International MUON Collider Collaboration

MuCol

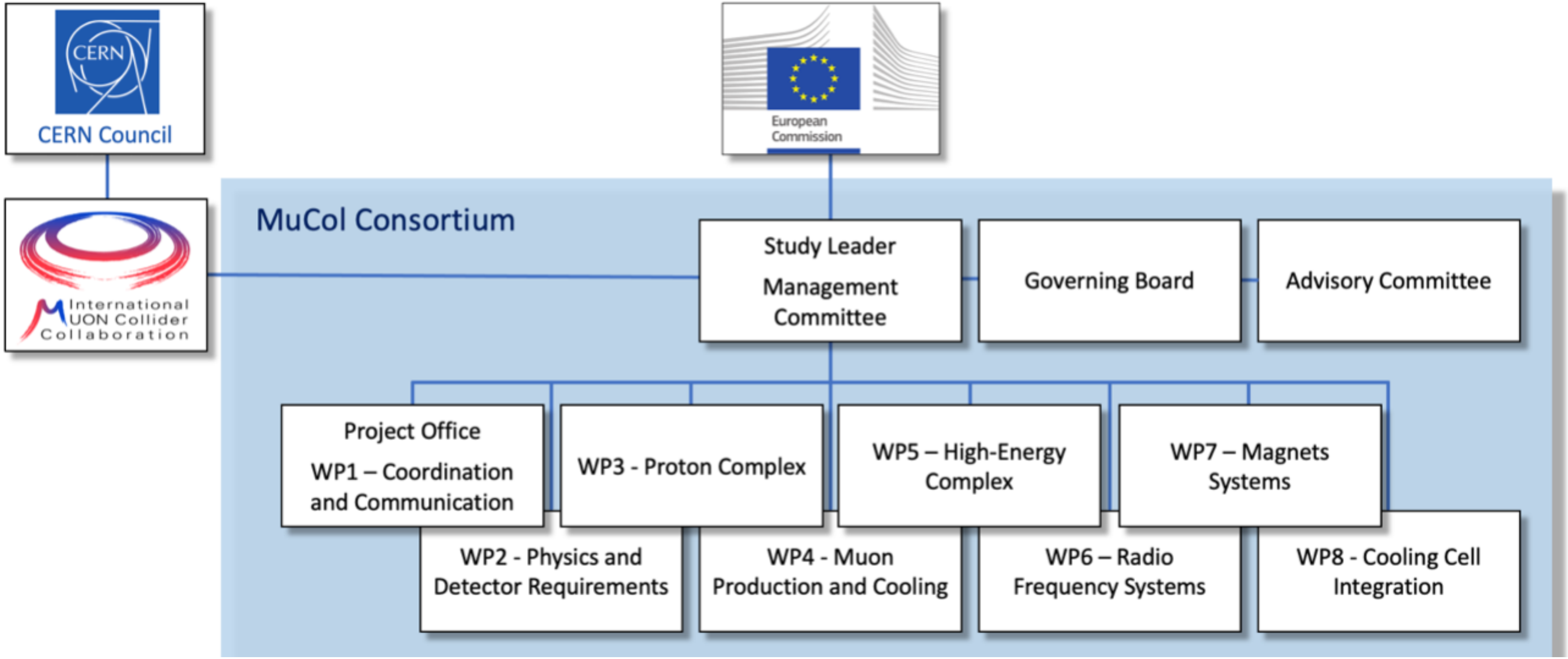
CERN

EU Project MuCol
Status and Plans

R. Losito
CERN

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

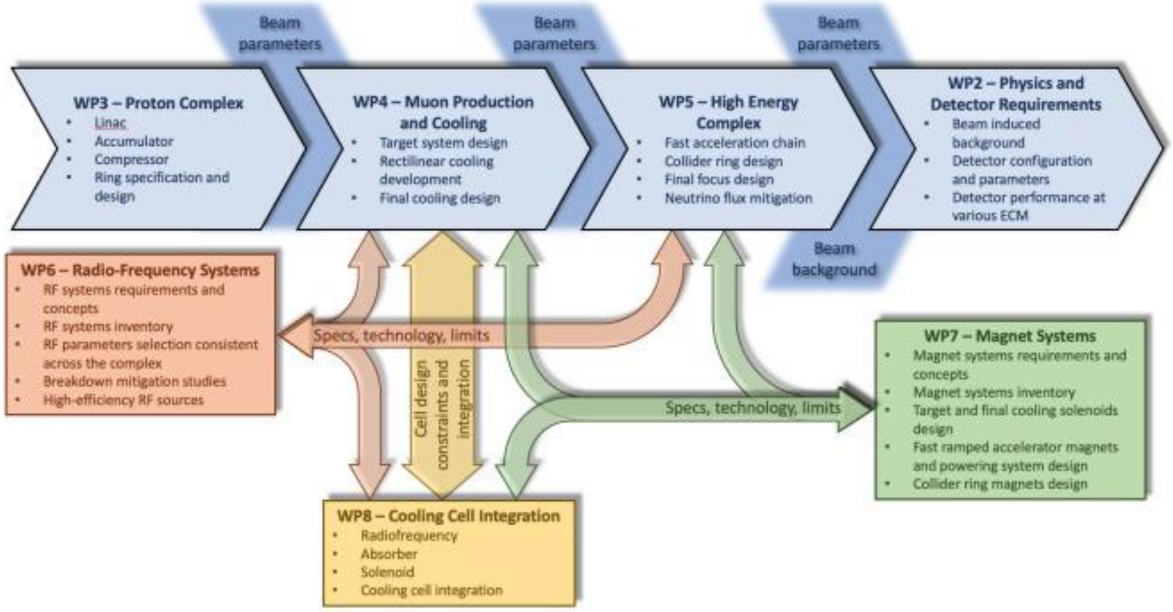
MuCol Organisation



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. Chance (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



Includes an important part of the work directly and much indirectly

Scientific and technical organization of the project

	WP2 - Physics and Detector Requirements	WP3 - Proton Complex	WP4 - Muon Production and Cooling	WP5 – High-Energy Complex	WP6 – Radio Frequency Systems	WP7 – Magnet Systems	WP8 - Cooling Cell Integration
High-Charge Proton Beams		●	●				
High-Charge Muon Beams			●			●	
Muon Beams Cooling			●		●	●	●
Muon Beams Acceleration				●	●	●	
Collider Ring	●			●		●	
Impact of Muon Decay and Loss	●			●		●	
Collective Effects		●	●	●			
Machine-Detector Interface	●			●			

EU Design Study

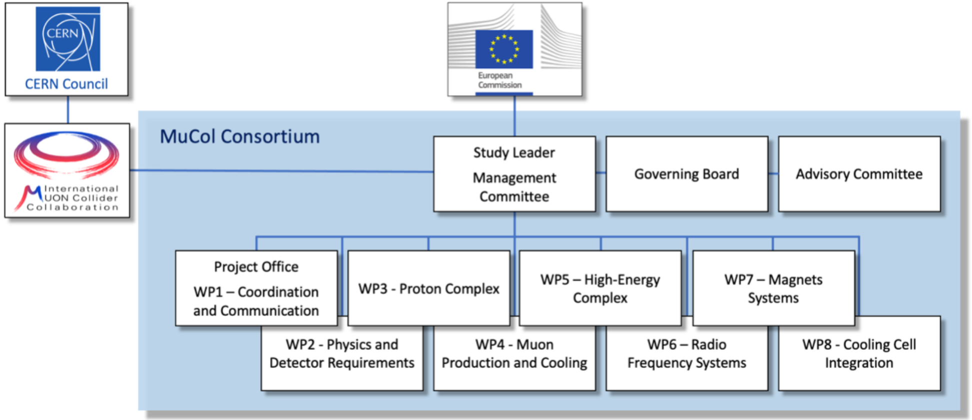
Kick-off meeting in March 2023:
https://indico.cern.ch/event/1219912

