Muon Collider Progress

42nd International Conference on High Energy Physics
Prague 18-24 July 2024

Donatella Lucchesi University and INFN of Padova

for the

International Muon Collider Collaboration

This project has received funding from the European Union's Research and Innovation programme under GAs No 101094300 and No 101004730.

The revived muon collider

2020 update of European strategy for particle physics

2021 International Muon Collider Collaboration

2022
Great support by community at Snowmass process
EU project, MuCol, approved

2023
“The muon shot” by P5, Particle Physics Project Prioritisation Panel

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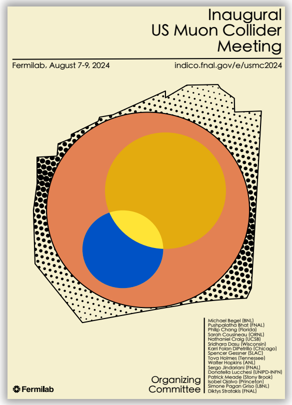
EDITORIAL | 17 January 2024

US particle physicists want to build a muon collider – Europe should pitch in

A feasibility study for a muon ... way to maintain particle physics uni...

2024:Starting US-IMCC



Just out of the press

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Transverse emittance reduction in muon beams by ionization cooling

The MICE Collaboration

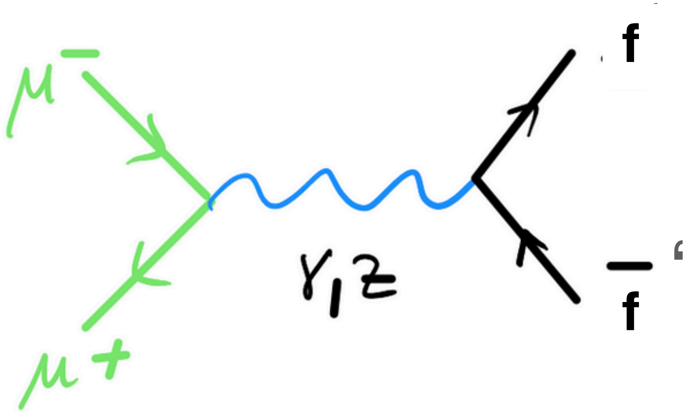
arXiv > physics > arXiv:2407.12450
Physics > Accelerator Physics
[Submitted on 17 Jul 2024]

Interim report for the International Muon Collider Collaboration (IMCC)

Multi-TeV muon collider will open a completely new regime

D. Zuliani

Energetic final states:
heavy particle or very boosted

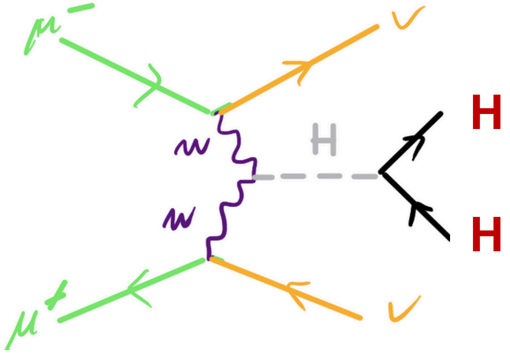


For example, Z' masses up 70 TeV can be excluded @95% CL depending on the model

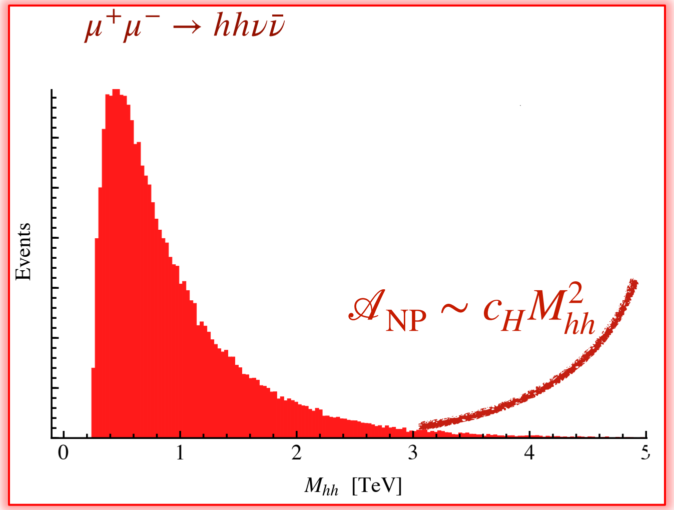
Mass limit:
LHC: 5 TeV, HL-LHC: 8 TeV
Future e^+e^-: 20 TeV

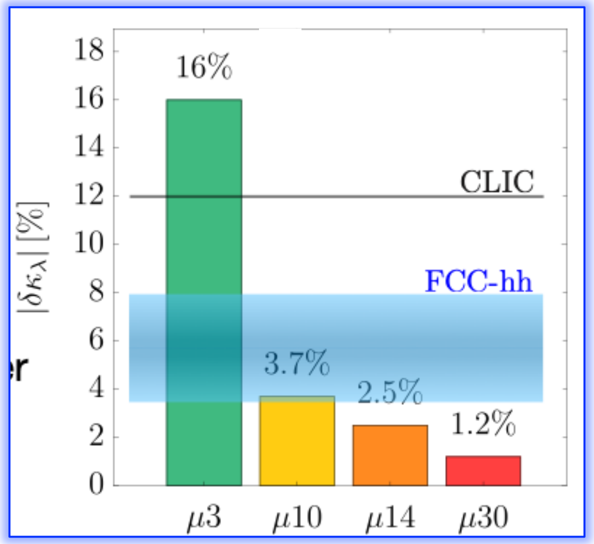
K. Korshynska et al.
https://doi.org/10.48550/arXiv.2402.18460

Guarantee "discovery": determination of Higgs field parameters



Most precise measurement with 10 ab^{-1} ~5 years data taking 1 experiment

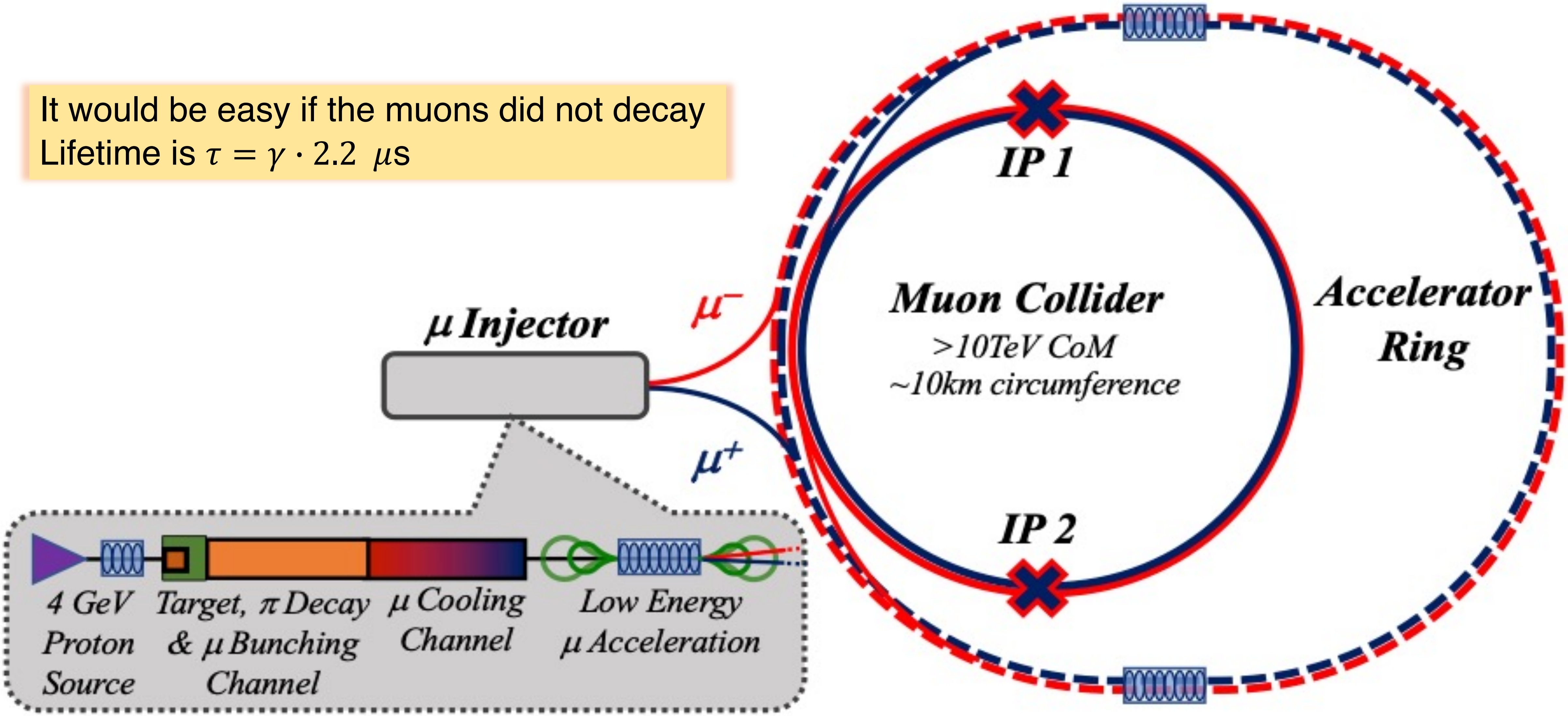




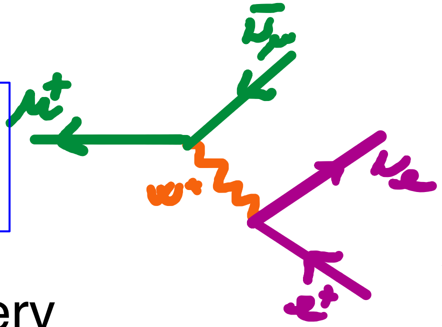
New Physics effects can appear at high double Higgs invariant mass

