International MUON Collider Collaboration

MuCol

IMCC Progress and Plans

D. Schulte, R. Taylor
On behalf of the International Muon Collider Collaboration

Daniel: Sorry that I cannot attend in person because of important family matters

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

USMCC Annual Meeting, Chicago, August 2025

Physics Case

Physics case is very strong and is supported by globally:

Snowmass, P5, and now National Academy Recommendation:

> A collider with approximately **10 times the energy of the Large Hadron Collider (LHC) is crucial** for addressing the big questions of particle physics and making discoveries.
> A **10-TeV muon collider** on the Fermi National Accelerator Laboratory (Fermilab) site would have **similar discovery reach as a 100-TeV proton collider**.
> A muon collider combines the physics **advantages** of an **electron-positron** and a **proton-proton collider**, with a **much smaller size**.

M. Spiropulu (*Co-Chair*), M. S. Turner (*Co-Chair*), N. Arkani-Hamed, B. C. Barish, J. F. Beacom, PH. H. Bucksbaum, M. Carena, B. Fleming, F. Gianotti, D. J. Gross, S. Habib, Y.-K. Kim, P. J. Oddone, J. R. Patterson, F. Pilat, C. Prescod-Weinstein, N. Roe, T. M.P. Tait, Staff: T. Konchady, D. Nagasawa, L. Walker, D. Wise, C. N. Hartman, A. Mozhi

At ESPPU in Venice, the muon collider impact on precision physics and BSM has been presented in all relevant sessions
- Some improvement potential remains
- Expect to get support of physics case in Europe

Strong physics case has strong complementary to FCC-ee + FCC-hh
- Need to continue in all cases

IMCC

International Muon Collider Collaboration

Collaboration formed 2021-2022, currently **hosted by CERN**

- **61 formal member institutions,** still growing, many from the US
- Waiting for CERN-DoE Agreement Addendum

- R&D progamme developed with global community
- Currently strong accelerator effort in Europe, strong and growing US contribution
- Plan to **move to co-hosting in Europe and US**

IMCC addresses a number of strategic requests:

- Last ESPPU demanded muon collider integration into European Accelerator R&D Roadmap
- EU is co-funding design study MuCol since 2023, expect results in 2027
- Different US recommendations to explore muon collider: Snowmass, P5 and National Academy

IMCC is site agnostic

Global Engagement

Expect to **continue R&D in Europe**

Expect increase in US P5 and now National Academy:
Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century. This requires the immediate creation of a national muon collider research and development program to enable the construction of a demonstrator of the key new technologies and their integration.

> Realisation of the plan above relies on **sustained and adequate funding in both the US and Europe**, and a **close collaboration between the two regions**, as outlined in the next section. Potential contributions from **other regions of the world would further strengthen** the program.

IMCC operation mode described in US Community submission to ESPPU

IMCC will carry out the *R&D together* and develop options to host the collider at CERN or at Fermilab and potentially also other sites
Envisage to **share leadership between CERN and Fermilab**

Organisation

Collaboration Board (ICB)

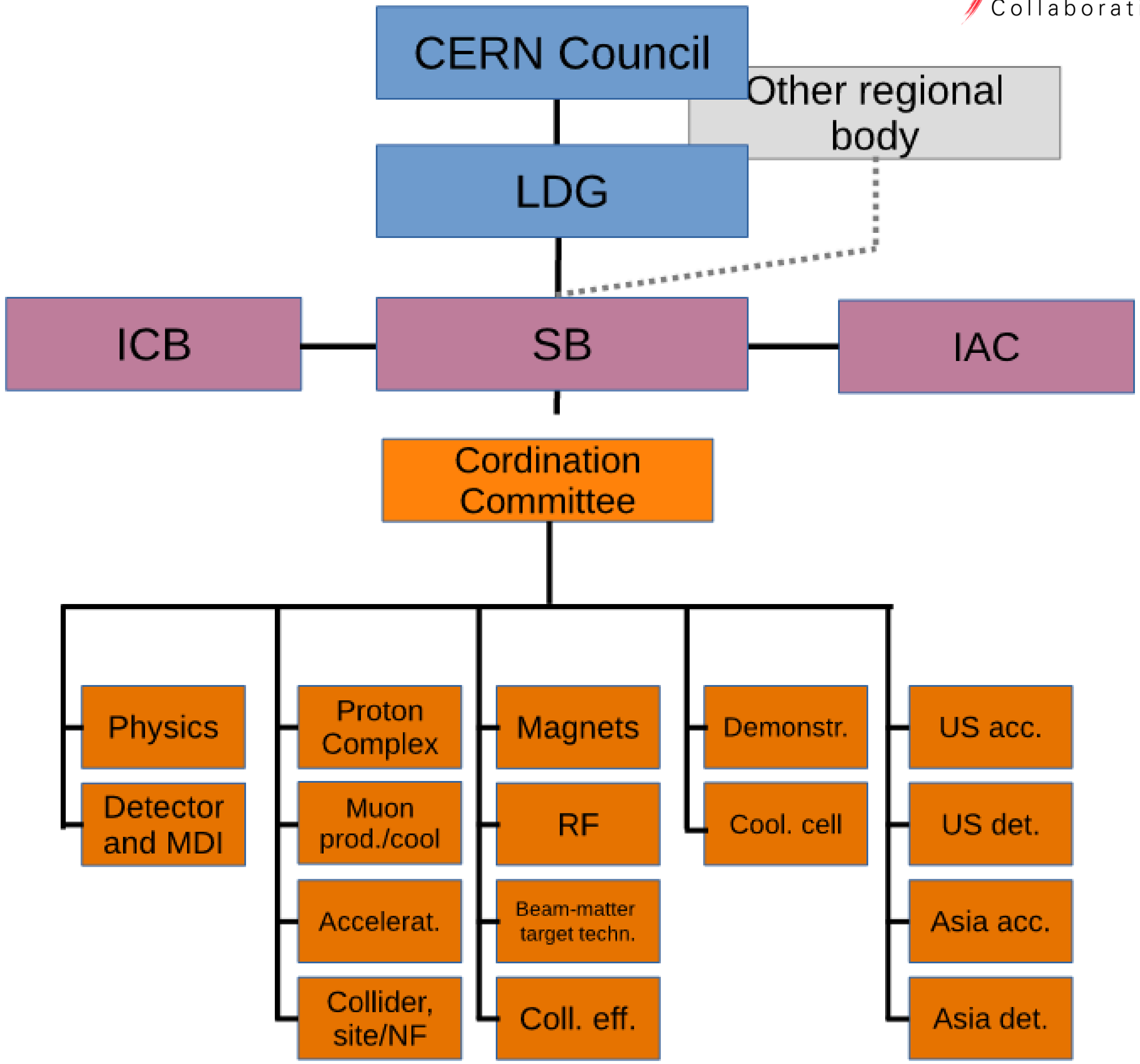
- Elected chair: **Nadia Pastrone**
- Represents partners

Steering Board (SB)

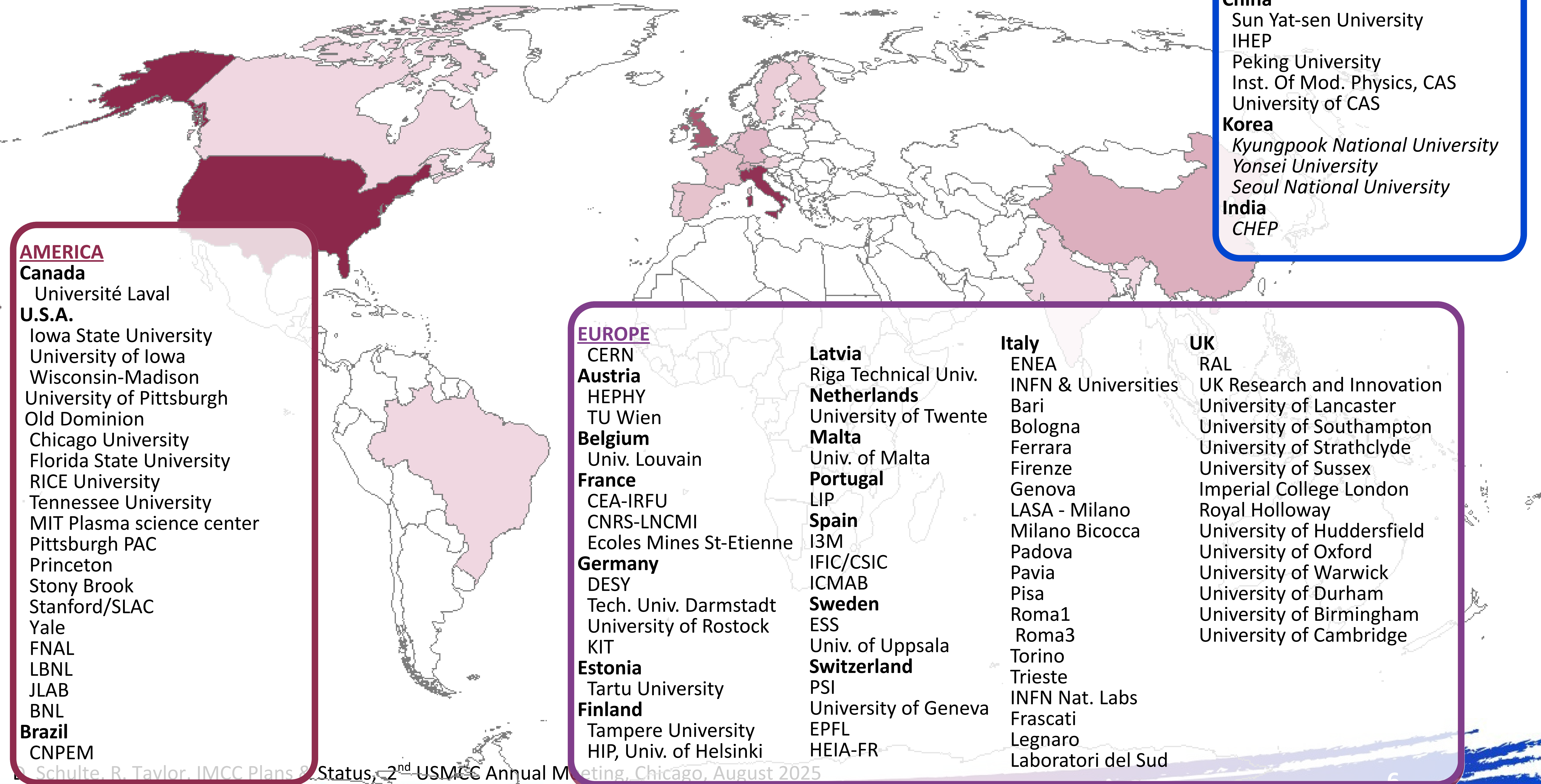
- Chair **Steinar Stapnes**
- Members from host lab members, ICB representatives, SL and deputies
- Reports to LDG (and CERN Council) and hopefully to DoE or other entity in the future
- Some US representation, **will enlarge this part together with US**

Coordination committee (CC)

- Study Leader Daniel Schulte, deputies: Andrea Wulzer, Donatella Lucchesi, Chris Rogers
- Several US members
- **Will evolve as resources become available in US**



IMCC Countries and Institutes



AMERICA

Canada
- Université Laval

U.S.A.
- Iowa State University
- University of Iowa
- Wisconsin-Madison
- University of Pittsburgh
- Old Dominion
- Chicago University
- Florida State University
- RICE University
- Tennessee University
- MIT Plasma science center
- Pittsburgh PAC
- Princeton
- Stony Brook
- Stanford/SLAC
- Yale
- FNAL
- LBNL
- JLAB
- BNL

Brazil
- CNPEM

ASIA

China
- Sun Yat-sen University
- IHEP
- Peking University
- Inst. Of Mod. Physics, CAS
- University of CAS

Korea
- *Kyungpook National University*
- *Yonsei University*
- *Seoul National University*

India
- *CHEP*

EUROPE
- CERN

Austria
- HEPHY
- TU Wien

Belgium
- Univ. Louvain

France
- CEA-IRFU
- CNRS-LNCMI
- Ecoles Mines St-Etienne

Germany
- DESY
- Tech. Univ. Darmstadt
- University of Rostock
- KIT

Estonia
- Tartu University

Finland
- Tampere University
- HIP, Univ. of Helsinki

Latvia
- Riga Technical Univ.

Netherlands
- University of Twente

Malta
- Univ. of Malta

Portugal
- LIP

Spain
- I3M
- IFIC/CSIC
- ICMAB

Sweden
- ESS
- Univ. of Uppsala

Switzerland
- PSI
- University of Geneva
- EPFL
- HEIA-FR

Italy
- ENEA
- INFN & Universities
- Bari
- Bologna
- Ferrara
- Firenze
- Genova
- LASA - Milano
- Milano Bicocca
- Padova
- Pavia
- Pisa
- Roma1
- Roma3
- Torino
- Trieste
- INFN Nat. Labs
- Frascati
- Legnaro
- Laboratori del Sud

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
- University of Birmingham
- University of Cambridge

ESPPU Submission Content

International
MUON Collider
Collaboration

Muon Collider Assessment

Present **physics case** and **green field** designs and technologies

- Parameters, lattice and component designs, beam dynamics, cost, …
- Aim for 10 TeV with 10 ab^{-1}
  - Aim for initial stage around 2050 (e.g. with 3 TeV and 1 ab^{-1})

R&D plan

- The main timeline driver
- Accelerator design, detector development, magnets, muon cooling technology, …

Implementation Considerations

- Currently for CERN and for FNAL
- Scaling from green field design, detailed lattice designs after ESPPU

  Technically limited schedule

  Cost and **power** consumption scales

Back-up document (406p, 450 signatories)

10 page submission with project summary

The Muon Collider
Input to the European Strategy for Particle Physics - 2026 update

20 page to answer ESPPU-specific questions

Addendum to: The Muon Collider
Input to the European Strategy for Particle Physics - 2026 update
The International Muon Collider Collaboration

400 page collider overview (to be published)

The Muon Collider
Supplementary report to the European Strategy for Particle Physics - 2026 update
The International Muon Collider Collaboration

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  Cost and **power** consumption scales

ESPPU Submission 2018

Muon Colliders

The Muon Collider Working Group

Jean Pierre Delahaye[1], Marcella Diemoz[2], Ken Long[3], Bruno Mansoulié[4], Nadia Pastrone[5] (chair), Lenny Rivkin[6], Daniel Schulte[1], Alexander Skrinsky[7], Andrea Wulzer[1,8]

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[2] INFN Sezione di Roma, Roma, Italy
[3] Imperial College, London, United Kingdom
[4] CEA, IRFU, France
[5] INFN Sezione di Torino, Torino, Italy
[6] EPFL and PSI, Switzerland
[7] BINP, Russia
[8] LPTP, EPFL, Switzerland and University of Padova, Italy

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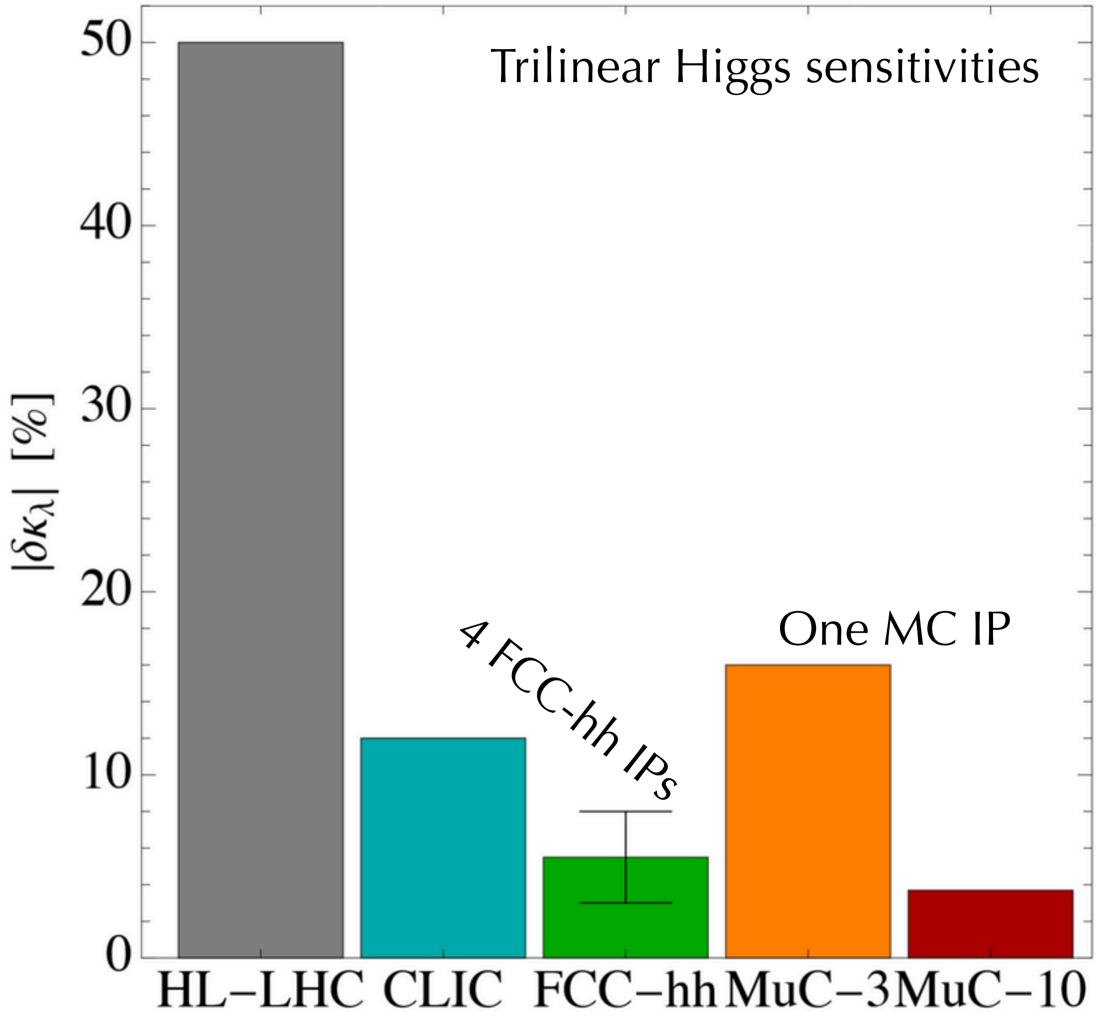
0 page collider overview (to be published)

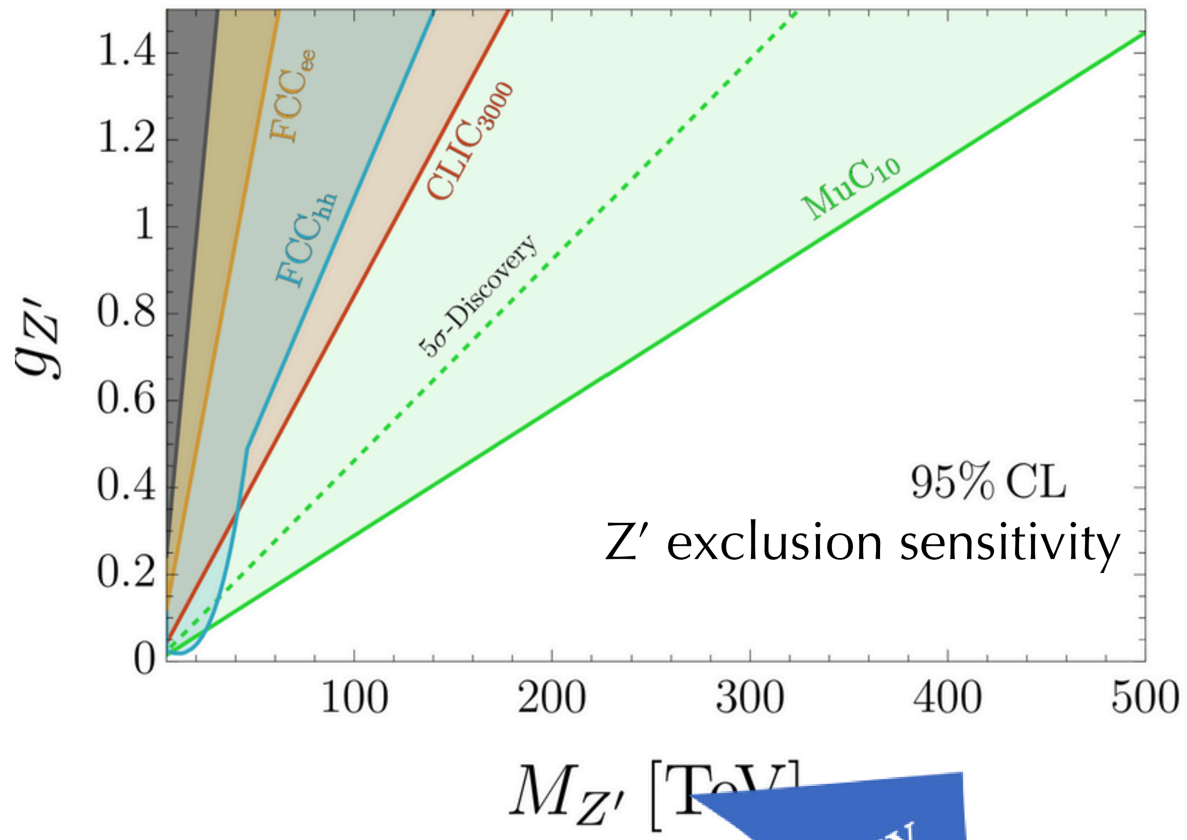
he Muon Collider

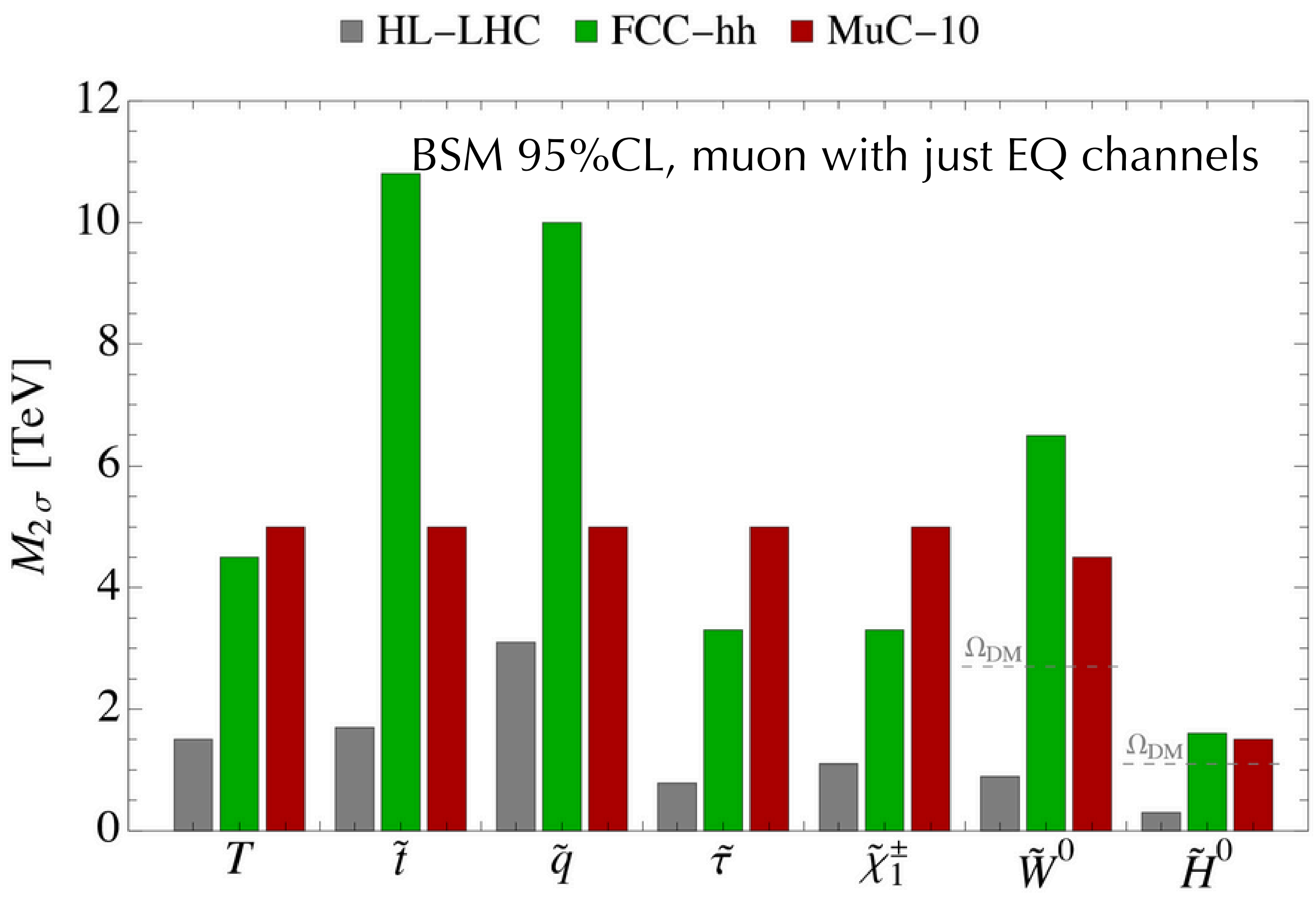
plementary report to the European Strategy for Particle Physics - 2026 update

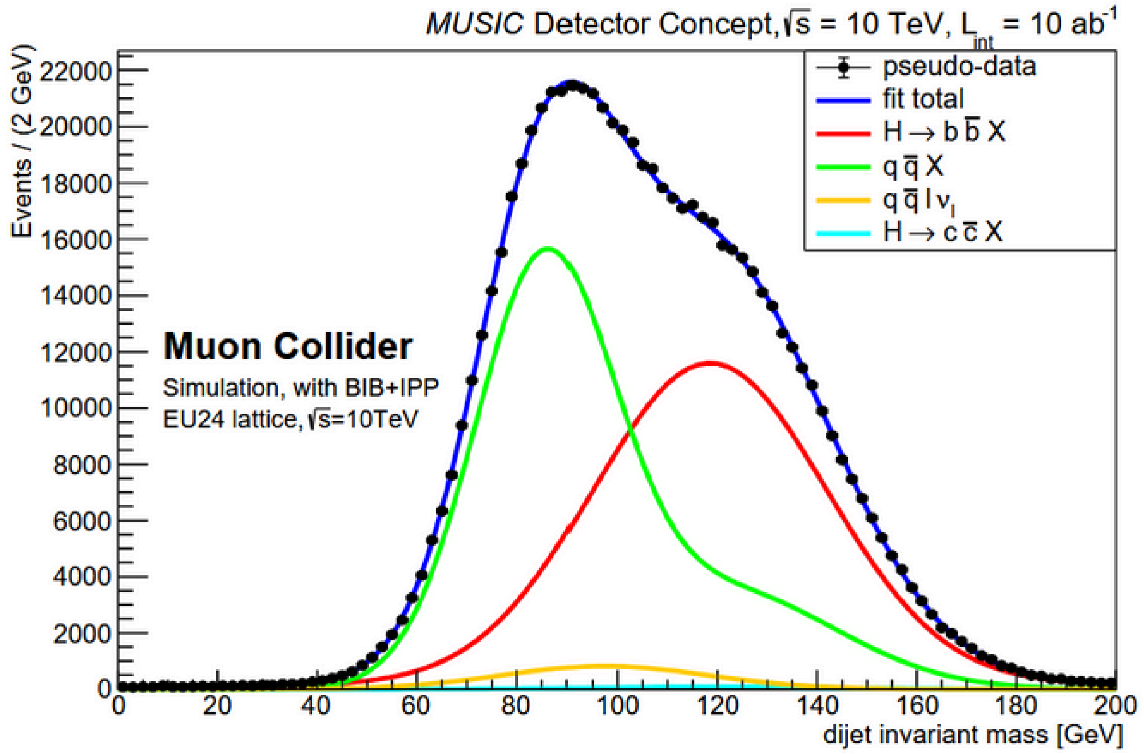
The International Muon Collider Collaboration

