SANS Study of Vortex Lattice Structural Transition in Optimally Doped $(Ba_{1-x}K_x)Fe_2As_2$

7 July 2014 | Sultan Demirdiş
Jülich Centre for Neutron Science at MLZ

Collaborators

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CNRS UMR 7642 & CEA-DSM-IRAMIS ,F 91128 PALAISEAU/France

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JCNS at MLZ, Lichtenberstr., D-85747, Garching, Germany

Thomas Wolf, Karlsruher Institut für Technologie, Institut für Festkörperphysik,
7602, Karlsruhe, Germany

Outline

Introduction:

- Superconductivity,discovery, type I and type II
- BCS theory
- Vortices in superconductors
- Fe-based superconductors, a new class of superconducting compounds

Motivation:

- Vortices in Fe-based superconductors : Co-122, P-122, K-122, and KFe_2As_2

SANS study of vortex lattice in $(Ba_{1-x}K_x)Fe_2As_2$:

- Form factor and structure factor, structural transition of VL

Magnetization measurements:

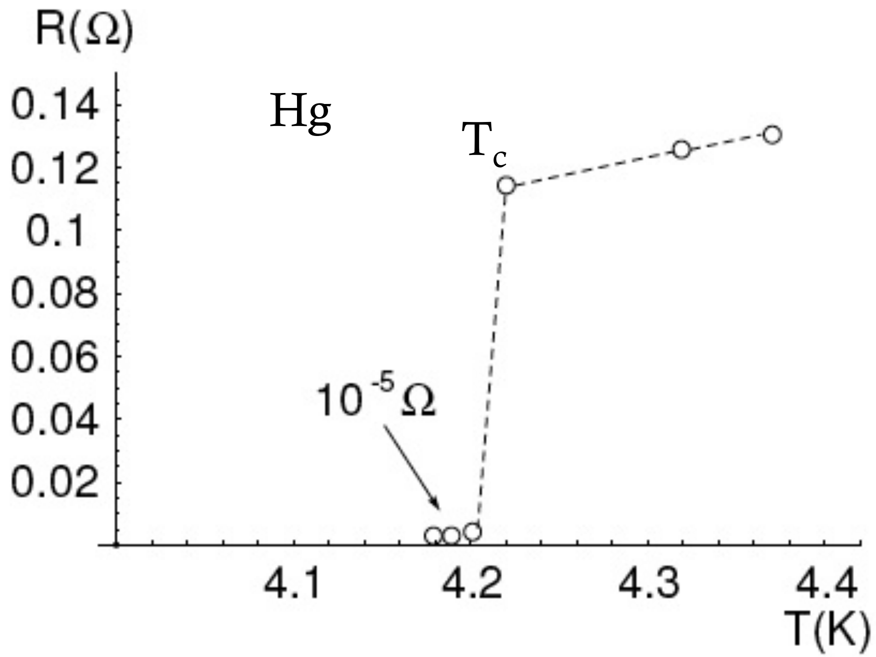
- Second magnetization peak in $(Ba_{1-x}K_x)Fe_2As_2$, effect of vortex creep

Order-disorder transition of vortex lattice in $(Ba_{1-x}K_x)Fe_2As_2$:

- Phase diagram,discussion

Introduction
Superconductivity: Discovery

Zero resistivity for $T<T_c$



H. Kamerlingh Onnes (1911)

H.K. Onnes. Leiden Comm., 120 B, (1911).

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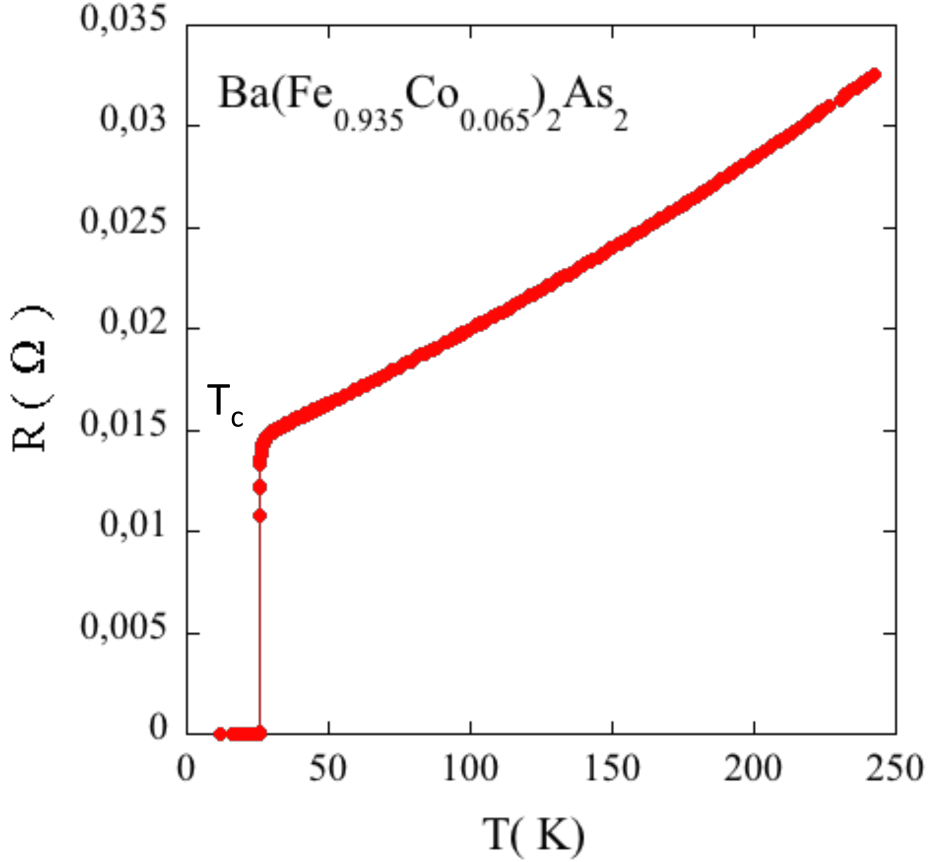
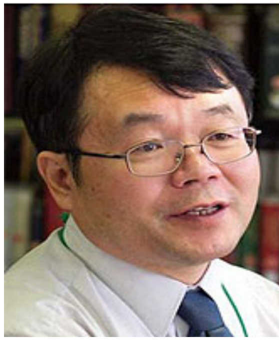




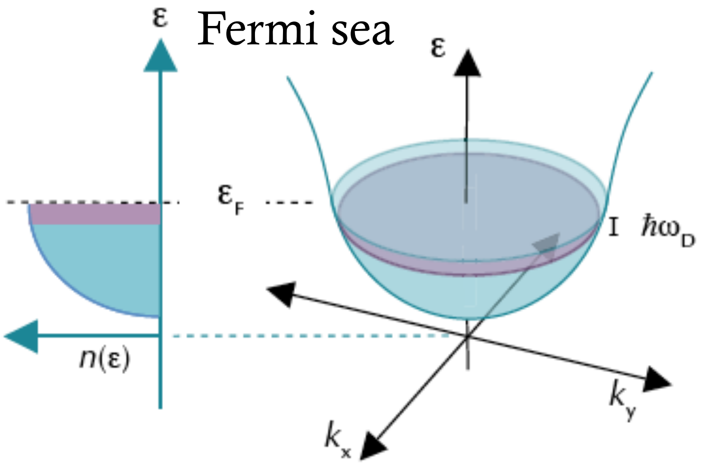
… 100 years later H. Hosono (2006) discovery of IBS

Y. Kamihara, H. Hosono et. al. J. Am. Chem. Soc., 128, (2006).
M. Rotter et. al. Angewandte Chemie, 47 (2008).
A. S. Sefat et. al. PRL., 101, (2008).

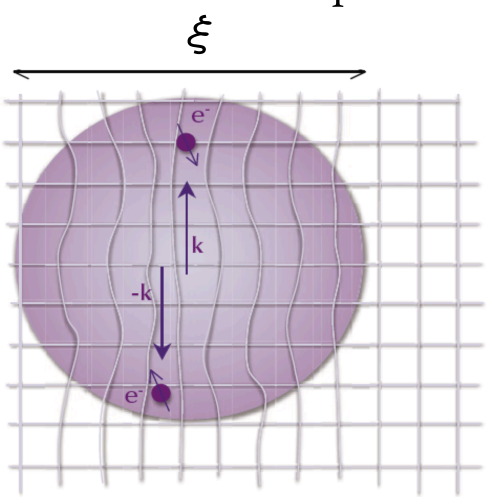
Introduction

Superconductivity: Cooper pairing and superconducting gap

BCS theory (1957) : Cooper pairing mediated by phonon



2 electrons with opposite momentum and spin



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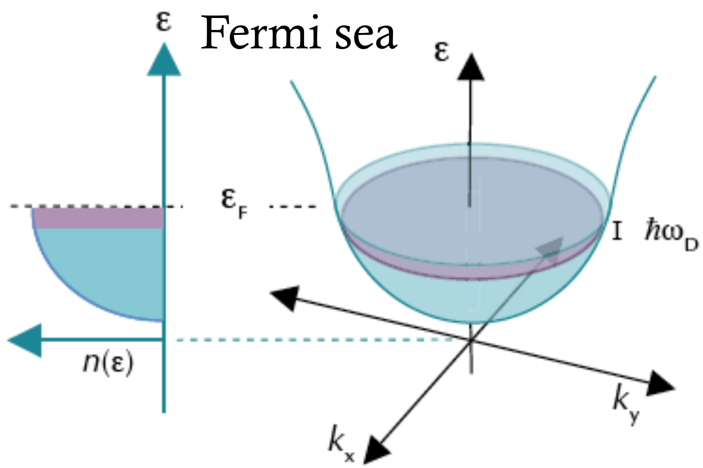
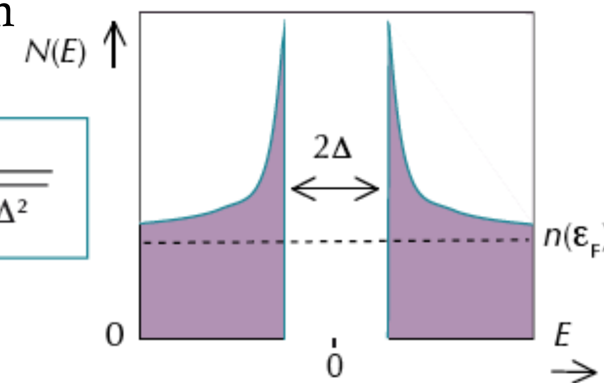
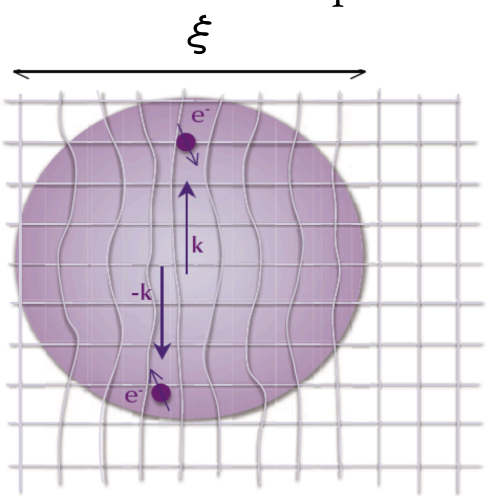


$$N(E) = n(\varepsilon_F)\,\frac{E}{\sqrt{E^2-\Delta^2}}$$



$2\Delta(0)=3.53\ k_BT_c$

2 electrons with opposite momentum and spin



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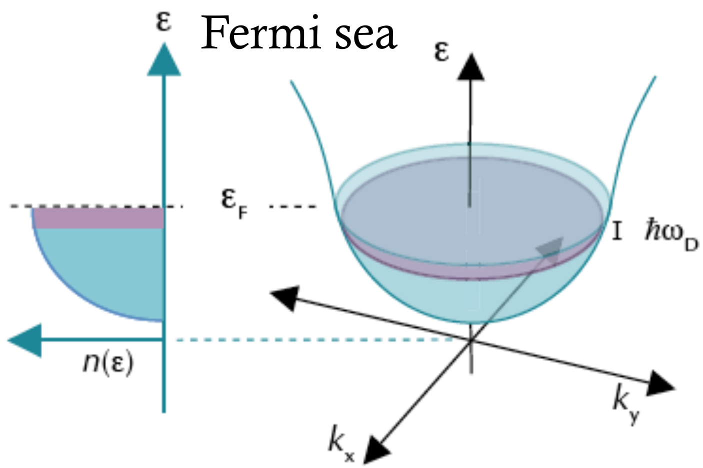

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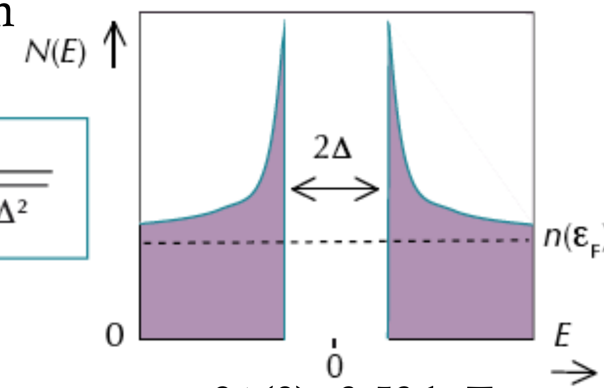

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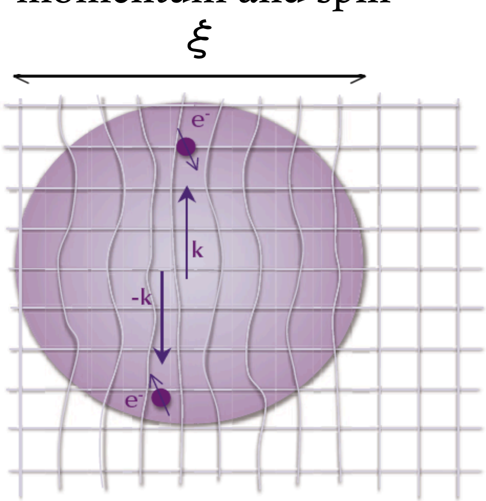

