High field magnets at the LNCMI

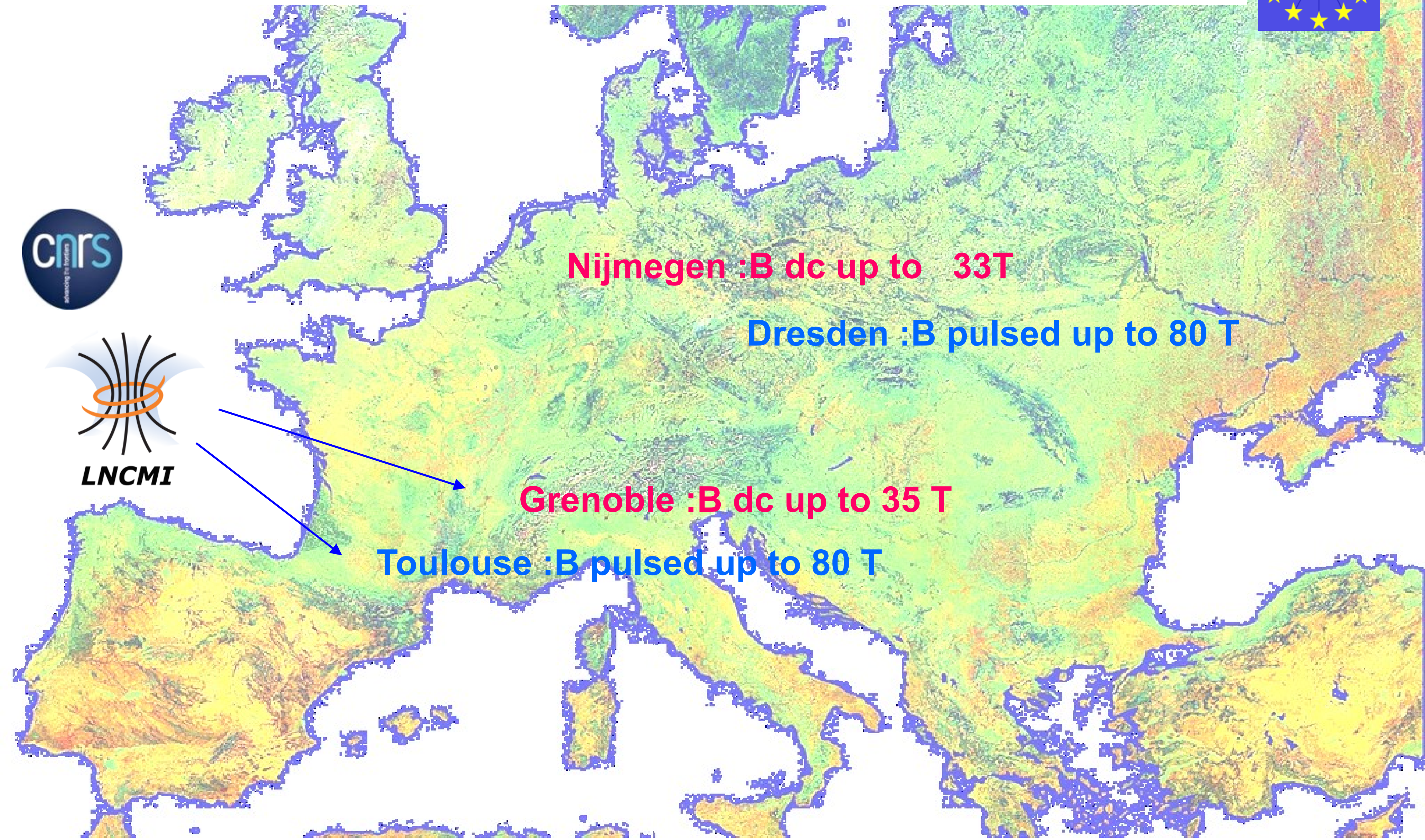
F. Debray, Laboratoire National des Champs Magnetiques Intenses
LNCMI CNRS, France

→ visit on Thursday

DC Magnetic Fields

	B (T)	Material	Projects
SUPER	12 T	NbTi	• 20000 IRM (+ 2000 each year) • 1232 dipoles for LHC (8.4 Teslas / 1.8 K) • High field MRI : Iseult : 1m diam /360 MJ/11,75 T (~2013)
SUPER	23 T	Nb3Sn	• NMR magnets record Magnet in operation 23.48 T (1 GHz proton res.) • ITER development
Copper	35 T	Cu alloy	In 3 places : Nijmegen (20 MW), Grenoble (24 MW), Tallahassee (48 MW)
HYBRIDS	35 to 45 T	NbTi, Nb3Sn & Cu Alloys	**Operationals :** ➔ Tsukuba, Japan 35 T = 14 T (Nb3Sn) + 21/23 T (~14 MW) ➔ Tallahassee, US 45 T = 11 T (Nb3Sn) + 34 T (~30 MW) **~ Planned for 2013/2015 :** ➔ Grenoble, France 42 T = 8 T (NbTi) + 34 T (24 MW) ➔ Nijmegen, The Netherlands 42 T = 12 T (Nb3Sn) + 30 T (20 MW) ➔ Hefei, China 42 T = 11 T (Nb3Sn) + 29 T (20 MW) ➔ Tallahassee, US 36 T = 14 T (Nb3Sn) + 22 T (12 MW)
HYBRIDS	Next generation 40 to 50 T with less power	Supra HTS YBaCuO BISCO MgB2 Copper Alloy	2005/20015 : R&D and prototypes : ➔ SMES : NEXANS/CNRS : 1MJ / 5,5 T ➔Inserts in 20 T environment : (NEXANS/CNRS/CEA FZK, Tallahassee) ➔R&D for futur accelerators (EUCARD) ➔Development of compact magnets : for futur hybrid magnets for others “communities” : neutron/XRay/ ions sources)

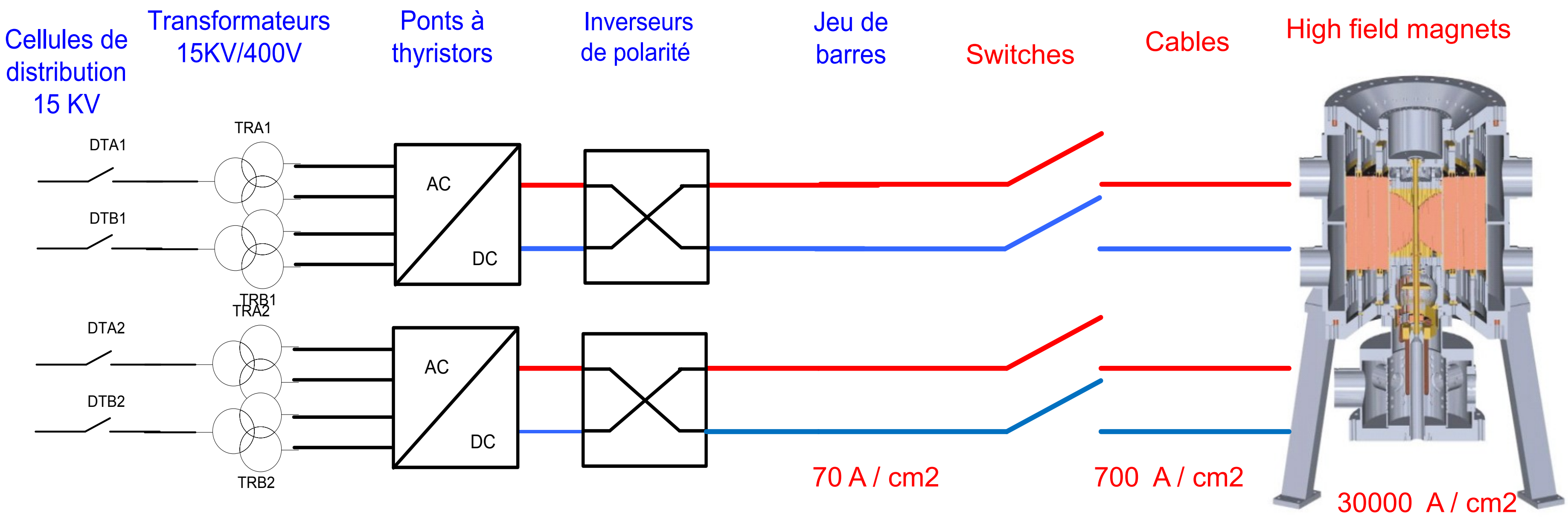
High field facilities open to users in Europe



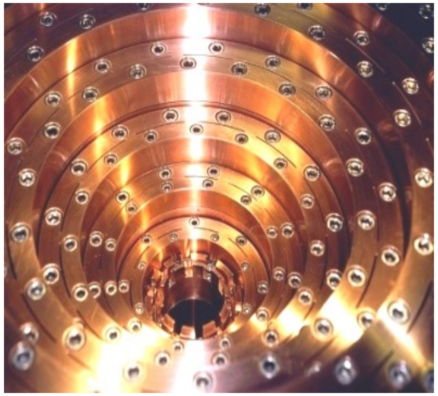
Jan. 2009 : fusion between Grenoble (GHMFL/LCMI and Toulouse(LNCMP)

