High magnetic fields for X ray and neutron scattering

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Why high magnetic fields?

How to generate high magnetic fields?

State of the art high field X ray/neutron scattering in high fields

Outlook

What I will not talk about

- The physics one can do using high magnetic fields
- Installations using commercial superconducting magnets

FAT SAM @ SNS
16 T, Nb_3Sn & NbTi

Why high magnetic fields ?

1) Manipulating matter: deflection
levitation
separation
alignment

‘engineering’

2) Probing matter: the field modifies electronic et magnetic properties:

Nuclear magnetic resonance (NMR, MRI)
cyclotron resonance, electron spin resonance (ESR)
(X)MCD, Hall effect, dHvA effect, SdH effect,….

‘materials science’

3) Thermo dynamics; Induce new states of matter:

Low T superconductor normal state
Field induced superconductivity
Quantum critical points
Magnetization plateau states
……………..

‘basic solid
state physics’

« High field »

16 Nobel prizes for magnetic field research

1 T

1902 Physics H.A. Lorentz & P. Zeeman: Magnetic effects on radiation

1922 Chemistry F. Aston: Mass spectrometer

1939 Physics E. Lawrence: Development of the cyclotron

1943 Physics O. Stern: Magnetic moment of the proton

1944 Physics I. Rabi: NMR of atoms and molecules

1952 Physics F. Bloch, E. Purcell: Condensed matter NMR

1955 Physics P. Kusch: Measurement of the electron magnetic moment

1970 Physics L. Neel: Anti-ferromagnetism, ferrimagnetism

1977 Physics Anderson, Mott, van Vleck: Magnetic and disordered systems

1985 Physics K. von Klitzing: Quantum Hall effect

1991 Chemistry R. Ernst: 2D and FT NMR

1998 Physics Laughlin, Stormer, Tsui: Fractional quantum Hall effect

2002 Chemistry K. Wuthrich: NMR of biological macromolecules

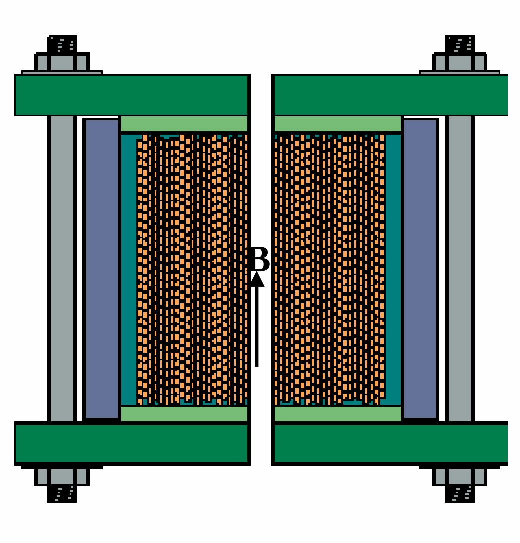
2003 Medecine P. Lauterbur, P. Mansfield: Magnetic resonance imaging

2007 Physics Fert & Grunberg, Giant magneto-resistance

2010 Physics, Geim & Novosolov, Electronic properties of graphene

30 T

How to generate high magnetic fields for general use?



One solution: circulate a current I in a coil:

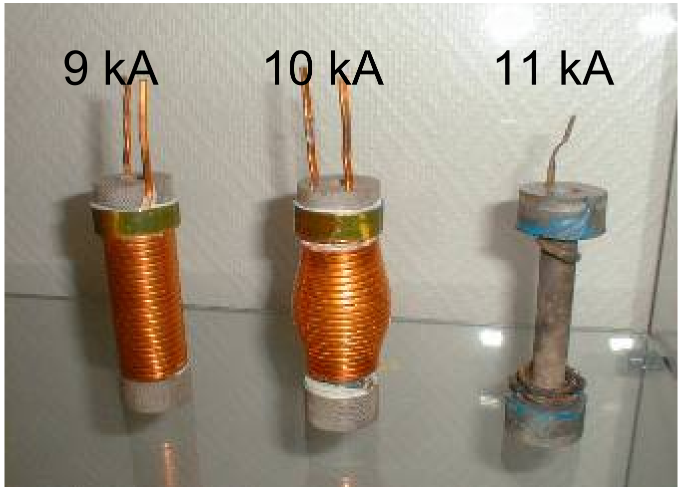
$$B \propto I$$

Problem 1: heating $P \propto RI^2 \propto B^2$

Solutions:
- superconductors $R = 0$ ($B < B_{crit}$)
- cooling: DC fields
- short current pulse (< 1 s): pulsed field

Problem 2: Lorentz forces $\propto \mathbf{B}\times\mathbf{I} \propto B^2$

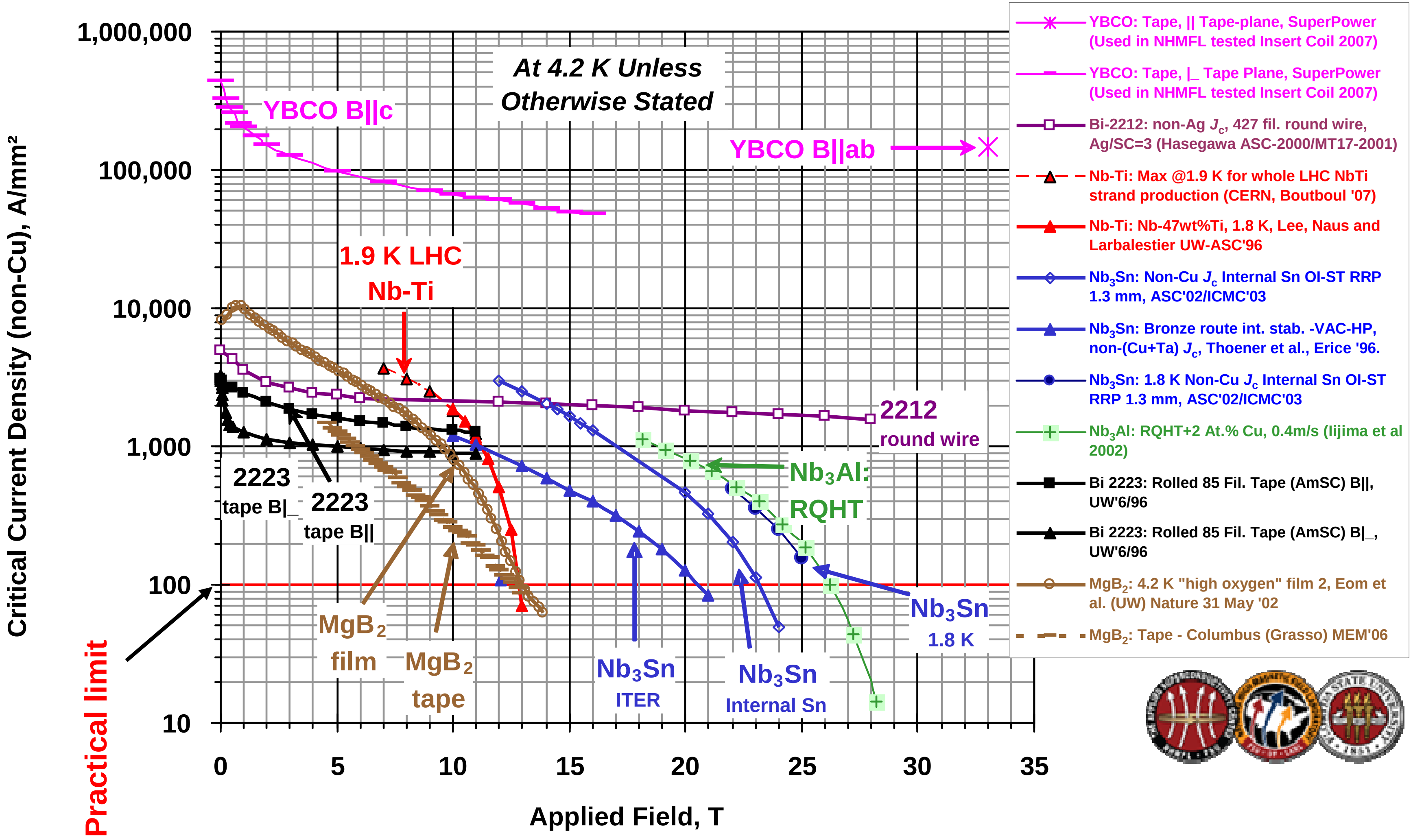
Solutions:
- strong conductor
- mecanical reinforcement



LNCMI

Why ‘resistive’ high magnetic fields?

Current maximum B_{crit} for ‘technical’ superconductors is 23 T!



Limitations of resistive magnets

Power/energy scaling (electrical and cooling):

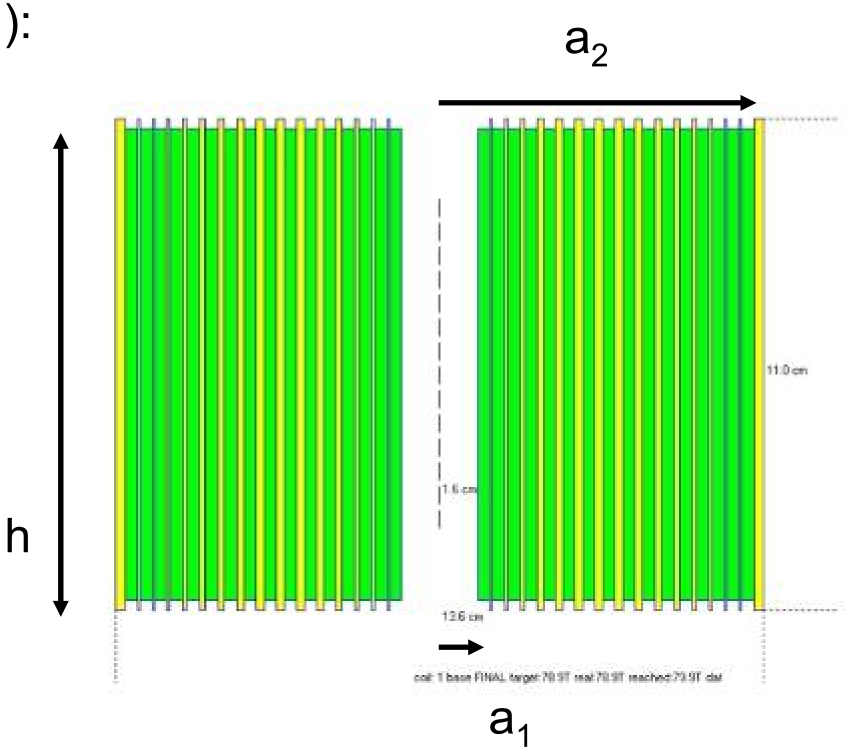
$$B \propto \sqrt{\frac{P}{\rho}} \approx \sqrt{\frac{E}{\rho\tau}}$$

Mechanical limit :

$$B_{\max} \approx \log\alpha \cdot \sqrt{\mu_0 \cdot \sigma_{\mathrm{UTS}} \cdot \lambda}$$

For Cu: $B_{max} \approx$ 35 Tesla

For steel $B_{max} \approx$ 110 Tesla



$$\alpha \equiv \frac{a_2}{a_1}, \quad \beta \equiv \frac{h}{a_1}$$

λ= wire filling factor

λ < 1 for cooling!

Pulsed high magnetic fields

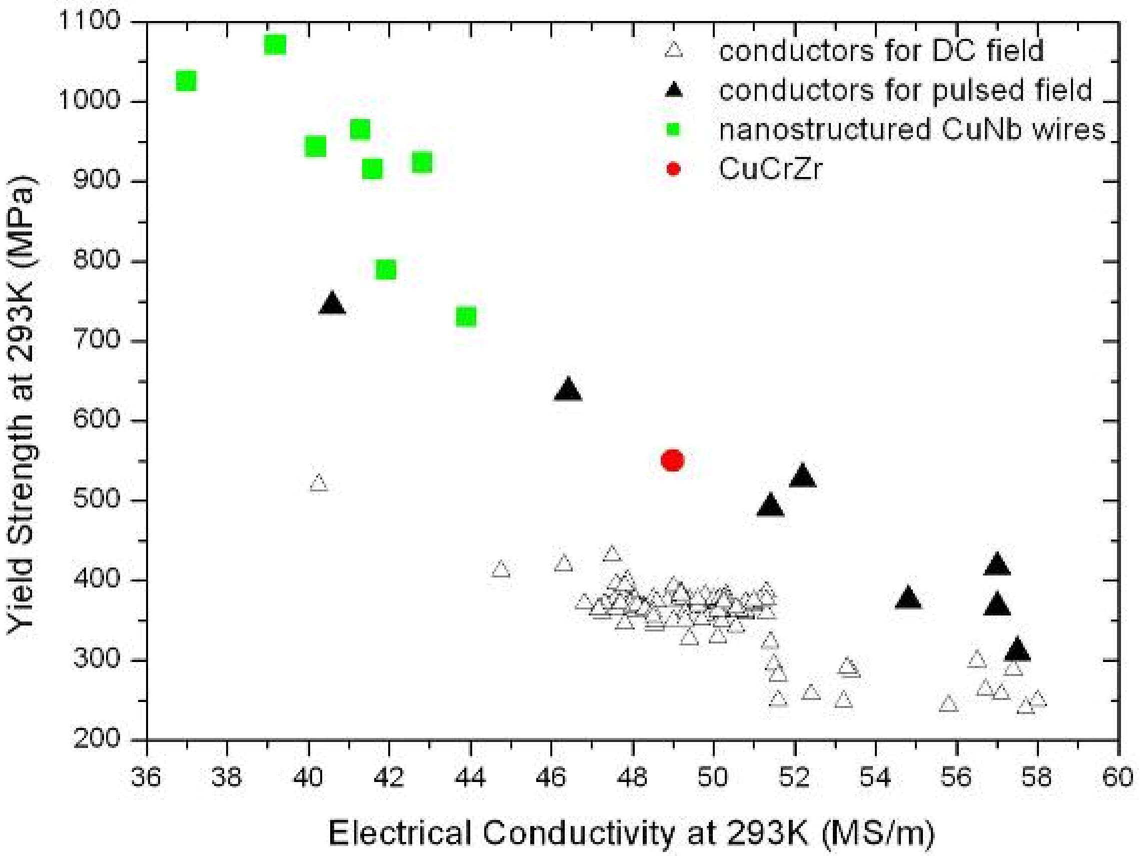
- High magnetic field generation is limited by thermal and mechanical constraints

- By pulsing the field, one is freed from the thermal constraints and has larger design freedom.

