DE LA RECHERCHE À L'INDUSTRIE

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Les aimants supraconducteurs Application à la physique des particules et à l'imagerie médicale

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Irfu/DACM

MAGNETS ARE EVERYWHERE!!!

The very first magnet!

0,5 Gauss / 5.10-5 T

Permanent magnet
(NdFeB, 0.5T)

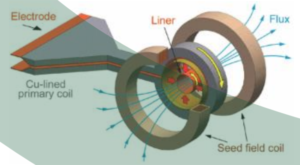
Resistive
magnet (2T)

MRI magnet
(Siemens 3T)

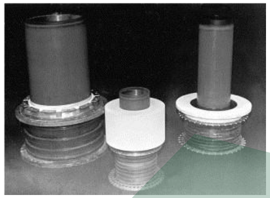
LHC Dipole
(8,3T)

Bruker 1 GHz NMR
(23,5T)

NHMFL
Tallahassee
Hybrid magnet
(40 T)

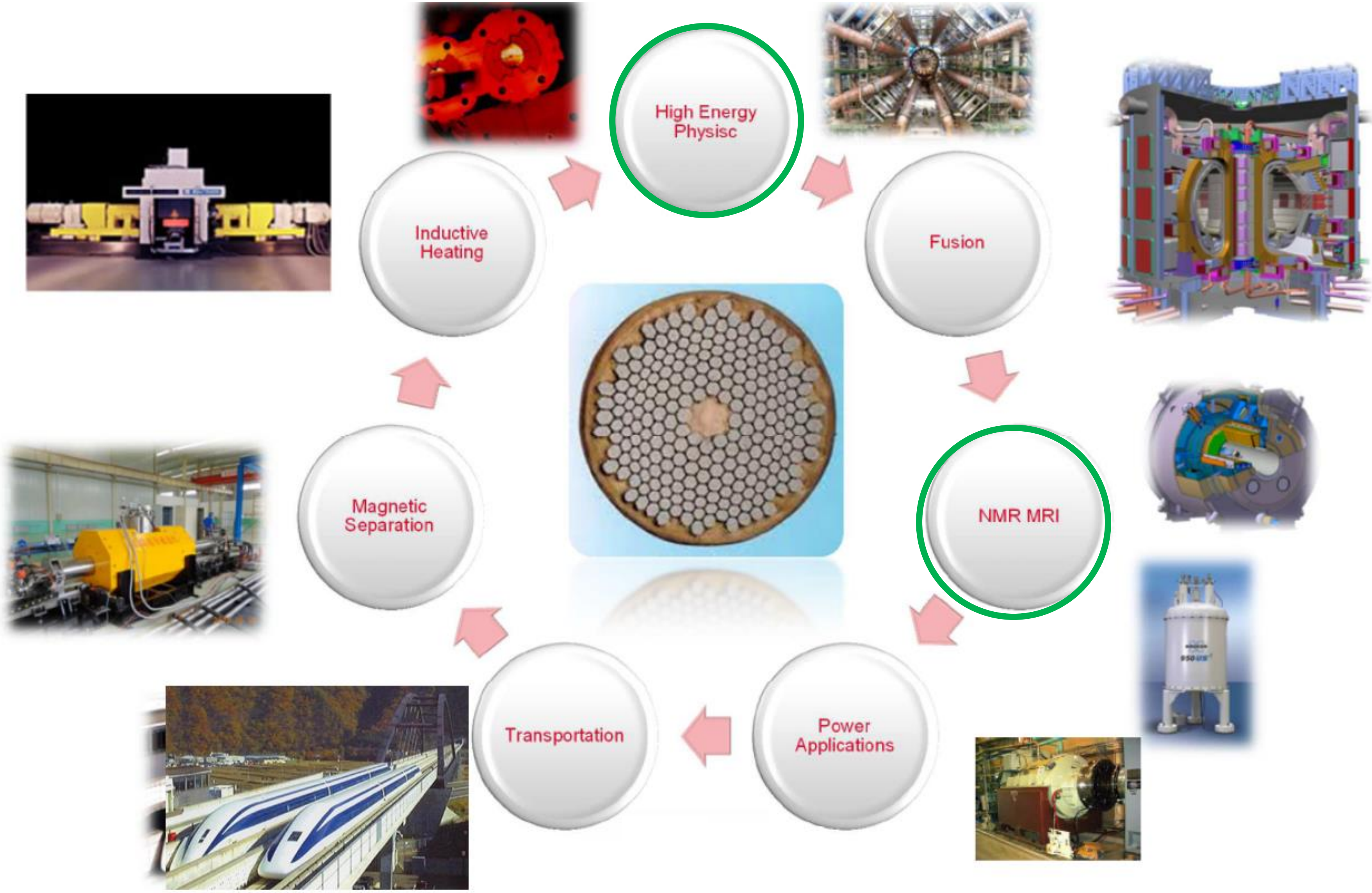


ISSP (Japan)
(750 T)



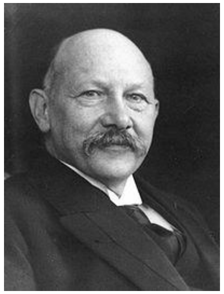
VNIIEF MC-1 (Russia)
2,8 kT

AND A LOT OF APPLICATIONS!

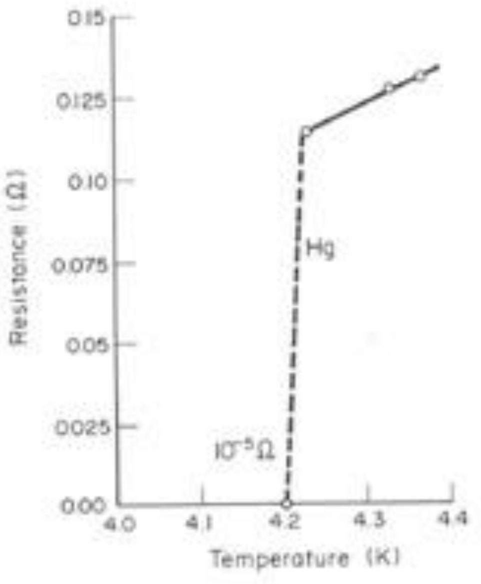


WHY SUPERCONDUCTIVITY ?

Gilles Holst, student of Kamerlingh Onnes writes a short note to the Royal Academy of the Netherlands on April 8th, 1911 :
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity…



1933: Meissner and Ochsenfeld discover perfect ***diamagnetic*** characteristic of superconductivity

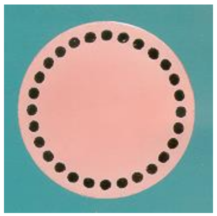
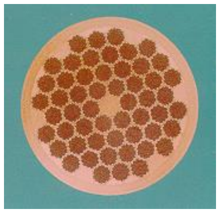
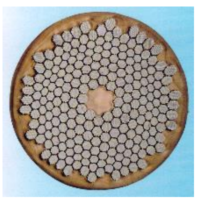
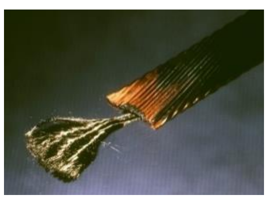


Ohms' law is not longer valid!

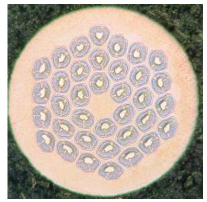
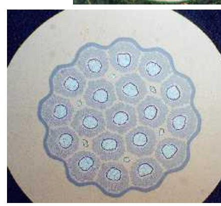
- **Low electrical consumption**
  (mainly to operate the cryogenic system)
- **High current density**
- **Compact winding** can be used to generate high magnetic fields in a large volume

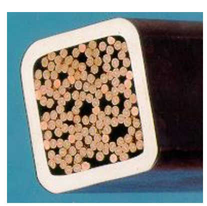
A LARGE CHOICE OF SC MATERIALS

NbTi

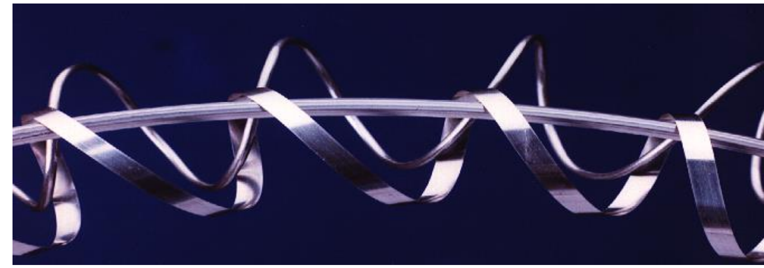





Nb_3Sn, Nb_3Al

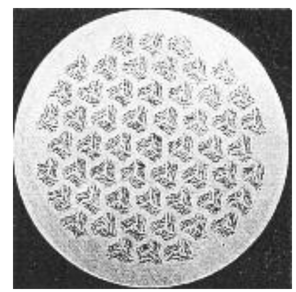
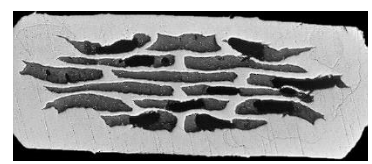





YBCO



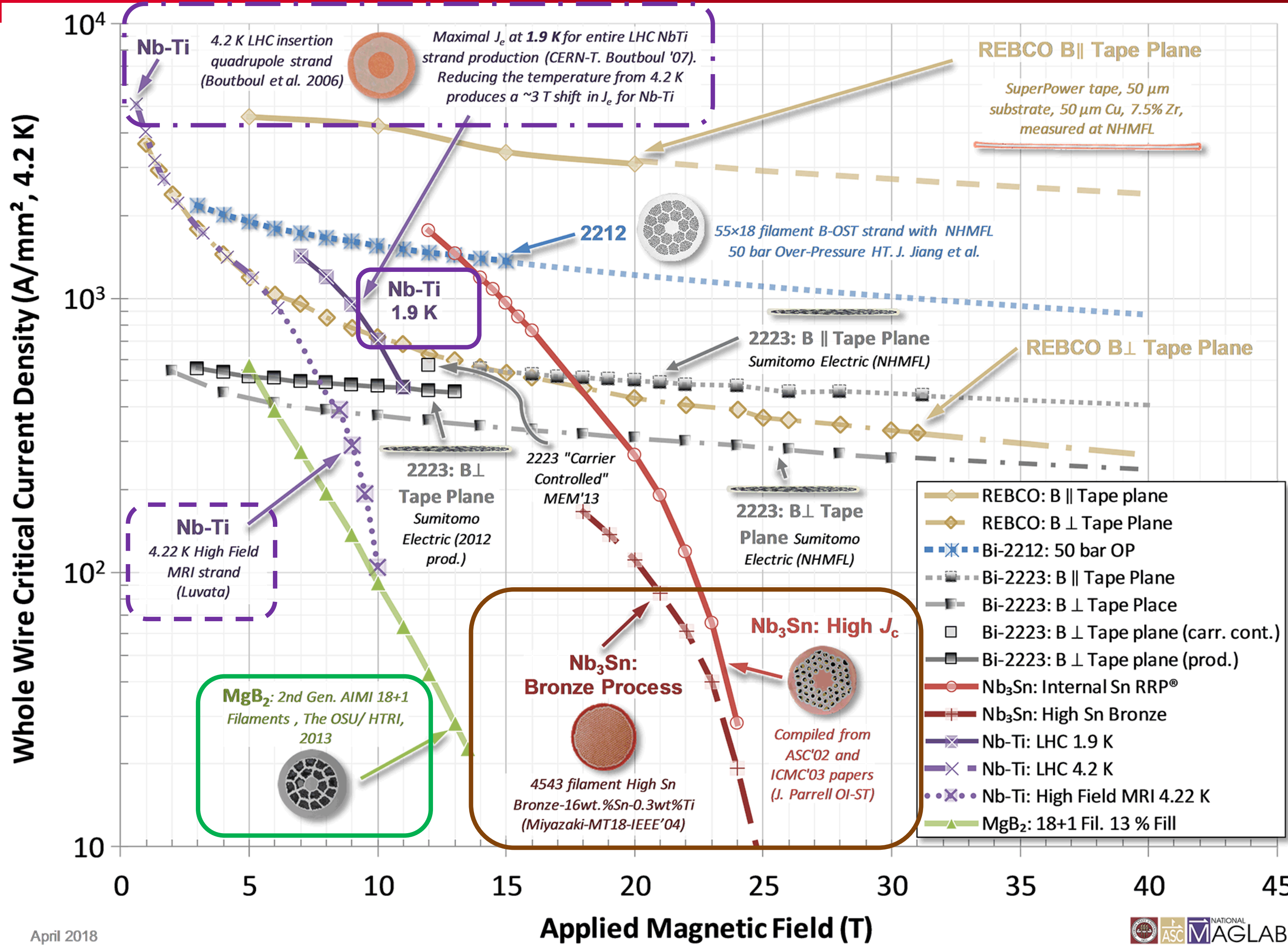
BSCCO


MgB_2

Large variety of wires/tapes/cables

Jeng in LTS and HTS conductors at 4.2K and 1.9K



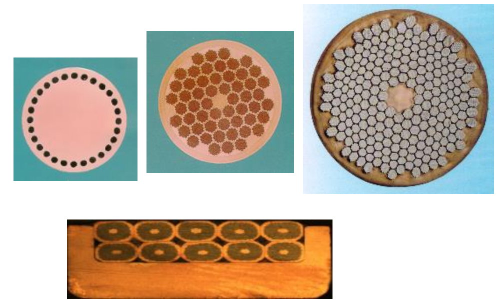
Conductor Source: http://fs.magnet.fsu.edu/~lee/plot/plot.htm

A LARGE CHOICE OF SC WIRES AND CABLES…

Cost is a key driver!

