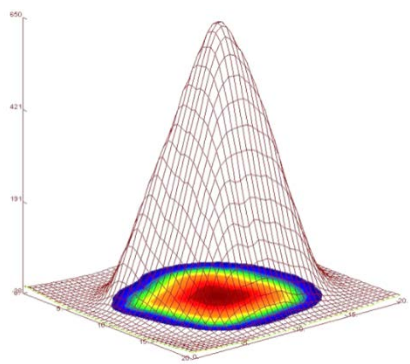
# Applications of superconductors in electrical engineering



Pr B. Douine & Dr K. Berger
GREEN - Lorraine University

# Outline

- About the GREEN
- Motor's realizations
  - Flux concentration motor
  - Synchronous motor
  - Axial motor with magnetic coupling
  - Flux barrier motor
- Bulk magnetization activities
  - Field cooling process with $MgB_2$ samples
  - Pulsed Field Magnetization with REBCO

# Research Team

- Permanent Members
  - Pr J. Lévêque (team leader)
  - Pr B. Douine
  - Pr A. Rezzoug (emeritus)
  - Dr K. Berger
  - Dr G. Didier
  - Dr M. Hinaje
  - Dr S. Mezani
  - Dr T. Lubin

- PhD Students
  - R. Alhasan
  - C.H. Bonnard
  - B. Dolisy
  - B. Gony
  - R. Linares

- ☹
  - ½ permanent technician
  - no permanent engineer

# Academic collaborations

- KIT (M. Noe, F. Grilli)
- University of Applied Science Mannheim (S. Elschner)
- Saarland University (M.R. Koblichka)
- Polytechnique Montréal, Quebec (F. Sirois)
- Center for Superconductivity, University of Houston, (P. Masson)
- University of Liège (P. Vanderbemden)
- University of Alger and Khémis-Miliana (E.H. Ailam)
- National Autonomous University of Mexico (F. Trillaud)
- French labs:
  - CRETA-CNRS (X. Chaud) and Grenoble Electrical Engineering Laboratory (P. Tixador),
  - Institut Jean Lamour in Nancy (S. Mangin and T. Hauet),
  - CRISMAT laboratory (J. Noudem and P. Bernstein)…

# Industrial collaborations

- Jeumont Electric: Project REIMS (Inductor of a machine)
- Converteam (now GE): ULCOMAP for ULtra-COmpact MArine Propulsion
- DCNS - French industrial group specialized in naval defense and energy
- EADS and Airbus Group (Design of superconducting machines for Aircrafts)
- Hispano-Suiza and Safran Group
- DGA for General Directorate for Armament (Design and realization of superconducting machines)

# Research topics and expertise

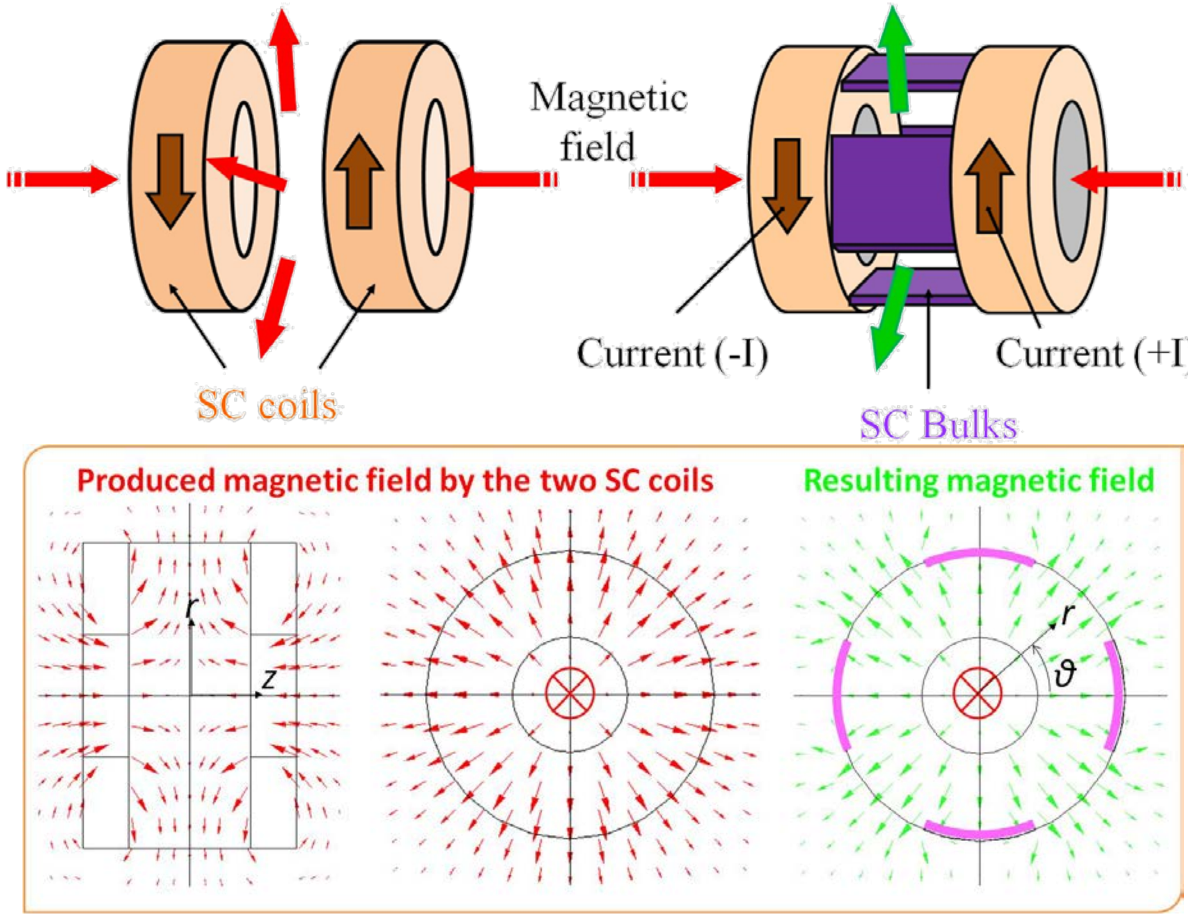
- Characterization of materials
- Modeling (FEM and analytical)
- **Superconducting motors**
- Magnetic coupling transmission
- Superconducting fault current limiter and electrical network
- … other applications

# Motors design and, their realization

- 5 motor's projects since 2006
- 4 motor's realizations since 2006
- 2 ANR grants (French National Research Agency)
- Most of our industrial collaborations

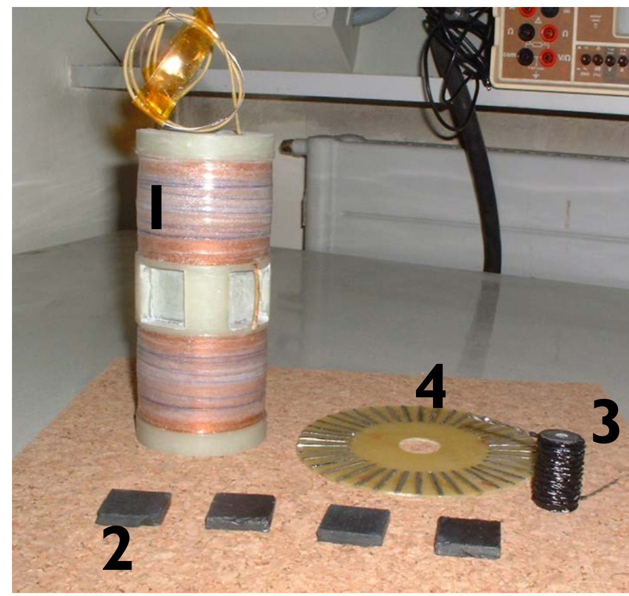
# The original idea of the GREEN

- 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

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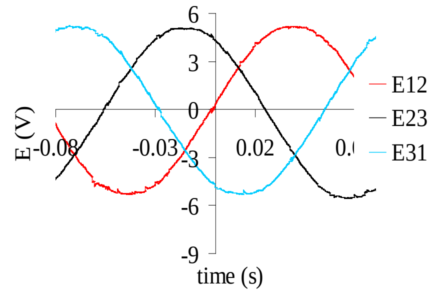
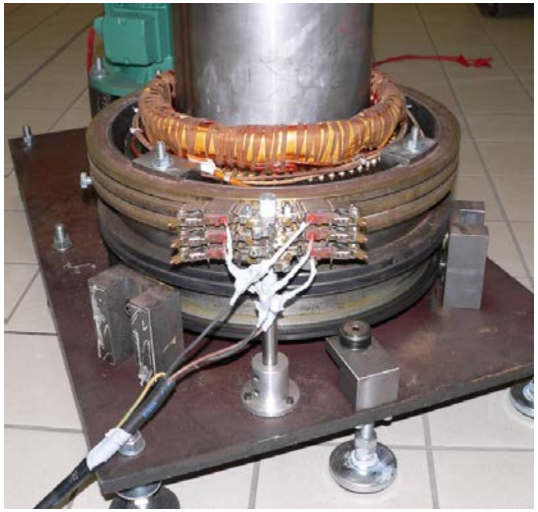
# 2nd - realization in 2006



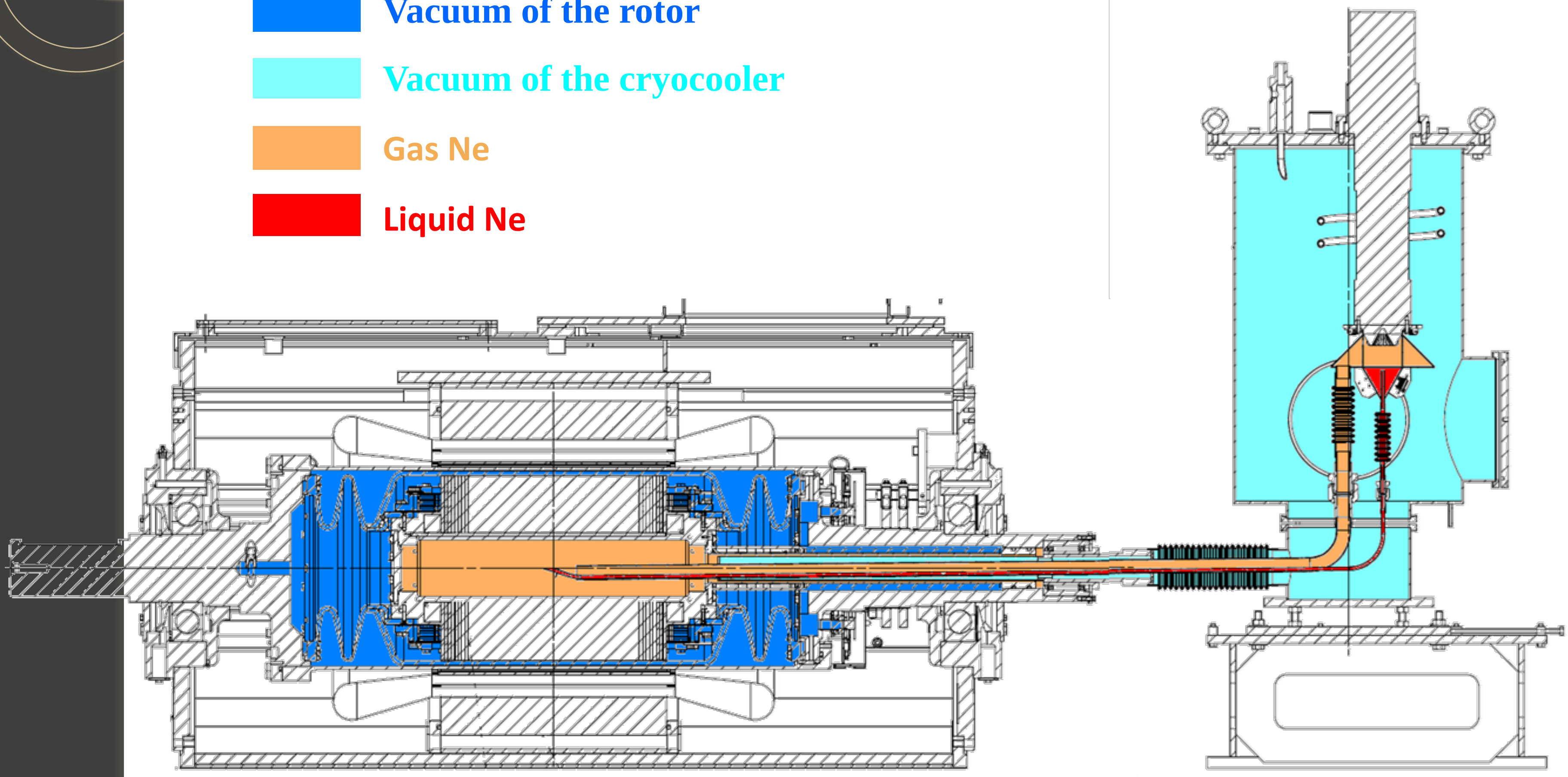
# ULCOMAP Project in 2008


| | | |
|---|---|---|
| 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 |

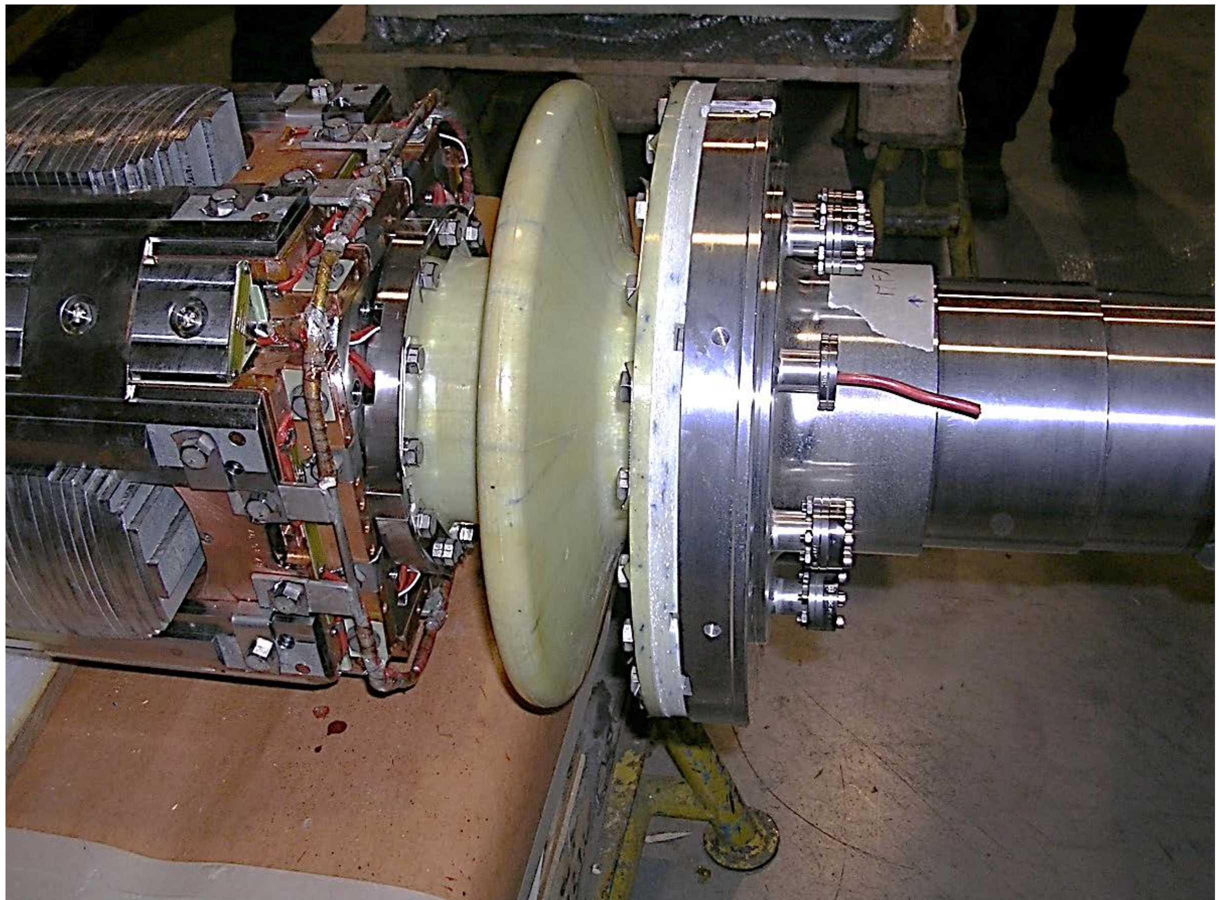
- Zenergy Power GmbH
- Werkstoffzentrum Rheinbach GmbH
- Futura composite
- Converteam (now GE)
- Silesian University
- University of Nancy

# ULCOMAP Project

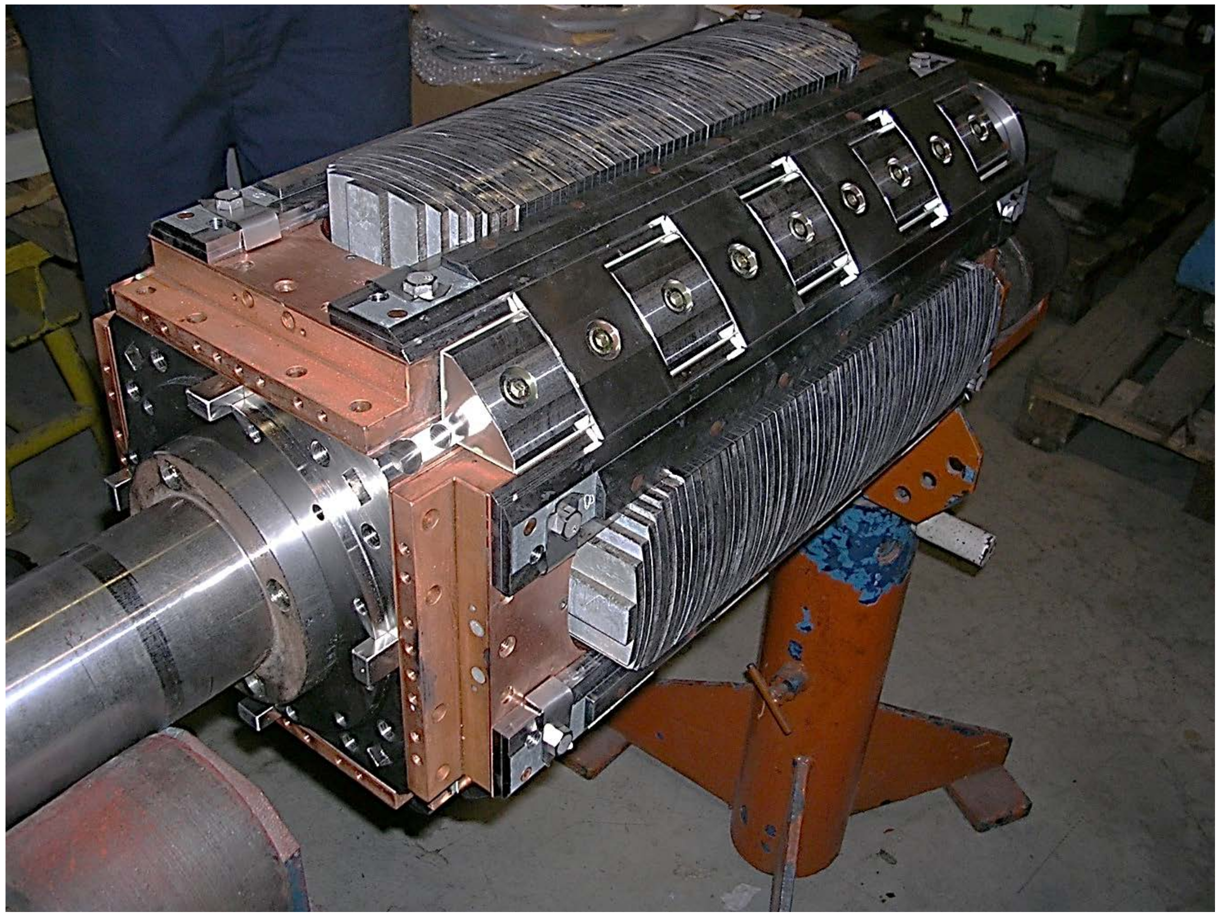
- Vacuum of the rotor
- Vacuum of the cryocooler
- Gas Ne
- Liquid Ne



