RADIATION EFFECTS ON FUSION MAGNET COMPONENTS

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Introduction: The ITER – Magnets
Superconductors
Stabilizer
Insulation
Conclusions

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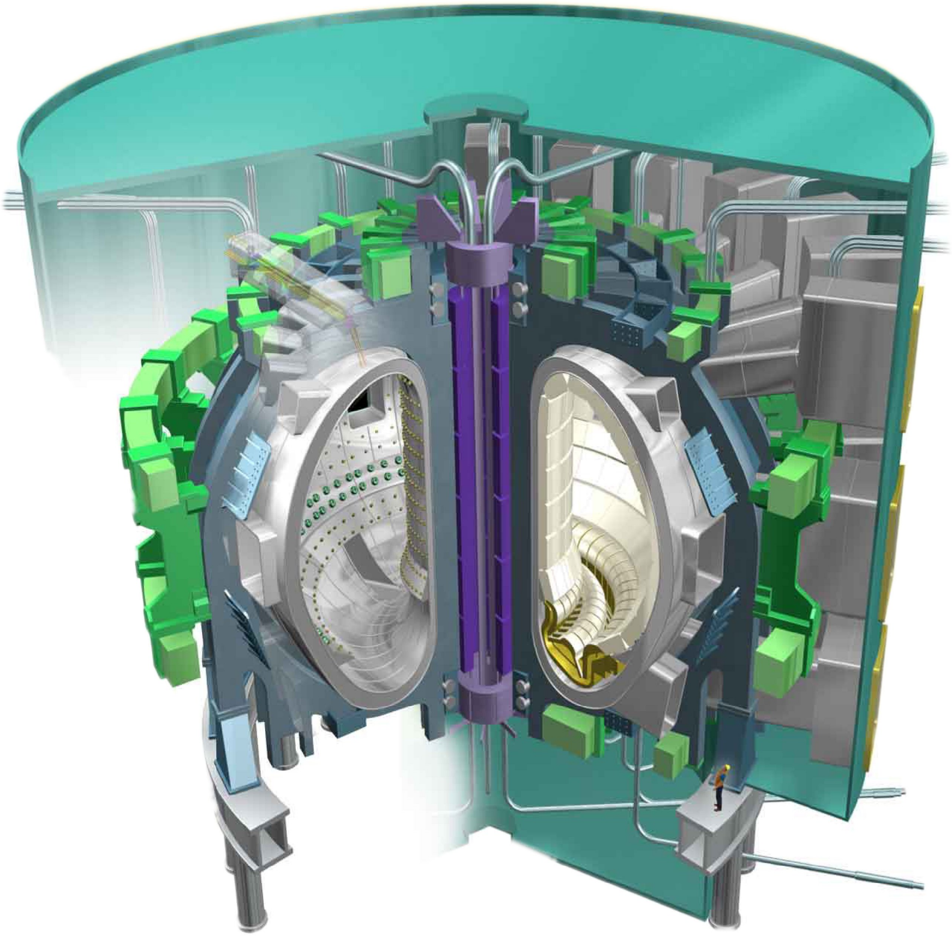
INTRODUCTION

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

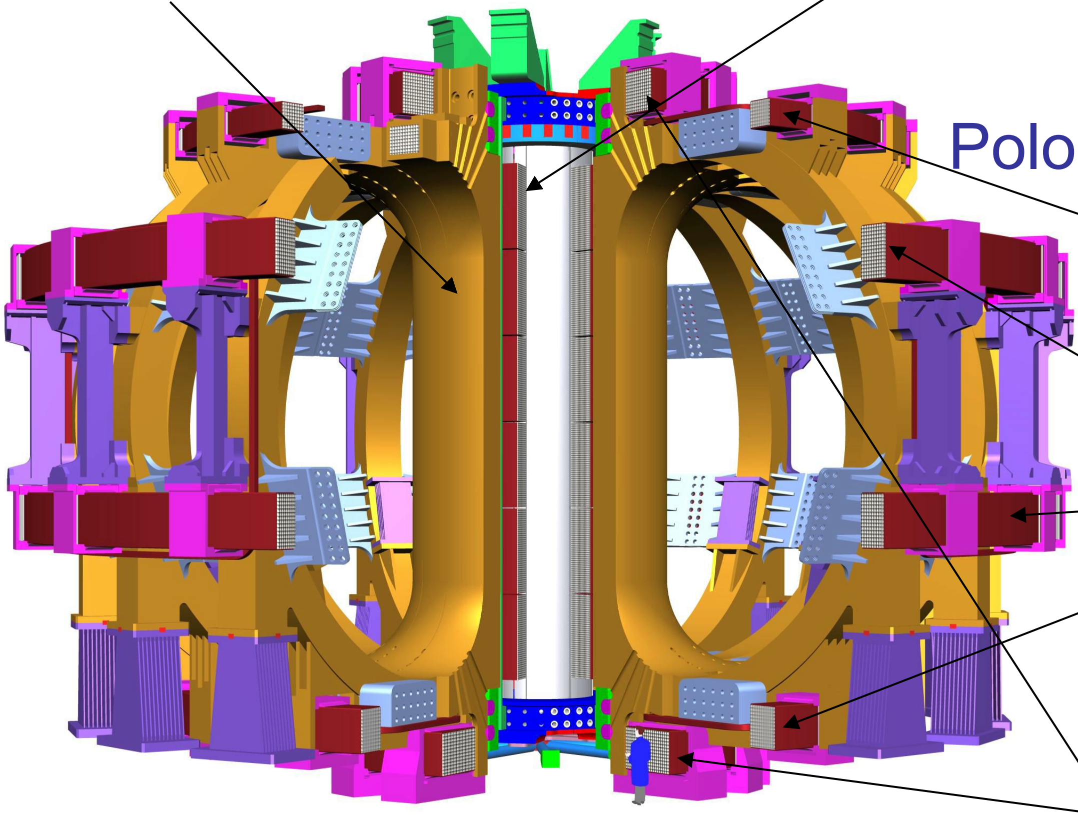


ITER Magnet System (5 K / 6.5 K)

Toroidal Field (TF) Coils
(B_{max}~12 T, I = ~ 70 kA)

Central Solenoid (CS)
(B_{max}~13 T)

