International
MUON Collider
Collaboration

MuCol

Muon Collider Progress

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On behalf of the International Muon Collider Collaboration

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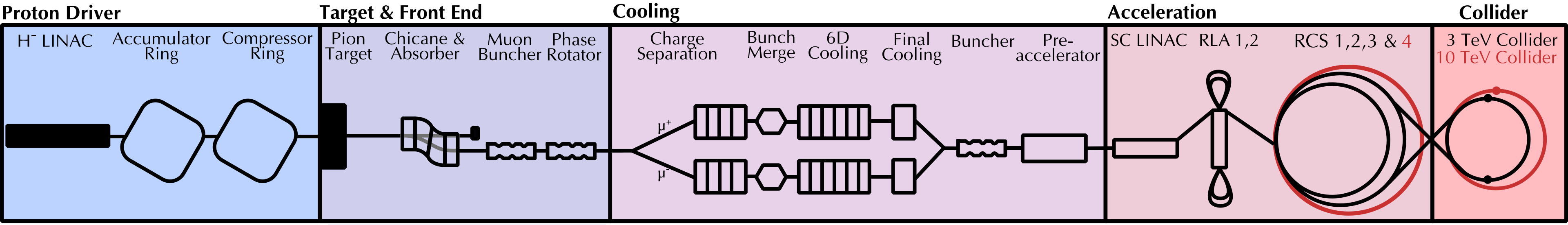
PECFA, November, 2024

Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$ (e.g. 3100 turns in collider ring)



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

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Develop high-energy muon collider as option for particle physics:

- Muon collider promises **sustainable** approach to the **energy frontier**
  - limited power consumption, cost and land use
- **Technology** and **design advances** in past years
- Reviews in Europe and US found **no unsurmountable obstacle**

Current LDG Accelerator R&D Roadmap identifies the required work

- Has been developed with the global community
- However coming ESPPU is a bit early …

Goals for ESPPU is to provide document with

- **Assessment of muon collider** concept, technologies and work progress
- An **R&D plan** for the next 5 and 10 years
- **Implementation considerations** (including site, timeline, …)

Label	Begin	End	Description	Aspirational [FTEy]	Aspirational [kCHF]	Minimal [FTEy]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	15.5	300	13.5	300
MC.NF	2022	2026	Neutrino flux mitigation system	22.5	250	0	0
MC.MDI	2021	2025	Machine-detector interface	15	0	15	0
MC.ACC.CR	2022	2025	Collider ring	10	0	10	0
MC.ACC.HE	2022	2025	High-energy complex	11	0	7.5	0
MC.ACC.MC	2021	2025	Muon cooling systems	47	0	22	0
MC.ACC.P	2022	2026	Proton complex	26	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	18.2	0	18.2	0
MC.ACC.ALT	2022	2025	High-energy alternatives	11.7	0	0	0
MC.HFM.HE	2022	2025	High-field magnets	6.5	0	6.5	0
MC.HFM.SOL	2022	2026	High-field solenoids	76	2700	29	0
MC.FR	2021	2026	Fast-ramping magnet system	27.5	1020	22.5	520
MC.RF.HE	2021	2026	High Energy complex RF	10.6	0	7.6	0
MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test cavities	10	3300	0	0
MC.MOD	2022	2026	Muon cooling test module	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	34.1	1250	3.8	250
MC.TAR	2022	2026	Target system	60	1405	9	25
MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	445.9	11875	193	2445

Table 5.5: The resource requirements for the two scenarios. The personnel estimate is given in full-time equivalent years and the material in kCHF. It should be noted that the personnel contains a significant number of PhD students. Material budgets do not include budget for travel, personal IT equipment and similar costs. Colours are included for comparison with the resource profile Fig. 5.7.

http://arxiv.org/abs/2201.07895

Collaboration Development

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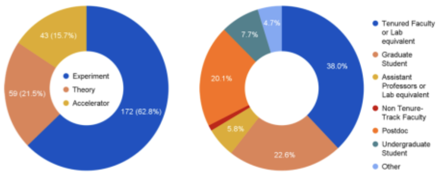
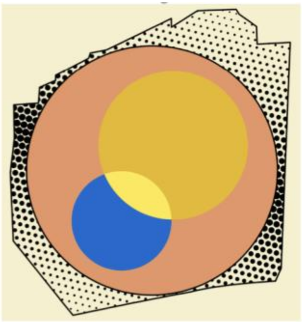
Many new partners have joined
- Roughly doubled since 2022
- From different regions
- Interest expressed by other potential partners in Japan

In particular US partners are joining/plan to join
- US Muon Collider Inauguration Meeting beginning of August at FNAL showed the strong interest (again)
- Full integration with US planned and started CERN-DoE agreement in preparation

Need to move forward with US, while US is still getting organised
In particular R&D plan has to be common plan
Also added some other experts from outside the collaboration

- In early August, held an open meeting of the US community
  - 274 (+25 virtual) participants





Michael Begel (BNL)
Pushpa Bhat (Fermilab)
Philip Chang (University of Florida)
Sarah Cousineau (ORNL)
Nathaniel Craig (University of California, Santa Barbara)
Sridhara Dasu (University of Wisconsin)
Karri DiPetrillo (University of Chicago)
Spencer Gessner (SLAC)
Tova Holmes (University of Tennessee)
Walter Hopkins (ANL)
Sergo Jindariani (Fermilab)
Donatella Lucchesi (University of Padova/INFN)
Patrick Meade (Stony Brook University)
Isobel Ojalvo (Princeton University)
Simone Pagan Griso (LBNL)
Diktys Stratakis (Fermilab)

And Mark Palmer, Stephen Gourlay, Kevin Black, Lawrence Lee

Use Organization Committee of FNAL and additional members as de facto US organisation
- Contributing authors of ESPPU report

“Open” publications rules are now very important during the transition
Anyone can send papers for IMCC endorsement to IMCC-PSC@cern.ch

IMCC Partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
	Mines St-Etienne
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
UK	**RAL**
	UK Research and Innovation
	University of Lancaster
	University of Southampton
	University of Strathclyde
	University of Sussex
	Imperial College London
	Royal Holloway
	University of Huddersfield
	University of Oxford
	University of Warwick
	University of Durham
	University of Birmingham
	University of Cambridge

IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, LASA, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	**Tartu University**
PT	**LIP**

Signed MoC (58), ***requested MoC***, contributor

SE	**ESS**
	University of Uppsala
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
BE	**Univ. Louvain**
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
	Inst. Of Mod. Physics, CAS
KO	**Kyungpook National University**
	Yonsei University
	Seoul National University
India	***CHEP***

US	**Iowa State University**
	University of Iowa
	Wisconsin-Madison
	University of Pittsburgh
	Old Dominion
	Chicago University
	Florida State University
	RICE University
	Tennessee University
	MIT Plasma science center
	Pittsburgh PAC
	Yale
	Princeton
	Stony Brook
	Stanford/SLAC
	…
DoE labs	FNAL
	LBNL
	JLAB
	BNL
Brazil	***CNPEM***

Key Challenges

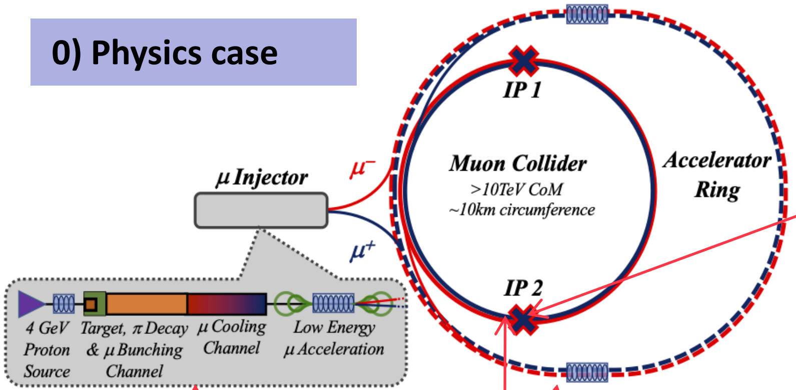
Environmental impact
- Neutrino flux mitigation
- Power, cost, CO_2, …

Key technologies for timeline
- **Magnet technology**
- **Muon cooling technology**
- **Detector**

Other technologies are instrumental for performance, cost, power consumption and risk mitigation
- Accelerator physics, cryogenics, superconducting cavities, ….

