RADIATION EFFECTS ON HIGH TEMPERATURE SUPERCONDUCTORS

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From ITER to DEMO

Neutron Spectra

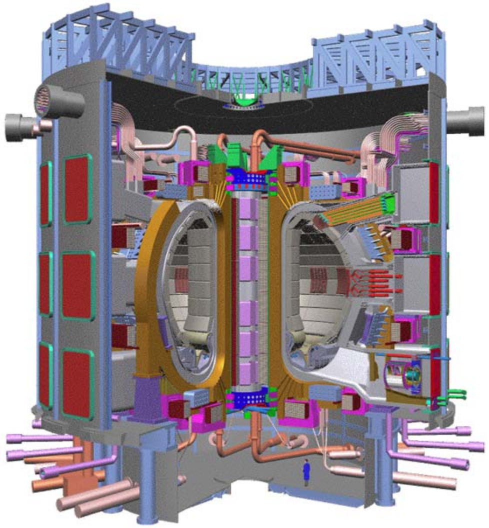
Neutron-induced Defects in HTS

Practical Materials

HTS[4]Fusion Conductor Workshop, KIT, 27 May 2011

From ITER to DEMO

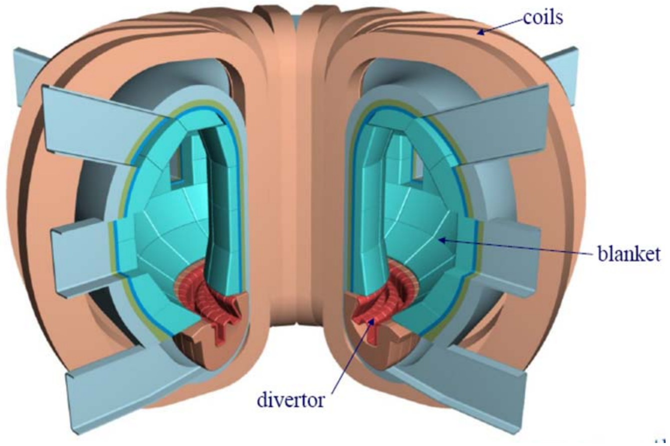
ITER



HTS Magnets ?

YBCO,
BiSCCO, MgB_2

DEMO



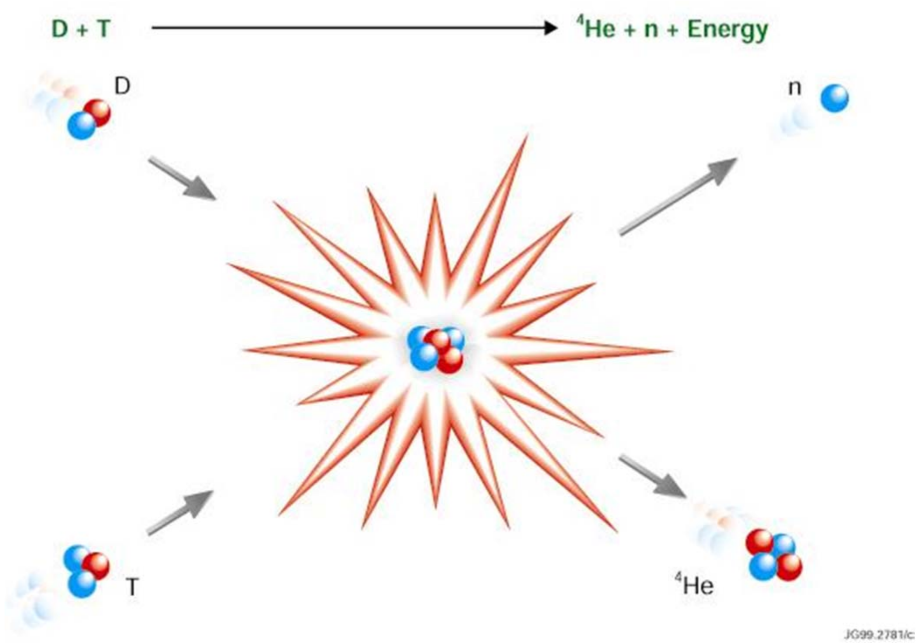
- The cooling power could be significantly reduced.
- The radiation shields could be significantly reduced and simplified.
- Higher magnetic fields could be achievable.
- Smaller coil geometries would become feasible.
- Could He be replaced?

Options / Materials

"Demo" design (magnetic field, temperature, fluence)

- Cheaper: MgB_2
- Higher fields: HTS
  - Bi-2212: ≤ 10 K
  - Bi-2223: ≤ 20 K
  - Coated conductors (RE-123): ≤ 50 K
- Higher temperatures:
  - Coated conductors (RE-123) ~ 65 -77 K

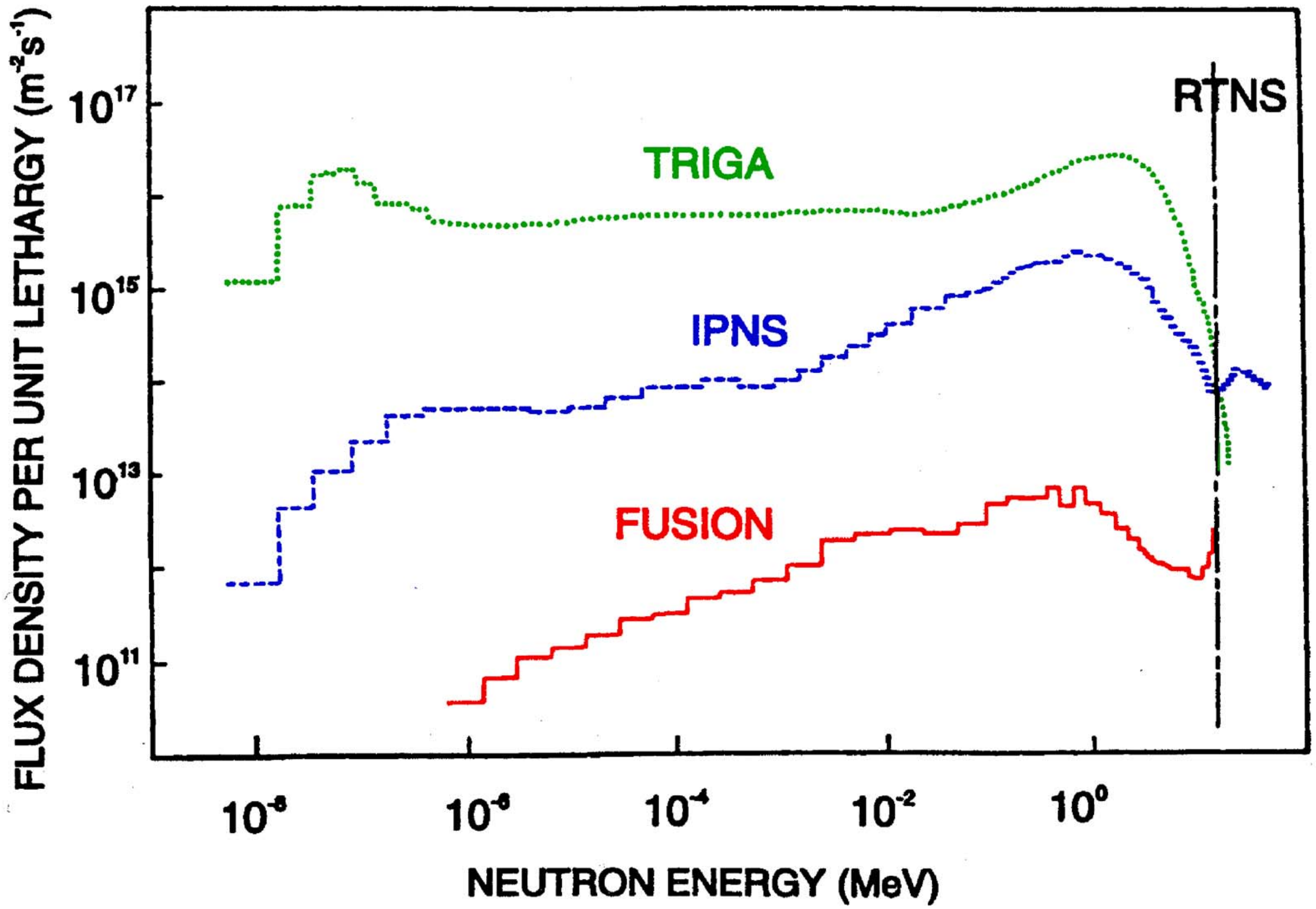
NEUTRON SPECTRA



Production of 14 MeV neutrons – deposition of energy in the "first wall" → substantial material problems (~1 MW/m²)!

At the magnet location: **Attenuation by a factor of ~ 10^6.** Scattering processes lead to a "thermalization" of the neutrons!

The **lifetime fluence** of the ITER magnets amounts to **1×10^{22} m^{-2}** (E > 0.1 MeV)


RTNS
TRIGA
IPNS
FUSION
10^{17}
10^{15}
10^{13}
10^{11}
FLUX DENSITY PER UNIT LETHARGY ($m^{-2}s^{-1}$)
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
NEUTRON ENERGY (MeV)

DAMAGE ENERGY SCALING

$\sigma(E)$	neutron cross section
$T(E)$	primary recoil energy distribution
$F(E)$	neutron flux density distribution
t	irradiation time in the neutron spectrum $F(E)$

⇨

$< \sigma(E) . T(E) >$	displacement energy cross section
$E_D = < \sigma(E) . T(E) > . F(E) . t$	damage energy (total energy transferred to each atom in the material)

SUCCESSFUL SCALING OF T_c AND J_c IN METALLIC SUPERCONDUCTORS

⇨

PREDICTIONS OF PROPERTY CHANGES IN AN UNAVAILABLE NEUTRON SPECTRUM ARE FEASIBLE!

DAMAGE PRODUCTION in SUPERCONDUCTORS

FAST NEUTRONS (E > 0.1 MeV)

Displacement cascade initiated by the primary knock-on atom, if its energy exceeds 1 keV

EPITHERMAL NEUTRONS (1 – 100 keV)

Point defect clusters

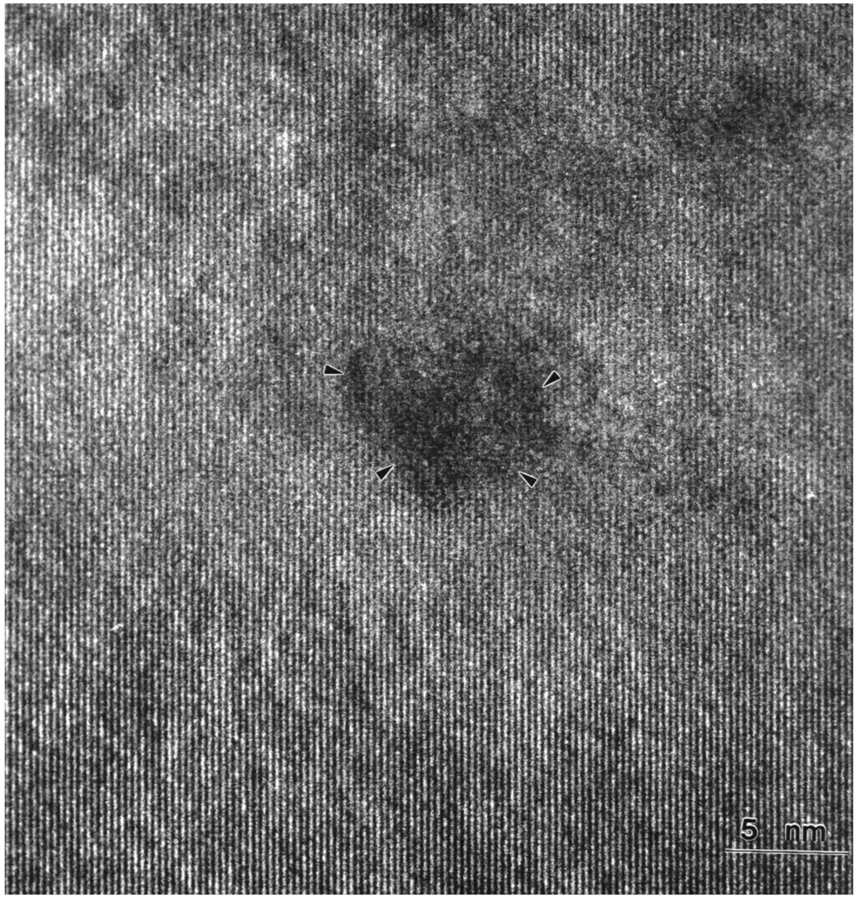
THERMAL NEUTRONS

Transmutations, point defects

γ-rays: No influence

HTS: Fast neutrons produce stable collision cascades because of their low conductivity

Neutron-induced Defects in HTS



STATISTICALLY DISTRIBUTED

~ SPHERICAL, ~ 2.5 nm Ø

SURROUNDED BY A STRAIN FIELD OF THE SAME SIZE

5 x 10^{22} defects m^{-3} per 10^{22} neutrons m^{-2}

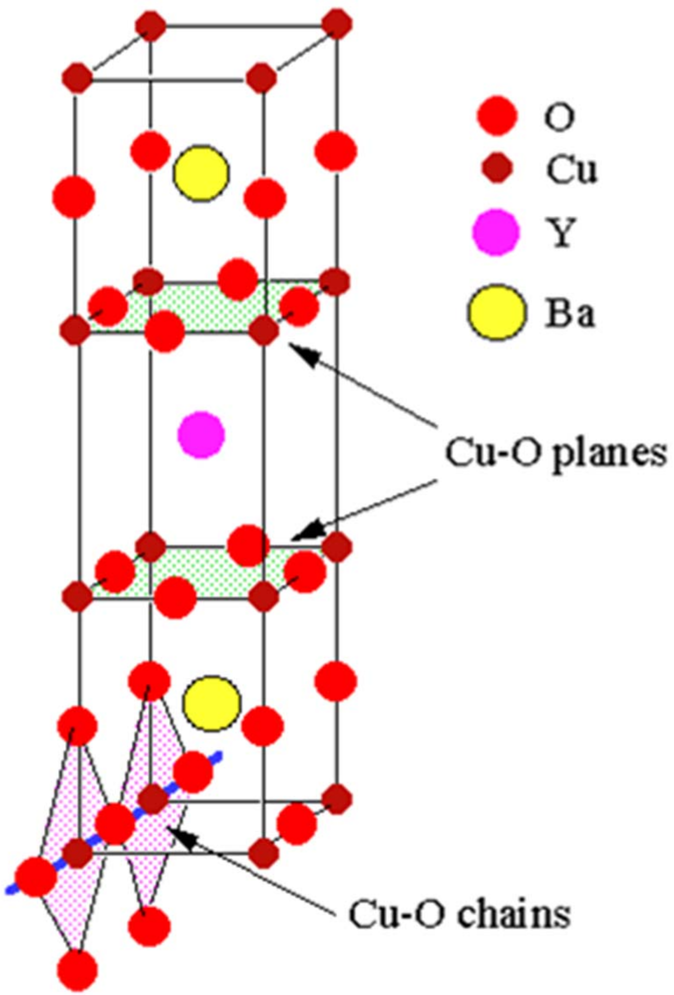
FAST NEUTRONS (E>0.1 MeV)

