The international effort towards a Muon Collider

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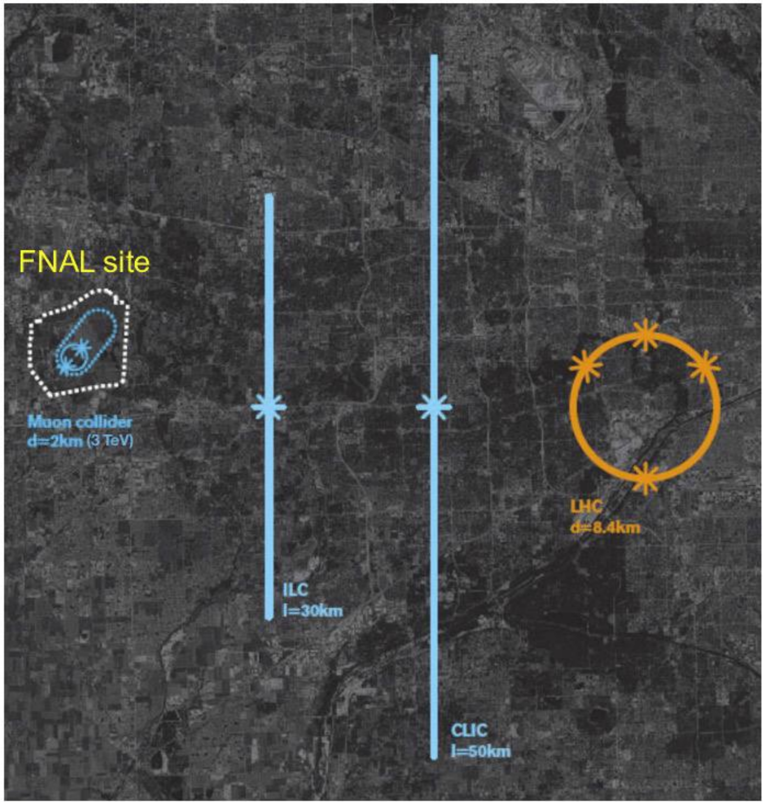
Outline

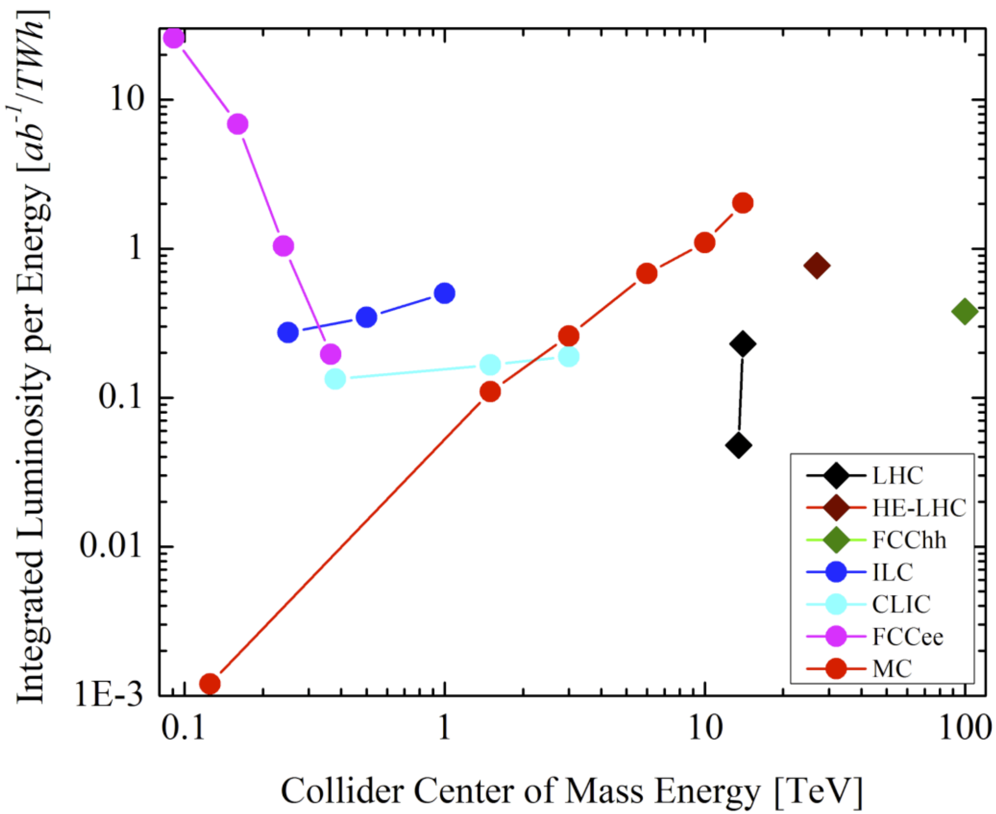
- Motivation
- History of Muon Colliders
- Accelerator design
- Feasibility
- International Muon Collider Collaboration & Muon Collider Forum
- Future work

Why muons?

