Muon Colliders and their Future R&D

EPS-HEP Marseilles
T13 Accelerators for HEP
Monday 7th July 2025

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Featuring work from 450 members of the International Muon Collider Collaboration

International
UON Collider
Collaboration

MuCol

Funded by
the European Union

CERN

Overview

International MUON Collider Collaboration

WHY	should we collide muons?
HOW	would we collide muons?
WHAT	do we need to do to collide muons?
WHERE	might we collide muons?
WHO	works on colliding muons?

Overview

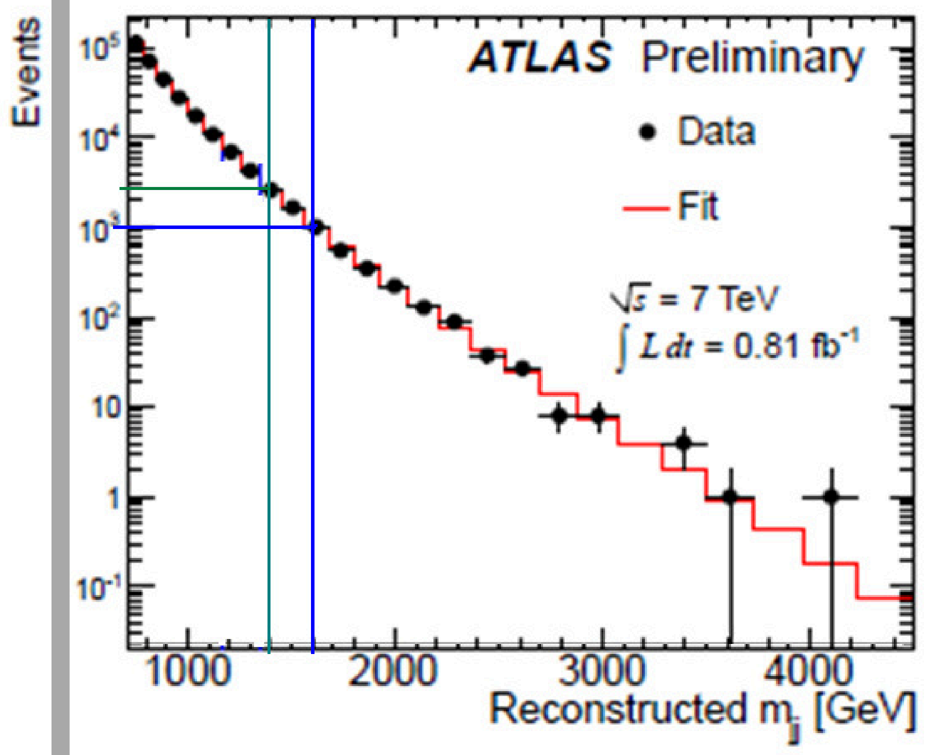
WHY	should we collide muons?	Physics!
HOW	would we collide muons?	Accelerator!
WHAT	do we need to do to collide muons?	R&D!
WHERE	might we collide muons?	Siting!
WHO	works on colliding muons?	Collaborators!

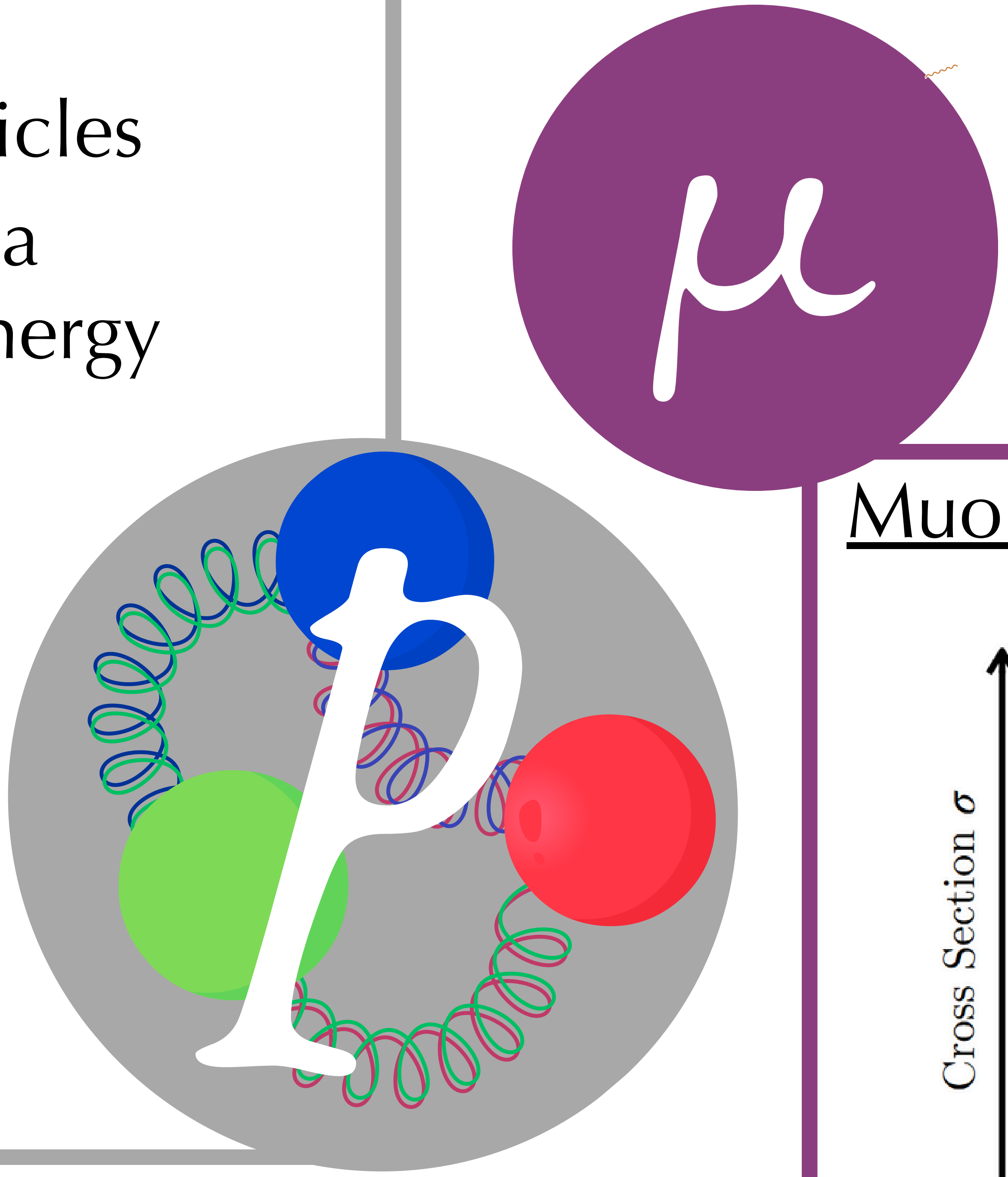
WHY should we collide muons?

Muons are:

- Fundamental particles

Hadrons collide with a fraction of their full energy





Muons are:

- 200x heavier than **electrons**

Emit 6×10^{-10} less bremsstrahlung / turn

$$\Delta E \propto \frac{E^4}{m^4 r}$$

Muon colliders are:

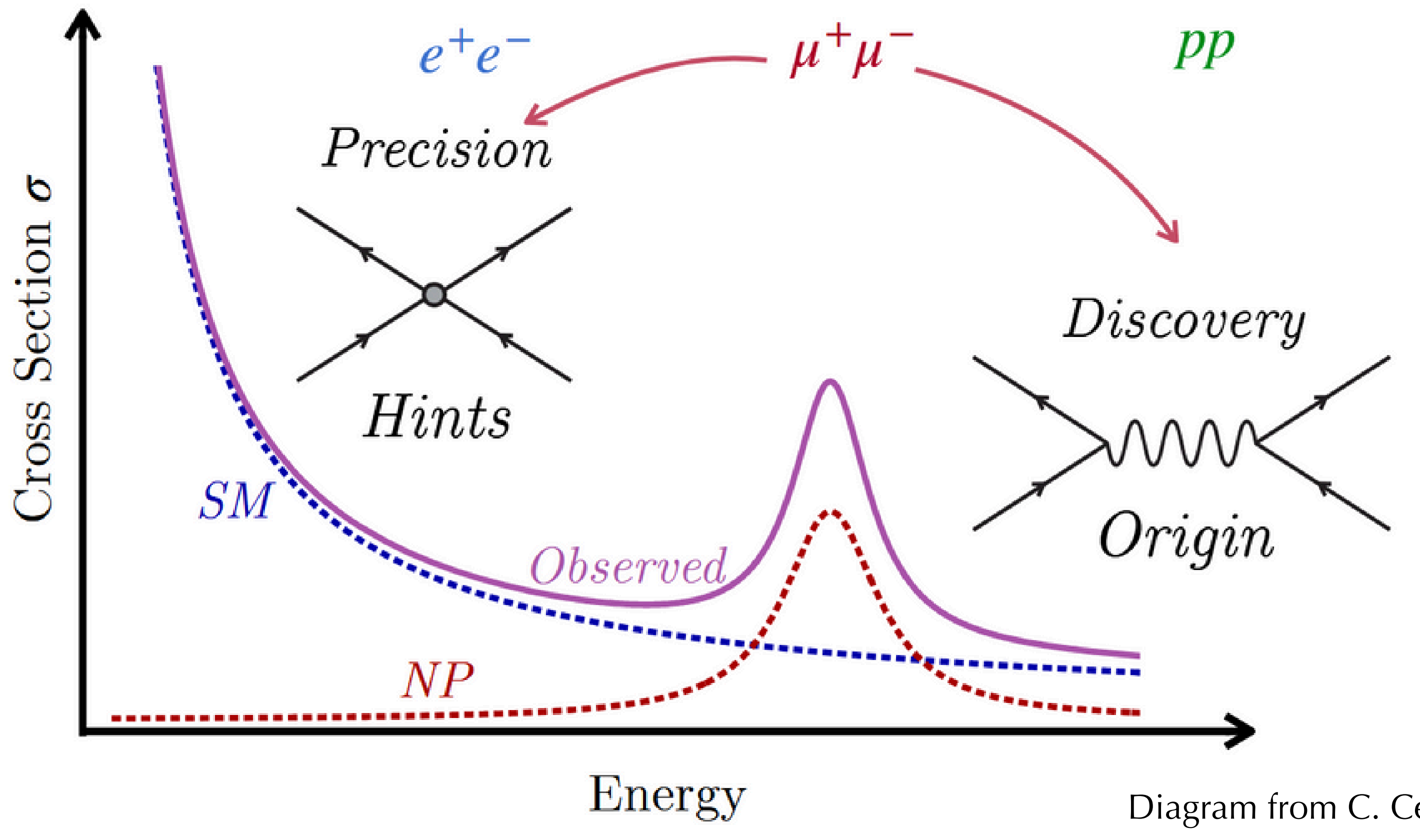
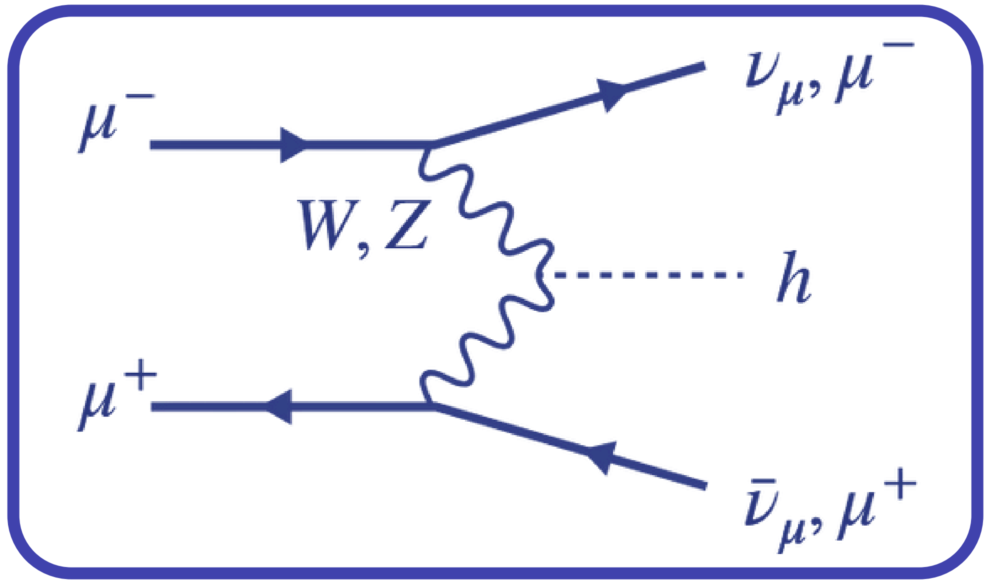
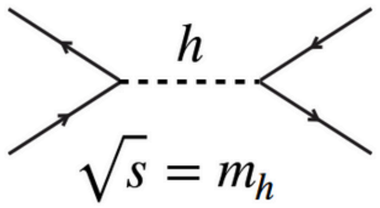


Diagram from C. Cesarotti

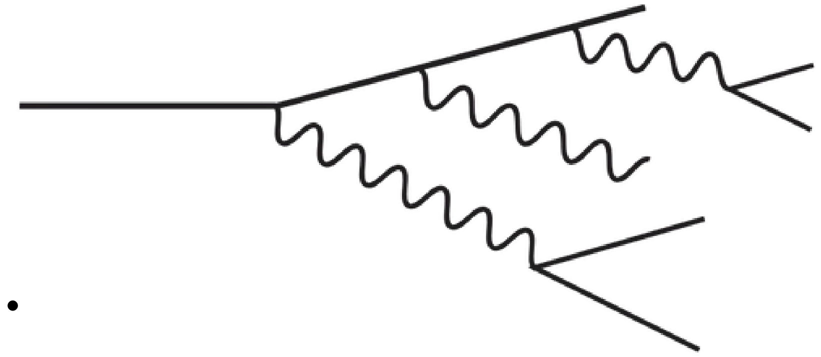
WHY should we collide muons?



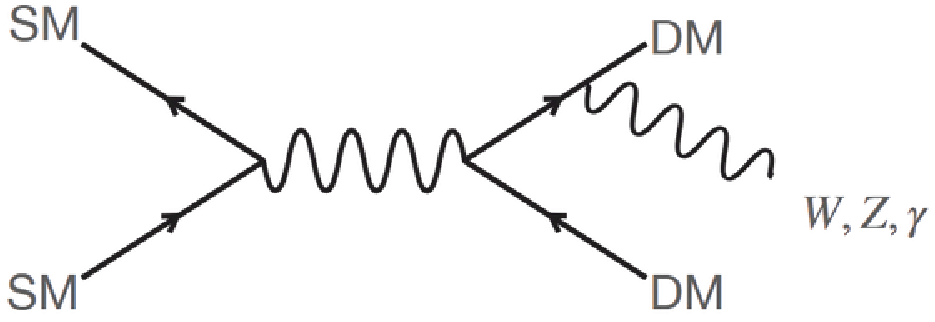
Muons at high energies are **vector boson fusion (VBF)** factories.
S-channel directly has lower cross-sections.



