EASITrain

October, 2019

High **T**emperature **S**uperconducting magnets and cryogenics

Thibault Lécrevisse, Philippe Fazilleau

IRFu *: Institute of Research into the Fundamental laws of the Universe*

DACM *: Accelerators, Cryogenis and Magnetism Division*

LEAS *: Laboratory for Superconductng Magnet Research – R&D HTS*

DE LA RECHERCHE À L'INDUSTRIE

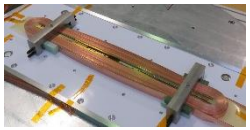
cea

SACLAY

- Introduction: Superconductivity LTS vs HTS

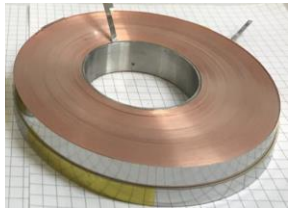
- HTS for Accelerators:

→ Eucard & Eucard2



- HTS for high-field magnets:

→ NOUGAT

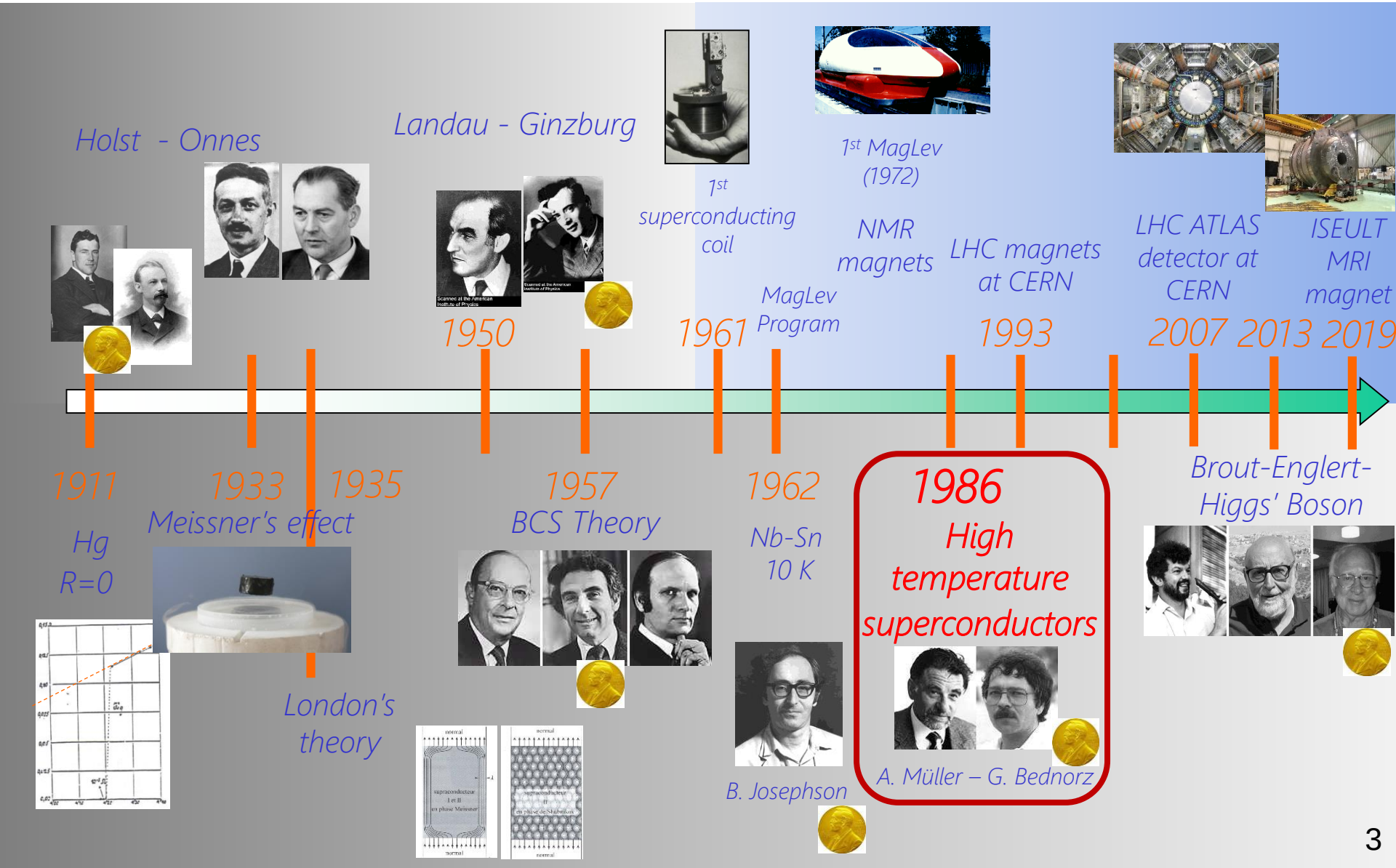


- Cryogenics for HTS

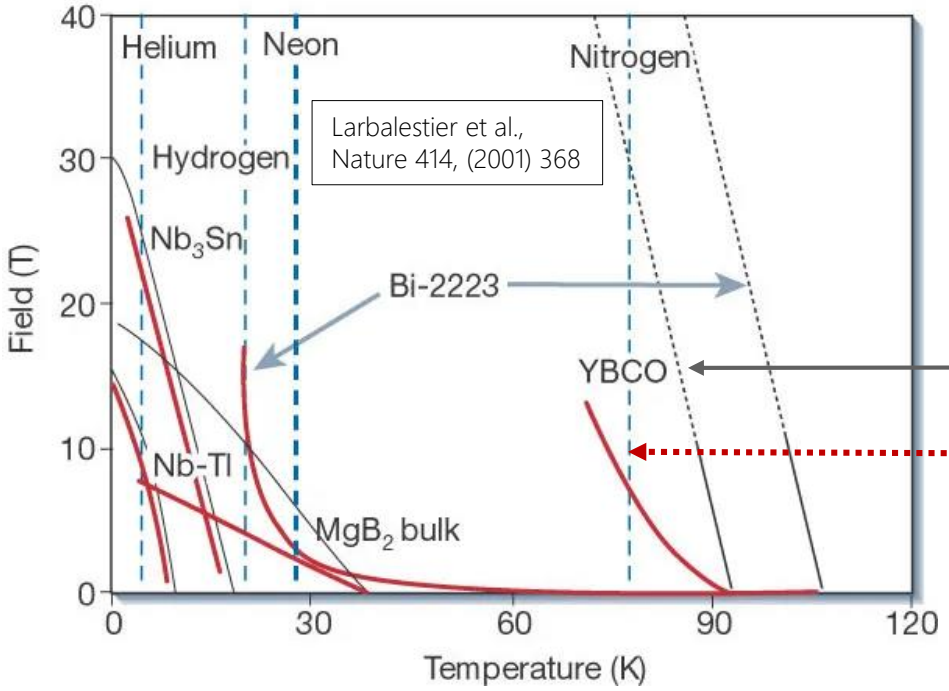
LN2 vs LHe and conduction

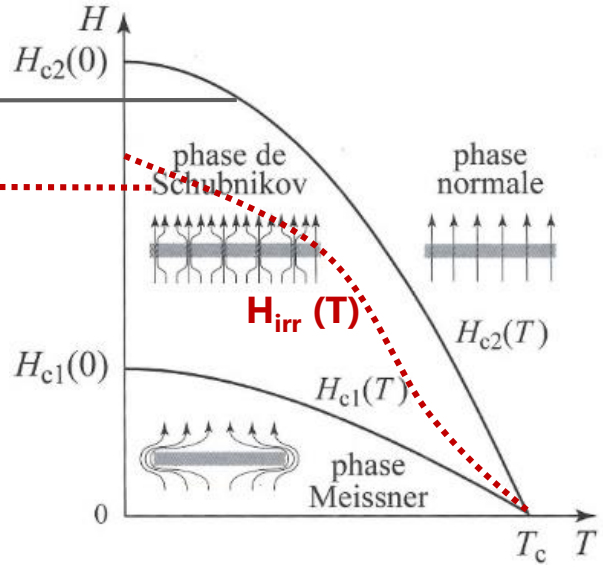
- Conclusion / Perspectives

Over 100 years of superconductivity



Irreversibility field : why we need low temperature





