International MUON Collider Collaboration

MuCol

Muon Collider

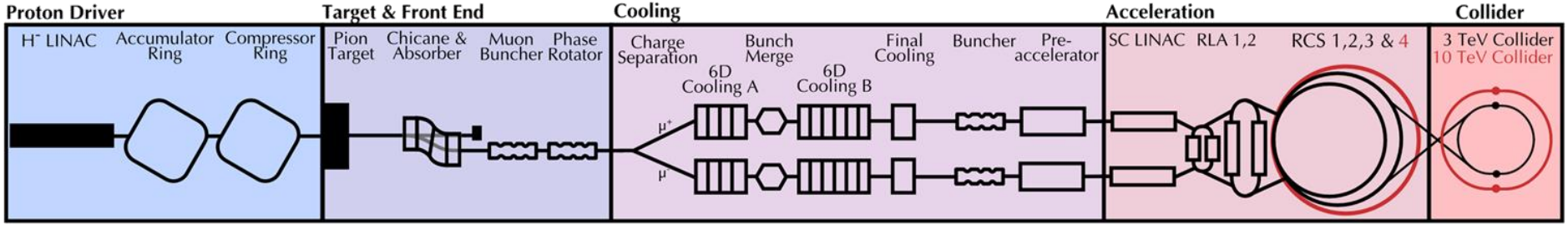
D. Schulte
On behalf of the International Muon Collider Collaboration

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.

WIN, Brighton, June , 2025

Muon Collider Concept

The main challenge is the short muon lifetime $\tau = \gamma \times 2.2\ \mu s$
Up to 100 ms at collision energy



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

IMCC

International Muon Collider Collaboration

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

- **61 full partner institutes**, more in the process
- From all regions

EU co-funded design study MuCol started 2023

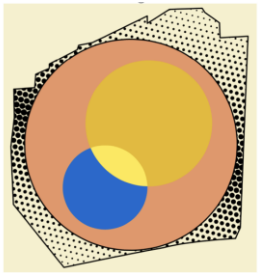
Strong recommendation from **P5** «**This is our muon shot**»

- Interest in hosting at FNAL

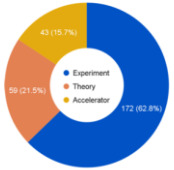
US partners are in the process of joining

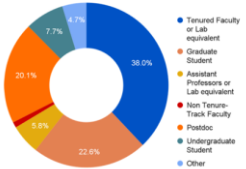
- US Muon Collider Inauguration Meeting in August 2024 at Fermilab (about 300 participants)
- Forming national organisation to participate
- Addendum to **CERN-DoE agreement** in preparation

Already strong US contribution to IMCC ESPPU documents
Work at universities started
Obtained several grants also at labratories



- In early August, held an open meeting of the US community
  - 274 (+25 virtual) participants





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

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

ESPPU Submission Content

Assessment

Present **green field** designs and technologies

- International collaboration
- Parameters, lattice and component designs, beam dynamics, cost, …

R&D plan

Including scenarios and timelines

- Magnets, muon cooling, detector, …
- **The muon cooling technology and test facility is critical for this**

Implementation Considerations

Civil engineering studies/considerations (for CERN and for FNAL)

Cost and power consumption scales

Parameter tables, scaled from green field

- Will develop detailed lattice designs after ESPPU

Schedule (strongly linked to R&D Plan)

- Aim for initial stage by around 2050

Back-up document

(406p, 450 signatories)

Key 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	10^{34} cm^{-2}s^{-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
B_{dipole}	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%, 205%, 70% of nominal.

Muon Collider CTEs

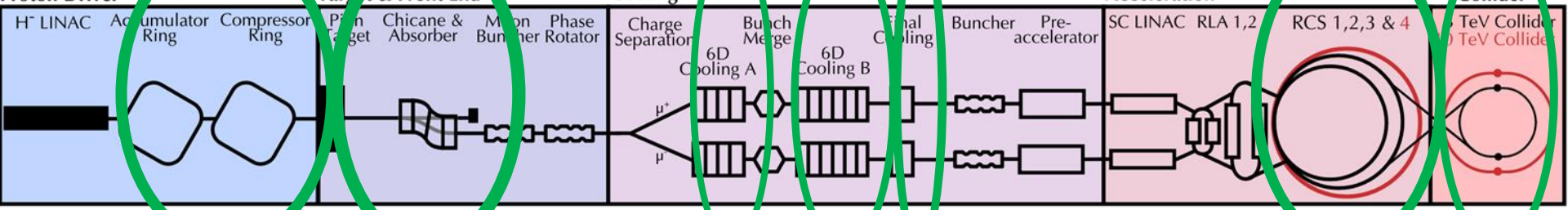
Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision



- Proton pulse accumulation and 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

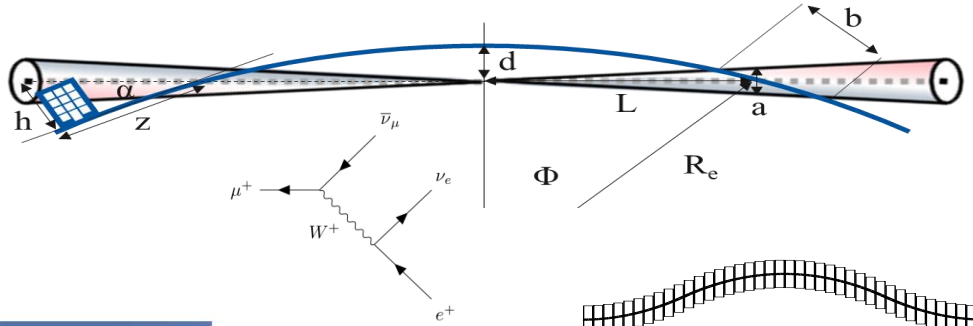
- Collider ring dipoles
- Final focus quadrupoles
- Machine-detector interface
- Neutrino flux

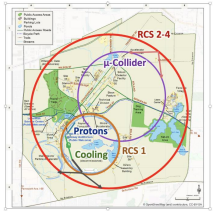
Identified and prioritized with community
Other areas need now also to be addressed (some work started)

Site

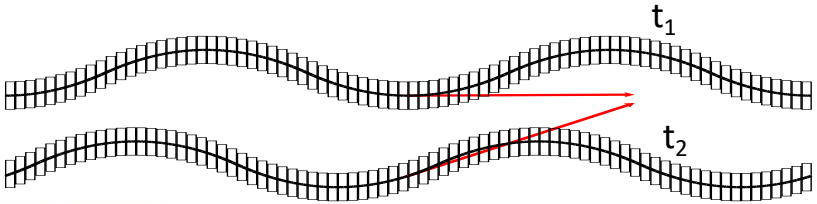
Challenge:
Obtain negligible neutrino flux

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

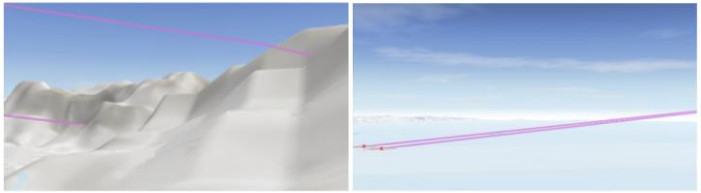


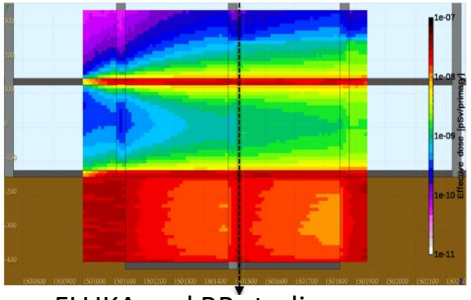


Fermilab site study

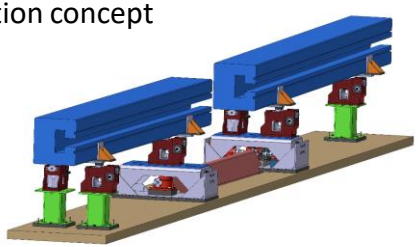


Arc mitigation concept

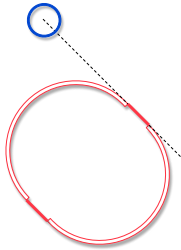




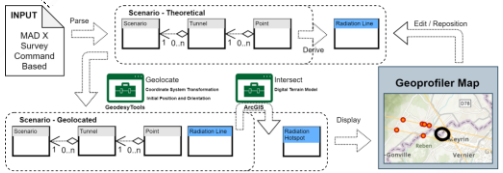
FLUKA and RP studies



Mover system design



Site study at CERN for experimental insertion

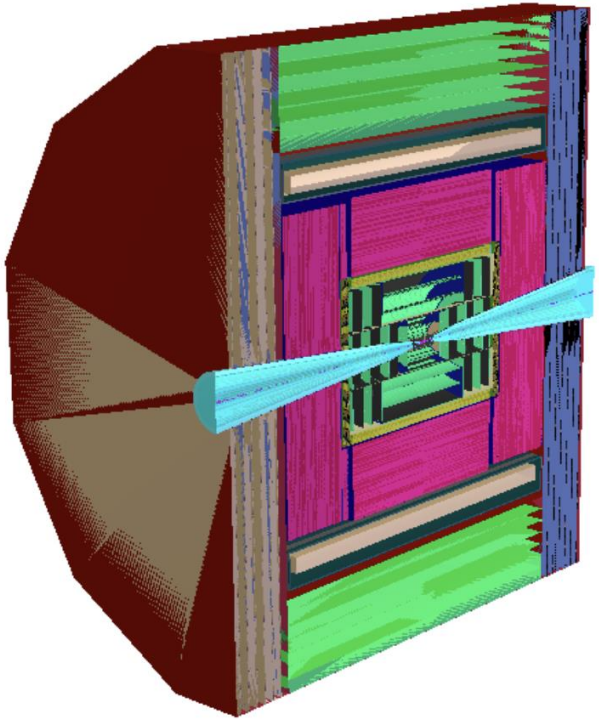


Key conclusions:
- Are close to a solution
- More work to be done

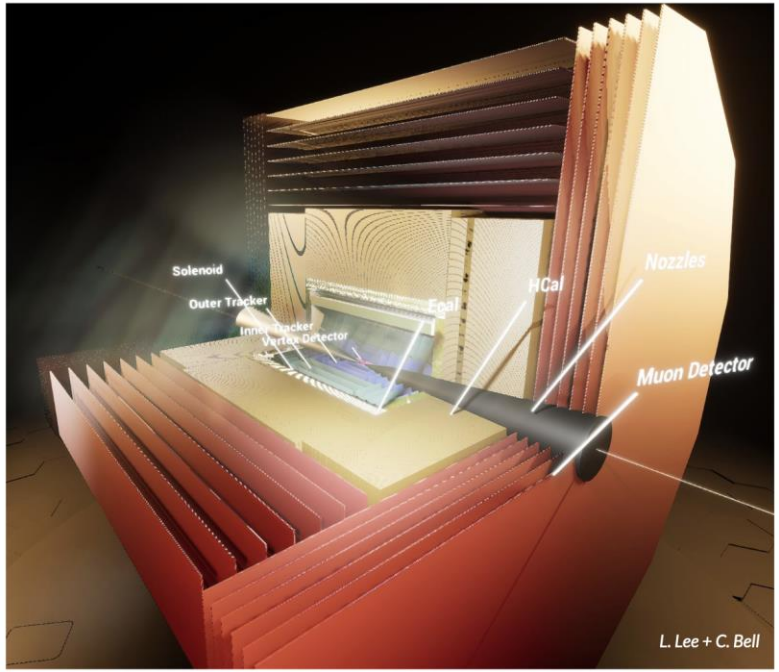
Physics and Detector Concepts

Two detector concepts are being developed

MUSIC
(MUon Smasher for Interesting Collisions)



