Workshop for Accelerator Magnets – HTS 5

April 2019

HTS activities at DACM

Thibault Lécrevisse on behalf of DACM HTS Team
Thibault.lecrevisse@cea.fr

People involved in HTS activities

P. Fazilleau: lead of HTS R&D activities, WP10 Eucard2 and NOUGAT coordinator
M. Durante: EuCARD and EuCARD2 cos θ project leader
C. Lorin: EuCARD2 cos θ design and follow-up, HTS Qpole
T. Lécrevisse: Cern-CEA collaboration WP HTS leader and HTS R&D
G. Dilasser: Junior expert in screening current and numerical modelling for HTS

Accelerator magnets

High Field and R&D


M. Durante


C. Lorin


P. Fazilleau


T. Lécrevisse


G. Dilasser

Technical support


R. Godon


E. Pepinter


Y. Rabti


S. Samson


R. Correia-Machado


M. Vaille :
Master Thesis
on HTS quadrupoles


I. Le Perff:
Internship
on *I windings


M. Alharake:
PhD on *magneto-mechanics of a 40-45 T HTS magnet*

Outline

HTS Roadmap

HTS Accelerator Magnets

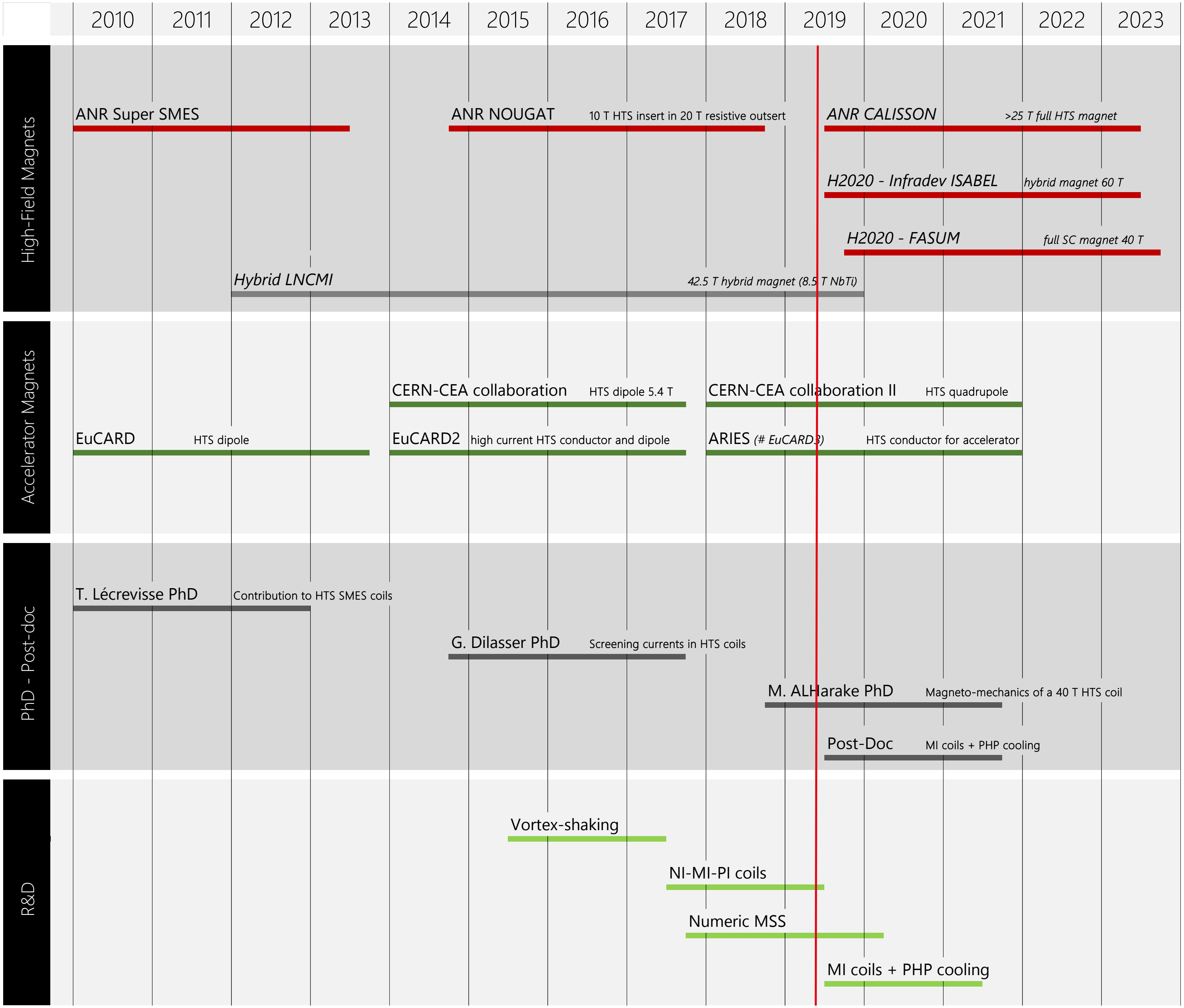
- EuCARD
- EuCARD2

HTS High-Field Magnets

- NOUGAT insert

HTS R&D activities

HTS Roadmap



2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

High-Field Magnets

ANR Super SMES

ANR NOUGAT 10 T HTS insert in 20 T resistive outsert

ANR CALISSON >25 T full HTS magnet

