Riunione Referee – 22 luglio 2025

R&D Muon Collider

Stato collaborazione internazionale IMCC attività INFN in corso e future - sinergie

Nadia Pastrone

International MUON Collider Collaboration

Gruppi **INFN** *in* ***RD_MUCOL @ CSN1*** **134 persone/33.2 FTE**

RD_MUCOL @ CSN1 – ESPP_A_MUCOL @ GE – UE-MUCOL – SIC_4DGAIN

BA BO FE GE MI MIB LNF LNL LNS PD PI PV RM1 RM3 TO TS

Physics, Detector R&D, MDI, Crystals/Targets, Accelerator Activities

MuCol

N.B. si chiudono nel 2025 sigle di progetti UE - importanti per fondi personale e di supporto ad attività di R&D di acceleratori e rivelatori

HORIZON-INFRA-2022-DEV-01-01

Motivation for a multi-TeV Muon Collider

International MUON Collider Collaboration

Strong interest in **high-energy, high-luminosity lepton collider**

- combines **precision physics** and **discovery reach**
- application of hadron collider technology to a lepton collider

Muon collider promises **sustainable** approach to the **energy frontier**

- limited power consumption, cost and land use ➔ **site evaluation and reuse of existing tunnels**

Technology and **design advances since the past ESPPU**

- reviews of the muon collider concept in Europe and US found **no insurmountable obstacle**
- **identified required R&D**, documented and reviewed within the LDG Accelerator R&D Roadmap
- co-funded mainly by CERN (MTP dedicated line since 2021) - EU-MUCOL project (2023-2027)
- strong dedicated contribution from INFN management + CSN1

Aim at **10+ TeV** and potential initial stage at **3 TeV**

Possible initial 10 TeV stage at reduced luminosity

New design to reuse existing CERN tunnels: SPS & LHC ➔ whole facility on CERN site

Interim report https://arxiv.org/abs/2407.12450

Strong support by US [P5 Report](#) @ December 2023

Reflections on a multi-TeV Muon Collider

International MUON Collider Collaboration

- A unique innovative and never attempted project capable to reach the energy frontier in a sustainable design:
  - ➔ no showstoppers identified so far
  - ➔ many crucial challenging R&D required

- Despite the fact that available resources were not sufficient to cover all the proposed and approved plan prepared by the Accelerator R&D Roadmap
  - ➔ priorities were identified
  - ➔ great progresses pave the baseline design completion
  - ➔ 10 TeV lattice and MDI design allow to demonstrate with full simulation the huge physics potential
  - ➔ remarkable synergies on R&D technologies both for science and society
  - ➔ review are encouraging

- To accomplish the required R&D plan
  - ➔ the first set of prototyping and test must be accomplished
  - ➔ the collaboration has to be strengthen to provide more resources

Muon Collider - Input Documents @ ESPPU

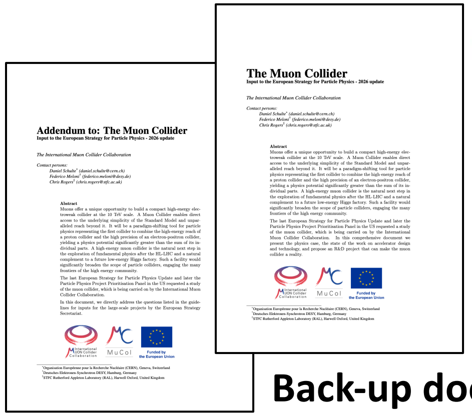
International MUON Collider Collaboration

IMPORTANTI CONTRIBUTI ITALIANI

Submitted Input 5+1/266

207. The Muon Collider

207-Update-ESPPU_MuonCollider_v02.pdf
207-Update-ESPPU_MuonCollider_Addendum_v03.pdf
ESPPU_Muon_Collider_Backup.pdf


Addendum to: The Muon Collider

The Muon Collider

Back-up document
(406p, 450 signatories)

152. United States Muon Collider Community White Paper for the ESPPU

105. Magnet R&D for the Muon Collider

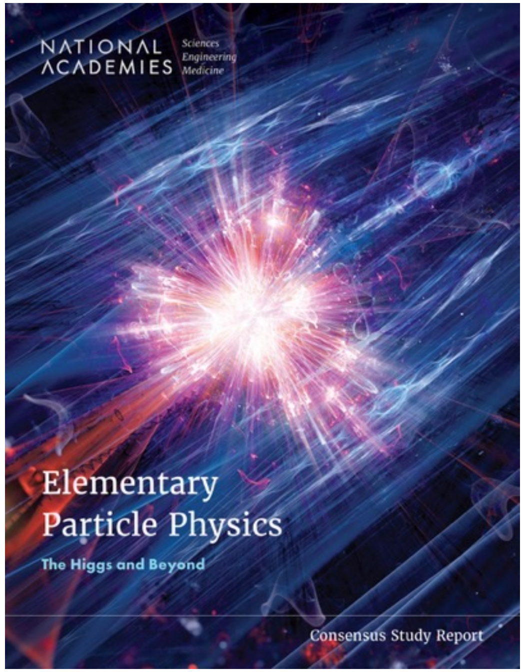
32. Performance study of the MUSIC detector in $\sqrt{s}$ = 10 TeV muon collisions

184. Sensitivity study on H→ $b\bar{b}$, H→ WW^* and H H → $b\bar{b}b\bar{b}$ cross sections and trilinear Higgs self-coupling with the MUSIC detector in $\sqrt{s}$ = 10 TeV muon collisions

251. Physics opportunities with high-brightness, high-intensity muon beams at CERN: a staged approach

National Academy of Science report - June 2025

International
MUON Collider
Collaboration



Elementary Particle Physics: Progress and Promise

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

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

OPEN SYMPOSIUM European Strategy for Particle Physics
2026 UPDATE
23-27 JUNE 2025

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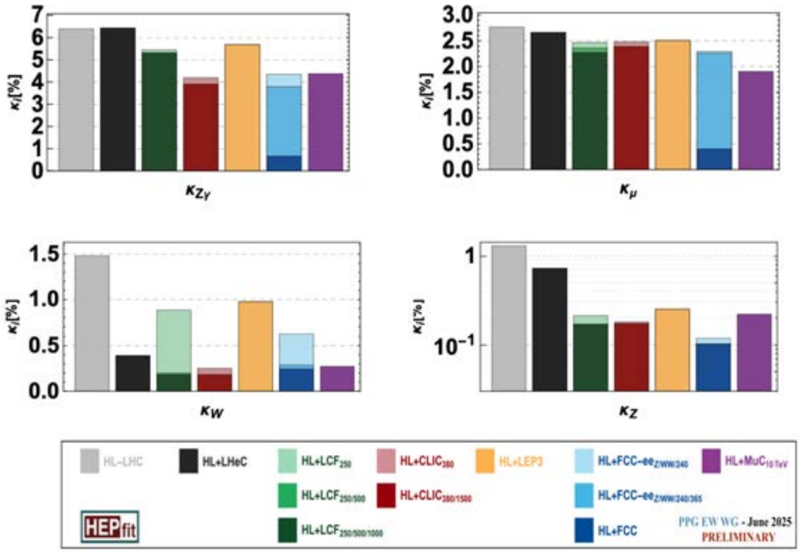
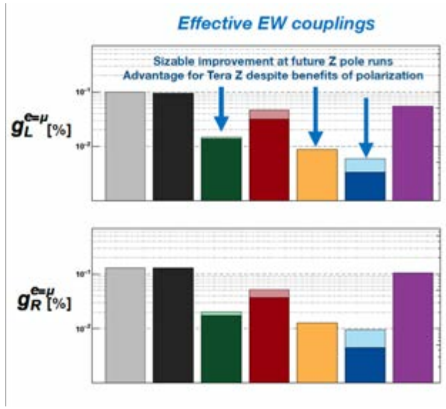
Electroweak Physics

- The **HL-LHC** will provide legacy measurements for top, ttH, λ_3 and rare decays until a top and high energy run
- **Multiple energy points in e^+e^- colliders** are important to Higgs precision (i.e. width, HWW, λ_3)
- **Tera-Z brings highest overall sensitivity to el.weak**
- Significantly improved high-precision tests of the el.weak sector are vital to guide future direct searches of new physics
- Precision and energy are strongly complementary
- A focus on both precision (→ smaller effects) and breadth (→ characterization of any eventual signal) is important in the search of the unknown.
- Fundamental advancements in theory techniques and tools needed

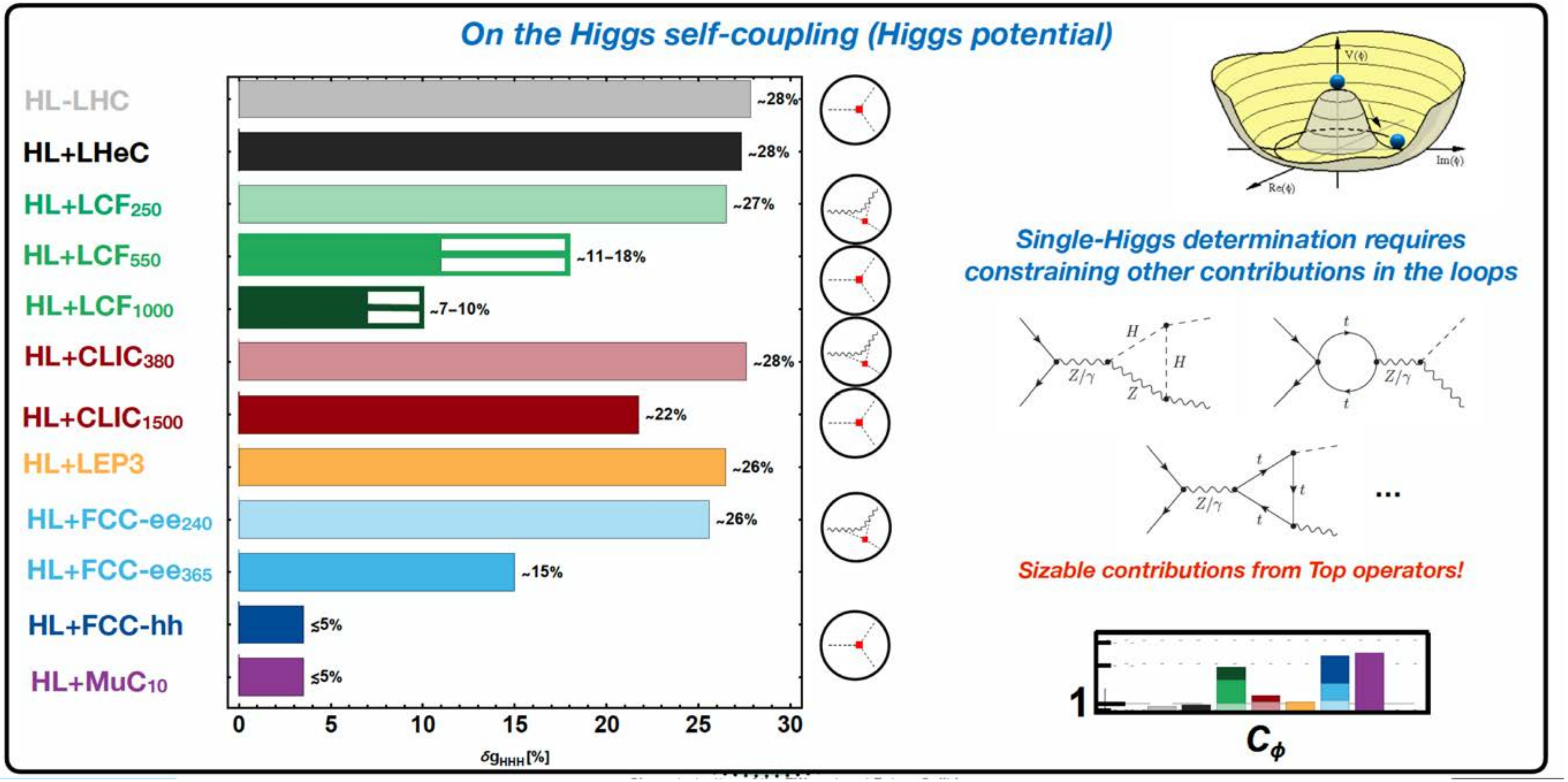
Higgs physics



Z pole physics



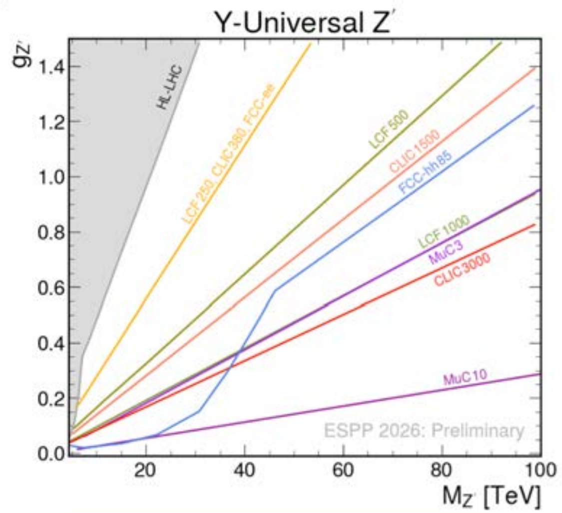
Electroweak Physics



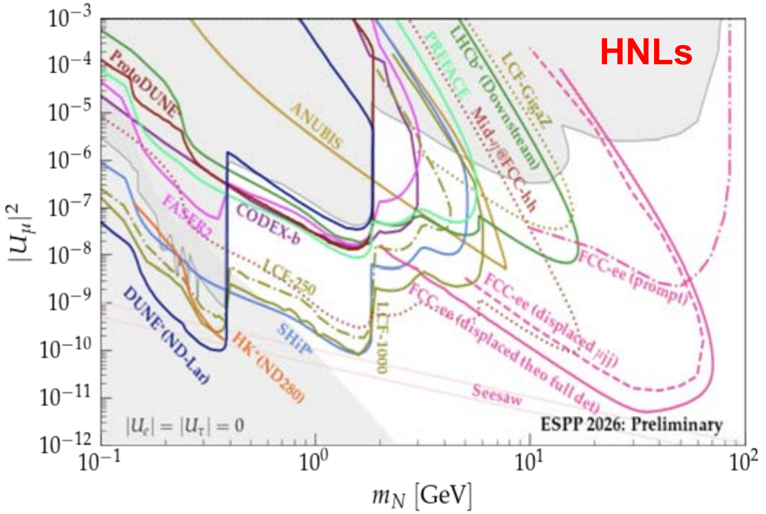
Searches for BSM Physics

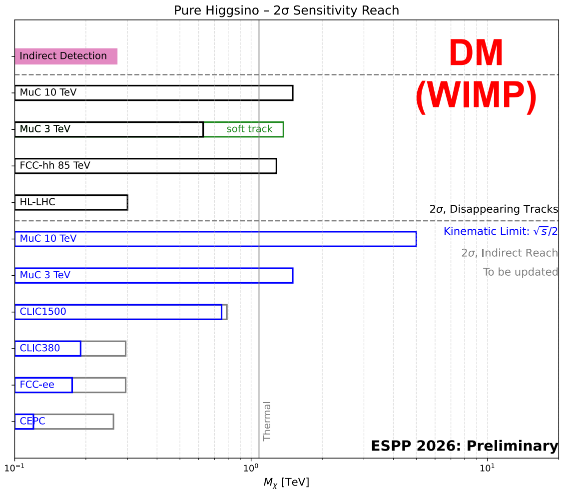
- Need for a future collider programme that can fully leverage both ***precision and energy***, *covering the widest range of observables at different scales* – below, at and above the weak scale –

- Sensitivity to new physics below the EW scale, typically feebly interacting particles, requires strong synergy with dedicated experiments and fixed target experiments to provide maximal coverage

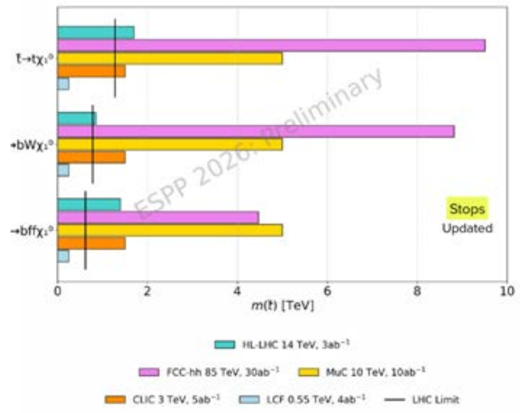


Exclusion reach of different colliders on the Y-universal Z' model parameters





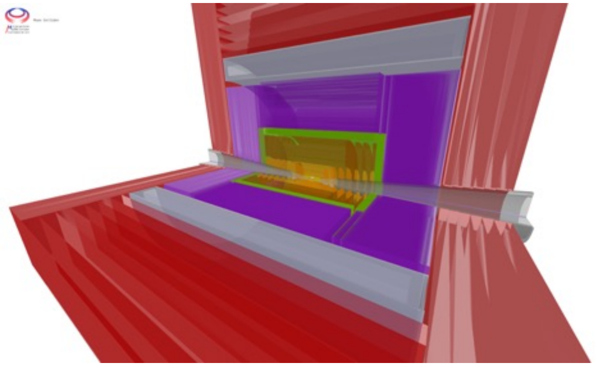
High energy hadron colliders offer the best coverage for gluino, stops and squarks



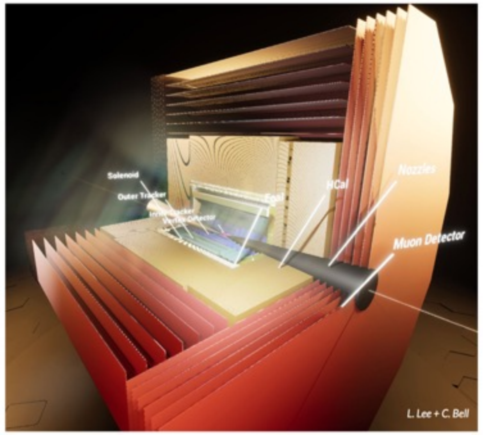
Physics and Detector Concepts

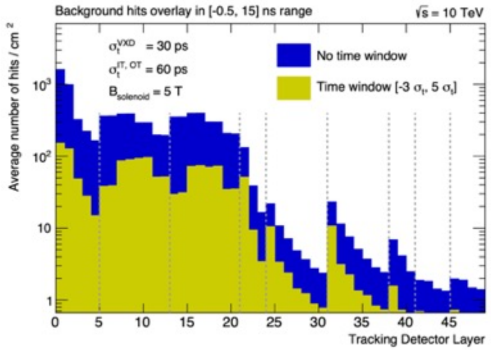
Challenges:
High-energy lepton detector requirements
Background from muon decay and beam-beam effects (BiB)