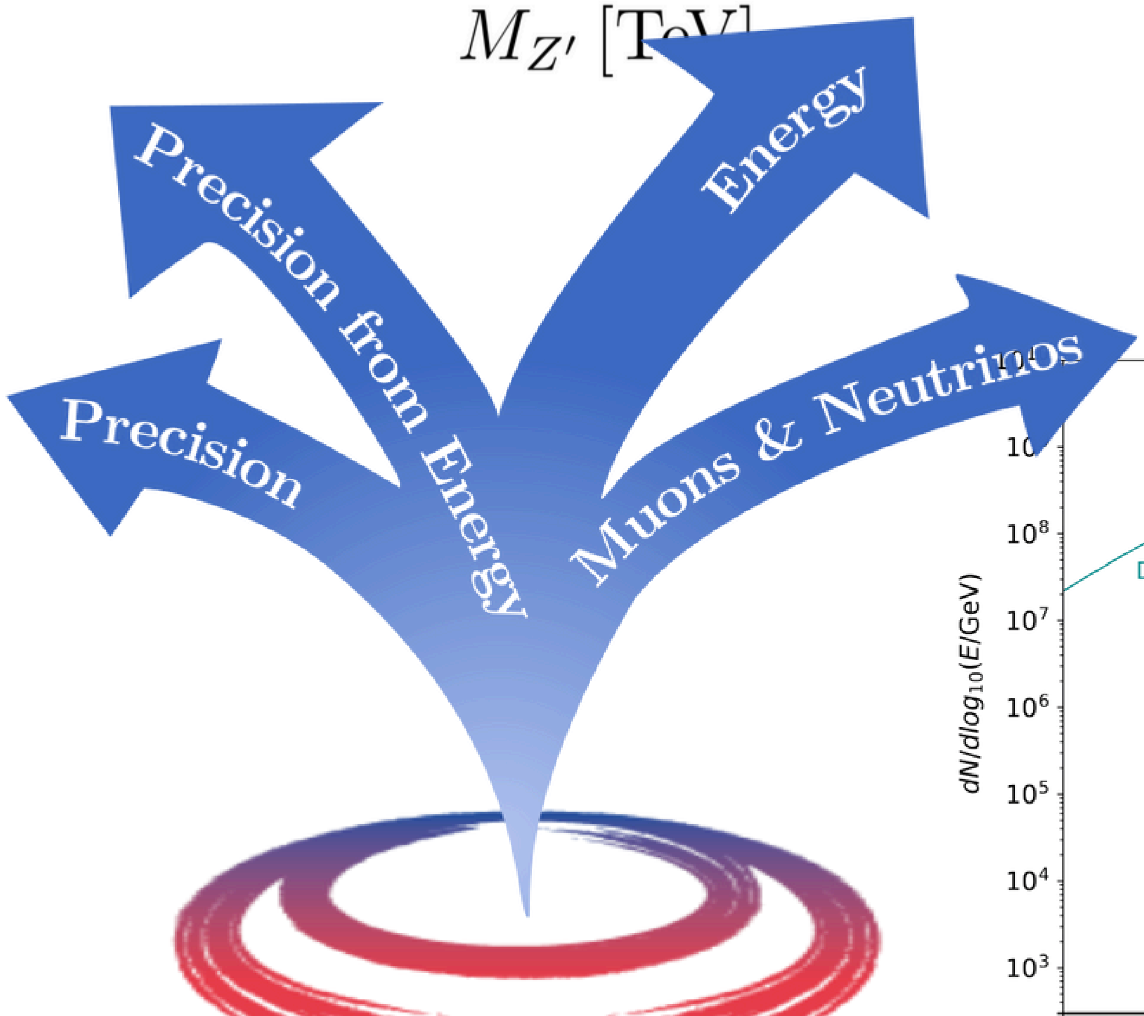
Evaluation Report: Physics

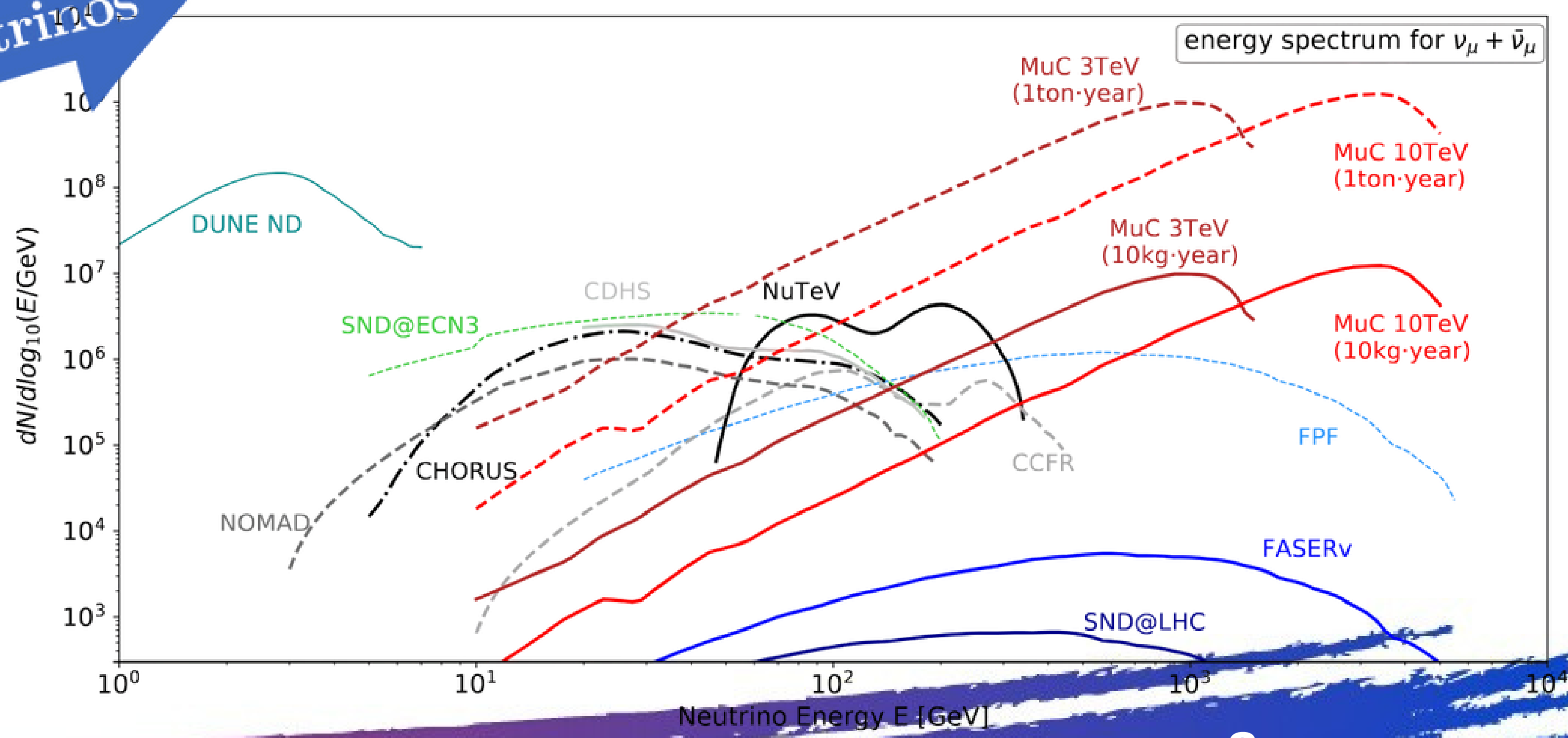








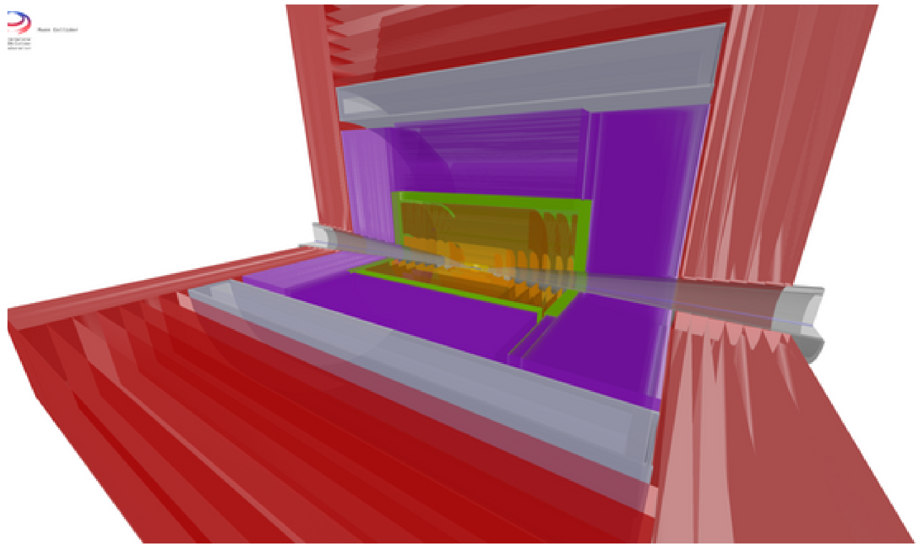




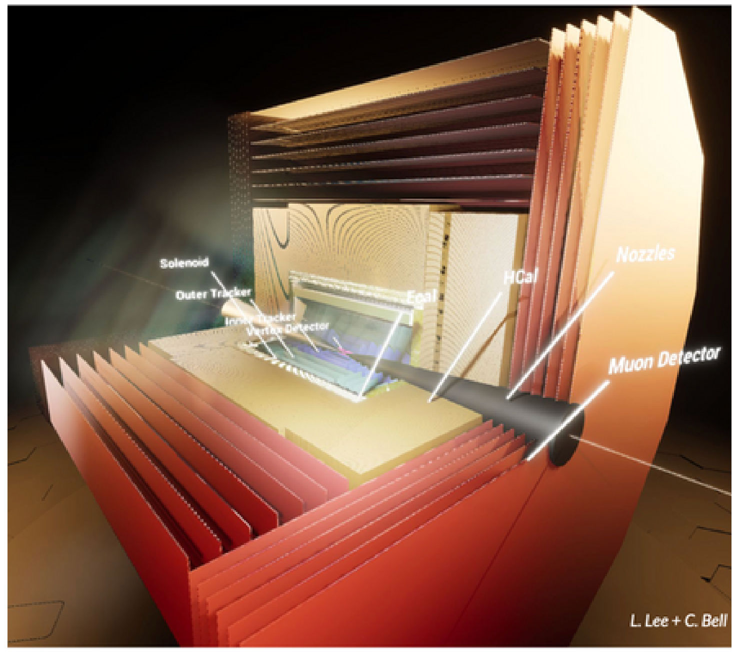
Physics and Detector Concepts

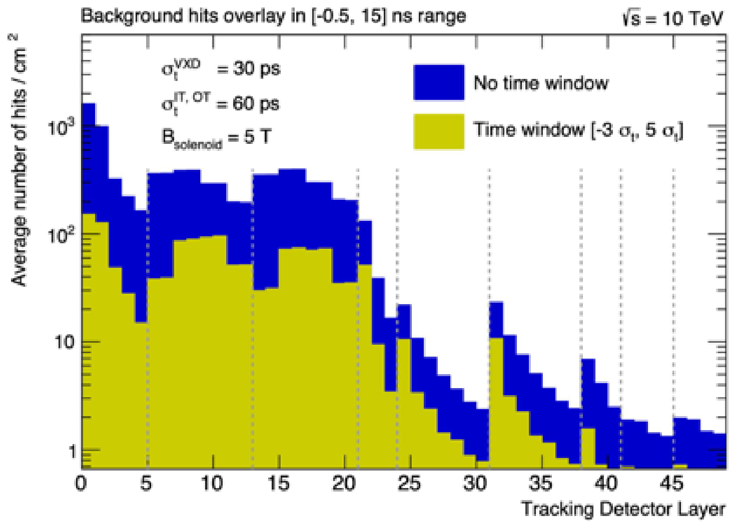
Challenges:
High-energy lepton detector requirements
Background from muon decay and beam-beam effects (BiB)

MUSIC
(MUon System for Interesting Collisions)

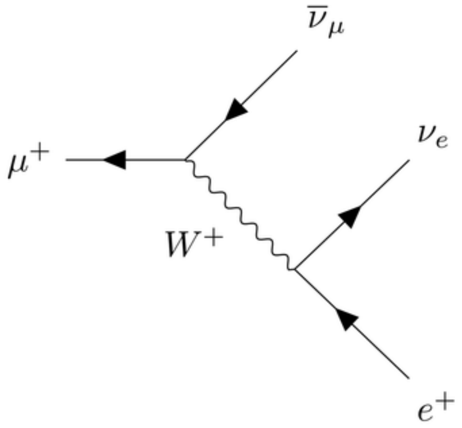


MAIA
(Muon Accelerator Instrumented Aperatus)



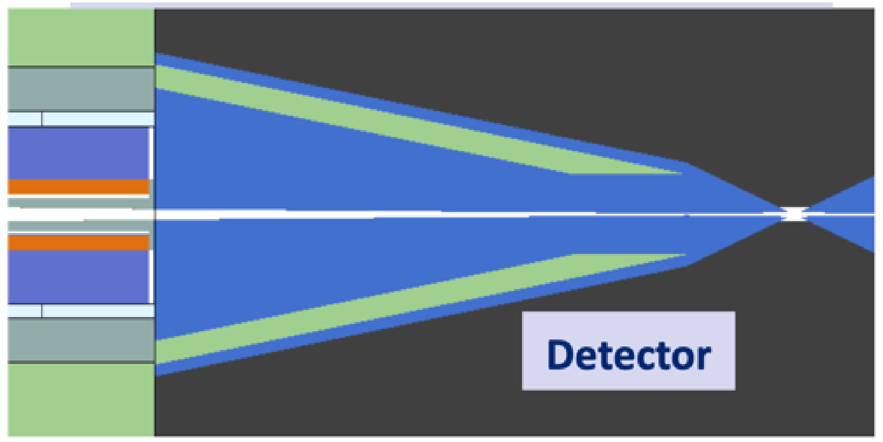


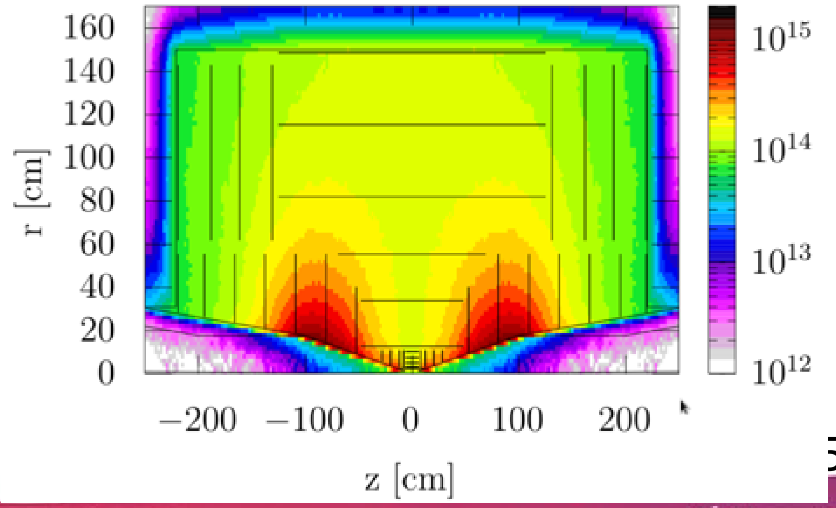
Achievements
Two detector concepts are being developed
Performance studies with GEANT
Detailed design and simulations of MDI and background suppression



Key conclusions:
Full simulations show good physics performance with near-term technology in spite of BiB

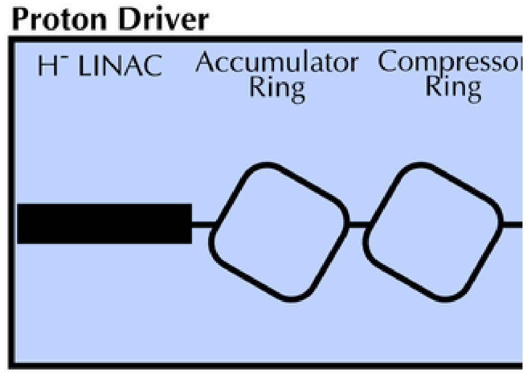
- But important improvements are possible
- Need strong R&D for **optimization** and **integration**
- **Proper investment crucial to enable exploitation of full muon collider potential** in available time using **new technologies, AI, and ML**

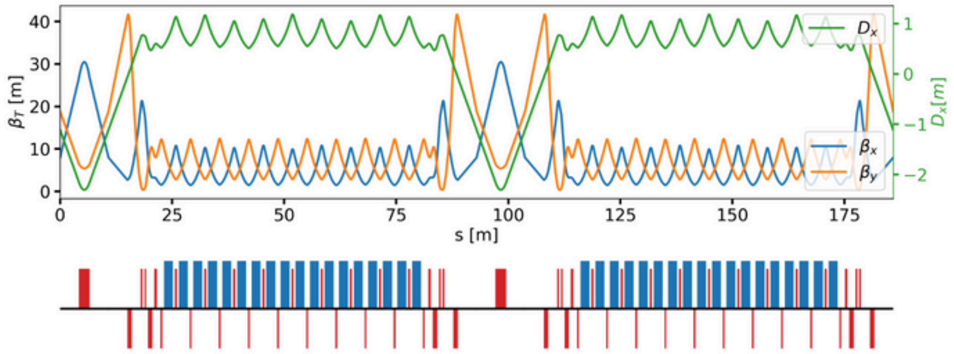


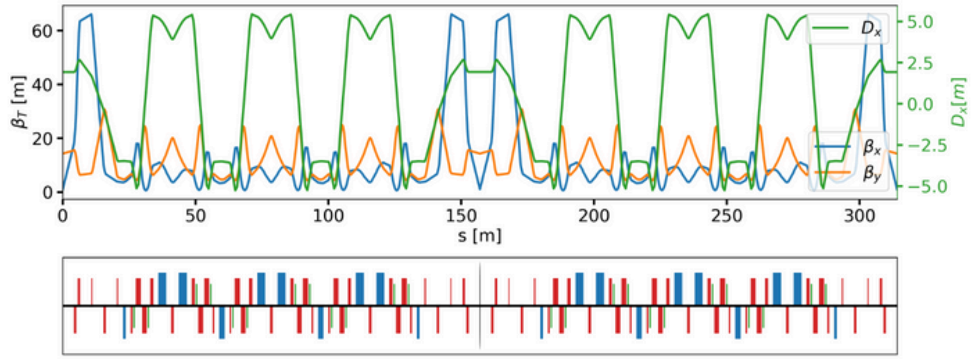


Proton Complex

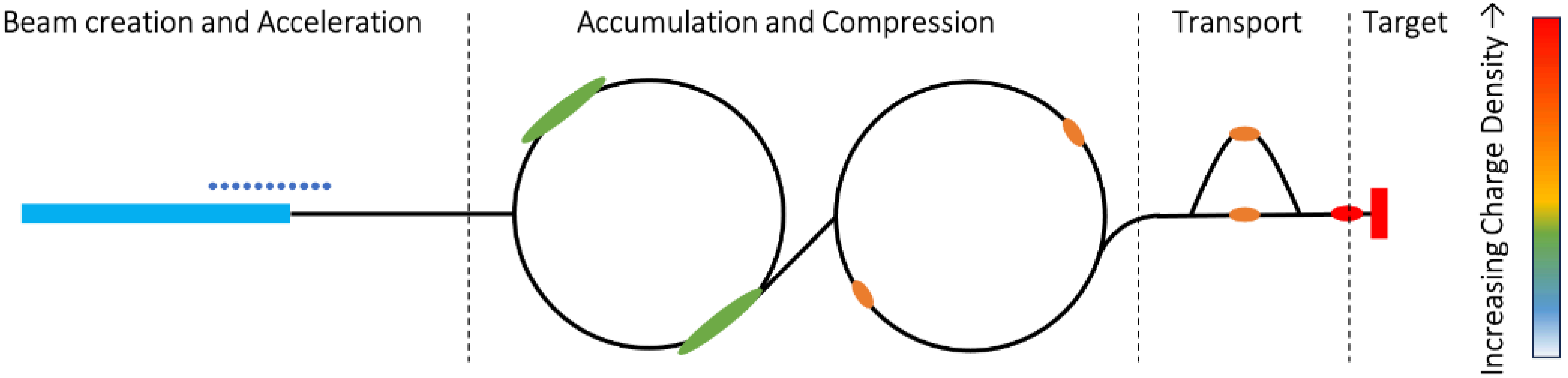
Challenge:
- 2 MW, 5 GeV, 5 Hz,
- 5 x 10^{14} protons/pulse
- Proton pulse accumulator and compressor rings

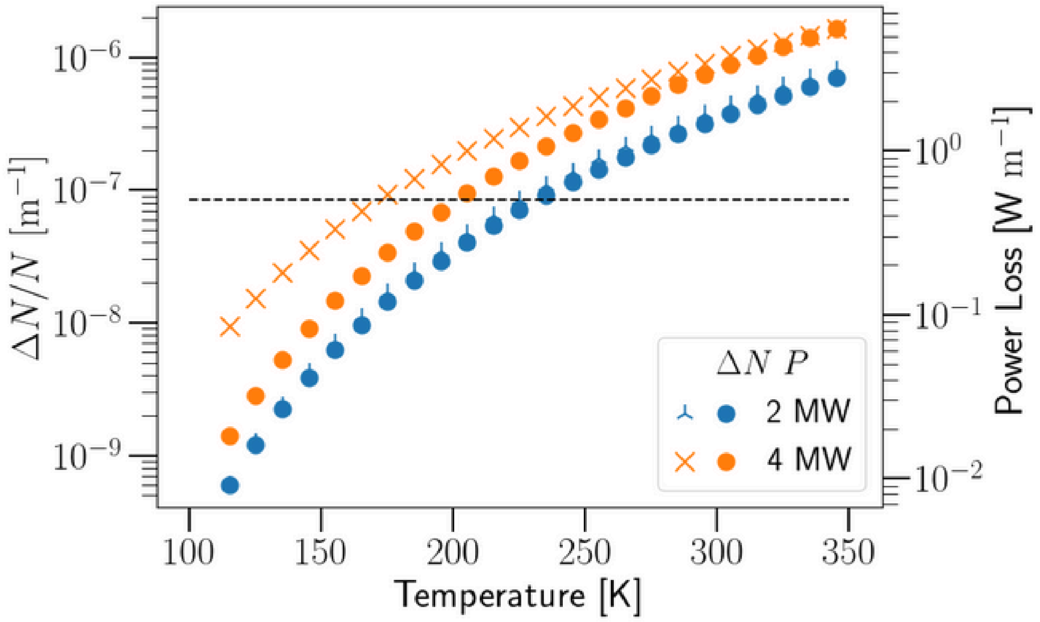






Achieved:
- Accumulator and combiner ring lattices
- First collective effects studies show stable beam
- Optimise between one or two bunches in compressor





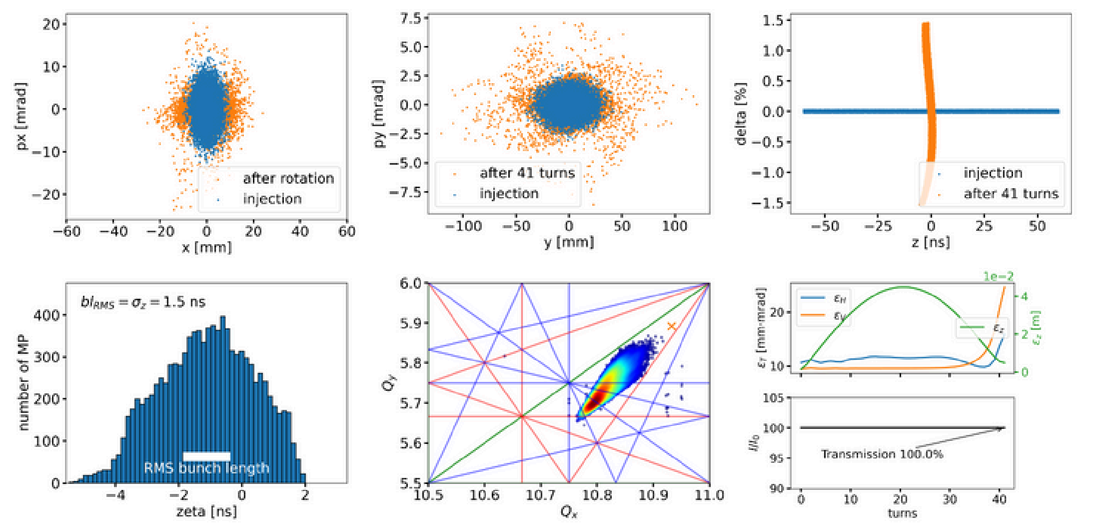


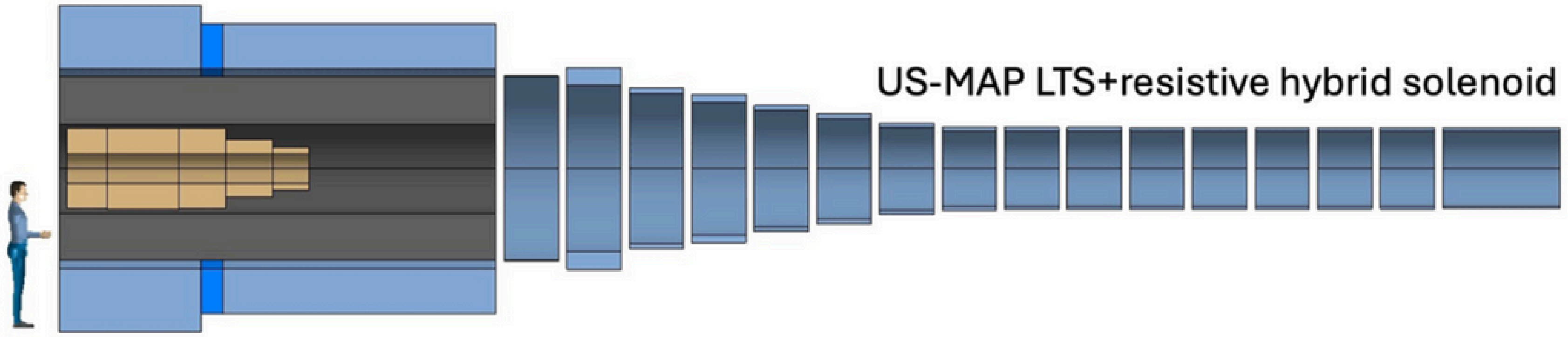
Fig. 5.1.8: Simulation of the full compression for one bunch at 5 GeV. Since this requires a 2 bunch solution scheme, this bunch has half of the full intensity shown in Table 5.1.1. Notice that at the end of the compression there is still some emittance blow up that need still to be addressed.

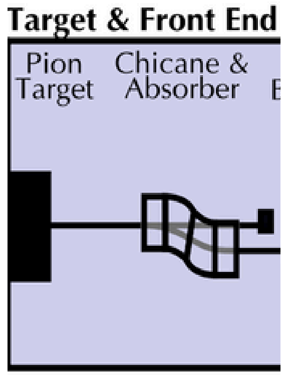
Key conclusions:
- Can compress 2 MW, 5 GeV proton beam to two 2 ns bunches, then merge them
  - Optimisation in compressor ring for collective effects ongoing
- For 4 MW need 10 GeV beam
- Cool beamline to avoid ion loss from black body radiation

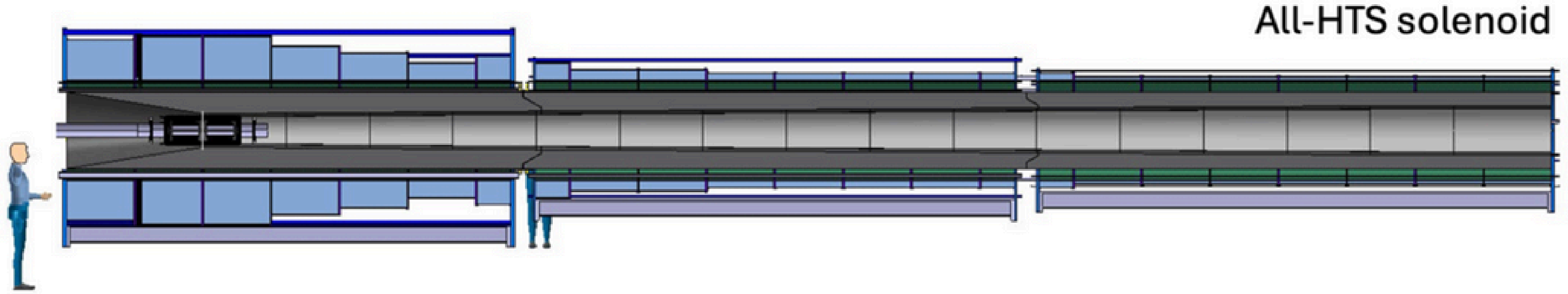
Target

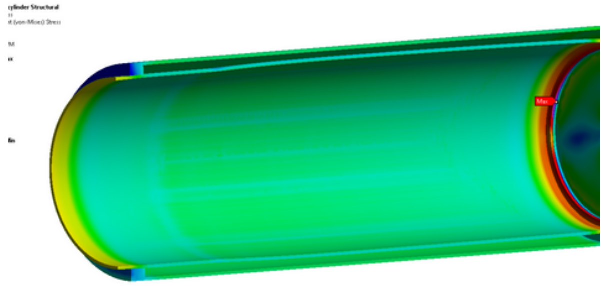
Challenges:
- 2 MW, 5 Hz, 400 MJ/pulse target
- Can we replace mercury with graphite?

