An R&D Programme for Bright Muon Beams

Science & Technology Facilities Council
ISIS Neutron and Muon Source

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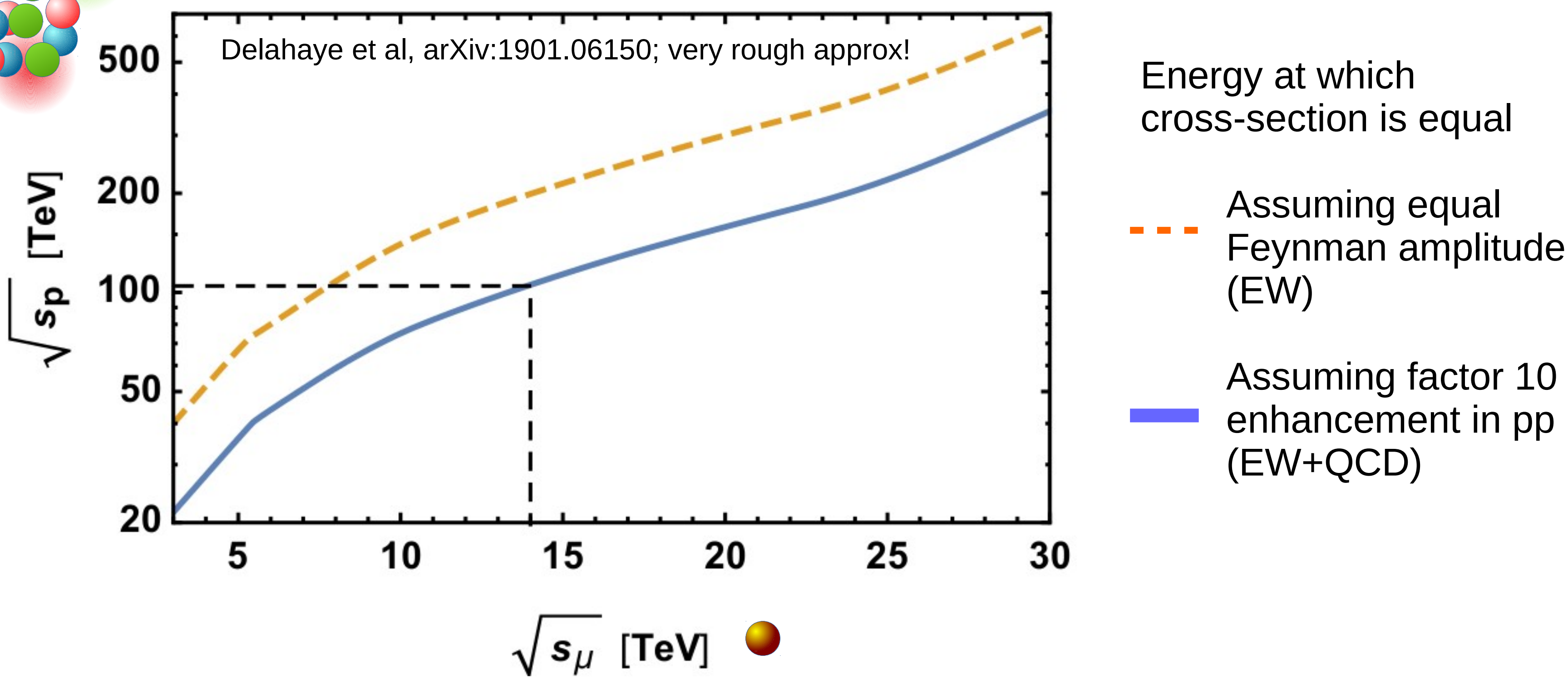
Bright muon beams