Muon Collider facility progress overview

It would be easy if the muons did not decay
Lifetime is $\tau = \gamma \cdot 2.2\ \mu s$



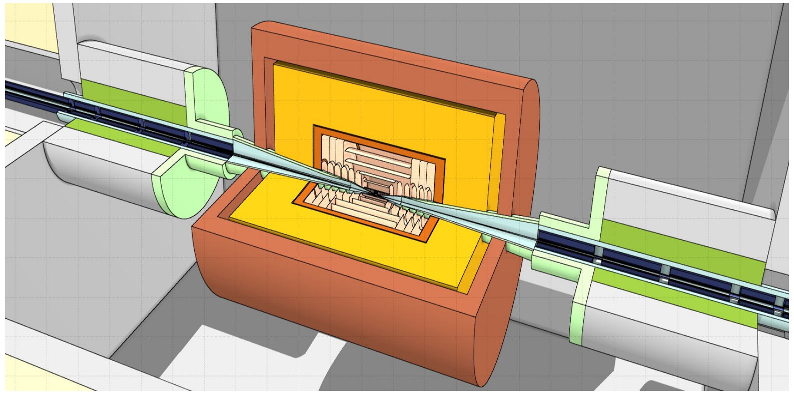
Main Muon Decay Consequences



Strategies to mitigate effects of high energy e^+ at interaction region

- Locate absorbers around the IP → very complex machine detector interface. New absorbers design for $\sqrt{S} = 10$ TeV

D. Calzolari



- Use new detector technologies to design detector & exploit advanced machine learning algorithms in physics object reconstruction. New detectors concept for $\sqrt{S} = 10$ TeV

M. Casarsa
C. Aimè
R. Gargiulo
L. Longo

Neutrino flux mitigation

Aim for negligible impact (~ LHC) in arc sections

- Almost done at $\sqrt{S} = 3$ TeV
- $\sqrt{S} = 10$ TeV go from acceptable to negligible with mover system

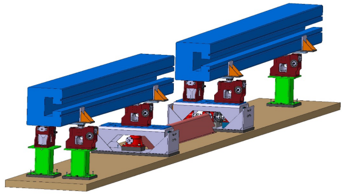
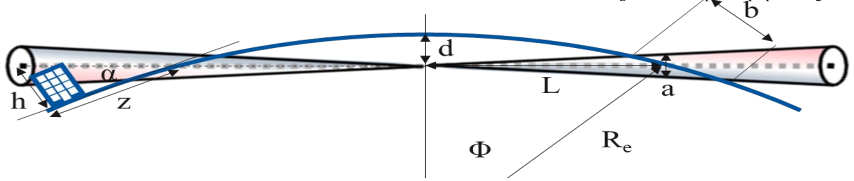
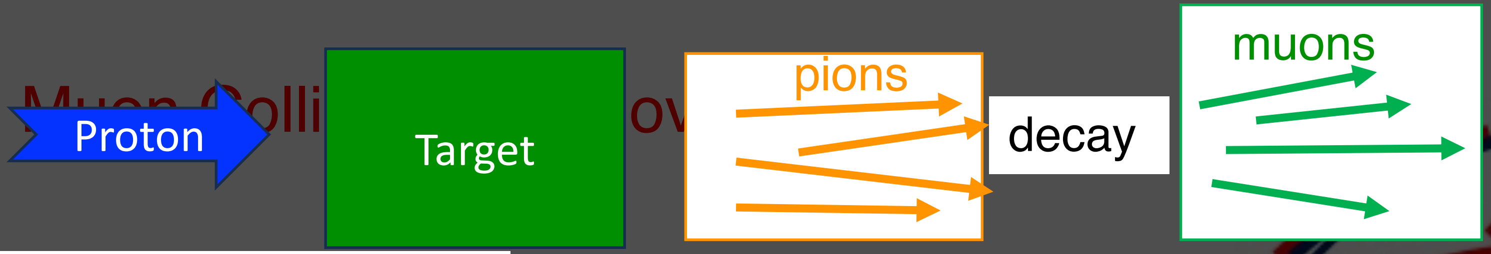


Fig. 7.23: Mock-up of the proposed magnet movement system.

Straight sections



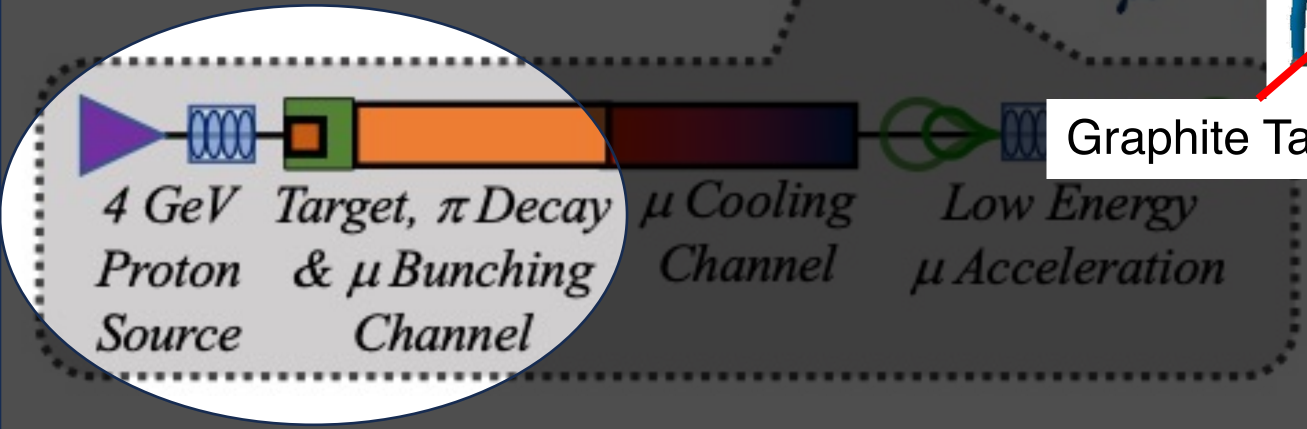
Strategies depend on the site. Identified possible layout for CERN location.

