Superconducting Vortices in $CeCoIn_5$: Toward the Pauli-Limiting Field

Michel Kenzelmann

ETH Zürich & Paul Scherrer Institute

University of Montreal	***Andrea D. Bianchi***
Paul Scherrer Institute	***Joel Mesot, Markus Zolliker, Joachim Kohlbrecher***
University of Birmingham	***Jon S. White, Edward M. Forgan***
University of Notre Dame	***Lisa DeBeer-Schmitt, Morten Ring Eskildsen***
Los Alamos National Lab	***Roman Movshovich, Eric. D. Bauer, John L. Sarrao, Joe Thompson***
Univ. of California, Irvine	***Zachary Fisk***
Brookhaven National Lab	***Cedomir Petrovic***

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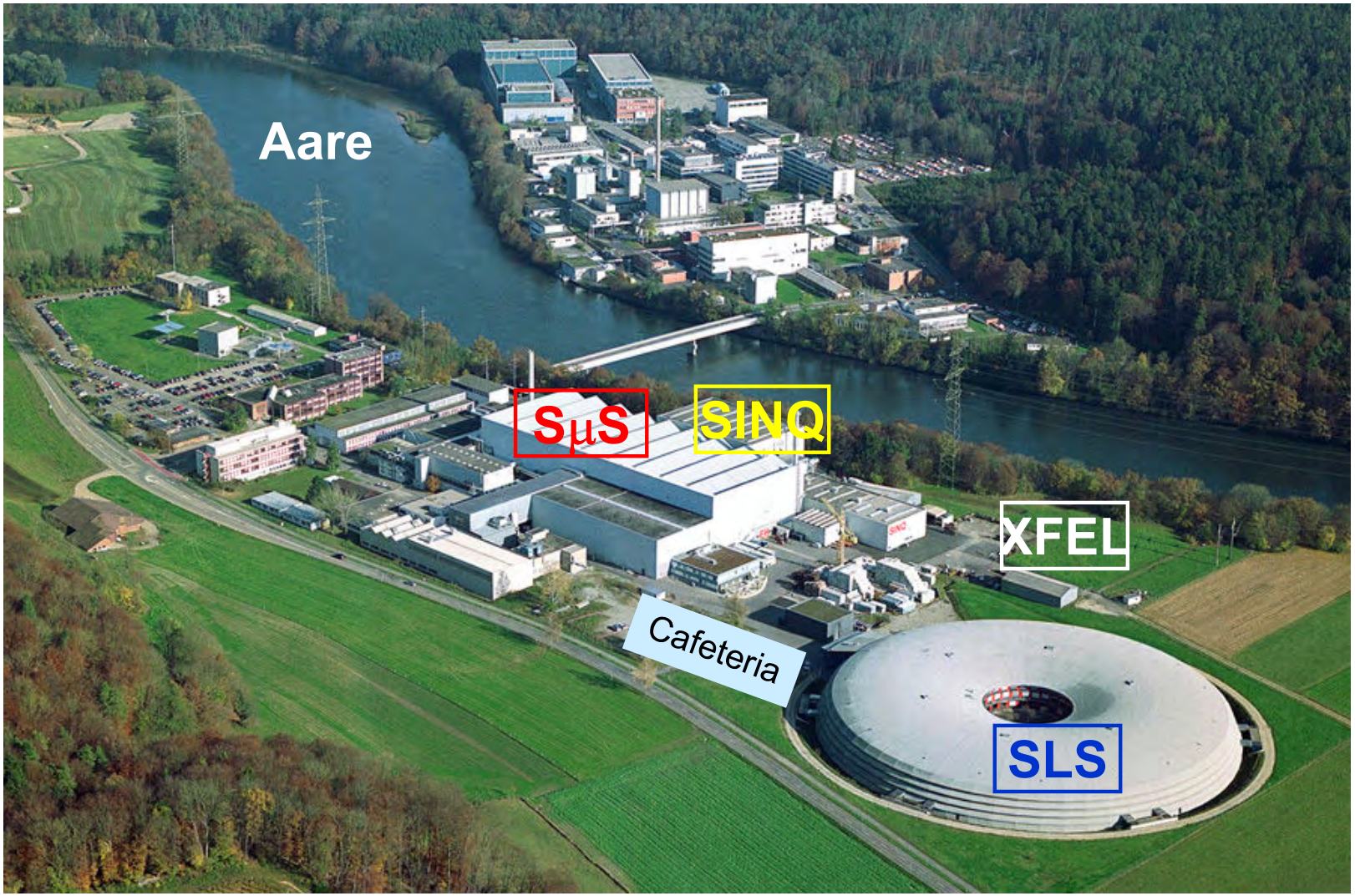

User facilities with neutron, muon and synchrotron sources, and soon a free-electron laser

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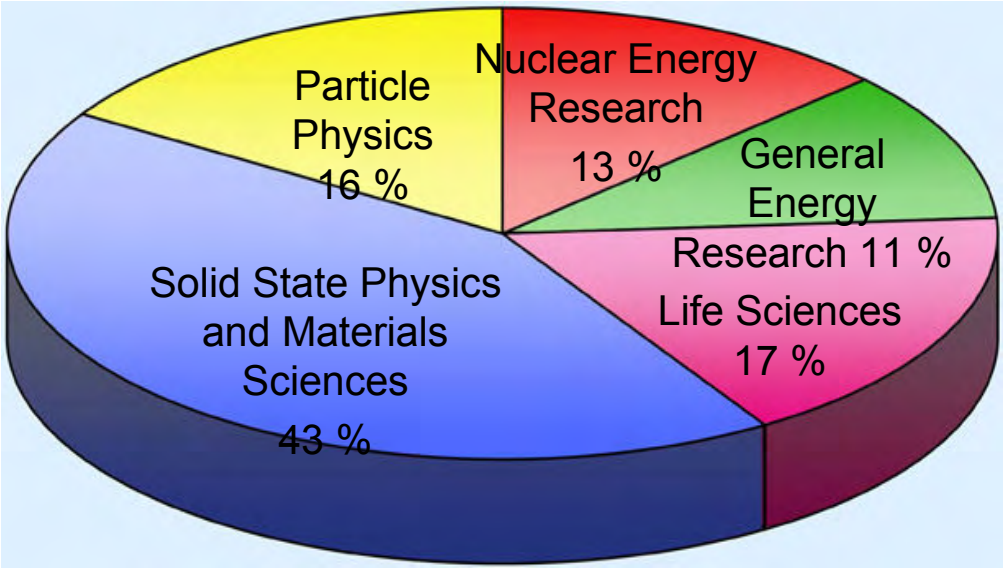
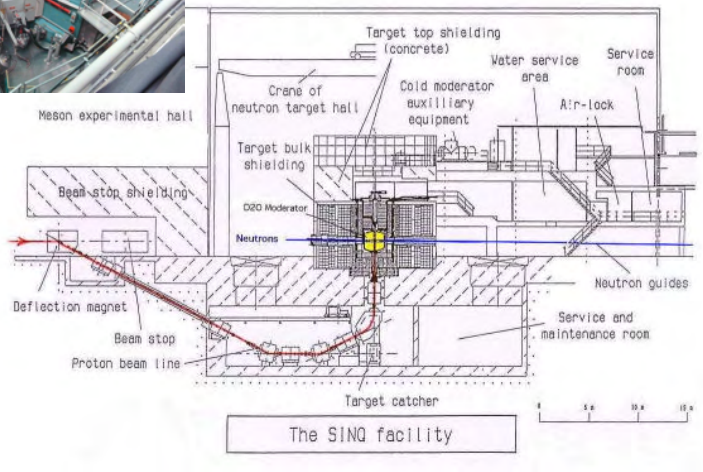
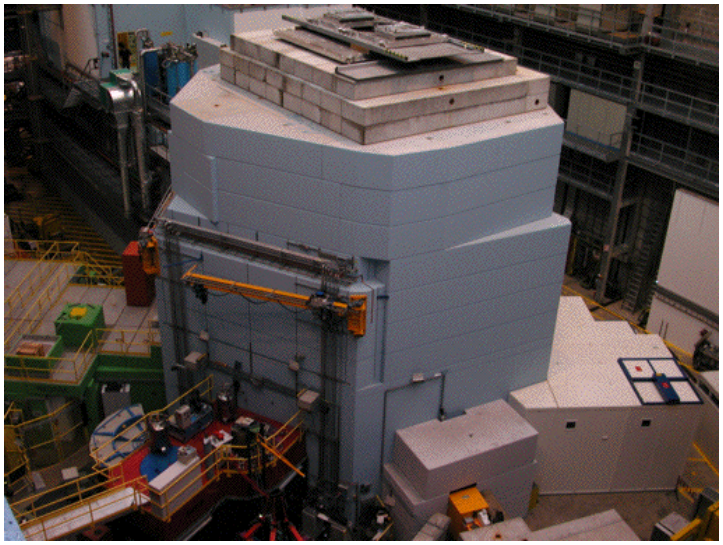
Key figures 2008