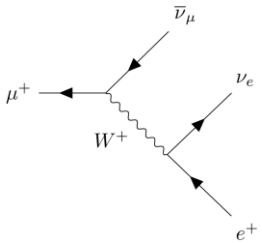
MAIA
(Muon Accelerator Instrumented Aperatus)



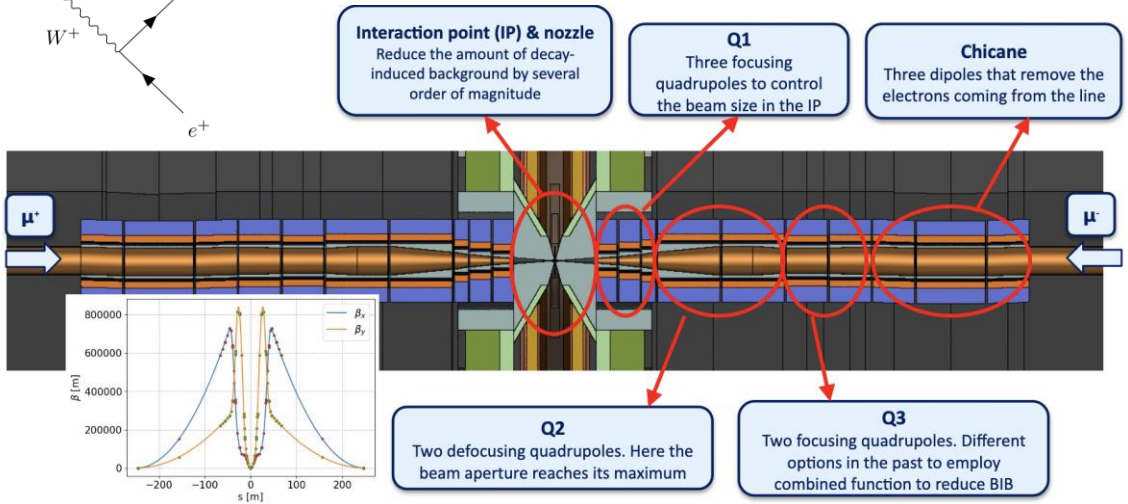
Beam-induced Background

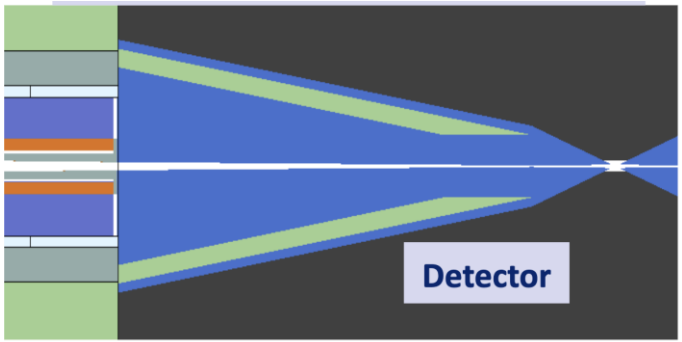
Challenges:
Muon decay can give important background
- 40 000 muons/m/bunch crossing
- 1/3 of energy in electrons and positrons

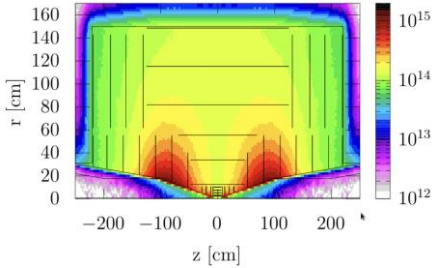
Achievements:
- Two conceptual detector designs
- Simulation studies with background also from machine
- Studies of different lattices
- Reconstruction algorithms
- Physics studies



Detailed studies with FLUKA







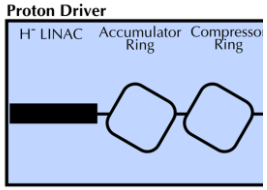
Conclusions:
- Can do the physics
  - Also thanks to HL-LHC technology
- But room for improvement
- Radiation level similar to HL-LHC

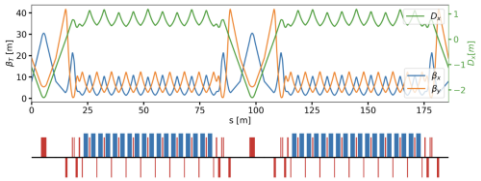
Proton Complex

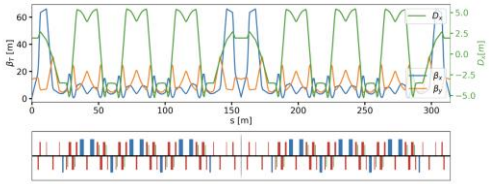
International UON Collider Collaboration

Challenge:

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

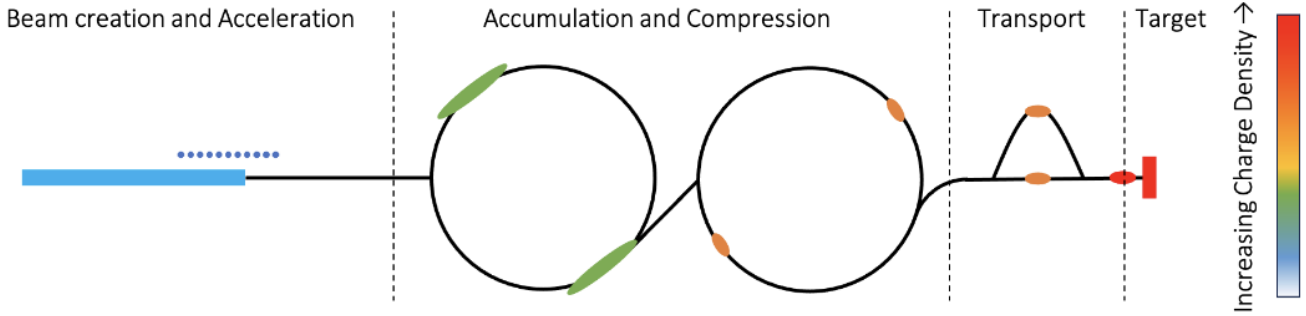


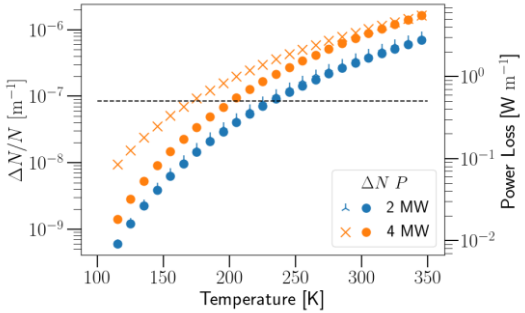




Achieved:

- Accumulator and combiner ring lattices
- First collective effects studies promising
- One or two bunches in compressor, to be decided





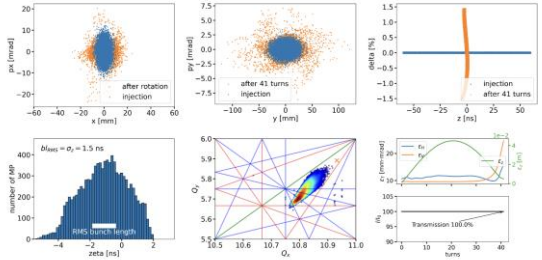


Fig. 5.1.8: Simulation of the full compression for one bunch at 5 GeV. Since this requires a 2 bunch solution scheme, this bunch has half of the full intensity shown in Table 5.1.1. Notice that at the end of the compression there is still some emittance blow up that need still to be addressed.

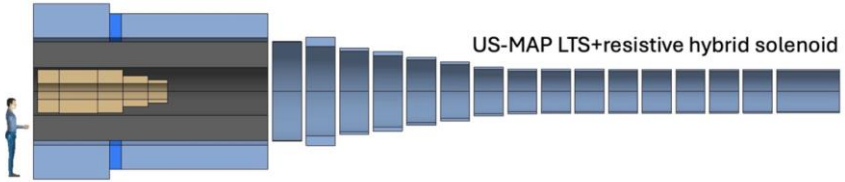
Key conclusions:

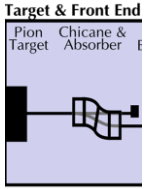
- Can compress 2 MW, 5 GeV proton beam to two 2 ns bunches, then merge them
    - Optimisation in compressor ring for collective effects ongoing
- For 4 MW need 10 GeV beam
- Cool beamline to avoid ion loss from black body radiation

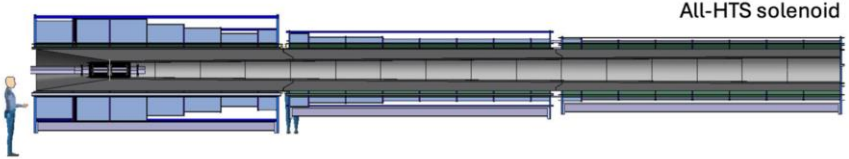
Target

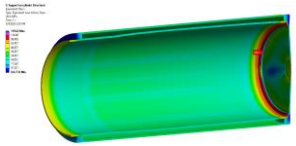
Challenges:
- 2 MW, 5 Hz, 400 MJ/pulse target
- Can we replace mercury with graphite?

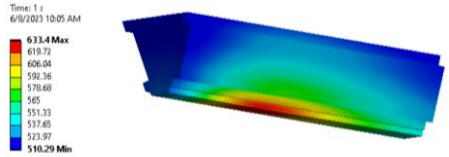
Achieved:
- Initial 2 MW graphite target conceptual design, pion yield optimised
- HTS solenoid and shielding concept developed
- Study of proton removal ongoing

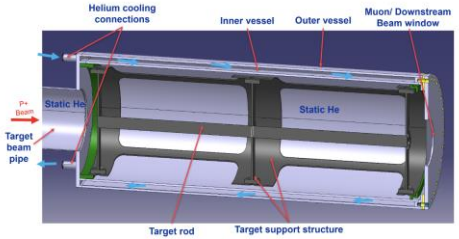


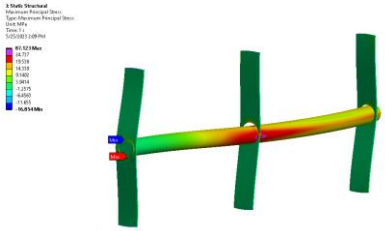












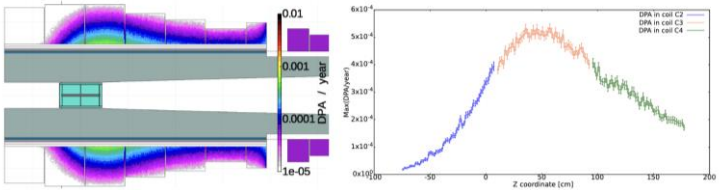


Fig. 6.5.1: 2D map of the displacement per atom (DPA) in the superconducting magnets of the target area (left) and the peak DPA in the coils most exposed to radiation (right).

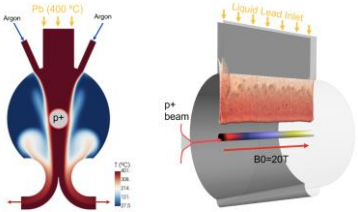


Fig. 6.4.4: Liquid lead target curtain concept.

