International
MUON Collider
Collaboration

MuCol

Muon Collider Progress and Plans

D. Schulte
for the International Muon Collider Collaboration

LDG Meeting, Frascati, July 2023

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

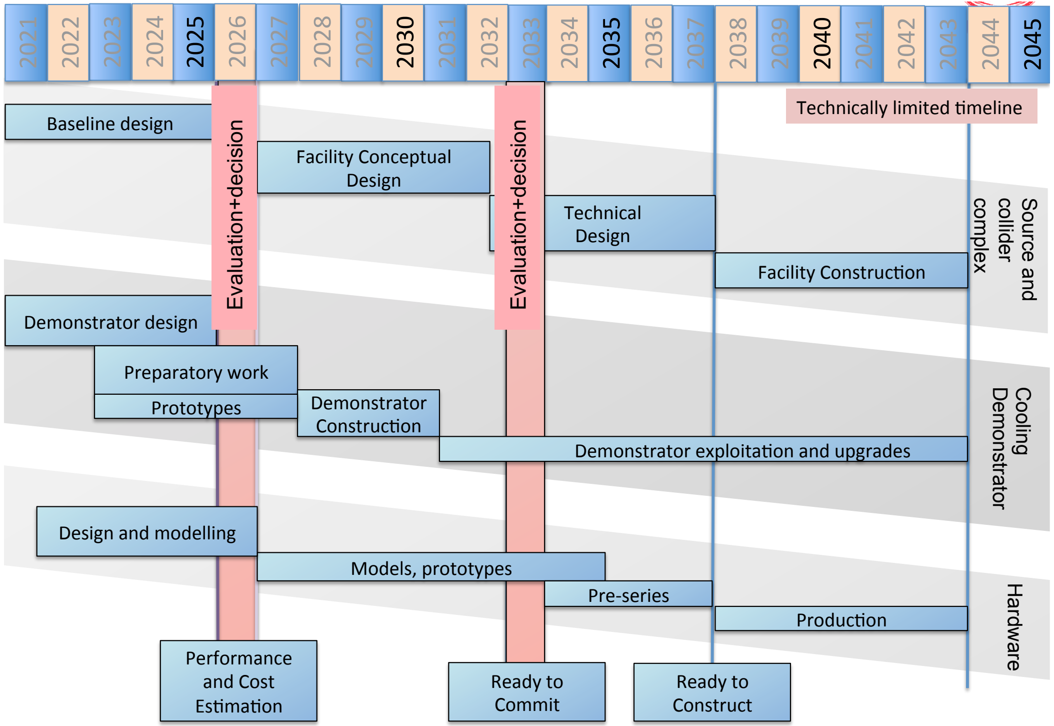
Accelerator R&D Roadmap

Main goal is **10 TeV** collider

Potential initial stage **3 TeV**

- For **fast implementation**, e.g. directly after HL-LHC
- Compromises will be made as required
- Physics case already good

http://arxiv.org/abs/2201.07895



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Evaluation+decision

Evaluation+decision

Source and collider complex

Baseline design

Facility Conceptual Design

Technical Design

Facility Construction

Cooling Demonstrator

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Hardware

Design and modelling

Models, prototypes

Pre-series

Production

Performance and Cost Estimation

Ready to Commit

Ready to Construct

Deliverables by next ESPPU/other processes

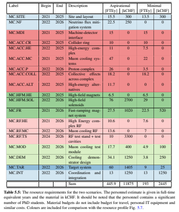
- **Project Evaluation Report**
- **R&D Plan**

Allows to make **informed decisions**

Interim report by end of 2023

Currently resources start approaching minimal scenario

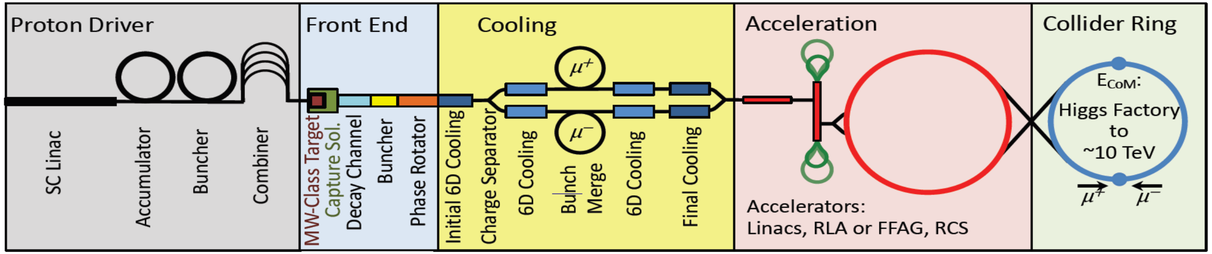
Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45



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.

Muon Collider Overview



Target integrated luminosities

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

Would be achieved with tentative parameters in 5 years

Aim for **10 TeV**

- The reason for muons

Potential initial stage **3 TeV**

- For fast implementation, e.g. directly after HL-LHC
- Compromises will be made as required
- Physics case already good

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

Organisation

Review next year when US joins

Collaboration Board (ICB)

- Elected chair: **Nadia Pastrone**

Steering Board (SB)

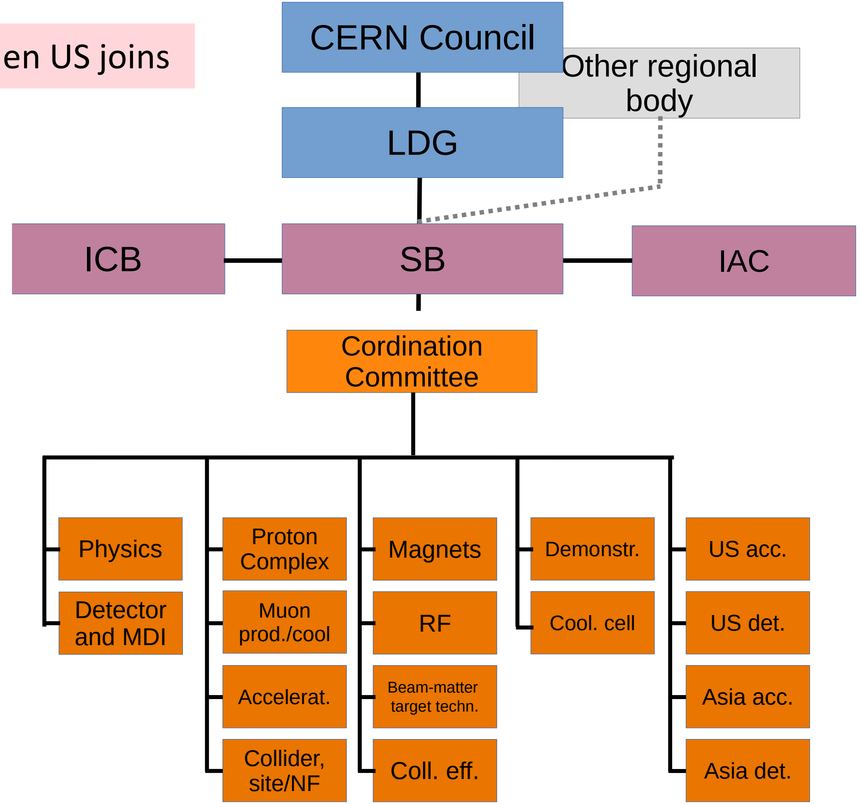
- Chair **Steinar Stapnes**
- CERN members: **Mike Lamont, Gianluigi Arduini**
- ICB members: **Dave Newbold** (STFC), **Mats Lindroos** (ESS), **Pierre Vedrine** (CEA), **N. Pastrone** (INFN)
- Study members: **SL and deputies**
- Will add US but wait for US decision on members

International Advisory Committee (IAC)

- To be proposed by SB

Coordination committee (CC)

- Study Leader: **Daniel Schulte**
- Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**



Coordination Committee Members

Physics	Andrea Wulzer
Detector and MDI	Donatella Lucchesi

Protons	Natalia Milas
Muon production and cooling	Chris Rogers
Muon acceleration	Antoine Chance
Collider	Christian Carli

Magnets	Luca Bottura
RF	Alexej Grudiev, Claude Marchand
Beam-matter int. target systems	Anton Lechner
Collective effects	Elias Metral

Cooling cell design	Lucio Rossi
Demonstrator	Roberto Losito

US (detector)	Sergo Jindariani
US (accelerator)	Mark Palmer
Asia (China)	Jingyu Tang
Asia (Japan)	tbd

A strengthening on the physics and detector side is planned

MoC and Design Study Partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
Mal	**Univ. of Malta**
BE	***Louvain***

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
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**

US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
China	***Sun Yat-sen University***
	IHEP
	Peking University
EST	***Tartu University***
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
CH	**PSI**
	University of Geneva
	EPFL

KO	**KEU**
	Yonsei University
India	***CHEP***

IT	**INFN Frascati**
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
US	FNAL
	LBL
	JLAB
	Chicago
	Tenessee

Steering Board

Will tune membership for diversity and strengthening physics and detector, continue to work with invited members from the US and Asia

SB wants to focus on:

- Project development strategies (1-5 year timeframe, e.g. demonstrators, synergies, …)
- Interfaces to various bodies and processes (roadmaps, funding opportunities and parallel projects (e.g. magnet development))
- International collaboration development – remain open and inclusive, while operative
- Links to the ECFA detector roadmap process – ongoing
- US planning related to the P5 process
- Will propose International Advisory Committee
  - First goal: review interim report early 2024
- Collaboration Organisation

Collaboration Development

Substantial increase of resources from new and existing partners and thanks to European Union Design Study approval

A range of collaboration meetings, including annual meetings 10/2022 and 6/2023, synergy meeting, …

Participation to other meetings, e.g. P5, FNAL ACE scientific workshop, muon4future, …

Actively supporting enlargement of the collaboration:

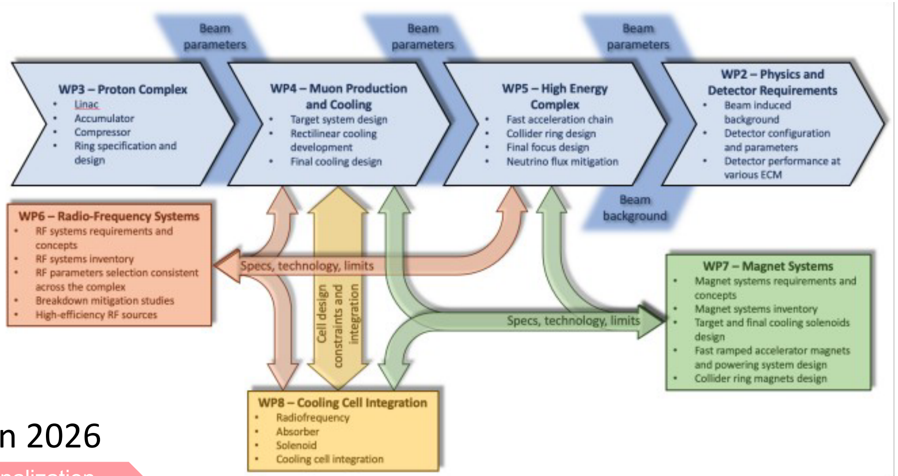
- Participation of US and Asian experts to CC and ICB
- Preparing **open data and code policy,** publication committee will allow **open publication policy**
- Small task force to understand with US how a common work programme can be developed
  - Plan to review organization next year to integrate US
  - Will find common timelines/scenarios
- Exploring synergies with other fields -> Chris
- Prepare new funding proposals
  - E.g. EU TECH proposal -> Luca

Web site to collect information on resources of partners

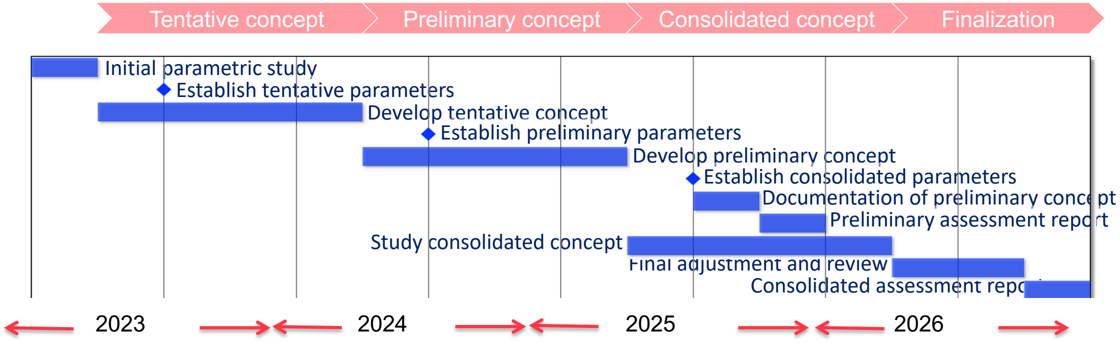
EU Design Study

Approved summer 2022/early 2023, best marks
3 MEUR from the European Union, UK and Switzerland,
and about 4 MEUR from the 32 partners

WPs:
Proton Complex, Muon Production and Cooling, High-energy Complex, Detector Requirements
RF, Magnets, Muon Cooling Cell Design



Preliminary report early 2026, in case EU strategy takes place in 2026



With some other contributions more than doubles our resources

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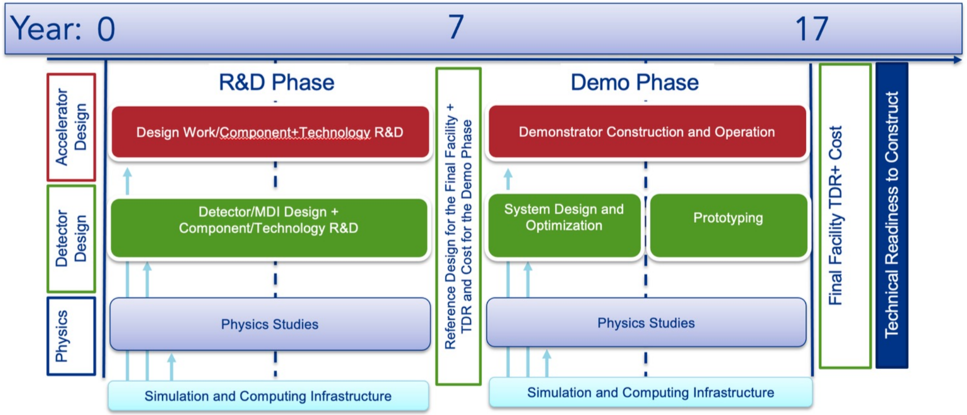
https://mucol.web.cern.ch

US P5 Ask



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Accelerator Design

Detector Design

Physics

R&D Phase

Design Work/Component+Technology R&D

Detector/MDI Design + Component/Technology R&D

Physics Studies

Simulation and Computing Infrastructure

Reference Design for the Final Facility + TDR and Cost for the Demo Phase

Demo Phase

Demonstrator Construction and Operation

System Design and Optimization

Prototyping

Physics Studies

Simulation and Computing Infrastructure

Final Facility TDR+ Cost

Technical Readiness to Construct

Figure 1: A sketch of the proposed muon collider R&D timeline, along with high-level activities, milestones, and deliverables.

S. Jindariani, D. Stratakis, Sridhara Dasu et al.

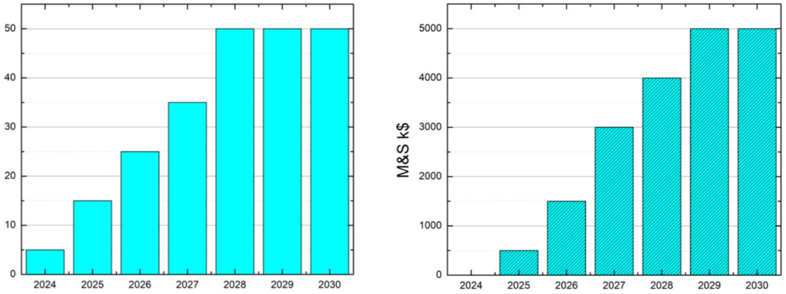
Goal is to contribute as much as Europe

Start of construction a bit later than in Roadmap

Will try to harmonise/define scenarios once US joins

Total resources would approach Roadmap

- Some increase in Europe and Asia assumed
- 1-2 years delay
- But profile is different



: FTE and M&S profiles for accelerator R&D corresponding to the first phase of the . We assume here that funding can start in 2024. The M&S is in FY23 dollars and n is not included in these estimates.

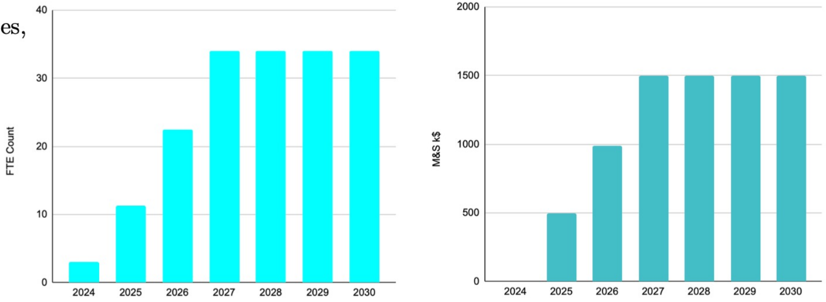
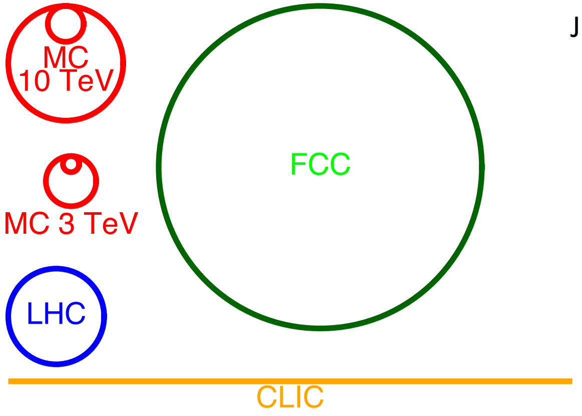
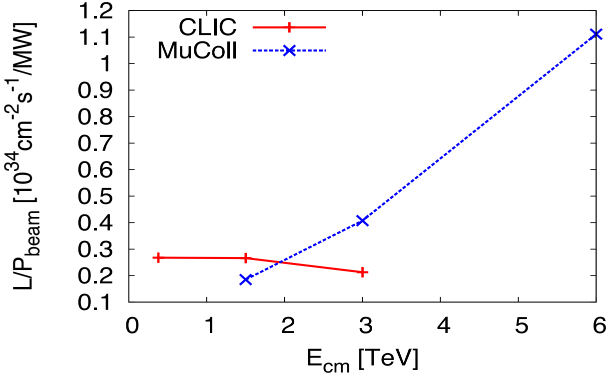


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

Note: Muon Collider Promises





US Snowmass Implementation Task Force: Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.

