Applications des supraconducteurs en génie électrique

Pr Dr Bruno Douine

Plan

- About GREEN lab
- Physic of Superconductors
- Superconducting material for Applications
- Characterization of HTS for applications
  - bulks
  - Tapes and coils
- Applications

GREEN lab Team

- Permanent Members
  - Pr J. Lévêque (team leader)
  - Pr B. Douine
  - Dr K. Berger
  - Dr T. Lubin
  - Dr S. Mezani
  - Dr. H. Menana
  - Dr. L. Belguerras
  - Pr Koblischka (associated)
  - Pr Trillaud (associated)

Academic collaborations

- KIT
- Saarland University (Dr M.R. Koblichka)
- Tokyo University of Science (Dr Pavan)
- University of Alger and Khémis-Miliana (Pr E.H. Ailam)
- National Autonomous University of Mexico (Pr F. Trillaud)
- Polytechnique Montréal, Quebec (Pr F. Sirois)
- University of Liège (Pr P. Vanderbemden)
- French labs:
  - LNCMI (X. Chaud) and Grenoble Electrical Engineering Laboratory (P.Tixador),
  - Institut Jean Lamour Nancy (S. Mangin and T. Hauet),
  - CRISMAT laboratory (J. Noudem and P. Bernstein)
  - GeePs Paris Saclay, (L. Queval)

Industrial collaborations

- Airbus Group and Safran Group (Design of SC machines for Aircrafts)
- SNCF (french railway compagny), (SC cables)
- Nexans France (IEC Standard of HTS tapes and cable)
- ASG Colombus (Italy)
- DGA linked to french army (Design and realization of superconducting machines)
- Naval Group - French industrial group specialized in naval defense and energy (SC motor)

Main current projects

- IMOTHEP (Electric aircraft, WP5 Superconductivity)
- SUPERRAIL (SNCF, Nexans, SC cables)
- SCRYPT (Superconducting and CRYogenic Powertrain Technologies, SAFRAN, Airbus)
- PEPR (Programme et équipements prioritaires de recherche exploratoire) SupraFusion (50 M€)

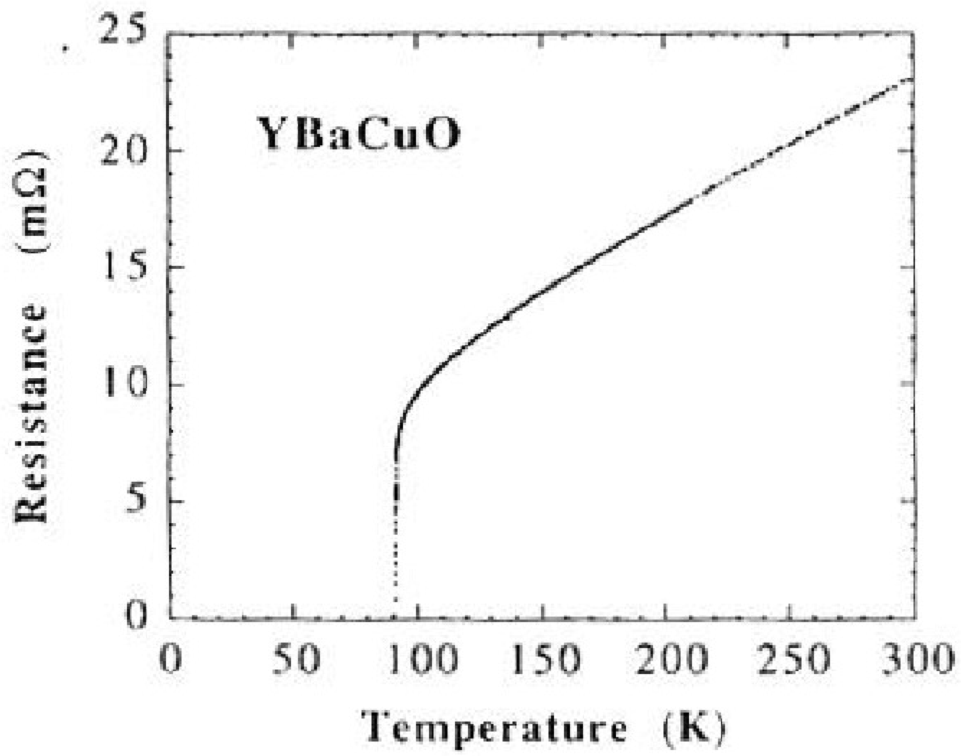
Research topics and expertise

- Characterization of HTS material
- Modeling (FEM and analytical)
- Applications in electrical engineering

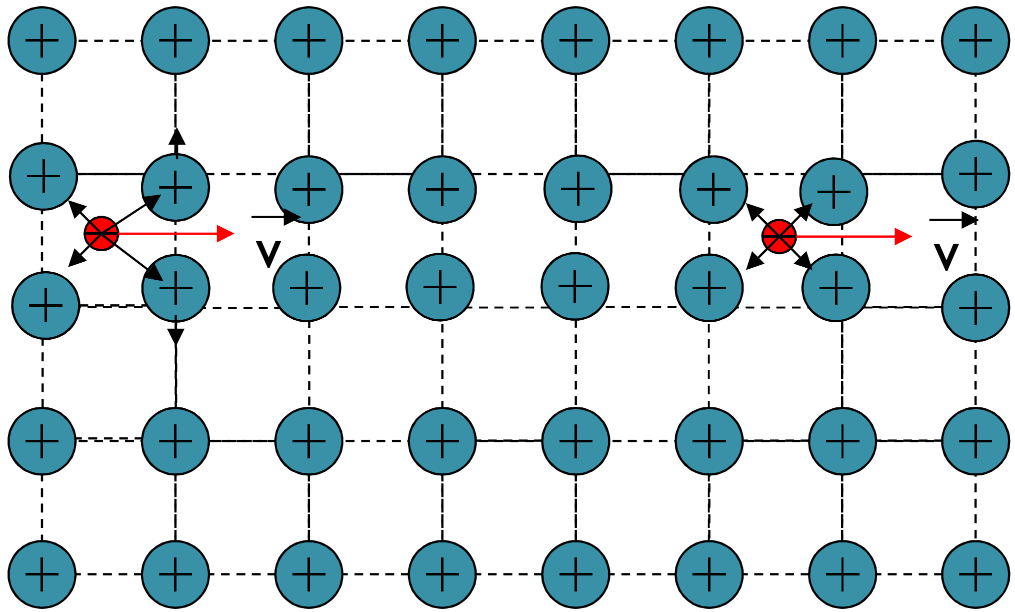
PHYSIC OF SUPERCONDUCTORS

a) Superconductor features :

- no resistance for T<Tc

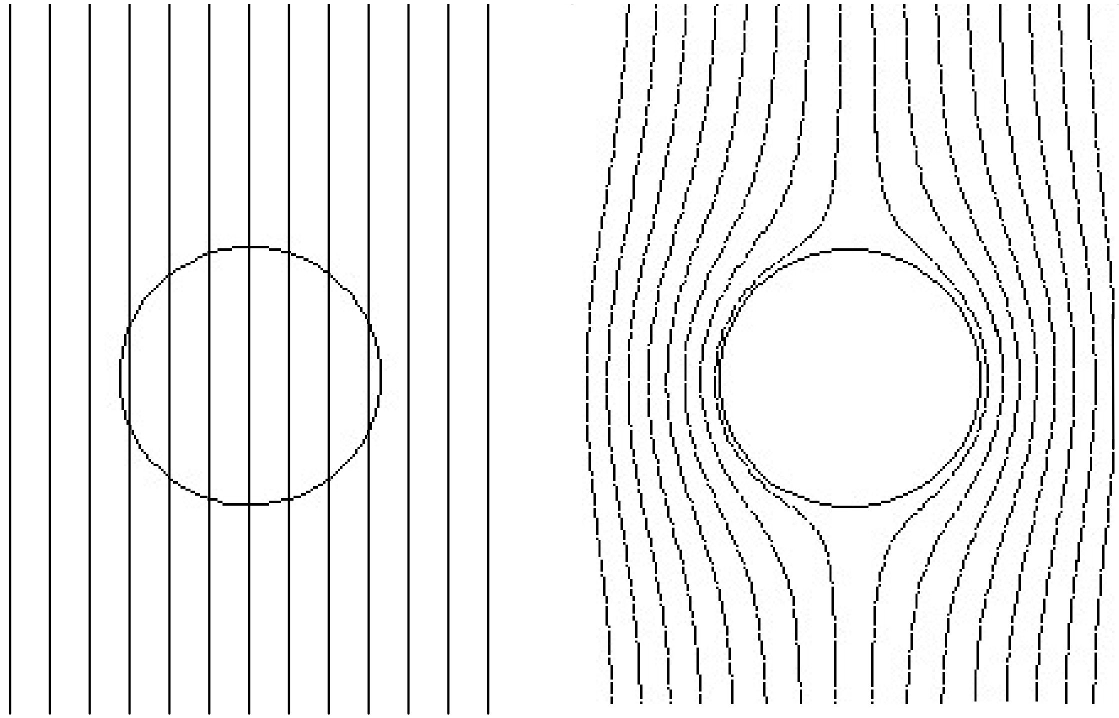


-Resistivity of normal metal



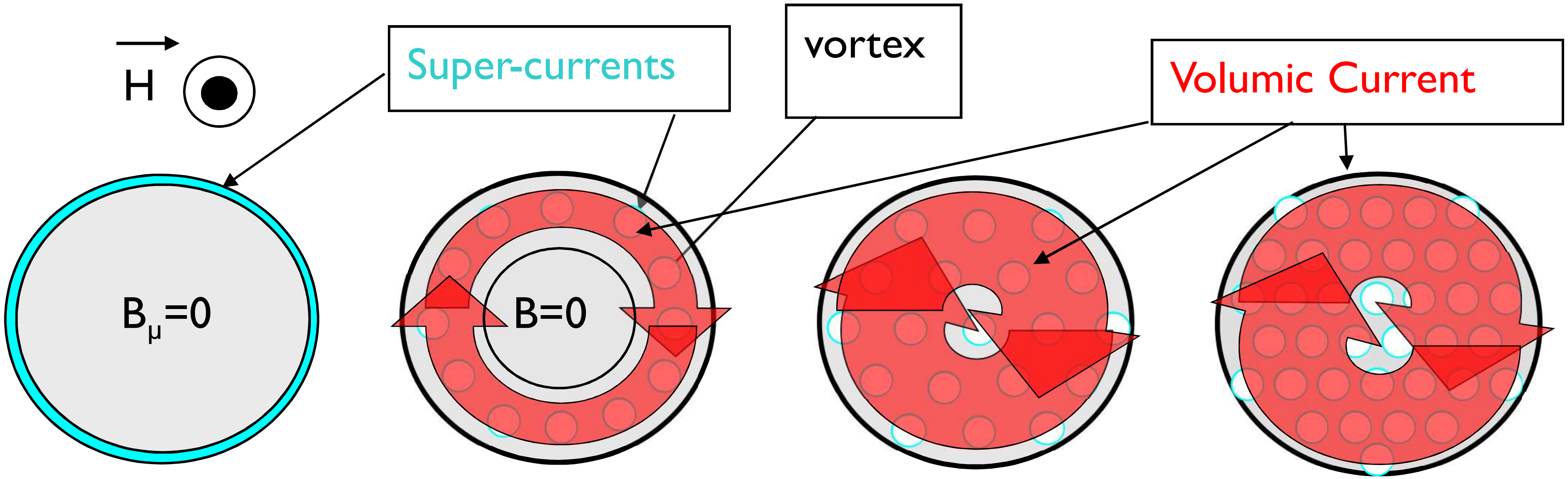
Superconductors for T<Tc
=> no interactions
=> no resistance

- Meissner Effect



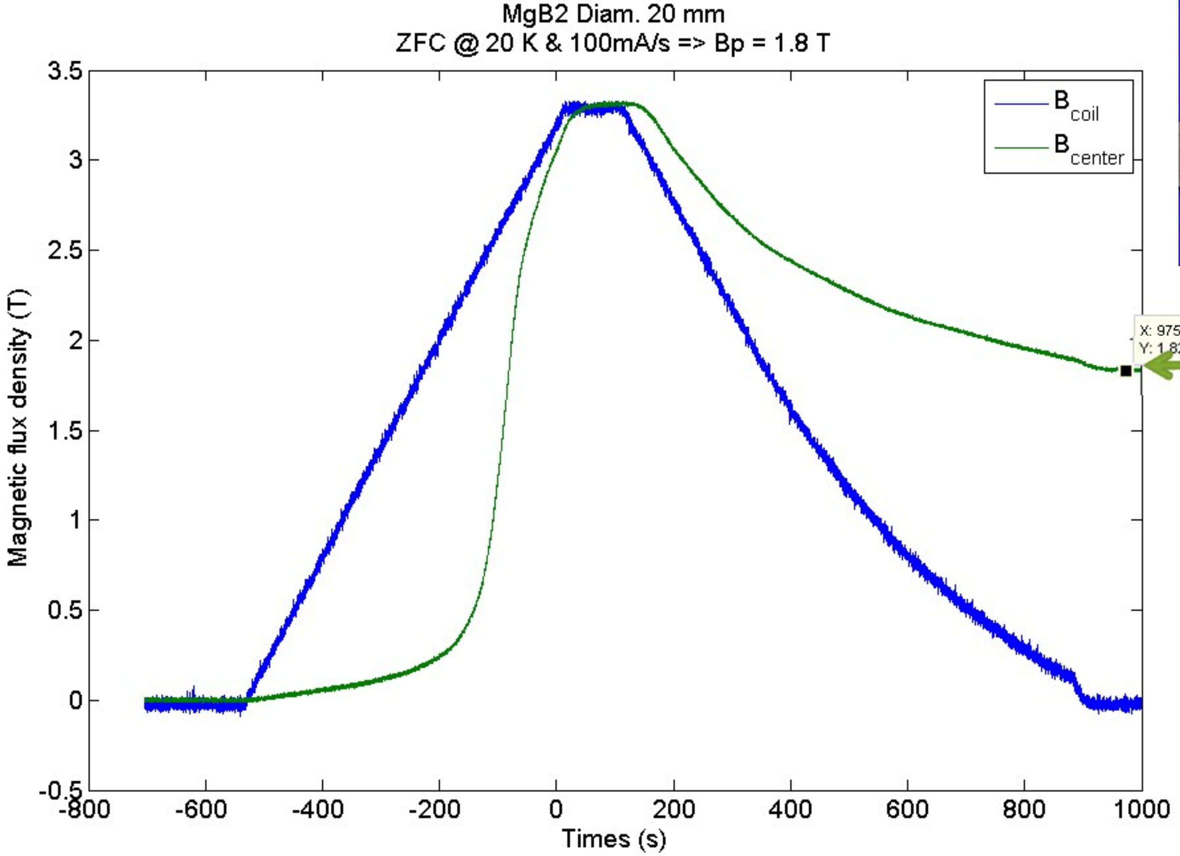
$T > T_C$ $T < T_C$

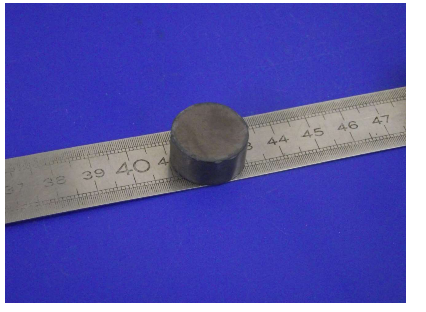
- Induced current in superconducting cylinder



$H_1<H_{C1}$	$H_{C1}<H_2<H_P$	$H_3=H_P$	$H_3<H_4<H_{C2}$

- Superconducting permanent magnet





Trapped field

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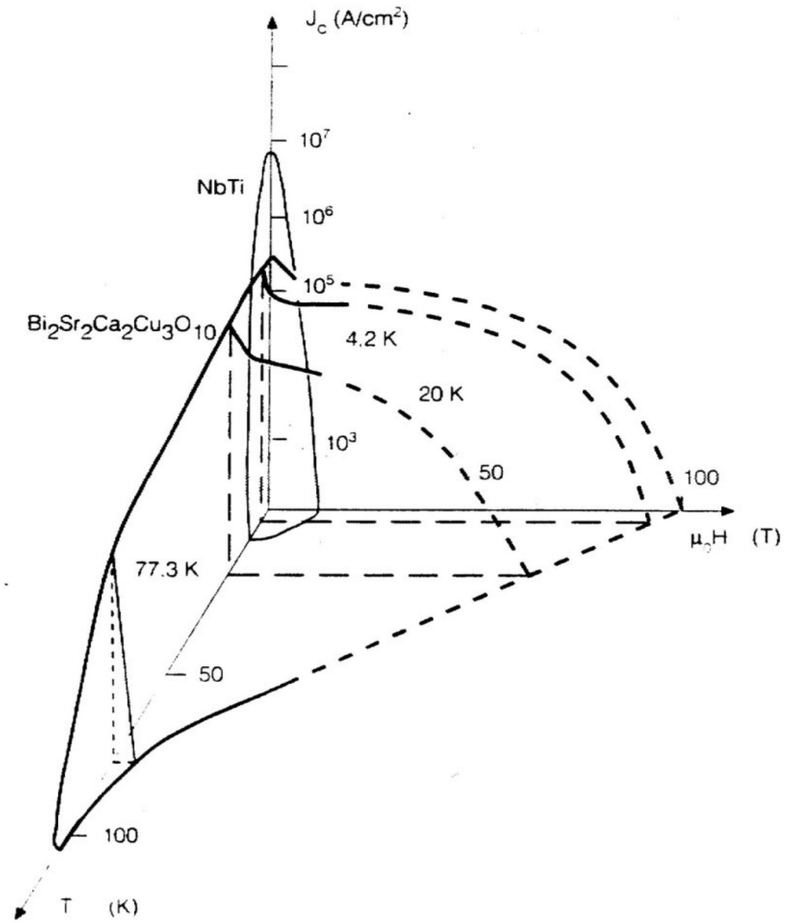
b) Critical surface

To be superconductor

T < Tc
B > Bc
J < Jc



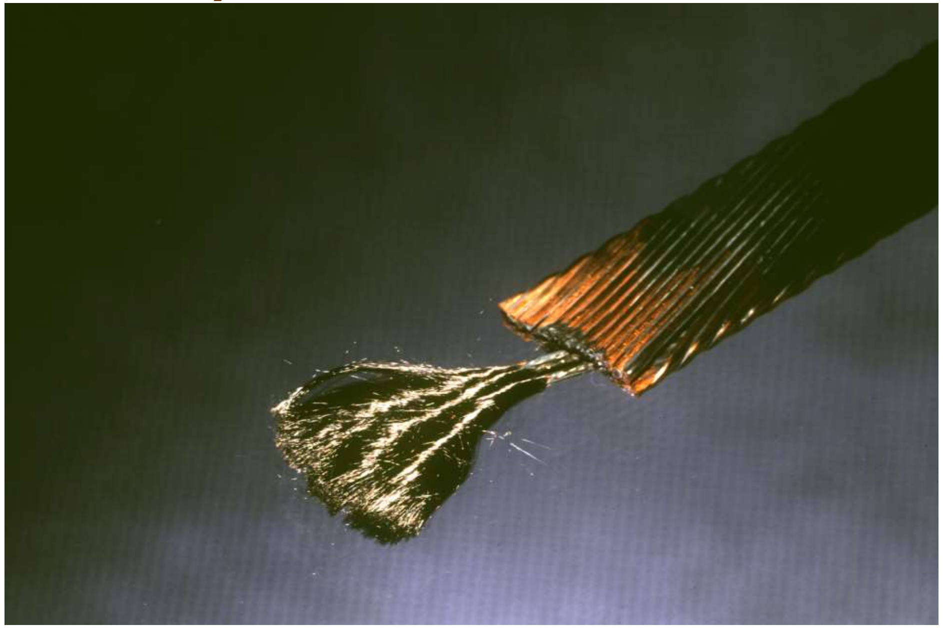
SUPERCONDUCTING MATERIAL FOR APPLICATIONS

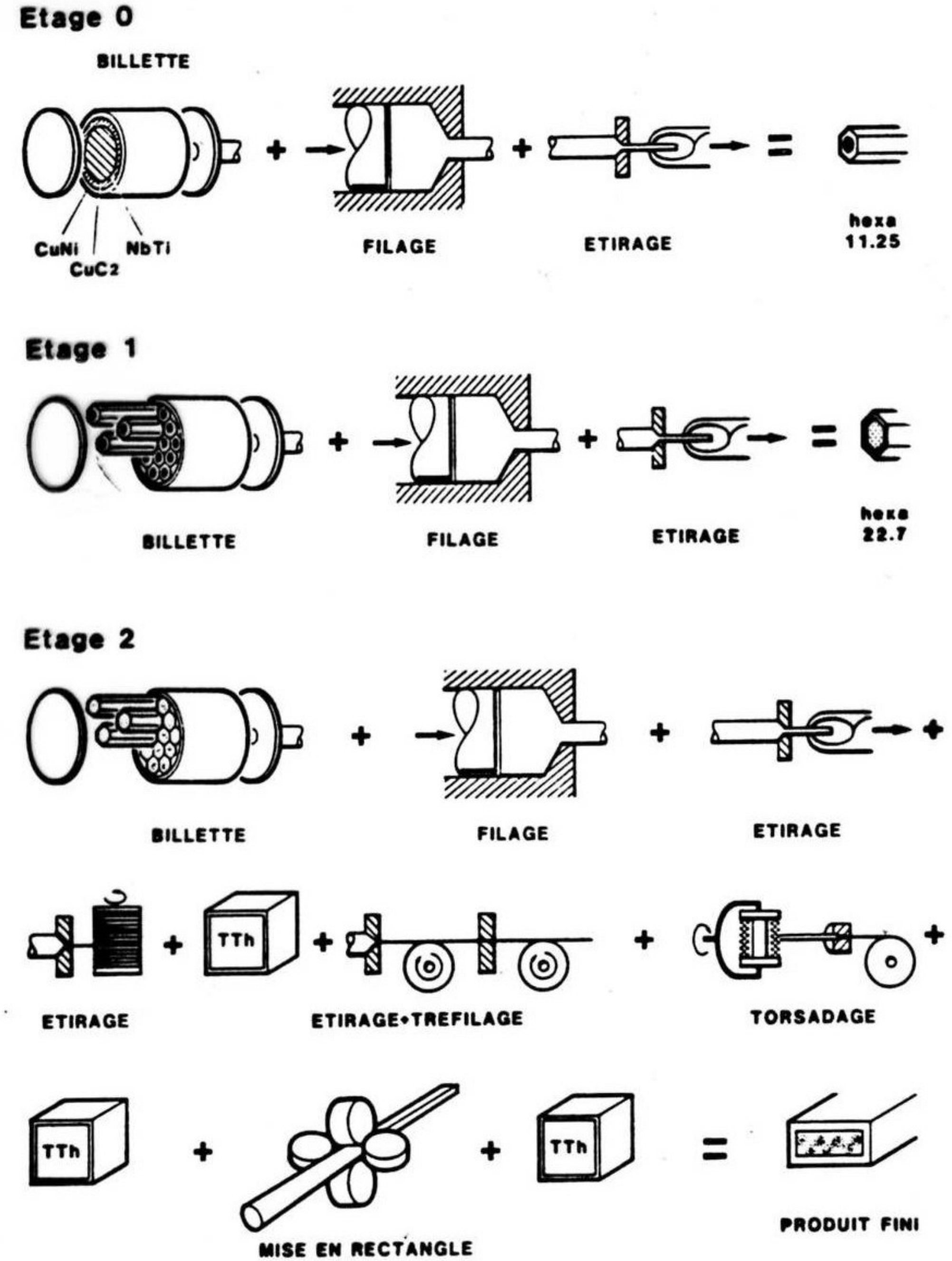
Low Temperature Superconductors (LTS) ($T_c<20K$)

Material	T_C (K)	$\mu_0 H_C$ (T) à 4,2K	J_C à 4,2K et 5T (kA/mm^2)
Nb_3Sn	18	22	15
NbTi	9	12	4