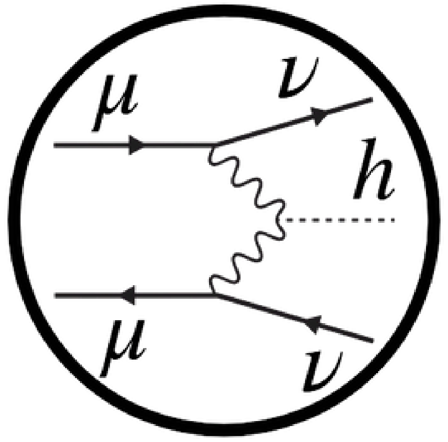
At high energies, muons radiate gauge bosons like photons.

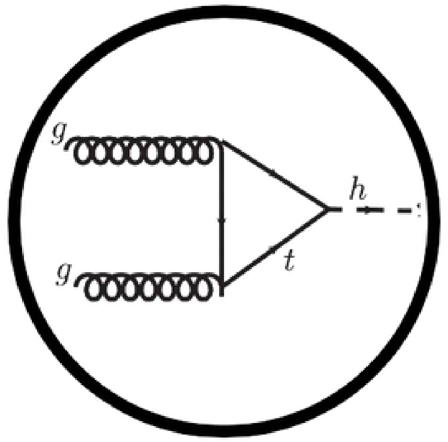


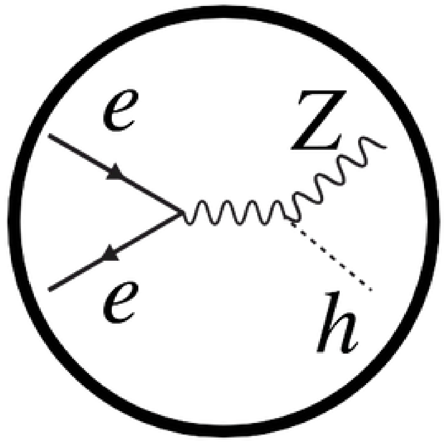
Ideal environment for **electroweak** studies, including WIMPS.



Higgs Production Mechanisms:







Information credit:
Cari Cesarotti (MIT)

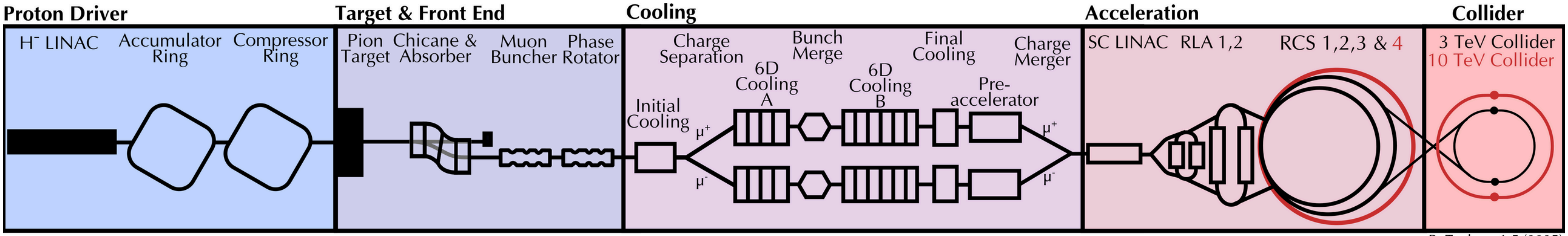
HOW would we collide muons?

Challenge 1: Need to produce the muons

- Produce a high power proton beam
- Target material to withstand high-power

Challenge 2: The muons decay

- Rapidly reduce the beam size
- Rapidly Accelerate
- Collide tight beams



R. Taylor v1.5 (2025)

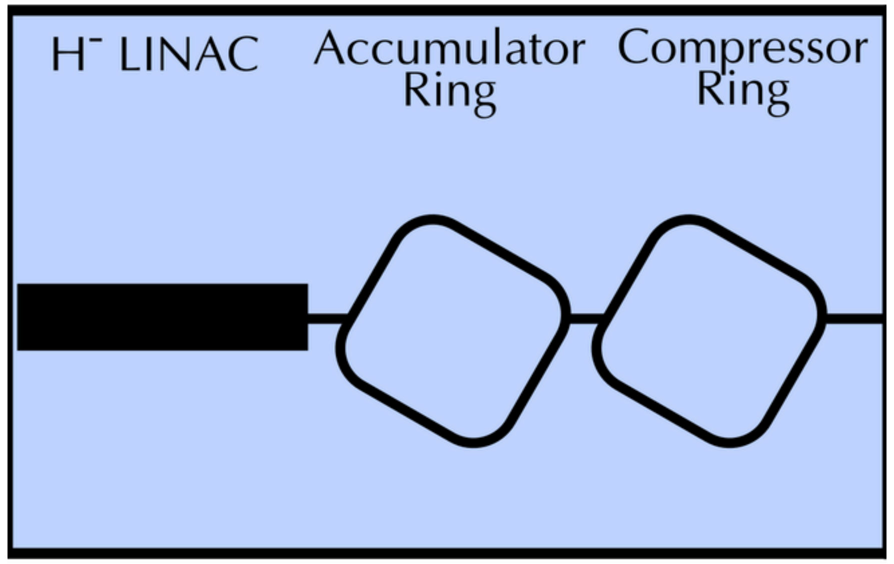
Challenge 3: Need to adjust for collective effects due to high intensity beam across the complex.

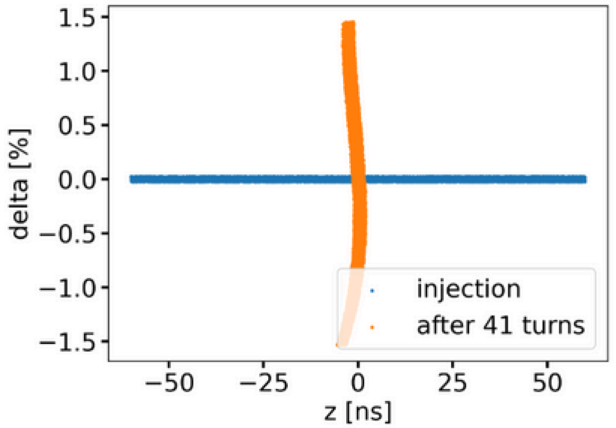
HOW would we **produce** muons?

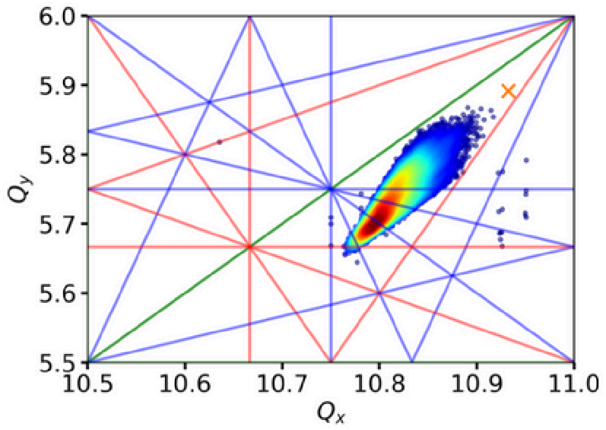
Challenges:
- High intensity proton beam
- 2 MW, 5 GeV or 4 MW, 10 GeV
- Accumulate 5×10^{14} p^+/pulse
- Compress to 2 ns

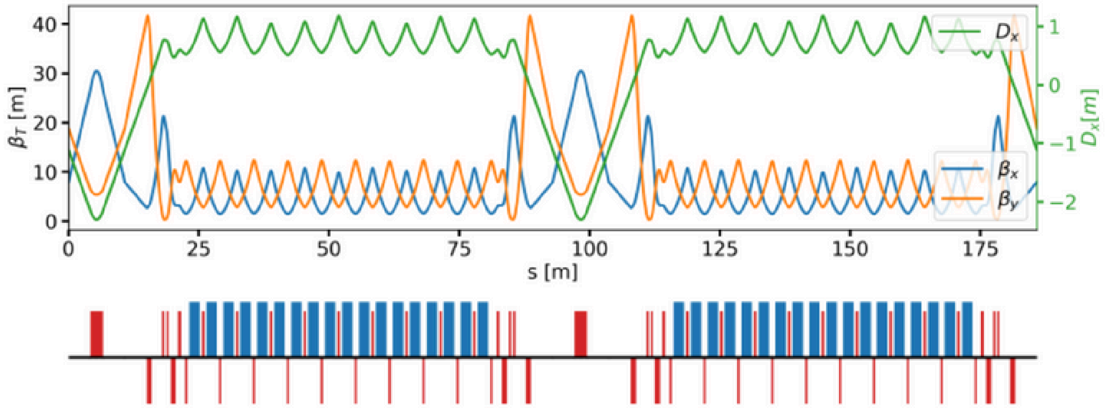
Achievements:
- Lattice designs for accumulator and compressor rings
- Collective effects studies

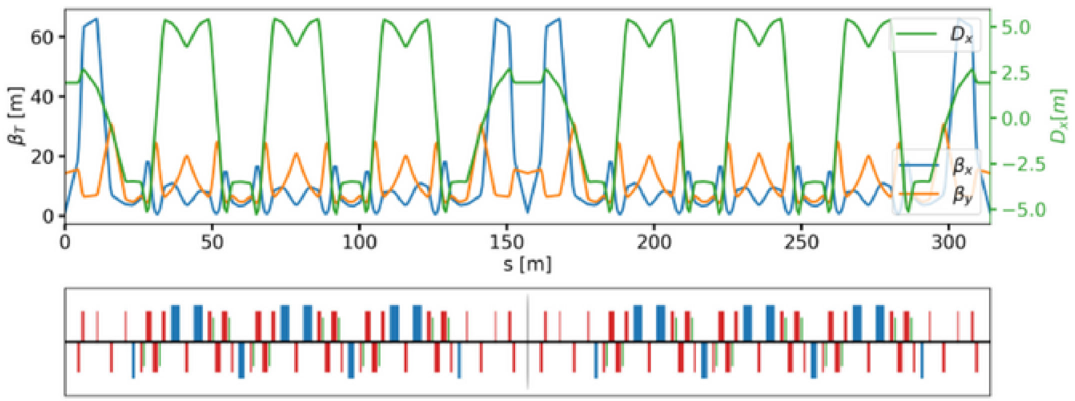
Proton Driver









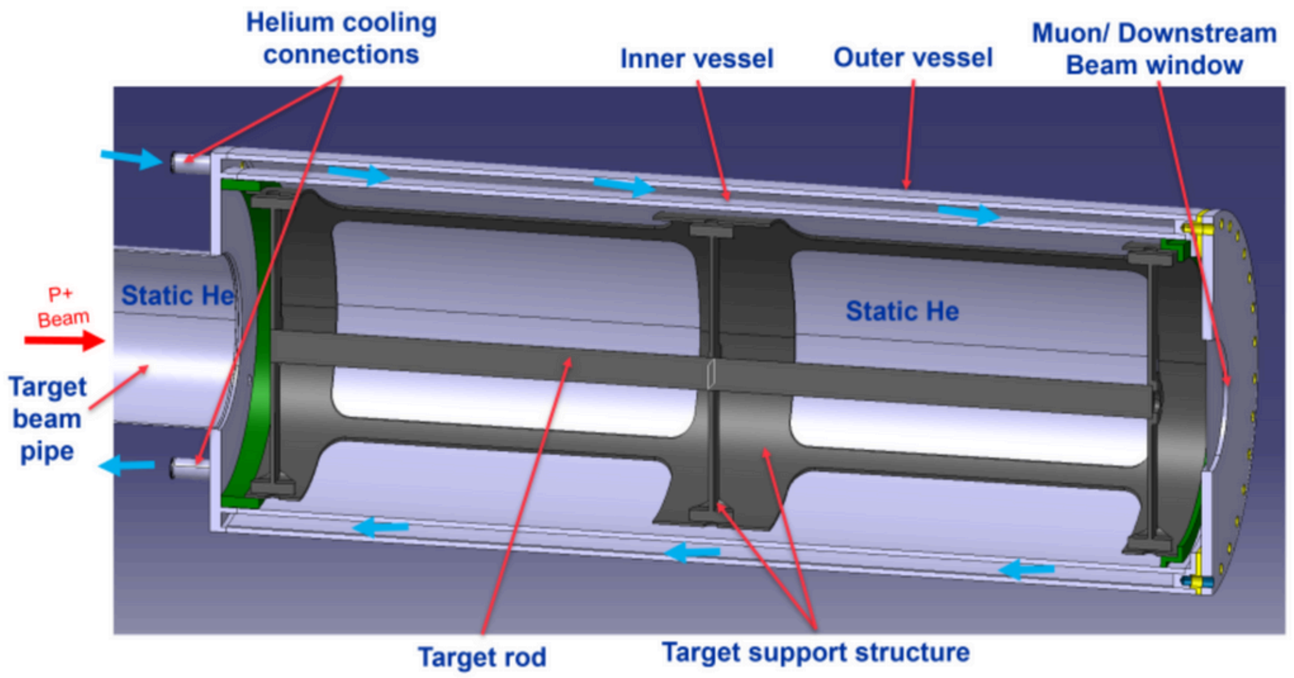


Future R&D:
- In parallel with other **high-intensity p^+** facilities (SNS, ESS, CERN, JPARC, ISIS)
- High intensity, large-aperture **H^- sources** and **laser-assisted charge exchange** injection
- High transmission, high current RFQs
- Limitation of high intensity compression schemes with high space-charge

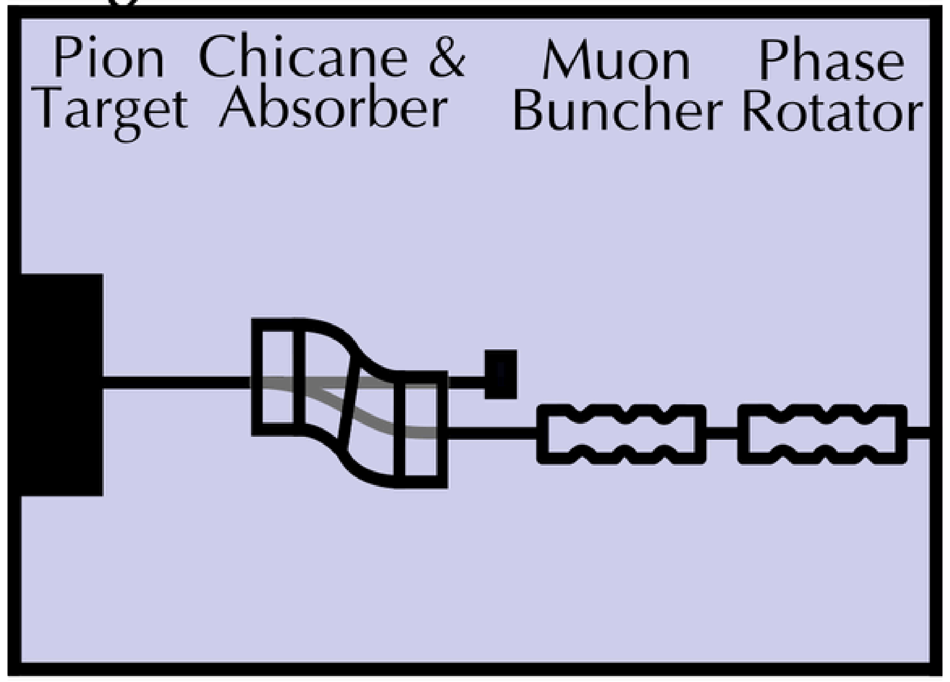
HOW would we **produce** muons?

