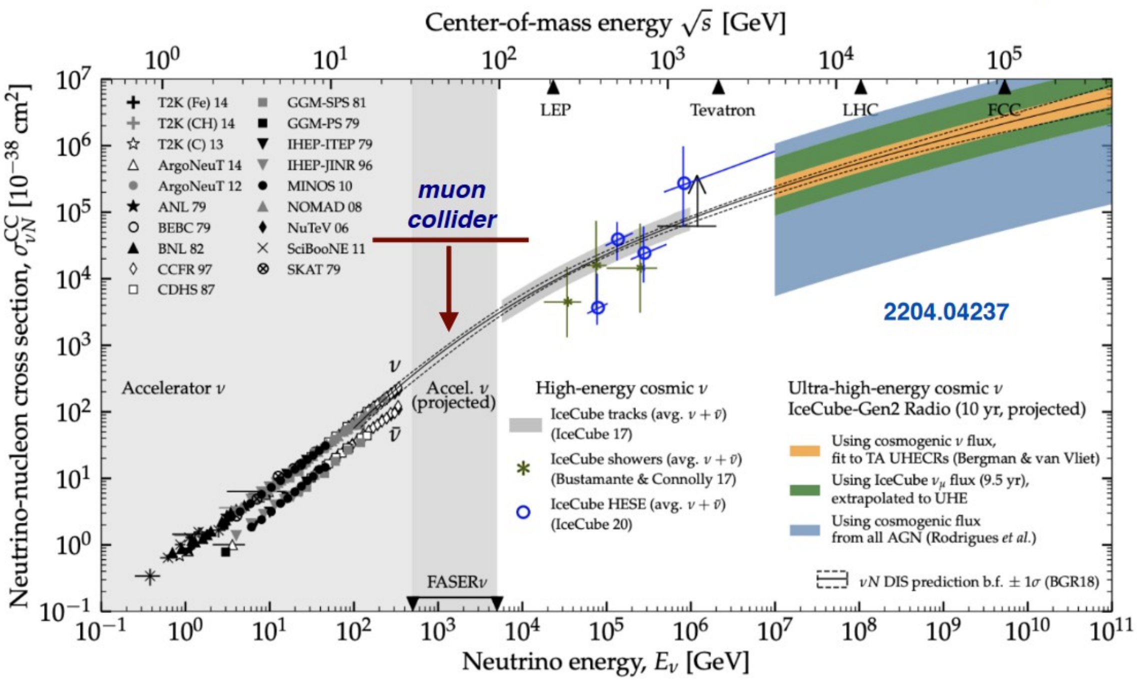
Requirement	Minimal		Aspirational
	$\sqrt{s}=3$ **TeV**	$\sqrt{s}=10$ **TeV**	
Angular acceptance	$\eta < 2.5$	$\eta < 2.5$	$\eta < 4$
Minimum tracking distance	~ 3 cm	~ 3 cm	< 3 cm
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2	4×10^{-5} GeV^{-1}	4×10^{-5} GeV^{-1}	1×10^{-5} GeV^{-1}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker)	$\sim 30(60)$ ps	$\sim 30(60)$ ps	$\sim 10(30)$ ps
Timing resolution (calorimeters)	100 ps	100 ps	10 ps
Timing resolution (muon system)	~ 50 ps for $\eta > 2.5$	~ 50 ps for $\eta > 2.5$	in progress
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

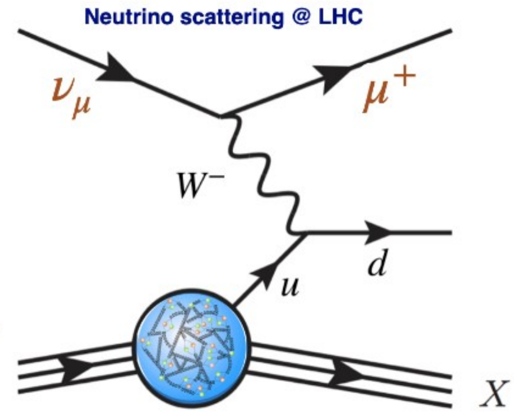
- Detector requirements are demanding but achievable

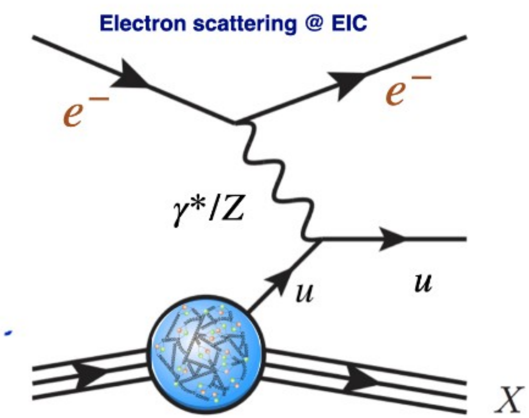
Neutrino beams – blessing and curse

- 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







- Muon collider neutrinos make a charged current analogue of the EIC
  - Huge neutrino flux O(10^{11}) per second @ TeV

Muon Accelerator R&D

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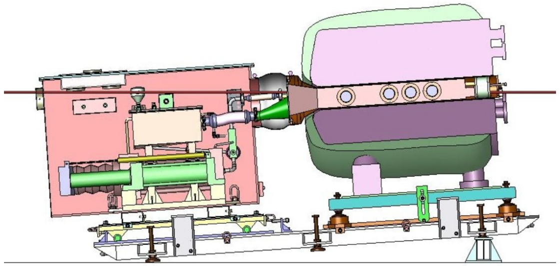
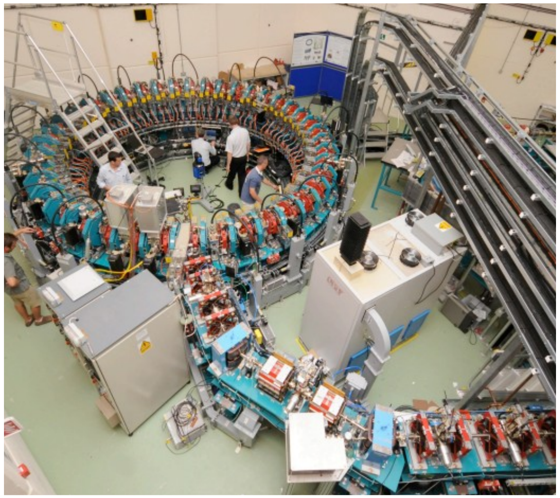
Muon Accelerator R&D

- 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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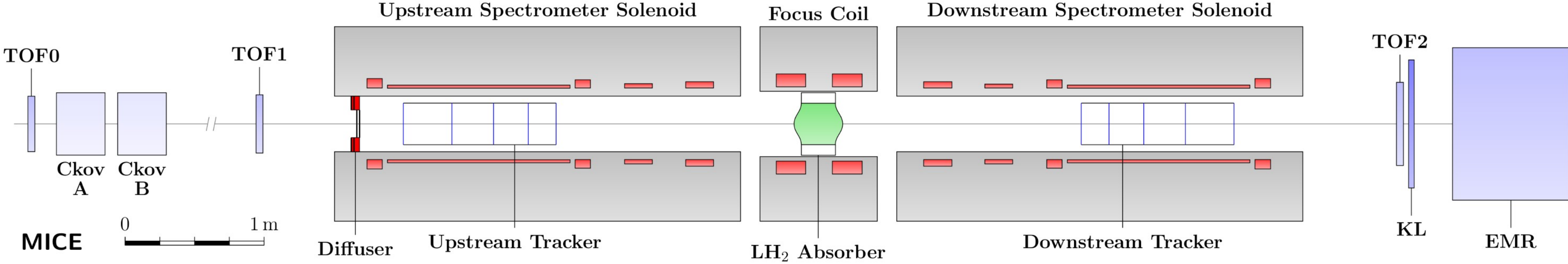