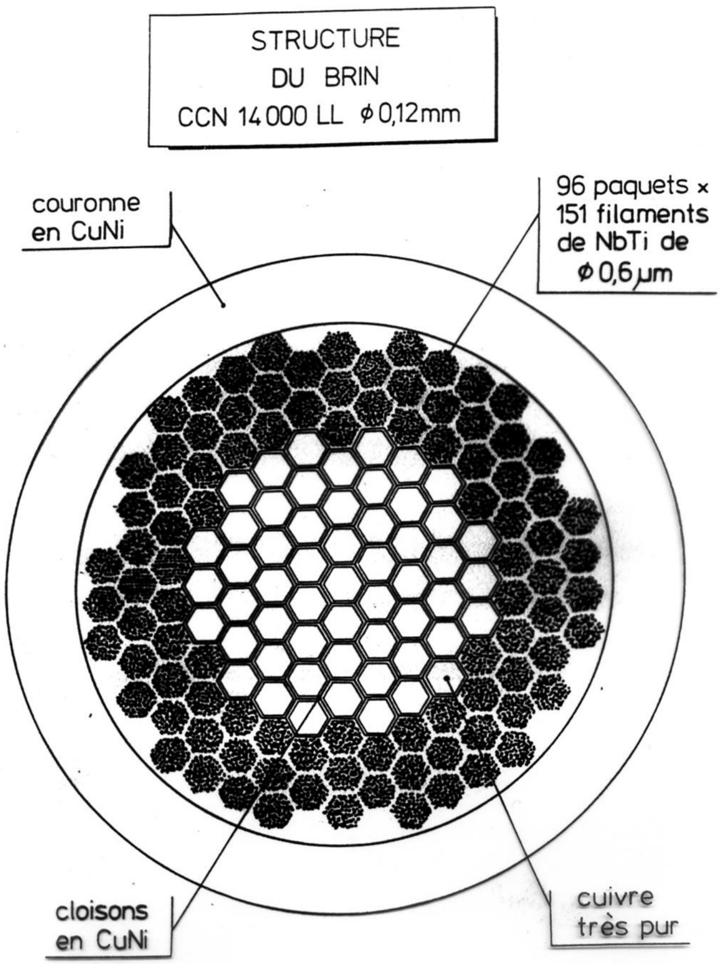
SUPERCONDUCTING MATERIAL FOR APPLICATIONS

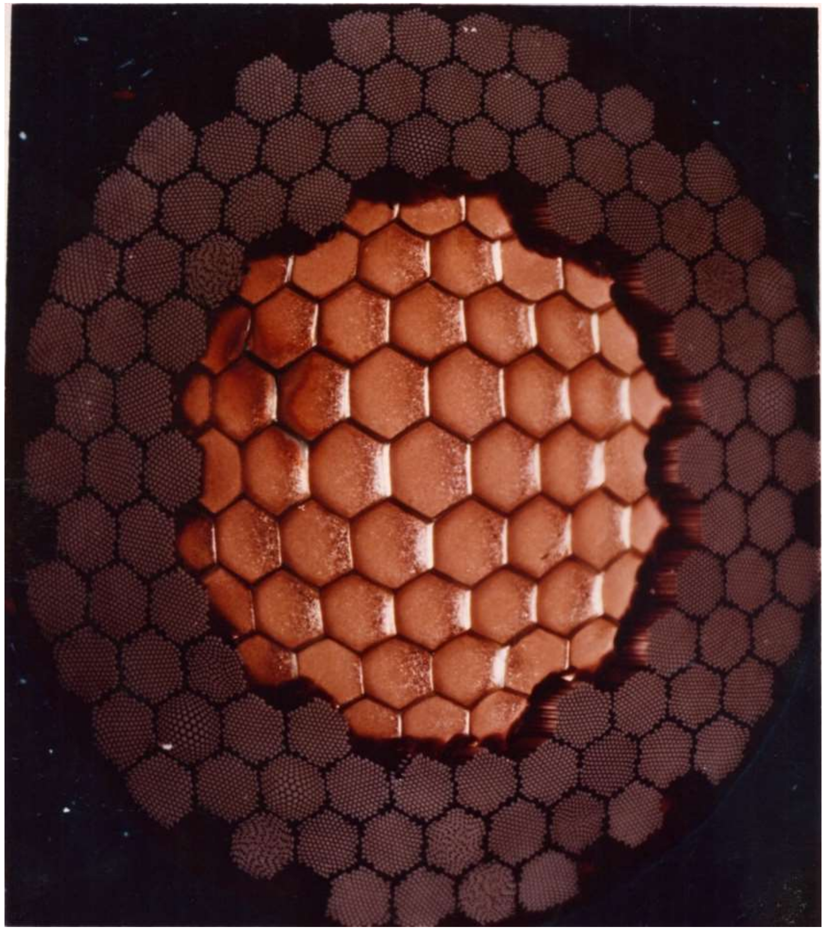
Low Temperature Superconductors (LTS)
To reduce AC losses, filaments of wire should be very thin (<10μm)




Etage 0
BILLETTE
CuNi
CuC2
NbTi
FILAGE
ETIRAGE
hexa
11.25
Etage 1
BILLETTE
FILAGE
ETIRAGE
hexa
22.7
Etage 2
BILLETTE
FILAGE
ETIRAGE
TTh
ETIRAGE
ETIRAGE+TREFILAGE
TORSADAGE
MISE EN RECTANGLE
PRODUIT FINI

Structure of LTS wire

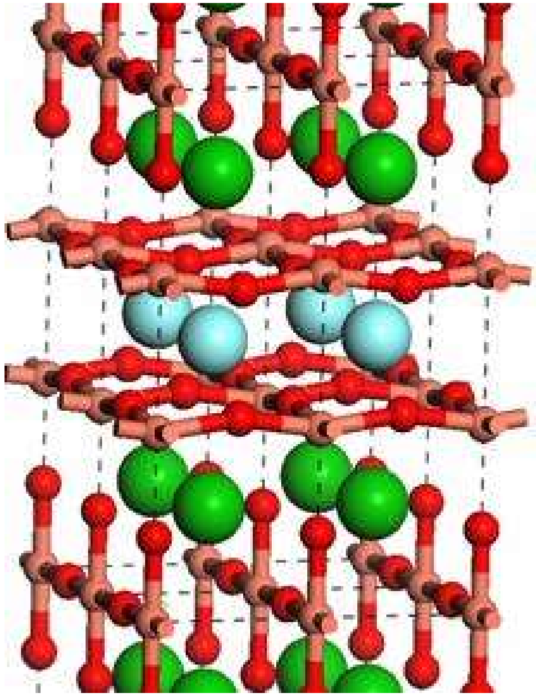




SUPERCONDUCTING MATERIAL FOR APPLICATIONS

“High”Temperature Superconductors (HTS) (Tc<120K) since 1986

=ceramic and anisotropic

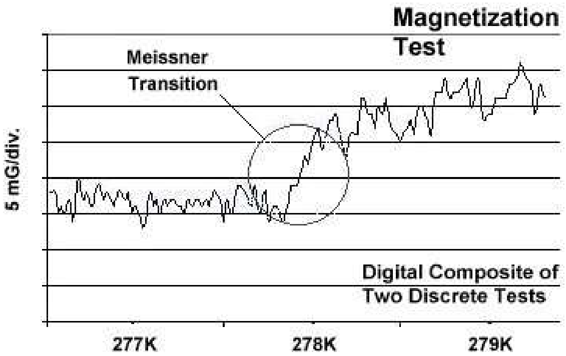


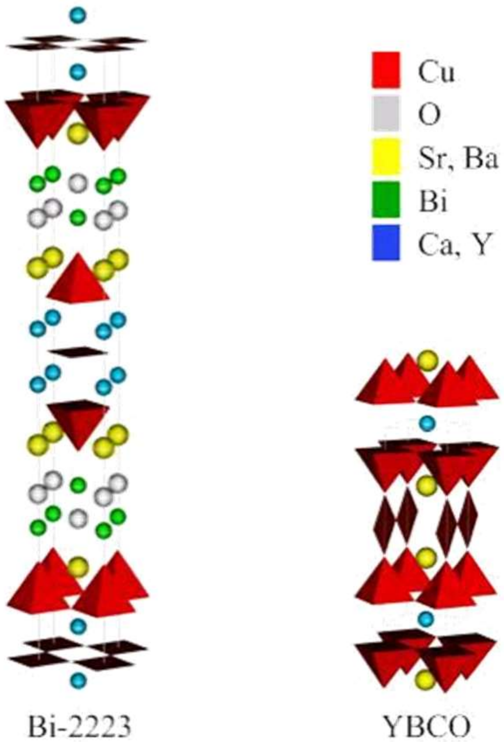
High Temperature Superconductors

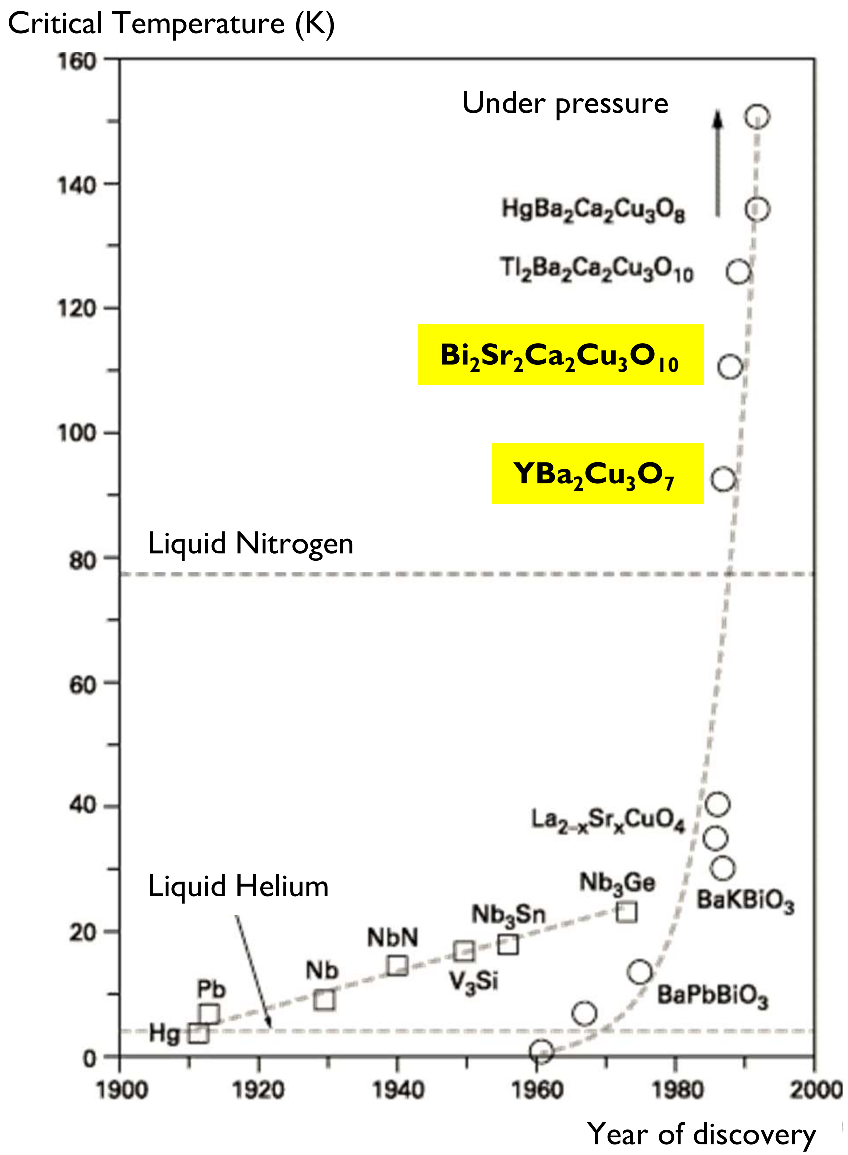
- They are the future for superconductors in Electrical Engineering applications
- Why?
  - High current-carrying capacitiy (≈ 500A/mm^2)
  - Even at high magnetic flux density (> 40T)
  - Easy to cool down (liquid Nitrogen)
- Present limitations
  - Cost
  - Difficulty to produce high length for coated conductors

High Temperature Superconductors

$(Tl_4Pb)Ba_2MgCu_8O_{13+}$	277 K	2010
$(Sn_5In)Ba_4Ca_2Cu_{11}O_y$	218 K	
$HgBa_2Ca_2Cu_3O_8$	135 K	
$Tl_2Ba_2Ca_2Cu_3O_{10}$	128 K	
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110 K	1988
$SnBa_4Y_2Cu_5O_x$	107 K	
$Pb_3Sr_4Ca_3Cu_6O_x$	106 K	
$YSrCa_2Cu_4O_{8+}$	101 K	
$AuBa_2Ca_3Cu_4O_{11}$	99 K	
$YBa_2Cu_3O_7$	92 K	1987
$Bi_2Sr_2CaCu_2O_8$	85 K	
$GdFeAsO_{1-x}$	53,5 K	2008
MgB_2	39 K	2001
$(La_{1.85}Ba_{.15})CuO_4$	30 K	1986
Nb_3Sn	18 K	
NbN	16,1 K	
C (Nanotubes)	15 K	
$Nb_{0.6}Ti_{0.4}$	9,8 K	
Nb	9,25 K	
$SrTiO_3$	0,35 K	







- Massif supraconducteur:
  - bloc mono ou polycristallin de taille centimétrique
  - Possibilité de « piéger » de très important champ magnétique (record du monde: 17.6 T à 26 K)
  - Facile à démagnétiser (réchauffer jusqu'à la température critique)
  - Peut être utilisé à la température de l'hydrogène liquide (20 K) ou celle de l'azote liquide (77 K)

➢ Une bonne alternative aux aimants permanents à base de terre rare

Lévitation d'un massif supraconducteur commercial en GaBaCuO refroidie par de l'azote liquide au dessus d'un aimant permanant

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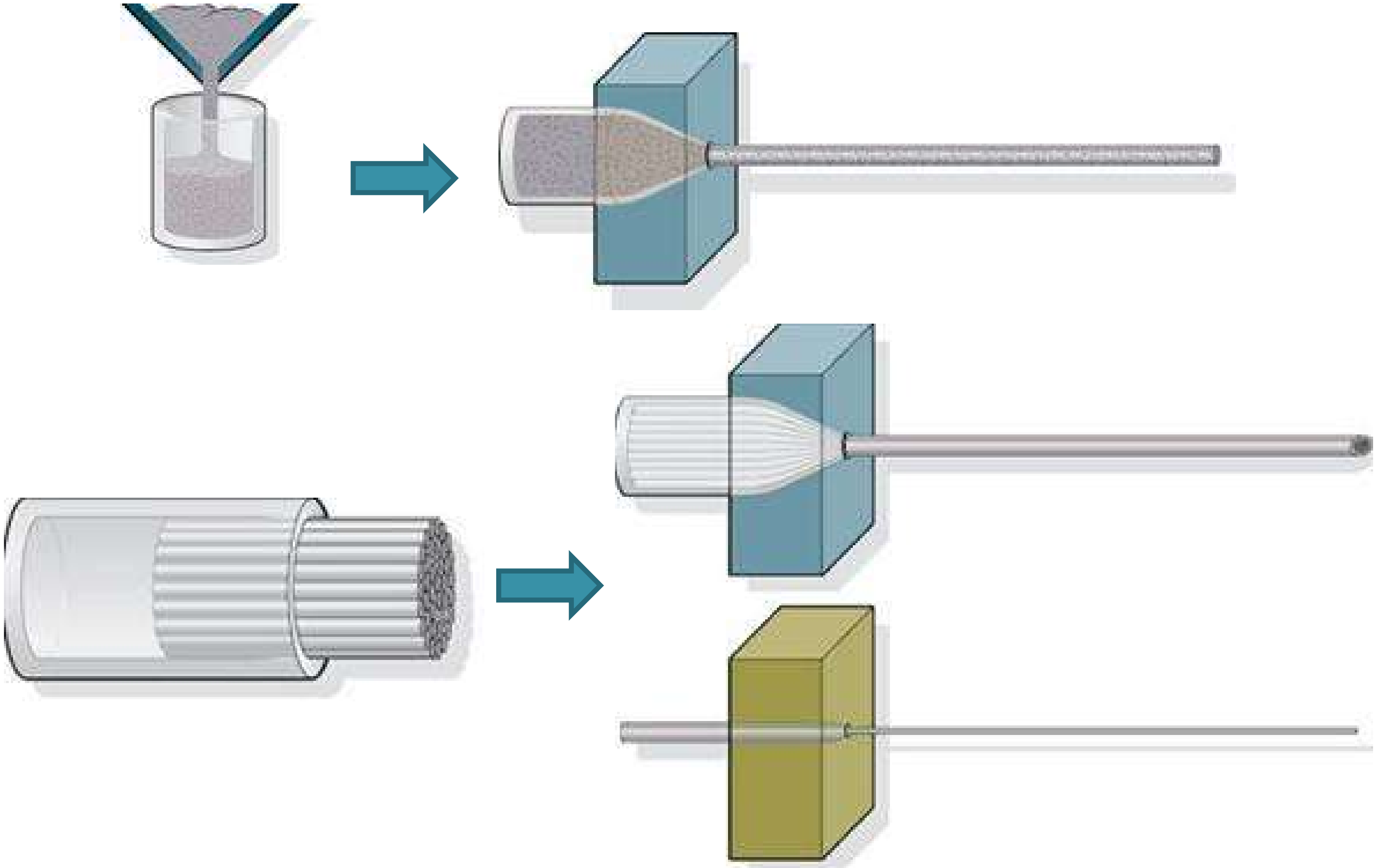
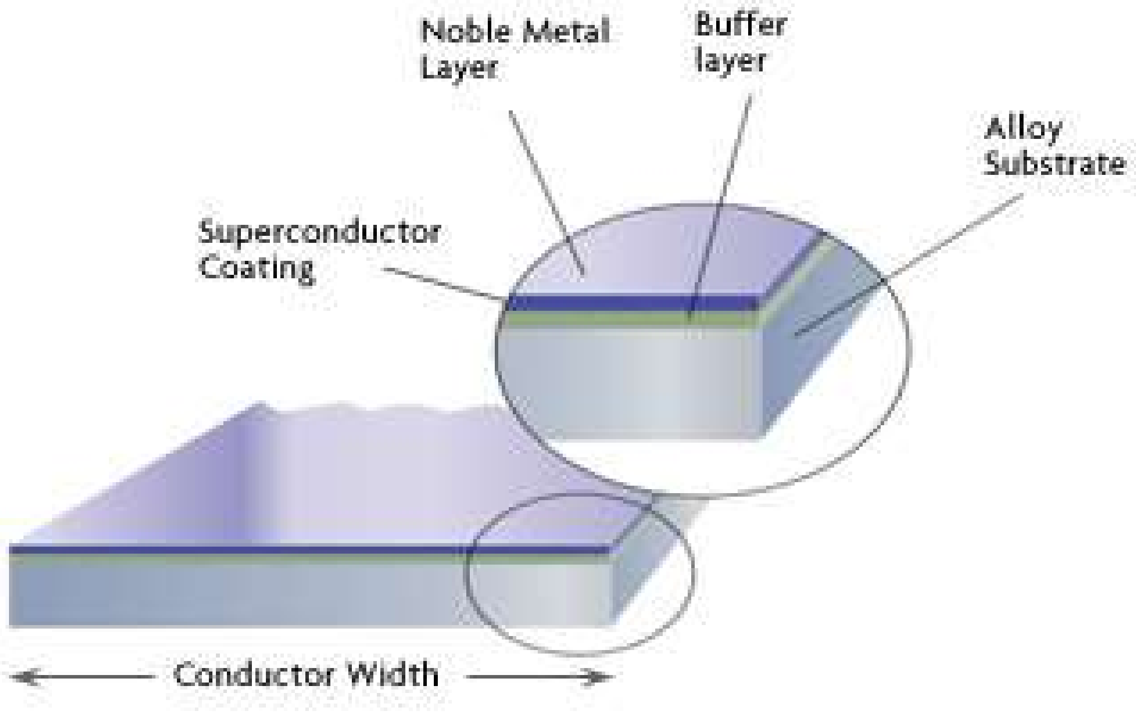
BiSrCaCuO **HTS TAPE**

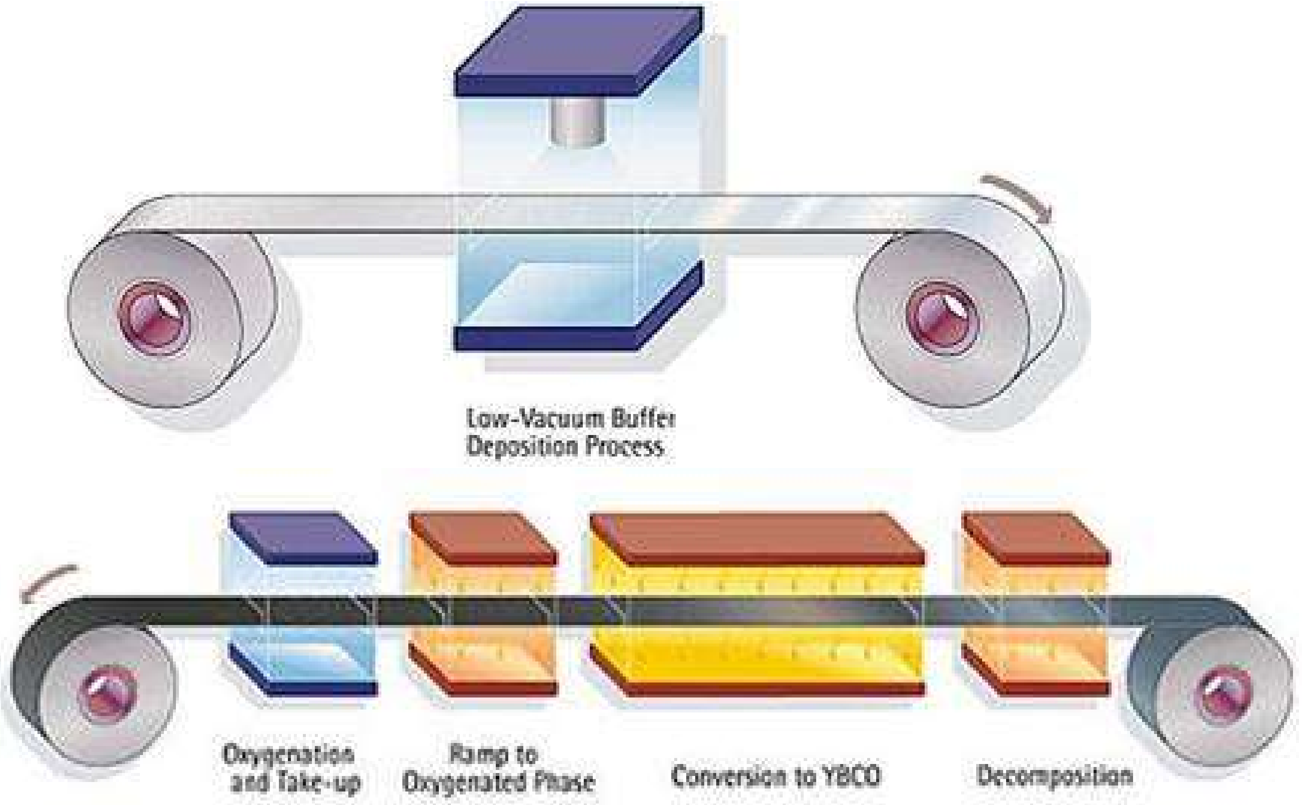


– Ic ~200A 77K

YBaCuO COATED HTS TAPE



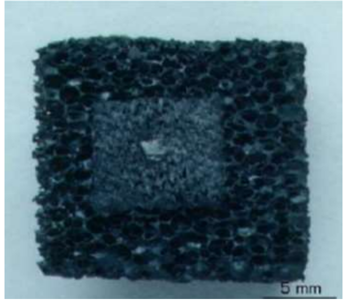
YBaCuO **COATED HTS TAPE**



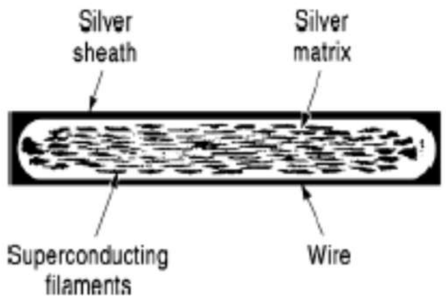
Characterization of HTS material

- Bulks

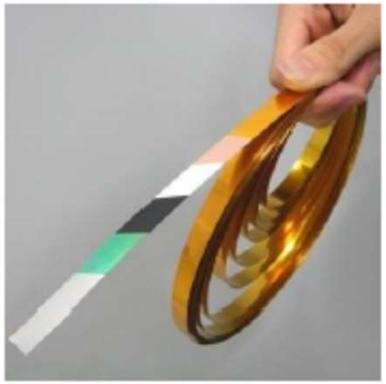
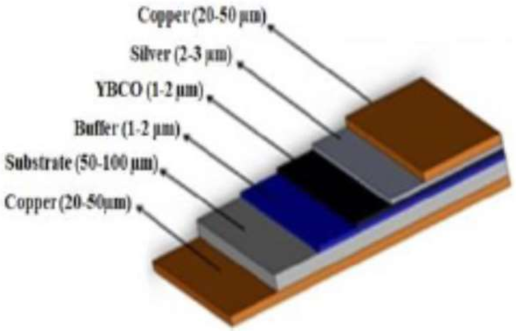
- T_c, $H_{c,irr}$, J_c for small samples
- Bp for entire bulks

