RADIATION EFFECTS ON FUSION MAGNET COMPONENTS – 1: SUPERCONDUCTORS

Harald W. Weber, Thomas Baumgartner, Michael Eisterer
Vienna University of Technology
Atominstitut, Vienna, Austria

Introduction: The ITER-Magnets, Neutron Spectra
Low Temperature Superconductors
Stabilizer
HTS
Conclusions

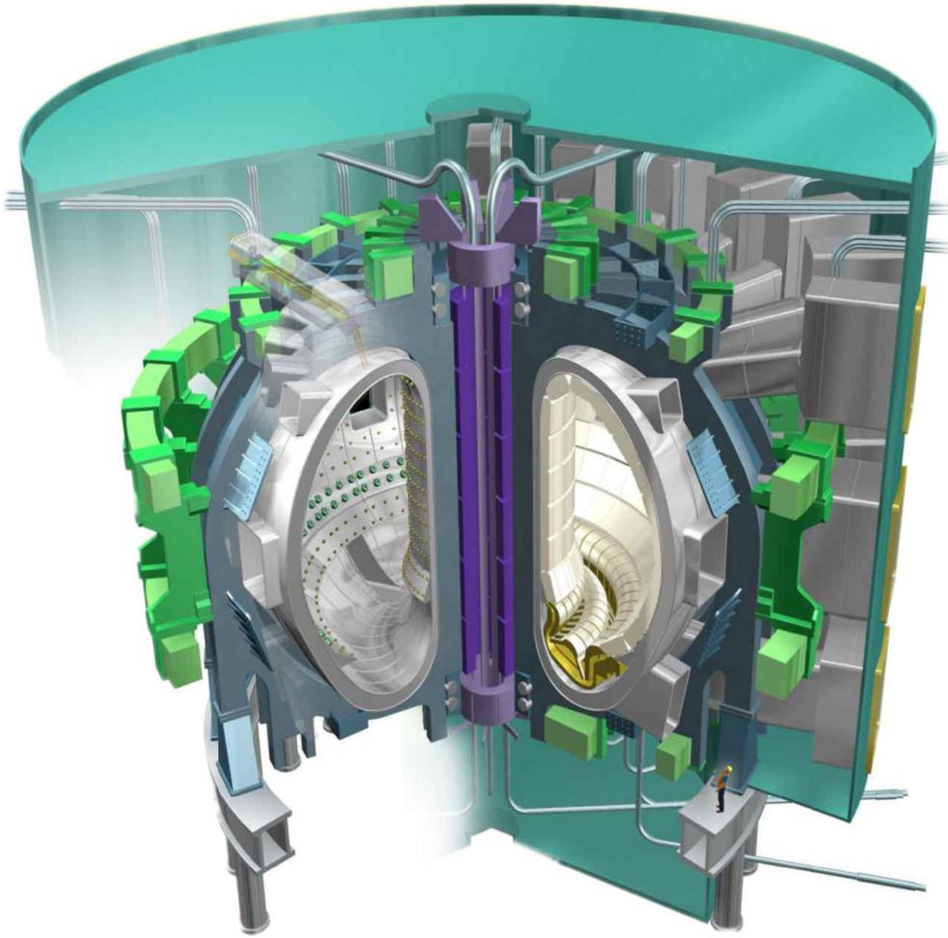
WAMSDO Workshop, Geneva
14 November 2011

INTRODUCTION

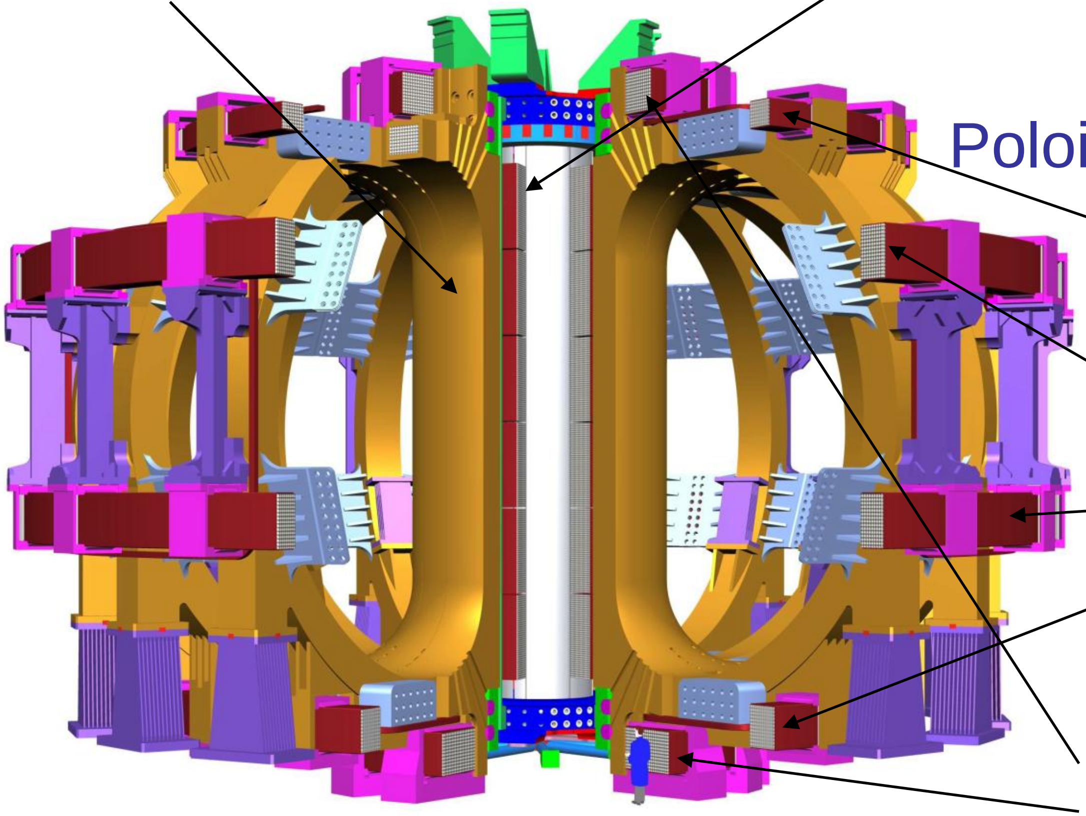
Overview: ITER

Main Parameters of ITER

Total fusion power	500 MW
Q	≥ 10
Average 14MeV neutron wall loading	≥ 0.5 MW/m^2
Plasma inductive burn time	**300-500 s**
Plasma major radius (R)	6.2 m
Plasma minor radius (a)	2.0 m
Plasma current (I_p)	15 MA
Toroidal field at 6.2 m radius (B_T)	5.3 T



ITER Magnet System (5 K / 6.5 K)



Nb_3Sn and NbTi

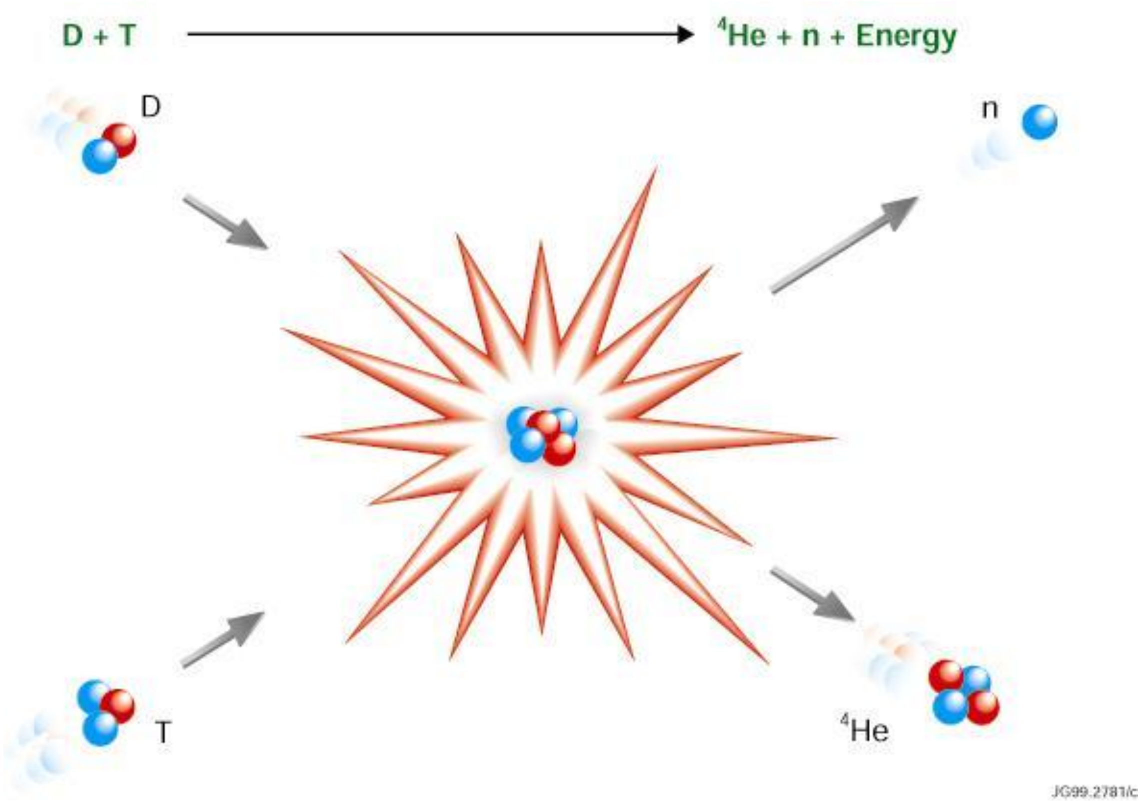
- The ITER project sets new limits for conductor and coil dimensions:

