HFM

High Field Magnets

WP3.5

Nb_3Sn ultimate performance dipole models
$14T^+$ Dipole

HFM Annual Meeting 2023

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https://indico.cern.ch/event/1302031/

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Scope of the Work Package

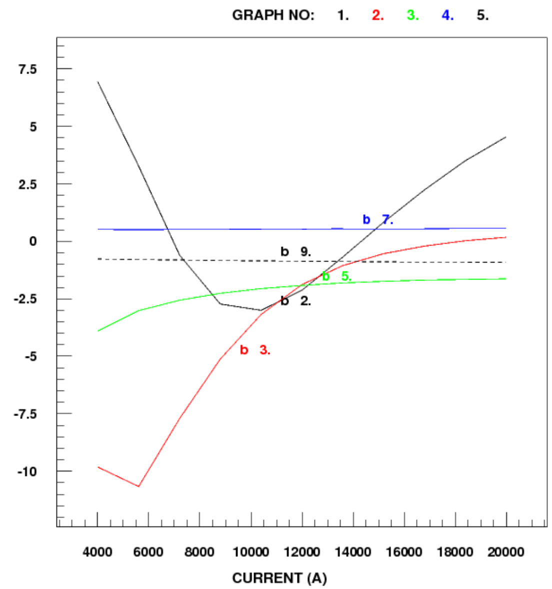
WP3.5: Nb_3Sn ultimate performance dipole models

- **Pursue the work started in the frame of the FCC Magnet development Program towards 16 T Dipole models**
  - Demonstrate Nb_3Sn potential above 14 T and in terms of ultimate performance (16 T target)
  - Design and construction of a 14 T+ accelerator quality dipole model magnet
  - Explore alternatives and develop design and technology for ultimate performance Nb_3Sn magnets

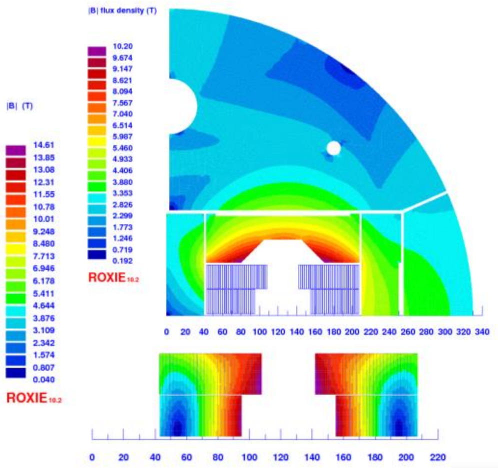
Initial Design Target

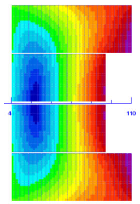
- > 14 T bore field with ≈ 20 % load line margin
- Protection time margin > 40 ms
- Aperture = 50 mm
- “Accelerator coil size”, i.e, < 60 mm
- Field quality within 10 units at all current levels (excluding PC effects)
- Magnet OD: take EuroCircol dimensions as reference
  - Intra-beam distance: 250 mm
  - Cold mass OD: 800 mm and Magnet OD : 760 mm
  - For the 1 in 1, we will scale down

Field errors as a function of the current (geometric + iron saturation)



Conceptual design with acceptable field quality (< 10 units at all current levels, excluding PC) for cable 44*1.1 mm (TDF magnet) and cable 48*1 mm completed





CABLE#1
R_{min} = 14.8 mm
Inner support = 4 mm
N_{turns} = 50
CABLE #2
R_{min} = 17 mm
Inner support = 5 mm
N_{turns} = 54

Parametric analysis for 14 T+ magnet based on block coils completed by E. Todesco
(https://indico.cern.ch/event/1292121/)

