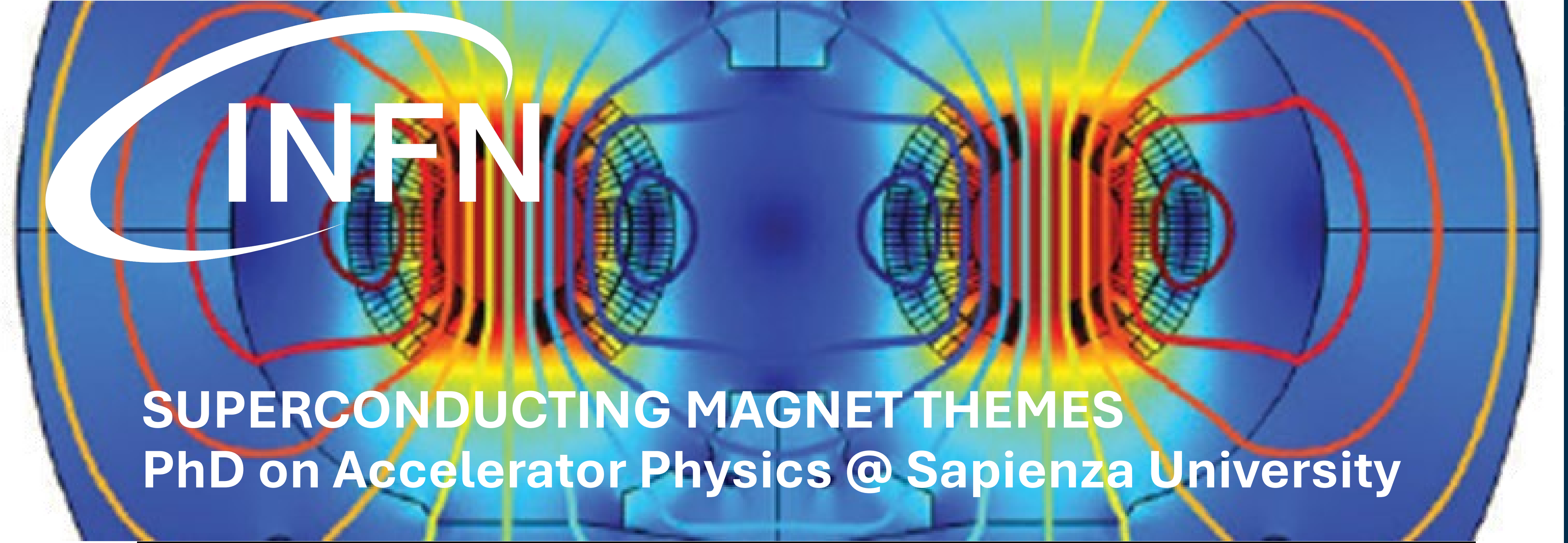

SUPERCONDUCTING MAGNET THEMES
PhD on Accelerator Physics @ Sapienza University

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THESE SLIDES ARE MOSTLY TAKEN FROM PREVIOUS PRESENTATIONS BY L.ROSSI

INFN Outline

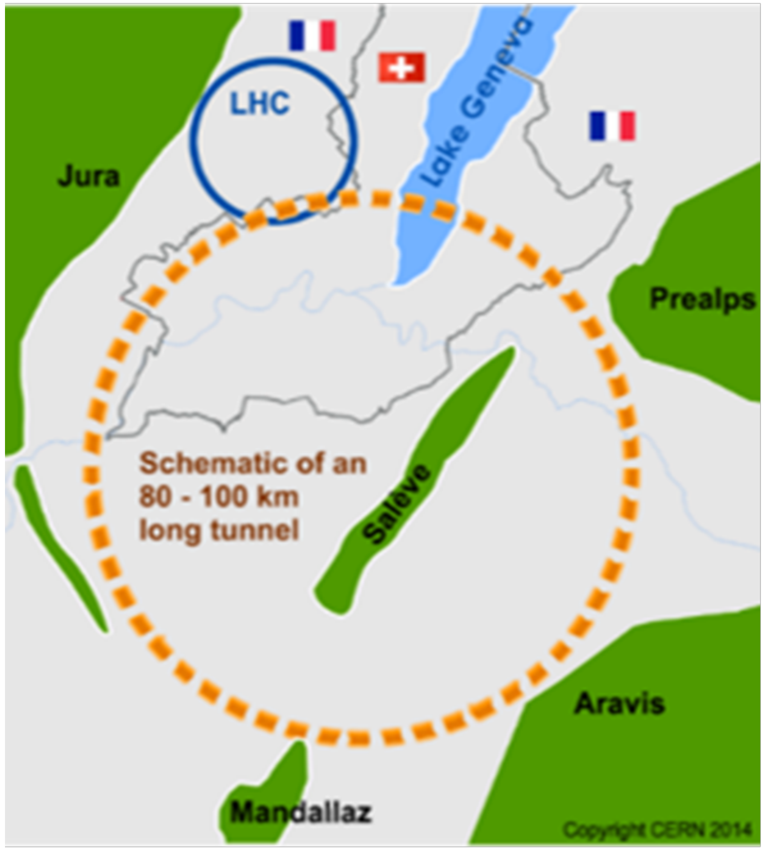
- SC magnets for high energy physics
- SC magnets for the Muon Collider
- SC magnets for medical applications

General information

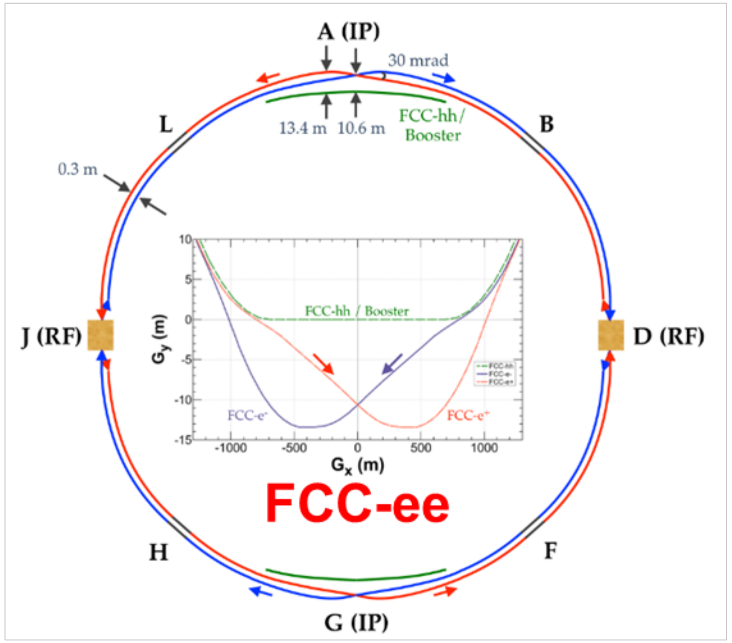
- The thesis locations can be:
  - **Milano,** at the LASA Laboratory of University and INFN
  - **Genova,** at the Physics Department
- To get more information you can contact (but many more people are involved):
  - Stefania Farinon stefania.farinon@ge.infn.it
  - Lucio Rossi lucio.rossi@mi.infn.it
  - Massimo Sorbi massimo.sorbi@mi.infn.it
  - Marco Statera marco.statera@mi.infn.it
- A related course will be offered:
  - Design of superconducting magnets (S.Farinon)

SC magnets for high energy physics

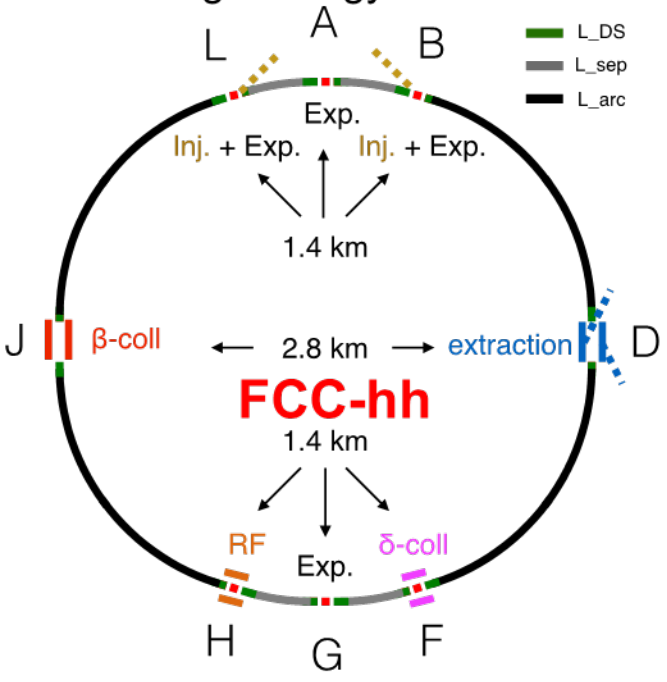
The FCC integrated program



Phase 1 : FCC-ee
collider electron - positon
Higgs, Z, W, ttbar



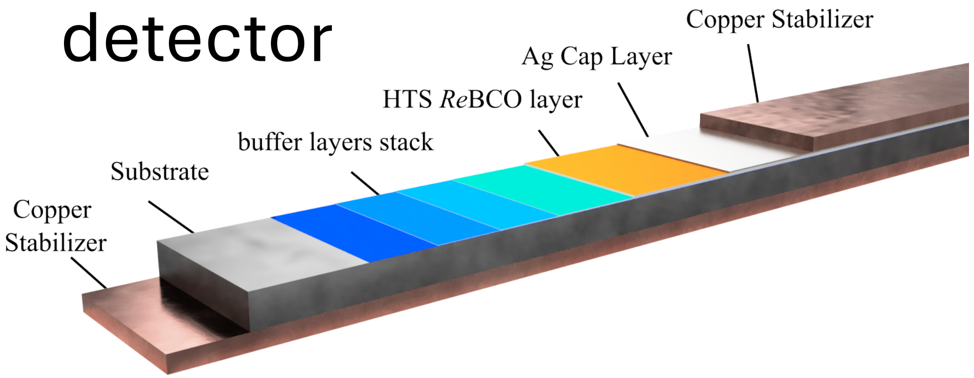
Phase 2 : FCC-hh
collider proton - proton
High energy frontier

