Peak effect and Vortex Lattice Structural Transition in Optimally Doped $Ba_{1-x}K_xFe_2As_2$

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Jülich Centre for Neutron Science at MLZ

Collaboration

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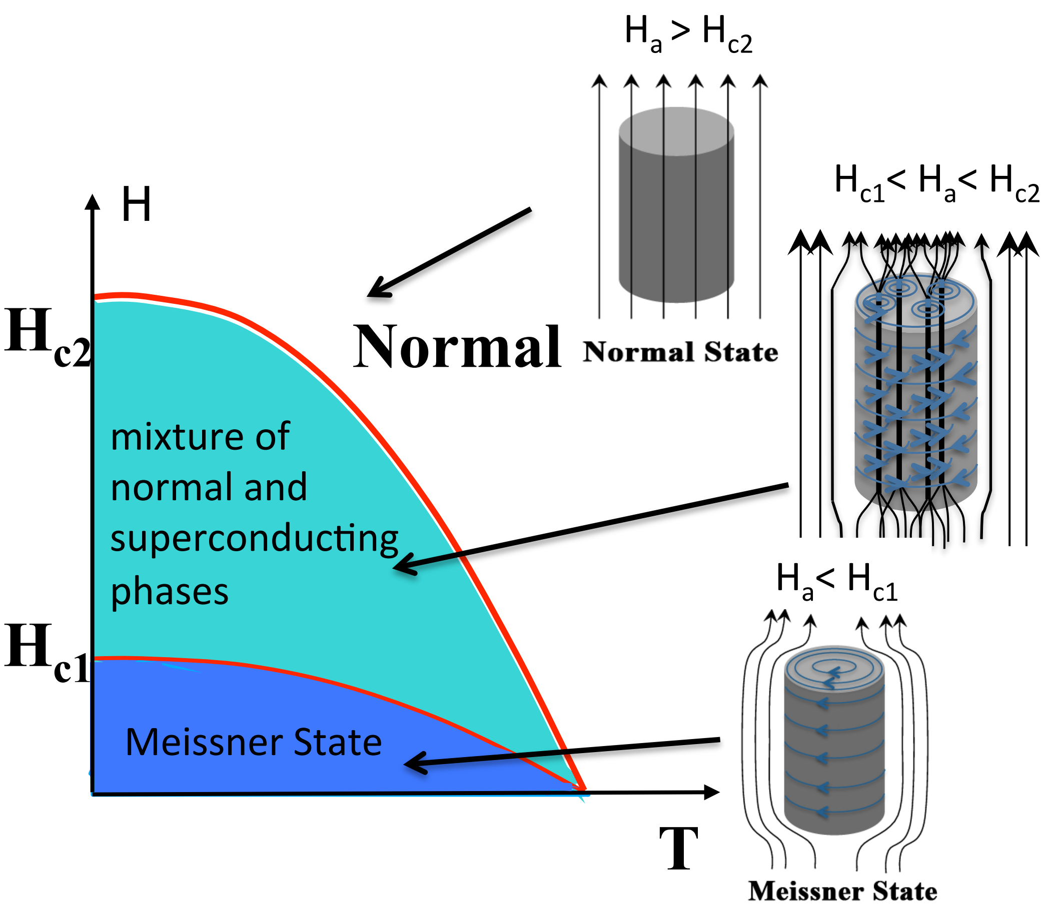
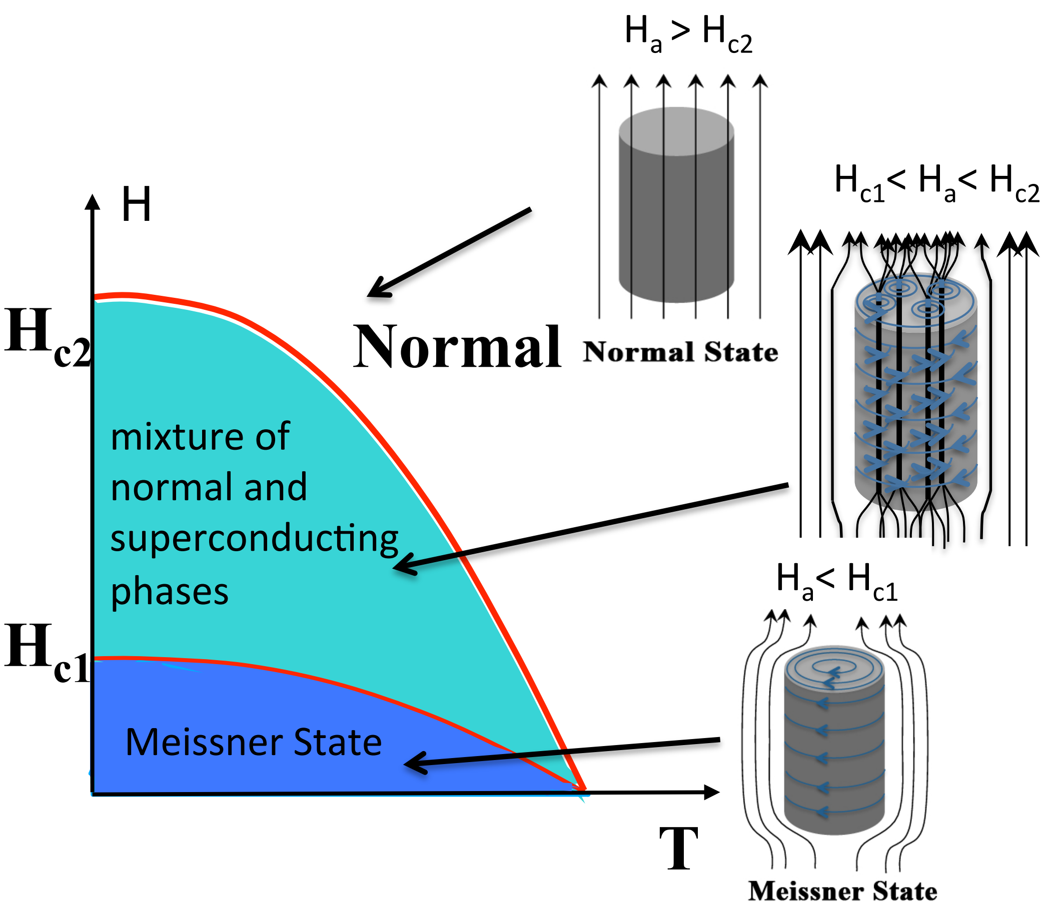
Type II superconductors, mixed state

R=0 for $T<T_c$
Expulsion of the magnetic flux



Type II superconductors, mixed state, vortex line

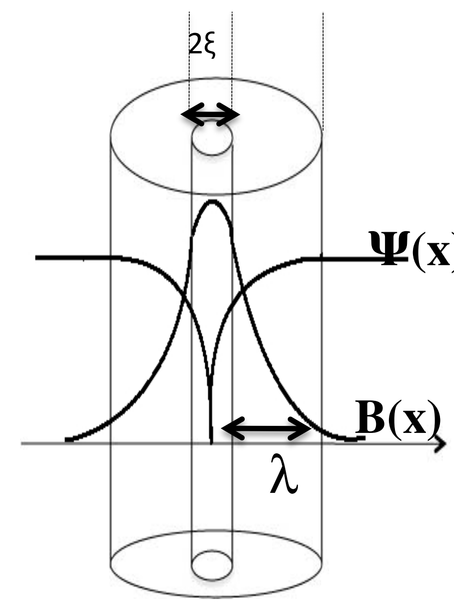
R=0 for T<T_c
Expulsion of the magnetic flux



Vortex line energy

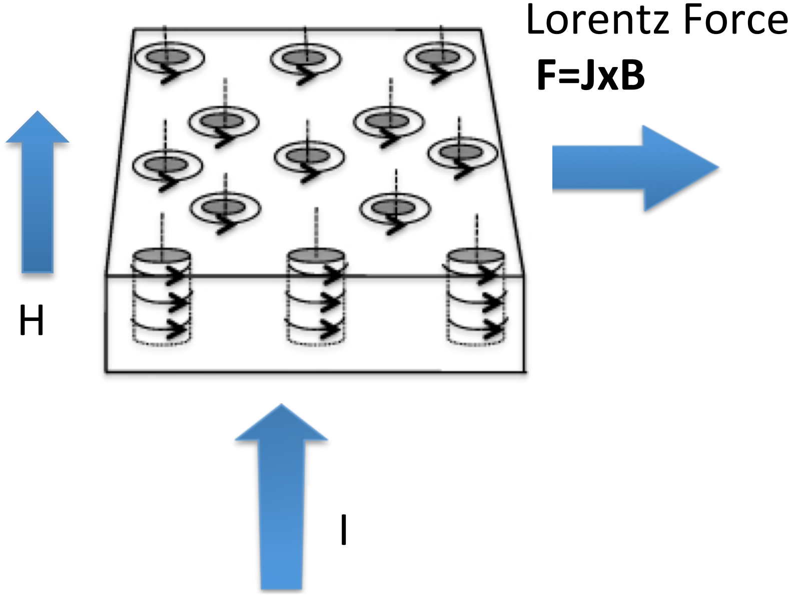
$$\varepsilon_0 = \Phi_0^2/4\pi\mu_0\lambda_{ab}^2$$

Φ_0=h/2e



In the absence of disorder:
triangular lattice, a_Δ=1.075 √(Φ_0/B)

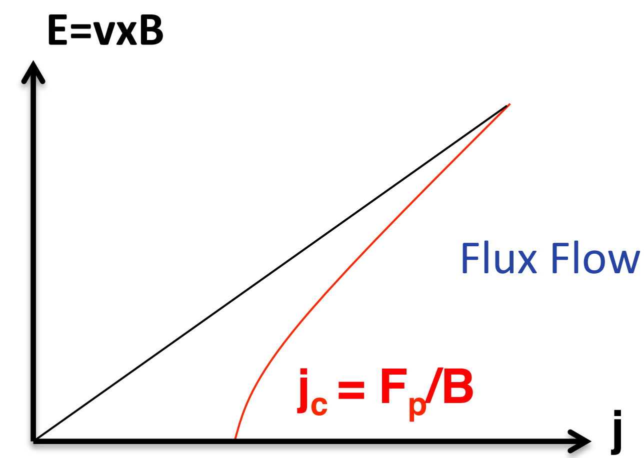
Vortex pinning and Critical current density j_c