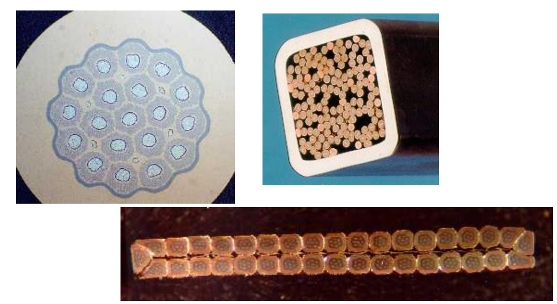
NbTi

- Dominant commercial superconductor
- **MRI is biggest user of NbTi SC wire**
- Bendable, ductile, low cost ($1/kA.m)
- Tc=9,3K, Bc2=11,4 @ 4,23K



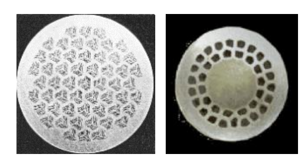
Nb3Sn

- Primary high field SC
- Brittle
- Tc=18K, Bc2 ≈ 23-29K
- Higher cost (x 5 price of NbTi)



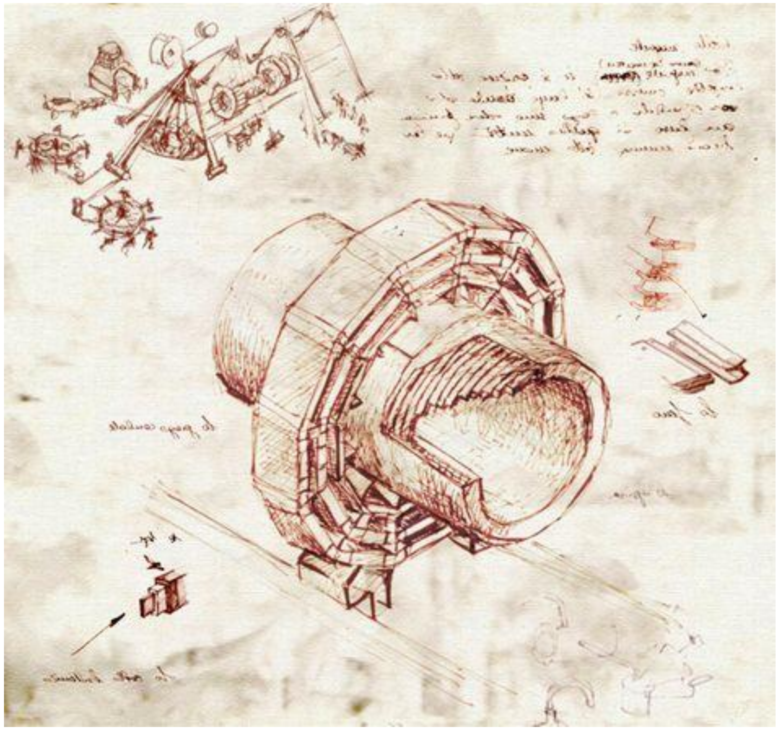
MgB2

- Brittle
- Tc=39K, Bc2=40T
- Higher cost (x 5 price of NbTi)



Technology based on ReBCO super expensive (x 10 to 20) and not mature enough for large industrial applications

MAGNET OPTIMISATION IS A COMPLEX PROBLEM…



How physicists depict the CMS detector…

How engineers built it…

MAGNETIC FIELD SPECIFICATION

The specification has to define several parameters

- Central field value (usually the highest…)
- Magnet aperture (usually the largest…)
- Magnet outer dimensions (usually the smallest…)
- Useful area or volume (usually the largest…)
- Field quality (dipole uniformity, field gradient, field integral, sagitta, momentum resolution,…)
- Fringe field (low, even close to the magnet)
- Operating mode (AC/DC)

RELEVANT PARAMETERS

Main parameters from the specification: *Field B, length L, radius R*

Parameters relevant for the physics

. *B, BL (deflection), d^mB/d^mR (gradients), BL^2 (sagitta), BL^2 (momentum resolution), B^3R^2, etc…*

Parameters relevant for the magnet designer

. *B^2 R (mechanical forces)*

. *B^2 R/e, with e coil thickness (stresses , protection in case of quench)*

Parameters relevant for the ressource manager

. *Cost :* $C = \alpha\,(RL)^{0.8} + \beta\,(B^2 R^2 L)^{0.7}$ *(from A. Hervé)*

$C(M\$) = 0.5(E_s(MJ))^{0.662}$

$C(M\$) = 0.4(B(T)V)^{0.635}$ *(from Green and Lorant)*

A complex problem…

- Field map specification
- Current transport capacity (choice of conductor)
- Operating temperature and cooling method
- Peak field on the conductor
- Quench protection
- Mechanical stresses
- Manufacturing techniques
- Economical constraints

MAIN TECHNICAL CHALLENGES

High magnetic field, high current, large useful volume, large stored energy, high mechanical forces and stresses

SC state requires low temperatures

Complex cryogenic system; it has to be optimized (compact, autonomous, minimum consumption)

Protection in case of quench

- Dissipate the stored energy
- Manage the quick temperature elevation in the SC system and the high voltages in the coils

Mechanical forces

- High strength/stress must be hold by the conductor and/or the external support structure
- Electrical insulation must also withstand the stress (shear stress in particular)

Advanced manufacturing techniques required

- Superconductors
- Electrical insulation
- Challenging manufacturing techniques

Dimensions:

- Manufacturing dimensions and tolerances, handling
- Road transportation R_{max} ~ 3.5 m

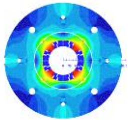
MAGNET PROJECTS AT CEA

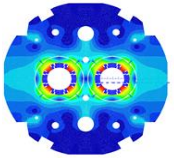
NbTi

Accelerator magnets for LHC

MQ

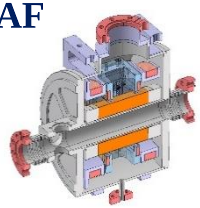
MQYY



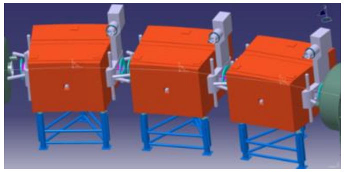


Other Accelerator Magnet

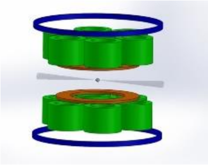
SARAF



SuperFRS



MRI magnet: **ISEULT**



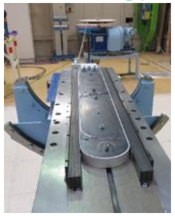
Special magnet

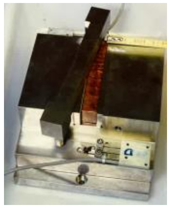
WAVE: neutron diffraction=> condensed matter physics

Nb_3Sn

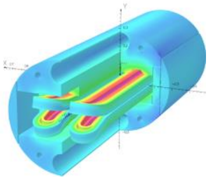
FRESCA 2

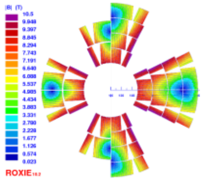
Technology development





Dipole and Quad for FCC





MgB_2

LOTUS: radio isotope production

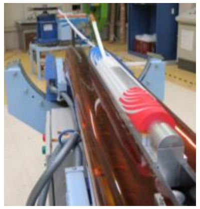
Conductor characterization

HTS => ReBCO

For accelerator magnets

EUCARD

EUCARD2



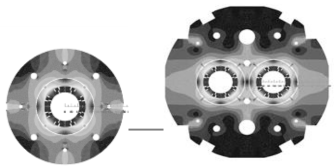
For high field magnets

MAGNET PROJECTS AT CEA

NbTi

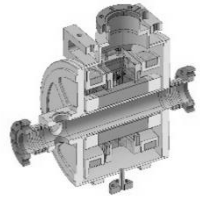
Accelerator magnets for LHC

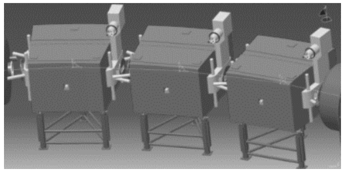
MQ **MQYY**



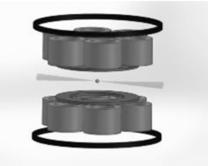
Other Accelerator Magnets

SARAF **Super FRS**





MRI magnet: **ISEULT**



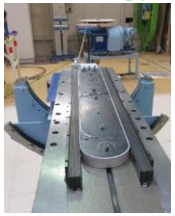
Special magnet

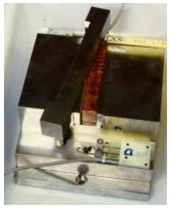
WAVE: neutron diffraction=> condensed matter physics

Nb_3Sn

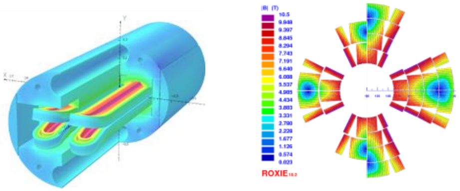
FRESCA 2

Technology development





Dipole and Quad for FCC

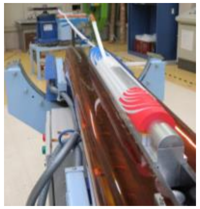


HTS => ReBCO

For accelerator magnets

EUCARD

EUCARD2



For high field magnets

MgB_2

LOTUS: radio isotope production

Conductor characterization

WHY USING MAGNETIC FIELDS IN PARTICLE ACCELERATORS?

A magnet creates a force that acts on any other magnet, electric current, or moving charged particle.

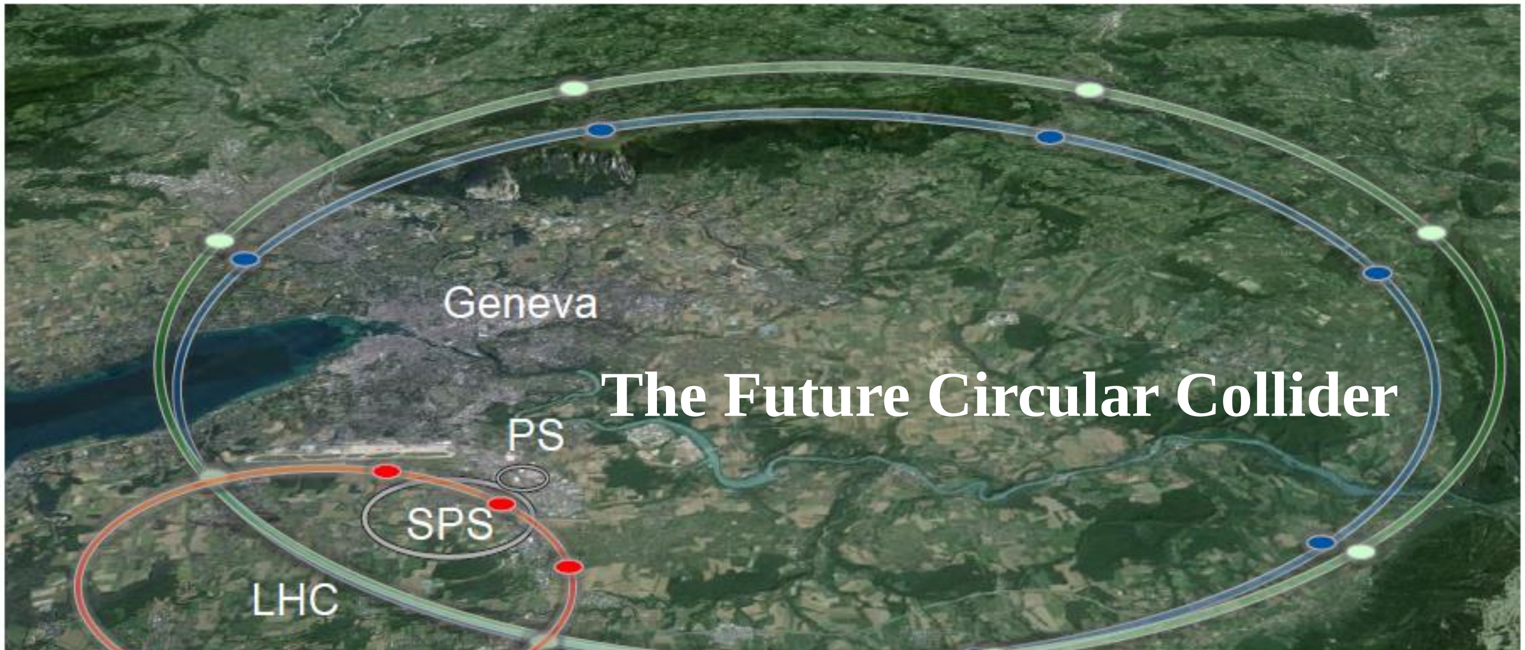
Dipoles to bend the beam:

Quadrupoles to focus it:

Sextupoles to correct chromaticity:

Example of magnetic configurations (room temperature magnets)

WHAT'S NEXT AFTER THE LHC…



LHC	HE-LHC	VHE-LHC	VHE-LHC
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

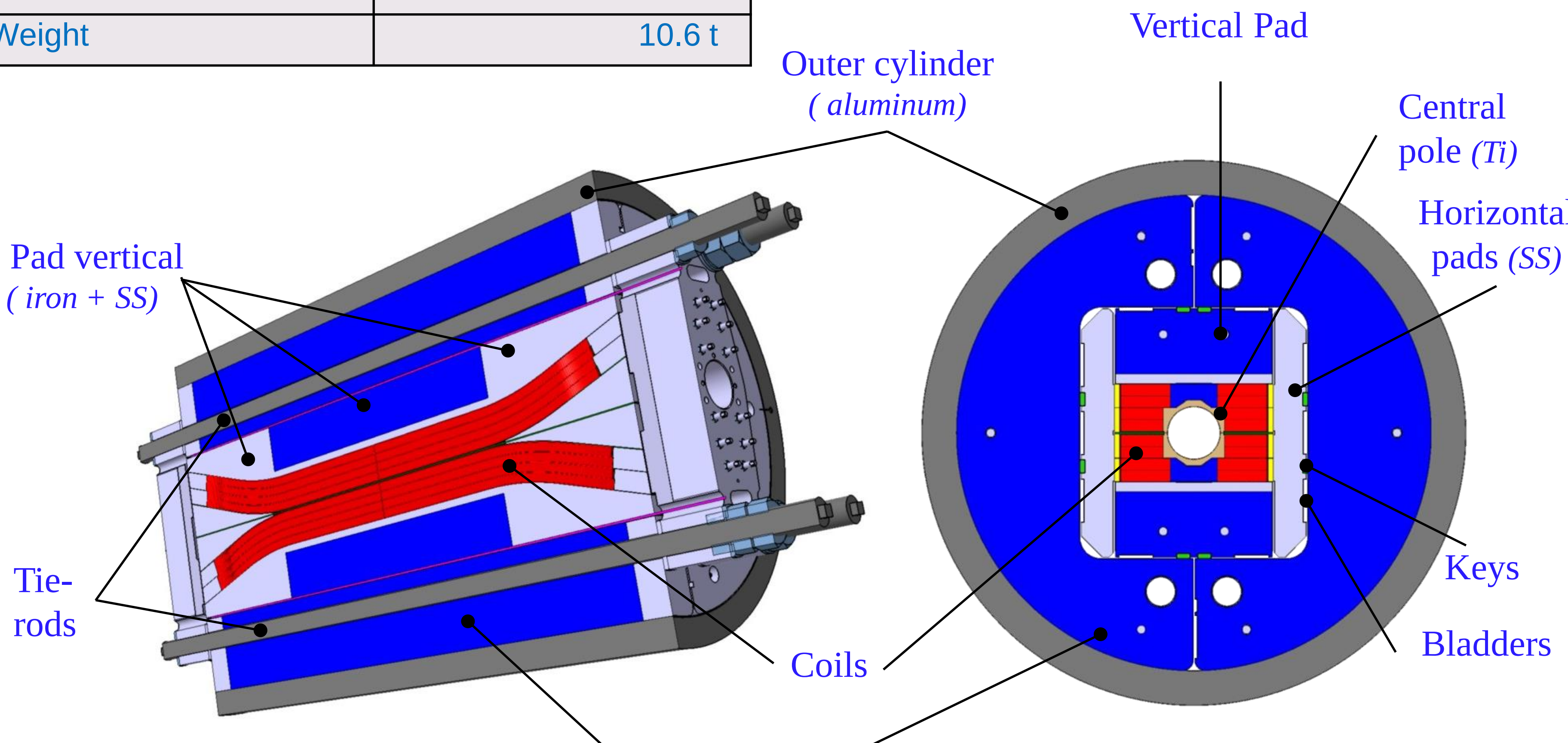
100 TeV !

Magnet cost: 8T-60%; 16T-70%-20T-80%

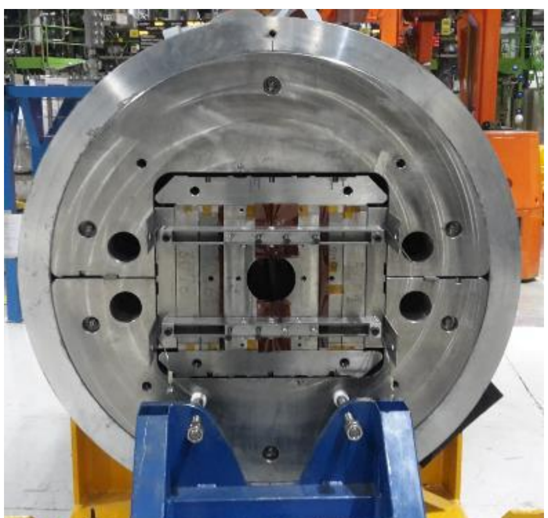
- Need to increase the field, while reducing the cost
- Not just innovations… But real breakthroughs are needed!

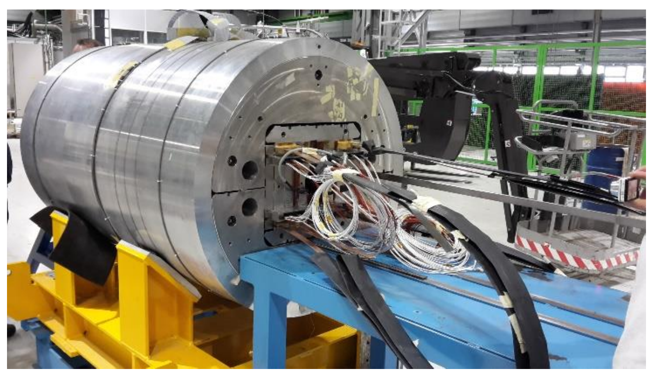
FRESCA 2 (NB3SN)

Central field	13T @ 4.2K 15T @ 1.9K
Bore aperture	100 mm
Length	1.6 m
Outer Diameter	1.03 m
Weight	10.6 t



FRESCA 2 (NB3SN)

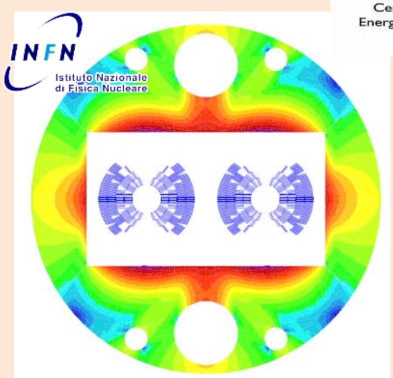




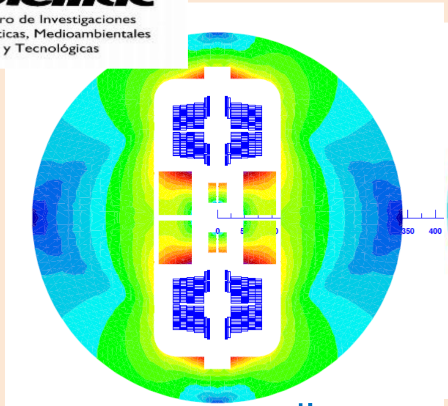
14.6T obtained in April 2018 (World record)

MAIN DIPOLE STUDIES (16T) AND ASSOCIED R&D

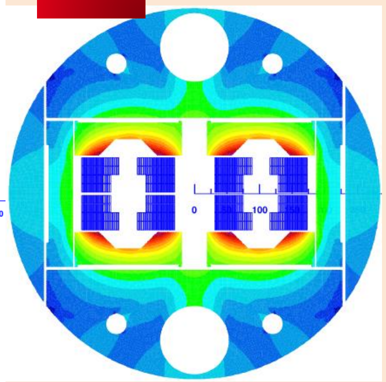
EuroCirCol
A key to New Physics



Cos-theta

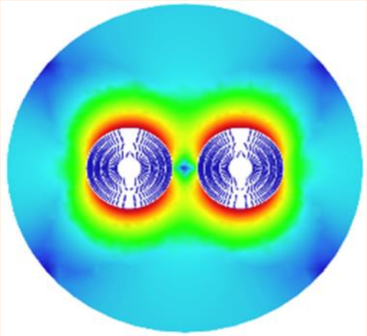


common-coil



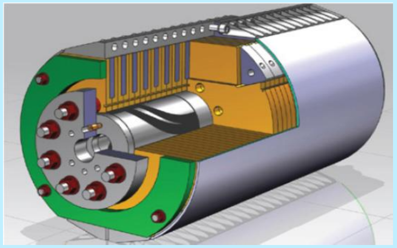
block

Swiss contribution
via PSI

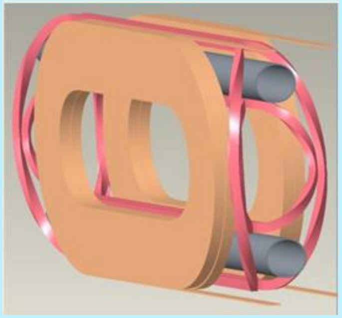


Canted Cos-theta (CCT)

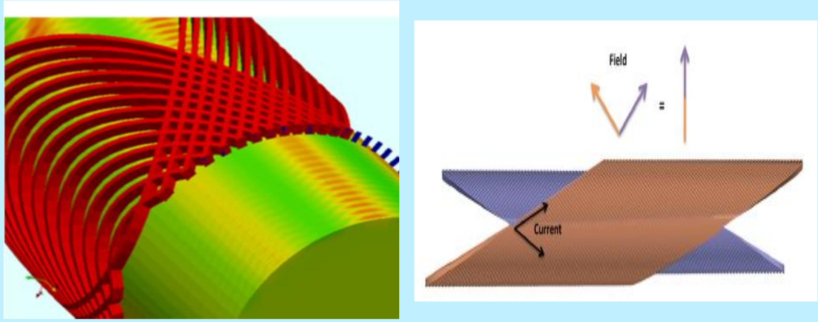
U.S. MAGNET DEVELOPMENT PROGRAM



Cos(theta) - Fermilab



common coil - BNL

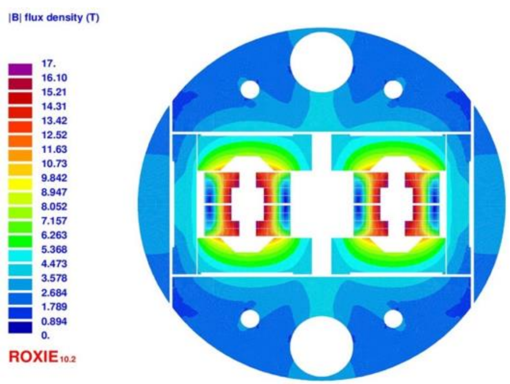


CCT LBNL

DIPOLE BLOCK DESIGN FOR EUROCIRCOL

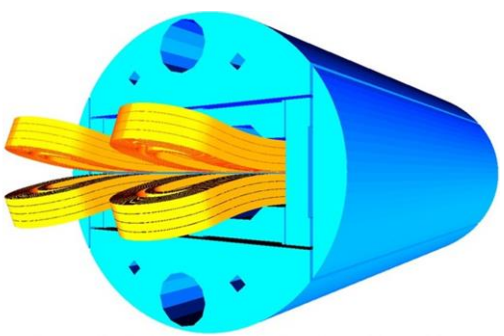
Within the ECC program => CEA Saclay in charge of the double aperture block-type configuration

2D magnetic model

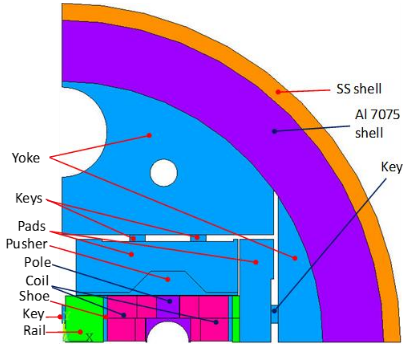


Aperture	50 mm
I_{op}	10176 A
LL margin HF	14.0 %
B_{bore}	16 T
B_{peak} HF	16.7 T
σ_x / σ_{VM}	
RT loading	-147 / 136 MPa
Cool-down	-180 / 165 MPa
Excitation	-185 / 167 MPa

