Muon Collider

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IAS, HKUST, January, 2026

Muon Collider Concept

The main challenge is the short muon lifetime $\tau = \gamma \times 2.2\ \mu s$
Up to 100 ms at collision energy

Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

IMCC
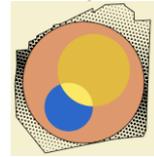## International Muon Collider Collaboration

Collaboration formed 2022, currently **hosted by CERN**

- **61 formal member institutions,** still growing
- Currently centred in Europe, strong US contribution
- R&D progamme developed with global community

In response to strategic requests:

- Last ESPPU demanded integration into European Accelerator R&D Roadmap
- EU is co-funding design study MuCol since 2023
- Different US recommendations: Snowmass, P5 and National Academy of Science

Goal is 10 TeV collider (green field) with potential initial stage
And implementations at specific sites, e.g. CERN and FNAL

Difference to most other projects: there could be competition for the site

IMCC Partners

IEIO	**CERN**	IT	**INFN**	FI	**Tampere University**	CA	Université Laval
FR	**CEA-IRFU**		**INFN, Univ., Polit. Torino**		*HIP, University of Helsinki*	US	**Iowa State University**
	CNRS-LNCMI		**INFN, LASA, Univ. Milano**	LAT	**Riga Technical University**		**University of Iowa**
	Ecoles des Mines St-Etienne		**INFN, Univ. Padova**	CH	**PSI**		**Wisconsin-Madison**
DE	DESY		**INFN, Univ. Pavia**		**University of Geneva**		*University of Pittsburgh*
	Technical University of Darmstadt		**INFN, Univ. Bologna**		EPFL		**Old Dominion**
	University of Rostock		**INFN Trieste**		HEIA-FR		**Chicago University**
	KIT		**INFN, Univ. Bari**	BE	**Univ. Louvain**		**Florida State University**
UK	**RAL**		**INFN, Univ. Roma 1**	AU	**HEPHY**		**RICE University**
	UK Research and Innovation		*ENEA*		TU Wien		**Tennessee University**
	University of Lancaster		**INFN Frascati**	ES	**I3M**		*MIT Plasma science center*
	University of Southampton		**INFN, Univ. Ferrara**		*IFIC/CSIC*		**Pittsburgh PAC**
	University of Strathclyde		**INFN, Univ. Roma 3**		**ICMAB**		Yale
	University of Sussex		INFN Legnaro	China	*Sun Yat-sen University*		*Princeton*
	Imperial College London		**INFN, Univ. Milano Bicocca**		**IHEP**		**Stony Brook**
	Royal Holloway		**INFN Genova**		**Peking University**		Stanford/SLAC
	University of Huddersfield		**INFN Laboratori del Sud**		**Inst. Of Mod. Physics, CAS**		…
	University of Oxford		INFN Napoli		**University of CAS**	DoE labs	FNAL
	University of Warwick	Mal	**Univ. of Malta**	KO	**Kyungpook National University**		LBNL
	University of Durham	EST	**Tartu University**		**Yonsei University**		JLAB
	University of Birmingham	PT	**LIP**		**Seoul National University**		BNL
	University of Cambridge	SE	**ESS**	India	*CHEP*	Brazil	*CNPEM*
NL	**University of Twente**		**University of Uppsala**				

Signed MoC (61), *requested MoC*, contributor

IMCC
International Muon Collider Collaboration

ESPPU Submission Content

Muon Collider Assessment

Present **physics case** and **green field** designs and technologies

- Parameters, lattice and component designs, beam dynamics, cost, …
- Aim for 10 TeV with 10 ab^{-1}
  - Aim for initial stage around 2050 (e.g. with 3 TeV and 1 ab^{-1})

R&D plan

- The main timeline driver
- Accelerator design, detector development, magnets, muon cooling technology, …

Implementation Considerations

- Currently for CERN and for FNAL
- Scaling from green field design, detailed lattice designs after ESPPU

Technically limited schedule

Cost and **power** consumption scales

Back-up document
(406p, 450 signatories)

Physics Case for 10 TeV

Strong physics case for 10 TeV parton-parton centre-of-mass collider, in particular muon collider:

Muon collider impact on precision physics and BSM has been studied extensively and should be presented in all relevant sessions
- So you can form your own opinion

Strong physics case complementary to FCC-ee + FCC-hh exists, see for example Snowmass and NAS report

National Academy of Science Recommendation:
M. Spiropulu (*Co-Chair*), M. S. Turner (*Co-Chair*), N. Arkani-Hamed, B. C. Barish, J. F. Beacom, PH. H. Bucksbaum, M. Carena, B. Fleming, F. Gianotti, D. J. Gross, S. Habib, Y.-K. Kim, P. J. Oddone, J. R. Patterson, F. Pilat, C. Prescod-Weinstein, N. Roe, T. M.P. Tait, *Staff:* T. Konchady, D. Nagasawa, L. Walker, D. Wise, C. N. Hartman, A. Mozhi

