Projects for pulsed and steady high magnetic fields at the ESRF

ESRF

C. Detlefs
European Synchrotron Radiation Facility, Grenoble.

- $250\,\mu\mathrm{s}$ Miniature pulsed magnetic field
  (P. van der Linden)
- $5\,\mathrm{ms}$ Pulsed magnetic field
  (LNCMP Toulouse)
- Future project: Steady magnetic fields

Why high magnetic fields?

- The magnetic field is a thermodynamic variable of fundamental importance, as temperature or pressure.
- All electrons carry a spin, and therefore a magnetic moment.
  Therefore, in principle, all condensed matter is concerned:

  Magnetically ordered systems (changes of magnetic structure),
  Polymers (orientation),
  Semiconductors (quantum Hall effect),
  Superconductors (flux line lattices, destruction of superconductivity)
  . . . and many others
- The higher the available field,
  the larger the number of phase transitions and other effects
  that can be observed.

Motivation/Scientific case

- There are many laboratories in Europe and elsewhere in the world which are dedicated to high magnetic field research.
- These labs employ a large number of different techniques:

→ Magnetization and susceptibility.

→ Transport (resistivity, Hall effect, magneto-resistance).

→ Specific heat.

→ Dilatometry and sound velocity.

→ De-Haas-van-Alphen effect (Fermi surface mapping)

→ NMR (Nuclear magnetic resonance)

→ Optical spectroscopy (Raman scattering, reflectivity, ellipsometry, . . .)

Synchrotron based techniques in magnetism research

Experimental stations at the ESRF are optimized for different techniques, many of which are relevant to magnetism research.

- Magnetic scattering

  Superstructures in antiferromagnets and orbitally ordered systems
- X-ray Magnetic Circular Dichroism

  Species resolved spectroscopy, determination of L/S
- Nuclear resonant scattering

  Synchrotron-variant of Moesbauer spectroscopy
- Inelastic scattering

  Measure electronics structures (resonant Raman scattering) or phonons
- Magnetic Compton scattering

  Spin-resolved momentum distribution

All are currently limited to superconducting magnets with fields of 7–15 T!

Beyond 15 T...

For fields higher than 15–20 T there are essentially two possible solutions:
Pulsed resistive or steady fields resistive (or hybrid) magnets.

	Pulsed fields		Steady fields	
Size of installation	scalable	⊕	large	⊖
Magnetic field	up to 80 T	⊕	up to 45 T	⊖
Duty cycle	10^{-5}	⊖	$\approx 100\%$	⊕

Pulsed fields when signals are strong and signal/noise ratio is good

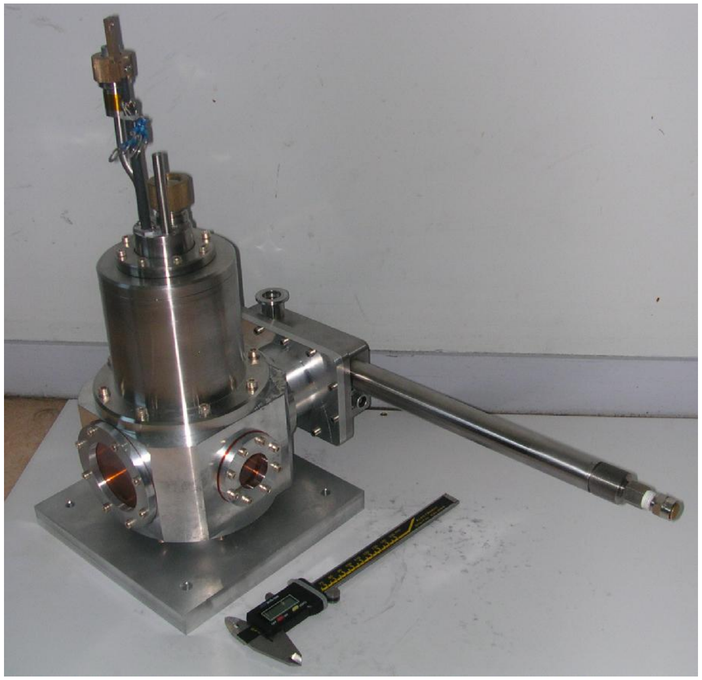
Steady fields for techniques with long counting times, many data points, etc