-For pulsed fields, $\mathbf{B_{max}}$ is basically limited by the ultimate tensile strength of the conductor. For a given field, the maximum **pulse duration** is determined by the electrical conductivity of the wire, the heat capacity of the coil and the electrical energy available.

- The maximum **duty cycle** depends on the cooling power and the *average* power supply

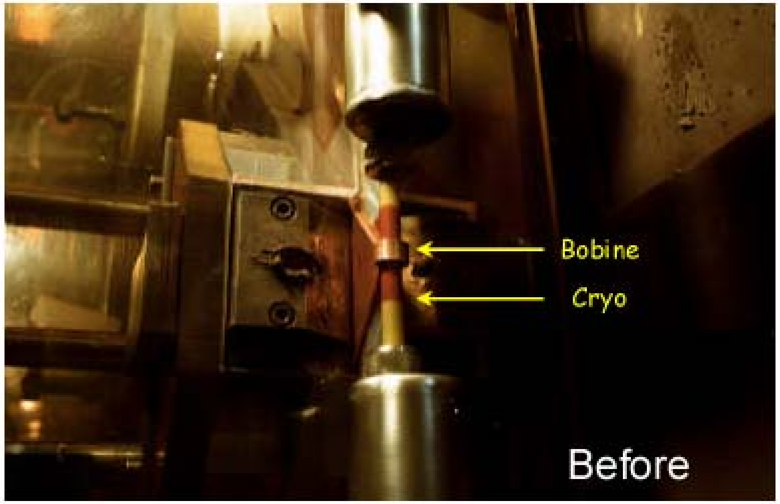
Magnet materials: trade-off strength vs. conductivity

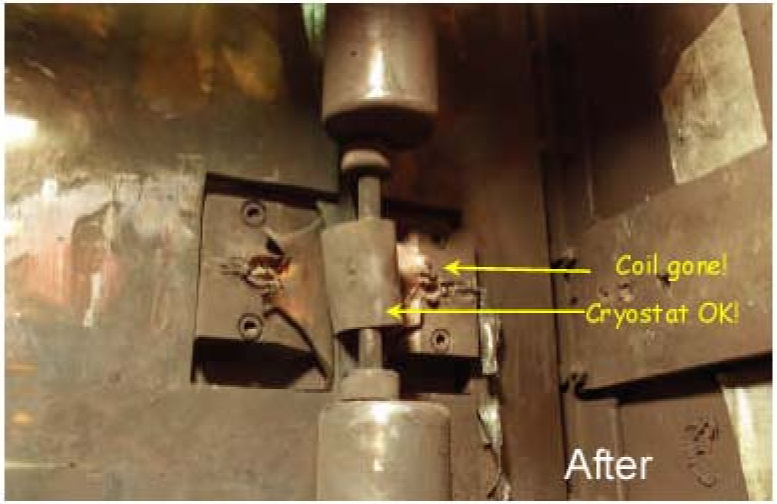


LNCMI

Single shot, destructive pulsed magnetic field generation LNCMI

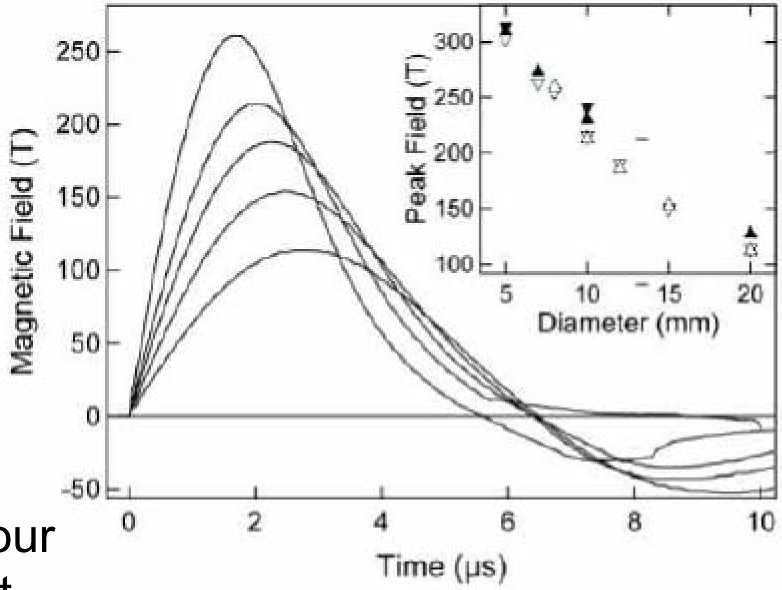
Single turn single shot installation (previously at Humboldt University);



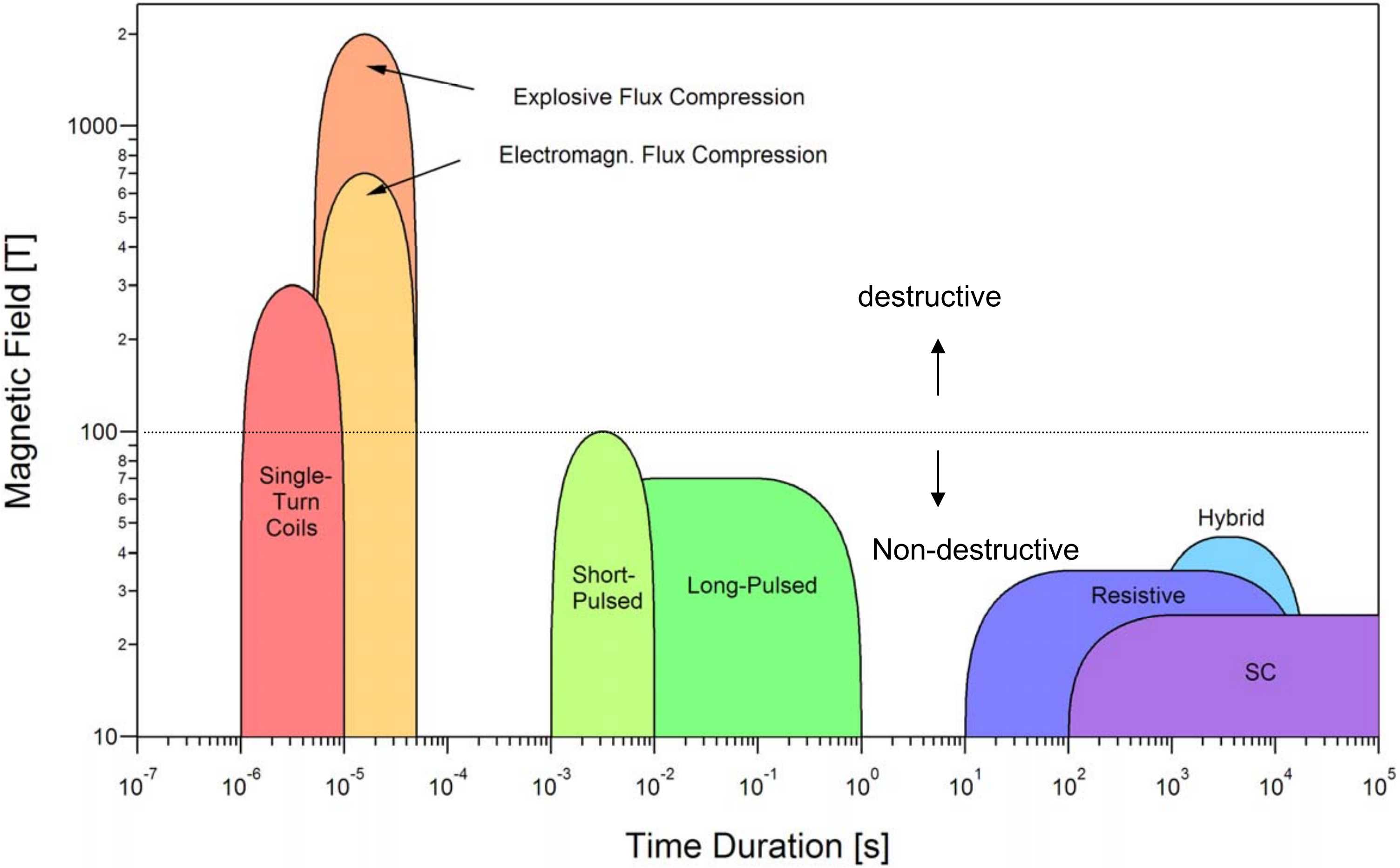


2 MA, 60 kV

1 shot/hour
10 €/shot

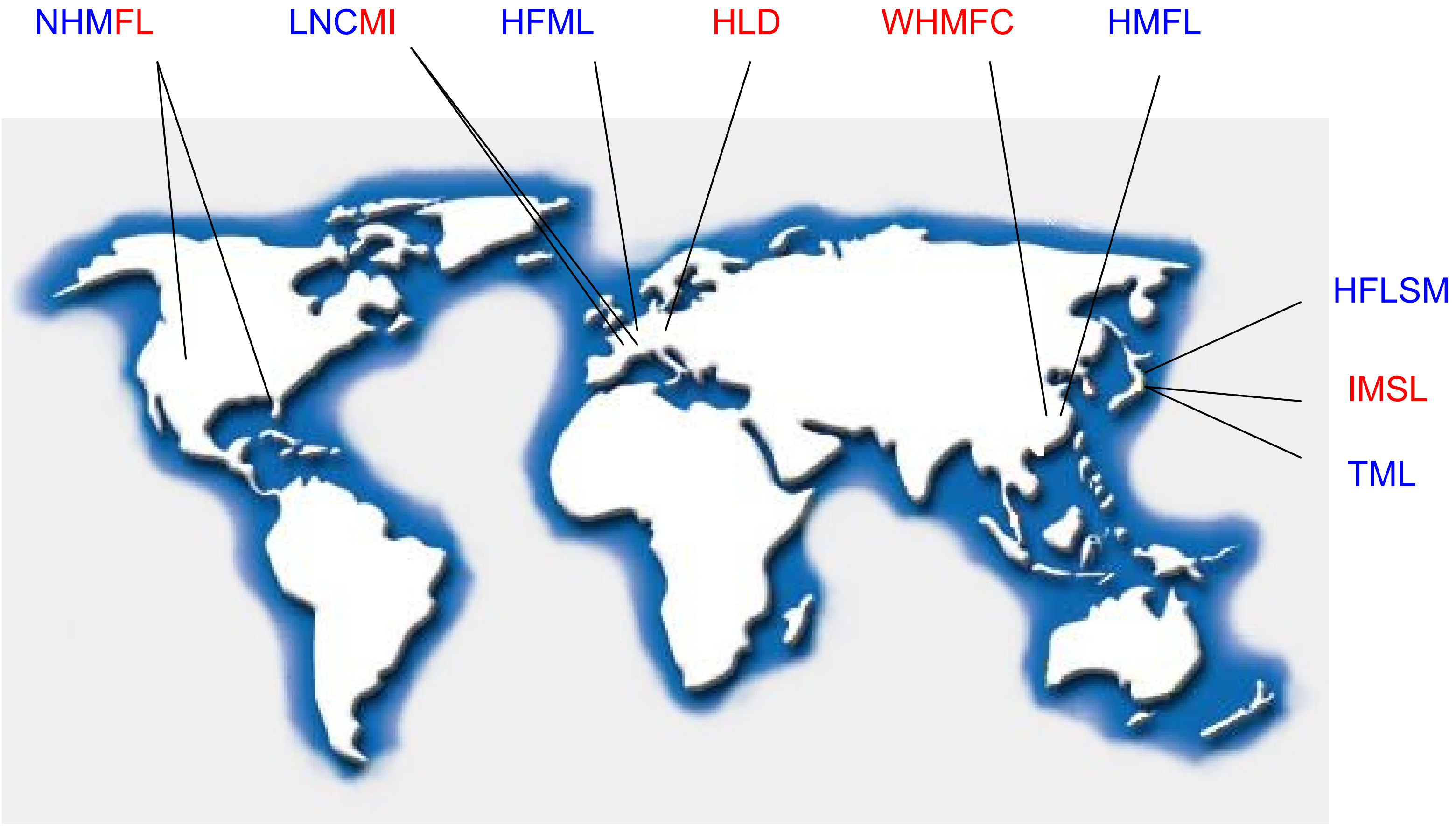


Summary of magnetic fields for research



LNCMI

Large high magnetic field facilities (pulsed and DC)



