HFM

High Field Magnets

eRMC/RMM Dipole Magnets

Past, present and future

Author: J.C. Perez,

Acknolegements to: S. Izquierdo, E. Gautheron, E. Rochepault, D. Tommasini

Table of contents

The origin

CERN
CH-1211 Geneva 23
Switzerland

the
Large
Hadron
Collider
project

LHC Project Document No.
FCC-ST-0001

CERN Div./Group or Supplier/Contractor Document No.
TE/BE/EN/PH

EDMS Document No.

Date: 2015-03-25

Work Package Description

FUTURE CIRCULAR COLLIDER

MAGNETS TECHNOLOGIES

Abstract

This document describes the FCC Magnet Technologies Work Package. The objective of this WP is to identify, develop and demonstrate the technologies to manufacture the high field magnets required for the FCC-hh collider ring.

Prepared by :	*Checked by :*	*Approval Leader :*
Michael Benedikt (CERN) Michael.Benedikt@cern.ch Davide Tommasini (CERN) Davide.Tommasini@cern.ch	Marta BAJKO (CERN) Amalia BALLARINO (CERN) Luca BOTTURA (CERN) Vittorio PARMA (CERN) Gijs DE RIJK (CERN) Stephan RUSSENSCHUCK (CERN) Frédéric SAVARY (CERN) Jean Philippe TOCK (CERN)	Michael Benedikt Michael.benedikt@cern.ch Frank Zimmermann Frank.zimmermann@cern.ch

Approval List :

Kick-off meeting held in March 2015

ORGANIZATION

The FCC magnets Technology Program is divided into 4 Tasks.
The tasks will be managed by a "core team" of CERN staff within the organizati
sections in the MSC Group, integrated by fellows and students as needed.

Task 0: Coordination (D.Tommasini)

Task 1: Strand development & procurement (A.Ballarino)
1.1 Material R&D
1.2 Industrial development & procurement
1.3 Characterization of electromechanical performance

Task 2: Wound conductor test facilities (J.Perez, F.Lackner)
2.1 Enhanced Short Model Coil (quicker lead time)
2.2 Impregnated wound conductor insert

Task 3: 16T RMM with 50 mm cavity (S.Izquierdo)
3.1 Design
3.2 Manufacture & Test

Task 4: 16T Demonstrator with 50 mm aperture (D.Schoerling)
4.1 Design
4.2 Manufacture & Test

Courtesy D. Tommasini

The initial strategy

1) Be representative of a regular straight section, first on a small aperture, thereafter on the 50 mm FCC aperture.

2) Allow the exploration of a wide parameter space, in particular the assembly parameters. Ability to act, in quantity, quality and sequencing of assembly, on transversal and longitudinal compression.

3) Adopt an “easy” structure, to simplify the understanding of what is being done and to allow fast re-assembly.

4) Allow, in the same structure and with similar design, to adopt “graded” coils as a second stage.

5) Minimize, by design, performance limitations coming from the coil ends. We want to study the straight section.

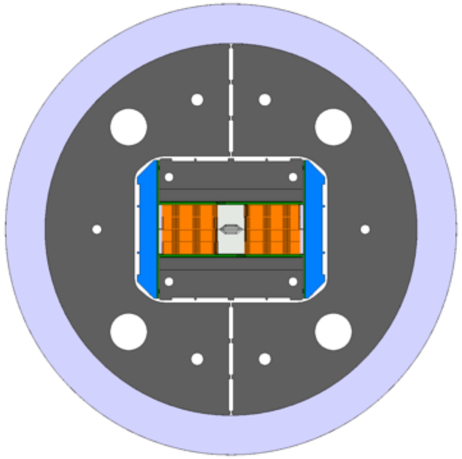
6) The ends will be specifically addressed by DEMO.

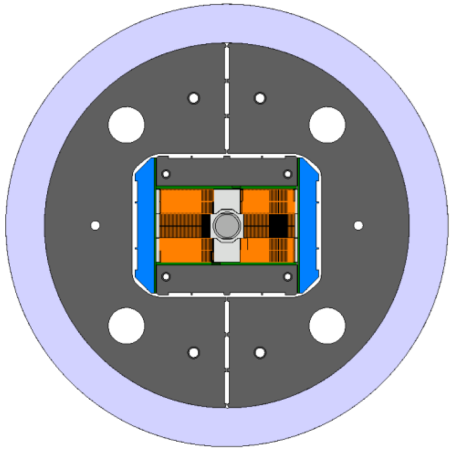
7) Maximize the probability of being successful at the first attempt:
   - fully exploit the past and present experience, **at any level** (technicians in the design meetings);
   - every design and constructional detail discussed collegially (every Monday morning);
   - every design and constructional detail cross-validated with FE models and/or with tailored experiments;
   - pay a specific attention to every transition, in the design, the manufacture and the assembly;
   - master, as much as possible, every assembly step;
   - perform the first assembly with conservative parameters.

Courtesy D. Tommasini

eRMC & RMM program

eRMC and RMM are the base for the development of the technology needed for the 14 +T dipole program at CERN for HFM activities





eRMC

Enhanced Racetrack Model Coil 16 T midplane field

- Demonstrate field on the conductor
- Coil technology development

RMM

Racetrack Model Magnet 16 T in a 50 mm cavity

- Demonstrate field on the aperture
- Mechanics (including inner coil support)

Nb_3Sn HFM development @ CERN

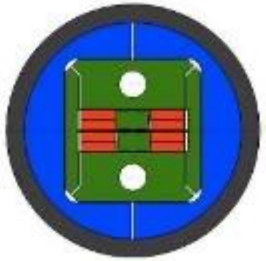
SMC

OD = 530 mm
L = 500 mm
No Ap.
B_{op}= n.a.
B_{ult} = 14 T

RMC

OD = 570 mm
L = 820 mm
No Ap.
B_{op}= n.a.
B_{ult} = 16 T

Hi-Lumi R&D



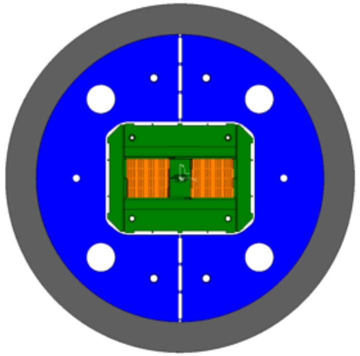
eRMC

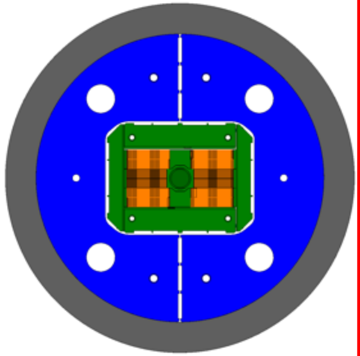
OD = 800 mm
L = 1.2-1.4 m
No Ap.
B_{op}= 16 T
B_{ult} = 18 T

RMM

OD = 800 mm
L = 1.2-1.4 m
50 mm closed Ap.
B_{op}= 16 T
B_{ult} = 18 T

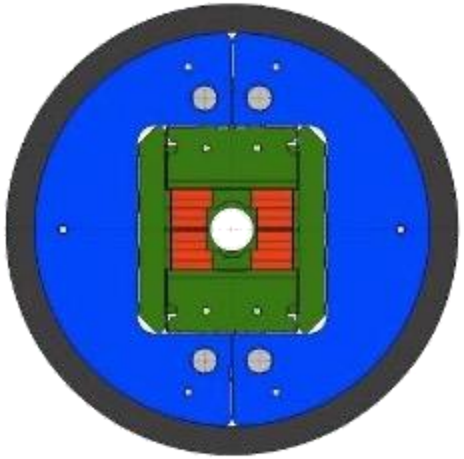
FCC R&D





FRESCA2

OD = 1.03 m
L = 1.6 m
100 mm Ap.
B_{op}= 13 T
B_{ult} = 15 T



OD = Outer diameter
L = Magnet length

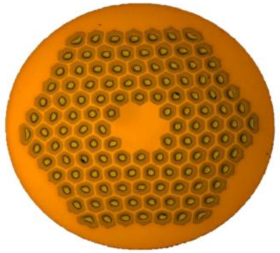
AP = Aperture
B_{ult}= Ultimate field, defined as the maximum design field for the magnet structure

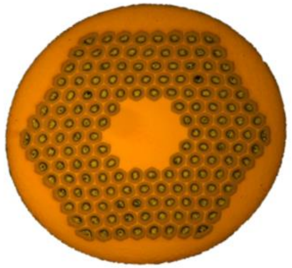
eRMC & RMM design strategy

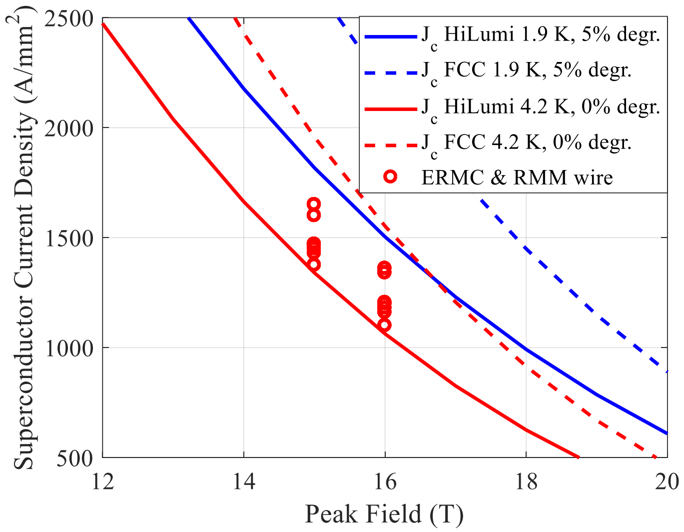
- Demonstrate the field
  - Design based on the “available” critical current density (~20% lower than FCC target at 18 T, 4.2 K)
  - As field quality is not an objective, profit from the use of an iron pole to decrease the ratio between the field in the aperture and in the coil to ~ 1
- Study the mechanics