3D magnetic model

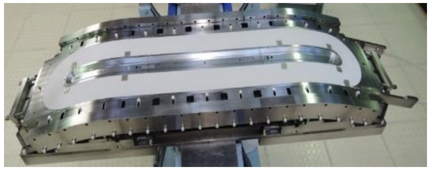


2D mechanical model



- Design Study ECC
- Fabrication experience with FRESCA2

FRESCA2

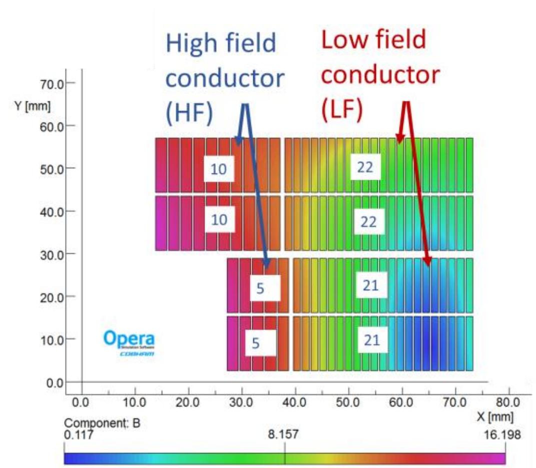


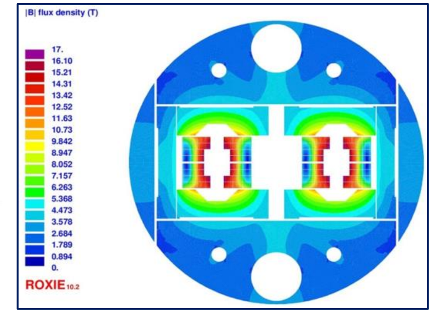
DIPOLE MODEL TOWARD FCC

CERN-CEA collaboration agreement to design and fabricate a single aperture block model at CEA

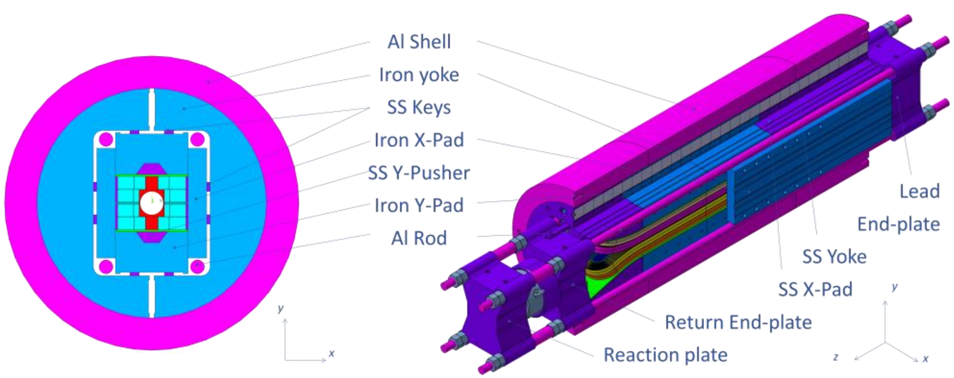
⇒ FCC Flared-ends Dipole Demonstrator: F2D2 => as close as possible to ECC

Conductor parameters	HF	LF
Strand diameter	1.1 mm	0.7 mm
Cu/nonCu ratio	0,8	2
Jc at 4.2 K and 16 T	1200 A/mm2	
Cable number of strands	21	34
Unreacted bare cable width	12.579 mm	
Unreacted bare cable thickness	1.969 mm	1.253 mm
HT cable thickness dim. change	4.6 %	4.5 %
HT cable width dim. change	1.3 %	
Reacted bare cable width	12.74 mm	
Reacted bare cable thickness	2.06 mm	1.31 mm
Insulation thickness at 50 MPa	0.150 mm	

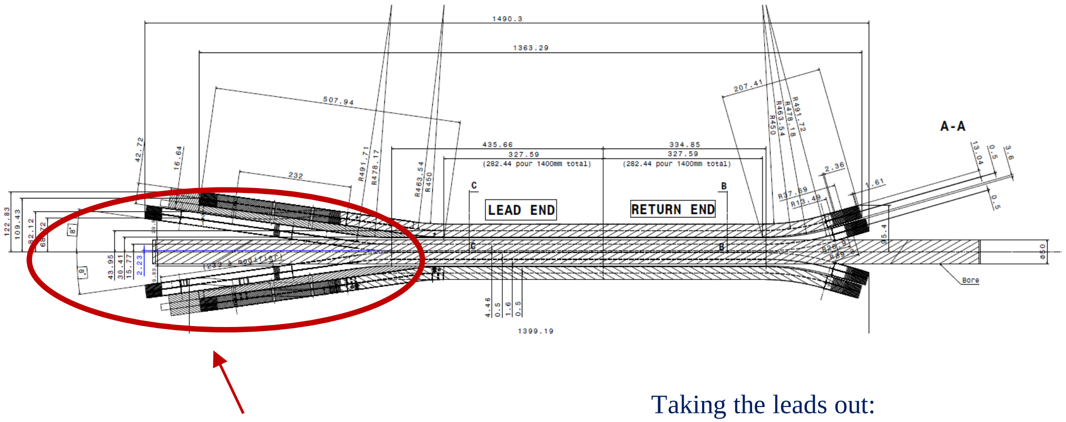


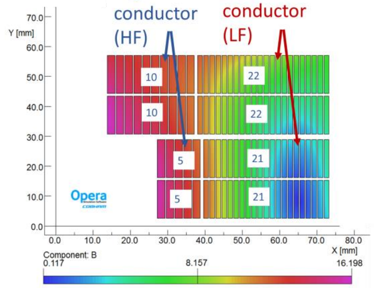


2D magnetic parameters	
I_{op}	10469 A
LL margin HF	14.0 %
LL margin LF	15.4%
B_{bore}	-15.54 T
B_{peak} HF	16.20 T
B_{peak} LF	11.85 T
b_3 at nominal	2.98
b_3 at injection	-14.80
b_5	-0.50
b_7	-2.98
b_9	-1.46

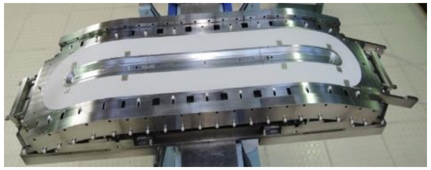


DIPOLE MODEL TOWARD FCC



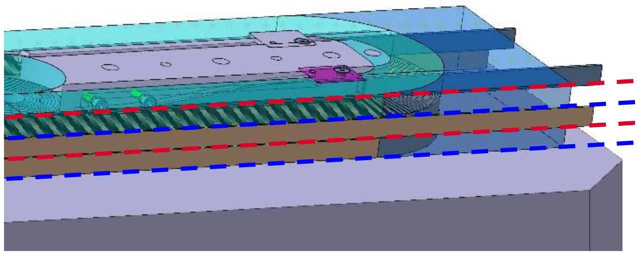


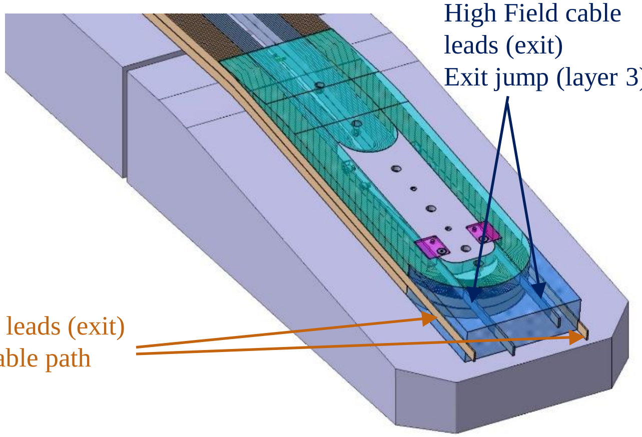
FRESCA2



Taking the leads out:
- Btw coil 1-2 and 3-1 for coil 3-4
- Toward the aperture for coil 1-2

- High complexity due to grading
- Baseline scenario: external joints

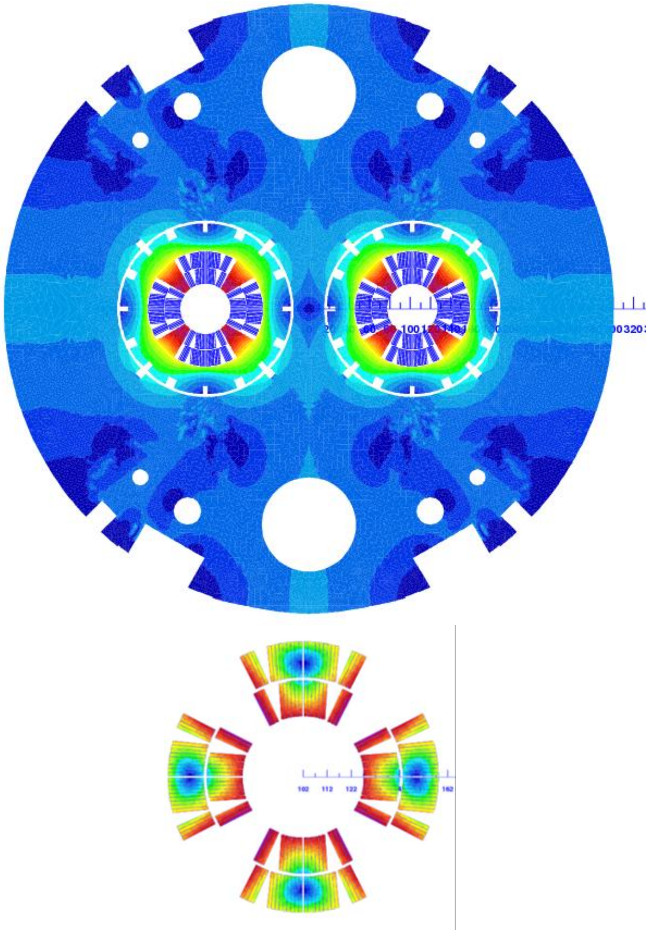




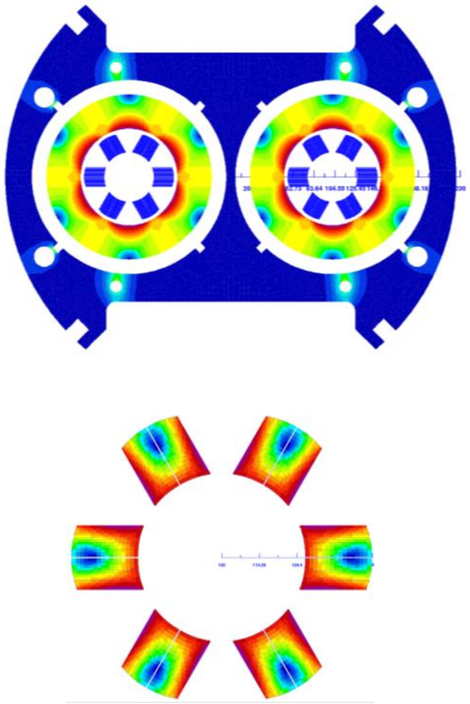
<u>Key challenge</u>: Coil and tooling engineering design
<u>Objectives</u>: fabricate and assemble F2D2 at CEA

FCC MAIN QUADRUPOLE/SEXTUPOLE/OCTUPOLE

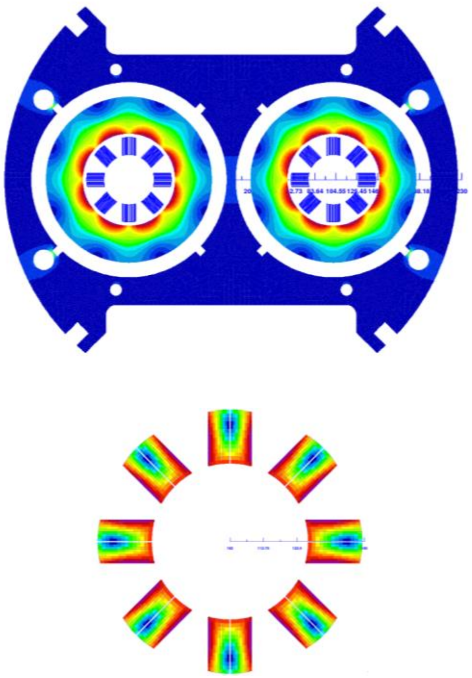
(MQ)



(MS)



(MO)



NB$_3$SN MAGNET TOWARD FCC
FCC MQ (I)

Within CERN-CEA collaboration
- In CEA tradition => design study of main quadrupole for FCC

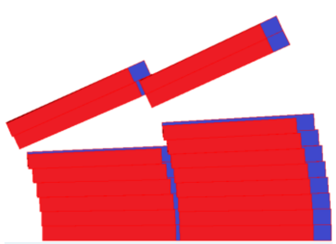
- **Design study:**
  - 2 layer versus 4 layer designs ?
  - Margin of the quadrupoles?

