Progress

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On behalf of the International Muon Collider Collaboration

Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

CERN, March 2024

Global Collaboration

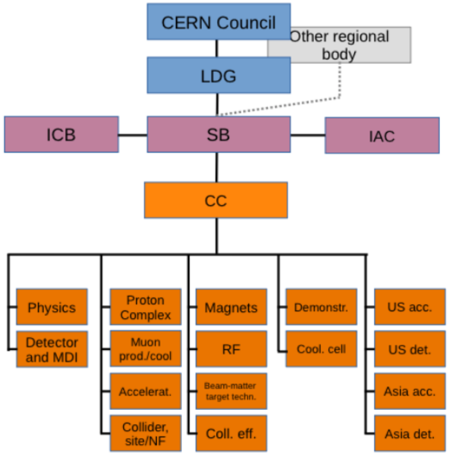
US Particle Physics Project Prioritisation Panel (P5) endorses muon collider R&D: ”This is our muon shot”

Recommend joining the IMCC
Consider FNAL as a host candidate

The New York Times

Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.



China	***Sun Yat-sen University***
	IHEP
	Peking University
KO	**KEU**
	Yonsei University
India	***CHEP***
US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	Florida State University
	RICE University
	Tennessee University
	University of Chicago

Should not forget other regions:

- E.g. Hokkaido Workshop on Particle Physics at Crossroads (https://conference-indico.kek.jp/event/248/overview)

US Integration

As already planned, we will **revise the distribution of R&D efforts and the organisation with your help in 2024**, reflecting the US efforts and resources. We look forward to **understanding US vision of the US participation**, both in R&D areas and organisation.

Several US institutes are already members of the IMCC and members of the US community are already engaged in important roles. We understand that it will take some time to ramp up the US effort. Three R&D areas are particularly critical for the timely implementation of a muon collider

- The development of **superconducting magnets** in the different parts of the accelerator. […]
- The development of the **muon production and cooling technology and its demonstration** in a facility. Developing more than one site option will make this effort more robust and US participation to the technology is essential.
- The **detector concept and technologies R&D**. The muon collider will reach lepton collision energies beyond those studied for other approaches, such as CLIC. The detector design and technologies will be challenging and should consider novel concepts of hard- and software. It appears to be prudent to develop alternative concepts to a good level of detail to ensure that we can take full advantage of the muon collider.

Physics considerations for implementation scenarios, consistent with the interest in all regions

- relative merits of an energy staging versus a luminosity staging;
- the overall physics performance and complementarity of a high-energy muon collider and a low energy Higgs factory;
- the complementarity of a high energy muon collider and a proton collider.

Evolution of Mindset

Actually an important change toward the end of the Interim Report preparation

In **European Accelerator Roadmap** main goal has been to be back into the field

- Focus on justifying our existence
- Focus on the ESPPU allowing us to continue

Several developments since

- With the **progress of work** are gaining confidence that collider can keep its promises
- Are becoming a **global effort**
  - **US expresses strong interest** in the collider
  - Also **interest in Asia,** might well increase
  - Are becoming less dependent on decisions in Europe

Will focus on the future, not the achievements in this talk

So we need to **focus on the longer term** and prepare the R&D programme

Parameters

First Parameter Report submitted in October 2023

The first parameter document has been important progress

- The teams took ownership of their parameters
- Now need to consolidate and update the parameters

Feel that we are in a position to start making trade-offs

- Cannot not at this moment make the final parameter set
- But consider different options
- Prepare what to do if not all parameters can be reached by 2026
    - For linear colliders much more effort has been required to sort out lattice design challenges

Start a parameter working group and some task forces to explore the different trade-offs

Interim Report

Reviewed by the IAC -> Steinar

Executive Summary

Overview of Collaboration Goals and R&D programme

Physics Potential

Physics, Detector and Accelerator Interface

Detector

Accelerator design

Accelerator technologies

Synergies

R&D programme development

Implementation Considerations

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Many thanks for the excellent work

