Critical current anisotropy in clean superconducting pnictide thin films

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Outline

- **Why pnictide thin films?**
- **Deposition methods**
- **Strain dependence of T_c**
- **Scaling of J_c**
- **Intrinsic Pinning**

Acknowledgment

PLD of 11 and 122:
K. Iida, F. Kurth, J. Engelmann, S. Trommler,
O. Rodriguez, S. Molatta
Targets: M. Schulze, S. Wurmehl
Pulsed field:
A. Kauffmann, J. Freudenberger, N. Kozlova
TEM: T. Thersleff, E. Reich
Discussions:
S. Haindl, L. Schultz, B. Holzapfel

High-field: C. Tarantini, J. Jaroszynski

MBE of 1111: S. Ueda, M. Naito

TEM: A. Ichinose, I. Tsukada

Discussion: M. Weigand, B. Maiorov

Why pnictide thin films?

Research:

- **Geometry: allows measurements on large areas (spectroscopy) or thin filaments (transport critical currents)**

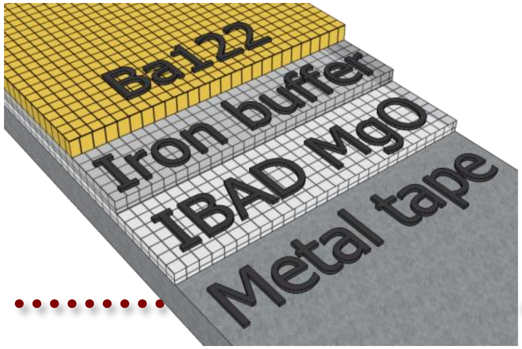
- **Dimensionality: allows investigation of 2D-3D crossover ($d \sim \lambda, \xi, l_0 \ldots$)**

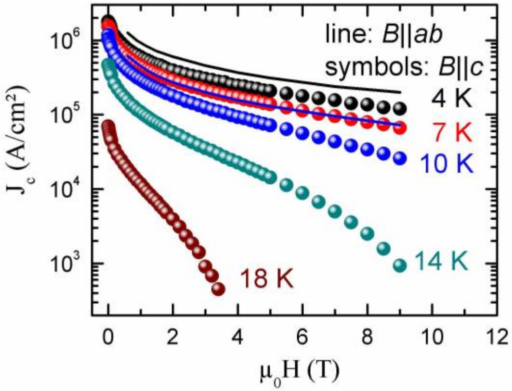
- **Kinetics: allows to grow metastable compounds, heterostructures and phases not available as single crystals**

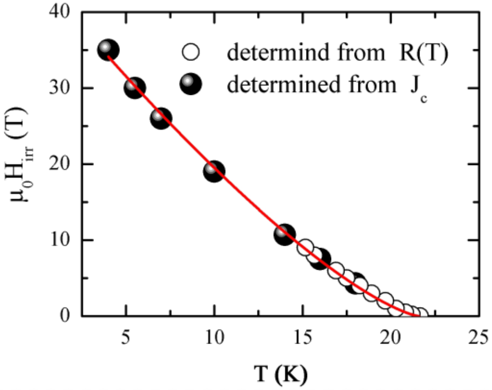
Applications (low *Gi*, *g*, high T_c, H_{irr}):

- **Electronics: Projects on SQUIDs, bolometers, …**

- **Wires and tapes: Coated conductors possible (prototypes already demonstrated)**

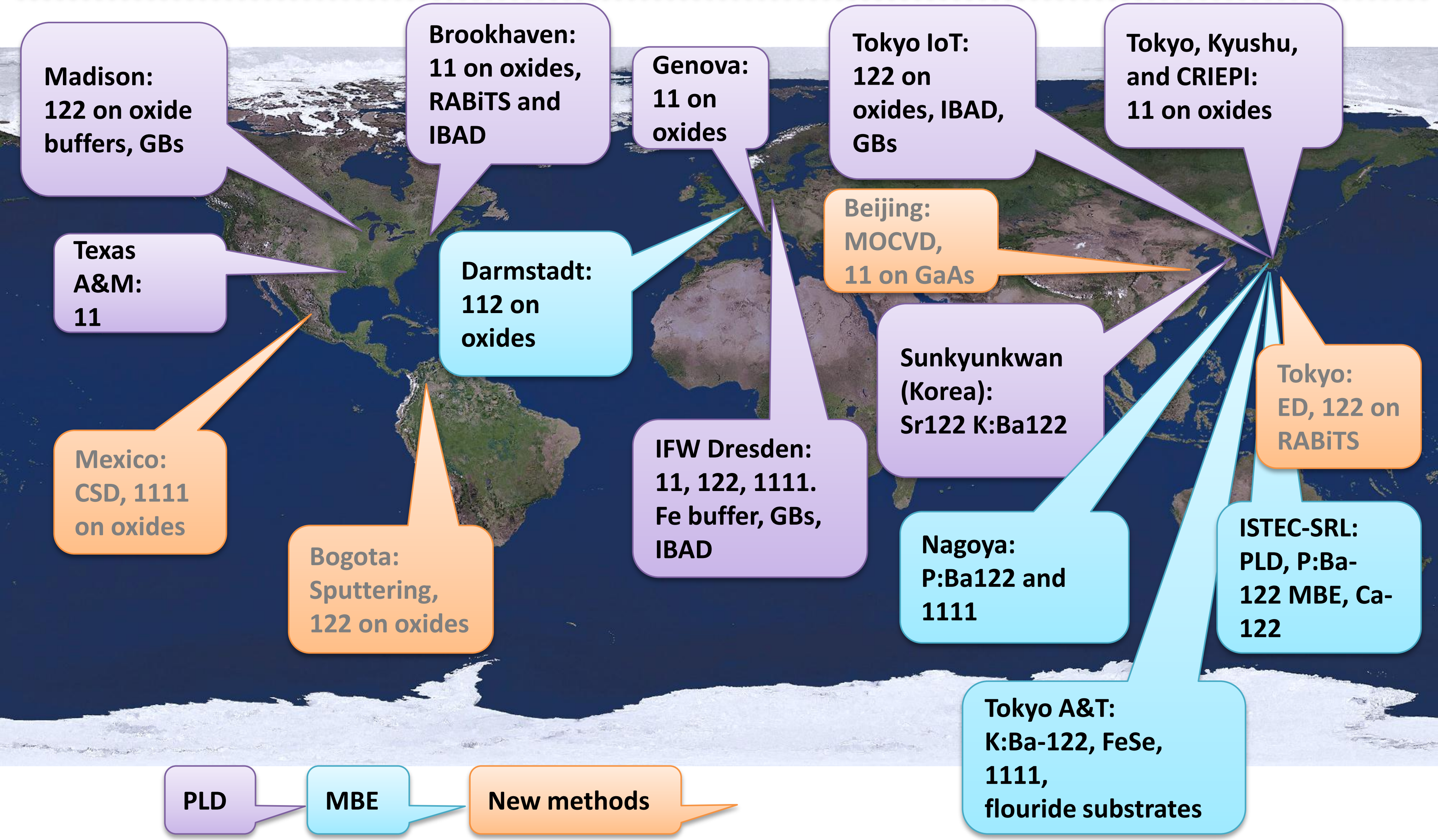






Trommler, SuST 25, 084019 (2012)

Fe-based sc thin film efforts around the world



Madison:
122 on oxide buffers, GBs

Brookhaven:
11 on oxides, RABiTS and IBAD

Genova:
11 on oxides

Tokyo IoT:
122 on oxides, IBAD, GBs

Tokyo, Kyushu, and CRIEPI:
11 on oxides

Texas A&M:
11

Darmstadt:
112 on oxides

Beijing:
MOCVD,
11 on GaAs

Sunkyunkwan (Korea):
Sr122 K:Ba122

Tokyo:
ED, 122 on RABiTS

Mexico:
CSD, 1111 on oxides

Bogota:
Sputtering,
122 on oxides

IFW Dresden:
11, 122, 1111.
Fe buffer, GBs, IBAD

Nagoya:
P:Ba122 and 1111

ISTEC-SRL:
PLD, P:Ba-122 MBE, Ca-122

Tokyo A&T:
K:Ba-122, FeSe, 1111,
flouride substrates

PLD

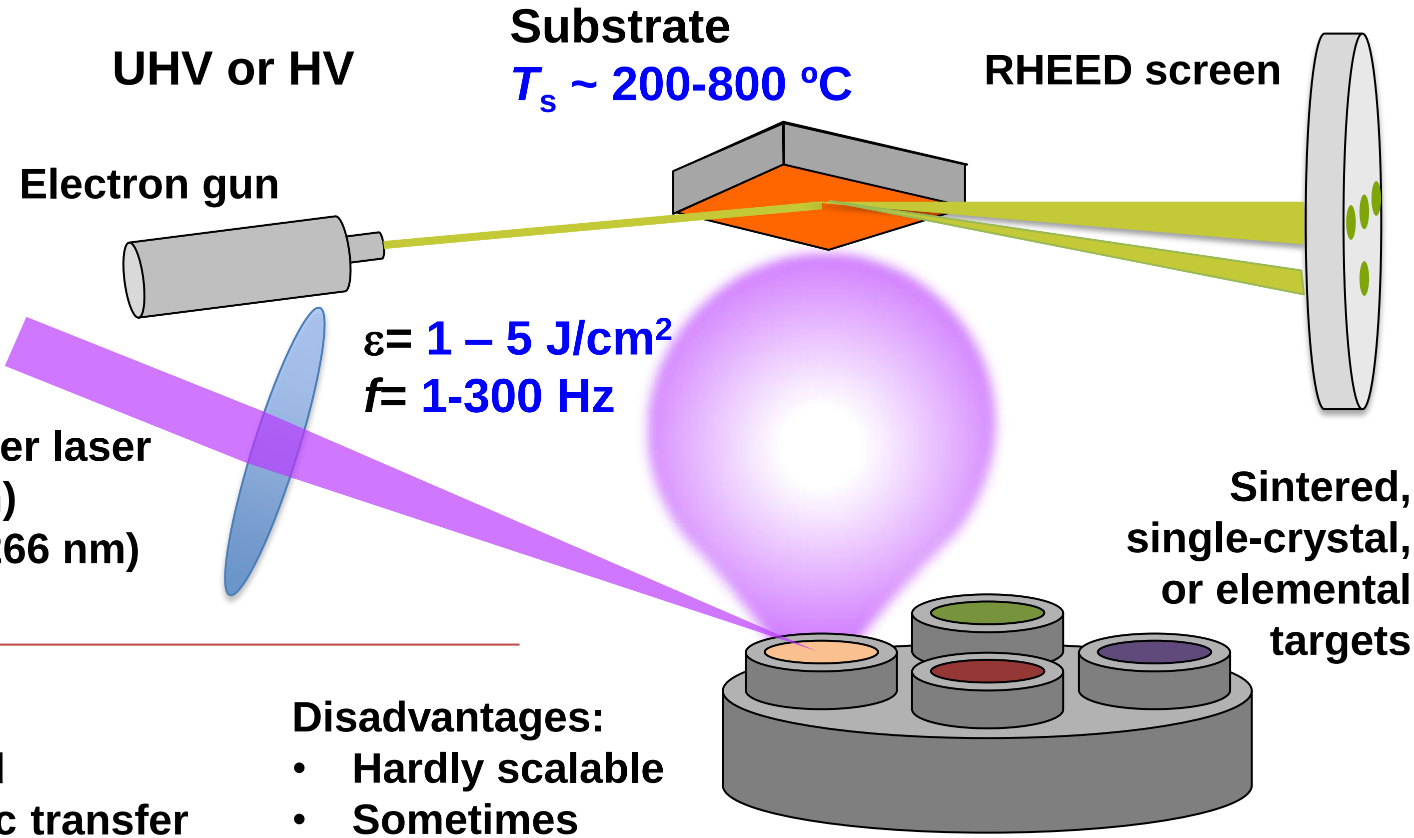
MBE

New methods

So far no films of 111 and 32522

Pulsed Laser Deposition (PLD)