Defects in the material are traps for vortices

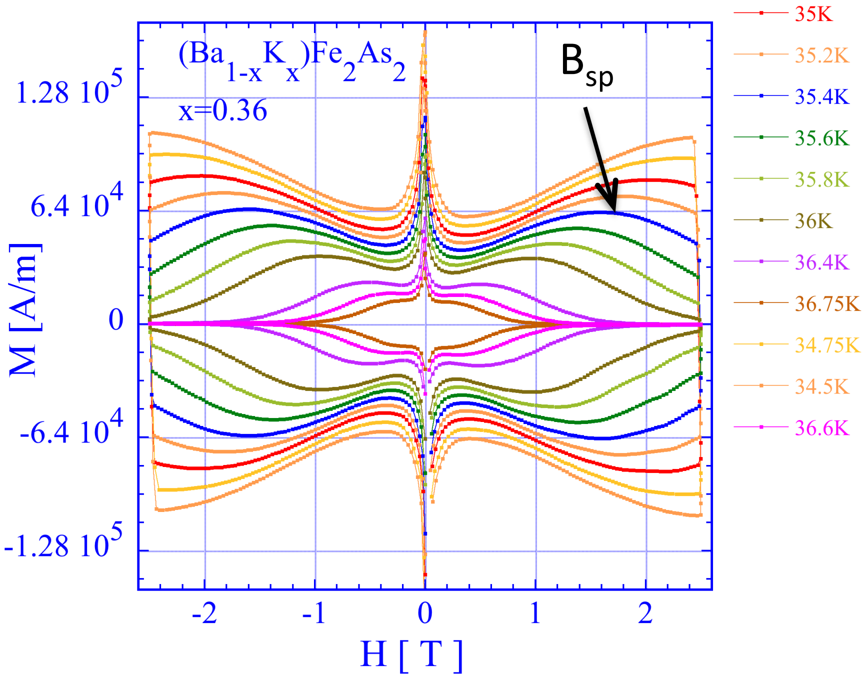
F_p: Force to untrap

$j_c = F_p/B$: critical current density



Critical current density j_c , and Peak effect

Peak effect in $(Ba,K)Fe_2As_2$



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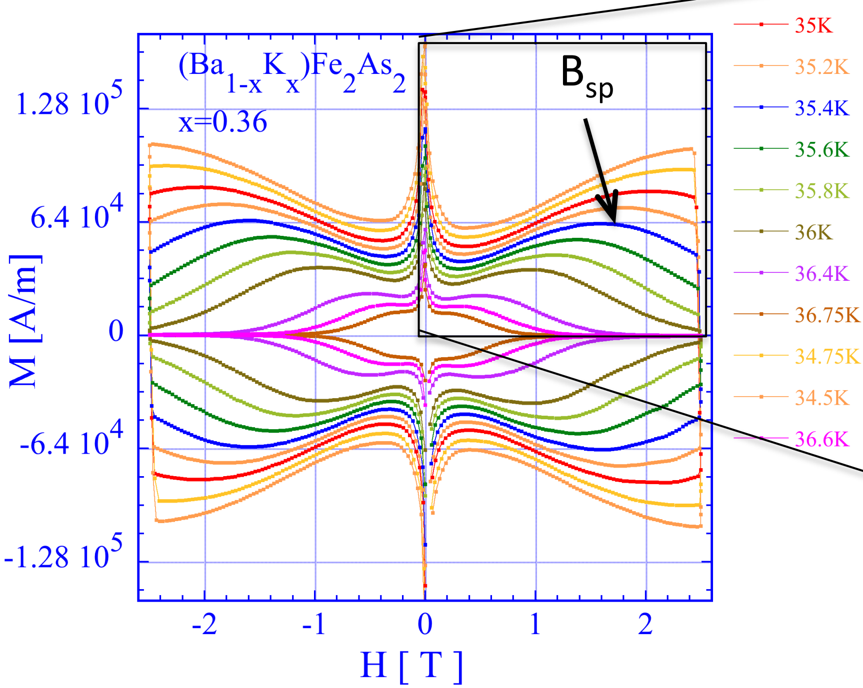
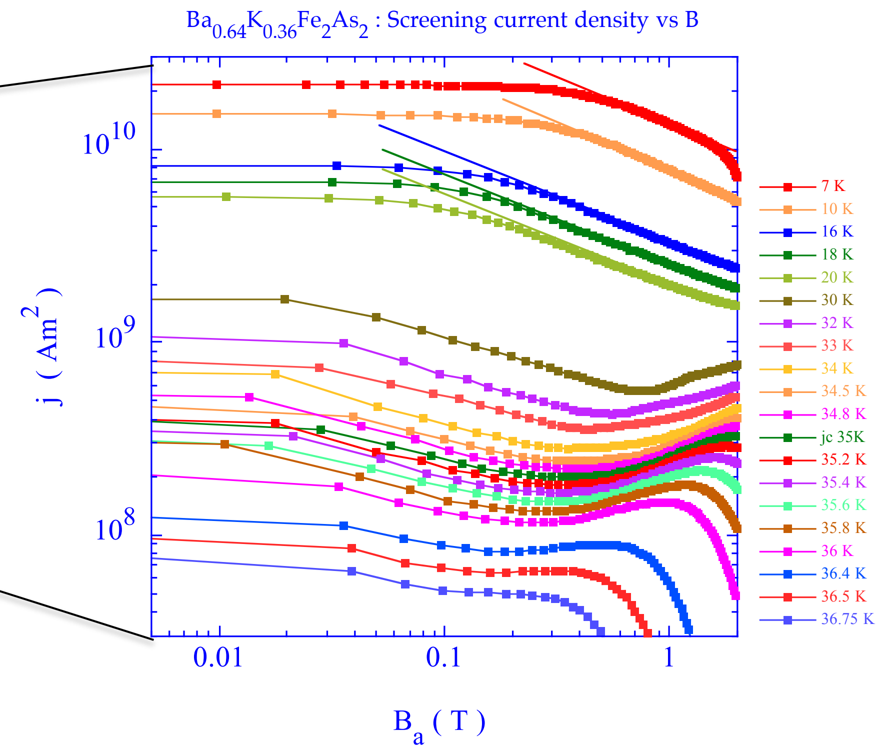
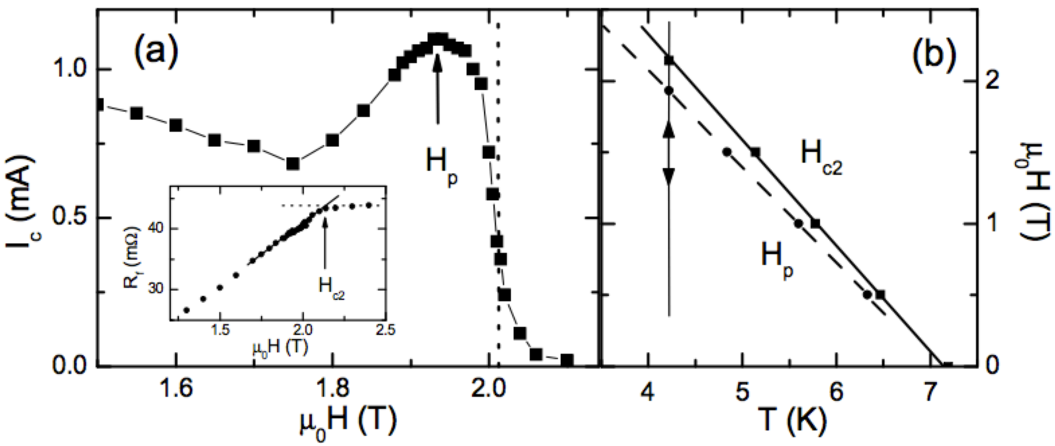
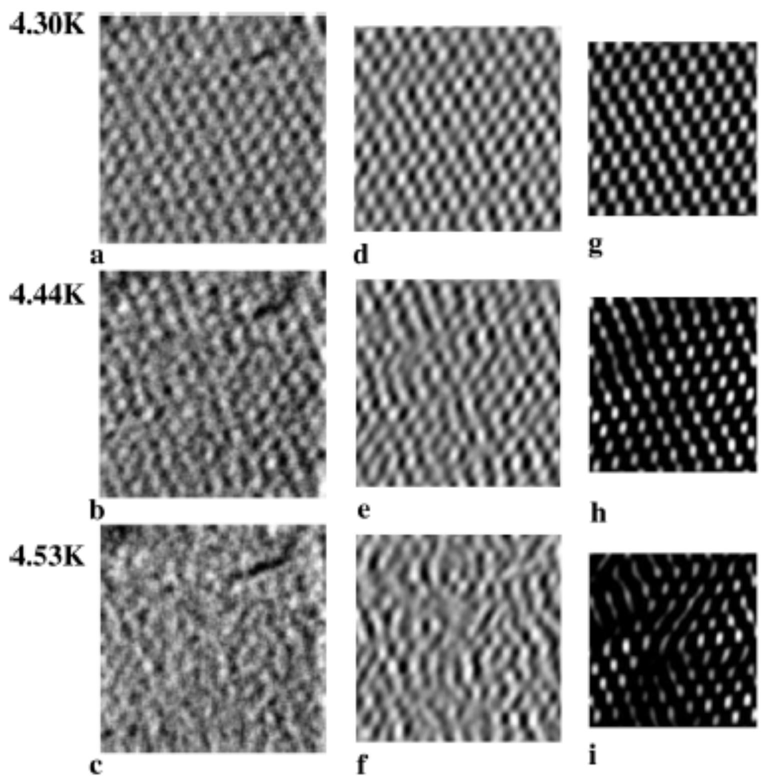




Peak effect in different systems : $NbSe_2$

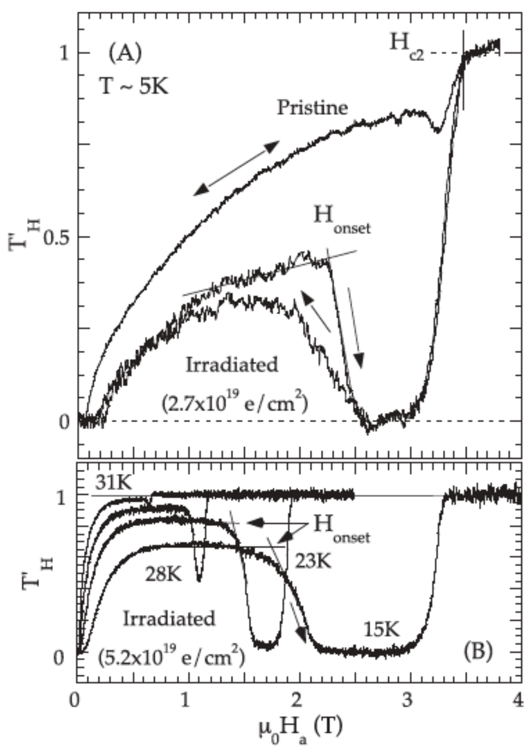
- 1^{st} order transition of vortex lattice (Paltiel, PRL **85**, 3712 (2000)).
- Relatively close to B_{c2}
- Weak pinning or edge pinning below B_{sp} (Koorevaar, Paltiel)
- Single crystal to polycrystal (Troainovski, PRL **89**, 147006 (2002))



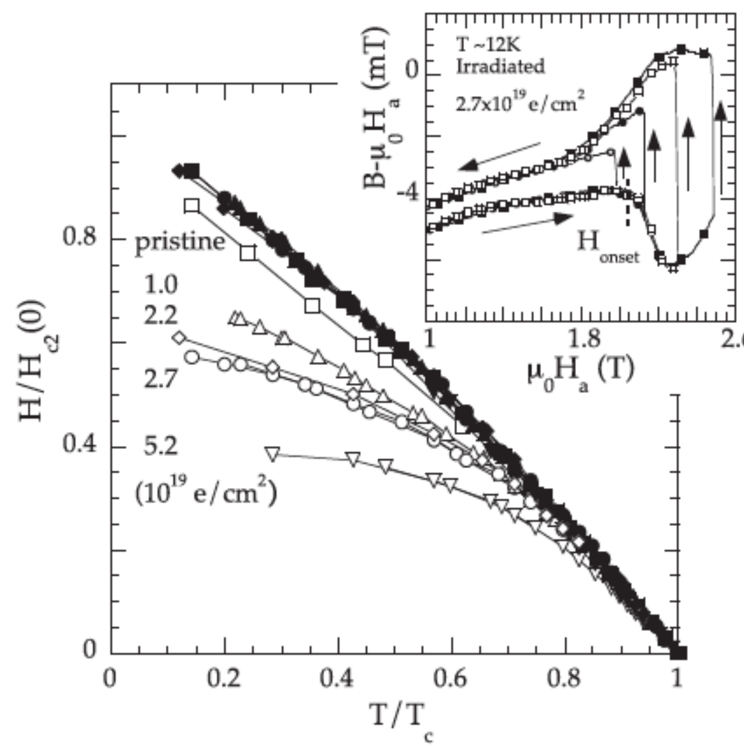


Peak effect in different systems : MgB_2

- 1^{st} order transition of vortex lattice, relatively close to B_{c2} (Klein, Nature (2000).)
- From ordered Bragg Glass to a disordered vortex phase tuned by artificial disorder is mediated by the proliferation of dislocations (point defects/irradiation (Klein, Phys Rev B (2010).)
- Weak pinning below B_{sp}



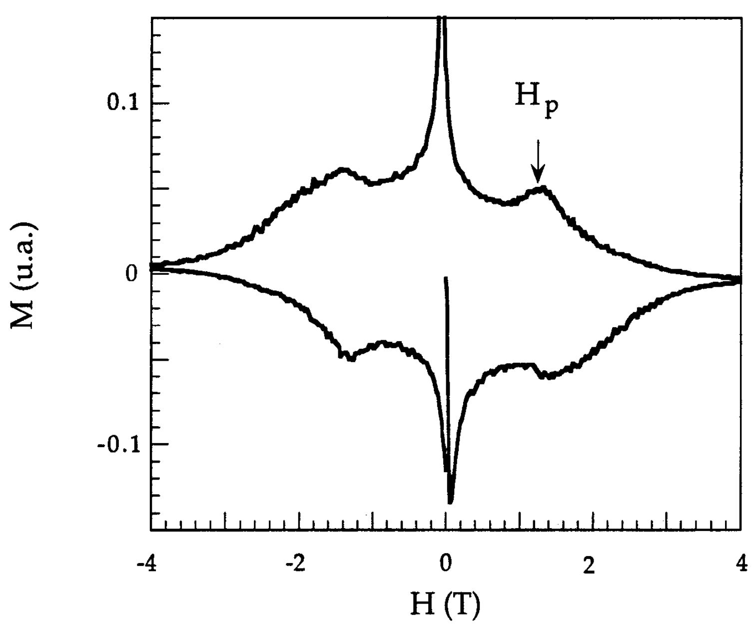
Field dependence of ac-transmittivity

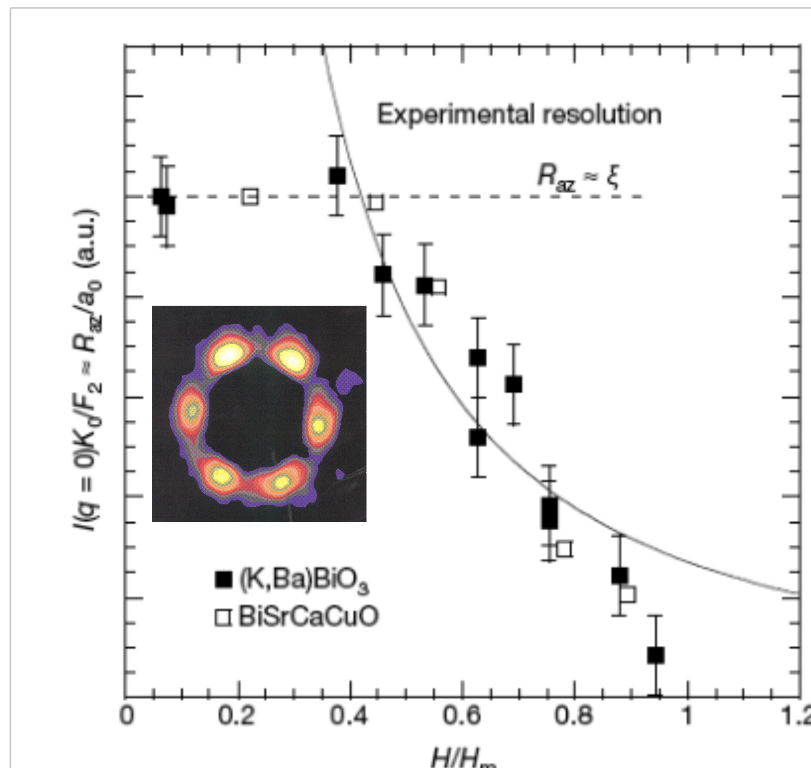


Onset of the peak effect shifted with increasing disorder

Peak effect in different systems : $Ba_{1-x}K_xBiO_3$

- Well below B_{c2} (Klein Nature 413, 404 (2001), Barilo Phys. Rev B (1998)).
- Weak pinning Bragg glass below B_{sp} that goes to a vortex glassy phase above B_{sp} (neutrons, Joumard et al 1999)
- Vanishing small angle neutron scattering (SANS) signal at B_m, B_{sp}



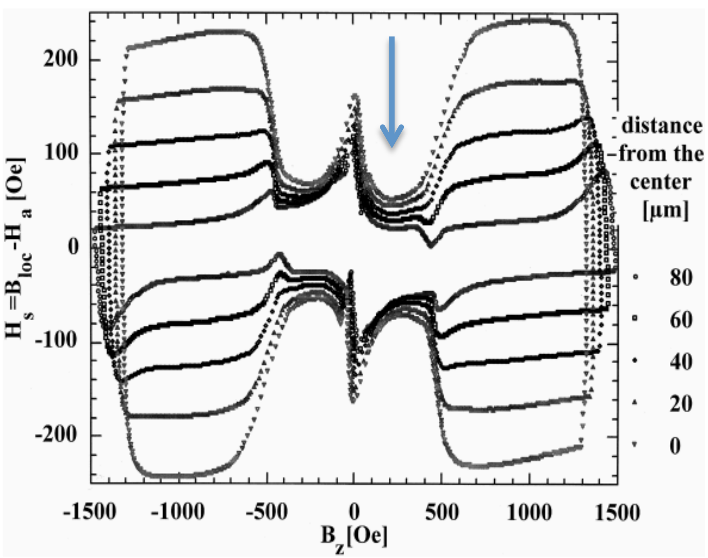


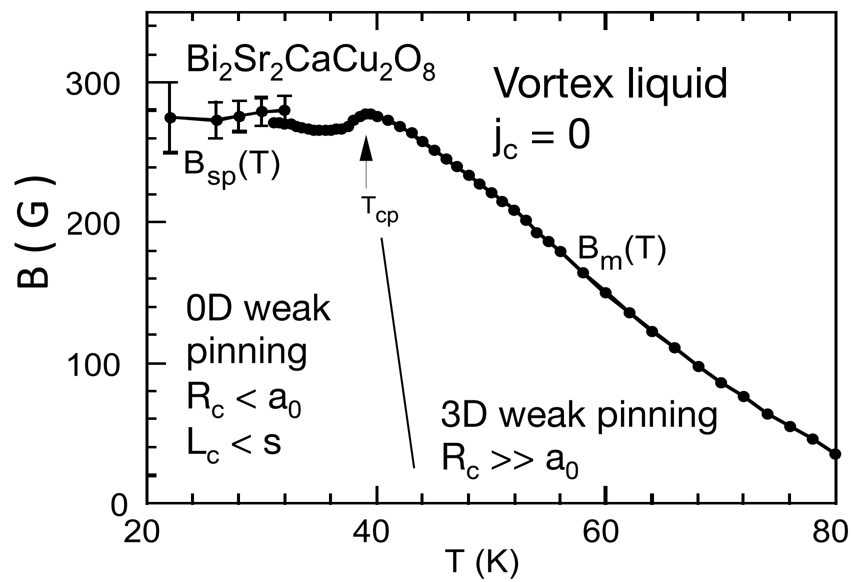
I. Joumard, T. Klein, J. Marcus, & R. Cubitt, PRL 1999

T. Klein et al, Nature 413, 404 (2001)

Peak effect in different systems : $Bi_2Sr_2CaCu_2O_8$

- 1^{st} order transition (van der Beek, Avraham) well below B_{c2} (Chikumoto)
- Continuation of melting line $B_m(T)$ (van der Beek, Konczykowski)
- Weak pinning, Bragg glass below B_{sp} (Kim, Fuchs, Fasano)
- Collapse of longitudinal (B // c axis) vortex line correlations (Colson)