→ start exploring using pulsed fields, invest in steady fields later

Miniature pulsed magnetic field coils

Peter van der Linden, Olivier Mathon (ESRF)

Goal: Build a small, portable system that can be used on any beamline without modifications



- Commercial generator (Metis, Belgium):

→ max. energy 4 kJ (3 kV, 1 mF)

→ max. current 20 kA

- Solenoid coil developed in-house:

→ Cu/Ag wire

→ L=20 mm, $\phi = 30\,\mathrm{mm}$, bore=11 mm

- half-sine pulse shape:

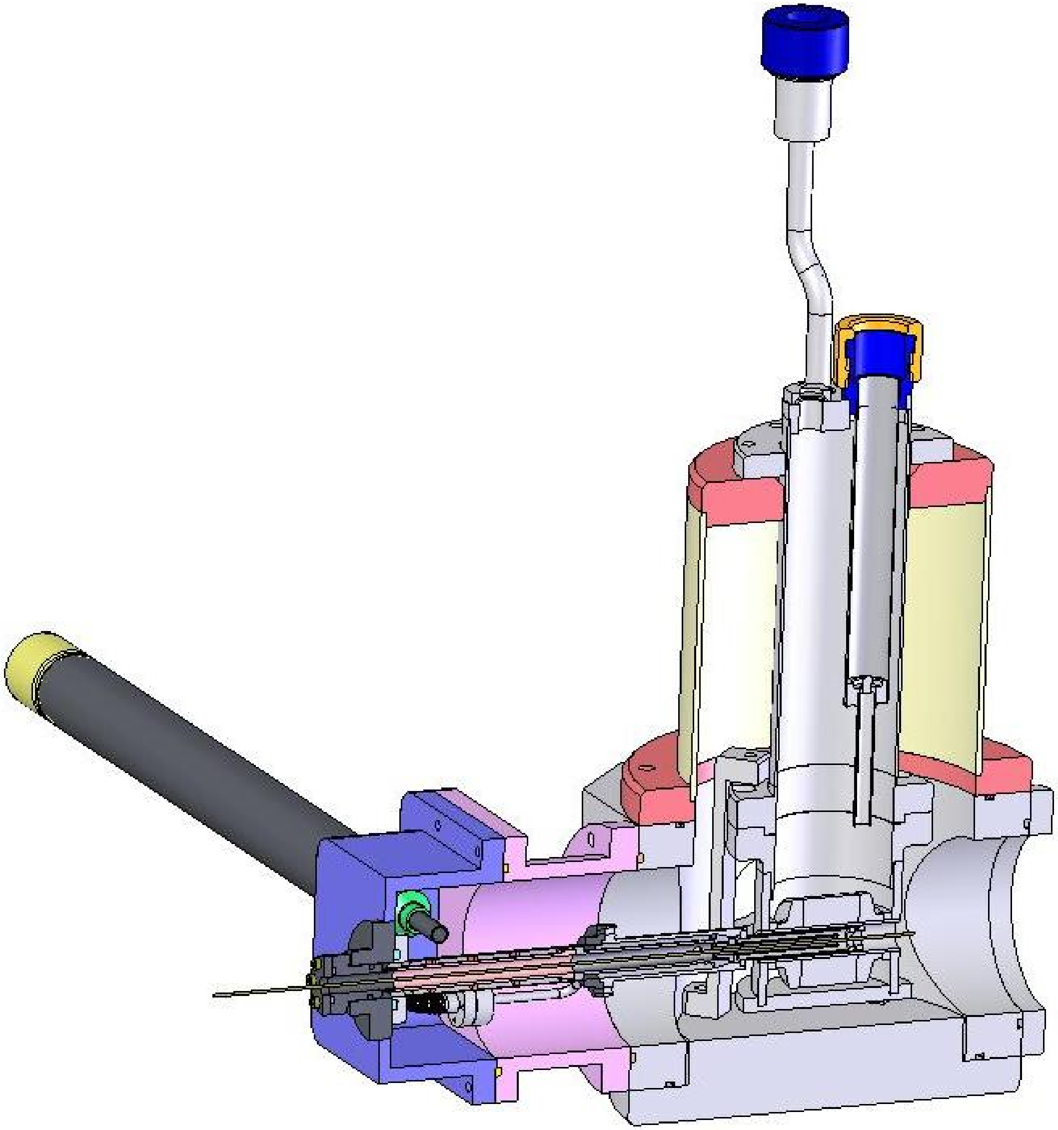