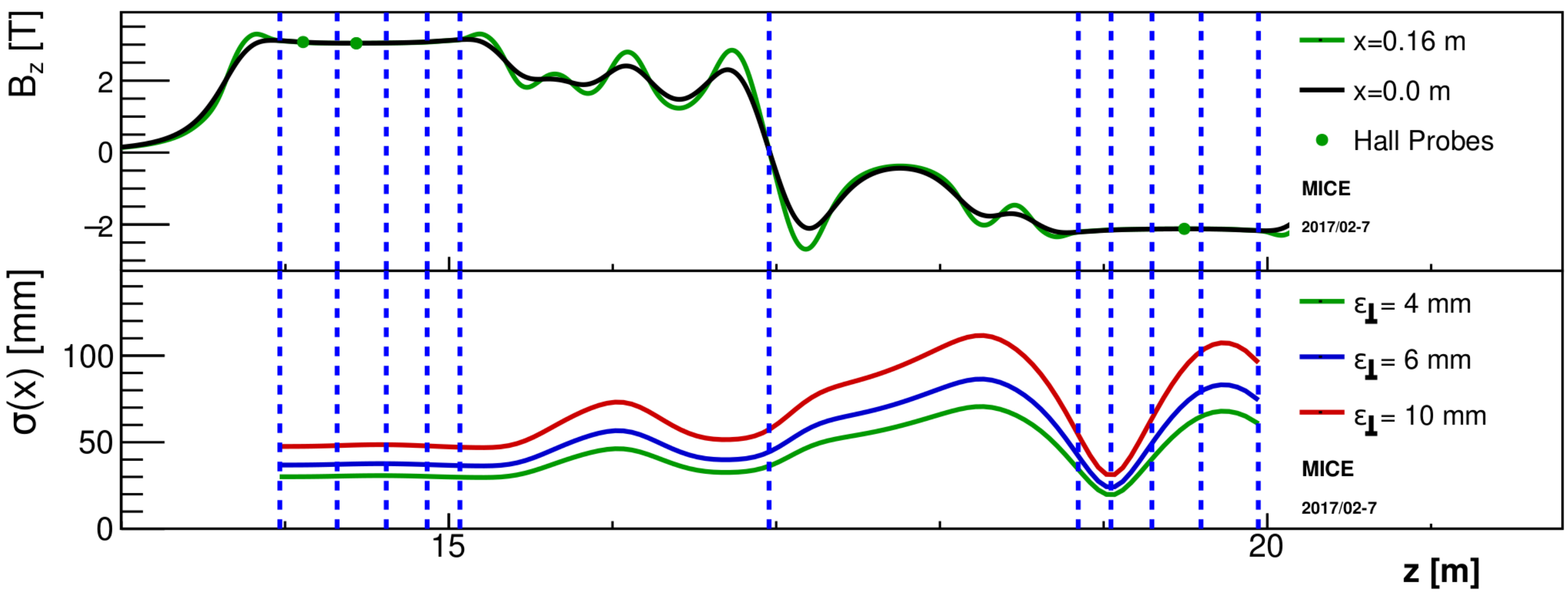

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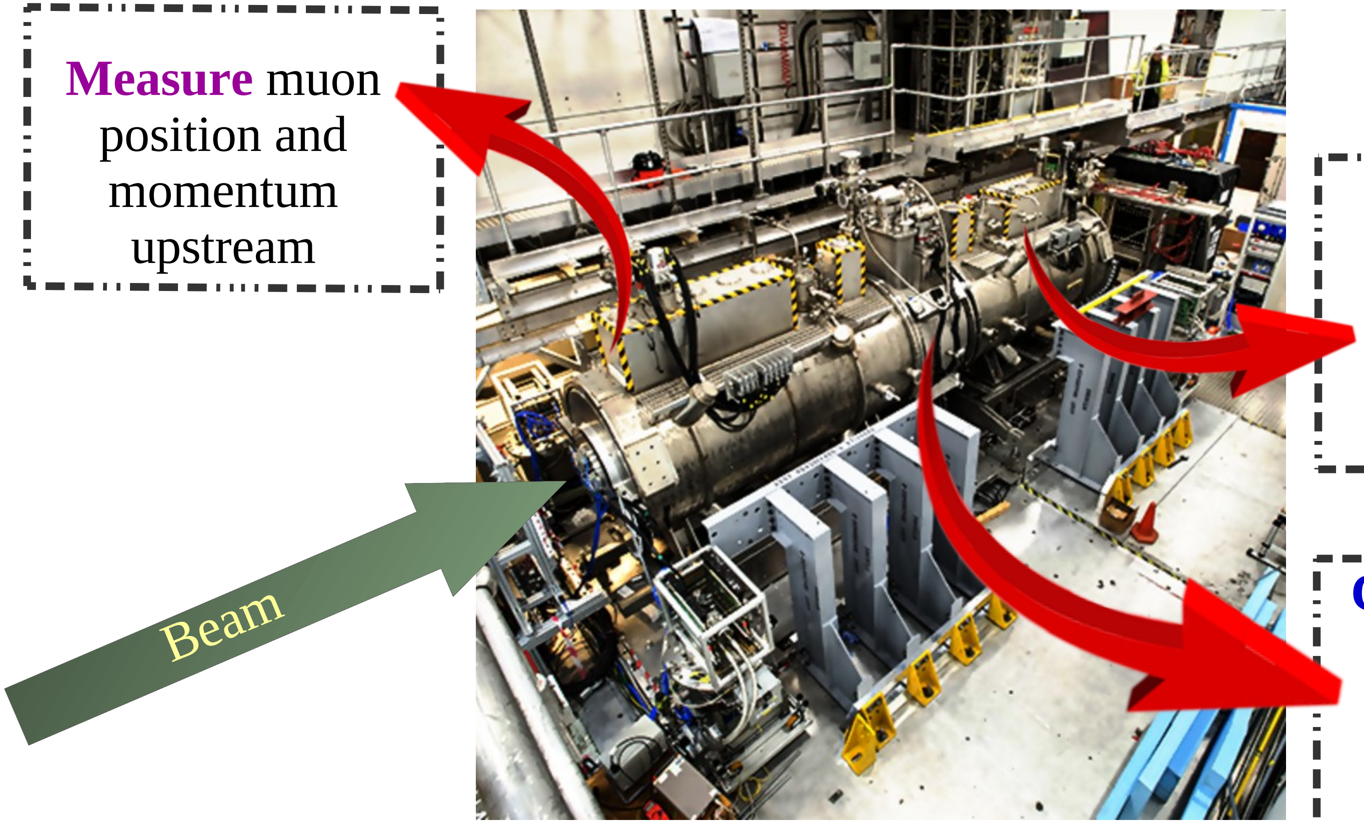
Experimental set up

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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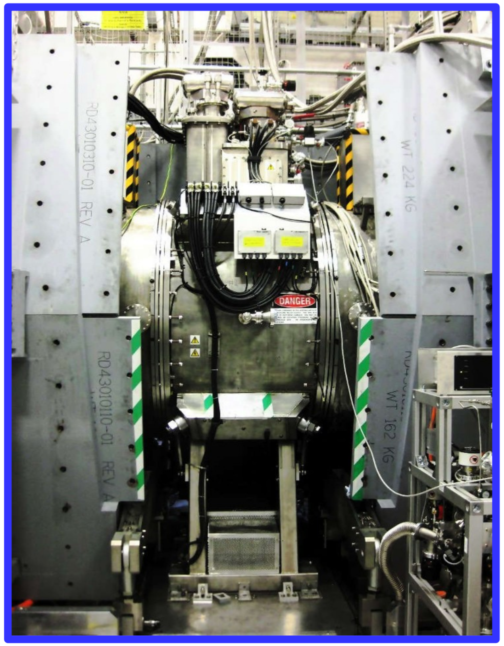
Superconducting Magnets