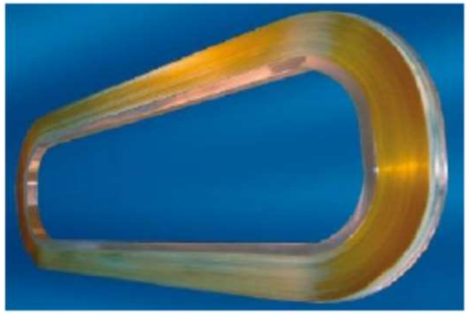

- Tapes and coils



BSCCO

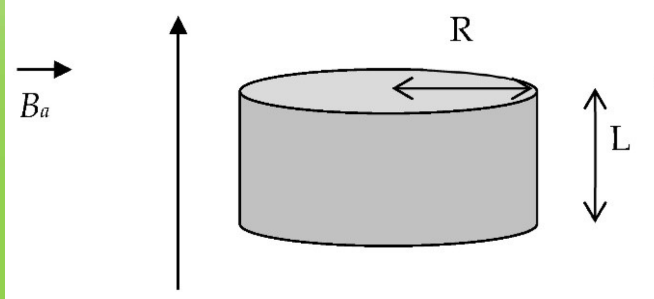



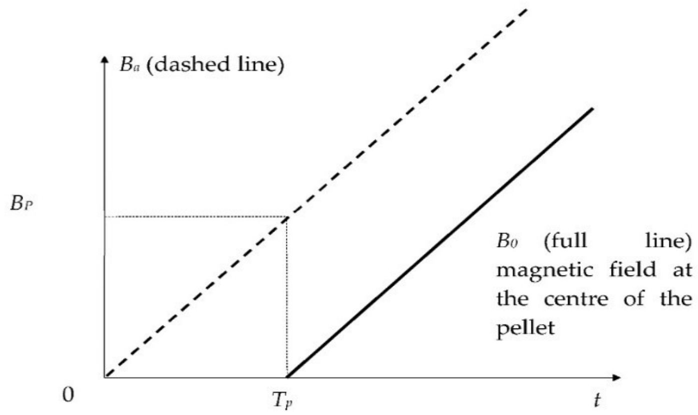
YBCO

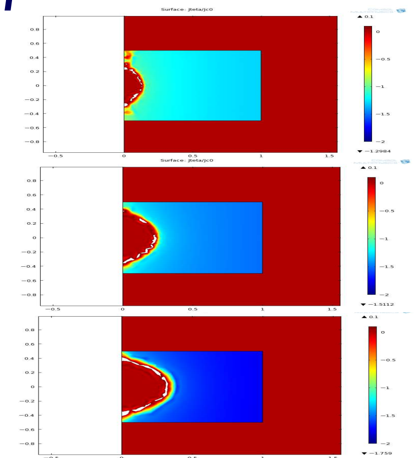


HTS bulks characterization

- Complete penetration magnetic field *Bp*







- With Bean model

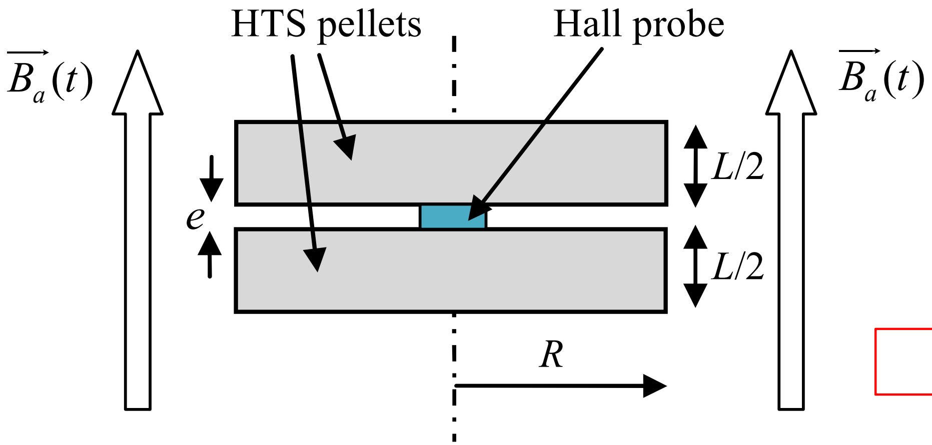
$$B_P = \frac{\mu_0 J_C \cdot L}{4} \cdot ln\left(\frac{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} + R}{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} - R}\right),$$

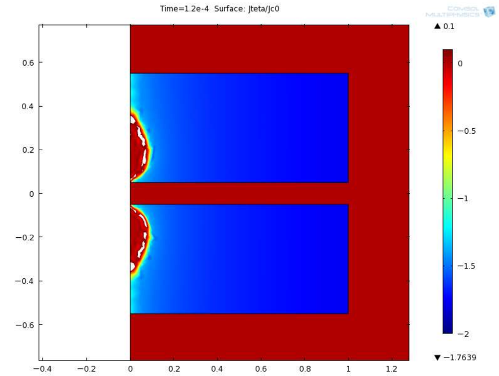
- With Power law model

$$E = E_C\left(\frac{J}{J_C}\right)^n = \frac{E_C \cdot}{J_C}\left(\frac{J}{J_C}\right)^{n-1} J$$

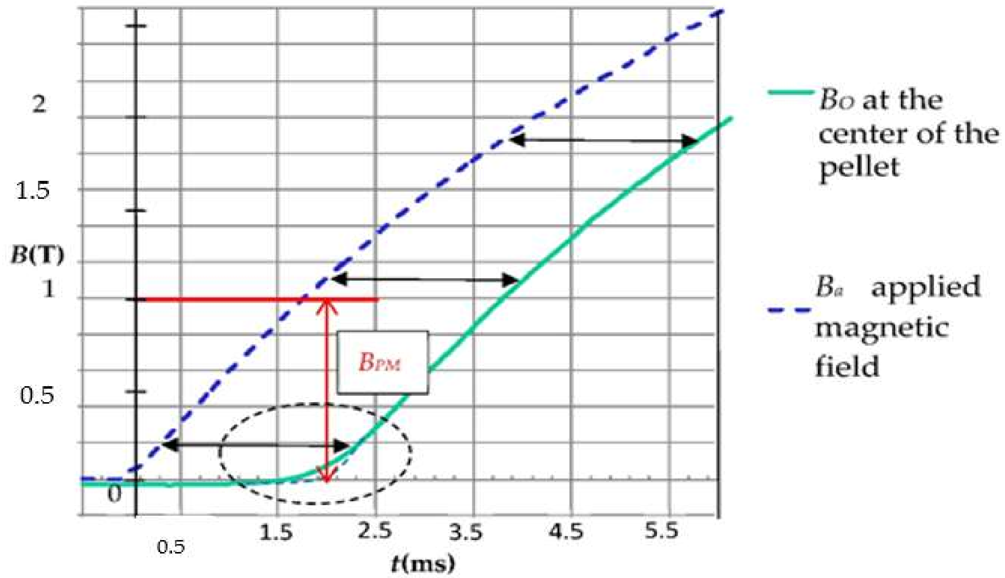
$$B_P = \frac{\mu_0 J_C \cdot L}{4} \cdot ln\left(\frac{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} + R}{\sqrt{R^2 + \left(\frac{L}{2}\right)^2} - R}\right)\left(1 + \frac{\alpha\, lnV_b + \beta}{n}\right),$$

- # Experimental characterization

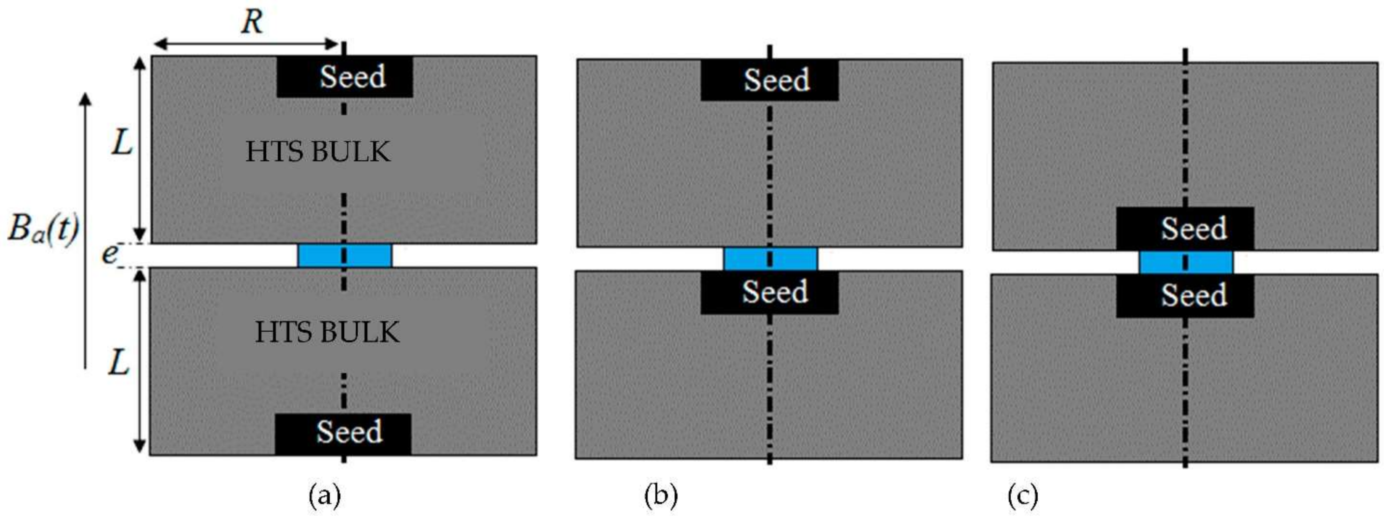




$$B_{Pm}(e = 1mm) = B_P(0.0350Ln(L) + 0.7233)$$



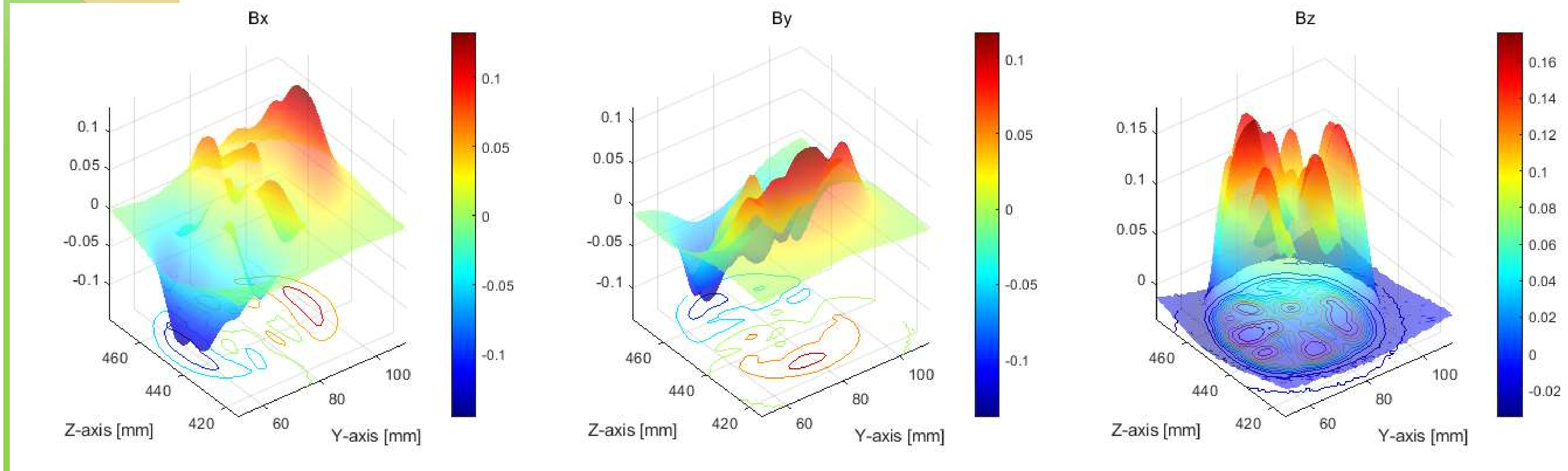
- Position of seeds



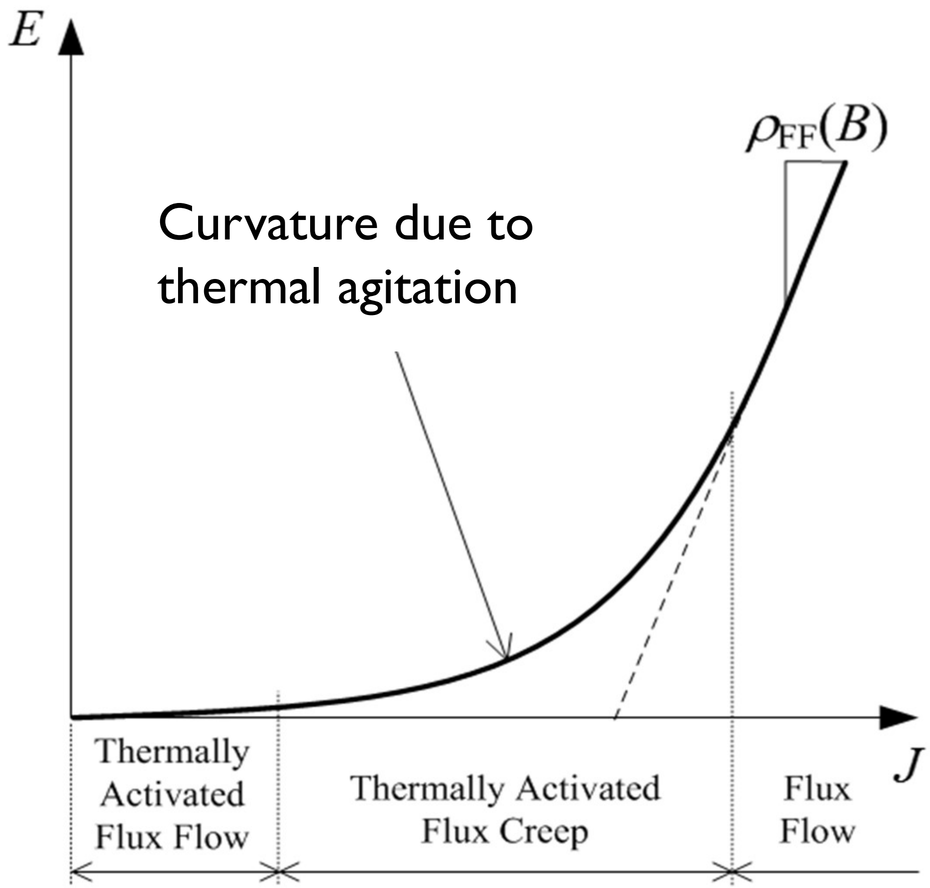
	Case (a)	Case (b)	Case (c)
T_P (10^{-3} s)	0.93	1.32	1.4
B_{PM} (T)	2.57	3.02	3.1

HTS bulks characterization

HTS bulks characterization



Electrical behavior of HTS tape



$$E(J,B,T) = E_c \left(\frac{J}{J_c(B,T)} \right)^{n(B,T)}$$

with $E_c = 1\mu V/cm$

- Mainly 2 parameters:
  J_c and n
- which depend on B and T

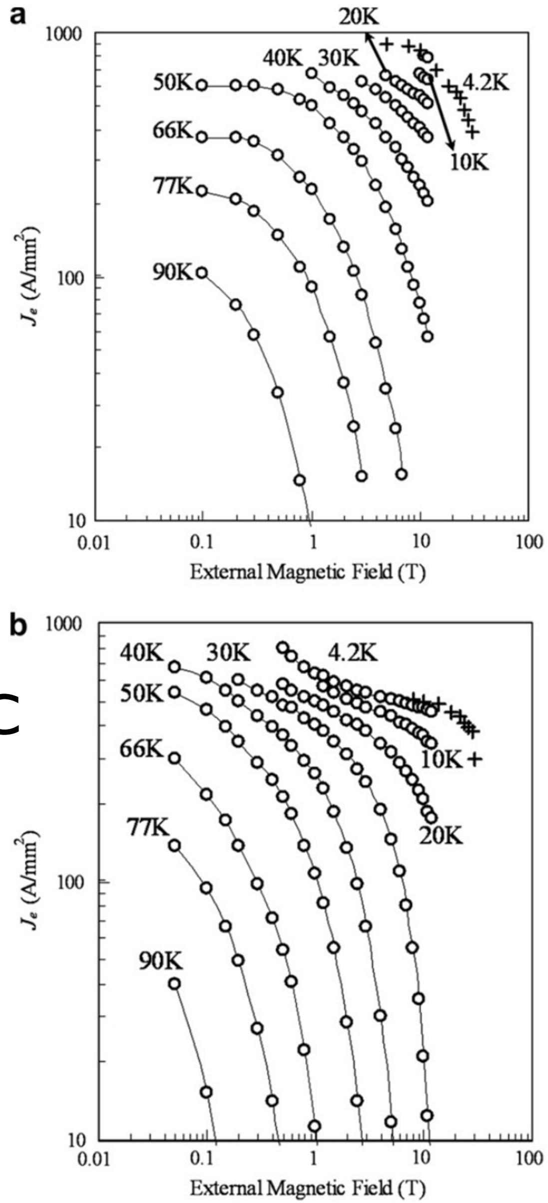
Characterization of HTS tapes

- *Jc*, *n* and their dependencies are crucial for the modeling and the design of devices
- Each characterization method has its own limitations:
  - Assumptions,
  - Experimental protocol,
  - Sensibility of measurements devices…

CHARACTERIZATION OF HTS TAPES

Electrical experimental determination of *Ic*

- Generally 4 points method described in IEC 61788-3; -24 and -26

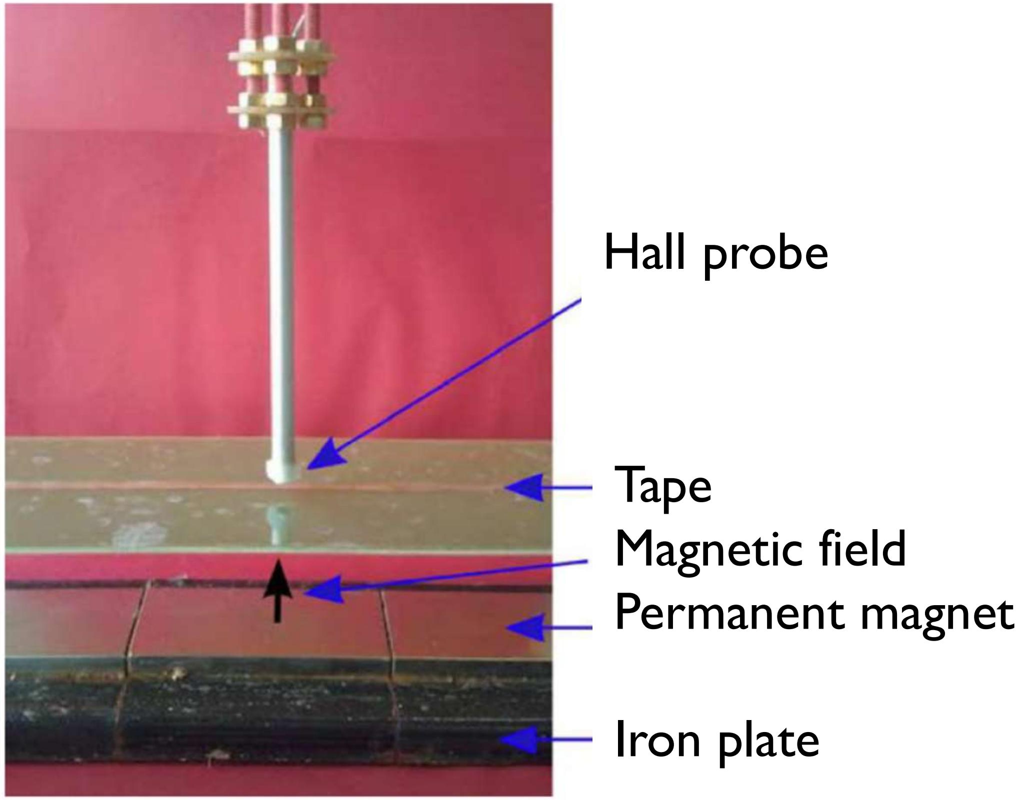


	Type H high-J_e
Width	~4.2 mm
Average thickness	~0.22 mm
I_c (77 K, self-field)	140–180 A
J_e (77 K, self-field)	15–20 kA/cm^2

Progress in performance of DI-BSCCO family
N. Ayai a,*, S. Kobayashi a, M. Kikuchi a, T. Ishida a, J. Fujikami a, K. Yamazaki a, S. Yamade a, K. Tatamidani a,
K. Hayashi a, K. Sato a, H. Kitaguchi b, H. Kumakura b, K. Osamura c, J. Shimoyama d,
H. Kamijyo e, Y. Fukumoto e
Physica C 468 (2008) 1747–1752

CHARACTERIZATION OF HTS TAPE

Magnetic experimental determination of Ic

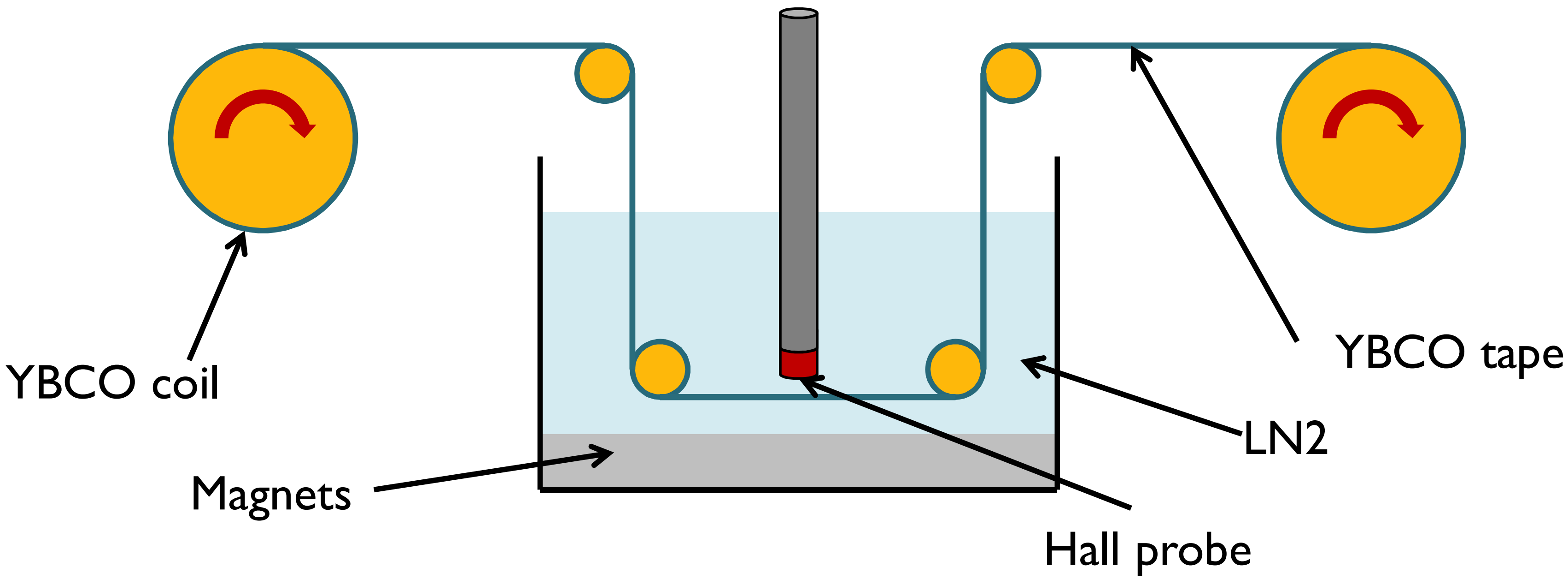


Experimental set up in GREEN lab

Tapestar, THEVA

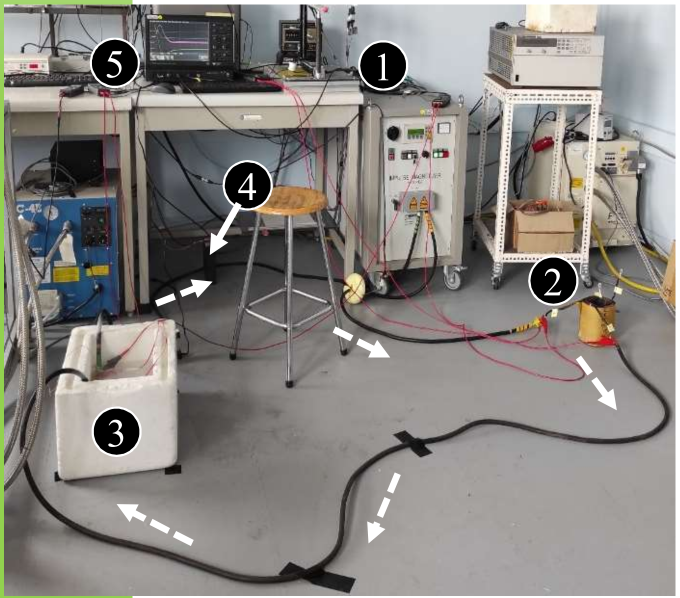
Experimental apparatus for reel-to-reel critical current measurements

- This non-destructive method could be used to characterize a YBCO tape along its length.