NHMFL

LNCMI

HFML

HLD

WHMFC

HMFL

HFLSM

IMSL

TML

National High Magnetic Field Laboratory

Pulsed Magnetic Field Facility

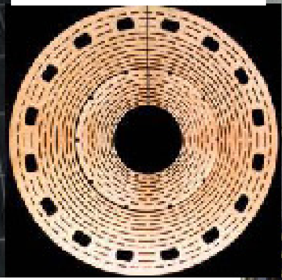
100 T Pulsed Magnet
10msec
15mm bore

Florida State University

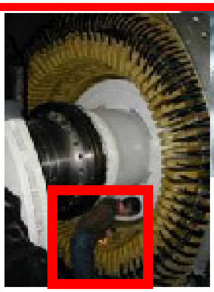
Los Alamos National Laboratory

University of Florida

45T Hybrid DC Magnet

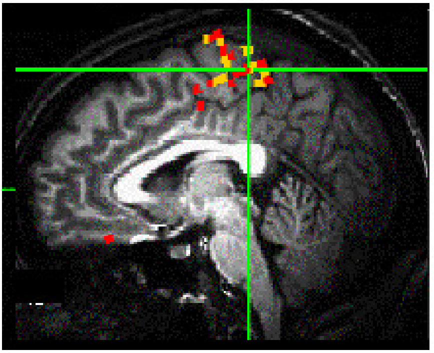


1.4GW Motor-Generator



11.4T MRI Magnet
400mm warm bore

Advanced Magnetic Resonance Imaging and Spectroscopy Facility



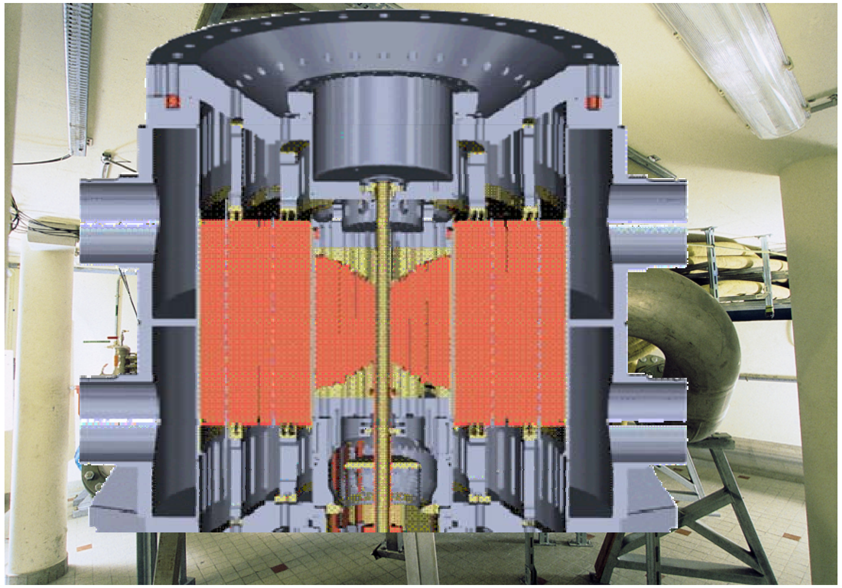
High B/T Facility
17T, 6weeks at 1mK

900MHz, 105mm bore NMR/MRI Magnet

DC field installation LNCMI Grenoble

24 MW

300 l/s



↓

35 Tesla

HLD: the world's largest high field capacitor bank : 50 MJ, 5 GW

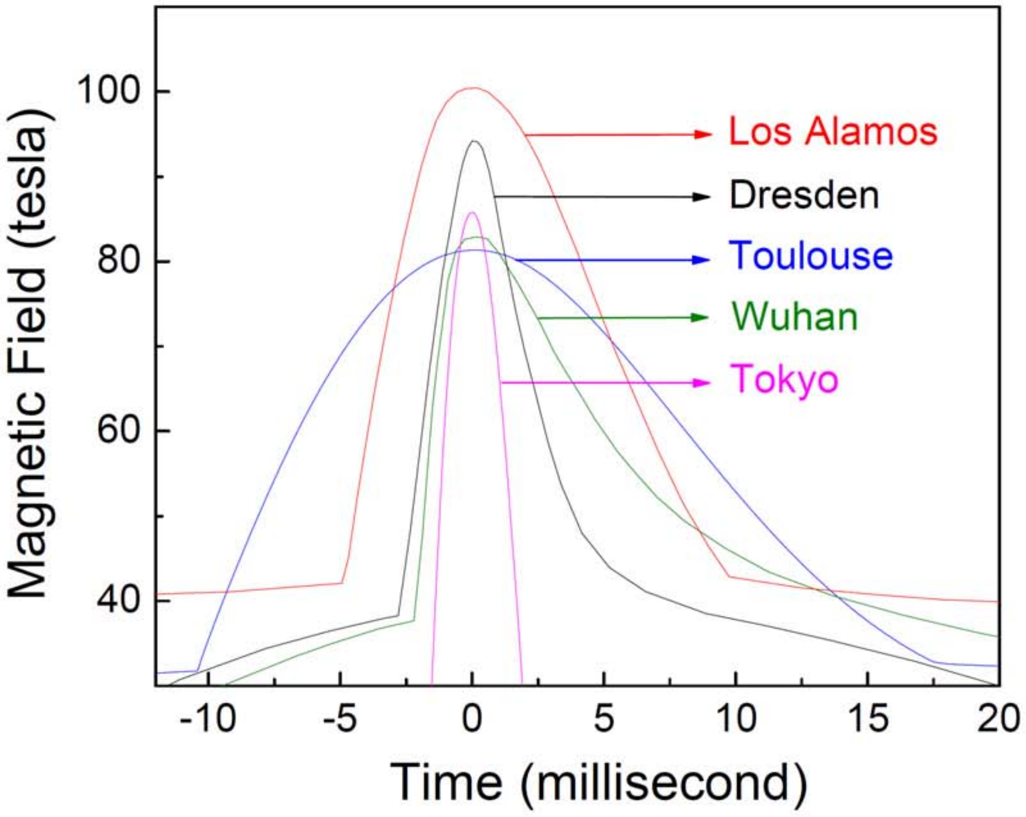
Technical state of the art

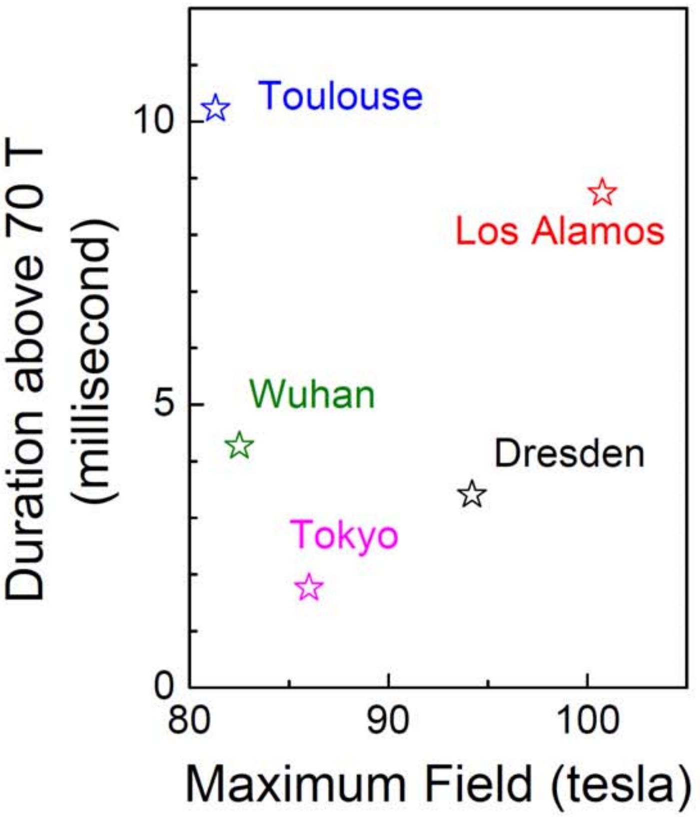
DC magnets: USA: 45,5 T (NHMFL, hybrid*)
Japan: 38,9 T (TML, hybrid)
Europe: 35 T (LNCMI, 43 T hybrid under construction)

Pulsed magnets: USA: 100,7 T (NHMFL)
Europe: 95 T (HLD)
Japan: 86 T (ISSP)
China: 85 T (WHMFC)
France: 82 T (LNCMI)

(**hybrid*: resistive inner coil, superconducting outer coil)

Size versus stamina





Experimental complications (pick-up, eddy currents) $\propto (\partial B/\partial t)^2$

Signal-to-noise scales with (pulse duration)$^{1/2}$

The European players

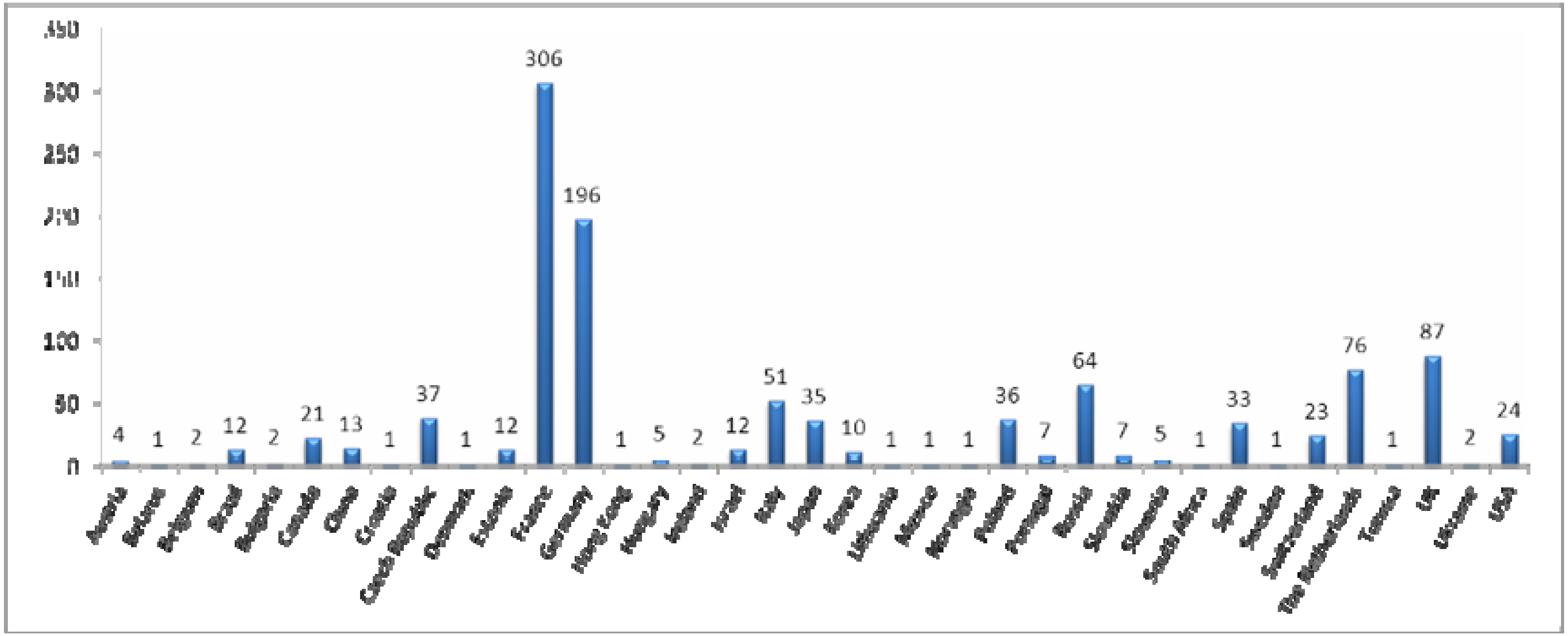
HLD Dresden

HFML Nijmegen

LNCMI Toulouse

LNCMI Grenoble

EuroMagNET2: joint user acces program LNCMI-HLD-HFML



2009-2012: 1100 access requests

Project ESFRI ‘ European Magnetic Field Laboratory’ (EMFL)

Ultimate aim: offer European scientists the same possibilities as in the USA

- Improve the efficiency of the 4 European facilities (LNCMI-G&T, HLD, HFML) through collaboration, specialization and coordination.

- Increase the financial and human resources of the 4 European infrastructures

The EMFL FP7 Preparatory Phase Project:

Identify legal and governance structure

Funding of investments and operation, staffing

Extension of the EMFL with other partners

Roadmap for the technical and scientific evolution of the EMFL

Prototyping of new magnets/equipment

……..

EMFL

European Magnetic Field Laboratory

↓

Ready-to-sign founding contract

(Starting date 1/1/2011, duration 3 years)

LNCMI

State of the art high field X ray/neutron scattering in high fields

Specificity of all scattering experiments

Acces for incoming and outgoing beam

Relative orientation $\mathbf{k}_i$, $\mathbf{k}_o$, and $\mathbf{B}$

Sensitive to vibrations

Specificity of neutron scattering experiments

Large sample volumes → Huge magnets or low fields

Long data acquisition times → Pulsed fields of limited use

Long data acquisition times → Huge electricity bill for resistive magnets

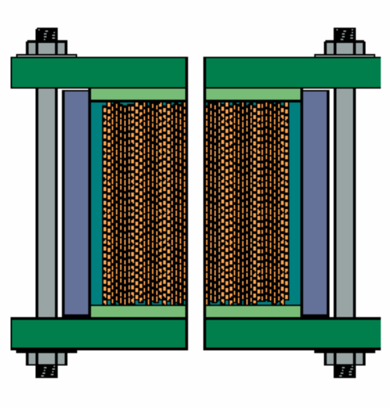
Magnet geometry and its limitations

1) $\mathbf{k}_i \parallel \mathbf{k}_o \parallel \mathbf{B}$ (eg. XMCD, SAXS, SANS): standard solenoid, $B_{max} = B_{uts}$

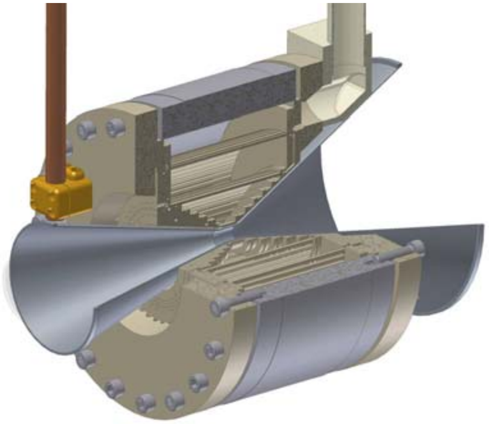
2) $\angle(\mathbf{B}, \mathbf{k}_o), \angle(\mathbf{B}, \mathbf{k}_i) < 30°$(eg. MAXS): conical solenoid, $B_{max} \approx 0{,}9\, B_{uts}$

3) $\mathbf{k}_o \perp \mathbf{B}, \mathbf{k}_i \perp \mathbf{B}$: split coil, $B_{max} \approx 0{,}7\, B_{uts}$

4) Any other geometry: difficult, $B_{max} \leq 0{,}5\, B_{uts}$??