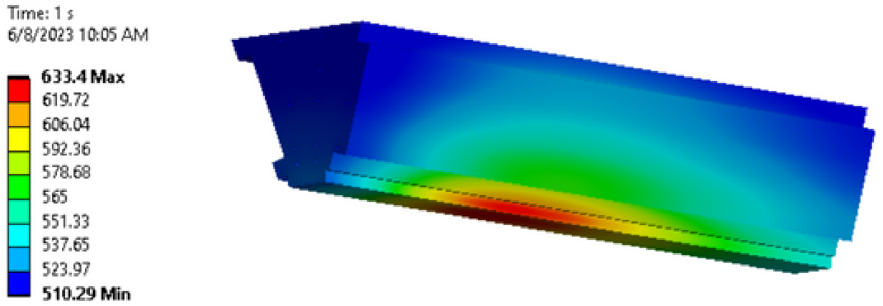
Achieved:
- Initial 2 MW graphite target conceptual design, pion yield optimised
- HTS solenoid and shielding concept developed
- Study of proton removal ongoing

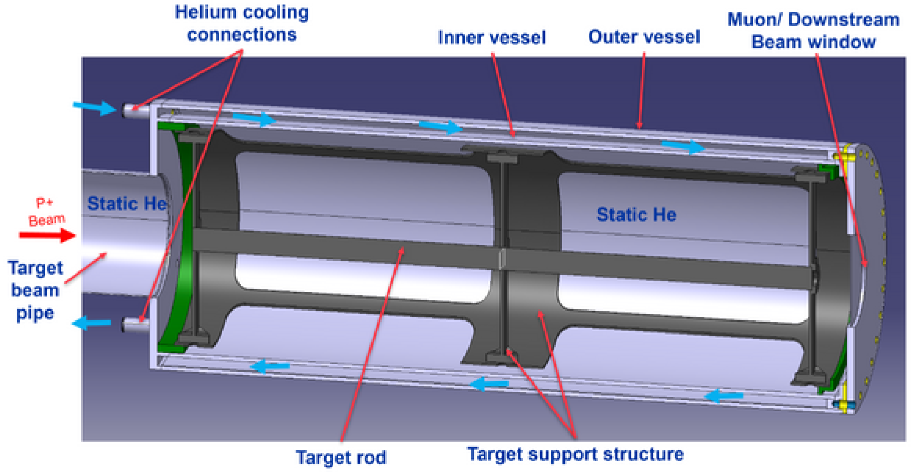


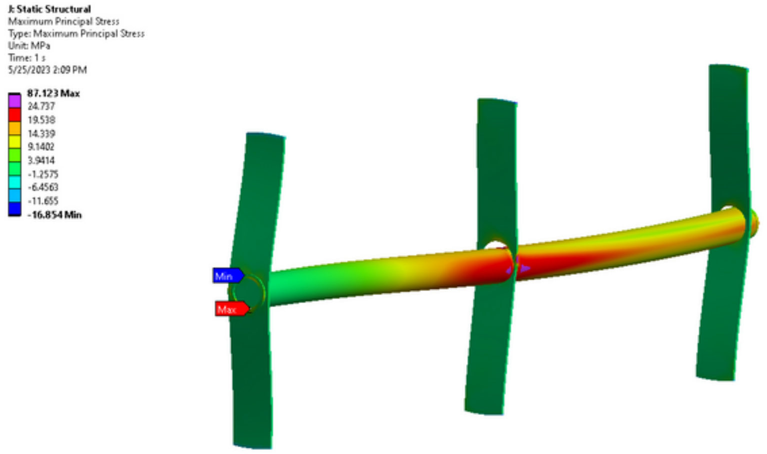












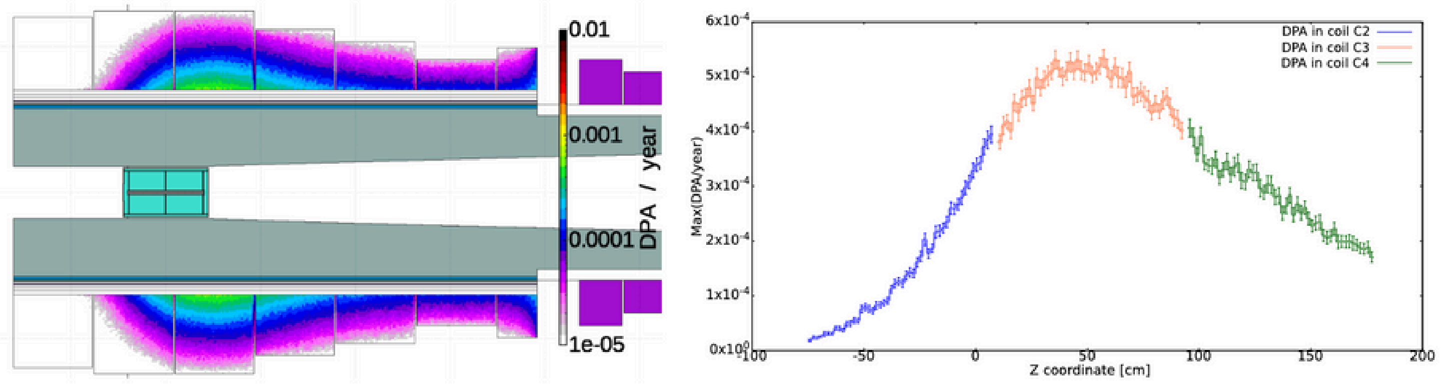


Fig. 6.5.1: 2D map of the displacement per atom (DPA) in the superconducting magnets of the target area (left) and the peak DPA in the coils most exposed to radiation (right).

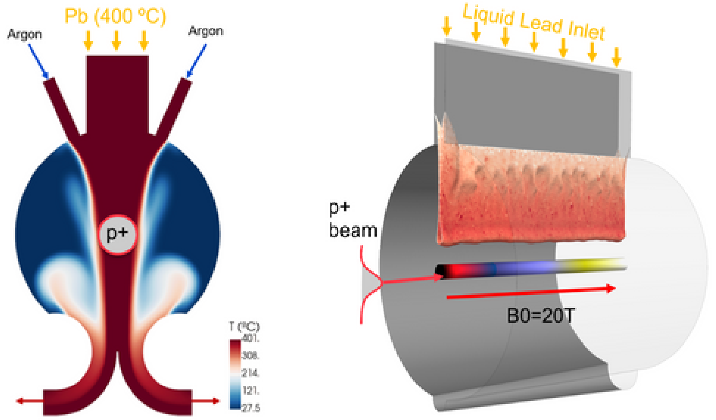
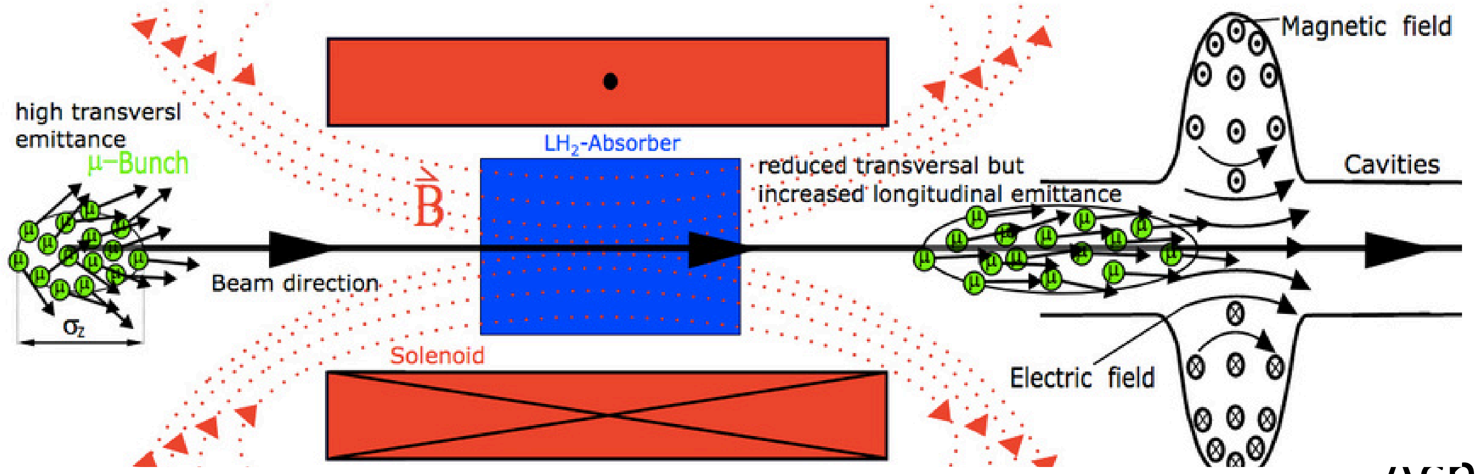


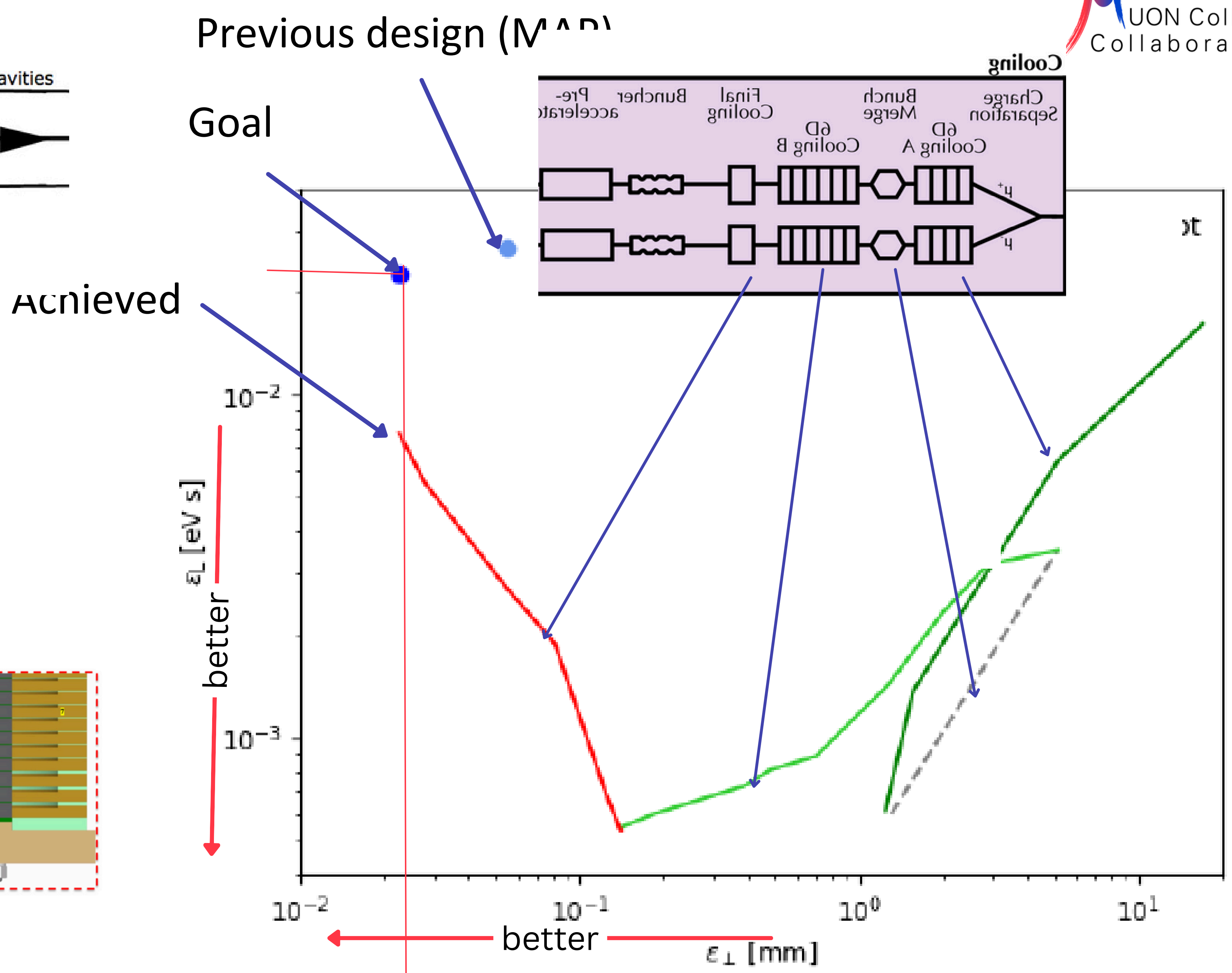
Fig. 6.4.4: Liquid lead target curtain concept.

Key conclusions:
- Yield, magnet shielding, target stress, cooling, radiation are OK
- Components survive 2 MW beam
- Higher power alternatives to study:
  - Graphite
  - Liquid metal

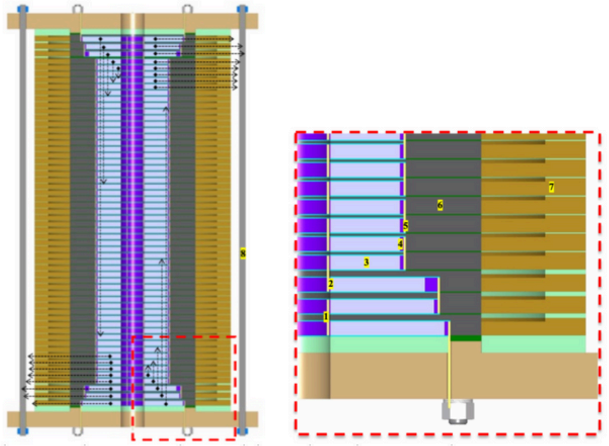
Muon Cooling Lattice Design

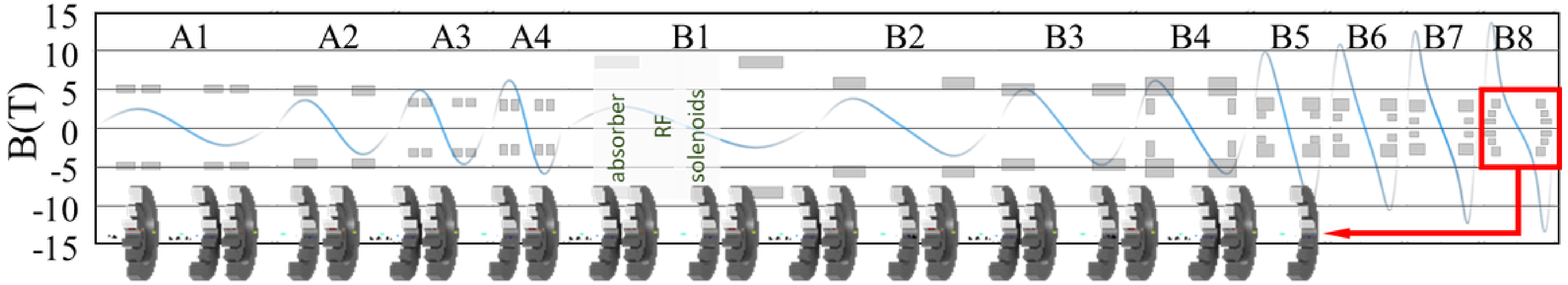
Challenges:
Novel, complex lattice with cavities and absorbers in solenoids
High magnetic field





Achieved:
Much improved lattice design
Developed simulation tools: BDSIM and RFTrack
This allowed to start collective effects studies
Magnet scaled and conceptual designs for 6D cooling
40 T final cooling solenoid conceptual design (55 T is identified to be the limit)



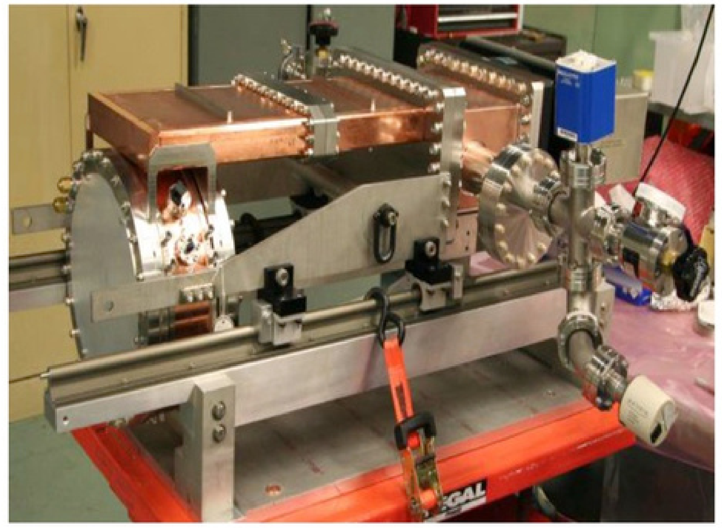


Key conclusions:

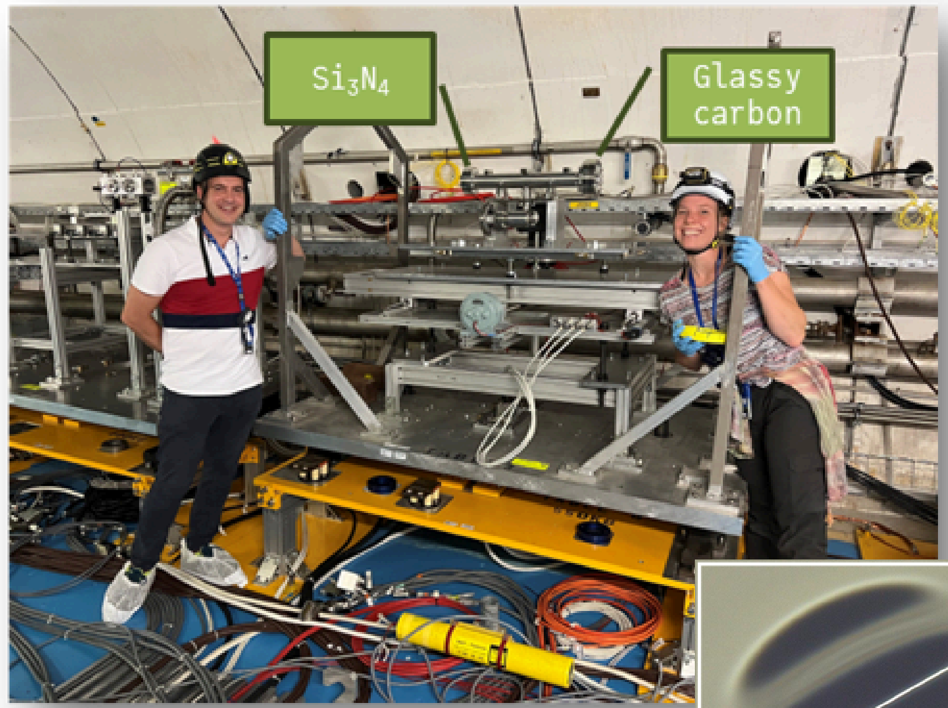
- Can in principle reach or exceed performance target
- Magnet models and prototypes need to be built
- Much improved longitudinal, is useful for collider ring
- Study of collective effects important

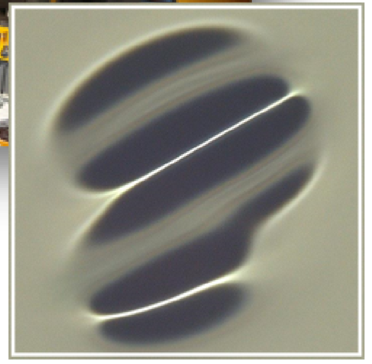
Muon Cooling Technology

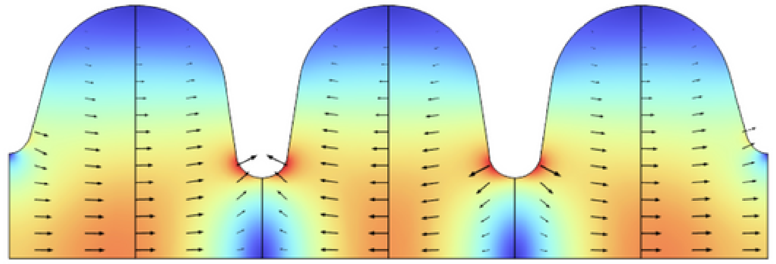
Challenges:
- NC RF cavities in magnetic field (30 MV/m)
- HTS magnets (up to 40 T in final cooling)
- Bright beam hard on absorbers and windows
  - Can evaporise liquid hydrogen



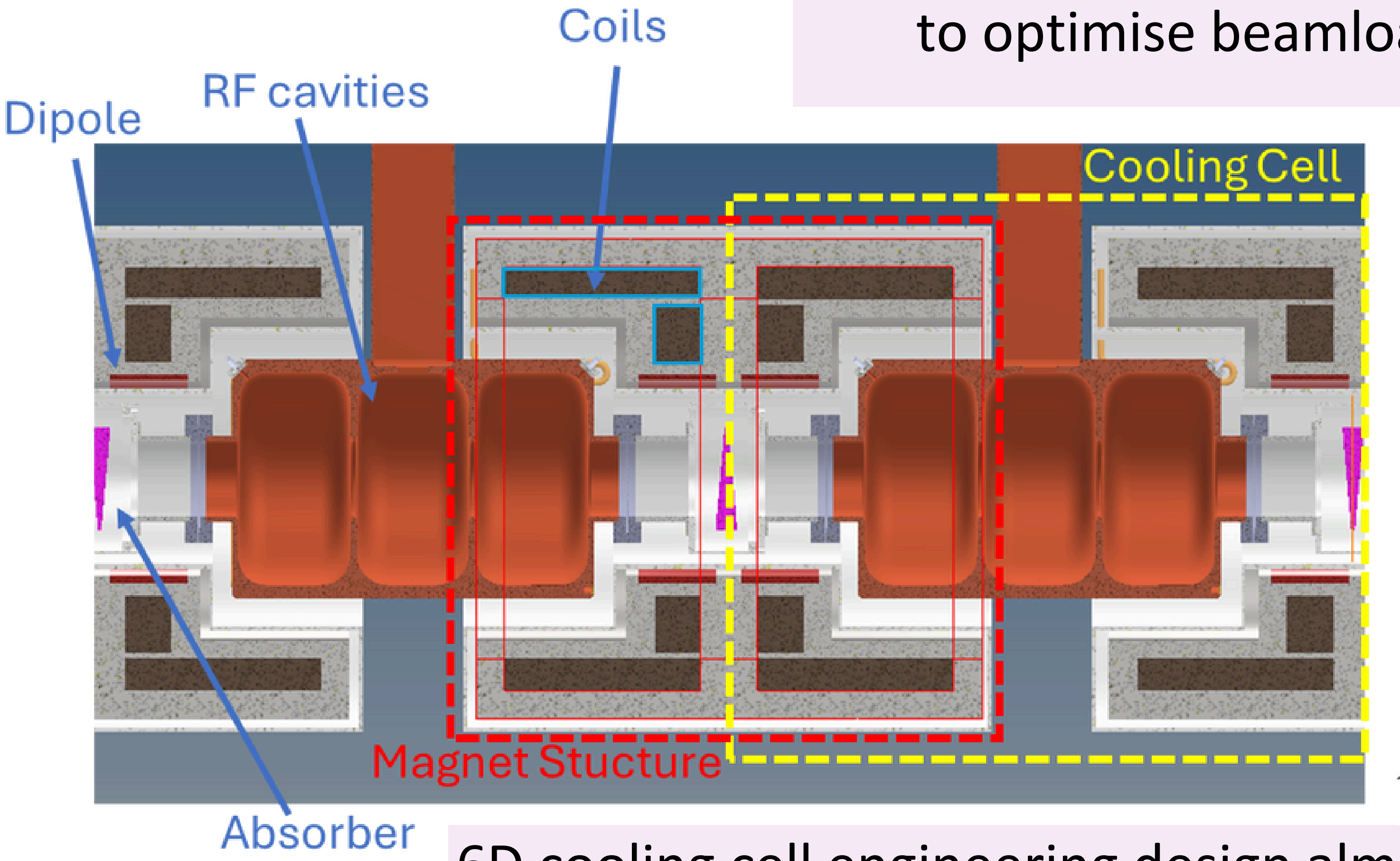
MuCool demonstrated >50 MV/m in 5 T
- H2-filled copper
- Be end caps

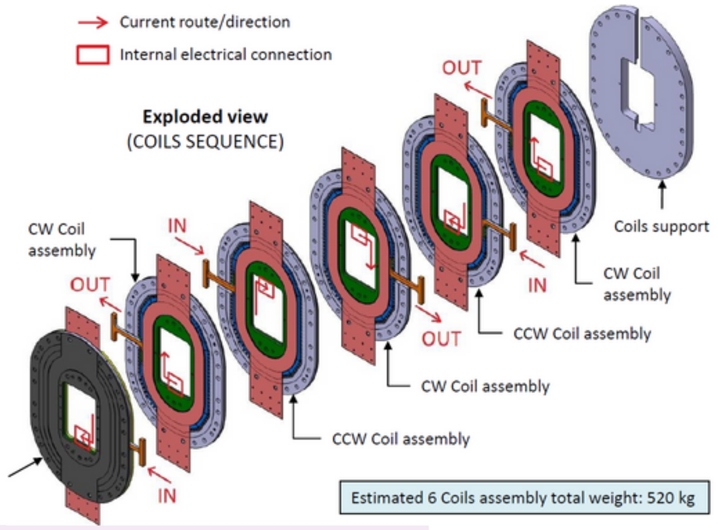






MAP proved gradient
- Initial RF designs
- More RF design ongoing to optimise beamloading





6D cooling cell engineering design almost ready

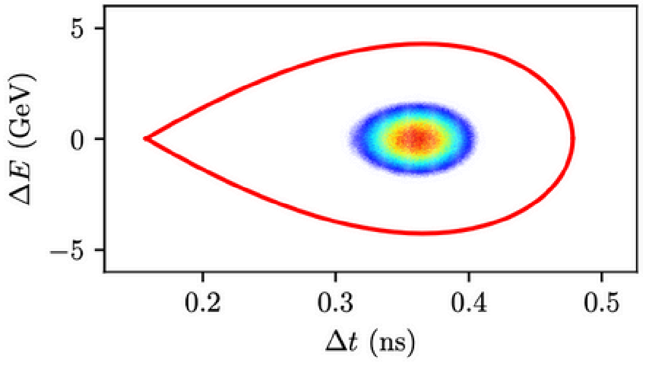
- First window tests performed with protons
- Use of H2 gas in final absorbers

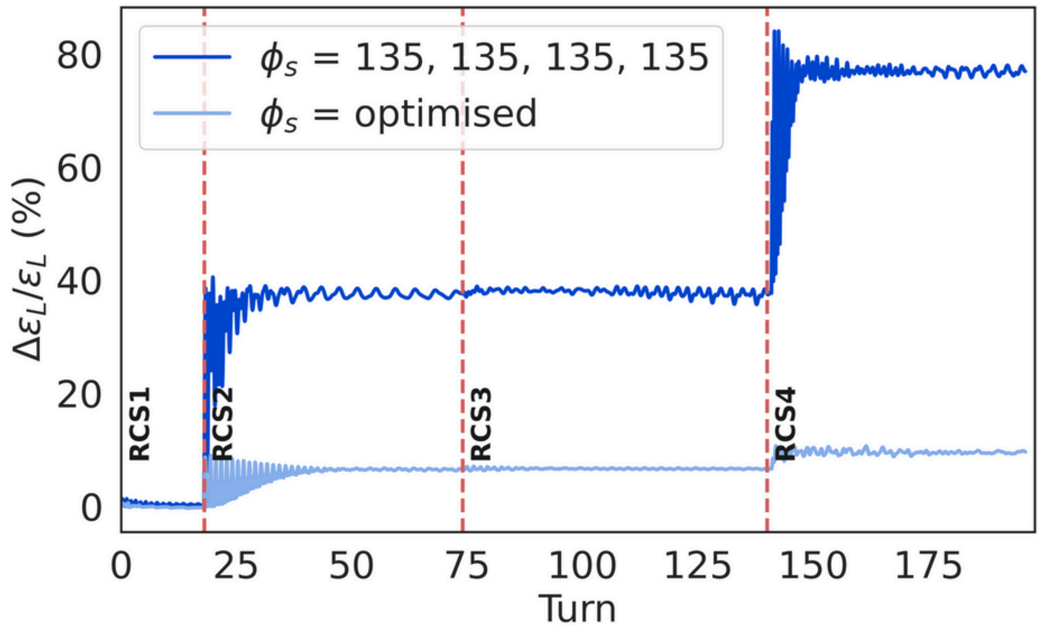
Key conclusions:
- Ready to **ramp-up effort**, in particular prototyping and experimental work, also beamdynamics
- **Need RF test stands** for experimental optimization