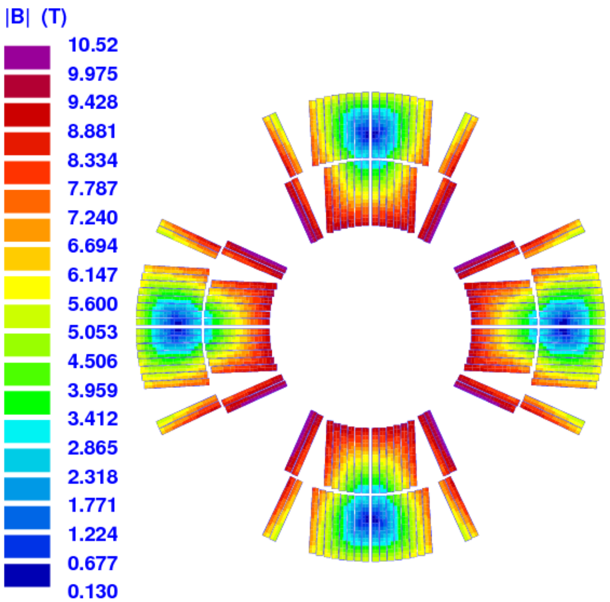
  - Reduce complexity of the quad vs the dipoles => 2 layer quad
  - 20 % margin (instead of 14 % for the dipoles)
  - Nominal gradient of 360 T/m

  - Conductor definition
    - Small aperture => cable windability is a concern

CABLE PARAMETER	FCC quad (v12)
Strand diameter	0.85 mm
Cu/NonCu	1.65
Nb of strands	35
Cable bare width (before/after HT)	15.956/16.120 mm
Cable bare mid-thick.(before/after HT)	1.493/1.538 mm
Cable width expansion	1.0 % (ECC)
Cable thickness expansion	3.0 % (ECC)
Keystone	0.40°
Insulation thickness per side (5 MPa)	0. 150 mm

Cable validation
Winding test with
MQXF cable



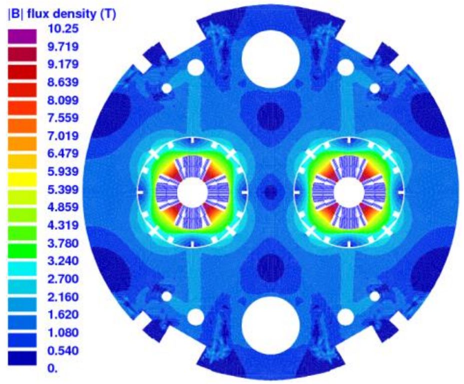


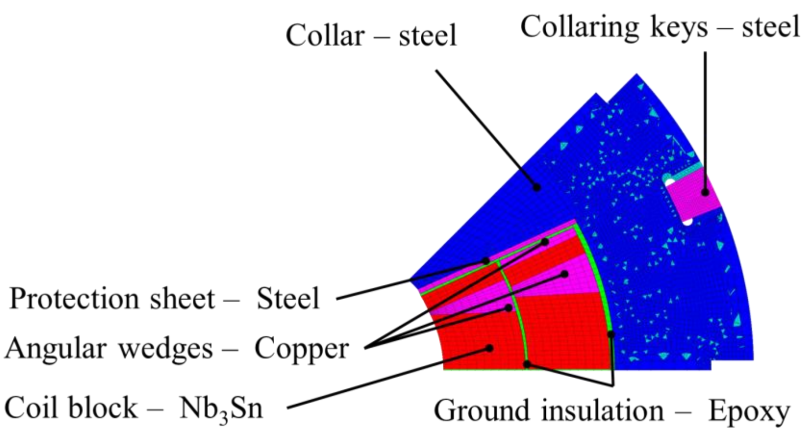
MAGNET PARAMETER	Values
Nominal current	22500 A
Peak field	10.52 T
Gradient	367 T/m
Loadline margin	20.0 %
Temperature margin	4.6 K

NB$_3$SN MAGNET TOWARD FCC
FCC MQ (II)

Magnet Parameter	Unit	Values
Nominal current	A	22500
Peak field	T	10.52
Gradient	T/m	367
Stored energy (2 apertures)	kJ/m	520
Azimuthal force (per ½ coil)	kN/m	1740
Radial force (per ½ coil)	kN/m	780

Support structure:
Self supported collar



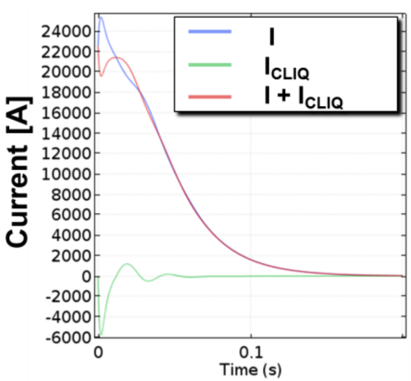


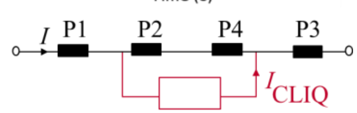
Modeled in Cast3M in 4 steps (in MPa)

Collaring	**Stress relaxation**	**Cold**	**Powering**
peak average	peak average	peak average	peak average
-101.5 -85.5	-91.4 -76.9	-88.5 -73.2	-111.1 -69.7

Protection
Tiina Salmi TUT

Use of a CLIQ Unit
Hot spot temperature < 350 K (ECC)





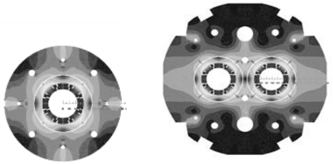
4 MATERIALS

NbTi

Accelerator magnets for LHC

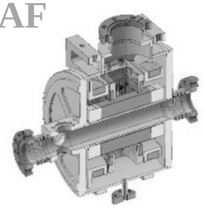
MQ

MQYY

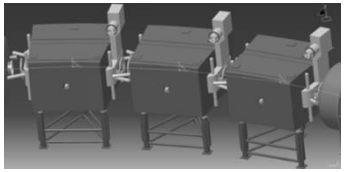


Other Accelerator Magnet

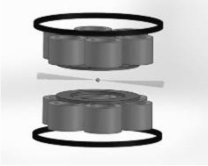
SARAF



SuperFRS



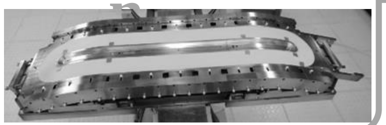
MRI magnet: **ISEULT**



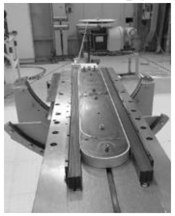
Special magnet
WAVE: neutron diffraction=> condensed matter physics

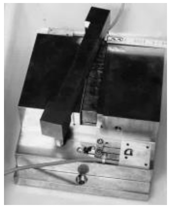
Nb_3Sn

FRESCA 2

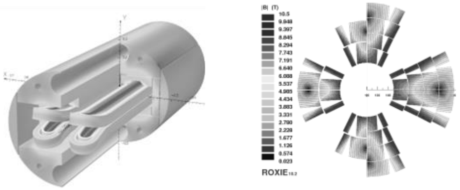


Technology development





Dipole and Quad for FCC



MgB_2

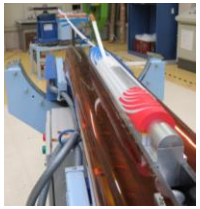
LOTUS: radio isotope production

Conductor characterization

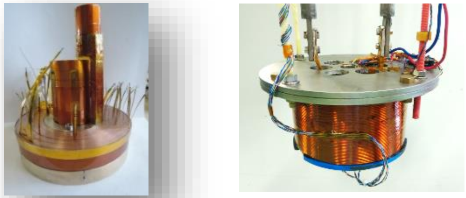
HTS => ReBCO

For accelerator magnets
EUCARD

EUCARD2



For high field magnets



HTS HIGH FIELD R&D OVERVIEW

Detection/Protection

Detection difficult due to very low propagation velocities during a quench.

Protection not easy due to very high energy margin (high Tc)

- *Numeric Magnet Safety System*, more accurate and faster (FPGA)

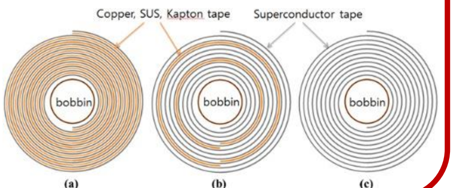
Remove/replace insulation between turns :

- *NOUGAT project*

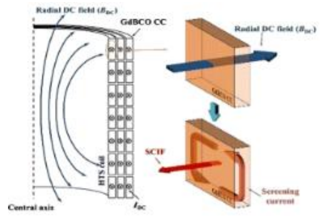
  # HTS insert HTS with Metal-as-insulation winding

- *Internal R&D "No Insulation-Partial Insulation –Metal-as-Insulation"*

  # study of stability/protection/ time constants of different windings



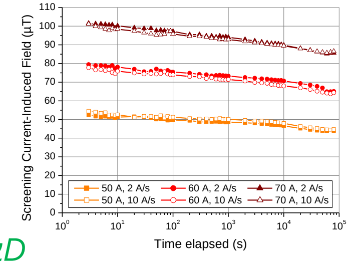
Stability/Homogeneity



Degradation of stability/homogeneity due to screening currents generation

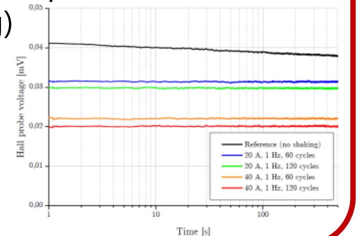
- *Guillaume Dilasser PhD*

  # Experimental and numerical studies of screening currents in REBCO tapes



- *Internal R&D*

  # experimental/numerical study of different techniques (overshoot, vortex shaking)

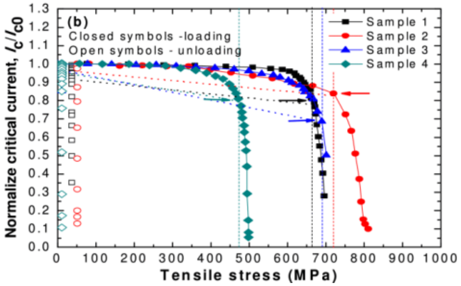


Mechanics

Issue for very high-field magnets (> 30 T)

Ex : JBr > 1000 MPa

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

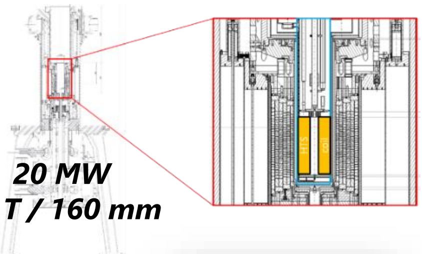


- *MI winding* co-wound tape is a strong mechanical reinforcement

- *M. ALHarake PhD* : mechanical study of non impregnated windings at very high fields

GOAL: 10 T HTS INSERT IN 20 T RESISTIVE OUTSERT

- 4 years project (oct 2014 -2018)
- Fundings from French National Research Agency (lead LNCMI)
- Collaborative project with CNRS Grenoble (LNCMI, Neel institute)



- Double pancakes, 6 mm-w ReBCO
- Metal-as-Insulation winding
- Prototypes (1 SP, 2 DP), codes (current dynamics…)
- 9 DP, ~ 2 kms of conductors

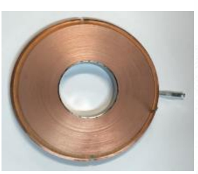
NOUGAT insert tests (9DP)

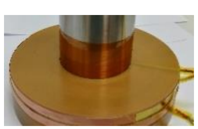
First phase (2018)

***12.8 T** + 8 T res*

Second phase (2019)