Strand and cable parameters

- 1 mm diameter wire, cu/sc =1
  - RRP 120/127
    - 62-64 µm
  - RRP 150/169
    - 54-55 µm©
- 40-strand cable
  - Bare width x thickness: 20.9 x 1.82 mm
  - SS core 14 mm wide and 25 µm thick
- Assumed growth during HT : 3% (thickness), 1% (width)

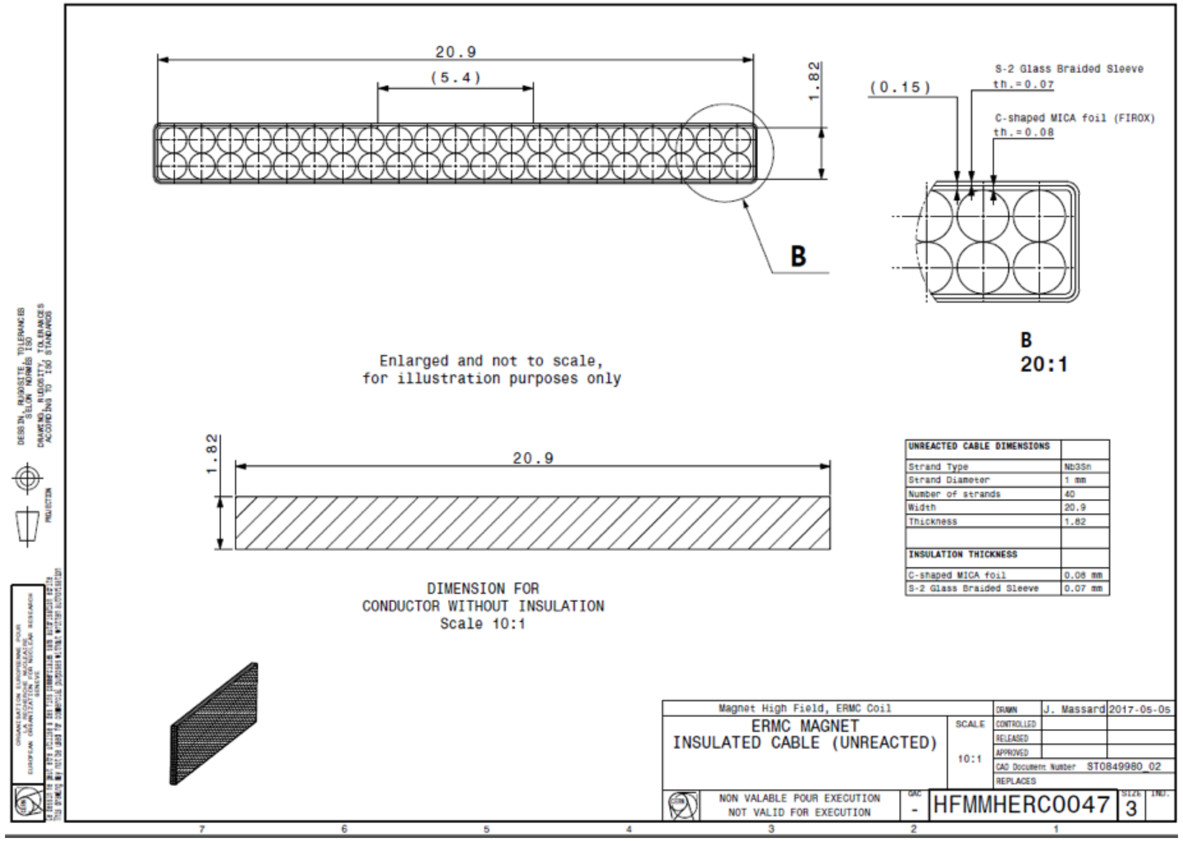


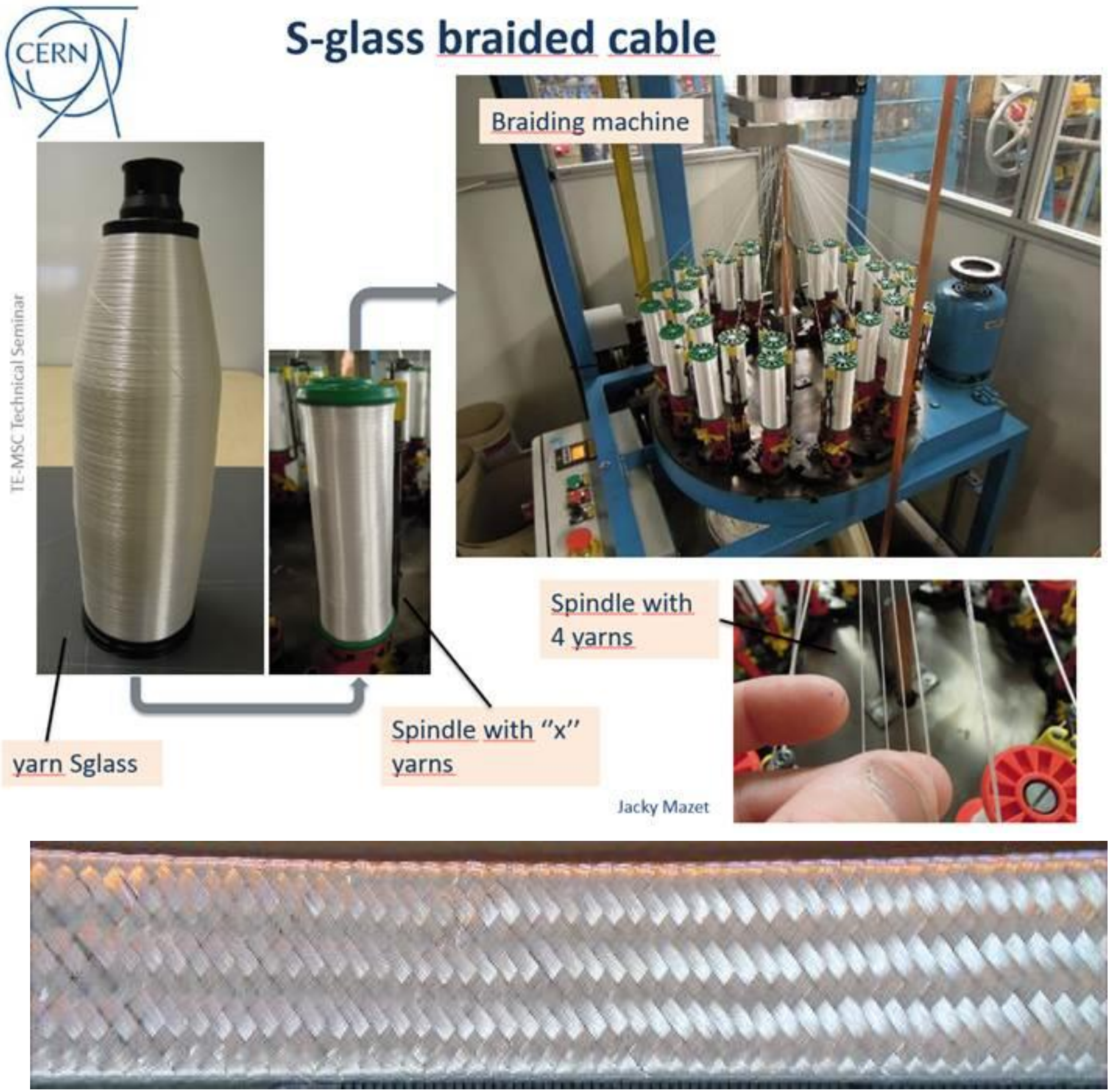




Cable insulation

- Baseline: 0.150 $^{+0.00/-0.02}$ mm Mica-Glass Insulation
- UIs insulated without any particular issue.
- Good control on the insulation thickness



