ITALIAN ACTIVITY IN THE HIGH FIELD MAGNET PROGRAM FOR FCC-hh

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Istituto Nazionale di Fisica Nucleare

THE MILANO-GENOVA INFN TEAM

- The Milan and Genoa sections of INFN have been close collaborators since the project for the design, construction and testing of a pulsed curved dipole for the SIS300 at GSI (started in 2005), especially thanks to the friendship between Giovanni Volpini and Pasquale Fabbricatore.
- The collaboration continued with the European project **EuroCircol**, intended as the first step towards the development of the 16 T Nb_3Sn dipoles for the FCC.
- We are presently collaborating on several projects:
  - **FalconD** (part of the High Field Magnet Program)
  - SIG – Superconducting Ion Gantry
  - HITRIplus – Heavy Ion Therapy Research Integration
  - I.FAST – Innovation Fostering in Accelerator Science and Technology

Milano LASA
- Lucio Rossi
- Massimo Sorbi
- Marco Statera
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- Ernesto De Matteis
- Samuele Mariotto
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- Filippo Levi (PhD)
- Sergio Burioli (PhD)
- Andrea Gagno (PhD)
- Michela Bracco (AdR)

Collaboration with CERN
- Amalia Ballarino
- Friedrich Lackner
- Diego Perini
- Davide Tommasini

EUROCIRCOL

Started in June 2015

Ended in December 2019

Istituto Nazionale di Fisica Nucleare

EuroCirCol

A key to New Physics

FCC

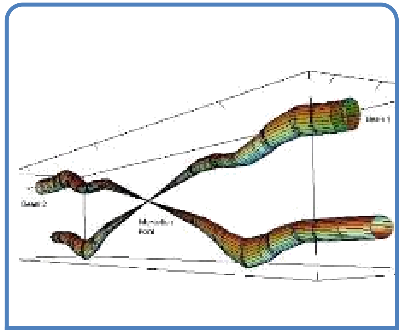
hh ee he

EuroCirCol project

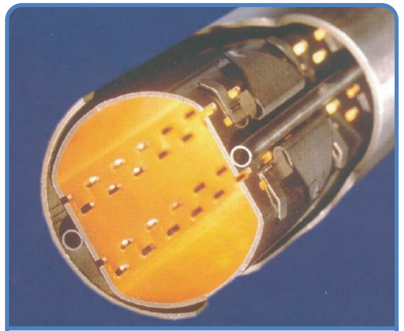
- The EuroCirCol project focused on the key design questions which determine the feasibility of a 100 TeV hadron collider in a 100 km long tunnel
- It consisted of 5 WPs:

WP1 - Management

WP2 - Arc design



WP3 – EIR design



WP4 - Cryo Beam Vacuum

WP5 – High field magnet

- Our group was involved in WP5, led by ***D.Tommasini***, for the development of the 16 T dipole magnet design:
  - Study and assess different dipole design options
  - Develop a cost model for the dipole
  - Develop EM and mechanical design
  - Devise a quench protection concept

From M.Benedikt presentation at EuroCirCol kick-off meeting
https://indico.cern.ch/event/389991/contributions/931909/

Participants person months

Partner	WP1	WP2	WP3	WP4	WP5	Total PM	Total Cost	EU Funding
CERN	128	90	42	84	80	424	€ 3,587,500	€ 138,000
TUT					40	40	€ 325,188	€ 166,000
CEA		108			36	144	€ 1,018,770	€ 514,000
CNRS		64				64	€ 508,667	€ 213,000
KIT				15		15	€ 124,500	€ 63,000
TUD		84				84	€ 553,905	€ 278,000
INFN			30	94	36	160	€ 836,938	€ 422,000
UT					38	38	€ 219,185	€ 110,000
ALBA				100		100	€ 332,858	€ 169,000
CIEMAT				54	48	102	€ 383,250	€ 193,000
STFC			48	96		144	€ 595,665	€ 299,000
UNILIV	22					22	€ 256,844	€ 192,000
UOXF			88			88	€ 760,691	€ 242,000
KEK		12			12	24	€ 158,445	€ 0
EPFL			36			36	€ 360,000	€ 0
UNIGE					24	24	€ 176,730	€ 0
SUM	150	358	244	443	314	1509	€ 10,199,135	€ 2,999,000

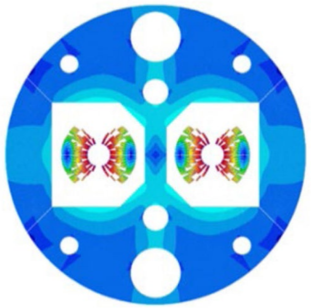
EU funding to INFN for WP5: 137 k€

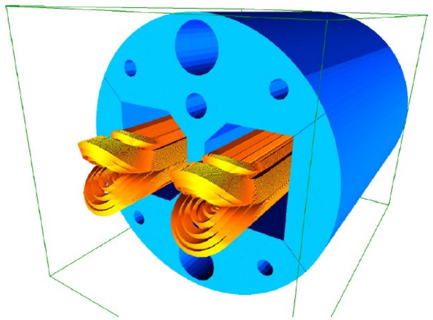
From M.Benedikt presentation at EuroCirCol kick-off meeting https://indico.cern.ch/event/389991/contributions/931909/

EuroCirCol WP5 strategy

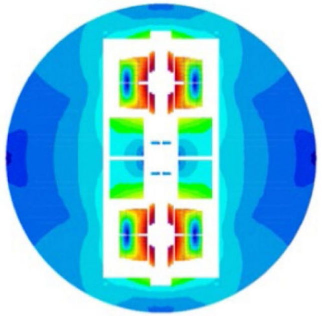
- The EuroCirCol WP5 strategy was grounded on the exploration of ***different design options*** for the 16 T Nb_3Sn dipoles ***based on the same parameter space***:

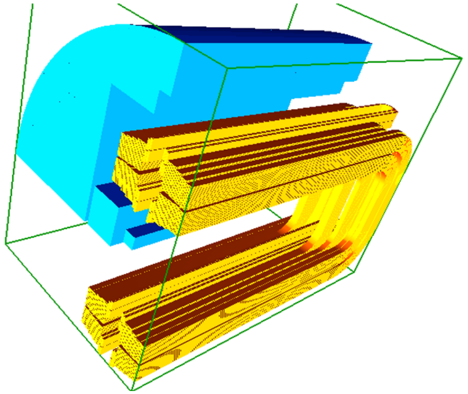
- Cosine theta



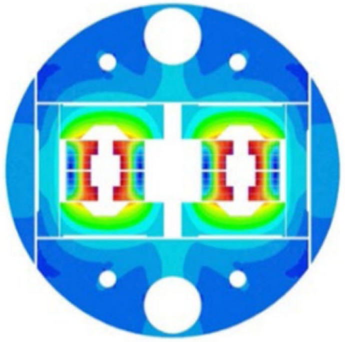


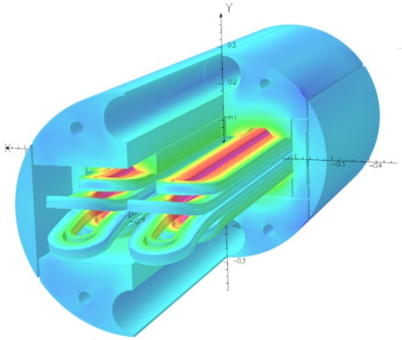
- common coil



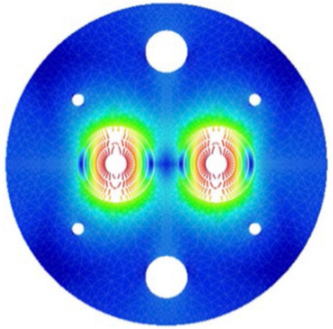


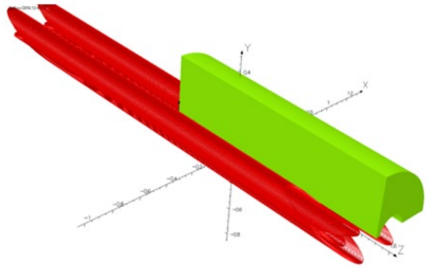
- block coil





- CCT





contribution external to EuroCirCol

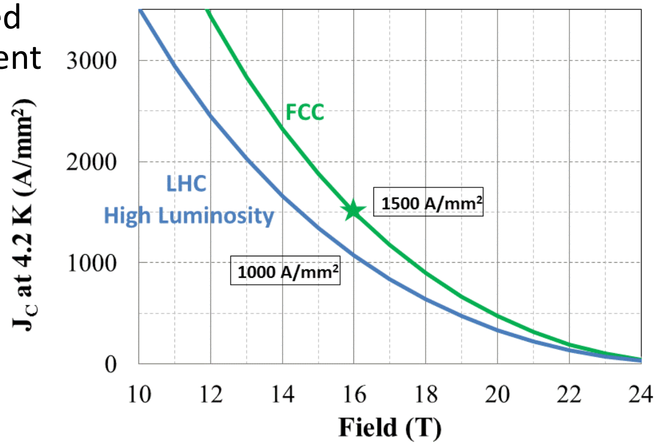
Common assumptions for the WP5 designs

To have a fair comparison of the 4 options, a common set of parameters was set:

Parameter	Value
bore inner diameter	50 mm
beam distance	250 mm
bore nominal field	16 T
operating temperature	1.9 K
field harmonics geo/sat	≤ 3/10 units
J_C @ 4.2 K, 16 T	1500 A/mm^2
Operation on the loadline	86%
outer yoke diameter	660 mm
min/max strand diameter	0.7/1.1 mm
max. Number of strand in cable	40
insulation thickness	0.15 mm
Min. Cu/nonCu ratio	0.8
stress limit on coil ambient/cold	150/200 MPa
Max hot spot temperature	350 K

- We initially tried to fit the FCC-hh dipoles in the same tunnel as the LHC (beam distance 194 mm), but because of the huge cross-talk, it was not possible to correct b2 better than 40 units

- In 2015, J_C(4.2K,16T)=1500 A/mm^2 was the target current density for the FCC dipole, which is still far enough away to be achieved in actual conductor development

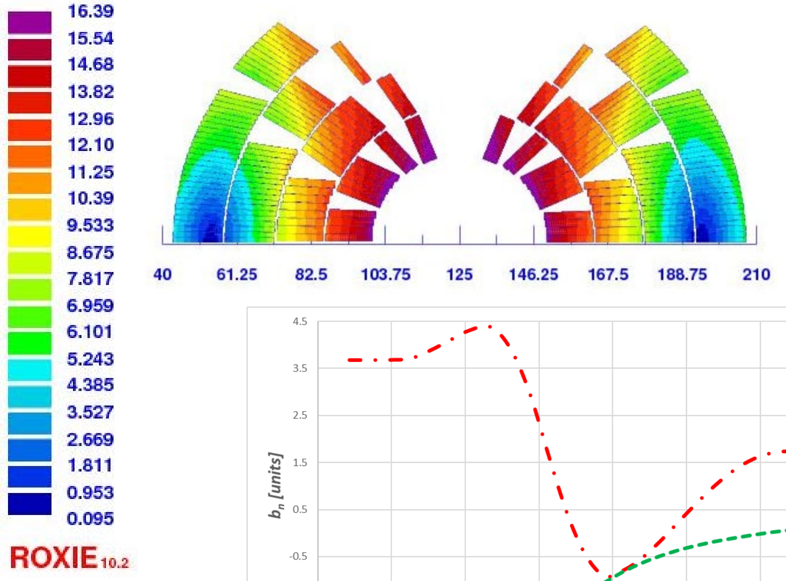


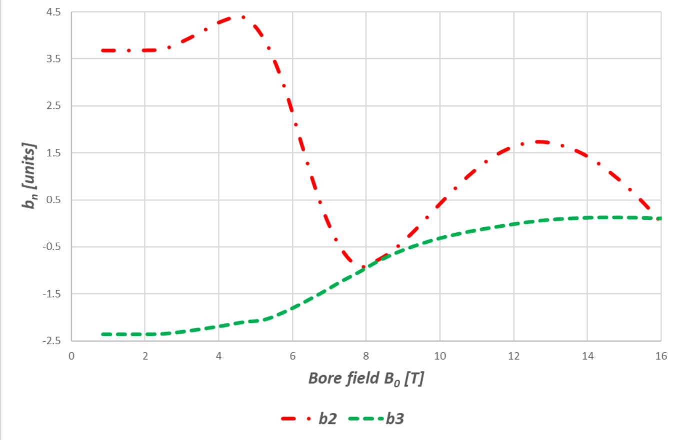
- Preliminary studies on Nb_3Sn cables seemed to indicate that 200 MPa could be withstood at cold without major degradation. More recently, it has been assessed that 150 MPa regardless of temperature is a safer upper limit (this raises doubts about the absolute technical feasibility of reaching 16 T with this type of magnets)

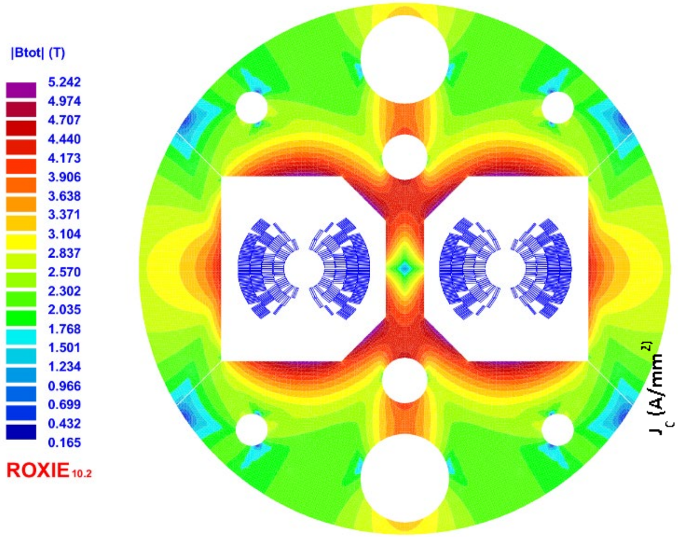
The INFN cosϑ option – electromagnetic design

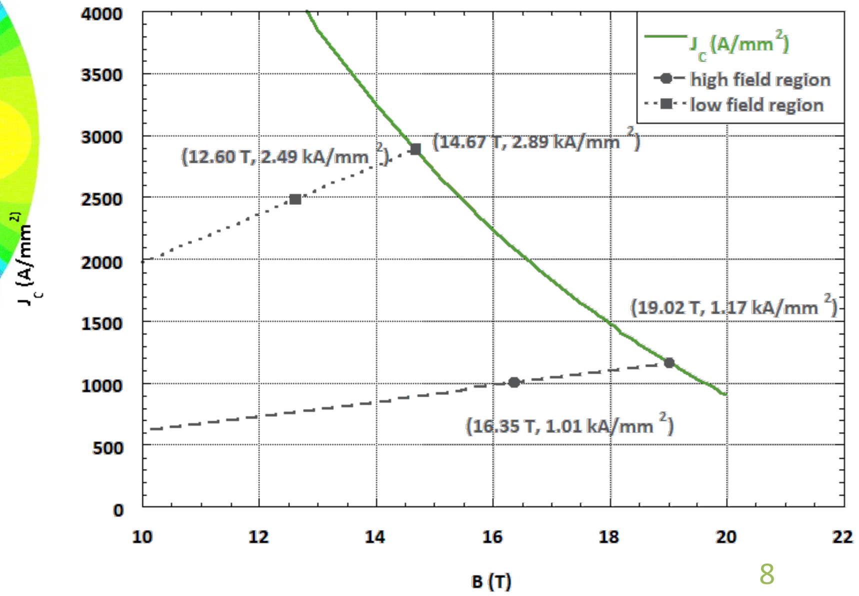
- the magnet is in 4 layers, 2 double pancakes, with 2 different kinds of cables:
- to satisfy the field quality requirements, the cross-talk has been corrected shaping the iron yoke and designing a-symmetric coils
- The margin on the load line is 14% for both high and low field region