- Documents the really good progress
- Helps define the future

Final editing required to take into account IAC

Interim Report Plan

Implement what we can in the next couple of weeks

- Chapter editors go through the detailed comments from IAC
  - Positive wording on “missing resources” parts, i.e. research opportunities
  - Magnets to comment on timeline
- Expand the “overview” chapter
  - More description of the collider
  - A bit history
  - Summary of work progress since Roadmap
  - Global assessment of required vs. available resources
  - Integrating the staging in more detail here
- Brief executive summary

IAC would like Interim Report to be more an early version of the final report

Implement other comments in the next document

- Our report to the strategy process in Europe
  - Time depends on external decisions, normally early 2026, maybe early 2025
- An improved version, also addressing specific US needs, somewhat later

Physics and Detector Questions

Further development of physics case

- Quantitative statements
- Clear split of results into classes of detail, e.g. maybe the following
  - DELPHES or equivalent
  - …
  - With full detector simulation including background
- Benchmark points are critical to link the different levels
  - Really important to maximise our effectiveness

Exploration of complementarity, with other communities

- Higgs factory and muon collider
- High-energy hadron collider and muon collider

Further development of detector design

- Quantitative assessment of the performance, including background
  - e.g. jet resolutions, tagging efficiencies

Physics and Detector Questions

MuCol

International MUON Collider Collaboration

Development of synergy case

- For the demonstrator (e.g. NuStorm, Mu2e, …)
- And the actual collider (e.g. neutrinos from the experimental insertions, …)

Different detector concepts

- We can have two different detectors at the collider
- Important to explore different approaches in some detail
- Include future technologies, including software, e.g. machine learning

Link to the technology development

- What is in the currently funded detector R&D technology?
- Is in time for our detector?
- Do we need further performance improvements?

Accelerator Questions

Continue to develop the machine design and the technologies

- Continue and further improve existing studies
  - Still much work left
- Increase level of integration (e.g. parameters)
  - Trade-off collider ring magnet field vs aperture vs cost vs luminosity
  - Define sequence of pulsed synchrotrons
  - Common optimization of RF and fast-ramping magnet in pulsed synchrotrons
  - Try to find resources to complete the lattice sequence
  - …

Include development of

- R&D plan
  - Including resource estimates
- Implementation scenarios, staging and timelines
- Site choices
- Cost and power consumption

Implementation Considerations

Reviewing timeline (still evolving)

- Uncertainties from physics case (e.g. HL-LHC), society development, budget profile etc.

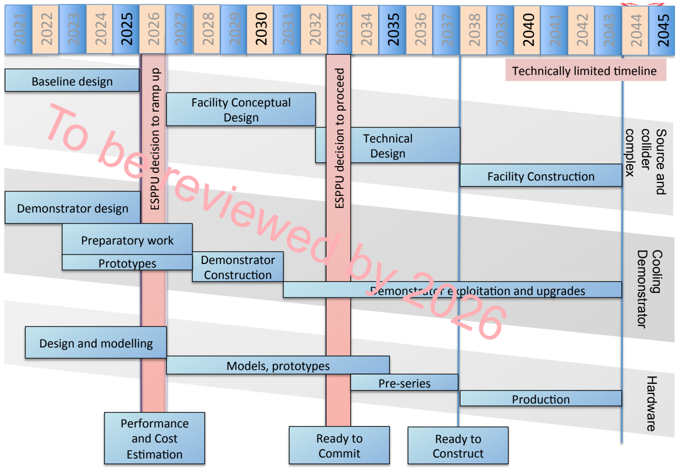
Can concept be mature for decision before 2040 and start operation before 2050?