Focussing or imaging of pulsed laser beam on target → stoichiometric plasma of target material → deposition on substrate



UHV or HV

Substrate

T_s ~ 200-800 °C

RHEED screen

Electron gun

ε= 1 – 5 J/cm^2

f= 1-300 Hz

KrF excimer laser
(λ=248 nm)
Nd:YAG (266 nm)

Sintered,
single-crystal,
or elemental
targets

Advantages:

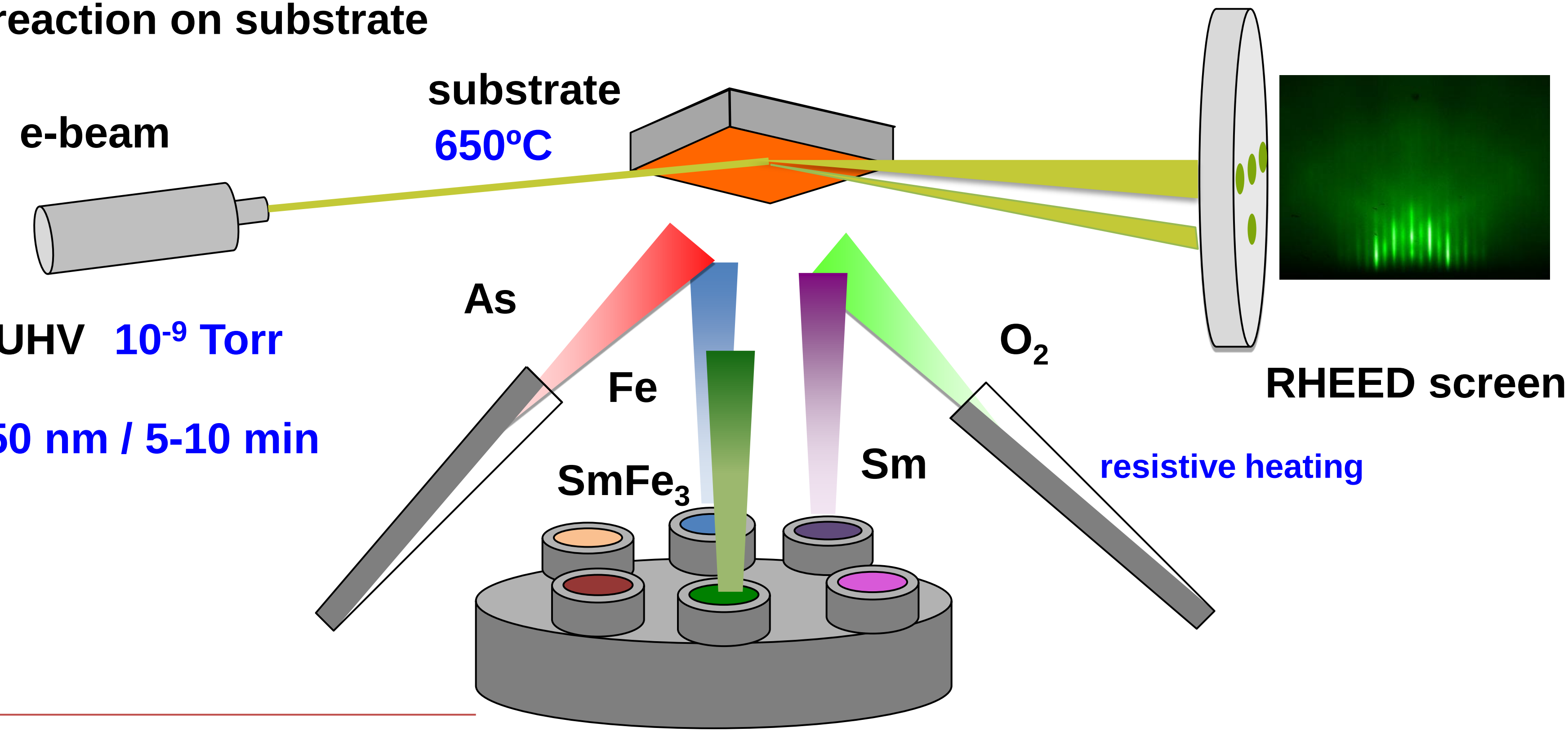
- **Quick method**
- **Stoichiometric transfer**
- **Layer-by-layer possible**

Disadvantages:

- **Hardly scalable**
- **Sometimes droplets**

Molecular Beam Epitaxy (MBE)

Individual sources (e.g. Knudsen cells) → atomar or „molecular“ beams → reaction on substrate



substrate

650ºC

e-beam

UHV 10^{-9} Torr

150 nm / 5-10 min

As

Fe

SmFe$_3$

Sm

O$_2$

RHEED screen

resistive heating

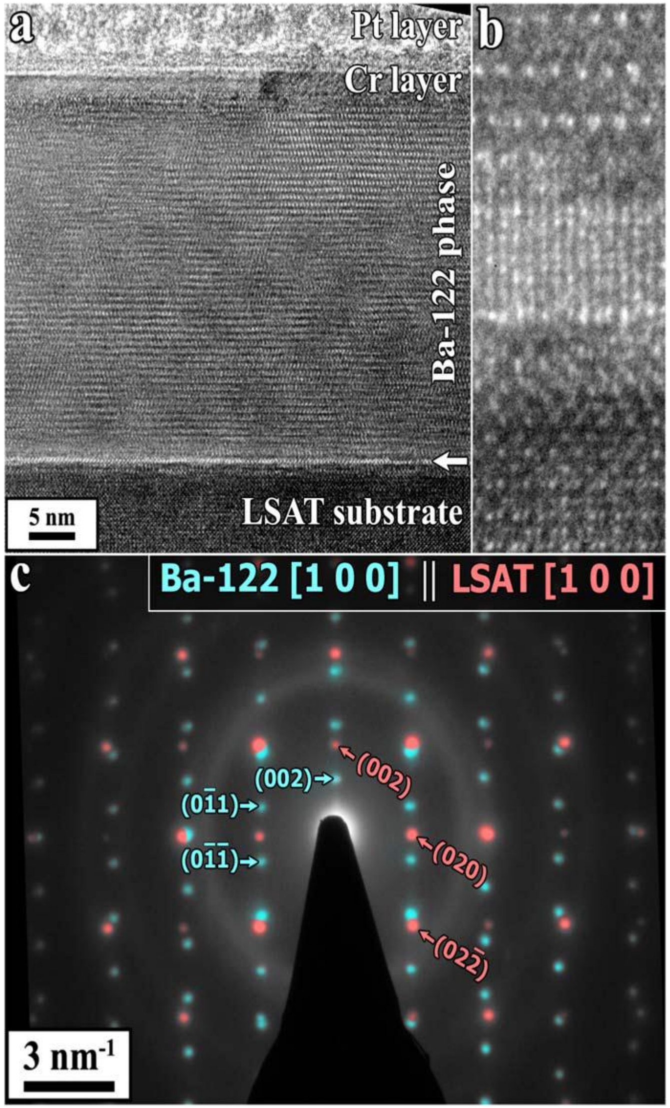
Advantages:

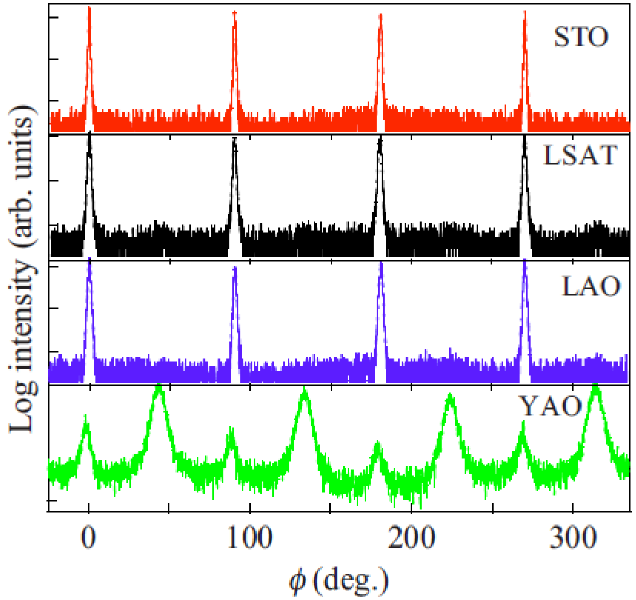
- Slow deposition rates possible
- Clean films
- Good epitaxy

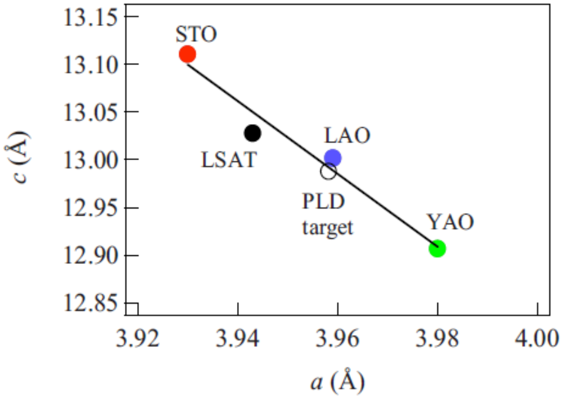
Disadvantages:

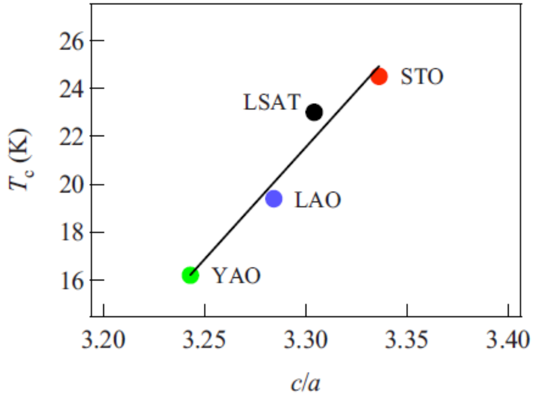
- Rather expensive
- UHV needed (low rates!)