  Currents of up to 68 kA

  Coils of up to 13 m (Nb_3Sn) and 24 m (NbTi) in diameter

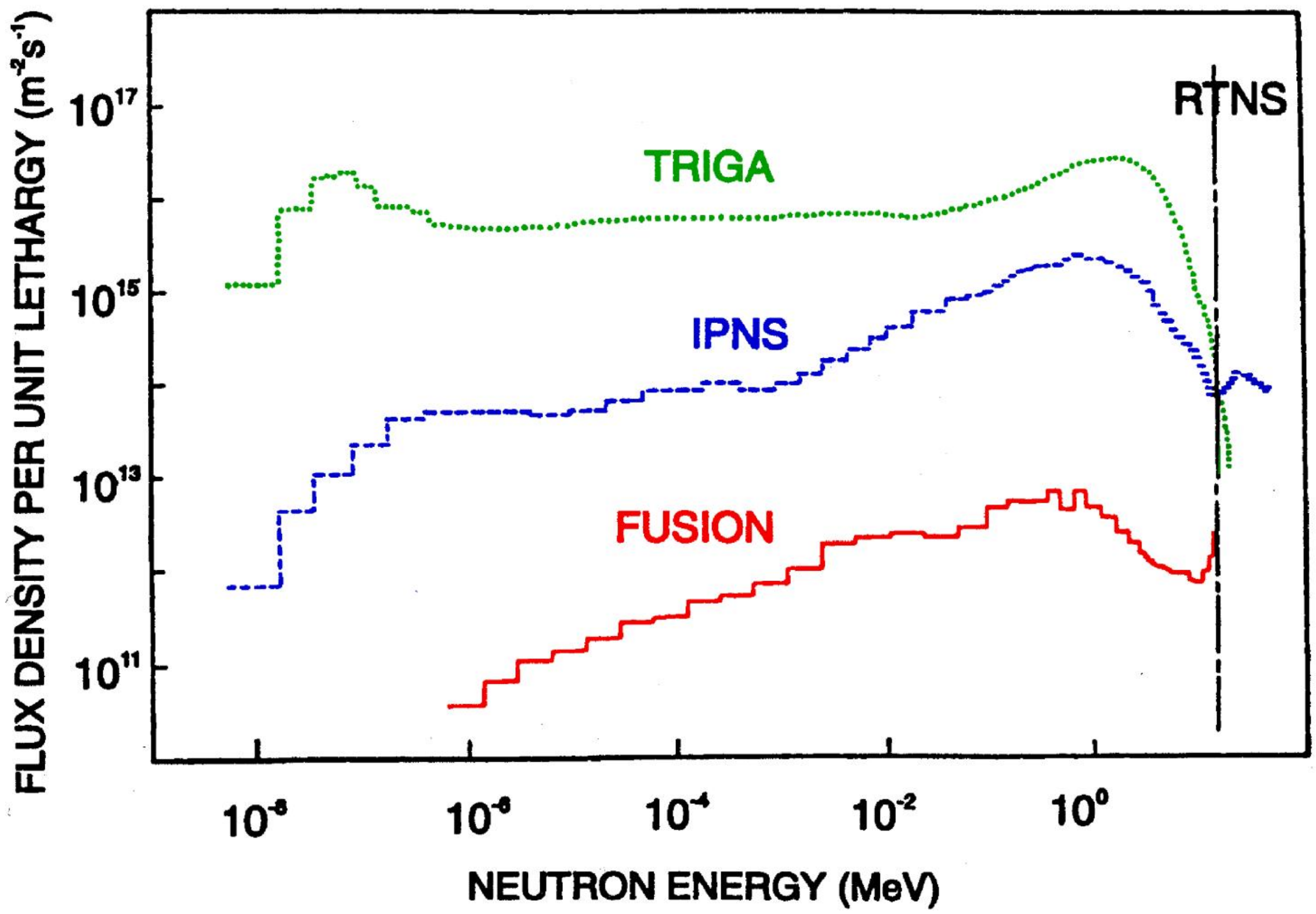
- More than 530 t of Nb_3Sn strands are required for the TF and CS coils
- About 300 t of NbTi strands are required for the PF and CC coils
- HTS current leads are fabricated using Bi-2223 tapes up to 68 kA

The ITER magnet system is a challenge for industry, worldwide …



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

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



FLUX DENSITY PER UNIT LETHARGY (m-2s-1)
10^17
10^15
10^13
10^11
RTNS
TRIGA
IPNS
FUSION
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)

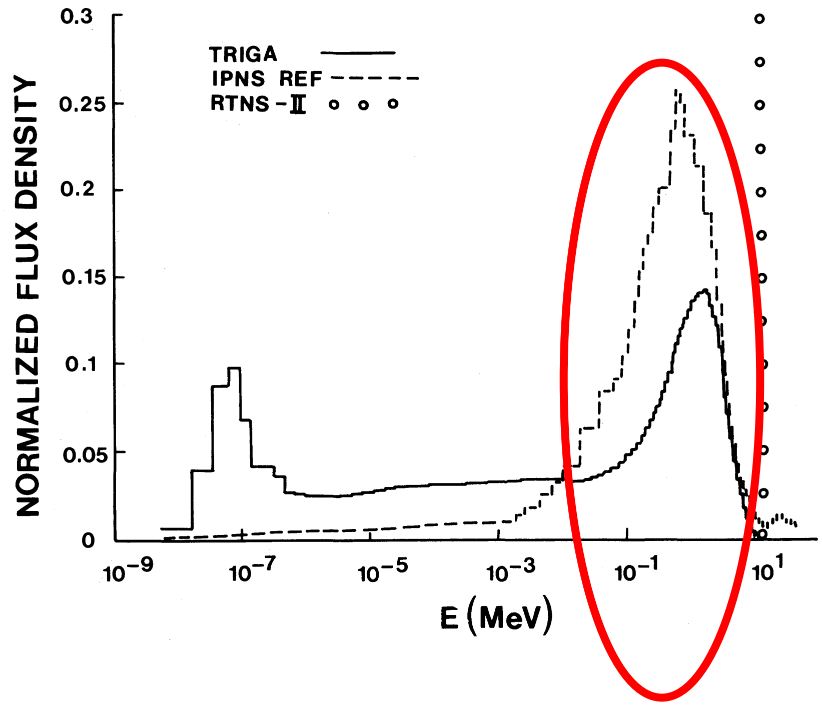
⇨

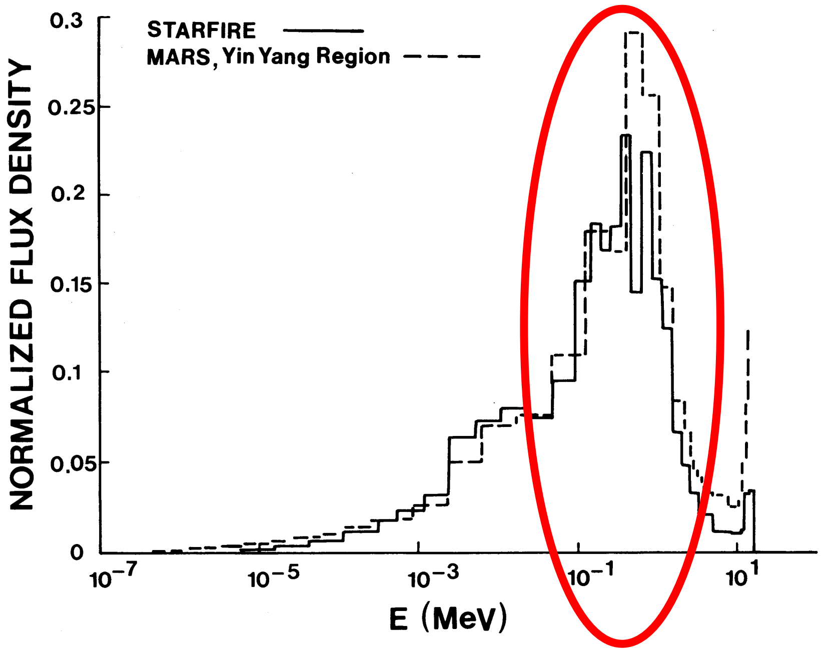
$< \sigma(E) . T(E) >$	displacement energy cross section
$E_D = < \sigma(E) . T(E) > . F(E) . t$	damage energy (total energy transferred to each atom in the material)

SUCCESSFUL SCALING OF T_c AND J_c IN METALLIC SUPERCONDUCTORS

⇨

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





Normalized group flux densities:

excellent agreement with power plant design studies

SUPERCONDUCTORS

Radiation will affect

⌧ TRANSITION TEMPERATURE T_c

- through disorder: ☞ unlikely in alloys

☞ effective in metals and ordered compounds

⌧ NORMAL STATE RESISTIVITY ρ_n

- through the introduction of additional scattering centers

☞ very small in alloys

☞ significant in metals and ordered compounds

⌧ UPPER CRITICAL FIELD H_{c2}

- through the same mechanism: $\rho_n \propto 1/\ell \propto \kappa \propto H_{c2}$

⌧ CRITICAL CURRENT DENSITY J_c

- through the production of pinning centers

DAMAGE PRODUCTION in LT 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

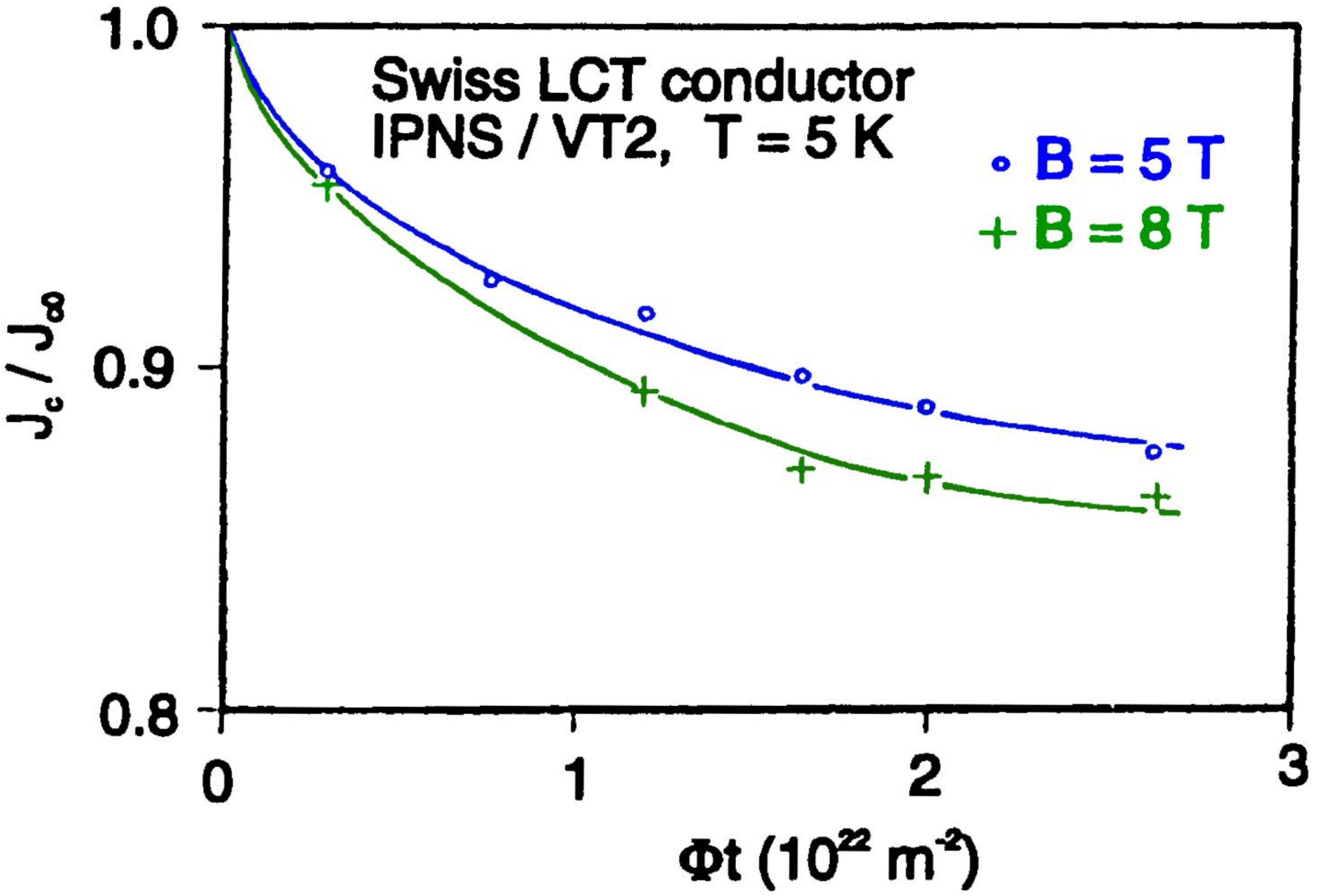
NB: Stable collision cascades in materials with low conductivity, e.g. HTS