# ULCOMAP Project



# ULCOMAP Project



# ULCOMAP Project

➔ **Total weight: 2 776 kg,  Power density: 90 W/kg**

| | 3rd October 2008 test | | 9th October 2008 test | | |
|---|---|---|---|---|---|
| Rotation speed N (rpm) | 1000 | | **1500** | | |
| i excit (Amp. d.c.) | 10 | 29 | 15 | 28 | **32.4** |
| U stator (V rms between phases) | 104.3 | 249.8 | 224.7 | 372.2 | **401.7** |
| I stator (A rms)) | 124.2 | 248.5 | 248.3 | 331.4 | **354.5** |
| Reactive power (KVA) | 3.16 | 15.16 | 13.6 | 30.1 | **34.8** |
| Active power at terminals (KW) | 22.2 | 106.4 | 95.7 | 211.5 | **244.2** |
| Cos. Phi (p.u.) | 0.99 | 0.99 | 0.99 | 0.99 | **0.99** |
| Voltage Total Harmonic Distorsion (%) | | 1.4 | | | |
| Current Total Harmonic Distorsion (%) | | 4.8 | | | |
| Shaft power (KW) | | | | 211.5 | **251.3** |
| Efficiency % | | | | 97.1 | **97.2** |

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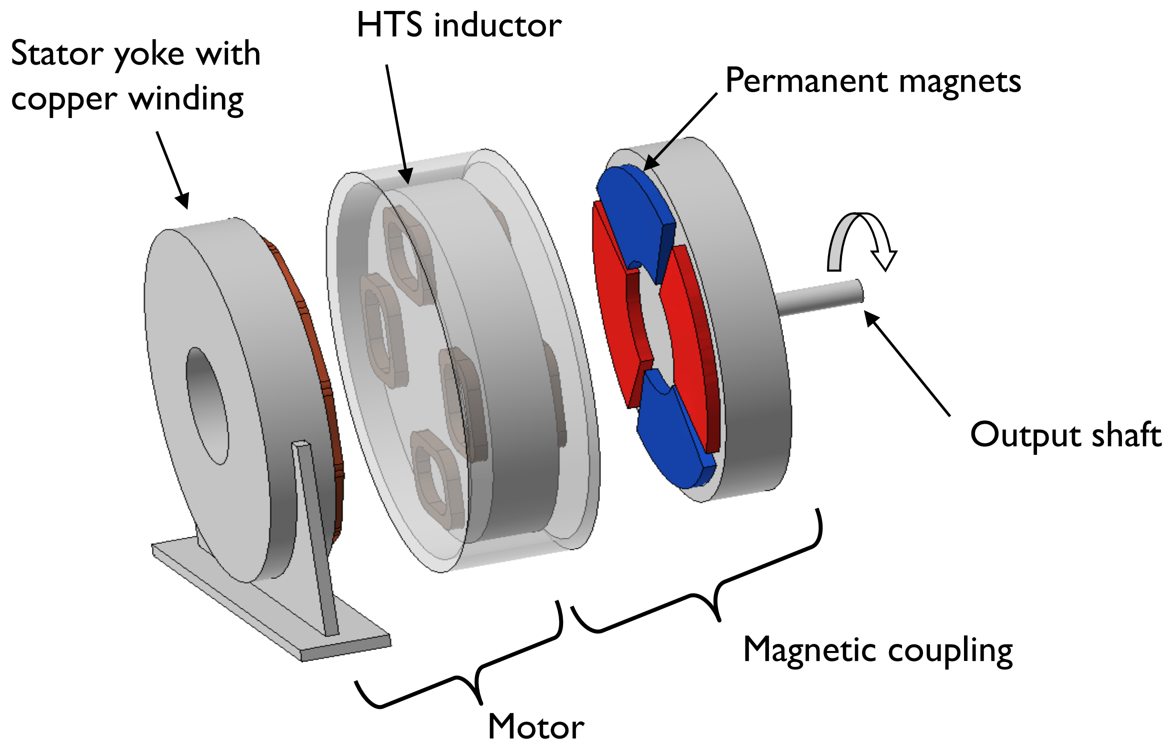
# New kind of axial HTS motor including a superconducting magnetic coupling for naval propulsion

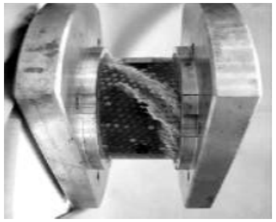
June 2014 – B. Dolisy's thesis

# 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

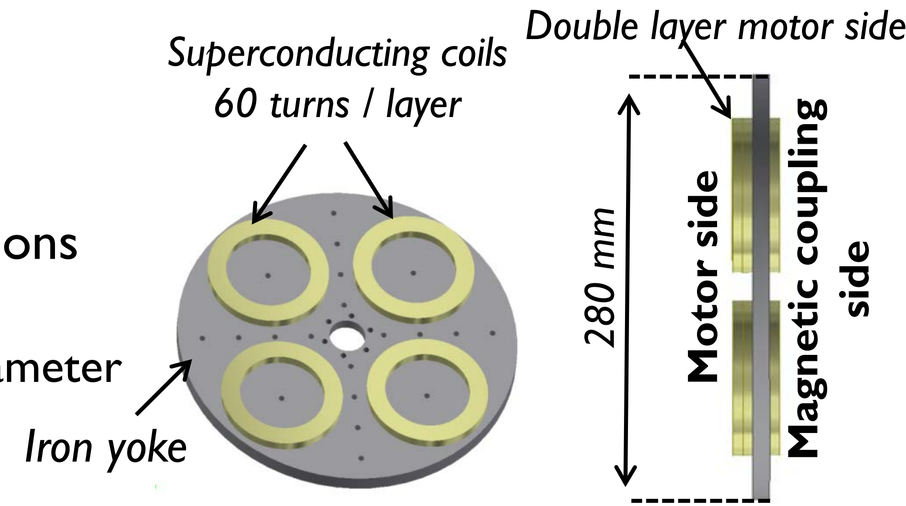
## Design choices

Restrict the external motor dimensions

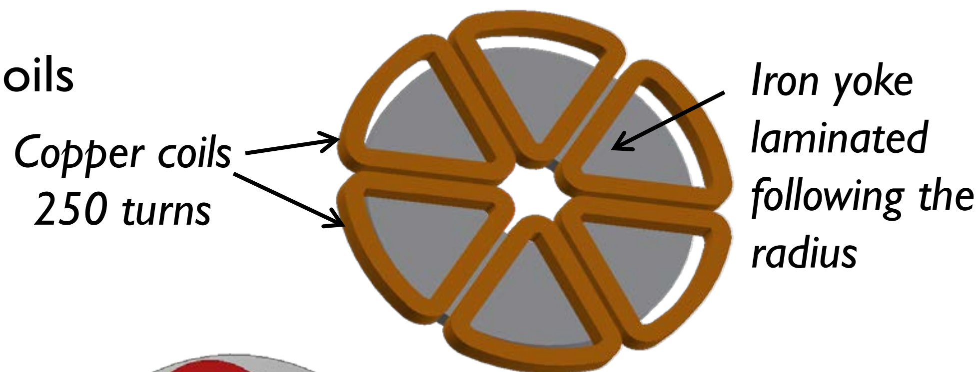
→ Round HTS coils

*Øint = 70 mm* minimal curvature diameter

*Øout = 100 mm*

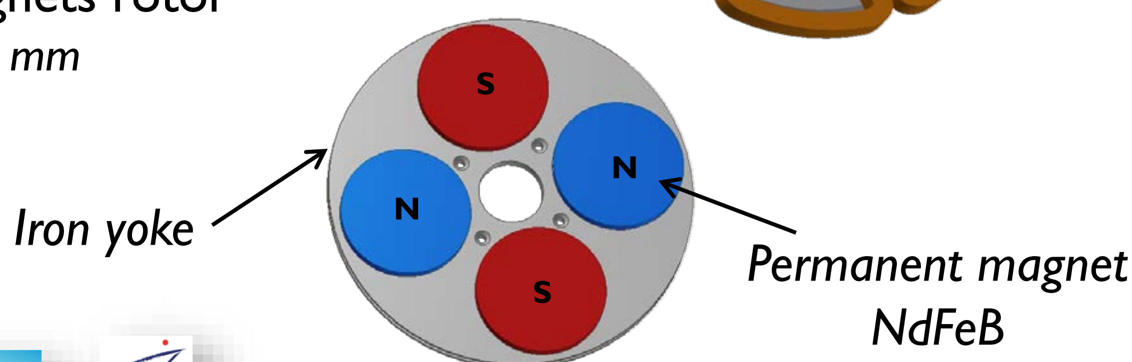



- Stator yoke with 6 copper coils



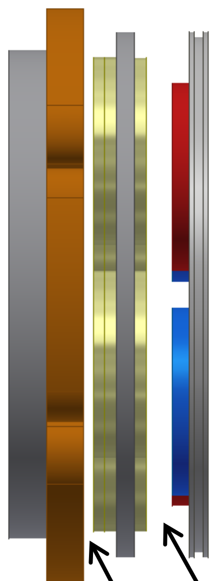

- Permanent magnets rotor

*Øout = 100 mm*



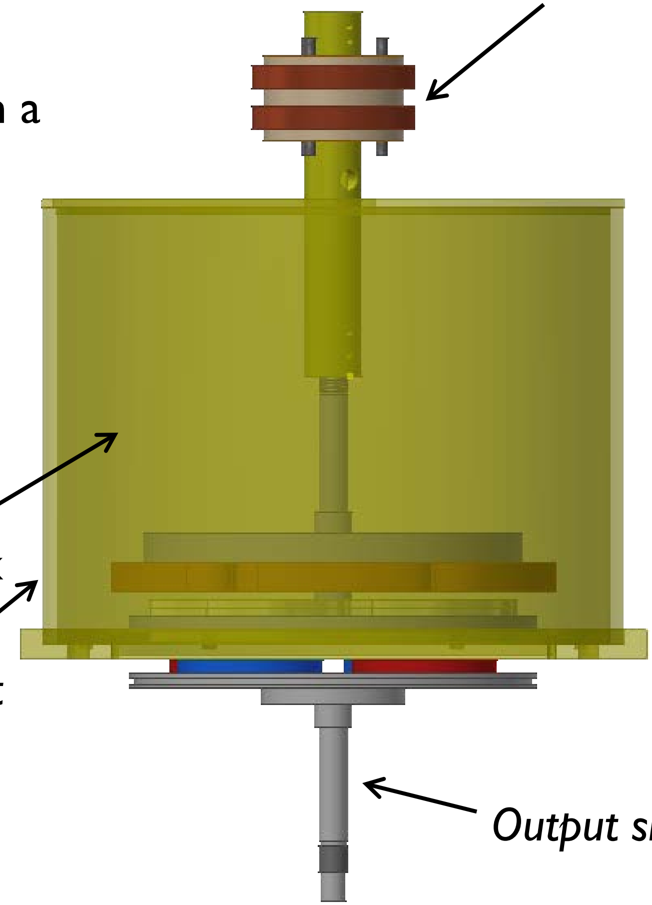
# Design and manufacture

## Design choices




Cooling by submersion in a liquid nitrogen bath

**Vertical machine**

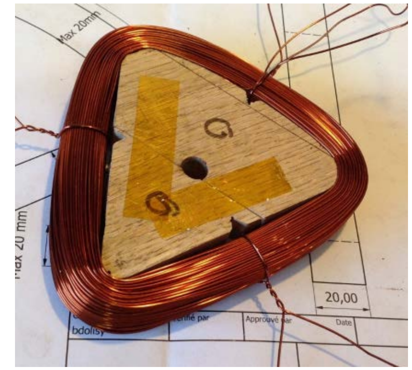


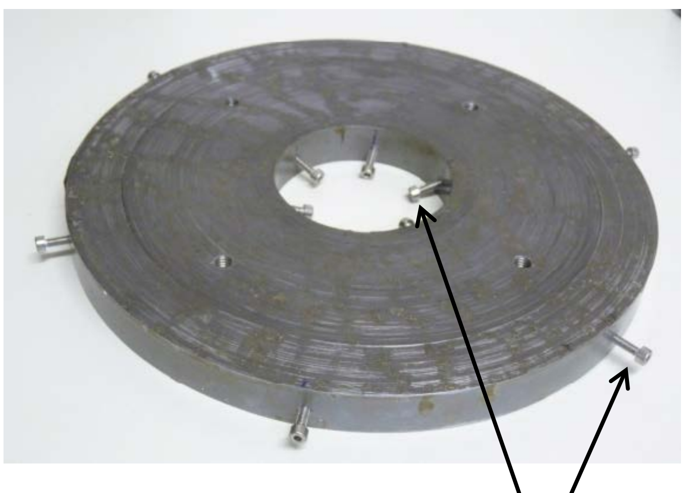

+ Efficient cooling of HTS coils
+ Easy installation
- High consumption of liquid nitrogen
- Bearings of inductor are cold
  → dry bearings

# 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*

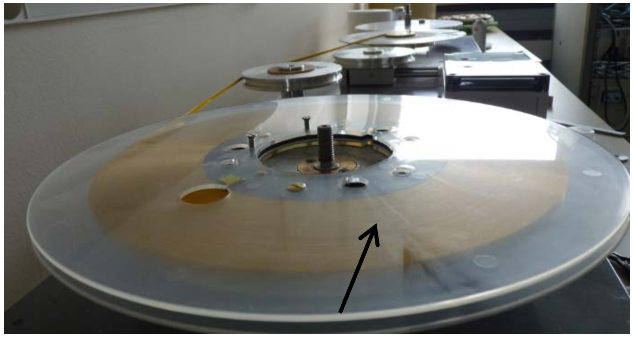
*Anchorage of the coils*

# Design and manufacture

## HTS inductor

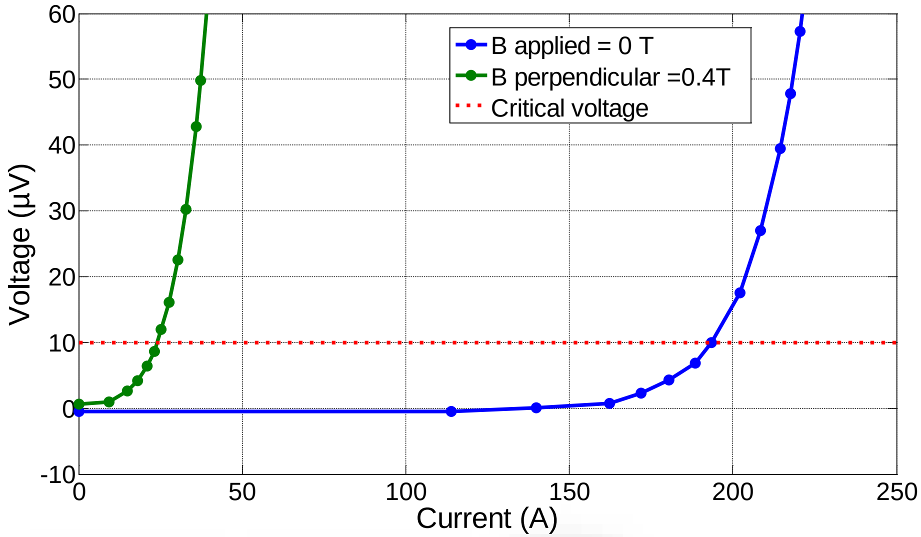
**BSCCO tape**

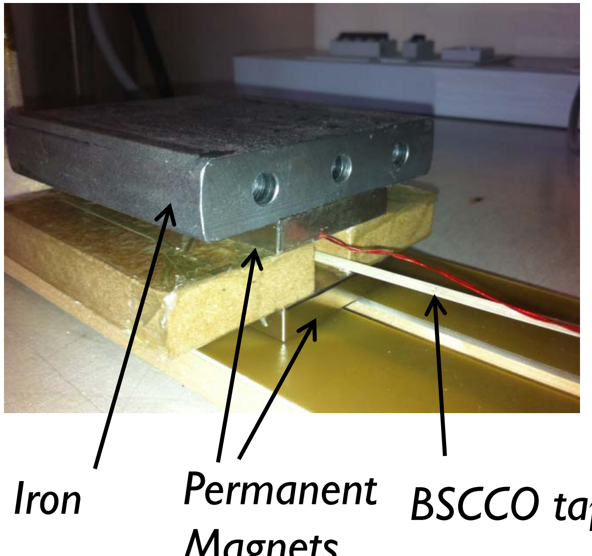
| Description | Unit | Value |
|---|---|---|
| Thickness of the tape | mm | 0.25 |
| Width of the tape | mm | 4.4 |
| Length | m | 240 |
| Ic @ 77K Self Field | A | 190 |