Other important timeline considerations are
- Civil engineering
- Decision making

0) Physics case



2) Beam-induced background

4) Muon production and cooling drives the **beam quality**
MAP put much effort in design
optimise as much as possible

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**

Environmental Impact

Limited study at this moment
Inherent muon collider benefits

- Compact size limits material use/CO_2 footprint
- Limited power consumption
- Limited land use, in particular if existing tunnels are reused

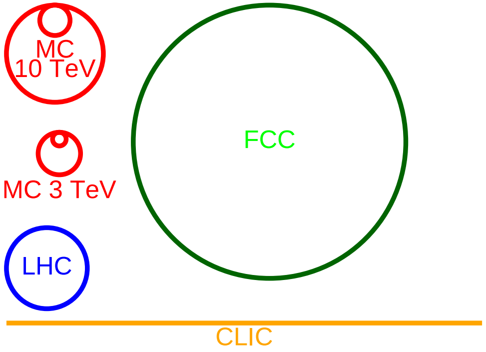
Aim at minimising neutrino flux

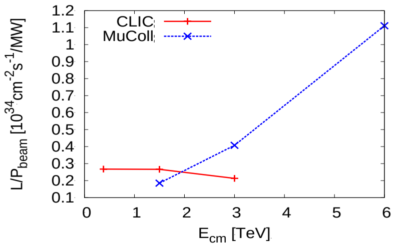
- Focus on collider ring for now
  - Need to expand later
- Working with **RP**
- Improved **geoprofiling tool** to place collider ring
- Mechanical system to avoid localized neutrino flux

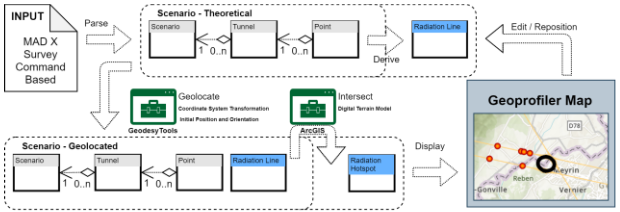
First **promising site and orientation** identified

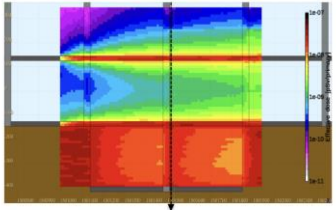
- Mitigates flux from experiments
- Arc flux likely negligible for 3 TeV
  - Approvable/negligible for 10 TeV

Further site optimization, detailed study, development of technical systems and beam study needed



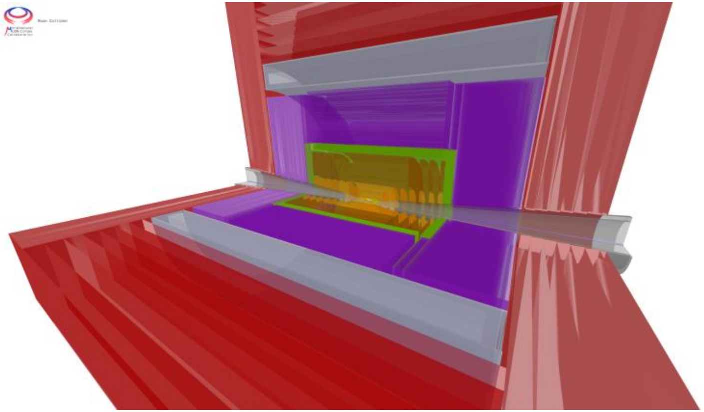




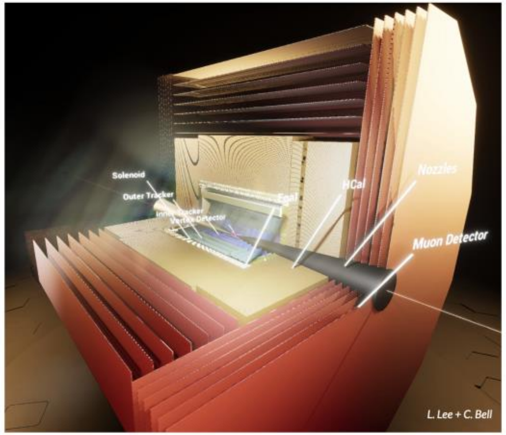


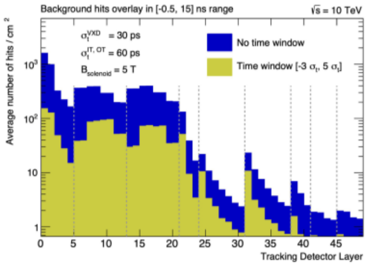
Physics and Detector Concepts

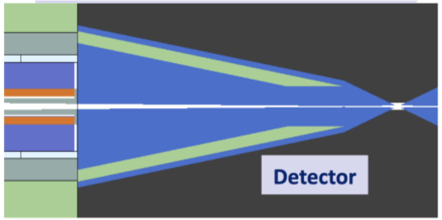
MUSIC
(MUon System for Interesting Collisions)



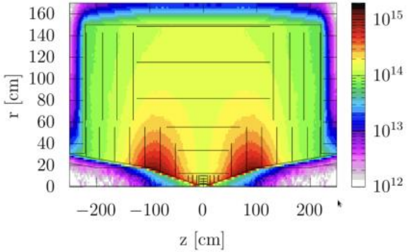
MAIA
(Muon Accelerator Instrumented Aperatus)







Two detector concepts are being developed
- Required resolutions
- MDI and background suppression
- …



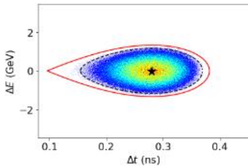
Can do the important physics with near-term technology also thanks to HL-LHC developments

Increasing effort to use available time for further improvements and exploiting **AI, ML** and **new technologies**

Closer **integration with ECFA detector R&D** highly welcome

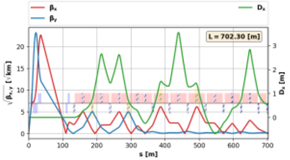
Facility Design

Good progress in the different system designs
- Proton complex, muon production and cooling, acceleration and collider ring, collective effects, …



Preliminary design of **cooling chain** advanced
- 24 to 30 um transverse emittance
- Goal 22.5 um, MAP achieved 55 um

Collider ring lattice design
- Achieve beta-function
- Need to improve energy acceptance (2-3 x)



Subsystem	Energy GeV	Length m	Achieved Transm. %	Achieved μ^-/bunch 10^{12}	Target μ^-/bunch 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

Preliminary **muon transmission** estimate
- 1.5 x 10^{12} muons at IP (goal 1.8 x 10^{12})
- Cooling transmission below target
- High-energy complex is above (would like to reduce for cost)

Need resources to improve system design

Will study higher power target (graphite or liquid metal)

Time to **increase design effort** to cover and integrate all systems (“**start-to-end simulation**”), improve codes, performances and consider alternatives

Magnets

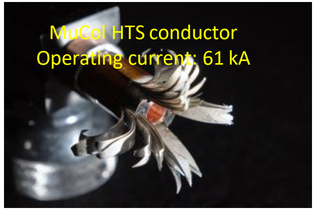
Systematic **dipole performance prediction** for **LTS** and **HTS**

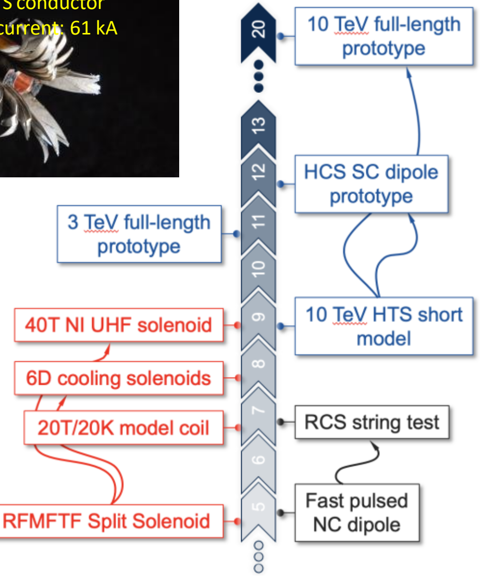
- Aperture, field, cost, stress, loadline, protection, …

HTS solenoid designs (6D cooling, final cooling, target)

Normal-conducting **fast-pulsed dipoles** (HTS as alternative)

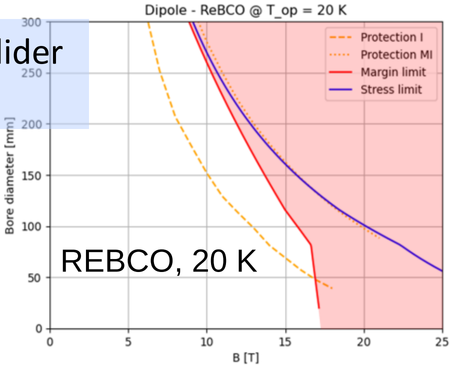
Technical timeline



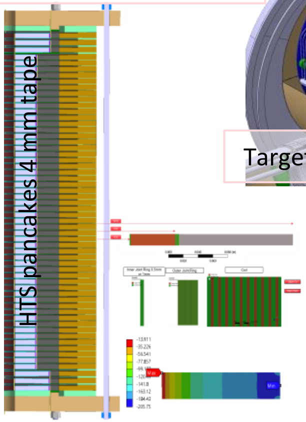


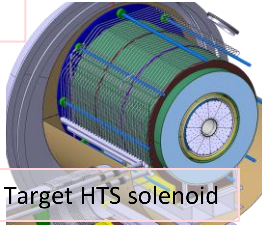
First **HTS winding tests**

Will slightly adjust collider ring field for cost



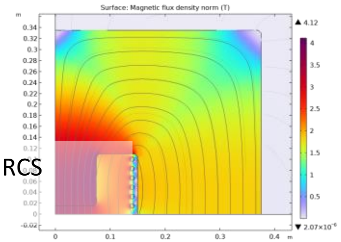
HTS final cooling solenoid mechanical design