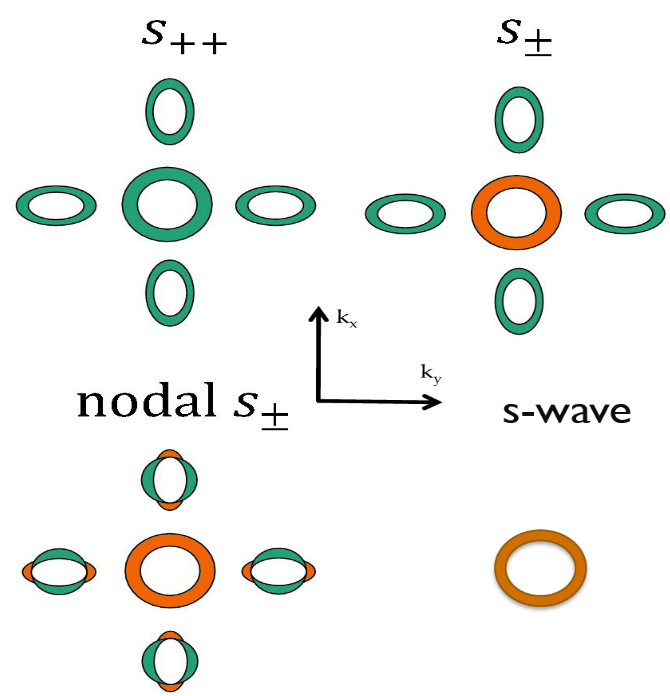

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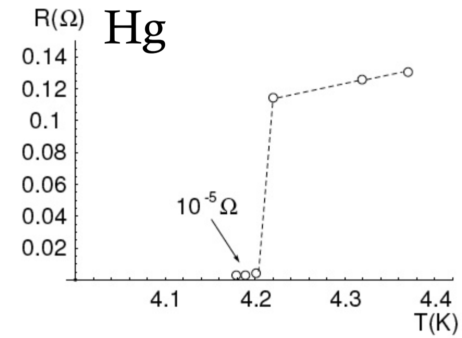
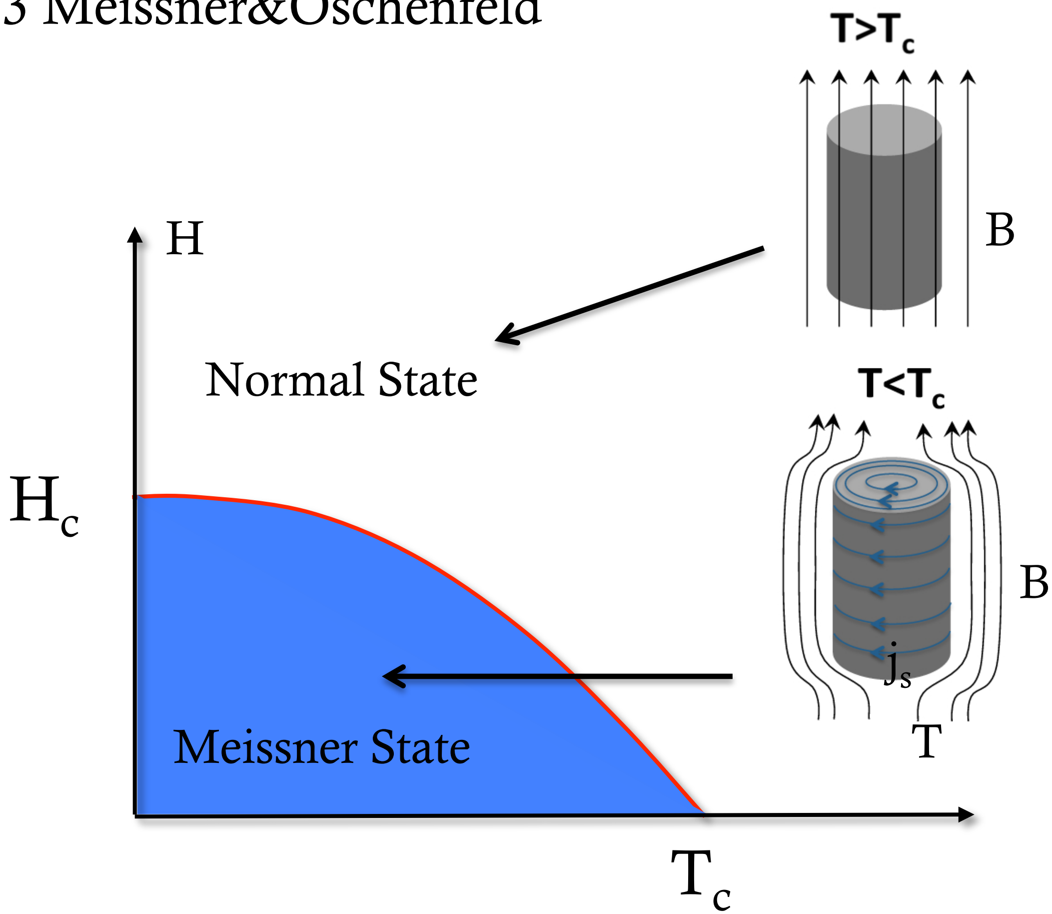
Superconductivity: Type I

Zero resistivity for $T<T_c$
Expulsion of magnetic flux
1933 Meissner&Oschenfeld



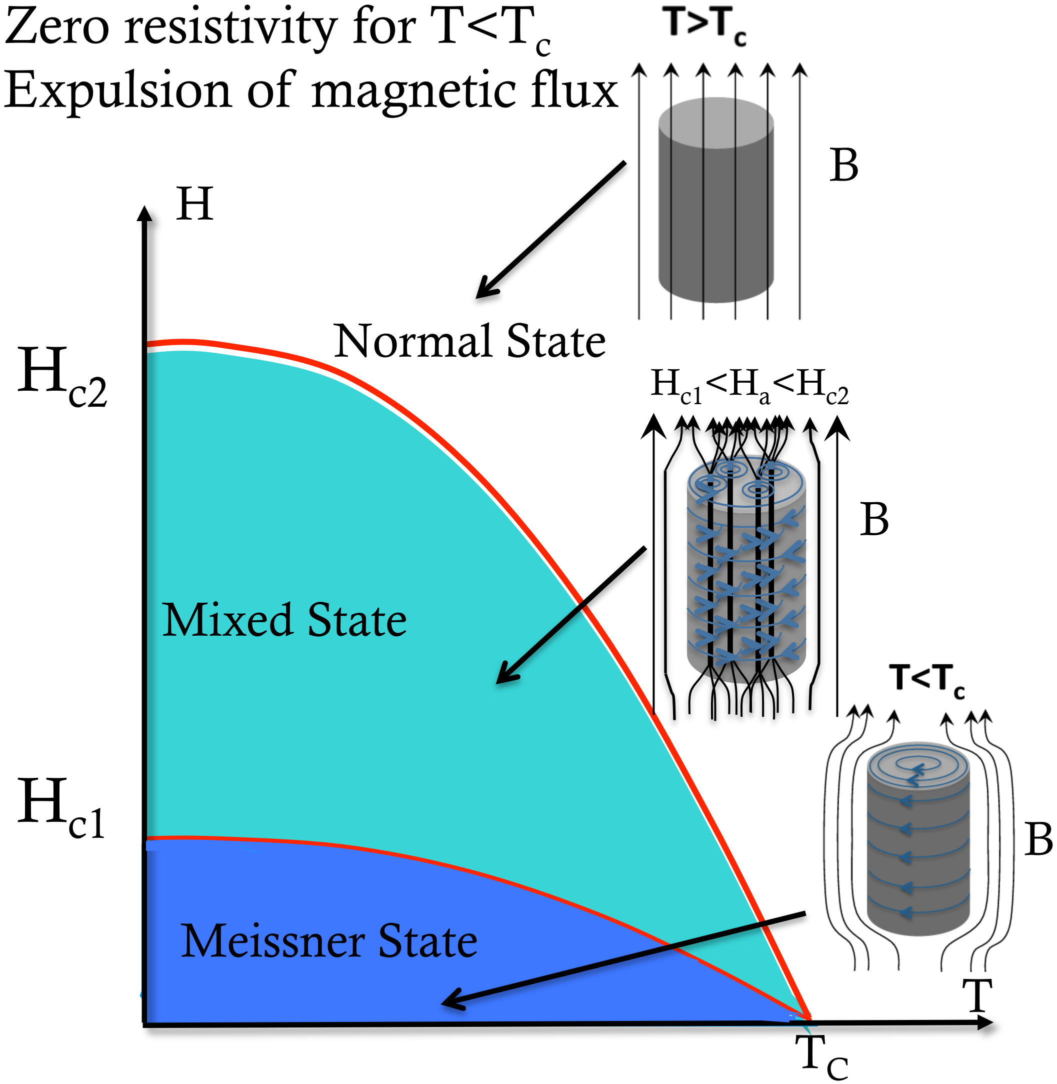


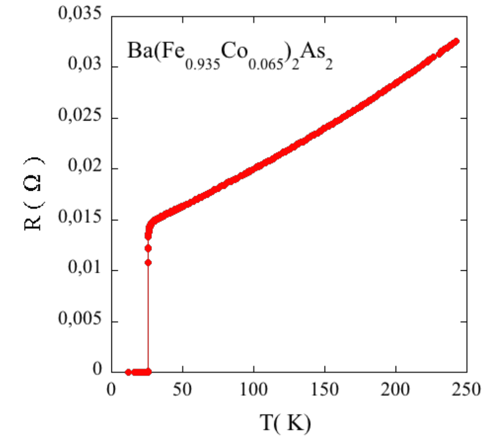
Introduction

Superconductivity: Type II

Zero resistivity for $T<T_c$

Expulsion of magnetic flux





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Superconductivity: Type II

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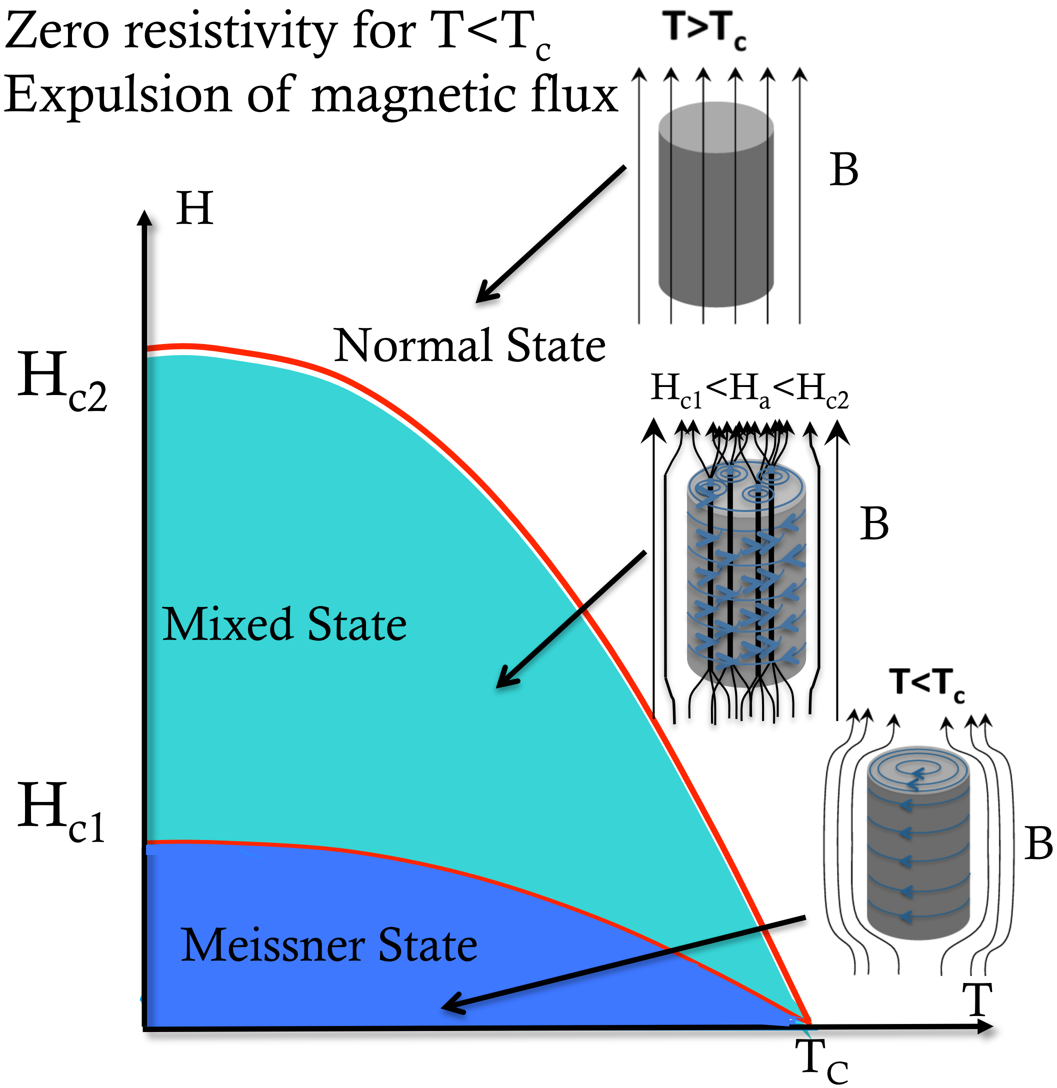
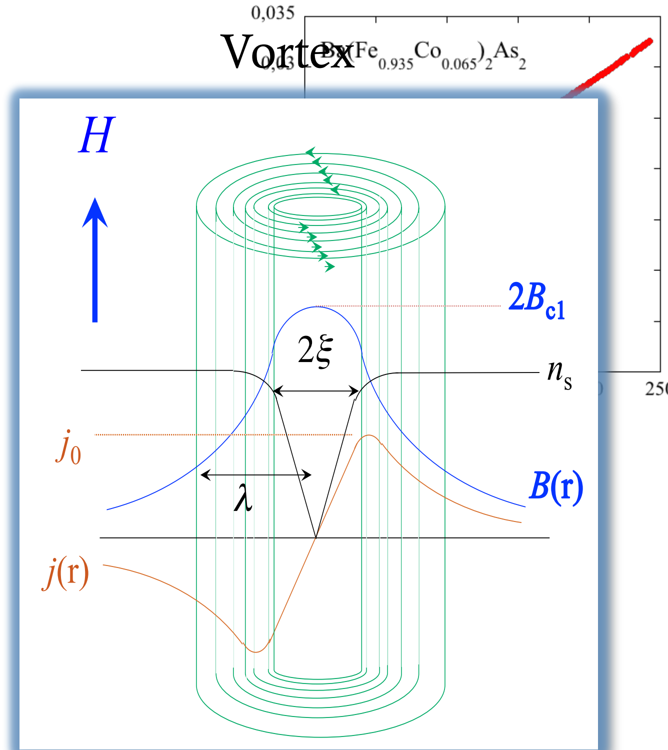


Vortex



Each vortex carries a flux quantum

$$\Phi_0 = h / 2e$$

λ : magnetic penetration depth
ξ : coherence length
vortex line energy:

$$\varepsilon_0 = \Phi_0 / 4\pi\mu_0\lambda_{ab}^2$$

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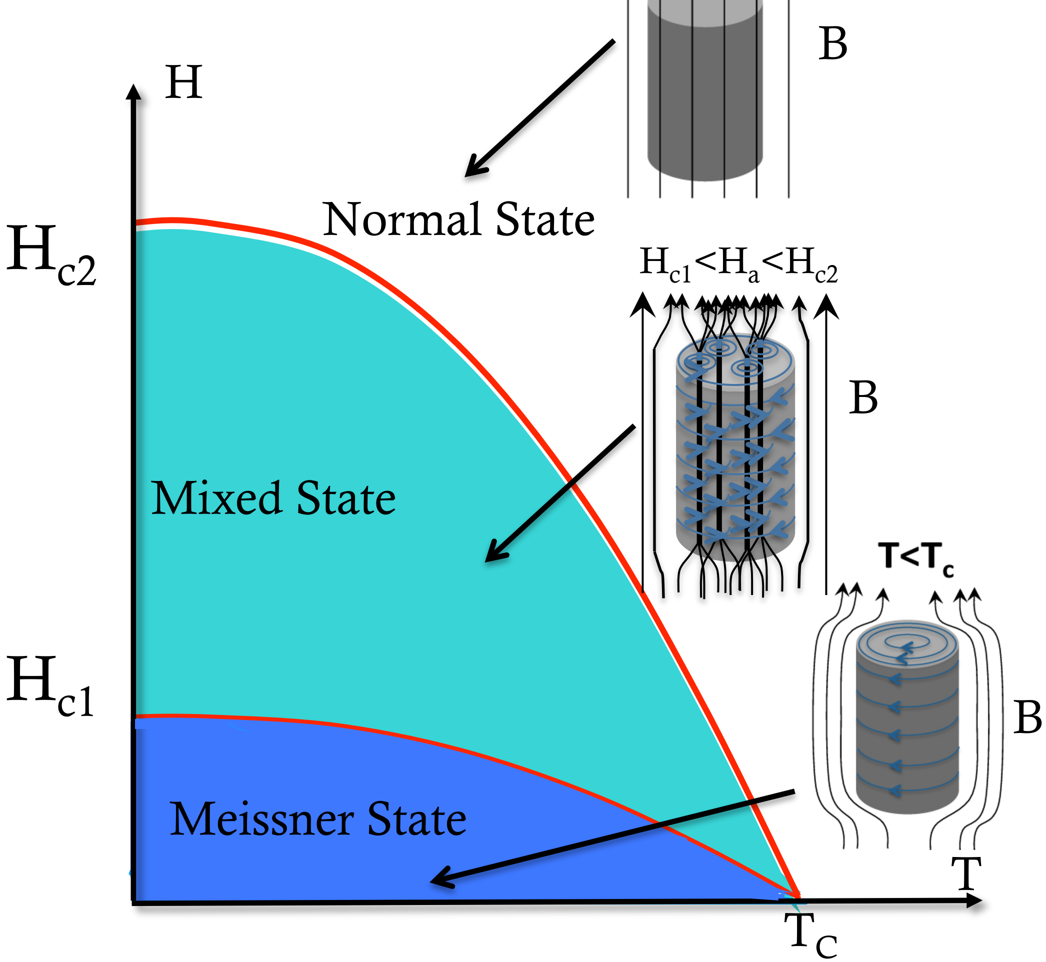
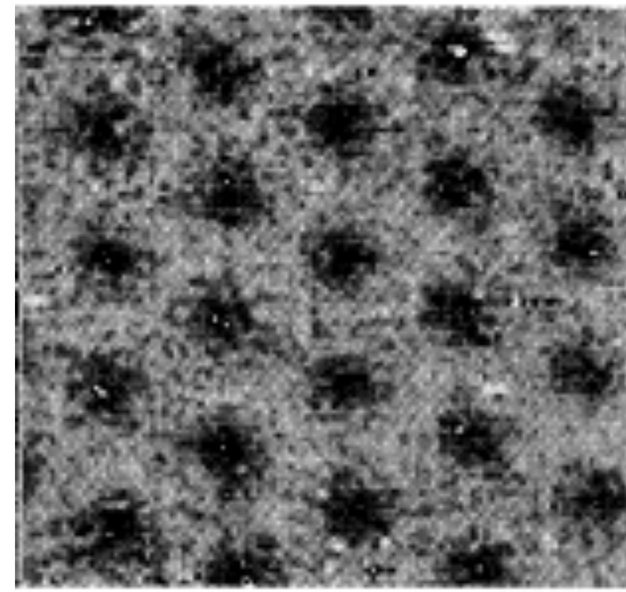