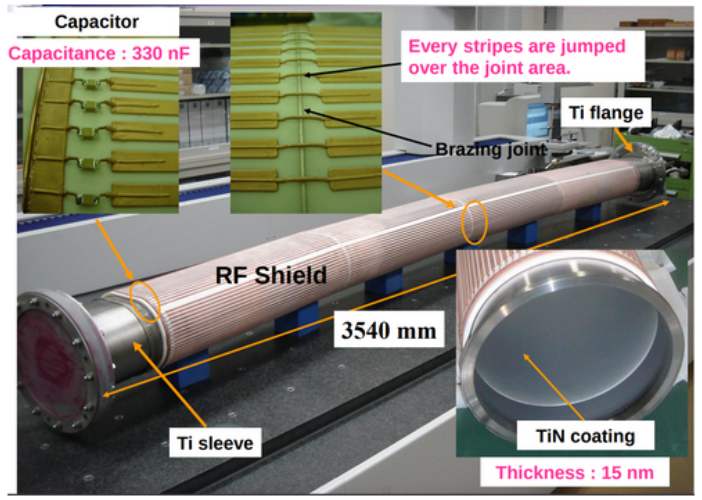
RCS Designs

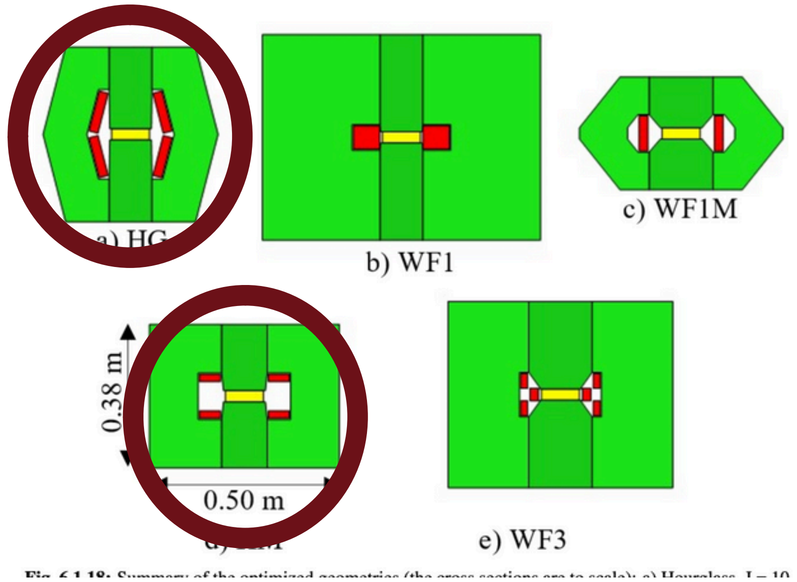
Challenge:
- Uses fast-pulsed normal magnets
- 5 Hz pulses of O(1-10ms)
- 6-35 km circumference
- Cost
- Recover energy from magnetic field
- High bunch charge
- Maintain beam quality

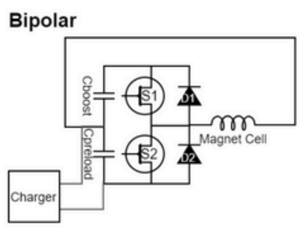
Achieved:
- Lattices for all site independent RCSs
- Beam propagation through complex
- Conceptual design of magnets and power converters
- Optimised design together with RF

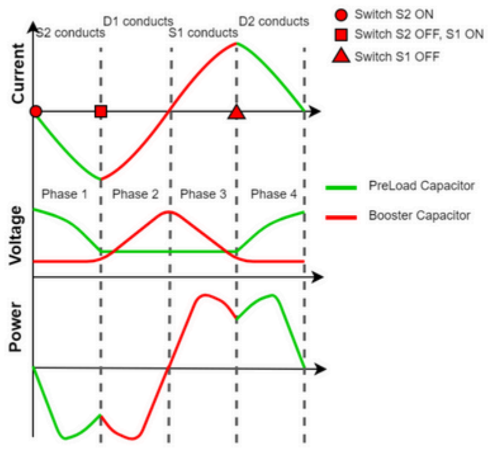




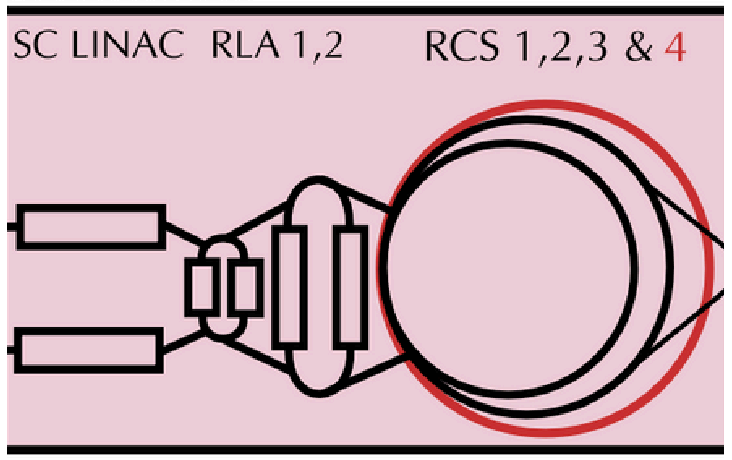


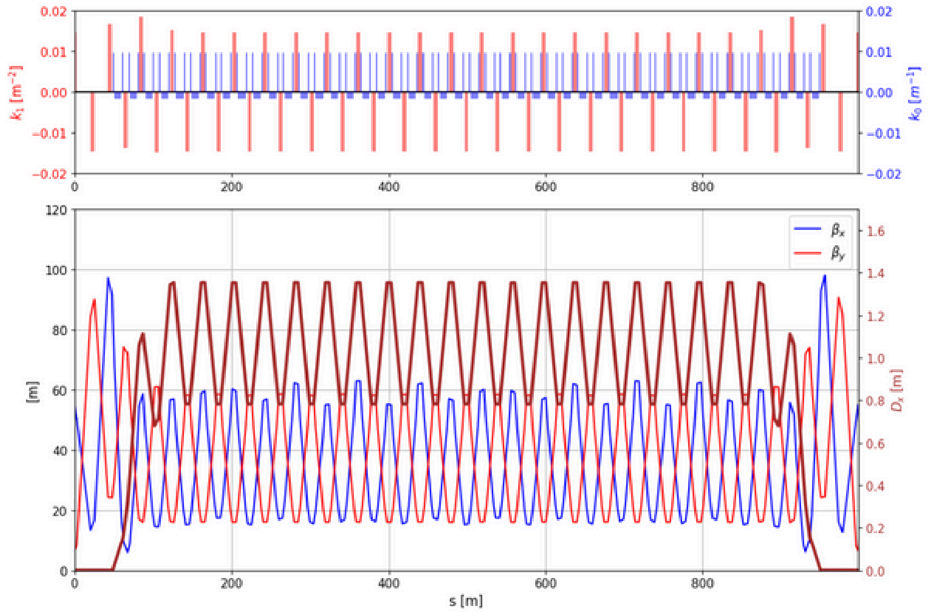






Acceleration





RCS	E [J/m]	Loss [%]	P [MW]
SPS 1	5447	**1.1**	1.9
LHC 1	5678	**1.6**	12.8
LHC 2	5752	**6.3/2**	26.6

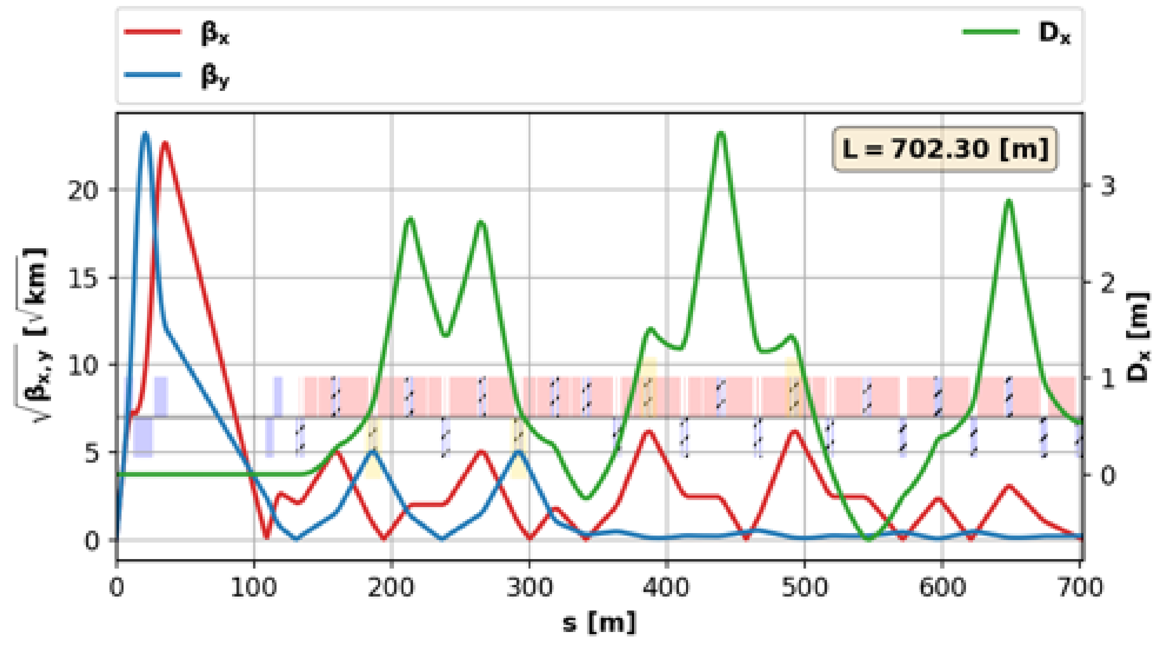
Key conclusions:
- 1.3 GHz TESLA-type cavities work
- Emittance transport is OK
- Cost and power is OK
- Need to connect to initial linacs

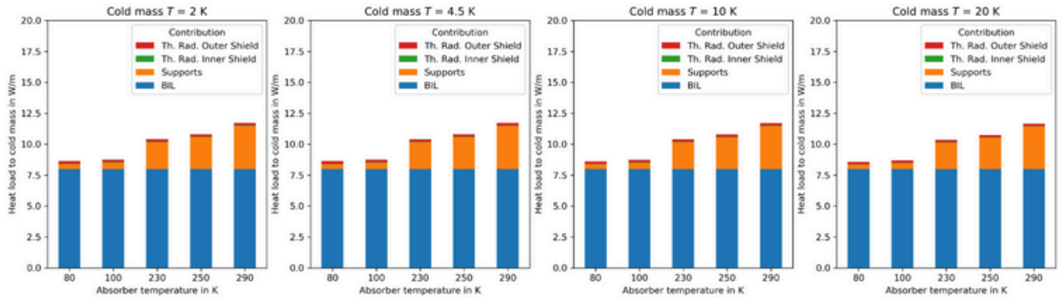
Collider Ring

Challenges:
500 W/m loss, magnet strength, lattice design with beta 1.5-5 mm, 0.1% beam energy spread

Achieved:

- Magnet shielding design
- Magnet performance model and conceptual designs
- Cryogenics conceptual design
- Lattice reaches target beta-functions but not yet full target energy acceptance
- First studies of mover system impact on beam
- Impedance is OK

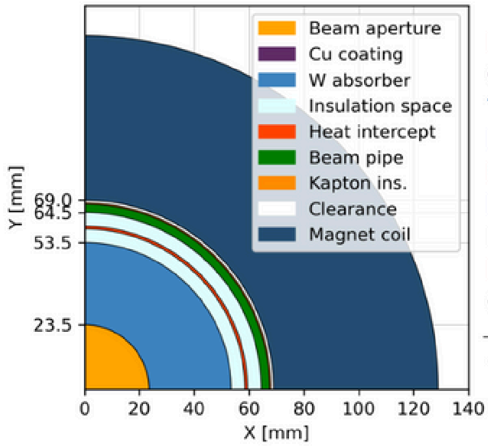




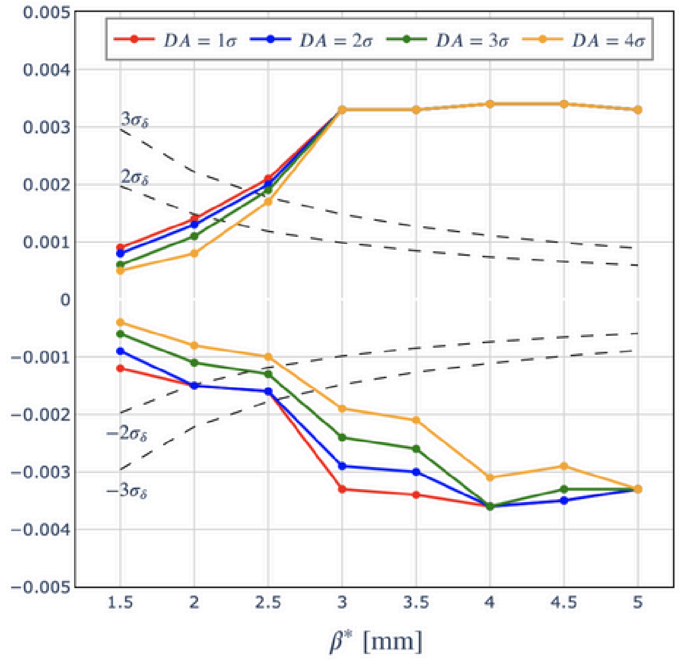
Cryogenic loads at different temperatures

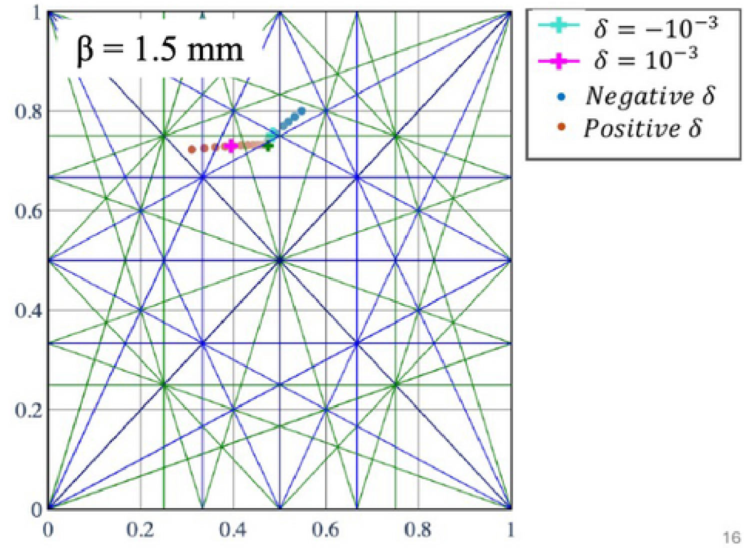
shield) are assumed to be at 80 K. In the legend, "BIL" stands for "beam-induced losses".

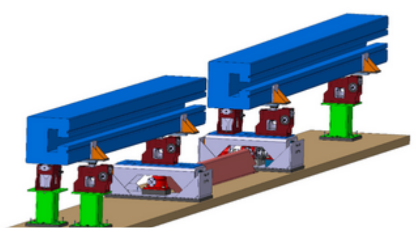
Shielding (30-40 mm)

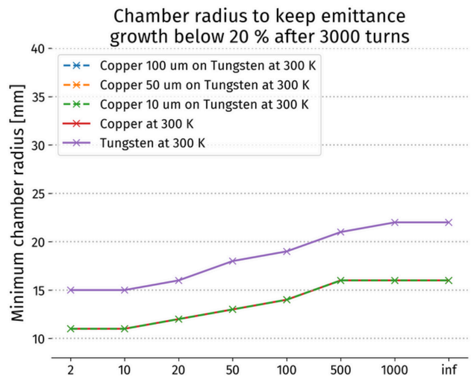


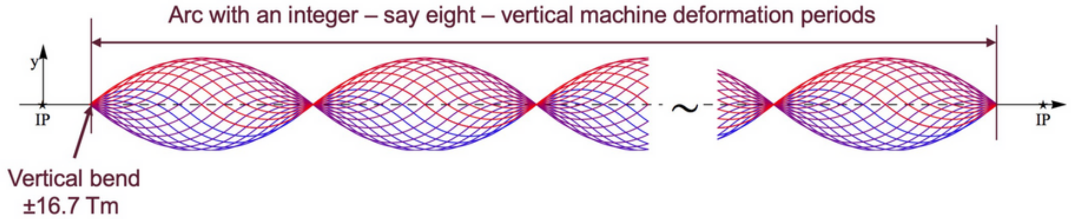
	Δr
Beam aperture (5σ)	23.49 mm
Cu layer beam screen	0.01 mm
Tungsten absorber	20-40 mm
Insulation space	5 mm
Heat intercept	1 mm
Insulation space	5 mm
Beam pipe	3 mm
Kapton insulation	0.5 mm
Clearance to coils	1 mm
Total magnet aperture	**118-158 mm (diameter)**

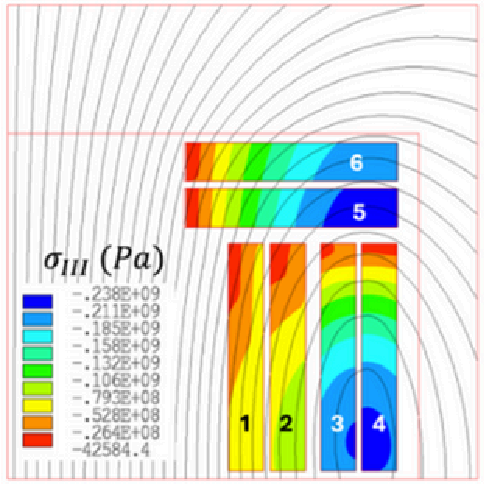


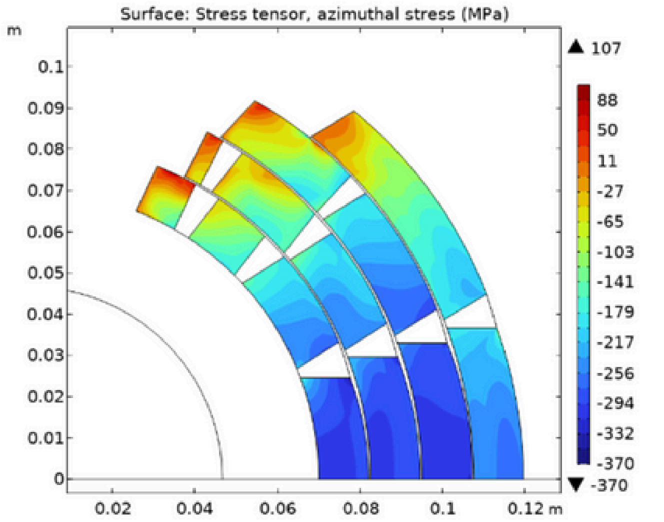












Magnet Designs

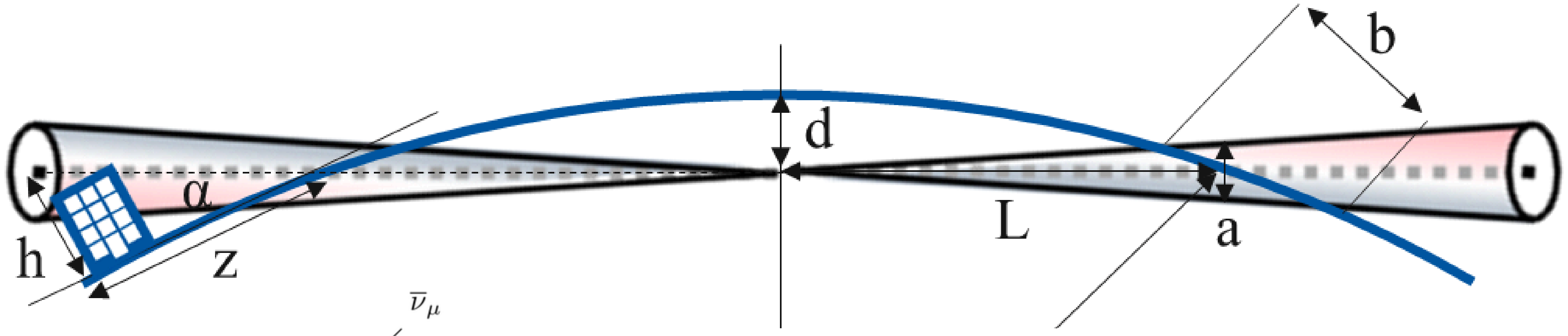
or under Lorentz Forces at nominal current for both block coil

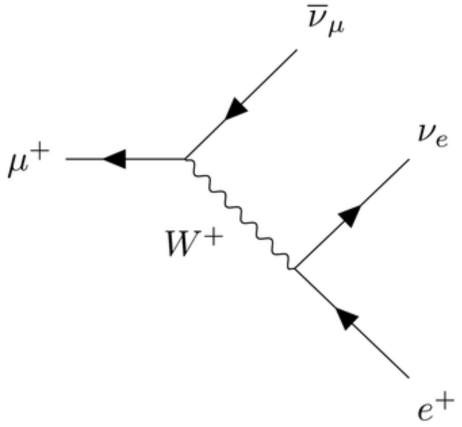
Key conclusions:
Further improve energy acceptance, but OK with energy spread predicted in muon cooling
Mover system OK for beam in regular arcs
Address imperfections next

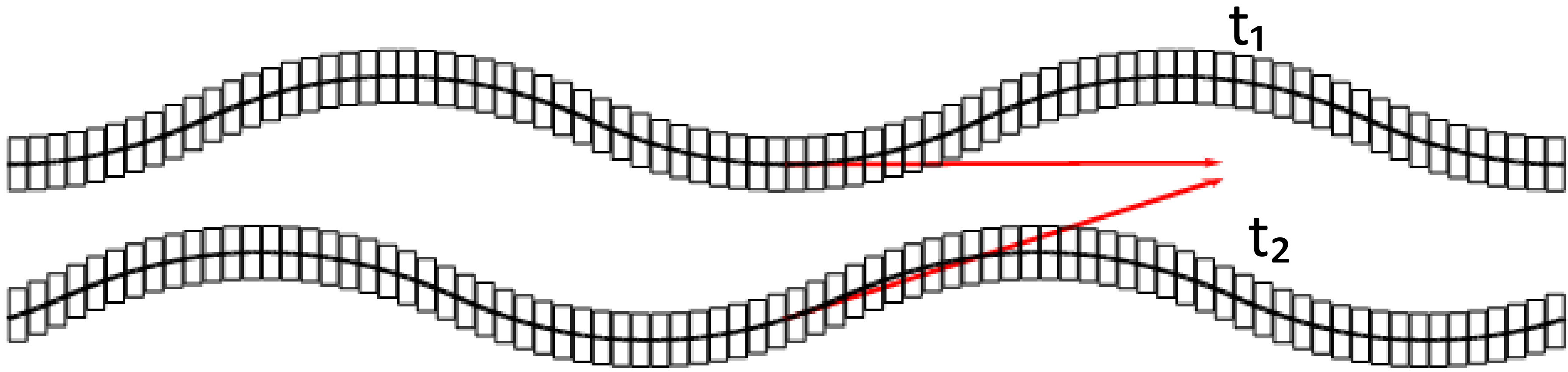
Placement Studies

Challenge:
Obtain negligible neutrino flux

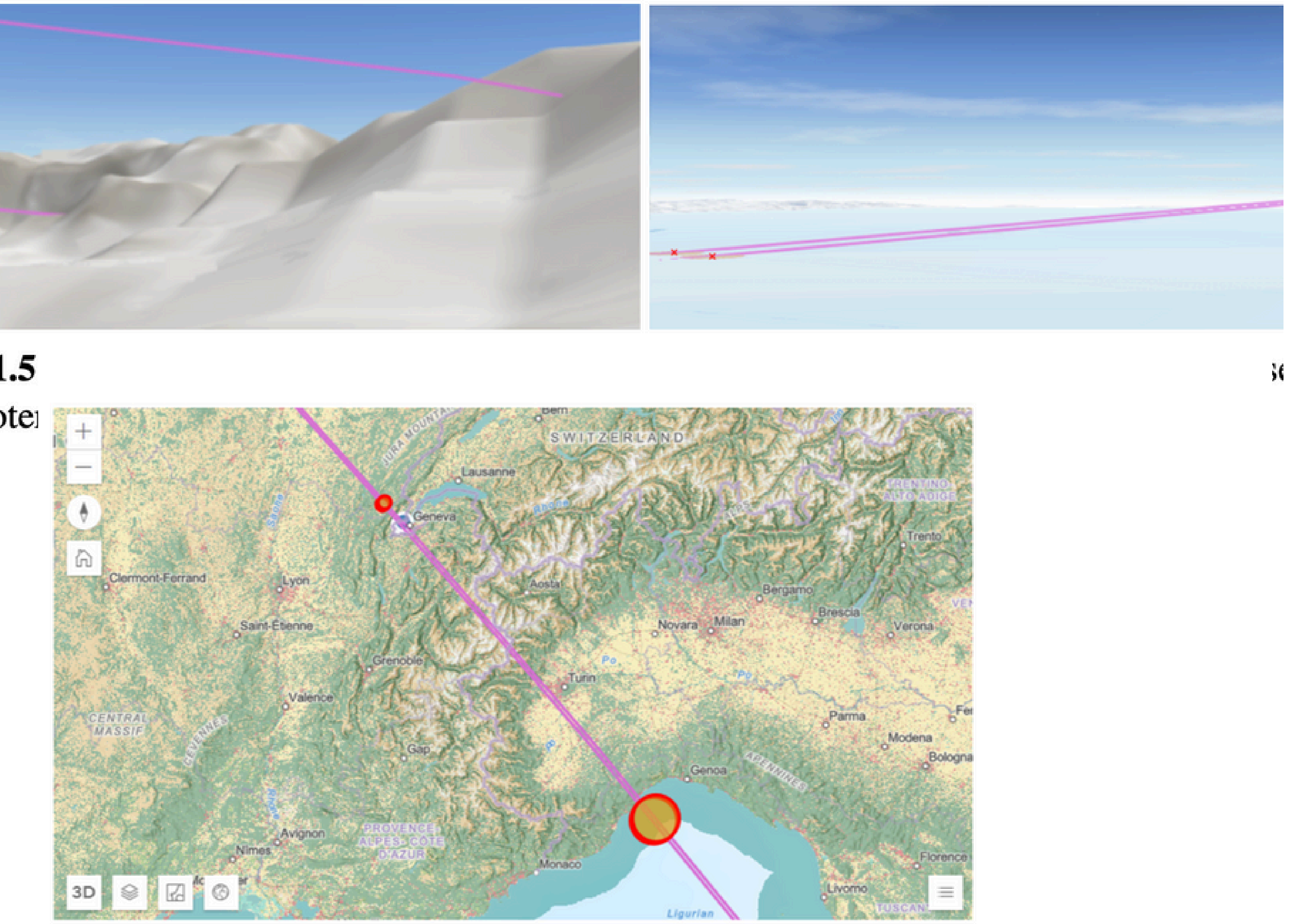
Achieved:
- Detailed modelling
- First good orientation found
- Mover system concept



