UK Muon Collider and Muon Beams

International
MUON Collider
Collaboration

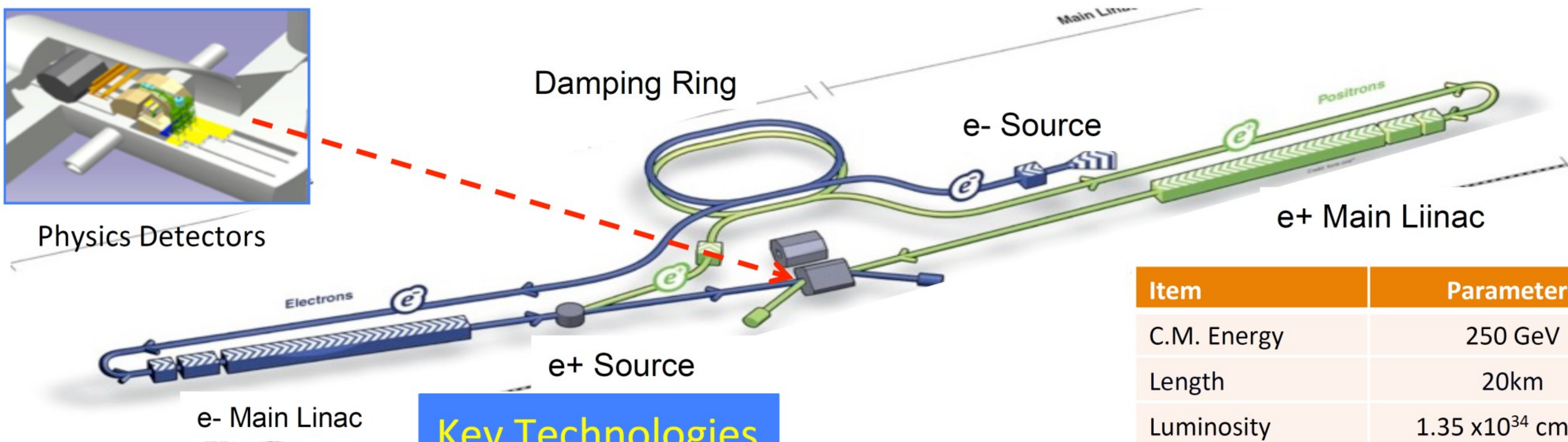
Science & Technology Facilities Council
ISIS

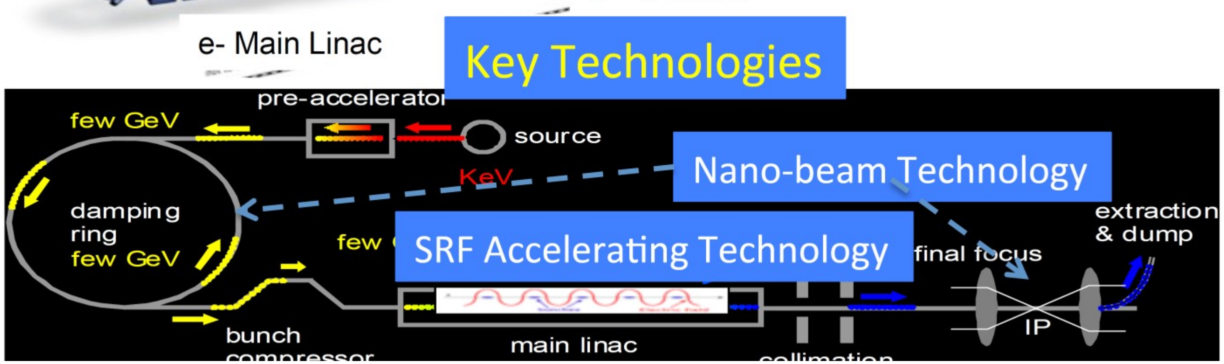
Muon Collider

- An interesting time in particle physics
- HL-LHC is under construction
  - Unlikely to be another upgrade
  - Finish operation in ~ 2040
- Lead time for next facility is ~ 25 years
  - Time now to decide on the future direction of CERN
- US programme also has 25 year timeline
  - DUNE phase I on the way
  - DUNE phase II under consideration
  - Further upgrades may be challenging → important systematics
- What are the options?
  - $e^+ e^-$
  - Protons
  - Muons