- Identifying shortest possible “technically limited” timeline
- Accept performance compromises that are required on this timescale

Tentatively identified main technologies that might limit the timeline

- **Muon cooling technologies and integration**
- **Magnet technology**
- **Detector technologies**

Needs to be reviewed



Expect that other technologies can be accelerated if funding is increased appropriately

- But **they are equally important** now to support that the muon collider can be done and can perform

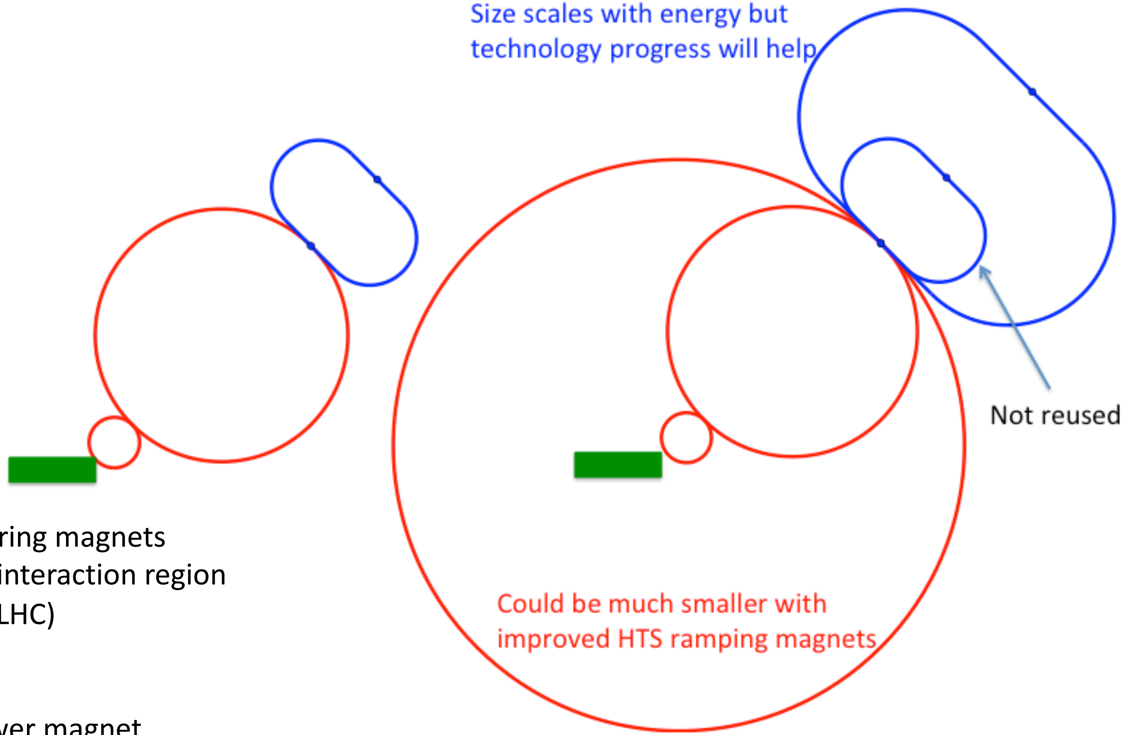
Staging Approaches

Assumptions:

- In O(15 years):
  - HTS technology available for solenoids
  - Nb_3Sn available for collider ring (11 T)
- In O(25 years):
  - HTS available for collider ring (up to 16 T)

Scenario 1: Energy staging

- Start at lower energy (e.g. 3 TeV)
- Build additional accelerator and collider ring later
- Requires less budget for first stage
- 3 TeV design takes lower performance into account



Scenario 2: Luminosity staging

- Start at with full energy, but less performant collider ring magnets
- Main sources of luminosity loss are collider arcs and interaction region
  - Can recover interaction region later (as in HL-LHC)
  - But need full budget right away
  - Some luminosity loss remains (O(1.5))
  - More power for the collider ring required (lower magnet temperature)

Initial Staged Target Parameters

Target integrated luminosities

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

Need to spell out scenarios

Need to integrate potential performance limitations for technical risk, cost, power, …