1)



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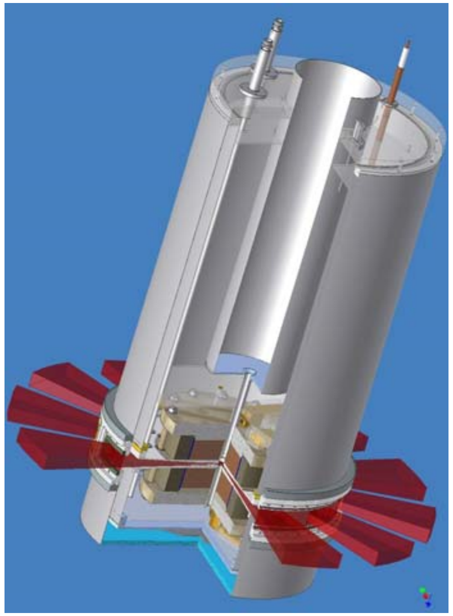
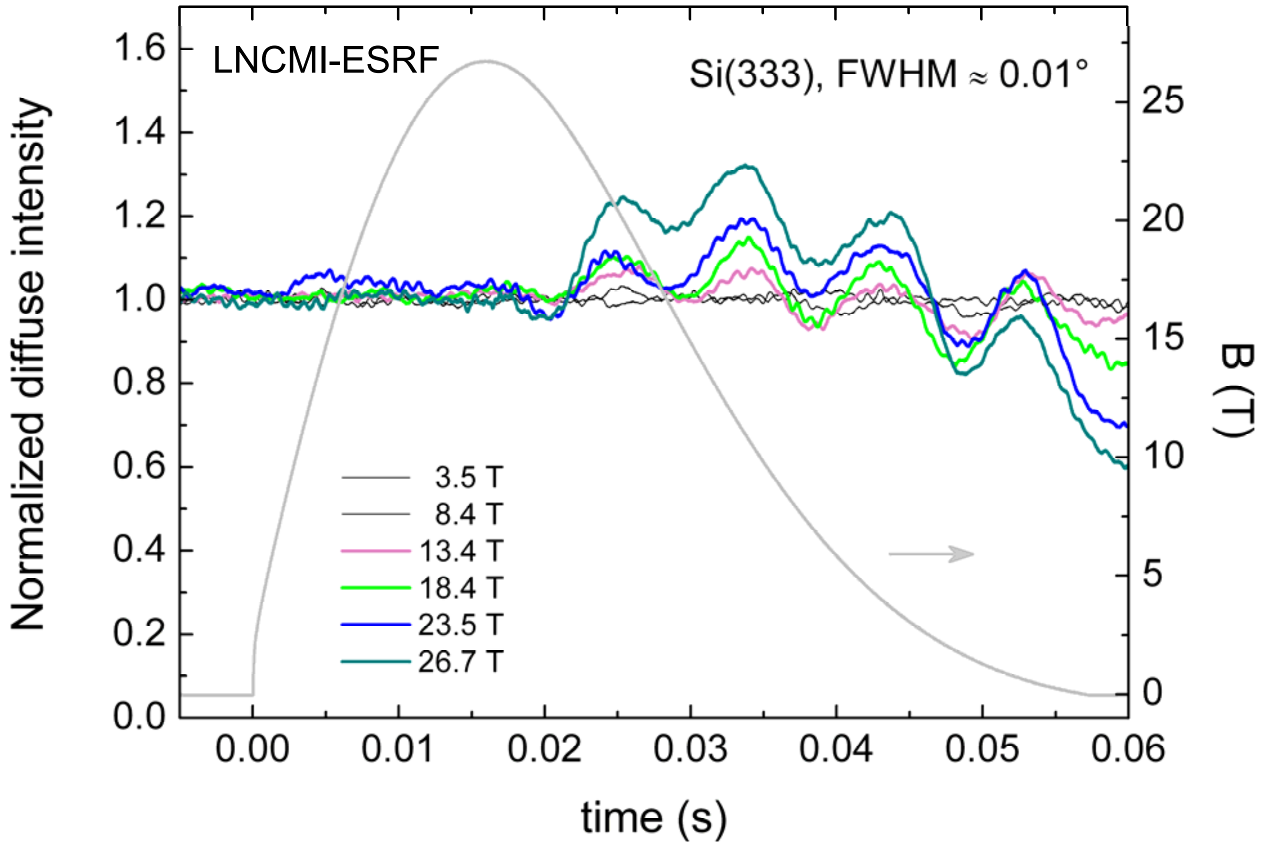


3)

Vibration sensitivity

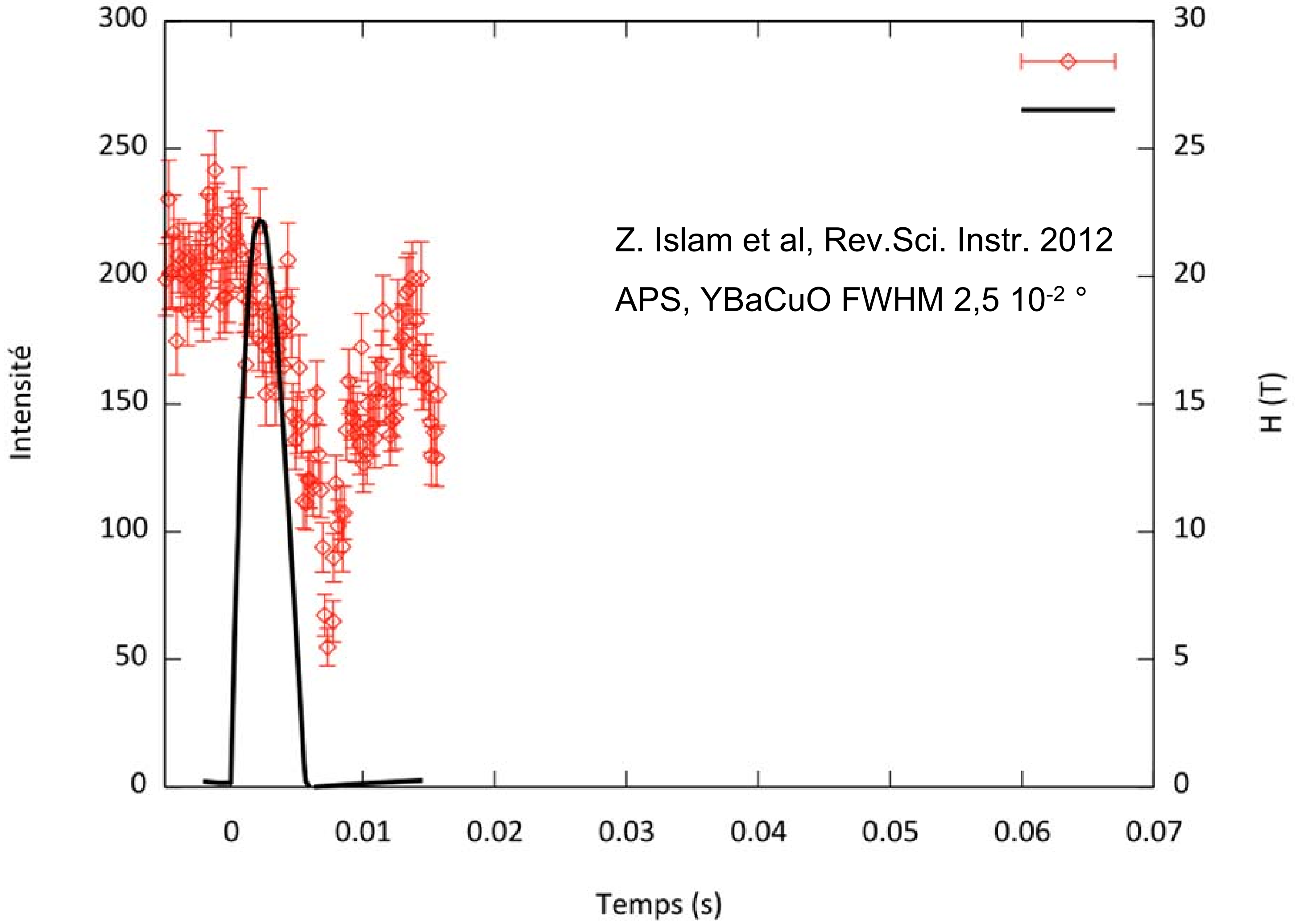
-Cooling water vibrations for resistive magnets: under control

-Coil vibrations for pulsed magnets: getting better



Alternative strategie for vibration « control »

Short pulses: measurement is over before any vibration hits the sample!

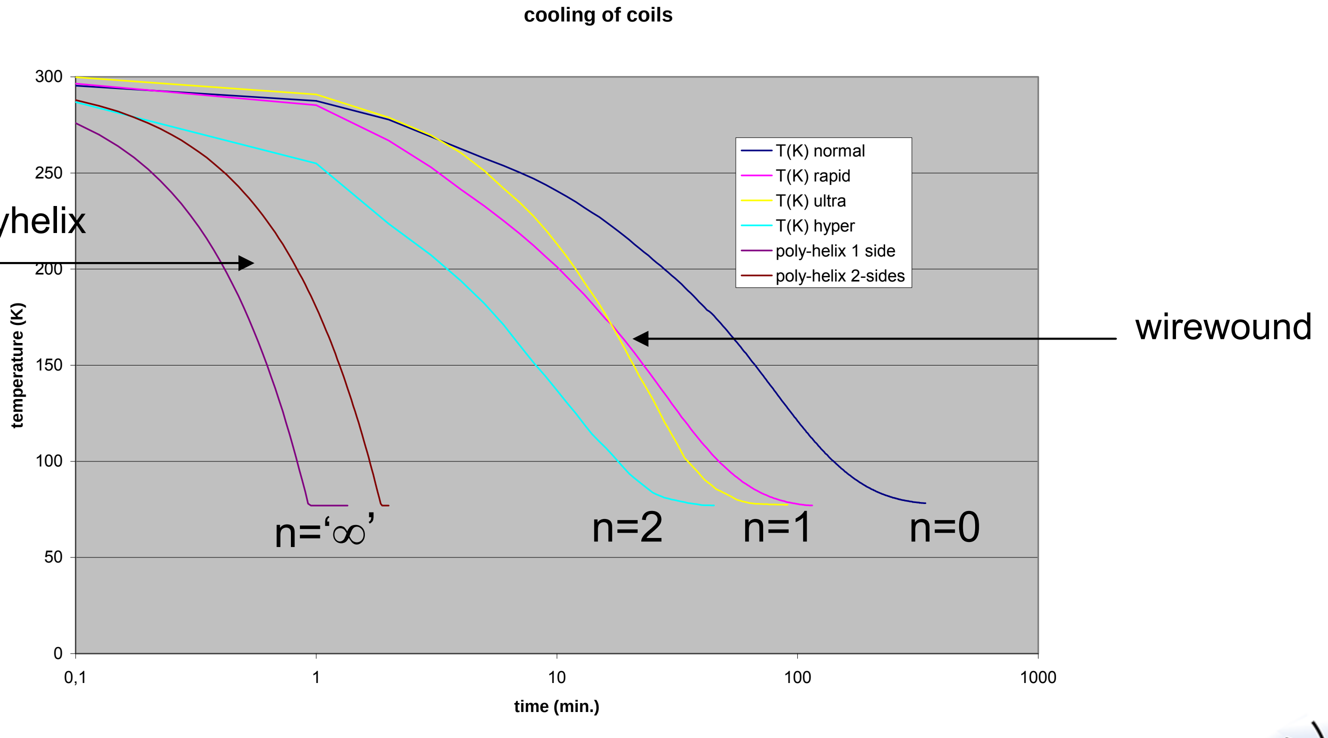


Z. Islam et al, Rev.Sci. Instr. 2012

APS, YBaCuO FWHM 2,5 10^{-2} °

Duty cycle of pulsed fields

- Duty cycle of standard pulsed magnets ≈ 10^{-5} , too low for many experiments!
- Duty cycle is limited by cooling rate at low values, and by *average* power at high values
- Increase duty cycle by introducing cooling *n* channels; gain $(n+1)^2$



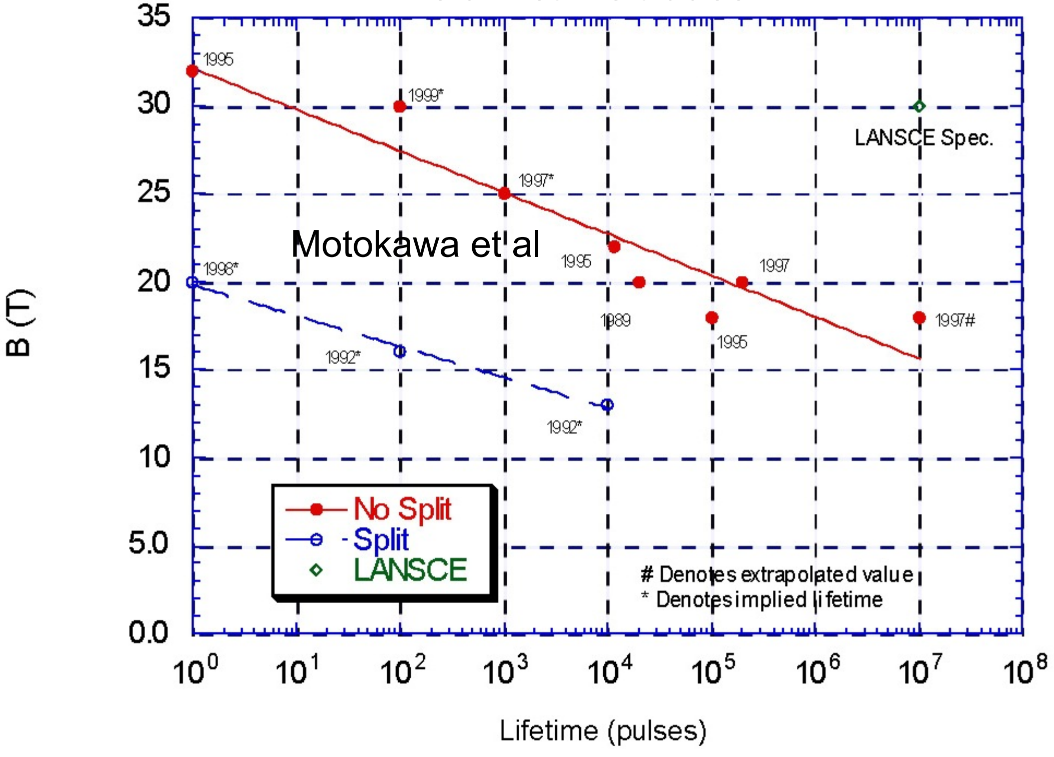
Magnet lifetime issues

Because of the large stresses, the lifetime of a resistive/pulsed magnet is finite

DC resistive magnets have lifetimes of several 1000 hours, and a soft failure mode (resistance increase, noise, field factor reduction)

Pulsed magnets have typical lifetimes of 500 shots at 95% of the design field. Lifetime seems independent of pulse duration. Failure mode is usually soft, but sometimes violent.