International MUON Collider Collaboration



- 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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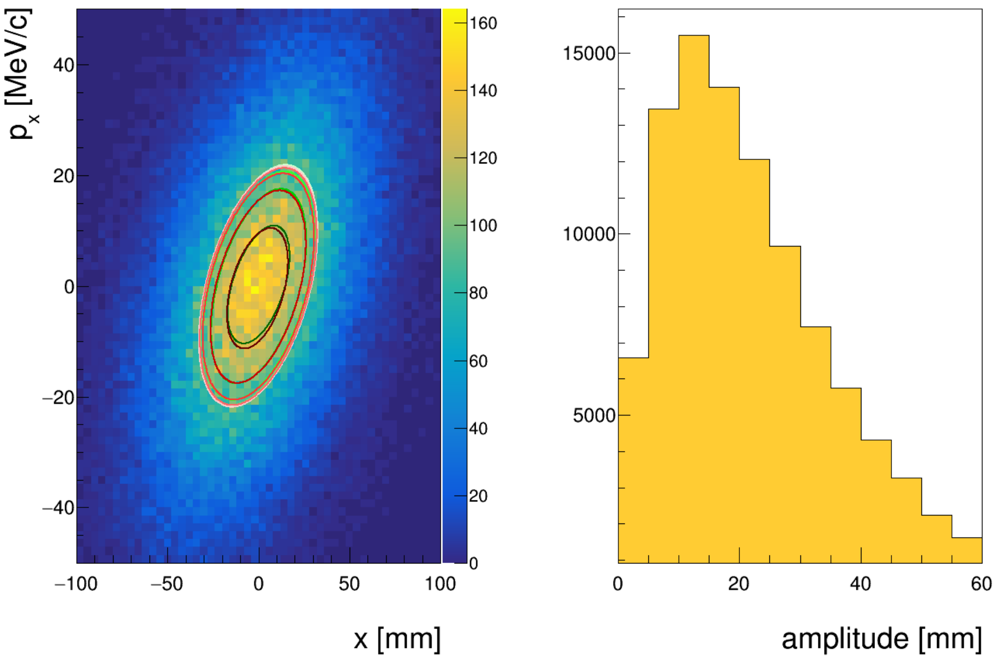
Absorber

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

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

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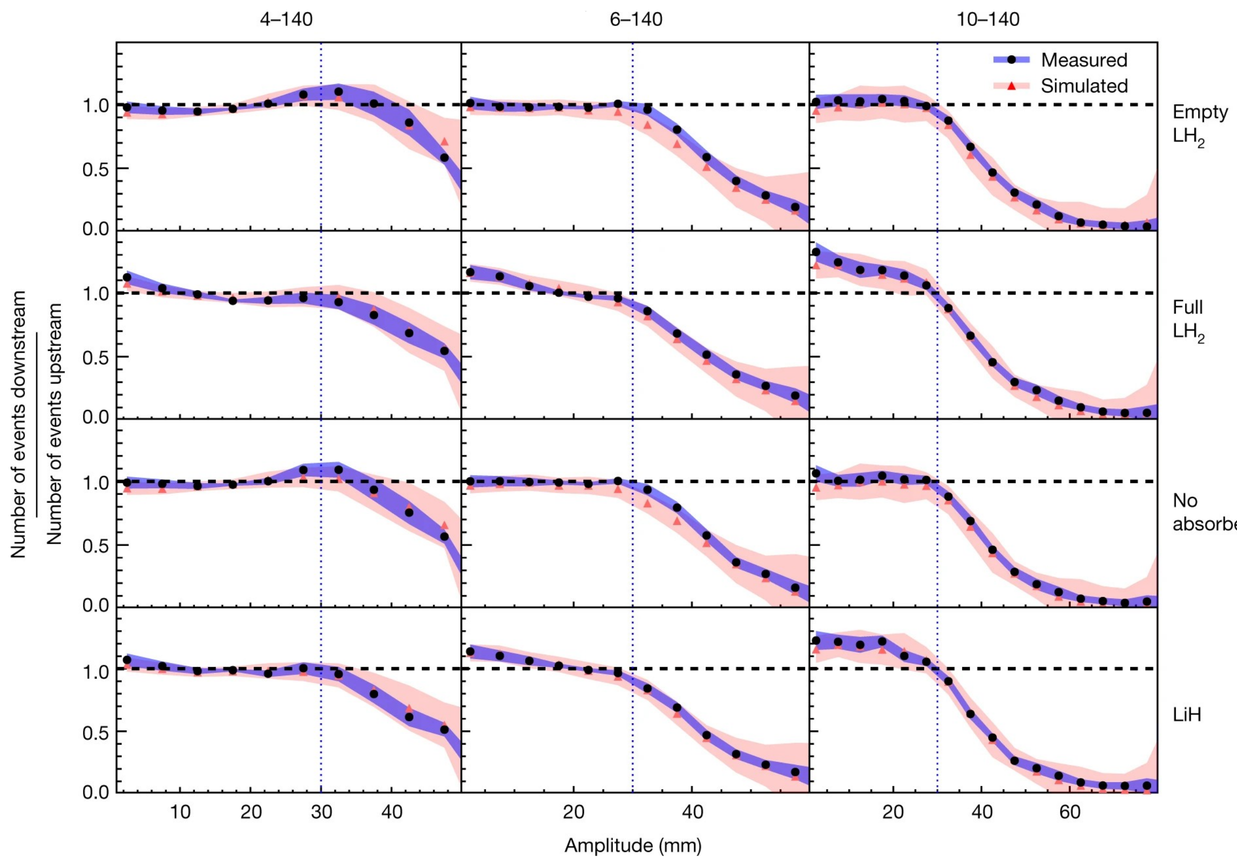
Demonstration of cooling by the Muon Ionization Cooling Experiment

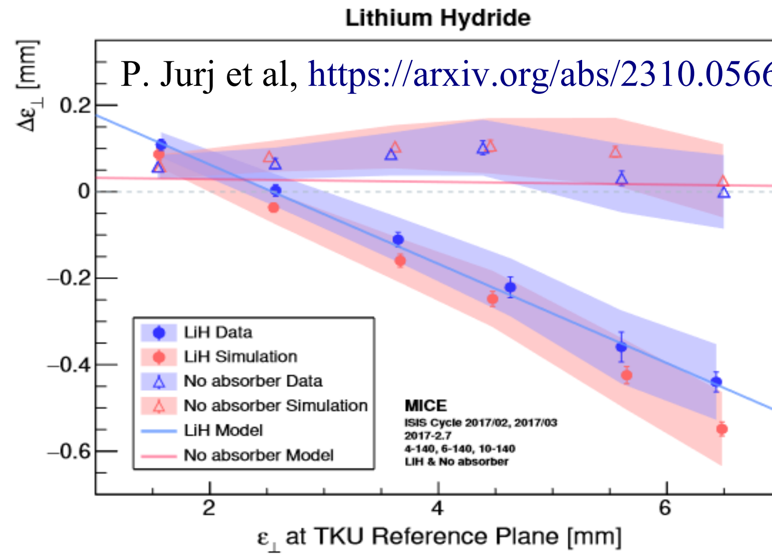
MICE collaboration

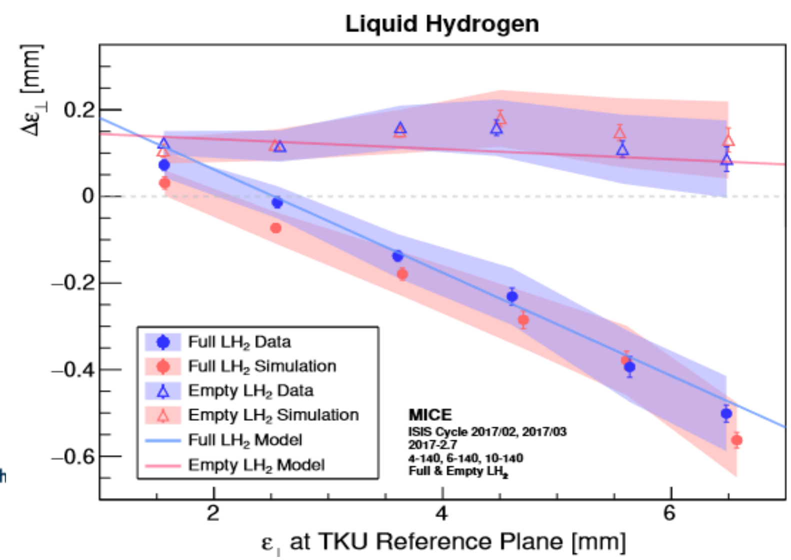


Emittance reduction

- When absorber installed:
  - Cooling above equilibrium emittance
  - Heating below equilibrium emittance
- When no absorber installed
  - Optical heating
  - Clear heating from Al window
- Breaking news!
  - Accepted for publication in Nat. Phys.

