The effect of neutron and gamma radiation on magnet components

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RESMM Workshop, Fermilab, 14 February 2012

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) and by the ITER Organization (IO) is acknowledged.

The contributions of the ATI crew are gratefully acknowledged.

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

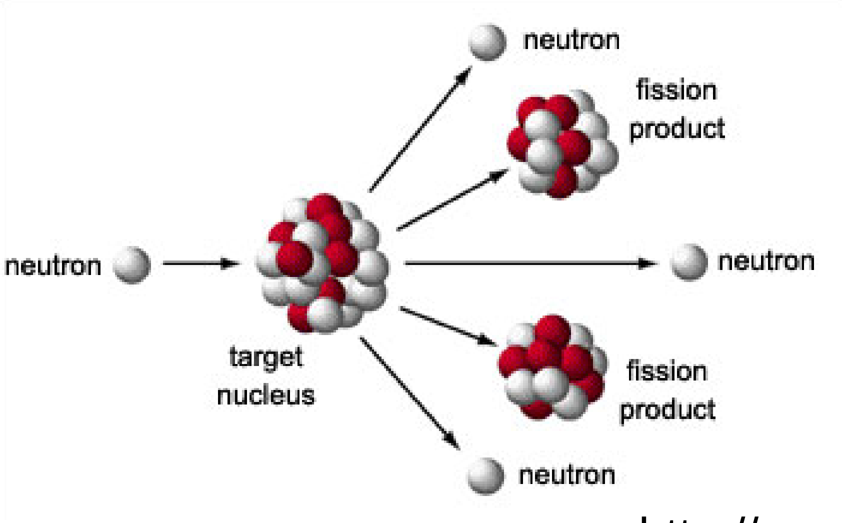
Post-docs: K. Bittner-Rohrhofer, R. Fuger, F. Hengstberger, R. Prokopec, M. Zehetmayer

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

Outlook

- Radiation environment in a fission reactor
  - Neutron and γ - spectrum
- Damage production
  - neutrons, γ - radiation
- Scaling: Prediction of behavior in other radiation environments
- Superconductors: NbTi, Nb_3Sn, MgB_2, cuprates
  - Transition temperature, critical current
- Insulators: epoxy resin, cyanate ester, bismaleimides
  - Dielectric strength
  - Mechanical properties
    - Ultimate tensile strength, iterlaminar shear strength, fatigue behavior
  - Gas evolution
- Conclusions

Fission of ^{235}U

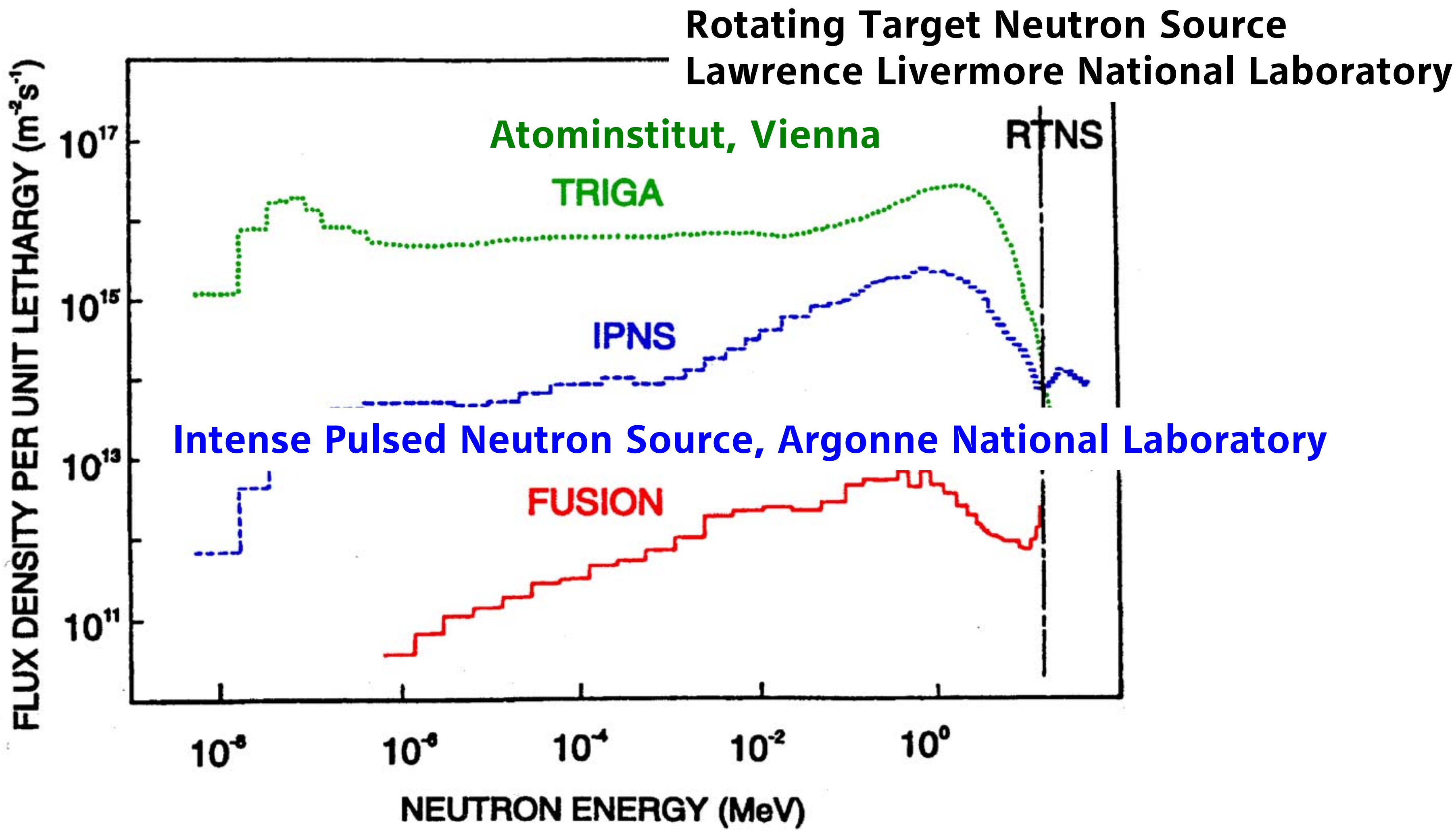


+ ~200 MeV

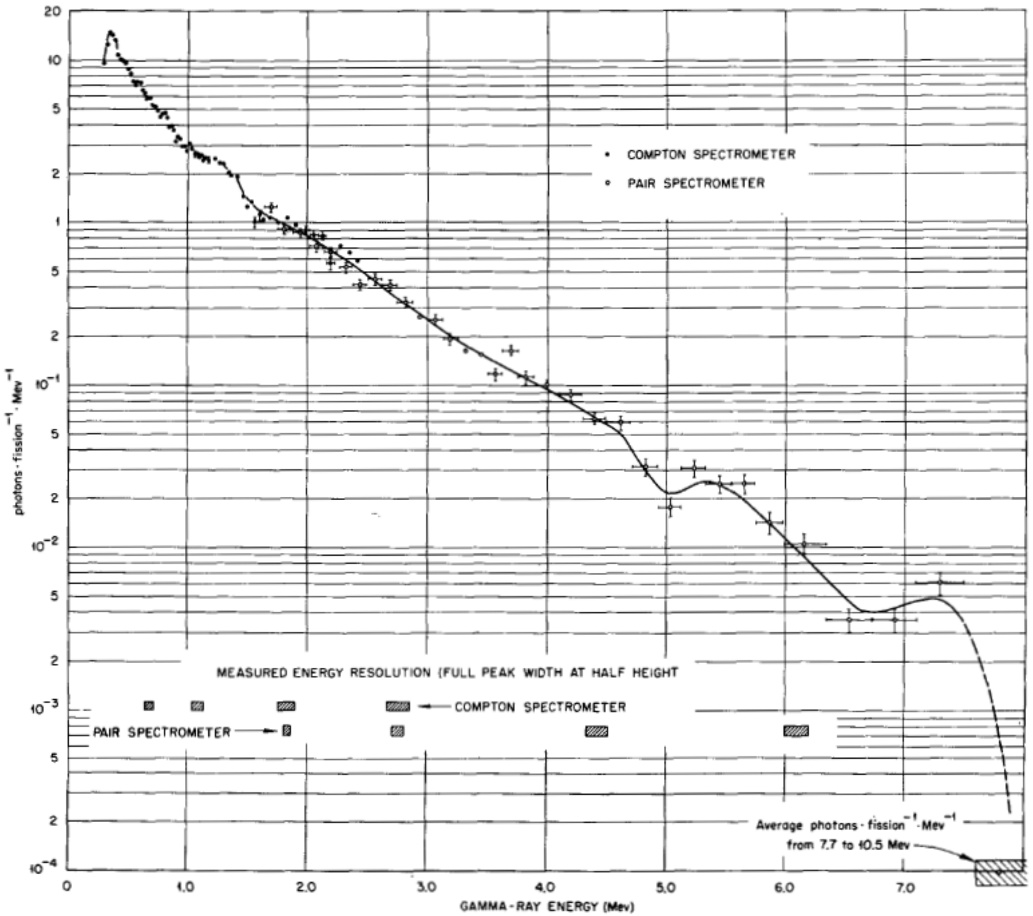
http://www.atomicarchive.com/Fission/Fission1.shtml

kinetic energy of fission products: ~165 MeV
prompt gamma rays: ~7 MeV
kinetic energy of the neutrons: ~6 MeV
energy from fission products (β-decay): ~7 MeV
gamma rays from fission products : ~6 MeV
anti-neutrinos from fission products : ~9 MeV

Neutron Energy Distribution



Fission: prompt γ emission



F.C. Maienschein
R.W. Peelle
W. Zobel
T. A. Love

Second United Nations International Conference on the Peaceful Uses of Atomic Energy 1958

Total: 1 MGy/h

7 photons/fission, 7 MeV/fission, ~100 keV to ~8 MeV, peak at 300 keV
In addition: radioactive decay, e^--e^+ annihilation (511 keV), n-capture, Bremsstrahlung

Damage Production: Neutrons

"Elastic" collision with lattice atoms:

$$E_p \le \frac{4 m_L m_n}{(m_L + m_n)^2} E_n \quad \begin{aligned} &= E_n && \text{(Hydrogen)} \\ &\approx 4 \frac{1}{m_L} E_n && m_L >> 1 \end{aligned}$$

Minimum energy to displace one atom: $E_p > E_B$ ~4 eV C-H
(epithermal and fast neutrons) ~few eV in metals
~5-40 eV in ionic crystals

Stable?