H2020 - Infradev ISABEL hybrid magnet 60 T

H2020 - FASUM full SC magnet 40 T

Hybrid LNCMI 42.5 T hybrid magnet (8.5 T NbTi)

Accelerator Magnets

CERN-CEA collaboration HTS dipole 5.4 T

CERN-CEA collaboration II HTS quadrupole

EuCARD HTS dipole

EuCARD2 high current HTS conductor and dipole

ARIES *(# EuCARD3)* HTS conductor for accelerator

PhD - Post-doc

T. Lécrevisse PhD Contribution to HTS SMES coils

G. Dilasser PhD Screening currents in HTS coils

M. ALHarake PhD Magneto-mechanics of a 40 T HTS coil

Post-Doc MI coils + PHP cooling

R&D

Vortex-shaking

NI-MI-PI coils

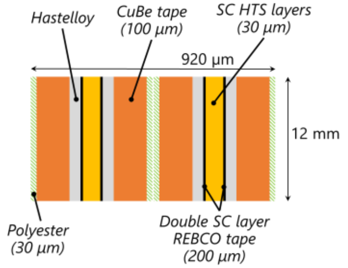
Numeric MSS

MI coils + PHP cooling

Accelerator magnets EuCARD (M. Durante & P. Fazilleau)

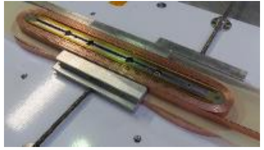
EuCARD 6 T HTS insert

- The EuCARD High Temperature Superconductor (HTS) insert is a **dipole magnet** designed to **operate at 18 T** within the FRESCA2 test facility.
- Tests in SF : done in 2017 → **5.4T** reached @ 4.2 K with 3.2 KA
- Ongoing work : adaptation from standalone to insert configuration
- Target : Test the magnet in FRESCA2 test facility by end of 2019.

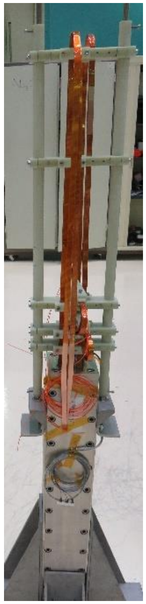


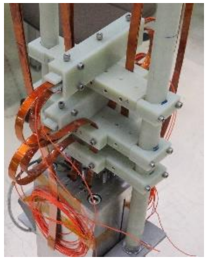
Magnet conductor (SP)

