Muon Collider Magnet Technology Options for 6D cooling

Marco Statera, INFN LASA – S. Fabbri, CERN, J. Pavan, UNIMI

Orsay ,21-06-2023

Outline 6D cooling

- Where in muon collider
- Magnet zoo
- Technology drivers and options
- objectives, schedule and team: what who and when are we doing

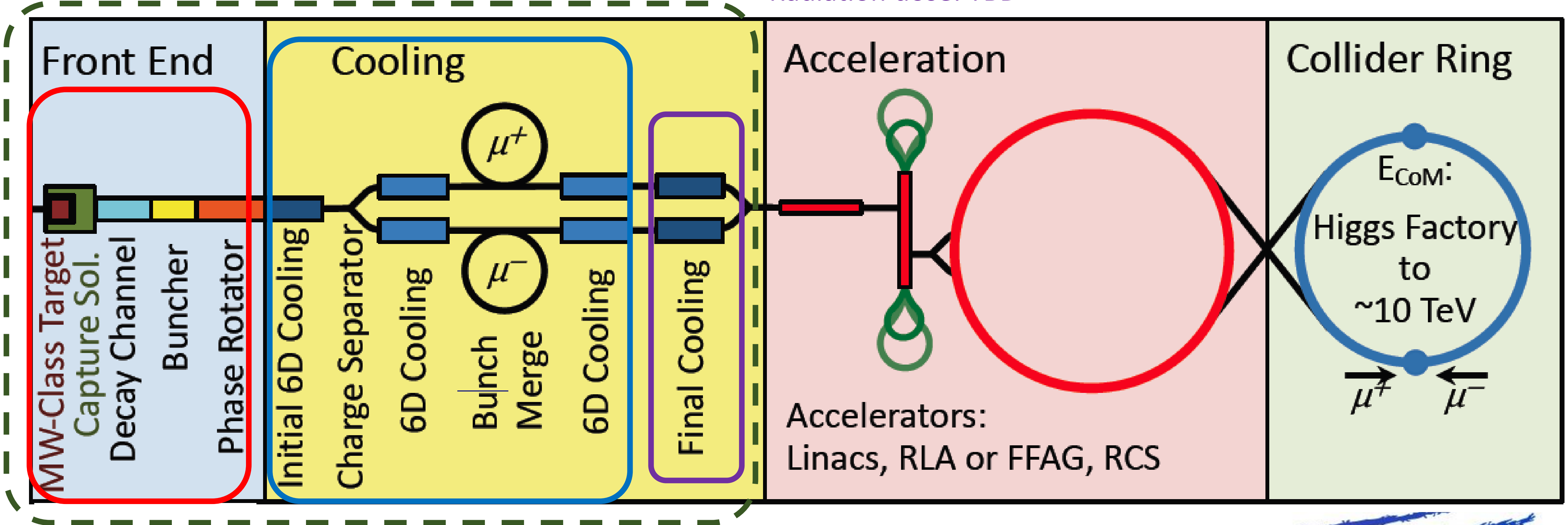
Muon Collider magnet “specs”

Target solenoids
Field: 20 T… 2T
Bore: 1200 mm
Length: 18 m
Radiation heat: ≈ 4.1 kW
Radiation dose: 80 MGy

6D Cooling solenoids
Field: 4 T … 19 T
Bore: 90 mm … 600 mm
Length: 500 mm (x 17)
Radiation heat: TBD
Radiation dose: TBD

Final Cooling solenoids
Field: > 40 T (ideally 60 T)
Bore: 50 mm
Length: ≈ 1 km (x 2)
Radiation heat: TBD
Radiation dose: TBD

TASK 7.2



Muon Collider magnet “catalog”

2432 solenoids
18 coil families

Complex	Sector	Baseline	Magnet Type	Magnet technology	Field (T)	Gradient (T/m)	Aperture (mm)	Gap (mm)	Width (mm)	Length (m)	Number (-)	Ramp time (s)	Field rate (T/s) / (T/m/s)	Homogeneity (units)	Persistance (units/s)	Beam power deposition (kW/m)	Comments
Target and Capture	Target	baseline	solenoid	LTS	15		2400			2	1	21600	0.0007	100		1	baseline 15 T, 2.4 m bore design, assumes 6 hours ramp-up time and 5 kW deposited total power
		baseline	solenoid	NC	5		150			0.5	1	1	5.0000	100		100	baseline 5 T resistive insert
		option	solenoid	HTS	20		600			1.5	1	21600	0.0009	100	0.1	5	option based on a HTS cable, reduced bore and shielding, operating at 10...20 K
	Capture and decay channel		solenoid	TBD													
Cooling	Ionization Cooling	baseline	solenoid	TBD	2.2		600			2	66	21600	0.0001	100	0.1		cell A1
		baseline	solenoid	TBD	3.4		500			1.32	130	21600	0.0002	100	0.1		cell A2
		baseline	solenoid	TBD	4.8		380			1	107	21600	0.0002	100	0.1		cell A3
		baseline	solenoid	TBD	6		264			0.8	88	21600	0.0003	100	0.1		cell A4
		baseline	solenoid	TBD	2.2		560			2.75	20	21600	0.0001	100	0.1		call B1
		baseline	solenoid	TBD	3.4		480			2	32	21600	0.0002	100	0.1		call B2
		baseline	solenoid	TBD	4.8		360			1.5	54	21600	0.0002	100	0.1		call B3
		baseline	solenoid	TBD	6		280			1.27	50	21600	0.0003	100	0.1		call B4
		baseline	solenoid	TBD	9.8		180			0.806	91	21600	0.0005	100	0.1		call B5
		baseline	solenoid	TBD	10.5		144			0.806	77	21600	0.0005	100	0.1		call B6
		baseline	solenoid	TBD	12.5		98			0.806	50	21600	0.0006	100	0.1		call B7
		baseline	solenoid	TBD	13.6		90			0.806	61	21600	0.0006	100	0.1		call B8
	Final Cooling	baseline	solenoid	HTS	30		50			0.5	17	21600	0.0014			0	baseline design from US-MAP
		minimal option	solenoid	HTS	40		60			0.5	17	21600	0.0019	100	0.1	0	HTS NI option, including aperture margin
		target option	solenoid	HTS	60		60			0.5	17	21600	0.0028	100	0.1	0	HTS NI option, including aperture margin
Accelerator	RCS1		dipole	NC	1.8			30	100	8.08	432	7.35E-04	2448.980	10			
	RCS2		dipole	LTS	10		100			2.4	288	1000	0.010	10			
			dipole	NC	1.8			30	100	6.06	432	1.80E-03	1000.000	10			
	RCS3		dipole	LTS	10		100			2.6	288	1000	0.010	10			
			dipole	NC	1.8			30	100	5.05	432	1.80E-03	1000.000	10			
	RCS4		dipole	LTS	10		100			2.6	288	1000	0.010	10			
			dipole	NC	1.8			30	100	5.05	432	8.46E-03	212.716	10			
Collider	Arc		dipole	HTS	10	300	150					1000	0.010	10		0.5	
	IR		quadrupole	HTS		466.32	171.4			2	4	1000	0.000	10			IQF1
			quadrupole	HTS		376.93	212.2			2	4	1000	0.000	10			IQF1a
			quadrupole	HTS		300.71	266			2	4	1000	0.000	10			IQF1b
			quadrupole	HTS		191.41	417			13.6	4	1000	0.000	10			IQD1
			quadrupole	HTS		214.03	411.2			5	4	1000	0.000	10			IQF2