Field-lifetime tradeoff!

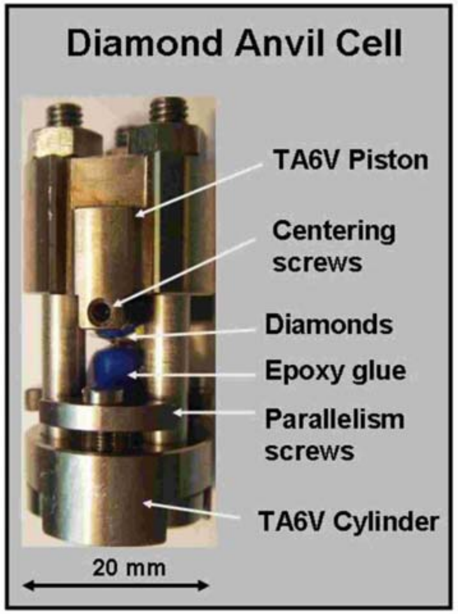


1 Hz LANSCE design

Sample environment

Resistive magnets offer almost the same possibilities in terms of high pressure, low temperatures as SC magnets. Only T < 30 mK is difficult because of field noise.

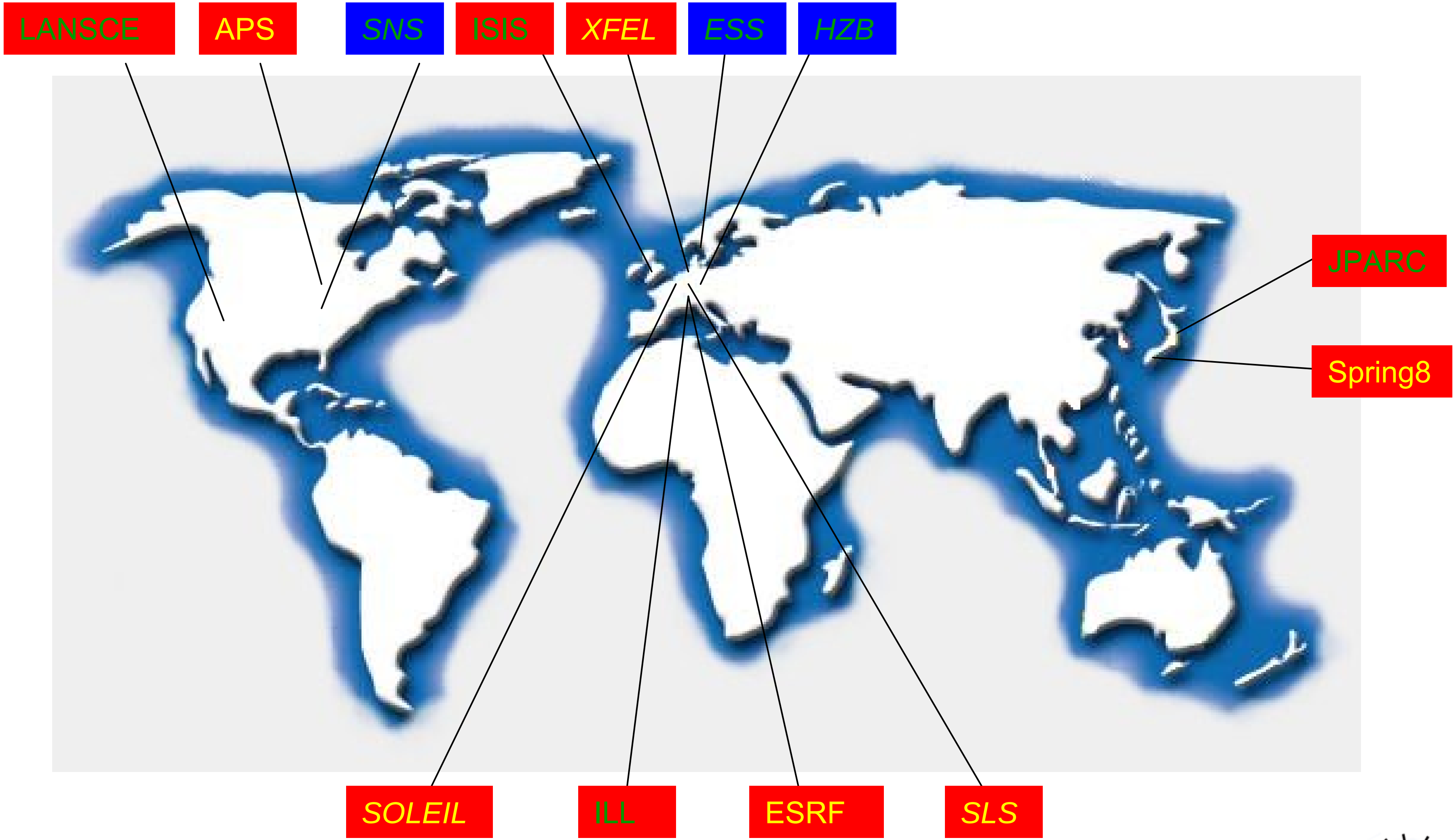
Pulsed magnets are somewhat more limiting; temperatures down to 50 mK and pressures up to 10 GPa have been realised in 60 T solenoids.



10 GPa DAC, 60 T

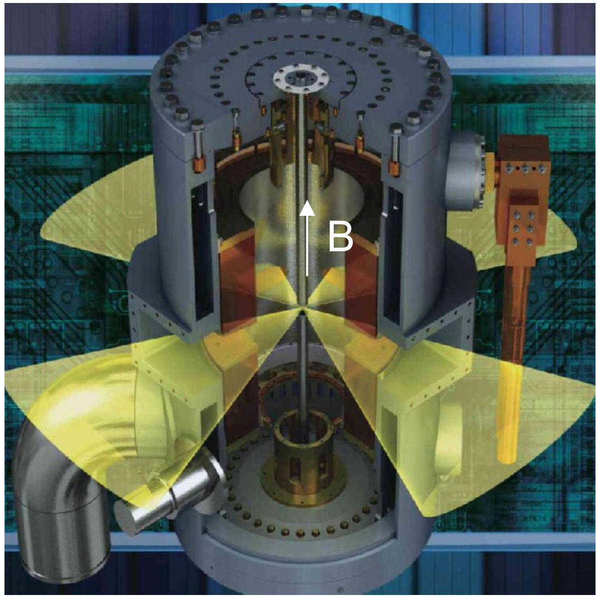
(Millot et al, High Pressure Research 28, 627 (2008))

X ray and neutron sources with DC or pulsed high field activities/*projects*



LNCMI

NHMFL-Tallahassee scattering magnet

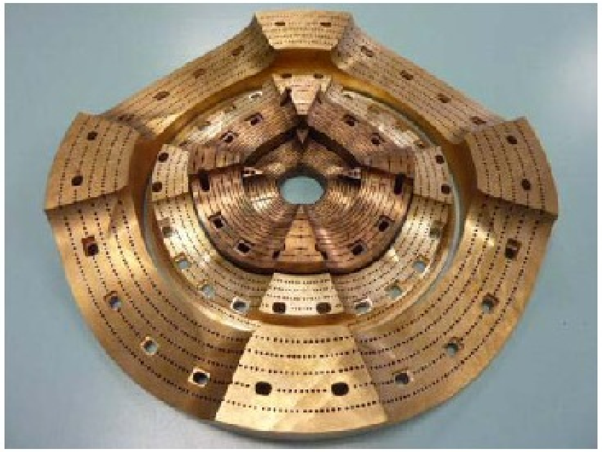


25T, 28 MW split coil

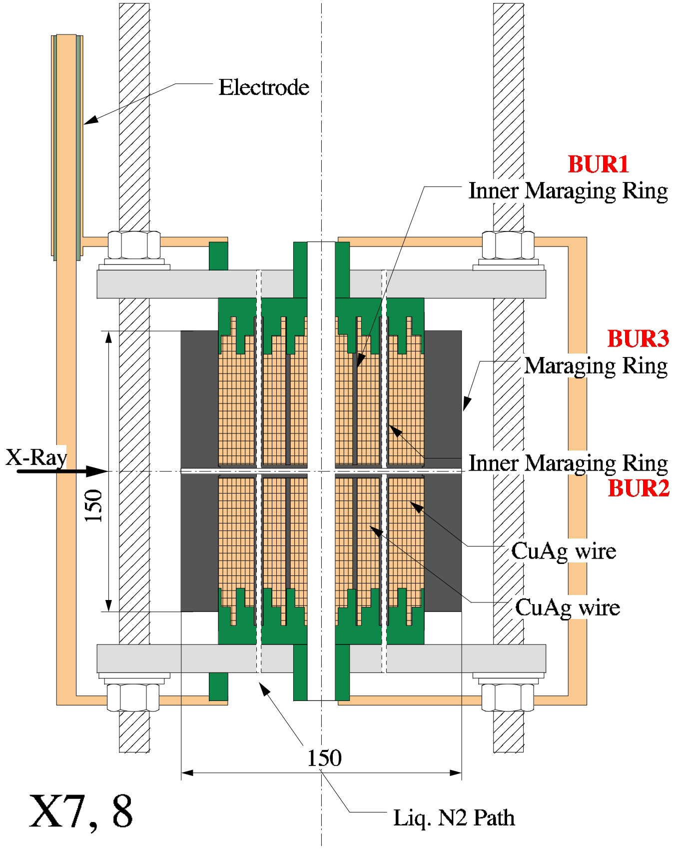
Operational since june 2011

4 x 45° x 10° ports

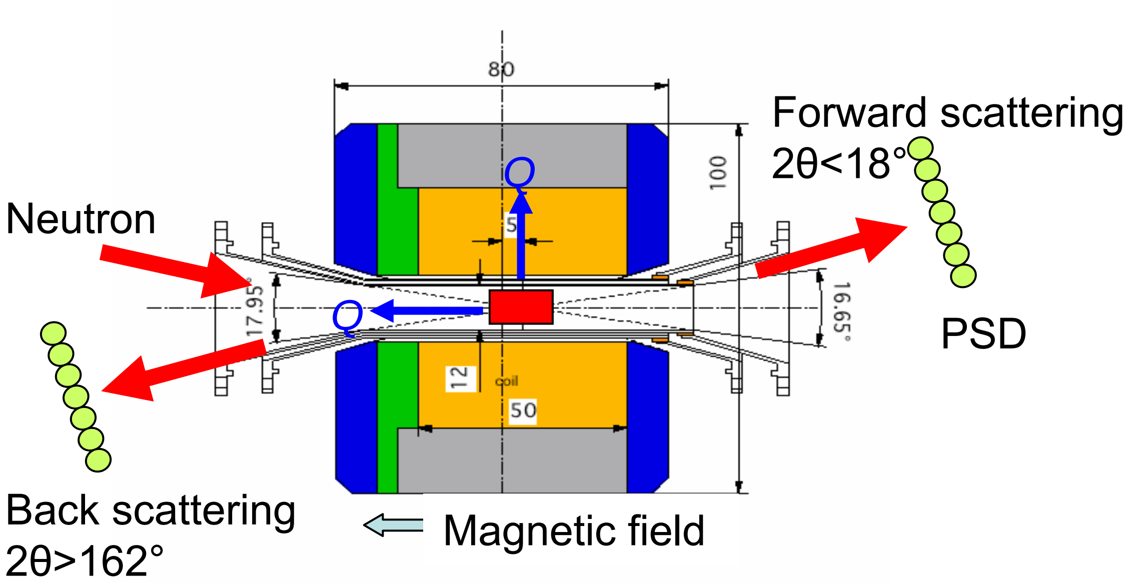
However, no X rays, no neutrons!