Poloidal Field (PF) Coils



B_{max}~ 5 T

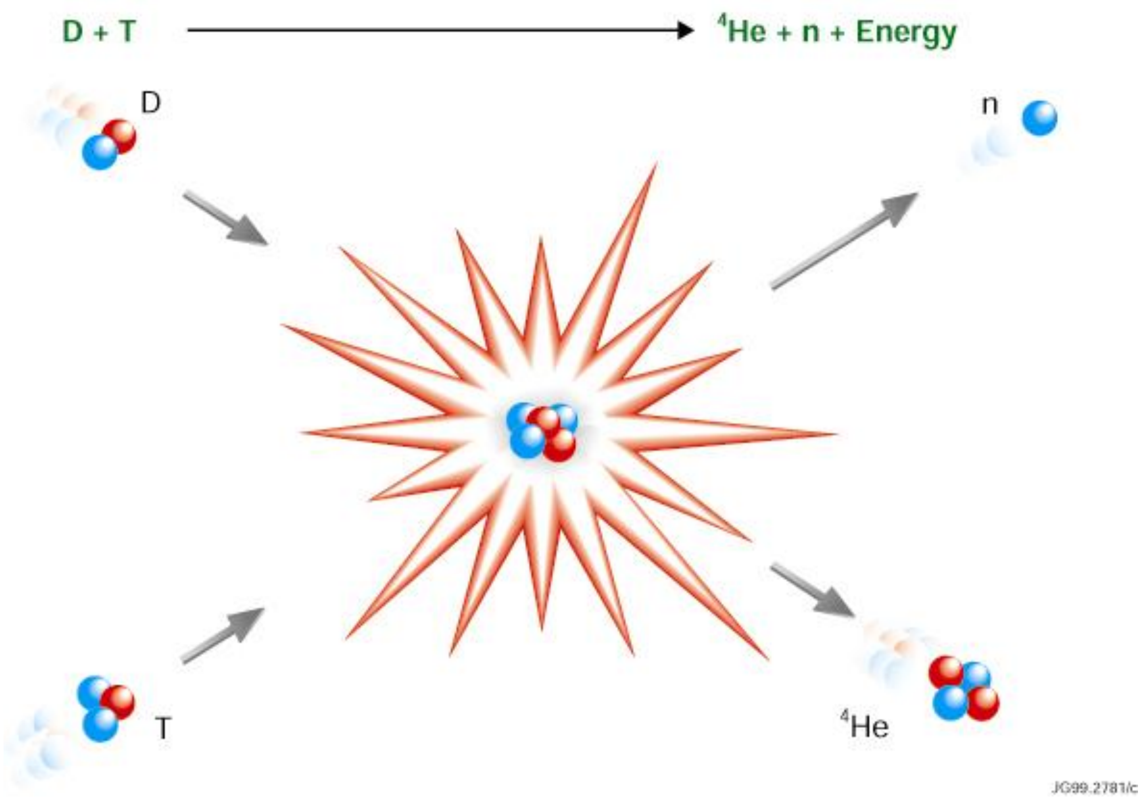
B_{max}~ 4 T

B_{max}~ 6 T

Nb_3Sn and NbTi

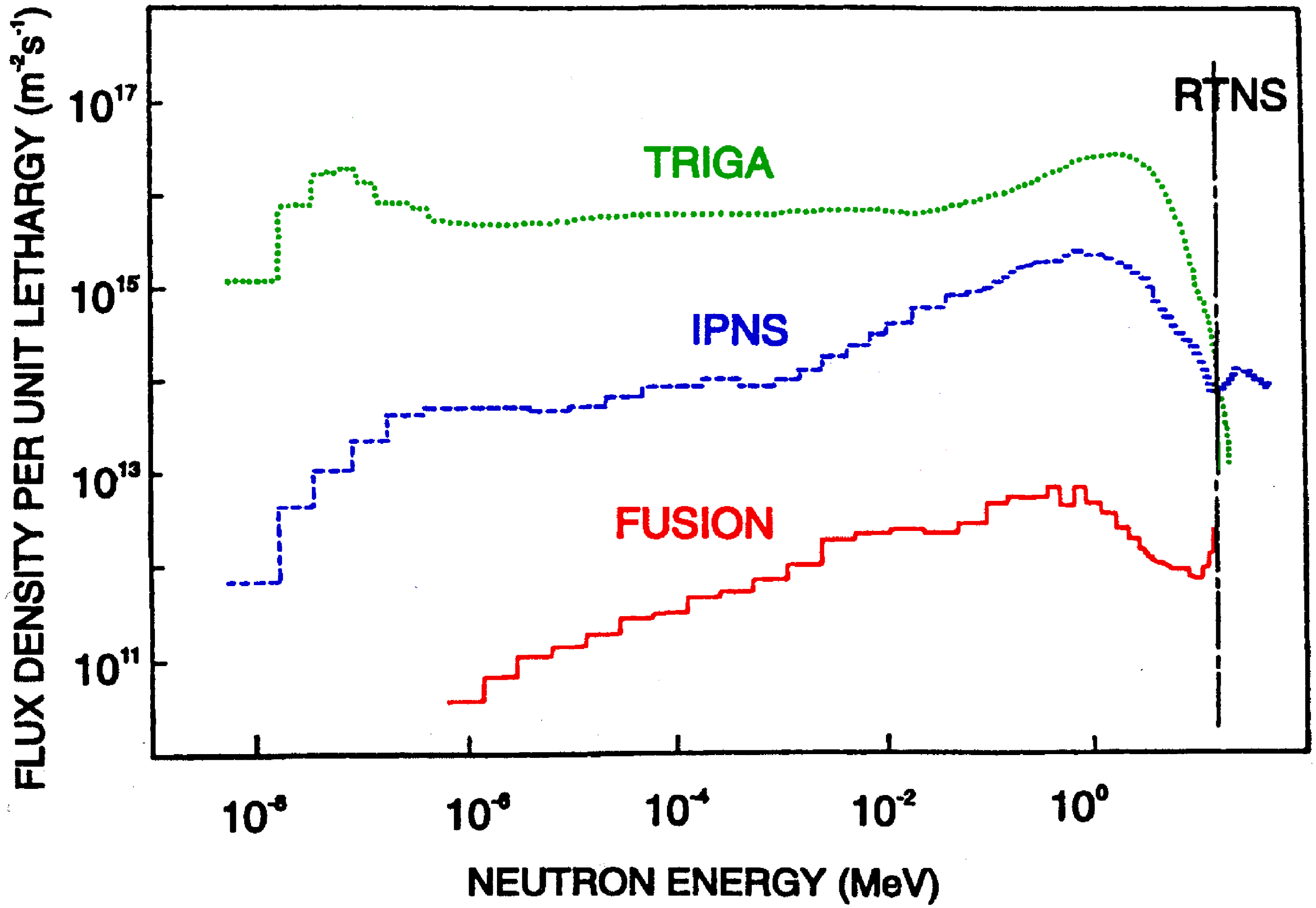
- **The ITER project sets new limits for conductor and coil dimensions:**
  - **Currents of up to 68 kA**
  - **Coils of up to 13 m (Nb_3Sn) and 24 m (NbTi) in diameter**
- **More than 530 t of Nb_3Sn strands are required for the TF and CS coils**
- **About 300 t of NbTi strands are required for the 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!


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

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: $\rho_n \propto 1/l \propto \kappa \propto H_{c2}$

⌦ 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

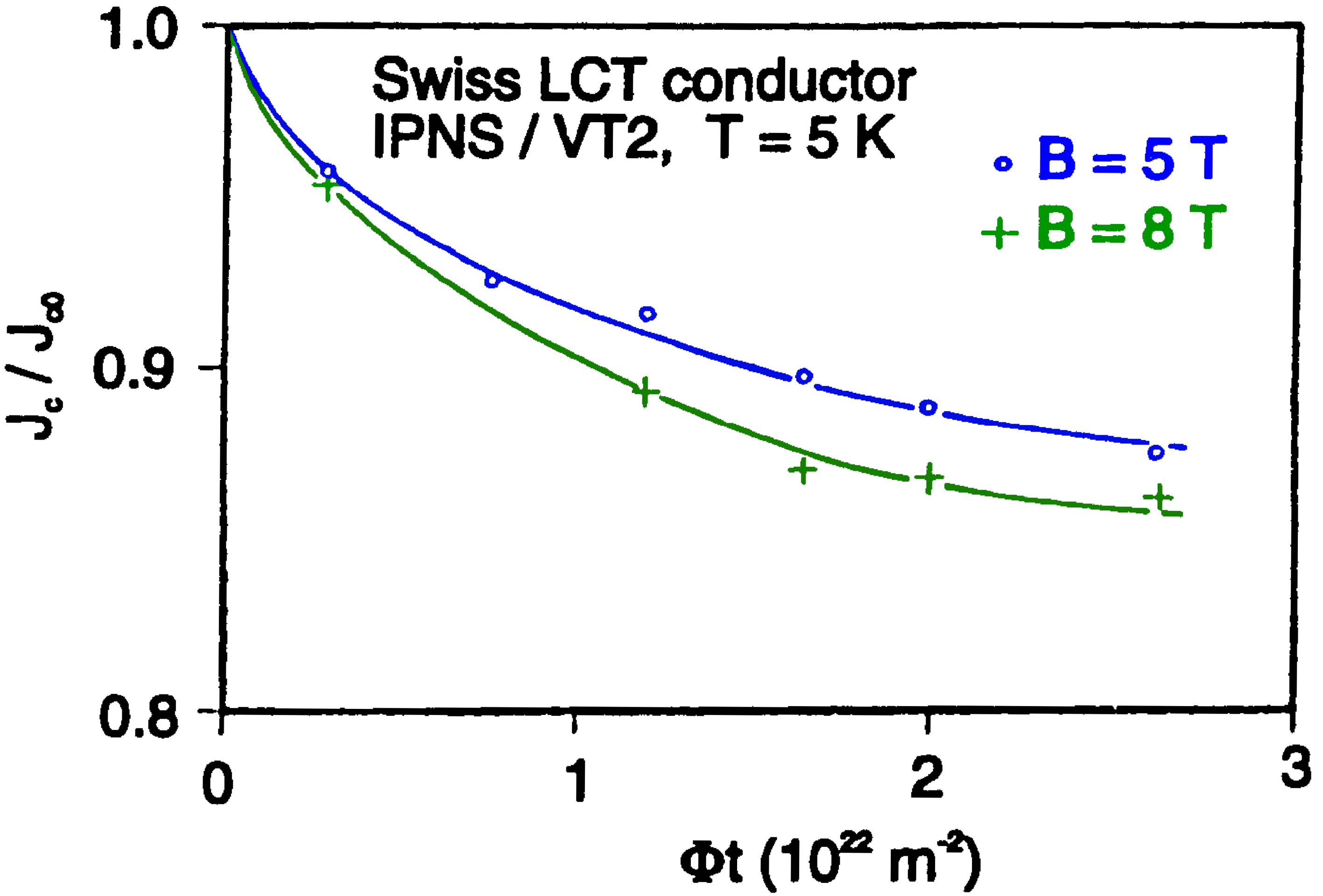
NB: Stable collision cascades in materials with low conductivity, e.g. HTS

RESULTS

The "Workhorse": NbTi

A15 Superconductors:

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


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})

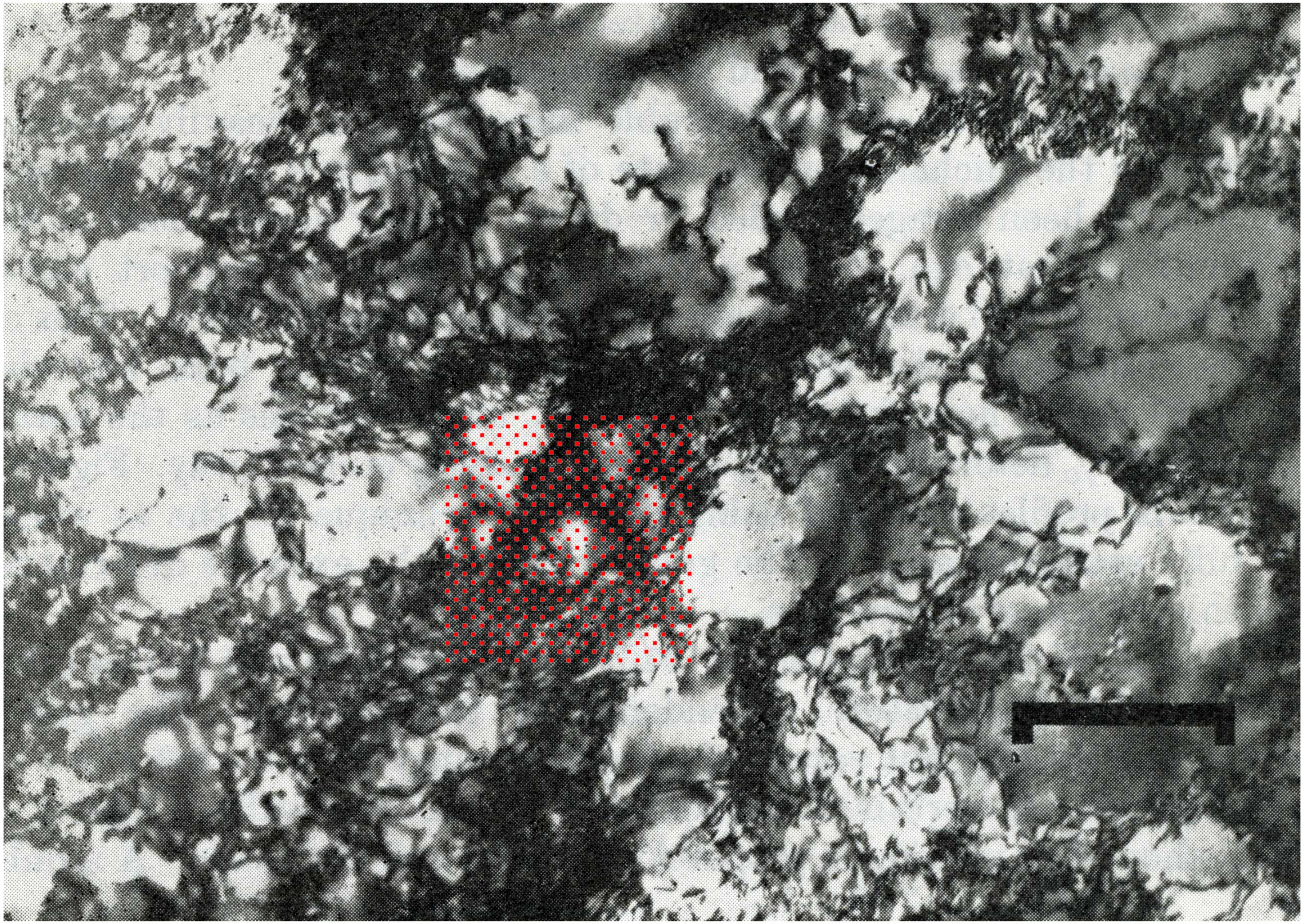
Results on NbTi

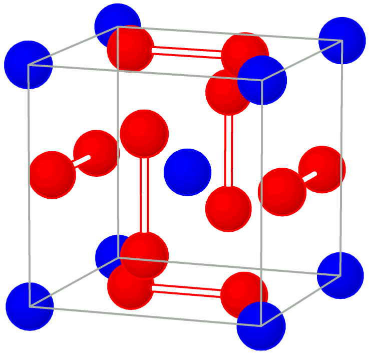
SMALL EFFECTS on J_c - depending on the initial
micro-structure for flux pinning