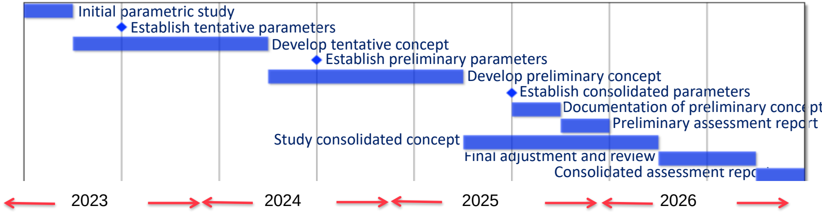
Joint Annual Meeting with IMCC with the participation of the EU Project Officer **Angela Lahuerta Marin**

https://indico.cern.ch/event/1250075/

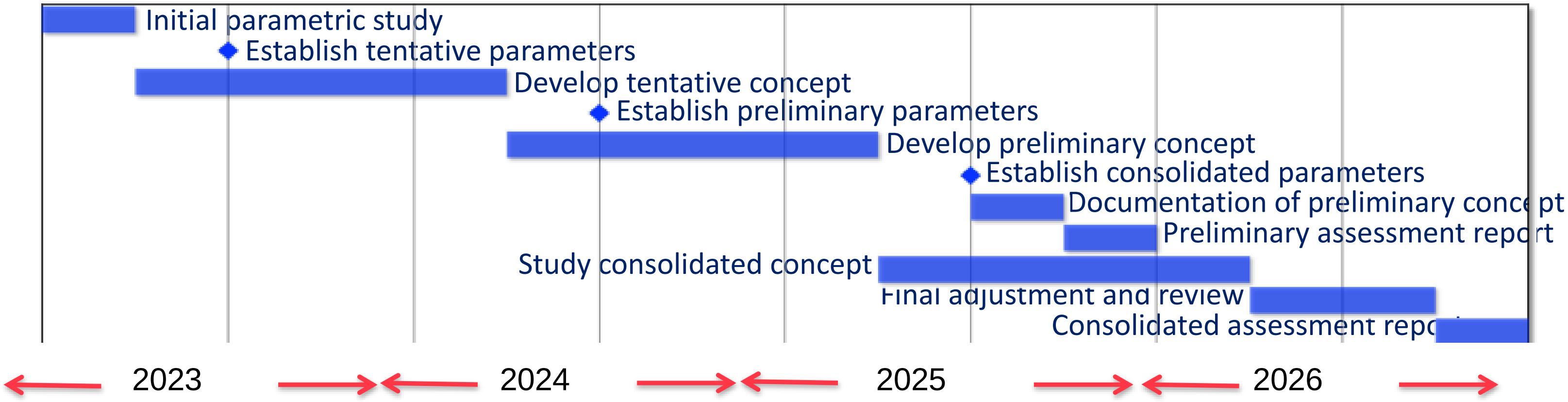
Many thanks to all that contributed

https://mucol.web.cern.ch





MuCol Timeline



Finish February 2027
Preliminary report by early 2026 as an input to EU strategy process
Consolidated report available before the end of EUSPP

Iterating on parameters and design each year

Specific meetings

- **Training on Detector Design and physics performance tools**
  - https://indico.cern.ch/event/1277924/

- **Review of the Magnet programme**
  - Took place during the Annual meeting in Paris
  - Draft report presented to the Muon Magnet Working group, soon to be published in final form
    - https://indico.cern.ch/event/1313015/

WorkPackages

- Good progress on all WPs
- Some examples in spare slides..
- Regular WP meetings
- In general, enthusiastic participation

Milestones & Deliverables

- **Deliverables for year 1**:
  - *Data Management Plan*, **M5 (M8)**: **WP1 (CERN) + all**
    - Draft now ready, being "cleaned up", will be sent to the board for endorsement
  - *Preliminary ESPPU report No. 1* **M12**: **WP1 (CERN) + all**
    - **Approval of the first report will provide the green light to CERN's administration to proceed with the second payment (about 15% of total).**

Milestones & Deliverables

- **Milestones for year 1**:
  - ✓ *Website online*, M2: **WP1 (CERN)**
  - ✓ *Kick-off meeting*, by M3: M2
  - ✓ *Training on detector design and physics performance tools*, M6, **WP2**
  - *Tentative Parameters available*, M6 **(M8)**: **WP1 (SL) + all**

Milestone No	Milestone Name	Work Package No	Lead Beneficiary	Means of Verification	Due Date (month)
1	Website Available	WP1	1 -CERN	Website online	2
2	Kick-off meeting	WP1	1-CERN	Indico site	3
3	Tentative parameters available	WP1	1-CERN	Database	8
4	First annual meeting	WP1	1 -CERN	Indico site	15
5	*Preliminary parameters*	*WP1*	*1-CERN*	*Database*	***20***
6	Second annual meeting	WP1	1-CERN	Indico site	27
7	*Consolidated parameters*	*WP1*	*1-CERN*	*Database*	***32***
8	Third annual meeting	WP1	1-CERN	Indico site	39
9	Training on detector design and physics performance tools	WP2	8-UNIPD	Training material	6
10	Workshop on MDI and IR design	WP2, WP5	8-UNIPD	Indico site	13
11	*Release of simplified detector performance model (DELPHES card or/and similar format)*	*WP2*	*8-UNIPD*	*Model published on the website*	***20***
12	Workshop on detector design and physics performance with a public lecture on Muon Collider	WP2	8-UNIPD	Indico site	25
13	Publication of report of detector performance with major physics process at several ECM	WP2	8-UNIPD	Article ready for submission	48
14	Mini-Workshop on pulsed magnets	WP7, WP5	5-CEA	Indico site	15
15	*Tentative design of the interaction region*	*WP2, WP5*	*1-CERN*	*Optics files*	***20***
16	Tentative optics of the collider ring and pulsed synchrotrons	WP5	5-CEA	Optics files	19
17	Tentative design of the FFA	WP5	5-CEA	Optics files	25
18	Tentative impedance budget in the collider and pulsed synchrotron	WP5	5-CEA	Dataset	26
19	*Workshop on ultra-high-field solenoids*	*WP7*	*1 -CERN*	*Indico site*	***32***
20	*Workshop on high-field collider magnets*	*WP7, WP5*	*1-CERN*	*Indico site*	***44***
21	Cooling cell design 3D model	WP8	7-UMIL	3D model completed & Report	33

Deliverable Name	Work Package No	Lead Beneficiary	l'pc	Date
Data-management plan	*WPI*	*1 -CERN*	*DMP — Data Management Plan*	***8***
Preliminary ESPPU report No. 1	WPI	1 - CERN	R — Document, report	12
Preliminary ESPPU report No. 2	WPI	1 -CERN	R — Document, report	24
Intermediate ESPPU report	WPI	- CERN	R — Document, report	36
Consolidated ESPPU report	WPI	1 - CERN	R — Document, report	48
Beam-induced background and detector configuration	*WP2*	*8 - UNIPD*	*DATA — data sets, microdata, et*	***32***
Detector performance by using physics processes	WP2	2 - DESY	R — Document, report	36
Final report on parameters and initial study for the Proton Complex	WP3	11 -ESS	R — Document, report	45
Development of BDSIM simulation	WP4	16 -UKRI	OTHER	24
Preliminary Report on key subsystems for ESPPU input	WP4	16 -UKRI	R — Document, report	33
Consolidated Report on key subsystems	WP4	16 -UKRI	R — Document, report	45
Report on the collider ring design	WP5	5 - CEA	R — Document, report	44
Report on the design of the HEC	WP5	5 - CEA	R — Document, report	45
Report on design of high power and high efficiency RF power sources	*WP6*	*5 - CEA*	*R — Document, report*	***44***
Report on RF for MCC and HEC	WP6	5 - CEA	R — Document, report	45
Preliminary report on muon collider magnets	WP7	1 - CERN	R — Document, report	33
Consolidated report on muon collider magnets	WP7	1 - CERN	R — Document, report	45
Presentation of cooling cell conceptual design	WP8	7 - UMIL	OTHER	15
Final report on cooling cell design	*WP8*	*7 - UMIL*	*R — Document, report*	***44***

