International
MUON Collider
Collaboration

MuCol

Muon Collider

Daniel Schulte and Steinar Stapnes
On behalf of the International Muon Collider Collaboration

LDG Meeting, CERN, November 2023

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

Collaboration Development

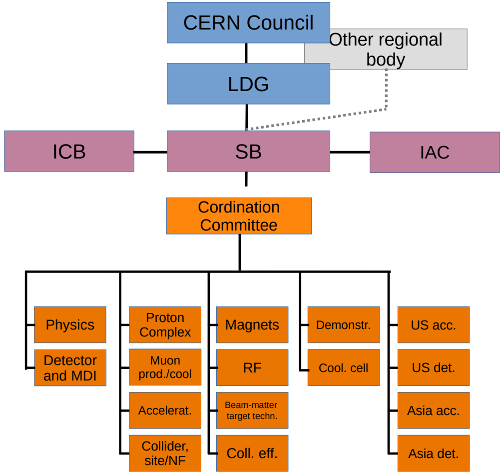
Collaboration is developing with new members joining

Annual meetings CERN October 2022 and Orsay June 2023

Many other meetings

- e.g. synergy meeting Orsay June 2023, …
- Design meetings on Mondays, …

Next Annual Meeting at CERN March 12-15, 2024


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.

Governance is active: ICB 4 times, SB once, MuCol GB twice, …

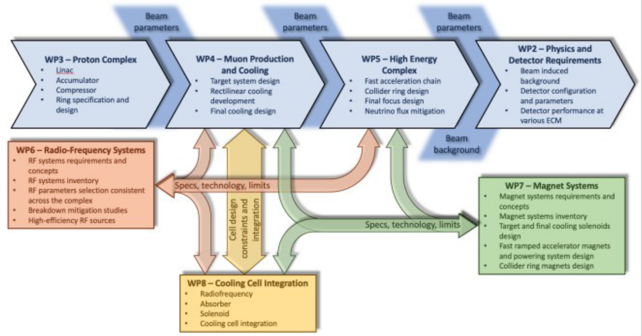
Publication policy defined (Publication and Speakers Committee)

Web site to collect information on resources of partners

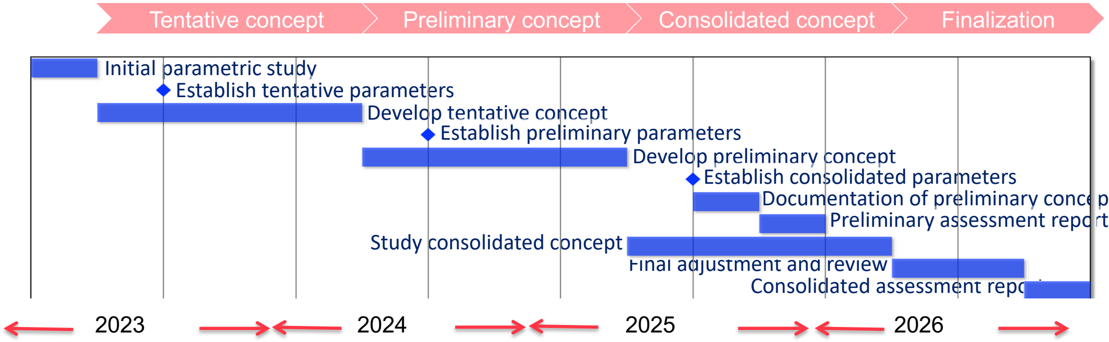
- Are now in “grey book”
- Started signing addenda to MoC

MuCol

3 MEUR from the European Union, UK and Switzerland, and about
4 MEUR from the 32 partners



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



WPs:

Integration (R. Losito), Detector Requirements (D. Lucchesi, Padua), Proton Complex (N. Milas, ESS), Muon Production and Cooling (Chr. Rogers, STFC), High-energy Complex (A. Chance, CEA-IRFU), RF (D. Giove, Milano), Magnets (L. Bottura, CERN), Muon Cooling Cell Design (L. Rossi, INFN)
Study Leader/Deputy: D. Schulte/Chr. Rogers

https://mucol.web.cern.ch

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Technical work integrated with IMCC

Provided all deliverables and milestones

- Data-management plan
- Interim Report
- Website available
- Kick-off meeting
- Tentative parameters
- Training on detectors design and physics performance tools

MuCol

MoC and Design Study Partners

International
MUON Collider
Collaboration

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
SE	**ESS**
	University of Uppsala
PT	**LIP**
NL	**University of Twente**
FI	**Tampere University**
LAT	**Riga Technical Univers.**
CH	**PSI**
	University of Geneva
	EPFL
EST	***Tartu University***
BE	**Univ. 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
US	**Iowa State University**
	Wisconsin-Madison
	Pittsburg University
	Old Dominion
	BNL
	Florida State University
	RICE University
	Tennessee University

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
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**

China	***Sun Yat-sen University***
	IHEP
	Peking University
AU	**HEPHY**
	TU Wien
ES	**I3M**
	CIEMAT
	ICMAB
KO	**KEU**
	Yonsei University
India	***CHEP***

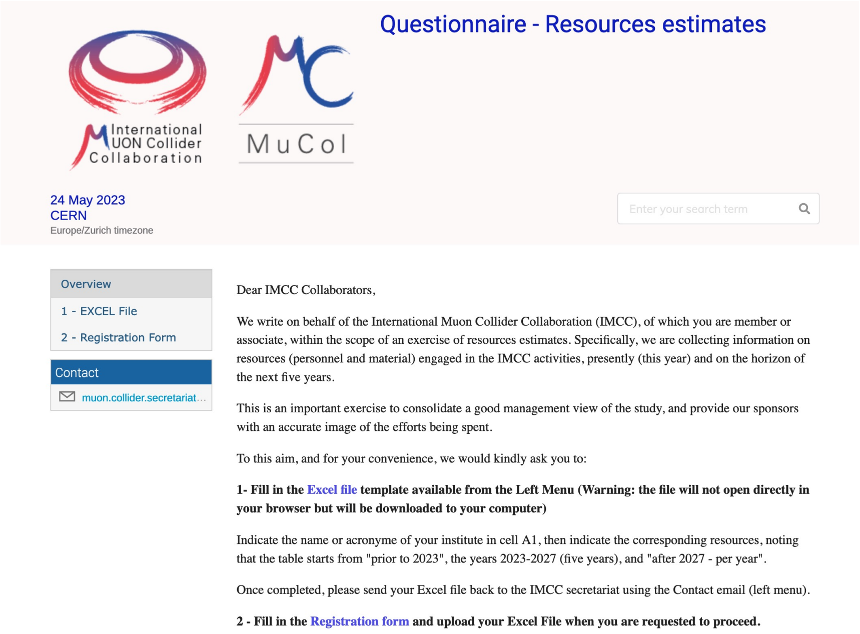
US	FNAL
	LBL
	JLAB
	Chicago

Resources

Collecting resource information from partners
Currently close to 30 replies

Categories:

- Physics (Physics potential, theory, phenomenology)
- Detector (Concept, design, physics performance)
- Detector technologies
- Accelerators Design (Protons, Muon Production and cooling, Accelerators, Collective Effects, MDI, Collider Site-Neutrino flux)
- Accelerator technologies (Magnets, RF, Beam Matter interaction and Target technologies)
- Demonstrator, Test facilities and infrastructure
- Software and Computing
- Other and reserves



Questionnaire - Resources estimates

24 May 2023
CERN
Europe/Zurich timezone

Dear IMCC Collaborators,

We write on behalf of the International Muon Collider Collaboration (IMCC), of which you are member or associate, within the scope of an exercise of resources estimates. Specifically, we are collecting information on resources (personnel and material) engaged in the IMCC activities, presently (this year) and on the horizon of the next five years.

This is an important exercise to consolidate a good management view of the study, and provide our sponsors with an accurate image of the efforts being spent.

