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International MUON Collider Collaboration

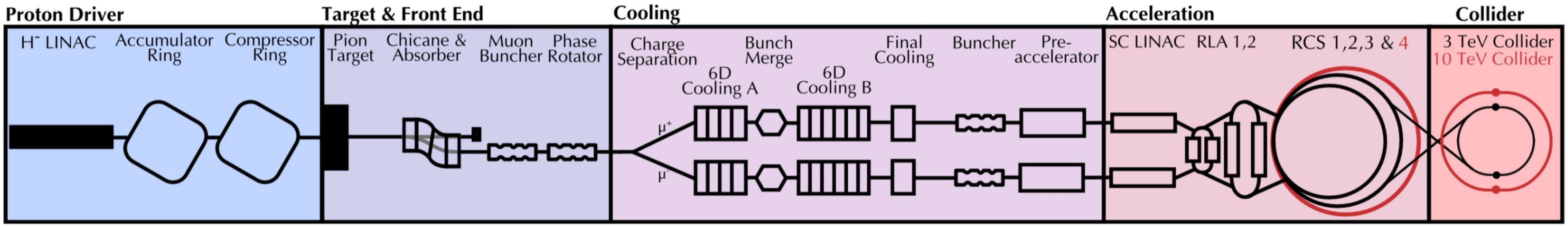
MuCol

Magnets
Timeline, R&D Plan and Cost

L. Bottura[1], F. Boattini[1], B. Bordini[1], B. Caiffi[2], S. Fabbri[1], S. Mariotto[3,4], M. Statera[3]

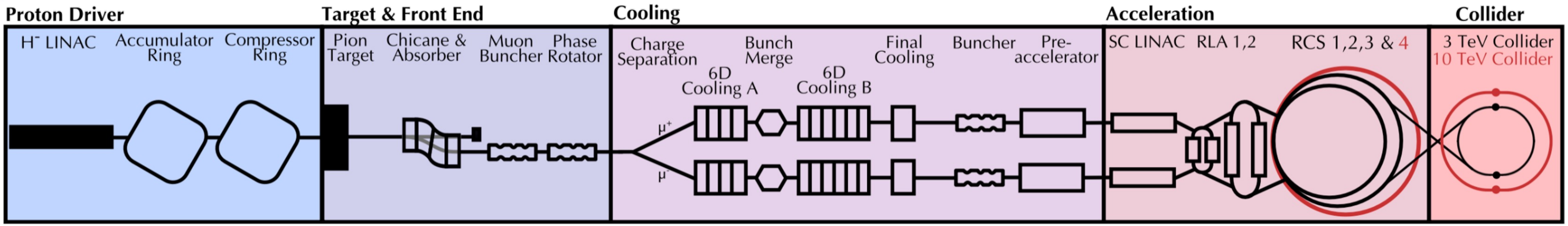
[1] CERN , [2] INFN – Genova, [3] INFN – Milano, [4] University of Milan

OUTLINE



- References
- Magnet timeline
- R&D plan
- Cost evaluation
- Summary

OUTLINE



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REFERENCES

The Muon Collider

402 pages

31 March 2025
EDMS: 3284315
arXiv: 2503.21185

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

The International Muon Collider Collaboration

The material presented here is detailed and discussed extensively in the documents prepared for submission to the 2026 ESPPU process

11 pages

Magnet R&D for the Muon Collider
European Strategy Input

L. Bottura, B. Auchmann, F. Boattini, B. Bordini, B. Caiffi, L. Cooley, S. Fabbri, S. Gourlay, S. Mariotto, T. Nakamoto, S. Prestemon, M. Statera

31 March 2025
EDMS: 3231359
arXiv: 2503.21179

Much space and attention was given to building a bottom-up and analytical R&D program

42 pages

Magnet R&D for the Muon Collider

L. Bottura, B. Auchmann, F. Boattini, B. Bordini, B. Caiffi, L. Cooley, S. Fabbri, S. Gourlay, S. Mariotto, T. Nakamoto, S. Prestemon, M. Statera

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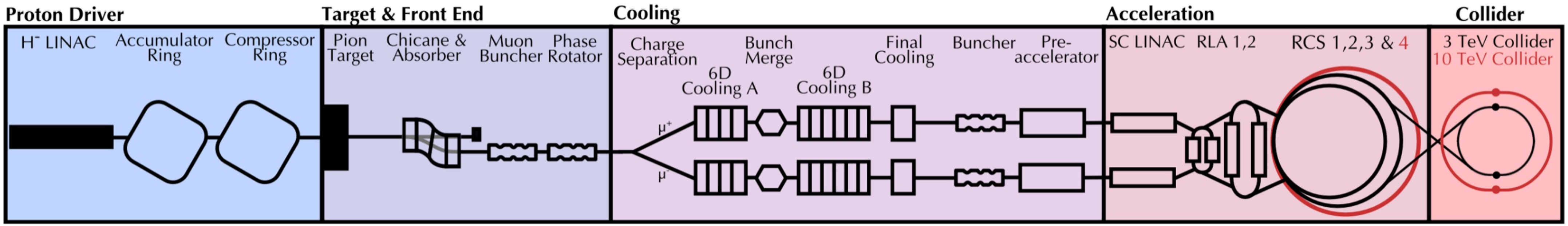

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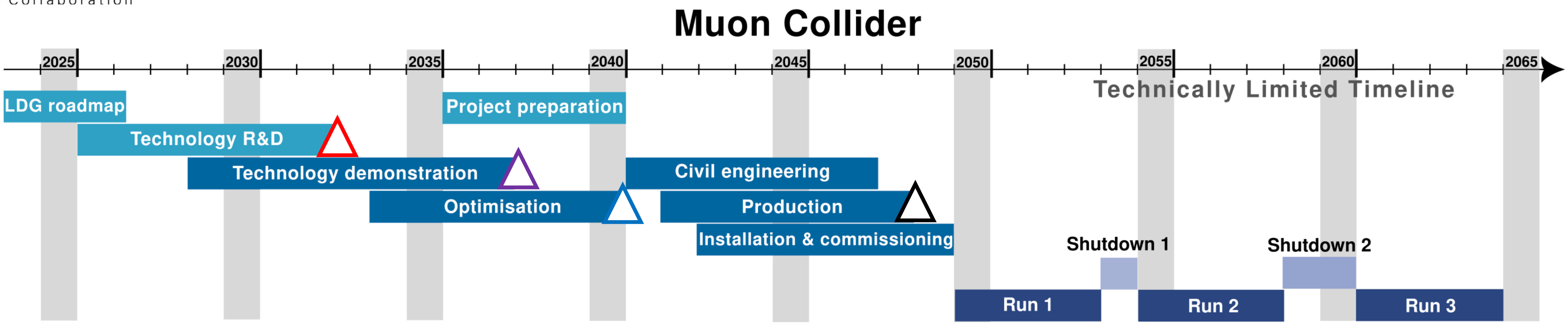
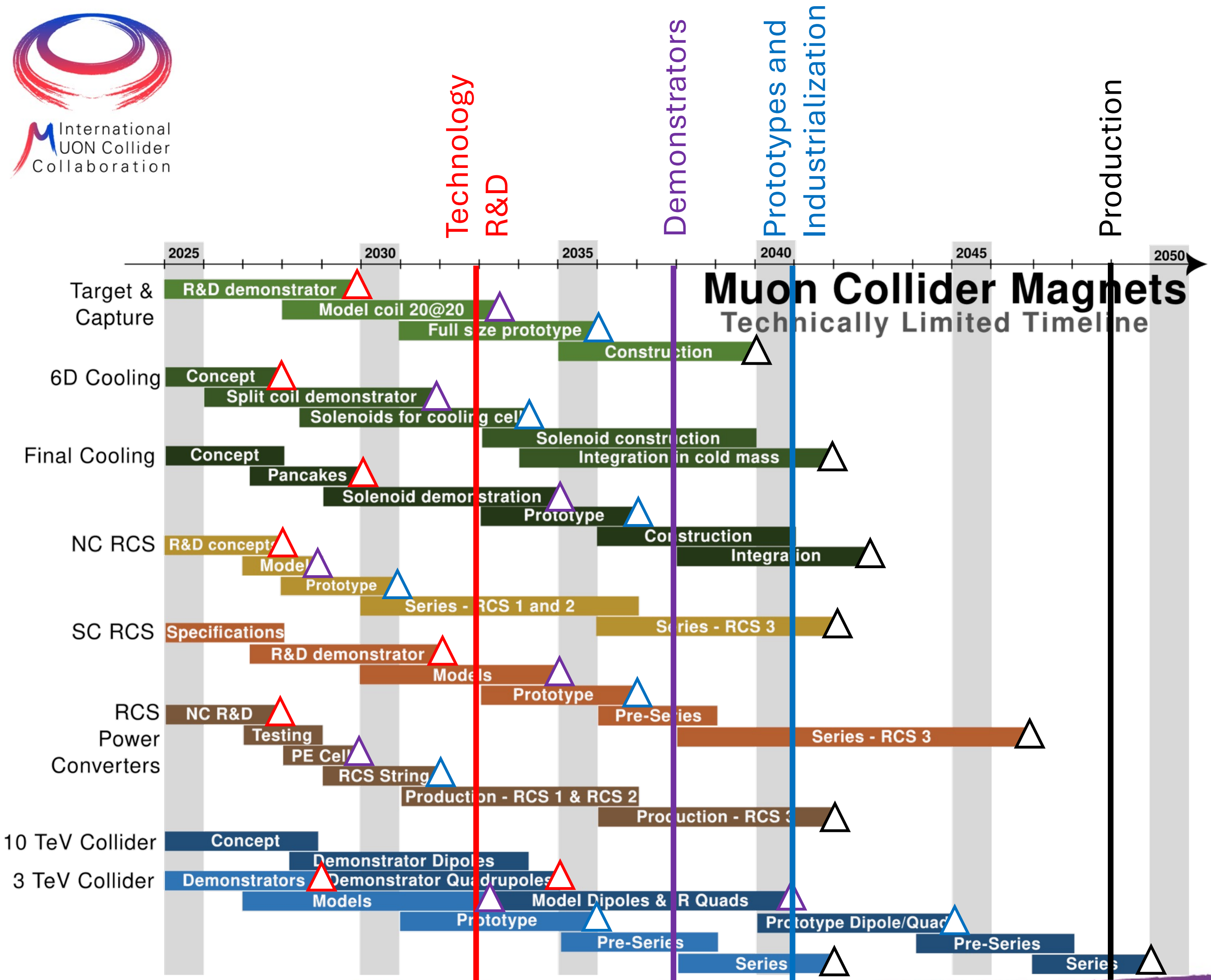
PROJECT TIMELINE