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

High-field Magnet Technology

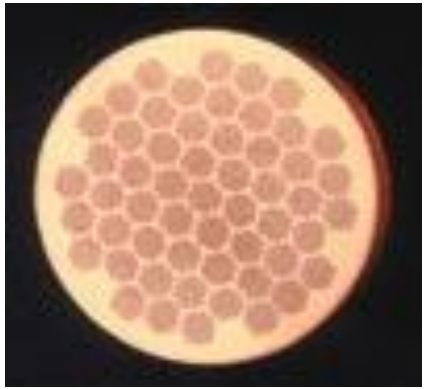
Superconducting magnets reach highest fields, three main technologies for the cables

NbTi (niob-titanium, operating at 2-4 k)
- is standard, **used in LHC** limited to O(8 T)

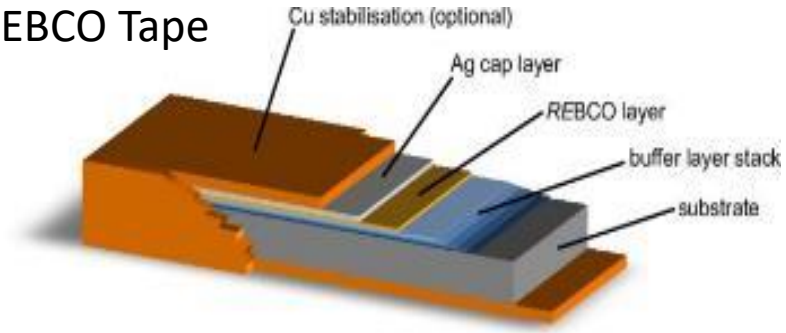
Nb_3Sn (niobium-tin, operating at 2-4 K)
- Can reach O(16 T)
- Difficult technology, needs to mature further
- Expensive
- Used in some points for HL-LHC
- Foreseen for FCC-hh also in arcs

HTS (high-temperature superconductor, operating up to 20 K)
- Different options exist, e.g. REBCO
- In solenoids > 30 T demonstrated
- Still expensive and technology challenges
- Applications in other fields, e.g. medical, fusion reactors, power generators for wind energy, engines, …

Cut through a cable with superconductor embedded in copper, so some remains conductivity in case of a quench

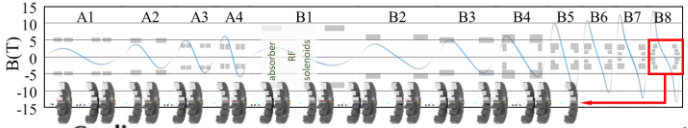


REBCO Tape

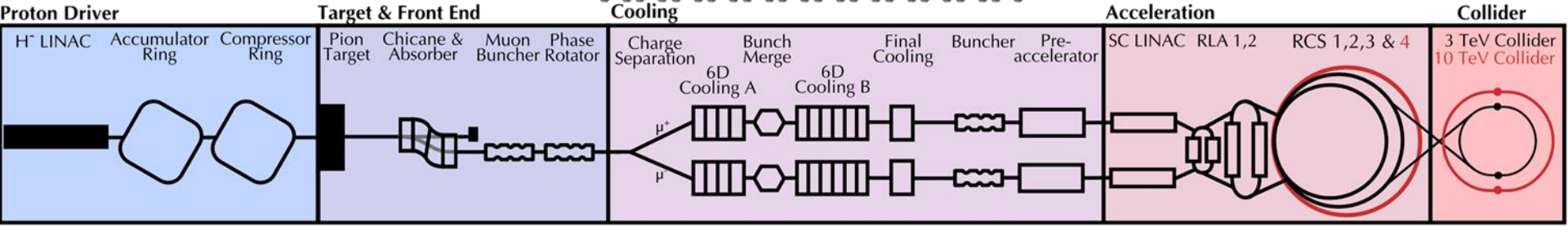


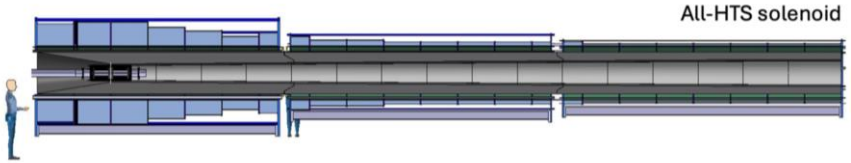
Magnets

6D cooling solenoids



- Pulsed magnets and power converters





20 T large aperture target solenoid

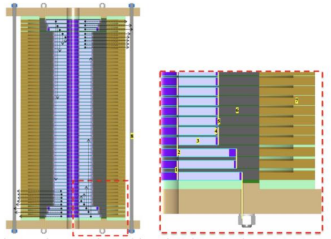
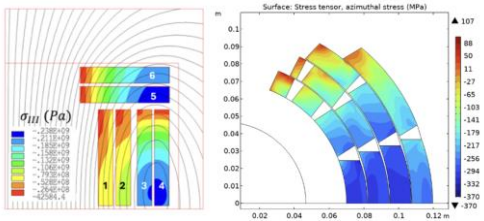


Fig. 6.1.7: Cross-section of the 40 T solenoid; the arrows indicate the axial and radial Lorentz forces acting on each pancake. The lengths of the radial arrows have been scaled down by a factor of 3.

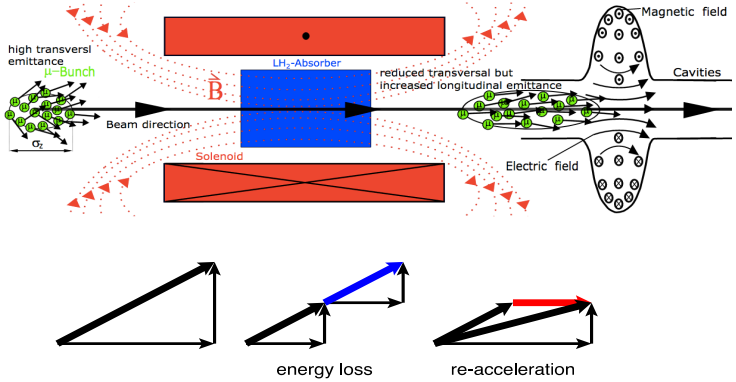
40 T small aperture final cooling solenoids



14 T, 14 cm HTS collider ring dipoles

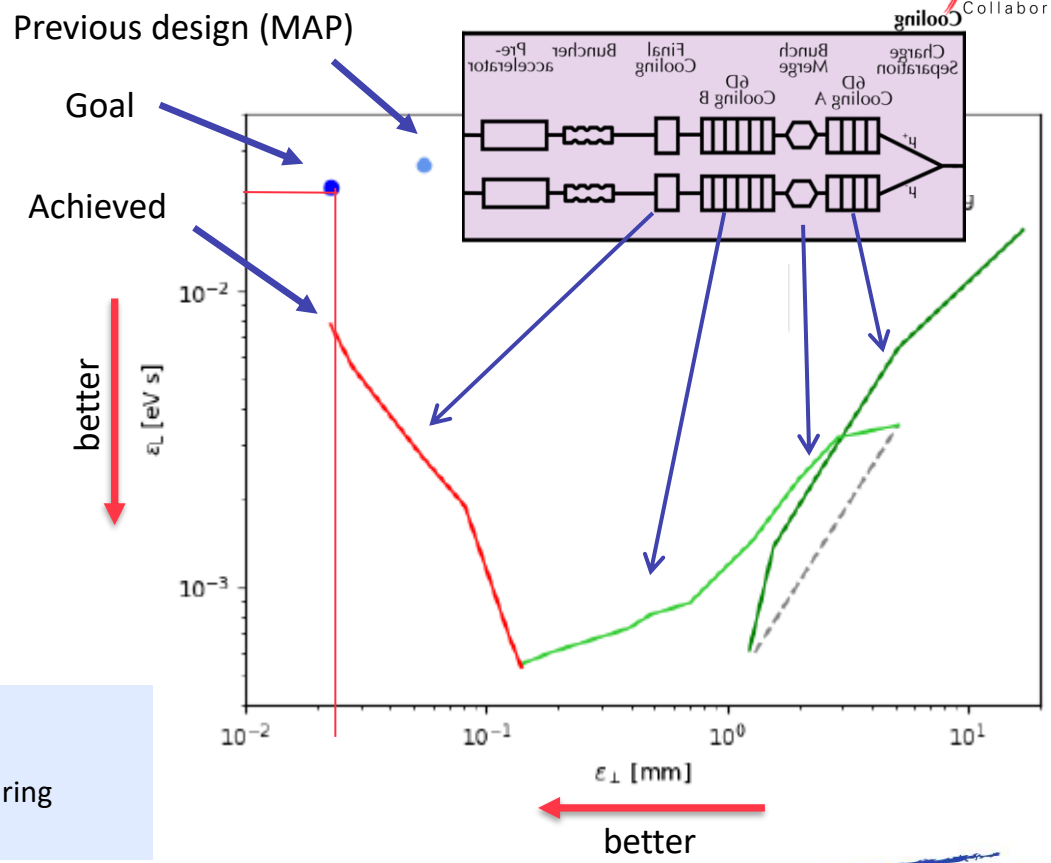
Muon Cooling Lattice Design

Challenge:
Novel, complex lattice with cavities and absorbers in solenoids



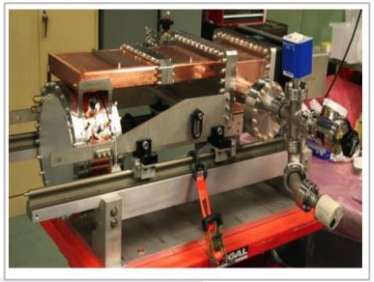
Achieved:
Much improved lattice design
Improved simulation tools: BDSIM and RFtrack

Key conclusions:
- Can in principle reach or exceed performance target
- Much improved longitudinal, may be useful for collider ring
- Study of collective effects important

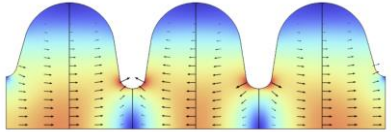


Muon Cooling Technology

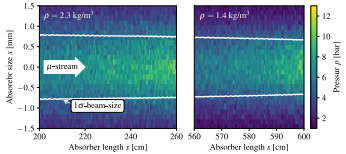
Challenges:
- NC RF cavities in magnetic field (30 MV/m)
- HTS magnets (up to 40 T in final cooling)
- Bright beam hard on absorbers and windows
  - Can evaporise liquid hydrogen