Courtesy of S. Izquierdo Bermudez

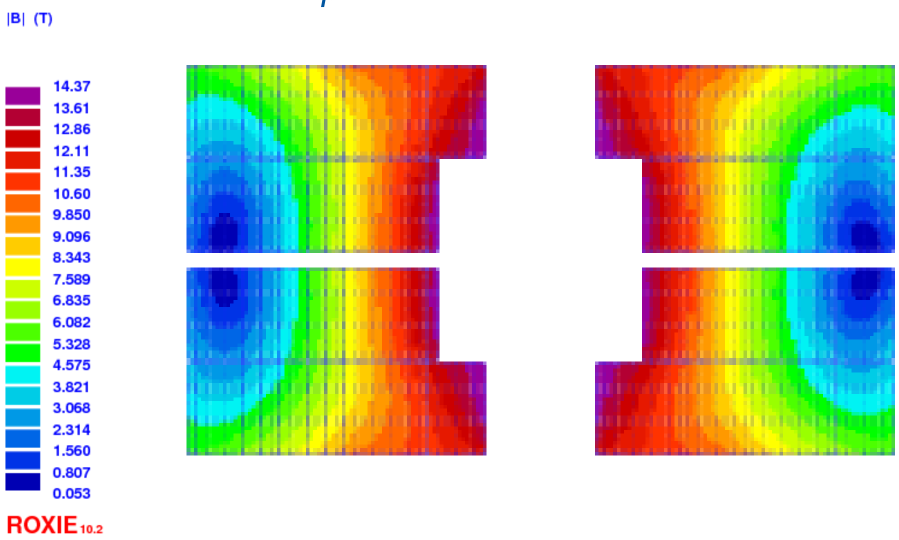
Change of design target

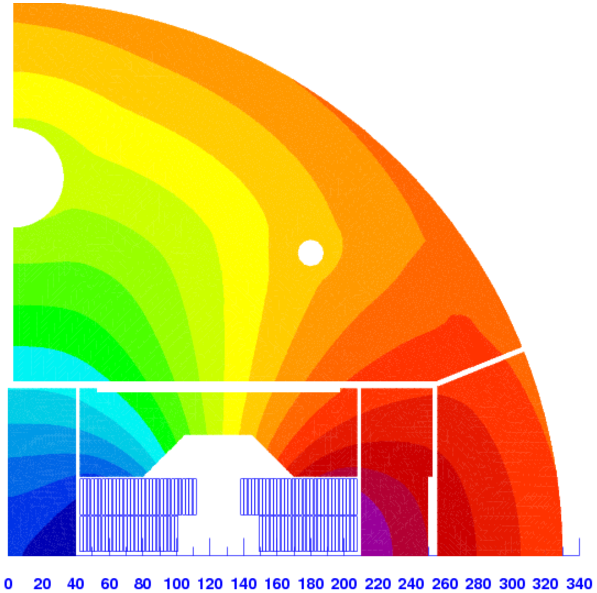
- > 14 T bore field with 20 % load line margin
- Protection time margin > 40 ms
- Aperture = ~~50 mm~~ → ≈40 mm (40 strands cable 1 mm diam. to be produced at CERN)
- 'Accelerator coil size', i.e, < 60 mm
- Field quality within 10 units at all current levels (excluding PC effects)
- Magnet OD, take Euro-Circol dimensions as reference (Intra-beam distance: 250 mm; Cold mass OD: 800 mm; Magnet OD : 760 mm
  - For the 1in1, we will scale down

2 in 1 Reference Design

- Electro-magnetic design studies completed. Mechanical design ongoing.
- Final parameters to be adapted based on winding tests (minimum bending radius) and detailed engineering design (inter-layer and mid-plane shim) and mechanical design (structural components) for a Bladder&Keys structure
- Twin-aperture dipole magnet, with Nb_3Sn block coils has never been built.
- It is a very challenging configuration.