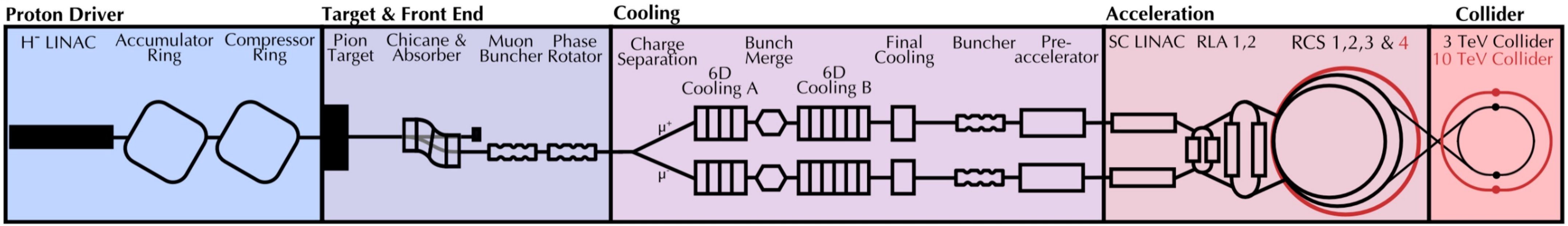


- Technology R&D completed: 2032
- Demonstrators built and tested: 2037
- Prototypes and industrialization (Optimisation): 2040
- Production completed: 2048



- This is one of the possible plans, prepared as a **technically limited timeline**
- Most magnet milestones are well aligned with the overall project plan
- A 3TeV option (consisting of HTS solenoids, NC RCS1+RCS2 and Nb-Ti collider) appears to be feasible *with contingency* by the desired start in 2050
- A 10TeV option (HTS solenoids, NC RCS1+RCS2, HTS HCS3 and HTS collider) misses the desired 2050 milestones by 2…3 years

Outline



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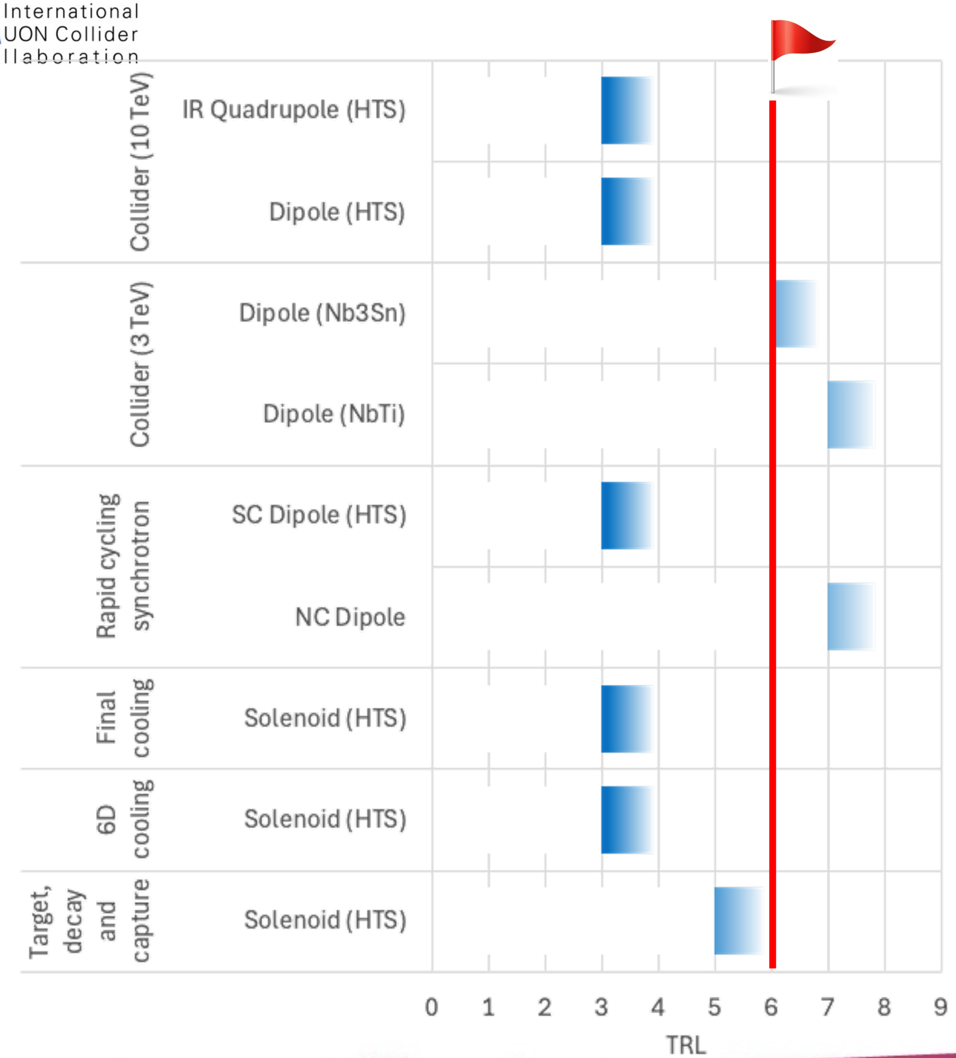
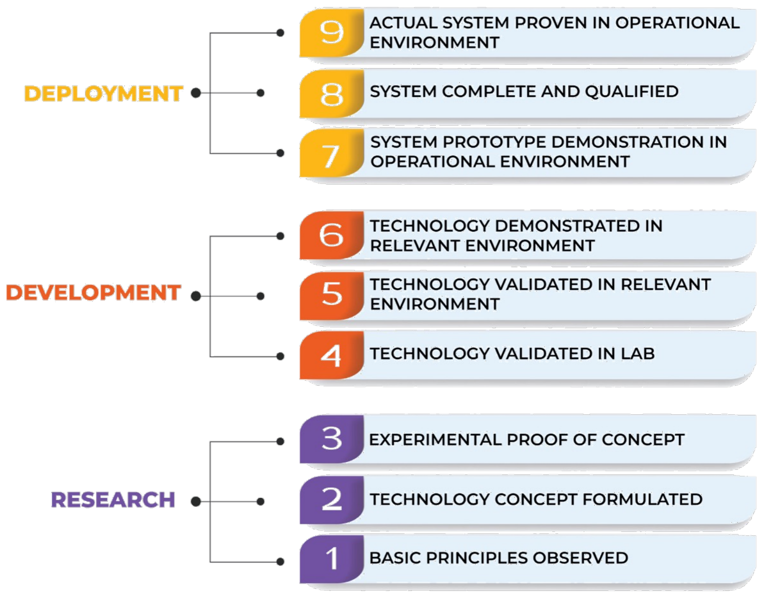
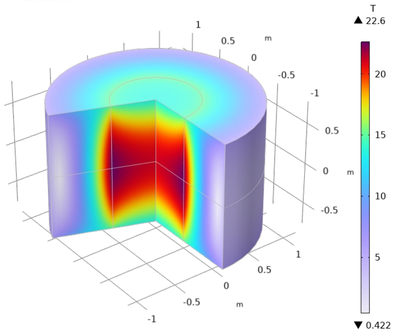
TRL Drives the R&D



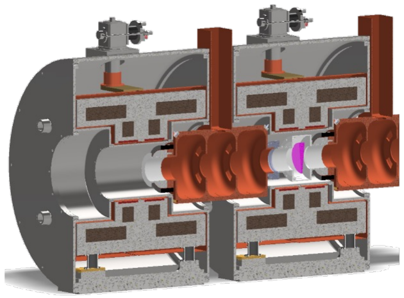


- We wish to reach TRL6 to de-risk cost and timeline, as required for project decision
- TRL6 is appropriate to initiate industry prototype engineering and construction

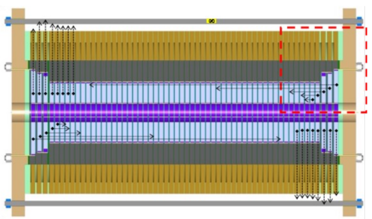
R&D Technology Milestones - 1/3



Technology: Target solenoid model coil (20@20)
Objectives: Develop conductor, winding and magnet technology suitable for a target solenoid, generating a bore field of 20 T, and operating at a temperature of 20 K.
Time: 2033
Resources: 30 MCHF, 37 FTEy

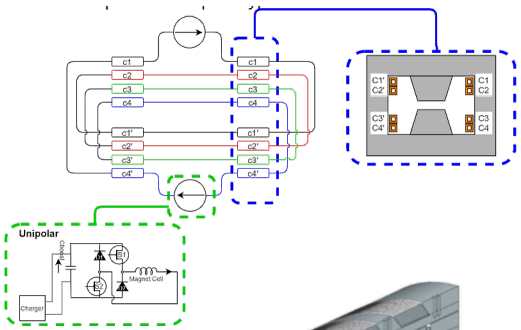


Technology: Split Solenoid integration for 6D cooling cell (SOLID)
Objectives: Demonstrator of HTS split solenoid performance, including integration in its support structure submitted to mechanical and thermal loads representative of a 6D cooling cell.
Time: 2032
Resources: 7.1 MCHF, 42 FTEy

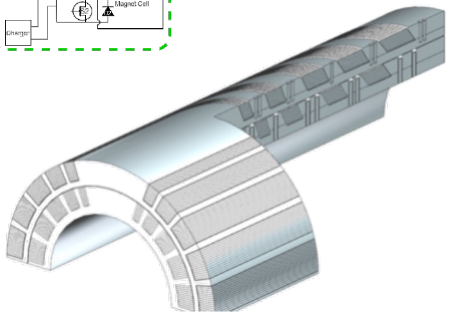


Technology: Final cooling UHF solenoid (UHF-Demo)
Objectives: Build and test a demonstrator HTS final cooling solenoid, producing 40 T in a 50 mm bore, and total length of 150 mm.
Time: 2034
Resources: 5.6 MCHF, 52 FTEy