- **Muons** can be more beneficial than **protons**
  - Muons are elementary particles and all their energy in a collision is used (and not spread among partons)
  - As a result the equivalent energy reach of muon collisions is about x7 times higher than in proton collisions. That allows Muon Colliders to x7 smaller compared to protons ones
- **Muons** can be more beneficial than **electrons**
  - Muons are ~200 times heavier than electrons therefore no synchrotron radiation. This makes acceleration in rings possible up to many dozens of TeV instead of just 300-500 GeV
  - For the same reason, no beamstrahlung – and small dE/E at IP of O(0.1%) vs O(10%) in e+e-;
  - Some cross sections prefer higher mass (e.g. S-channel reactions scale as m^2)

Muon Collider sustainability





- A MC would offer a precision probe of fundamental interactions, in a smaller footprint as compared to electron or proton colliders
- Most power efficient machine at high energies

History (1)

- Early mentions of Muon Colliders date back to 1960s with design studies during1990s-2010s through US institutional collaborations
- Between 2011-2016 the Muon Accelerator Program (MAP) was approved and supported by DOE to address key feasibility issues of a MC
  - Focused on a proton-driver based solution and considered a staged approach.
  - End-to-end design for a Neutrino Factory & a 125 GeV Higgs Factory. Considered colliders at 1.5, 3 and 6 TeV
- In 2021, CERN Council has charged the EU Laboratory Directors Group to develop the Accelerator R&D Roadmap for next decade:
  - A dedicated Muon Panel organized community meetings and working groups with conveners from global community.
  - Assessed MC challenges and defined prioritized work packages with resource estimates

History (2)

- Muon Colliders are now part of the European Accel. R&D Roadmap
  - CERN asked for implementation of the plan
  - International Muon Collider Collaboration (IMCC) has been initiated
  - Goal is a 10+ TeV collider – intermediate staging at 3 TeV will be considered
  - EU Design Study Proposal for the Muon Collider has been approved
- Snowmass 2022 Summer Study: Strong interest on Muon Colliders
  - Delivered Muon Collider Forum Report: a coherent vision for muon colliders from the US perspective
    - Has 170+ authors/supporters
  - A US national accelerator R&D program on Future Colliders has been proposed

Initial target parameters (IMCC)

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

Feasiblity addressed, will evaluate luminosity performance, cost and power consumption

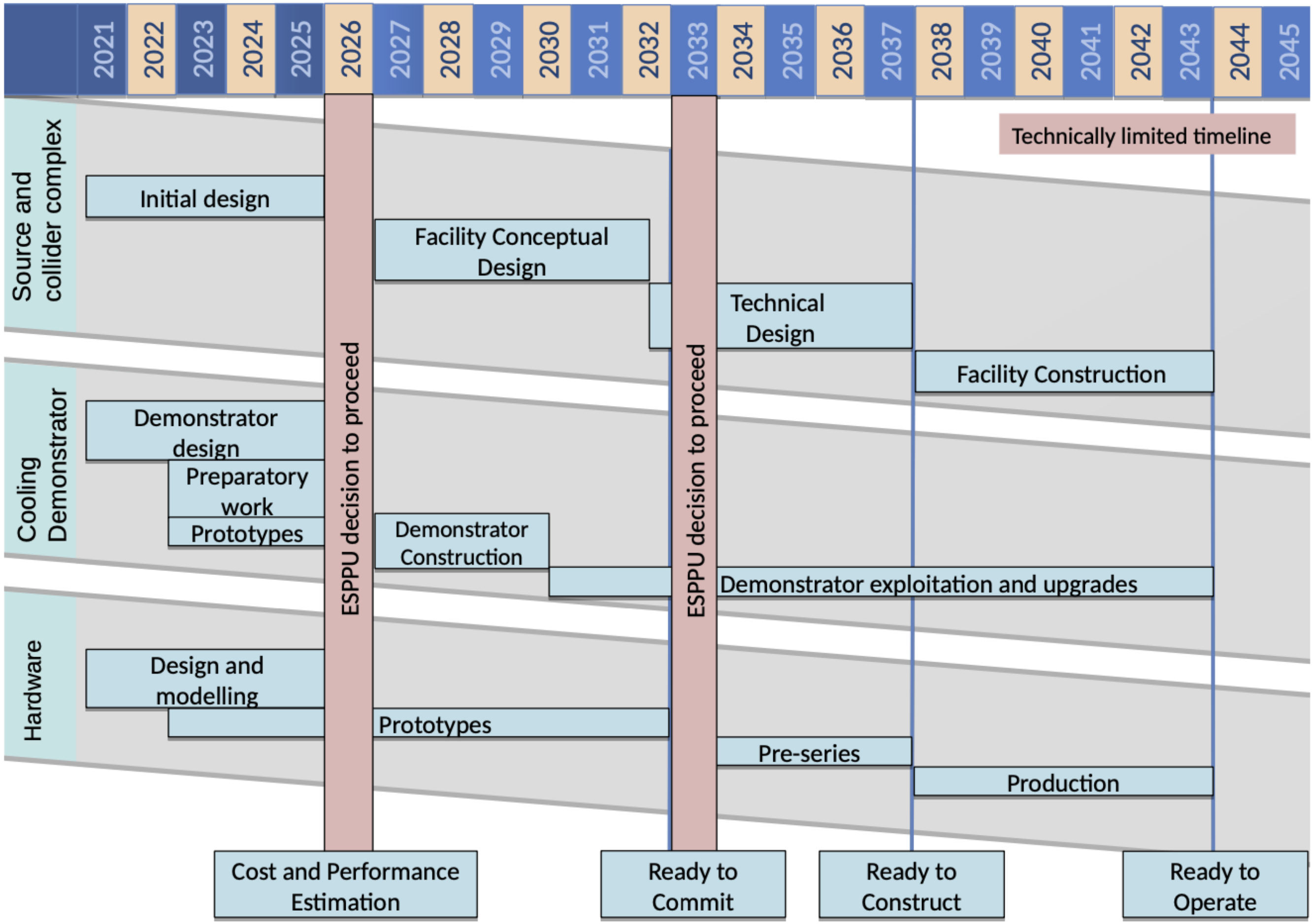
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Daniel Schulte, IPAC, June 2022