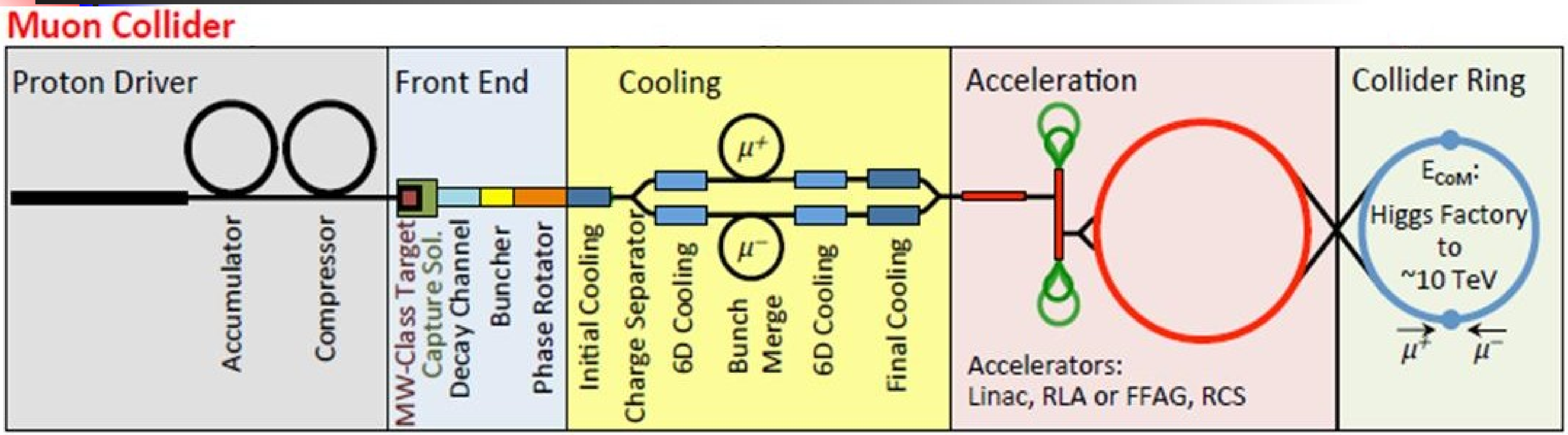
- Muon beams important part of the STFC programme
  - Insight into materials
  - Fundamental physics
- R&D into bright muon beams High Priority Initiative for European particle physicists
  - Muon collider only route to energy frontier before 2050
  - Technically – very challenging
- How can the UK contribute?
- How does it build into the existing and ongoing muon beam studies?

Muon Collider



- Muons → extend energy reach of next-generation colliders
  - Synchrotron radiation limits electron collider energy
  - Proton effective CoM energy decreased due to composite nature
- Muons are not composite and synchrotron radiation suppressed
- What would a muon collider look like?

Muon Collider Facility



- Proton based Muon Collider (MC) facility
  - Protons on target → pions, muons et alia
  - Transverse and longitudinal capture and cooling
  - Acceleration
  - Collider ring
- Challenges
  - Targetry and capture
  - Cooling
  - Acceleration
- Promising route to next-generation collider → international support

International Perspective

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

3

High-priority future initiatives

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

The bright muon beams and muon colliders panel has examined the choice of parameters for a future muon collider concept, and suggests to focus in particular on a 10 TeV machine with a 3 TeV intermediate-scale facility. They have considered the challenges to be met in the construction of a 3 TeV machine targeted for the mid-to-late 2040s, and the immediate feasibility studies that must be carried out in the next five years. The goal for 2026 will be to demonstrate that further investment into a well-specified R&D plan is scientifically justified, and to have developed concrete plans for an intermediate-scale technology demonstrator with scientific utility in its own right.

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3 High-priority future initiatives

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The Future of US Particle Physics

The Energy Frontier Report

2021 US Community Study on the Future of Particle Physics

The US EF community proposes to develop plans to site an e^+e^- collider in the US. A muon collider remains a highly appealing option for the US, and is complementary to a Higgs Factory. For example, some options which are considered as attractive opportunities for building a domestic EF collider program are:

- A US-sited linear e^+e^- (ILC/CCC) Collider
- Hosting a 10 TeV range muon collider
- Exploring other e^+e^- collider options to fully utilize the Fermilab site

UK Perspective

PPAP 2021 Roadmap

Particle Physics Advisory Panel

Recommendation 4.6: The UK should maintain its recognized expertise in Muon Collider studies concentrating on medium-term projects focused on feasibility demonstration exploring synergies with neutrino physics such as nuSTORM.

- UK has leadership of the muon collider facility design
  - In particular, UK leads the muon source work package

Consortium Request

STFC is taking a new approach to funding accelerator science following the publication of the new Accelerator Strategic Framework. Proposals will shortly be invited for consortia to form around themed R&D areas.