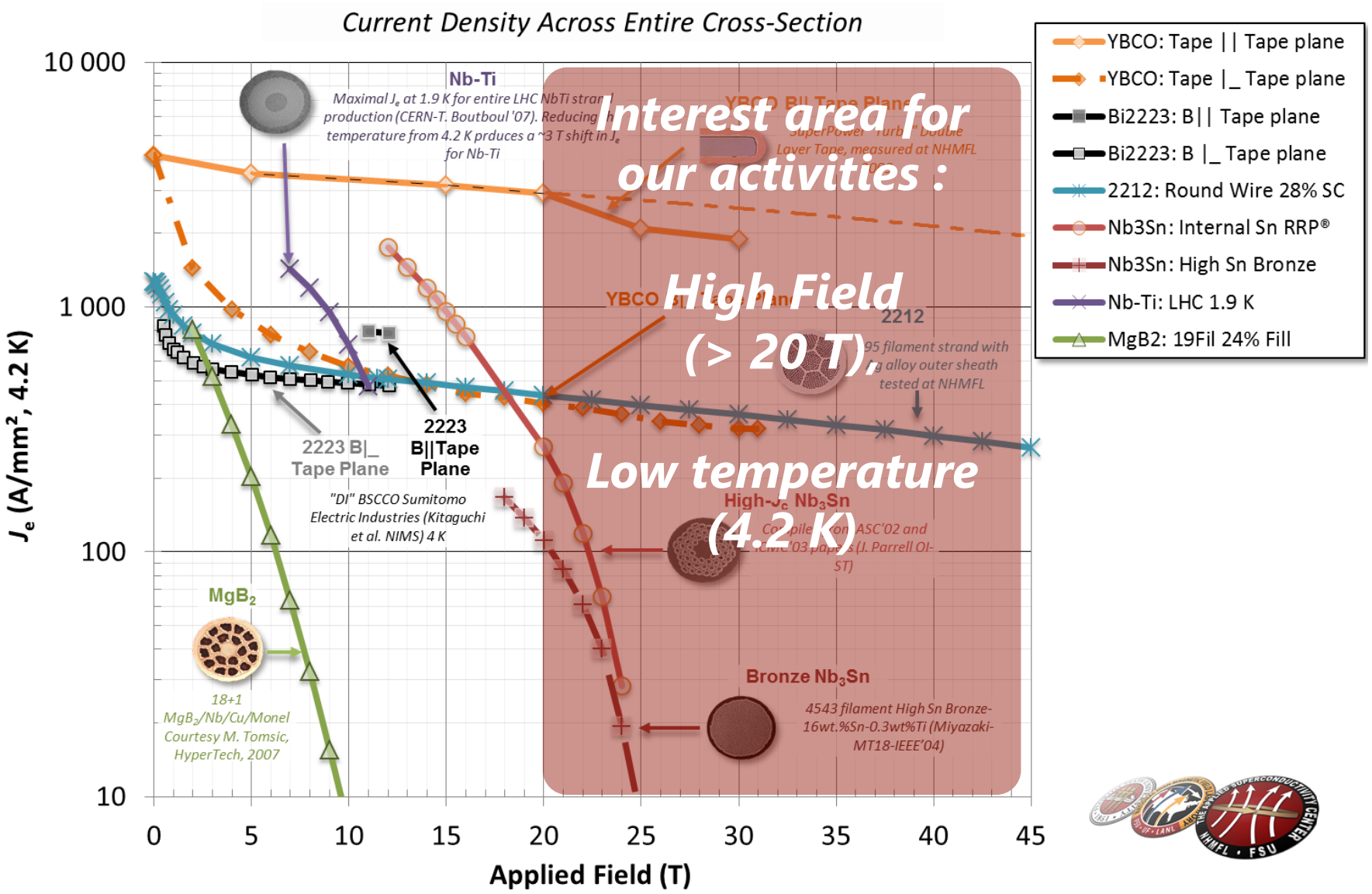
YBCO $Hc_2(0) > 200$ T → Great !

Field limits :

H_{c2} >> H_{irr}

(superconductivity destroyed) (critical current density goes to 0)

Current density versus B @ 4.2 K

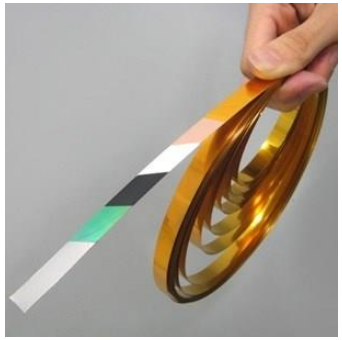


HTS materials for magnets?

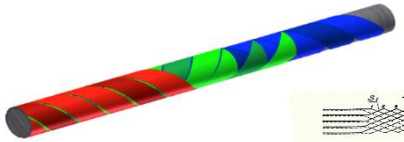
YBCO (REBCO) Rare Earth

Yttrium
Barium
Copper
Oxide

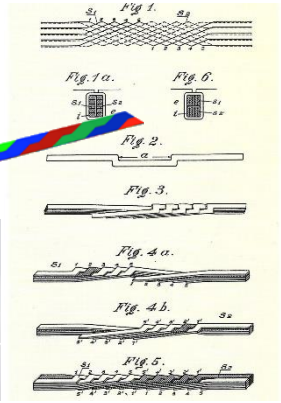
Twisted stacked-tapes (TST)



Tapes around a core (CORC)

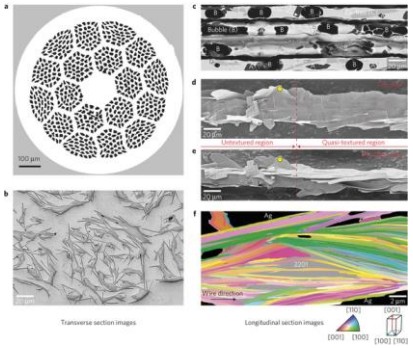


Roebel



- High current density J_e
- Mechanically strong
- Direct winding
- Available with many suppliers

Rutherford cable



BI2212

Bismuth
Strontium Calcium
Copper
Oxide

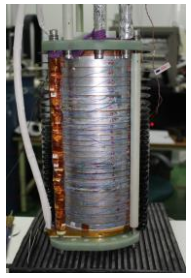
- Less sensible to magnetization
- High current cable

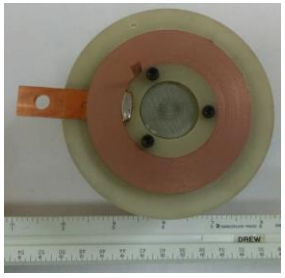
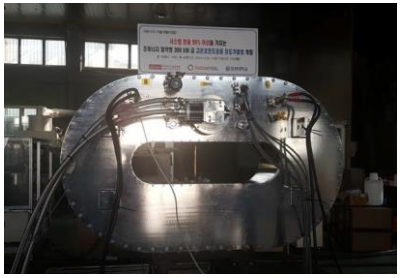
HTS applications : DACM domain