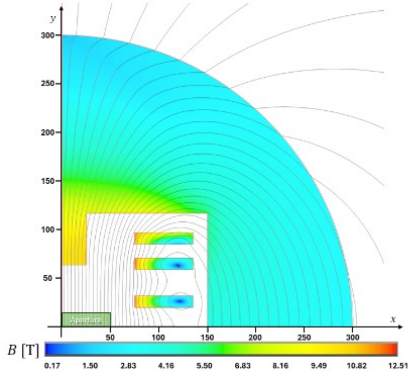
R&D TECHNOLOGY MILESTONES - 2/3



Technology: RCS fast pulsed magnet string and power system (RCS-String)
Objectives: Build and test a string of resistive pulsed dipoles, including powering system and capacitor-based energy storage.
Time: 2032
Resources: 6 MCHF, 20 FTEy

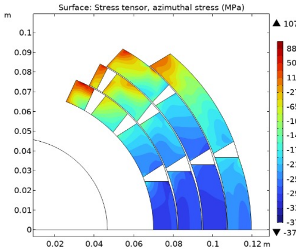


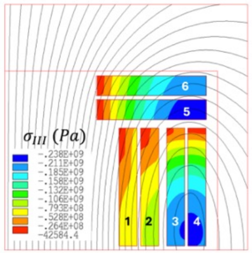
Technology: Wide-aperture, steady state Nb_3Sn dipole for the collider (MBHY)
Objectives: Demonstrate LTS dipole performance for collider arc.
Time: 2036
Resources: 11.1 MCHF, 71 FTEy



Technology: Rectangular aperture HTS dipole (MBHTS)
Objectives: Demonstrate performance of rectangular aperture HTS dipole for the accelerator.
Time: 2035
Resources: 8.3 MCHF, 60 FTEy

R&D TECHNOLOGY MILESTONES - 3/3



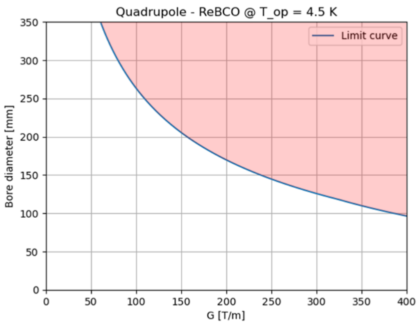


Technology: Wide aperture HTS dipole (MBHTSY)

Objectives: Demonstrate wide aperture HTS dipole for the collider arc.

Time: (2045)

Resources: 7.9 (15.8) MCHF, 75 (126) FTEy

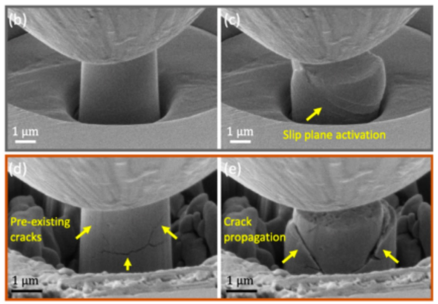


Technology: Wide aperture HTS IR quadrupole (MQHTSY)

Objectives: Demonstrate wide aperture HTS quadrupole for the collider IR.

Time: (2045)

Resources: 3.5 (8.8) MCHF, 27 (60) FTEy



Materials and Methods

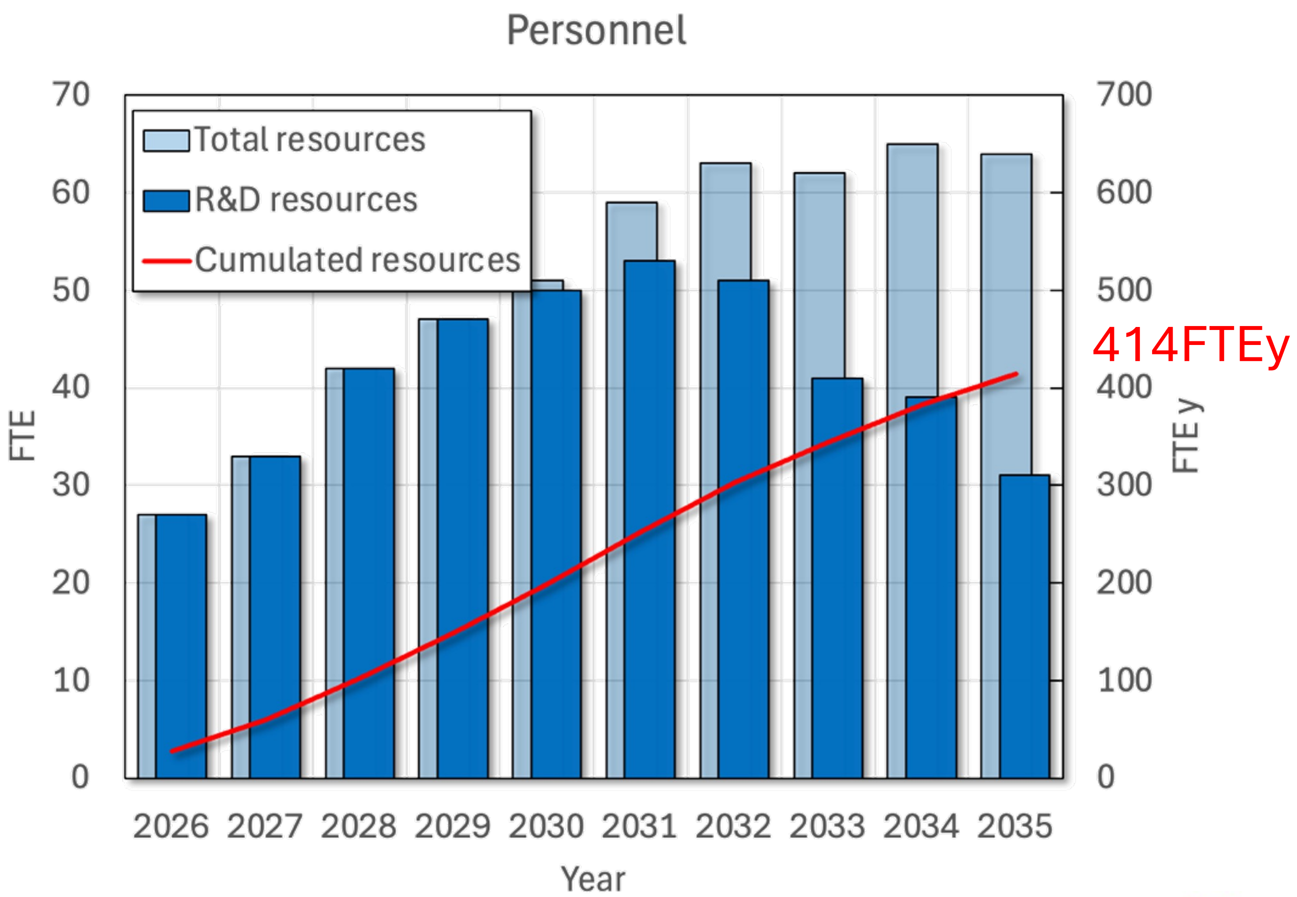
Objectives: Host and coordinate methods and materials R&D, characterization and testing common to magnet demonstrators design, manufacturing and testing.