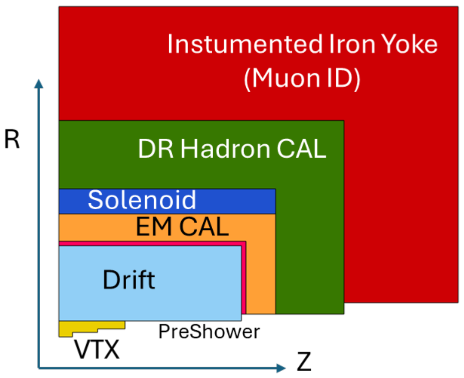


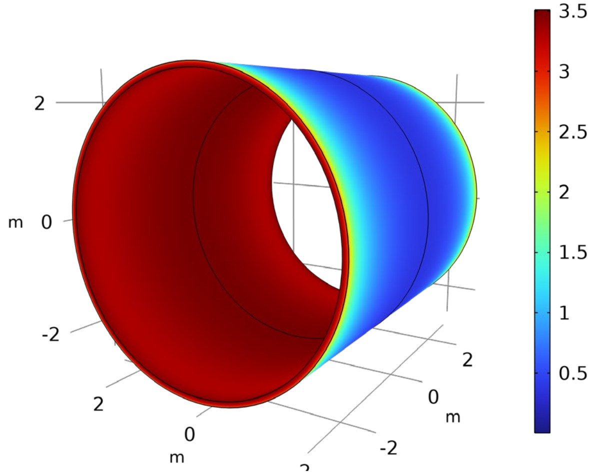
2020 - 2040 | 2040 - 2055 | 2060 - 2090

FCC-ee magnets

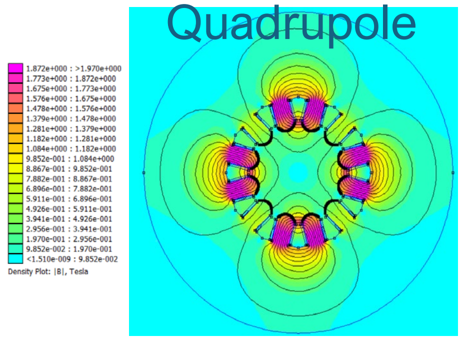
- 3T HTS solenoid for the IDEA detector

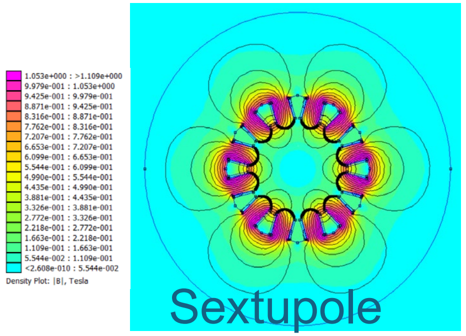


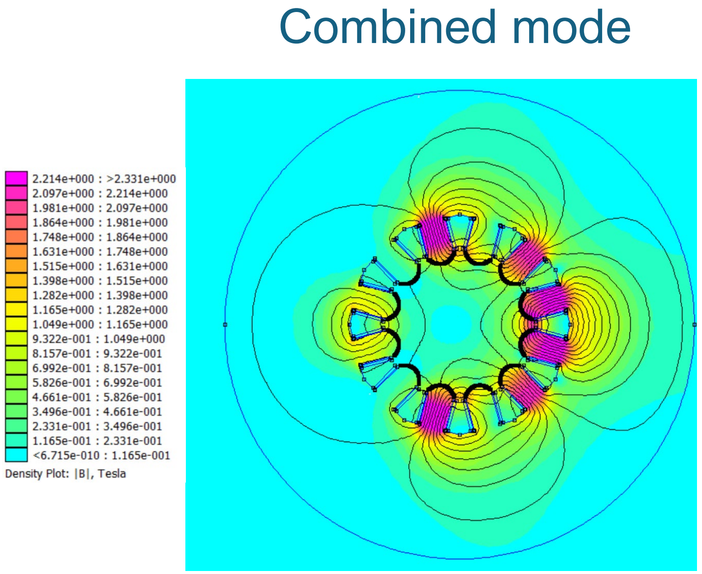




- HTS superferric combined function quadrupole and sextupole magnet

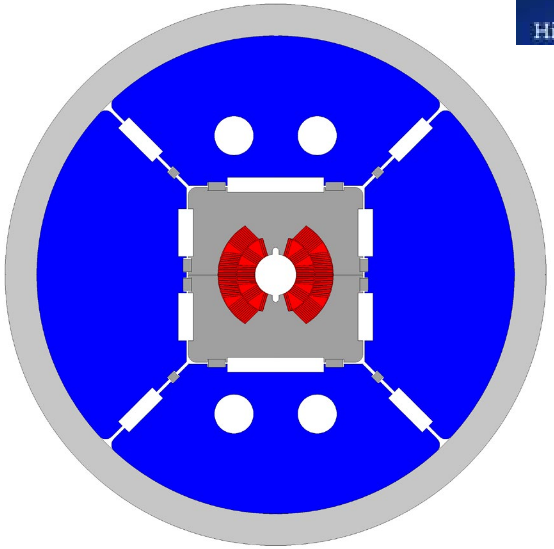






FCC-hh magnets

- The FalconD project involves the development and construction of a short model Nb_3Sn dipole with the following specifications:
  - Single aperture with an inner bore of 50 mm.
  - 2-layer cos-theta coil, providing a bore field of 12 T at 1.9 K.
  - Mechanical assembly using bladder & key technology.
  - The total coil length is 1.5 m.