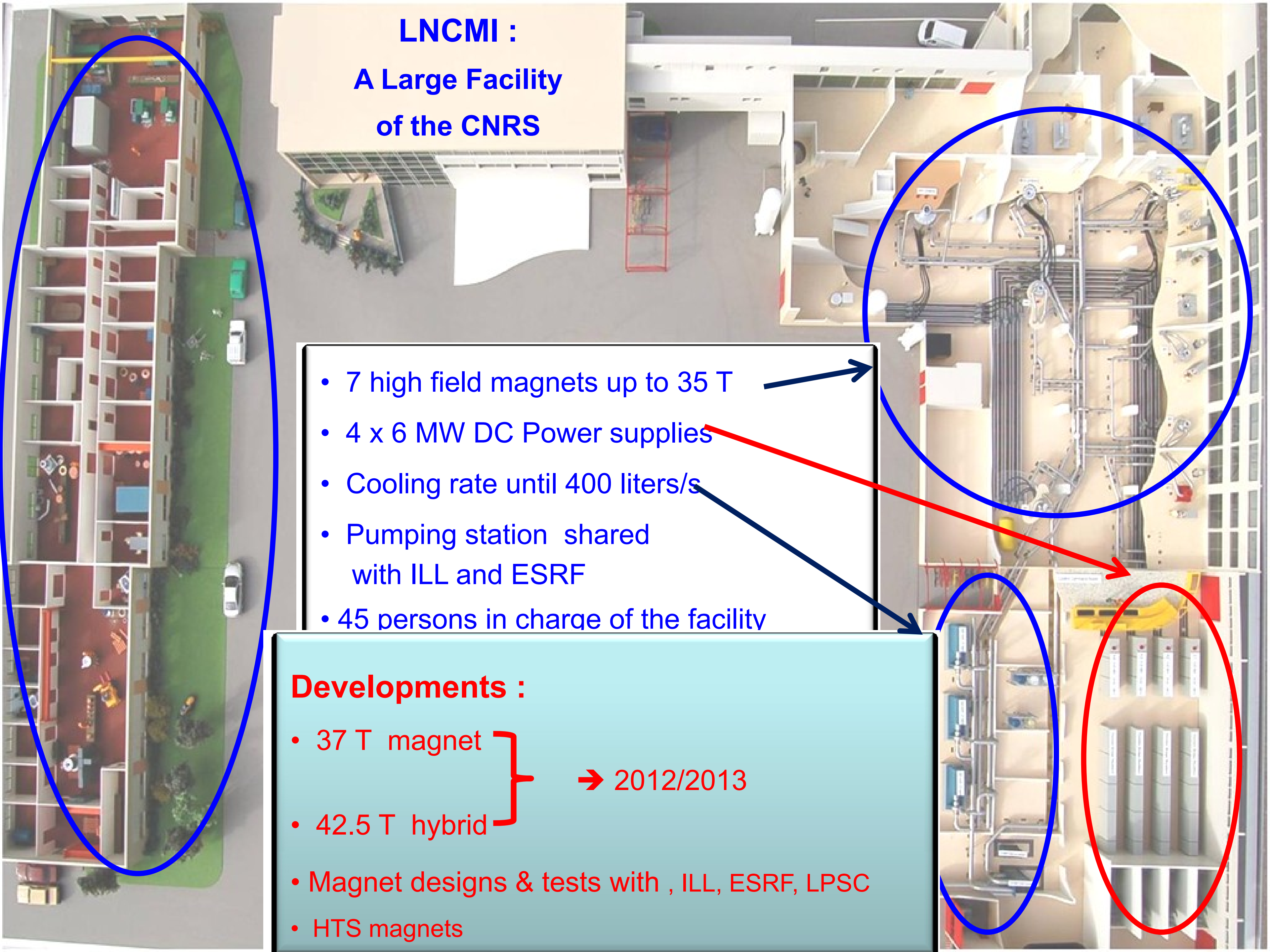
➔creation of the French National High Magnetic Field Facility (LNCMI)

Shematic of a DC High Field Facility
(Nijmegen, Tallahassen, Grenoble, Tsukuba..)



I = 16000 A (20 ppm)
U = 400 V





LNCMI :
A Large Facility of the CNRS

- 7 high field magnets up to 35 T
- 4 x 6 MW DC Power supplies
- Cooling rate until 400 liters/s
- Pumping station shared with ILL and ESRF
- 45 persons in charge of the facility

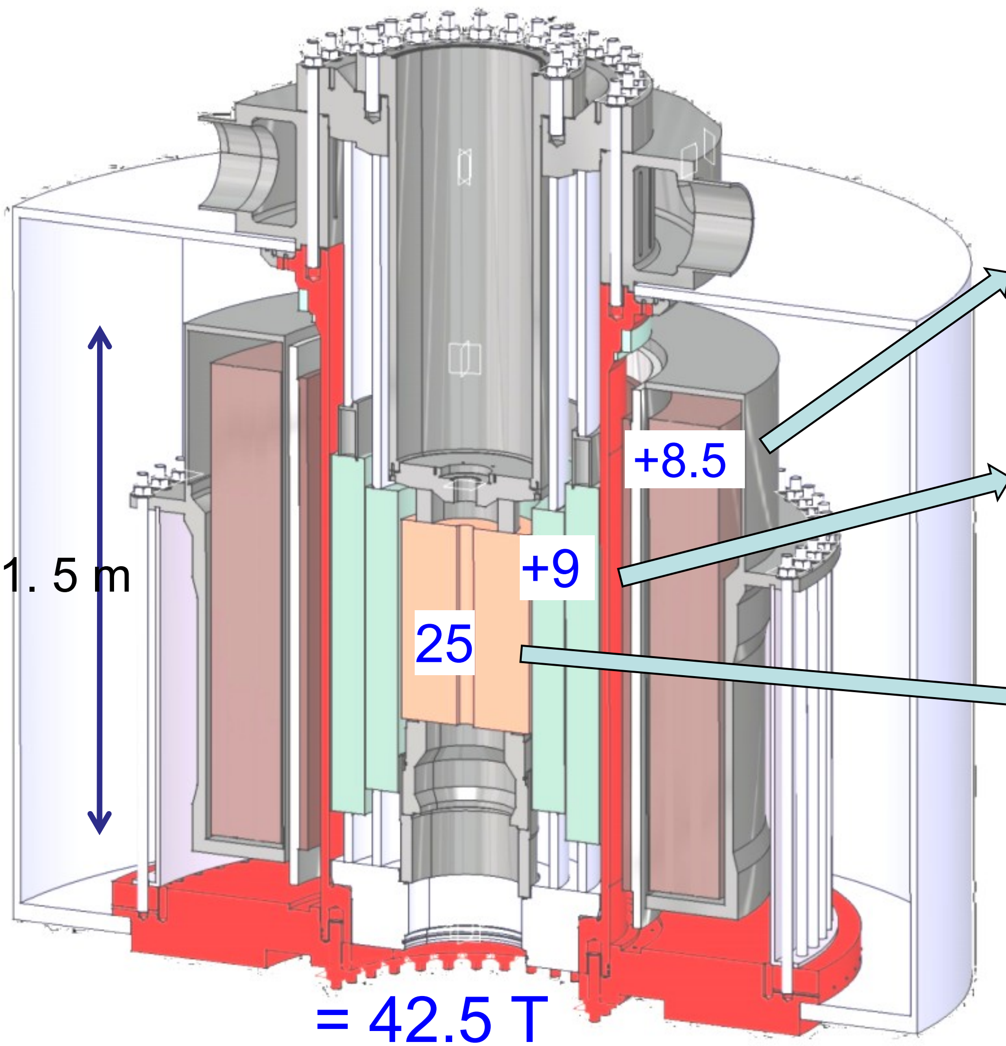
Developments :

- 37 T magnet
- 42.5 T hybrid

→ 2012/2013

- Magnet designs & tests with , ILL, ESRF, LPSC
- HTS magnets

Hybrid Project at the LNCMI (CEA- CNRS collaboration)
Objective : from 35 T to 42.5 T



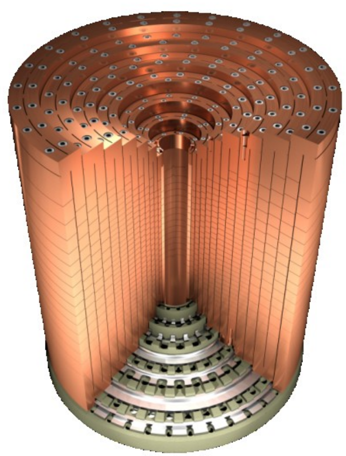
- **Construction of a NbTi outsert**

Rutherford Cable on Conduit Conductor

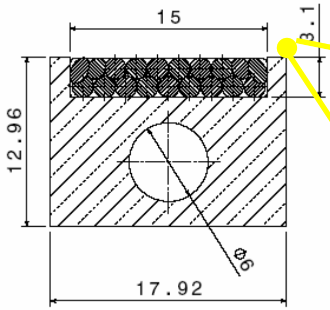
- **Construction of resistive magnets**

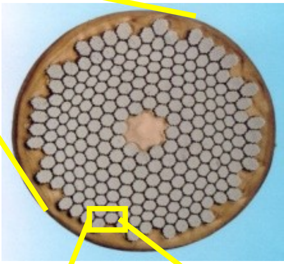
➔ from 35 T (existing magnet)

to 34 T in 8.5 T environment at minimum.



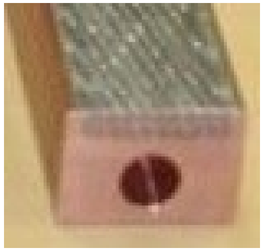
Nb-Ti outsert : 8. 5 T @ 1.8 K
within a CEA- CNRS collaboration



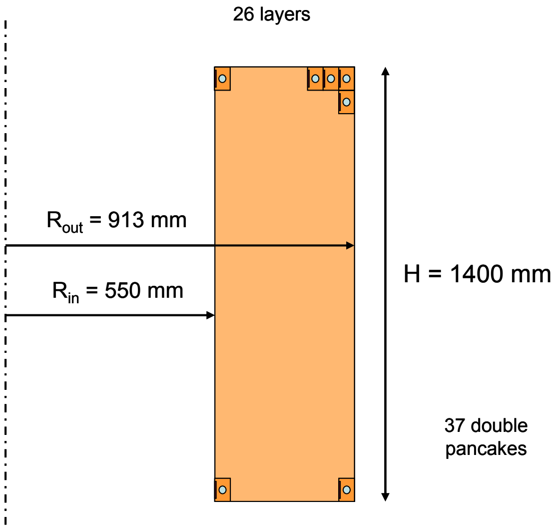


CABLE : Rutherford Cable On Conduit Conductor

- Flat Rutherford cable of 19 strands diam = 1.62 mm
- 6264 filaments, diam = 14 μm per strand
- Extruded Cu-Ag$_{0.05\%}$ stabiliser (RRR ≈ 50)