Parameter	Unit	3 TeV	10 TeV	10 TeV	10 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	6?	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
ε_L	MeV m	7.5	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.05?	0.1
σ_z	mm	5	1.5	3?	1.5
β	mm	5	1.5	3?	1.5
ε	µm	25	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	1.3	0.9

Examples as discussion basis
numbers will change

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Example Timeline

Fast-track 10 TeV Collider

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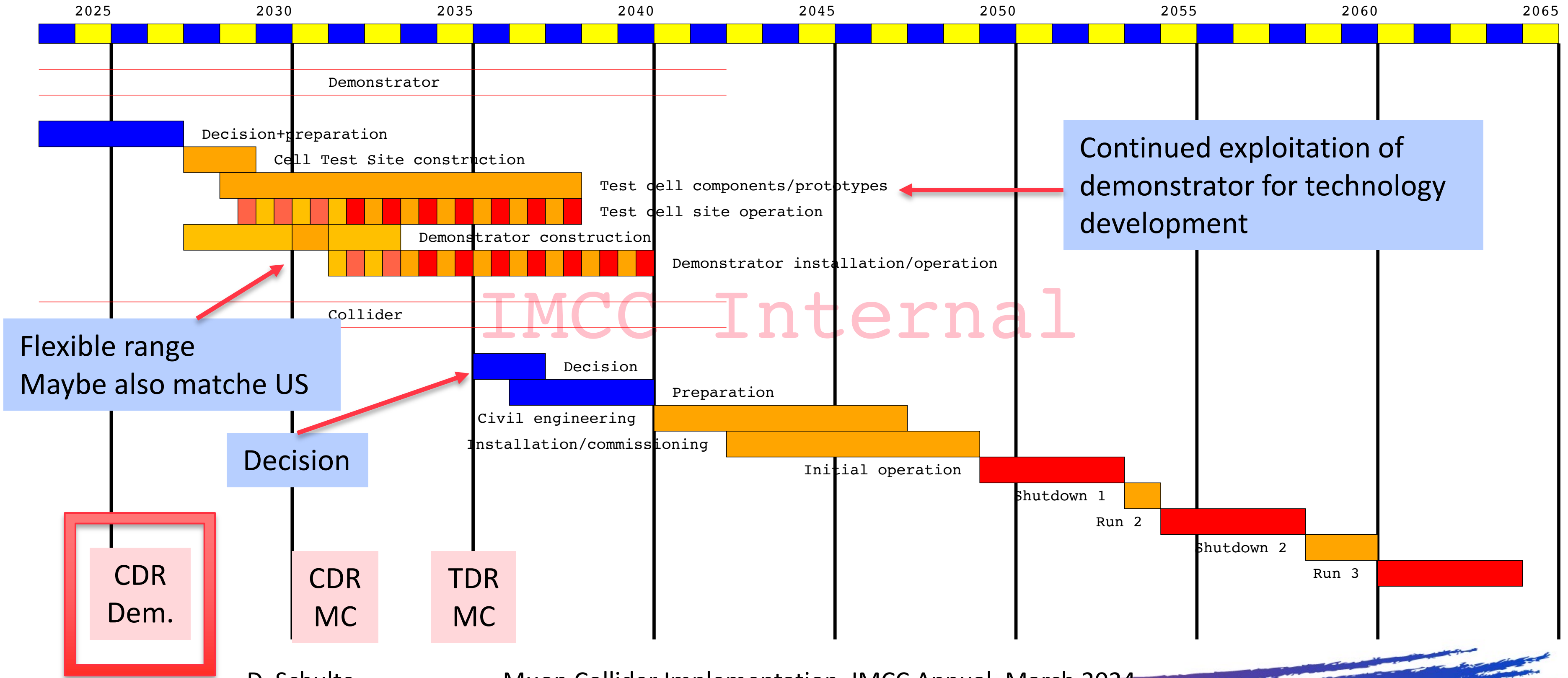
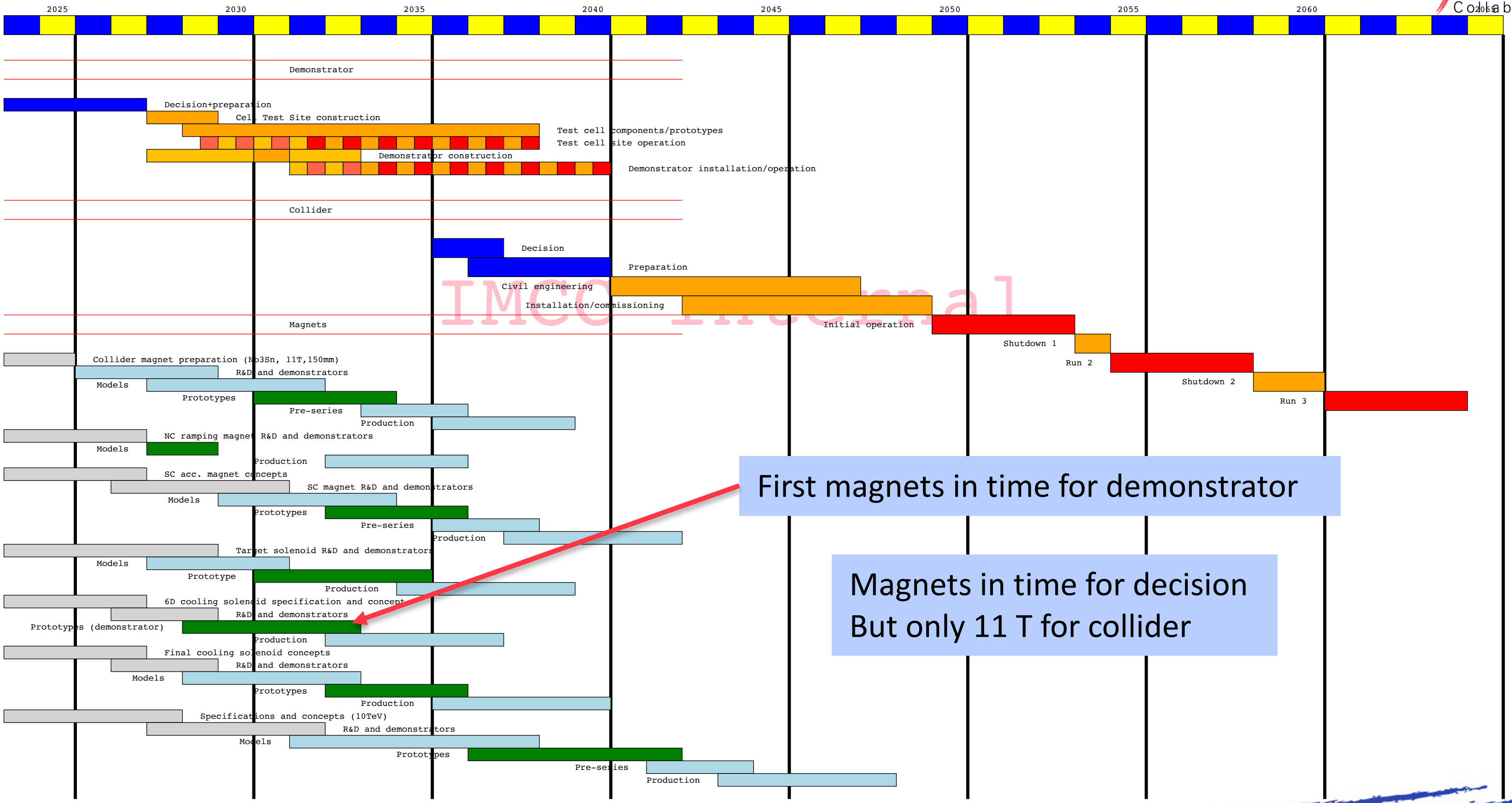