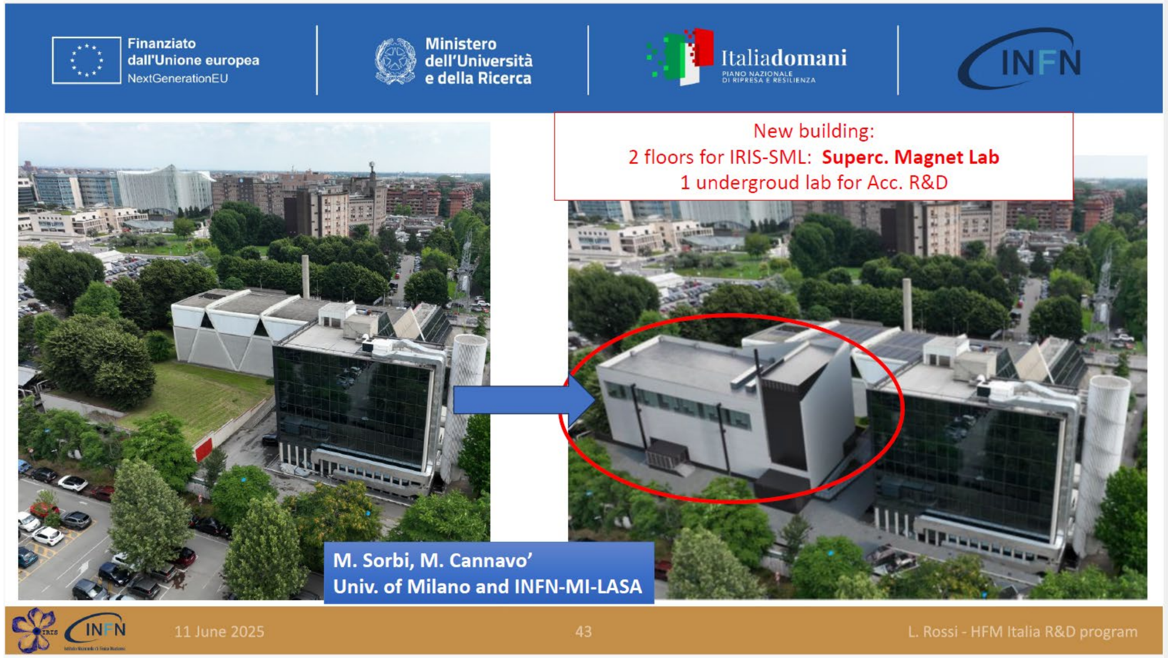


Furnace for coil heat treatments

SS end spacers

HFM–Italia program

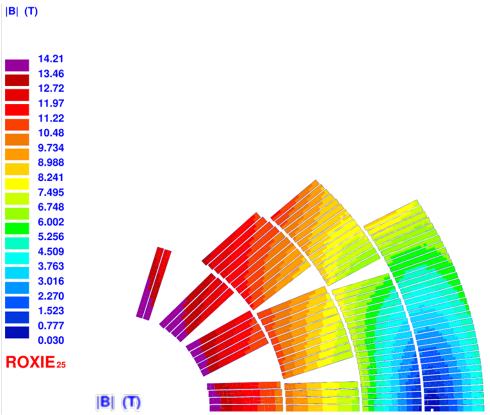
- Recently, CERN and INFN signed a new collaboration agreement aimed at **designing** (including all the necessary R&D), **building**, and **cold-testing**
  - a 14 T Nb_3Sn dipole for the FCC-hh (6-year program)
  - a 10 T HTS dipole (3-year program)
- Development and fabrication performed in the new IRIS facilities at LASA, the SML (Superconducting Magnet Lab)



14 T Nb_3Sn dipole

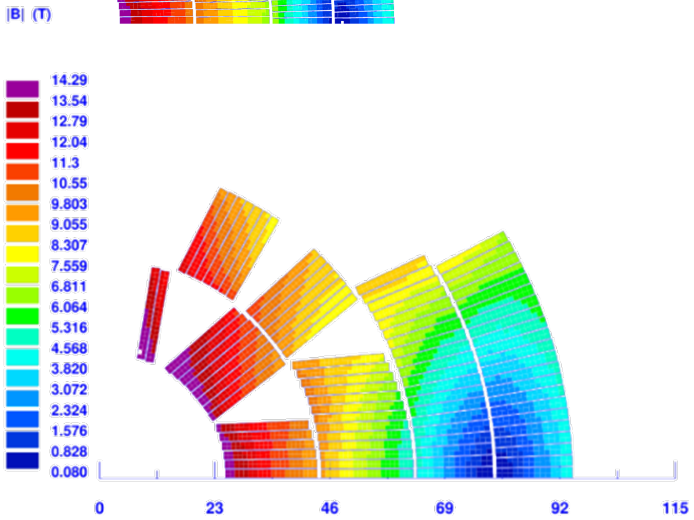
- We started working on 2 options:
  - Full-Nb_3Sn

	Full Nb_3Sn			
	HF 1.9K	HF 4.2K	LF 1.9K	LF 4.2K
Achieved bore field [T]	14			
Current [A]	9800			
Peak field [T]	14.21		11.28	
Current density [A/mm^2]	280		400	
Supercond. current density [A/mm^2]	950		1400	
Copper current density [A/mm^2]	792		1167	
Loadline fraction [%]	80	87.5	73	80
Temperature margin [K]	4.4	2.2	5.6	3.3
Enthalpy margin [mJ/cm^3]	12.4	8.9	19.3	16
b_3 / b_5 / b_7 / b_9 at nominal [unit]	0.47 / -5.81 / 3.57 / 1.33			
Equivalent width [mm]	55.4			
N° of turns (per pole)	39		69	
N° blocks (per pole)	7		3	
Aperture [mm]	50			
Maximum azimuthal stress [MPa]	83			
Maximum radial stress [MPa]	97			



  - Hybrid Nb_3Sn /NbTi

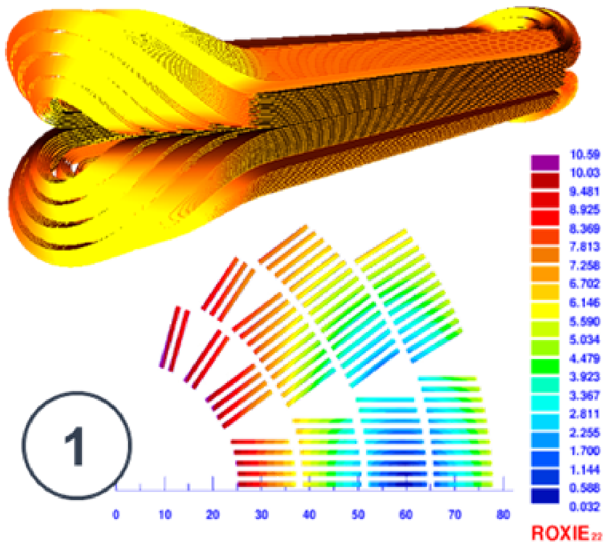
	HF (1.9 K)	LF (1.9 K)
Achieved bore field [T]	14	
Current [A]	11800	
Peak field [T]	14.3	8.98
Current density [A/mm^2]	337	351
Superconducting current density [A/mm^2]	988	899
Copper current density [A/mm^2]	1098	999
Load-line fraction [%]	81	80.9
Temperature margin [K]	4.3	2.05
Enthalpy margin [mJ/cm^3]	12.5	2.5
b_3 / b_5 / b_7 / b_9 [unit]	−0.009 / −1.09 / 8.44 / 2.69	
Equivalent width [mm]	59	
Number of turns (per quadrant)	43	42
Number of blocks (per quadrant)	6	2
Aperture [mm]	50	

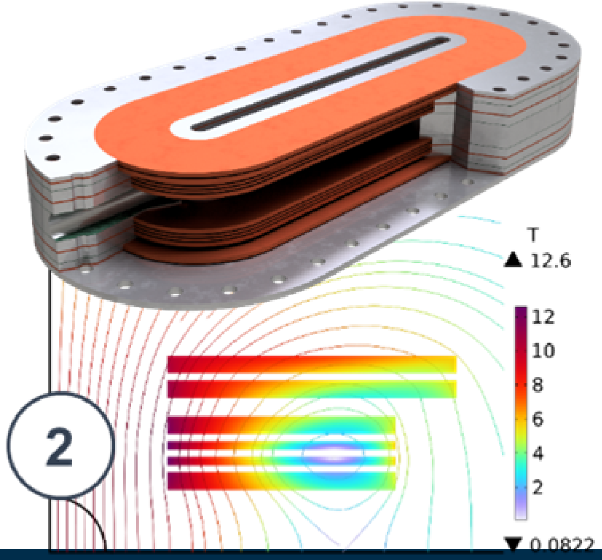


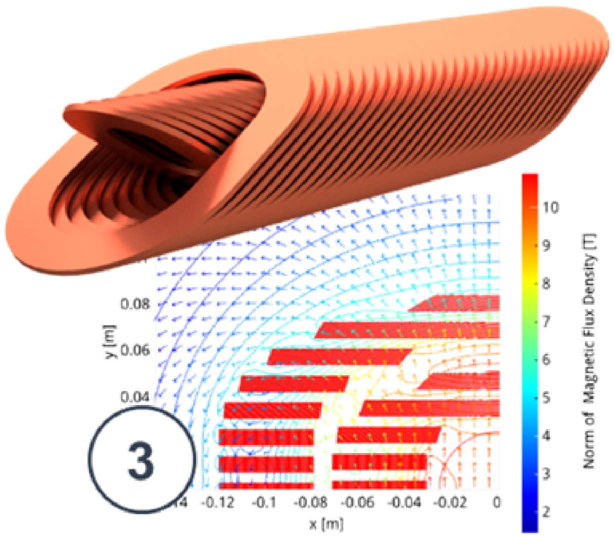
10 T HTS dipole demonstrator

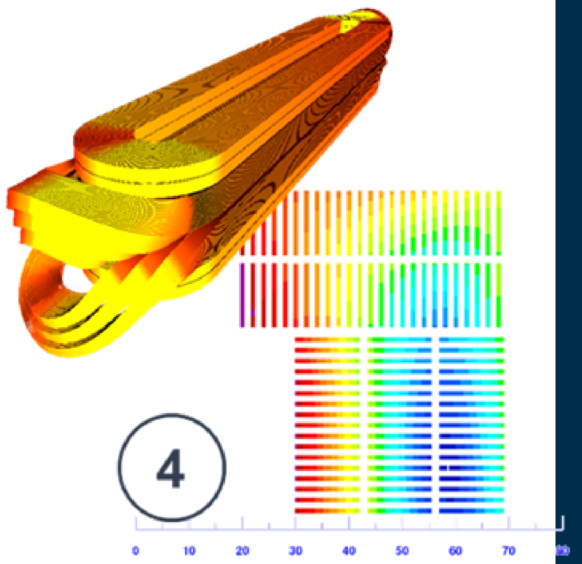
Common	B centre	Aperture diameter[1]	T_{op}	Straight section	Tape quality[2]	Max. Unit Length	Target J_{Cu}
	10 T	50 mm	20 K	700 mm	FFJ 2021	200 m	800 A/mm^2