Electron-positron colliders

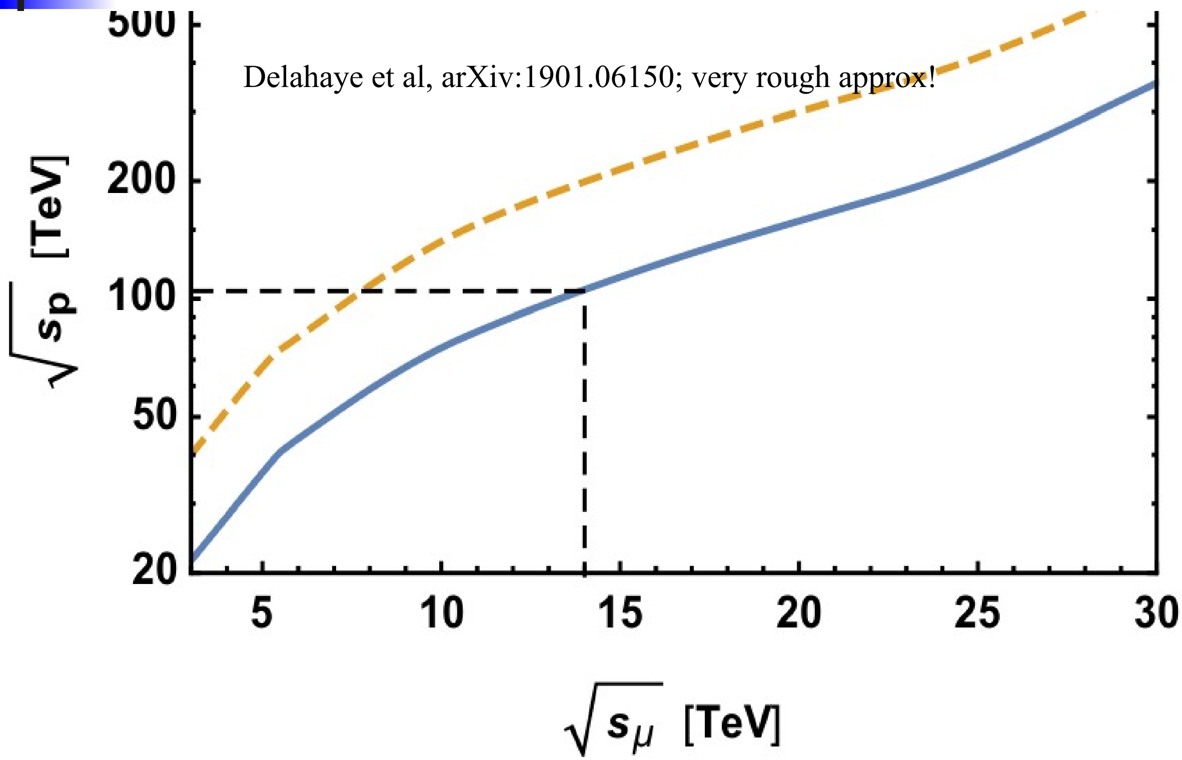
- Circular e^+e^- machines limited by synchrotron radiation
  - Power emitted ~ E^4/m^4
  - Practically limits centre-of-mass energy to ~ 100s GeV
- Linear e^+e^- machines limited by available RF acceleration
  - Practically limits centre-of-mass energy to ~ 100s GeV
  - Luminosity limitations also important





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!**

European Strategy

International MUON Collider Collaboration

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

• 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.***

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

areas identified in the Strategy update. The R&D objectives include: improvement of the performance and cost-performance of magnet and radio frequency acceleration systems; investigations of the potential of laser / plasma acceleration and energy-recovery linac techniques; and development of new concepts for muon beams and muon colliders. The goal of the roadmap is to document the collective view of the field on the next steps for the R&D programme, and to provide the evidence base to support subsequent decisions on prioritisation, resourcing and implementation.

A 10 TeV lepton collider is uncharted territory and poses a number of key challenges.

- The collider can potentially produce a high neutrino flux that might lead to increased levels of radiation far from the collider. This must be mitigated and is a prime concern for the high-energy option.
- The machine detector interface (MDI) might limit the physics reach due to beam-induced background, and the detector and machine need to be simultaneously optimised.
- The collider ring and the acceleration system that follows the muon cooling can limit the energy reach. These systems have not been studied for 10 TeV or higher energy. The collider ring design impacts the neutrino flux and MDI.
- The production of a high-quality muon beam is required to achieve the desired luminosity. Optimisation and improved integration are required to achieve the performance goal, while maintaining low power consumption and cost. The source performance also impacts the high-energy design.

Science & Technology Facilities Council ISIS

Snowmass Outcome

Report of the
2021 U.S. Community Study on the
Future of Particle Physics
(Snowmass 2021)

organized by the APS Division of Particles and Fields

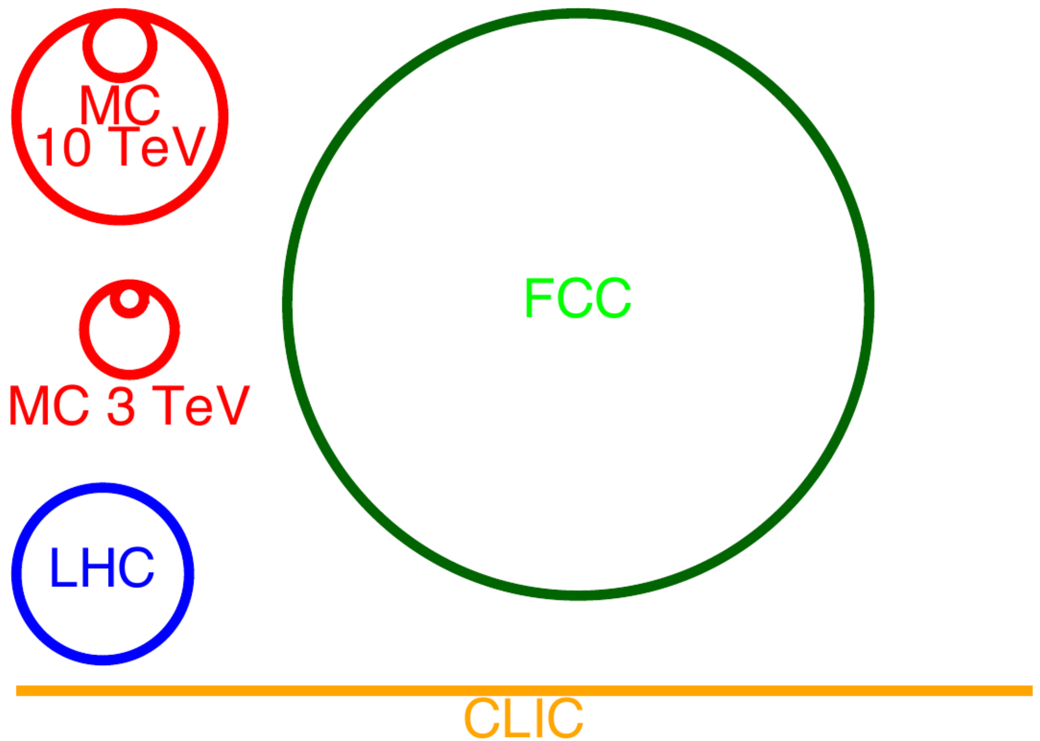
https://arxiv.org/abs/2301.06581

	Decadal Overview of Future Large-Scale Projects	
	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	Spectroscopic Survey - S5*	Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific*

