International
MUON Collider
Collaboration

MuCol

Muon Collider

D. Schulte
for the International Muon Collider Collaboration

Annual meeting, Orsay, June 2023

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

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(40-50 FTE) for accelerator
- Efforts to increase resources

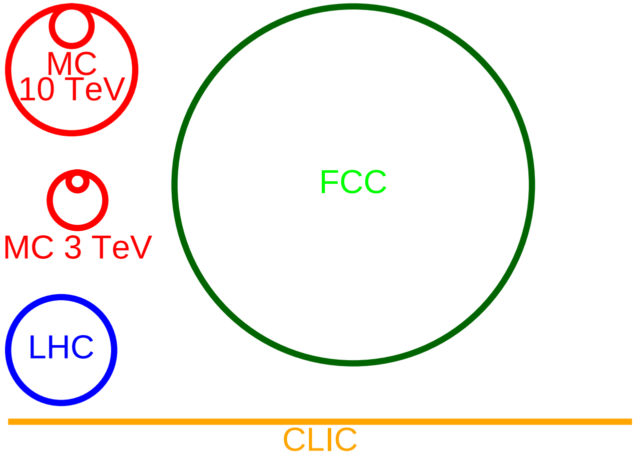
Scenario	FTEy	M MCHF
Full scenario	445.9	11.9
Reduced scenario	193	2.45

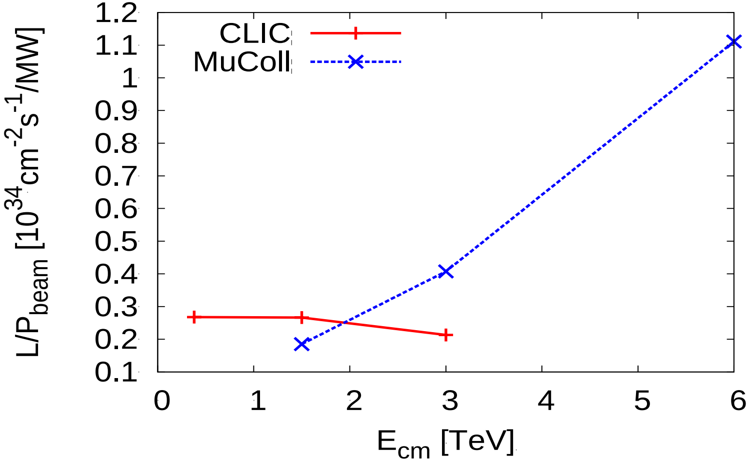
http://arxiv.org/abs/2201.07895

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.

Cost and Sustainability





Compactness promises **cost effectiveness**
And low CO_2 footprint for construction

Increasing luminosity per beam power promises **power efficiency**

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

Roadmap: Technically Limited Timeline

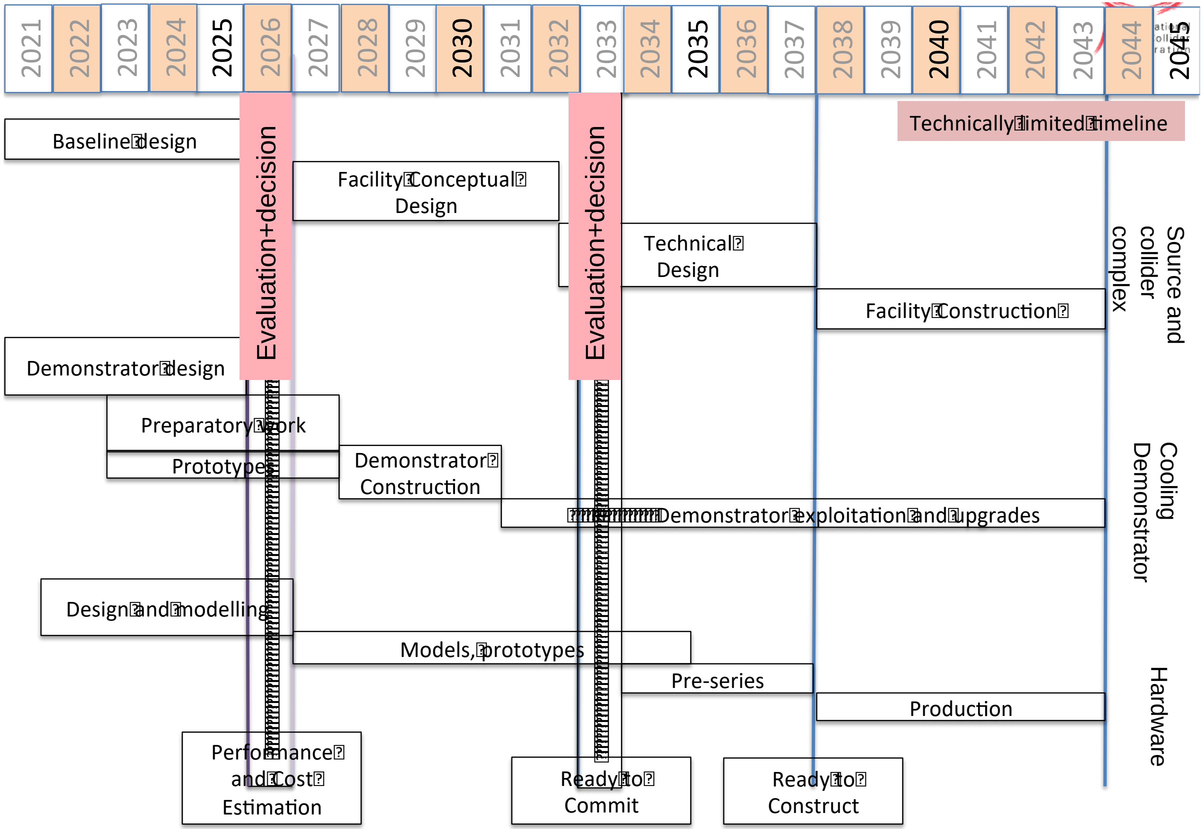
To be reviewed considering progress, funding and decisions

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


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

Baseline design

Facility Conceptual Design

Technical Design

Facility Construction

Source and collider complex

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Cooling Demonstrator

Design and modelling

Models, prototypes

Pre-series

Production

Hardware

Performance and Cost Estimation

Ready to Commit

Ready to Construct

Roadmap Schedule

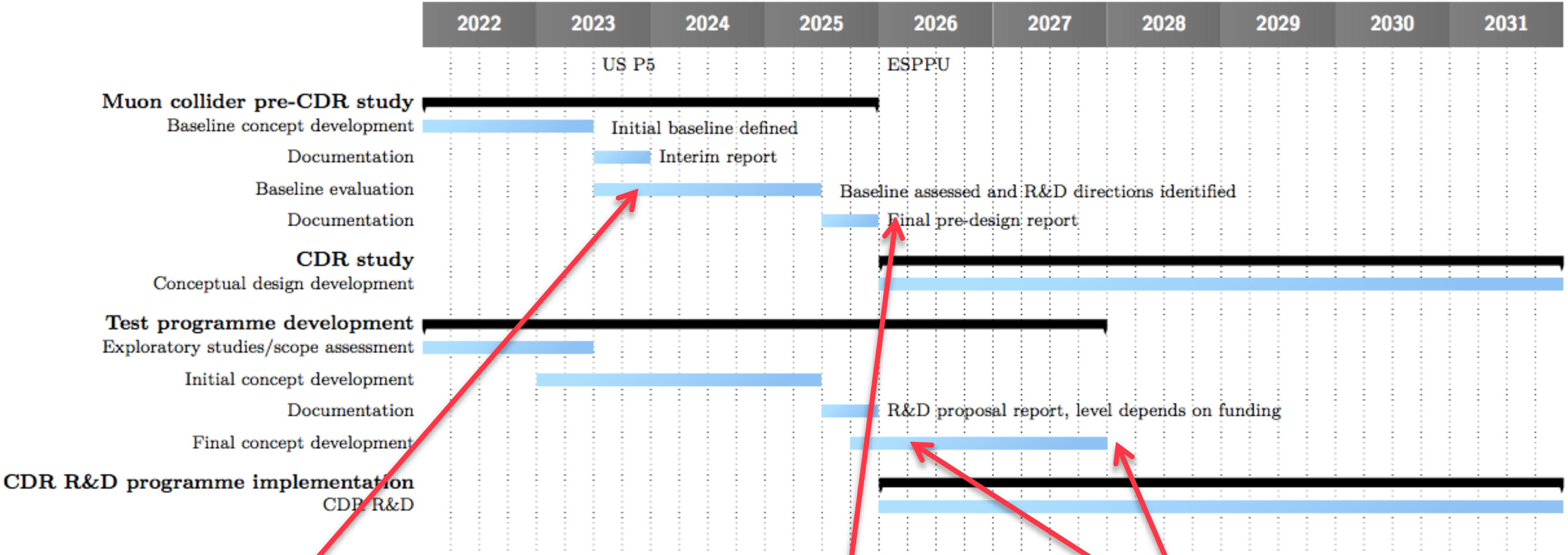


Fig. 5.4: Overall timeline for the R&D programme.

2023

Interim Report to gauge progress

Initial baseline defined

2025

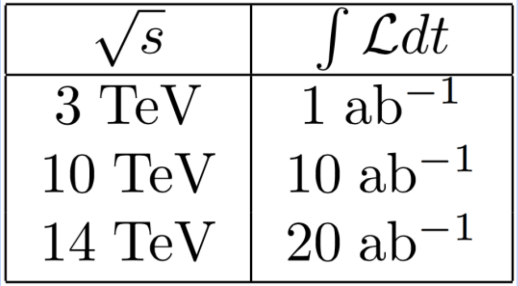
Assessment Report

2025-2027

R&D plan will be refined

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}

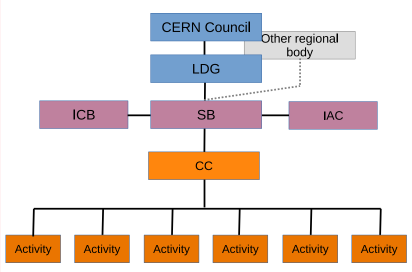
Note: currently focus on 10 TeV, also explore 3 TeV

- 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 Collider Community

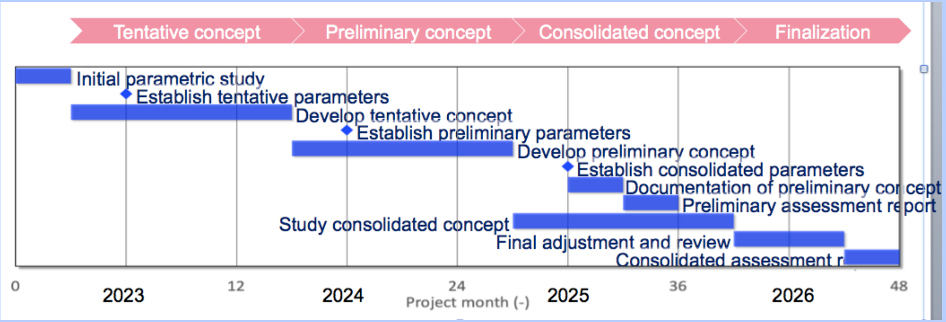
Formed **collaboration** to implement and R&D Roadmap for CERN Council



50+ partner institutions
30+ already signed formal agreement

EU Design Study approved

(EU+Switzerland+UK and partners)



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

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

TIARA wants magnet proposal

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

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

Organisation

Collaboration Board (ICB)

- Elected chair: **Nadia Pastrone**

Steering Board (ISB)

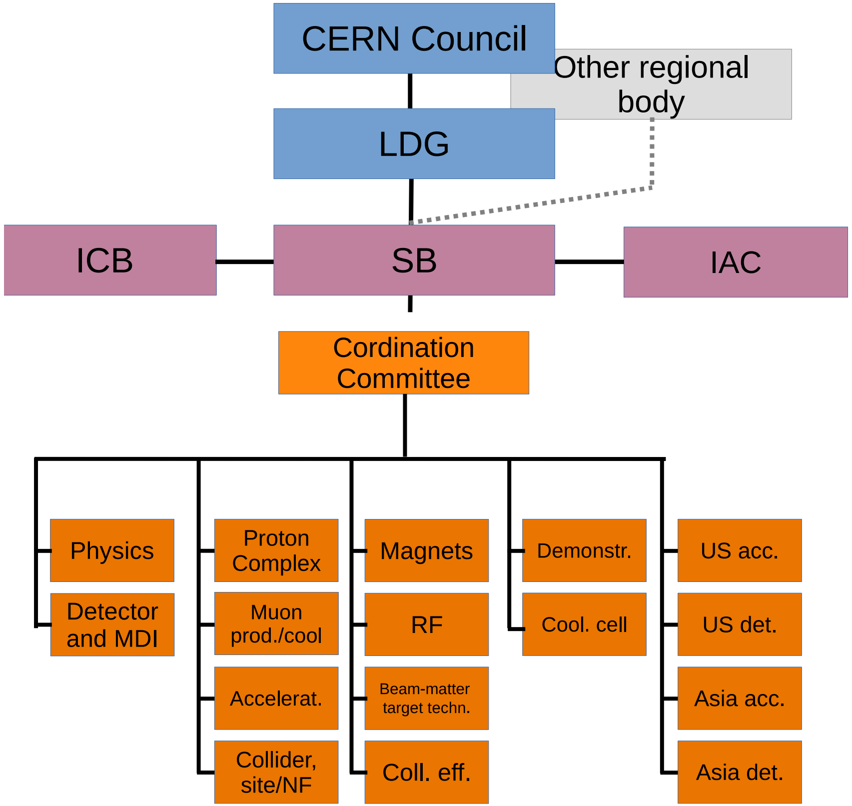
- Chair **Steinar Stapnes**
- CERN members: Mike Lamont, Gianluigi Arduini
- ICB members: Dave Newbold (STFC), Mats Lindroos (ESS), Pierre Vedrine (CEA), N. Pastrone (INFN)
- Study members: SL and deputies
- Will add US but wait for US decision on members

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.