	HF conductor	LF conductor
Strand diameter (mm)	1.1	0.7
Number of strands	22	38
Material	Nb_3Sn	Nb_3Sn
Bare width (mm)	13.2	14
Bare inner thickness (mm)	1.892	1.204
Bare outer thickness (mm)	2.0072	1.3261
Insulation thickness (mm)	0.15	0.15
Keystone angle	0.5°	0.5°
Cu/Non-Cu	0.82	2.08
Operating current (A)	11441	11441
Operating point on Load Line (1.9 K)	86.0%	85.8%
Peak field (T)	16.4	12.71



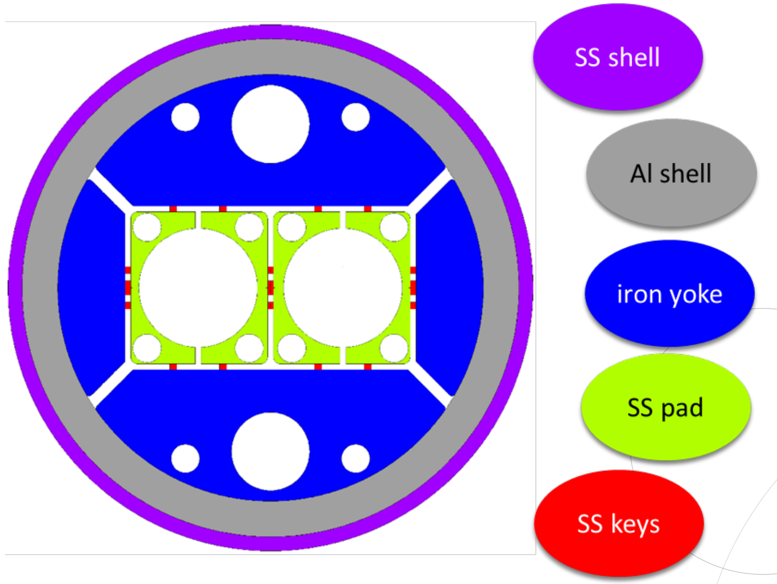






The INFN cosϑ option – mechanical design

- the design of the mechanical structure is ***highly critical***; roughly: $< \sigma_\vartheta > \sim \frac{F_{L\vartheta}}{w} = 2\frac{r_m}{w}\frac{B_0^2}{2\mu_0} = 2\frac{53}{56}\frac{16^2}{2\mu_0} = 193\ MPa$
- it is based on the ***bladder&key*** concept:

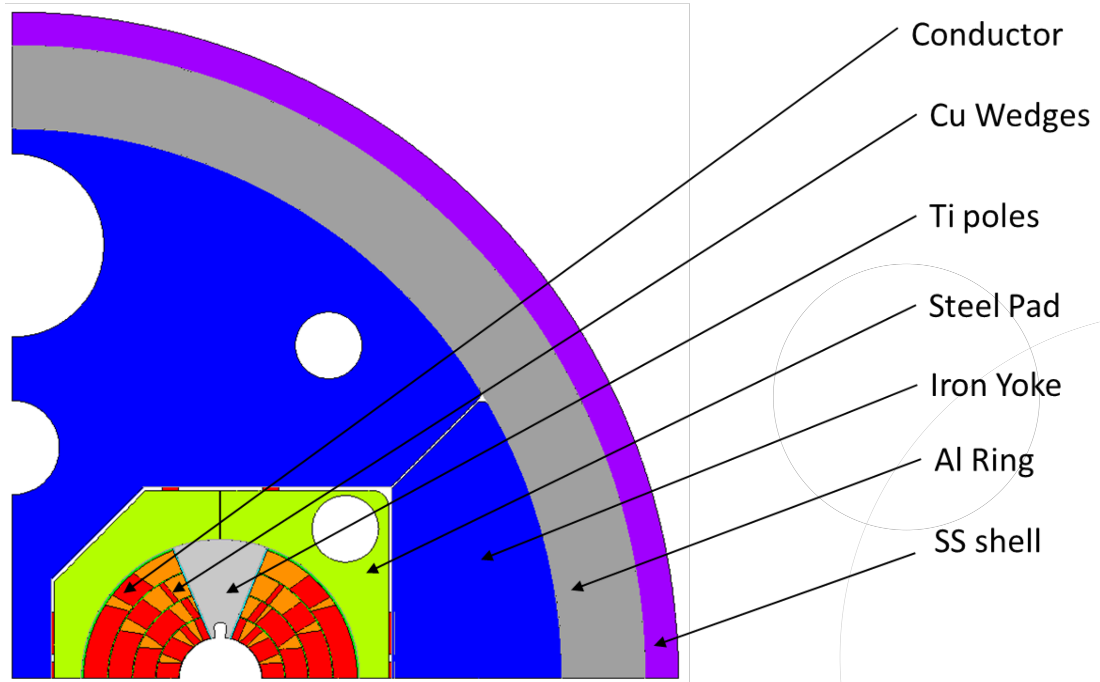


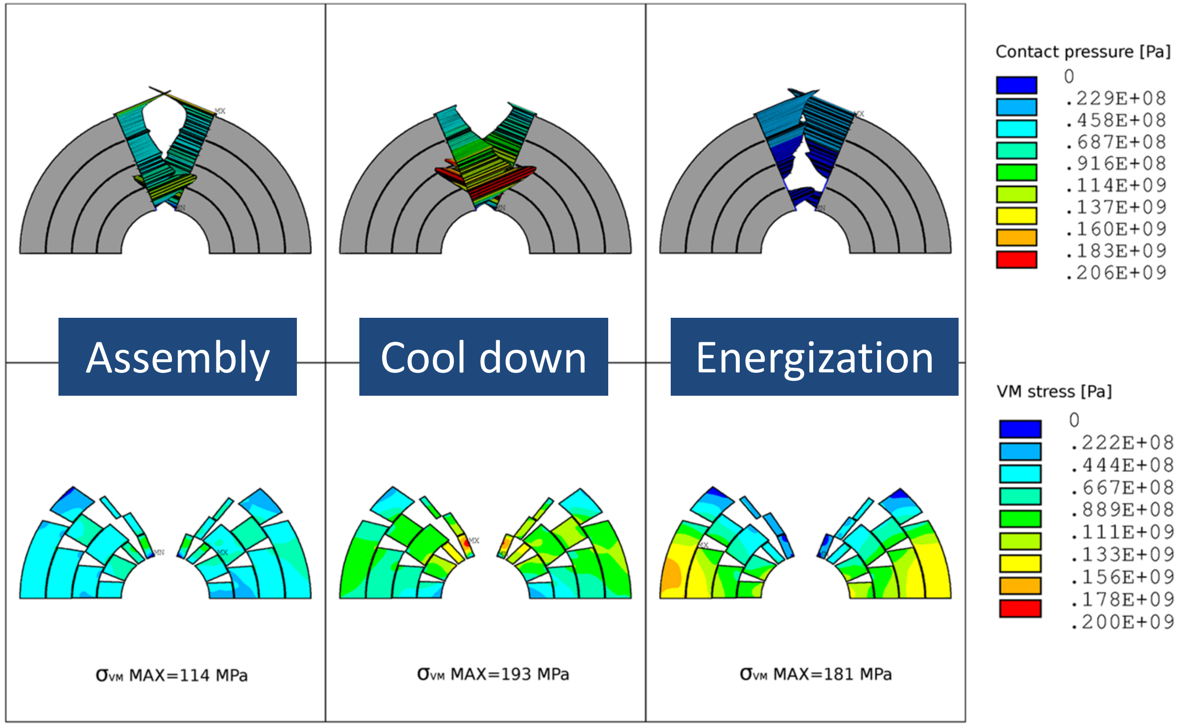
- around half of the preload at room temperature is provided by assembling **SS keys** with interference using water pressurized bladders