	CME [TeV]	Lumi per IP [10^{34}cm^{-2}s^{-1}]	Years to physics	Cost range [B$]	Power [MW]
FCC-ee	0.24	8.5	13-18	12-18	290
ILC	0.25	2.7	<12	7-12	140
CLIC	0.38	2.3	13-18	7-12	110
ILC	3	6.1	19-24	18-30	400
CLIC	3	5.9	19-24	18-30	550
MC	3	1.8	19-24	7-12	230
MC	10	20	>25	12-18	300
FCC-hh	100	30	>25	30-50	560

Judgement by ITF, take it *cum grano salis*

Neutrino Flux

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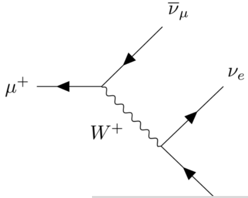
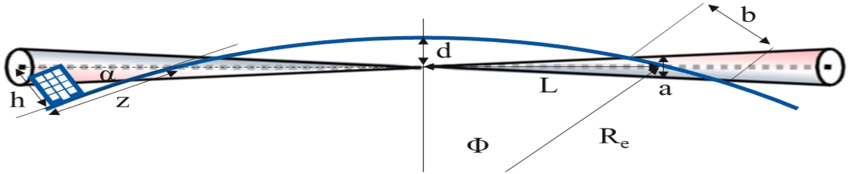
Strategy to limit neutrino flux to have **negligible impact (similar to LHC)**, i.e. **“fully optimised”** (10% of MAP goal)

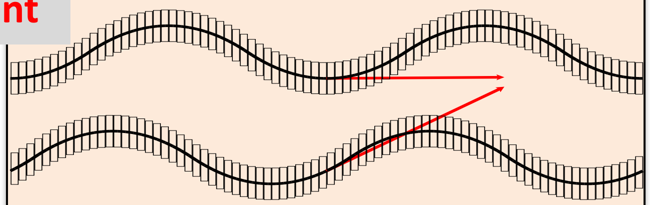
Mechanical system can achieve this





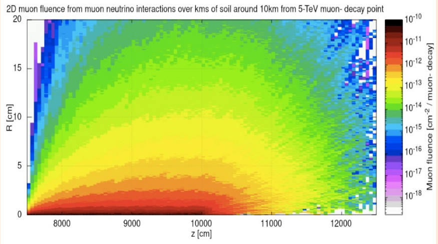
Are buying movers to test system with existing equipment

Mover and support system



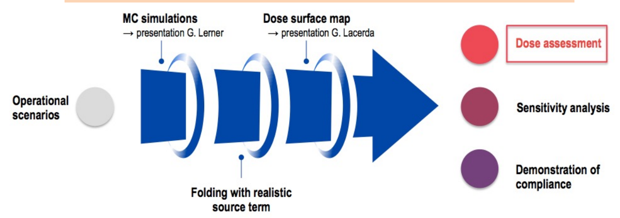
F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies



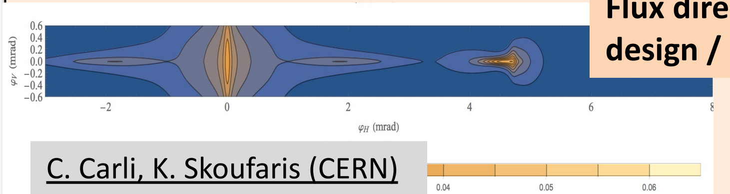
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke

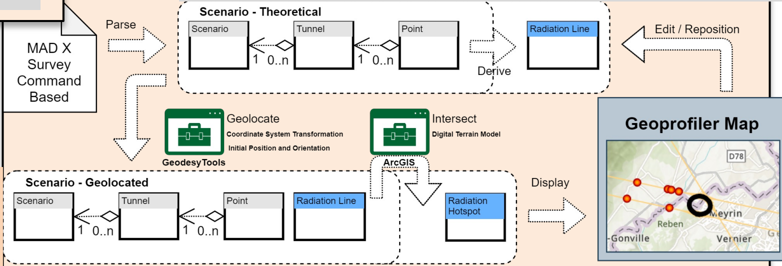
Flux direction map / lattice design / mover impact on beam



C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

G. Lacerda, Y. Robert, N. Guilhaudin (CERN)



Detector Studies (in a Nutshell)

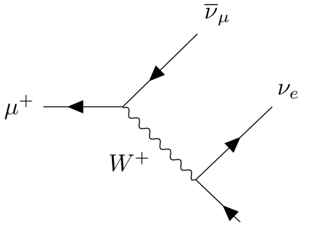
3 TeV:

- Have **tentative detector design**, started from CLIC
- **Detector simulation** including BiB (beam-induced Background) is available, based on CLIC software
- BiB has no impact on some physics channels but significant impacts on others
- Described by DELPHES card at https://muoncollider.web.cern.ch/node/14

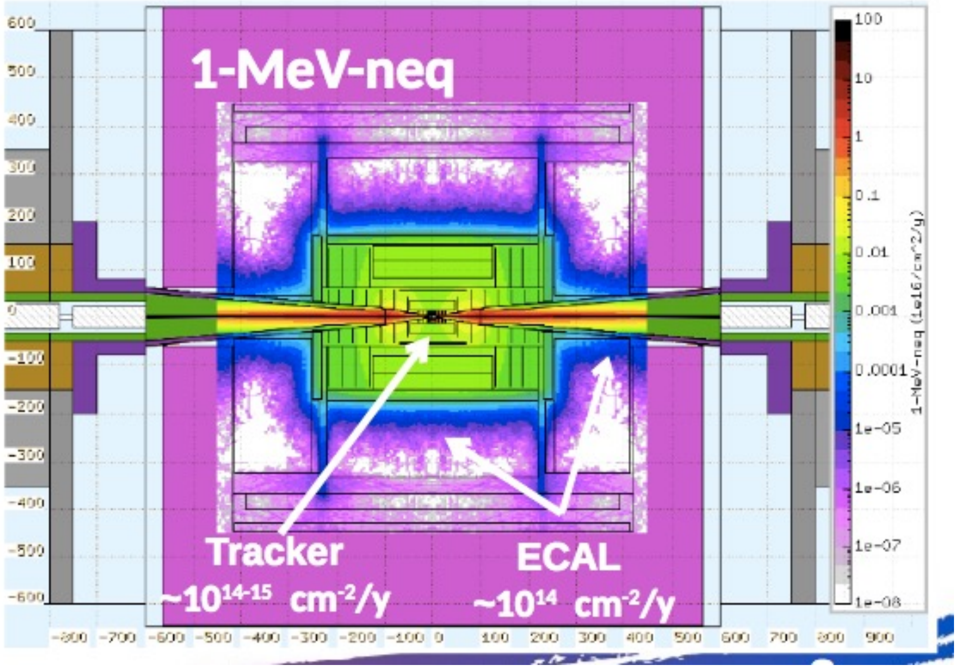
10 TeV:

- **Detector design** started (first model by end 2023)
- Some studies with **10 TeV background** in 3 TeV detector
- Background does not strongly depend on energy

Integration into **Key4HEP planned** (by end 2023)



D. Lucchesi et al.

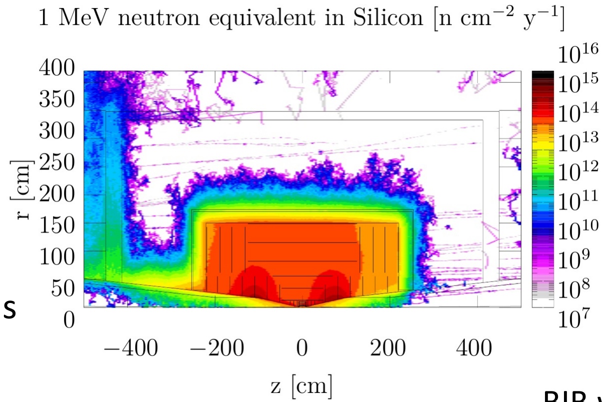


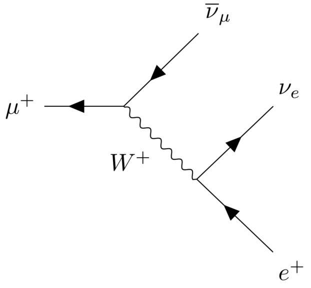
Machine-detector Interface

Beam-induced background from muon decays

Simulations of beamline and detector with FLUKA

Focus on √s = 3 TeV and √s = 10 TeV



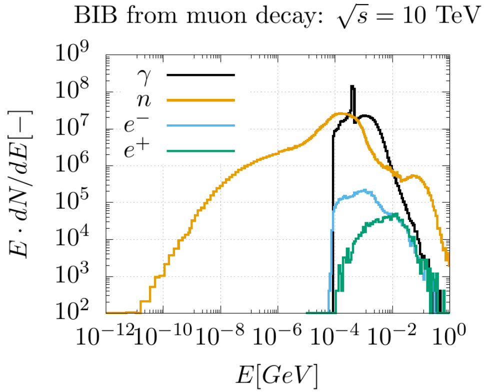


Presently studying **latest 10 TeV** optics (K. Skoufaris et al.) and **nozzle optimization**

Initial conclusions:

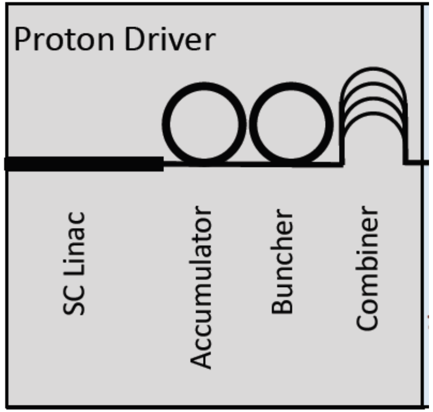
- BIB multiplicity comparable for all collider energies
- HL-LHC radiation levels
- Nozzle is the determinant component for the BIB. Started from 1.5 TeV MAP design (N. Mokhov)
- Adding dipole components in beamline reduces BIB slightly O(/2)

BIB with different lattice and nozzle configurations



D. Calzolari, A. Lechner et al.

Proton Complex and Target



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

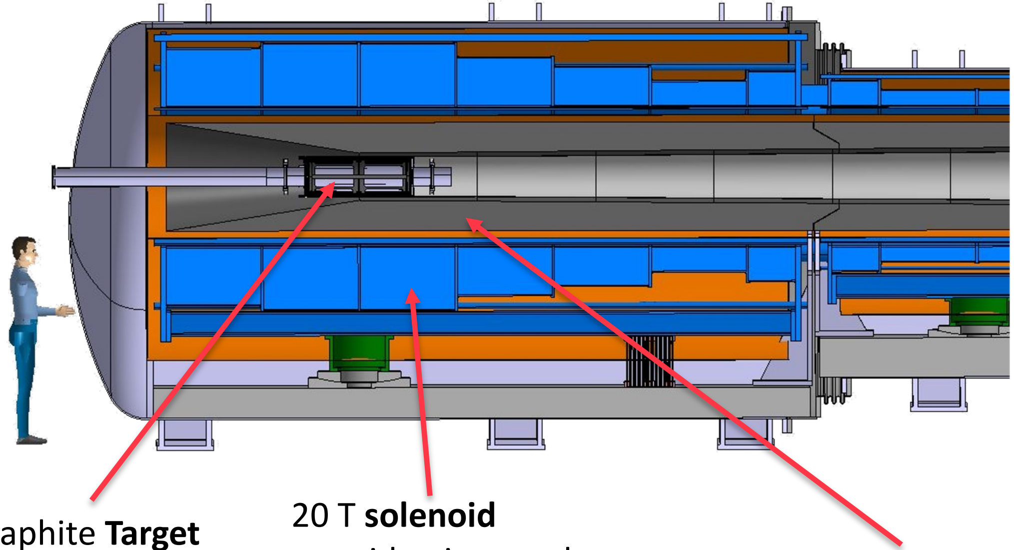
ESS and Uppsala will focus on merging beam into high-charge pulses

Optimisation of parameters planned

N. Milas, A. Lombardi et al.

protons $\xrightarrow{\text{in target}}$ pions $\xrightarrow{\text{decay}}$ muons

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



Graphite **Target**

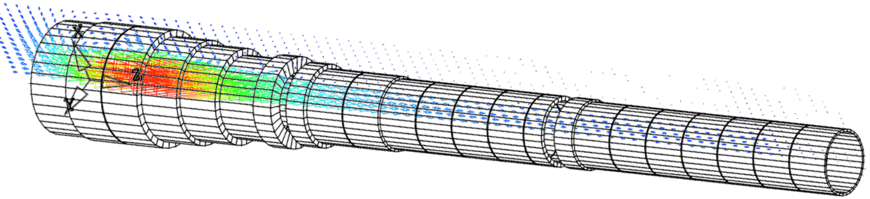
20 T **solenoid**
to guide pions and muons

Tunsten shielding
To protect magnet

Target Studies

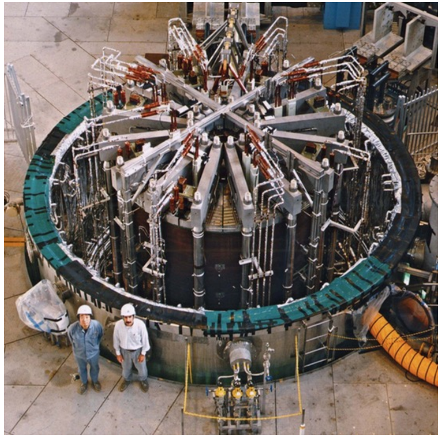
Target solenoid ongoing

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



ITER model coil: 13 T
Nb_3Sn 1.7 m diameter

Our work is relevant for fusion

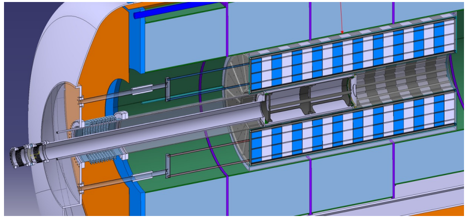
FLUKA studies:

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

Need to have closer look at window

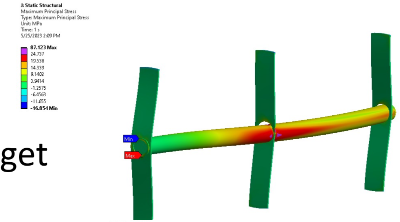
Cooling OK

Integration

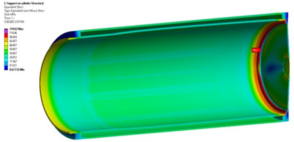


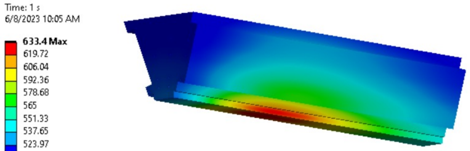
Cooling, vacuum, mechanics, …

Target



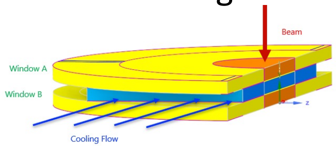
Vessel





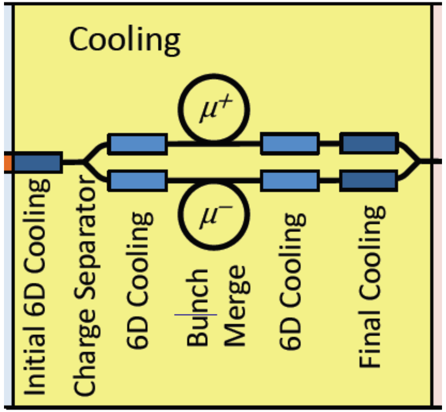
Tunsten shielding

Window

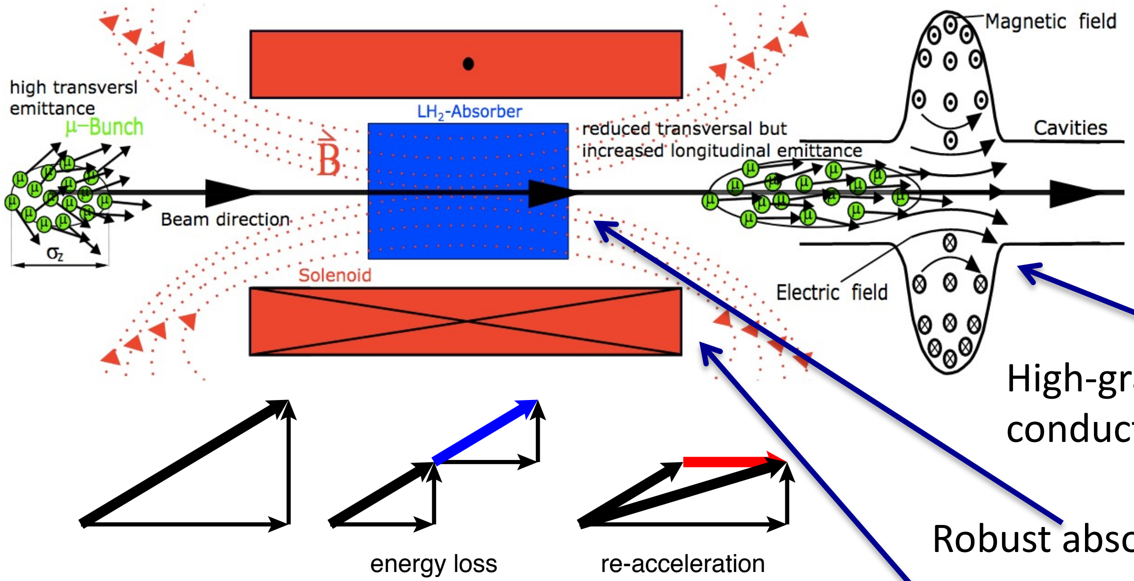


A. Lechner, R. Franqueira Ximenes et al.

Muon Cooling Principle (for Reference)



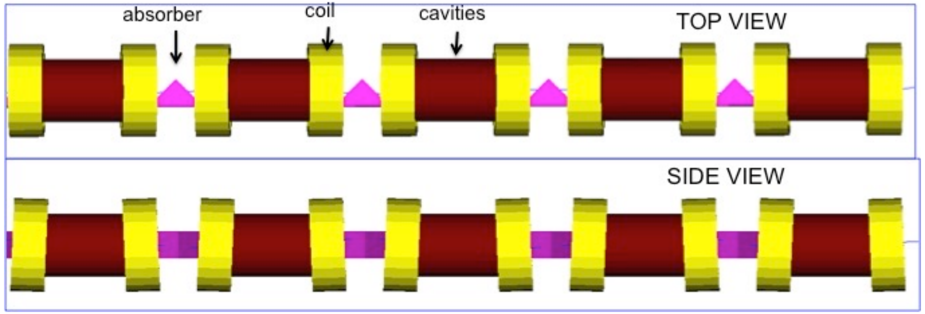
C. Rogers, B. Stechauner, E. Fol et al. (RAL, CERN)



High-gradient normal-conducting cavities

Robust absorbers

High-field, superconducting solenoid



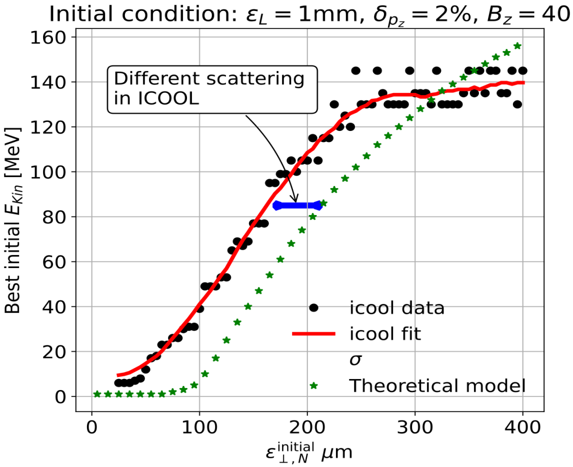
Muon Cooling Performance

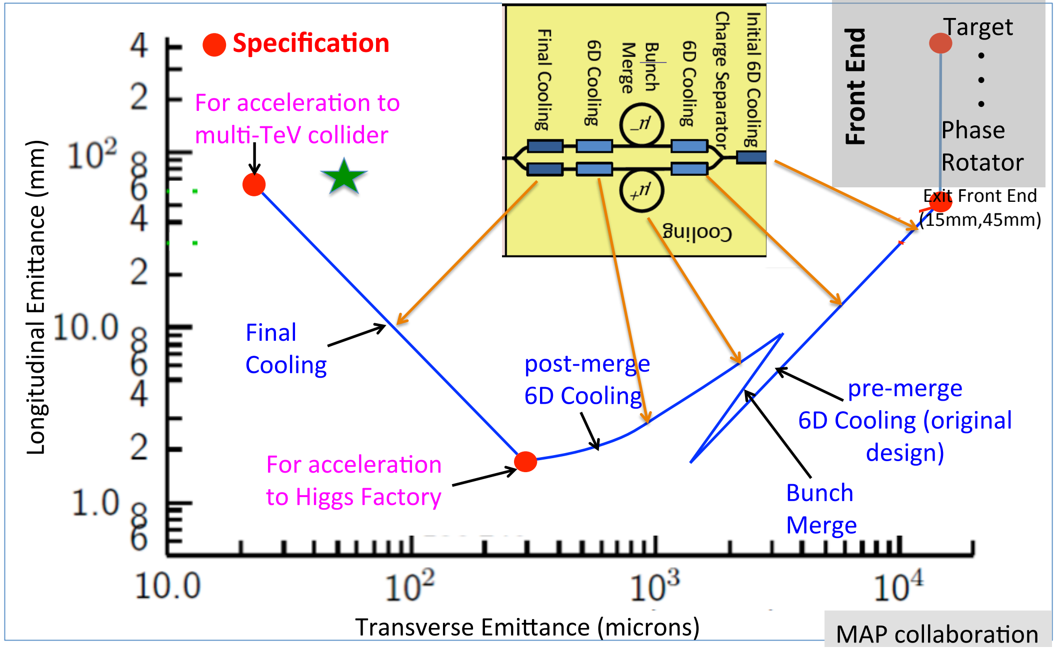
MAP design achieved 55 um based on achieved fields