IMCC Timeline

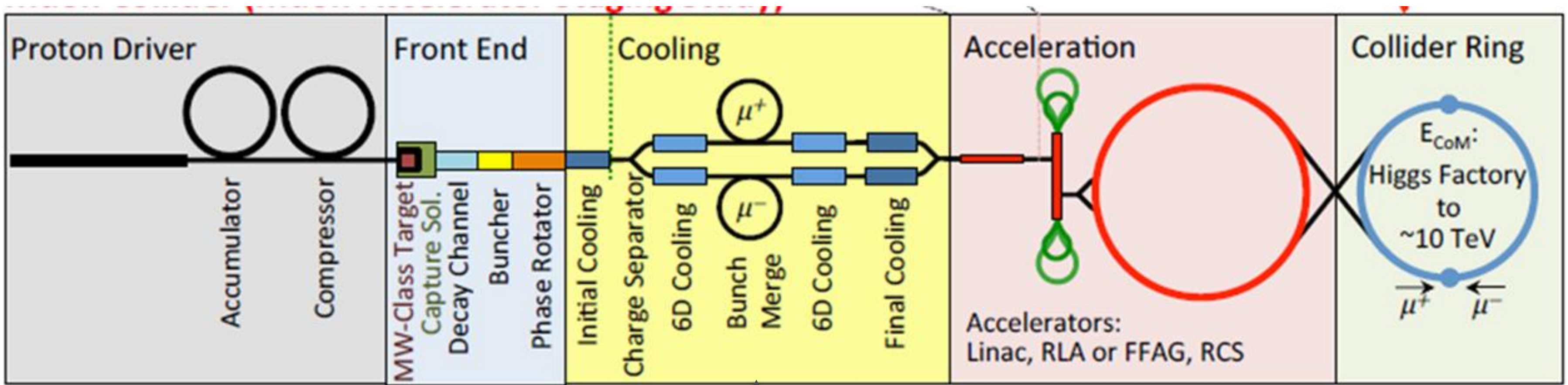
Goal is to know by next ESPU if a MC is credible option for a next project

- MC potential assessment report (pre-CDR)
- R&D plan that describes a path towards a MC



More details: https://arxiv.org/abs/2201.07895

Machine overview



High power proton driver

Muon production target

Capture 200 MeV bunches

Ionization cooling to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter propagating muons

Required key accelerator technologies (1)

- High power proton driver development
  - Delivery of high intensity H- ion source (2-4 MW, 5-8 GeV, 5-10Hz rep. rate)
  - Bunch compressor to deliver ~ 2 ns proton bunches
- Target system capable of managing large instant power
  - Shielding system that can protect capture magnet and target surrounds
  - SC capture solenoid that can contain the required shield (15-20 T, ~1 m bore)
- Cooling system to reduce 6D emittance by 6 orders of magnitude
  - Cells of tightly packed magnets, NC cavities and absorbers
  - Demand of high B-fields in the 30-40 T range
  - Operation of high-gradient NC RF cavities within multi-T B-fields
- Acceleration scheme towards TeV scale energy before decay
  - Fast ramping magnets to deliver ramp times of few T on a few-10 ms timescale
  - High-gradient SC cavities robust to beam loading

Required key accelerator technologies (2)

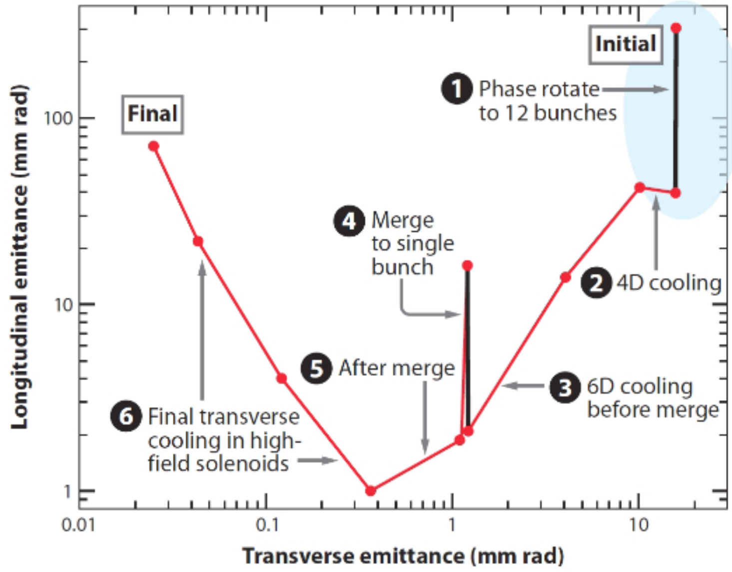
- Collider ring
  - Dipole magnets operating at high-fields (12-16 T)
  - Large bore (~150 mm) to accommodate shielding from muon decays
  - Neutrino flux mitigation system
  - High gradient final focus quadrupoles, comparable to HL-LHC at 3 TeV and more demanding at 10 TeV
  - Detector system capable of distinguishing signal from the beam induced background