By S. Fabbri and J. Pavan

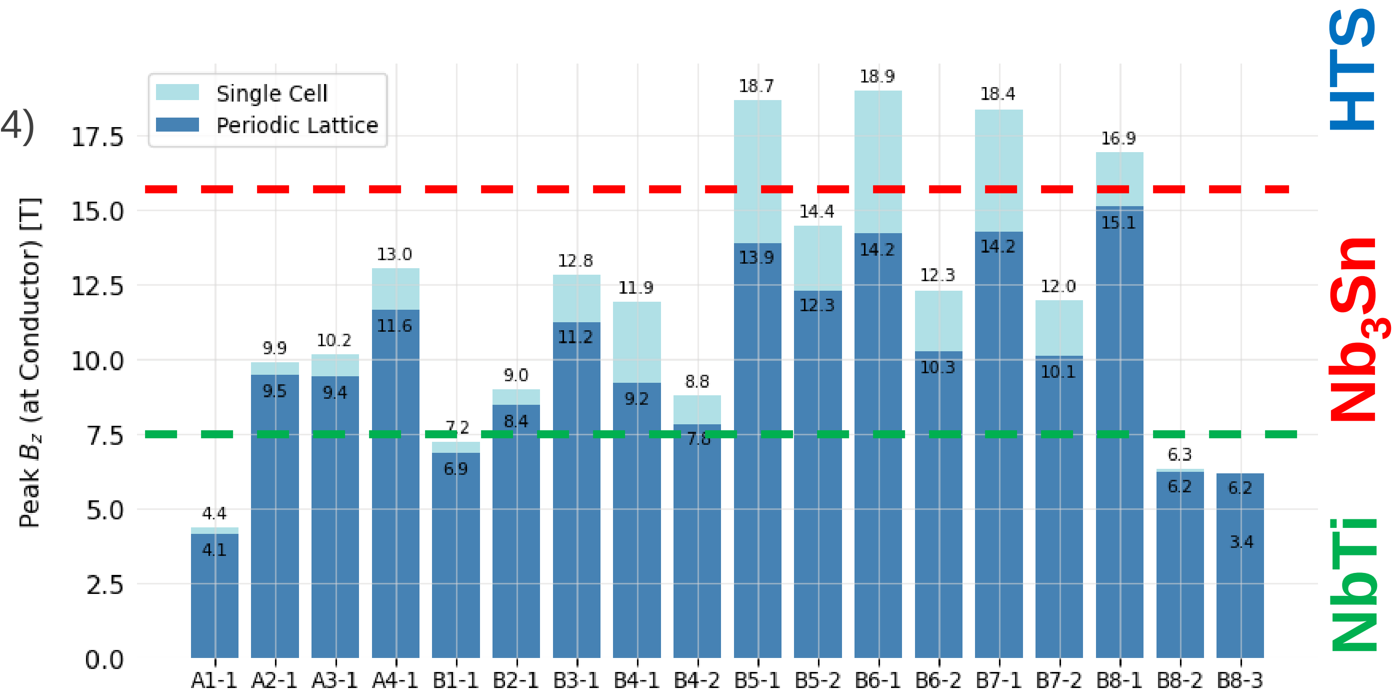
Selected features

We have a full catalogue based on US MAP original design (field on axis)

- 12 unique stages:
    - 4 cooling stages *before* bunch recombination (A1-A4)
    - 8 cooling stages *after* bunch recombination (B1-B8)
- *Each stage has a repeating series of a cell type*
- High field, very compact solenoids
- Each cell has symmetric solenoids of opposite polarity

Some stats:

- Fields on axis: 2 to 14 T
- Cell Lengths: 0.8 to 2.7 m
- Total length of all Stages: ~ **1 km**
- Total number of solenoids: 2432



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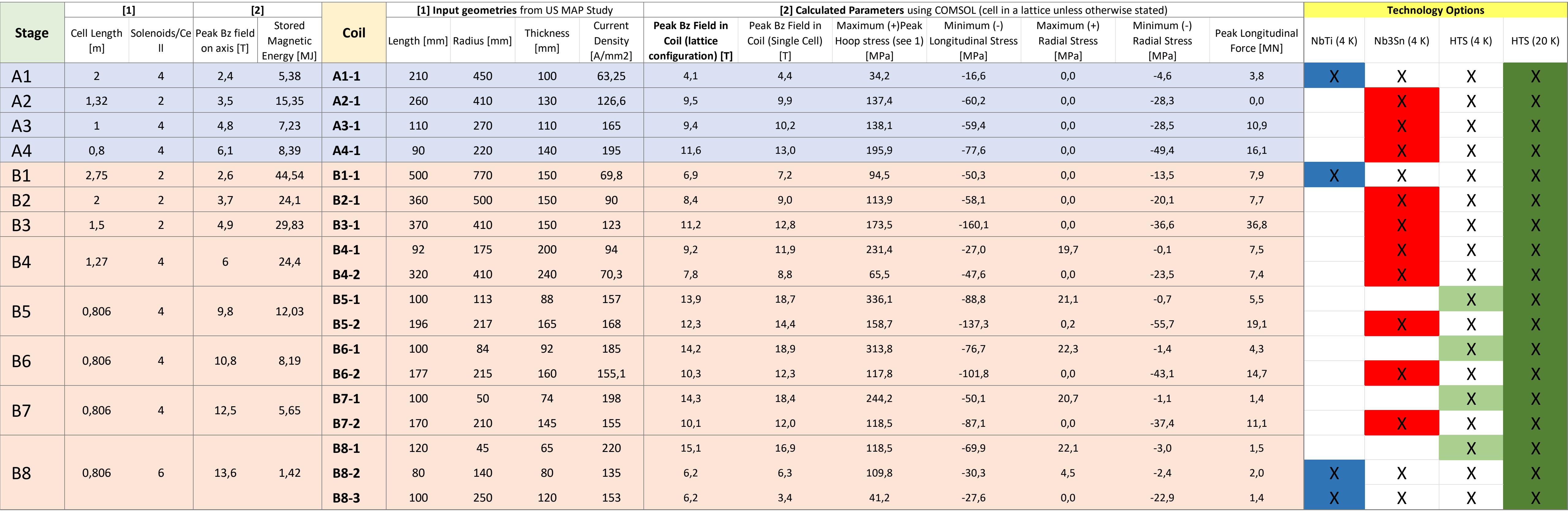
Technologies within cells