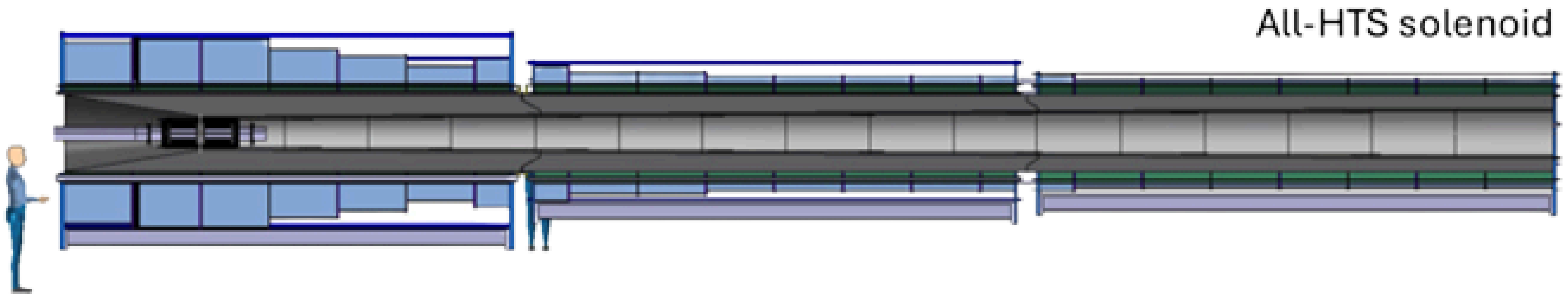
Challenges:
- 2 MW, 400 MJ/pulse on target
- Optimising for pion yield
- HTS solenoid capture system
- Extraction of spent proton beam

Achievements:
- Radial build of graphite target
- Studied radiation load on HTS
- Begin 4 MW targets, e.g. liquid Pb, fluidized W



Target & Front End





Future R&D:
- 1400 mm, 20 K, 20 T HTS solenoids with 80 MGy radiation. Synergies with fusion magnets.
- 20 MV/m RF cavities within 3 T, over large range of frequencies.
- Beam loading and collective effects in Front-End.

HOW would we **cool** muons?

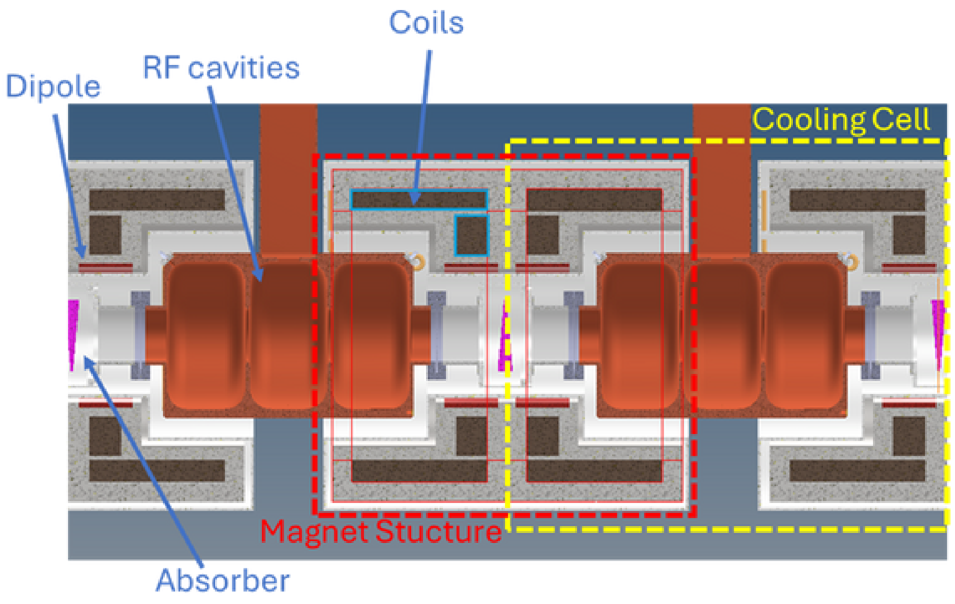
Reduce beam area in (x,px,y,py,z,pz)

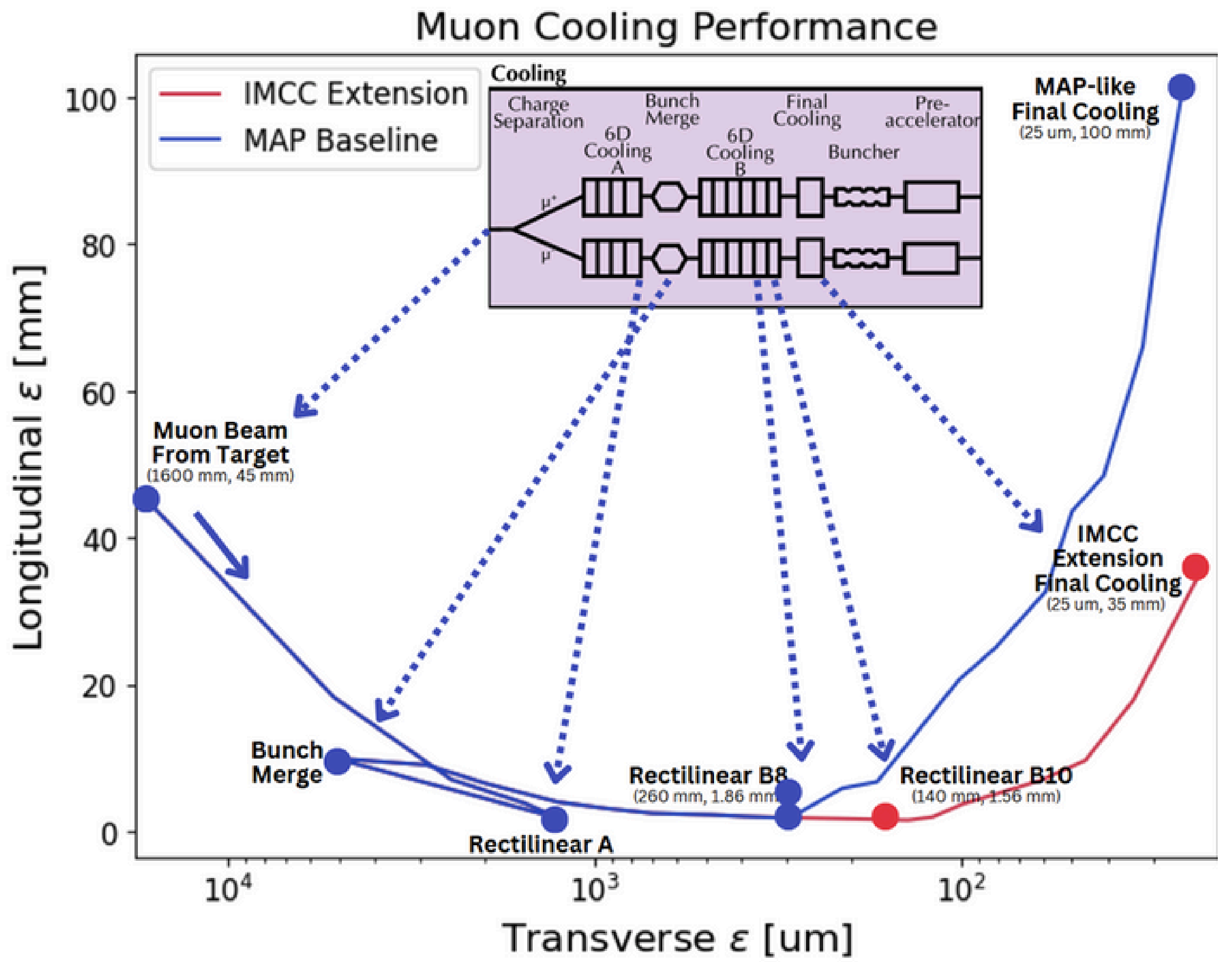
Challenges:

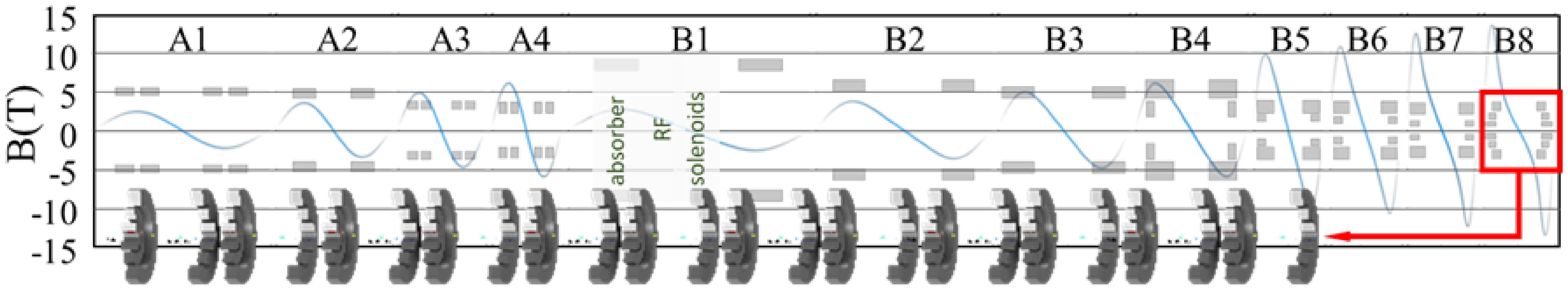
- Overlapping dipoles, absorbers and RF cavities within solenoids.
- Bright beam on liquid hydrogen
- Beam loading and space charge

Achievements:

- Benchmarked codes, RF Track, BDSIM, G4Beamline, ICOOL
- Improved 6D cooling design







6D Future R&D:

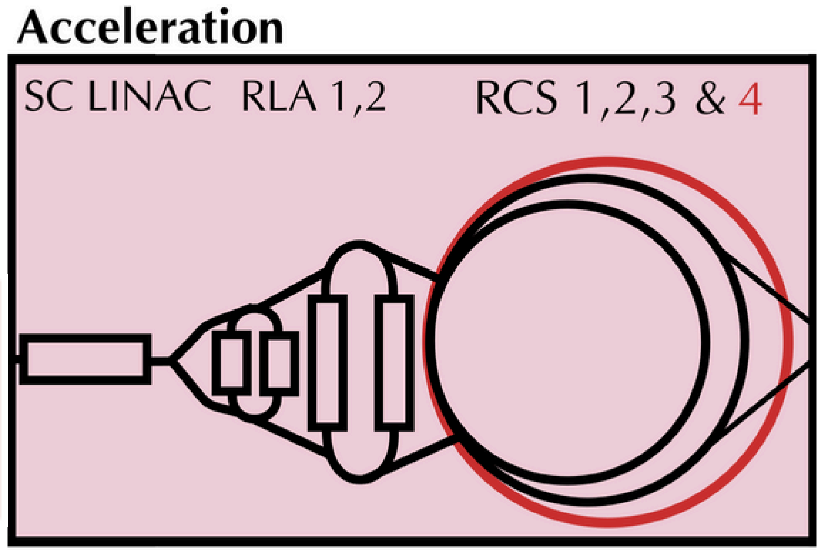
- 2.6 - 17.9 T solenoids with 800 - 60 mm bore.
- >30 MV/m in fields >10 T.
- Develop **cooling demonstrator** to verify integration.

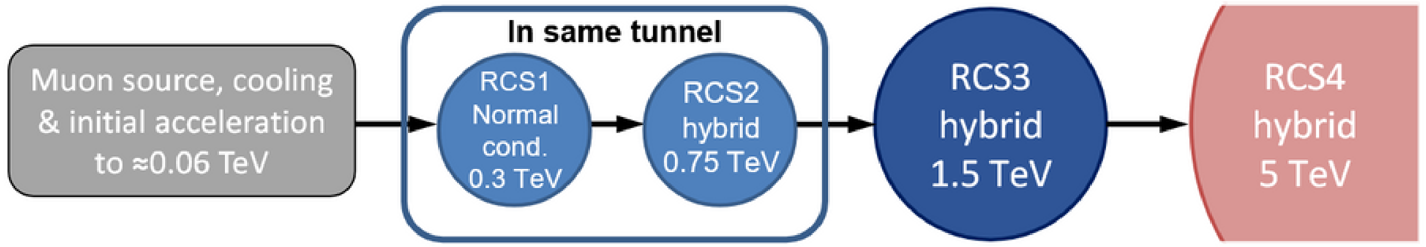
Final Cooling Future R&D:

- 40 T, 50 mm solenoids for final cooling.
- ~20 MV/m in 4 T fields from 200 - 5 MHz
- LH_2 pressure and windows

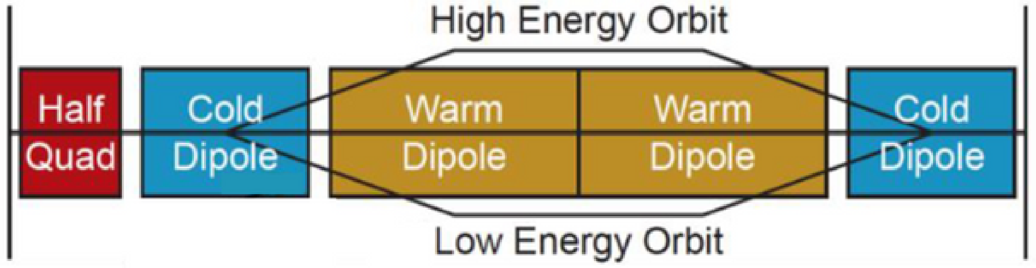
HOW would we **accelerate** muons?