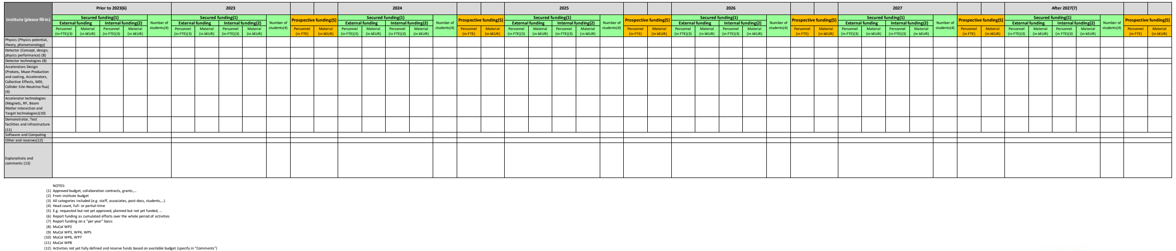
To this aim, and for your convenience, we would kindly ask you to:

1- Fill in the Excel file template available from the Left Menu (Warning: the file will not open directly in your browser but will be downloaded to your computer)

Indicate the name or acronyme of your institute in cell A1, then indicate the corresponding resources, noting that the table starts from "prior to 2023", the years 2023-2027 (five years), and "after 2027 - per year".

Once completed, please send your Excel file back to the IMCC secretariat using the Contact email (left menu).

2 - Fill in the Registration form and upload your Excel File when you are requested to proceed.



Institute (please fill-in)	Prior to 2023(6)					2023						
	Secured funding(1)				Number of students(4)	Secured funding(1)				Number of students(4)	Prospective funding(5)	
	External funding		Internal funding(2)			External funding		Internal funding(2)				
	Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)	Material (in kEUR)
Physics (Physics potential, theory, phenomenology)												
Detector (Concept, design, physics performance) (8)												
Detector technologies (8)												
Accelerators Design (Protons, Muon Production and cooling, Accelerators, Collective Effects, MDI, Collider Site-Neutrino flux) (9)												
Accelerator technologies (Magnets, RF, Beam Matter interaction and Target technologies)(10)												
Demonstrator, Test facilities and infrastructure (11)												
Software and Computing												
Other and reserves(12)												
Explanations and comments (13)												

Institute (please fill-in)	2024							2025						
	Secured funding(1)				Number of students(4)	Prospective funding(5)		Secured funding(1)				Number of students(4)	Prospective funding(5)	
	External funding		Internal funding(2)					External funding		Internal funding(2)				
	Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)	Material (in kEUR)
Physics (Physics potential, theory, phenomenology)														
Detector (Concept, design, physics performance) (8)														
Detector technologies (8)														
Accelerators Design (Protons, Muon Production and cooling, Accelerators, Collective Effects, MDI, Collider Site-Neutrino flux) (9)														
Accelerator technologies (Magnets, RF, Beam Matter interaction and Target technologies)(10)														
Demonstrator, Test facilities and infrastructure (11)														
Software and Computing														
Other and reserves(12)														
Explanations and comments (13)														

Institute (please fill-in)	2026							2027							After 2027(7)						
	Secured funding(1)				Number of students(4)	Prospective funding(5)		Secured funding(1)				Number of students(4)	Prospective funding(5)		Secured funding(1)				Number of students(4)	Prospective funding(5)	
	External funding		Internal funding(2)					External funding		Internal funding(2)					External funding		Internal funding(2)				
	Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)	Personnel (in FTE)(3)	Material (in kEUR)		Personnel (in FTE)	Material (in kEUR)
Physics (Physics potential, theory, phenomenology)																					
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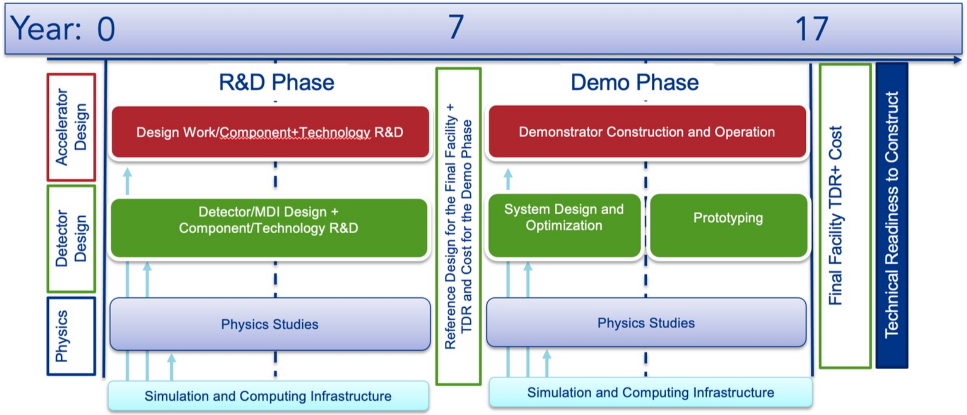
Demonstrator, Test facilities and infrastructure (11)																					
Software and Computing																					
Other and reserves(12)																					
Explanations and comments (13)																					

NOTES:
(1) Approved budget, collaboration contracts, grants,...
(2) From institute budget
(3) All categories included (e.g. staff, associates, post-docs, students,...)
(4) Head count, full- or partial-time
(5) E.g. requested but not yet approved, planned but not yet funded, ...
(6) Report funding as cumulated efforts over the whole period of activities
(7) Report funding on a "per year" basis
(8) MuCol WP2
(9) MuCol WP3, WP4, WP5
(10) MuCol WP6, WP7
(11) MuCol WP8
(12) Activities not yet fully defined and reserve funds based on available budget (specify in "Comments")
(13) Expand on activities, funding sources, more details on personnel, any other comments

US P5 Ask


Year: 0 7 17

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

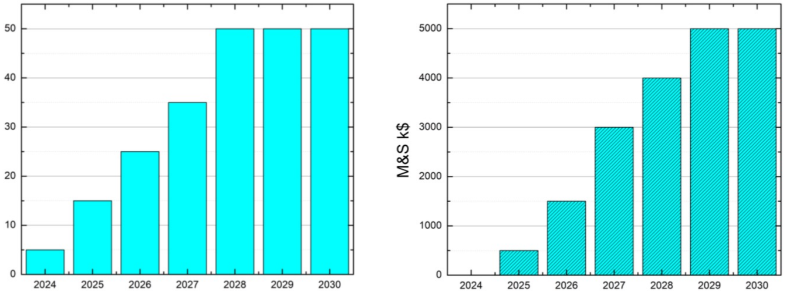
Physics Studies

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.



: 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.

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

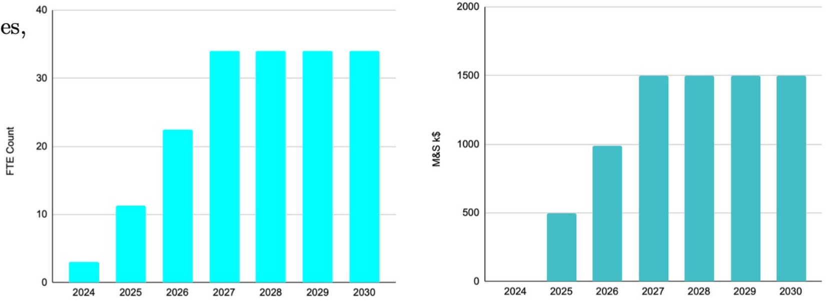


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

Important Reports

Parameter Document

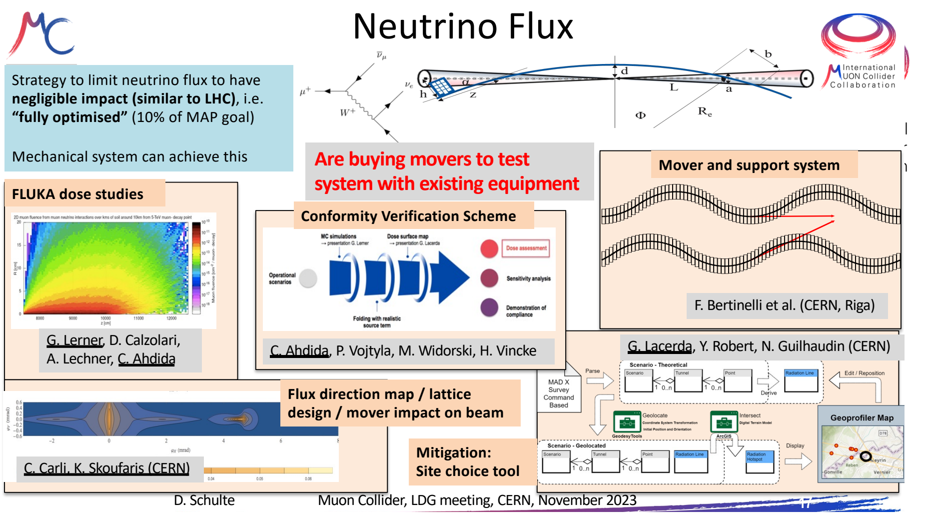
- Establishing a set of basic parameters and how they are derived
- Good basis to harmonise and identify trade-offs
- Concise version has been submitted as milestone to EU
- Longer version will be published, also explains derivation of parameters