Target HTS solenoid

Normal-conducting RCS **pulsed magnets**



Opportunity to **ramp up** effort

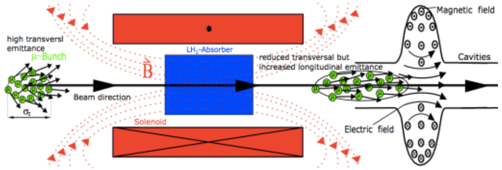
- Engineering designs
- Tests of cables, building models, …

With sufficient resources **HTS solenoids** and **Nb_3Sn dipoles** could be **ready for decision in 10-15 years**

HTS dipoles likely take longer

Muon Production and Cooling

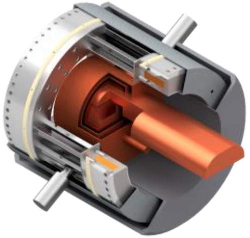
Muon cooling technology and **demonstrator**
- Most integrated technology
- Operational demonstrator in O(10 years), with enough resources
- Allows to perform final optimization of cooling technology



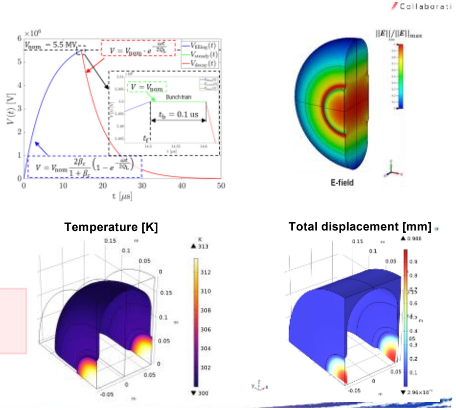
Very bright muon beam challenges **absorbers** and **windows**
- First tests of absorber windows performed

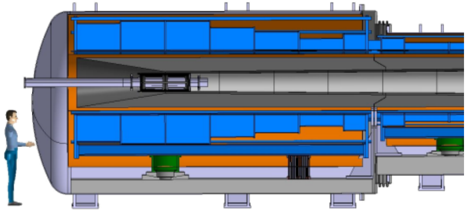
Strong theoretical and experimental programme required

Engineering **module design** started
Including solenoid



RF design ongoing





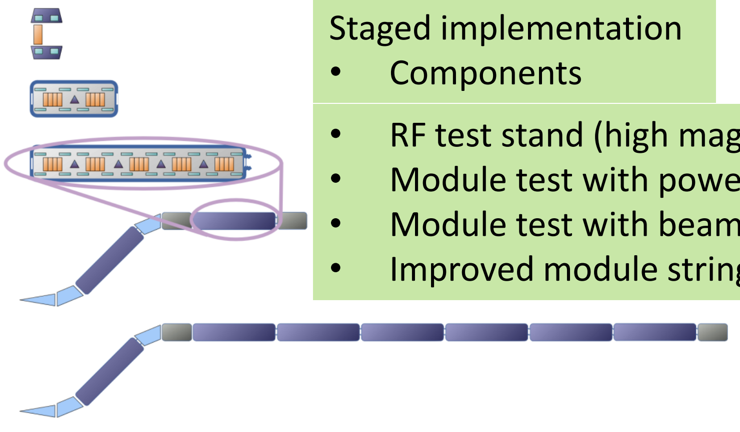
2 MW graphite target looks very promising
- Some work on windows remains

Will study alterative higher power (4 MW) target
- Graphite, liquid metal, fluidized tungsten

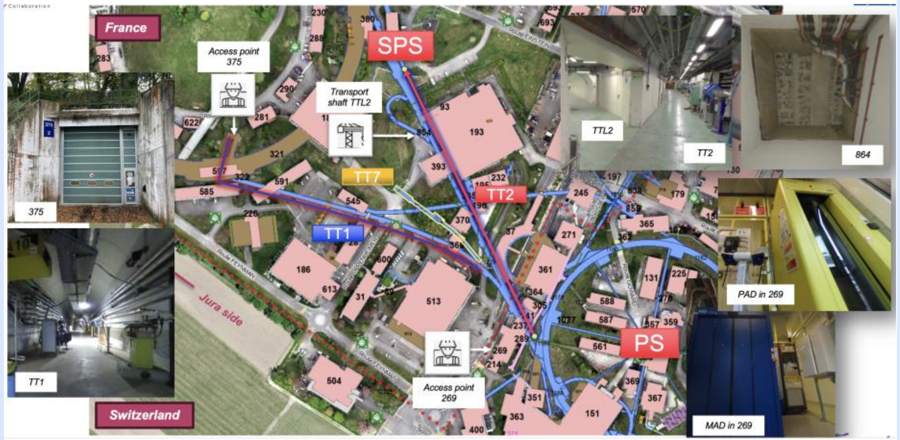
Ready to **widen effort**, in particular beamdynamics, prototyping and experimental work

Demonstrator

Ultimate **6D cooling technology integration**
- Components: Magnets, RF systems, absorbers, vacuum, instrumentation, cryogenics, …
- Integration, operation, performance with beam
- Gradual upgrades as cell design evolves, confidence grows
- Will be important part of commissioning preparation after the decision to build the muon collider



Staged implementation
- Components
- RF test stand (high magnetic field)
- Module test with power
- Module test with beam
- Improved module string



Detailed studies of site at CERN ongoing, considering TT7 tunnel
US plan to start detailed study at FNAL

Effort **ramp-up** in several stages
Modular plan will allow quickly moving forward
- adjust to developments in Europe and the US

Other R&D Programme

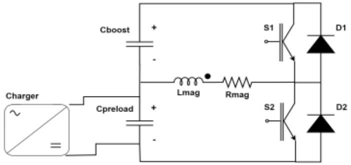
R&D on other technologies also needed
Power converter, high-field superconducting cavities, efficient RF power sources, cryogenics (e.g. **liquid hydrogen**), instrumentation, …

Most important is training of **young people**
- Strong interest by early career experts
  - e.g. https://indico.cern.ch/event/1422393/
- Motivating challenges
- Most important resource

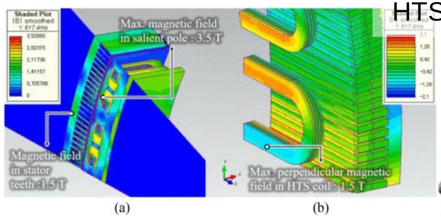
Exploit synergies with other fields (technology and physics)
- Strong **synergy** with **LDG HFM** and **RF**

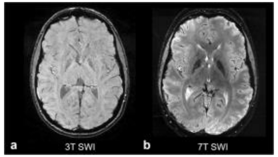
HTS solenoids have important potential
- Fusion
- Power generators for windmills and motors
- Life sciences
- Important step toward FCC-hh HTS dipoles
- …

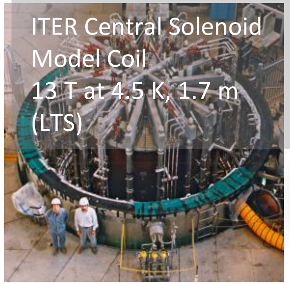
Detector technology development
- AI, ML, …



Design of 10 MW HTS wind generator







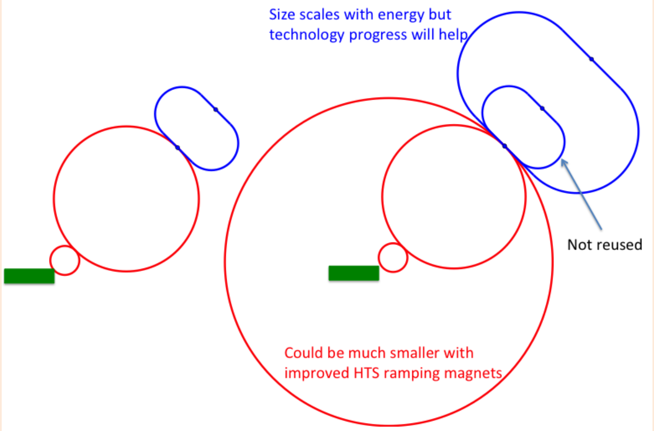
28.2 T LTS+HTS, 54 mm

Opportunities to profit from synergies
Attract young generation
R&D programme can be distributed world-wide