Three technologies at lower temperature (4 K) or one technology at 20 K



Stage	[1]		[2]		Coil	**[1] Input geometries** from US MAP Study				**[2] Calculated Parameters** using COMSOL (cell in a lattice unless otherwise stated)							**Technology Options**			
	Cell Length [m]	Solenoids/Cell	Peak Bz field on axis [T]	Stored Magnetic Energy [MJ]		Length [mm]	Radius [mm]	Thickness [mm]	Current Density [A/mm2]	**Peak Bz Field in Coil (lattice configuration) [T]**	Peak Bz Field in Coil (Single Cell) [T]	Maximum (+)Peak Hoop stress (see 1) [MPa]	Minimum (-) Longitudinal Stress [MPa]	Maximum (+) Radial Stress [MPa]	Minimum (-) Radial Stress [MPa]	Peak Longitudinal Force [MN]	NbTi (4 K)	Nb3Sn (4 K)	HTS (4 K)	HTS (20 K)
A1	2	4	2,4	5,38	**A1-1**	210	450	100	63,25	4,1	4,4	34,2	-16,6	0,0	-4,6	3,8	X	X	X	X
A2	1,32	2	3,5	15,35	**A2-1**	260	410	130	126,6	9,5	9,9	137,4	-60,2	0,0	-28,3	0,0		X	X	X
A3	1	4	4,8	7,23	**A3-1**	110	270	110	165	9,4	10,2	138,1	-59,4	0,0	-28,5	10,9		X	X	X
A4	0,8	4	6,1	8,39	**A4-1**	90	220	140	195	11,6	13,0	195,9	-77,6	0,0	-49,4	16,1		X	X	X
B1	2,75	2	2,6	44,54	**B1-1**	500	770	150	69,8	6,9	7,2	94,5	-50,3	0,0	-13,5	7,9	X	X	X	X
B2	2	2	3,7	24,1	**B2-1**	360	500	150	90	8,4	9,0	113,9	-58,1	0,0	-20,1	7,7		X	X	X
B3	1,5	2	4,9	29,83	**B3-1**	370	410	150	123	11,2	12,8	173,5	-160,1	0,0	-36,6	36,8		X	X	X
B4	1,27	4	6	24,4	**B4-1**	92	175	200	94	9,2	11,9	231,4	-27,0	19,7	-0,1	7,5		X	X	X
					B4-2	320	410	240	70,3	7,8	8,8	65,5	-47,6	0,0	-23,5	7,4		X	X	X
B5	0,806	4	9,8	12,03	**B5-1**	100	113	88	157	13,9	18,7	336,1	-88,8	21,1	-0,7	5,5			X	X
					B5-2	196	217	165	168	12,3	14,4	158,7	-137,3	0,2	-55,7	19,1		X	X	X
B6	0,806	4	10,8	8,19	**B6-1**	100	84	92	185	14,2	18,9	313,8	-76,7	22,3	-1,4	4,3			X	X
					B6-2	177	215	160	155,1	10,3	12,3	117,8	-101,8	0,0	-43,1	14,7		X	X	X
B7	0,806	4	12,5	5,65	**B7-1**	100	50	74	198	14,3	18,4	244,2	-50,1	20,7	-1,1	1,4			X	X
					B7-2	170	210	145	155	10,1	12,0	118,5	-87,1	0,0	-37,4	11,1		X	X	X
B8	0,806	6	13,6	1,42	**B8-1**	120	45	65	220	15,1	16,9	118,5	-69,9	22,1	-3,0	1,5			X	X
					B8-2	80	140	80	135	6,2	6,3	109,8	-30,3	4,5	-2,4	2,0	X	X	X	X
					B8-3	100	250	120	153	6,2	3,4	41,2	-27,6	0,0	-22,9	1,4	X	X	X	X

By S. Fabbri

To be investigated

We are defining technologies

- Conductor
- Operation condition, i.e. temperature an cooling method

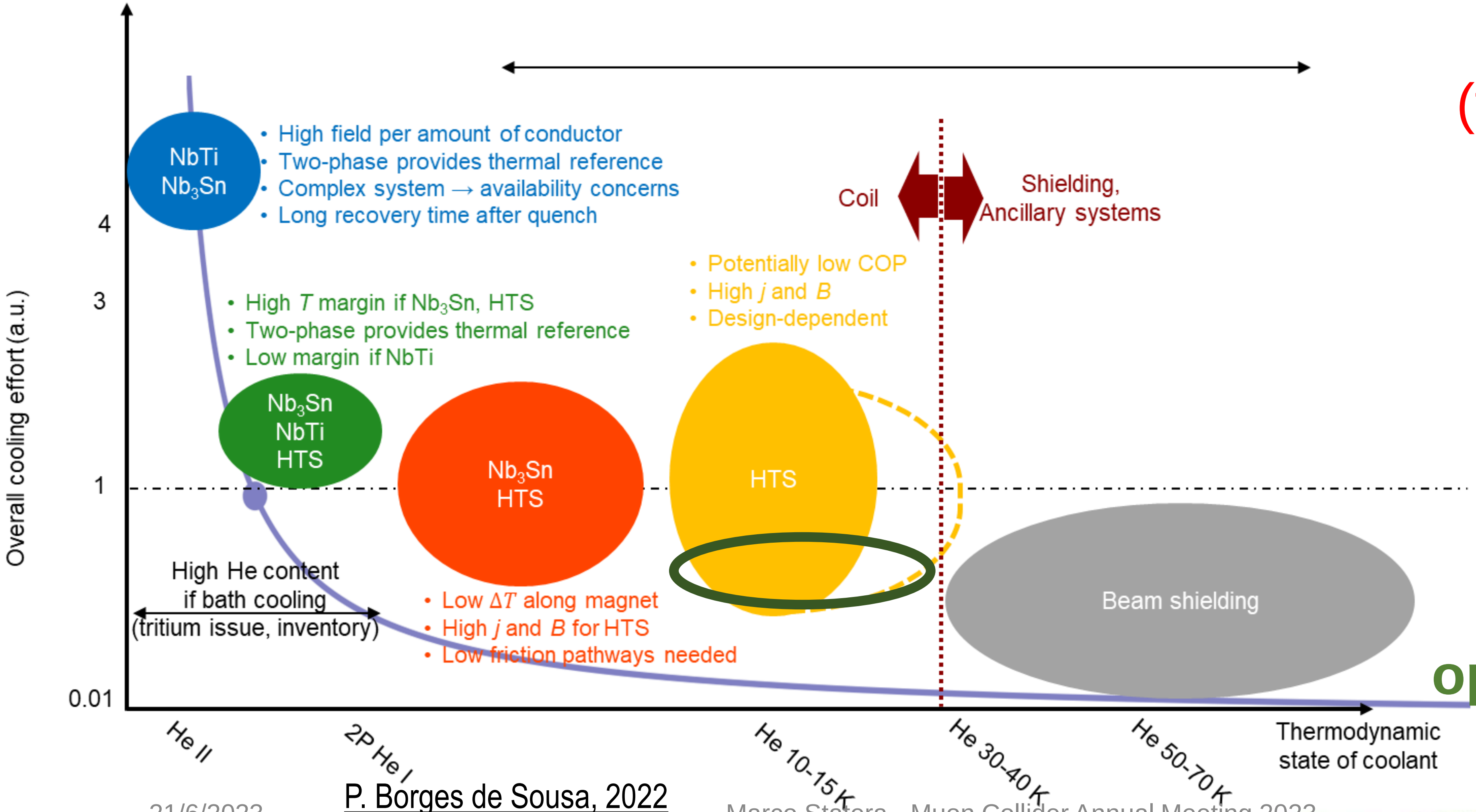
To be investigated

- Conductor performance
- Conductor configuration
- Field quality
- Thermal/mechanical configuration

Technologies 6D cooling solenoids

Technology	Pro's	Con's
LTS	Known technology (TRL 9)	Operating temperature
HTS ReBCCO Insulated	More compact than LTS/HTS Allows for operation at higher temperature Batch above 100 m demonstrated	R&D at low readiness (TRL 4/5) Quench detection protection Production of km batches to be demostrated
HTS ReBCCO Non-insulated	Most compact magnet winding Synergies with other fields of science and societal applications Batch above 100 m demonstrated Can profit from development by others (e.g. NHMFL)	R&D at low readiness (TRL 3/4/5) Ramping time and field stability need to be demonstrated Quench detection and protection Production of km batches to be demostrated
HTS BiSSCO/IBS	Round wire demonstrated for BiSSCO	R&D at low readiness (TRL 3/4) for IBS Production lengths (?)