Timeline Considerations



First magnets in time for demonstrator

Magnets in time for decision
But only 11 T for collider

R&D Programme

Broad R&D programme can be distributed world-wide

- **Models** and **prototypes**
  - Magnets, Target, RF systems, Absorbers, …
- **CDR** development
- **Integrated tests**, also with beam

Demonstrator is a key ingredient

- It is good to have more than one site option
- Candidate sites **CERN, FNAL,** potentially others **(**ESS, JPARC, …)
  - Will have a workshop at FNAL to discuss demonstrator and potential sites (date to be defined)

Will try to develop a common, global demonstrator design

- With variations only where required because of site limitations
- Prototype development before the demonstrator can be distributed globally
  - E.g. RF test stand, muon cooling module
- Production of components can be distributed globally

Collider Site Studies

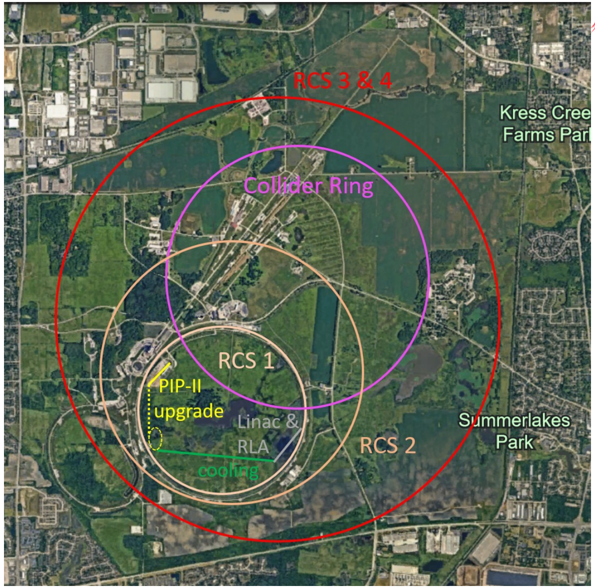
Candidate sites **CERN, FNAL,** potentially others **(**ESS, JPARC, …)

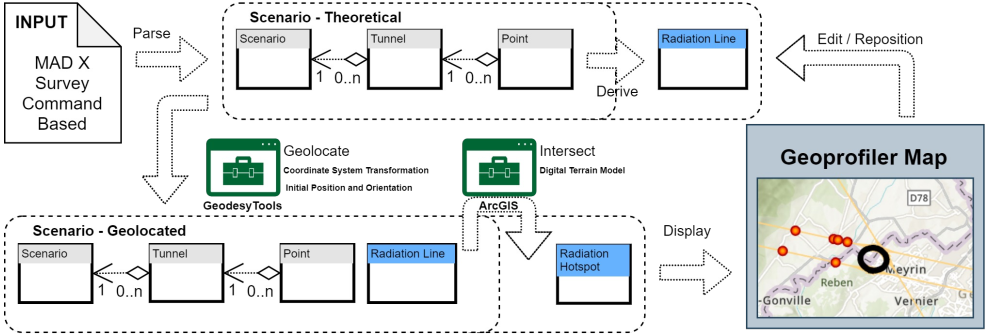
Study is mostly site independent

- 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)

Costing Effort

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Starting cost estimate
- Develop PBS for the whole project, considering PBS for FCC and CLIC
- But are very limited in resources, compared to other efforts

PBS will allow to
- Identify where information is available
- Understand uncertainty of estimate

Carlo Rossi (CERN) will lead the effort

Planned work
- Some bottom-up estimates for key unique components
  - E.g. fast-ramping magnets and power converter
- Generic and scaled estimates for other components
  - Where possible with the relevant groups but do not have a dedicated budget for the group personnel

Proposal: EuMAHTS

MuCol

Luca Botture et al.