Interim Report

- Cover physics, detector, accelerator and technologies
- Report progress since Roadmap
- Specify what can be done by 2026
- Prepare key elements of the R&D programme
    - e.g. RF test stand (needs funding and site)
- Very compact, <4 pages per area
- Currently being written
- Due by **end of February 2024**

Important technical progress
But cannot cover it here

Technical progress



Neutrino Flux

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

FLUKA dose studies

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

Conformity Verification Scheme

MC simulations → presentation G. Lerner

Dose surface map → presentation G. Lacerda

Operational scenarios

Folding with realistic source term

Dose assessment

Sensitivity analysis

Demonstration of compliance

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

Mover and support system

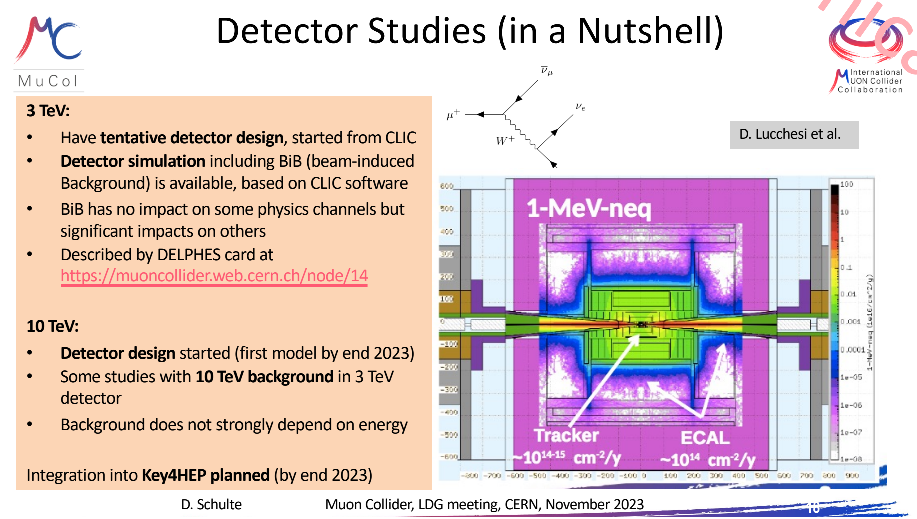
F. Bertinelli et al. (CERN, Riga)

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:

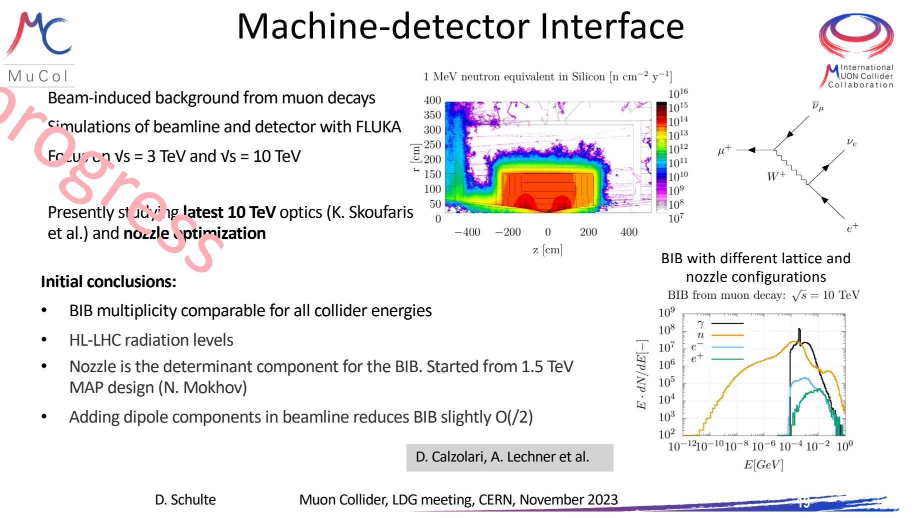
- Have **tentative detector design**, started from CLIC
- **Detector simulation** including BiB (beam-induced Background) is available, based on CLIC software
- BiB has no impact on some physics channels but significant impacts on others
- Described by DELPHES card at https://muoncollider.web.cern.ch/node/14

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

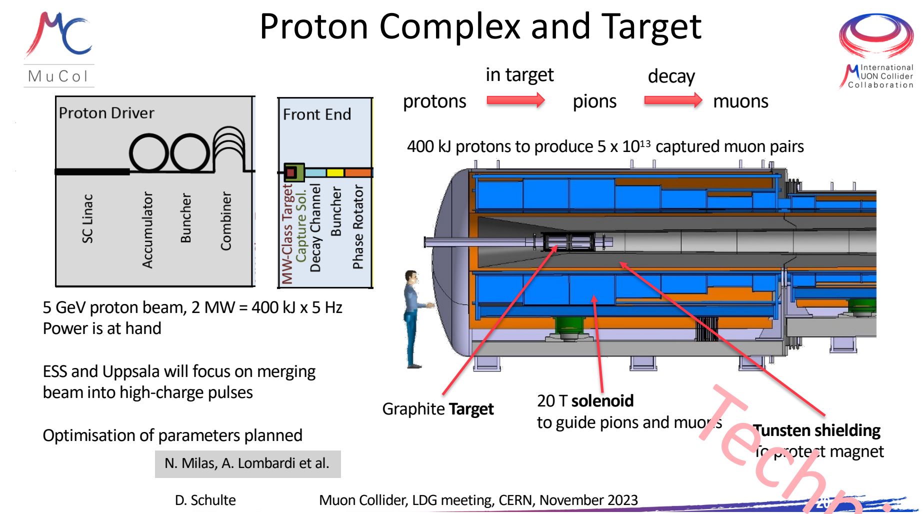
Presently studying **latest 10 TeV** optics (K. Skoufaris et al.) and **nozzle optimization**