- Muon collider and technologies are relevant to 3-4 Snowmass future large-scale projects

Why Muon Collider



- Muon collider facility scale compatible with existing CERN, Fermilab site
  - Likely to be reflected also in power consumption
  - Likely to be reflected also in cost scale

Why Muon Collider

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https://arxiv.org/abs/2208.06030

On the Feasibility of Future Colliders: Report of the Snowmass'21 Implementation Task Force

(Published 2022)

Thomas Roser,[1] Reinhard Brinkmann,[2] Sarah Cousineau,[3] Dmitri Denisov,[1] Spencer Gessner,[4] Steve Gourlay,[5,6] Philippe Lebrun,[7] Meenakshi Narain,[8] Katsunobu Oide,[9] Tor Raubenheimer,[4] John Seeman,[4] Vladimir Shiltsev,[6] Jim Strait,[5,6] Marlene Turner,[5] Lian-Tao Wang.[10]

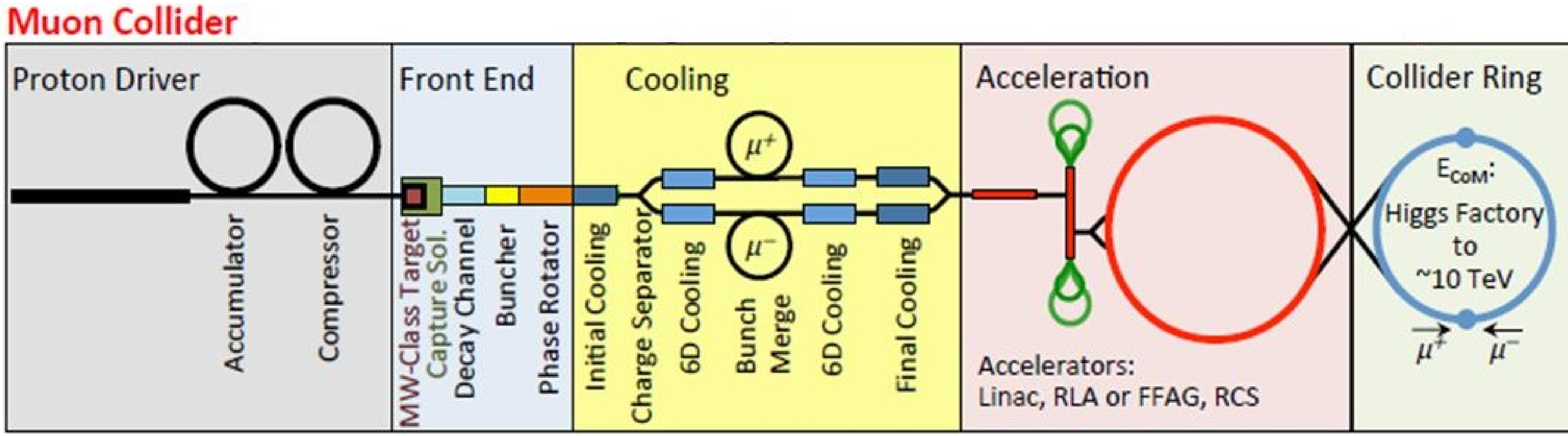
- Report by team of very knowledgeable experts
  - Drawn from wide spectrum of backgrounds
- Tasked with collating and assessing different collider options

Why Muon Collider

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} $cm^{-2}s^{-1}$]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
LWFA - LC (Laser-driven)	15 (1-15)	50	>10	>25	18-80	~1030
PWFA - LC (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~620
Structure WFA (Beam-driven)	15 (1-15)	50	>10	>25	18-50	~450
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

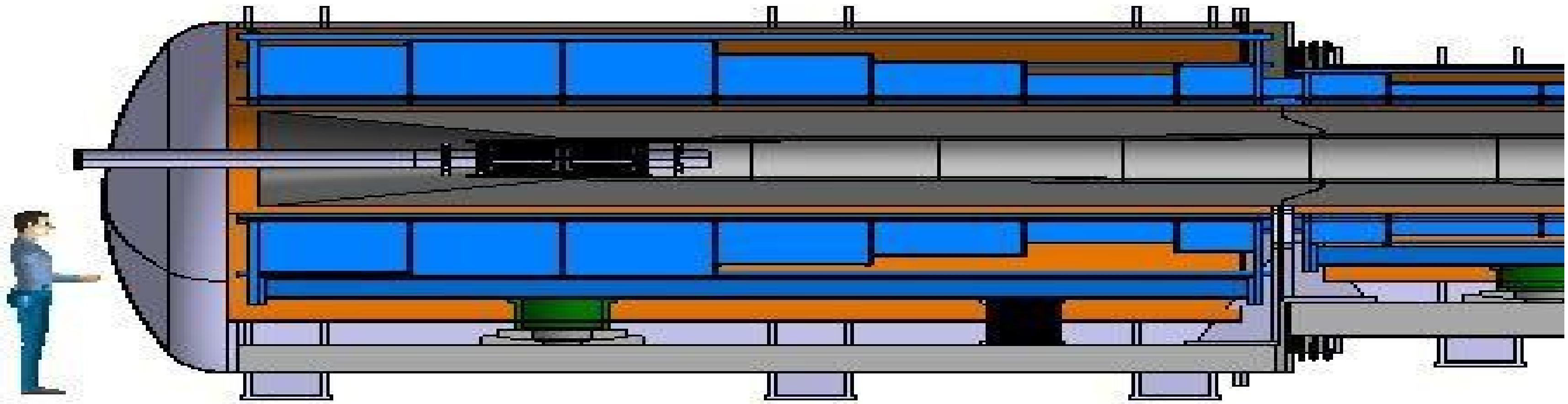
- Options for energy frontier colliders look challenging
- Costs ($, power, R&D) look high
- Muon collider compares well to other energy frontier machines