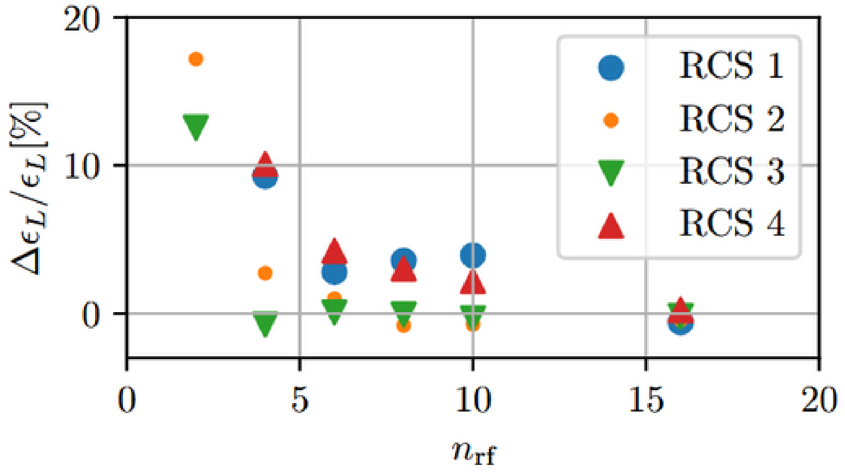
Rapid-Cycling Synchrotrons (RCS)



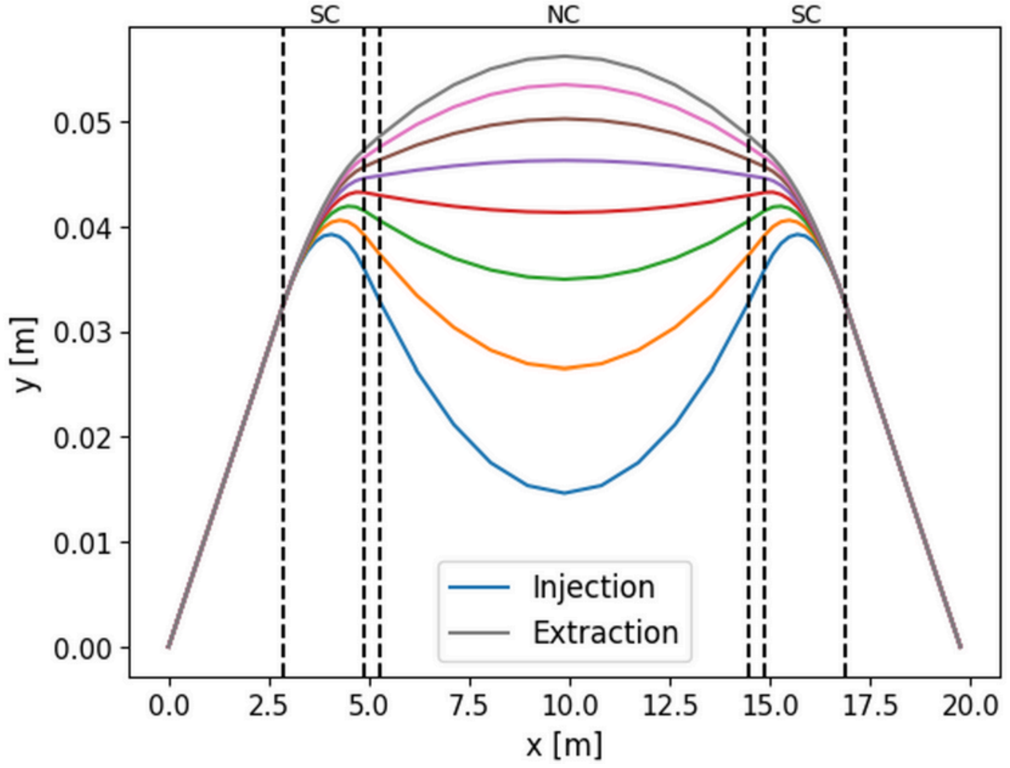


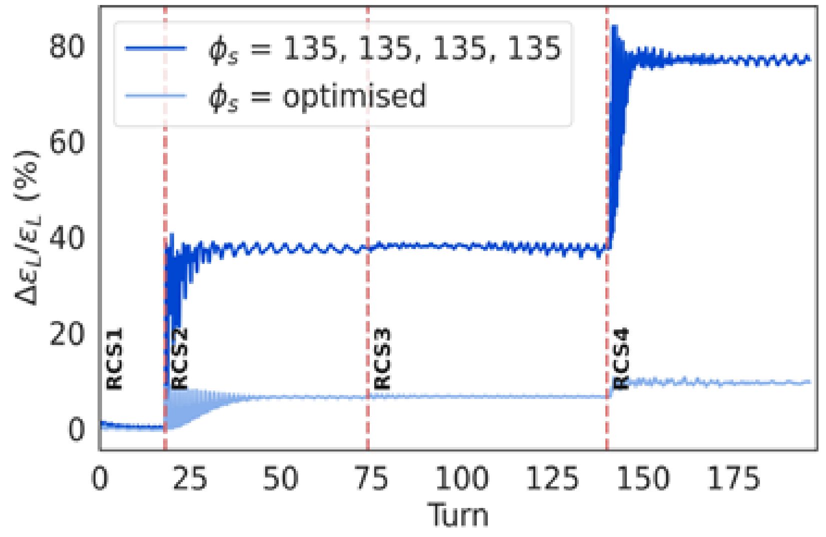
Challenges:
- Fast-Ramping NC magnets hybrid with static SC magnets
- Multiple RF stations throughout
- Large aperture from orbit



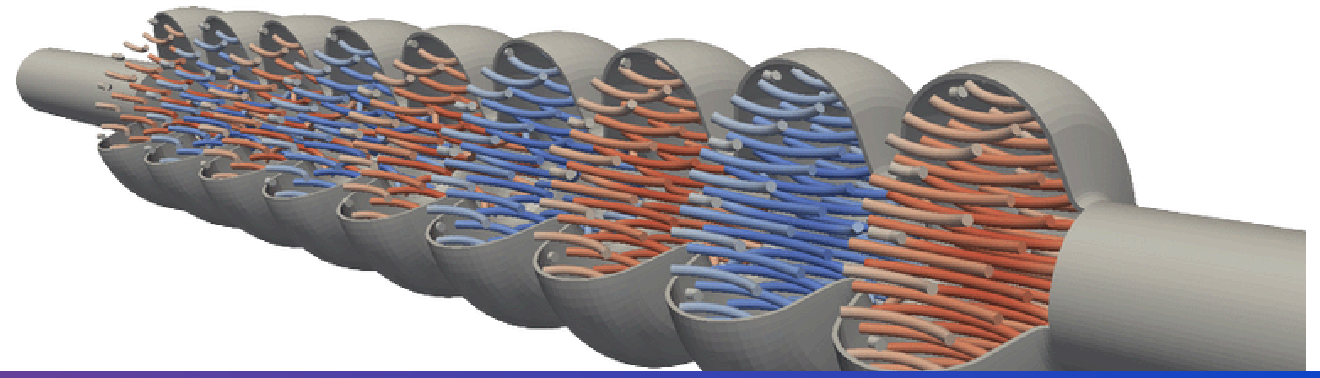


Achievements:
- Lattice designs & matching for greenfield and CERN RCS
- 1.3 GHz Tesla Cavities
- Impedance studies of RCSs

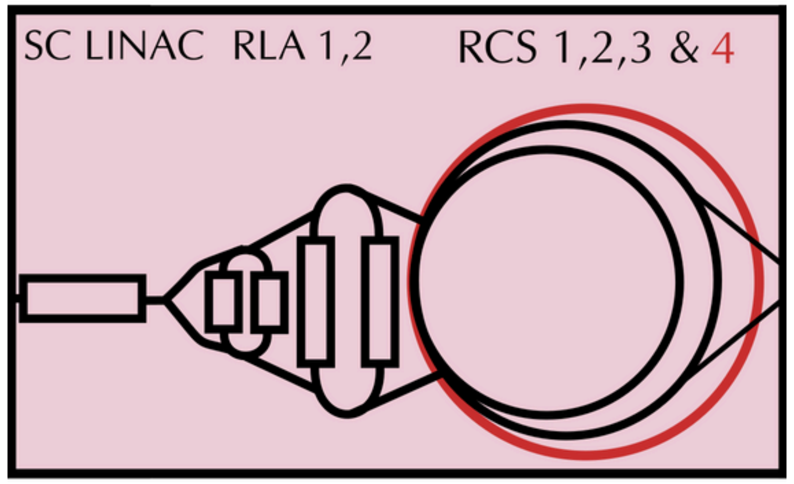




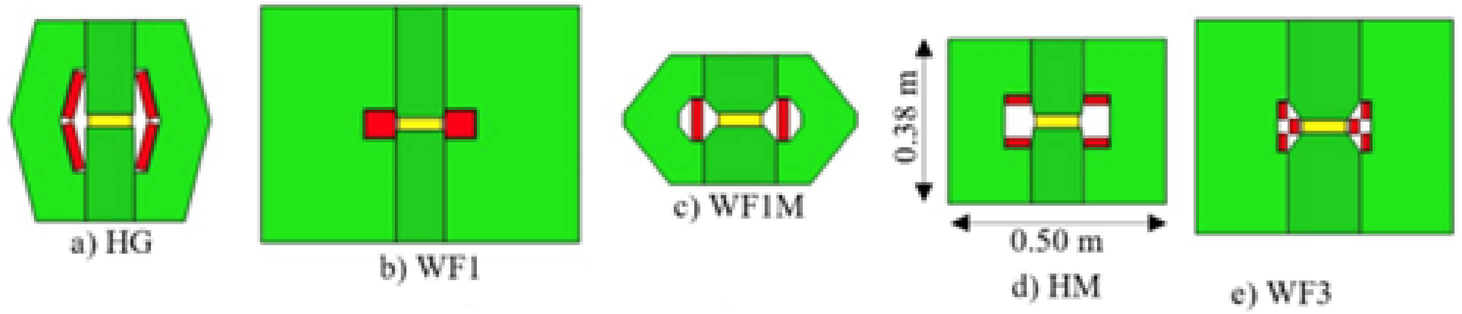
Future R&D:
- Designs of SC LINAC and Recirculating LINACS
- Validate power sources for 1.3 GHz
- Higher order mode damping schemes



HOW would we **accelerate** muons?

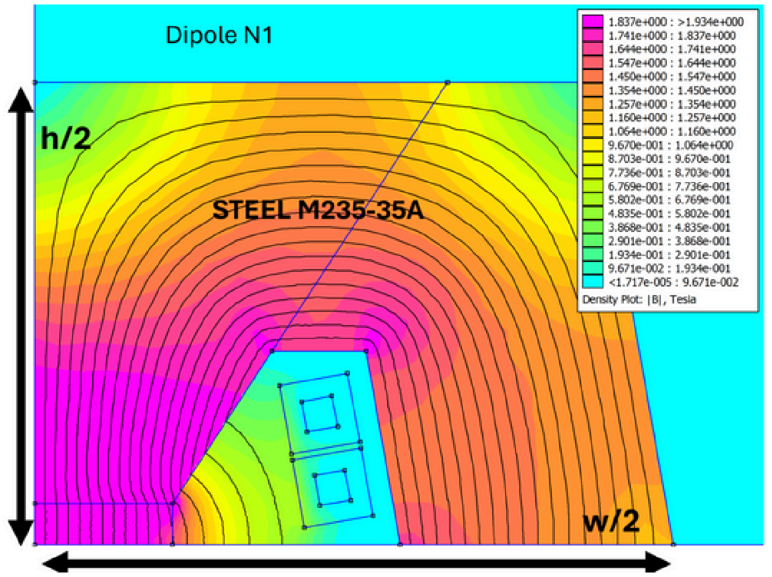


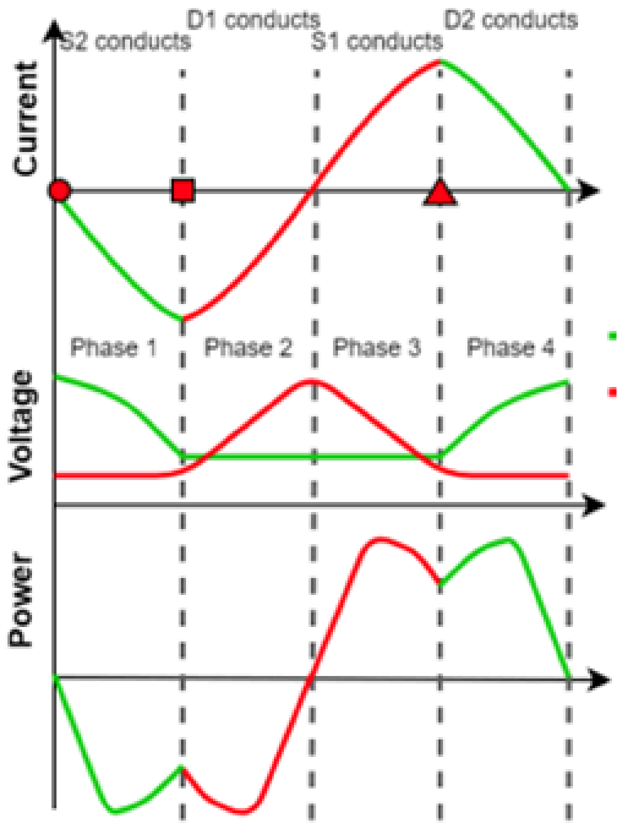
Challenges:
- 1-10 ms ramping NC magnets with 98-99% energy recovery of 200 MJ stored in magnets

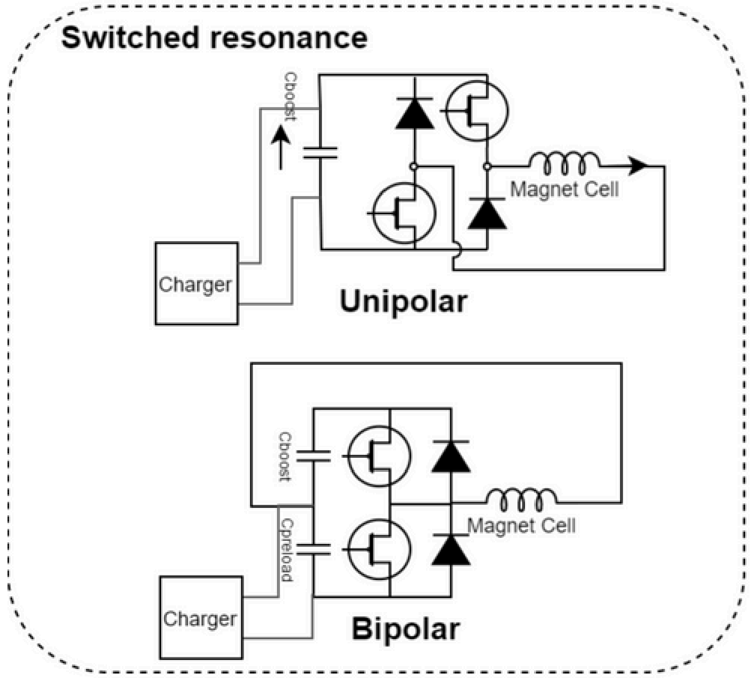


RCS	E [J/m]	E_iron [J/m]	E_copper [J/m]	Loss [%]	P [MW]
SPS 1	5447	10	52	**1.1**	1.9
LHC 1	5678	9.2	80.6	**1.6**	12.8
LHC 2	5752	63.4	298	**6.3/2**	26.6

Achievements:
- Design of magnets, power converters, optimised together with RF
- Power converters switching magnet sign magnets without changing voltage direction





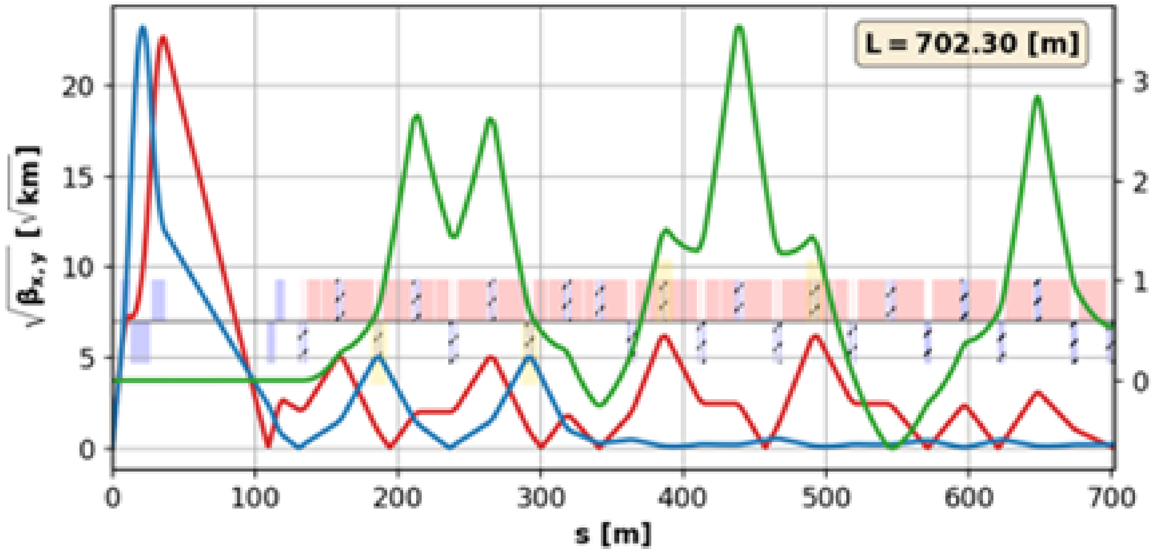


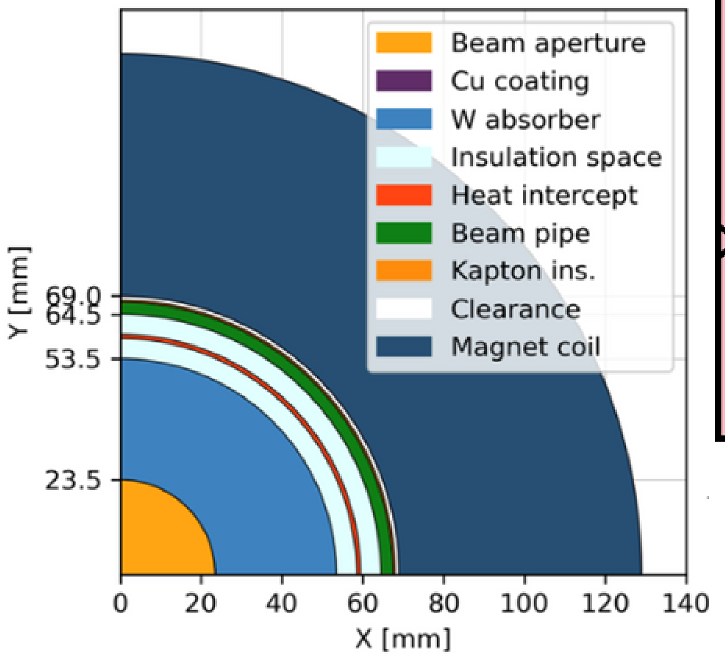
Future R&D:
- 4 kT/s ramp rate
- Synergies with infineon for sustainable energy sources

HOW would we **collide** muons?