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

EU Design Study

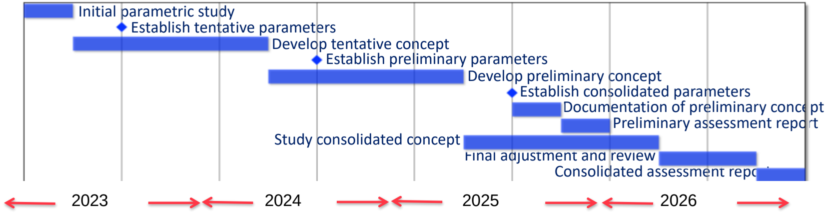
Has been approved summer 2022

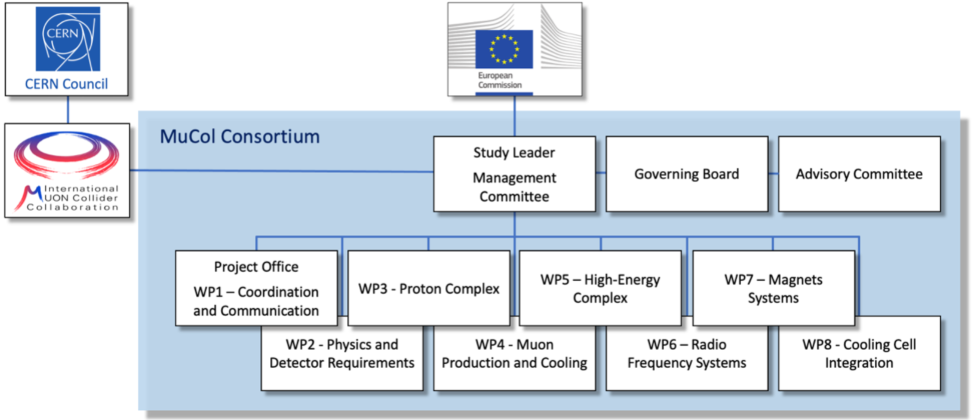
- Very helpful to kick-start collaboration

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





CERN Council

MuCol Consortium

Study Leader
Management Committee

Governing Board

Advisory Committee

Project Office
WP1 – Coordination and Communication

WP2 - Physics and Detector Requirements

WP3 - Proton Complex

WP4 - Muon Production and Cooling

WP5 – High-Energy Complex

WP6 – Radio Frequency Systems

WP7 – Magnets Systems

WP8 - Cooling Cell Integration

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

Many thanks to all that contributed

https://mucol.web.cern.ch

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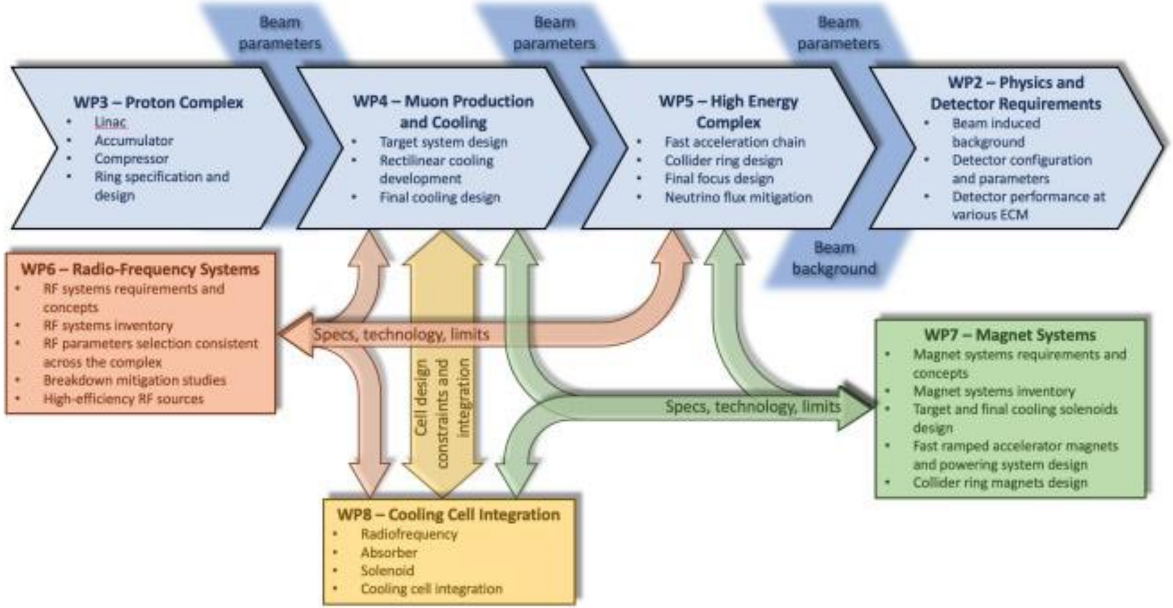
EU Design Study Work Programme

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



Beam parameters

Beam parameters

Beam parameters

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

Beam background

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

Specs, technology, limits

Cell design constraints and integration

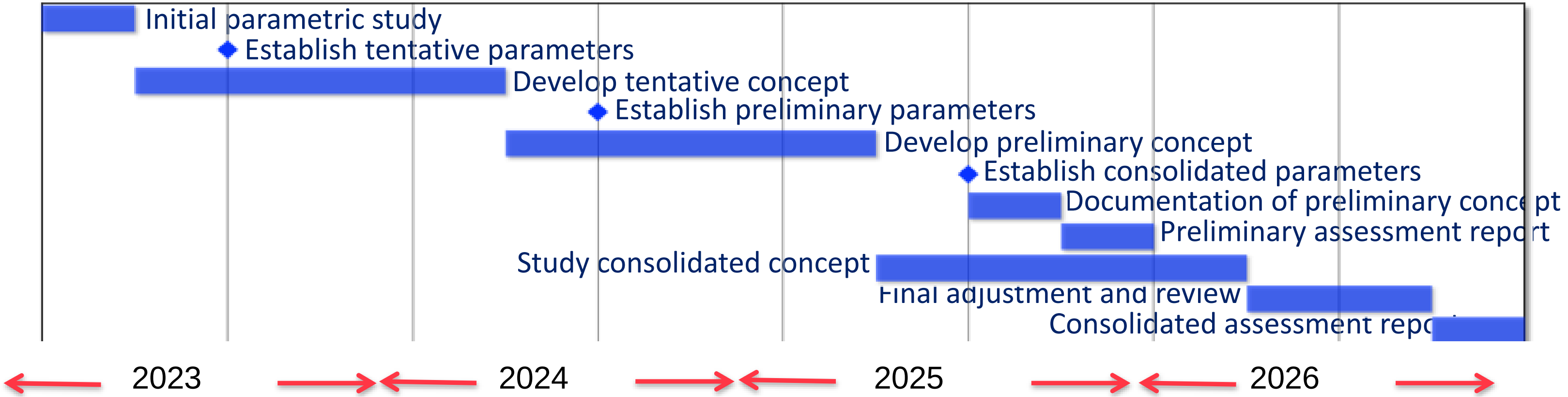
Specs, technology, limits

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

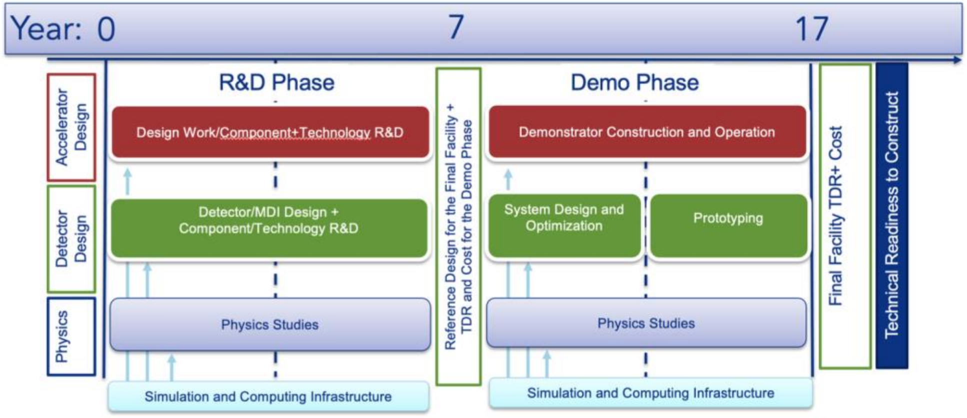
MuCol Timeline



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

US P5 Ask



Year: 0 7 17

R&D Phase

Demo Phase

Accelerator Design

Detector Design

Physics

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

Demonstrator Construction and Operation

System Design and Optimization

Prototyping

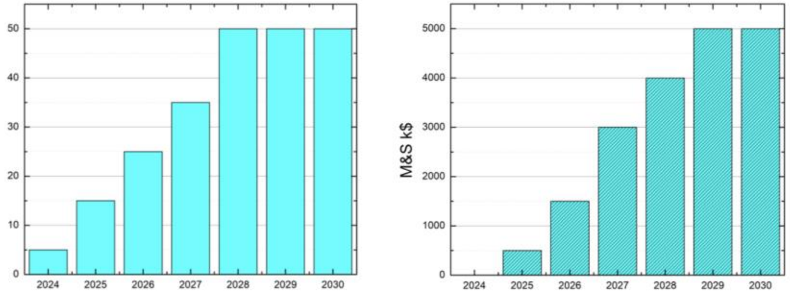
Physics Studies

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

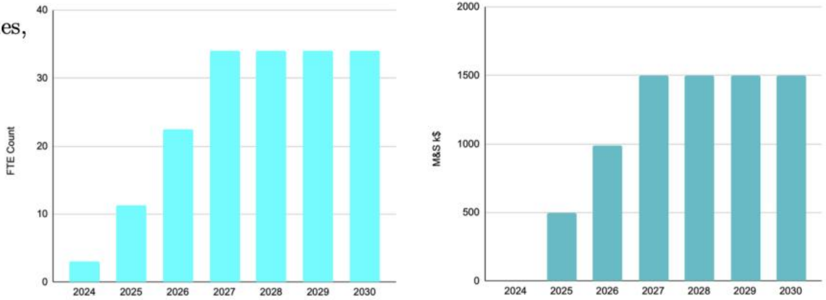


Figure 3: FTE and M&S profiles for detector R&D corresponding to the first phase of the program. We assume here that funding can start in 2024. The M&S is in FY23 dollars and escalation is not included in these estimates.