$B_{ap} = 14\ T,\ I = 15.36\ kA$

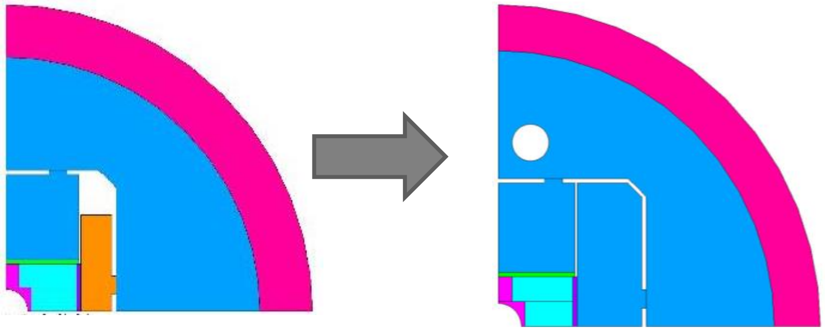




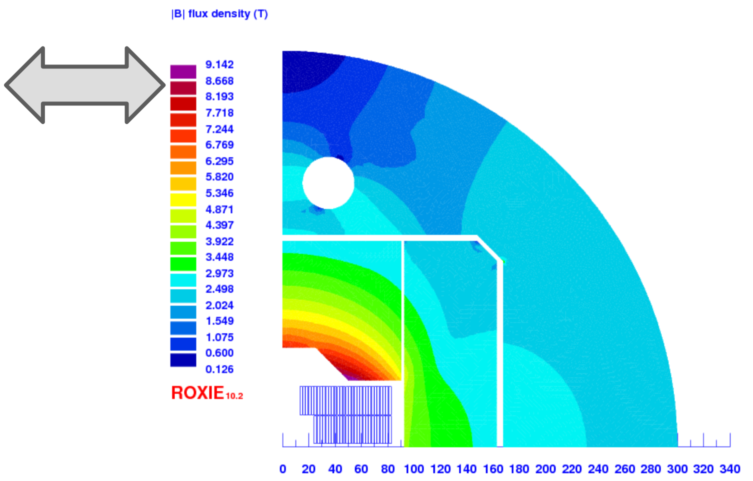
Courtesy of S. Izquierdo Bermudez

1 in 1 Reference Design

- Iterative 2D electro-magnetic and mechanical design
  - Final parameters to be adapted based on winding tests (minimum bending radius) and detailed engineering design (inter-layer and mid-plane shim)
- Main features for the reference design:
  - Thick iron horizontal pad
  - Rods for axial loading integrated in the yoke
  - Non-magnetic pole and insert in the vertical pad for field quality (we could gain 0.5-0.7 T, but hundreds of units of b_3, for more details see (https://indico.cern.ch/event/1299122/)
- Mockups will be built to check the cable stability, bending radius, layer-jump geometry, …. before starting the detailed CAD design
- We expect to start winding coils in Q4-2024 and have the first short single aperture model magnet tested in 2025-2026