SMALL DECREASE of H_{c2} - caused by a

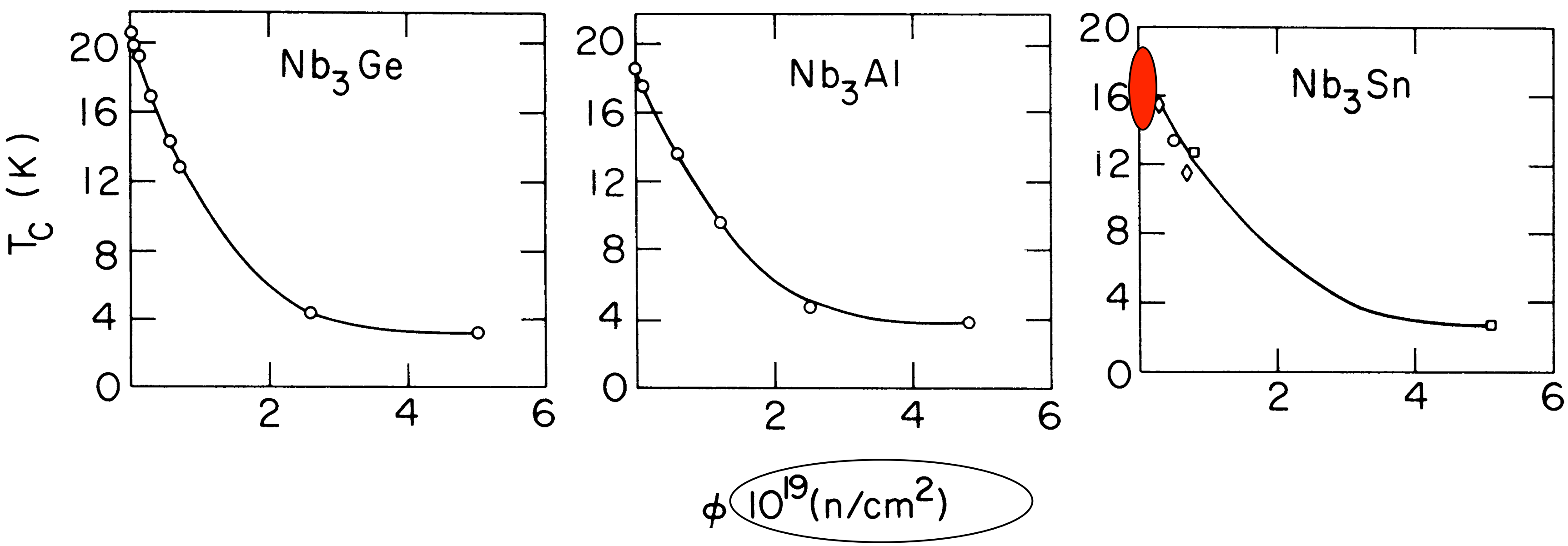
SMALL DECREASE of T_c

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

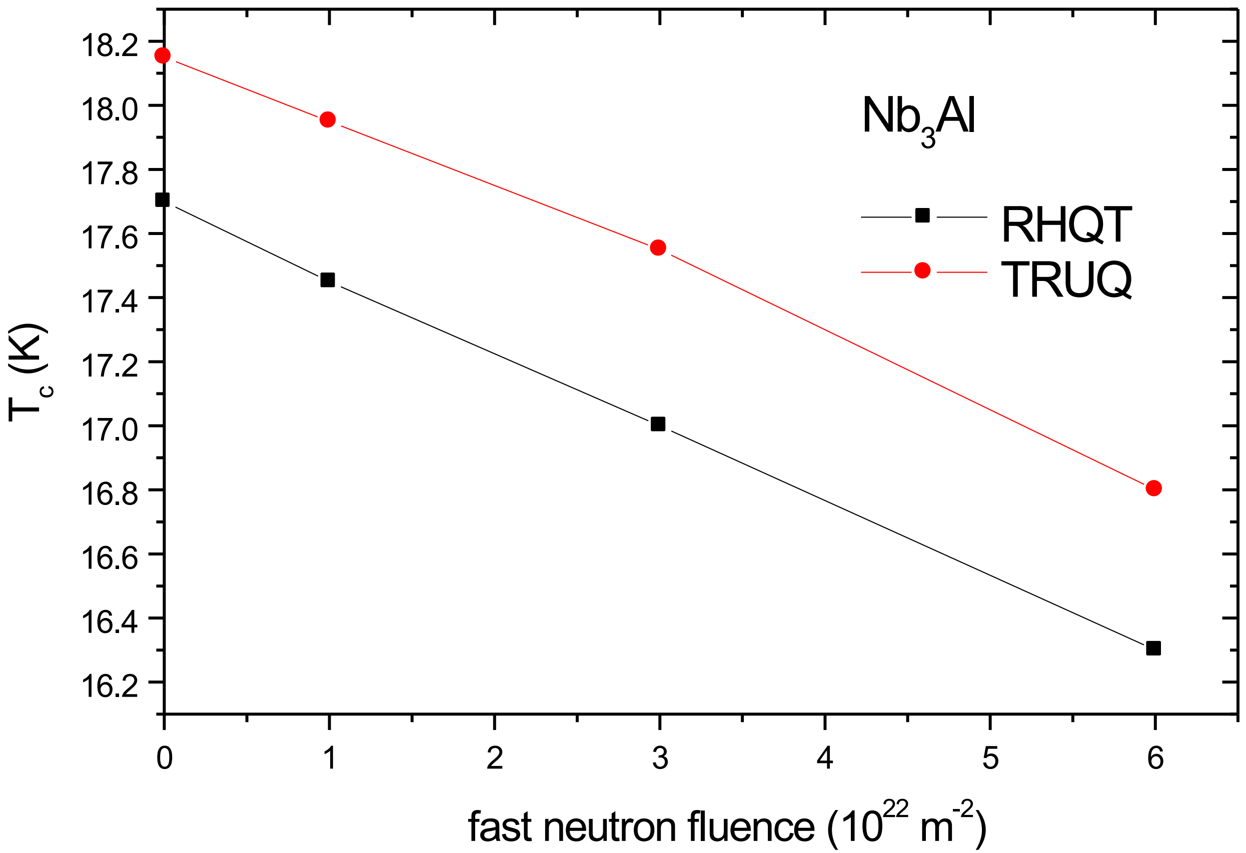




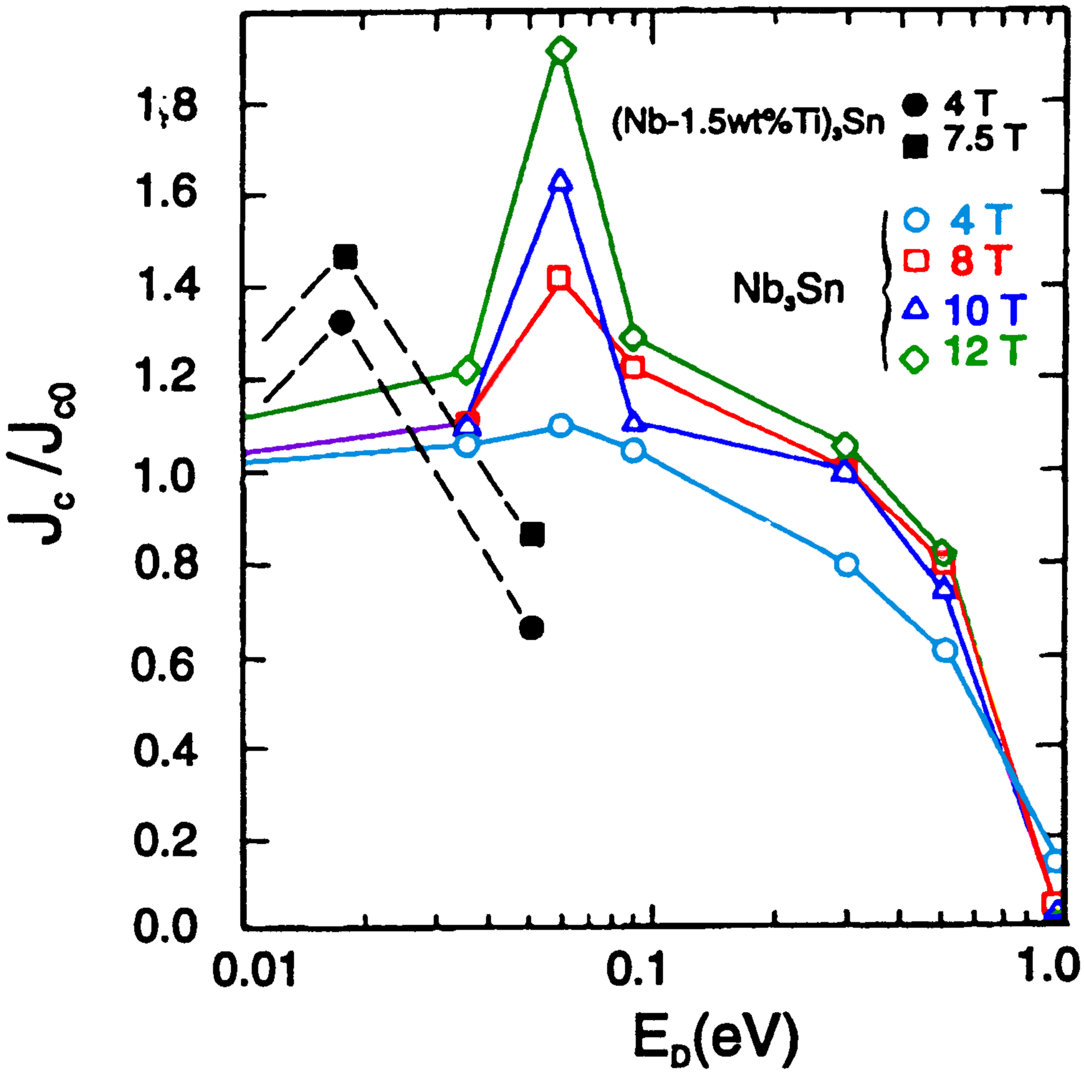
A15 SUPERCONDUCTORS

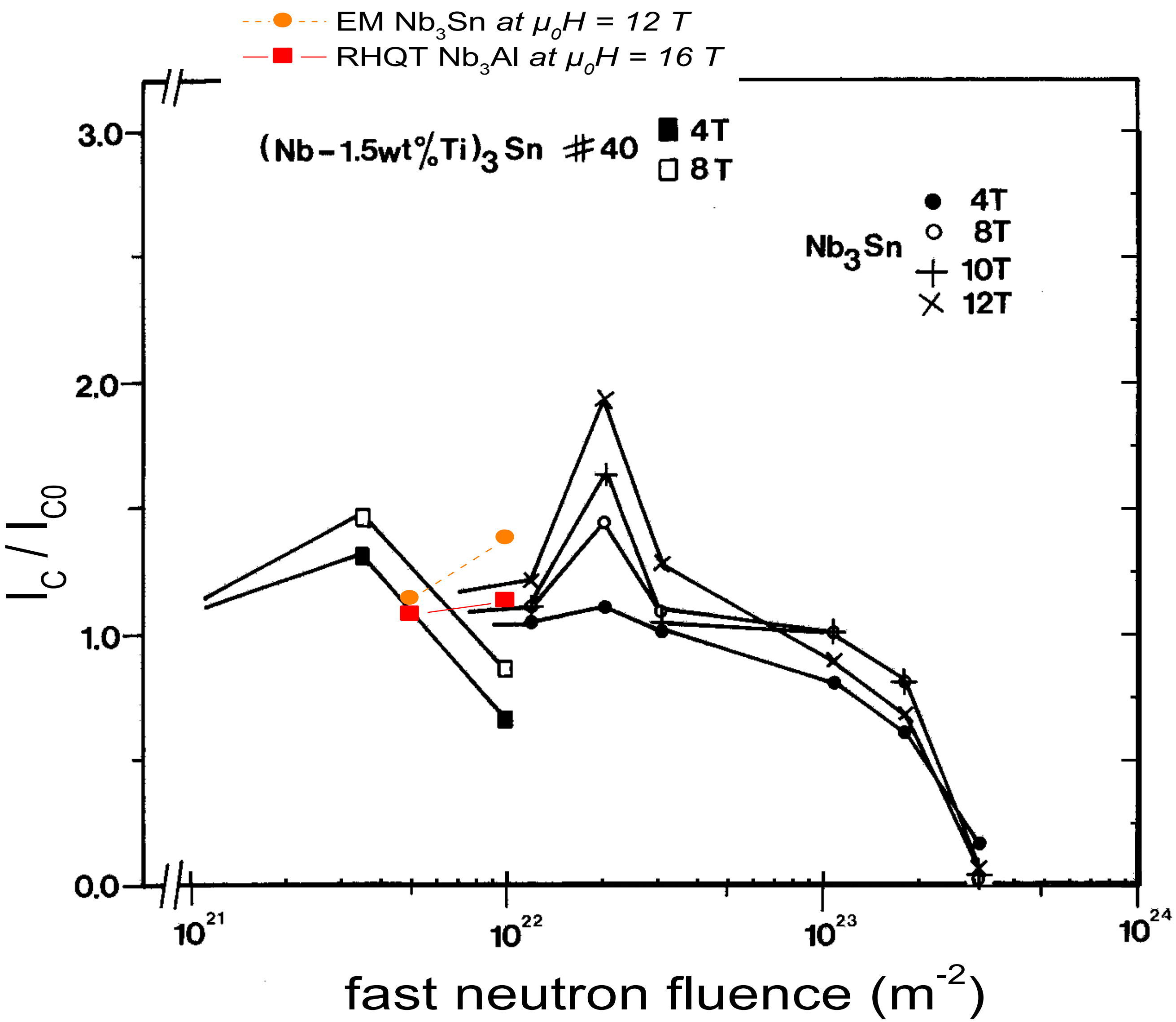


