Physics Beyond Colliders

Superconductivity Technologies in the CERN Magnet Group (TE-MSC)

Amalia Ballarino

25/09/2024

5th PBC technology mini workshop: Superconductivity Technologies

Superconducting Technologies in the CERN Magnet Group

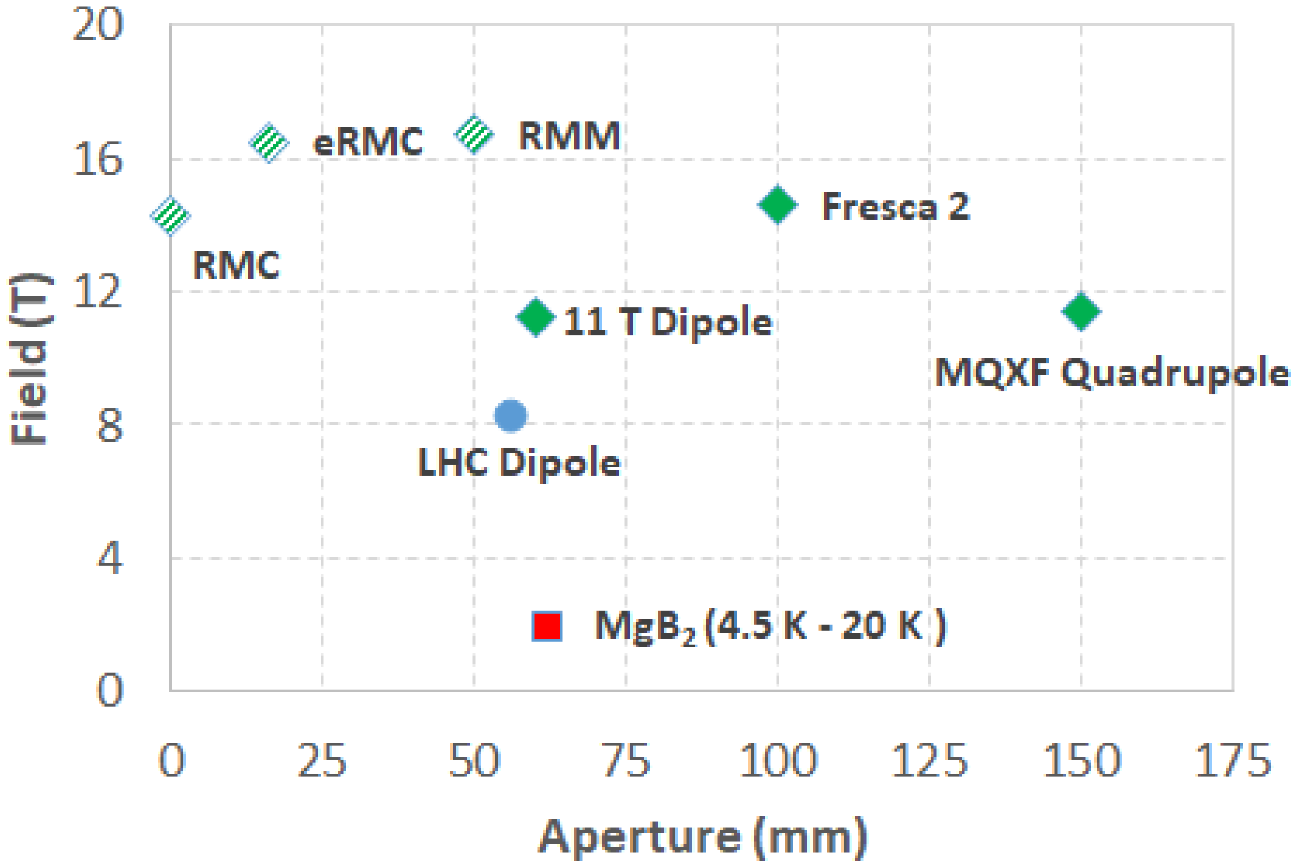
- Superconducting **magnets** for the **CERN accelerator complex** and for **future colliders**
  - **Construction of HL-LHC Magnets**
  - **Magnets R&D in the framework of the HFM program**
  - **Diversification projects,** e.g. magnets for medical applications
- Superconducting **technology** for accelerators
  - Superconducting **wires** and **cables, LTS and HTS**
  - **Insulation/impregnation** techniques
  - **Magnetic measurement** techniques
  - **Cryostats** for magnets and superconducting transmission
  - Superconducting **current leads**
  - Superconducting **transmission lines**

Superconducting Technologies in the CERN Magnet Group

- **Large magnet facility** (building 180)
- **Short models** and Nb_3Sn magnets R&D (building 927)
- **Polymer lab** (building 927)
- Measurement of **superconductors** (building 163)
- **Rutherford cabling** (building 103)
- **Measurement of magnets** (SM-18)
- **Magnetic measurements** (building 311)
- **Cryostats/Cryostating** (SMI2)
- **HTS Laboratory** (building 180, under preparation)

MSC Magnets in a nutshell

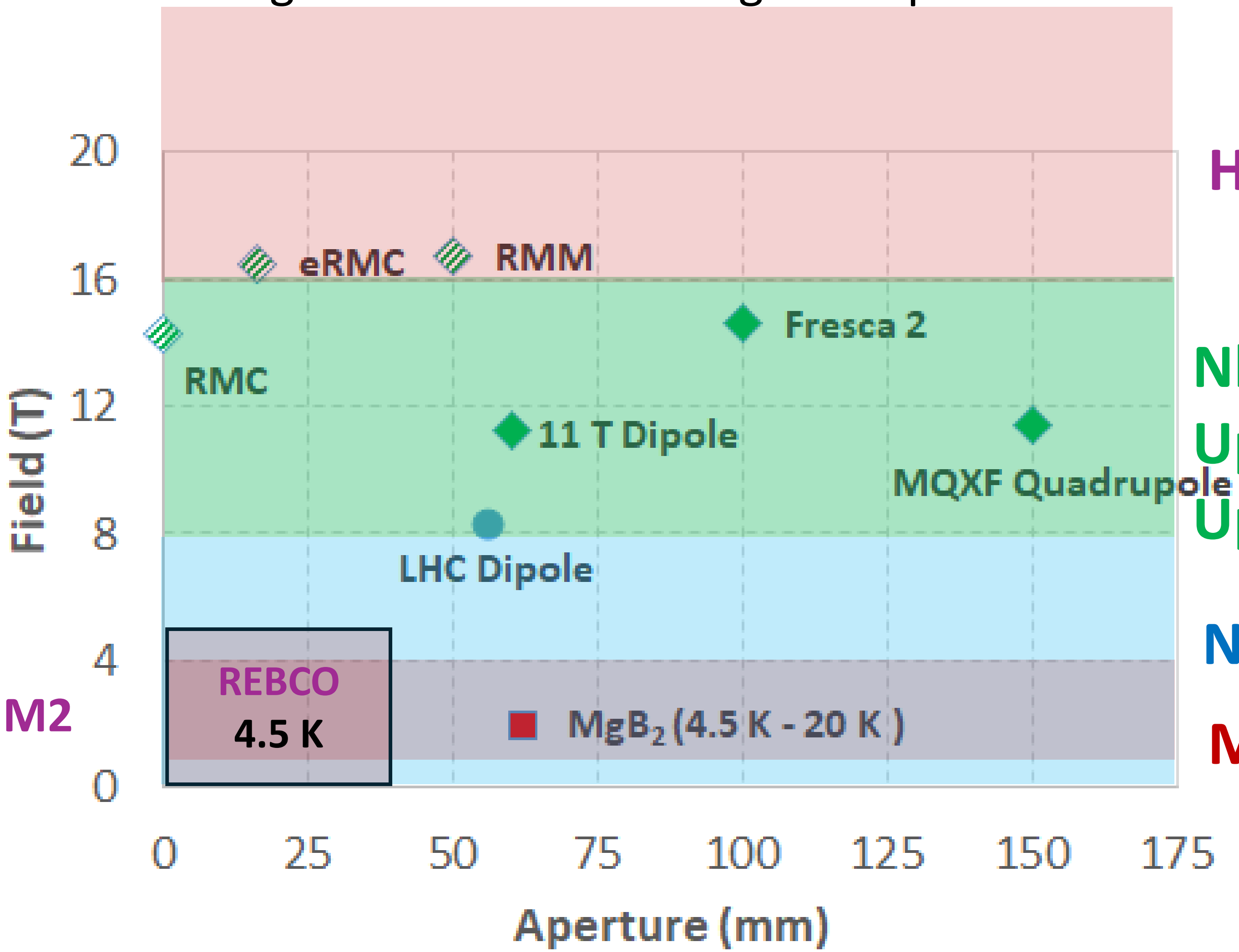
Magnetic field versus magnet's aperture



1.9 K, unless differently specified

MSC Magnets in a nutshell

Magnetic field versus magnet's aperture



HTS

Nb_3Sn

Up to ~ 12 T: Magnets

Up to ~ 16 T: Demo coils

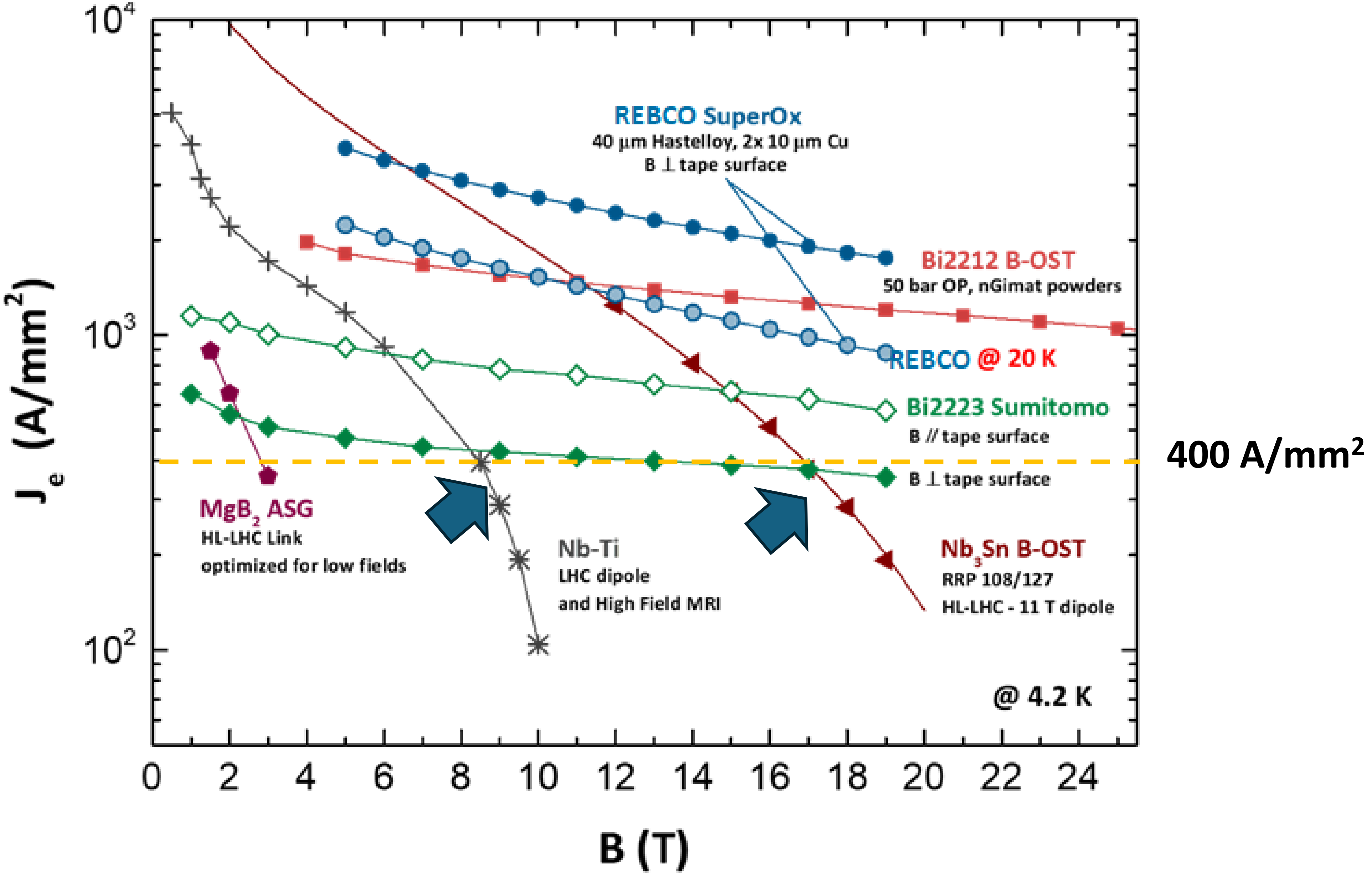
Nb-Ti, up to ~ 9 T

MgB_2, up to ~ 3 T

Eucard 2, Feather M2 Racetracks (77 K)