US Integration

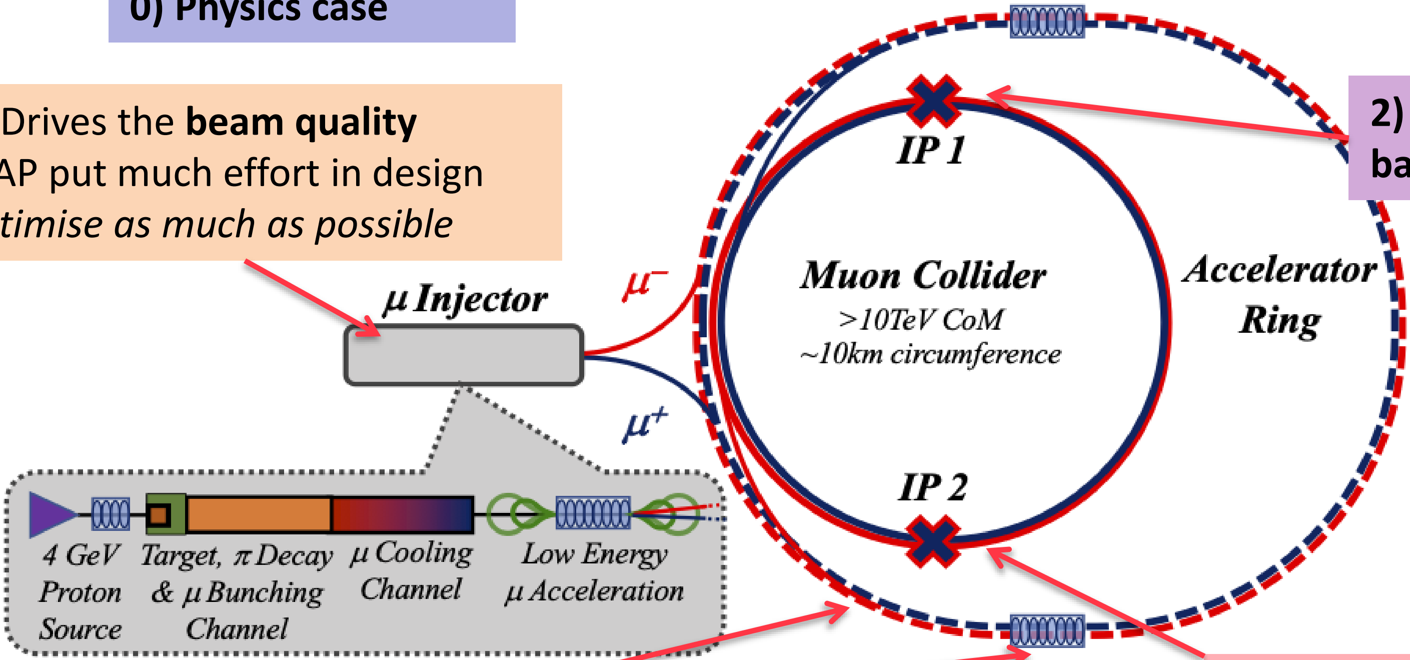
- Participation of US experts to CC and ICB
- Preparing open data and code policy
  - You can use data and codes from the collaboration, as far as we own them
- Want to allow everyone to publish under the IMCC or to speak for the IMCC
  - Provided our procedures are respected
- Small task force to understand how a common work programme can be developed
  - Progress will have to synchronise with US progress
- Plan to review organization next year to integrate US
  - But have to wait for US decisions
- Will find common timelines/scenarios

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

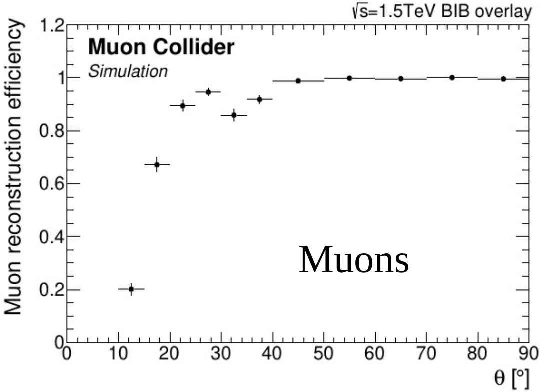


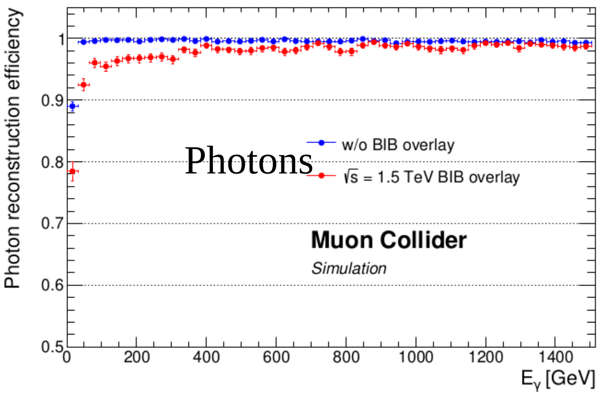
1) Dense neutrino flux
mitigated by mover system
and site selection

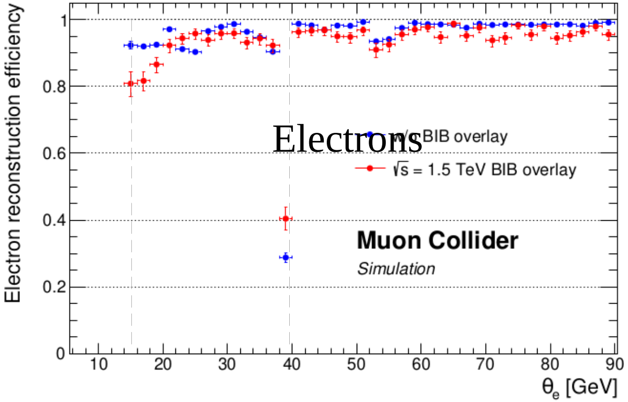
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

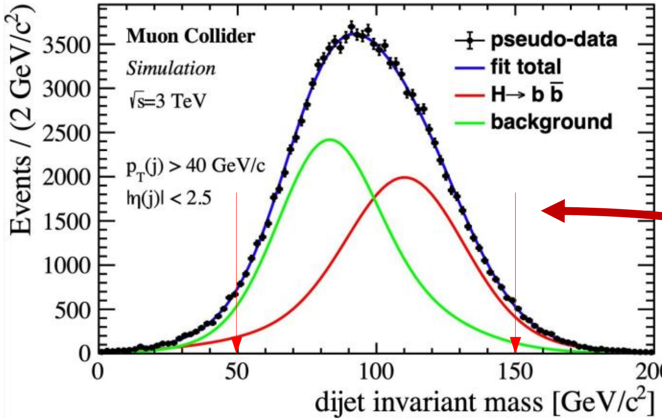
Detector Study Status

A non optimized detector used to evaluate major physics performance by using detailed simulation









- Use MAP BIB files with $\sqrt{S} = 1.5$ TeV configuration
- Still missing:
  - PID
  - Taus

Tracking+jets+b-tag
Meet requirements for
precision SM measurements

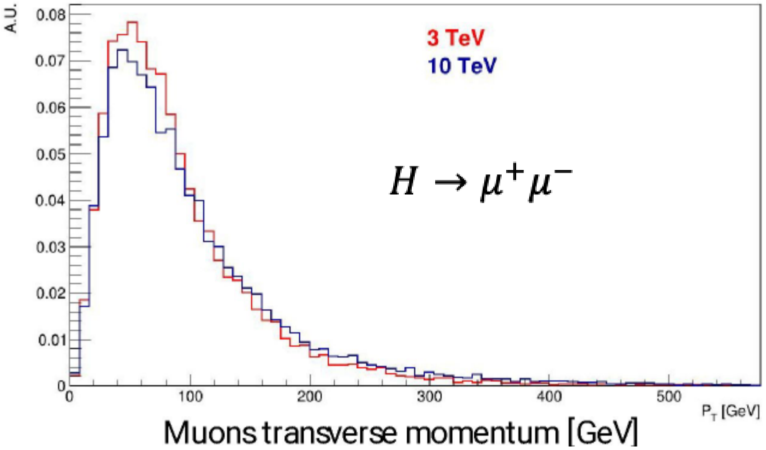
D. Lucchesi et al.

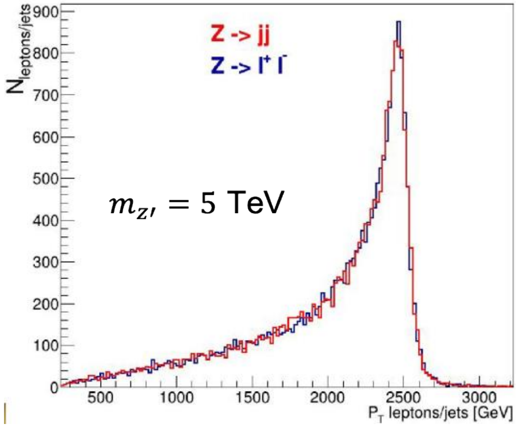
Strategy Toward 10 TeV Detector

Strategy:

- Definition of the working hypothesis
  - BIB at the same level, it is dominated by the nozzle
- Definition of detector requirements
  - Use experience gained on 1.5/3 TeV
- Use two physics cases to study physics objects characteristics:
  - Higgs decay channels @ 10 TeV
  - Heavy Z' produce via vector bosons fusions

L. Buonincontri IMCC October 2022





D. Lucchesi et al.

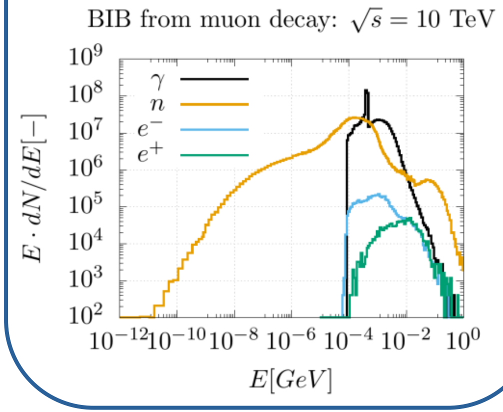
Machine-detector Interface

- Study the **beam-induced background (BIB)** and identify mitigation strategies.
- Achieve a conceptual **interaction region (IR) design** compatible with detector operations
- Address **different centre-of-mass energies**, with particular focus on √s = 3 TeV and √s = 10 TeV

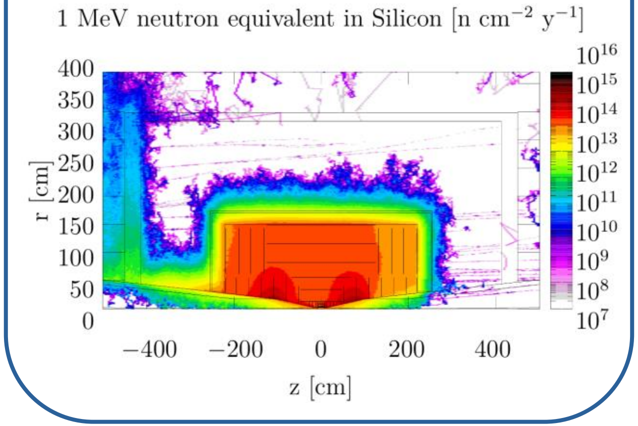
- FLUKA studies with various lattice configurations:
  - A dipole component mitigates only slightly the BIB
  - Nozzle is the determinant component for the BIB. As starting point, the 1.5 TeV MAP design (N. Mokhov) was taken
- Similar BIB multiplicity for all collider energies
- Simulation with the latest 10 TeV optics (K. Skoufaris et al.) and nozzle optimization currently ongoing

D. Calzolari, A. Lechner et al.

Evaluate BIB with different lattice and nozzle configurations



Long term radiation damage assessment in detectors



Proton Complex

N. Milas et al.

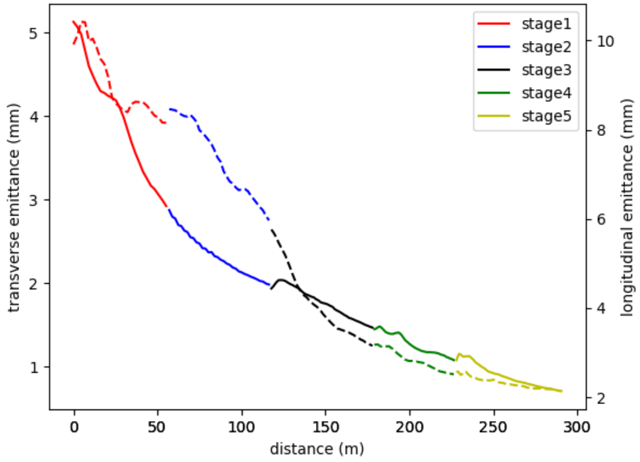
- Review of linac parameters is ongoing.
  - High intensity machine development through LINAC4 : high intensity beam (35mA peak) has reached the end of the linac and it has been successfully injected in the PSB
- We have a baseline lattice for accumulator compressor
  - Based on the lattice for the neutrino factory) for the 5 GeV case.
- Work ongoing on limitations to accommodate the 2MW beam at 5 Hz
- PhD student at ESS for accumulator/compressor selected, will start in August.
- Hiring postdoc (ESS/Uppsala) is in the process.
- Discussions about possible machine development at the CERN injector complex to verify ideas/simulations for the accumulator/compressor are ongoing.