NOUGAT, high field HTS insert
French national agency fundings

Eucard, EuCARD2, dipoles
european fundings

- High Field
  - Commercial
    - Medical
      - MRI
        - LHe-free MRI
        - Dedicated MRI
      - Treatment
        - Drug Delivery
        - Surgery
    - Environment
      - Magnetic Separation
        - Ore Separation
        - Oil Separation
        - Water/air Purification
    - Transportation
      - Air/Ocean
        - Supersonic
        - MHD
      - Ground
        - Chuo Shinkansen (Tokyo-Nagoya)
        - Hyperloop
        - Electric Car
    - Military
      - Offense
        - Railgun
      - Defense
        - Degaussing
  - Science
    - Materials
      - Biochemistry
        - Ultra High Field
        - Scattering
        - GHz NMR
        - >21 T FT-ICR
        - EPR
      - Biology
        - 28 T Mouse MRI
        - 20 T Human MRI
      - Space
        - Micro Gravity
    - Fusion
    - Axion Detector
    - Accelerator
      - LHC
      - IBS-RAON
- Large Power
  - Generation
    - MW Wind Turbine
    - GW Generator
  - Transmission
    - Power Cable
    - Current Limiter
  - Conversion
    - Ship Propulsion Motor
    - Induction Heater
  - Storage
    - SMES
    - SFES

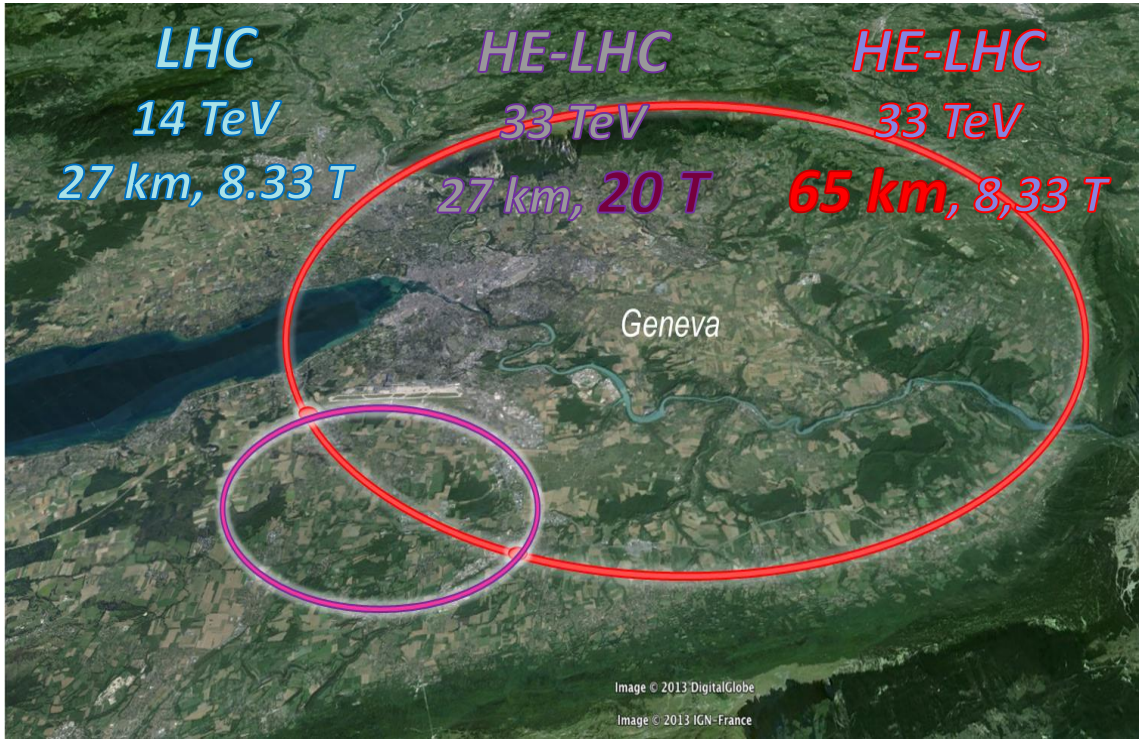


HTS interest for accelerators

$$E\ (TeV) = 0{,}3 \times B\ (T) \times r\ (km)$$

Beam energy — *Magnetic Field* — *Dipole magnetic radius*

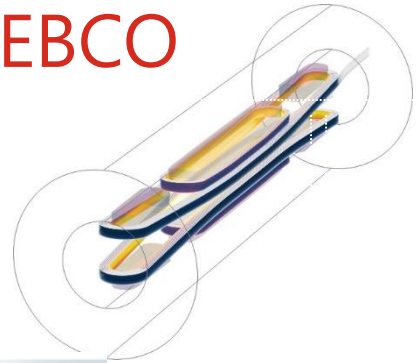


HTS for which accelerator magnets ?

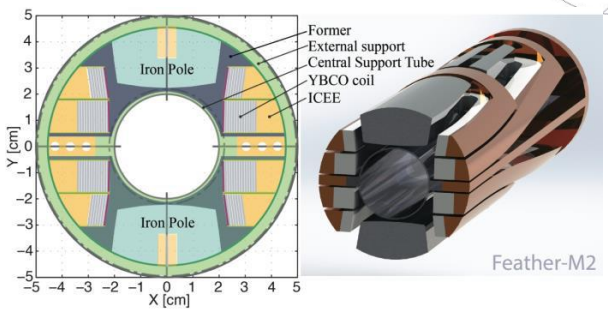
→ Mainly Dipoles

Examples of REBCO

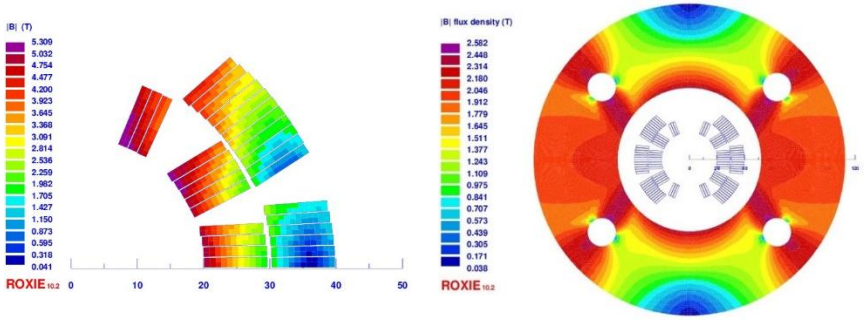
Roebel cable



Align block

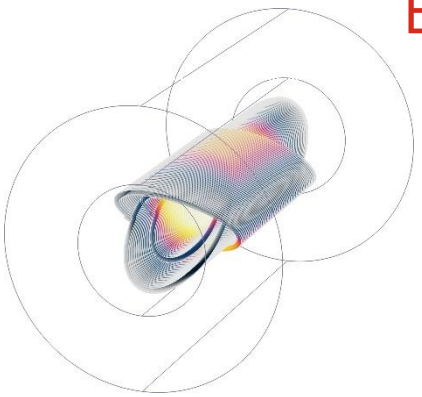


Cosine theta



Example of BI2212

Tilted solenoid
*Or **C**anted **C**osine **T**heta*

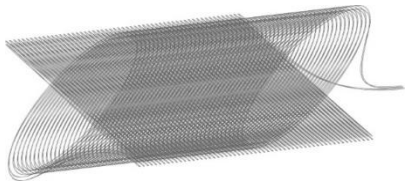


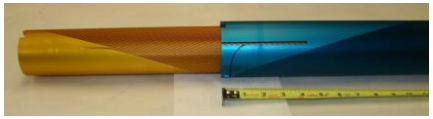
A NEW CONFIGURATION FOR A DIPOLE MAGNET
FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