EuMAHTS Accelerating HTS

International MUON Collider Collaboration

Submitted to INFRA-2024-TECH-01-01

Focus on HTS development
O(10 Meur) request

Strategy and context

Material and technology

Three core components (6 MEUR)

- 40 T solenoid, 50 mm bore
- 10 T/10 MJ/300 mm solenoid
- HTS undulator

Test infrastructure

WP1 - Coordination and Communication (L. Bottura, P. Vedrine)
WP2 – Strategic Roadmap (A. Ballarino, L. Rossi)
WP3 – Industry Co-innovation (J.M. Perez, S. Leray)
WP4 – HTS Magnets Applications Studies (P. Vedrine, M. Statera)
WP5 – Materials and Technologies (D. Bocian, A. Bersani)
WP6 – 40T-class all-HTS solenoid (B. Bordini, P. Vedrine)
WP7 – 10T/10MJ-class all-HTS solenoid (S. Sorti, C. Santini)
WP8 – K=2 all-HTS undulator (S. Casalbuoni, M. Calvi)
WP9 – Test Infrastructures (G. Willering, E. Beneduce)

Short name	Country	Status
CERN	IERO	B
EMFL	Belgium	B
TAU	Finland	B
CEA	France	B
ESRF	France	B
EUXFEL	Germany	B
GSI	Germany	B
KIT	Germany	B
INFN	Italy	B
UMIL	Italy	B
UTWENTE	Netherlands	B
IFJ-PAN	Poland	B
PK	Poland	B
CIEMAT	Spain	B
CSIC	Spain	B
PSI	Switzerland	A
TERA-CARE	Switzerland	A
UNIGE	Switzerland	A
CNRS	France	A
HZDR	Germany	A
RU-NWO	Netherlands	A

Publications

Defined the rules for the publications

- Accepted by the ICB and GB

The rules are inclusive

- Anyone who contributed can be author of the IMCC publications
- But you have to register, due to some data protection laws
- Using it for the Interim Report

The newly established PSC started to work

- User friendly publication guidelines should appear online soon
- Including templates etc.
- Please send talks and papers to them before publications

Identified past publications that are from the collaboration

- Added 68 publications on CDS with the muon collider tag

https://cds.cern.ch/collection/Muon%20Collider%20study?ln=en

Synergies and Outreach

Need to exploit this to have more experts for the field and the muon collider

Training of young people

- Novel concept is particularly challenging and motivating for them

Technologies

- Need HTS, in particular solenoids
- Fusion reactors
- Power generators
- Nuclear Magnetic Resonance (NMR)
- Magnetic Resonance Imaging (MRI)
- Magnets for other uses (neutron spectroscopy, detector solenoids, hadron collider magnets)
- Target is synergetic with neutron spallation sources, in particular liquid metal target
- High-efficiency power sources
- RF in magnetic field can be relevant for some fusion reactors
- High-power proton facility
- Facilities such as NuStorm, mu2e, COMET, highly polarized low-energy muon beams

(Need to add: detector technologies, AI, physics)

Conclusion

Collaboration is increasing

- More requests to EC and other funding agencies
- The US partners will join
- Hope to also grow in Asia
- Feel that there is **important synergy with other facilities and technologies**

Work is progressing but is still budget limited

- Continue to secure more resources
- Similar to MuCol, which is an active part of the IMCC

Need now to move more focus to the R&D programme

http://muoncollider.web.cern.ch To join contact muon.collider.secretariat@cern.ch

Reserve

Risks

Risk	Potential cause	Mitigation	
Reduced N_0	Less charge from target	Alternative target Increase f_r	
	Larger loss in cooling	Increase target charge	
	Larger loss in acceleration	Increase target charge	
Larger transverse IP emittance	Larger emittance from cooling	Cooling lattice design Larger charge	
	Larger emittance increase	Beam-based tuning Larger charge	
Larger longitudinal IP emittance	Larger emittance from cooling	Cooling lattice design Larger charge	
	Larger emittance increase	Beam-based tuning Larger charge	