N. Avraham et al, **Nature** (2001)

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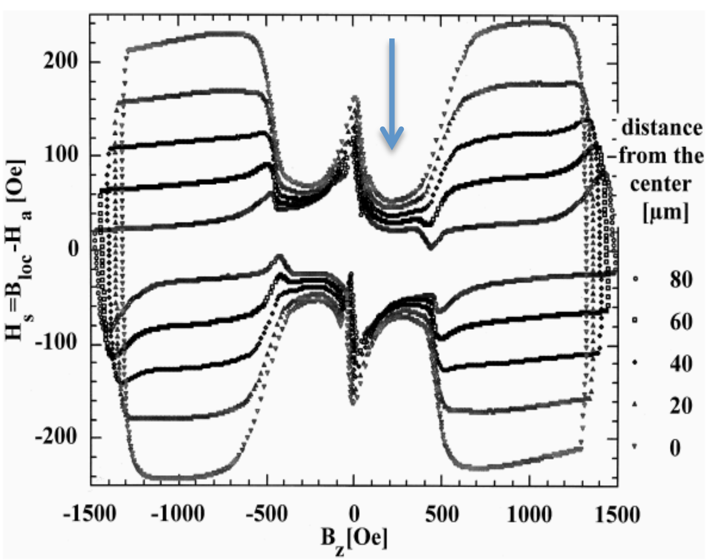
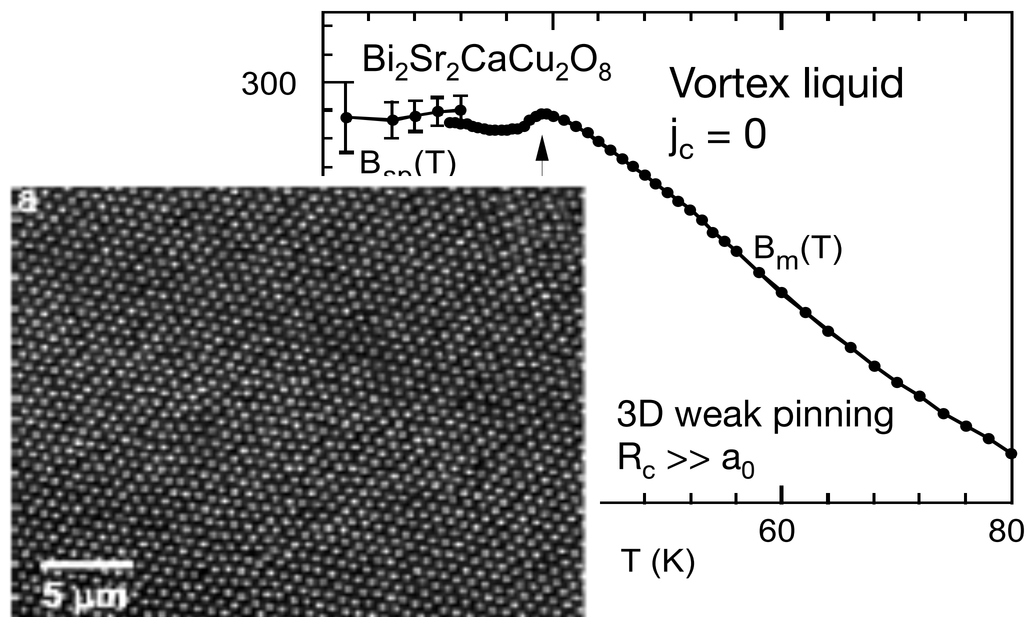




Single crystal $Bi_2Sr_2CaCu_2O_{8+d}$ (Y. Fasano)

Peak effect in different systems : $Bi_2Sr_2SrCu_2O_8$

- 1^{st} order transition (van der Beek, Avraham) well below B_{c2} (Chikumoto)
- Continuation of melting line $B_m(T)$ (van der Beek, Konczykowski)
- Weak pinning, Bragg glass below B_{sp} (D. T. Fuchs,Y. Fasano)
- Collapse of longitudinal (B // c axis) vortex line correlations (S. Colson)
- Melting regardless of positional order
  (Banerjee, Menghini, Konczykowski, Colson)
- Vanishing SANS signal at B_m, B_{sp} (Cubitt)

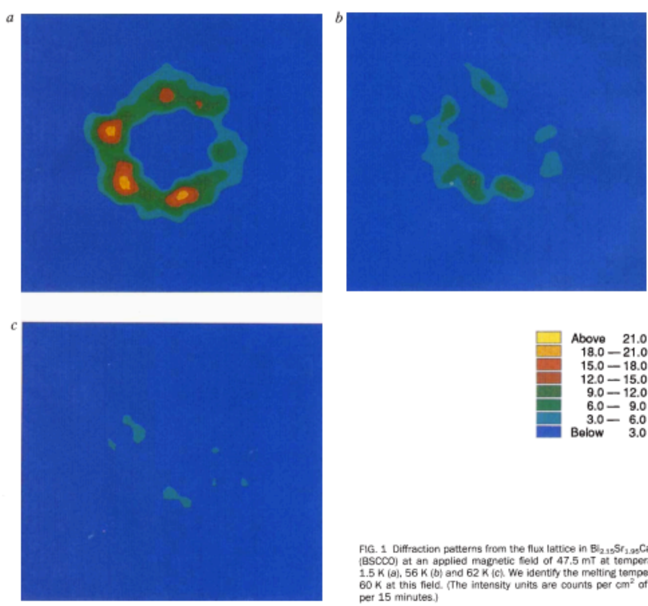
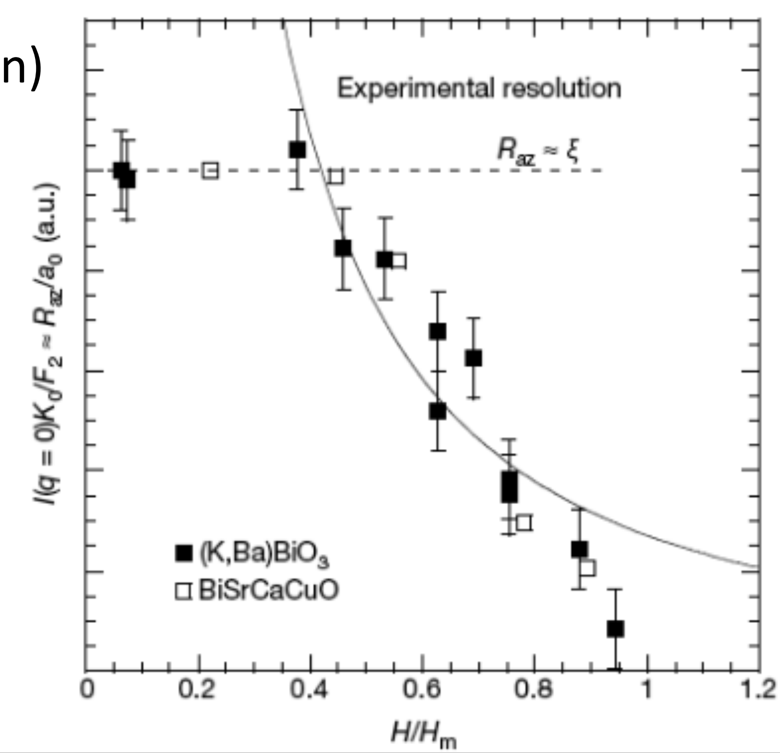
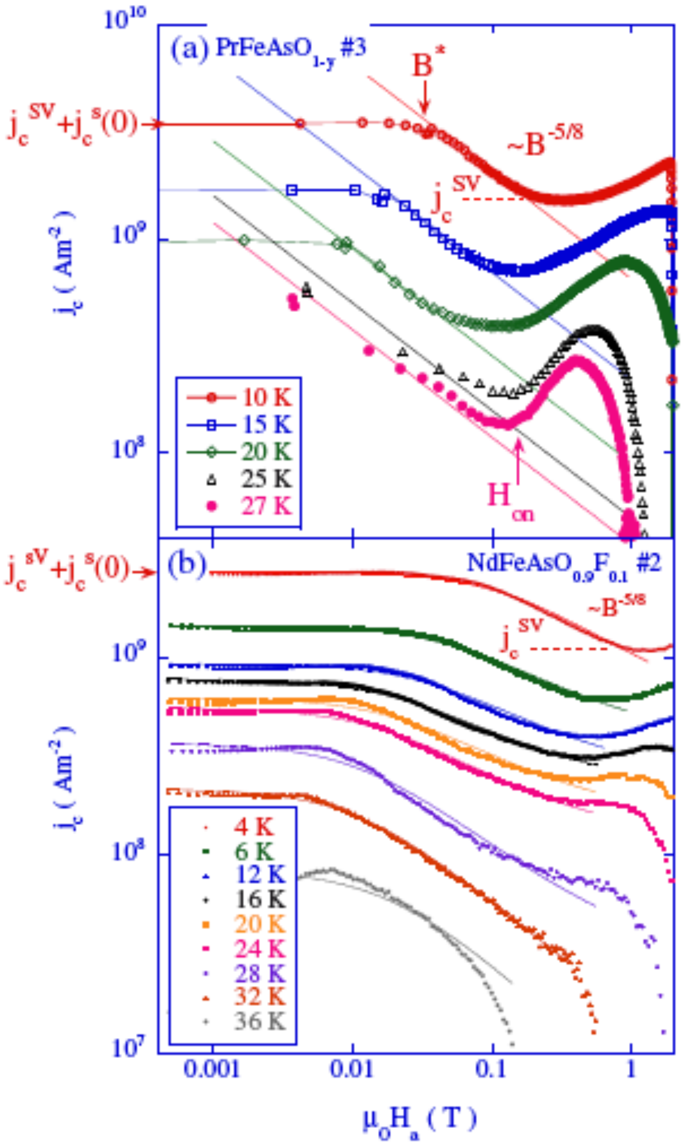


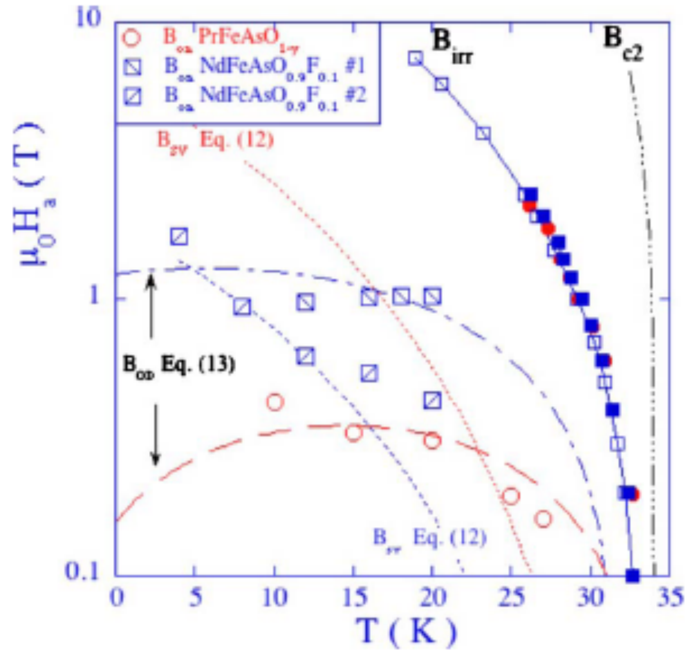
FIG. 1 Diffraction patterns from the flux lattice in $Bi_{2.15}Sr_{1.95}CaCu_2O_{8+x}$ (BSCCO) at an applied magnetic field of 47.5 mT at temperatures of 1.5 K (*a*), 56 K (*b*) and 62 K (*c*). We identify the melting temperature as 60 K at this field. (The intensity units are counts per cm^2 of detector per 15 minutes.)



R. Cubitt Nature (London) 365, 407 (1993)

Peak effect in different systems : iron-based s.c.: $PrFeAsO_{1-y}$, NdFeAsO





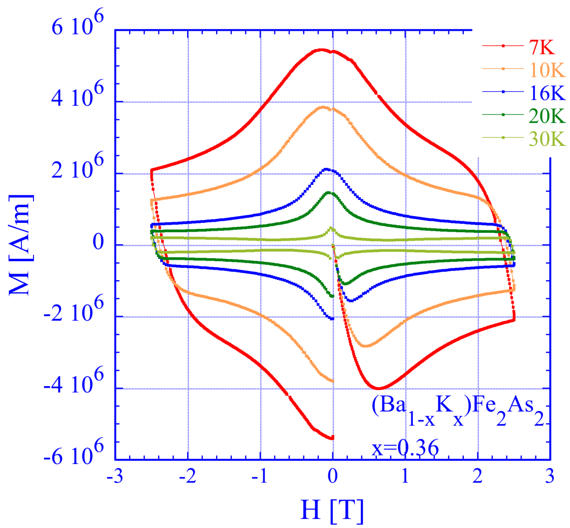
C.J. van der Beek et al., Phys. Rev. B **81**,174517 (2010)

G.P. Mikitik and E.H. Brandt, Phys. Rev. B **64**, 184514 (2001);
Phys. Rev. B **71**, 012510 (2005).

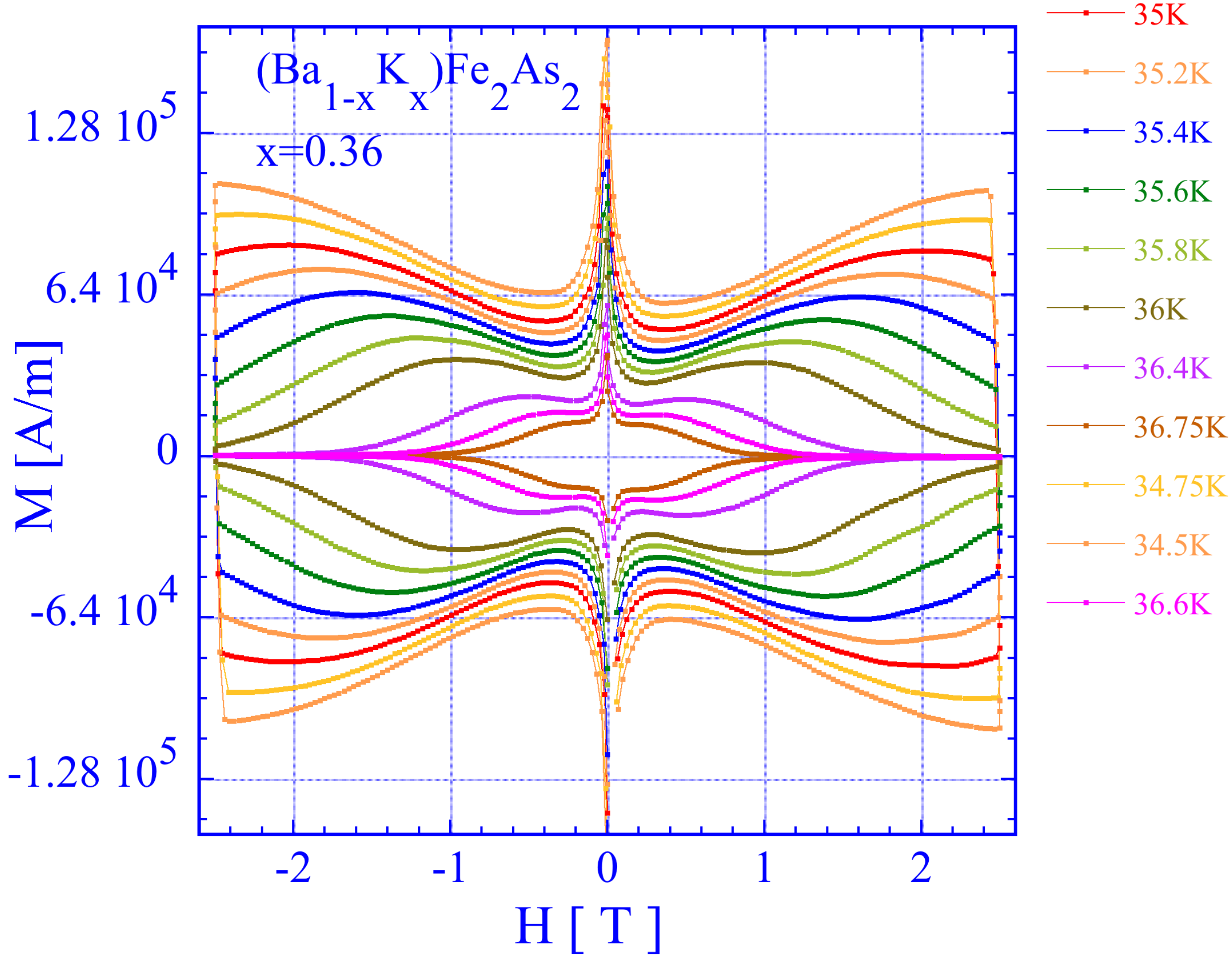
Peak effect in different systems : iron-based s.c. and $Ba_{1-x}K_xAs_2Fe_2$