*@**10 T**+20 T res VM # 500 MPa*



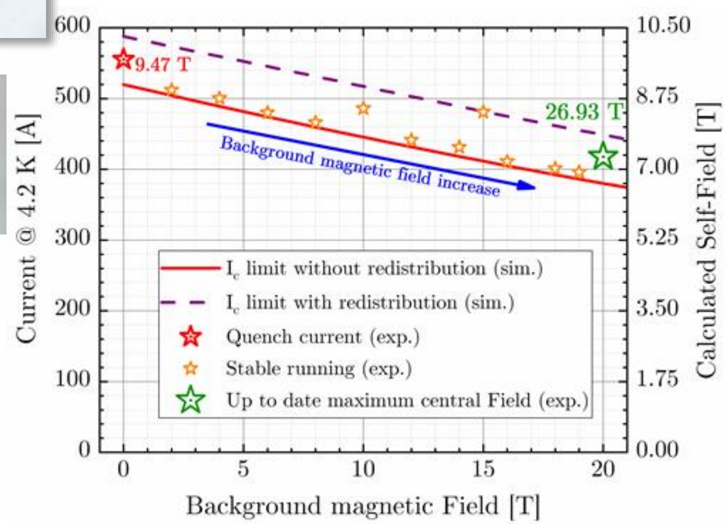


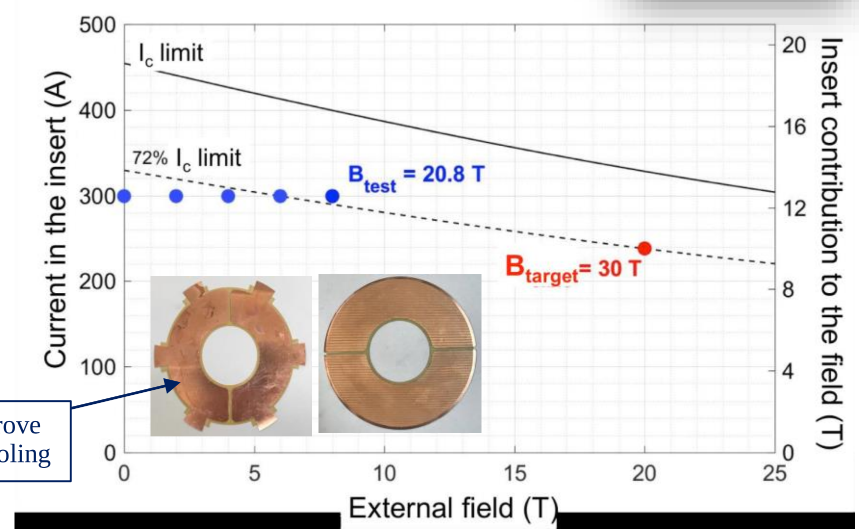
2 DP proto tests

***6.93 T** + 20 T res*

VonMises> 800 MPa

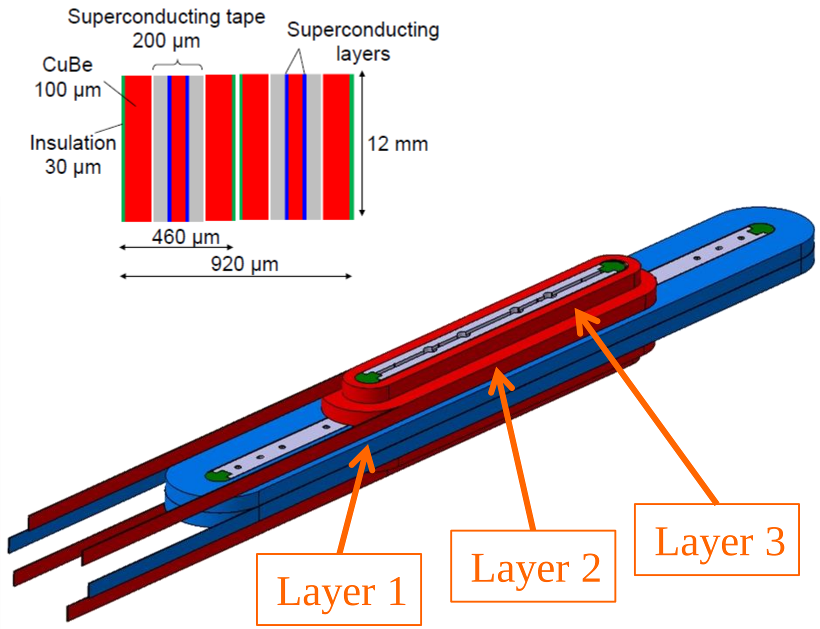
Validation of fabrication, assembly and testing techniques and mechanics

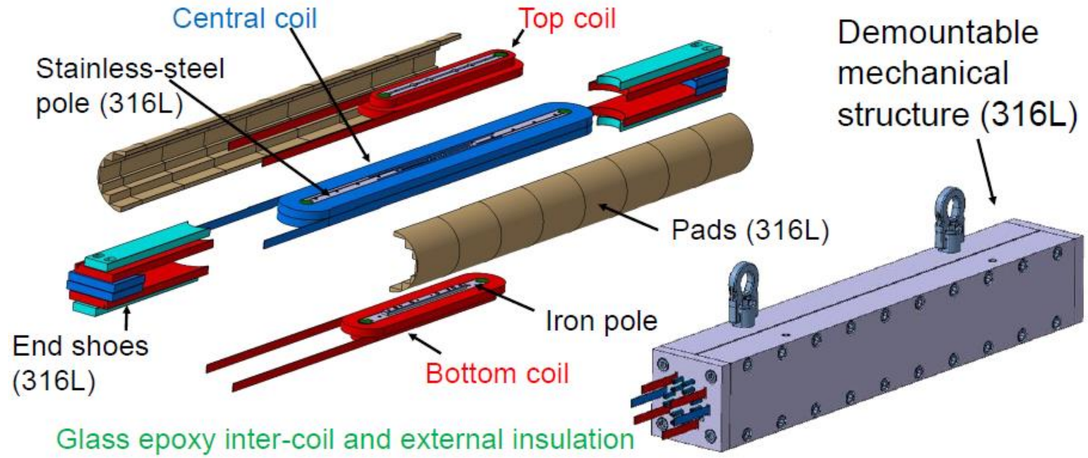




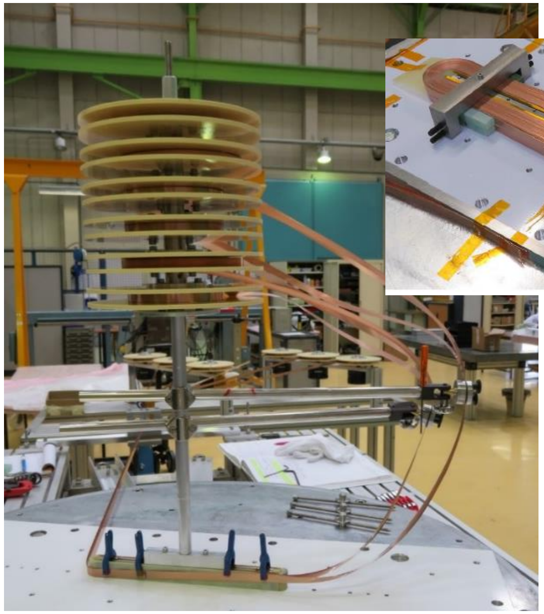
TOWARD HTS ACCELERATOR MAGNETS: EUCARD

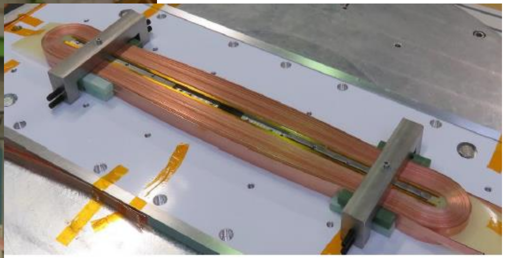
6 co-wound tapes: 2 SC + 4 CuBe





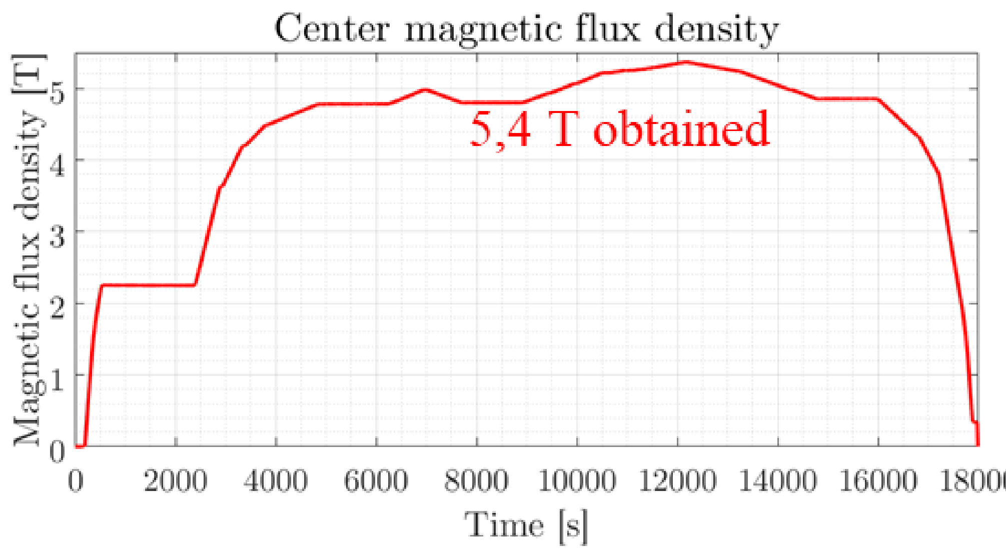
Parameter	Built Magnet	Unit
# of turns central coil layer 1	30	turns
# of turns external coils layer 2	24	turns
# of turns external coils layer 3	10	turns
Engineering current density	235	A/mm^2



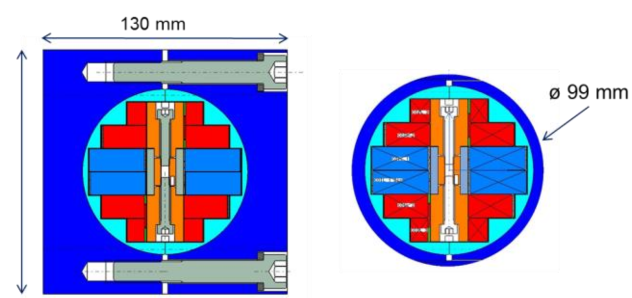


TOWARD HTS ACCELERATOR MAGNETS: EUCARD

Nominal current	A	2800
Central field wo / w SCIF (screening current induced field)	T	5.4 / 4.7
Temperature	K	4.2
Stocked energy	kJ	12.5
Inductance	mH	3.2
Temperature margin	K	29
Load line margin	%	47



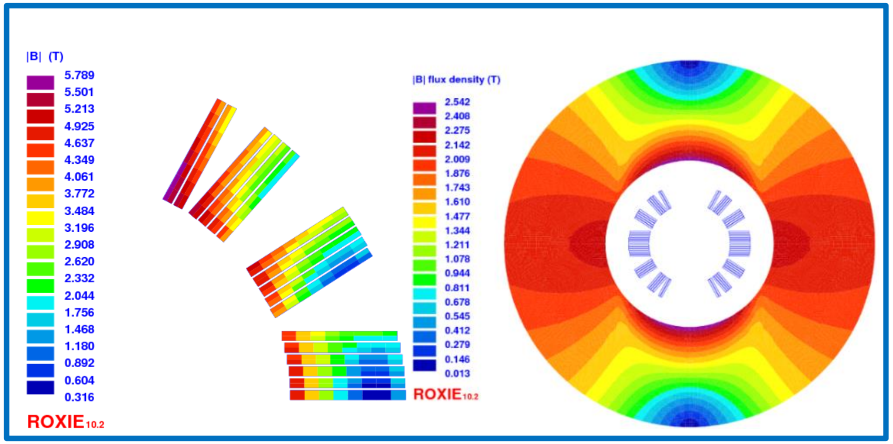
- Tested at CEA Paris Saclay and reached 5.4 T
- Next step: insertion of EUCARD in FRESCA2
  - Preparation is ongoing



Phase 1 Phase 2

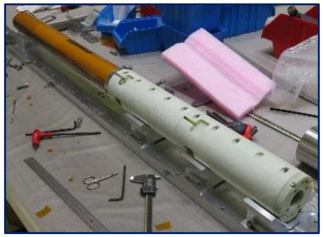
TOWARD HTS ACCELERATOR MAGNETS: EUCARD2 COSθ

	Unit	Cosθ	In FRESCA 2
Iop	kA	10.06	7.1
Bop	T	5	**2.6** + 13
Ic	kA	15.2	7.9
LL margin	(%)	34	10
T margin	K	30	8
Bore radius	mm	24	16



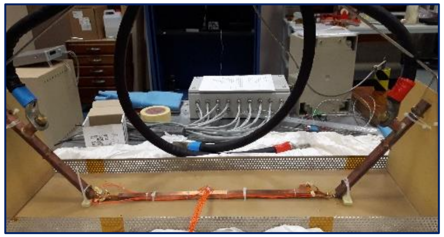
- Roebel cable 12 x 1.0 mm^2 , 15 tapes, 300 mm twist pitch
- 2x125µm insulation, fiberglass
- **17 turns**

Dummy coil with SS Roeble cable



Practice assembly

Practice yoke stacking



Practice SC splice

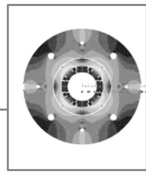
- Magnet assembly by Summer 2019
- Standalone test in INFN LASA Sept 2019
- Test in FRESCA2 under discussion