1.9 K, unless differently specified

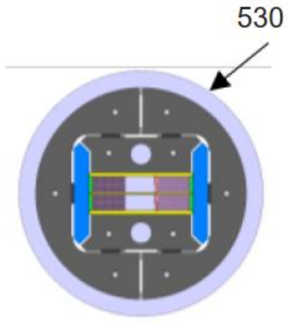
Superconductors for High Field Magnets



MSC Magnets in a nutshell – Nb_3Sn

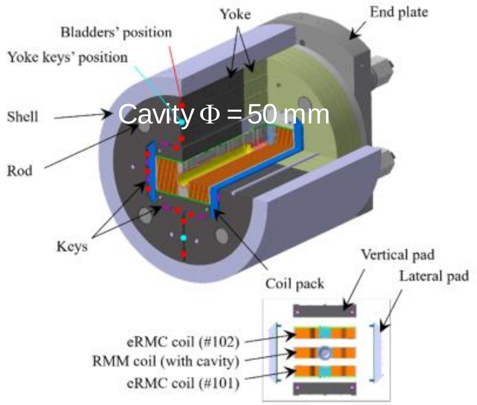
RMC: 2015

14.3 T (midplane)



RMM: 2023

16.7 T (in the coil)



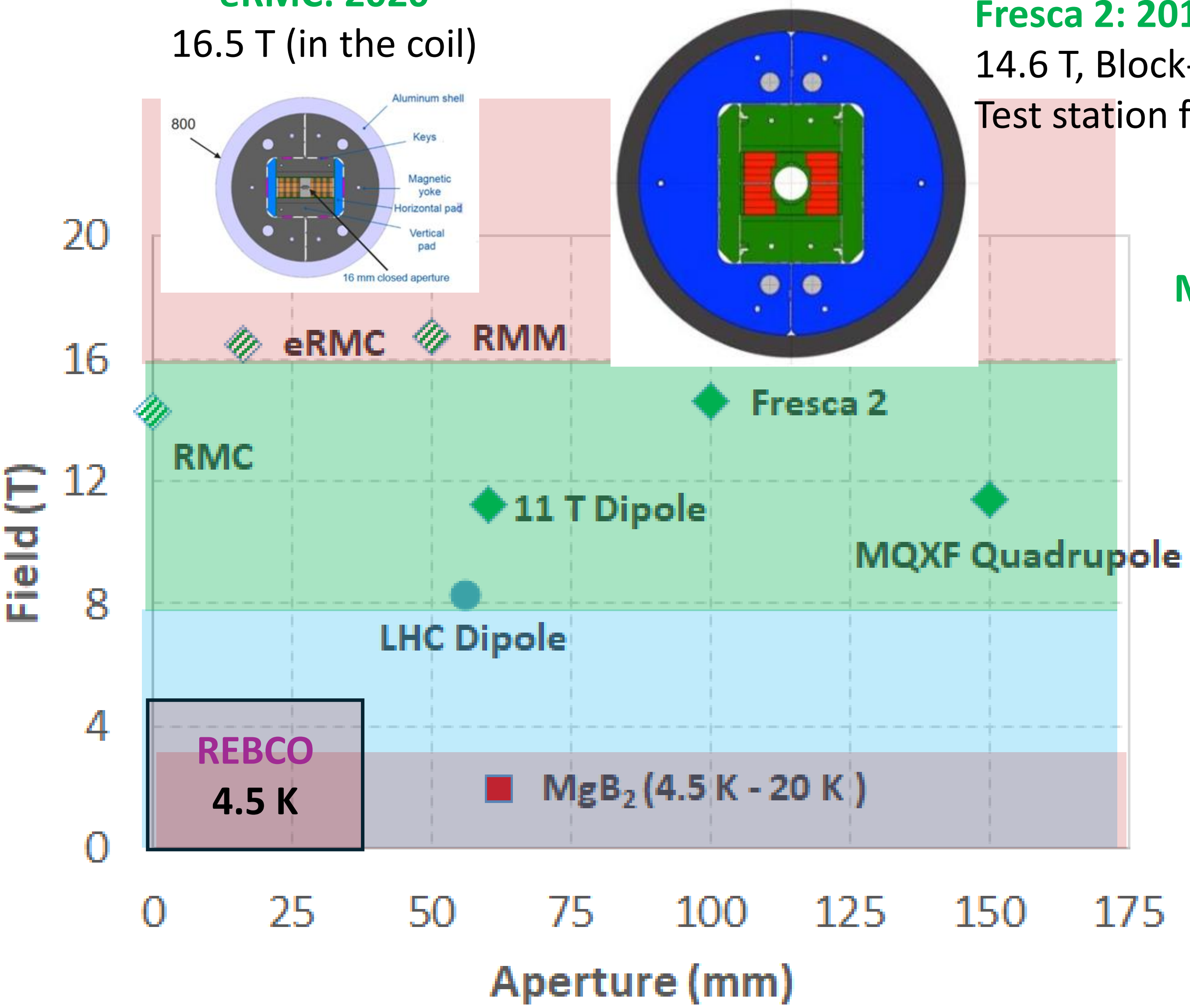
eRMC: 2020

16.5 T (in the coil)

Fresca 2: 2014-2018. CERN/CEA

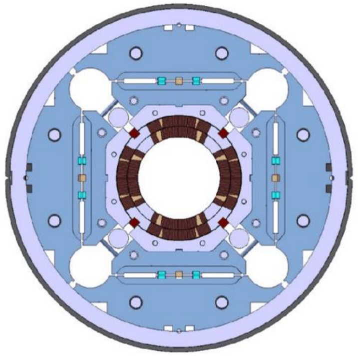
14.6 T, Block-coil design, flared ends

Test station for cables



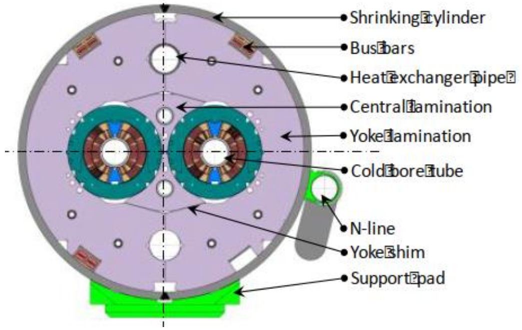
1.9 K, unless differently specified

MQXF (143.2 T/m, Φ=630mm)



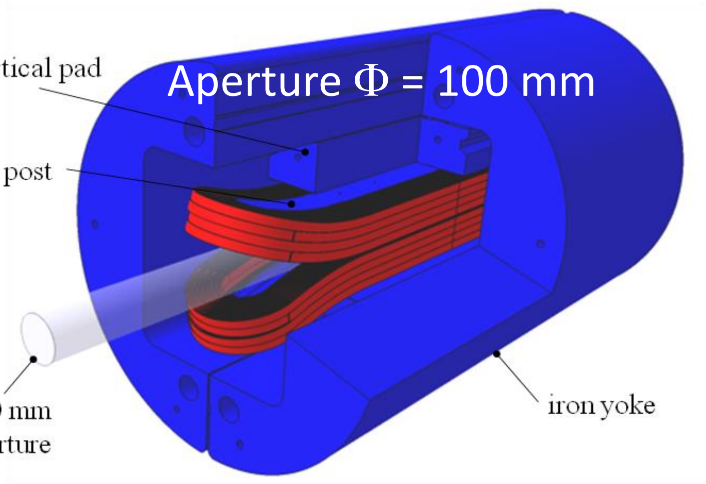
11 T

11 T (Φ=570mm)



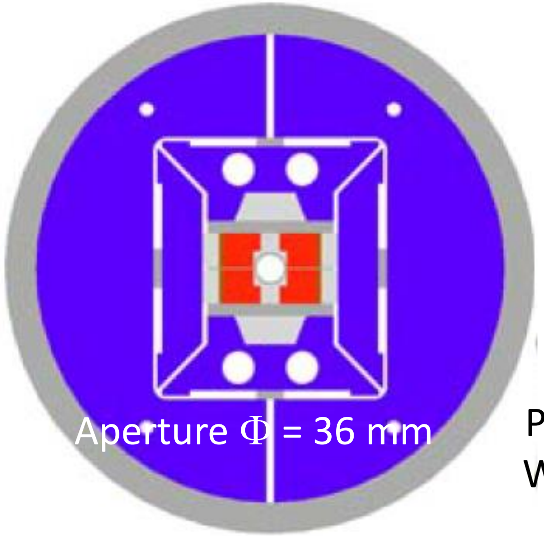
Highest fields – Nb$_3$Sn

FRESCA 2, 14.6 T (1.9 K), CERN/CEA


Aperture Φ = 100 mm

HD2,13.3 T (4.5 K), LBNL

Block-coil, flared ends

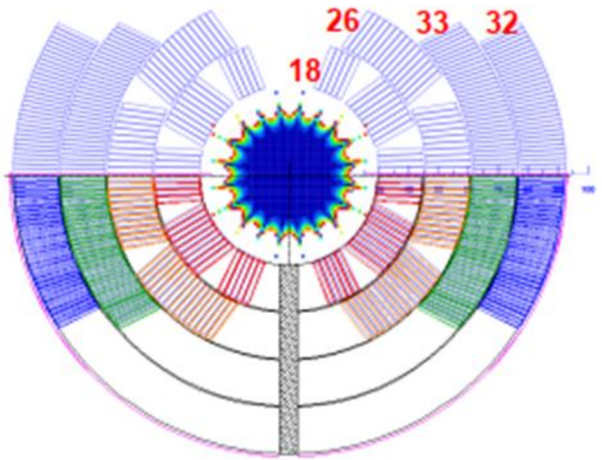

Aperture Φ = 36 mm

P. Ferracin et al
WAMSDO 2009

MDPCT1,14.1 T (4.5 K), Fermilab

Cos-theta, 4 layers

Aperture Φ = 60 mm



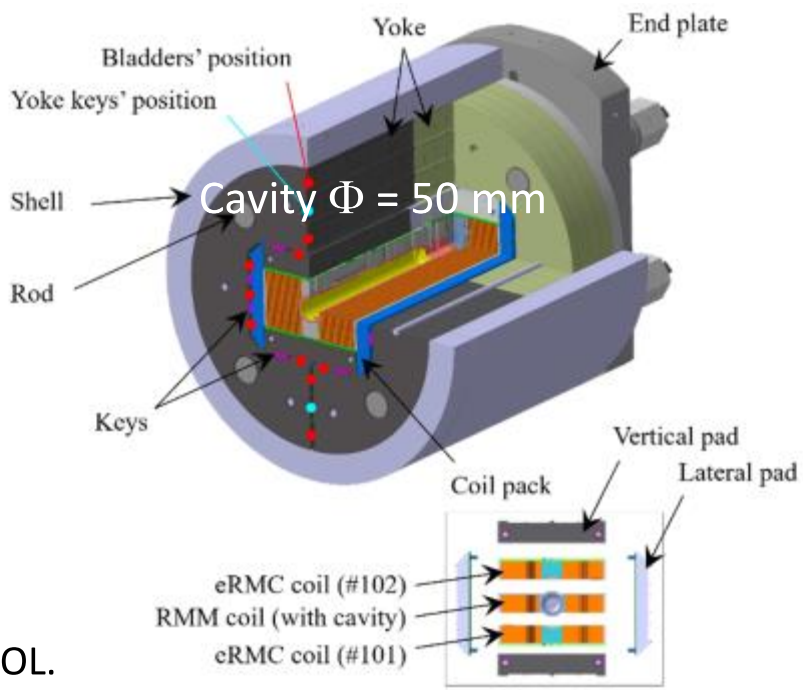
A. Zloblin et al, IEEE TRANS. ON APPL. SUPERCON., VOL. 30, NO. 4, 2020