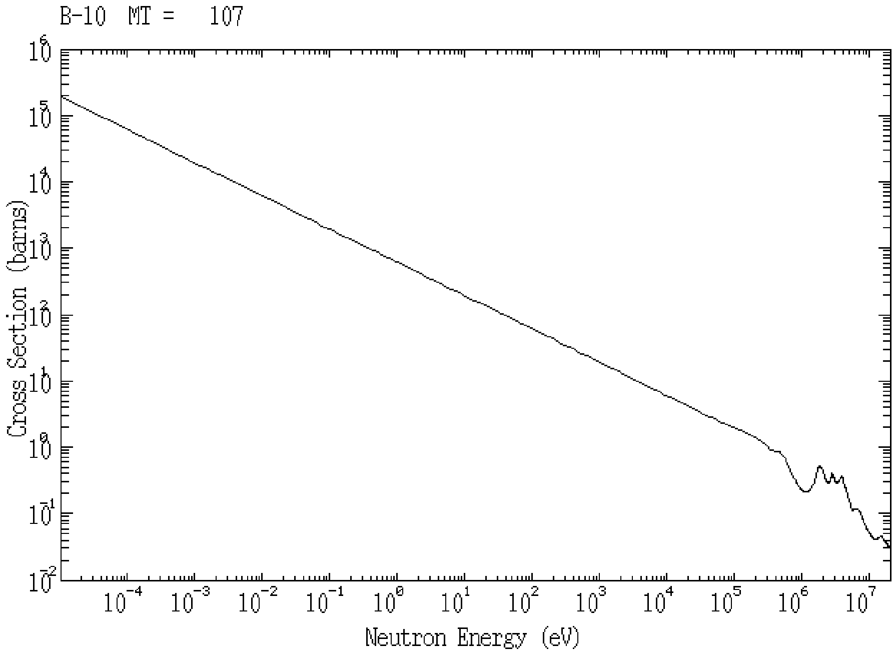
$E_p > \approx$ 1 keV: Displacement cascades

Stable in HTS
Disintegrate at room temperature to small clouds of point defects in LTS

Damage Production: Neutrons

Nuclear reactions: (n,γ), (n,β), (n,α) ,fission

Example: $^{10}B + n \rightarrow {}^{7}Li$ (1 MeV) + ^{4}He (1.7 MeV)



Neutron caption cross sections are most often largest at low neutron energies.

(n,γ), (n,β): point defects

Damage Production: Gamma rays

Interaction via electronic system:

Compton scattering: $E_p \leq \frac{4E_\gamma^2}{mc^2 + 2E_\gamma}$

Photoelectric effect: $E_e = E_\gamma$

Pair production: $E_\gamma > 1.022$ MeV

Ionization!

- Breaks chemical bonds in organic molecules.
  (plastic deteriorates in sunlight.)
- Little effect in crystalline materials (superconductors).

Damage Calculation: Neutrons

Fast neutron fluence: 4×10^{22} m^{-2} (E > 0.1 MeV)

Superconductors:

Element	Damage energy cross-section (keV barn)	Damage energy per atom (eV)	Displacements per atom ($\times10^{-3}$)	Helium production (at ppb)	Hydrogen production (at ppb)
Nb	70.2	0.28	2.81	0.17	1.55
Ti	81.7	0.33	3.27	1.73	7.80
Ta	46.6	0.19	1.41	0.004	0.24
Sn	76.2	0.30	2.01	0.04	0.15
V	91.4	0.37	3.66	0.04	1.50
Mo	77.6	0.31	2.07	0.43	3.11
Cu	70.1	0.28	2.81	0.79	34.90
Al	88.2	0.35	5.23	2.09	11.59

Insulators:

Element	Total absorbed energy ($\times10^{8}$ Gy)	Displacements per atom ($\times10^{-3}$)	Helium production (at ppb)	Hydrogen production (at ppb)
H	9.09	0.89	—	—
B (20% ^{10}B, 80% ^{11}B)	458.66	777.17	1.94×10^{6}	4.97
C	0.14	2.83	6.33	0.01
N	0.37	2.90	248.56	4733.30
O	0.09	4.21	24.67	0.17
F	0.09	5.37	63.12	2.95
Na	0.08	5.80	2.00	3.87
Mg	0.04	5.86	8.53	3.45
Si	0.03	5.52	7.04	14.97
K	0.06	2.93	72.02	356.15
Ca	0.06	3.10	145.73	302.99
S	n.a.	3.69	179.28	181.08
Fe	0.01	2.90	0.91	16.05
Al	0.06	cf. Table 2		

Other Radiation Environments?

Scaling

Superconductors:

$$\langle \sigma T \rangle = \frac{\int \sigma(E) T(E) \frac{d\Phi}{dE} dE}{\int \frac{d\Phi}{dE} dE}$$ displacement energy cross section

$$E_D = \langle \sigma T \rangle \Phi t$$ **damage enegy**

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

Insulators:

Dose (total absorbed energy) [Gy]=[J/kg]

Prediction of property changes in other radiation environments (?)

Changes of Superconducting Properties

Transition Temperature T_c

- through disorder

Normal state resistivity ρ_n

- through the introduction of additional scattering centers

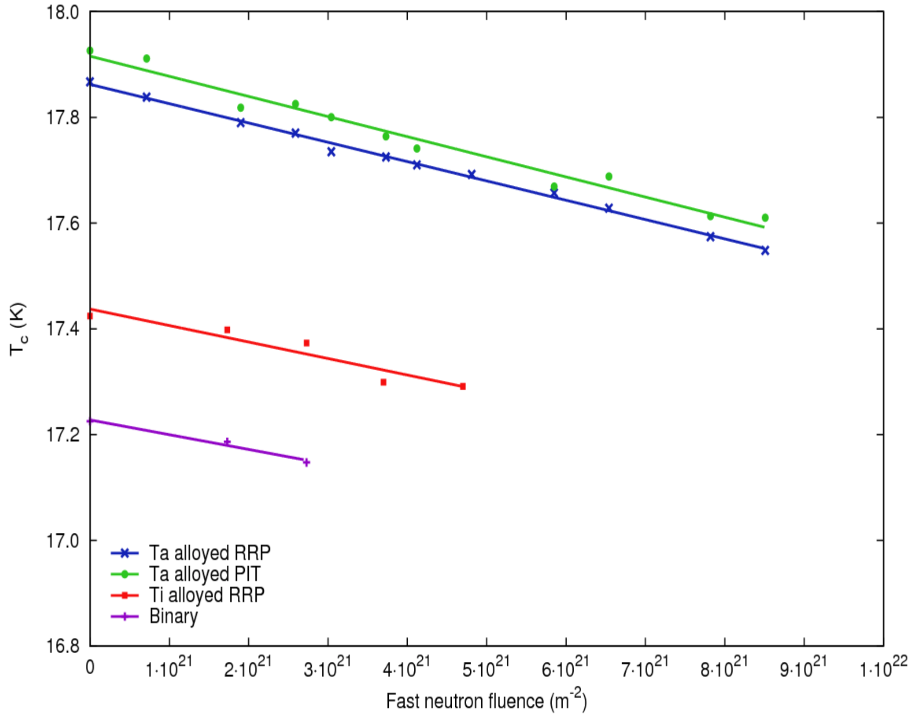
Upper critical field H_{c2}

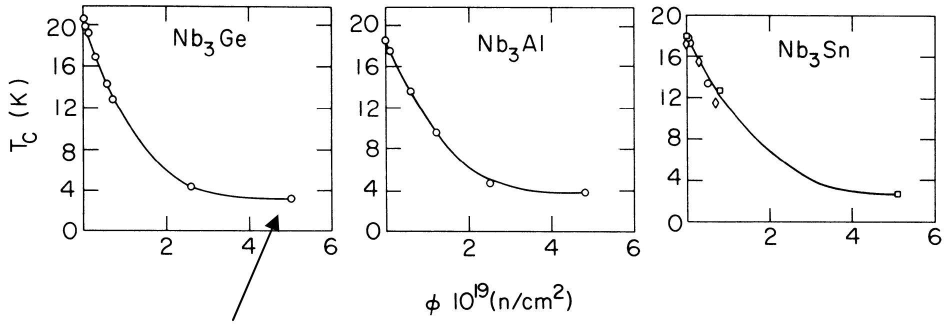
- through the same mechanism: $\rho_n \propto 1/l \propto \kappa \propto H_{c2}$

Critical current density J_c

- through the production of pinning centers

Changes in Transition Temperature





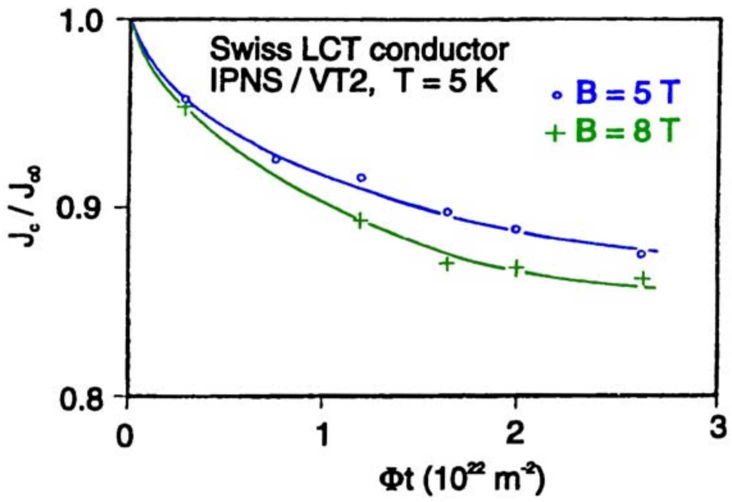
maximum fluence around
7-10 x 10^{23} m^{-2} (E>0.1 MeV)

Decrease at a fast fluence of 10^{22} m^{-2}:

- NbTi: ~ 0.015 K
- A-15: ~ 0.3 K
- Cuprates: ~ 2 K
- MgB_2: ~ 4 K (n,α)!

Changes of the Critical Current

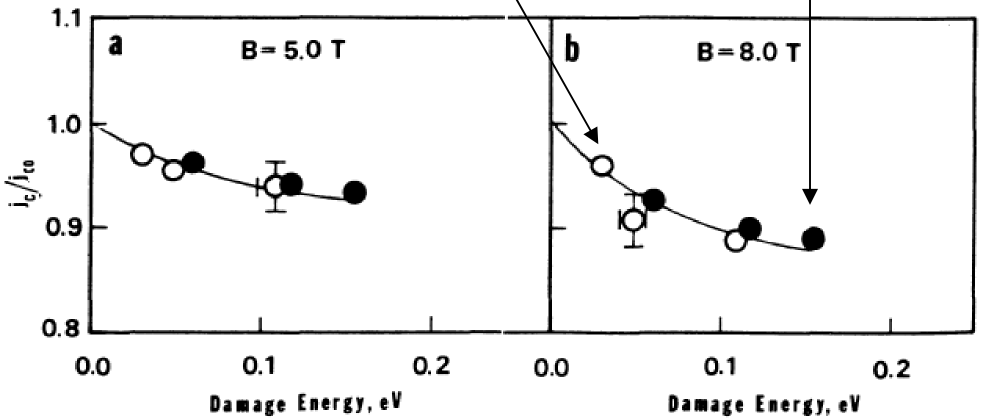
NbTi, 4.2 K



Damage energy scaling:

IPNS (distr.)