Hiring Status

- Positions are publicised in the mucol website

JOBS

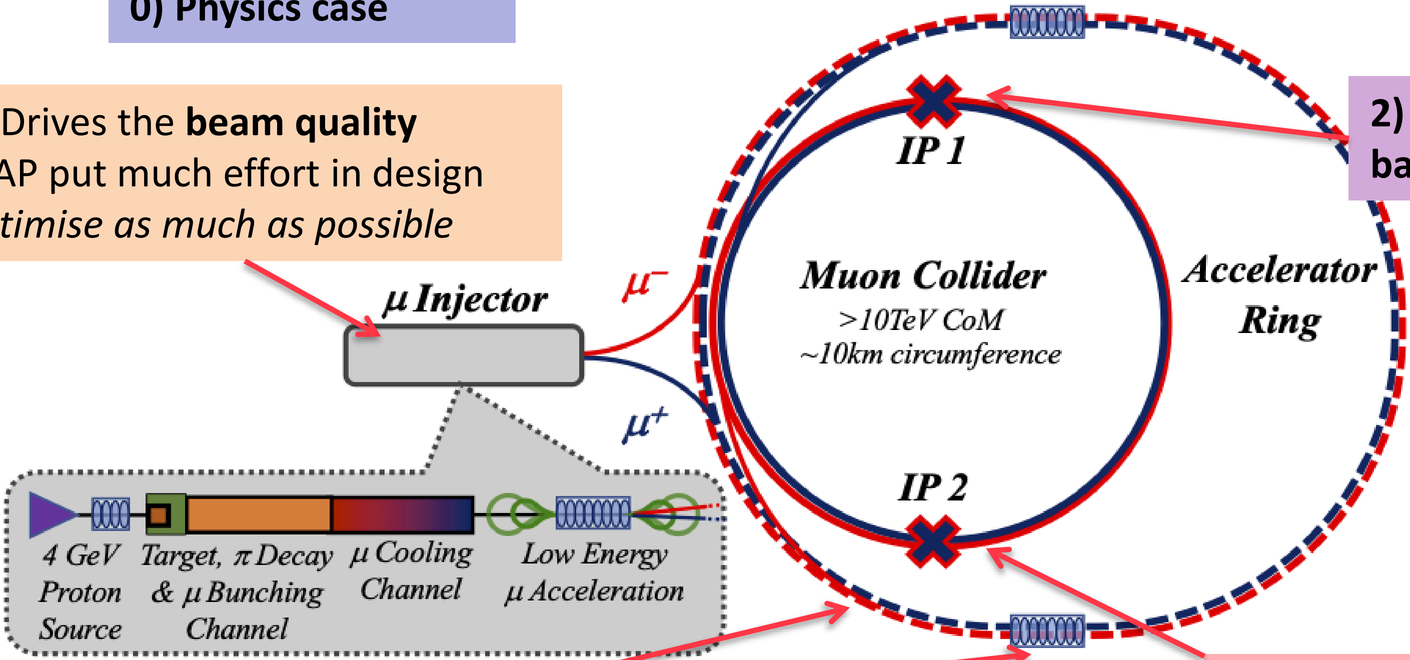
Job title	Institute	Info	Status
Postdoctoral researcher in Accelerator Physics	ESS	Postdoctoral Position	OPEN
PhD on Design of pulsed synchrotrons for the high-energy acceleration chain for a muon collider	CEA	Proposal PhD Subject	OPEN
Postdoctoral in Saclay and Trieste	CEA / INFN	Postdoctoral Position	OPEN
PhD Student for High Intensity Beam Dynamics Project	ESS	https://europeanspallationsource.se/careers/vacancies?rmpage=job&rmjob=1516&rmlang=UK	FILLED

SPARE SLIDES

Key Challenges

0) Physics case

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



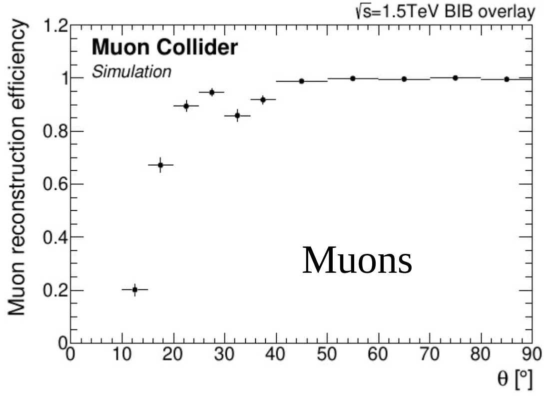
2) Beam-induced background

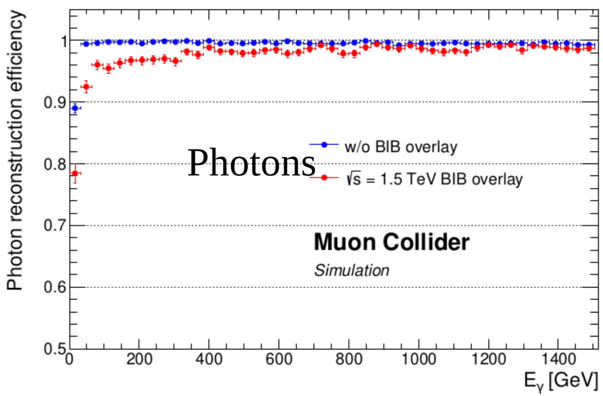
1) Dense neutrino flux
mitigated by mover system and site selection

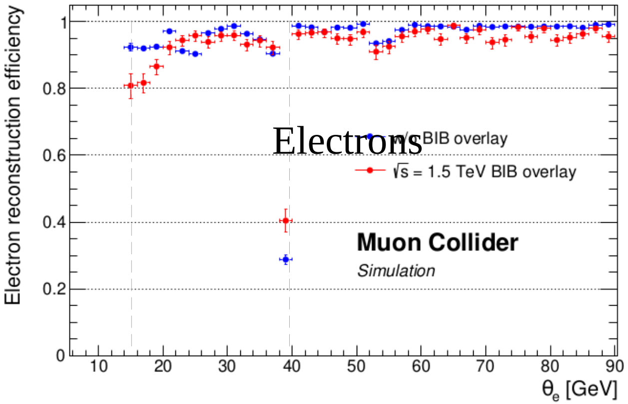
3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