Can expect better hardware

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

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

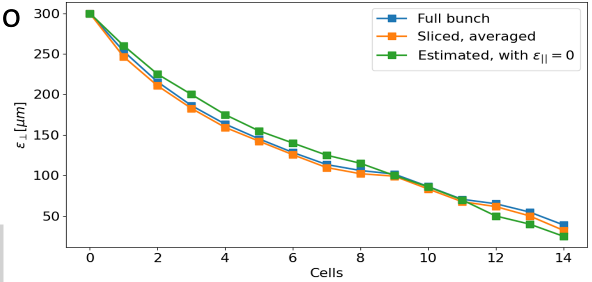




Working on **improved, systematic design**, also using better magnets and RF

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

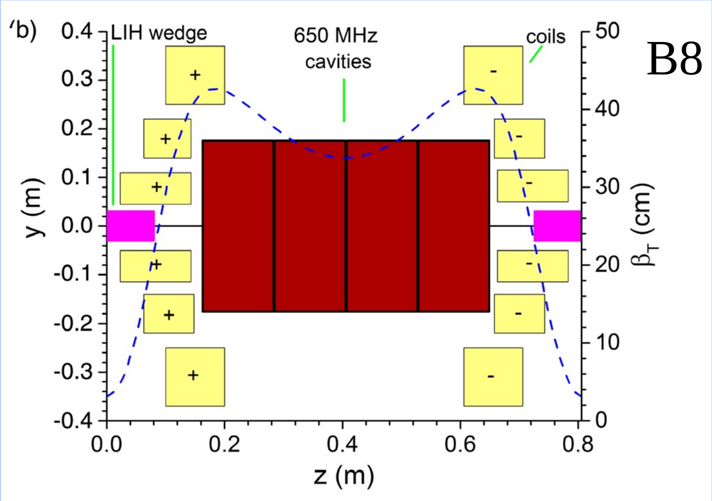
Ch. Rogers, Zhu Ruihu, B. Stechauner, E. Vol et al.



Cooling Cell Technology

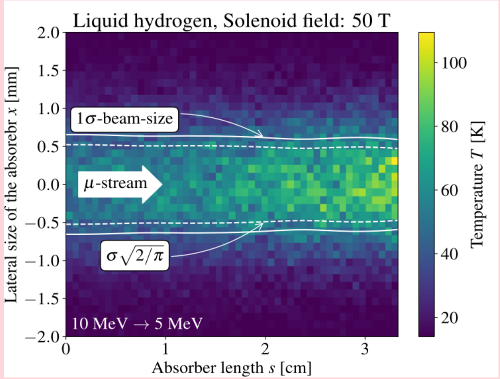
Develop example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

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



Most complex example 12 T

Windows and absorbers for high-density muon beam
- Pressure rise mitigated by gas density
- Plan window test in HiRadMat

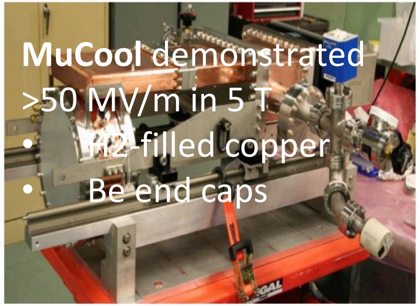


RF cavities in magnetic field

MAP demonstrated higher than goal gradient

Improve design based on theoretical understanding

Preparation of **new test stand**, but needs funding
- Test stand at CEA (700 MHz, need funding)
- Test at other frequencies in the UK considered
- Use of CLIC breakdown experiment considered



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

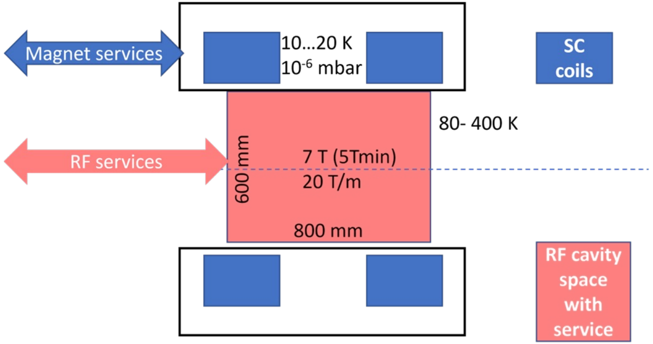
C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

RF Test Stand

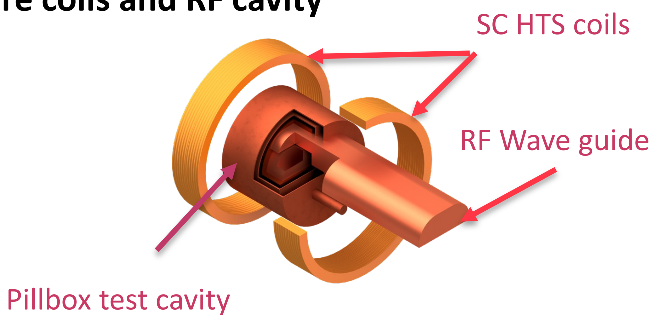
Module work currently focuses on RF test stand

- Important ensure timely R&D plan
  - Simple module example
  - To test cavities for prototype cooling modules
- Try to identify **infrastructure** for this
  - CEA, INFN, Cockroft, CERN, …
  - Will not be cheap so need to find resources

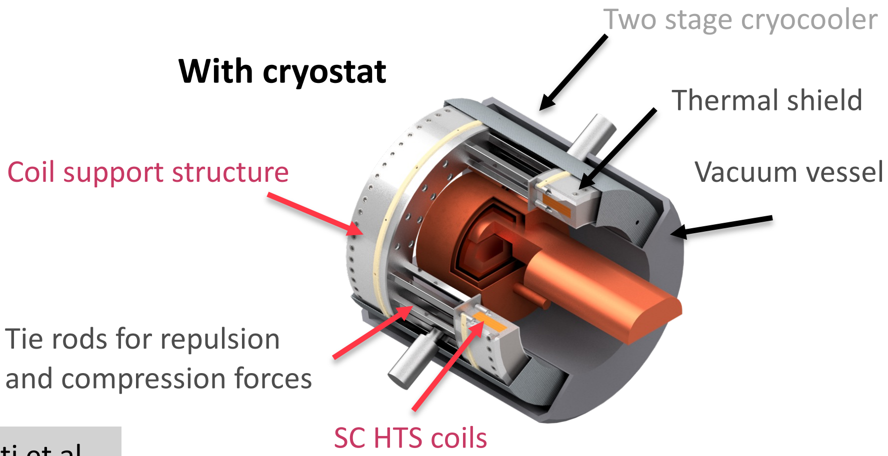
Schematic of the RFMF test facility single cryostat



Bare coils and RF cavity



With cryostat

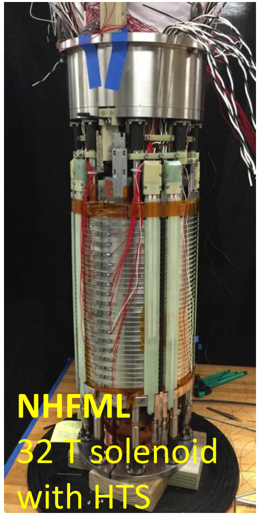


L. Rossi, C. Marchand, D. Giove, A. Gurdiev, G. Ferrand, M. Castoldi, S. Sorti et al.

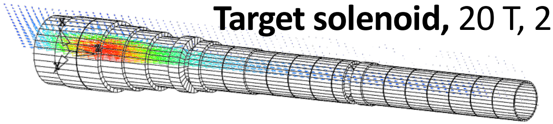
Solenoid R&D (-> Luca)

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

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



32 T LTS/HTS solenoid demonstrated



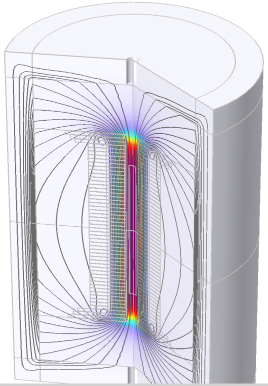
Target solenoid, 20 T, 20 K

Final Cooling solenoid

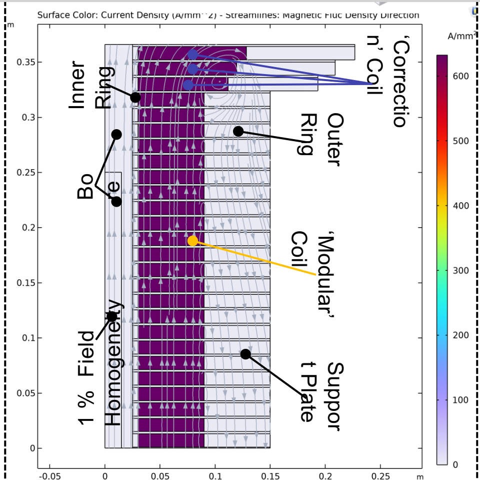
$$\mathbf{B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}}$$

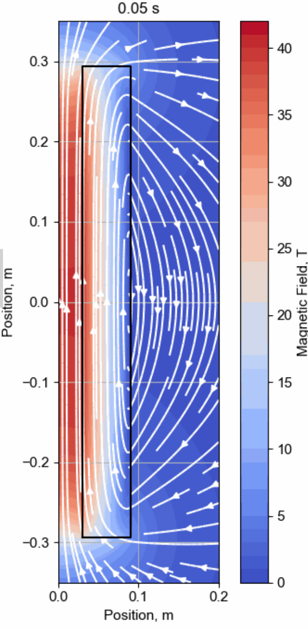
σ_{max} = 600 MPa

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

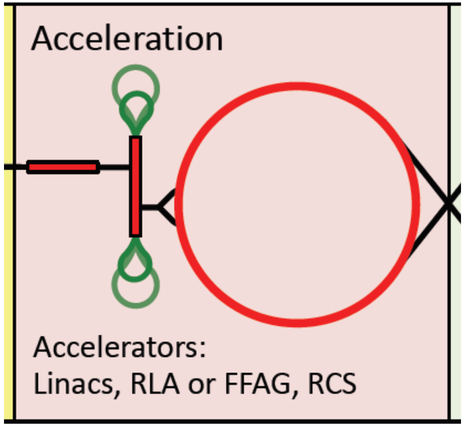


A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



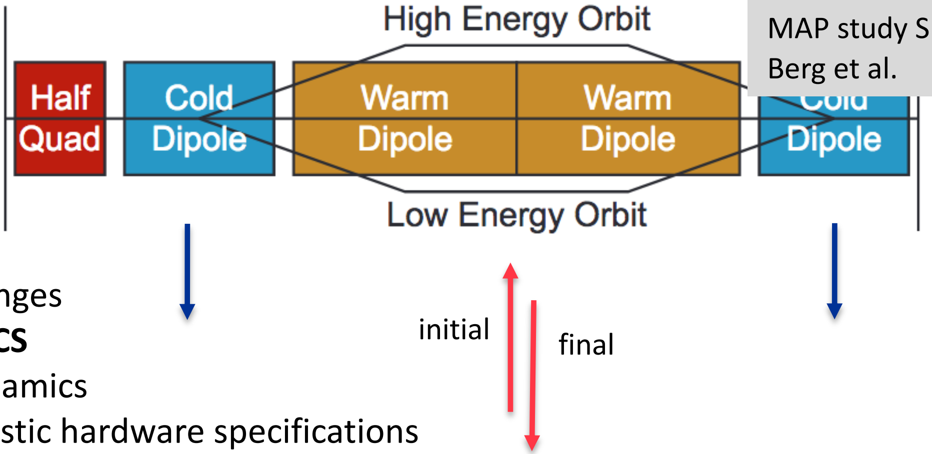


Acceleration Complex



Core is sequence of hybrid pulsed synchrotron (0.4-11

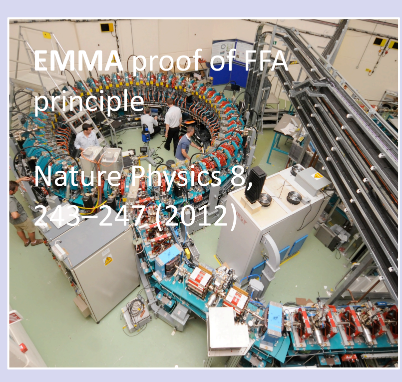
- Alternative FFA



MAP study S. Berg et al.

Started work on key challenges

- **Integrated design of RCS**
    - Longitudinal dynamics
    - Lattice with realistic hardware specifications
    - Collective effects
- **Concept of key components**
    - Fast-ramping normal magnets
    - HTS alternative
    - Efficient power converters
    - RF with transient beam loading



EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)

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)

Collective Effects and RF Design

Longitudinal dynamics and RF important due to high bunch charge

- > 30 RF stations needed
- Orbit length changes require frequency tuning required
- Single-bunch HOM power loss up to 10 kW during pulse
- CW average is lower, development of high-capacity couplers needed

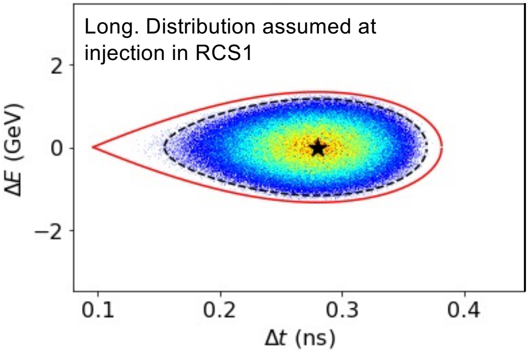
A. Chance, H. Damerell, F. Batsch, U. van Rienen, A. Grudiev et al. (CEA, Rostock, Milano, CERN)
E. Metral, D. Amorim et al. (CERN)

Collider ring single beam instability limits

Conservative feedback

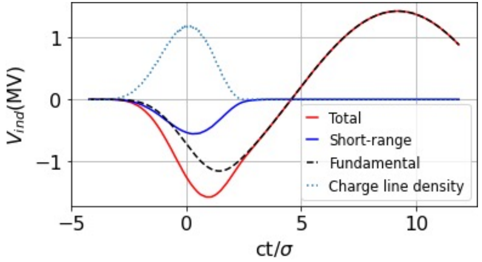
Copper coating beneficial (few microns)

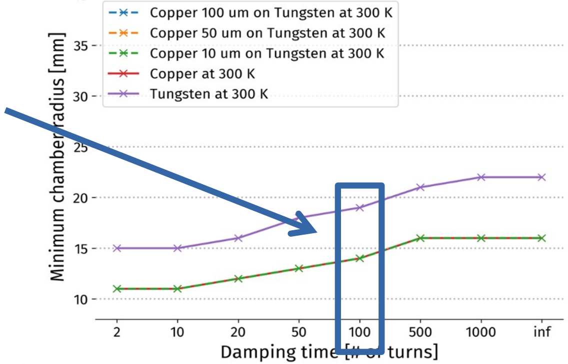
Beam-beam studies started



1.3 GHz appears possible for longitudinal effects and stability

Induced voltages in RCS1 for a single bunch

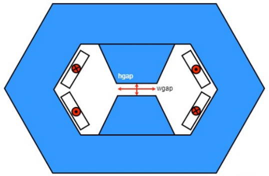



Chamber radius to keep emittance growth below 20 % after 3000 turns

Fast-ramping Magnet System (-> Luca)

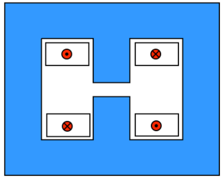
F. Boattini et al.