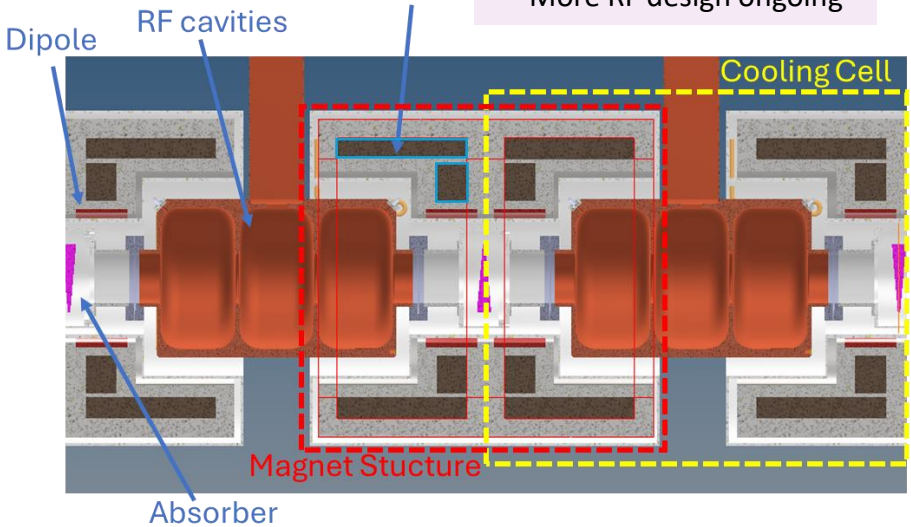


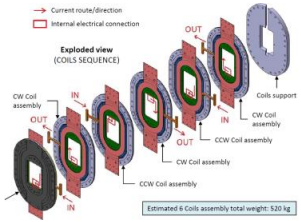
MuCool demonstrated >50 MV/m in 5 T
H2-filled copper
Be end caps



- MAP proved gradient
- Initial RF designs
- More RF design ongoing







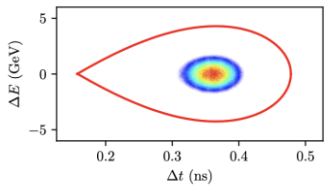
- First window tests performed with protons
- Use of H2 gas where required

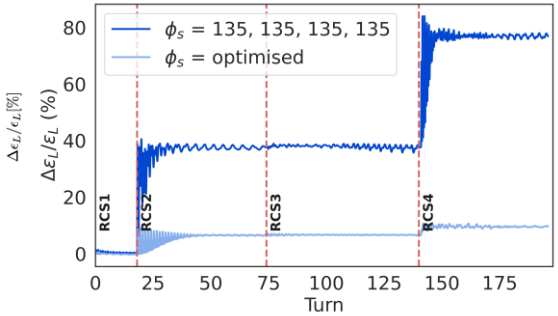
Key conclusions:
- Ready to **ramp-up effort**, in particular prototyping and experimental work, also beamdynamics

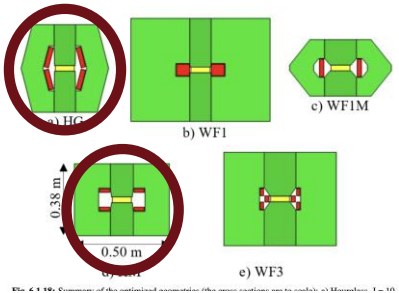
RCS Designs

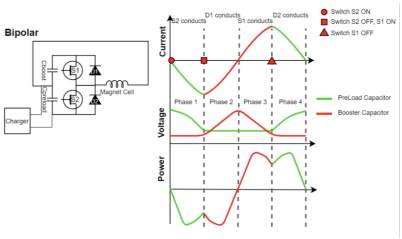
Challenge:
- Uses fast-pulsed normal magnets
- 5 Hz pulses of O(1-10ms)
- 6-35 km circumference
- Cost
- Recover energy from magnetic field
- High bunch charge
- Maintain beam quality

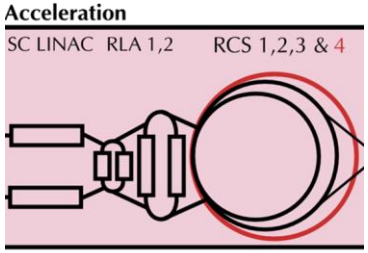
Achieved:
- Lattices for all site independent RCSs
- Beam propagation through complex
- Conceptual design of magnets and power converters
- Optimised design together with RF

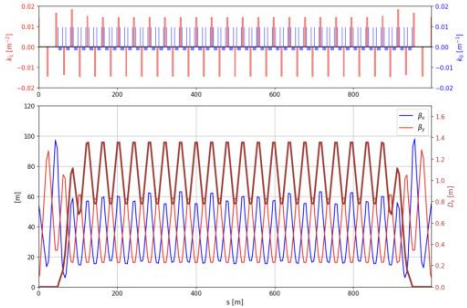












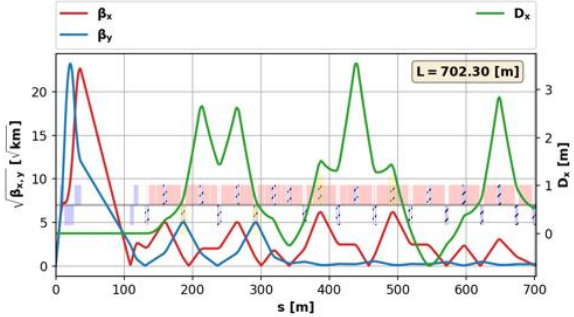
RCS	E [J/m]	Loss [%]	P [MW]
SPS 1	5447	**1.1**	1.9
LHC 1	5678	**1.6**	12.8
LHC 2	5752	**6.3/2**	26.6

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 conceptual designs
- Cryogenics concept
- Lattice reaches target beta-functions but not yet full target energy acceptance
- First studies of mover system impact on beam



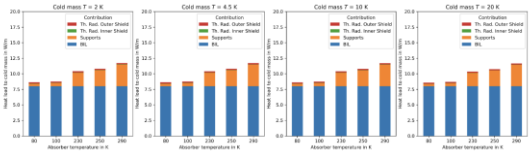
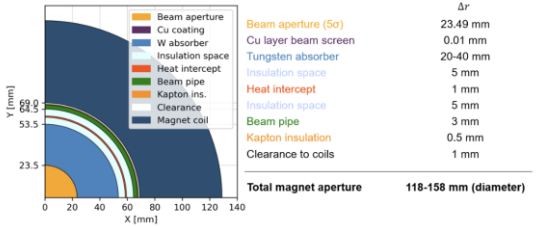


Fig. 6.7.2: Estimated heat load deposited on the cold mass in W/m, as a function of absorber temper-

Cryogenic loads at different temperatures

Shielding (30-40 mm)



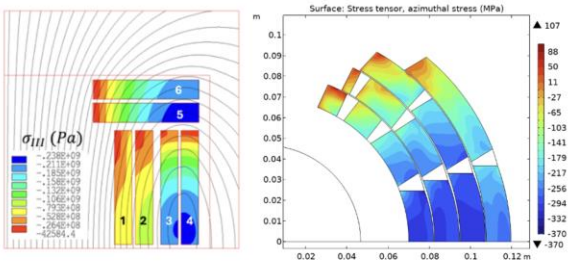
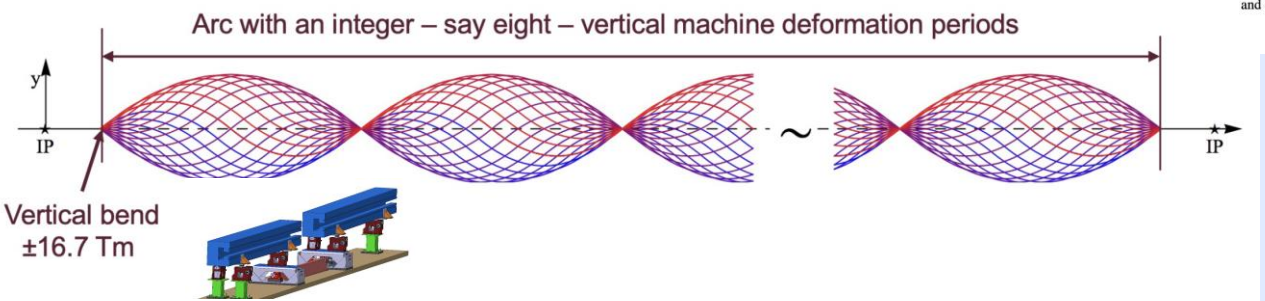


Fig. 6.1.31: Mechanical stress on conductor under Lorentz Forces at nominal current for both block coil and cos-theta magnet configurations.



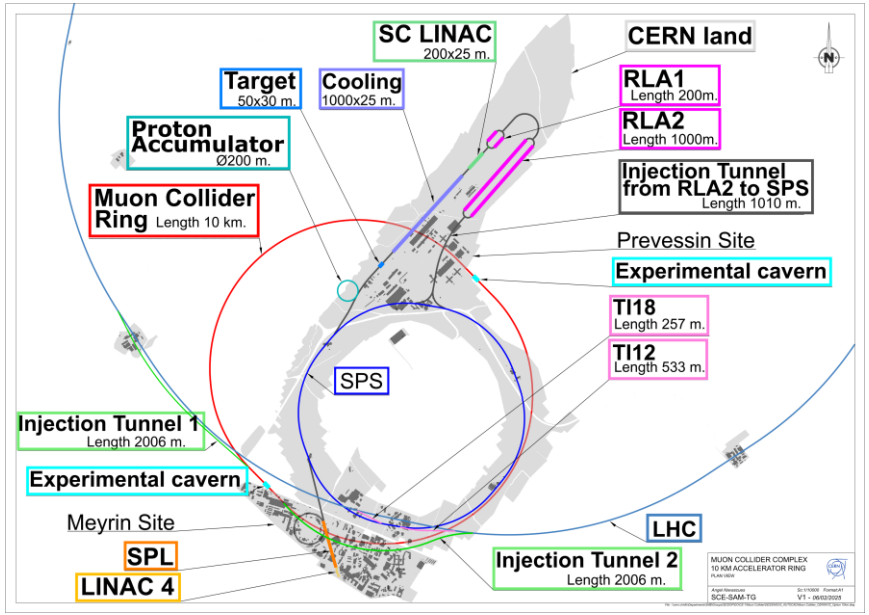
Key conclusions:
- Should improve energy acceptance should somewhat
- OK with energy spread predicted in muon cooling
- Mover system does not compromise beam in regular arcs

Site Specific Designs

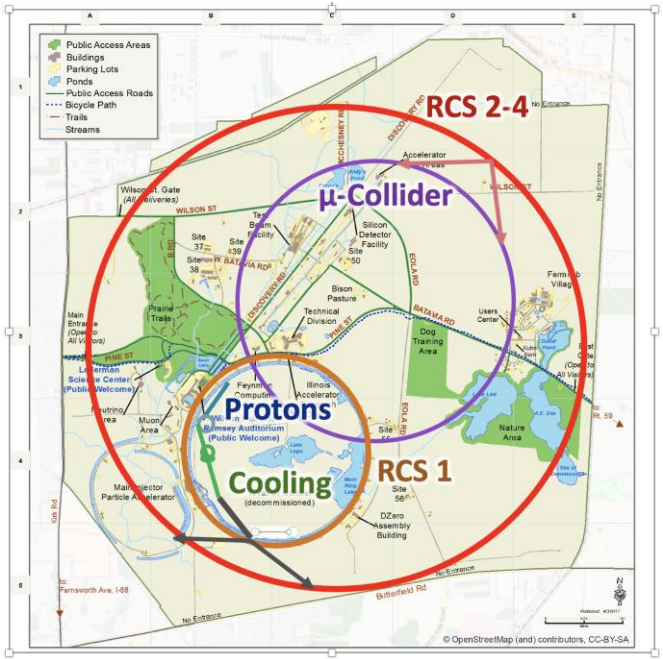
Started studies for concrete site at CERN and Fermilab, looks very promising

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 RCS in one site-filler tunnel



Cost and Power Scale

Design of many collider areas/components has progressed
but uncertainties remain

- No overall optimisation
- HTS cost model

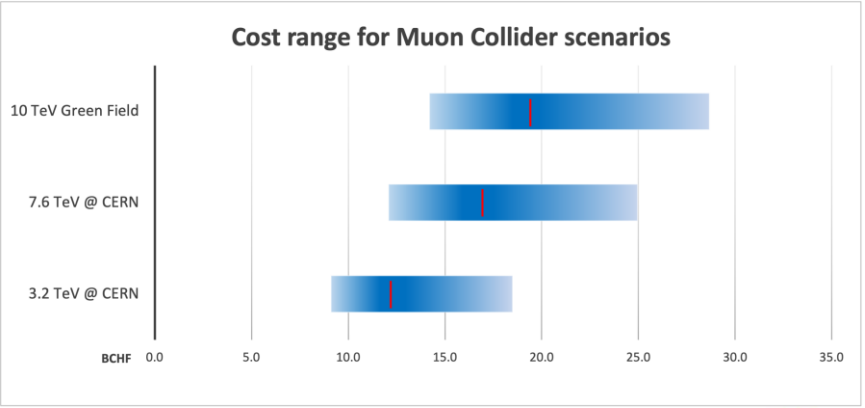
Power estimate based on conceptual designs and scaling from know components, e.g.