The Strategic Framework will guide individual targeted funding over the medium term. To this end, a more specific way ahead is defined below; a fusion of top down and community-driven bottom-up approaches, building on the momentum in accelerator science built up over recent years:

- Community consortia are invited to form and generate themed R&D programmes for a four-year programme of work that supports the development of UK strengths directly aligned with the Strategic Framework priorities, with an emphasis on exploiting existing facilities and the sustainable construction and operation of the UK's and CERN's priority infrastructures.
- STFC will support a few substantive (up to ~£1M/year) programmes. Outline programmes should be submitted in early 2023. These will be considered by STFC to ensure fit to the Accelerator Strategic Framework mission statement and themes, before inviting a subset to submit full proposals to be peer reviewed later that year.
- STFC aims to support work in up to three pillars:

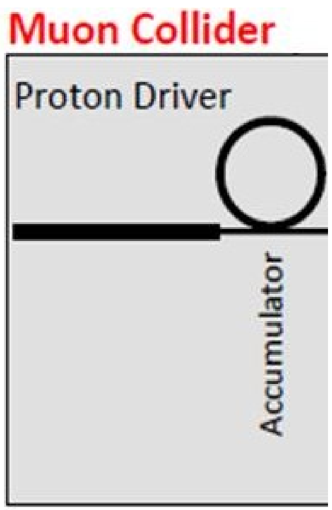
§ LHC and its upgrades (including future machines), exploiting UK strengths aligned with the European Roadmap

§ Novel acceleration technologies (including exploiting CLARA, EPAC, and similar facilities)

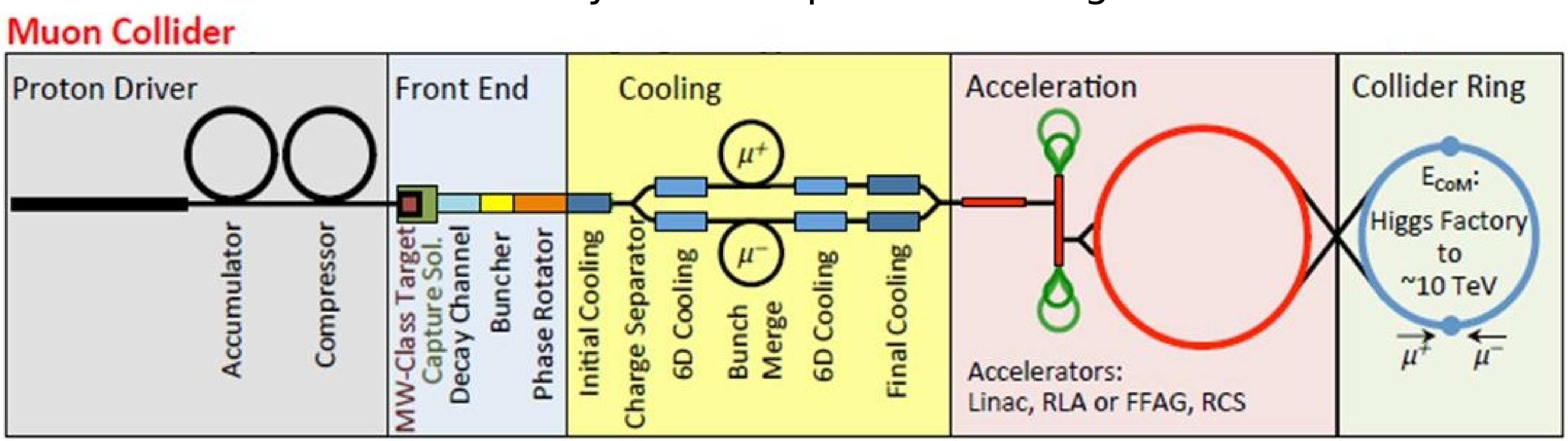
§ The route to UK FEL capabilities

From here… to there…

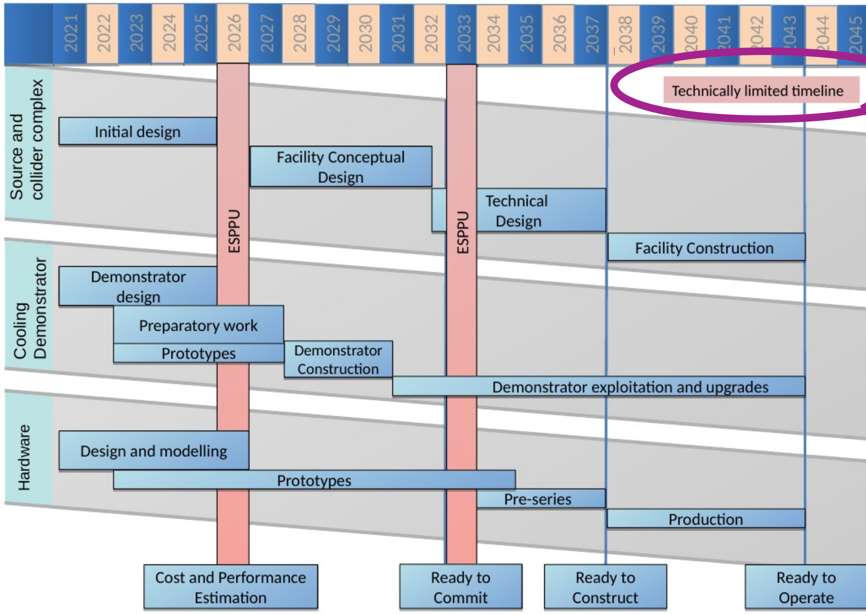
- How do we get from here:



  - Need to prove we can build
    - Front end
    - Cooling
    - Acceleration
    - Collider
  - Technical challenges
    - Muon source
    - Neutrino radiation
    - Decay electron/positron background in detector
- To there:

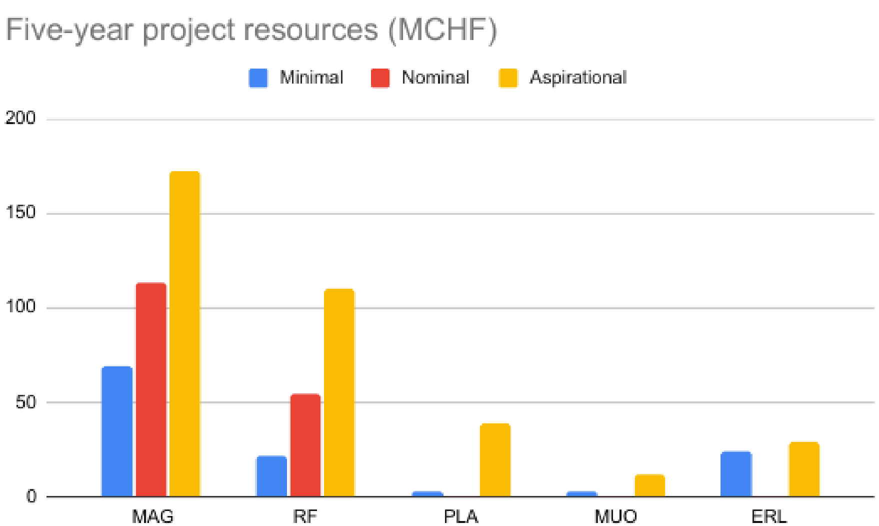


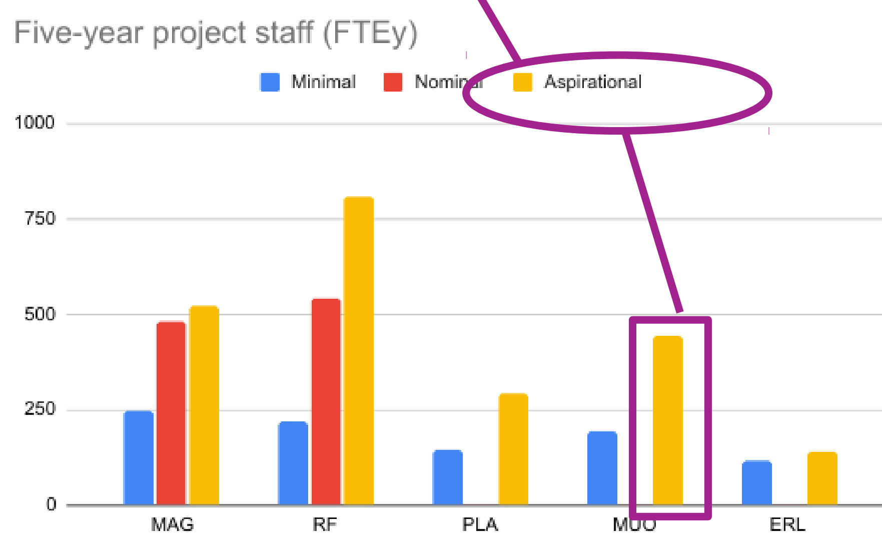
Time scale and resources



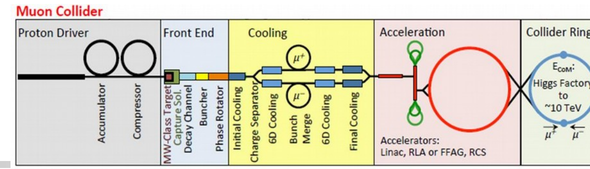
EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