A collider with approximately 10 times the energy of the Large Hadron Collider (LHC) is crucial for addressing the big questions of particle physics and making discoveries.
A 10-TeV muon collider on the Fermi National Accelerator Laboratory (Fermilab) site would have similar discovery reach as a 100-TeV proton collider.
A muon collider combines the physics advantages of an electron-positron and a proton-proton collider, with a much smaller size.
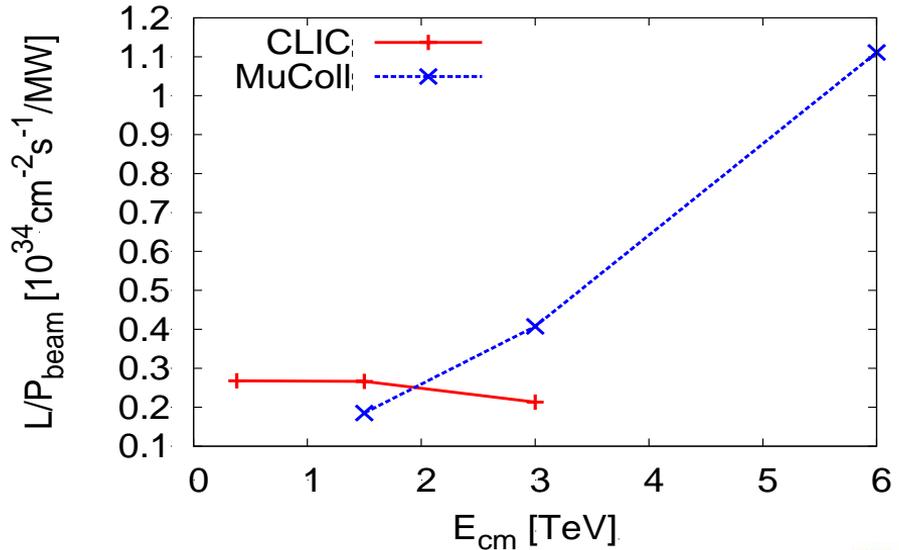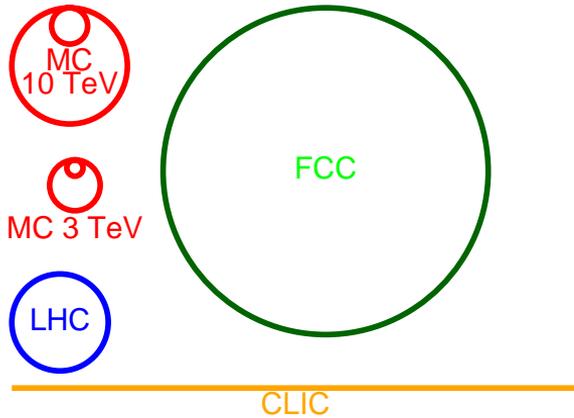
Muon Collider Promises

Higher gradients could constrain length of linear collider

Constant technology scaling:
Luminosity is proportional to beam power at different energies
- Could reduce vertical emittance, but tried hard for decades
- Could shorten bunch to reduce beamstrahlung, but trident cascade process will set in
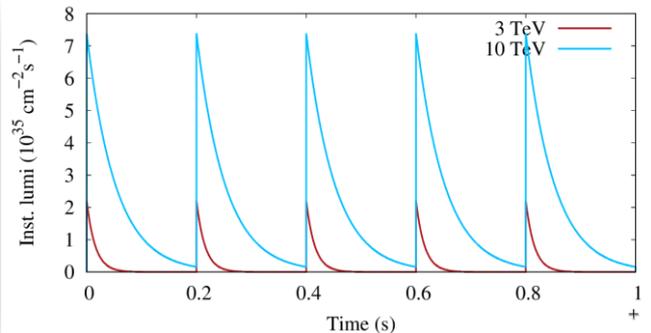
Muon Collider Luminosity Scaling

Fundamental limitation
Requires emittance preservation and advanced lattice design
Applies to MAP scheme

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

Large energy acceptance

Dense beam

High beam power

Luminosity per power increases with energy
Provided technologies can be made available

Constant current for required luminosity scaling

Key Parameters

Param.	Unit	Site independent		CERN 2 tunnels		CERN 1 tunnel	
Sqrt(s)	TeV	3	10	3.2	7.6	3.2	7.6
N	10^{12}	2.2	1.8	2.2	1.8	2.2	1.8
ε	μm	25	25	25	25	25	25
$\sigma_z = \beta^*$	mm	5	1.5	4.7	2	4.7	2
L/IP	10^{34} cm^{-2}s^{-1}	1.8	17.5	2	10	0.9	7.9
Int L	ab^{-1}	1	10	1	10	1	10
Acc. time	years	2+2.8	2+2.9	2+2.5	2+5	2+5.6	2+6.3
C	km	4.5	11.4	4.8	8.7	11	11
B_{dipole}	T	11	14	11	14	4.8	11
Collider dipole technology		Nb3Sn	HTS	Nb3Sn	HTS	NbTi	Nb3Sn or HTS

Luminosity Drivers

The beam emittances result from design, physics and technology of the cooling system

Aim for limited emittance increase downstream

The total number of muons per bunch is given by the proton pulses in the target

Important decay of muons afterwards

The total beam power is given by the high energy complex power consumption, cost, neutrinos

Muon Beam Production and Transmission

Subsystem	Energy	Length	Achieved Transm.	Achieved μ^-/bunch	Target μ^-/bunch
	GeV	m	%	10^{12}	10^{12}
Proton Driver	5 (p^+)	1500	–	500 (p^+)	
Front End	0.17	150	9	45.0	
Charge Sep.	0.17	12	95	42.8	
Rectilinear A	0.14	363	50	21.4	
Bunch Merge	0.12	134	78	16.7	
Rectilinear B	0.14	424	32	5.3	
Final Cooling	0.005	100	60	3.2	
Pre-Acc.	0.25	140	86	2.8	4.0
Low-Energy Acc.	5	–	90^*	2.5	
RLA2	62.5	○2430	90	2.3	
RCS1	314	○5990	90	2.1	
RCS2	750	○5990	90	1.9	
RCS3	1500	○10700	90	1.7	
3 TeV Collider	1500	○4500	–	1.7	2.2
RCS4	5000	○35000	90	1.5	
10 TeV Collider	5000	○10000	–	1.5	1.8

Need to produce many muons

Efficient muon transport is key to the luminosity
- Need to have compact cooling system
- Need fast acceleration

Note: 1.67 TeV to produce muons for one pair at collision point, compared to 10 TeV muon pair energy

Need some improvement in muon production or in transport
- Being studied

Note: μ^+ can be 30% higher

Key Challenges

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible

μ **Injector**

μ^-

μ^+

Muon Collider
>10TeV CoM
~10km circumference

IP 1

IP 2

Accelerator Ring

2) Beam-induced background

4 GeV Proton Source | Target, π Decay & μ Bunching Channel | μ Cooling Channel | Low Energy μ Acceleration

1) Dense neutrino flux
mitigated by mover system and site selection

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

Physics and Detector Concepts

Challenges:
High-energy lepton detector requirements
Background from muon decay and beam-beam effects (BiB)