Strain dependence of T_c - Oxides



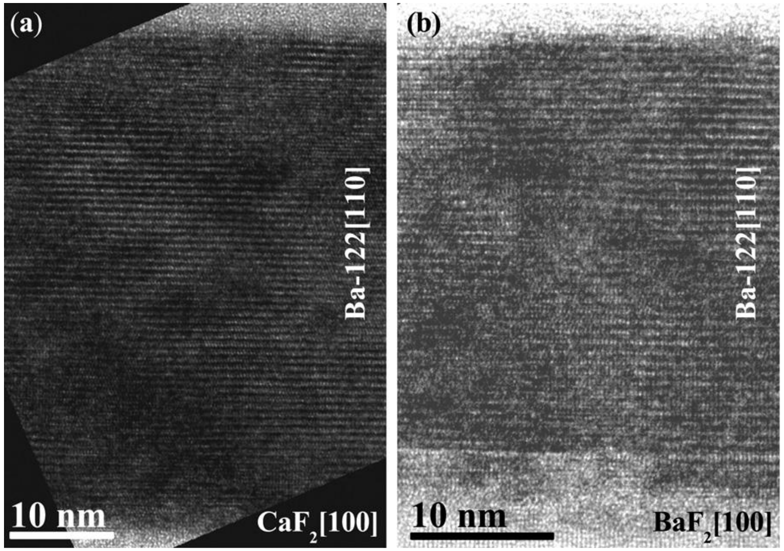


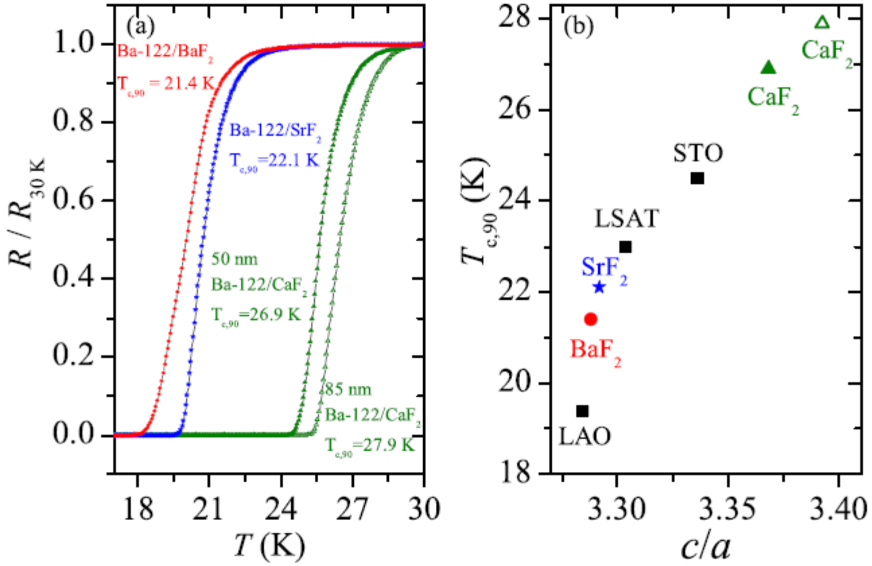


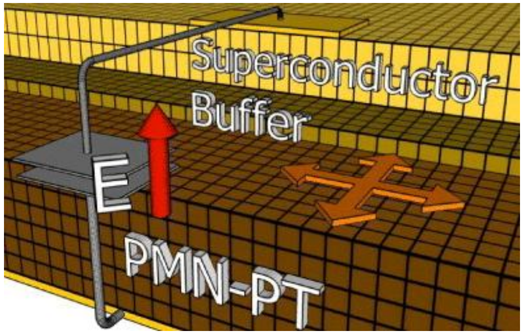


K. Iida et al., APL 95, 192501 (2009)
K. Iida et al., PRB 81, 100507(R) (2010)
T. Thersleff et al., APL 97, 022506 (2010)

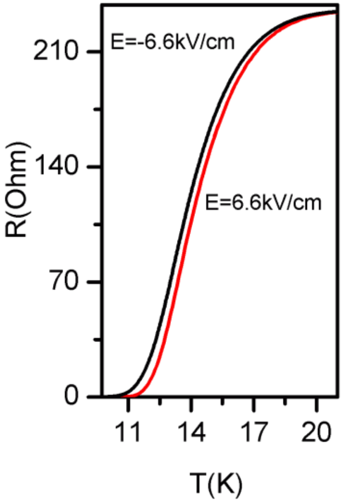
Strain dependence of T_c – Flourides and Piezo







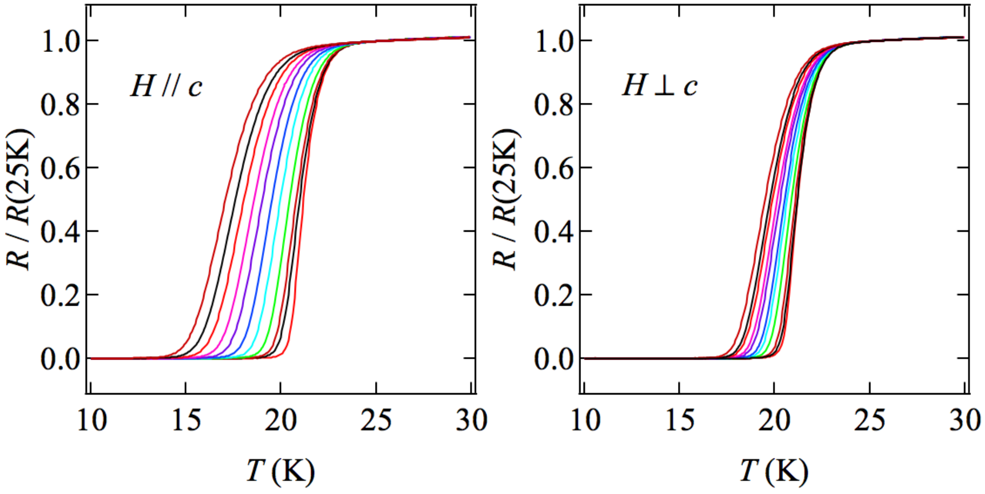
SrTiO$_3$ buffered PMN-PT



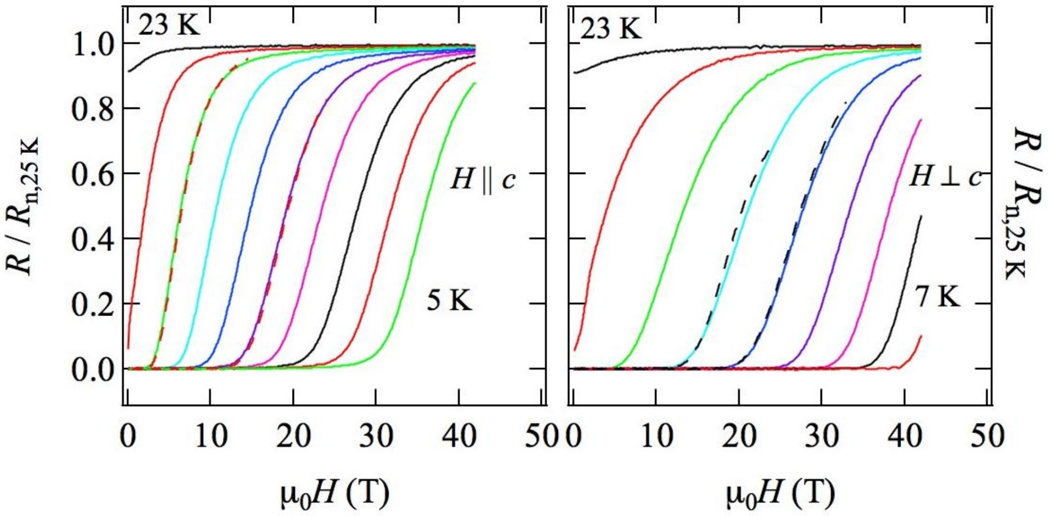
$$\boxed{\frac{\Delta T_c}{\varepsilon_{ab}} = 17\,\frac{K}{\%}}$$

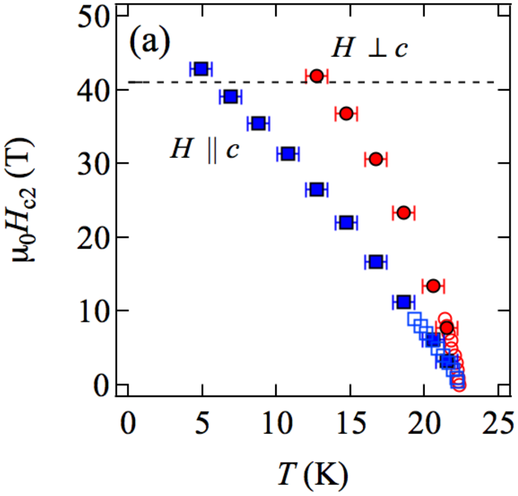
Kurth, APL 102, 142601 (2013)
S. Trommler et al., NJP 12, 103030 (2010)

Ba-122: Resistive Measurements

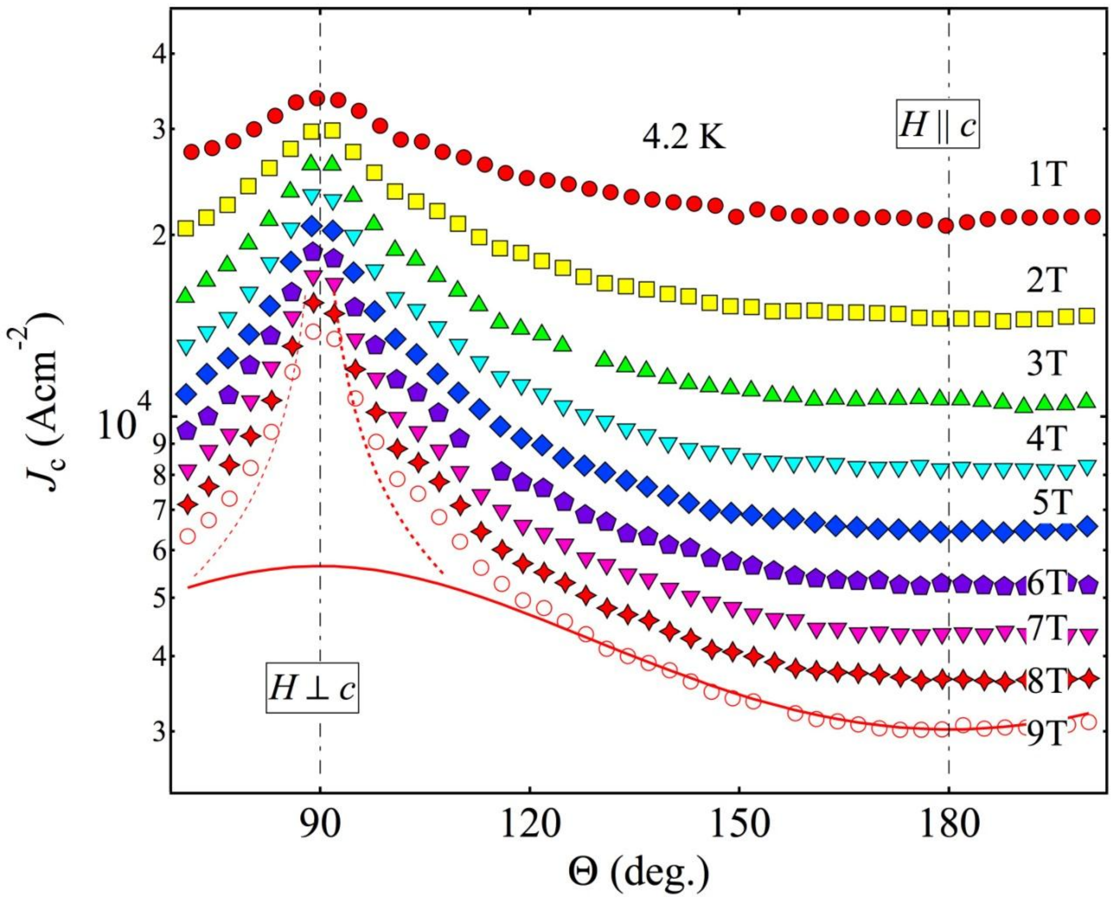


- *R(T)* static fields ≤ 9 T (PPMS)
- *R(B)* pulsed fields ≤ 45 T
- T_c, H_{c2} defined at 90% R(25K)
- Ba122 shows anisotropic H_{c2} $H_{c2}^{\|c} < H_{c2}^{\perp c}$