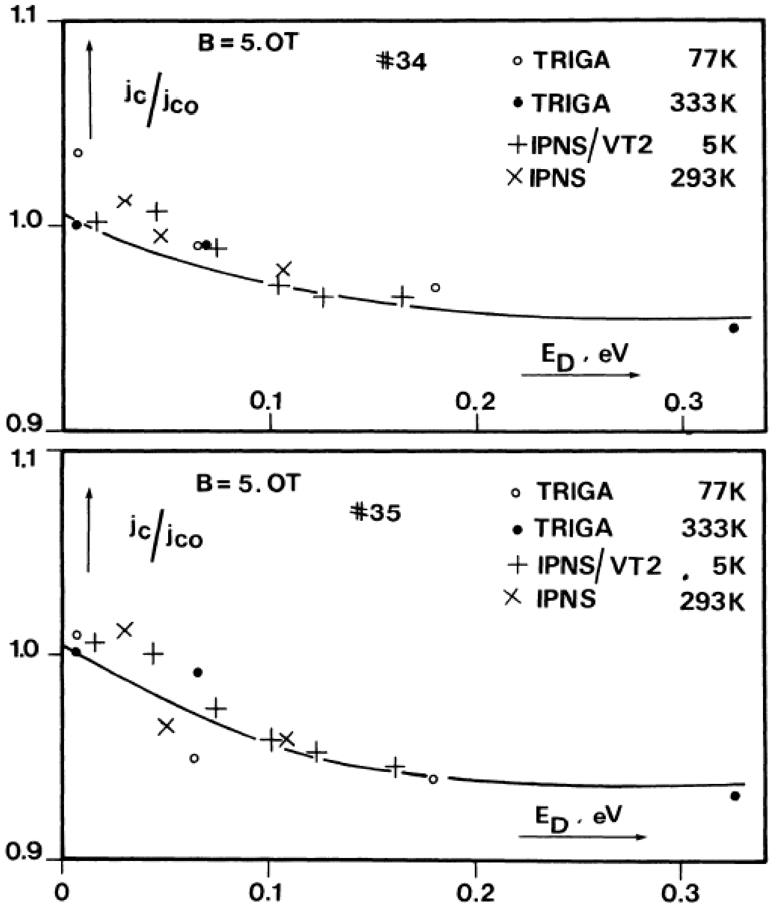
RTNS (14 MeV)



H.W. Weber, Int. J. Mod. Phys. E 20 (2011) 1325

Changes of the Critical Current

NbTi, 4.2 K

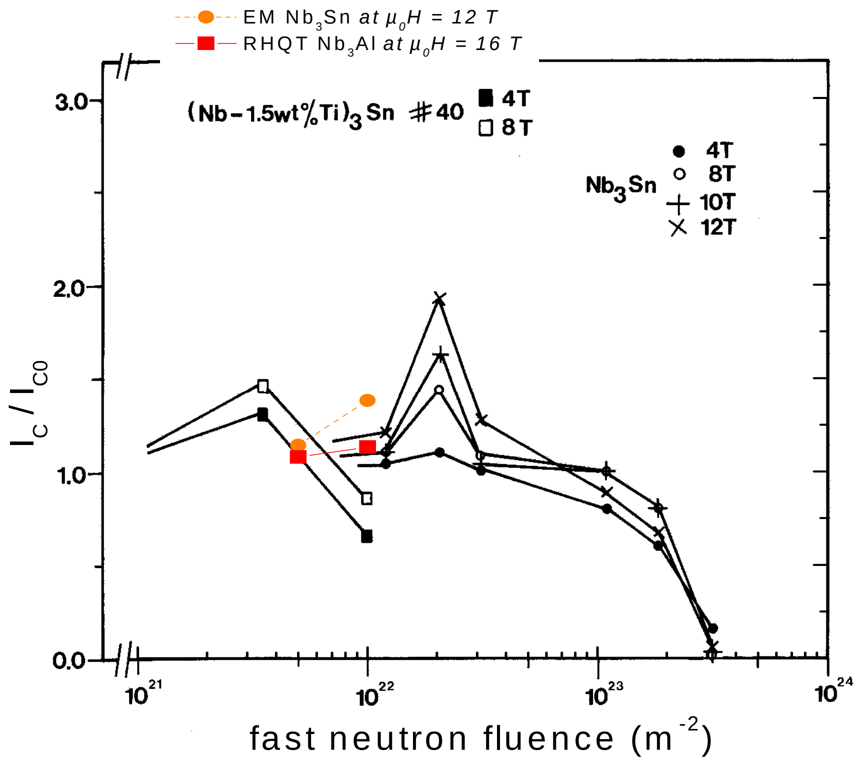


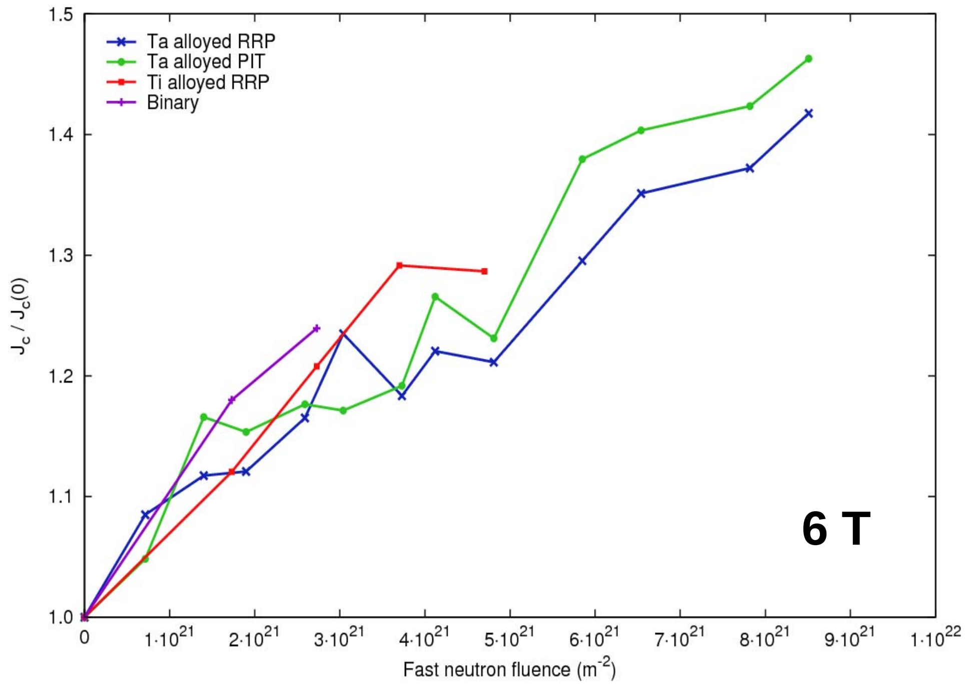
Irradiation temperature is rather unimportant! (intermediate warm-up)