Hourglass frame magnet



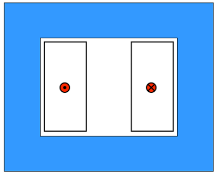
5.07 kJ/m

H magnet



5.65…7.14 kJ/m

Window frame magnet



5.89 kJ/m

Management of the **power in the resistive dipoles** (several tens of GW):
- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

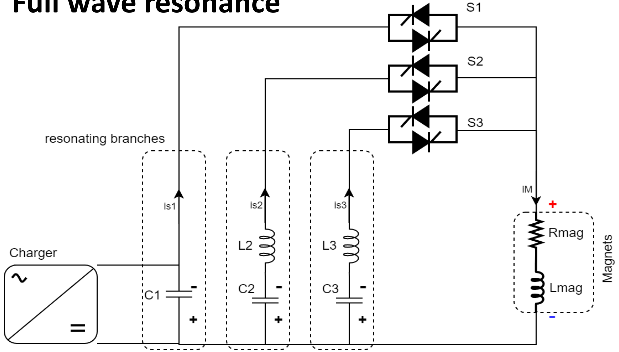
FNAL 300 T/s HTS magnet

Could also use HTS driven dipoles

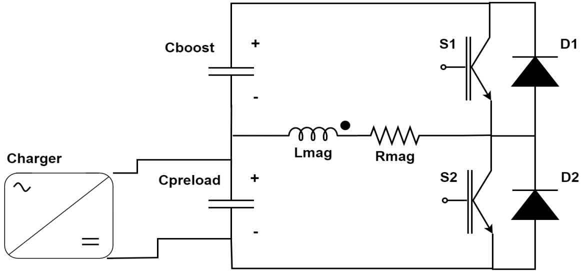
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Full wave resonance



Commutated resonance (new)



Collider Ring

Challenges:

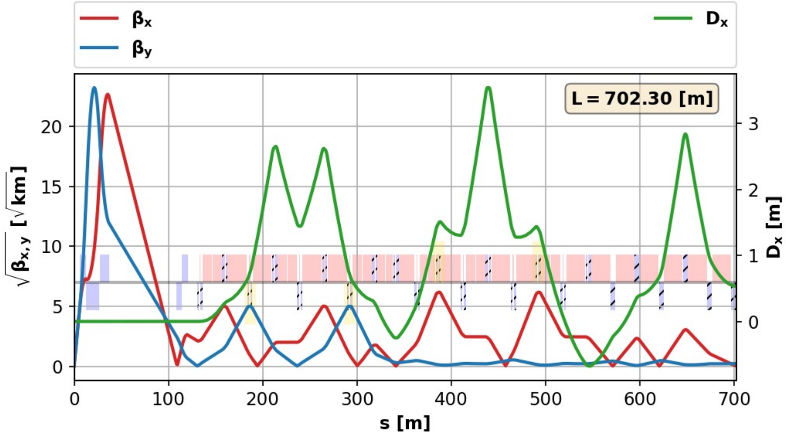
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn

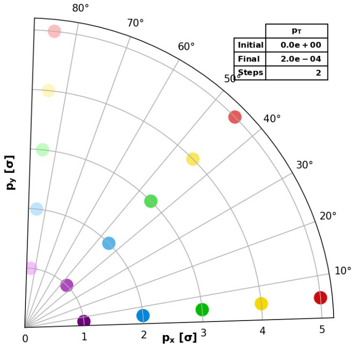
- magnet specifications in the HL-LHC range

Important progress on **10 TeV collider ring**

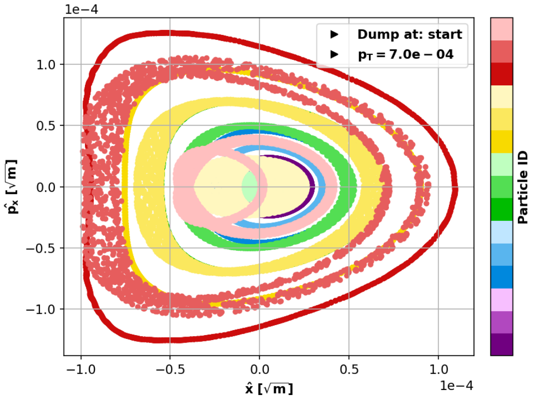
- around 16 T HTS dipoles (lower Nb_3Sn to come)
- final focus based on HTS



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



pT [%]	DAmin [σ]
0.07	5
0.08	4
0.09	3
0.1	<1



V0.6 good dynamic aperture at almost 0.1% off-energy, approaching the target

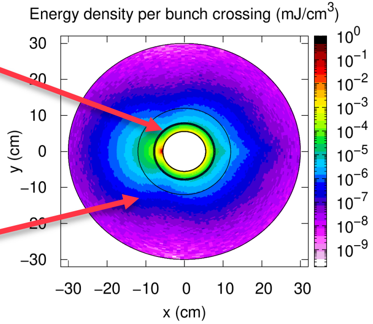
Collider Ring Technology

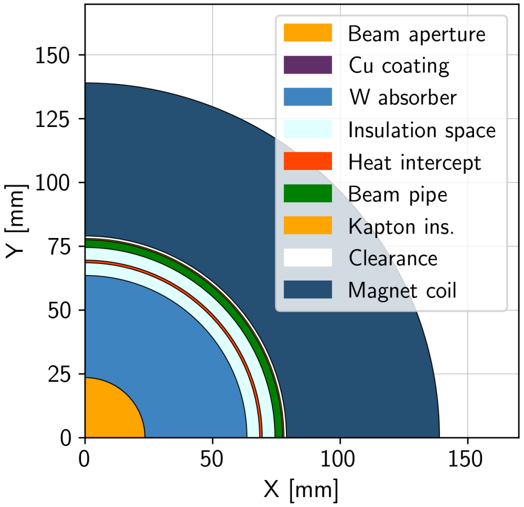
Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten
- Few W/m in magnets
- No problem with radiation dose

Shielding

A. Lechner
D. Calzolari
(CERN)

Coil

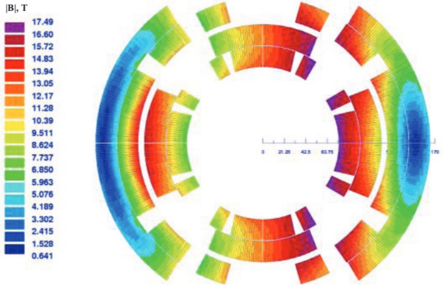


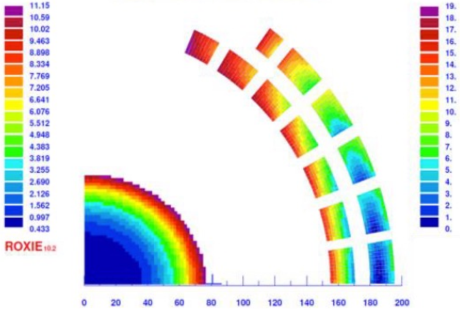


K. Skoufaris, Ch. Carli, D. Amorim, A. Lechner, R. Van Weelderen, P. De Sousa, L. Bottura et al.

L. Bottura et al.

Initial **estimate of magnet field limits**:
9 T for NbTi, 14 T for Nb_3Sn
Need **stress management**





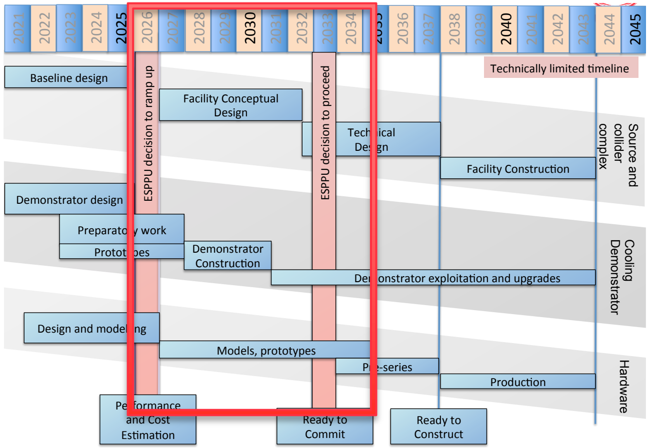
Different **cooling scenarios** studied
< 25 MW power for cooling possible
Shield with CO_2 at 250 K (preferred) or water
Support of shield is important for heat transfer
Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa

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



Cooling demonstrator is a key facility

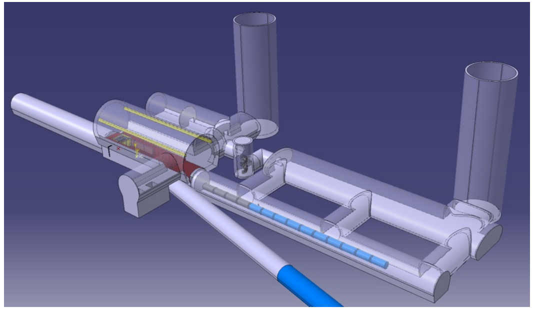
- look for an existing proton beam with significant power

Different sites are being considered

- CERN, FNAL, ESS …
- **Discussed at ACE at FNAL**
- J-PARC also interesting as option

Could be used to house physics facility

- **Synergies workshop** to explore good options



Several potential **RF test stations** have been discussed at workshop

- This is important for the timely demonstrator
- Proposals have different advantages and compromises
- Need to develop a common plan

Interim Report

Purpose

- Help to increase support from Council and other funding agencies, the laboratories and the community
- Manage expectation for next reports
- Prepare key elements of the R&D programme

Scope

- Cover physics, detector, accelerator and technologies
- Describe progress in funding and work
- Describe what we are doing by 2025
- Identify further resource needs and motivate further increase of support
- Earmark key elements of the study
  - e.g. RF test stand to support the need of an infrastructure
  - e.g. highlight that options exist to site the demonstrator

Due **end of 2023 or early 2024**

Conclusion

- Very motivated teams achieved important progress on design, technologies, detector and physics potential
- Managed to more than double resources
  - New/increased contributions from different partners
  - European Union Design Study
- Organisation is in place

- Aim to improve further
  - Resources are still not at the level of the full scenario
  - Hope to further increase effort
    - In particular when the US joins
    - More partners, increased contributions
    - EU TECH study
    - …

Many thanks to all that contributed

http://muoncollider.web.cern.ch

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

- Short term: Interim Report to describe progress and expectations

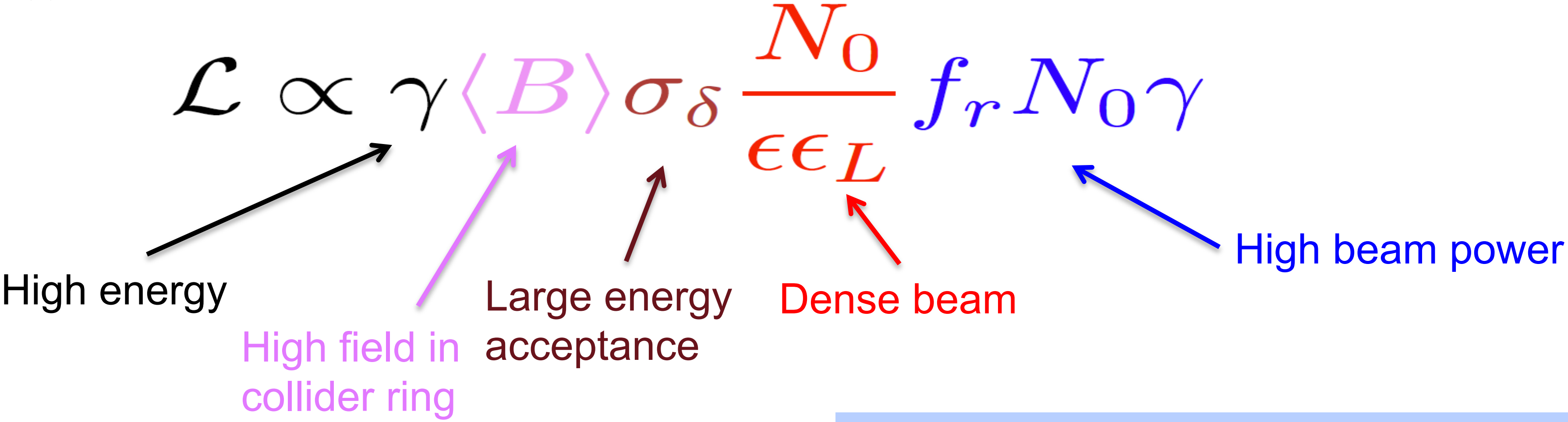
Reserve

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

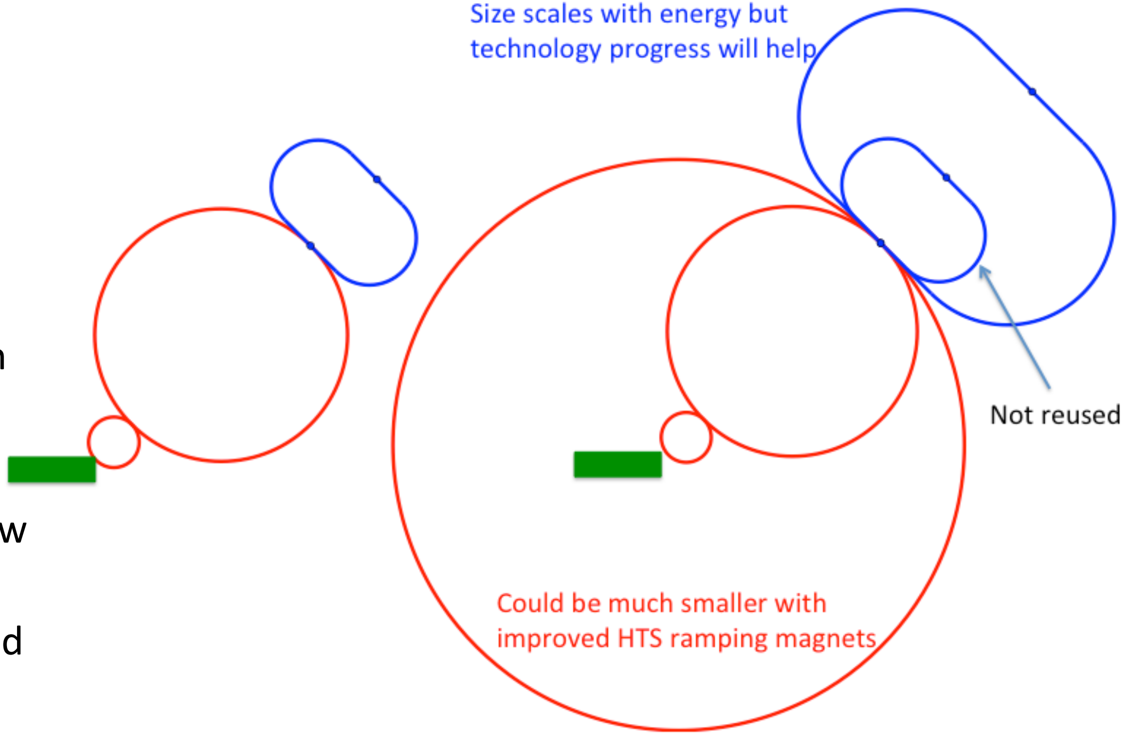
Staging

Ideally would like full energy right away, but staging could lead to faster implementation

- Substantially less cost for a first stage
- Can make technical compromises
  - e.g. 8 T NbTi magnets would increase collider ring from 4.5 to 6 km and reduce luminosity by 25%
- Timeline might be more consistent with human lifespan

Upgrade adds one more accelerator and new collider ring

- only first collider ring is not being reused

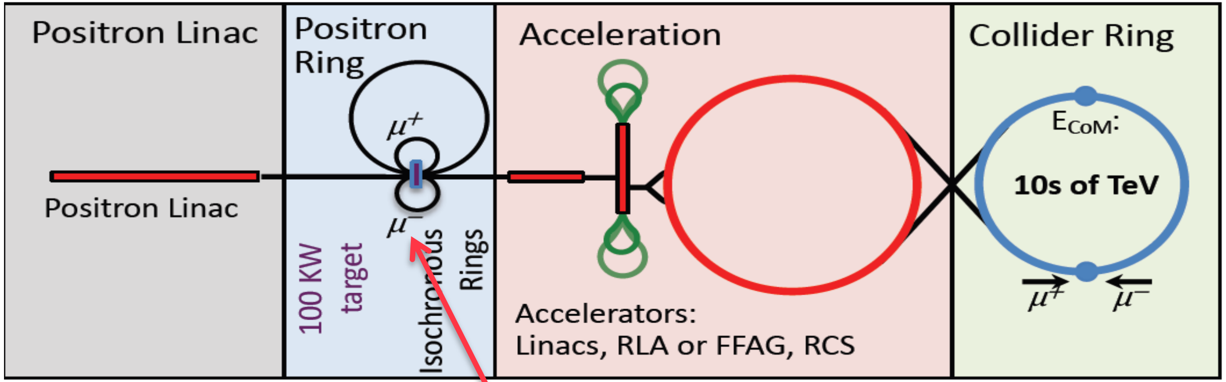

Size scales with energy but technology progress will help

Not reused

Could be much smaller with improved HTS ramping magnets

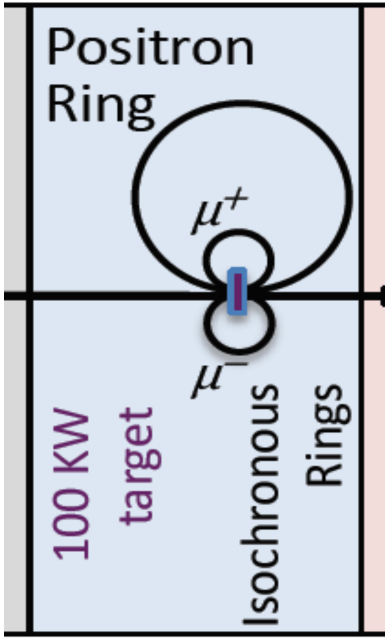
Alternatives: The LEMMA Scheme

LEMMA scheme (INFN) P. Raimondi et al.



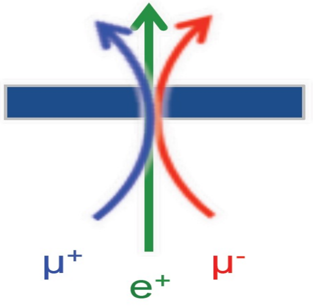
Note: New proposal by C. Curatolo and L. Serafini needs to be looked at

- Uses Bethe-Heitler production with electrons



45 GeV positrons to produce muon pairs
Accumulate muons from several passages

$$e^+e^- \to \mu^+\mu^-$$

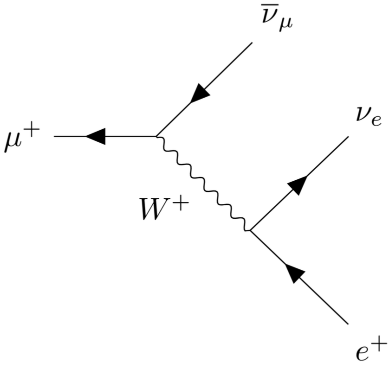


Excellent idea, but nature is cruel

Detailed estimates of fundamental limits show that we require a very large positron bunch charge to reach the same luminosity as the proton-based scheme

$\Rightarrow$ **Need same game changing invention**

Muon Decay



About 1/3 of energy in electrons and positrons:

Experiments needs to be protected from **background** by masks

- simulations of 1.5, 3 and 10 TeV
- optimisation of masks and lattice design started
- first results look encouraging
- will be discussed at ICHEP

Collider ring magnets need to be shielded from losses

Losses elsewhere will also need to be considered but are less severe

D. Lucchesi, A. Lechner, C Carli et al.

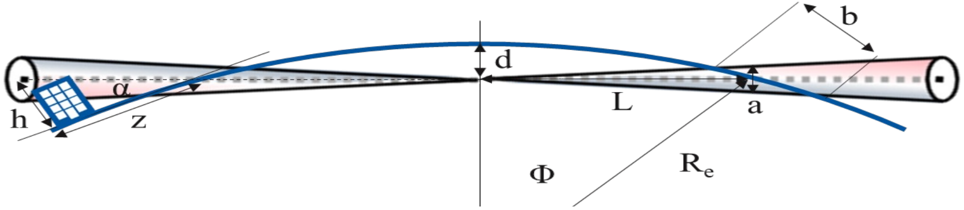
Neutrino flux to have negligible impact on environment

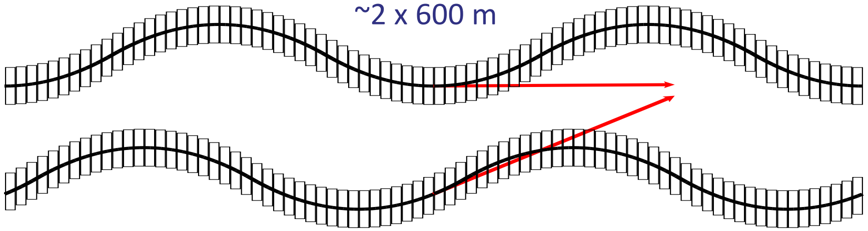
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

Above about 3 TeV need to make beam point in different vertical directions

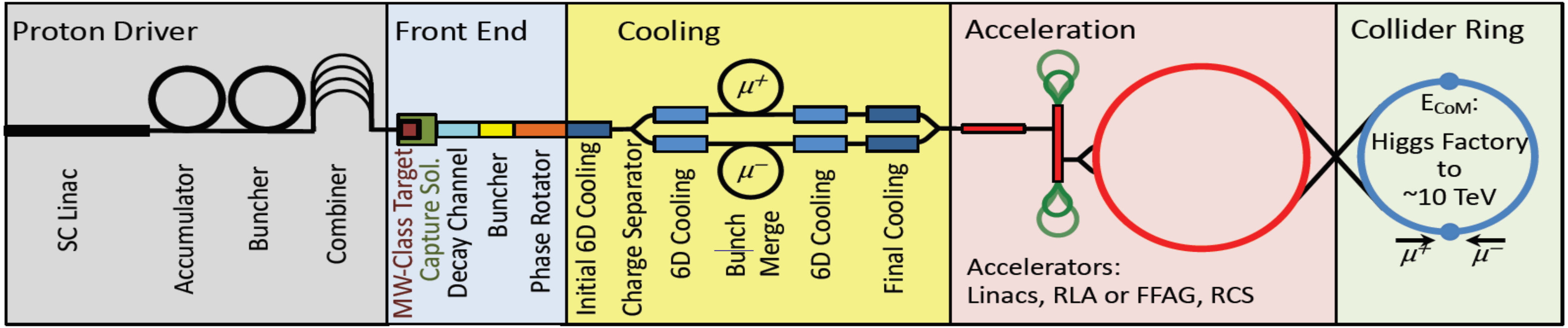
Mechanical system with 15cm stroke, 1% vertical bending

Length of pattern to be optimised for minimal impact on beam





Key Challenges



Proton complex
- Compressing protons to few bunches

Target
- Target
- Solenoid

Cooling channel
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

RCS
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

Collider ring
- Optics
- Magnets
- Neutrino flux
- Detector background

Roadmap

In **aspirational scenario** can make **informed decisions**:

Three main deliverables are foreseen:

- a **Project Evaluation Report** for the next ESPPU will contain an assessment of whether the 10 TeV muon collider is a promising option and identify the required compromises to realise a 3 TeV option by 2045. In particular the questions below would be addressed.
  - What is a realistic luminosity target?
  - What are the background conditions in the detector?
  - Can one consider implementing such a collider at CERN or other sites, and can it have one or two detectors?
  - What are the key performance specifications of the components and what is the maturity of the technologies?
  - What are the cost drivers and what is the cost scale of such a collider?
  - What are the power drivers and what is the power consumption scale of the collider?
  - What are the key risks of the project?
- an **R&D Plan** that describes an R&D path towards the collider;
- an **Interim Report** by the end of 2023 that documents progress and allows the wider community to update their view of the concept and to give feedback to the collaboration.