Magnet winding



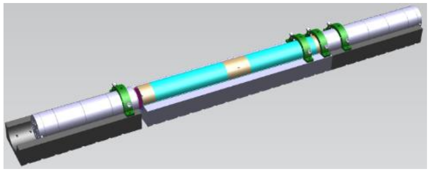
Standalone magnet





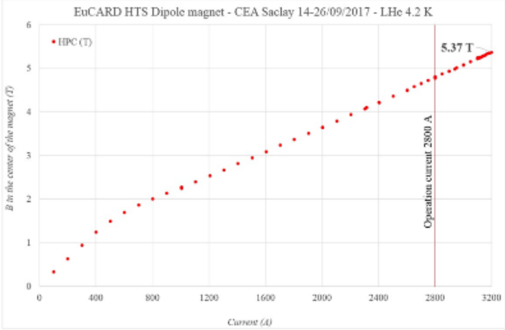
Demountable structure and connections

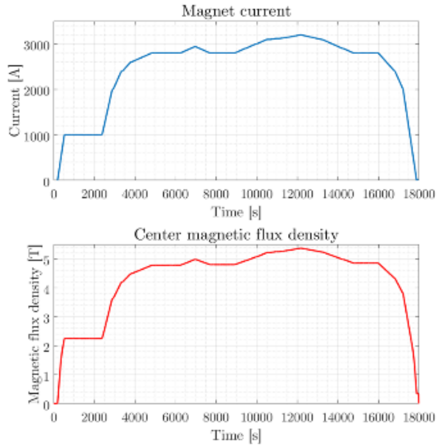
Ongoing work



Tools for tube insertion

1 cable current measurement calibration



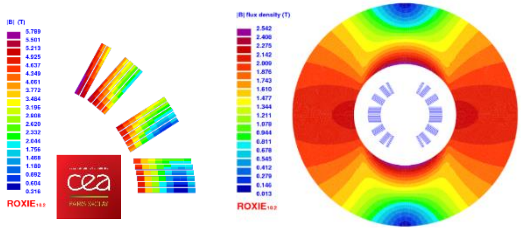


Standalone tests at 4.2 K

Accelerator magnets EuCARD2 (M. Durante & C. Lorin)

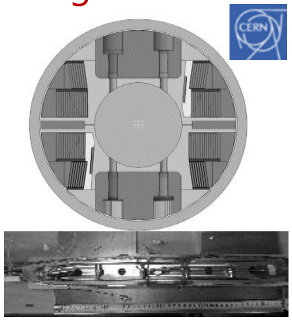
Design, Manufacture and test **a first accelerator quality, small prototype, 5 T dipole**

Cos theta



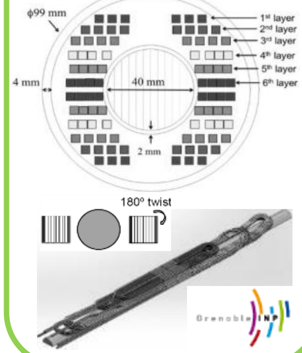
C. Lorin

Baseline design
Aligned blocks



FM0.4 subsize coil
Successfully test : 12 kA

Stacked tapes
transposition



Design parameters (**SuperPower** Cable)

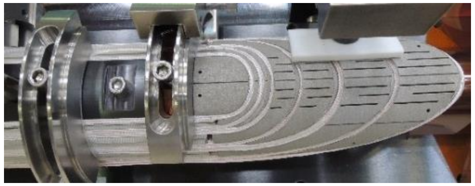
Layout	Unit	Cosϑ B
Iop	kA	10.06
Bop	T	5
Bpeak	T	5.8
Ic	kA	15.2
LL margin	(%)	34
T margin	K	30
Sd. inductance	mH/m	0.73
coil inner radius	mm	24
yoke inner radius	mm	50
yoke outer radius	mm	110
Nb. of turns	-	17
Unit len. of cond.	m	24

Ongoing work : magnet fabrication (**SuperOx** cable)

Tests done on dummy cable

Final magnet fabrication

Roebel cable with insulated copper wire



Target : **magnet ready for test during summer 2019**

HTS High-Field Magnets

NouGAT insert : a collaboration work

NOUvelle **G**énération d'**A**imants pour la production de **T**eslas

 # New generation of magnets for production of Teslas

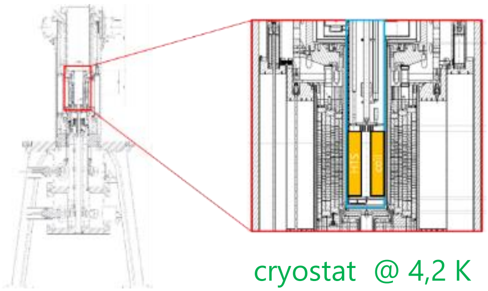
Collaboration : **CEA, LNCMI and Grenoble univ.**