RESULTS

The “Workhorse”: NbTi

A15 Superconductors:

- Nb_3Sn
- Alloyed A15’s: $(Nb,Ti/Ta)_3Sn$
- Advanced A15’s: Nb_3Al
- Recently developed A15’s



Swiss LCT conductor
IPNS / VT2, T = 5 K
∘ B = 5 T
+ B = 8 T
1.0
0.9
0.8
0
1
2
3
J_c / J_{c0}
Φt (10^{22} m^{-2})

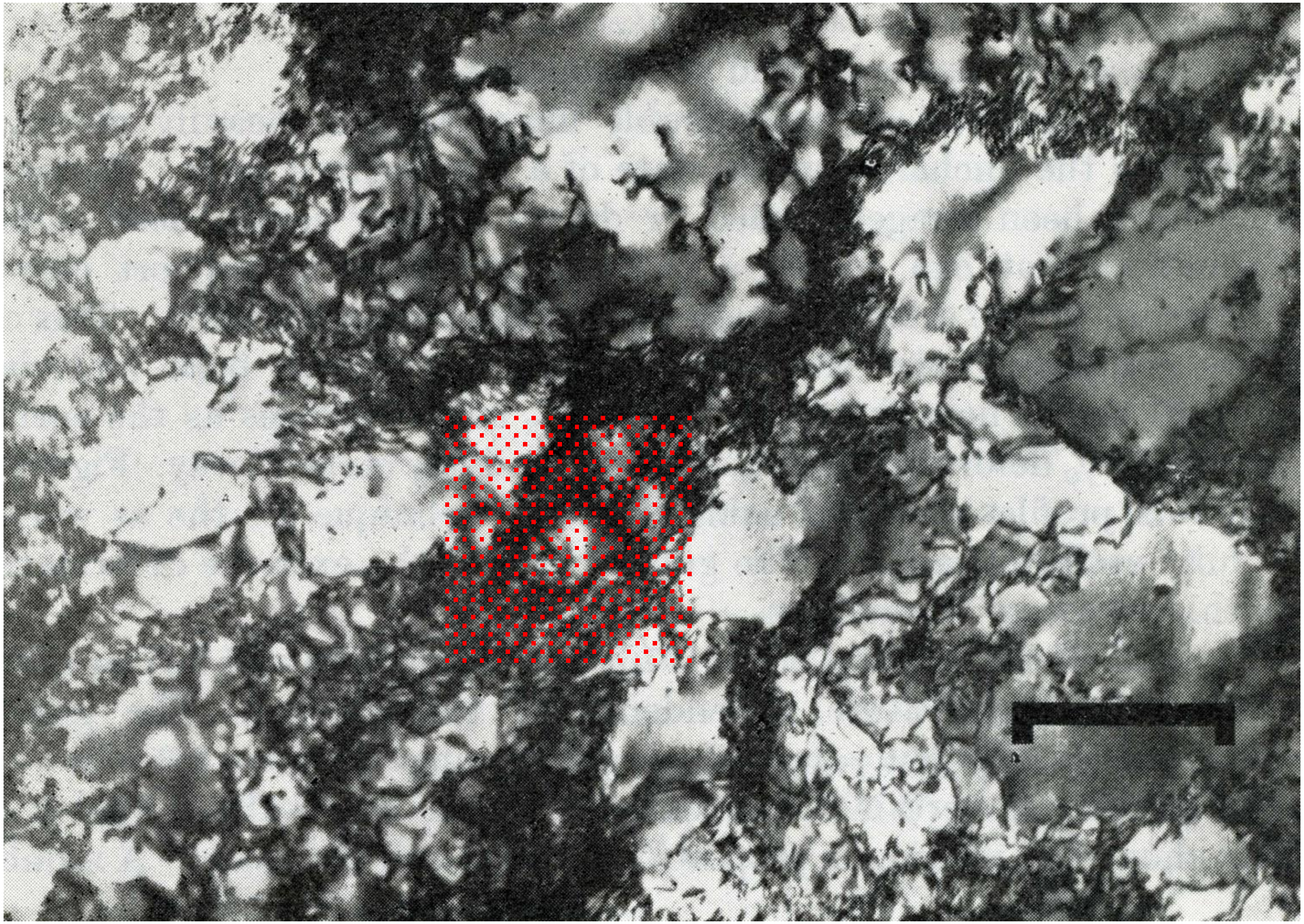
Results on NbTi

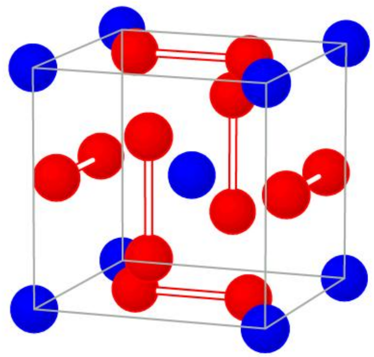
SMALL EFFECTS on J_c - depending on the initial micro-structure for flux pinning

SMALL DECREASE of H_{c2} - caused by a

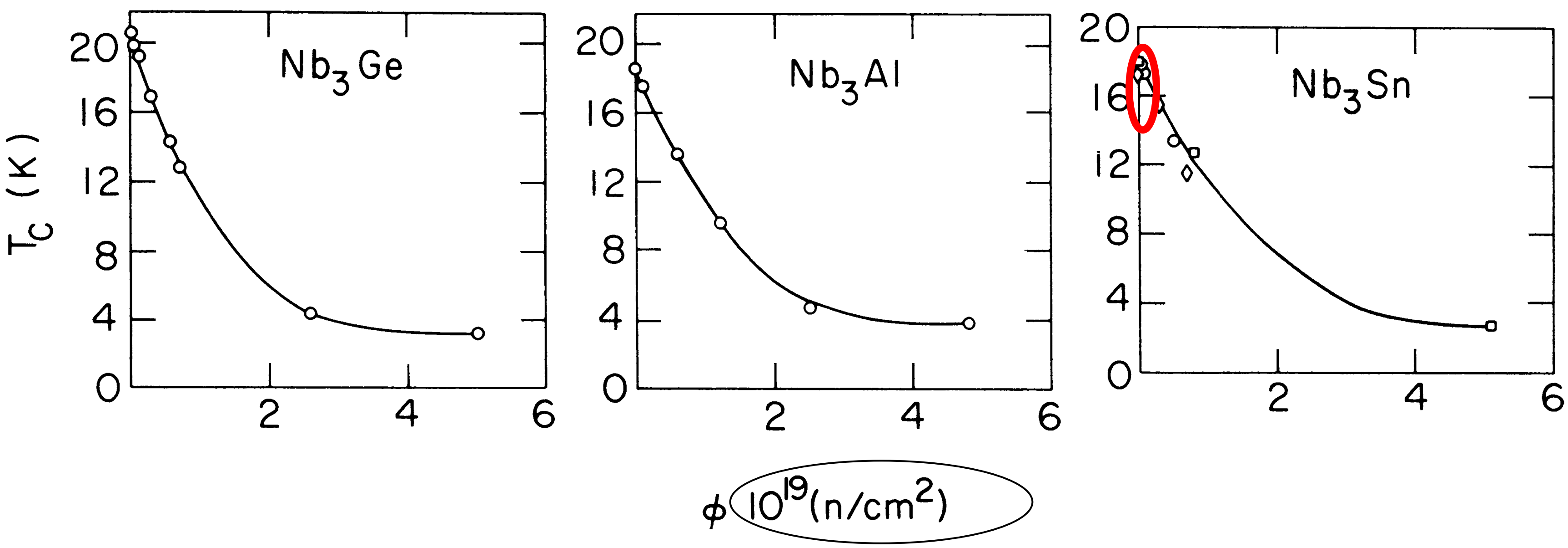
SMALL DECREASE of T_c

- Results typical for materials with a ***high degree of disorder***
- Initial optimized defect structure for flux pinning is ***"disturbed"***



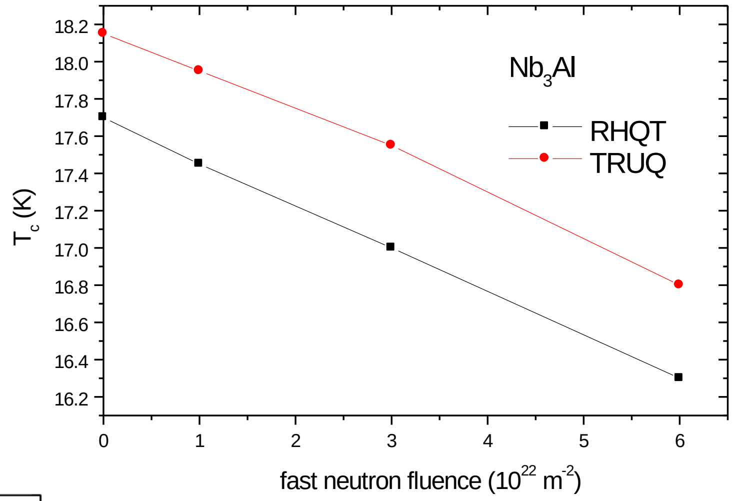


A15 SUPERCONDUCTORS

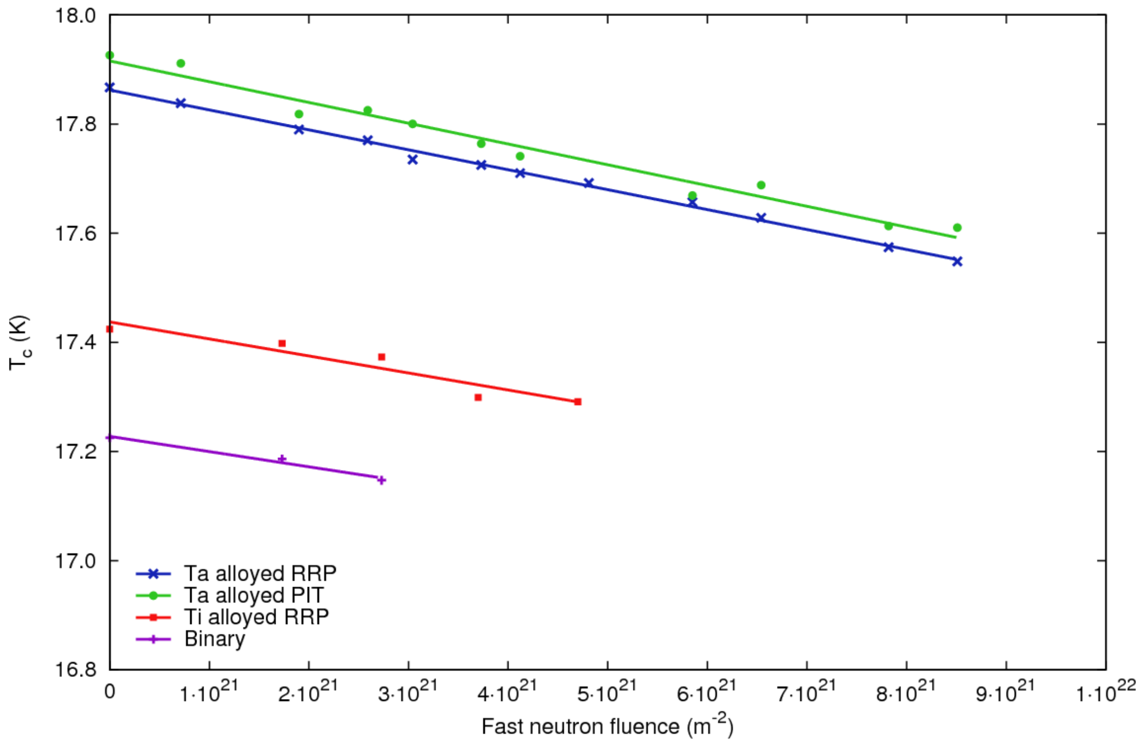


!! Scale not accurate: maximum fluence around 7-10 x 10^{23} m^{-2} (E>0.1 MeV) !!