- the other half is provided by cooling the **Al shell**
- SS shell may or may not be present

The INFN cosϑ option – mechanical design

- peak stresses in the winding are lower but very close to 200 MPa
- the EuroCirCol design requirements (set in 2015) are met, but today's knowledge suggests that the reasonable limit for conductors developed so far should be set at 150 MPa





Conceptual Design Report

- The INFN cosϑ option has been chosen as baseline design for the Conceptual Design Report published in 2019
- the other configurations could not be definitively discarded on a design basis alone

Eur. Phys. J. Special Topics 228, 755–1107 (2019)

https://doi.org/10.1140/epjst/e2019-900087-0

THE EUROPEAN PHYSICAL JOURN/
SPECIAL TOPICS

Regular Article

FCC-hh: The Hadron Collider

Future Circular Collider Conceptual Design Report Volume 3

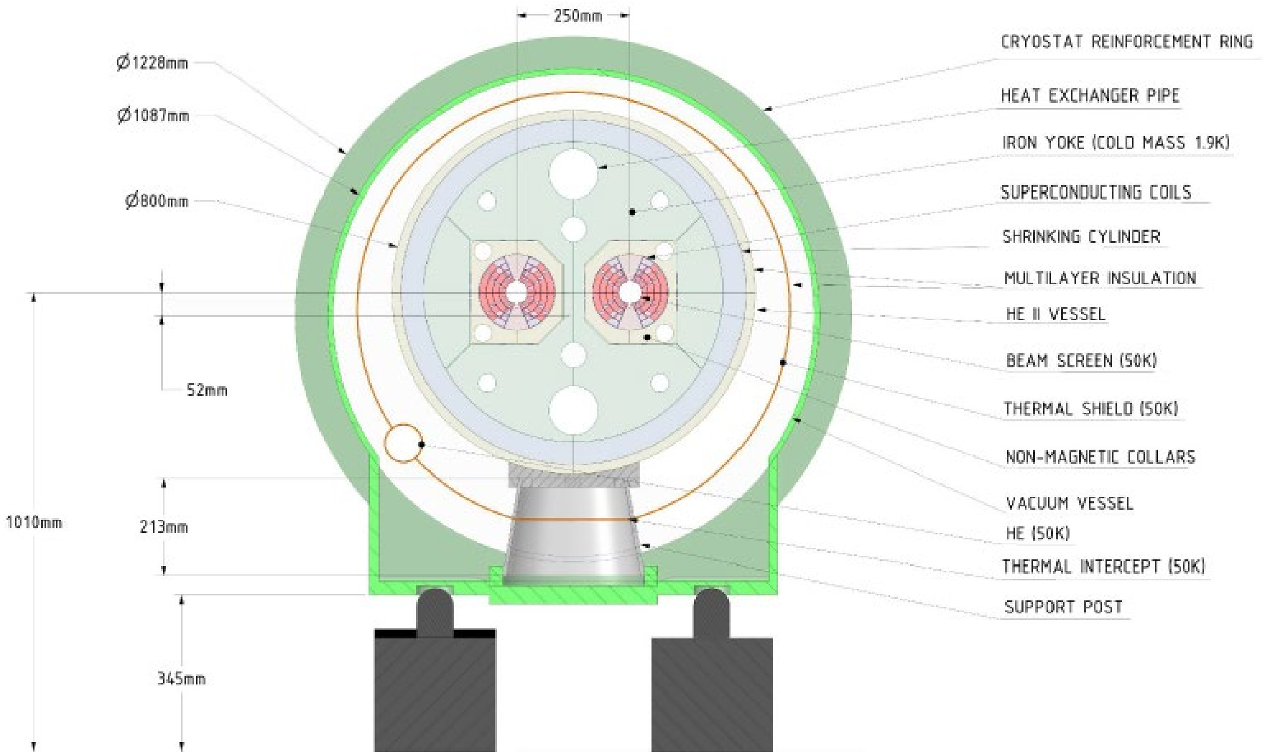


Fig. 3.1. Main dipole cross-section.

FALCOND

Started in June 2018

Currently to be completed by June 2023

The birth of FalconD project

Future Accelerator post-LHC Cos-theta Optimised Nb_3Sn Dipole

- The natural continuation of the EuroCirCol experience, was the fabrication of a demonstrator
- An agreement CERN-INFN was signed on Sept. 20th 2018
  - Addendum No. KE4102/FCC to FCC Memorandum of Understanding FCC-GOV-0004/17.10.2014
  - Collaboration on 16 T –Nb_3Sn Short Model Magnet Production in the framework of the FCC Study hosted by CERN
  - Develop a single aperture 16 T 4-layer cosϑ demonstrator
  - 2 practice and 2 + 1 spare Nb_3Sn coils
- In 2019 an international tender was launched, and the corresponding industrial contract was awarded to ASG Superconductors in June 2020 (1.5 M€)
  - ASG is responsible for the construction of the coils
  - The mechanical assembly is planned to be performed by INFN at the LASA Laboratory

ADDENDUM No. KE4102/FCC

to

FCC Memorandum of Understanding (FCC-GOV-CC-0004/17.10.2014)

between

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

and

THE ISTITUTO NAZIONALE DI FISICA NUCLEARE ("INFN")

concerning

Collaboration on 16 T - Nb_3Sn Short Model Magnet Production in the framework of the FCC Study hosted by CERN

2.1 Financial values of the contributions

The resources for the five years of the Project shall be allocated between CERN and INFN as follows:

- total financial value of the project: **4300 k€**;

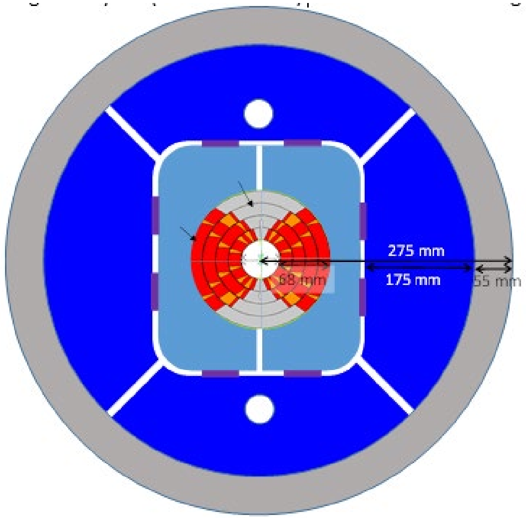
- total financial value of INFN's contribution: **3050 k€**;

- total financial value of CERN's contribution: **2750 k€** (in kind contribution of **1250 k€** and cash contribution of **1500 k€**).