MUSIC
(MUon System for Interesting Collisions)

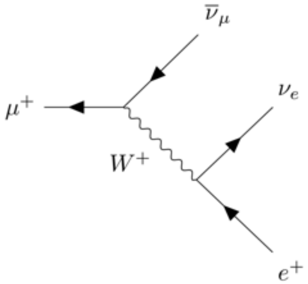


MAIA
(Muon Accelerator Instrumented Aperatus)





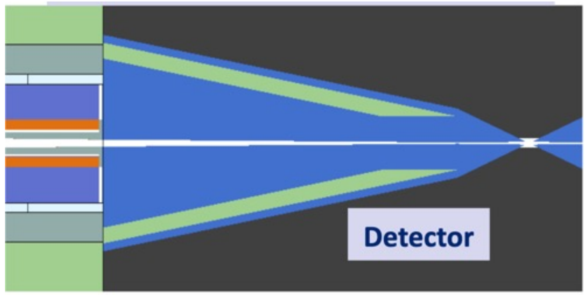
Achievements
Two detector concepts are being developed
Performance studies with GEANT
Detailed design and simulations of MDI and background suppression

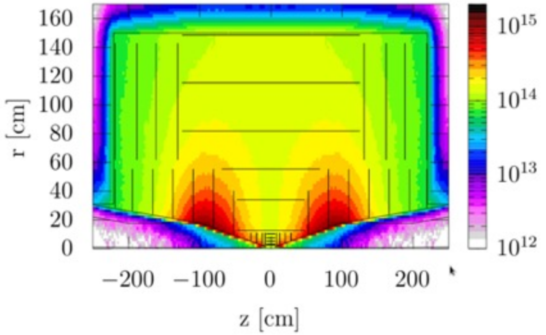


Key conclusions:
Full simulations show good physics performance with near-term technology in spite of BiB
- But important improvements are possible

Need strong R&D for **optimization** and **integration**

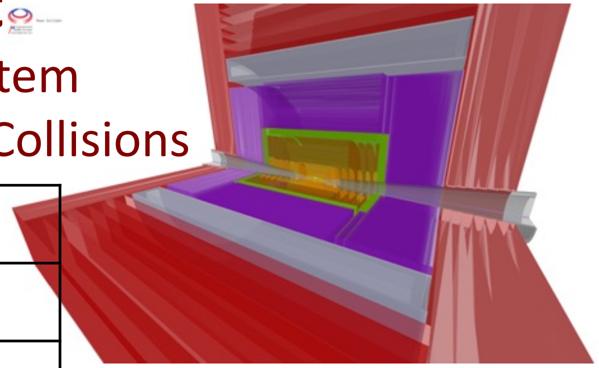
Proper investment crucial to enable exploitation of full muon collider potential in available time using **new technologies, AI, and ML**





Detector R&D - next presentations

MUSIC
MUon System
for Interesting Collisions



SEDE	RICHIESTA [keu]	Attività	commento
BA	64.5	HCAL (MPGD-RPC)	sinergia DRD1/DRD6
LNF	54	CRILIN	sinergia DRD6
PD	10	Infrastruttura Si pixel	Cofinanziamento FCC/PD
PD	6	Test beam setup	laboratorio
PV	10	picosec	sinergia DRD1
TO	5	LGAD	laboratorio
BA	24	TPC	sinergia DRD1
MI	325	Cavo HTS - attrezzatura RF	Sinergia ESPP_A_MUCOL

Muon demonstrator

Cooling cell test set up

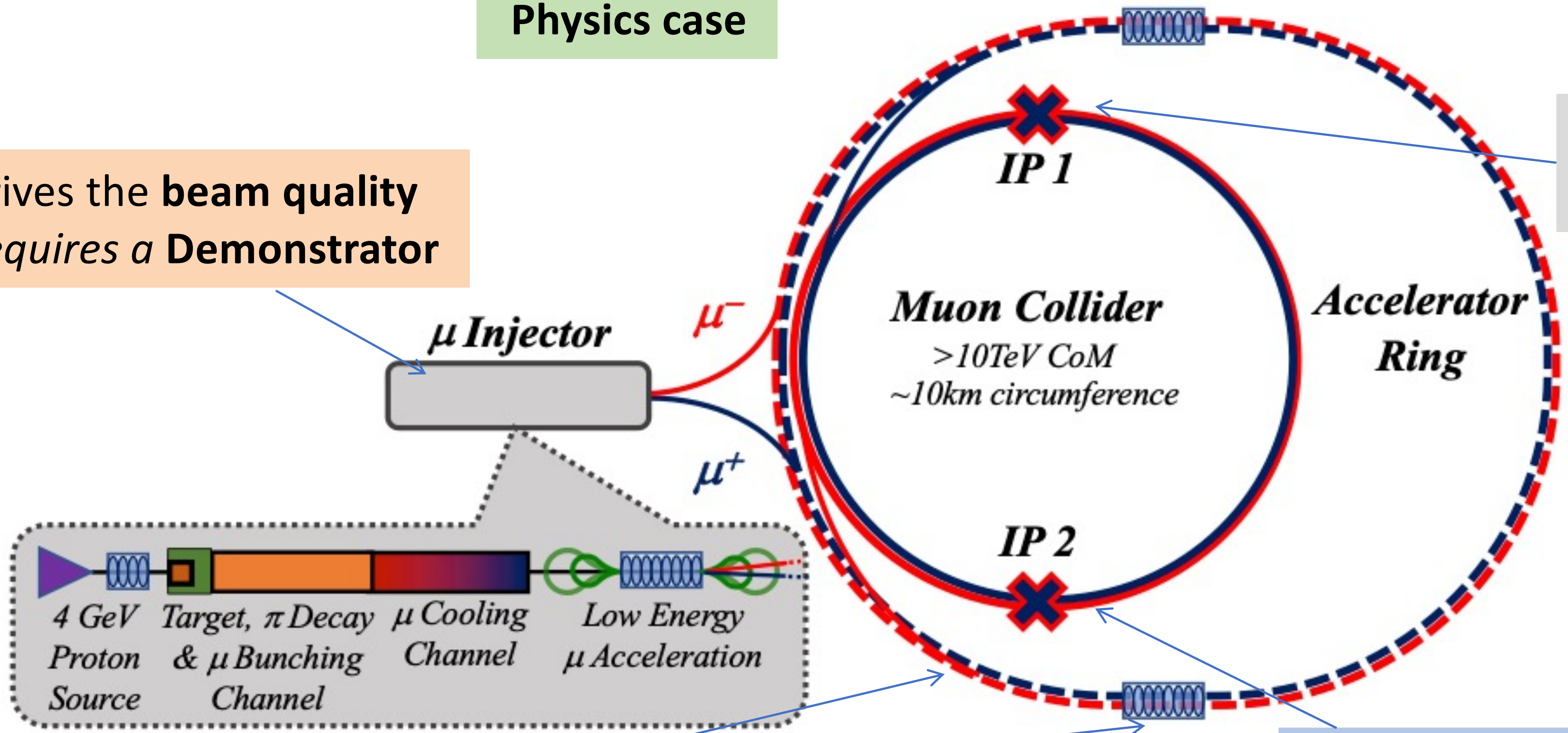
Accelerator R&D - next presentation

Key Challenges @ 10 TeV

Physics case

Experiment design

Drives the **beam quality**
Requires a **Demonstrator**



Beam-induced background

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Target integrated luminosities based on physics
Increase as E_{cm}^2

Dense neutrino flux mitigated by mover system and **site selection**

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

Key Target Parameters

Param.	Unit	Site independent		CERN 2 tunnels		CERN 1 tunnel	
Sqrt(s)	TeV	3	10	3.2	7.6	3.2	7.6
L/IP	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%, 25%, 70% of nominal.

Accelerator R&D Roadmap

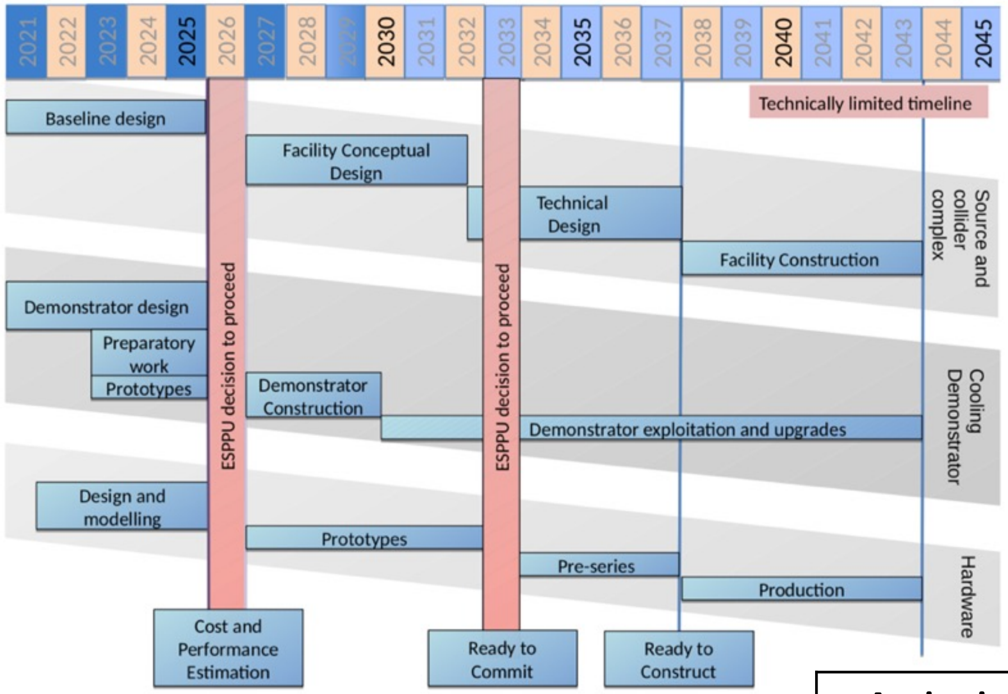
International MUON Collider Collaboration

Bright Muon Beams and Muon Colliders

Panel members: **D. Schulte**,(Chair), M. Palmer (Co-Chair), T. Arndt, A. Chancé, J. P. Delahaye, A.Faus-Golfe, S.Gilardoni, P.Lebrun, K.Long, E.Métral, **N.Pastrone**, L.Quettier, T.Raubenheimer, C.Rogers, M.Seidel, D.Stratakis, A.Yamamoto
Associated members: A. Grudiev, R. Losito, **D. Lucchesi**

presented to CERN Council in December 2021
published https://arxiv.org/abs/2201.07895
now under implementation by LDG + Council…

Technically limited timeline



Development path to deliver a 3 TeV muon collider by 2045

Scenarios

Aspirational		Minimal	
[FTEy]	[kCHF]	[FTEy]	[kCHF]
445.9	11875	193	2445

~70 Meu/5 years

Roadmap Plan

MDI

Dipoles/solenoids High field (Nb3Sn, HTS?)

RF cavities SC e NC

Cooling cell Demonstrator

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

R&D Plan Reviews

LDG Mid-term Review

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

Found **good progress for Roadmap implementation**

- "75% of Roadmap goals have been achieved"

Recommendations:

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

MuCol mid-term review by EU

Very good technical progress

IAC review:

Permanent members: Ursula Bassler (chair), Mauro Mezetto, Hongwei Zhao, Akira Yamamoto, Maurizio Vretenar, Stewart Boogert, Sarah, Demers, Giorgio Apollinari

Additional experts confirmed: Pierre Vedrine, Stephen Gourlay, Lyn Evans, Alessandro Gallo, Barbara Dalena, Pantaleo Raimondi

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

Site Specific Designs

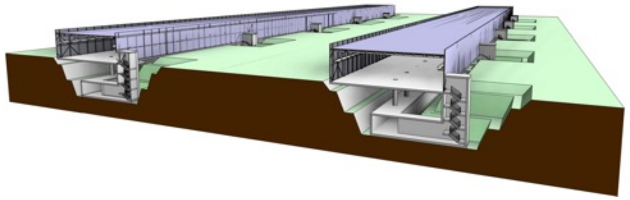
Started studies for concrete site at CERN and Fermilab, looks very promising

CERN:

One RCS in SPS and two in LHC

Construct facility on CERN land

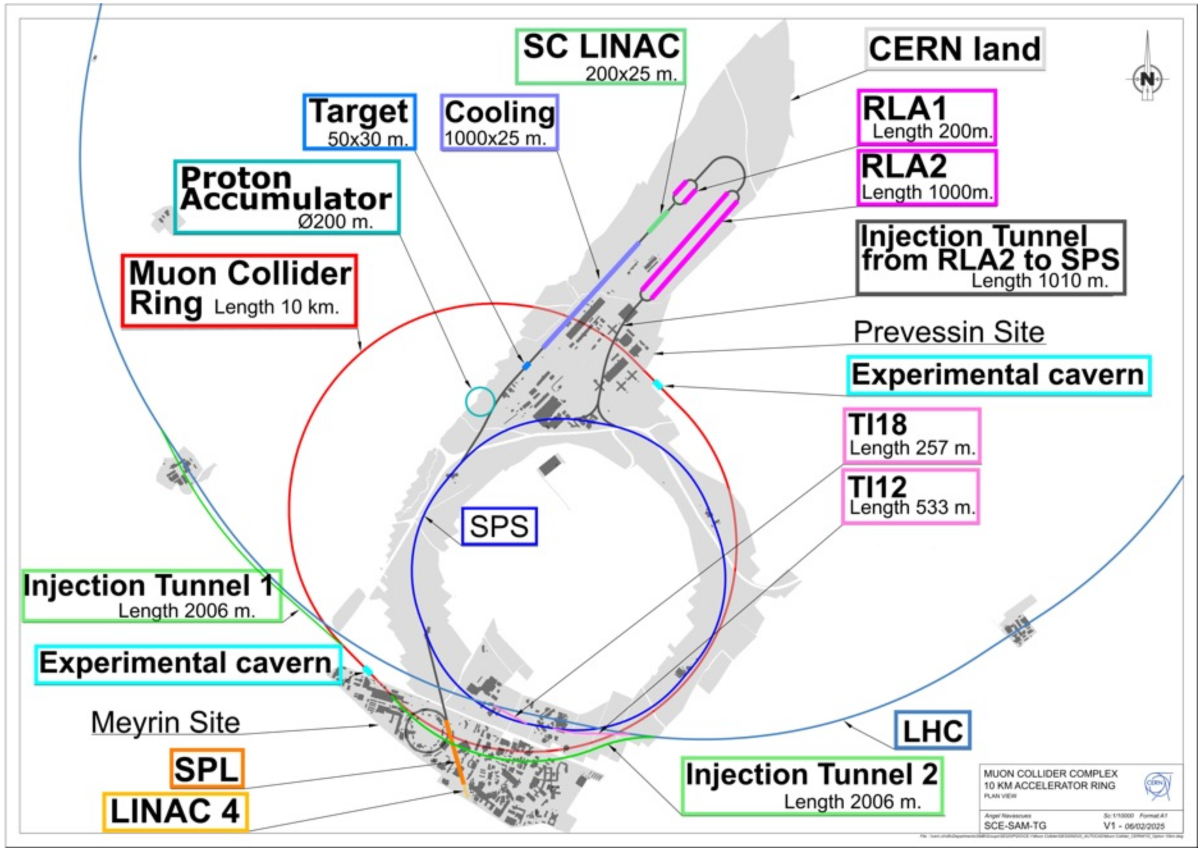
- Natural energy stages: 3.2 and 7.6 TeV
- 10 TeV maybe possible with better technology

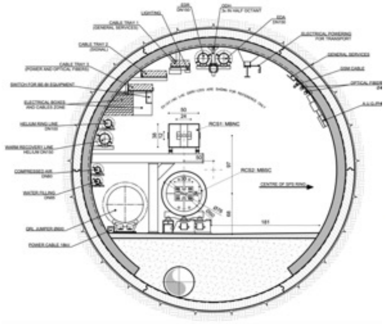


Fermilab:

One RCS in Tevatron tunnel,

Three RCSs in one site-filler tunnel

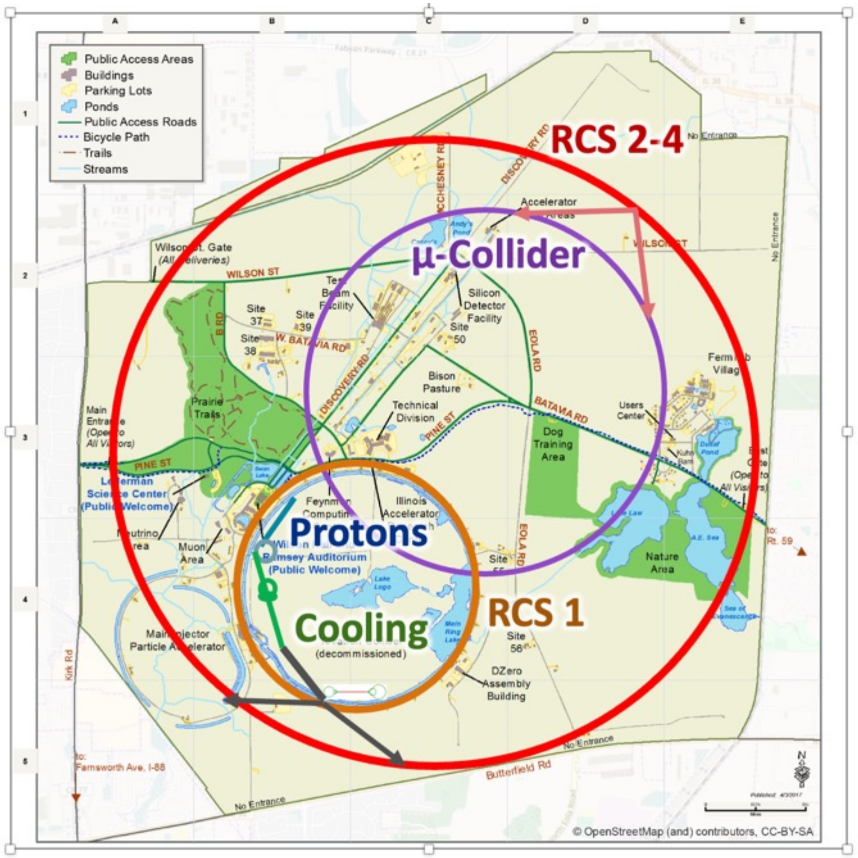




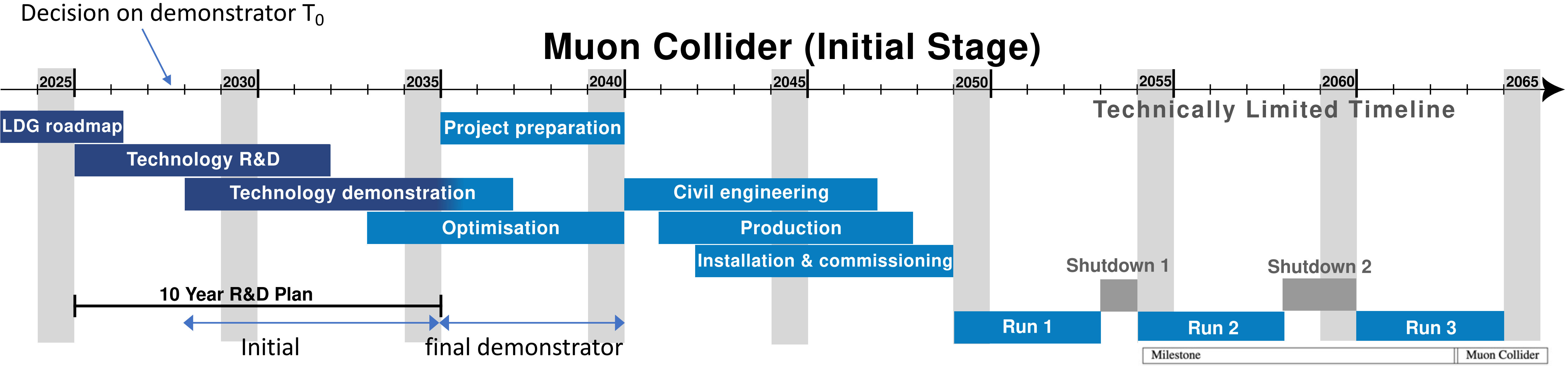
Key conclusions:

Looks promising

Detailed study needed



Timeline and R&D Programme Proposal



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

Timeline is **driven by R&D**

Most ambitious example to define R&D programme priorities

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

Other options

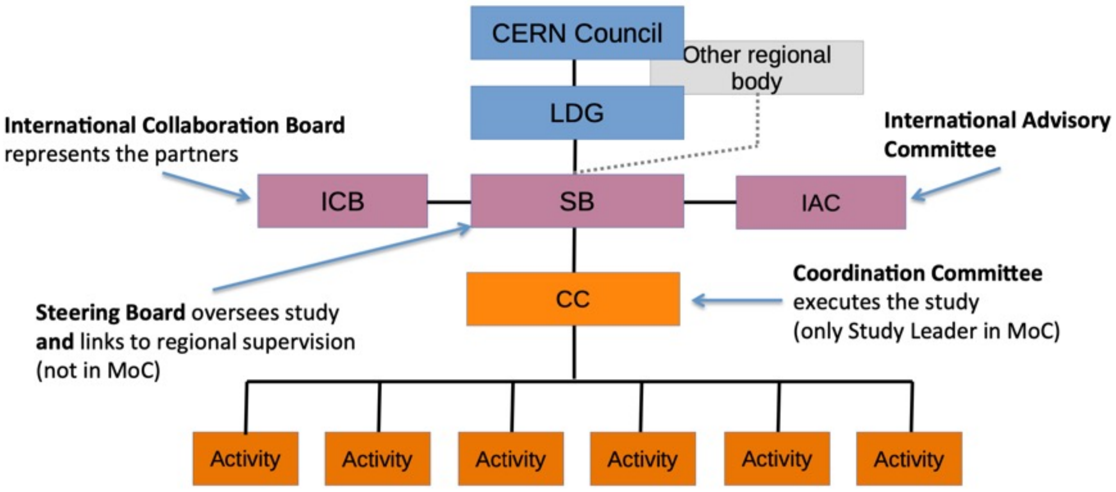
- In Europe after a higgs factory
- In the US to become leader at the energy frontier

https://indico.cern.ch/event/1439855/contributions/6542430/

IMCC Organization after the Roadmap

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

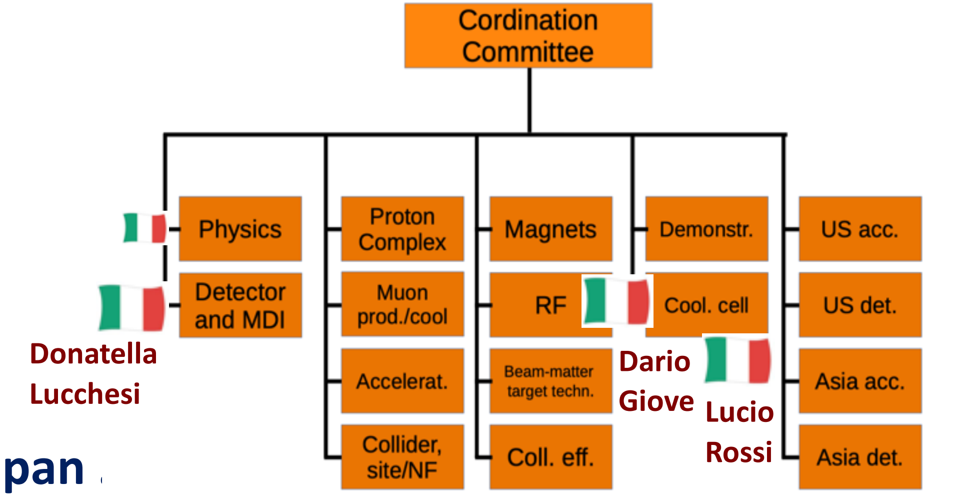
CERN is host organisation, can be transferred to other partner on request of CERN and with approval of ICB
Will review governance in 2024, US could join at that time



MoC signed by CERN CEA INFN STFC-RAL ESS IHEP and different universities in EU, US, China

- **Collaboration Board (ICB)**
  - Elected chair : **Nadia Pastrone**
- **Steering Board (SB)**
  - Chair **Steinar Stapnes**,
  - CERN members: Mike Lamont, Gianluigi Arduini,
    Dave Newbold (STFC), Pierre Vedrine (CEA),
    Beate Heinemann (DESY)
    ICB chair and SL and deputies
- **International Advisory Committee (IAC)**
  - Chair **Ursula Bassler (IN2P3)**

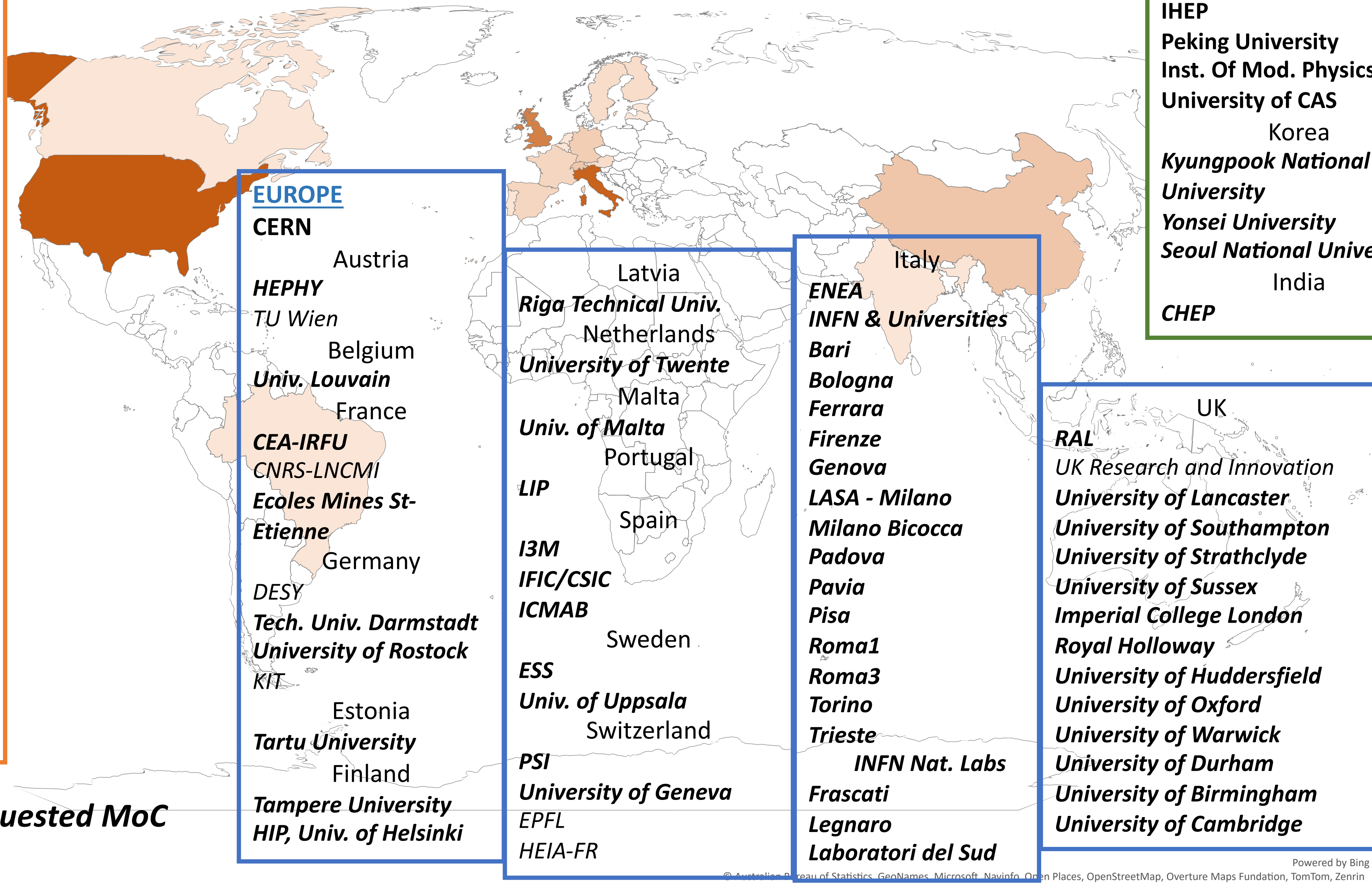
Coordination Committee



Resources Addenda Grey Book @ CERN

19 countries: CERN, IT, US, UK, FR, DE, CH, ES……
CHINA, KOREA, INDIA….. Interest from Japan
80 institutes

IMCC Countries and Institutes



AMERICA

Canada

Université Laval

U.S.A.

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

Brazil

CNPEM

EUROPE

CERN

Austria

HEPHY
TU Wien

Belgium

Univ. Louvain

France

CEA-IRFU
CNRS-LNCMI
Ecoles Mines St-Etienne

Germany

DESY
Tech. Univ. Darmstadt
University of Rostock
KIT

Estonia

Tartu University

Finland

Tampere University
HIP, Univ. of Helsinki

Latvia

Riga Technical Univ.

Netherlands

University of Twente

Malta

Univ. of Malta

Portugal

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ASIA

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IHEP
Peking University
Inst. Of Mod. Physics, CAS
University of CAS

Korea

Kyungpook National University
Yonsei University
Seoul National University

India

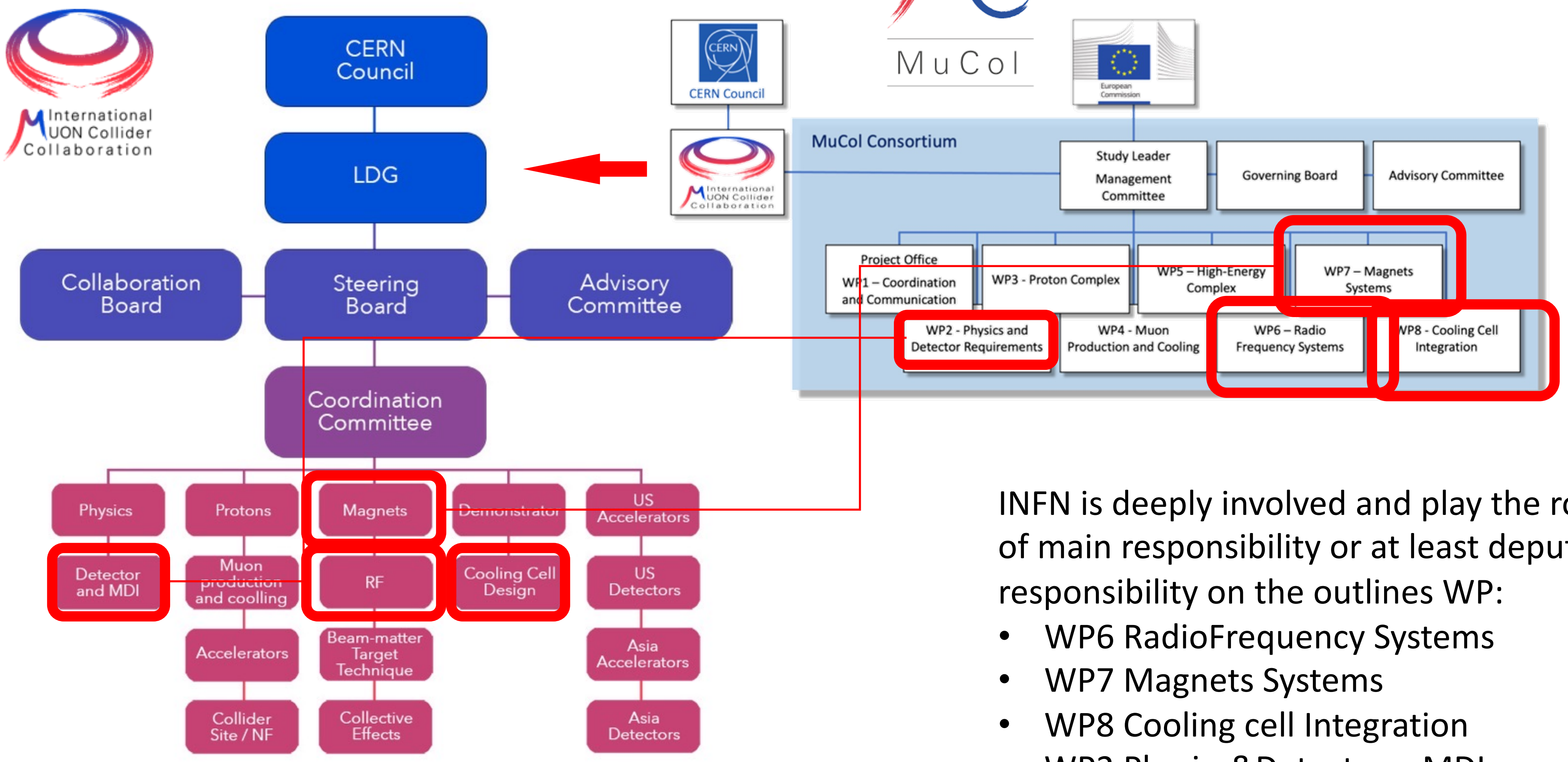
CHEP

Signed MoC (61) or *requested MoC*
contributor

Project Organization

International Muon Collider Collaboration

MuCol EU Design Study



INFN is deeply involved and play the role of main responsibility or at least deputy responsibility on the outlines WP:

- WP6 RadioFrequency Systems
- WP7 Magnets Systems
- WP8 Cooling cell Integration
- WP2 Physics&Detector – MDI

Design Study activities: EU project

Total EU budget: 3 Meu start March 1 2023 – 4 years
18(+14) beneficiaries (associated) END 28 FEB 2027

HORIZON-INFRA-2022-DEV-01-01:
Research infrastructure concept development

MuCol

International MUON Collider Collaboration

INFN 510 keu **UniMI** 300 keu **UniPD** 100 keu + associate partners: UniBO, UniPV INCLUSO OVERHEAD

MuCol study will produce a coherent description of a novel particle accelerator complex that will collide muons of opposite charge at the energy frontier. The study will target a centre-of-mass energy (ECM) of 10 TeV with 3 TeV envisaged as a first stage.

The main outcome of MuCol will be a **report** documenting the facility design that should demonstrate that:

- the **physics case** of the muon collider is sound and **detector systems** can yield sufficient resolution and rejection of backgrounds;
- there are **no principle technology showstoppers** that will prevent the achievement of a satisfactory performance from the accelerator or from the detectors side;
- the muon collider provides **a highly sustainable energy frontier facility** as compared to other equivalent colliders;
- **exploiting synergies with other scientific and industrial R&D projects**, a valuable platform to provide Europe a leading edge not only in terms of discovery potential, but also for the development of associated technologies.

The final report will include a thorough assessment of benefits and risks of the accelerator and detector complex, including an evaluation of the scientific, industrial and societal return beyond high-energy physics, the cost scale and sustainability of the complex and the impact arising from an implementation on the CERN site.