Time: 2035

Resources: 3 MCHF, 30 FTEy

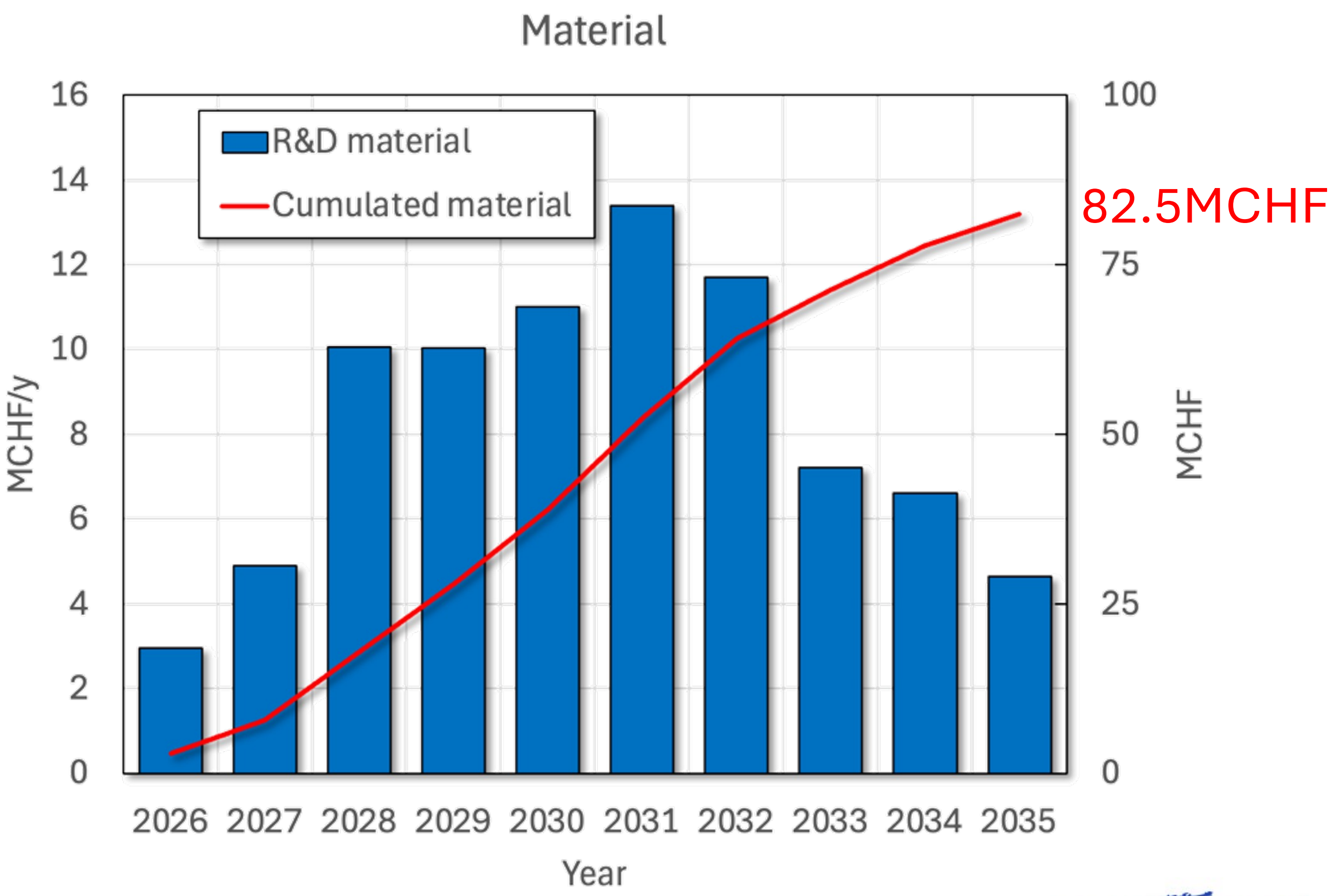
R&D Resources - Personnel

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Target solenoid demonstrator (20@20)										
Staff	0.6	0.9	0.9	1.5	3	4	3.5	2.1		
Post doc	0.8	1.2	1.2	2	1.8	2.4	2.1	0.6		
Student	0.6	0.9	0.9	1.5	1.2	1.6	1.4	0.3		
Material (kCHF)	1000	2000	5000	4000	5000	7000	5000	1000		
Solenoid Integration Demonstrator for 6D cooling cell										
Staff	0.9	2.1	2.4	2.4	2.1	2.5	2			
Post doc	1.2	2.8	3.2	3.2	2.8	1.5	1.2			
Student	0.9	2.1	2.4	2.4	2.1	1	0.8			
Material (kCHF)	400	900	1400	1700	1200	1000	500			
Final cooling UHF solenoid demonstrator (UHF-Demo)										
Staff	1.2	1.2	1.8	1.8	1.8	2.1	2.1	3.5	2.5	
Post doc	1.6	1.6	2.4	2.4	2.4	2.8	2.8	2.1	1.5	
Student	1.2	1.2	1.8	1.8	1.8	2.1	2.1	1.4	1	
Material (kCHF)	300	300	500	500	500	750	750	1000	1000	
RCS magnet string and power systems (RCS-String)										
Staff	1.4	1.4	2.8	3.6	3.6	3	1			
Post doc	0.4	0.4	0.8	0.4	0.4	0	0			
Student	0.2	0.2	0.4	0	0	0	0			
Material (kCHF)	250	300	950	1500	1500	1000	500			
Wide-aperture, steady state Nb3Sn dipole (MBHY)										
Staff	2	2	3	3.5	3.5	3.5	6.3	6.3	6.3	6.3
Post doc	1.2	1.2	1.8	2.1	2.1	2.1	1.8	1.8	1.8	1.8
Student	0.8	0.8	1.2	1.4	1.4	1.4	0.9	0.9	0.9	0.9
Material (kCHF)	300	500	750	845	750	750	1750	2000	2000	1500
Rectangular aperture HTS dipole (MBHTS)										
Staff	1.6	1.6	2.4	2.4	2.4	3.2	4	3.5	4.9	2.8
Post doc	1.2	1.2	1.8	1.8	1.8	2.4	2.4	2.1	1.4	0.8
Student	1.2	1.2	1.8	1.8	1.8	2.4	1.6	1.4	0.7	0.4
Material (kCHF)	200	200	500	500	850	1500	1500	1250	1250	500
Wide aperture HTS dipole (MBHTSY)										
Staff	2	2.4	2.4	3.2	4	4	4	4	4.5	6.3
Post doc	1.5	1.8	1.8	2.4	2.4	2.4	2.4	2.4	2.7	1.8
Student	1.5	1.8	1.8	2.4	1.6	1.6	1.6	1.6	1.8	0.9
Material (kCHF)	300	500	750	800	800	800	800	800	1100	1250
Wide aperture HTS IR quadrupole (MQHTSY)										
Staff	0	0	0	0	1.5	2	2	2	3	4.2
Post doc	0	0	0	0	0.9	1.2	1.2	1.2	1.8	1.2
Student	0	0	0	0	0.6	0.8	0.8	0.8	1.2	0.6
Material (kCHF)	0	0	0	0	200	200	500	750	850	1000
Muon Collider Magnets - Materials and methods R&D in support of magnet demonstrators										
Staff	1.2	1.2	1.2	1.2	1.2	1.2	2.1	2.1	2.1	2.1
Post doc	0.9	0.9	0.9	0.9	0.9	0.9	0.6	0.6	0.6	0.6
Student	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.3	0.3	0.3
Material (kCHF)	200	200	200	200	200	400	400	400	400	400
TOTALS										
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



R&D RESOURCES - MATERIAL

Year	I	II	III	IV	V	VI	VII	VIII	IX	X
Target solenoid demonstrator (20@20)										
Staff	0.6	0.9	0.9	1.5	3	4	3.5	2.1		
Post doc	0.8	1.2	1.2	2	1.8	2.4	2.1	0.6		
Student	0.6	0.9	0.9	1.5	1.2	1.6	1.4	0.3		
Material (kCHF)	1000	2000	5000	4000	5000	7000	5000	1000		
Solenoid Integration Demonstrator for 6D cooling cell										
Staff	0.9	2.1	2.4	2.4	2.1	2.5	2			
Post doc	1.2	2.8	3.2	3.2	2.8	1.5	1.2			
Student	0.9	2.1	2.4	2.4	2.1	1	0.8			
Material (kCHF)	400	900	1400	1700	1200	1000	500			
Final cooling UHF solenoid demonstrator (UHF-Demo)										
Staff	1.2	1.2	1.8	1.8	1.8	2.1	2.1	3.5	2.5	
Post doc	1.6	1.6	2.4	2.4	2.4	2.8	2.8	2.1	1.5	
Student	1.2	1.2	1.8	1.8	1.8	2.1	2.1	1.4	1	
Material (kCHF)	300	300	500	500	500	750	750	1000	1000	
RCS magnet string and power systems (RCS-String)										
Staff	1.4	1.4	2.8	3.6	3.6	3	1			
Post doc	0.4	0.4	0.8	0.4	0.4	0	0			
Student	0.2	0.2	0.4	0	0	0	0			
Material (kCHF)	250	300	950	1500	1500	1000	500			
Wide-aperture, steady state Nb3Sn dipole (MBHY)										
Staff	2	2	3	3.5	3.5	3.5	6.3	6.3	6.3	6.3
Post doc	1.2	1.2	1.8	2.1	2.1	2.1	1.8	1.8	1.8	1.8
Student	0.8	0.8	1.2	1.4	1.4	1.4	0.9	0.9	0.9	0.9
Material (kCHF)	300	500	750	845	750	750	1750	2000	2000	1500
Rectangular aperture HTS dipole (MBHTS)										
Staff	1.6	1.6	2.4	2.4	2.4	3.2	4	3.5	4.9	2.8
Post doc	1.2	1.2	1.8	1.8	1.8	2.4	2.4	2.1	1.4	0.8
Student	1.2	1.2	1.8	1.8	1.8	2.4	1.6	1.4	0.7	0.4
Material (kCHF)	200	200	500	500	850	1500	1500	1250	1250	500
Wide aperture HTS dipole (MBHTSY)										
Staff	2	2.4	2.4	3.2	4	4	4	4	4.5	6.3
Post doc	1.5	1.8	1.8	2.4	2.4	2.4	2.4	2.4	2.7	1.8
Student	1.5	1.8	1.8	2.4	1.6	1.6	1.6	1.6	1.8	0.9
Material (kCHF)	300	500	750	800	800	800	800	800	1100	1250
Wide aperture HTS IR quadrupole (MQHTSY)										
Staff	0	0	0	0	1.5	2	2	2	3	4.2
Post doc	0	0	0	0	0.9	1.2	1.2	1.2	1.8	1.2
Student	0	0	0	0	0.6	0.8	0.8	0.8	1.2	0.6
Material (kCHF)	0	0	0	0	200	200	500	750	850	1000
Muon Collider Magnets - Materials and methods R&D in support of magnet demonstrators										
Staff	1.2	1.2	1.2	1.2	1.2	1.2	2.1	2.1	2.1	2.1
Post doc	0.9	0.9	0.9	0.9	0.9	0.9	0.6	0.6	0.6	0.6
Student	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.3	0.3	0.3
Material (kCHF)	200	200	200	200	200	400	400	400	400	400
TOTALS										
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



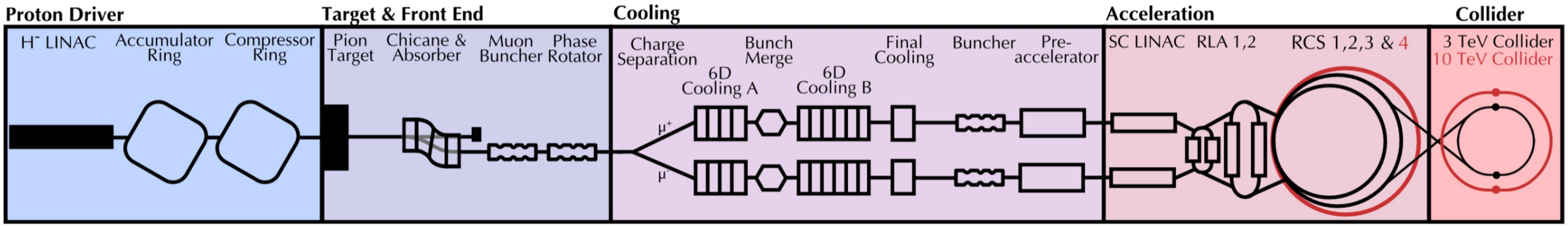
R&D Impact

	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

Practical 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
- 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

OUTLINE



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Cost Model

The cost is evaluated analytically, for all magnets and systems as:

(Cost of material + Cost of manufacturing) * Quantity

$C_{Cable} = f_{Cable}\, C_{SC}$

$C_{Coils} = C_{SC} + C_{Cable} + C_{CoilManufacturing}$

$C_{SC} = M_{Strand}\, c_{Strand}$

$M_{Strand} = d_{Strand}\, A_{Strand} / \cos(\theta)$

$C_{ColdMass} = C_{ColdMassMaterials} + C_{ColdMassManufacturing}$

$C_{ColdMassMaterials} = B/B^{Ref}\, C_{ColdMassMaterials}^{Ref}$

Example for accelerator magnets:

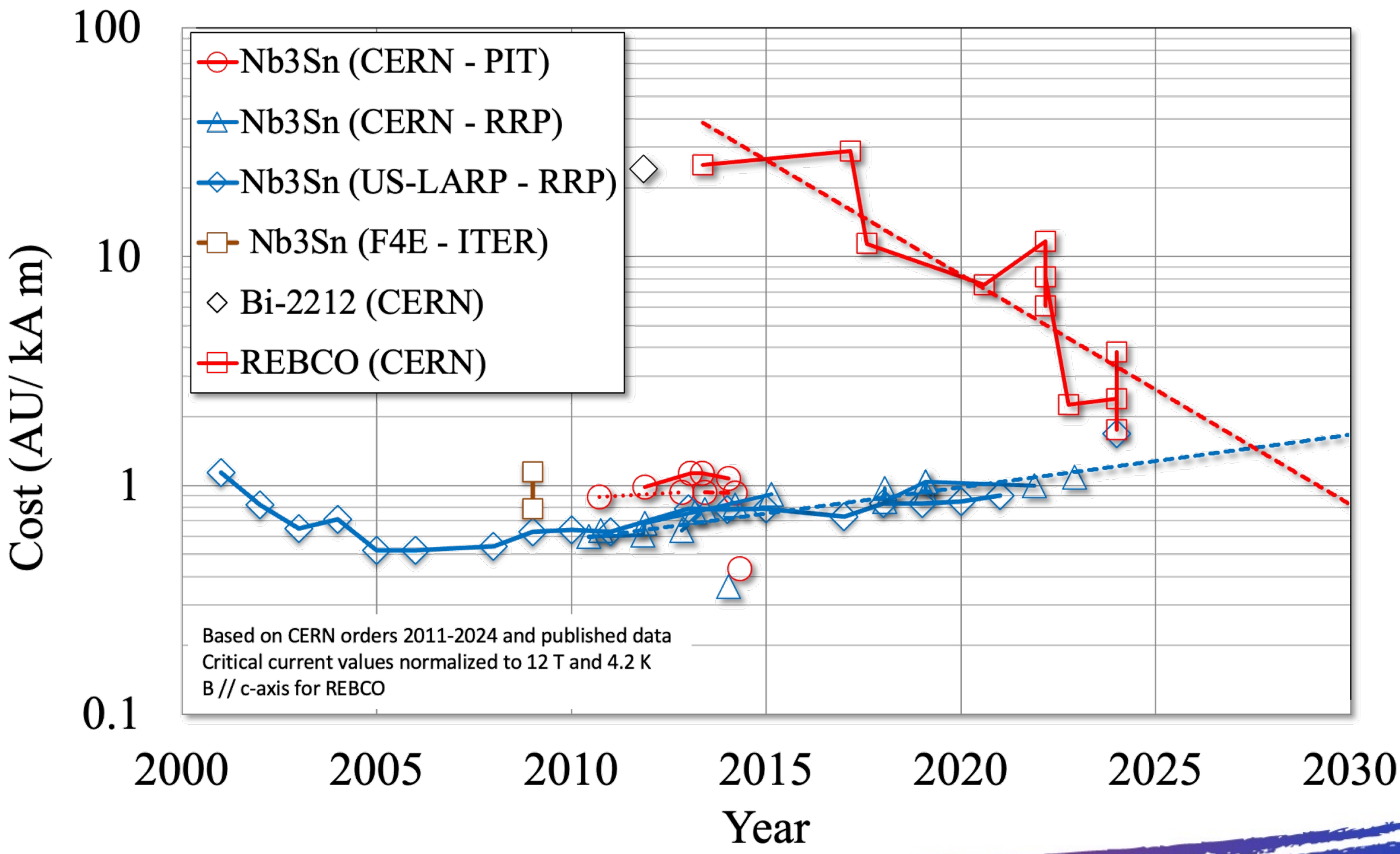
$$C = (C_{Coils} + C_{ColdMass} + C_{CryoMagnet})\, L_{Magnet}$$

		Nb-Ti	Nb_3Sn (present)	Nb_3Sn (aspirational)	REBCO (present)	REBCO (aspirational)	BSCCO (present)	BSCCO (aspirational)
c_{Strand}	(EUR/kg)	159	2274	758	8013	2671	17700	5900
d_{Strand}	(kg/m^3)	8000	8000	8000	7800	7800	9000	9000
f_{Cable}	(-)	0.1	0.1	0.1	0	0	0.1	0.1
$C_{CoilManufacturing}$	(kEUR/m)	9.9	11.9	11.9	9.9	9.9	15	15
$C_{ColdMassMaterials}^{Ref}$	(kEUR/m)	25						
B^{Ref}	(T)	8.33						
$C_{ColdMassManufacturing}$	(kEUR/m)	26.4	31.7	31.7	26.4	26.4	31.7	31.7
$C_{CryoMagnet}$	(kEUR/m)	8.0						

Remarks on Cost Model

- The costing has uncertainty that will reduce thanks to the results of the R&D. The cost, hopefully, as well
- The result of the costing exercise has already brought focus on R&D of the most expensive items, besides the most challenging ones
- There is a strong focus on HTS in the R&D because of the present evolution of magnet science and technology, as well as clear market potential

Cost of Superconductors



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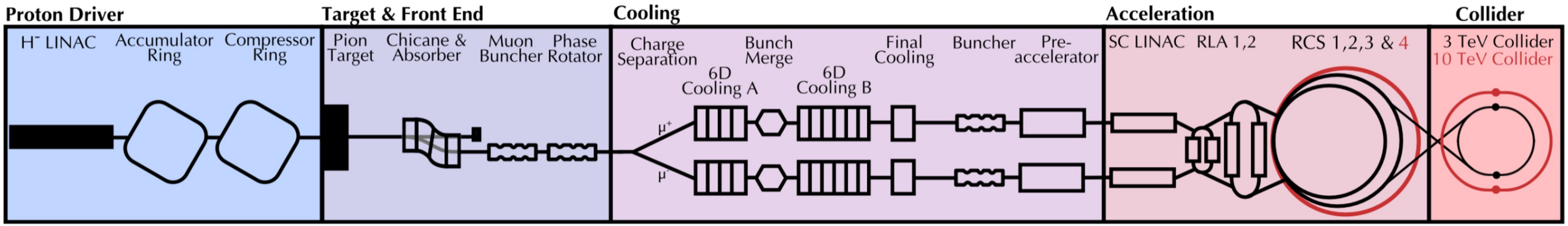

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- Magnet timeline
- R&D plan
- Cost evaluation
- Summary

SUMMARY

- A challenging program of R&D is proposed for the muon collider magnets, with the intention to:
  - Develop and de-risk the magnet and powering technology critical for a project decision, by advancing TRL from present values of TRL3…4 to TRL6
  - Reduce timeline and cost uncertainty, making the 2050 *first light* target for the muon collider possible
  - Profit from synergies and produce impact on multiple other fields of scientific and societal applications
- The magnet technology selected is largely based on HTS because of the present evolution of magnet science and technology, as well as clear market potential
- The R&D milestones in the years 2032-2035 will allow control and revision, as necessary to adapt to the results and new demands (e.g. combined function demonstrator magnet)

HIC SVNT LEONES

Magnet R&D Targets

		Target, decay and capture	6D cooling	Final cooling	Rapid cycling synchrotron		Collider ring			
Magnet type	(-)	Solenoid	Solenoid	Solenoid	NC Dipole	SC Dipole	Dipole	Dipole	Dipole	Quadrupole
SC material options	(-)	HTS	HTS/LTS[2]	HTS	N/A	HTS	Nb-Ti	Nb_3Sn	HTS	HTS
Aperture	(mm)	1400	60...800[3]	50	30x100	30x100	160	160	140	140
Length	(m)	19	0.08...0.3[3]	0.5...1[4]	5	2	4...6[4]	4...6[4]	4...6[4]	3...9[4]
Number of magnets	(-)	20	2 x 3030	20	7000[6]	3000[6]	1250[8]	1250[8]	1250[8]	28
Bore Field/Gradient	(T)/(T/m)	20	2.6...17.9[3]	> 40	± 1.8[5]	10	5	11	14	300
Ramp-rate	(T/s)	SS	SS	SS	3320...810[7]	SS	SS	SS	SS	SS
Stored energy	(MJ)	1400	5...75	4	0.03	3.4	5	20	24	60
Heat load	(W/m)	2[1]	TBD	TBD	1200	5	5	5	10	10
Radiation dose	(MGy)	80	TBD	TBD	TBD	TBD	30	30	30	30
Operating temperature	(K)	20	20	4.5	300	20	4.5	4.5	20	4.5...20

NOTES:
(1) Intended as linear heat load along the conductor wound in the solenoid. Total heat load in the target, decay and capture solenoid is approximately 4 kW.
(2) Superconducting material and operating temperature to be selected as a function of the system cost. Present baseline study is oriented towards HTS at 20 K.
(3) The range indicated covers the several solenoid magnet types that are required for the cooling cells. Extreme values typically do not occur at the same time.
(4) Specific optics are being studied, the length range indicated is representative.
(5) Rapid Cycled Synchrotrons require uni-polar swing, from zero to peak field. Hybrid Cycled Synchrotrons require bi-polar swing, from negative to positive peak field
(6) Considering the CERN implementation (SPS+LHC tunnels)
(7) Required ramp-rate decreases from the first to the last synchrotron in the acceleration chain
(8) Considering a collider of the final size (approximately 10 km length)