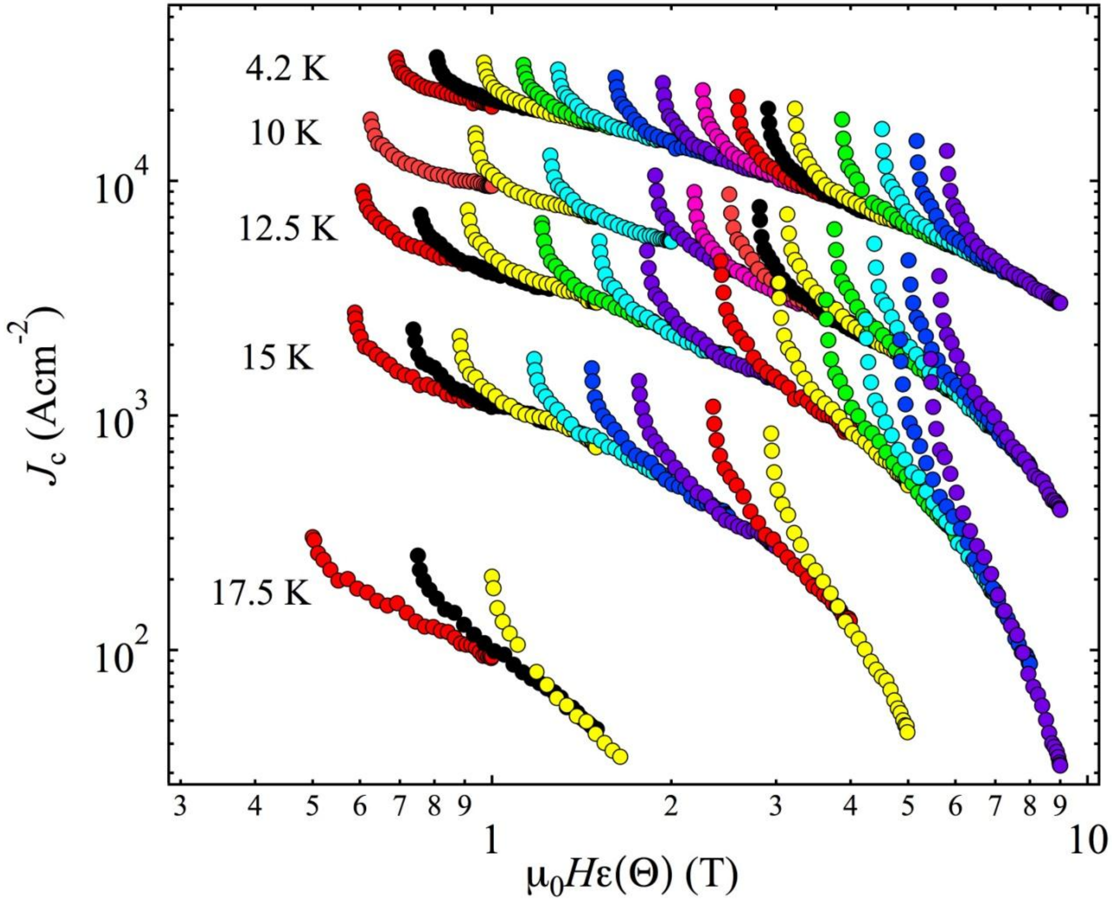
J_c anisotropy



- J_c from $J(E)$ curves,
  E_c = 1 μV/cm,
  w = 1 mm, l = 5 mm
- Overall low absolute J_c values (clean structure without strong pinning centres)
- Maximum at B||ab: due to
  1. electronic anisotropy
  2. pinning at occasional planar defects/surfaces
- No second peak for B||c (absence of correlated defects, cf. TEM)

K.Iida et al., PRB 81, 100507(R) (2010)

J_c scaling



If:

- **anisotropic Ginzburg-Landau theory holds**
- **only random and isotropic pinning centers**
- **angle θ well defined:**
    - **Large magnetic fields ($\kappa >> B_{c2}/B$)**
    - **c-axis textured growth**

Then:

$J_c(\theta)$ can be scaled with:

$$J_c(H,\Theta) = J_c(\tilde{H}),$$

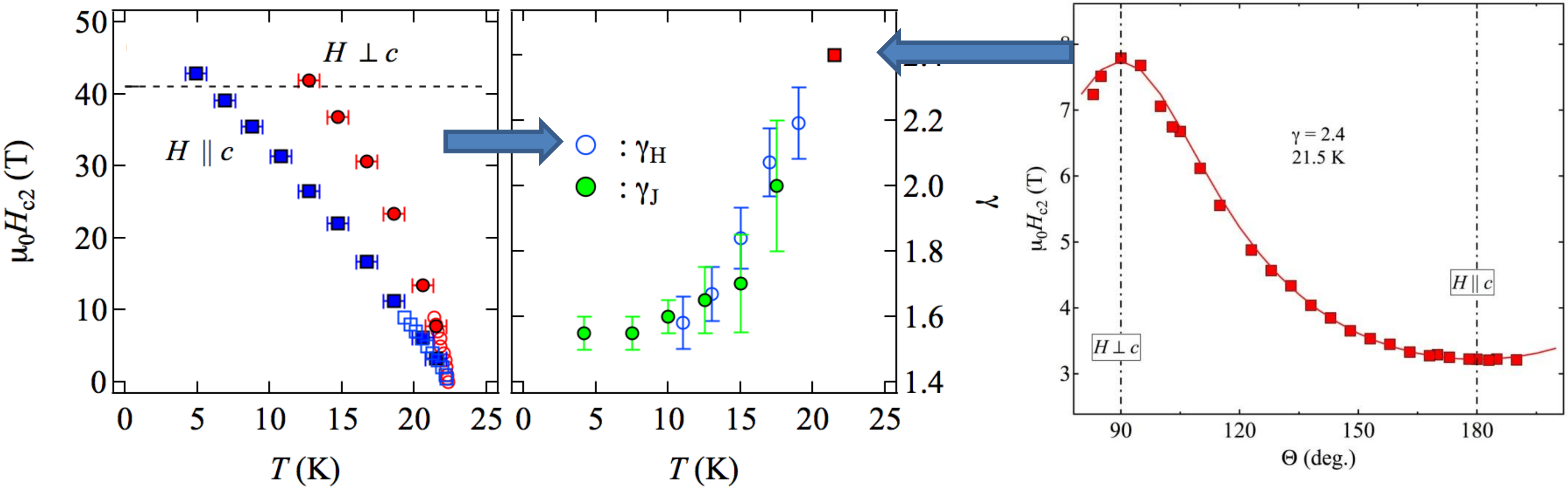
$$\text{where } \tilde{H} = \varepsilon(\Theta)H$$

$$\varepsilon(\Theta) = \sqrt{\cos(\Theta)^2 + \gamma^{-2}\sin(\Theta)^2}$$

Blatter et al., RMP 66, 1125 (1994)

K.Iida et al., PRB 81, 100507(R) (2010)