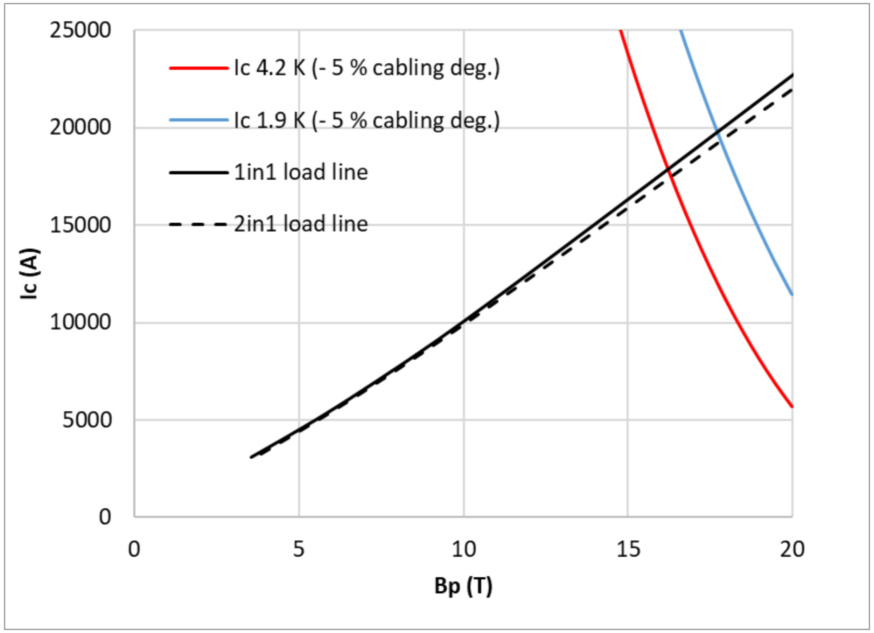
Reference design



Courtesy of S. Izquierdo Bermudez

Magnet parameters for reference design

		RMM	14 T 2in1	14 T 1in1
strand diameter	mm	1	1	1
Cu/SC	--	1	0.9	0.9
# of strands/cable	--	40	40	40
# turns/quadrant	--	132	59	59
Eq. coil width	mm	86	55	55
I_{nom}	A	11546	15363	15757
$J_{overall}$	A/mm²	248	330	338
J_{cu}	A/mm²	735	1032	1059
J_{sc}	A/mm²	735	929	953
B_0 at I_{nom}	T	16.07	14.00	14.00
B_p at I_{nom}	T	16.06	14.54	14.56
B_{ss} at 1.9 K*	T	18.77[1]	17.83[2]	17.73[2]
B_{ss} at 4.2 K*	T	17.07[1]	16.31[2]	16.23[2]
F_x/h at I_{nom}	MPa	122	123	123
F_y/w at I_{nom}	MPa	-46	-38	-39
F_z/aperture at I_{nom}	MN	2.16	0.85	0.85
Stored energy density (overall)	MJ/m³	87.95	77.79	77.39



[1] Based on extracted samples reacted with the coil

[2] Reference HFM Jc, including 5 % cabling degradation

First single aperture demonstrator magnet characteristics

- Double layer pancake coil with layer-jump in the straight part Main Post configuration
  - Main post geometry (experience from HD2 & Fresca2)
  - Interlayer configuration to be carefully study
- Flared-ends configuration
  - Central-post transition to the wedge
  - Impregnated or non-impregnated wedge???
- Heat treatment mold configuration
  - Sliding pieces to compensate thermal expansion
  - Coil bore deformation during heat treatment
- External coil geometry
  - How to get identical coils geometry to easy the assembly
  - Impregnated loading plates allowing machining of the coil to tune the transversal dimension
  - Scalable techniques for longer coils
- Magnet protection
  - If QH are used for magnet protection, they will not be impregnated with the coil
  - Collaboration with MPE for CLIQ redundant protection and efficient at low current
- Mechanical structure
  - Well known Bladders & Key structure
  - We will profit from the experience gained during Race-track coils development and from HL-LHC quadrupoles production

What can be explored at a later stage?

- 2in1 mechanical optimization
- Production of a bigger cable with the new CERN cabling machine (2026/2027?)
- Use of new strand architectures from SCD future R&D program for HFM
- Open to study novel mechanical structures
- Stress management for a block-coil configuration if required
- New magnet cooling system to be investigated and develop in collaboration with TE-CRG
- Magnet protection system (QH, CLIQ, E-CLIQ…) to be studied and qualify with TE-MPE
- New coil and magnet instrumentation

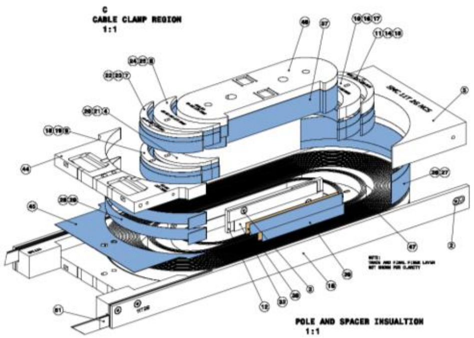
We have been working for several years on Nb_3Sn magnet development for :
Fresca2, HL-LHC, FCC via EuroCircol.
The 14T+ program is using this experience and profit of lessons learned from US-LARP.