Staging

Expect to be ready for implementation in 15 years

- **Detector**
- **Muon cooling technology**
- **HTS solenoid technology**
- **Nb_3Sn dipoles** for collider ring, maybe lower field HTS
- High field HTS dipoles for collider ring are likely later



Energy staging

- Current 3 TeV, design takes lower performance into account
- Cost split over two stages, little increase in integrated cost

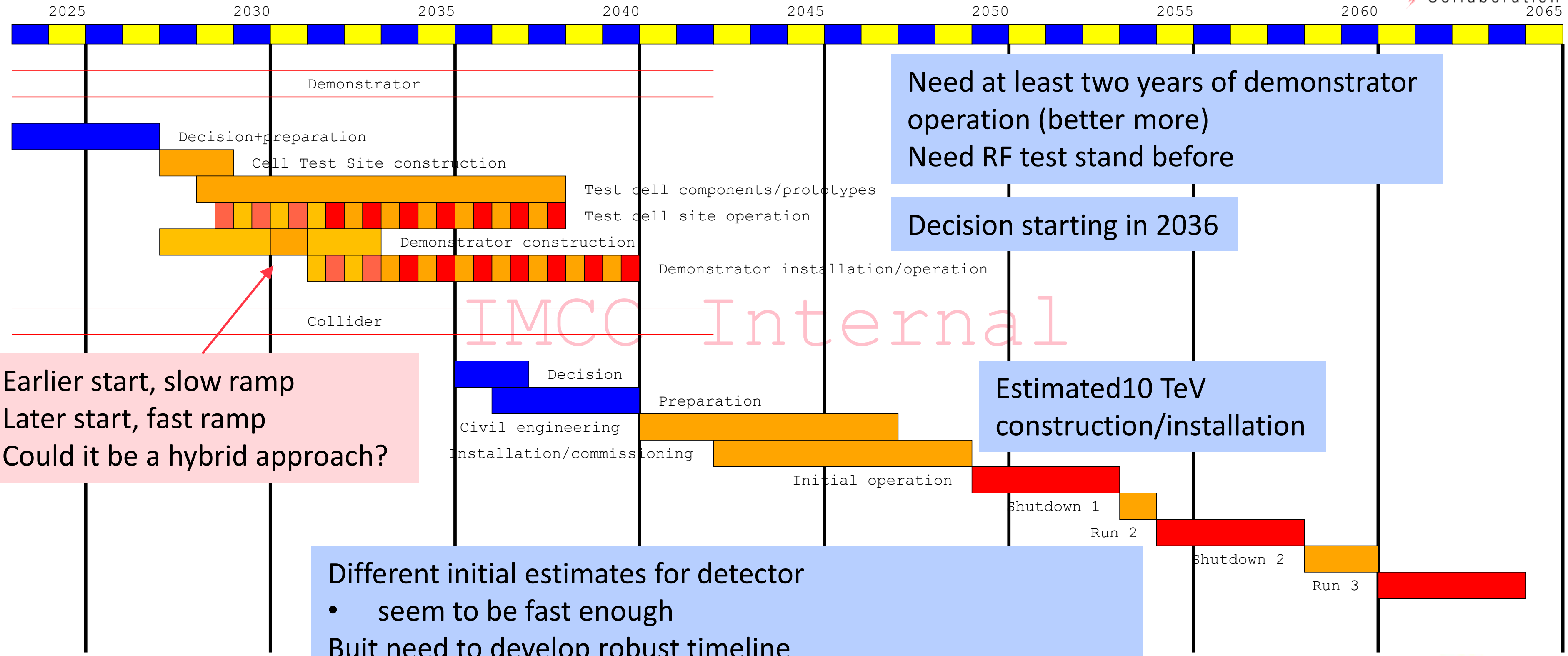
Luminosity staging

- Longer collider ring arcs and less performant interaction region lead to less luminosity in first stage
- Can later upgrade interaction region (as in HL-LHC)
- Full cost at first stage

Parameter	Unit	3 TeV	10 TeV	10 TeV	10 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	tbd	13
N	10^{12}	2.2	1.8	1.8	1.8
f_r	Hz	5	5	5	5
P_{beam}	MW	5.3	14.4	14.4	14.4
C	km	4.5	10	15	15
<B>	T	7	10.5	7	7

Potential Timeline (Fast-track 10 TeV)

Only a basis to start the discussion, being reviewed



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

Estimated10 TeV construction/installation

Earlier start, slow ramp
Later start, fast ramp
Could it be a hybrid approach?

Different initial estimates for detector
- seem to be fast enough

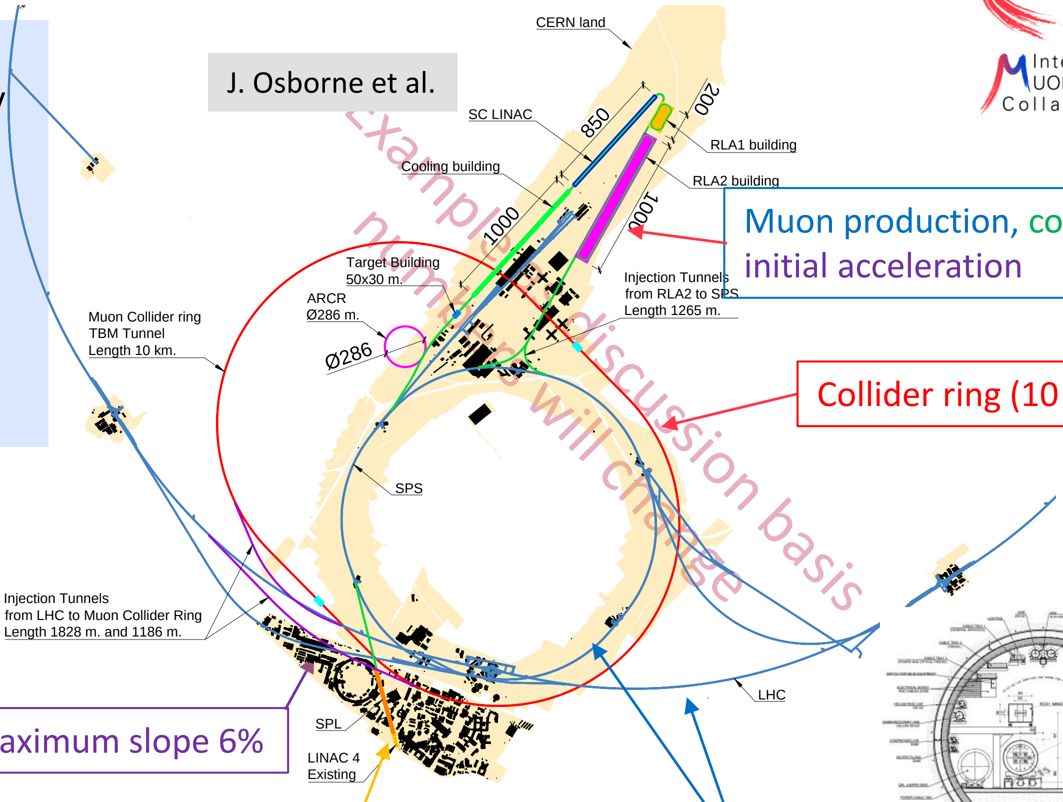
Buit need to develop robust timeline

Exploratory Site Studies

At **CERN**, first look is promising:

- First collider ring site identified that largely **mitigates neutrino flux from experiments**
  - Some more work required
- SPS and LHC tunnels reused
- All construction on CERN land (maybe one experiment not)
- Energy stages maybe 2.5 and 8 TeV
- More studies will be required in the future

J. Osborne et al.

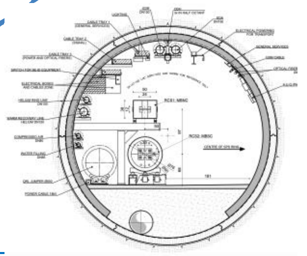


Muon production, cooling, initial acceleration

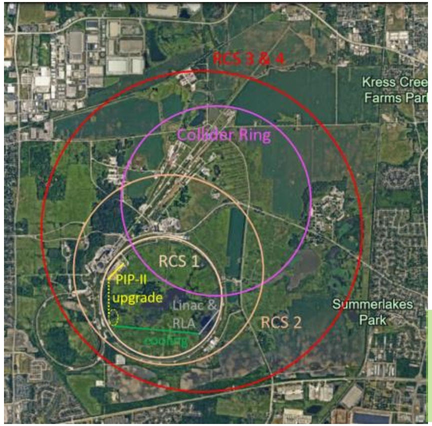
Collider ring (10 TeV)