!! Scale not accurate: maximum fluence around 7-10 x 10^{23} m^{-2} !!

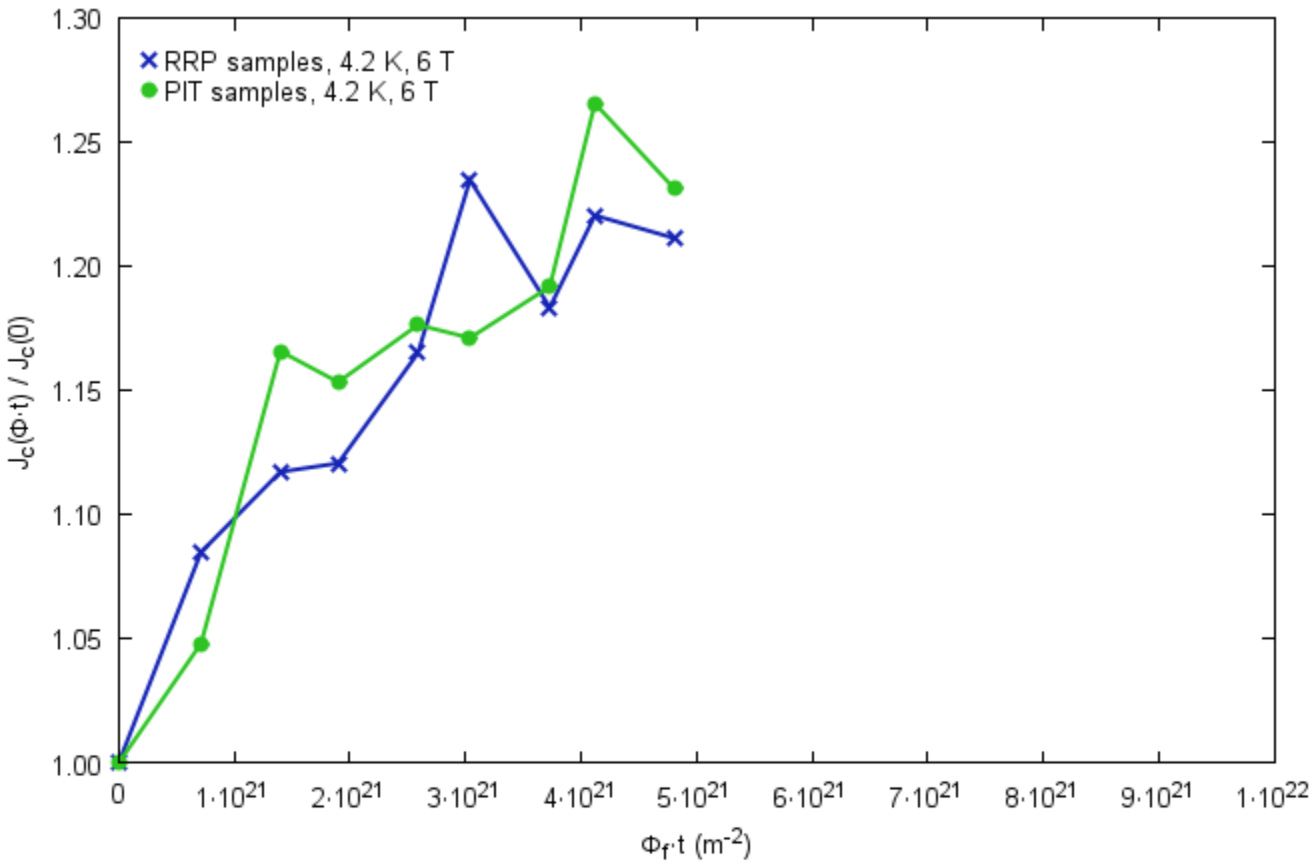


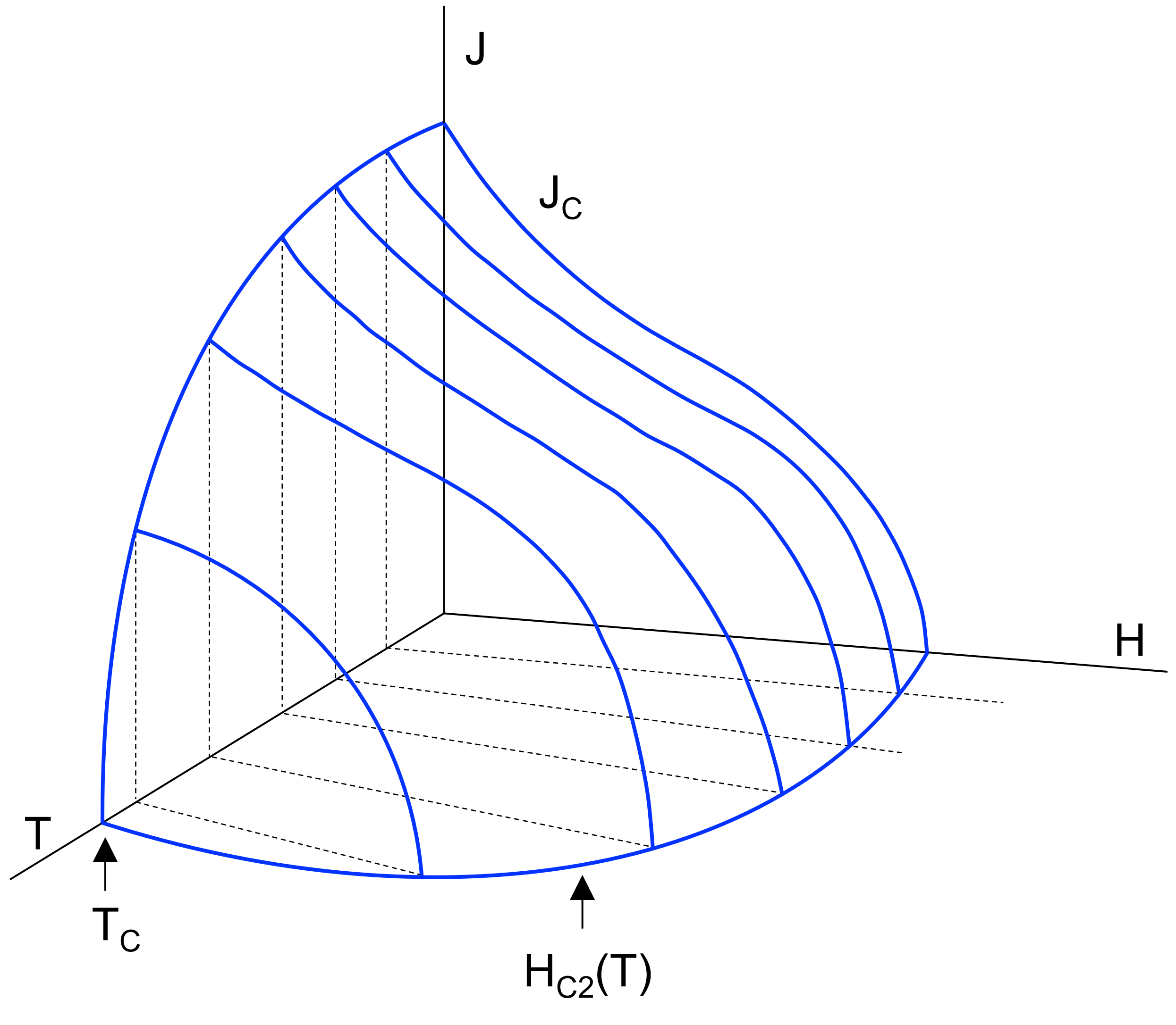
Nb_3Al
RHQT
TRUQ
T_c (K)
18.2
18.0
17.8
17.6
17.4
17.2
17.0
16.8
16.6
16.4
16.2
0
1
2
3
4
5
6
fast neutron fluence (10^{22} m^{-2})