COIL : 37 double-pancakes (260 m long) in series



I = 7.1 kA
E = 76 MJ
L = 3 H
Mass : 20 tons

$(JBr)_{max}$ = 140 MPa

$\sigma_{max,total}$ = 170 MPa

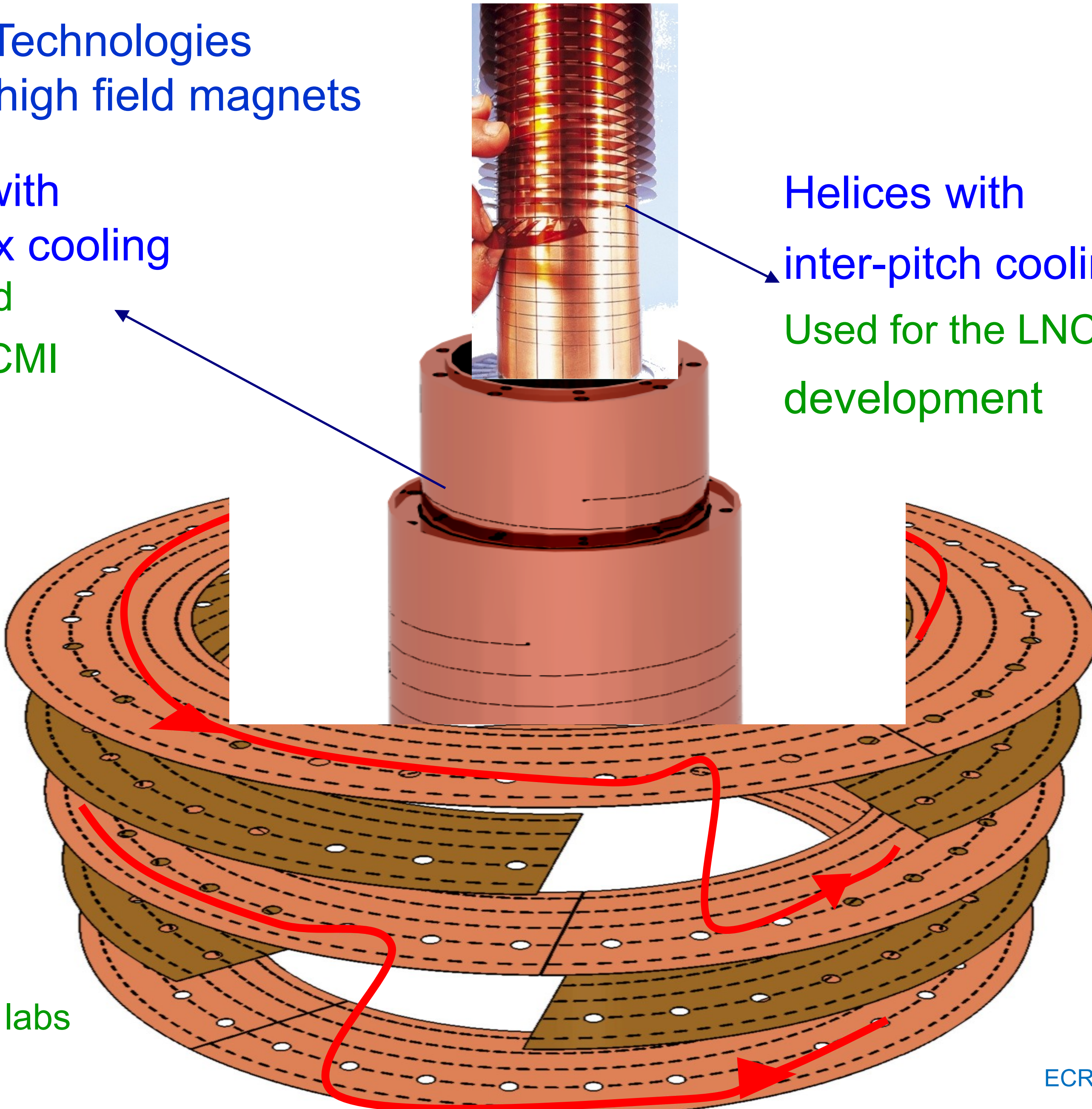
Energy extraction 70 mΩ, 60 K 500 V

2009	2010	2011	2012	2013

Cable (2009–2010) · Insertion (2011) · Coil Winding (2011–2012) · Integration and tests (2012–2013)

3 Technologies
for the high field magnets

Helices with
inter-helix cooling
Developed
at the LNCMI



Helices with
inter-pitch cooling
Used for the LNCMI/LPSC
development

J X Bz

J X Bz

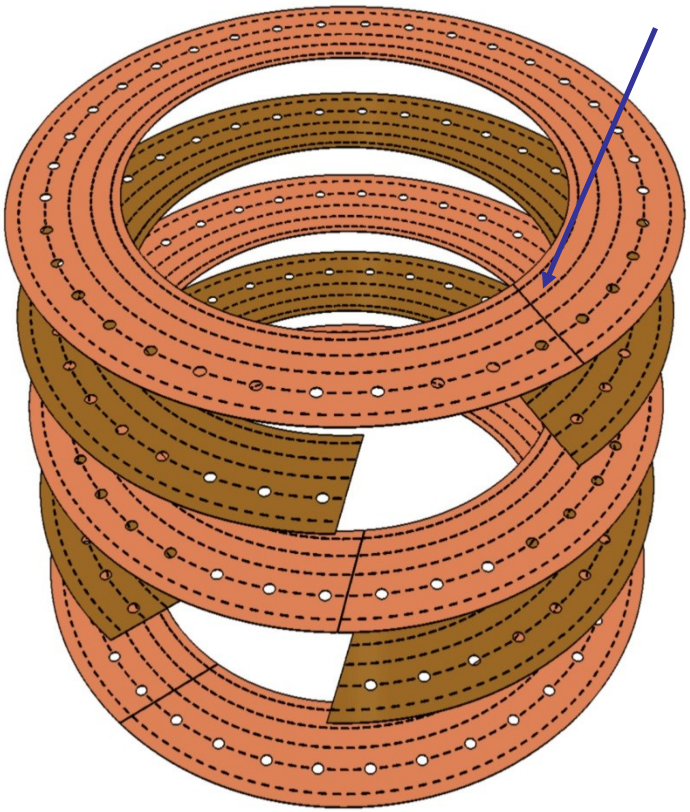
Bitter

Widely used in
main high field labs

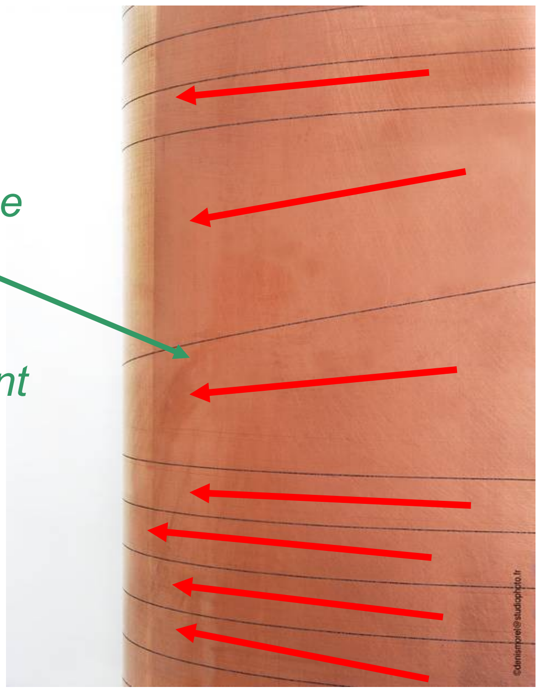
Field Optimization : advantage of the helix technique

Bitter Technique

Discrete change of current density



Helix Technique



Continuous change of the current density

➔ allows a fine optimization of the current distribution

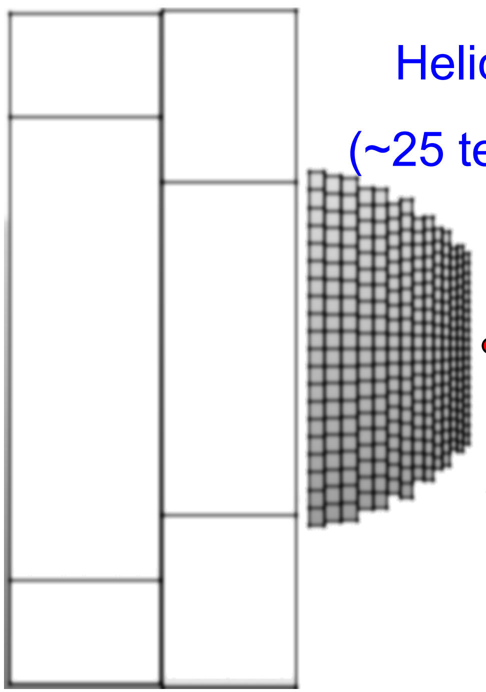
➔Helix technique well adapted for design of

- homogeneous magnets
- Split magnets, high gradient magnets, ECR magnets

Magnets with enhanced homogeneity

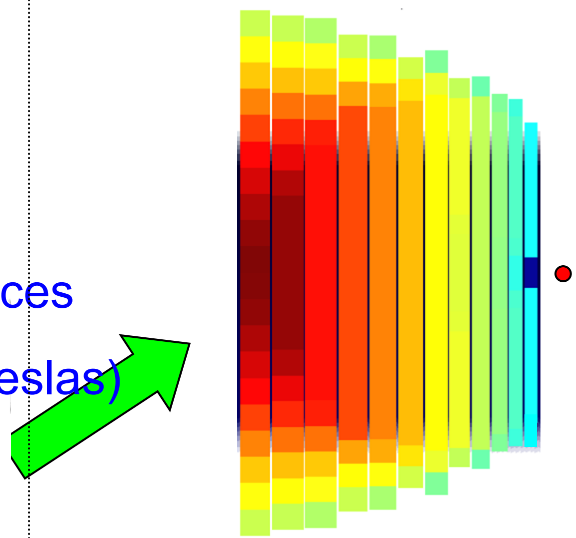
Bitter or LTS

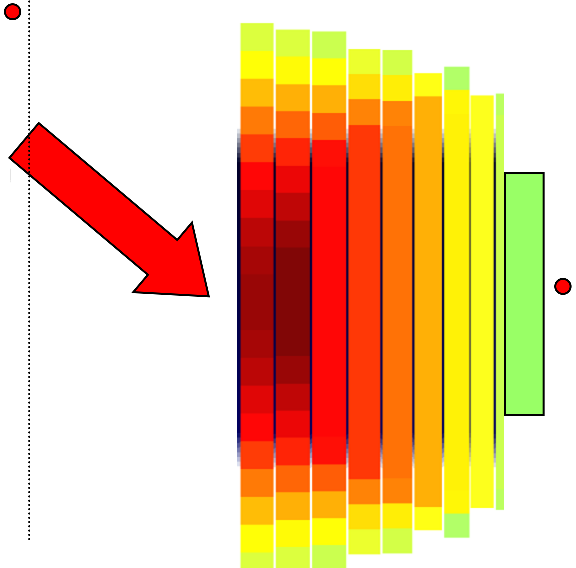
(~10 teslas)