Technology drivers



- High field per amount of conductor
- Two-phase provides thermal reference
- Complex system → availability concerns
- Long recovery time after quench

- High T margin if Nb_3Sn, HTS
- Two-phase provides thermal reference
- Low margin if NbTi

- Potentially low COP
- High j and B
- Design-dependent

- Low ΔT along magnet
- High j and B for HTS
- Low friction pathways needed

P. Borges de Sousa, 2022

Performance

(field and field quality)

Cost

Sustainability

10 K to 20 K

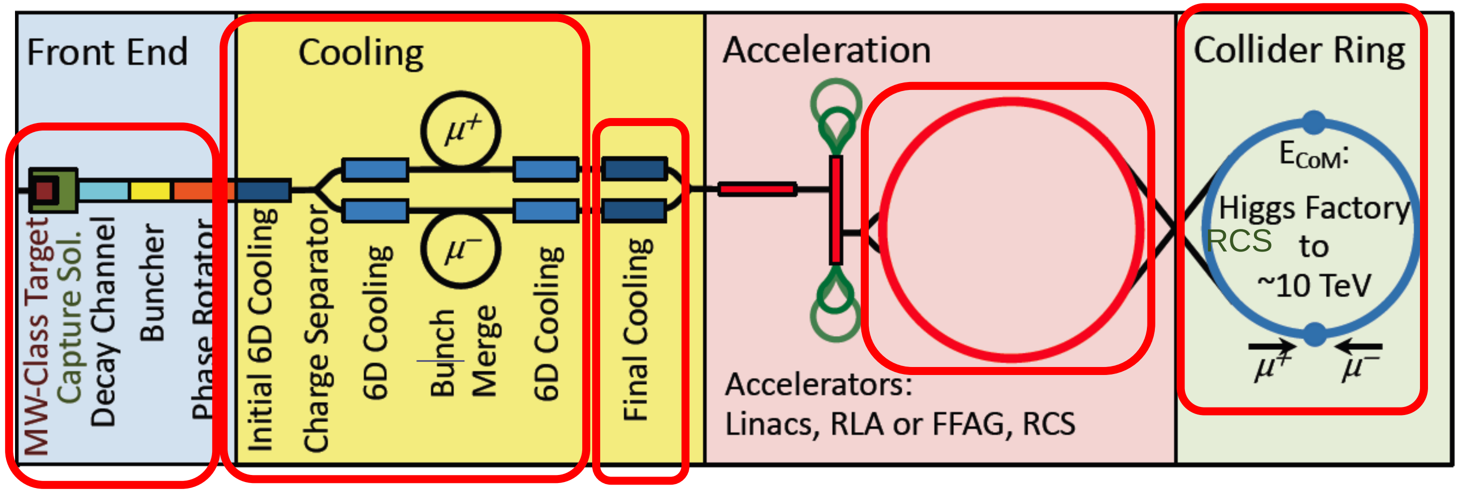
operating temperature

Muon Collider magnet “team”

CERN
F4E (Barcelona)
F4E (Garching)

INFN
CERN
UniMI
KIT

CERN
UniBO
TUDa
UniTwente



CERN
INFN
CEA
CNRS
PSI
UniGE
SO’TON
uniTwente

INFN
CERN
TUT

Muon Collider magnet “team”

- CERN-EP
  - Contribution to development of HTS technology for UHF solenoids
  - Contact person: A. Dudarev

  Baseline studies for HF solenoids
  Engineering design
  R&D pancakes

- PSI
  - Contribution to target and cooling solenoids design and technology R&D
    - Instrumentation and analysis of NI coils (in synergy with other projects that provide the coils)
    - Powered samples to test mechanical limitations (NOTE: need to brainstorm)
    - Integrated conceptual target-magnet design, in close iteration loops with particle-shower simulations
  - Contact person: Dr. B. Auchmann

  Instrumentation for test coils (vtap, protection schemes and devices)
  R&D pancakes

- University of Geneva
  - Measurements in support to R&D on HTS
    - Electro-Mechanical characterization and limits at high field (NOTE: need to brainstorm)
  - Contact person: Prof. C. Senatore

  Characterization measurements and conductor review

- INFN LASA
  - Critical current measurement
  - Contact person: Dr. Marco Statera

  Coordination
  Define reference geometries fo r small coils (L. Bottura)
  Design of test coils devices (together with CERN, CEA…)
  R&D pancakes
  Test of small coils

- University of Southampton
  - Design of solenoids and measurement of HTS properties
  - Test in background field (10 T, 110 mm)
  - Contact person: Prof. Y. Yang

  Review of material options REBCO, Bi-2212, Bi-2223, IBS
  Evaluate current distribution in multi tape windings
  Mechanical and electro-mechanical properties
  R&D pancakes
  Test of small coils

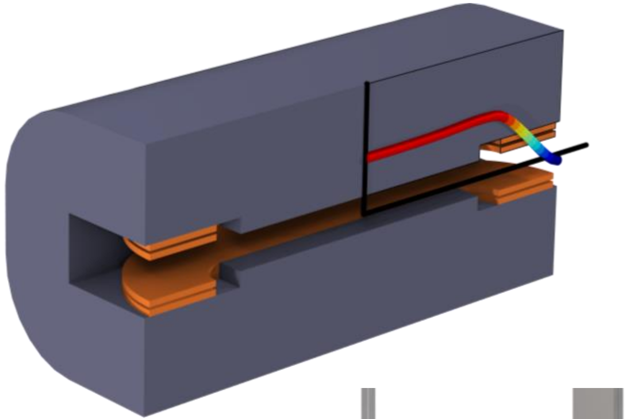
- University of Twente
  - Contribute to the design and conductor effort
    - HTS conductor design (both ReBCO and B2223) at the level of basic strand/tape, shape optimization and reinforcements
    - HTS smart innovative cabling to allow for higher current, current sharing redundancy and quench protection
    - HTS conductor characterization/review for limiting strain and cycling degradation
    - HTS coil windings with controlled resistance to smartly balance conflicting requirements of ramp loss and quench stability
  - Contact person: Prof. A. Kario

  Mechanical and electro-mechanical properties

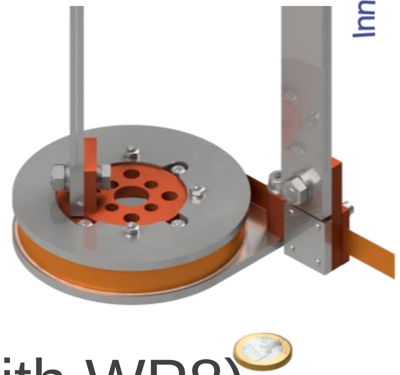
- KIT
  - R&D on coils and tests
  - Contact person: Dr T. Arndt

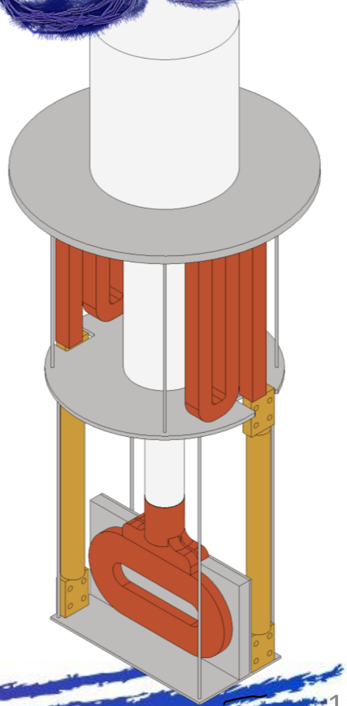
  Test coils winding and test, model development