INFN – BUDGET
Total: 408 keu

AdR: 362 keu
Altro: 46 keu

GE: 10 keu missioni
MI: 8 keu missioni
MI: 16 keu consumo
MI: 8 keu licenze
TO: 4 keu progetto

Cost and Power Scale

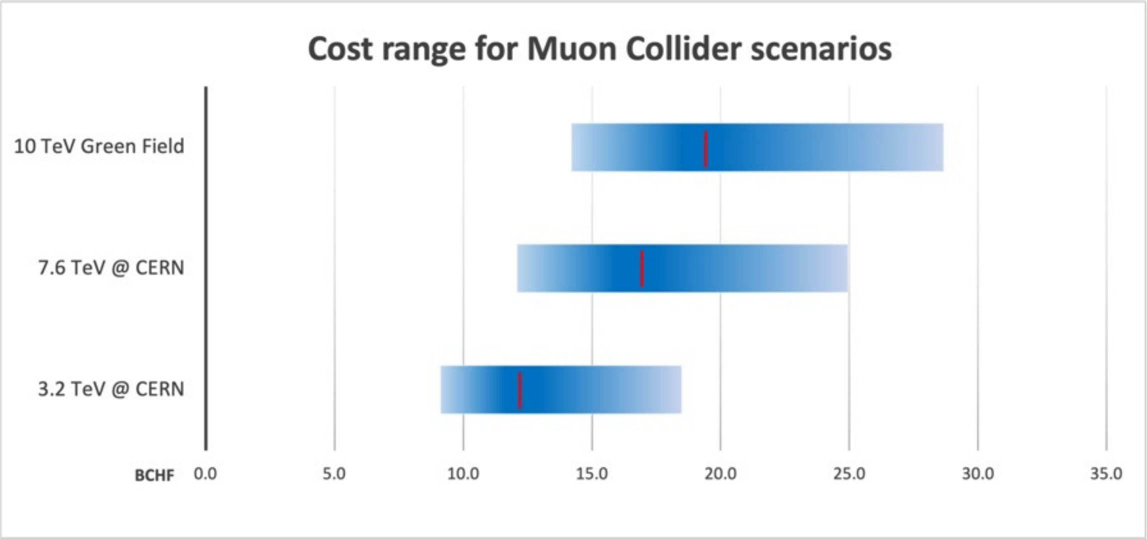
Design of collider and components advanced enough to estimate cost and power

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

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

More work to be done

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



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

R&D Programme

Accelerator design

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

Muon cooling technology

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

Detector

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

Magnet programme

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

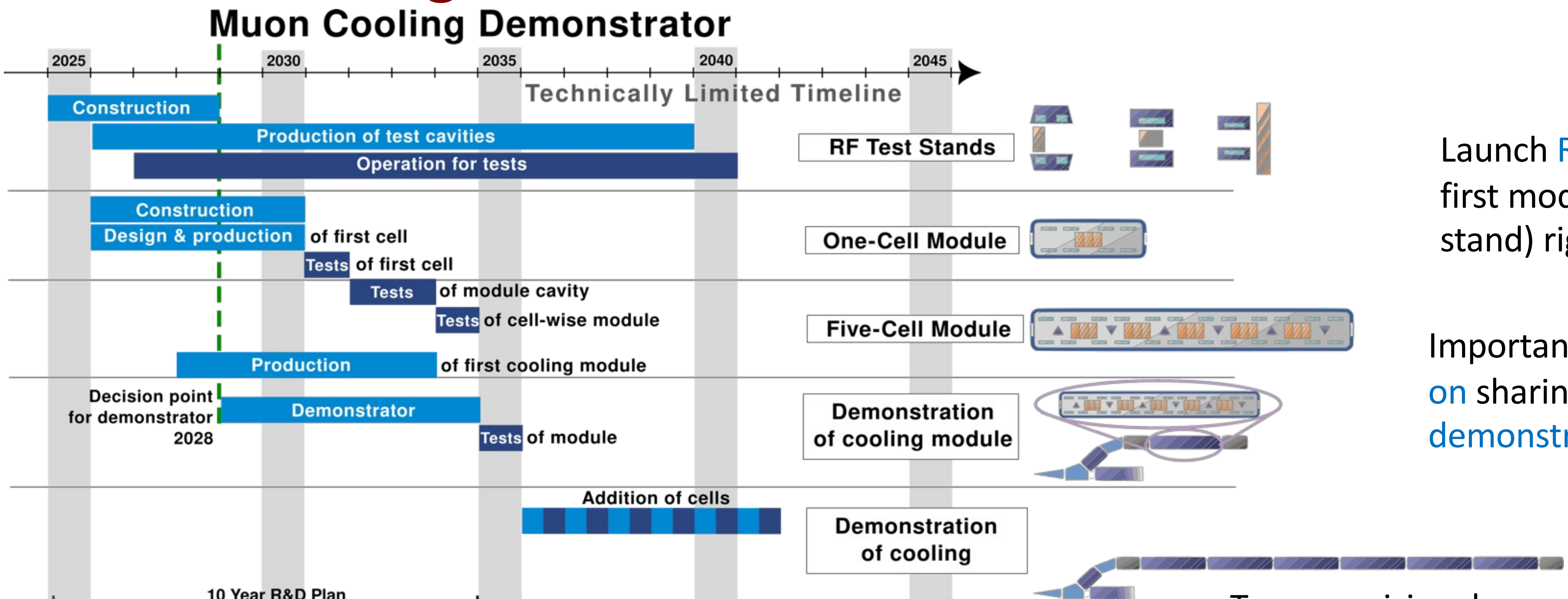
Detailed R&D programme proposal with deliverables defined

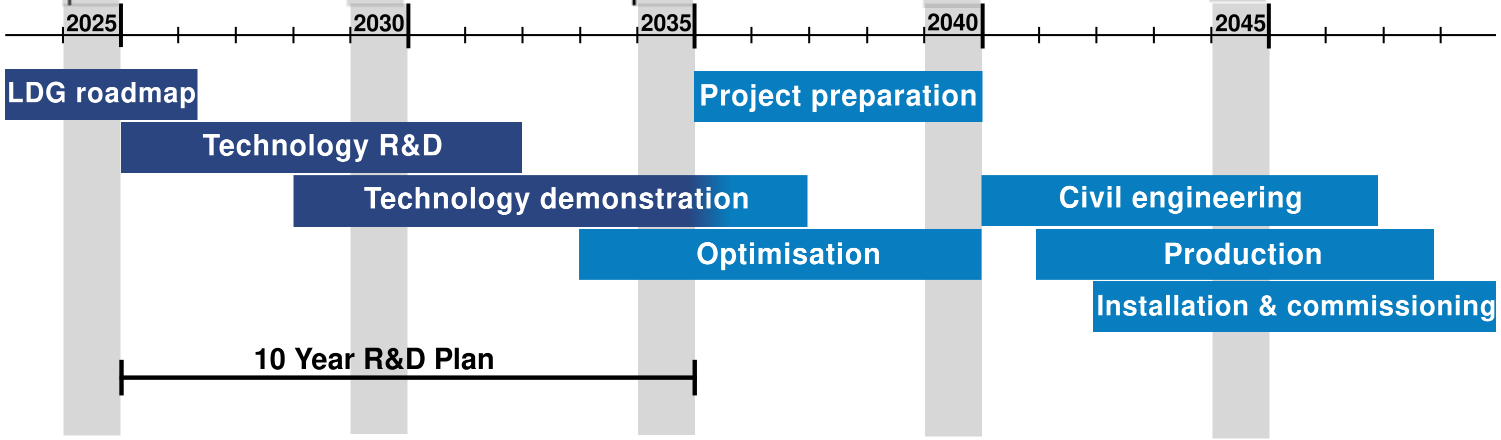
Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Accelerator Design and Technologies										
Material (MCHF)	1.6	3.2	4.8	6.4	9.6	10.8	12.0	12.0	12.0	12.0
FTE	47.1	60.6	75.0	85.0	100.0	120.0	150.0	174.6	177.2	185.1
Demonstrator										
Material (MCHF)	0.6	2.2	3.9	5.4	7.8	15.1	25.9	32.4	31.8	12.6
FTE	9.5	11.0	12.5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

Key conclusions:

- Need the budget
- Start in Europe using exiting momentum
- Ramp up in the US and other regions

Muon Cooling Demonstrator





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

Important decision in 2028 on sharing of effort and demonstrator location

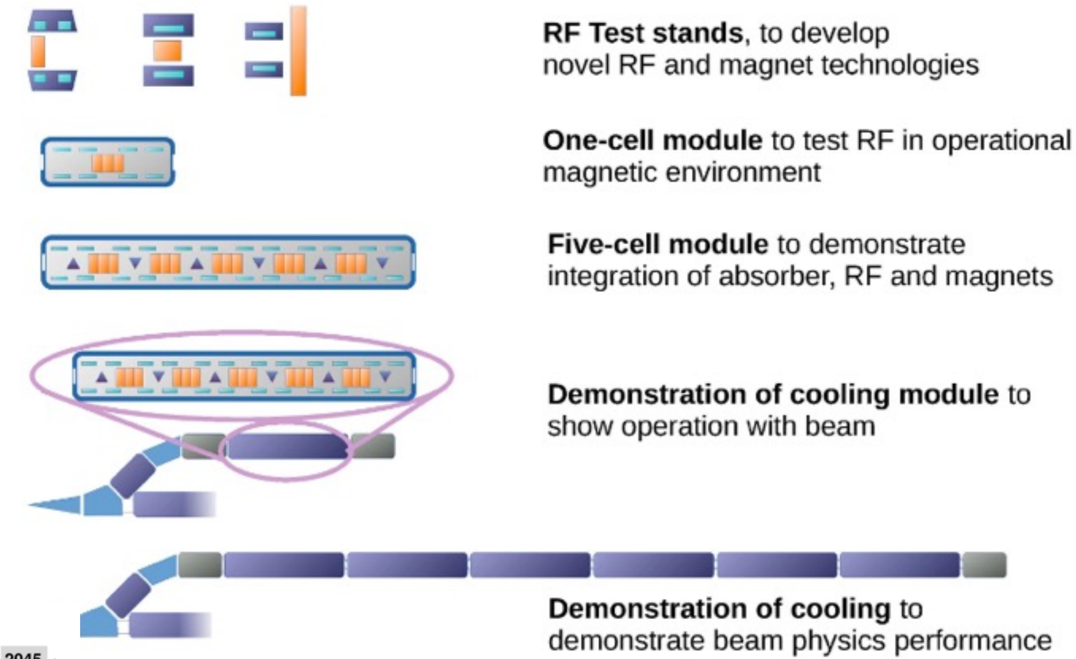
Two promising demonstrator site studies at at CERN

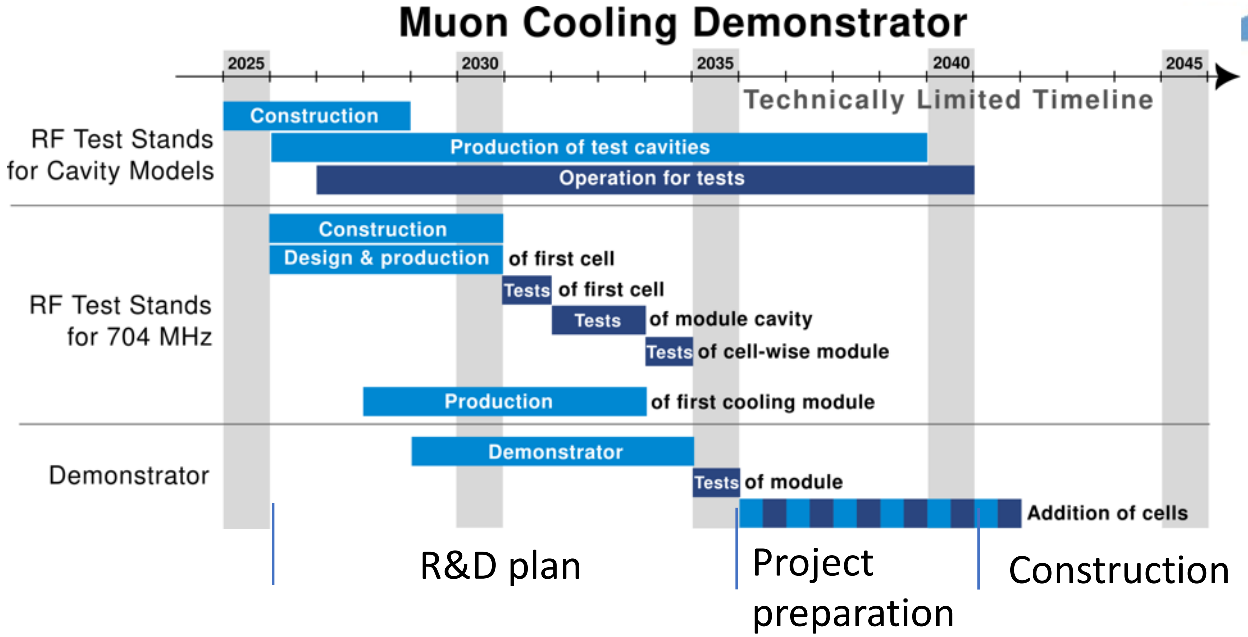
Budget for site Fermilab study approved

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
- Fermilab has approved a study
- RF test stands are critical and urgent
- Consistent with implementation timeline

Demonstrator Workshop @ Milano November 5-7, 2025

Way Forward

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

- Prepare sharing of work between partners
- Central funding through CERN and other partners is instrumental
- Identify additional funding sources
- Need strong support of ESPPU

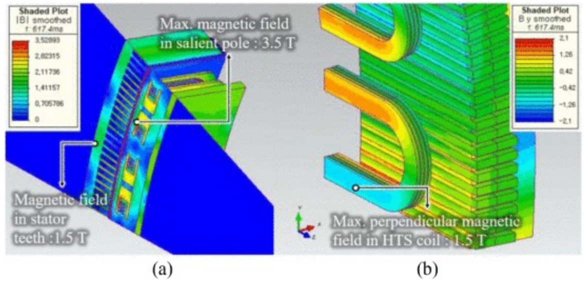
Started a task force to prepare the implementation

Exploit synergy with other particle physics and accelerators

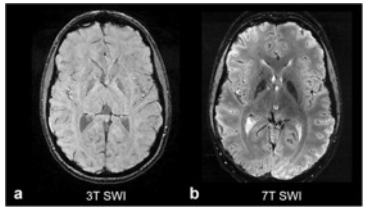
- Muons, neutrinos, …

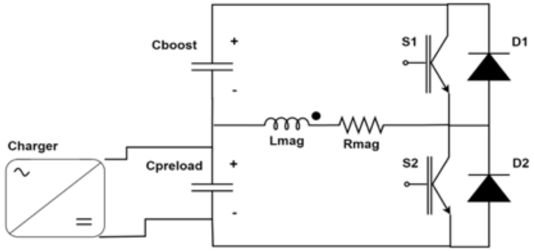
Strong synergy with societal applications exist

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



Design of 10 MW HTS wind generator





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

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

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

Attività R&D Acceleratori
simulazioni – prototipi – misure di laboratorio

International MUON Collider Collaboration

MI, GE, LNL, LNS, NA, PD, TO, TS (FE, RM1, RM3)

- Magneti (MI-LASA, GE) ➔ progetto ESPP, EU-MuCol (WP7)
- Radiofrequenze SC (SC-RF) (MI-LASA) ➔ progetto ESPP , EU-MuCol (WP6)
- Radiofrequenze NC-RF (MI-LASA,LNL,LNS,NA) ➔ progetto ESPP , EU-MuCol (WP6)
- Integrazione cooling cell (MI-LASA,LNL,LNS,NA,TO) ➔ EU-MuCol (WP8)
- Machine Detector Interface ➔ progetto ESPP (personale), EU-MuCol (WP2-WP5)

CRUCIALE PER STUDI DI FISICA E DETECTOR – PERFORMANCE MACCHINA

- *Cristalli per i fasci, misure di laboratorio per finestre sottili in fase di definizione*

ESPP_A_MUCOL ➔ approvato dal MAC INFN
WP1 - Machine Detector Interface
WP2 - Ionizing Cooling Cell design and integration:
- normal-conducting RF cavities
- high field solenoidal magnets

WP3 - Superconducting RF cavities: fast frequency tuner system
WP4 - High Field dipole Magnets technologies

Attività INFN – FTE progetti in sinergia da cambiare

Progetti con % SINERGICHE:
UE-MUCOL: GE, LNS, PD, RM1, TO, TS + MI Univ e PD Univ
PRIN_20229TBY8B:in chiusura
SIC_4DGAIN nuova sigla CSN5

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SEDE		FTE TOTALE	MuCol	ALTRO	ATTIVITA'					
		*100			FISICA/SIMULAZIONI	R&D DETECTOR	ACCELERATORI	COMMENTO	PRIN	DRD
BA		550			x	x		Fisica HCAL HPTPC	calo	x
BO	DTZ	80			x		x	Fisica teo e Fast ramping Magnets		
FE	DTZ	100				x	x	Cristalli		x
FI	DTZ	130			x	x		Fisica Detector		
GE		280	120			x	x	Magneti		
LNF		280				x		CRILIN	calo	x
LNL	DTZ	10					x	RF +(bersagni sottili)		
LNS	DTZ	15	15				x	RF		
MI		370	65				x	Magneti e RF		
MIB	DTZ	10					x	Test facility-dimostratore		
PI	DTZ	50			x	x		Fisica Detector		
PD		550	20		x	x	x	Fisica Detector Calcolo MDI Dimostratore		x
PV		285			x	x		Fisica e picosec+ generatori teo	gas - no FTE	x
RM1		165	20		x		x	MDI fisica e bersagli/materiali		x
RM3	DTZ	20			x			fisica		
TO		420	25	120	x	x	x	fisica R&D detector MDI e accel	gas - no FTE	x
TS	DTZ	30	20		x			fisica e ricostruzione		x

		RD_MUCOL	MuCol	CSN5/altro in preparazione
TOT FTE	33,2	27,75	4,2	1,2

Always investigating synergies on physics and technologies

Grazie!
domande?

High-priority future initiatives [..]
In addition to the high field magnets the **accelerator R&D roadmap** could contain:
[..] an **international design study** for a **muon collider**, as it represents
a **unique opportunity** to achieve a ***multi-TeV energy domain*** *beyond the reach of* e^+e^- *colliders*, and potentially within a *more compact circular tunnel* than for a hadron collider. The **biggest challenge** remains to produce an intense beam of cooled muons, but *novel ideas are being explored.*

extras

International Muon Collider Collaboration @ CERN

International MUON Collider Collaboration

After the ESPPU recommendation in June 2020:
Laboratory Directors' Group (LDG) initiated the Muon Collider Collaboration July 2, 2020

Project Leader: *Daniel Schulte*

Objective:
In time for the next European Strategy for Particle Physics Update, the Design Study based at CERN since 2020 aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.
It will **provide a baseline concept**, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers.
It will also **identify an R&D path to demonstrate the feasibility of the collider**.