→ rise time $250\,\mu\mathrm{sec}$

Miniature pulsed magnetic field coils

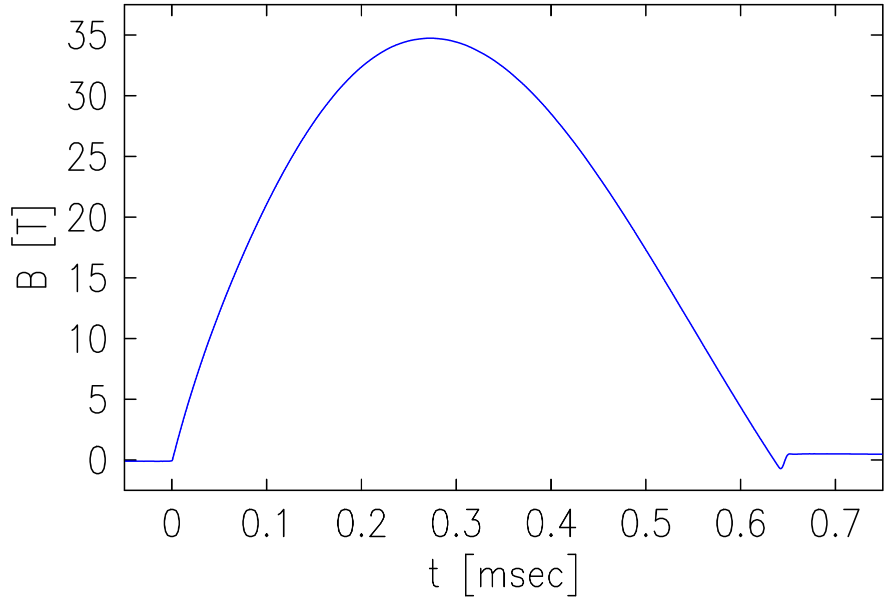
Independent cryostats for sample and coil:

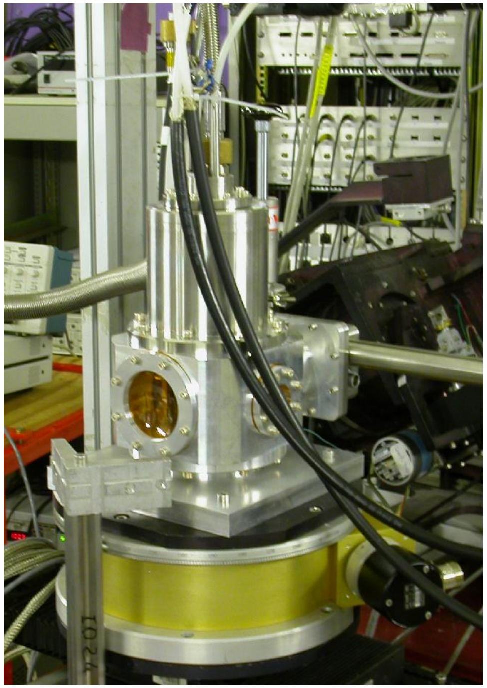
Sample:
liquid He flow cryostat
min. temperature $\approx 5\,\mathrm{K}$

Coil:
immersed in
liquid nitrogen



Miniature pulsed magnetic field coils





Successfully tested in X-ray magnetic circular dichroism (XMCD) experiments on ID24

First results will be presented by O. Mathon and P. van der Linden at the poster session.