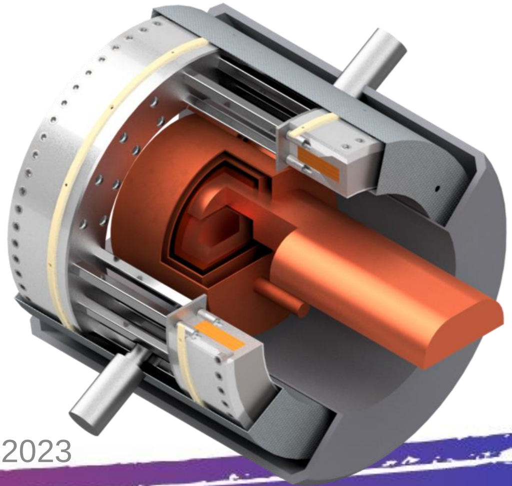
Ongoing activities



- Tape characterization
- Preliminary design of coils and cell
  - Design of a HTS dipole for IRIS, Next Gen EU
  - Winding tests of small pancakes
  - Test of small pancakes (also in field)
  - Design of the RF test station (in collaboration with WP8)
- Coil design for the cells
  - Field and forces
  - Integration of cooling system
  - Field quality definition and optimization



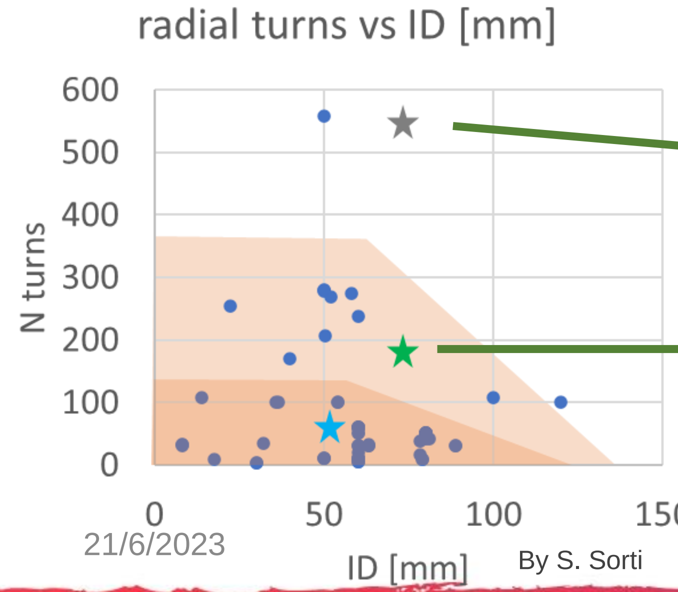




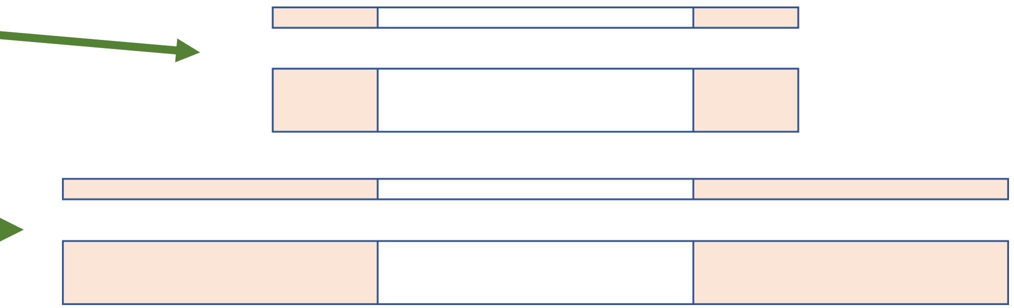
Test coils

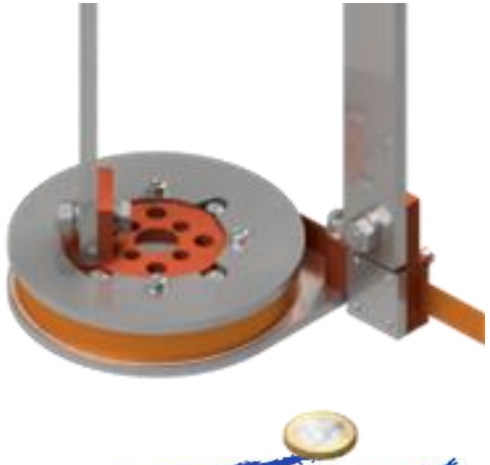
- Test coils Identical/similar configurations used at CERN, INFN, PSI
- Geometry
- Configuration
- Tests self field and in field
- Validate handling procedures and models

60 mm inner diameter
20 mm and 60 mm thickness
4 mm and 12 mm tape width
Single and double pancakes winding
One- and two-in-hand winding
Pancakes can be stacked in mini-coils



By S. Sorti

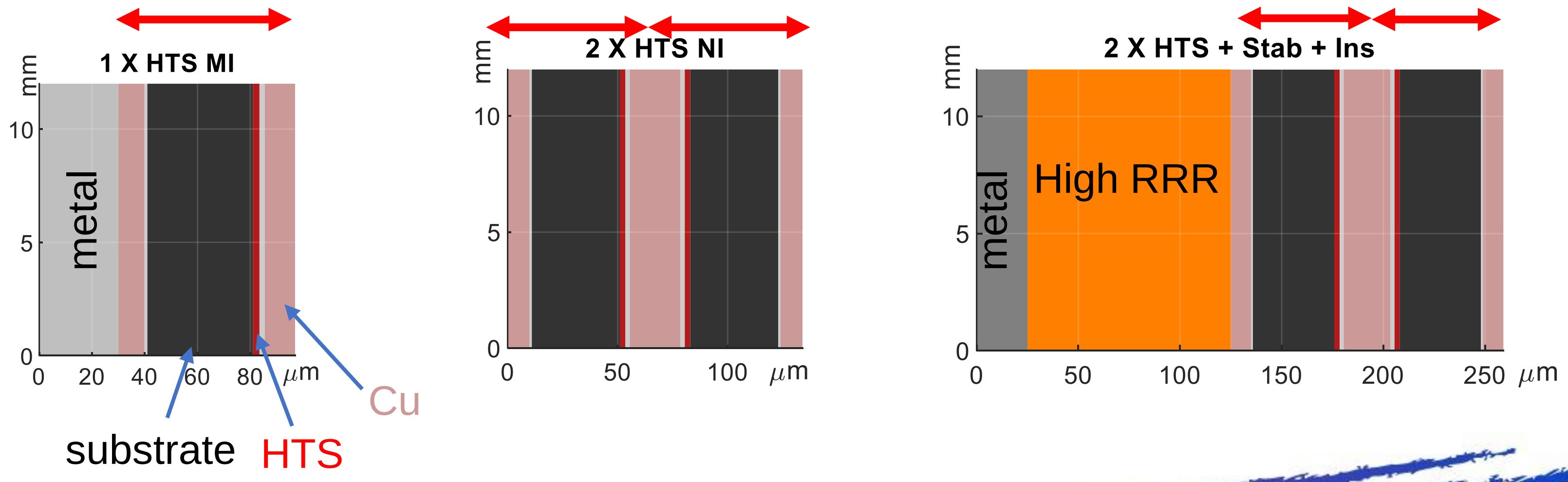




Conductor configurations

- Explore the Controlled-Insulation vs non-insulation solutions.
- Multi-tape winding is foreseen, including different materials and technologies to impact the inter-turn resistance.
- The goal of this campaign is to asses and improve the TRL of such technologies in magnet-like conditions.