Achievements
Two detector concepts are being developed
Performance studies with GEANT
Detailed design and simulations of MDI and background suppression

MUSIC
(MUon System for Interesting Collisions)

MAIA
(Muon Accelerator Instrumented Aperatus)

L. Lee + C. Bell

Key conclusions:
Full simulations show good physics performance with near-term technology in spite of BiB
- But important improvements are possible

Need strong R&D for **optimization** and **integration**

Proper investment crucial to enable exploitation of full muon collider potential in available time using **new technologies**, **AI**, and **ML**

Proton Complex

Challenge:
- 2 MW, 5 GeV, 5 Hz,
- 5×10^{14} protons/pulse
- Proton pulse accumulator and compressor rings

Achieved:
- Accumulator and combiner ring lattices
- First collective effects studies promising
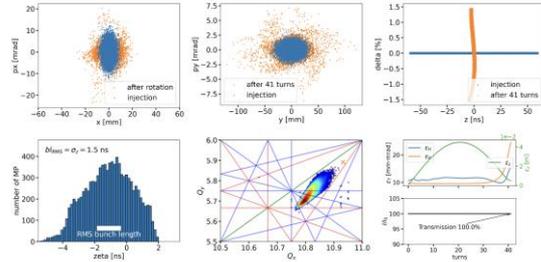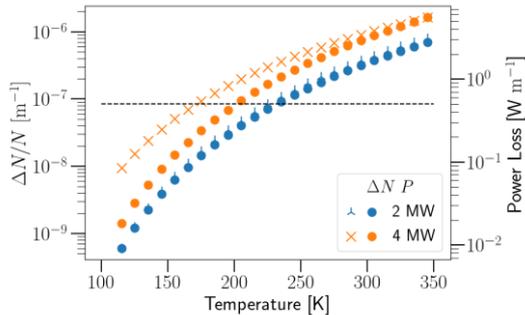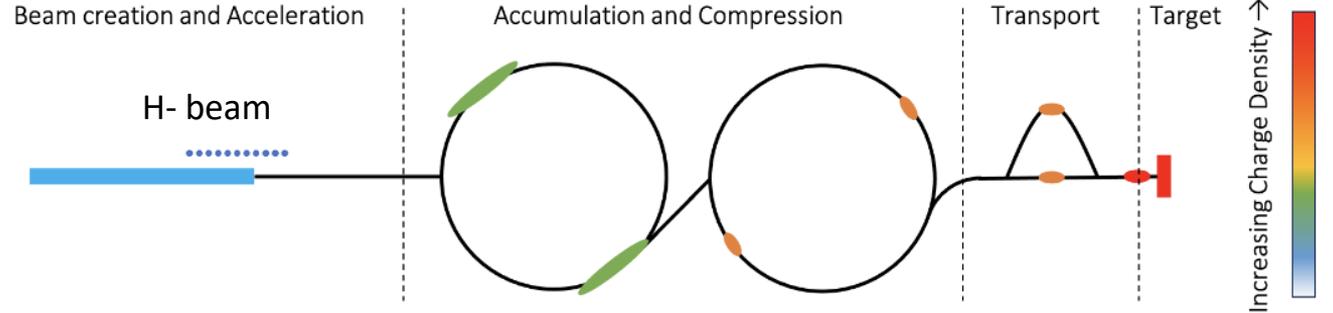- One or two bunches in compressor, to be decided

Beam creation and Acceleration | Accumulation and Compression | Transport | Target

H- beam

Increasing Charge Density →

Fig. 5.1.8: Simulation of the full compression for one bunch at 5 GeV. Since this requires a 2 bunch solution scheme, this bunch has half of the full intensity shown in Table 5.1.1. Notice that at the end of the compression there is still some emittance blow up that need still to be addressed.

Key conclusions:
- Can compress 2 MW, 5 GeV proton beam to two 2 ns bunches, then merge them
  - Optimisation in compressor ring for collective effects ongoing
- For 4 MW need 10 GeV beam
- Cool beamline to avoid ion loss from black body radiation

Target

Challenges:
- 2 MW, 5 Hz, 400 MJ/pulse target
- Can we replace mercury with graphite?

Achieved:
- Initial 2 MW graphite target conceptual design, pion yield optimised
- HTS solenoid and shielding concept developed
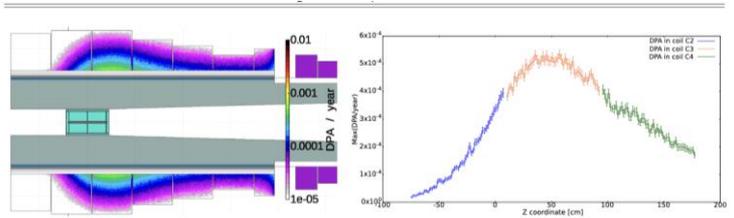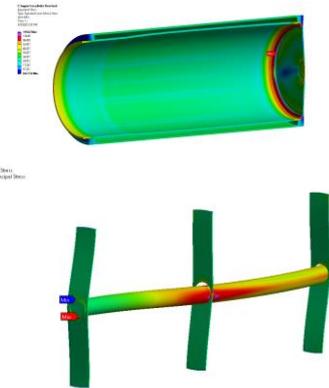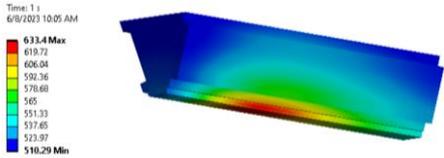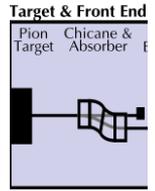- Study of proton removal ongoing