- Simulations of fast-ramping magnet and power converter
- Detailed scaling for RCS cavities

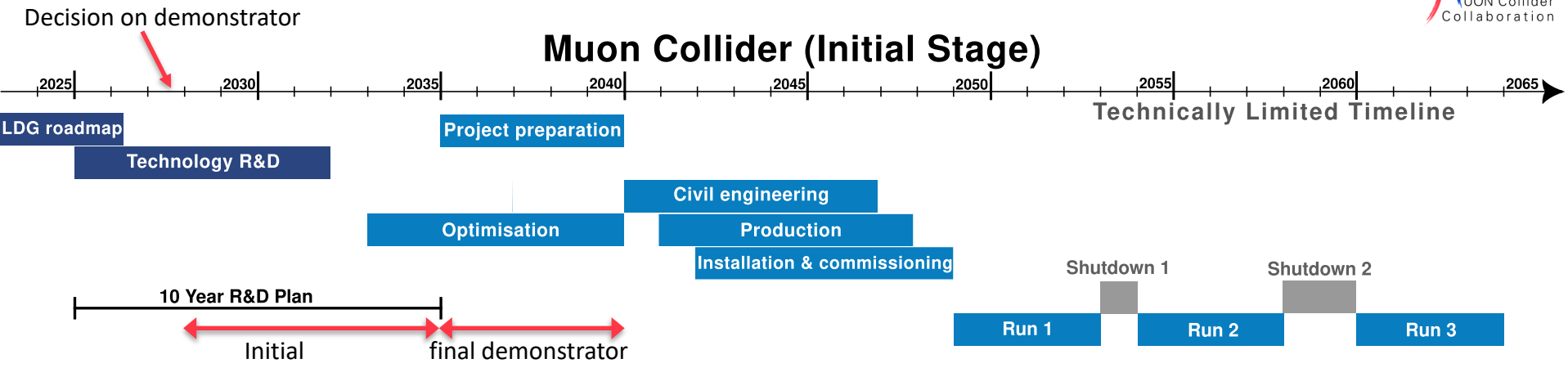
CERN-specific muon collider parameters

Parameter	Symbol	unit	Scenario 1		Scenario 2	
			Stage 1	Stage 2	Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3.2	7.6	3.2	7.6
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.9	7.9	2.0	10.1
Collider circumference	C_{coll}	km	11	11	4.8	8.7
Collider arc peak field	B_{arc}	T	4.8	11	11	14
Collider dipole technology			NbTi	Nb_3Sn or HTS	Nb_3Sn	HTS

	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

- Muon collider next flagship after HL-LHC

Other options

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

R&D timeline drivers

- Superconducting magnets
  - Collider ring with no HTS dipoles for first stage
- Muon cooling demonstration
  - RF cavities, solenoids, absorbers, integration, demonstration with beam

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

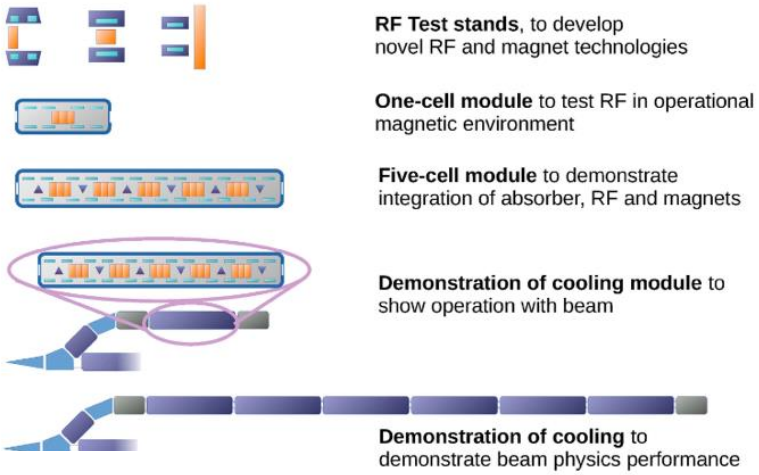
Technologies	Deliverables	Key parameters and goals
	Magnets	
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K
Final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

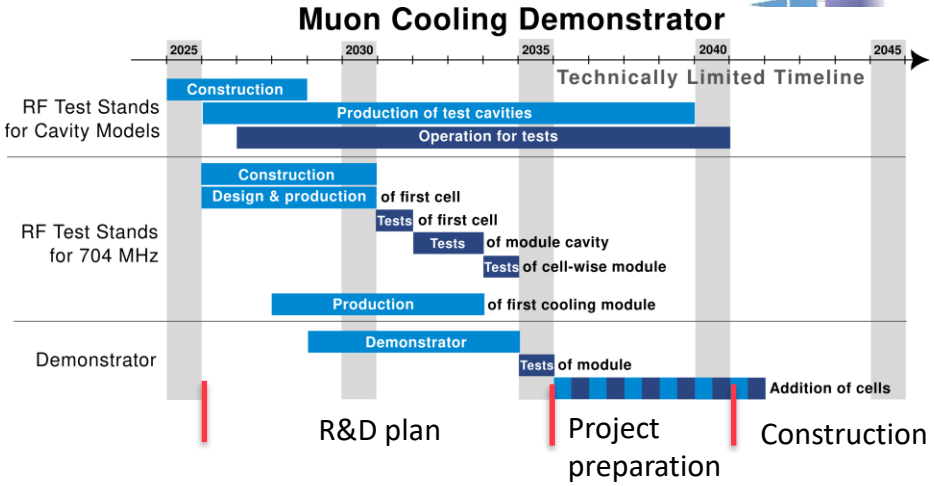
Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5	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

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





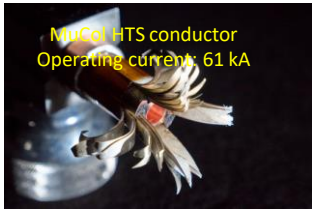
Key conclusions:
- Installation of demonstrator at CERN appears possible with limited cost (O(10kW)) proton beam
- Expensive solution with O(80 kW) would allow future upgrade
- Fermilab has approved a study
- RF test stands are critical and urgent
- Consistent with implementation timeline

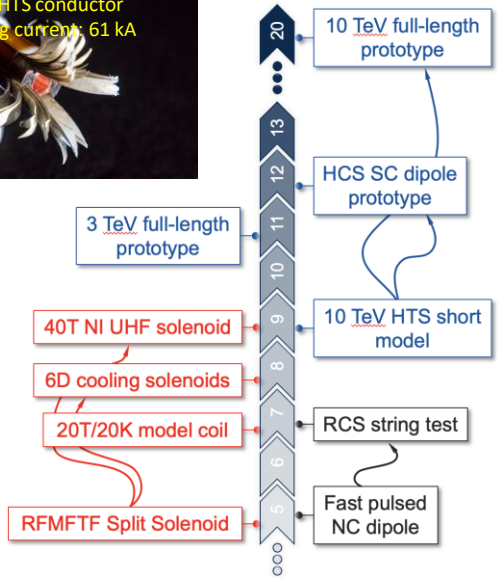
D. Schulte, Muon Collider, WIN, Brighton, June 2025

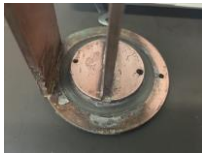
Magnets

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

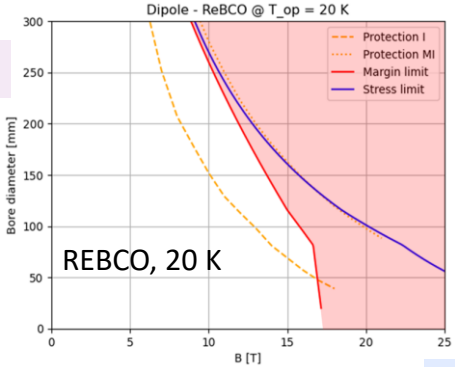




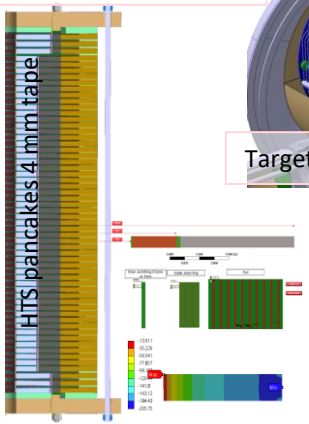


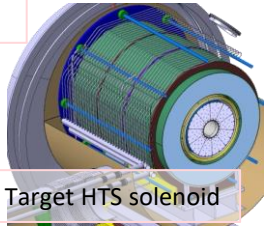
First **HTS winding tests**

Did adjust collider ring field

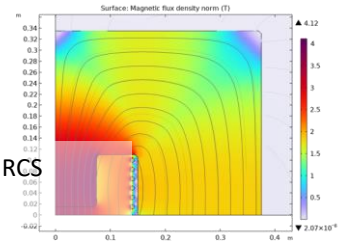


HTS final cooling solenoid mechanical design





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

Way Forward

Continue to execute the Design Study

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

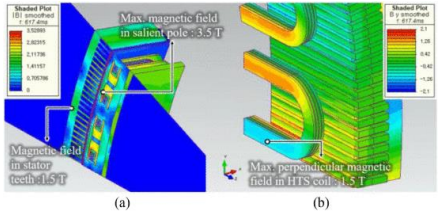
- **Identify resources, sharing of work between partners**

Synergy with other particle physics and accelerators

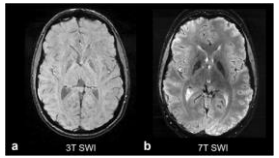
- Muons, neutrinos, …

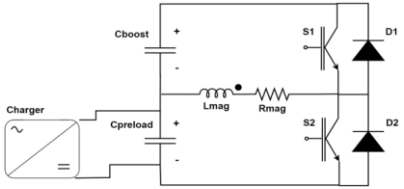
Strong synergy with societal applications exist

- HTS magnets for fusion reactors, wind power generators, motors, material science, health applications
- Power converter
- RF in magnetic field can be relevant for fusion
- …



Design of 10 MW HTS wind generator





Examples:

- Collaboration on target solenoid/fusion with F4P, ERUOFusion, GaussFusion, ENI
- Common EU request with Infineon for power converter

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

Conclusion

Muon collider has a compelling physics case
R&D progress is increasing confidence that the collider is a unique, sustainable path to the future

- Much improved design, no showstopper identified, but more work to be done

Need to ramp up the momentum globally

- Full start to end modelling
- Actual hardware development
- HTS solenoid and other magnet development
- Preparation of the muon cooling demonstrator