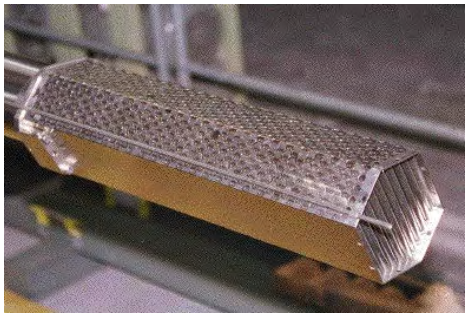


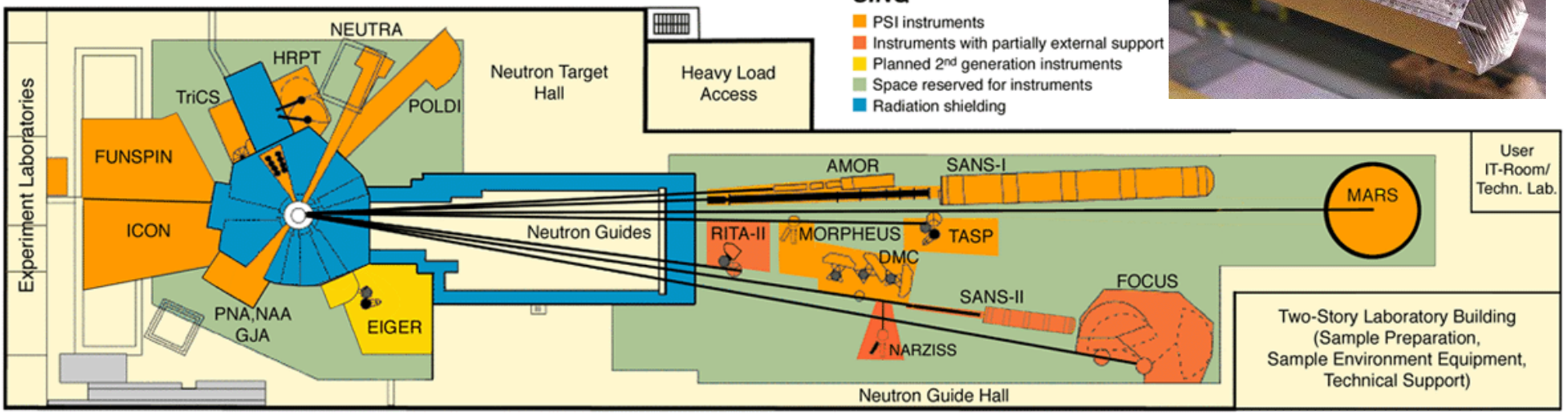
Staff	~1280
Of which externally financed	~ 300
Doctoral students	~ 270
Apprentices	80
External users	~1700
Number of scientific publications	~ 800
PSI-employees with teaching duties at ETH and universities	~ 70