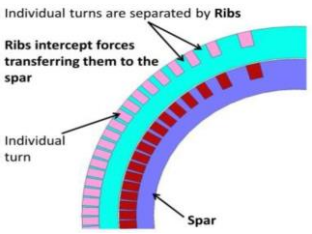
D. I. MEYER and R. FLASCK

Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

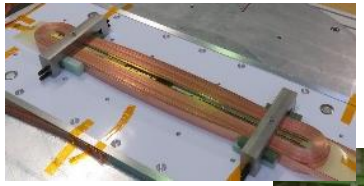




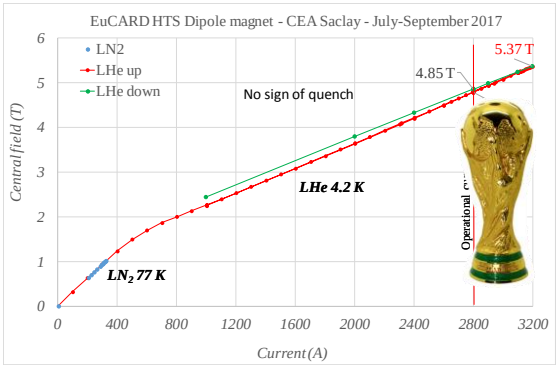


HTS accelerator magnets at CEA

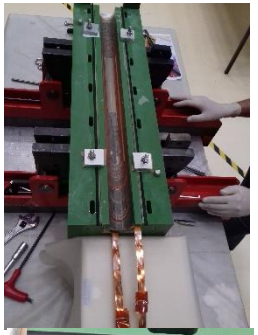
EuCARD

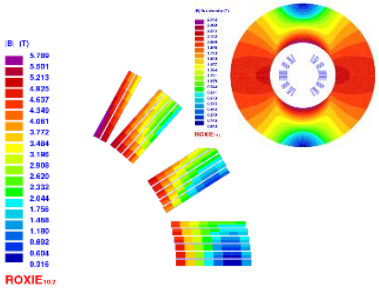


5.4 T
World record

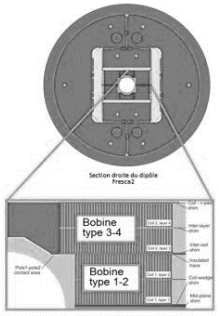


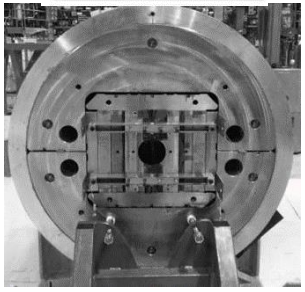
EuCARD2

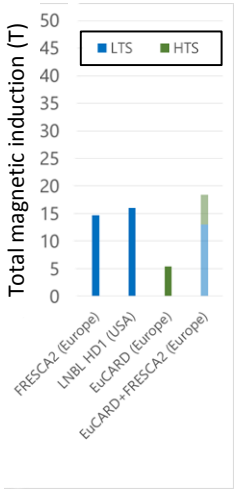




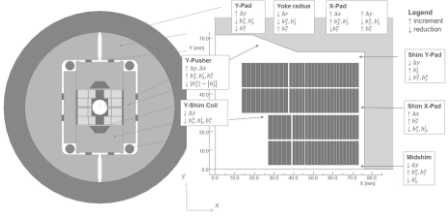
FRESCA2





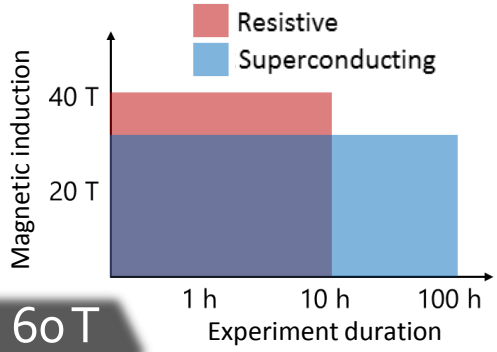


F2D2



EuCARD, CEA-CERN…	EuCARD2, CEA design	FRESCA2, CERN-CEA	F2D2
5.4 T (Alone) **~18 T (in FRESCA2) ?**	***2.6 T*** **~15.5 T (in FRESCA2)?**	**14.7 T (@ 1.9 K)** 13 T (@4.2 K)	15.5 T
Dipole	Dipole cosine theta	Dipole	Dipole
REBCO, 4 Sc tapes, 4.2 K	Roebel cable with REBCO, 4.2 K	Nb3Sn Rutherford, 4.2 K	Nb3Sn Rutherford, 4.2 K

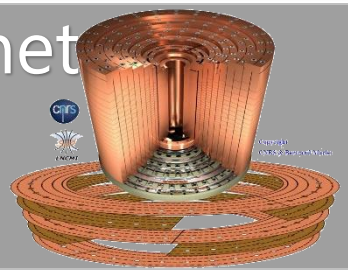
Very high field magnets (solenoids)



5T 10T 15T 20T 25T 30T 35T 40T 45T 50T 55T 60T

Resistive DC magnet

Polyhelix
Bitter



41.4 T
NHMFL

?

Magnetic induction

LTS

MgB_2
NbTi
Nb_3Sn

14.7 T
FRESCA2

16 T
LBNL
HD1

19 T
Solenoids

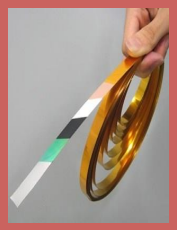
25 T
Nb3Sn

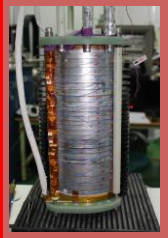
~10^6 x Earth magnetic induction
at France center