Transition temperatures vs. neutron fluence



Nb_3Sn

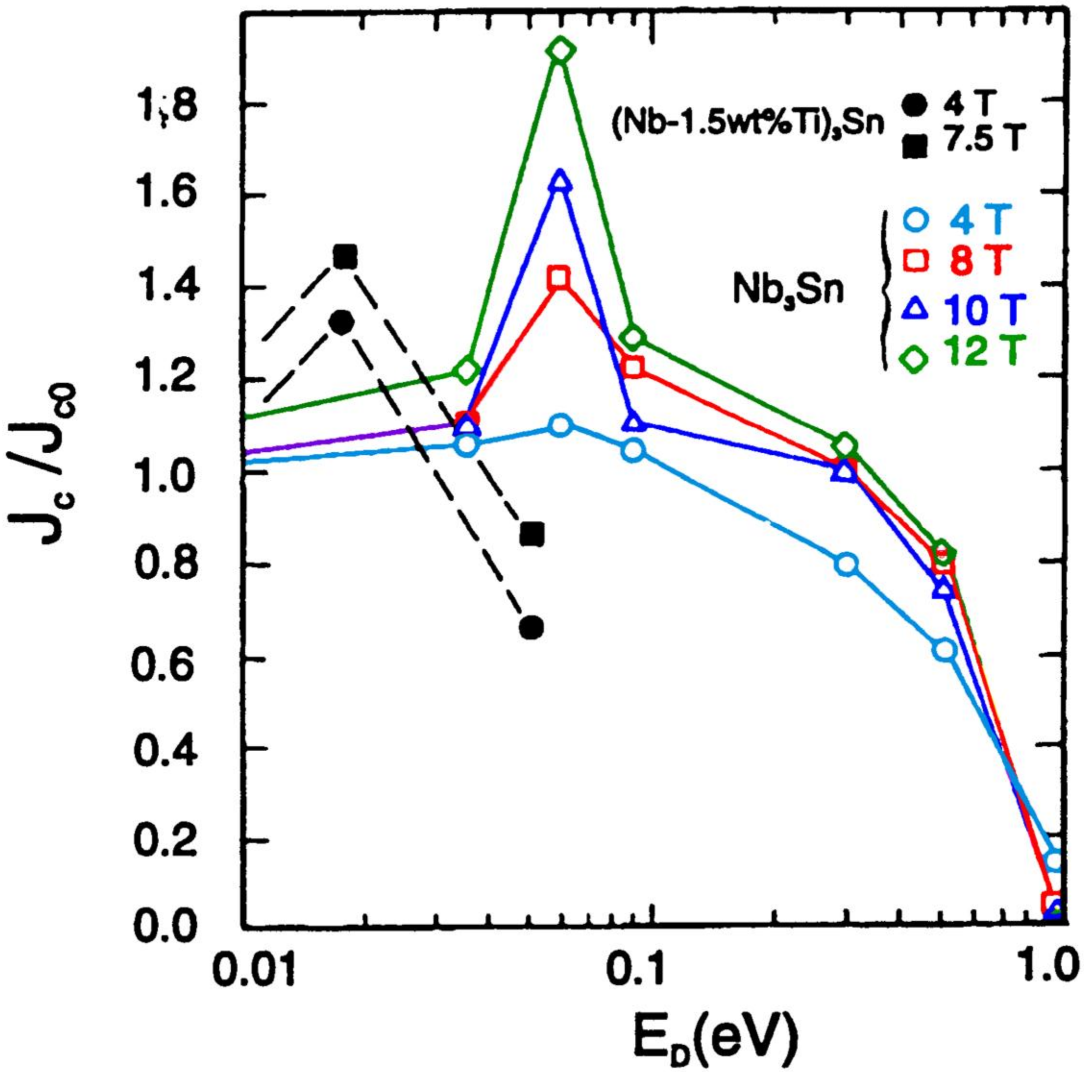


Nb_3Al

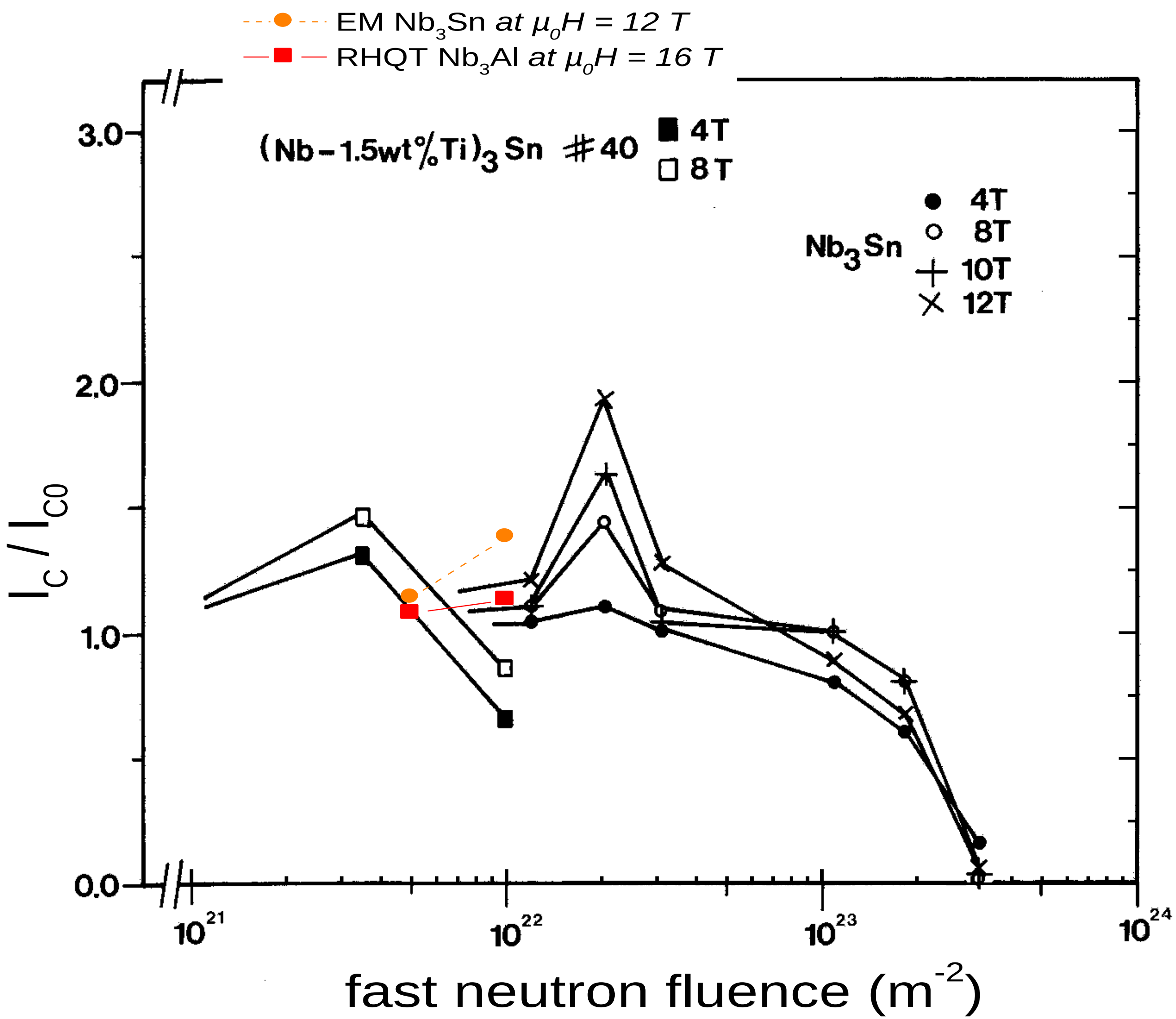
In both cases:

ca. - 0.3 K per

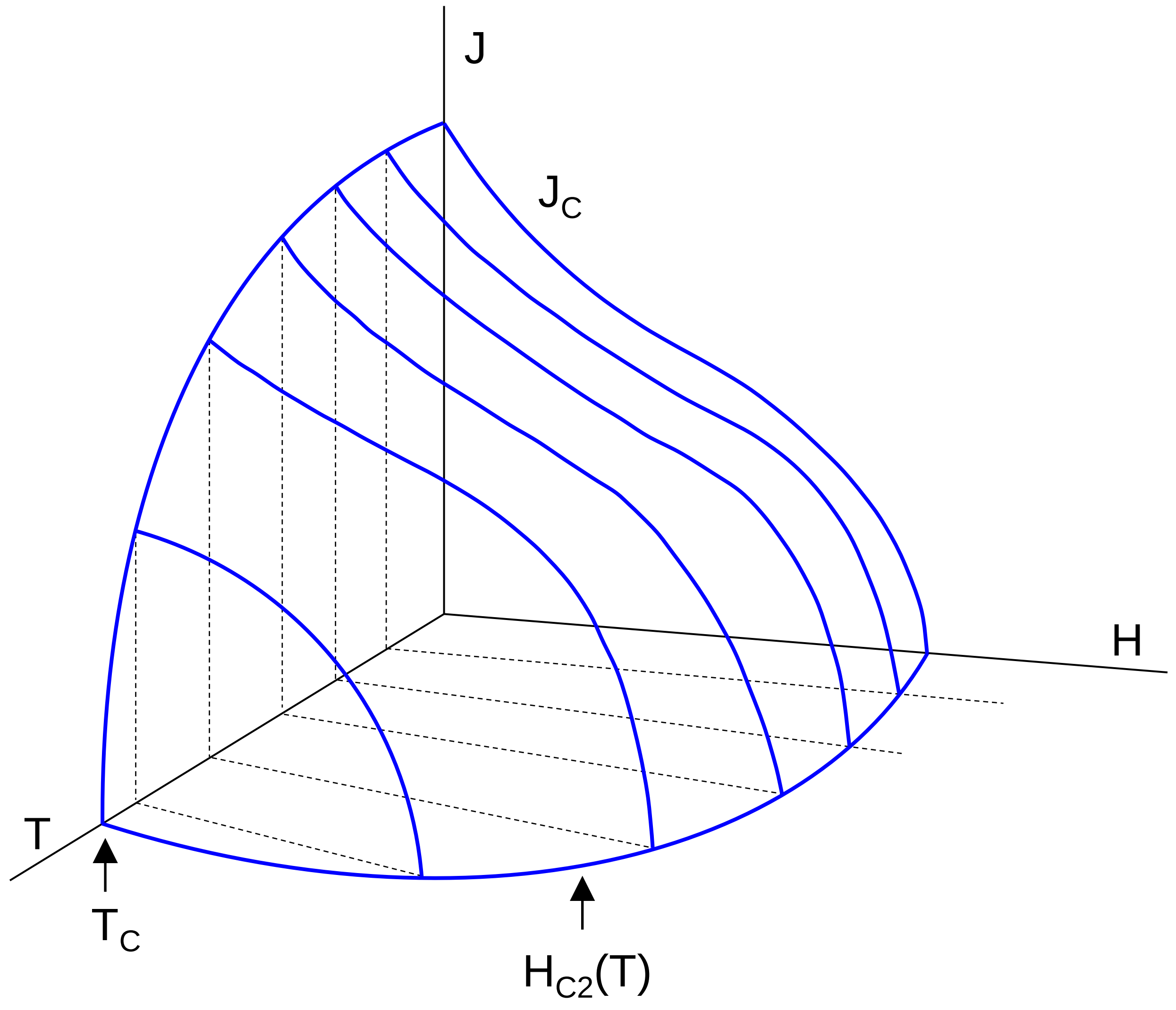
1×10^{22} m^{-2}

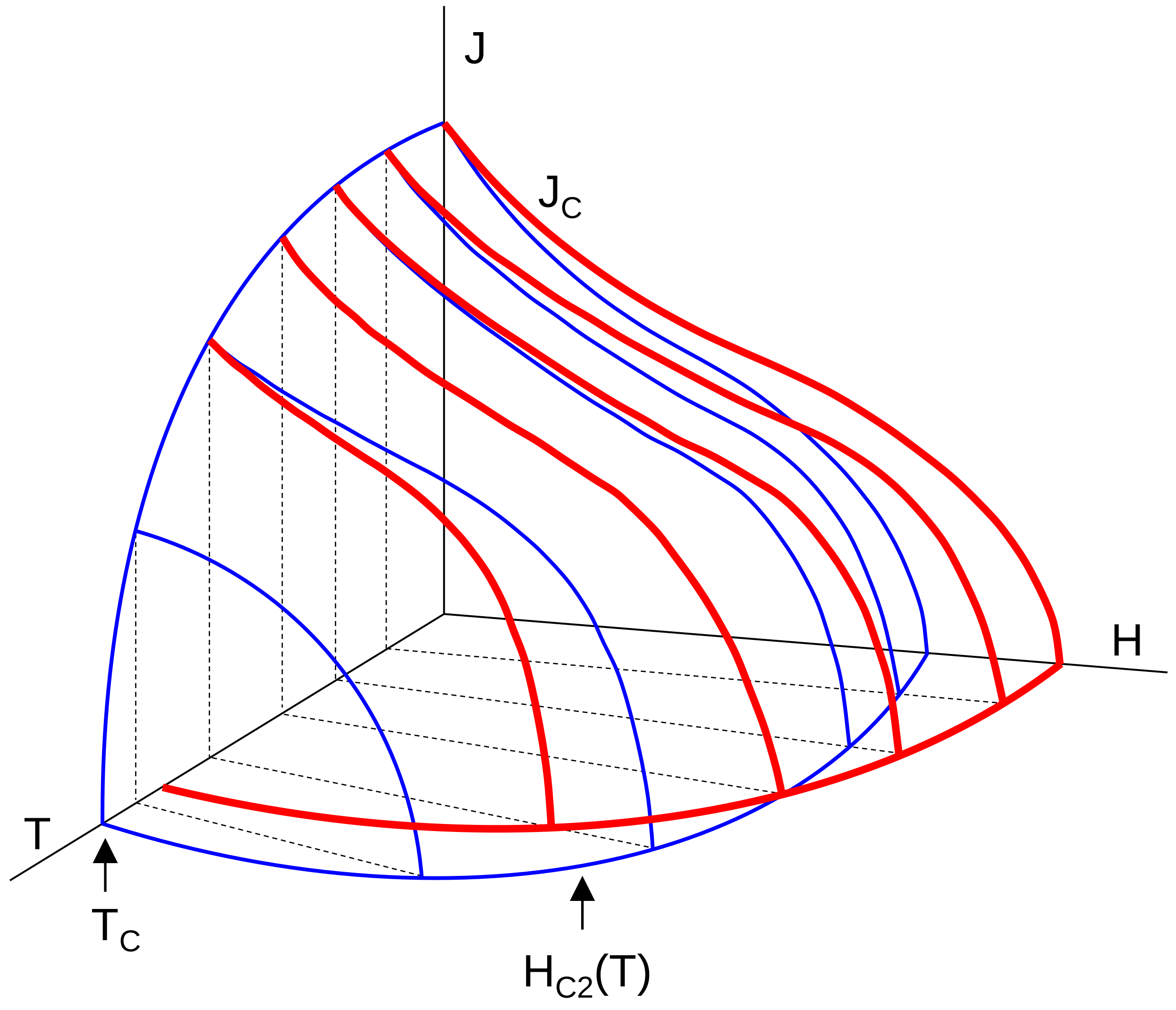


1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
J_c / J_{c0}
0.01
0.1
1.0
E_D(eV)
(Nb-1.5wt%Ti)$_3$Sn
4 T
7.5 T
Nb$_3$Sn
4 T
8 T
10 T
12 T



EM Nb3Sn at μ0H = 12 T
RHQT Nb3Al at μ0H = 16 T
(Nb-1.5wt%Ti)3Sn #40
4T
8T
Nb3Sn
4T
8T
10T
12T
3.0
2.0
1.0
0.0
IC / IC0
10^21
10^22
10^23
10^24
fast neutron fluence (m^-2)


J
J_C
H
T
T_C
H_C2(T)


J
J_C
H
T
T_C
$H_{C2}(T)$

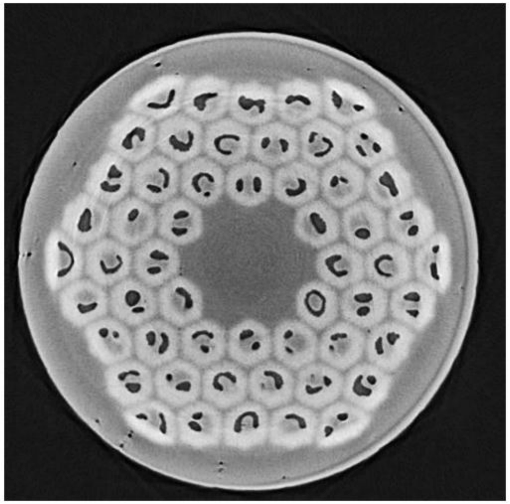
New set of irradiation experiments

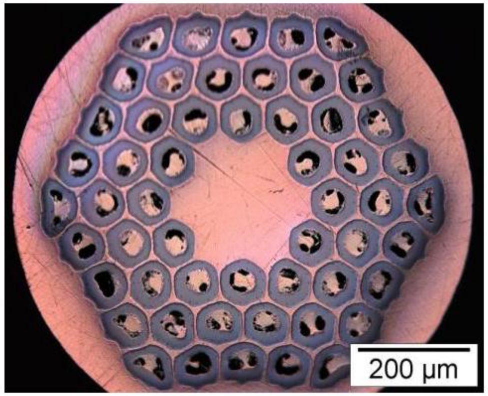
RRP (OST): $(NbTa)_3Sn$

RRP (OST): $(NbTi)_3Sn$

PIT (Bruker EAS): $(NbTa)_3Sn$

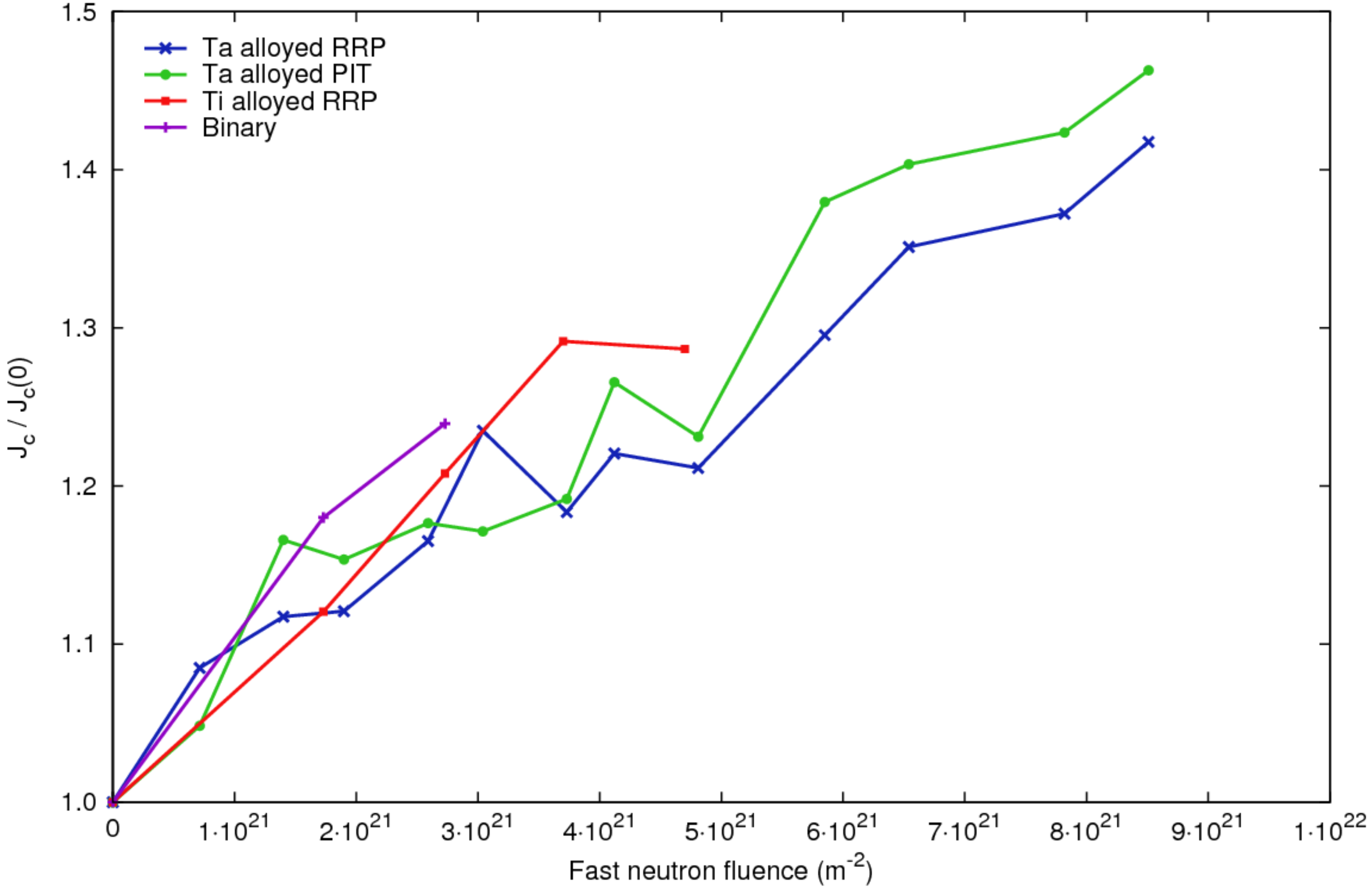
(OST): Nb_3Sn





RRP-Ta

T = 4.2 K, 6 T



Ta alloyed RRP
Ta alloyed PIT
Ti alloyed RRP
Binary
1.5
1.4
1.3
1.2
1.1
1.0
Jc / Jc(0)
0
1·10^21
2·10^21
3·10^21
4·10^21
5·10^21
6·10^21
7·10^21
8·10^21
9·10^21
1·10^22
Fast neutron fluence (m^-2)