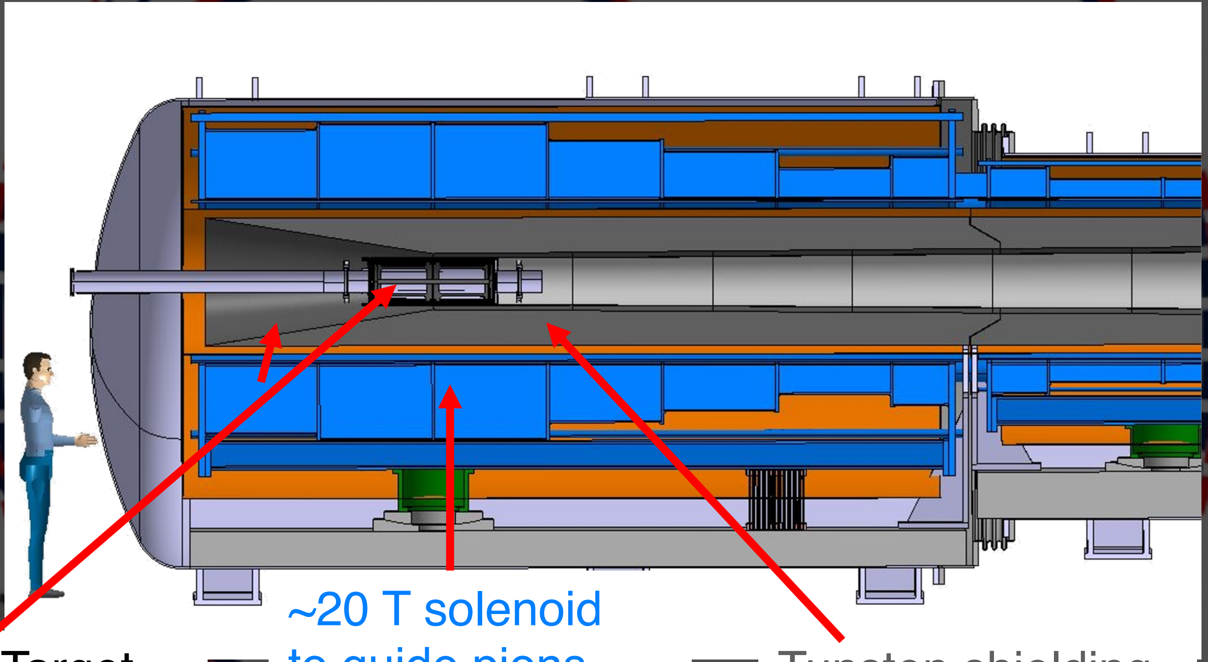


5×10^{13} captured muon pairs

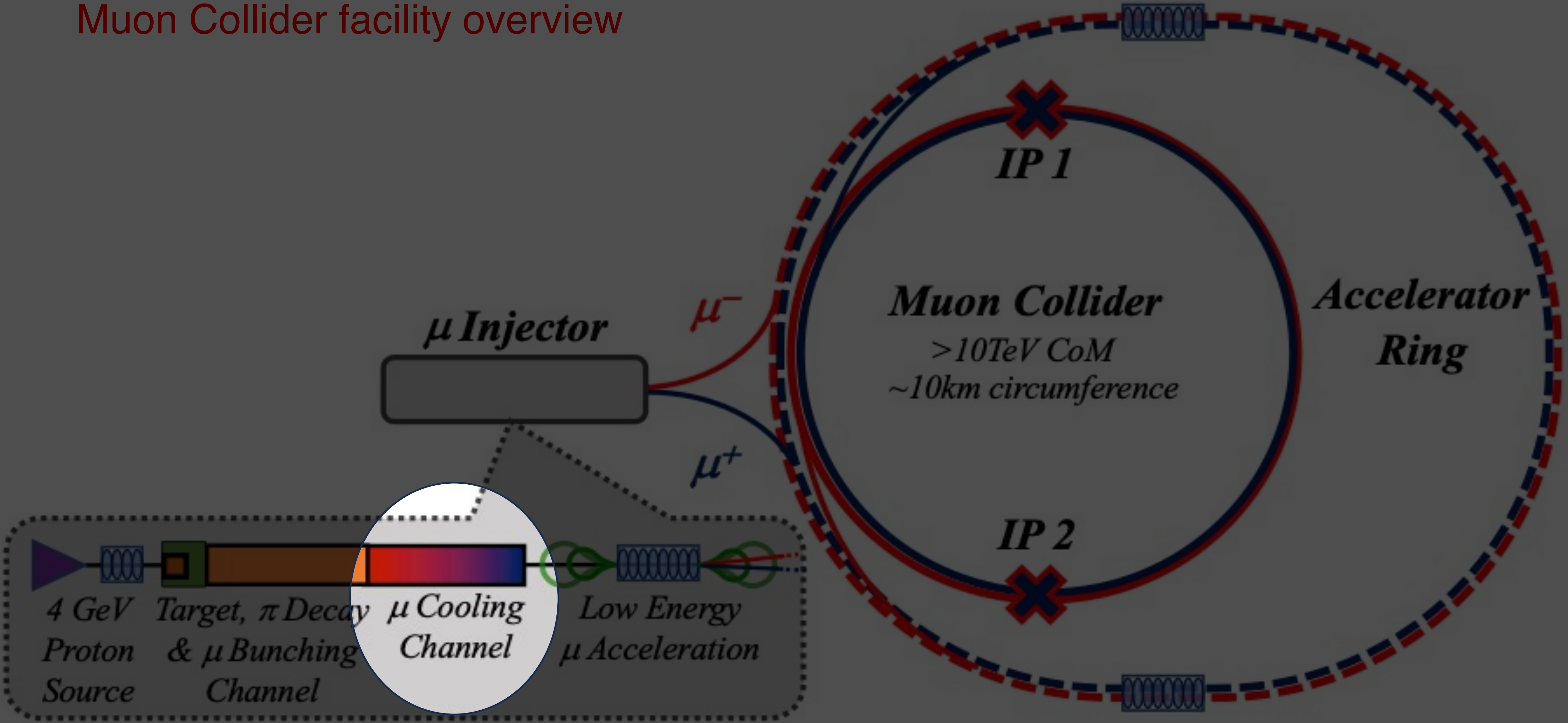
5 GeV
400 kJ x 5 Hz = 2 MW

Progress:
- Investigation of new target materials e.g. liquid target.
- Target solenoid design.
- System integration study.



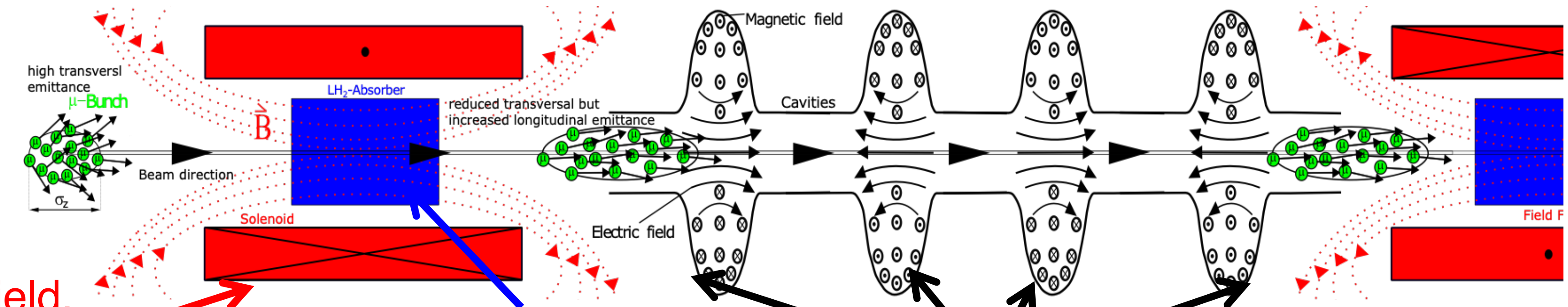


Muon Collider facility overview



Muon ionization cooling principle

D. Fu talk



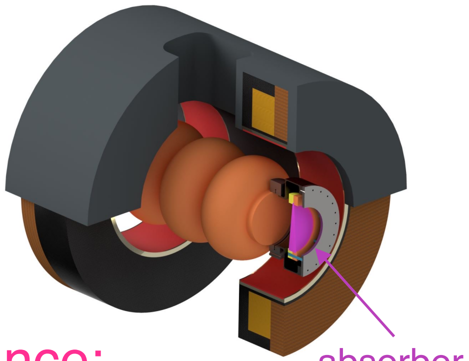
High-field, superconducting solenoid to minimize multiple scattering effect

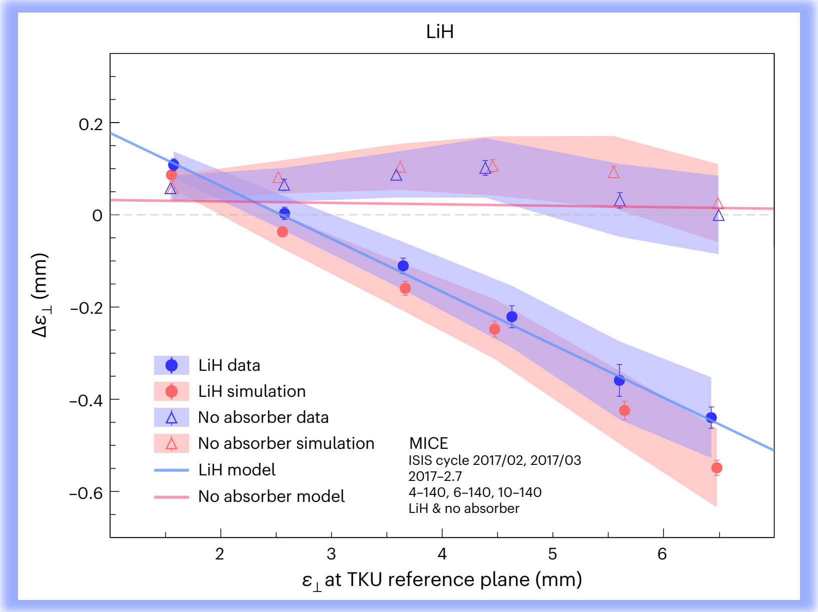
Absorbers, Low Z material: Lithium hydride, liquid H

High-gradient normal-conducting RF cavities

IMCC new activities:

- systematic design of the different cells



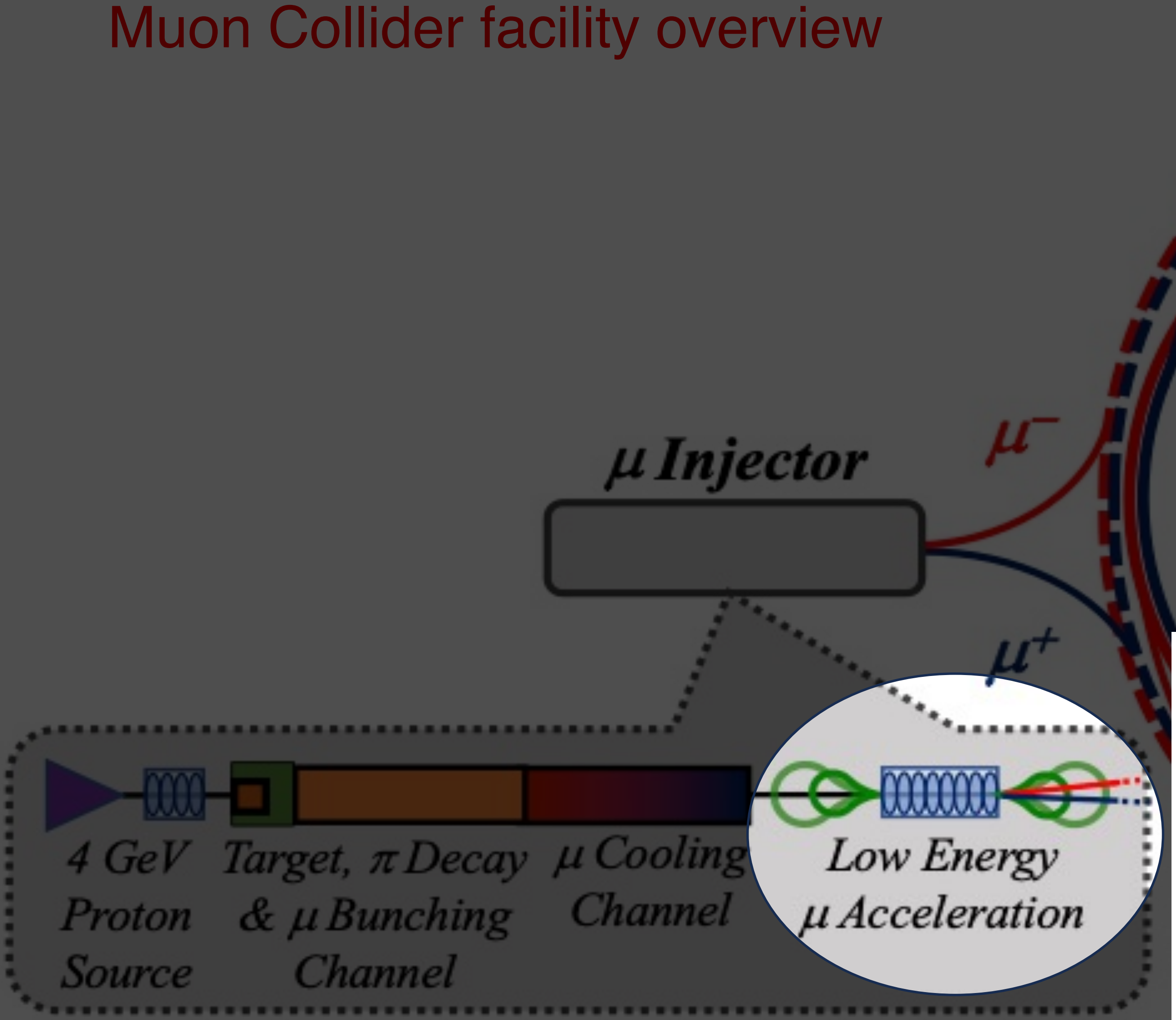


Improvement on expected simulated emittance: from 55 μm (MAP, Muon Accelerator Program) to 33 μm

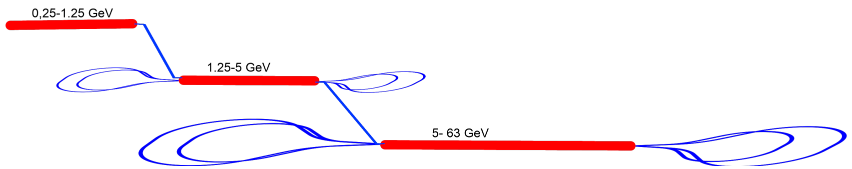
Goal of the final emittance: 25 μm

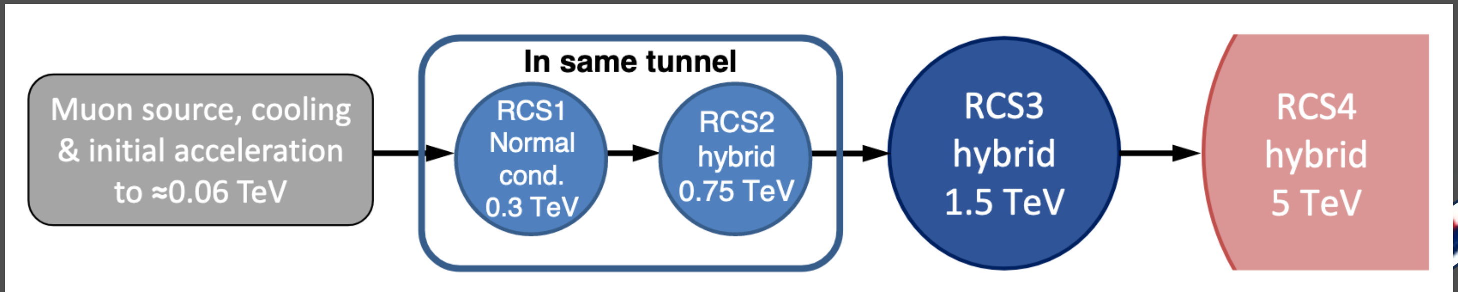
Simulation of transverse emittance well reproduced by MICE data

Muon Collider facility overview

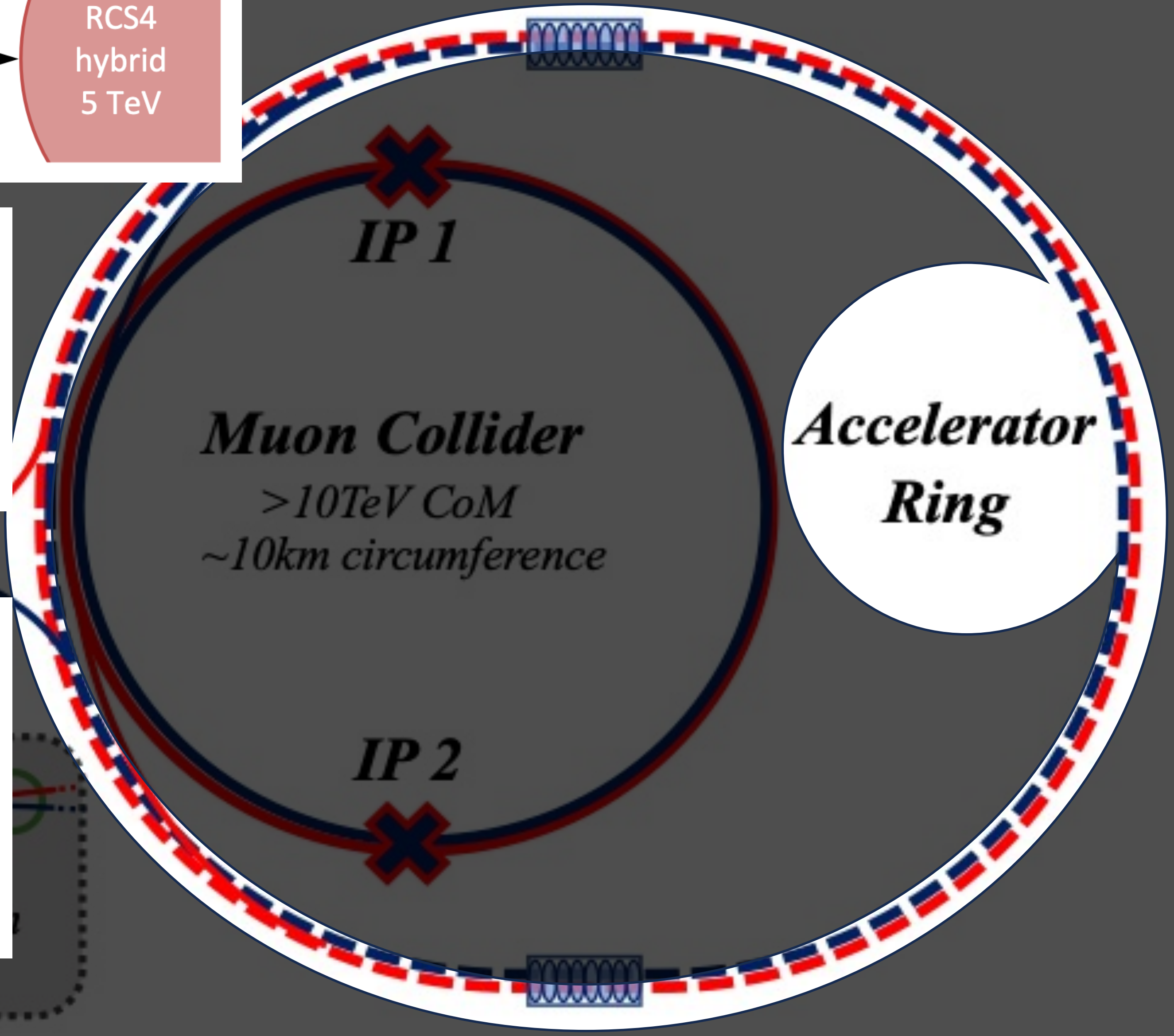


Rapid acceleration is crucial:
Linac (255 MeV to 1.25 GeV) and two stages of Recirculating Linac (1.25 GeV to 63 GeV)
New preliminary design





Chain of rapid cycling synchrotrons with repetition rate of 5 Hz.
Hybrid magnets: strong fixed-field, superconducting magnets interleaved with normal conducting magnets.



Recent achievements
- First lattice of RCS2.
- Simulation of usage of 1.3 GHz cavities → acceptable results.
- Study of shapes of fast ramping magnet and design possible power converter.