H.W. Weber, Int. J. Mod. Phys. E 20 (2011) 1325

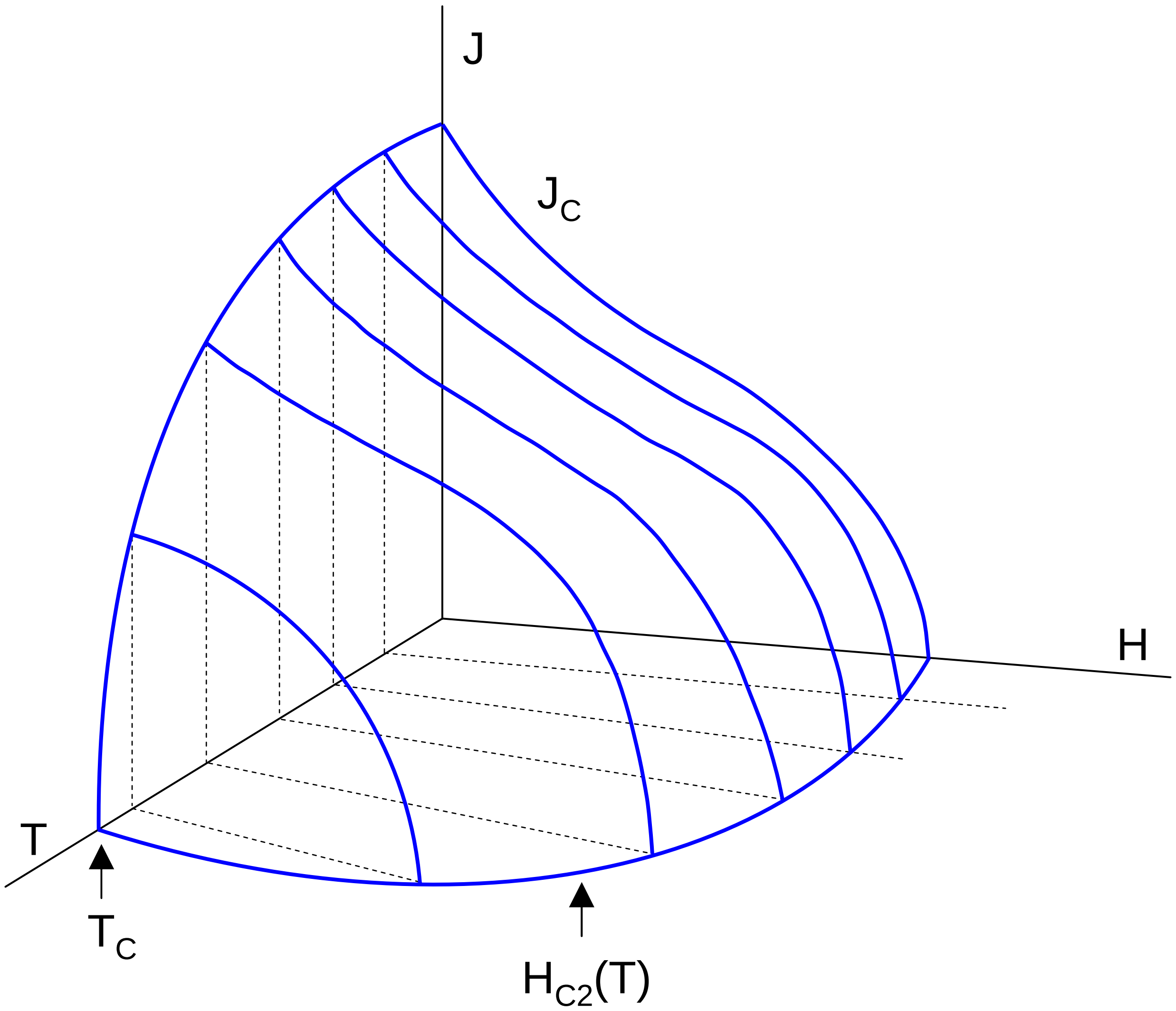
Changes of the Critical Current

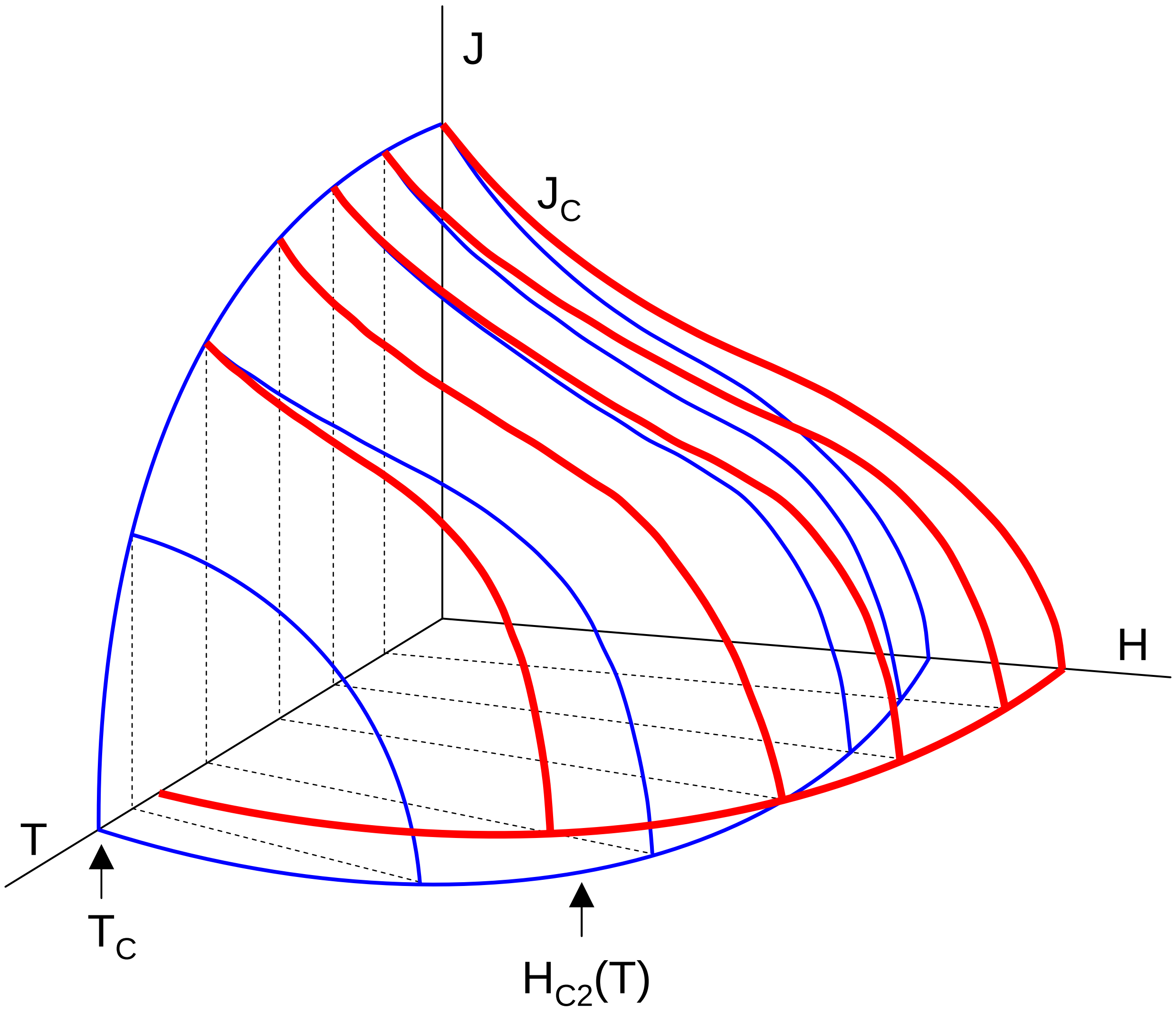
Nb_3Sn, 4.2 K





H.W. Weber, Adv. Cryog. Eng. **32** (1986) 853

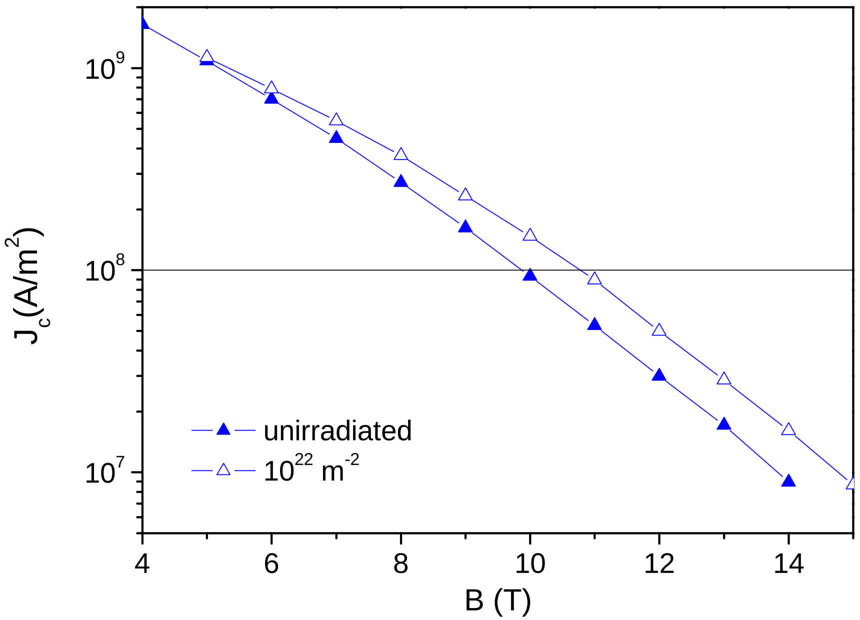

J
J_C
H
T
T_C
H_C2(T)

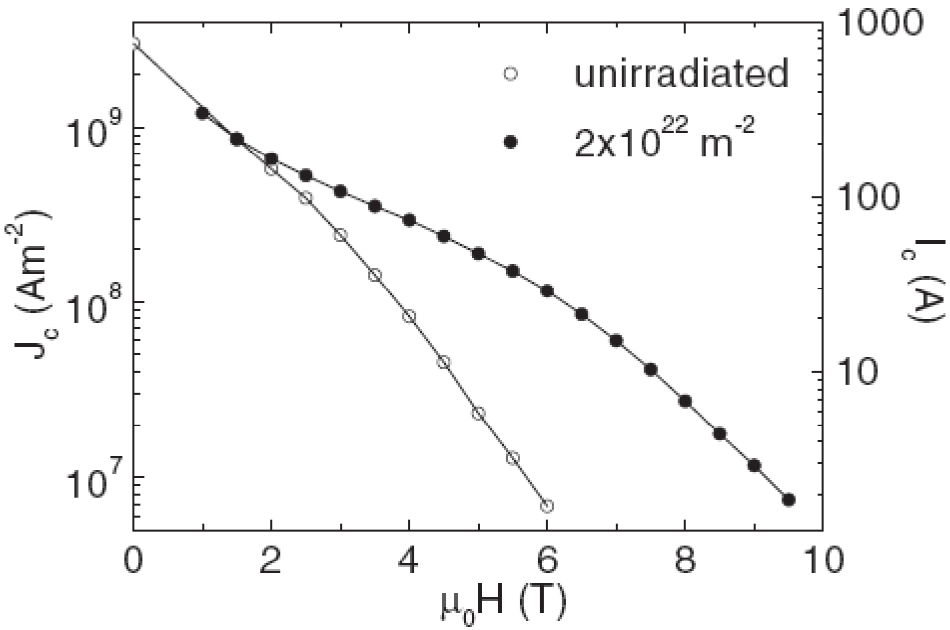

J
J$_C$
H
T
T$_C$
H$_{C2}$(T)

Changes of the Critical Current

MgB_2, 4.2 K

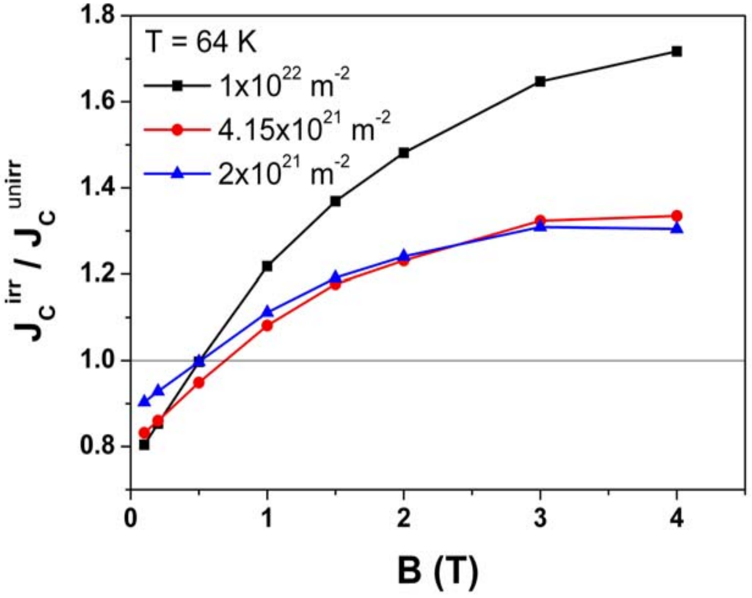
fast neutron fluence: 10^{22} m^{-2}



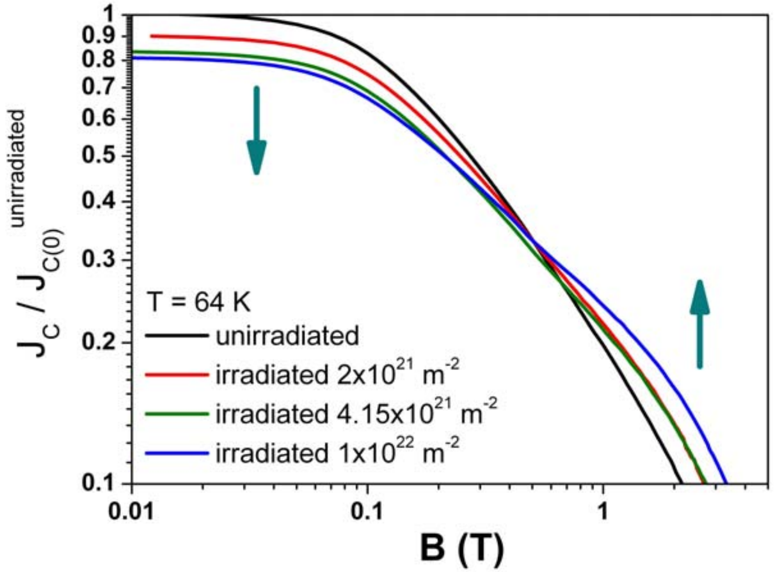


Maximum at around 1-2×10^{22} m^{-2} depending on T_c^{unirr}.