Triangular vortex lattice in $NbSe_2$ obtained by STS (Scanning Tunneling Spectroscopy)



4000 Å x 4000 Å, H_a=0.3 T, at 1.3K

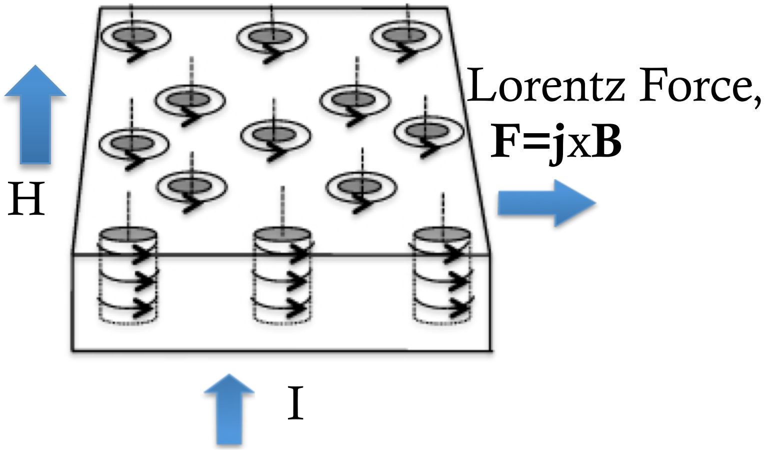
In the absence of disorder, vortices form triangular lattice

$$a_\Delta = 1.075\sqrt{\Phi_0 / B}$$

C. Renner et. al. PRL 67,(1991)

Introduction

Vortex Dynamics: Pinning, interaction with current



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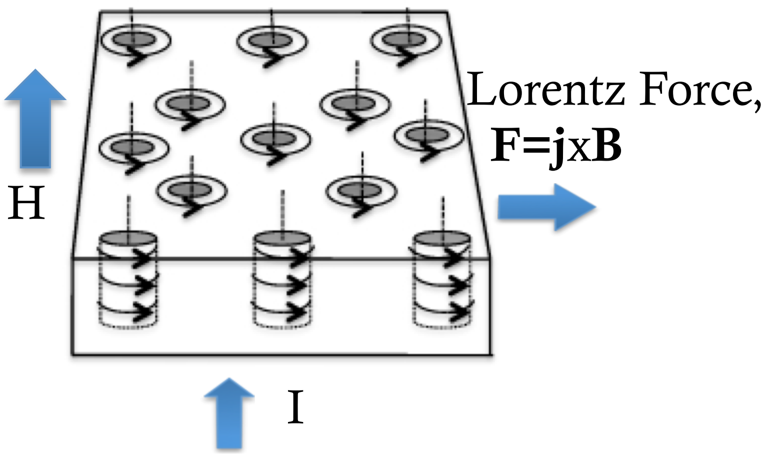
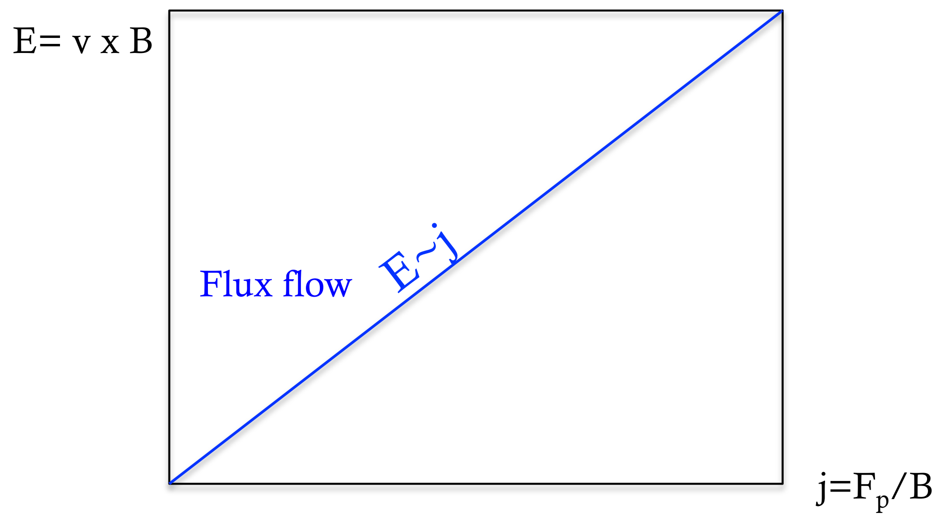


E-j characteristic

Lorentz Force: F= j x B

Vortex motion: $v= F/\gamma$ ⟶ Non-zero Electric field E= v x B

Flux flow resistivity: $\rho_f = B^2/\gamma$



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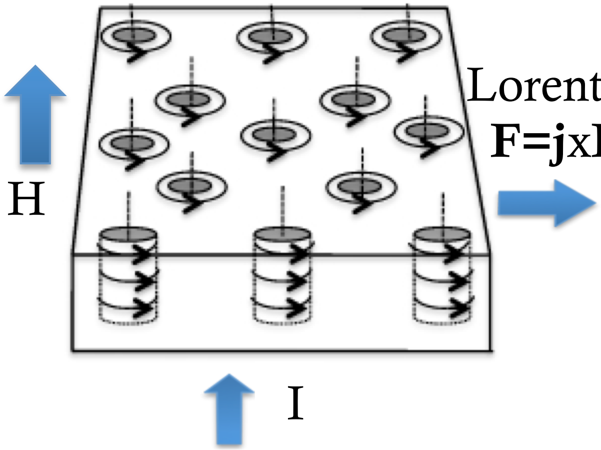


Pinning by crystalline defects counteracts vortex flow as long as $j < j_c$

F_p: force to untrap

$j_c = F_p/B$: critical current density

E-j characteristic

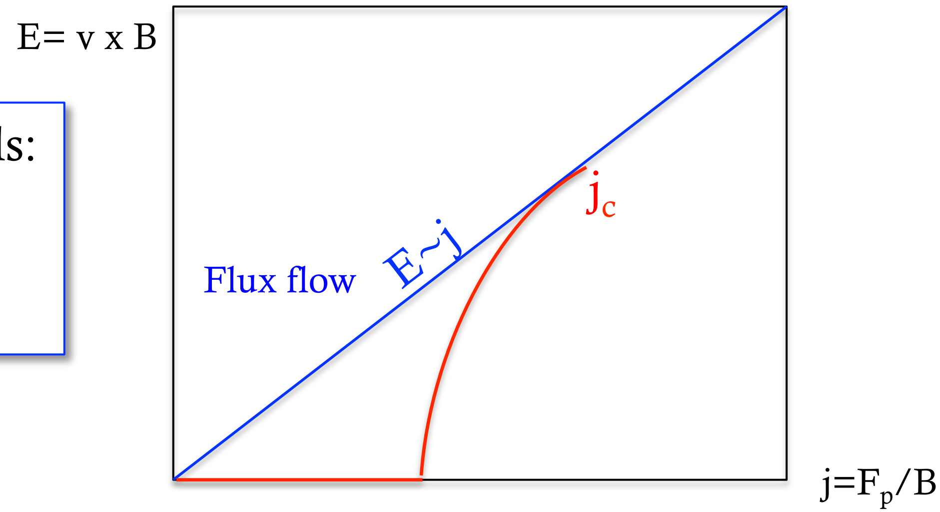
Lorentz Force: $F = j \times B$

Vortex motion: $v = F/\gamma$ ⟶ Non-zero Electric field $E = v \times B$

Flux flow resistivity: $\rho_f = B^2/\gamma$

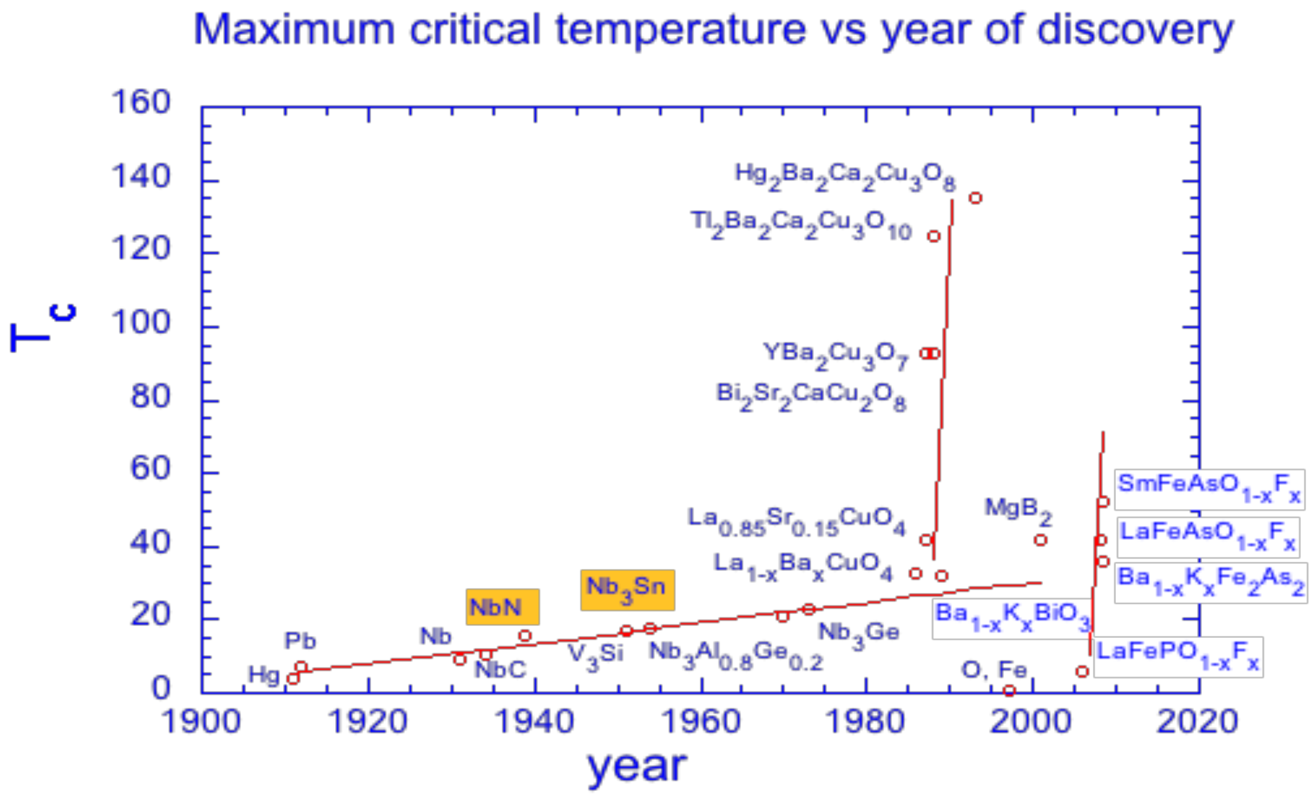
But there are many defects in crystals:

- dislocations, vacancies
- chemical inhomogeneity
- artificial disorder

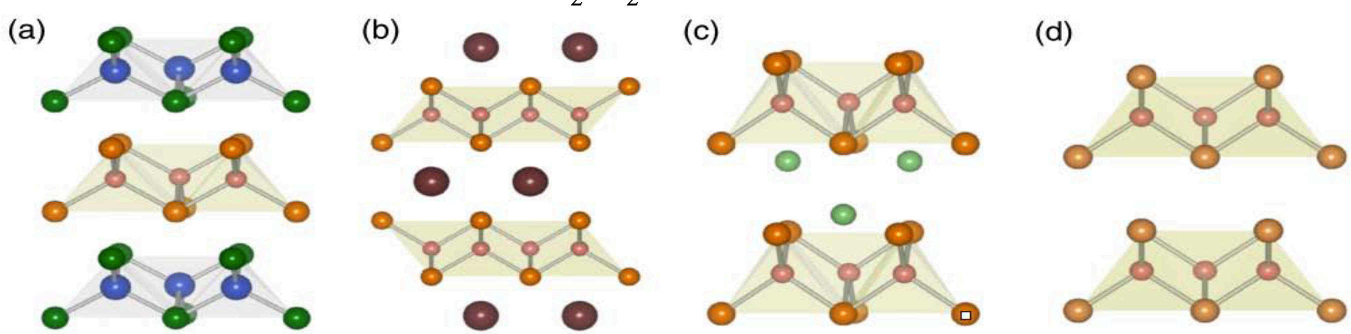


Introduction

Iron-based superconductors: discovery H.Hosono 2006



“1111” LaFeAsO   “122” $BaFe_2As_2$ “111” LiFeAs   “11” FeSe



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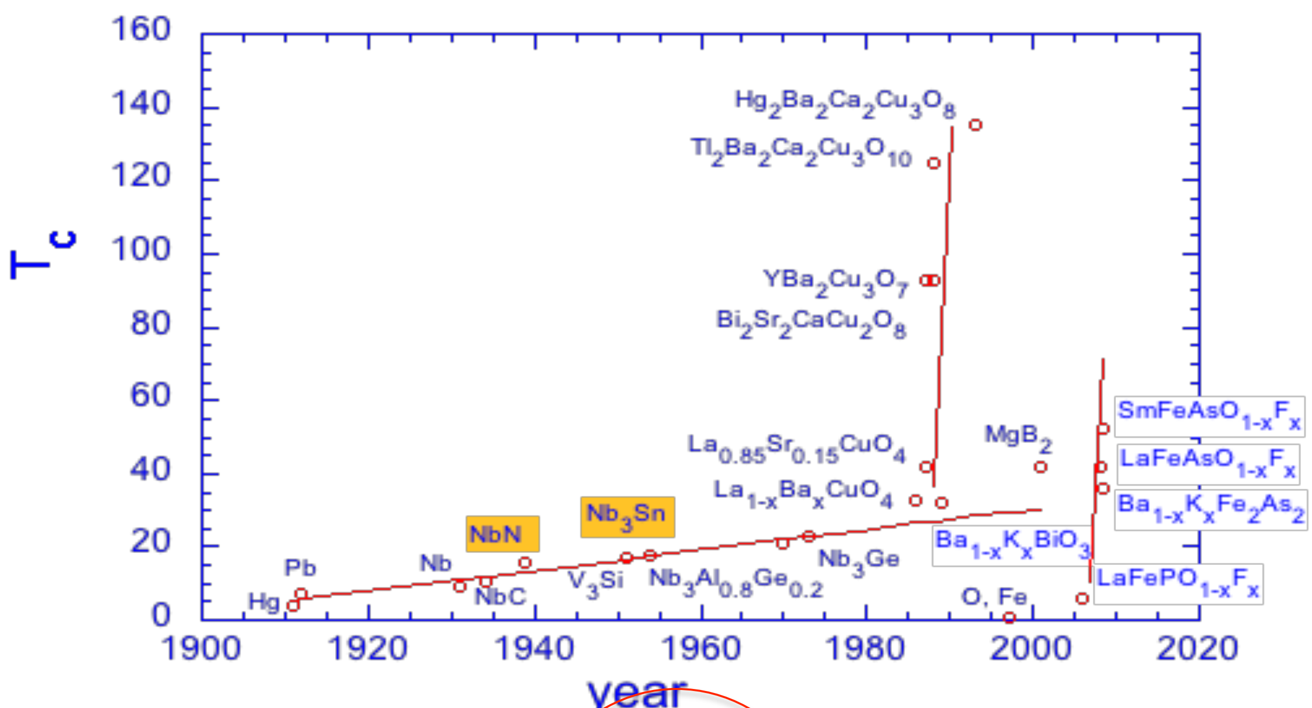
Maximum critical temperature vs year of discovery