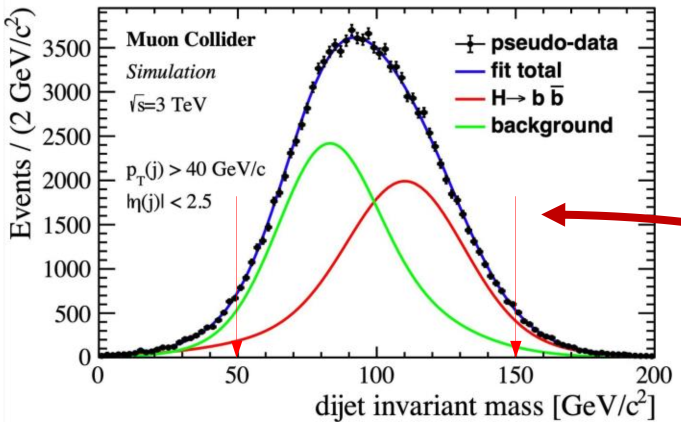
Detector Study Status

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

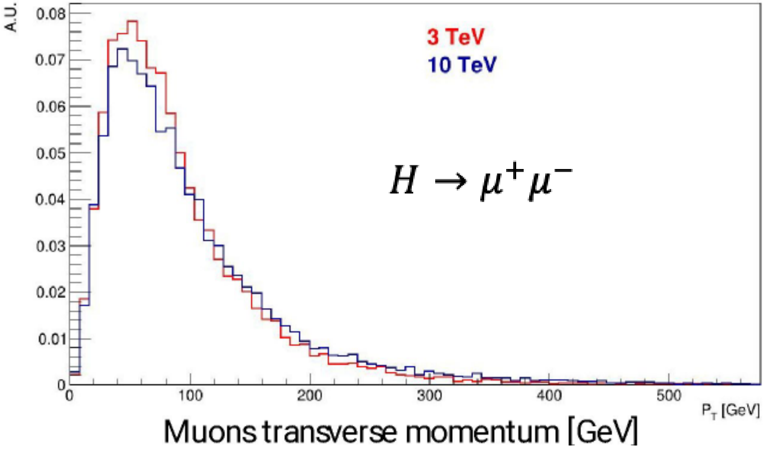
D. Lucchesi et al.

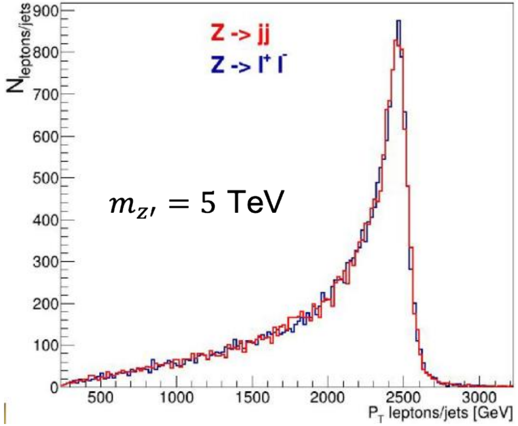
Strategy Toward 10 TeV Detector

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.

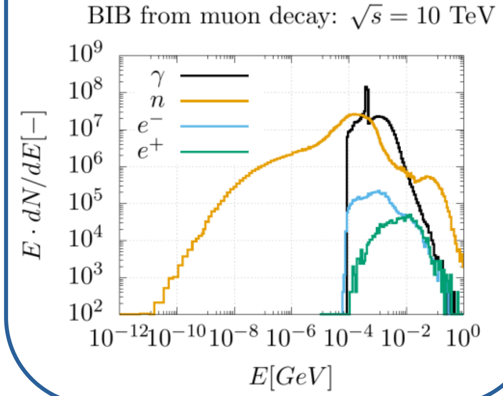
Machine-detector Interface

- 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

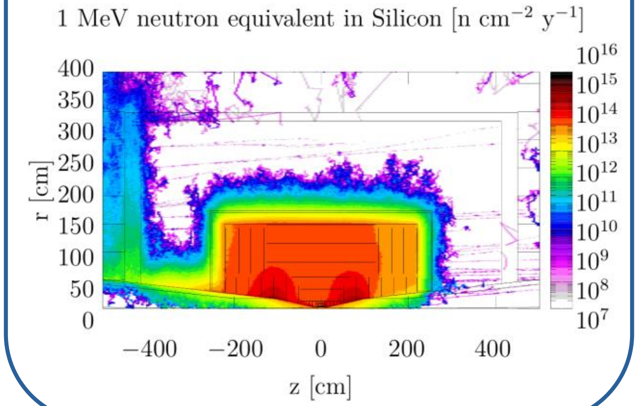
- FLUKA studies with various lattice configurations:
  - A dipole component mitigates only slightly the BIB
  - Nozzle is the determinant component for the BIB. As starting point, the 1.5 TeV MAP design (N. Mokhov) was taken
- Similar BIB multiplicity for all collider energies
- Simulation with the latest 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.

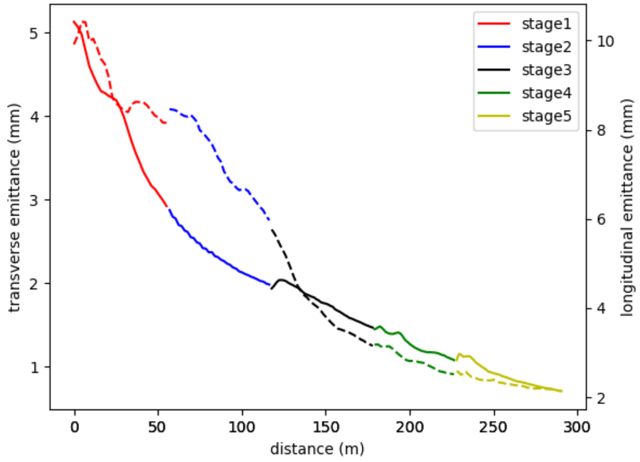
- Review of linac parameters is ongoing.
  - High intensity machine development through LINAC4 : high intensity beam (35mA peak) has reached the end of the linac and it has been successfully injected in the PSB
- We have a baseline lattice for accumulator compressor
  - Based on the lattice for the neutrino 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

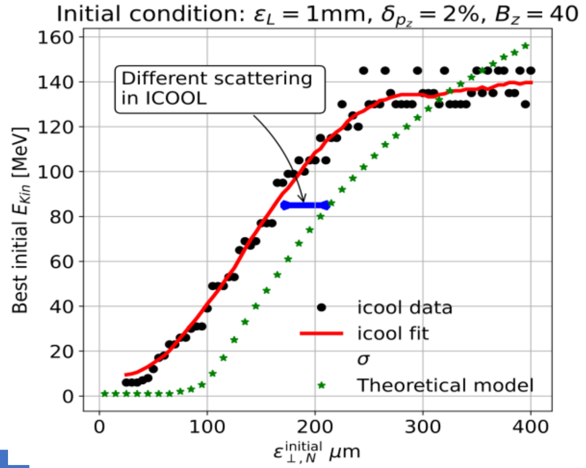


Ch. Rogers, Zhu Ruihu et al.

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

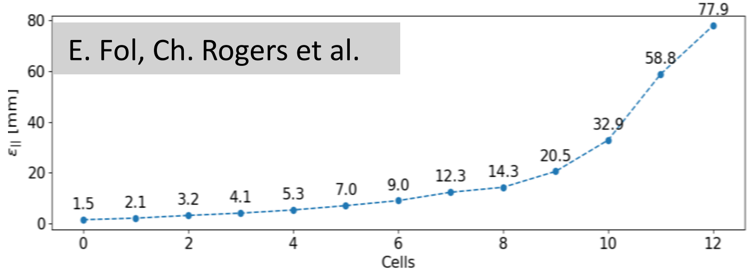
B. Stechauner et al.