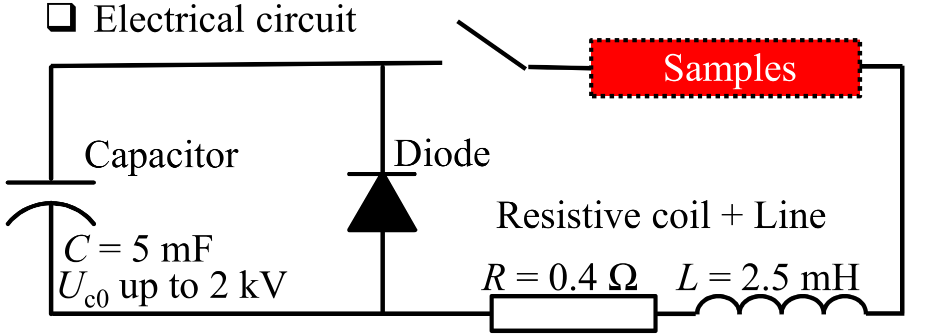
Electrical and thermal stability test of tapes under overcurrent conditions

❑ Setup and measurement



1 Capacitor bank
2 Resistive coil
3 Samples+ Cryostat
4 Current clamp
5 Oscilloscope with differential probe

❑ Electrical circuit

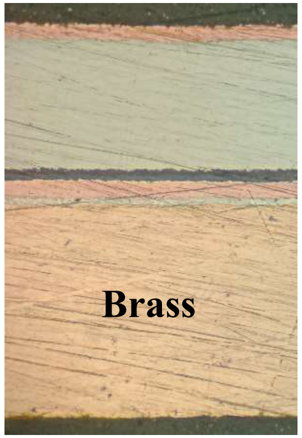


❑ Geometric parameters

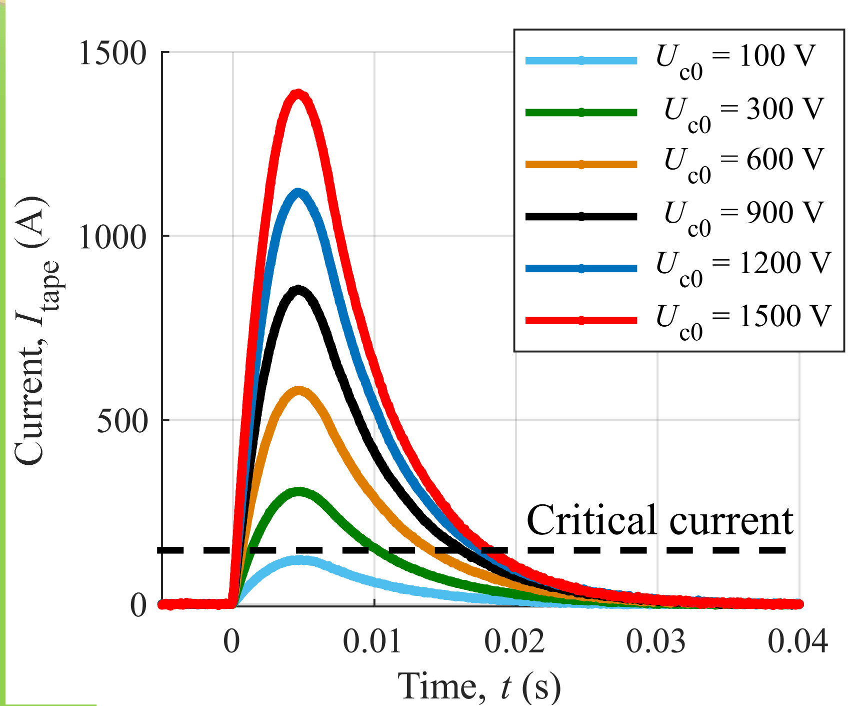
Tape reference: THEVA Pro-Line TPL 2301

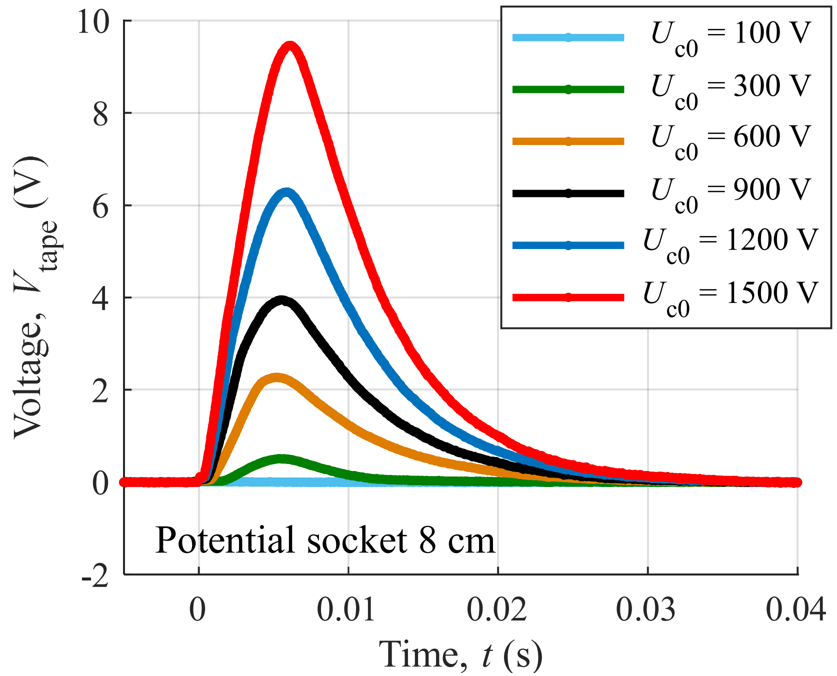
Brass	157.4 µm
Upper Copper	13 µm
YBaCuO	8.5 µm
Hastelloy	96.4 µm
Lower copper	10.9 µm
Total thickness ≈ 286.2 µm	
Tape width 3 mm	

❑ Microscopic view



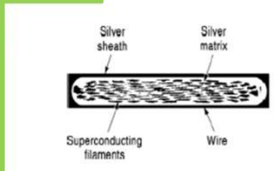
Electrical and thermal stability test of tapes under overcurrent conditions



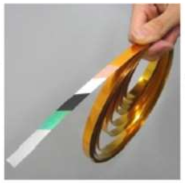


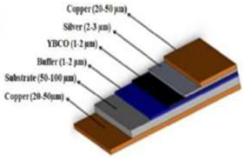
- Pulses up to 10 times the critical sample current
- 30 second relaxation time after each pulse

FROM HTS TAPES TO HTS COILS…

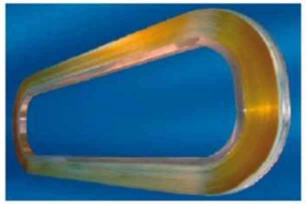


BSCCO





YBCO



Tape

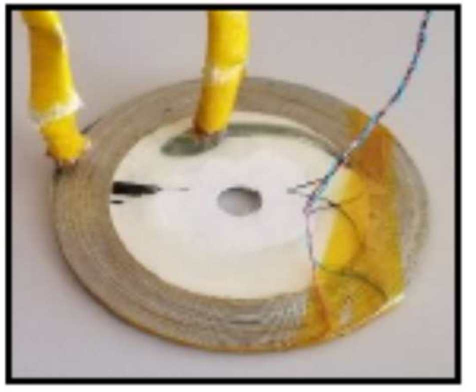
Experimental determination of Ic

HTS Coil

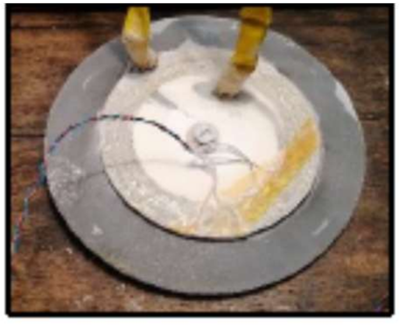
Experimental determination of I?
Critical current ?
Quench current ?
Which Standards ?
Which application?

•DC Characterization of HTS coils

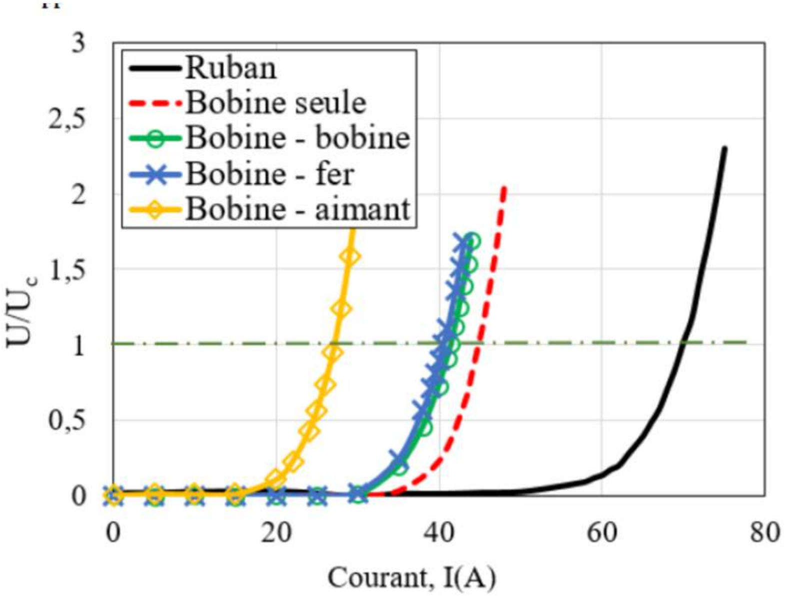
- HTS BiSCCO coil



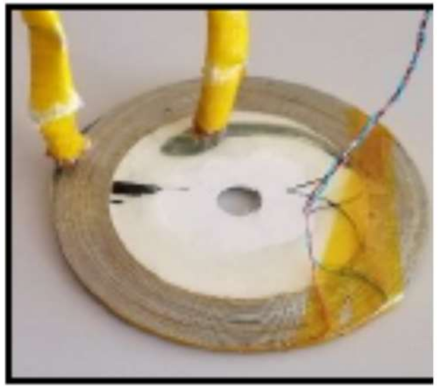
- Close to iron

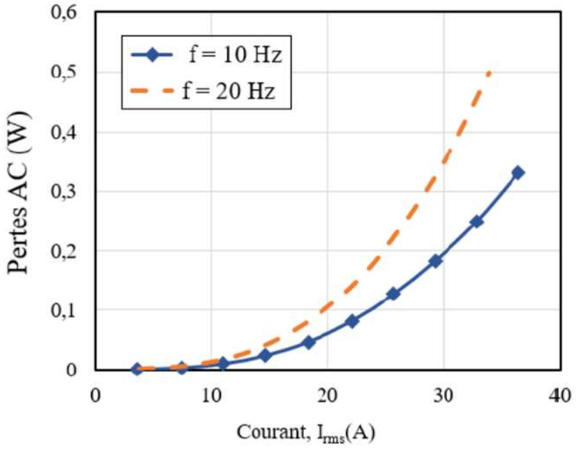


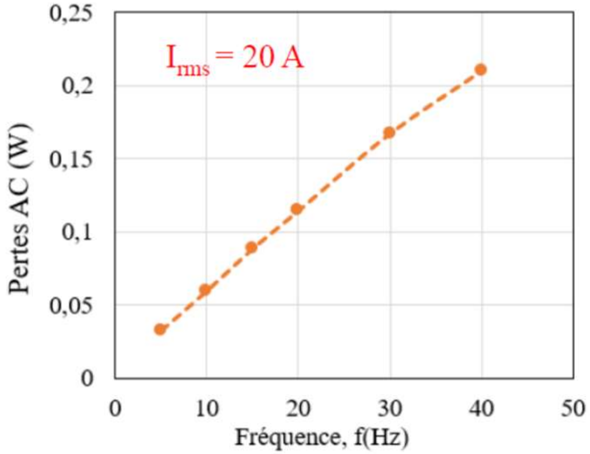
- Close to permanent magnet

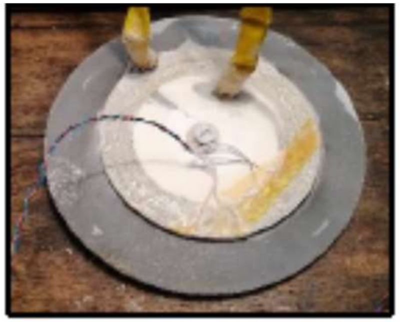


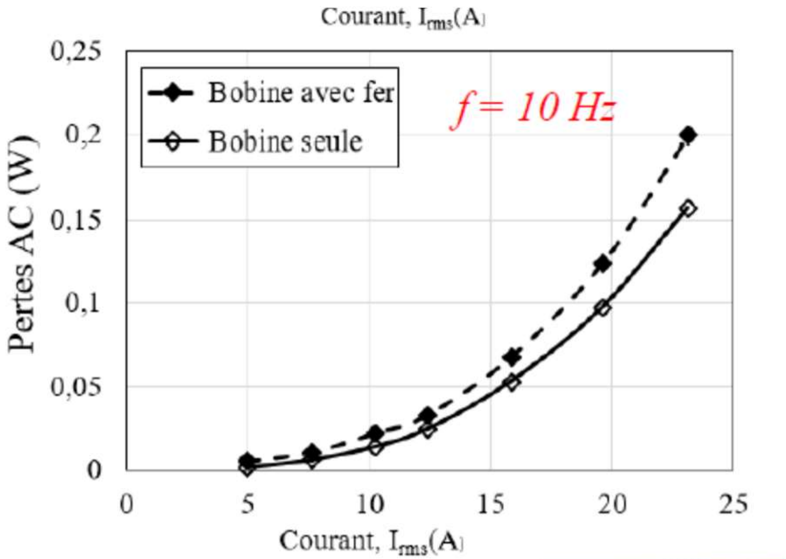
• AC loss Characterization of HTS coils











Applications in electrical engineering

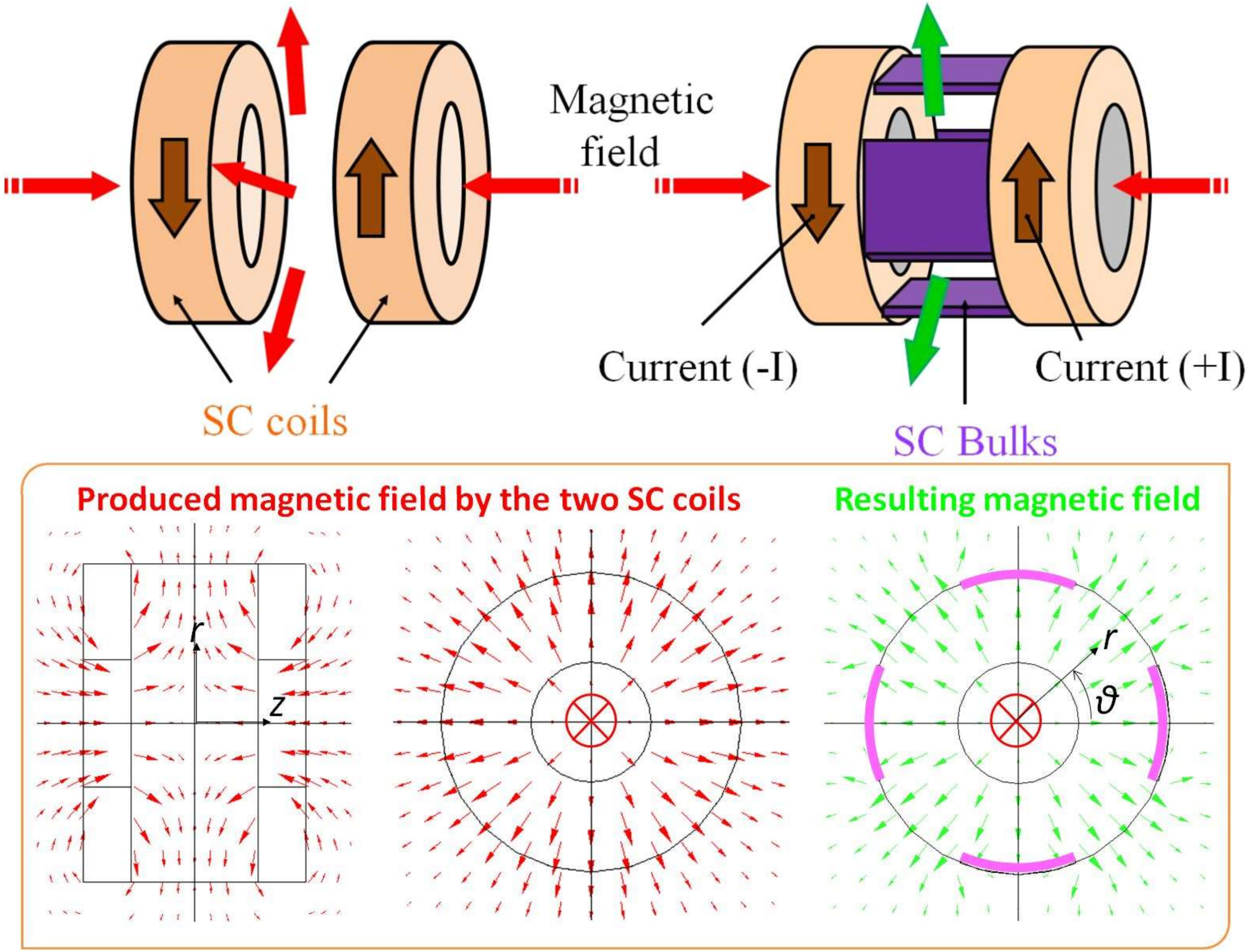
- **Superconducting motors**
- Cables
- Superconducting fault current limiter and power filter
- … other applications

Motors design and realization

- 8 motor’s projects since 2006
- 6 motor’s realizations since 2006
- 2 ANR grants (French National Research Agency)
- 3 national project (SCRYPT, Airbus, Safran…)
- 1 European project (IMOTHEP)
- Most of our industrial collaborations (GE, Jeumont, Safran, Airbus…)

The original idea of the GREEN

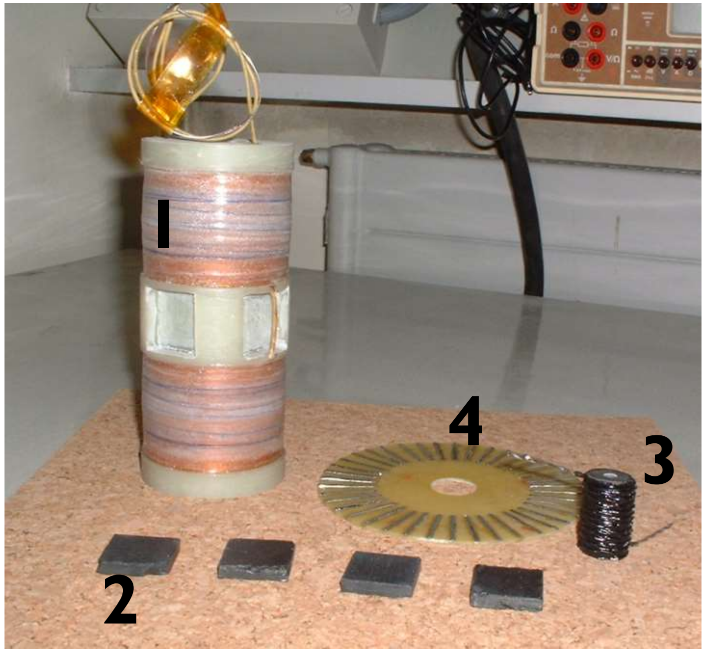
- Superconducting magnetic field concentration motor



1st - study of an inductor in 2002

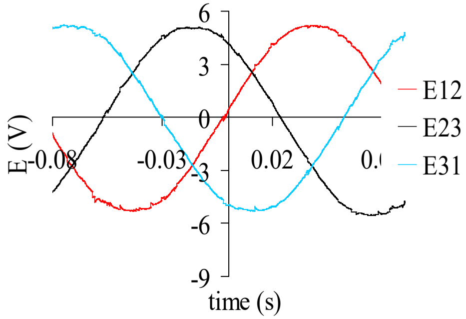
Coils:

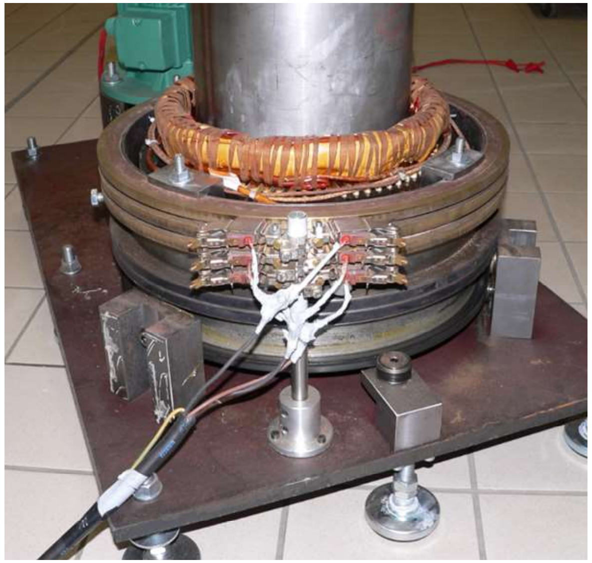
- NbTi wires
- 260 A
- 880 turns



(1) Coils
(2) YBaCuO HTS bulks
(3) Protection resistor
(4) Hall probe connections

2nd - realization in 2006





ULCOMAP Project in 2008

250 kW	2 poles pairs	HTS inductor
1500 rpm	50 Hz	Bi 2223
400 V	Xd : 0.22 pu	30 A
360 A	Xq : 0.1 pu	30 K

- Zenergy Power GmbH
- Werkstoffzentrum Rheinbach GmbH
- Futura composite
- Converteam (now GE)
- Silesian University
- University of Nancy

