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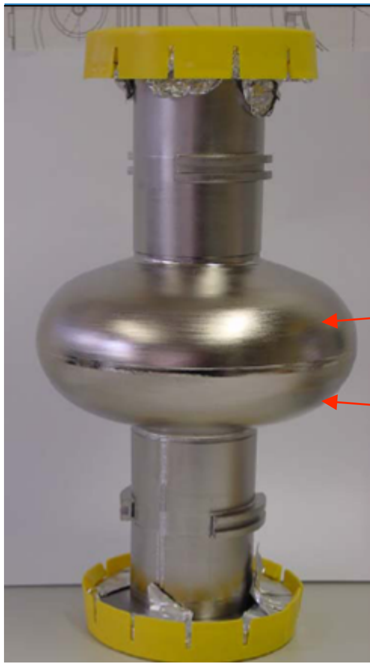

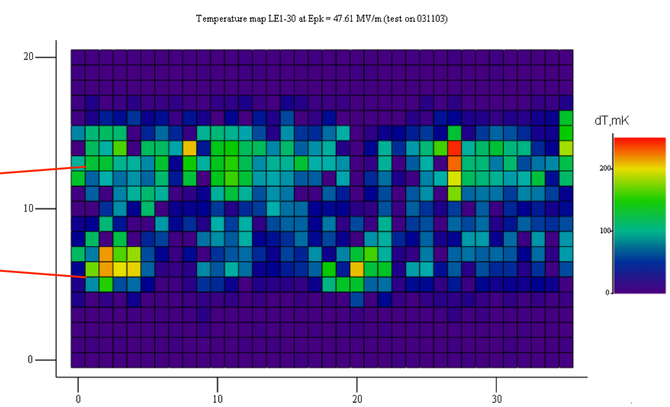

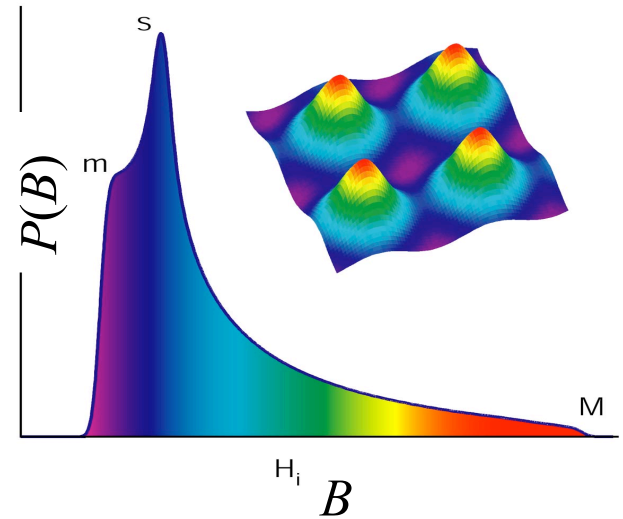

Muon Spin Rotation/Relaxation Studies of Niobium for SRF Applications

Anna Grassellino, Ph.D. Candidate, University of Pennsylvania

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

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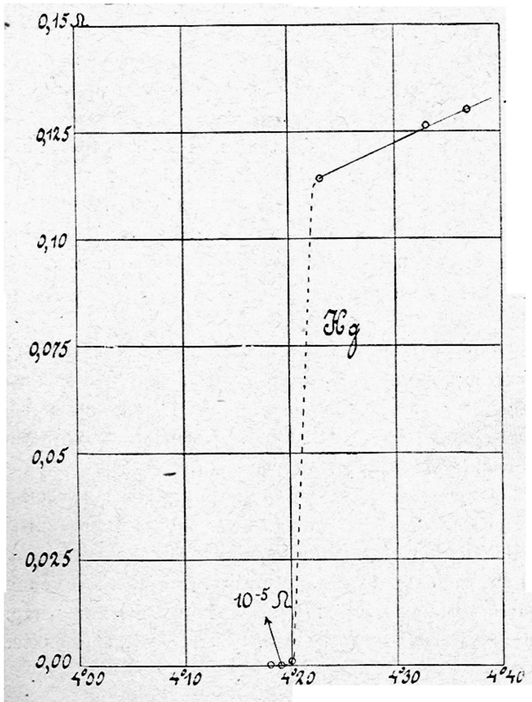
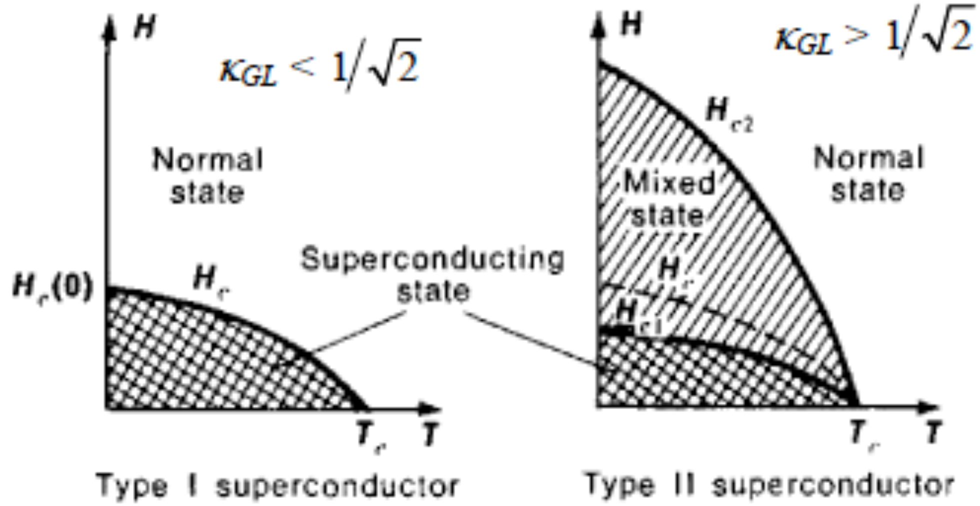
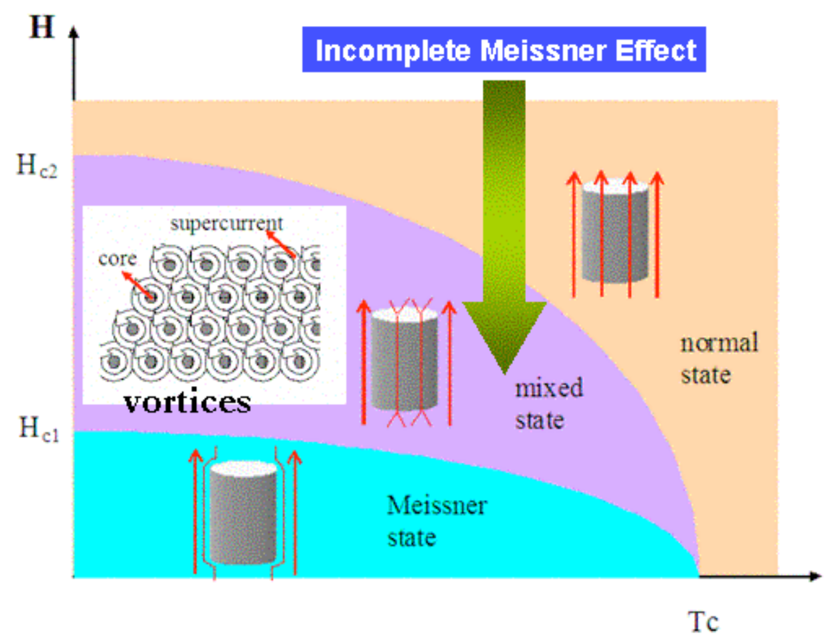
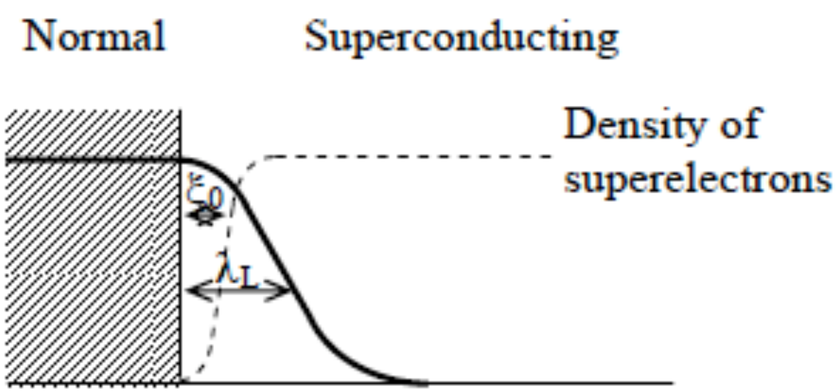
Superconductivity





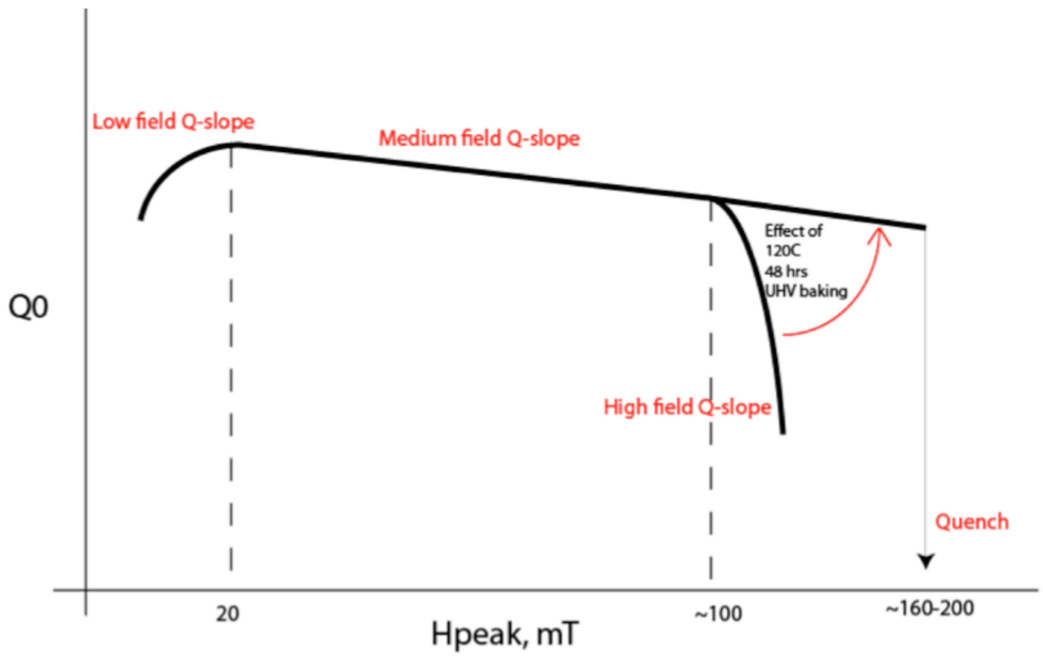
Nb: (marginal) type 2





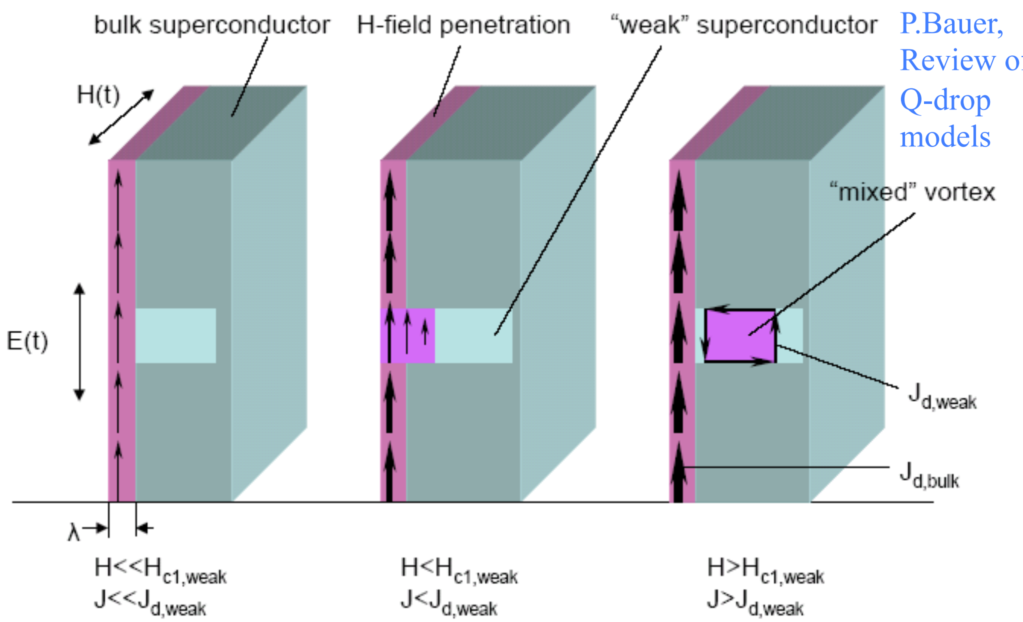
Q-slope in Nb cavities

- Degradation of quality factor with the applied RF field
- Medium field Q-slope: gradual decrease in range Hpk~20-100 mT
- **<u>Problem we want to study: High field Q-drop: sharp losses above peak field ~80-100 mT</u>**
- HFQS signature: 120C bake 48 hrs UHV improves/removes HFQS



- **Huge number of models in the history of SRF to explain HFQS**
- **<u>None so far unconfutably proves causes or mechanisms</u>**

HFQS: early magnetic flux entry?



P.Bauer, Review of Q-drop models

Table 1. H_P and H_{C2} at 2 K and T_C of various samples of Nb.

Sample	T_C (K)	H_P (Oe)	H_{C2} (Oe)
Nb S_1-LG	9.2	1800	6500
Nb S_2-LG	9.05	1050	3700
Nb S_3-LG	9.08	1250	3800
Nb S_1-FG	9.26	1600	7500
Nb S_2-FG	9.05	950	3800
Nb S_3-FG	9.08	1100	4000

Roy et al, Supercond. Sci. Technol. 22 (2009) 105014

- **'Weaker' superconducting regions allow 'premature' magnetic flux entry in the Nb surface**
- **Model never proved, but there are experimental hints towards it, eg**:

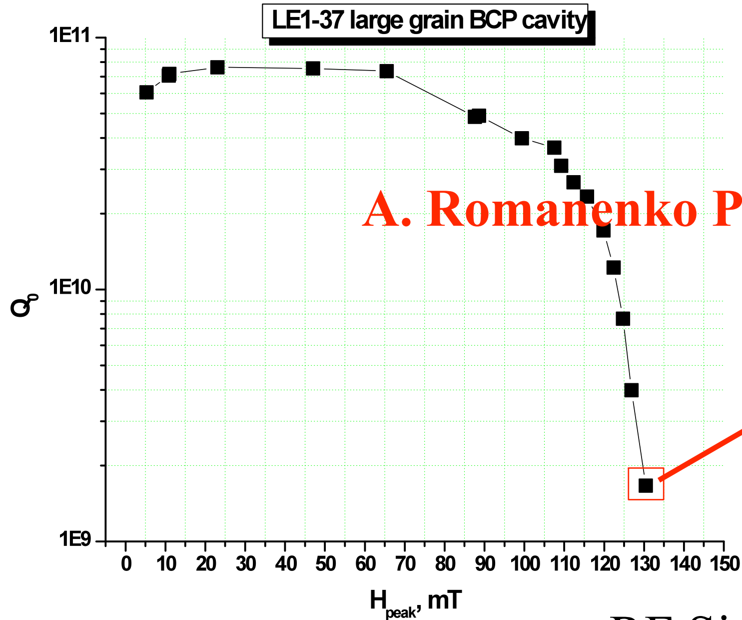
-Magnetization measurements of Nb samples with different treatments (Roy, Myneni): field of entry varies in agreement with RF cavity performance

-Cutout samples studies (Romanenko, Padamsee): decrease in average dislocation density observed by EBSD after 120C baking -working hypothesis – surface dislocations provide sites for early flux penetration (below bulk Hc1)

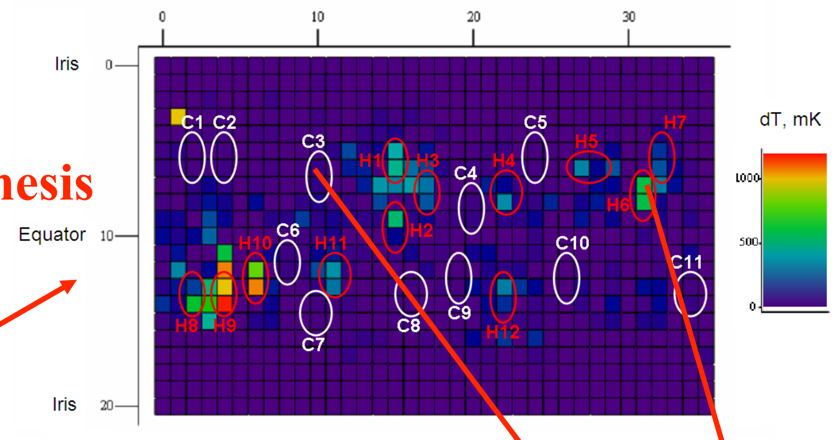
HFQS: how to prove if it's early flux penetration?