- Hysteretic magnetization

Low T



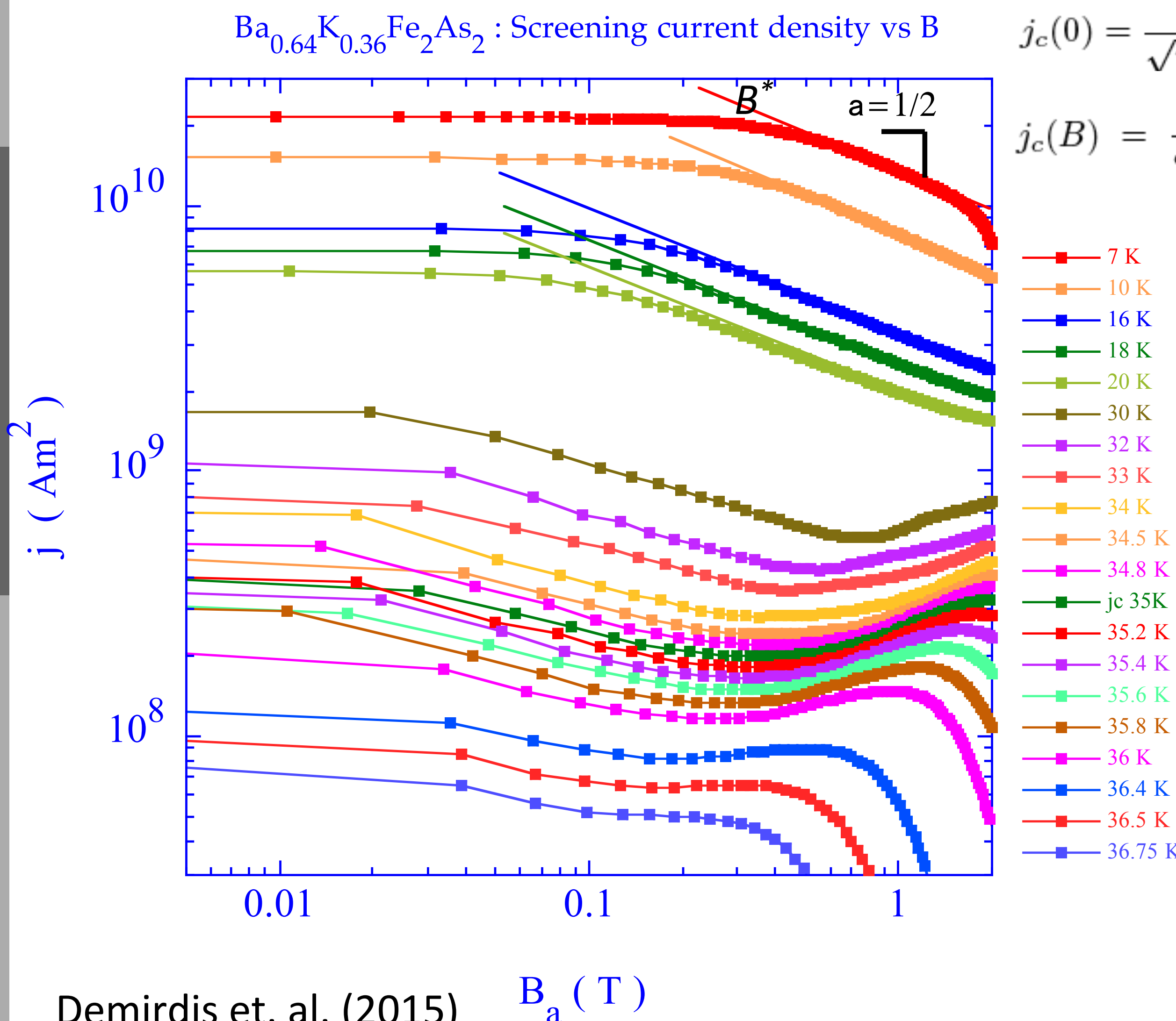
High T



Demirdis et. al. (2015)

Vortex Pinning in $Ba_{1-x}K_xAs_2Fe_{2l}$

- Hysteretic magnetization, the screening current density…



Demirdis et. al. (2015)

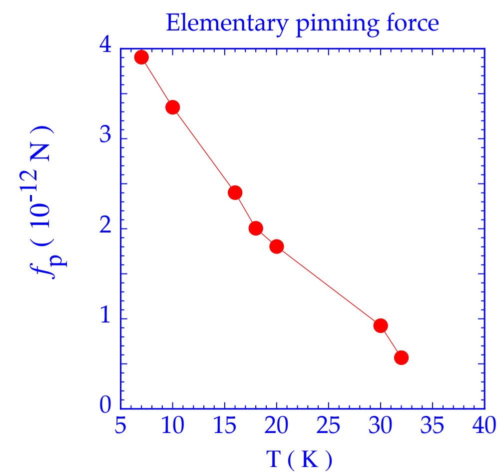
$$j_c(0) = \frac{f_p}{\sqrt{\pi}\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)^{1/2} \qquad (B < B^*)$$

1D strong pinning

$$j_c(B) = \frac{f_p}{\Phi_0\varepsilon}\left(\frac{U_p n_i}{\varepsilon_0}\right)\left(\frac{\Phi_0}{B}\right)^{1/2} \qquad (B > B^*)$$

3D strong pinning

Extended point-like defects with $n_i x^3 \ll 1$

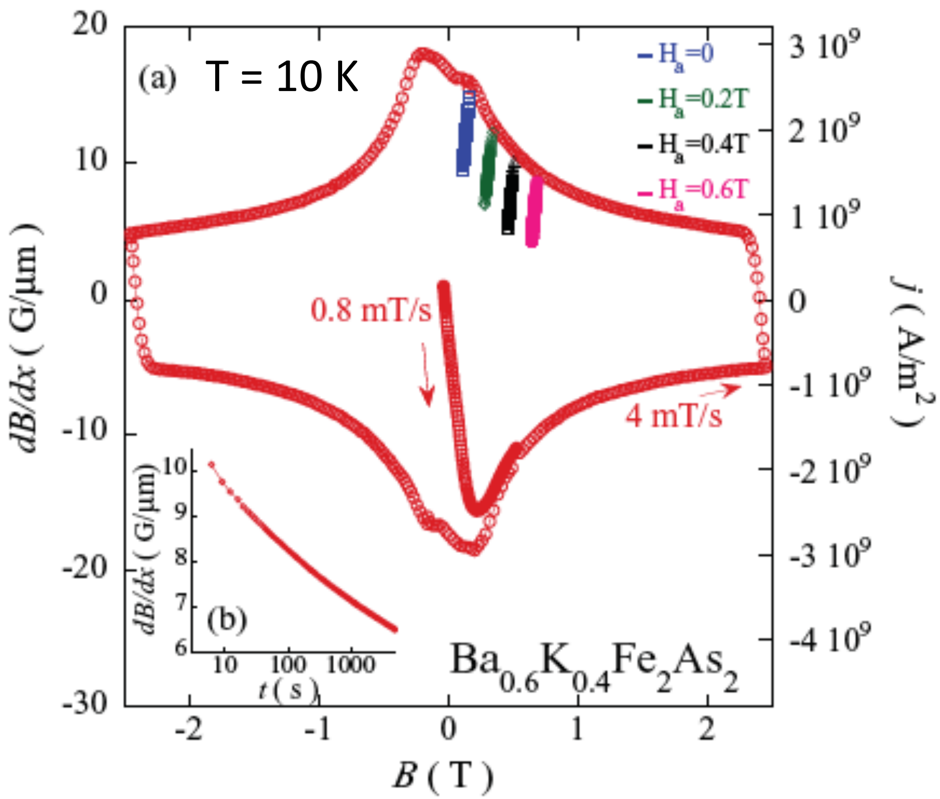


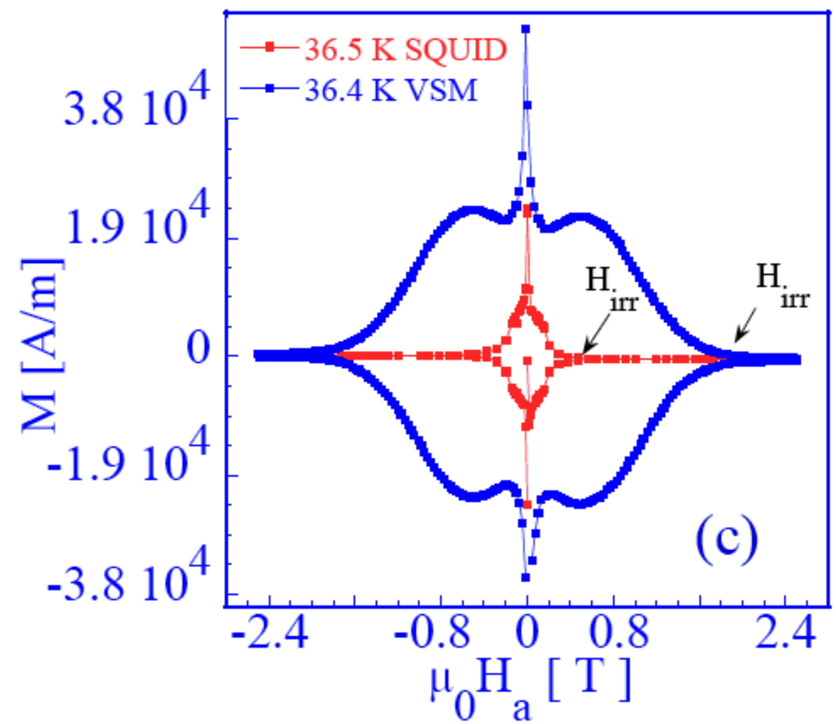
$$\left(\frac{U_p n_i}{\varepsilon_0}\right) = 4 \times 10^{13}\mathrm{m}^2$$

$$n_i \approx 9 \times 10^{21}\mathrm{m}^{-3}$$

Vortex Pinning in $Ba_{1-x}K_xAs_2Fe_{2l}$

- The effect of thermally activated vortex creep (relaxation)

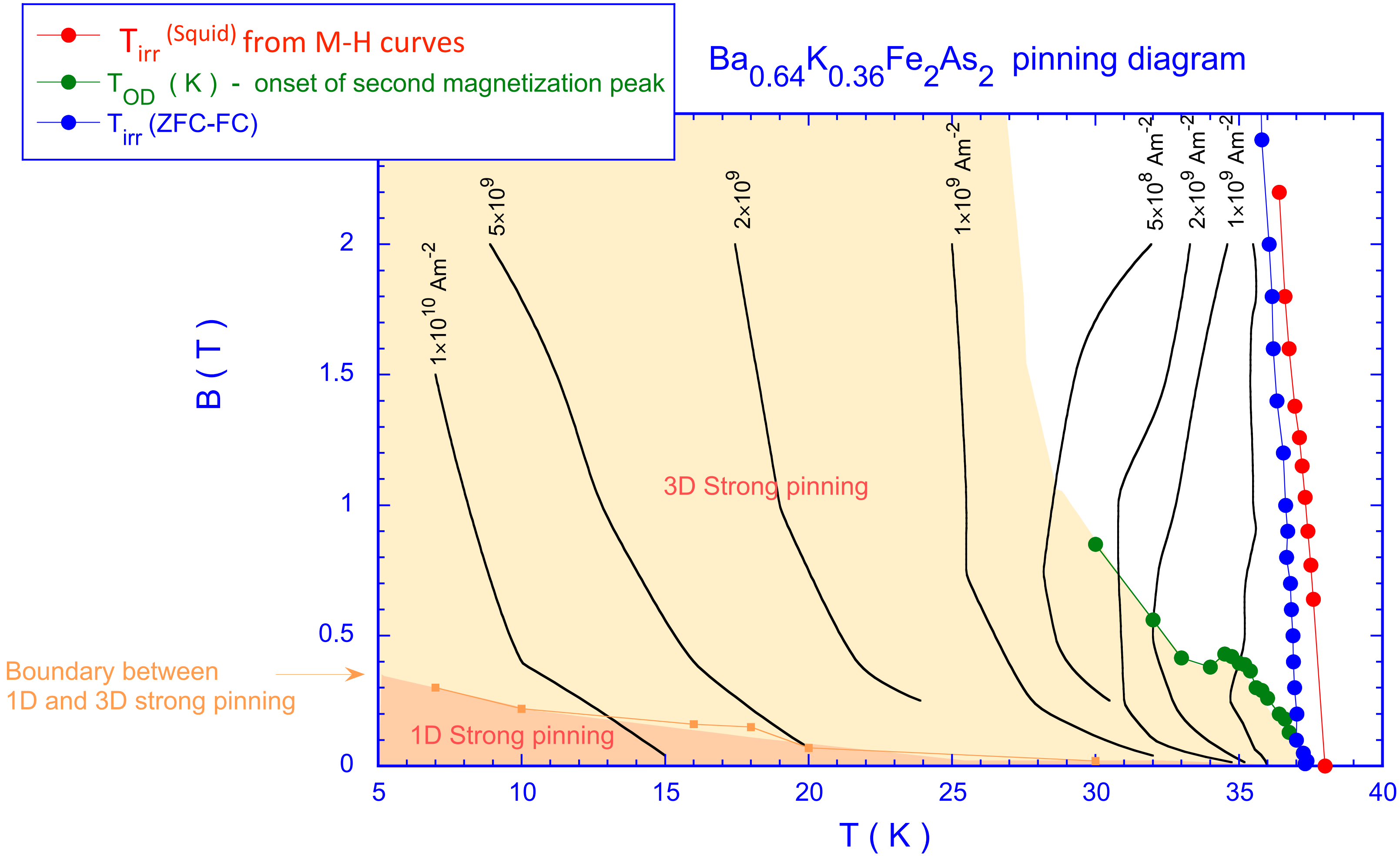




M. Konczykowski et al, Phys Rev. B **86**, 024515 (2012).

Vortex Pinning in $Ba_{1-x}K_xAs_2Fe_{2l}$

- Strong pinning below B_{sp} : chemical disorder
- Weak pinning around B_{sp}: dopant atoms, Fe vacancies



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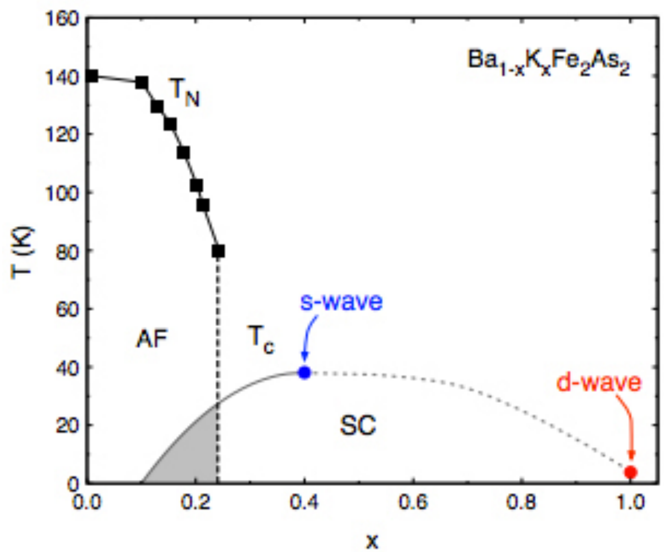
SANS on the vortex ensemble in $Ba_{1-x}K_xFe_2As_2$

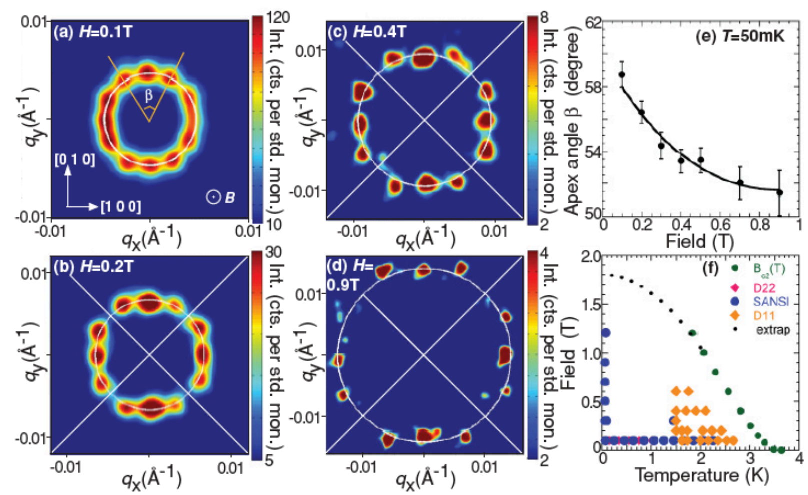
- Motivation:

  - How do we go “dirty” to “clean”?