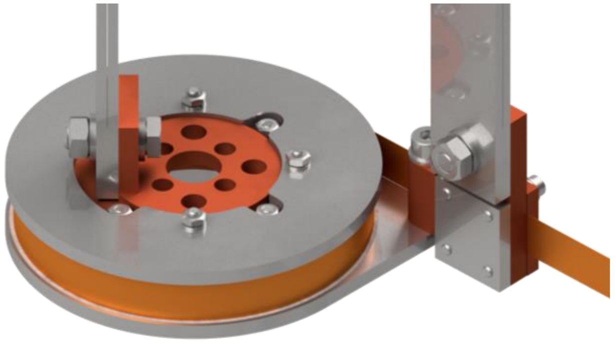
Examples of target technologies: Metal-Insulated (MI), multi-tape NI, multi-tape resistive layer + stabilizer.



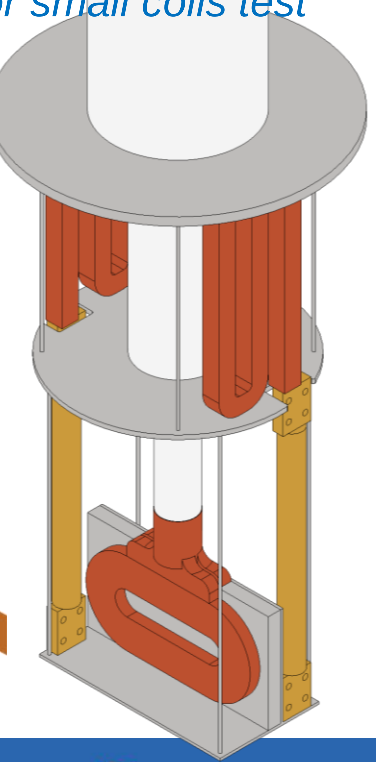
Test of small coils

- Synergies with IRIS (NextGenerationEU)
  1. Operation at T in the range 10 K – 30 K;
  2. Induction of flux densities in the tesla range
  3. Test in field up to 20+ T
  4. Non-round geometries (PNRR-IRIS project)
- The goal is to test magnet-like conditions for NI coils and further validate models.
- Target time: begin 2024

Coils are tested in **CERN, INFN LASA, PSI, LNCMI, CEA**



Draft of Variable Temperature system for small coils test

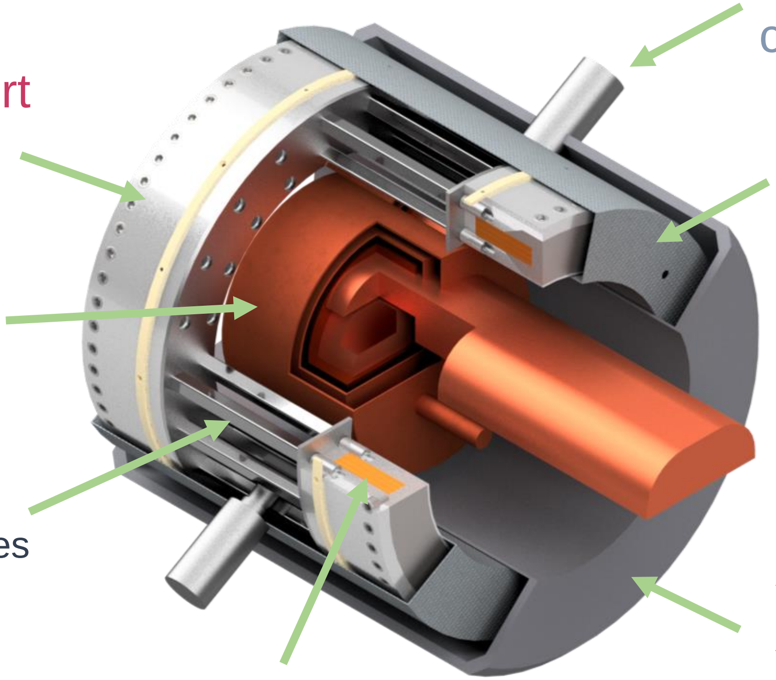


Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

RF test station

- Select and validate a technology and design options
- Design and commission a real size cell-like magnetic system
- Synergy between two WPs

600 mm RT bore for RF
7 T (to 10 T)
+- 5 Tons range forces



Sc magnet/cryostat sketch by M. Castoldi & Stefano Sorti,
UMIL & INFN-LASA

(RF drawing by Guillaume Ferrand –CEA

Schedule general task 7.2

Review of conductor requirements and of material options started

			Today:		15/6/2023		2023				2024				2025				2026				2027			
							gen	apr	lug	ott	gen	apr	lug	ott	gen	apr	lug	ott	gen	apr	lug	ott	gen	apr	lug	ott
							1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	OBJECTIVES (can be in Parallel)	COLLABORATORS	PROGRESS	MONTHS	START	END	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
	General tasks related to this workpackage	**Institutes: INFN, CERN, Utwente, Ugeneva, Usouthampton** **Persons: M. Statera, L. Bottura, H. Ten Kate, A. Kario, C. Senatore, Y. Yang, S. Fabbri, L. Quettier**																									
1	Review and define broad conductor requirements (operating temperature, materials, electrical, mechanical, etc.) for various types of solenoids (target, 6D cooling, final cooling): tapes, wires, and cables.	M. Statera, L. Bottura, H. Ten Kate, A. Kario, C. Senatore, Y. Yang	0%	6,0	1-Jan-23	30-May-23																				
2	Review material options for HF and UHF HTS solenoids (REBCO, Bi-2212, Bi-2223, IBS), providing broad evaluation of potential of each material for high field and temperature higher than liquid He, with Pro's and Con's	Y. Yang (SO'TON)	0%	15,0	1-Jan-23	30-Mar-24	🟩	🟩	▨	▨																
3	Cost and power estimate	M. Statera, L. Bottura, S. Fabbri, L. Quettier		54,0							▨	▨	▨	▨	▨	▨	▨	▨								
	Draft version June 2025		0%	30,0	1-Jan-23	30-Jun-25													▨	▨	▨	▨				
	Final version June 2027		0%	24,0	1-Jul-25	1-Jun-27																				
4	**Milestone (M7.1)**: Report on solenoids and TPL experiments - by Mar. 1 2024				1-Mar-24	1-Mar-24																				
5	**Milestone (M7.3)**: Workshop on ultra-high-field solenoids - by Aug. 30 2025				30-Aug-25	30-Aug-25																				
6	**Milestone (M7.6)**: Report on solenoid conceptual design - by Jan. 1 2026				1-Jan-26	1-Jan-26	🟩	🟩	▨	▨	▨	▨														