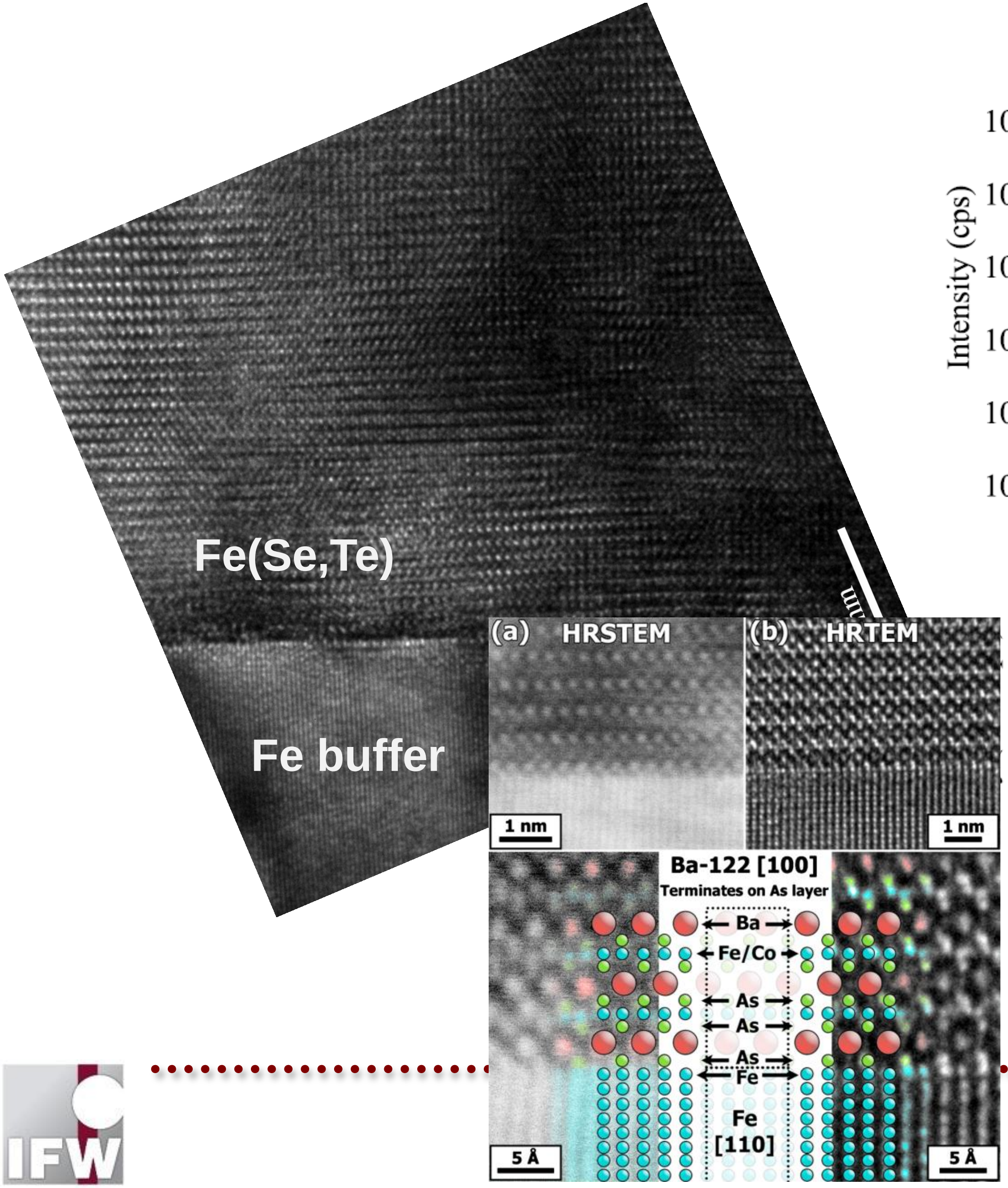
Electronic Anisotropy

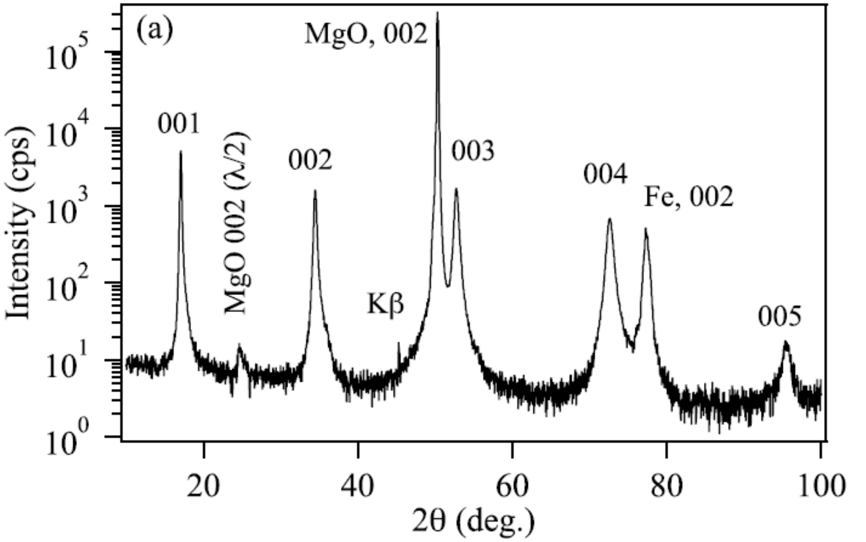


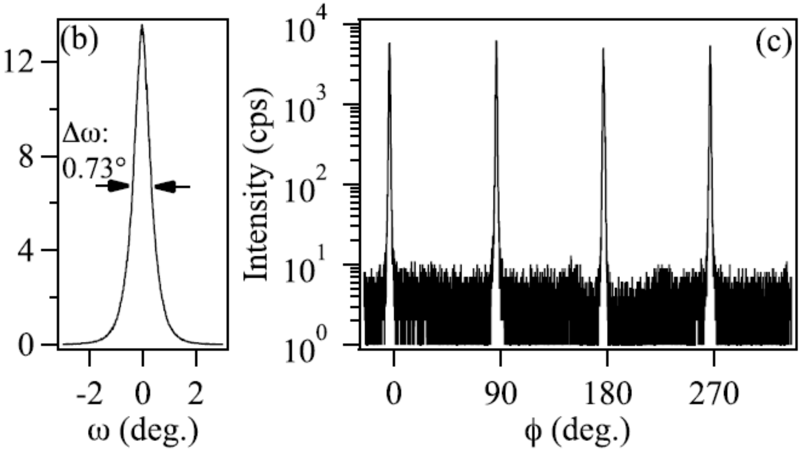
- Low T: J_c scaling, medium T: $H_{c2}^{\perp c}/H_{c2}^{\parallel c}$, high T: full GL fitting of $H_{c2}(\theta)$
- H_{c2} anisotropy temperature dependent
  → evidence for multiband superconductivity (in 3D limit)
- J_c scaling probes anisotropy of upper critical field

K. Iida et al., PRB 81, 100507(R) (2010)
J. Hänisch et al., IEEE 21, 2887 (2011)

Fe(Se,Te): XRD, TEM



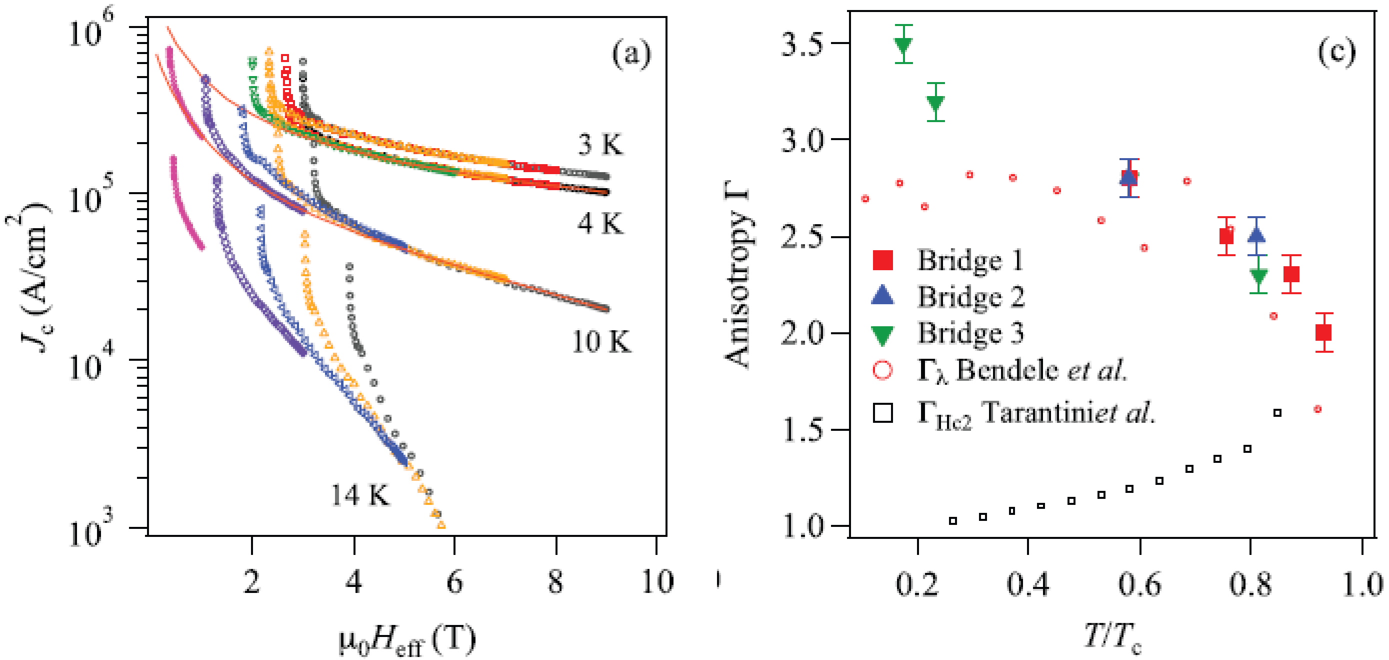




K. Iida et al., PRB 87, 104510 (2013)

T. Thersleff et al., APL 97, 022506 (2010)

Fe(Se,Te): J_c and *N* Scaling



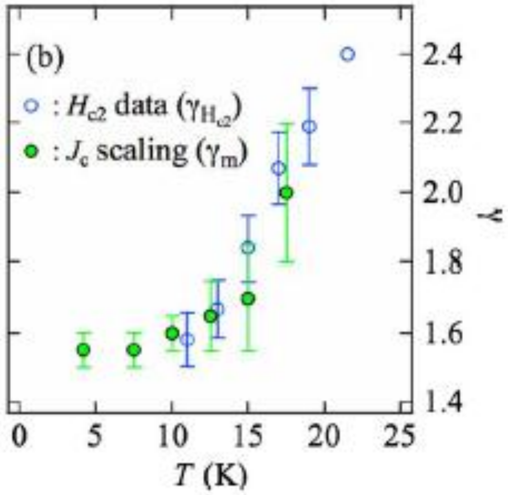
$$H_{\text{eff}} = H\varepsilon(\Theta)$$

$$\epsilon(\Theta) = \sqrt{\cos^2(\Theta) + \Gamma^{-2}\sin^2(\Theta)}$$

Scaling parameter Γ follows Γ_λ
(in contrast to Ba-122, RE-1111)

Scaling with ξ or λ?

In general, $H_{\rm irr}$ is extrinsic. But in absence of strong, extended defects, $H_{\rm irr}$ is governed by properties of the flux line lattice (intrinsic) rather than the defect structure (extrinsic).

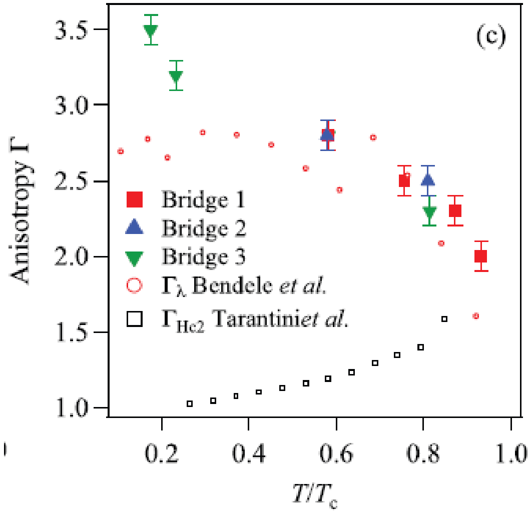


<u>Melting line:</u>

3D: **Ba-122**

$$B_{\rm m}^{\rm J}(T) = \frac{\pi^2 c_{\rm L}^4}{Gi}\boxed{H_{c_2}(0)}\frac{T_c^2}{T^2}\left(1-\frac{T^2}{T_c^2}\right)^2$$

2D: **Fe(Se,Te)**



$$B_{\rm m}^{\rm em}(T) \approx \frac{c_{\rm L}^2}{2\beta}\boxed{B_\lambda}\frac{\varepsilon_0 d}{T}$$