SINQ spallation neutron source

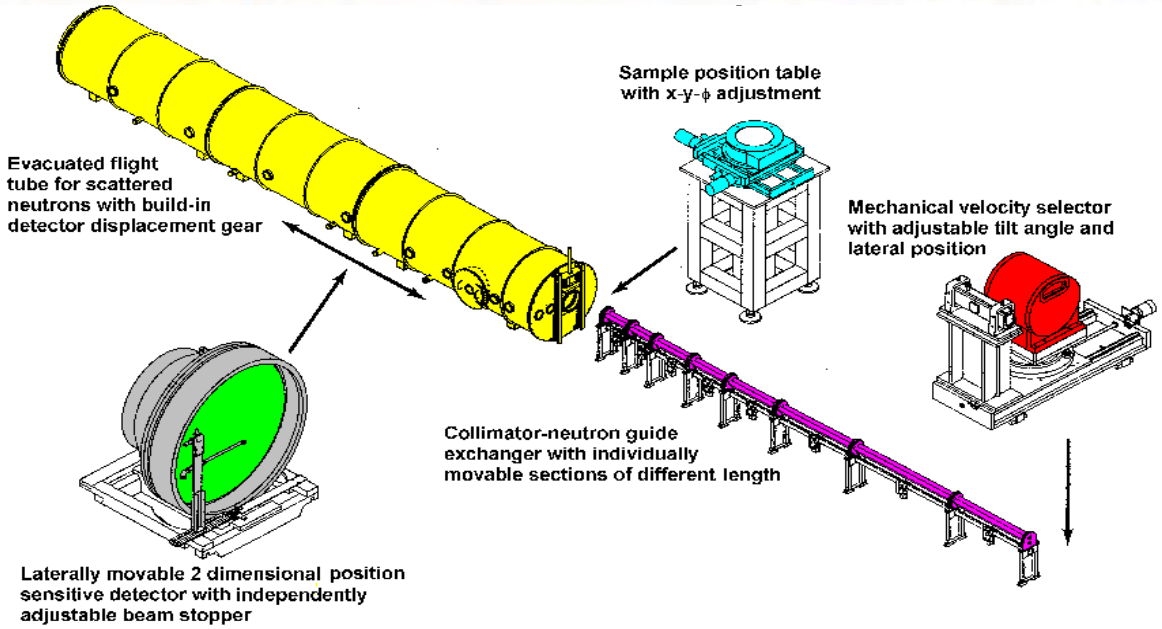




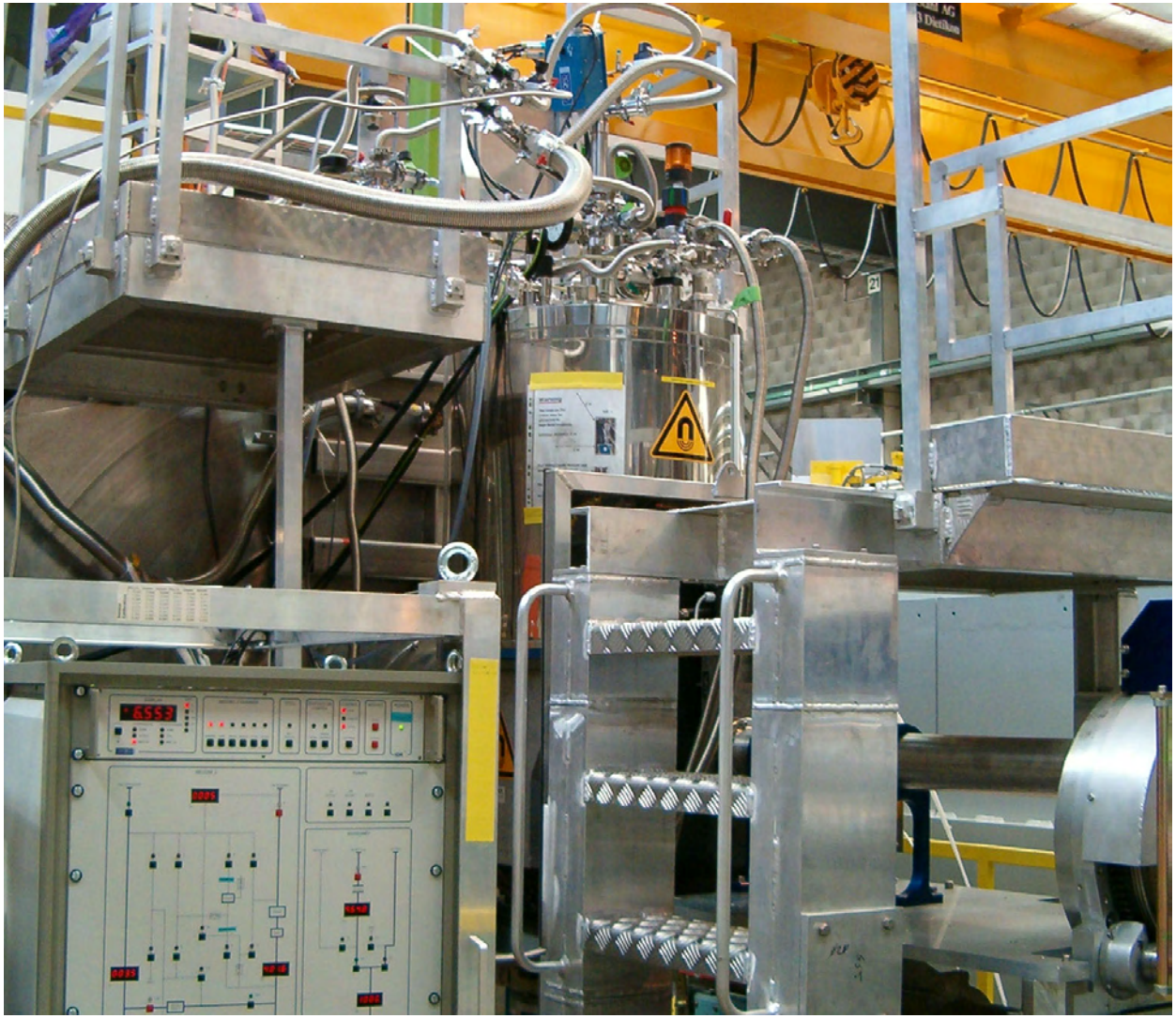




SANS-I at Paul Scherrer Institute

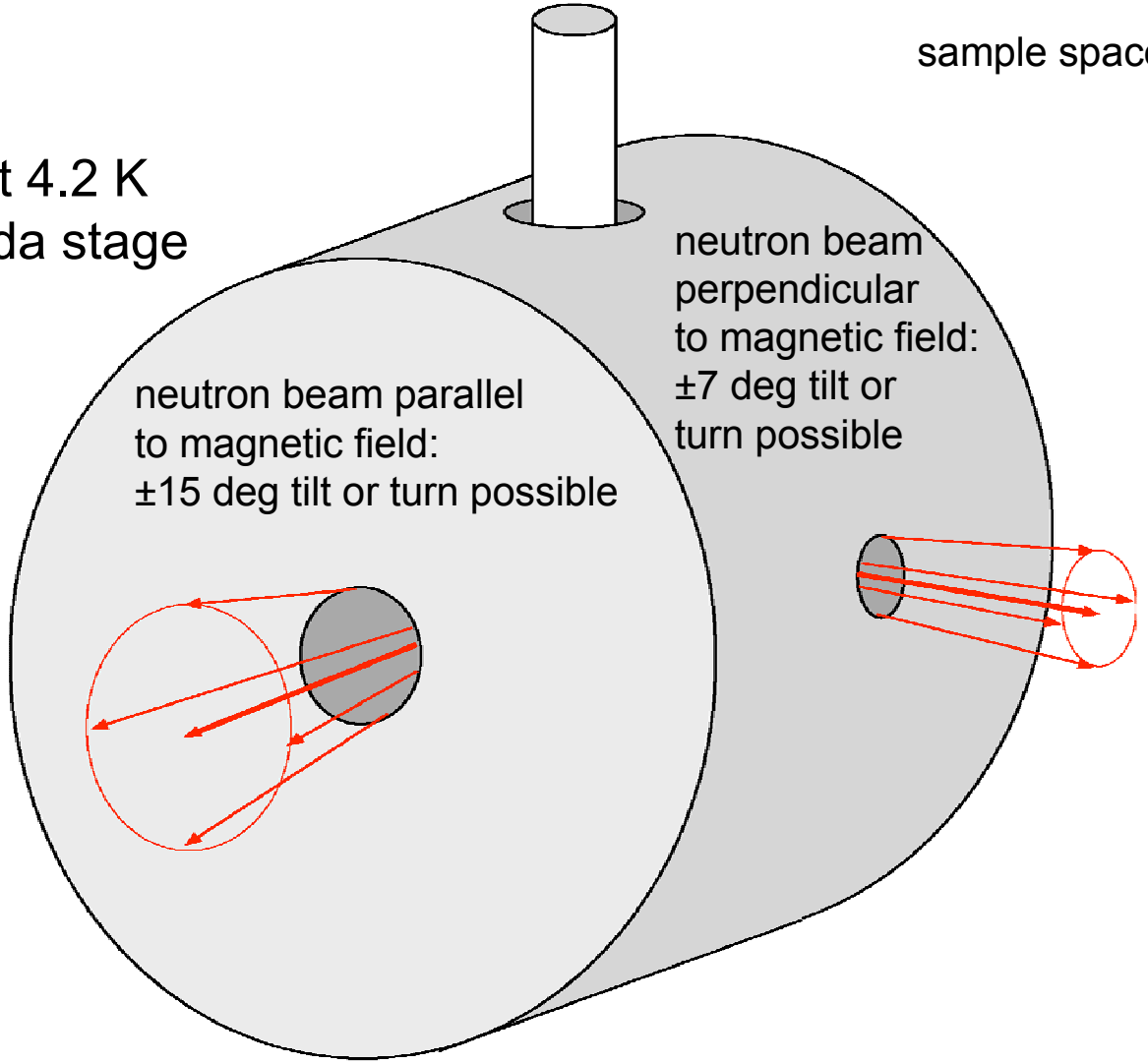