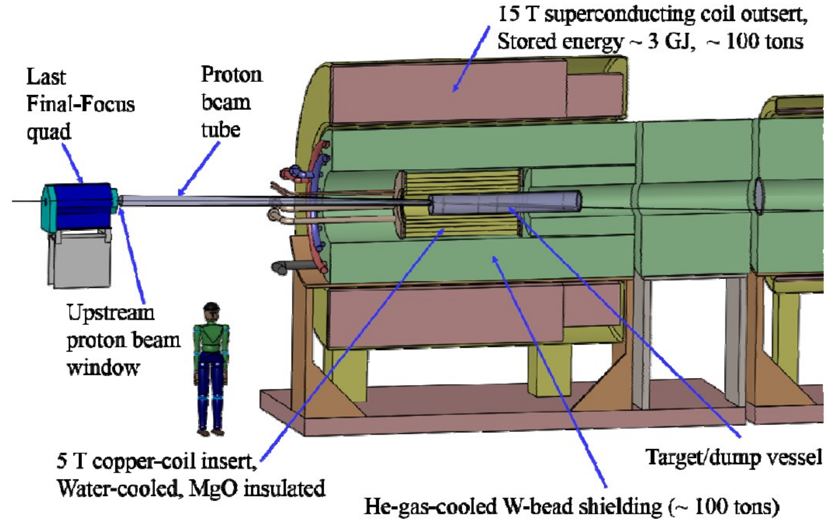




Solenoid-focused target

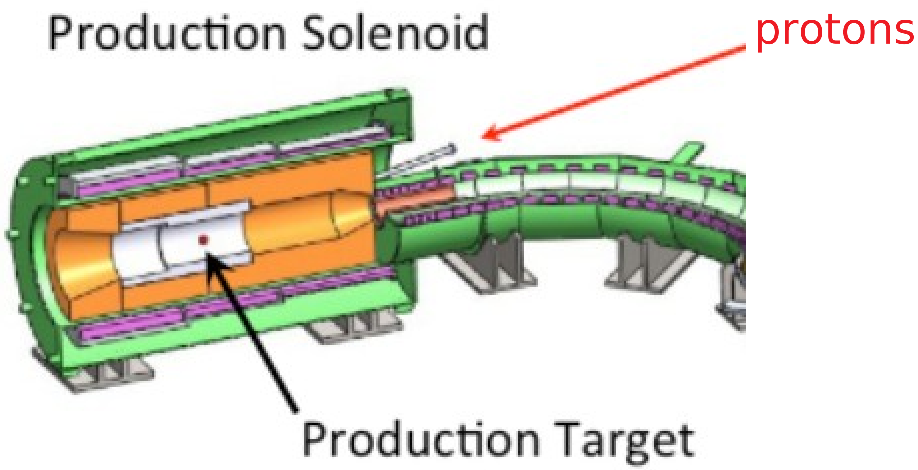


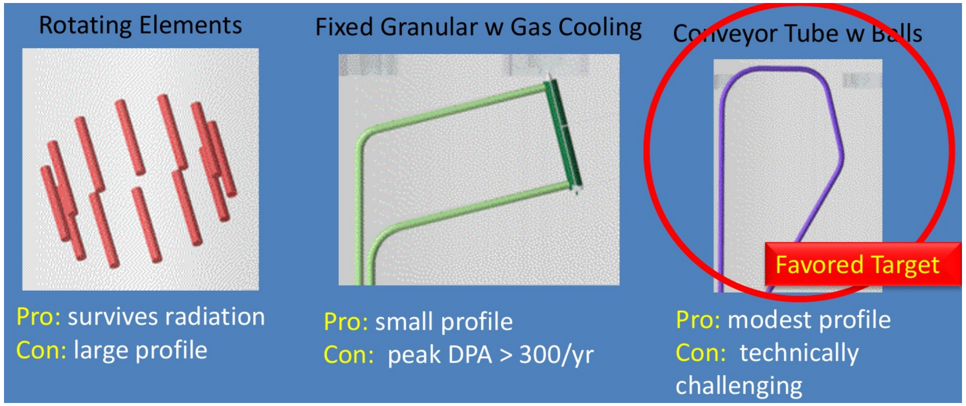
- State of the art is muon to electron targets
  - Few kW target
  - Few T superconducting solenoid
- Also note neutrino targets
  - 1-2 MW target
  - Normal conducting horn focusing
- Muon collider baseline
  - 20 T
  - 2.5 MW



- Target development
  - Next generation solenoid-focused target → O(0.1) MW, few T
    - Relevant for standalone ISIS2 muon target station
  - Consideration of target horns as a contingency/fall-back
    - → nuSTORM