  - Can we observe the vortex lattice in a doped iron-based superconductor?



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

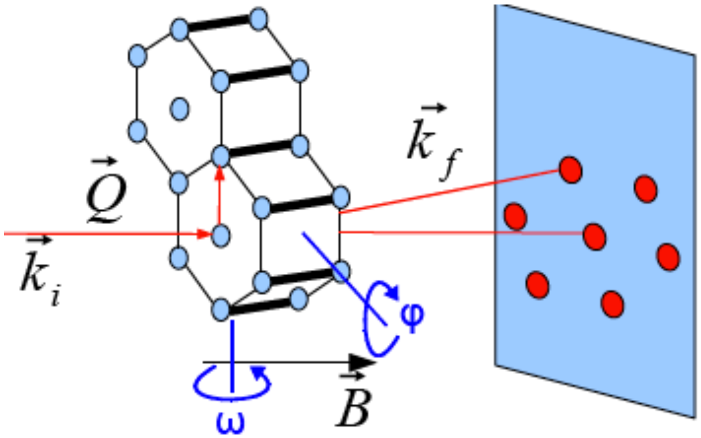


Nearly isotropic hexagonal VL
with no symmetry transitions up to high fields

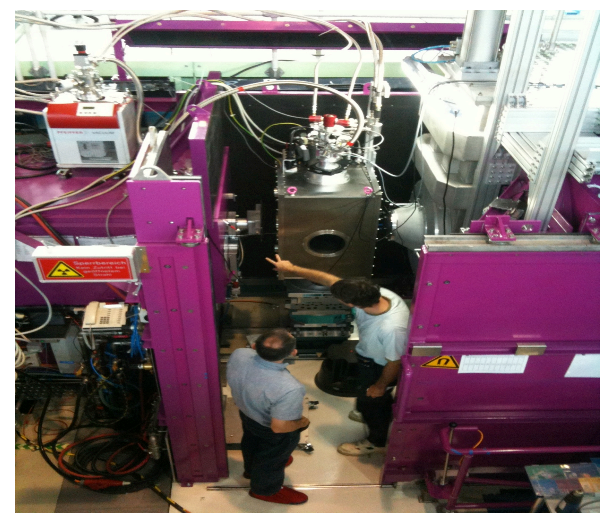
H. Kawano-Furukawa et. al. PRB **84**, 024507 (2011)

SANS on the vortex ensemble in $Ba_{1-x}K_xAs_2Fe_2$

- @SANS 1 instrument



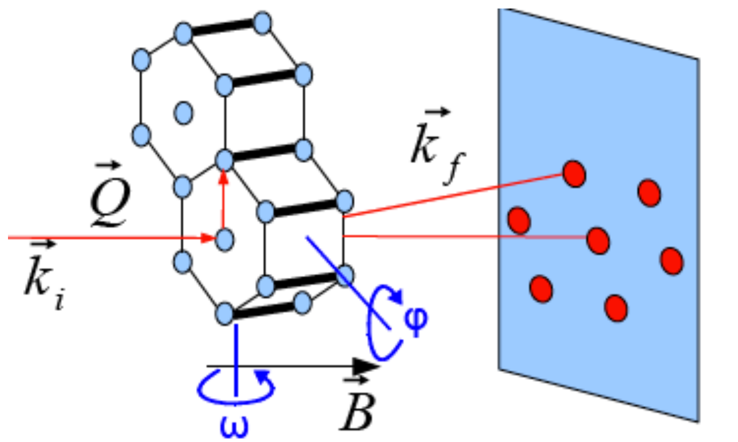
Neutrons sensitive to magnetism
Rocking the sample gives all lattice Bragg peaks

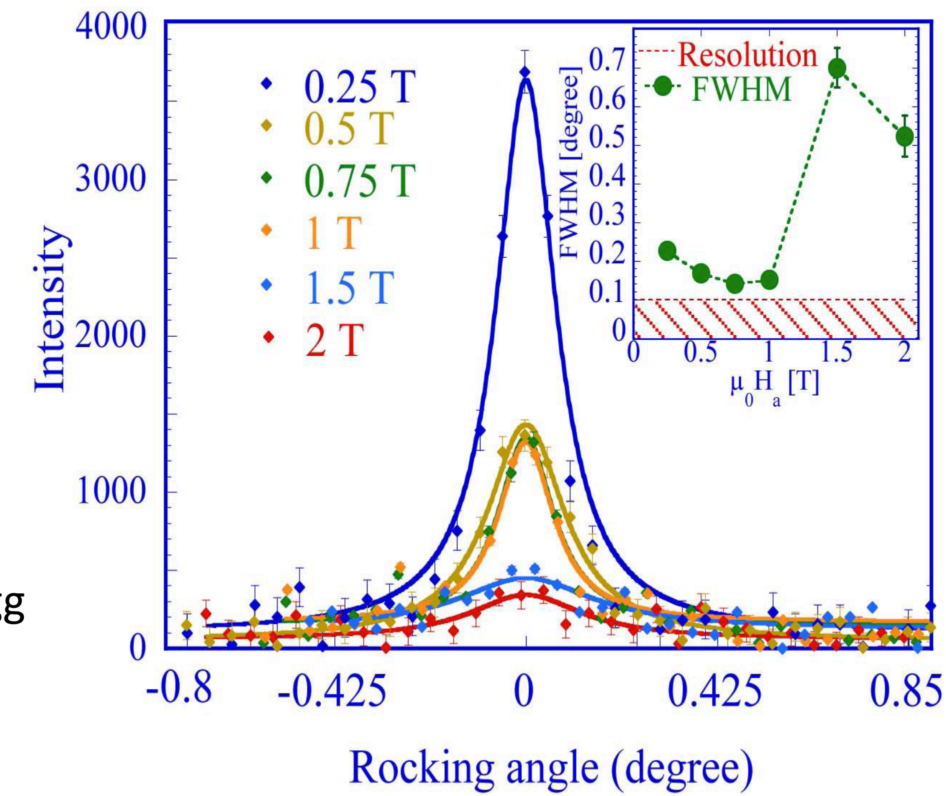


$(Ba_{1-x}K_x)Fe_2As_2$, x = 0.36
FC conditions for T = 3.5 - 45 K
Under different fields B = 0.25-2 T
For each field configuration the bck has been measured

SANS on the vortex ensemble in $Ba_{1-x}K_xAs_2Fe_2$

- Heinz Maier-Leibnitz Zentrum (Garching)





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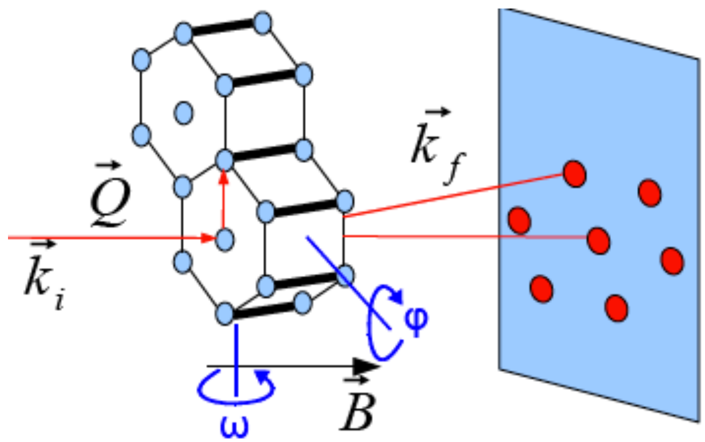
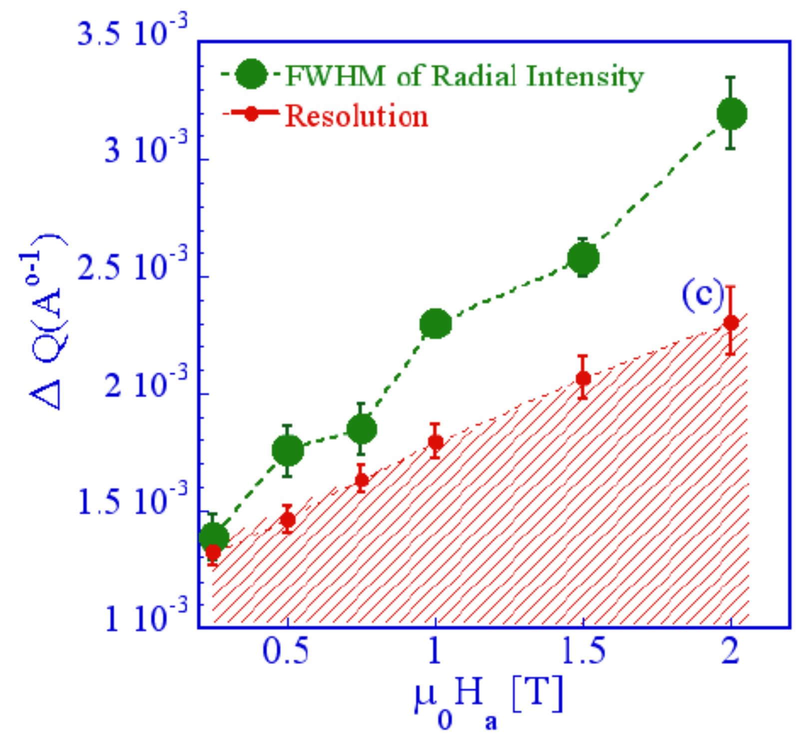


Neutrons sensitive to magnetism
Rocking the sample gives all lattice Bragg peaks

Resolution of SANS instrument



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FC conditions for T = 3.5 - 45 K
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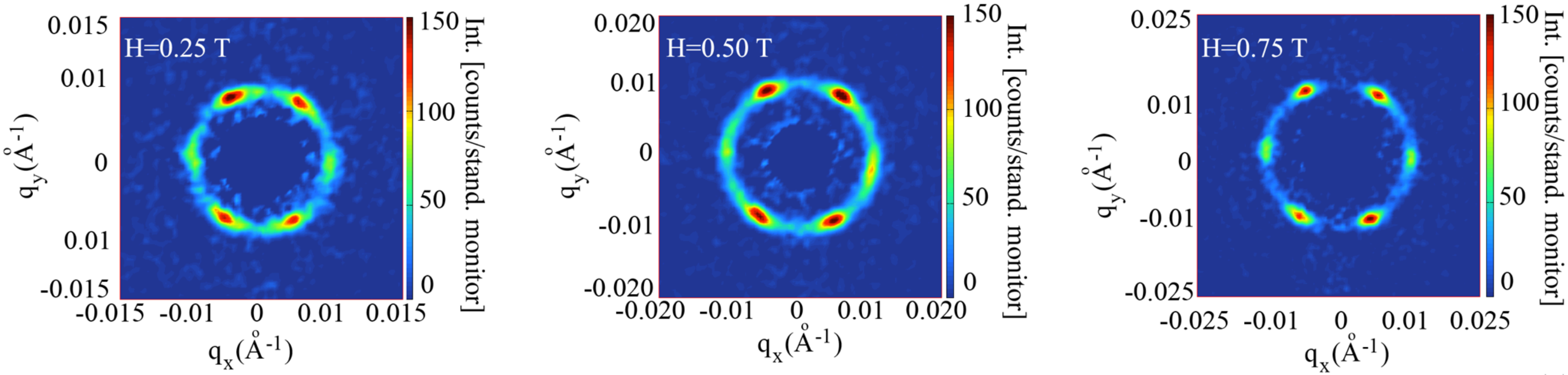
$$\sigma_{res} = \sqrt{4\pi^2(\delta\theta/\lambda_n)^2 + q^2(\Delta\lambda_n/\lambda_n)^2}$$

Vortex orientational order in $Ba_{1-x}K_xAs_2Fe_2$



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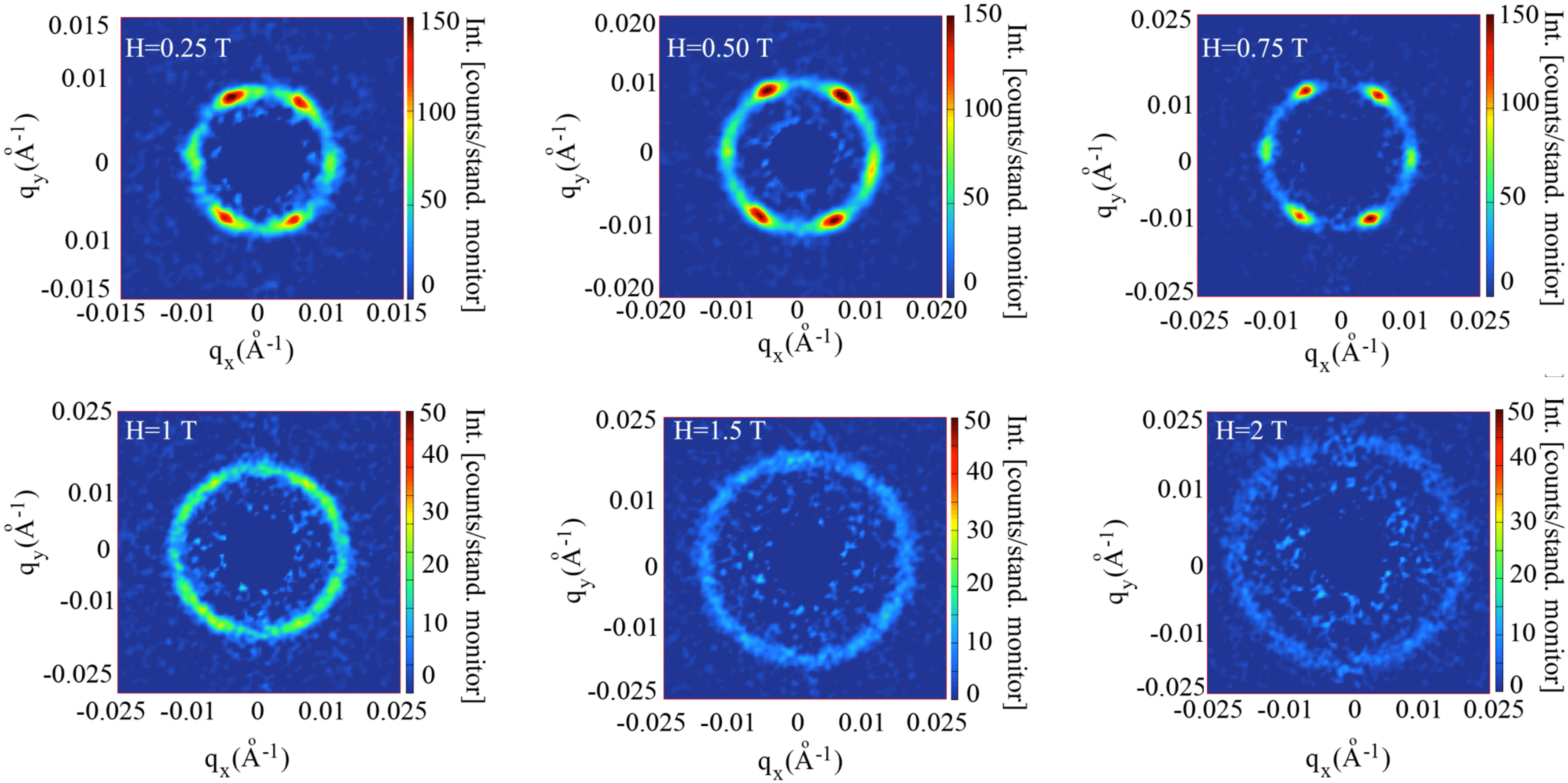
Vortex orientational order in $Ba_{1-x}K_xAs_2Fe_2$