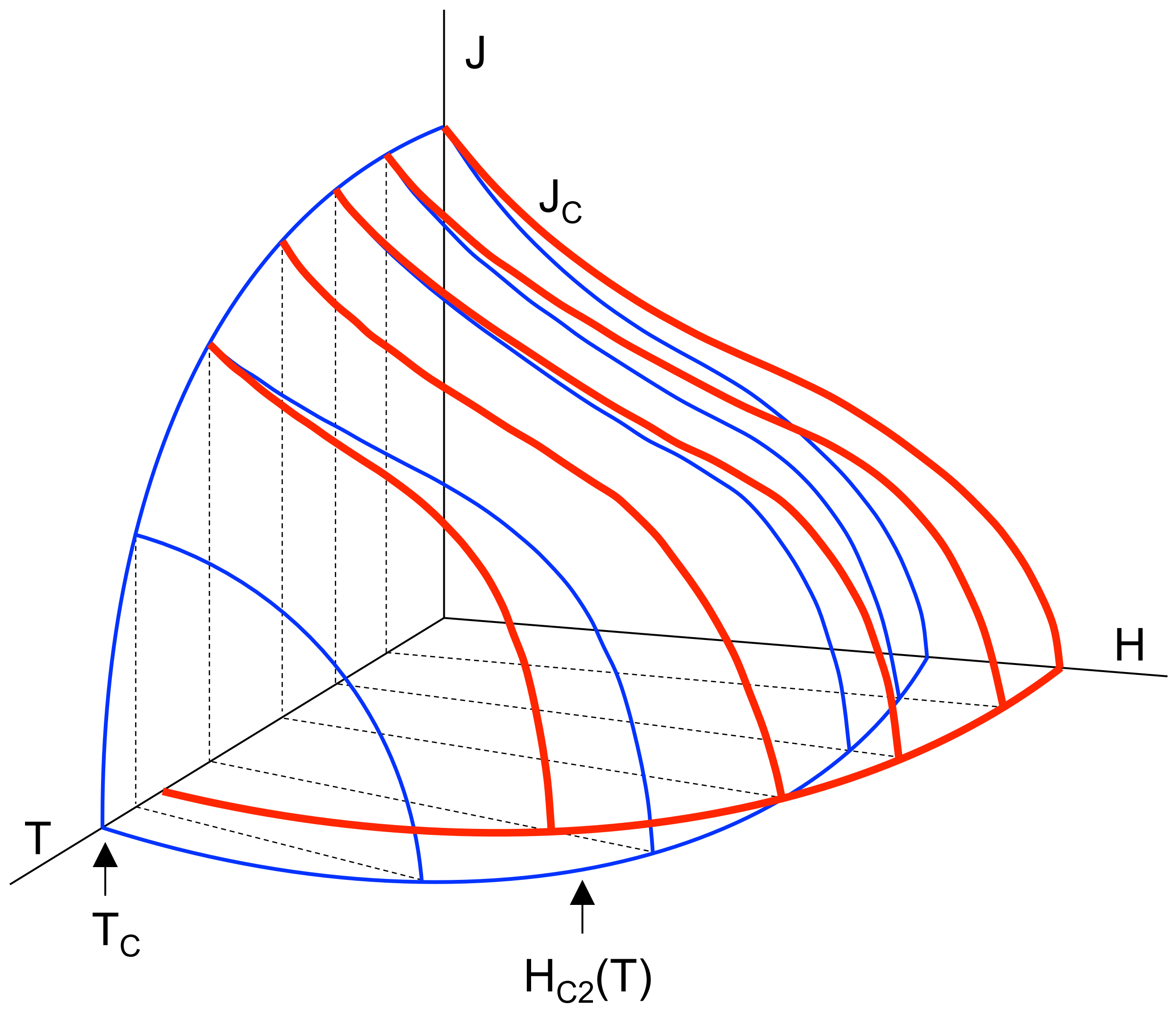

(Nb-1.5wt%Ti)$_3$Sn
4 T
7.5 T
Nb$_3$Sn
4 T
8 T
10 T
12 T
J_c / J_{c0}
E_D(eV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.01
0.1
1.0


EM Nb_3Sn at μ_0H = 12 T
RHQT Nb_3Al at μ_0H = 16 T
$(Nb-1.5wt\%Ti)_3Sn$ #40
4T
8T
Nb_3Sn
4T
8T
10T
12T
3.0
2.0
1.0
0.0
I_C / I_{C0}
10^{21}
10^{22}
10^{23}
10^{24}
fast neutron fluence (m^{-2})

RRP (OST): $(NbTa)_3Sn$ – PIT (Bruker EAS): $(NbTa)_3Sn$




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


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

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 increases $H_{c2} \Rightarrow$ ENHANCEMENT OF J_c

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

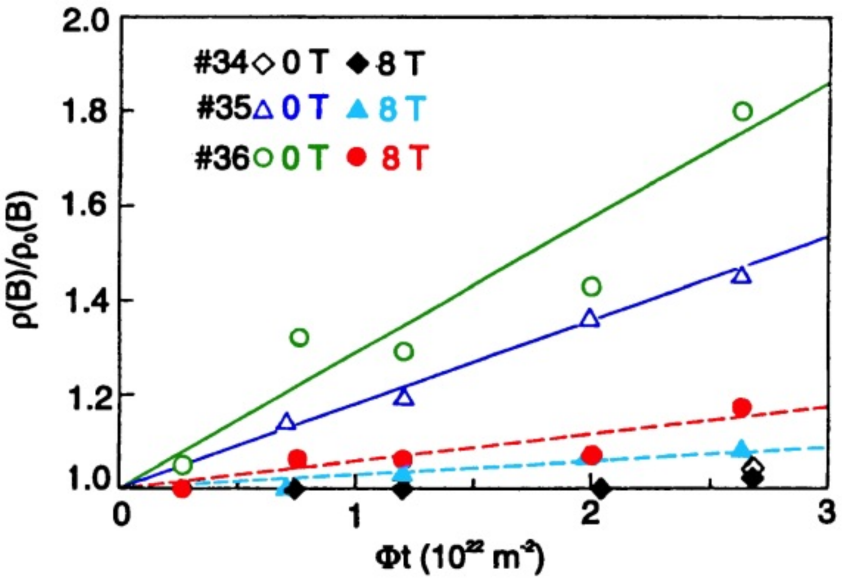
Normal state resistivity essential for stabilization and quench protection