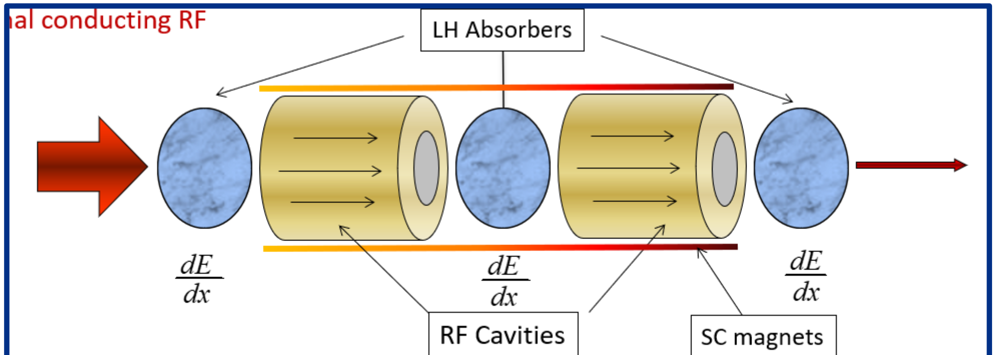
An important outcome of MAP was that progress in each of the above areas was sufficient to suggest that there exist a viable path forward

Principle of ionization cooling

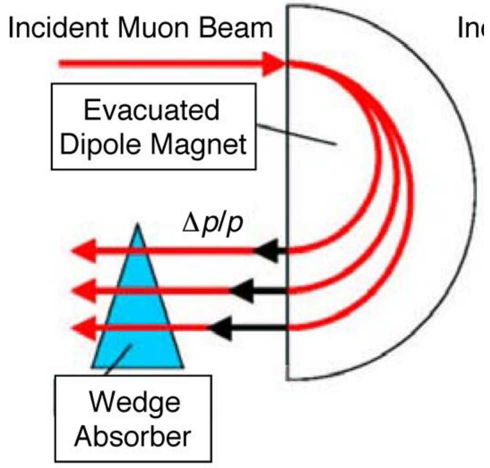
- 6D emittance must be reduced by 6 orders of magnitude before acceleration
  - Muon Ionization can do this before muons decay
  - Uses strong B-fields to confine beams in absorbers
  - Requires NC cavities for lost longitudinal energy

6D cooling baseline for a MC



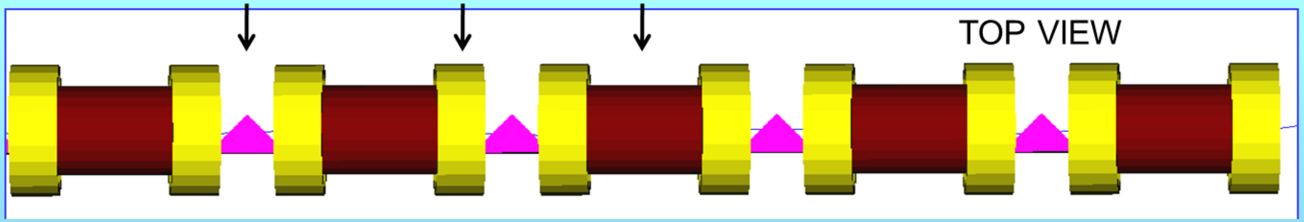


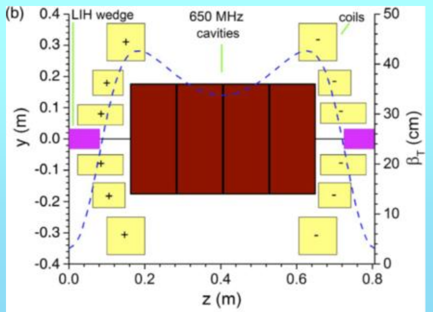
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$



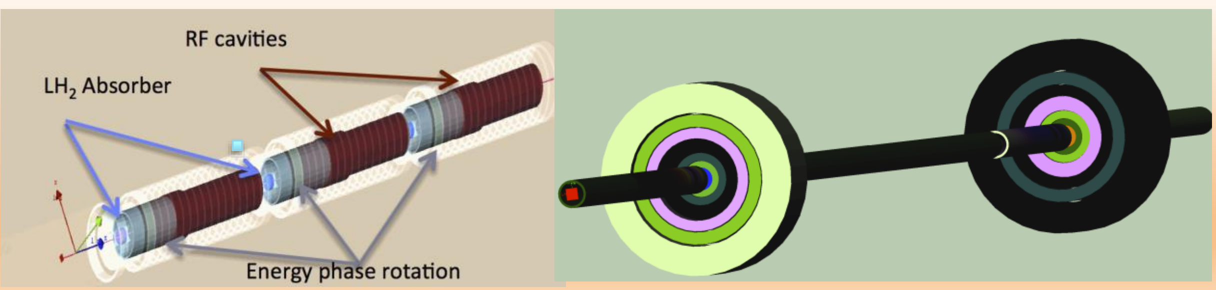
Ionization cooling design for a MC

- Sufficient progress was made in all ionization cooling section designs
  - Design of cooling lattices in place with realistic assumptions
  - They came only by a factor of two to the MC requirement.
  - Very conservative limits were placed in both magnet and rf technology