Record field, but degradation (**11.3 T**) after cycling

U.S. MAGNET DEVELOPMENT PROGRAM

RMM, CERN,16.5 T (1.9 K), CERN

Block-coil, no flared ends


Cavity Φ = 50 mm

IEEE TRANS. ON APPL. SUPERCON., VOL. 33, NO. 5, 2023

MSC Magnets – Nb_3Sn

- **Cos-theta**
  - Collared structure (11 T)
  - Bladders & Keys (MQXF)
- **Block-coil**
  - Flared ends (Fresca 2)
- **Racetrack models**
  - Model coils with flat ends Bladders & Keys

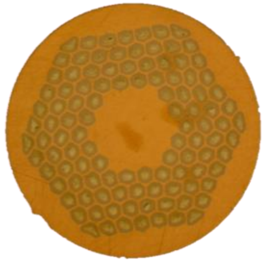
React & Wind Technology

- **Brittle conductor** and Ic(B, T,ε)
- **Brittle coils** - after reaction
- Required **stress management** of the coil during lifetime
- Higher temperature margin (Tc ~ 18.3 K) than Nb-Ti, but much more **complex technology**

Nb_3Sn for HL-LHC MQXF - Conductor

The wire

Series - RRP®
108/127



		MQXF
Φ	**mm**	**0.85**(±0.03)
Jc(12 T, 4.2 K)	**A/mm²**	**> 2450**
Ic(12 T, 4.2 K)	A	> 632
n-value (12 T, 4.2 K)	-	> 30
D*eff*	μm	< 55
Twist pitch	mm	19(±3)
Cu to non-Cu ratio	%	1.15(±0.1)
RRR	-	> 150

Total quantity procured ~ 2000 km (~ **10 tons**)

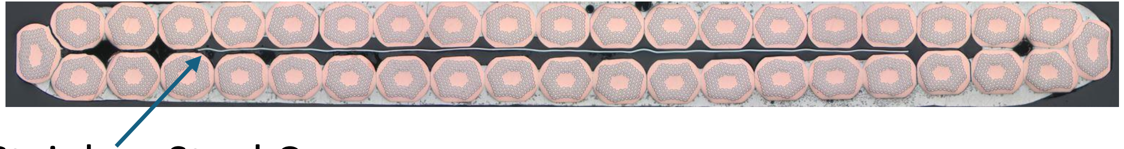
LHC ~ 1200 tons of Nb-Ti

The Rutherford cable

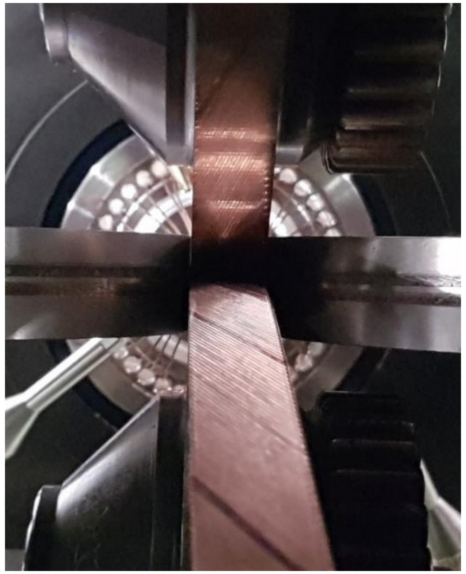
MQXF Cable, 40 Nb_3Sn wires (Φ = 0.85 mm)

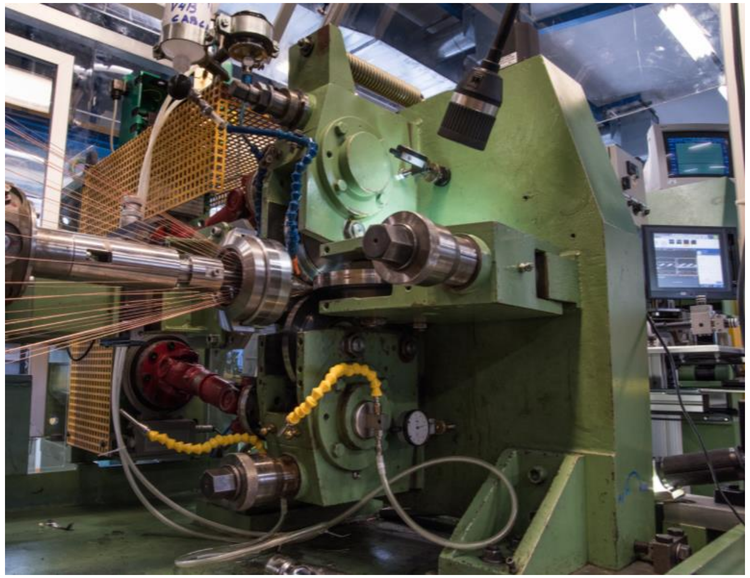
Width = 18.15 mm, mid-thickness = 1.525 mm

16.23 kA @ 11.4 T



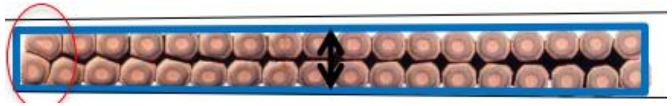
Stainless Steel Core

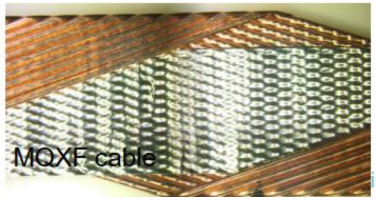


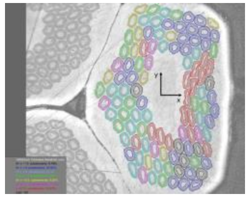


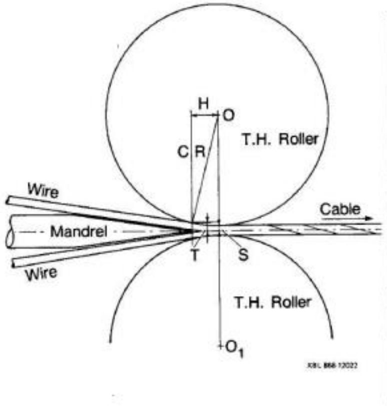
Total production at CERN ~ 40 km

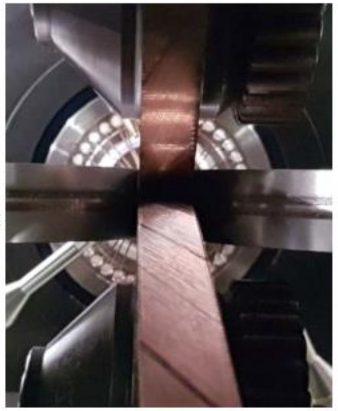
Rutherford cables











Series production for HL-LHC

- High **compaction** (Je ~ 500 A/mm^2)
- Controlled **geometrical dimensions**
- Up to **40 strands** (**60 strands** in the future)

Upgraded for HL-LHC

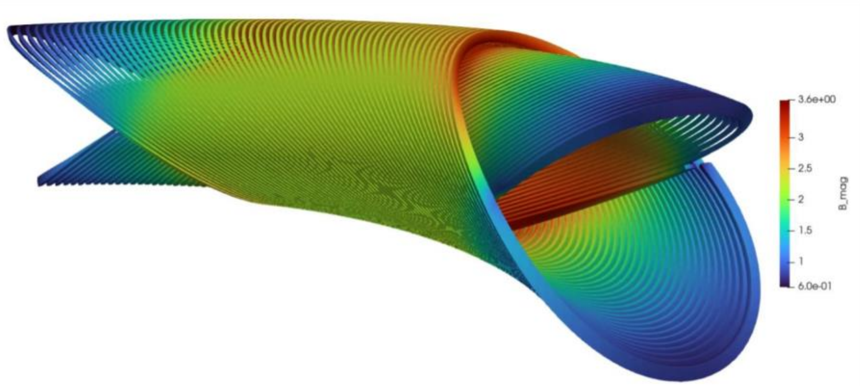
A. Ballarino

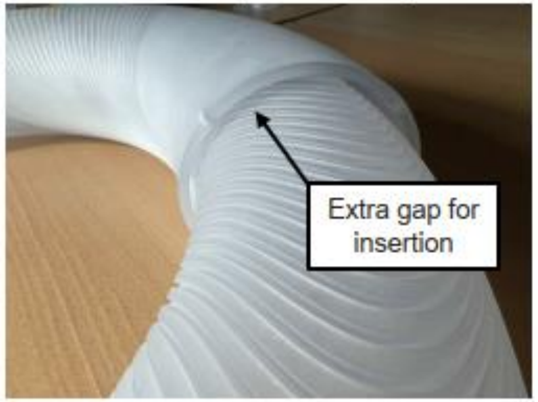
Fusillo

Curved-Canted-Cosine-Theta (Nb-Ti)

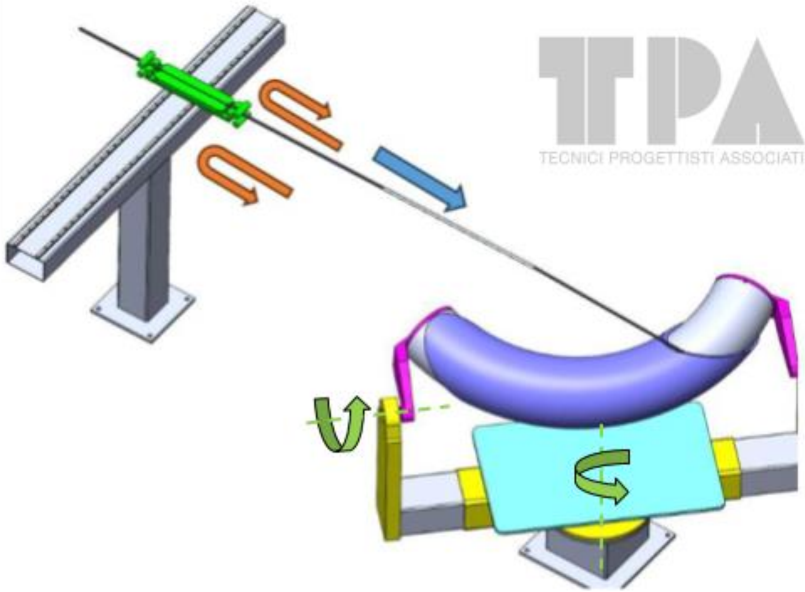
3 T (central field) **CCT dipole**, 230 mm aperture, **bent over 90° with 1 m radius**
Application in **compact accelerators** and in **ion therapy gantry** systems