Goal : design and realize a **High-Field 10 T HTS insert working @ 4.2 K**

- HTS conductor (ReBCO)
- Design, stability and protection (CEA)

Constraints: HTS insert operation in external 20 T

- Design and tests at 30 T (central field)
- max OD 125 mm



20 MW
20 T / 170 mm

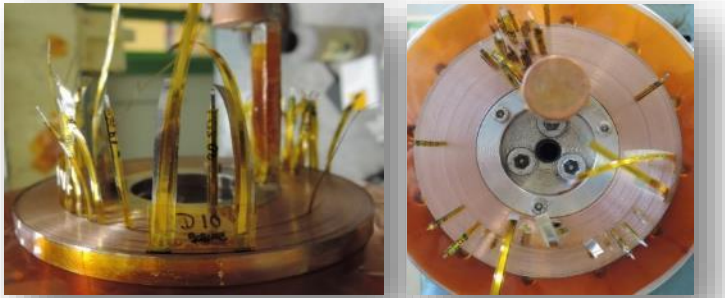
cryostat @ 4,2 K
Max. OD_{coil}: 125 mm
L_{max} : 220 mm

- Double pancakes with inner joints design,
- ReBCO 2G HTS tape / 6 mm width,
- **MI winding** *'Metal as Insulation'* = co-winding of the HTS tape with a stainless steel tape: compactness, reduction of charge time constant, mechanical reinforcement, self protected,
- Suppliers : SuperPower (SP) (other for prototypes)
- 9 Double-Pancakes
- ~ 1.4 kms of conductors (in the magnet)

HTS High-Field Magnets

NouGAT insert – Experiments : step by step approach

1- Tests of a single pancake under external magnetic field at LNCMI

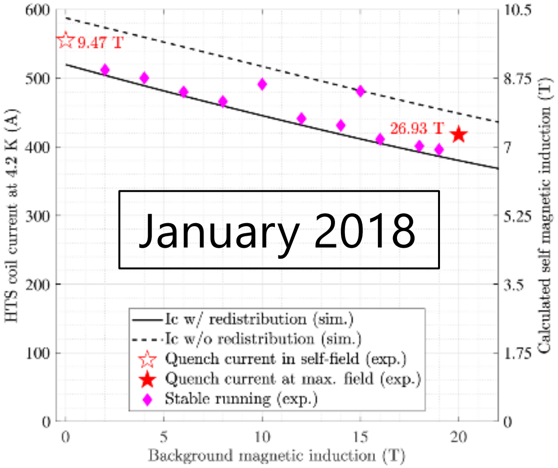


- Dimensions # NouGAT pancakes,
- SuperPower SCS6050-AP tape
- 3 heaters,
- 32 voltage taps.

2016-2017

- 'MQE' measurements [0-16 T] [200-375 A]
- Measurements of external junctions with current leads: 8-10 nΩ
- More than 60 quenchs
- Quench $J > 800$ A/mm^2 in the SC coil

2 - MI sub-scale prototype tests under High Background Magnetic Field

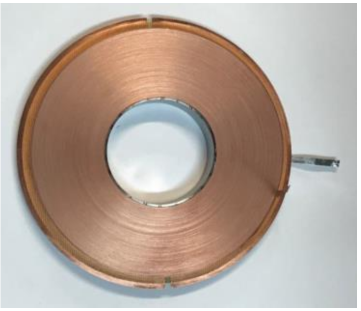


January 2018

HTS High-Field Magnets

3- NouGAT insert – design and fabrication (at LNCMI)