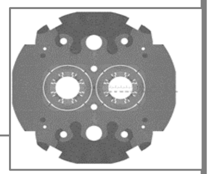
MAGNET PROJECTS AT CEA

NbTi

Accelerator magnets for LHC

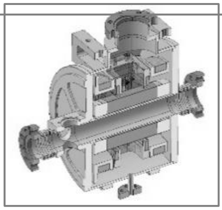
MQ **MQYY**

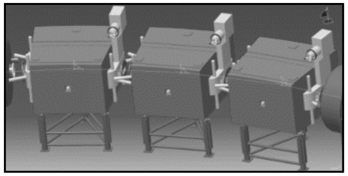




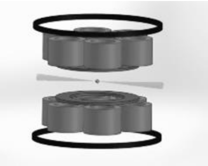
Other Accelerator Magnets

SARAF **Super FRS**





MRI magnet: **ISEULT**



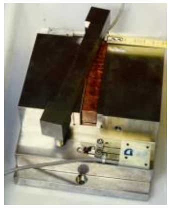
Special magnet

WAVE: neutron diffraction=> condensed matter physics

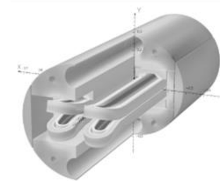
Nb_3Sn

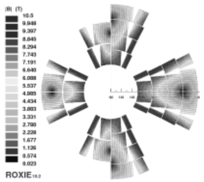
FRESCA 2

Technology development



Dipole and Quad for FCC





MgB_2

LOTUS: radio isotope production

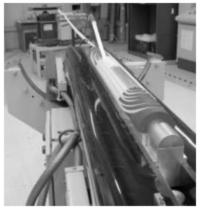
Conductor characterization

HTS => ReBCO

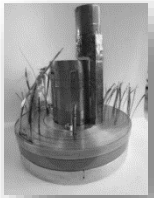
For accelerator magnets

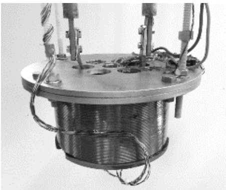
EUCARD

EUCARD2

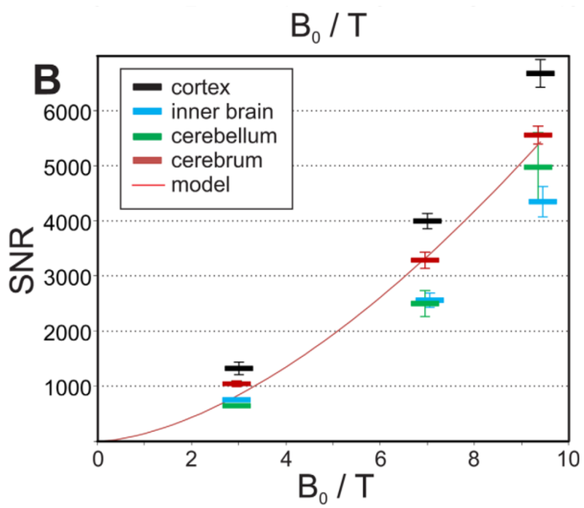


For high field magnets





Why high magnetic fields for MRI systems?



$SNR \sim B_0^{1.65}$

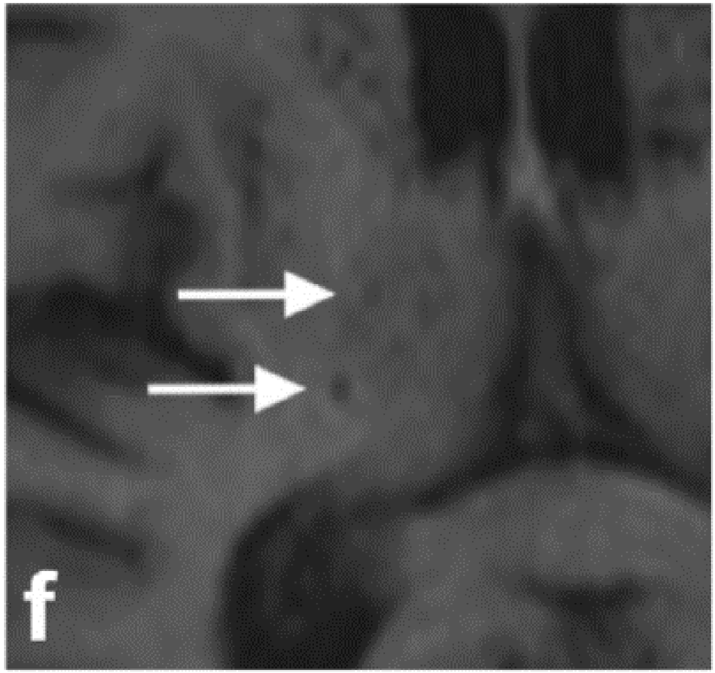
Pohmann et al.
Magn Reson Med 2016;75:801–809

Improvement of spatial and temporal resolution

3T

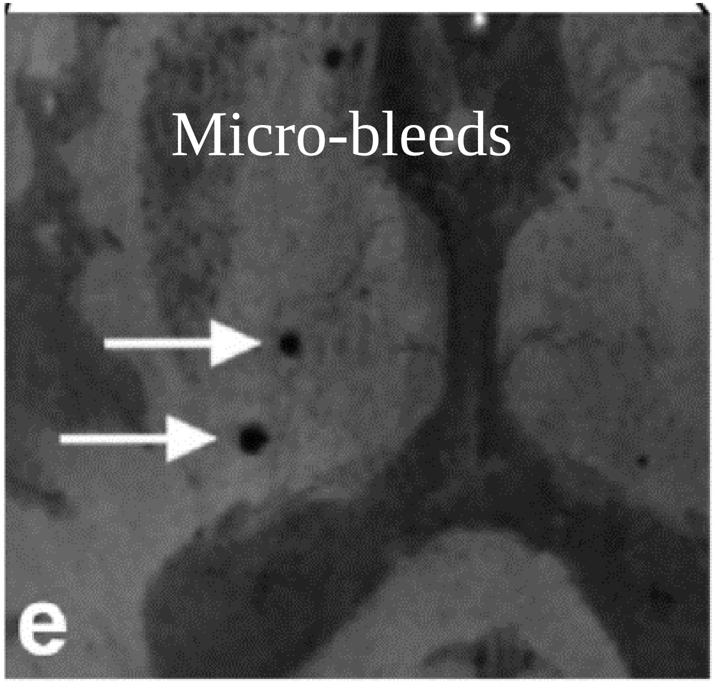
7T

IMAGE QUALITY VS. MAGNETIC FIELD



1.5T

1 to 2 mm resolution

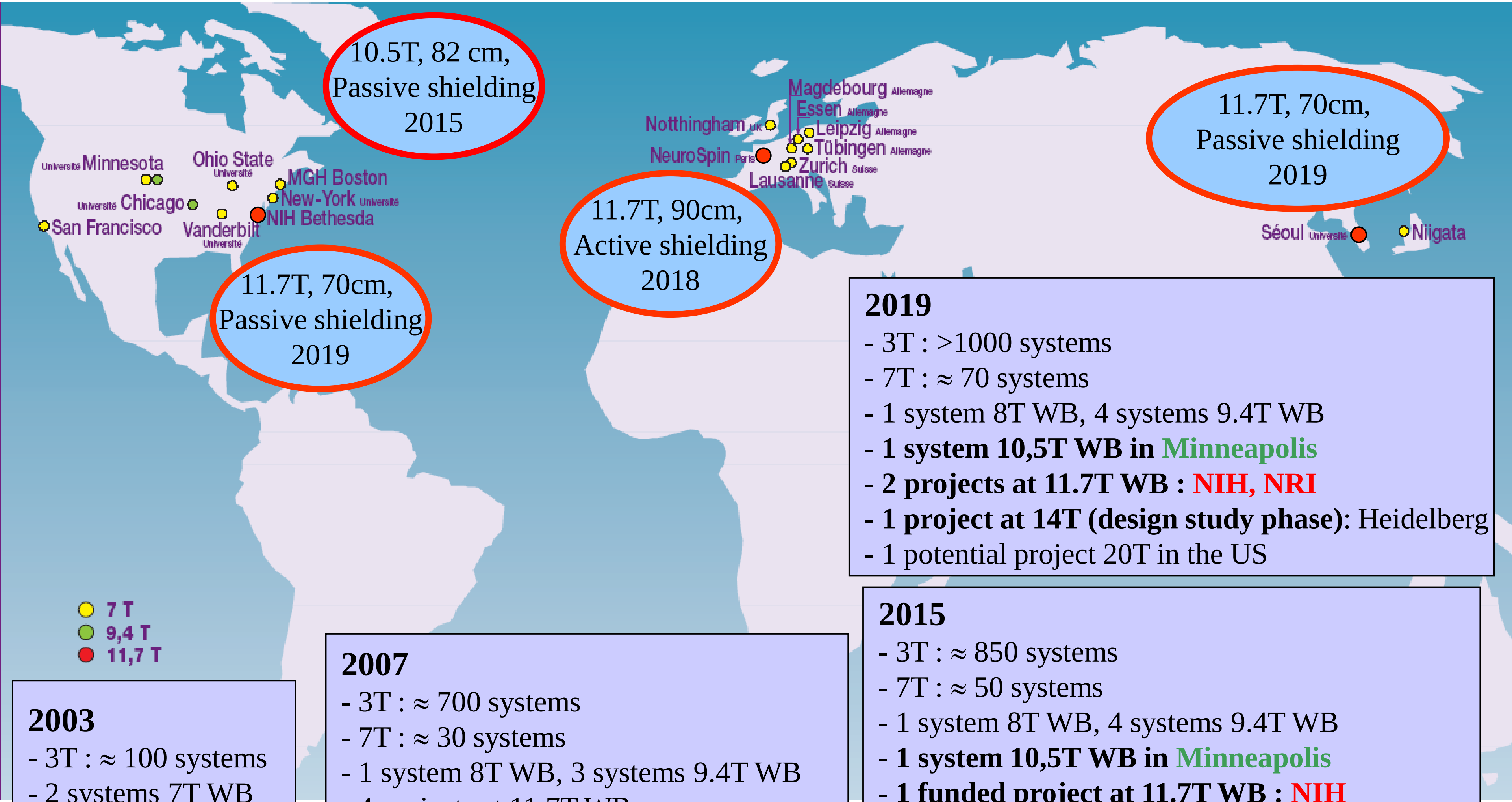


7T

≈ 0.3 mm resolution

Van der Kolk et al. Euro J Radiol 2013; 82: 708-718

WORLD UHF MRI PARK 2001-2017



2019

- 3T : >1000 systems
- 7T : ≈ 70 systems
- 1 system 8T WB, 4 systems 9.4T WB
- **1 system 10,5T WB in Minneapolis**
- **2 projects at 11.7T WB : NIH, NRI**
- **1 project at 14T (design study phase)**: Heidelberg
- 1 potential project 20T in the US

2015

- 3T : ≈ 850 systems
- 7T : ≈ 50 systems
- 1 system 8T WB, 4 systems 9.4T WB
- **1 system 10,5T WB in Minneapolis**
- **1 funded project at 11.7T WB : NIH**
- 3 potential projects : Tokyo, Gifu, Boston
- 1 project 11,7T potentiel à Seoul

2003

- 3T : ≈ 100 systems
- 2 systems 7T WB
- 1 system 8T WB

2007

- 3T : ≈ 700 systems
- 7T : ≈ 30 systems
- 1 system 8T WB, 3 systems 9.4T WB
- 4 projects at 11.7T WB (NeuroSpin, Tokyo, Berkeley, Bethesda)