Strong synergies with other fields ranging from particle physics to societal application exist

- Fusion reactors
- High-field solenoids
- Power converter
- …

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

Reserve

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

Totals:
Duration 10 years

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

Year	I	II								
Accelerator Design and Technolo										
Material (MCHF)	1.6	3.2								
FTE	47.1	60.6								
Demonstrator										
Material (MCHF)	0.6	2.2								
FTE	9.5	11.0								
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
magnet system	converter	
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

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

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Practical 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
- 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

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European Accelerator R&D Roadmap

International MUON Collider Collaboration

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 ma [illegible] ant number of PhD students. M [illegible] and similar costs. Colours are ir [illegible]

http://arxiv.org/abs/2201.07895

Muon Collider Roadmap CT

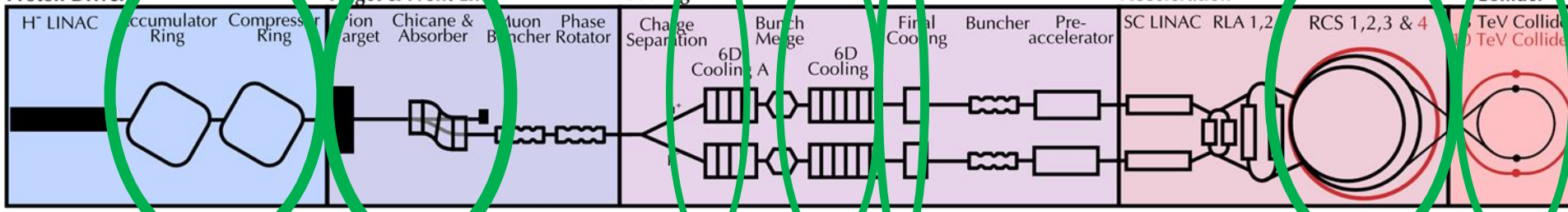
Short, intense proton bunch

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

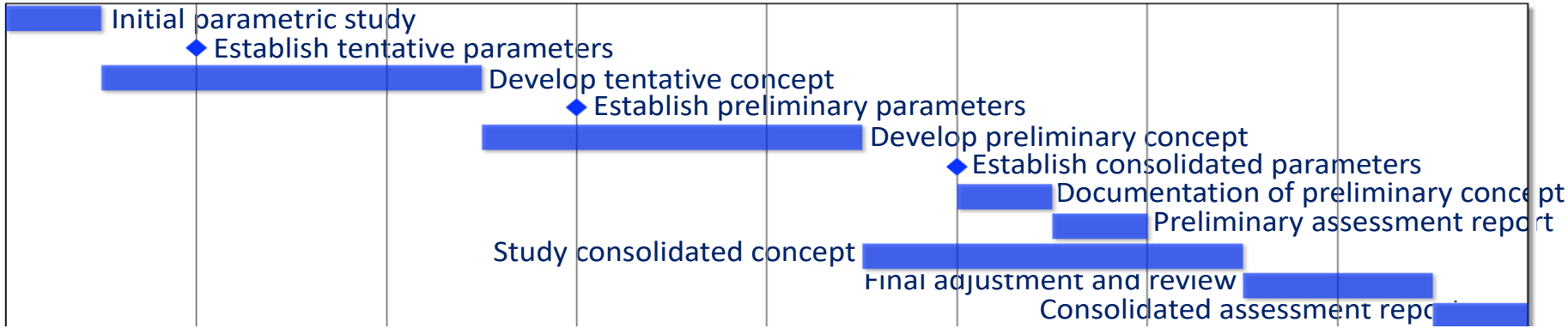
- Pulsed magnets and power converters
- RCS RF system

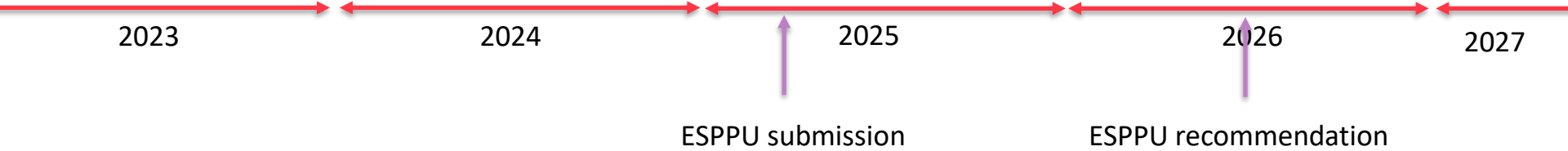
- Collider ring dipoles
- Final focus quadrupoles
- Machine-detector interface

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

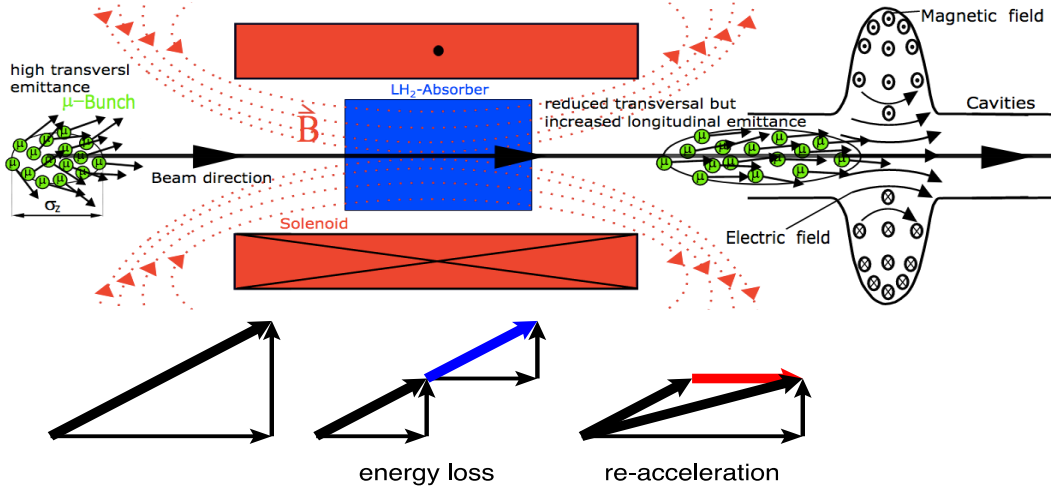
MuCol Timeline

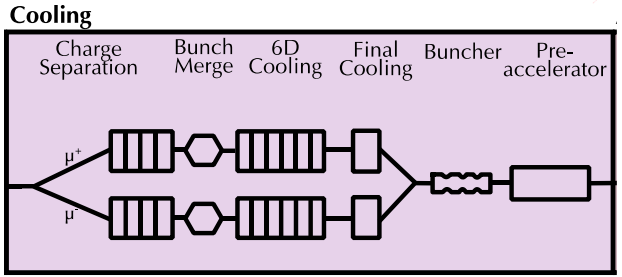
LDG anticipated input to next ESPPU by 2026
The ESPPU has been advanced to early 2025





Muon Cooling Challenges





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

Energy loss = cooling

Multiple scattering = heating

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

ESPPU Submission March 2025

Collaboration produced ESPPU input:

- Short, **ten-page** report (10p)
- **Addendum** to answers specific questions from ESPPU (18p)
- **Back-up document** (406p, 450 signatories)
  - Assessment of collider status based on progress of R&D
  - R&D Plan
  - Final polishing is ongoing, you Urgently sign up to support

IMCC

International Muon Collider Collaboration

International MUON Collider Collaboration

Develop high-energy muon collider as option for particle physics:

- Implement globally defined accelerator R&D roadmap (2022) to justify CDR phase
- Mid-term roadmap review found 75% of goal achieved

Focus on feasibility of **10 TeV with 10 ab^{-1}** (site independent)

- Explore **initial stage by 2050**, maybe around 3 TeV with 1 ab^{-1} or lower luminosity 10 TeV

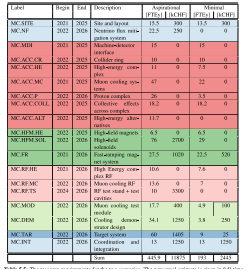
Explore implementation at specific sites reusing infrastructure

Provided ESPPU with

- **Assessment of muon collider** concept, technologies and work progress
- An **R&D plan** for the next 10 years
- **Implementation considerations** (including site, timeline, …)
- **Back-up document** (406p, 450 signatories)

Will inform other strategy processes

Param.	Unit	3 TeV	10 TeV
L/IP	10^{34} cm^{-2}s^{-1}	1.8	17.5
Int L	Ab^{-1}	2.2	1.8
f_r	Hz	5	5
C	km	4.5	11.4
B_{dipole}	T	11	14
Collider techn.		Nb3Sn	HTS



Label	Begin	End	Description	Aspirational [FTEs]	Aspirational [kCHF]	Minimal [FTEs]	Minimal [kCHF]
MC.SITE	2021	2025	Site and layout	12.5	300	11.5	900
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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	20	0	3.5	0
MC.ACC.COLL	2022	2025	Collective effects across complex	16.2	0	10.2	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
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MC.RF.MC	2022	2026	Muon cooling RF	13.6	0	7	0
MC.RF.TS	2024	2026	RF test stand + test facilities	10	3500	0	0
MC.MOD	2022	2026	Muon cooling test modules	17.7	400	4.9	100
MC.DEM	2022	2026	Cooling demonstrator design	54.1	1250	3.8	250
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MC.INT	2022	2026	Coordination and integration	13	1250	13	1250
			Sum	443.9	11875	193	2445

Roadmap:
http://arxiv.org/abs/2201.07895

The Muon Collider

Supplementary report to the European Strategy for Particle Physics – 2026 update

The International Muon Collider Collaboration

The most up-to-date version of this document can be found at the following link:
https://cdsx.cern.ch/document/3264602/1

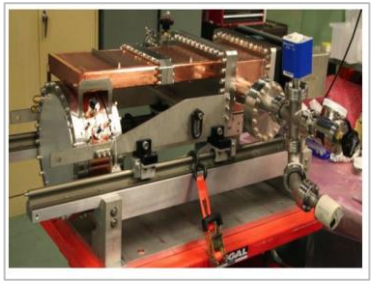
Abstract

Muons offer a unique opportunity to build a compact high-energy electroweak collider at the 10 TeV scale. A Muon Collider enables direct access to the underlying complexity of the Standard Model and unprecedented reach beyond it. It will be a paradigm-shifting tool for particle physics representing the first collider to combine the high-energy reach of a proton collider and the high precision of an electron-positron collider, yielding a physics potential significantly greater than the sum of its individual parts. A high energy muon collider is the natural next step in the exploration of fundamental physics after the HL-LHC and a natural complement to a future low-energy Higgs factory. Such a facility would significantly broaden the scope of particle colliders, engaging the main frontiers of the high energy community.

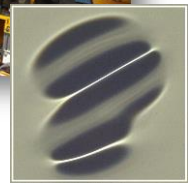
The last European Strategy for Particle Physics Update and later the Particle Physics Project Prioritisation Panel in the US supported a study of the muon collider, which is being carried out by the International Muon Collider Collaboration. In this comprehensive document we present the physics case, the state of the work on accelerator design and technology, and propose an R&D project that can make the muon collider a reality.