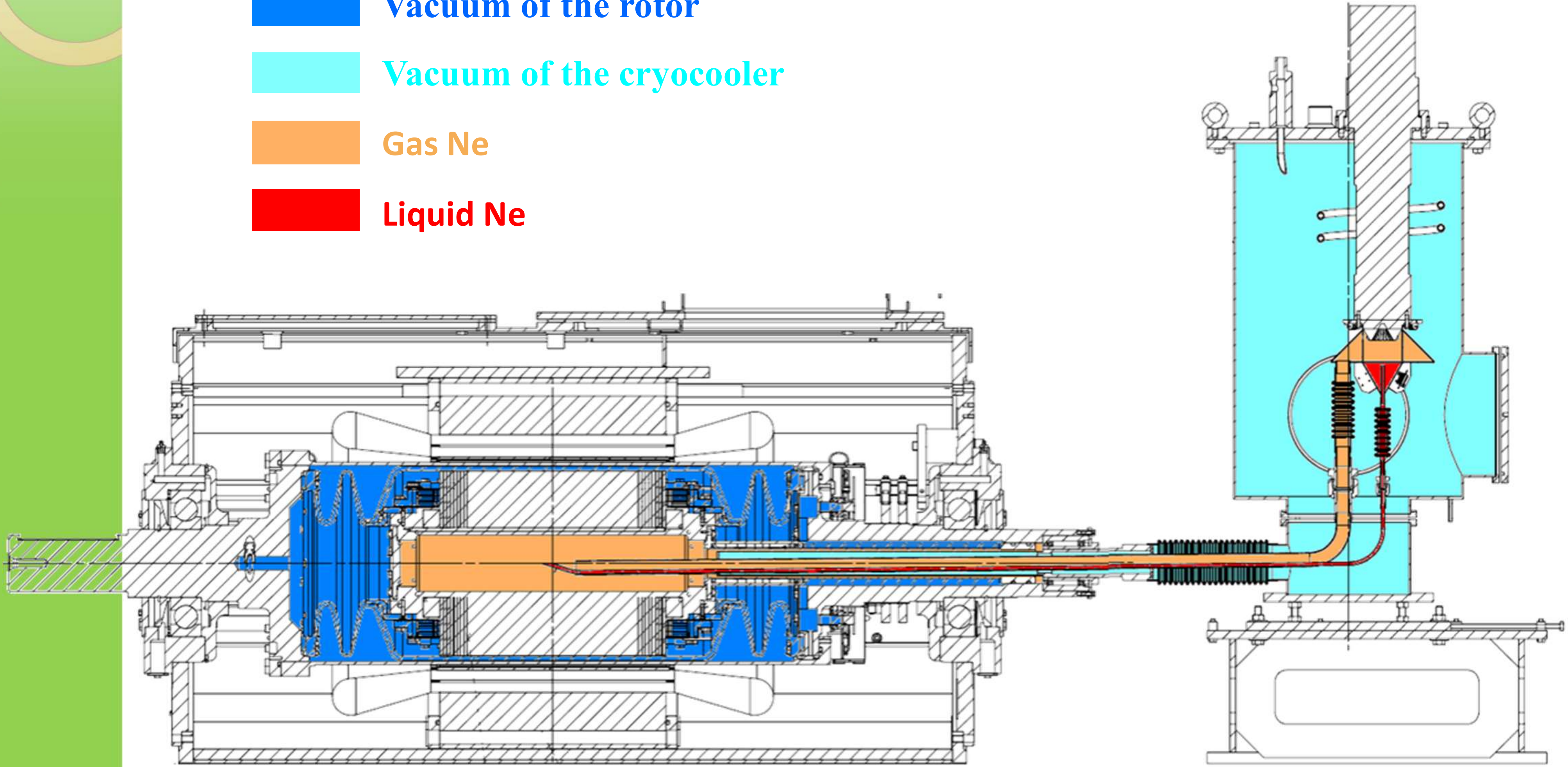
ULCOMAP Project

Vacuum of the rotor

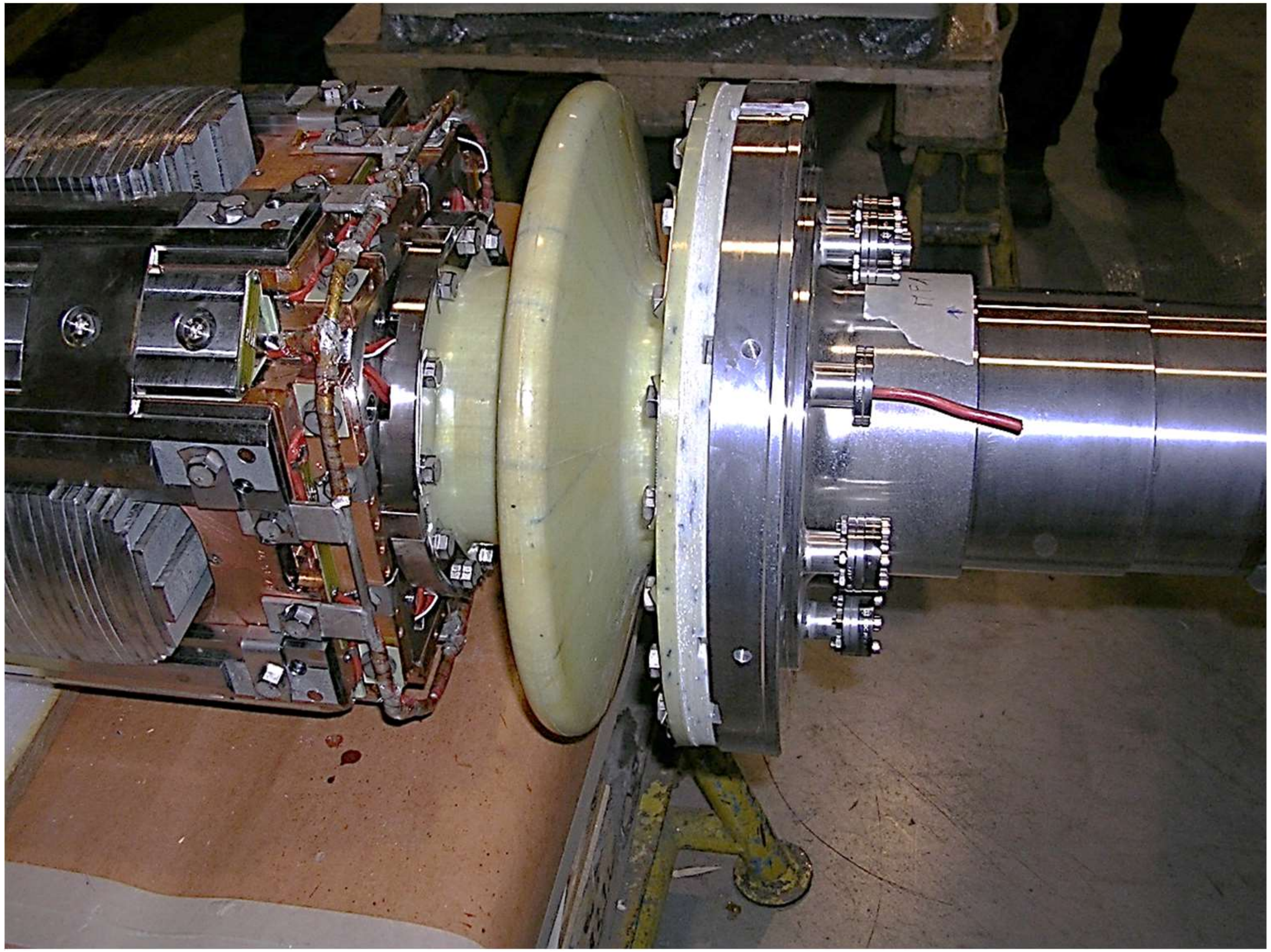
Vacuum of the cryocooler

Gas Ne

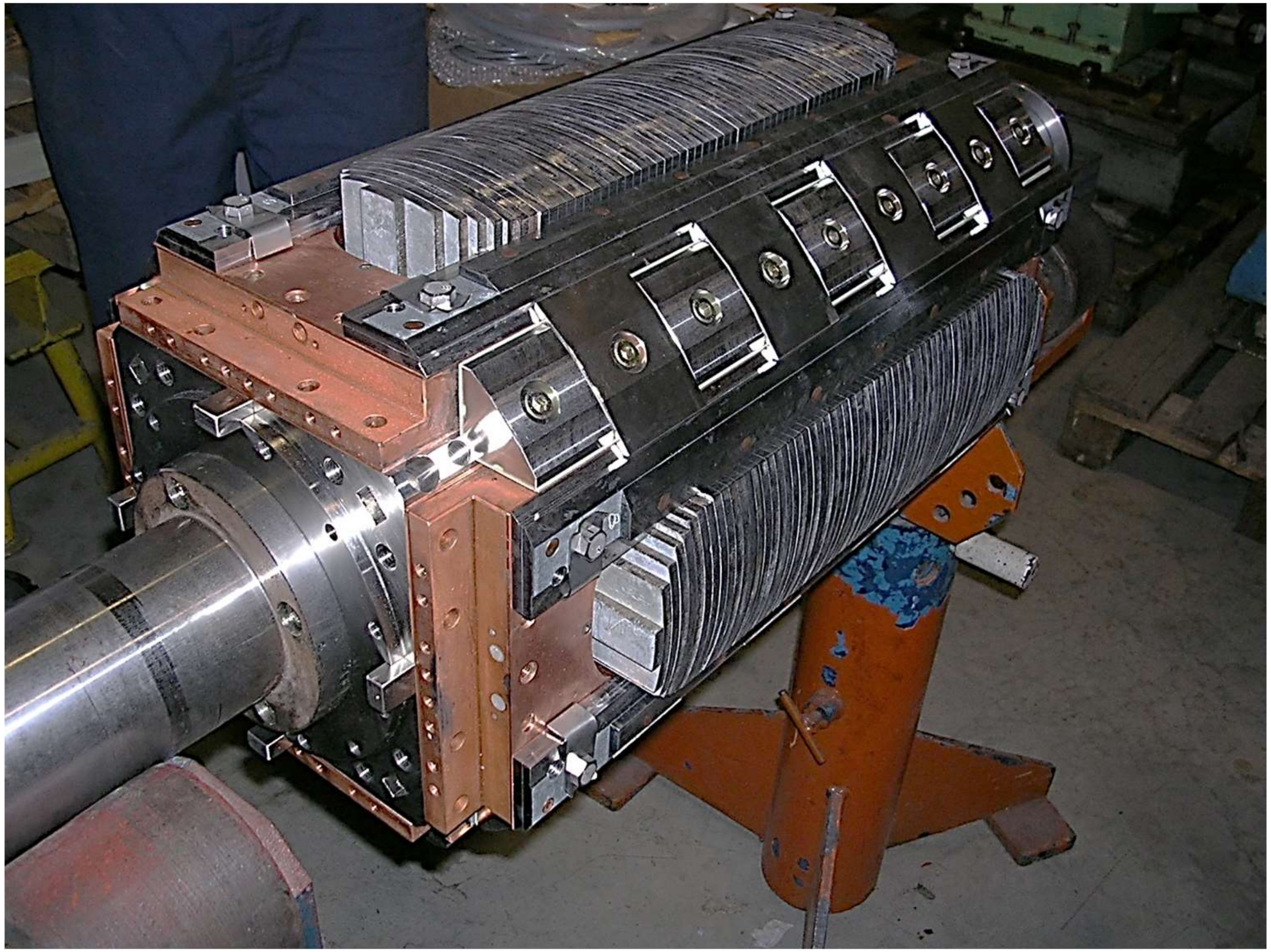
Liquid Ne



ULCOMAP Project



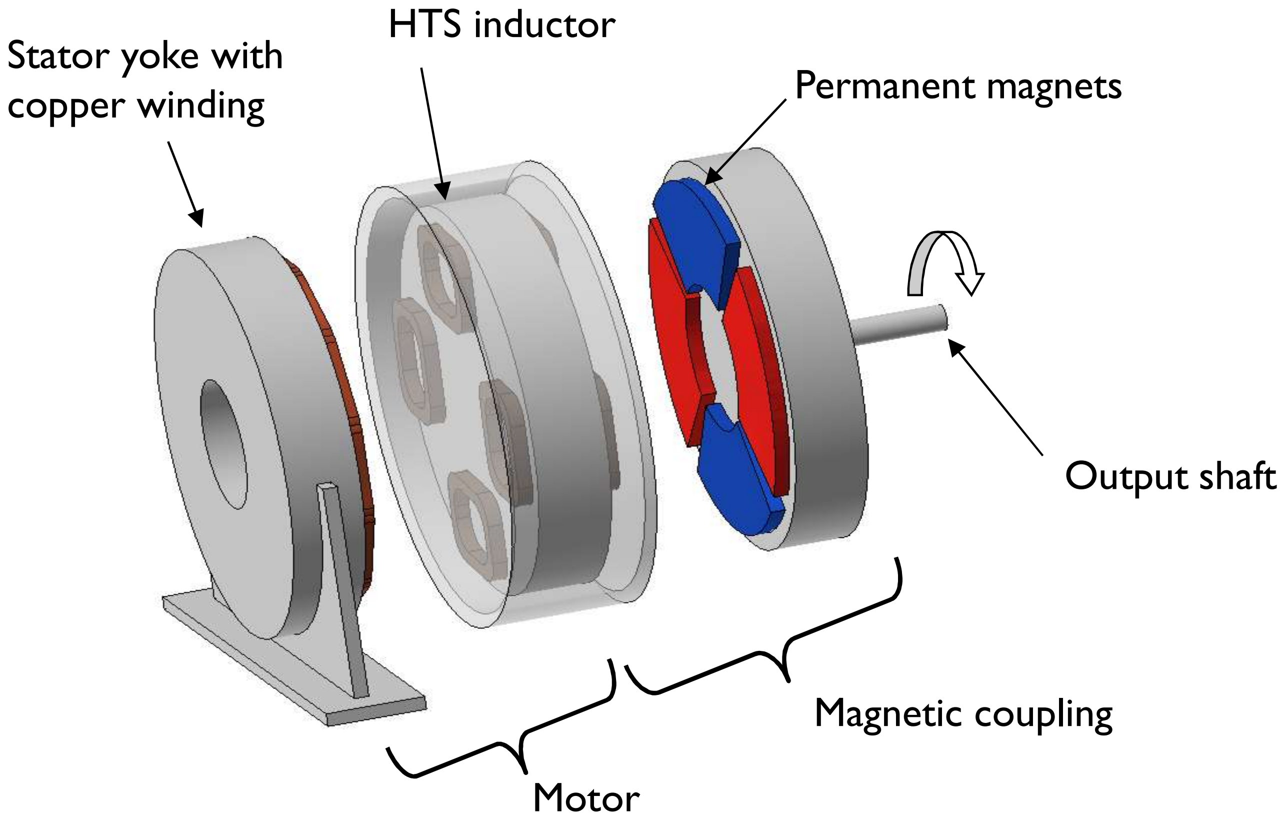
ULCOMAP Project



New kind of axial HTS motor including a superconducting magnetic coupling for naval propulsion

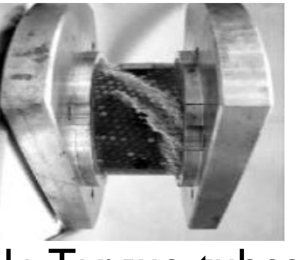
June 2014 – B. Dolisy's thesis

Motor principle



ADVANTAGES

- Increases the compactness
- Better efficiency
- Torque transmission without contact



No Torque-tubes

Design and manufacture

Goals and difficulties

Goals

- Study the behavior of the complete system (motor and magnetic coupling)
- Validate the superconducting tape modeling
- Increase the know-how of the laboratory

Difficulties

- Manufacturing the stator without ferromagnetic tooth
- Winding of the superconducting coil
- Design the rotating parts in cryogenic atmosphere

Design and manufacture

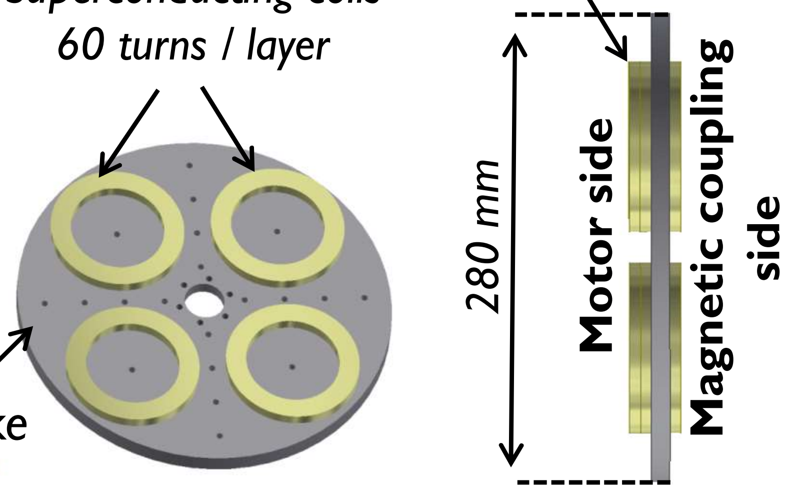
Design choices

Restrict the external motor dimensions

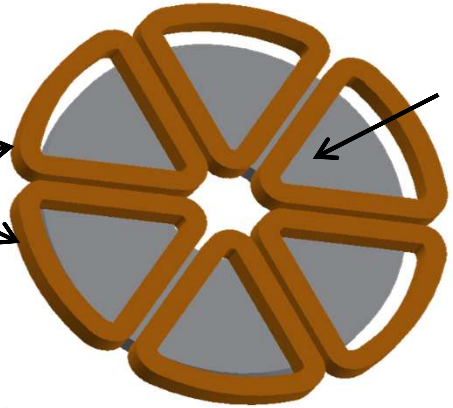
→ Round HTS coils

Øint = 70 mm minimal curvature diameter

Øout = 100 mm

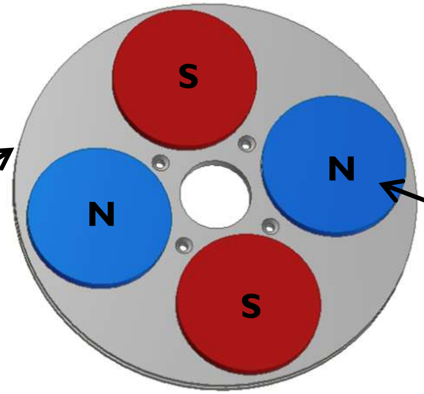


- Stator yoke with 6 copper coils



- Permanent magnets rotor

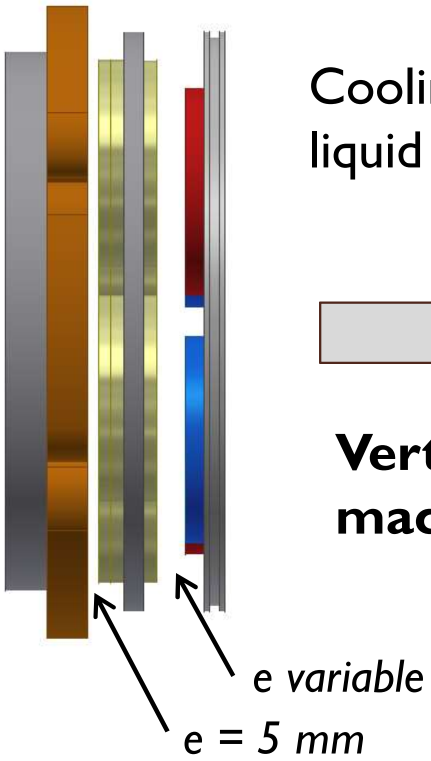
Øout = 100 mm



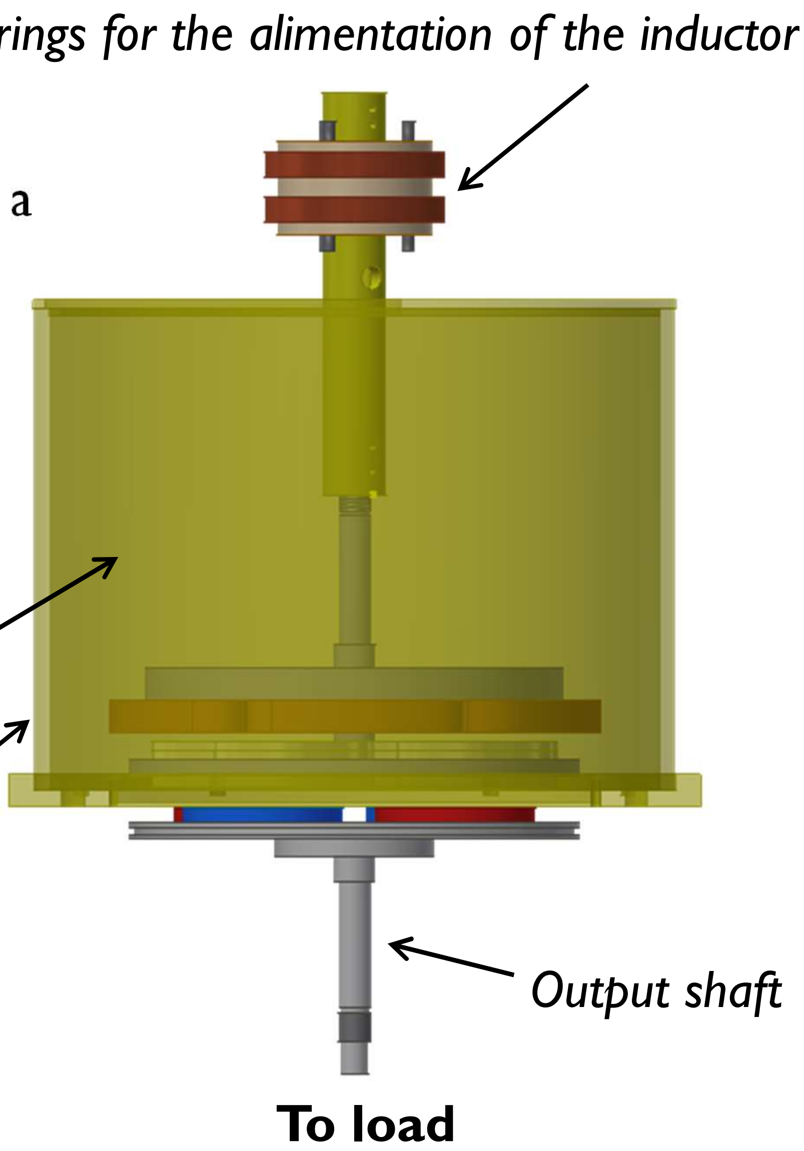
Design and manufacture

Design choices

Cooling by submersion in a liquid nitrogen bath



Vertical machine



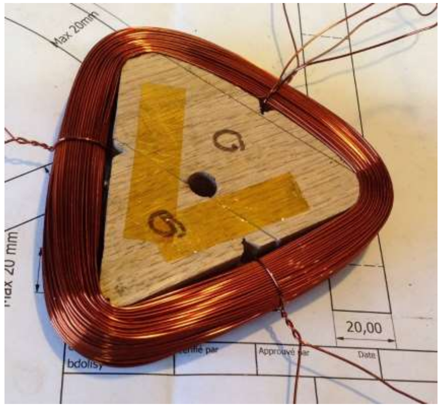
- \+ Efficient cooling of HTS coils
- \+ Easy installation
- \- High consumption of liquid nitrogen
- \- Bearings of inductor are cold
  → dry bearings

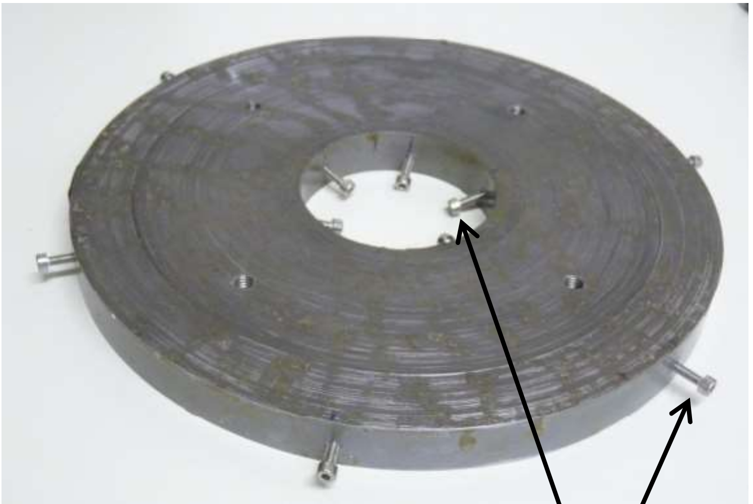
DGA

Design and manufacture

Stator with copper winding

Description	Unit	Value
Thickness of a coil	mm	15
Opening of a coil	-	60°
Conductor cross-section	mm²	0.75
Number of turns per coil	-	250
Nominal current	A	7.5
Maximum power	kW	1





FeSi Thickness 0.3 mm
Øout = 260 mm
Øint = 80 mm

Anchorage of the coils

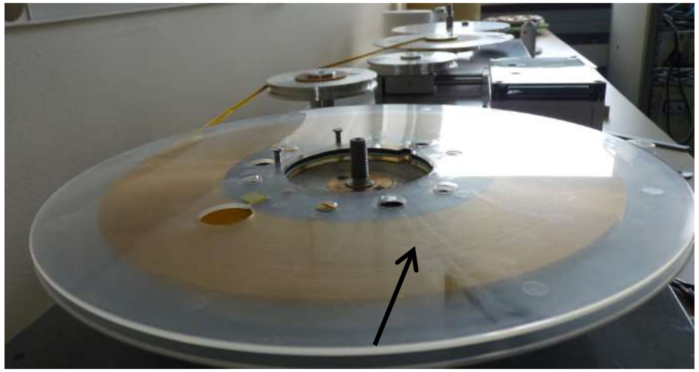
DGA

Design and manufacture

HTS inductor

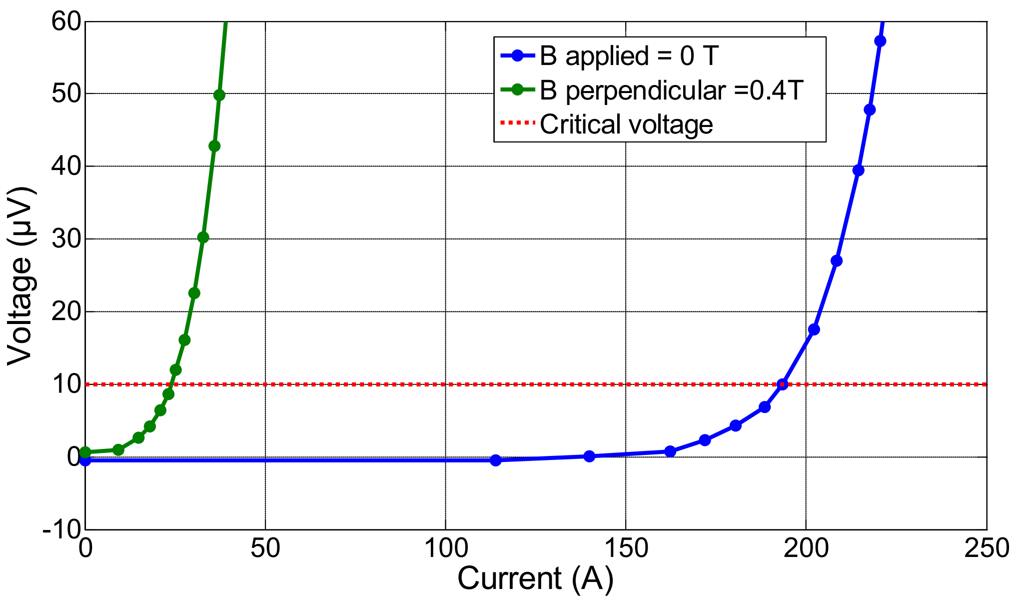
BSCCO tape

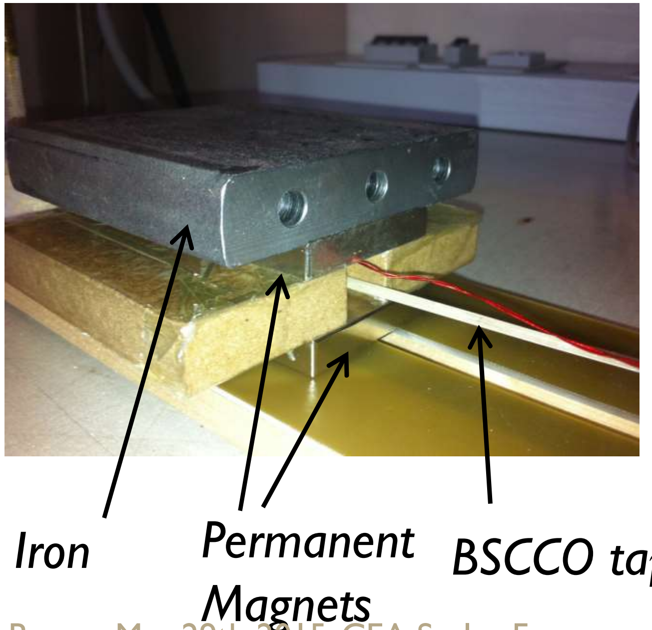
Description	Unit	Value
Thickness of the tape	mm	0.25
Width of the tape	mm	4.4
Length	m	240
Ic @ 77K Self Field	A	190