Configurations	#	Coil geometry	L of tape (km) 12-mm *equivalent*	I_{op} (A)	I×n	i= I/I_c (%)	ΔT (K) *margin*	Loadline Margin (%)	Field q. (10^{-4})[3]
	1	Cos-Theta	3.9	9230	1.5 MA	68.5	10	22	<1
	2	Racetrack	7.3	3330	3.4 MA	67	10	22	<20
	3	Pancake CCT	5.5	1440	2.1 MA	69	10	23	100
	4	Hybrid	4.5	9170	1.8 MA	58	10	18	<10







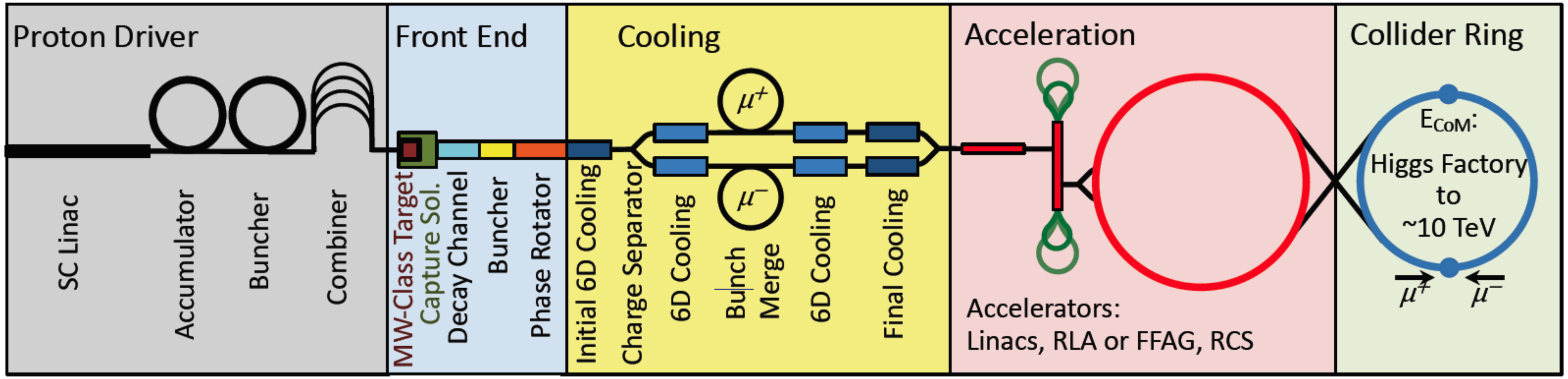


SC magnets for the Muon Collider

International MUON Collider Collaboration

The Muon Collider

- The **Muon Collider** represents a rising hope for an energy-frontier collider, offering both high energy and high precision.
- Its design is entirely dictated by the **muon lifetime**, which is just **2.2 μs at rest**, and the critical need for rapid and efficient cooling!



Short intense proton bunches produce muons that are captured

6D - Ionization cooling of muon in matter

Acceleration to collision energy

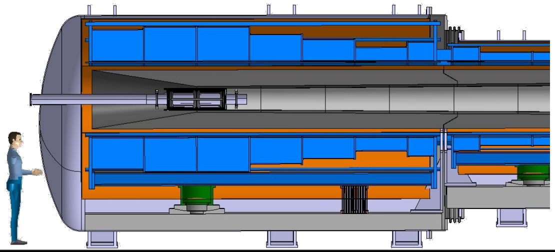
Collision

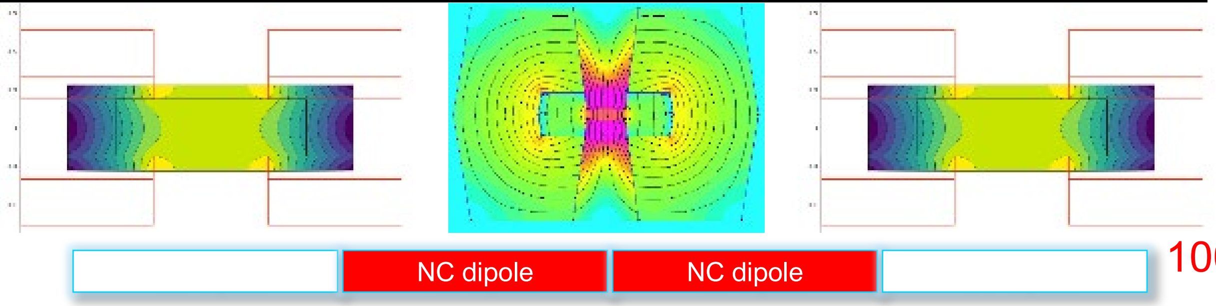
- Fast and efficient cooling of muons is essential to transform a "cloud of particles" into a cold, focused beam. The cooling cell is the most critical component of the accelerator—without cooling, there are no muons to collide. The cooling process works by absorbing energy in all directions and then restoring energy in a single direction. This requires: Efficient absorbers, Large-acceptance RF cavities, Strong, **very large-acceptance superconducting magnets** for focusing

Muon collider magnets

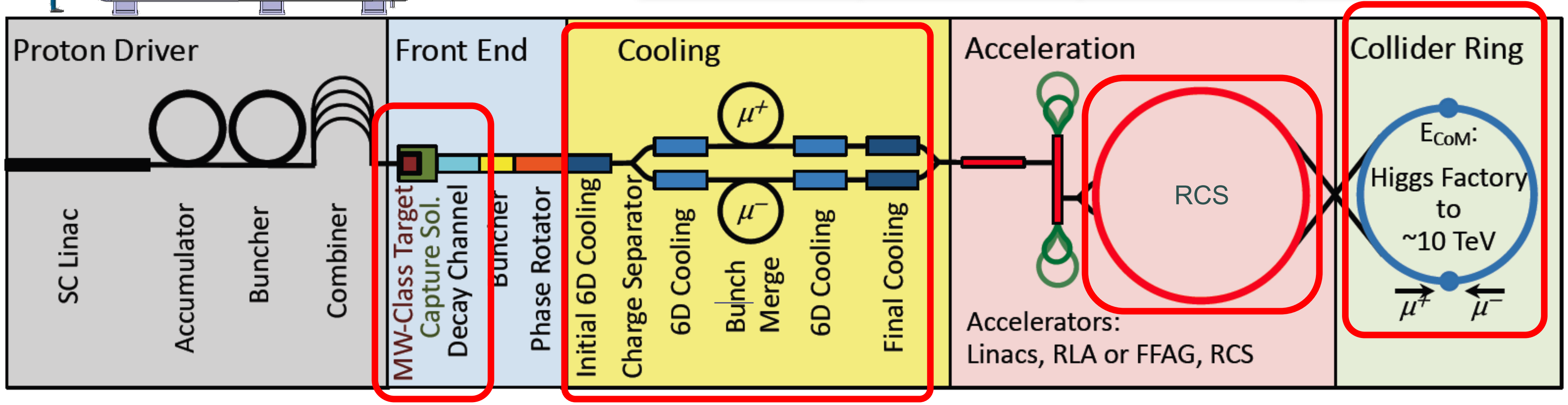
NC ±1.8 T, 400 Hz
100 mm x 30 mm

20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

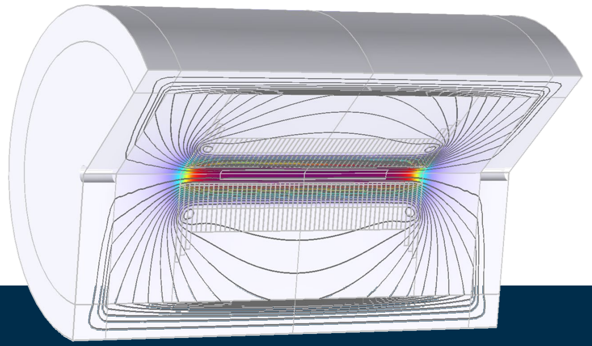




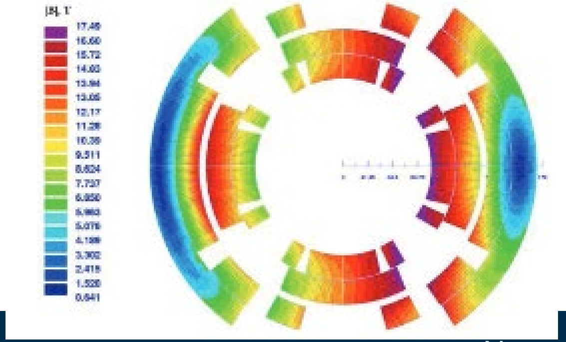
SC < 10T
100 mm x 30 mm



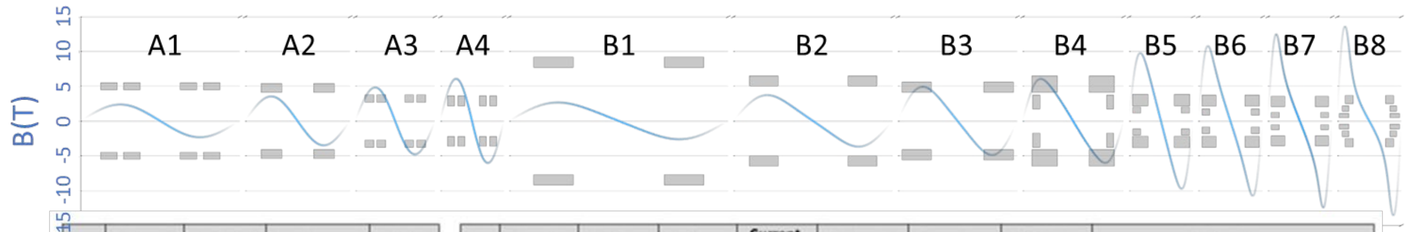
\> 40 T, 60 mm



16 T peak, 160 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy



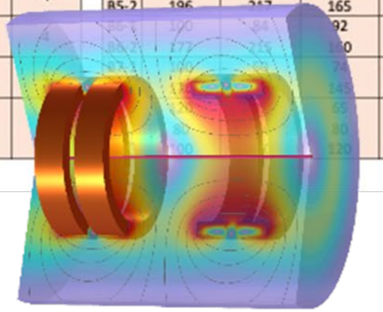
6D Cooling Cells (HTS @ 20 K)