6D Cooling design

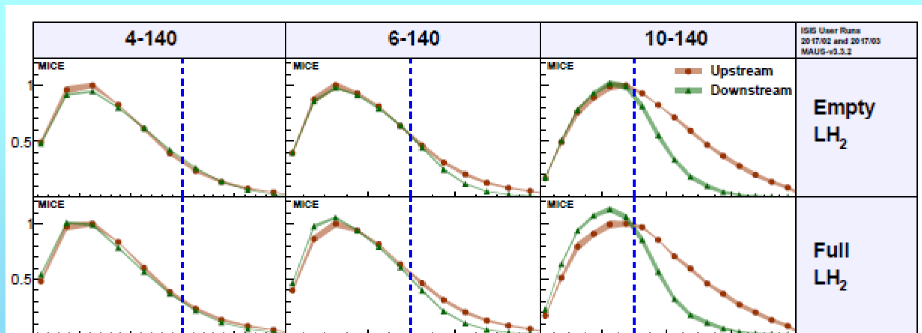


Final cooling lattice design

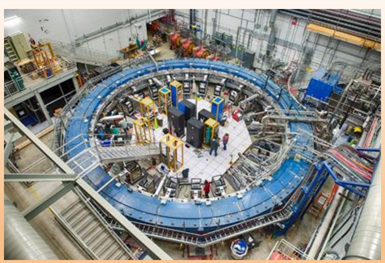
- Next generation design effort will combine the latest technology with new optimization methods to further enhance performance

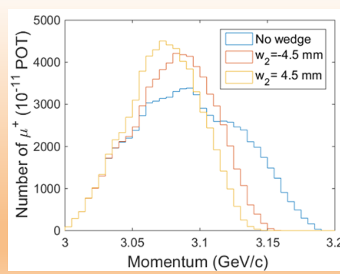
Ionization cooling demonstration

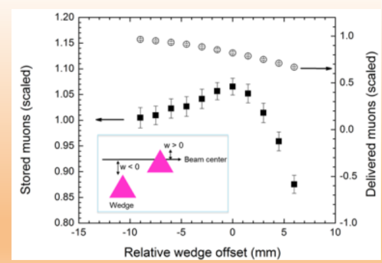
- Ionization cooling has been **demonstrated** in two occasions
  - MICE demonstrated O(10%) **transverse** cooling with different absorbers
  - Fermilab demonstrated **longitudinal** cooling for the Muon g-2 Experiment



Transverse cooling demo in MICE





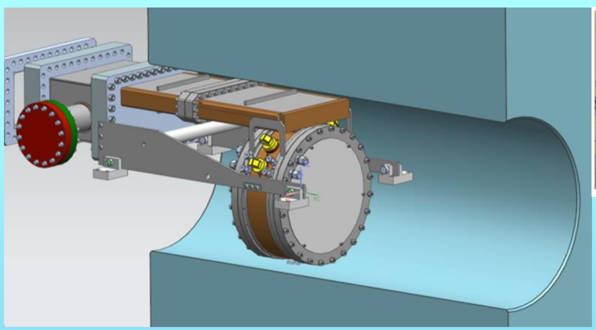


Longitudinal cooling demo for the Muon g-2 Experiment

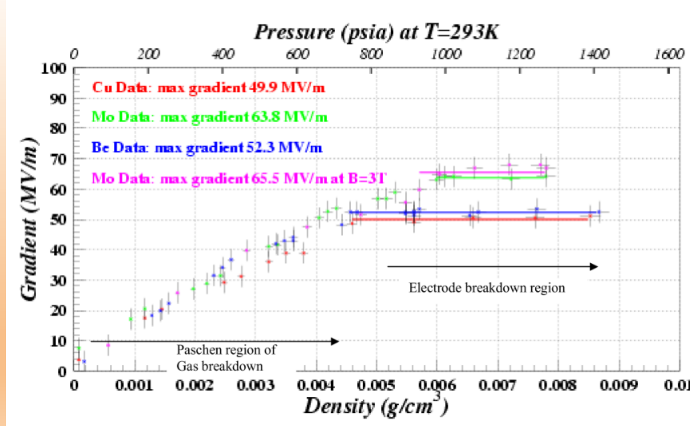
- Need to develop a full 6D cooling demonstrator with a MC cell
  - Test absorbers, tight constraints, instrumentation under realistic conditions

NC RF cavities in magnetic field

- Two promising solutions for sustaining cavity gradient in B-fields
  - Use-low density materials (like Be) to reduce damage from field-emission
  - Use high-pressure gas inside the cavity
- Both techniques have been experimentally verified with a 3 T field
  - No degradation in achievable gradient for the applied B-field



Demo of 50 MV/m at 0 and 3 T with **vacuum**

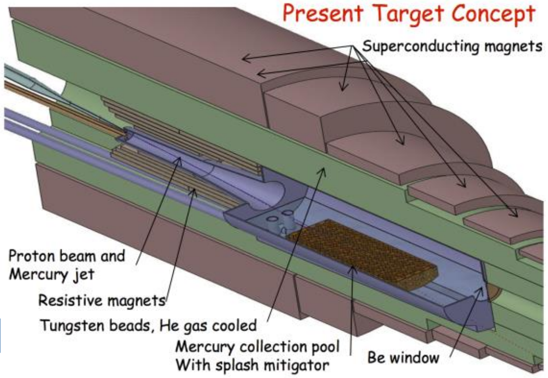


Demo of 50+ MV/m at 0 and 3 T with **gas**

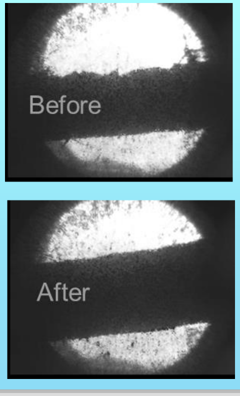
- Need to develop a test facility for design, construction and testing of rf in magnetic fields under MC conditions