Changes of the Critical Current



Y-123

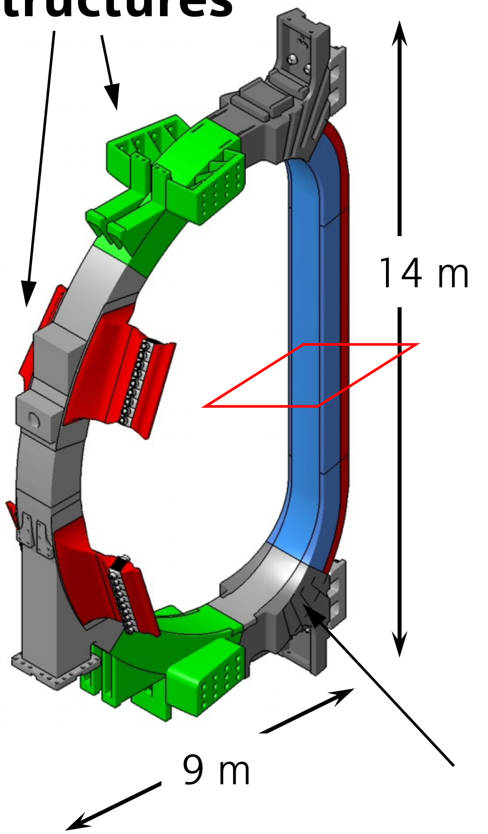


- Decrease of J_C at low fields
- Increase of J_C at higher field
- Start of (overall) degradation depends on temperature ($1\text{-}2\times10^{22}$ m^{-2} at 77 K)

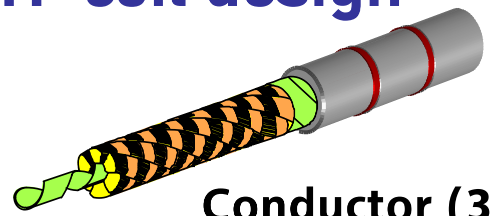
Crossover field (mT)	$2x10^{21}$ m^{-2}	$4x10^{21}$ m^{-2}	$1x10^{22}$ m^{-2}
77 K	244	382	630
64 K	114	219	440
50 K	130	195	334

ITER TF coil design

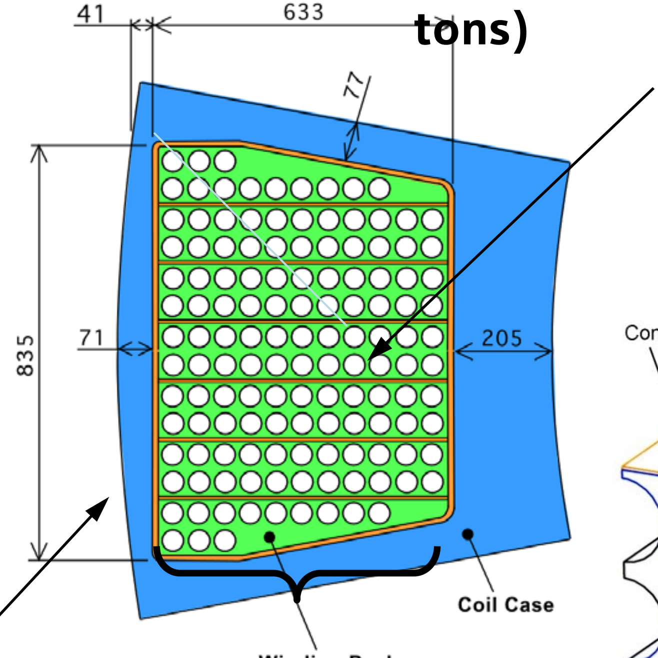
Structures



TF Coil (300 tons)
Boeing 747: ~185 t
A380: ~280 t



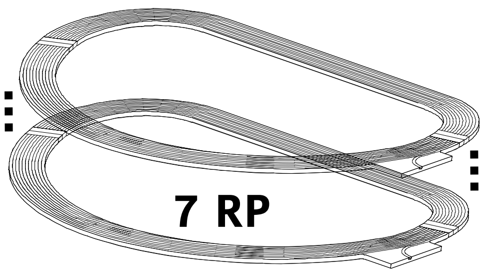
Conductor (35 tons)

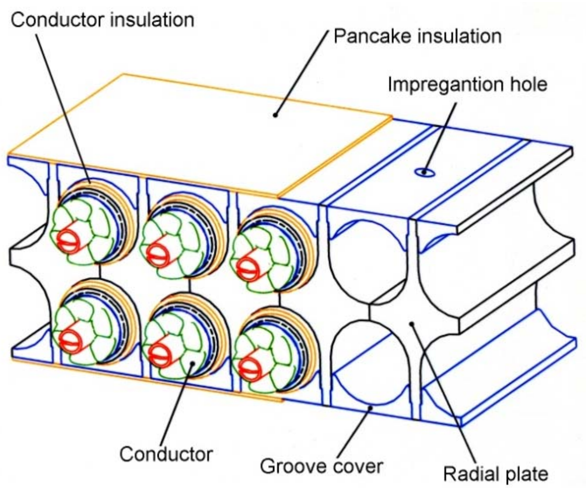


Coil Case (200 tons)

Winding (7 double pancakes)

Radial Plate (RP) (60 tons)

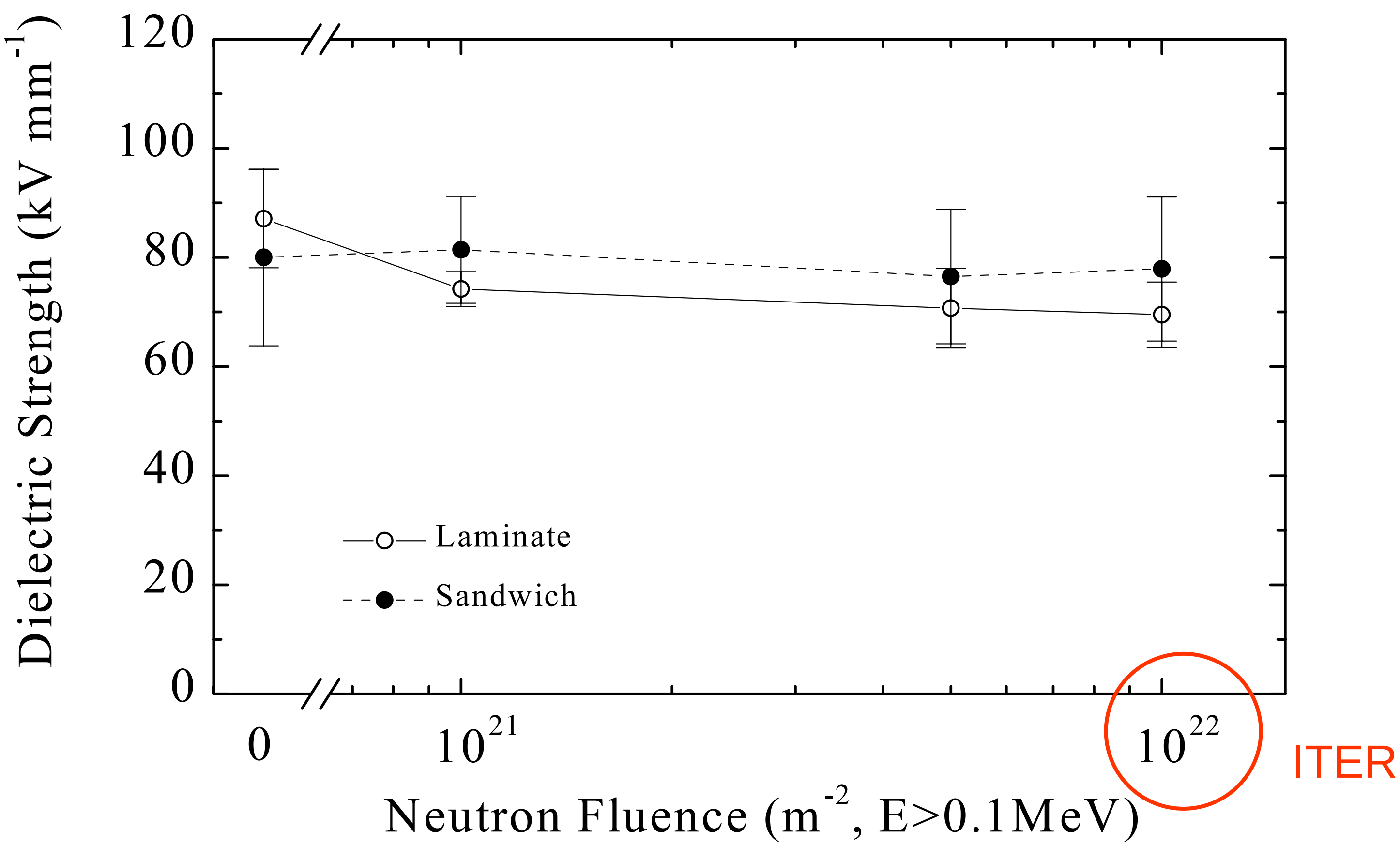




Insulation (glass and resin) ~ 5 tons

Impregnation of TF Model Coil

Dielectric strength at 77 K after reactor irradiation



Radiation effects on insulators

Neutrons directly deposited energy by the entire neutron spectrum (via computer codes and damage parameters for each constituent of resin, i.e. H, C, O, N, ...) production of H, He → gas production

γ-rays Dose rate (Gy/h) times irradiation time (h)

⇒ Total absorbed energy (Gy)

⇒ Scaling quantity ?

Element	Total absorbed energy ($\times 10^8$ Gy)	Displacements per atom ($\times 10^{-3}$)	Helium production (at ppb)	Hydrogen production (at ppb)
Hydrogen	9.09	0.89	—	—
Boron[a]	458.66	777.17	1.94×10^6	4.97
Carbon	0.14	2.83	6.33	0.01
Nitrogen	0.37	2.90	248.56	4733.30
Oxygen	0.09	4.21	24.67	0.17
Fluorine	0.09	5.37	63.12	2.95
Sodium	0.08	5.80	2.00	3.87
Magnesium	0.04	5.86	8.53	3.45
Silicon	0.03	5.52	7.04	14.97
Potassium	0.06	2.93	72.02	356.15
Calcium	0.06	3.10	145.73	302.99
Sulphur	—	3.69	179.28	181.09
Iron	0.01	2.90	0.91	16.05
Aluminium	0.06			

[a] 20% ^{10}B, 80% ^{11}B.
[b] Data not available.