Demonstrator: **3 T** (bore field), LHC Main Dipole wire: Φ = 0.825 mm

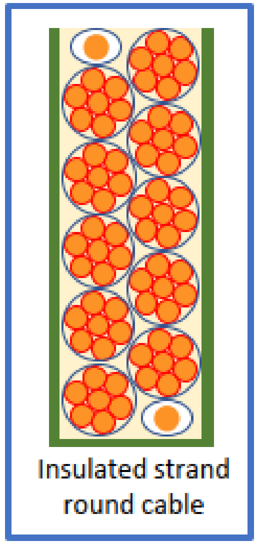




Winding machine

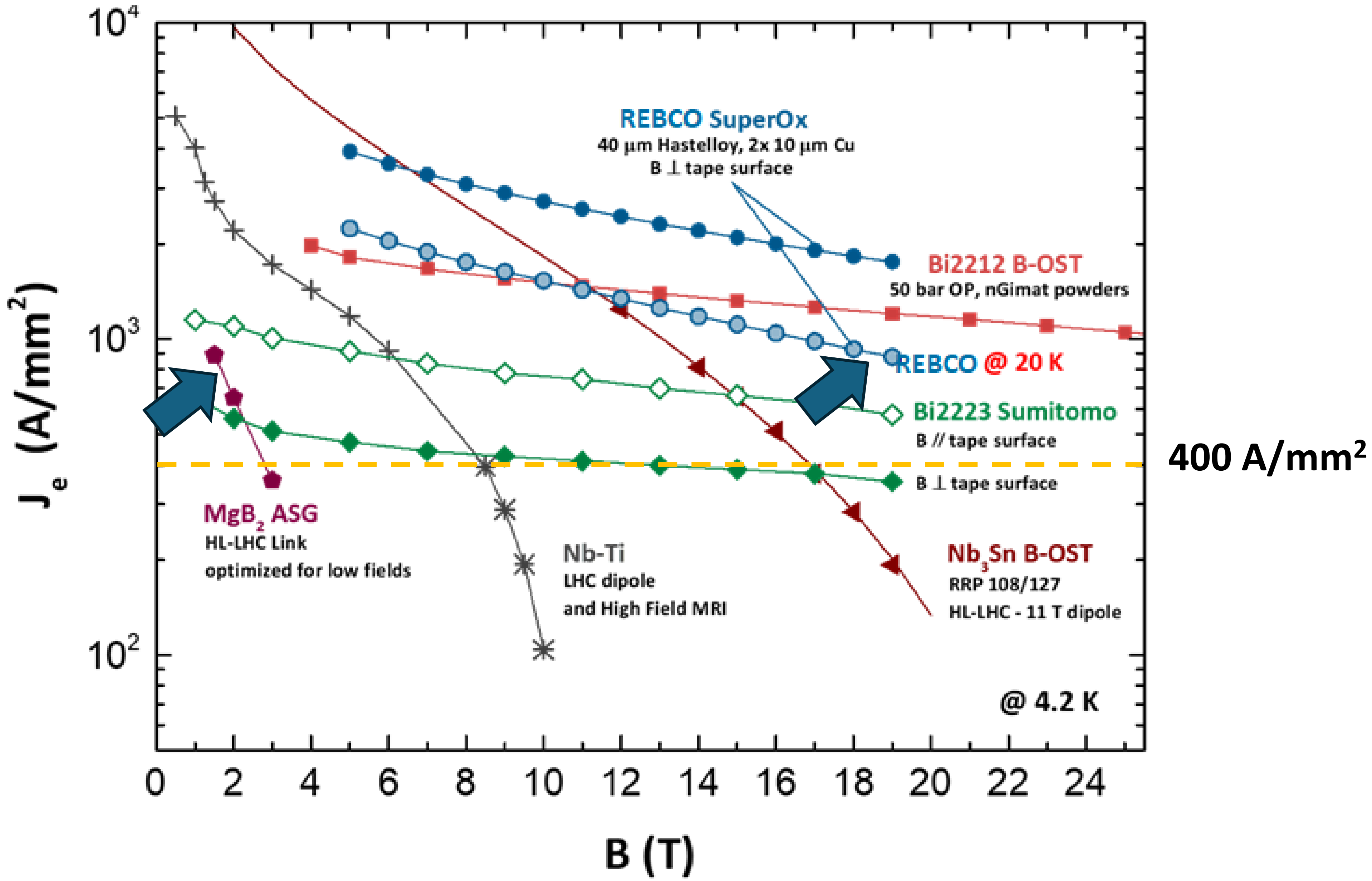


Round cable
Insulated strands



A. Haziot, https://indico.cern.ch/event/1271260/

High Temperature Superconductors



High Temperature Superconductors

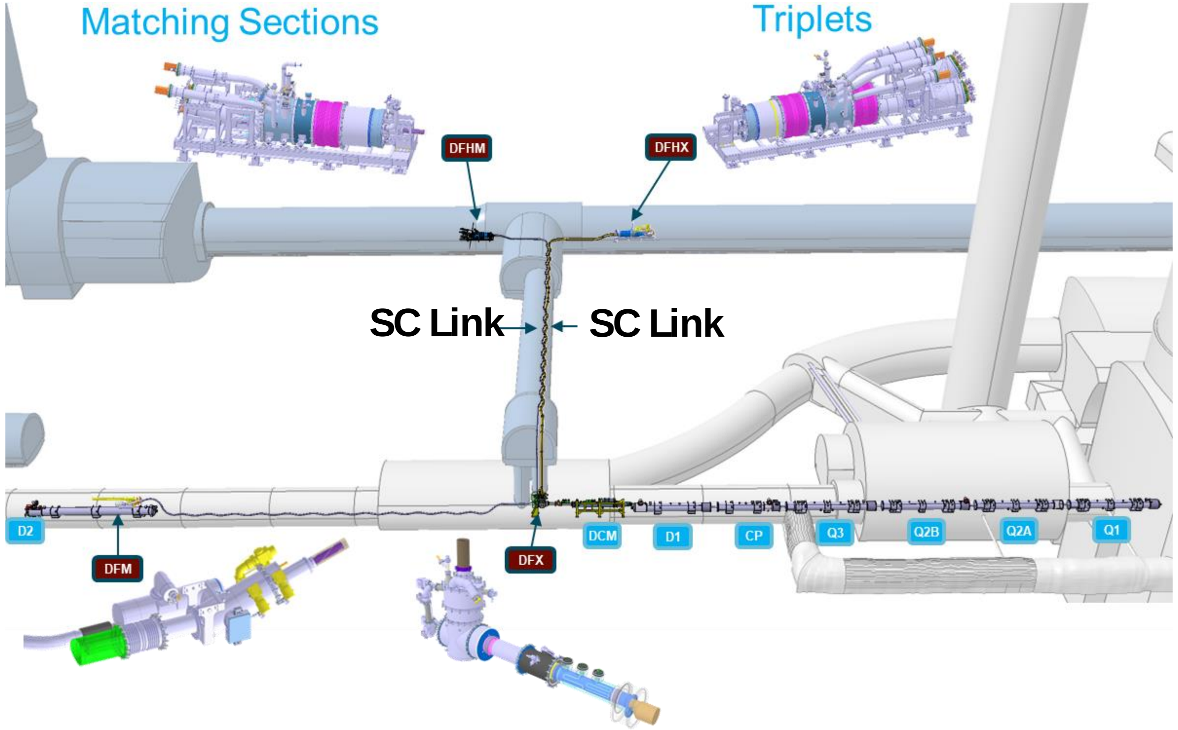
- **MgB_2**
  - **Low** and **medium field** applications (**4.2 K up to ~ 25 K**). A **sustainable alternative** to Nb-Ti
- **REBCO**
  - **Enabling technology** for **high (> 15 T) field** applications (high Jc, no training, no magneto-thermal instability, high MQE,…);
  - **Sustainable technology** for **low and medium field** applications at **higher temperatures** (above liquid helium and up to liquid nitrogen). Temperature margin encourages indirect cooling of systems

HTS Today at MSC

MgB_2 and **REBCO** for **High Luminosity LHC:** established and industrialized technologies

|**120**| **kA DC**, **MgB_2 @ 25 K**, **REBCO @ 60**, **GHe Cooling, Flexible** simplified (no active shield) **lines**

LHC Underground



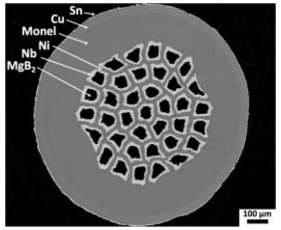
System tested in SM-18

MgB_2 Wire and MgB_2 cabling - Industrialized

MgB_2 wire: development with industry (ASG). **React & Wind** Technology

MgB_2 cable(s): developed at CERN and then industrialized (ICAS)

ASG SUPERCONDUCTORS



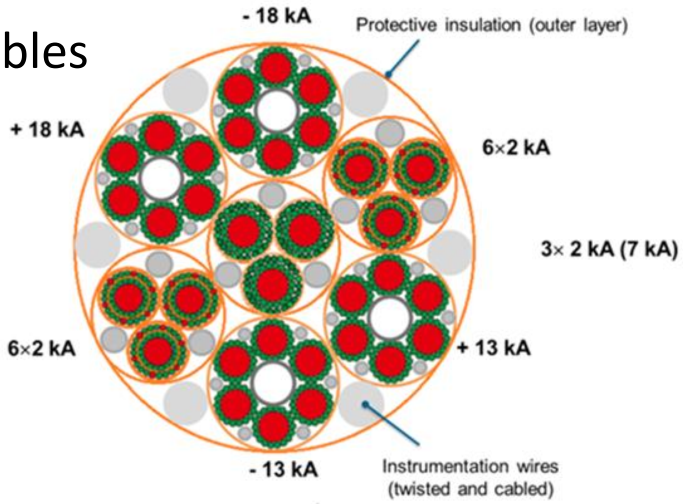
Φ= 1 mm
37 MgB_2 filaments
Tw = 100 mm
Ic(25 K, 0.5 T) ≥ 320 A