Target station

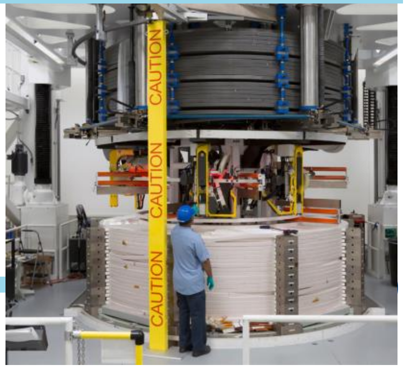
- MAP considered 2-4 MW liquid mercury or Gallium jets @ 15-20 T
  - MERIT exp. demonstrated liquid Mercury jet in high field solenoid. Technology is OK but some safety concerns
- IMCC is considering a beam power of ~ 2 MW
  - This opens a path for solid targets. Simulations with a Graphite target are promising
  - Mature technology for ~ 1 MW targets @ Fermilab with plans to expand > 2 MW for its neutrino program in the following years – synergies possible
- SC solenoid design is demanding & needs R&D
  - 20 T with large aperture (~ 1m) to allow shielding
  - Experience with ITER center solenoid can be used – size and field strength are comparable.



Liquid Mercury demo (MERIT)



ITER 13 T solenoid



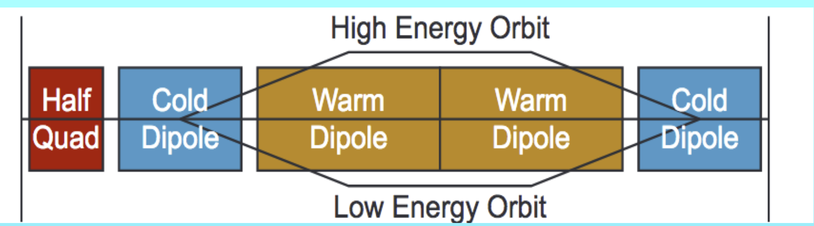
Acceleration

- Technologies include:
  - Superconducting linacs
  - Recirculating linear accelerators (RLAs)
  - Fixed field alternating gradient rings (FFAs)
  - Hybrid rapid synchrotrons (RCS)

Designs to 125 GeV CoM (Superconducting linacs, RLAs)

Needed for Multi-TeV scale (FFAs, Hybrid RCS)

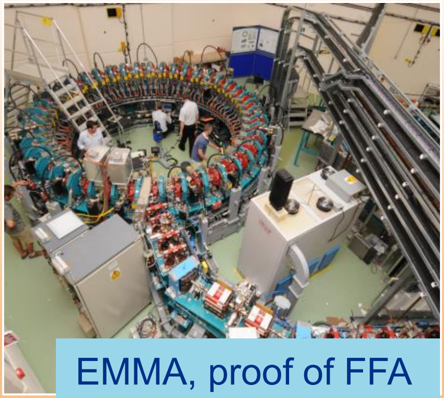
- Designs in place for acceleration to energies up to 125 GeV



Hybrid RCS combines static and fast-ramping magnets. Pulsed magnet designs and their power supply system and efficiency are main challenges

TeV accel. options

FFA allow acceleration without pulse magnets. Has challenging lattice design and beam dynamics



EMMA, proof of FFA principle

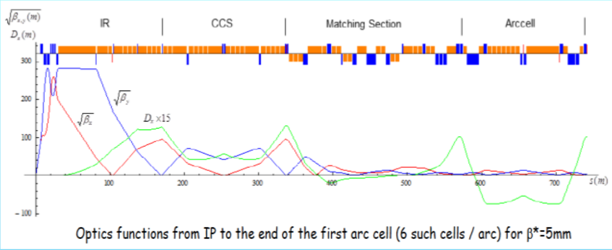
- Both concepts will be explored, by attempting to expand the capabilities of both technologies

Fermilab

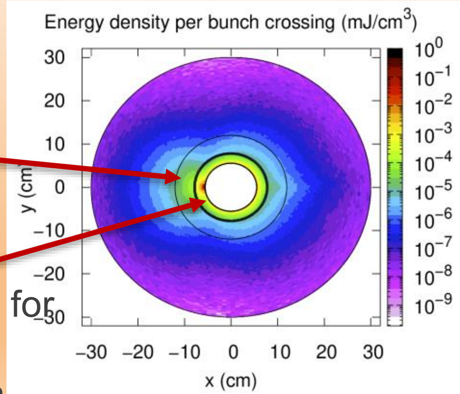
Collider Ring design

- MAP developed 4.5 km ring for 3 TeV with Nb_3Sn
  - Optics and magnet parameters have been specified
  - Specifications in the HL-LHC range
  - 5 mm beta function at the IP
- Design of 10 TeV ring is a key ongoing effort
  - Stress management in the coils is crucial
  - First studies indicate that radiation effect at 10 TeV is comparable to 3 TeV
  - 16 T Nb3Sn or HTS dipole around 150 mm bore
  - 1.5 mm beta-function at the IP
  - Alternatives with HL-LHC performances under consideration but slight reduction in luminosity

3 TeV solution by MAP



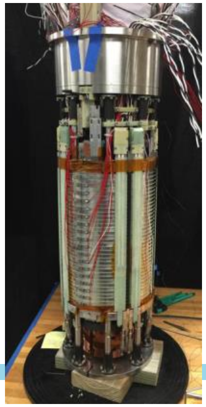
10 TeV radiation studies (IMCC)