*BSCCO type Hi 240 m*

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

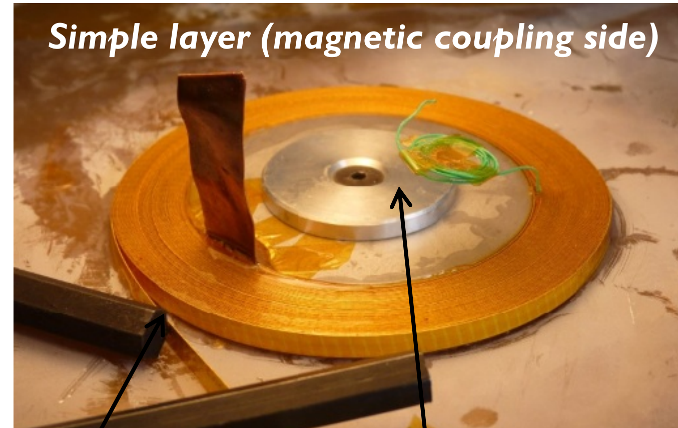


# Design and manufacture

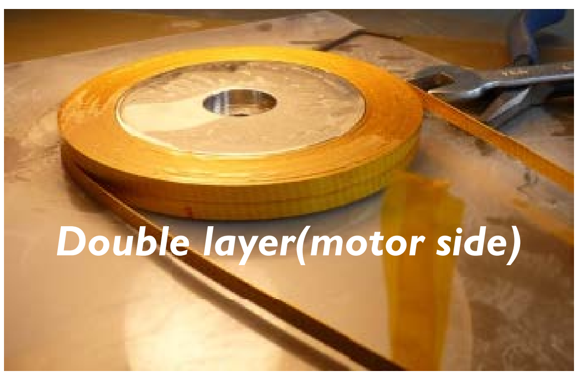
## HTS inductor

| 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 |

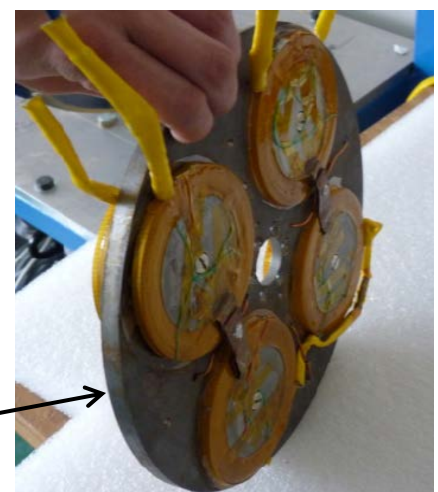



*Current lead*

*Inox core*



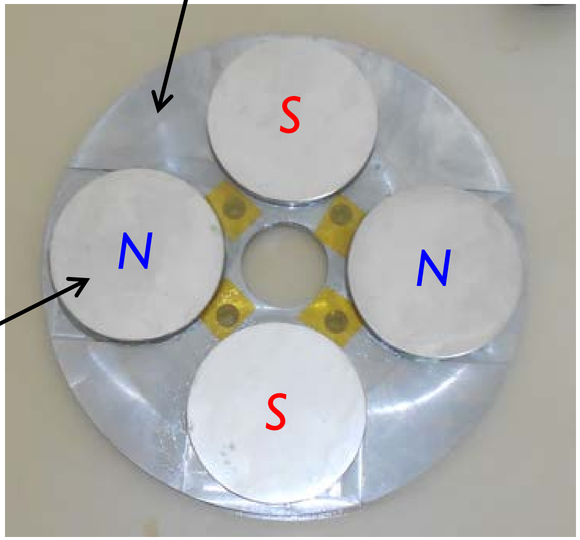

*Ferromagnetic yoke*



# Design and manufacture

## Permanent magnets rotor

| Description | Unit | Value |
|---|---|---|
| External diameter | mm | 100 |
| Thickness | mm | 10 |
| Remanence of the permanent magnets | T | 1.25 |


*L. Belguerras, PhD Thesis, « Etudes Théoriques et Expérimentales d'Accouplements Magnétiques Supraconducteurs », may 2014.*

# Design and manufacture

## Final assembly



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# Tests

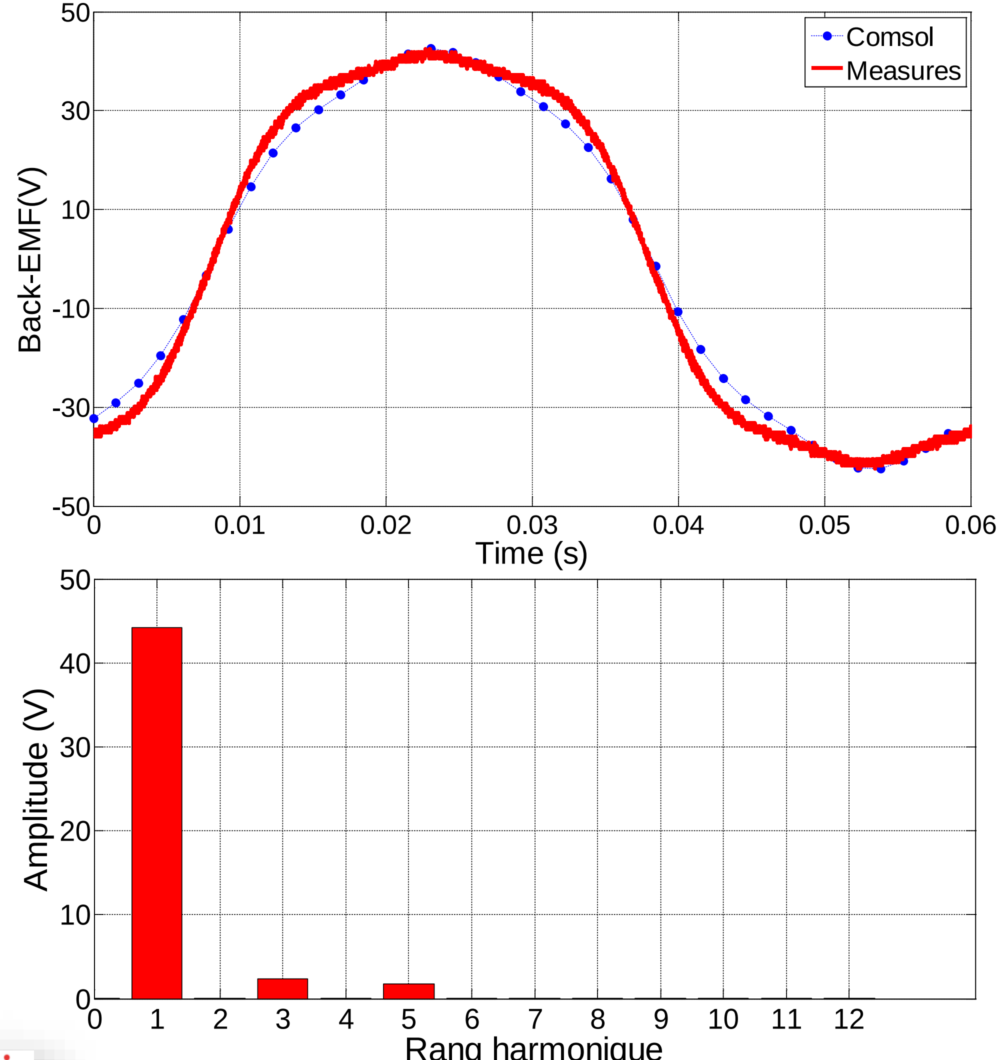
## Under rotation

**Back EMF**

*Single voltage*

*N = 500 rpm*
*Ie = 50 A*

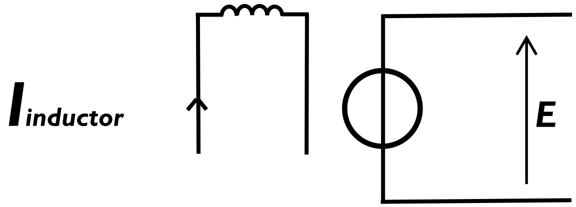
Good agreement with the design

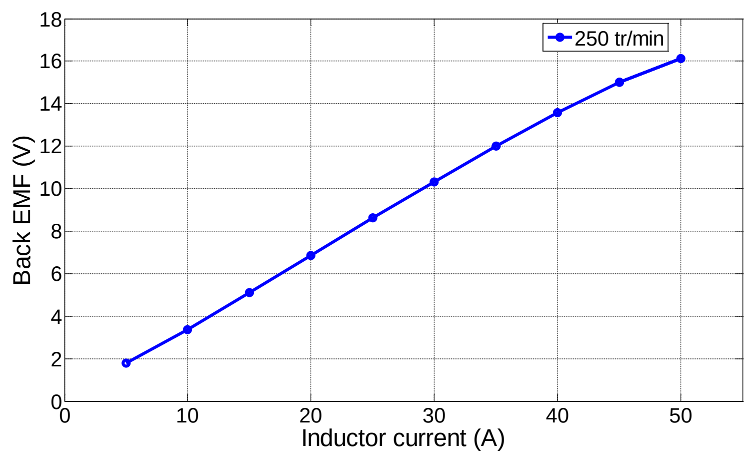


# Tests

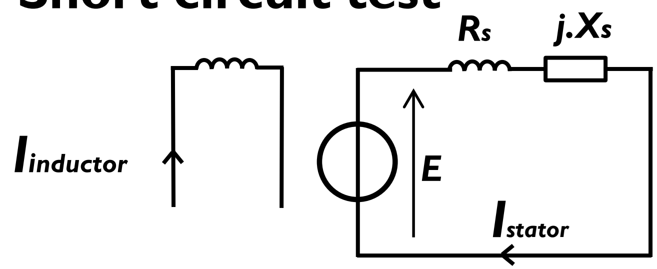
## Behn-Eschenburg model

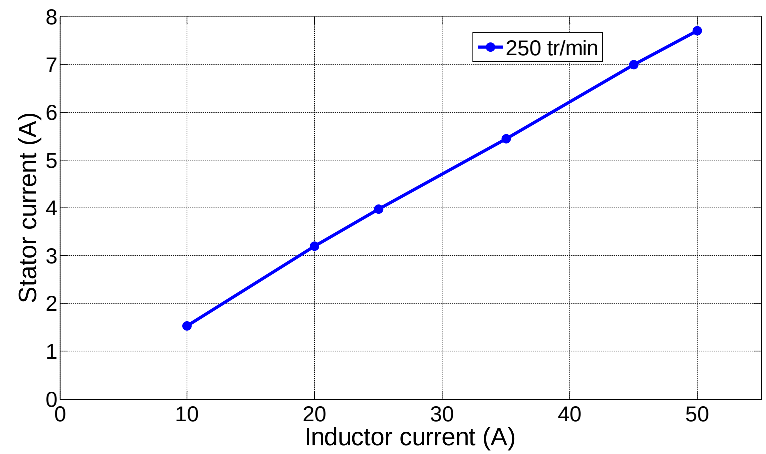
### No-load test




### Short circuit test




### Motor parameters

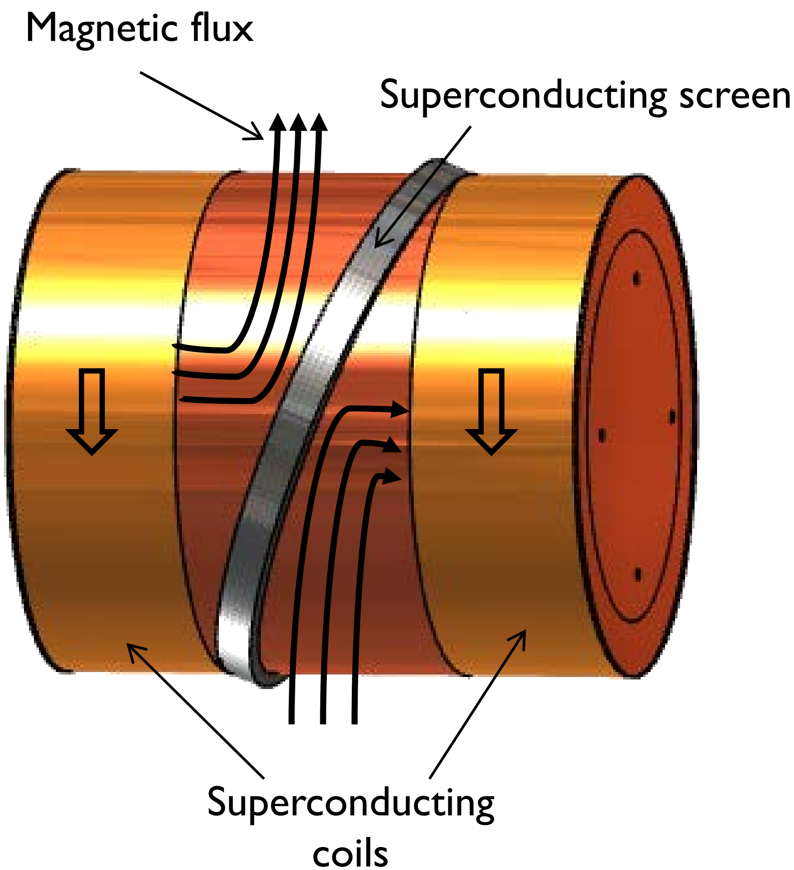
$R_s \approx 0.82\ \Omega$ $X_s \approx 1.98\ \Omega$