For technology development, while pushing the field higher, we used the **S**hort **M**odel **C**oils (**SMC**) or their bigger brothers :
RMC, **eRMC**, **RMM**

(all of them using flat coils and B&K technology for the fast and easy tuning capability)

In the next slides I will summarise the activities and results we obtained via these
" test bed type magnets"

Impact of the resin on magnet performance
using SMC11T 2nd generation coil design



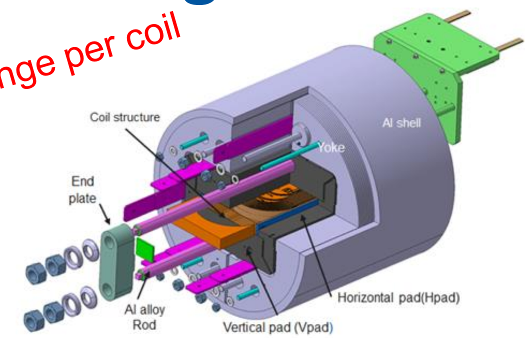
Objectives

- Training reduction

Exploration

- resins
- adhesion condition
- conductor
- electrical insulation

One parameter change per coil



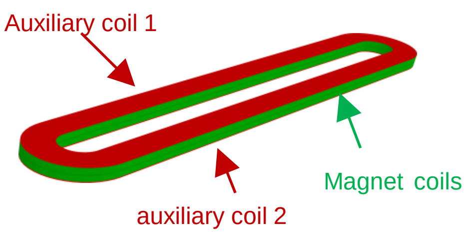
Naming	Cable	Pole	Epoxy	Cable insulation	Status
SMC2G-101	SMC-11T	Impregnated	CTD 101K	S2 Glass / 150 μm	Tested
SMC2G-102	SMC-11T	Impregnated	Araldite®MY750 + Aradur®HY5922	S2 Glass / 150 μm	Tested
SMC2G-103b	SMC-11T	Impregnated	Mix 61	S2 Glass / 150 μm	Tested
SMC2G-104	SMC-11T	Impregnated	Araldite®MY740 + Aradur®HY609 +DY062 (MSU)	S2 Glass / 150 μm	Tested
SMC2G-105	SMC-11T	Impregnated	CTD 101K	S2 Glass / 150 μm	Ready
SMC2G-106	SMC-11T	Impregnated	Best performing	S2 Glass / 150 μm	Not started
SMC2G-107	SMC-11T	Impregnated	CTD 101K New PoLab. Formulation	S2 Glass / 150 μm	Ready

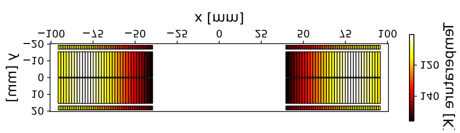
See resins studies WP 4.3 presentation by R. Piccin

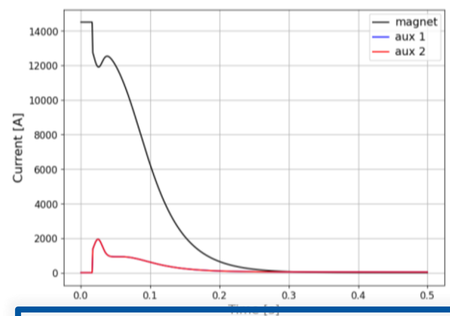
Other Studies using SMC

ESC (Energy Shift with Coupling)

- ✓ As fast as CLIQ or faster
- ✓ Extracts part of the magnet energy
- ✓ Sudden current drop → lower ohmic loss
- ✓ Electrically insulated from coil
- ✓ Easier redundancy







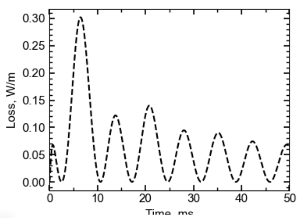
Simulations performed using STEAM

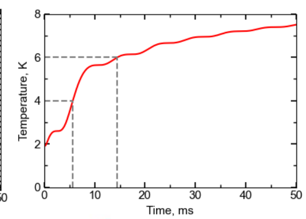
https://indico.cern.ch/event/1321217/

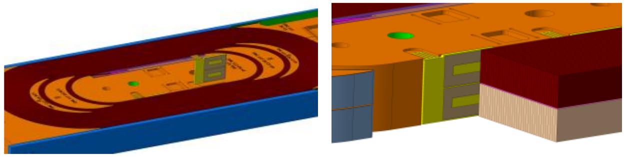
Courtesy of E. Ravaioli

E-CLIQ

- ✓ E-CLIQ coils are inductive quench heaters: AC current → AC magnetic field → AC loss in the conductor.
- ✓ New E-CLIQ coils designed and produced for testing in combination with a SMC.
- ✓ Two coils on 1 PCB -> 1 for each layer of the SMC.
- ✓ Sudden current drop → lower ohmic loss
- ✓ Each coil has 14 layers and an inductance of 3 mH.
- ✓ Potential to initiate a quench within some milliseconds.