Magnet technology

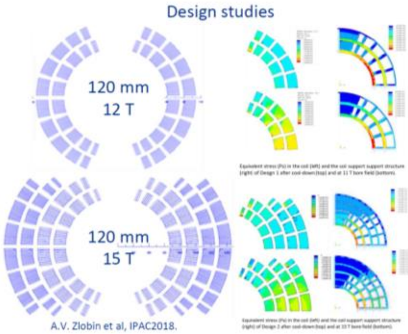
- **Cooling:** Designs consider B-fields in the 30-40 T range
  - This field has been demonstrated with commercial MRI 29 T magnets
  - Record 32 T achieved at NHMFL. A funded proposal to design purely SC 40 T magnet in place [ref]
- **Acceleration:** Designs considered rapid cycling synchrotrons with fast cycling magnets
  - Demonstrated record ramp rate of 300 T/s with HTS – upgrades for higher fields proposed [ref].
- **Col. Ring:** 10 TeV designs consider 150 mm bore, 16 T arc dipoles
  - US-MDP plans in 4-5 years demonstration of a 12-15 T (120 mm) Nb_3Sn dipole

Record SC 32 T @ NHMFL

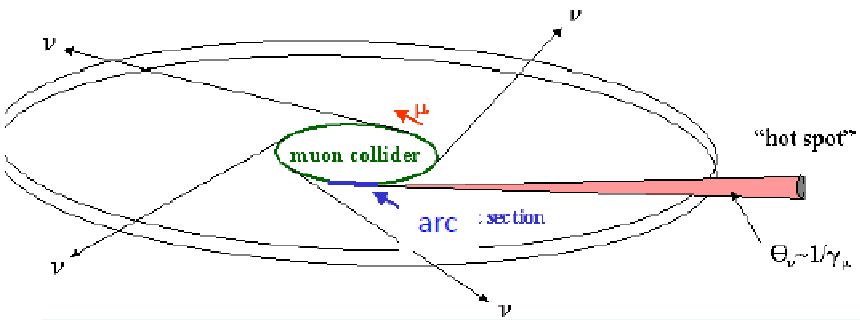


~ 300 T/s HTS demo at Fermilab

US-MDP future magnet developments

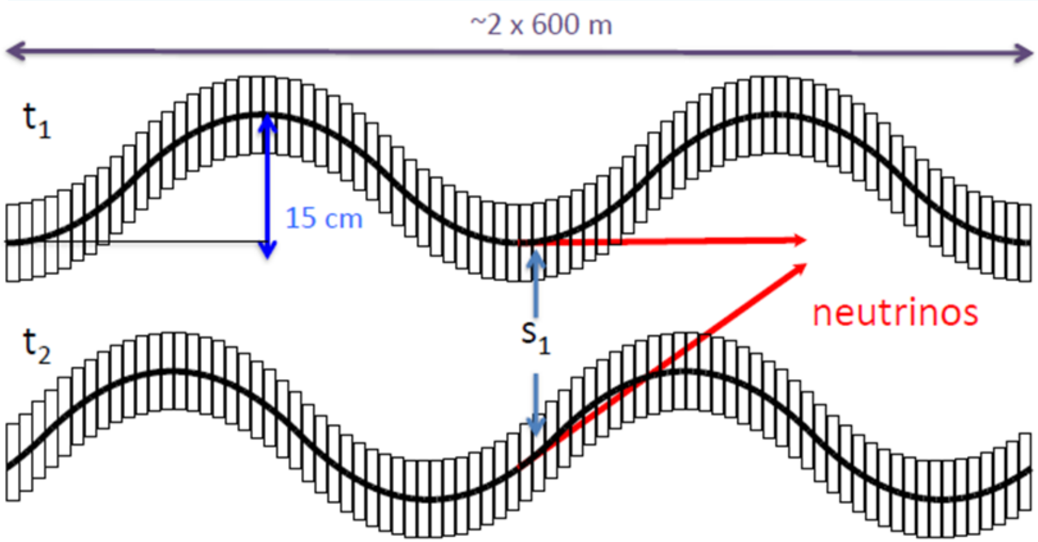


Neutrino flux



Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 μSv/year
LHC : <5 μSv/year

Solution: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers; (Schulte, IPAC 22)



Could work even for 14 TeV collider at 200 m

Need to study mover system, magnet, connections and impact on beam

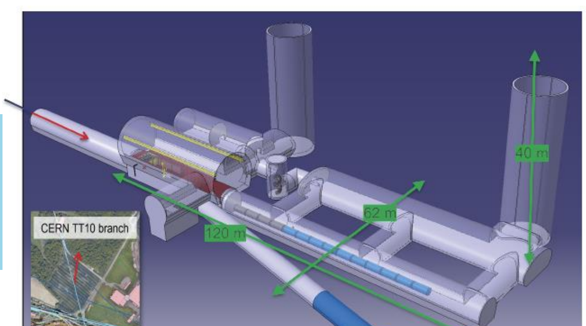
Working on different approaches for experimental insertion

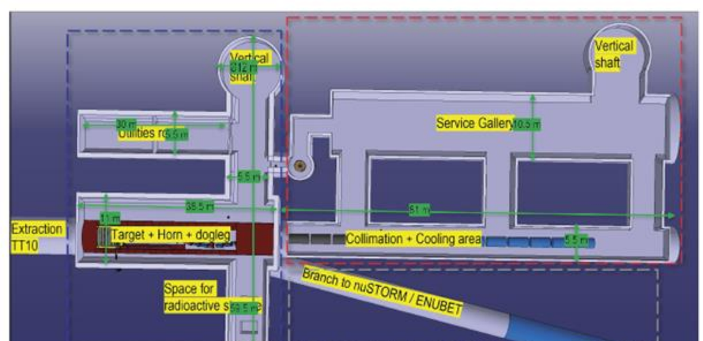
Alternatively: Fast beam wobbling (Mokhov & Van Ginneken, PAC 1999)