protons ➡ pions ➡ muons

US-MAP LTS+resistive hybrid solenoid

All-HTS solenoid

Target & Front End
Pion Target | Chicane & Absorber

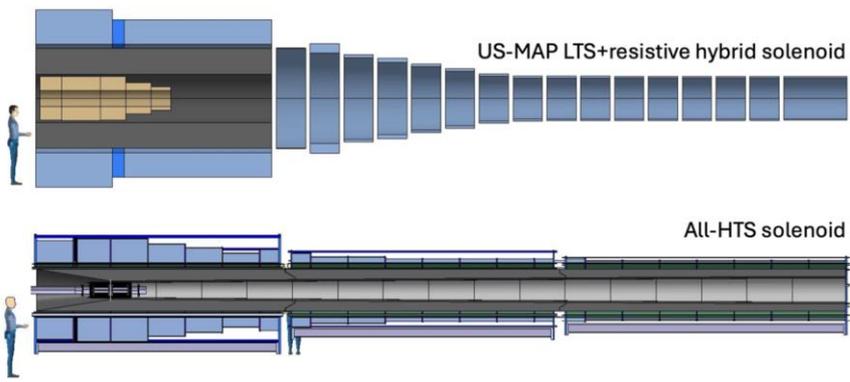International MUON Collider Collaboration

Fig. 6.5.1: 2D map of the displacement per atom (DPA) in the superconducting magnets of the target area (left) and the peak DPA in the coils most exposed to radiation (right).
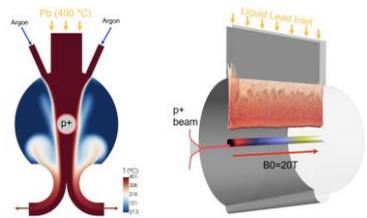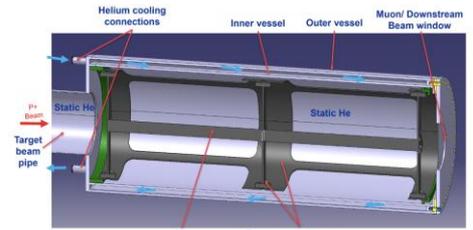
Helium cooling connections | Inner vessel | Outer vessel | Muon/ Downstream Beam window

P+ Beam — Static He — Static He
Target beam pipe
Target rod | Target support structure

Pb (400 °C) | Argon | Argon
p+ | B0=20T
p+ beam | Liquid Lead Inlet

Fig. 6.4.4: Liquid lead target curtain concept.

Key conclusions:
- Yield, magnet shielding, target stress, cooling, radiation are OK
- Components survive 2 MW beam
- Higher power alternatives to study:
  - Graphite
  - Liquid metal

Note: High-field Magnet Technology

NbTi (niob-titanium, operating at 2-4 k)
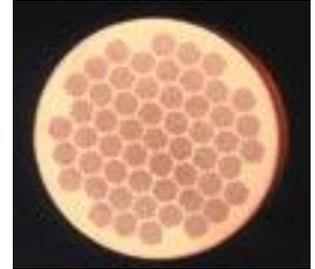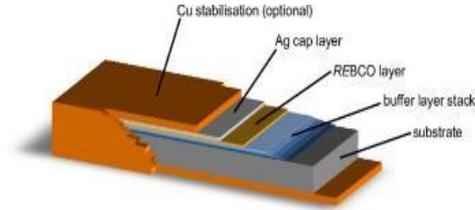
- is standard, **used in LHC**
- Expect 5 T in MC

Nb$_3$Sn (niobium-tin, operating at 2-4 K)

- Expect O(11 T) in MC
- Stil not mature
- Used in some points for HL-LHC
- Foreseen for FCC-hh also in arcs

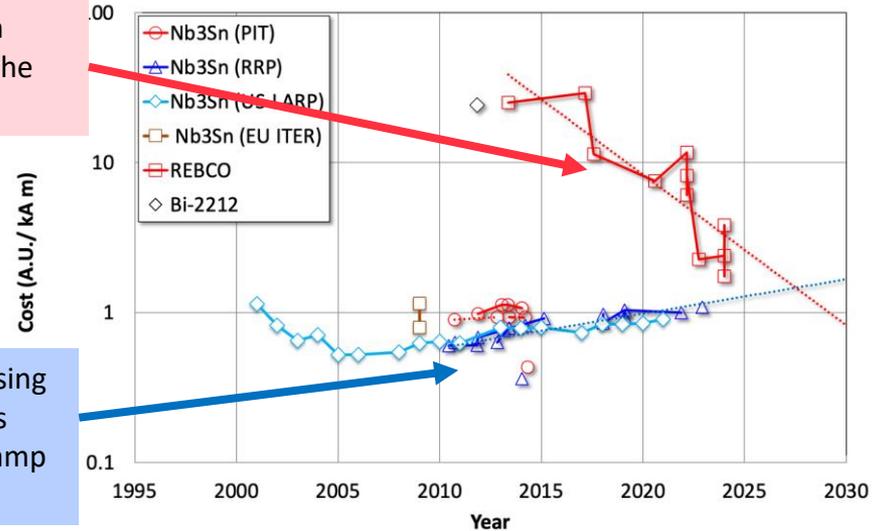**HTS** (high-temperature superconductor, operating up to 20 K)