R&D Plan

The R&D plan will describe the R&D path toward the collider, in particular during the CDR phase, and will comprise the elements below.

- An integrated concept of a muon cooling cell that will allow construction and testing of this key novel component.
- A concept of the facility to provide the muon beam to test the cells.
- An evaluation of whether this facility can be installed at CERN or another site.
- A description of other R&D efforts required during the CDR phase including other demonstrators.

This R&D plan will allow the community to understand the technically limited timeline for the muoncollider development after the next ESPPU.

Minimal Scenario

Will allow **partially informed decisions**

- No conceptual design of neutrino flux and alignment system
- No alternative superconducting fast-ramping magnet system
- Several collider systems would (almost) not be covered, in particular
  - the linacs
  - the target complex
  - the proton complex
  - engineering considerations of the muon cooling cells
  - alternative designs for the final cooling system, acceleration, collider ring
- No RF test stand would be constructed for the muon cooling accelerating cavities
- No conceptual design of a muon cooling cell for the test programme
- No conceptual design of a muon cooling demonstrator facility
- No concept of RF power sources
- No tests/models to develop solenoid technology.

Key Technologies

Magnets

- Superconducting solenoids for target and cooling profit from developments for society
  - target solenoid comparable to ITER central solenoid fusion
  - 6D cooling solenoids similar and wind power generators, motors
  - final cooling solenoids synergetic with high-field research, NMR
- Collider ring magnets
  - profit from developments for other colliders FCC-hh, stress-managed magnets
- Fast-ramping normal-conducting magnet system
  - HTS alternative, power converter

RF systems

- superconducting RF, normal-conducting RF, efficient klystrons

Target, cooling absorbers, windows, shielding

Neutrino mitigation mover system, cooling cell integration, …

Detector

Key Technologies, cont.

RF systems

- Normal-conducting cooling cavities in magnetic field
  - profit from CLIC work
- Superconducting accelerator RF
  - profit from ILC, …
- Efficient power sources
  - profit from CLIC work

Beam-matter interaction

- Proton target
- Cooling absorbers
- Shielding (accelerator and detector)

Mechanical system

- Neutrino flux mitigation system
- Muon cooling cell integration

Collaboration Vision

IMCC is an **international** collaboration and aims to

- Enlarge the collaboration
  - Physics interest in all regions, strong US contribution to the muon collider physics and detector, interest in Japan
  - First US university have joined collaboration, try to see how to move forward, also with labs
- Combine the R&D efforts for the design and its technologies
  - Critical contributions in all relevant fields in the US
- Consider several sites for the collider
  - CERN would be one, FNAL and others should also be considered
  - A proposal with alternative sites is stronger for a single site
- Consider several sites for the demonstrators
  - E.g. Muon production and cooling demonstrator at CERN, FNAL, ESS, JPARC
  - e.g. RCS at ESRF or elsewhere
  - Target tests
  - …

Initial Target Parameters

Target integrated luminosities

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

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

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

Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**40**	**2 (6)**
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	**MW**	**5.3**	**14.4**	**20**	**28**
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	μm	25	25	25	
$\sigma_{x,y}$	μm	3.0	0.9	0.63	

US Snowmass

Strong interest in the US community in muon collider
- seen as an energy frontier machine
- decoupled from LC

US community wants funding for **R&D**
- **Goal: match European effort**

Community interested in the US to **host a muon collider**

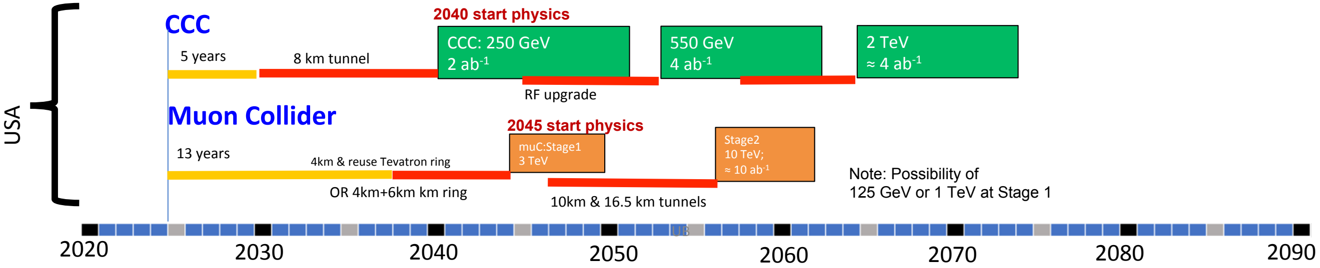
Possible scenarios of future colliders

🟦 Proton collider
🟩 Electron collider
🟧 Muon collider

🟥 Construction/Transformation
🟨 Preparation / R&D

Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

Consider proposing hosting ILC in the US.

Meenakshi Narain: Energy Frontier / Large Experiments, Snowmass Community Summer Study July 17-26, 2022

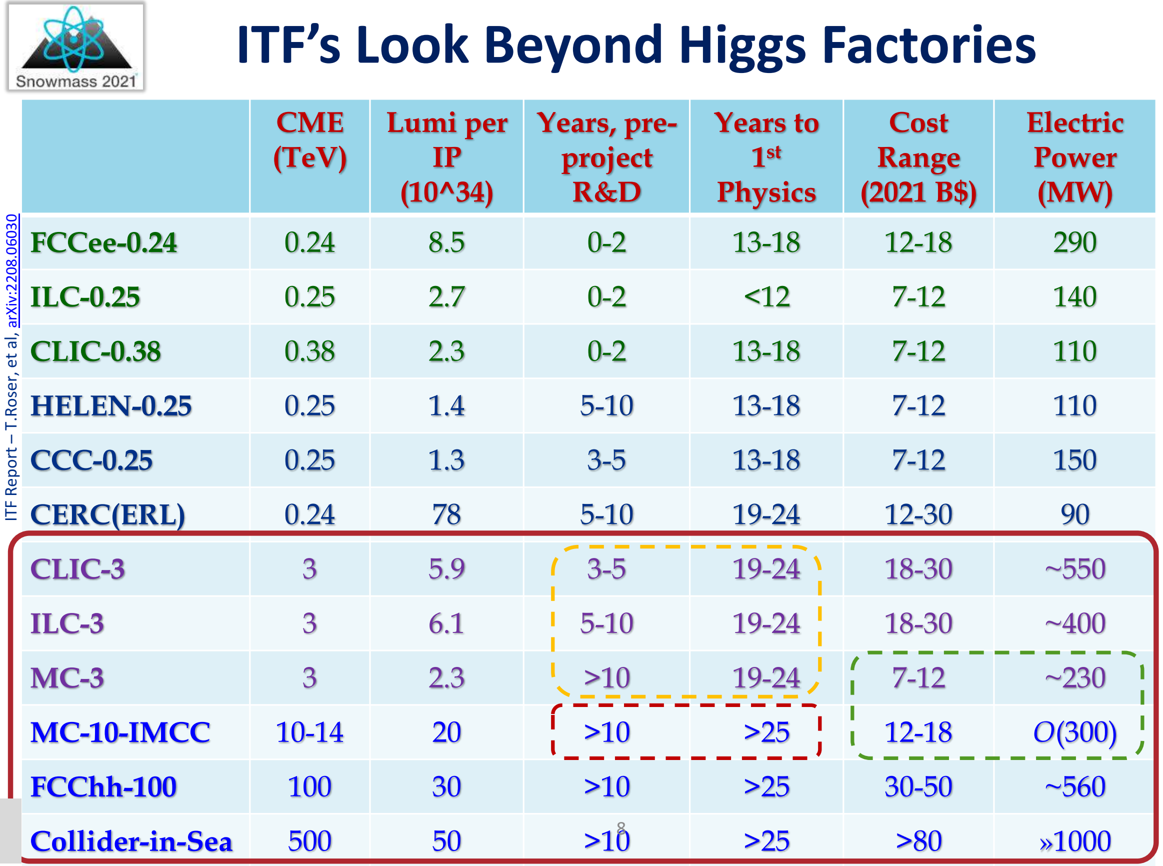
US Snowmass, cont.

Implementation Task Force

Muon Collider is a viable option for the HEP future

They made cost and power estimate for muon collider take it *cum grano salis*

Place MC in same risk tier as FCC-hh



ITF's Look Beyond Higgs Factories

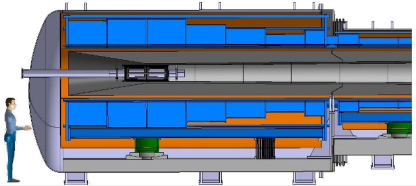
ITF Report – T.Roser, et al, arXiv:2208.06030

	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	$O(300)$
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

Thomas Roser et al

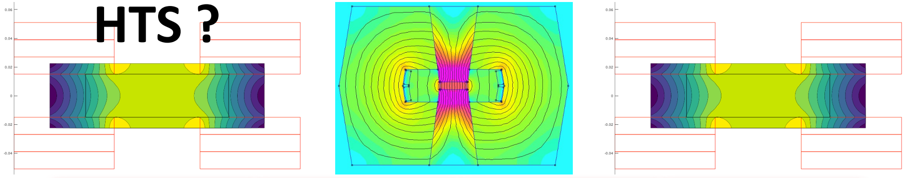
Muon Collider magnets

20 T, 200 mm **HTS !**
Radiation heat load ≈ 5...10 kW
Radiation dose: 80 MGy

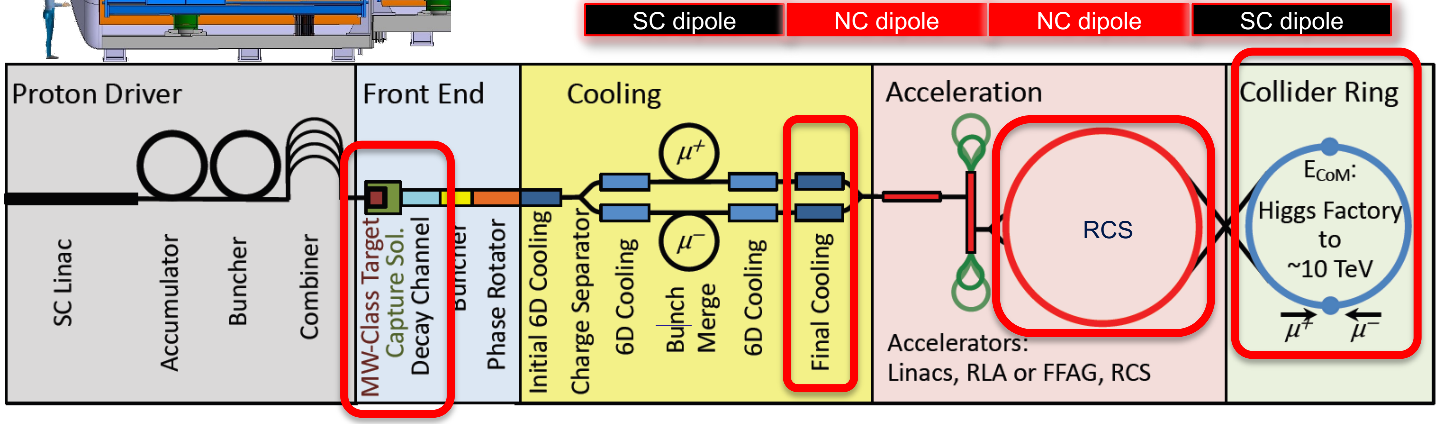


NC ±1.8 T, 400 Hz
100 mm x 30 mm

SC < 10T
100 mm x 30 mm



HTS ?



SC dipole
NC dipole
NC dipole
SC dipole

Proton Driver
- SC Linac
- Accumulator
- Buncher
- Combiner

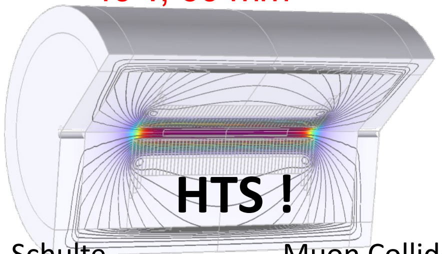
Front End
- MW-Class Target
- Capture Sol.
- Decay Channel
- Buncher
- Phase Rotator

Cooling
- Initial 6D Cooling
- Charge Separator
- 6D Cooling
- Bunch Merge
- 6D Cooling
- Final Cooling

Acceleration
- RCS
- Accelerators: Linacs, RLA or FFAG, RCS

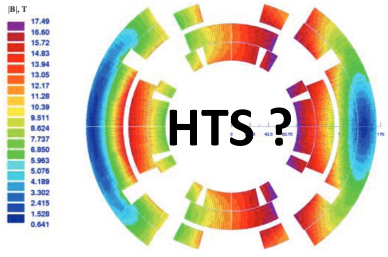
Collider Ring
- E_{CoM}: Higgs Factory to ~10 TeV

> 40 T, 60 mm



HTS !

16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20...40 MGy



HTS ?

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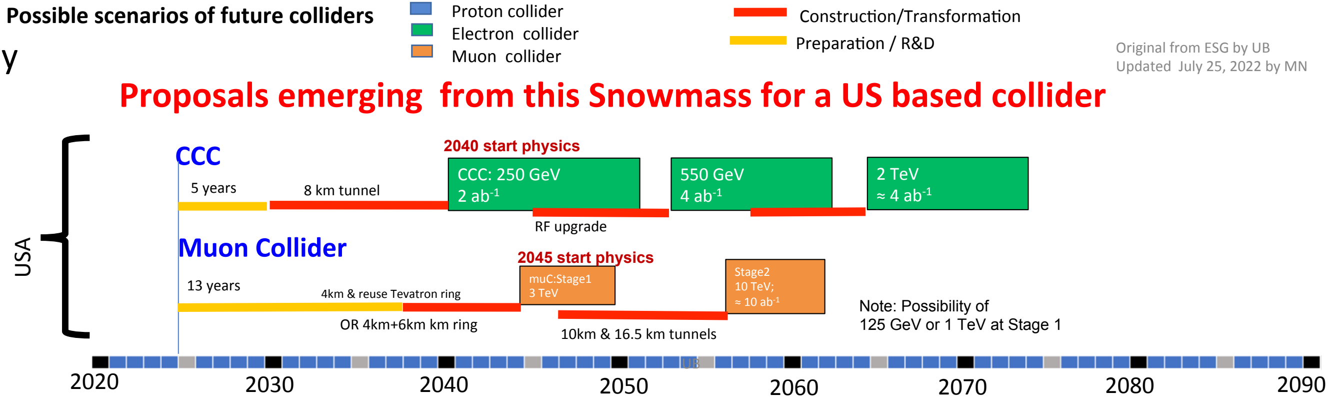

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Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider

USA

CCC
5 years
8 km tunnel
2040 start physics
CCC: 250 GeV
2 ab^{-1}
RF upgrade
550 GeV
4 ab^{-1}
2 TeV
≈ 4 ab^{-1}

Muon Collider
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage1
3 TeV
10km & 16.5 km tunnels
Stage2
10 TeV;
≈ 10 ab^{-1}

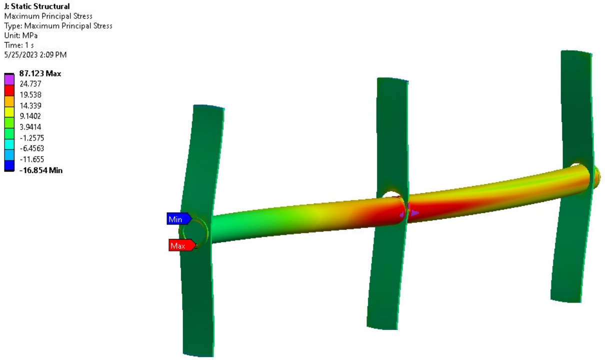
Note: Possibility of
125 GeV or 1 TeV at Stage 1

- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

Consider proposing hosting ILC in the US.