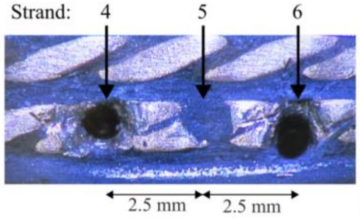


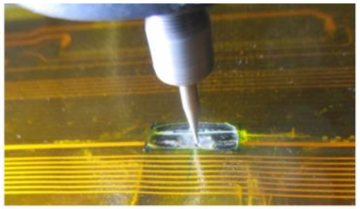




Courtesy of T. Mulder

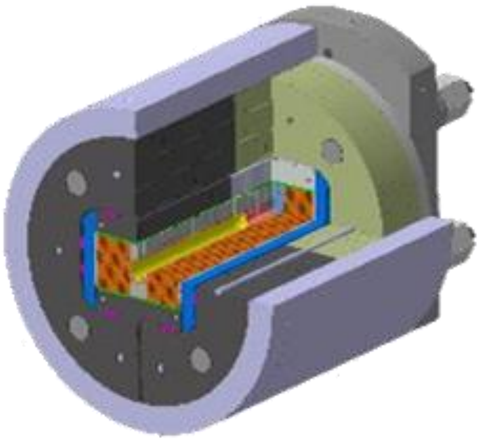
Effect of intentionally introduced **strand damage** in a Nb_3Sn Rutherford cable on the performance of a short racetrack magnet PhD thesis of R. Keijzer (University of Twente) presented at MT28



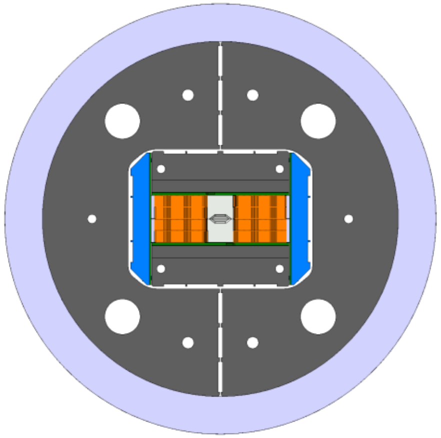


Study of a **New coil design** using a **32 strands** cable with 0.85 mm diameter **MQXF** type strand started

eRMC & RMM



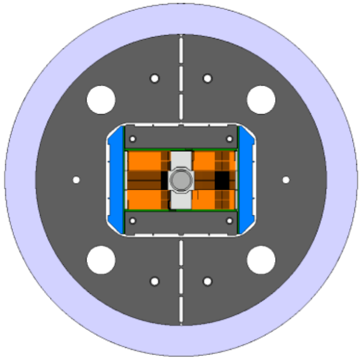
eRMC (enhanced Racetrack Model Coil)



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

- 16 T at the midplane
- Demonstrate field in the conductor
- Coil technology development

RMM (Racetrack Model Magnet)



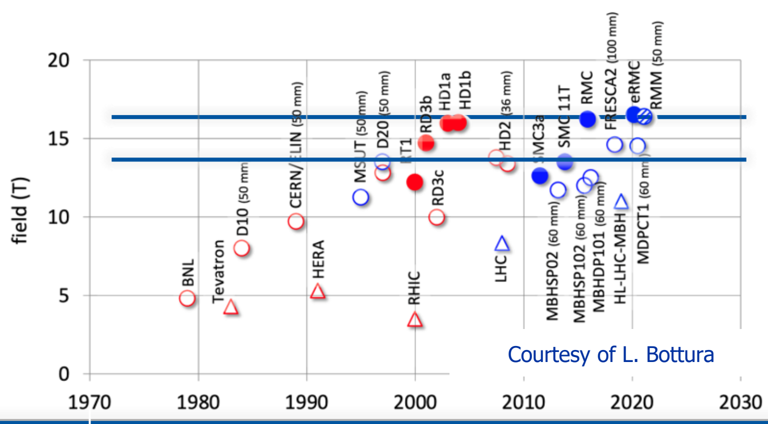
OD = 800 mm
L = 1.2-1.4 m
Ø 50 mm closed Ap.
B_{op}= 16 T
B_{ult} = 18 T