COLLISION CASCADES,

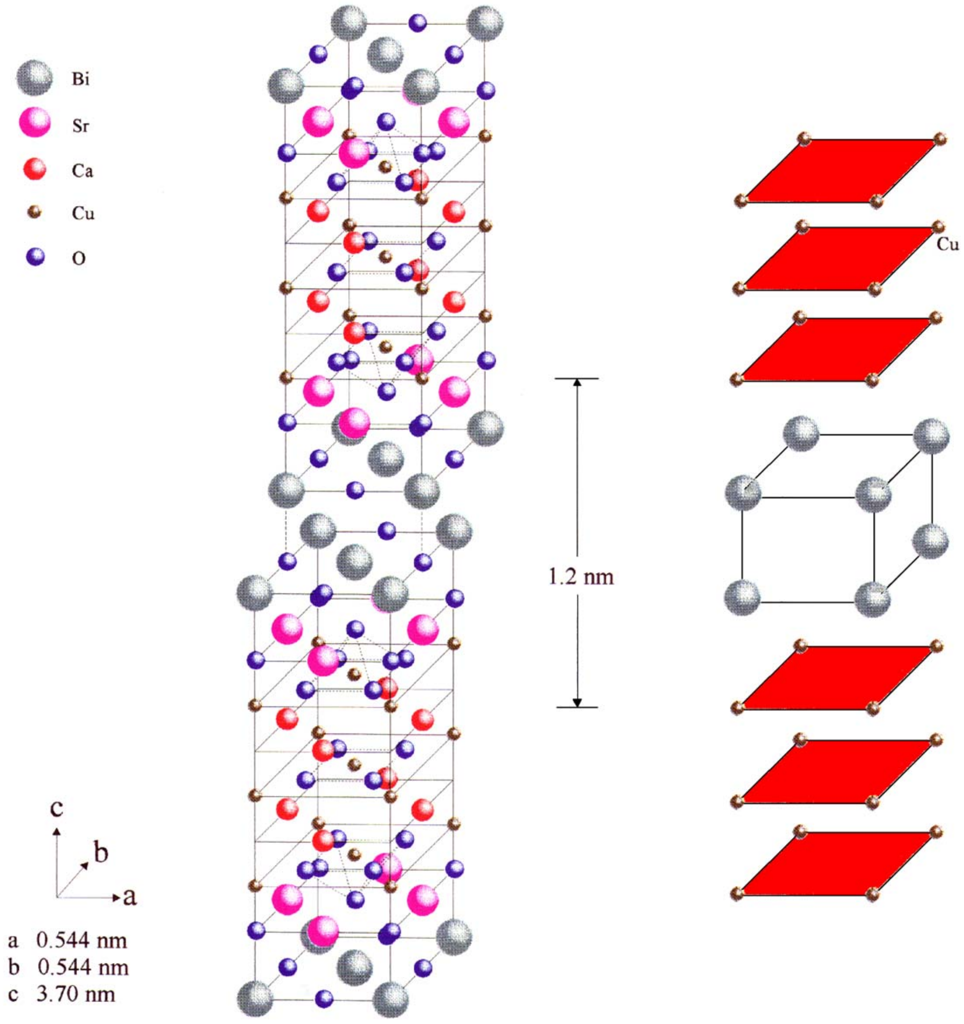
IF THE ENERGY OF THE PRIMARY KNOCK-ON ATOM EXCEEDS **~ 1 keV**

M. Frischherz et al.: Physica C 232, 309 (1994)

$YBa_2Cu_3O_{7-\delta}$ - Y-123

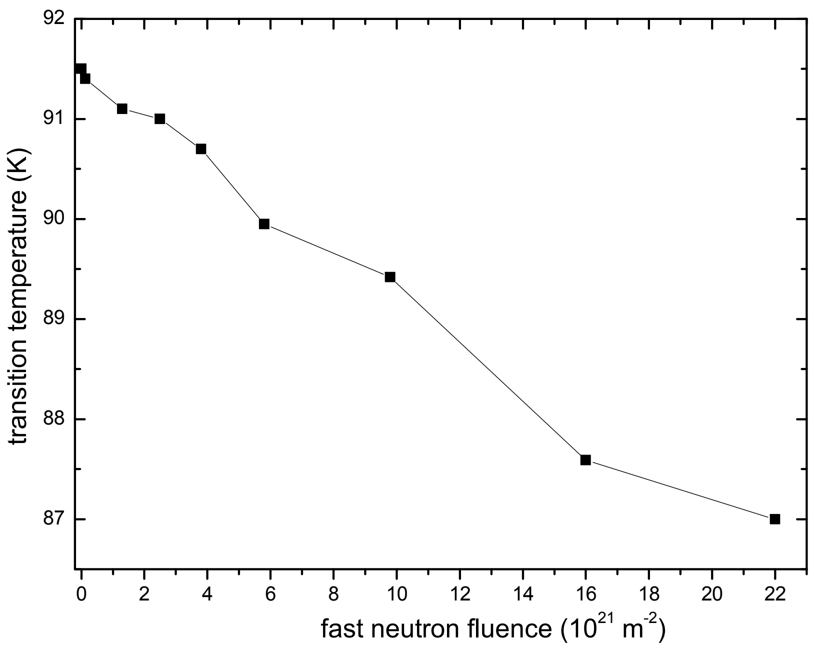


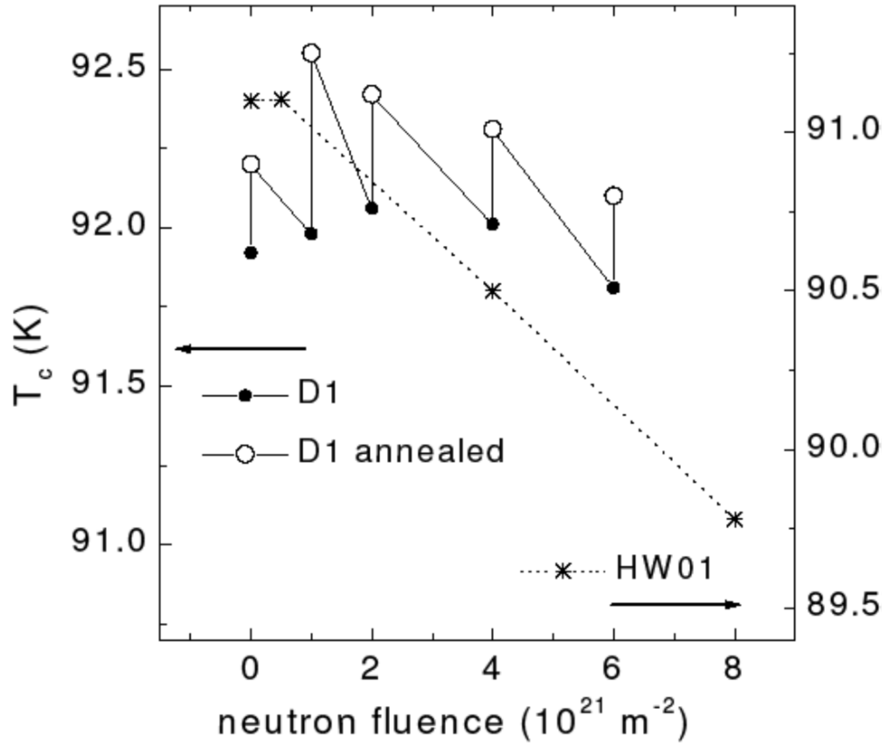
$Bi_2Sr_2Ca_2Cu_3O_{10}$ - Bi-2223



CONSEQUENCES FOR THE PRIMARY SUPERCONDUCTIVE PROPERTIES:

Introduction of disorder – mainly O-displacements

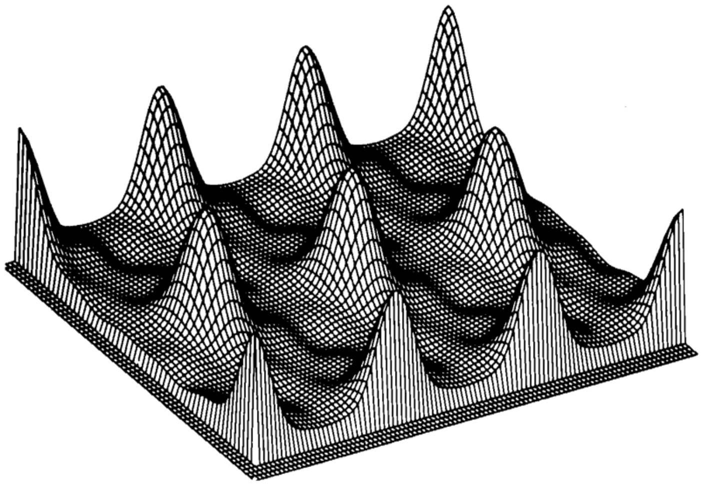


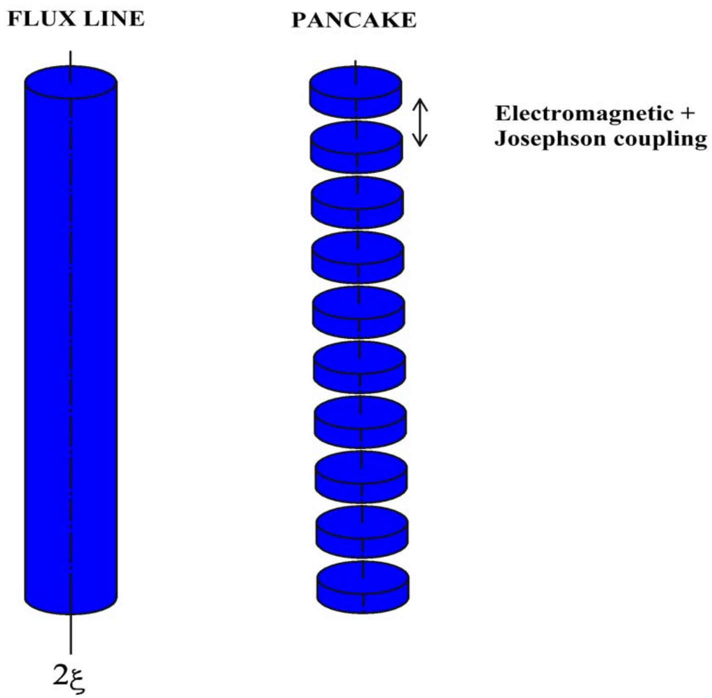


M. Eisterer et al.: Adv. Cryog. Eng. 46, 655 (2000)

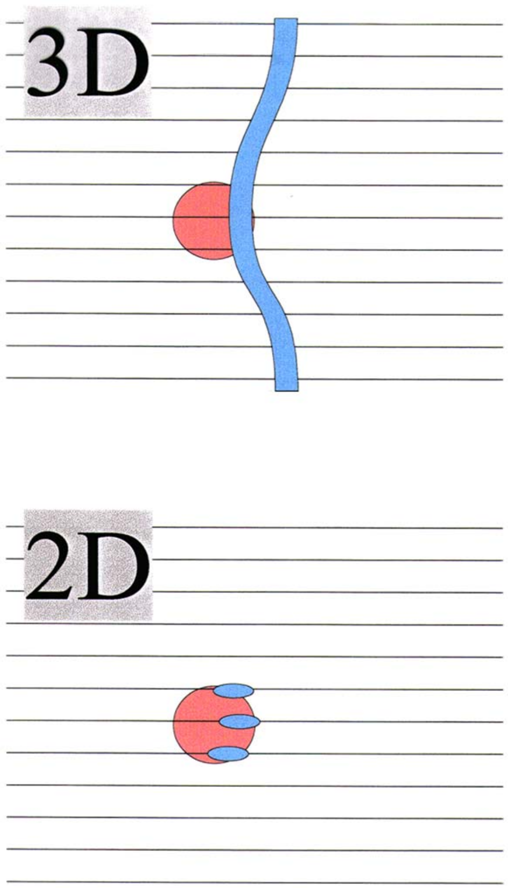
F.M. Sauerzopf: PRB 57, 10959 (1998)