1500 km of wire procured

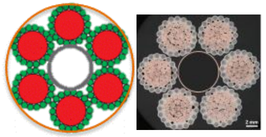
Unit lengths up to ~ 3.5 km

|120| kA @ 25 K, Φ~90 mm

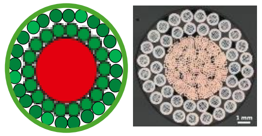
19 Cables



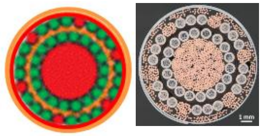
18 kA @ 25 K
Φ~24 mm



7 kA @ 25 K
Φ~10.5 mm



± 2 kA @ 25 K
Φ~11.5 mm

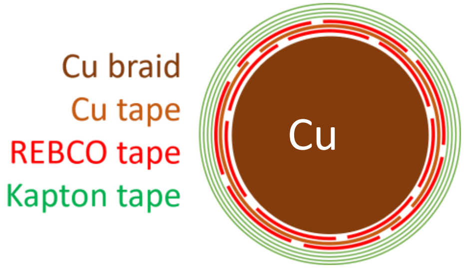


18 kA @ 25 K, Φ~24 mm

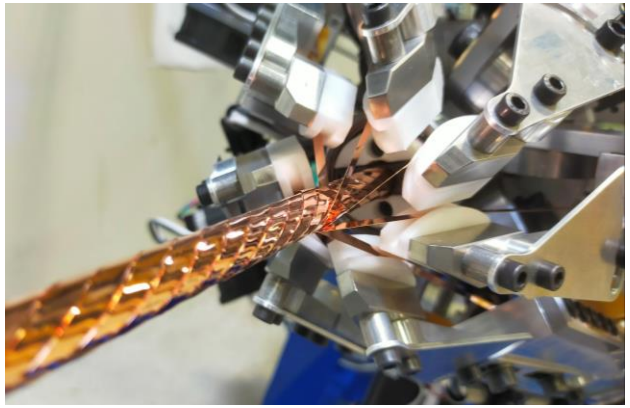
REBCO Cables and REBCO cabling at MSC

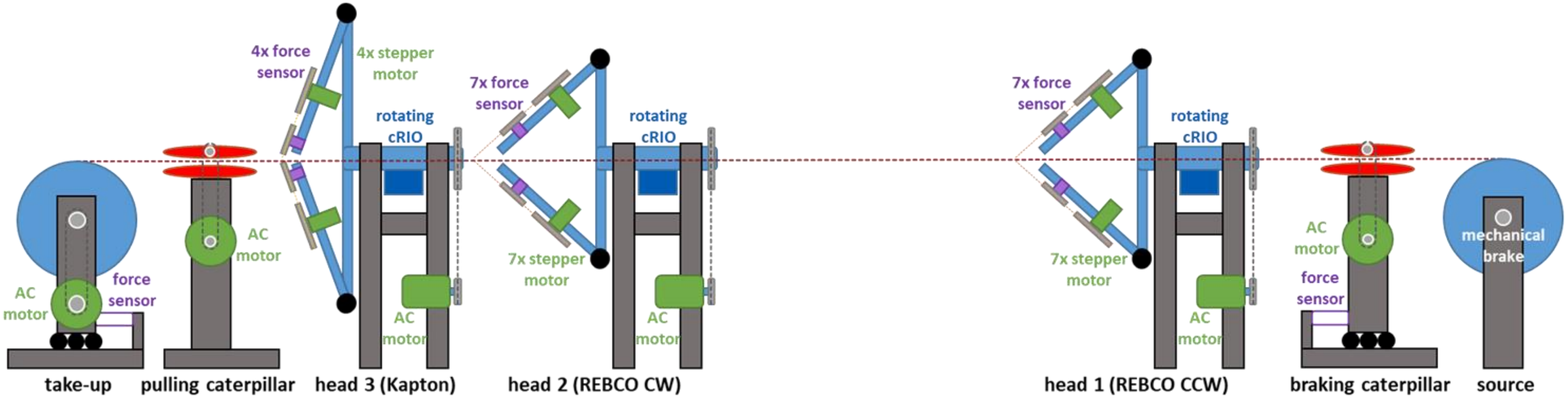
2 kA @ 77 K, s.f.
22.4 kA @ 4.2 K, s.f.

Round and flexible multi-layer REBCO cable. Reel-to-reel. Polyimide insulation

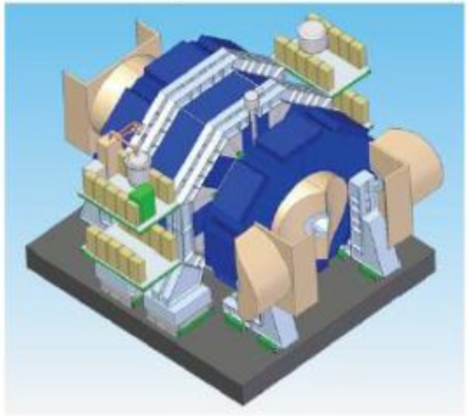


Standard cable and
Lighter cable (240 g/m, |4| kA @ 70 K)



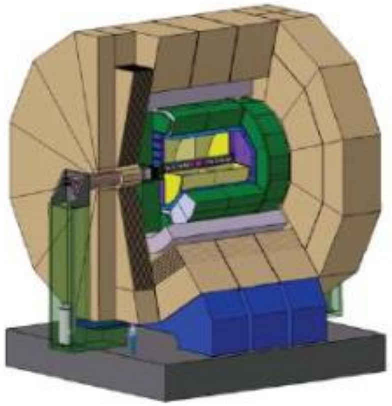


Superconducting Transmission in "Pull-push" experiments

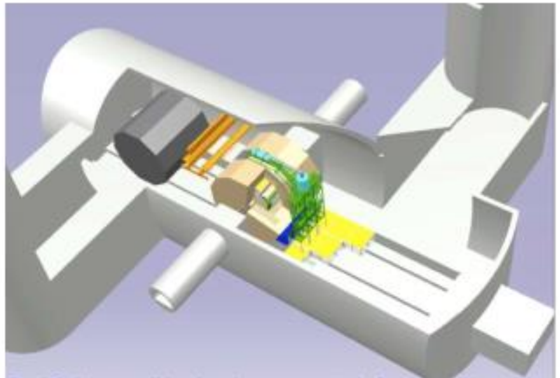


SiD with Platform

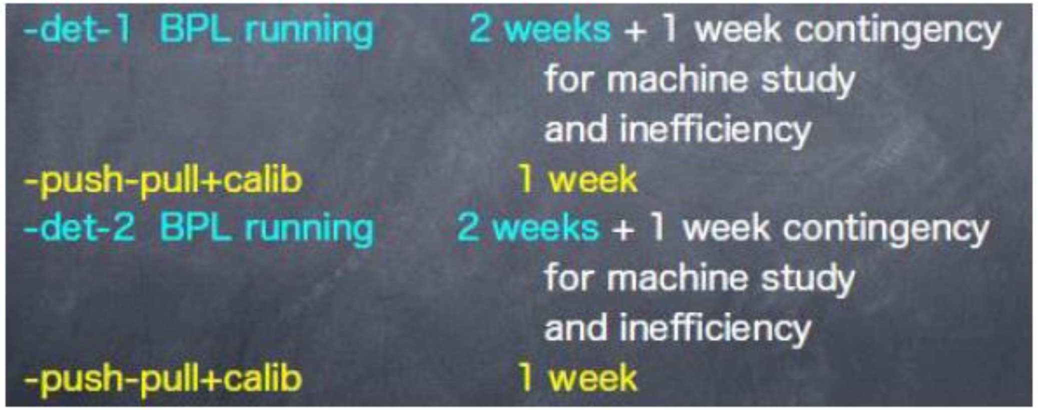
ILC



ILD with Platform



The ILD detector will be placed on a concrete platform to avoid possible damages due to non-synchronised movements or from vibrations during push-pull and also to ease internal alignment challenges. (ILD-LOI)



-det-1 BPL running	2 weeks + 1 week contingency for machine study and inefficiency
-push-pull+calib	1 week
-det-2 BPL running	2 weeks + 1 week contingency for machine study and inefficiency
-push-pull+calib	1 week

Proposed running schedule (ILC) based on an 8-week cycle

- In CLIC/ILC it is foreseen to install **2 experiments** that **share the single interaction point** on a "pull-push" basis

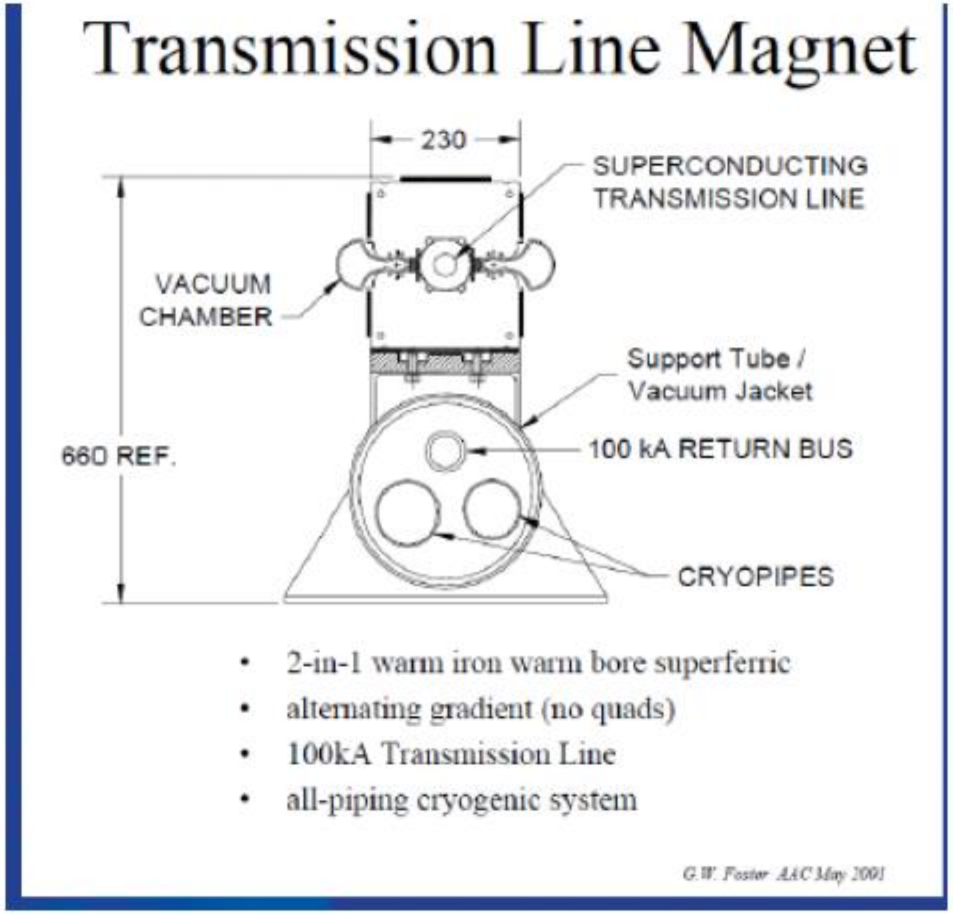
- There can be an advantage to **keep cryogenics and busbars connected** for such frequent movements.
  This could be achieved using semi-flexible MgB_2 and/or REBCO based transmission lines of the type developed for HL-LHC

Transmission Line HTS Magnets

The Pipetron

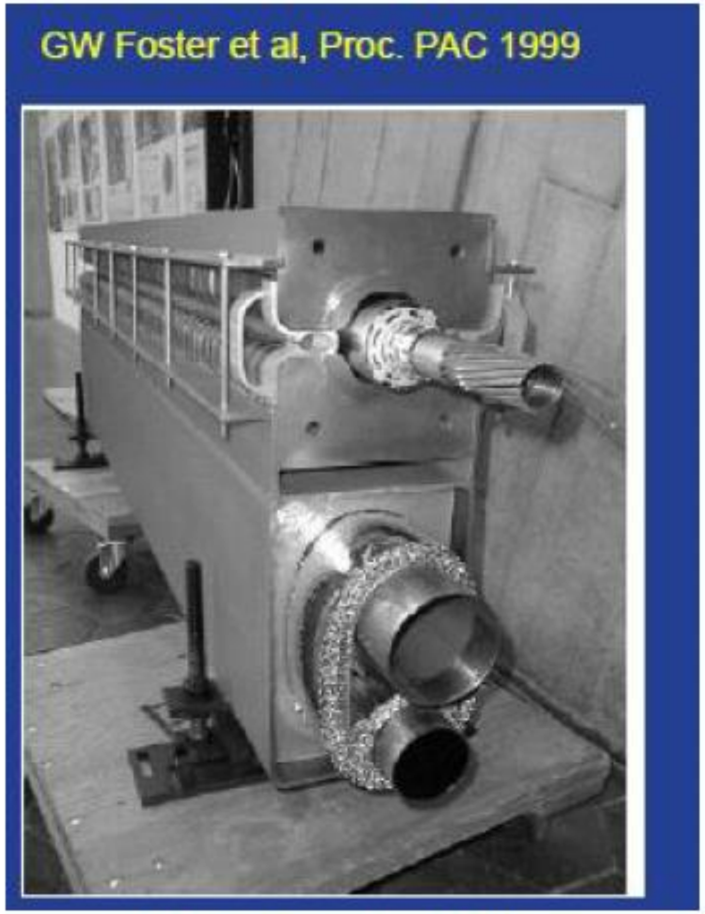
Combined-function lattice magnet for a collider with a very large tunnel