BSCCO type Hi 240 m

Characterization of a sample (10 cm) of BSCCO tape @77K

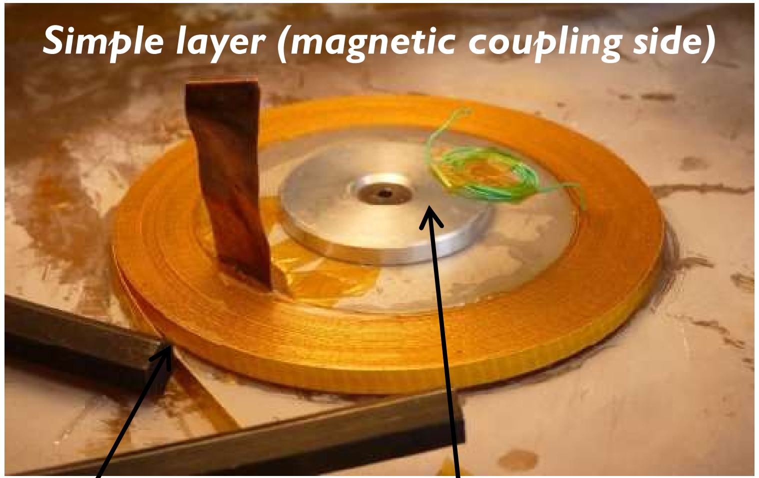




Design and manufacture

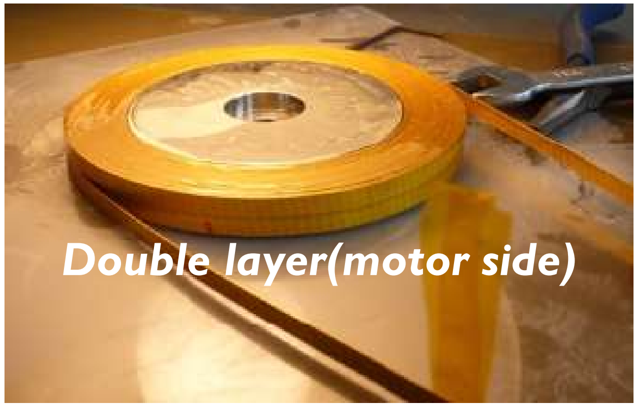
HTS inductor

Description	Unit	Value
External diameter	mm	100
Internal diameter (minimal bending diameter)	mm	70
Thickness / layer	mm	5
Turns / layer	-	60
Length / layer	m	16



Current lead

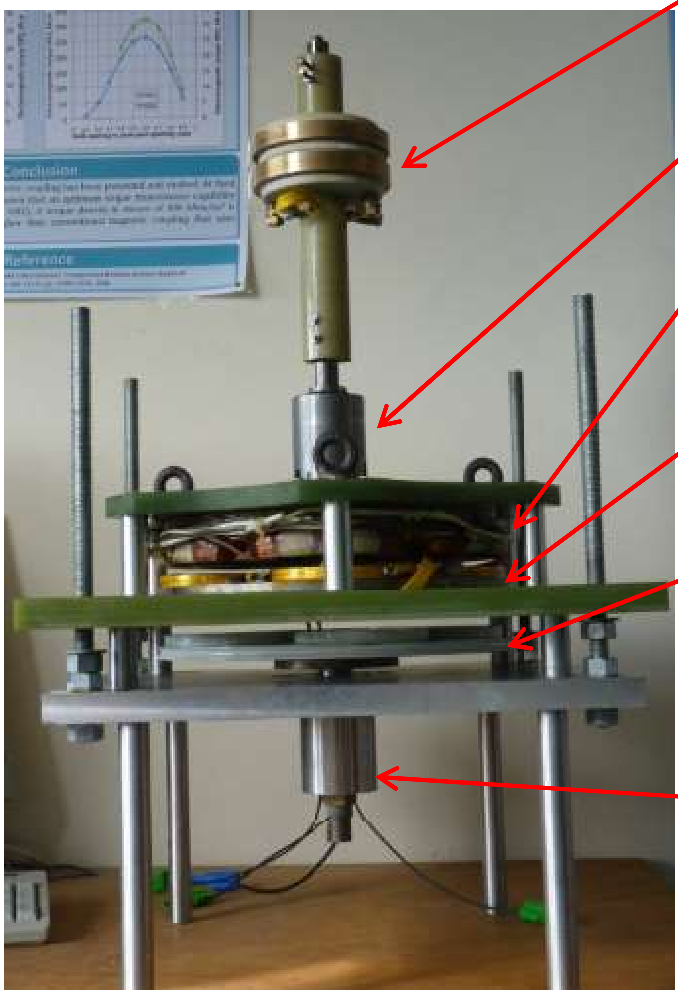
Inox core



Ferromagnetic yoke

Design and manufacture

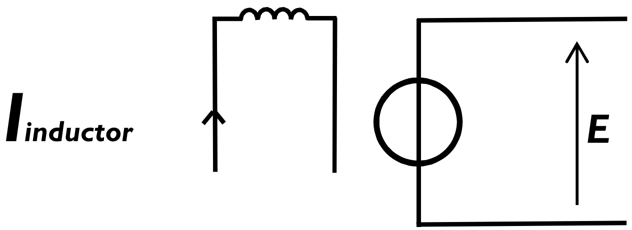
Final assembly

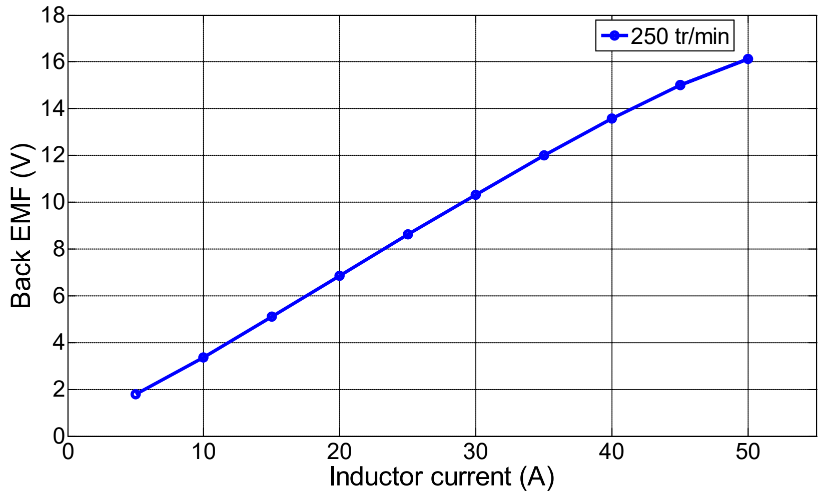


Tests

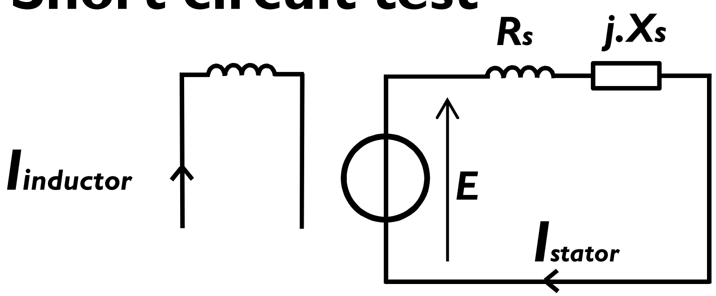
Behn-Eschenburg model

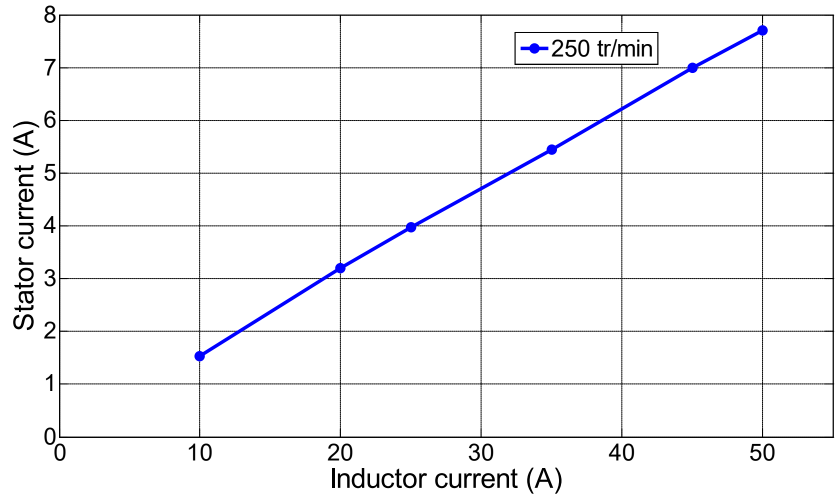
No-load test





Short circuit test





Motor parameters

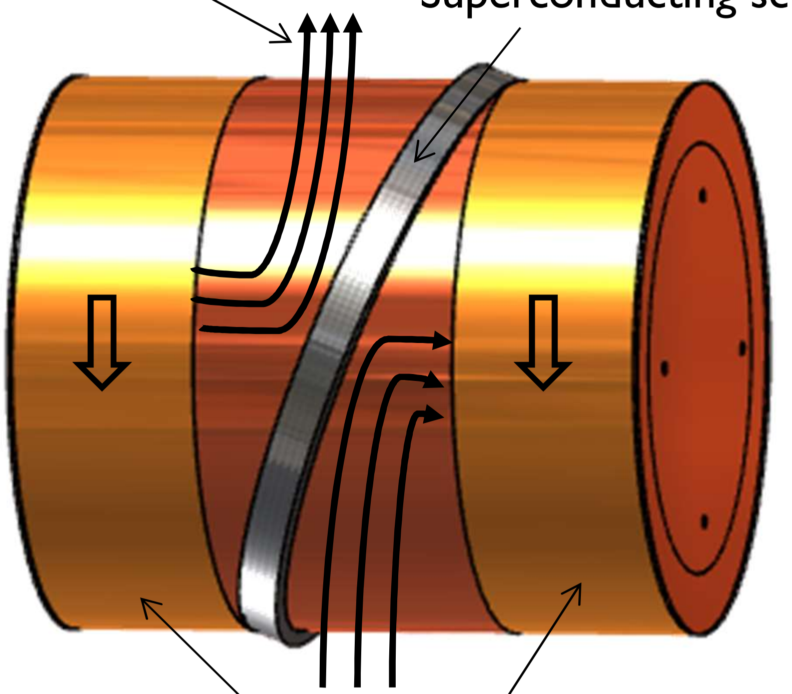
$R_s \approx 0.82\ \Omega$ $X_s \approx 1.98\ \Omega$

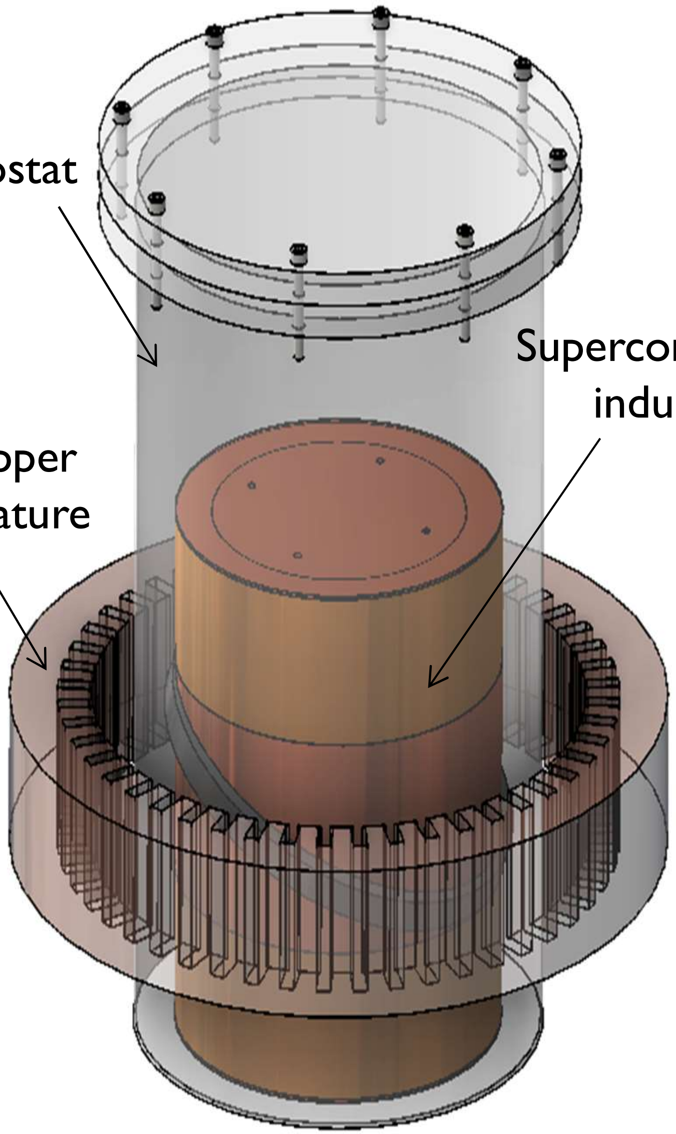
$(X_{s\ comsol} \approx 1.78\ \Omega)$

Study and realisation of a flux barrier synchronous superconducting motor

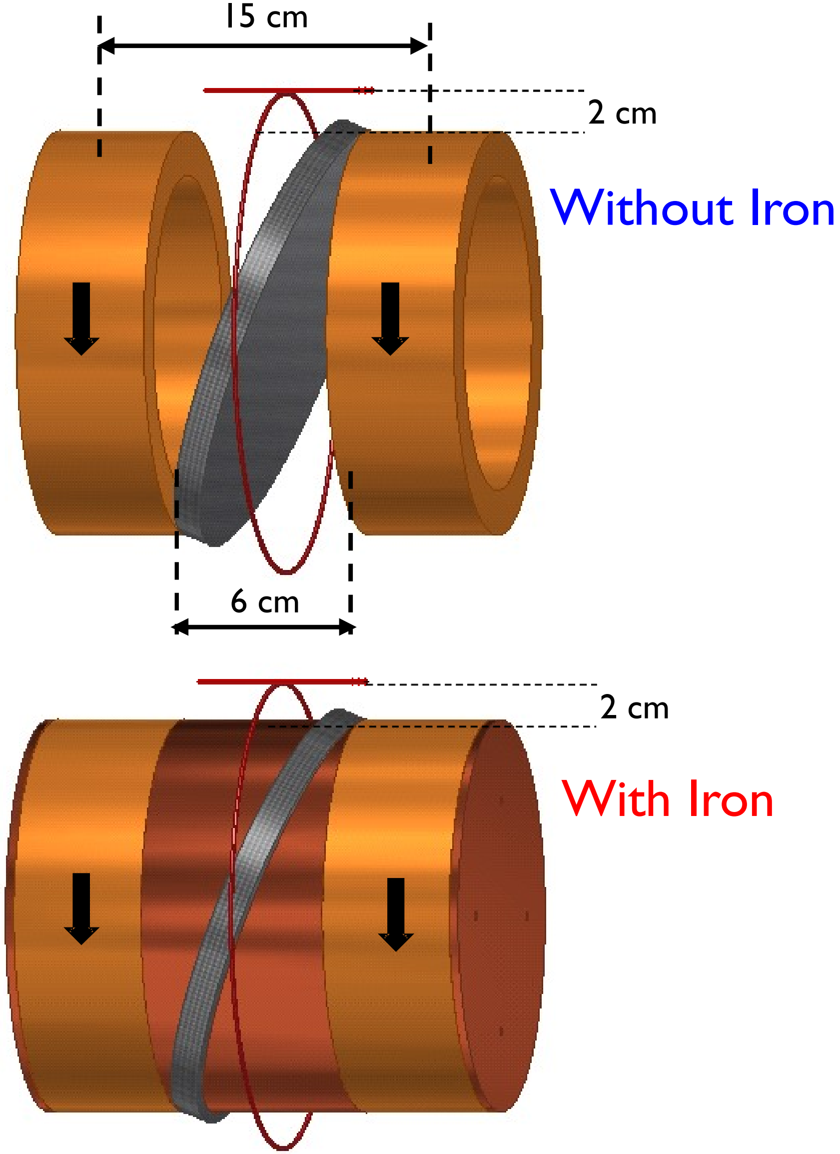
October 2014 – R. Alhasan's thesis

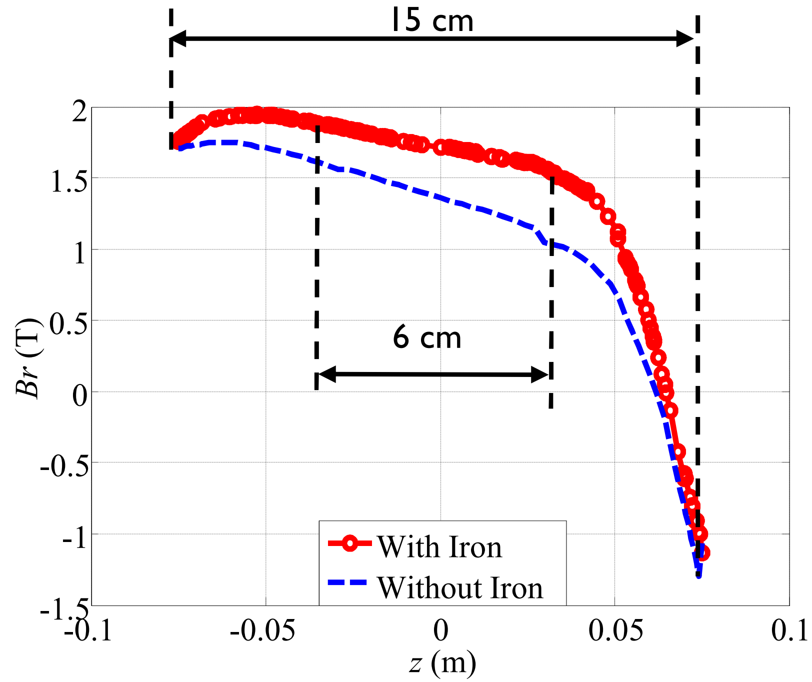
Motor principle

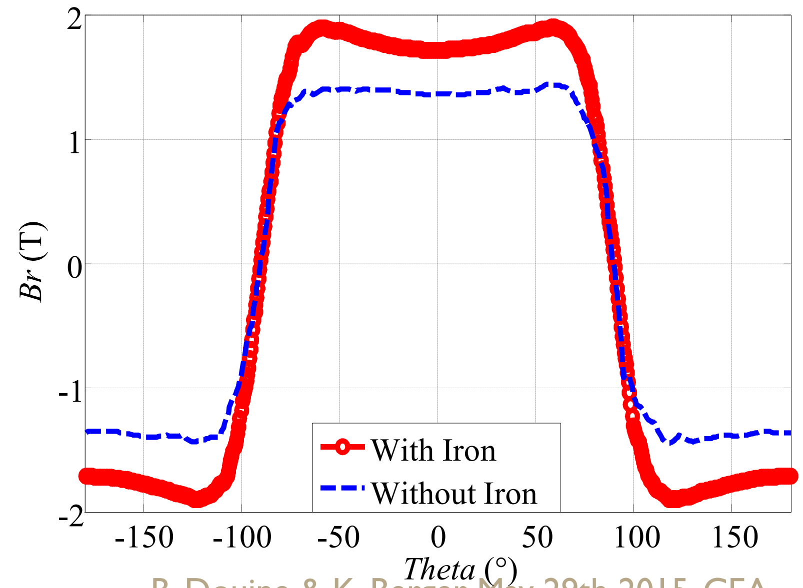




Influence of the iron



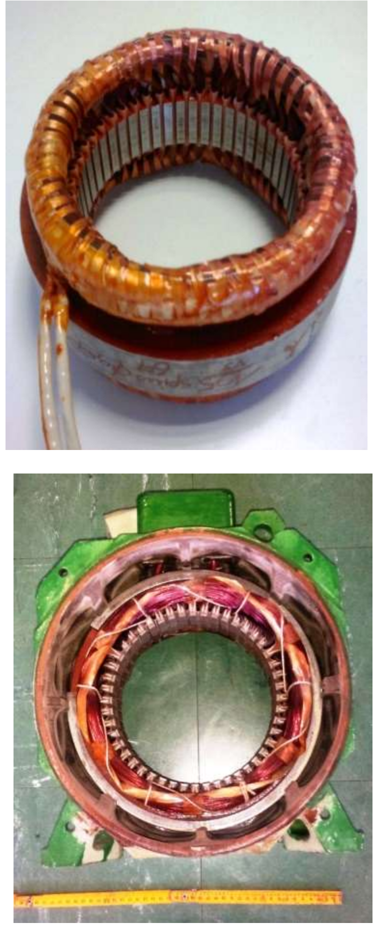




Assembly

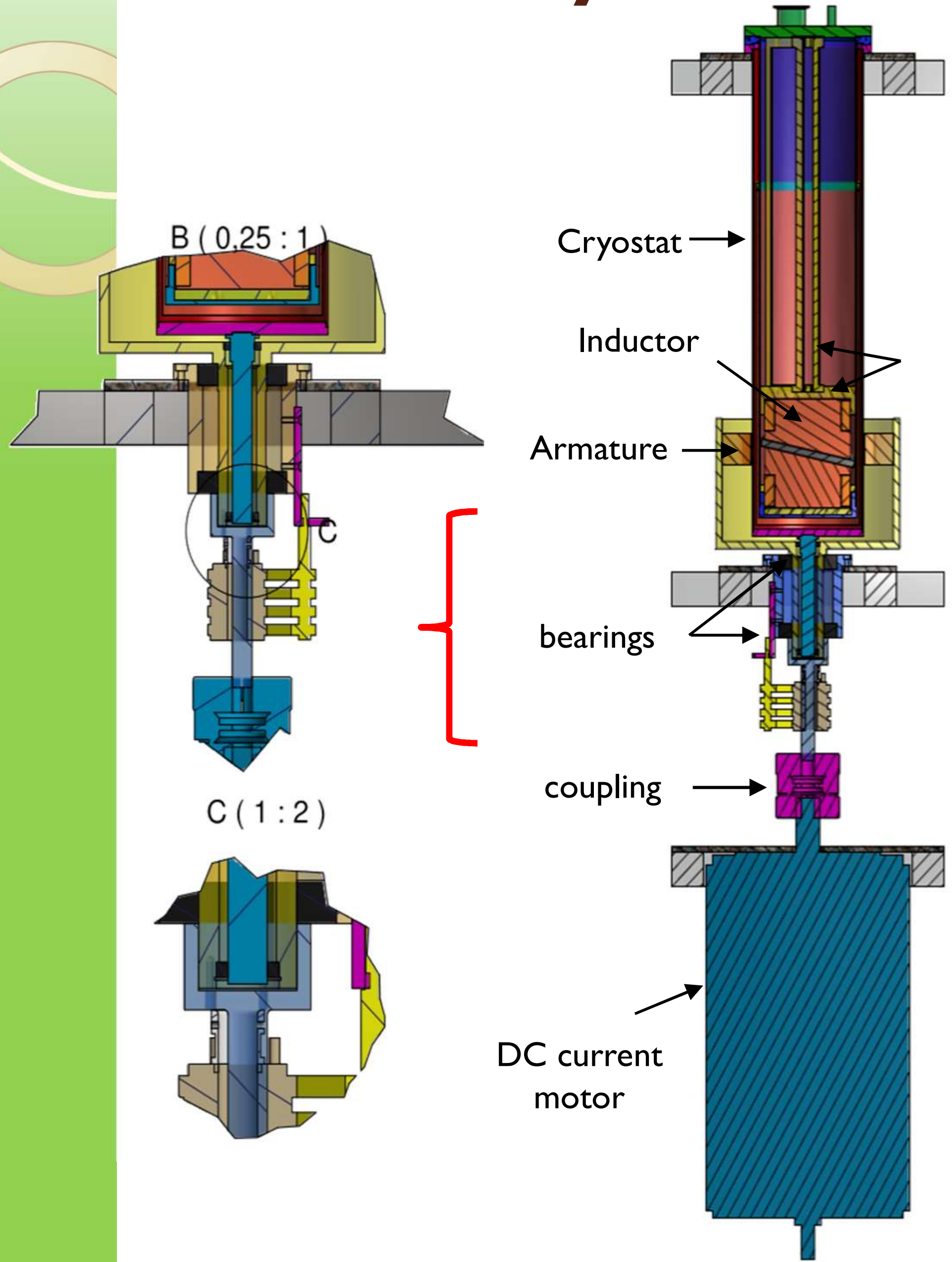
Inductor coil
NbTi (4.2K)
L_{total}=17 cm
L_{active} = 4.5 cm
D_{wire}= 0.75 mm
N= 850 turns