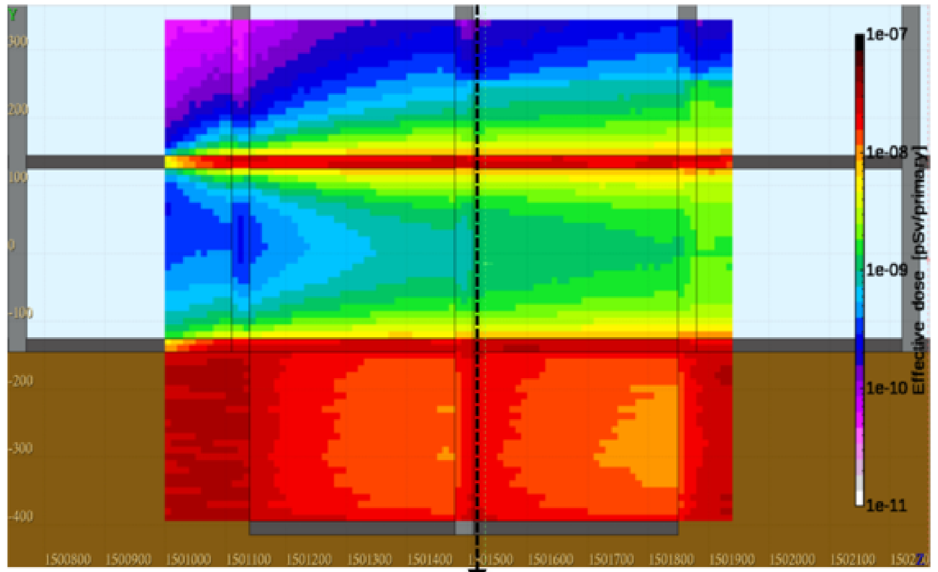




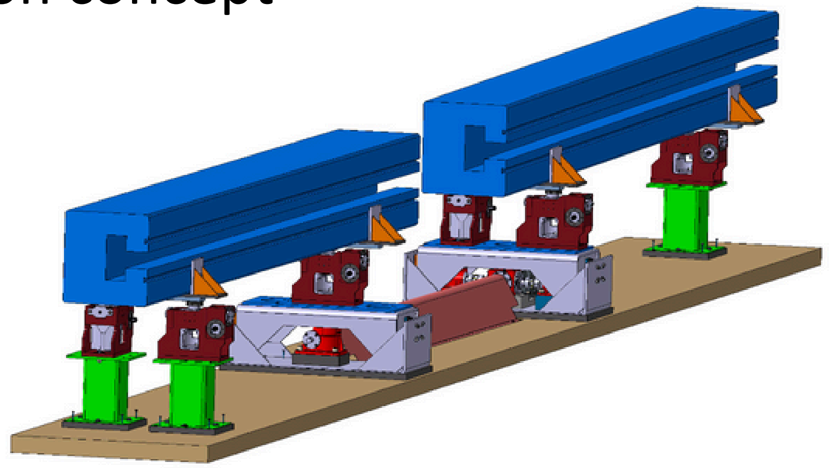
Arc mitigation concept



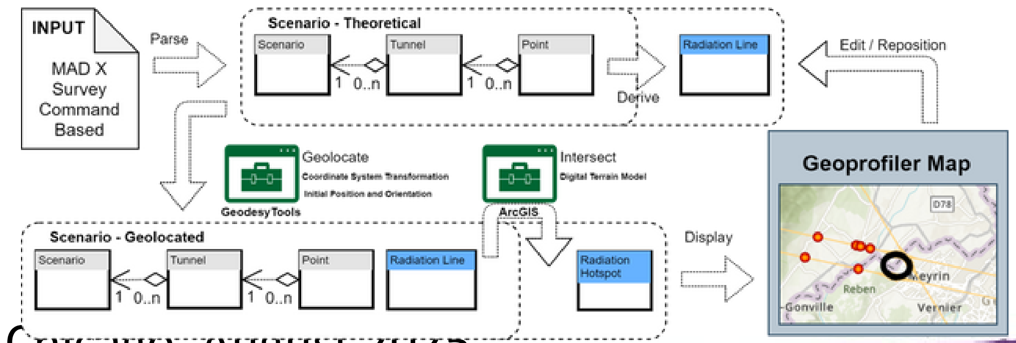
Site study at CERN for experimental insertion



FLUKA and RP studies



Mover system design



Key conclusions:
- Are close to a solution
- Need to continue working

Site Specific Designs

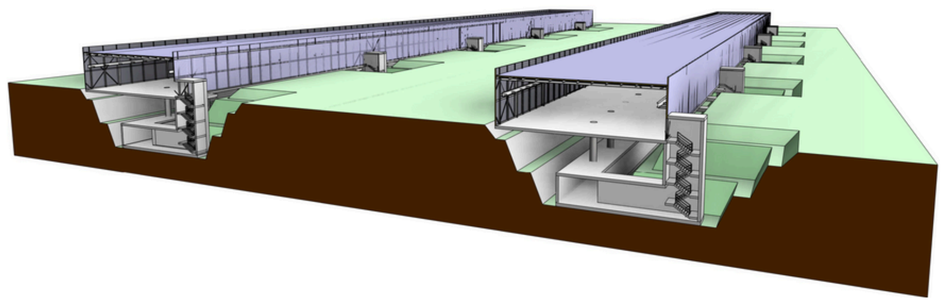
Started studies for concrete sites at CERN and Fermilab, looks very promising

CERN:

One RCS in SPS and two in LHC

Construct facility on CERN land

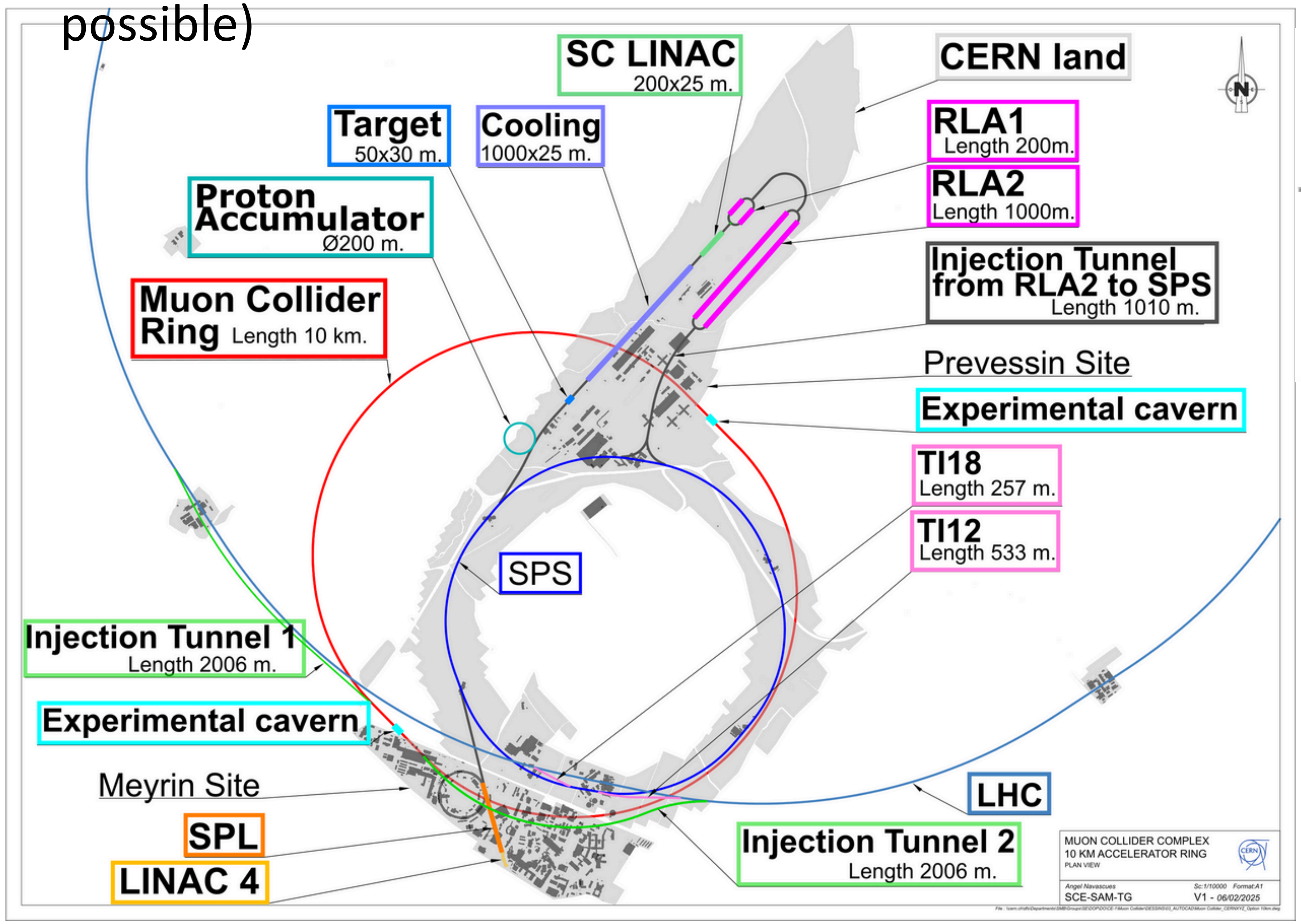
- Adjusted parameters
  (3.2 and 7.6 TeV, 10 TeV maybe possible)

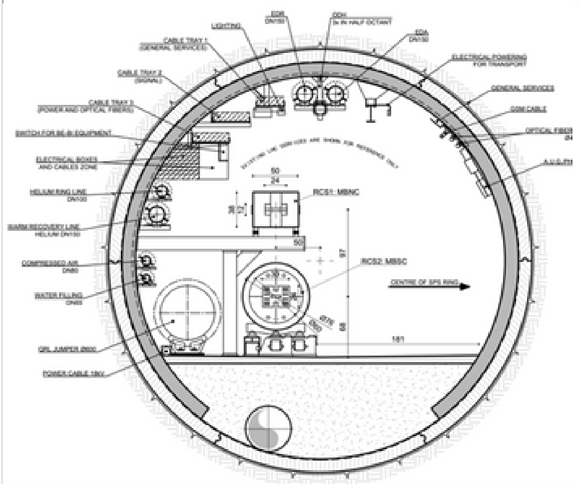


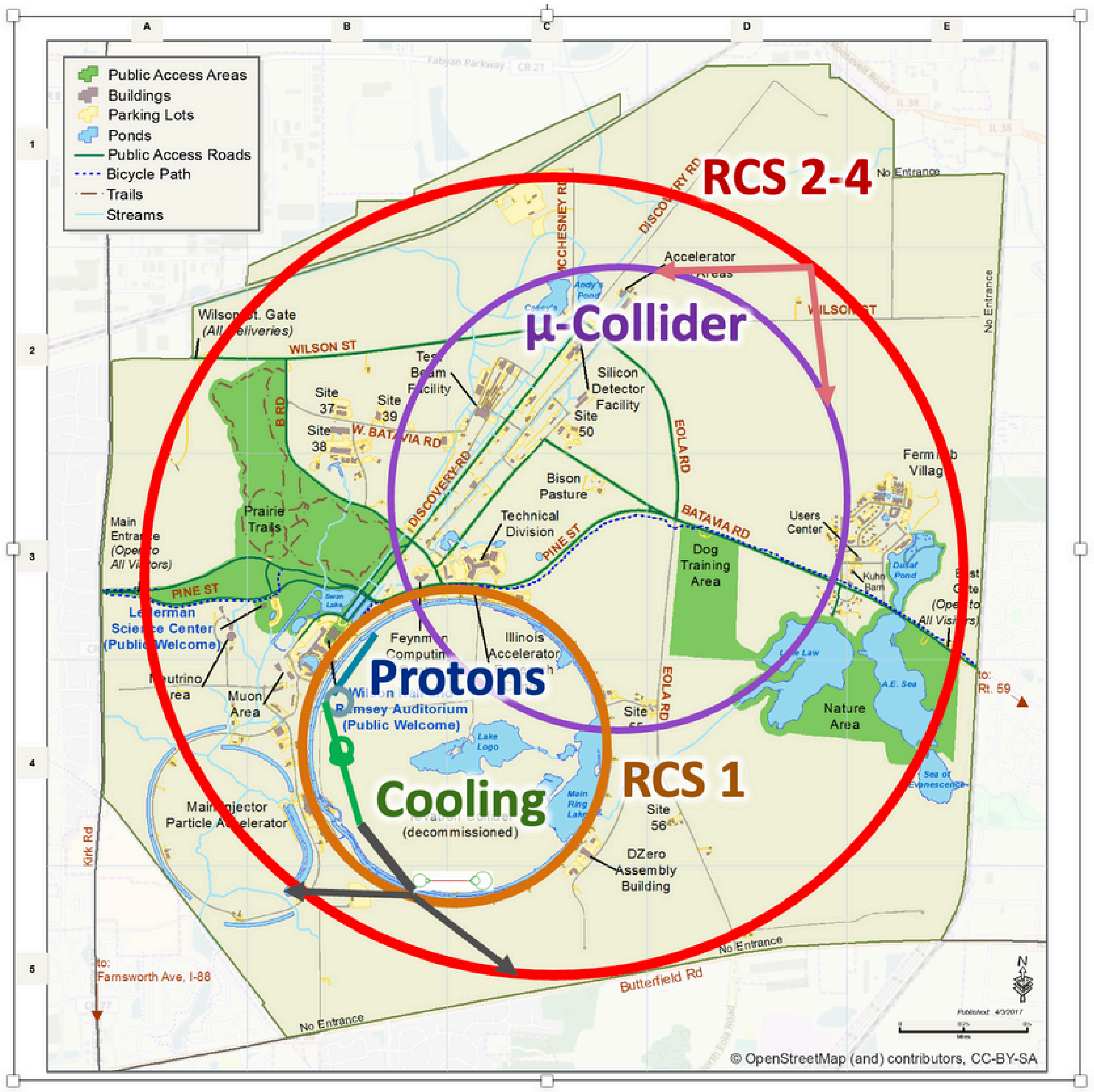
Fermilab:

One RCS in Tevatron tunnel,

Three RCSs in one site-filler tunnel







Cost and Power Scale

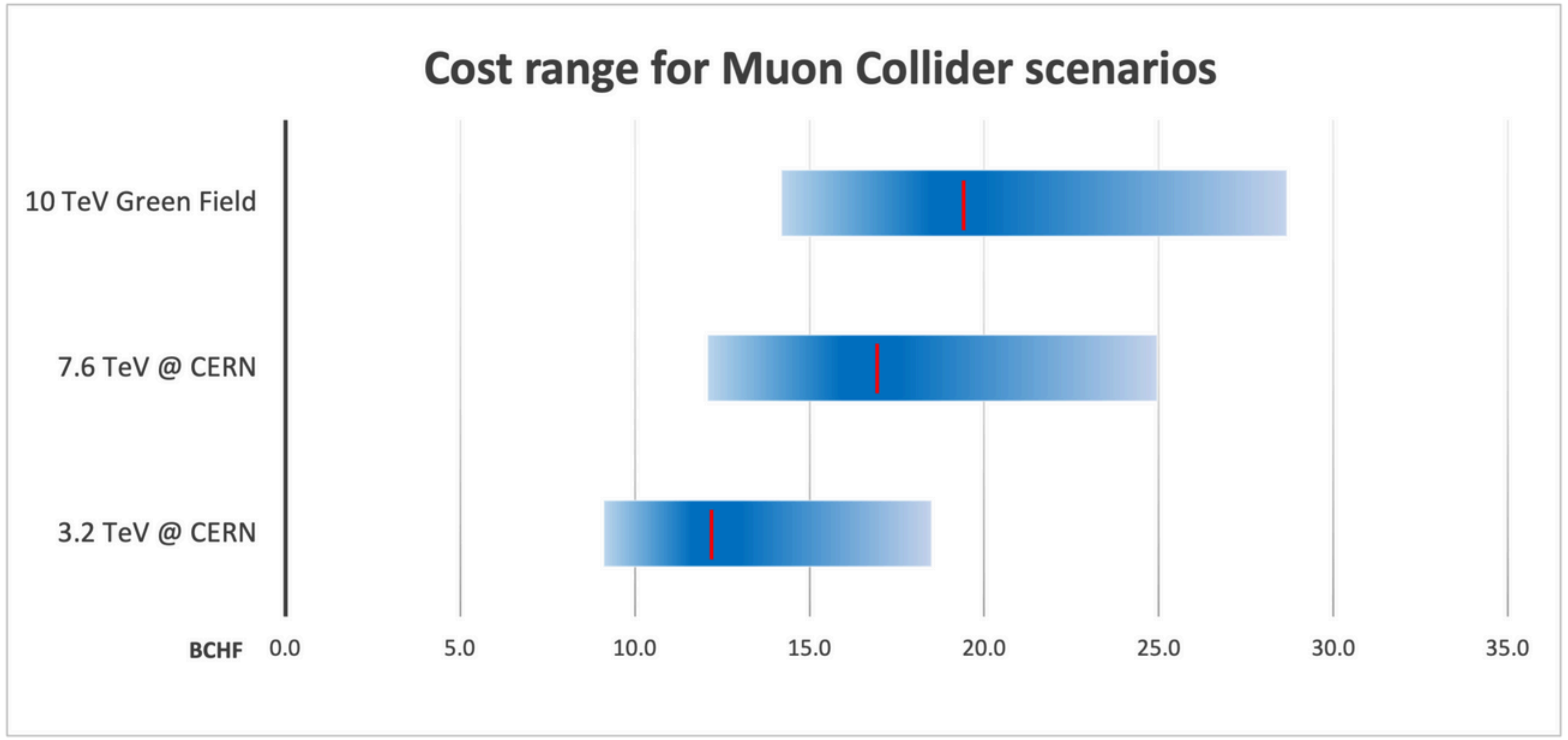
Design of collider and components advanced enough to estimate cost and power

Cost and power estimates based on conceptual designs and scaling from know components, e.g.

- Conceptual design and simulations of fast-ramping magnets and power converter
- Detailed scaling from ILC cryostats and cavities to RCS
- Beam loss studies for cryogenics power
- …

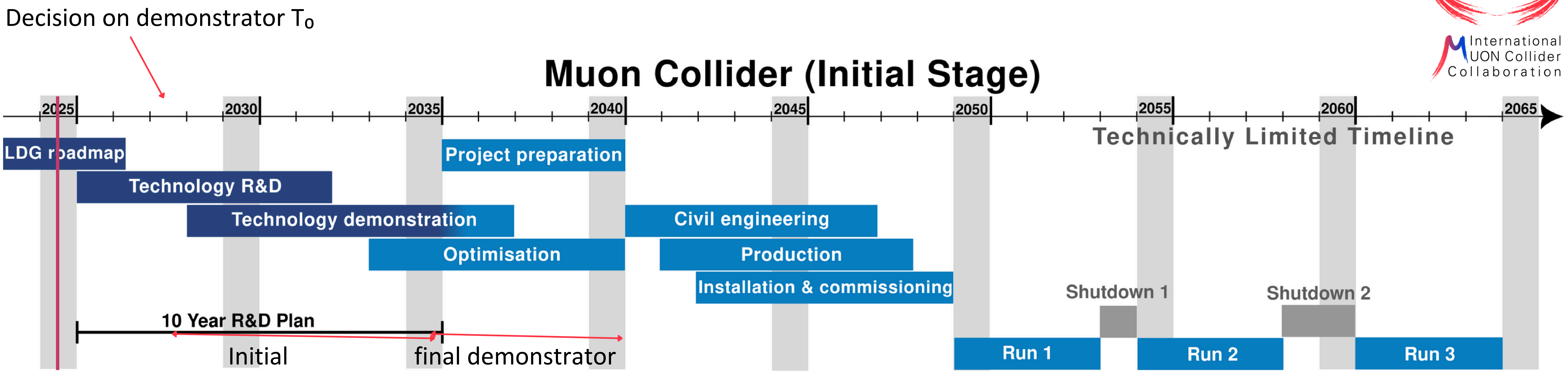
More work to be done

- Will perform and overall optimization
- Further R&D will reduce cost uncertainty (e.g. HTS solenoids)



	Unit	3.2 TeV	7.6 TeV
Operation power	MW	117	182
Energy consumption	TWh	0.53	0.82
Stand-by power	MW	73	111
Energy consumption	TWh	0.09	0.14
Off state power	MW	58	69
Energy consumption	TWh	0.17	0.21
Yearly energy consumption	TWh	0.8	1.2

Timeline and R&D Programme Proposal



Timeline is **driven by R&D**

Most ambitious example to define R&D programme priorities

- Assumes firm commitment to enable the muon collider as next flagship after HL-LHC
- R&D is fully successful
- No delays due to decision making

Other options

- In Europe after a higgs factory
- In the US to become leader at the energy frontier

Our timeline is consistent with CERN Directorate Working Group (table):
Demonstration Phase 7 years
Project Preparation Phase 5 years
Construction Phase 9 years

Milestone	Muon Collider
Construction of RF test stands	2025 – 2028
Production of test cavities	2026 – 2039
Operation of test stands	2027 – 2040
Demonstration Phase	$T_0 - (T_0 + 7)$
Demonstrator technical design	
Construction of initial demonstrator	
Construction of muon cooling module (5 cells)	
Definition of the placement scenario for the collider	
Project Preparation Phase	$T_1 - (T_1 + 5)$
Final demonstrator	
Implementation studies with the Host states	
Environmental evaluation & project authorisation processes	
Main technologies R&D completion	
Industrialisation of key components	
Engineering Design completion	
Construction Phase (from ground breaking)	$T_2 - (T_2 + 9)$
Civil engineering	
TI installation	
Component construction	
Accelerator HW installation	
HW commissioning	
Beam commissioning	
Physics operation start	$T_2 + 10$

R&D Programme

International MUON Collider Collaboration

Accelerator design

- Complete start-to-end design to validate and optimize performance, cost, power and risk

Muon cooling technology

- Implementation in steps important for timeline
- Need hardware, in particular RF test stands
- New detector technologies useful for instrumentation
- Cooling RF requires urgent test infrastructure

Detector

- Strong potential for further improve physics potential with technologies, AI and ML

Magnet programme

- Have conceptual designs, need hardware
- HTS solenoids have important synergy with society (also power converter)
  - Industry is ready to invest
  - Must not miss the opportunity

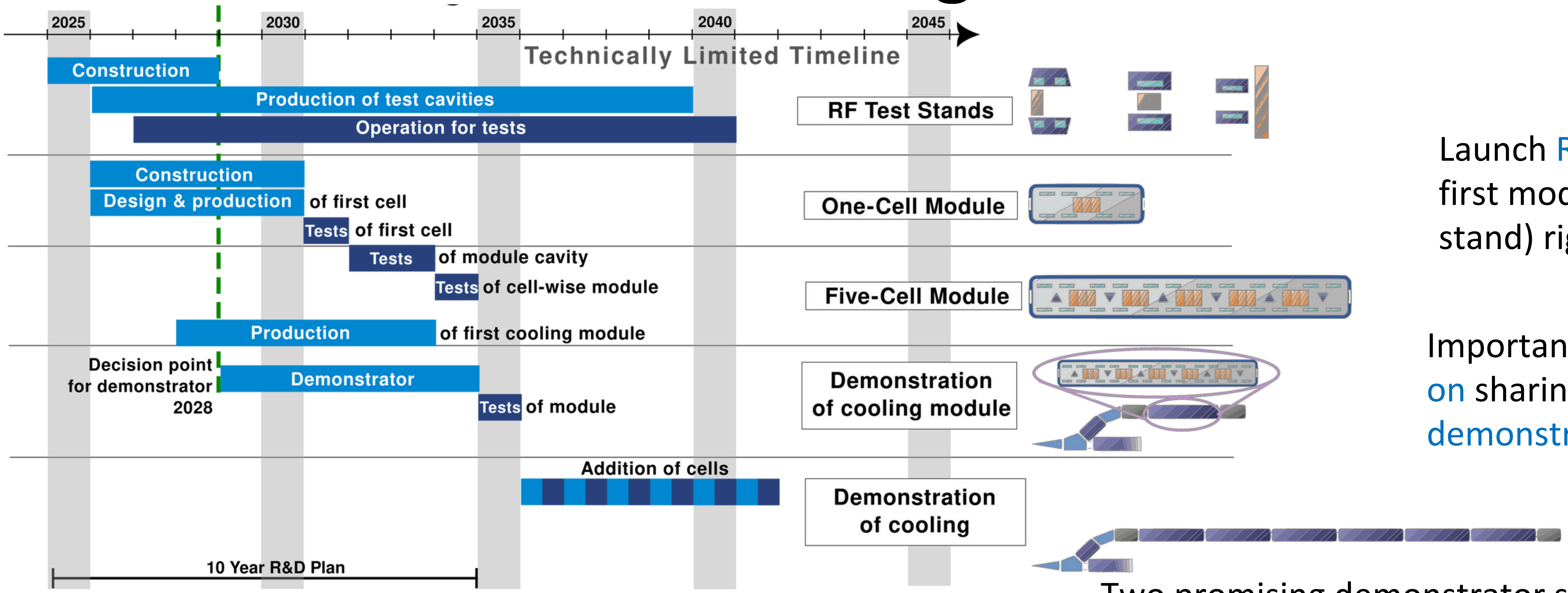
Detailed R&D programme proposal with deliverables defined

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Totals:
Duration 10 years

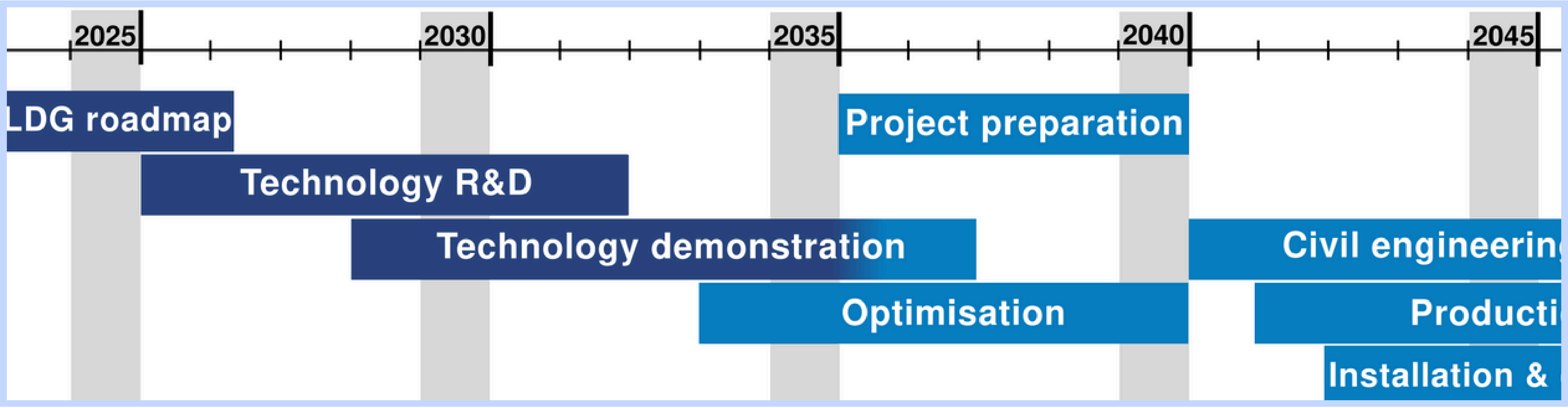
Accelerator: 300 MCHF material, 1800 FTEy
Detector: 20 MCHF material, 900 FTEy

Muon Cooling Demonstrator



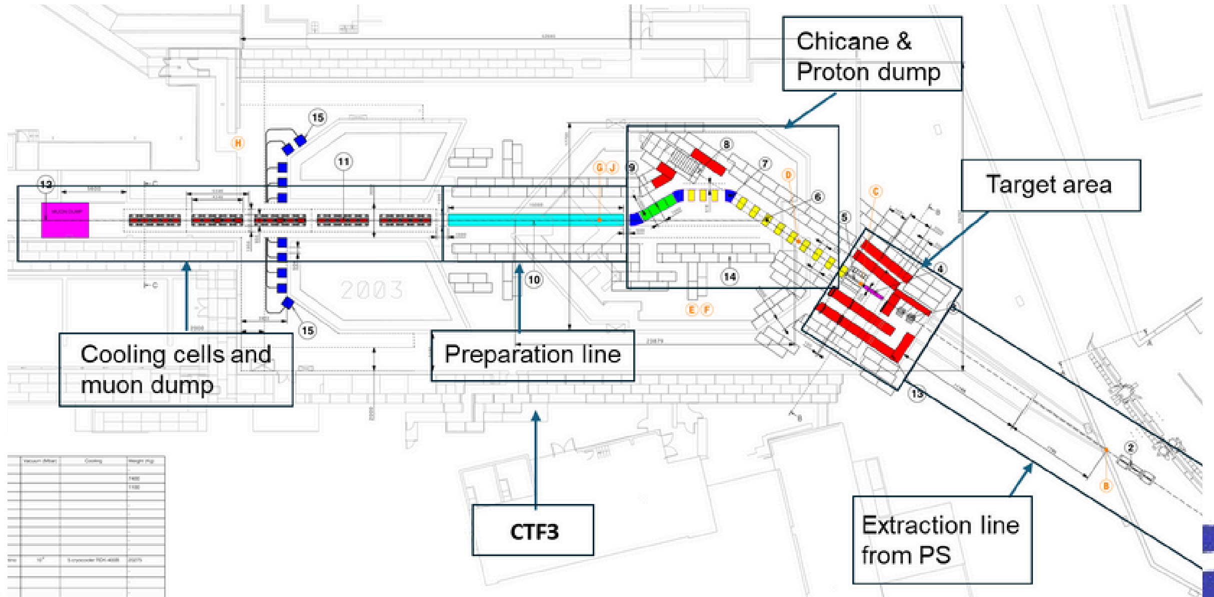
Launch RF test stands and first module (700 MHz test stand) right away