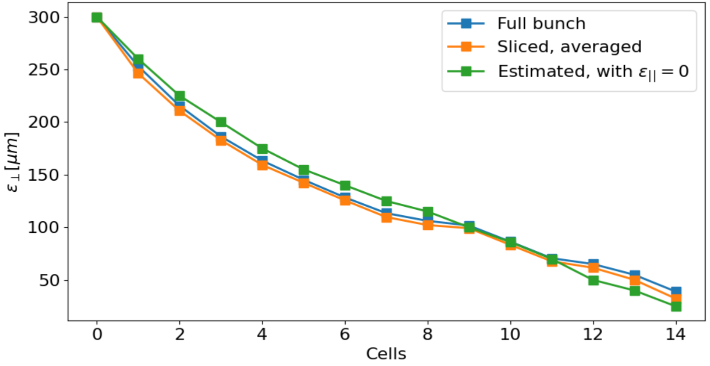
Muon Cooling

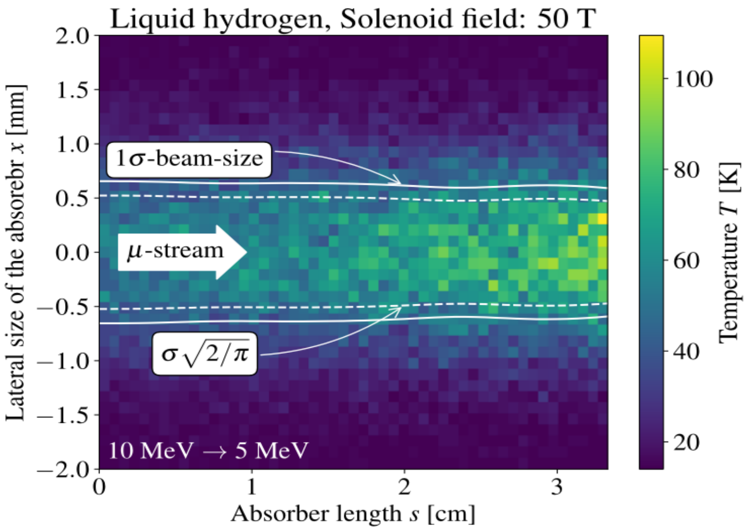
Final cooling design

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

- Comes closer to target performance







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

B. Stechauner, J. Ferreira et al.

RCS Design

A. Chance, F. Batsch et al.

- **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).

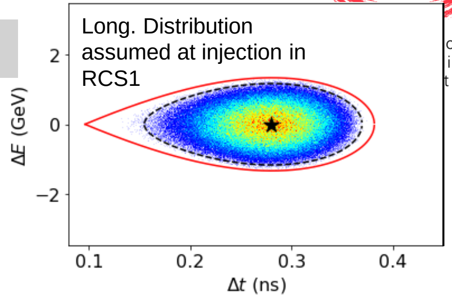
Example parameters for the muon RCSs

	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.

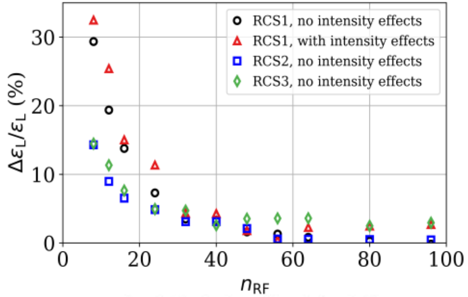


Longitudinal emittance target value (norm.):

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

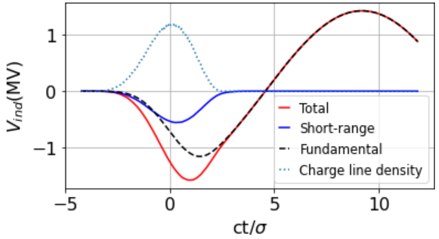
30 MV/m as baseline and demonstrated, 45 MV/m as optimistic option

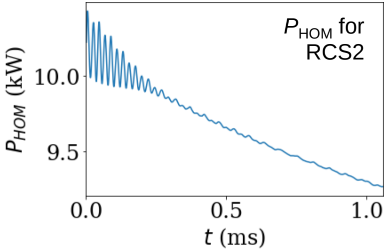
Emittance blow-up from final cooling to IP budgeted with 10% → challenge assuming 3% to 4% per RCS and beam transfers

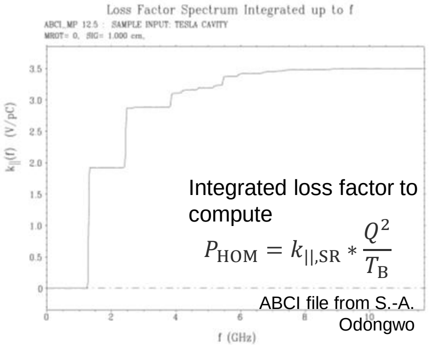


- Around 30 RF stations needed for longitudinal stability and focusing
- Changes in orbit length require frequency tuning required (A. Chancé)
- Single-bunch HOM power loss up to 10 kW averaged over the acceleration time
- CW average is lower, development of high-capacity couplers needed

Induced voltages in RCS1 for a single bunch →







ABCI file from S.-A. Odongwo

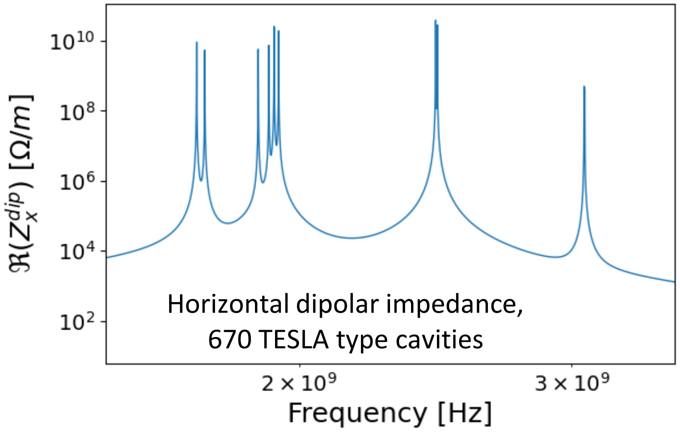
Collective Effects

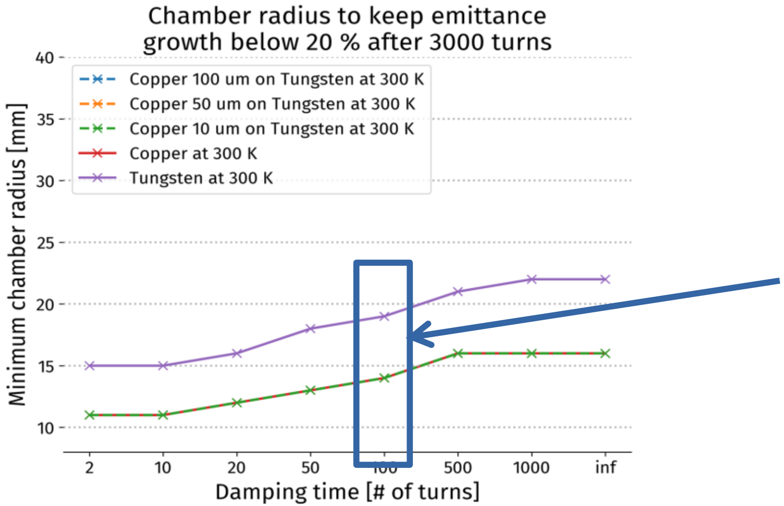
D. Amorim, E. Metral, X. Buffat

RCS:

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

- Two beam under investigation





Collider ring

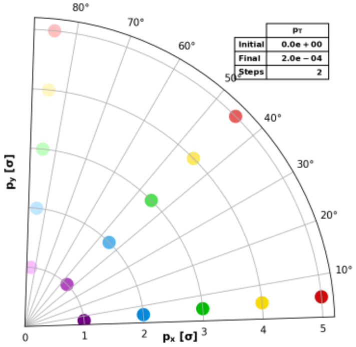
- Single beam instability limits
  - Conservative feedback
- Copper coating beneficial (few microns)
- Minimum radius from impedance:
  - 14mm with copper coating
  - 19mm for direct tungsten