Damage calculations

Examples:

ZI-003 (Epoxy Resin)
15 wt% H, 75 wt% C, 3 wt% N, 7 wt% O

irradiated to $5x10^{22}$ m^{-2} (E>0.1 MeV) in:

ZI-005 (Bismaleimide Triazine)
5 wt% H, 73 wt% C, 10 wt% N, 12 wt% O

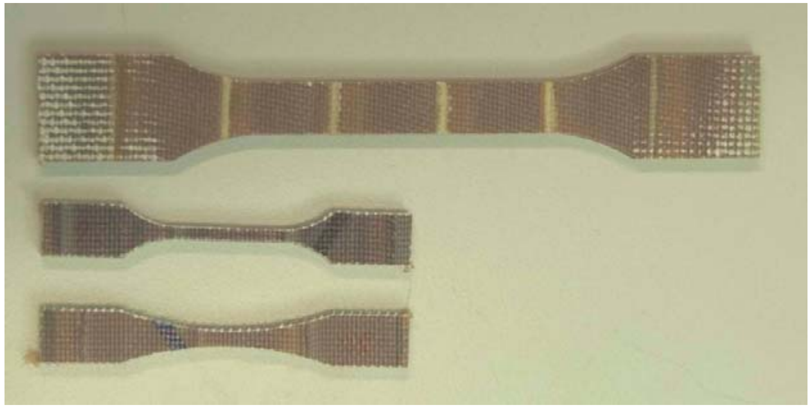
irradiated to $7.8x10^{21}$ m^{-2} (E>0.1 MeV)

		TRIGA Vienna:		IPNS Argonne:	
ZI-003:	from neutrons:	186 MGy	(50 %)	16.3 MGy	(39 %)
	from gamma rays:	182 MGy	(50 %)	25.9 MGy	(61 %)
		368 MGy	(100%)	42.2 MGy	(100%)
ZI-005:	from neutrons:	76 MGy	(30 %)	6.5 MGy	(20 %)
	from gamma rays:	182 MGy	(70 %)	25.9 MGy	(80 %)
		258 MGy	(100%)	32.4 MGy	(100%)

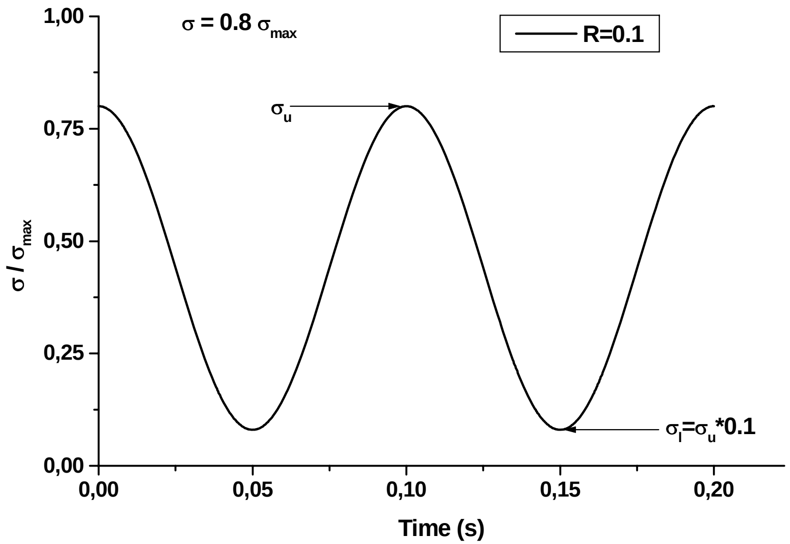
Mechanical Tests

MTS 810 test facility

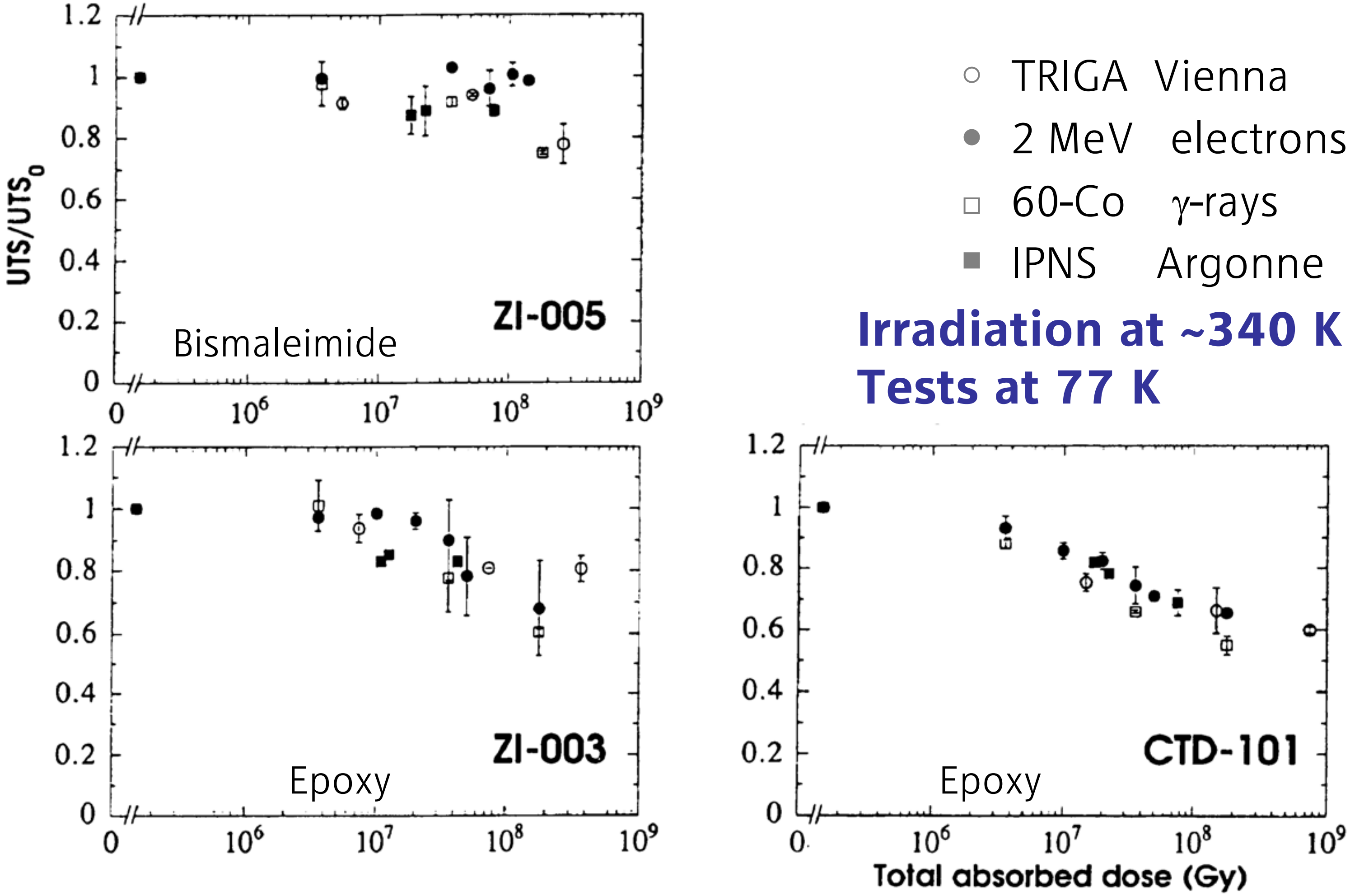
Tensile test specimen geometries



Fatigue measurements



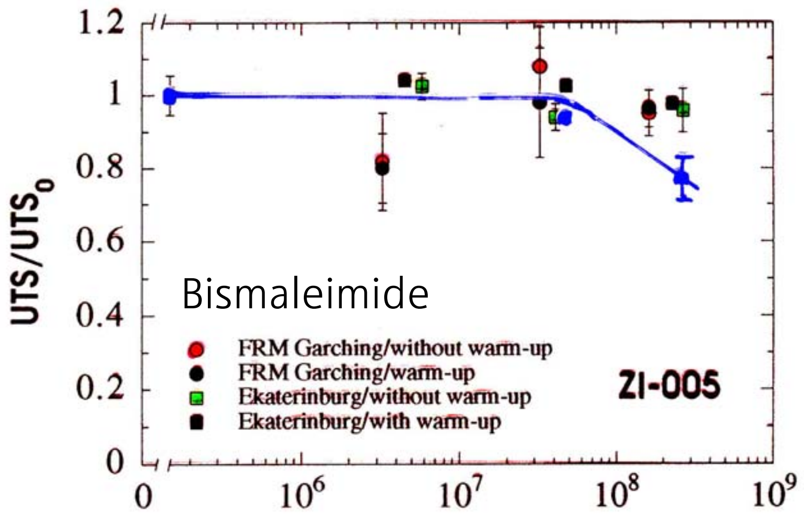
Influence of radiation environment and resin composition



Irradiation at ~340 K
Tests at 77 K

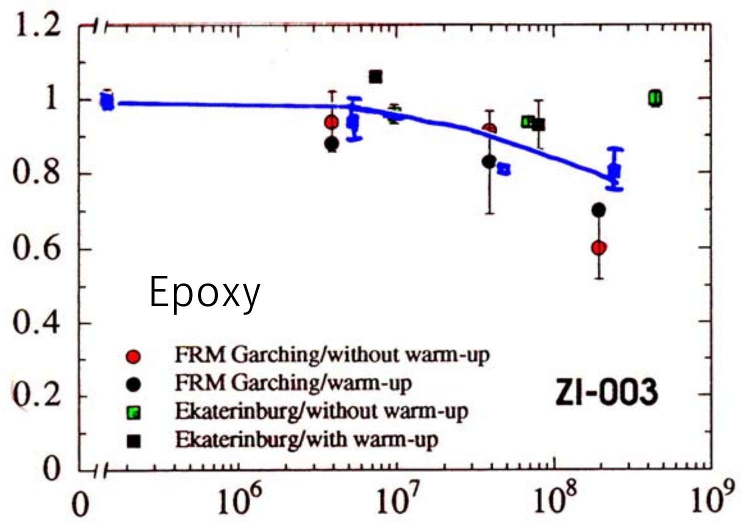
Scaling works well!