Stage	Cell length (m)	Peak axis B (T)	Stored energy (MJ)	Coils/cell (-)
A1	2	2.4	5.4	4
A2	1.32	3.5	15.4	2
A3	1	4.8	7.2	4
A4	0.8	6.1	8.4	4
B1	2.75	2.6	44.5	2
B2	2	3.7	24.1	2
B3	1.5	4.9	29.8	2
B4	1.27	6	24.4	4
B5	0.806	9.8	12	4
B6	0.806	10.8	8.2	[illegible]
B7	0.806	12.5	5.7	[illegible]
B8	0.806	13.6	1.4	[illegible]

Coil	Length (mm)	Radius (mm)	Thickness (mm)	Current density (A/mm^2)	Peak coil B (T)	Hoop stress (MPa)	Radial stress (MPa)	Technology: Nb-Ti 4K	Technology: Nb_3Sn 4K	Technology: HTS 4K/20K
A1-1	210	450	100	63.25	4.1	34	-4.6	✓	✓	✓
A2-1	260	410	130	126.6	9.5	137	-28.3		✓	✓
A3-1	110	270	110	165	9.4	138	-28.5		✓	✓
A4-1	90	220	140	195	11.6	196	-49.4		✓	✓
B1-1	500	770	150	69.8	6.9	95	-13.5	✓	✓	✓
B2-1	360	500	150	90	8.4	114	-20.1		✓	✓
B3-1	370	410	150	123	11.2	174	-36.6		✓	✓
B4-1	92	175	200	94	9.2	231	-0.1/19.7		✓	✓
B4-2	320	410	240	70.3	7.8	66	-23.5		✓	✓
B5-1	100	113	88	157	13.9	336	-0.7/21.1		...	✓
B5-2	196	[illegible]	165	168	12.3	159	-55.7		✓	✓
[illegible]	[illegible]	[illegible]	92	185	14.2	314	-1.4/22.3		...	✓
[illegible]	[illegible]	[illegible]	[illegible]	155.1	10.3	118	-43.1		✓	✓
[illegible]	[illegible]	[illegible]	[illegible]	198	14.3	244	-1.1/20.7		...	✓
[illegible]	[illegible]	[illegible]	[illegible]	155	10.1	119	-37.4		✓	✓
[illegible]	[illegible]	[illegible]	[illegible]	220	15.1	119	-3.0/22.1		...	✓
[illegible]	[illegible]	[illegible]	[illegible]	135	6.2	110	-2.4/4.5	✓	✓	✓
[illegible]	[illegible]	[illegible]	[illegible]	153	6.2	41	-22.9	✓	✓	✓

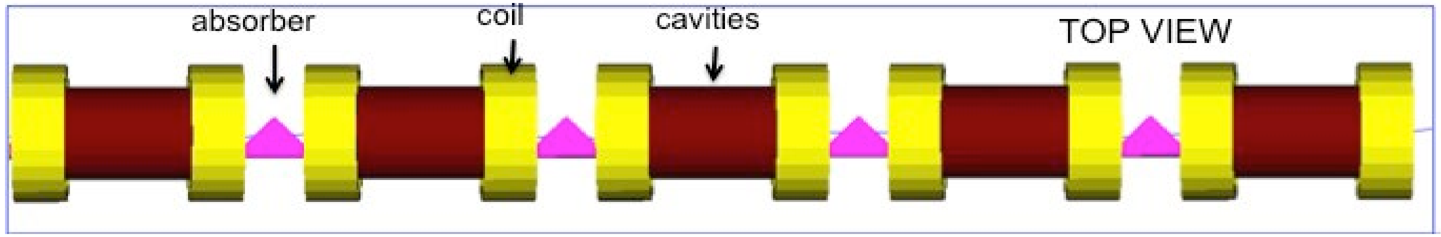
Coil size



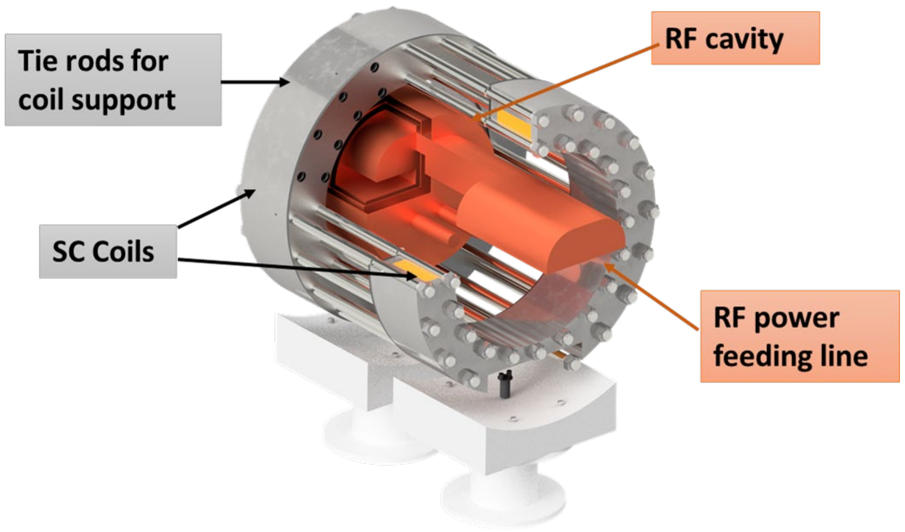
Quench protection

Margin

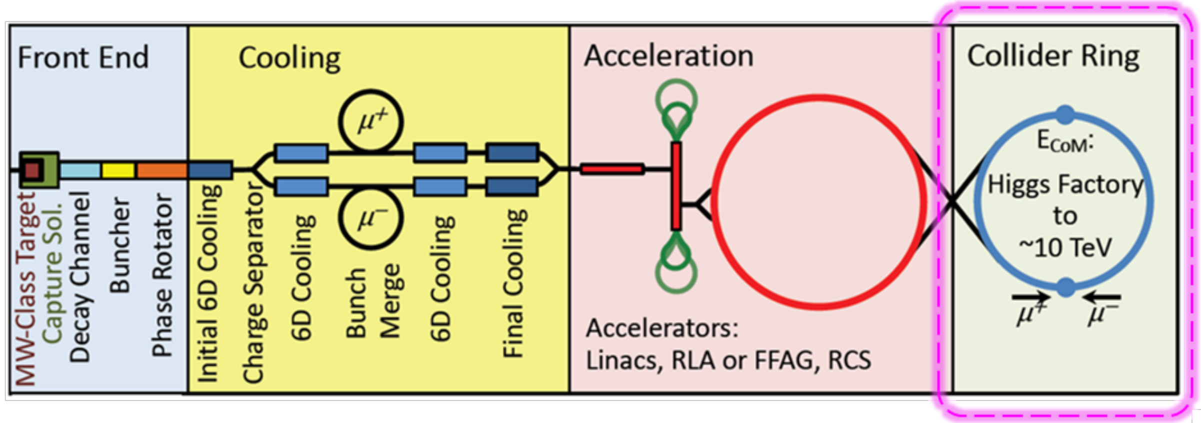
Mechanics



Facility under design at LASA lab
7 T splice coil in HTS, cryogen-free, for RF cavity test