Meenakshi Narain: Energy Frontier / Large Experiments,
Snowmass Community Summer Study July 17-26, 2022

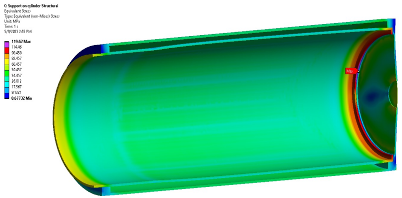
CARBON TARGET



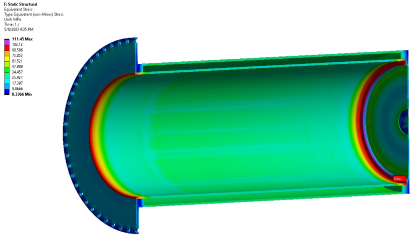
Graphite rod & supports: stress field

- Baseline updated form 1.5 to **2MW**
- Modeling **supports in the model**
- Studying **tilted beam**:
  - ✓ Effect found **positive**. Reduction of peak temperature from 3280 K (straight) to 2940 K (tilted) due to the lower energy deposition.
  - ✓ **Mechanical stresses**: stress wave expected to be "small" but **dynamic** analysis is ongoing

TARGET VESSEL



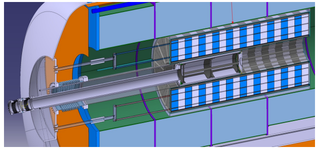
Simply supported vessel – stress field



Cantilever supported vessel – stress field

- Update to **2 MW**
- **Titanium** vessel
- Thermomechanical studies made to check the resistance to **high temperatures** and **cooling pressures**
  - ✓ Titanium vessel capable of **withstanding the requirements**
- No significant dynamic effects observed. Quasi-steady state behavior
- Two concepts being studied: simply supported cylinder and cantilever

- Evolutions from the **design**, **manufacturing & assembly** point of view of every component
- Also progress on **integration** with the **solenoid cryostat**



EU Design Study

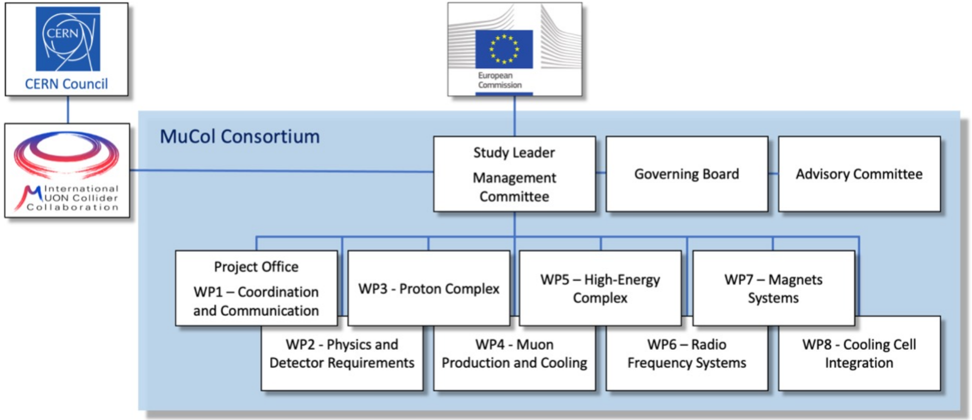
Has been approved summer 2022

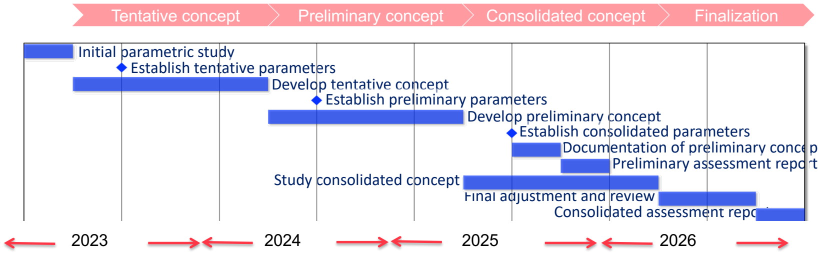
- Very helpful to kick-start collaboration

Reapproved early 2023

- It appears that there has been some issue with the refereeing of several projects, probably not directly with the muon collider

Brings 3 MEUR from the European Commission, the UK and Switzerland and about 4 MEUR from the partners
Basically nothing for CERN





Kick-off meeting in March 2023:
https://indico.cern.ch/event/1219912

Many thanks to all that contributed

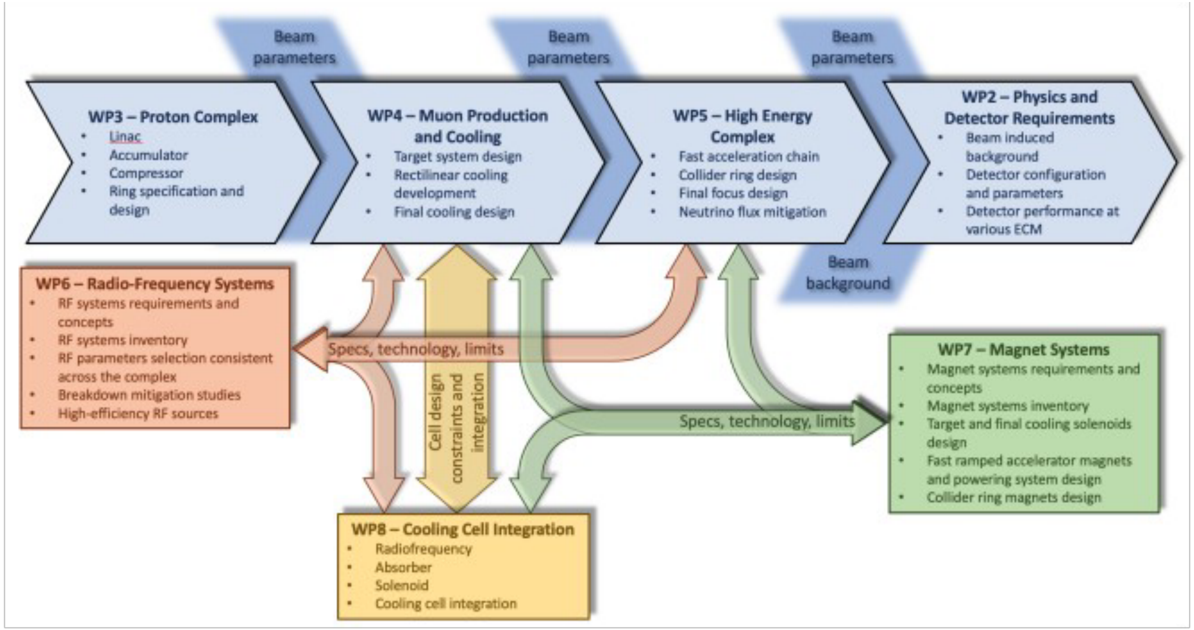
https://mucol.web.cern.ch

Sat celeriter fieri quidquid fiat satis bene

EU Design Study Work Programme

Workpackage leaders:
WP 1: R. Losito (CERN)
WP 2: D. Lucchesi (INFN, Padua)
WP 3: N. Milas (ESS)
WP 4: Ch. Rogers (RAL)
WP 5: A. Choince (CEA)
WP 6: C. Marchand (CEA)
WP 7: L. Bottura (CERN)
WP 8: L. Rossi (U. Milano)

Study Leader: D. Schulte (CERN)
Deputy Study Leader: Ch. Rogers (RAL)
Technical Coordinator: R. Losito (CERN)
Gender Advisor: E.J. Bahng (ISU)
Publications: E. Metral



WP3 – Proton Complex
- Linac
- Accumulator
- Compressor
- Ring specification and design

WP4 – Muon Production and Cooling
- Target system design
- Rectilinear cooling development
- Final cooling design

WP5 – High Energy Complex
- Fast acceleration chain
- Collider ring design
- Final focus design
- Neutrino flux mitigation

WP2 – Physics and Detector Requirements
- Beam induced background
- Detector configuration and parameters
- Detector performance at various ECM

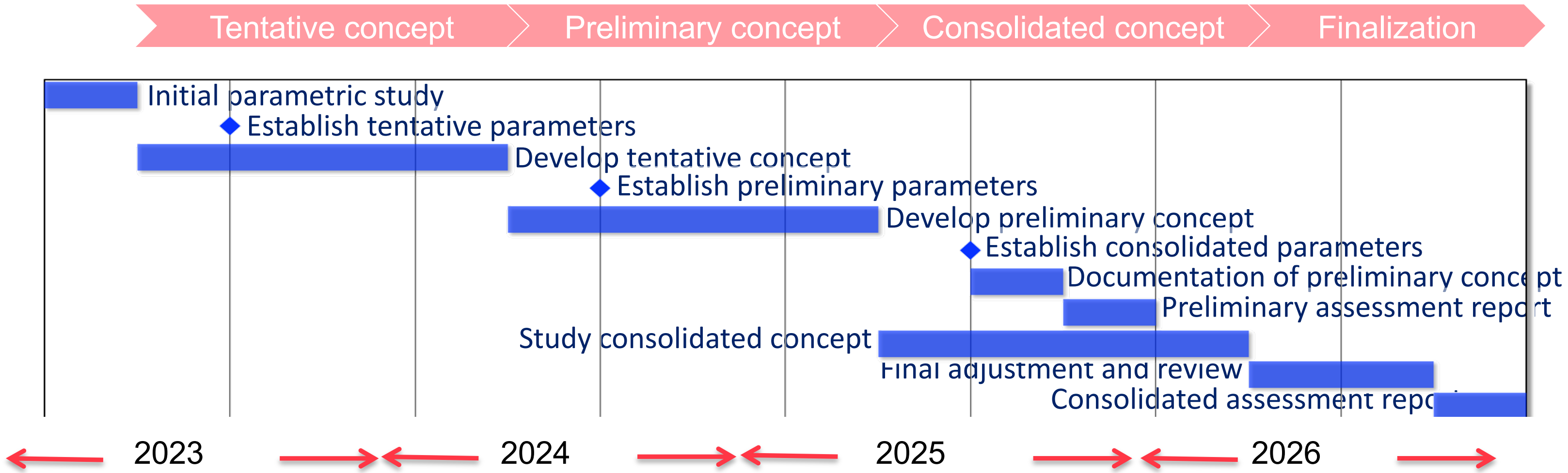
WP6 – Radio-Frequency Systems
- RF systems requirements and concepts
- RF systems inventory
- RF parameters selection consistent across the complex
- Breakdown mitigation studies
- High-efficiency RF sources

WP7 – Magnet Systems
- Magnet systems requirements and concepts
- Magnet systems inventory
- Target and final cooling solenoids design
- Fast ramped accelerator magnets and powering system design
- Collider ring magnets design

WP8 – Cooling Cell Integration
- Radiofrequency
- Absorber
- Solenoid
- Cooling cell integration

Includes an important part of the work directly and much indirectly

MuCol Timeline



Tentative concept
Preliminary concept
Consolidated concept
Finalization

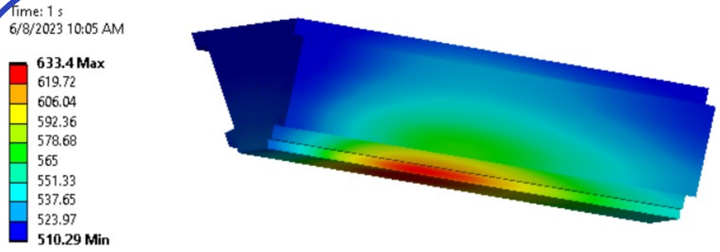
Initial parametric study
Establish tentative parameters
Develop tentative concept
Establish preliminary parameters
Develop preliminary concept
Establish consolidated parameters
Documentation of preliminary concept
Preliminary assessment report
Study consolidated concept
Final adjustment and review
Consolidated assessment repo

2023
2024
2025
2026

Finish February 2027
Preliminary report by early 2026, in case EU strategy takes place in 2026
Iterating on parameters ad design each year

More detail in Roberto’s presentation

RADIATION SHIELDING

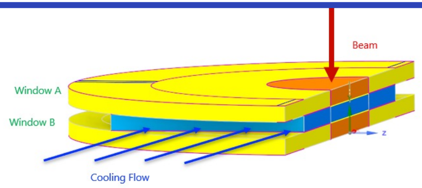


Tungsten slice – Temperature field

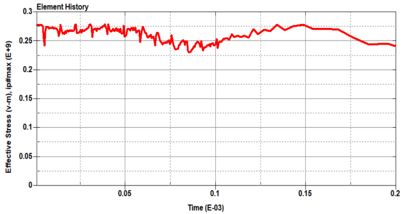
- Baseline updated to **2 MW**
- **Improved and more detailed concept** aiming for a more realistic implementation:
  Tungsten slices bounded by a stainless steel **vessel** filled with pressurized **He coolant**
- **Optimization** of the helium cooling **operational point** in function of:
  - Number of pipes
  - Diameter
  - Mass flow
  - Max. admissible flow speed & pumping power
  - Heat transfer coefficient and temperature
- **Operational Point**: Helium / ø5 mm/0.3 kg/s / 10 bar / 150 pipes

- Subsequent **thermomechanical analysis** found that **temperatures** and **stresses** are **acceptable** for tungsten (633 K at the core)
- Temperature at the **interface** with solenoid around **300 – 310 K**

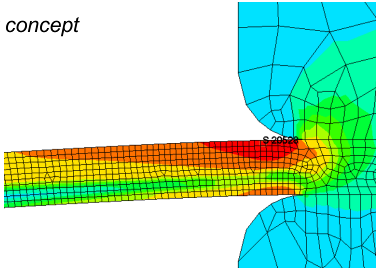
BEAM WINDOW



Cooled window concept



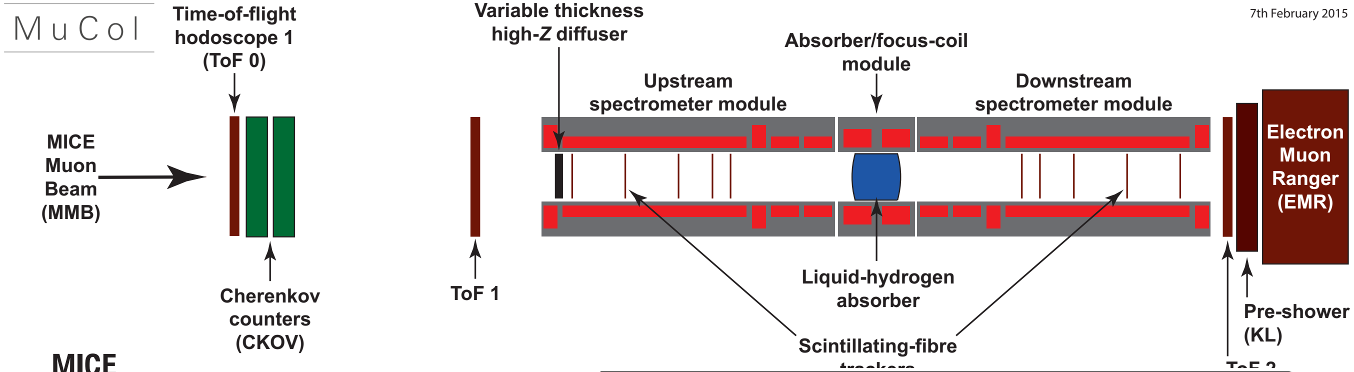
Dynamic stress waves due to one beam shot (at joint)

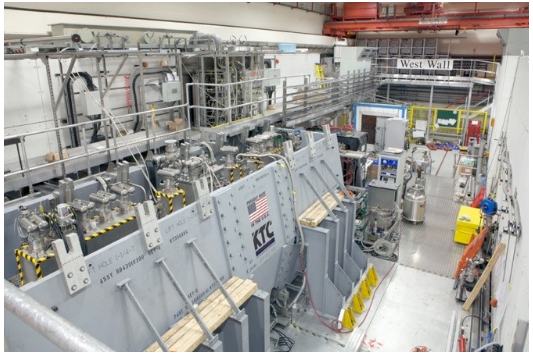


Stress field shape around the window joint

- **High requirements** in terms of energy density and cooling capabilities
- Parametric study made in function of material, thickness, and cooling pressure
- Found that **250 microns Berylium** can survive one single beam shot far from plasticity.
- There is still **little safety factor** to guarantee the **fatigue** endurance. More work will be done at this aspect
- Radiation damage is biggest challenge. Work on progress to mitigate it.

MICE: Cooling Demonstration

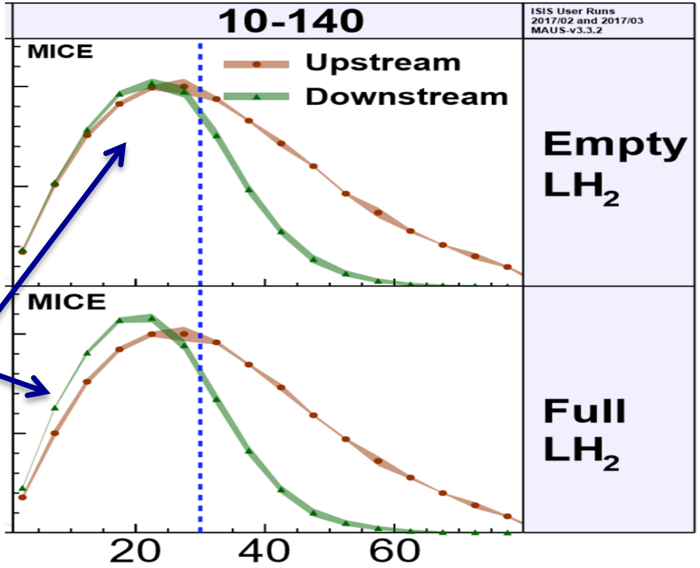




Nature vol. 578, p. 53-59 (2020)

Principle of ionisation cooling has been demonstrated

Use of data for benchmarking is still ongoing



More particles at smaller amplitude after absorber is put in place

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

Organisation

Collaboration Board (ICB)

- Elected chair: **Nadia Pastrone**

Steering Board (ISB)

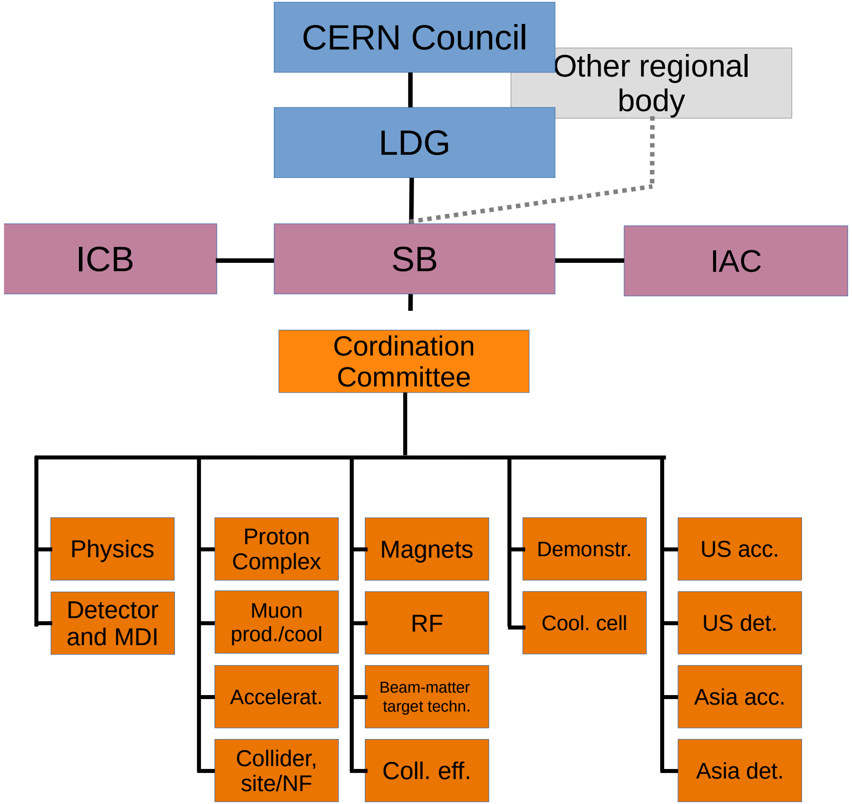
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members

Advisory Committee

- To be defined, discussion in SB

Coordination committee (CC)

- Study Leader: **Daniel Schulte**
- Deputies: **Andrea Wulzer, Donatella Lucchesi, Chris Rogers**



CERN Council

Other regional body

LDG

ICB

SB

IAC

Cordination Committee

Physics

Detector and MDI

Proton Complex

Muon prod./cool

Accelerat.

Collider, site/NF

Magnets

RF

Beam-matter target techn.

Coll. eff.

Demonstr.

Cool. cell

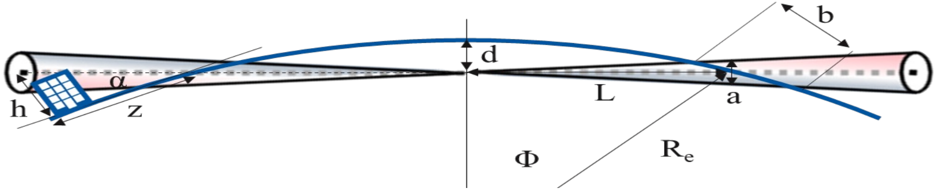
US acc.

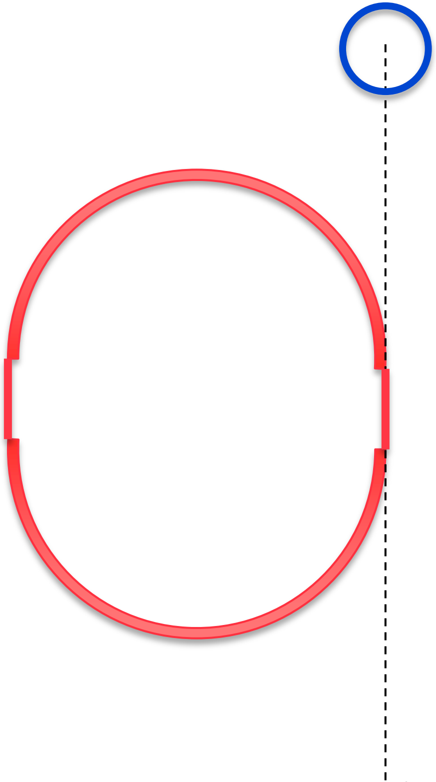
US det.