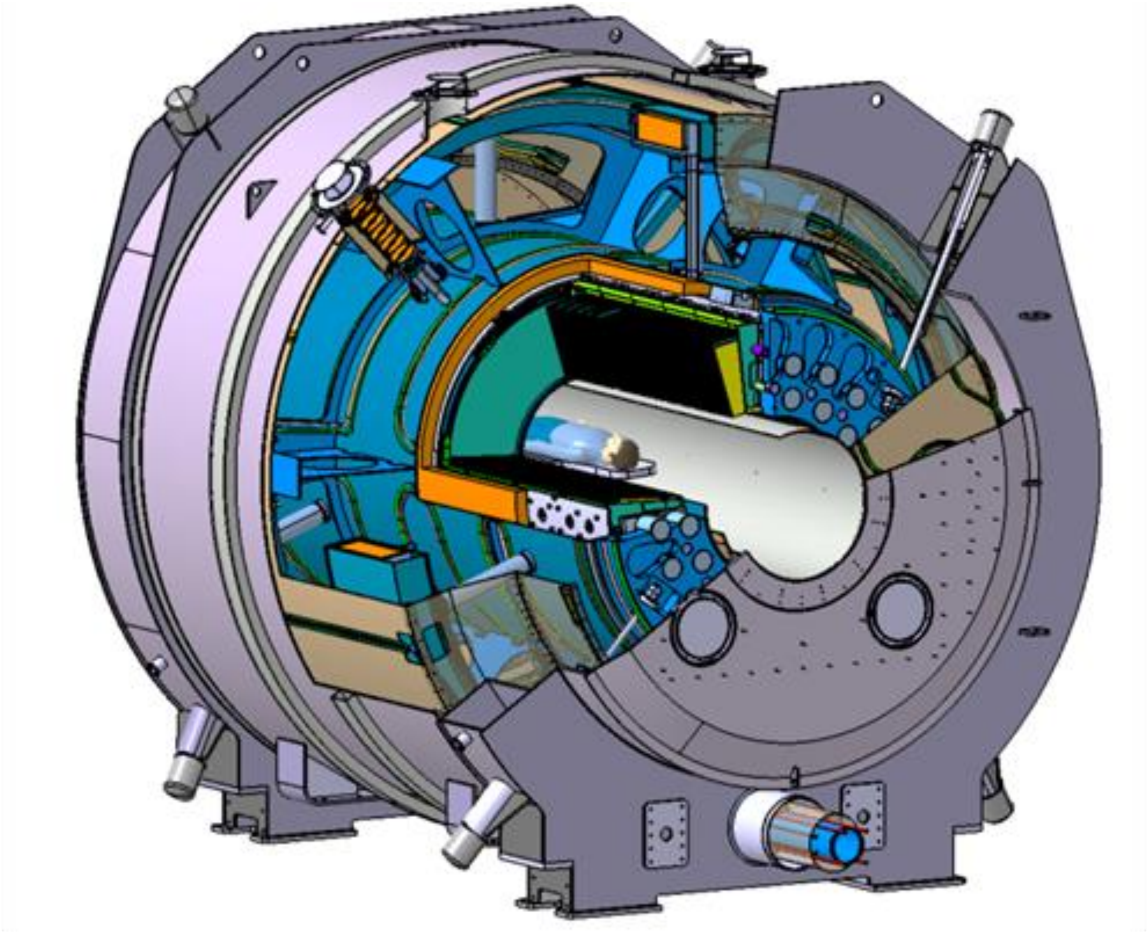
THE ISEULT 11.7 T MRI PROJECT

- B0 / Aperture 11.75 T / 900 mm
- Field stability 0.05 ppm/h
- Homogeneity < 0.5 ppm on 22 cm DSV
- 170 wetted double pancakes for the main coil
- 2 shielding coils to reduce the fringe field
- NbTi conductor @ 1.8 K

Stored Energy	338 MJ
Inductance	308 H
Current	1483 A
Length	5.2 m
Diameter	5 m
Weight	132 t

Magnet parameters

Neurospin Center
CEA Saclay, France

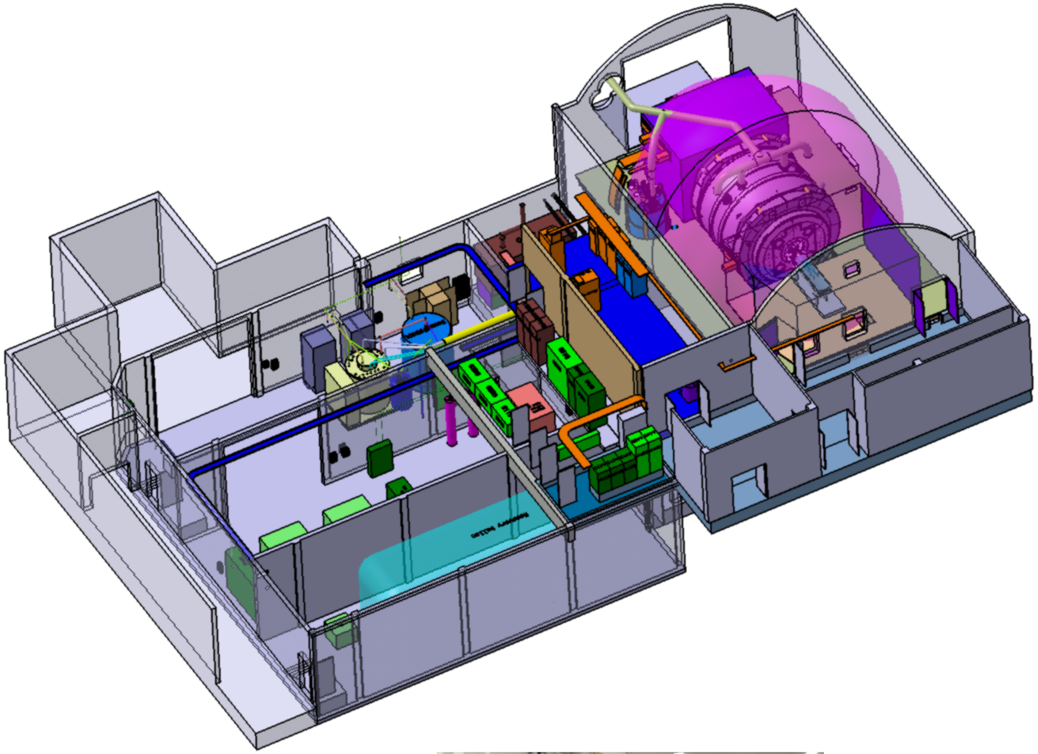


11.7 T magnet windings (orange) / mechanical structure at 1.8 K (blue)/ cryostat (gray)

A DEDICATED COMPLEX INSTALLATION TO OPERATE THE MAGNET

Vacuum circuit

Power supplies



MCS/MSS/DAQ

Cryo-lines

Dump resistor

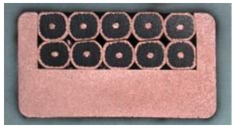
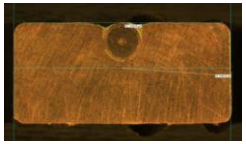
48 V Batteries

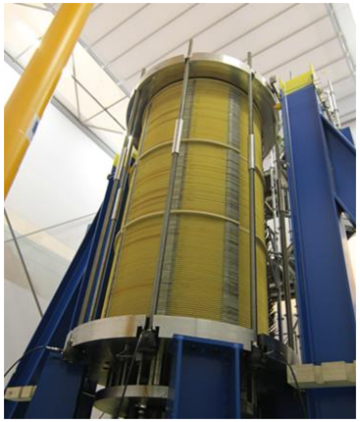
Control room

THE ISEULT MAGNET

- Main coil made of 170 DPs
- NbTi conductors @ 1.8 K
- Quench protection based on an external resistance
- Operation in semi-persistent mode (power supply + FCL)

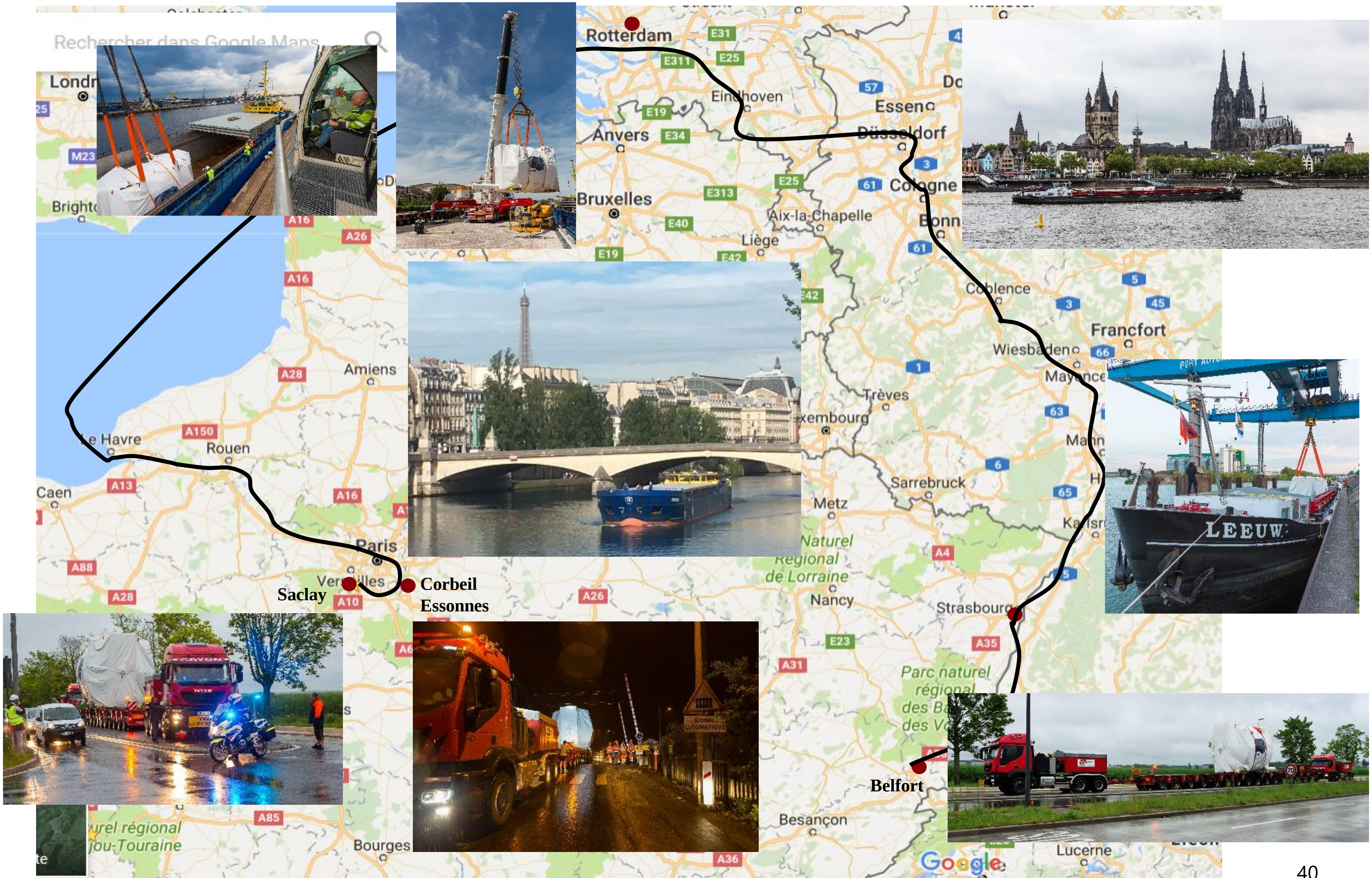
Lots of innovations compared with classical MRI magnets!

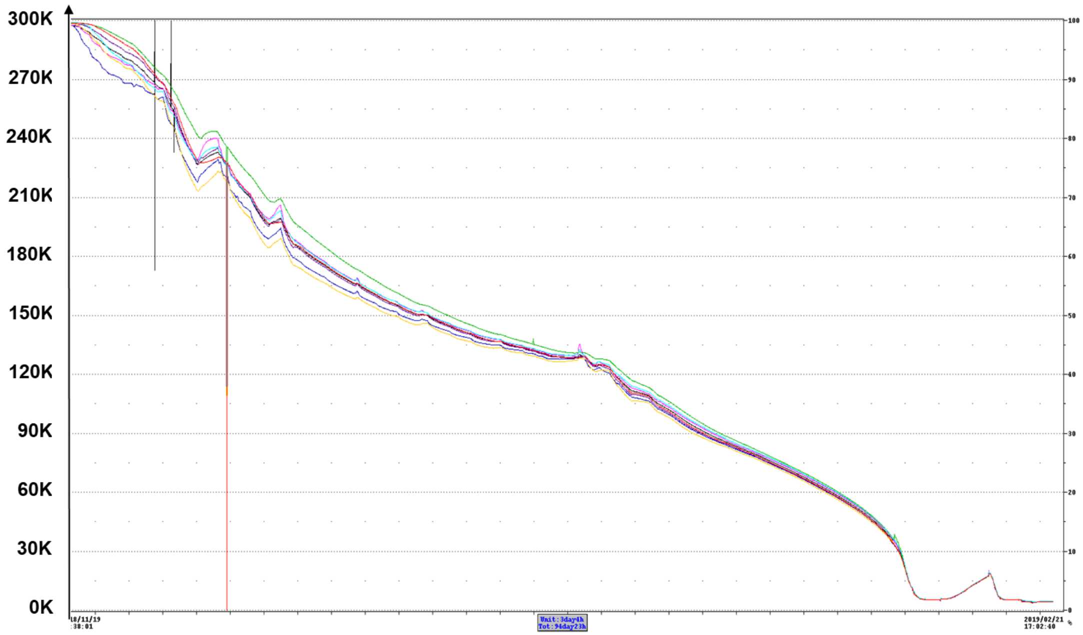






2 WEEKS OF TRANSPORT FROM BELFORT TO SACLAY





- **Cooldown in progress (4K at the moment)**
- **Nominal field expected in october 2019**

CONCLUSIONS

- Magnets are everywhere, specially SC magnets

- Very important developments in superconductivity technologies over the last 40 years, thanks to particle physics and MRI business

- Technical challenges to build bigger and stronger magnets:
  - use of Nb_3Sn is the most mature option for future accelerators (i.e. FCC); use of HTS still need high tech R&D (from material science to electromagnetic/electromechanical engineering)
    - increase the operating temperature and simplify the cryogenics
    - **reinforce conductor mechanical strength** and **protect the coils against quenches**.

- **HTS/Nb3Sn developments will strongly depends on the strategy chosen for future particles accelerators**

Thank you for your attention

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D. Simon, E. Rochepault, Pierre Védrine