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



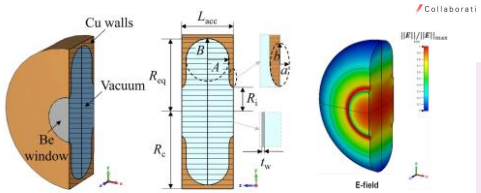
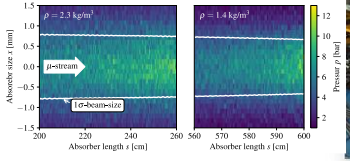
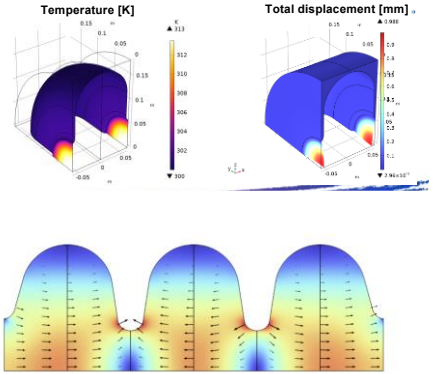


Fig. 6.3.1: Design of the 704 MHz cavity for muon cooling.

- MAP proved gradient
- Initial RF designs
- More RF design ongoing



- First window tests performed with protons
- Use of H2 gas where required



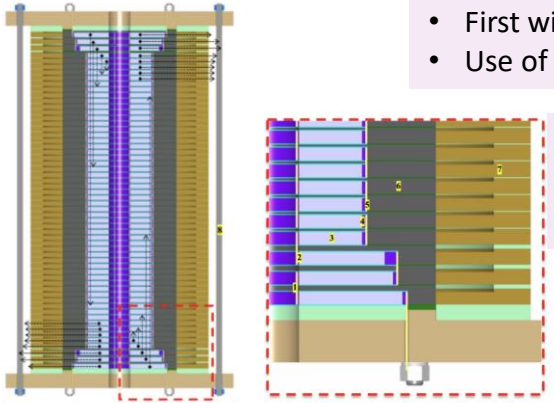


Fig. 6.1.7: Cross-section of the 40 T solenoid; the arrows indicate the axial and radial Lorentz forces acting on each pancake. The lengths of the radial arrows have been scaled down by a factor of 3.

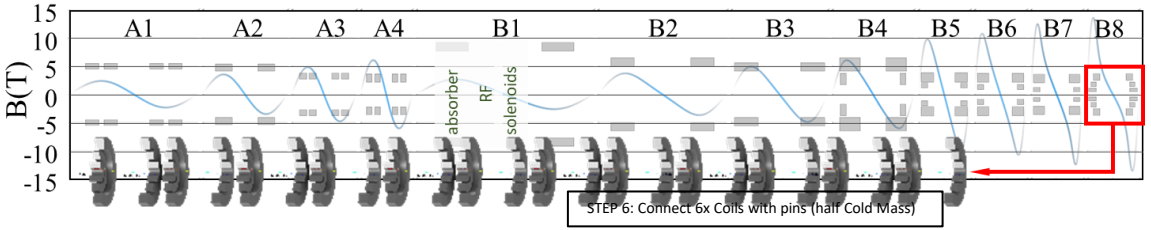
- 40 T final cooling solenoid conceptual designs exist
- 55 T might be possible

Key conclusions:
- Ready to **ramp-up effort**, in particular prototyping and experimental work, also beamdynamics

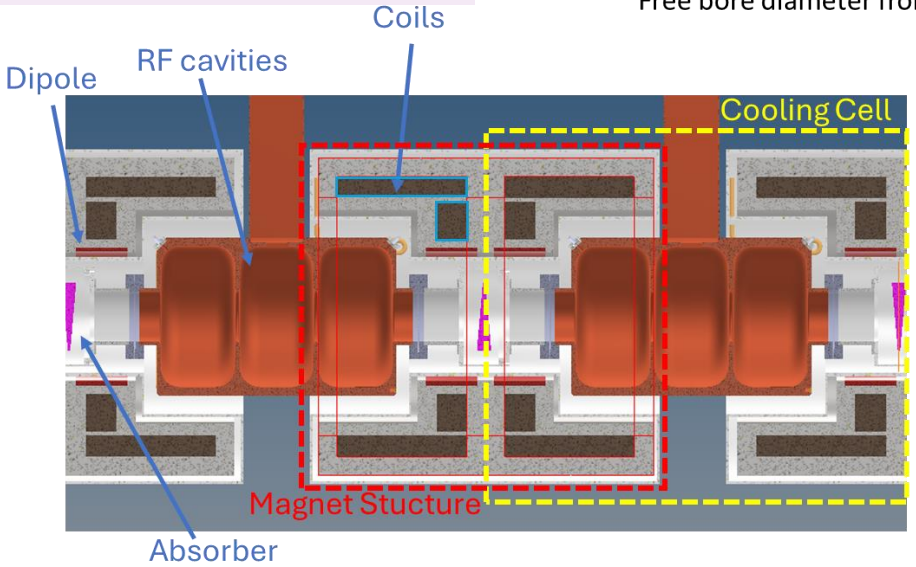
Muon 6D Cooling Cell

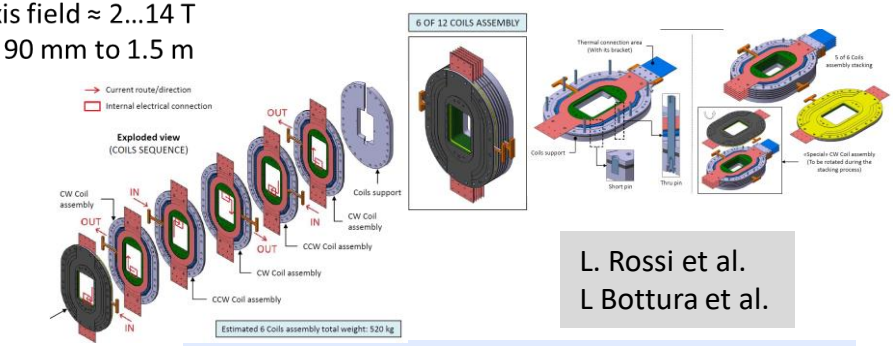
Challenge:
- Integrated 6D cooling cell
- HTS solenoid designs

Achieved:
- Cooling cell engineering design almost ready
- Solenoid models for use in beamdynamics optimisation



Cooling cells, ≈ 1 km length channel: absorber, RF, solenoid
About 3000 solenoids, axis field ≈ 2…14 T
Free bore diameter from 90 mm to 1.5 m





CW Coil assembly
(Rotated + Cover + Special plate)

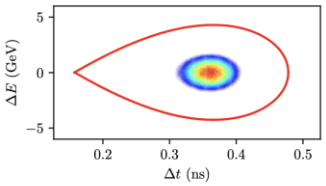
L. Rossi et al.
L Bottura et al.

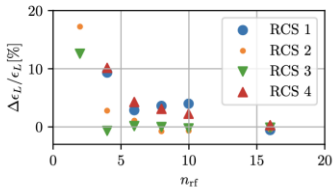
Key conclusions:
- Key challenge is force from magnetic field
- Concept to connect flanges developed
- Iterations to improve overall and components design also considering beam dynamics is required/ongoing
- Conceptual design ready in a few months

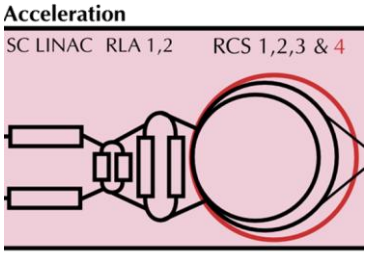
RCS Designs

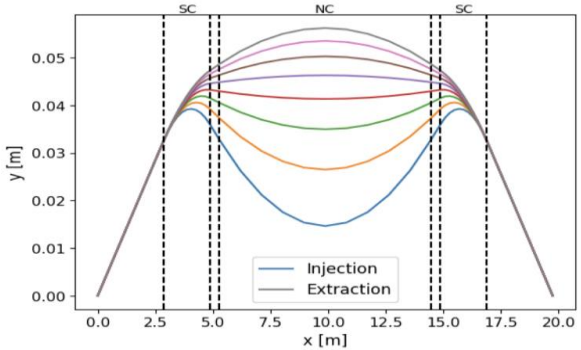
Challenge:
- Uses fast-pulsed normal magnets
- 5 Hz pulses of O(1-10ms)
- 6-35 km circumference
- Cost and power efficient acceleration
- High bunch charge
- Maintain beam quality

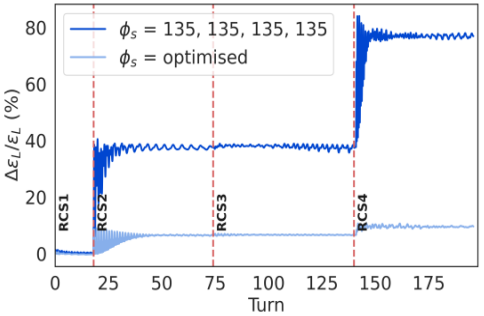
Achieved:
- Lattices for all site independent RCSs
  - Strong synchrotron motion
  - Including hardware specifications
- Beam propagation through complex works

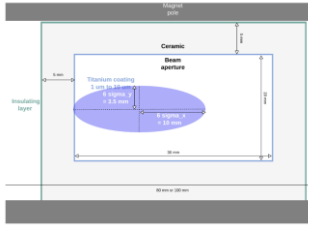


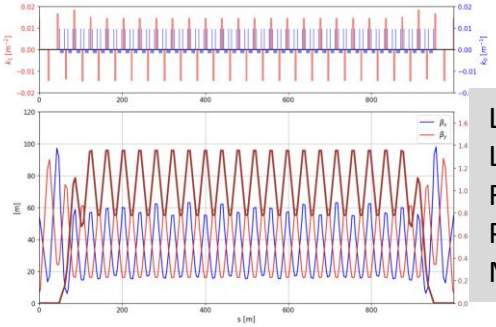












Lattice: A. Chance et al.
Long. dynamics: H. Damerell et al.
RF: Alexej Grudiev et al.
Power converter: F. Boattini et al.
Magnets: L. Bottura et al.

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

Fast-ramping RCD Dipoles

Challenge:
Fast ramping normal magnets (1-10 ms) with efficient energy recovery in power converter (200 MJ stored in magnets)

Achieved:
- Conceptual design of magnets and power converters
- Optimised design together with RF
- Power converters can switch sign of magnets without changing direction of voltage on capacitors

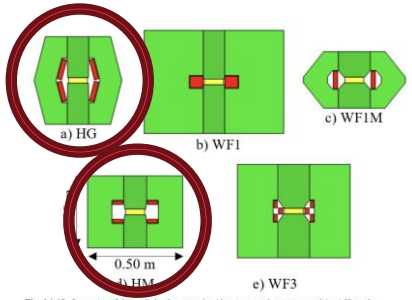
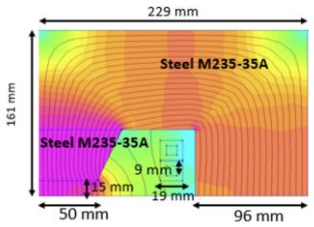
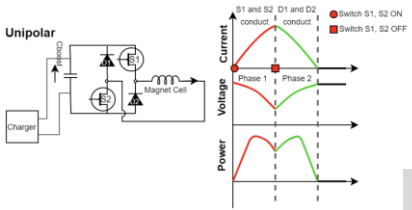
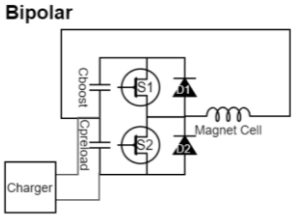
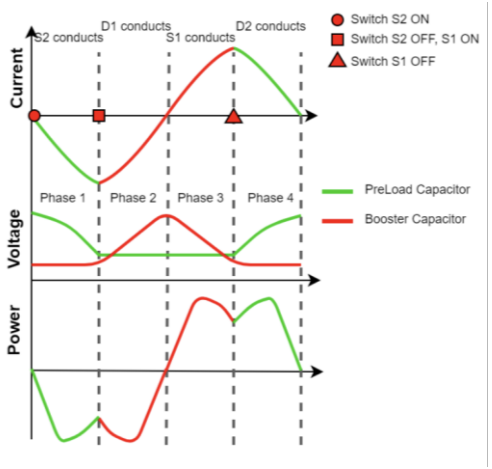


Fig. 6.1.18: Summary of the optimized geometries (the cross sections are to scale): a) Hourglas A/mm2, b) Window-frame WF#1, J = 10 A/mm2, c) Window-frame WF#1M, J = 20 A/mm2, d HM, J = 20 A/mm2; e) Window-frame WF#3, J = 20 A/mm2.