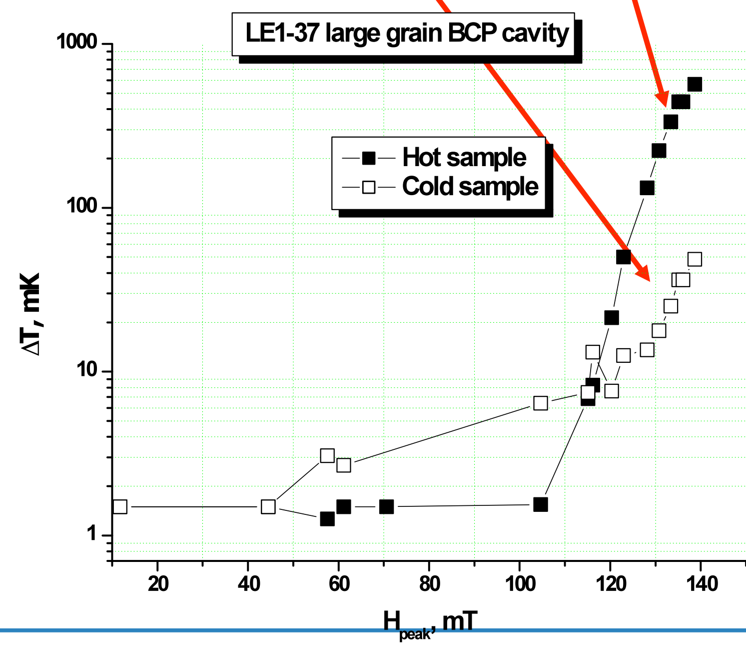
- **GOAL: Design an experiment to prove magnetic flux entry as the right or wrong mechanism behind HFQS**
- We study for the first time the field of first flux entry in RF characterized samples → **HFQS limited cutout samples**:
  - Hot vs cold
  - **Baked vs unbaked**
- Look for correlation field of flux entry – onset of HFQS (as per thermometry characterization and after surface treatments like 120C baking and BCP)
- Need of local, sensitive magnetic field probe: **Muon Spin Rotation**
- We will see that the probe is able to measure with extreme precision what fraction of the sample contains magnetic flux

Samples used: cutouts from large/small grain BCP 1.5 GHz cavities (courtesy of Cornell)

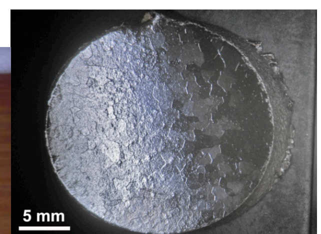


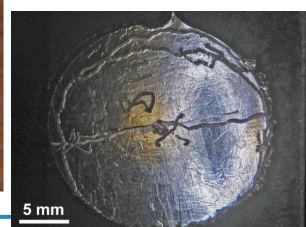
A. Romanenko Ph.D. thesis



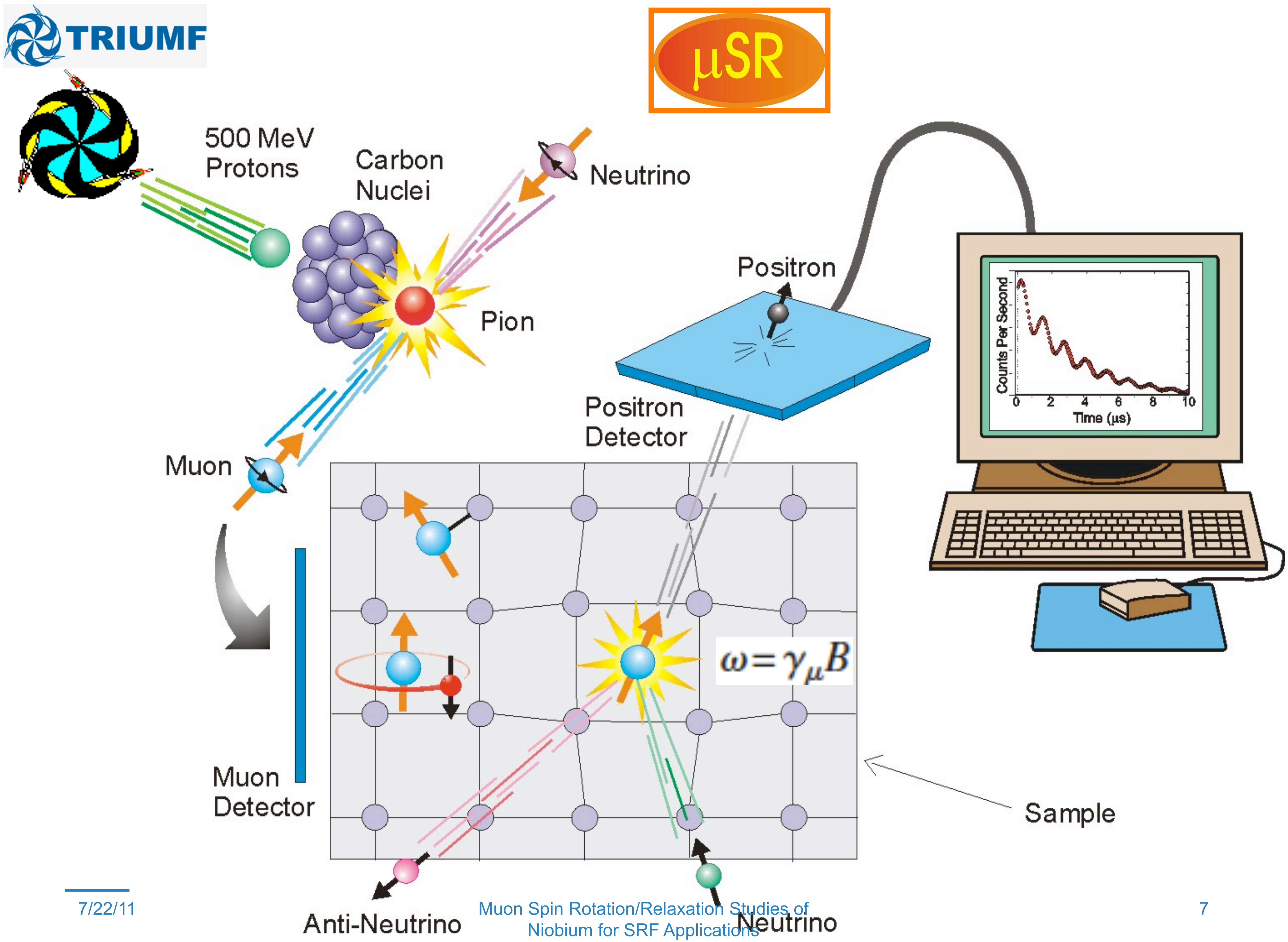


RF Side

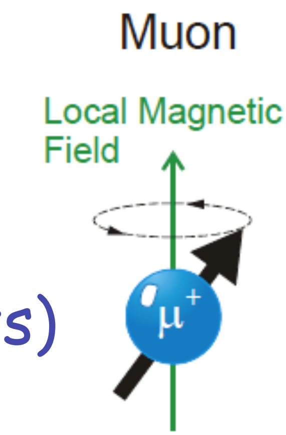




Outer Side


TRIUMF
µSR
500 MeV
Protons
Carbon
Nuclei
Neutrino
Pion
Positron
Positron
Detector
Counts Per Second
0 2 4 6 8 10
Time (µs)
Muon
Muon
Detector
$\omega = \gamma_\mu B$
Sample
Anti-Neutrino
Neutrino

The muon is sensitive to the **vector sum** of the local magnetic fields at its stopping site. The local fields consist of:



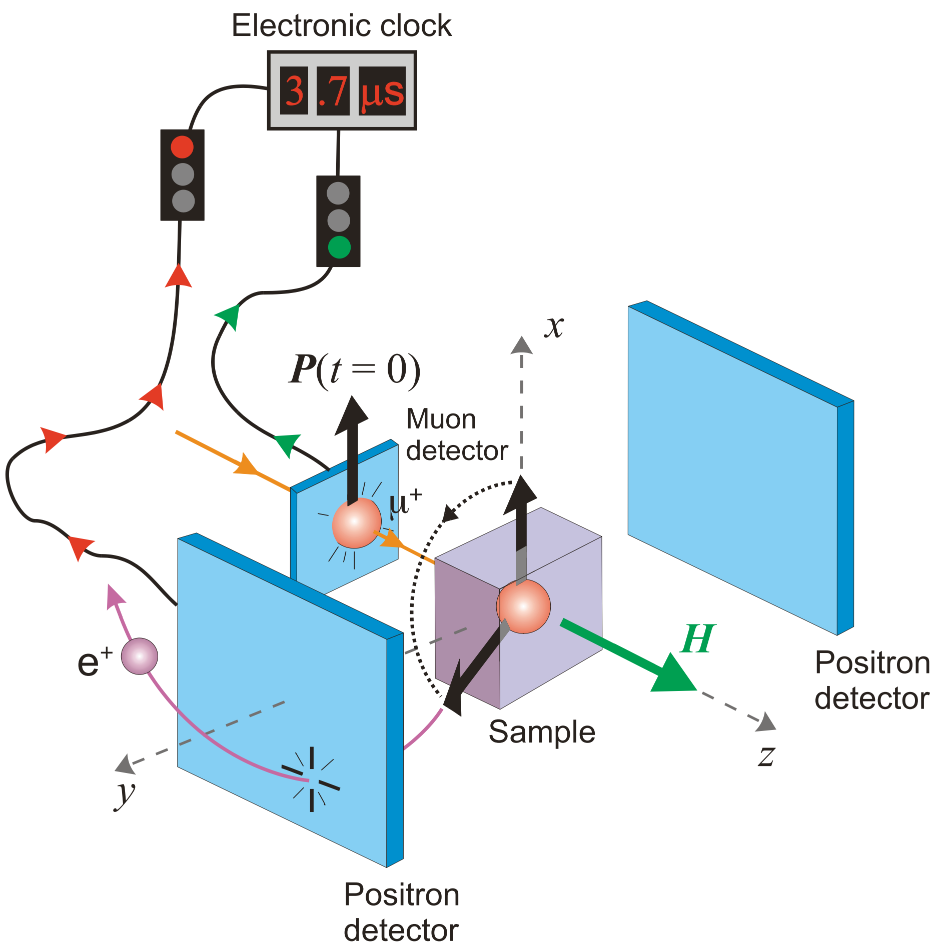
- those from **nuclear** magnetic moments
- those from **electronic** moments
 (100-1000 times larger than from nuclear moments)
- **external** magnetic fields

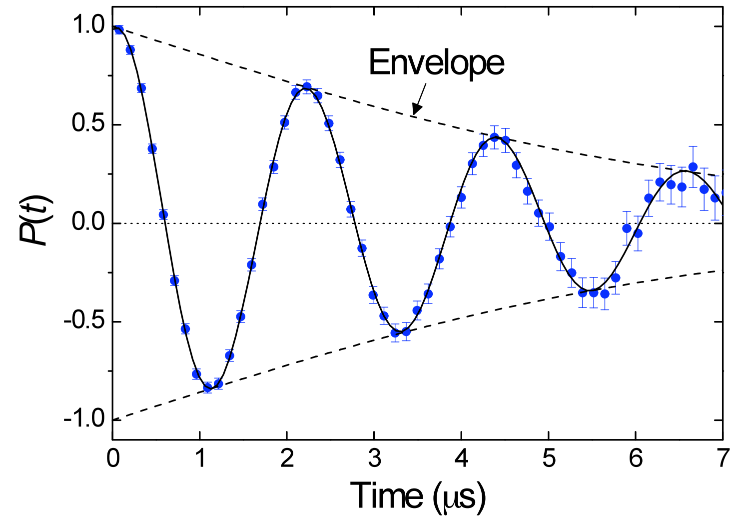
$$\omega = \gamma_\mu B$$

•**As a local probe, μSR can be used to deduce Magnetic volume fractions**

•So we will be able to measure what fraction of the sample is penetrated by magnetic flux as function of the field, and look for correlation with the RF performances

Field of first entry measurement: Transverse-Field μSR



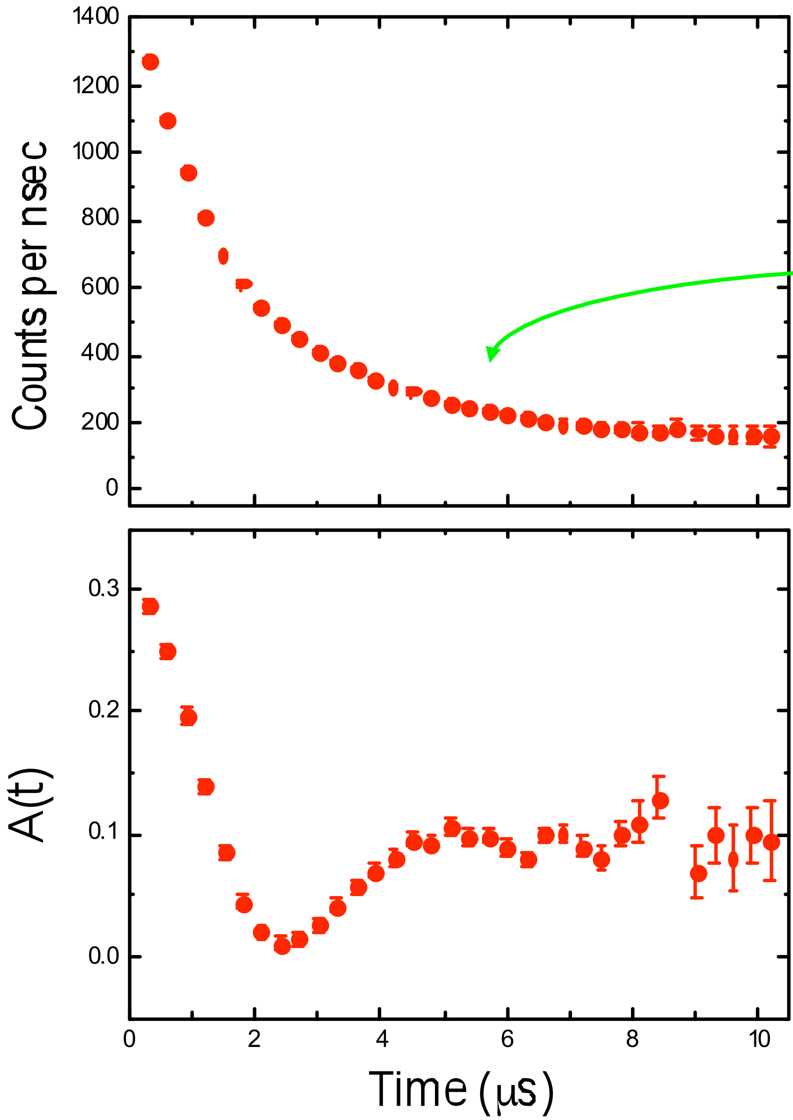


The information on local fields is contained in the time evolution of the muon spin Polarization which is described by:

$$P(t) = G(t)\cos(\gamma_\mu B_\mu t + \phi)$$

where $G(t)$ is a relaxation function describing the ***envelope*** of the TF-μSR signal that is sensitive to the width of the static field distribution or temporal fluctuations.