Consequences for flux pinning

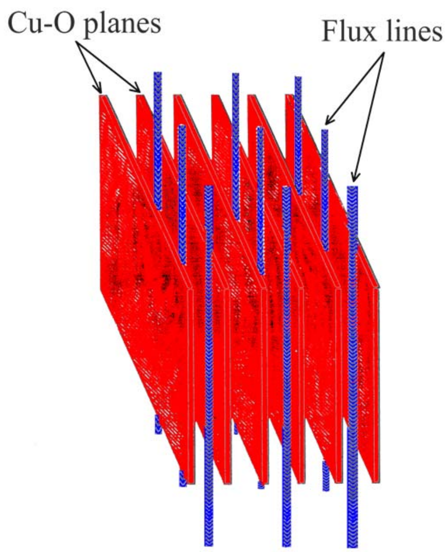




H || c

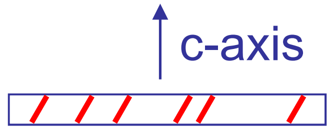


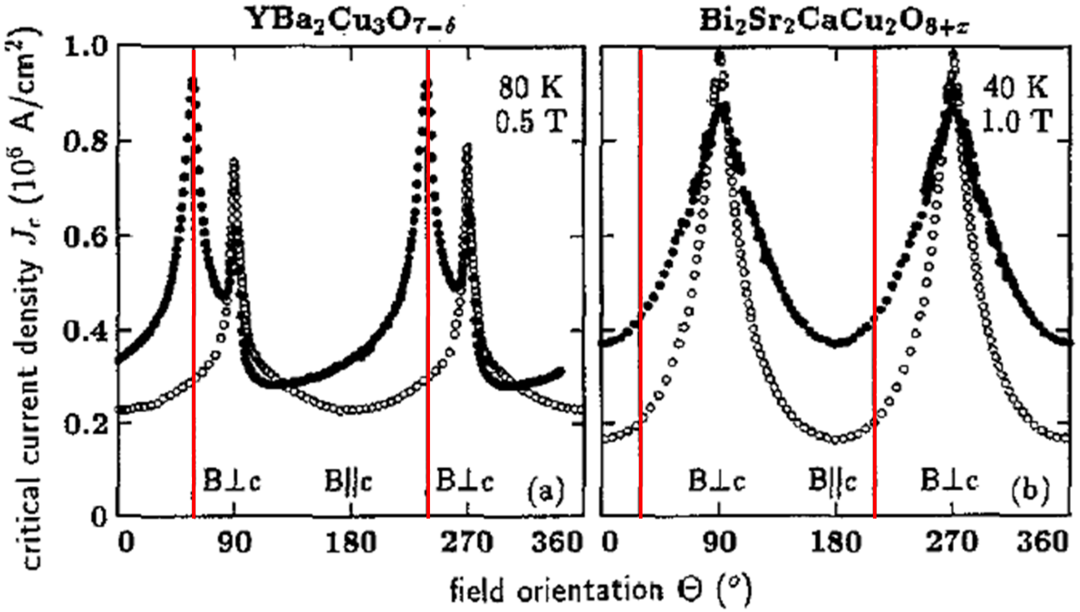
H || a,b



The same defects act differently in different materials

Example: parallel columnar defects



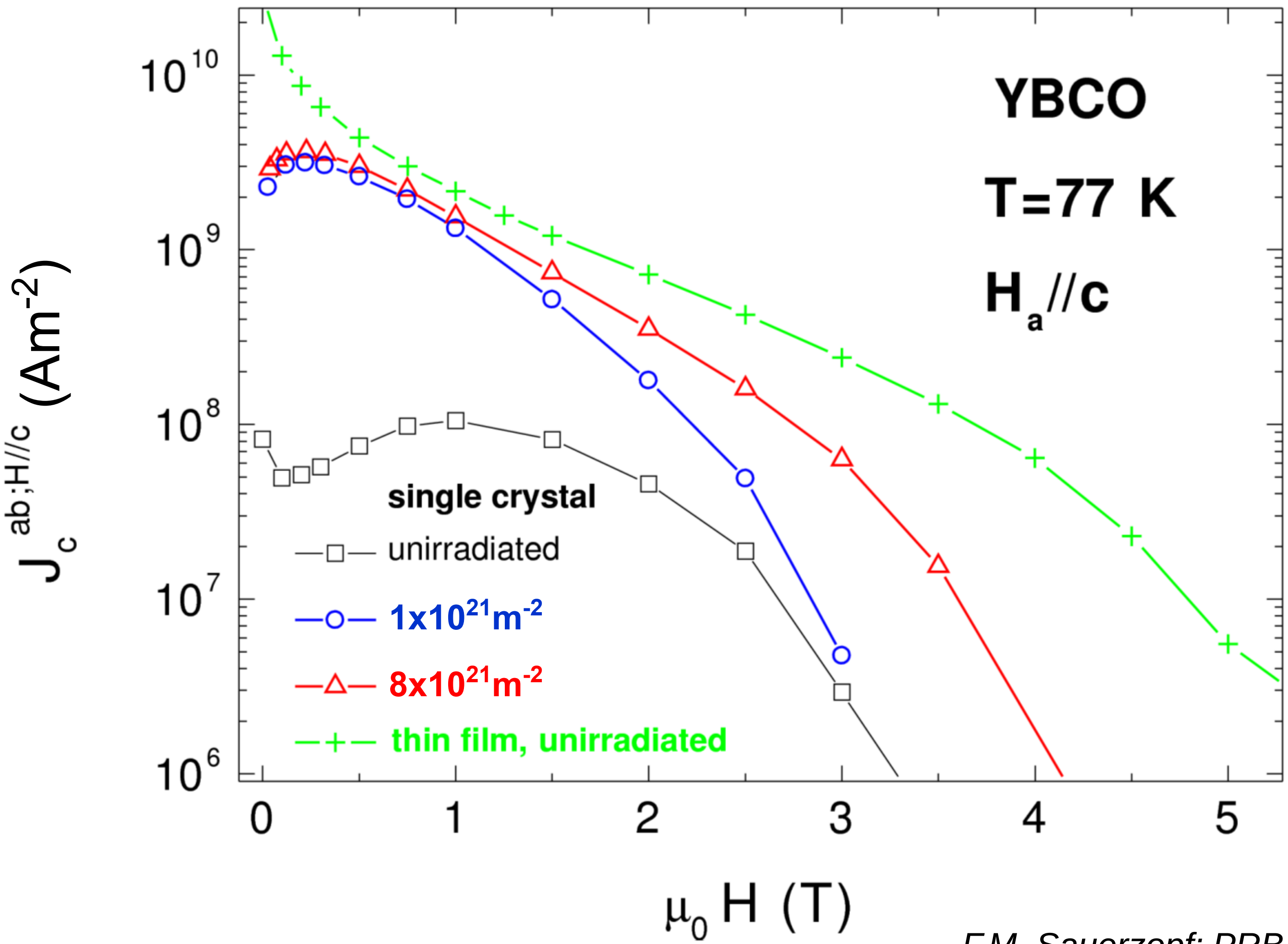


Y-123 (“3D”): Peak for H parallel to columns

Bi-2212 (“2D”): Reduction of J_c anisotropy

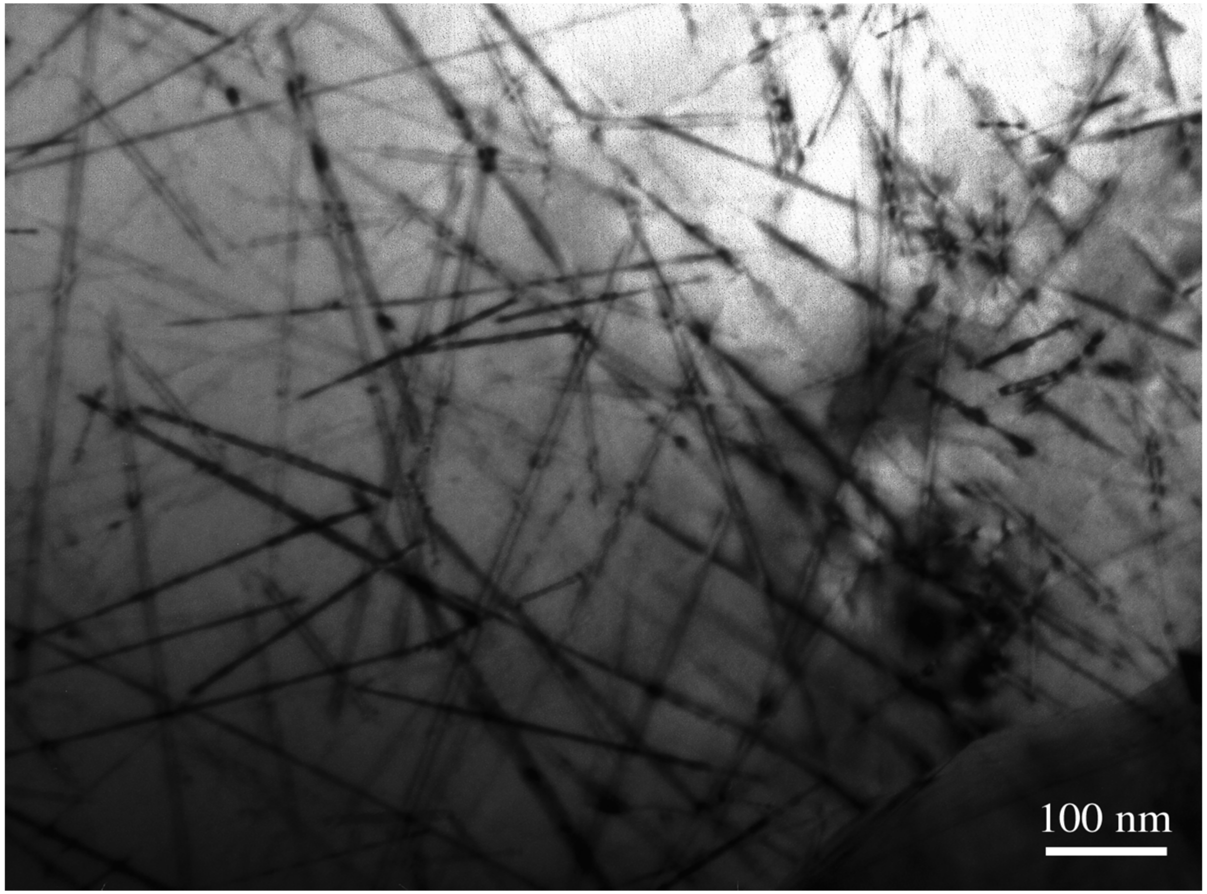
M. Kraus et al.: Phys. Bl. 50, 333 (1994)

Experimental J_c data



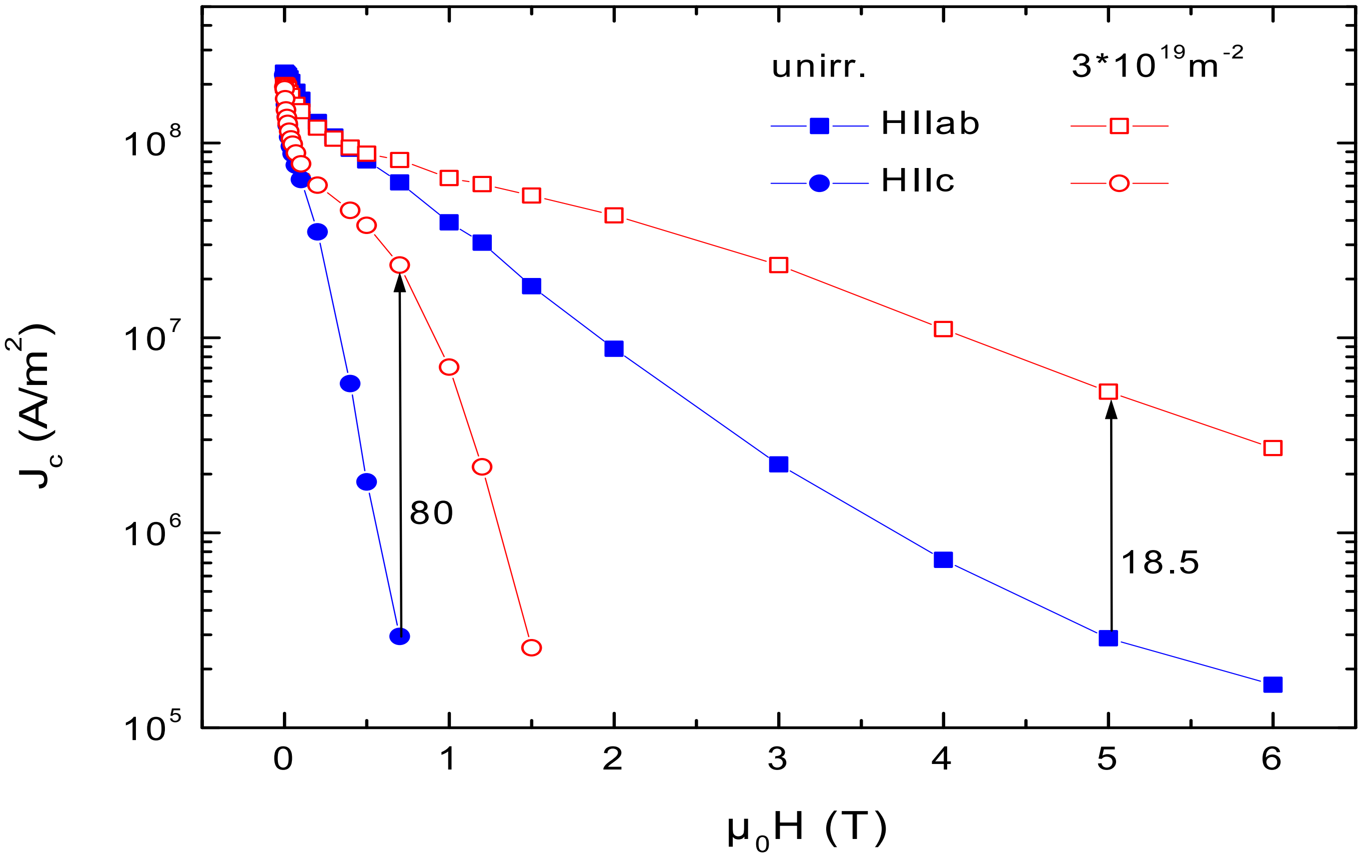
F.M. Sauerzopf: PRB 57, 10959 (1998)