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



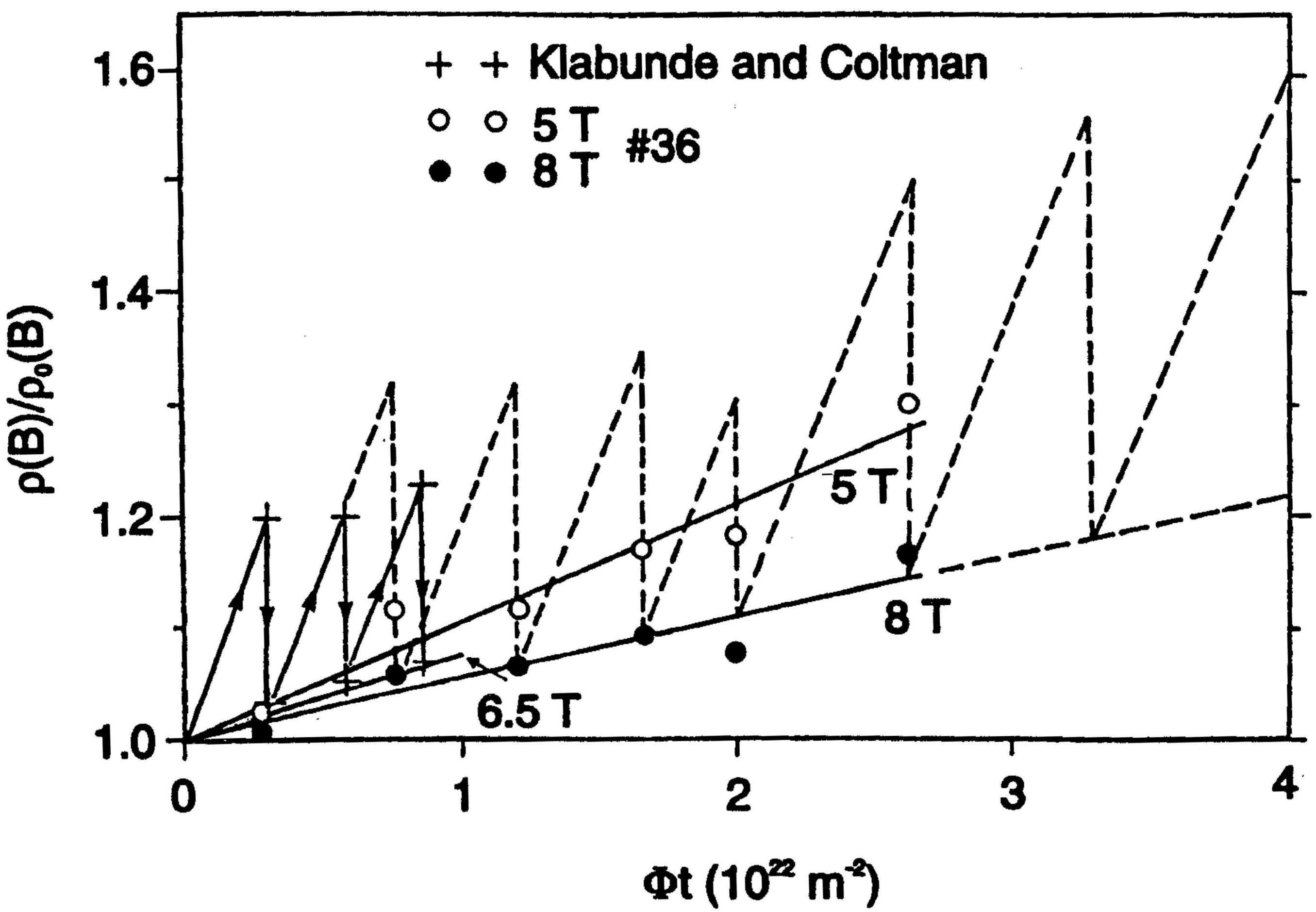
Multifilamentary

NbTi-conductors

#34: RRR ~ 60

#35: RRR ~ 120

#36: RRR ~ 120


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

INSULATION

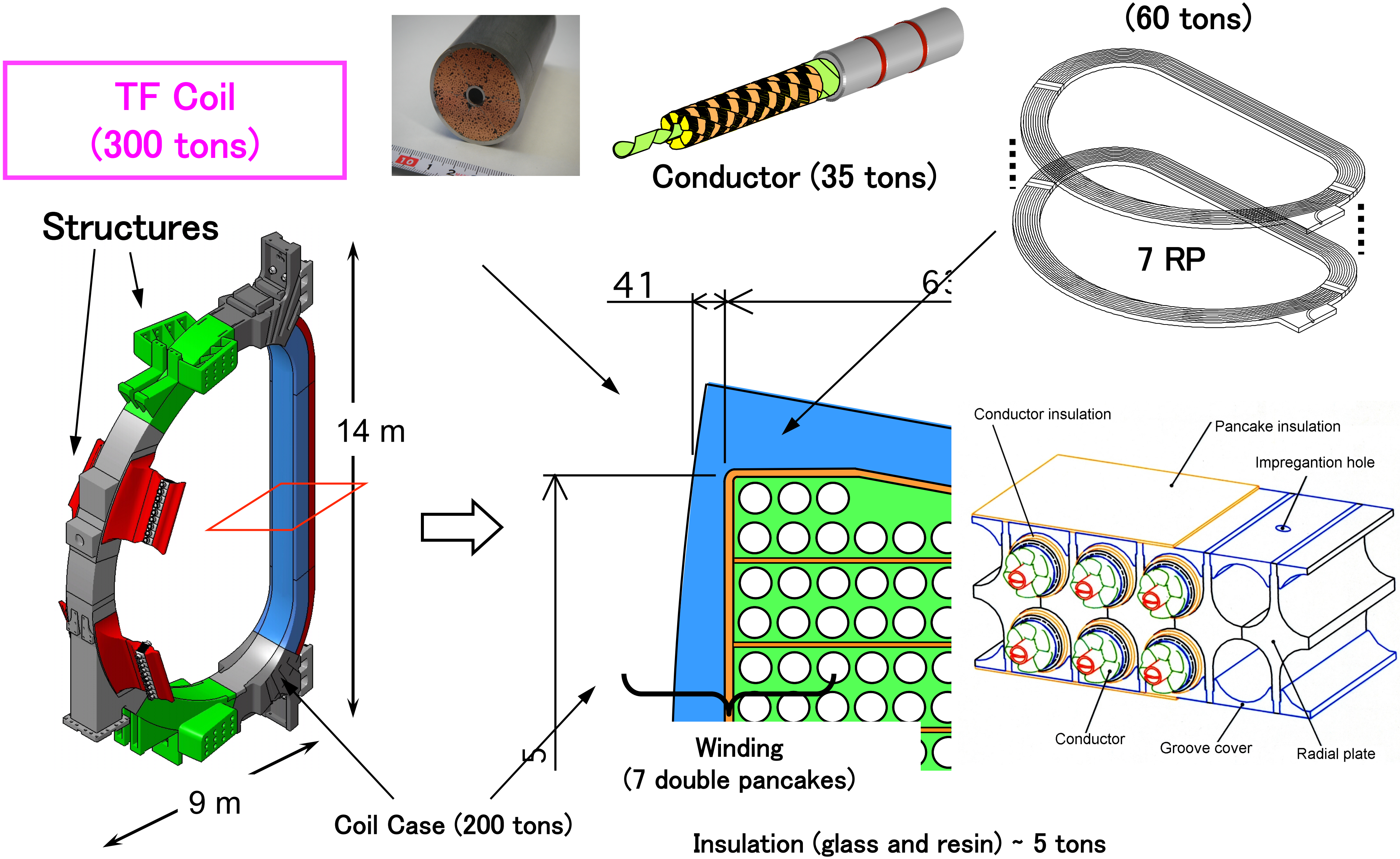
Most critical component of the magnet in a radiation environment

Has to provide **electrical insulation (✓)**

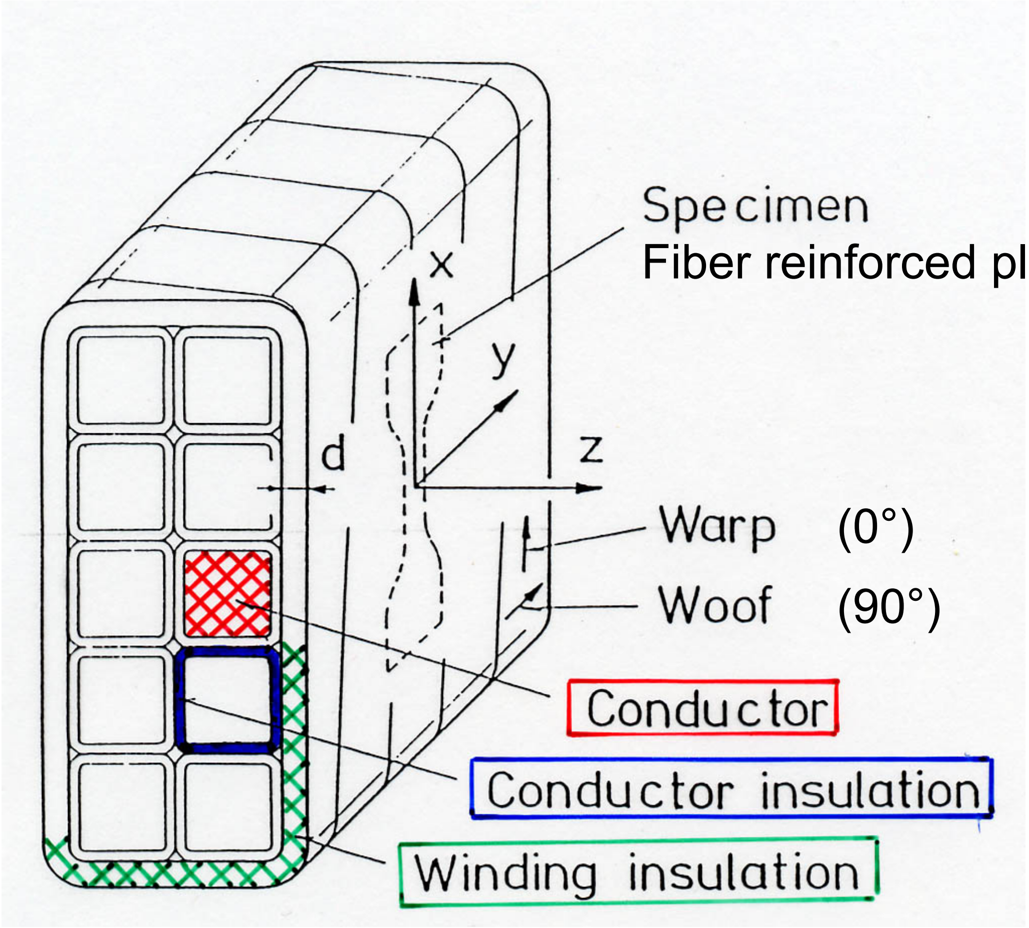
Has to provide **mechanical strength** and to withstand thermal contraction / expansion and Lorentz forces

Must be suitable for a vacuum-pressure impregnation process – “pot life”

TF Coil Design

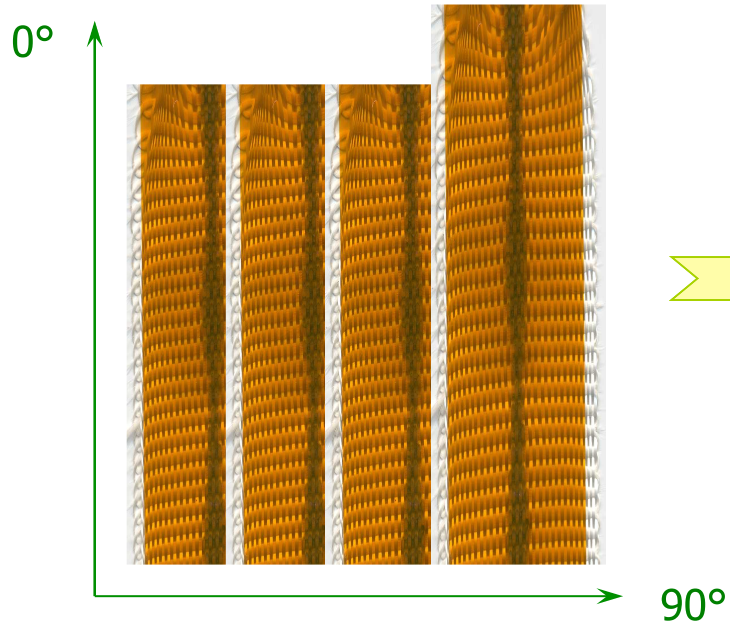


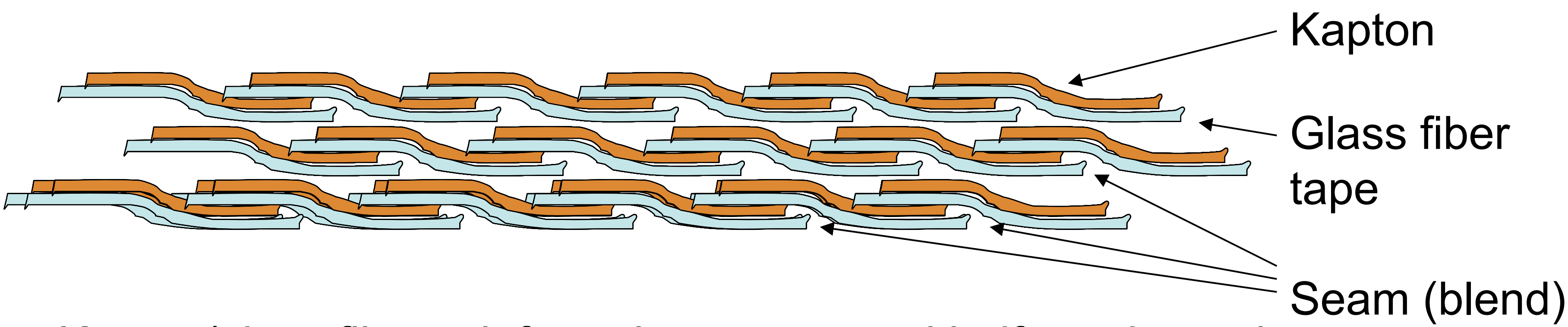
Typical magnet insulation build-up



TF Coil Insulation

strongly orthotropic material properties

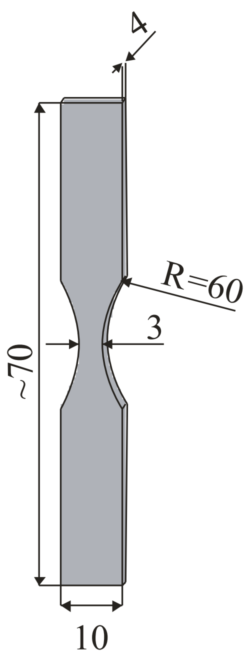




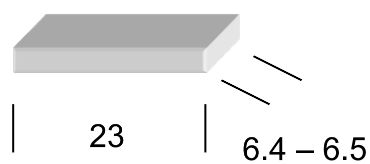
Kapton/glass fiber reinforced tape wrapped half-overlapped