Signal obtained: **asymmetry spectrum**



The **count rates** for opposing e^+ detectors:

$$N_B(t) = N_0 e^{-t/\tau_\mu}\left[1 + a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)\right]$$

$$N_F(t) = N_0 e^{-t/\tau_\mu}\left[1 - a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)\right]$$

Forming the B-F count rate ratio:

$$\frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)} = a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)$$

$$= a_0 P(t) \equiv A(t)$$

μSR asymmetry spectrum

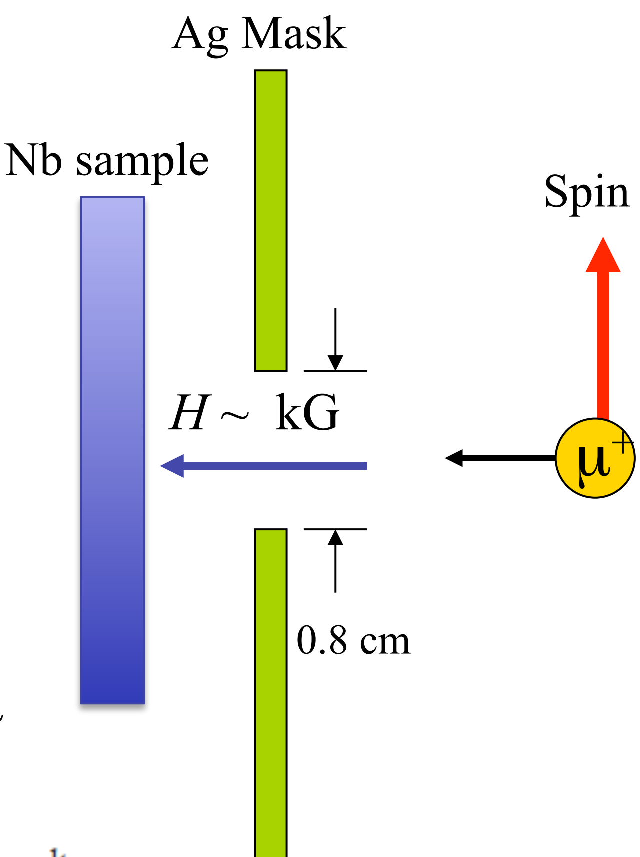
- **Frequency of oscillation → amplitude of local field**
- **Amplitude of asymmetry → magnetic volume fraction**

TF-muSR setup for cutout samples studies

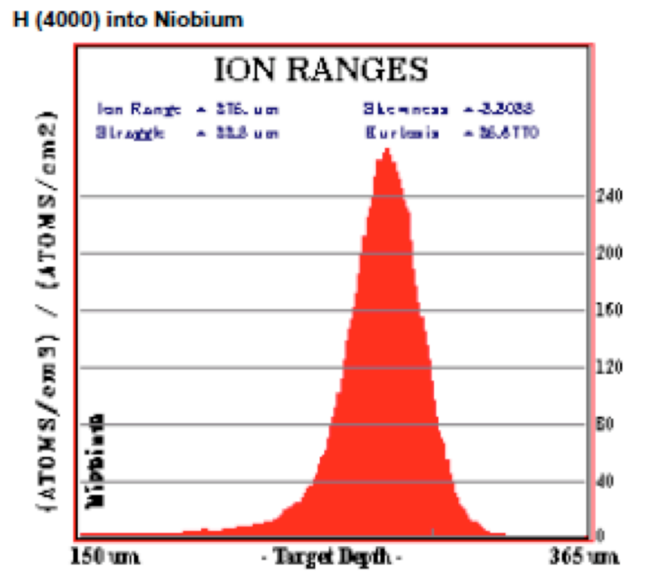
- **DC magnetic field perpendicular to sample, T=2.3K (and measurements at 4.5K up to 8K), full scan in field 0-270mT**

Samples:
•3 mm thick
•2cm diameter

•Field at the center ~ applied field (in the field range of interest -above 70mT, $B_y(0,0)$ ~ 15mT behind B_{appl})

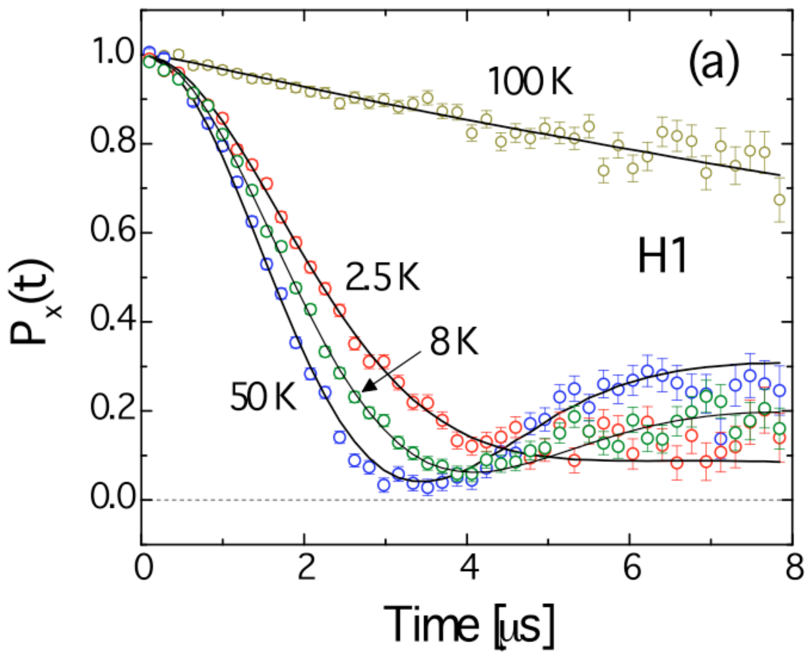


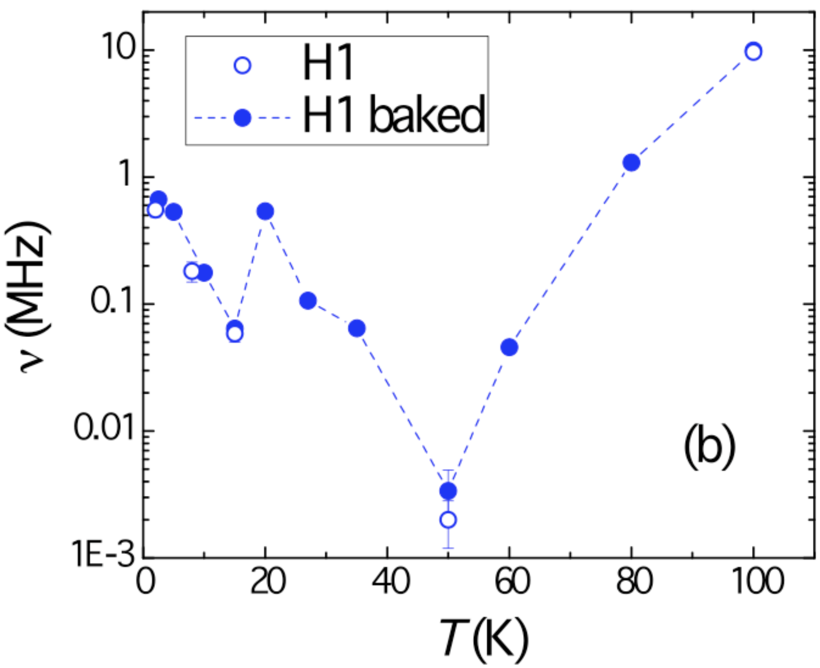
Muon stopping depth ~300μm



Ernst Helmut Brandt Irreversible magnetization of pin-free type-II superconductors PHYSICAL REVIEW B VOLUME 60, NUMBER 17

Zero Field muSR results

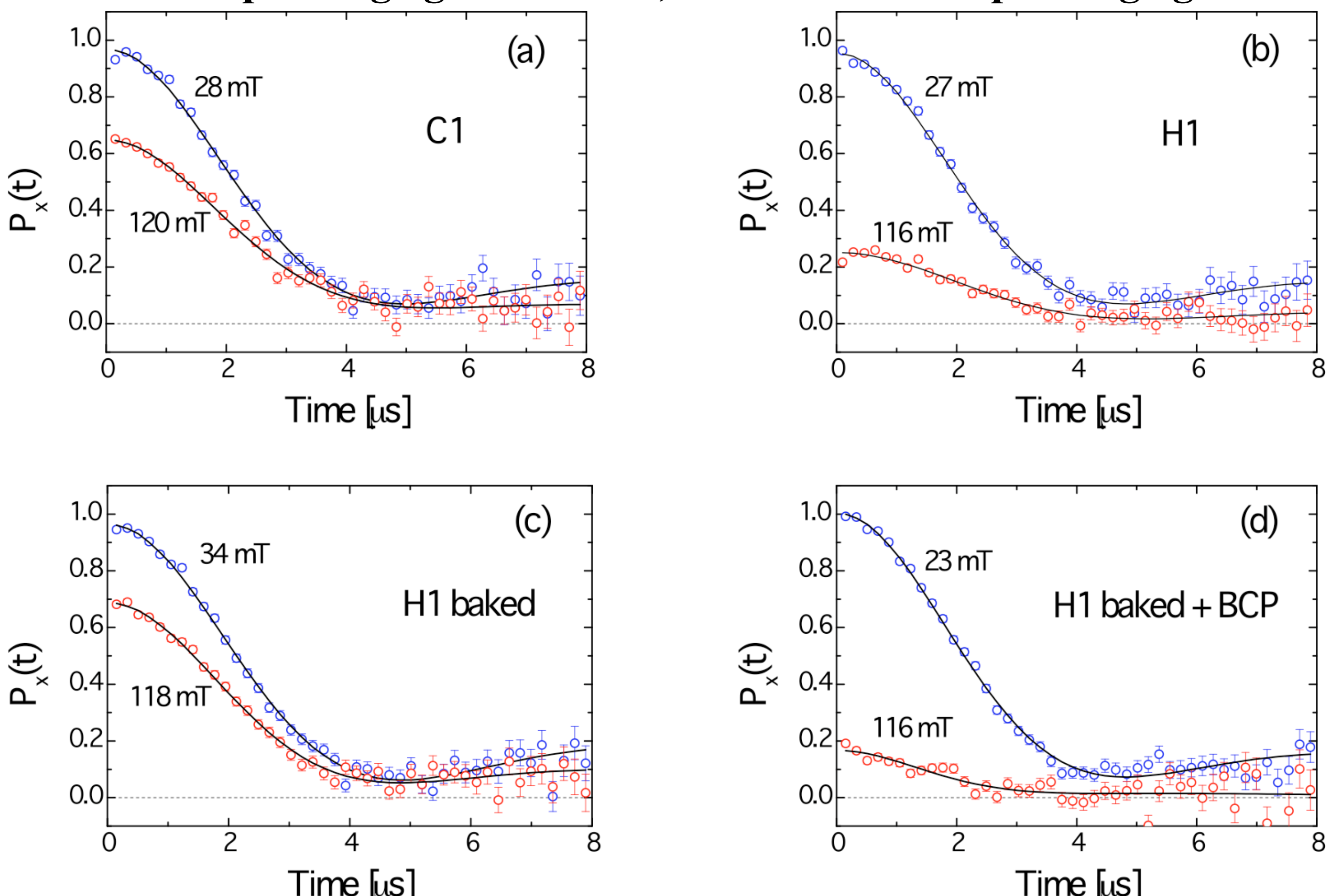




- Representative ZF-μSR spectra of sample H1 at different temperatures, which depends on lattice properties and impurity content
- Temperature dependence of the muon hop rate in sample H1 before and after baking
- Results consistent with what observed in previous μSR experiments on nitrogen doped Nb
- **Measurement very interesting to be done in the surface layer to study hydrogen trapping at the surface before/after baking**

Example of asymmetry signals, 30 and 120mT, 2.3K

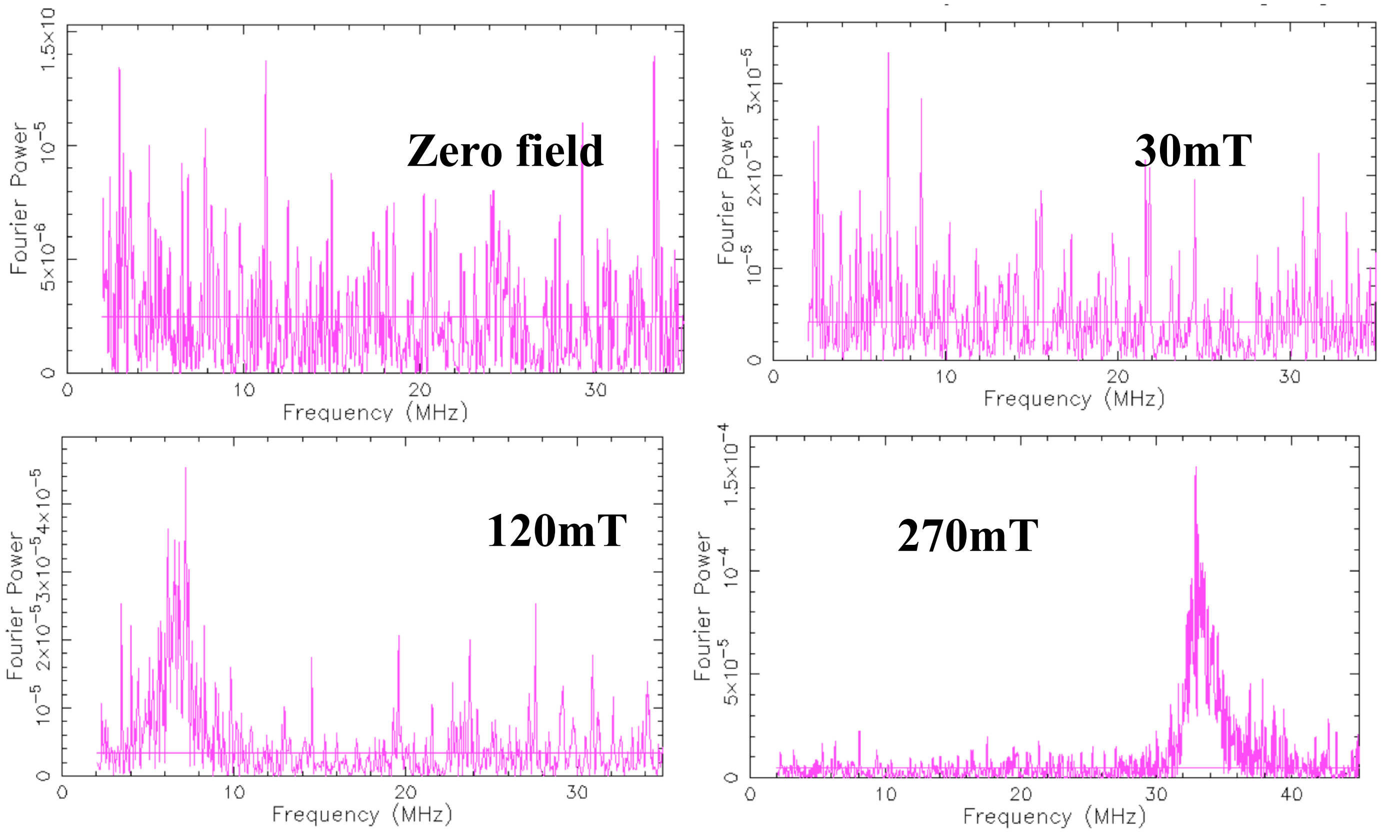
C1- cold spot large grain cutout, **H1 – hot spot large grain cutout**



H1 after 48 hours UHV 120C baking

H1 after 48 hours UHV 120C baking plus 5μm BCP

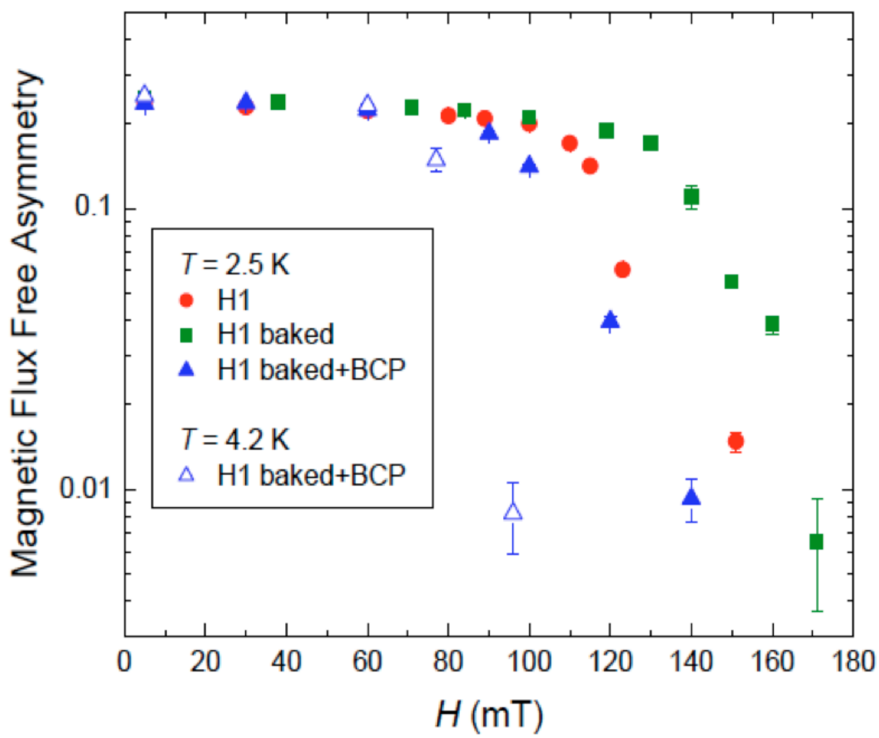
Fast Fourier Transform: internal field distribution