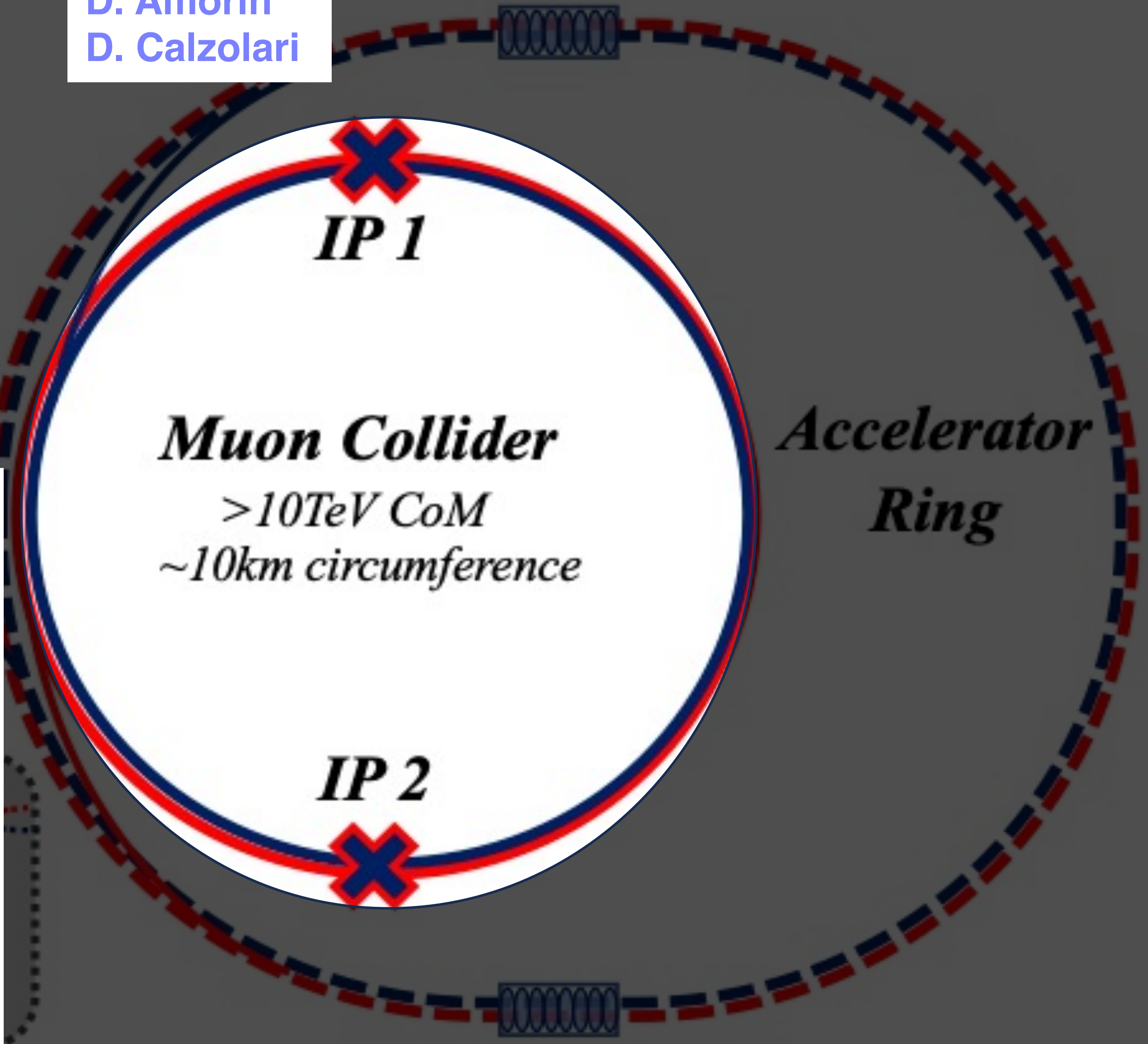
First design of $\sqrt{S} = 10$ TeV collider ring almost complete

Main challenges to have high performance:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

Assumed 16 T dipole magnet with different configurations.

Recent progress
- Interaction region configuration, based on HTS, frozen for detector and physics study for Eu strategy update
- Study magnet limitations
  - stress, protection, etc. against bore diameter vs. magnetic field for different conductor material and temperature.

D. Amorin
D. Calzolari



Possible implementations

Energy staging: Start at lower center-of-mass energy, e.g. $\sqrt{S}$= 3 TeV or more suited energy, move later at higher energy

Luminosity staging: Start $\sqrt{S}$=10 TeV with low luminosity, upgrade later to high luminosity as in HL-LHC

Expected integrated luminosity in 5 years one experiment

$\sqrt{s}$ = 3 TeV 1 ab^{-1}

$\sqrt{s}$ = 10 TeV 10 ab^{-1}

Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10	10	10
Target integrated luminosity	$\int \mathcal{L}_{target}$	ab^{-1}	1	10	10	
Estimated luminosity	$\mathcal{L}_{estimated}$	$10^{34}cm^{-2}s^{-1}$	2.1	21	tbc	14
Collider circumference	C_{coll}	km	4.5	10	15	15
Collider arc peak field	B_{arc}	T	11	16	11	11
Luminosity lifetime	N_{turn}	turns	1039	1558	1040	1040
Muons/bunch	N	10^{12}	2.2	1.8	1.8	1.8
Repetition rate	f_r	Hz	5	5	5	5
Beam power	P_{coll}	MW	5.3	14.4	14.4	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25	25	25
IP bunch length	σ_z	mm	5	1.5	tbc	1.5
IP betafunction	β	mm	5	1.5	tbc	1.5
IP beam size	σ	µm	3	0.9	tbc	0.9

Study on how to use LHC tunnel and/or other infrastructures

R&D programs and “demonstrator”

Very Broad R&D program

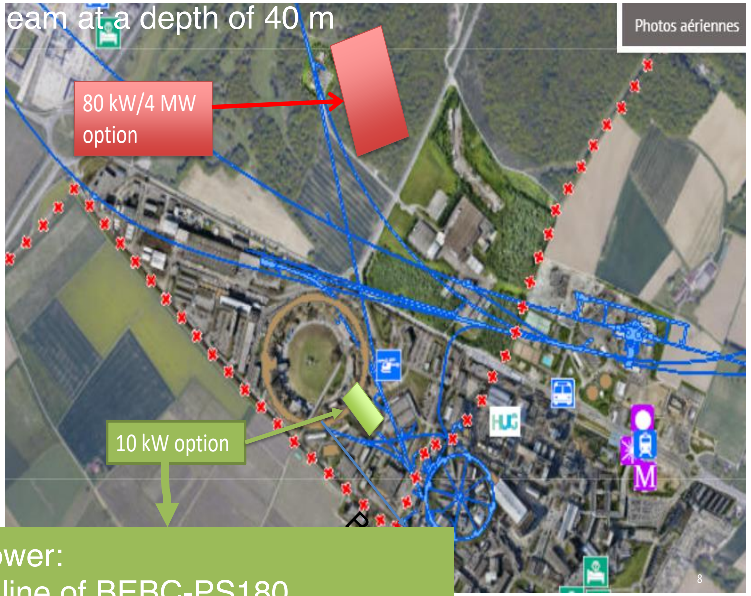
- Detector components
- Facility
  - Magnets, Target, RF systems, Absorbers, …

Including integrated tests also with beam

Aim at a “demonstrator” facility that shall

- Demonstrate that full chain of ionization cooling performs as expected.
- Test materials for absorbers, target and beam dump strategies, high temperature superconducting magnet, …
- Become a physics facility (for neutrino for example).

High power
O(80kW) on target easily achievable
No showstopper for 4 MW with
eam at a depth of 40 m



Low power:
Reuse line of BEBC-PS180 Collaboration, decommissioned, extending it towards B181 (now

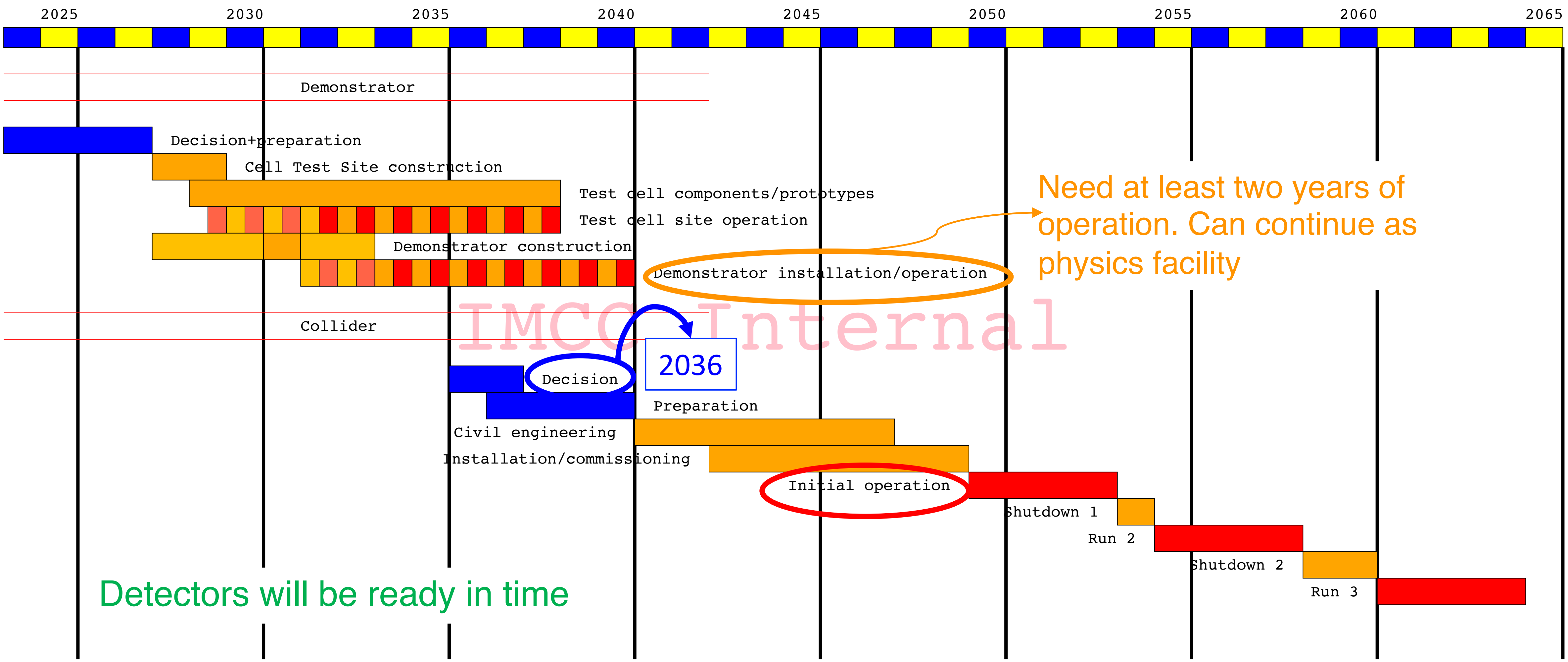
Need place with existing proton beam with significant power
Possible sites: CERN and Fermilab under study

Recent achievements:

- Design of prototype of cooling cell ready → go to construction
- Design of lattice target region and transport line started

Tentative Timeline (Fast-track for $\sqrt{S}$=10 TeV)

IMCC Internal means ”it is only a basis to start the discussion, it will be reviewed soon”



Summary

Muon collider facility has super-strong physics and technology case.