Important decision in 2028 on sharing of effort and demonstrator location



Two promising demonstrator site studies at CERN

Budget for site Fermilab study approved



Way Forward

Implement the proposed R&D plan, with deliverables and resources estimates for the next 10 years

- Prepare **sharing of work** between partners
- Central funding through CERN, DoE and other partners is instrumental
- Identify additional funding sources
- Need strong support of ongoing ESPPU
- Turn US support into resources

Started a task force to prepare the implementation

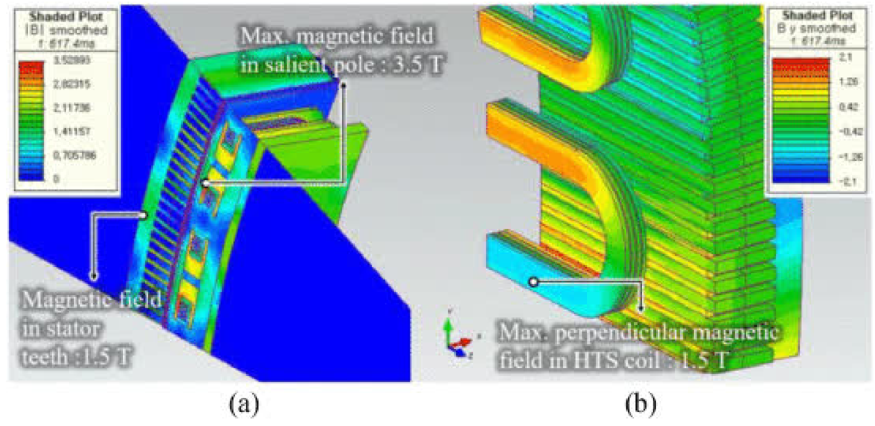
Led by F. Meloni and E. Nanni

Exploit synergy with other particle physics and accelerators

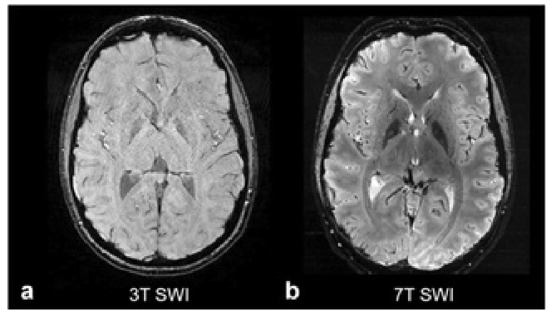
- Muons, neutrinos, …

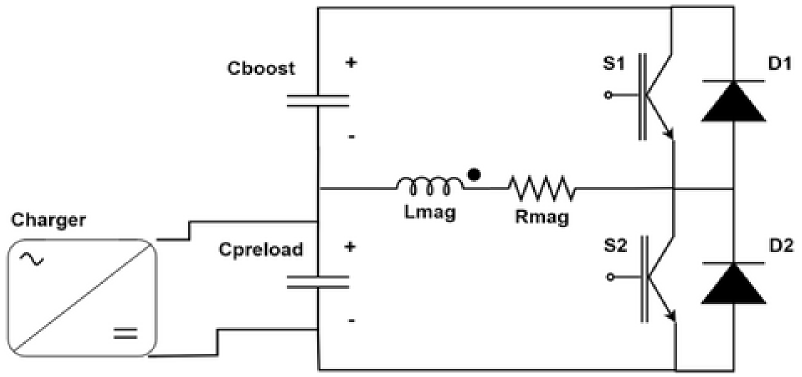
Strong synergy with societal applications exist

- HTS magnets for fusion reactors, wind power generators, motors, material science, health applications
- Power converter
- …



Design of 10 MW HTS wind generator





Collaboration on target solenoid/fusion with F4P, ERUOFusion, GaussFusion, ENI is key example

- Have agreements that will lead to resources
- An opportunity for particle physics to make an important impact on society

https://indico.cern.ch/event/1439855/contributions/6461515/

Early career experts are very motivated by the required and possible innovations

Practical Approach

R&D Task Force will start soon

- Led by F. Meloni and E. Nanni
- Will include all interested partners

Existing R&D plan has been developed with global community, very strong US contribution

- Some polishing still remains to be done

Goal is to prepare plan for **practical implementation of R&D**:

Potential sharing of work between partners according to interest, expertise, and resources

- obviously will have to deal with uncertainties of future funding

Integration of R&D into programmes and applications for (co-) funding

- e.g. DoE funding, LDG Roadmap in Europe, High-field Magnet Programme, CERN MTP, programmes in different countries, …

Will need to be aware of ongoing R&D efforts and plans

- Ensure lines of communication between efforts and existing WGs
- Also helps ensure support of ECRs performing new R&D efforts

Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K
Fast-ramping magnet system	Prototype magnet string and power converter	30 mm x 100 mm, 1.8 T, 3.3 T/s
LTS collider dipole	Demonstrate Nb_3Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
	Radiofrequency	
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
	Muon Cooling	
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 μm emittance, 40 T field
	Design & Other Technologies	
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O(±1mradian)
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

Conclusion

Excellent technical progress has been made, in spite of resource limitations

- Supported by review committees from LDG, MuCol, and IAC reviews

Have global R&D programme proposal that needs to be funded

IAC composition:
Permanent members: Ursula Bassler (chair), Mauro Mezetto, Hongwei Zhao, Akira Yamamoto, Maurizio Vretenar, Stewart Boogert, Sarah Demers, Giorgio Apollinari
Additional experts: Pierre Vedrine, Stephen Gourlay, Lyn Evans, Alessandro Gallo, Barbara Dalena, Pantaleo Raimondi

During its current IMCC review, the IAC was highly impressed by the **significant progress** and the **marked improvement** in the robustness and quality of the studies. The muon collider presents an **extraordinary technical opportunity**, and encouragingly**, all major technical challenges are being actively tackled**. In particular, **launching and supporting a cooling demonstrator and test stands as soon as possible** will be crucial to sustaining this strong momentum.

IAC review (just before ESPPU Venice meeting)

Now need:

- US to further ramp up resources also for the accelerator
- Support of ESPPU for our global R&D programme
- Global support

Many thanks to the collaborators for all the work

Our web page: http://muoncollider.web.cern.ch
If you want to join: muon.collider.secretariat@cern.ch

Reserve

R&D Plan Reviews

LDG Mid-term Review
Reviewers: Norbert Holtkamp (chair), Mei Bai, Frederick Bordry, Nuria Catalan-Lasheras, Barbara Dalena, Massimo Ferrario, Andreas Jankowiak, Robert Rimmer, Herman ten Kate, Peter Williams

Found **good progress for Roadmap implementation**

- "75% of Roadmap goals have been achieved"

  Recommendations:
- **Develop a Start-to-End Performance Simulator:**
  - This is (one of) the most urgent and crucial parts of the R&D plan
- **Define and fund a High-Field HTS and RF Development Strategy:**
  - This is an important part of the R&D plan
  - New funding needed
- **Conduct an Independent Review of Scope, Schedule, and Costs:**
  - Initial review by our International Advisory Committee (IAC)

MuCol mid-term review by EU
Very good technical progress

IAC review:
Permanent members: Ursula Bassler (chair), Mauro Mezetto, Hongwei Zhao, Akira Yamamoto, Maurizio Vretenar, Stewart Boogert, Sarah, Demers, Giorgio Apollinari
Additional experts confirmed: Pierre Vedrine, Stephen Gourlay, Lyn Evans, Alessandro Gallo, Barbara Dalena, Pantaleo Raimondi

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Muon Collider Greenfield Overview

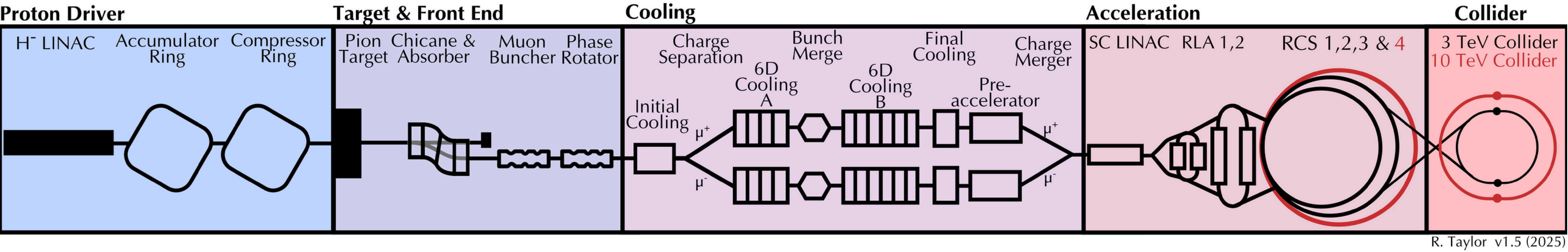
Produce a high power proton beam

Target material to withstand high-power

Rapidly reduce the beam size

Rapidly Accelerate

Collide tight beams

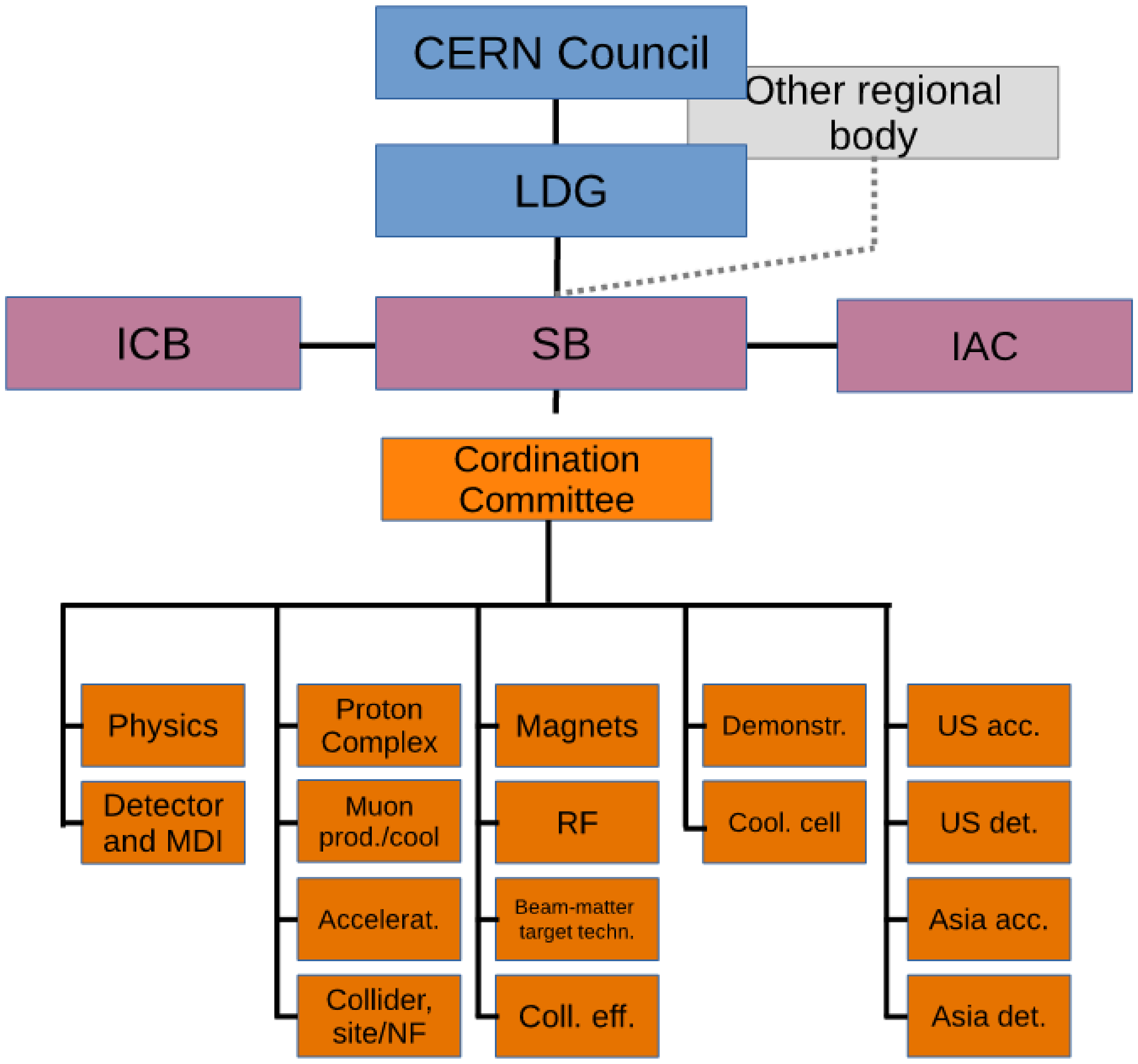


- Based on MAP diagram, made as .svg for easy addition as machine evolves.
- Currently on version 1.5 (added initial cooling).
- Please email me if you have updates to subsystems of complex overview.
- Design is currently the same for Greenfield, CERN and Fermilab, sans RCS.

IMCC Organisation

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

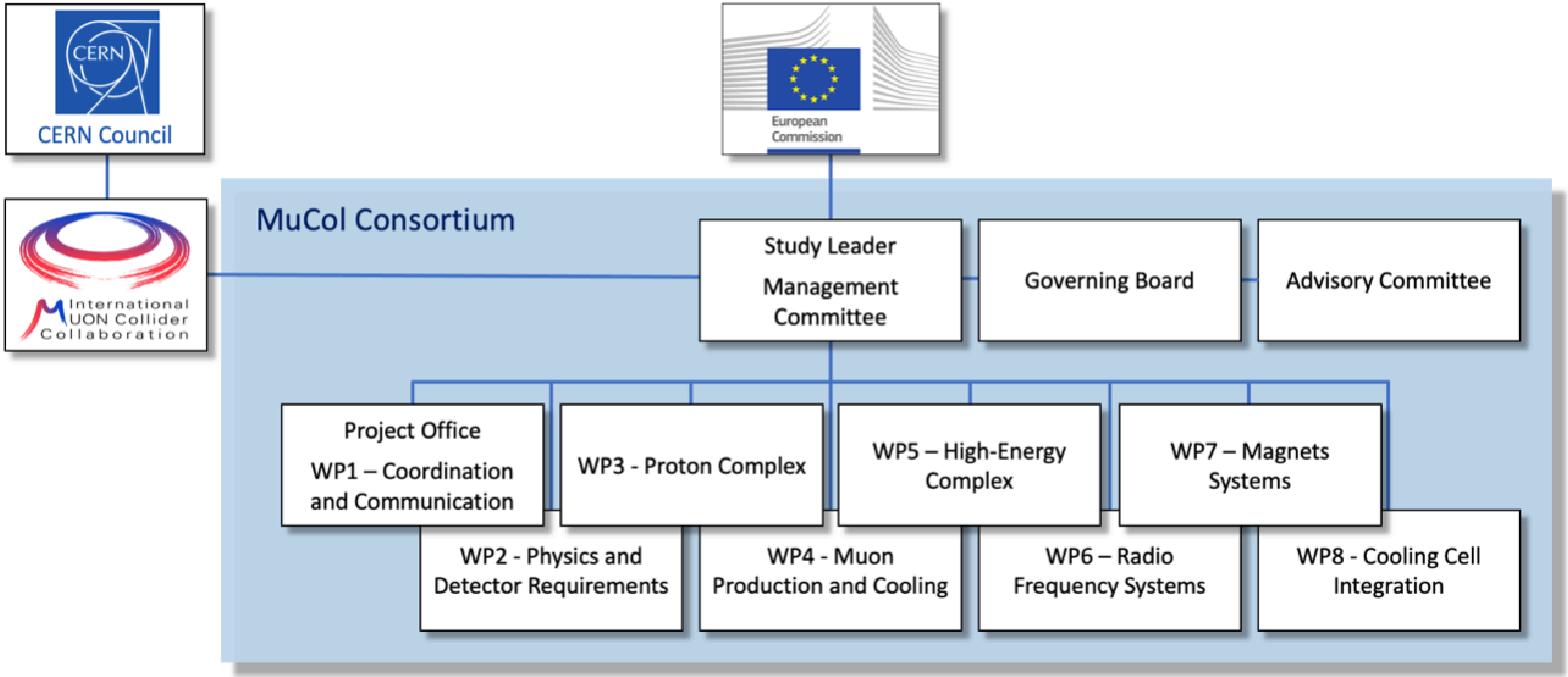
Physics: Andrea Wulzer
Detector and MDI: Donatella Lucchesi
Protons: Natalia Milas
Muon Production and Cooling: Chris Rogers
Muon Accelerator: Antoine Chance
Collider: Christian Carli
Magnets: Luca Bottura
RF: Alexej Grudiev, Claude Marchand
Beam-matter / Target System: Anton Lechner
Collective effects: Elias Metral
Demonstrator: Roberto Losito
Cooling cell design: Lucio Rossi
US (Accelerator): Mark Palmer
US (detector): Sergo Jindariani
Asia (China): Jingyu Tang



Each block has ~monthly progress meetings

IMCC Annual Meeting

MuCol Organisation



MuCol Deliverables

D1.2	Preliminary ESPPU report No. 1
D1.3	Preliminary ESPPU report No. 2
D1.4	Intermediate ESPPU report
D1.5	Consolidated ESPPU report
D2.1	Beam-induced background and detector configuration
D2.2	Detector performance by using physics processes
D3.1	Final report on parameters and initial study for the Proton Complex
D4.1	Development of BDSIM simulation
D4.2	Preliminary Report on key subsystems for ESPPU input

MuCol Milestones

No.	Milestone Name
1	Website Available
2	Kick-off meeting
3	Tentative parameters available
4	First annual meeting
5	Preliminary parameters
6	Second annual meeting
7	Consolidated parameters
8	Third annual meeting

Each with laboratory leads and deadlines. (CERN, DESY, UKRI, CEA, UMIL, UNIPD)

MuCol Deliverables

N°	Deliverable Name
D1.1	Data-management plan
Del.	Dissemination and Exploitation plan
D1.2	Preliminary ESPPU report No. 1
D1.3	Preliminary ESPPU report No. 2
D1.4	Intermediate ESPPU report
D1.5	Consolidated ESPPU report
D2.1	Beam-induced background and detector configuration
D2.2	Detector performance by using physics processes

MuCol Milestones

4	First annual meeting
5	Preliminary parameters
6	Second annual meeting
7	Consolidated parameters
8	Third annual meeting
9	Training on detectors design and physics performance tools
10	Workshop on MDI and IR design
11	Release of simplified detector performance model (DELPHES card or/and similar format)

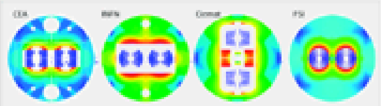
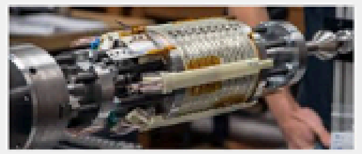
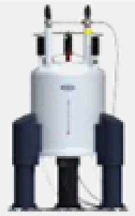
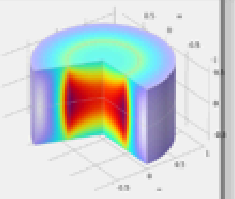
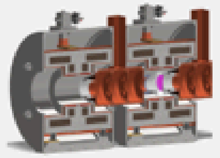
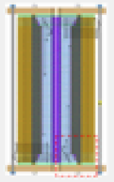
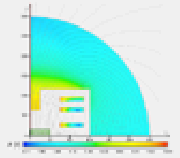
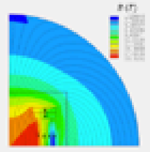
Each with laboratory leads and deadlines. (CERN, DESY, UKRI, CEA, UMIL, UNIPD)

Key Target Parameters

Param.	Unit	Site independent		CERN 2 tunnels		CERN 1 tunnel	
Sqrt(s)	TeV	3	10	3.2	7.6	3.2	7.6
L/IP	1034 cm-2s-1	1.8	17.5	2	10	0.9	7.9
Int L	ab-1	1	10	1	10	1	10
Accumulation time	years	2+2.8	2+2.9	2+2.5	2+5	2+5.6	2+6.3
C	km	4.5	11.4	4.8	8.7	11	11
Bdipole	T	11	14	11	14	4.8	11
Collider dipole technology		Nb3Sn	HTS	Nb3Sn	HTS	NbTi	Nb3Sn or HTS

Accumulation time: Time to obtain the integrated luminosity with two IPs.
Ramp-up over the first three years 5%, 25%, 70% of nominal.

Magnet R&D Impact

	HEP and NP 	High-field science 	NMR 	MRI	Fusion 	Motors/generators 
TM1 20@20 	→	High field, low consumption	→	→	High-field, large bore and large stored energy	
TM2 SOLID 	→	High field, low consumption	→	High-field large bore, cryo-free technology		
TM3 UHF-DEMO 	FCC-ee, CLIC (e+ source)	Ultra-high-field	Ultra-high-field	→	→	High-field, compact windings
TM4 RCS-String	→	High pulsed power and energy recovery	→	→	High pulsed power and energy recovery	
TM5 MBHY	FCC-hh, SppC					
TM6 MBHTS 	FCC-hh, SppC	→	→	→	→	3D, compact pole winding
TM7 MBHTSY 	FCC-hh, SppC	→	→	→	→	3D, compact pole winding
TM8 MQHTSY	FCC-hh, SppC	→	→	→	→	3D, compact pole winding

L. Bottura

R&D Impact Examples

- **Fusion for Energy** (ITER EU Domestic Agency)
  - Framework agreement and first addendum in final negotiation
  - Contribution to the design of the HTS target solenoid, relevant to the central solenoid of DTT
- **EUROFusion** (next step European fusion reactor)
  - Framework agreement signed in 2023, first addendum signed in 2024
  - Contribution to the design of the HTS target solenoid, relevant to the magnets of a Volumetric Neutron Source proposed as next step in the European fusion strategy
- **Gauss Fusion** (one of the leading EU fusion start-ups)
  - Consultancy agreement signed in 2023
  - CERN contribution to the design of the LTS/HTS GIGA stellarator magnets, based on advances in the HTS target solenoid
- **ENI** (oil and gas energy giant)
  - Framework agreement and first addendum signed in 2024
  - Collaboration on the conceptual design and project proposal for the CERN construction of a large bore HTS solenoid (20@20 model coil) relevant to the muon collider and fusion
- **Infineon Technologies Bipolar** (world leader bipolar high-power semiconductors, focus on green grid)
  - IFAST-2 proposal to **INFRA-2025-TECH-01-02** (CERN, INFINEON, PSI)
  - Proposal of fast pulsed power cell + magnet system sent to IFAST-2 coordination for ranking at TIARA
  - Industrial interest in rapidly pulsed and large energy/power supplies

Note: Examples in Europe because we restarted here
Expect similar interest in all regions

Start-to-end Model

This is an important part of the proposed R&D plan

Due to resource limitations we had to set priorities in the LDG Roadmap:

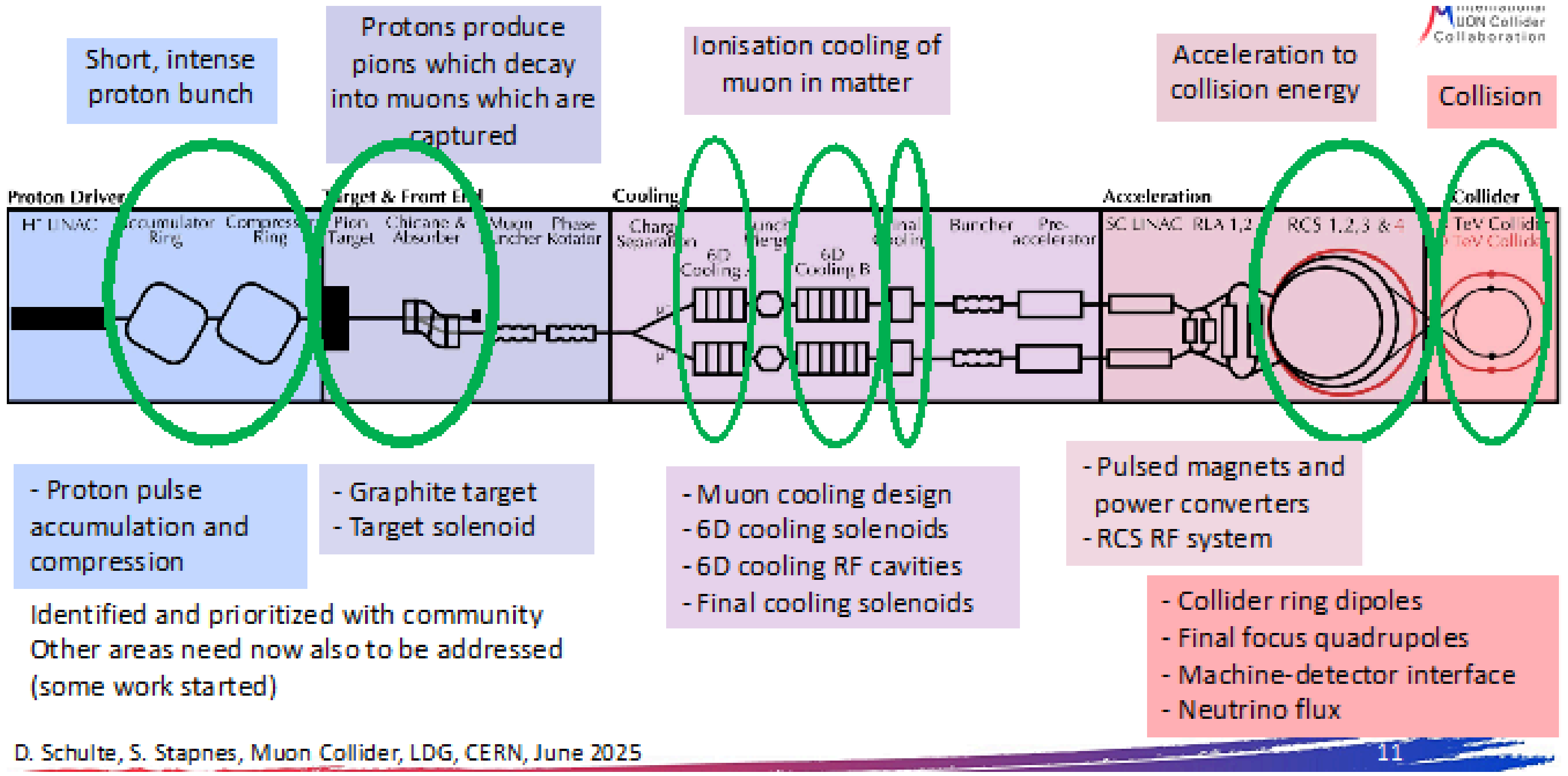
- Design of the collider areas with **lattice challenges** and contained **Critical Technology Elements**
- Address the key challenges such as neutrino flux and beam-induced detector background
- Development of missing critical simulation tools
- Development of realistic performance targets for the components

Now available:

- Initial cost model
- Initial power consumption model

With increased resources can:

- Design missing connecting systems
- Further improve existing system designs
- Refine cost and power consumption model
- Optimise for risk and cost



Are introducing a **formalized configuration management** for the overall optimisation