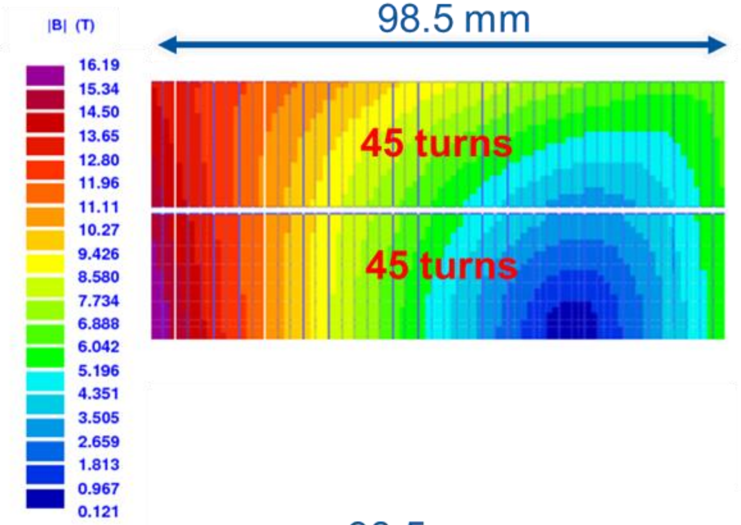


Magnetic design

	Units	eRMC	RMM
Nominal current (I_{nom})	kA	13.1	11.4
Overall current density	A/mm²	282	245
Bore field	T	15.7	16.0
Peak field at I_{nom}	T	16.0	16.2
Stored energy at I_{nom}	MJ/m	1.5	2.1

eRMC

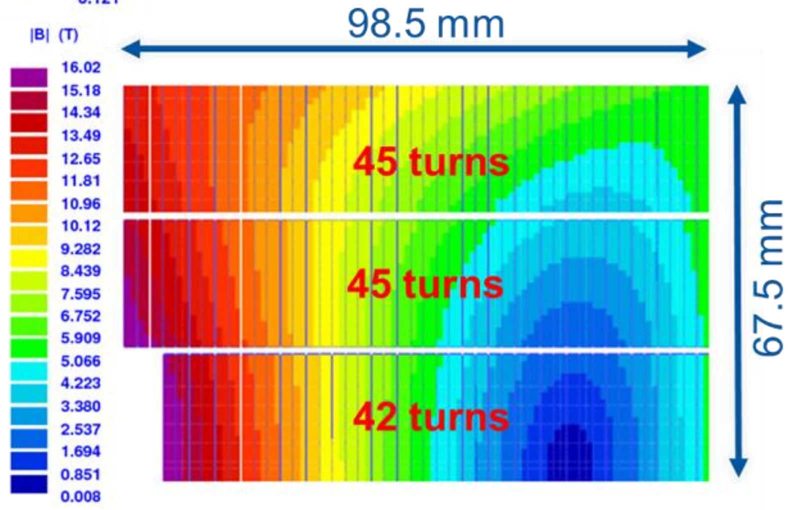
- Two double-layers with 45 turns each wounded around a magnetic pole
- B_p/B_o = 1.097

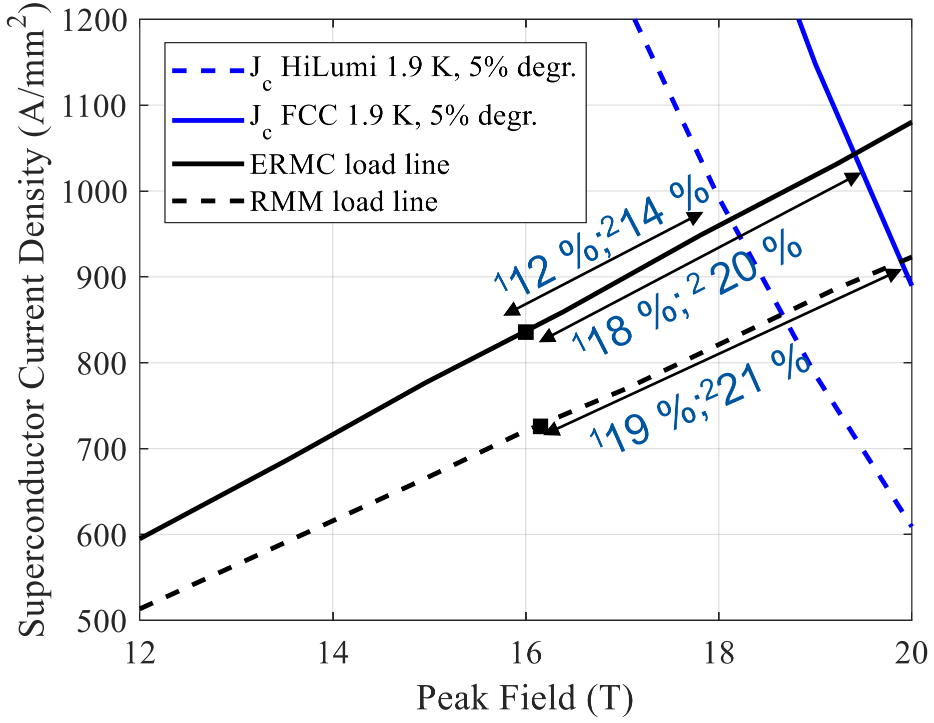


RMM

(eRMC double layers +)

- Middle double layer with 42 turns each wound around a titanium closed cavity
- Coil aperture radius = 31 mm
- Closed aperture radius = 25 mm
- B_p/B_o = 1.097

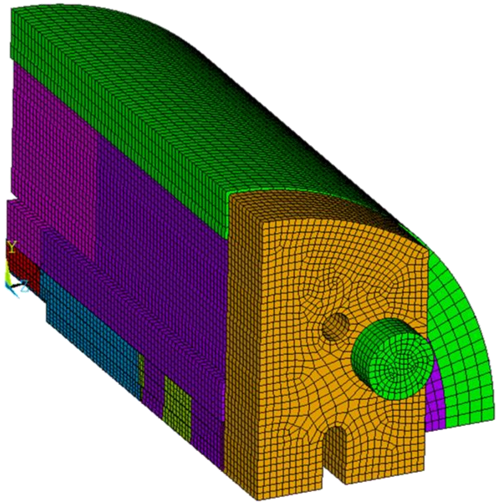


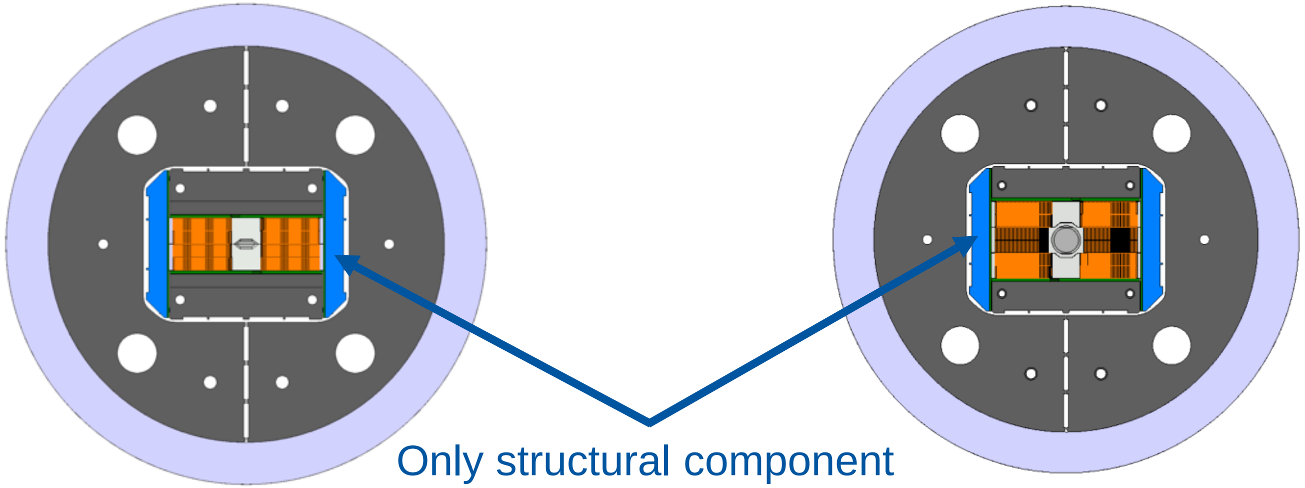


Courtesy B. Bordini, J. Fleiter and A. Bonasia

Mechanical design

- Mechanical structure capable to load the magnet up to 18 T, with enough margin to perform an experimental exploration of the different parameters relevant to magnet performance.
- Critical structure components during optimization:
  - Yield strength of the iron yoke during assembly (design criteria σ_{eq_warm} < 180 MPa) and tensile strength at cold (σ_{1_cold} < 200 MPa)
    - After a mechanical characterization of ARMCO samples, these limits have been raised to σ_{eq_warm} < 230 MPa; σ_{1_cold} < 370 MPa)
  - Bending of the horizontal pads during bladders operation (Nitronic).