A huge amount of work was accomplished in every part of the facility with limited resources, thanks to the contribution of an enthusiastic community.

Technology R&D toward MuC facility has synergies with:

- ✓ fusion reactors, power generators, Nuclear Magnetic Resonance (NMR), Magnetic Resonance Imaging, High-power proton facility, Facilities such as NuStorm, mu2e, COMET, highly polarized low-energy muon beams, detector for any other future experiments, advanced AI algorithms
- ✓ Many other, unimaginable now, await in this uncharted territory.

Results from simulation studies and R&D progress are increasing confidence that the muon collider represents a unique and sustainable path to the future.

If interested contact:

Study Leader: D. Schulte

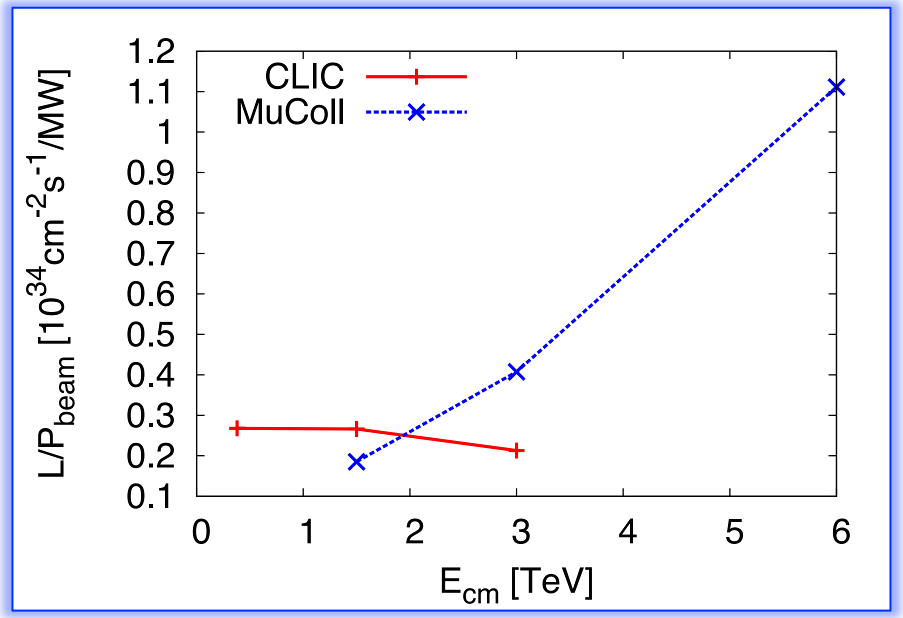
Deputies: A. Wulzer, D. Lucchesi, C. Rogers

CB chair: N. Pastrone

Additional material

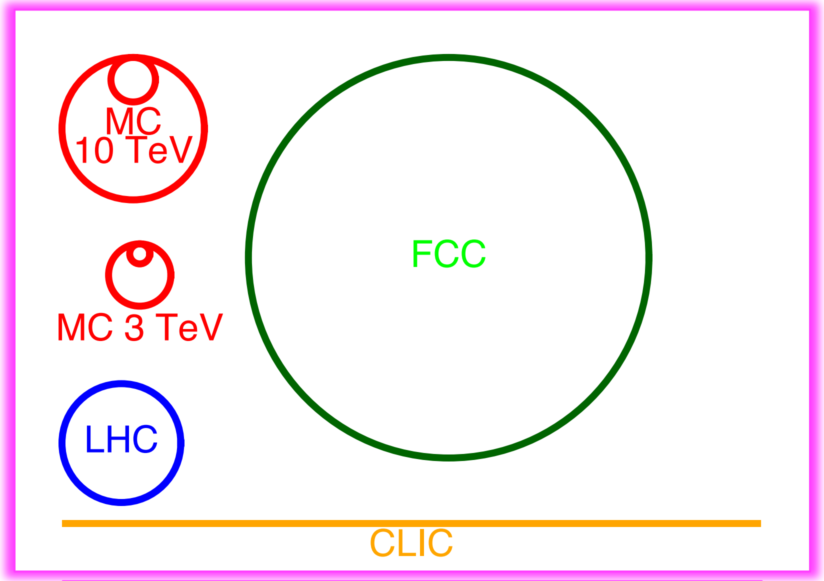
Technology and social motivations

Muons do not suffer too much from synchrotron radiation in the considered energy range



luminosity increase per beam power vs. E_{CM}

High center of mass energy & high luminosity & power efficient machine



A sustainable accelerator complex

Compact → cost effective

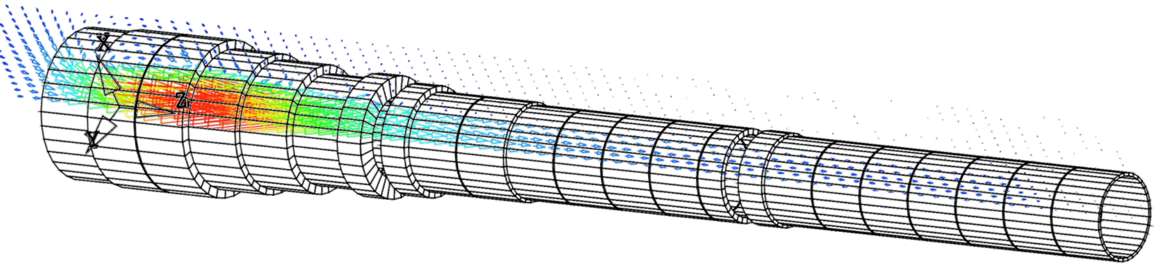
Important technology and design advances in past years

Project reviews in Europe and US did not find any showstoppers

Target Technologies

Target solenoid design ongoing

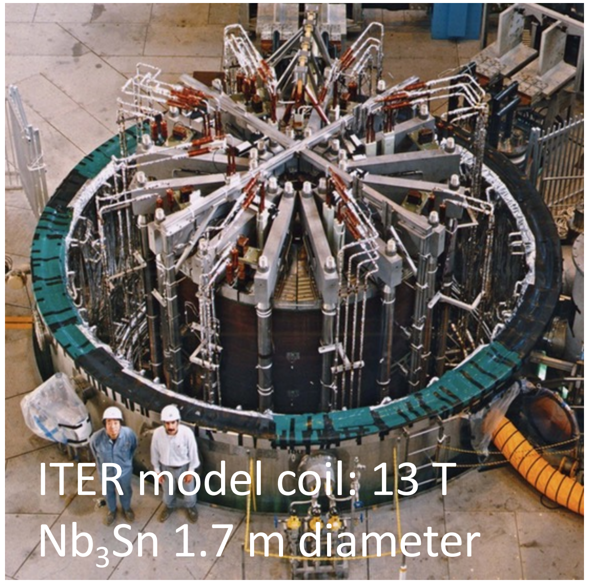
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

A Portone, P. Testoni,
J. Lorenzo Gomez, F4E

Our work is relevant for fusion



ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

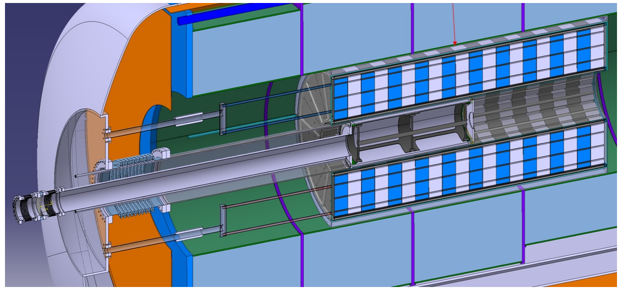
FLUKA studies:

2 MW target: stress in target, shielding, vessel OK

Need to have closer look at window

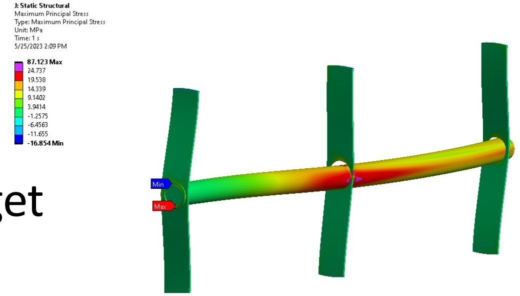
Cooling OK

Integration

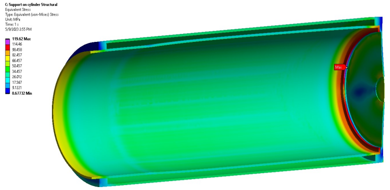


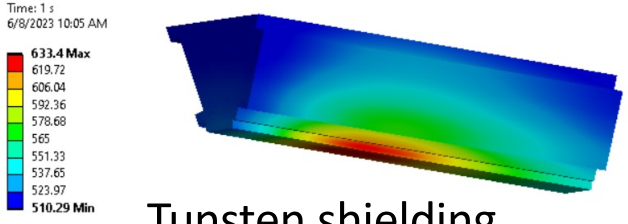
Cooling, vacuum, mechanics, …

Target



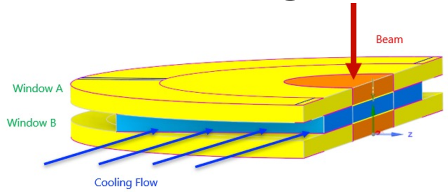
Vessel





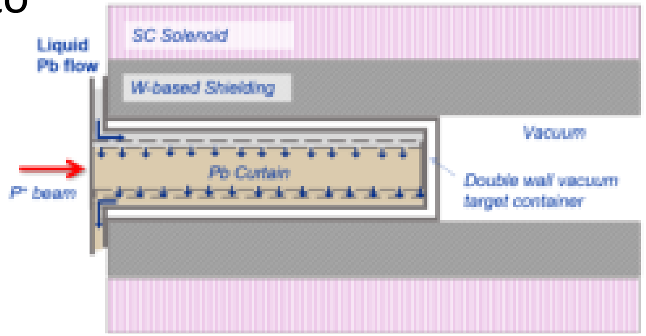
Tunsten shielding

Window



Liquid metal target

Serious alternative to graphite



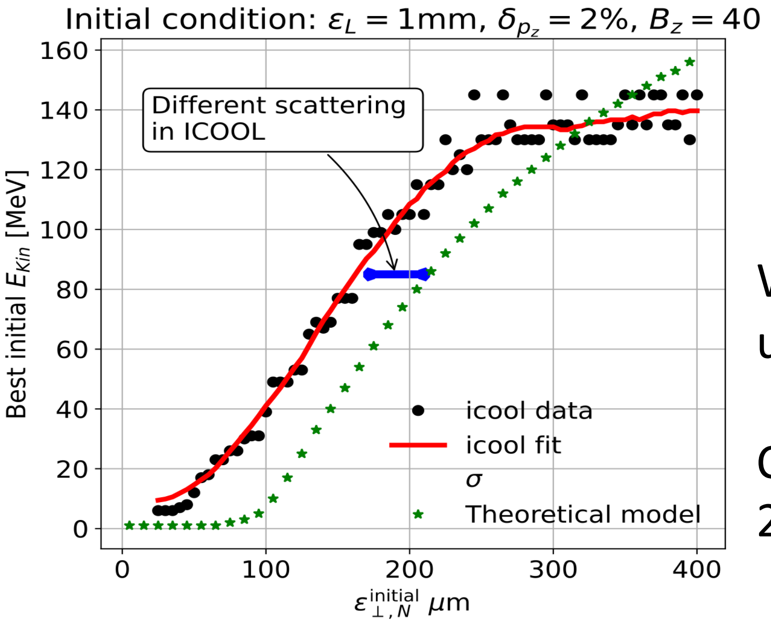
Muon Cooling Performance

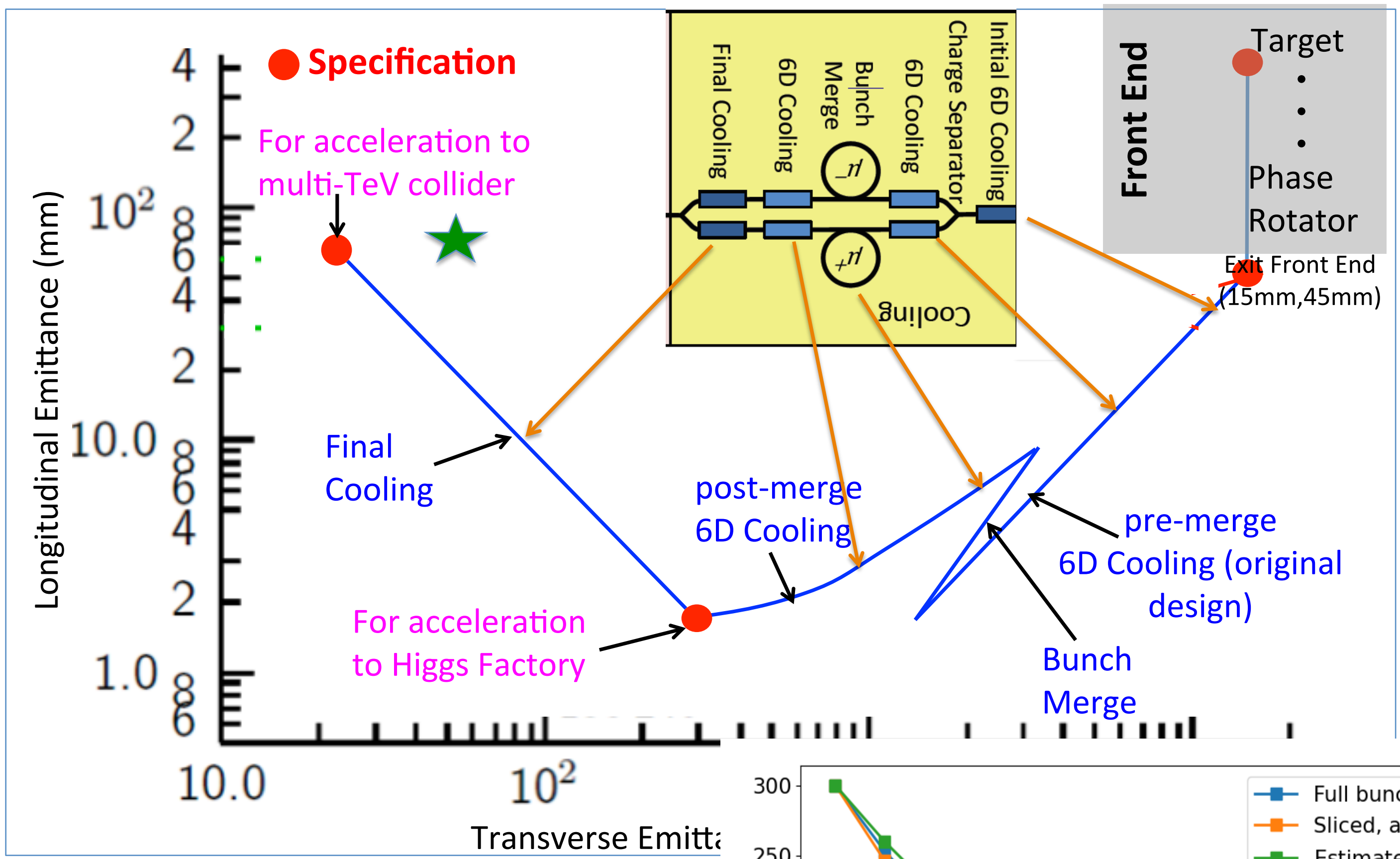
MAP design achieved 55 um based on achieved fields

Can expect better hardware

Integrating physics into **RFTRACK**, a CERN simulation code with single-particle tracking, collective effects, …

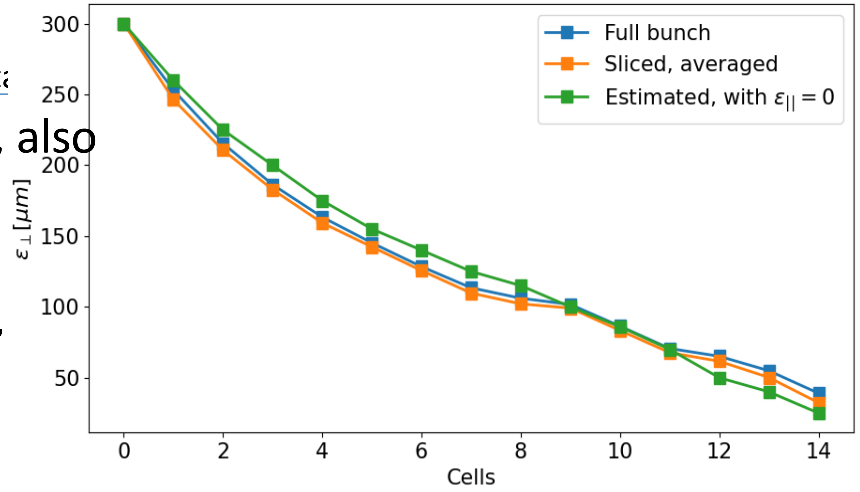
A. Latina, E. Fol, B. Stechauner at al.