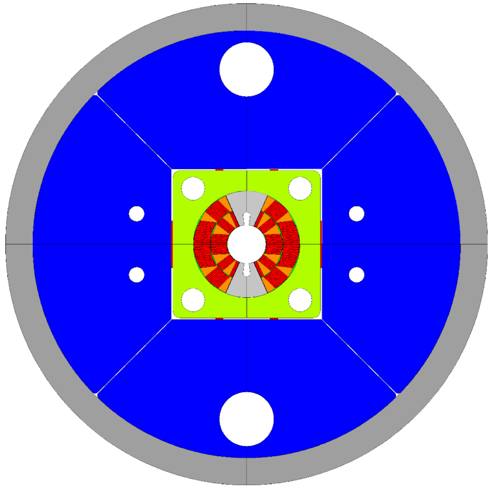
Kick-off meeting at ASG – July 2020

- Compared to the original Technical Specification (2018), several changes had already been agreed with CERN at the time of the kick-off meeting (July 2020), because
  - a 4 layer 16 T dipole is an extremely challenging magnet, a step too far beyond the state of the art
  - current conductors do not have the performance required to reach 16 T – J_C(4.2K,16T)=1500 A/mm^2
  - a 2 layer dipole in the range 12−14 T would already be a significant advancement with respect to the state of the art
- FalconD characteristics *(➡ Addendum to be updated):*
  - 2 layers
  - design magnetic field: 12 T (ultimate field of mech. structure/prot. system: 14 T)
  - 40 strand Rutherford cable Φ=1 mm
  - bladder&key mechanical structure confirmed
  - stress in conductors < 150 MPa in any conditions
  - max outer dimension 650 mm (to make cold test at LASA feasible)
- ***due to several reasons (overbooking of the engineering department at ASG, Covid19 pandemic limitations, unavailability of the conductor from CERN) the project did not progress until the end of 2021***

Technical specification design:



Kick-off meeting design:



the Technical Design Report

- only design activities were able to progress, and on October 15th 2021 the ***FalconD Technical Design Report*** was submitted to the CERN Collaboration
- the TDR was the 1st Deliverable of the CERN/INFN agreement
- in January this year, the TDR was approved by the HFM CERN/INFN Steering Committee
- after approval, the TDR was published as INFN Technical Note and can be downloaded from http://www.lnf.infn.it/sis/preprint/getfilepdf.php?filename=INFN-22-01-GE.pdf

INFN Istituto Nazionale di Fisica Nucleare

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezioni di Genova e Milano

INFN-22-01/GE
31 Gennaio 2022

TECHNICAL DESIGN REPORT OF THE FalconD Nb_3Sn COS-THETA DIPOLE MODEL FOR THE FCC-hh AT CERN

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THE TDR DESIGN

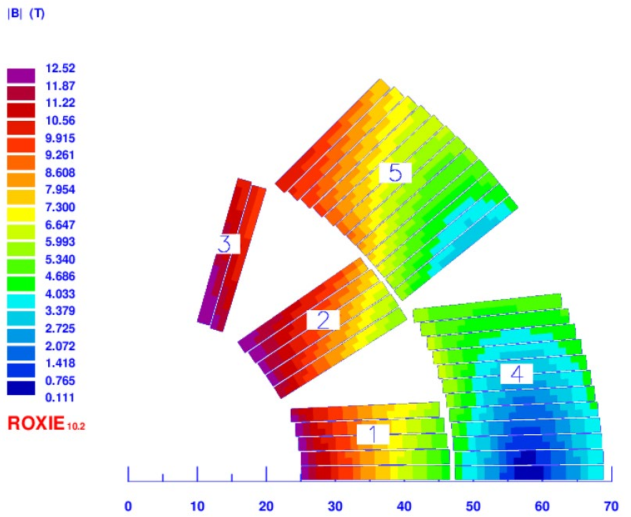
Istituto Nazionale di Fisica Nucleare

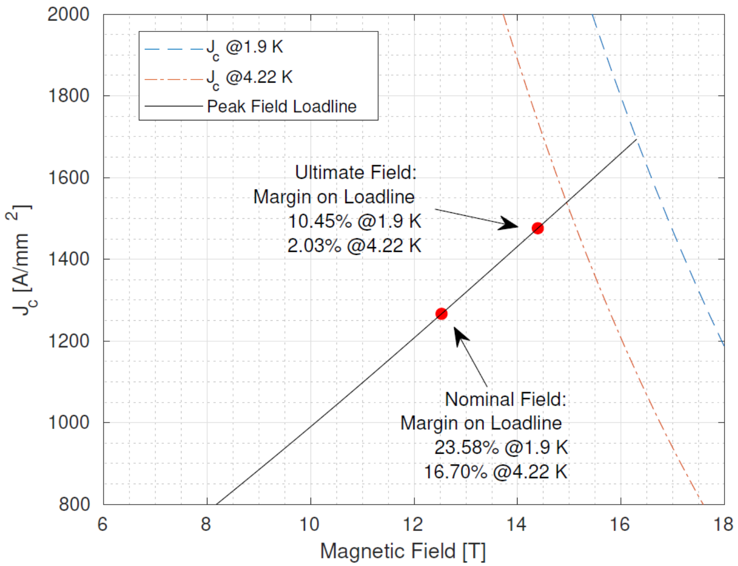
FALCON DIPOLE

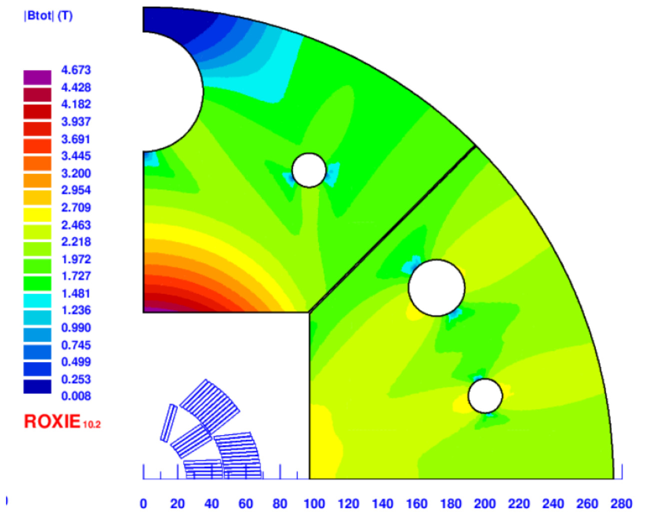
CERN HFM High Field Magnets

Electromagnetic design

- The magnet is designed to reach a bore field of 12 T with two layers of keystoned Rutherford cable wound using the double pancake technique.
- In each quadrant there are 3 blocks in the first layer and 2 blocks in the second one, for a total of 36 turns.
- The main goal of the project is to achieve the target field by prioritizing technical feasibility rather than absolute field quality (minimum bending radius around 10 mm and minimum copper wedge size around 1 mm).
- Field quality is not at accelerator level, as it is a secondary goal to achieving the nominal field.
- The margin on the loadline @ 12 T, 1.9 K is 23.6%, which is consistent with other magnets of the same type (MQXF).