Nb-Ti, 100 kA @ 6.5 K and 1 T, InvarTM Transmission Line piping (Φ ≥ 80 mm)


Transmission Line Magnet

- 2-in-1 warm iron warm bore superferric
- alternating gradient (no quads)
- 100kA Transmission Line
- all-piping cryogenic system

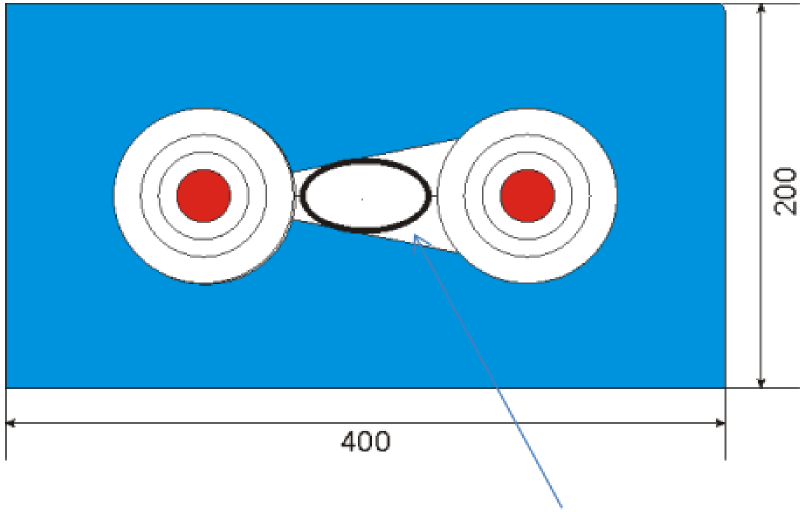
G.W. Foster AAC May 2001

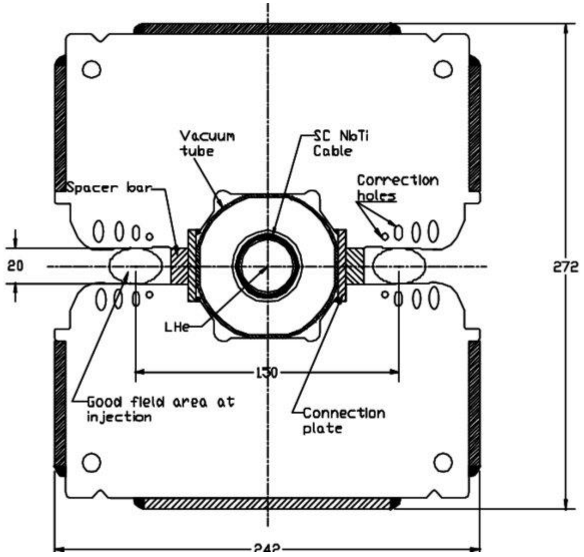

GW Foster et al, Proc. PAC 1999

W. Foster, H. Piekarz

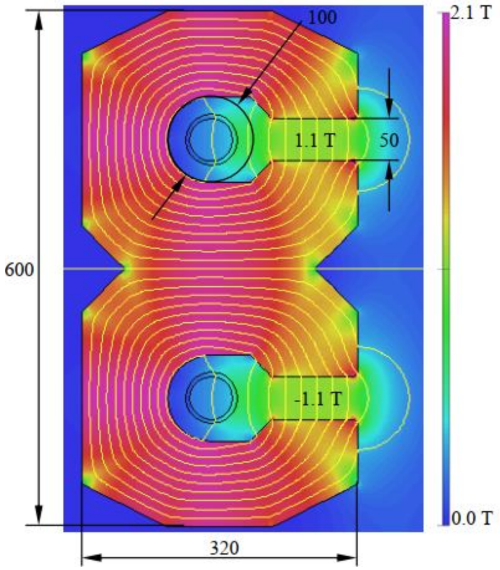
Transmission Line HTS Magnets

- Compact combined function **MgB_2** (up to ~ 25 K) or **REBCO** (up to ~ 77 K) **transmission line magnets**
- Ex: magnets for injectors for proton machines (up to ~ 2 T)

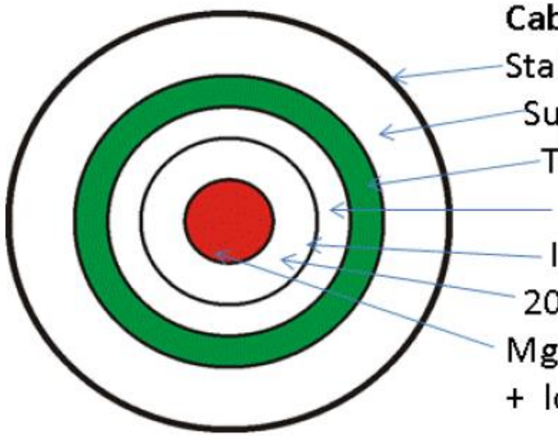




FERMILAB-CONF-05-392-TD
20 TeV Stage I, VLHC
2 T, Fermilab, LHe, Nb-Ti, 87.5 kA
Vertical pole aperture: 20 mm



50 kA, 100 mm cryostat
2-in-1 Dipole, Superferric
https://doi.org/10.18429/JACoW-IPAC2014-TUOCB01

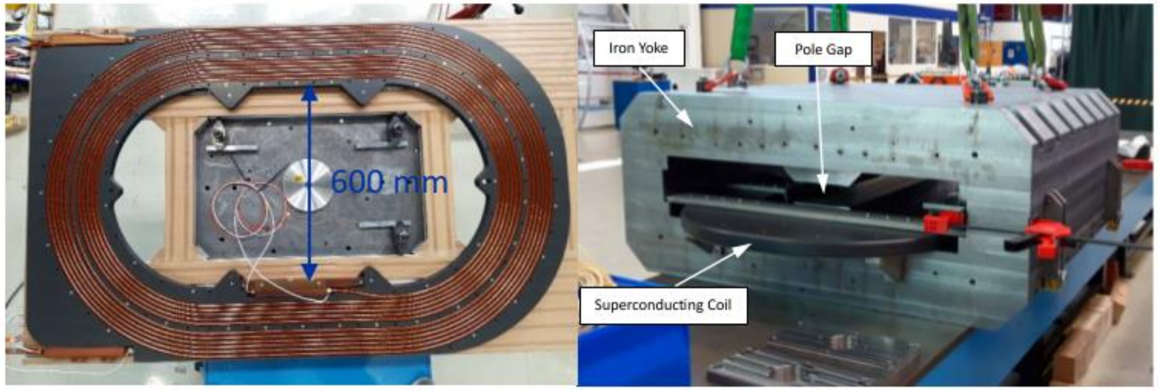


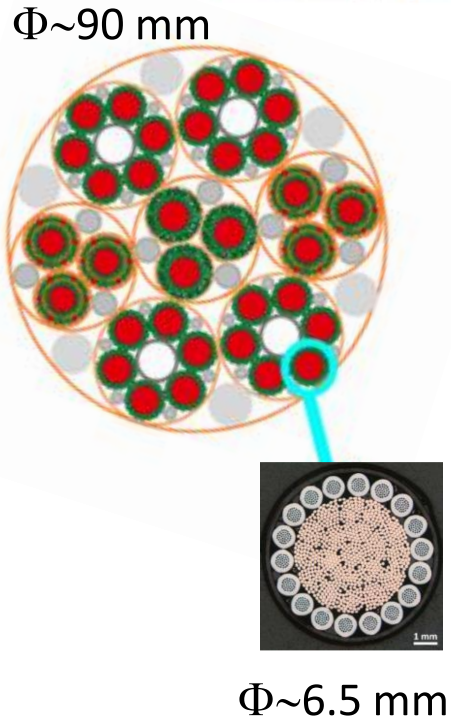
Cable in cryostat (notional)
Stainless steel envelope, Ø 100
Superinsulation + vacuum
Twin-walled gas-cooled heat screen
Insulating vacuum
Invar tube, Ø 40
20 K He gas
MgB_2 + Cu cable, Ø 20
+ low loss supports to centre the cable

Superferric HTS Magnets – MgB_2

- **MgB_2 Superferric Dipole**
  - Technology developed for the Superconducting Link of HL-LHC
  - MgB_2 cable suitable for **React & Wind applications**
- **H-Type Iron yoke** with **62** mm gap
- **Double pancake** coil in Al alloy former. Electrically insulated MgB_2 cable (85 m) inside a groove in the former
- Successfully measured at **4.5 K (1.95** 5 kA) and at up to ~ **20 K**
- Technology available also for a **REB** version (for operation at higher temperatures)

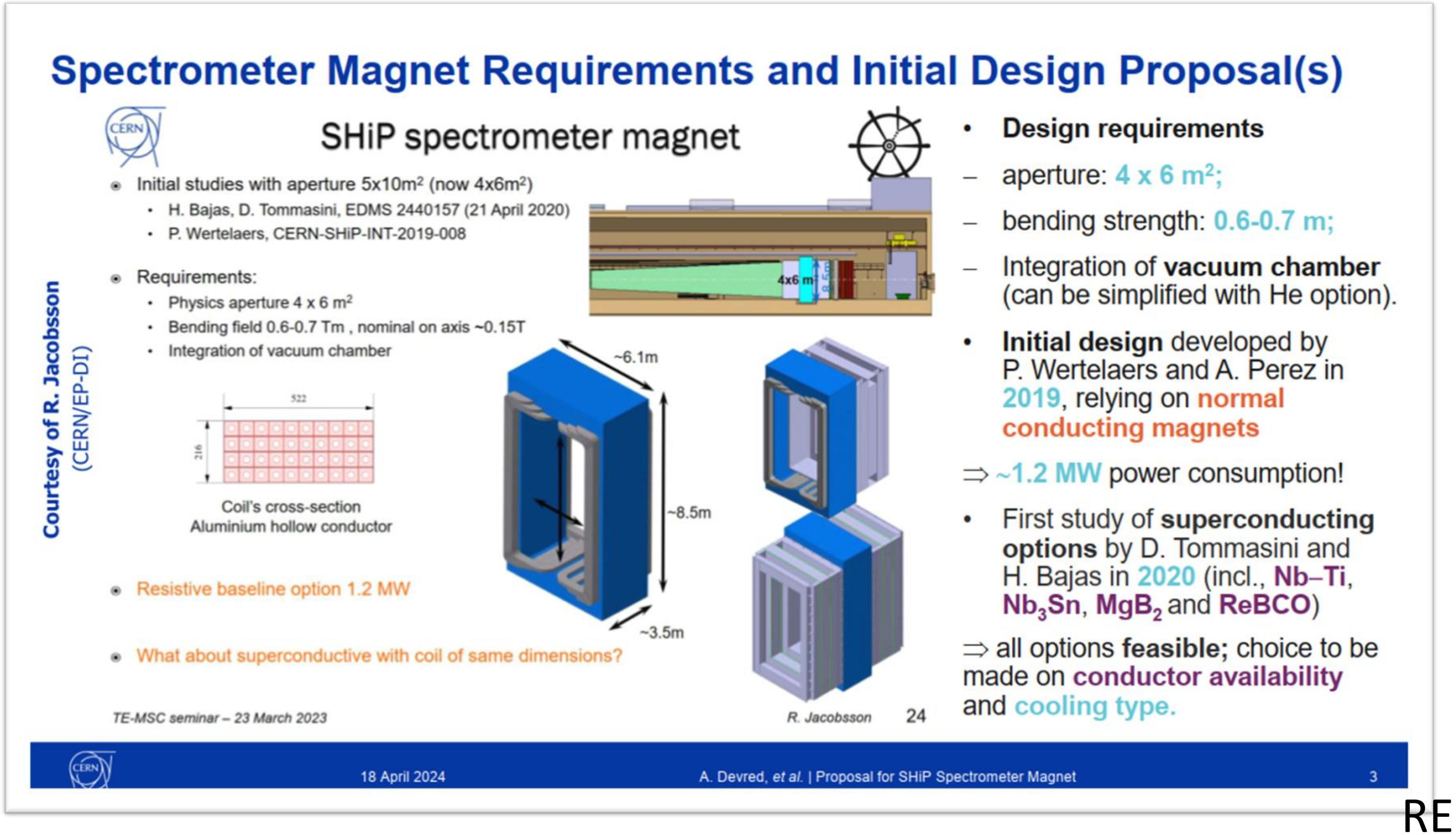
EESD Demonstrator (MgB_2)