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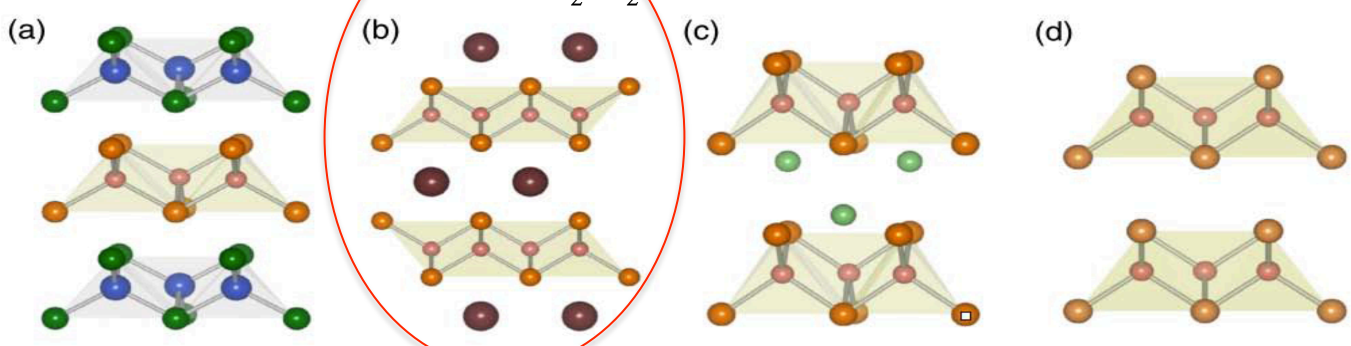
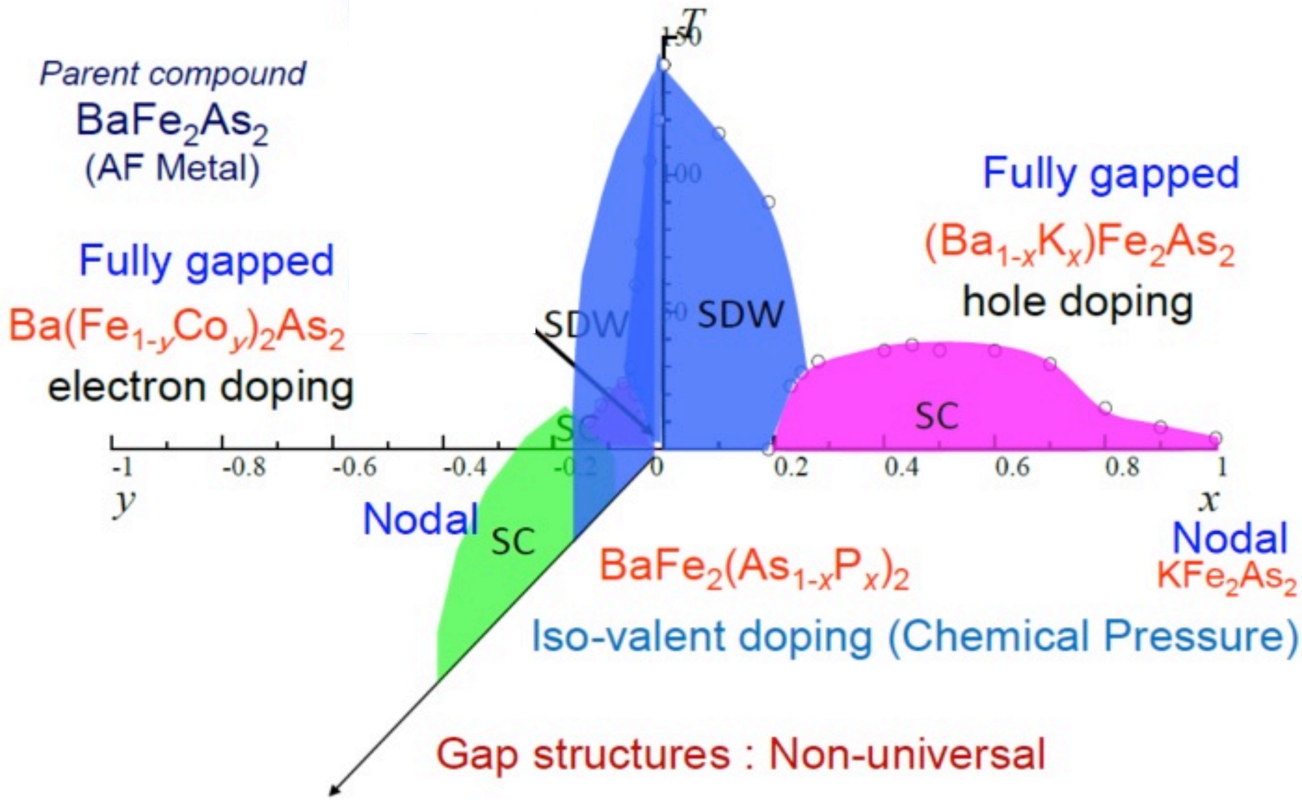
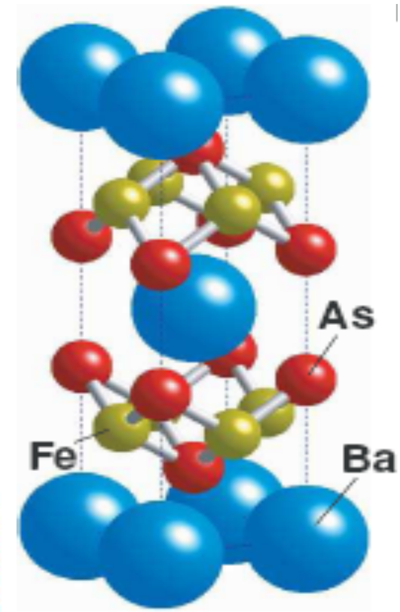


Introduction:

Iron-based superconductors (IBS) : 122-type , generic phase diagram





$BaFe_2As_2$

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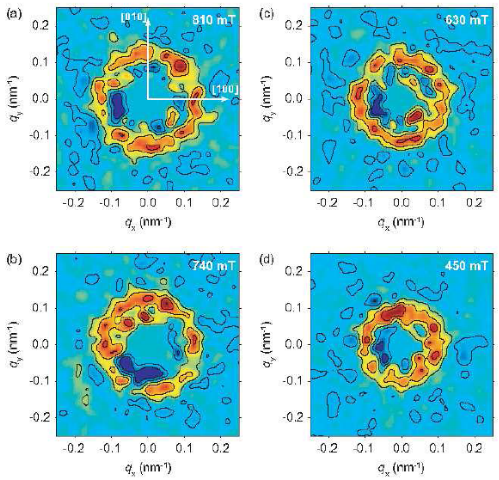

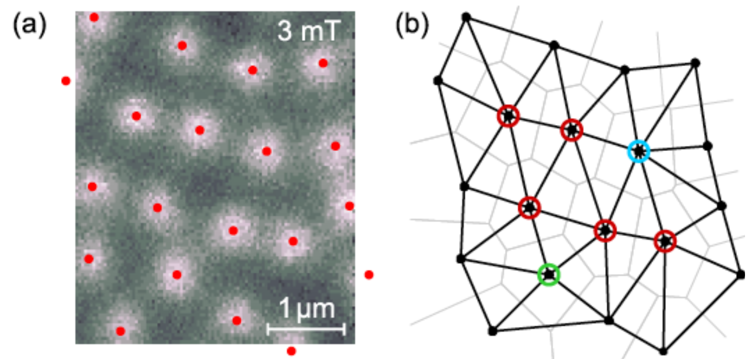

Single crystalline MFM+SANS
$Ba(Fe_{0.905}Co_{0.095})_2As_2$ D.S. Inosov et. al. Phys. Rev. B, 2010

Single crystalline SANS+BD
$Ba(Fe_{0.93}Co_{0.07})_2As_2$ M.R. Eskildsen, L. Ya. Vinnikov et al,
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Jülich Centre for Neutron Science

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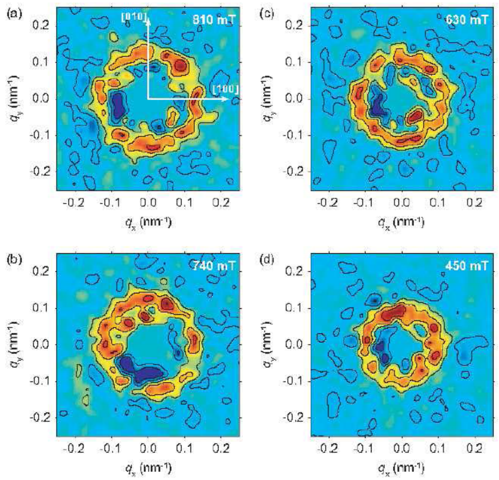

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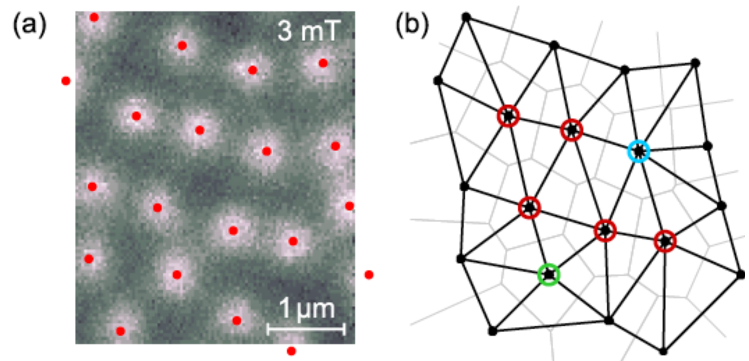

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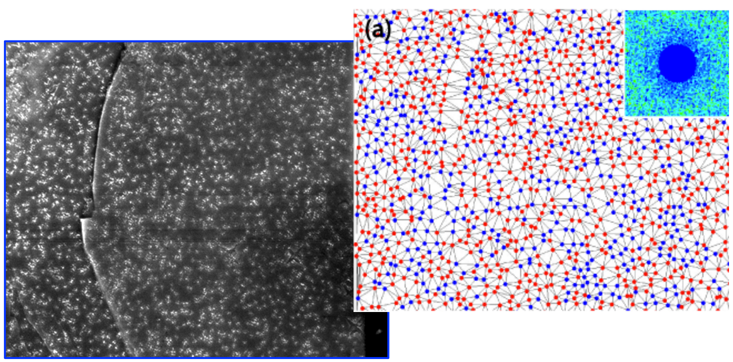

Single crystalline BD ``Strong pinning by nm-scale disorder``
$Ba(Fe_{1-x}Co_x)_2As_2$ x=0.75, 0.1
S. Demirdis et. al. PRB **84**, 094517 (2011),
Physica B 407 (2012) 1746–1749

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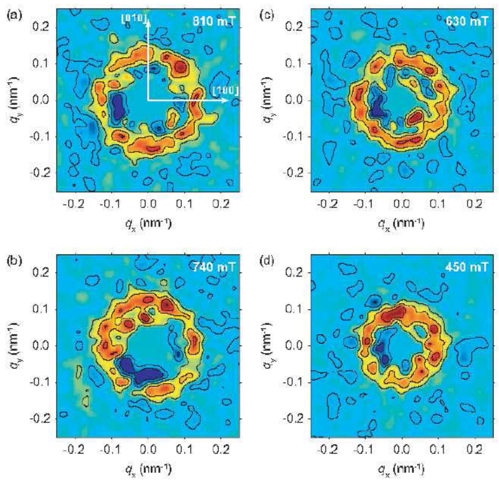

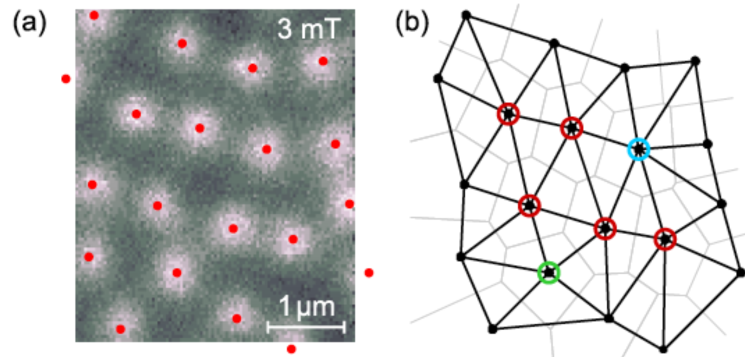

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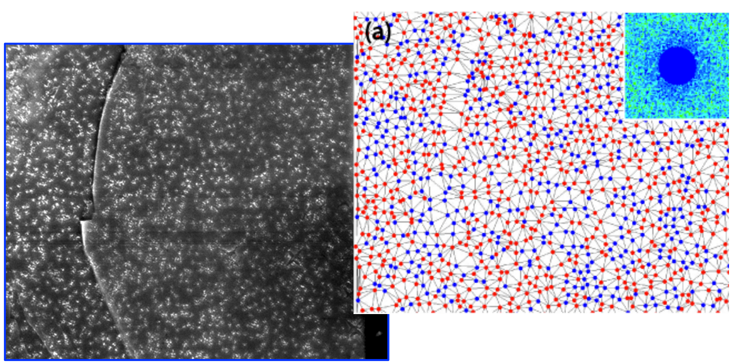

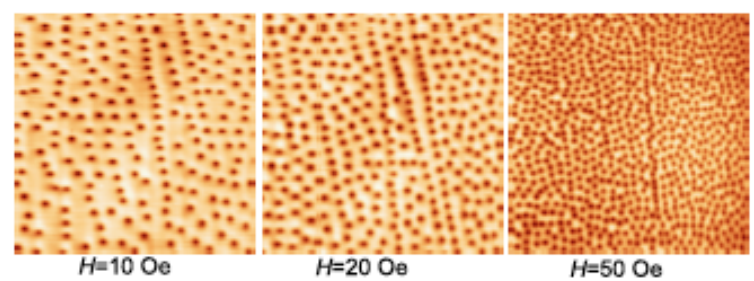

$Ba_{1-x}K_xFe_2As_2$ x=0.40 MFM
Hai-Hu Wen et. al. PRB 85, 014524 (2012) MFM

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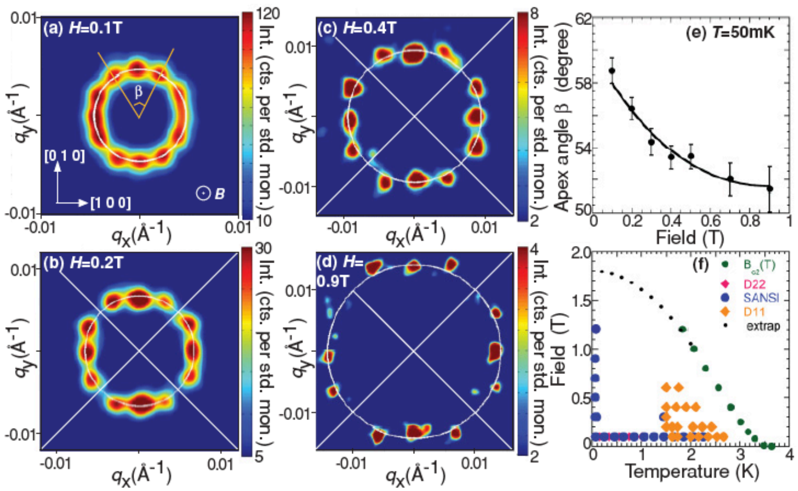
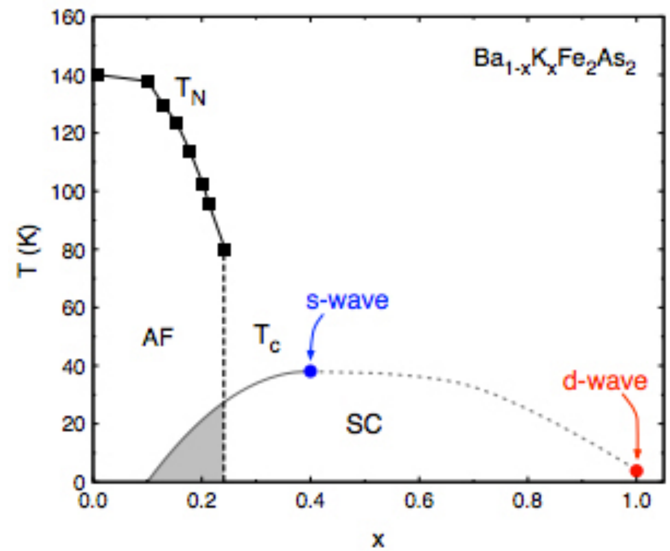
Motivation: Transition from disordered to ordered vortex ensemble



Nearly isotropic hexagonal VL is formed, with no symmetry transitions up to high fields