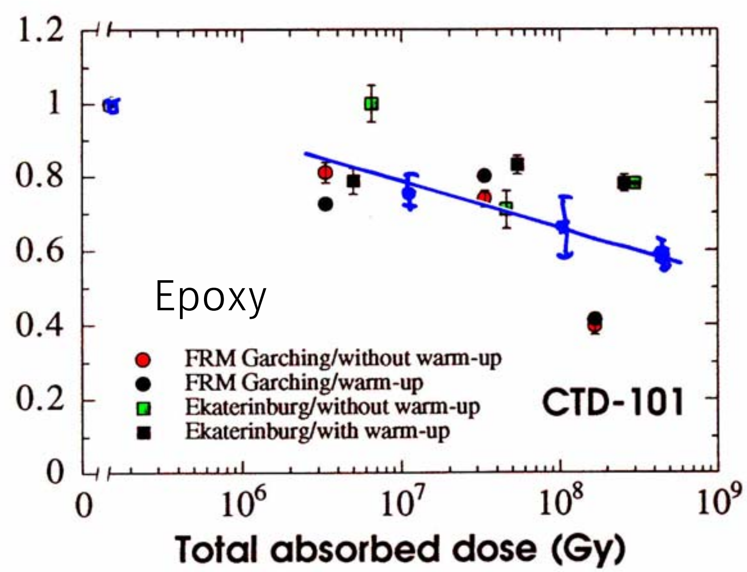
Influence of irradiation temperature and of annealing to RT



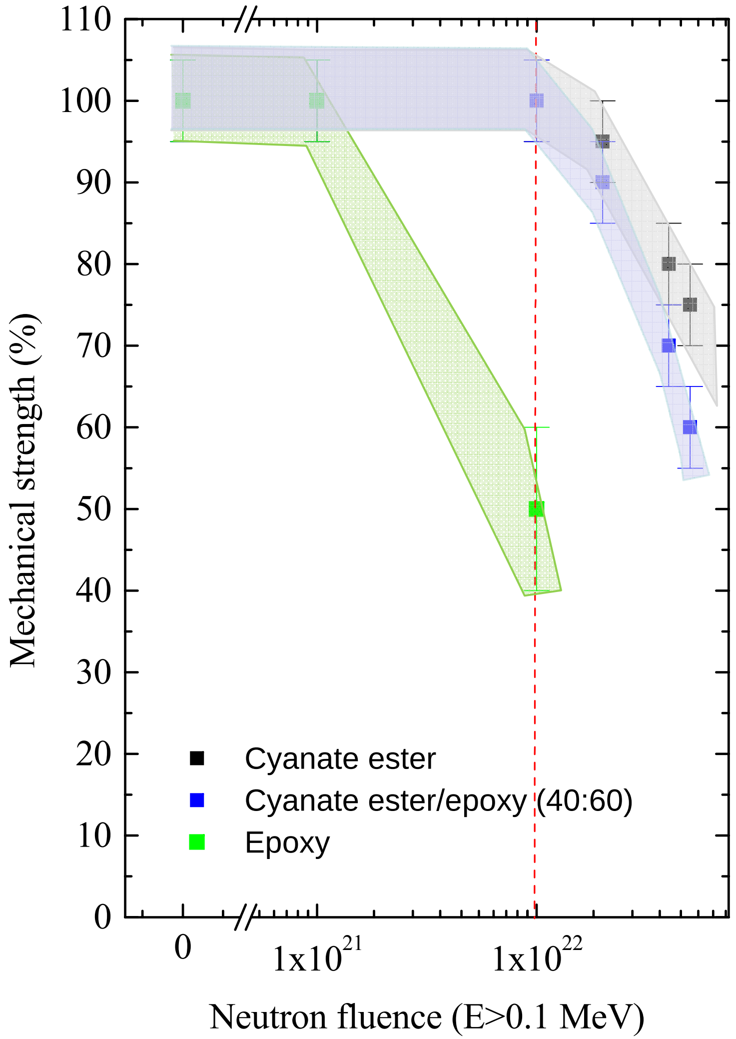
Garching ~ 5 K
Ekaterinburg 77 K
ATI ~340 K

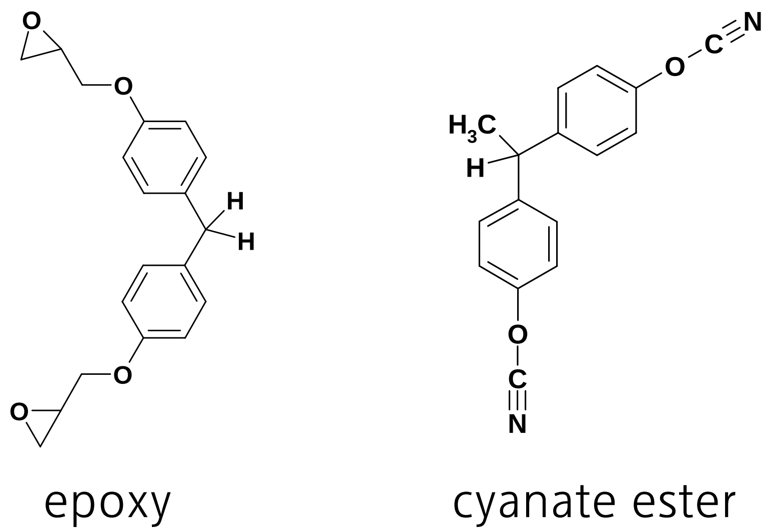
Tests at 77 K





Radiation Effects on Different Resins Tested for ITER



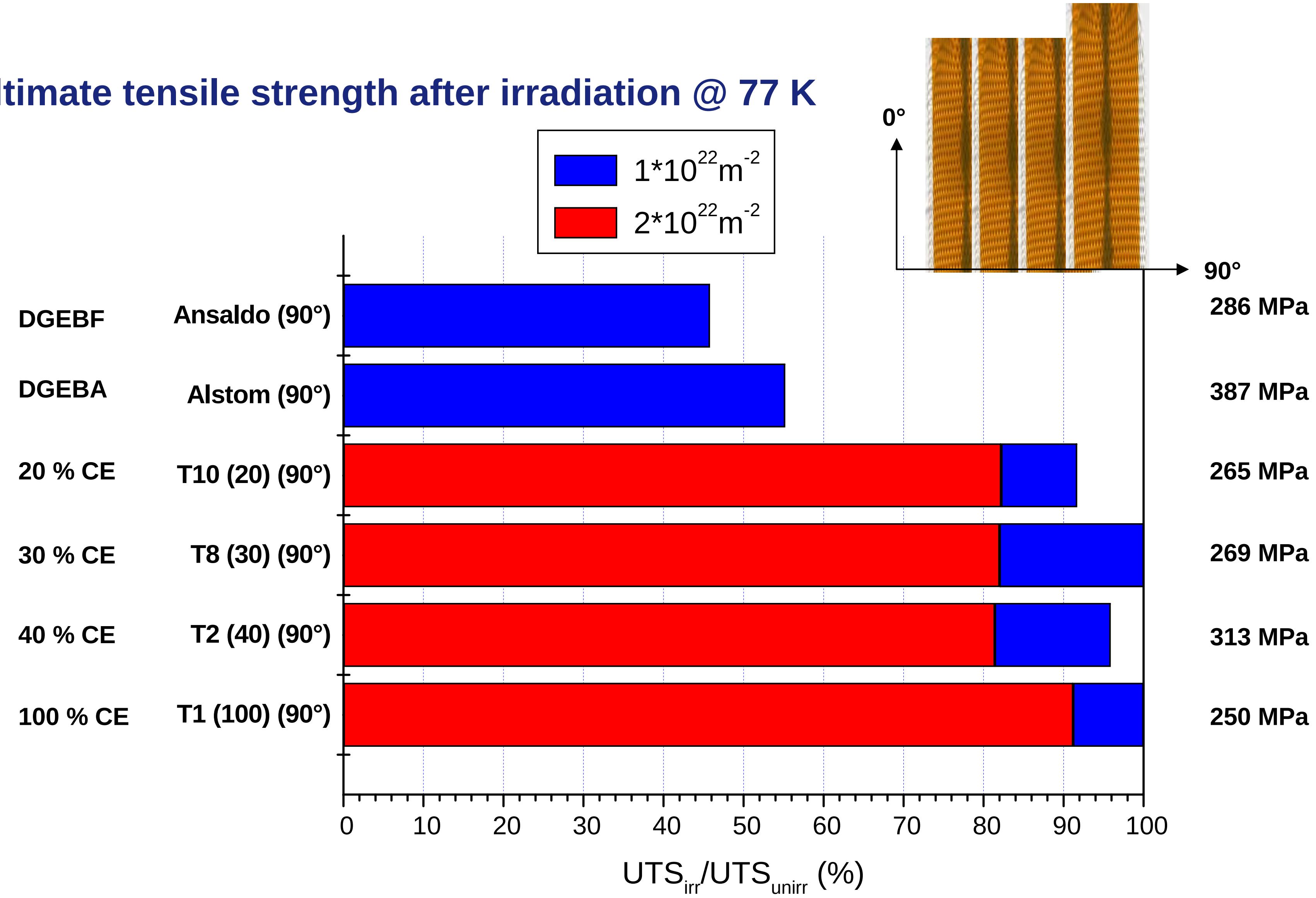


- Costs of CE up to 10 times higher than for epoxies
- CE can be mixed with epoxies for reducing costs