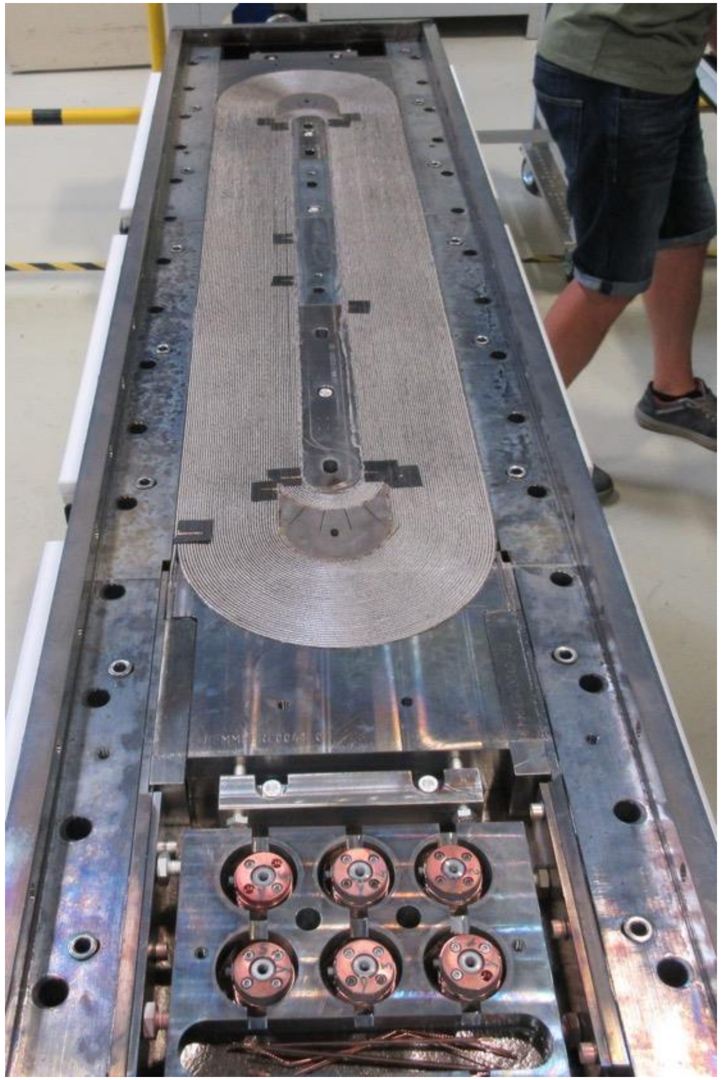




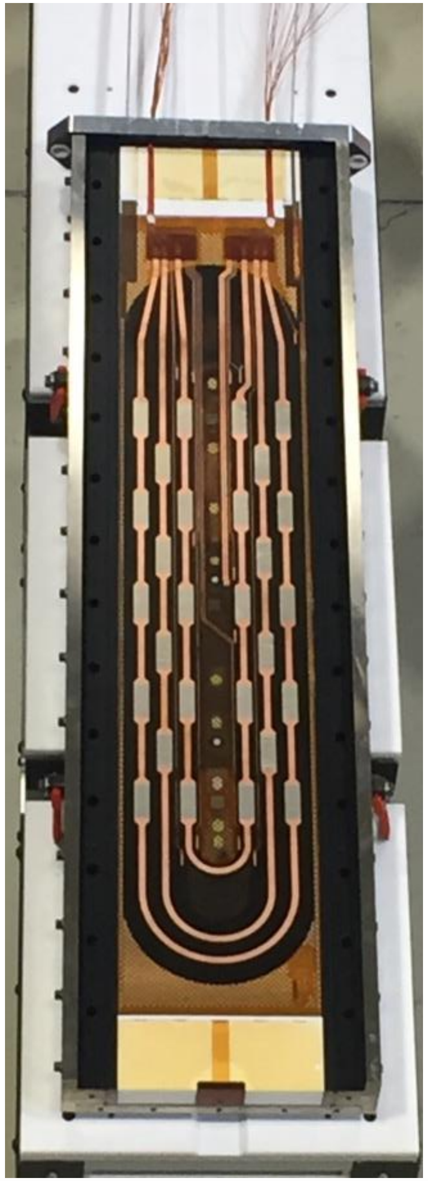
Coil production

Coil winding operation

Reacted coil

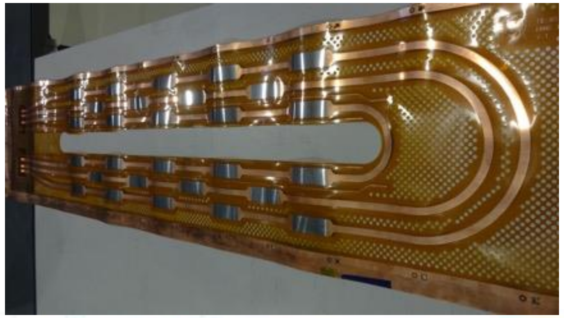
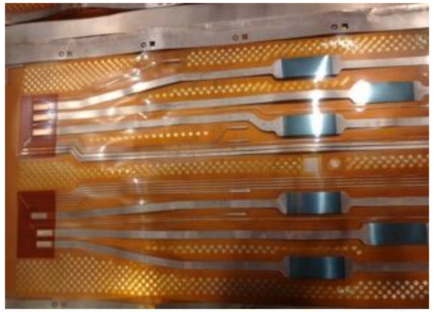
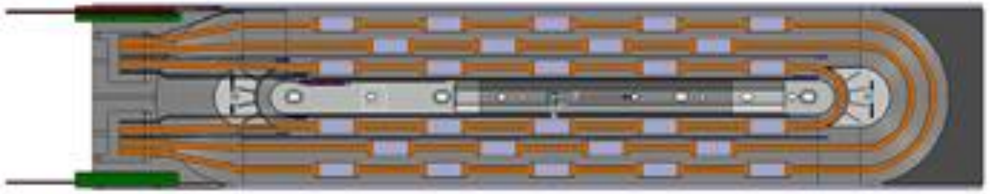


Impregnated coil

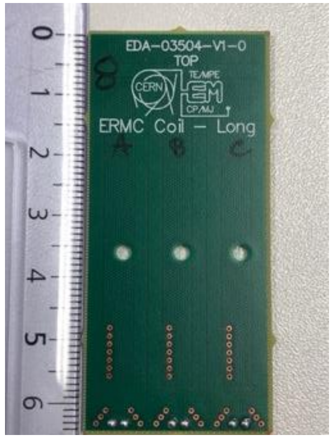


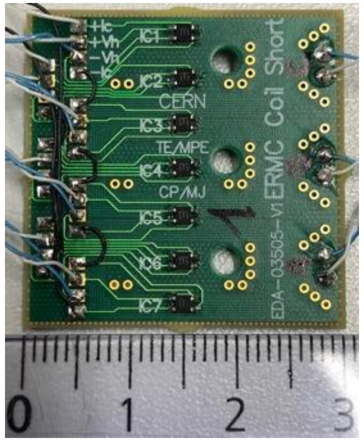
Coil instrumentation

- Quench heaters and voltage taps integrated in the so-called trace, using the same technology as for MQXF/SMC/RMC/FRESCA2…
  - Trace has been designed accounting with the possibility to install a spot heater for quench protection studies.

- Hall sensors and PCB probes have been produced, both for eRMC and RMM configuration to characterize the field.

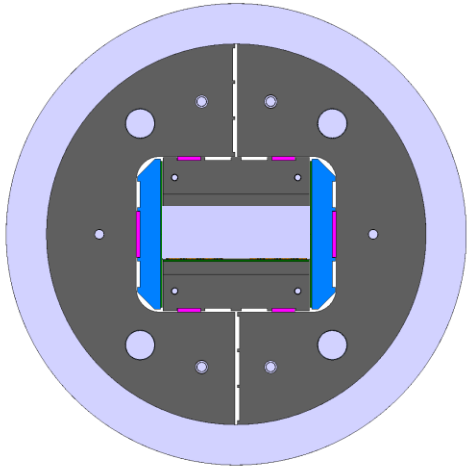


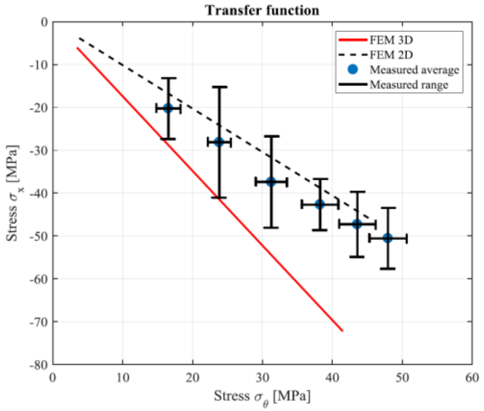


Courtesy C. Petrone

Magnet Structure

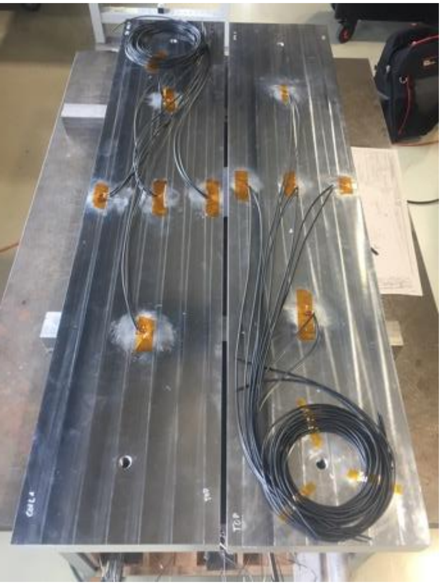
- In order to explore different assembly parameters:
  - Full aluminum shell and half-length shell options available.
  - Aluminum and Stainless-Steel rods available for the longitudinal loading.
- A first assembly with dummy aluminum coils was done, using full length shell and aluminum rods for structure validation.
- The same configuration was later used for eRMC1 and RMM1