HTS

YBCO

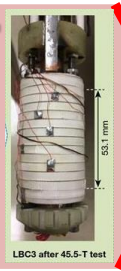
BISSCO





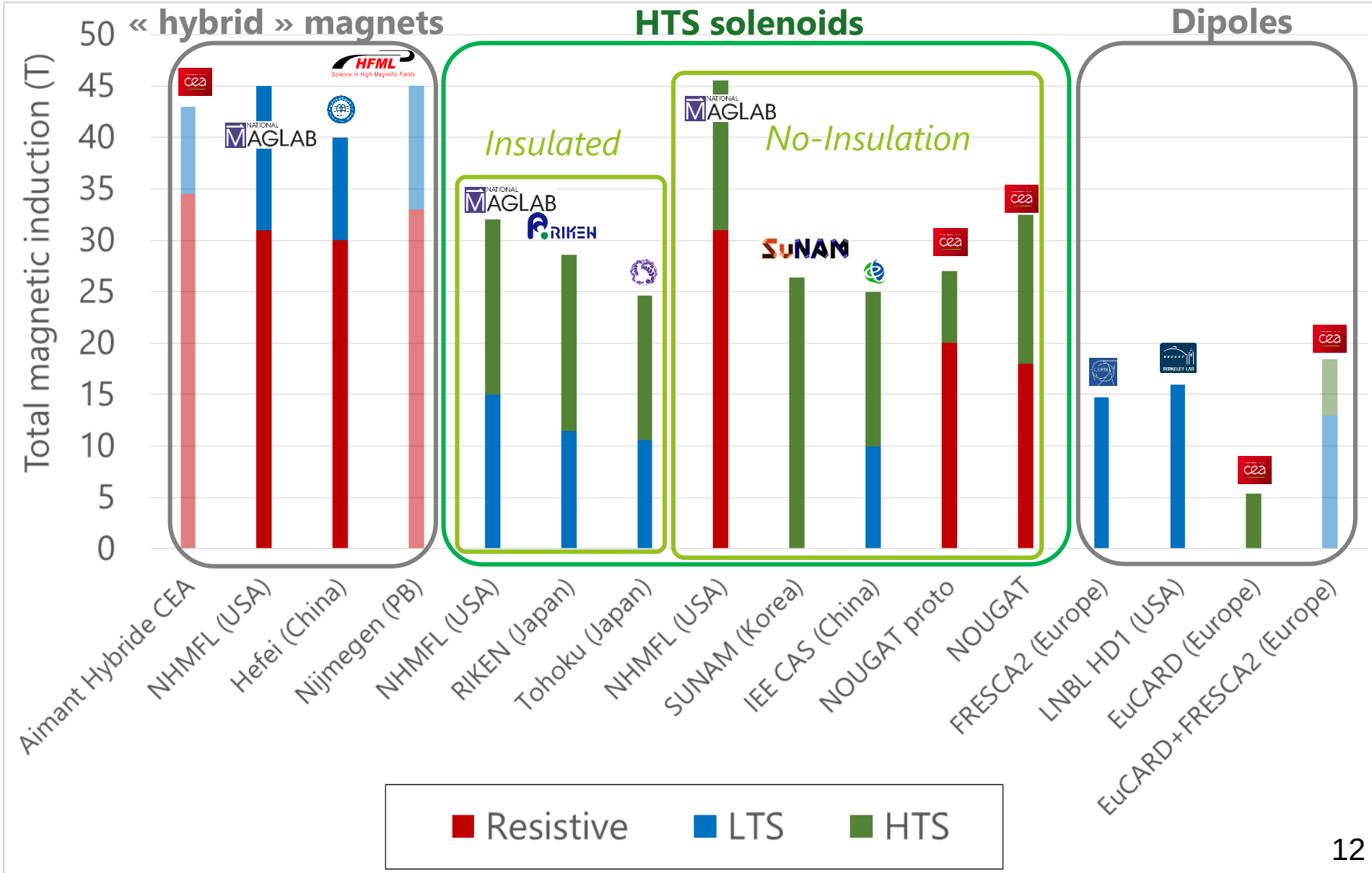
26.4 T
SUNAM NI

45,5 T
NHMFL
NI pancakes

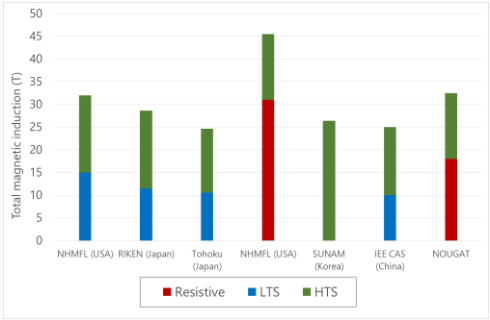


> 100 T
REBCO

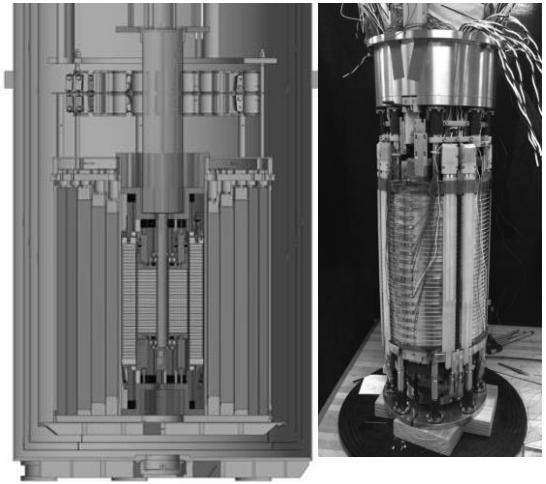
Which configuration ?



HTS solenoids

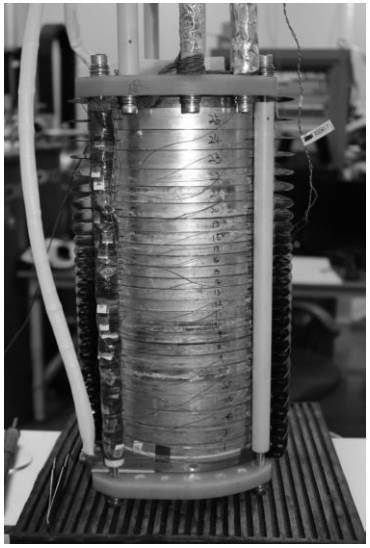


NATIONAL HIGH MAGNETIC FIELD LABORATORY



NATIONAL HIGH MAGNETIC FIELD LABORATORY

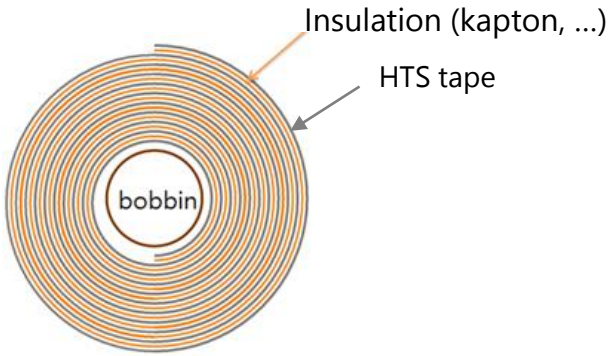
SUNAM



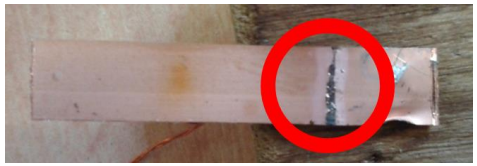
NHMFL, USA	LBC3, NHMFL, USA	SUNAM, Korea	NOUGAT, CEA, France
17 T (HTS) + *15 T (LTS)*	14.5 T (HTS) + *31 T (rés)*	**26.4 T** (HTS)	14.5 T (HTS) + *18 T (res)*
32 T	**45.5 T**		**32.5 T**
Aimant isolé	No-Insulation (NI)	No-Insulation (NI)	Magnet-as-Insulation (MI)
REBCO 4 mm-w, 4.2 K	REBCO 4 mm-w, 4.2 K	REBCO 4-8 mm-w, 4.2 K	REBCO 6 mm-w, 4.2 K
ID 40 mm	ID 14 mm	ID 35 mm	ID 50 mm

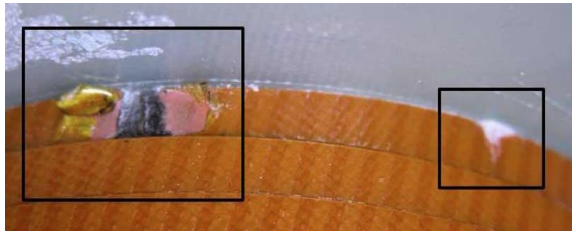
A brief view of winding possibilities for HTS

Classical insulated



BUT in HTS quench are very localized

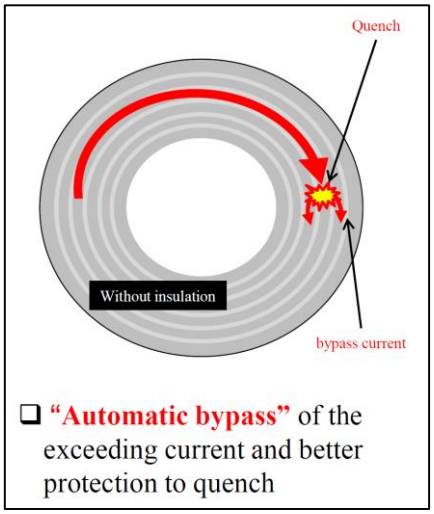




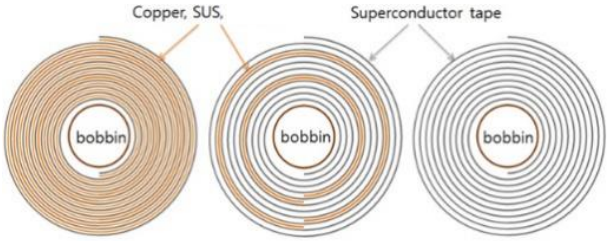
S. Matsumoto et al, IEEE trans. on Super., Vol.22, NO.3, June 2012