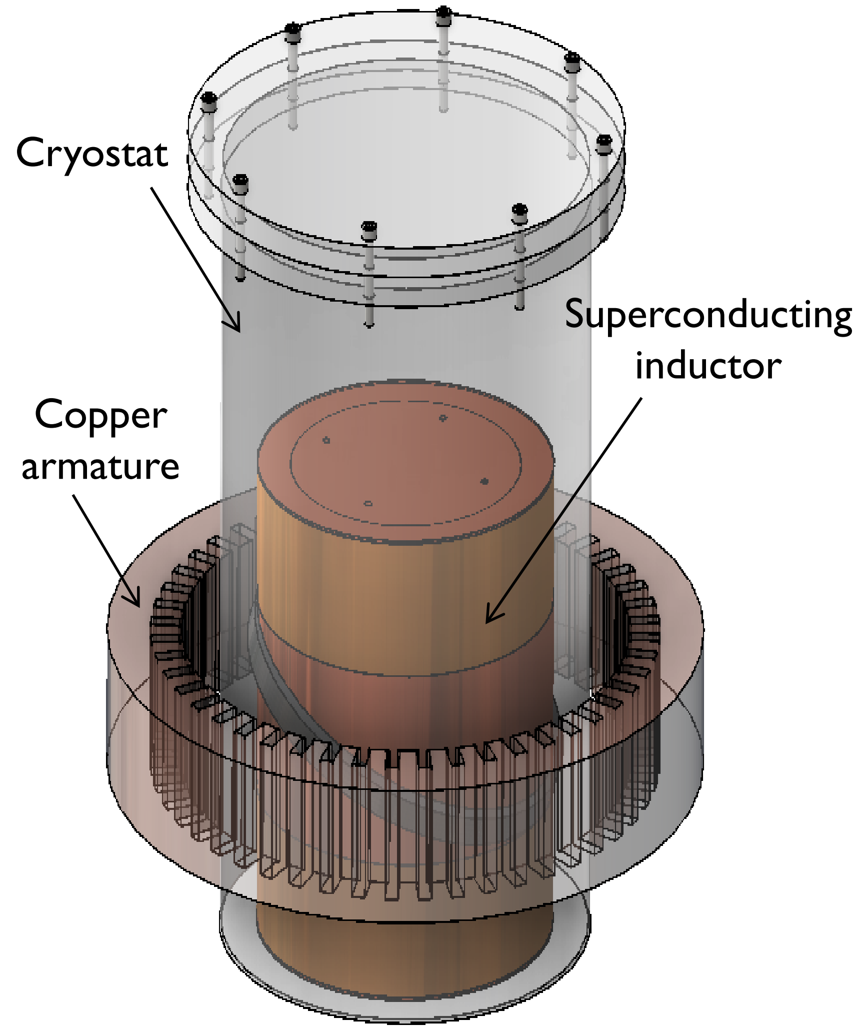
$(X_{s\ comsol} \approx 1.78\ \Omega)$

# Study and realisation of a flux barrier synchronous superconducting motor

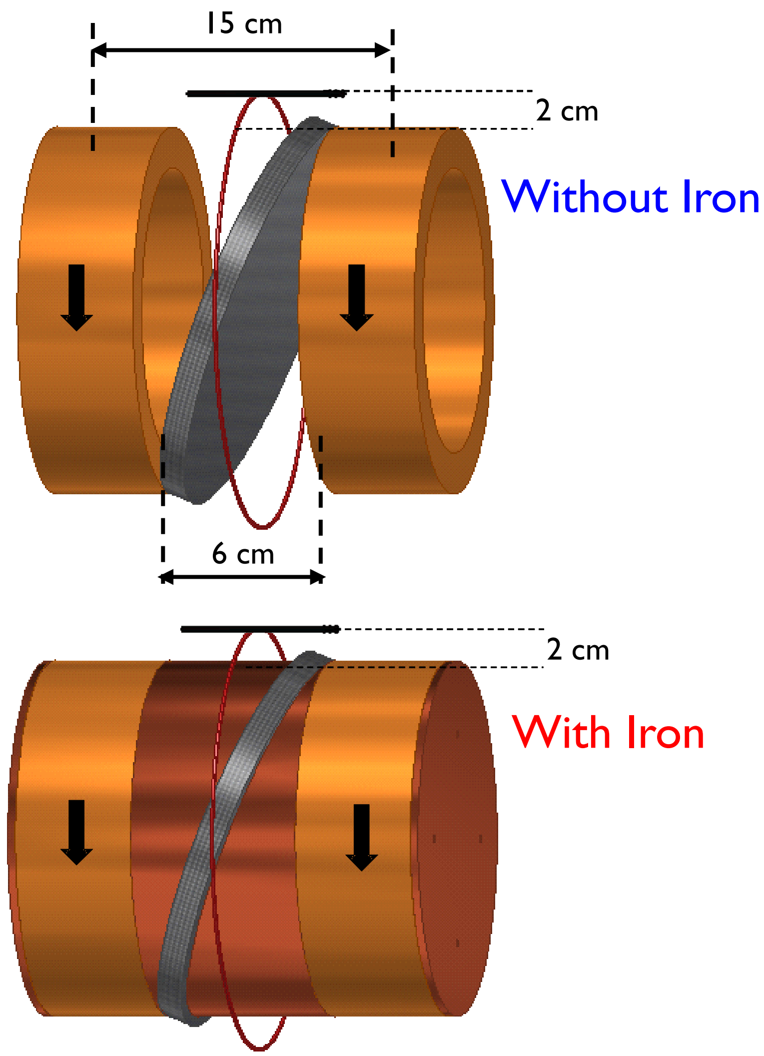
**October 2014 – R. Alhasan's thesis**

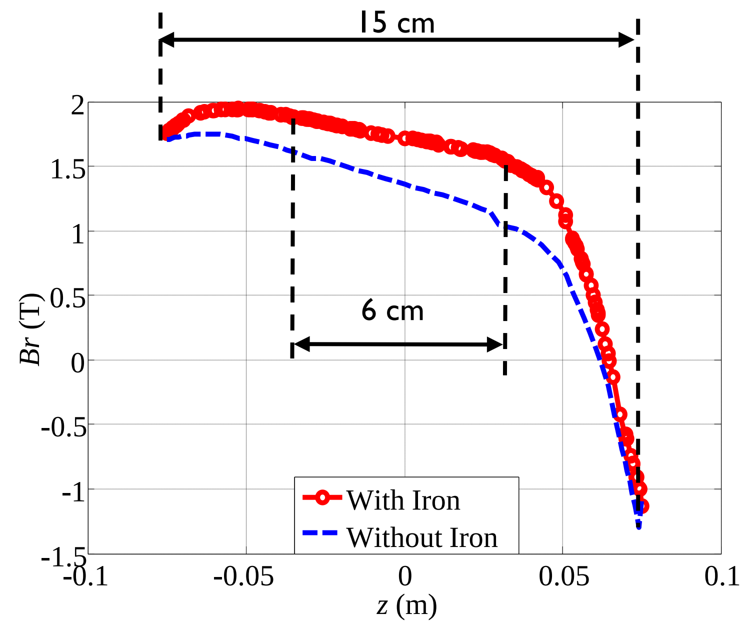
# Motor principle

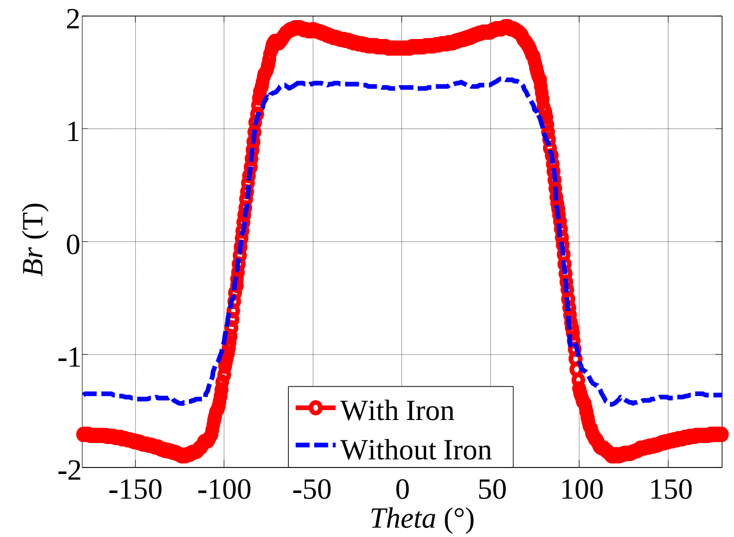


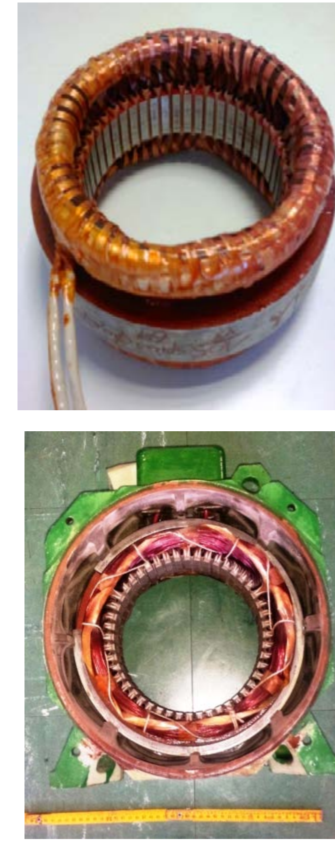
# Influence of the iron



# 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$^2$

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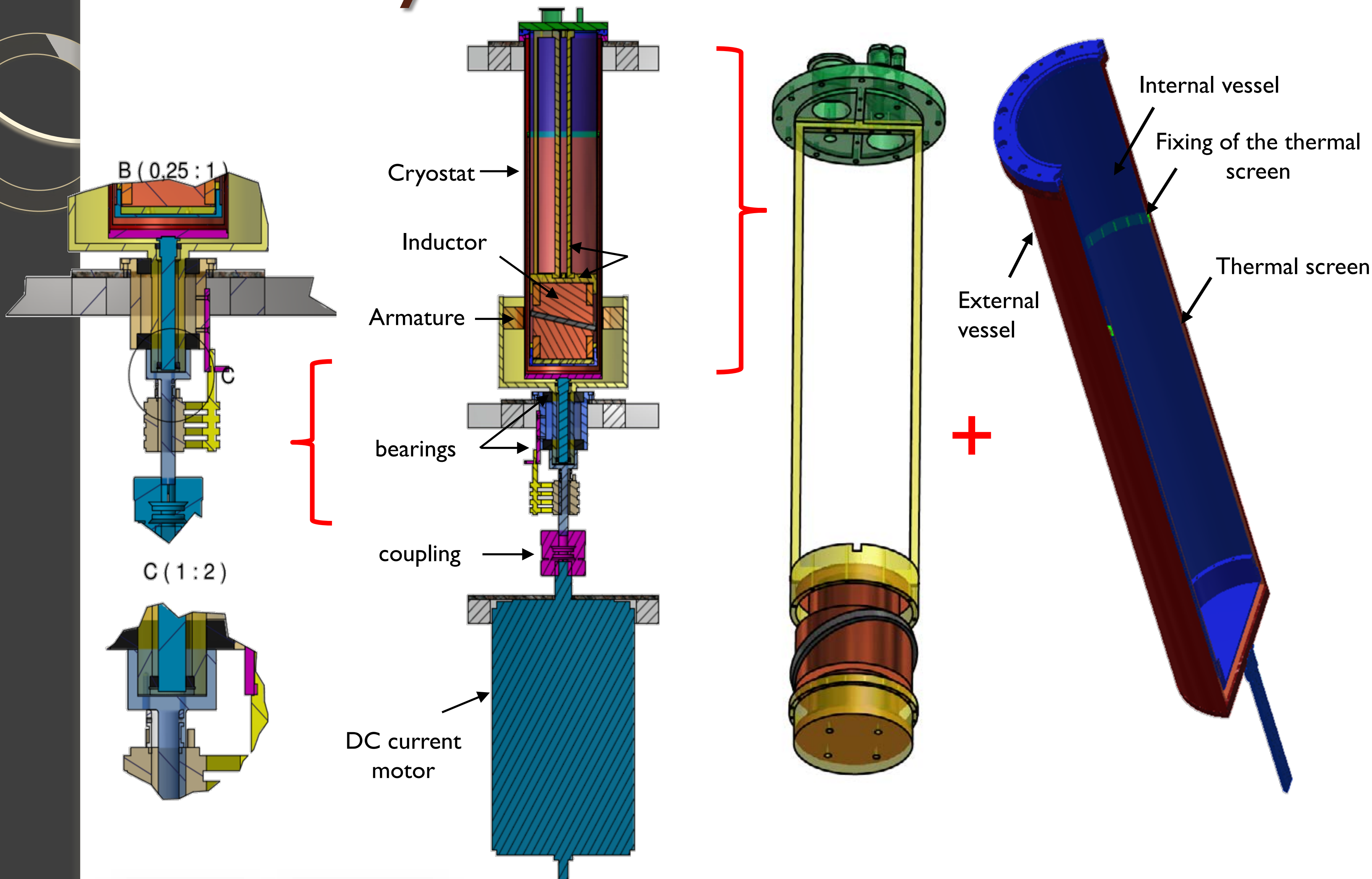
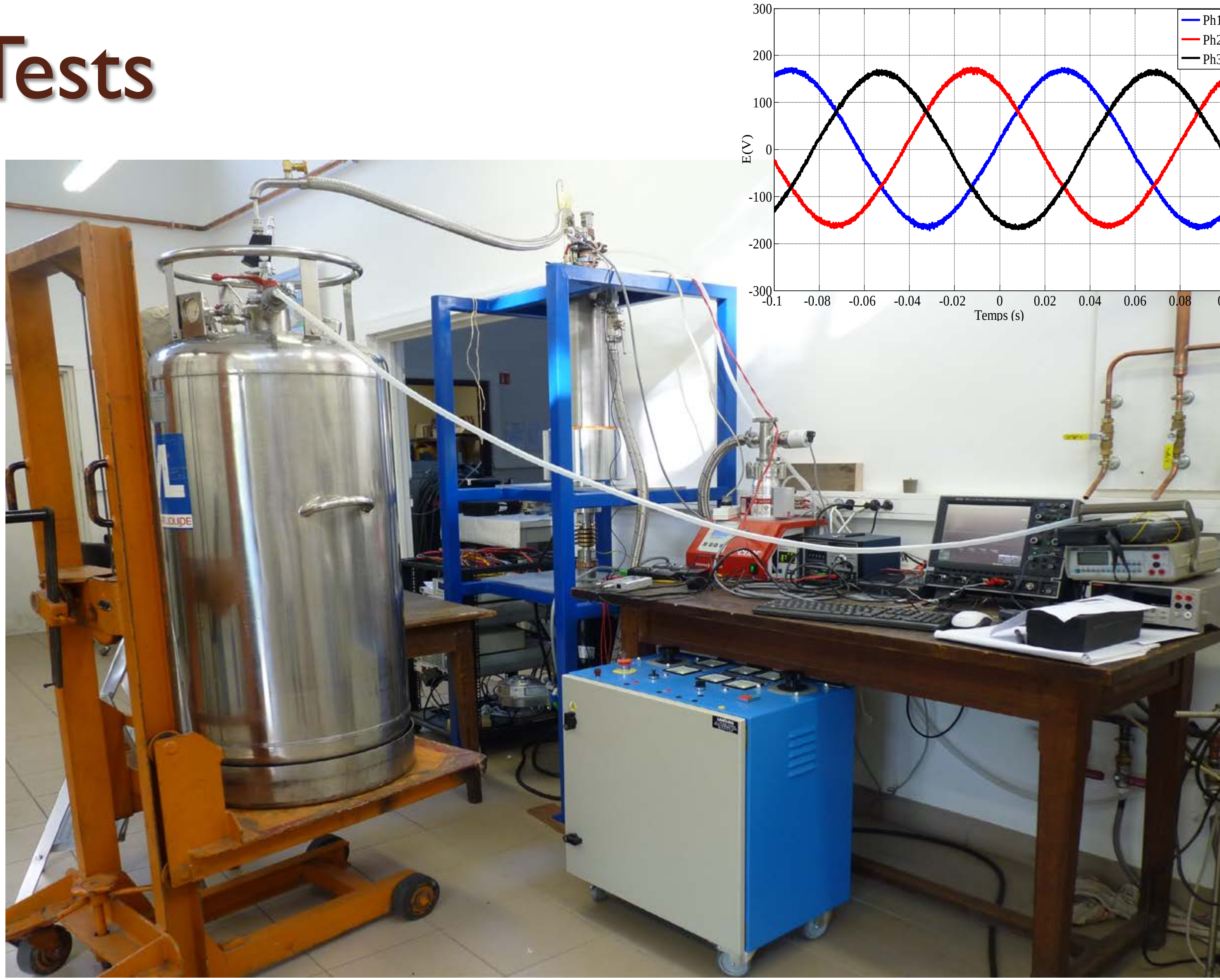
# Assembly



B ( 0,25 : 1 )
C
C ( 1 : 2 )
Cryostat
Inductor
Armature
bearings
coupling
DC current motor
External vessel
Internal vessel
Fixing of the thermal screen
Thermal screen
+

# Assembly

# Tests



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

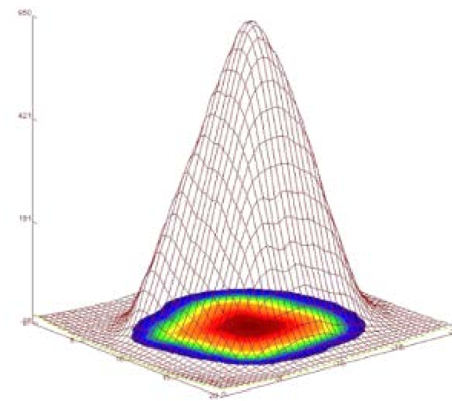
# Summary

- GREEN has a good expertise in superconducting motors
  - AC losses measurements/modeling are linked to this topic
  - The characterization of tapes is also needed
  - Magnetic coupling is a kind of synchronous machine

- Most of the motors developed by the GREEN involve bulk superconductors
  - They can trap or screen very high magnetic fields
  - They are the key for a major technological advance

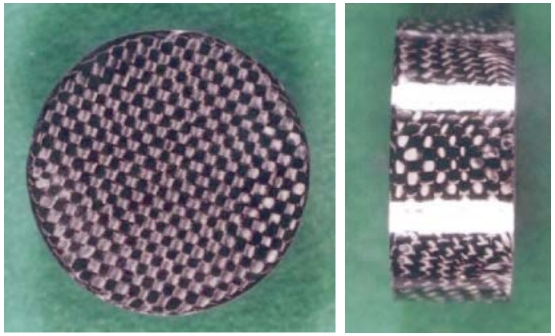
# Outline - High magnetic flux generation with superconductors

- How high?
- For what purpose?
- How it works?
- How we made it?
  - Example of field cooling on MgB2 measurements
  - Pulsed Field Magnetization on YBCO @ 77 K

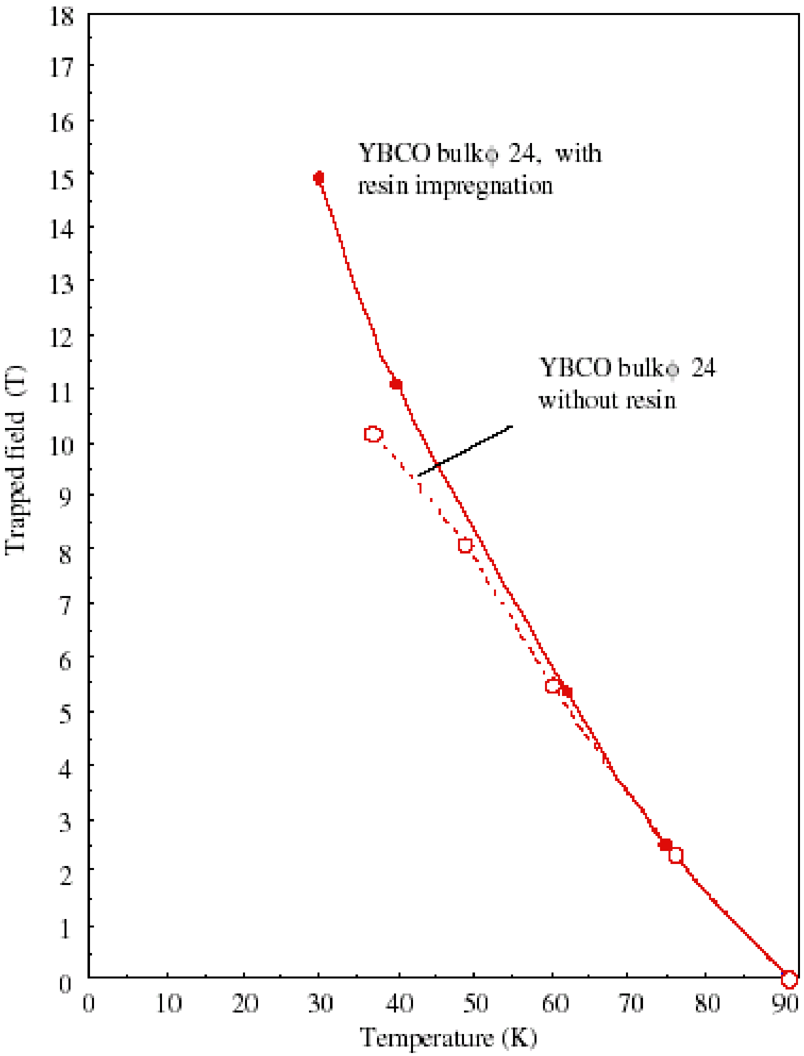


# How high?

Resin impregnated YBCO pellets



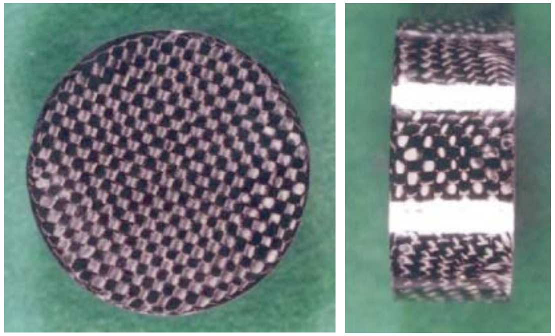
- 15 T can be trapped at 30 K using field cooling method
- The behavior is different from permanent magnets:
  - Permanent magnets operate at "constant flux"
  - HTS operate at "constant current"

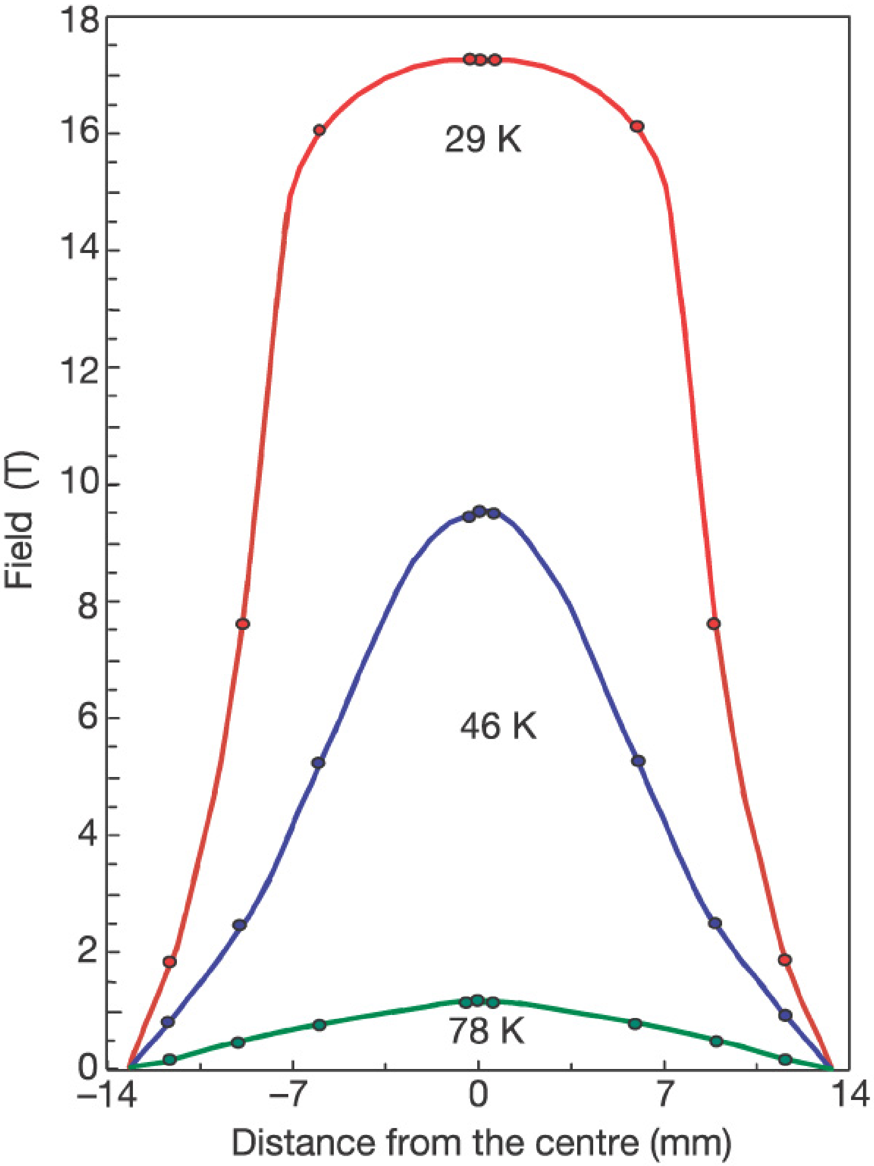


# How high?

M. Tomita et M. Murakami., « High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 tesla at 29 K », *Nature* 421, pp. 517-520, 2003.