Test procedures

Test specimen



Tensile



SBS

All tests @ 77 K

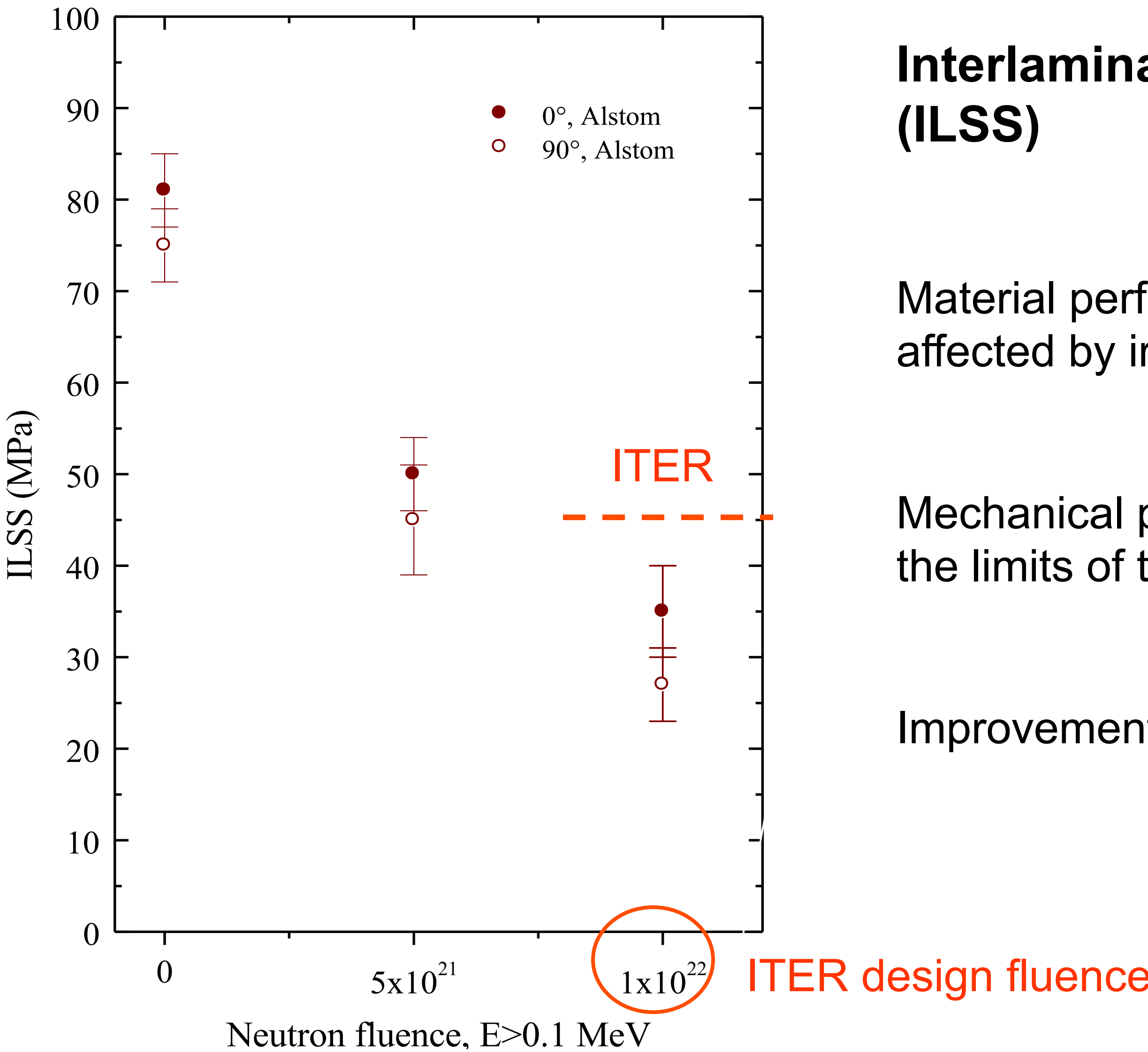
Static and dynamic tensile tests (90 ° direction)

Short-beam-shear (SBS) test with span to thickness ratio of 4:1 and 5:1 (0 ° and 90 ° direction)

Neutron irradiation in the TRIGA reactor (Vienna) to a fast neutron fluence of 1, 2 and 4×10^{22} m^{-2} (E > 0.1 MeV)

Total absorbed dose of ~50, 100 and 200 MGy

EUHT DGEBA Epoxy (Alstom)



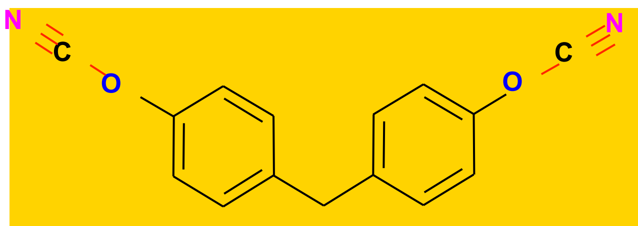
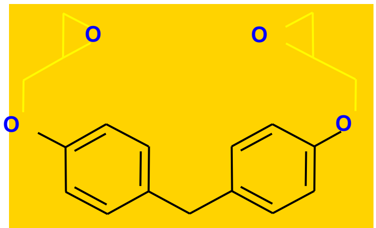
Interlaminar shear strength (ILSS)

Material performance drastically affected by irradiation

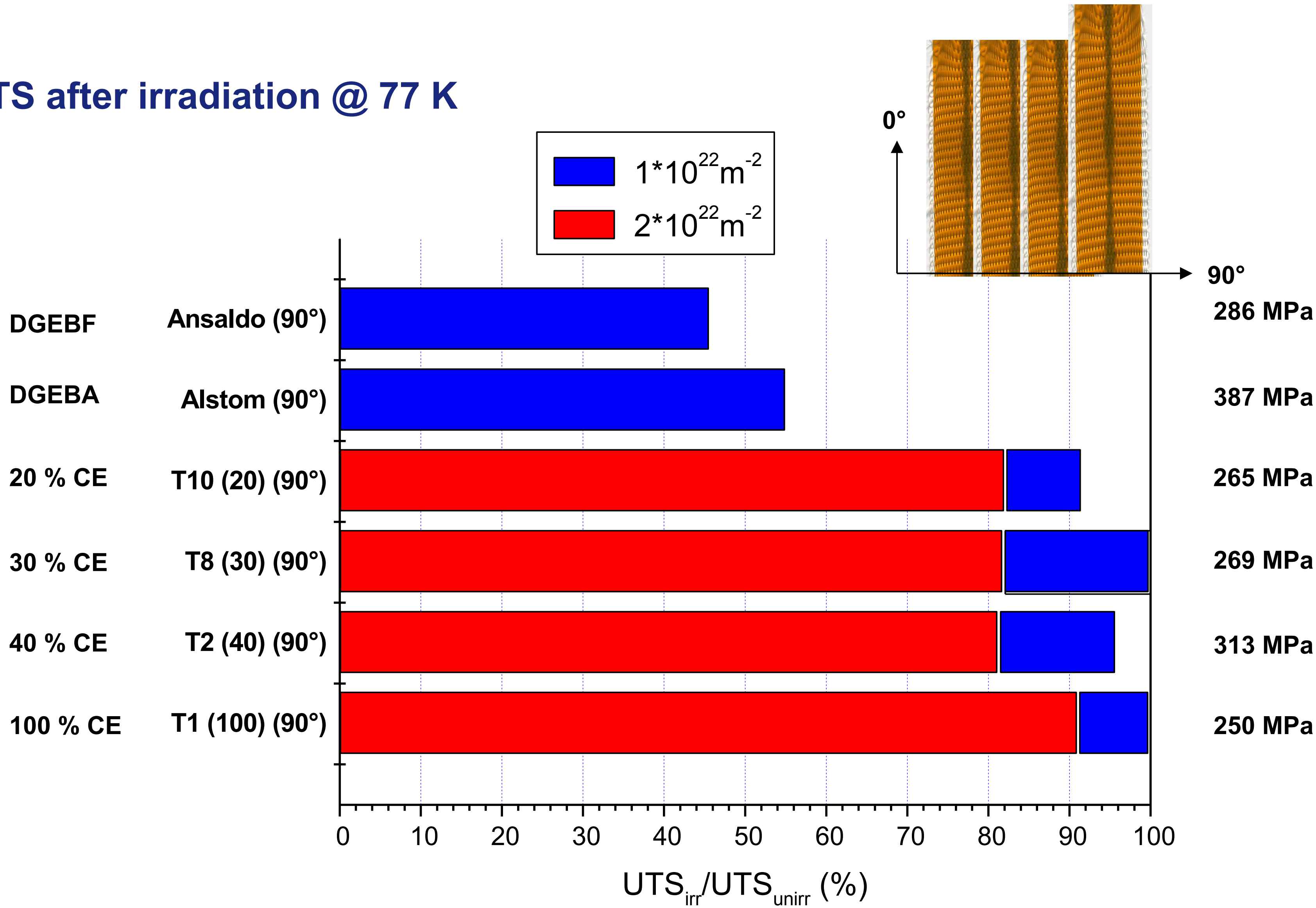
Mechanical properties are close to the limits of the ITER specifications

Improvement of the matrix stability!!