Transferline maximum slope 6%

Injector similar to SPL



SPS and LHC used for RCSs



Initial concepts at **FNAL** are being considered

Conclusion

The status

Interest in Muon collider is rising and collaboration is growing

- EU co-funding, contributions from increasing number of partners
- Very strong interest in the US

Made important progress addressing identified challenges but still on our way

- Identified some additional challenges
- Moved much closer to our target

First exploration of CERN site motivates more detailed studies

- FNAL is also exploring their site

The future

Timeline with focus on fast scenario with physics starting around 2050

Will provide an R&D plan to ESPPU

- Identifying priorities for the next five and ten years

Excellent opportunity for Europe to maintain muon collider as option

- Magnets, cooling technology, detector, accelerator physics, …
- Profit from synergies and contribute to society
- Engage young generation

Many thanks to the collaboration for all the work

To join contact muon.collider.secretariat@cern.ch

Reserve

Demonstrator

The ultima
- Compo
- Integr

going,

NAL

Plan for ESPPU

March 2025 deliver promised ESPPU report containing

Assessment

Present **green field** designs and technologies

- International collaboration
- Parameters, lattice designs, component designs, beam dynamics, cost, …

R&D plan

Including scenarios and timelines

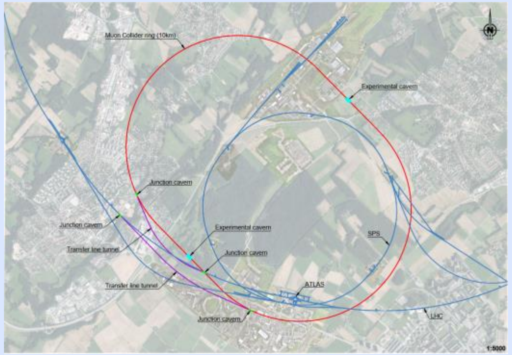
- Magnets, muon cooling, detector, …
- **The muon cooling technology and test facility is critical for this**

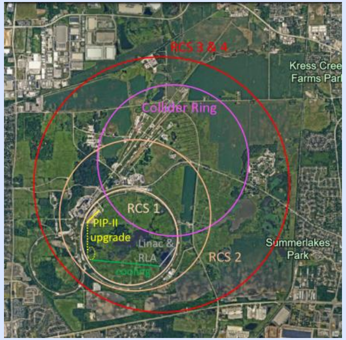
Implementation Considerations

Civil engineering studies/considerations

- For CERN and for FNAL
- Provide parameter tables for these implementations, scaled from green field
  - Do not have resources/time to redo detailed lattice designs for ESPPU

Schedule (strongly linked to R&D Plan)

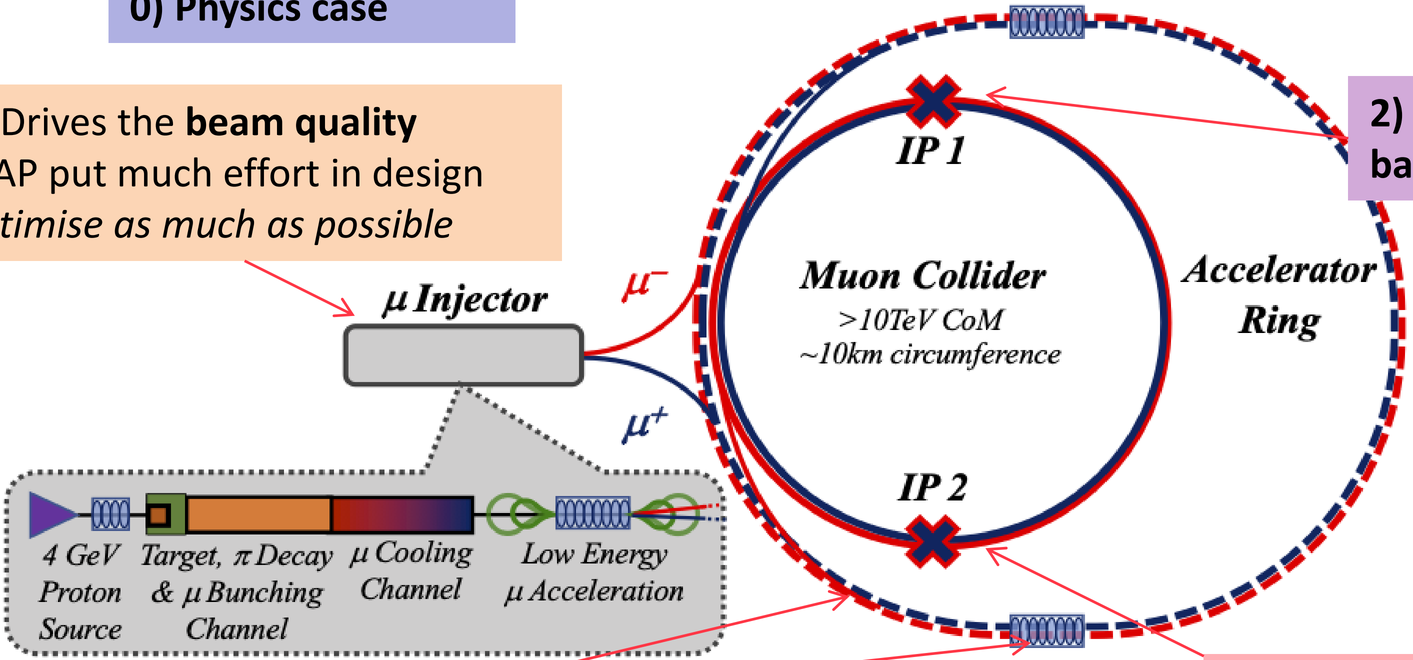




Key Challenges

0) Physics case

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



2) Beam-induced background

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

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

Important technical progress
But cannot cover it here


arXiv > physics > arXiv:2407.12450

Search... Help | Advan

Physics > Accelerator Physics

[Submitted on 17 Jul 2024]

Interim report for the International Muon Collider Collaboration (IMCC)

C. Accettura, S. Adrian, R. Agarwal, C. Ahdida, C. Aimé, A. Aksoy, G. L. Alberghi, S. Alden, N. Amapane, D. Amorim, P. Andreetto, F. Anulli, R. Appleby, A. Apresyan, P. Asadi, M. Attia Mahmoud, B. Auchmann, J. Back, A. Badea, K. J. Bae, E. J. Bahng, L. Balconi, F. Balli, L. Bandiera, C. Barbagallo, R. Barlow, C. Bartoli, N. Bartosik, E. Barzi, F. Batsch, M. Bauce, M. Begel, J. S. Berg, A. Bersani, A. Bertarelli, F. Bertinelli, A. Bertolin, P. Bhat, C. Bianchi, M. Bianco, W. Bishop, K. Black, F. Boattini, A. Bogacz, M. Bonesini, B. Bordini, P. Borges de Sousa, S. Bottaro, L. Bottura, S. Boyd, M. Breschi, F. Broggi, M. Brunoldi, X. Buffat, L. Buonincontri, P. N. Burrows, G. C. Burt, D. Buttazzo, B. Caiffi, S. Calatroni, M. Calviani, S. Calzaferri, D. Calzolari, C. Cantone, R. Capdevilla, C. Carli, C. Carrelli, F. Casaburo, M. Casarsa, L. Castelli, M. G. Catanesi, L. Cavallucci, G. Cavoto, F. G. Celiberto, L. Cel[illegible], A. Cemmi, S. Ceravolo, A. Cerri, F. Cerutti, G. Cesarini, C. Cesarotti, A. Chancé, N. Charitonidis, M. Chies[illegible] Chiggiato, V. L. Ciccarella, P. Cioli Puviani, A. Colaleo, F. Colao, F. Collamati, M. Costa, N. Craig, D. [illegible]rtin, L. D'Angelo, G. Da Molin, H. Damerau, S. Dasu, J. de Blas, S. De Curtis, H. De Gersem et al. (287 [illegible] authors not shown)

The International Muon Collider Collaboration (IMCC) [1] was esta[illegible]ished [illegible] 202[illegible] following the recommendations of the European Strategy for Particle Physics (ESPP) and the impleme[illegible] the E[illegible]rop[illegible]n Strategy for Particle Physics–Accelerator R&D Roadmap by the Laboratory Directors Group [2], [illegible]reinafter [illegible]ed to as the the European LDG roadmap. The Muon Collider Study (MuC) covers the accelerat[illegible], de[illegible]ctors and physics for a future muon collider. In 2023, European Commission support was obtained for [illegible] design [illegible] a muon collider (MuCol) [3]. This project started on 1st March 2023, with work-packages aligned with t[illegible] mu[illegible] collic[illegible] studies. In preparation of and during the 2021–22 U.S. Snowmass process, the muon collid[illegible] proje[illegible]ara[illegible]ters, technical studies and physics performance studies were performed and presented in great detail. [illegible] the P[illegible] panel [4] in the U.S. recommended a muon collider R&D, proposed to join the IMCC and envisages tha[illegible] should prepare to host a muon collider, calling this their "muon shot". In the past, the U.S. Muon Accelerat[illegible] Programme (MAP) [5] has been instrumental in studies of concepts and technologies for a muon collider.