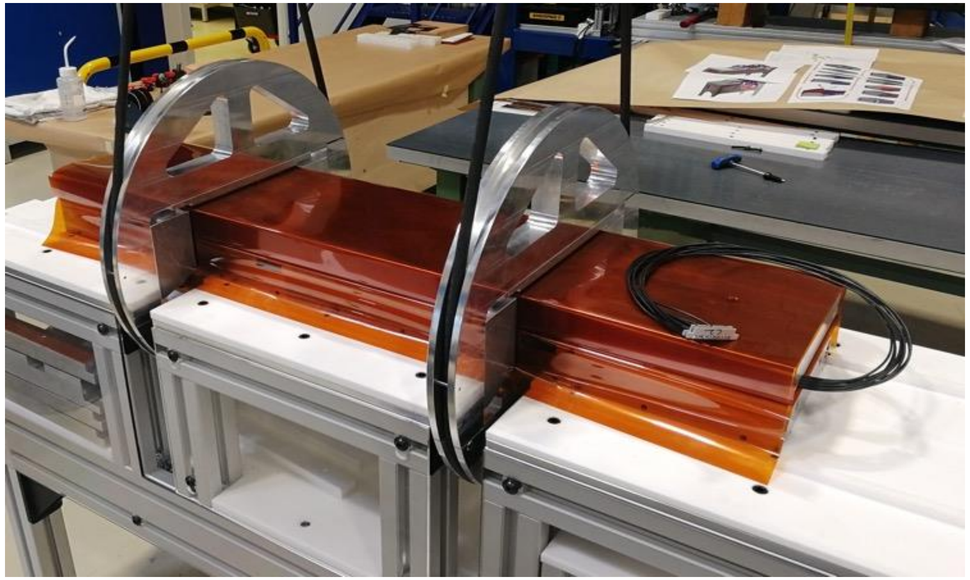


Mechanical assembly test (1/2)

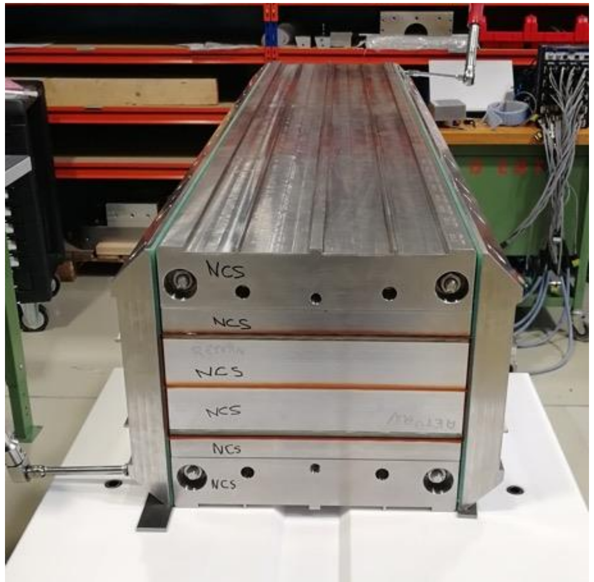
Instrumented Aluminum Dummy Coils



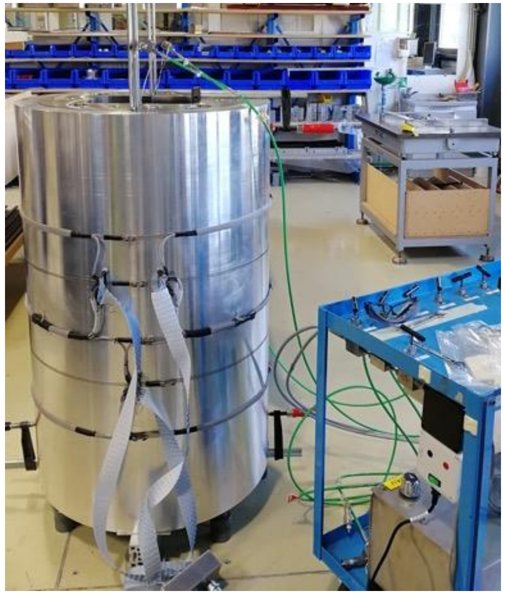
Coil rotation tooling and ground insulation



Coil Pack



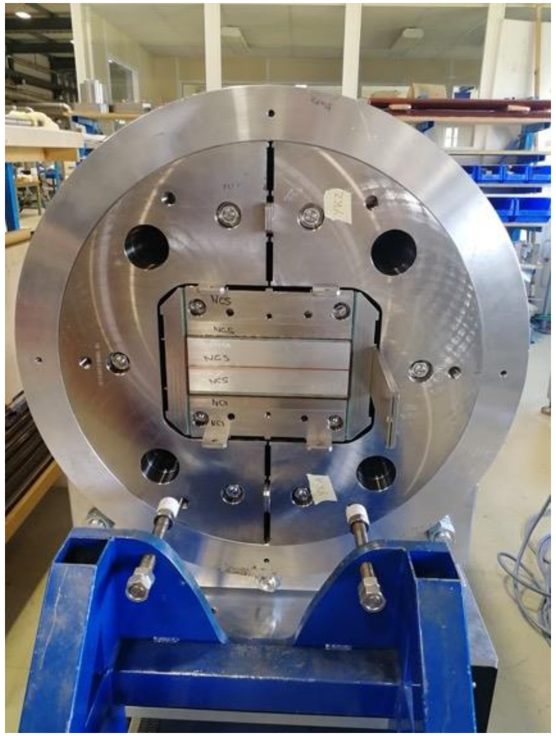
Shell-yoke pre-assembly



Mechanical assembly test (2/2)

Shell-yoke rotation

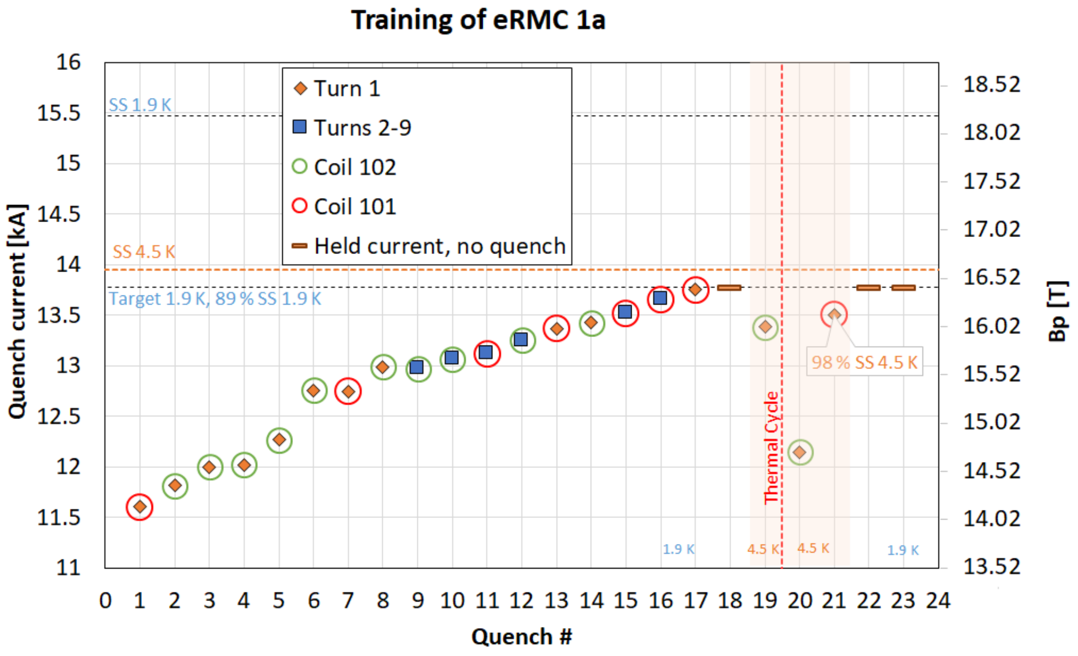
Magnet pre-assembly, including yoke keys (to be removed before the first loading step)