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

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

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

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

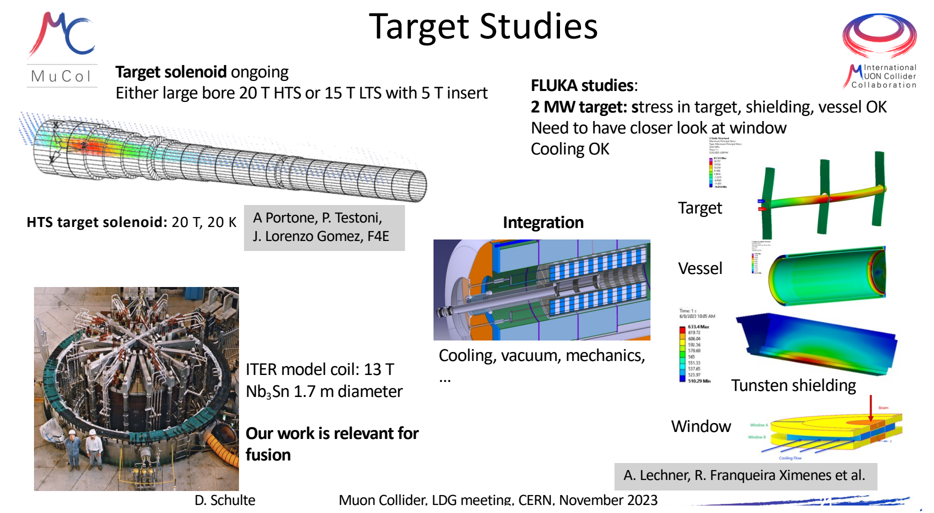
Optimisation of parameters planned

N. Milas, A. Lombardi et al.

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

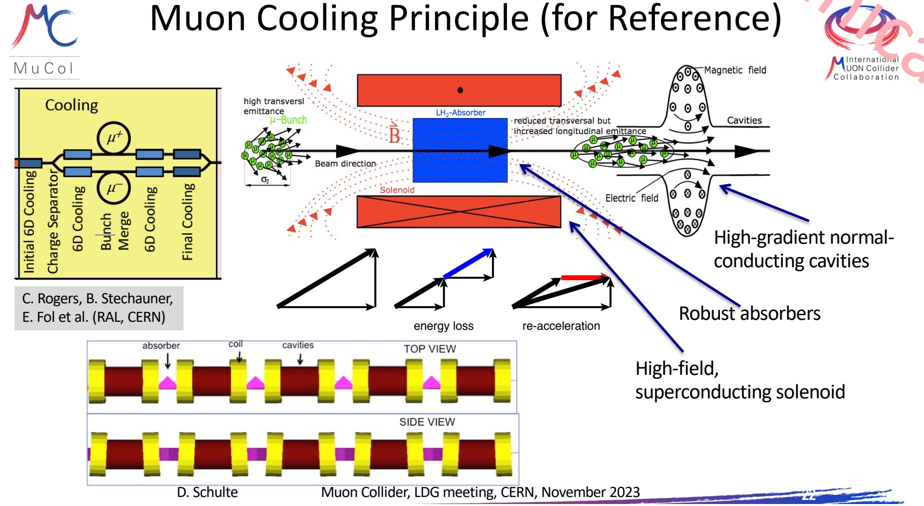
Our work is relevant for fusion

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

Integration

Cooling, vacuum, mechanics, …

A. Lechner, R. Franqueira Ximenes et al.



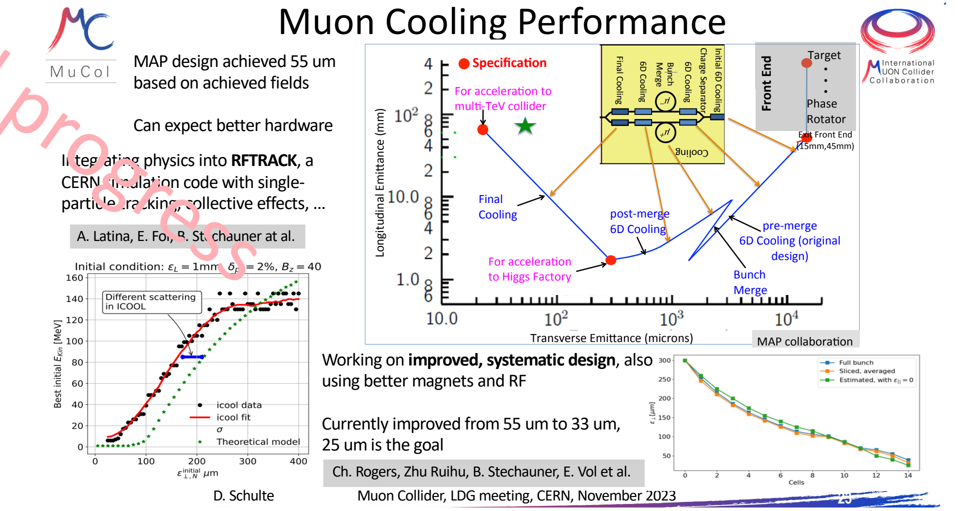
Muon Cooling Principle (for Reference)

C. Rogers, B. Stechauer,
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. Stechauer at al.

MAP collaboration

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

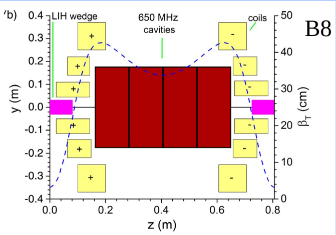
Currently improved from 55 um to 33 um, 25 um is the goal

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

Cooling Cell Technology

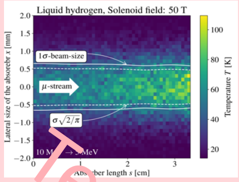
Develop example **cooling cell with integration**
- tight constraints
- additional technologies (**absorbers**, instrumentation,…)
- early preparation of **demonstrator facility**

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

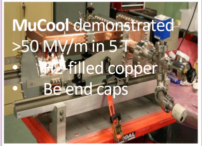


RF cavities in magnetic field

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
- H2-filled copper
- Be end caps

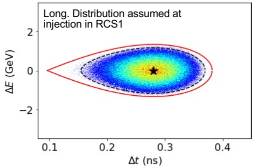
C. Marchand, Alexej Grudiev et al. (CEA, Milano, CERN, Tartu)

Collective Effects and RF Design

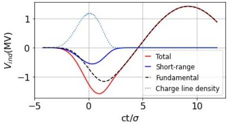
Longitudinal dynamics and RF important due to high bunch charge

- > 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)



1.3 GHz appears possible for longitudinal effects and stability

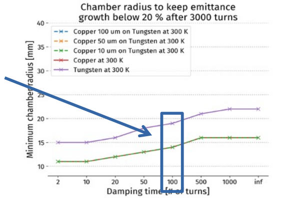


Collider ring single beam instability limits

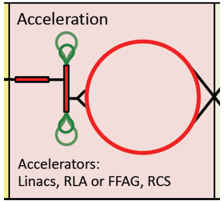
Conservative feedback

Copper coating beneficial (few microns)

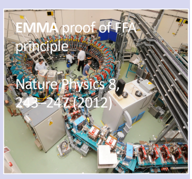
Beam-beam studies started



Acceleration Complex



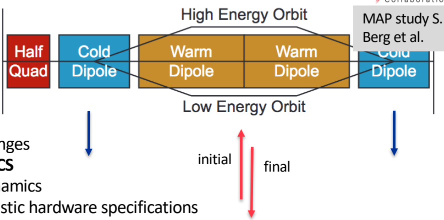
Accelerators:
Linacs, RLA or FFAG, RCS



EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)

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

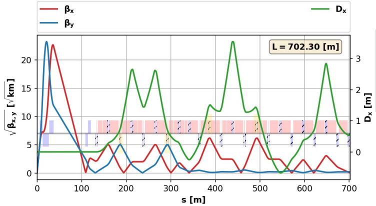
Lattice and integration: A. Chance et al. (CEA)
Long. dynamics and RF systems: H. Damerell, U. van Rienen, A. Grudiev et al. (Rostock, Milano, CERN)
Power converter: F. Boattini et al.
Magnets: L. Bottura et al. (LNCMI, Darmstadt, Bologna, Twente)
FFA: S. Machida et al. (RAL)

Collider Ring

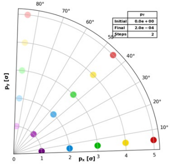
Challenges:
- Very small beta-function (1.5 mm)
- Large energy spread (0.1%)
- Maintain short bunches

MAP developed 4.5 km ring for 3 TeV with Nb_3Sn
- magnet specifications in the HL-LHC range

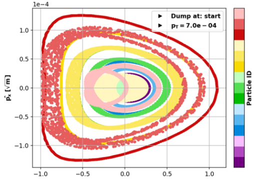
Important progress on **10 TeV collider ring**
- around 16 T HTS dipoles (lower Nb_3Sn to come)
- final focus based on HTS



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

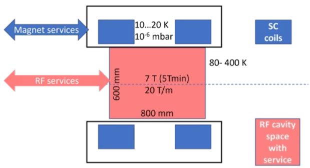


V0.6 good dynamic aperture at almost 0.1% off-energy, approaching the target

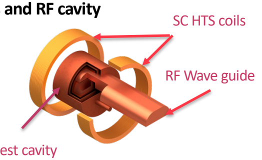
RF Test Stand

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

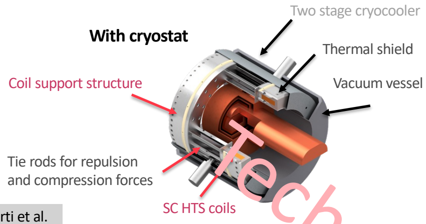
Schematic of the RFMF test facility single cryostat



Bare coils and RF cavity



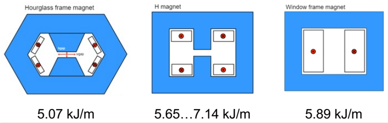
With cryostat



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

Fast-ramping Magnet System (-> Luca)

F. Boattini et al.



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

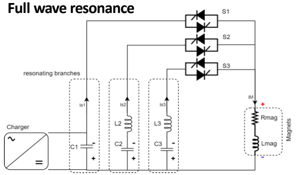
FNAL 300 T/s HTS magnet

Could also use HTS driven dipoles

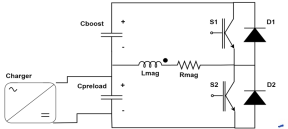
Simple HTS racetrack dipole could match the beam requirements and aperture for static magnets