SUMMARY: Nb_3Sn

SIGNIFICANT (and later on drastic) EFFECTS on $\mathbf{T_c}$ - caused by disorder

SIGNIFICANT ENHANCEMENTS OF $\mathbf{J_c}$ (followed by a precipitous drop)

- increase caused by an increase of H_{c2} - mean-free-path effect
- drop caused by the T_c degradation

Typical for materials with *a **high degree of order***

SUMMARY: alloyed Nb_3Sn (Addition of small amounts of Ti or Ta)

Mean-free-path effect enhances $H_{c2} \Rightarrow$ ENHANCEMENT OF J_c (at low temp)

But additional scattering centres due to neutron irradiation lead to an *earlier decrease of J_c* (at lower fluence)

Similar results on Nb_3Al

STABILIZER

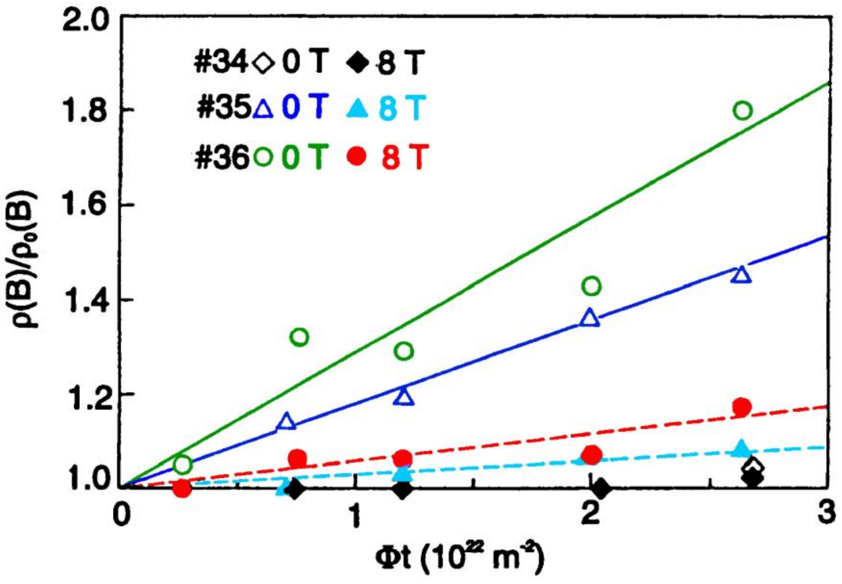
Normal state resistivity essential for stabilization and quench protection

In-field resistivity experiments on copper

Irradiation *must* be done at low temperature (~ 5 K) due to substantial annealing

(most low temperature irradiation facilities have been shut down, only one 14 MeV source available in Japan)

- Resistivity measurement at 10 K
- Neutron irradiation at the IPNS spallation source at 5 K
- Warm-up cycle to RT
- Resistivity measurement at 10 K



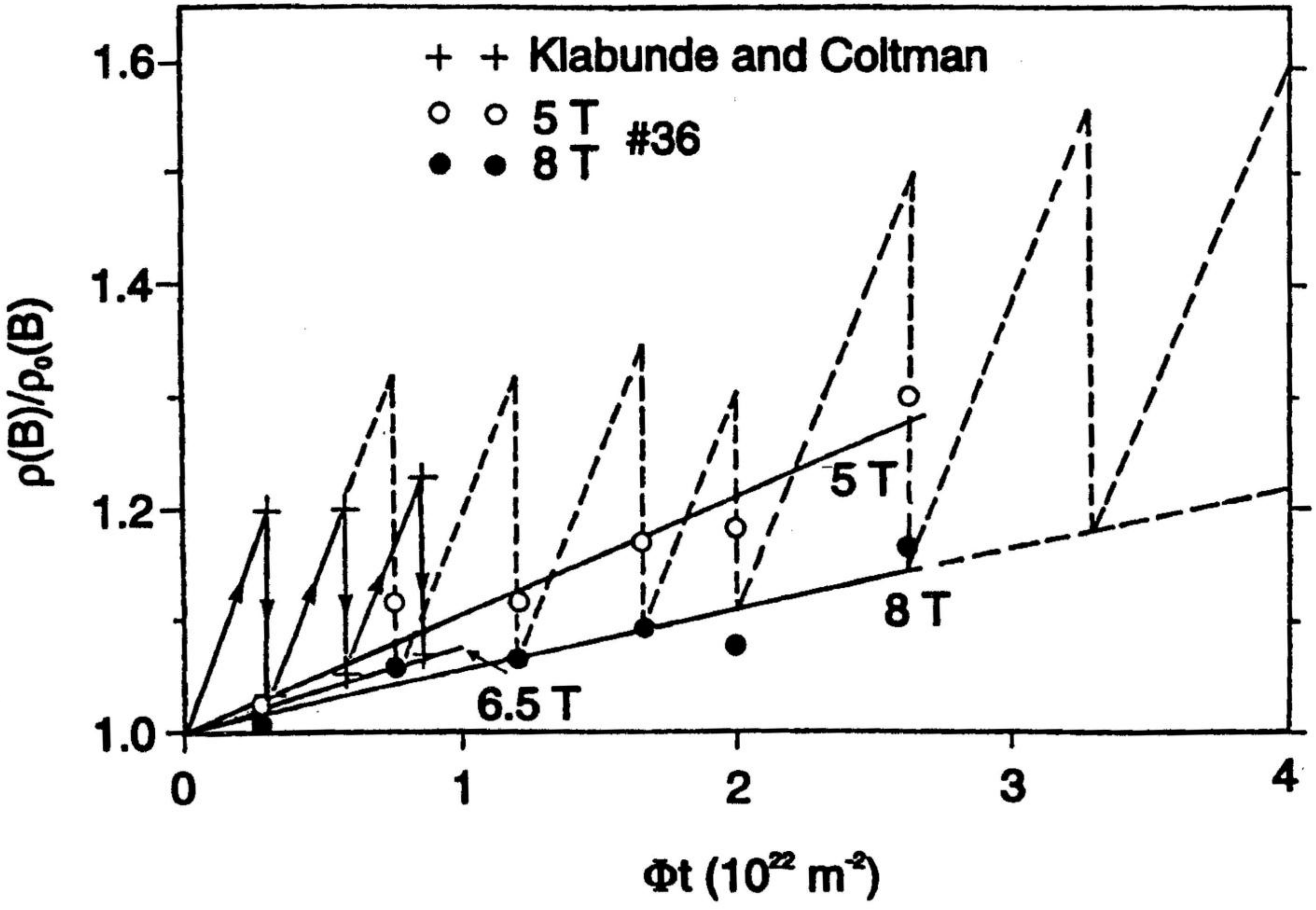
Multifilamentary

NbTi-conductors

#34: RRR ~ 60

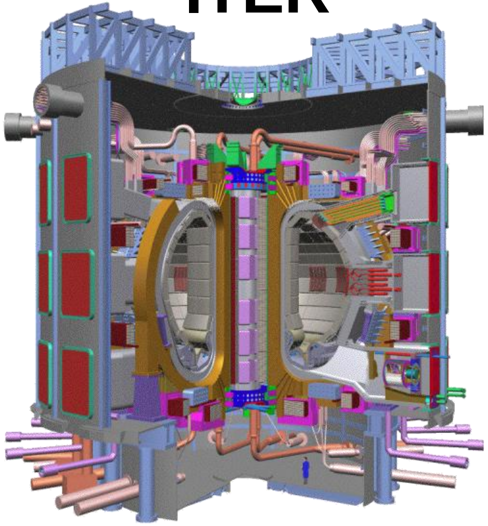
#35: RRR ~ 120

#36: RRR ~ 120


+ + Klabunde and Coltman
○ ○ 5 T
● ● 8 T
#36
1.6
1.4
1.2
1.0
ρ(B)/ρ₀(B)
5 T
8 T
6.5 T
0
1
2
3
4
Φt (10²² m⁻²)

The challenge: HTS for DEMO ??

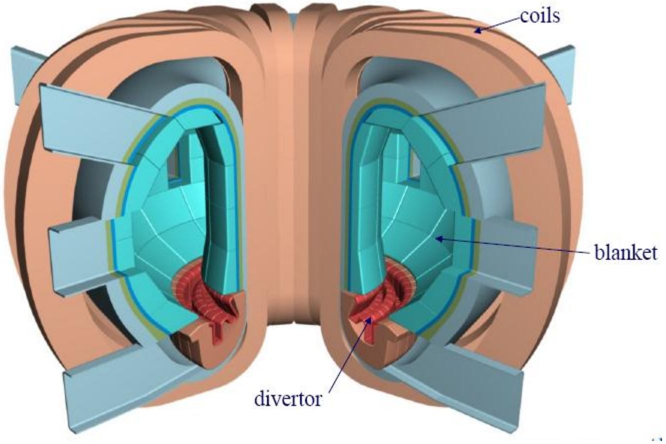
ITER



HTS Magnets ?

YBCO,
BiSCCO, MgB_2

DEMO



- The cooling power could be reduced by 21 %, if operation at 50 K instead of 4.5 K could be achieved.
- The radiation shields could be significantly reduced and simplified.
- Higher magnetic fields could be achievable.
- Smaller coil geometries would become feasible.

HTS for high field applications at higher temperatures
$\rightarrow$ higher operating fields and/or less cryogenics

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

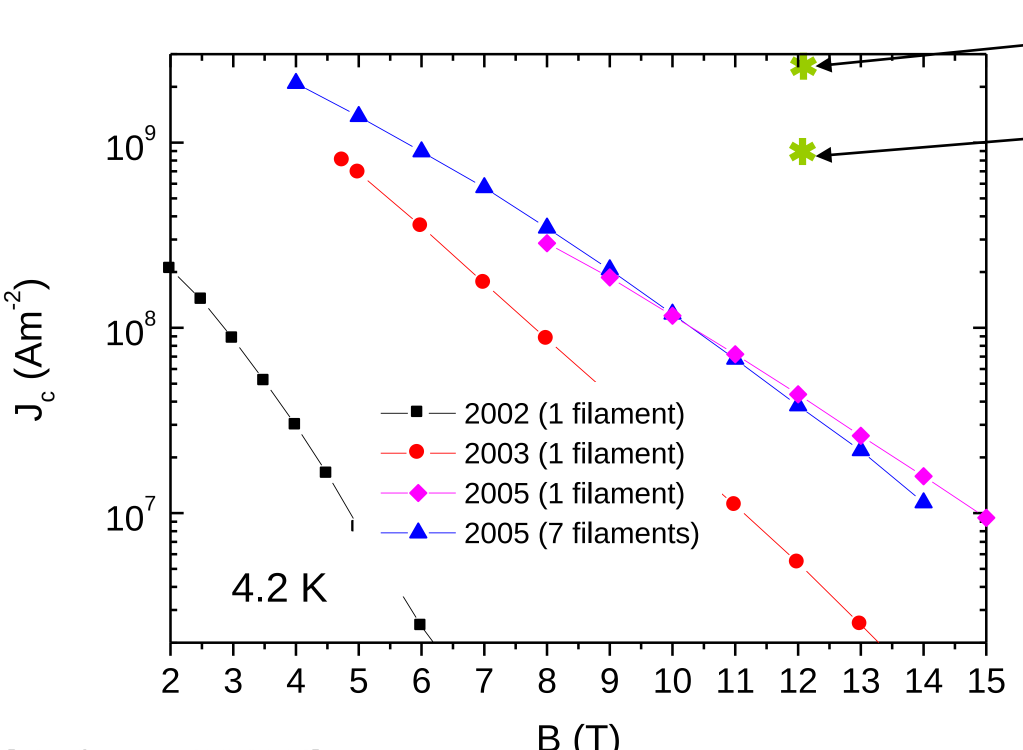
2) **Bi-2212 (T_c ~87 K)**
   ITER like fields up to 25 K (intrinsic limit)