P. Jurj et al, https://arxiv.org/abs/2310.05669





The Muon Collider – Future R&D

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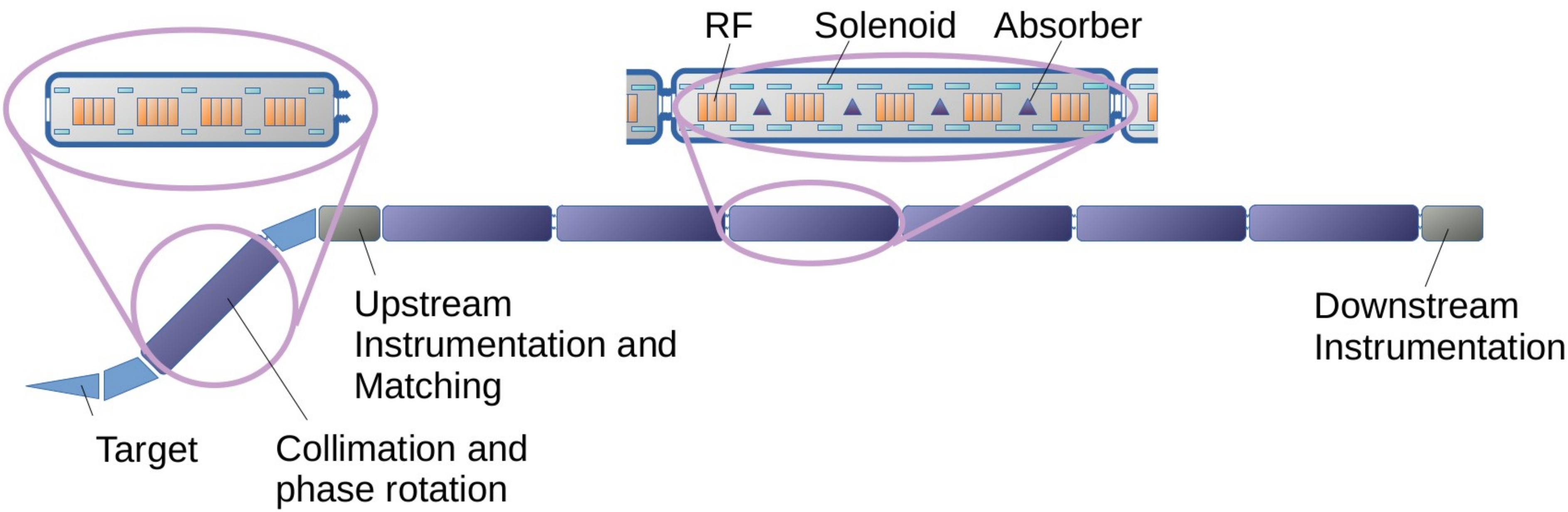
Cooling Demonstrator



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

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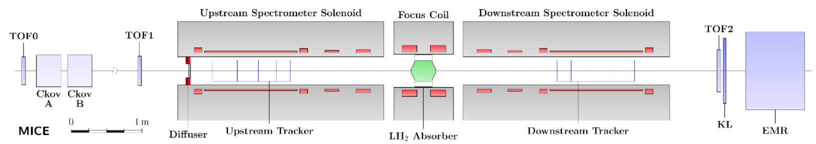
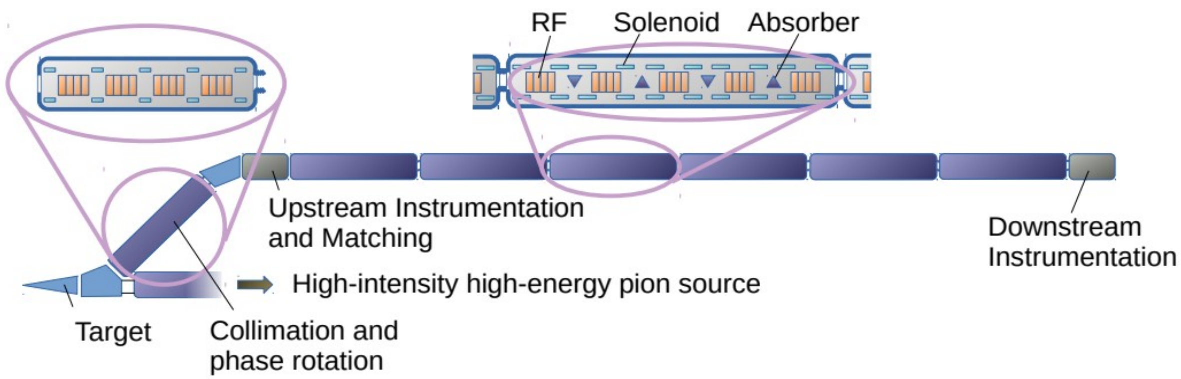
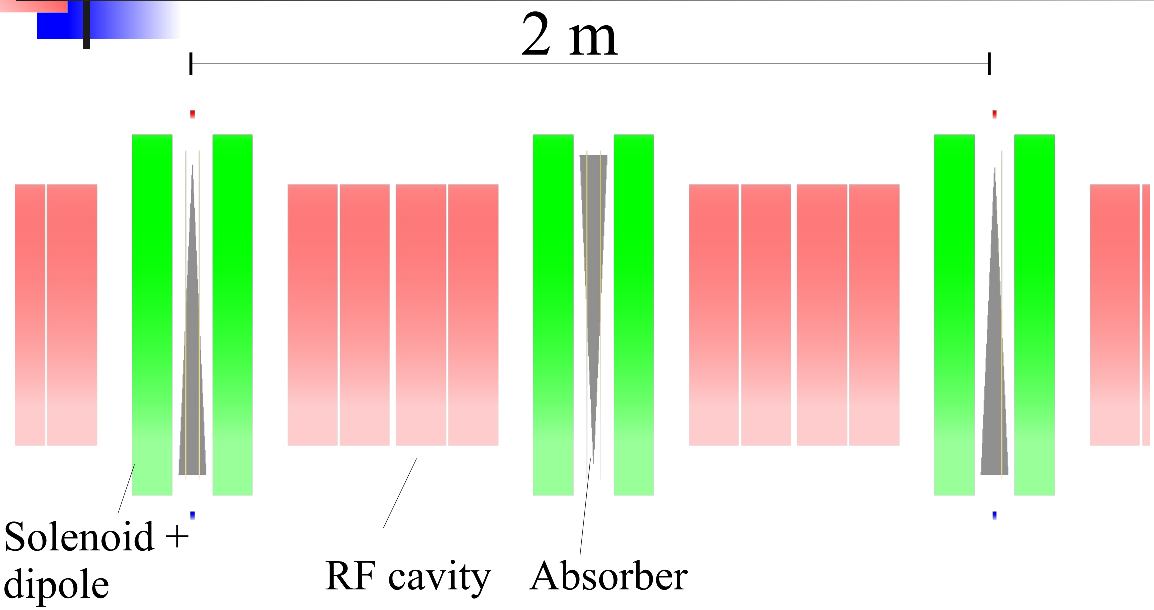
Comparison with MICE