Demonstrator facility consideration

- IMCC considers demonstrators for muon source & high-energy complex
  - Demonstration of radiation and shock resistance of materials
  - Demonstration of high field muti-Tesla magnets for muon production, cooling, acceleration and collision
  - Demonstration of high gradient, normal conducting rf cavities for cooling and power-efficient superconducting rf for acceleration
  - Demo of an integrated ionization cooling module as an engineering prototype
- Land at CERN exists but other sites (internationally) are explored
- Construction between 2026-2030 with R&D to follow

Layout using CERN PS proton beam





US Muon Collider activities (1)

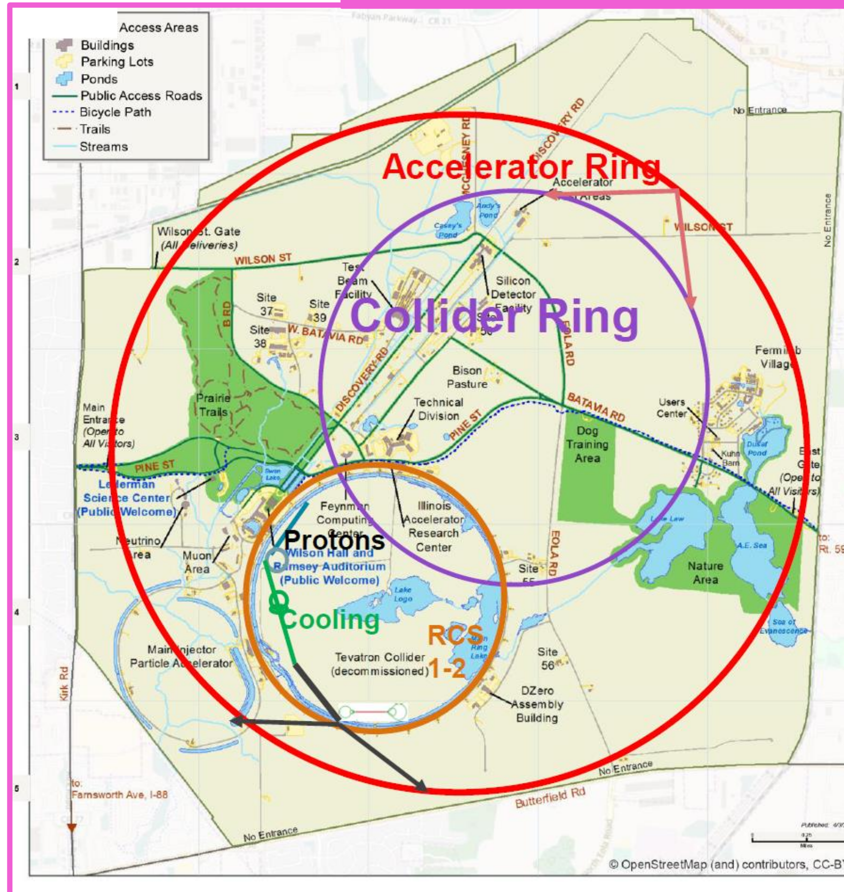
- There has been a strong physics interest about Muon Colliders in the US HEP community
- In 2020, the Snowmass EF+AF+TF have created a Muon Collider Forum to provide input to Snowmass on the Muon Collider
  - Build a strong collaboration between the particle physics and accelerator communities for MuC research and make a strong physics case
- Forum was very active with monthly meetings & dedicated workshops
- The final product was the Muon Collider Forum Report
  - Emphasize potential US role for R&D, explore US siting for a MC, and a vision of a US program by the next Snowmass
  - Identify key areas where US can provide critical contributions to the international MC R&D efforts.

More details: https://snowmass21.org/energy/muon_forum

US Muon Collider activities (2)

- A conceptual for Fermilab 6-10 TeV MC site-filler is in place
- Proton source
  - PIP-II upgrade -> Target
- Ionization cooling channel
- Acceleration (3 stages)
  - Linac + Recirculating Linac → **65 GeV**
  - Rapid Cycling Synchrotrons #1, #2 → **1 TeV (Tevatron size)**
  - RCS #3 → **5 TeV (site filler)**
- 10 TeV collider
  - Collider radius: 1.65 km
- Staging @125 GeV (Higgs), 1 TeV, and 3 TeV possible

David Neuffer, [Details]



Fermilab

Moving forward

- Formation of IMCC, currently hosted by CERN
- IMCC will turn the Roadmap into an evolving plan
  - Secure resources
    - Different institutes
    - EU Design Study has been approved – funding agreement is in progress
- During Snowmass, strong support from EF for a path that would put us on a path of pre-CDR document in 2030 and a TDR in 2040.
- We hope that Snowmass 2022 & P5 report will lead to strong US involvement
  - Globally join forces to open a road to exciting physics
  - Enable collaboration with IMCC
  - Provide further funding for accelerator and detector R&D
  - Provide funding for the US future collider R&D proposal

Summary

- MC offers a unique opportunity for energy frontier collider with high luminosity
- Physics & technology landscape has significantly changed recently
  - Explosion of physics interest in muon colliders as indicated by the number of publications, activities in IMCC, Muon Collider Forum, and Snowmass white papers
- No fundamental show-stoppers in physics and technology have been identified
  - Nevertheless, engineering challenges exist in many aspects of the design and targeted R&D is necessary in order to make further engineering and design progress
- IMCC is currently considering two options
  - Goal is 10+ TeV, potential 3 TeV intermediate stage explored