H. Kawano-Furukawa et. al. PRB **84**, 024507 (2011)



J. Ph. Reid et. al. Supercond. Sci. Technol. 25, 084013 (2012).

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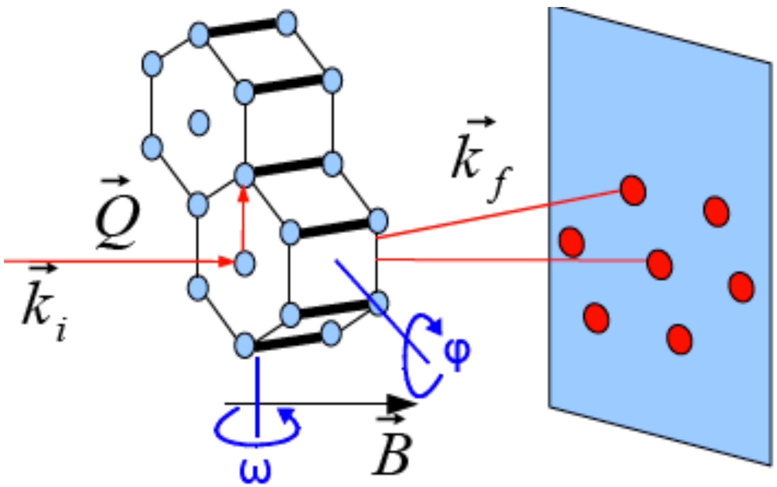
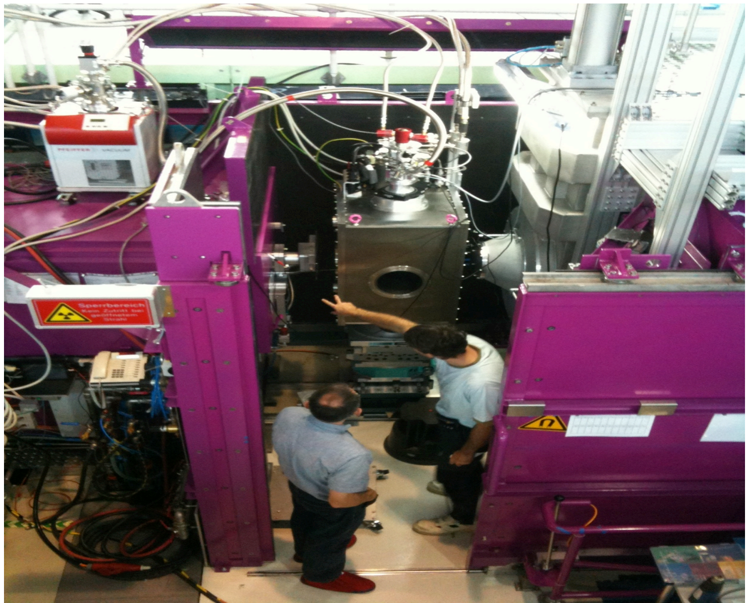
Optimally doped $(Ba_{1-x}K_x)Fe_2As_2$: neutrons as a probe for vortex lattice

SANS experiment



SANS 1 instrument @ MLZ

Neutrons sensitive to magnetism
Rocking the sample gives all lattice bragg peaks



$(Ba_{1-x}K_x)Fe_2As_2$ x=0.36
FC conditions for T=3.5-45 K
Under different fields H=0.25-2 Tesla
For each field configuration the bckgrd has been measured

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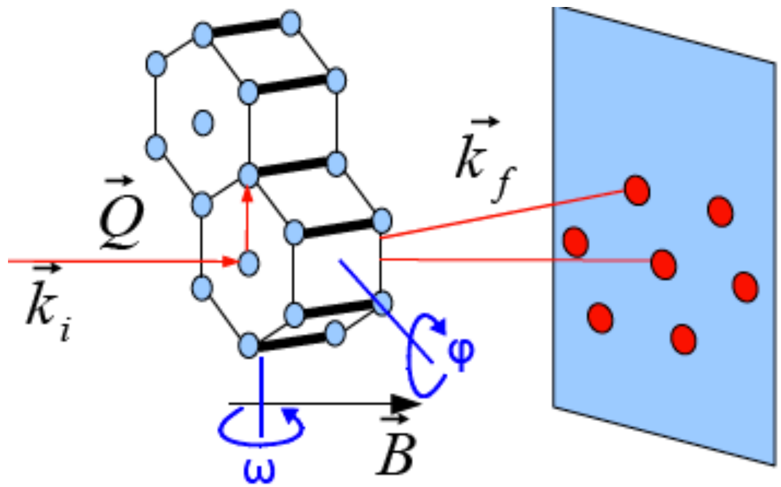
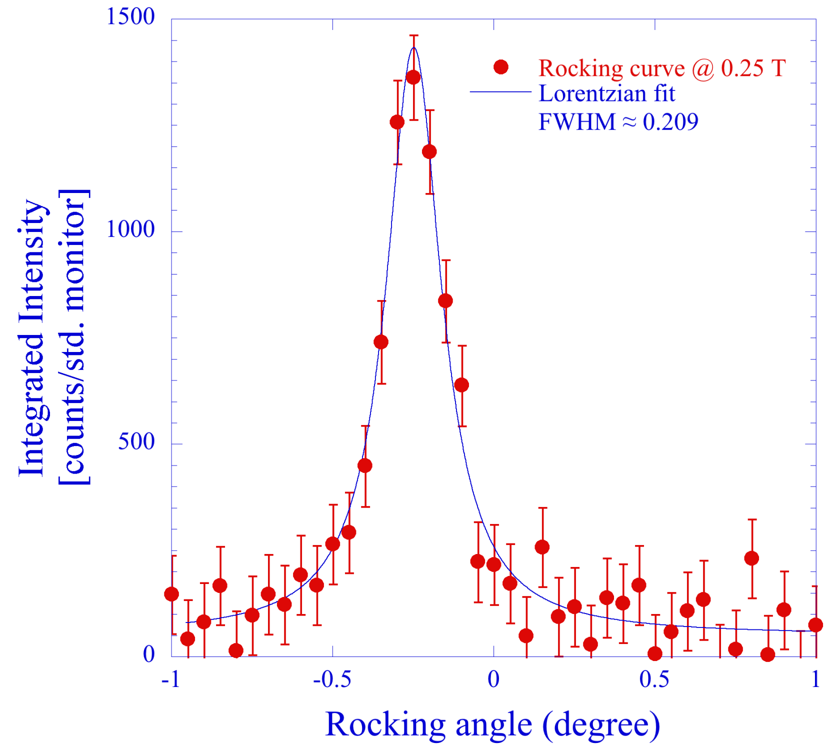


Typical rocking curve



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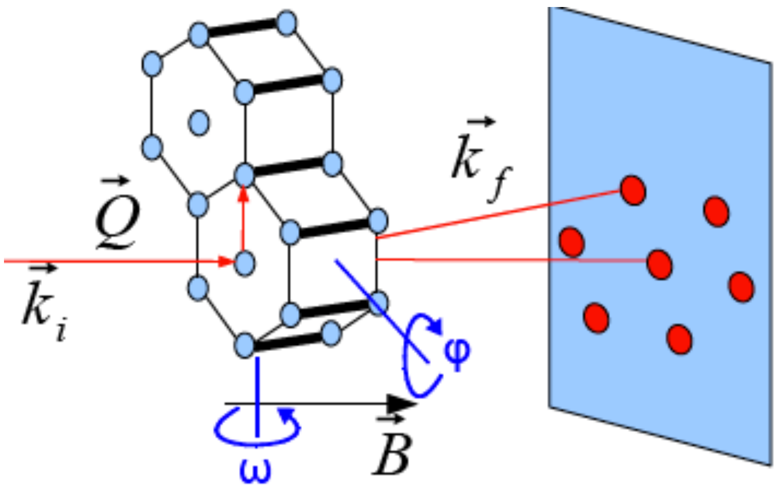

Neutrons sensitive to magnetism
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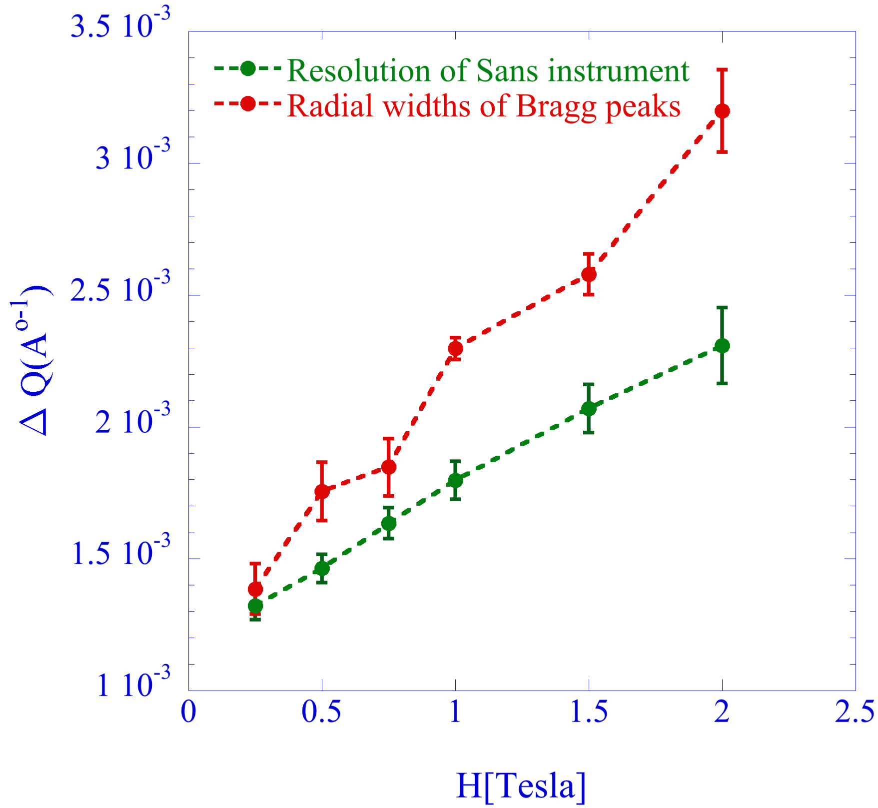
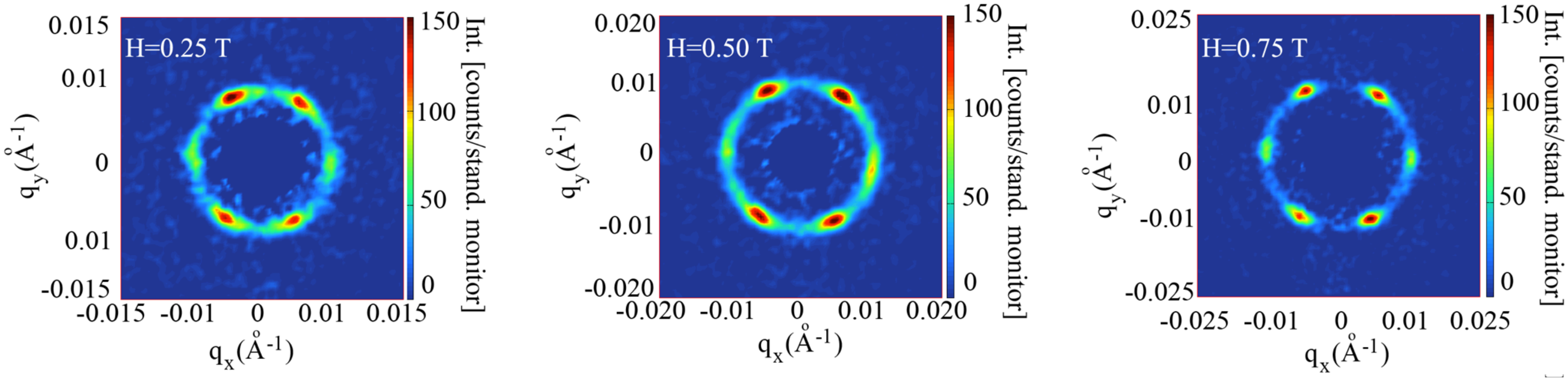
Resolution of SANS instrument



$$\sigma_r = \sqrt{4\pi^2(\delta\theta/\lambda_n)^2 + q^2(\Delta\lambda_n/\lambda_n)^2}$$

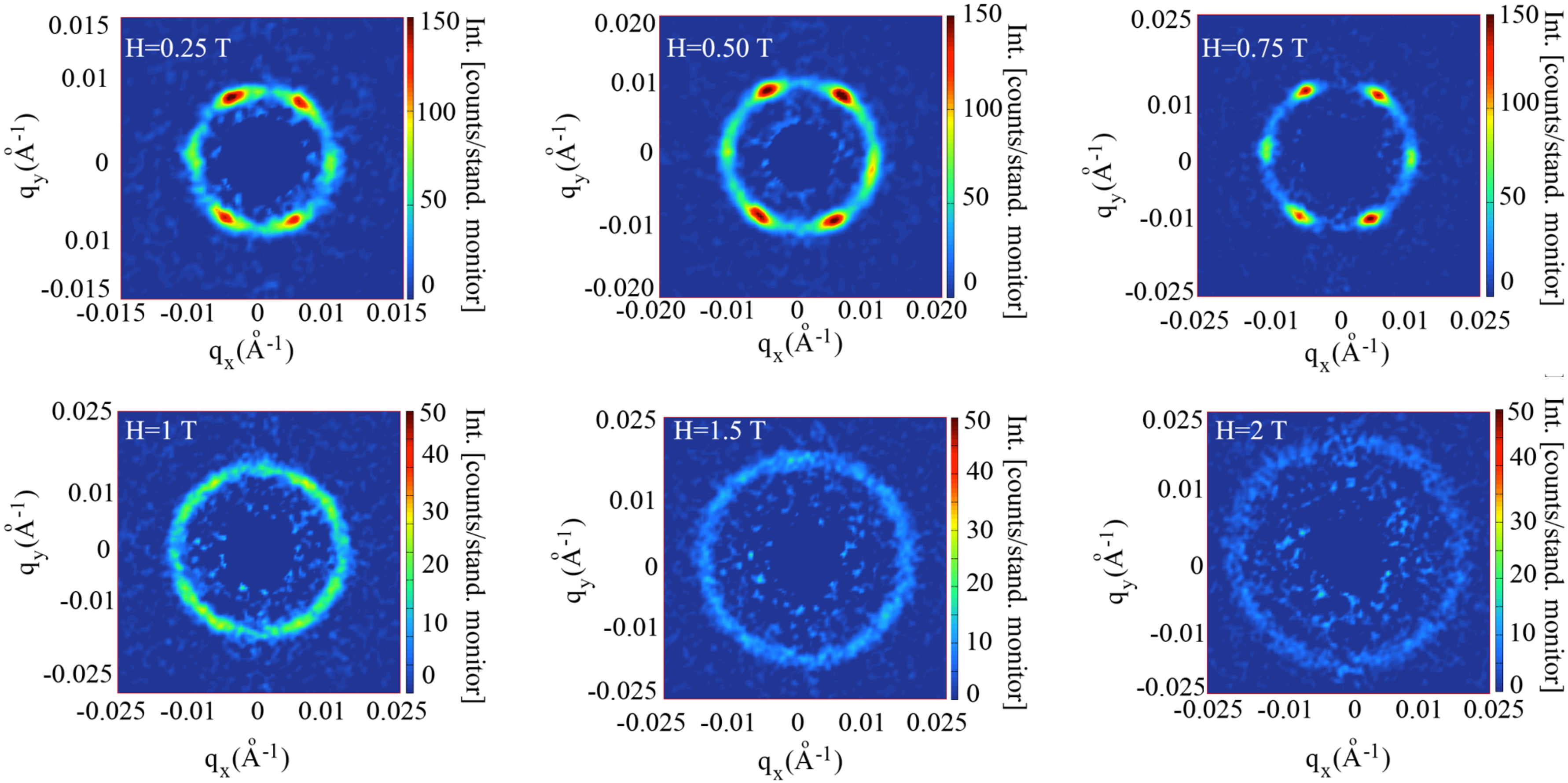
$(Ba_{1-x}K_x)Fe_2As_2$ x=0.36
FC conditions for T=3.5-45 K
Under different fields H=0.25-2 Tesla
For each field configuration the bckgrd has been measured

Optimally doped $(Ba_{1-x}K_x)Fe_2As_2$: Orientational long-range ordered vortex lattice



S. Demirdis et. al. to be published

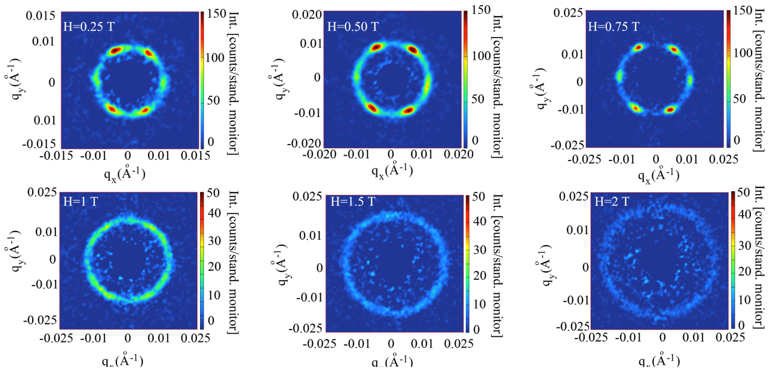
Optimally doped $(Ba_{1-x}K_x)Fe_2As_2$:structural transition of vortex lattice