Resin impregnated YBCO pellets





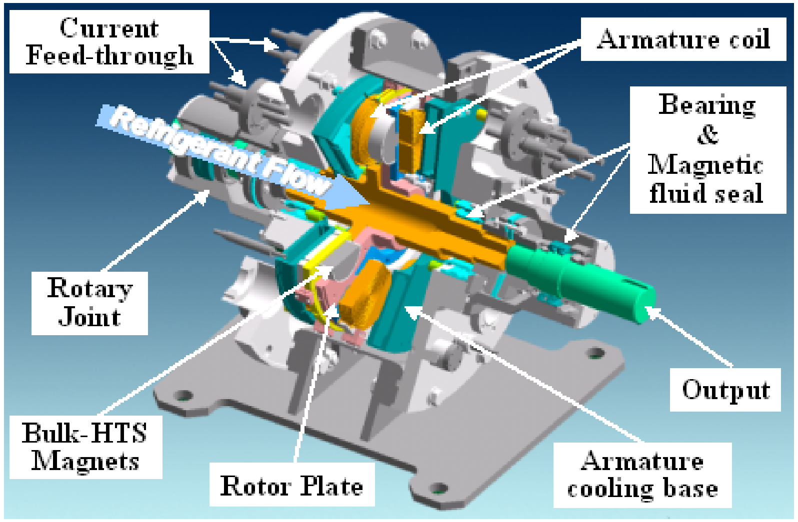

- Record: 17 T trapped
- Higher fields are theoretically possible

- Cryo-magnets are promising, but they are difficult to implement

# For what purpose?

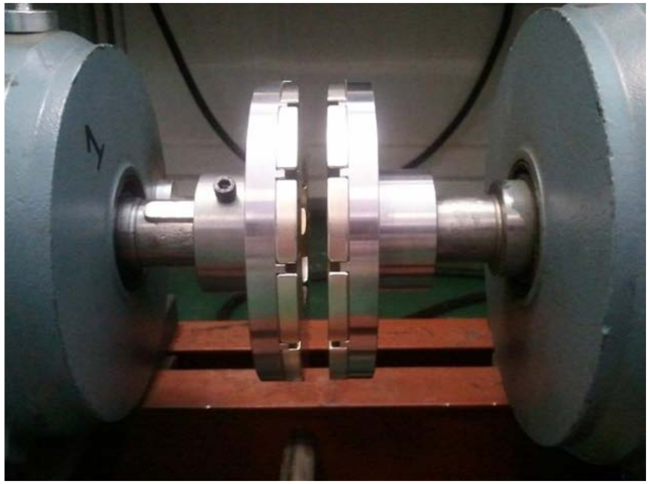
- Electrical machines

**Design of bulk-HTS synchronous motor**




H. Matsuzaki et al., « HTS Bulk Pole-Field Magnets Motor With a Multiple Rotor Cooled by Liquid Nitrogen », *IEEE Trans. Applied Superconductivity* 147 (2), pp. 1553-1556, 2007.

- Magnetic coupling
  - Replacing PM by YBCO bulks



T. Lubin et al., « Experimental and Theoretical Analyses of Axial Magnetic Coupling Under Steady-State and Transient Operations », *IEEE Trans. Industrial Electronics* 61 (8), 2014.

# How it works?

- Lenz's law:
  - When a variation of the magnetic field is applied to a superconductor, there are induced currents
  - Even if the applied field is null, the currents remain indefinitely in the superconductor producing a magnetic field like a coil
  - The interaction of the induced currents with a perpendicular magnetic field, (e.g. PM) results in a force according to the Laplace formula $F_z = J_\theta \times B_r$

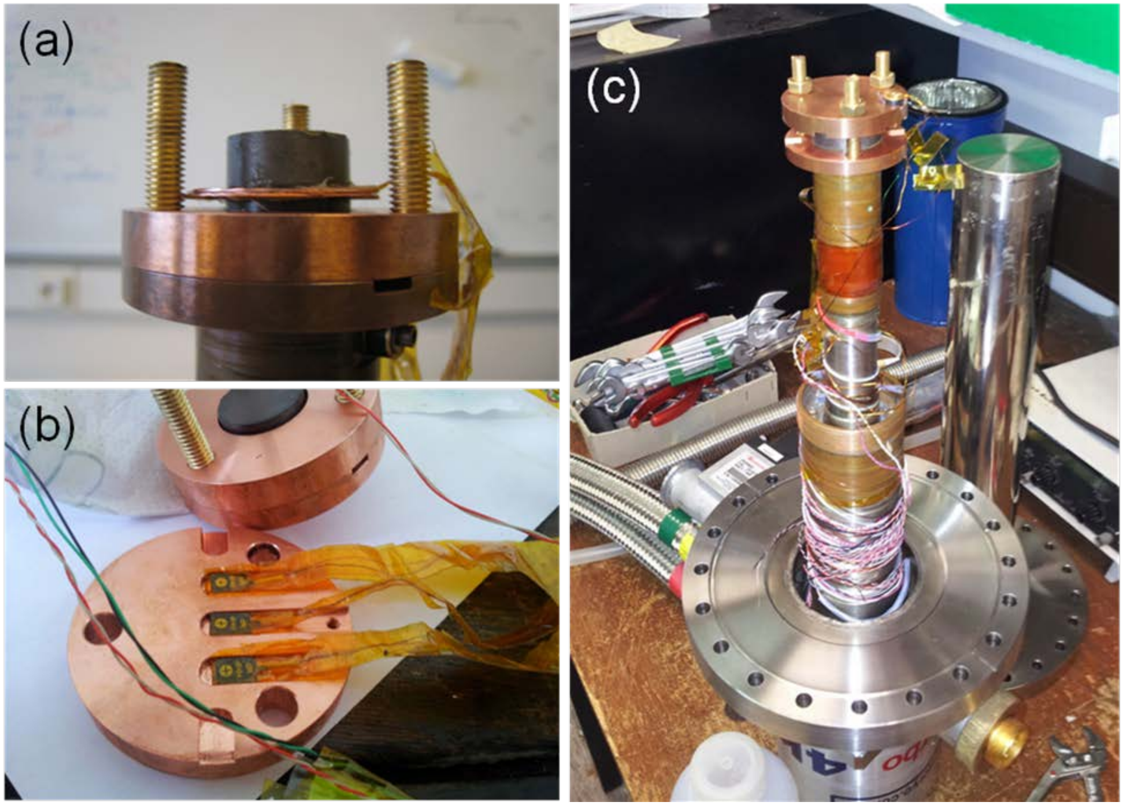
↳ Levitation principle

# How we made it?

- Cryocooler capabilities
  - For cooling the HTS down to 10 K
    - 70W @ 30 K (CH 110, 45 cm bore)
    - 2W @ 10 K (CH 204 with 2 stages)
    - 0.1W @ 5 K (ARS 202 with 2 stages)
  - The HTS with the cryocooler is put inside the bore of the LTS coil

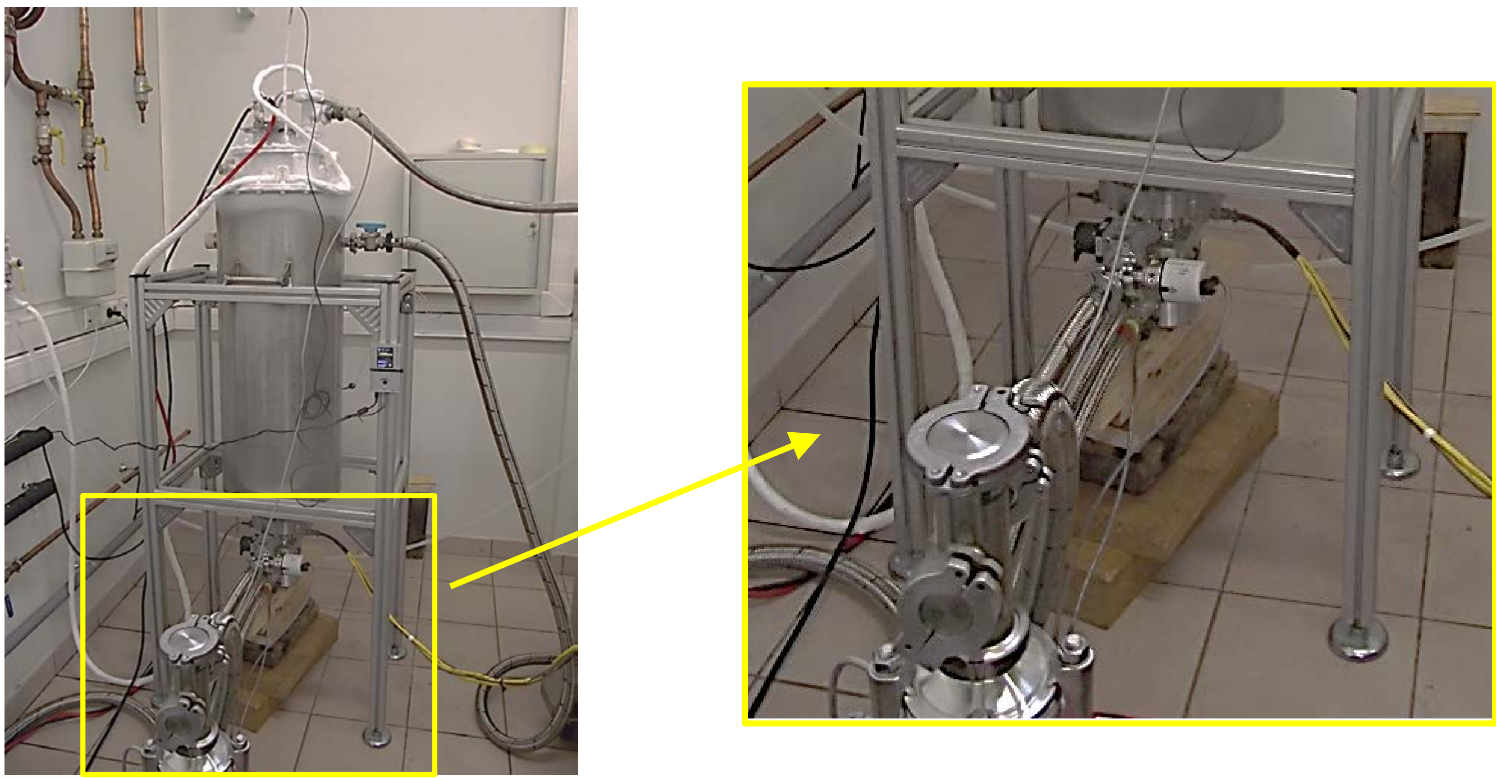
# How we made it?

- Cryogenic Hall probes array



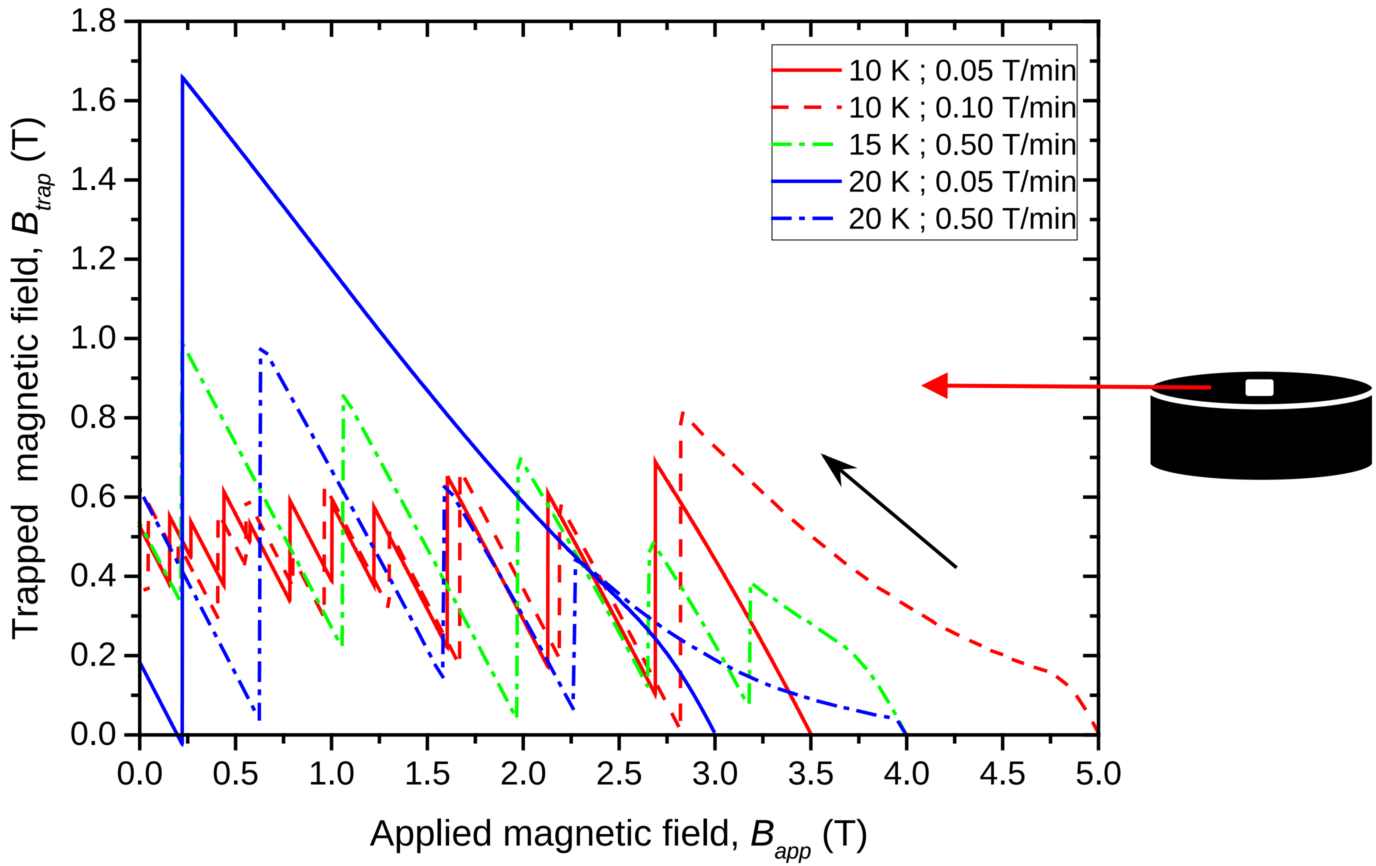
# How we made it?

- By Field Cooling process using:
  - Home made LTS coil 4 T with Ø 10 cm bore (Nancy)
  - Oxford Instruments ±5 T, Ø 7.5 cm bore (Saarbrücken)