The Muon Collider



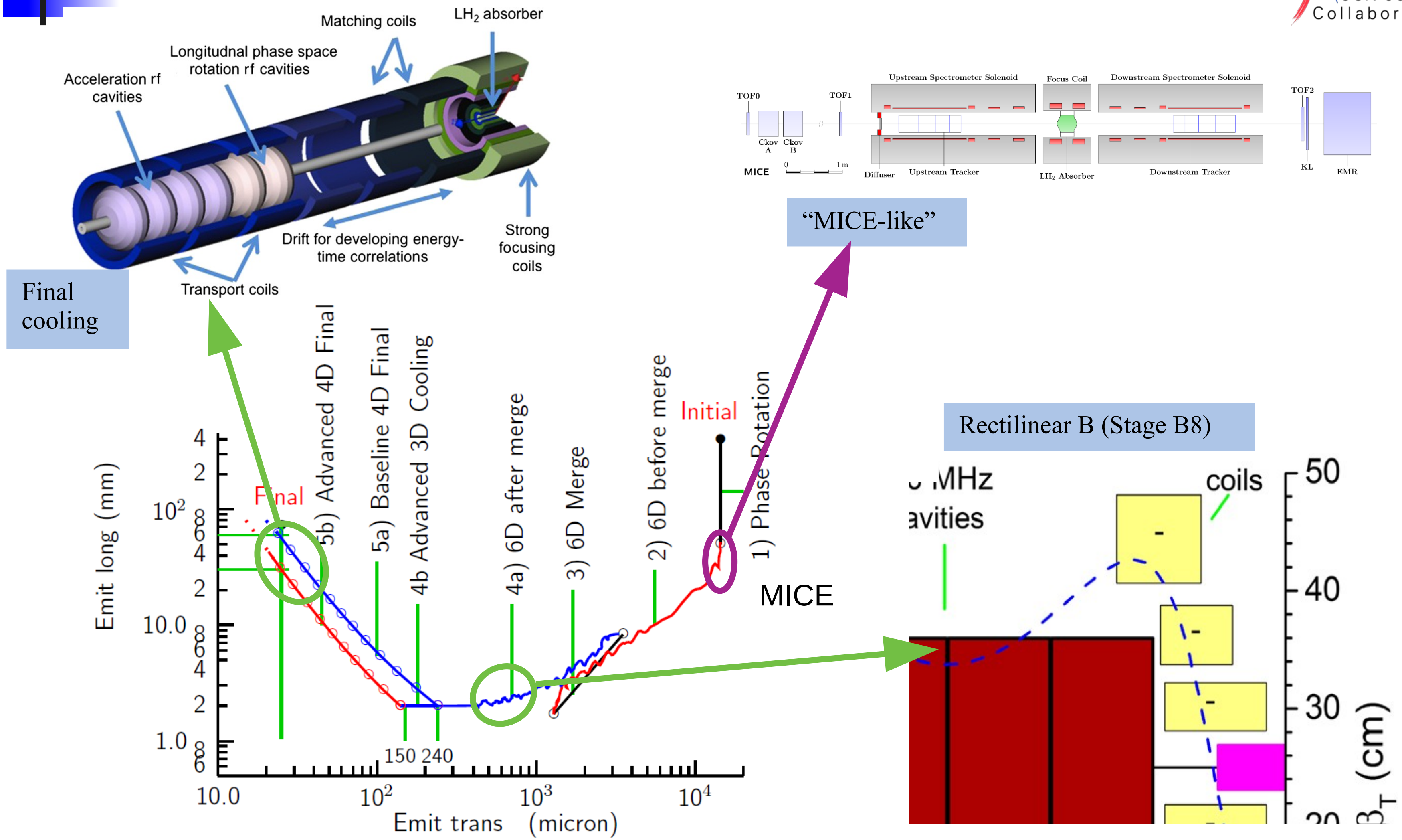
- MW-class proton driver → target
- Pions produced; decay to muons
- Muon capture and cooling
- Acceleration to TeV & Collisions
- Detector and physics