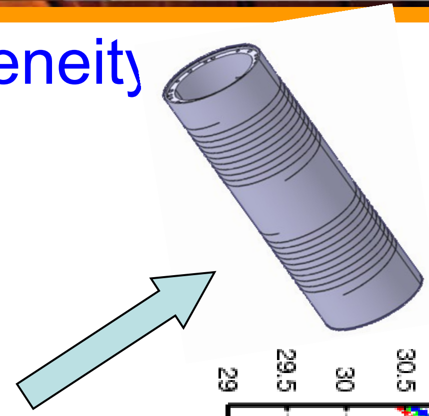


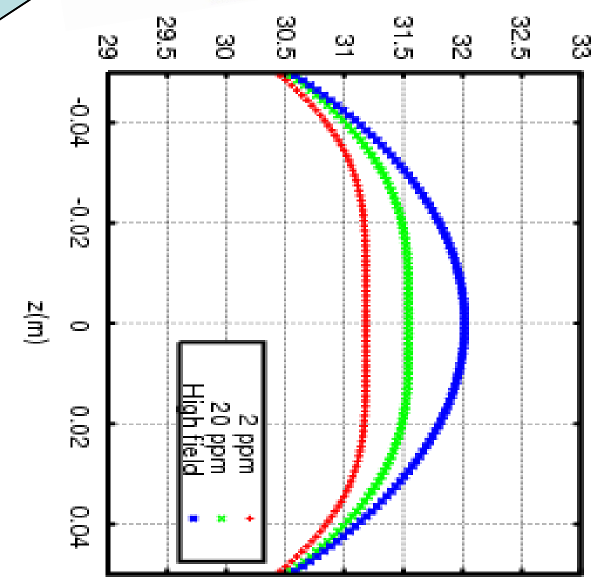
Helices

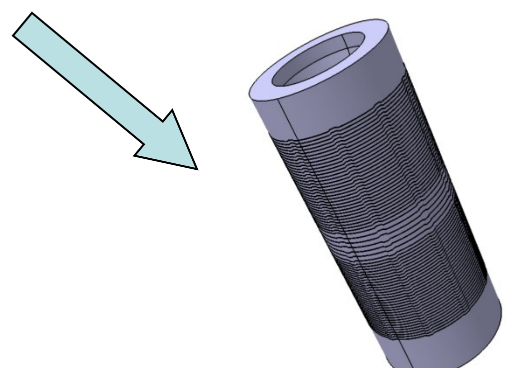
(~25 teslas)





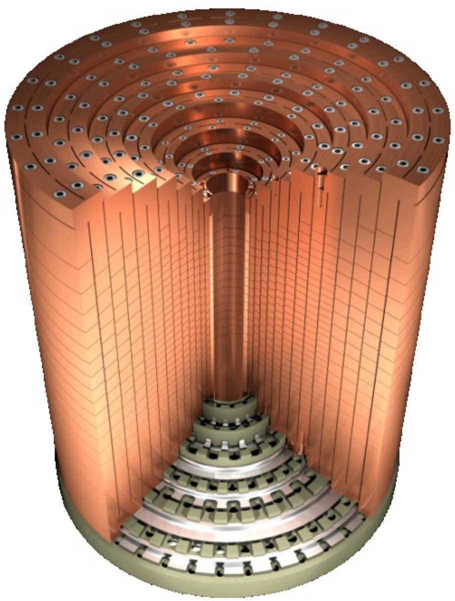


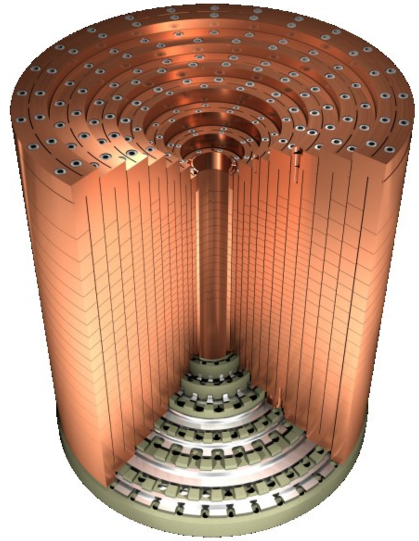




Magnet development

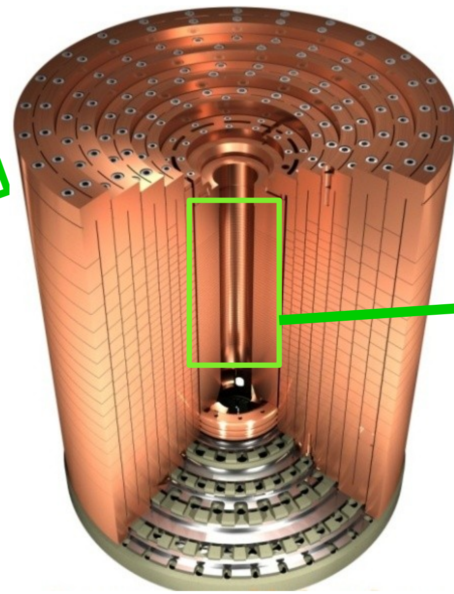
March 2009
35 T /34 mm





2011/12 : 37 T in 34 mm

➔will be the first insert for the 42.5 T hybrid



Aim 2013:

38 T in 34 mm (suitable for THz generation)

35 T with high homogenity < 50ppm

in mixing
Longitudinaly
&
radially cooled techniques

2009	2010	2011	2012	2013
35 T (34 mm)	31 T (50 mm)	36 T (34 mm)	37 T (34 mm)	42 .5 T hybrid test

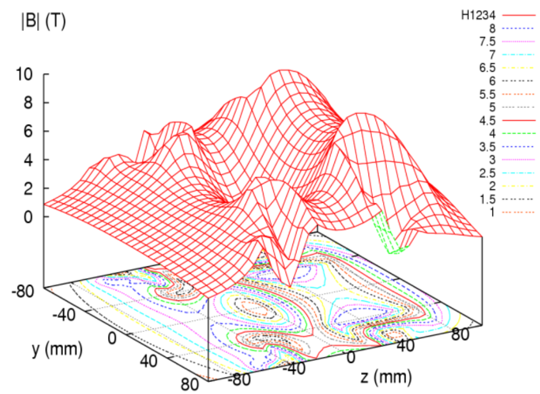
New geometries for high field magnets

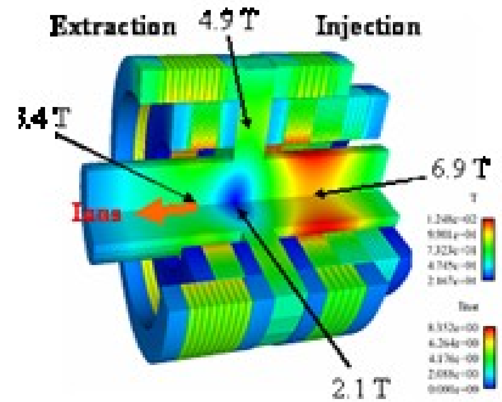
ILL and ESRF

High fields for Neutrons and X Ray :
From 15 T (existing) to 30 T in split geometry

LPSC

Electron Cyclotron Resonance Ion Source (ECRIS) :
from 28 GHz ➔ 60 GHz



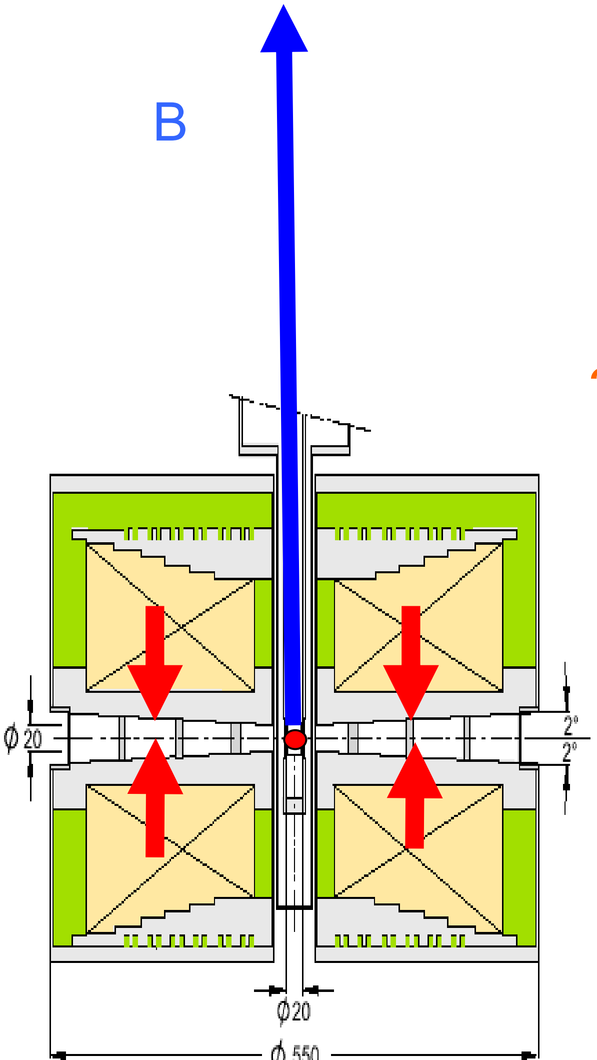


Design
founded
by «ESRF Up» FP7
programm (2008/2009)