Superconcting screen
YBaCuO
D =15 cm, e =1 cm
Circular Shape

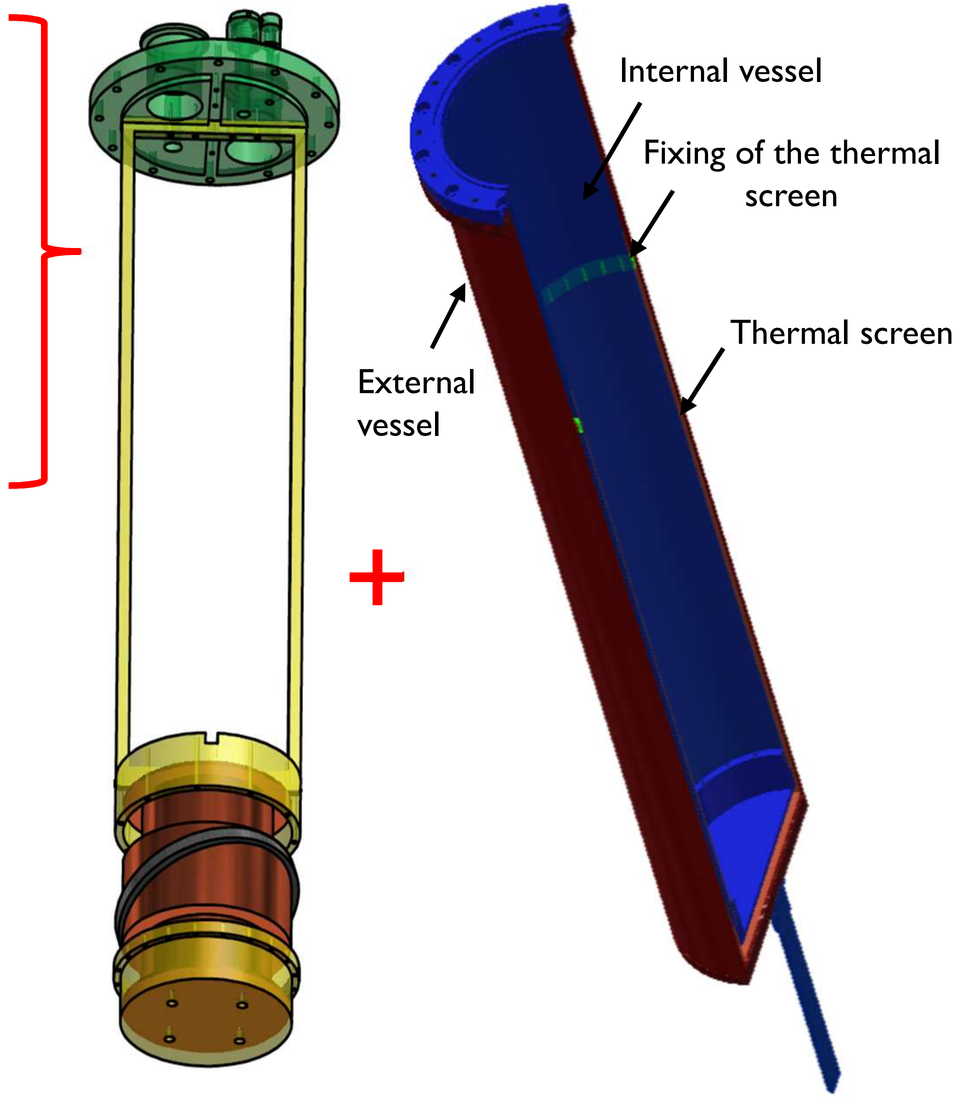


Armature
Copper
1680 turns
S_{wire}= 0.4 mm^2

Assembly

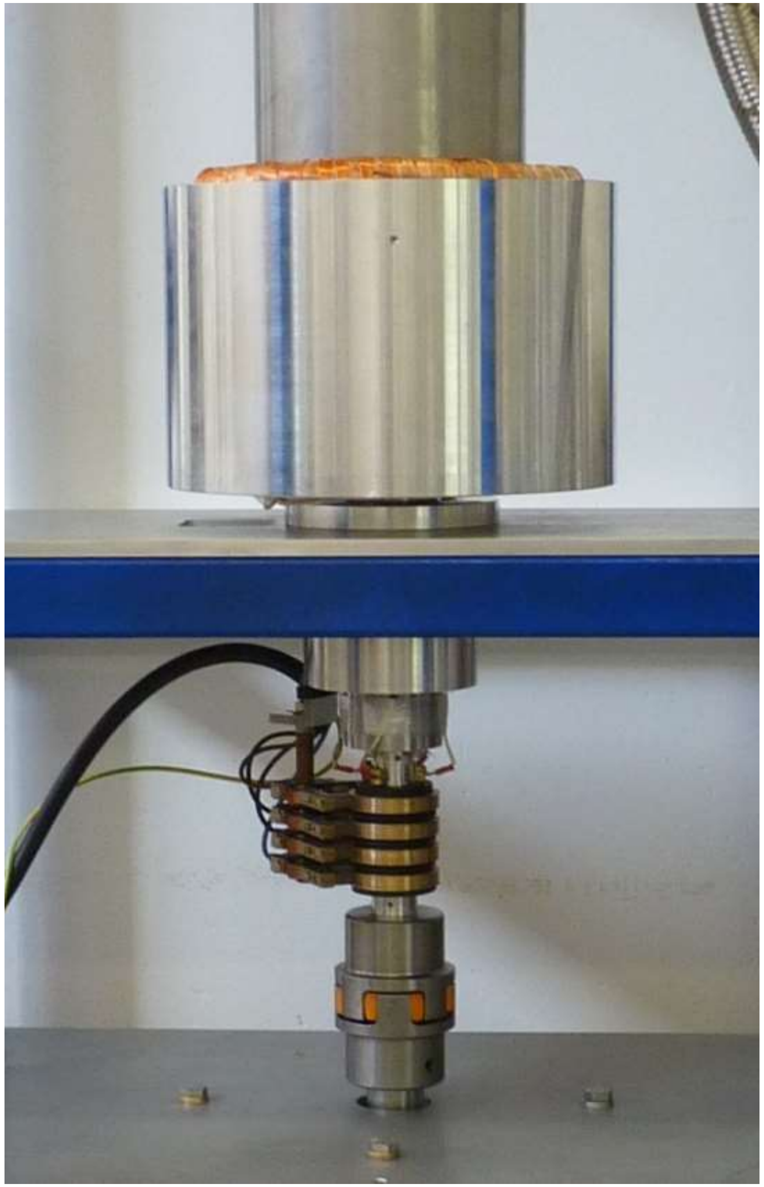


B (0.25 : 1)
C
C (1 : 2)
Cryostat
Inductor
Armature
bearings
coupling
DC current motor

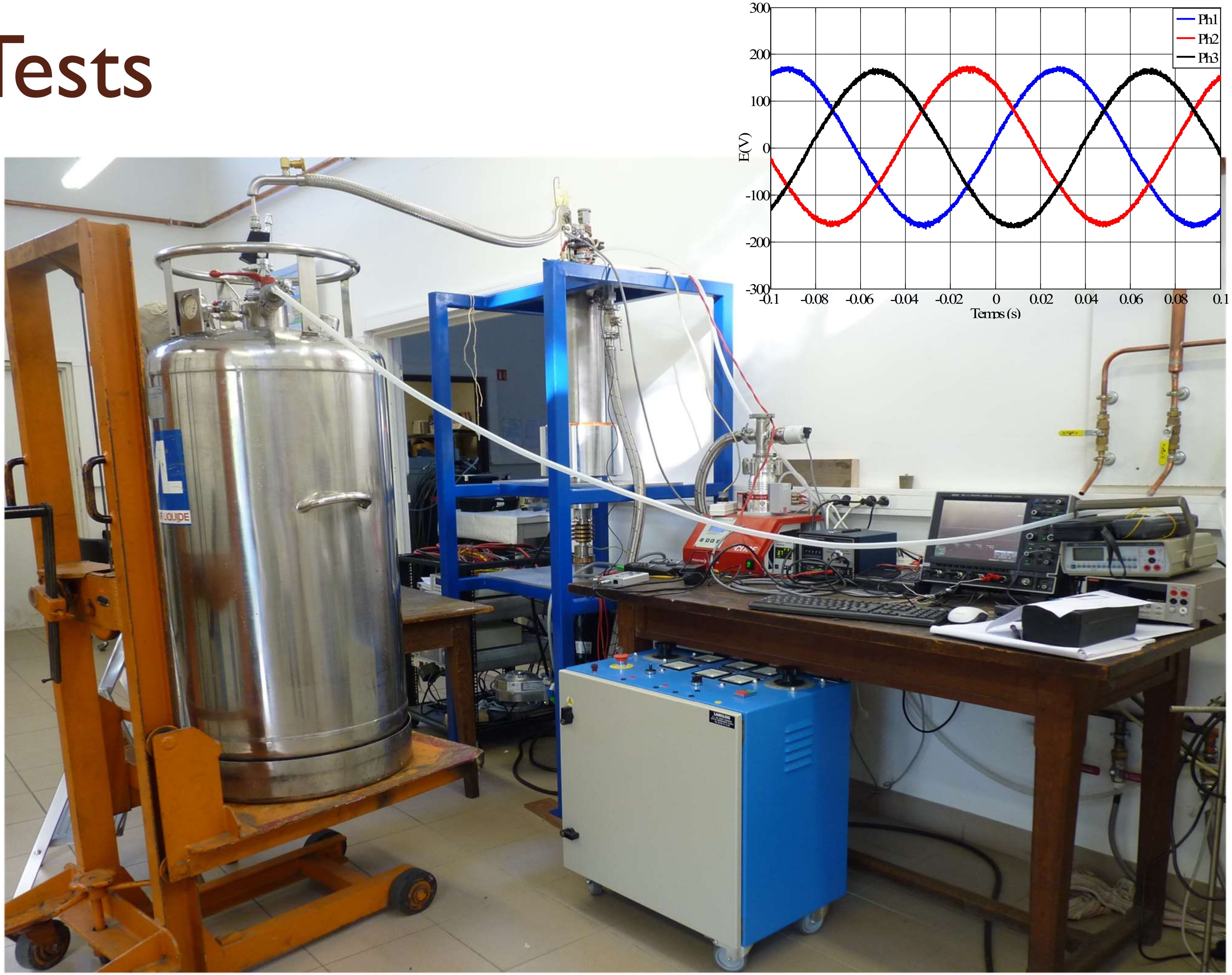


Internal vessel
Fixing of the thermal screen
Thermal screen
External vessel

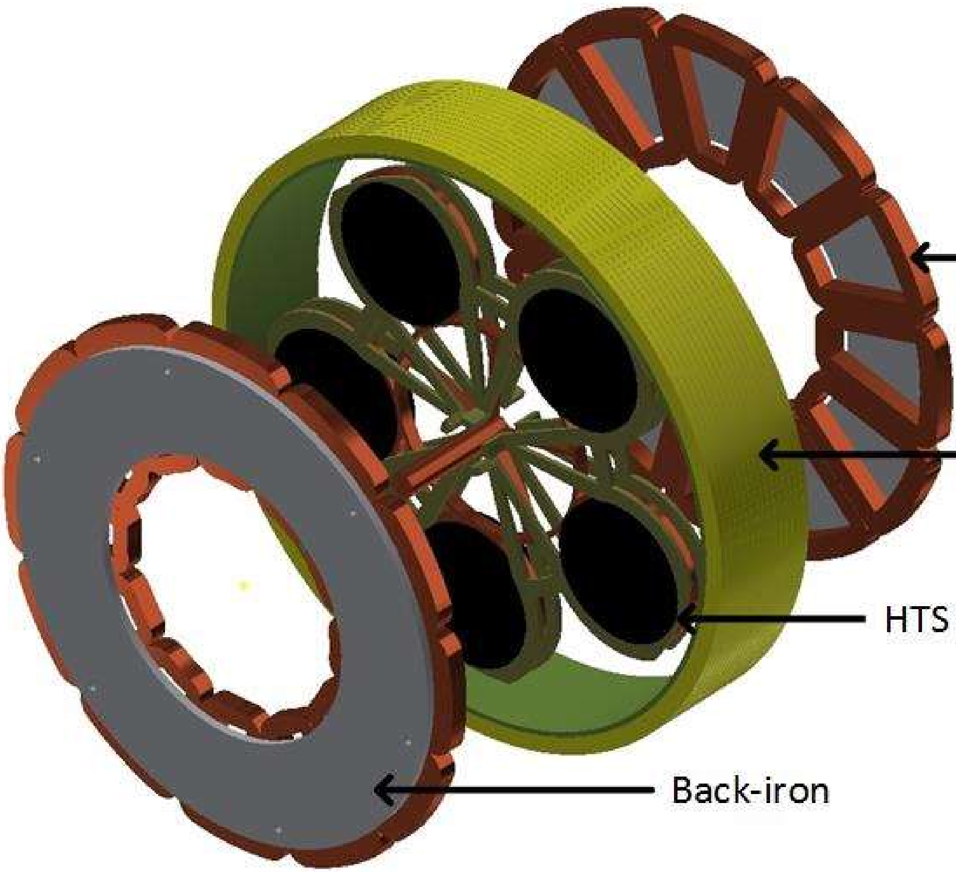
Assembly



Tests

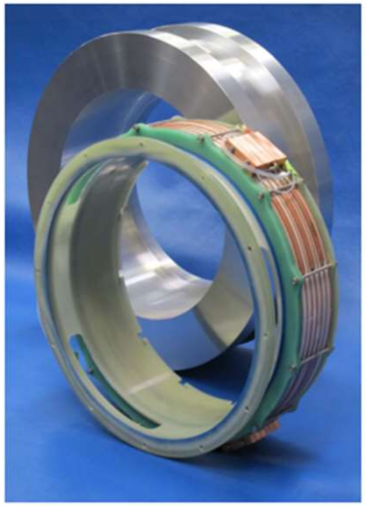

Ph1
Ph2
Ph3
E(V)
300
200
100
0
-100
-200
-300
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
Temps (s)

SUPERCONDUCTING ELECTRIC MOTORS WITH SAFRAN
(PHD A. COLLE, R. DORGET)



SUPERCONDUCTING ELECTRIC MOTORS WITH SAFRAN
(PHD A. COLLE, R. DORGET)

HTS coil wound
with DI-BSCCO tape



3D view of
the superconducting machine

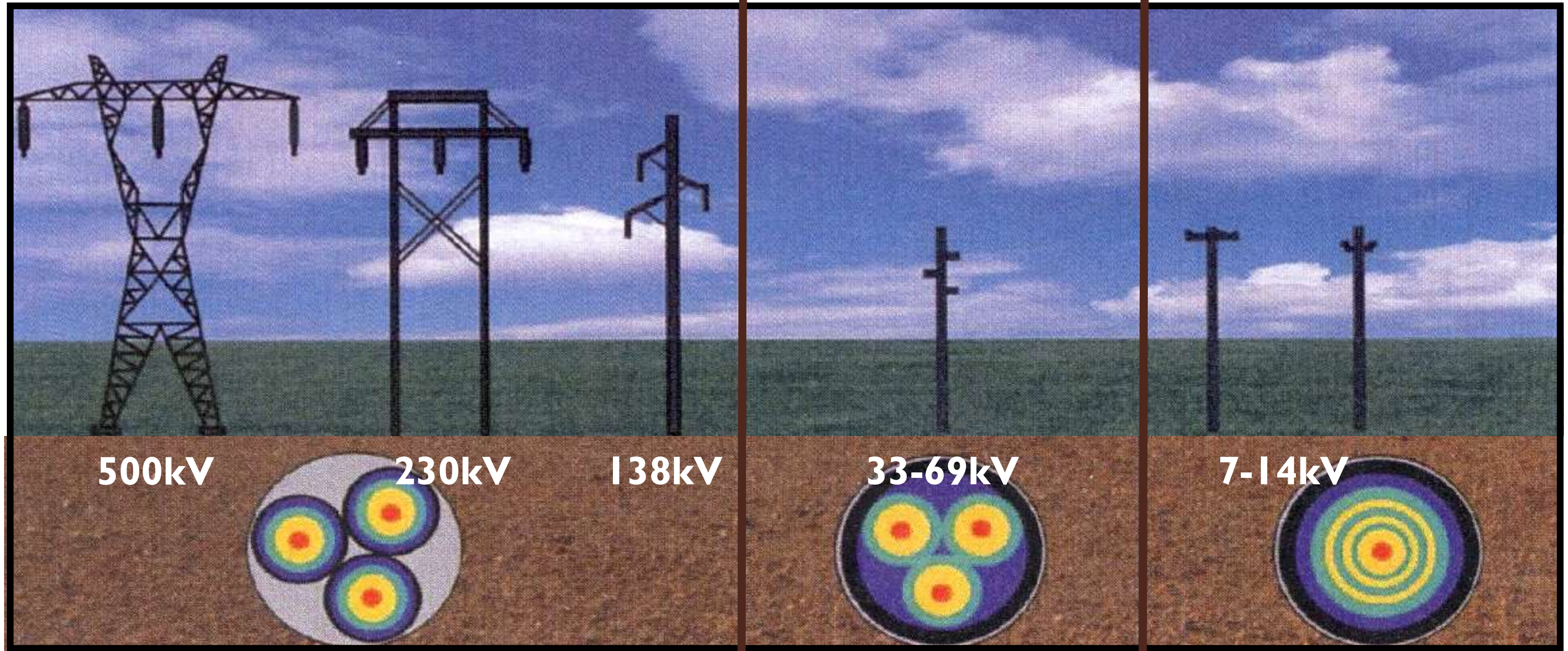
Multi-seed YBCO Φ 80 mm from ATZ

Armature winding
with Litz wire

SUPERCONDUCTING ELECTRIC MOTORS WITH SAFRAN

(PHD A. COLLE, R. DORGET)

Superconducting cable



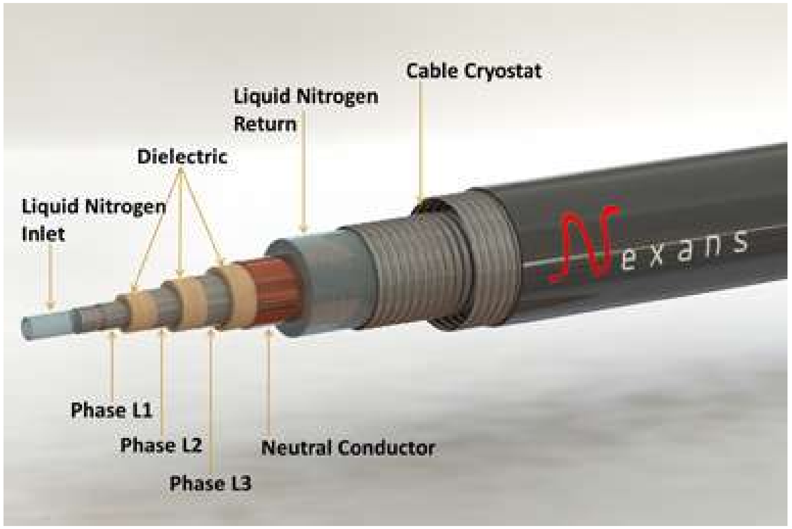
Long Island Power Cable
Câble 138kV : New-York long-Island

Albany Power Cable
Câble 34.5kV

Columbus Power Cable
Câble 13.2kV

AMPACITY project in ESSEN (Germany)

- 1 kilometre long high-voltage cable
- three-phase concentric cable
- 22 BiSCCO tapes by phase
- three-phase Current Limiter
- 10 kV, 40MW
- KIT, Nexans, RWE

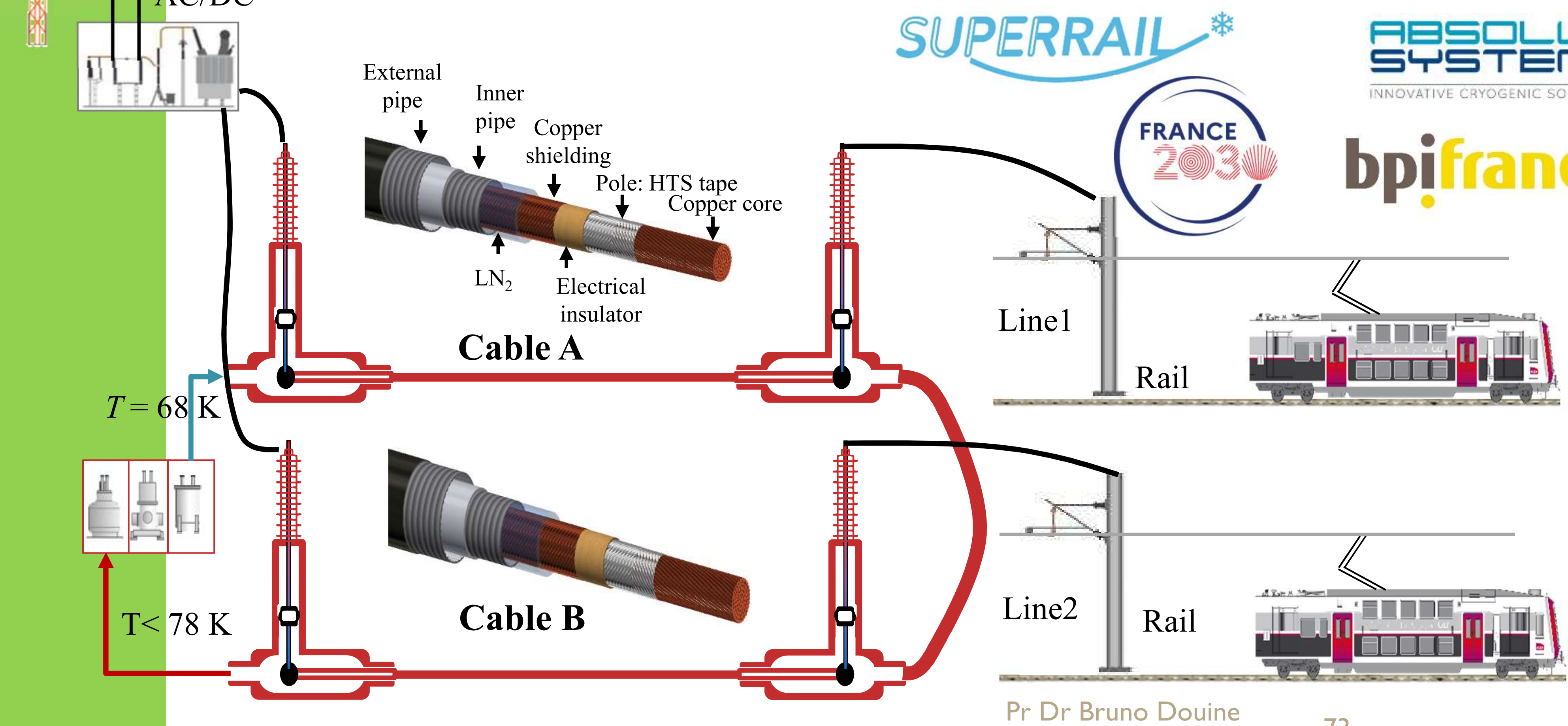


Nexans Cable

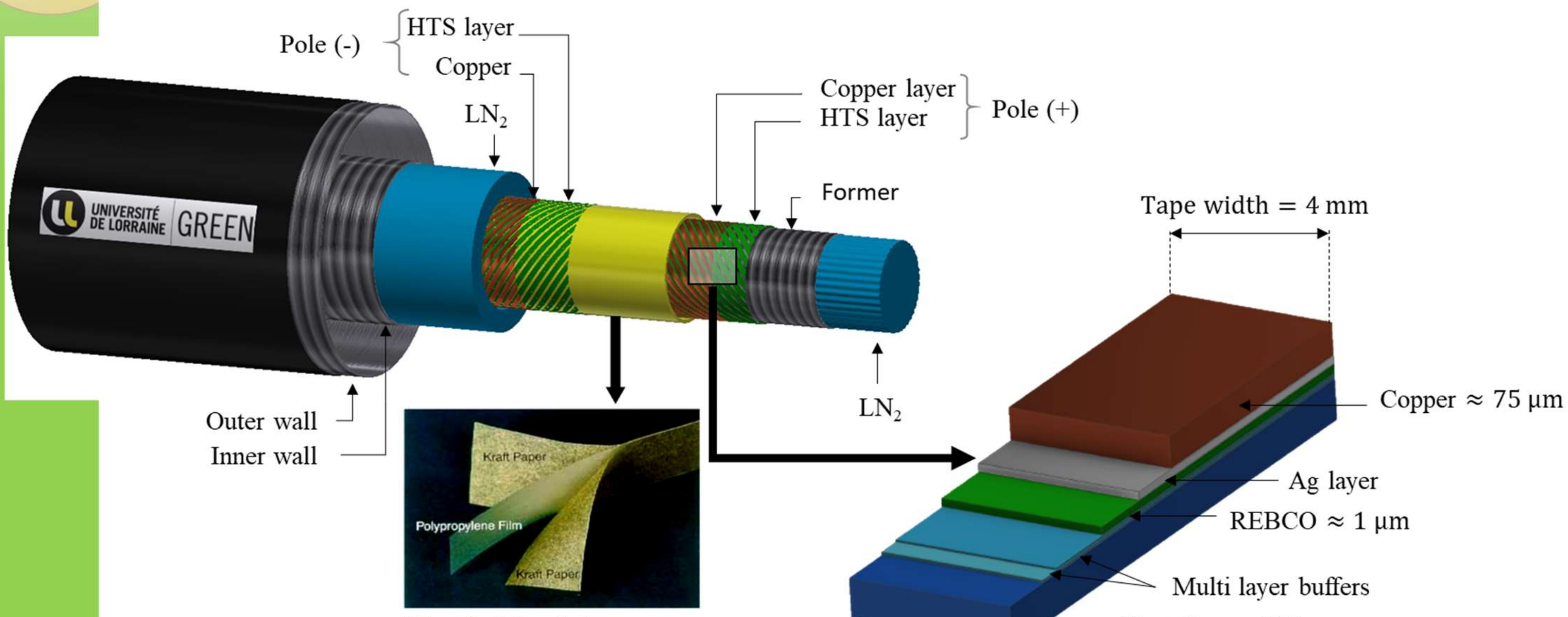
SUPERCONDUCTING CABLE FOR RAILWAY (GHAZI HAJIRI)

- ❑ Both cables have a length of **80 m**.
- ❑ 1500V DC current grid
- ❑ The two cables are feeding **two different lines**.
- ❑ **Only one cooling system** for both cables.