11 Tesla horizontal-field cryomagnet with dilution insert on SANS-I

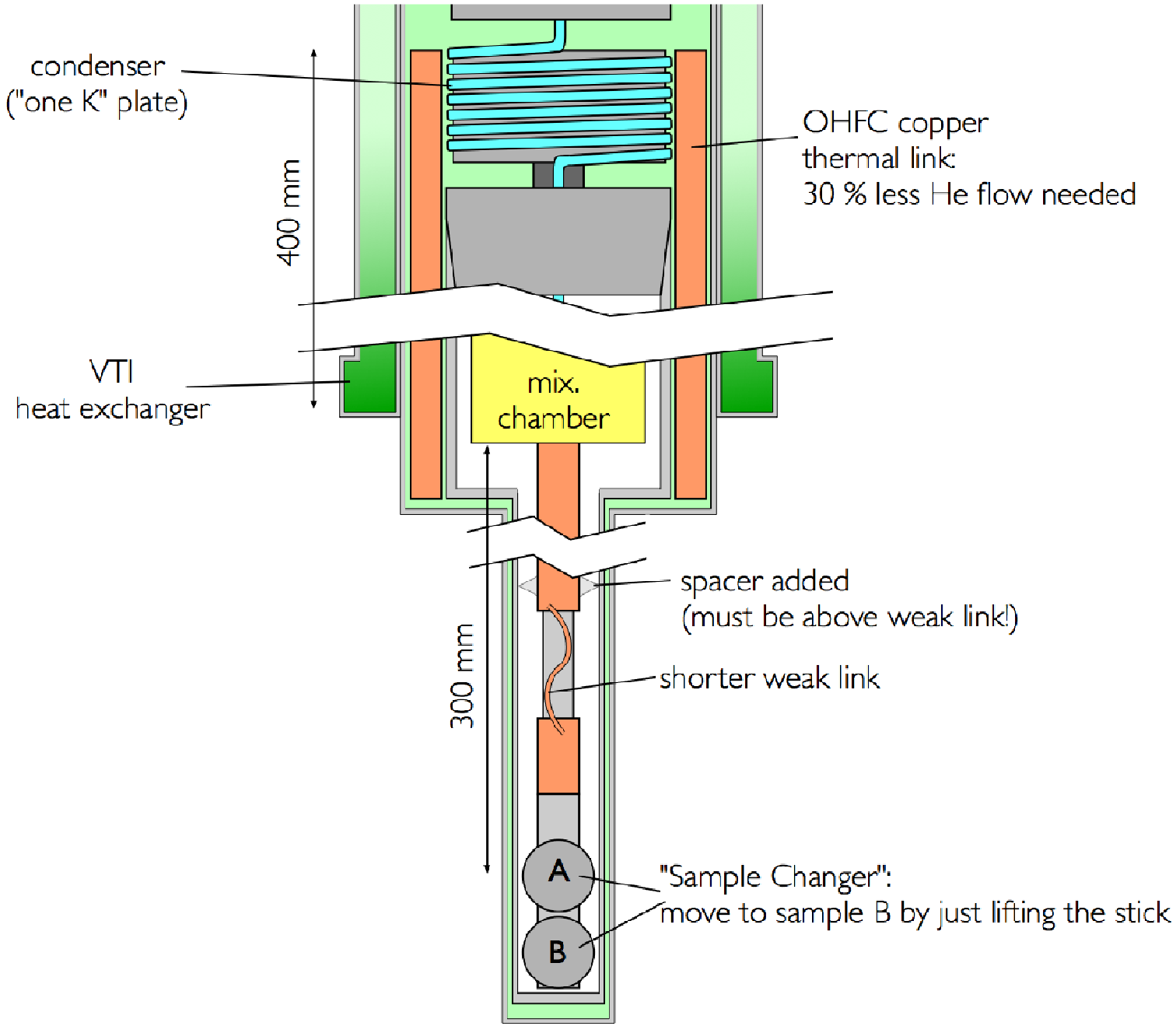


11 Tesla horizontal cryomagnet

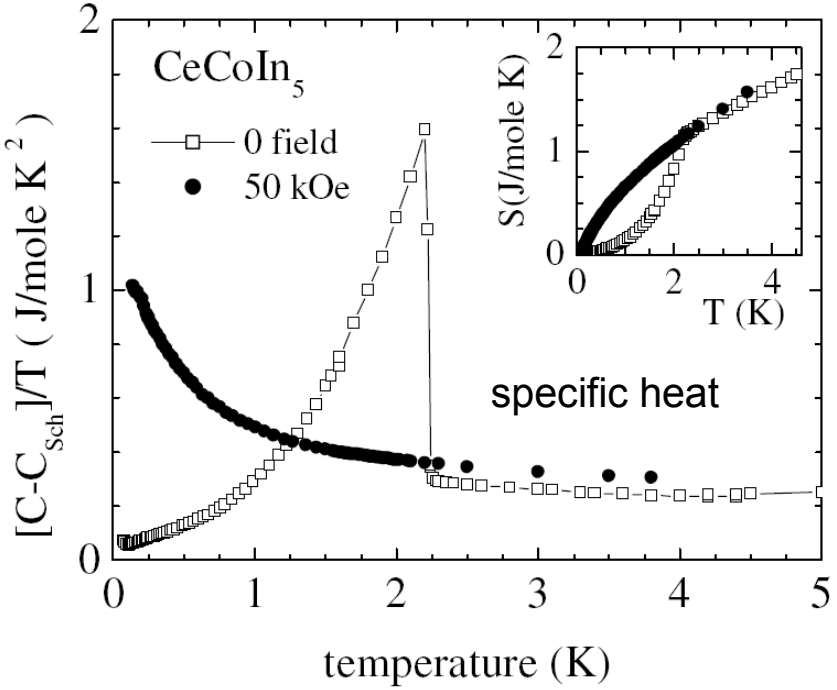
Max. Field:
10 Tesla with coil at 4.2 K
11 Tesla with lambda stage