Design & construction
founded
by Eurisol & Euro nu FP7
programm (2007/2012)

➔ Common feature : highly constrained geometries

Split magnet (State of the Art)



Split magnet Nb3Sn

	B solenoid config.	Material	
Super	12 T	NbTi	
	22 T	Nb_3Sn	
Copper	~ 35 T	Copper alloys	Nijmegen Grenoble, Tallahassee

Consequences

- B goes down with the gap size
- Attractives forces : (J0XBr) ~ 20 MPA
- Limited acces to the centre:

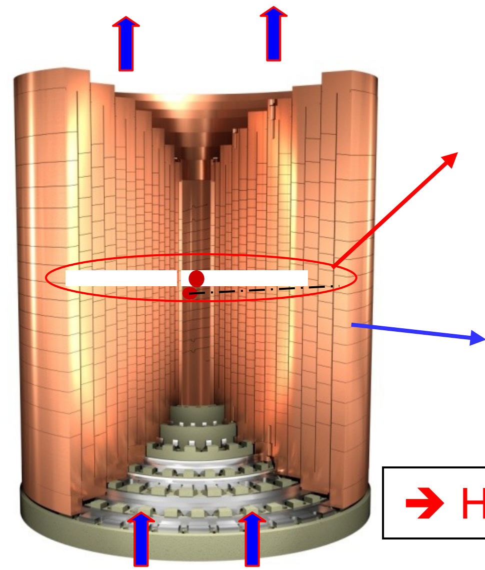
~ 30 % B losses as compared to solenoids

➔State of the Art for split magnet 15 T

Choice of the radially cooled technology for Split and ECR magnets

Longitudinal cooling

Hydraulic channels are ⊥ to the split plane



Heat conduction length = helix thickness
➔Possible thermal limitation near the mid plane

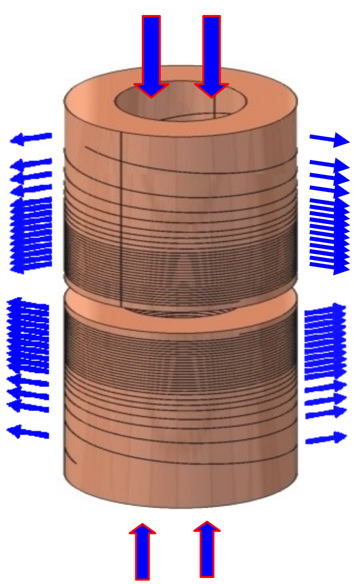
High flow rates and electric currents have to pass through the mid plane

➔ High constrains for the mid plane conception

Radial cooling

Hydraulic channels are // to the split plane

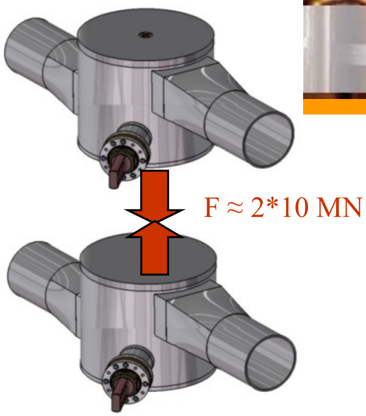
Cooling is performed between each turn of the winding.



Heat conduction length = pitch of the helix

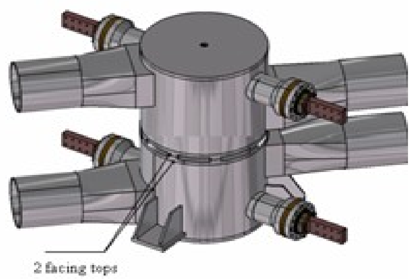
Less hydraulics and electric constrains near the mid plane

➔ High versability to fit the users needs.

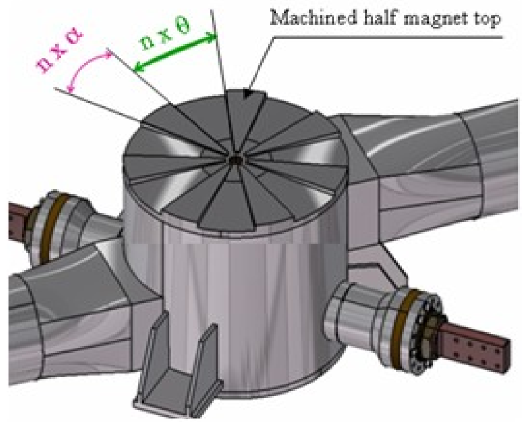


Design study results (2008/2009) for Esrf Up FP7

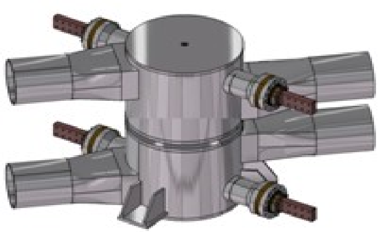
13th October 2009 : special ESRF tuesday event



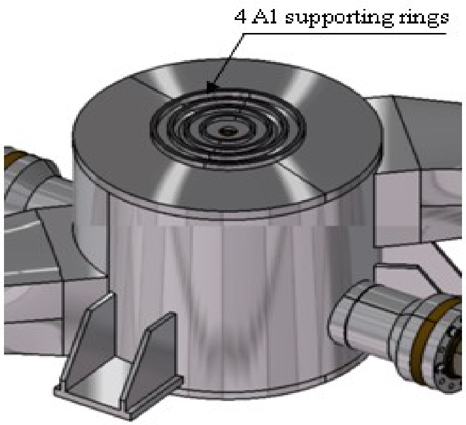
A light for science ESRF



B..............	28.8 T
Air gap	10 mm
Take off.......	2x3°
n...............	7
θ....................	36°
α....................	15°
WB.............	34 mm



NEUTRONS FOR SCIENCE

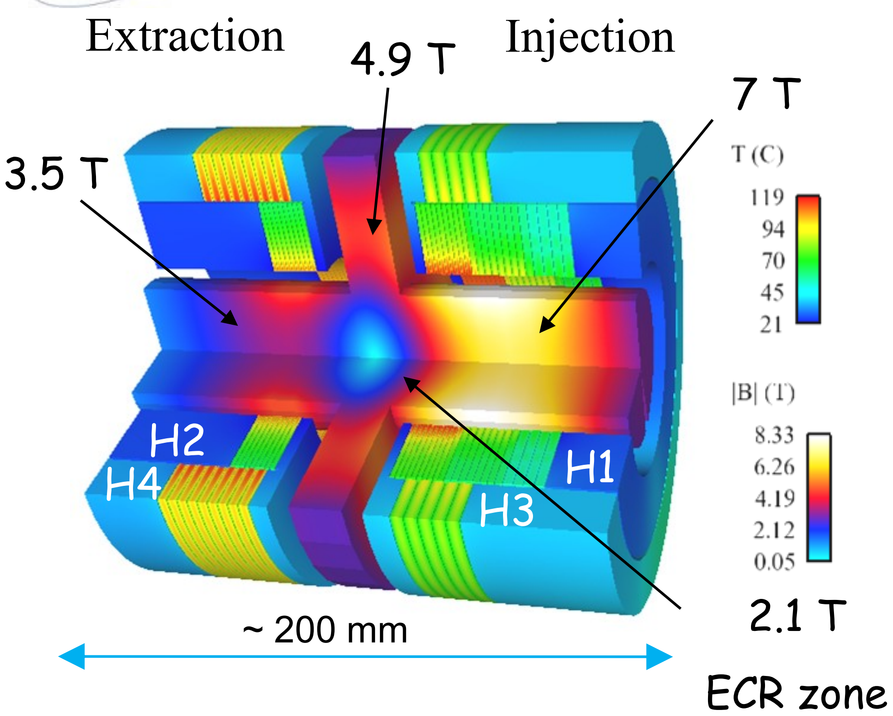


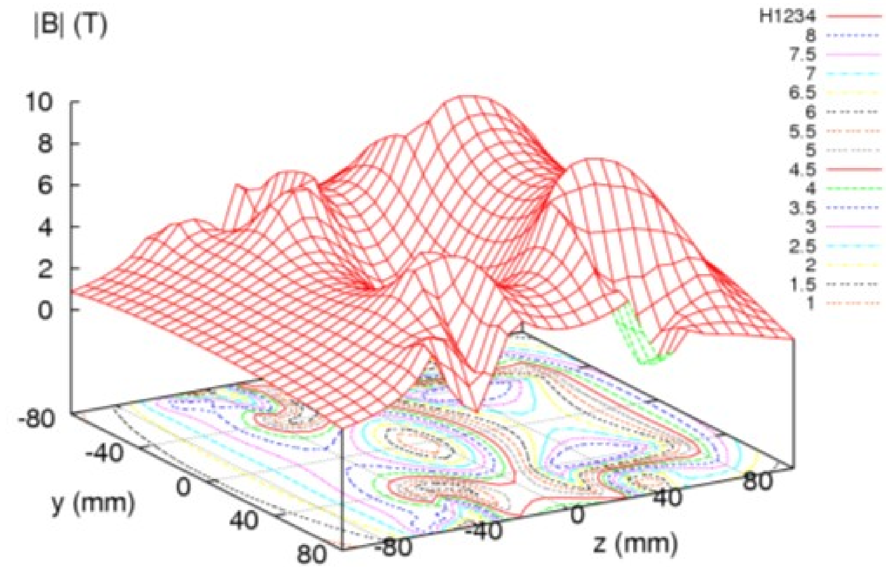
B..............	30 T
Air gap	10 mm
Take off.......	2x3°
Al thickness...	35 mm
WB.............	34mm

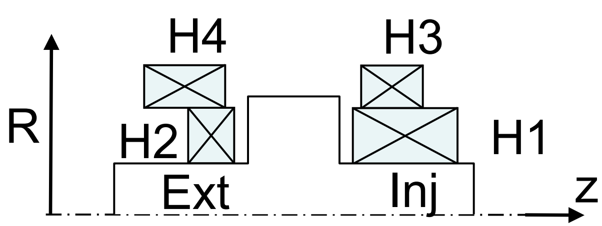
➔ **Next step :** hybrid studies in the frame of the HMFL FP7 (2011/2013)