"This project is funded by France 2030 program through BPI"



SUPERCONDUCTING CABLE FOR RAILWAY (GHAZI HAJIRI)

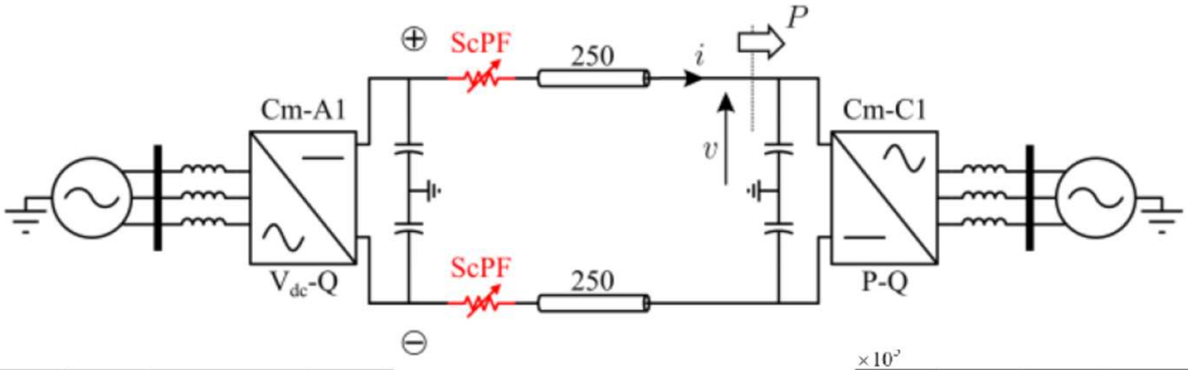


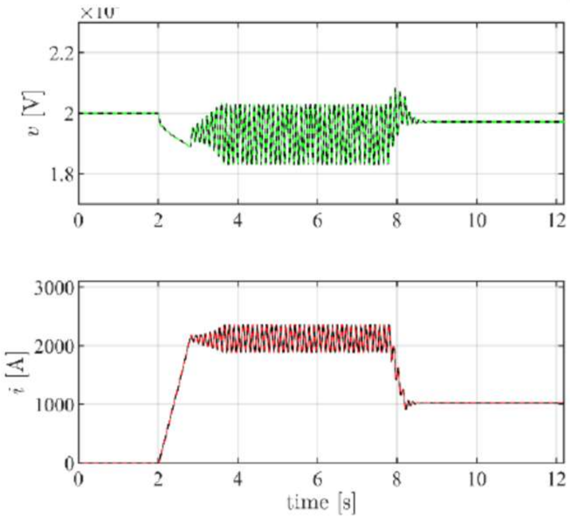
Electrical insulation
Dielectric rigidity (50 kV/mm).

SUPERCONDUCTING POWER FILTER

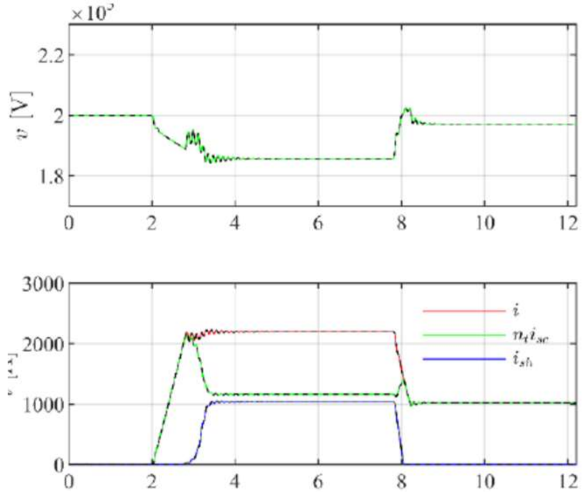
with Pr. Quéval (Paris) and Pr. F.Trillaud (Mexico):

- Modeling and characterization





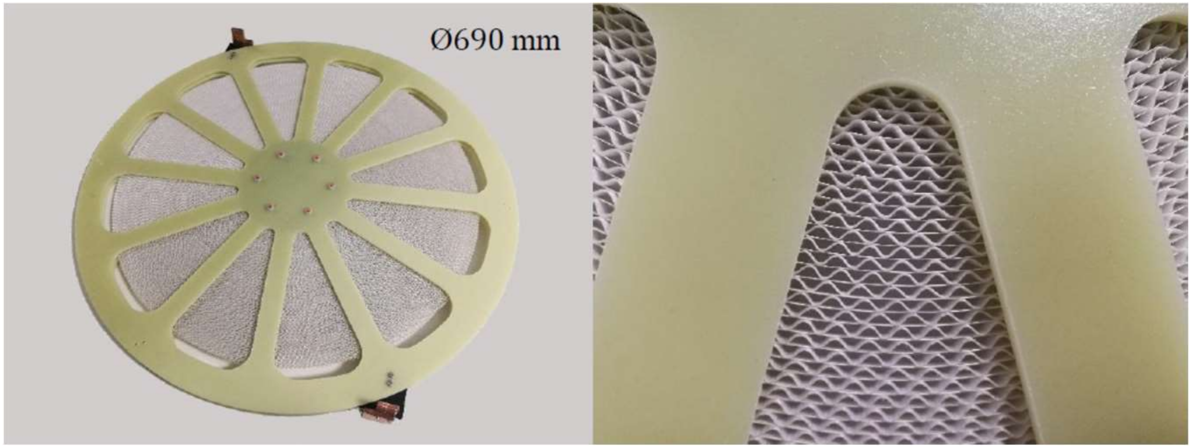
Without SPF

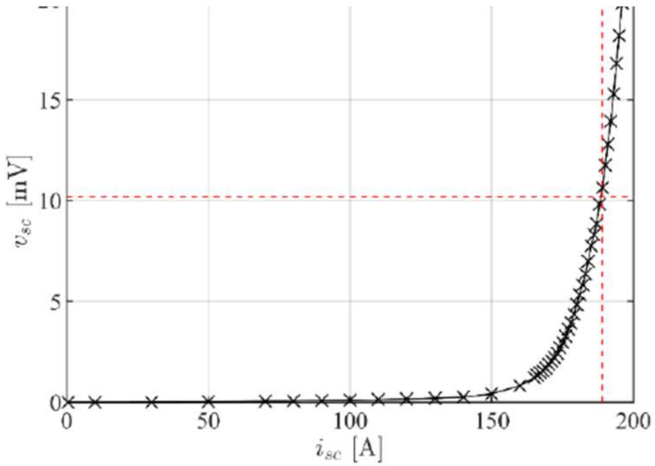


With SPF

SUPERCONDUCTING POWER FILTER

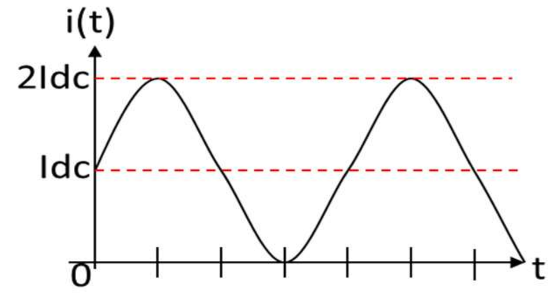
DC Characterization

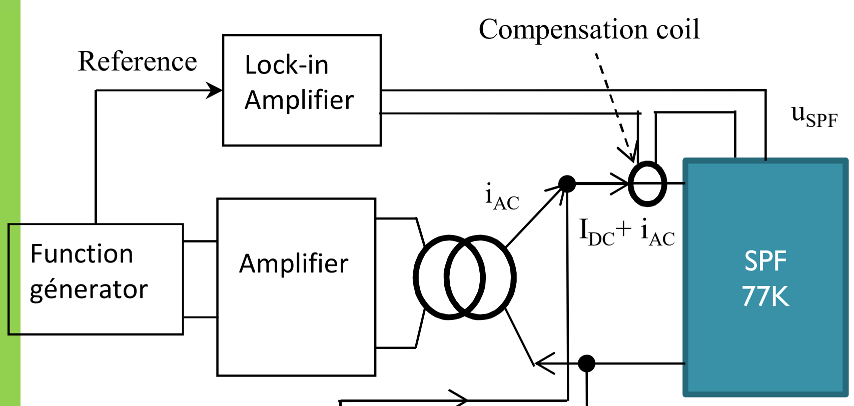




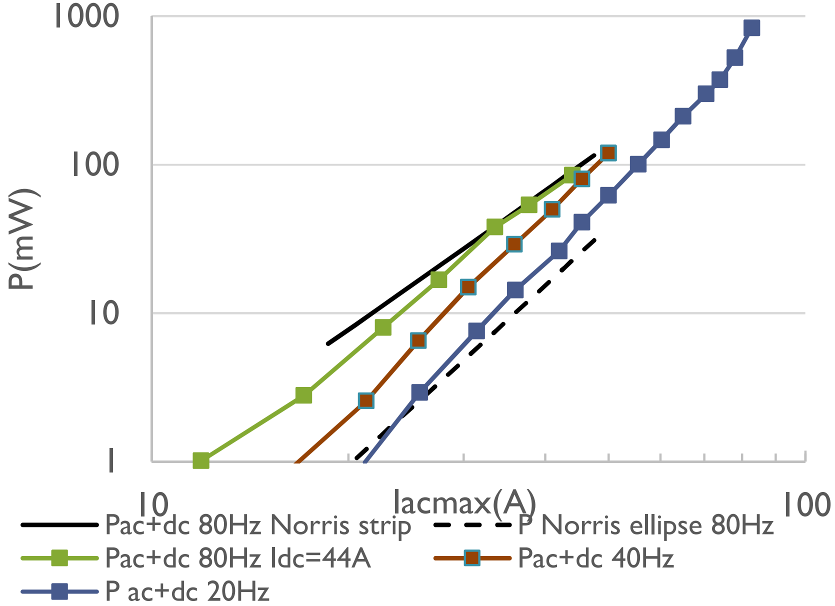
SUPERCONDUCTING POWER FILTER

AC +DC Characterization





AC+DC losses Ic=155A



MRI

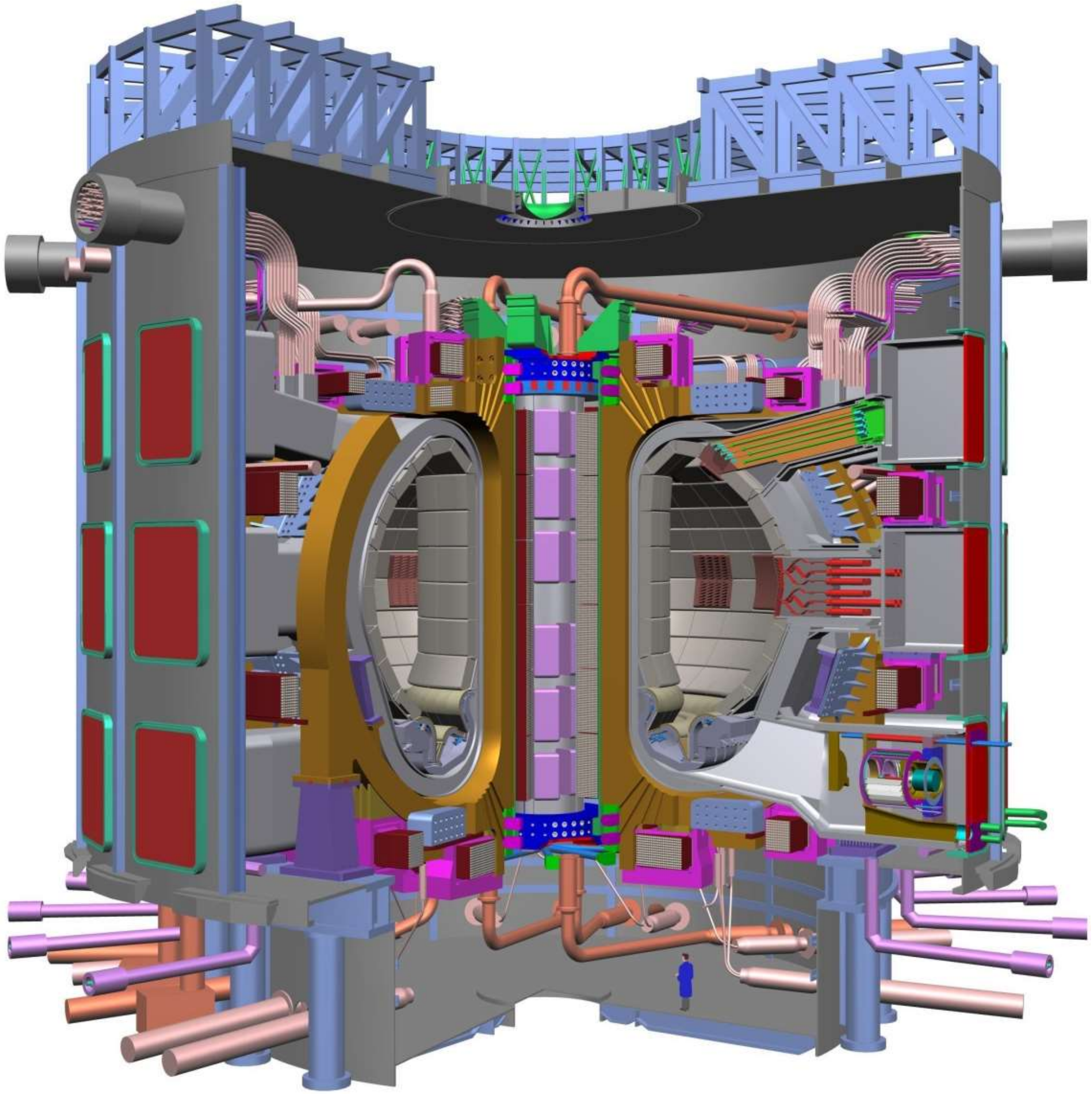
-LTS coil
Liquid Helium 4,2K

- MgB2 coil 10K

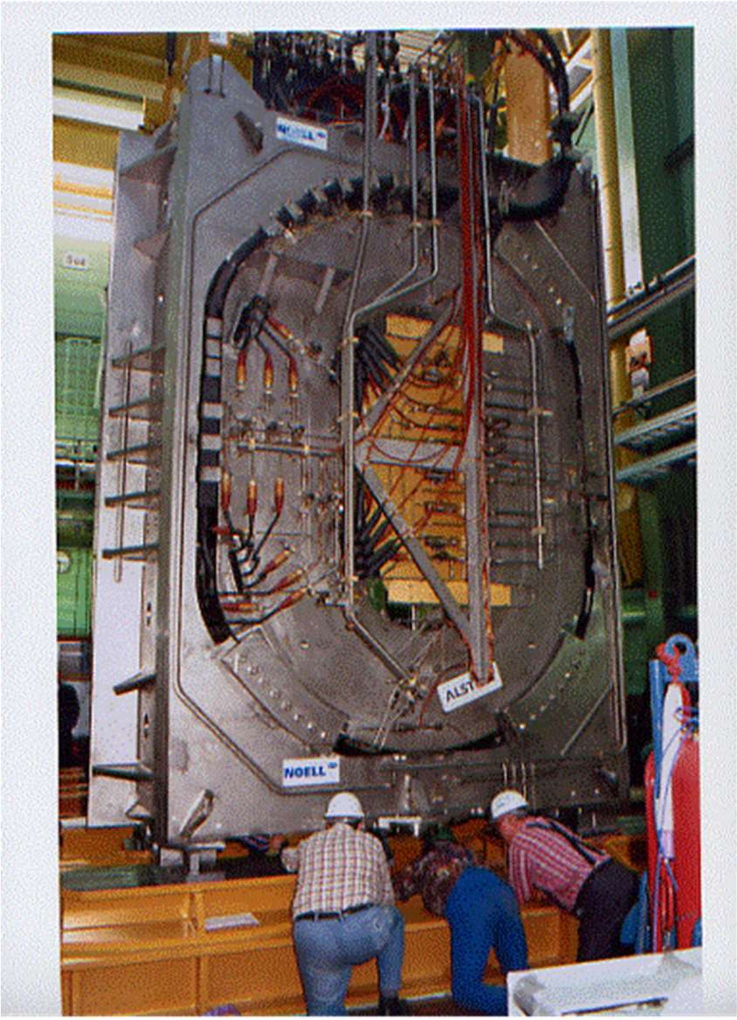
FUSION

ITER

LTS



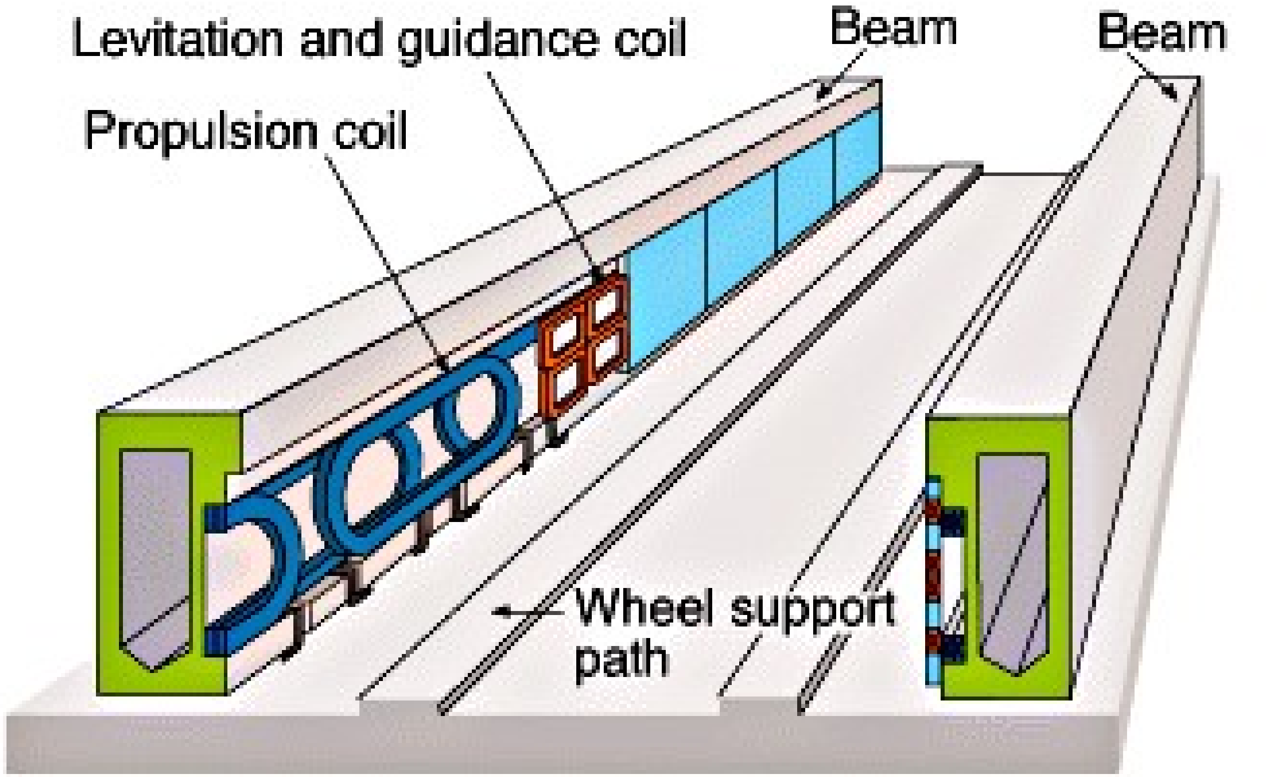
ITER
LTS coil



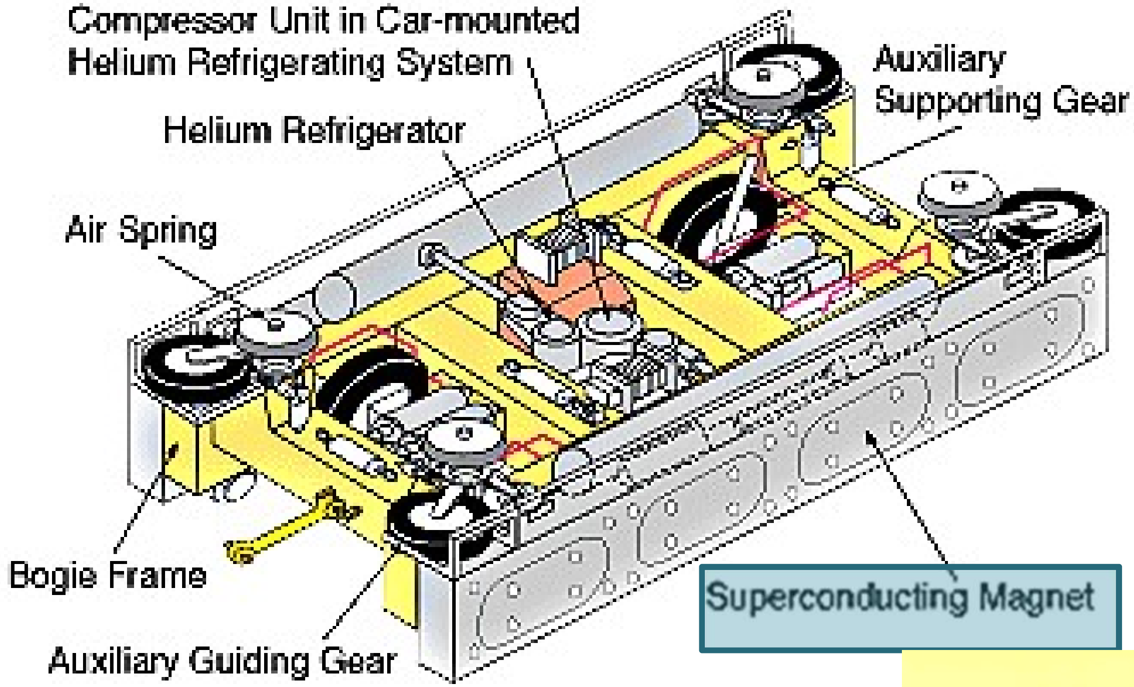
MAGNETIC LEVITATION TRAIN

Maglev MLX01 : 581 km/h (2011, Yamanashi, Japan)

MAGNETIC LEVITATION TRAIN



MAGNETIC LEVITATION TRAIN



Thank you for your attention