https://arxiv.org/abs/2407.12450

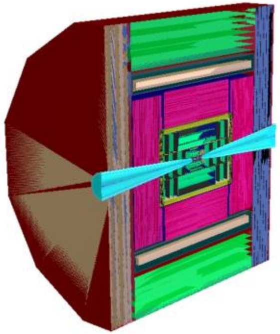
And ESPPU report in preparation

Technical progress

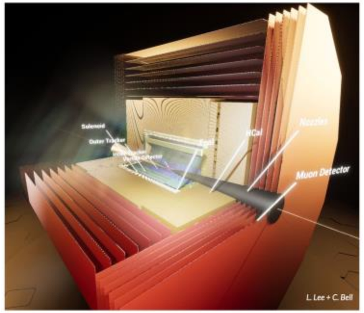
Physics and Detector Concepts

Two detector concepts are being developed

MUSIC
(MUon Smasher for Interesting Collisions)



A "New Detector Concept",
maybe a flashier name can be found



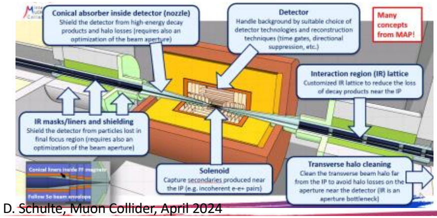
D. Schulte, Muon Collider, Birmingham, July 2024

MDI and beam-induced background

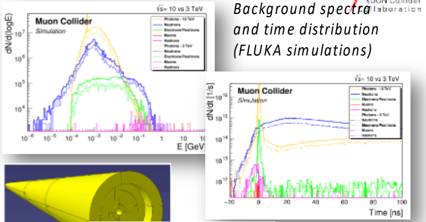
Activities in SY/STI:

- Detailed simulation of detector background and radiation damage by means of FLUKA
- Optimization of MDI (nozzle, shielding) and IR for 10 TeV collider ongoing,
- First engineering considerations for nozzle

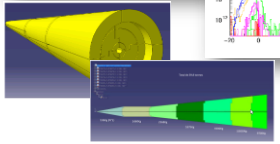
Integral approach for MDI design:



D. Schulte, Muon Collider, April 2024



Background spectra and time distribution (FLUKA simulations)



First engineering considerations for nozzle

Achievements (selection):

- Development of a 10 TeV IR lattice → impact of lattice design choices on the decay background
- First comparison of decay background for 3 TeV and 10 TeV + first BIB samples for detector studies
- First study of the incoherent pair production background and halo background (10 TeV)
- First estimates of the cumulative radiation damage in the detector (3 TeV and 10 TeV)
- First study of the nozzle optimization potential
- First study of forward muons (10 TeV)

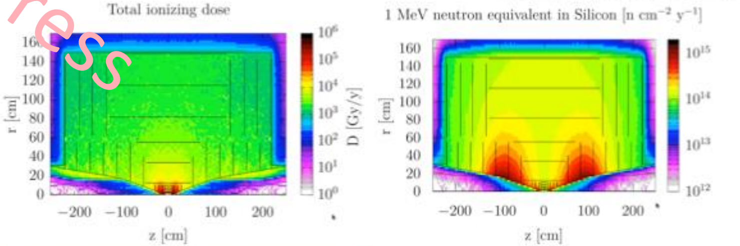
Main goals for ESPPU report:

- Optimization of the nozzle, absorbers, shielding for 3 TeV and 10 TeV, respectively
- Continue 10 TeV IR lattice development
- Engineering considerations for nozzle and integration with detector and solenoid
- Study the permissible halo-induced background in the IR (derive specs for halo cleaning)
- Refinement of incoherent pair production background
- Study radiation damage in IR magnets & detector

Radiation damage in detector (10 TeV)

For IMCC lattice version v0.4

Radiation damage estimates for 10 TeV (MAP nozzle, CLIC-like detector) Includes only contribution of decay-induced background!



Per year of operation (140d)	Ionizing dose	Si 1 MeV neutron-equiv. fluence
Vertex detector	200 kGy	3×10^{14} n/cm^2
Inner tracker	10 kGy	1×10^{15} n/cm^2
ECAL	2 kGy	1×10^{14} n/cm^2

IMCC plans for final ESPPU report:

- Redo radiation damage calculations with optimized 10 TeV nozzle and lattice (and new detector design)
- Calculate contribution of other source terms (e.g. incoherent pairs, halo losses)

Muon Decay and Neutrino Flux

Muon decays in collider ring
- Impact on detector
- Have to avoid dense neutrino flux

Aim for **negligible impact from arcs**
- Similar impact as LHC
- At 10 TeV go from acceptable to negligible with mover system
  - Mockup of mover system planned
  - Impact on beam to be checked

Detailed studies by RP and FLUKA experts
- Impact on surface
- Considering buildings

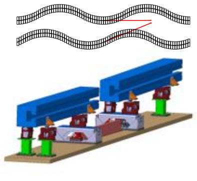
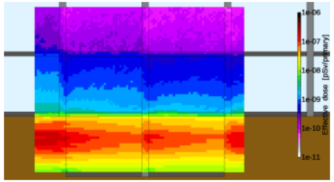
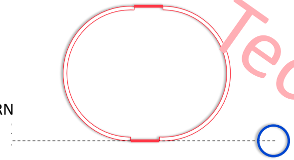


Fig. 7.23: Mock-up of the proposed magnet movement system.





Impact of experimental insertions
- 3 TeV design acceptable with no further work
- But better acquire land in direction of straights, also for 10 TeV
- Detailed studies identified first location and orientation close to CERN
  - Poiint to uninhabited area in Jura and Mediterranian sea

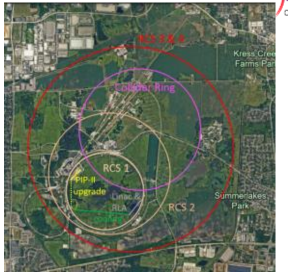
D. Schulte, Muon Collider, Birmingham, July 2024

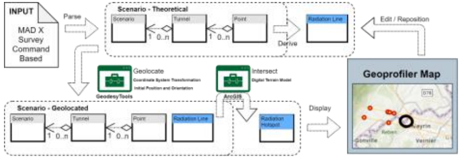
Site Studies

Candidate sites **CERN, FNAL,** potentially others (ESS, JPARC, …)

Study is mostly site independent
- Main benefit is existing infrastructure
- Want to avoid time consuming detailed studies and keep collaborative spirit
- Will do more later

Some considerations are important
- Neutrino flux mitigation at CERN
- Accelerator ring fitting on FNAL site





Potential site next to CERN identified
- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

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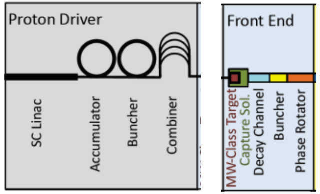
Proton Complex and Target



protons → (in target) pions → (decay) muons

400 kJ protons to produce 5 x 10^{13} captured muon pairs

5 GeV proton beam, 2 MW = 400 kJ x 5 Hz
Power is at hand

ESS and Uppsala are woring on merging beam into high-charge pulses
- Indication is that 10 GeV would be preferred

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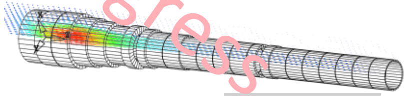
Target Technologies

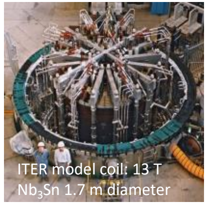
Target solenoid design ongoing
Either large bore 20 T HTS or 15 T LTS with 5 T insert



HTS target solenoid: 20 T, 20 K

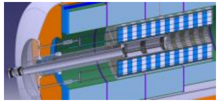
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Our work is relevant for fusion



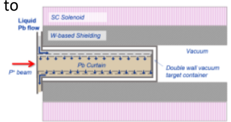
FLUKA studies:
2 MW target: stress in target, shielding, vessel OK
Need to have closer look at window
Cooling OK

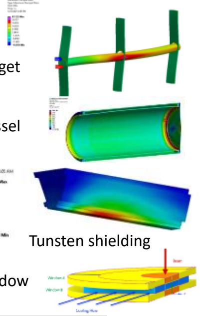
Integration



Cooling, vacuum, mechanics, …

Liquid metal target
Serious alternative to graphite

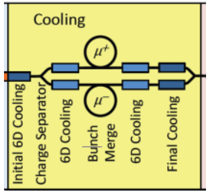




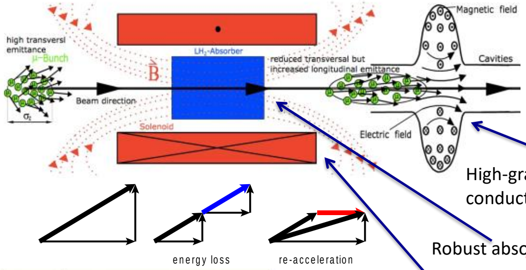
A. Lechner, D. et al.