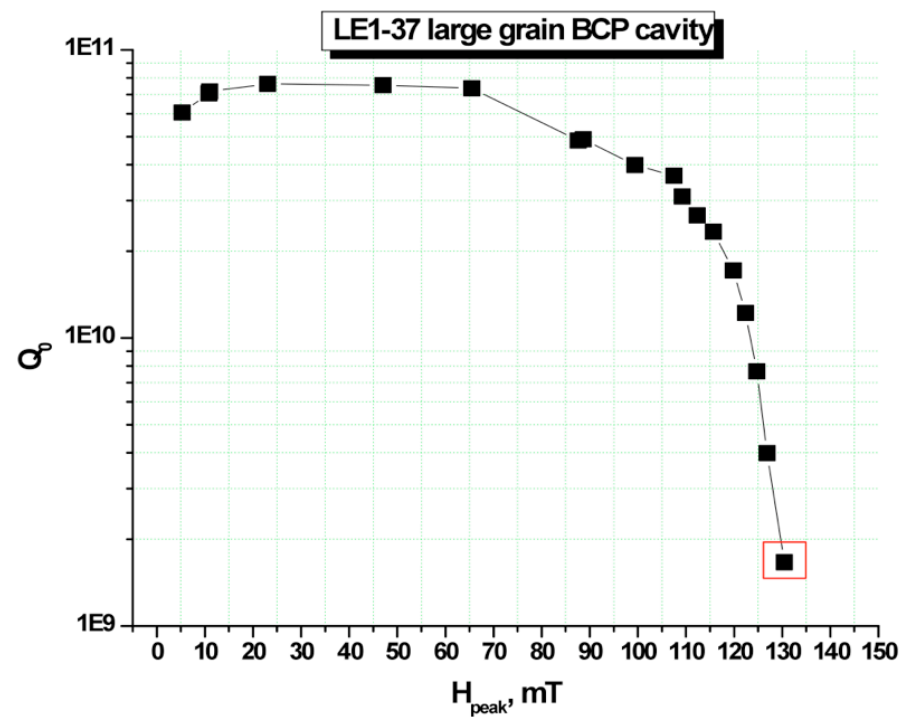


Fast Fourier transforms for sample H1 at 2.3K and respectively field levels: zero, 30mT, 120mT (peak of flux appearing at ~50mT), 270mT (peak of flux ~260mT)

→ Suggests an **inhomogeneous** surface with **preferential sites for flux entry**

Strong correlation fraction of sample NOT containing flux vs RF cavity performance



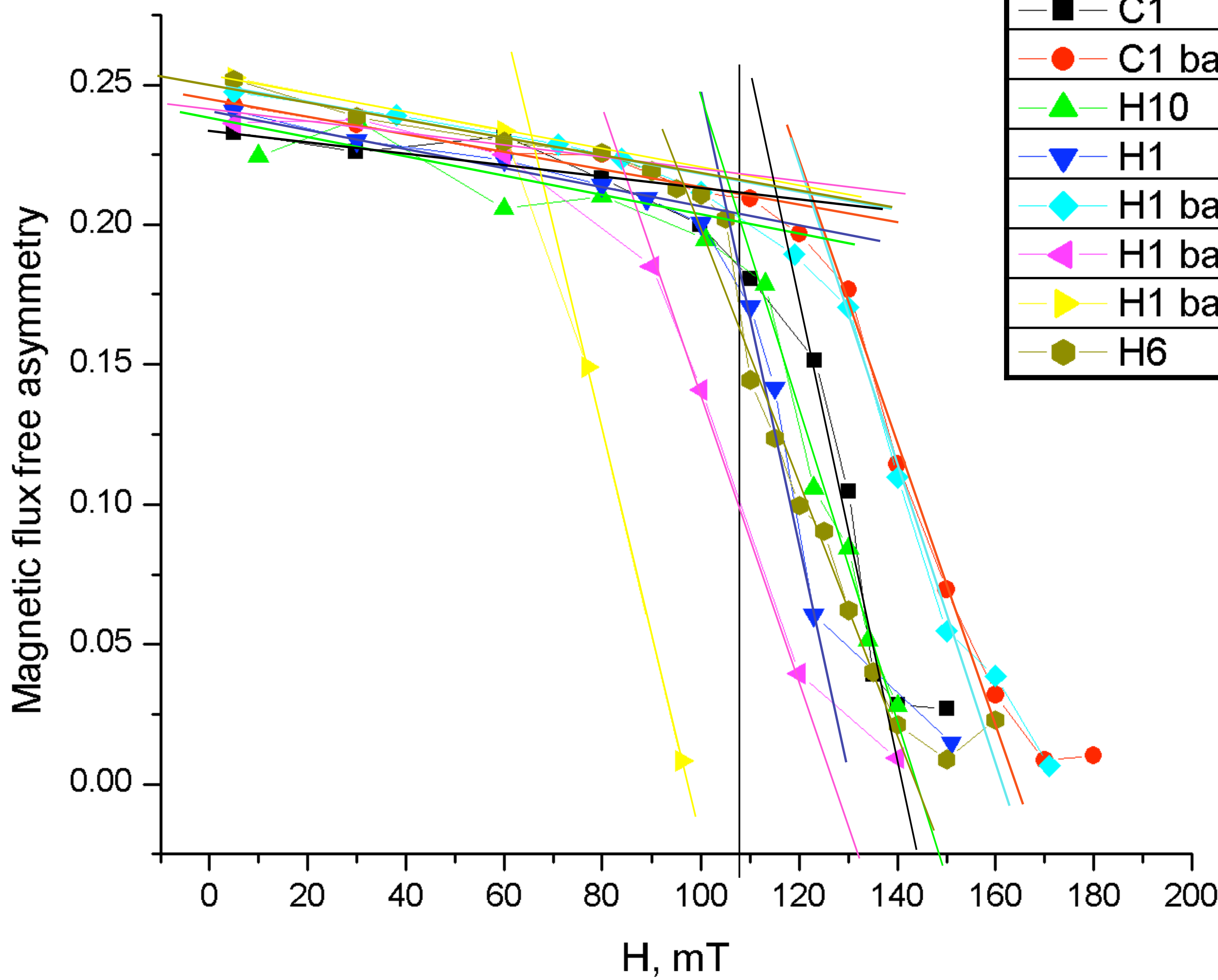


•Onset of flux entry measured with muSR strongly correlates with onset of RF HF losses as for thermometry characterization

•Measurements consistent among all 6 samples tested

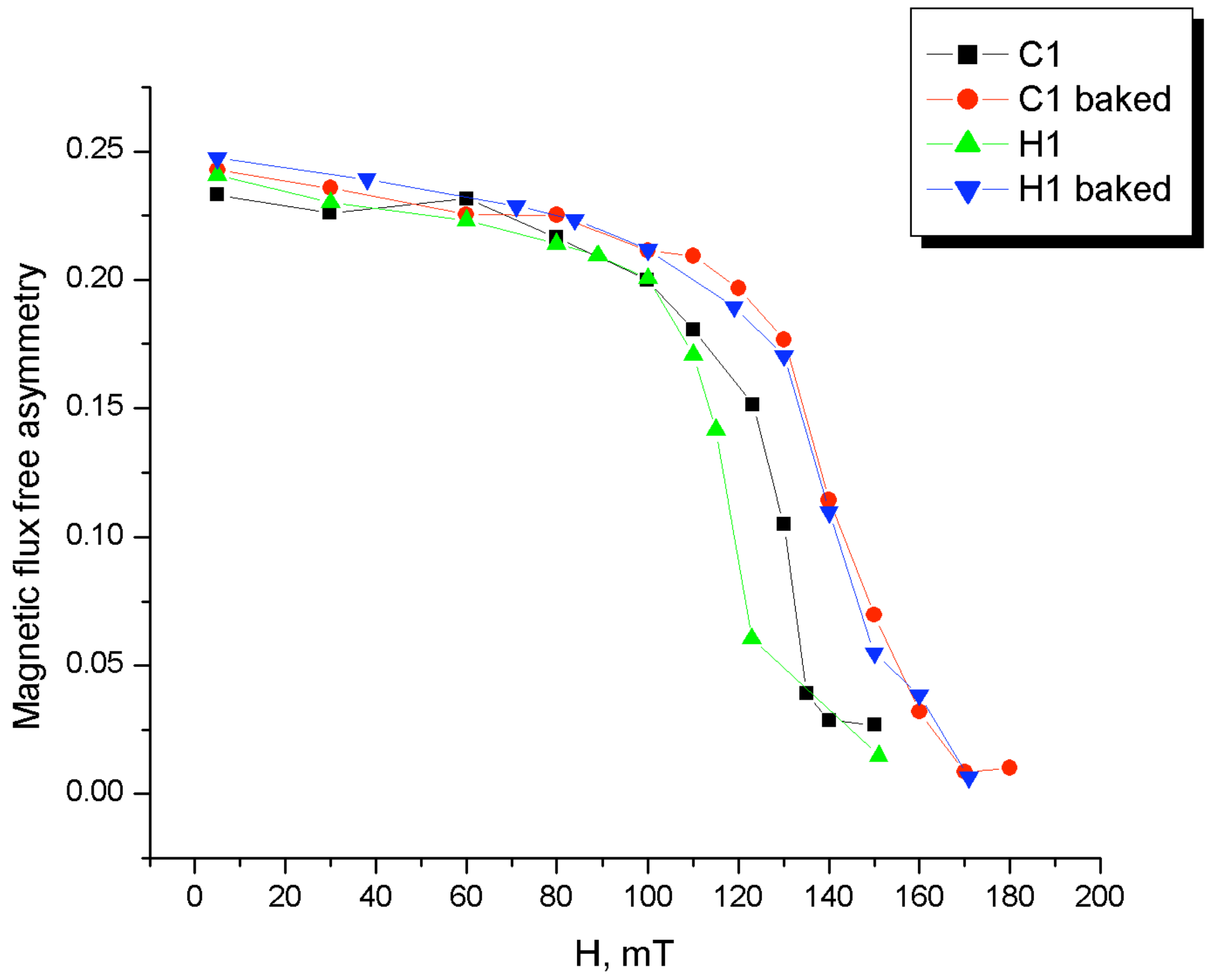
TRIUMF

Results - all samples



	B_{ent}
C1	115
C1 baked	123
H10	108
H1	106
H1 baked	122
H1 baked BCP	83
H1 baked BCP 4	66
H6	95

Hot vs Cold sample before/after bake



In conclusion

- Muon spin rotation used @ TRIUMF for SRF applications for the first time
- Experiment results strongly suggest early magnetic flux entry at ‘weaker spots’ as high field Q-slope losses mechanism in SRF Nb cavities
- Invaluable tool for studying superconducting parameters (λ, ξ, Hc1, Hc2…) and their temperature/field dependence

Future direction

- First establish **baseline**: study **ultrapure Nb** single crystal (field of entry, superconducting parameters)
- Understand **which step of Nb processing for cavities causes early flux entry** → systematic study of field of entry for niobium with different treatments, degree of cold work, RRR…
- **Q_0 and medium field losses** studies: design apparatus for parallel field measurements
- Study **quench** and **post baking losses** spots (Romanenko, FNAL)
- **Thin films and multilayer**: accurate tool for field of entry
- Beamtime already approved for these studies, to be scheduled in fall
- LEM for penetration depth and role of hydrogen in surface

Thanks for your attention!

Back up slides

Pion Decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

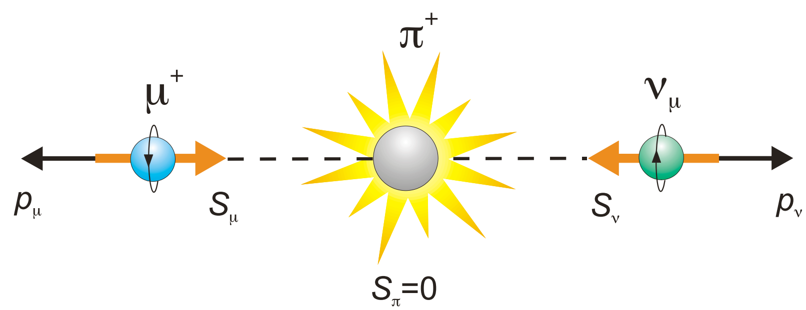
A pion resting on the downstream side of the primary production target has zero linear momentum and zero angular momentum.

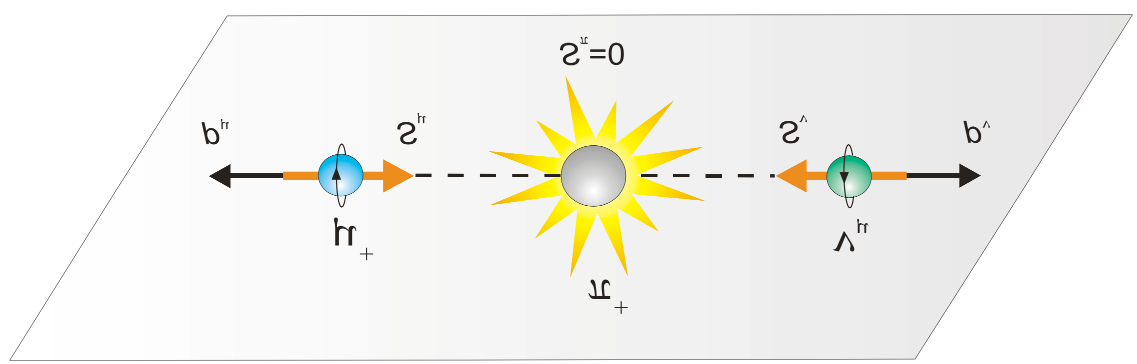
Conservation of Linear Momentum: μ^+ emitted with momentum equal and opposite to that of the ν_μ

Conservation of Angular Momentum: μ^+ and the ν_μ have equal and opposite spin

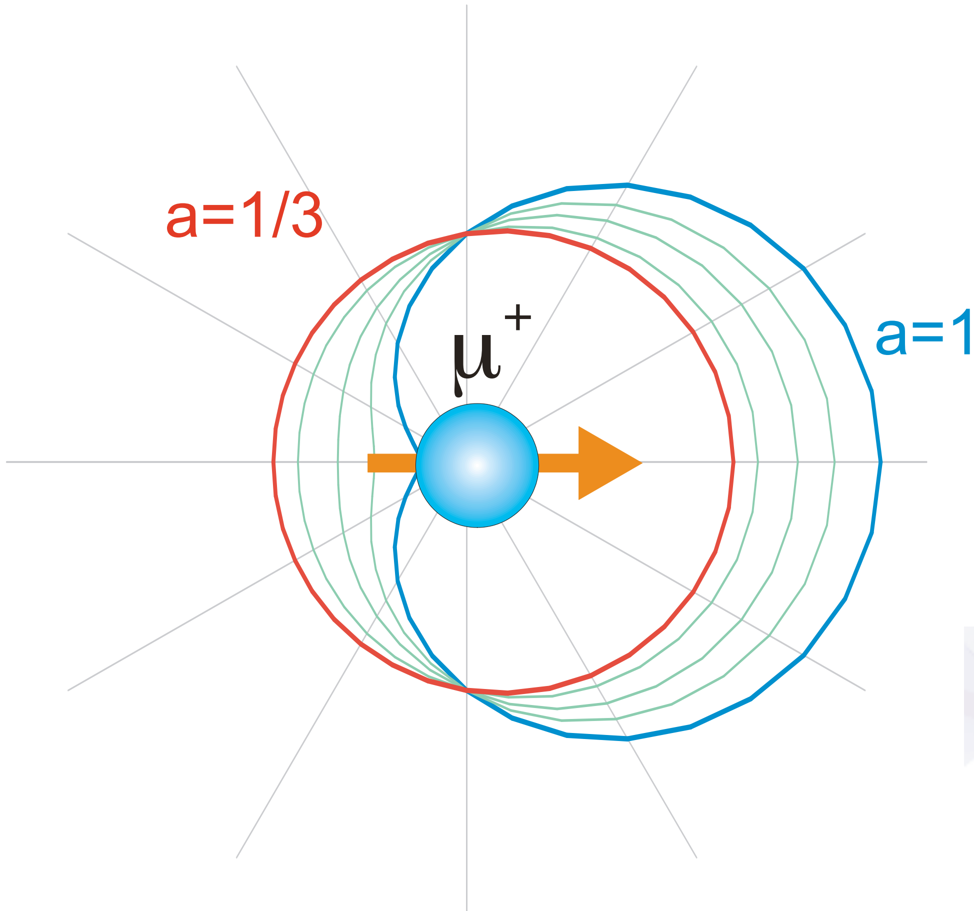
Weak Interaction: only "left-handed" ν_μ are created. **Therefore the emerging μ^+ has its spin pointing antiparallel to its momentum direction**

→ 100% spin polarized!