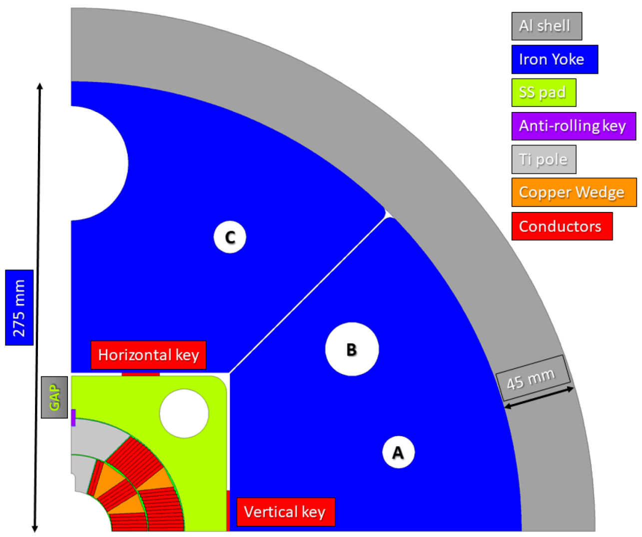


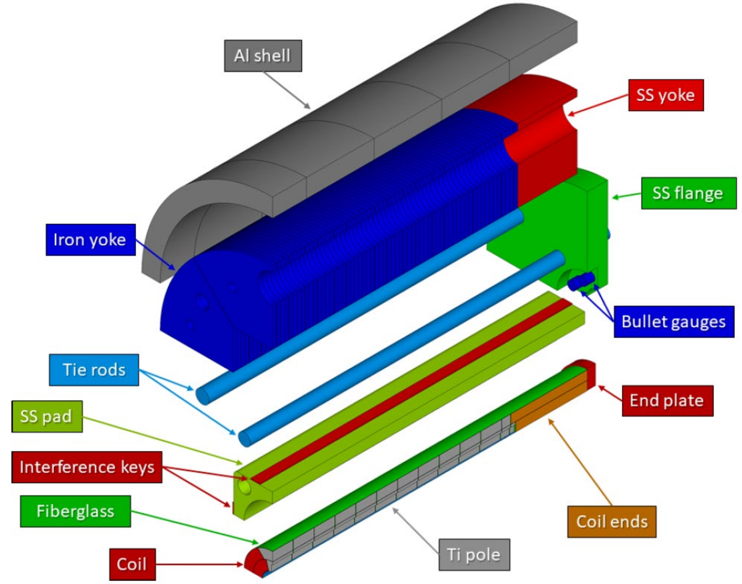


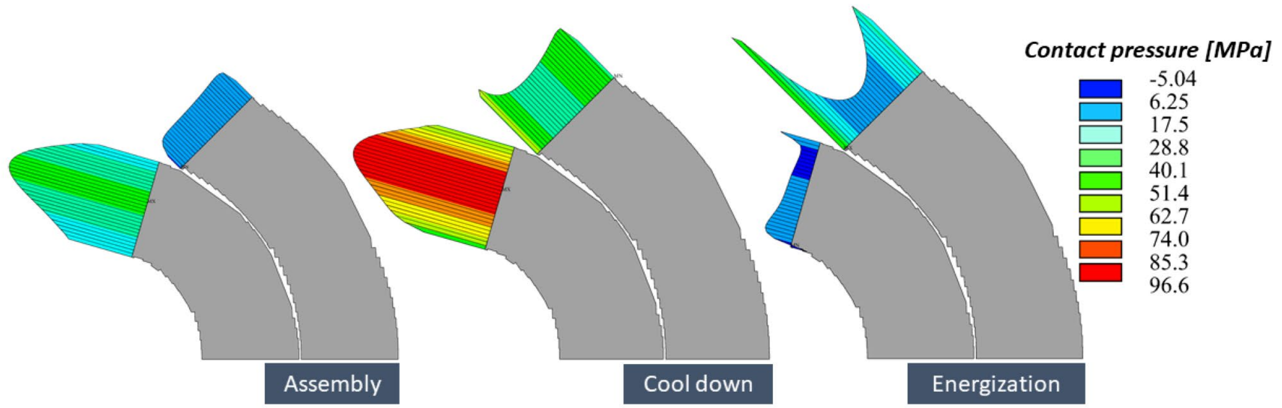
Courtesy of R.Valente (INFN LASA)

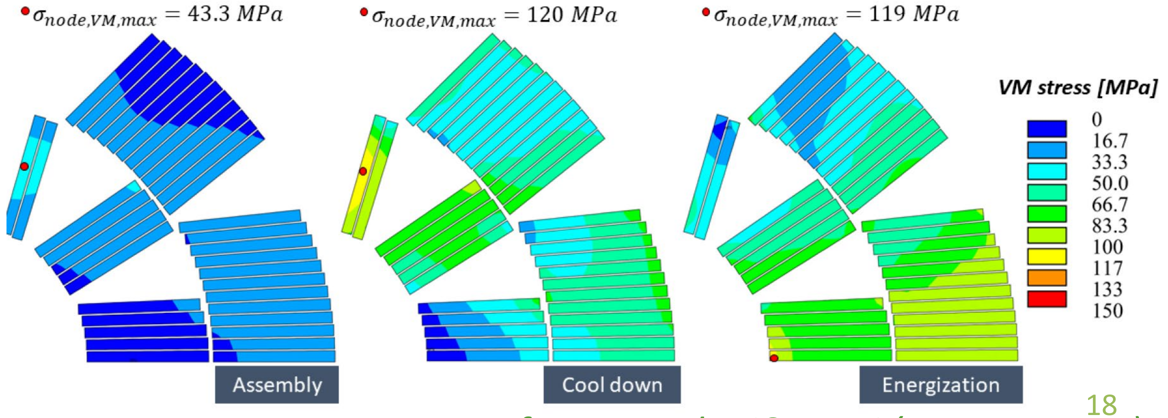
Mechanical design

- as already mentioned, the mechanical structure adopts the bladder&key concept
- the vertical keys preload the coil by imposing a mild ovalization that counterbalance the effect of the Lorentz forces
- the goal is to ensure contact pressure between coil and collar pole in any conditions while keeping the stress in the conductors below 150 MPa





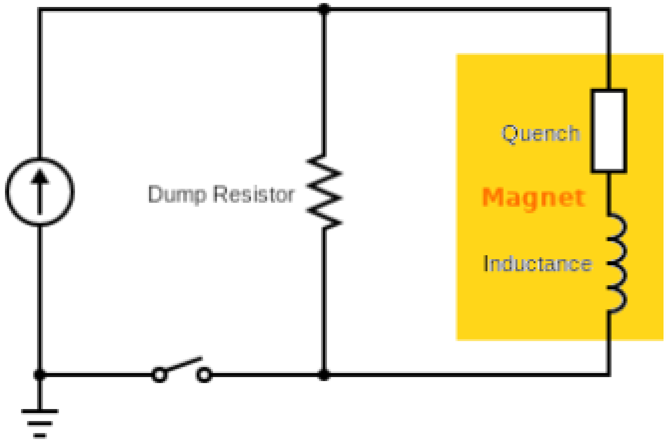


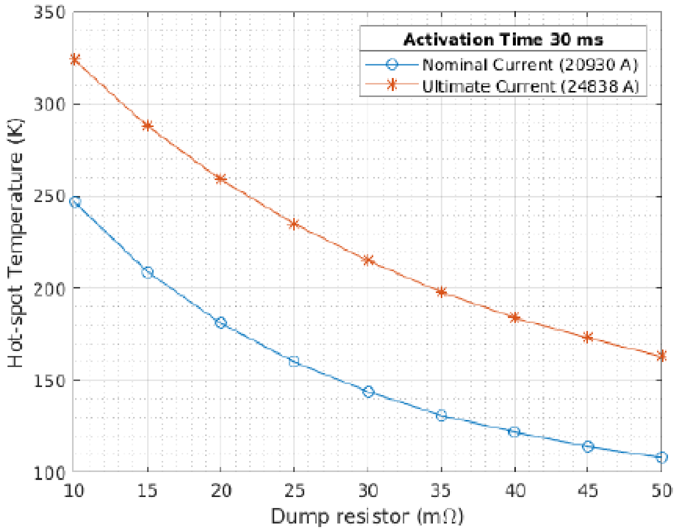


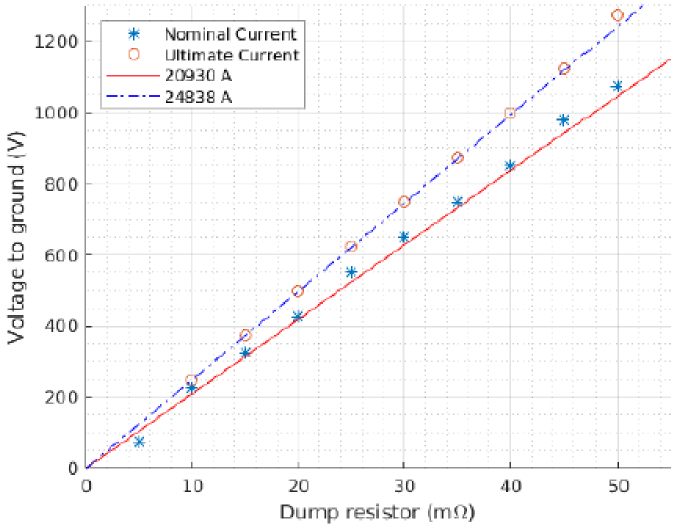
Courtesy of A.Pampaloni&F.Levi (INFN Genova)

Quench protection

- The magnet can be protected by energy extraction only, without using quench heaters (with considerable construction simplification).
- At 12 T the optimized dump resistor of 25 mΩ gives hot spot temperature of 160 K and max. voltage to ground 525 V