D. Schulte, Muon Collider, INFN, May 2024 36

Muon Cooling Principle



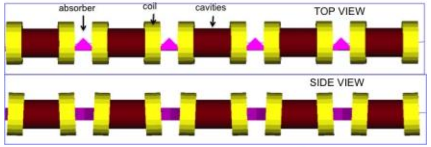
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



Principle has been demonstrated in MICE
Nature vol. 578, p. 53-59 (2020)

D. Schulte, Muon Collider, INFN, May 2024

37

Muon Cooling Simulations

Reminder: multiple scattering is not straightforward to simulate

Developed RFTrack to allow simualtion of the muon cooling

Integration of novel model in RFTrack

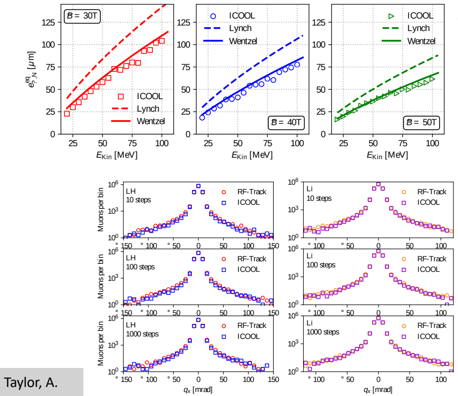
Benchmarking confirms validity

Recently discovered:

- Some bug in data extraction routine
- Step size dependence

Both seem to be solved by now

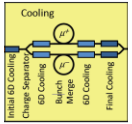
- But would like to review previous results

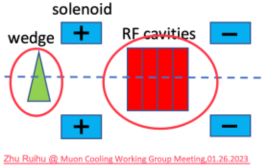


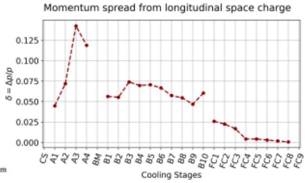
B. Stechauner, E. Fol, Taylor, A. Latina, P. Valdor et al.

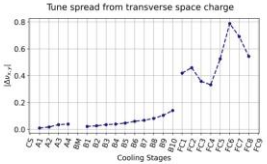
D. Schulte, Muon Collider, May 2024

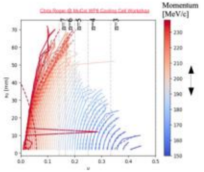
Collective Effects











Activity started recently

J. Potdevin, T. Poeiloni, X. Buffat et al. (CERN)

D. Schulte, Muon Collider, May 2024

Muon Cooling Performance

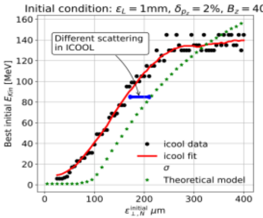
MAP design achieved 55 um based on achieved fields

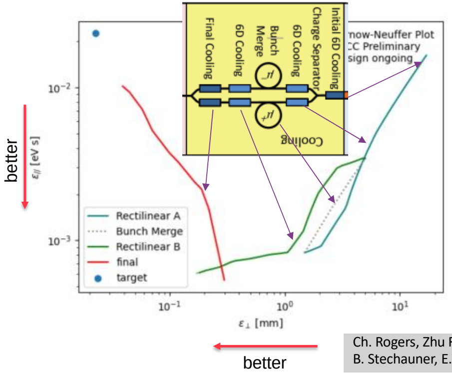
Currently in 30-40 um range

- Need careful checks

Identification of optimum energy for cooling as function of emittance

B. Stechauner at al.





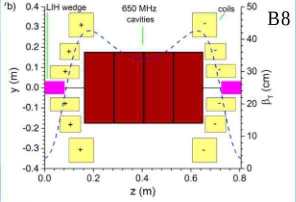
Ch. Rogers, Zhu Ruihu, R. Taylor, B. Stechauner, E. Vol et al.

D. Schulte, Muon Collider, May 2024

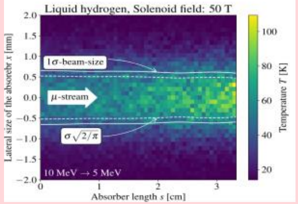
Cooling Cell Technology

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

Integrated cooling cell
- tight constraints
- additional technologies (**absorbers**, instrumentation,...)
- early preparation of **demonstrator facility**



Most complex example 12 T



Identified windows and absorbers as critical for high-density muon beam
- Pressure rise mitigated by using H-gas with calibrated density
- First window test in HiRadMat

B. Stechauner, J. Ferreira Somoza et al.

Test of 1 um Si_3N_4:
Very high energy deposition (15x) leads to deformation but no rupture

Solenoid R&D

Started **HTS solenoid** development for high fields
Synergies with fusion reactors, NRI, power generators for windmills, ...

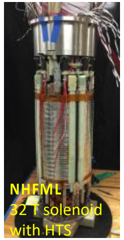
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Final Cooling solenoid

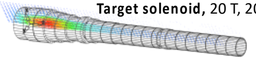
$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$$

s_{max} = 600 MPa

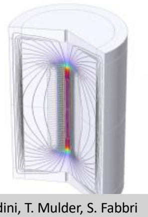
$B_{max} \approx$ **55 T**

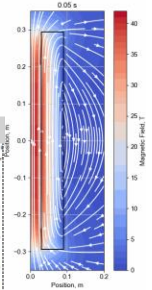


32 T LTS/HTS solenoid demonstrated

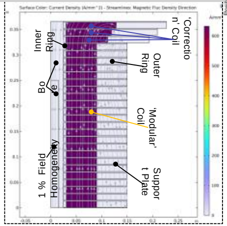


Target solenoid, 20 T, 20 K

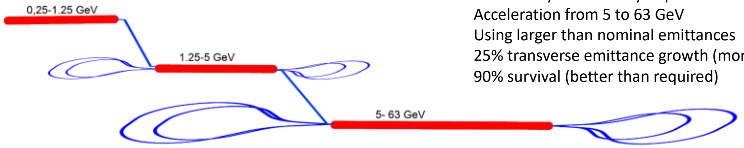




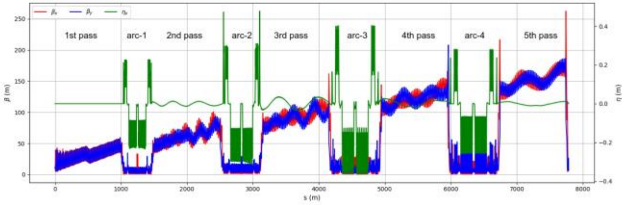
A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



Muon Initial Acceleration



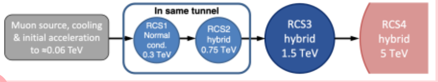
Preliminary and actually unplanned study of RLA2:
Acceleration from 5 to 63 GeV
Using larger than nominal emittances
25% transverse emittance growth (more work required)
90% survival (better than required)

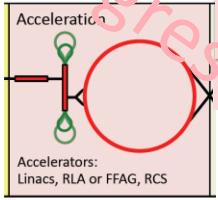


A. Aksoy

No more resources!
Avni left!

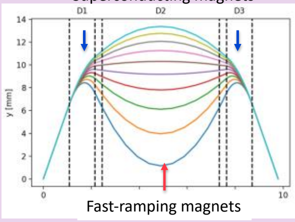
Acceleration Complex



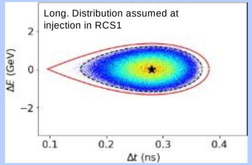


Core is sequence of pulsed synchrotron (0.4-11 ms)
Alternative FFA

Superconducting magnets



Fast-ramping magnets



RF:
1.3 GHz cavities appear possible
- in spite of high bunch charge

Lattice:
Hybrid design works
Can spread RF in the arcs

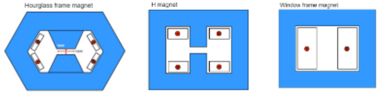
Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

Technical progress

Fast-ramping Magnet System

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

Synchronisation of magnets and RF for power and cost



5.07 kJ/m | 5.65…7.14 kJ/m | 5.89 kJ/m

FNAL 300 T/s HTS magnet

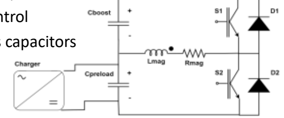
Could consider using HTS dipoles for largest ring

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

Differerent power converter options investigated

Commutated resonance (novel)

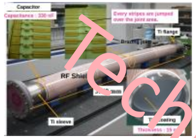
Attractive new option
- Better control
- Much less capacitors



Beampipe study

Eddy currents vs impedance

Maybe ceramic chamber with stripes

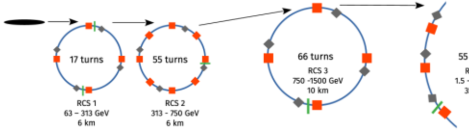


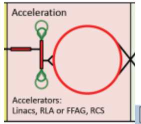
F. Boattini et al.