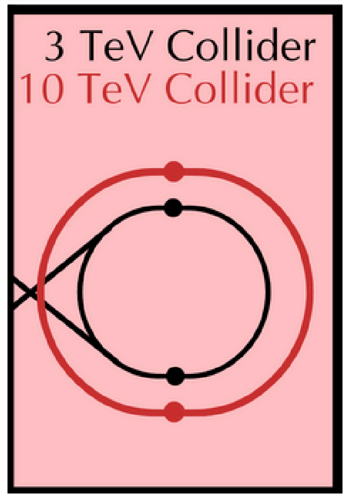
Challenges:
- Lattice design with β^* 1.5 – 5 mm
- 0.1% beam energy spread
- High radiation, 500 W/m loss
- High magnetic field / aperture

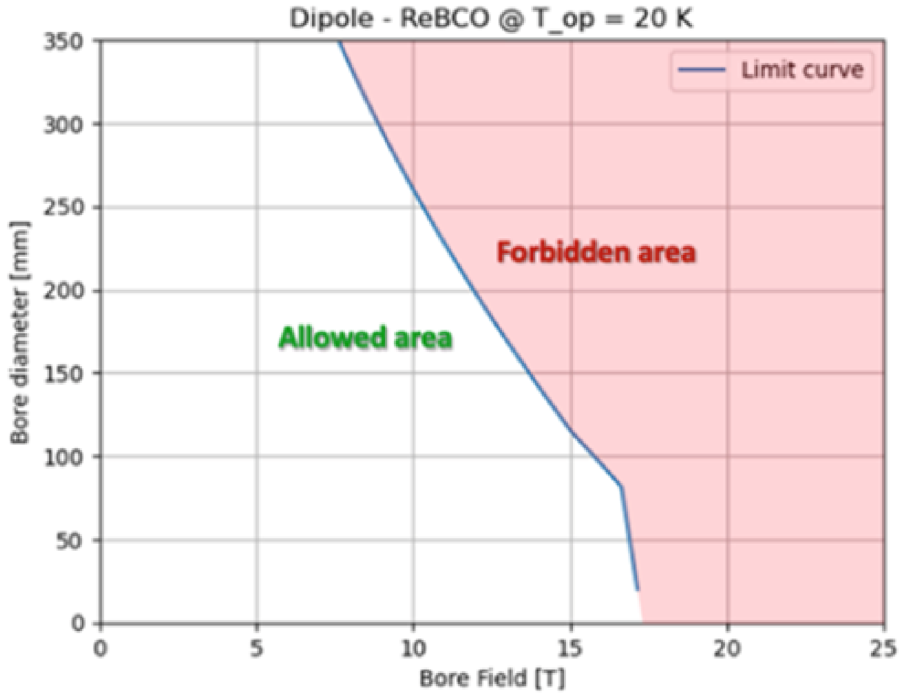
Achievements:
- Magnetic shielding design
- Cryogenic concept
- Impedance models

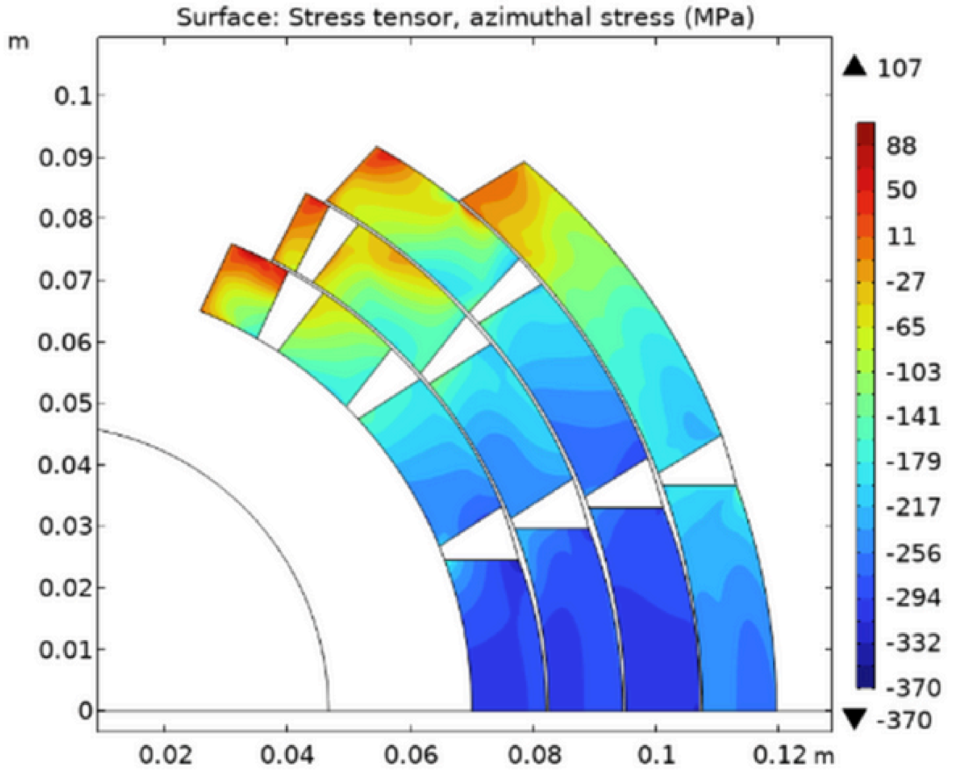




Collider



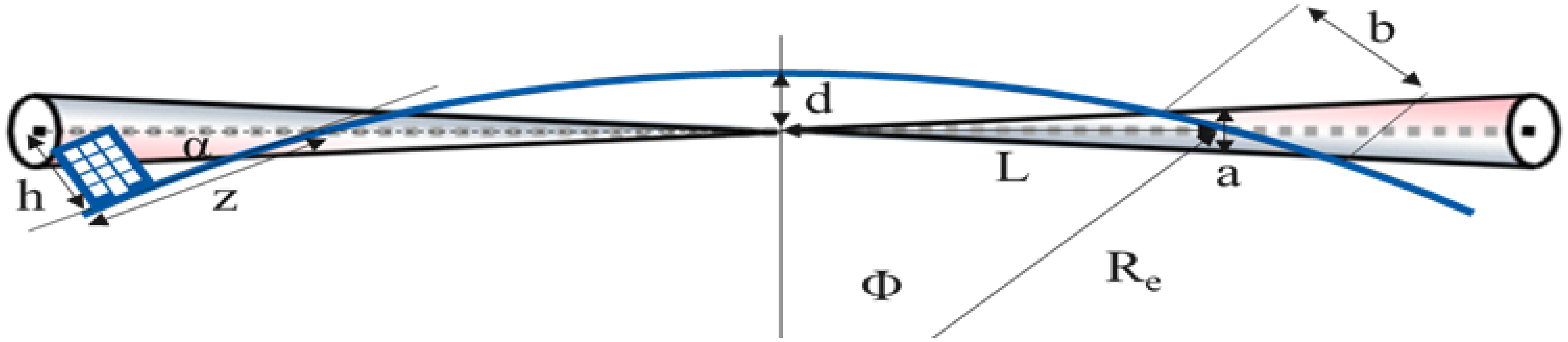


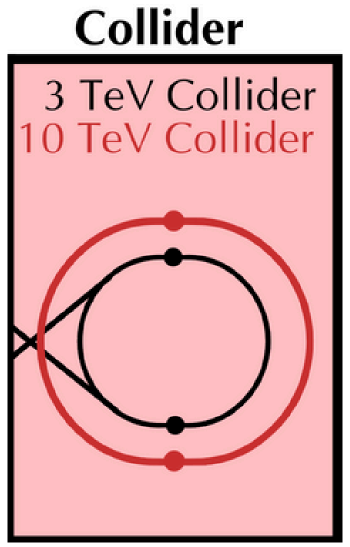


Future R&D:
- Studies on machine imperfections and misalignment
- Improve energy acceptance compensating chromatic effects
- *NbTi*: 4.8 T, 16 cm / *Nb3Sn*: 11 T, 16 cm / *HTS*: 14 T, 14 cm

Experimental programme is now essential

HOW would we **collide** muons?



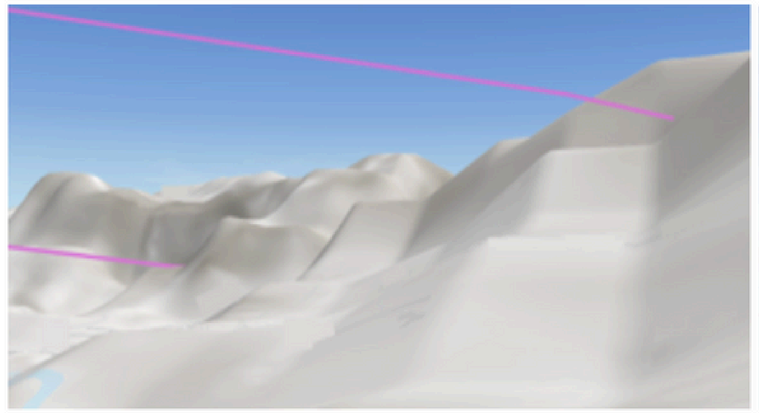


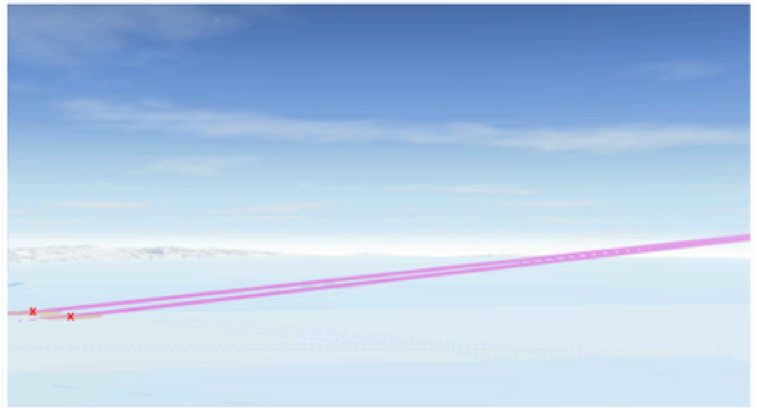
Challenges:

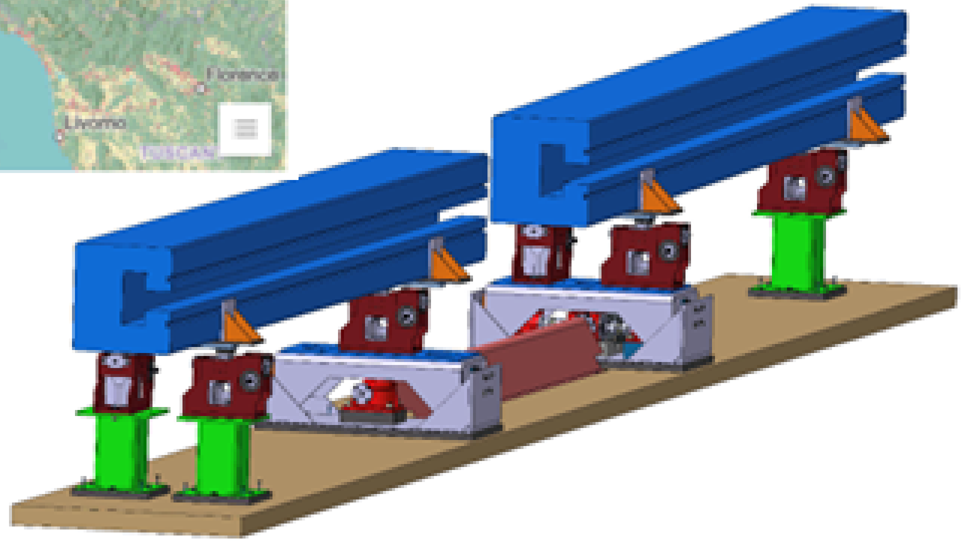
- Negiliable neutrino flux
- Orient collider to benefit neutrino detector studies

Achievements:

- Geoprofiler for detailed modelling
- Orientation options found
- Conceptualised mover system







Future R&D:

- Jack development programme to reach 1 mrad with 0.004 mrad tolerance
- Further iteration with collider lattice