ECRIS project - 3D Magnetic Simulation

2008







- Solution with 2 sets of 2 radially cooled concentric helices
- 7 T injection (spec. 6T)
- 3.5 T ion extraction (spec. 3T)
- 4.9 T radial mirror (spec. 4T)

Magnetic simulation | Construction | Integration & tests

2008	2009	2010	2011	2012

ECRIS : On-site installation and measurements

2009/ 2010

Magnet time from July 2009,
for experiments on a 10 MW magnet
Purpose : B map at 28 GHz

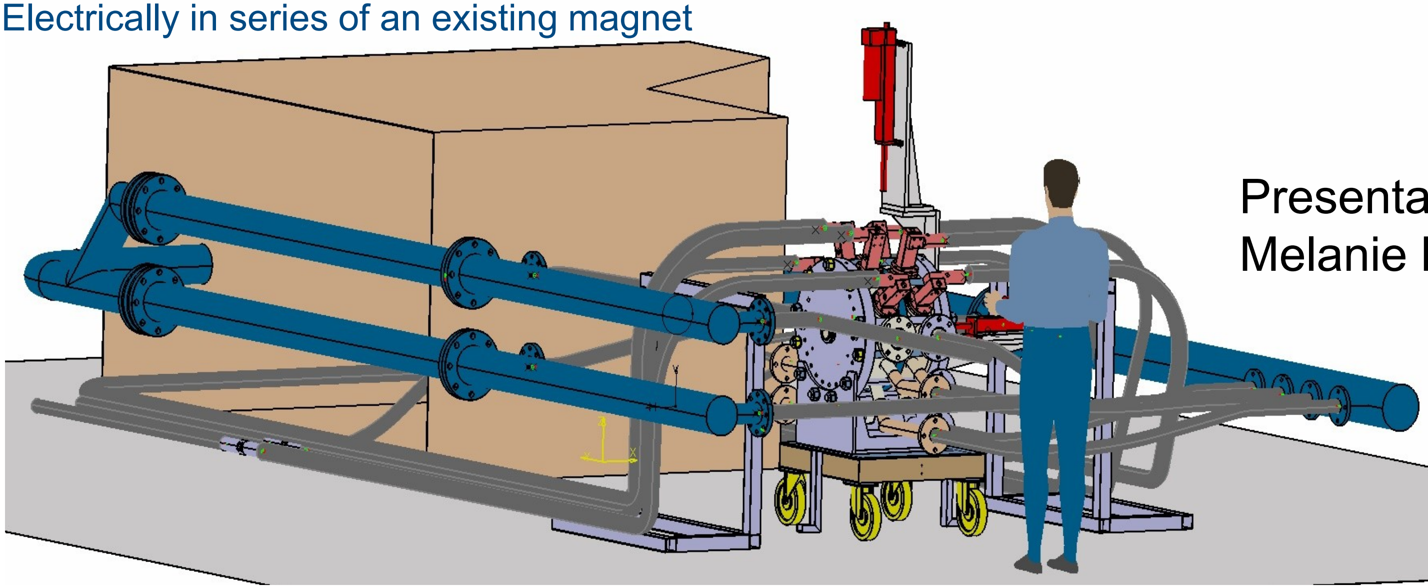
B tests

- 15 kA on each side : P = 0.75 MW
- B measurements up to 18 GHz (July 2010)

Magnetdesign for 60 Ghz ECR operation
➔ Measurement to be continued

1st step : ECRIS connected to the high field facility:

- Hydraulically in parallel
- Electrically in series of an existing magnet



Presentation of
Melanie Marie Jeanne

Magnetic simulation | Construction | Integration & tests

2008	2009	2010	2011	2012

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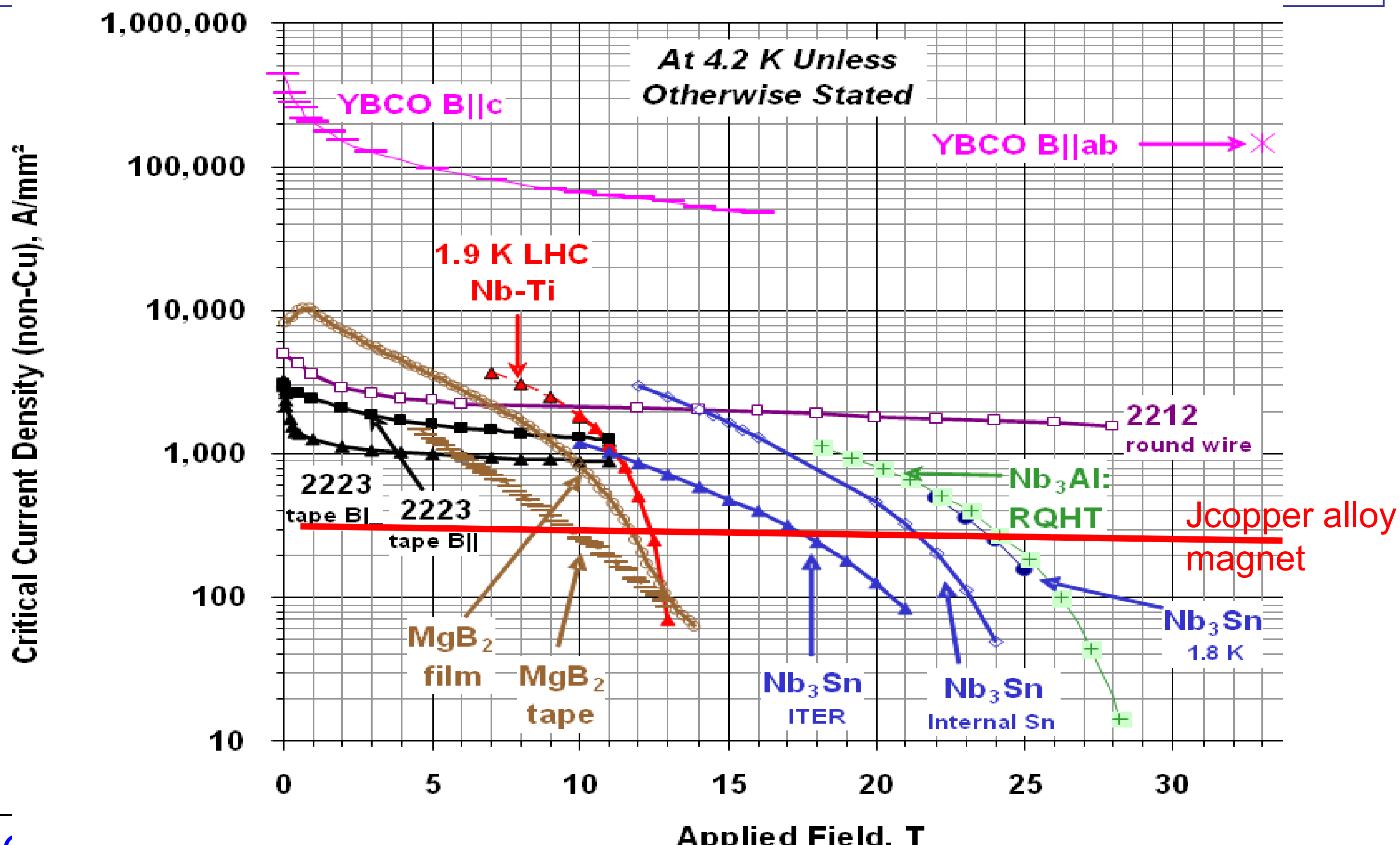
R&D on HTS tapes and wires in High Field Facilities

- Platform for Superconductor Characterization (access to high B and variable Temp.)
- HTS conductors development (with labs, institutes and industrial partners)
- Magnetic systems (SMES, insert coils)

HTS conductors show the highest critical current density (*Jc*) at B > 15 T

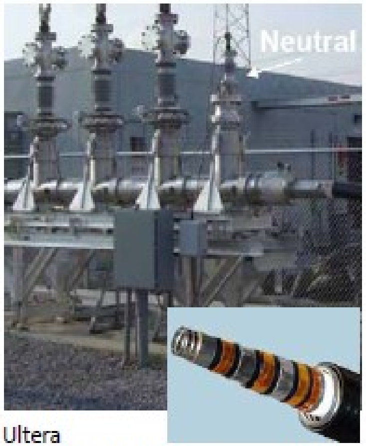


- Cu oxides (1986) :YBCO, Bi-2212 & 2223,
- Borides (2001): MgB_2

➔ Now mature for industrial applications

Superconducting AC Cables
State-of-the-Art

Columbus



Ultera
13.2 kV, 3 kA, 200 m
Triaxial™ Design
BSCCO 2223
Energized 2006
High reliability

Figure: Ultera

LIPA

Nexans
138 kV, 2.4 kA, 600 m
Single coaxial design
BSCCO 2223
Energized 2008

Figure: Nexans

Gochang

LS Cable
22.9 kV, 50 MVA, 100 m
BSCCO 2223
Energized 2007
500 m field test with YBCO in 2011

M. Noe, KIT, ASC 2010, Superconductivity for Power Applications is getting more and more attractive

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M.Noe, KIT
ASC 2010

Superconducting Transformers
State-of-the-Art of Current Limiting Transformers

Karlsruhe Institute of Technology

60 kVA Demonstrator
1kV/0.6 kV
Primary copper
Secondary YBCO tapes
Successful test in 2010
Recovery under nominal load

Nagoya University

2 MVA Demonstrator
22kV/6.6 kV
Primary Bi 2223 tapes
Secondary YBCO tapes
Successful test in 2009
Larger prototype planned

Waukesha/SuperPower

28 MVA Prototype
69 kV
Primary and secondary with YBCO tapes
Test planned in 2012

M. Noe, KIT, ASC 2010, Superconductivity for Power Applications is getting more and more attractive

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Superconducting AC Cables
State-of-the-Art of HTS AC Cables