Asia acc.

Asia det.

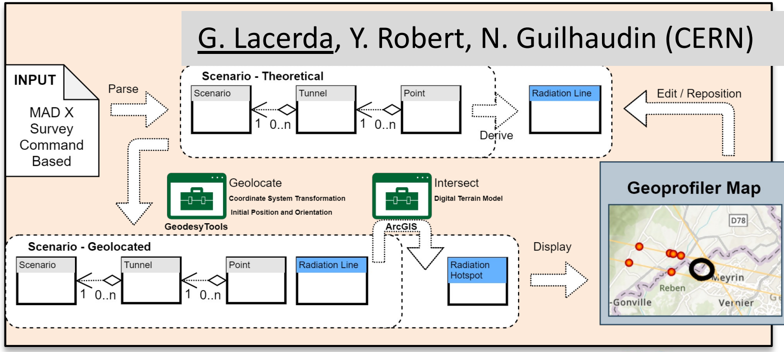
Neutrino Flux





O(10^{11}-10^{12}) neutrinos per second
Plan to either dilute or likely aquire the land around this spot

Important to know if this is helpful becsause depends on the lattice design



G. Lacerda, Y. Robert, N. Guilhaudin (CERN)

INPUT
MAD X Survey Command Based

Parse

Scenario - Theoretical
Scenario — 1 0..n — Tunnel — 1 0..n — Point
Derive
Radiation Line

Edit / Reposition

Geolocate
Coordinate System Transformation
Initial Position and Orientation
GeodesyTools

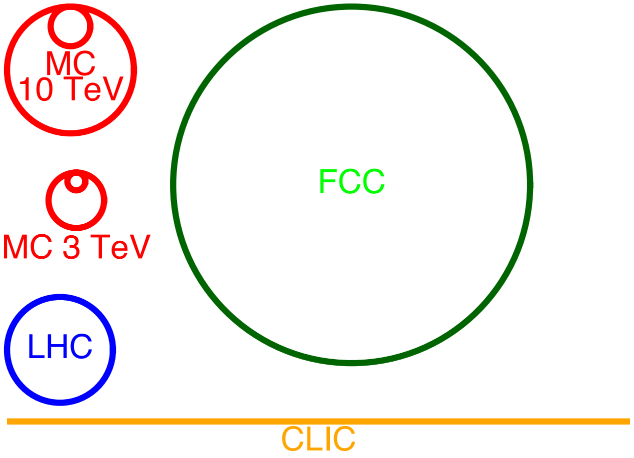
Intersect
Digital Terrain Model
ArcGIS

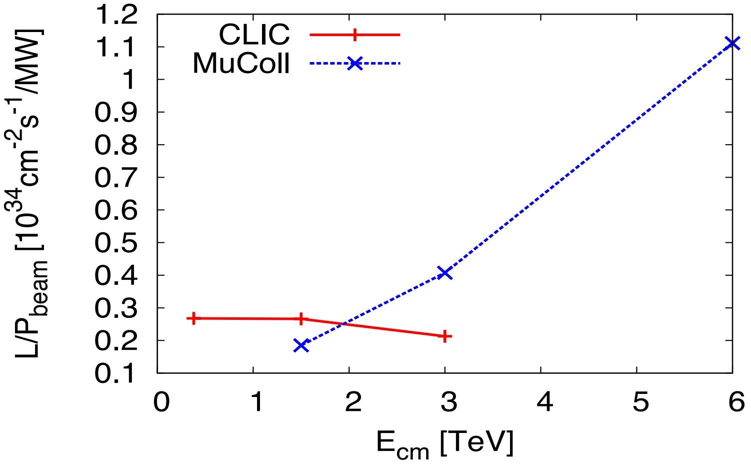
Scenario - Geolocated
Scenario — 1 0..n — Tunnel — 1 0..n — Point
Radiation Line
Radiation Hotspot

Display

Geoprofiler Map

Cost and Sustainability





CLIC is highest energy proposal with CDR

- No obvious way to further improve linear colliders (decades of R&D)
- Cost 18 GCHF, power approx. 500 MW

Rough rule of thumb:

- cost proportional to energy
- power proportional to luminosity

Muon Collider goals (10 TeV), challenging but reasonable:

- Much **more luminosity** than CLIC at 3 TeV **($L=20\times10^{34}$, CLIC: $L=2\times10^{34}/6\times10^{34}$)**
- **Lower power consumption** than CLIC at 3 TeV ($P_{beam,MC}=0.5P_{beam,CLIC}$)
- **Lower cost**

Staging is possible

Synergies exist (neutrino/higgs)

Unique opportunity for a **high-energy, high-luminosity lepton collider**

MuCol

US Snowmass Implementation Task Force

ional
lider
tion

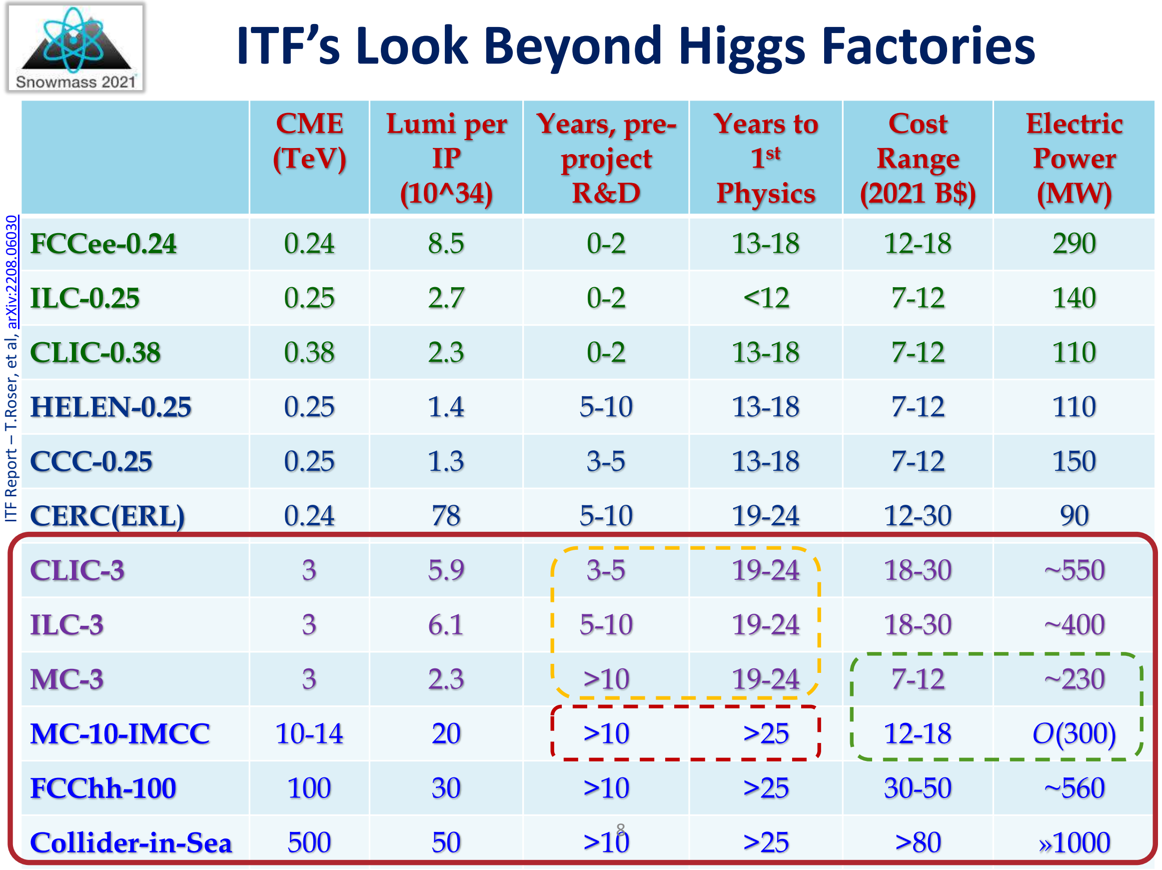
ITP investigated the muon collider and concluded:

- Muon Collider is a viable option for the HEP future

ITP provided parametric cost and power estimate for muon collider take it *cum grano salis*

ITP places MC in same risk tier as FCC-hh

Th. Roser, R. Brinkmann, S. Cousineau, D. Denisov, S. Gessner, S. Gourlay, Ph. Lebrun, M. Narain, K. Oide, T. Raubenheimer, J. Seeman, V. Shiltsev, J. Straight, M. Turner, L. Wang et al.



Snowmass 2021

ITF's Look Beyond Higgs Factories

ITF Report – T.Roser, et al, arXiv:2208.06030

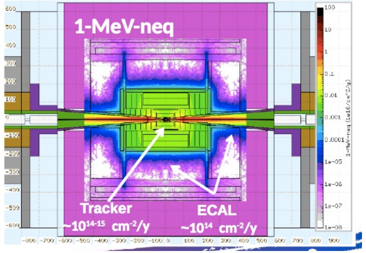
	CME (TeV)	Lumi per IP (10^34)	Years, pre-project R&D	Years to 1st Physics	Cost Range (2021 B$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	290
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	$O(300)$
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10	>25	>80	»1000

Muon Collider R&D Examples

Detector studies

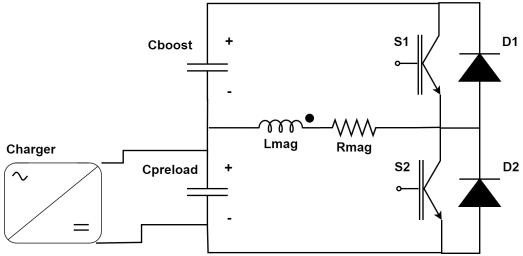
- 10 TeV design
- Beam-induced background

Promising but more work required

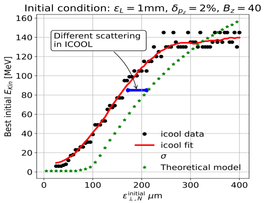


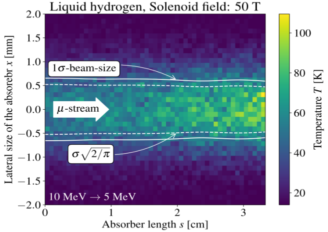
Efficent power converters

Energy recovery for fast-ramping magnets

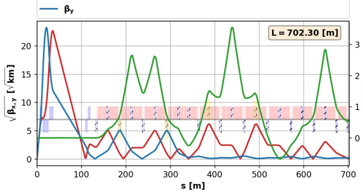


Muon ionisation cooling

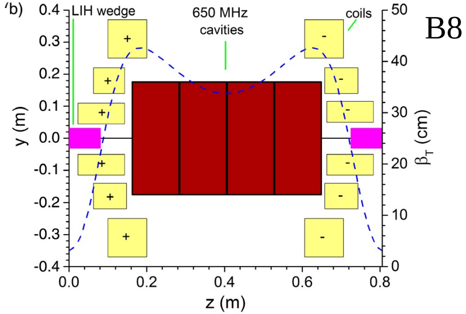




Beam physics



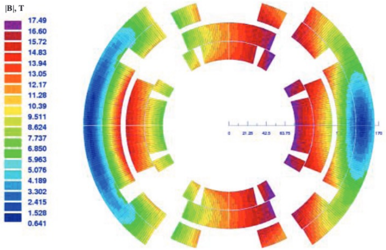
High-field HTS solenoids



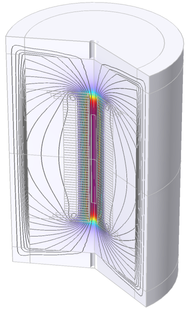
Cooling Cell Design

RF in magnetic field

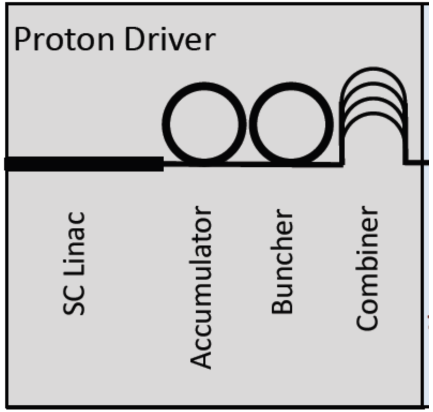
High-field dipoles (HTS or Nb_3Sn)

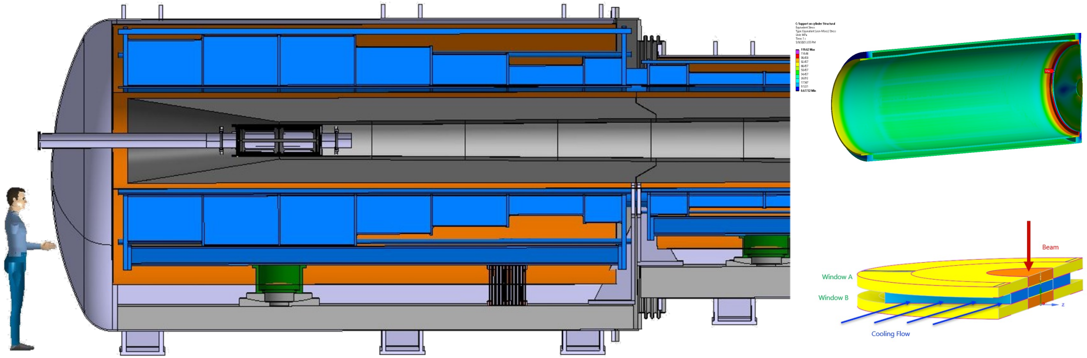


40 T HTS solenoid



Proton Complex and Target





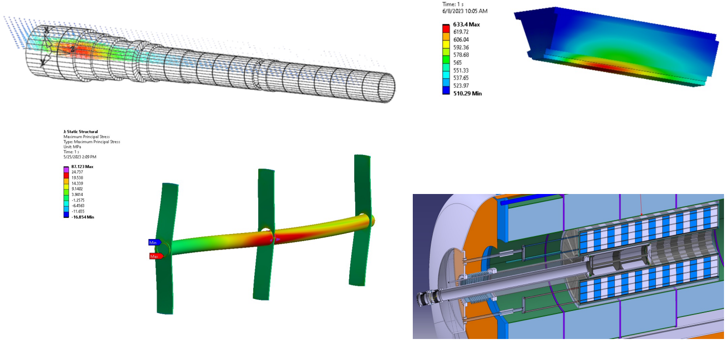
2 MW proton beam 5 GeV
5 Hz from the combiner

Will explore parameters to optimise proton compolex and target

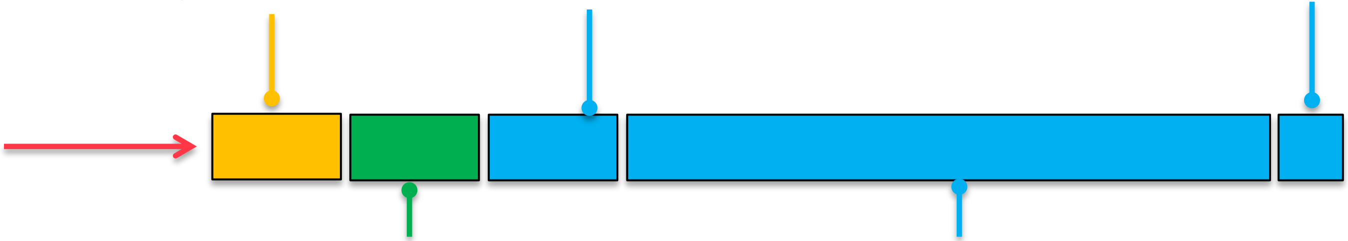
Will explore higher power

Graphite target baseline with tungsten shield for surrounding solenoid

Good progress on 20 T HTS solenoid design, stress in target, vessel, shielding, more to be done for the window



Test Facility Dimensions



Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

Collimation and **upstream diagnostics** area, 10 m

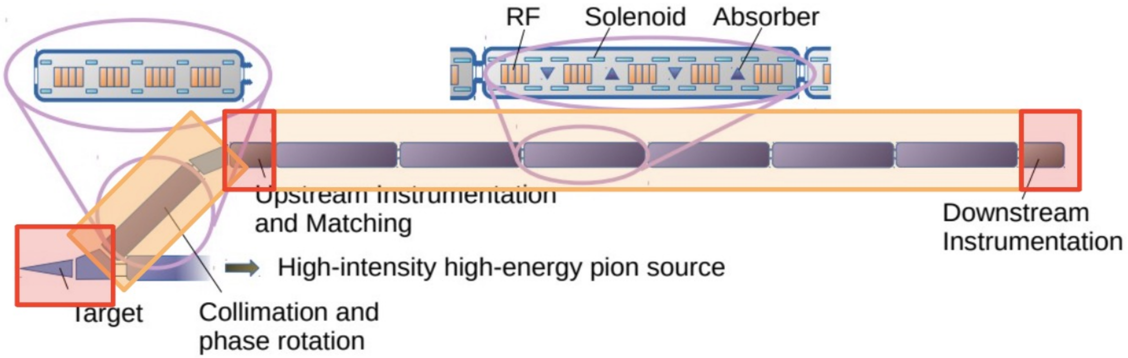
Downstream diagnostics area, 5 m

Momentum selection chicane, 10 m

Cooling area, 50 m

Look for an existing proton beam with significant power

Different sites are being considered
- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option

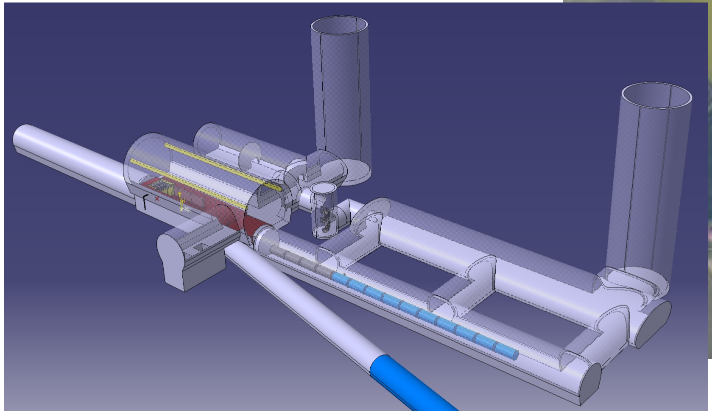


Possible CERN Locations

Consider nTOF-like beam from PS for cooling experiment:

- 1 pulse of 10^{13} p at 20 GeV per 1.2 s, i.e. 27 kW
- maybe O(100kW) possible

If SPL were, installed could use its beam, e.g. 5 GeV, 4 MW



M. Calviani

Physics Studies

Details on physics case, detector and accelerator can be found in

- Snowmass white papers https://indico.cern.ch/event/1130036/
- EPJC report in preparation

Used tentative detector performance specifications in form of DELPHES card

- based on FCC-hh and CLIC performances, including masks against beam induced background (BIB)
- Please find the card here: https://muoncollider.web.cern.ch/node/14

M. Selvaggi, W. Riegler, U. Schnoor, A. Sailer, D. Lucchesi, N. Pastrone, M. Pierini, F. Maltoni, A. Wulzer et al.

Initial detector simulation studies at 1.5 and 3 TeV indicate that this is a **good model**

Now moving to 10 TeV

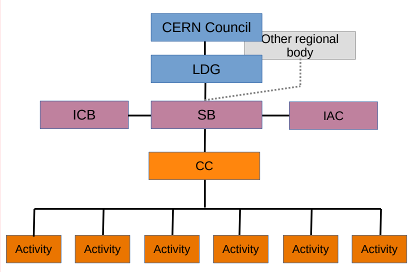
D. Lucchesi, F. Meloni et al.