Muon Cooling

Rectilinear cooling channel:

Building on MAP design

- Optimising baseline cooling channel
- Examining alternative arrangements
    - e.g. High pressure gas in RF cavities

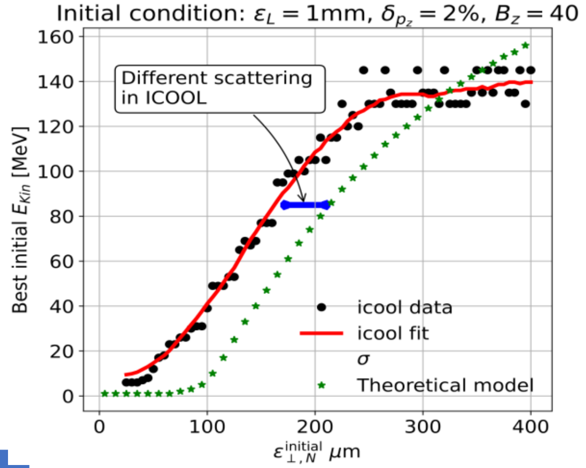


Ch. Rogers, Zhu Ruihu et al.

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

Code development: Integrating multiple scattering in **RFTRACK**, code maintained at CERN, including collective effects

	$\varepsilon_\perp$(mm)	$\varepsilon_\parallel$(mm)	ε_{6D}(mm^3)	T(%)
initial	5.13	9.91	260	
Stage 1	2.92	8.16	71.6	87.1
Stage 2	1.99	5.97	24	91.2
Stage 3	1.47	3.16	7.12	88
Stage 4	1.08	2.52	3.11	92.2
Stage 5	0.712	2.14	1.14	89.2



Final Cooling 1:

Determine optimum cooling energy based on emittances

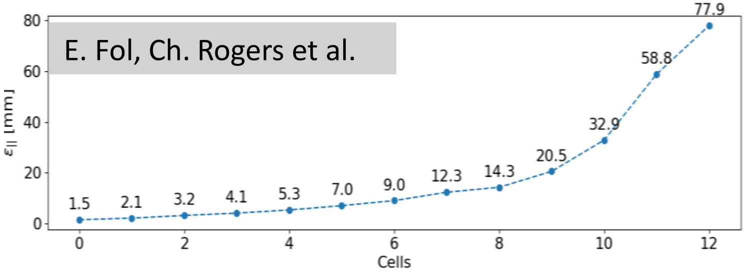
B. Stechauner et al.

Muon Cooling

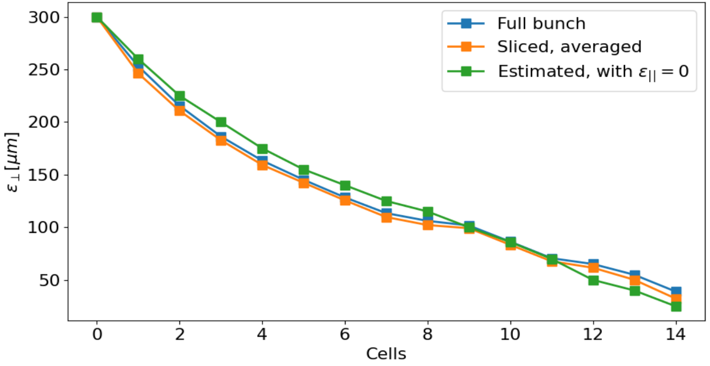
Final cooling design

Simplified RF, 40 T solenoids, 4 MeV after last window

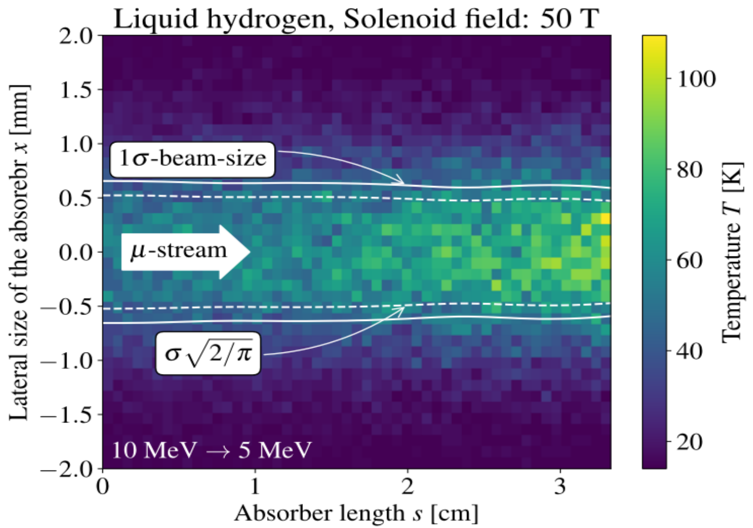
- Comes closer to target performance



E. Fol, Ch. Rogers et al.



B. Stechauner, J. Ferreira et al.



Cooling technology

Started considering absorber for final cooling

- Muon beam is dense, have to consider heating
- Can limit pressure rise limited with gas density
  - Leads to acceptable absorber lengths
- Windows are under investigation
  - Plan experiments at HiRadMat

RCS Design

A. Chance, F. Batsch et al.

Example parameters for the muon RCSs

- **Detailed parameter table (by F. Batsch):** https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz
- Parameters of the 4th RCS under study.
- **Several proceedings at IPAC'23:**
  - "Parameter Ranges For A Chain Of Rapid Cycling Synchrotrons For A Muon Collider Complex"
  - "Longitudinal beam dynamics and RF requirements for a chain of muon RCSs"
  - "Transverse impedance and beam stability studies for the Muon collider Rapid Cycling Synchrotrons"
- Next steps:
  - To refine the parameters tables.
  - To improve the lattice generator to get a full optics of the RCS (integration of the RF cavities).

	RCS1	RCS2	RCS3	RCS4
Hybrid RCS	No	Yes	Yes	Yes
Circumference [m]	5990	5990	10700	26659
Injection/extr. energy [TeV]	0.06/0.30	0.30/0.75	0.75/1.5	1.5/4.2
Survival rate [%]	90	90	90	90
Acceleration time [ms]	0.34	1.10	2.37	5.75
Number of turns	17	55	66	65
Energy gain/turn [GeV]	14.8	7.9	11.4	41.5
NC dipole field [T]	0.36/1.8	-1.8/1.8	-1.8/1.8	-1.8/1.8
SC dipole field [T]	-	10	10	16
NC/SC dipole length [m]	2.6/-	4.9/1.1	4.9/1.3	8.0/1.3
Number of arcs	34	26	26	26
Number of cells/arc	7	10	17	19
Cell length [m]	21.4	19.6	20.6	45.9
Path length diff. [mm]	0	9.1	2.7	9.4
Orbit difference [mm]	0	12.2	5.9	13.2
Min. dipole width [mm]	17.4	19.6	10.7	18.8
Min. dipole height [mm]	14.8	6.4	4.2	4.4

Collective effects and shielding not included

RF Progress

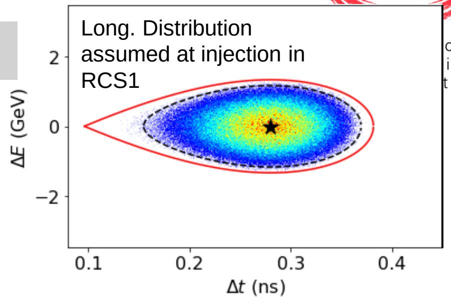
F. Batsch, H. Damerau, A: Grudiev, U. van Rienen et al.

Longitudinal emittance target value (norm.):

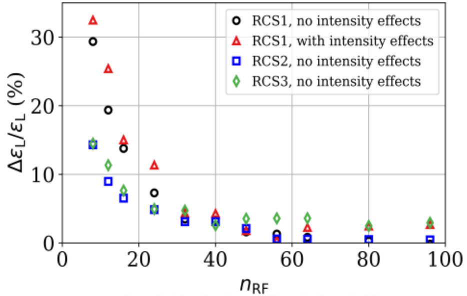
- $\sigma_z \cdot \sigma_E = 7.5$ MeVm $\triangleq$ 0.025 eVs $\rightarrow$ $4\pi \cdot \sigma_t \cdot \sigma_E = 0.31$ eVs for ellipse

30 MV/m as baseline and demonstrated, 45 MV/m as optimistic option

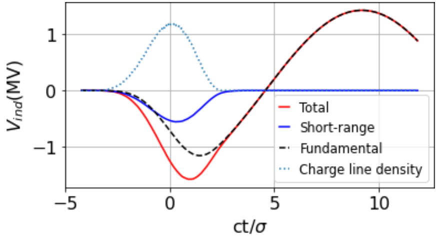
Emittance blow-up from final cooling to IP budgeted with 10% → challenge assuming 3% to 4% per RCS and beam transfers

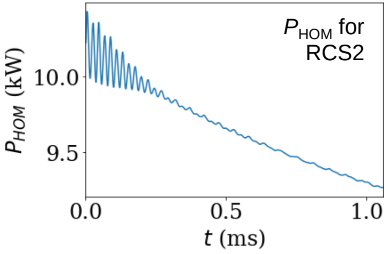

Long. Distribution assumed at injection in RCS1

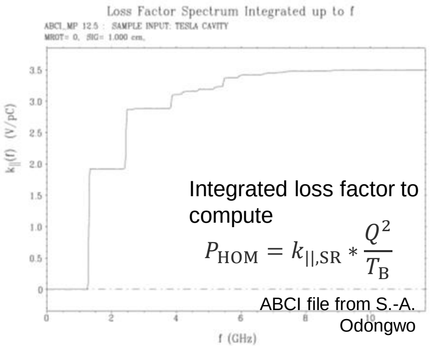
- Around 30 RF stations needed for longitudinal stability and focusing
- Changes in orbit length require frequency tuning required (A. Chancé)
- Single-bunch HOM power loss up to 10 kW averaged over the acceleration time
- CW average is lower, development of high-capacity couplers needed



Induced voltages in RCS1 for a single bunch →




P_{HOM} for RCS2



Integrated loss factor to compute

$$P_{\mathrm{HOM}} = k_{||,\mathrm{SR}} * \frac{Q^2}{T_{\mathrm{B}}}$$

ABCI file from S.-A. Odongwo

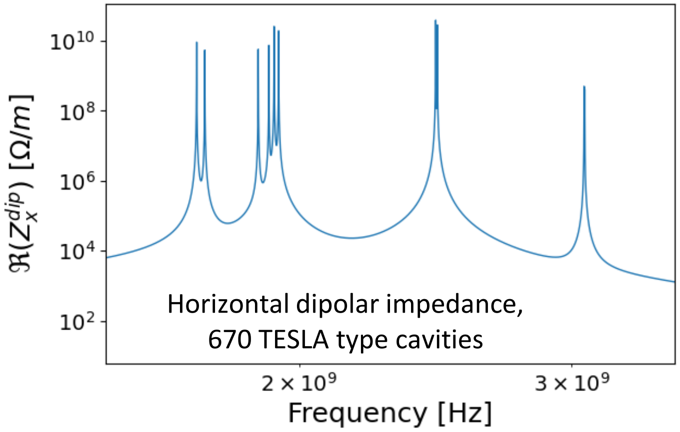
Collective Effects

D. Amorim, E. Metral, X. Buffat

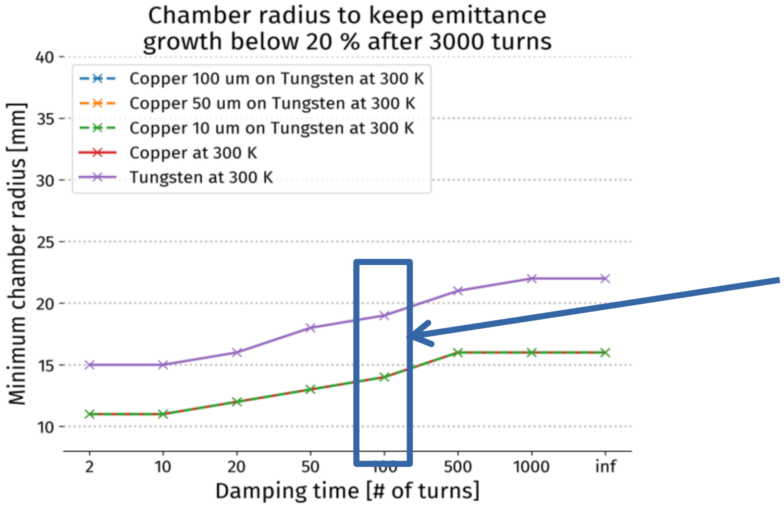
RCS:

- Assuming O(700) **TESLA type RF** cavities
- Impact of initial transverse offset for single beam

- Two beam under investigation



Horizontal dipolar impedance,
670 TESLA type cavities



Collider ring

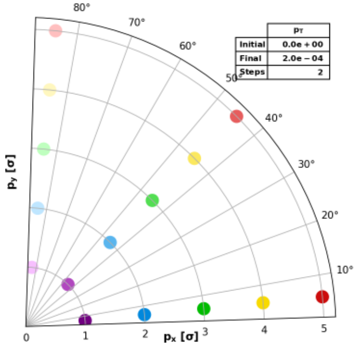
- Single beam instability limits
  - Conservative feedback
- Copper coating beneficial (few microns)
- Minimum radius from impedance:
  - 14mm with copper coating
  - 19mm for direct tungsten

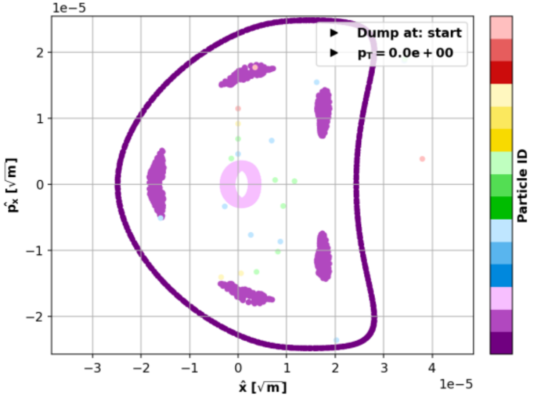
Collider Ring Lattice

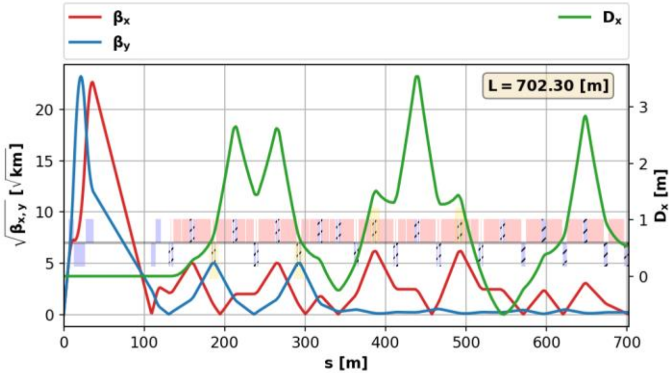
K. Skoufaris, Ch. Carli, support from
P. Raimondi, K. Oide, R. Tomas

Important progress:

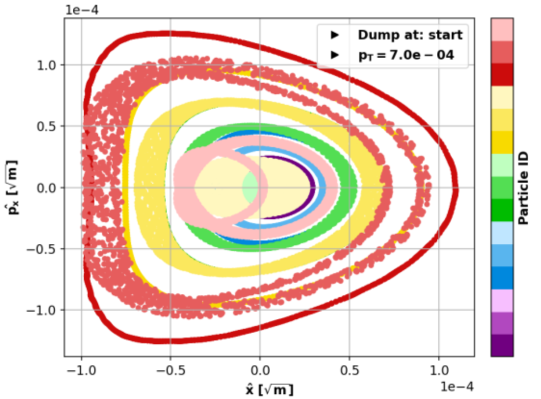
- V0.4 (last annual meeting) almost no dynamic aperture for on-energy particles
    - Very challenging lattice design and becomes harder at higher energies
- V0.6 good dynamic aperture at almost 0.1% off-energy
    - Approaching the target







p_T [%]	DA_{min} [σ]
0.07	5
0.08	4
0.09	3
0.1	<1



Collider Ring Technology

Started definition of cross section

- Lattice
- Impedance
- Shielding
- Cooling
- Vacuum
- Magnets

	thickness	outer
Beam aperture	23.49	23.49
Copper coating	0.01	23.5
Tungsten shield	40	63.5
Support/ins.	11	74.5
Cold bore	3	77.5
Kapton	0.5	78
Clearance	1	79

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

Important progress on **cooling**

Different cooling scenarios being followed

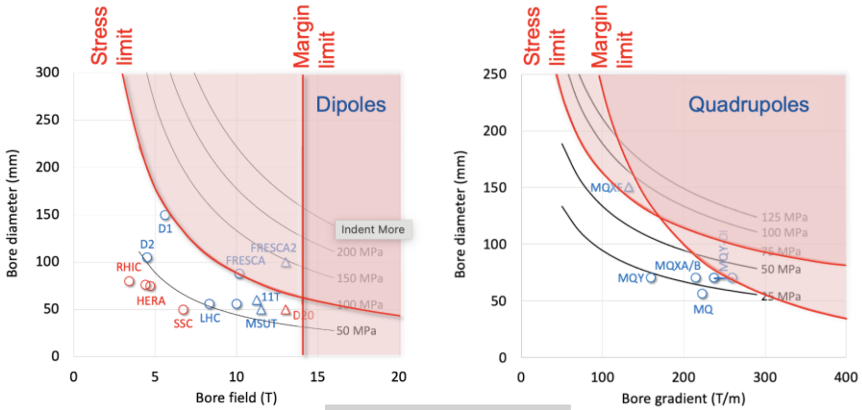
- Tungsten shield cooled close to room temperature CO_2 (preferred) or water (to be verified)

Support of shield is important for heat transfer

Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa

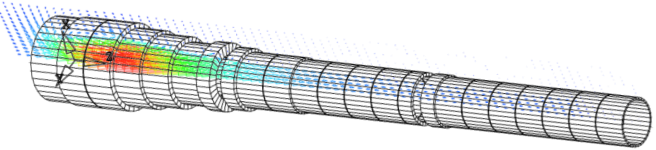
Initial **estimate of field limits** for magnets: 9 T for NbTi, 14 T for Nb_3Sn



L. Bottura et al.

Solenoids

Target solenoid
Operating field: 20 T
Operating temperature: 20 K



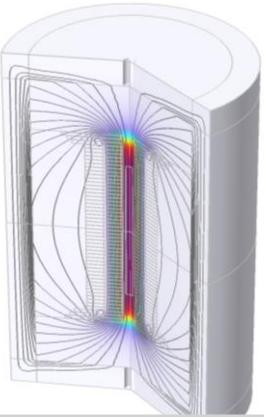
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Final Cooling solenoid

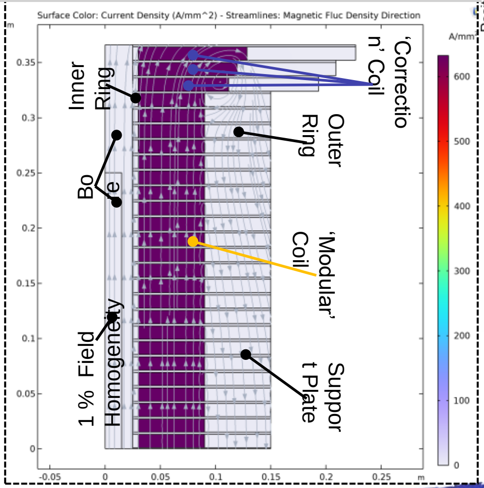
$$B_{max} = 2 \cdot \sqrt{\sigma_{max} \cdot \mu_0}$$

σ_{max} = 600 MPa

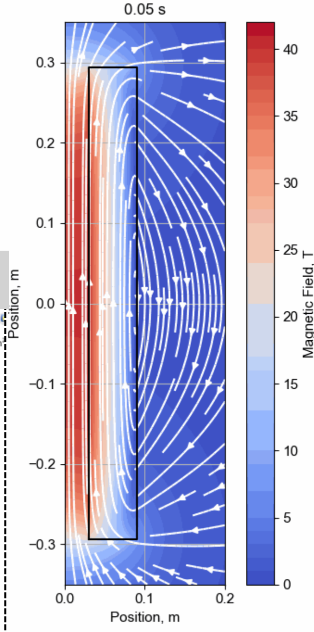
$$B_{max} \approx 55\ \text{T}$$



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



Surface Color: Current Density (A/mm^2) - Streamlines: Magnetic Fluc Density Direction



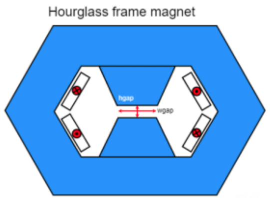
MIT “VIPER” conductor

MuCol HTS conductor
Operating current: 61 kA

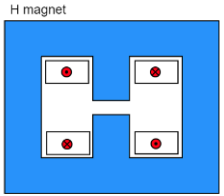
M. Takayasu et al., IEEE TAS, 21 (2011) 2340
Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

Fast-ramping Magnets

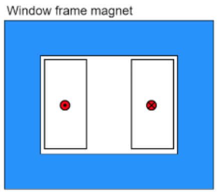
F. Boattini et al.



5.07 kJ/m



5.65…7.14 kJ/m

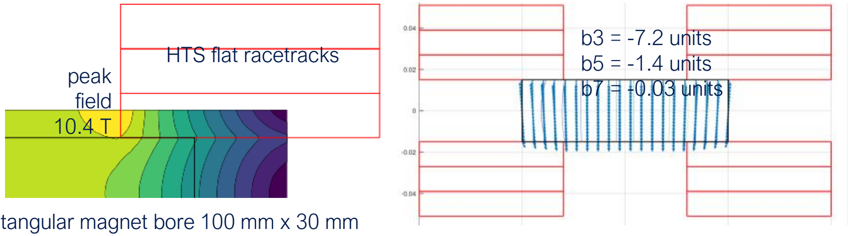


5.89 kJ/m

Main challenge is management of the power in the resistive dipoles (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

Simple HTS racetrack dipole could match the beam requirements and aperture

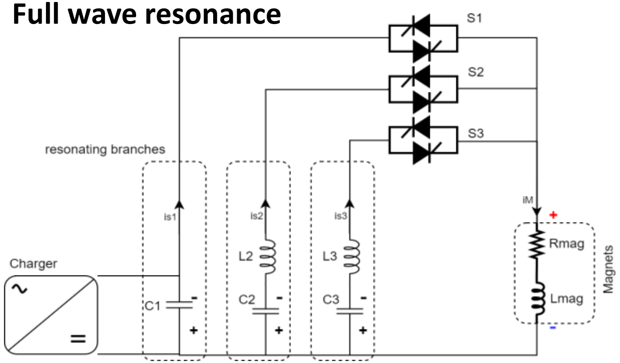


b3 = -7.2 units
b5 = -1.4 units
b7 = -0.03 units

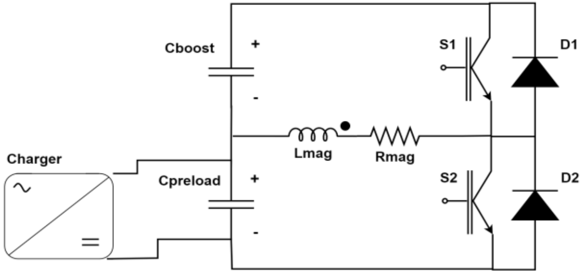
Rectangular magnet bore 100 mm x 30 mm

Differerent power converter options investigated

Full wave resonance



Commutated resonance (new)