Spectrometer Magnets

- **Large ampere-turns, large aperture**
  - Lower field: MgB_2
  - High(er) field: REBCO
- **SHiP – Superconducting Dipole**



Spectrometer Magnet Requirements and Initial Design Proposal(s)

SHiP spectrometer magnet

- Initial studies with aperture 5x10m^2 (now 4x6m^2)
  - H. Bajas, D. Tommasini, EDMS 2440157 (21 April 2020)
  - P. Wertelaers, CERN-SHiP-INT-2019-008
- Requirements:
  - Physics aperture 4 x 6 m^2
  - Bending field 0.6-0.7 Tm , nominal on axis ~0.15T
  - Integration of vacuum chamber

Coil's cross-section
Aluminium hollow conductor

- Resistive baseline option 1.2 MW
- What about superconductive with coil of same dimensions?

TE-MSC seminar – 23 March 2023

R. Jacobsson 24

Courtesy of R. Jacobsson (CERN/EP-DI)

- **Design requirements**
  - aperture: 4 x 6 m^2;
  - bending strength: 0.6-0.7 m;
  - Integration of **vacuum chamber** (can be simplified with He option).
- **Initial design** developed by P. Wertelaers and A. Perez in 2019, relying on **normal conducting magnets**

⇒ ~1.2 MW power consumption!

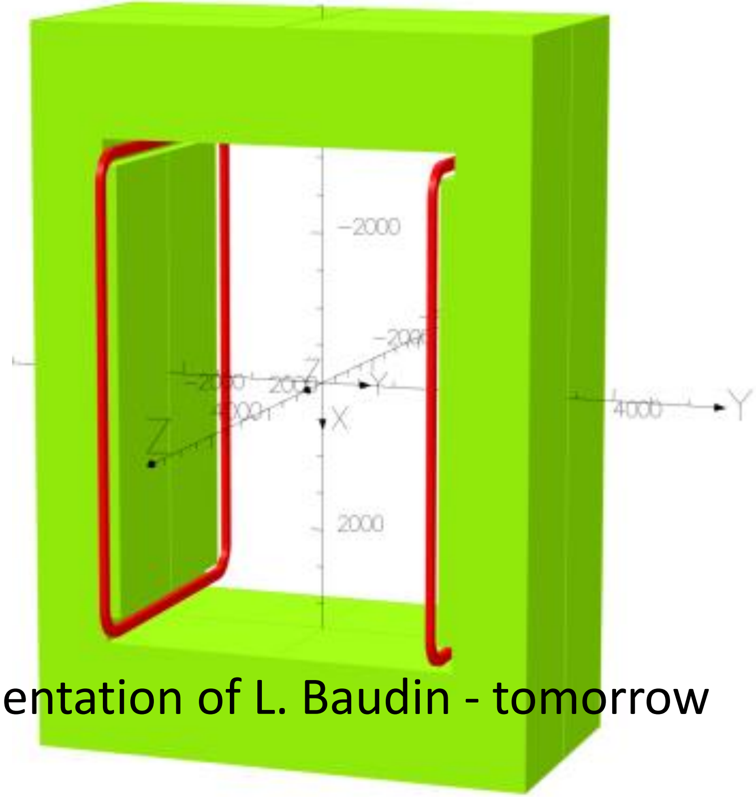
- First study of **superconducting options** by D. Tommasini and H. Bajas in 2020 (incl., **Nb–Ti**, **Nb_3Sn**, **MgB_2** and **ReBCO**)

⇒ all options **feasible;** choice to be made on **conductor availability** and **cooling type.**

18 April 2024 A. Devred, *et al.* | Proposal for SHiP Spectrometer Magnet 3

MgB_2 Technology developed for HL-LHC Superconducting Link

Superferric, H-type iron yoke
Two symmetric racetrack coils
Double-pancake, MgB_2 cable (Φ=6.5 mm)



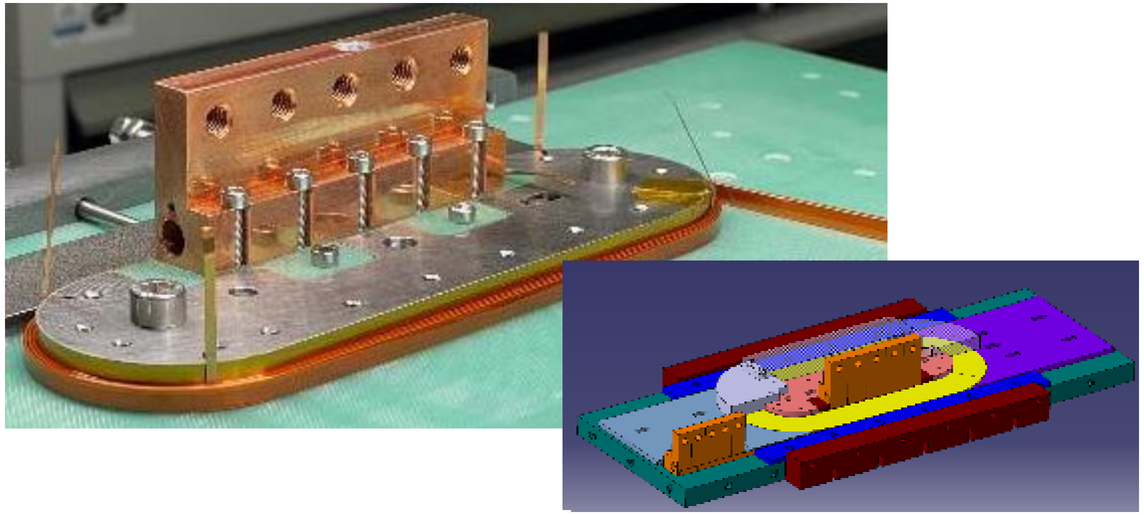
See presentation of L. Baudin - tomorrow

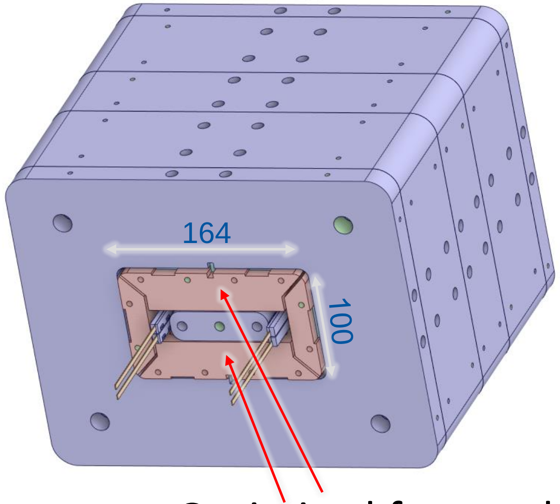
REBCO racetrack coils would also be an option

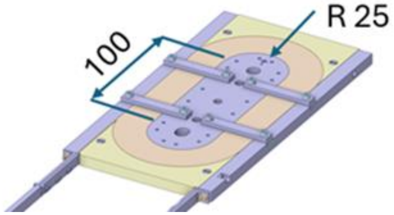
REBCO Racetrack Coils

Modular approach, Intermediate milestones

- **Racetrack Model Program**
  - **Single Racetrack Demonstrators**. Fast throughput. Development of winding techniques, qualification of different REBCO cables (as from Q2 2024)
  - **Double Racetrack** Demonstrators (as from Q3 2024)
- **Mechanical structure for Common Coil Demonstrators (CCD):**
  - **Two Double Racetracks (3 T at 4.5 K)**
  - **Four Double Racetracks (5 T at 4.5 K)**
  - **Six Double Racetracks (10 T at 4.5 K)**