Non-insulated

S. Hahn et al. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 21, NO. 3, JUNE 2011



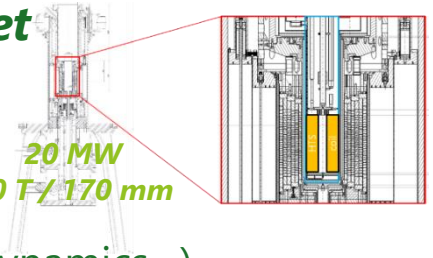
… and variants: MI, PI, …



NOUvelle Génération d'Aimants pour la production de Teslas

Goal : 10 T HTS insert in a 20 T resistive magnet

- DP (inner splices), ReBCO 6 mm-w, **MI** winding
- **SuperPower (SP)** / SuperOx (SO)
- 9 DP, ~ 2 kms of conductors
- Prototypes (1 SP, 2 DPs), codes (Mechanics, current dynamics…)



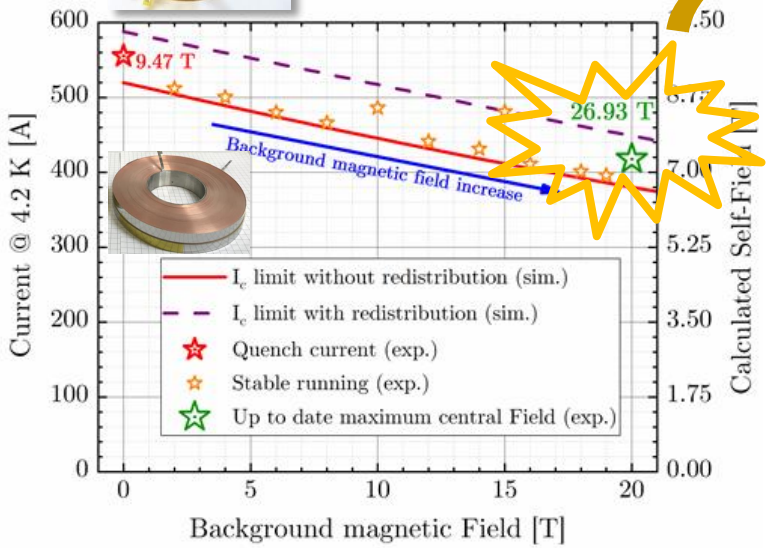
cryostat @ 4.2 K
Max. OD_{coil}: 125 mm
L_{max} : 220 mm