Manufacturer	Place/Country/Year [1]	Type	Data	HTS
Innopower	Yunnan, CN, 2004	WD	35 kV, 2 kA, 33 m, 3-ph.	Bi 2223
Sumitomo	Albany, US, 2006	CD	34.5 kV, 800 A, 350 m, 3-ph.	Bi 2223
Ultera	Columbus, US, 2006	Triax	13.2 kV, 3 kA, 200 m, 3-ph.	Bi 2223
Sumitomo	Gochang, KR, 2006	CD	22.9 kV, 1.25 kA, 100 m, 3-ph.	Bi 2223
LS Cable	Gochang, KR, 2007	CD	22.9 kV, 1.26 kA, 100 m, 3-ph.	Bi 2223
Sumitomo	Albany, US, 2007	CD	34.5 kV, 800 A, 30 m, 3-ph.	YBCO
Nexans	Hannover, D, 2007	CD	138 kV, 1.8 kA, 30 m, 1-ph.	YBCO
Nexans	Long Island, US, 2008	CD	138 kV, 1.8 kA, 600 m, 3-ph.	Bi 2223
Nexans	Spain, 2008	CD	10 kV, 1 kA, 30 m, 1-ph	YBCO
Ultera	New York, US, 2010	Triax	13.8 kV, 4 kA, 240 m, 3-ph.	YBCO
Ultera	Amsterdam, NL, -	Triax	50 kV, 2.9 kA, 6000 m, 3-ph.	YBCO
Nexans	Long Island, US, 2011	CD	138 kV, 2.4 kA, 600 m, 1-ph.	YBCO
LS Cable	Gochang, KR, 2011	CD	154 kV, 1 GVA, 100 m, 3-ph.	YBCO
LS Cable	Seoul, KR, 2011	CD	22.9 kV, 50 MVA, 500 m, 3-ph.	YBCO
Sumitomo	Yokohama, JP, 2012	CD	66 kV, 200 MVA, 200 m, 3-ph.	Bi 2223
Sumitomo	TEPCO, JP	CD	66 kV, 5 kA	to be defined
Furukawa	TEPCO, JP	CD	275 kV, 3 kA	Bi 2223
Sumitomo	Chubu U., JP, 2010	CD	10 kV, 3 kA DC, 20 m, 200 m	Bi 2223
VNIIKP	Moscow, RU, 2010	CD	20 kV, 200 m	Bi 2223
Nexans	Spain	CD	10 kV, 3.2 kA, 30 m, 1 ph.	Bi 2223

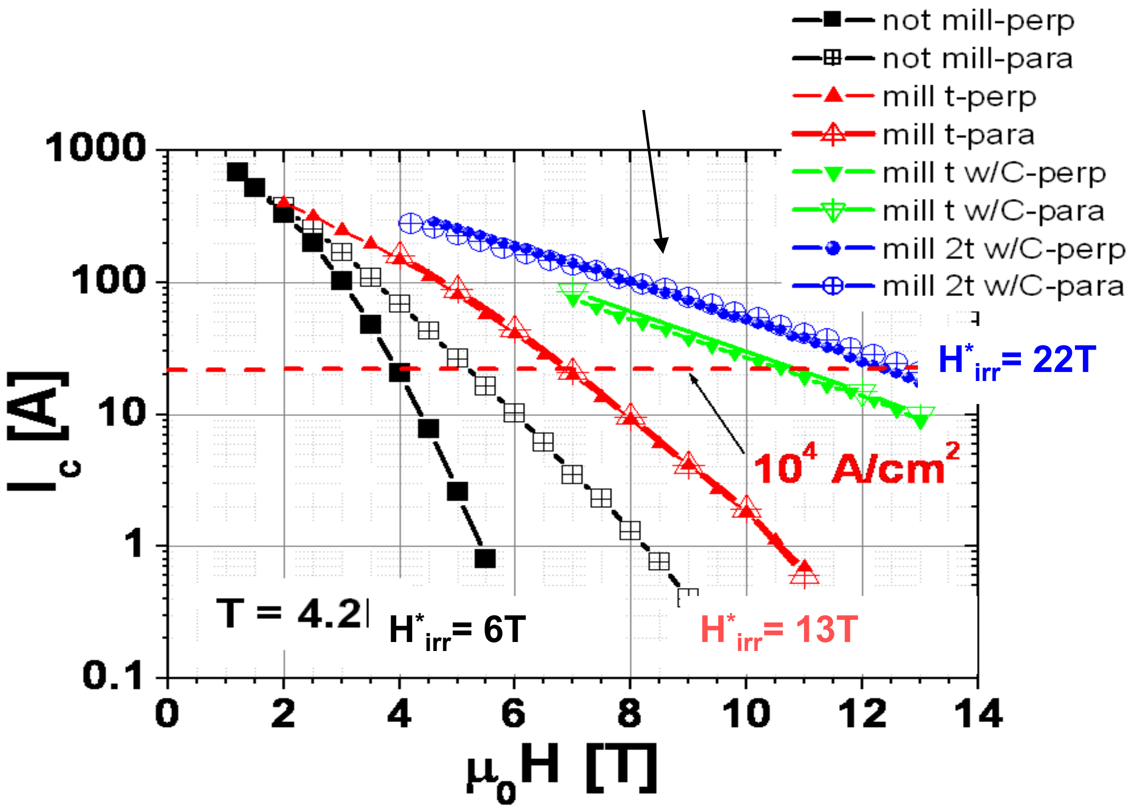
Superconducting Transformers
State-of-the-Art

Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA/18,42 kV/420 V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric Kyushu Uni	Demonstrator	500 kVA/6,6 kV/3,3 kV	1	1998	Bi 2223
Germany	Siemens	Demonstrator	100 kVA/5,5 kV/1,1 kV	1	1999	Bi 2223
USA	Waukesha	Demonstrator	1 MVA/13,8 kV/6,9 kV	1		Bi 2223
USA	Waukesha	Demonstrator	5 MVA/24,9 kV/4,2 kV	3 Dy		Bi 2223
Japan	Fuji Electric U Kyushu	Demonstrator	1 MVA/22 kV/6,9 kV	1	< 2001	Bi 2223
Germany	Siemens	Railway	1 MVA/25 kV/1,4 kV	1	2001	Bi 2223
EU	CNRS	Demonstrator	41 kVA/2050 V/410 V	1	2003	P-YBCO S- Bi 2223
Korea	U Seoul	Demonstrator	1 MVA/22,9 kV/6,6 kV	1	2004	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA/22 kV/6,6 kV	1	2009	P-Bi 2223 S-YBCO
Germany	KIT	Demonstrator	60 kVA	1	2010	P-Cu/S-YBCO
USA	Waukesha	Prototyp	28 MVA/69 kV	3	2010	YBCO

M.Noe, KIT
ASC 2010

Properties of MgB_2 tapes and wires (Columbus Superconductors, Genova, Italy)

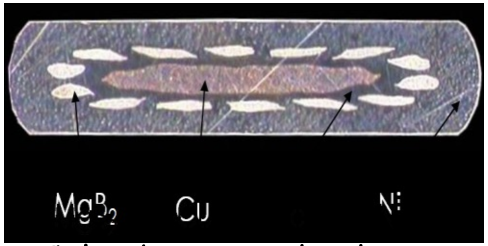
Measurement campaigns with the LNCMI since 2003



- Conductors with a large number of filaments, high filling factor (>25%) and wire shaped are preferable
- Improvment of $J_c(B,T)$ behaviour by ball-milling : best sample I_c (4.2 K, 13 T) = 20 A ➔ $J_c = 10^4$ A/cm², H^*_{irr} = 22 T

Effect of grain refinement on enhancing critical current density and upper critical field in undoped MgB_2 ex situ tapes, A. Malagoli et al., Journal of Applied Physics, **104** (10) : Art. No. 103908 (2008)

MgB2 magnet for MRI (Columbus Superconductors)

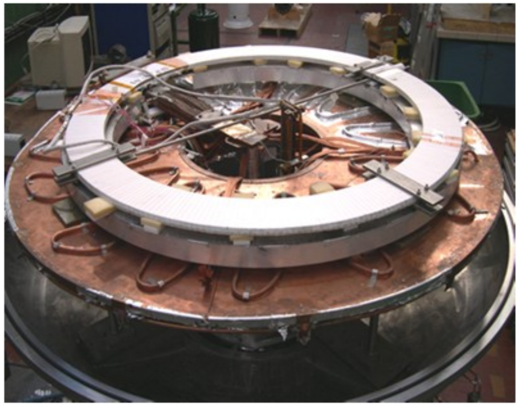


Columbus standard tape

1st MRI machine using MgB_2:
2 parts
each part = 6 double pancakes
1 double pancake = 1,6 km
MgB_2 tape

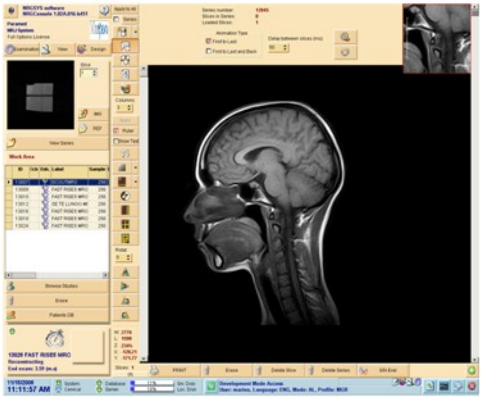
Main Magnet Parameters	
Nominal Field	0.5 T
Peak Field on the Conductor	1.3 T
Nominal Current	90 A
Number of Pancakes	12
Conductor Length (total)	18 Km
Inductance	60 H
Overall Dimensions	2x2x2.4 m
Patient Available Gap	0.6 m
Weight	25000 Kg

First commercial system installed in hospital



MRopen

First MRI image

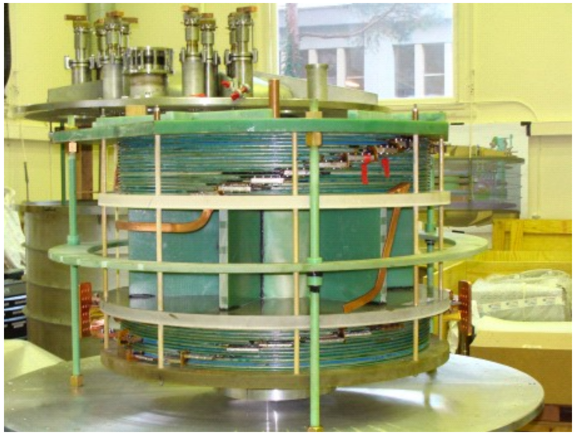


Development of magnetic systems using HTS

Objectives : to study the most suitable HTS for high B magnets and to develop the technology