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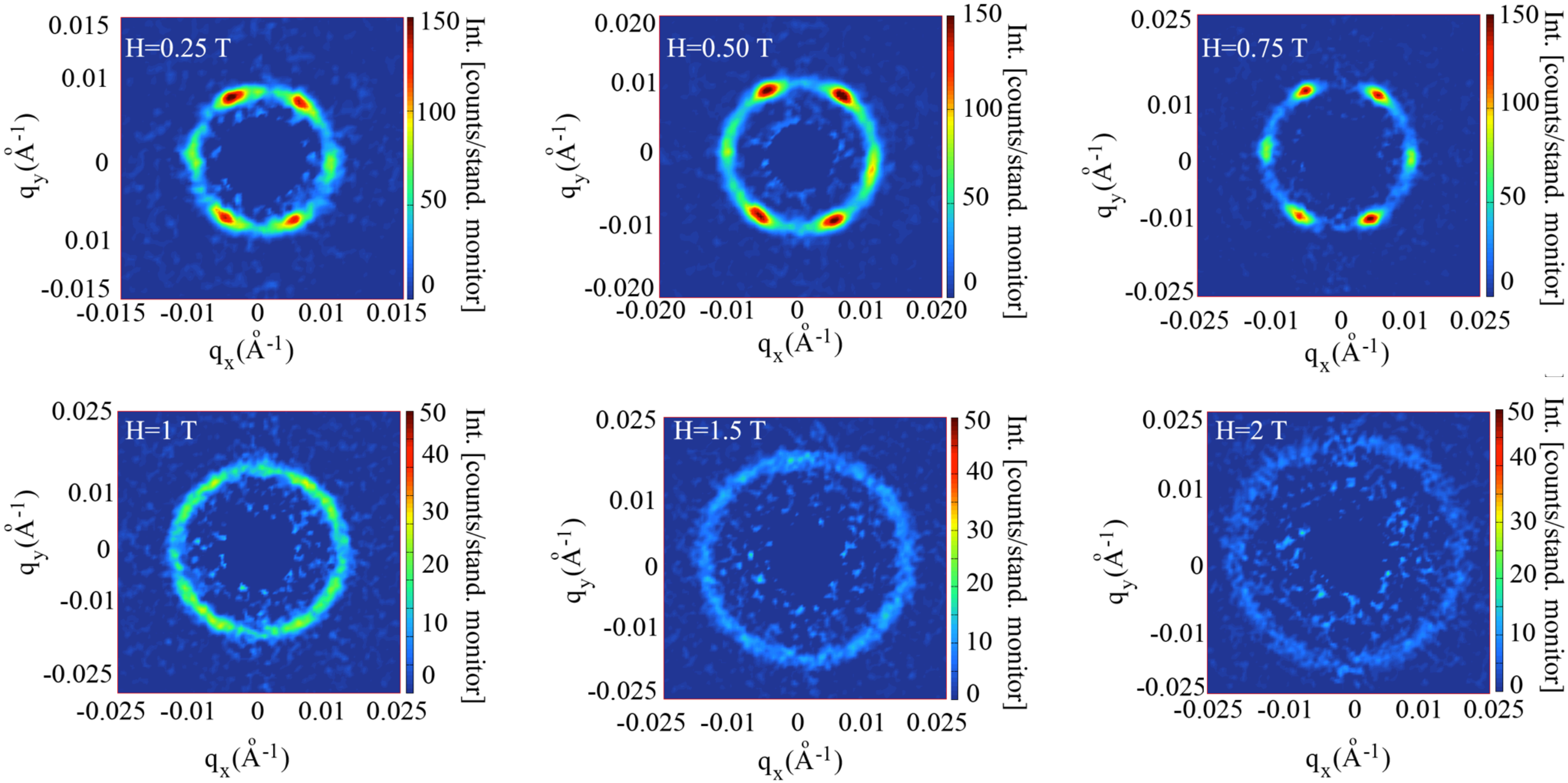
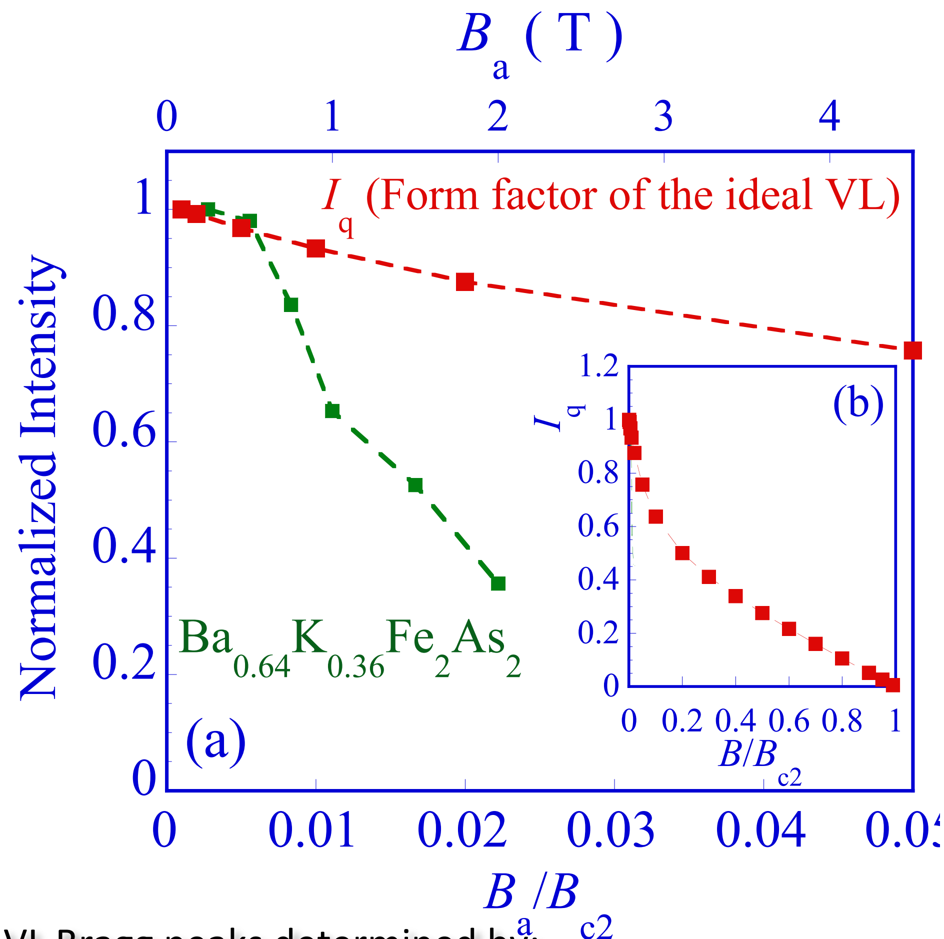
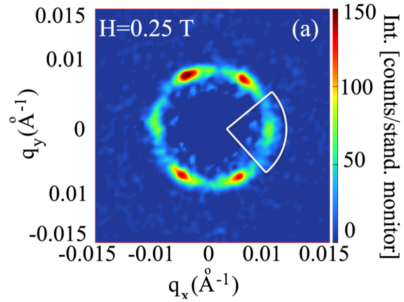


Structural transition of the vortex ensemble

Analysis of SANS signal of the vortex ensemble in $Ba_{1-x}K_xAs_2Fe_2$





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

Precision Ginzburg-Landau Solution of Ideal Vortex Lattices for any induction and symmetry: prediction of the vortex lattice form factor F

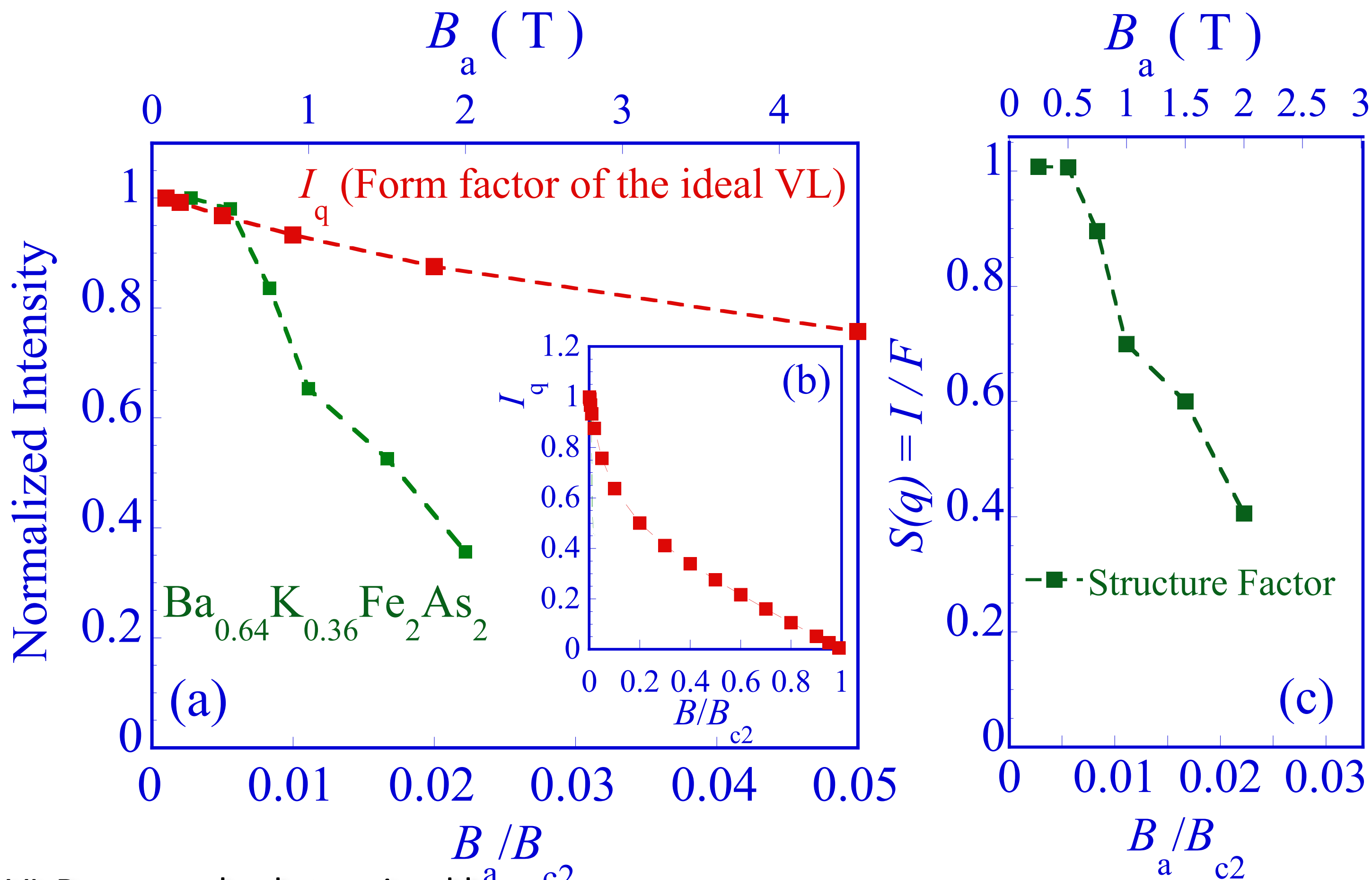
E. H. Brandt PRL 78, 11 (1997)

VL Bragg peaks determined by:

- Form factor F (local field distribution)
- Structure factor S (lattice structure) - For ideal VL, $S = 1$

$$I = F^2 S = F^2(T) \int dq_x \int dq_y S(q_x, q_y, K_0\omega)$$

Analysis of SANS signal of the vortex ensemble in $Ba_{1-x}K_xAs_2Fe_2$



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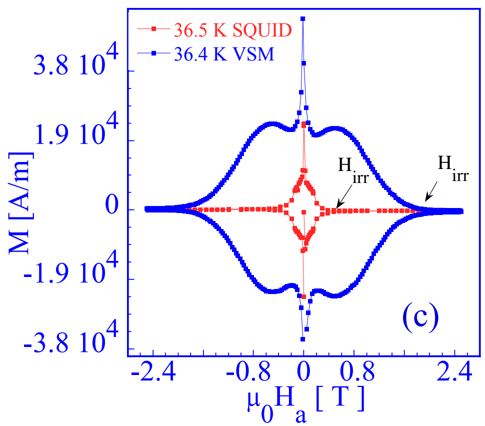
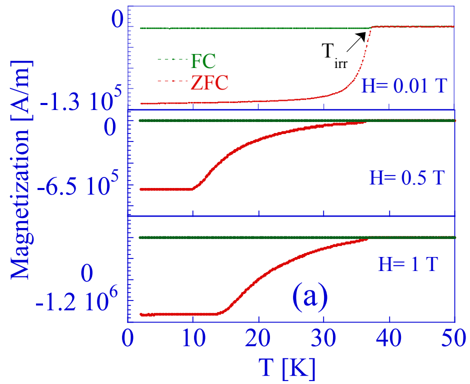
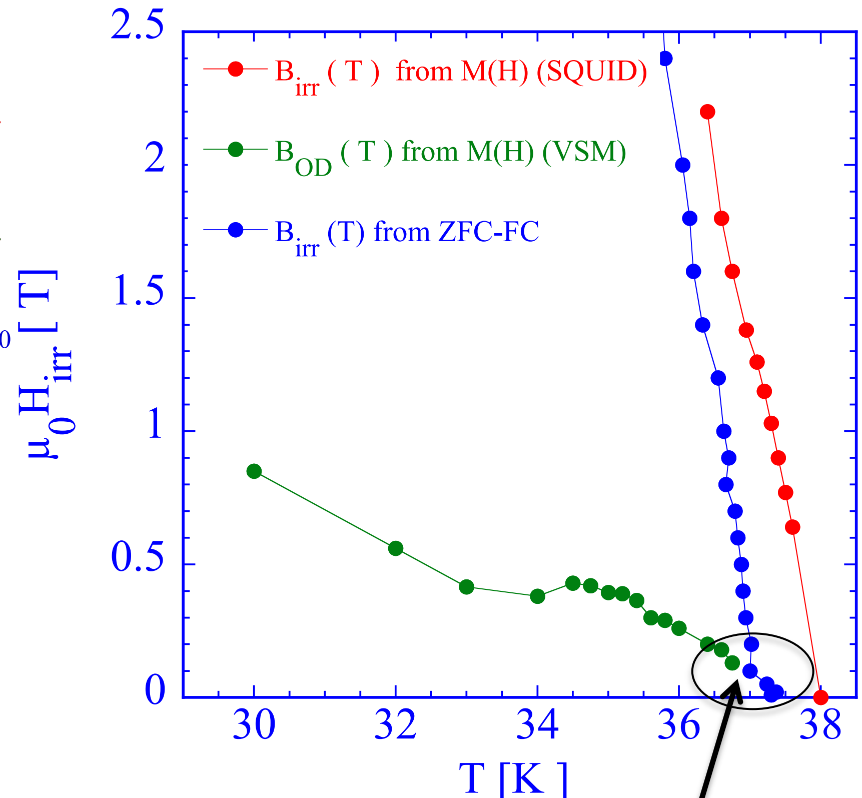
How does vortex order come about in $Ba_{1-x}K_xAs_2Fe_2$?