30T pulsed magnetic field setup for X-ray powder diffraction

P. Frings[1], J. Vanacken[2], C. Detlefs[3], F. Duc[1], J. E. Lorenzo[4], M. Nardone[1],
J. Billette[1], A. Zitouni[1], W. Bras[5], and G. L. J. A. Rikken[1]

[1] Laboratoire National des Champs Magnetiques Pulsés, CNRS, Toulouse.
[2] Pulsveldengroep, Institute for Nanoscale Physics and Chemistry, Leuven.
[3] European Synchrotron Radiation Facility, Grenoble.
[4] Laboratoire de Crystallographie, CNRS, Grenoble.
[5] DUBBLE CRG at the ESRF, Grenoble.

P. Frings et al., Rev. Sci. Instr. 77, 063903 (2006)

Toulouse 30T magnet system

Transportable generator:

- 2 storage modules,
  1 charger/control module
- $C = 1\,\mathrm{mF}$, $V_{\max} = 16\,\mathrm{kV}$, $E_{\max} = 130\,\mathrm{kJ}$
- Total weight $\approx 2.8\,\mathrm{t}$
- Total size $(h \times d \times w)$
  $1.25 \times 1.30 \times 2.85\,\mathrm{m}^3$
- Generator and load magnet installed in radiation hutch.
- Interlocked through radiation hutch PSS.
- Remote control over fiber optical cables.

Generator design: P. Frings (LNCMP).

Toulouse 30T magnet system

- High field magnet (J. Billette, LNCMP)

→ Solenoid magnet, lq. N_2 cooled, maximum field 30 T, bore 22 mm, max. opening angle 22°.

→ rise time 5 msec, FWHM $\approx$ 18 msec, 10 shots per hour.

- Cryostat (M. Nardone, A. Zitouni, LNCMP)

→ Separate cryostats for high field magnet and sample

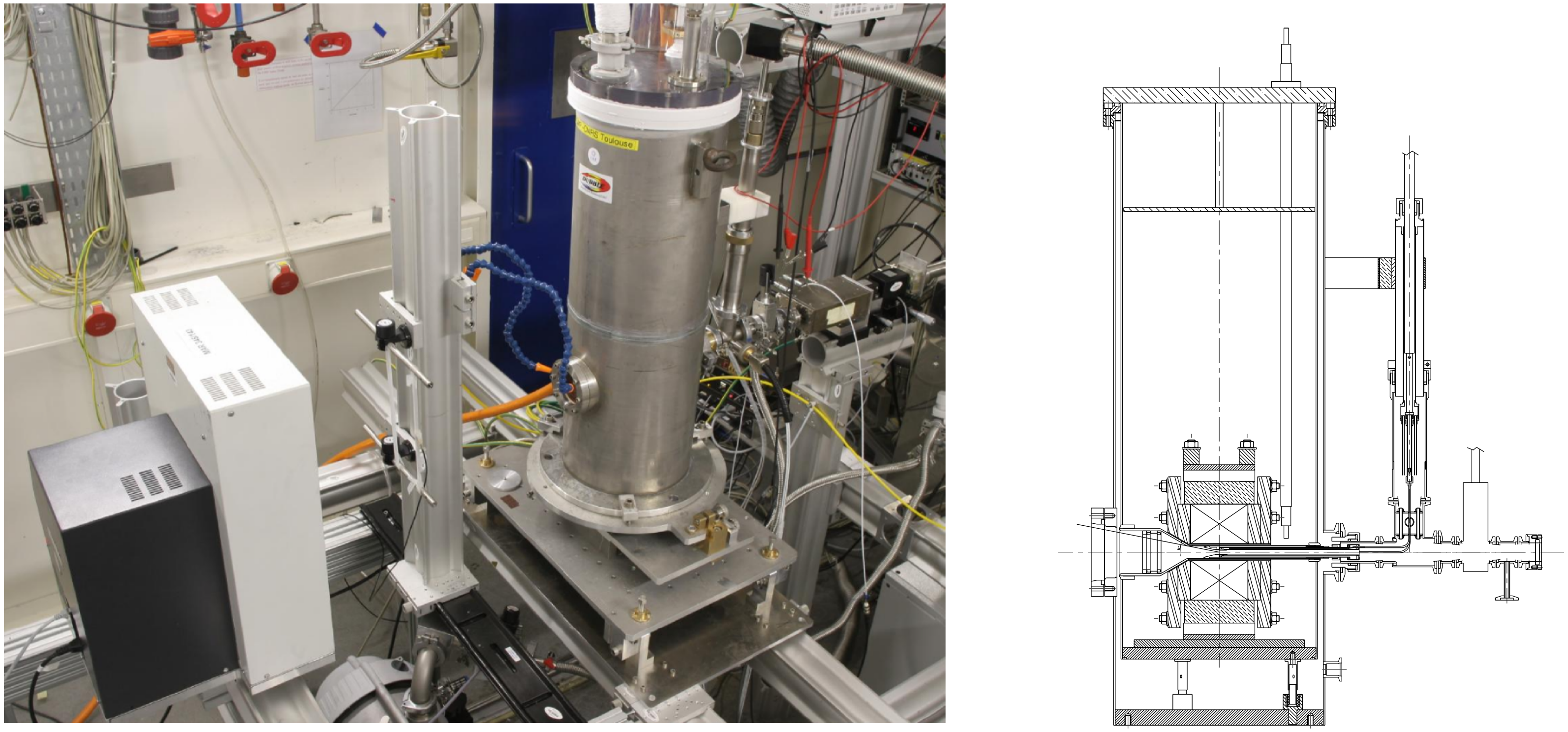
→ He flow cryostat for sample, min. Temperature $\approx$ 7 K.