Scope:
- Focus on the high-energy frontier and two energy ranges:
– **3 TeV** if possible with technology ready for construction in 10-20 years
– **10+ TeV** with more advanced technology, **the reason to choose muon colliders**
- Explore synergies with other options (neutrino/higgs factory)
- Define **R&D path**

Do not yet have the resources of the reduced scenario
Priorities with available expertise and resources
Are approaching O(40 FTE)
Efforts to increase resources

Energy efficiency of present and future colliders

Thomas Roser et al., Report of the Snowmass 2021 Collider Implementation Task Force, Aug 2022

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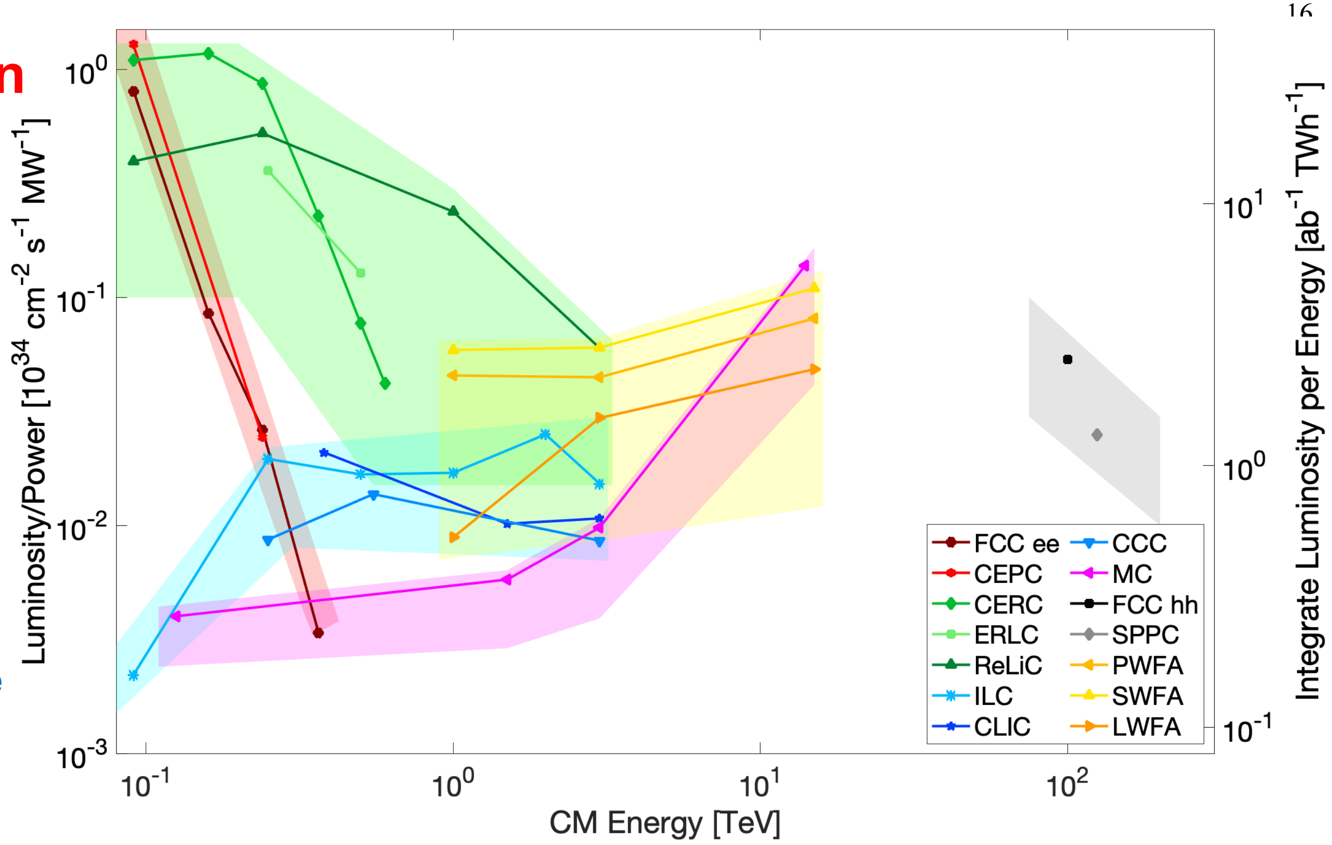
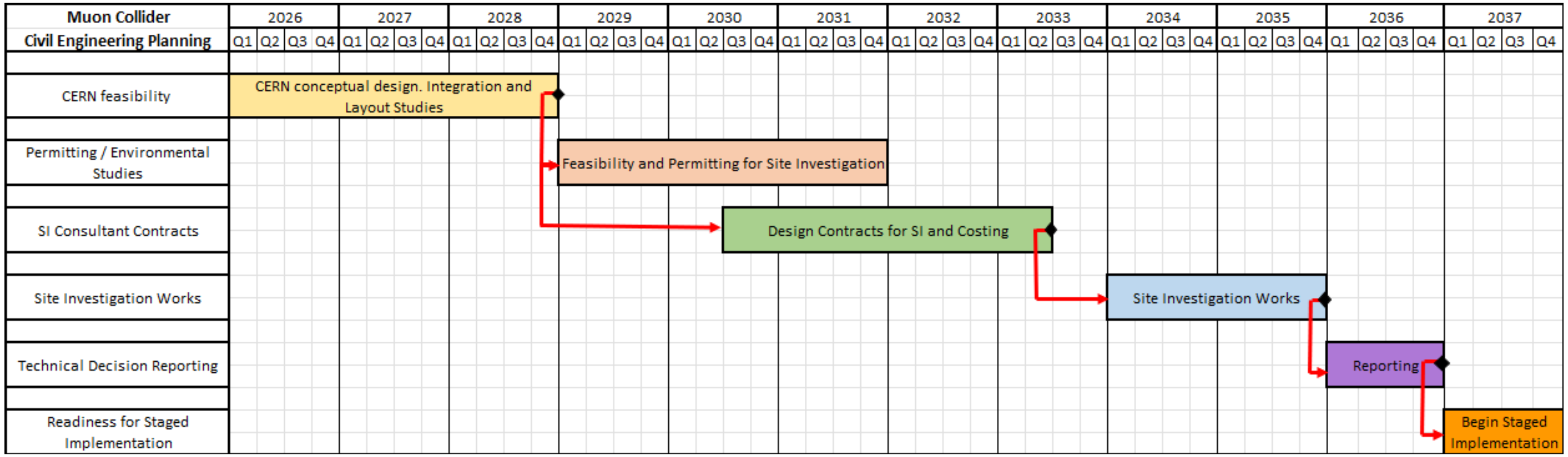
Luminosity per power consumption

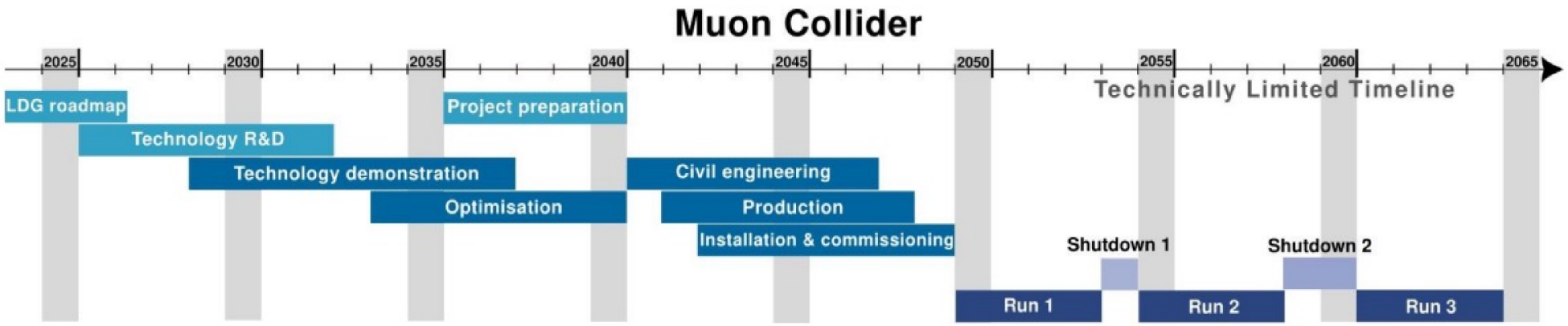
- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Luminosity is per IP and integrated luminosity assumes 10^7 sec/year
- Data points are provided to the ITF by proponents of the respective machine
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



The effective energy reach of hadron colliders (LHC, HE-LHC and FCC-hh) is approximately a factor of seven lower than that of a lepton collider operating at the same energy per beam

Long Term R&D





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

RF and High-Field HTS Development Strategy

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

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

This is therefore a part of the muon cooling technology development

Had good discussions with the LDG RF panel
SLAC is investing into an RF test stand

- Also efforts at INFN and in the UK

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

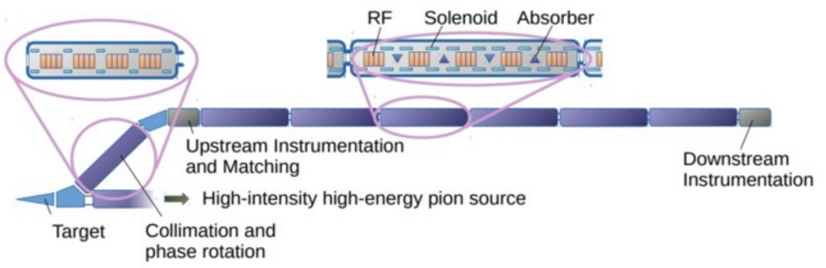
- The LDG should play an important role

The HTS solenoid technology is of high importance for societal applications

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

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

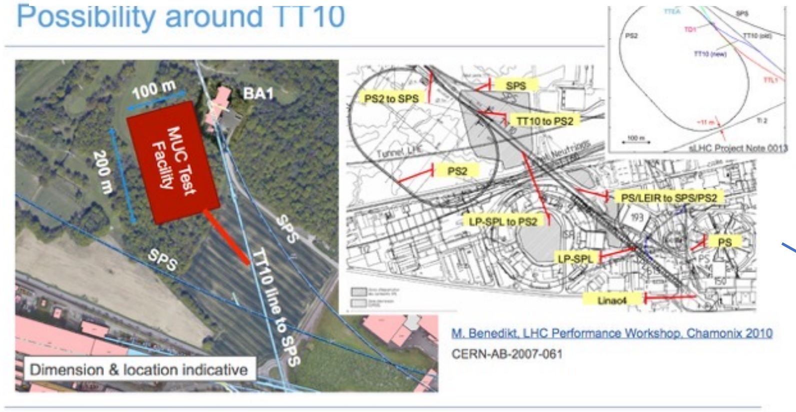
Demonstrator Facility: a crucial step forward!



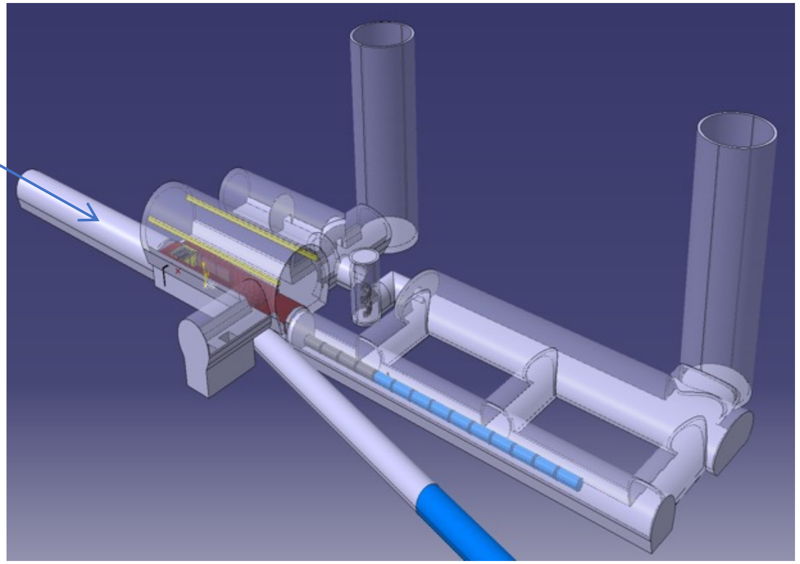
Planning **demonstrator** facility with muon production target and cooling stations

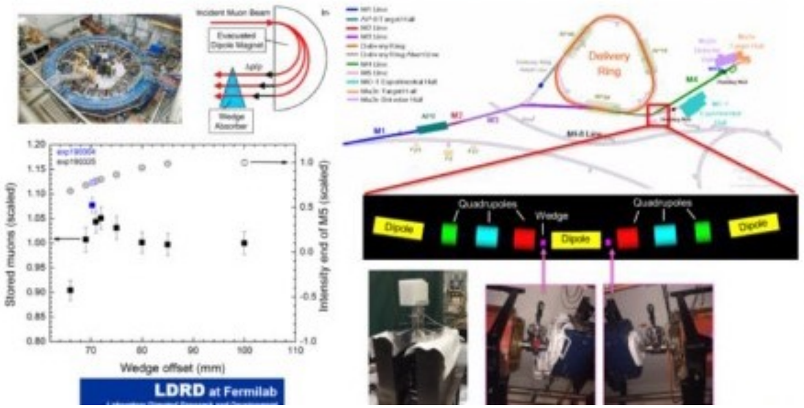
Suitable **site exists** on CERN land and can use **PS proton beam**

- could combine with **NuStorm** or other option



@ CERN





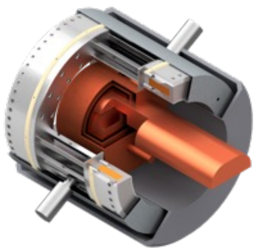
@ FNAL

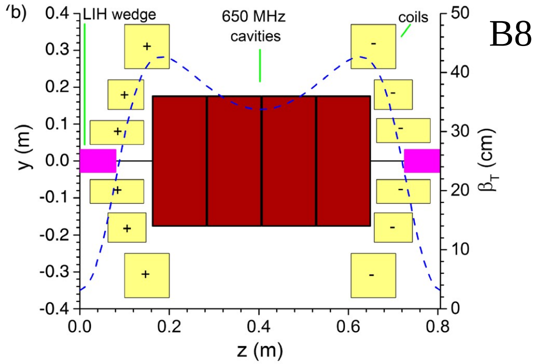
[International Muon Collider Collaboration: Demonstrator Workshop](#)

@ FNAL October 30 – November 1, 2024

Time-critical Developments

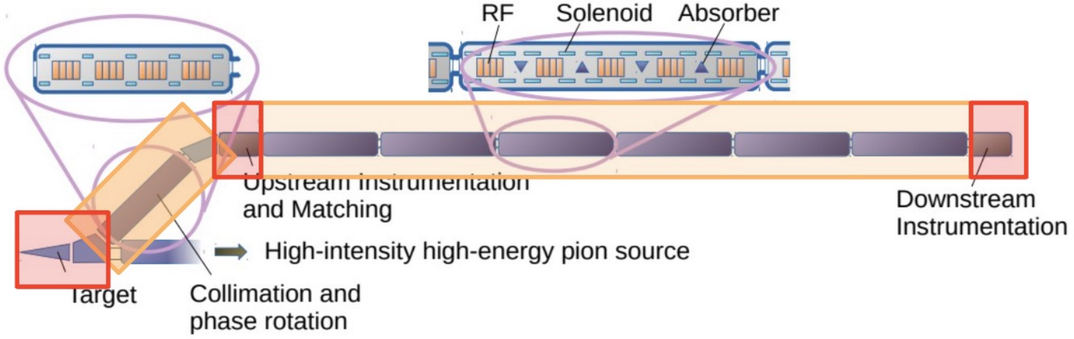
Identified three main technologies that can limit the timeline





Muon cooling technology

- **RF test stand** to test cavities in magnetic field
- **Muon cooling cell** test infrastructure
- **Demonstrator**
  - Muon beam production and cooling in several cells



Magnet technology

- HTS solenoids
- Collider ring magnets with Nb3Sn or HTS

Important Developments

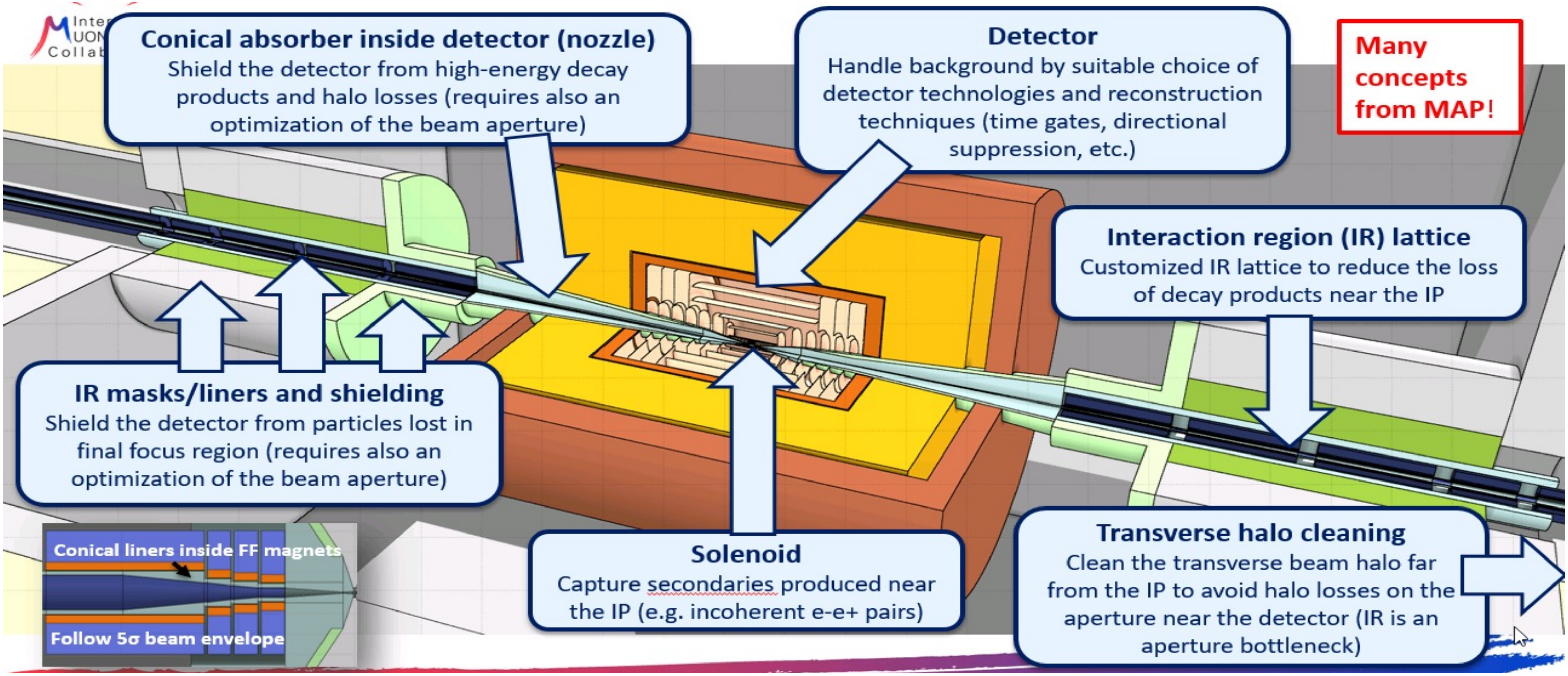
Detector technology and design

- Can do the important physics with near-term technology
- But available time will allow to improve further and exploit AI, MI and new technologies