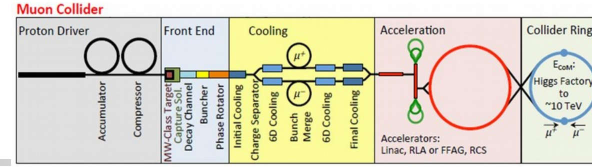
E.g. mu2e

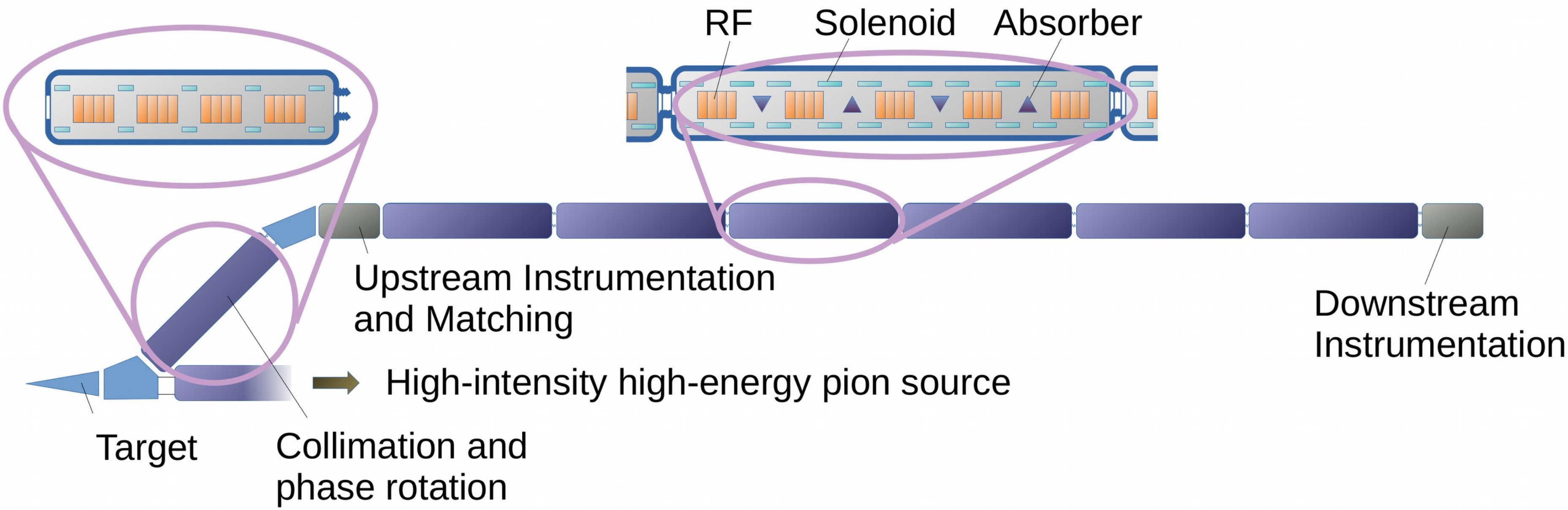




- Mu2e phase 1
  - Under construction
  - 8 GeV & 8kW
  - 4.6 T solenoid
- Mu2e phase 2
  - Proposal stage
  - 800 MeV & O(100) kW
  - 4.6 T solenoid
- Various proposed targets
  - Carries significant technical risk
- Solenoid
  - Concerns about shielding
  - May need new one

Muon cooling



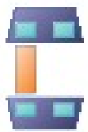


- Muon cooling highly novel
  - Needs demonstrator
- Cooling Demonstrator
  - Challenging RF gradients
  - Target/Switchyard design lacking
  - Integration issues