➔ CE/epoxy blends

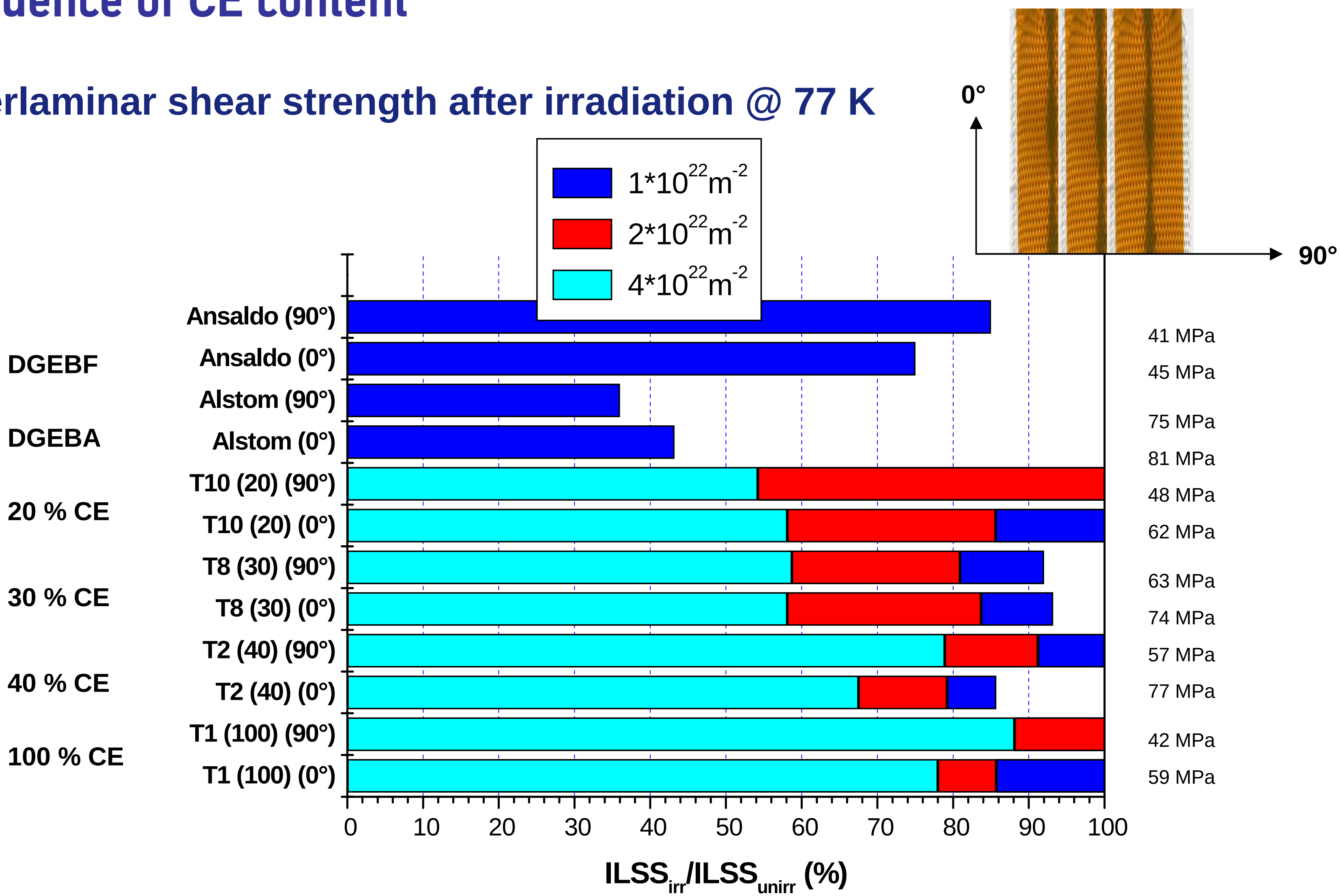
Influence of CE content

ultimate tensile strength after irradiation @ 77 K

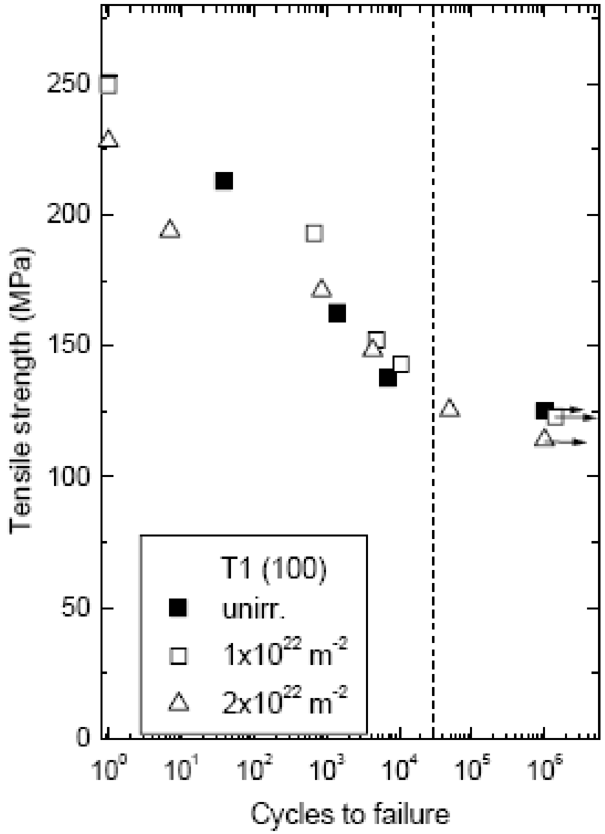


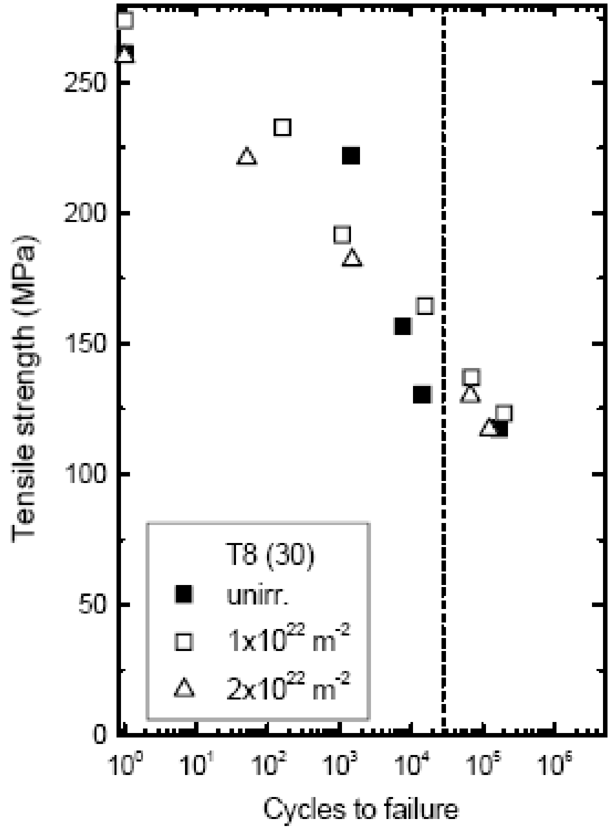
Influence of CE content

Interlaminar shear strength after irradiation @ 77 K



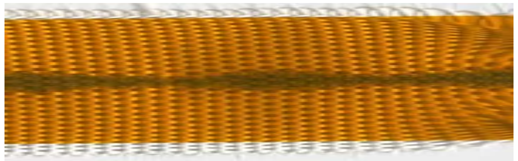
Fatigue measurements @ 77 K

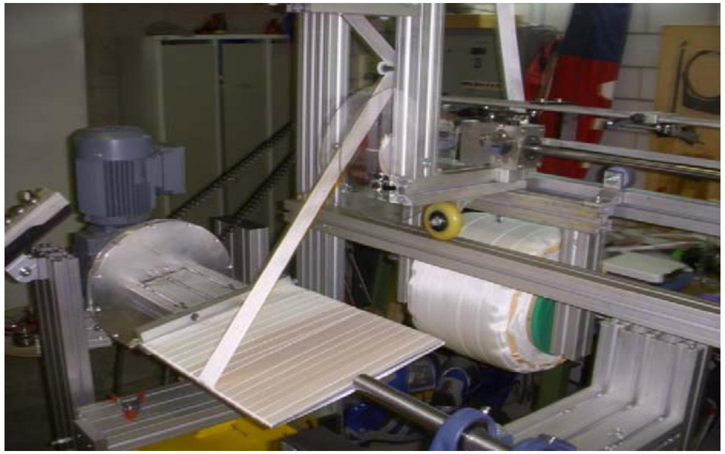


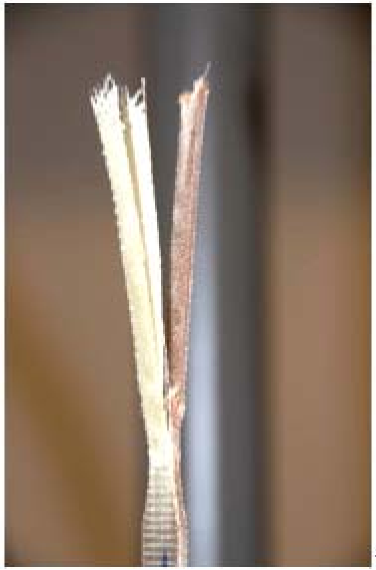


No significant influence of the irradiation!

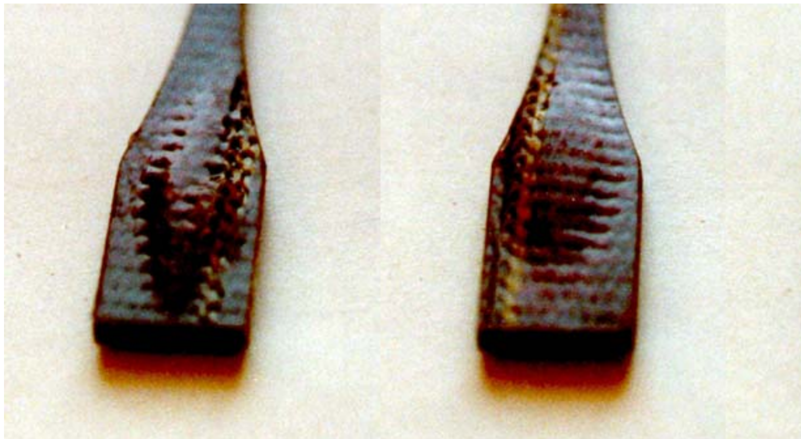
Bonded Glass/Polyimide tapes







Delamination caused by weak bonding between resin and polyimide



Radiation resistant bonding agent necessary!

Gas Evolution Rates

Material	Chemistry	Neutron Fluence (E>0.1 MeV) (10^{21} m^{-2})	Total absorbed Dose (MGy)	Gas Evolution Mean ± Sdev (mm^3)	Gas Evolution Rate Mean ± Sdev ($mm^3 g^{-1} MGy^{-1}$)
CTD-422	Cyanate Ester/Epoxy	1	4.19	105 ± 0	68.9 ± 2.4
CTD-10x	Cyanate Ester/Epoxy/BMI	1	4.05	83 ± 11	57.1 ± 6.8
CTD-101K	Epoxy/Anhydride	1	4.14	165 ± 0	108.4 ± 1.9
CTD-7x	Cyanate Ester/Epoxy/PI	1	3.90	75 ± 0	48.2 ± 0.4
CTD-15x	Cyanate Ester/BMI	1	4.46	60 ± 0	38.9 ± 0.3
CTD-101	Epoxy/Anhydride	1	4.11	165 ± 21	114.3 ± 10.3
CTD-HR3	Cyanate Ester/PI	1	4.31	60 ± 0	33.9 ± 0.5
CTD-404 CTD-404	Cyanate Ester	1 5	4.04 20.18	68 ± 11 200 ± 9	47.0 ± 7.4 30.4 ± 1.1
ER Baseline	Epoxy/Anhydride	1	4.15	263 ± 11	176.2 ± 10.3

Conclusions

- Minor influence of irradiation temperature
- Superconductors
  - Defects mainly caused by high energy neutrons (except MgB_2)
  - Decrease of transition temperature
  - Critical current initially increases (except NbTi) then decreases ($1\text{-}2 \times 10^{22}$ m^{-2})
  - Scaling by damage energy
- Insulators
  - Defects caused by (nearly) all neutrons and γ rays
  - Degradation of mechanical properties
  - Gas evolution
  - Scaling by total absorbed energy (dose)