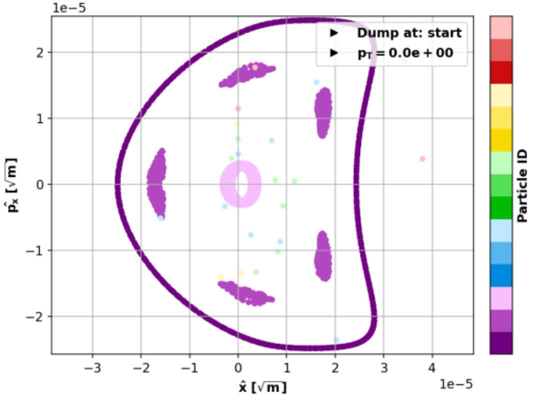
Collider Ring Lattice

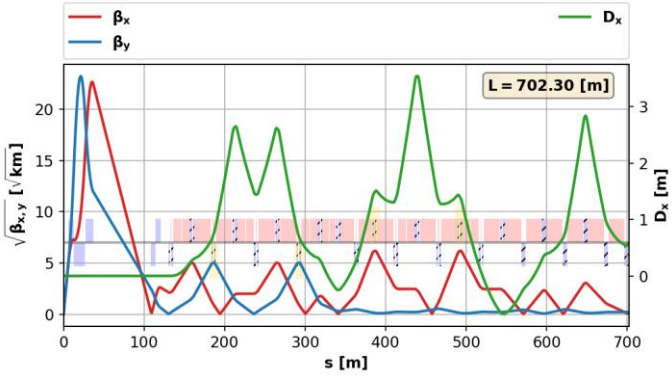
K. Skoufaris, Ch. Carli, support from
P. Raimondi, K. Oide, R. Tomas

Important progress:

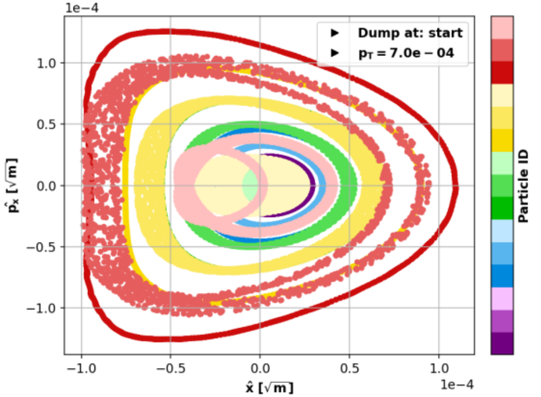
- V0.4 (last annual meeting) almost no dynamic aperture for on-energy particles
  - Very challenging lattice design and becomes harder at higher energies
- V0.6 good dynamic aperture at almost 0.1% off-energy
  - Approaching the target







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



Collider Ring Technology

MuCol

International UON Collider Collaboration

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**

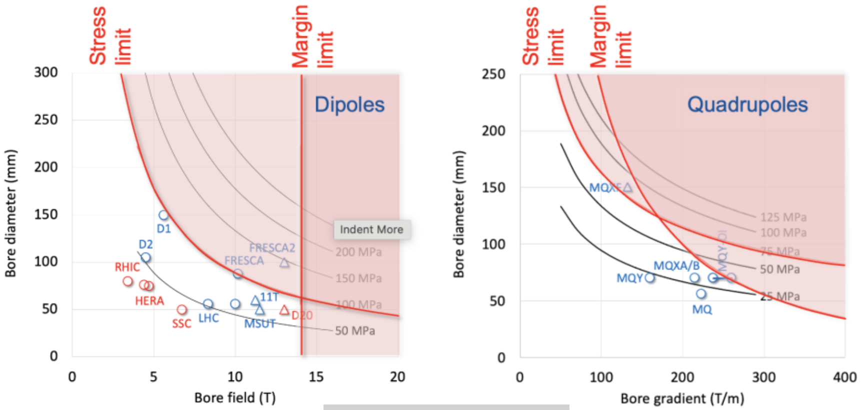
Different cooling scenarios being followed
- Tungsten shield cooled close to room temperature CO_2 (preferred) or water (to be verified)

Support of shield is important for heat transfer

Discussion on options for magnet cooling

R. Van Weelderen, P. De Sousa

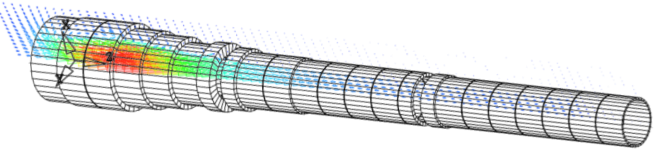
Initial **estimate of field limits** for magnets: 9 T for NbTi, 14 T for Nb_3Sn



L. Bottura et al.

Solenoids

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



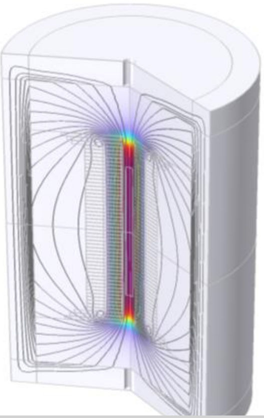
A Portone, P. Testoni, J. Lorenzo Gomez, F4E

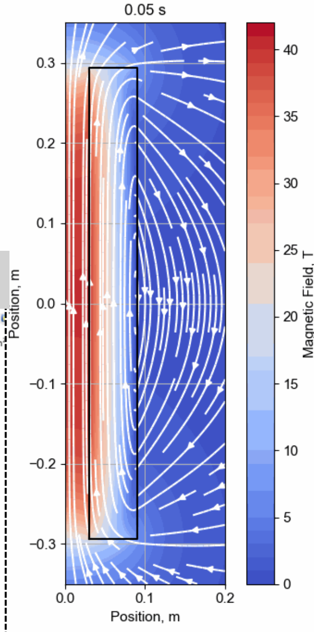
Final Cooling solenoid

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

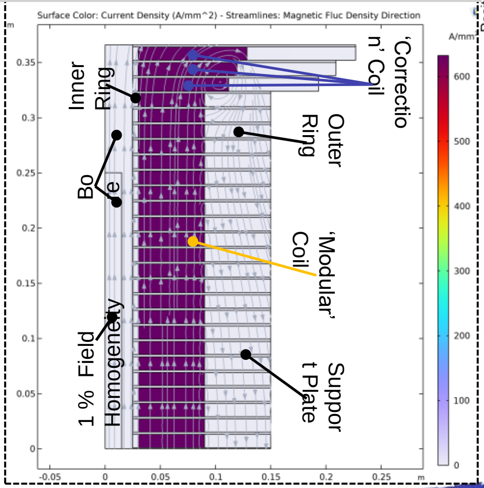
σ_{max} = 600 MPa

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





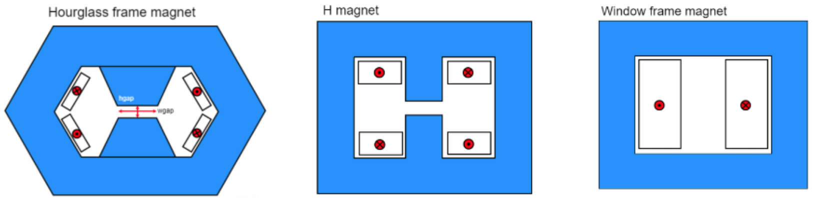
A. Dudarev, B. Bordini, T. Mulder, S. Fabbri



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.