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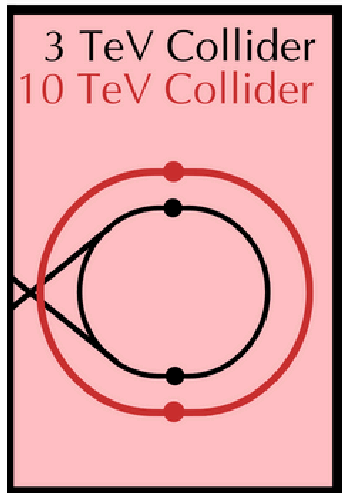
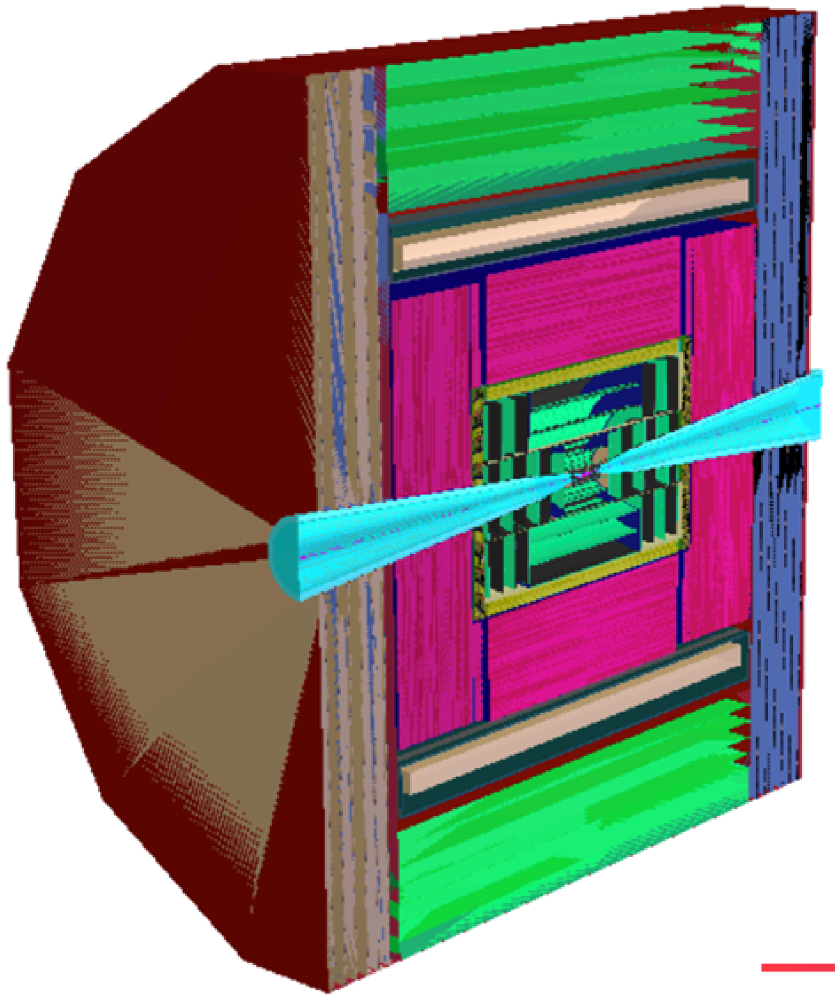


MUSIC

Muon Smasher for Interesting Collisions



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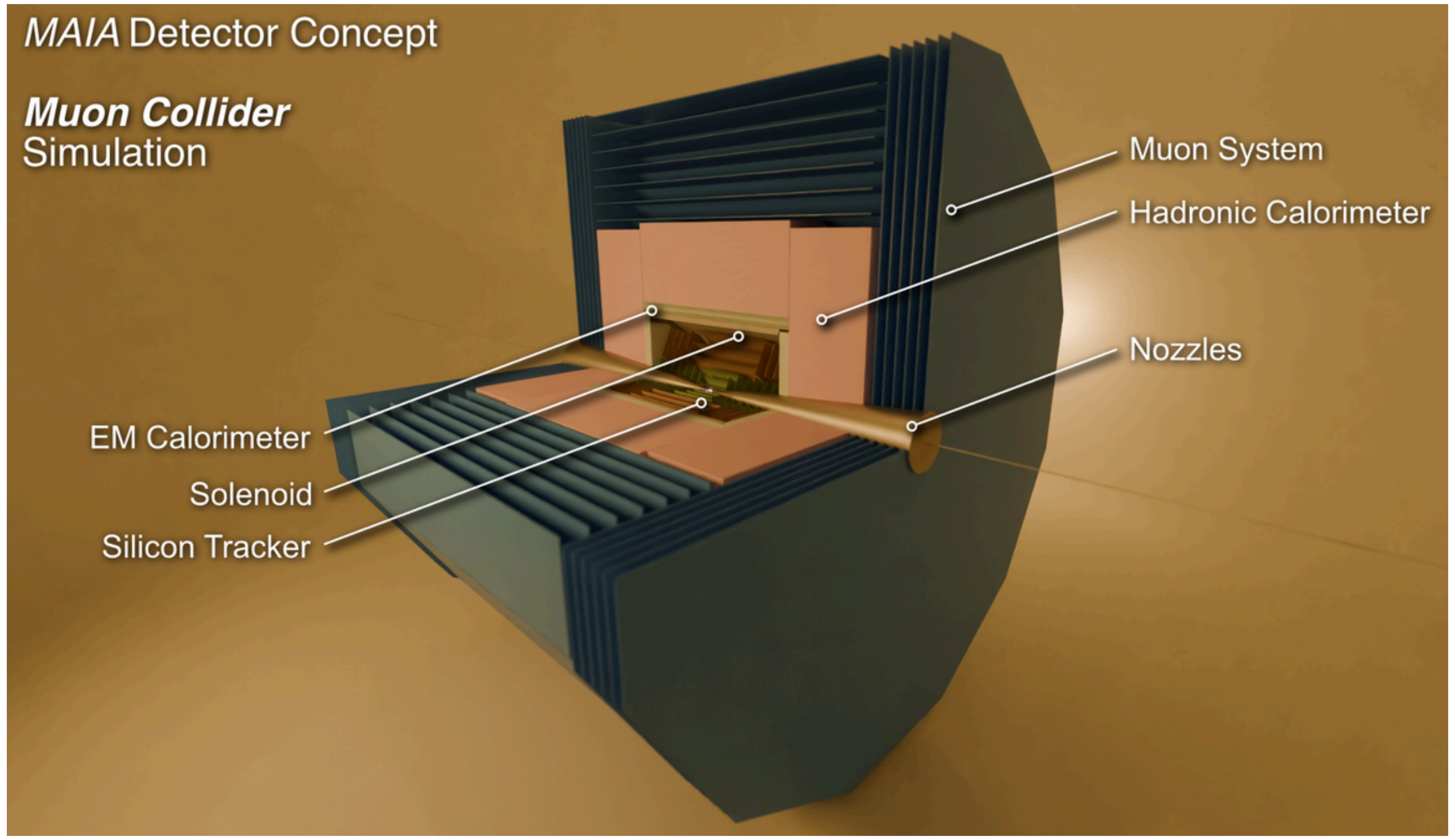
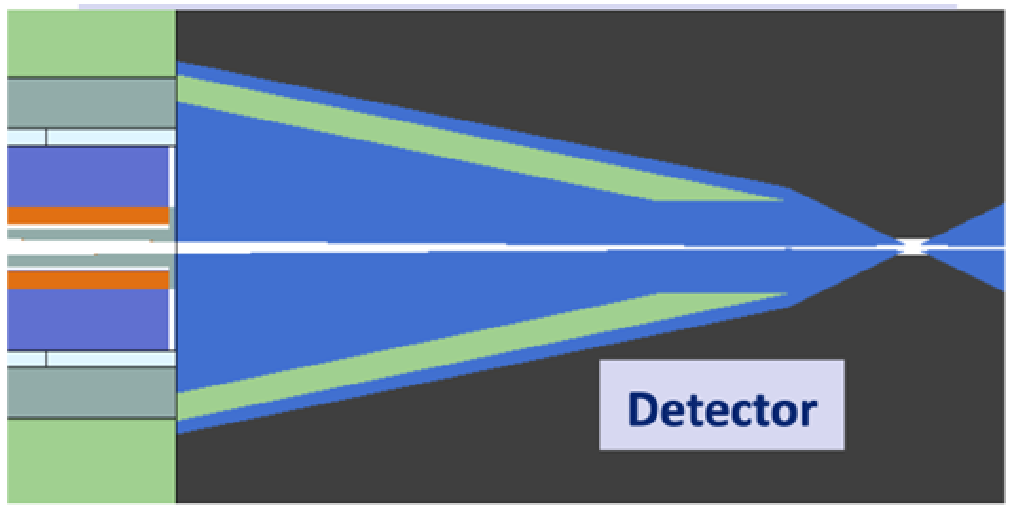
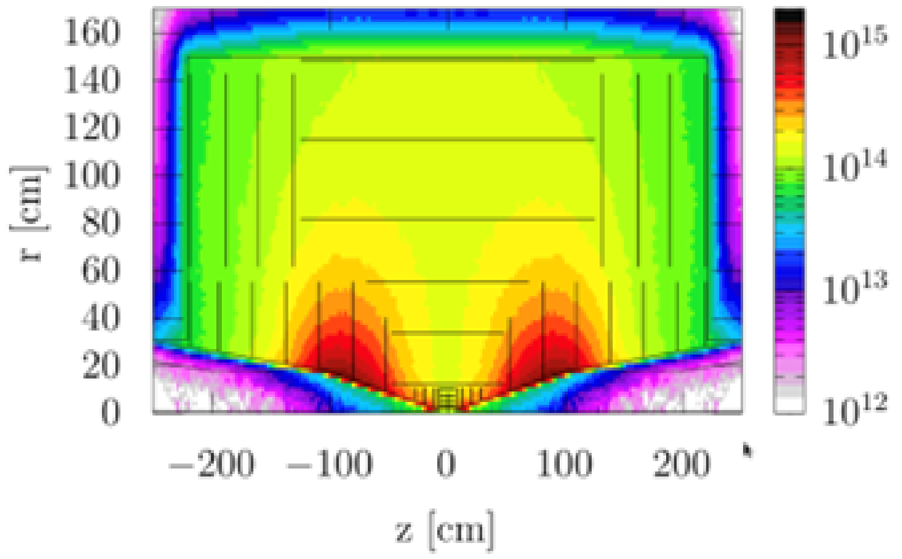
Muon Accelerator Instrumented Apparatus



Future R&D:

- Reconstructing events with high BIB
- Tungsten nozzle configuration
- State-of-the-art detector technologies





WHAT do we need to do to collide muons?

Future R&D

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

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HTS RCS dipole	Demonstrate RCS HT	
HTS collider dipole	Demonstrate HTS col	
HTS collider quadrupole	Demonstrate HTS IR	

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		20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
		352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
		Infrastructure to test cooling modules with muon beam
		3×10^{12} muons, 22.5 µm emittance, 40 T field

Totals:

Duration 10 years

Accelerator: 300 MCHF material, 1800 FTEy

Detector: 20 MCHF material, 900 FTEy

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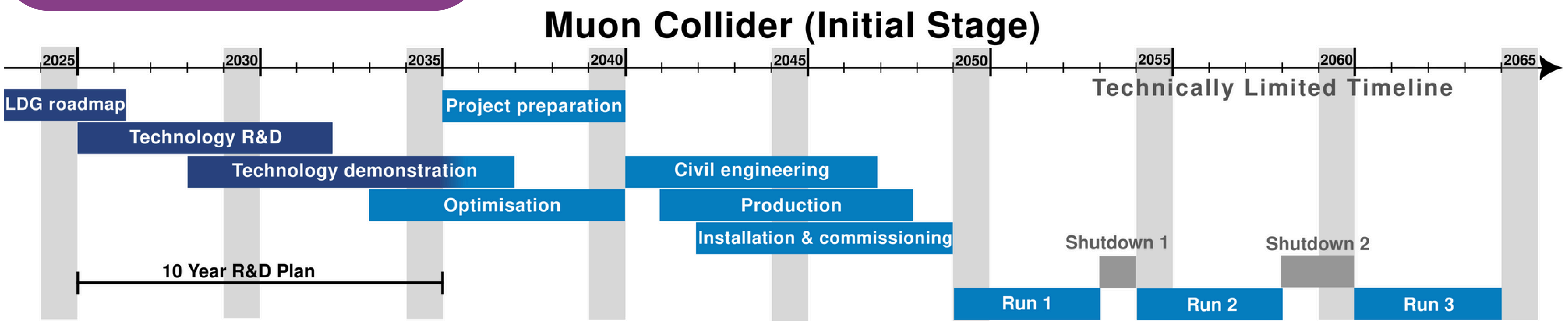
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures

WHAT do we need to do to collide muons?



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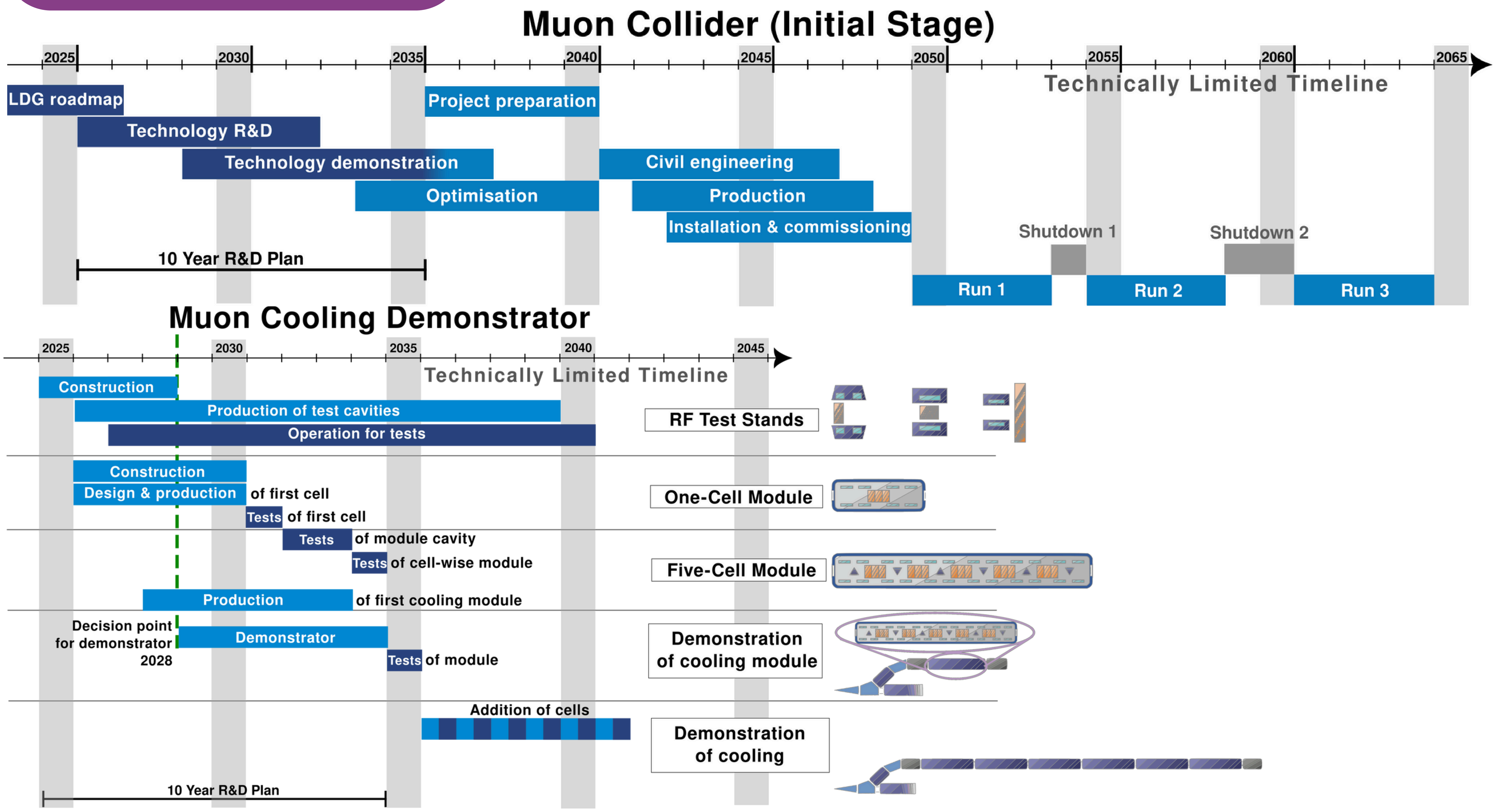
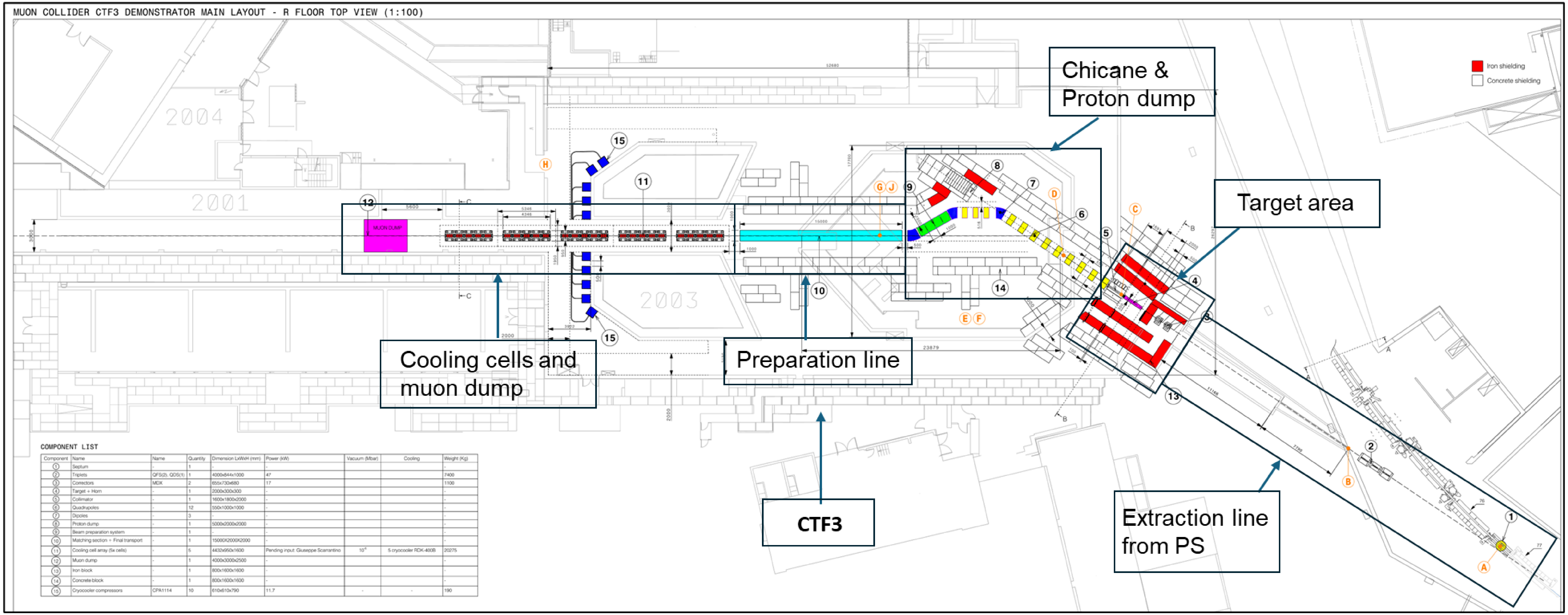