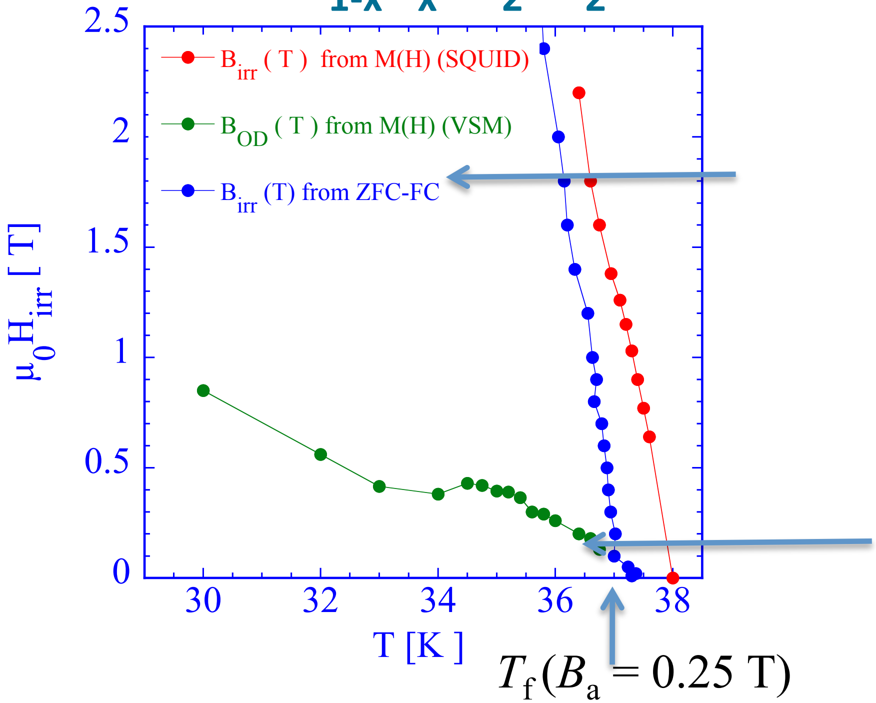




Below 0.25 T, $B_{OD}(T)$ and $T_{irr} \approx T_f$ coincides

How does vortex order come about in $Ba_{1-x}K_xAs_2Fe_2$?

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



The FC protocol of SANS reflects the vortex ensemble as quenched at $T_{irr}(B)$ that plays the role of freezing temperature T_f

How does vortex order come about in $Ba_{1-x}K_xAs_2Fe_2$?

Field [Tesla]	$T_{freezing}$ (K)
0.25	36.99
0.5	36.8
0.75	36.7
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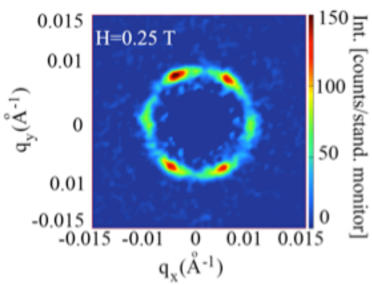

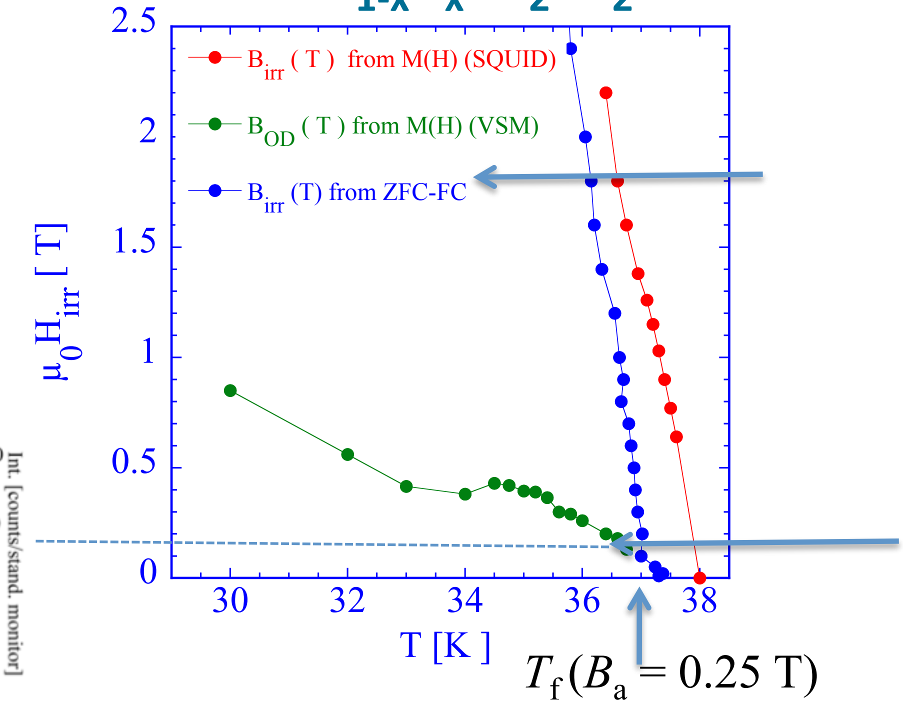

- $B_a \leq 0.25$ T the field cooling across the high field phase has no effect: thermal activation (creep) equilibrates the VL in the experiment time scale and only at the B_{OD}(T) the VL is fixed. VL is quenched in the low field vortex state where S=1.

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How does vortex order come about in $Ba_{1-x}K_xAs_2Fe_2$?

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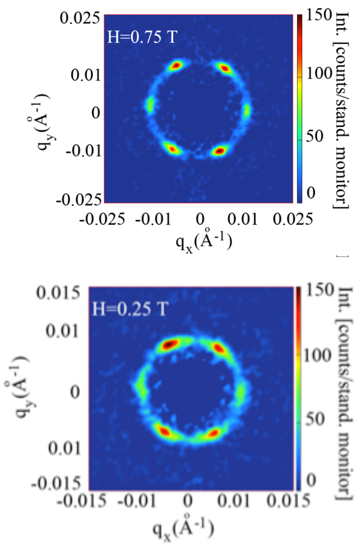

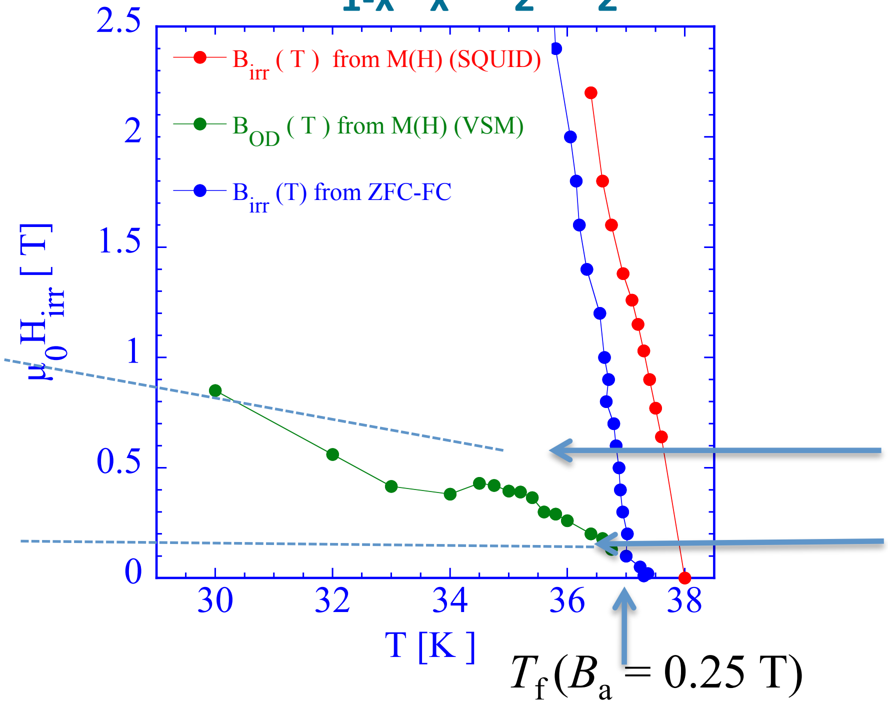

- $B_a \leq 0.25$ T the field cooling across the high field phase has no effect: thermal activation (fast creep) equilibrates the VL in the experiment time scale and only at the B_{OD}(T) the VL is fixed. VL is quenched in the low field vortex state where *S*=1.

- $0.25\ T \leq B_a \leq 1$ T the field cooling across the high field phase starts to effect the vortex positions: this results to a progressive disordering in the VL and a concomitant decrease in the *S*.

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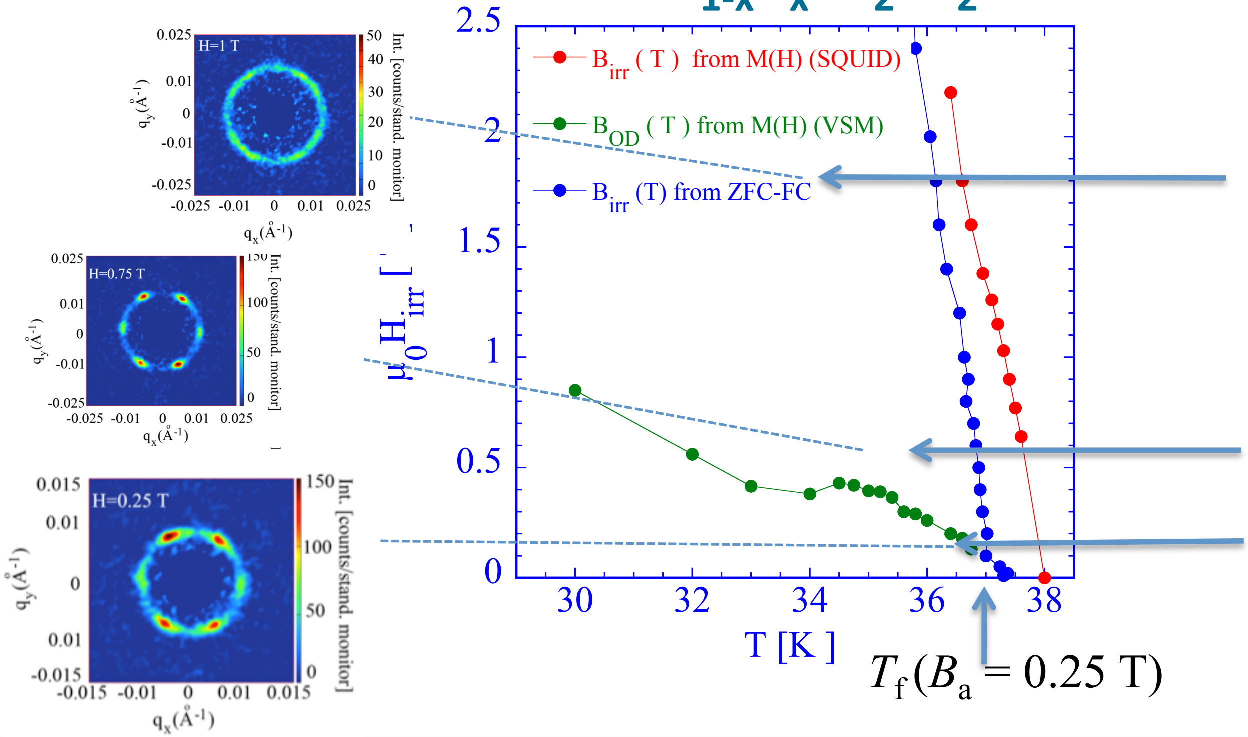

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- $B_a \geq 1$ T the applied field is bigger then B_{OD} at all T, the low field ordered phase in never reached (slow creep). The VL is quenched as a disordered polycrystal in the high field phase.

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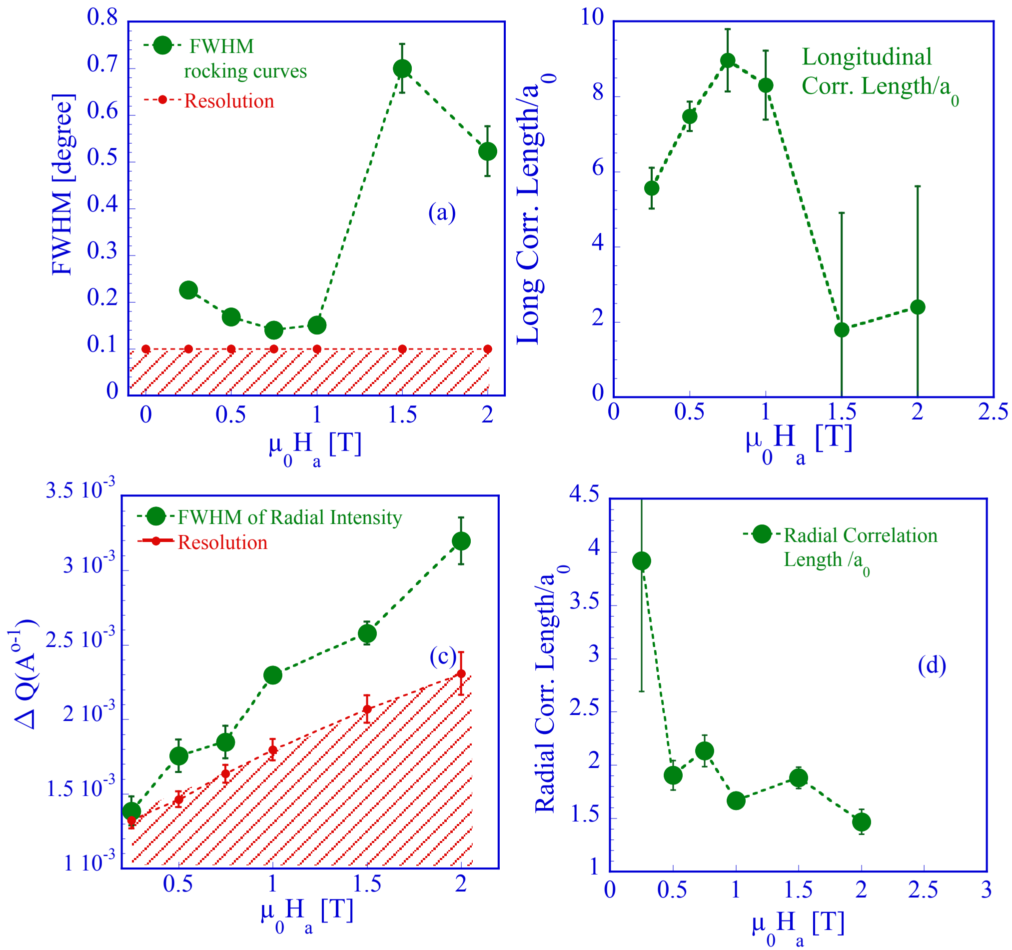
How does vortex order come about in $Ba_{1-x}K_xAs_2Fe_2$?