S. Demirdis et. al. to be published

Optimally doped $(Ba_{1-x}K_x)Fe_2As_2$:structural transition of vortex lattice

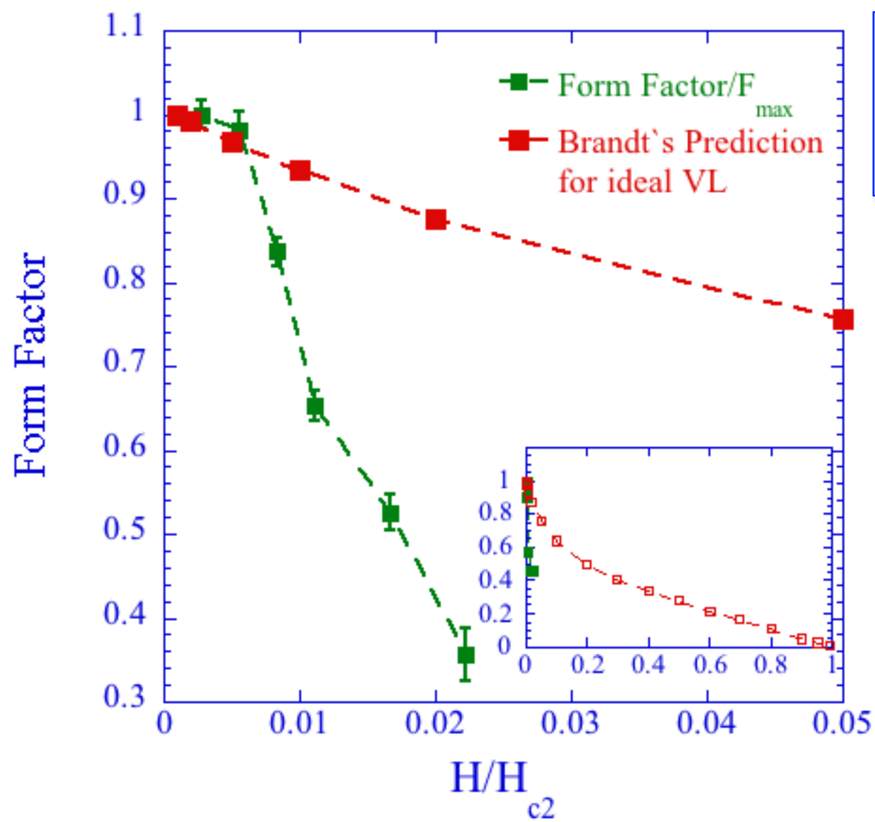
Jülich Centre for Neutron Science



SANS pattern of VL is determined by:

- Form factor [F] (vortex core structure)
- Structure factor [S] (lattice structure)

For ideal VL S=1



$$I_q = 2\pi V\phi \left(\frac{\gamma}{4}\right)^2 \frac{\lambda_n^2}{\Phi_0^2 q}|F(q)|^2.$$

Precision Ginzburg-Landau Solution of Ideal Vortex Lattices for any induction and symmetry:form factor prediction for SANS

E. H. Brandt PRL **78**, 11 (1997)

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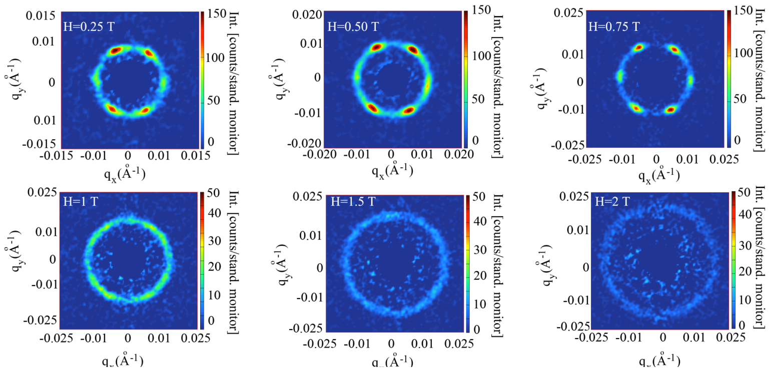

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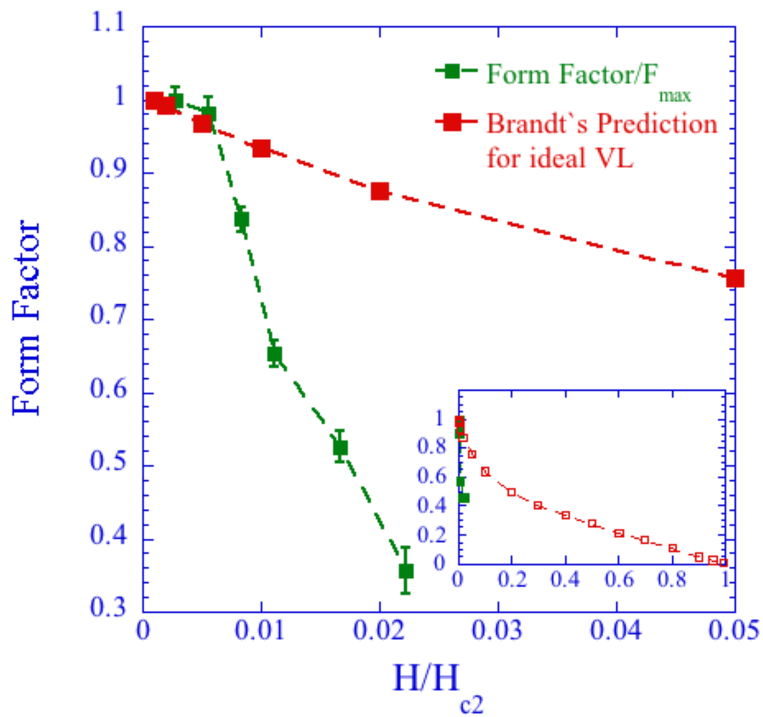
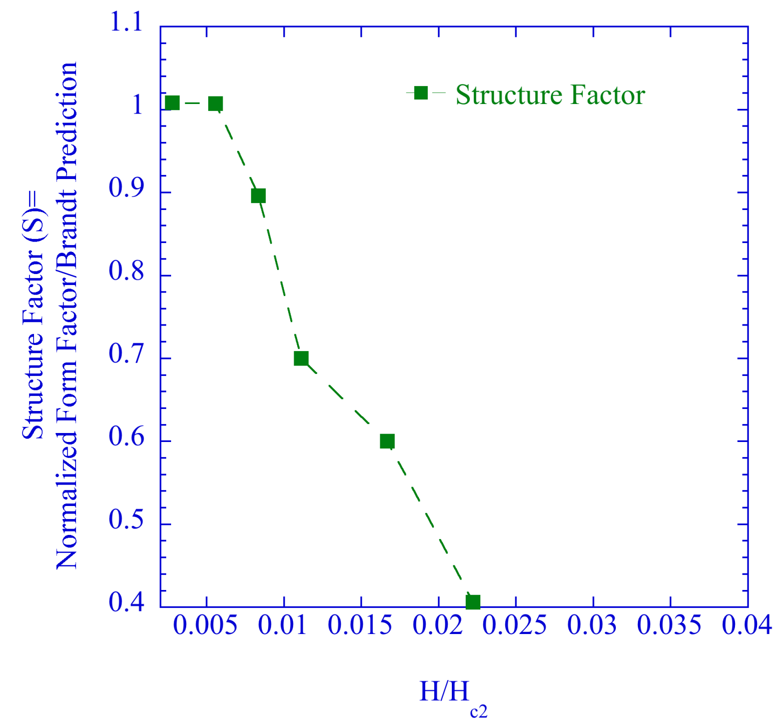


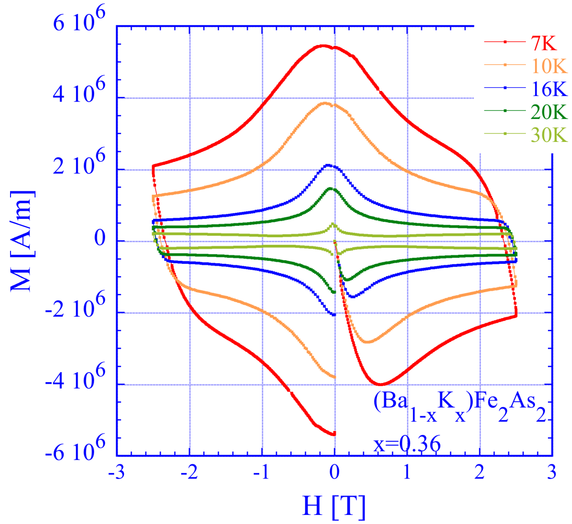


H_{c2} experimental based on X.-L. Wand et. al. PRB **82**, 024525 (2010)
M. M. Altarawneh et. al. PRB **78**, 220505R 2008

S. Demirdis et. al. to be published

$(Ba_{1-x}K_x)Fe_2As_2$: structural transition of VL, ``second magnetization peak``

Low T



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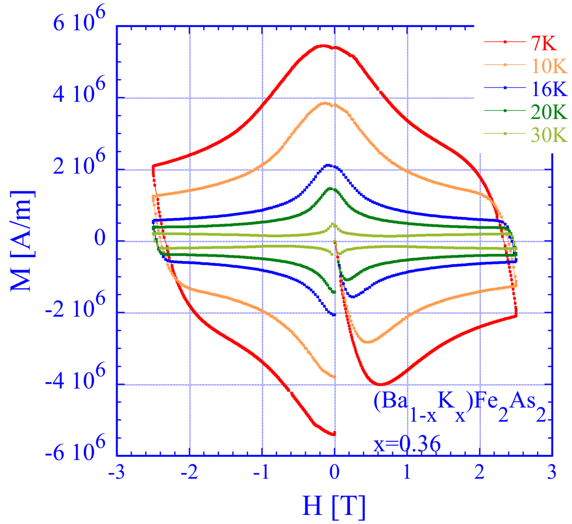
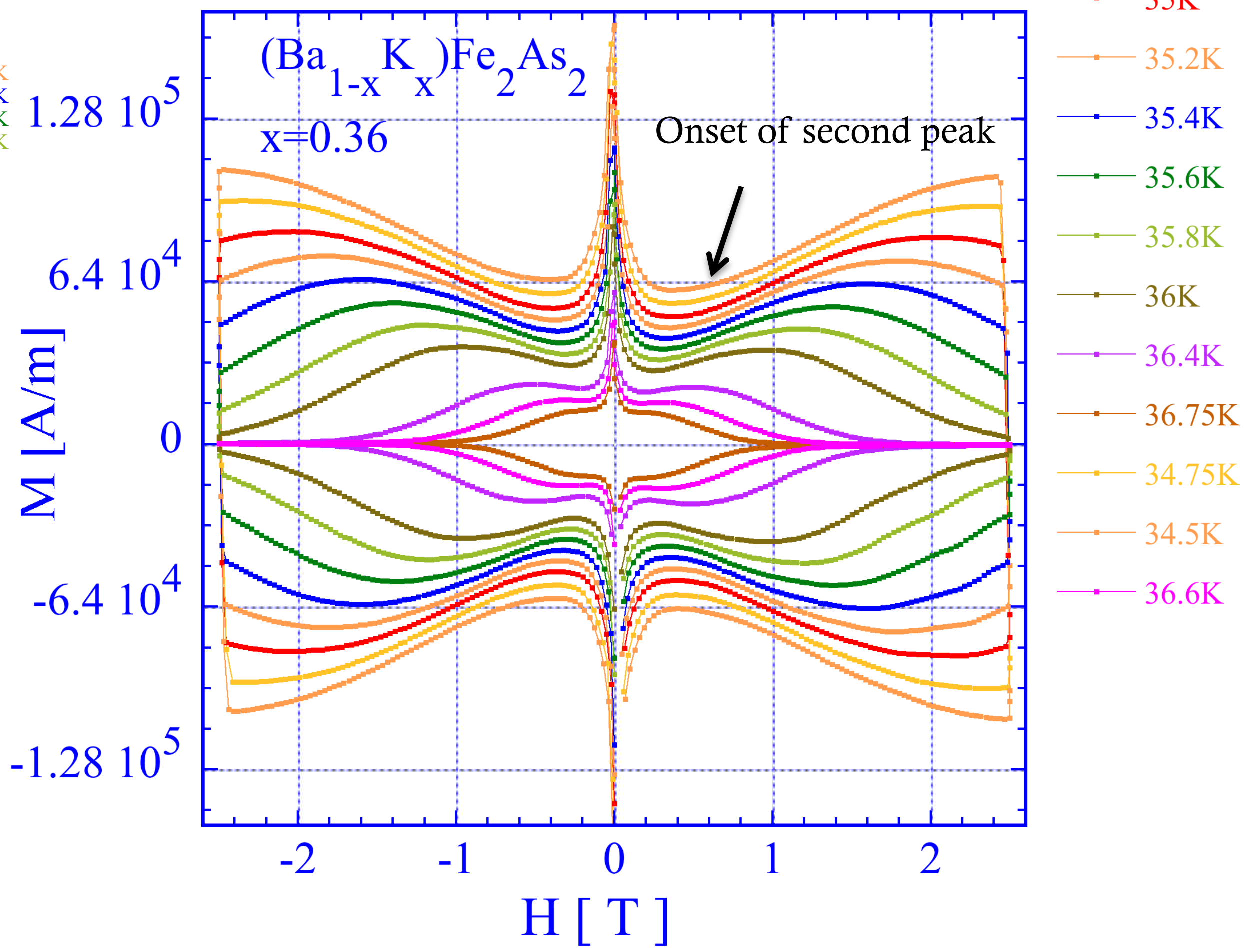
Low T