WHAT do we need to do to collide muons?

The Cooling Demonstrator

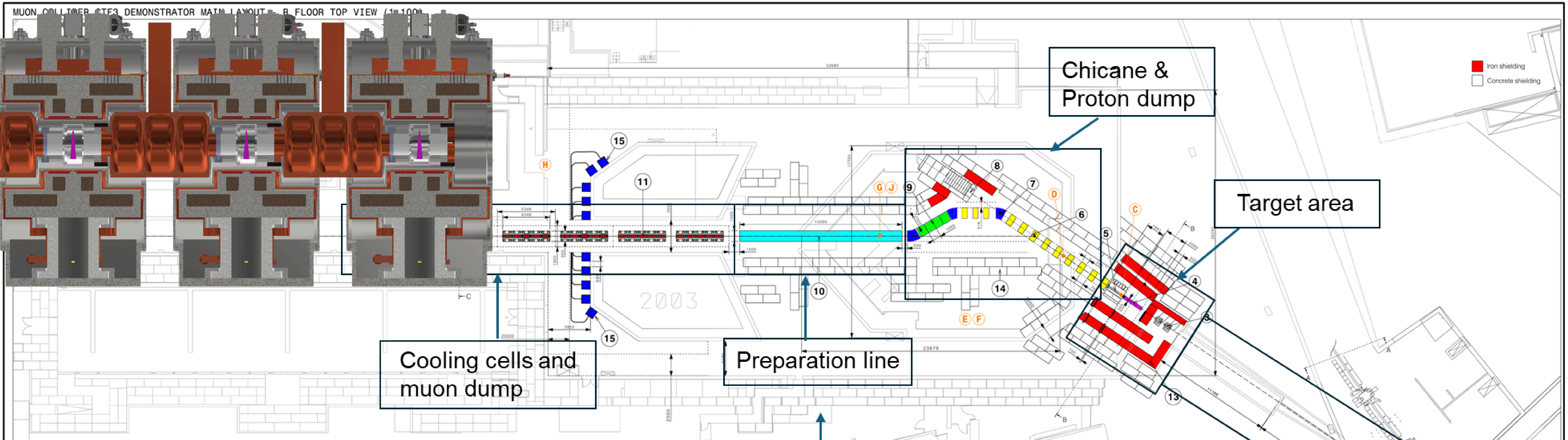


COMPONENT LIST

Component	Name	Name	Quantity	Dimension LxWxH (mm)	Power (kW)	Vacuum (Mbar)	Cooling	Weight (Kg)
1	Septum	-	1	-	-			-
2	Triplets	QFS(2), QDS(1)	1	4000x844x1000	47			7400
3	Correctors	MDX	2	655x730x680	17			1100
4	Target + Horn	-	1	2000x300x300	-			-
5	Collimator	-	1	1600x1800x2000	-			-
6	Quadrupoles	-	12	550x1000x1000	-			-
7	Dipoles	-	3	-	-			-
8	Proton dump	-	1	5000x2000x2000	-			-
9	Beam preparation system	-	1	-	-			-
10	Matching section + Final transport	-	1	15000X2000X2000	-			-
11	Cooling cell array (5x cells)	-	5	4432x950x1600	Pending input: Giuseppe Scarantino	10^{-4}	5 cryocooler RDK-400B	20275
12	Muon dump	-	1	4000x3000x2500	-			-
13	Iron block	-	1	800x1600x1600	-			-
14	Concrete block	-	1	800x1600x1600	-			-
15	Cryocooler compressors	CPA1114	10	610x610x790	11.7	-	-	190

WHAT do we need to do to collide muons?

The Cooling Demonstrator



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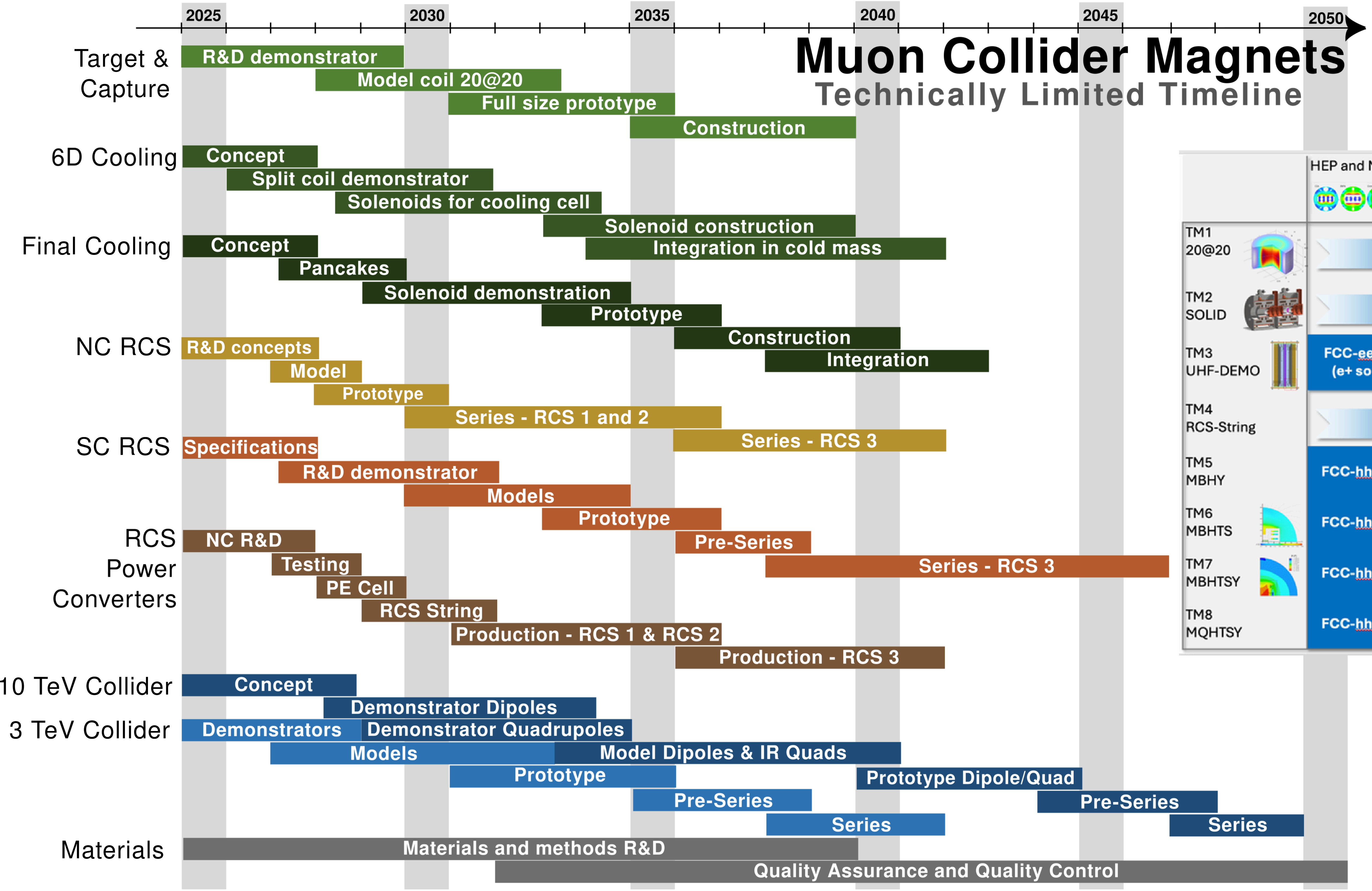
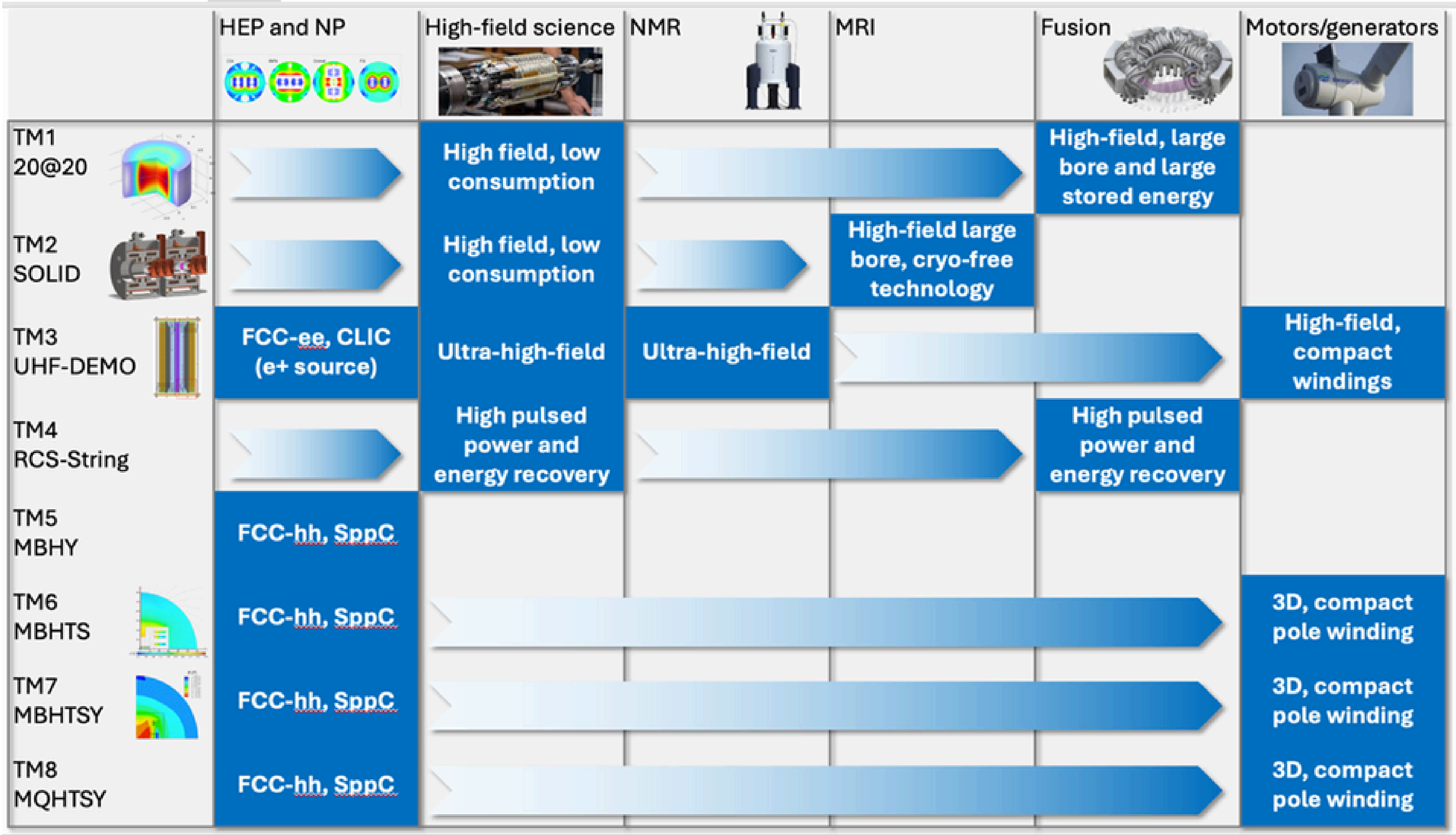
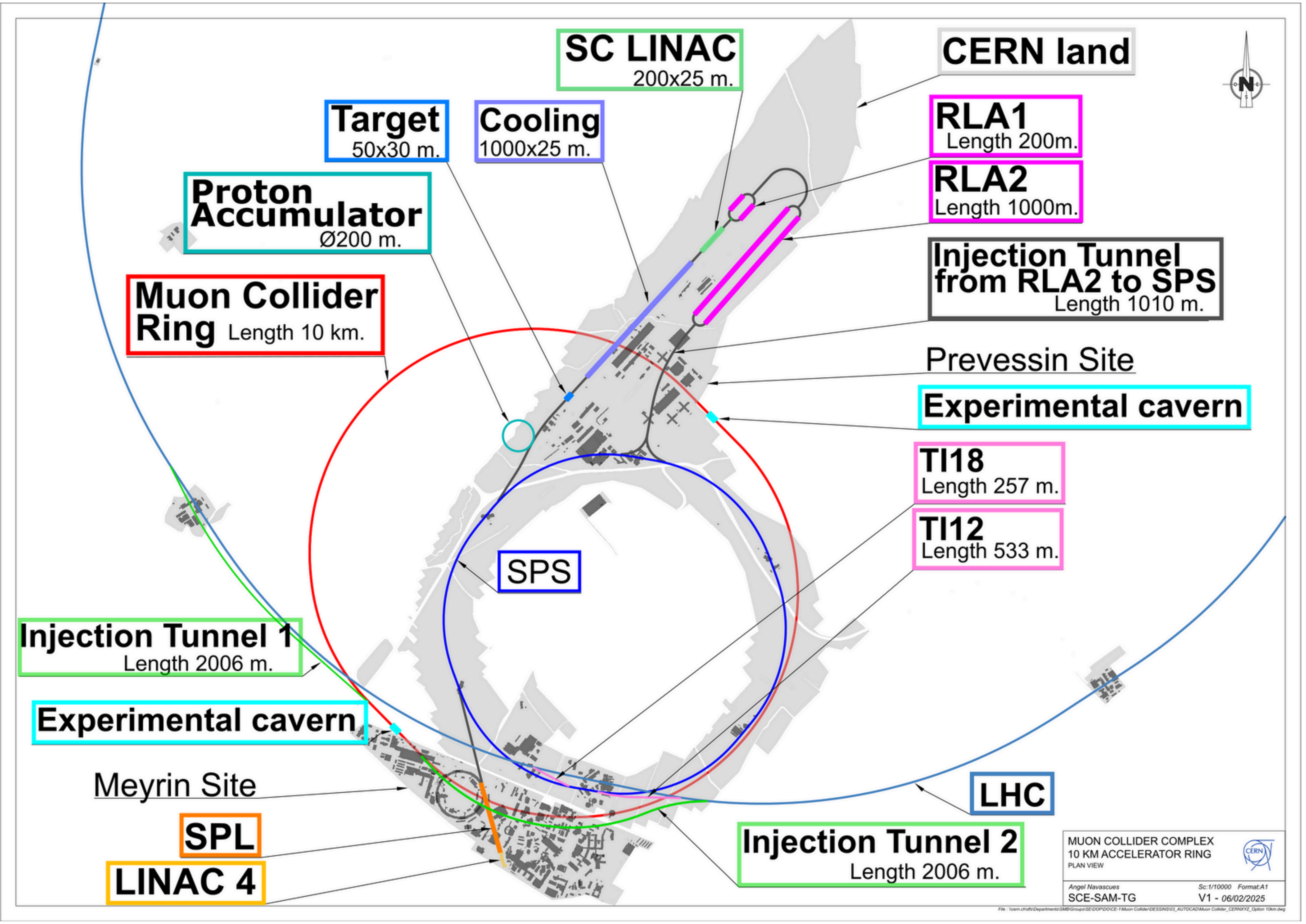
WHAT do we need to do to collide muons?