- The observed vortex structure is determined by the high T vortex dynamics
- The quenched vortex ensemble is fixed by strong pinning
- Representative of the high T structure :



$$L_a \sim \xi_{\parallel} = 1/(q\sigma_m)$$

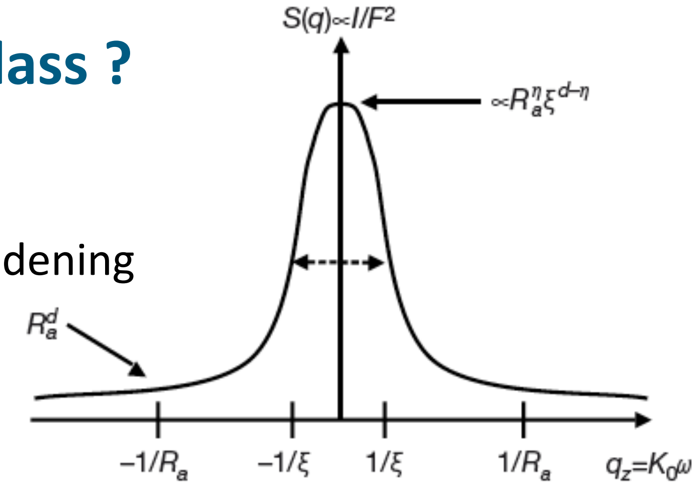
$$\sigma_m^2 = (\sigma_{rock}^2 - \sigma_{res}^2)$$

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

$$R_a \sim \xi_{\perp} = (\sigma_q^2 - \sigma_{res}^2)^{-1/2}$$

Is the low-field phase a Bragg glass ?

- Bragg peak has power law shape, I ~ q^{3-h}
- Rocking curve Intensity decreases without broadening
- Structure factor height corresponds to R_a
- Bragg peak height decreases as $B^{-3/2}$



T. Klein et al, Nature 413, 404 (2001)

Is the low-field phase a Bragg glass ?

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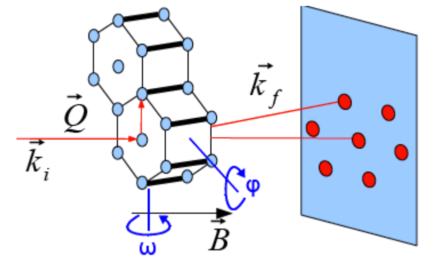

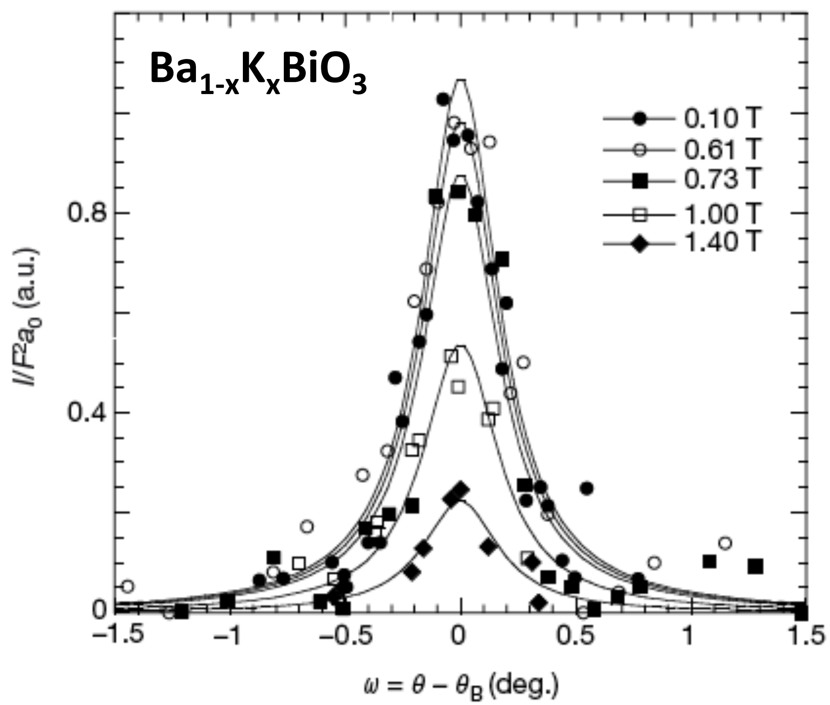

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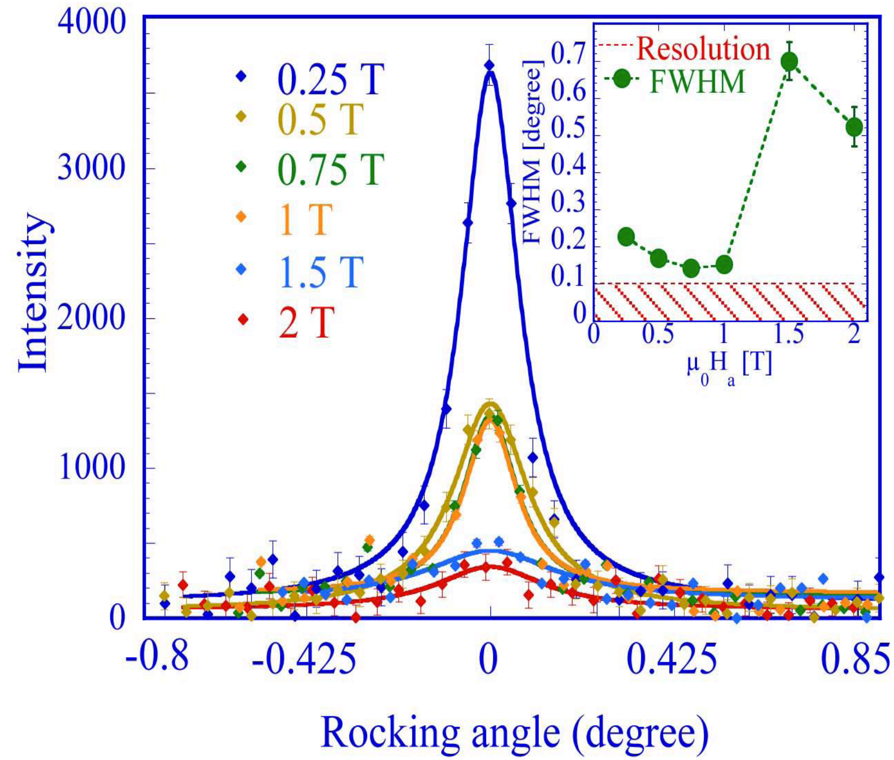

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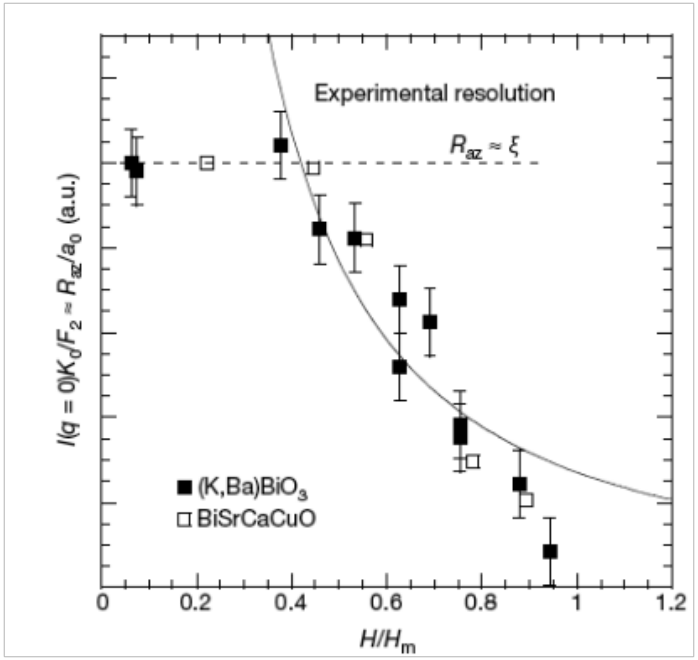

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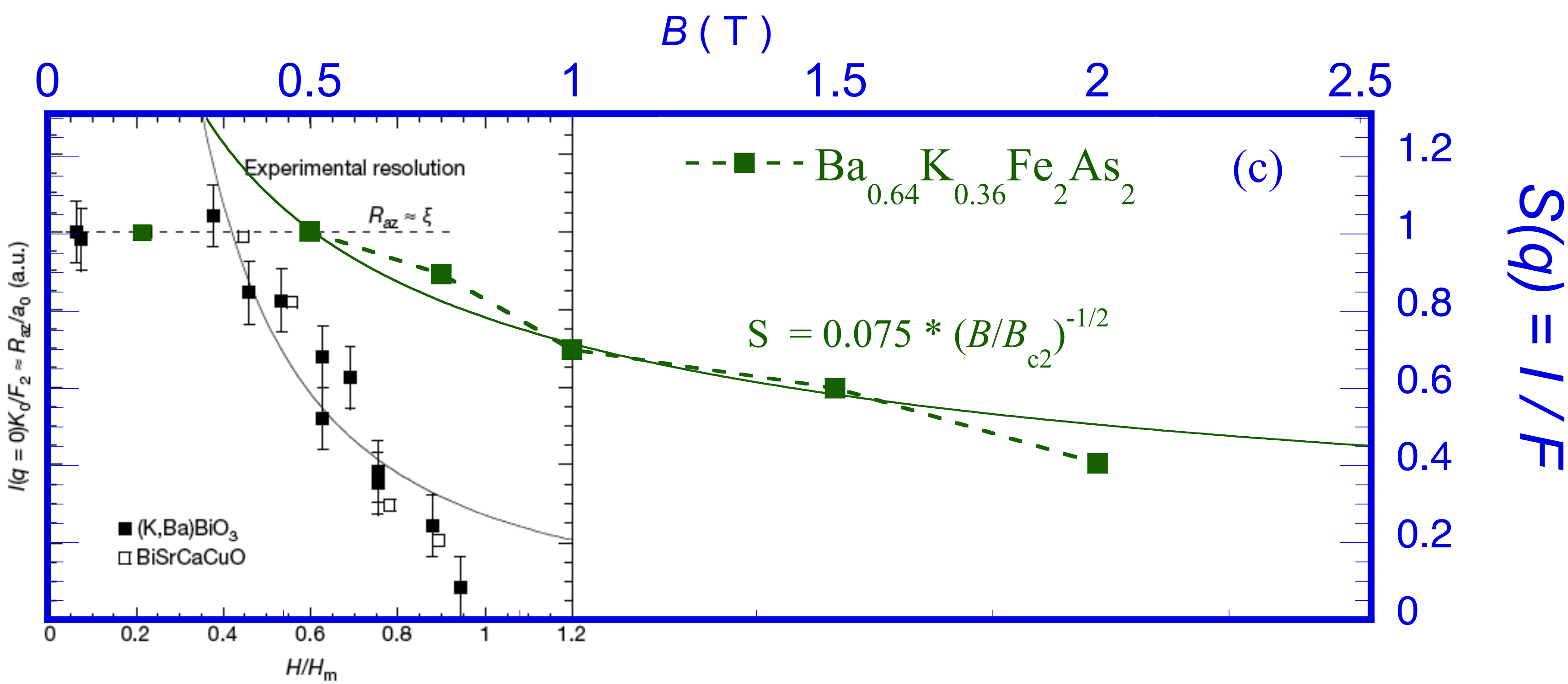

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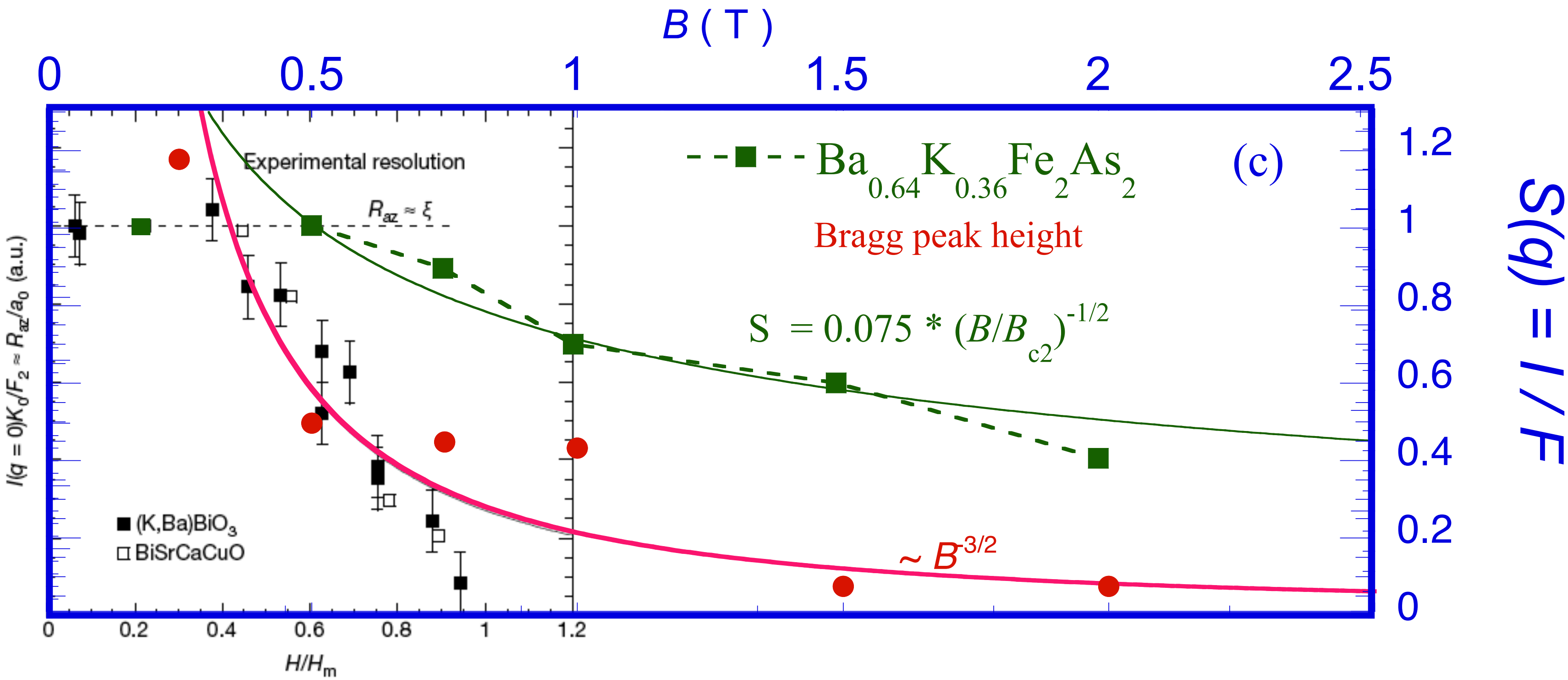

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Conclusions

- SANS Observation of orientationally ordered vortex lattice in a doped iron-based superconductor

  (which is a strong pinning system)

- Structural transition (Order-Disorder) of VL in optimally doped $(Ba_{1-x}K_x)Fe_2As_2$
- 2^{nd} magnetization peak observed (similar to NdFeAsO, $YBa_2Cu_3O_{7-d}$)

  ] The two are correlated

- Low field vortex phase, B < 0.5 T : structure factor ~ 1 but Bragg glass not obvious
- High field vortex phase is a vortex polycrystal ,B > 0.5 T : steep drop of the VL structure factor
- VL order and Bragg peak intensity determined by dynamics of the high field state

Thank you!