- Different options exist, e.g. REBCO
- In solenoids > 30 T demonstrated
- Still expensive and technology challenges
- Applications in other fields, e.g. medical, fusion reactors, power generators for wind energy, engines, …
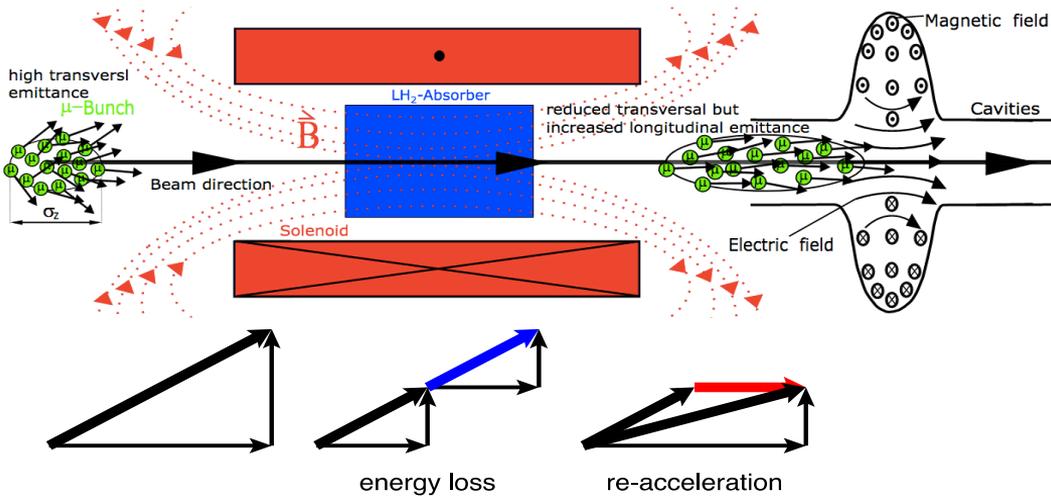
REBCO Tape

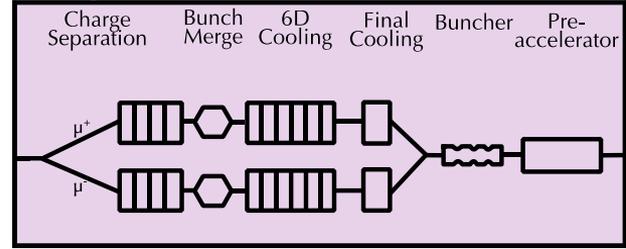HTS cost is coming down
How much depends on the overall use of HTS

Nb3Sn cost slowly increasing
We may be the only users
Industry would have to ramp up just for us

Legend: Nb3Sn (PIT), Nb3Sn (RRP), Nb3Sn (US LARP), Nb3Sn (EU ITER), REBCO, Bi-2212

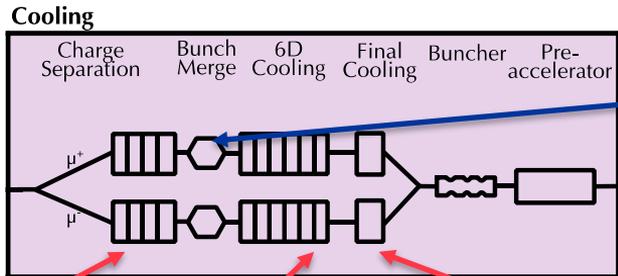Cost (A.U./ kA m)

Year

Muon Cooling Concept

High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling   Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\text{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$
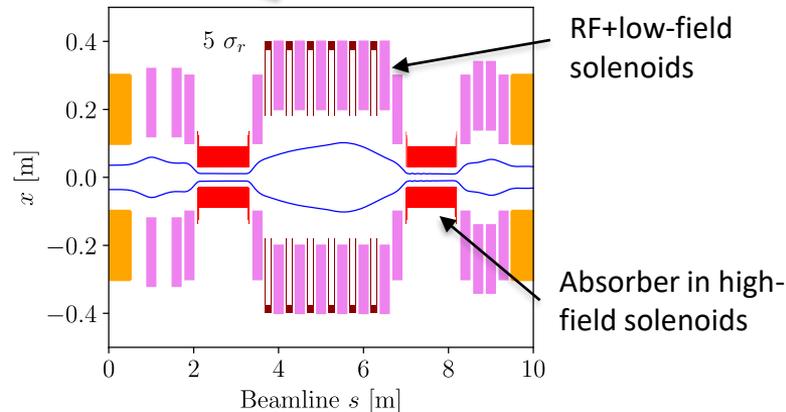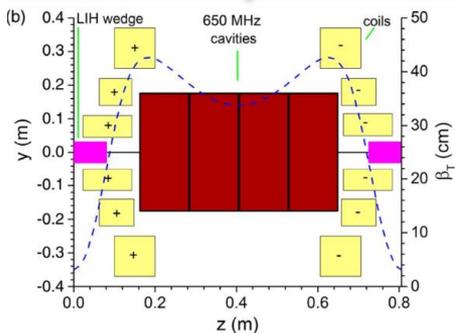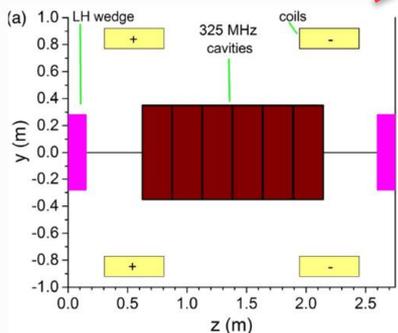
Layout

Total length O(1 km)

18 sequences with one cell design each

Apertures decrease toward end
- Beam emittance shrinks

Fields increase
- To reduce equilibrium emittance

Here we pack the short train of bunches into one with large emittances

Final cooling has O(10) stages/cells

RF+low-field solenoids

Absorber in high-field solenoids

Solenoids act as focusing lenses
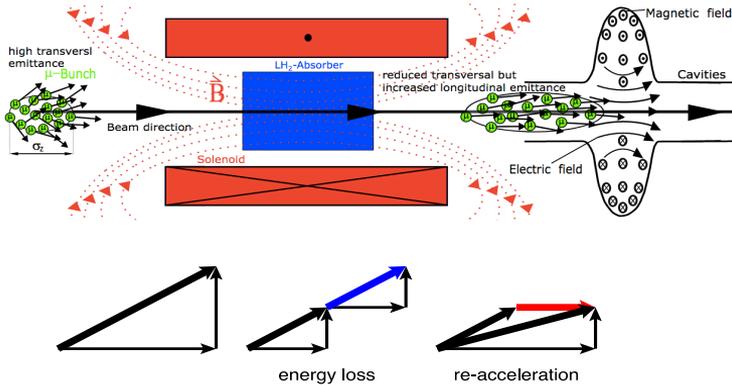RF, absorbers and solenoids are highly integrated