Model defects in "2D" Bi-2223 tapes



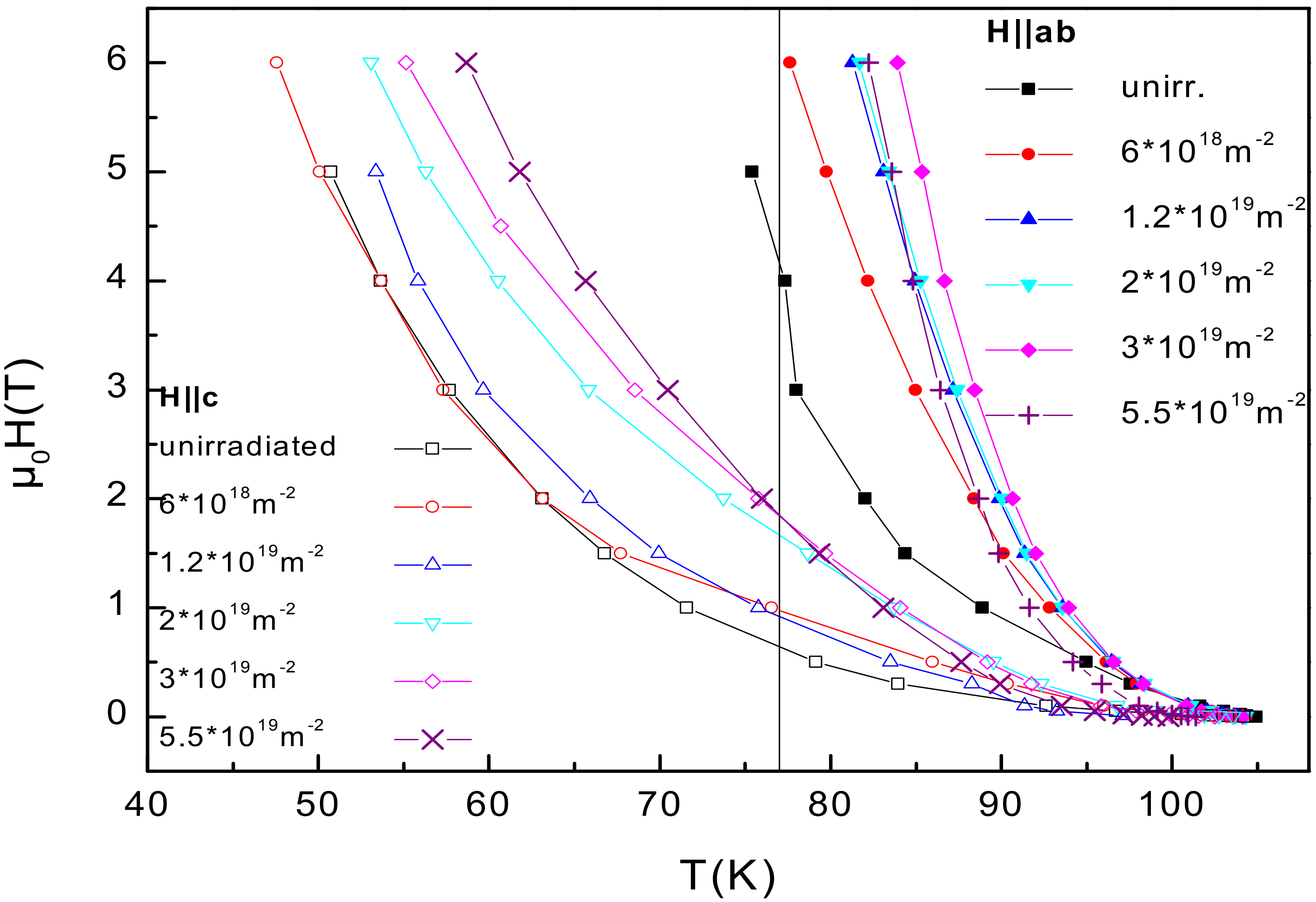
Connolly et al., TU-Delft 2000

Critical Currents at 77 K

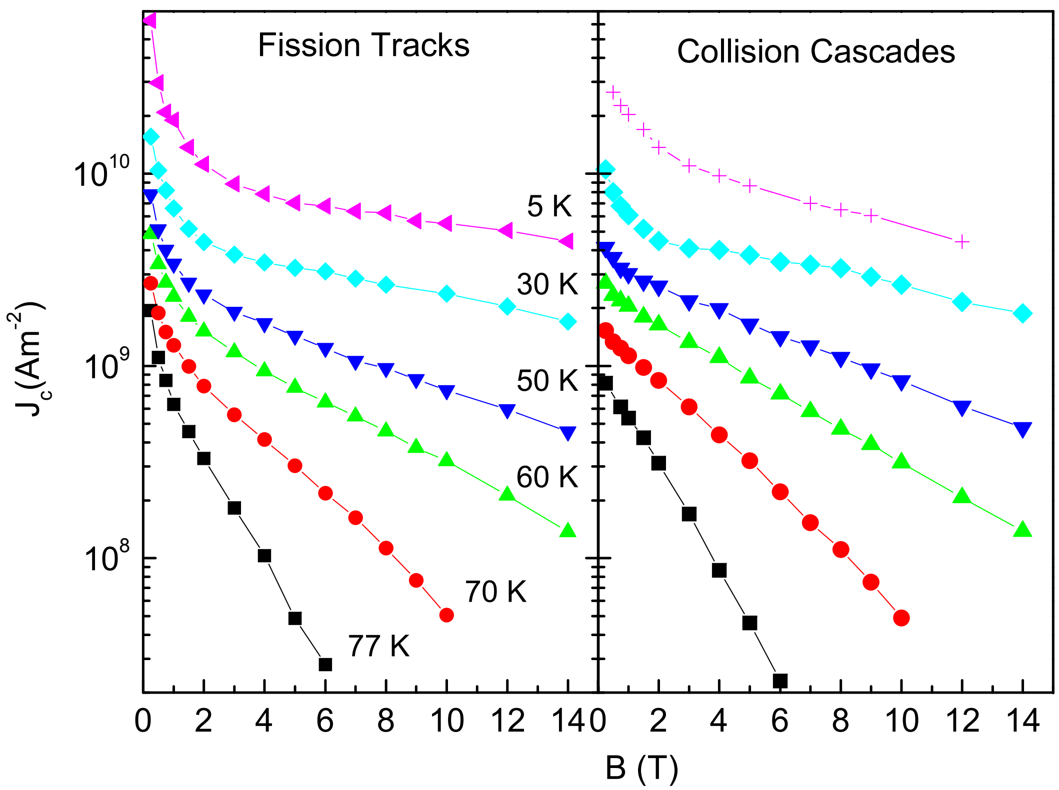


S. Tönies et al.: IEEE Trans. Appl. Supercond. 11, 3904 (2001)

Irreversibility Lines



Y-123: Similar behavior of fission tracks and collision cascades



M. Eisterer et al.: SUST 11, 1001 (1998)

SUMMARY: NEUTRON - INDUCED DEFECTS

- **"3D" HTS:**

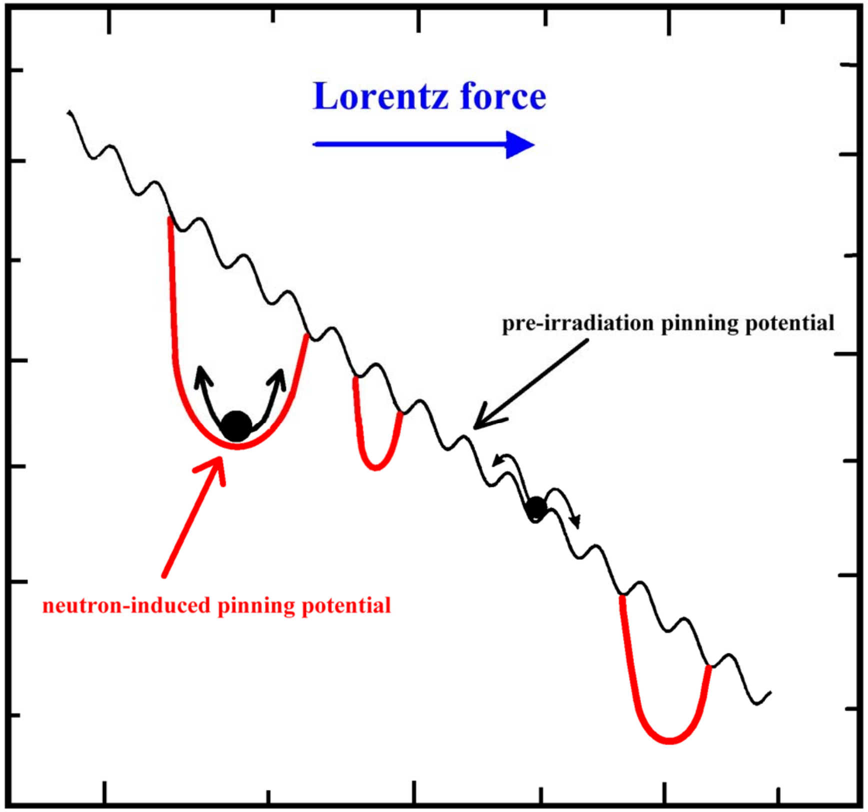
Strong pinning of flux lines for H || c

Reduced intrinsic pinning through disorder (H || a,b)

- **"2D" HTS:**

Pinning of a few individual pancakes

Reduced intrinsic pinning through disorder (H || a,b)



PRACTICAL MATERIALS

4 HTS compounds suitable for fusion applications

1) **MgB_2 (T_c ~ 39 K)**
   Low temperature (5 – 10 K) and intermediate field (< 10 T) application (PF)

2) **Bi-2212 (T_c ~ 87 K)**
   ITER like fields up to 25 K (intrinsic limit)

3) **Bi-2223 (T_c ~ 110 K) – 1G conductors → are now being replaced by RE-123 coated (2G) conductors**
   ITER like fields up to 30 K (intrinsic limit)

4) **RE-123 (T_c ~ 92 K)**
   ITER like fields up to 60 K, higher T operation possible

Magnetic field applications at T > 50 K only with RE-123 HTS compounds

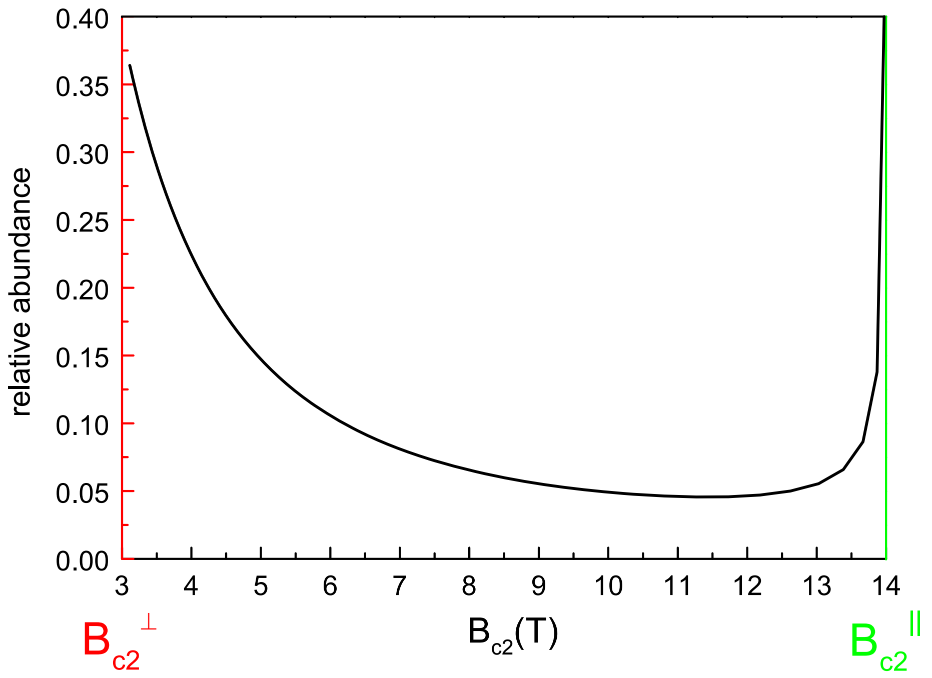
MgB_2 Wires

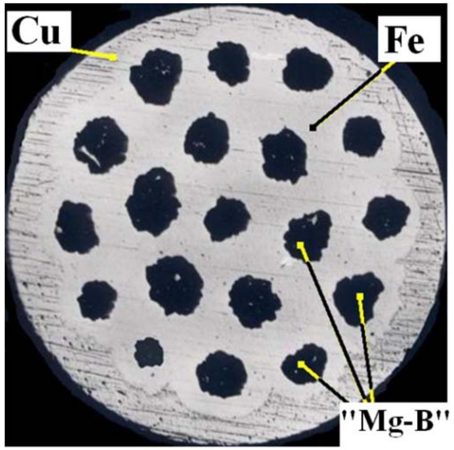
Pure MgB_2 is anisotropic: $\gamma = H_{c2}^{ab}/H_{c2}^{c} \sim 5$

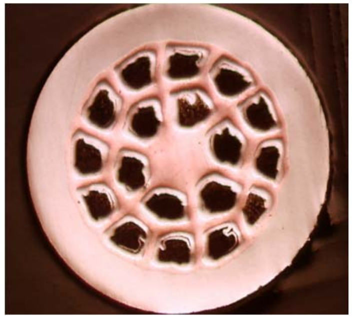
Grains are randomly oriented:

different upper critical fields in different grains!