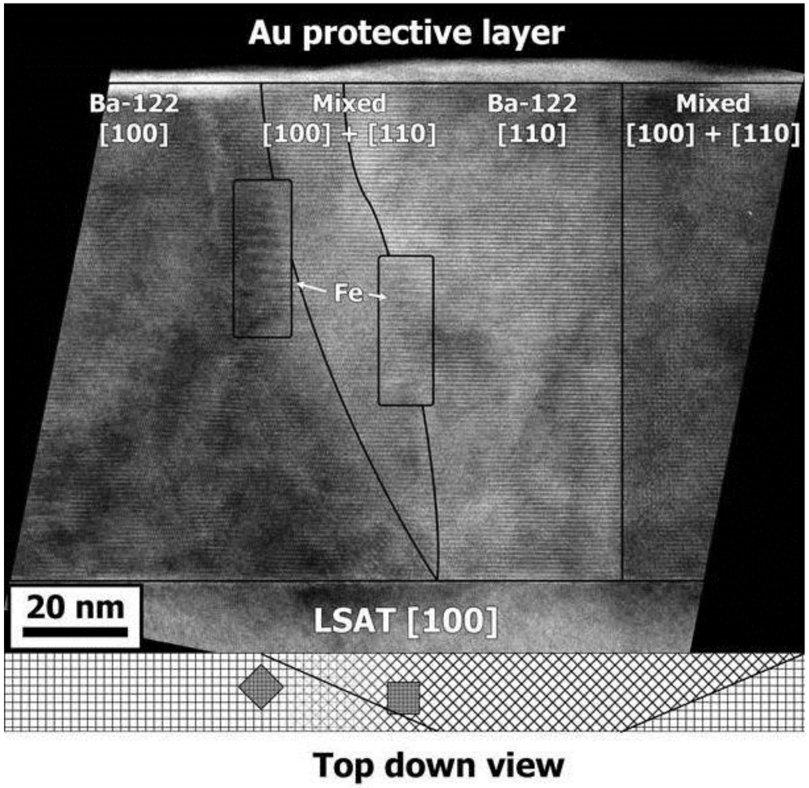
$$B_\lambda = \Phi_0/\lambda^2$$

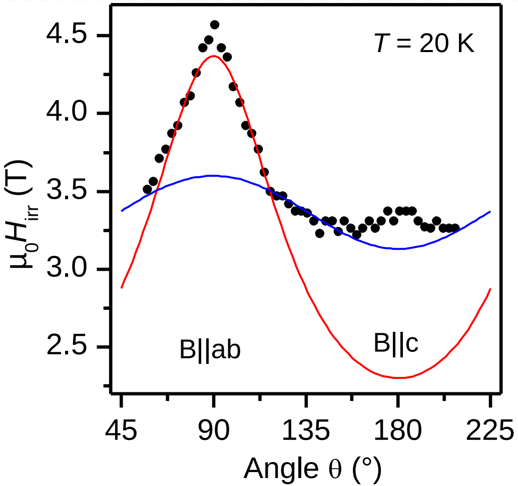
(same holds for glass-liquid transition)

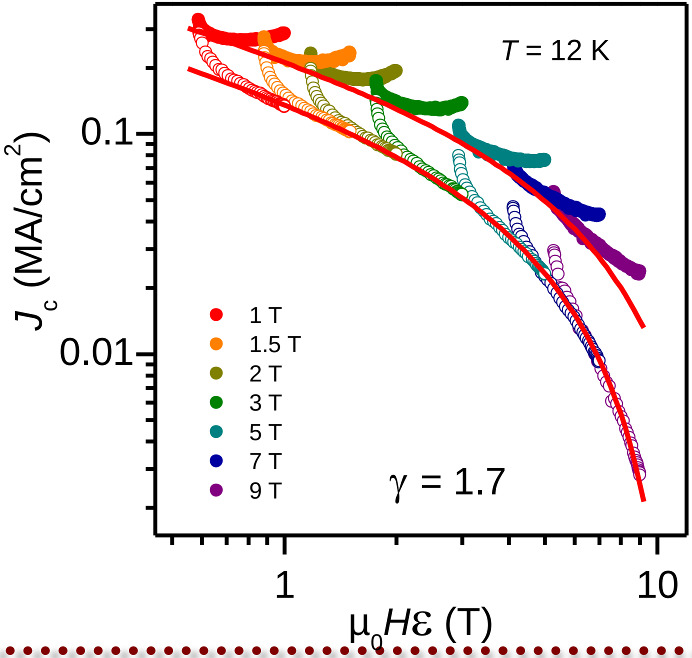
Effect of multiband + anisotropy!

Blatter et al., RMP 66, 1125 (1994)

Scaling with extended defects



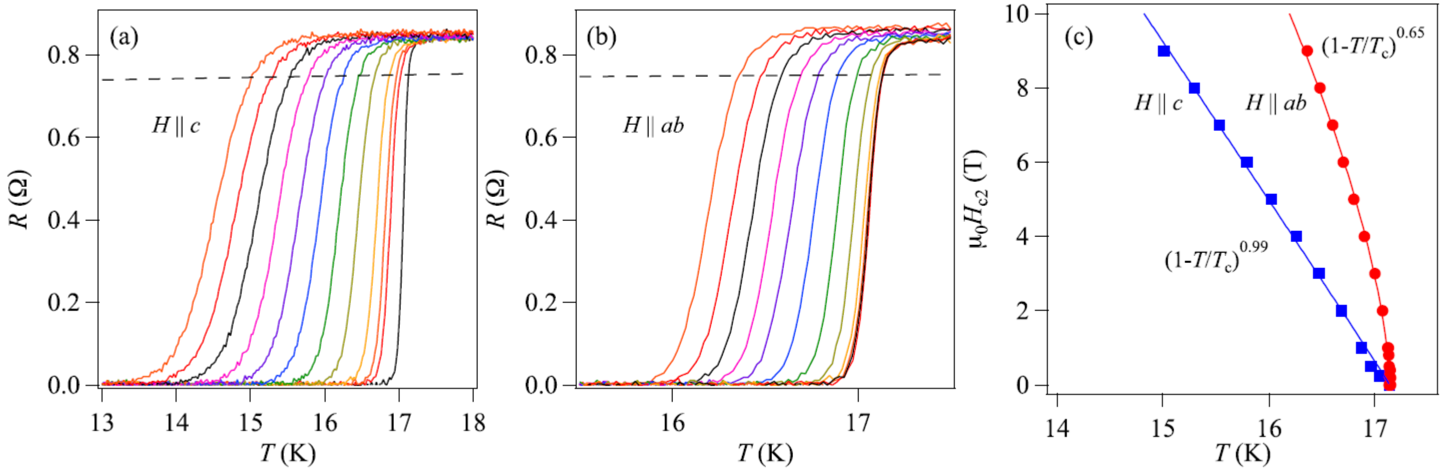




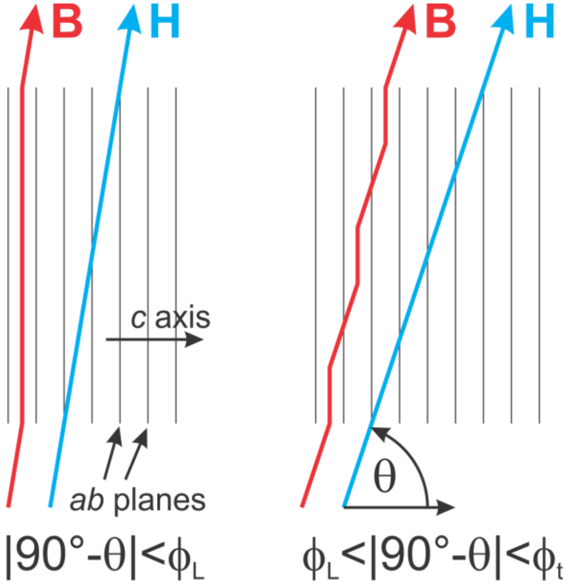
- **Ba-122 with 45º c-axis tilt GBs + Fe particles → enhanced c-axis pinning**
- **Scaling with H_{c2} anisotropy only possible in small angular region**

→ J. Hänisch, CEC-ICMC procedings

Fe(Se,Te): Upper critical field



Steep slope of $H_{c2}||ab$ and negative curvature ⟹ 2D behaviour



⟹ trapping and lock-in of flux lines

$$\varphi_t = \left[\frac{2\varepsilon_{TP}}{\varepsilon_l}\right]^{1/2}$$

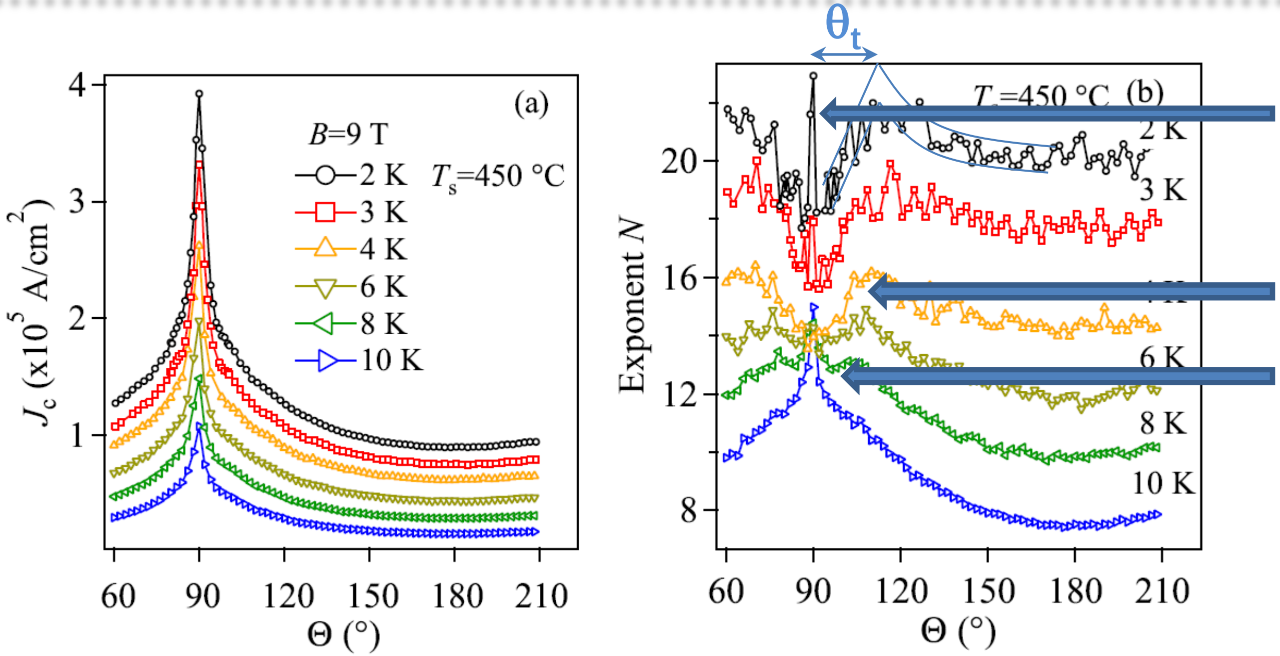
$$\varphi_L = \frac{4\pi\varepsilon_l}{\Phi_0 H}\varphi_t$$

- **At angles smaller than the trapping angle ϕ_t vortices form staircases.**
- **At angles smaller than the lock-in angle ϕ_L vortices lock into the *ab*-planes.**