Collider Magnets Requirements

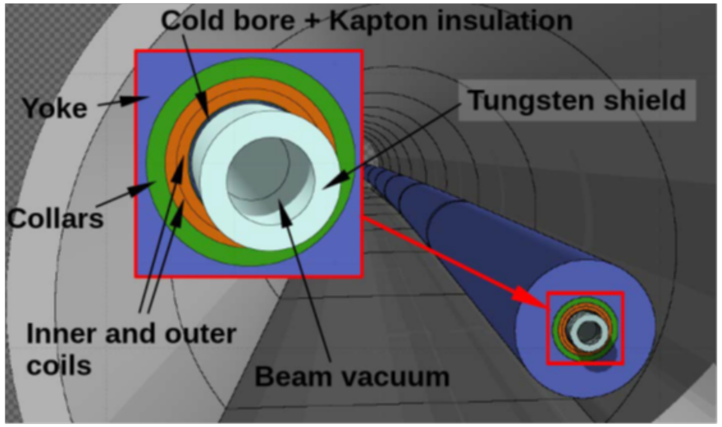


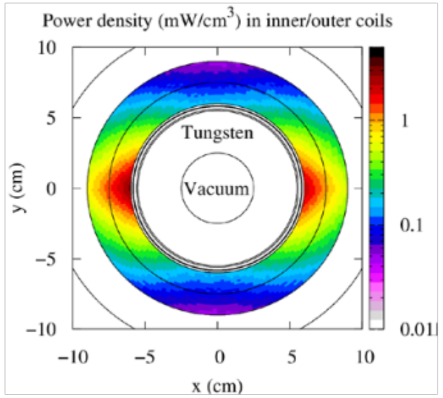
Field: 16 T peak (IR 20 T)

Length: 10…15 m (x 700)
Space between magnets: 300 mm
Radiation heat load: 5 W/m
Cumulative dose: 20…40 MGy

Aperture

Courtesy of Patricia Borges de Sousa
https://indico.cern.ch/event/1250075/contributions/5357594/

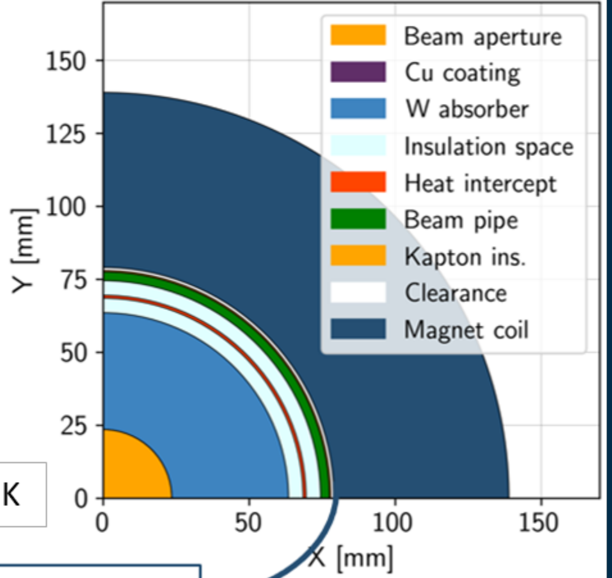




- Beam aperture (5σ) — 23.5 mm radius
- Cu layer beam screen — 0.01 mm thick
- Tungsten absorber — 40 mm thick
- Insulation space — 5 mm thick
- Heat intercept — 1 mm thick
- Insulation space — 5 mm thick
- Beam pipe — 3 mm thick
- Kapton insulation — 0.5 mm thick
- Clearance — 1 mm thick
- Coil pack* — (60 mm thick)

*thickness TBD, placeholder

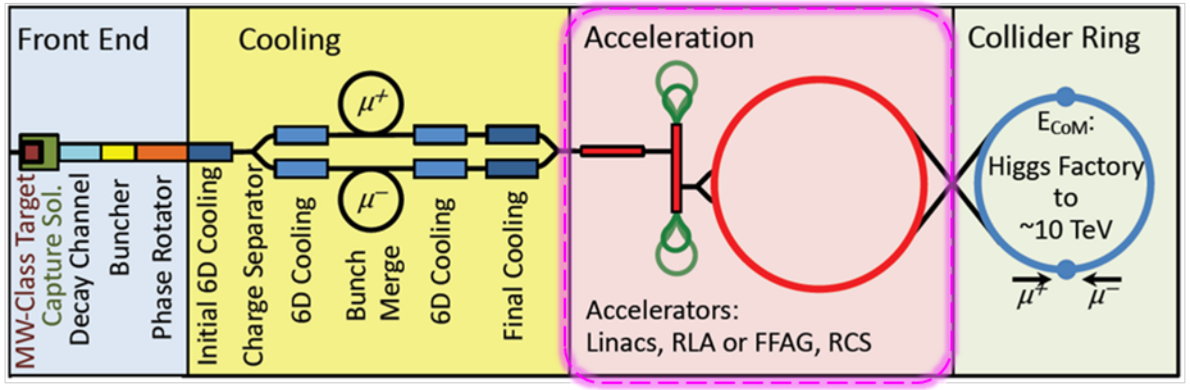
Assuming 10 TeV machine and coil at 4.5 K



Coil aperture 158 mm

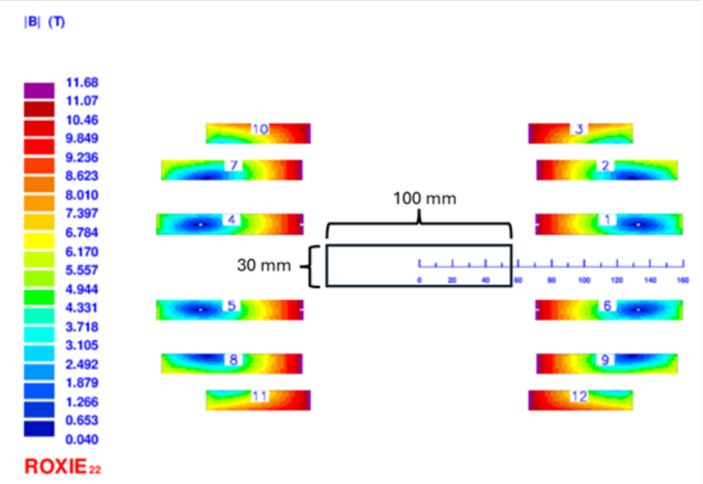
! Need for large fields in large apertures → discussion on parameter limits

Accelerator magnets



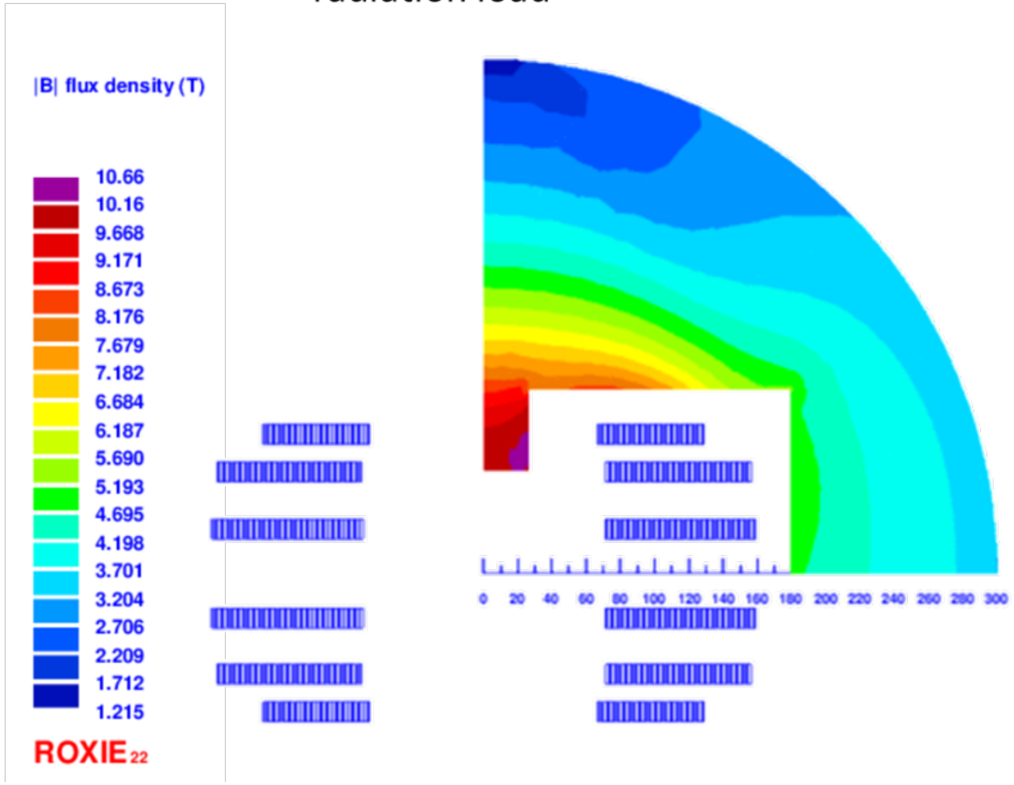
Field: 10 T

Aperture: large aspect ratio 100 mm×30 mm
no conductor on the midplane due to radiation load



$B_0 = 10\,T$

Field homogeneity @ 25mm = 0.425%



SC magnets for medical applications

What's next for particle therapy?