Parameter	unit	value
Winding ID / OD	mm	50 / 111
OB thickness	mm	5.5
# of DP	-	9
Coil height	mm	119
Tape lenght (pancake/total)	m	75 /1350
Tape I_c 77K,SF	A	211-264 (226 bottom pancake)
Coil inductance (calc.)	mH	846.3
Magnetic constant (calc.)	mT/A	45.60
Current to generate 10 T	A	220



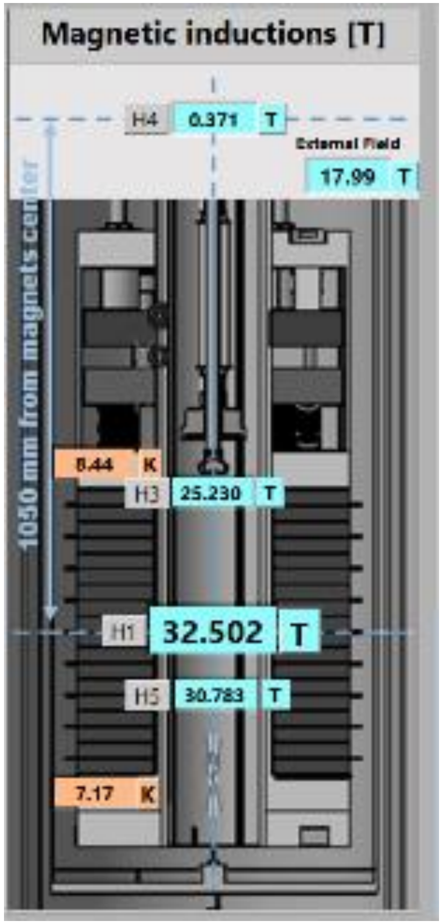
HTS High-Field Magnets

3- NouGAT insert – Final Tests at LNCMI Grenoble

Final tests under external magnetic field at LNCMI

321 A @ 0.5 A/s (~22.8 mT/s)
(**717A/mm^2 in HTS tape**)

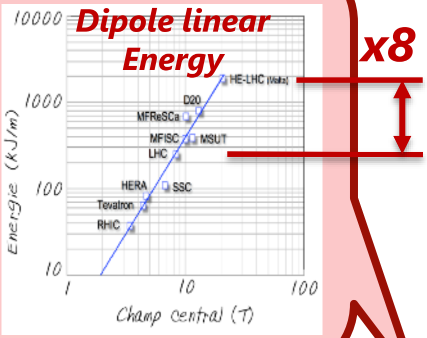
03/26/2019



HTS magnets: main issues

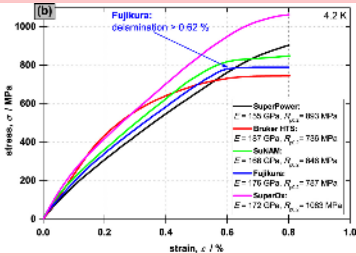
HTS quench protection

- **I winding*
- *Insulated coils (accelerator magnets) :* *numerical MSS*

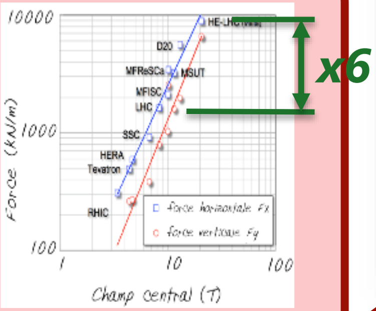


Mecanics,

Laplace forces in B^2



Tape mechanics

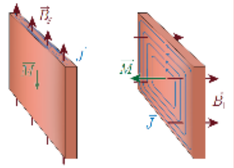


Dipole linear force

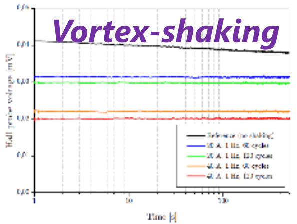
- *MI co-winding* *add reinforcement*
- *Impregnated winding: used of low gluing materials (fluored resin) and low ratio ID/OD to avoid delamination*