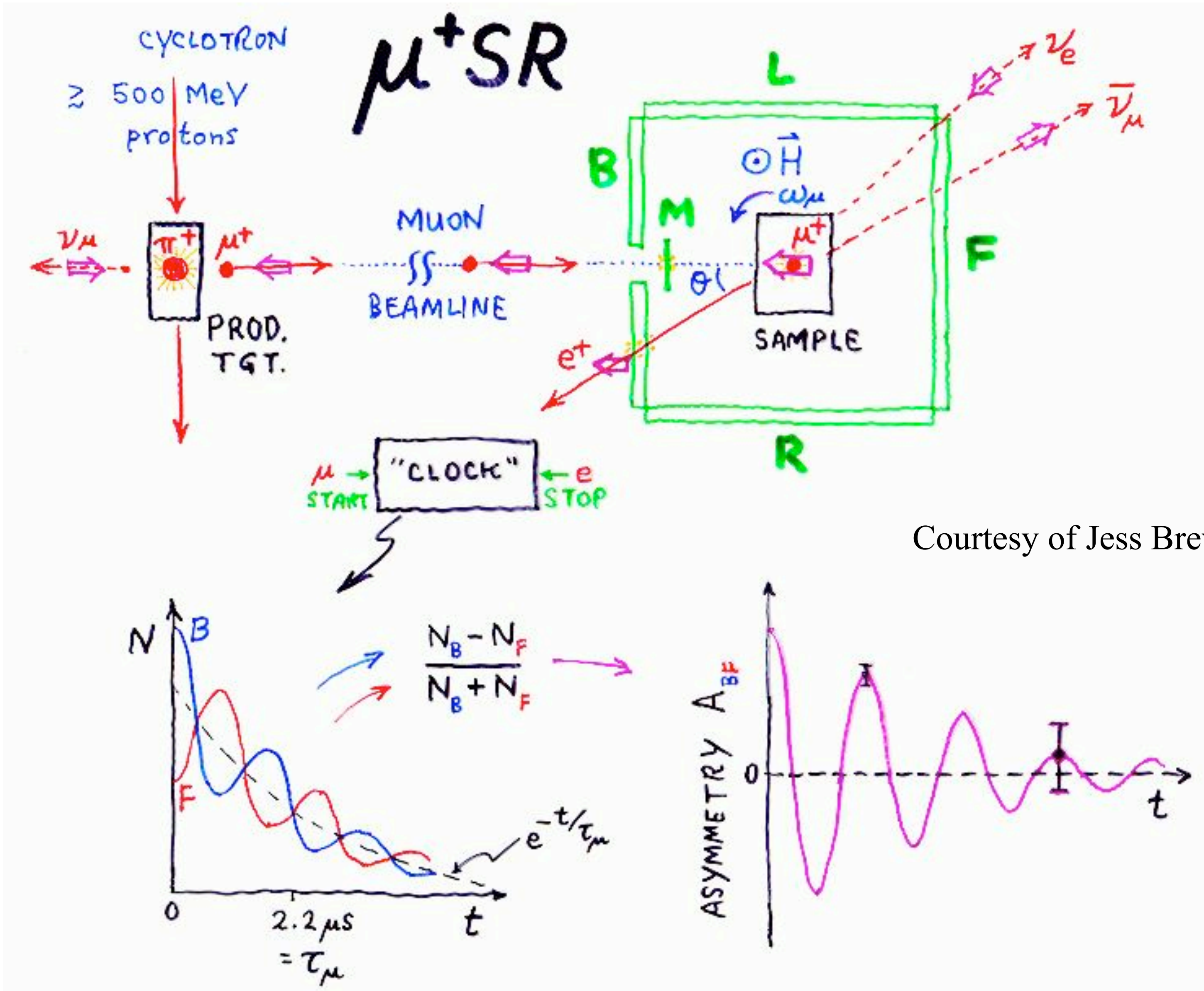
μ^+-Decay Asymmetry



$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

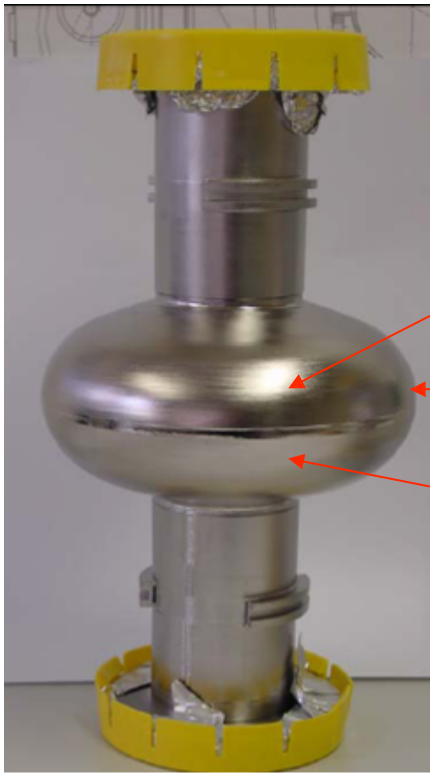
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

Angular distribution of positrons from the μ^+-decay. The asymmetry is a = 1/3 when all positron energies are sampled with equal probability.

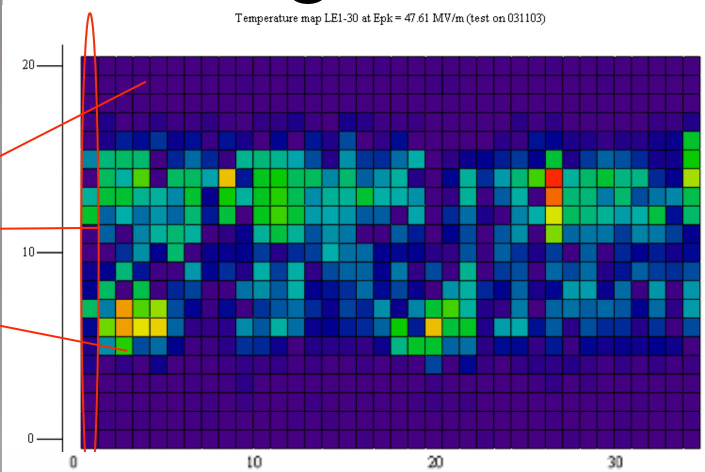


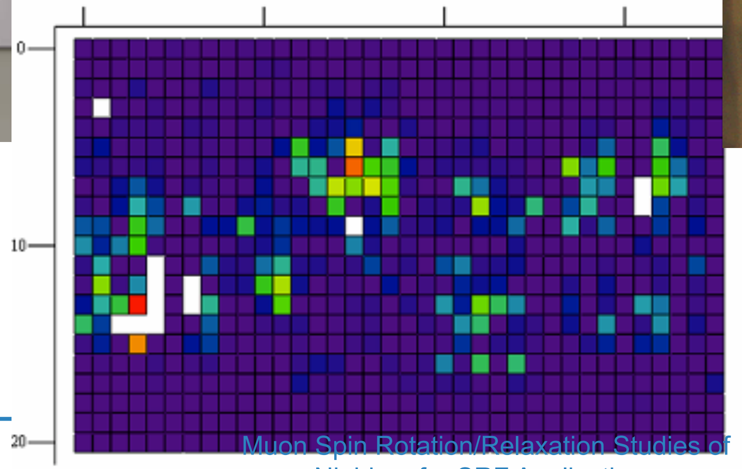
Courtesy of Jess Brewer, TRIUMF

Thermometry characterization of losses

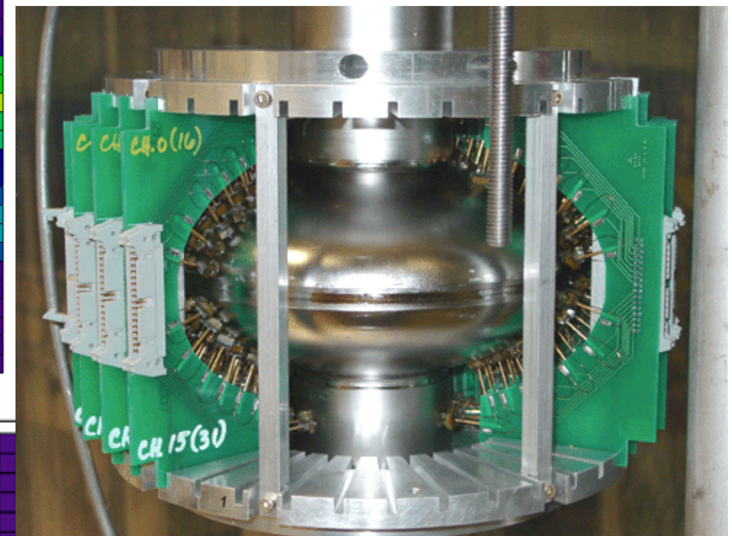


Fine grain





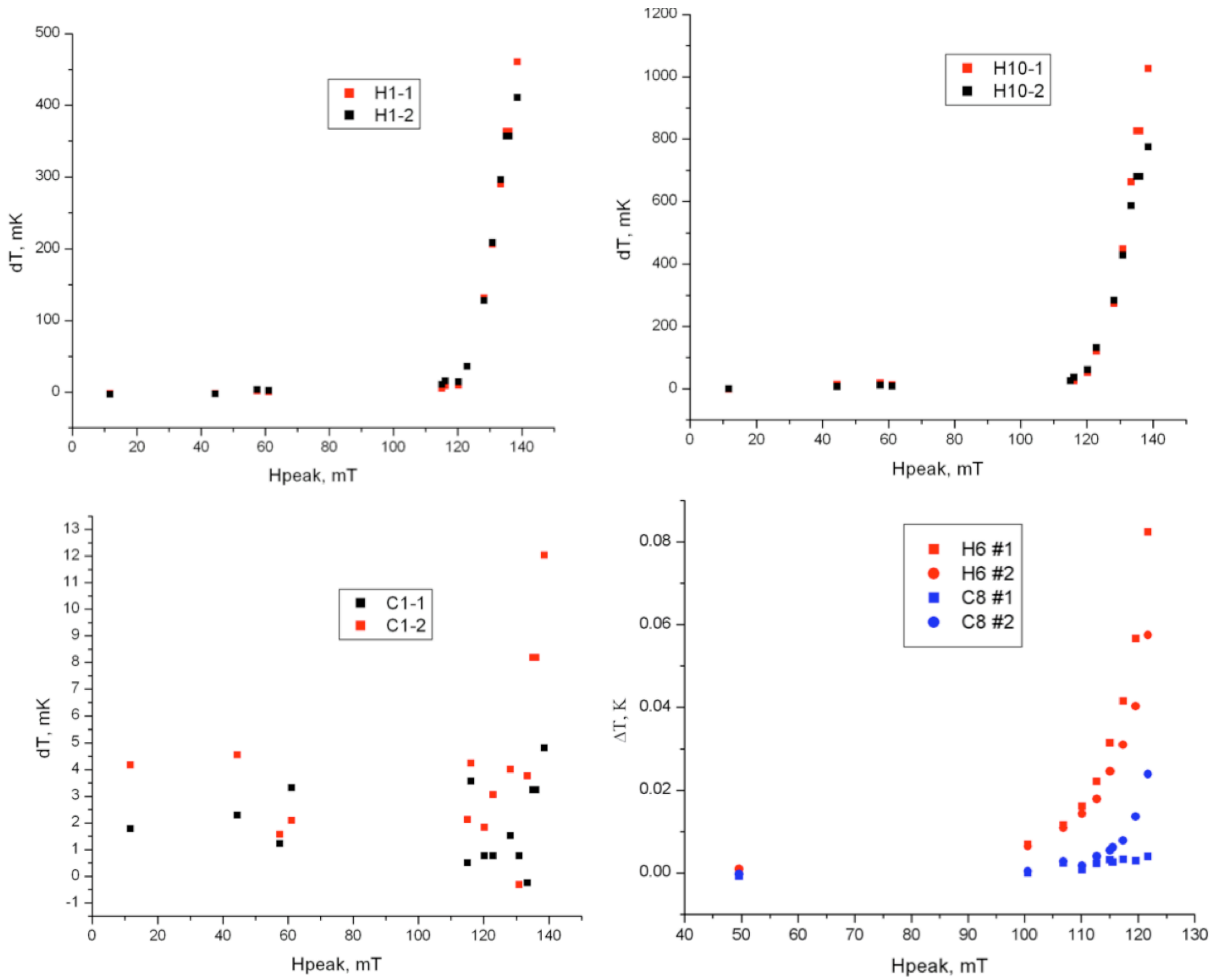
Large grain



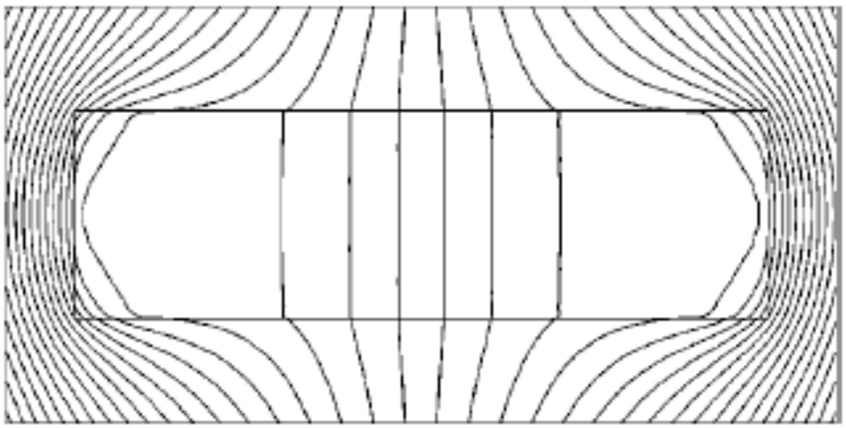
Example of T-map system, G.Ciovati Ph.D. thesis

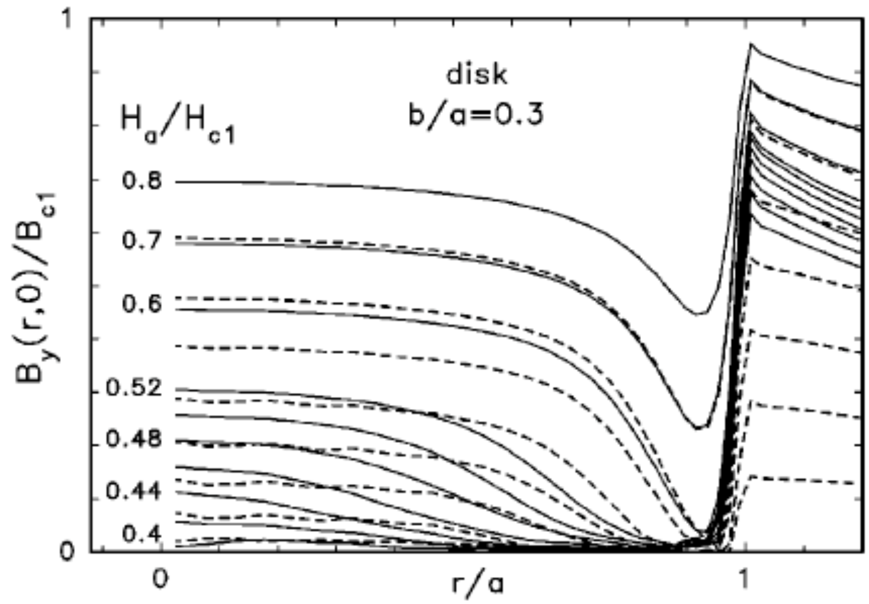
Thermometry maps, courtesy of Cornell

RF characterization of samples studied (A.Romanenko)