« SUPER-SMES » Project ➔ energy storage

- Objectives: Energy density enhancement for SMES with HTS
- Partners: CNRS-CEA/IRFU-Nexans
- Conceptual study of 20 kJ/kg SMES @ 1 MJ / 50 MW



800 kJ Bi-2212 SMES
DGA / CNRS /Nexans project
(P. Tixador InP-G CNRS)

FP7 – European Project EUCARD ➔ magnets for accelerators

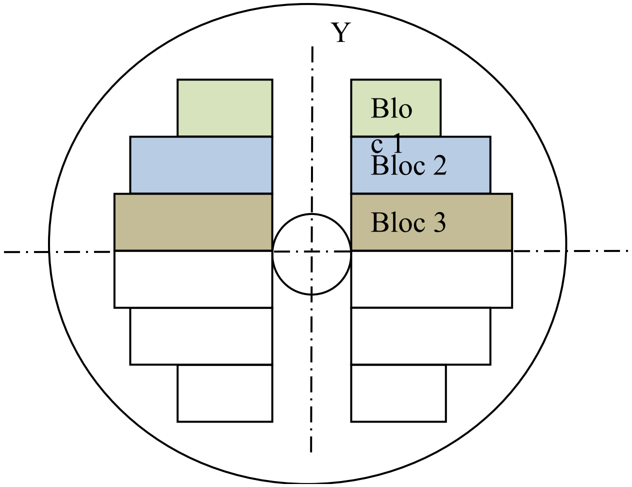
- 4 years (2009-2013), 37 european partners
- WP7: Superconducting High Field Magnets for higher luminosities and energies

➔ **Task 4: construction of a Very High Field HTS Dipole Insert (6 T) within a Nb3Sn dipole magnet (13 T)**

- Objectives: to upgrade the large European research accelerators
- Partners: CNRS-CEA/IRFU-FZK-LASA/INFN-TUT-UNIGE-PWR

The EuCARD project is co-funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, under Grant Agreement no 227579.

Dipole design

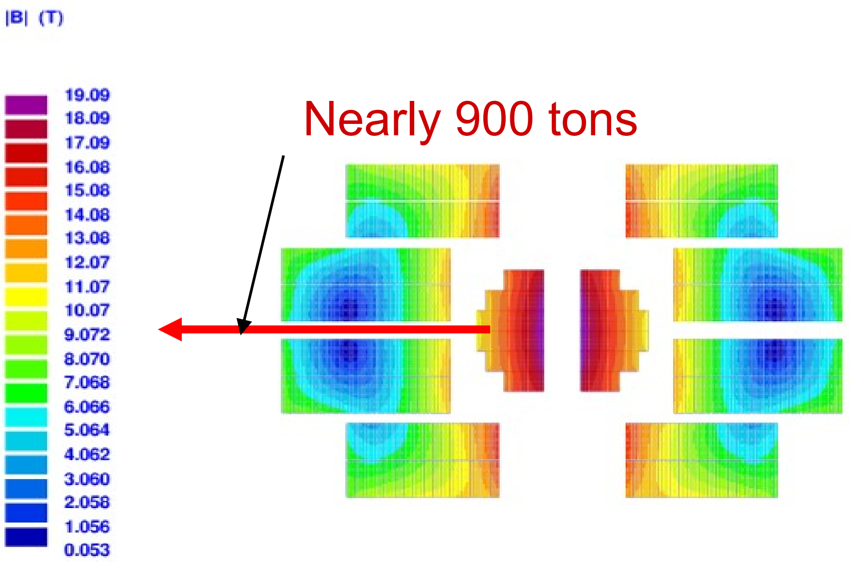


Inner bore diameter: 20 mm
Outer bore diameter : 98 mm

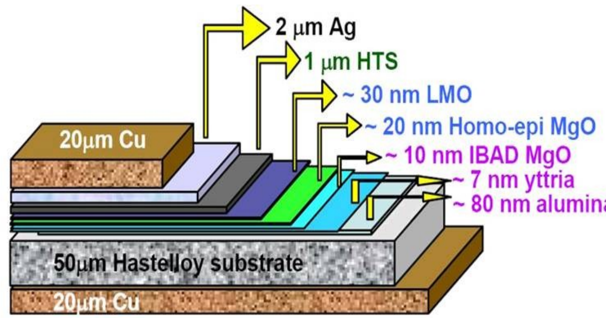
➔Peak field 6.1T with 254 A/mm² needed

3 double pancakes (2 flat one)
1 with bent end, each pancake
(symetrical / mid plane)

(JM Rey CEA)



Bi-2212 & YBCO

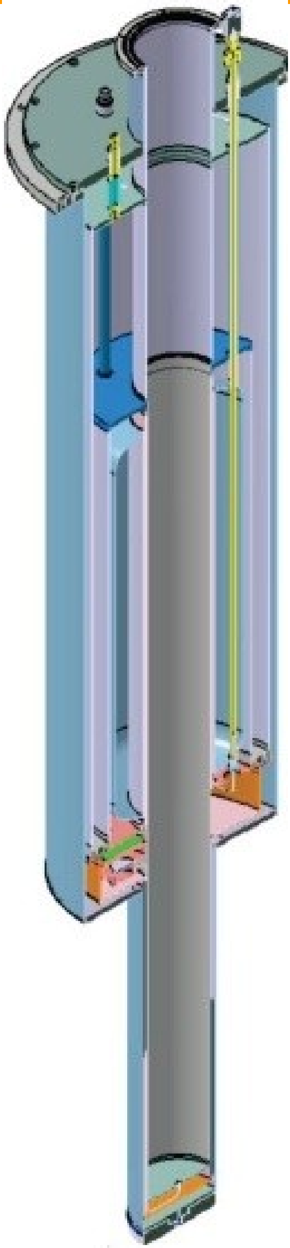


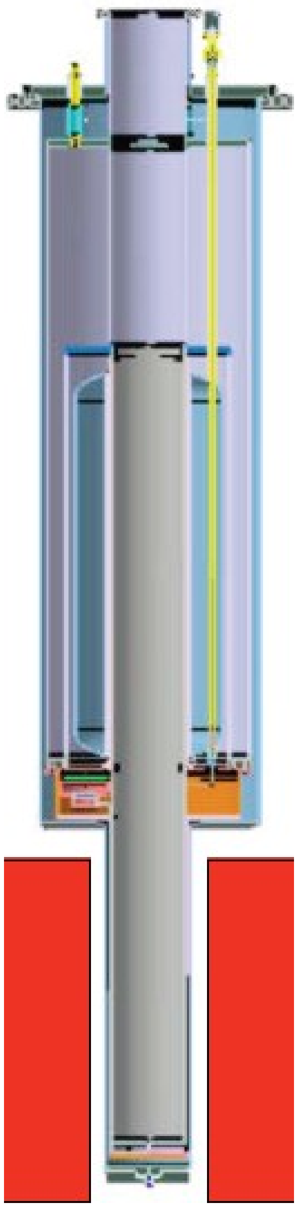
	Bi-2212	YBCO
+	Round wire (0.8 mm) High current cable	High Jc Mechanical stability
-	Mechanical performances Heat treatment	High current cable Length (hundreds of m)

Bi-2212 Nexans wire ϕ = 0.8 mm

Bi-2212
Nexans
OST

YBCO
SuperPower
AMSC





Undergoing Experiments :
Tests of HTS coils in high B : 2010/2012

Variable temperature cryostat for small coil

➔Operation planned for June 2010 at 20 T in 160 mm magnet

➔ Upgrade to 27 T when hybrid is completed (2013)

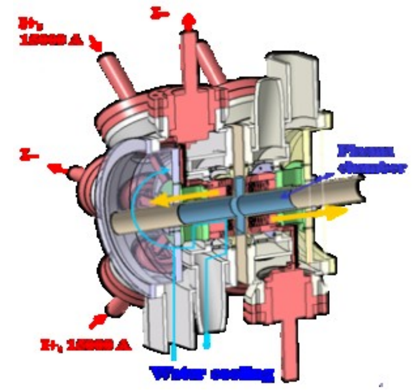
Small coils in high field environment

➔ Bi-2223 with a NIMS collaboration

➔YBCO and Bi-2212 (under fabrication)

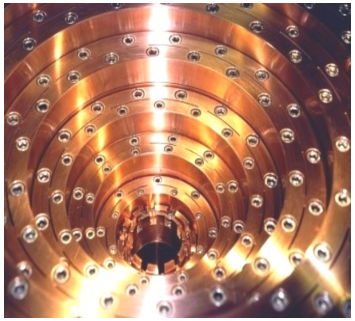
Small YBCO coil

To summarize

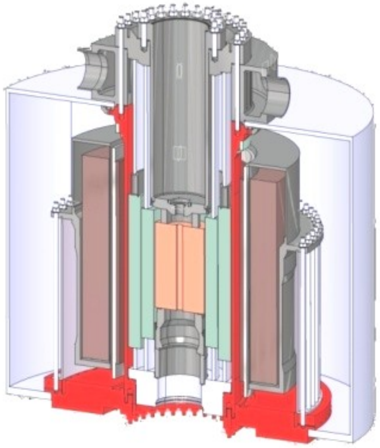


- Resistive technologies permit to developp and test complex magnetic configurations within relatively short time scale & with moderate investment (LPSC collaboration)
- High TS materials (BISCO, YBACUO, MgB2)
  - are now ready for industrial applications
  - are becoming attractice for high field magnetic structures.

(R& D projects, choice between Nb3Sn& HTS)



Visit on Thursday



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JM. Rey (CEA),
Pascal Tixador (INP-G), Jean-Paul Leggeri, Xavier Chaud, Frederic Hatanian, Christophe Trophime (CNRS)

…non exhaustiv list !