Homogeneity

Screening currents

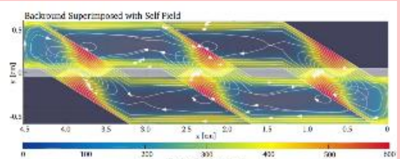


- *tapes : 'over-shoot', 'vortex-shaking' technics*



Courtesy G. Dilasser

- *Roebel cable less critical*



Screening current in Roebel cable

Courtesy J. Van Nugteren

Cryogenics

- *DP cooling « in the mass », thermal drains, PHP*
- *LHe cooling, high B^2 gradient induces levitation*

Copper drain

Diamagnetism « grad B^2 »

Courtesy A. Geim

R&D activities

Stability & protection

*Very slow propagation velocity of the quench: **difficult to detect a resistive voltage**,*
► Small volume dissipating the energy generating very high temperatures.
The system of active protection (detect and dump, discharge resistor, heaters…) usually made for LTS must be very accurate (voltage measurement) and fast.
► complex and expensive

*Solution : **remove/replace insulation** between turns so that the current can skirt the highly resistive quench zone,*
► ANR NOUGAT
 # insert HTS with MI coils
► Internal "NI-PI-MI" R&D
 # study of different winding techniques (stability, charge time constant)
 # visualization of a quench with a fast camera

NI = No Insulation
MI = Metal as Insulation
PI = Partial Insulation

Multi-physics code for NI/MI coils

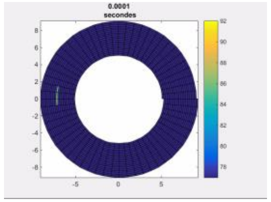
- *Electricity (Partial Equivalent Electrical Circuit),*
- *Magnetism (unique analytical formulas of B and A for an arc of a tape)*
- *Thermic (2D finite differences, power law for SC conductor)*

Benchmarks done :

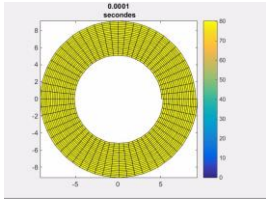
- *Simulation from publication IEEE (2016)*
- *30 turns MI pancake,*

MATLAB

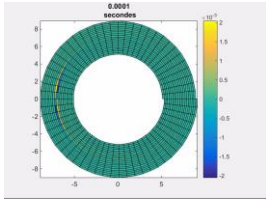
Quench propagation (temperature distribution)



Azimutal current



Radial current

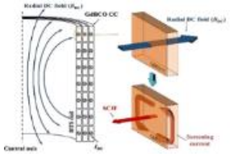


P. Fazilleau

R&D activities

Screening currents

Due to their particular shape as tape, HTS 2G (YBCO), all variation of the magnetic field induces ***screening currents****.*
In return, these currents generate a magnetic field, (« ***Screening Current Induced Field*** *») opposed to the main one (decrease of its magnitude, homogeneity degradation, temporal drift).*



Problem solved with very fine filaments for LTS.

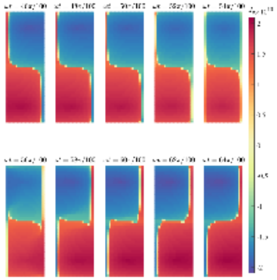
- ***Guillaume Dilasser PhD***
  # experimental and numerical study of screening currents in HTS REBCO magnets

- ***Internal R&D***
  # experimental study of vortex shaking

Simulation code for calculating screening currents
- *Matlab (2D, A-V formulation)*
- *CAST3M (3D, T formulation)*
- *GetDP (2D, H formulation)*

MATLAB

Tape current density during vortex-shaking



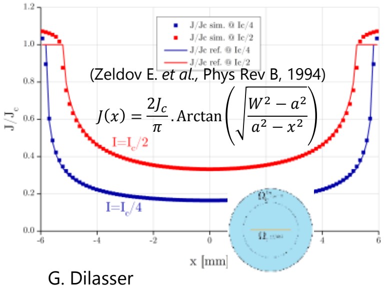
P. Fazilleau

CAST3M

T field in pancake and layers wound coils

GetDP

Tape current density vs analytical formulas



(Zeldov E. *et al.*, Phys Rev B, 1994)