Working on **improved, systematic design**, also using better magnets and RF

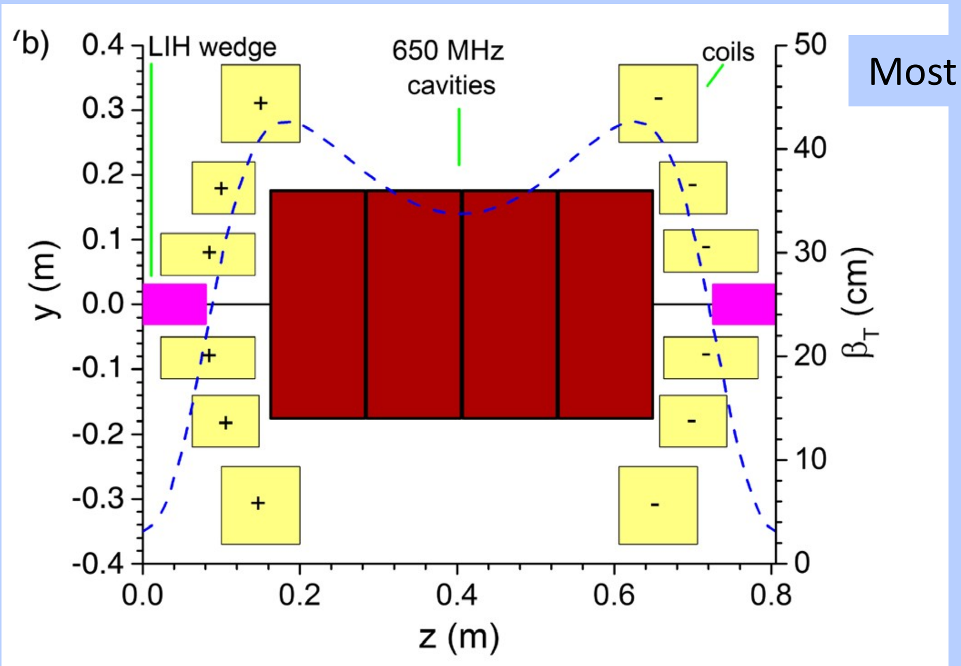
Currently improved from 55 um to 33 um, 25 um is the goal



Cooling Cell Technologies

Are developing example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

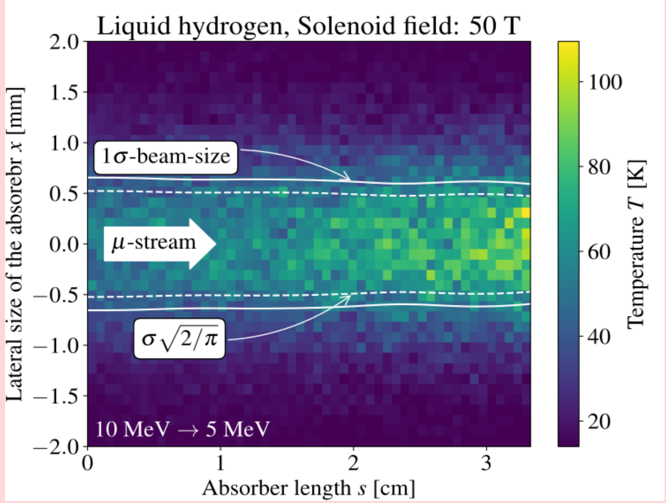
L. Rossi et al. (INFN, Milano, STFC, CERN), J. Ferreira Somoza et al.



Most complex example 12 T

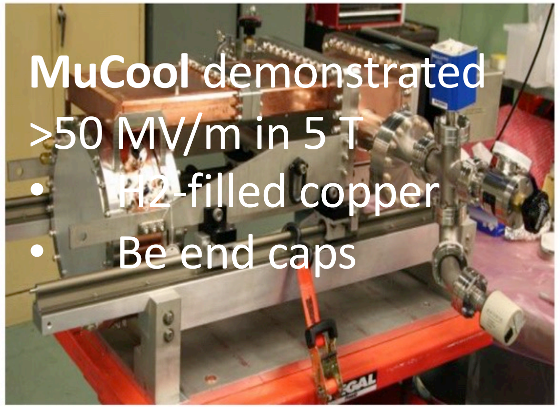
HTS solenoids
Ultimate field for final cooling
Also consider cost

Windows and absorbers
- High-density muon beam
- Pressure rise mitigated by vacuum density
- First tests in HiRadMat



RF cavities in magnetic field
Gradients above goal demonstrated by MAP
New test stand is important
- Optimise and develop the RF
- Different options are being explored
- Need funding

D. Giove, C. Marchand, Alexej Grudiev et al. (Milano, CEA, CERN, Tartu)



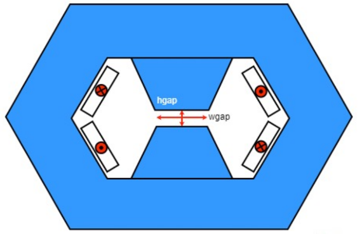
MuCool demonstrated >50 MV/m in 5 T
- H2-filled copper
- Be end caps

Fast-ramping Magnet System

Efficient energy recovery for resistive dipoles (O(100MJ))

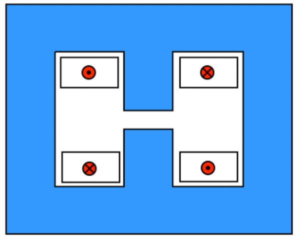
Synchronisation of magnets and RF for power and cost

Hourglass frame magnet



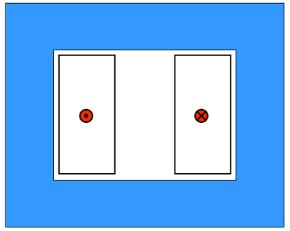
5.07 kJ/m

H magnet



5.65…7.14 kJ/m

Window frame magnet



5.89 kJ/m

FNAL 300 T/s HTS magnet

Could consider using HTS dipoles for largest ring

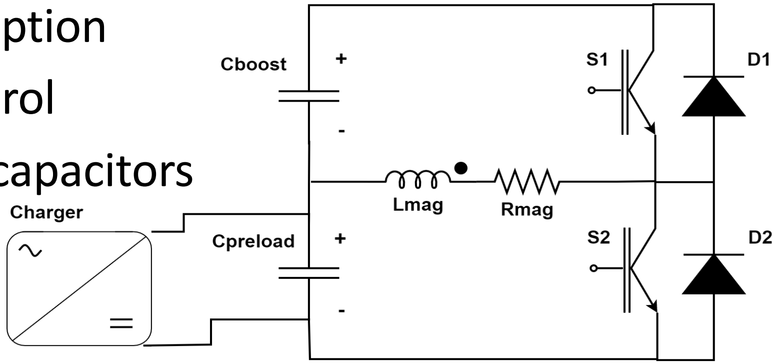
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Commutated resonance (novel)

Attractive new option

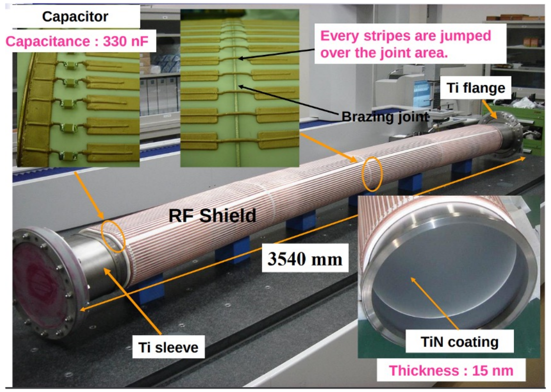
- Better control
- Much less capacitors



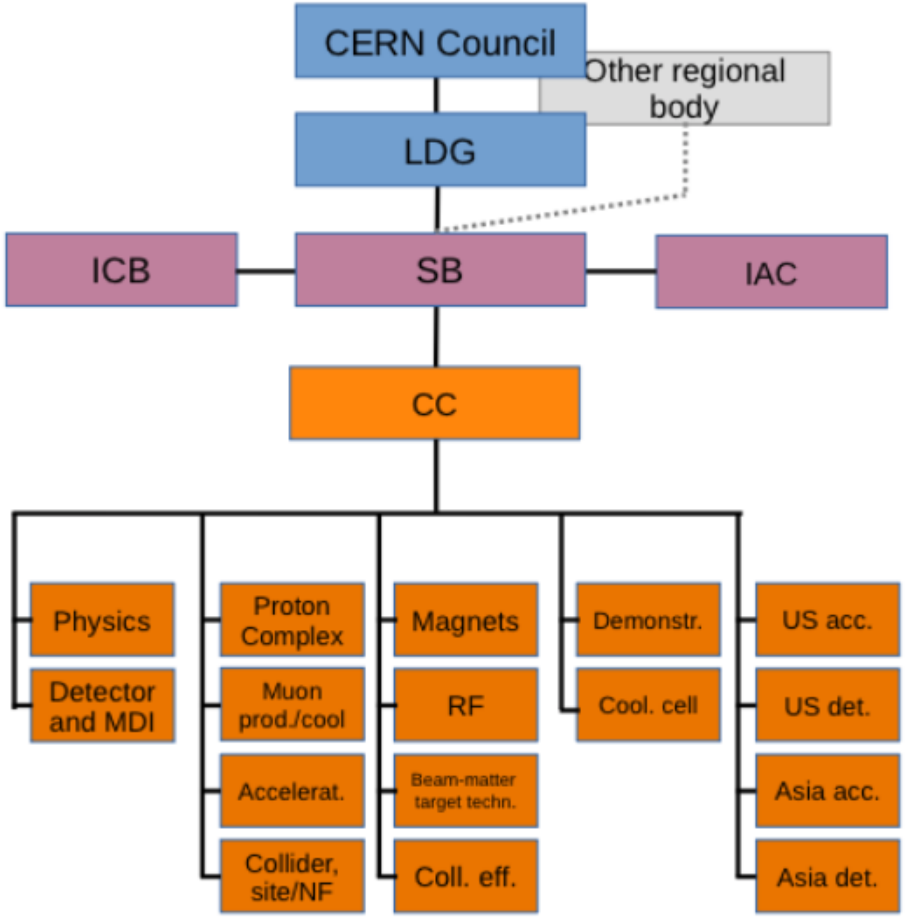
Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes



IMCC organization



IMCC was founded in 2021

- Reports to CERN Council
- Anticipate it will also report to DoE and other funding agencies