→ Load-lock for in-situ sample changes.

- X-ray powder diffraction at 21 keV

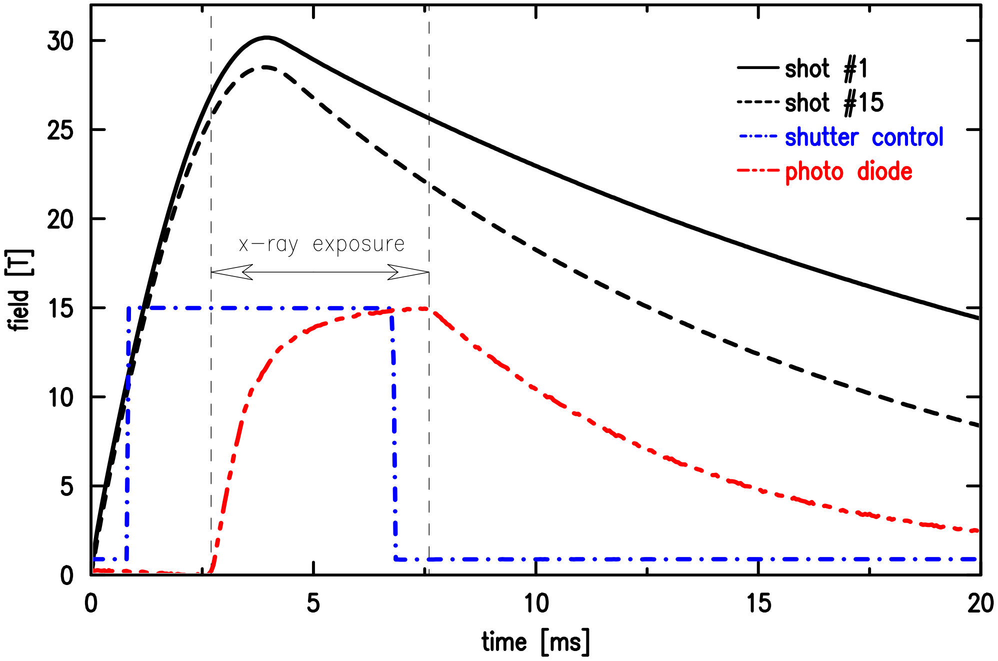
→ Online-image plate detector

X-ray powder diffraction on BM26B DUBBLE



Coil design: J. Billette (LNCMP), cryostat design: M. Nardone, A. Zitouni (LNCMP).

X-ray powder diffraction on BM26B DUBBLE



- Shutter synchronized to magnetic field pulse
- Warming of coil after sequence of pulses.
- Signal integrated over $\approx 5\,\mathrm{ms}$ per pulse.

Not ultra-fast, but not stroboscopic: Small number of pulses.
Fatigue life: Design system such that 1 shot is enough.