Distribution function:







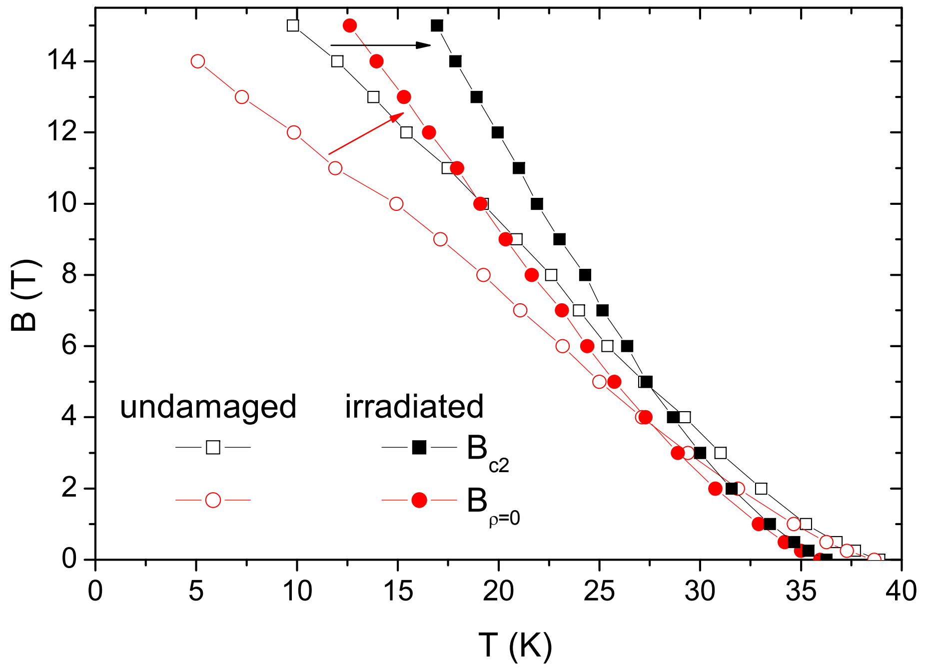
M. Eisterer et al.: JAP 98, 033960 (2003)

“Irreversibility line” can be shifted by an increase of B_{c2} and / or by a reduction of the anisotropy:

$$B_{\rho=0} = \frac{1}{\sqrt{(\gamma^2 - 1)p_c^2 + 1}} B_{c2}^{ab}$$

M. Eisterer et al.: JAP 98, 033960 (2003)

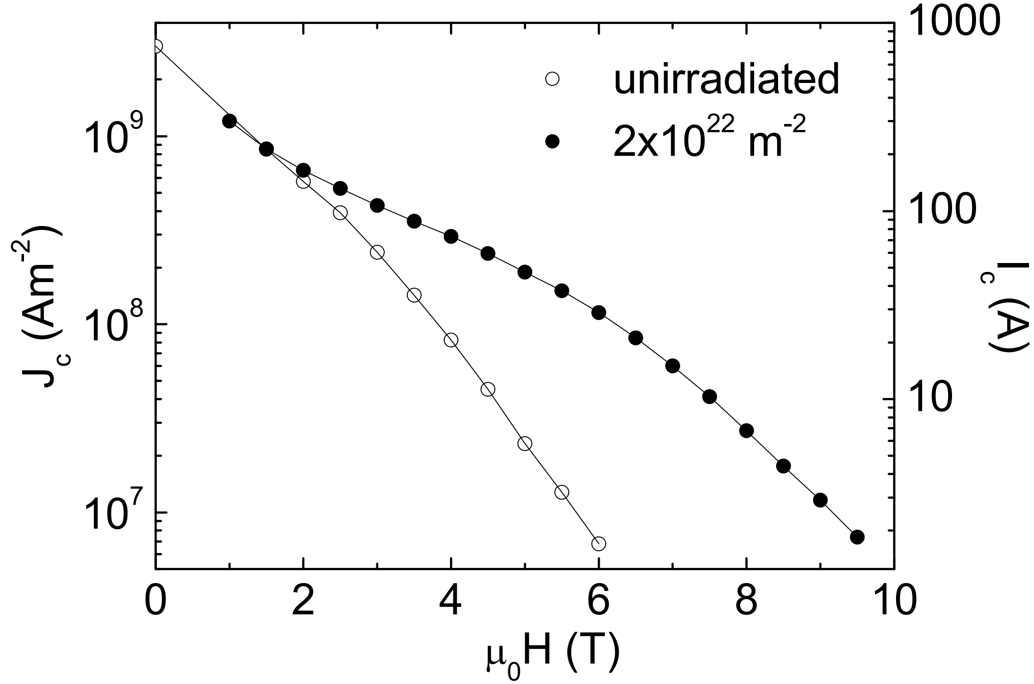
Neutron irradiation increases B_{c2} *and* decreases γ.



Neutron irradiation:

$B_{c2}\uparrow$ ⇨ $B_{\rho=0}\uparrow$ ⇨ $J_c(B)\uparrow$ at high magnetic fields

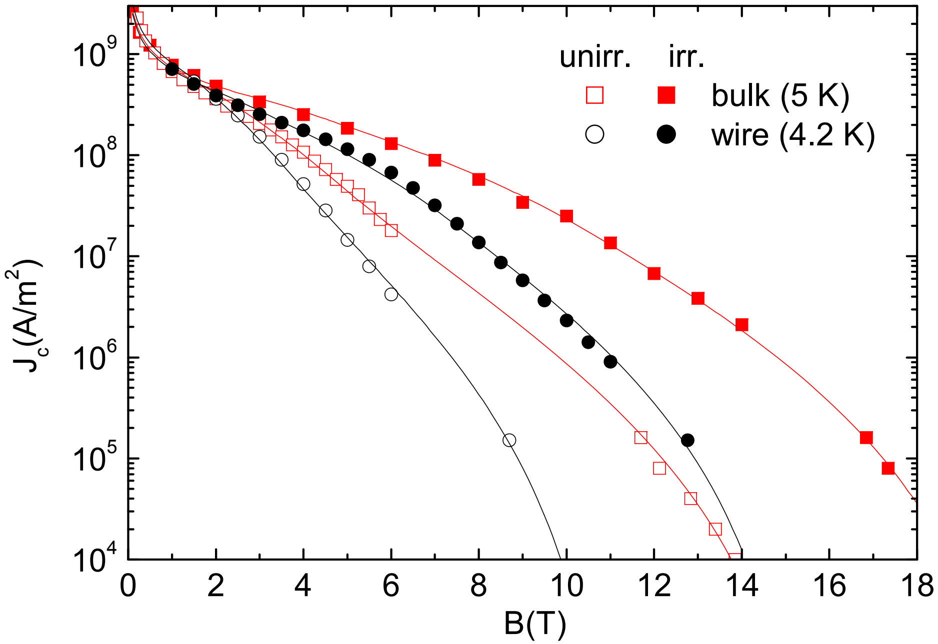
Cu-sheathed wire



Introduction of defect cascades is less important, grain boundary pinning is dominant !

M. Eisterer et al.: SUST 15, 1088 (2002)

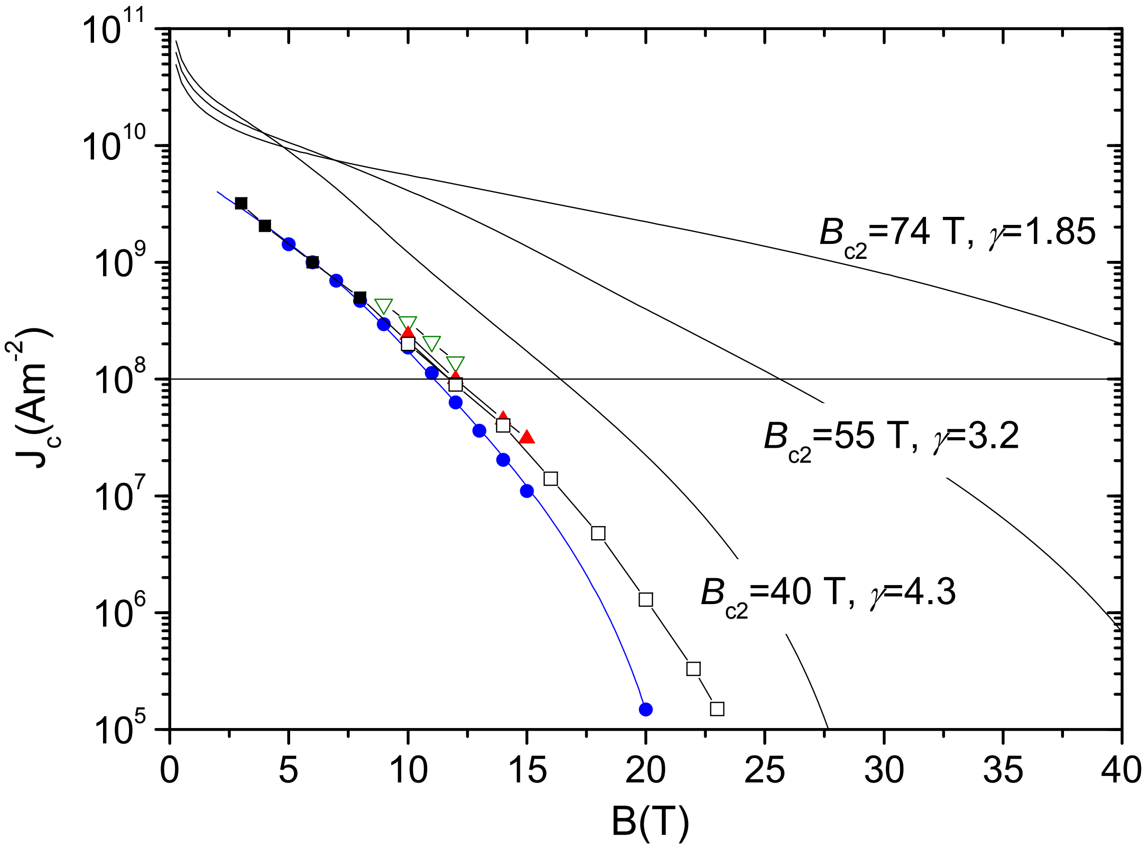
Critical currents can be fully explained by a percolation model (solid lines)



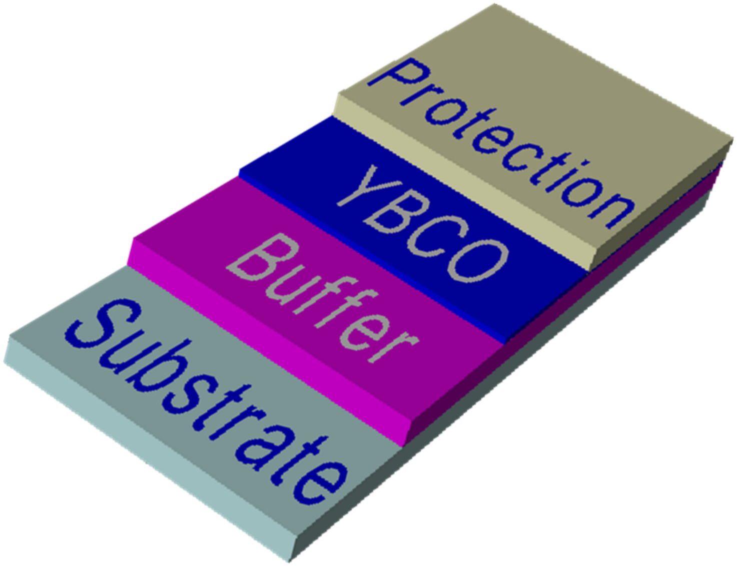
$$J_c(B) = \int \left(\frac{p(J) - p_c}{1 - p_c} \right)^{1.79} dJ$$