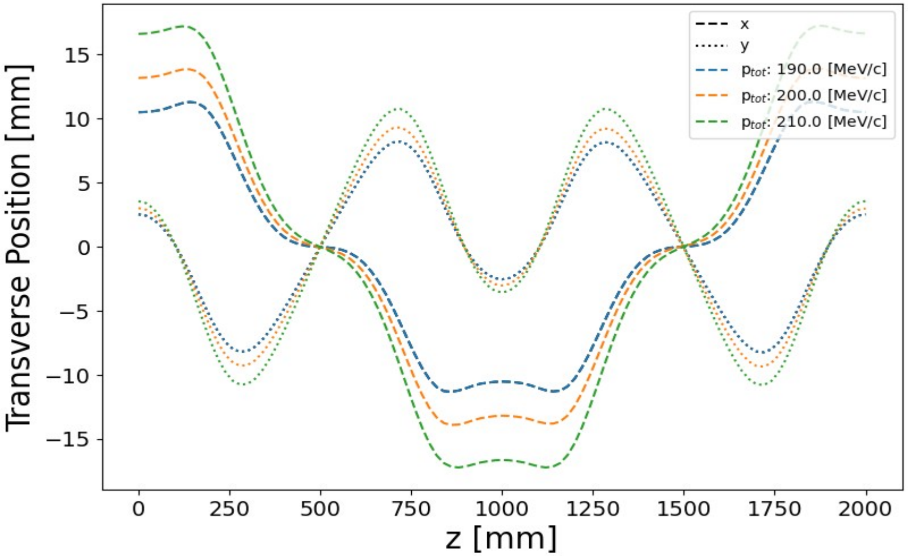


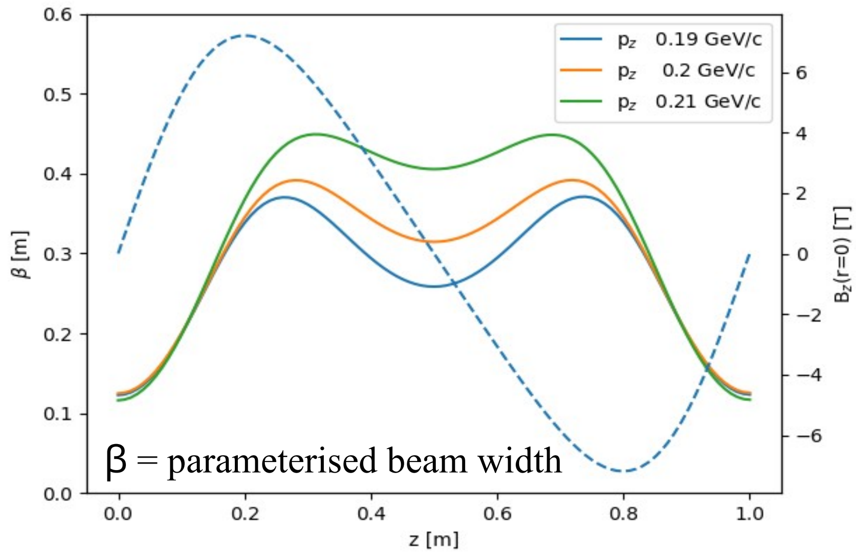
	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

Cooling Cell Concept



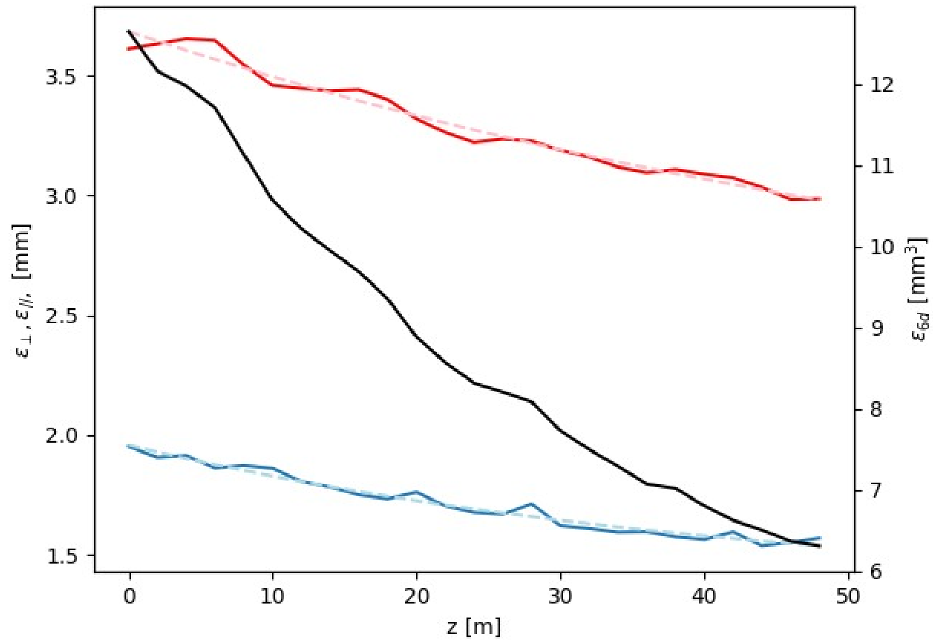
Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH





Performance

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



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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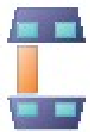
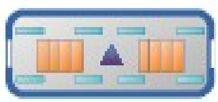
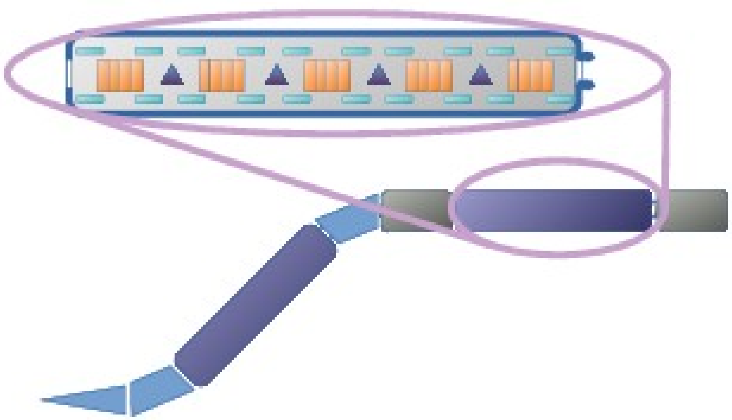
Muon cooling - plan