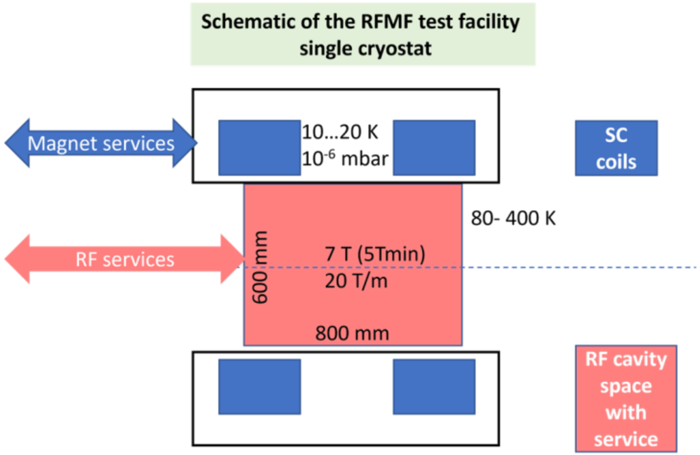
RF Test Station Layout

Module work focuses on RF test stand at this moment

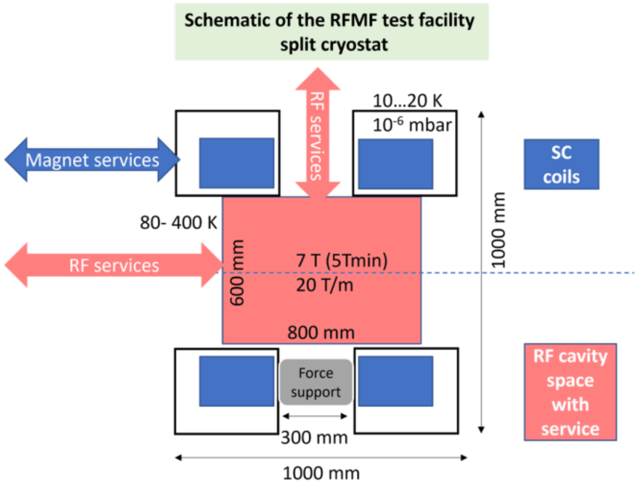
- One of the most **urgent actions** to ensure timely implementation of R&D programme
- Try to identify infrastructure for this
  - CEA, INFN, Cockroft, CERN, …
  - Will not be cheap so need to find resources

L. Rossi, C. Marchand, D. Giove, A. Gurdiev, G. Ferrand et al.

Scheme 1: single cryostat



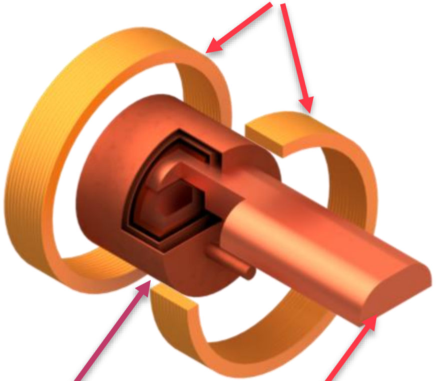
Scheme 2: split cryostat



- Two coils to vary magnetic field distribution
- Preliminary design allows down to **700 MHz** system → ∅600 RT free bore for RF → **∅700 mm minimum SC coil diameter**
- Currently study single cryostat, next split cryostat
- Coils are expensive

First Sketches

Bare coils and RF cavity

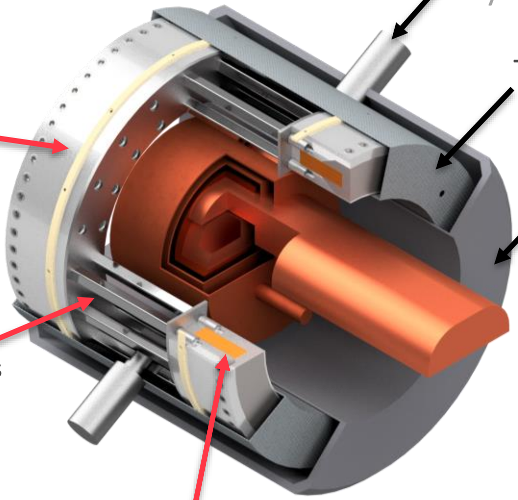


SC HTS coils

Pillbox test cavity

RF Wave guide

With cryostat



Two stage cryocooler

Coil support structure

Thermal shield

Vacuum vessel

Tie rods for repulsion and compression forces

SC HTS coils

Sc magnet/cryostat sketch by M. Castoldi & Stefano Sorti, UMIL & INFN-LASA

(RF drawing by Guillaume Ferrand –CEA)

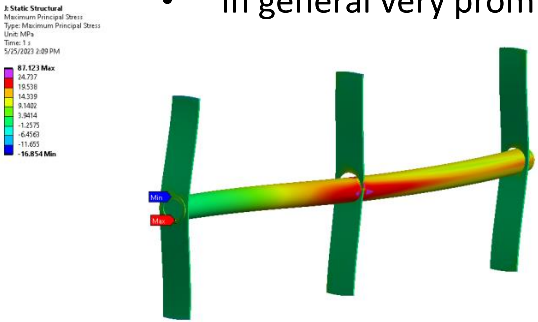
Target Studies

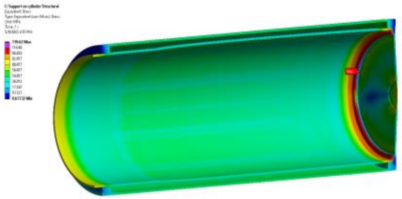
Studying 2 MW target

A. Lechner, et al.

Stress in target, shielding, vessel and window being studied

- In general very promising, need to have closer look at window

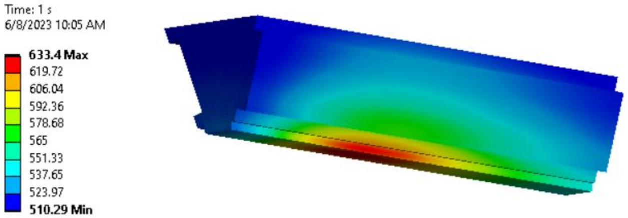


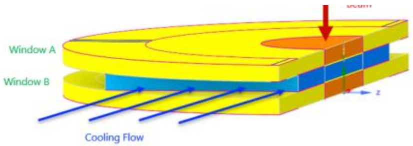


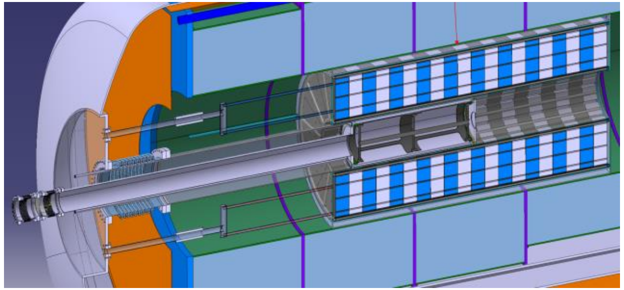
Integration with magnet is being addressed

Cooling of the shield also

Radiation to magnet has been studied



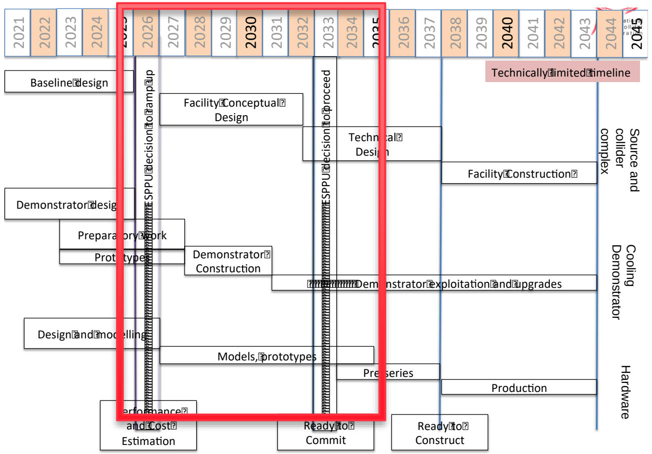




CDR Phase, R&D and Demonstrator Facility

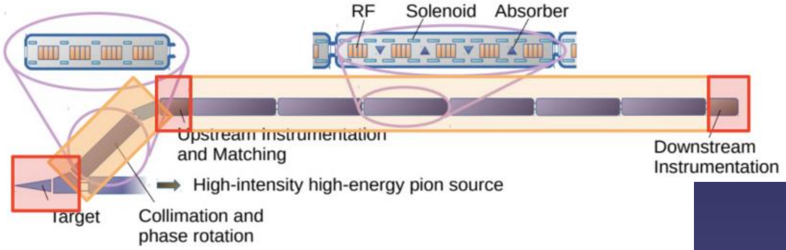
Broad R&D programme required and can be distributed world-wide

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



Integrated cooling demonstrator is a key facility

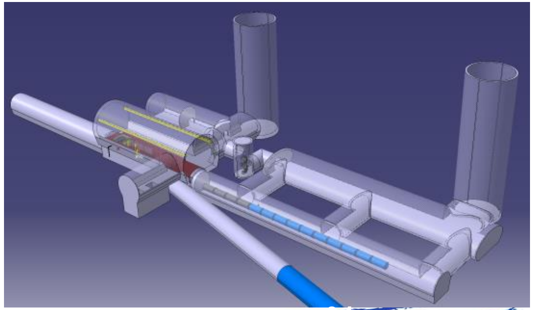
- look for an existing proton beam with significant power



C. Rogers, R. Losito, et al.

Different sites are being considered

- CERN, FNAL, ESS are being discussed
- J-PARC also interesting as option
- **FNAL is considering this in the ACE**

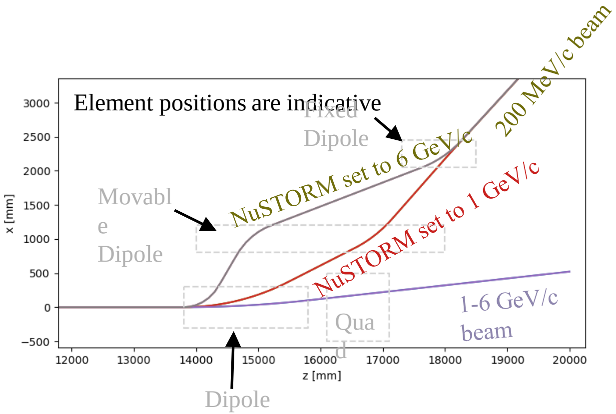


Could be used to house physics facility

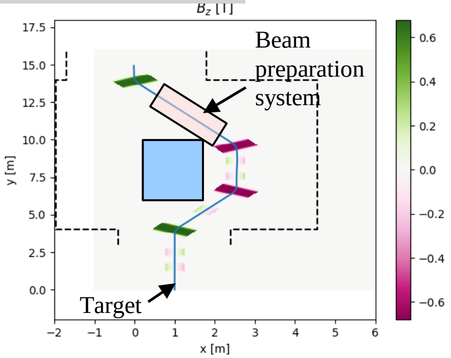
- Are trying to explore what are good options

Demonstrator Progress

FNAL consideres the demonstrator in the Accelerator Complex Evolution (ACE)



Ch. Rogers et al.