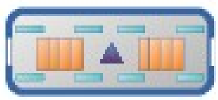
Main risk

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

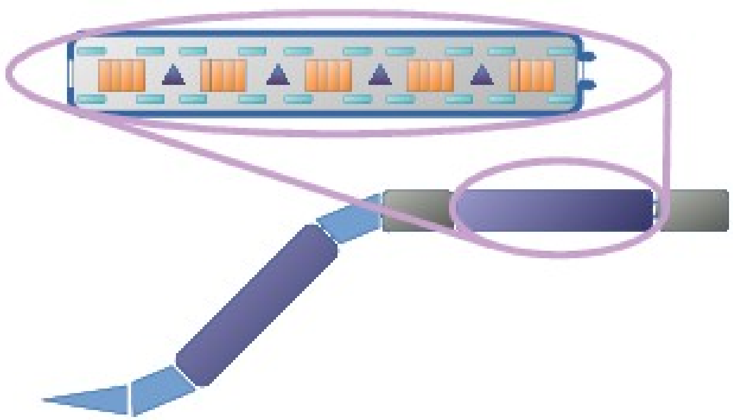
Muon cooling - plan



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



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

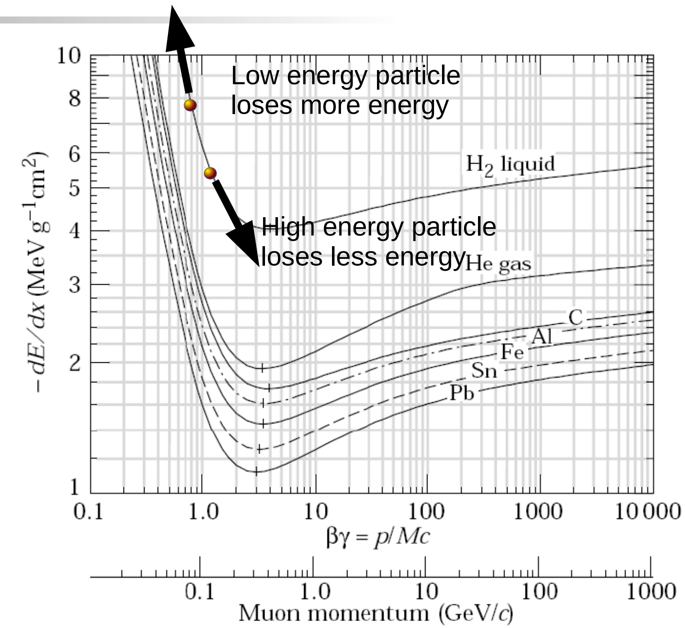


Full cooling cryostat with beam

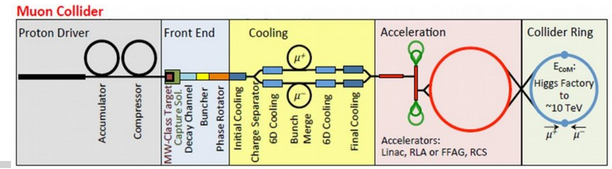
Full cooling lattice with beam

An alternative route

- Ionisation cooling effect goes with dp/p
  - iMCC cooling scheme has dp/p O(10) @ about 200 MeV
  - 1 km long, including magnets and RF
- At lower momenta, cooling becomes dramatically shorter
  - Cooling **harder**
    - Magnets/RF get easier
  - Application to low energy muon beams? MuSR, muon to electron, etc
    - Transmission is not so critical in some cases
- Low-energy cooling is
- PSI has demonstrated such a system
  - Long pulse
- J-PARC system proposed

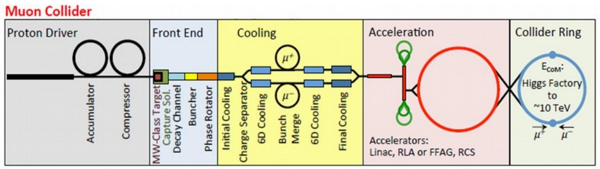


Novel Acceleration



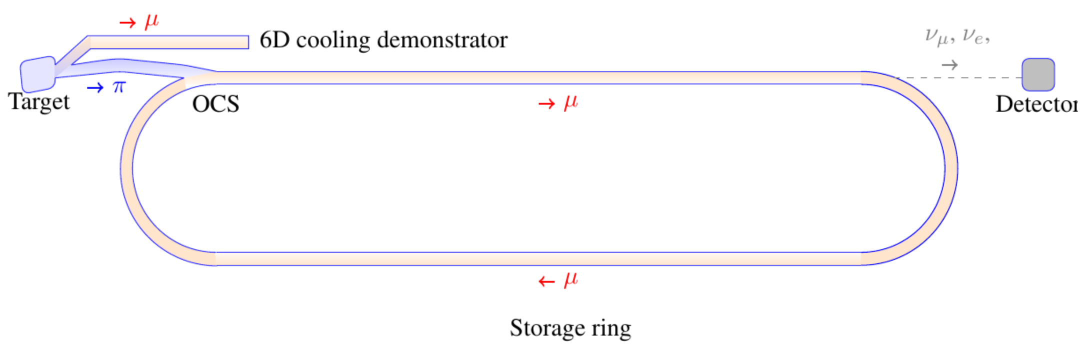
- Rapid acceleration of muons → key challenge
- Muon Acceleration baseline → VRCS
  - O(0.1-1) ms magnet rise time @ 5 Hz
    - Need to compete with muon lifetime
  - Magnets likely very power hungry (no real estimate yet)
- FFA may be a sustainable alternative
  - Needs lattice design
  - Include e.g. dispersion suppression to bring beam into RF cavities
  - Minimise tunnel length/magnet length → D/F ratio choice
- Collider ring
  - Novel vFFA-like skew quadrupole optics
  - Enables delivery of very short bunch
- Study of machine detector interface
  - Beam stability, beam-induced-background, final focus optics