LNCMI

Dec. 2017 – fev. 2018

Proto 2 DP
6.93 T *+ 20 T res.*

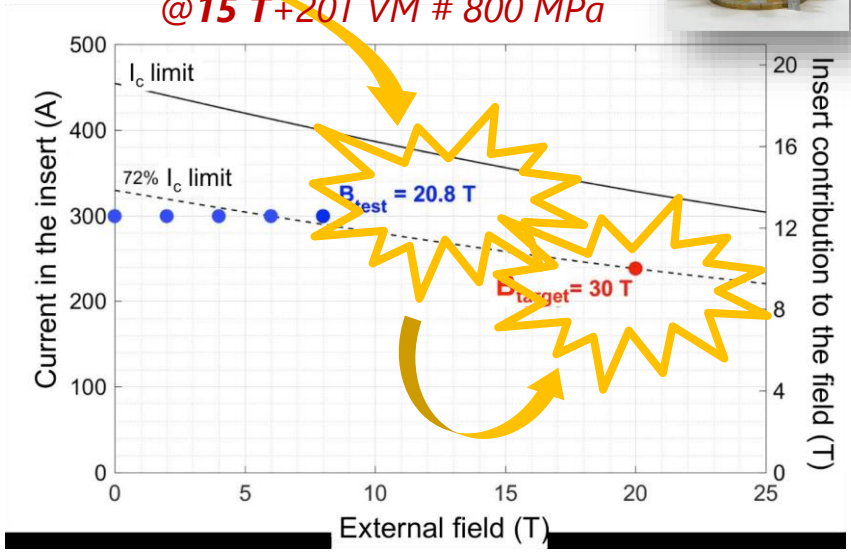
VonMises > 800 MPa



Sept. 2018

NOUGAT Insert
12.8 T *+ 8 T res.*

*@**10 T**+20 T VM # 500 MPa*
*@**15 T**+20T VM # 800 MPa*

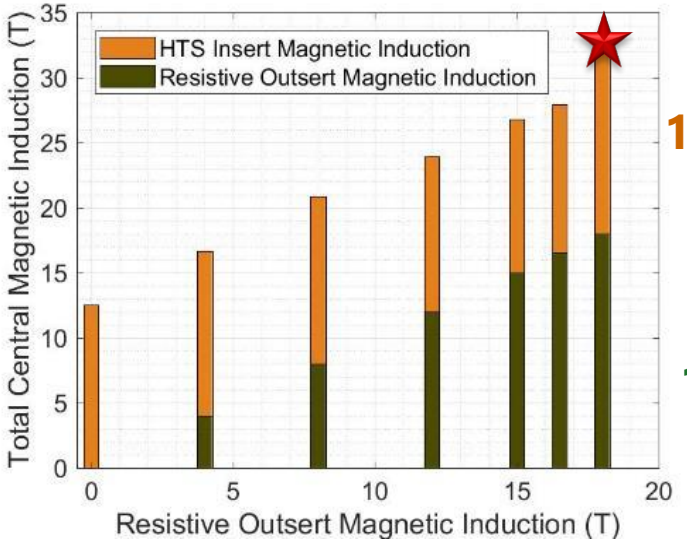


Final tests of NOUGAT Insert

World field record for insert of these dimensions

32.5 T # **14.5 T (HTS)** + 18 T (resistive)

03/26/2019 **32.5 T**

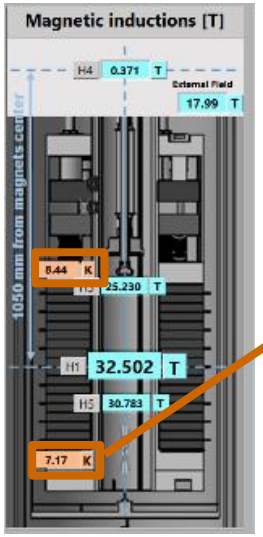


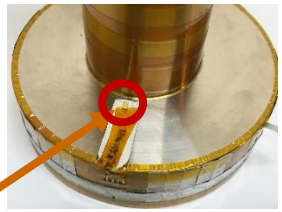
=

14.5 T

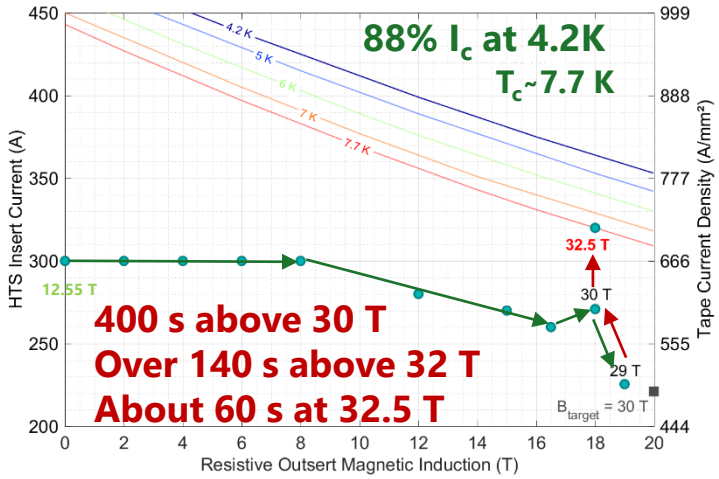
+

18 T



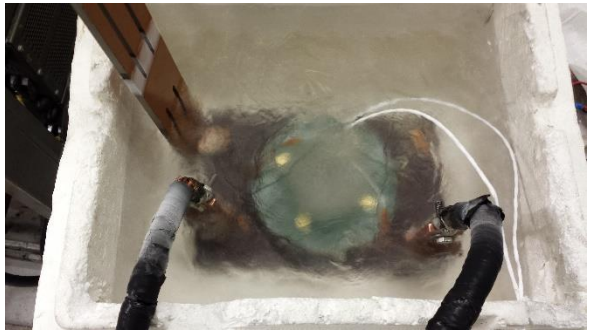


Cooling issue

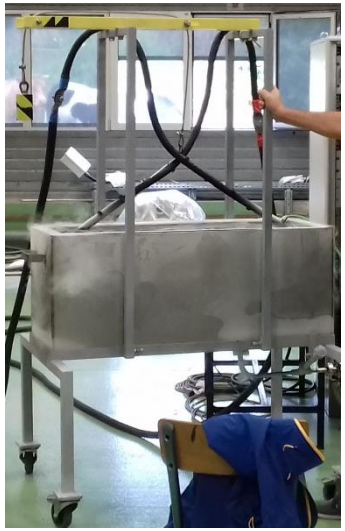


Cryogenics for HTS magnets : why?

Why talking about complex cryogenic for HTS magnets??
→ T_c of 90 K so a bath of LN_2 is fine!

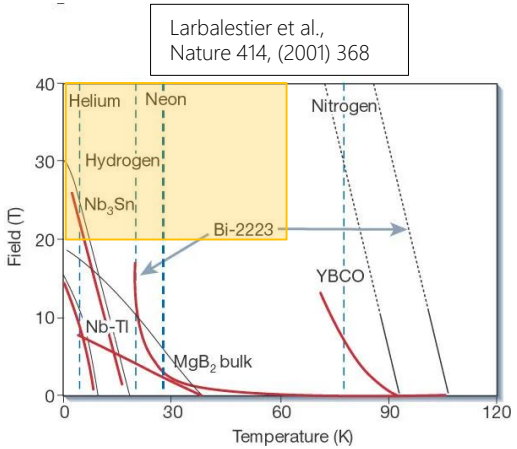


Ex: A "Complex" cryogenics fish box !



More complicated !

Fine to check parts or elements but not **for high field**



High Field
=
low temperature
(< 30-40 K)

Need of more complex cryogenics (low temperature) in a **high field** environment

Cryogenics for HTS magnets

- 1- Baths:
  - ► LN_2: low field / low operating cost
  - ► LHe: high Field / high operating cost
- 2- Conduction cooled (maintenance cost) :
  - ► Cryo-coolers +
    - Solids thermal drain,
    - Pulsated Heat Pipes

It allows other temperatures that 4.2 K

- 3- Circulation: no needs for flow with HTS

LHe normalized price

2016	2017	2018
100	111	163

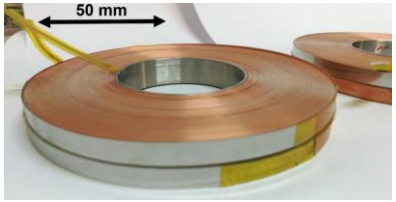
From 2019 numbers of the Bureau of Land Management

Baths : Most spread principle

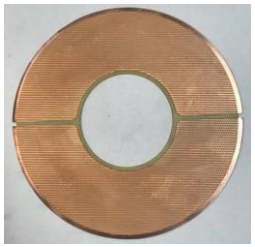
The story of NOUGAT Project: LHe

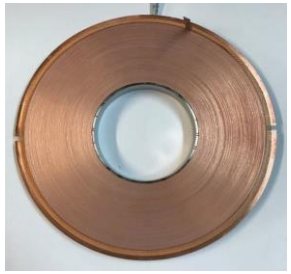
From 1 pancake : Good cooling

To a 2 DP prototype:
→ Compact so poor cooling



And finally a magnet with copper drains: better but not enough





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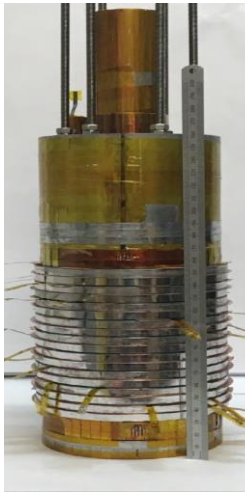
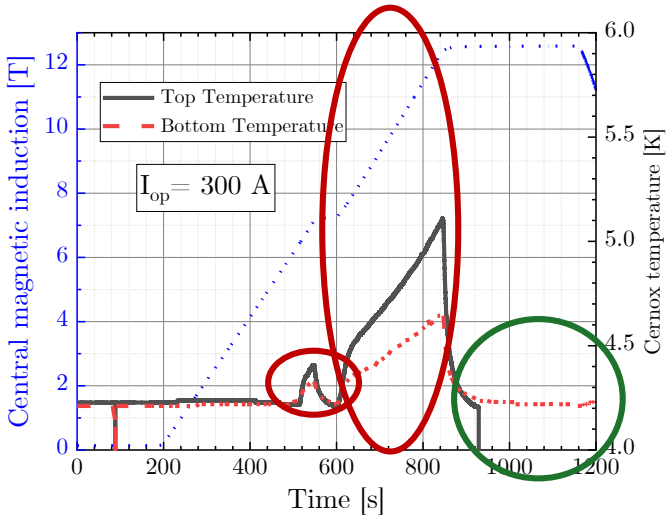


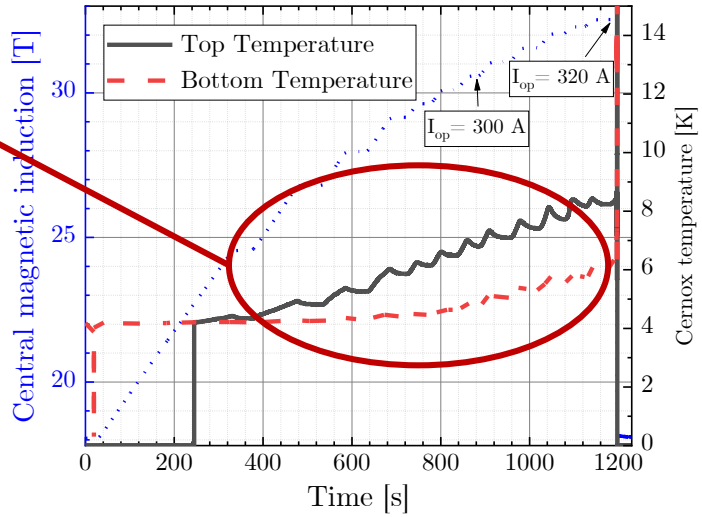
Baths : Most spread principle

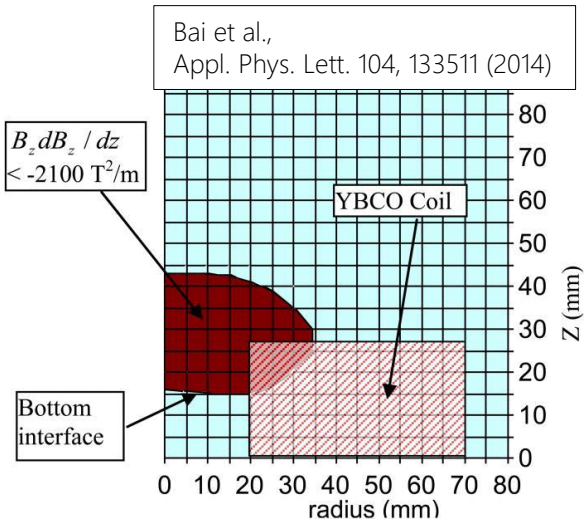
- Still some issues with NI / MI magnets:
  - → dissipations during charging/discharging
  - → limit the ramping rate
  - → Fine in steady state