High T



S. Demirdis et. al. to be published

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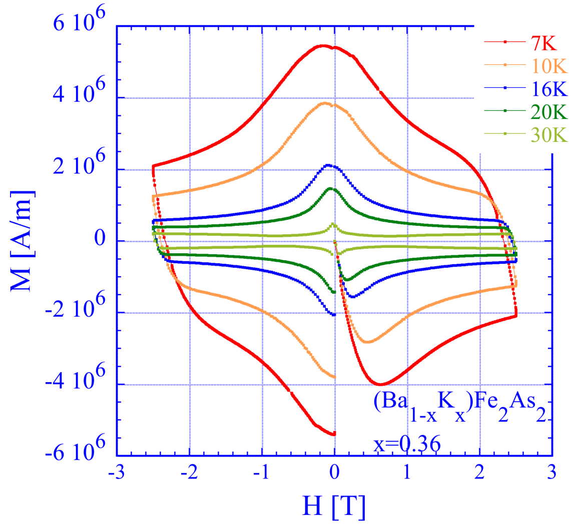
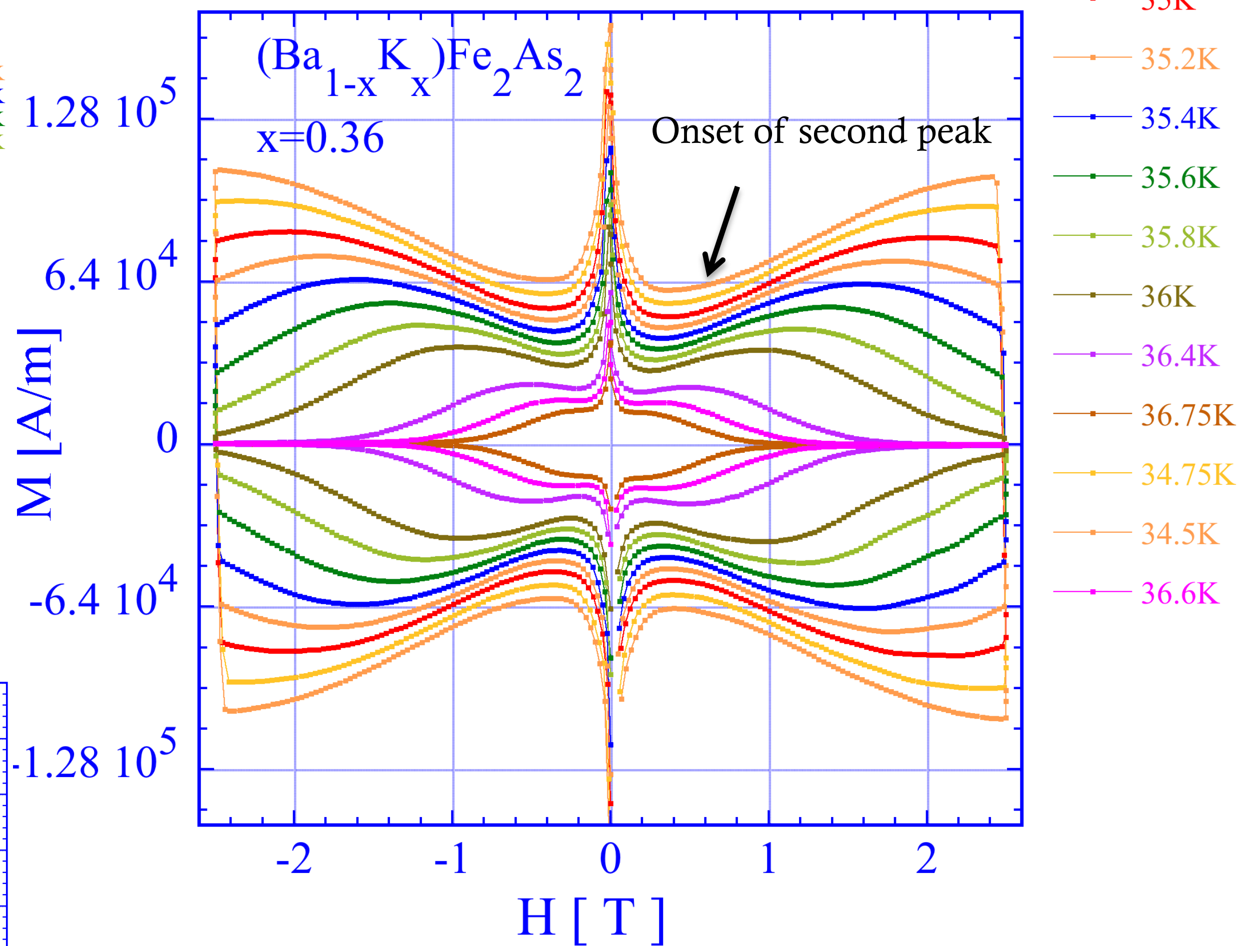
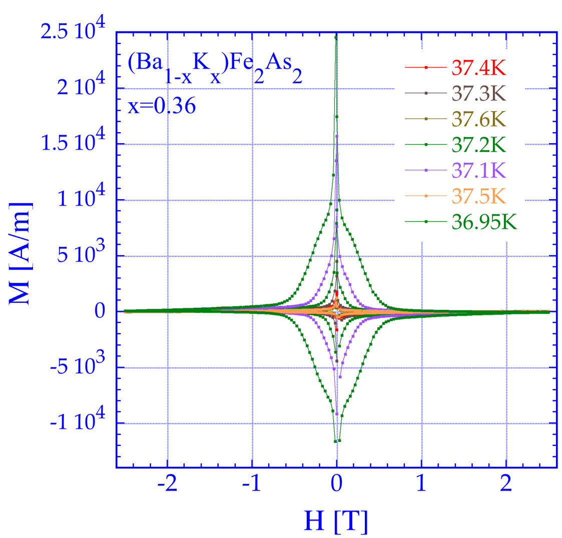


High T

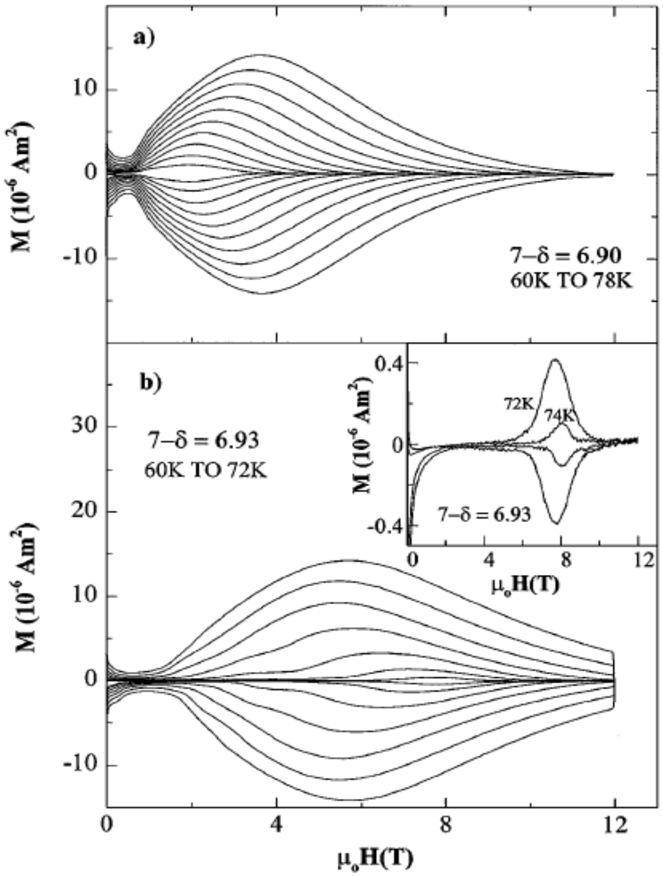


Very High T

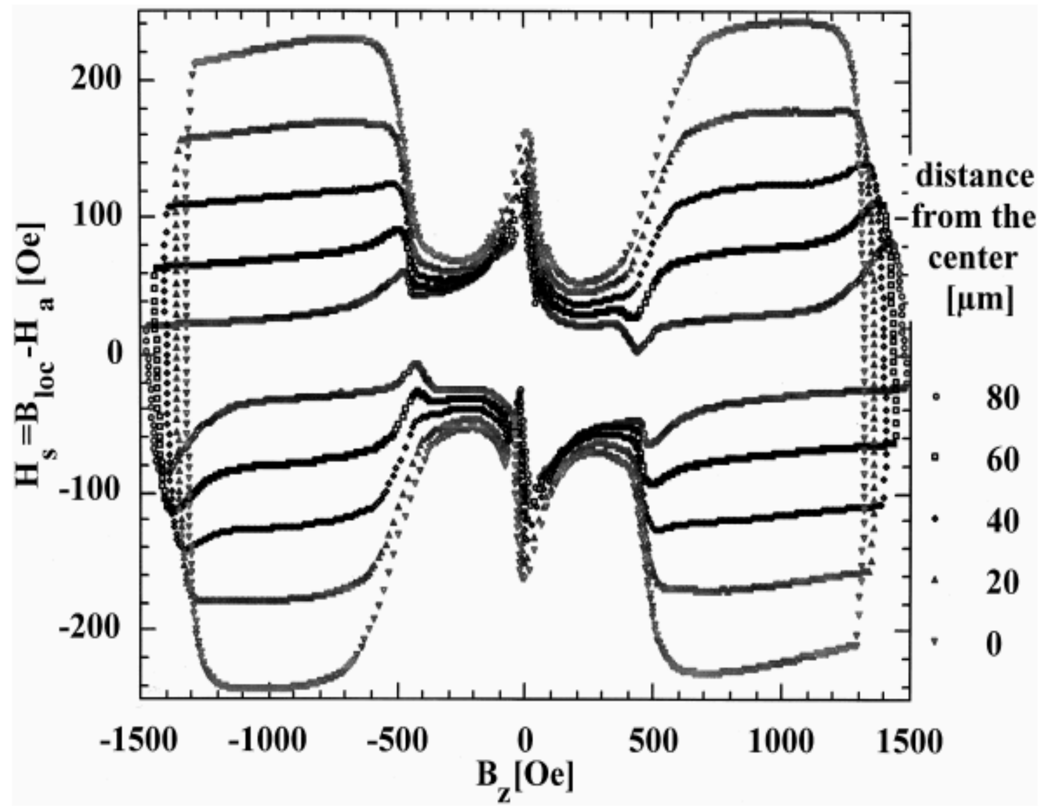


$(Ba_{1-x}K_x)Fe_2As_2$: ``second magnetization peak``, similarity with High-T_c cuprates

New Features in the Vortex Phase Diagram of $YBa_2Cu_3O_{7-d}$
K. Deligiannis et. al.PRL 79, 11 (1997)



Magnetic relaxation in the vicinity of second magnetization peak in BSCCO crystals
M. Konczykowski Physica C 332, 219-224 (2000)



($NbSe_2$) Y. Paltiel et. al Nature 403, 398-401 (2000)
(MgB_2) T. Klein PRL 105, 047001 (2010)

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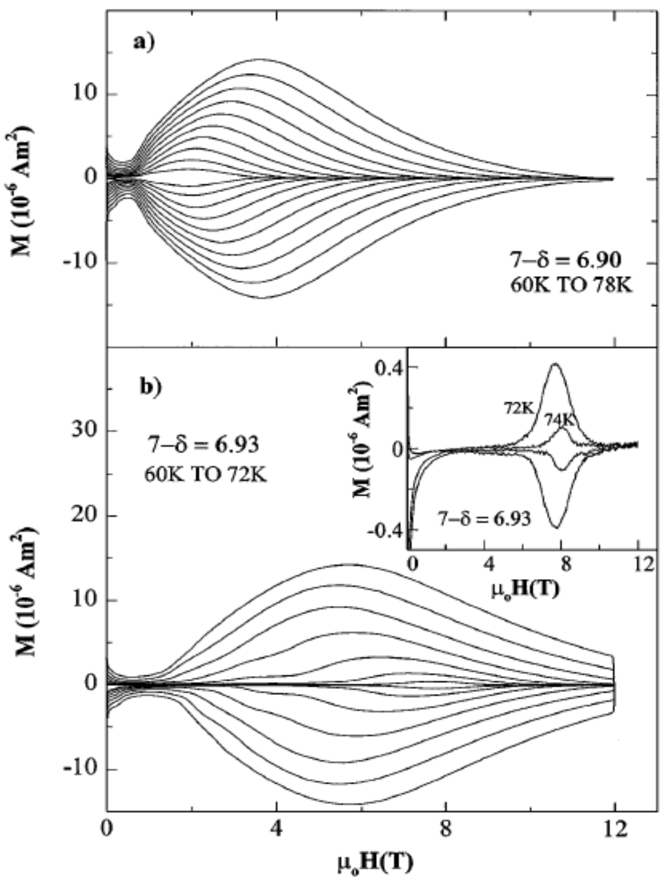
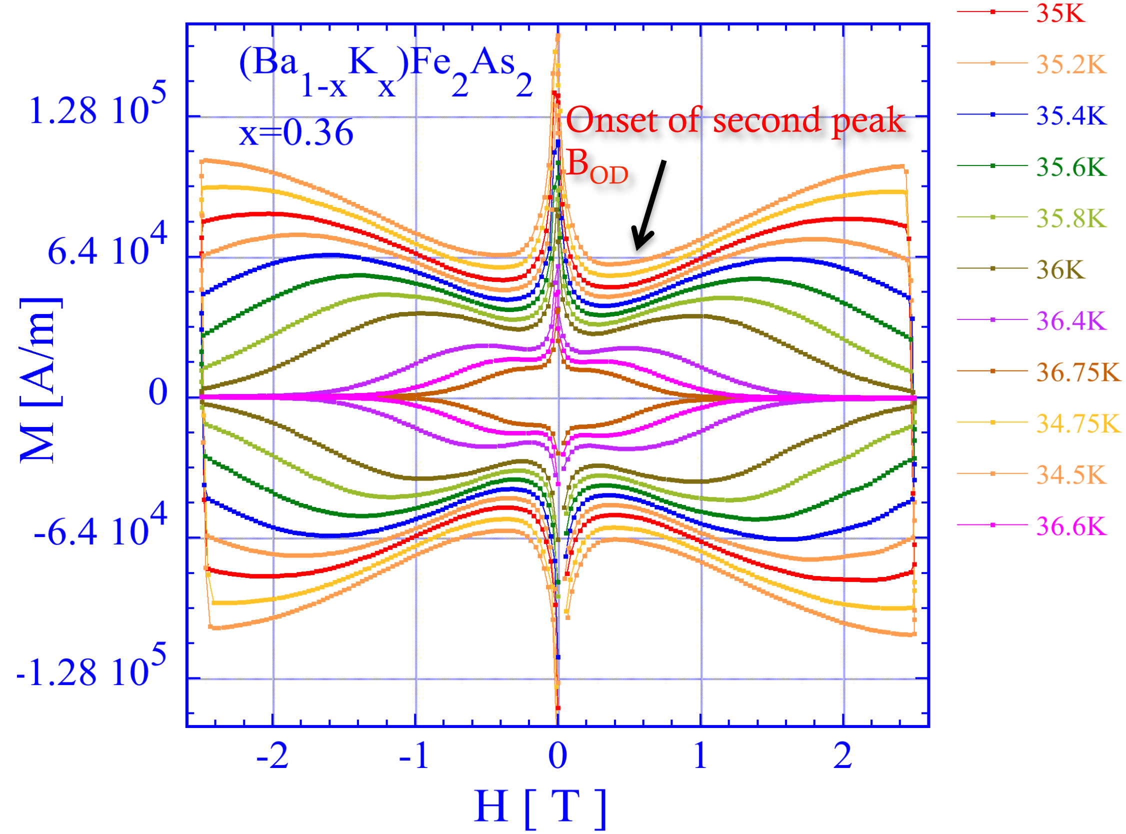
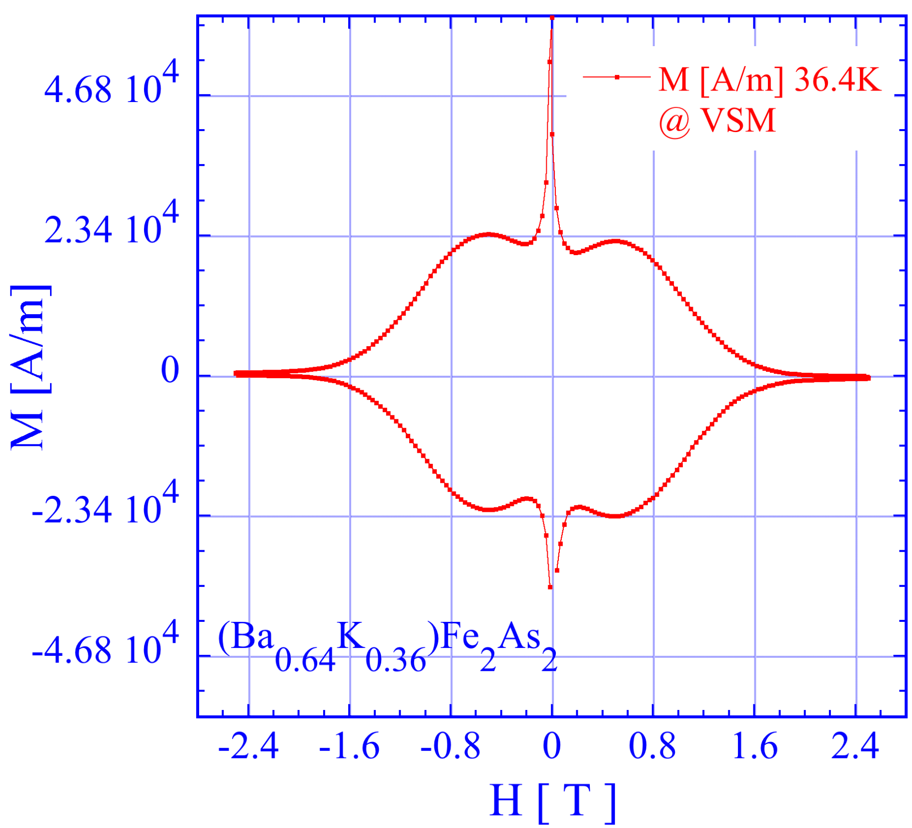




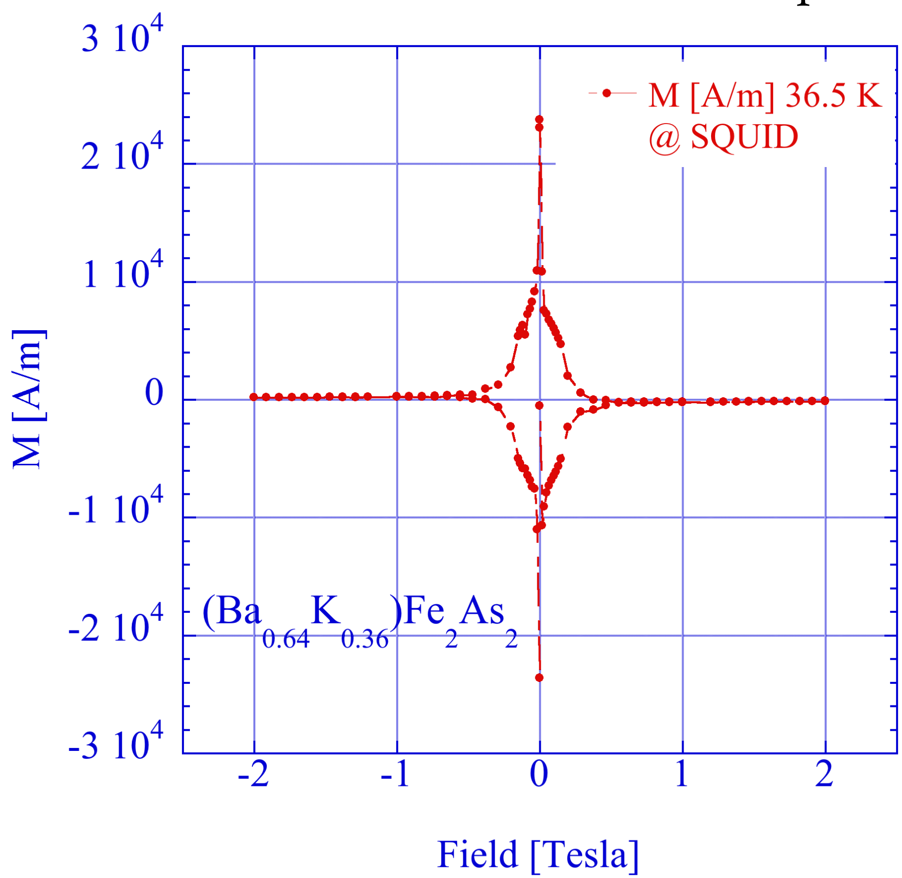
$(Ba_{1-x}K_x)Fe_2As_2$: ``second magnetization peak``, similarity with High-T_c cuprates

Vortex creep is very important and has to be taken into account !