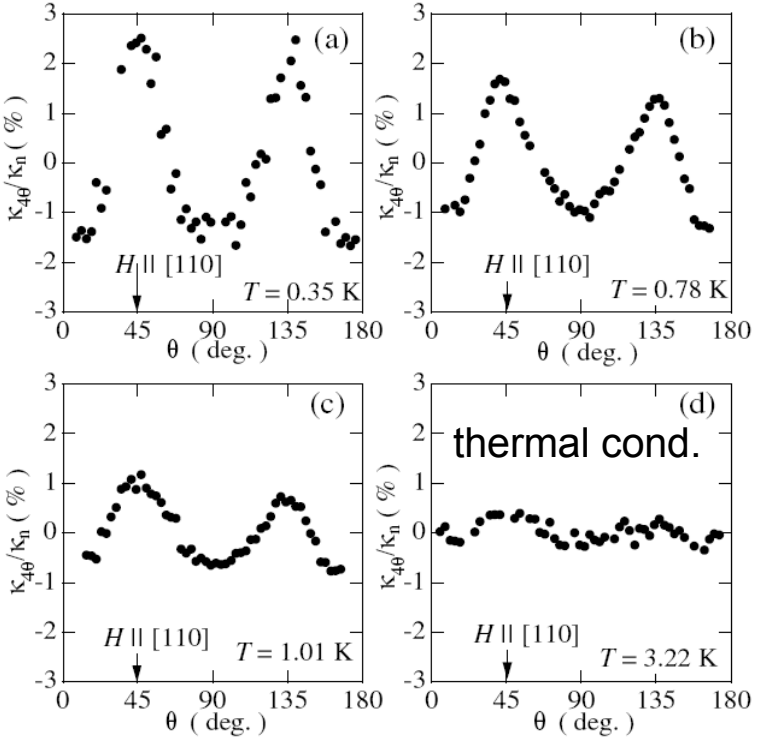


Improvements to the dilution insert



$CeCoIn_5$ – model unconventional superconductor

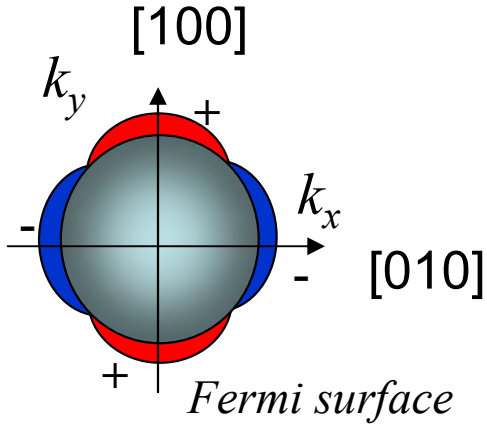




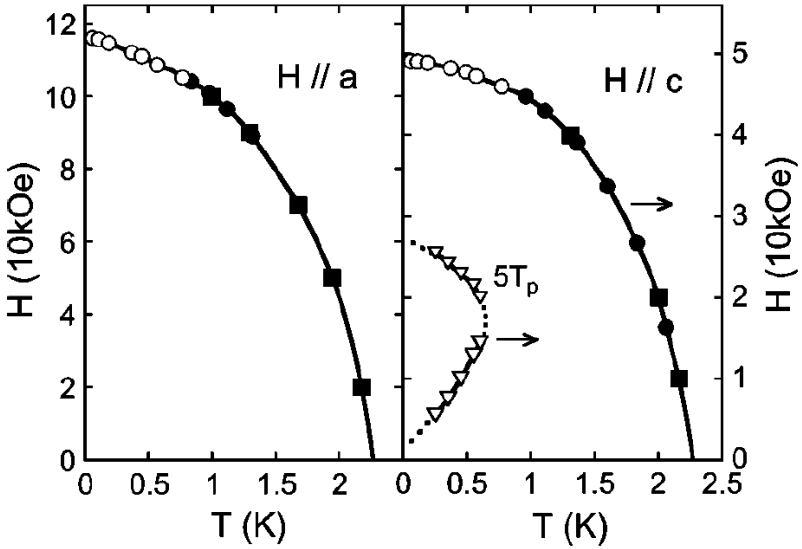
C. Petrovic et al., J. Phys.: Condens. Matter **13**, L337 (2001)

K. Izawa et al., Phys. Rev. Lett. **87**, 057002 (2001)

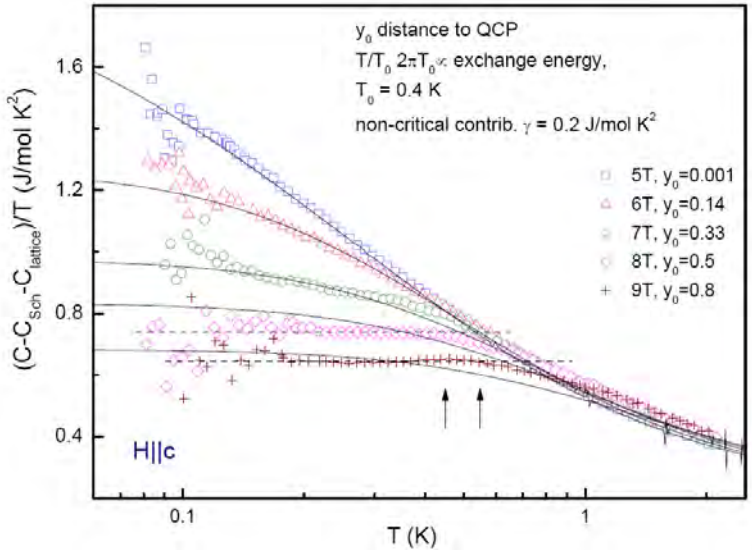
- large γ=1J/mole/K^2 : heavy-fermion superconductor
- line nodes in the superconducting gap function
- spin singlet superconductivity
- four-fold symmetry indicates d-wave symmetry → $d_{x^2-y^2}$
- two-dimensional Fermi surface



Field-tunable superconductor



Tayama et al., Phys. Rev. B **65**, R180504 (2002)



A. D. Bianchi et al., Phys. Rev. Lett **91**, 257001 (2003)

Orbital limiting fields:

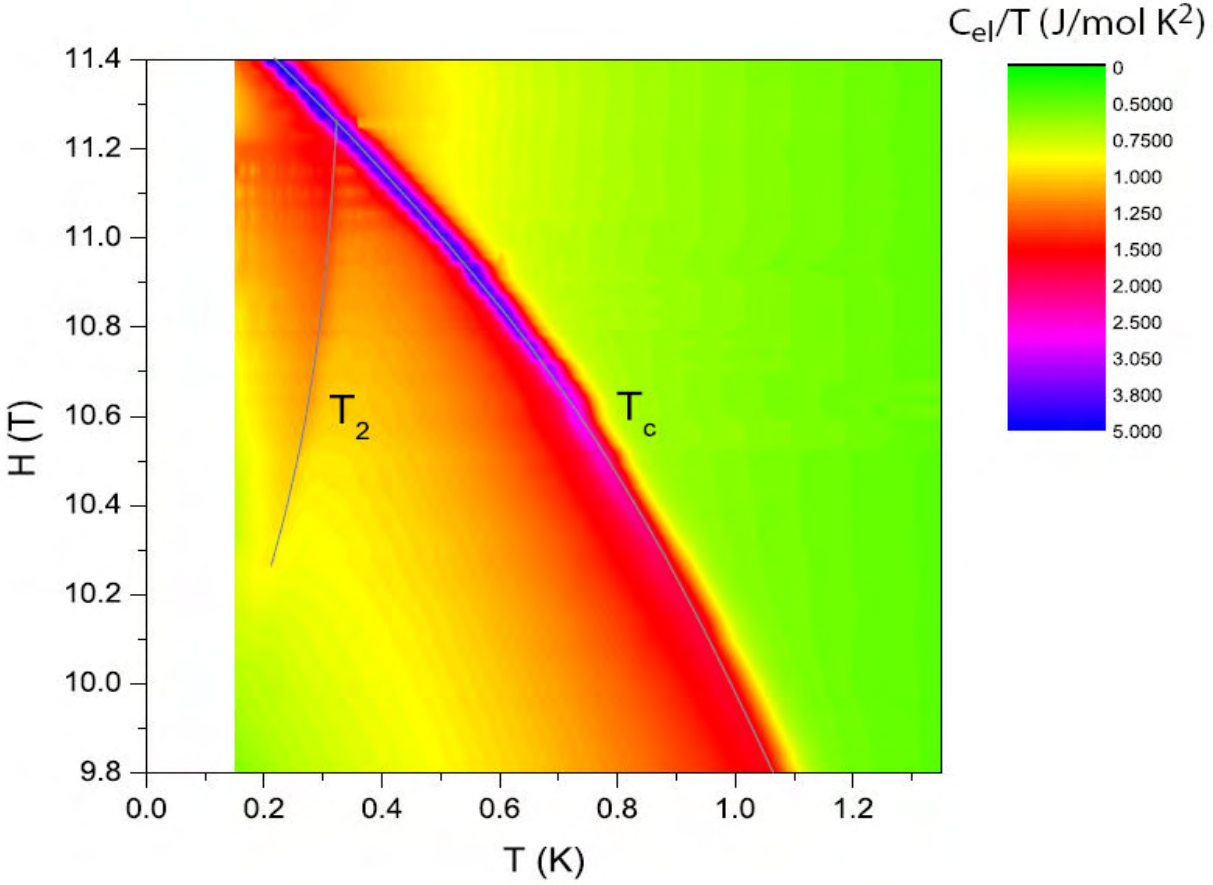
H || c : H_{c20} = 15 Tesla
H || a : H_{c20} = 35 Telsa