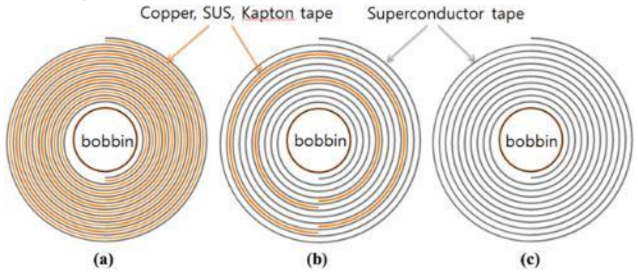
$$J(x) = \frac{2J_c}{\pi}.\mathrm{Arctan}\left(\sqrt{\frac{W^2-a^2}{a^2-x^2}}\right)$$

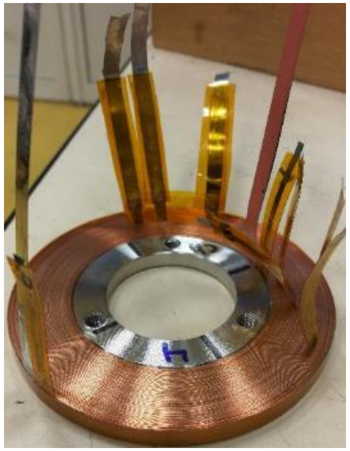
G. Dilasser

Internal R&D –Pi – Ni – Mi coils

*Study on different *I winding*

→ ***Winding NI (No-Insulation)***
→ ***Winding PI (Partial insulation)***
→ ***Winding MI (Metal as Insulation)***





Stability and magnet constants study

1. ***Study of stability and quench behavior*** *(using small SuS heater),*
2. ***Compare the time constant*** *by discharging on an external dump or on the winding itself*

(* stand for M, N, P, MC, S)

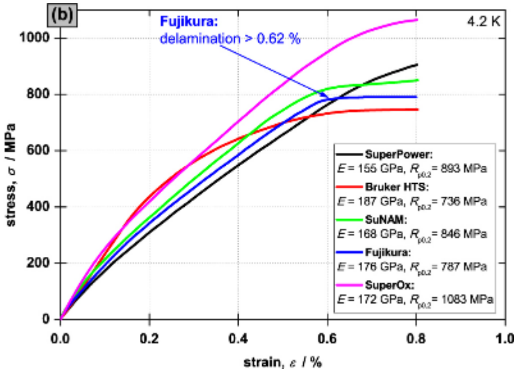
R&D activities

Mechanics

Concern n°1 *for very high-field magnets is mechanics.*

JBr > 1000 MPa

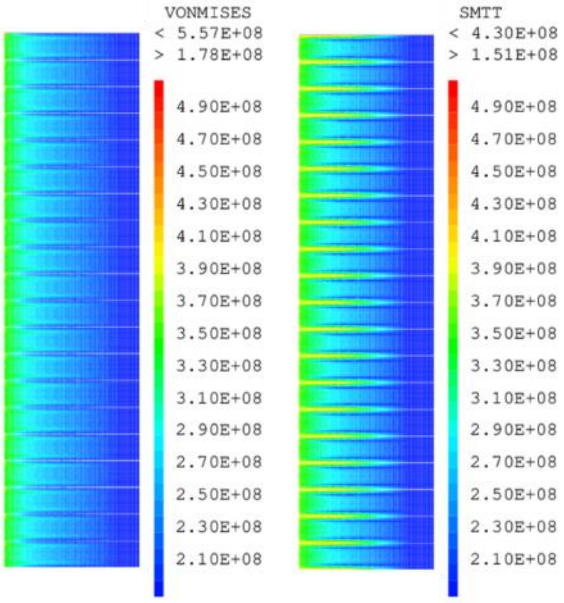
$J=500\ A/mm^2$, B = 40 T, r=5 cm



- ***MI windings*** *provide an additionnal stiff material*
- ***Mohammad ALHarake PhD*** *magneto-mechanics of a 40-45 T HTS magnet*

MI coils of NOUGAT insert mechanics

CAST3M



Thank you for your attention