IMSL scattering magnets used at Spring 8 and JPARC



40 T, rapid cooling split coil



40 T, small angle scattering magnet

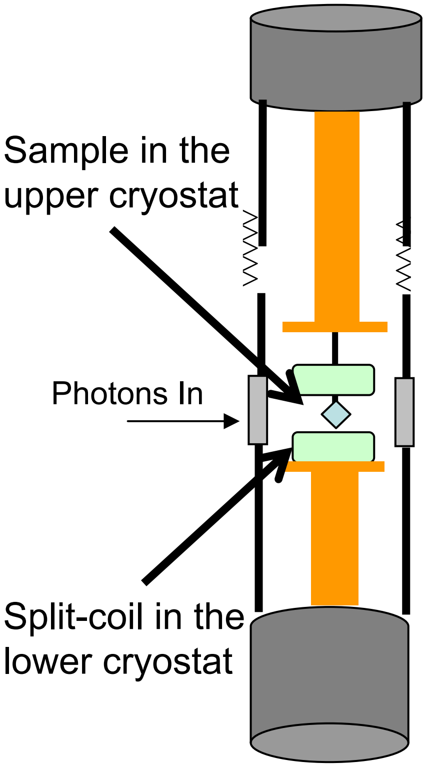
The University of Tokyo
The Institute for
Solid State Physics

(courtesy of prof. K. Kindo)

APS scattering magnets

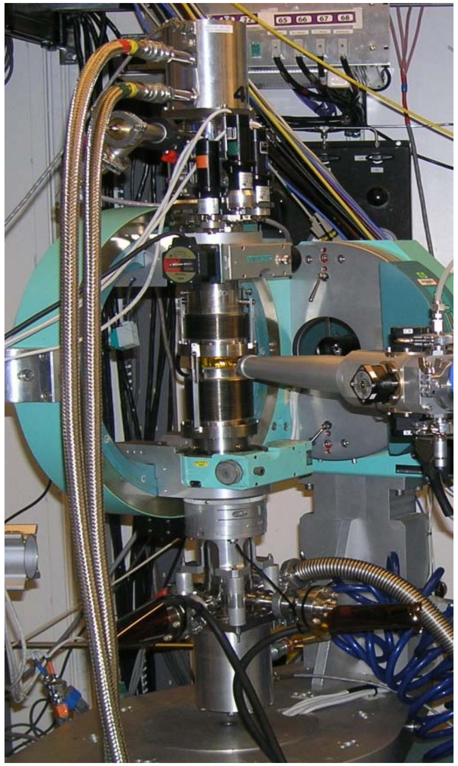
30T pulsed split-pair dual-cryostat magnet

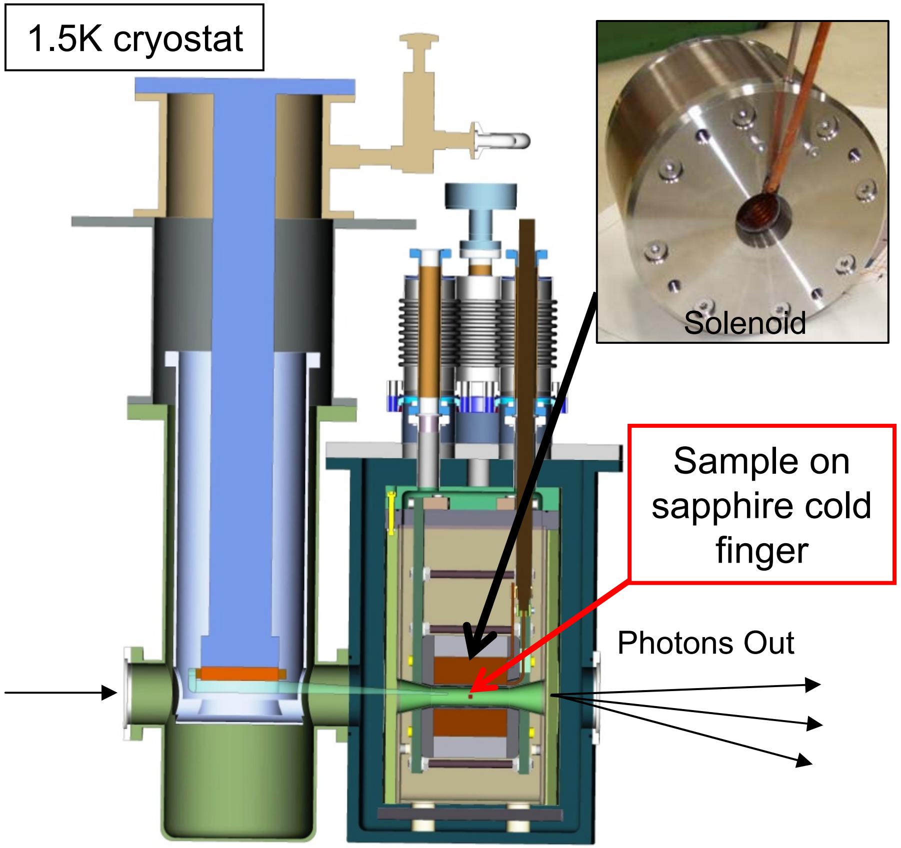
30T solenoid for single-crystal diffraction


Sample in the upper cryostat

Photons In

Split-coil in the lower cryostat




1.5K cryostat

Solenoid

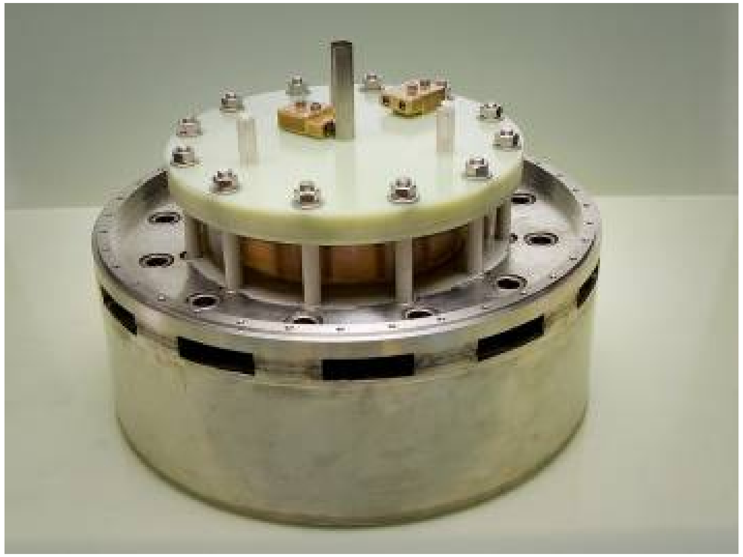
Sample on sapphire cold finger

Photons Out

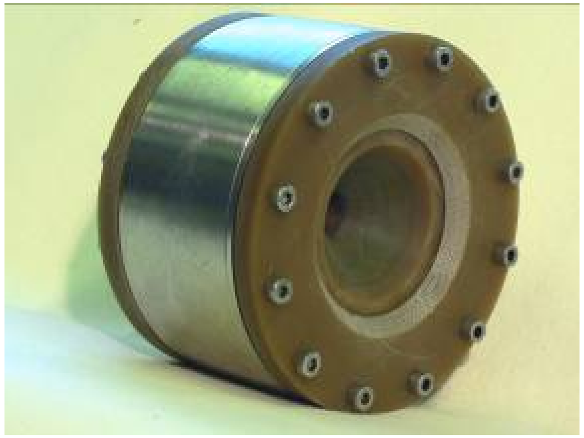
Developped in collaboration with prof. Nojiri (IMR-Tohoku)

Courtesy of dr. Z. Islam - APS

LNCMI scattering magnets used at ILL, ESRF, *SLS, SOLEIL*

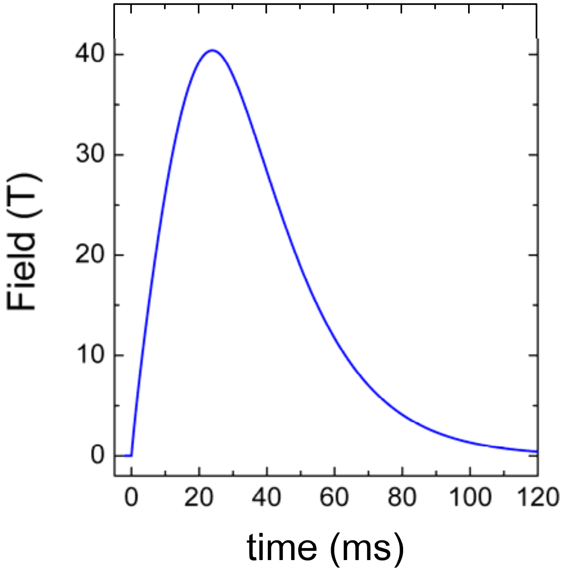


30 T split coil



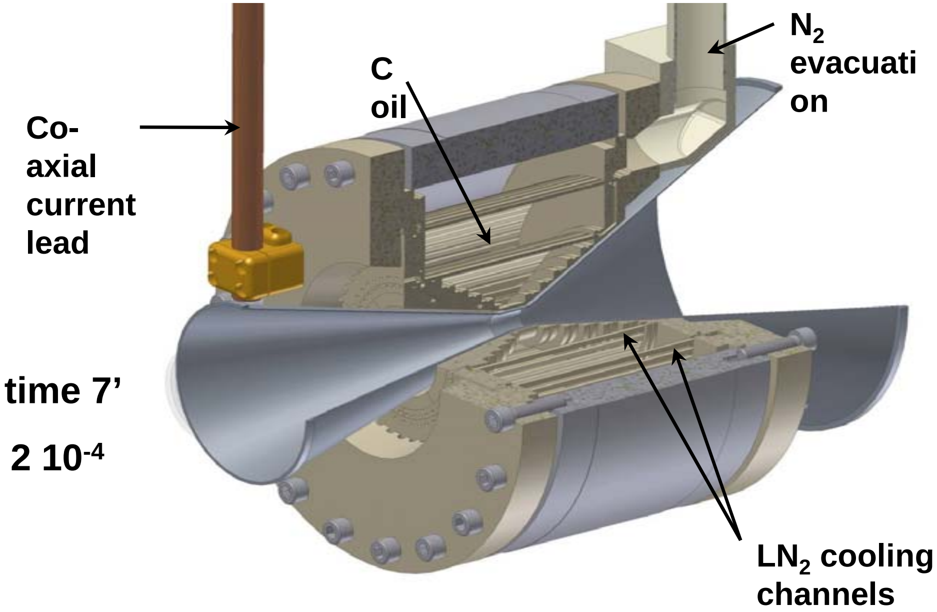
30 T WAXS coil, > 750 shots!

40 T long pulse rapid cooling



Cooldown time 7'

Duty cycle 2 10^{-4}



Co-axial current lead

Coil

N_2 evacuation

LN_2 cooling channels

Other scattering magnets

IMR-Tohoku pulsed magnets; H. Nojiri, next speaker

ESRF pulsed field system; C. Strohm, Thursday 9h45

HZB series connected hybrid; A. Tennant, Thursday 11h

ISIS pulsed field system; P. Manuel, Thursday 15h

LNCMI

Outlook for X ray and neutron scattering in high magnetic fields

Magnet side:

High Tc superconducting magnets

Resistive magnets

Hybrid magnets

Pulsed magnets

Beam side:

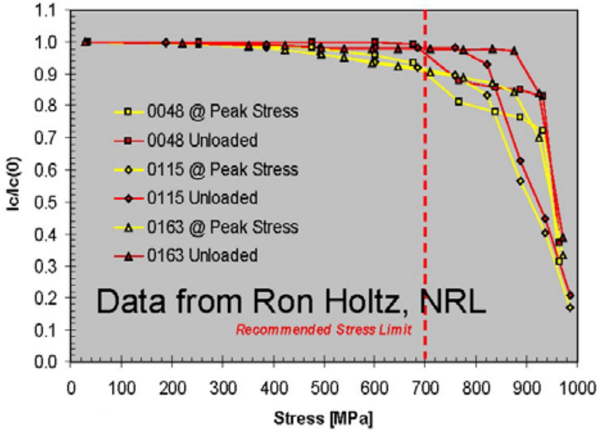
Adapted beam optics, instrumentation and detectors

LNCMI

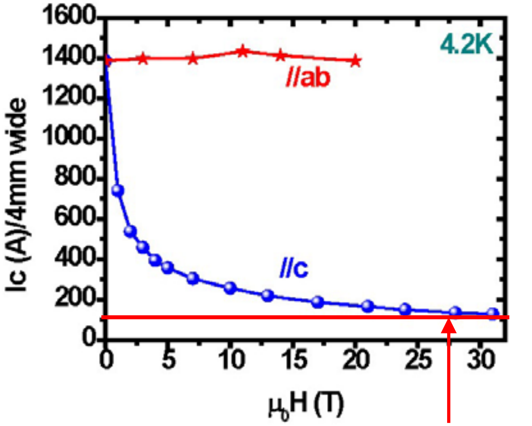
High T_c superconducting magnets

Commercial HTc cables are now available:

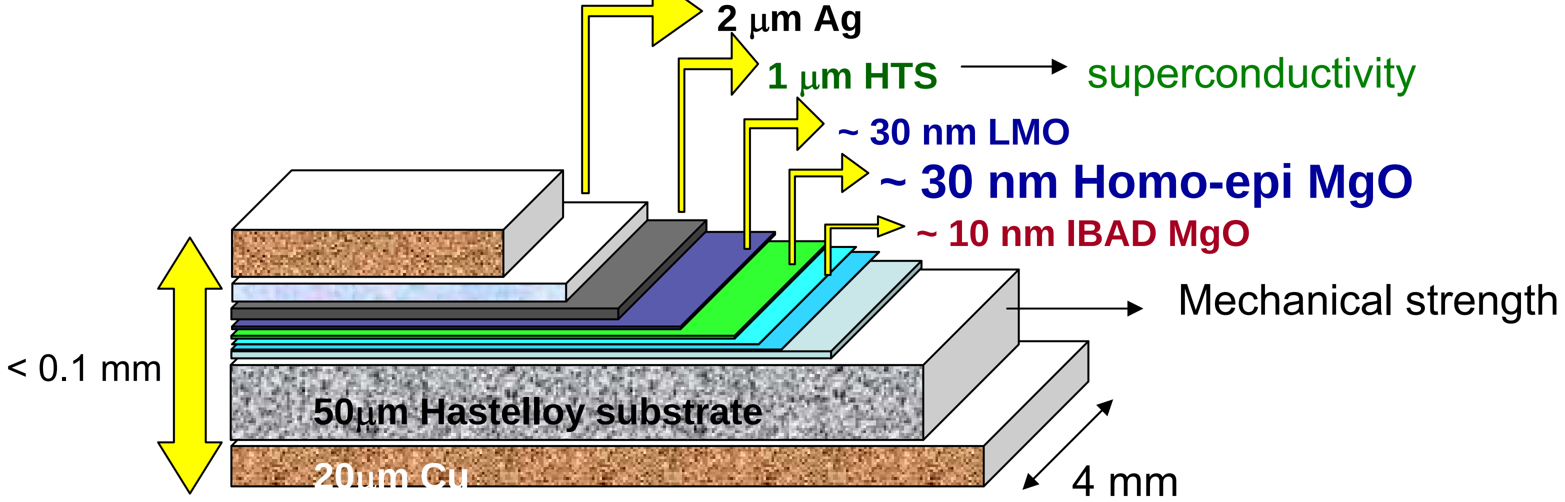
Superpower SCS4050



Data from Ron Holtz, NRL



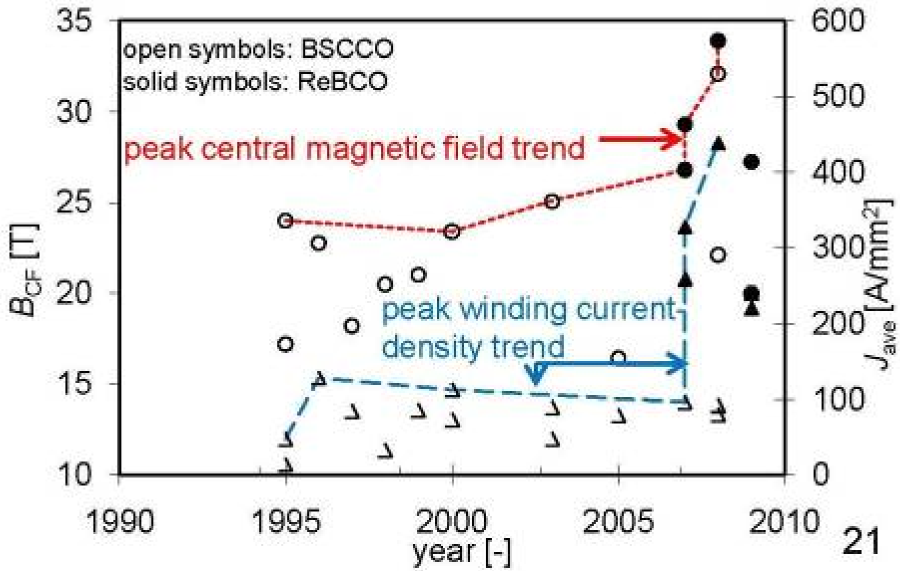
Practical limit



- High price (100 €/m)
- Moderate UTS: 700 MPa for YBaCuO tapes, much less for BiScO wire
- Limited availability
- Quench protection problematic