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

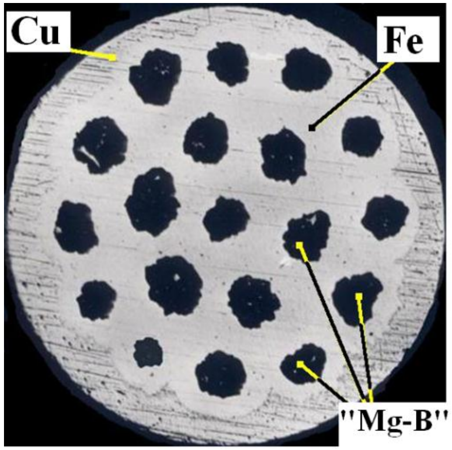
4) **RE-123 (T_c ~92 K)**
   ITER like fields up to 60 K, higher temperature operation possible

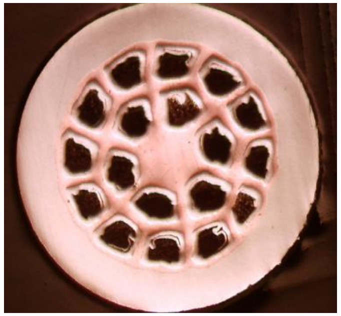
MgB_2

- Performance settled after 2006
- Production of ~1 km long wires: ex-situ ok, in-situ improving, many suppliers
- Higher field applications only at lower T



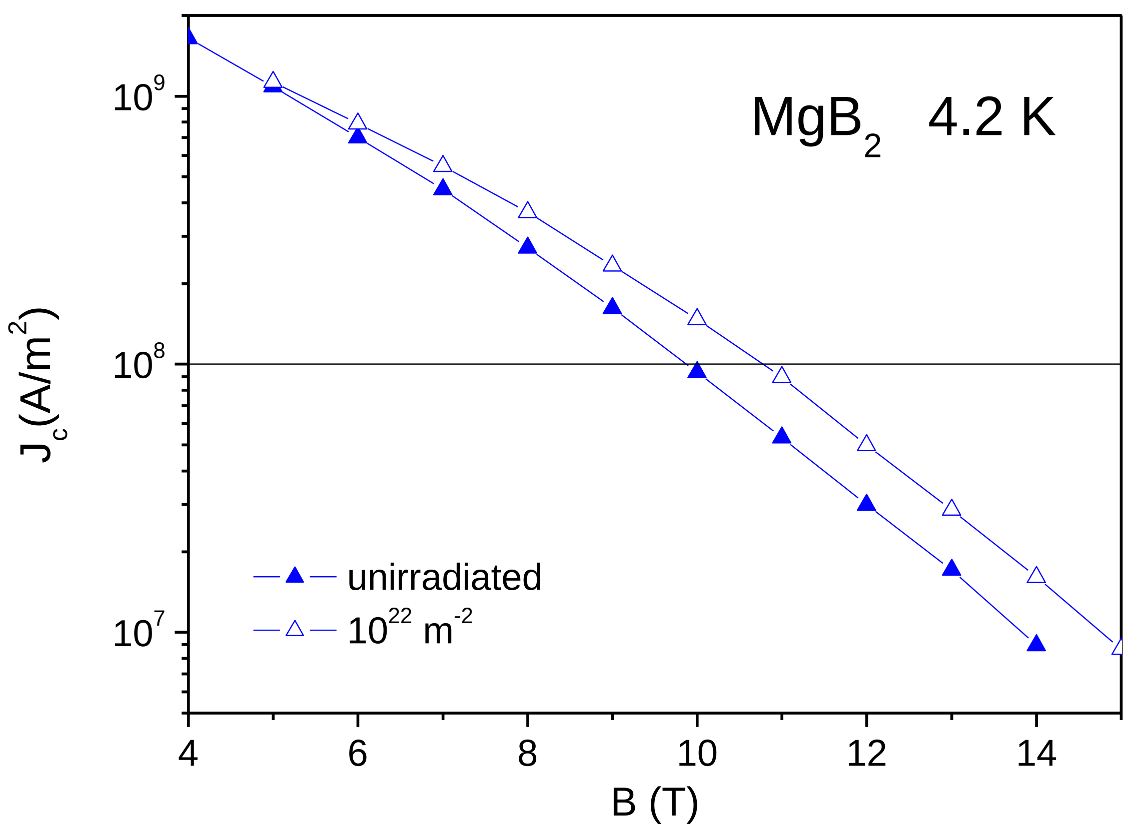
[M. Eisterer, ATI 2006]





Columbus, Hypertech

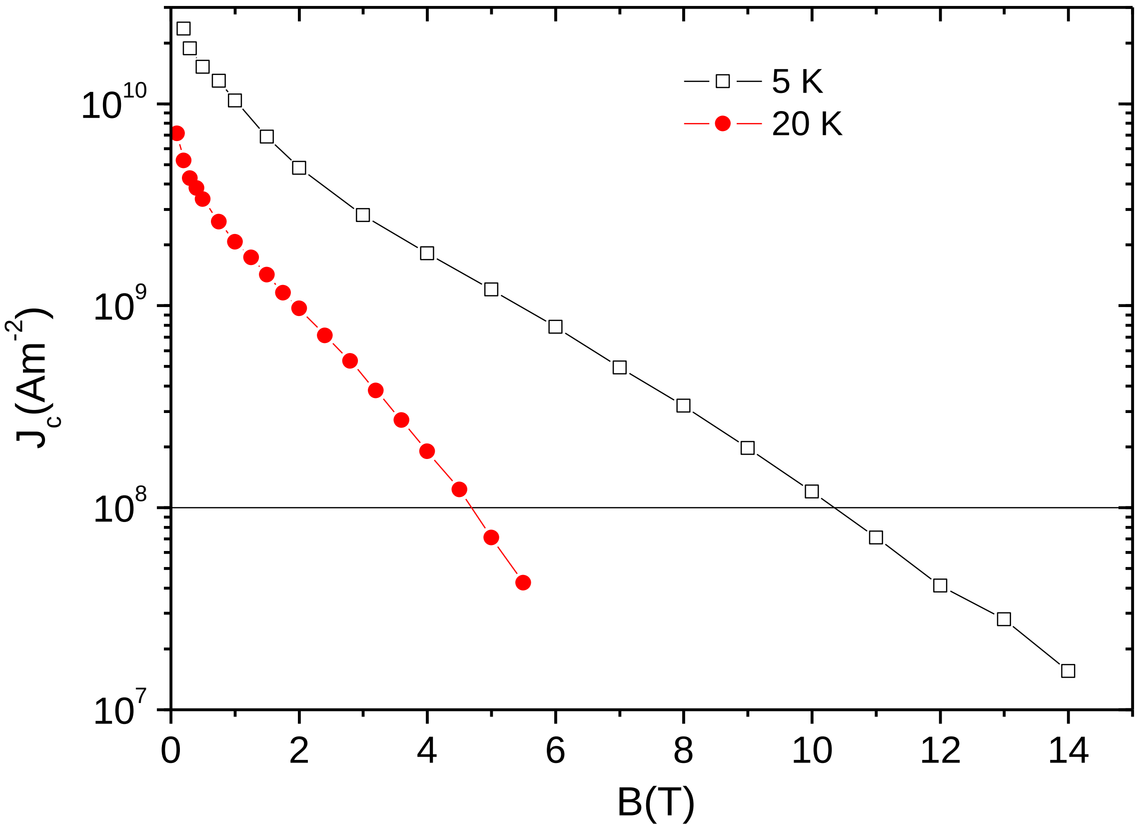
Critical Current Densities at 4.2 K



Fluence: 10^{22} m^{-2}

Sufficient current densities only at fields below ~ 10 T

Low cost alternative at low temperatures (< 10 K, PF coils) ?