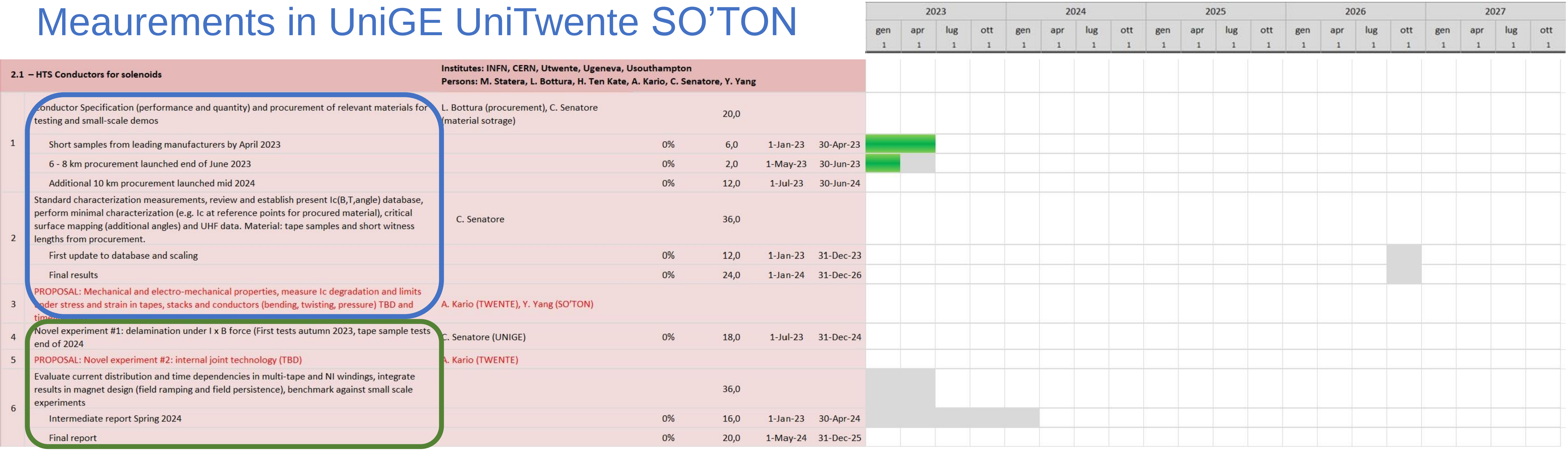
Milestones preparation started: workshop in UHF Solenoids, technology and design reviews

Schedule conductor R&D

Conductor characterization: Ic vs stress/strain, angle, field…

Procurement of updated tapes available in engineering lengths ongoing

Meaurements in UniGE UniTwente SO’TON



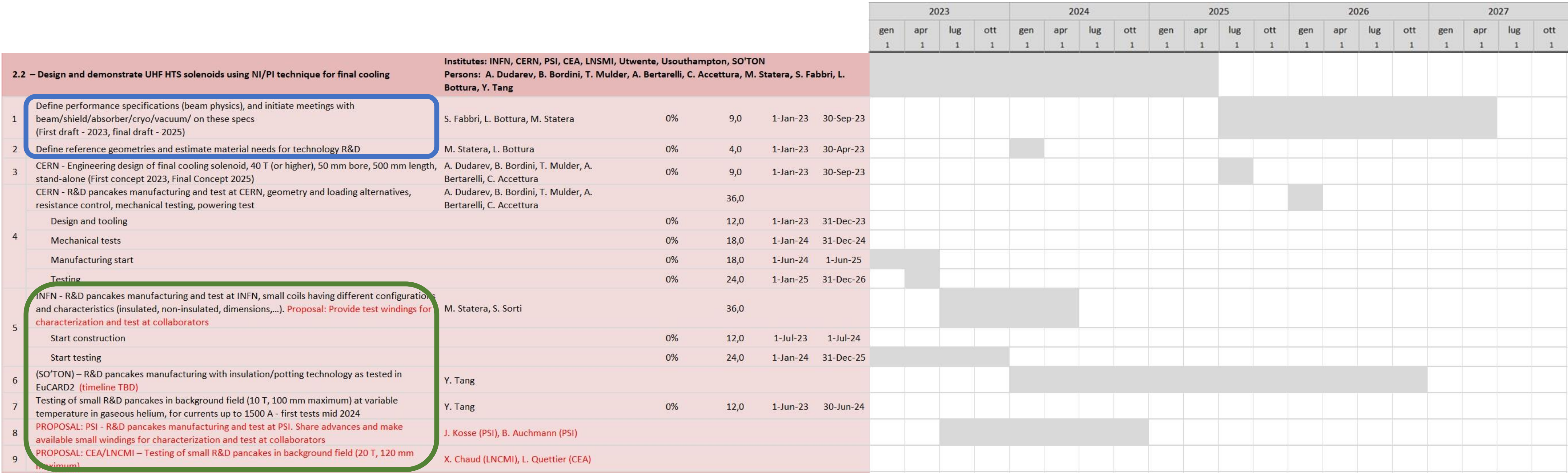
	2.1 – HTS Conductors for solenoids	Institutes: INFN, CERN, Utwente, Ugeneva, Usouthampton Persons: M. Statera, L. Bottura, H. Ten Kate, A. Kario, C. Senatore, Y. Yang				
1	Conductor Specification (performance and quantity) and procurement of relevant materials for testing and small-scale demos	L. Bottura (procurement), C. Senatore (material sotrage)		20,0		
	Short samples from leading manufacturers by April 2023		0%	6,0	1-Jan-23	30-Apr-23
	6 - 8 km procurement launched end of June 2023		0%	2,0	1-May-23	30-Jun-23
	Additional 10 km procurement launched mid 2024		0%	12,0	1-Jul-23	30-Jun-24
2	Standard characterization measurements, review and establish present Ic(B,T,angle) database, perform minimal characterization (e.g. Ic at reference points for procured material), critical surface mapping (additional angles) and UHF data. Material: tape samples and short witness lengths from procurement.	C. Senatore		36,0		
	First update to database and scaling		0%	12,0	1-Jan-23	31-Dec-23
	Final results		0%	24,0	1-Jan-24	31-Dec-26
3	PROPOSAL: Mechanical and electro-mechanical properties, measure Ic degradation and limits nder stress and strain in tapes, stacks and conductors (bending, twisting, pressure) TBD and tim	A. Kario (TWENTE), Y. Yang (SO’TON)				
4	Novel experiment #1: delamination under I x B force (First tests autumn 2023, tape sample tests end of 2024	C. Senatore (UNIGE)	0%	18,0	1-Jul-23	31-Dec-24
5	PROPOSAL: Novel experiment #2: internal joint technology (TBD)	A. Kario (TWENTE)				
6	Evaluate current distribution and time dependencies in multi-tape and NI windings, integrate results in magnet design (field ramping and field persistence), benchmark against small scale experiments			36,0		
	Intermediate report Spring 2024		0%	16,0	1-Jan-23	30-Apr-24
	Final report		0%	20,0	1-May-24	31-Dec-25

Modeling and measurements of magnetization and current distribution in stacks and joints

Schedule 6D solenoids

Specification of parameters and reference geometries for the solenoids (1 km)