Differerent power converter options investigated

Full wave resonance



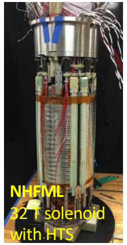
Commutated resonance (new)



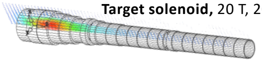
Solenoid R&D

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

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



32 T LTS/HTS solenoid demonstrated



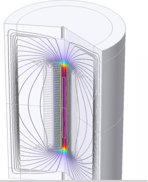
Target solenoid, 20 T, 20 K

Final Cooling solenoid

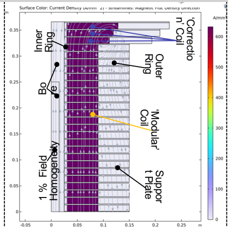
$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$$

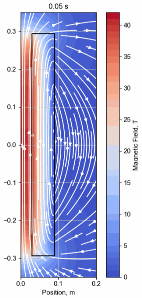
σ_{max} = 600 MPa

$B_{max} \approx 55$ T



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





Collider Ring Technology

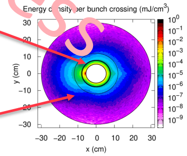
L. Bottura et al.

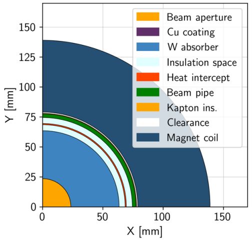
Power loss due to muon decay 500 W/m
FLUKA simulation of **shielding:**
Require 30-40 mm tungsten
- Few W/m in magnets
- No problem with radiation dose

Shielding

A. Lechner
D. Calzolari
(CERN)

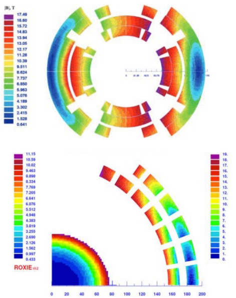
Coil





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

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

Implementation Considerations

Reviewing timeline (still evolving)

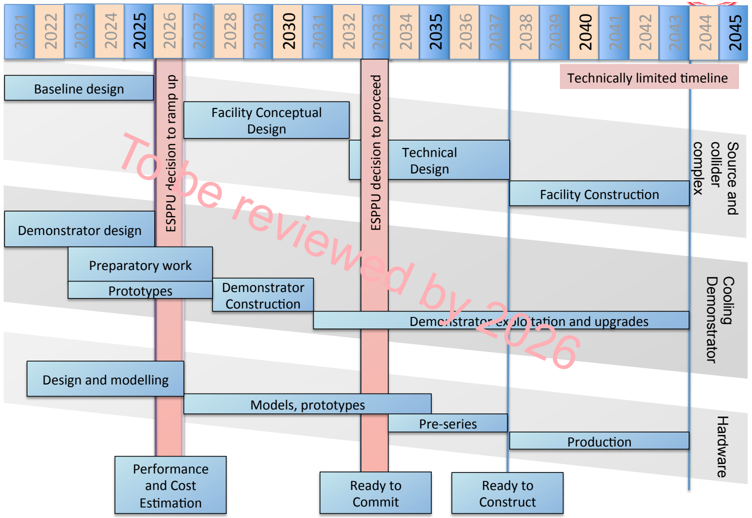
- Uncertainties from physics case (e.g. HL-LHC), society development, budget profile etc.

Goal:

- Identifying shortest possible timeline
    - Technically limited, success-oriented schedule

- On the critical path
    - Muon cooling technologies and integration
    - Magnet technology
    - Detector technologies (not discussed in here)

- Technology appears to be ready before 2040
    - Provided funding is being made available
    - Initial stage to start physics before 2050 appears possible
    - To be confirmed before next ESPPU



Staging Approaches

Assumptions:

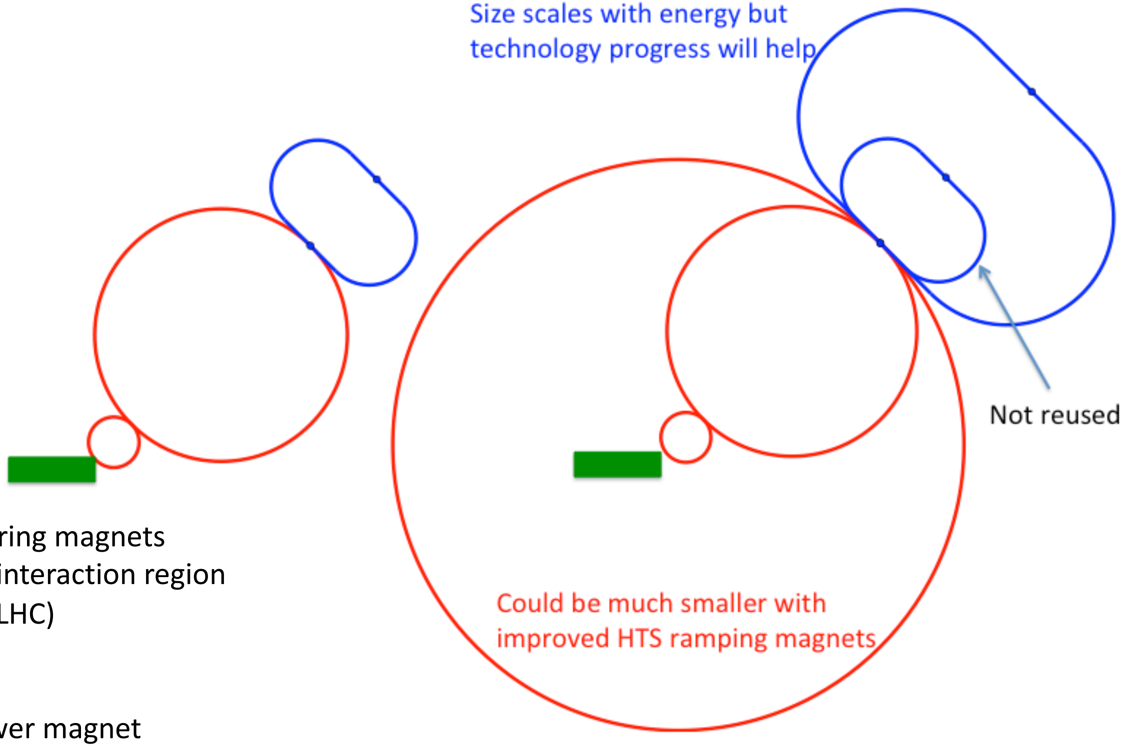
- In O(15 years):
  - HTS technology available for solenoids
  - Nb_3Sn available for collider ring
- In O(25 years):
  - HTS available for collider ring

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)



Size scales with energy but technology progress will help

Not reused

Could be much smaller with improved HTS ramping magnets

Magnet Roadmap

Consensus of experts (review panel):

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

Still under discussion:

- Timescale for HTS/hybrid collider ring magnets
- For second stage can use **HTS or hybrid collider ring magnets**

Strategy:

- HTS solenoids
- Nb_3Sn accelerator magnets
- HTS accelerator magnets

Seems technically good for any future project

New EU Proposal

MuCol

INFRA-2024-TECH-01-01
Discussed in TIARA

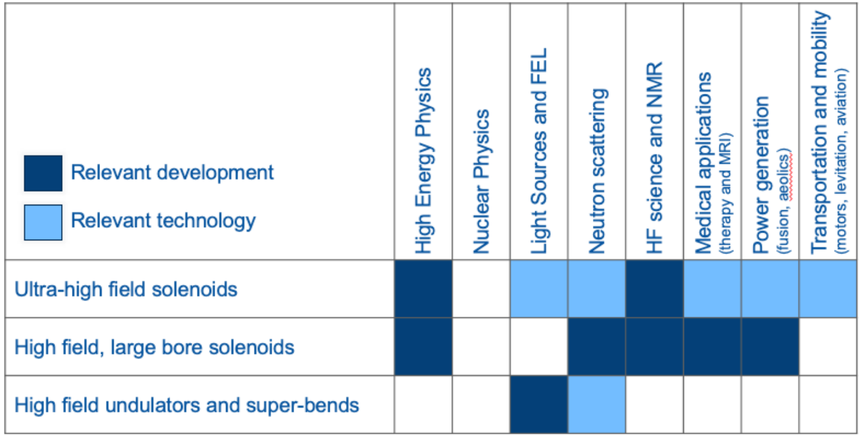
L. Bottura with help from M. Calvi, S. Casalbuoni, X. Chaud, C. Darve, F. Debray, K. Foraz, R. Losito, L. Garcia Tabares, J.M. Jimenez, E. Lelievre, J.M. Perez, L. Rossi, D. Schulte, P. Vedrine, M. Vretenar