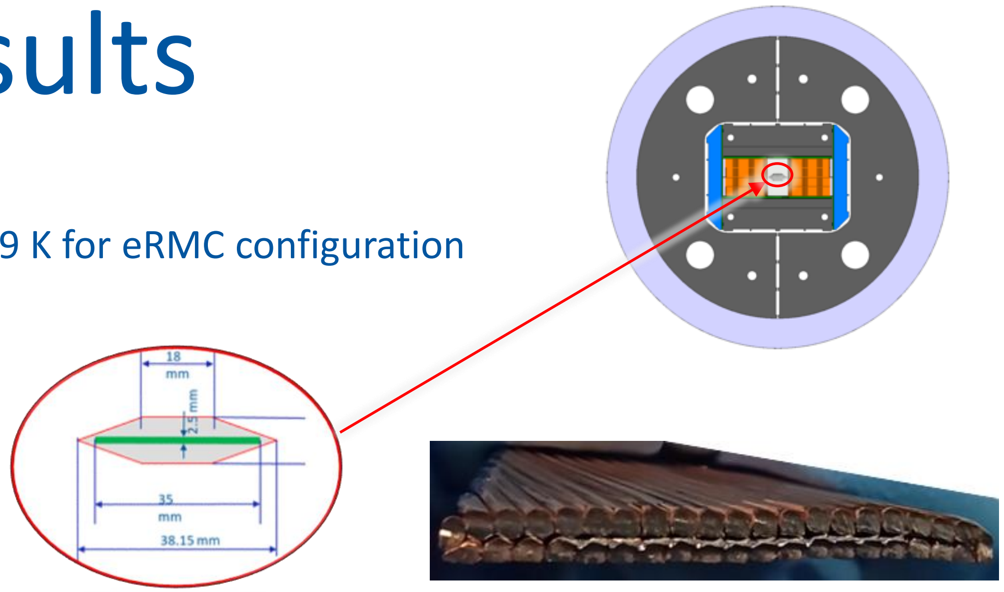


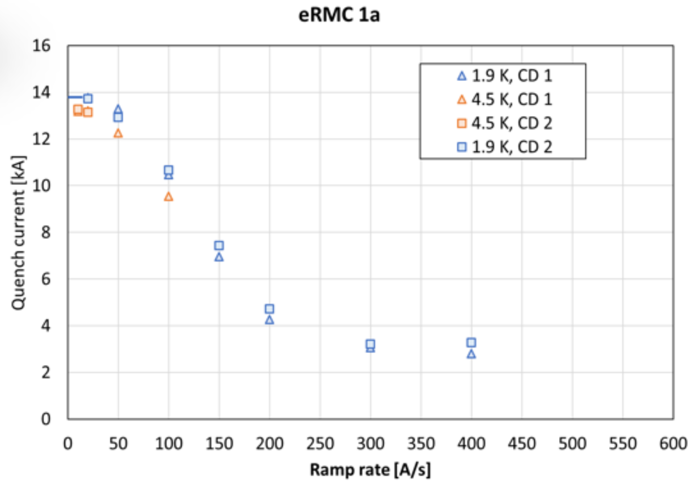
Magnet including axial loading system

eRMC 1a powering tests results

- eRMC1 magnet was assembled using coils #101 & #102
- The magnet reached 13.77 kA (Bp 16.5 T) pre-defined as maximum current at 1.9 K for eRMC configuration
- The magnet reached 98% of SS at 4.5 K
- Strong quench current-ramp rate dependency
- 20 A/s showed to be too high dI/dt
- Good memory after the thermal cycle: Only one training quench

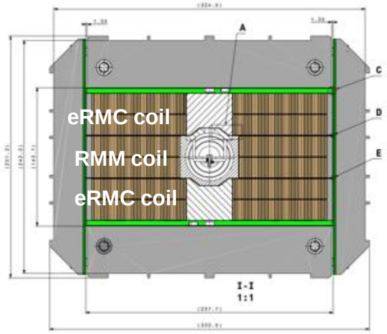




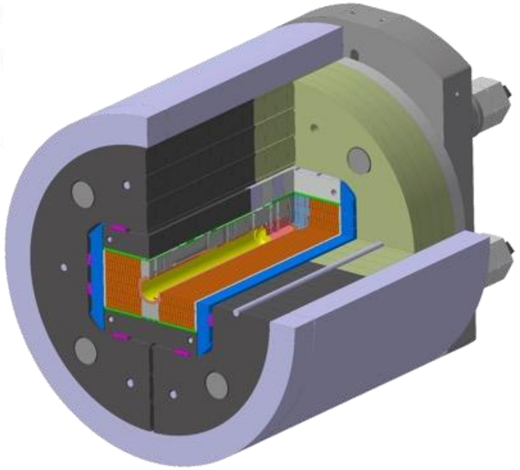


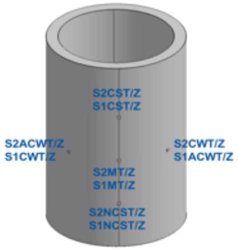
Courtesy S. Ferradas & G. Willering

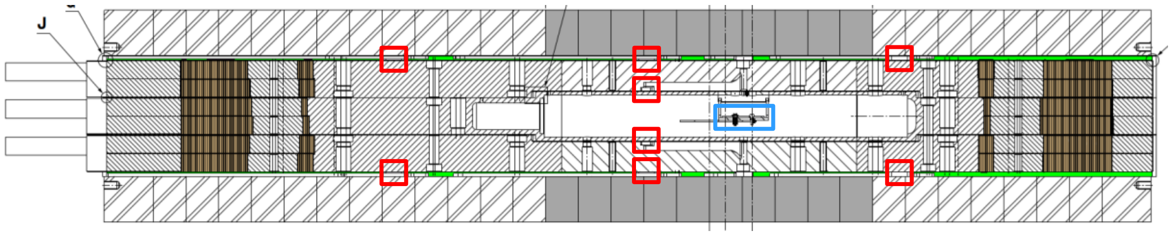
RMM1 magnet configuration



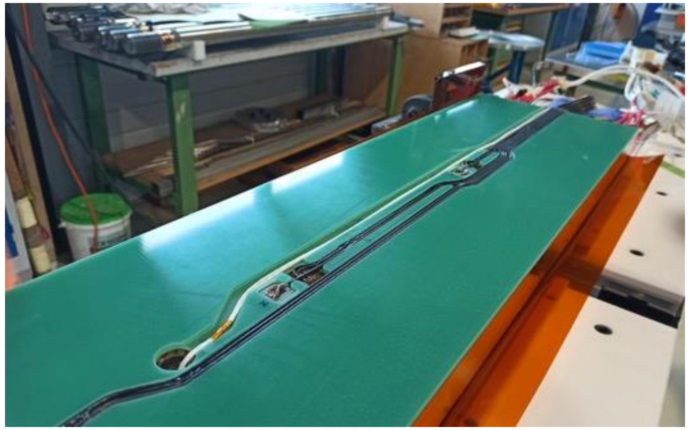
	eRMC #101	eRMC #102	RMM #101
Strand Type	RRP 120/127	RRP 150/169	RRP 120/127
Cable ID	H19OC0226A, HT 406	H19OC0225B, HT 415	H19OC0287A, HT 600

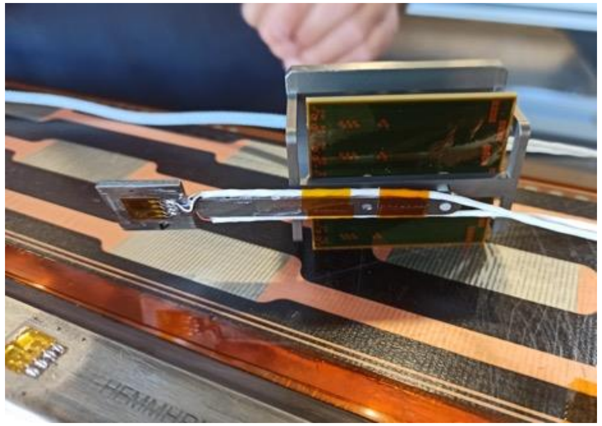


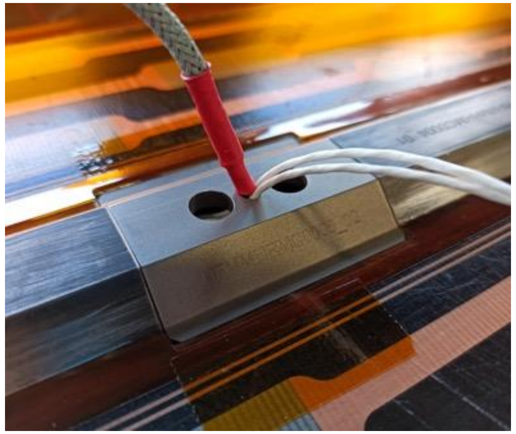




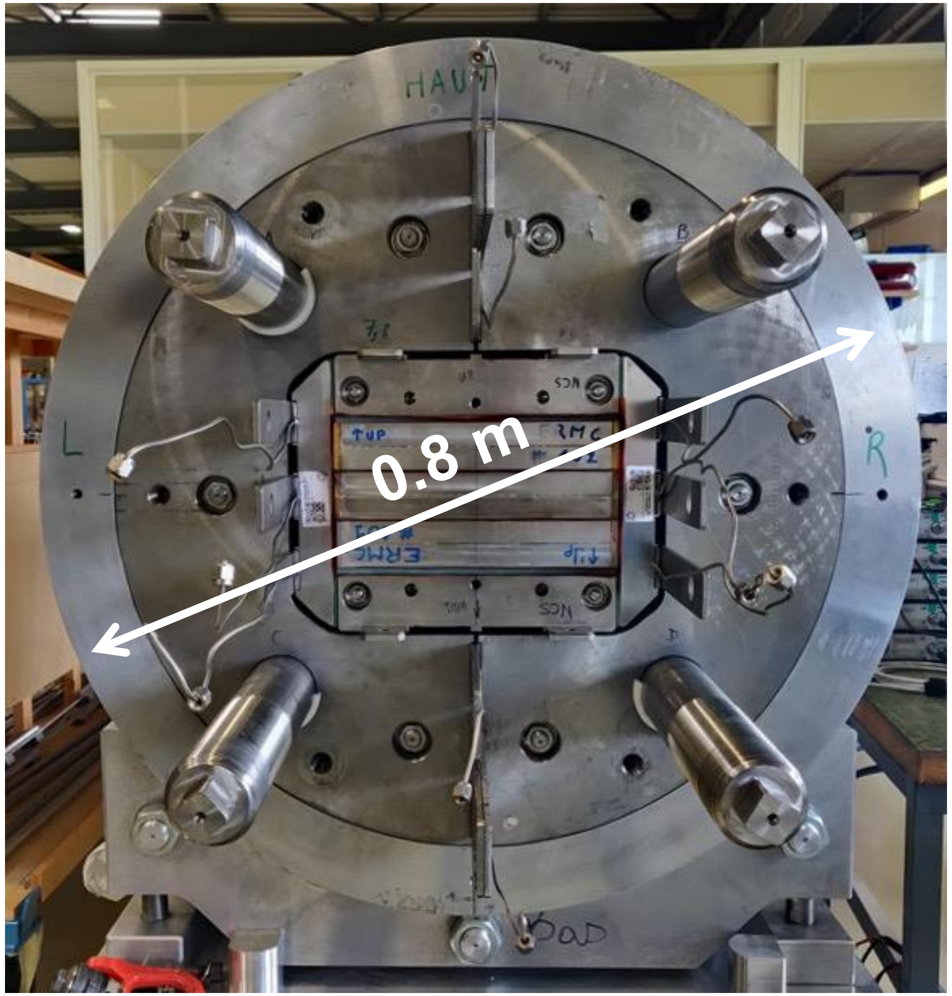
- Close cavity Ø 50 mm
- $L_{cavity\ total}$: 526 mm
- $L_{cavity\ 50\ mm}$: 431 mm