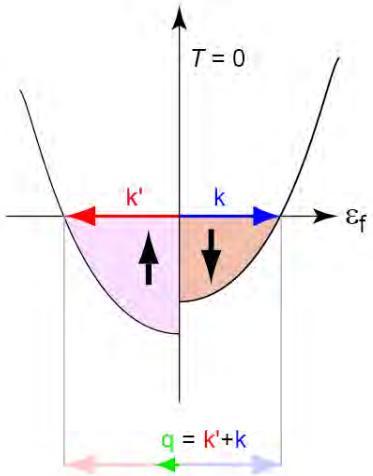
Maki parameters

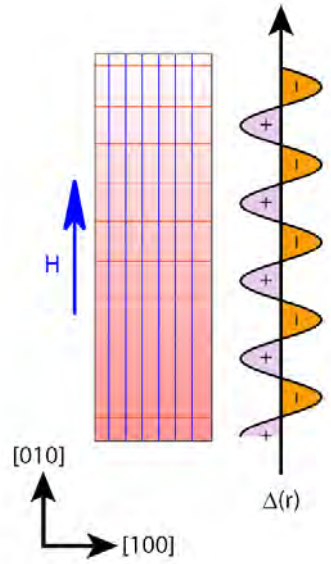
$H_p=\Delta_0/ (8\mu_B\pi\chi_{spin})^{1/2}$

- Non-Fermi liquid behavior intensifies close to the upper critical field
- $CeCoIn_5$ is in the proximity of a quantum critical point
- H_{c2} transition becomes first-order for T < 1K

Extended second superconducting phase at high fields H ⊥ **c**



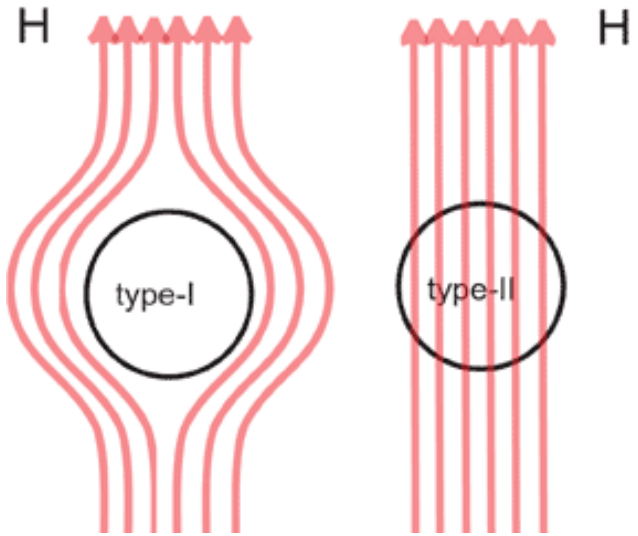


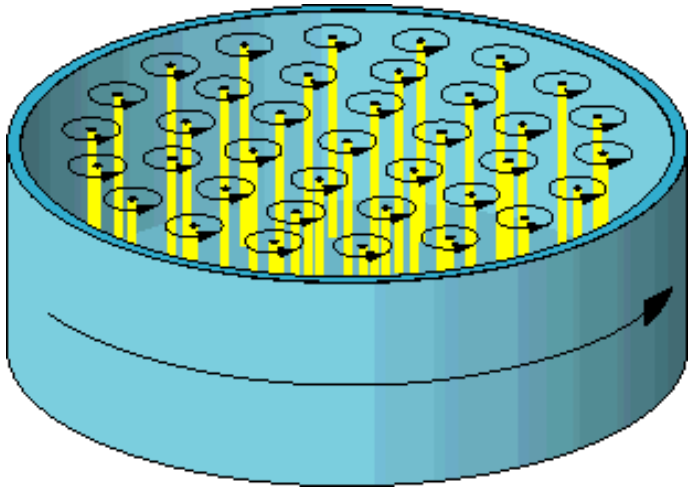


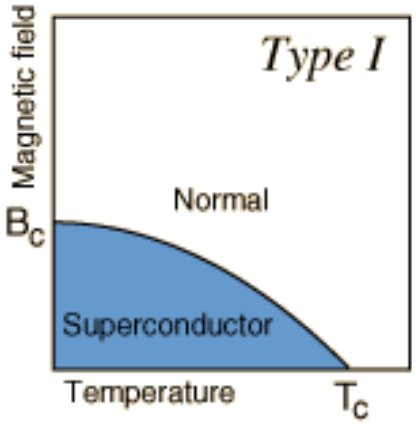
A. D. Bianchi et al, Phys. Rev. Lett. **91**, 187004 (2003)

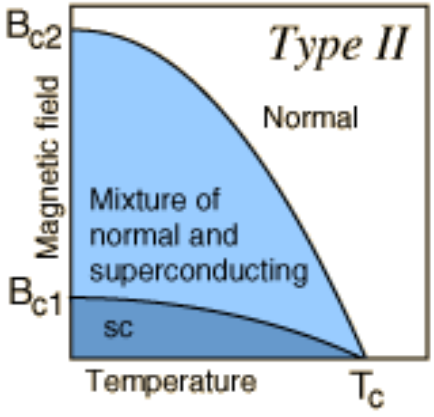
Fulde and Ferrell, Phys. Rev. **135**, A550 (1964)
Larking and Ovchinnikov, Zh. Eksp. Teor, Fiz **47**, 1136 (1964)