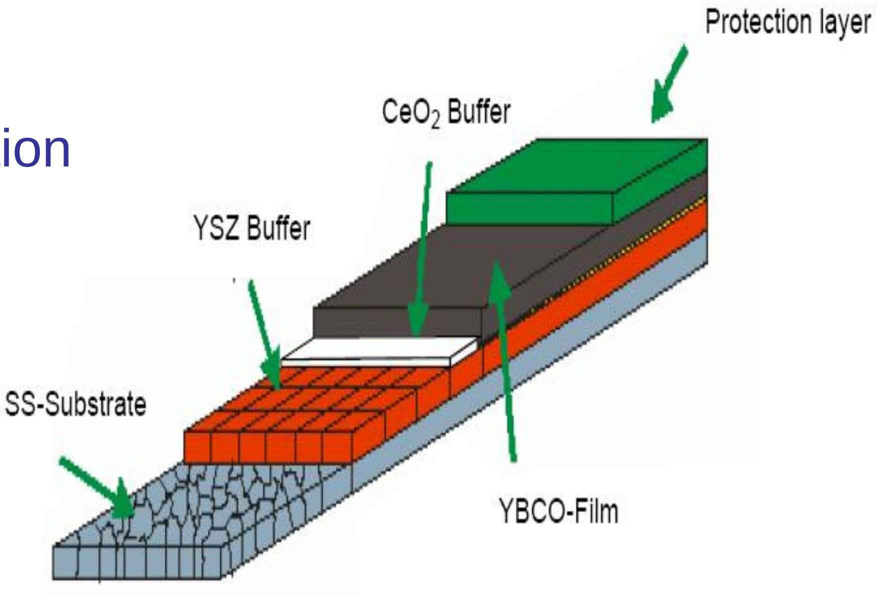


Ti-doped n-irradiated MgB_2: “state-of-the-art” properties

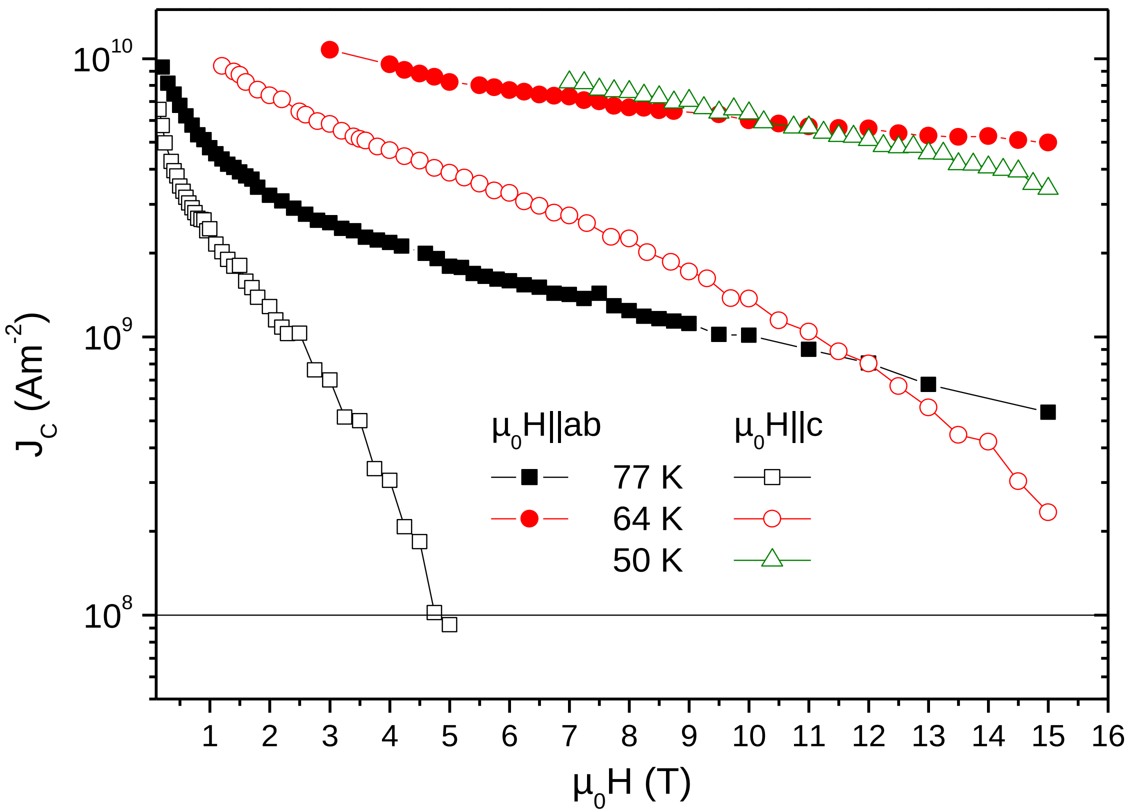
Coated Conductors

European High Temperature Superconductors (EHTS)

- Substrate: Cr-Ni stainless steel
- Buffer stack: Y_2O_3/YSZ/CeO_2
  - YSZ: Ion beam assisted deposition (IBAD)
- YBCO (2.5 µm)
  - Pulsed-laser-deposition (PLD)
- Silver or gold protection layer
  - Vapor deposition
- Stabilization: Copper (~ 17 µm)
  - Galvanic plating process
- Total thickness: 0.120 mm $\rightarrow$ $J_c/J_e = 50$



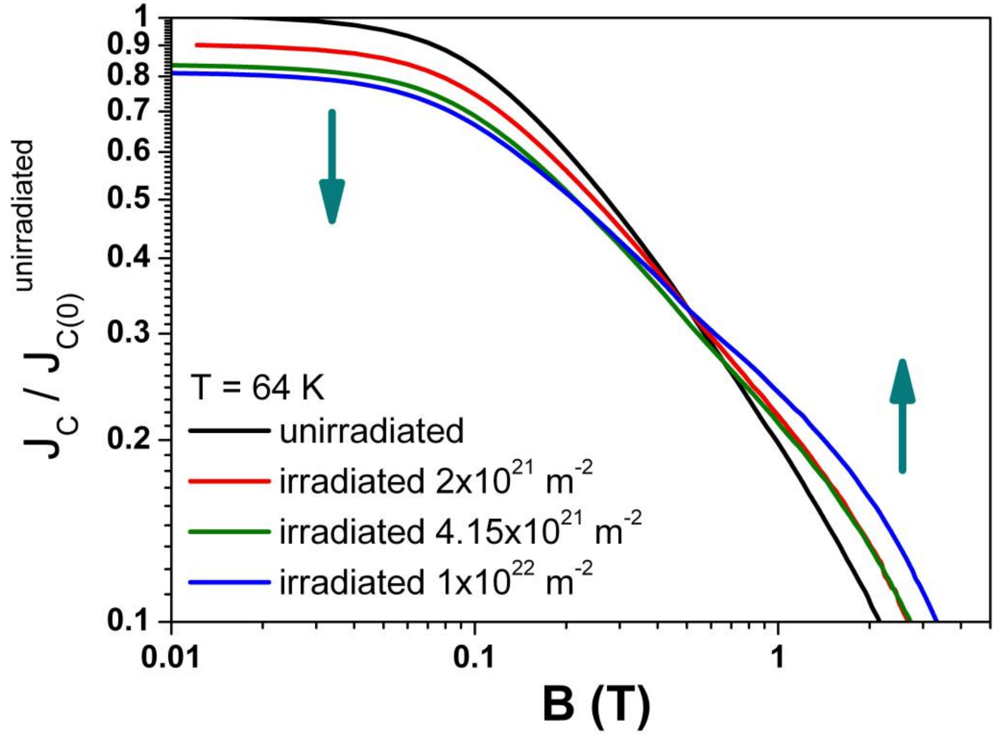
Critical Current Densities

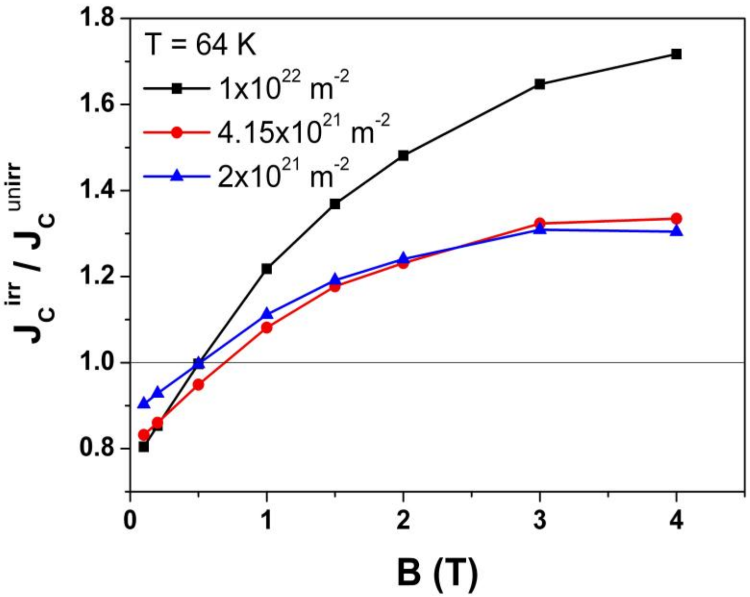


Y-substituted (or mixed) RE-123 compounds (not yet commercially available):
J_c is less field dependent at high temperatures!!

Neutron irradiation effects on J_c for fields parallel c: AMSC

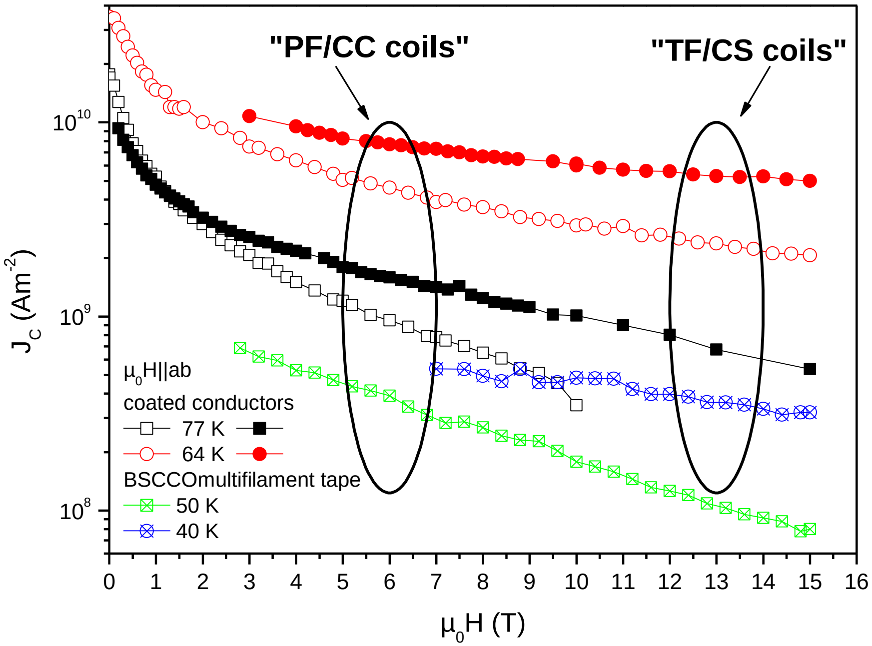
- Decrease of J_C at low fields
- Increase of J_C at higher field
- The crossover indicates a change in flux pinning

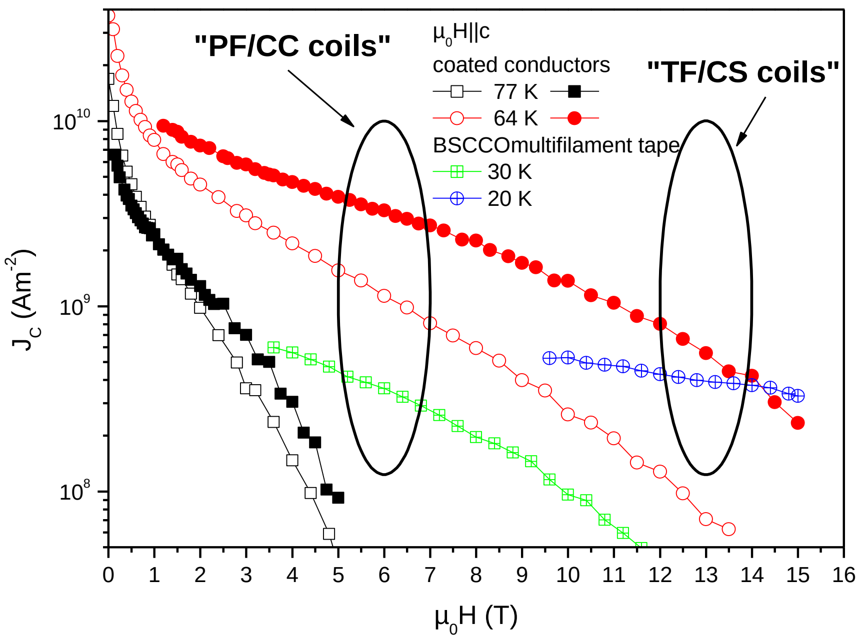




Crossover field (mT)	$2x10^{21}$ m^{-2}	$4x10^{21}$ m^{-2}	$1x10^{22}$ m^{-2}
77 K	244	382	630
64 K	114	219	440
50 K	130	195	334

Summary: Critical Current Density (J_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.

SUMMARY and CONCLUSIONS

- LT Superconductors: No problems regarding radiation effects expected for ITER
- Stabilizer: Degradation must be kept in mind
- HTS: Substantial R&D still required, especially with regard to high-amperage cables

ACKNOWLEDGEMENTS

Work on the superconductors started at ATI in 1977 and was done partly at Argonne, Oak Ridge and Lawrence Livermore National Laboratories as well as at FRM Garching.

Many graduate students and post-doctoral fellows have been involved.

Substantial support by the European Fusion Programme (EFDA) is acknowledged.

The contributions of the present ATI crew are gratefully acknowledged.

Senior scientists: M. Eisterer, F.M. Sauerzopf

Post-docs: R. Fuger, F. Hengstberger, M. Zehetmayer

Graduate students: T. Baumgartner, M. Chudy, J. Emhofer