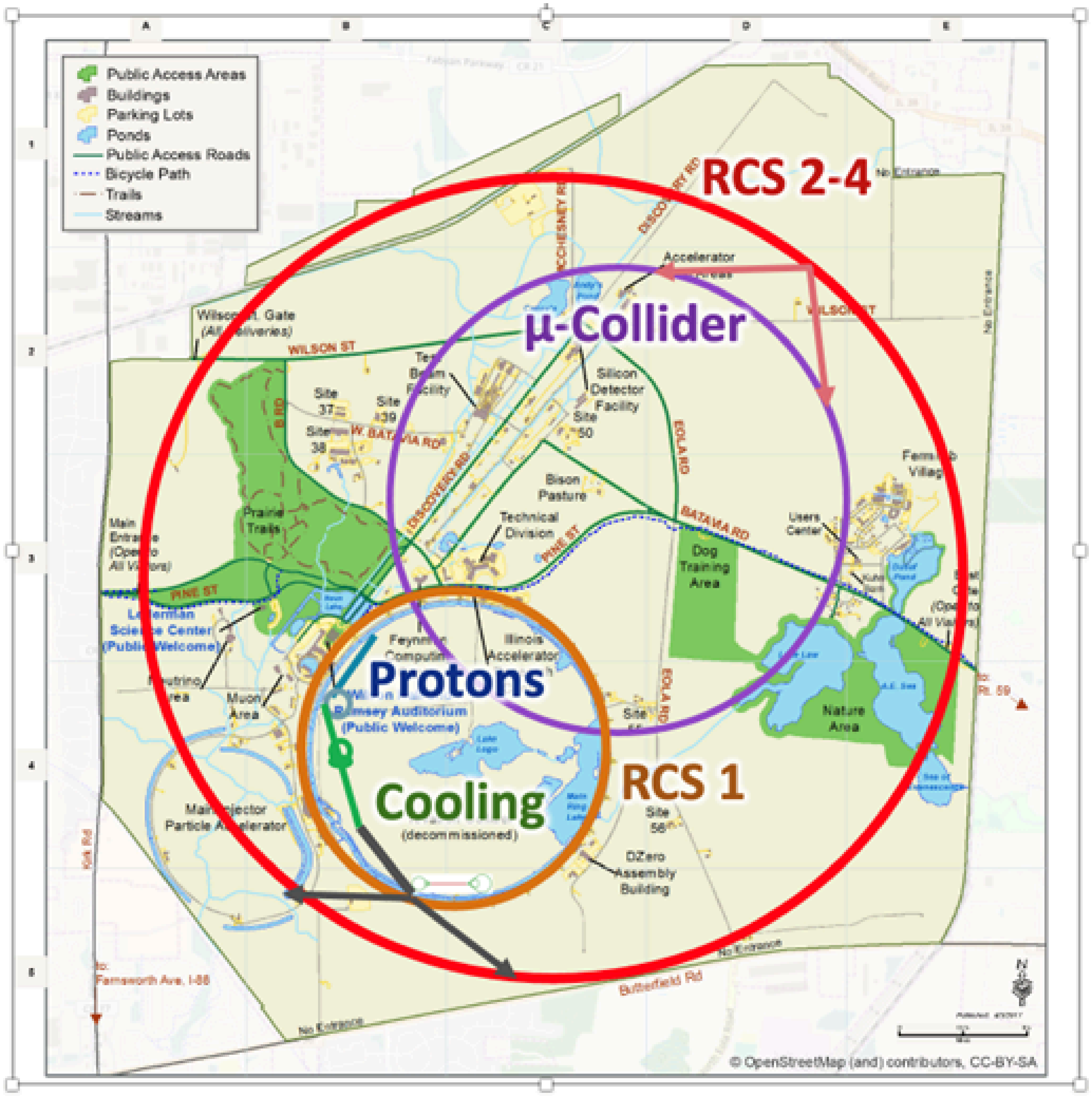




	HEP and NP	High-field science	NMR	MRI	Fusion	Motors/generators
TM1 20@20		High field, low consumption			High-field, large bore and large stored energy	
TM2 SOLID		High field, low consumption		High-field large bore, cryo-free technology		
TM3 UHF-DEMO	FCC-ee, CLIC (e+ source)	Ultra-high-field	Ultra-high-field			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

WHERE might we collide muons?





WHO works on colliding muons?

International MUON Collider Collaboration

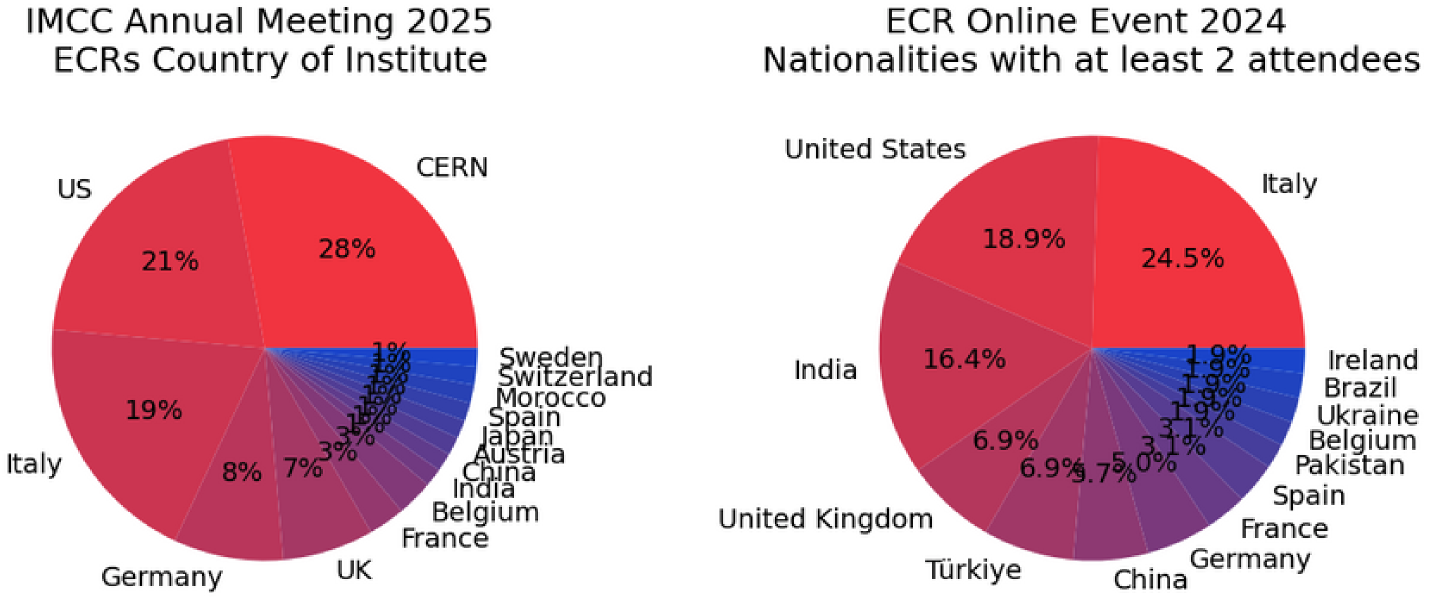
- Formed by LDG after ESPPU 2022 R&D Roadmap
- 61 partner institutes, more joining regularly
- Follows from US Muon Accelerator Programme (2010-2017) 3 TeV study

MuCol

- EU Horizon project dedicated to 10 TeV design
- Began in 2023, resources until 2027
- Coordinates monthly milestones and deliverables, considering realistic performance goals

- USMCC initiated in 2024
- Following P5 *"Shoot For the Muon"*
- In the process of joining IMCC (CERN-DOE agreement)
- Strong collaboration, contribution to our ESPPU input
- Further support from National Academy of Sciences
- Grants obtained from labs and universities

Motivated Early Career community with dedicated events



IMCC Partners

IEIO	**CERN**
FR	**CEA-IRFU**
	CNRS-LNCMI
	Ecoles des Mines St-Etienne
DE	DESY
	Technical University of Darmstadt
	University of Rostock
	KIT
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
NL	**University of Twente**

IT	**INFN**
	INFN, Univ., Polit. Torino
	INFN, LASA, Univ. Milano
	INFN, Univ. Padova
	INFN, Univ. Pavia
	INFN, Univ. Bologna
	INFN Trieste
	INFN, Univ. Bari
	INFN, Univ. Roma 1
	ENEA
	INFN Frascati
	INFN, Univ. Ferrara
	INFN, Univ. Roma 3
	INFN Legnaro
	INFN, Univ. Milano Bicocca
	INFN Genova
	INFN Laboratori del Sud
	INFN Napoli
Mal	**Univ. of Malta**
EST	**Tartu University**
PT	**LIP**
SE	**ESS**
	University of Uppsala

FI	**Tampere University**
	HIP, University of Helsinki
LAT	**Riga Technical University**
CH	**PSI**
	University of Geneva
	EPFL
	HEIA-FR
BE	**Univ. Louvain**
AU	**HEPHY**
	TU Wien
ES	**I3M**
	IFIC/CSIC
	ICMAB
China	***Sun Yat-sen University***
	IHEP
	Peking University
	Inst. Of Mod. Physics, CAS
	University of CAS
KO	**Kyungpook National University**
	Yonsei University
	Seoul National University
India	***CHEP***

CA	Université Laval
US	**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
	Yale
	Princeton
	Stony Brook
	Stanford/SLAC
	...
DoE labs	FNAL
	LBNL
	JLAB
	BNL
Brazil	***CNPEM***

Signed MoC (61), ***requested MoC***, contributor

Conclusion

Physics:
Vector-Boson Fusion Factory with strong physics case at high energies, especially for EW searches

Accelerator:
Many different systems with no technological showstoppers identified

R&D:
10 year plan proposed Includes magnets, RF test stands and cooling demonstrator

Community & Siting:
Growing collaboration at both CERN and Fermilab. Contributions from INFN, STFC and universities.

Increasing confidence that the muon collider is a unique, sustainable path to the future of High Energy Physics.

Need to ramp up momentum globally to achieve ambitious programme.

Synergies and knowledge transfer already opening up for magnets and power systems.

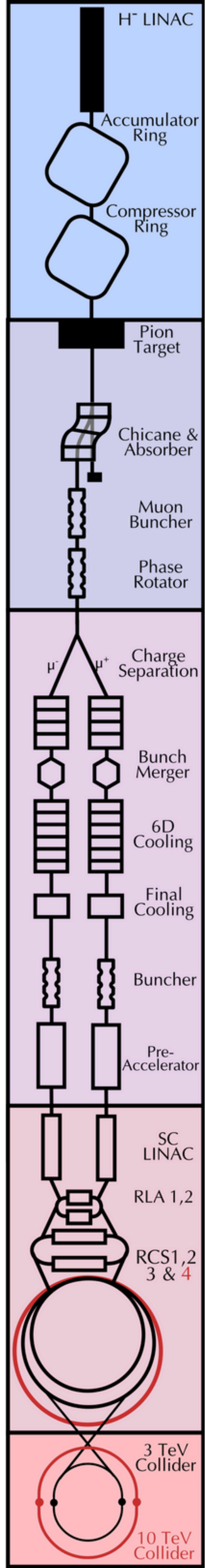
Enthusiastic and motivated international community of:

- theorists
- experimentalists,
- detector designers
- beam optics physicists,
- magnet engineers
- RF engineers
- Civil engineers

With equal mix of senior and early career

Many thanks to the collaboration for all the work

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



Thank you

International
UON Collider
Collaboration

MuCol

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the European Union

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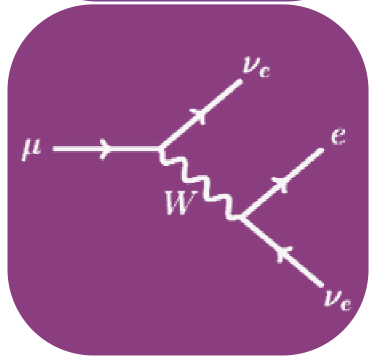
End-To-End Simulation: Challenges

Simulation code wish-list includes…

Particle interactions with matter
Target, Cooling, MDI

Radiation effects on surrounding materials
Target, Collider

Overlapping elements in high Bz fields
Target, Front-End, Cooling



Muon decay and tracking secondaries
Everywhere

Low-energy linear acceleration of a long beam
Cooling, Acceleration

Matching beam conditions between synchrotrons
Accelerator, Collider, (Everywhere)

Non-linear effects
Collider

Collective effects including space-charge, beam-beam and wakefields
Everywhere