Magnetic field response in type-II Superconductors



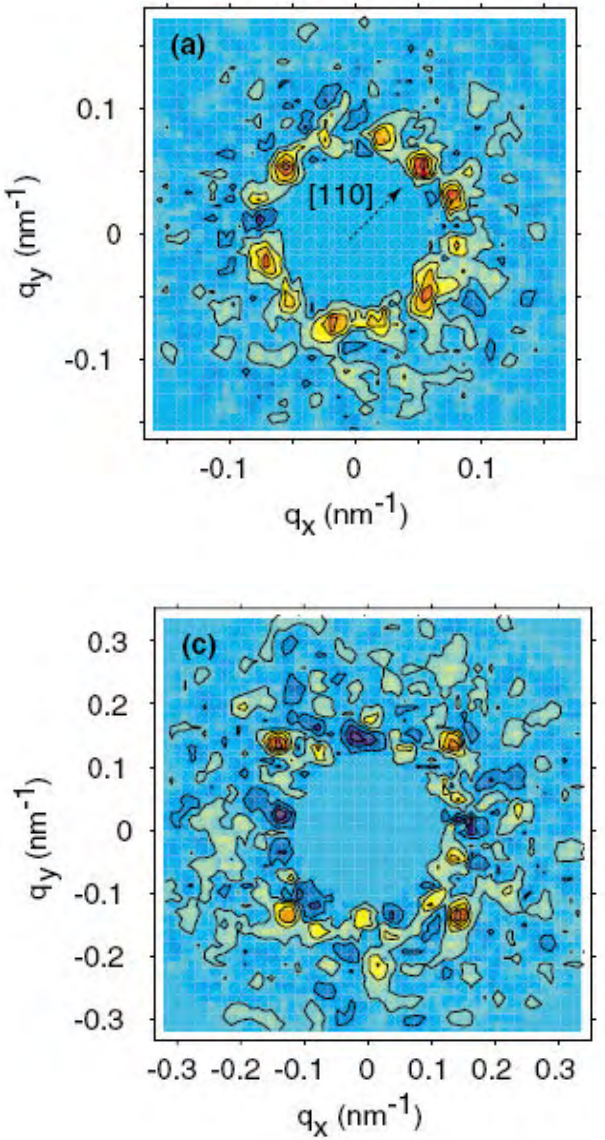




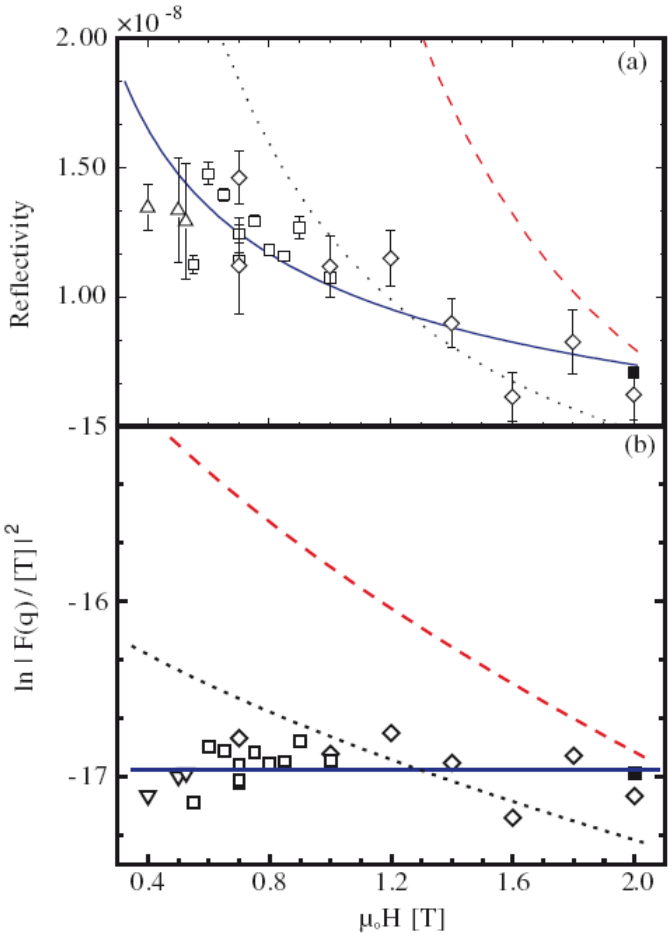


Measurement of diffraction
Pattern from flux lattice
Large distance → small angles

Previous studies on $CeCoIn_5$



m = 36 mg, λ = 6 Angstrom, D11 (ILL),
Eskildsen et al. Phys. Rev. Lett 90, 187001 (2003)



m = 86 mg, λ = 4.5 Angstrom, D11/D22 (ILL),
DeBeer-Schmitt et al. Phys. Rev. Lett. 97, 127001 (2006)

Neutron scattering intensity generally decreases with increasing field

Requirements of experiment

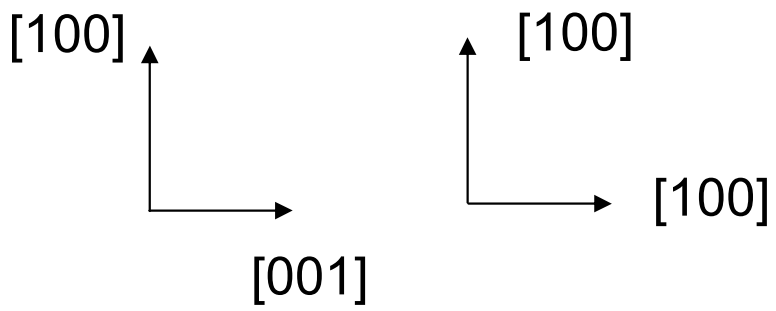
- Small-angle neutron scattering instrument
- High fields: H > 4T ~ 11T
- Low temperatures: T ~ 50 mK
- High scattering intensity → large mass ~ 500mg

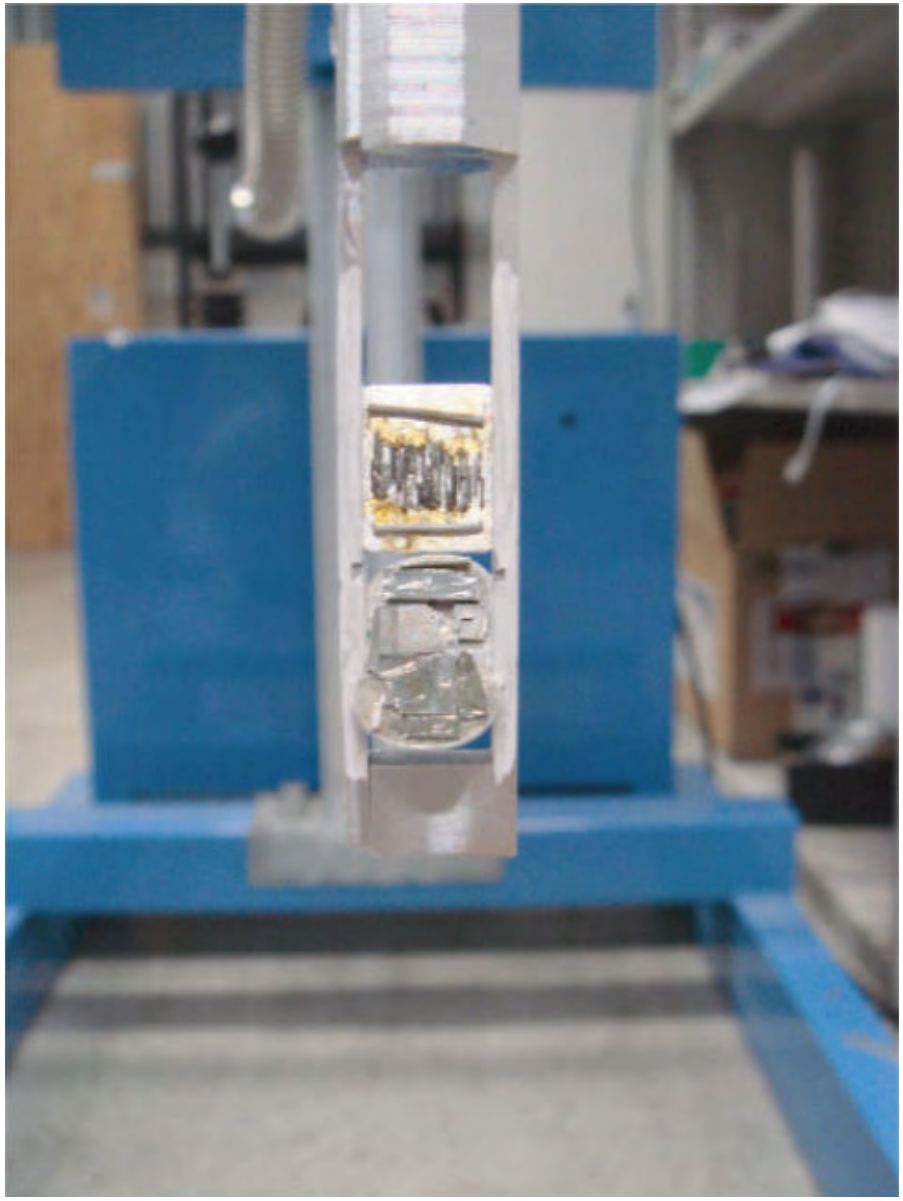
Vertical field magnet on a SANS instrument?
No, too high background