State of the art high T_c superconductor prototype

Progress HT_c insert coils



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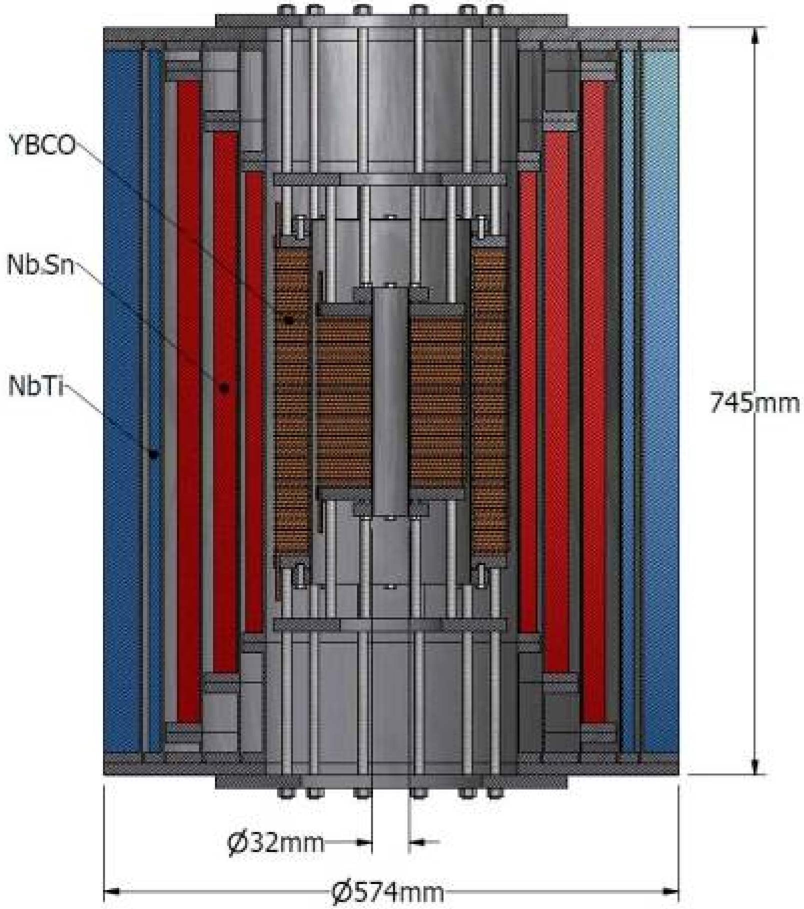
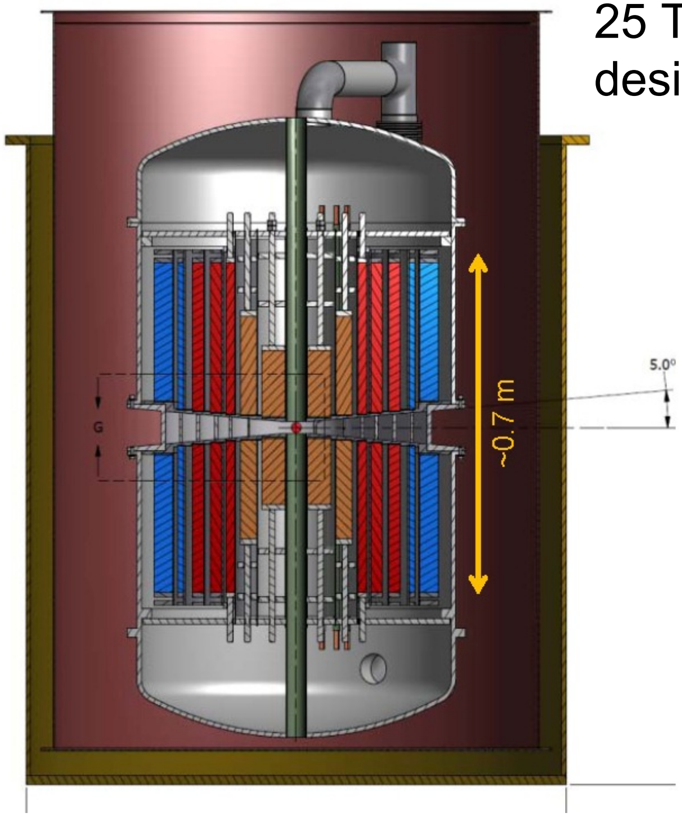
NHMFL 32 T HT_c magnet project

4 M€, 4 years development

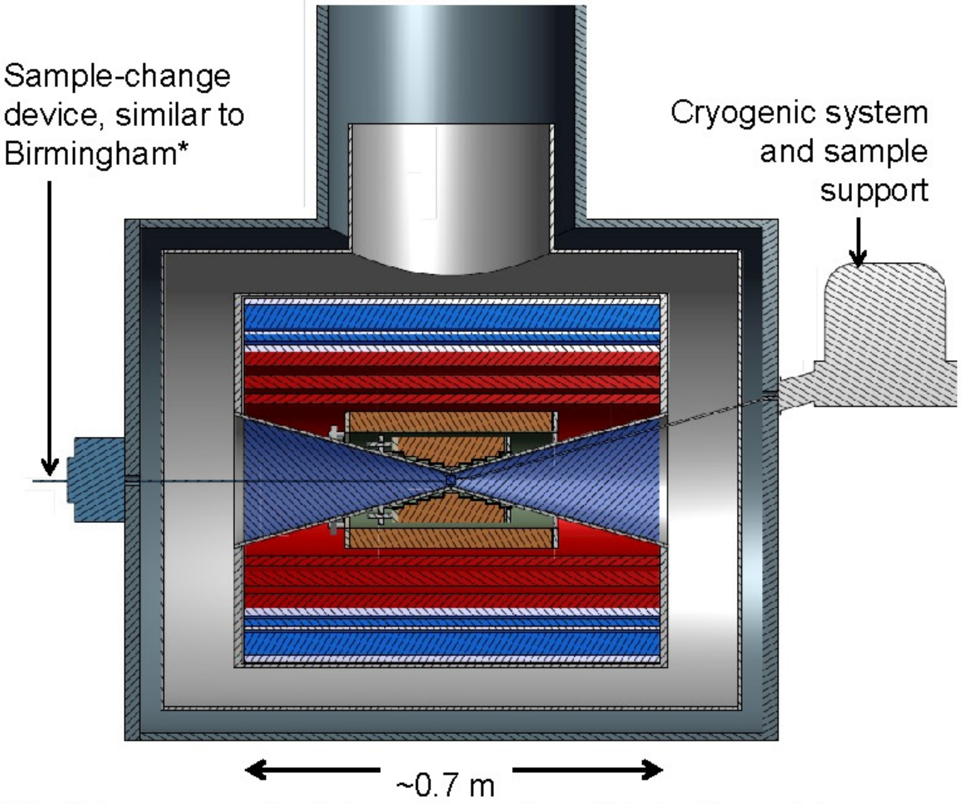


User magnet operationnal 2014!

And more to come:



25 T HTc split coil design



*Alex Holmes, presented at *Status and Perspectives of Neutron Research in High Magnetic Fields*, HZB, Berlin, Germany, March 2011.

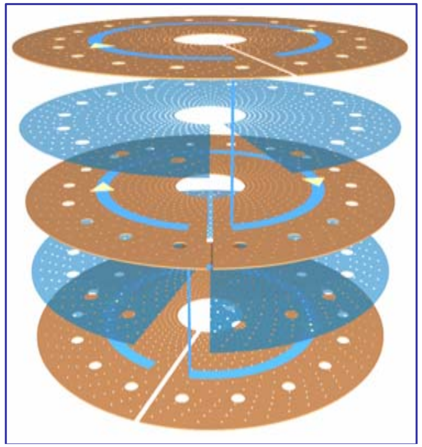
30 T HTc conical design

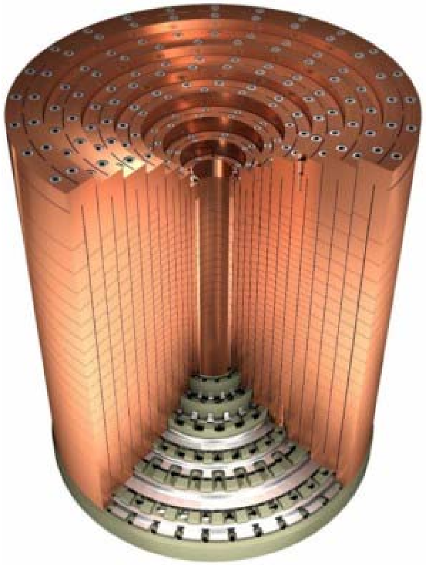
Resistive magnets for scattering

- Resistive magnet technology (Polyhelix/Bitter) is mature up to 35 T, room for improvement up to 40T, flexible, with rapid turnaround.
- A 30 T all SC magnet will cost 10 M€, a 30 T resistive magnet 1 M€
- Large initial investments are needed in power supply and cooling (15 M€)
- Operating costs are high (1000 h = 20 GWh = 1 M€)