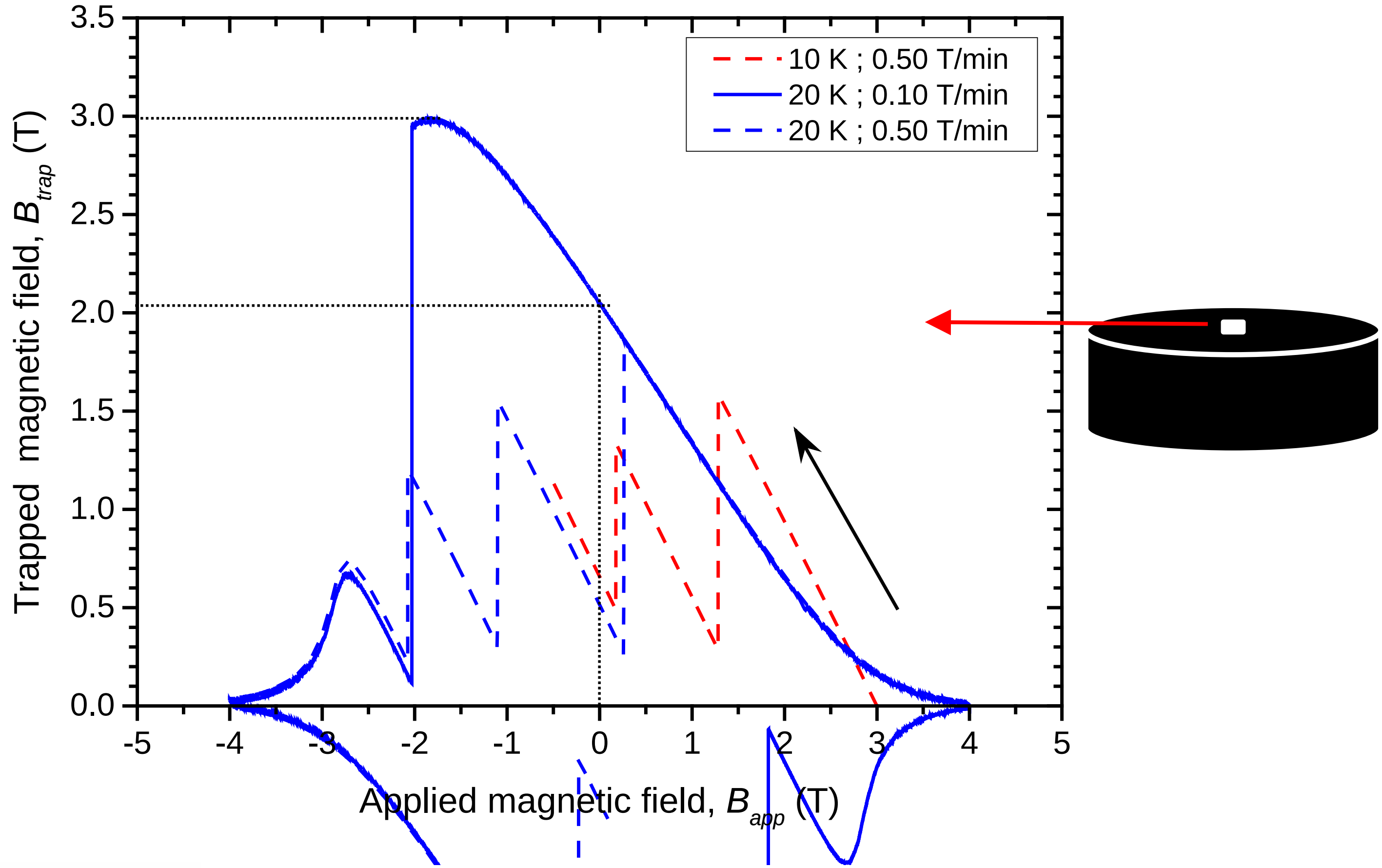
# MgB2 sample with 4% Ag
## Ø 20 mm

- Sweep rate influence on the flux jumps



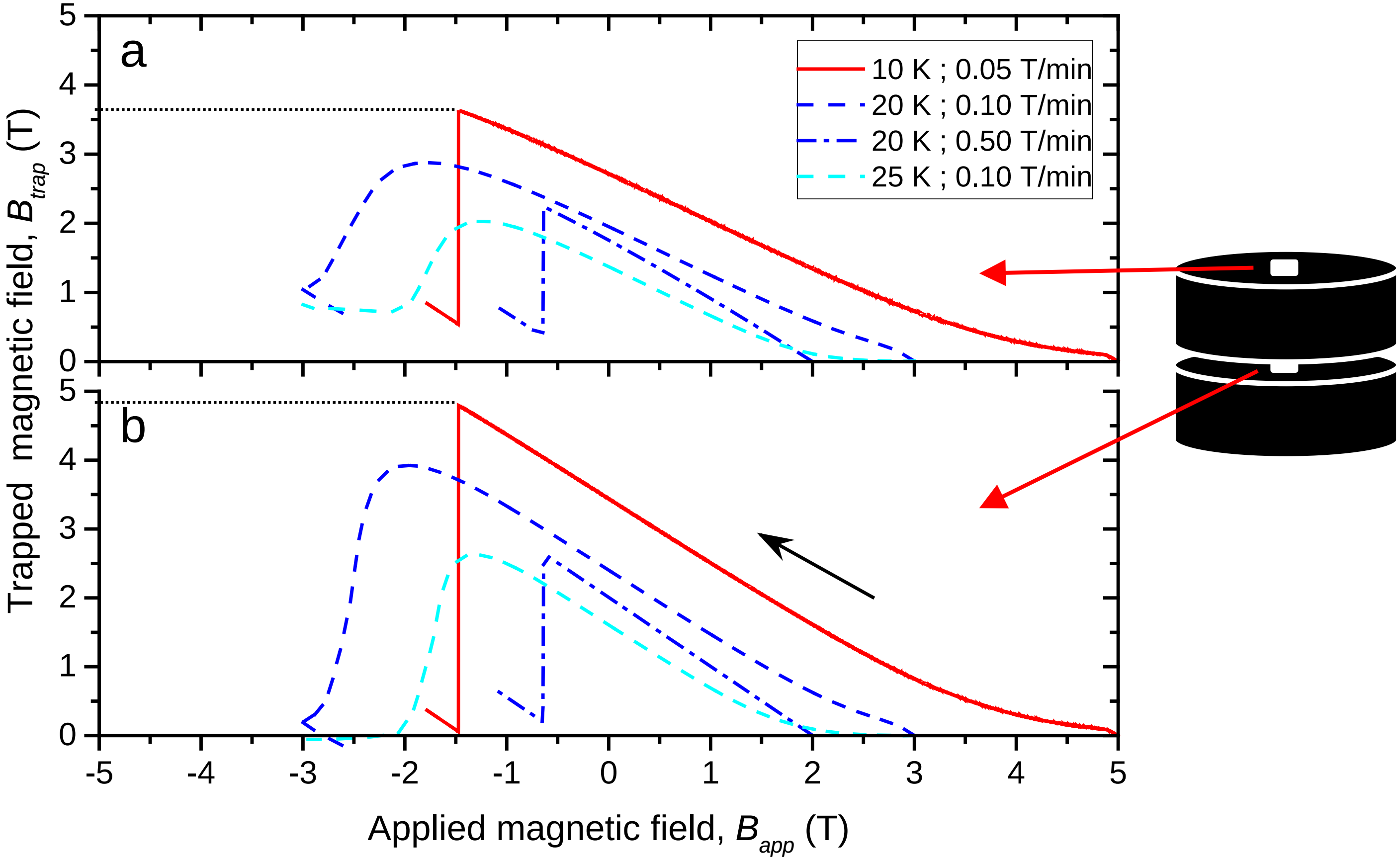
# MgB2 sample produced by SPS
## Ø 30 mm

- Sweep rate influence on the flux jumps



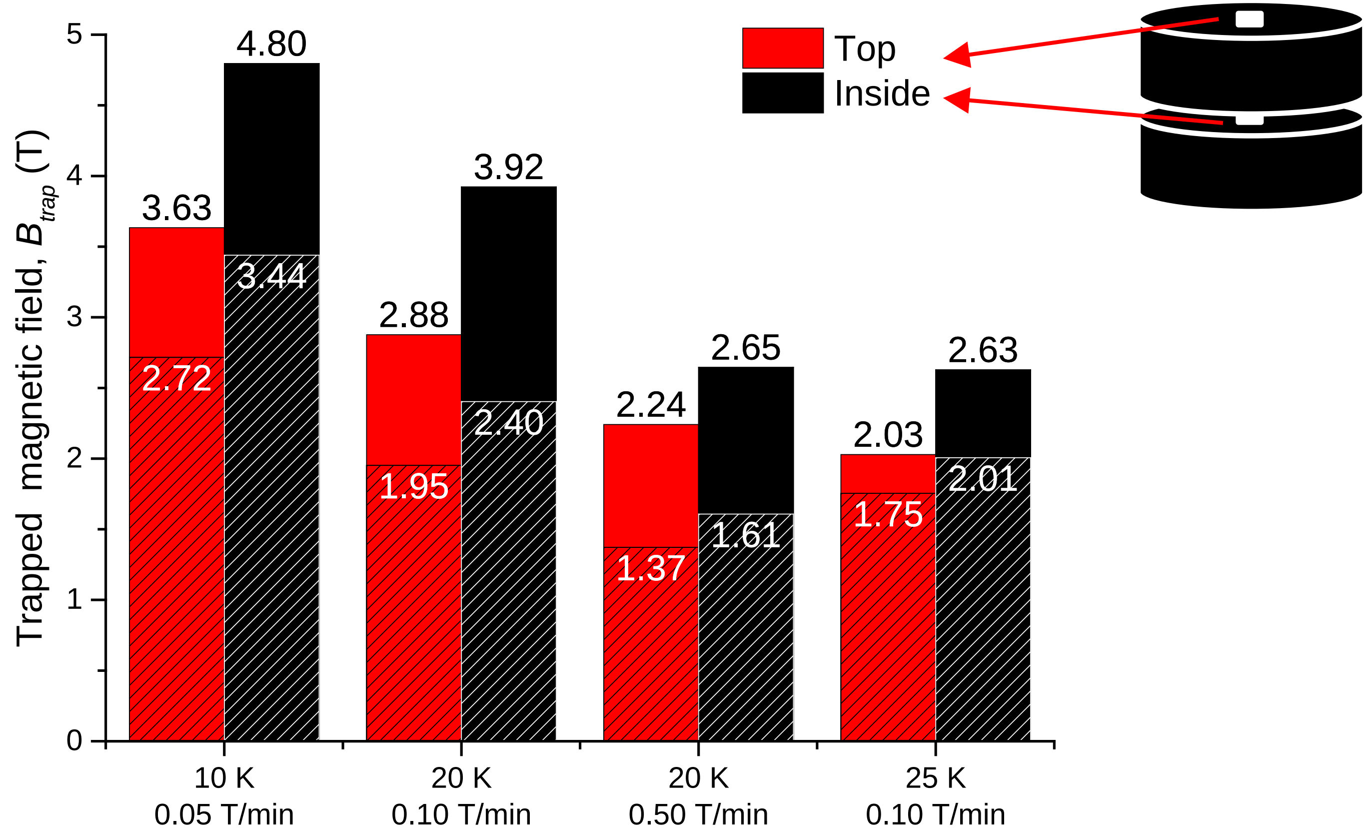
# 2xMgB2 samples produced by SPS
## Ø 20 mm

- Higher trapped fields inside the pellet



# 2xMgB2 samples produced by SPS
## Ø 20 mm

- Higher trapped fields inside the pellet

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# Pulsed Field Magnetization technique

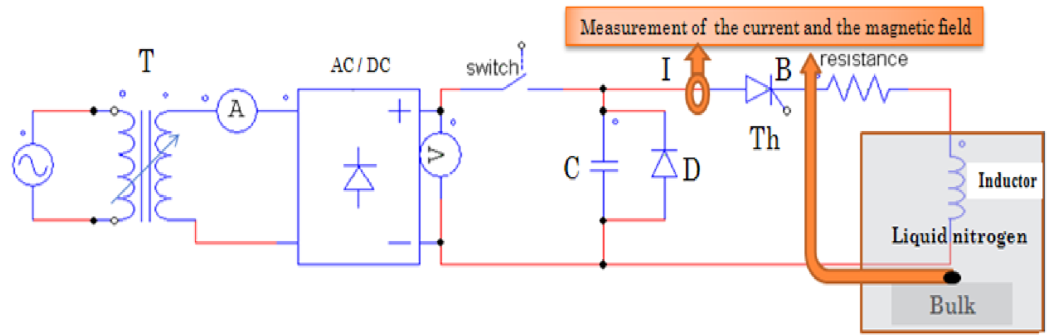
- The most convenient and most common way to magnetize a superconducting pellet is to use a Pulsed Magnetic Field,
- It can generate strong magnetic fields while using a relatively small and simple coil,
- Thus, the pellet can be directly magnetized into the final application, e.g., a machine.

# Experimental apparatus

220 Vac + Rectifier
350 Vdc

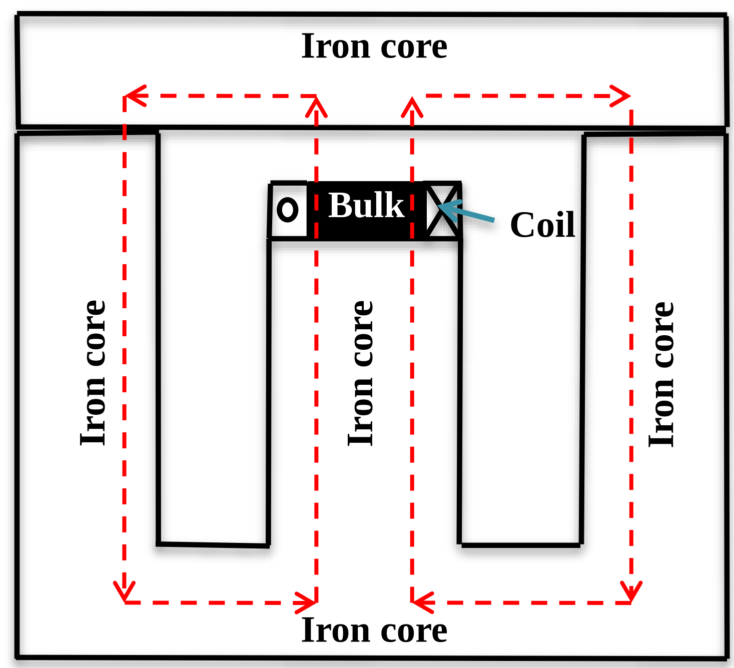
Capacitor bank
115 mF

Thyristor 16 kA max

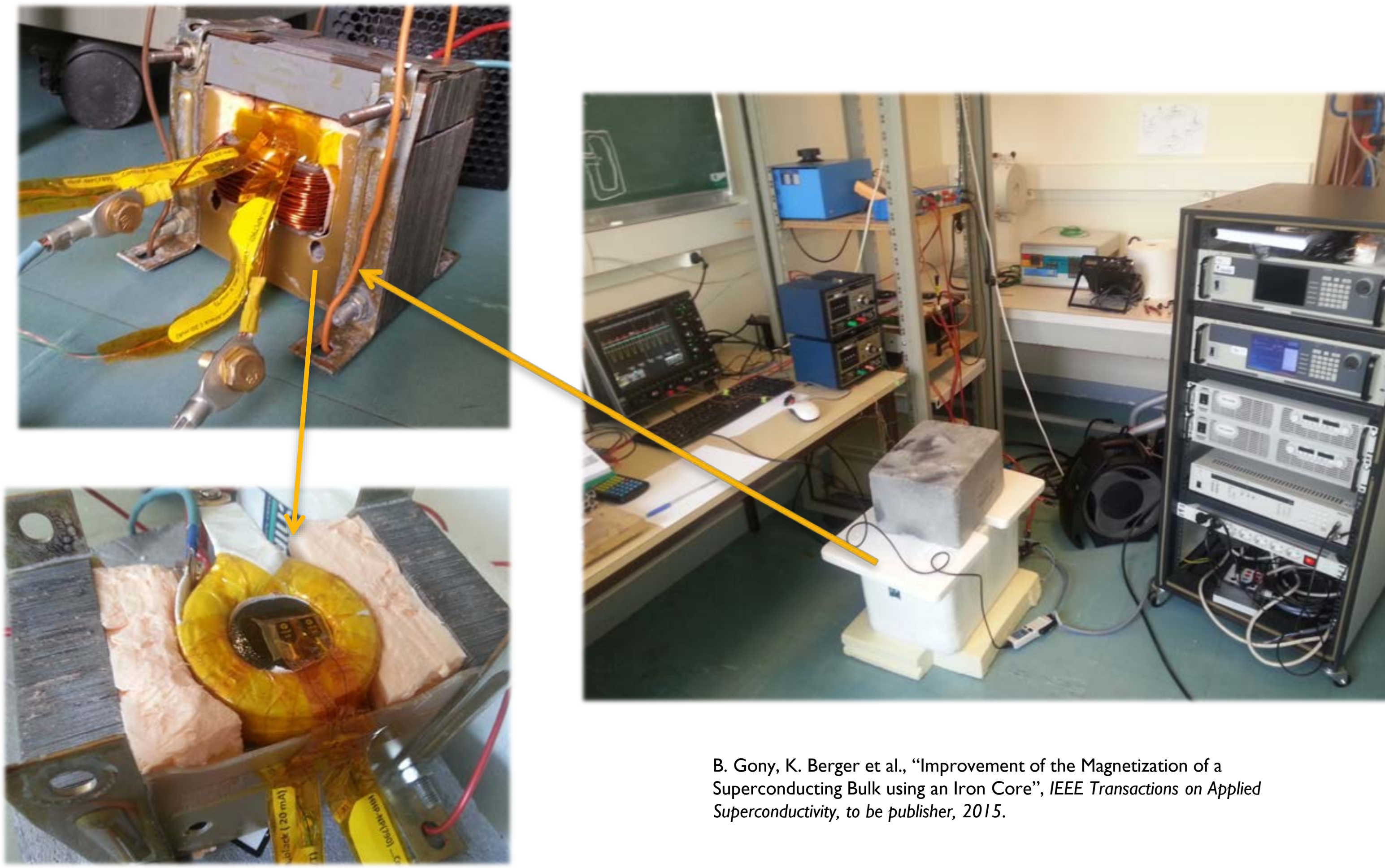


# Experimental apparatus

- PFM within an iron core:
  - To reproduce the classical motor structure
  - To increase the trapped magnetic field in the HTS



# Experimental apparatus @ 77K



B. Gony, K. Berger et al., "Improvement of the Magnetization of a Superconducting Bulk using an Iron Core", *IEEE Transactions on Applied Superconductivity, to be publisher, 2015.*