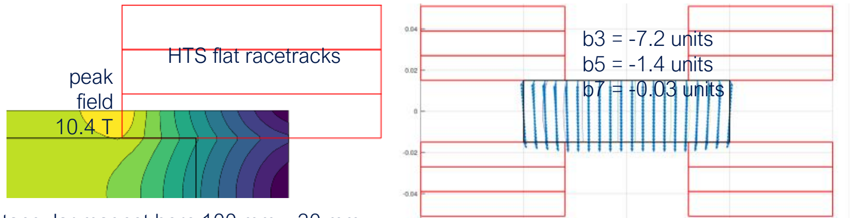


5.07 kJ/m | 5.65…7.14 kJ/m | 5.89 kJ/m

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

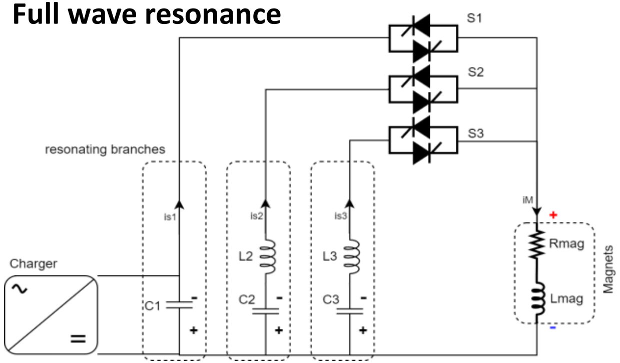
Simple HTS racetrack dipole could match the beam requirements and aperture



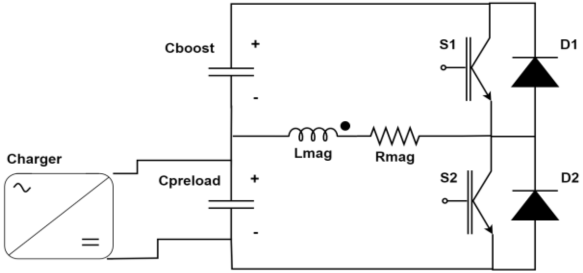
Rectangular magnet bore 100 mm x 30 mm

Differerent power converter options investigated

Full wave resonance



Commutated resonance (new)



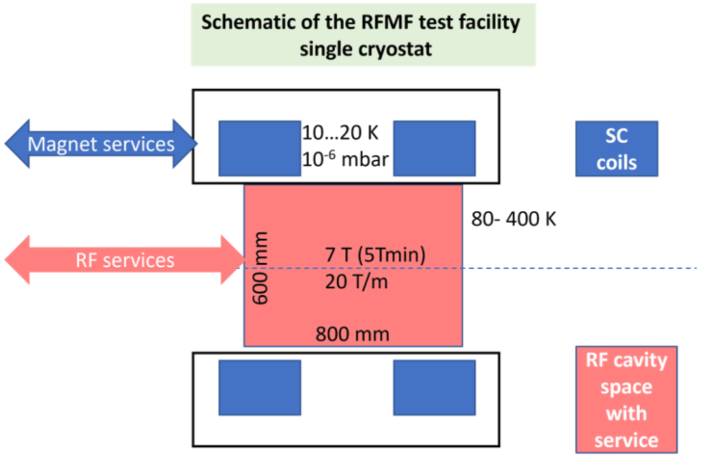
RF Test Station Layout

Module work focuses on RF test stand at this moment

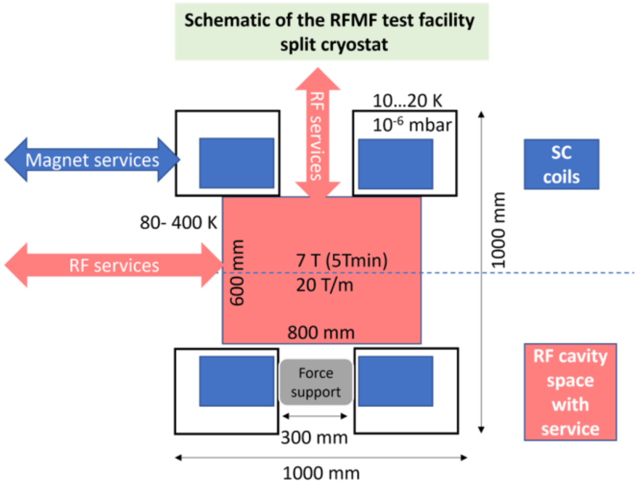
- One of the most **urgent actions** to ensure timely implementation of R&D programme
- Try to identify infrastructure for this
  - CEA, INFN, Cockroft, CERN, …
  - Will not be cheap so need to find resources

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

Scheme 1: single cryostat



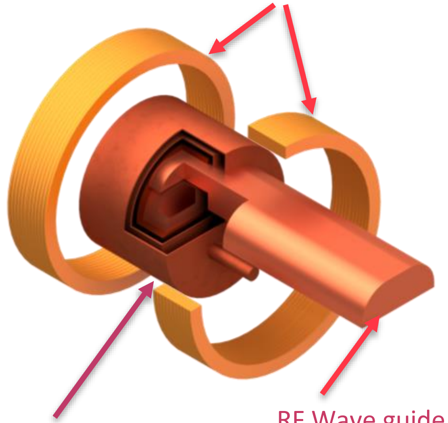
Scheme 2: split cryostat



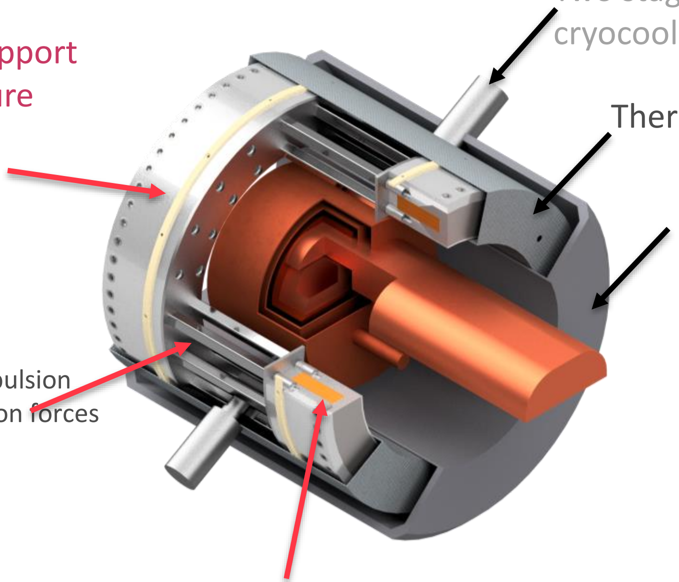
- Two coils to vary magnetic field distribution
- Preliminary design allows down to **700 MHz** system → ∅600 RT free bore for RF → **∅700 mm minimum SC coil diameter**
-
- Currently study single cryostat, next split cryostat
- Coils are expensive

First Sketches

Bare coils and RF cavity



With cryostat



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

(RF drawing by Guillaume Ferrand –CEA)

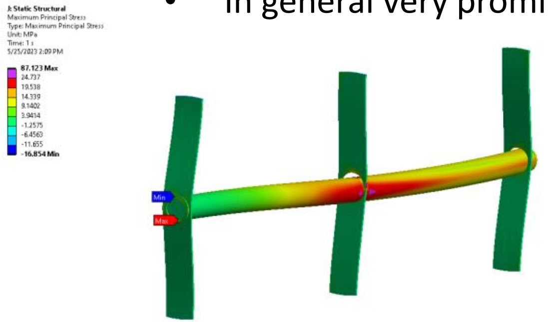
Target Studies

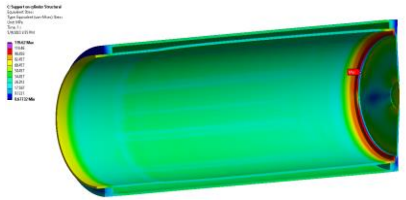
Studying 2 MW target

A. Lechner, et al.

Stress in target, shielding, vessel and window being studied

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

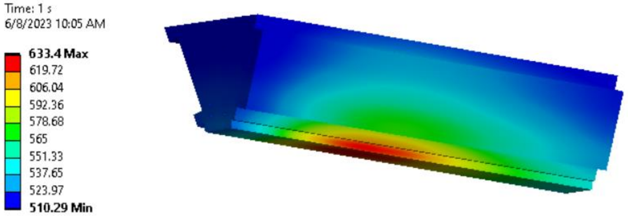


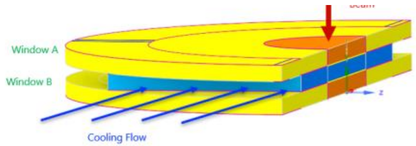


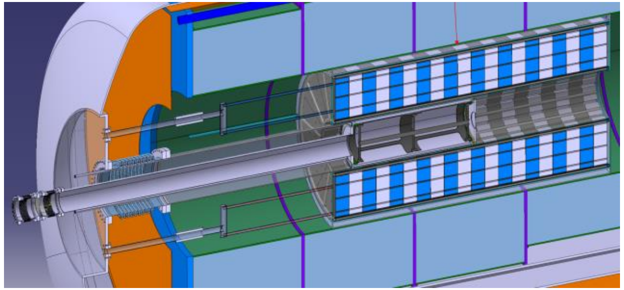
Integration with magnet is being addressed