Absorbers are in constant solenoid field
RF is more separated and has less focusing

Muon Cooling Lattice Design

Challenge:
Novel, complex lattice with cavities and absorbers in solenoids

Achieved:
Much improved lattice design
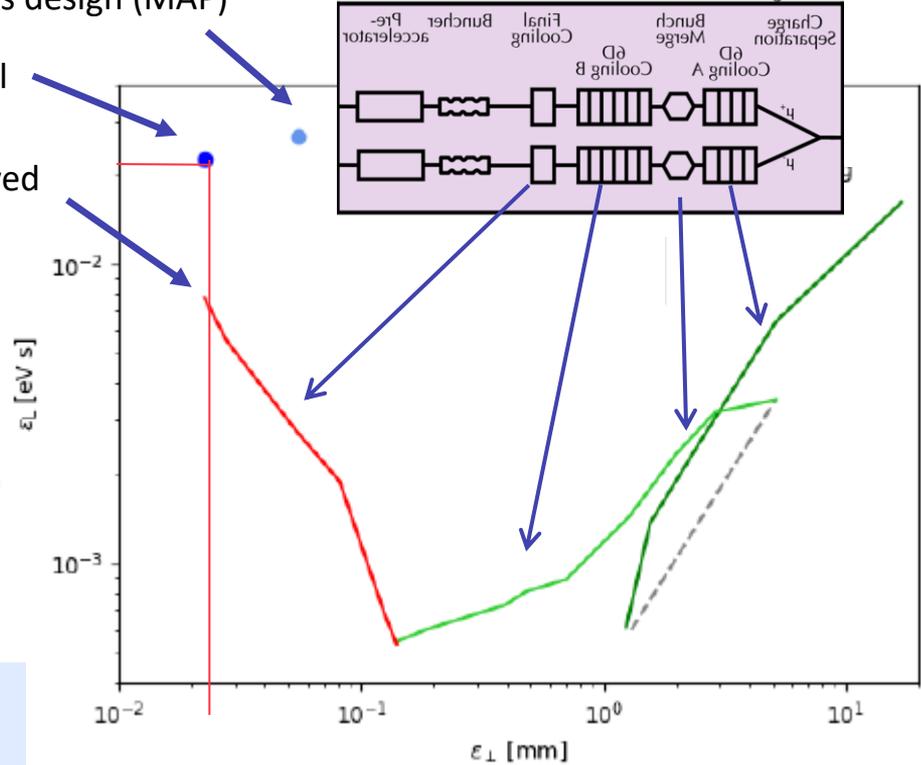Improved simulation tools: BDSIM and RFtrack

Key conclusions:
- Can in principle reach or exceed performance target
- Much improved longitudinal, may be useful for collider ring
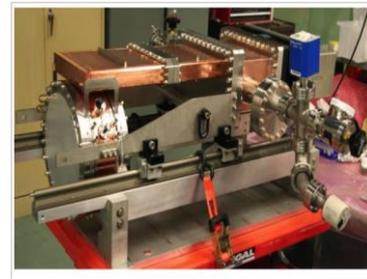- Study of collective effects important

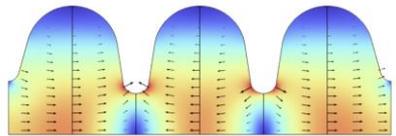Previous design (MAP)

Goal

Achieved

better

better

ε_L [eV s]
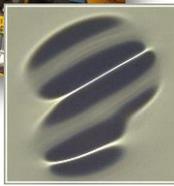
$\varepsilon_\perp$ [mm]

Muon Cooling Technology

Challenges:
- NC RF cavities in magnetic field (30 MV/m)
- HTS magnets (up to 40 T in final cooling)
- Bright beam hard on absorbers and windows
  - Can evaporise liquid hydrogen

MuCool demonstrated >50 MV/m in 5 T
- H_2-filled copper
- Be end caps

MAP proved gradient
- Initial RF designs
- More RF design ongoing to optimise beamloading

- First window tests performed with protons
- Use of H_2 gas in final absorbers

Coils

Dipole RF cavities

Cooling Cell

Magnet Stucture

Absorber

6D cooling cell engineering design almost ready

Key conclusions:
- Ready to **ramp-up effort**, in particular prototyping and experimental work, also beamdynamics
- **Need RF test stands** for experimental optimization

RCS Designs

Challenge:
- Uses fast-pulsed normal magnets
- 5 Hz pulses of O(1-10ms)
- 6-35 km circumference
- Cost
- Recover energy from magnetic field
- High bunch charge
- Maintain beam quality

Achieved:
- Lattices for all site independent RCSs
- Beam propagation through complex
- Conceptual design of magnets and power converters
- Optimised design together with RF

RCS	E [J/m]	Loss [%]	P [MW]
SPS 1	5447	**1.1**	1.9
LHC 1	5678	**1.6**	12.8
LHC 2	5752	**6.3/2**	26.6

Key conclusions:
- 1.3 GHz TESLA-type cavities work
- Emittance transport is OK
- Cost and power is OK
- Need to connect to initial linacs

Collider Ring

Challenges:
500 W/m loss, magnet strength, lattice design with beta 1.5-5 mm, 0.1% beam energy spread

Achieved:
- Magnet shielding design
- Magnet performance model and conceptual designs
- Cryogenics conceptual design
- Lattice reaches target beta-functions but not yet full target energy acceptance
- First studies of mover system impact on beam
- Impedance is OK

Cryogenic loads at different temperatures

shield) are assumed to be at 80 K. In the legend, "BIL" stands for "beam-induced losses".

Magnet Designs

or under Lorentz Forces at nominal current for both block coil

Shielding (30-40 mm)

Key conclusions:
Further improve energy acceptance, but OK with energy spread predicted in muon cooling
Mover system OK for beam in regular arcs
Address imperfections next

Placement

Challenge:
Obtain negligible neutrino flux
Similar impact as LHC

Achieved:
- Detailed modelling
- First good orientation found
- Mover system concept

Experiment?