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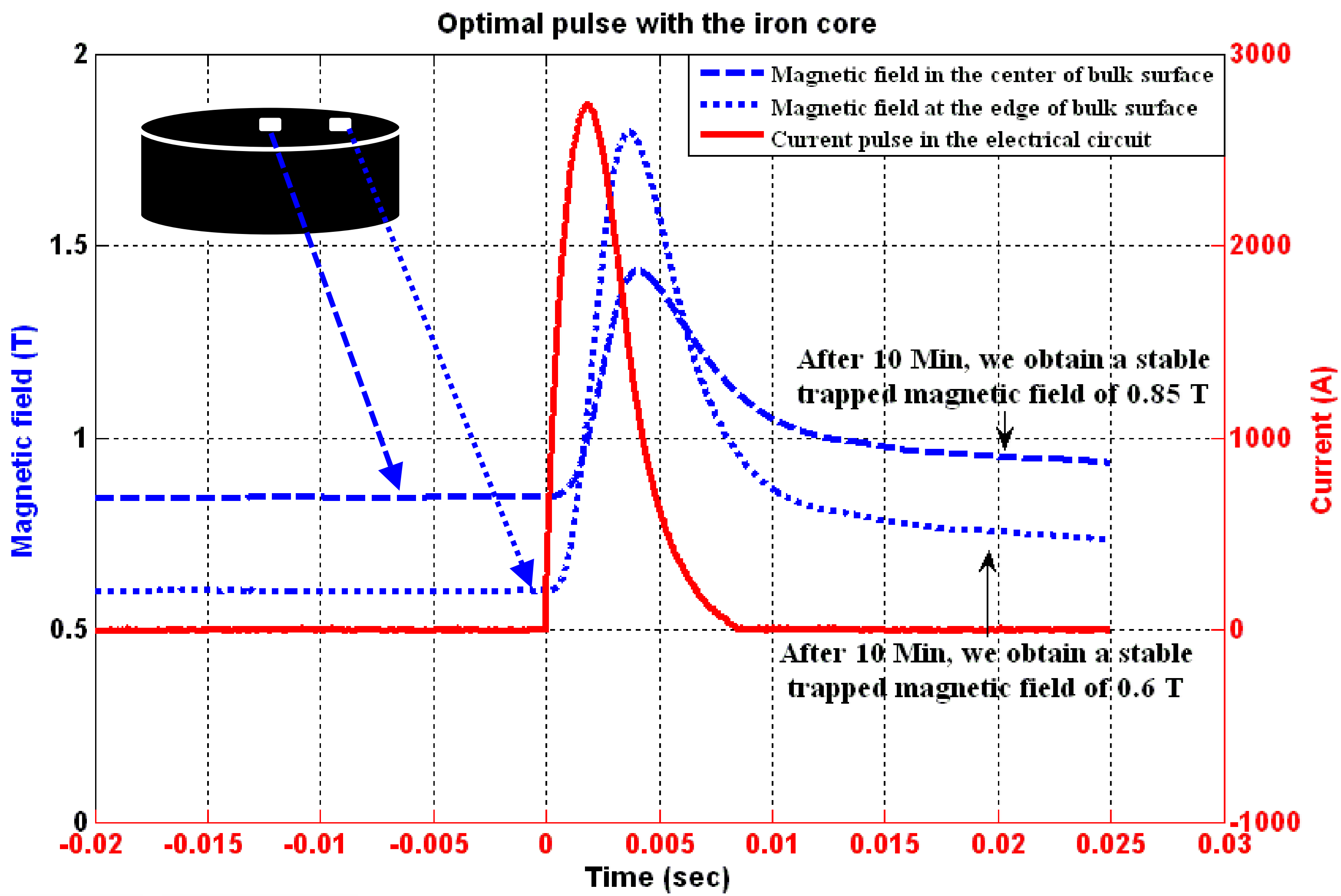
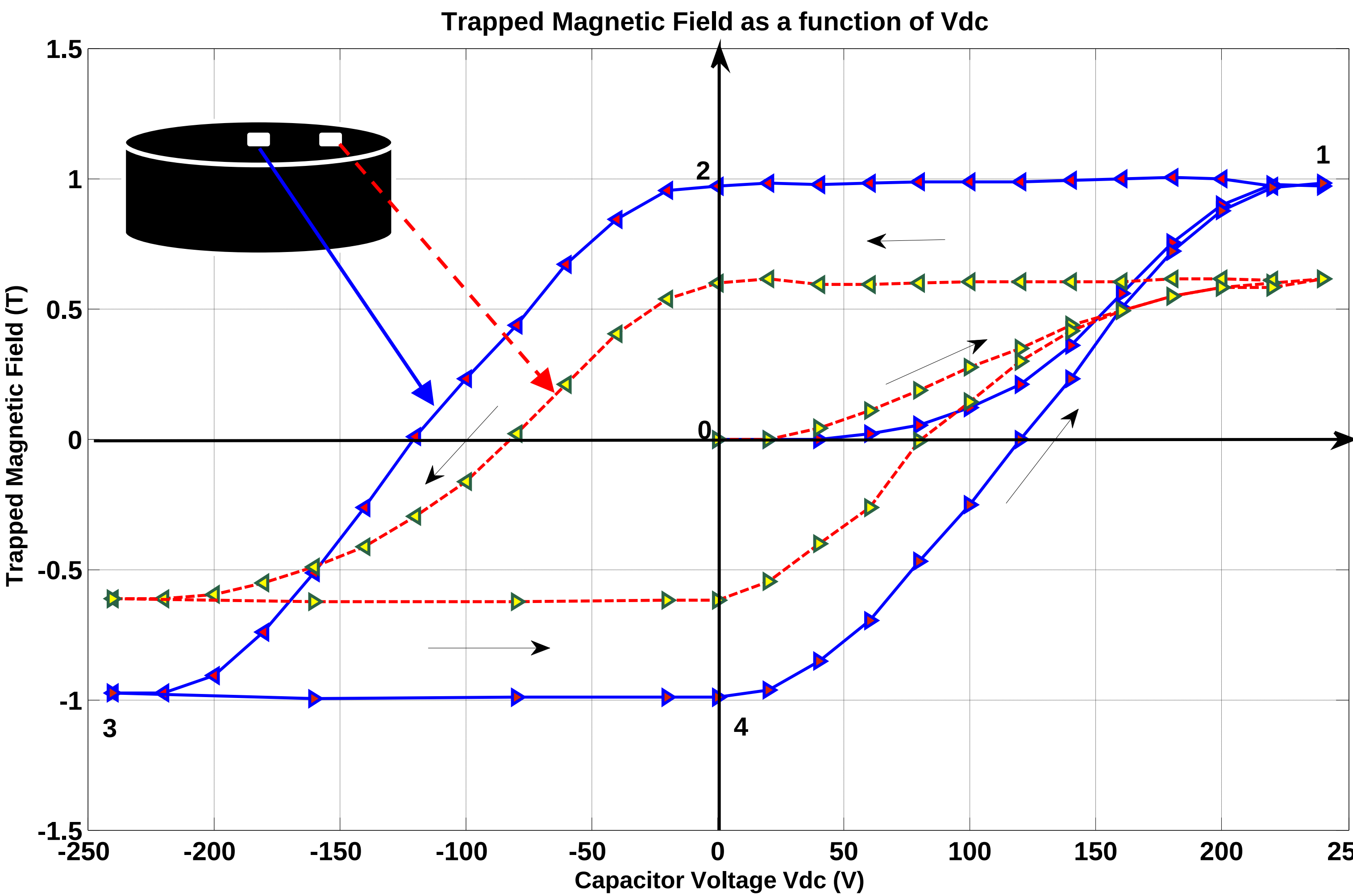
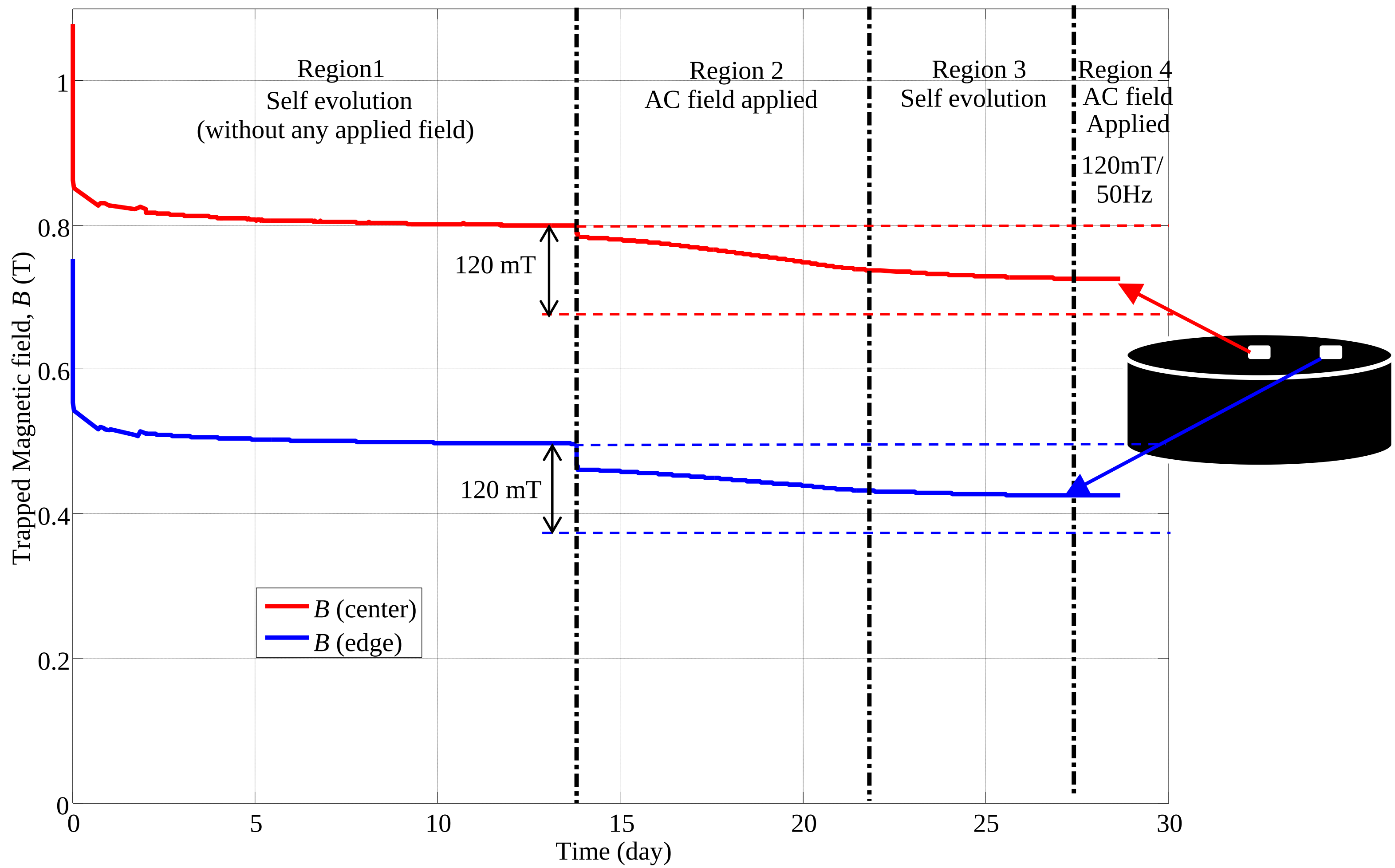
# Pulsed current and magnetic field



# Magnetization behavior of YBCO



# Study of the demagnetization



# Advantages and future works on PFM

- Increased of 35% of the trapped magnetic field by using the iron core,

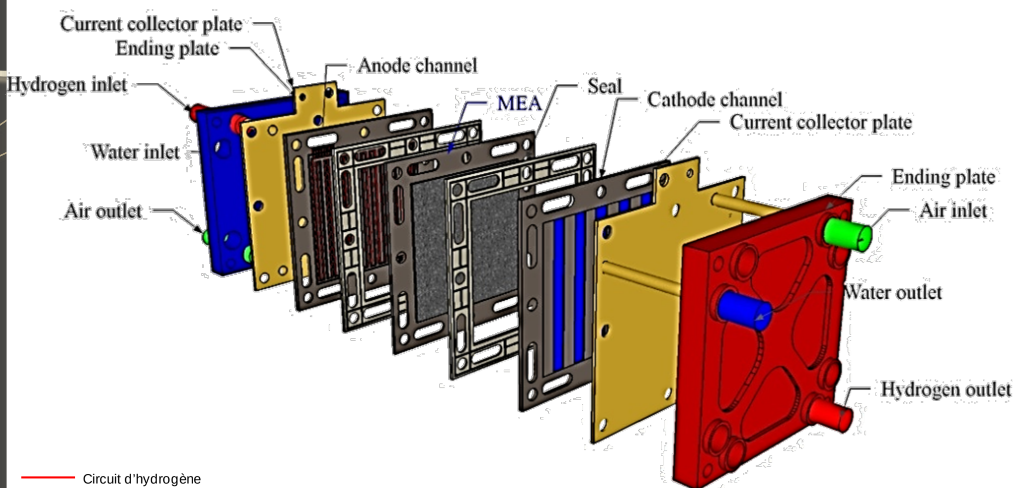
B. Gony, K. Berger, B. Douine, M. Koblischka, J. Lévêque. "Improvement of the Magnetization of a Superconducting Bulk using an Iron Core.", *IEEE Transactions on Applied Superconductivity*, 2015.

- Maximal current of the discharge 40% lower with the iron core,

- The PFM with an iron core will be studied at low temperature using a CH-110 cryocooler.

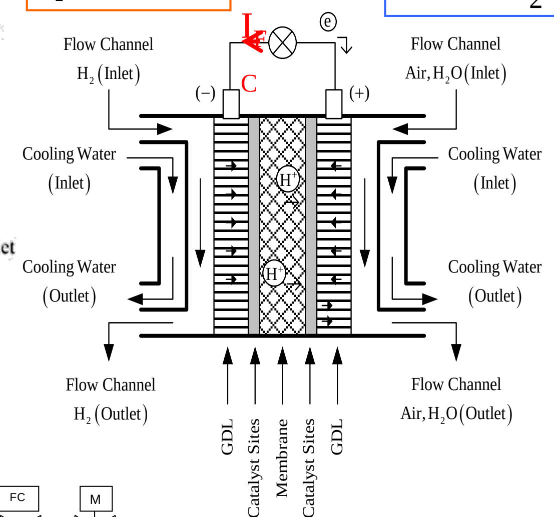
# New activities at the GREEN

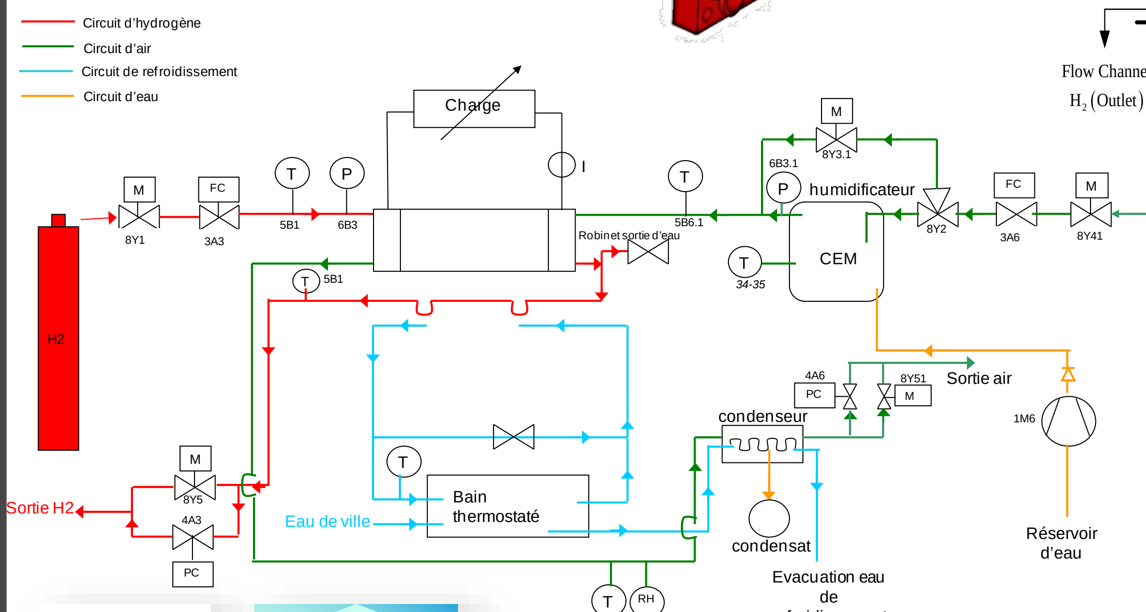
- Using Fuel cell as a Power Supply for Superconducting Coil




$$H_2 \rightarrow 2H^+ + 2e^-$$

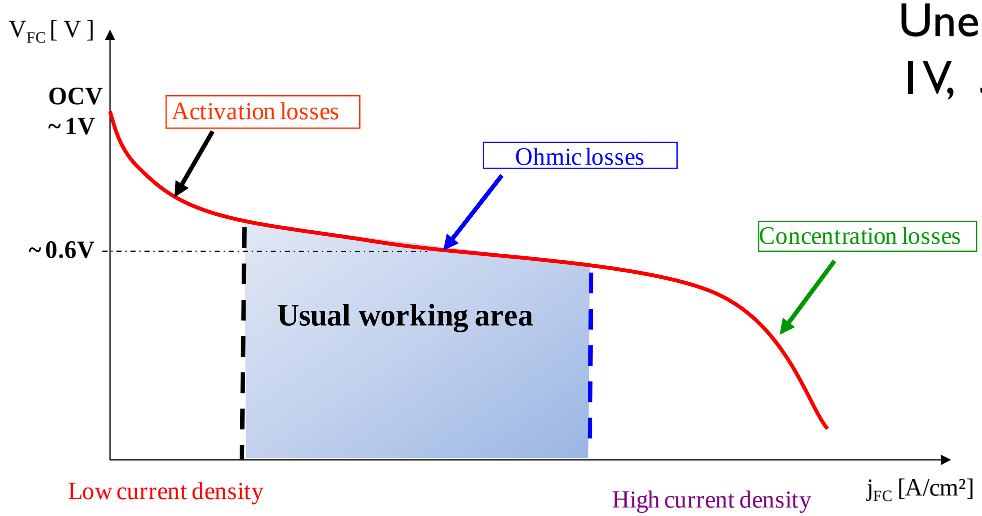
$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O$$



# New activities at the GREEN

- Using Fuel cell as a Power Supply for Superconducting Coil

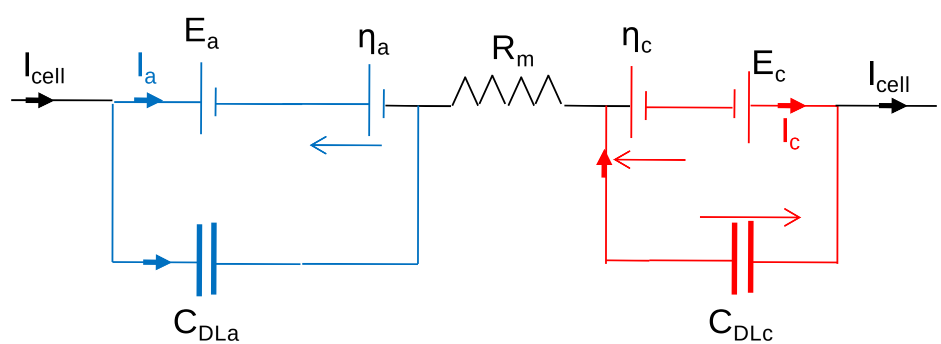



Une cellule :
1V, 50A pour 100 cm²

$$\begin{cases} I_a(t) = I_{cell}(t) - C_{dla} \cdot \dfrac{d\eta_a}{dt} \\ I_c(t) = I_{cell}(t) - C_{dlc} \cdot \dfrac{d\eta_c}{dt} \end{cases}$$