Machine Detector Interface - beam-induced background

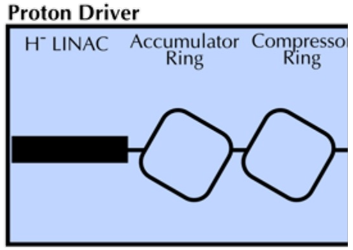
Background is a significant driver for MDI design - background sources:

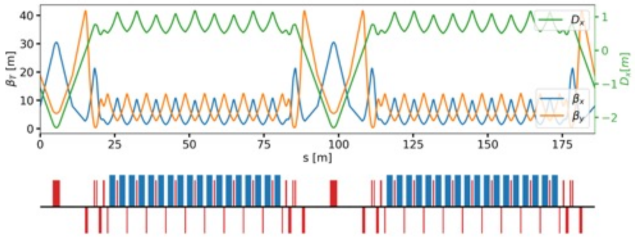
- **Muon decay**
- Beam halo losses and Beam-beam (mainly incoherent e-/e+ pair production)

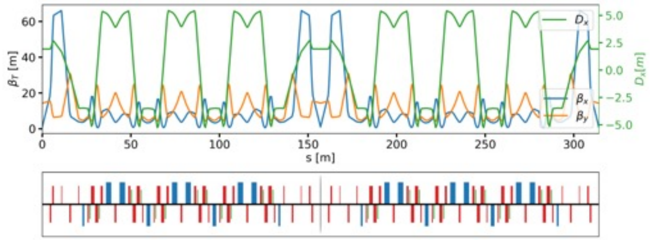


Proton Complex

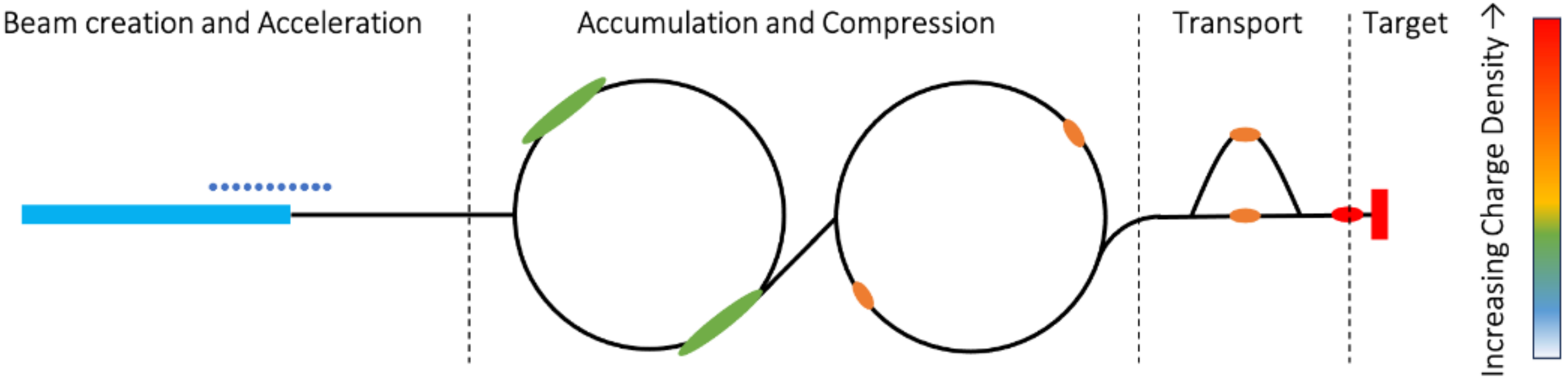
Challenge:
- 2 MW, 5 GeV, 5 Hz,
- 5 x 10^{14} protons/pulse
- Proton pulse accumulator and compressor rings

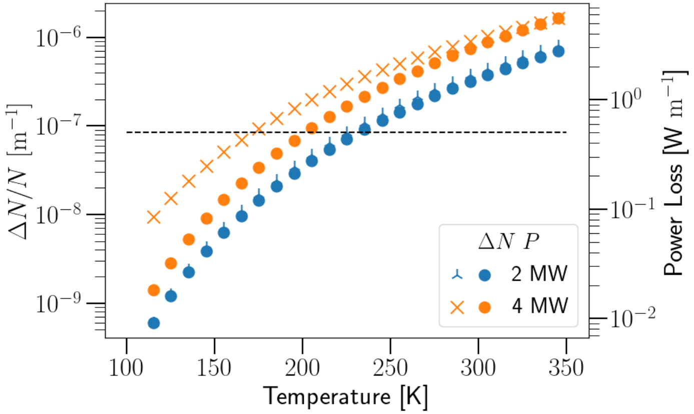






Achieved:
- Accumulator and combiner ring lattices
- First collective effects studies show stable beam
- Optimise between one or two bunches in compressor





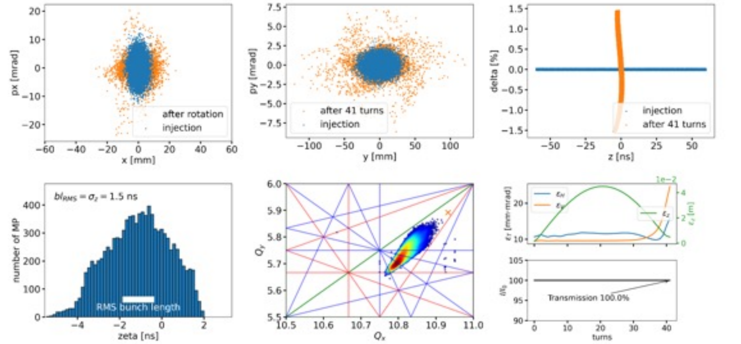


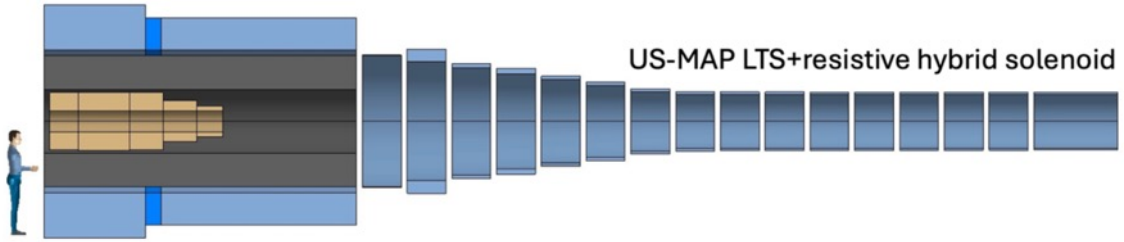
Fig. 5.1.8: Simulation of the full compression for one bunch at 5 GeV. Since this requires a 2 bunch solution scheme, this bunch has half of the full intensity shown in Table 5.1.1. Notice that at the end of the compression there is still some emittance blow up that need still to be addressed.

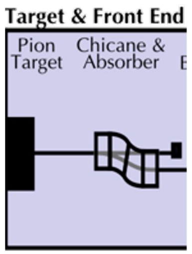
Key conclusions:
- Can compress 2 MW, 5 GeV proton beam to two 2 ns bunches, then merge them
  - Optimisation in compressor ring for collective effects ongoing
- For 4 MW need 10 GeV beam
- Cool beamline to avoid ion loss from black body radiation

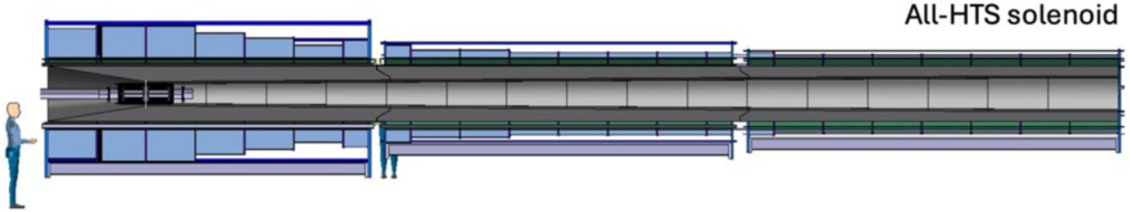
Target

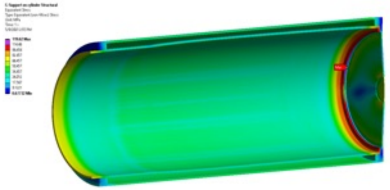
Challenges:
- 2 MW, 5 Hz, 400 MJ/pulse target
- Can we replace mercury with graphite?

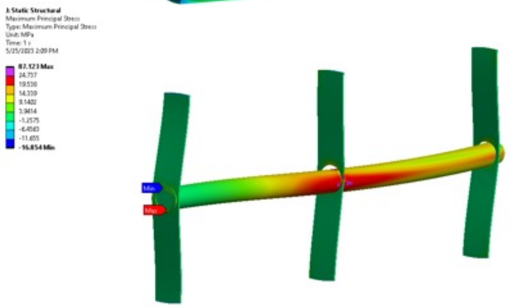
Achieved:
- Initial 2 MW graphite target conceptual design, pion yield optimised
- HTS solenoid and shielding concept developed
- Study of proton removal ongoing

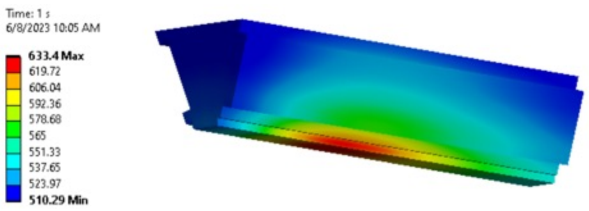


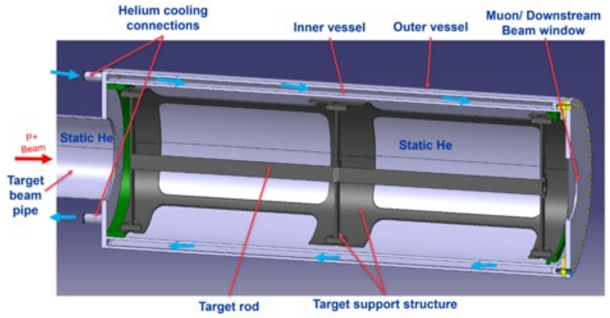












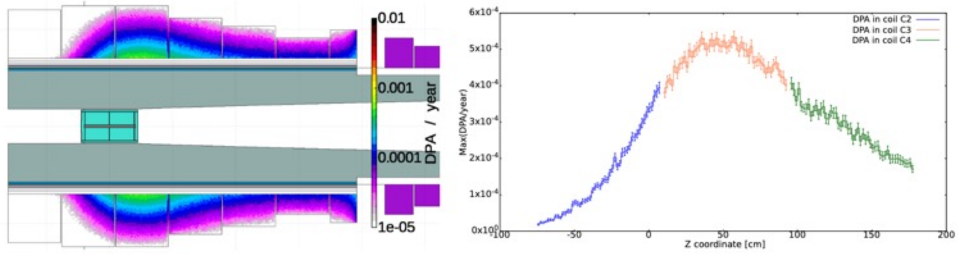


Fig. 6.5.1: 2D map of the displacement per atom (DPA) in the superconducting magnets of the target area (left) and the peak DPA in the coils most exposed to radiation (right).

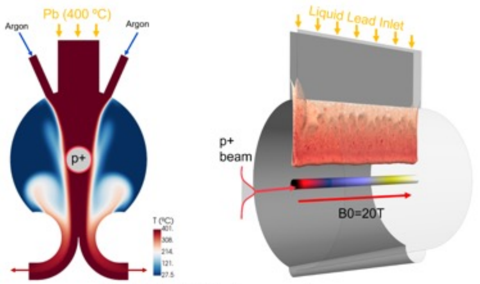


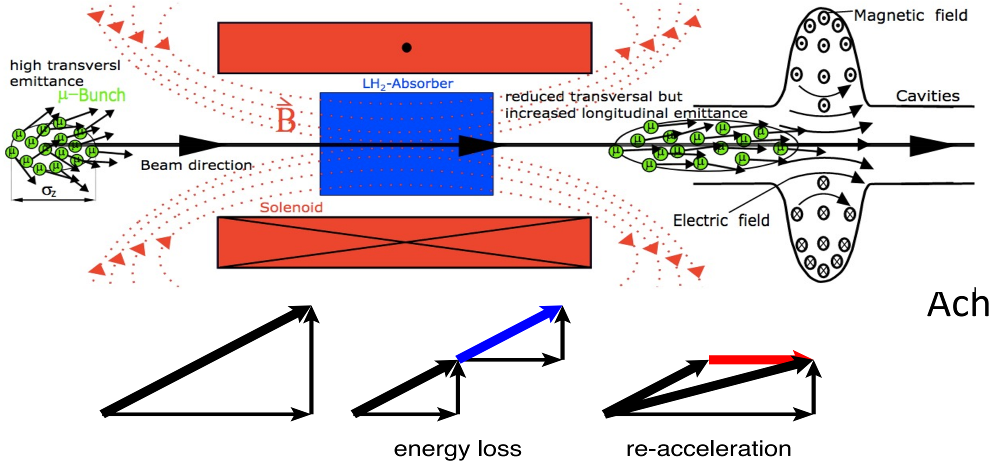
Fig. 6.4.4: Liquid lead target curtain concept.

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

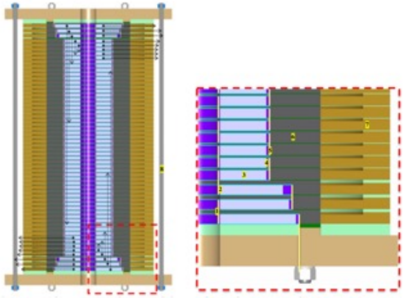
Need magnet hardware

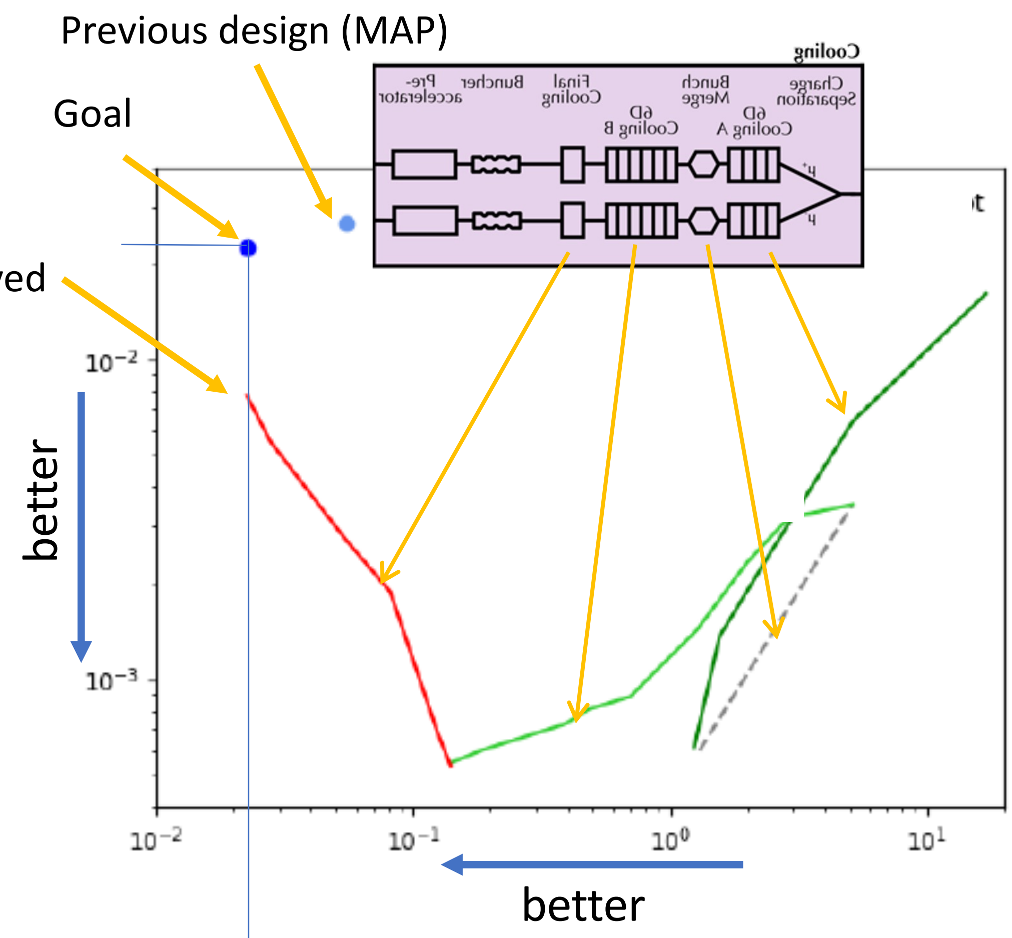
Muon Cooling Lattice Design

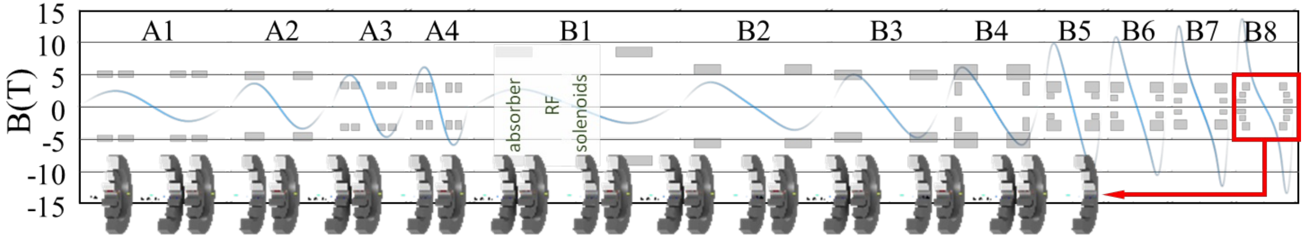
Challenges:
Novel, complex lattice with cavities and absorbers in solenoids
High magnetic field