M. Eisterer et al.: Phys. Rev. Lett. 90, 247002 (2003)

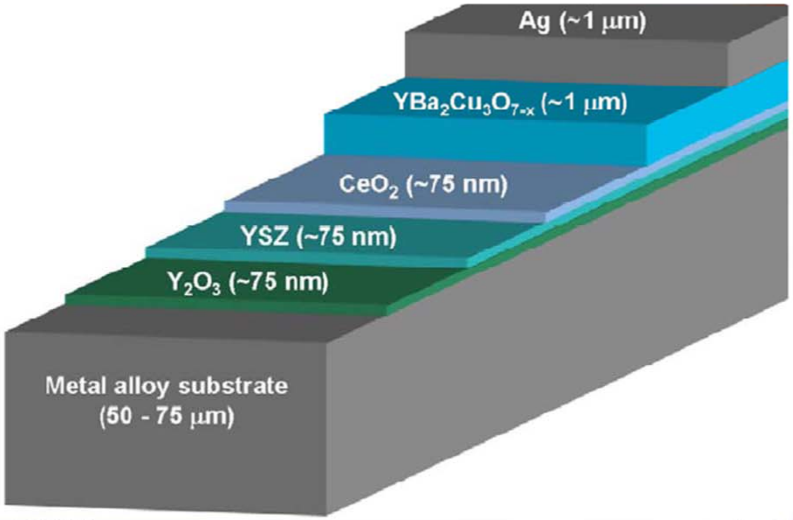
EXTRAPOLATED PERFORMANCE at 4.2 K

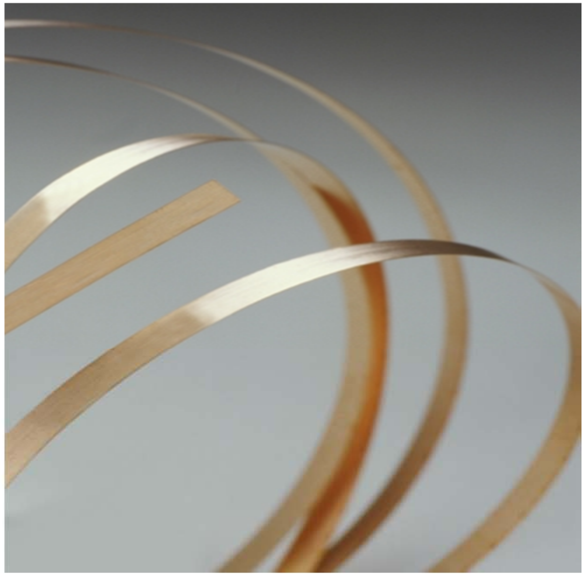


Coated conductors

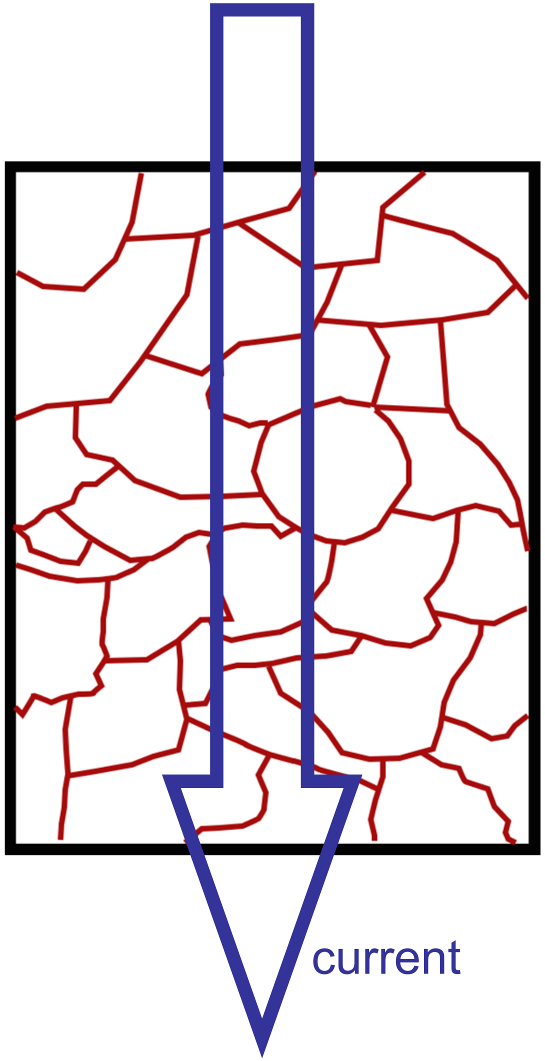


Focus on commercial tapes





Microstructure

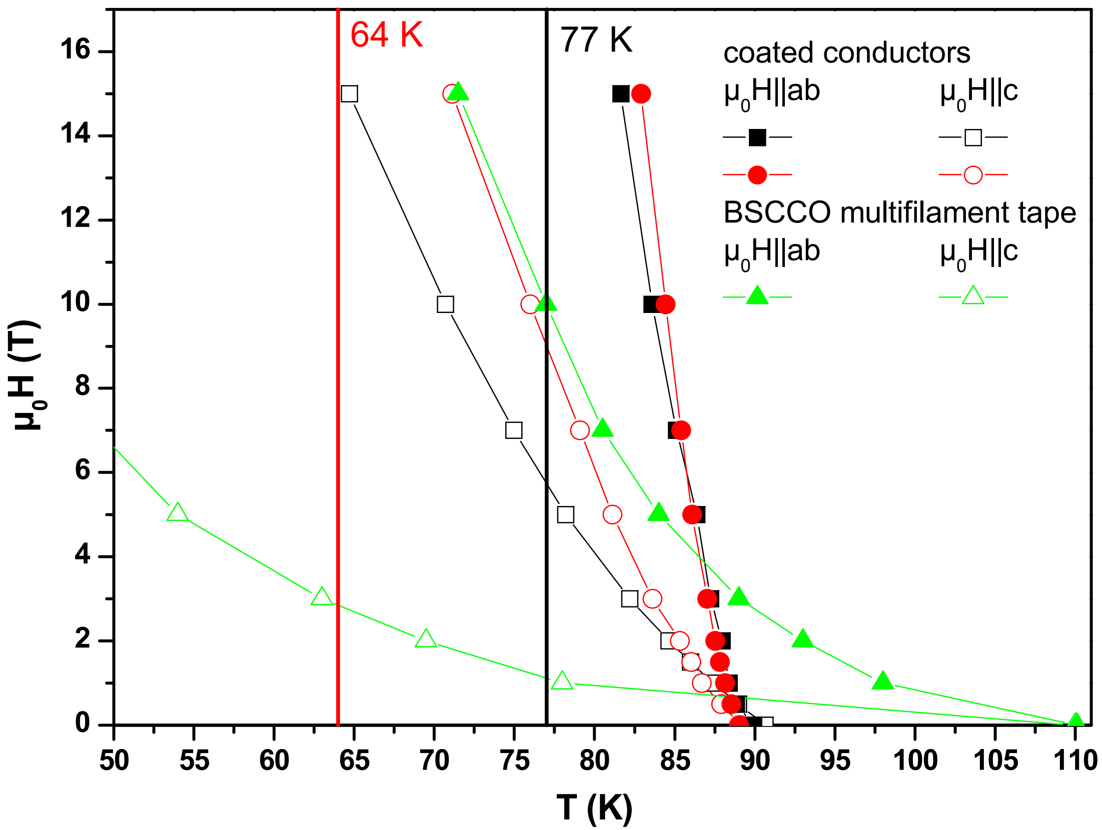


Key elements:

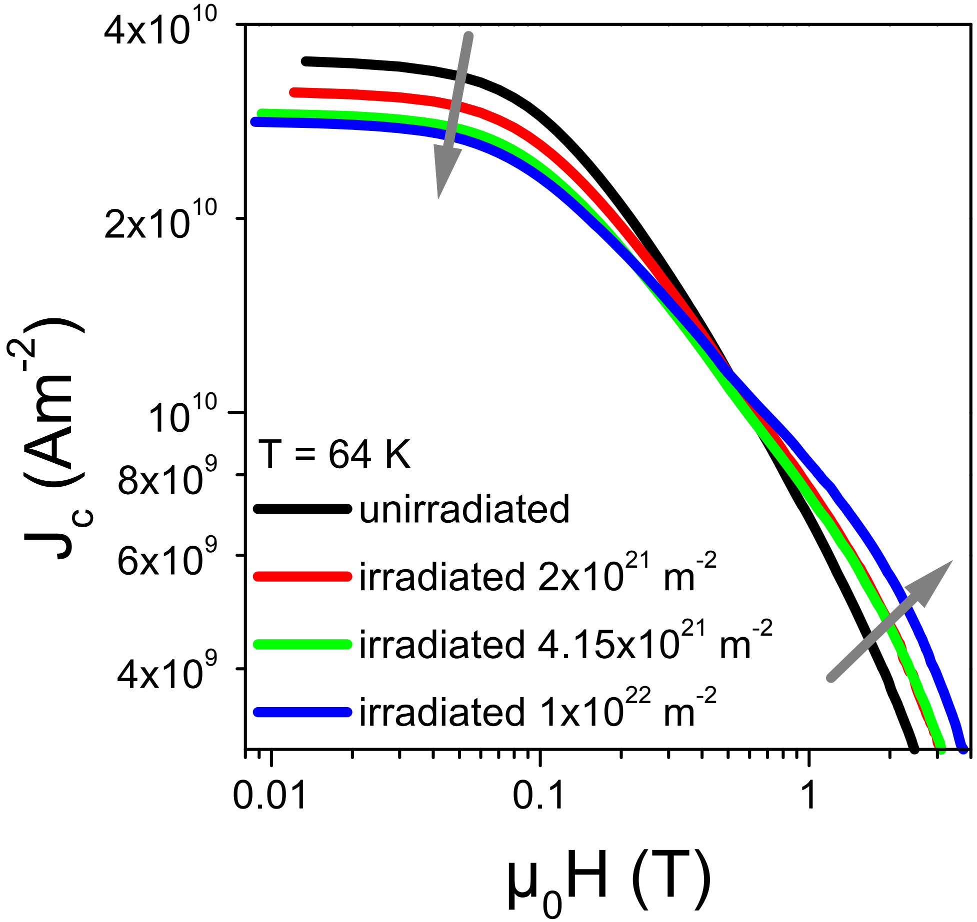
- J_c^{GB} (grain boundaries – inter-grain currents)
  - relevant at small fields
  - grain boundary angle
  - doping
- J_c^{G} (grains – intra-grain currents)
  - relevant at high fields
  - pinning centres
- J_c vs. field orientation
- Homogeneity along (long) lengths

Irreversibility Lines

77 K	H||c
AMSC	5.6 T
Bruker	7.7 T
Sumitomo	1.15 T

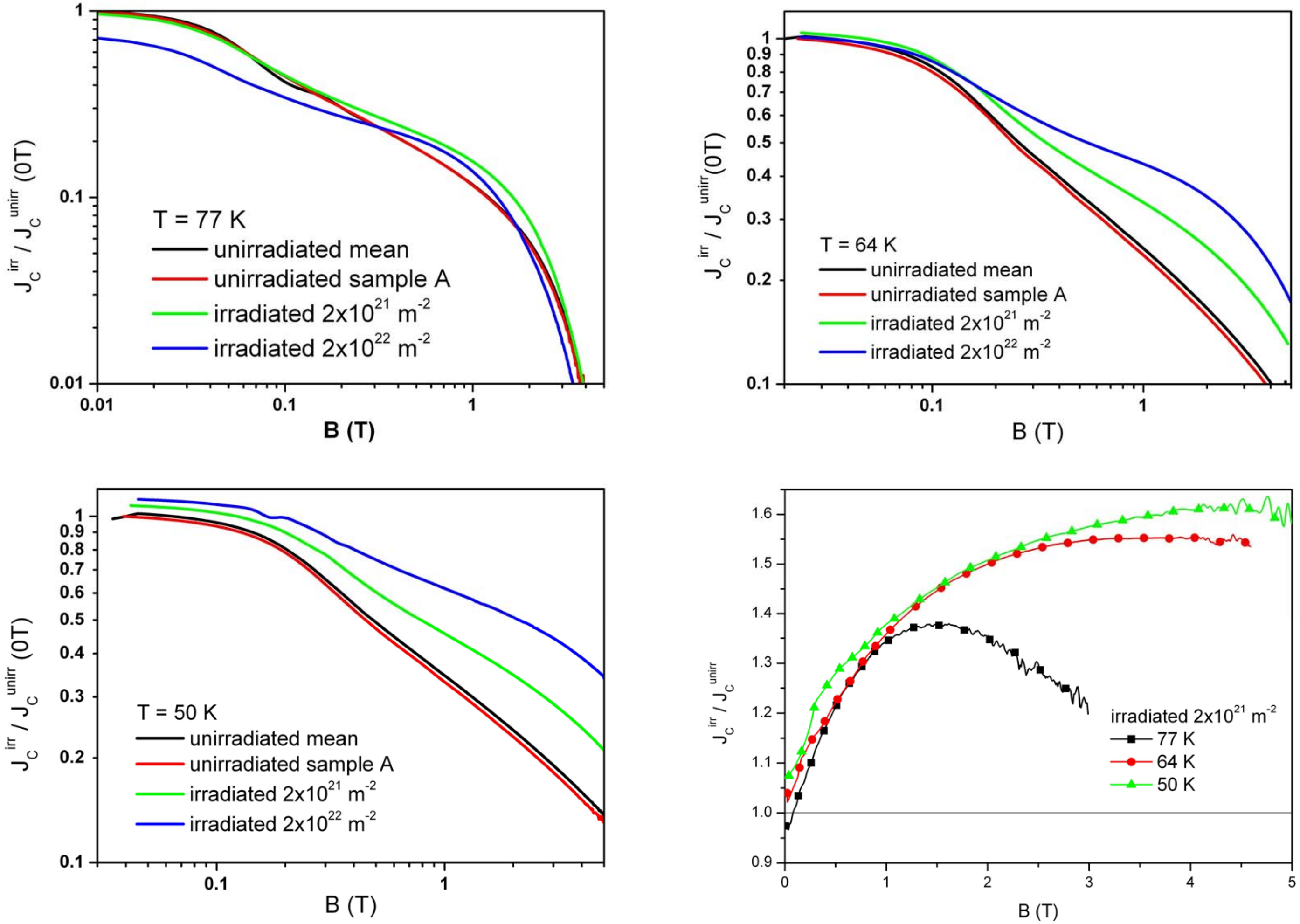


Neutron irradiation



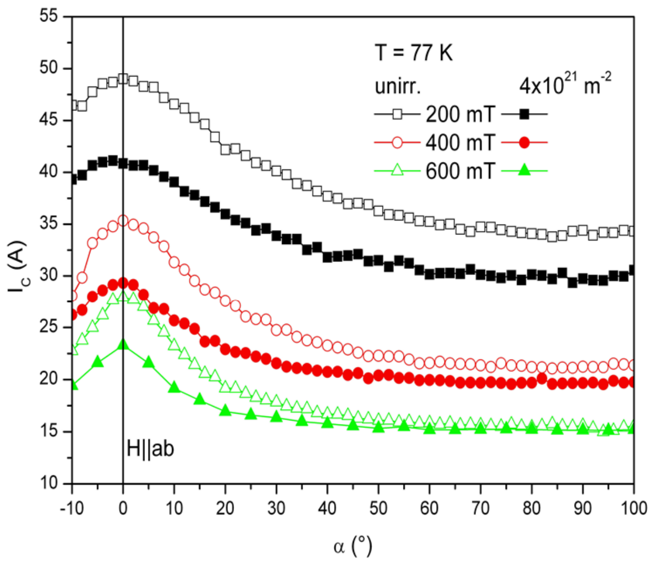
- J_c^{intra}: improved
- J_c^{inter}: degraded

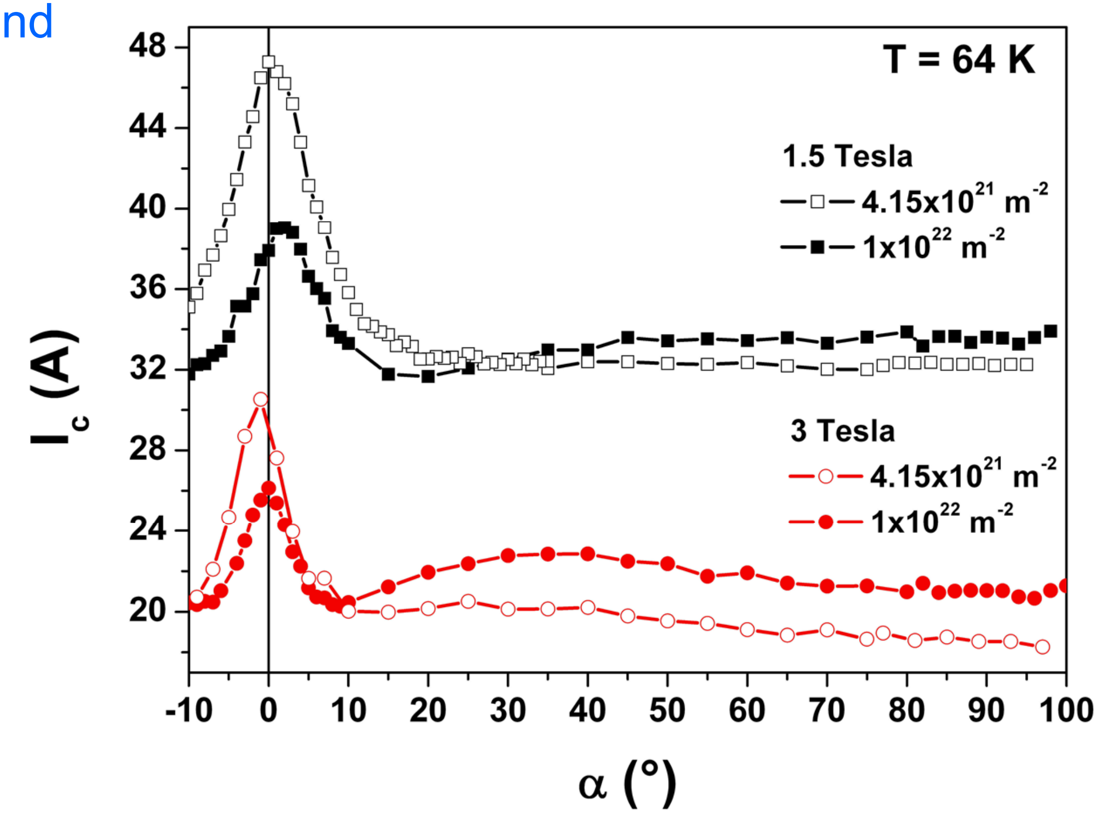
Neutron irradiation effects on J_c for H parallel c: Bruker HTS