If you are interested to contribute please contact me or the responsible deputies:

Andrea Wulzer (Physics) and **Donatella Lucchesi (Detector and MDI)**

Muon Collider Community

Formed **collaboration** hosted by CERN to implement R&D Roadmap for CERN Council



60+ partners, 40+ already signed MoC

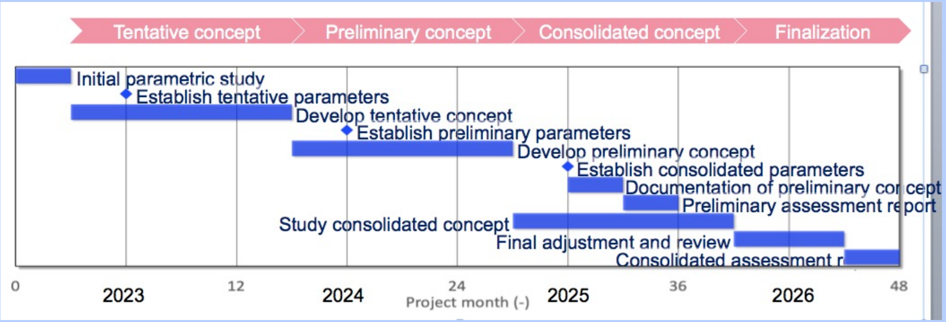
Plan to participate to **HORIZON-INFRA-2024-TECH**

Goal: prepare experimental programme, e.g. **demonstrator, prototypes, …**

TIARA wants magnet proposal

EU Design Study approved

(EU+Switzerland+UK and partners)



US Snowmass has **strong support**

- to contribute to R&D
- as a collider in the US

Lia Merminga appointed team to prepare P5 ask

Some first contacts with others

Tentative Interim Report Structure

Collaboration Development

Physics Potential
Detector Design
Detector Technologies
MDI
Detector Performance

Accelerator Design
Accelerator Technologies

Synergies
- Technologies, facilities, experiments

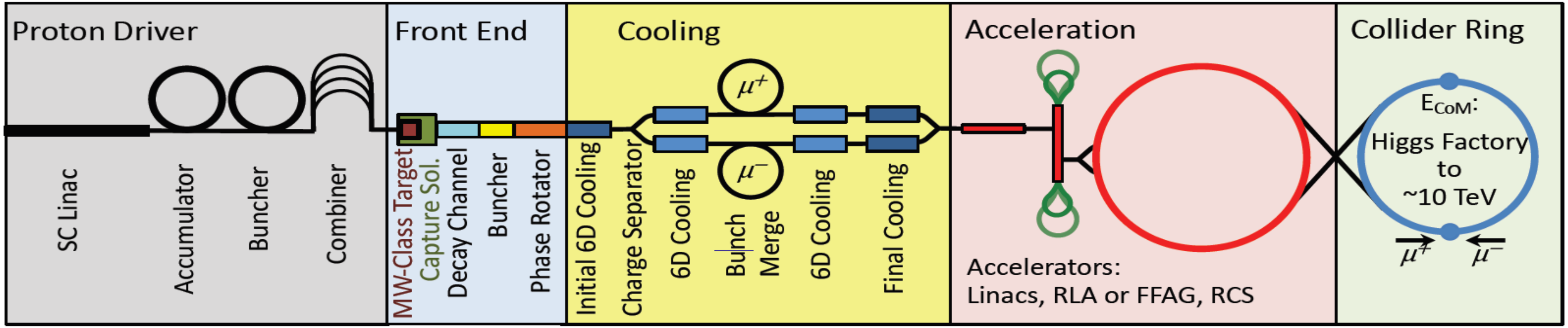
R&D Programme Development
- Demonstrator, RF test stand

Executive Summary

Section layout:
- **System Overview**
    - Short description of the system
- **Key challenges**
    - Reminder of key challenges of the system?
- **Work progress since Roadmap**
    - Status of the current concept
- **Work planned for Evaluation Report**
    - Based on existing resources
- **Important missing Effort**
    - What would be important to add?

Muon Collider Overview

Would be easy if the muons did not decay
Lifetime is τ = γ x 2.2 μs



Short, intense proton bunch

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Protons produce pions which decay into muons
muons are captured

Roadmap: Technically Limited Timeline

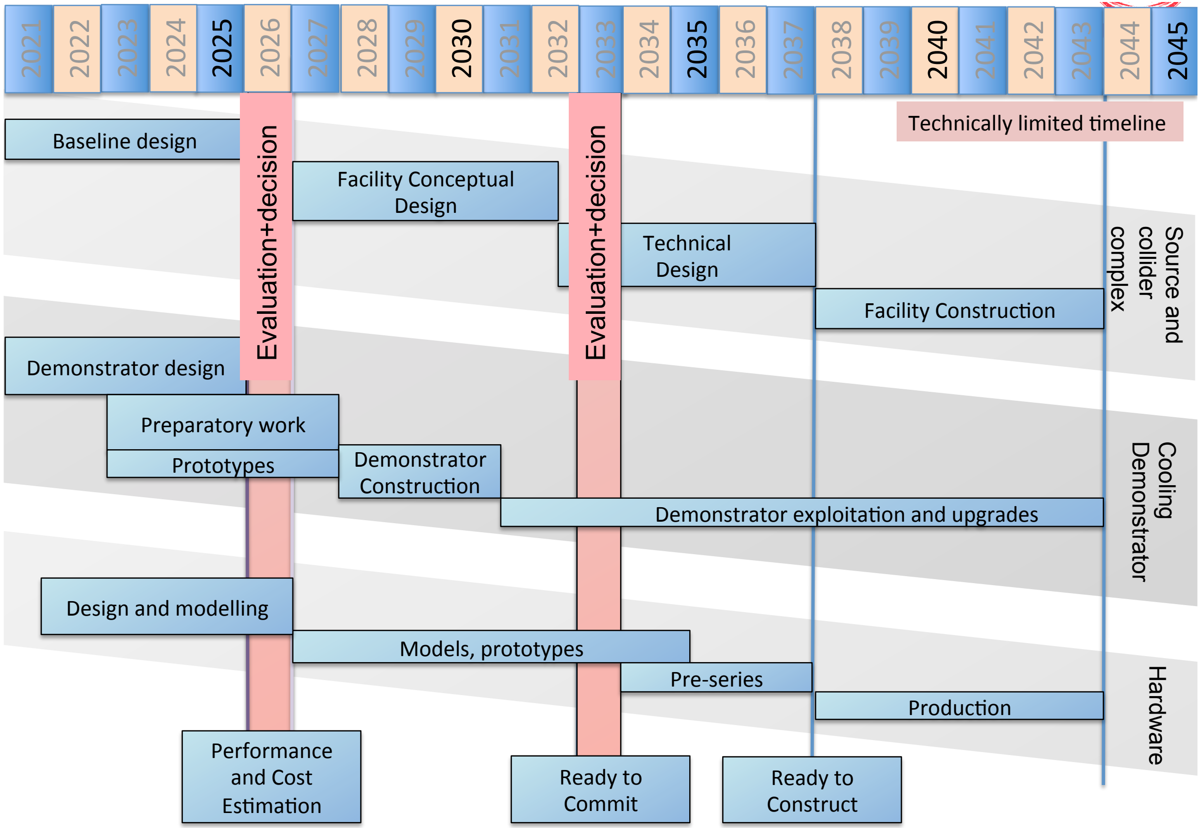
Muon collider important in the long term

Fastest track option with important ramp-up of resources to see if muon collider could come directly after HL-LHC

- Compromises in performance, e.g. 3 TeV

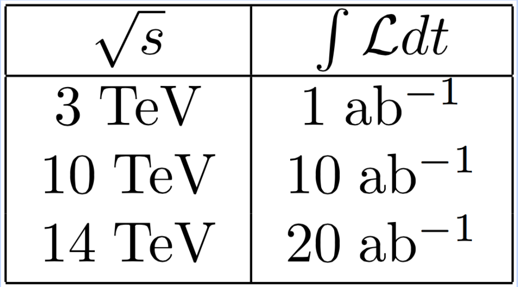
Needs to be revised but do not have enough information at this point for final plan

To be reviewed considering progress, funding and decisions



Initial Target Parameters

Target integrated luminosities



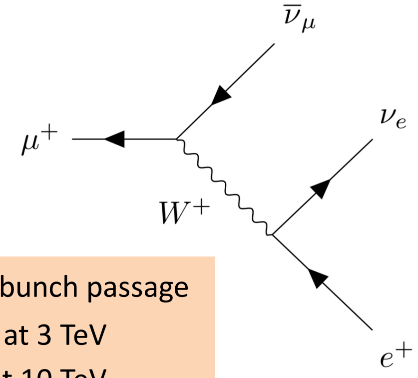
$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

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

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

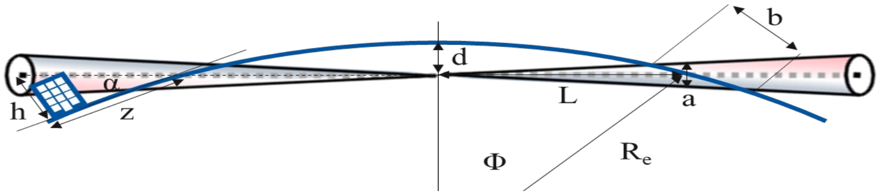
Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**40**	**2 (6)**
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	**MW**	**5.3**	**14.4**	**20**	**28**
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	μm	25	25	25	
$\sigma_{x,y}$	μm	3.0	0.9	0.63	

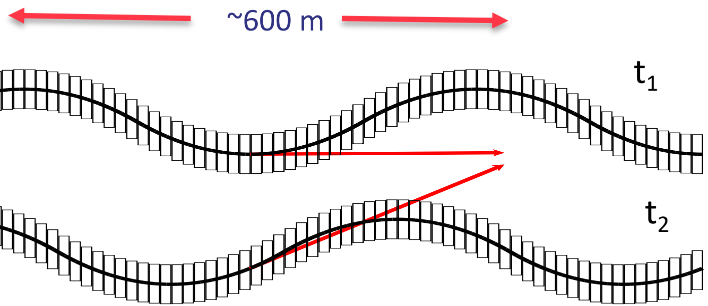
Muon Decay and Neutrino Flux



Muon decays per bunch passage

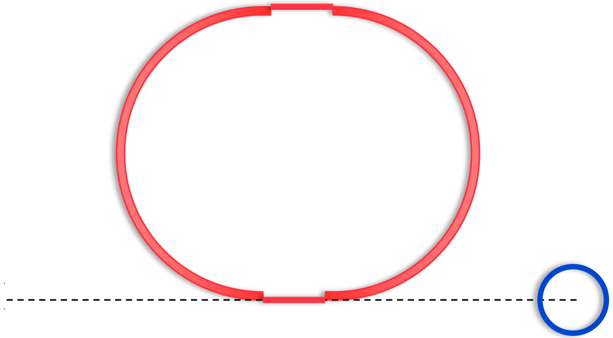
- 235,000 m^{-1} at 3 TeV
- 58,000 m^{-1} at 10 TeV





But want to have **negligible impact from arcs**

- Similar impact as LHC
- At 3 TeV this is the case for 200 m depth
- At 10 TeV use angle change of +/- 1 mradian to go from acceptable to negligible level
  - Mockup of mover system planned
  - Impact on beam to be checked



Impact of experimental insertions

- 3 TeV design acceptable with no further work
- Maybe acquire land in direction of experiment, also for 10 TeV

Other Points

- Preparing **publication policy**
  - Devil is in the detail, will profit from CLIC model
  - Goal is to be open, anyone following our procedure can talk or publish for the muon collider collaboration

- Preparing **data policy**
  - As open as possible: instill confidence in our results, profit from voluntary contributions

- Started INDICO page to collect information about **resources from partners**

- CERN extended MTP for muon collider until 2028
  - Total material budget has increased, but needs to redistributed

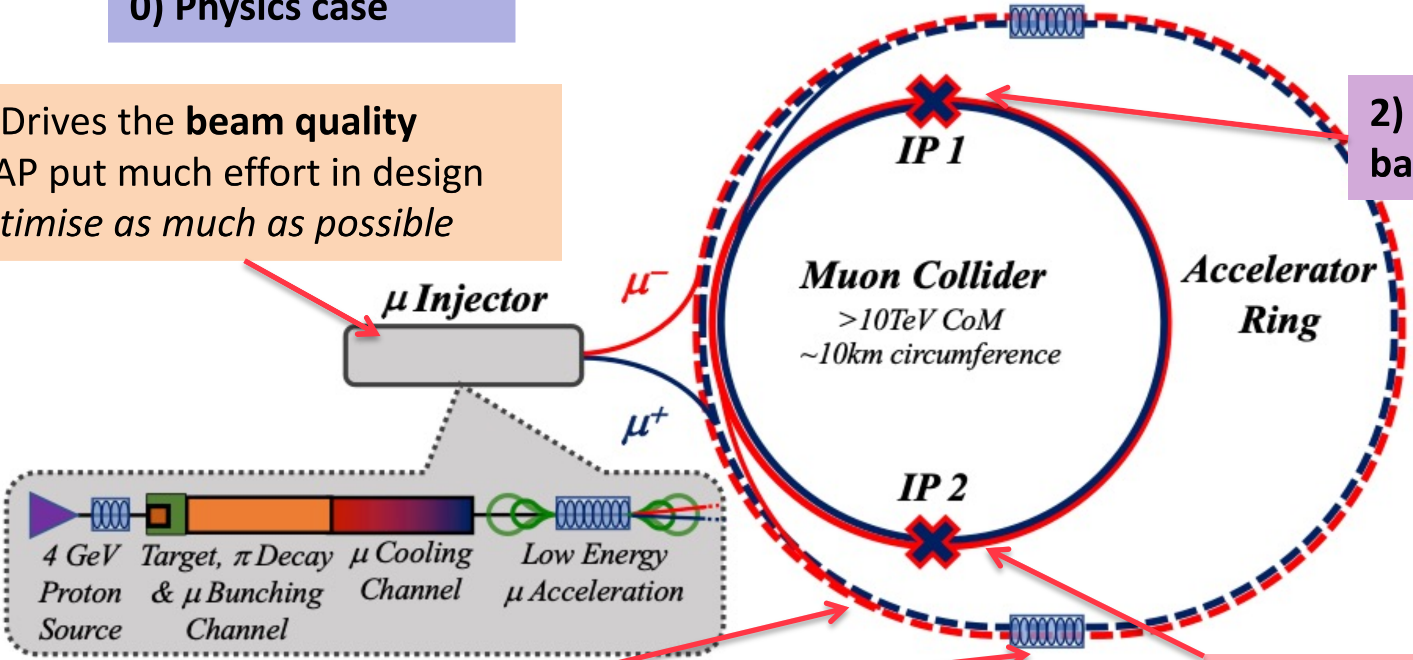
- CERN will create an EP-UMC unit to ease inscription of users, moving forward with grey book

- EPJC article covering physics, detector and accelerator is almost ready

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

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**

Accelerator R&D Roadmap

No insurmountable obstacle found for the muon collider

- but important need for R&D

Aim at **10+ TeV** and potential initial stage at **3 TeV**

Full scenario deliverables by next ESPPU/other processes

- **Project Evaluation Report**
- **R&D Plan** that describes a path towards the collider;

Allows to make **informed decisions**

Interim report by end of 2023

Do not yet have the resources of the reduced scenario

- Following priorities and available expertise and resources
- Are approaching O(40 FTE)
- Efforts to increase resources

Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45

http://arxiv.org/abs/2201.07895

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.

Accelerator R&D Roadmap

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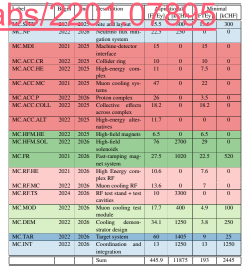

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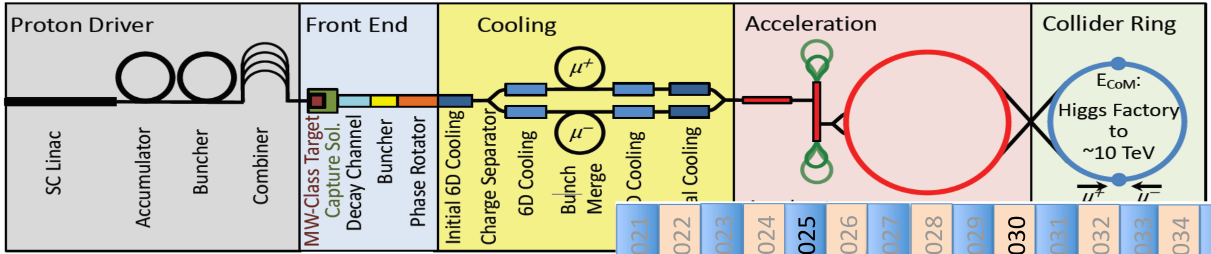
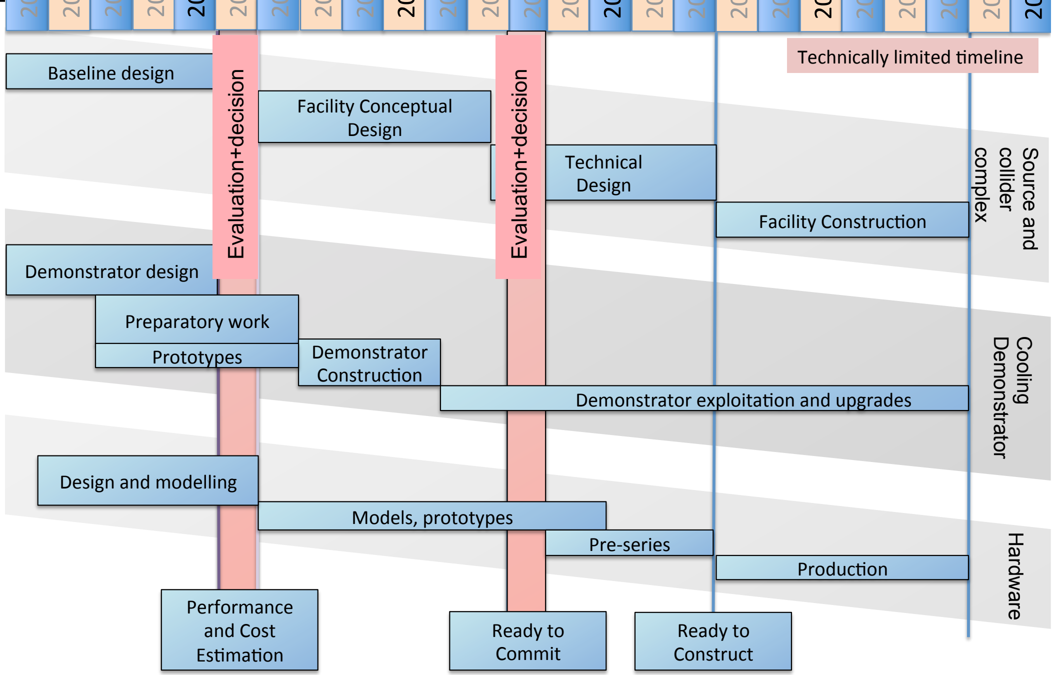
Muon Collider Overview





Aim for **10 TeV**

- The reason for muons

Potential initial stage **3 TeV**

- For fast implementation, e.g. directly after HL-LHC
- Compromises will be made as required
- Physics case already good

Integrated luminosities goals (5 yrs)

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