MuC Target

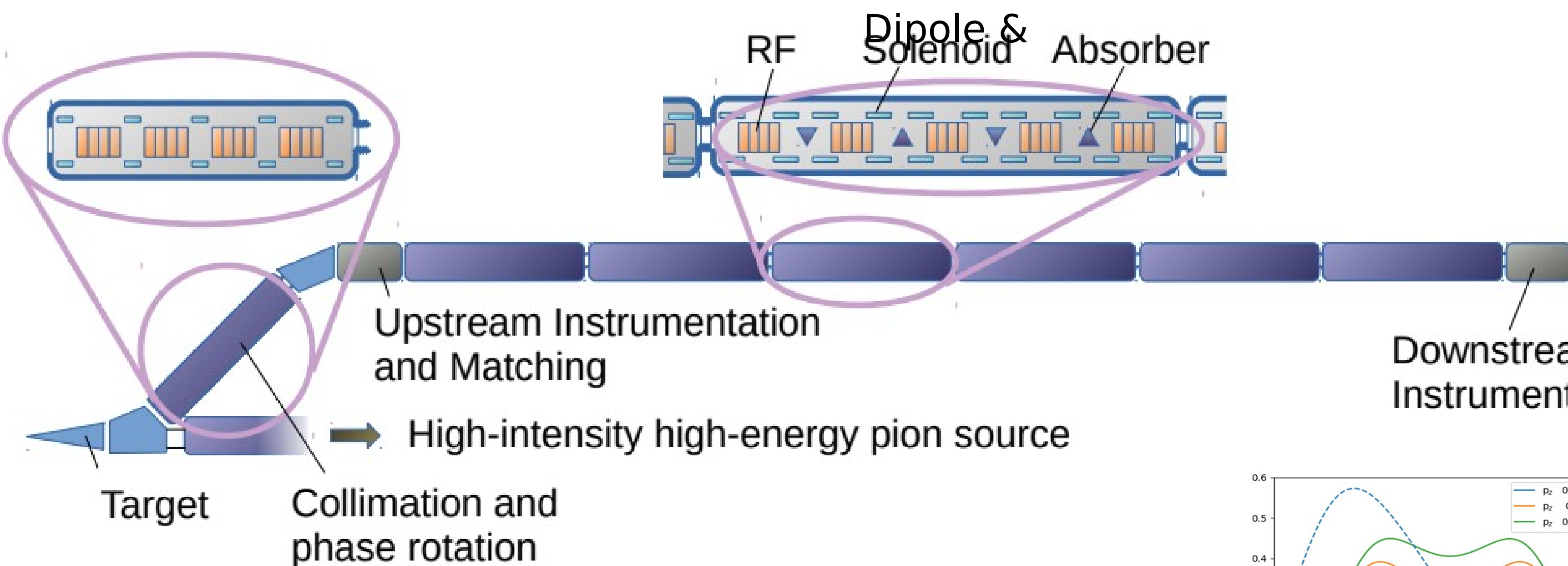


- Protons on target → pions → muons
  - Graphite target takes proton beam to produce pions
    - Back up options under investigation
  - Heavily shielded, very high field solenoid captures π^+ and π^-
- Challenge: Solid target and windows lifetime
- Challenge: Energy deposition and shielding of solenoid

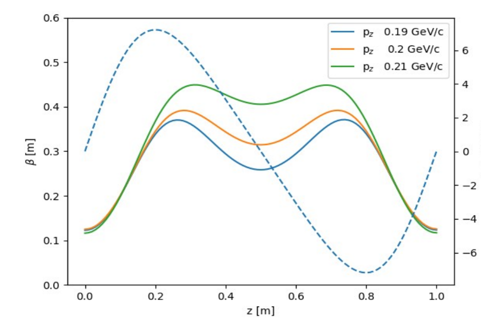
Cooling for a Muon Collider

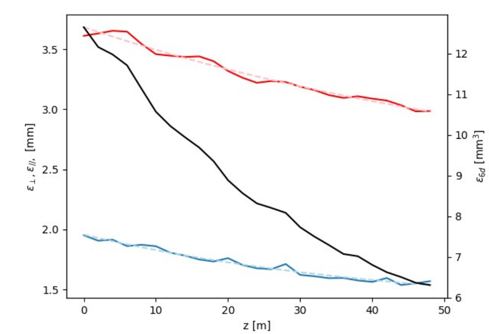


Cooling Demonstrator

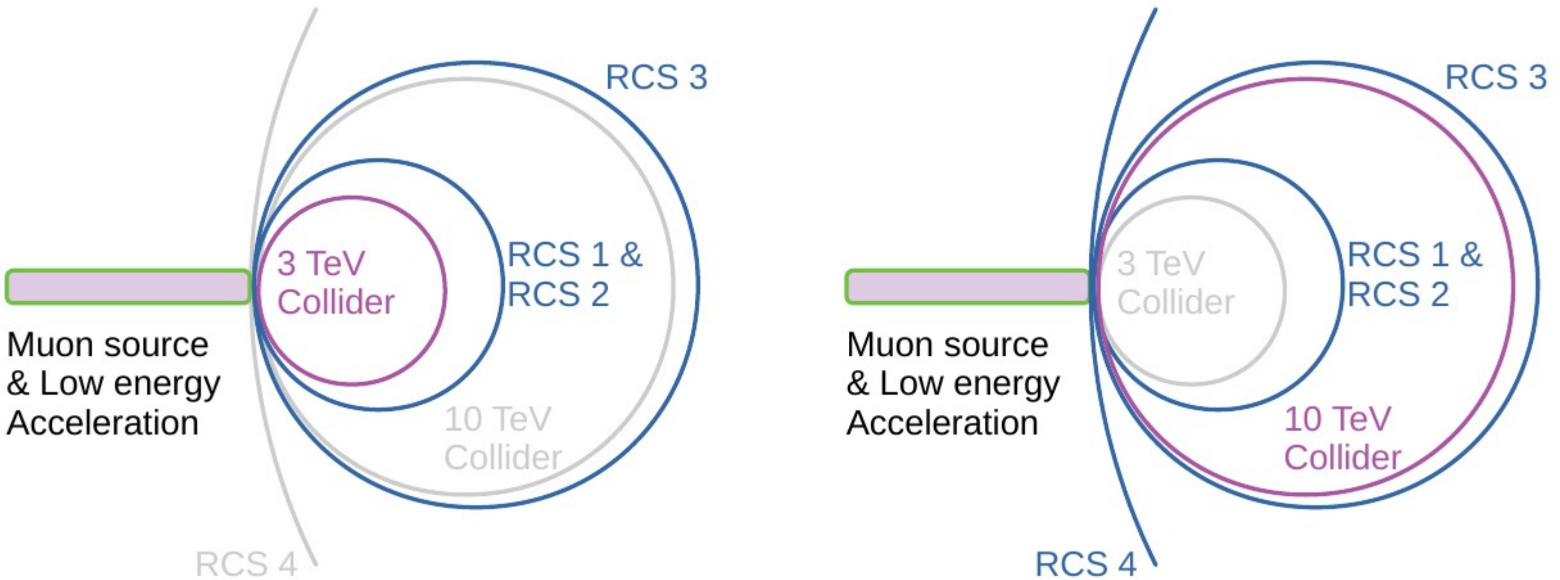


- Cooling demonstrator design in progress
- Investigating synergy with muSR/low energy muons