Neutron irradiation effects on J_c anisotropy: AMSC

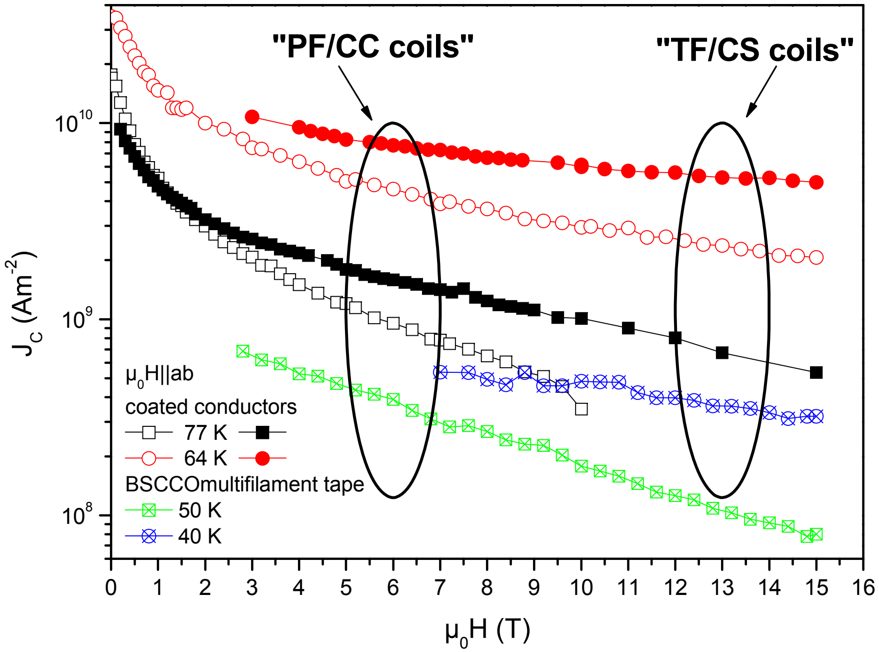
- Reduced critical currents for fields parallel a,b
- Improved critical currents for fields parallel c
- At higher neutron fluence: second peak



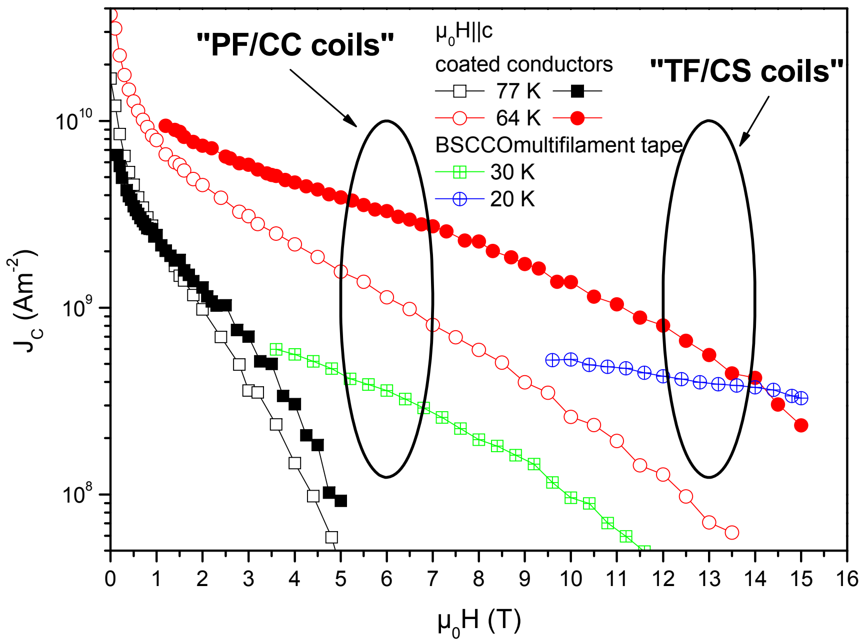


Summary: Critical Current Densities (J_C)

H||a,b

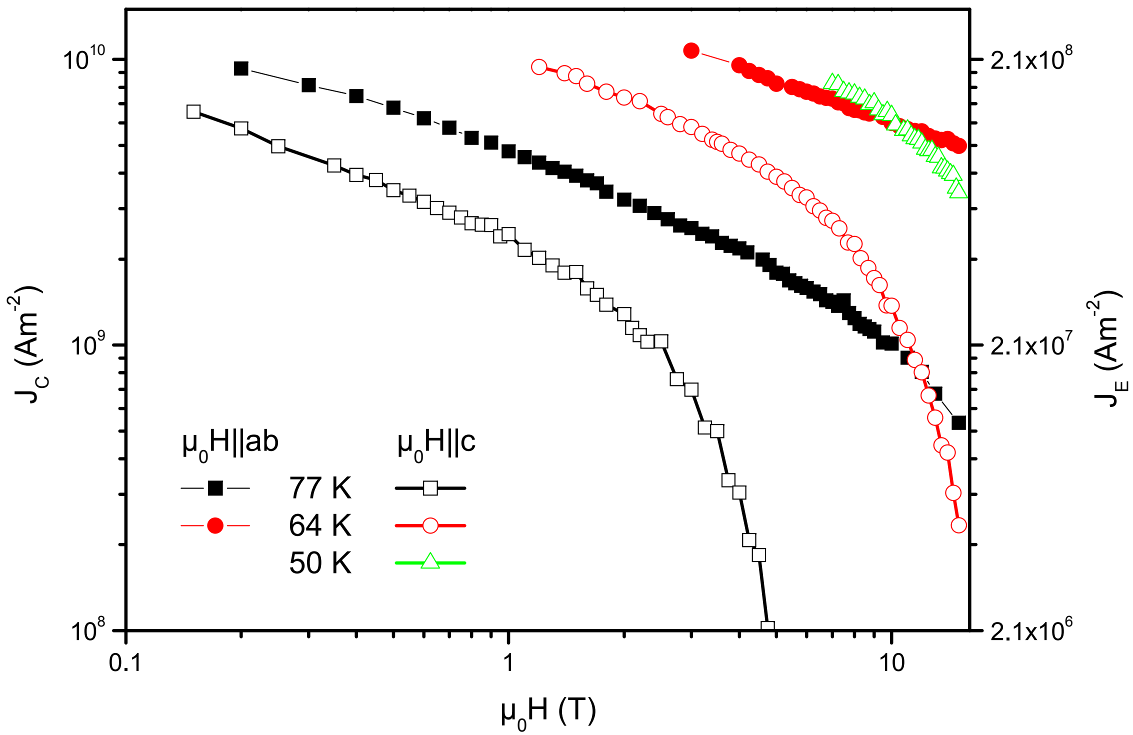


H||c



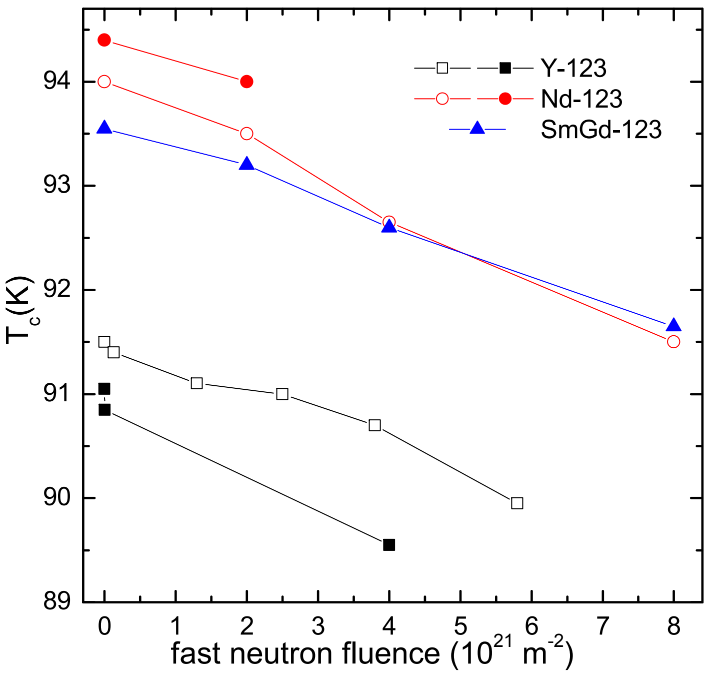
- The ellipses represent possible design requirements for fusion magnets (ITER specification). A field of around 6 T is specified for the ITER PF coils and of around 13 T for the CS/TF coils.
- The range of current densities between 10^8 Am^{-2} and 10^{10} Am^{-2} is highlighted.

The engineering critical current densities J_E need to be improved!

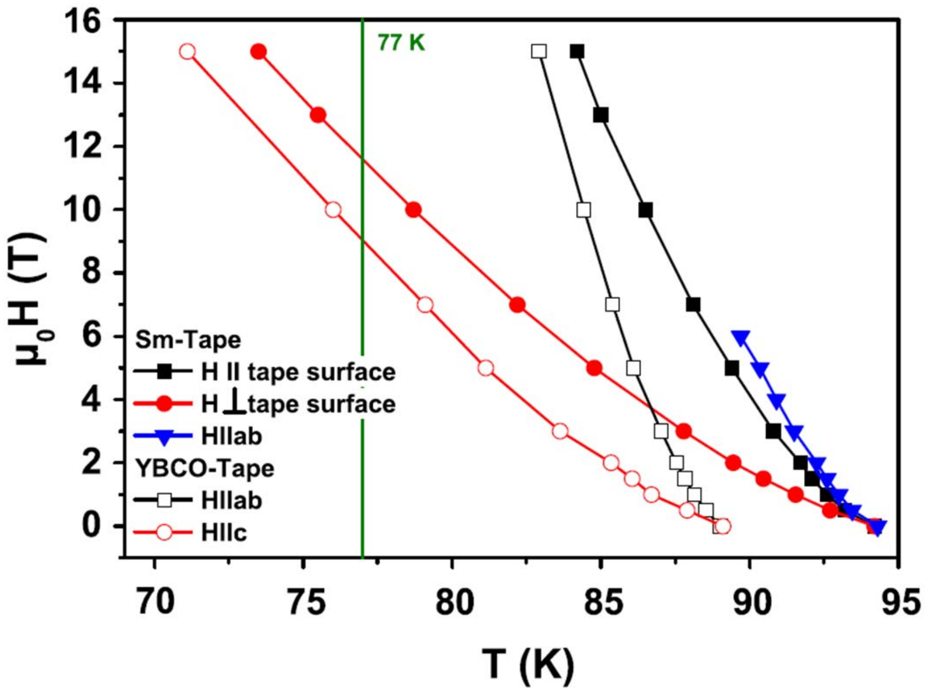


… but alternative materials exist … RE-123 (RE = Nd, Sm, Gd)