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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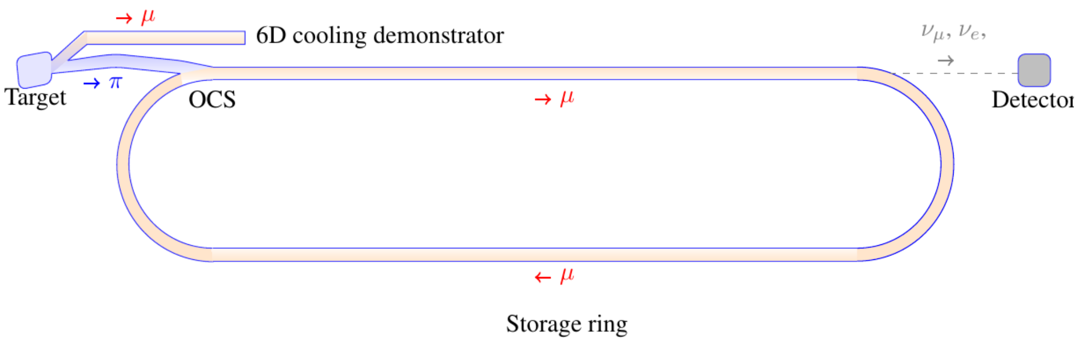
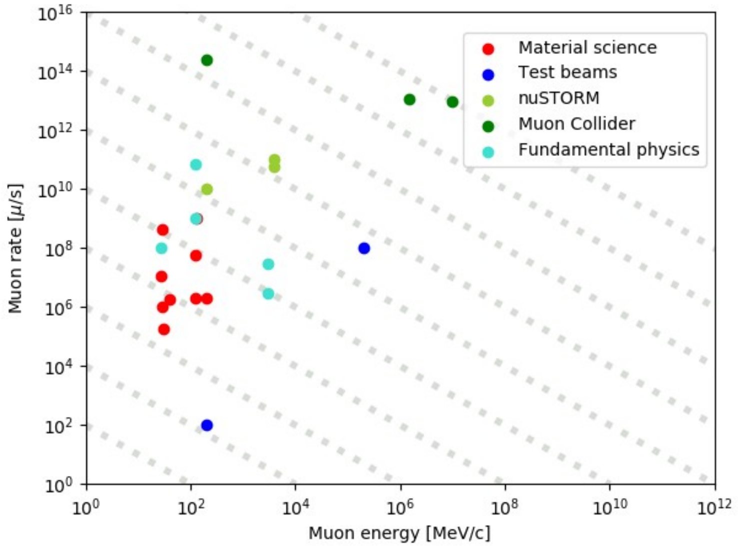
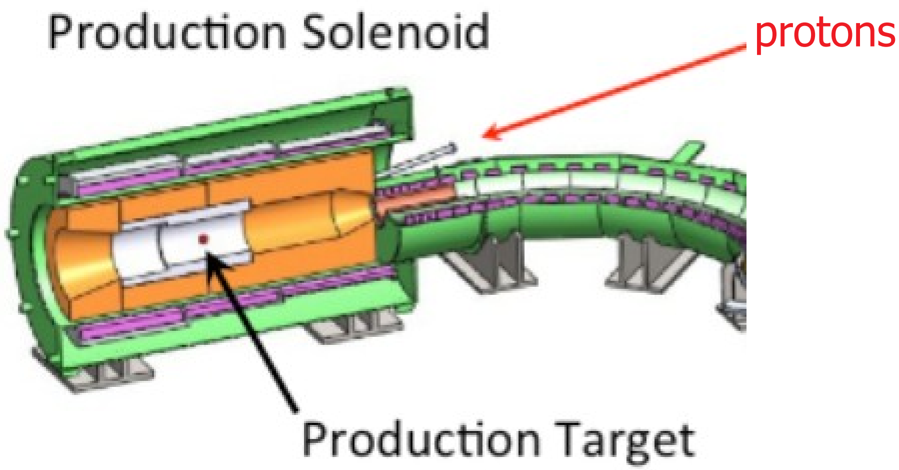
Synergy with nuSTORM





- 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/comet



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

Technology applications

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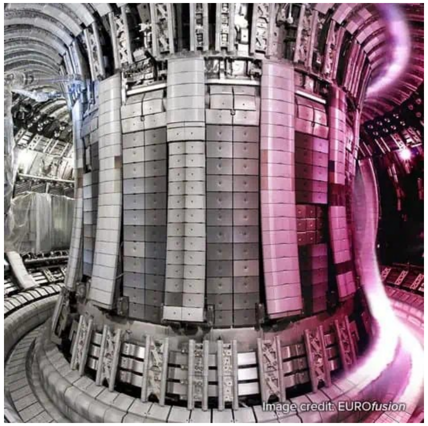
- High field solenoids have many important application
  - Developing collaboration with fusion experts
  - MRI magnets
- Muon beam techniques have application in many other fields
  - Muon spin resonance (muSR)
  - Muon tomography
- Delivery of such a muon beam is a unique achievement – we don’t know what is the impact!



Status & Prospects

Collaboration

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FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
Mal	**Univ. of Malta**
BE	***Louvain***

UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
AU	**HEPHY**
	TU Wien
ES	**I3M**
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	ICMAB
CH	**PSI**
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WARWICK THE UNIVERSITY OF WARWICK

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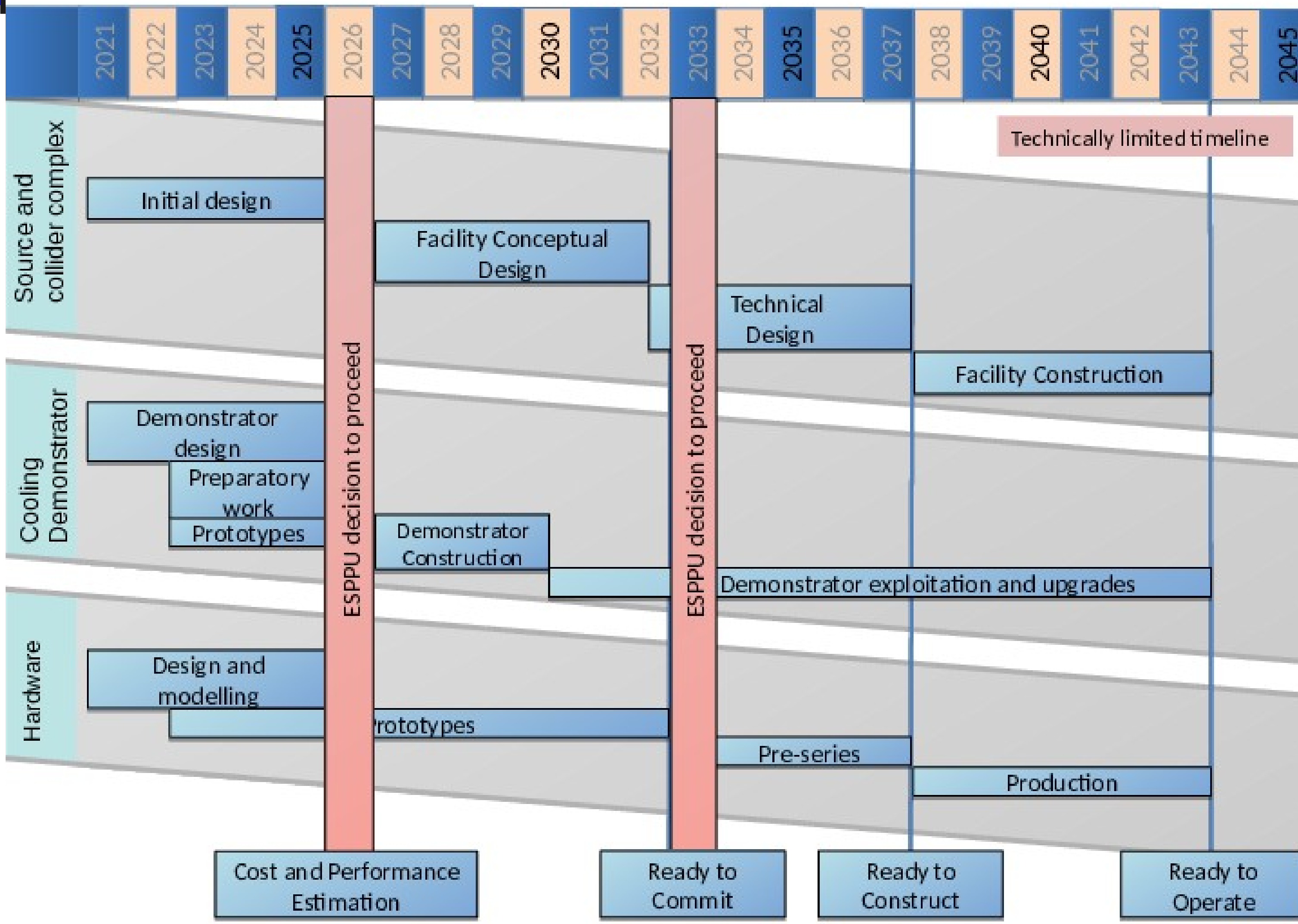
Muon Collider - Timeline



- Assumes full support of a major lab

2020 Update to the European Strategy for Particle Physics

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High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

• the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

• Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. ***The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.***

P5 Report

International MUON Collider Collaboration

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

Recommendation 3: Create an improved balance between small-, medium-, and large-scale projects to open new scientific opportunities and maximize their results, enhance workforce development, promote creativity, and compete on the world stage.

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Recommendation 5: Invest in initiatives aimed at developing the workforce, broadening engagement, and supporting ethical conduct in the field. This commitment nurtures an advanced technological workforce not only for particle physics, but for the nation as a whole.