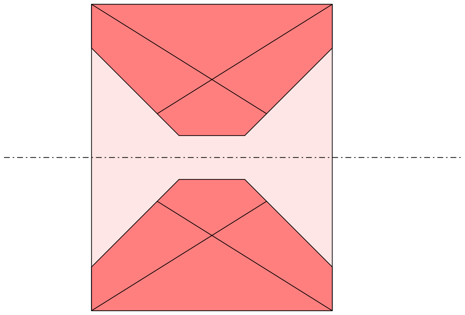
Toulouse 30T magnet system: Second generation

- New coil design for increased optical access

  → Coil wound onto a double-cone

  → opening angle up to 31°

  → more powder lines available for measurement



- Installation on undulator beamline ID20

→ $\approx \times 50$ gain in intensity

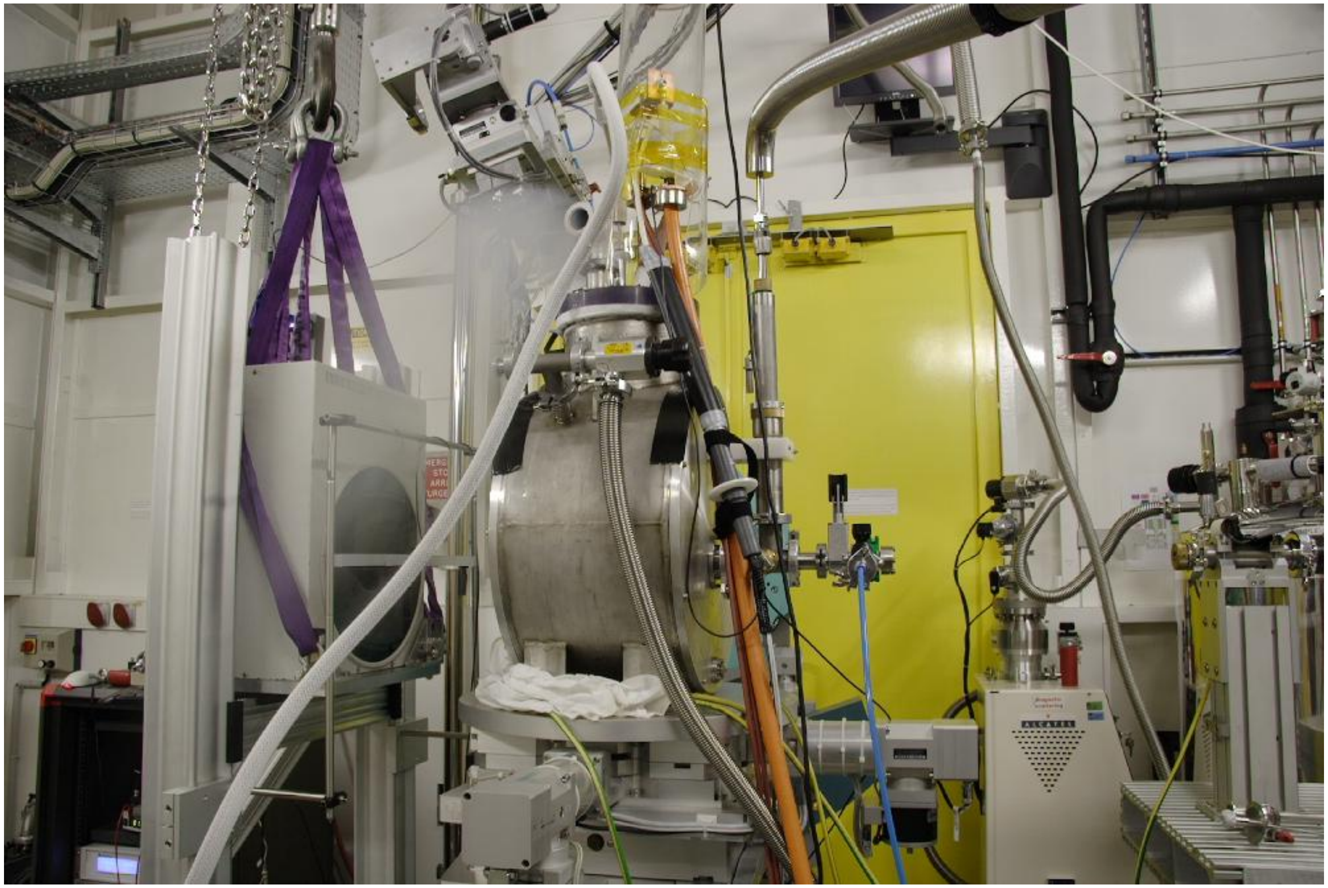
→ Generator installed outside the radiation hutch