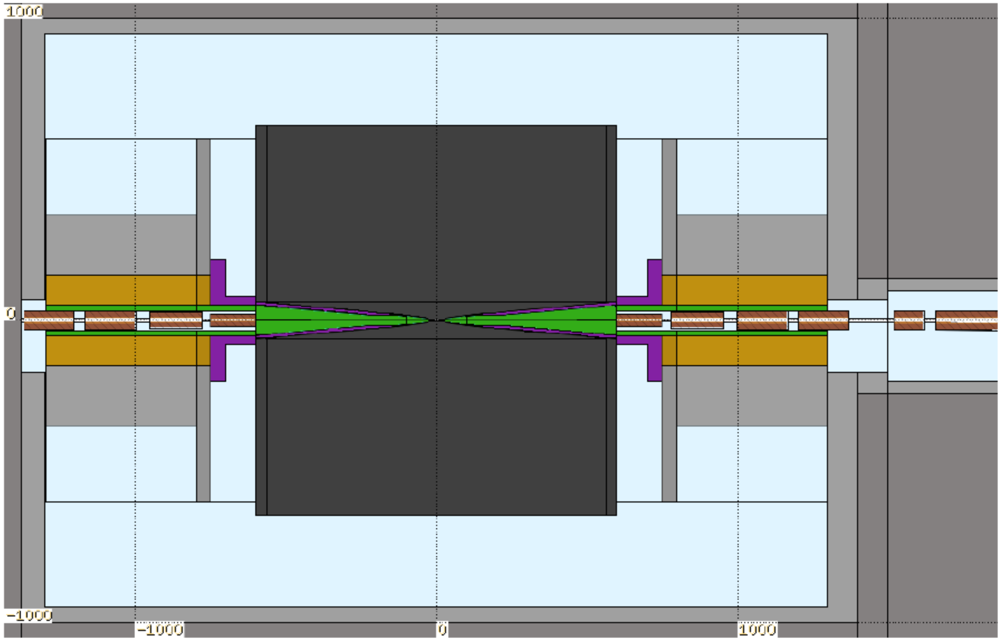


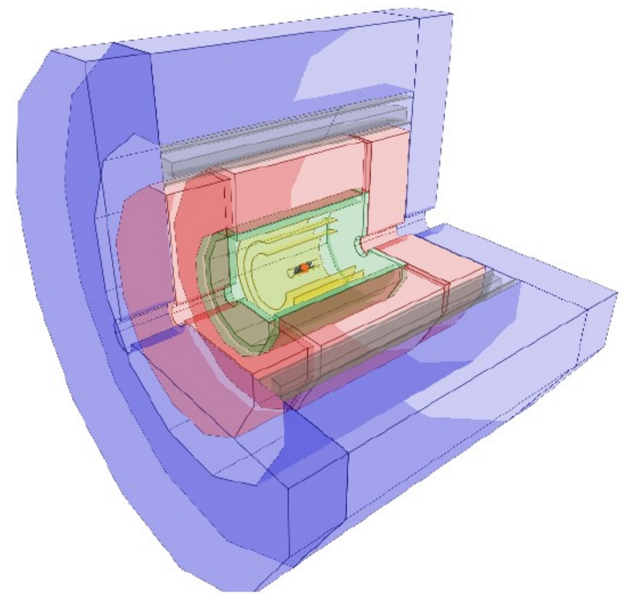
High Energy Complex



- Baseline for acceleration is 4 pulsed synchrotrons
  - Deliver 5 TeV muons
- Smallest collider ring possible
  - Minimise time of flight → maximise collisions before decay
- Single muon pulse
  - Maximum luminosity for a given power on target