Power converter: F. Boattini et al.
Magnets: L. Bottura et al.

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

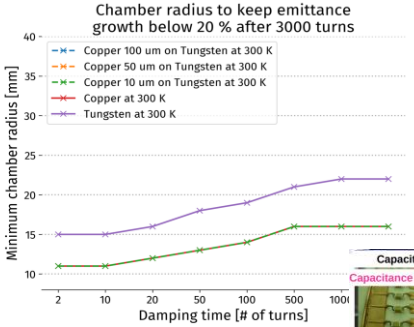
Energy in magnets, losses per cycle and total power at 5 Hz including cooling

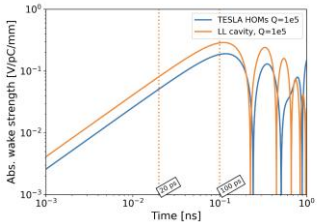
Key conclusions:
- High recovery efficiency for RCSs (98-99%)
- Ready for experimental optimization/models/protoypes

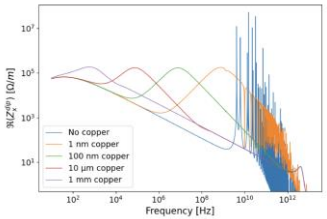
Collective Effects

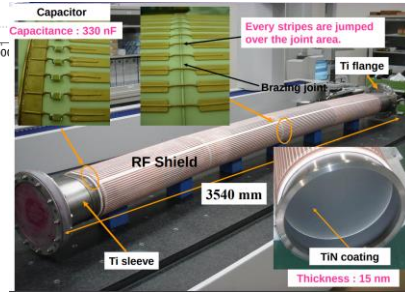
Goal:
Identify collective effects intensity bottlenecks

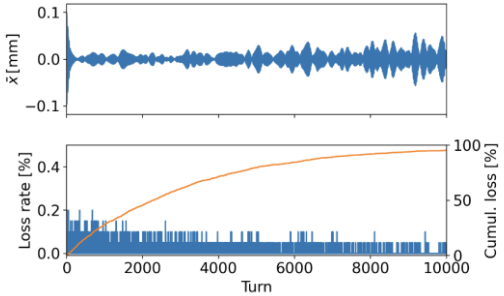
Achieved:
- Initial studies for proton complex
- Assessed impedances (beam screen and RF cavities) in RCSs and collider ring
    - Studying counter-rotating beam impedance
- Studies started on muon cooling

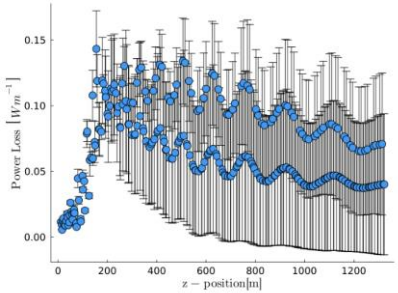


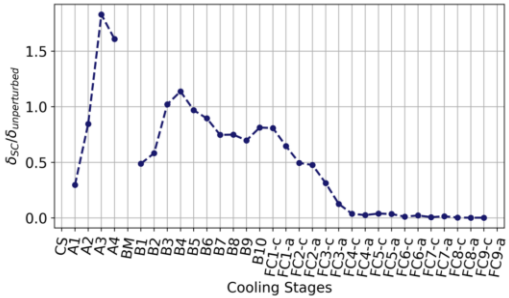






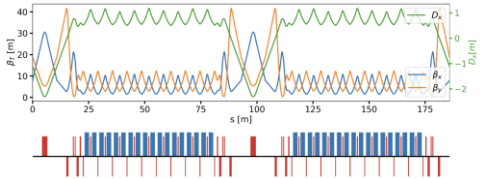


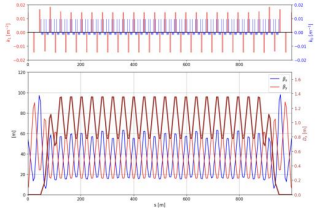


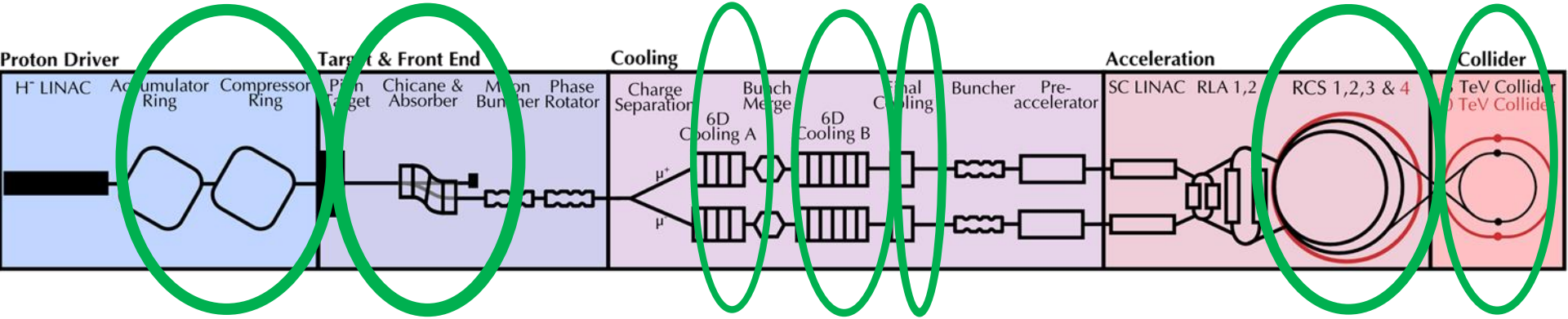


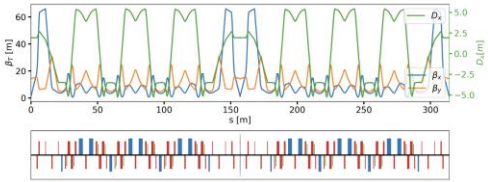
Key conclusions:
- Impedances in RCSs and collider ring can be taken care of by design
- Beam-beam can be handled by 20 turn feedback
- Resistive wall in muon cooling is OK
- Further key detailed studies: beam loading, longitudinal and transverse space charge in 6D cooling, impedance of cooling absorbers

Lattice Designs

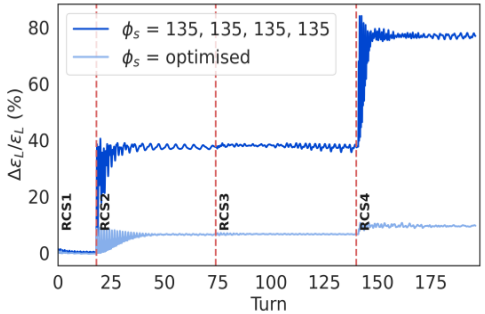








Lattice design is progressing well

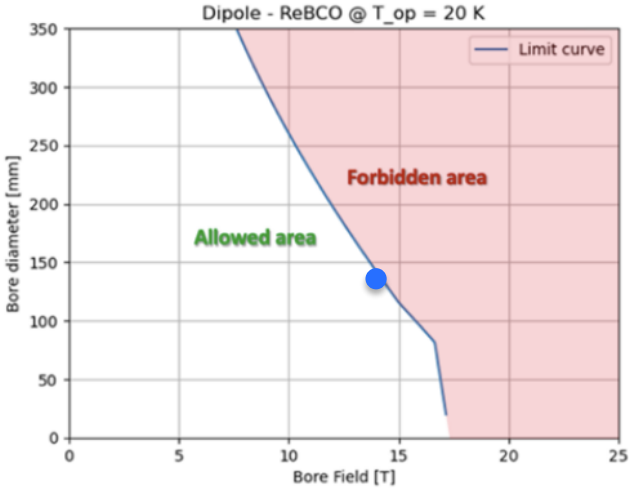


Collider Ring Magnets

Challenge:
High-field collider ring magnets with large aperture

Achieved:

- New method developed to identify field limit, depending on technology, temperature, cost, aperture, considering current, stress and protection (quadrupoles, dipoles, combined function magnets)
- Different conceptual dipole designs (block coil, cos-theta)
- Combined function design ongoing



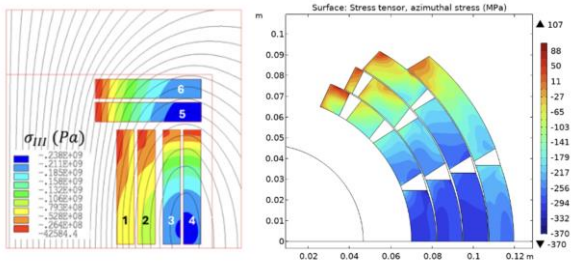
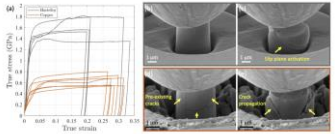
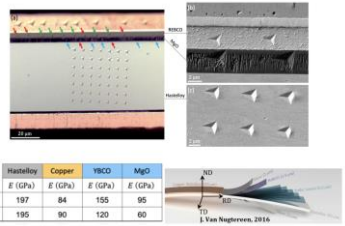


Fig. 6.1.31: Mechanical stress on conductor under Lorentz Forces at nominal current for both block coil and cos-theta magnet configurations.



Hastelloy		Copper	
σ^y / GPa	* ε^y / %	σ^y / GPa	* ε^y / %
1.2 – 1.6	0.61 – 0.82	0.4 – 0.6	0.42 – 0.66



	Hastelloy	Copper	YBCO	MgO
	E (GPa)	E (GPa)	E (GPa)	E (GPa)
RD	197	84	155	95
TD	195	90	120	60

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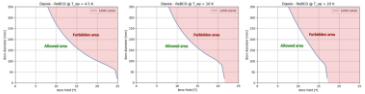

Fig. 6.1.26: A-B plot for dipoles built with REBCO and operated at 4.5 K, 10 K and 20 K.

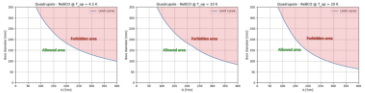

Fig. 6.1.27: A-G plot for quadrupoles built with REBCO and operated at 4.5 K, 10 K and 20 K.

Key conclusions:

- Dipoles appear feasible:
  - NbTi at 4 K, 4.8 T, 16 cm aperture
  - Nb3Sn at 4 K, 11 T, 16 cm aperture
  - HTS at 20 K, 14 T, 14 cm aperture
- Quad in dipole best combined solution
- Experimental programme is now essential