- First tests on the beamline 08–14/11/2006

→ Sufficient intensity with 2–4 msec exposure time

→ Need only one shot per spectrum

Toulouse 30T magnet system: Second generation



Toulouse 30T magnet system

- Very reliable system that produces magnetic fields up to 30T
- Large opening angle for diffraction experiments

→ Powder diffraction

→ Laue diffraction on single crystals

- Stable, economic and easy to use sample cryostat

→ Base temperature $\approx 4\,\mathrm{K}$

→ In-situ sample changes through load-lock

- The system is transportable and can be used on different beamlines with small modifications (chicane for HV coax cable)

F. Duc will present the scientific results
More technical details during the poster session.

Future developments

Short term:

→ The technical solution we are using now has a lot of potential.

→ Significant improvements are necessary before this can become a standard experiment with a user program.

→ For most experiments a split coil geometry with $\vec{B} \perp \vec{k}$ is desired.

→ Try other x-ray techniques: Spectroscopy (EXAFS, XMCD), Laue diffraction can be done by installing our equipment on different beamline.

Medium/long term:

→ Need to improve the detection efficiency. Fast 2D pixel detector?

→ Very low temperatures, down to $100\,\mathrm{mK}$.

→ Higher field, up to $60\,\mathrm{T}$. Improved duty cycle of the magnet system.

→ A permanent setup for capacitor banks, optimized detection system, etc.

Steady magnetic field above 17T

The dominant disadvantage of the pulsed magnetic fields is the low duty cycle.

→ Many x-ray techniques are not compatible as they require long integration times (up to several minutes per data point)

→ XMCD for K-edges or small magnetic moments

→ X-ray magnetic scattering at K-edge resonances or non-resonant

→ Inelastic scattering

→ Nuclear resonant scattering off Moesbauer isotopes other than ^{55}Fe.

→ . . .

(The same is true for neutron techniques)

There is therefore a significant scientific case
for a DC high magnetic field facility at the ESRF.

Steady magnetic field above 17T

The project of DC high magnetic field facility
is included in the ESRF Upgrade Programme

- ILL is very interested in a DC high magnetic field facility for neutron scattering

→ As both institutes are located on the same site, it makes sense to combine our efforts

→ In particular, it might be possible to build a common power supply that alternatively serves load magnets at ILL or at ESRF.

Steady magnetic field above 17T

The possibility of a DC high magnetic field facility shared between ESRF and ILL is being taken into account in the ESRF Upgrade Programme

- The beamlines ID06, ID08 and ID12
  have been selected for DC high field end stations.

  They will be specialized for:

→ Magnetic scattering (ID06)

→ Inelastic scattering and nuclear resonant scattering (ID08)

→ X-ray magnetic circular dichroism and optical activity (ID12)

The time scale of the Upgrade Programme is 10 years (2008–2018)

Summary/Conclusions

- X-ray diffraction under high magnetic fields is virtually virgin ground.
  There is plenty to be done.
- Steady magnetic fields have the advantage that we can use proven measurement strategies, measure very small signals, etc.
- Pulsed magnetic fields require much more development of x-ray diffraction.
- But because of sample volume, time structure, etc, they can boldly go where no neutron has gone before (and very likely will ever go*).

→ There is a scientific case for both of them.

→ Steady fields solution is lower risk, but limited to 30–40 T.

→ Pulsed fields solution is much more speculative. But it also requires less capital investment, and the ms time resolved x-ray techniques may be of interest in other fields, such as on-line chemistry, shock waves, ...

* . . . with the possible exception of neutron stars!