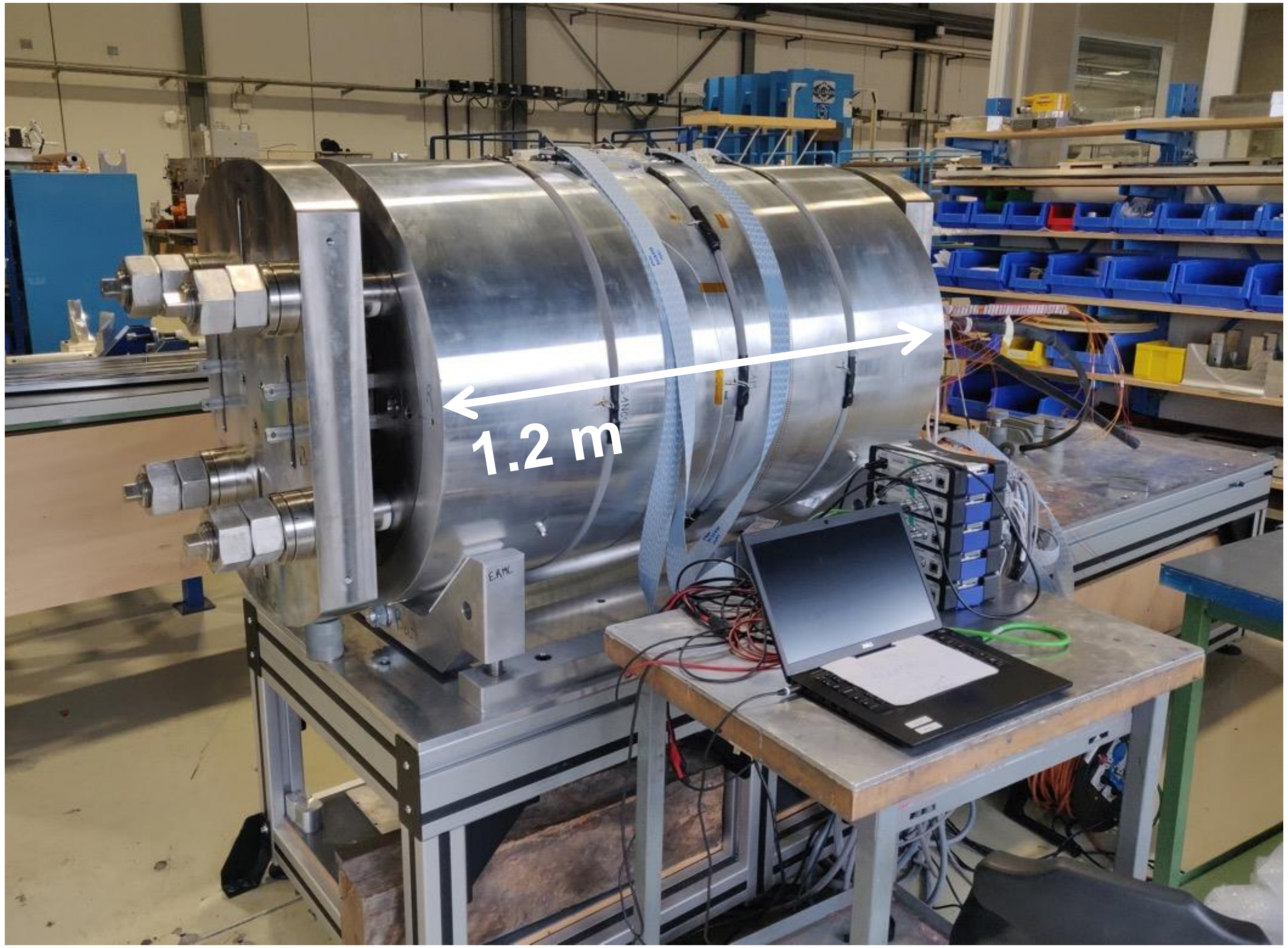




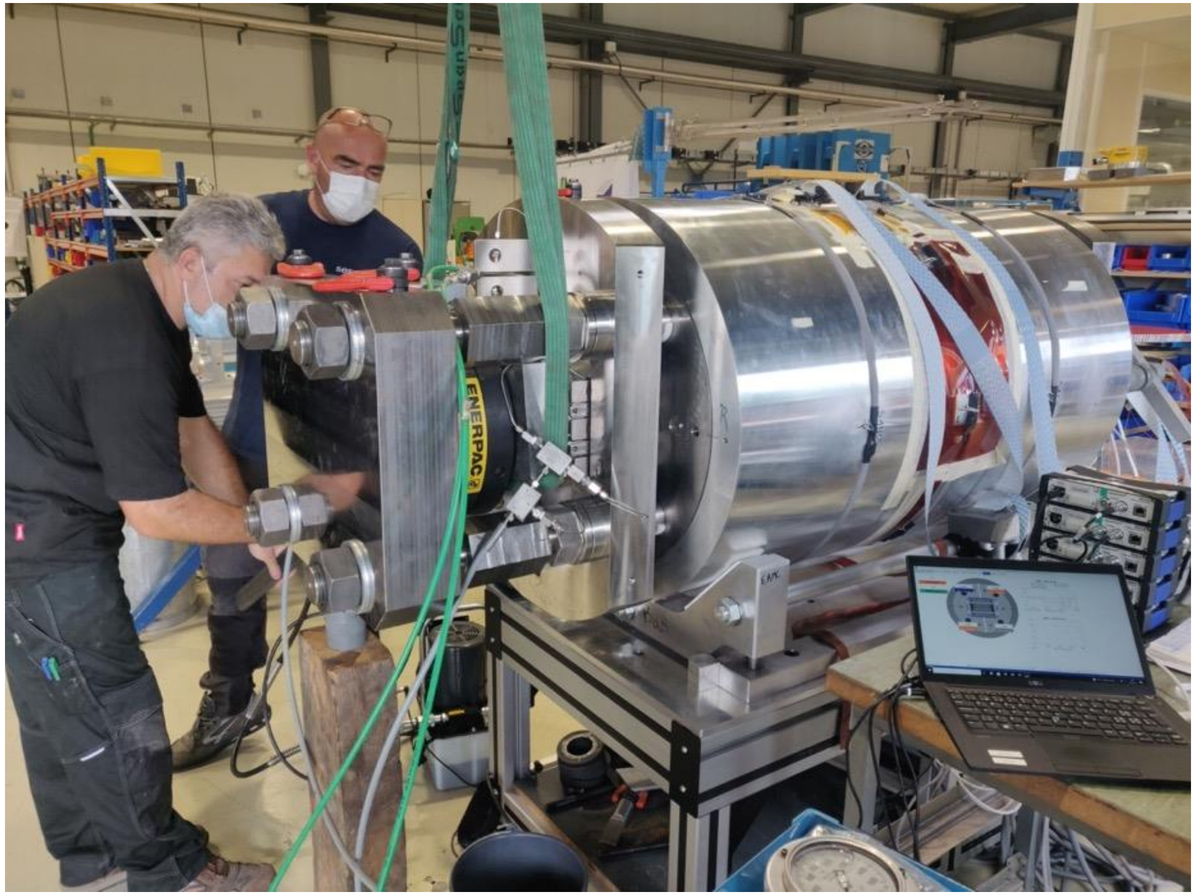


RMM is a big dipole

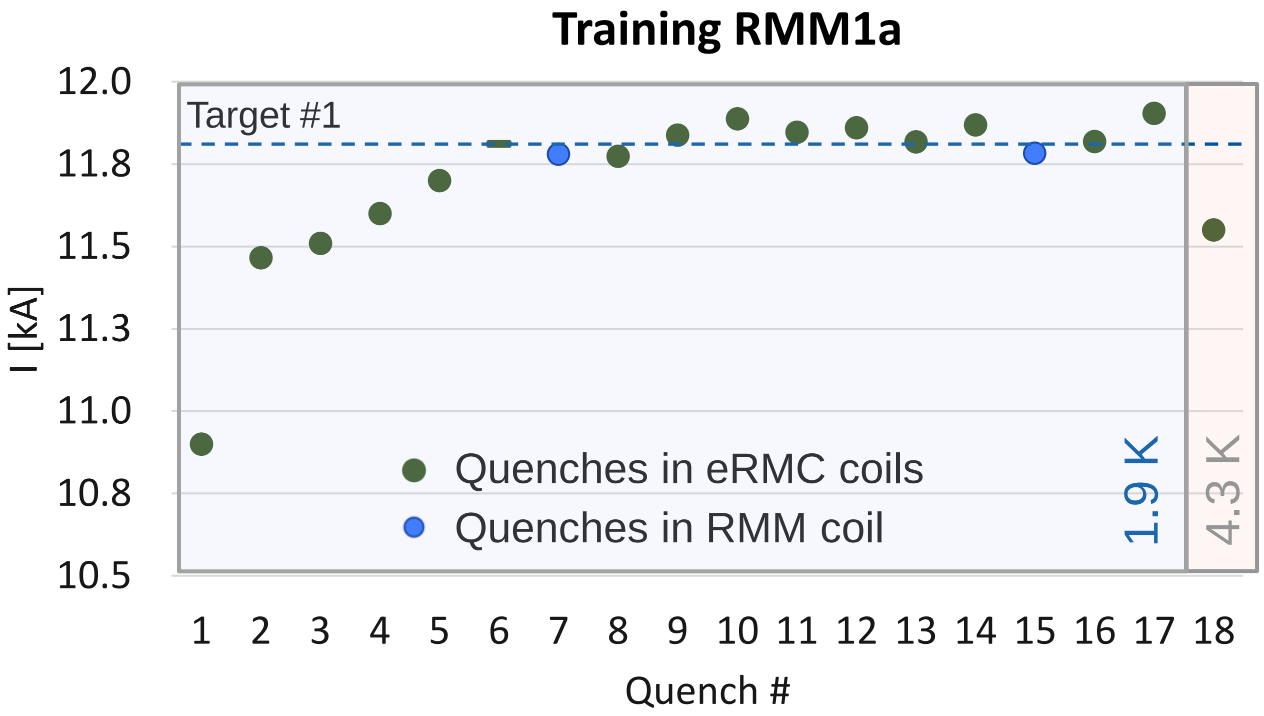




RMM magnet assembly

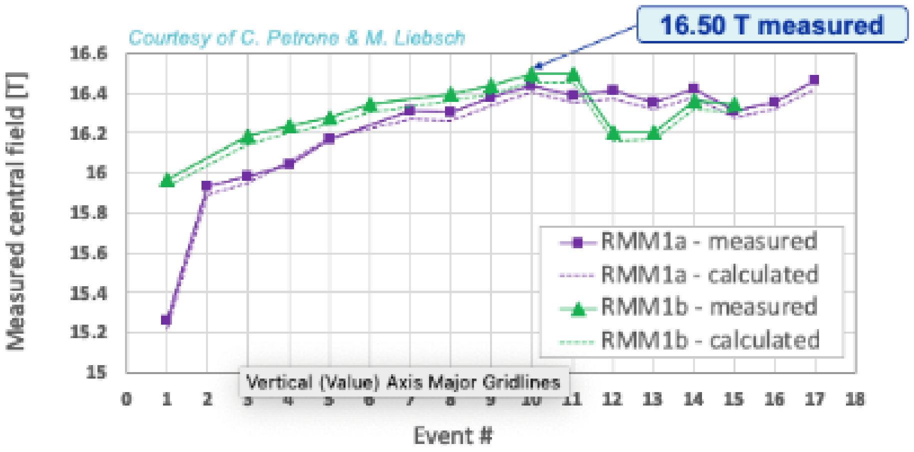


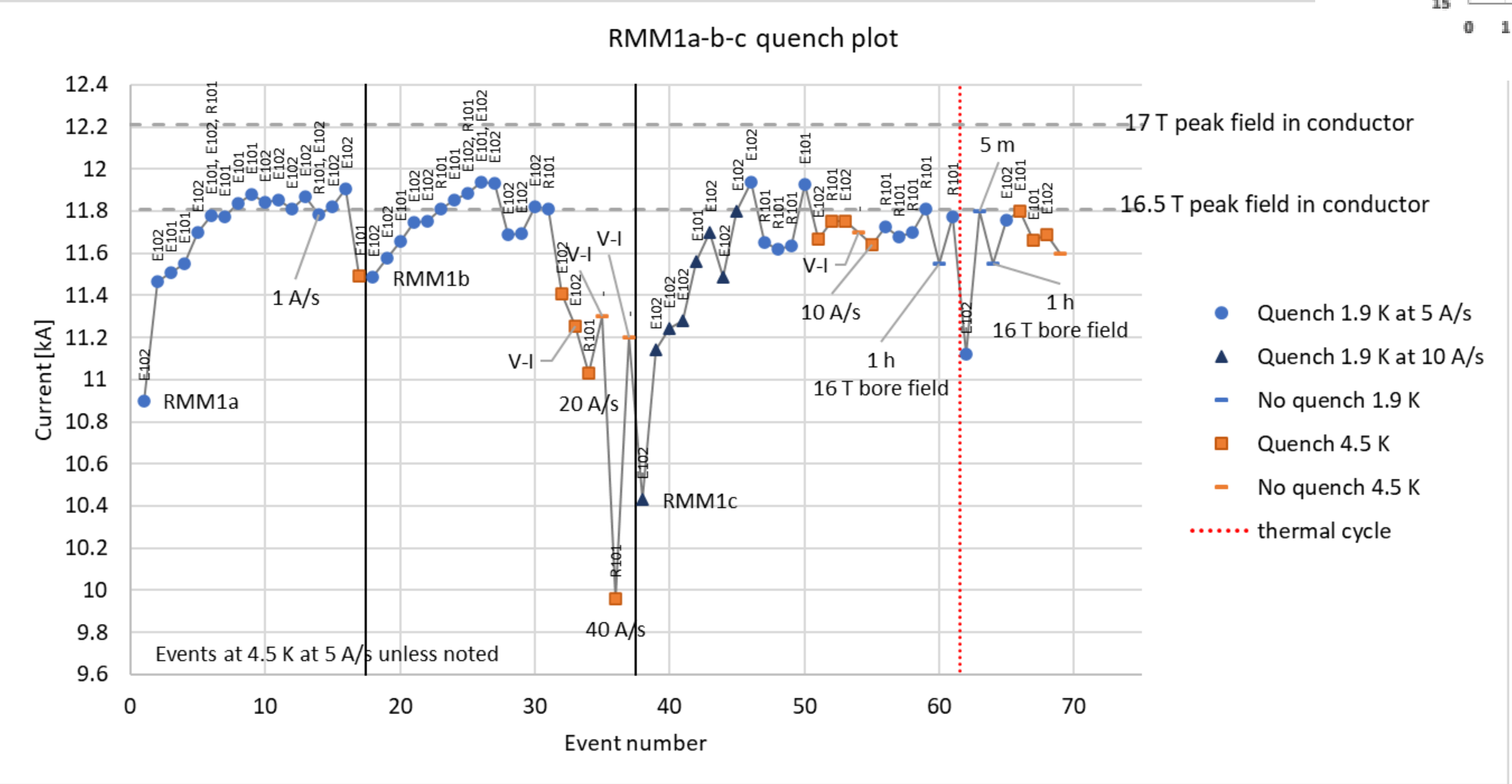
RMM1a powering tests results



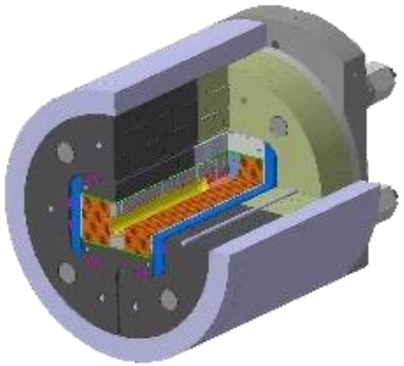
Max current reached	I (kA)	Bp (T)	Bo (T)	I/Iss (%)
1.9 K	11.90	**16.62**	16.42	87.3
4.3 K	11.55	**16.18**	16.00	94.2

RMM 1a, b & c





- Reduction of the longitudinal rods diameter to avoid interference with the iron yoke for RMM1b assembly
- Transverse preload increase for conservative preload study
- Most of the quenches are located in eRMC coils
- The shim thickness of eRMC coils will be increased for RMM1d assembly



Conclusion & next steps

- RMM is used for exploration of high field in the straight section of a dipole block configuration
- Field record of 16.5 T (87.5 % of the short sample limit at 1.9 K)
- No sign of conductor degradation after several assemblies and powering tests
- Next steps:
  - Study of conservative transverse preload on RMM1 on going
  - Production of 3 new eRMC coils will start in summer 2024
  - Assembly and tests of eRMC2 by end 2024
  - RMM2 will be tested during Q1_2025

Thank you for your attention!