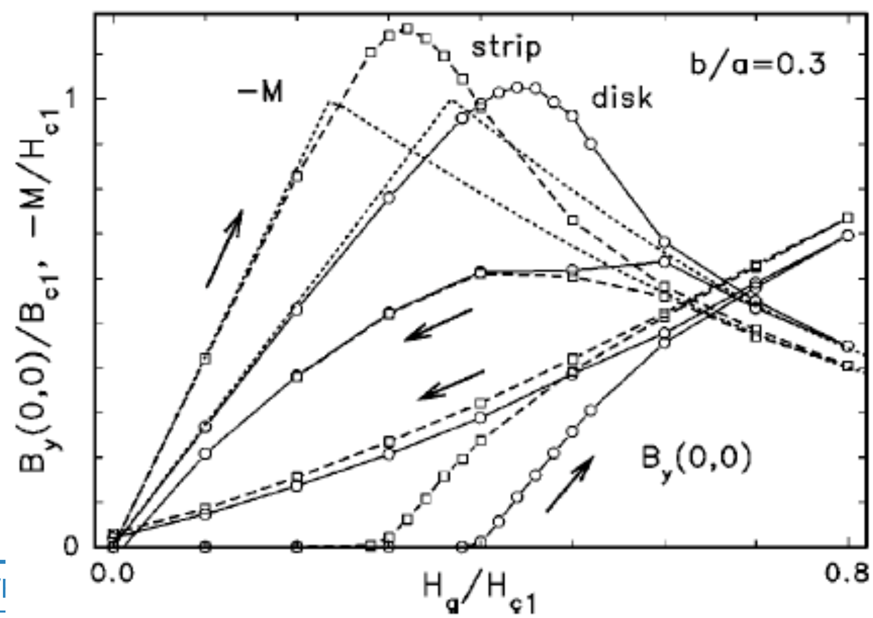
Brandt – demagnetization





$$H_{en}^{strip}/H_{c1} = \tanh\sqrt{0.36b/a},$$

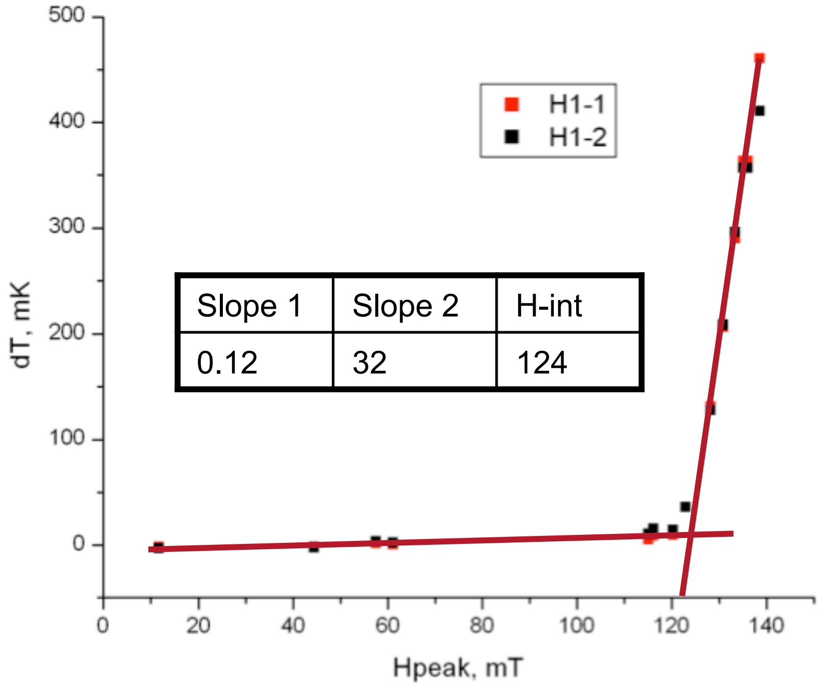
$$H_{en}^{disk}/H_{c1} = \tanh\sqrt{0.67b/a}.$$

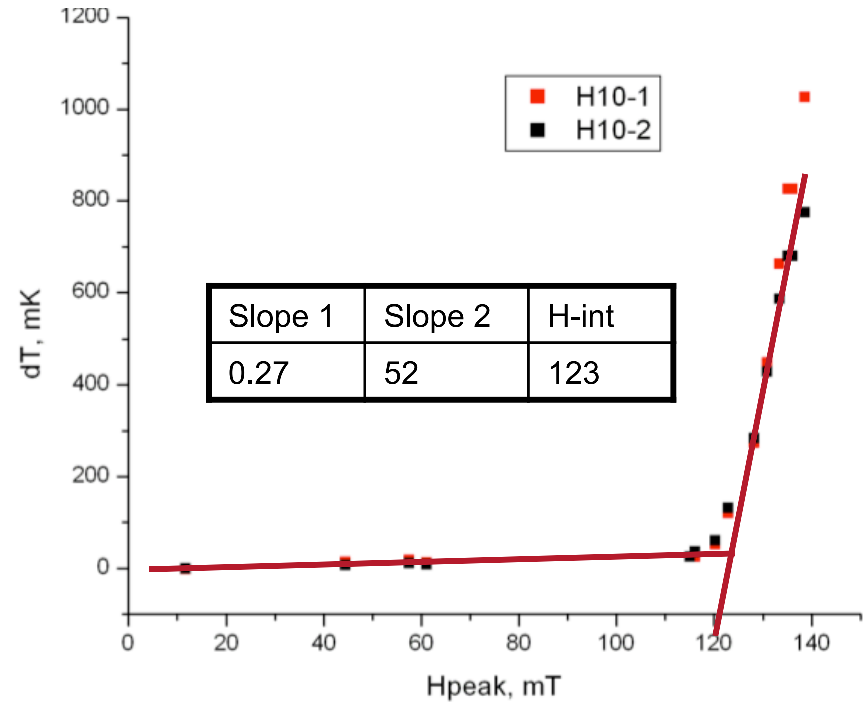


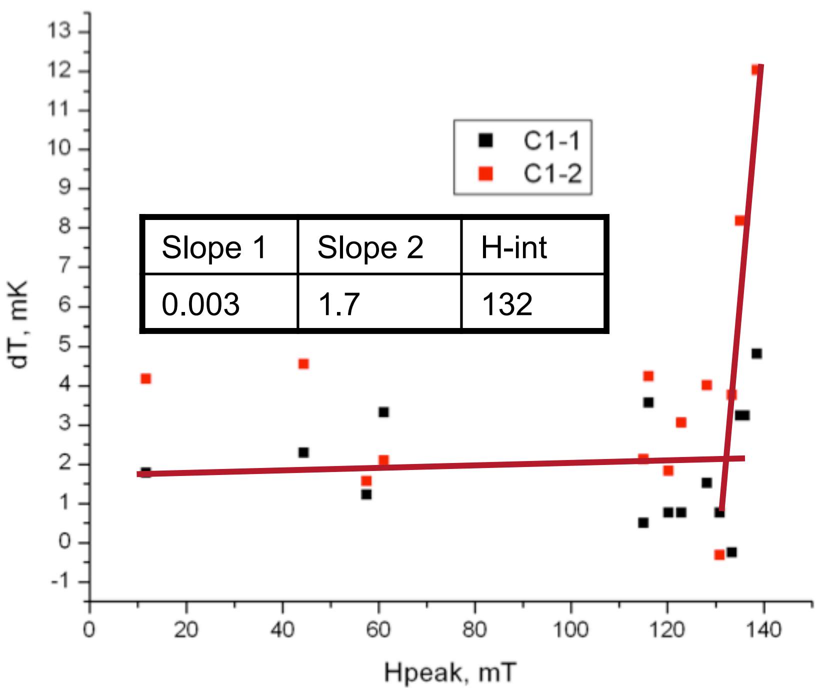
Ernst Helmut Brandt

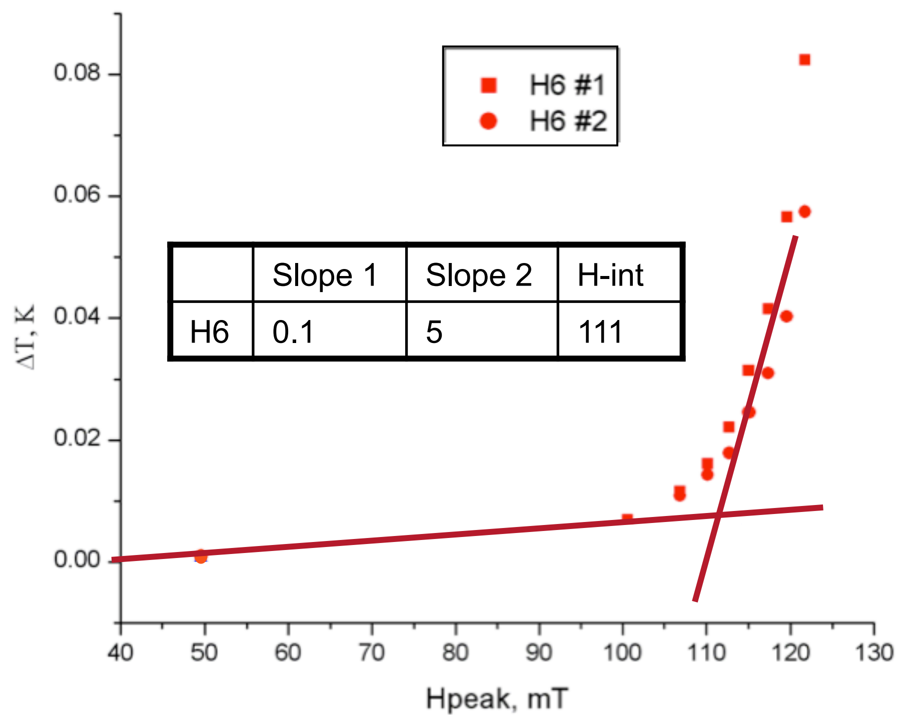
Irreversible magnetization of pin-free type-II superconductors

PHYSICAL REVIEW B VOLUME 60, NUMBER 17

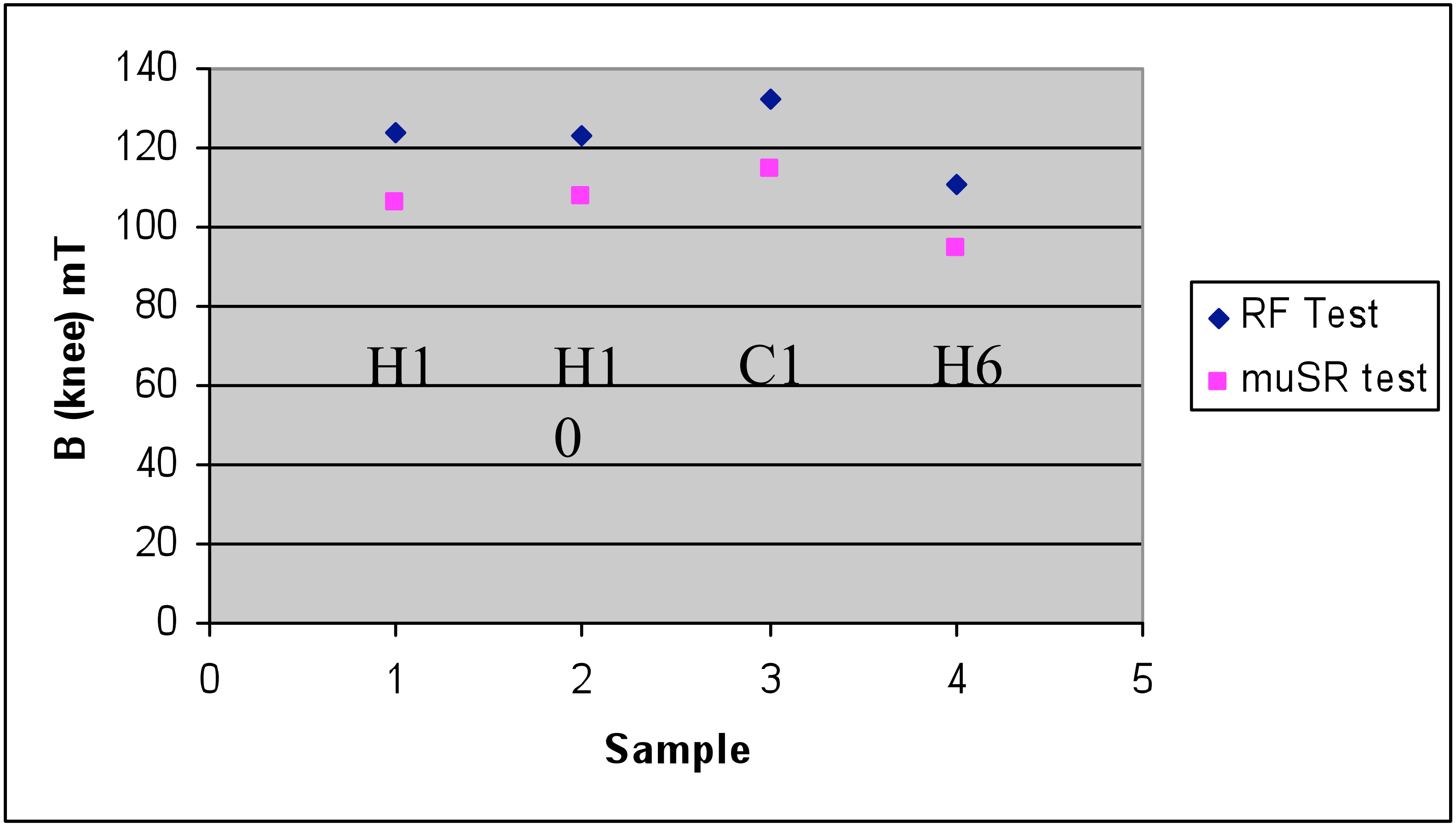

H1-1
H1-2
Slope 1 | Slope 2 | H-int
0.12 | 32 | 124
dT, mK
Hpeak, mT


H10-1
H10-2
Slope 1 | Slope 2 | H-int
0.27 | 52 | 123
dT, mK
Hpeak, mT


C1-1
C1-2
Slope 1 | Slope 2 | H-int
0.003 | 1.7 | 132
dT, mK
Hpeak, mT


H6 #1
H6 #2
Slope 1 | Slope 2 | H-int
H6 | 0.1 | 5 | 111
ΔT, K
Hpeak, mT

Knee points (RF heating vs field entry)