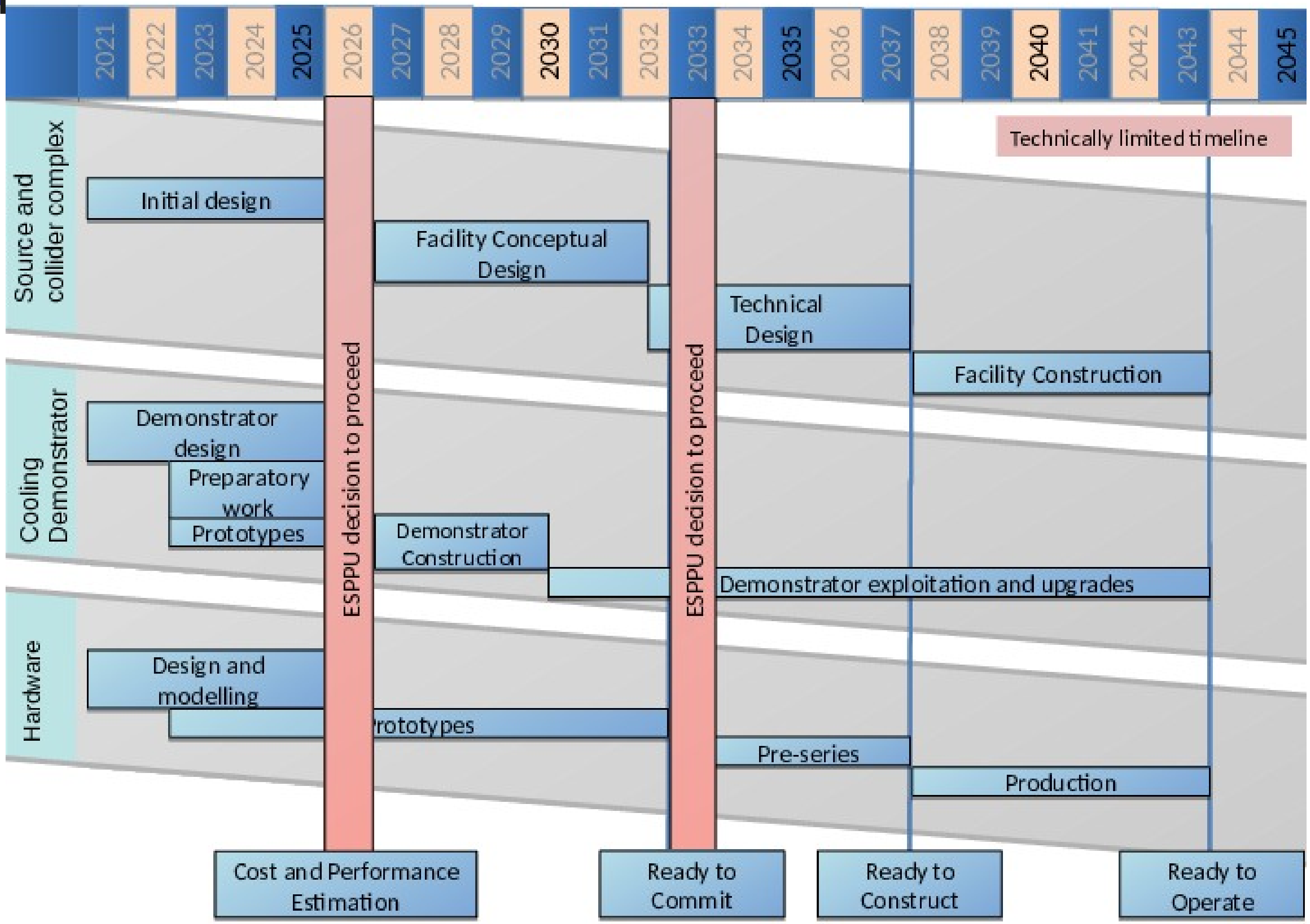
Detector





- Detector is "standard" particle physics detector
- Beam-induced-background O(HL-LHC) levels
  - Shielding to protect from muon decay products
  - Fast timing resolution and position resolution to resolve backgrounds

Muon Collider - Timeline



- **Assumes full effort of major lab e.g. CERN, Fermilab**

UK Role in MuCol

Coordination Committee
- RAL/ISIS

WP2 - Detector
- Birmingham
- Sussex
- RAL/PPD
- Cambridge
- Durham

WP3 – Protons
- RAL/ISIS
- RHUL

WP4 – Target & Cooling
- RAL/ISIS
- Imperial College
- RAL/TD
- Warwick

WP5 – High Energy Complex
- Huddersfield
- Manchester
- Oxford

WP7 - Magnets
- Southampton

WP6 - RF
- Lancaster
- Strathclyde

WP8 – Cooling Cell
- RAL/ISIS
- Imperial College

R&D Path

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Opportunities

- CLFV
- Top, higgs
- neutrinos
- Energy frontier
- muSR

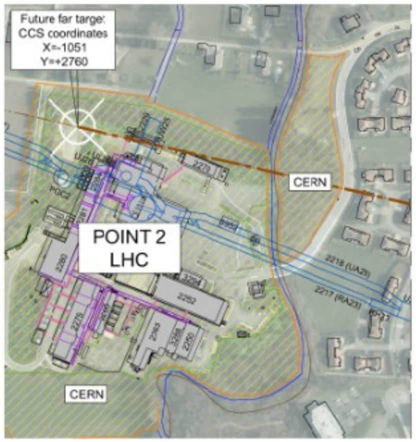
Required Facility

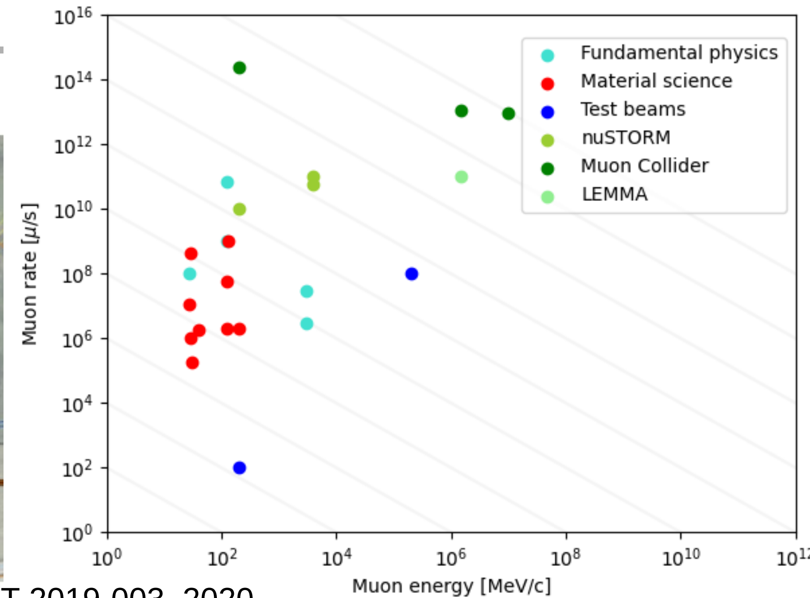
- Proton Driver
- 100s-1000s GeV Muons
- 10s-100s GeV Muons
- 1-10 TeV Muons

Required R&D

- High power targets
- Muon cooling++
- Rapid acceleration
- Muon cooling
- Rapid acceleration++