R&D Technology Milestones

Technology	Technology Milestone Demonstrator	Objectives and Deliverables	Key Parameters and Targets	Time	Resources
Solenoid for target, decay and capture channel	Target solenoid model coil (20@20)	Develop conductor, winding and magnet technology suitable for a target solenoid, generating a bore field of 20 T, and operating at a temperature of 20 K.	Model coil, 1m ID /2.3 m OD, 1.4 m lenght. Bore field of 20 T at 20 K operating temperature.	2033	30 MCHF 37 FTEy
Solenoids for cooling	Split Solenoid integration demonstrator for 6D cooling cell (SOLID)	Demonstrator of HTS split solenoid performance, including integration in its support structure submitted to mechanical and thermal loads representative of a 6D cooling cell.	Target field 7 T, bore 510 mm, gap 200 mm, operating at 20 K	2032	7.1 MCHF 42 FTEy
	Final cooling UHF solenoid demonstrator (UHF-Demo)	Build and test a demonstrator HTS final cooling solenoid, producing 40 T in a 50 mm bore, and total length of 150 mm	40T in a 50 mm bore, and total length of 150 mm, operated in the vicinity of liquid helium conditions, 4.5 K	2034	5.6 MCHF 52 FTEy
RCS fast pulsed field system	RCS fast pulsed magnet string and power system (RCS-String)	Build and test a string of resistive pulsed dipoles, including powering system and capacitor-based energy storage.	Resistive dipole magnet string, +/-1.8 T field swing in a 30×100 mm aperture.Maximum ramp-rate of 3.3 kT/s, and energy recovery efficiency better than 99 %	2032	6 MCHF 20 FTEy
LTS accelerator magnets	Wide-aperture, steady state Nb3Sn dipole for the collider (MBHY)	Demonstrate LTS dipole performance for collider arc	Prototype LTS dipole, field target of 11 T, large bore target of 160 mm, 5 m long, operating with forced-flow of helium at 4.5 K	2036	11.1 MCHF 71 FTEy
HTS accelerator magnets	Rectangular aperture HTS dipole (MBHTS)	Demonstrate performance of rectangular aperture HTS dipole for the accelerator	Demonstrator HTS dipole, field target of 10 T, aperture of 30x100 mm, 1 m long, operating at 20 K	2035	8.25 MCHF 60 FTEy
	Wide aperture HTS dipole (MBHTSY)	Demonstrate wide aperture HTS dipole for the collider arc	Demonstrator HTS dipole, field target of 14 T, large bore target of 140 mm, 1 m long, operating at 20 K	2045	7.9 (15.8) MCHF 75 (126) FTEy
	Wide aperture HTS IR quadrupole (MQHTSY)	Demonstrate wide aperture HTS quadrupole for the collider IR	Demonstrator HTS quadrupole, gradient target of 300 T/m, large bore target of 140 mm, 1 m long, operating at 4.5 K	2045	3.5 (8.8) MCHF 27 (60) FTEy

TM1 – 20@20

Objectives

Develop conductor, winding and magnet technology suitable for a target solenoid, generating a bore field of 20 T, and operating at a temperature of 20 K. The geometry is based on a model coil, a single solenoid coil with reduced bore size and height, scaled to reduce conductor needs and cost

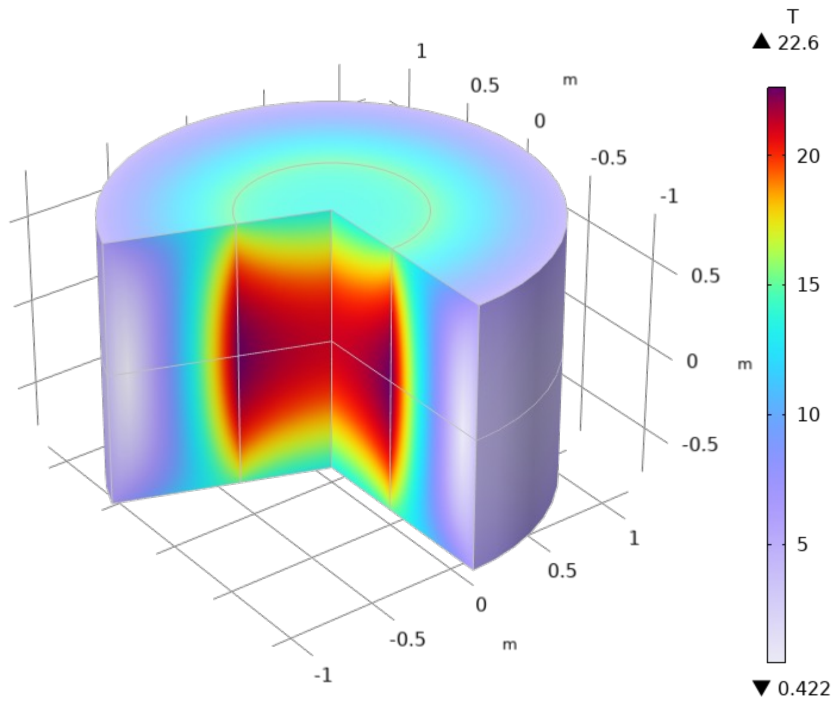
High-level Deliverables

1) HTS conductor, designed, manufactured and tested on industrial scale for force flow-cooled large bore high field solenoids (1 km) (3Y)
2) Reduced scale windings of final conductor, designed and manufactured with industrial participation, tested in self- and background field (5Y)
3) Model coil, designed and manufactured with industrial participation, tested for performance and endurance (8Y)

Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	0.6	0.9	0.9	1.5	3	4	3.5	2.1		
Postdoc/GRAD	0.8	1.2	1.2	2	1.8	2.4	2.1	0.6		
Student	0.6	0.9	0.9	1.5	1.2	1.6	1.4	0.3		
Material	1000	2000	5000	4000	5000	7000	5000	1000		

Interested partners

Academia: CERN, INFN, University of Bologna, Politecnico of Torino, University of Twente, EPFL/SPC, KEK
Industry: Tape manufacturers, ASG, ICAS



TM2 – SOLID

Objectives

Demonstrator of HTS split solenoid performance, including integration in its support structure submitted to mechanical and thermal loads representative of a 6D cooling cell. Target field 7 T, bore 510 mm, gap 200 mm, operating at 20 K

High-level Deliverables

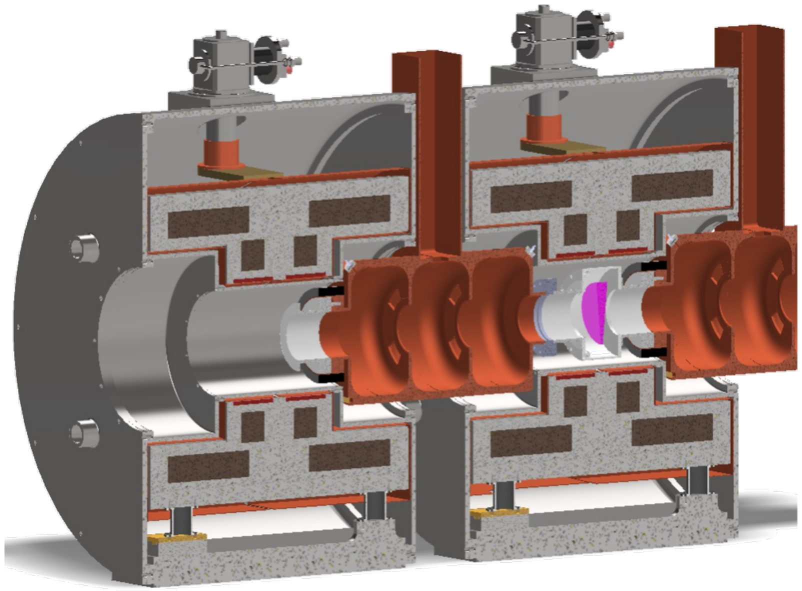
1) Split HTS solenoid design completed (1Y)
2) Small scale solenoid demonstration tests, validating technology selections (3Y)
3) Split solenoid built and tested (7Y)

Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	0.9	2.1	2.4	2.4	2.1	2.5	2			
Postdoc/GRAD	1.2	2.8	3.2	3.2	2.8	1.5	1.2			
Student	0.9	2.1	2.4	2.4	2.1	1	0.8			
Material	400	900	1400	1700	1200	1000	500			

Interested partners

Academia: INFN, CERN, University of Southampton, Technical University Tampere

Industry: Tape manufacturers



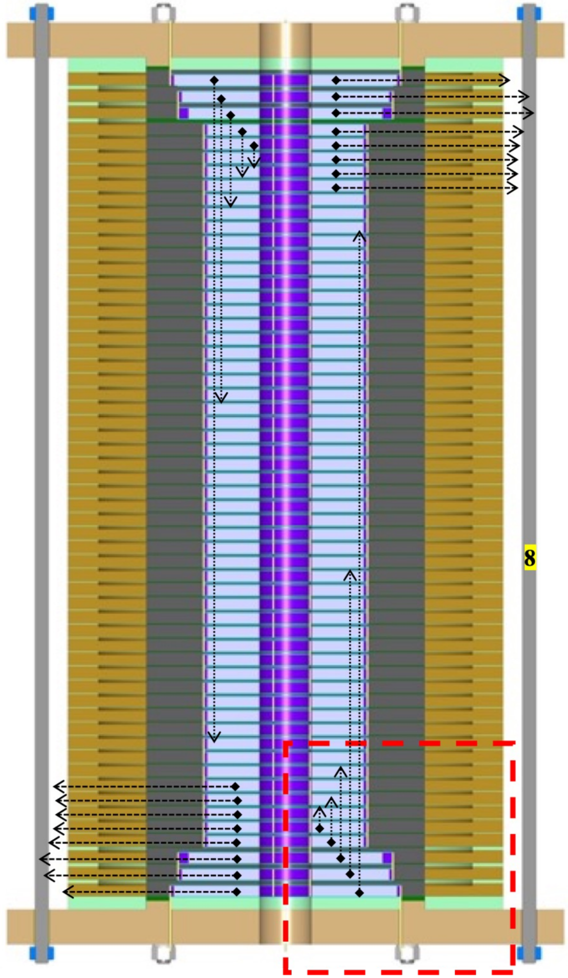
TM3 – UHF-DEMO

Objectives
Build and test a demonstrator HTS final cooling solenoid, producing 40 T in a 50 mm bore, and total length of 150 mm (limit cost)

High-level Deliverables
1) Single pancake, final configuration, stand-alone test (2Y)
2) Stacked pancake, final configuration, achieve 20 T (5Y)
3) Demonstrator construction and test (9Y)

Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	1.2	1.2	1.8	1.8	1.8	2.1	2.1	3.5	2.5	
Postdoc/GRAD	1.6	1.6	2.4	2.4	2.4	2.8	2.8	2.1	1.5	
Student	1.2	1.2	1.8	1.8	1.8	2.1	2.1	1.4	1	
Material	300	300	500	500	500	750	750	1000	1000	

Interested partners
Academia: CERN, INFN, PSI, CEA, University of Twente, University of Southampton, Technical University Tampere
Industry: Tape manufacturers



TM4 – RCS-STRING

Objectives

Build and test a string of resistive pulsed dipoles, including powering system and capacitor-based energy storage, aiming at field swing of +/- 1.8 T, maximum ramp-rate of 3.3 kT/s, and energy recovery efficiency better than 99 %