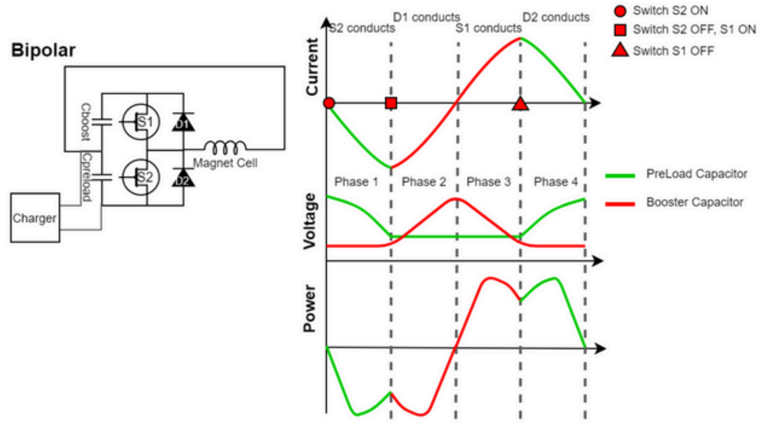
Power Consumption Estimate

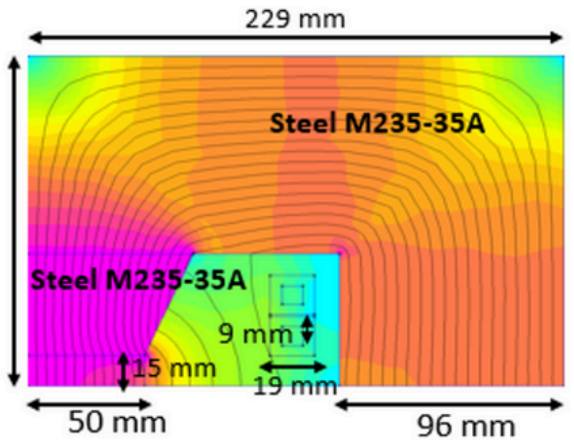
Power estimate is based on

- Conceptual designs, e.g. fast-ramping magnets and power converter
- Detailed estimates for RF systems
- Cryogenics power estimates include beam losses and shielding
    - More study for beam loss in RCS RF, maximum range (-4 to +9 MW for 3.2 TeV and -10 to 19 MW for 7.6 TeV)
- For cryostats detailed scaling (e.g. pulse length, rate, etc.) from known cryostats has been applied
- An overall estimate for general cooling and ventilation has been added

No overall optimization has been performed for the power consumption

	Unit	3.2 TeV	7.6 TeV
Operation power	MW	117	182
Energy consumption	TWh	0.53	0.82
Stand-by power	MW	73	111
Energy consumption	TWh	0.09	0.14
Off state power	MW	58	69
Energy consumption	TWh	0.17	0.21
Yearly energy consumption	TWh	0.8	1.2



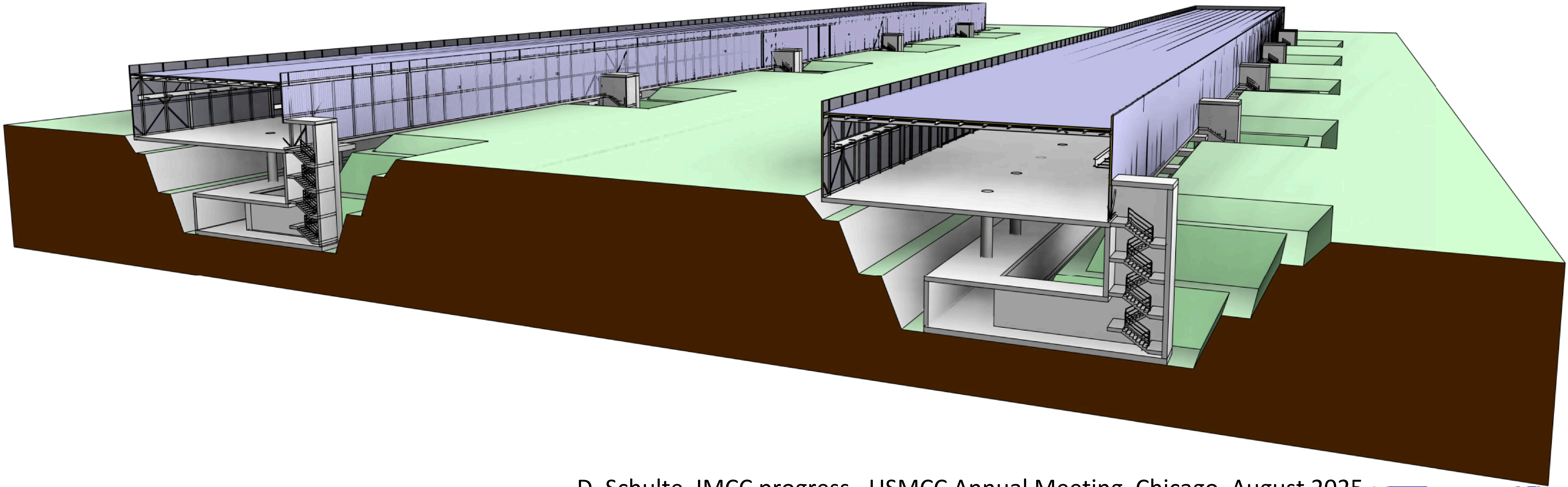


RCS	E [J/m]	Eiron [J/m]	Ecopper [J/m]	Loss [%]	P [MW]
SPS 1	5447	10	52	**1.1**	1.9
LHC 1	5678	9.2	80.6	**1.6**	12.8
LHC 2	5752	63.4	298	**6.3/2**	26.6

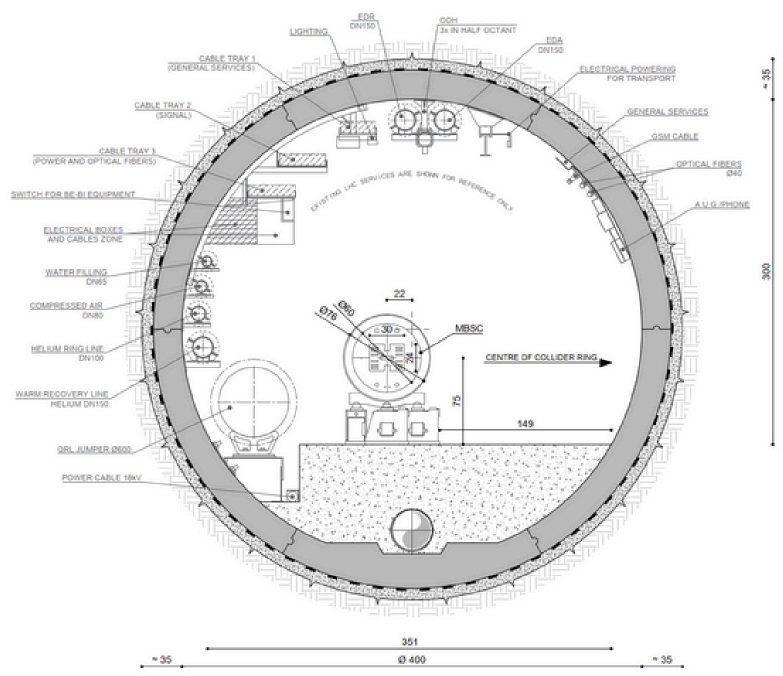
Energy in magnets, losses per cycle and total power at 5 Hz including cooling

Injector Complex

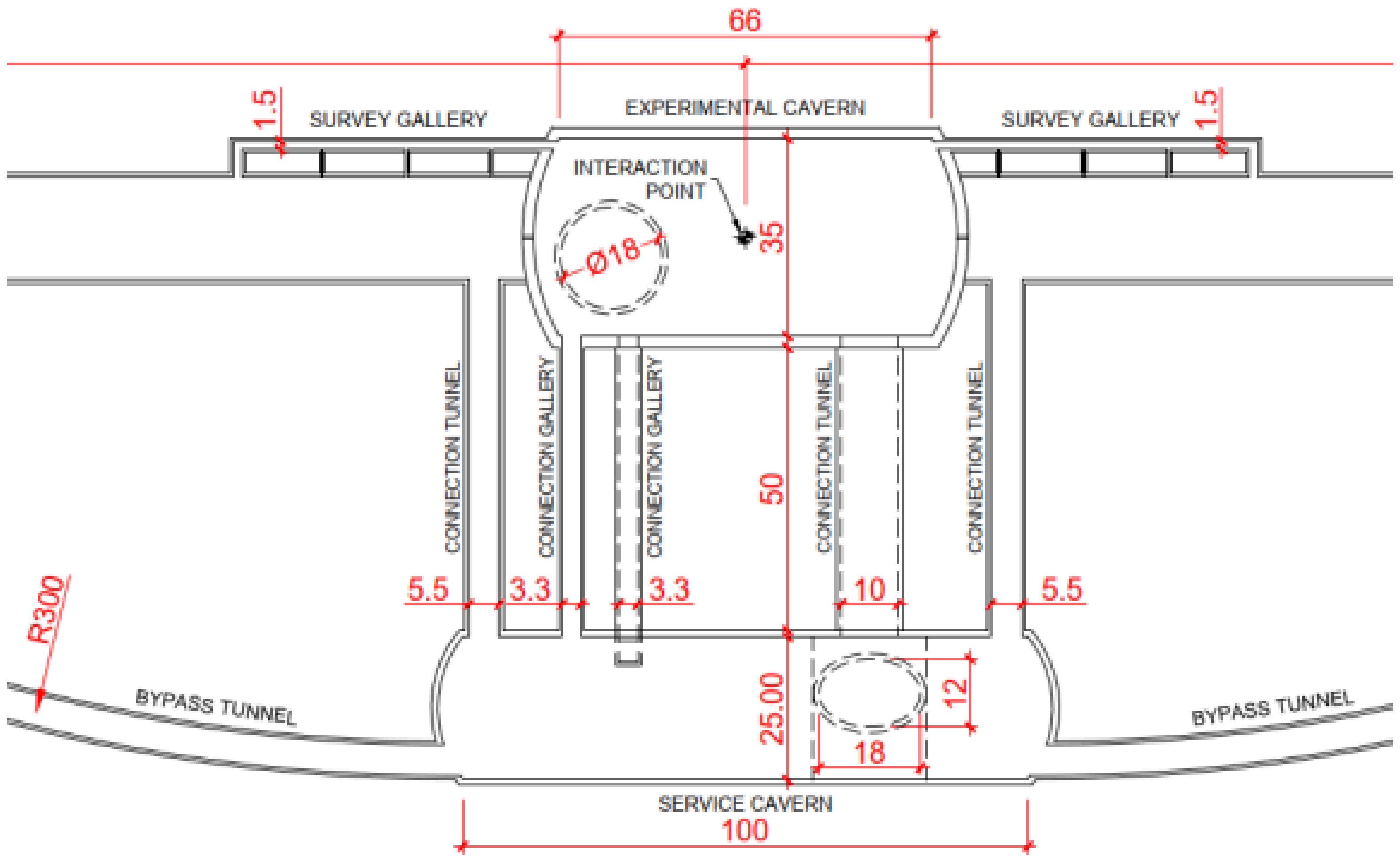
- The injector complex needs to undergo optimization before detailed design.
- Each component of the surface injector complex needs tailored civil engineering design based on individual component requirements.
- Upon freezing the layout, detailed studies into the environment, topography and below ground services can be conducted.



Collider Ring and Interaction Region

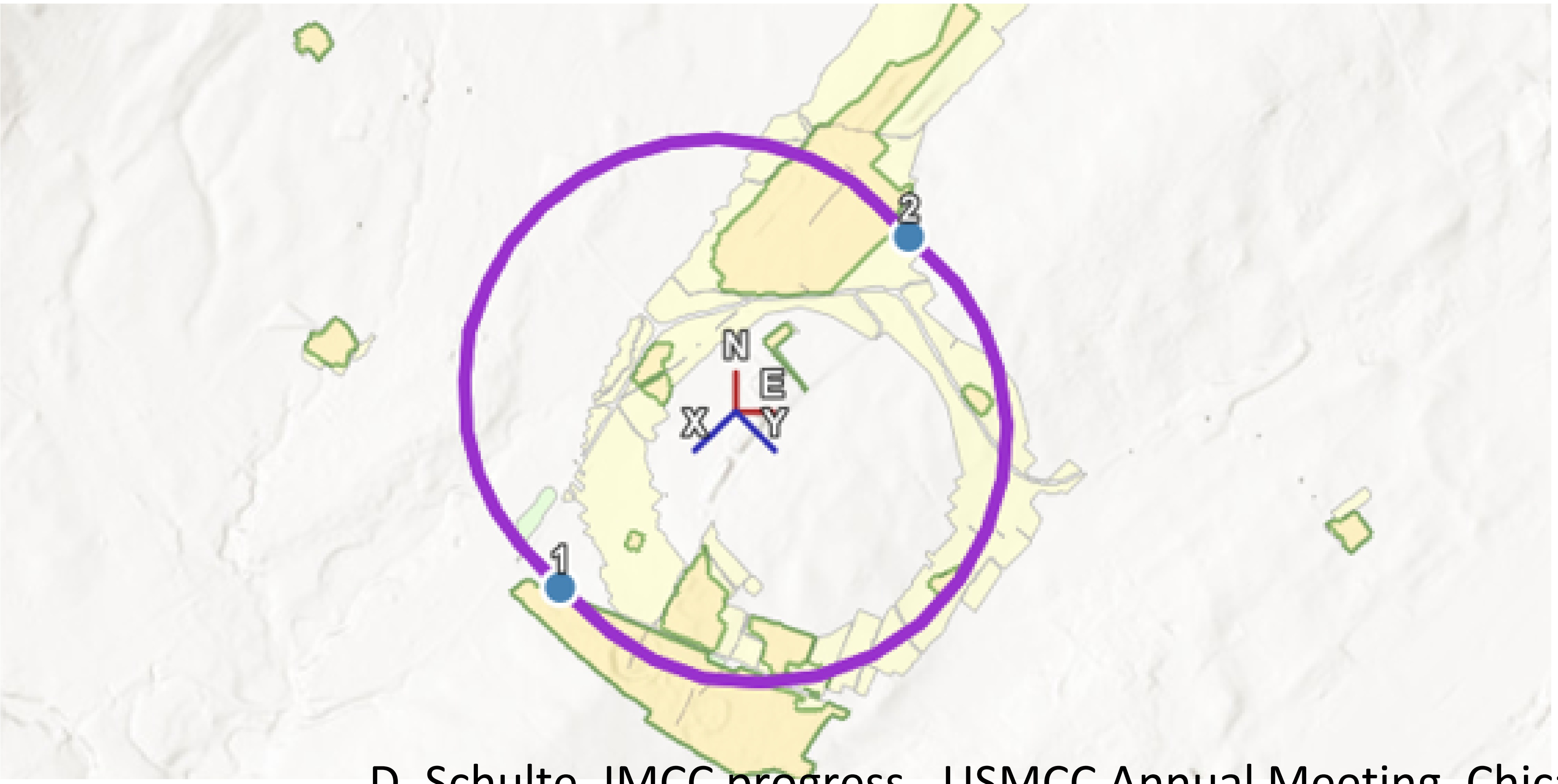


- A preliminary cross section of the Collider Ring has been established based on an LHC cross section.
- The Interaction Regions haven't yet been designed.
- An Interaction Region from the FCC housing a single detector has been used for the preliminary costing exercise as well as the affiliated shafts and surface sites.
- Therefore, specific designs tailored to the Muon Collider Ring need to be developed, specifically, cavern and shaft sizes for the Interaction Region as well as any further areas necessary to accommodate the required services.

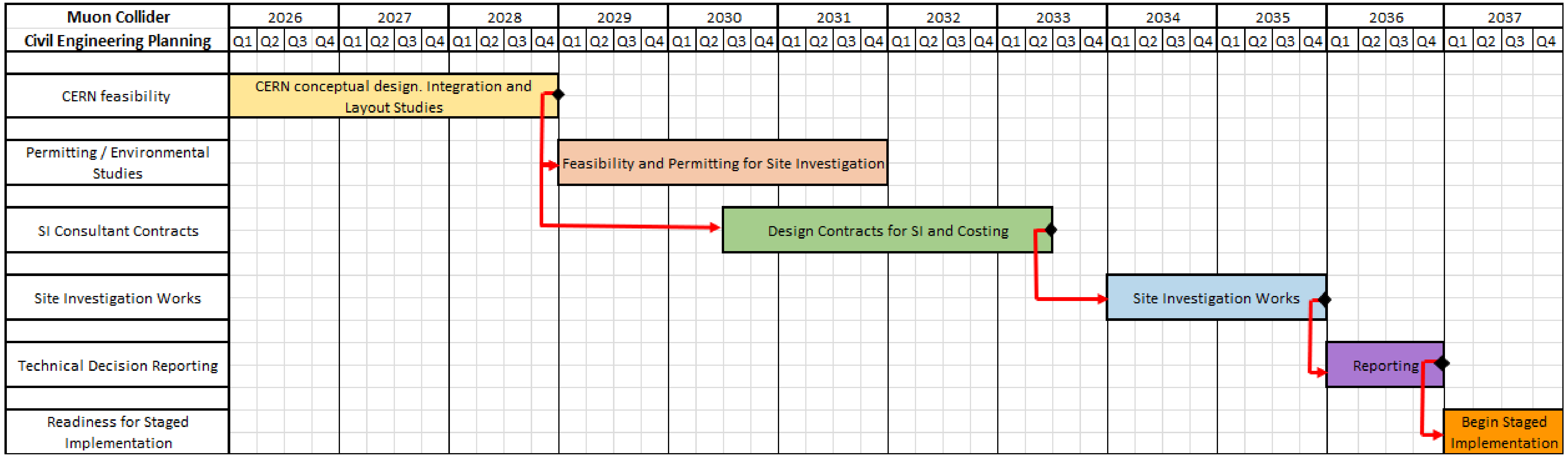


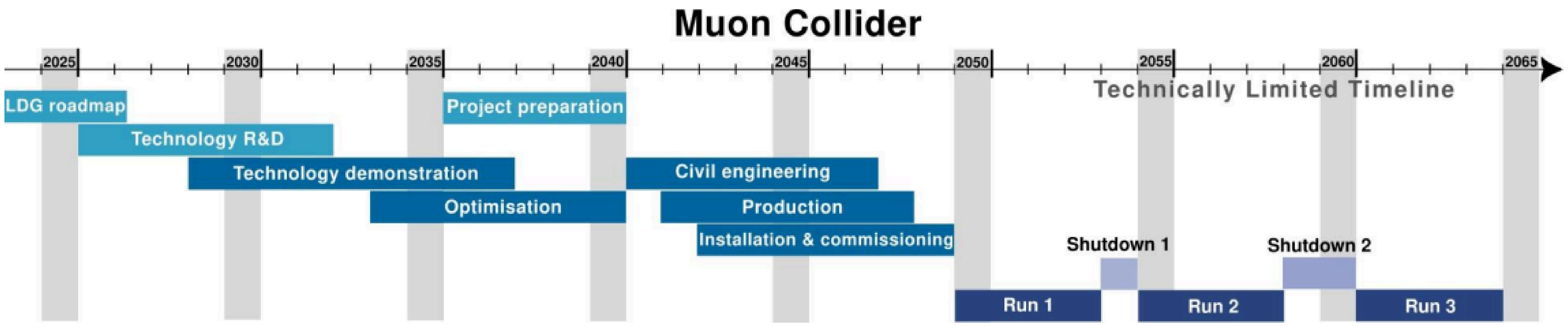
Surface Structures

- Ensuring the surface structures are housed where possible on CERN owned land is of upmost importance.
- Geographical studies will confirm surface placement of the injector complex and particularly, the surface experimental sites if not to be housed on CERN land. Ensuring these surface sites are in turn located on feasible plots of land.
- The Neutrino Flux model, however, aims to find an optimal Collider Ring placement with the surface experimental sites housed on CERN land.



Long Term R&D





- With the aim to begin Civil Construction in 2040.
- Site specific technical designs, site preparation, an environmental impact study and all the corresponding procedures in preparation for construction need to be conducted.
- As well as the preparation for civil engineering construction works, obtaining all required permits, preparation of technical documentation, tenders and commercial documents.

RF and High-Field HTS Development Strategy

For the RF development:

The key challenge is the normal conducting RF in the muon cooling section

- Attempt to remain within state of the art for the other parts
- This might change once the commitment to a muon collider becomes stronger

  This is therefore a part of the muon cooling technology development

  Had good discussions with the LDG RF panel

  SLAC is investing into an RF test stand
- Also efforts at INFN and in the UK

A clear Roadmap for the development of HTS magnets exists and funding needs to be secured

- The LDG should play an important role

The HTS solenoid technology is of high importance for societal applications

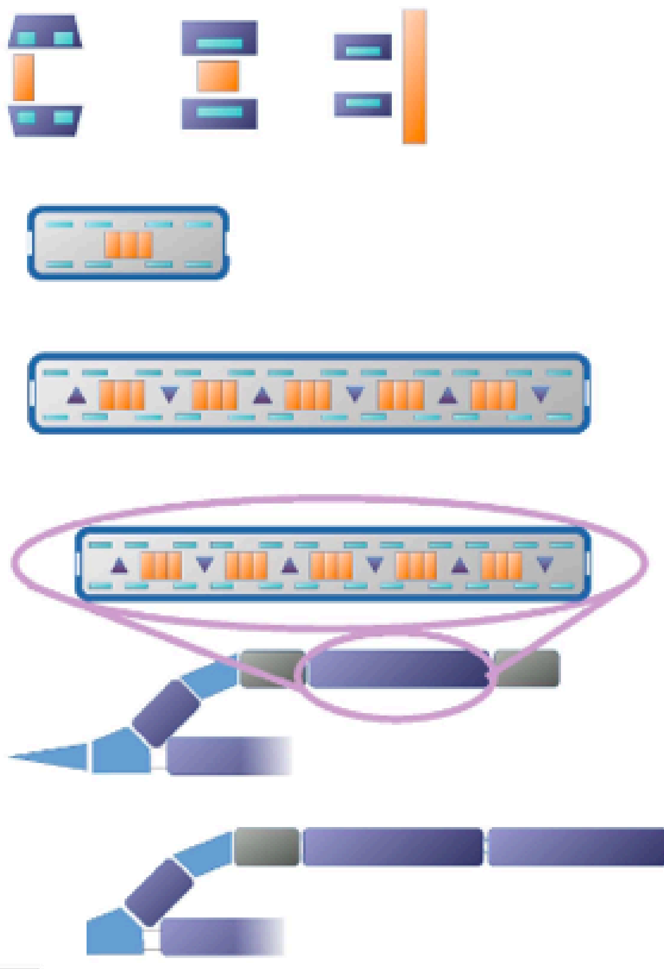
- We can profit from developments driven by society
- We can contribute to society
- We see that this is leading to additional support for R&D

  The power converter for the fast-ramping magnets are of high relevance for society

Muon Cooling Demonstrator

Challenge:
Demonstrate muon cooling technology in stages
Critical for timeline

Achieved:
- Defined the scope and concept, made initial cost estimate, investigated three promising locations at CERN
- Staged timeline to implement demonstrator
- SLAC is moving forward building a 3/1.3 GHz test stand



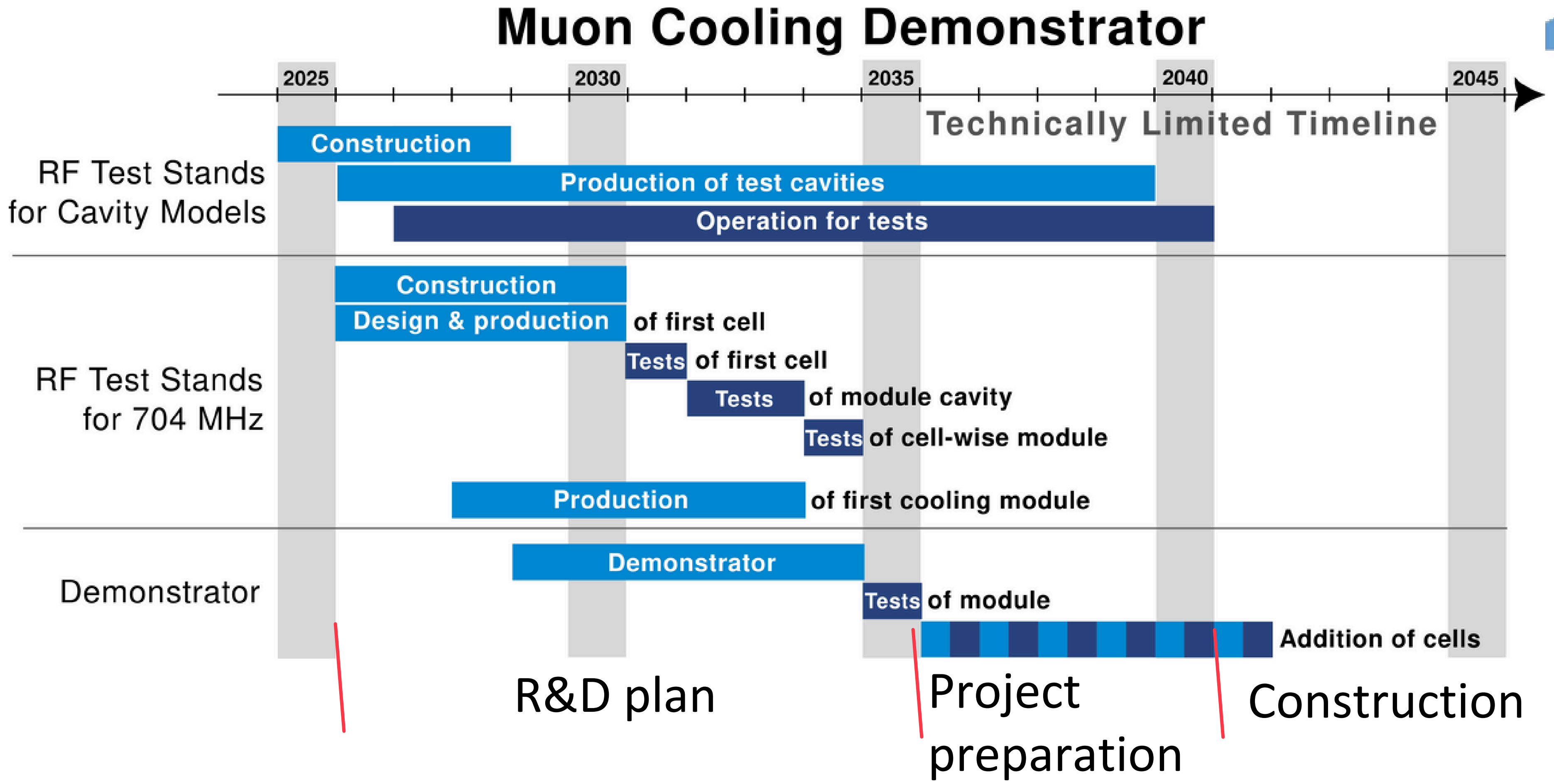
RF Test stands, to develop novel RF and magnet technologies

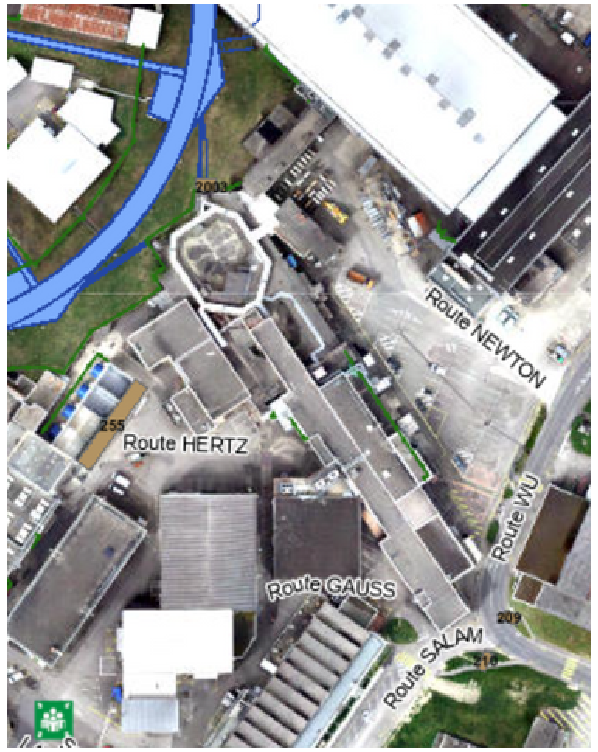
One-cell module to test RF in operational magnetic environment