Arc mitigation concept

Fermilab site study

t_1

t_2

FLUKA and RP studies

Mover system design

Site study at CERN for experimental insertion

Key conclusions:
- Close to a solution
- Arcs impact similar to current CERN impact
- Hottest spot inside fence is like sitting in a plane
- More work to be done

Site Specific Designs

Started tentative studies for concrete site at CERN and Fermilab, looks very promising

CERN:

One RCS in SPS and two in LHC

Construct facility on CERN land

- Adjusted parameters
  (3.2 and 7.6 TeV, 10 TeV maybe possible)

Fermilab:

One RCS in Tevatron tunnel,
Three RCSs in one site-filler tunnel

Summary of cost

The cost range for the single tunnel CERN implementation was evaluated and compared to the Green Field scenario, where a cost for Civil Engineering of 50kCHF/m was assumed in the absence of a detailed study.

Cost is bottom up

- Based on existing conceptual designs, e.g. fast-ramping magnets and power converter

- Detailed scaling from known components, e.g. ILC main linac modules, FCC-ee, ..

Uncertainties

- From components

- No optimisation performed

Good agreement with ITF

Cost range for Muon Collider scenarios

Project Cost (no esc., no cont.)	4	7	12	18	30	50
MC-3						
MC-10						

Cost Drivers

Cost drivers:
- RF systems
- Superconducting solenoids
- Other superconducting magnets
- Fast-ramping magnet systems

Legend:
- RF
- Other Magnets
- Power Converters
- Solenoids
- Civil Engineering
- General infrastructure
- Other

Relative cost for 3.2 TeV

- 31.6%
- 12.1%
- 5.4%
- 22.6%
- 9.8%
- 8.2%
- 10.2%

Relative cost for 7.6 TeV

- 27.7%
- 25.2%
- 7.9%
- 17.0%
- 7.4%
- 8.3%
- 6.6%

Sensitivity Analysis for 7.6 TeV

- SC Magnets
- RF
- Solenoids
- Other (p driver, target, shielding)
- General infrastructure
- Power Converters
- Civil Engineering
- NC Magnets
- Cryogenics

-1'500 -1'000 -500 0 500 1'000 1'500 2'000 2'500

MCHF

- "Negative variance"
- "Positive variance"

Sensitivity Analysis for 3.2 TeV

- Solenoids
- RF
- Other (p driver, target, shielding)
- Civil Engineering
- General infrastructure
- SC Magnets
- Power Converters
- NC Magnets
- Cryogenics

-1'500 -1'000 -500 0 500 1'000 1'500 2'000

MCHF

- "Negative variance"
- "Positive variance"

Power Drivers

Key power drivers
- RCSs
- Infrastructure
- Proton complex
- 6D Cooling
- RLAs
- Collider

Have to add cryogenics to remove beam loss power from RCS cavities (Estimate included in the ESPPU submission)

Summary TABLE full power			
	3.2 TeV	7.6 TeV	10 TeV
	MW	MW	MW
P driver	16.700	16.700	16.700
6D Cooling	11.765	11.765	11.765
RLA2	10.770	10.770	10.770
RCS	44.190	108.930	124.680
Collider	10.000	4.100	4.100
General CV	20.000	20.000	20.000
TOTAL	113.425	172.265	188.015

R&D Programme

Accelerator design
- Complete start-to-end design to validate and optimize performance, cost, power and risk

Muon cooling technology
- Implementation in steps important for timeline
- Need hardware, in particular RF test stands
- New detector technologies useful for instrumentation
- Cooling RF requires urgent test infrastructure

Detector
- Strong potential for further improve physics potential with technologies, AI and ML

Magnet programme
- Have conceptual designs, need hardware
- HTS solenoids have important synergy with society (also power converter)
  - Industry is ready to invest
  - Must not miss the opportunity

IAC review:
"The committee would like first to congratulate the International Muon Collider Collaboration for the tremendous progress made over the last year on the technical studies, the overall project planning and the organization of the collaboration. The committee welcomes the idea to evaluate the priority setting of these R&D activities, in view of the IMCC activities beyond the European Strategy Process.
In general, all the R&D proposals presented are impressive and complete, and the committee expressed support of this R&D program in the long term. The R&D plan is quite thorough and will provide a valuable foundation for prioritizing R&D plans as the programme matures.

IAC composition:
Permanent members: Ursula Bassler (chair), Mauro Mezetto, Hongwei Zhao, Akira Yamamoto, Maurizio Vretenar, Stewart Boogert, Sarah, Demers, Giorgio Apollinari
Additional experts: Pierre Vedrine, Stephen Gourlay, Lyn Evans, Alessandro Gallo, Barbara Dalena, Pantaleo Raimondi