Performance, Cost, Sustainability and series production compatibility



	2.2 – Design and demonstrate UHF HTS solenoids using NI/PI technique for final cooling	Institutes: INFN, CERN, PSI, CEA, LNSMI, Utwente, Usouthampton, SO'TON Persons: A. Dudarev, B. Bordini, T. Mulder, A. Bertarelli, C. Accettura, M. Statera, S. Fabbri, L. Bottura, Y. Tang				
1	Define performance specifications (beam physics), and initiate meetings with beam/shield/absorber/cryo/vacuum/ on these specs (First draft - 2023, final draft - 2025)	S. Fabbri, L. Bottura, M. Statera	0%	9,0	1-Jan-23	30-Sep-23
2	Define reference geometries and estimate material needs for technology R&D	M. Statera, L. Bottura	0%	4,0	1-Jan-23	30-Apr-23
3	CERN - Engineering design of final cooling solenoid, 40 T (or higher), 50 mm bore, 500 mm length, stand-alone (First concept 2023, Final Concept 2025)	A. Dudarev, B. Bordini, T. Mulder, A. Bertarelli, C. Accettura	0%	9,0	1-Jan-23	30-Sep-23
4	CERN - R&D pancakes manufacturing and test at CERN, geometry and loading alternatives, resistance control, mechanical testing, powering test	A. Dudarev, B. Bordini, T. Mulder, A. Bertarelli, C. Accettura		36,0		
	Design and tooling		0%	12,0	1-Jan-23	31-Dec-23
	Mechanical tests		0%	18,0	1-Jan-24	31-Dec-24
	Manufacturing start		0%	18,0	1-Jun-24	1-Jun-25
	Testing		0%	24,0	1-Jan-25	31-Dec-26
5	INFN - R&D pancakes manufacturing and test at INFN, small coils having different configurations and characteristics (insulated, non-insulated, dimensions,…). Proposal: Provide test windings for characterization and test at collaborators	M. Statera, S. Sorti		36,0		
	Start construction		0%	12,0	1-Jul-23	1-Jul-24
	Start testing		0%	24,0	1-Jan-24	31-Dec-25
6	(SO'TON) – R&D pancakes manufacturing with insulation/potting technology as tested in EuCARD2 (timeline TBD)	Y. Tang				
7	Testing of small R&D pancakes in background field (10 T, 100 mm maximum) at variable temperature in gaseous helium, for currents up to 1500 A - first tests mid 2024	Y. Tang	0%	12,0	1-Jun-23	30-Jun-24
8	PROPOSAL: PSI - R&D pancakes manufacturing and test at PSI. Share advances and make available small windings for characterization and test at collaborators	J. Kosse (PSI), B. Auchmann (PSI)				
9	PROPOSAL: CEA/LNCMI – Testing of small R&D pancakes in background field (20 T, 120 mm maximum)	X. Chaud (LNCMI), L. Quettier (CEA)				

R&D on smal coils and cabling options

Test in self field and in field – CERN, INFN LASA, PSI, LNCMI, CEA

Deliverables

T_0 March 2023

T_0+ 20 months	M7.3 Workshop on Ultra High Field Solenoids
T_0+ 33 months	D 7.1 Intermediate Report
T_0+ 45 months	D 7.2 Consolidated report

Higher TRL allows civil application

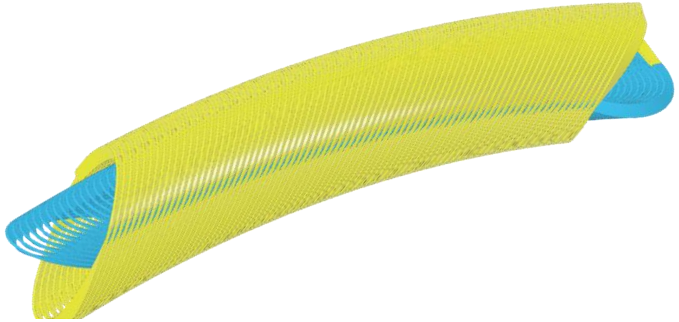
Example of an application having the same pillars : Performance, Cost, Sustainability

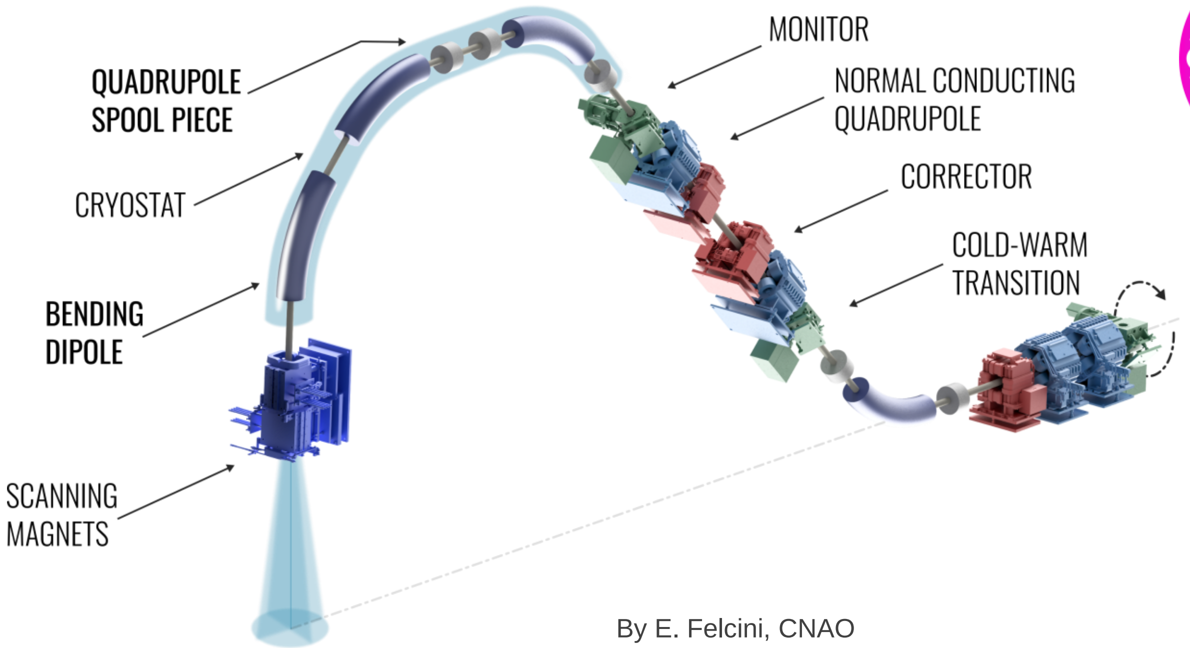
hadron therapy

HITRI plus
Heavy Ion Therapy Research Integration

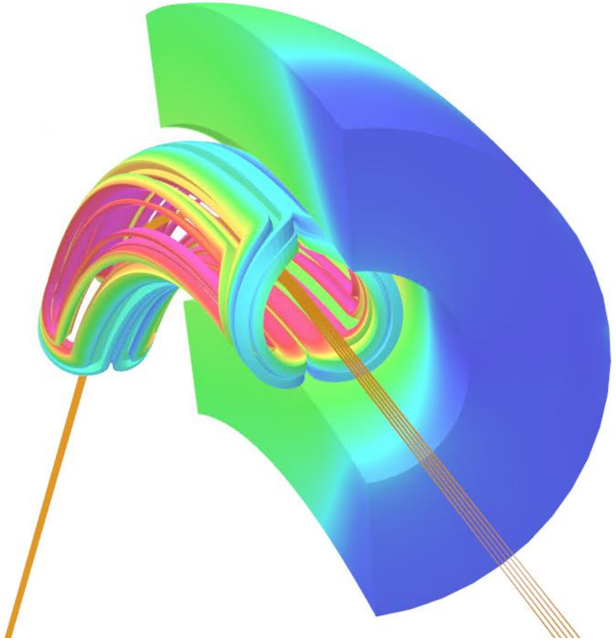
iFAST

Superconducting
Ion
Gantry





By E. Felcini, CNAO



Conclusion

- An overview of the required coils
    - 12 cells
    - 18 different coils
    - 1 km of 6D cooling
- We set the driving parameters and the technology we are aiming to
- A full R&D program for tape characterization and conductor development
- Focus on modeling (magnetization, current distribution…)
- Many synergies in the project and in other applications
- Performance-Cost-Sustainability togheter with compatibility with series production

THANKS