Five-cell module to demonstrate integration of absorber, RF and magnets

Demonstration of cooling module to show operation with beam

Demonstration of cooling to demonstrate beam physics performance



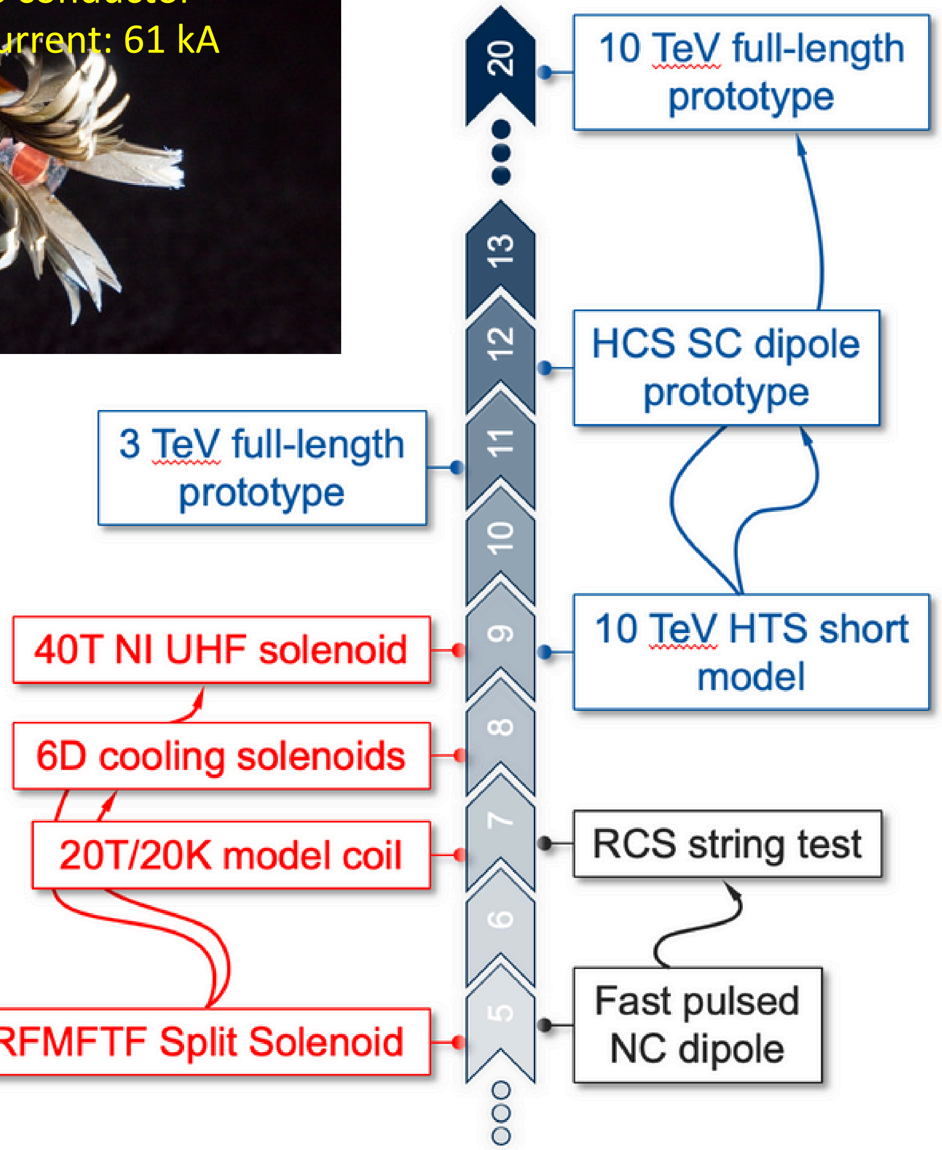


Key conclusions:
- Installation of demonstrator at CERN appears possible with limited cost
- Fermilab has approved a study
- RF test stands are critical and urgent
- Consistent with implementation timeline

Magnets

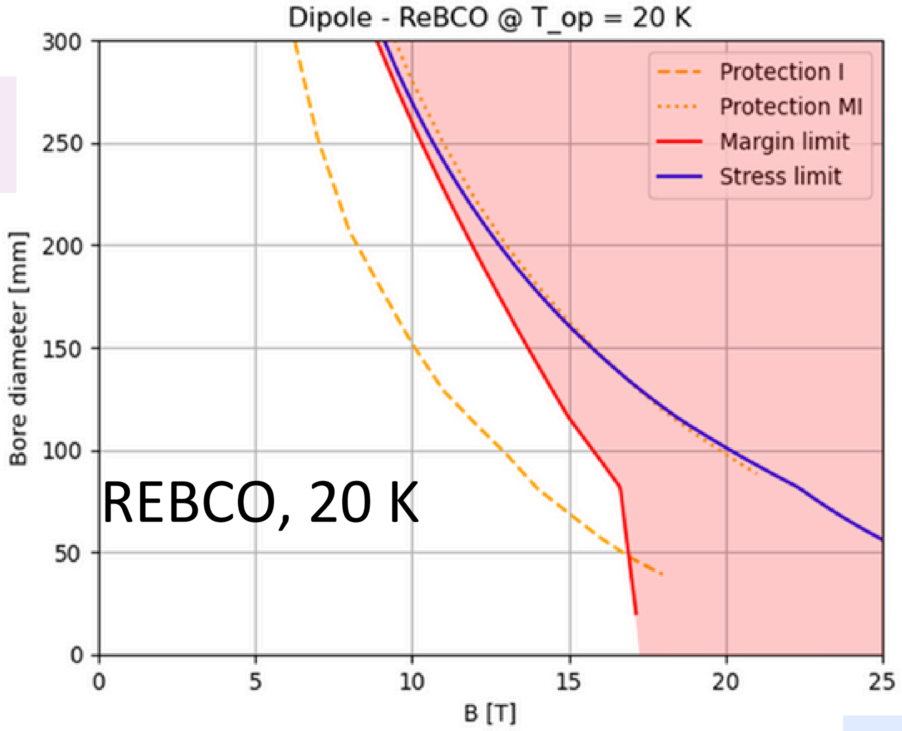
Achieved:

- Systematic **dipole/solenoid performance prediction (LTS** and **HTS)**
    - Aperture, field, cost, stress, loadline, protection, …
- **HTS solenoid designs (6D cooling, final cooling, target)**
- Normal-conducting **fast-pulsed dipoles** (HTS as alternative)
- Technically limited R&D timeline developed

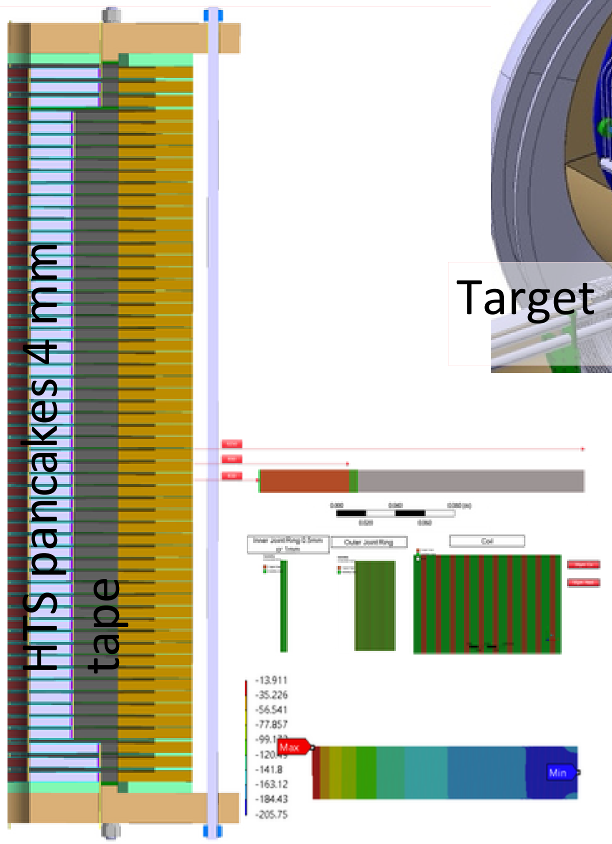


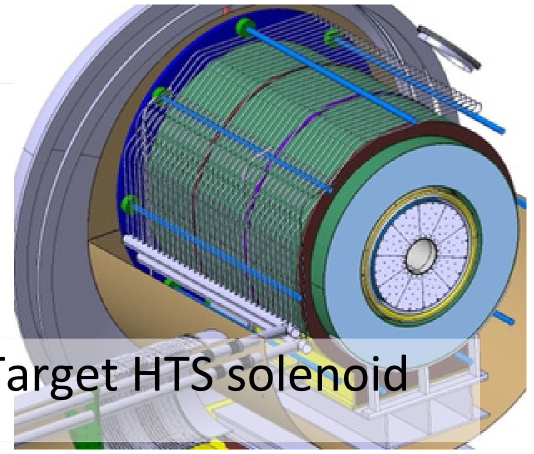
First **HTS winding tests**

Did adjust collider ring field

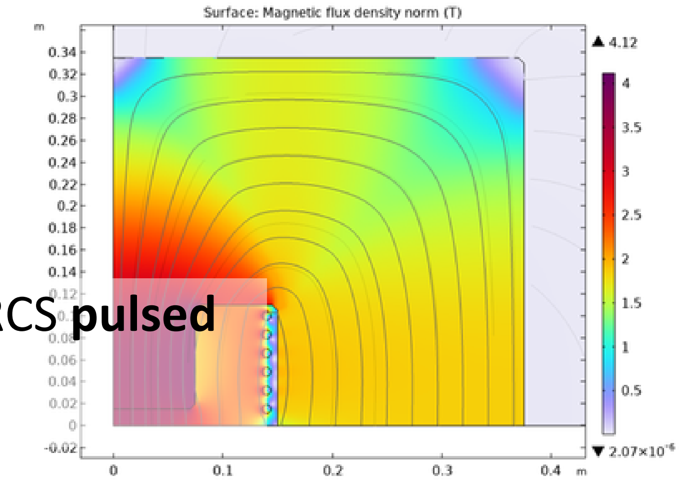


HTS final cooling solenoid mechanical design





Target HTS solenoid



Normal-conducting RCS **pulsed magnets**

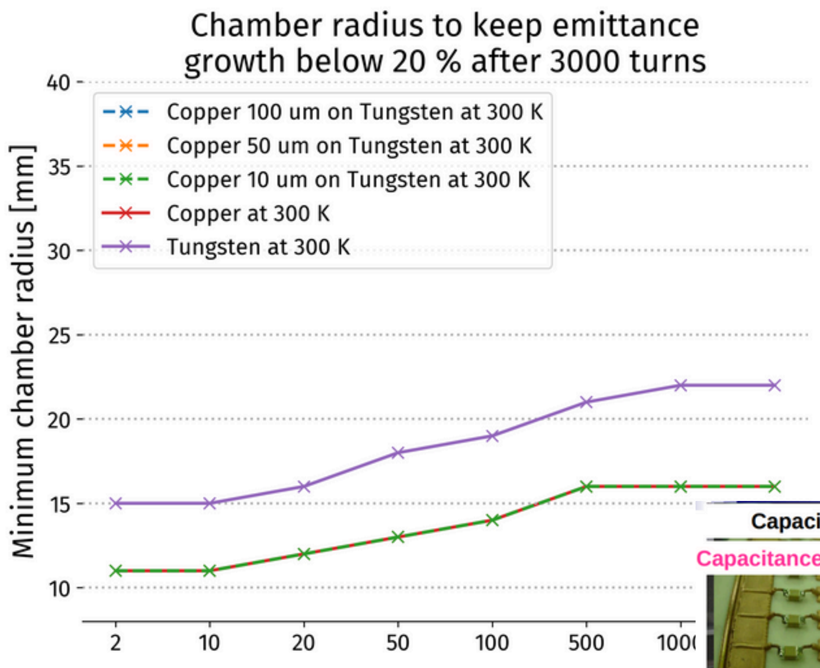
Key conclusions:

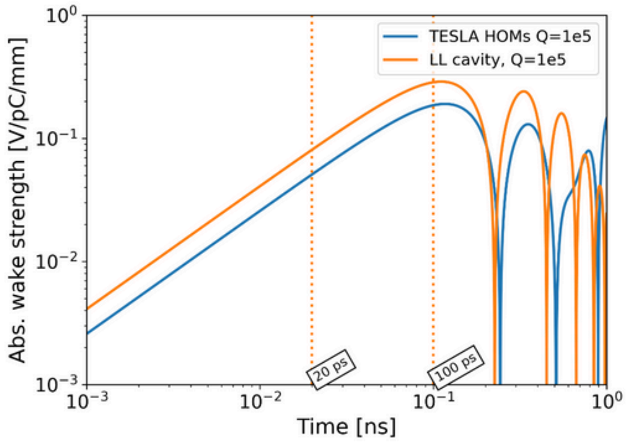
- Design work is basically done
- Opportunity to **ramp up** effort (engineering designs, building models, …)
- With sufficient resources **HTS solenoids** and **Nb_3Sn dipoles** could be ready for decision in 10-15 years, **consistent with implementation timeline**
- **HTS dipoles** likely take longer

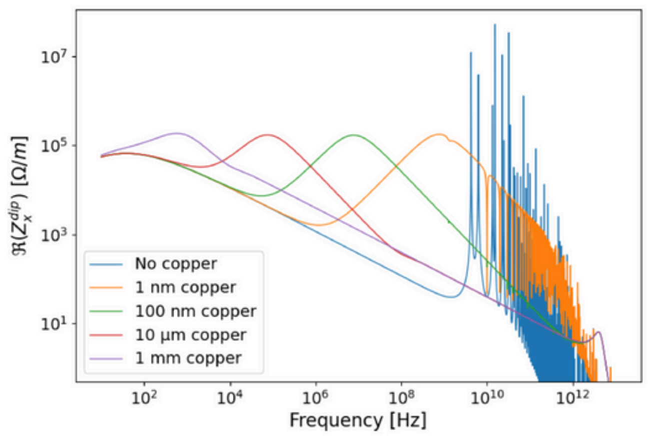
Collective Effects

Goal:
Identify collective effects intensity bottlenecks

Achieved:
- Initial studies for proton complex
- Assessed impedances (beam screen and RF cavities) in RCSs and collider ring
  - Studying counter-rotating beam impedance
- Studies started on muon cooling







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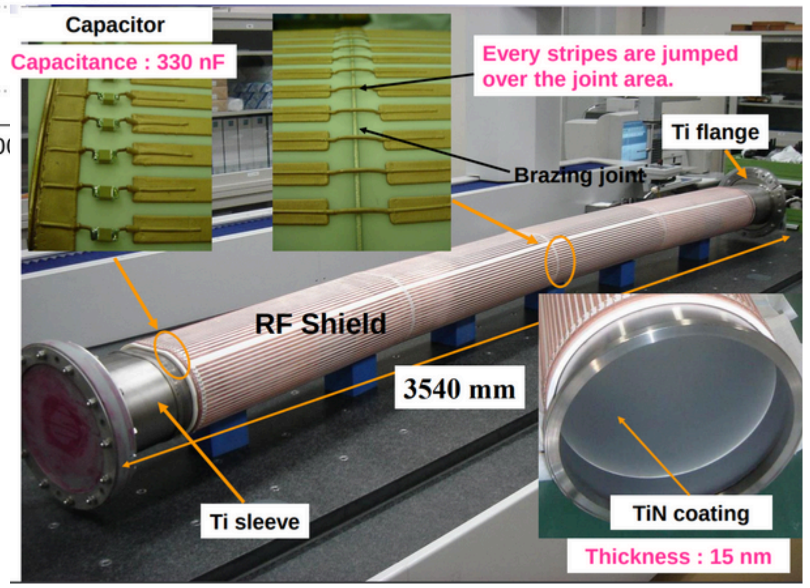

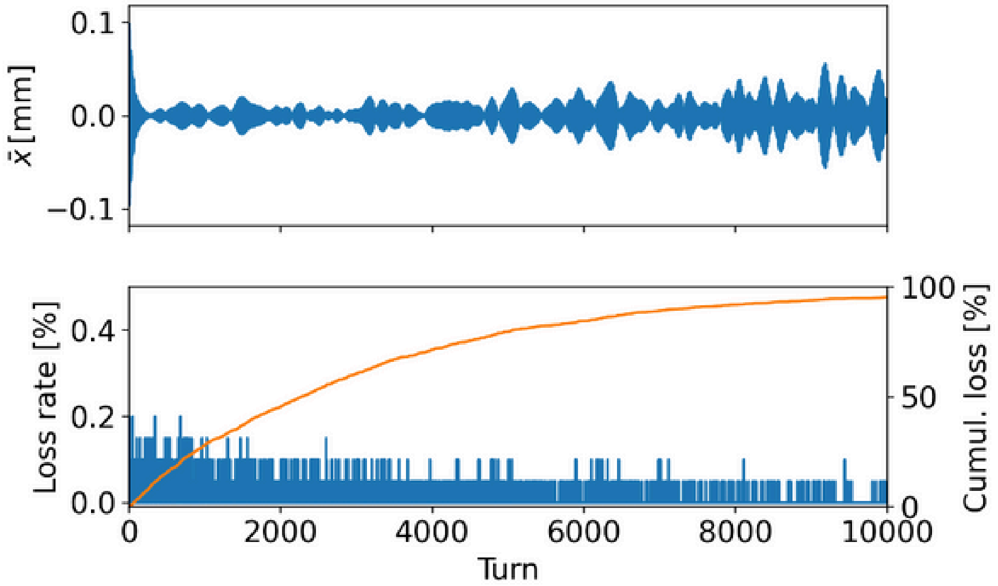

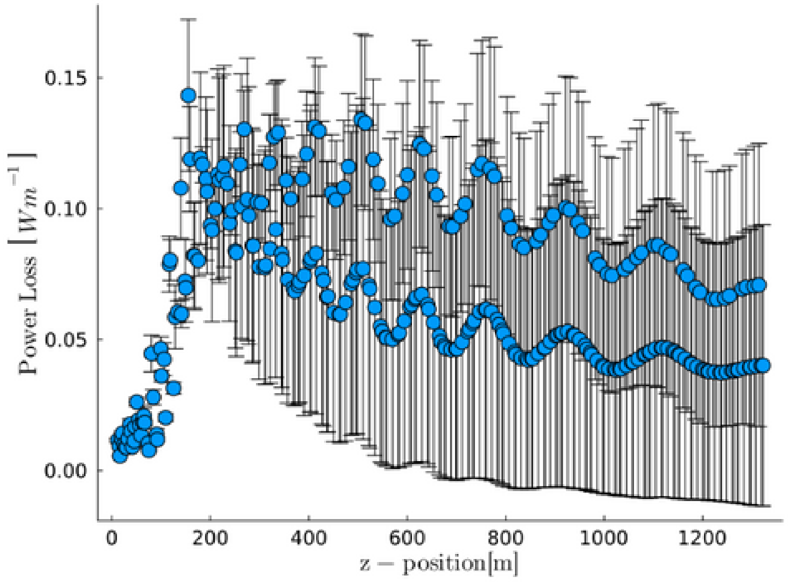

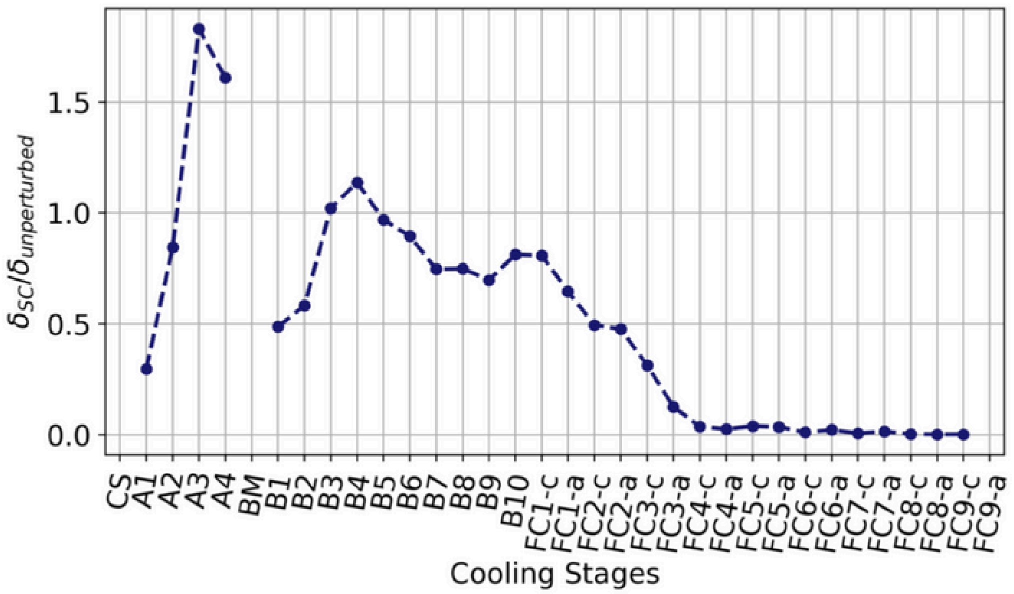

Key conclusions:
- Impedances in RCSs and collider ring can be taken care of by design
- Beam-beam can be handled by 20 turn feedback
- Resistive wall in muon cooling is OK
- Further key detailed studies: beam loading, longitudinal and transverse space charge in 6D cooling, impedance of cooling absorbers

R&D Plan Deliverables and Resources

International MUON Collider Collaboration

Technologies	Deliverables	Key parameters and goals
Magnets		
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	29.2	29.7	30.5	25.5	27.7	26.7	25.5
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Technologies	Deliverables	Key parameters and goals
Magnets		
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K
[illegible] magnet system	[illegible] converter	[illegible]
LTS collider dipole	Demonstrate Nb_3Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
Radiofrequency		
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
Muon Cooling		
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 µm emittance, 40 T field
Design & Other Technologies		
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O(±1mradian)
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

R&D Plan Deliverables and Resources

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Totals:

Duration 10 years

Accelerator: 300 MCHF material, 1800 FTEy

Detector: 20 MCHF material, 900 FTEy

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technolo[illegible]										
Material (MCHF)	1.6	3.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FTE	47.1	60.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Demonstrator										
Material (MCHF)	0.6	2.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
FTE	9.5	11.0	[illegible]	29.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Detector										
Material (MCHF)	0.5	1.1	1.6	2.1	2.1	2.1	2.1	2.6	3.1	3.1
FTE	23.4	46.5	70.0	93.0	93.0	93.0	93.0	116.4	139.5	139.5
Magnets										
Material (MCHF)	3.0	4.9	10.1	10.0	11.0	13.4	11.7	7.2	6.6	4.7
FTE	23.3	28.4	36.4	40.9	44.3	47.1	46.2	37.7	36.1	29.4
TOTALS										
Material (MCHF)	5.7	11.4	20.3	23.9	30.6	41.4	51.7	54.2	53.5	32.4
FTE	103.3	146.5	194.0	248.1	267.0	290.6	314.8	356.3	379.4	379.6

Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K
[illegible] magnet system	[illegible] converter	[illegible]
LTS collider dipole	Demonstrate Nb_3Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long
	Radiofrequency	
Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
	Muon Cooling	
First 6D cooling cell	Build and test first cooling cell	
5-cell module	Build and test first 5-cell cooling module	
Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 µm emittance, 40 T field
	Design & Other Technologies	
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O(±1mradian)
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

European Accelerator R&D Roadmap

Reviews in Europe and the US found muon collider promising

- Requires important innovation

  European Strategy for Particle Physics Update (**ESPPU**) supported muon collider R&D in 2020

  CERN Council charged Laboratory Directors Group (**LDG**) to develop Accelerator R&D Roadmap
- Directors of institutes, e.g. INFN Frascati, PSI, DESY, RAL, CERN, …

  LDG formed five panels, one on Muon Collider

  Muon Collider panel developed an **R&D Roadmap** with the help of the global community until end of 2021

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.

http://arxiv.org/abs/2201.07895

Muon Collider Roadmap CT

International MUON Collider Collaboration

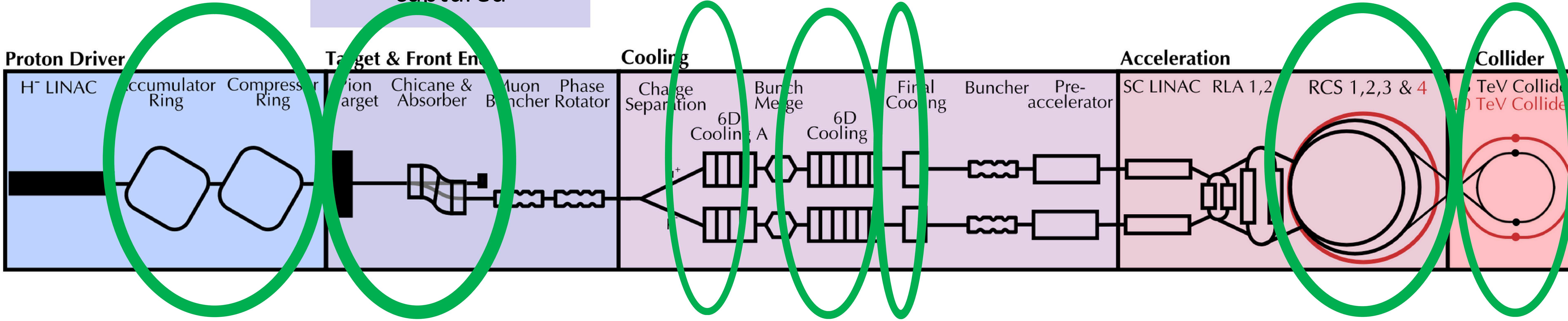
Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision



- Proton driver
  bunch compression

- Graphite target
- Target solenoid

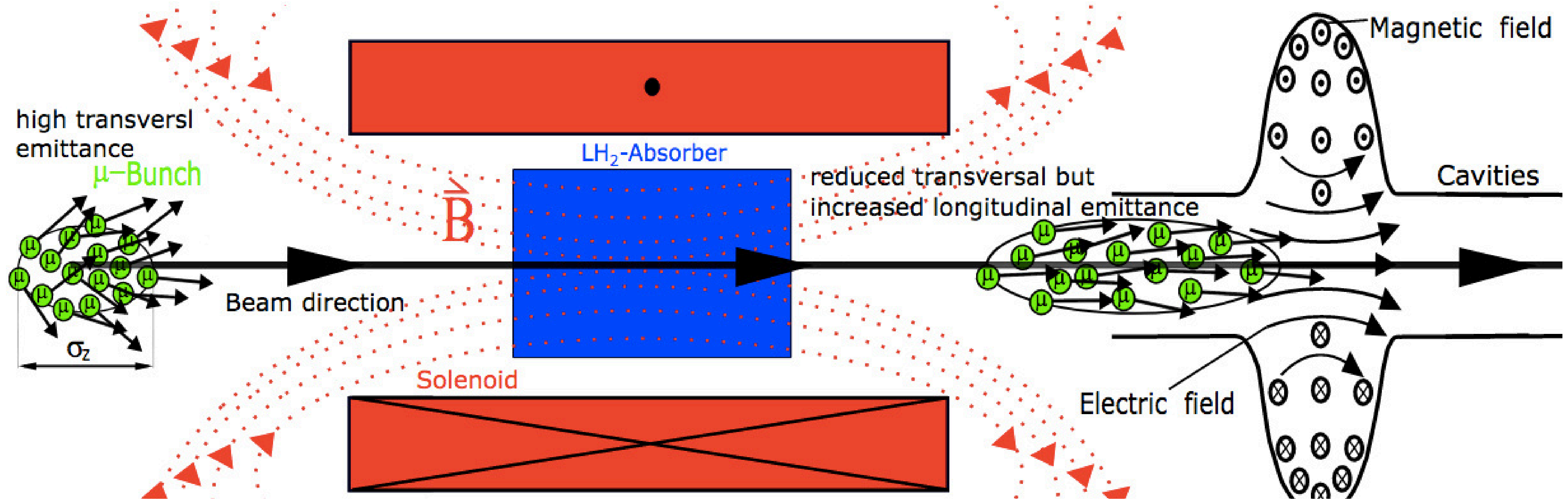
- Muon cooling design
- 6D cooling solenoids
- 6D cooling RF cavities
- Final cooling solenoids

- Pulsed magnets and
  power converters
- RCS RF system

- Collider ring dipoles
- Final focus quadrupoles
- Machine-detector interface

Identified and prioritized with community
Other areas need now also to be addressed
(some work started)

Muon Cooling Challenges



High field solenoids minimise beta-function and impact of multiple scattering

Energy loss = cooling

Multiple scattering = heating

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$