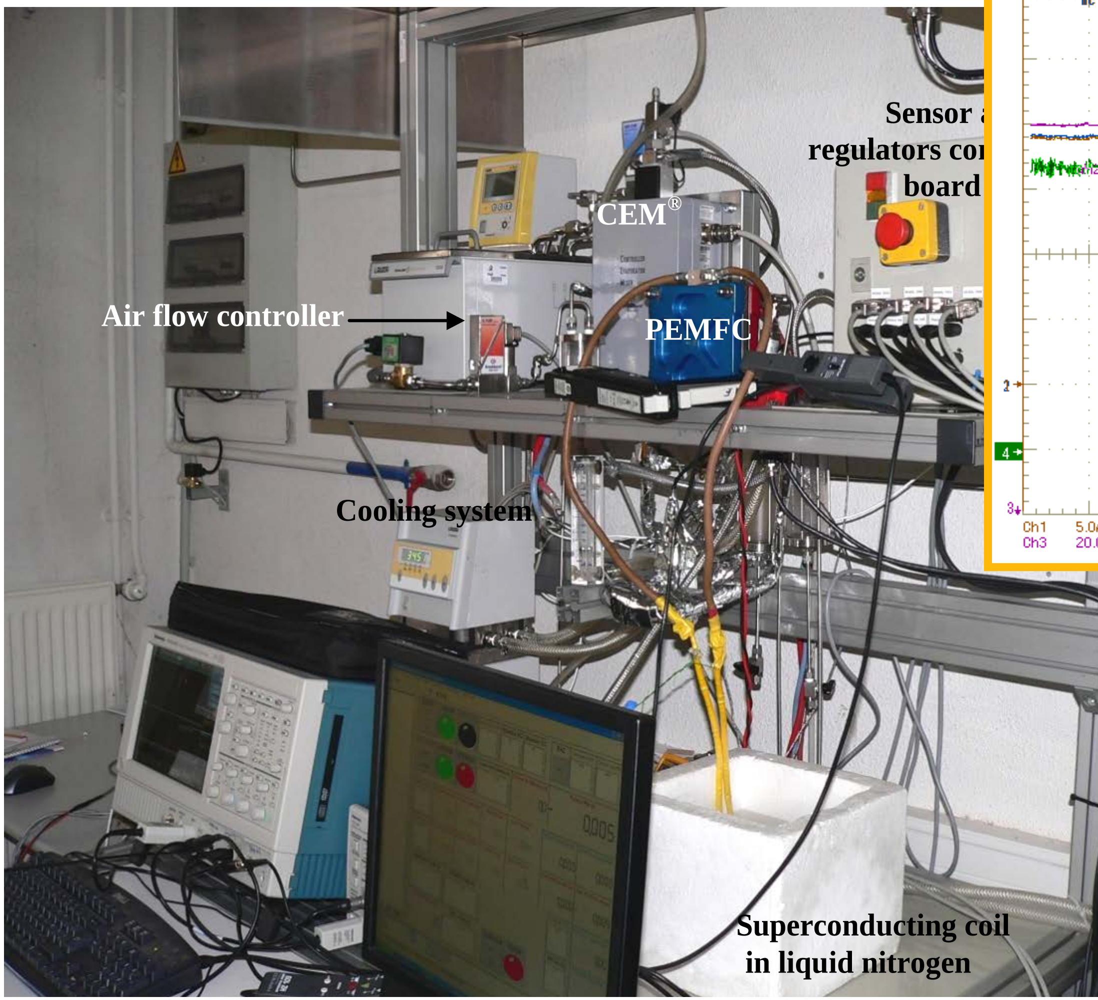
$$V_{FC} = (E_c - \eta_c) - (E_a + \eta_a) - \eta_m$$

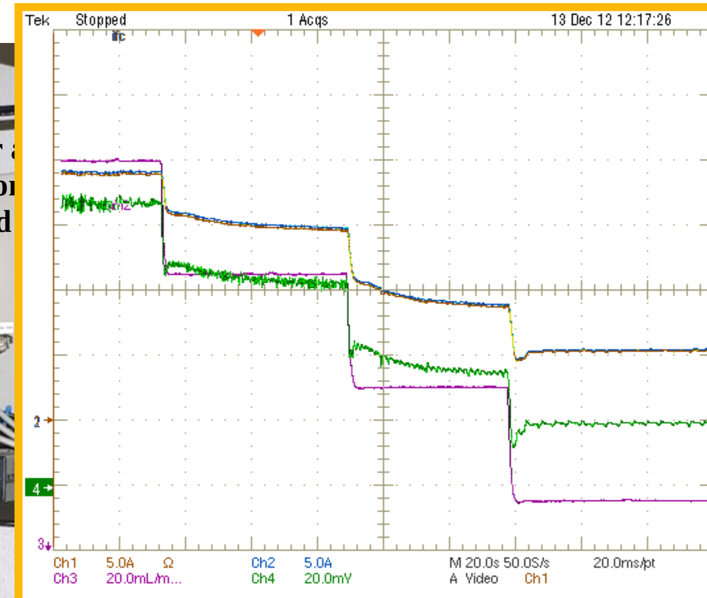
$$\begin{cases} \eta_c = \eta_{c,act} + \eta_{c,conc} \\ \eta_{c,act} = \dfrac{RT}{F} \cdot \ln\left(1 + \dfrac{J_c}{J_{oc}}\right) \\ \eta_{c,conc} = -\dfrac{RT}{F} \cdot \ln\left(1 - \dfrac{J_c}{J_L}\right) \end{cases}$$

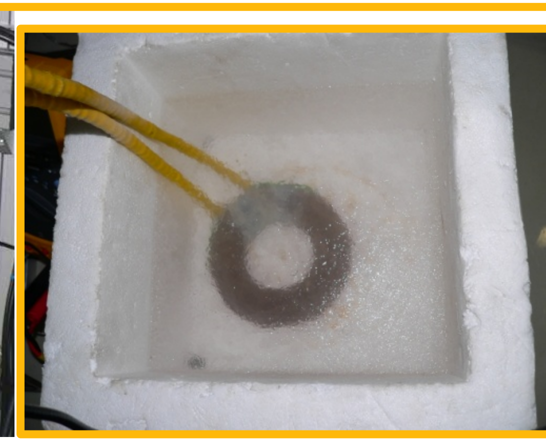


# New activities at the GREEN

- Using Fuel cell as a Power Supply for Superconducting Coil

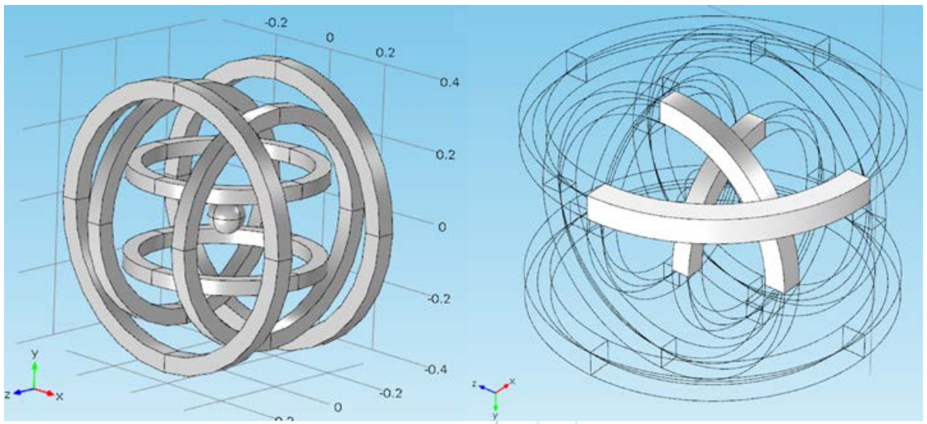


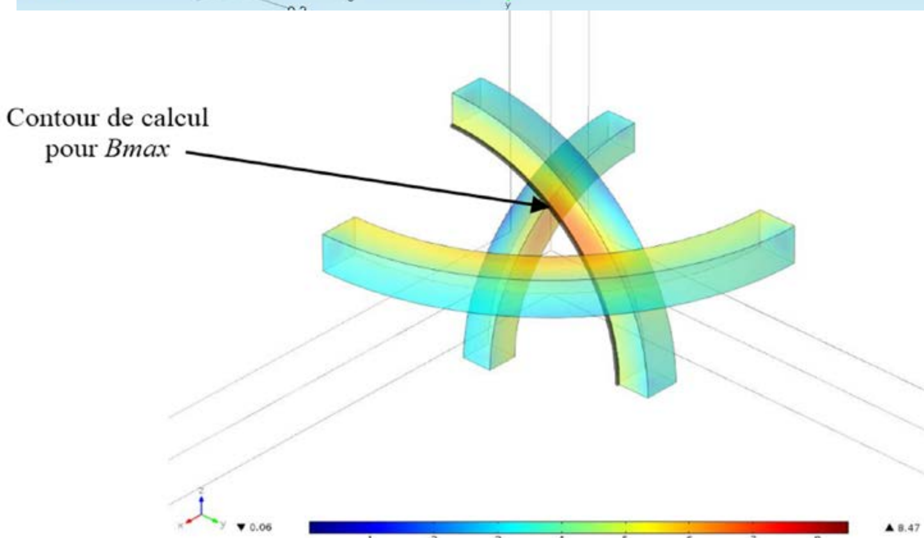



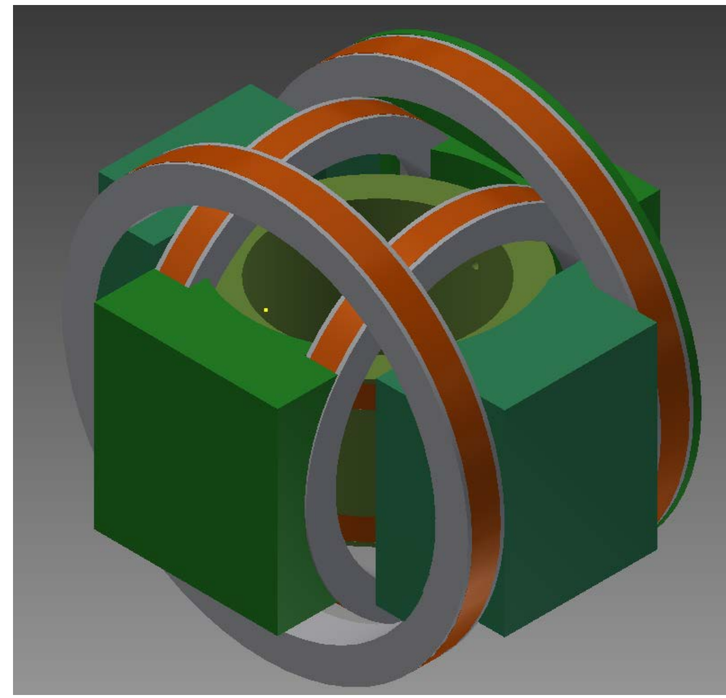



# New activities at the GREEN

- A vector magnet generating up to 3 T with 3 axis orientation
  - homogeneity greater than 95% in a sphere of 10 cm diameter

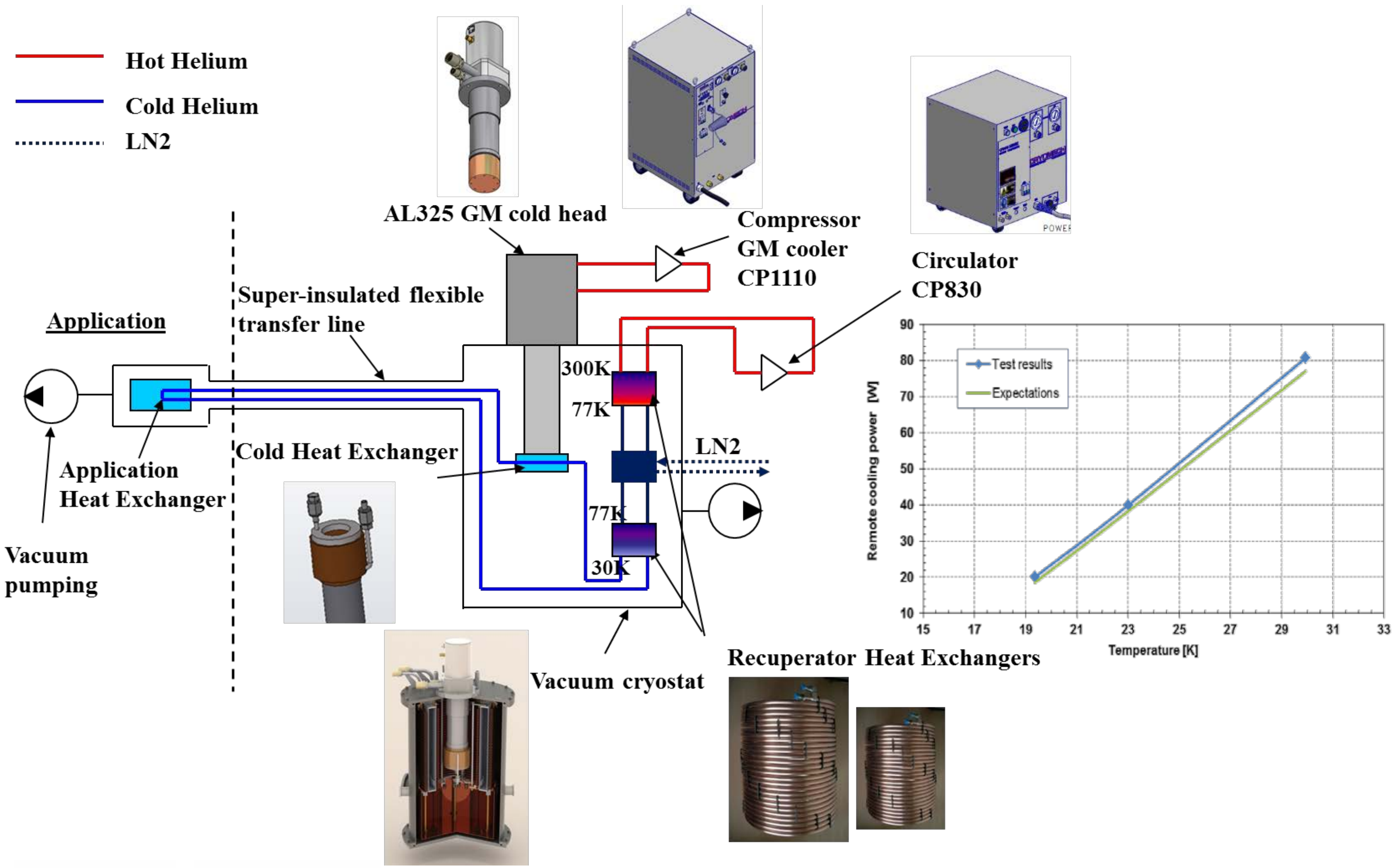




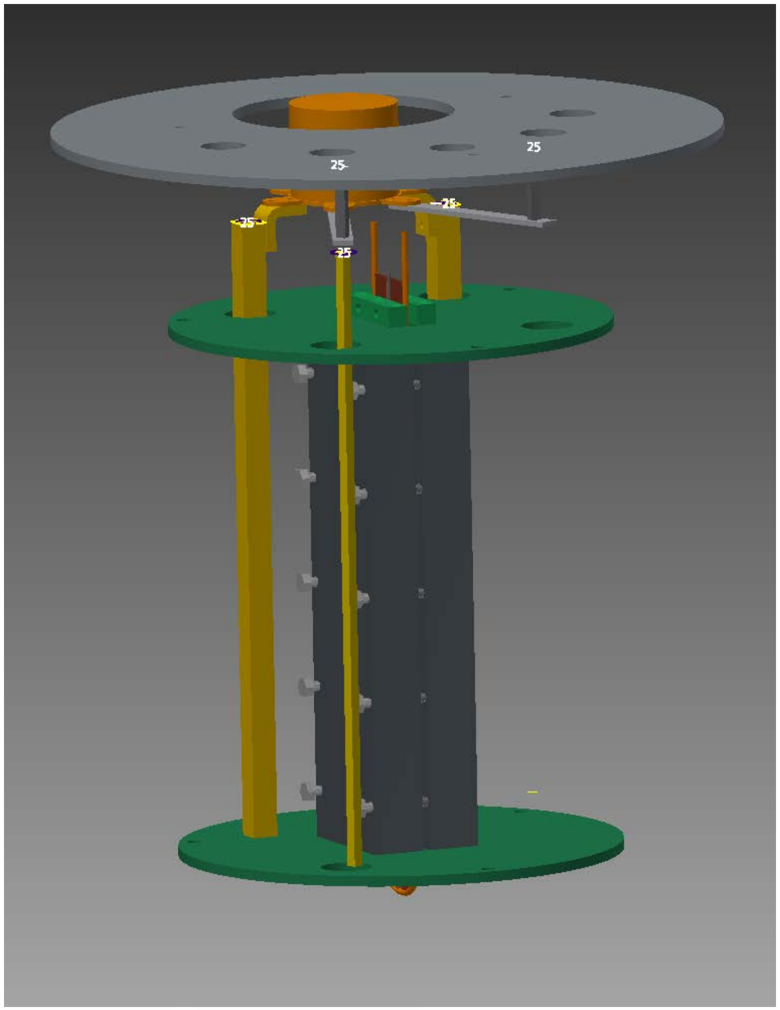
# New activities at the GREEN

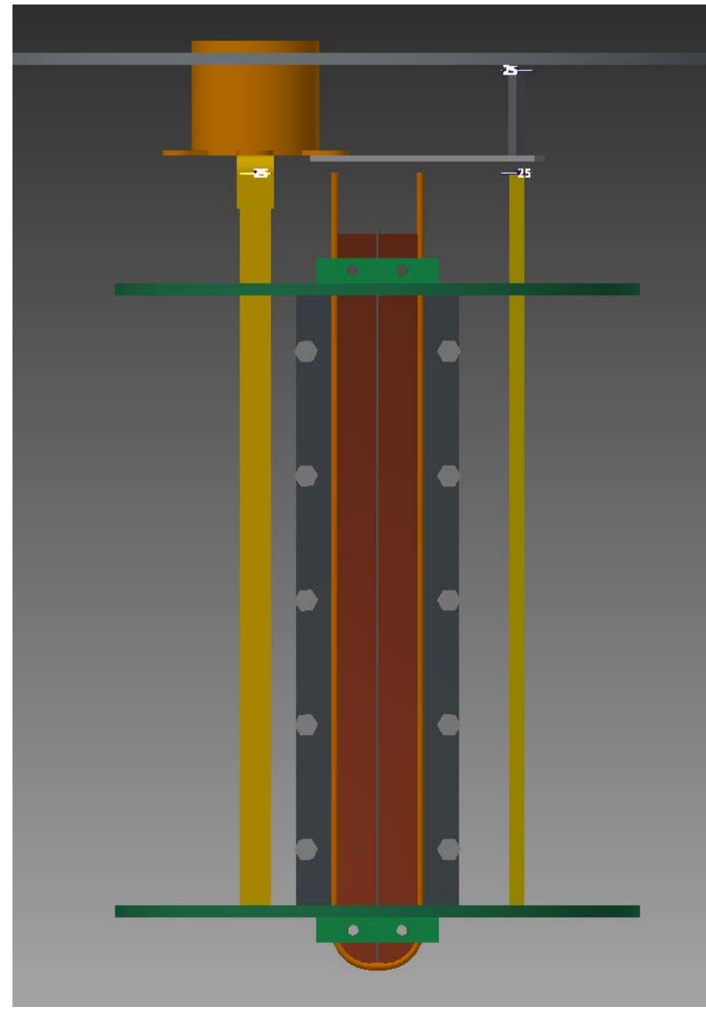
- Characterization bench for MgB2 wires: 15-40 K, 1 T, 600 A



# New activities at the GREEN

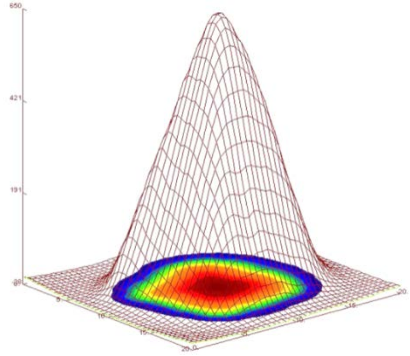
- Characterization bench for MgB2 wires: 10-40 K, 1 T, 600 A



# Thanks for listening!

## We are looking for PhD Students…



Pr B. Douine & Dr K. Berger
GREEN - Lorraine University