- Multiple ions delivered with light-weighted Gantry
- Rotatable gantry allows non-coplanar irradiation, enhancing effectiveness
- Treatment rooms equipped with patient imaging
- Dose Delivery and Range Verification Systems abl to adapt online the dose delivered

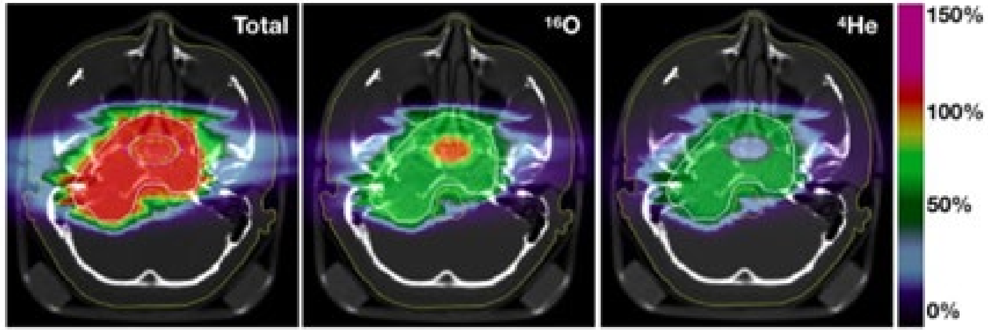
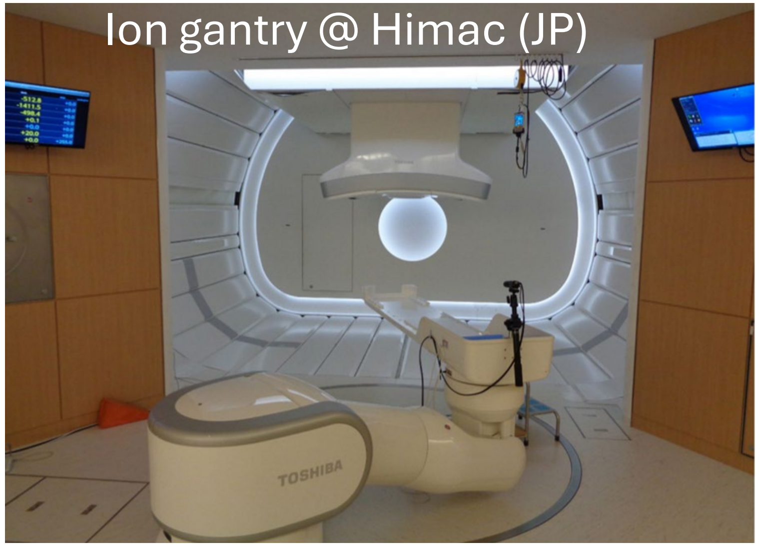
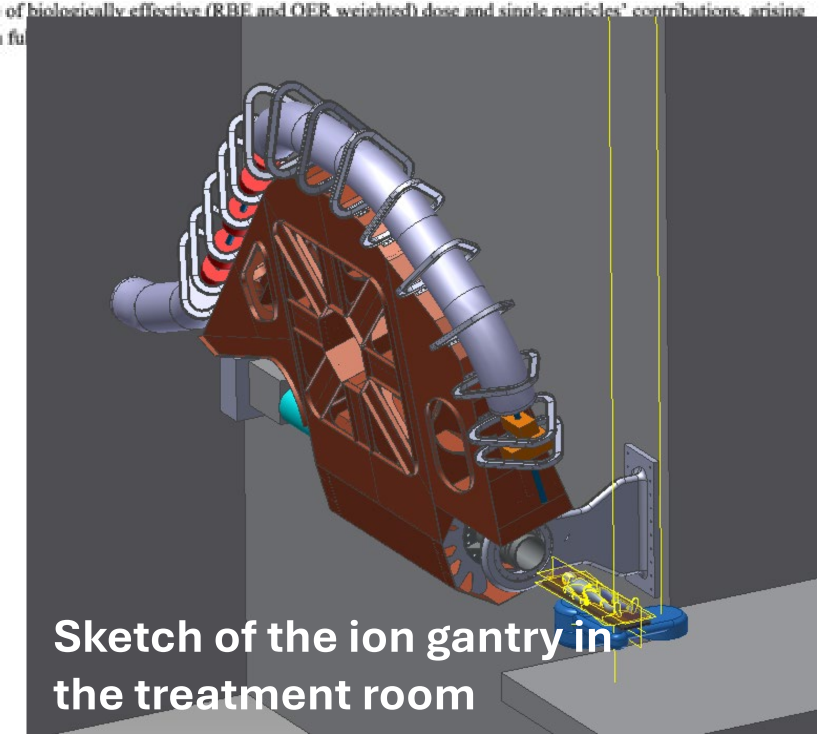


Figure1: Total profile of biologically effective (RBE and OER weighted) dose and single particles' contributions, arising from the Multiple-ion fu



Ion gantry @ Himac (JP)

Gantry and imaging system of a proton therapy center

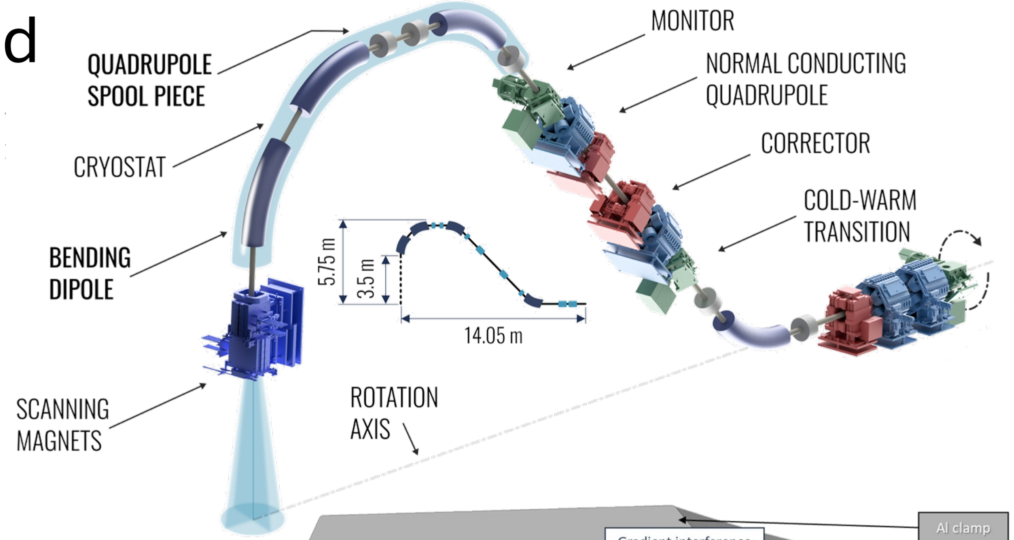


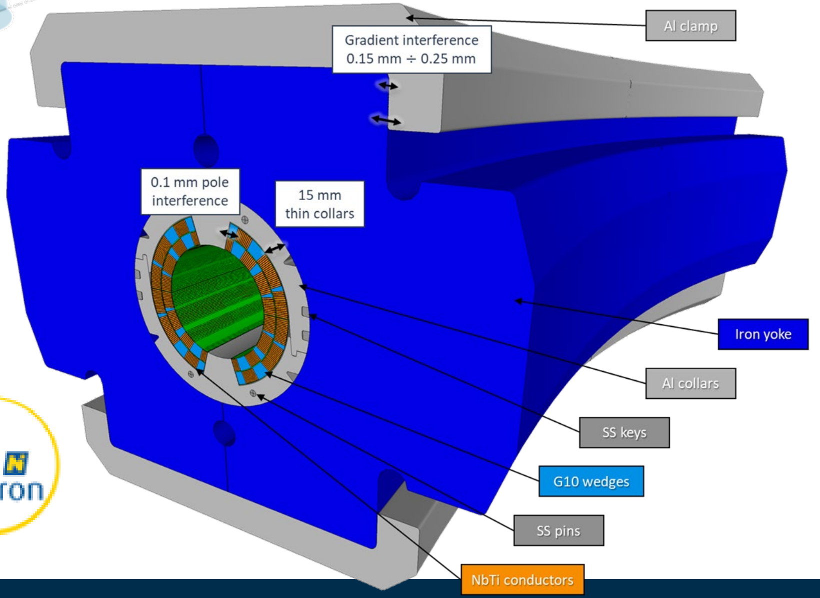
Sketch of the ion gantry in the treatment room

INFN SIG WP2

Superconducting Ion Gantry

- Design, construction and test of a curved superconducting demonstrator magnet (SDM-c) for ion gantries
- Main demo. magnet params
  - NbTi superconducting Rutherford cable
  - Cos-θ coils
  - Pure dipolar field: 4 T
  - Bore diameter: 80 mm
  - Small curvature radius: 1.65 m (Challenge #1)
  - Angular sector: 30°
  - High field ramp-rate: 0.15 T/s - 0.4 T/s (Challenge #2)
  - Compatible with conduction cooling (no LHe) but no optimization (Challenge #3)