Higher T_c → Higher irreversibility fields at 77 K

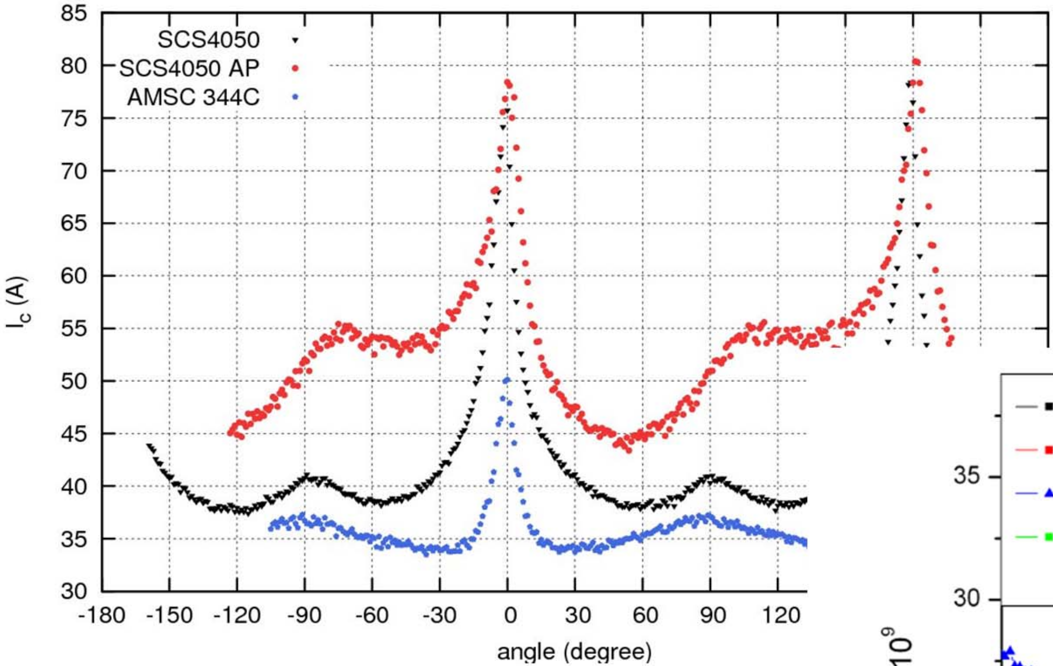


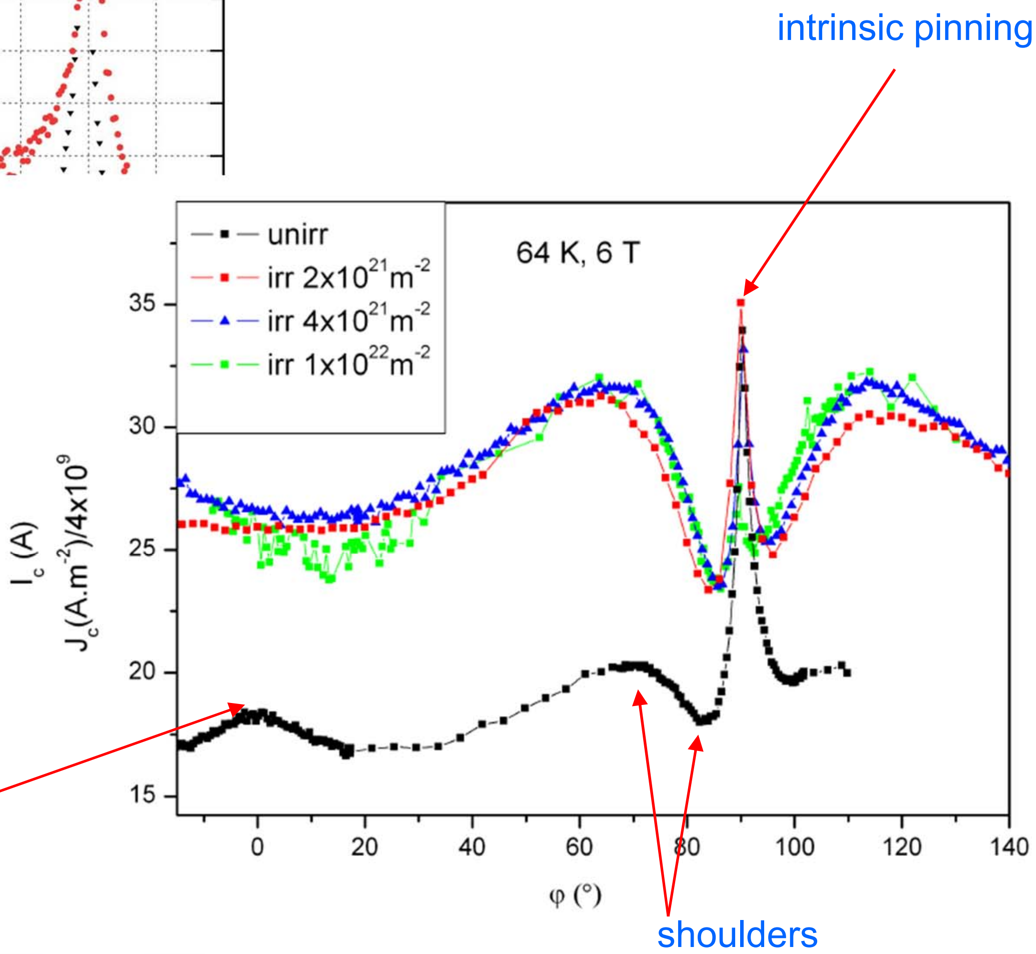
M. Eisterer et al.: Adv. Cryog. Eng. 46, 655 (2000)



R. Fuger et al.: Physica C 470, 323 (2010)

… and new commercial cc's, partly with artificial pinning centers



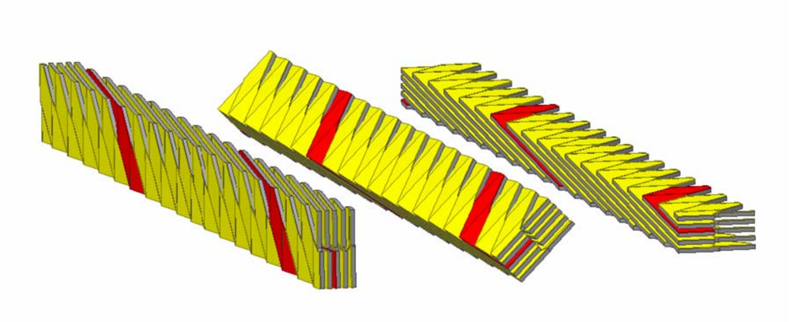


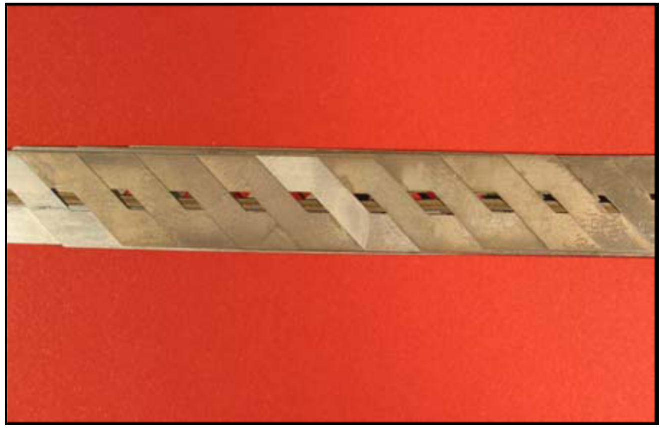
… but we need

cables with highly demanding performance at high fields and temperatures

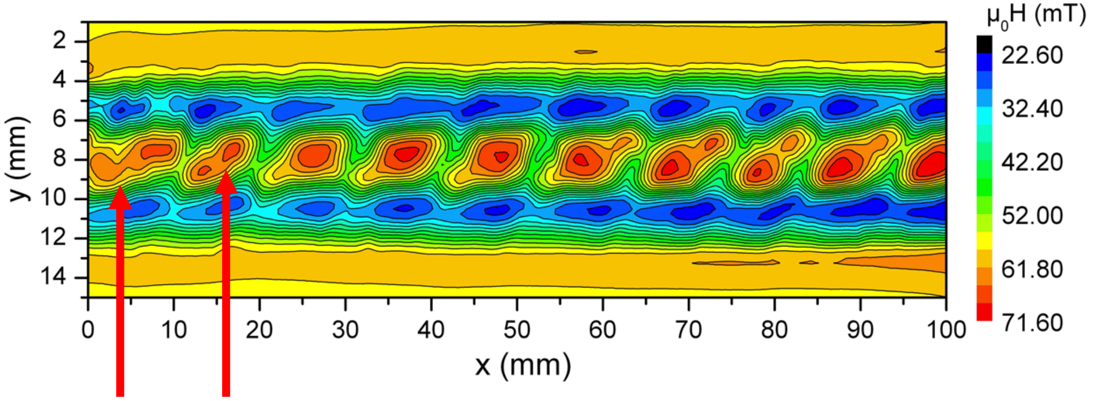
- ⌧ high amperage (some 10 kA)
- ⌧ long lengths
- ⌧ high homogeneity
- ⌧ low J_c anisotropy
- ⌧ low ac losses
- ⌧ high stress tolerance

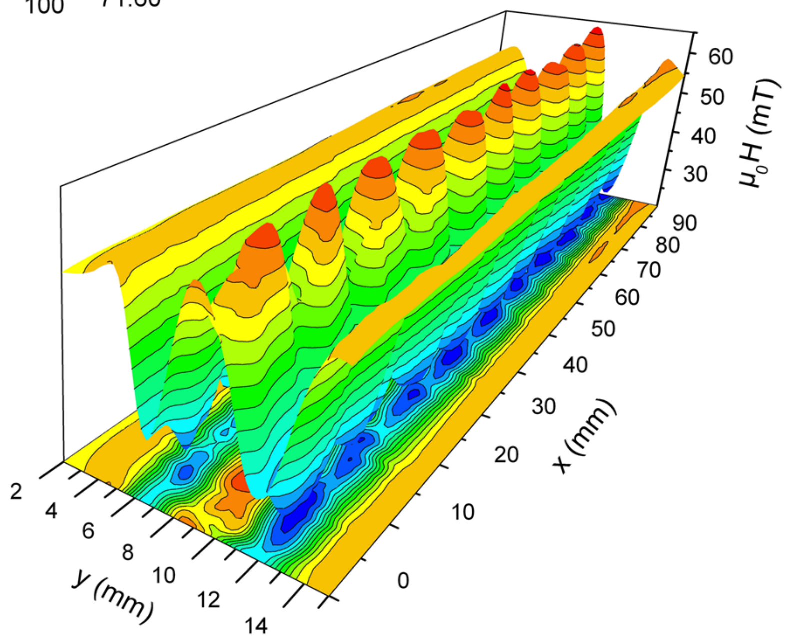
e.g. Roebel cables or striated conductors





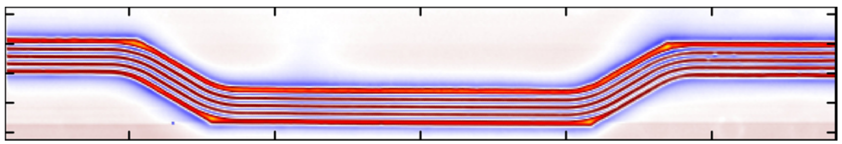
Homogeneity of cables or striated tapes (magnetoscan analysis)

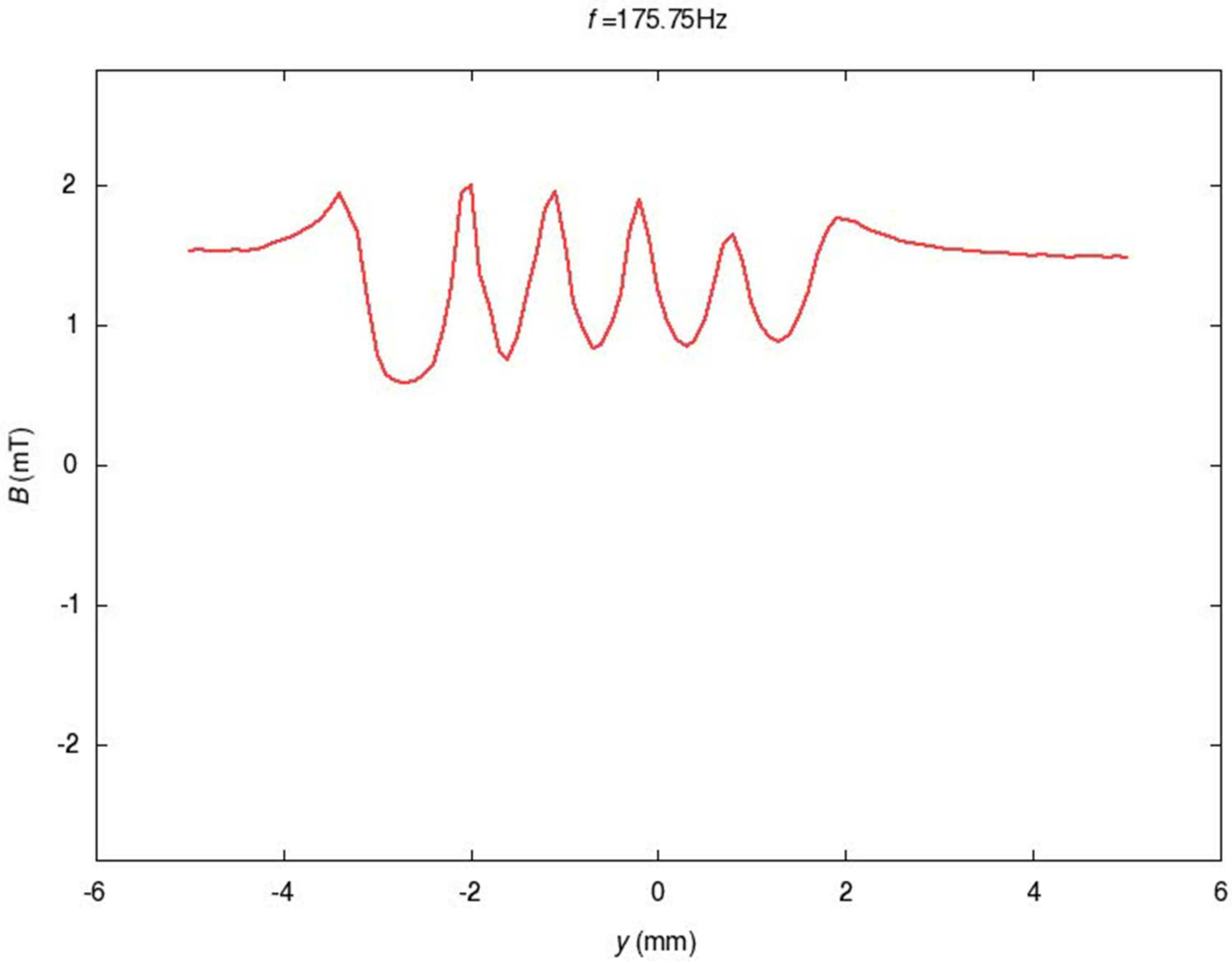




- Homogeneity of the cable
- Identify damage of single strands

Striated tape




f =175.75Hz
B (mT)
y (mm)
2
1
0
-1
-2
-6
-4
-2
0
2
4
6

CONCLUSIONS

- Cc's are *close to* the field requirements of ITER / DEMO magnets at elevated temperatures
- Neutron irradiation is beneficial as long as T_c is not too much depressed (✓)
- Neutron irradiation reduces the J_c anisotropy (may not be so important – AP's!)

but

- Cable development is needed
- Y-substitution may be advisable
- Neutron irradiation to higher fluences is required
- Homogeneity issues must be carefully addressed

and

- all the other issues discussed at this conference must be solved!!

CO-WORKERS and COLLABORATIONS

CO-WORKERS at ATI

Michael Eisterer
René Fuger
Florian Hengstberger
Martin Zehetmayer
Johann Emhofer
Michal Chudy

COLLABORATIONS

SuperPower / University of Houston: V. Selvamanickam
American Superconductor: A. Malozemoff
Bruker HTS: A. Usoskin
Industrial Research: N. Long
Hypertech: M. Sumption
Sumitomo Electric Industries: K. Sato
FZ Karlsruhe: W. Goldacker