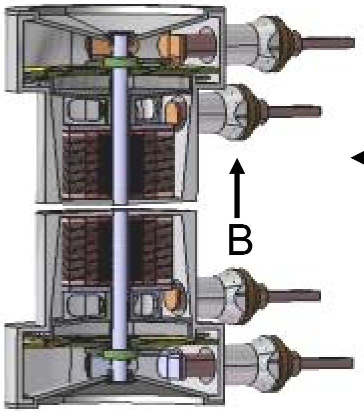
Poly-helices

Bitter plates



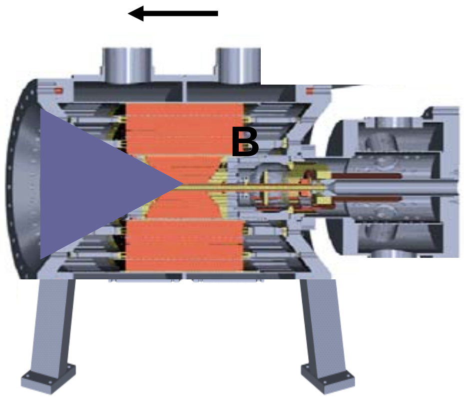


Dedicated LNCMI coil designs for scattering experiments



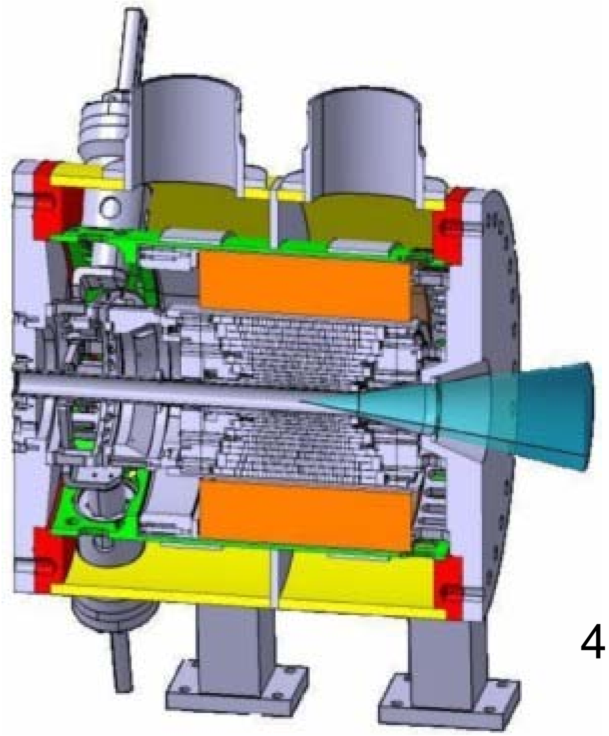
ILL

ESRF



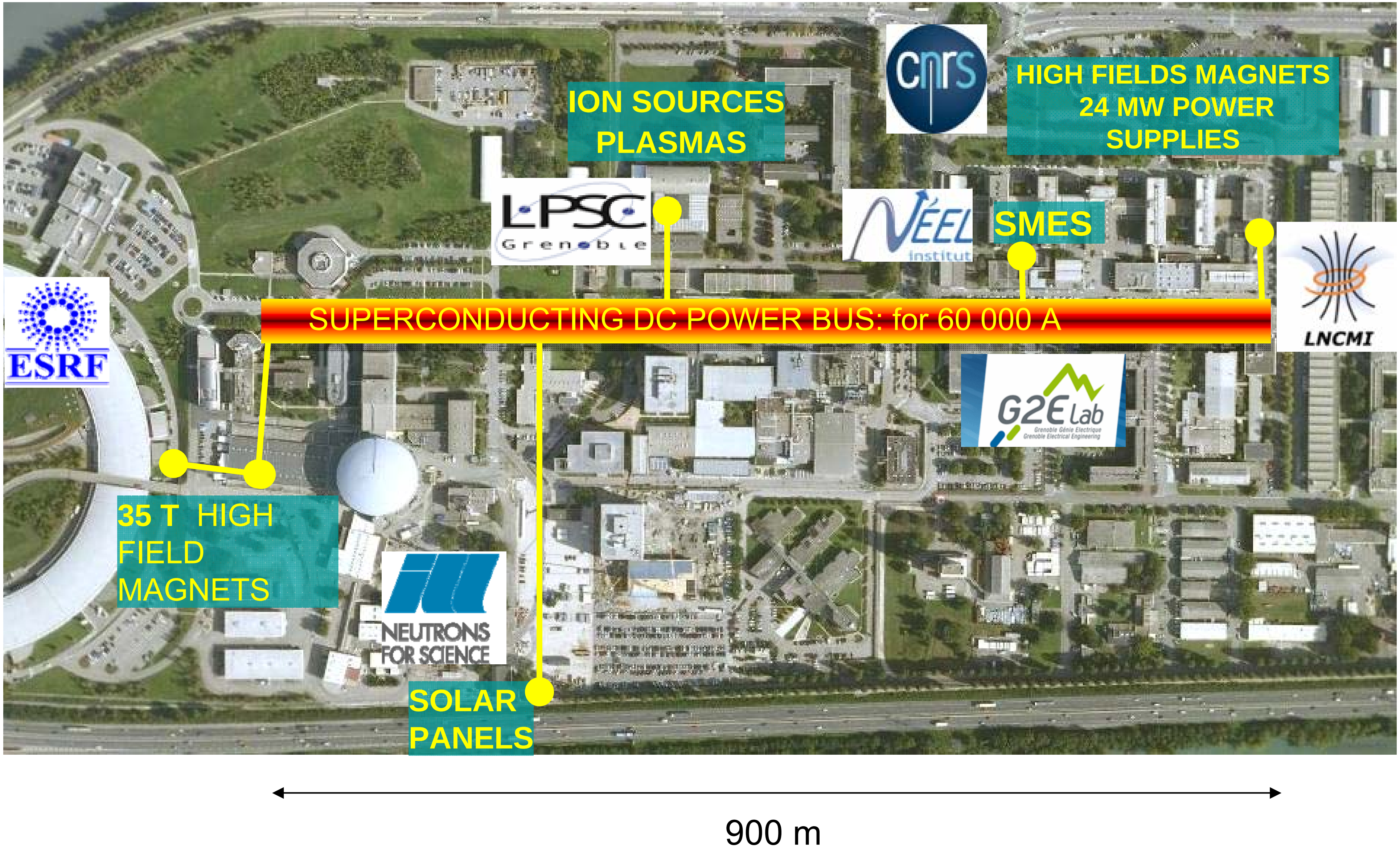
Split coil 30 T, 30 MW

30+ T, 25 MW

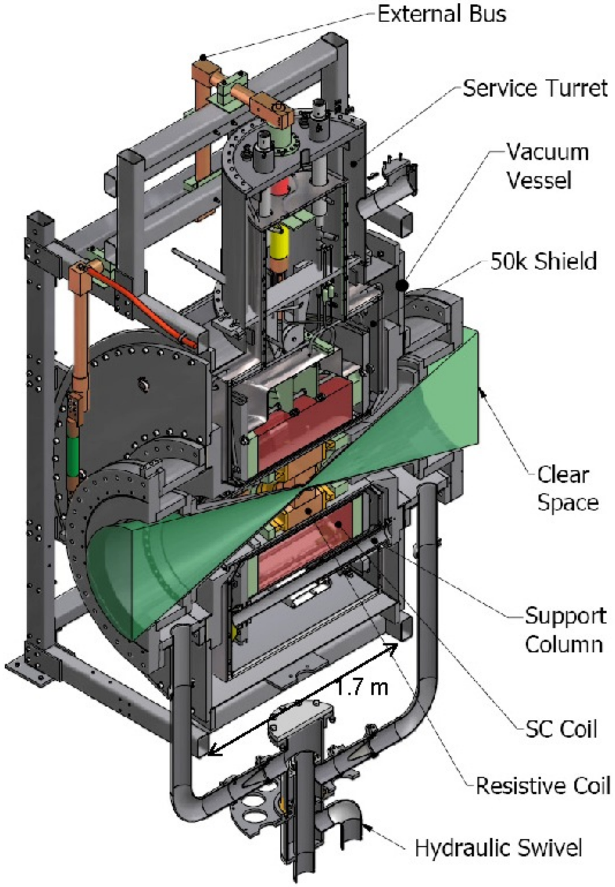


40 T, 40 MW

CONNECTING **LO**CAL **S**UPERPOWER **S**YSTEMS FOR **US**ERS



NHMFL hybrid magnet designs for scattering

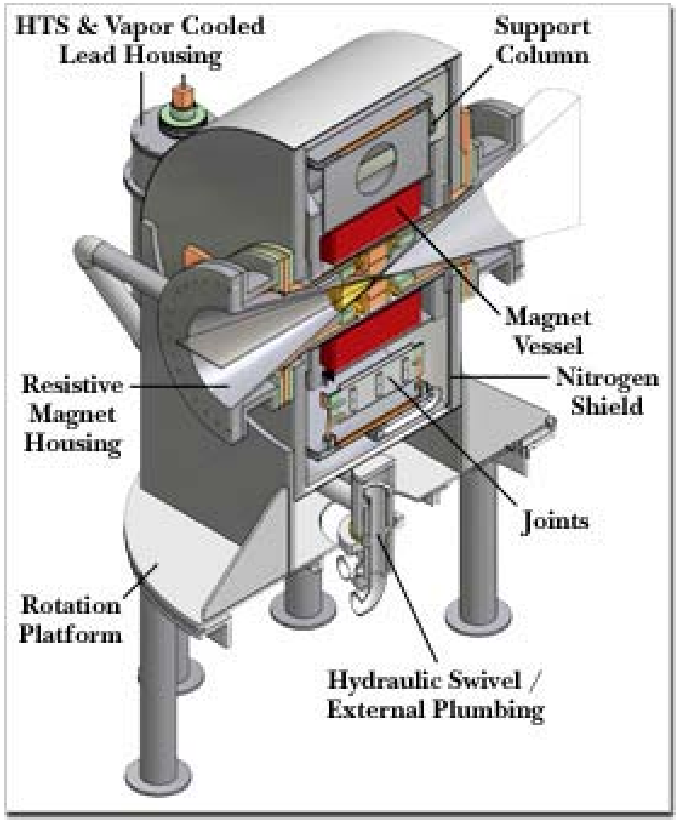


25 T, 4 MW HZB/NHMFL series connected hybrid operationnal mid 2014, 9 M$

Possible upgrades:

30T all SC, with HTc insert

30 T with 8 MW resistive insert



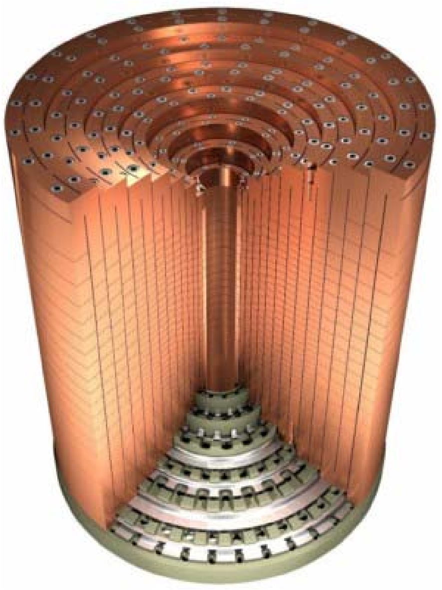
30 T, SNS/NHMFL series connected hybrid design

Pulsed magnets for scattering

- Higher field (80+ T) through better materials & design and more energy

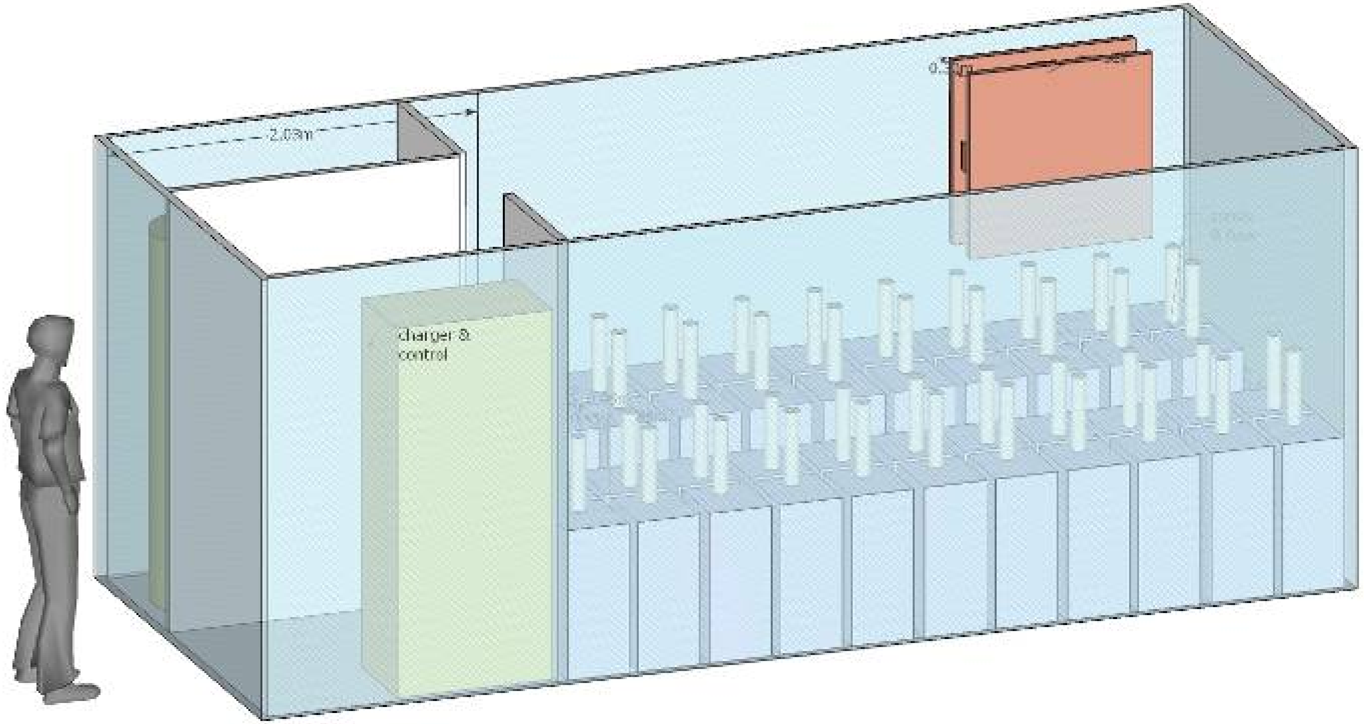
↓

- Longer lifetime at current maximum fields
- Longer pulses for better data acquisition
- Higher duty cycle through polyhelix technology ($\approx 10^{-3}$)



LNCMI

Next generation mobile pulsed field installation: more energy



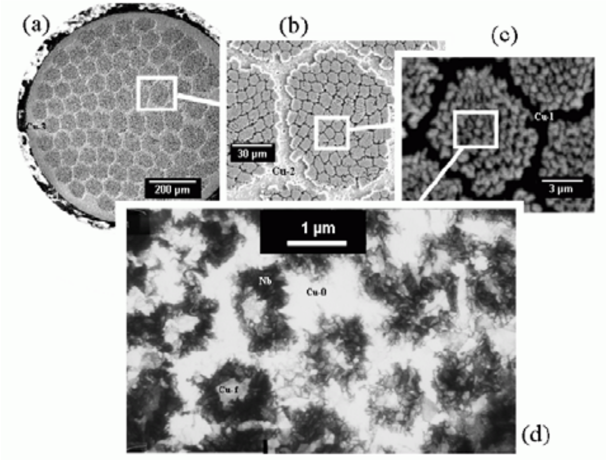
x 2

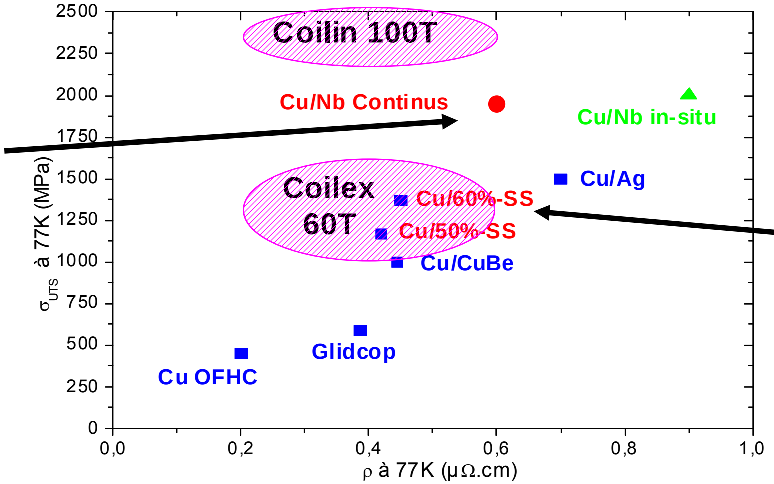
6 MJ, 24 kV in 2 x 20 foot sea containers → **80 T anywhere**, **100+ T in Toulouse**

(under construction, available Feb. 2013)

Materials development for high field magnets

Conductors: better conductivity-strength trade-off:





Reinforcements:

material	UTS (GPa)
Maraging steel	2,7
Zylon	5,5
graphene	130 !!

Conclusion

-High magnetic fields for X ray and neutron scattering are now rapidly developping

-There is still a big development potential

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