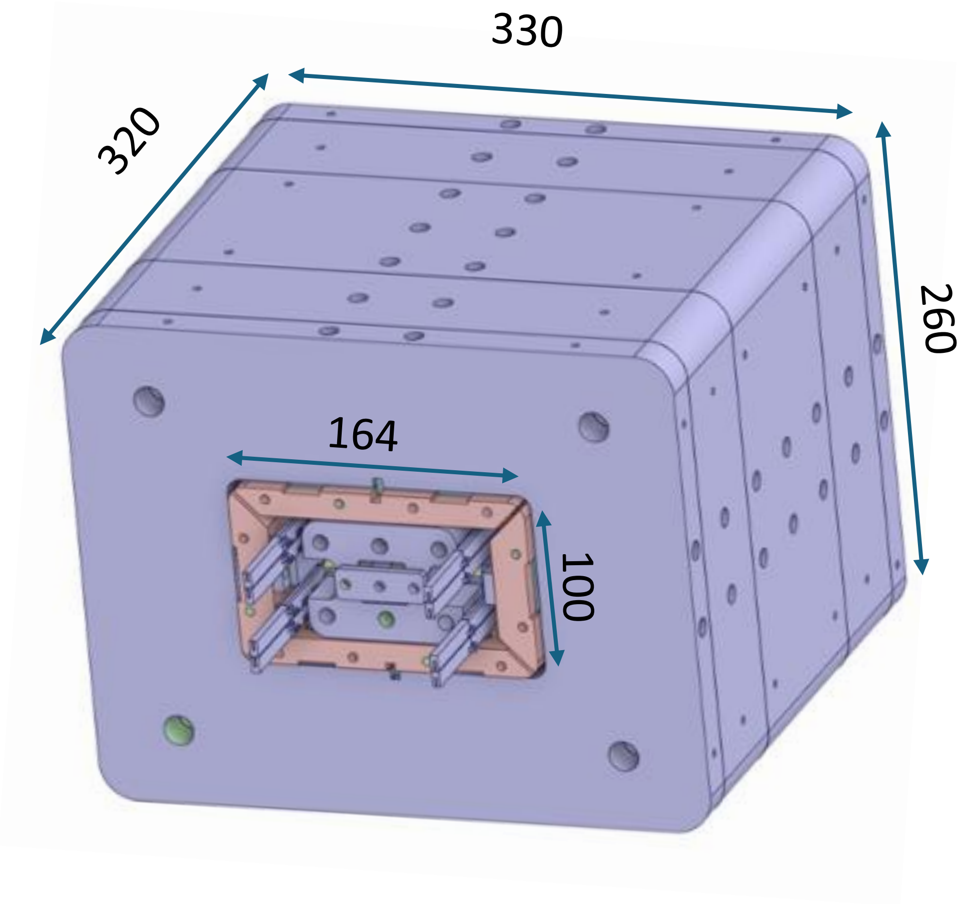


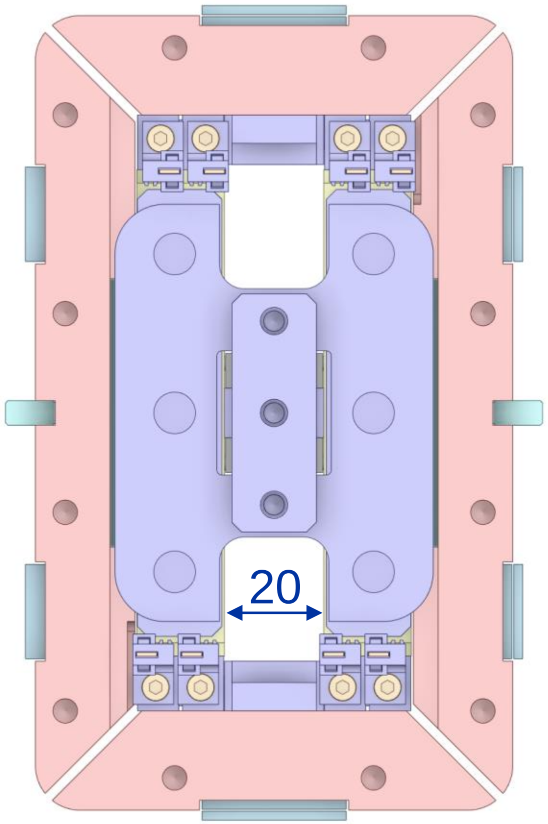


Optimized for number of racetracks

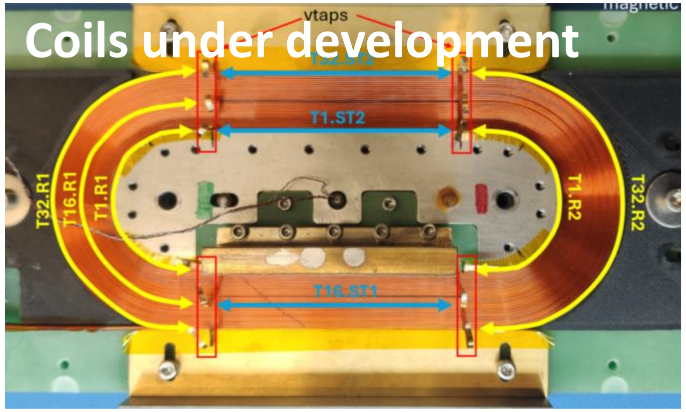
Development of electrically insulated REBCO cables

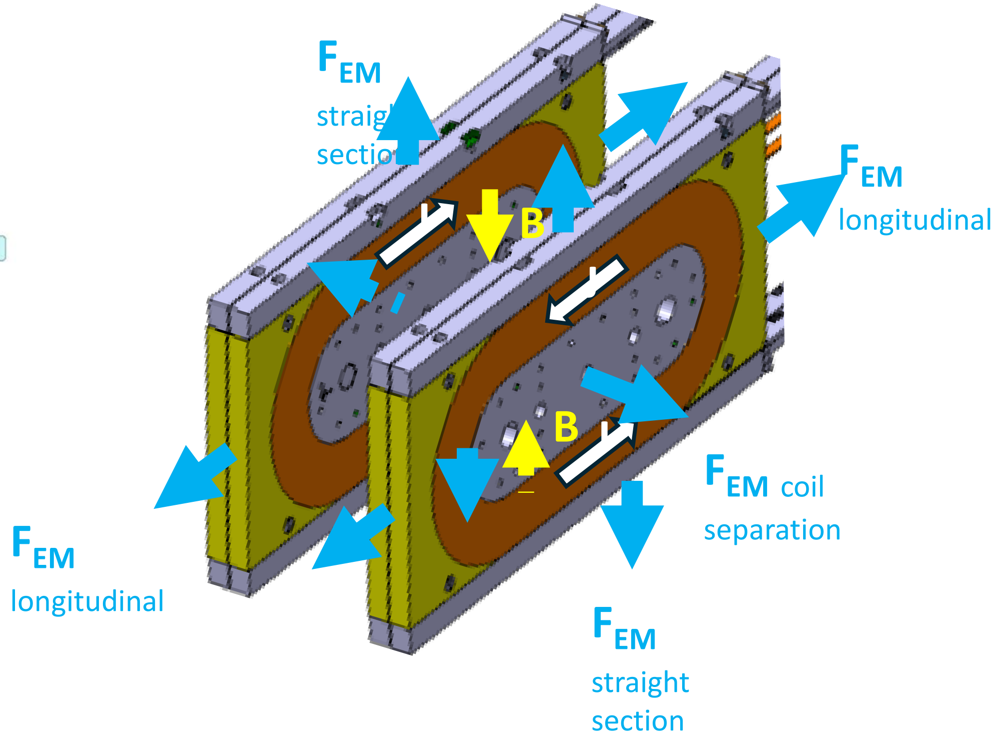
REBCO Common Coil Demo





Weight ~ 300 kg





Moving toward higher temperatures

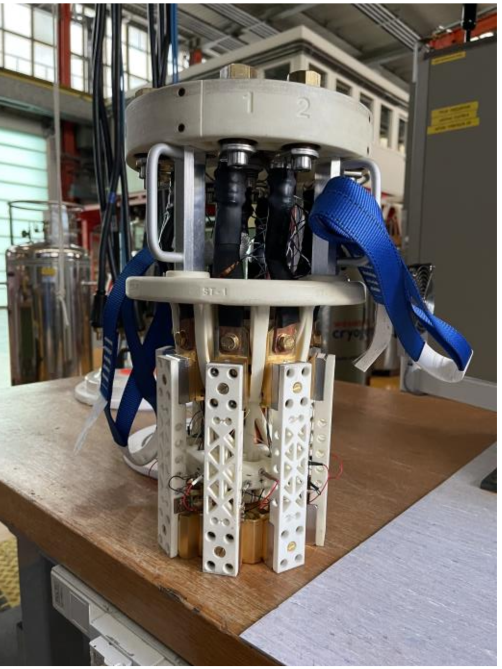
Coils will be measured also at higher temperatures

For **three double racetracks**: **Bbore = 10 T @ 4.5 K**, Bpeak = 12.7 T @ 4.5, ~ 7.7 T **@ 20 K**)

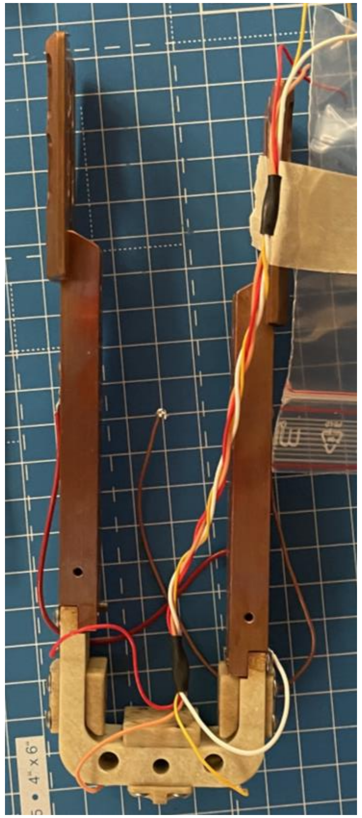
REBCO Racetrack Coils

- We can produce **round REBCO cables** (n-layers) in long lengths. This cable is suitable, for instance, for use in CCT magnets
- We are developing **flat**, **high Je**, **REBCO cables** for use in demonstrator **racetrack coils** and **common coil dipoles,** as well as in other dipole geometries. We are presently working with stack of REBCO tapes – electrically insulated. Other geometries under study. **Magnet design relies on availability of long optimized cables**
- We test cables also in the configuration of small **solenoids**
- Magnets in **haloscopes for axion dark matter search experiments**, e.g. BabyIAXO: **common-coil layout**, with two flat racetrack coils of 10 m length spaced by 0.8 m. Al-stabilized Rutherford Nb-Ti cable, 2 T in the bores. HTS could be an option

Measurement of HTS Conductor

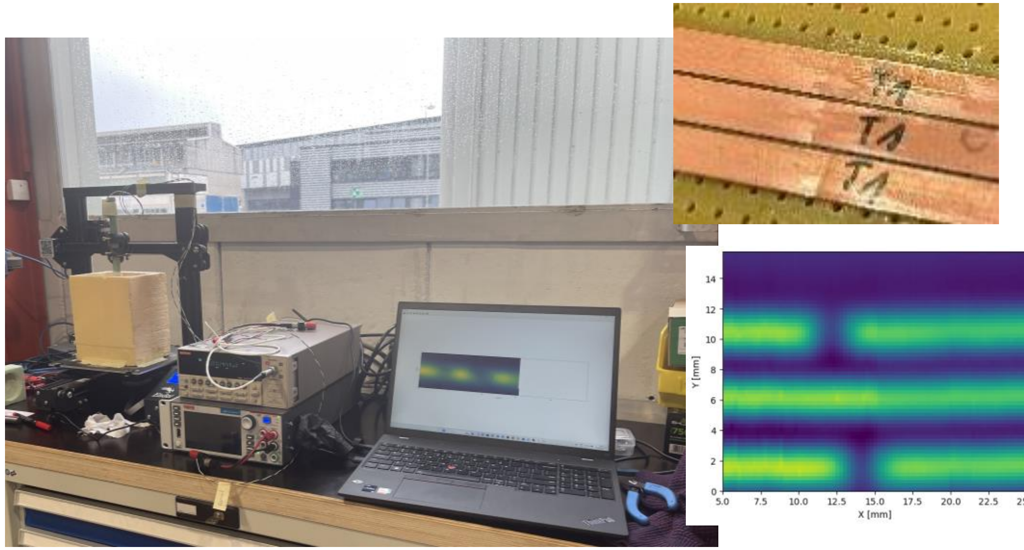


Critical current
77 K at s.f.
I_c and lap-joint

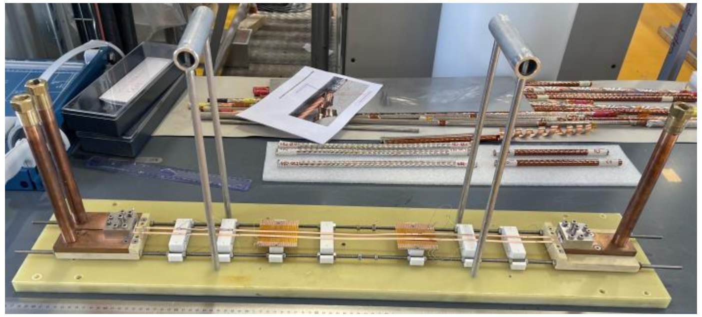


Critical current
U-shape, B⊥
Up to15 T, 4.2 K

Reel-to-reel
Critical current
200 m/h
Self-field and 1 T
From ~ 67 to 77 K



Vibrating sample
magnetometer
0-10 T, 4.2–80 K



Extracted strand testing
77 K, self-field

PAUL SCHERRER INSTITUT
PSI

cea

CNR

SPIN

KIT
Karlsruher Institut für Technologie

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

INFN
Istituto Nazionale di Fisica Nucleare

ETH zürich

University of Twente
The Netherlands

TU BERGAKADEMIE FREIBERG
TECHNISCHE UNIVERSITÄT
BERGAKADEMIE FREIBERG
Die Ressourcenuniversität. Seit 1765.

UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES

CERN

University of
Southampton

TU
WIEN
TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

We also work with many key collaborators !

Thanks for your attention !