International MUON Collider Collaboration

- **Research and Innovation action**: EU expects proposals in the range of 5…10 MEUR from consortia with at least 3 ESFRI/ERIC. Total budget 62 MEUR
- **EU-MAHTS**: European **M**agnet technology **A**dvances through **HTS**, for science and societal applications:
  - Physics – High Energy Physics (MuCol, FCC-hh), Nuclear Physics, Detectors
  - Material and Life Sciences – Synchrotron Light and FEL, High Field Science, Neutron Spectroscopy, NMR
  - Energy and Mobility – Magnetically confined fusion, motors and generators
  - Medicine – Particle therapy, MRI
- **Bridge the gap** between laboratory realizations and deployment (i.e. advance TRL by 2…3 units) by :
  - Developing technology bricks required for the next step in HTS magnets (presently TRL3 to TRL4)
  - Build and test demonstrators, “usable” in field, and engineering templates for transfer to industry (achieve TRL5 to TRL6):
    - 40T class, small bore, all-HTS solenoid (increase field reach)
    - 10T-class, large bore, large stored energy solenoid (manage large magnet dimensions and forces)
    - 2T, 10mm period, 5mm gap undulator (extend photon energy range)

New EU Proposal, cont.

WP1: Organisation
WP2: Applications
WP3: Material and technologies
WP4: Demonstrators
WP5: Test infrastructure



■ Relevant development
▨ Relevant technology

	High Energy Physics	Nuclear Physics	Light Sources and FEL	Neutron scattering	HF science and NMR	Medical applications (therapy and MRI)	Power generation (fusion, aeolics)	Transportation and mobility (motors, levitation, aviation)
Ultra-high field solenoids	■		▨	▨	■	▨	▨	▨
High field, large bore solenoids	■			■	■	■	■	
High field undulators and super-bends			■	▨				

Beneficiaries *(agreed, under discussion)*

- High Energy Physics – CERN (**ESFRI**) and associated laboratories (INFN+UMIL, CEA, CIEMAT)
- Synchrotron light sources and FEL facilities – EUXFEL (**ESFRI**) and associated laboratories (PSI)
- *Nuclear physics – FAIR (**ESFRI**) and GSI*
- *Neutron scattering – ESS (**ESFRI**)*
- *High Field Science – EMFL (**ESFRI**) laboratories (LNCMI, HLD, HFML)*

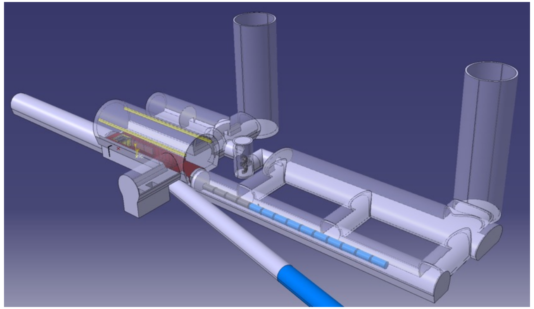
Association planned of several other partner institutes and universities, including fusion, and a substantial participation from European Industry

Demonstrator Site Study

Cooling demonstrator is a key facility
Different sites are being considered

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

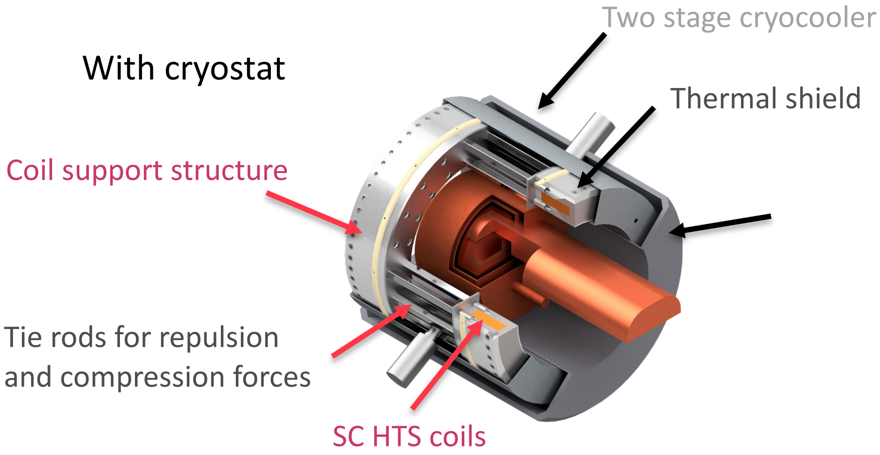
Plan workshop to discuss options



Are developing **schedule**

- Site dependence exists
- Need some infrastructure early
  - E.g. infrastructure to test RF cavities in magnetic field
- Also understand decision making, administrative procedures, civil engineering, …
- Currently looks promising
  - Assuming we and the funding agencies are determined

With cryostat



Collider Site Studies

Study is mostly site independent

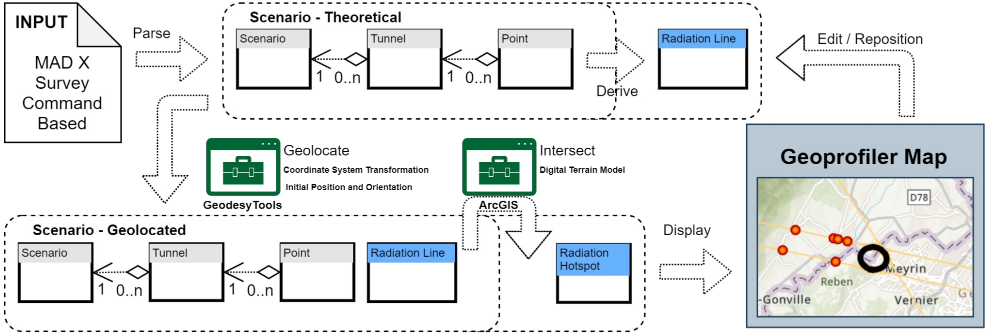
However, some considerations are being made

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

- FNAL takes test facility into account in their ACE plans

But need some site considerations

Main site concern:
Neutrino flux mitigation
Neutrinos in direction of experimental insertions need to be mitigated by site choices


INPUT
MAD X Survey Command Based
Parse
Scenario - Theoretical
Scenario
Tunnel
Point
1 0..n
1 0..n
Derive
Radiation Line
Edit / Reposition
Geolocate
Coordinate System Transformation
Initial Position and Orientation
GeodesyTools
Intersect
Digital Terrain Model
ArcGIS
Scenario - Geolocated
Scenario
Tunnel
Point
Radiation Line
1 0..n
1 0..n
Radiation Hotspot
Display
Geoprofiler Map

Main site benefit:
Potentially significant cost saving from reusing exiting infrastructure

Will study this later

Potential site next to CERN identified

- Mitigates neutrino flux
  - Points toward mediterranean and uninhabited area in Jura
- Detailed studies required (280 m deep)

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

Tentative agenda SB meeting January 2024

- Updates and recent LCB input (20’)
  - Highlighting a few main issues only
- Towards the interim report (20’)
  - Description and status of report
- International Advisory Committee (15’)
  - First task: review the interim report early 2024
  - Proposal in this meeting - with mandate.
  - Small number of fixed members, one or two SB members ex-officio, specialists chosen review by review
- Updates from the US (after P5) and other regions and implications for the muon collider studies (20’)
- Collaboration organisation in more detail (this is likely to slide into next meeting)
  - Structure of scientific and technical studies and tasks/duties, interfaces, coordinators (in some cases more than one person) -> offer new members opportunities and welcome new initiatives