- Low background → horizontal field magnet with sapphire windows

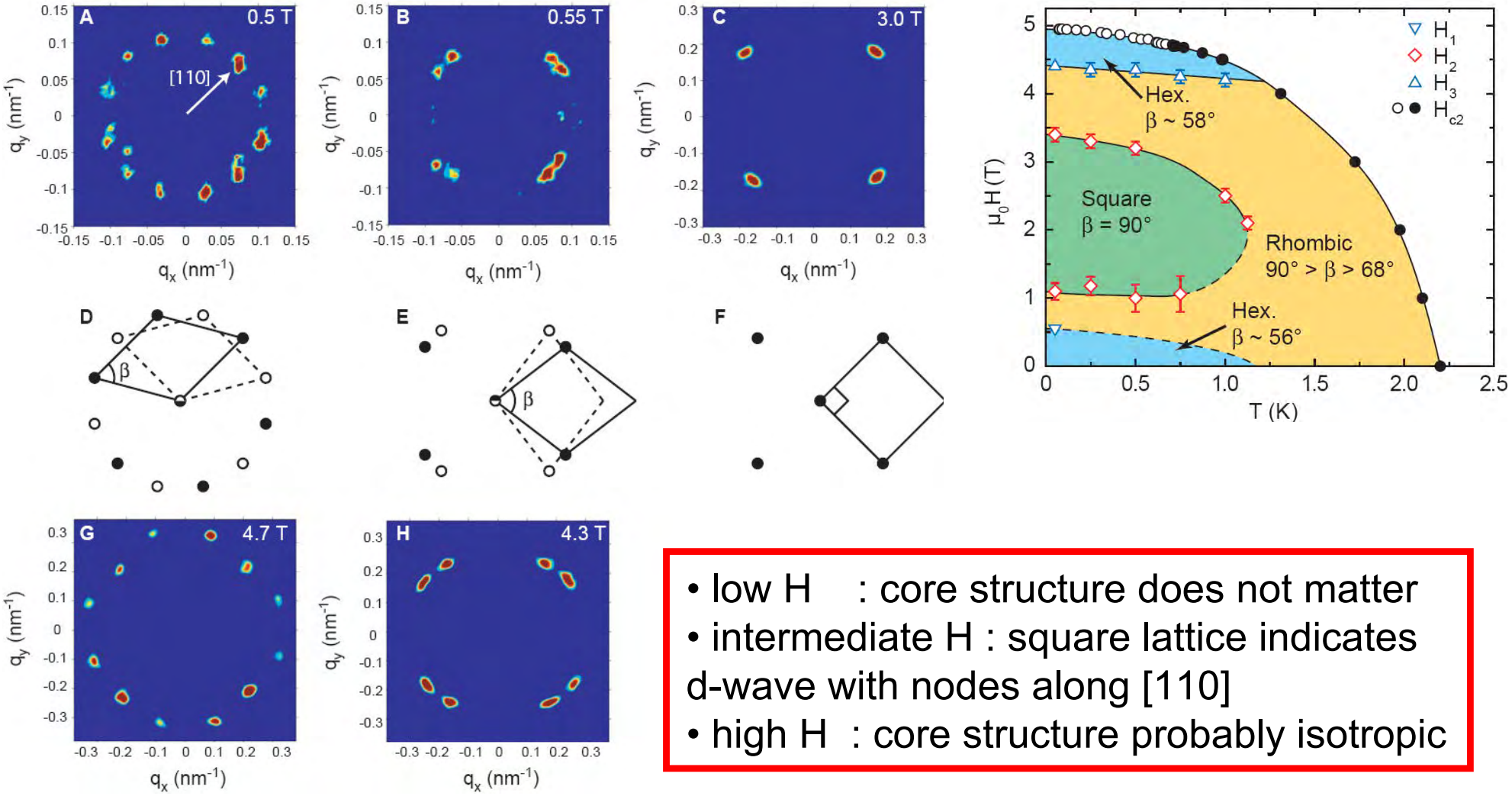
Waiting for new dilution insert at PSI, arrived fall 2006
→ SANS-I experiment

Experiment on $CeCoIn_5$





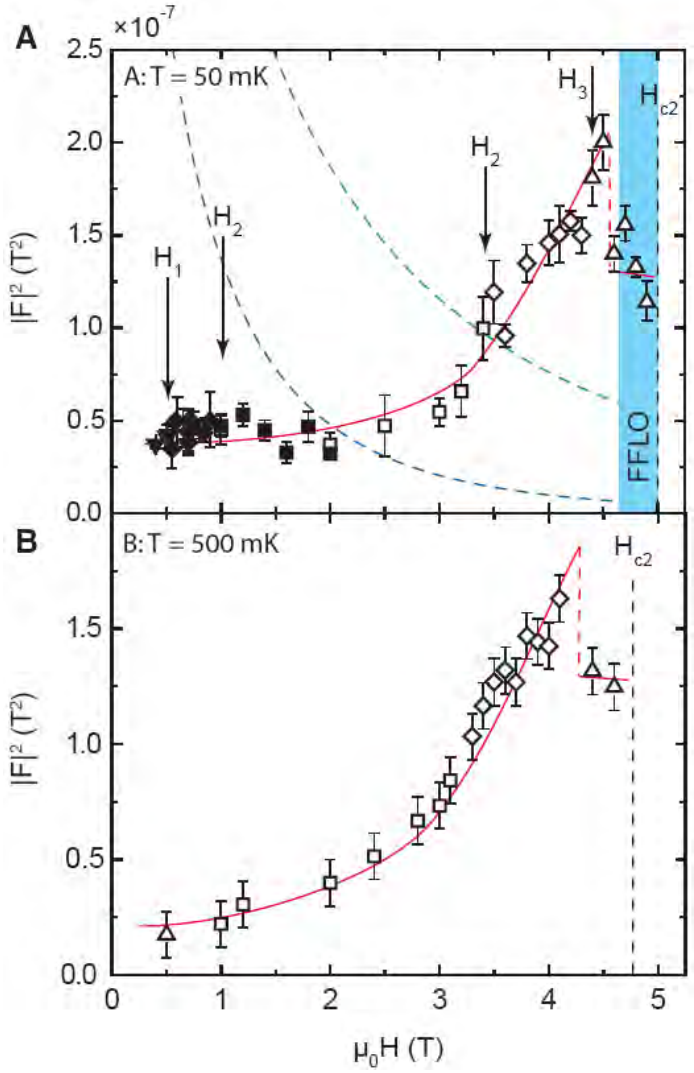
Vortex flux lattice as a function of field H || **c**



- low H : core structure does not matter
- intermediate H : square lattice indicates d-wave with nodes along [110]
- high H : core structure probably isotropic

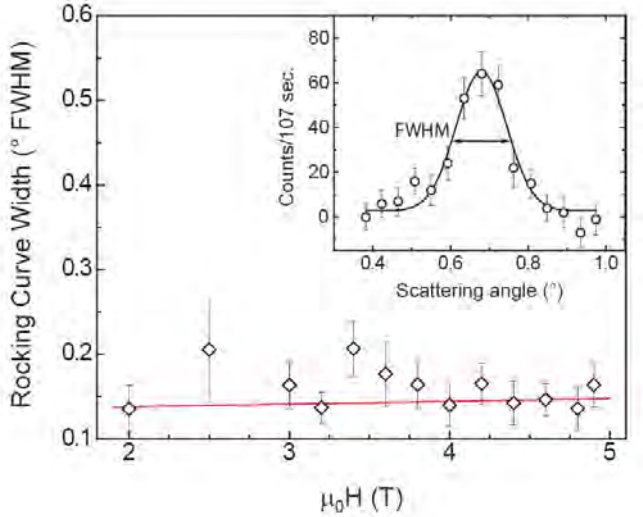
A. D. Bianchi et al, Science **319**, 177 (2008)

Vortex form factor



Penetration depth:
$\lambda \sim 4000\text{-}5000$ Å

Scattering intensity should decrease with increasing field (loss of contrast)
→ not observed in $CeCoIn_5$



→ Correlation length does not depend on the magnetic field strength

Novel vortex structure with paramagnetic cores

A. D. Bianchi et al, Science **319**, 177 (2008)

Summary

- $CeCoIn_5$ is a singlet d-wave superconductor close to magnetic quantum critical point
- novel vortex structure
- High-field/low-temperature on a non-magnetic neutron scattering instrument was crucial for a successful study