M. Weigand et al., ASC 2012
Blatter et al., RMP 66, 1125 (1994)

K. Iida et al., PRB 87, 104510 (2013)

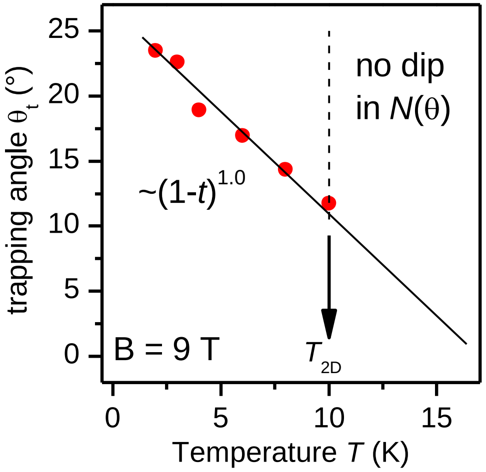
Temperature Dependence



Lock-in of flux lines

Trapping of flux lines

Pinning at ab defects/ surface pinning

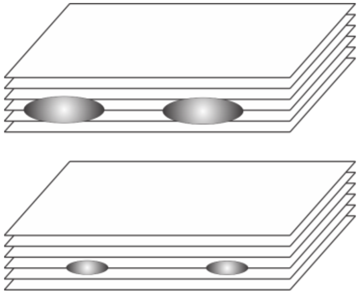


Transition between anisotropic 3D and quasi-2D:

$$T_{cr} = (1-\tau_{cr})T_c < T_c$$

$$\tau_{cr} = 2\xi_c^2(0)/d^2$$

→ **ξ_c = 0.2 nm**



$T > T^*$

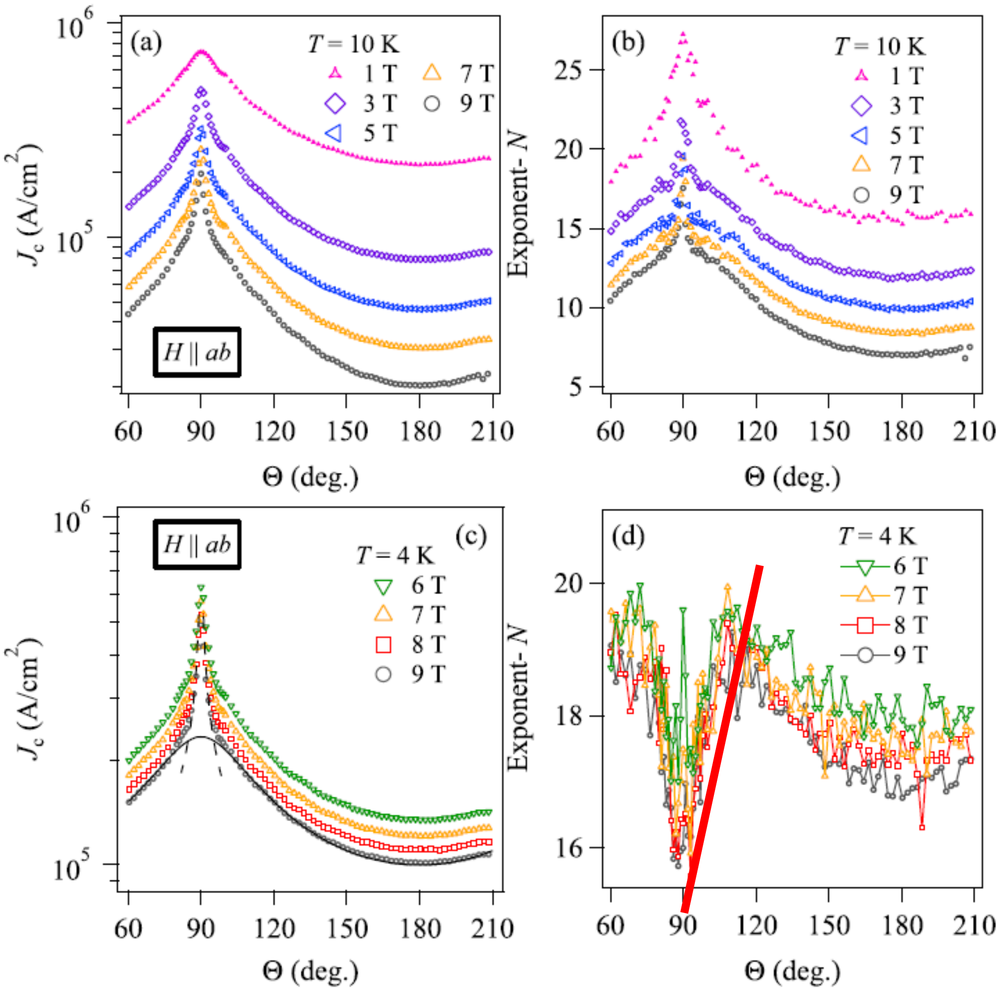
$T < T^*$

$2\xi_c < d$

M. Weigand et al., ASC 2012

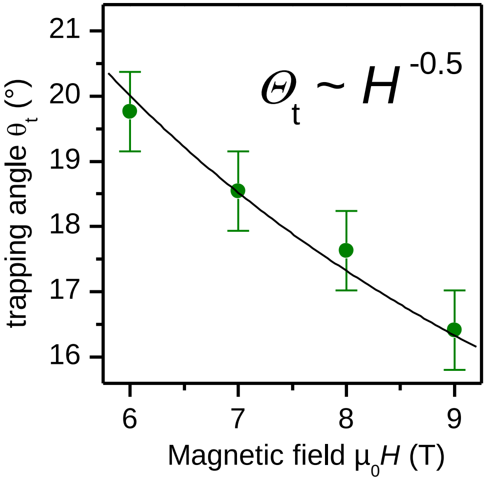
K. Iida et al., PRB 87, 104510 (2013)

Field Dependence



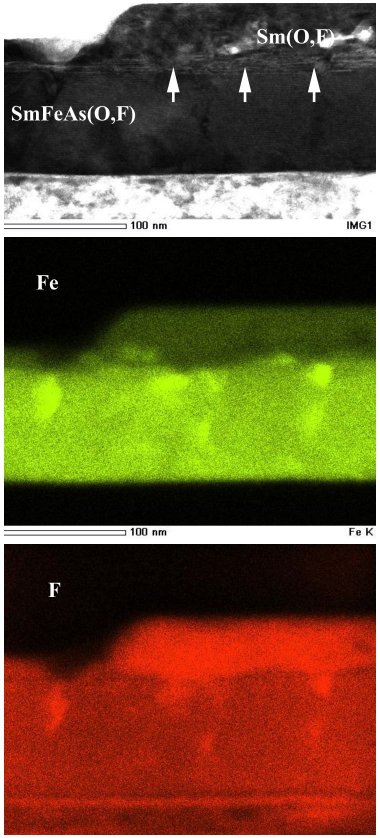
dN/dθ in trapping region:

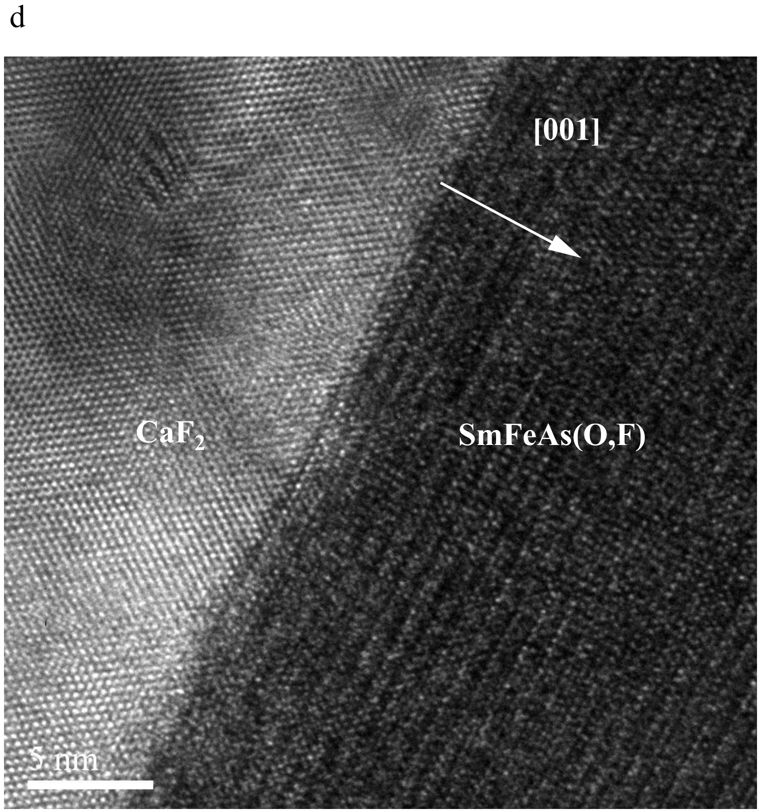
+ independent of *B* and *T*,
+ depends on double-kink density per line

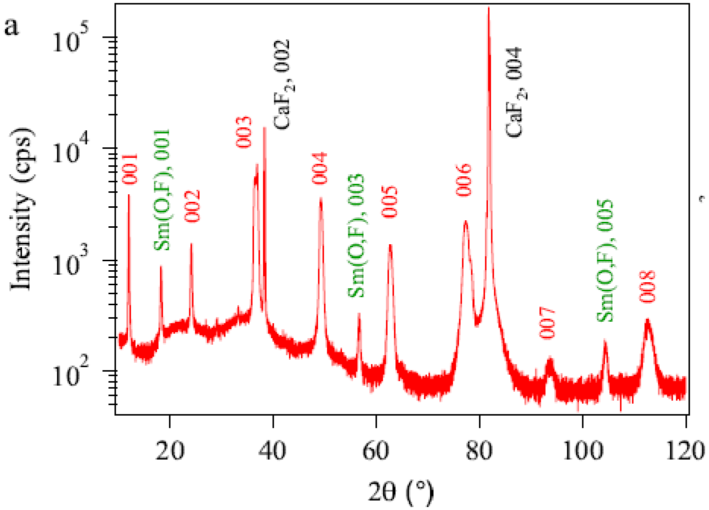


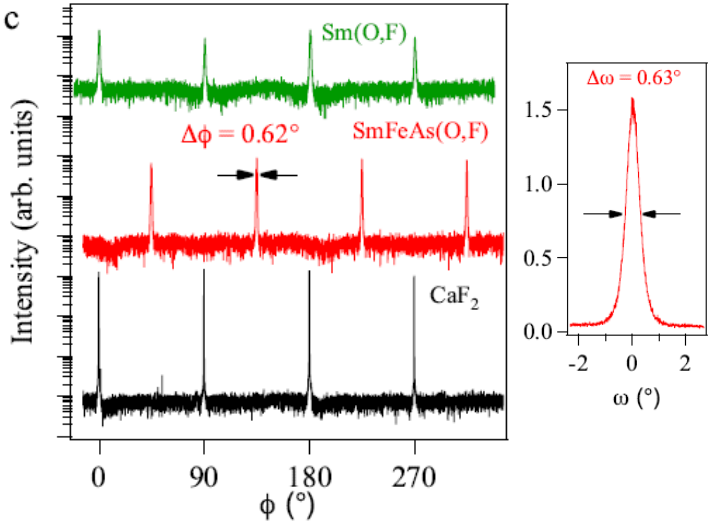
K. Iida et al., PRB 87, 104510 (2013)