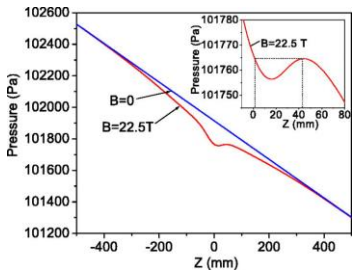
- High Field: bad cooling at ends of the solenoid, probably helium gas bubble trapped due to strong $B_z dB_z/dz$

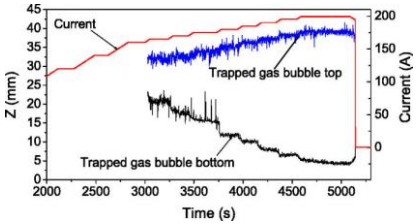


?









Baths : Magnet energy dissipation issue

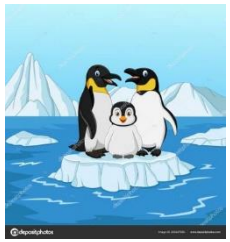
Stored energy : $E_m = \int_V \frac{B^2}{2*\mu_0} dV$ → high field = high Energy

If E_m discharged inside the cryostat : high vaporization / high pressure

→ case for NI/MI HTS magnets

MIT coil 1 Power Supply fault

Some are happy :



Other less…

Issues

Helium lost (2-3 k$)
High pressure (risk)

→ Simple cryo not possible

Solutions

Find a way to discharge energy outside

OR

Dry cooling with Cryo-coolers and thermal drains (solids or PHP)

Feasible But much complex

Cryo-coolers for HTS magnets

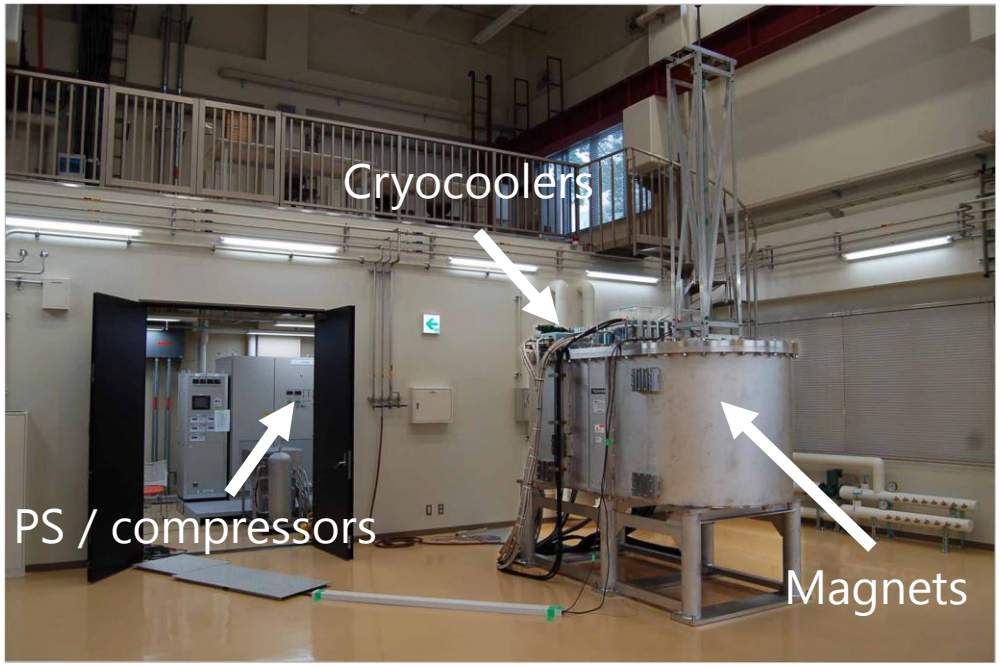
Example: 25 T cryogen-free superconducting magnet at Tohoku University / Toshiba (Japan) : **Impregnated and insulated** BSCCO HTS part with solid drains

Magnetism

3 x NbTi coils **6 T**
+
3 x Nb3Sn coils **8 T**
+
1 x HTS coil
BSCCO **10.6 T**
(GdBCO Q@ 9.6 T)

Cryogenics

2 x 4K GM cryocoolers for HTS
+
2 x GM/JT for LTS
+
2 x single stage GM cryocoolers for shields/current leads



Magnet is well running since many years

Pulsed Heat Pipes

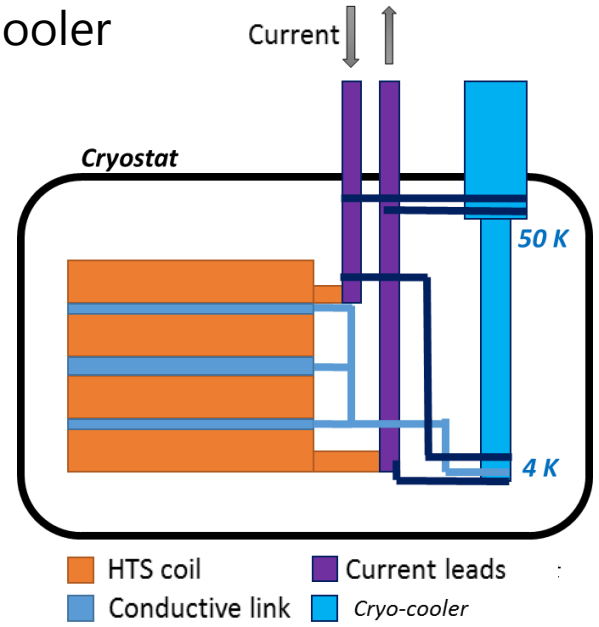
Conduction principle

See next presentation on "Cryogenic Pulsating heat pipes" from Maria BARBA.

Internal R&D on HTS magnet cryogenic part:

- Association of a MI pancake with a PHP/cryo-cooler
- Internal fundings
- 2 years post-doc

- <u>Aspects:</u>
  - PHP Conductive links and coil structure
  - Current leads and losses
  - Cooling power and temperature range



Conclusion

- HTS materials allow **simplest** cryogenics **BUT at low field**
- High field HTS magnets require **medium to low** temperature
- **Very high fields are** putting usual bath cooling using LHe **complicated** (Helium bubble trap → poor cooling ; LHe cost)
- NI / MI HTS windings induce **internal dissipation or discharge** → **safety**

- Solutions **are existing and emerging** :
  - Cryo-cooler with solids drain → already **HTS magnets are working**
  - Cryo-cooler with **PHP** → A very promising technology depending on temperature and power (See next presentation from Maria BARBA)
    - Easy operation once parameters are known
    - Very efficient thermal conduction to be confirmed at low temperature
    - He, (H), Ne, N or mixt for different temperatures (< 10 K or 28-32 K or 77-80 K)
    - Light drain
    - Long length possible (> 2 m?) for very high field (He Diamagnetism effect ?)

Thank you for your attention

DE LA RECHERCHE À L'INDUSTRIE

cea

SACLAY