Fast field ramping
Continuous data measurement

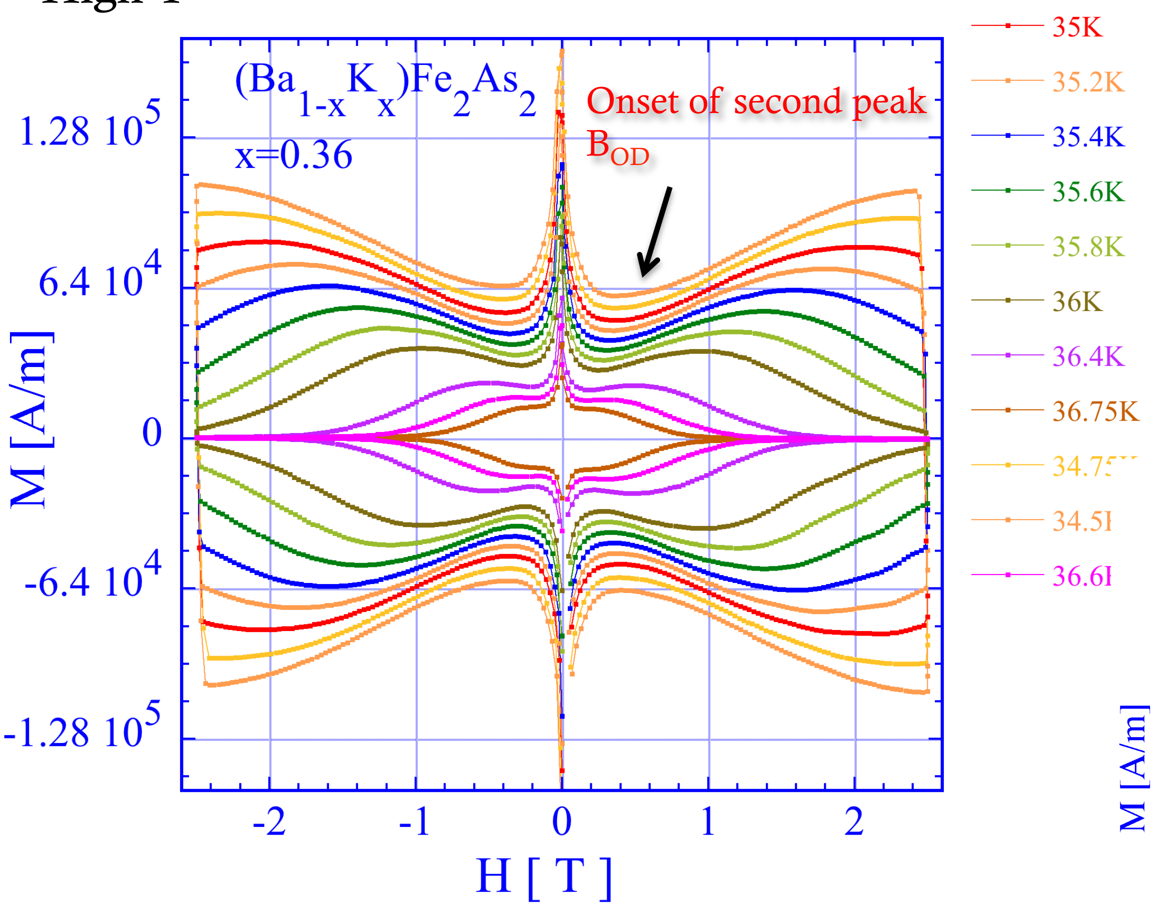


Slow field ramping
Data measurement at the field setpoint



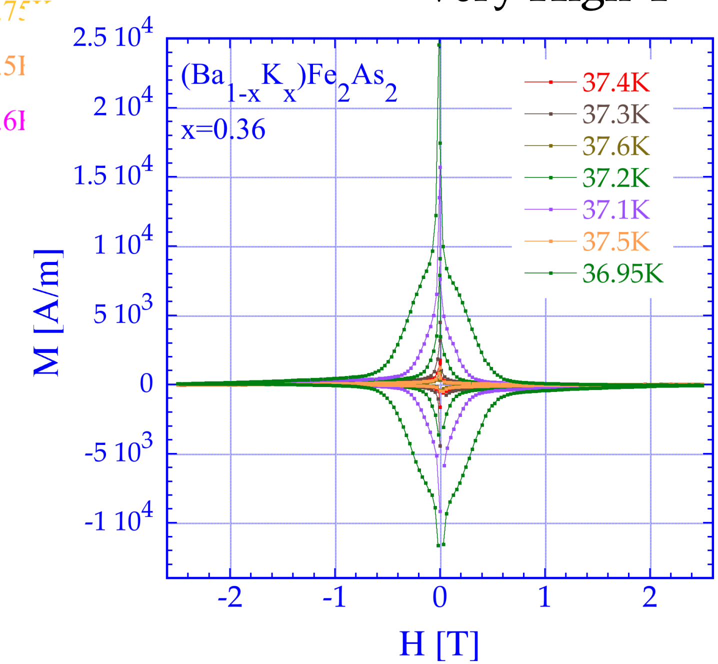
$(Ba_{1-x}K_x)Fe_2As_2$: ``second magnetization peak``, similarity with High-T_c cuprates

High T



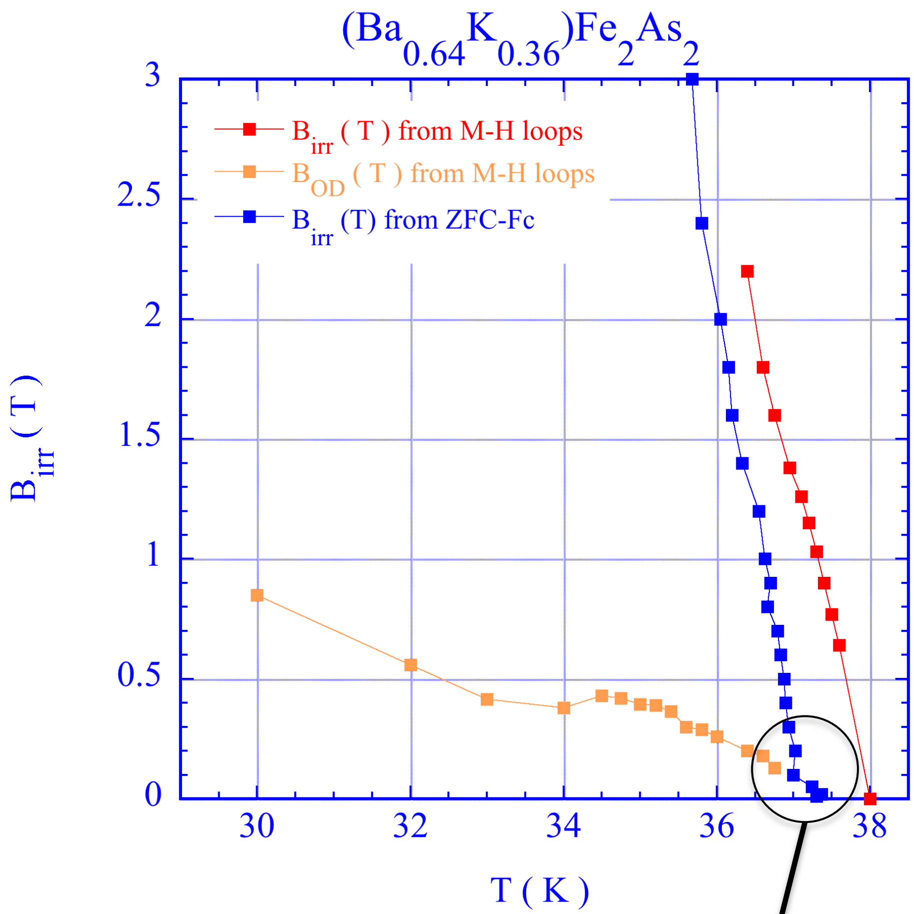
Different creep rates for different field phases can explain the M-H curves evolution in temperature !

Very High T

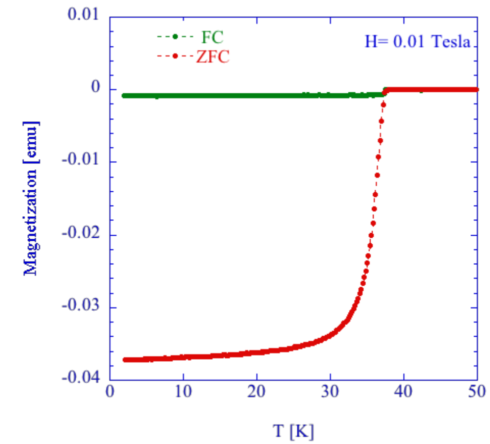


S. Demirdis et. al. to be published

$(Ba_{1-x}K_x)Fe_2As_2$: structural transition of VL, vortex phase diagram, O-D transition



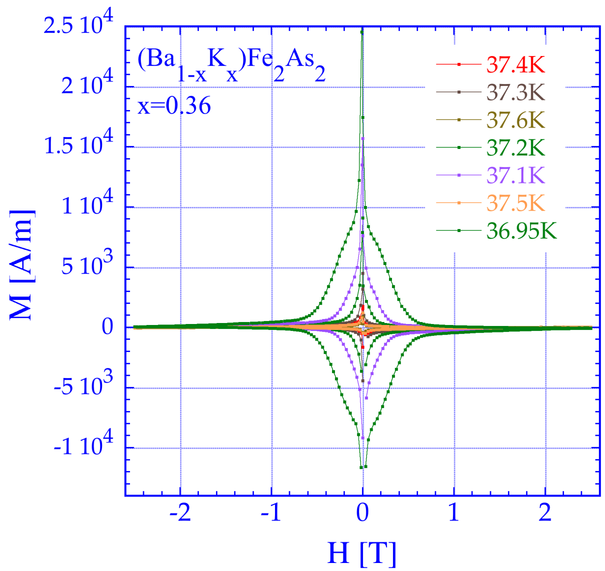
B_{OD} joins B_{irr}
for fields below ≈0.2 Tesla

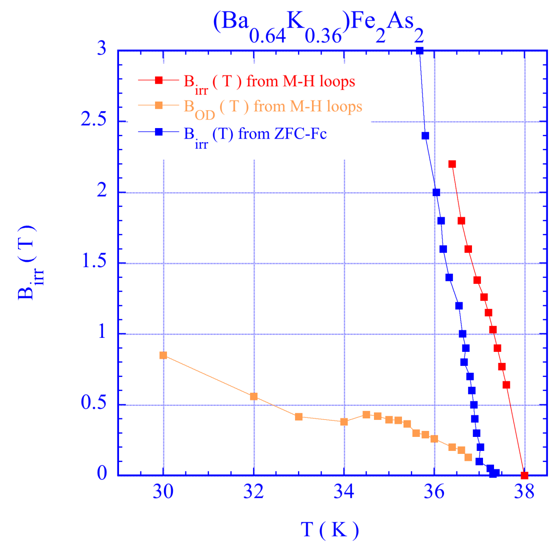


Field [Tesla]	$T_{freezing}$ (K)
0.25	36.99
0.5	36.8
0.75	36.7
1	36.4
1.5	36.2
2	36

S. Demirdis et. al. to be published

$(Ba_{1-x}K_x)Fe_2As_2$: structural transition of VL, vortex phase diagram, O-D transition





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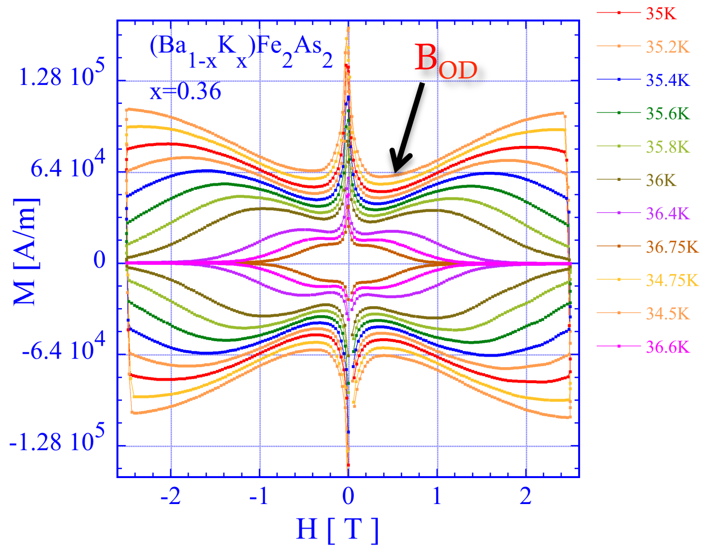
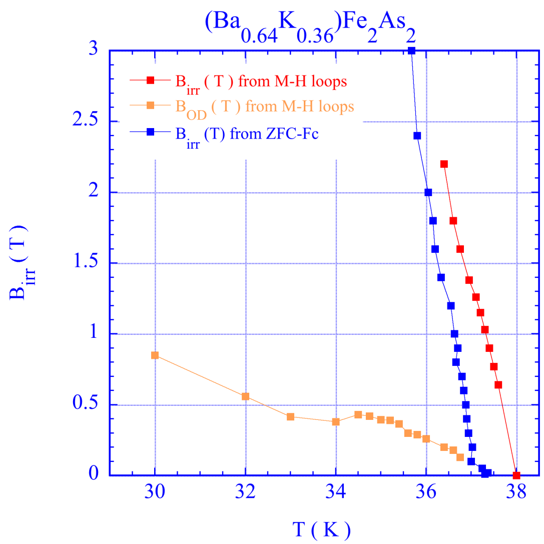
- SANS low fields <0.25 Tesla : T_f is high, vortices cross the B_{OD} in the fast creep regime at high field phase and they are not affected by pinning. The VL is frozen only at low field phase where the stucture factor is 1. Above this field spatial correlations start to decrease.

$(Ba_{1-x}K_x)Fe_2As_2$: structural transition of VL, vortex phase diagram, O-D transition





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- SANS higher fields>0.25 Tesla : T_f starts to decrease, vortices cross the B_{OD} in the slow creep regime at high field phase. VL is free to accomodate itself it is affected by the effective pinning at this high field phase before totally freezing. For very high fields VL has a liquid-like sructure with a correlation length not larger then a_0

Summary

- First Observation of ordered Vortex Lattice for doped 122-type Fe-based superconductors
- Structural transition (Order-Disorder) of VL in optimally doped $(Ba_{1-x}K_x)Fe_2As_2$
- Second magnetization peak observed in optimally doped $(Ba_{1-x}K_x)Fe_2As_2$, similar to $YBa_2Cu_3O_{7-d}$ system
- Vortex creep rates at different magnetic field ranges determines the M-H loops shape
- VL structural transition has clear correlation with features observed around the so-called `second magnetization peak`
- For H< 0.25 T, (high structure factor), characteristic result of low field phase for VL.
- For H>0.25 T, where the structure factor drops down, characteristic result of high field phase for VL.