High-level Deliverables

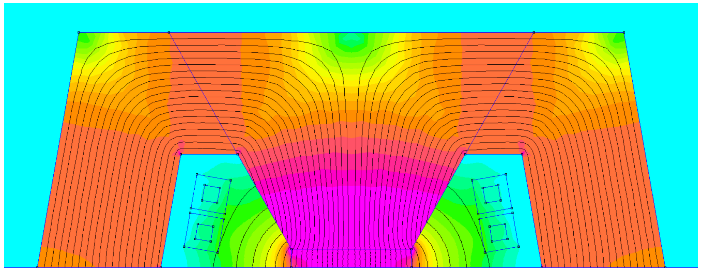
1) Dipole magnet stand-alone test (3Y)
2) Power converter and energy storage stand-alone test (3Y)
3) String construction and test (7Y)

Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	1.4	1.4	2.8	3.6	3.6	3	1			
Postdoc/GRAD	0.4	0.4	0.8	0.4	0.4	0	0			
Student	0.2	0.2	0.4	0	0	0	0			
Material	250	300	950	1500	1500	1000	500			

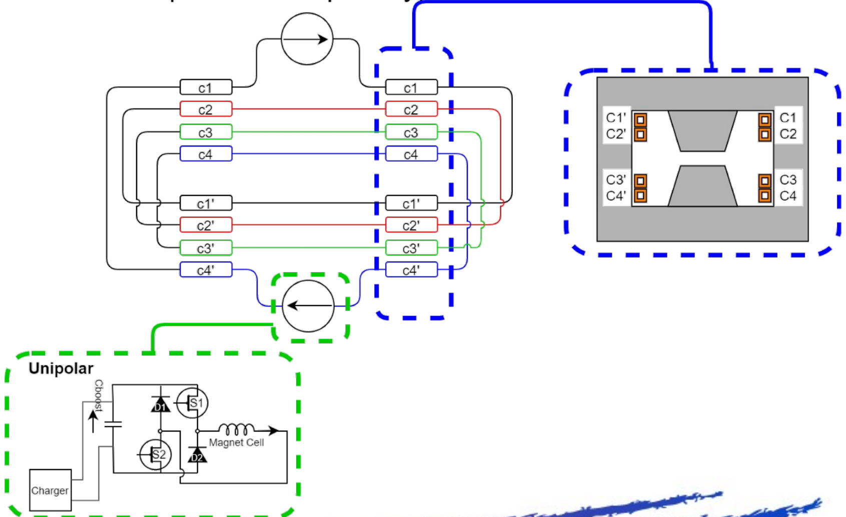
Interested partners

Academia: CERN, University of Bologna, Technical University of Darmstadt

Industry:



Two dipoles prototypes
Two power cells prototypes



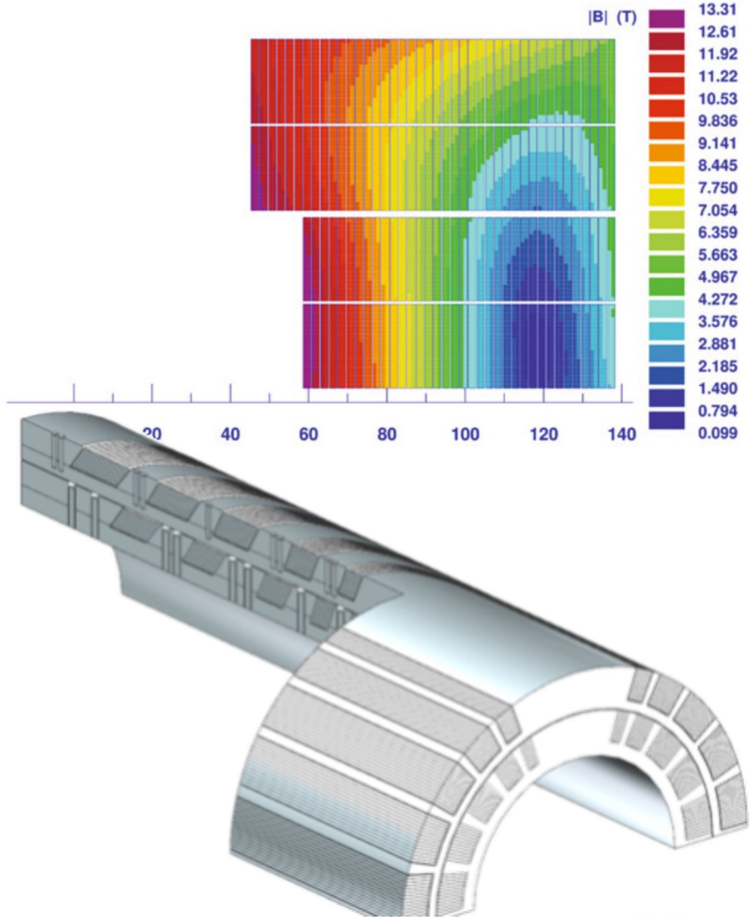
TM5 – MBHY

Objectives
Build and test Nb3Sn demonstrator dipole with field target of 11 T, large bore, target 160 mm, 5 m long, operating with forced-flow of helium at 4.5 K

High-level Deliverables
1) Dipole magnet engineering and validation tests (demonstrators) completed (5Y)
2) Short model construction and test (9Y)
3) Magnet long prototype construction and test (11Y)

Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	2	2	3	3.5	3.5	3.5	6.3	6.3	6.3	6.3
Postdoc/GRAD	1.2	1.2	1.8	2.1	2.1	2.1	1.8	1.8	1.8	1.8
Student	0.8	0.8	1.2	1.4	1.4	1.4	0.9	0.9	0.9	0.9
Material	300	500	750	845	750	750	1750	2000	2000	1500

Interested partners
Academia: CERN, INFN
Industry: Nb3Sn manufacturers



TM6 – MBHTS

Objectives

Build and test a 1 m long demonstrator for a HTS, 10 T, 30x100 mm bore dipole operating at 20 K

High-level Deliverables

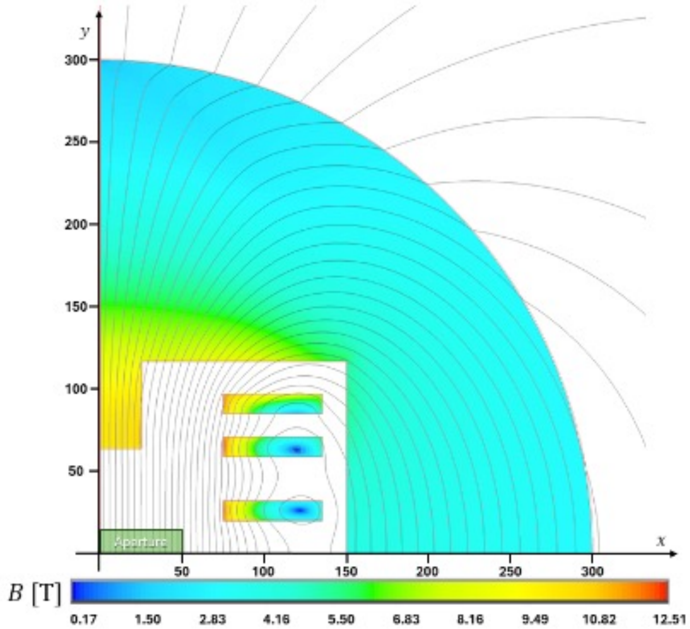
1) Dipole magnet engineering and validation tests (demonstrator) completed (5Y)
2) Model construction and test (10Y)

Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	1.6	1.6	2.4	2.4	2.4	3.2	4	3.5	4.9	2.8
Postdoc/GRAD	1.2	1.2	1.8	1.8	1.8	2.4	2.4	2.1	1.4	0.8
Student	1.2	1.2	1.8	1.8	1.8	2.4	1.6	1.4	0.7	0.4
Material	200	200	500	500	850	1500	1500	1250	1250	500

Interested partners

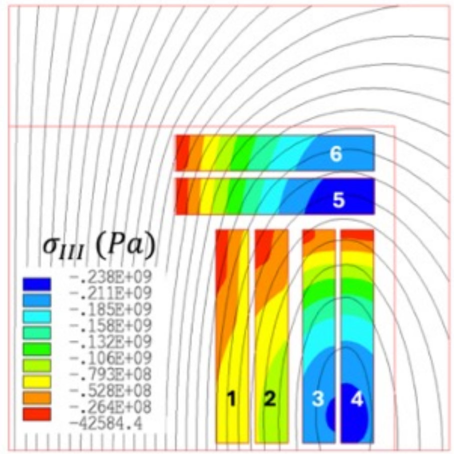
Academia: CERN, INFN, Technical University Tampere

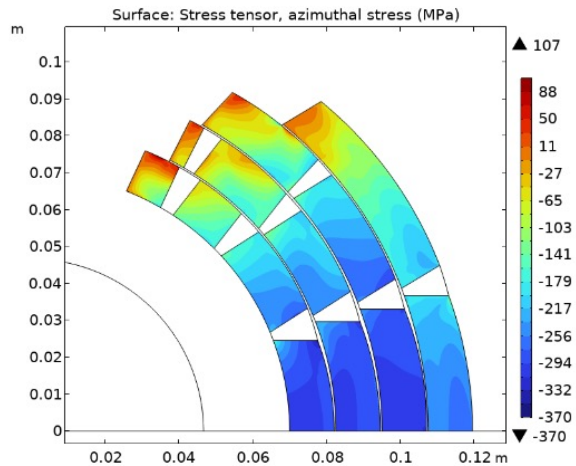
Industry: Tape manufacturers



TM7 – MBHTSY

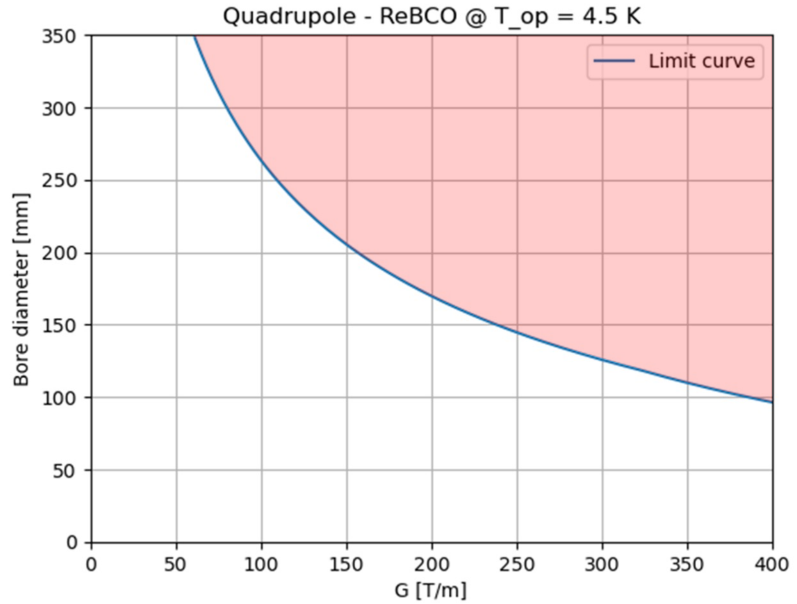
Objectives										
Build and test a 1 m long demonstrator for a HTS, 14 T, 140 mm bore dipole operating at 20 K										
High-level Deliverables										
1) Dipole magnet engineering and validation tests (demonstrator) completed (6Y) *2) Short model construction and test (16Y)* *3) Long prototype construction and test beyond the scope of this proposal (20Y)*										
Resources	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Staff	2	2.4	2.4	3.2	4	4	4	4	4.5	6.3
Postdoc/GRAD	1.5	1.8	1.8	2.4	2.4	2.4	2.4	2.4	2.7	1.8
Student	1.5	1.8	1.8	2.4	1.6	1.6	1.6	1.6	1.8	0.9
Material	300	500	750	800	800	800	800	800	1100	1250
Interested partners										
Academia: CERN, INFN, Technical University Tampere										
Industry: Tape manufacturers										