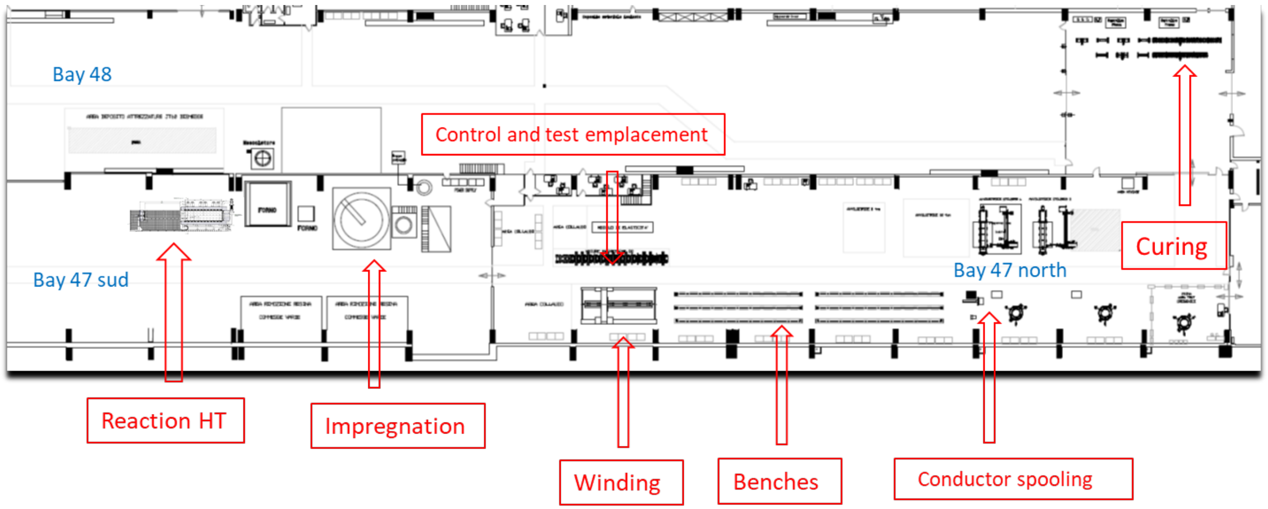


Courtesy of R.Valente (INFN LASA)

ADVANCEMENTS SINCE THE TDR DRAFTING

Advancements @ ASG Superconductors

- the manufacturing layout in the ASG premises has been set up

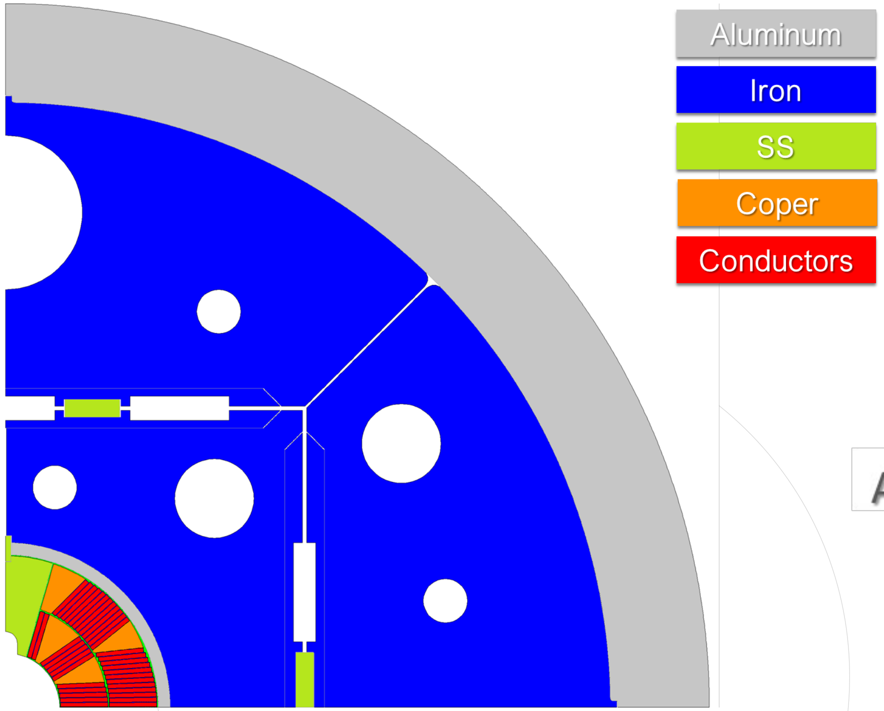


- the construction of the furnace for the thermal treatment of Nb3Sn was completed by HTS-Furnaces Mozzanica-BG and the furnace was installed at ASG in January this year

Advancements @ INFN

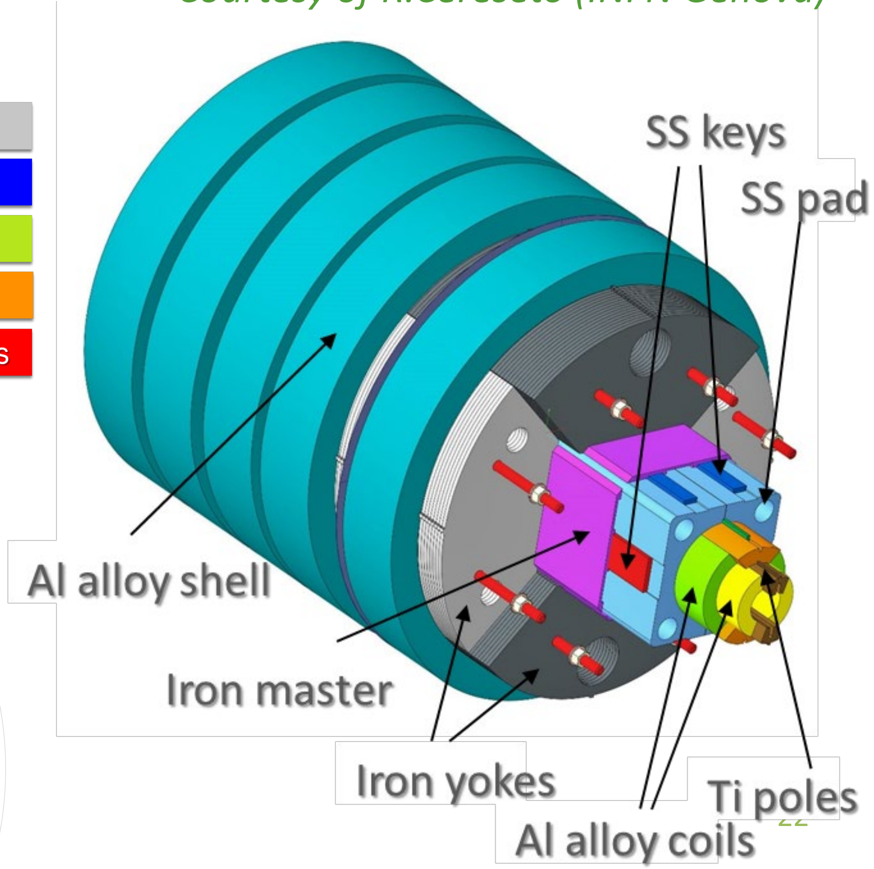
- We started an activity to assemble a mock-up of the FalconD magnet. The reasons are:
  - Consolidate the mechanical FE analysis to predict magnet the stress/strain conditions (straight part only) during the B&K assembly and cooling (at 77 K)
  - Study the influence of mechanical tolerances on the mechanical system
  - Determine the most convenient assembly sequence

- we are working on a new design that brings the iron yoke closer to the coils, which helps to reduce current and increase the margin