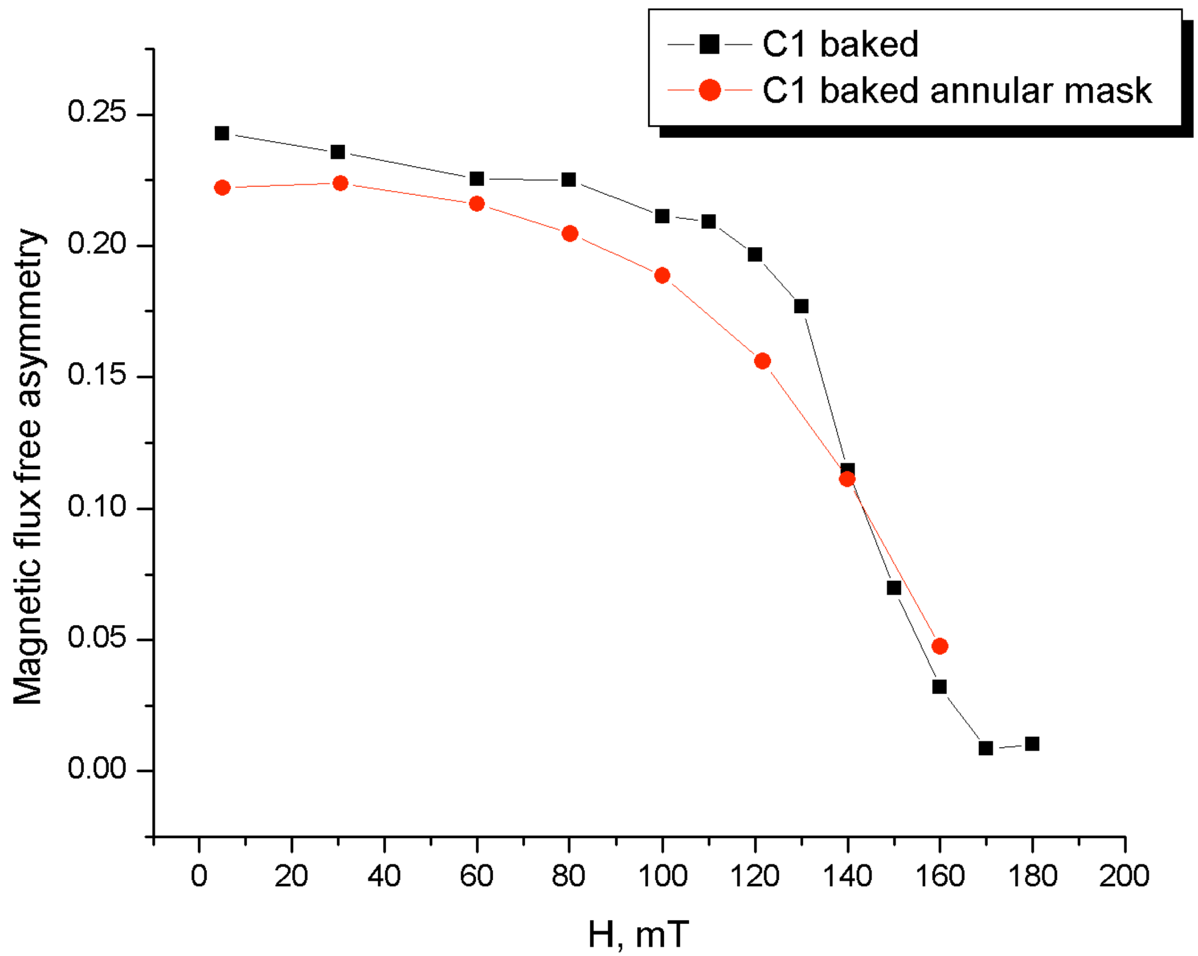
ΔB=16mT±1.5mT

Processing

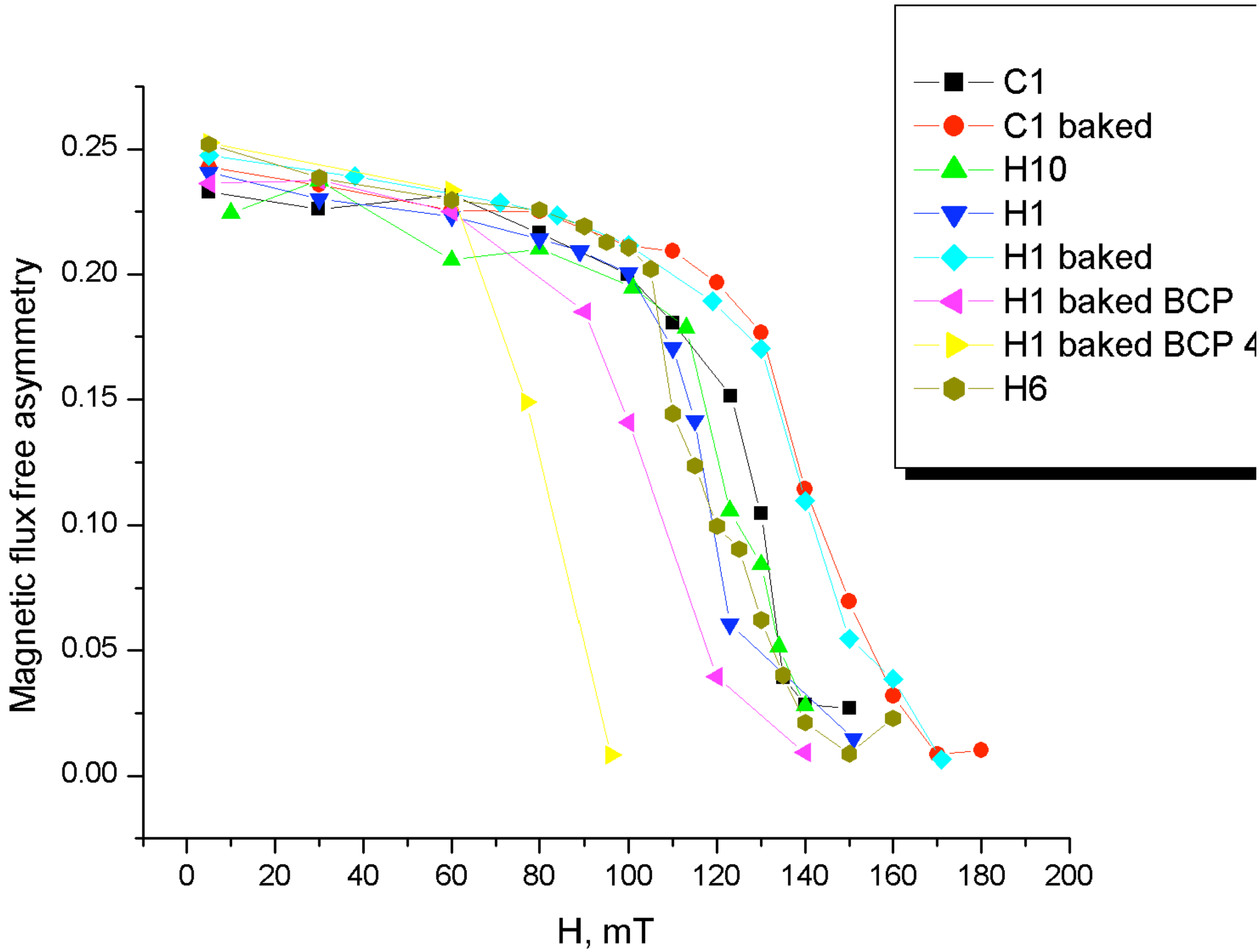
	musR	~RF	T	Brf (T=0)	BmuSR (T=0)
H1	106	122	2.3	130.13	113.07
H1baked	122	138	2.3	147.20	130.13
H1baked+BCP	83	99	2.3	105.60	88.53
H1baked+BCP @4.5K	66	82	4.5	107.79	86.76

$$H_c(T) = H_c(0) \cdot \left[1 - \left(\frac{T}{T_c} \right)^2 \right]$$

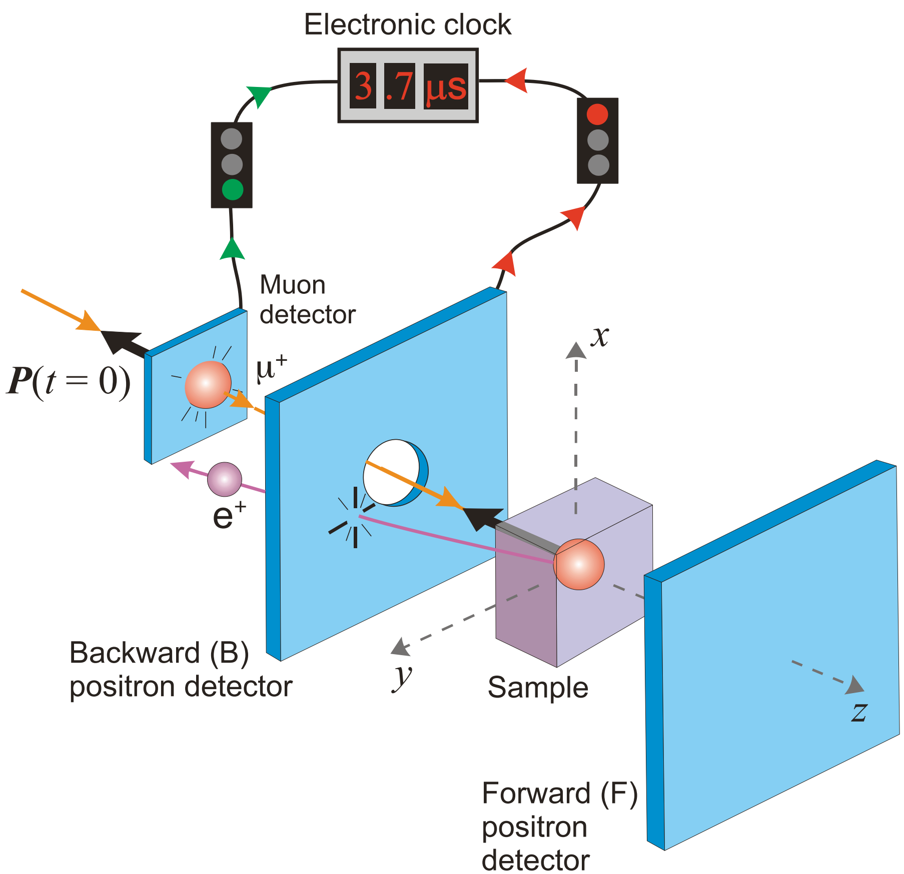
Center vs Annular mask



All samples results



Zero-Field μSR: internal field distribution, magnetic impurities, trapped flux



The **count rates** for opposing e^+ detectors:

$$N_B(t) = N_0 e^{-t/\tau_\mu}\left[1 + a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)\right]$$

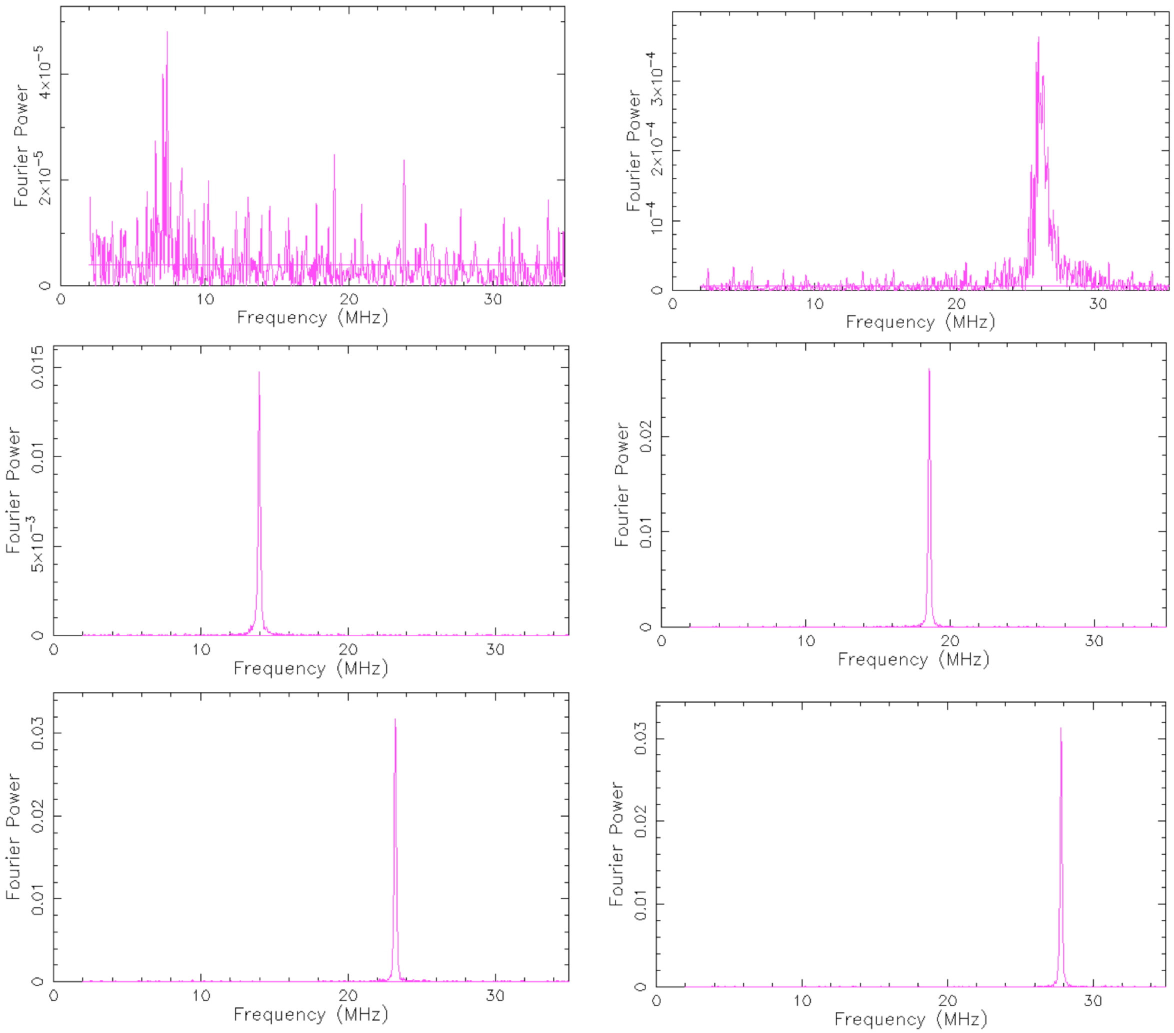
$$N_F(t) = N_0 e^{-t/\tau_\mu}\left[1 - a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)\right]$$

The corresponding μ^+ spin relaxation function is known as the ***Kubo-Toyabe function***

$$G_z(t) = \frac{1}{3} + \frac{2}{3}\left(1 - \Delta^2 t^2\right)\exp\left(-\frac{1}{2}\Delta^2 t^2\right)$$

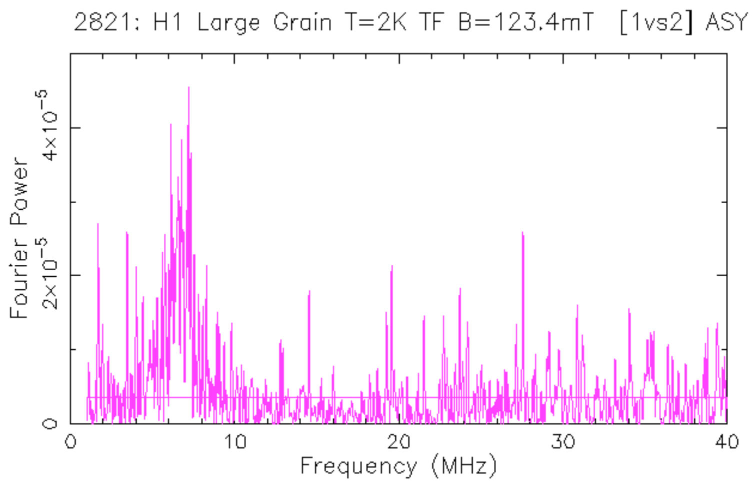
TRIUMF

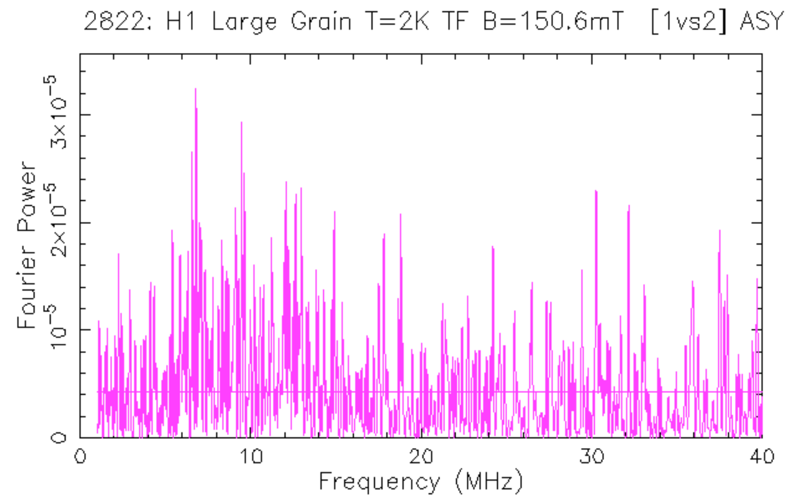
Upper critical field measurement

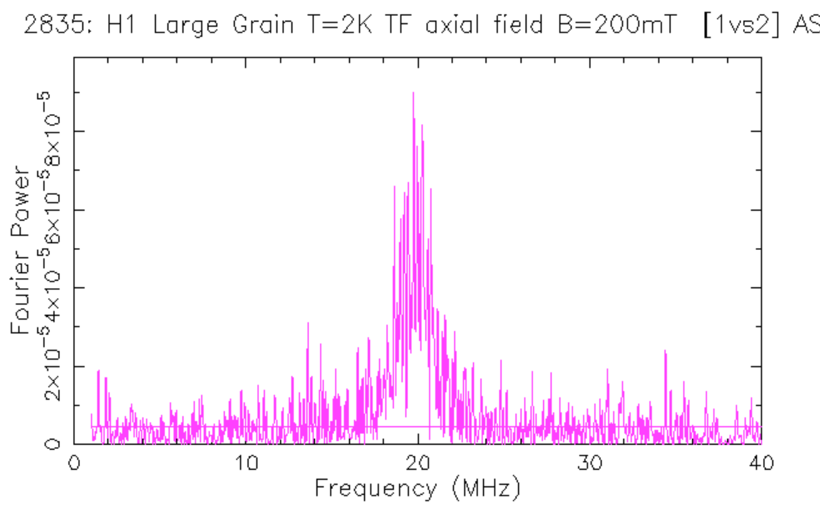


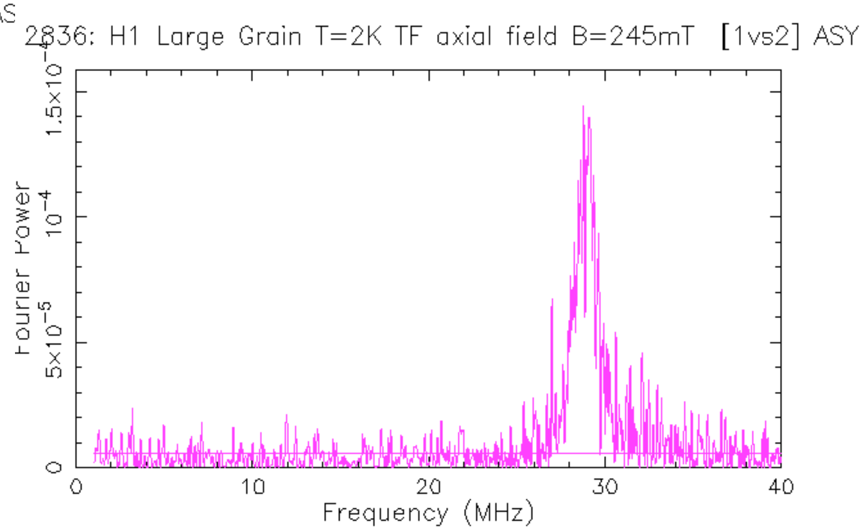
FFTs for sample H10 respectively for temperature and fields: (2.3K, 130mT), (4.5K, 200mT), (7.5K, 100mT), (7.5K, 140mT), (7.5K, 170mT), (7.5K, 200mT)

Coexistence of different 'superconducting' regions?