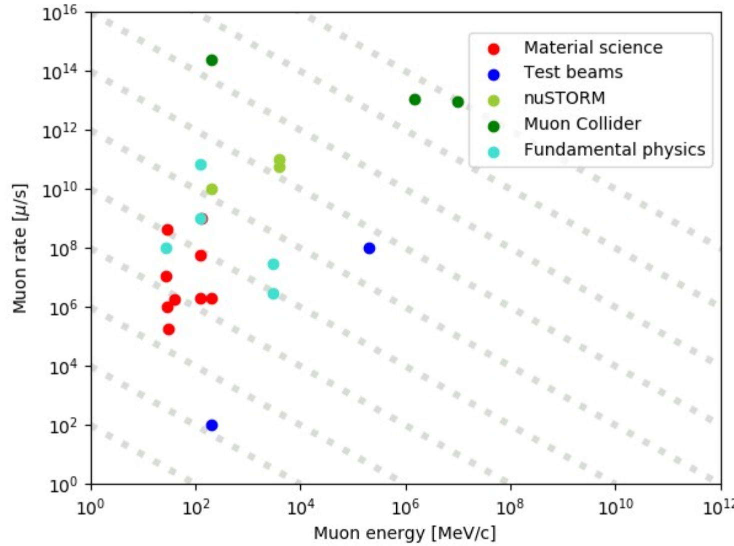
Proton driver



- Proton driver including bunch compression → key challenge
  - SPL+Accumulator+Booster+Compressor
  - SPL+combined accumulator/booster/compressor → FFA?
- Note previous designs by Prior, Rees et al
  - For muon collider, optimisation → lower rep rate
  - Space charge more severe

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
  - E.g. interest from nuclear physics
  - Sensitivity to Beyond Standard Model physics

Projects and Plans

	Muon production	Muon cooling	Novel acceleration
Muon collider	X	X	X
Muon cooling demonstrator	X	X	
ISIS2	X	X	X
ITRF/LhARA			X
Muon to electron conversion	X	X	
nuSTORM	X		X

- Relationship to existing/proposed projects
  - R&D programme complements well the STFC accelerator strategy
  - Hope it is distinct

Final Thoughts

- R&D programme to deliver the next generation of bright muon beams
  - Strong synergy with current and proposed projects in STFC portfolio
  - Final goal to deliver muon collider
- Discuss
  - Where are the strengths?
  - Where are the weaknesses?
  - Path forwards

Backup

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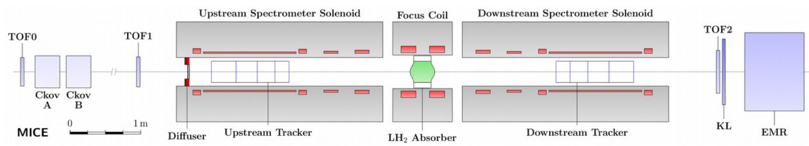
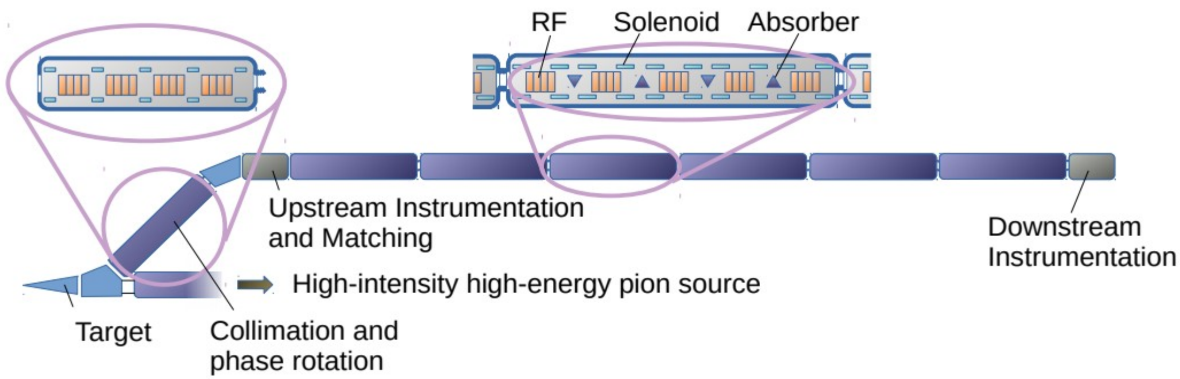
Comparison with MICE





	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