Continue to explore **synergies**

- Past meeting in Venice
- Synergy workshop after the annual meeting

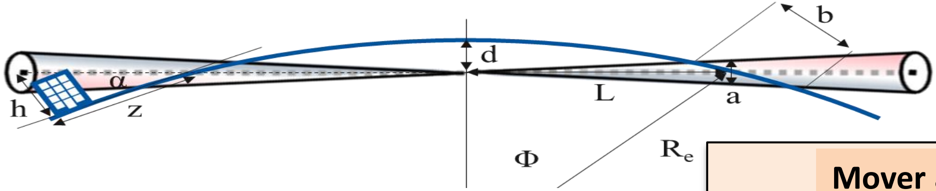
Design Studies are ongoing

- Studying layout options from target
  - NuSTORM-compatible option
  - TT7-compatible option
- Optimisation of rectilinear cooling system ongoing

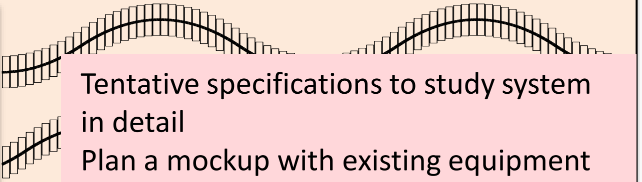
Neutrino Flux

Goal: **similar to LHC**: limit neutrino flux to have **negligible impact**, “fully optimised” (10% of MAP goal)

Verify performance of concept to be good for 14 TeV



Mover and support system

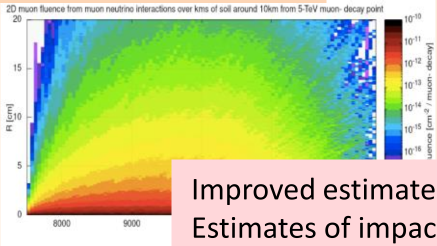


Tentative specifications to study system in detail

Plan a mockup with existing equipment and new movers to verify system

F. Bertinelli et al. (CERN, Riga)

FLUKA dose studies

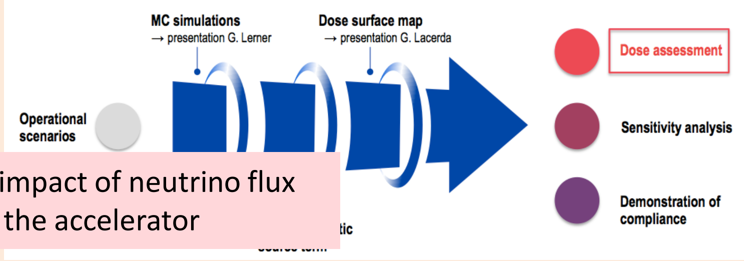


Improved estimates of impact of neutrino flux

Estimates of impact on the accelerator

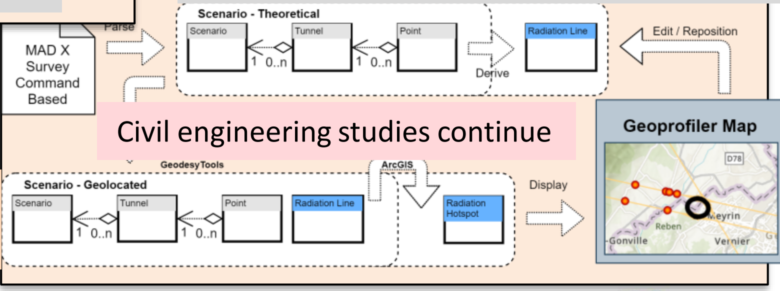
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



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

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



Civil engineering studies continue

Flux direction map / lattice design / mover impact on beam

C. Carli, K. Skoufaris (CERN)

Mitigation: Site choice tool

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

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**

Tentative Interim Report Structure

Collaboration Development

Physics Potential

…

Accelerator technologies

Synergies

- Technologies
- Facilities
- Experiments

R&D programme development

- Demonstrator
- RF test stand

Executive Summary

Layout for each section

- But maybe group differently
- After all a matrix

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?

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 by all partners
  - Thanks to Luca and Alexia Augier, help also from Steinar, Chris, Sergo, and Nadia

- CERN extended MTP for muon collider until 2028
  - Total material budget has increased by a factor two, but needs to redistributed
- CERN will create an EP-UMC unit to ease inscription of users, moving forward with grey book

- EPJC article still under review (thanks to all contributors, in particular Andrea and Federico)

Conclusion

- The study is moving forward at good speed
- Will prepare **Interim Report**
- Will define **tentative parameters**
- Hope to further increase rate of progress
    - More team getting up to speed, often in MuCol
    - US contribution
    - …

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

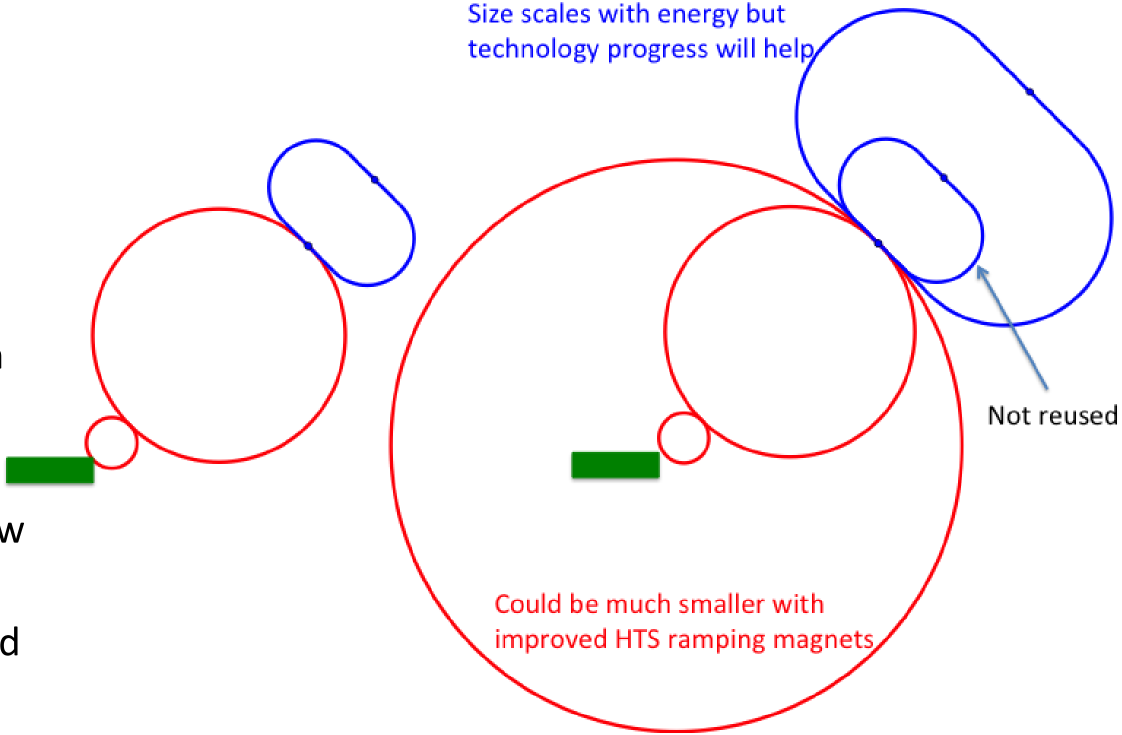
Staging

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

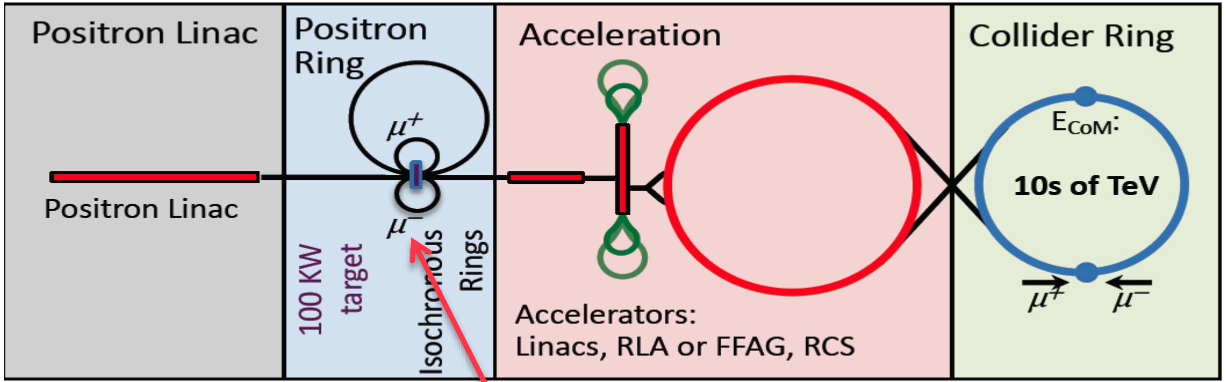
Could be much smaller with improved HTS ramping magnets

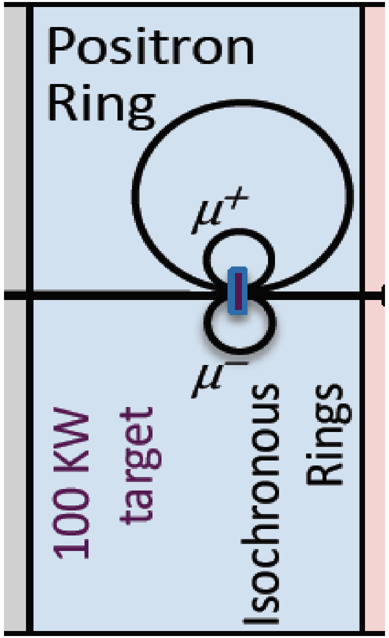
Alternatives: The LEMMA Scheme

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

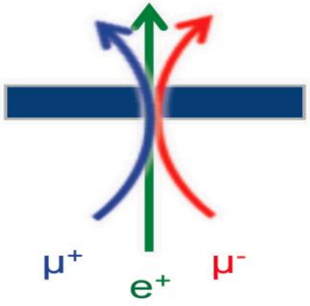




45 GeV positrons to produce muon pairs

Accumulate muons from several passages

$$e^+e^- \rightarrow \mu^+\mu^-$$

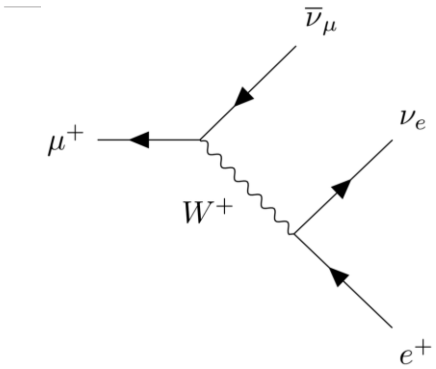


Excellent idea, but nature is cruel

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

⇒ **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.

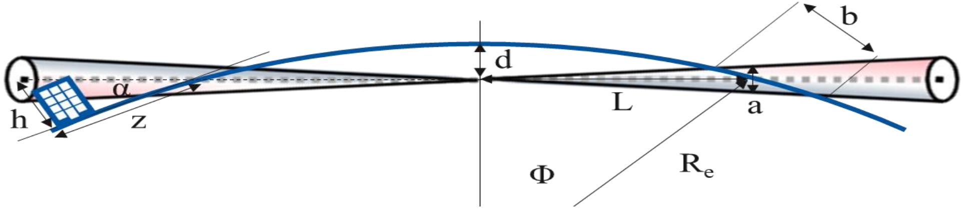
Neutrino flux to have negligible impact on environment

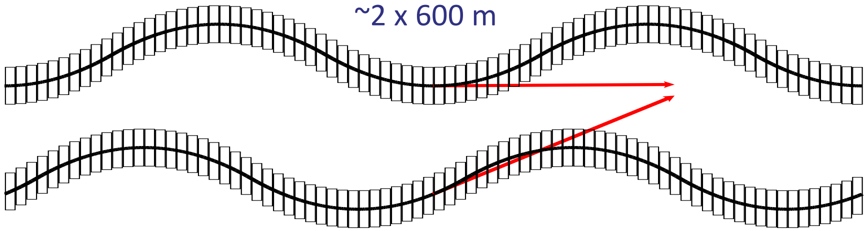
- want to be **negligible** (same level as LHC)
- opening cone decreases, cross section and shower energy increase with energy

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

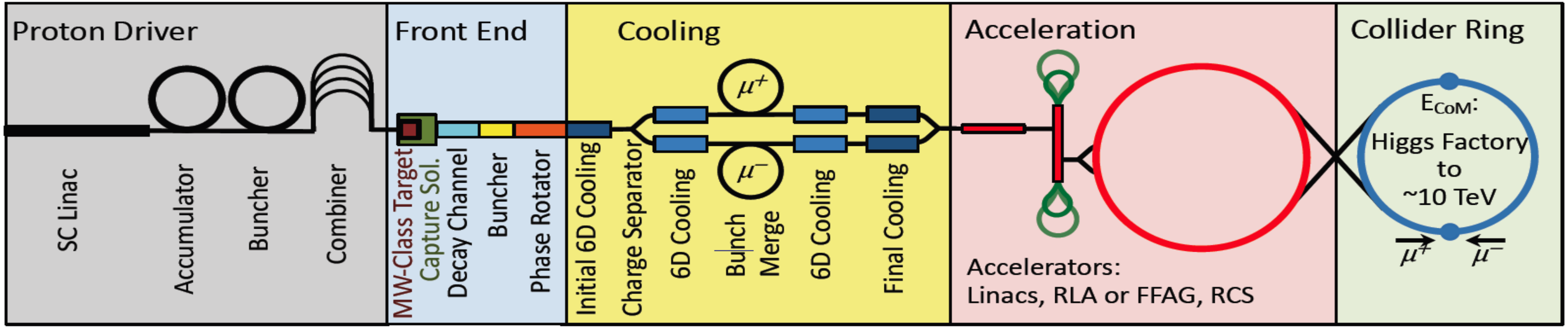
Mechanical system with 15cm stroke, 1% vertical bending