TM8 – MQHTSY

Objectives										
Build and test a 1 m long demonstrator for a HTS, 300 T/m, 140 mm bore quadrupole operating at 20 K										
High-level Deliverables										
1) Quadrupole magnet engineering and first validation tests (demonstrator) completed (7Y)										
2) Short model construction and test beyond the scope of this proposal (16Y)										
3) Long prototype construction and test beyond the scope of this proposal (20Y)										
Resources	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Staff	0	0	0	0	1.5	2	2	2	3	4.2
Postdoc/GRAD	0	0	0	0	0.9	1.2	1.2	1.2	1.8	1.2
Student	0	0	0	0	0.6	0.8	0.8	0.8	1.2	0.6
Material	0	0	0	0	200	200	500	750	850	1000
Interested partners										
Academia: CERN, INFN, Technical University Tampere										
Industry: Tape manufacturers										



MATERIALS AND METHODS R&D

Objectives										
Host and coordinate methods and materials R&D, characterization and testing common to magnet demonstrators design, manufacturing and testing										
High-level Deliverables										
1) HTS magnets design code (5Y)										
Resources	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Staff	1.2	1.2	1.2	1.2	1.2	1.2	2.1	2.1	2.1	2.1
Postdoc/GRAD	0.9	0.9	0.9	0.9	0.9	0.9	0.6	0.6	0.6	0.6
Student	0.9	0.9	0.9	0.9	0.9	0.9	0.3	0.3	0.3	0.3
Material	200	200	200	200	200	400	400	400	400	400
Interested partners										
Academia: CERN, INFN, University of Twente, University of Southampton, Technical University Tampere, KEK										
Industry:										

- High-field measurement of **transport properties of REBCO conductors**, also necessary to define scaling laws required for the design and analysis of the magnet demonstrators;
- **Micrography, Micro-structure and mechanical properties** of REBCO conductors and winding;
- **Radiation effects** in REBCO conductors;
- Tailored experiments to establish **design rules for HTS magnets**, e.g. allowable hot-spot temperature, or allowable peak stress and strain;
- **Multi-physics modeling** of transient electromagnetics, mechanics and thermal fields in HTS magnets, relevant to the electro-mechanical design, operation and quench protection of NI HTS magnets.

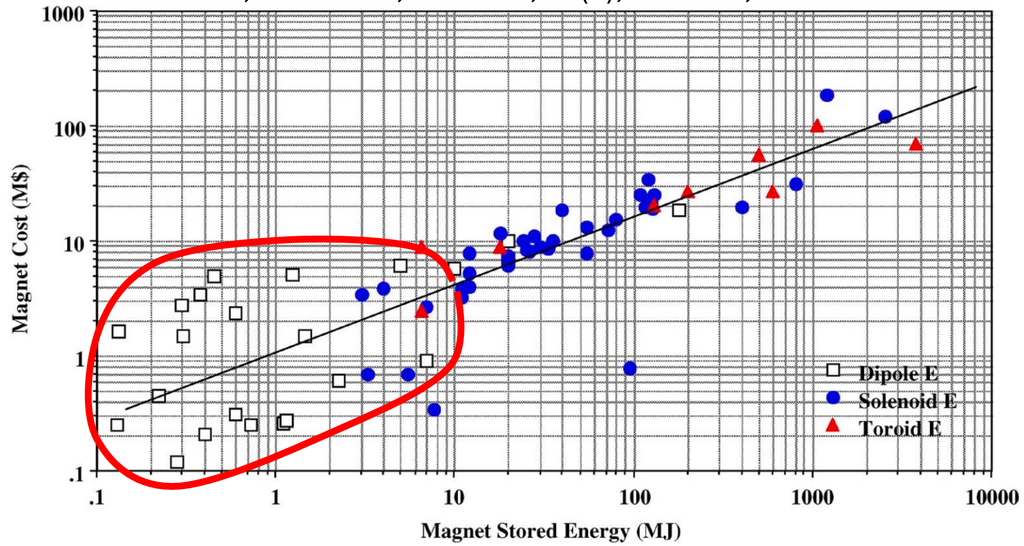
Cost Scaling Expectation

Sector dipole

$$B = \frac{2\mu_0}{\pi} Jw \sin(\varphi)$$

$$A \approx \begin{cases} \frac{B}{J} & for\ w \ll R_{in} \\ \frac{B^2}{J^2} & for\ w \gg R_{in} \end{cases}$$

M.A. Green, B. Strauss, IEEE TAS, 18(2), 248-251, 2008



$$C_1' \approx \sqrt{E}$$

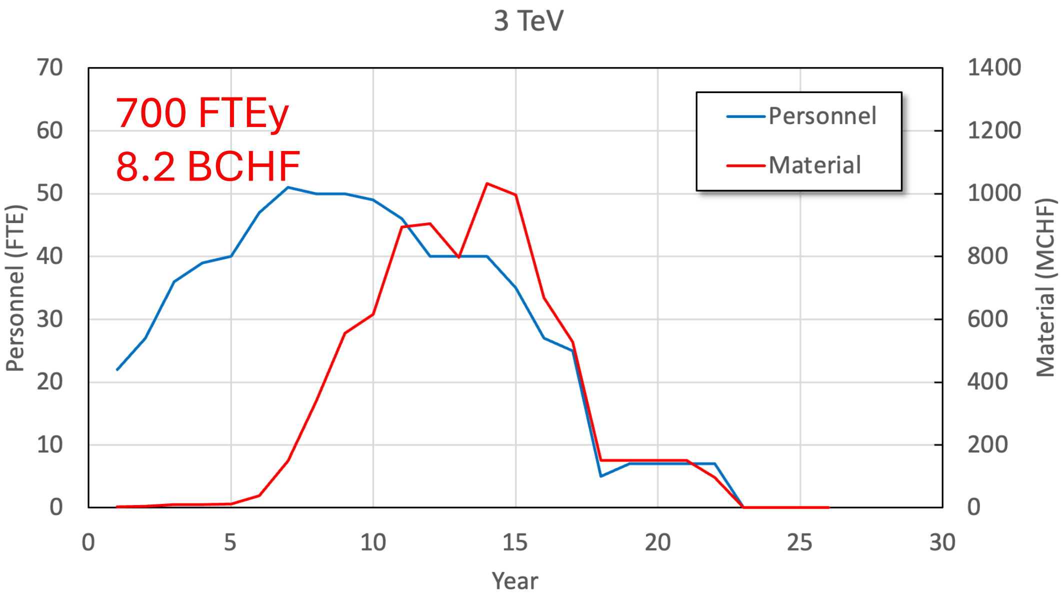
Material cost per unit length is proportional to coil cross section

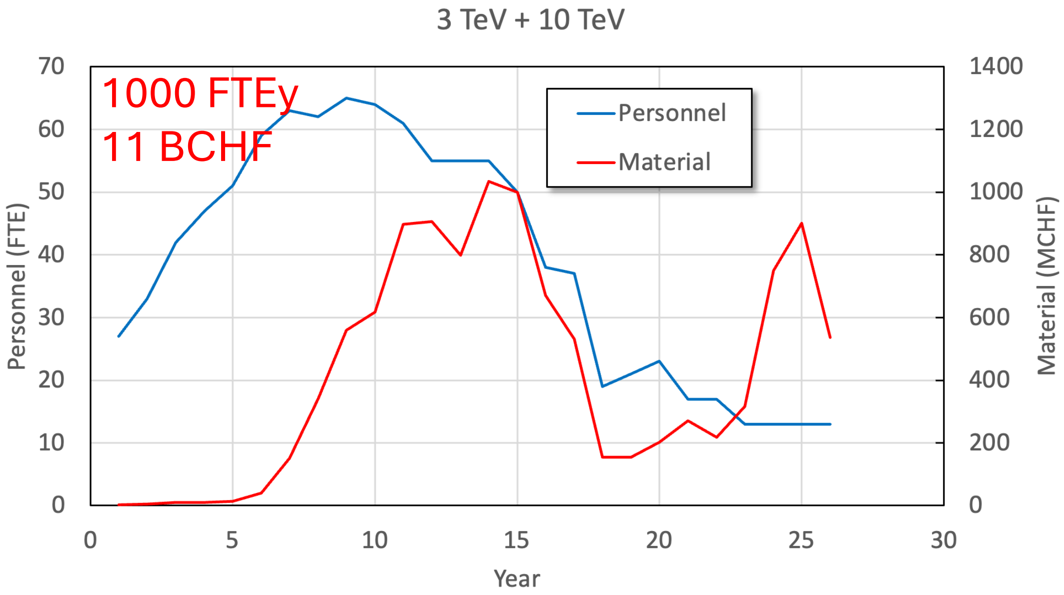
Magnet stored energy is proportional to B^2 and length

$$C_1 \approx \frac{B^n}{J^n} L \qquad C_1' \approx B\sqrt{L}$$

Green-Strauss scaling does not apply to accelerator magnets

Cost Estimate Examples





CAVEAT: THIS IS ONLY AN ESTIMATE
WORK IN PROGRESS