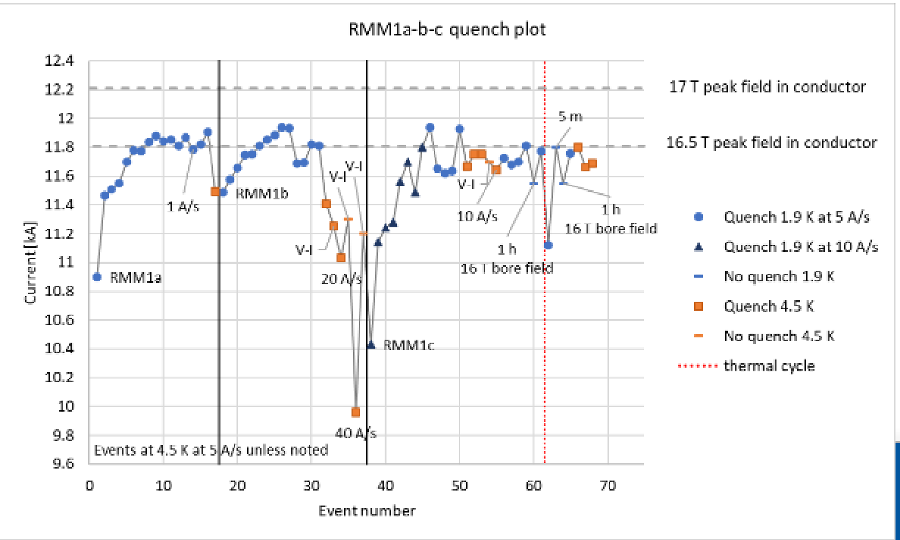
- 16 T inside a closed cavity of Ø 50 mm
- Demonstrate field in the aperture
- Mechanics (inner coil support)

→ Demonstrate the field & Study the mechanics (focus straight section)
→ Field quality not an objective

eRMC/RMM activities & Results

- 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) in a 50 mm diameter and 431 mm long closed cavity during summer 2022
- No sign of conductor degradation
- Transverse preload increase for conservative preload study on RMM1c ongoing
- RMM1c with modified eRMC coils shimming tested in SM18 in July 2023
- 3 eRMC cable UIs produced and being insulated
- Coil fabrication expected second half on 2023 (delays on cable insulation)





Running and future activities

- The feasibility study for a 14 T+ dipole block-coil type with flared-end is well advanced
  - We propose a double layer coil block configuration, using a 40 strands cable for a 40 mm aperture.
  - The main magnet parameters are a bit 'less challenging' than HL-LHC magnets (lower current density, lower energy density, similar stress level due to electromagnetic forces)
- Electro-magnetic design study for 2 in 1 configuration expected to be completed by the end of the year. Mechanical design will follow.
- A detailed conceptual and engineering design of the 1 in 1 is ongoing
  - Mechanical design started, feedback will be included in the electromagnetic design
  - Winding test in the coming months will define the baseline cable and the main parameters for the detailed 3D electromagnetic design.
  - The two activities must progress in parallel for a quick and smooth transition to the engineering design of the 1 in 1 configuration.
- SMC program will continue running
- SMC lessons learned will be implemented in the 14 T+ design
- eRMC/RMM program will run in parallel to further explore the straight section of a coil block configuration:
  - RMM conservative preload study running until end of 2023. RMM1c tested in July 2023 reached again 16.5 T in the 50 mm cavity
  - Winding of 3 eRMC coils will start Q4-2023
  - eRMC2 magnet will be assembled and tested in 2024
  - RMM2 powering tests scheduled end of 2024

Thank you for your attention