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



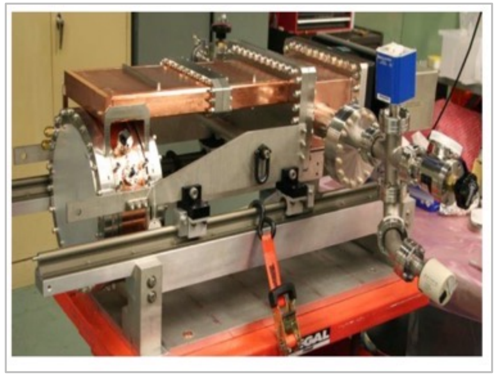




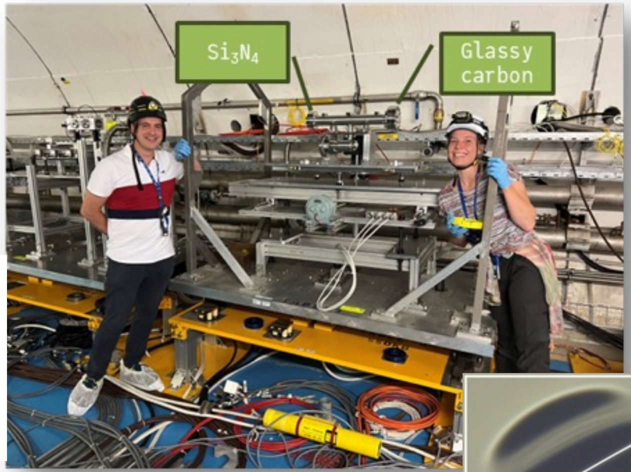
Key conclusions:
- Can in principle reach or exceed performance target
- **Need to build magnet models and prototypes**
- Much improved longitudinal, is useful for collider ring
- Study of collective effects important

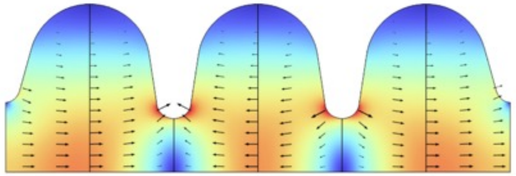
Muon Cooling Technology

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

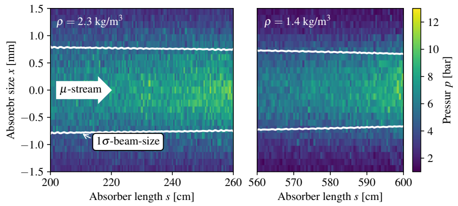


MuCool demonstrated >50 MV/m in 5 T
- H2-filled copper
- Be end caps

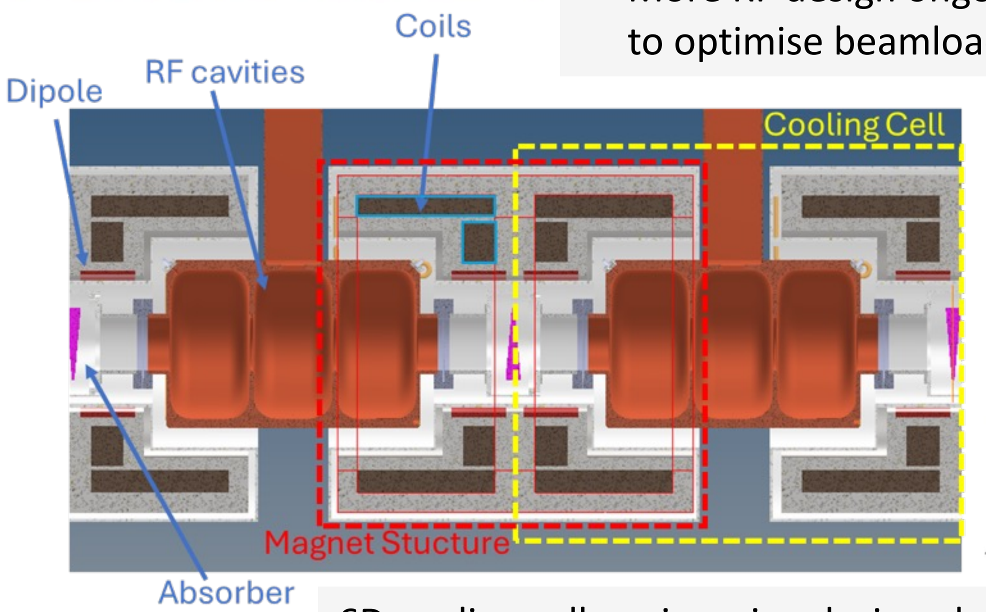


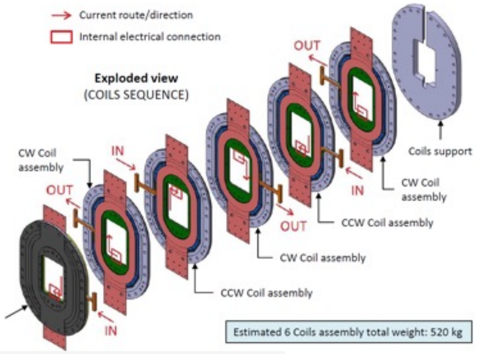


MAP proved gradient
- Initial RF designs
- More RF design ongoing to optimise beamloading



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





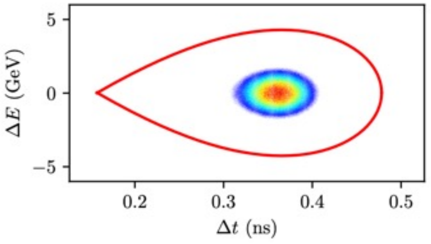
6D cooling cell engineering design almost ready

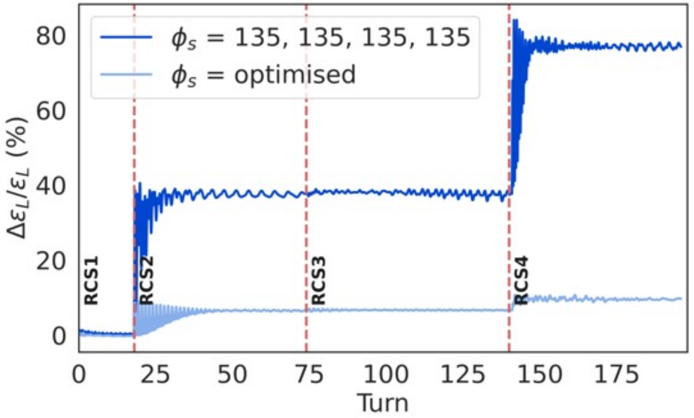
Key conclusions:
- Ready to **ramp-up effort**, in particular prototyping and experimental work, also beamdynamics
- **Need RF test stands** for experimental optimization
- SLAC is building one, INFN and UK are preparing
- **Need test cell prototype**

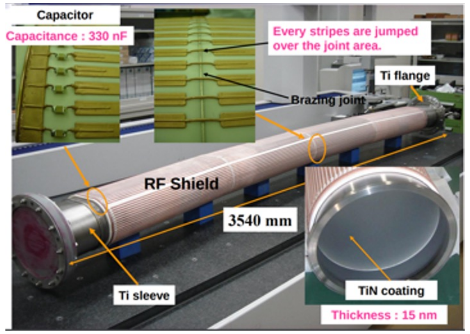
RCS Designs

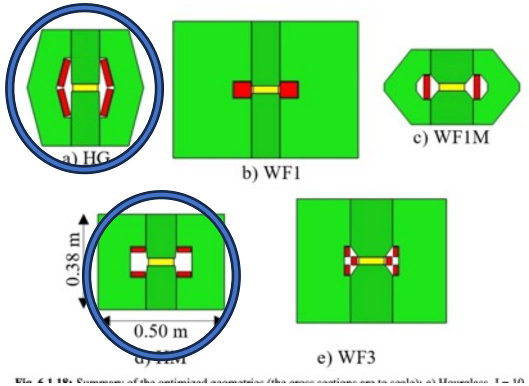
Challenge:
- Uses fast-pulsed normal magnets
- 5 Hz pulses of O(1-10ms)
- 6-35 km circumference
- Cost
- Recover energy from magnetic field
- High bunch charge
- Maintain beam quality

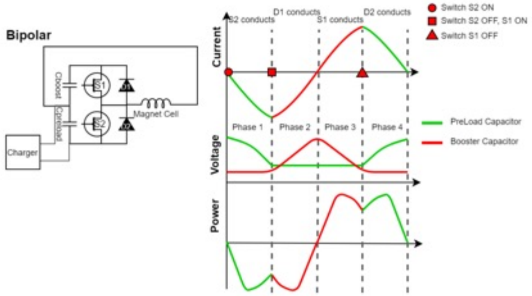
Achieved:
- Lattices for all site independent RCSs
- Beam propagation through complex
- Conceptual design of magnets and power converters
- Optimised design together with RF

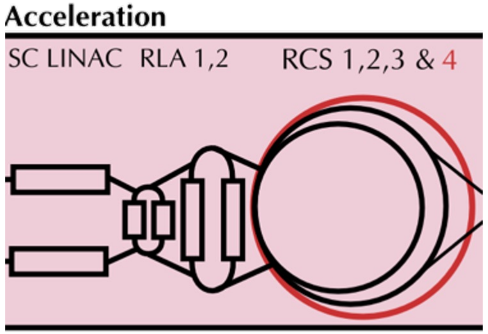


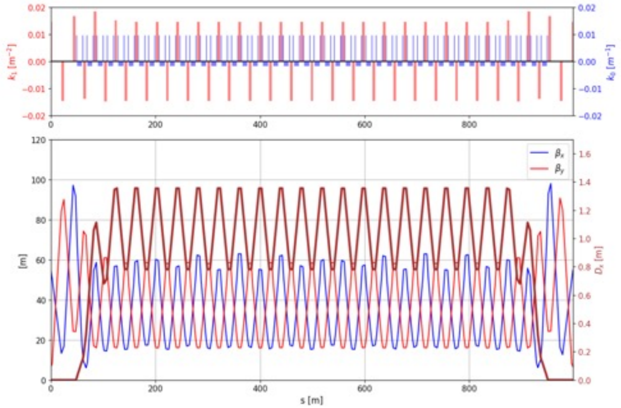












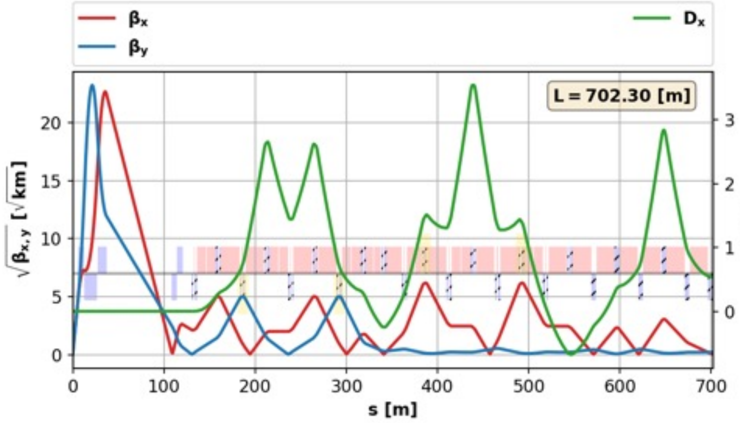
RCS	E [J/m]	Loss [%]	P [MW]
SPS 1	5447	**1.1**	1.9
LHC 1	5678	**1.6**	12.8
LHC 2	5752	**6.3/2**	26.6

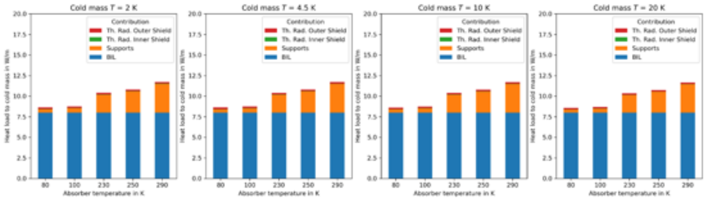
Key conclusions:
- 1.3 GHz TESLA-type cavities work
- Emittance transport is OK
- Cost and power is OK
- Need to connect to initial linacs
- **Need to build prototypes**

Collider Ring

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

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

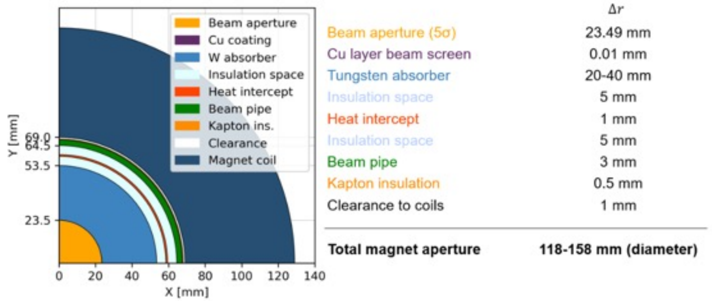


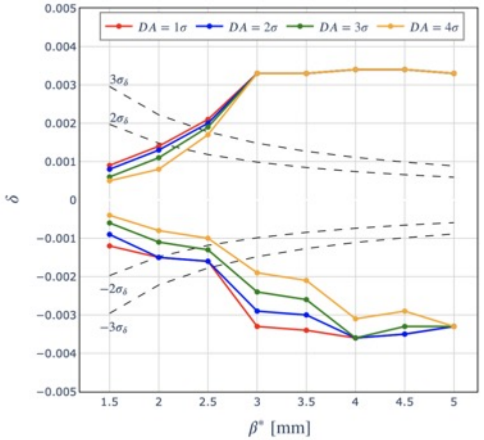


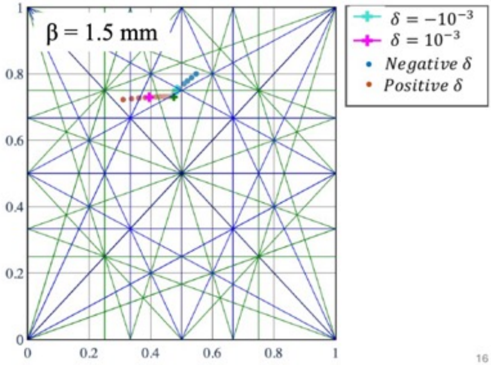
Cryogenic loads at different temperatures

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

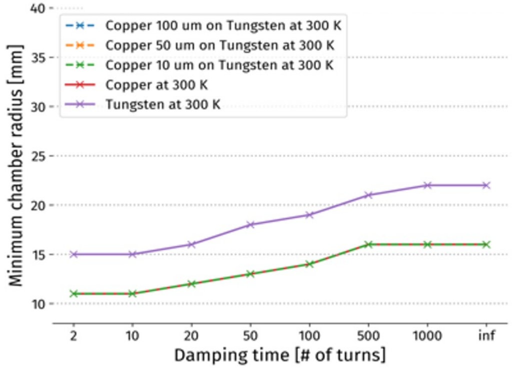
Shielding (30-40 mm)

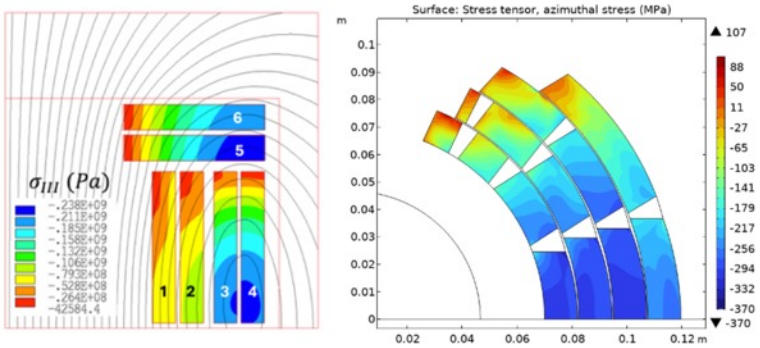






Beam pipe impedance





Magnet Designs

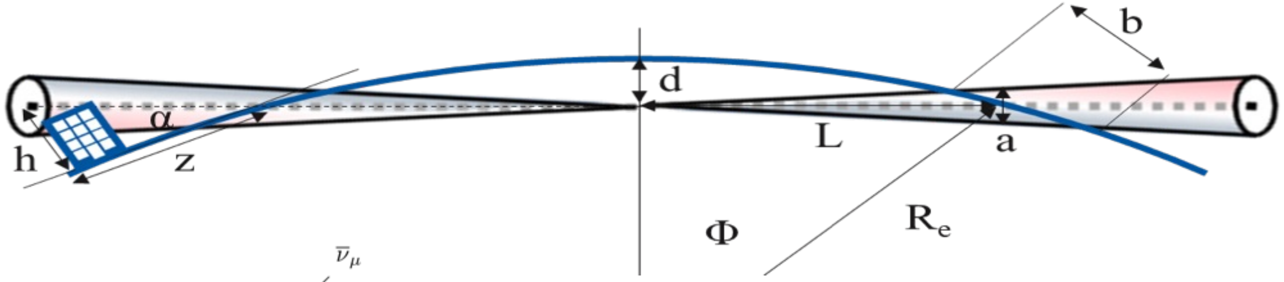
tor under Lorentz Forces at nominal current for both block coil

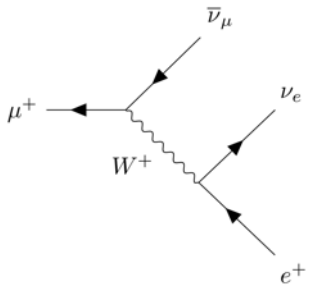
Key conclusions:
Magnets, shielding, cooling concepts are OK
Further improve energy acceptance, but OK with energy spread predicted in muon cooling
Imperfection mitigation next
Magnet model/prototypes

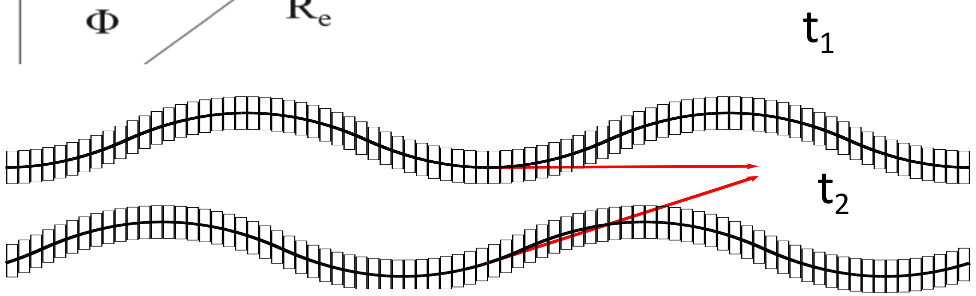
Placement Studies

Challenge:
Obtain negligible neutrino flux

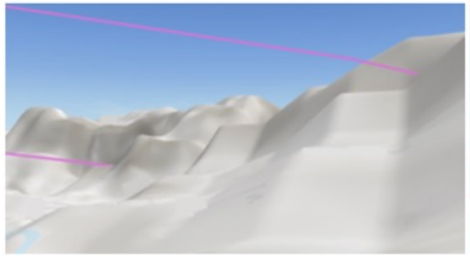
Achieved:
- Detailed modelling
- First good orientation found
- Mover system concept