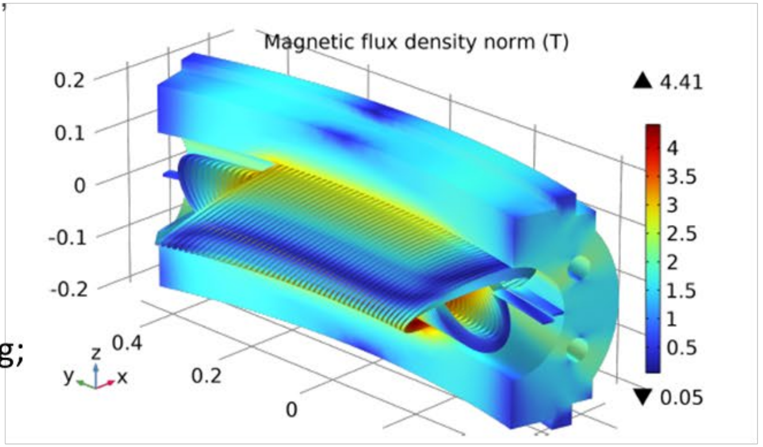


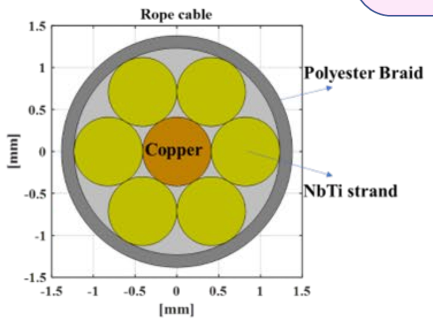
CERN CNAO Centro Nazionale di Adroterapia Oncologica INFN EuroSIG MedAustron

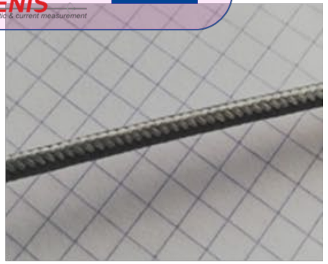
HITRIplus WP8 – Superconducting magnet design

Construction and test of a small demonstrator for feedback useful for accelerator as well as gantry final magnet design.

The decision to explore a **curved CCT layout magnet based on NbTi** (Low losses strand) and conductor (rope 6+1 strands);



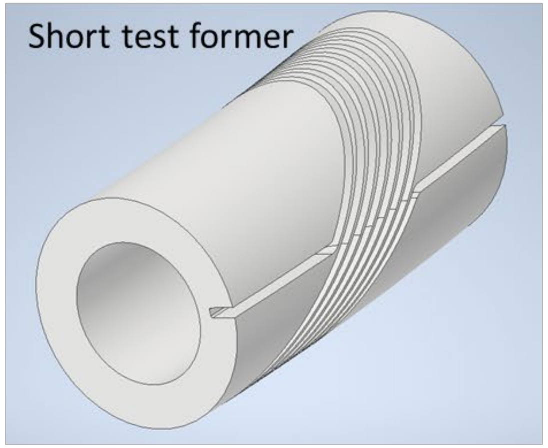


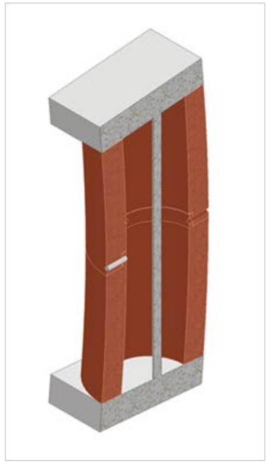


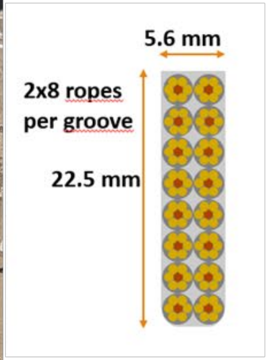
Main Parameters of demonstrator:

- **4 T pure dipole, Top of 4.7 K**;
- Bore diameter: 80 mm;
- Curvature radius: **1.65 m;**
- Angular sector: 30°;
- High field **ramp-rate: 0.4 T/s**;
- Compatible with conduction cooling;
- Wax impregnation test;
- Priority is to construct the curved former (AlBr);

The challenge is the heat extraction generated by superconductor and former (AC losses) without LHe cooling





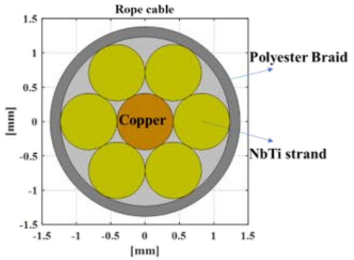


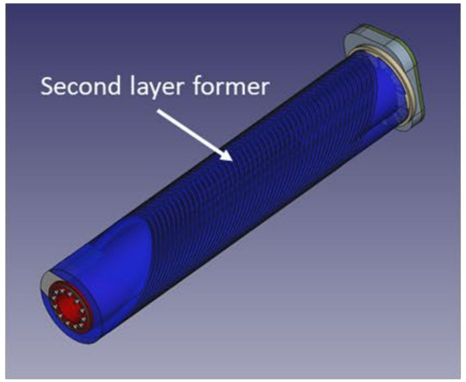
I.FAST WP8 – Innovative superconducting magnets

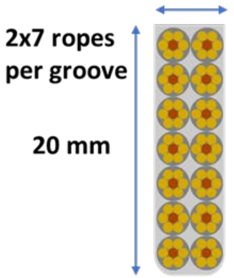
Exploring **Canted Cosine Theta with HTS superconductor (main goal),** preceded by a **combined function CCT based on LTS**

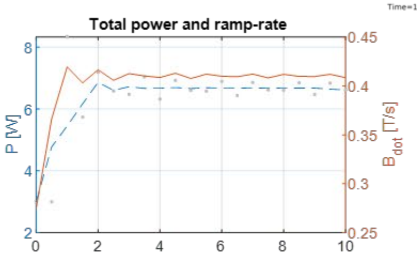
Construction of the two demonstrators: winding and magnet assembly, magnet test and validation:

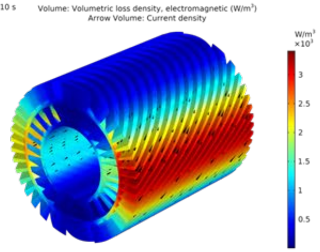
Combined CCT based on LTS (rope 6 NbTi + 1 copper strand as HITRIplus):
- 4 T dipole + 5 T/m quadrupole (important feature to test it for CCT);
- Demonstrator for testing the combined feature of CCT and thermal study of AC losses (0.4 T/s);

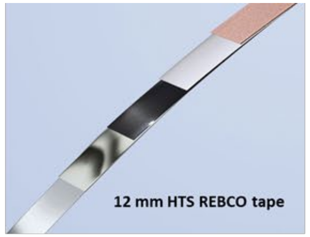




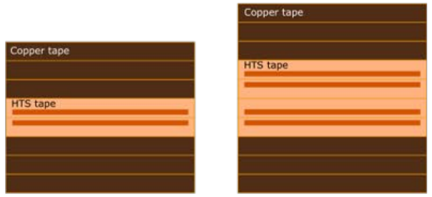


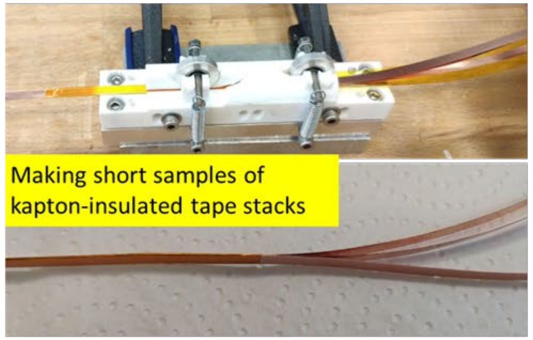


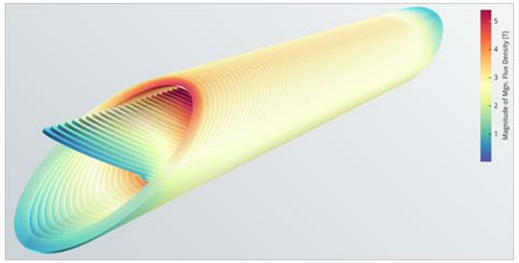




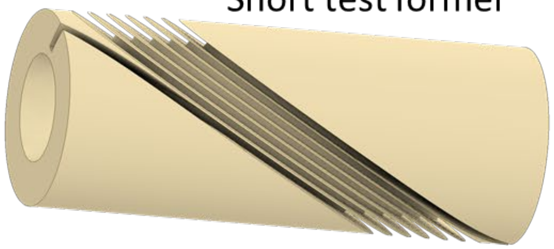
CCT based on HTS (REBCO tape 4 mm wide):
- 4 T dipole with a new Top of 20 K (> 10 K of margin);
- Frenet-Serret frame used for the conductor (avoid hard way bending);
- Straight geometry just to start the study (HTS is already difficult enough);
- Two design options: 2-tapes (980 A) and 4-tapes cable (1990 A);
- Quench protection is demanded (Cu stabilizer added for this);







Short test former



Thanks for the attention