MBE Sm-1111: Microstructure



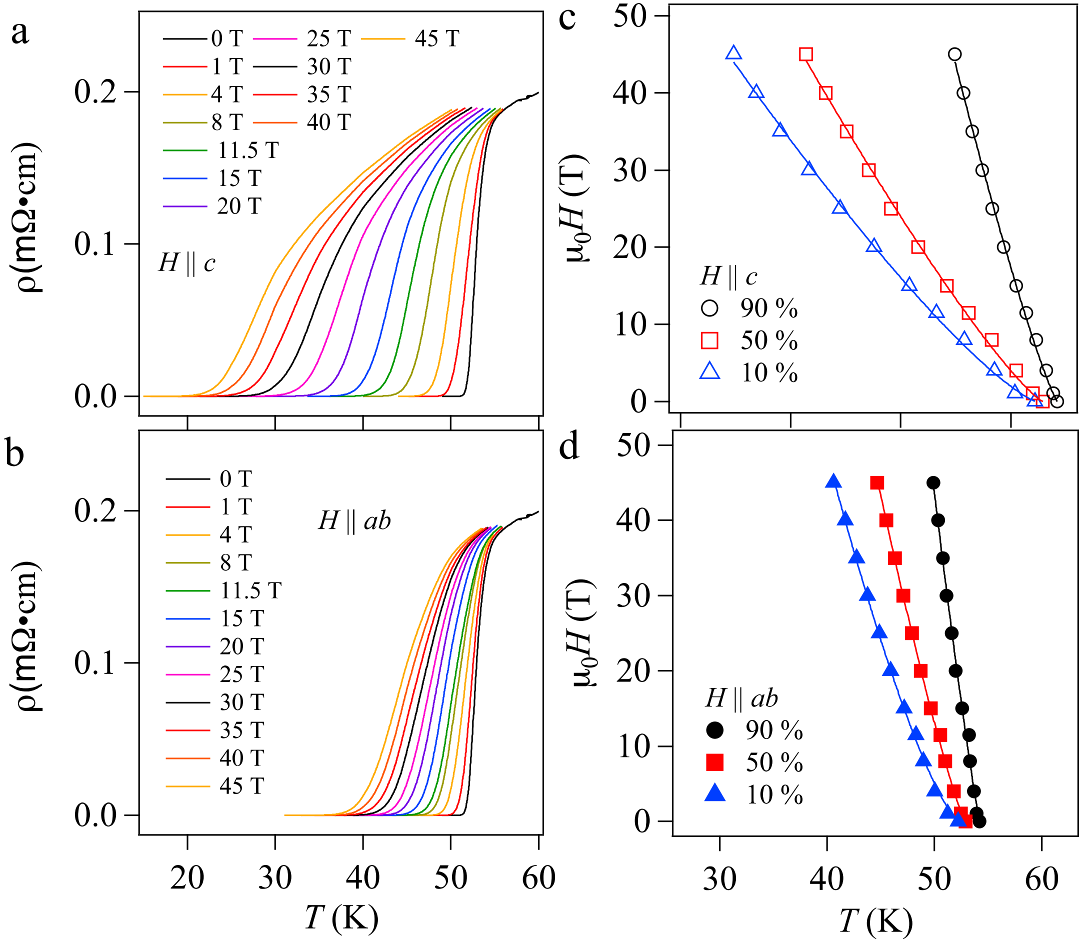






- Sharp biaxial texture
- Clean interface
- Occasional Fe-F particles

Sm-1111: resistive transition and H_{c2}

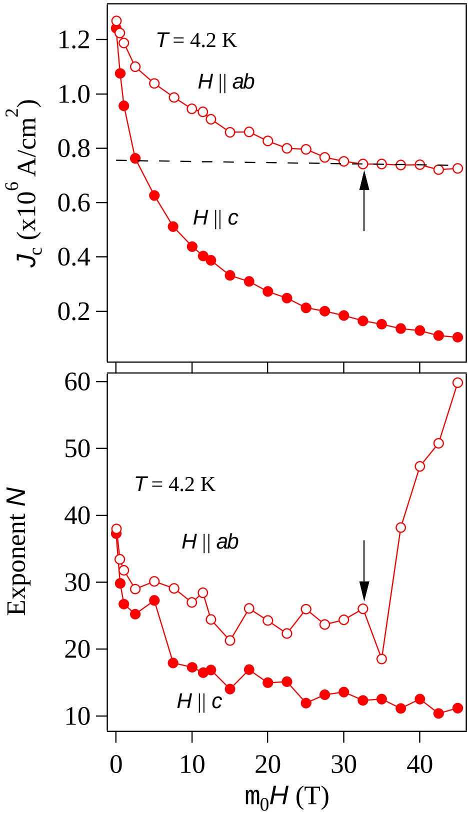


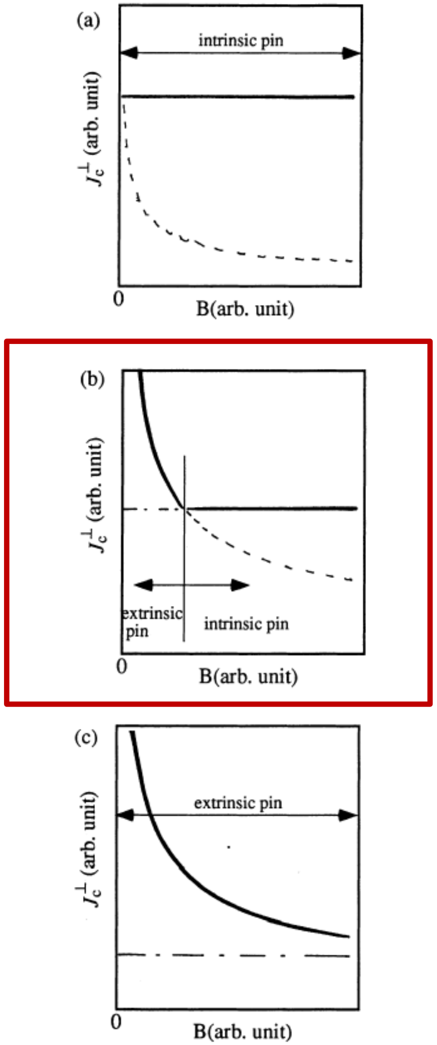
$$\left|\frac{d\mu_0 H_{c2}^{||ab}}{dT}\right|_{T_c} = 11.4 \text{ T/K}$$

⇒ ξ_c = 0.28 nm
< 0.858 nm = *d*

Extremely 2D superconductor

Sm-1111: $J_c(B)$





Above 35 T:

- **Constant J_c(B||ab)**
- **Sharpely Increasing *N*(*B*)**

→ Intrinsic Pinning dominant

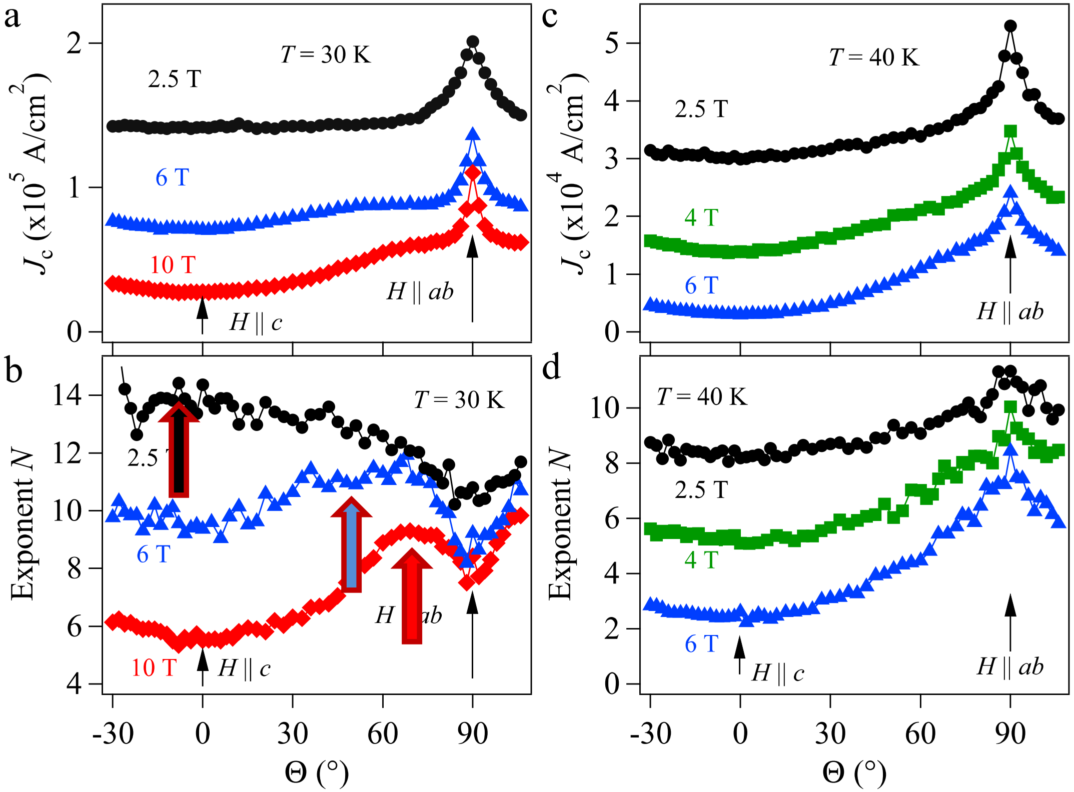
Below 35 T:

- **J_c and *N* scale (as for B||c)**

→ Extrinsic Pinning dominant

S. Awaji et al., Cryogenics 39, 569(1999)

Sm-1111: $J_c(\theta)$



$$T_{\mathrm{cr}} = (1-\tau_{\mathrm{cr}})T_c < T_c$$

$$\tau_{\mathrm{cr}} = 2\xi_c^2(0)/d^2$$

Above 40 K:

- **No dip in *N* observed**

→ Extrinsic Pinning dominant

Below 30 K:

- **Typical dip in *N* near *ab***

→ Intrinsic Pinning dominant
→ Large Lock-in angles
(due to large anisotropy)

→ 2D-3D transition at T_{cr} ~ 35 K leads to
ξ_c ~ 0.35 nm

Conclusion

- **Active and growing community for Fe-based sc thin films**
- **Basic investigations and evaluation of possible applications**
- **T_c strongly strain dependent**
- **J_c in clean films can be scaled with anisotropy of ξ (3D) or λ (2D)**
- **Intrinsic pinning clearly identified in Fe(Se,Te) and Sm-1111**