Synergy - nuSTORM



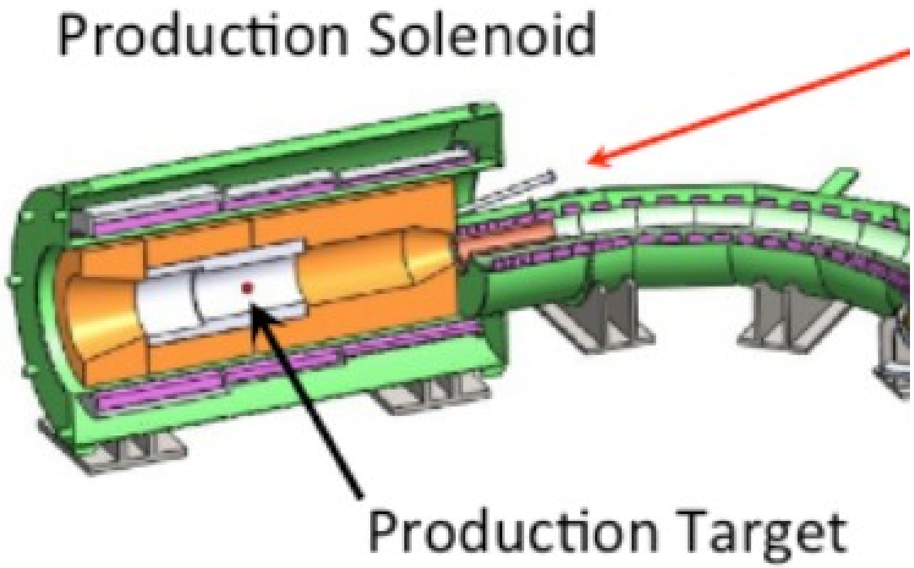


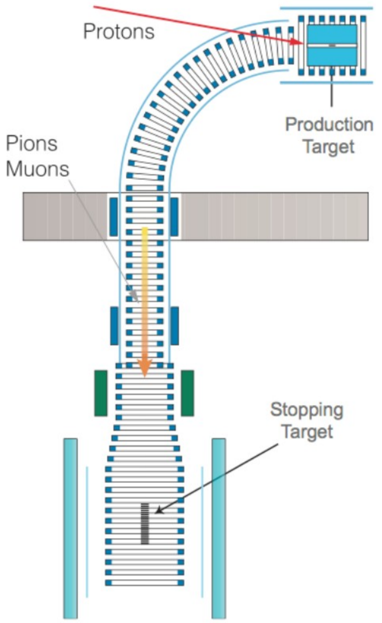
nuSTORM at CERN – Feasibility Study, Ahdida et al, CERN-PBC-REPORT-2019-003, 2020

- Main features
  - ~250 kW target station
  - Pion transport line
  - Stochastic muon capture into storage ring
  - Option for conventional FODO ring or high aperture FFA ring
- Well defined neutrino beam
  - Nuclear scattering processes
  - BSM physics

Synergy - cLFV

mu2e



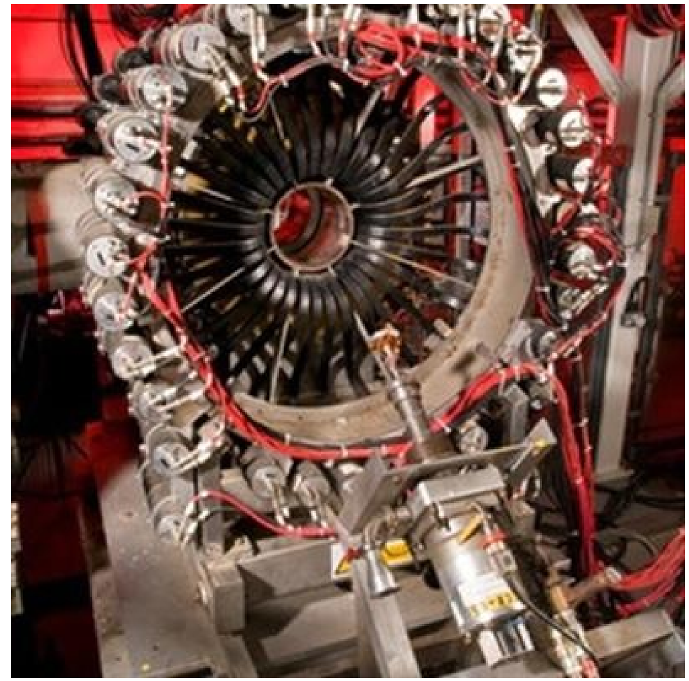


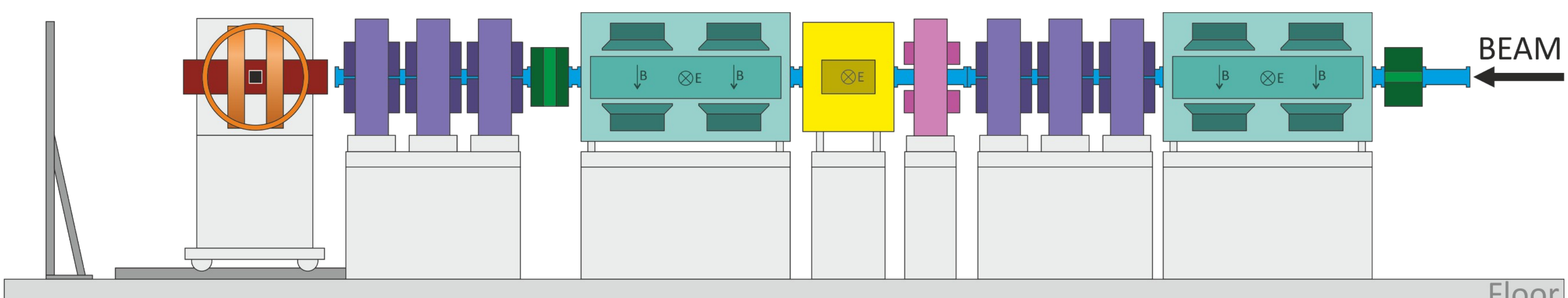
【COMET Phase-I】

- Muon-to-electron conversion experiments
  - Look for rare decay processes
- Under construction now
- R&D for phase 2 in progress
- Target station similar to MC target
  - But lower power, lower field
- Excellent opportunity to test ideas on target station

Synergy - muSR

- MuSR can be interesting in two places
  - Test bed for collider detectors
  - Test bed for muon cooling techniques





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Over to you!

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22