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

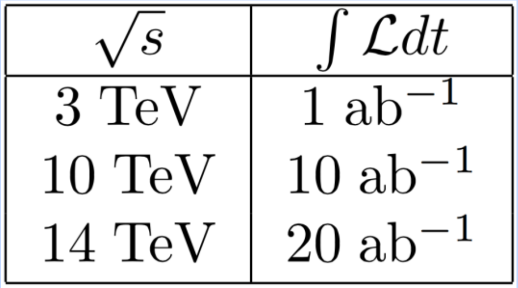
Collaboration Vision

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 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} $\text{cm}^{-2}\text{s}^{-1}$	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

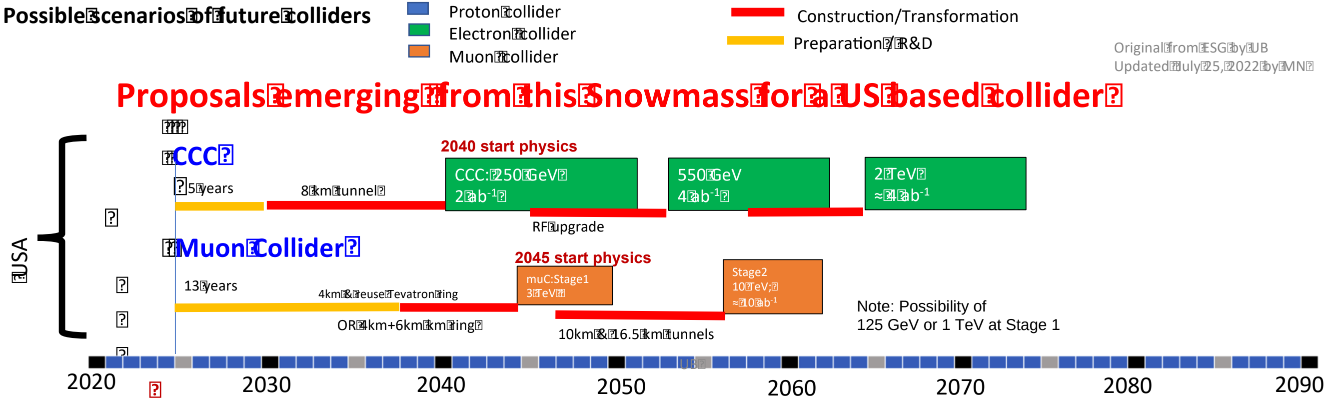
Strong interest in the US community in muon collider

- 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**



- **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

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

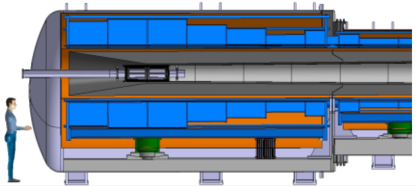
Thomas Roser et al

MuCol

Muon Collider magnets

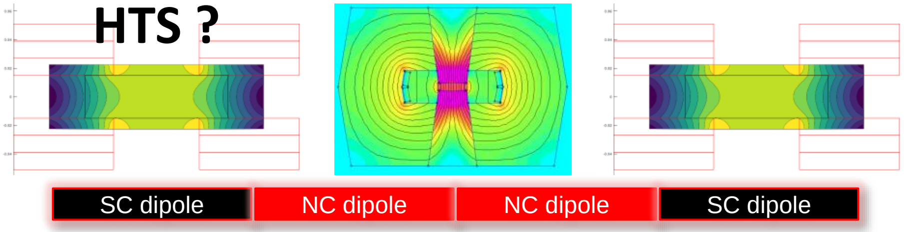
International MUON Collider Collaboration

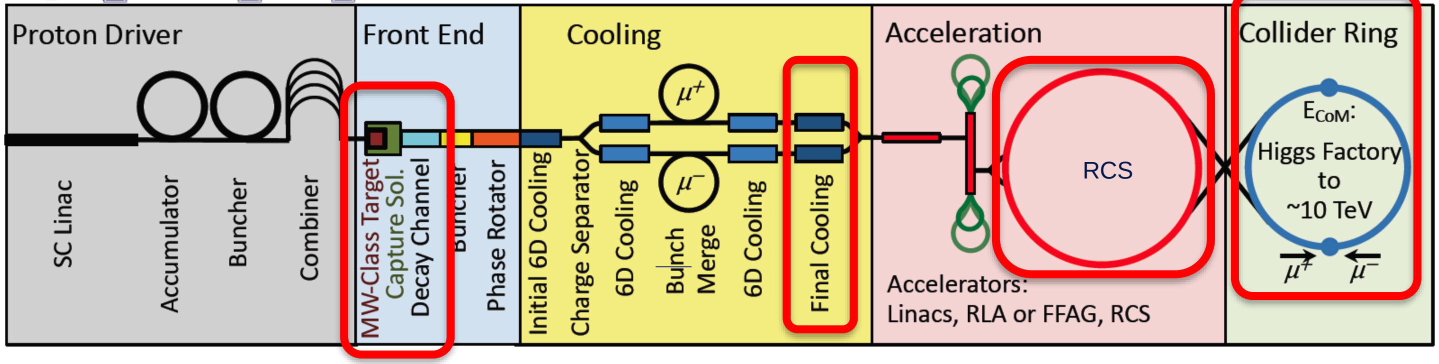
20 T, 200 mm **HTS !**
Radiation heat load ≈ 5...10 kW
Radiation dose: 80 MGy



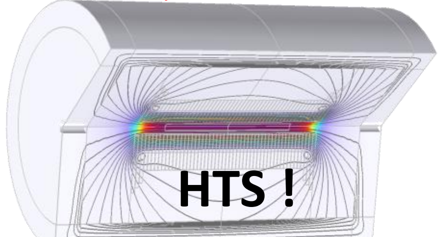
NC ±1.8 T, 400 Hz
100 mm x 30 mm

SC < 10T
100 mm x 30 mm

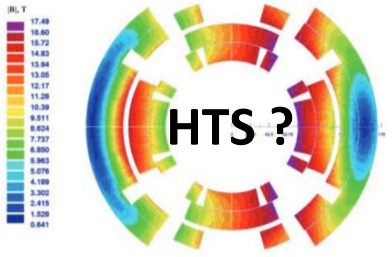




> 40 T, 60 mm



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



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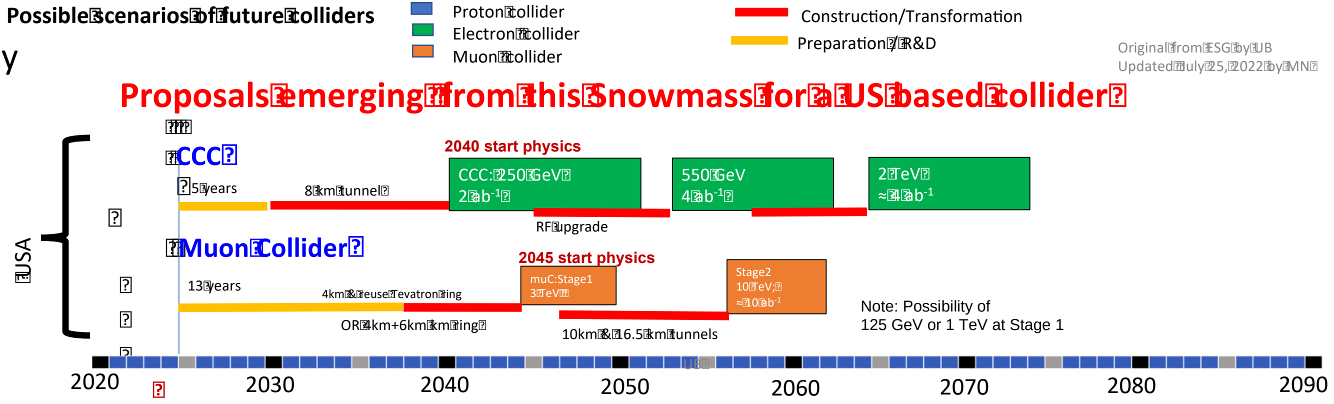

Possible scenarios of future colliders

🟦 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
$\approx 4\ ab^{-1}$

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;
$\approx 10\ ab^{-1}$

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

2020 2030 2040 2050 2060 2070 2080 2090

- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
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Meenakshi Narain: Energy Frontier / Large Experiments,
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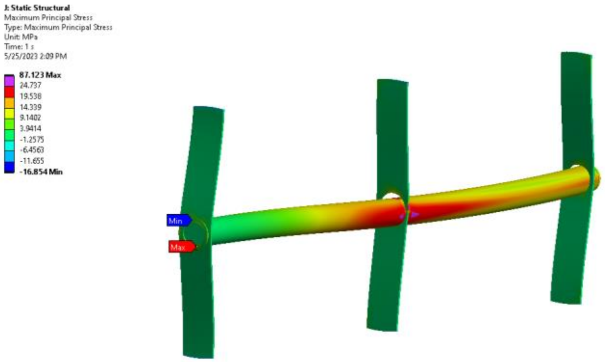
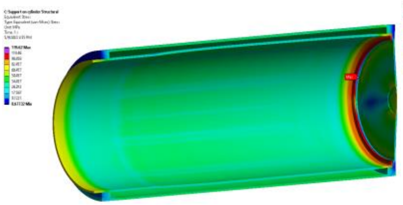
CARBON TARGET



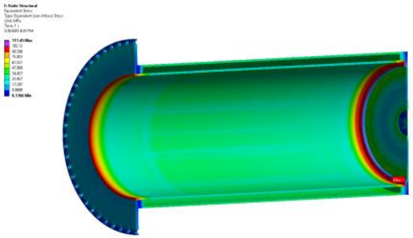
Graphite rod & supports: stress field

- 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



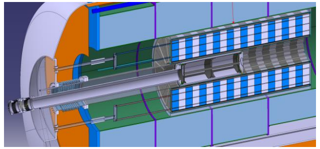
Simply supported vessel – stress field



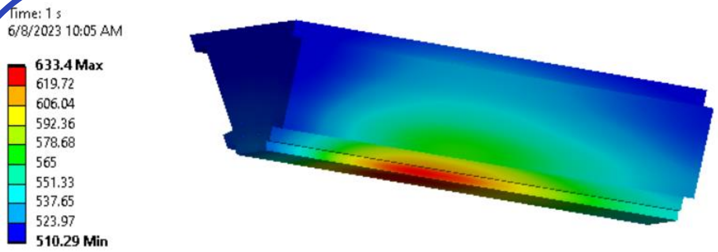
Cantilever supported vessel – stress field

- 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**



RADIATION SHIELDING

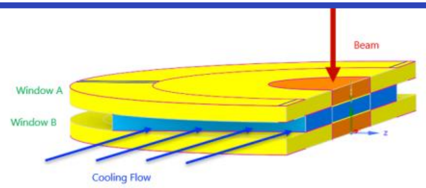


Tungsten slice – Temperature field

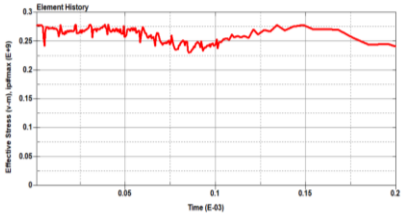
- Baseline updated to **2 MW**
- **Improved and more detailed concept** aiming for a more realistic implementation:
  Tungsten slices bounded by a stainless steel **vessel** filled with pressurized **He coolant**
- **Optimization** of the helium cooling **operational point** in function of:
  - Number 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**

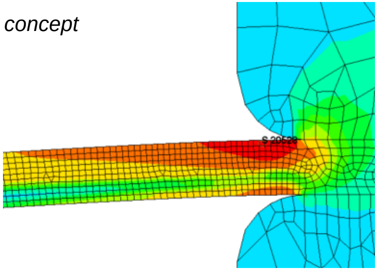
BEAM WINDOW



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.