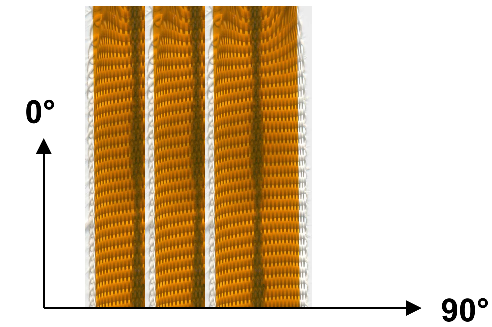
CE / epoxy blend

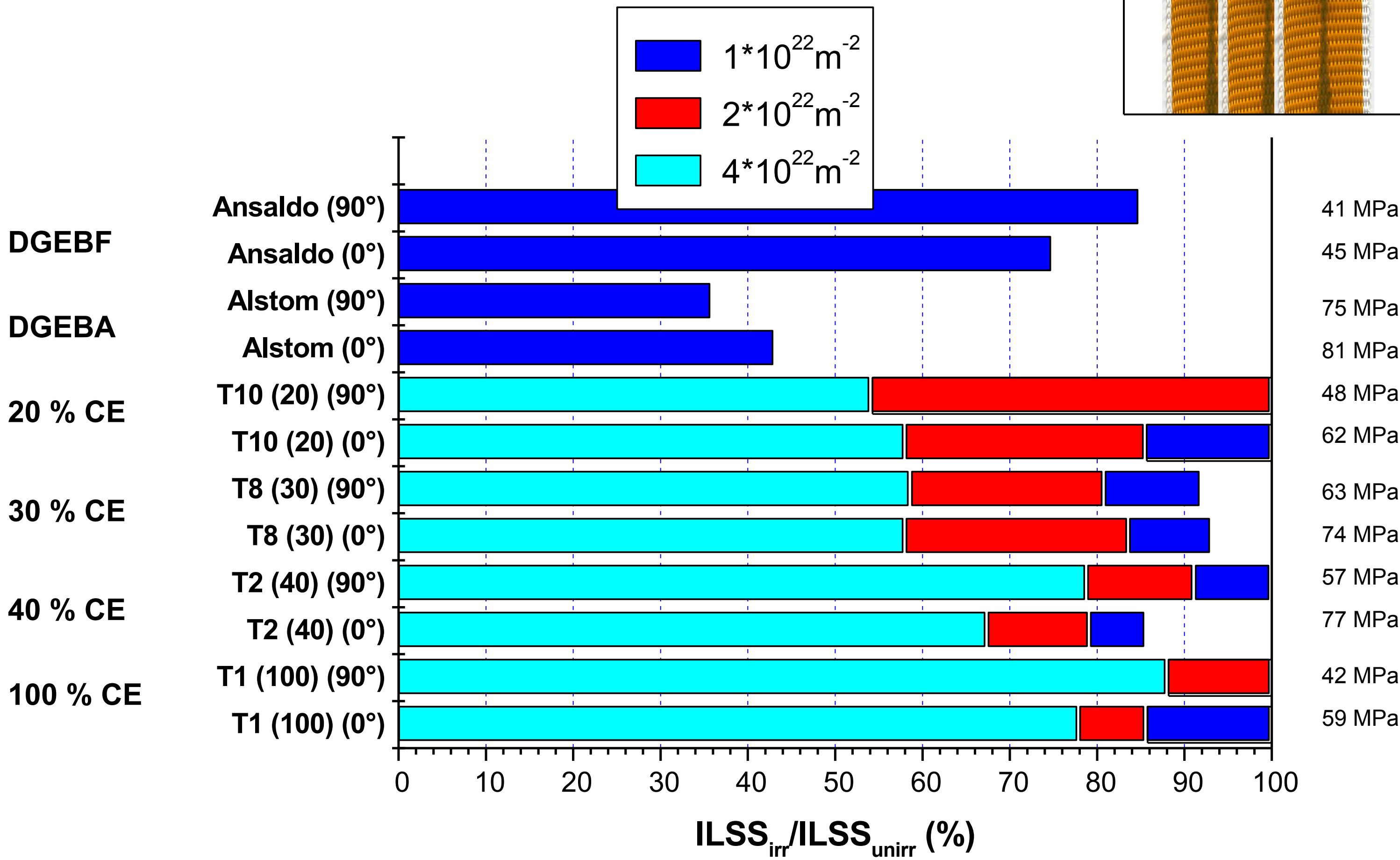
	AroCy L-10	PY 306
		
Safety precautions	Avoid local overheating (hot spots) Store in sealed containers in dry rooms Provide sufficient air exchange Take necessary actions to avoid static electricity	Provide sufficient air exchange Take necessary actions to avoid static electricity Avoid strong acids and bases
Viscosity	$\eta_{25\,°C}$ = 120 mPa s $\eta_{60\,°C}$ = 17 mPa s	$\eta_{25\,°C}$ = 1200-1600 mPa s
Pot life at high quantities	Dependent upon type and concentration of co-catalyst and catalyst used	Can be handled

UTS after irradiation @ 77 K



ILSS after irradiation @ 77 K





SUMMARY and CONCLUSIONS

- LT Superconductors: No problems regarding radiation effects expected for ITER
- Stabilizer: Degradation must be kept in mind
- Insulators: Excellent solution found – industrial tests completed; qualification of materials from different suppliers under way

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.

Work on the insulators started in 1983 and in systematic form in 1990.

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.

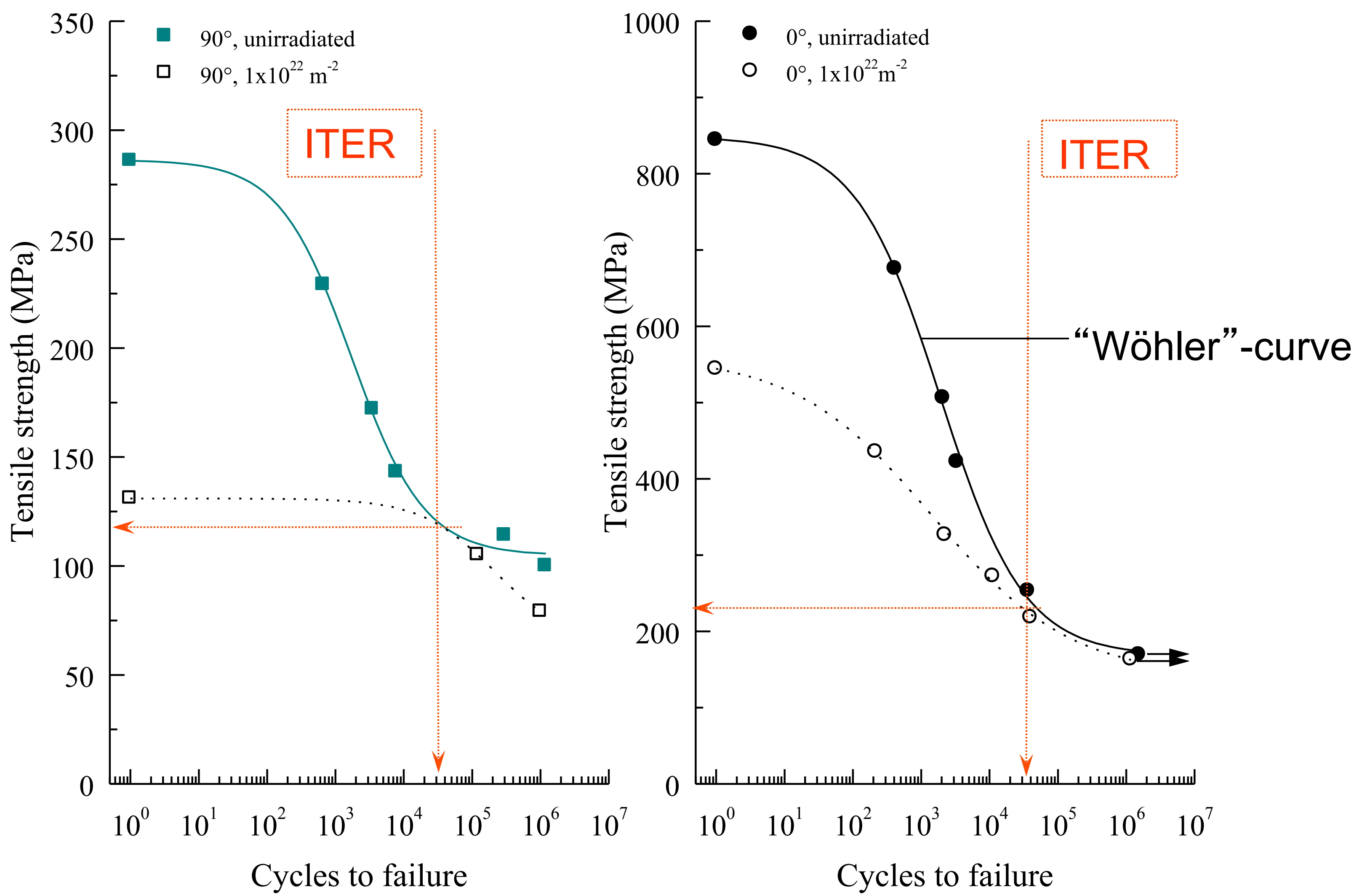
Senior scientists: M. Eisterer, H. Fillunger, K. Humer, R.K. Maix, F.M. Sauerzopf

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

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

EUHT DGEBA Epoxy Ansaldo (similar results for Alstom)

Tensile fatigue performance @ 77 K

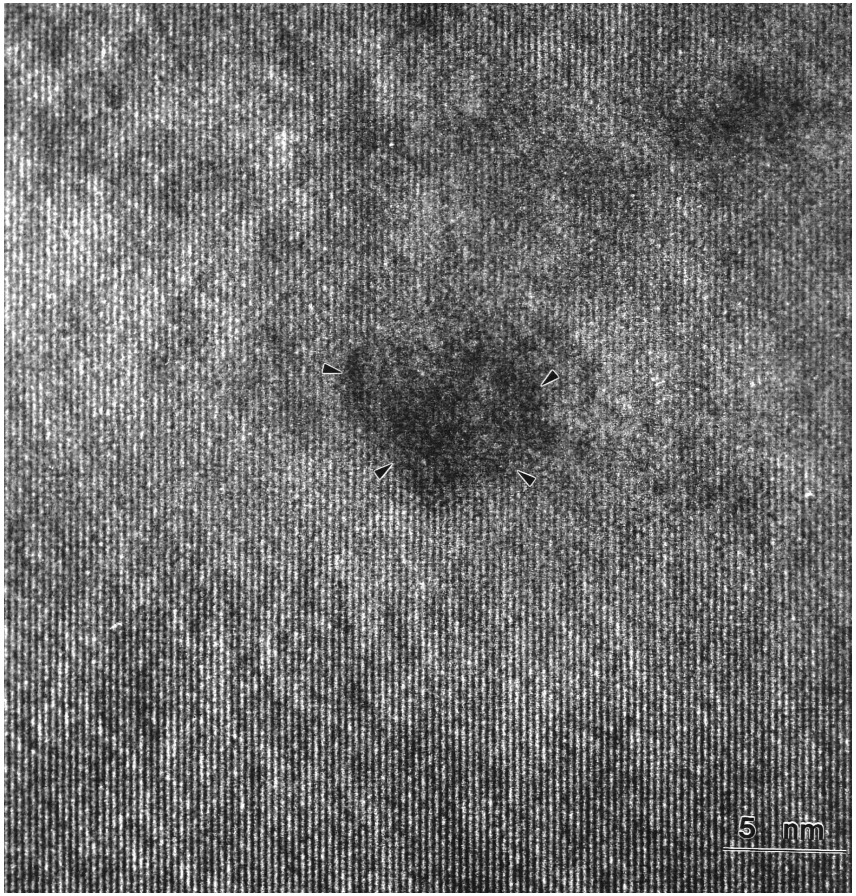


STATISTICALLY DISTRIBUTED

~ SPHERICAL, ~ 2.5 nm Ø

SURROUNDED BY A STRAIN FIELD
OF THE SAME SIZE

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



FAST NEUTRONS

COLLISION CASCADES,

IF THE ENERGY OF THE PRIMARY KNOCK-ON ATOM EXCEEDS

~ 1 keV

Collision Cascade (schematic)