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
        - …

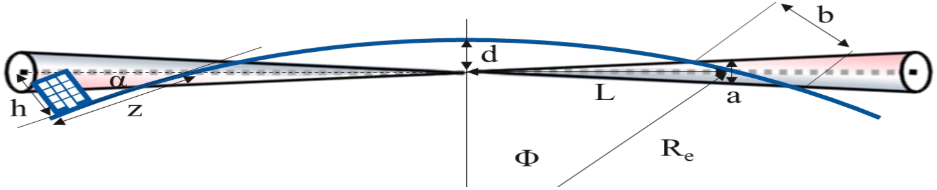
- Short term: Interim Report to describe progress and expectations

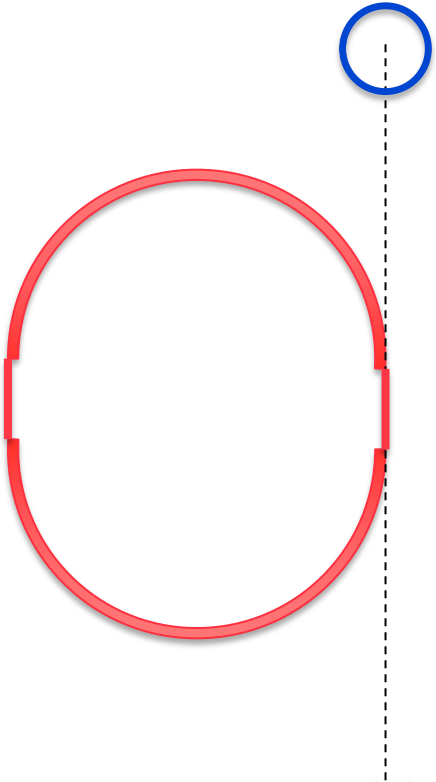
Many thanks to all that contributed

http://muoncollider.web.cern.ch

Reserve

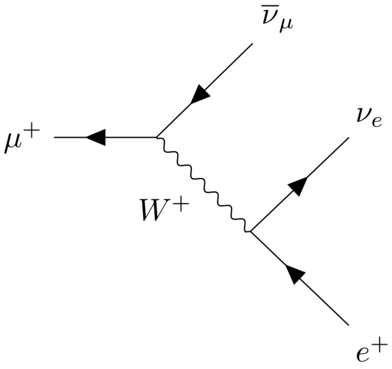
Neutrino Flux

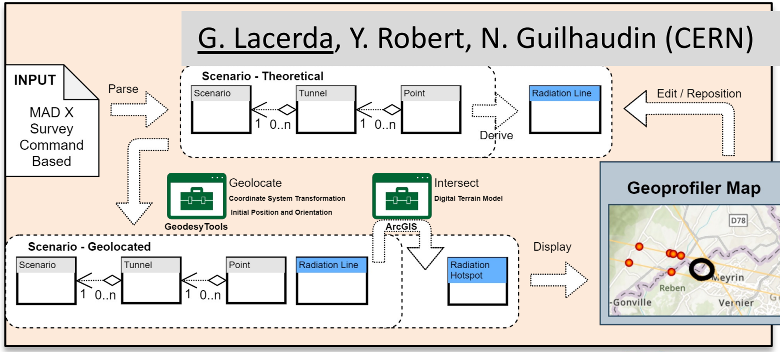




O(10^{11}-10^{12}) neutrinos per second
Plan to either dilute or likely aquire the land around this spot

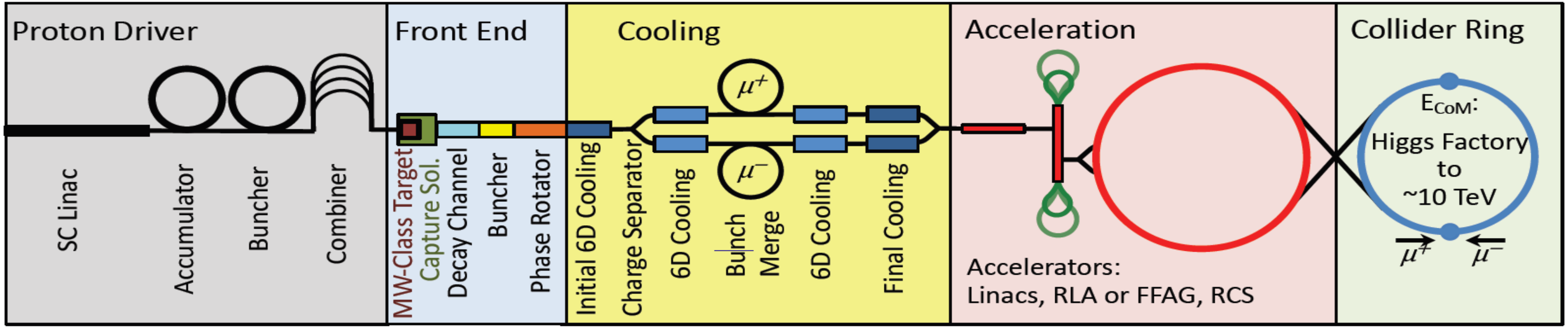
Important to know if this is helpful becsause depends on the lattice design





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

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 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	

US Snowmass

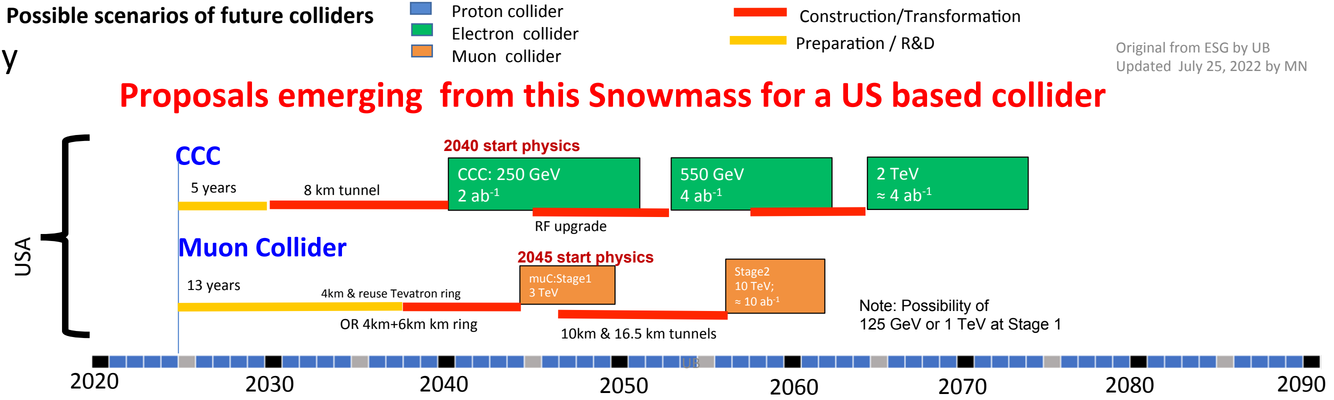
Strong interest in the US community in muon collider

- 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

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}

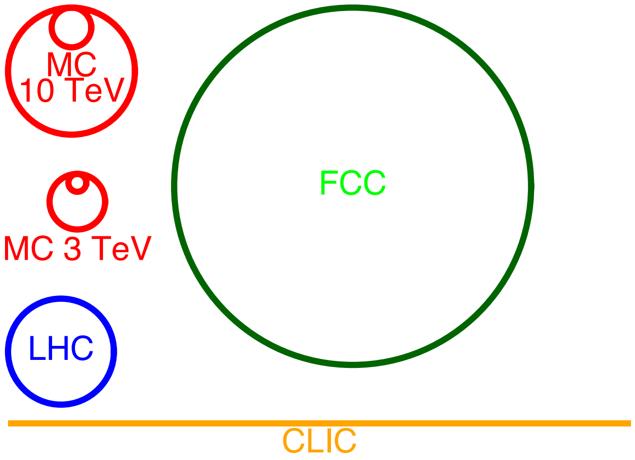
Muon Collider
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage1
3 TeV
10km & 16.5 km tunnels
Stage2
10 TeV;
≈ 10 ab^{-1}
Note: Possibility of
125 GeV or 1 TeV at Stage 1