Recommendation 6: Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

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P5 Report – Muon Shot

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2.3

The Path to 10 TeV pCM

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

Final Word

- 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

Backup

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Rutherford Appleton Laboratory

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Parameters

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.8	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	N	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.07
IP beta-function	β	mm	5	1.5	1.07
IP beam size	σ	µm	3	0.9	0.63

- Luminosity follows roughly ~ E^2
  - Beam size shrinks as energy increases
- Factor two surplus luminosity *on paper*
  - Compared with e.g. FCC-hh

Luminosity

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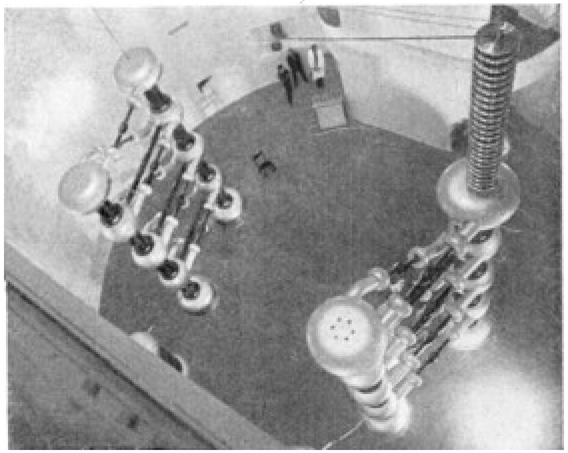
$$\mathfrak{L} \approx \underbrace{\frac{e\tau_\mu}{(4\pi m_\mu c)^2}}_{K_L} \frac{f_{hg}\sigma_\delta \overset{2}{\bar{B}}}{\underset{4}{\varepsilon_\perp \varepsilon_L} n_b \underset{3}{f_r}} \underbrace{\overset{4}{\eta_+\eta_-}(\overset{5}{\eta_\tau} P_p \overset{1}{\gamma} m_\mu c^2)^2}_{P_+P_-}$$

1) Luminosity increases with the square of muon energy/beam power
   - 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!

Accelerators in Physics

- First accelerators built in 1920s/30s
  - Accelerating protons, ions and electrons
- Antiproton acceleration in 1980s
  - Made possible by stochastic cooling
- Accelerators were originally a tool for fundamental physics
  - Now many uses
- Hadron colliders
  - E.g. LHC
  - “Discovery machines”
- Lepton colliders
  - E.g. Large Electron Positron Collider (LEP)
  - “Precision machines”
- Secondary+ particle production
  - Muons, pions, kaons, neutrinos ...



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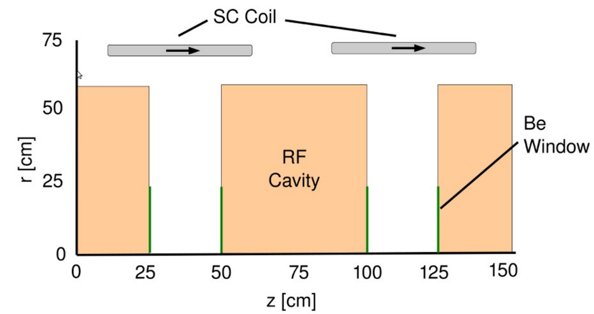
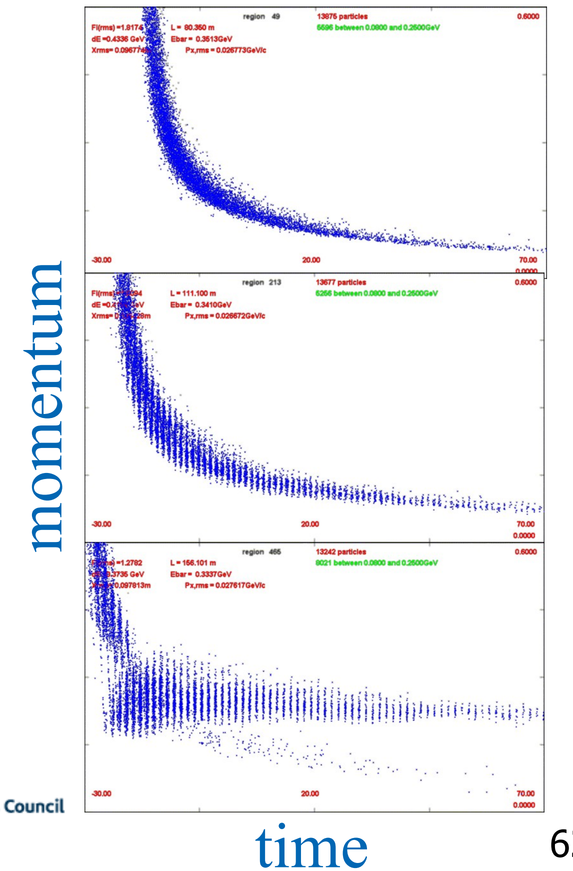
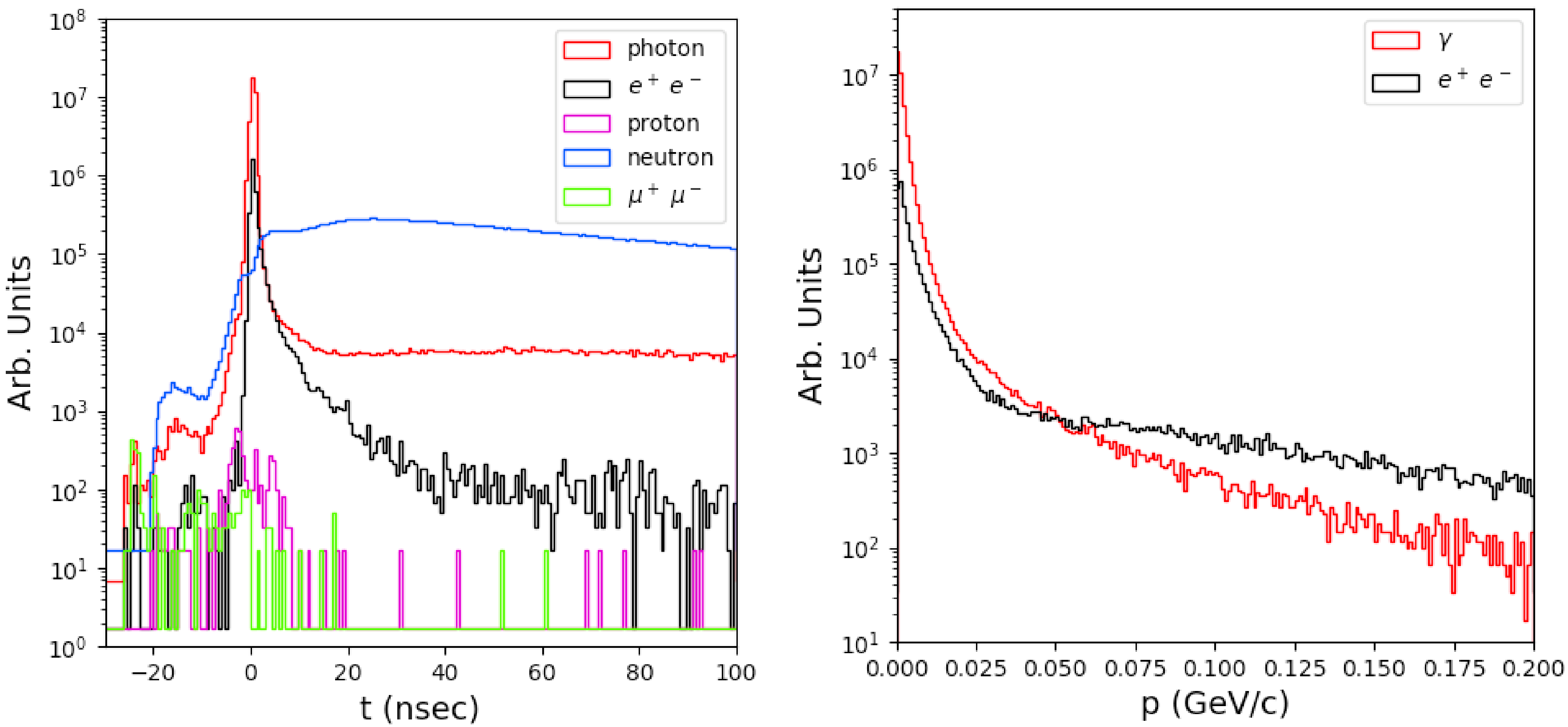
Buncher/Phase Rotator