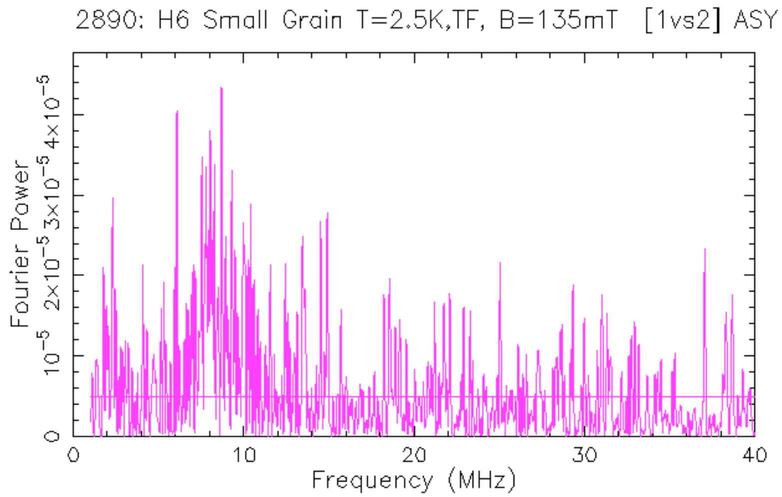


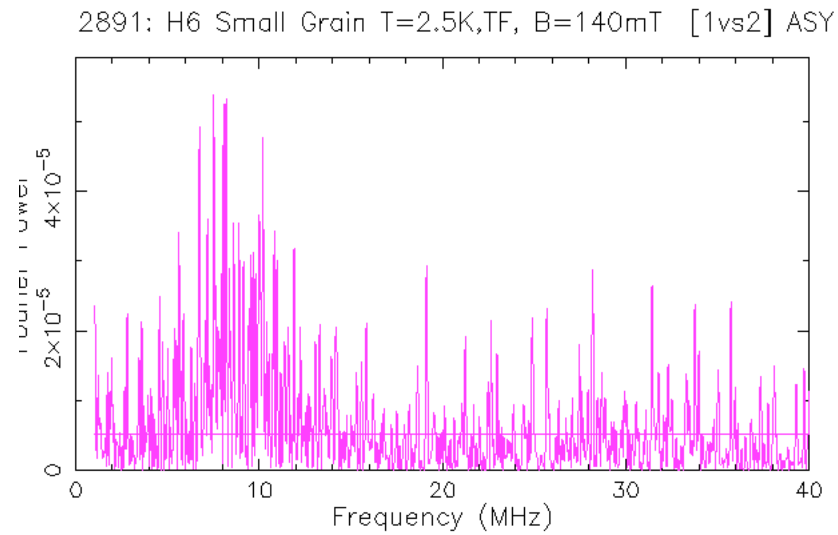


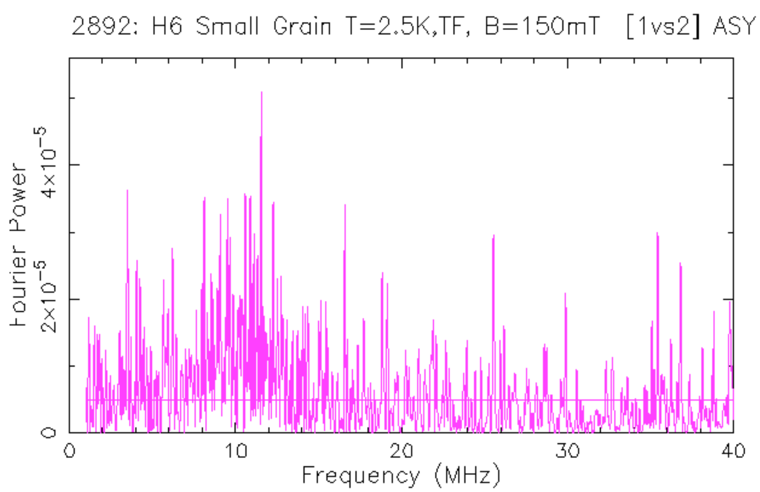


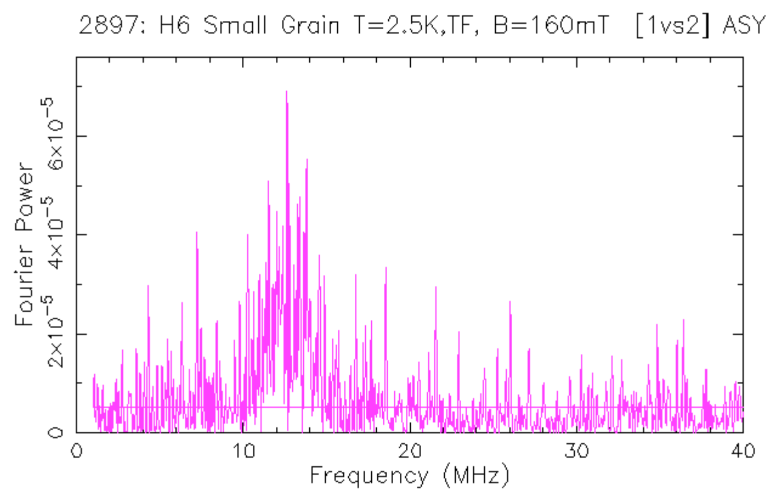


Coexistence of different ‘superconducting’ regions?









Nuclear Dipolar Relaxation

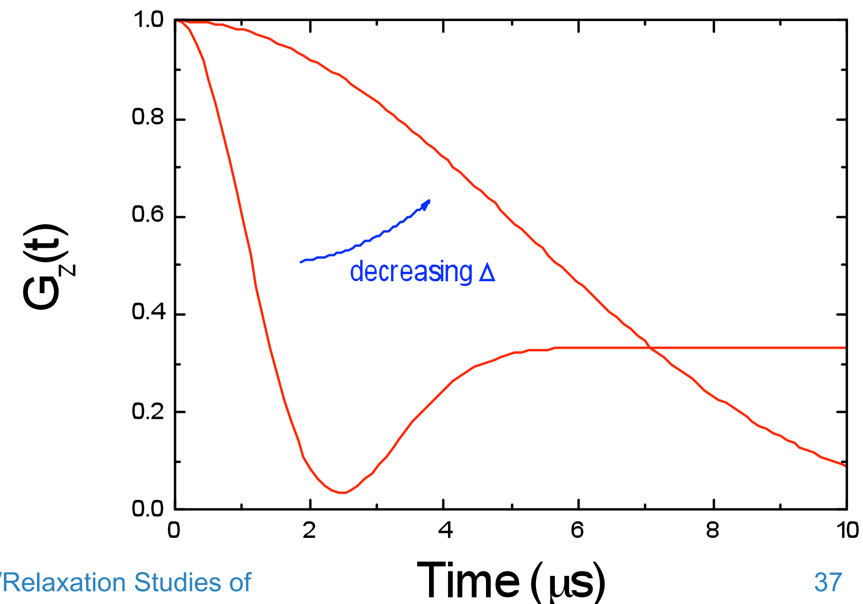
Nuclei with electric quadrupole moments (such as Cu and Y in $YBa_2Cu_3O_{6+x}$) exert an effective dipolar field B_{dip} on the μ^+. The static (in the μ^+SR time window) internal fields are Gaussian distributed in their values and randomly oriented

$$n(B_i) = \frac{1}{\sqrt{2\pi}} \frac{\gamma_\mu}{\Delta} \exp\left(-\frac{1}{2} \frac{\gamma_\mu^2 B_i^2}{\Delta^2} \right) \qquad (i = x, y, z)$$

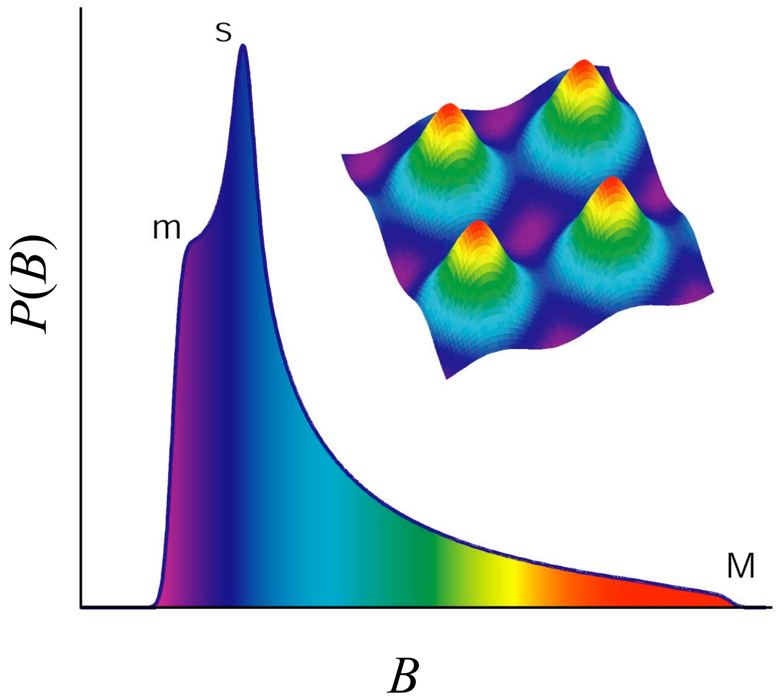
where Δ^2/γ_μ^2 is the second moment of the field distribution

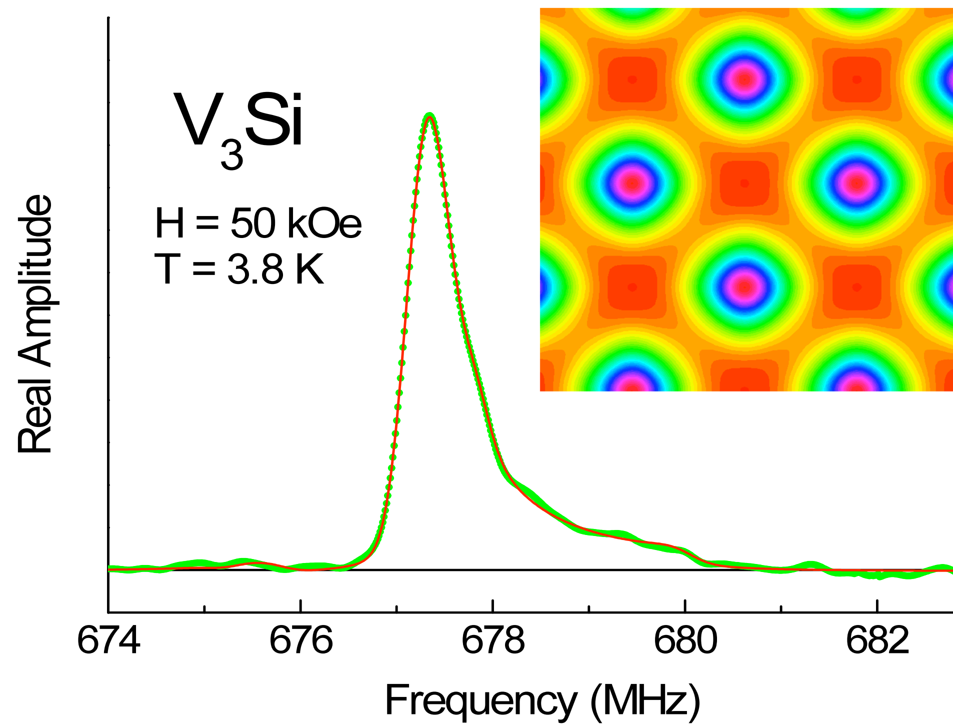
The corresponding μ^+ spin relaxation function is known as the ***Kubo-Toyabe function***

$$G_z(t) = \frac{1}{3} + \frac{2}{3}\left(1 - \Delta^2 t^2\right)\exp\left(-\frac{1}{2}\Delta^2 t^2 \right)$$

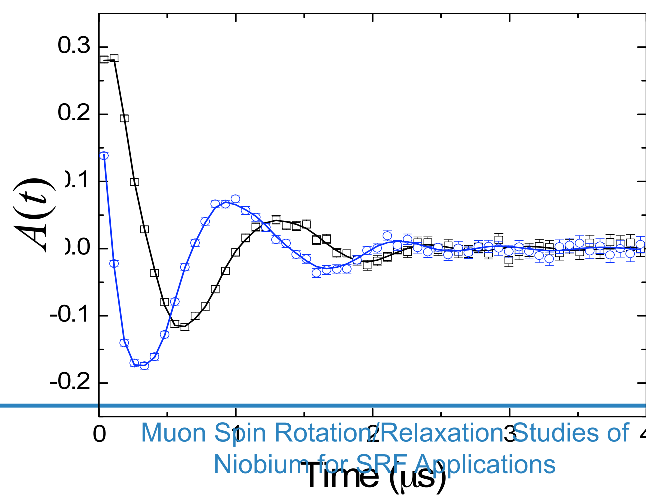


Magnetic field distribution of a vortex lattice



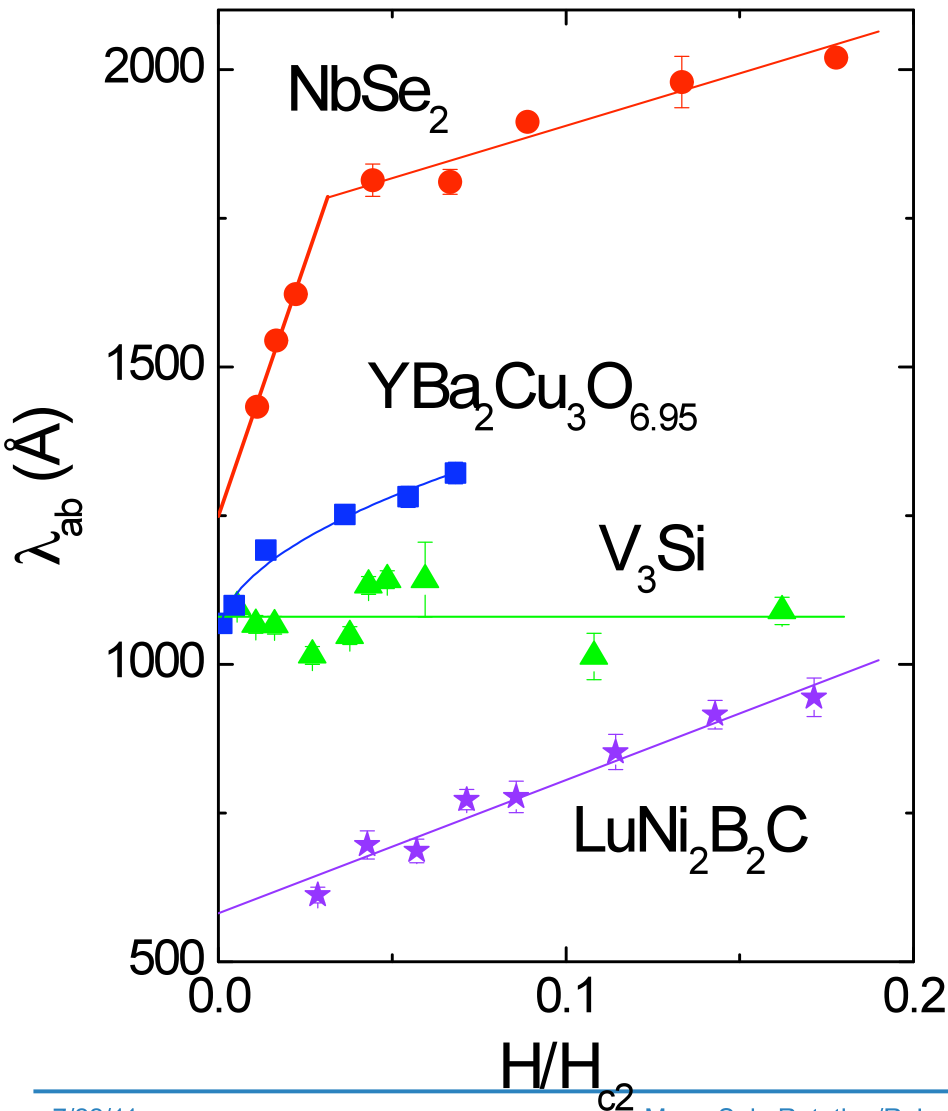


Asymmetry spectrum plotted in a rotating reference frame



Fourier transform

“Effective” Magnetic Penetration Depth: Magnetic Field Dependence



- V_3Si fully gapped
- $LuNi_2B_2C$ anisotropic gap
- $YBa_2Cu_3O_{6.95}$ $d_{x^2-y^2}$-wave gap
- $NbSe_2$ multiband

JES, Rep. Prog. Phys. **70**, 1717 (2007)

Detection in a cryogenic environment