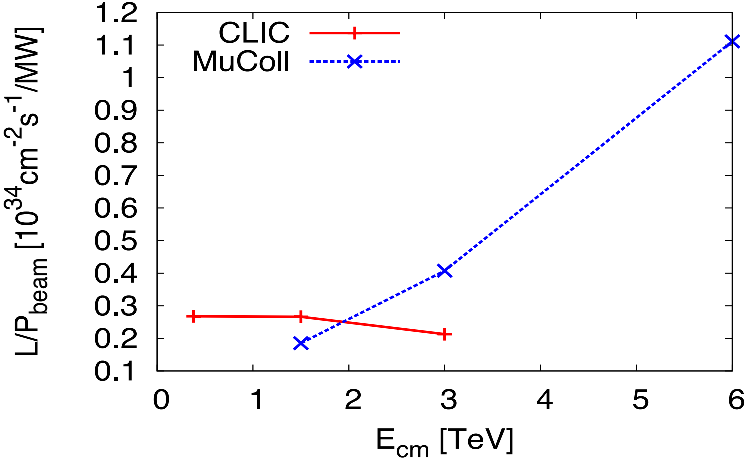
- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or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

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**

US Snowmass Implementation Task Force

ITP investigated the muon collider and concluded:

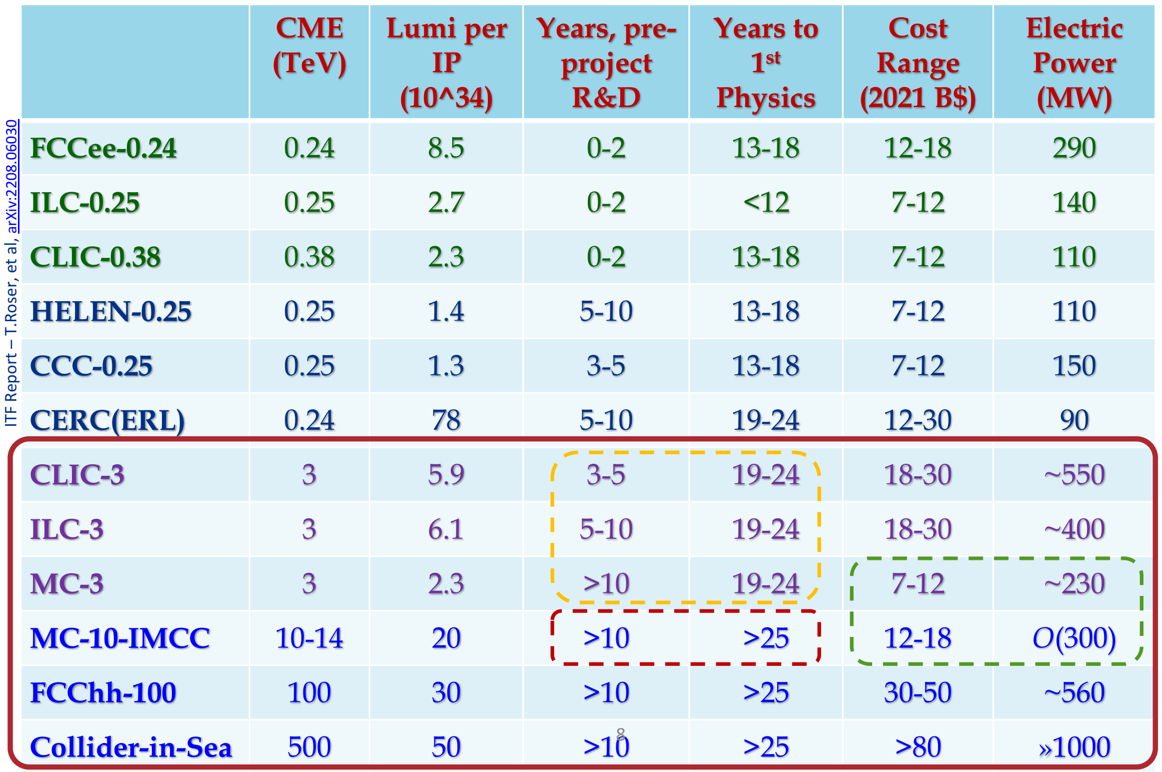
- Muon Collider is a viable option for the HEP future

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.

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

Possible CERN Locations

Consider nTOF-like beam from PS for cooling experiment:

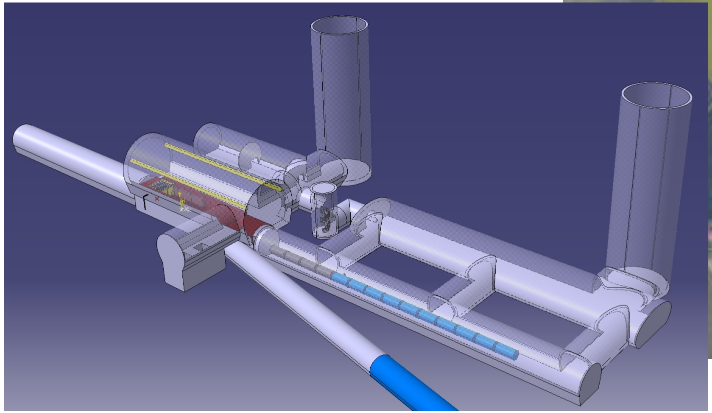
- 1 pulse of 10^{13} p at 20 GeV per 1.2 s, i.e. 27 kW
- maybe O(100kW) possible

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

M. Calviani

80 kW/4 MW option

10 kW option



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

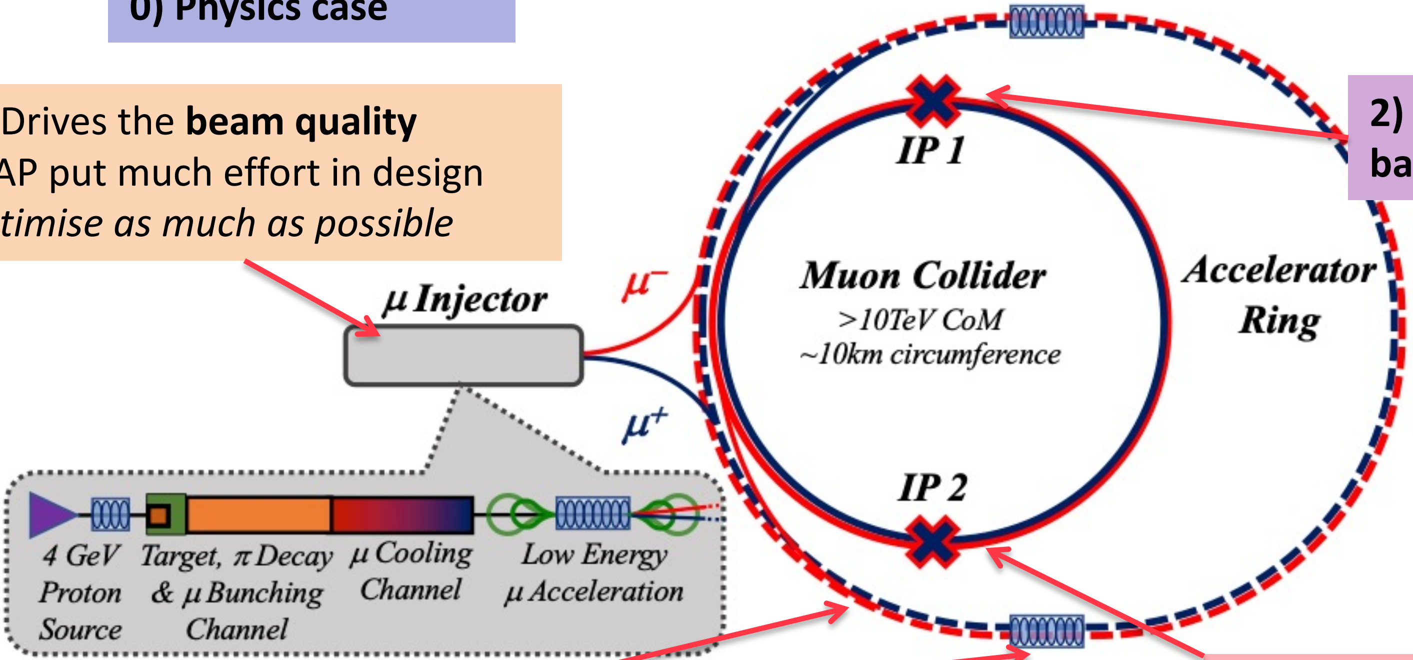
D. Lucchesi, F. Meloni et al.

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

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

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**