- E.g. longitudinal bunch capture
- Drift to develop energy-time relation
- Buncher adiabatically ramp RF voltages
- Phase rotator misphase RF
  - High energy bunches decelerated
  - Low energy bunches accelerated
- Challenge: Control of losses



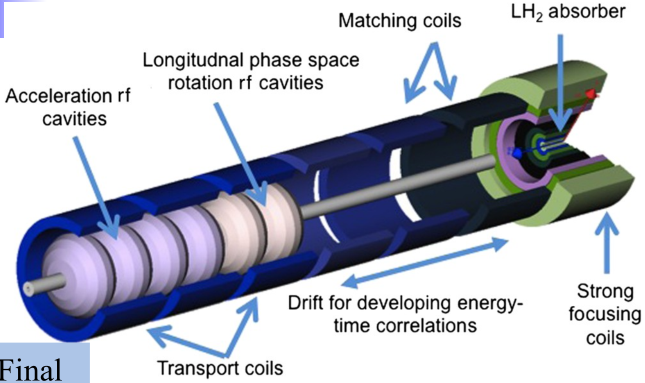


BIB Characteristics

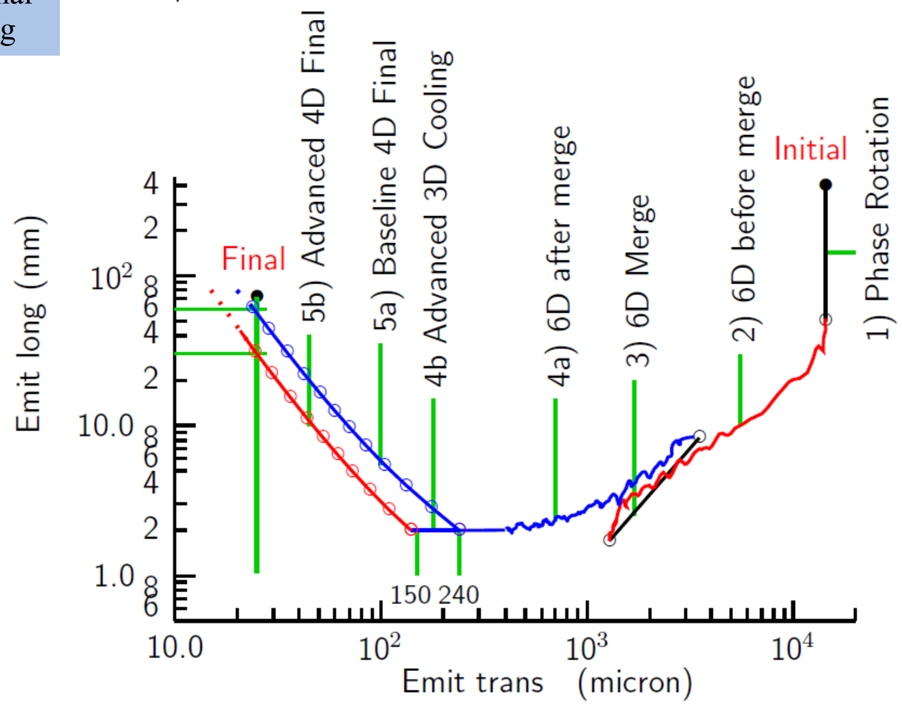


- Beam induced background (BIB) arising due to muon decays

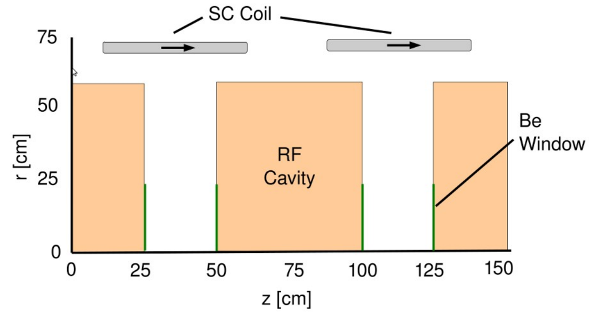
Muon Cooling



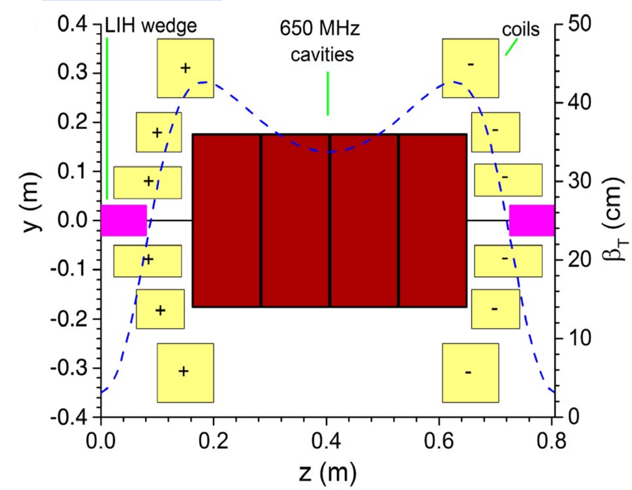
4D Final cooling



Phase rotation



6D cooling



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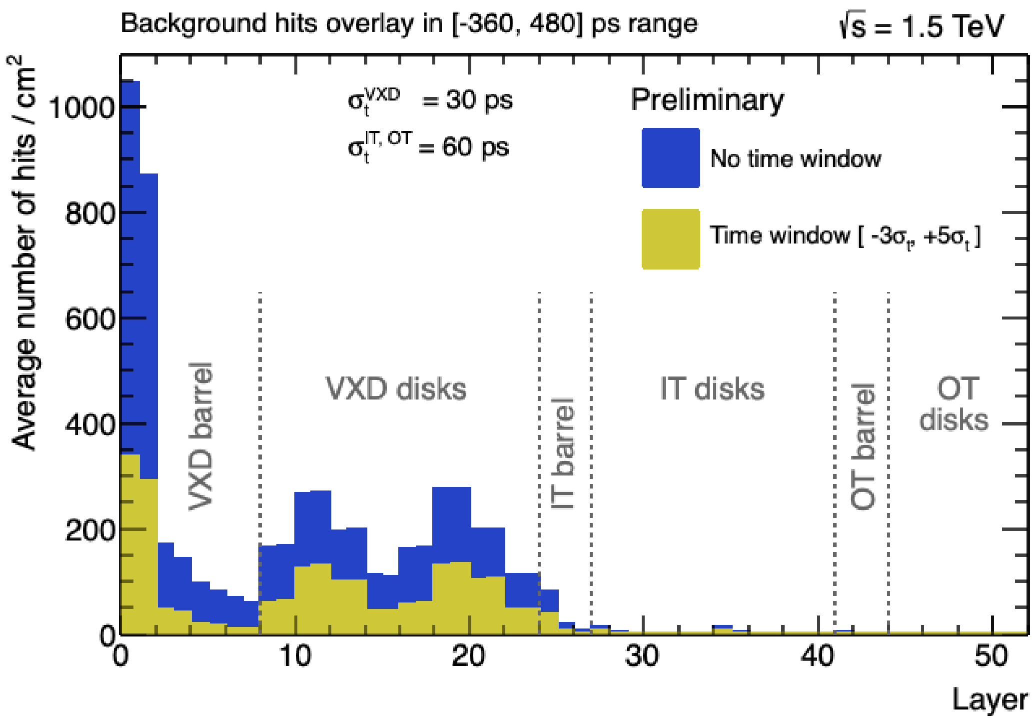
BIB Rejection



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

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