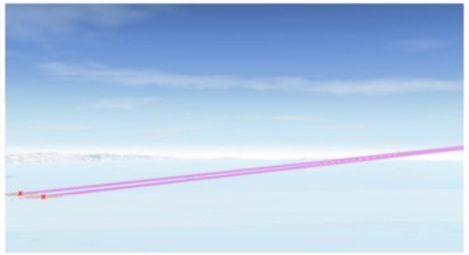




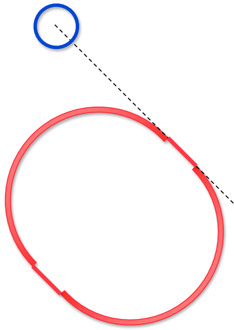


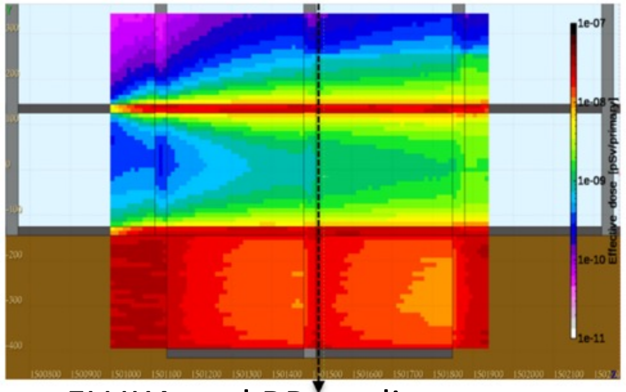
Arc mitigation concept



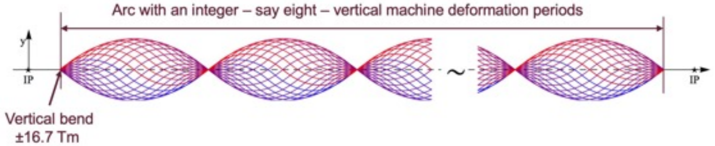


Site study at CERN for experimental insertion

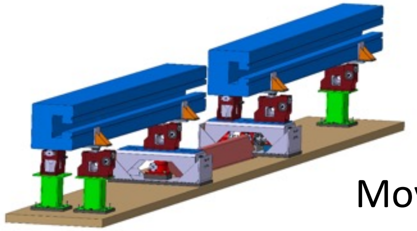




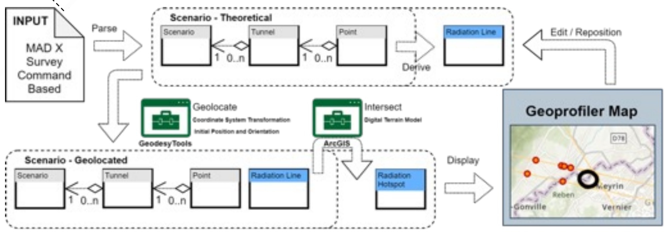
FLUKA and RP studies



Beam studies

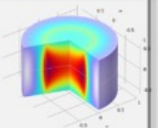
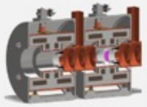
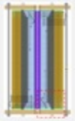
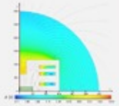
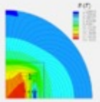


Mover system design



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

Magnet R&D Impact

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

L. Bottura

R&D Impact Examples

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

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

Start-to-end Model

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

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

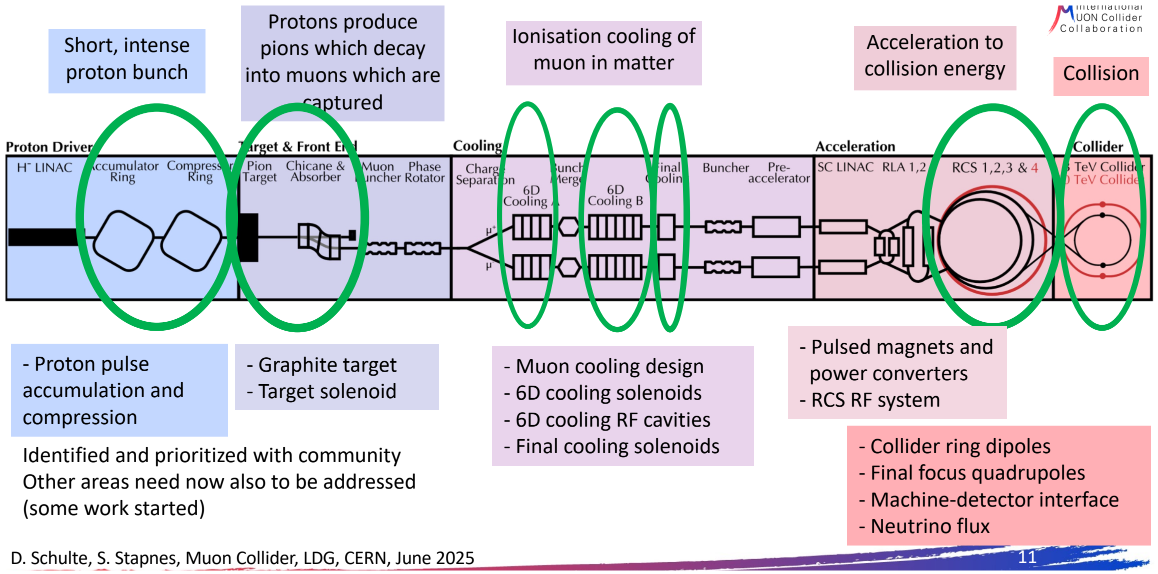
- Design of the collider areas with **lattice challenges** and contained **Critical Technology Elements**
- Address the key challenges such as neutrino flux and beam-induced detector background
- Development of missing critical simulation tools
- Development of realistic performance targets for the components

Now available:

- Initial cost model
- Initial power consumption model

With increased resources can:

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



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

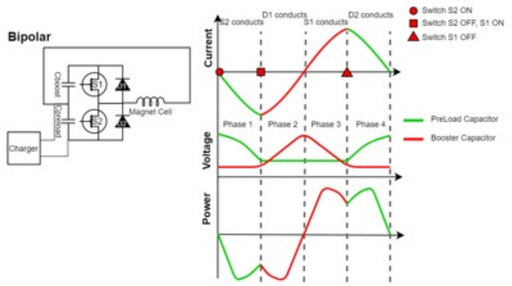
Power Consumption Estimate

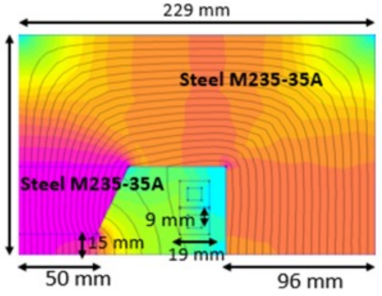
Power estimate is based on

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

No overall optimization has been performed for the power consumption

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



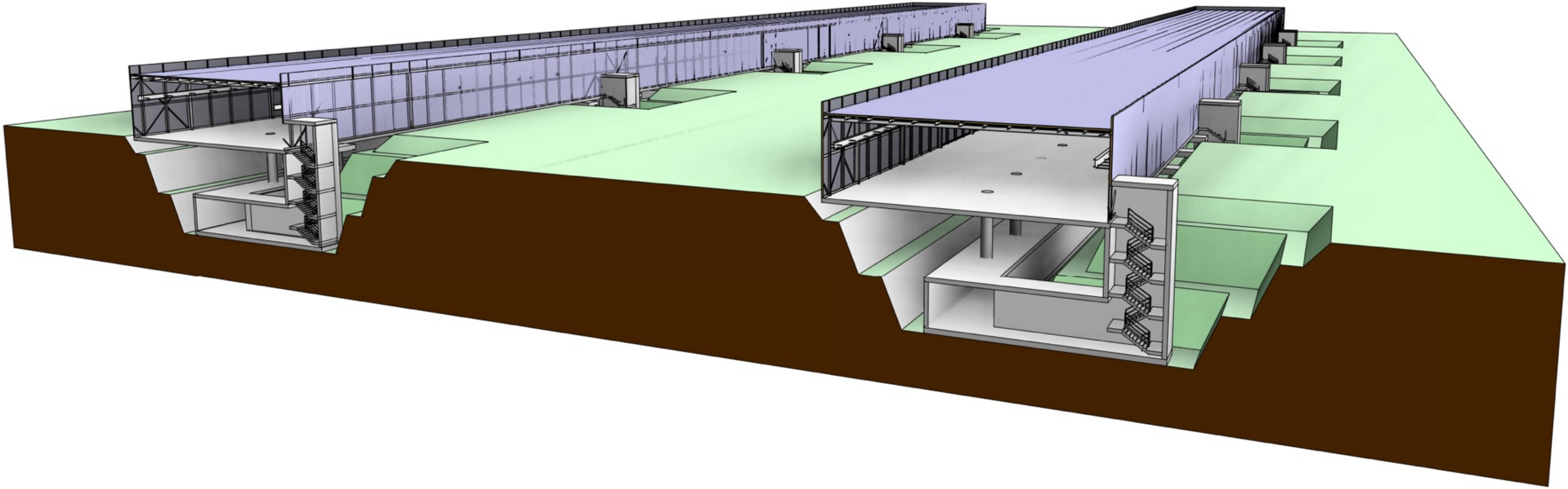


RCS	E [J/m]	E_{iron} [J/m]	E_{copper} [J/m]	Loss [%]	P [MW]
SPS 1	5447	10	52	**1.1**	1.9
LHC 1	5678	9.2	80.6	**1.6**	12.8
LHC 2	5752	63.4	298	**6.3/2**	26.6

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

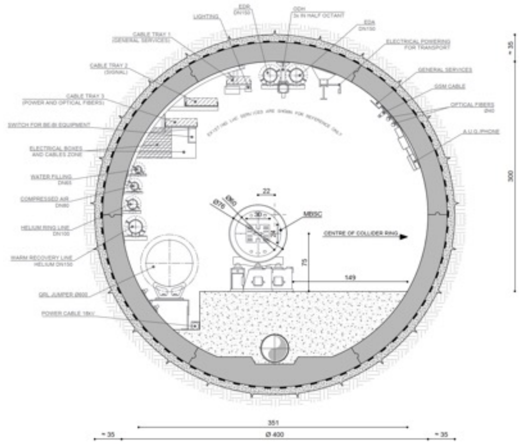
Injector Complex

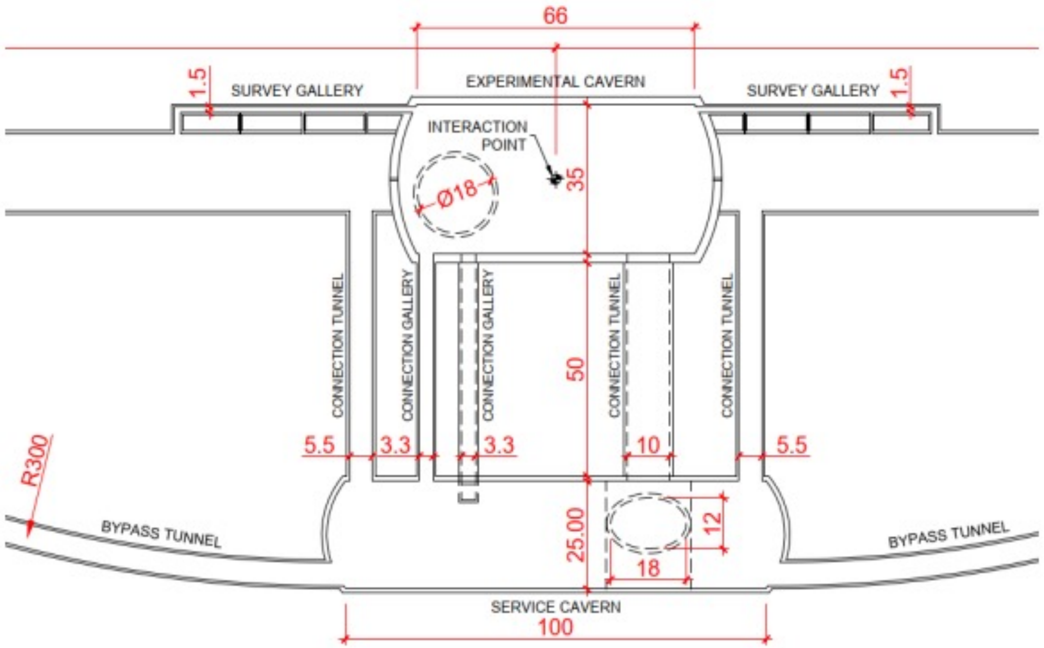
- The injector complex needs to undergo optimization before detailed design.
- Each component of the surface injector complex needs tailored civil engineering design based on individual component requirements.
- Upon freezing the layout, detailed studies into the environment, topography and below ground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



Collider Ring and Interaction Region

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



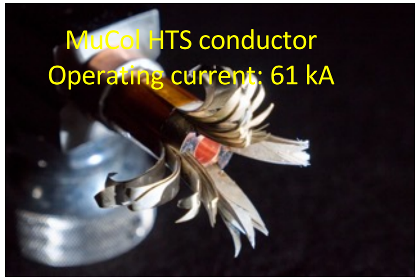


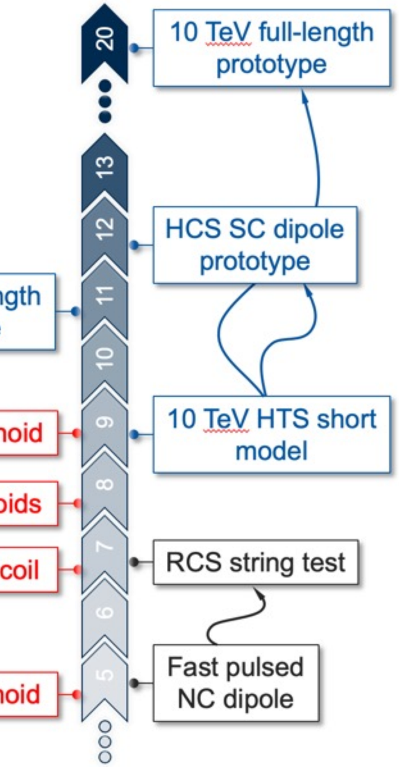
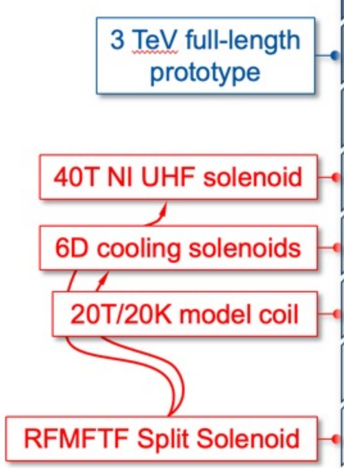
Surface Structures

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

Magnets

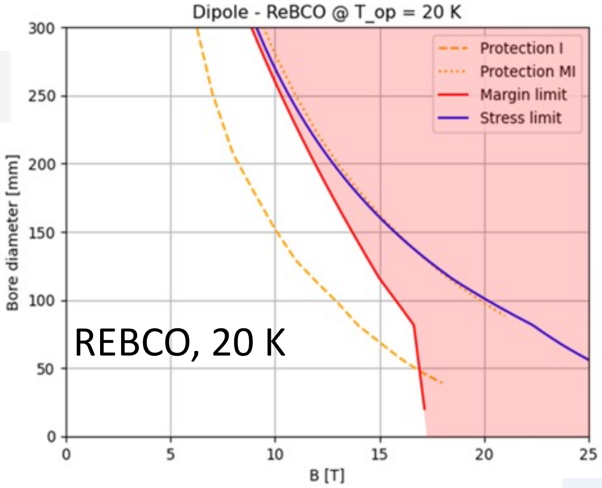
Achieved:
- Systematic **dipole/solenoid performance prediction (LTS** and **HTS)**
  - Aperture, field, cost, stress, loadline, protection, …
- **HTS solenoid designs (6D cooling, final cooling, target)**
- Normal-conducting **fast-pulsed dipoles** (HTS as alternative)
- Technically limited R&D timeline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



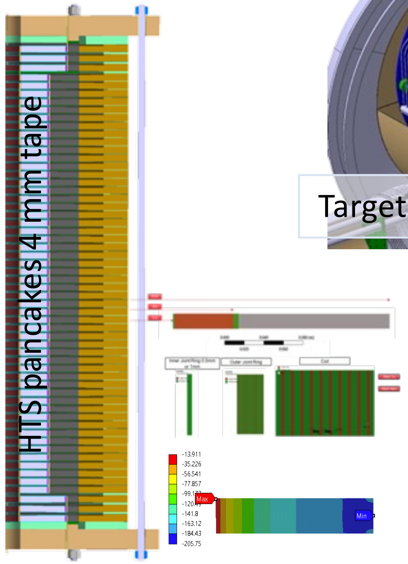



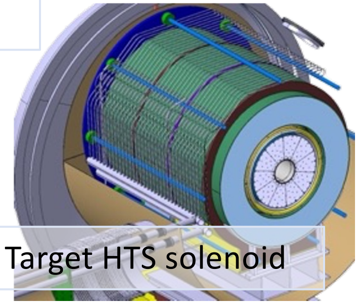
First **HTS winding tests**

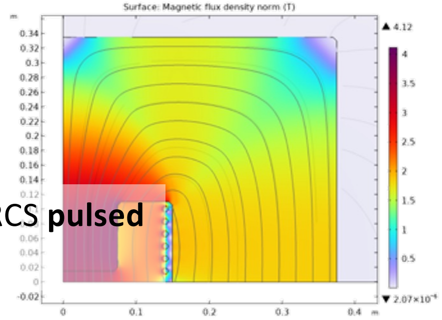
Did adjust collider ring field



HTS final cooling solenoid mechanical design







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

R&D Plan Deliverables and Resources

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

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

Technologies	Deliverables	Key parameters and goals
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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

R&D Plan Deliverables and Resources

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Totals:

Duration 10 years

Accelerator: 300 MCHF material, 1800 FTEy

Detector: 20 MCHF material, 900 FTEy

Year	I	II								
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	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
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