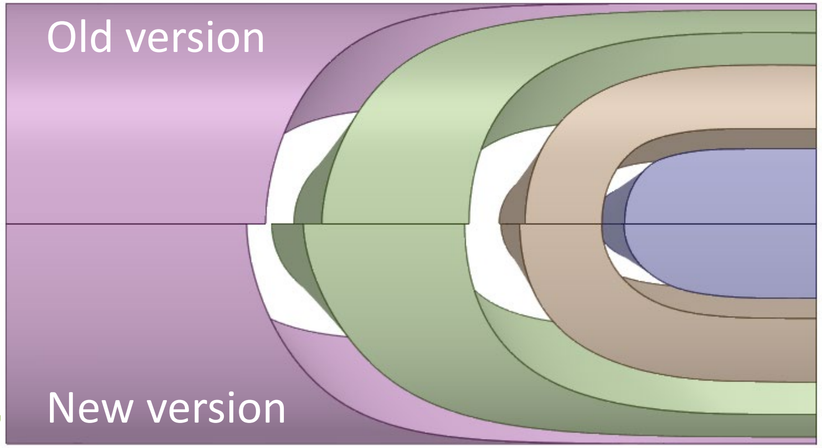
Courtesy of A.Pampaloni&F.Levi (INFN Genova)

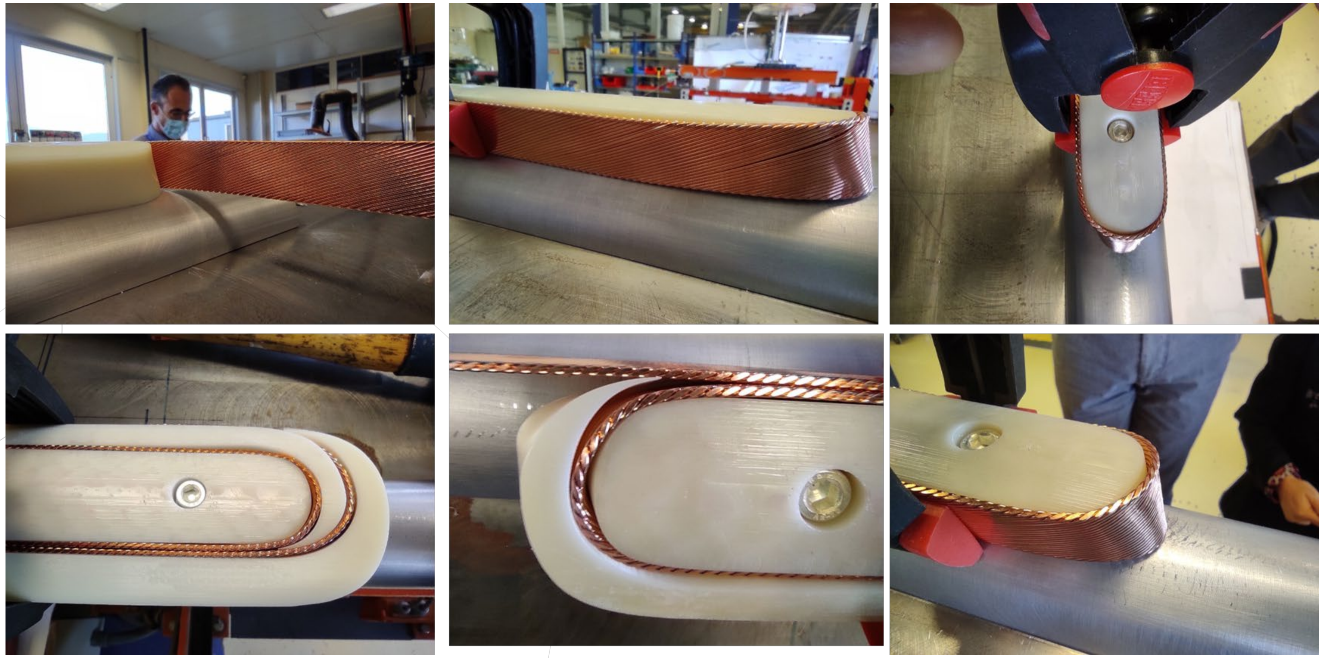
Courtesy of R.Cereseto (INFN Genova)



Winding trials @ CERN

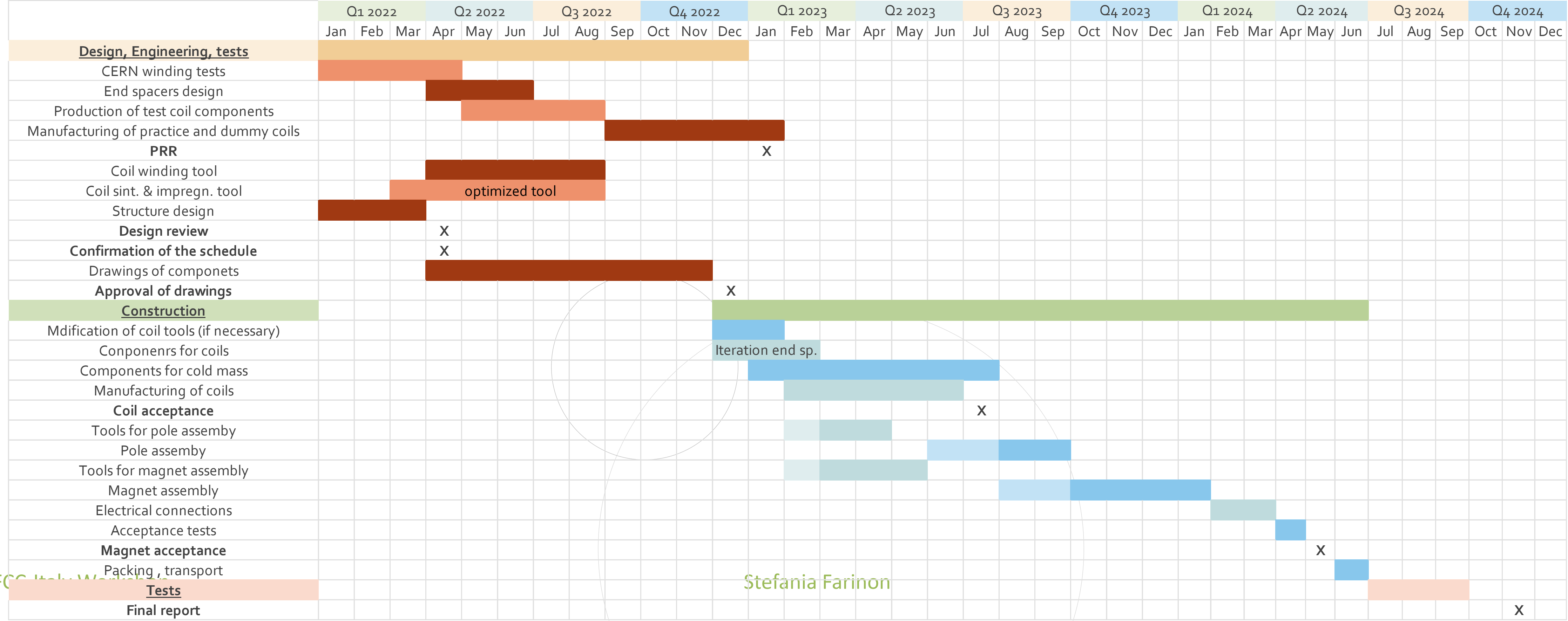
- in October 2021 a first run of winding trial was performed with machined Al mandrel and polymer wedges and spacers
- the results were not entirely good but encouraging (non-insulated Cu cable, very low tension due to the soft material of the wedges and spacers)
- in spite the non-optimal test conditions, we understood in which direction to act to improve the windability of the ends of the coil. New end spacers have already been designed for next winding test (transition is smoother and longer)
- new winding trials are planned by the end of March using machined Al wedges and spacers





Preliminary schedule

- a new program has been agreed upon between CERN and INFN that includes the construction and testing of the FalconD dipole by the end of 2024
- the Addendum will soon be modified accordingly



THANKS FOR YOUR ATTENTION

Istituto Nazionale di Fisica Nucleare