Cooling of the shield also

Radiation to magnet has been studied



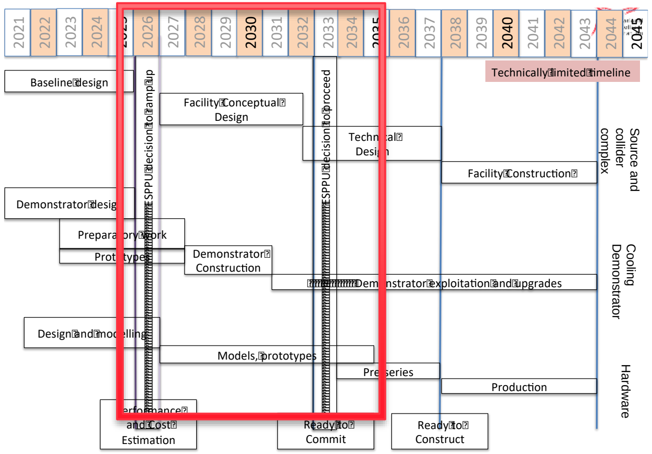




CDR Phase, R&D and Demonstrator Facility

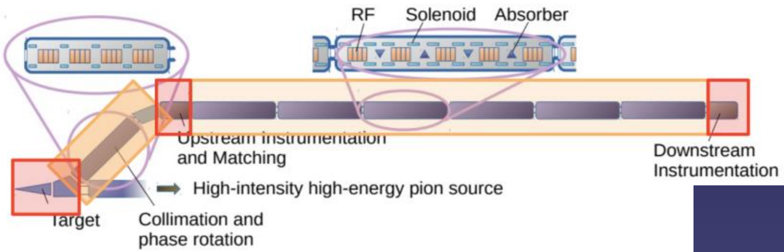
Broad R&D programme required and can be distributed world-wide

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

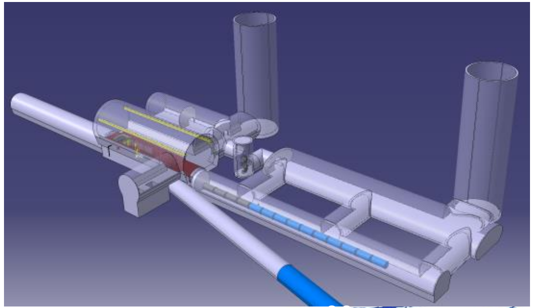


Integrated cooling demonstrator is a key facility

- 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**

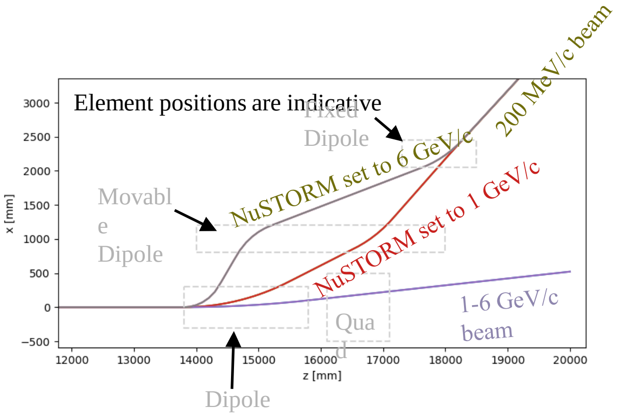
Could be used to house physics facility

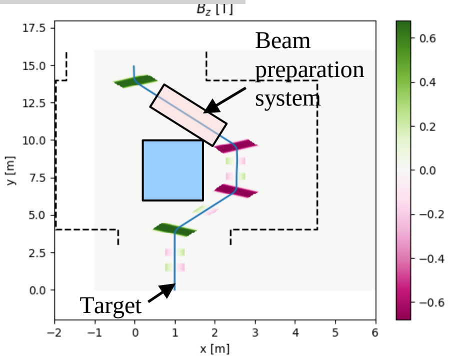
- Are trying to explore what are good options

Demonstrator Progress

Ch. Rogers et al.

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





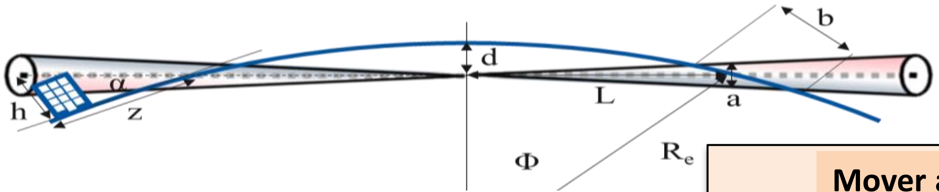
Continue to explore **synergies**

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

Design Studies are ongoing

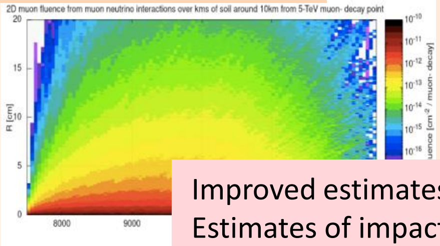
- Studying layout options from target
  - NuSTORM-compatible option
  - TT7-compatible option
- Optimisation of rectilinear cooling system ongoing

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

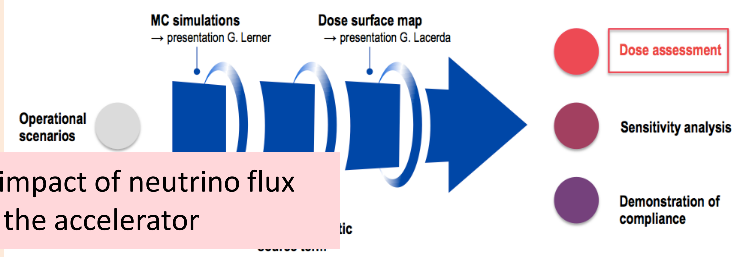
FLUKA dose studies



Improved estimates of impact of neutrino flux
Estimates of impact on the accelerator

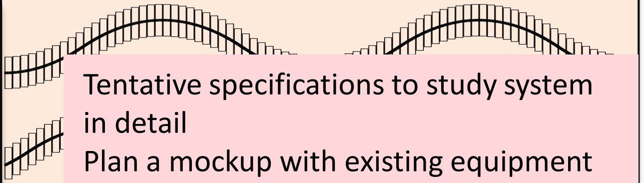
G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Conformity Verification Scheme



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

Mover and support system



Tentative specifications to study system in detail
Plan a mockup with existing equipment and new movers to verify system

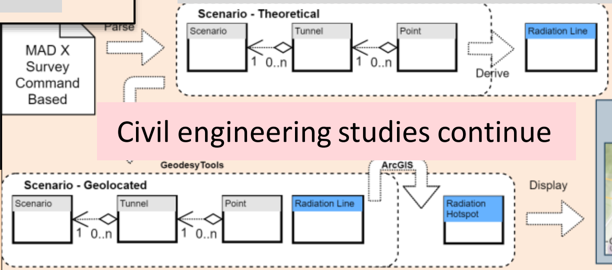
F. Bertinelli et al. (CERN, Riga)

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)



Civil engineering studies continue

Reserve