R&D Plan Deliverables and Resources

Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K

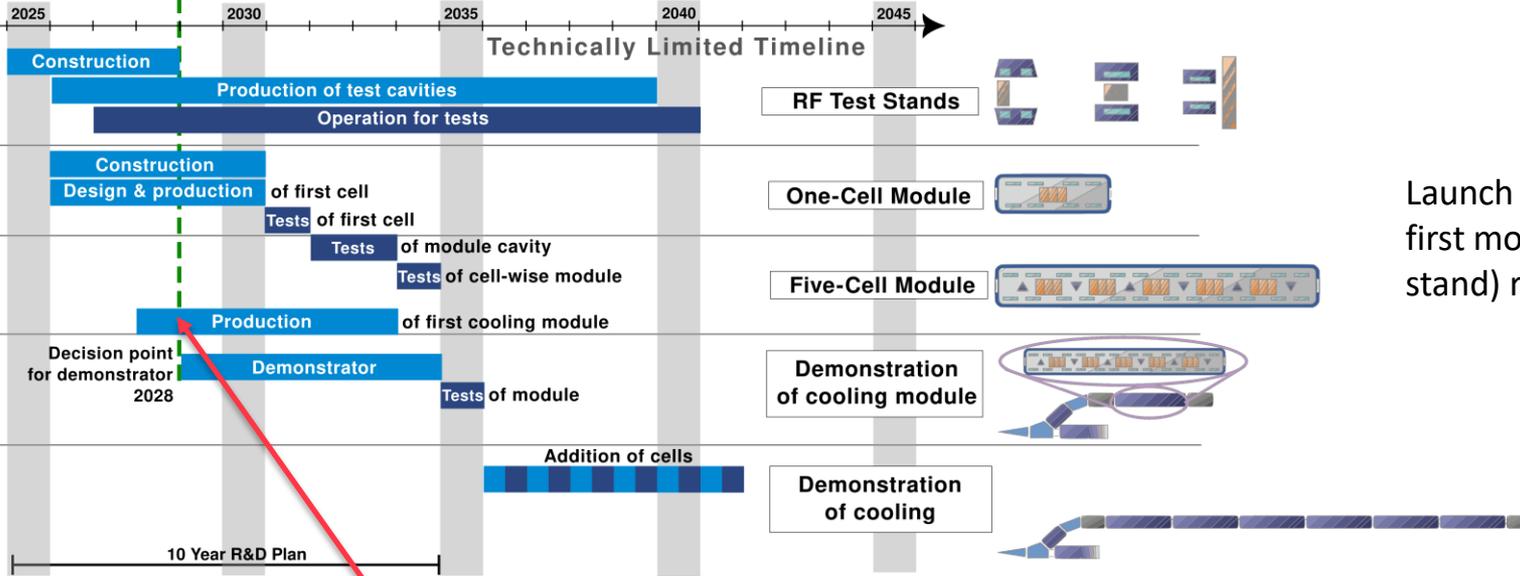| Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K
Fast ramping magnet system	Prototype superconducting solenoid converter	
LTS collider dipole	Demonstrate Nb_3Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
	Radiofrequency	
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
	Muon Cooling	
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 μm emittance, 40 T field
	Design & Other Technologies	
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O($\pm$1mradian)
Beam Instrumentation	Instrumentation component designs	Prototype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Muon Cooling Demonstrator

Muon Cooling Demonstrator

Launch RF test stands and first module (700 MHz test stand) right away

Important decision in 2028 on sharing of effort and demonstrator location

Two promising demonstrator site studies at CERN
Budget for site Fermilab study approved

Way Forward

Implement the proposed R&D plan, with deliverables and resources estimates for the next 10 years
- Prepare sharing of work between partners
- Central funding through CERN and other partners is instrumental
- Identify additional funding sources
- Need strong support of ESPPU

Started a task force to prepare the implementation

Exploit synergy with other particle physics and accelerators
- Muons, neutrinos, …

Strong synergy with societal applications exist
- HTS magnets for fusion reactors, wind power generators, motors, material science, health applications
- Power converter
- …

Design of 10 MW HTS wind generator

Collaboration on target solenoid/fusion with F4P, ERUOFusion, GaussFusion, ENI is key example
- Have agreements that will lead to resources
- An opportunity for particle physics to make an important impact on society

https://indico.cern.ch/event/1439855/contributions/6461515/

Early career experts are very motivated by the required and possible innovations

Global Engagement

National Academy of Science:

Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

US ESPPU submission:

Realisation of the plan above relies on sustained and adequate funding in both the US and Europe, and a close collaboration between the two regions, as outlined in the next section . Potential contributions from other regions of the world would further strengthen the program.
[https://arxiv.org/pdf/2503.23695]

IMCC will carry out the R&D together and develop options to host the collider at CERN or at Fermilab and potentially also other sites
Envisage to share leadership between CERN and Fermilab

Conclusion

Excellent technical progress has been made, in spite of resource limitations
- Supported by review committees from LDG, MuCol, and IAC reviews

Have global R&D programme proposal that needs to be funded
- Strong interest in different regions hopefully translates into resources

https://www.facebook.com/cern/videos/the-future-of-particle-physics-david-gross-cern70/509915295164473/

A muon collider is disruptive
- It will push beyond the current boundaries
- It will be the first of its kind
- High-risk, high-benefit

Important innovation is required
- Not all issues have been solved
- This means uncertainty and risk
- But also the potential to be creative and invent

Strong synergy with societal applications

Many thanks to the collaborators for all the work

Our web page:
http://muoncollider.web.cern.ch
If you want to join:
muon.collider.secretariat@cern.ch

Reserve

Timeline and R&D Programme Proposal

Muon Collider (Initial Stage)

Decision on demonstrator T_0

2025 2030 2035 2040 2045 2050 2055 2060 2065

Technically Limited Timeline

LDG roadmap

Project preparation

Technology R&D

Civil engineering

Optimisation

Production

Installation & commissioning

10 Year R&D Plan

Initial   final demonstrator

Shutdown 1   Shutdown 2

Run 1   Run 2   Run 3

Timeline is **driven by R&D**

Most ambitious example to define R&D programme priorities

- Assumes firm commitment to enable the muon collider as next flagship after HL-LHC
- R&D is fully successful
- No delays due to decision making

Other options

- In Europe after a higgs factory
- In the US to become leader at the energy frontier

Demonstration Phase 7 years
Project Preparation Phase 5 years
Construction Phase 9 years

Milestone	Muon Collider
Construction of RF test stands	2025 – 2028
Production of test cavities	2026 – 2039
Operation of test stands	2027 – 2040
Demonstration Phase	$T_0 - (T_0+7)$
Demonstrator technical design	
Construction of initial demonstrator	
Construction of muon cooling module (5 cells)	
Definition of the placement scenario for the collider	
Project Preparation Phase	$T_1 - (T_1+5)$
Final demonstrator	
Implementation studies with the Host states	
Environmental evaluation & project authorisation processes	
Main technologies R&D completion	
Industrialisation of key components	
Engineering Design completion	
Construction Phase (from ground breaking)	$T_2 - (T_2+9)$
Civil engineering	
TI installation	
Component construction	
Accelerator HW installation	
HW commissioning	
Beam commissioning	
Physics operation start	T_2+10