D. Schulte, Muon Collider, INFN, May 2024

42

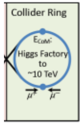
Collective Effects

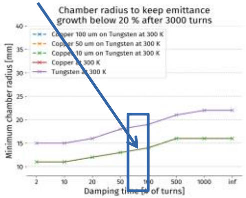




Impedance studies

Single beam instability limits OK with conservative feedback

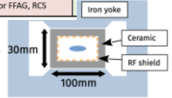




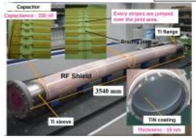
Beampipe study

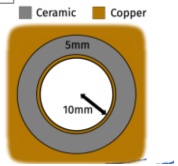
Eddy currents vs impedance

Maybe ceramic chamber with stripes



Impedance model





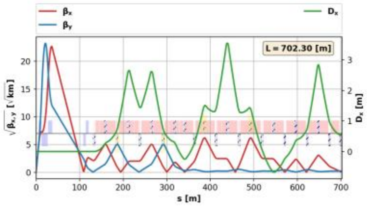
E. Metral, D Amorim, E. Kvikne et al. (CERN)

D. Schulte, Muon Collider, May 2024

Collider Ring

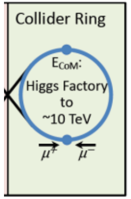
High performance 10 TeV challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

10 TeV collider ring in progress:
- around 16 T HTS dipoles or lower Nb_3Sn
- final focus based on HTS
- Need to further improve the energy acceptance by small factor



3 TeV:

MAP developed 4.5 km ring with Nb_3Sn
- magnet specifications in the HL-LHC range
- 5 mm beta-function

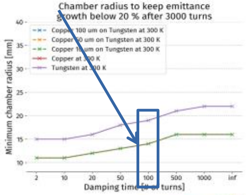


K. Skoufaris, Ch. Carli, support from P. Raimondi, K. Oide, R. Tomas

E. Metral, D Amorim et al. (CERN)

Impedance studies

Single beam instability limits OK with conservative feedback



D. Schulte, Muon Collider, INFN, May 2024

43

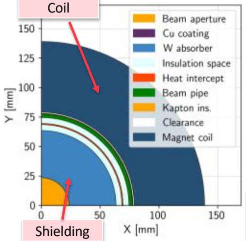
Collider Ring Technologies

Power loss due to muon decay 500 W/m

FLUKA simulation of required **shielding:**

20-40 mm tungsten shielding (about OK-safe)
- Few W/m in magnets
- No problem with radiation dose

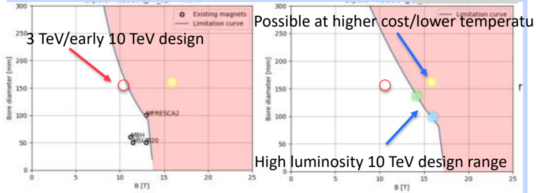
⇒ Magnet coil radius 59-79 mm



K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura, D. Calzolari et al.

Study of magnet limitations (stress, loadline, cost, …)

D. Novelli, L. Bottura et al.



Nb_3Sn at 4.5 K and 15 cm aperture

Can reach ~11 T, stress and margin limited

Maturity expected in 15 years

OK for current 3 TeV/early 10 TeV design

HTS at 20 K and 10-14 cm aperture

Can reach 16-14 T, cost limited
- Factor 3 cost reduction assumed

Can reach 16 T and 16 cm with more material or lower temperature

Maturity takes likely >15 years
- But maybe OK in 15 years at lower performance, similar to Nb_3Sn

Different **cooling scenarios** studied

< 25 MW power for cooling possible

Shield with CO_2 at 250 K (preferred) or water

Support of shield is important for heat transfer

Discussion on options for magnet cooling

20

Technical progress

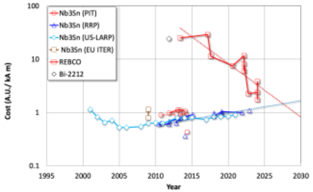
Dipole Cost

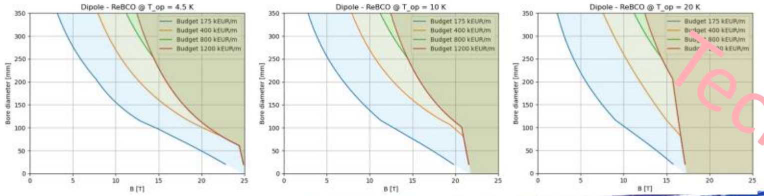
Key cost drivers are based on sound models
- E.g. RCS with trade-off between RF and magnet cost

A part of the cost will be based on scaling from other projects

A part of the cost depends on future developments of technology beyond our study
- E.g. cost of superconductor

Major cost optimisations remain to be done in the design



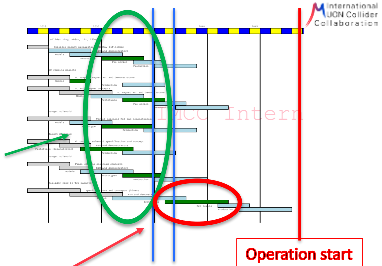


Magnet Roadmap

Assume: Need prototype of magnets by decision process

Consensus of experts (review panel):
- Anticipate technology to be **mature in O(15 years):**
  - **HTS solenoids** in muon production target, 6D cooling and final cooling
    - HTS tape can be applied more easily in solenoids
    - Strong synergy with society, e.g. fusion reactors
  - **Nb_3Sn 11 T magnets** for collider ring (or HTS if available): 150mm aperture, 4K
- This corresponds to 3 TeV design
- Could build 10 TeV with reduced luminosity performance
  - Can recover some but not all luminosity later

Still under discussion:
- Timescale for 10 TeV HTS/hybrid collider ring magnets
- For second stage can use **HTS or hybrid collider ring magnets**



Operation start

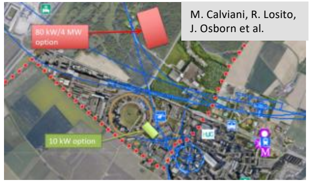
2036+2037 decision process

Strategy:
- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

Seems technically good for any future project

CDR Phase, R&D and Demonstrator Facility

Broad R&D programme can be distributed world-wide
- **Models** and **prototypes**
  - Magnets, Target, RF systems, Absorbers, …
- **CDR** development
- **Integrated tests**, also with beam



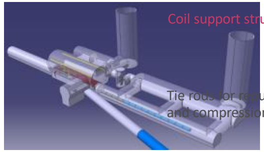
M. Calviani, R. Losito, J. Osborn et al.

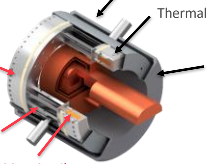
Cooling demonstrator is a key facility
- look for an existing proton beam with significant power

Different sites are being considered
- CERN, FNAL, ESS …
- Two site options at CERN

Muon cooling module test is important
- INFN is driving the work
- Could test it at CERN with proton beam

With cryostat





Coil support structure

Tie rods for repulsion and compression forces

Two stage cryocooler

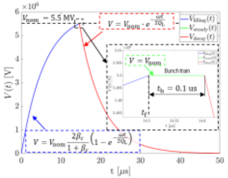
Thermal shield

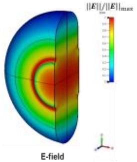
SC HTS coils

704 MHz cavity for the Muon Cooling (MC) Demonstrator

RF design and coupler RF-thermo-mechanical simulations

- RF simulations in CST Studio Suite®
  - Calculation of the pulse shape
  - Computation of the main RF figure of merits
  - Optimization of the cavity shape

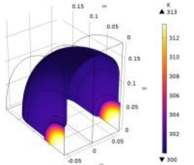




E-field

- RF-thermo-mechanical simulations in COMSOL Multiphysics®
  - Thermally-induced stress-strain state and frequency detuning
  - Mechanical stress and deformations and Lorentz Force Detuning (LFD) analysis

Temperature [K]



Total displacement [mm]