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RADIATION EFFECTS ON FUSION MAGNET MATERIALS

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An overview of work on the subject
carried out by ATI and many collaboration partners
over the past 20 years

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OPERATION OF SUPERCONDUCTING MAGNETS IN A RADIATION ENVIRONMENT

- TYPE OF RADIATION
- FLUX DENSITY
- TOTAL DOSE
- LIFETIME FLUENCE
- OPERATING TEMPERATURE
- OPERATING CONDITIONS

MAGNET COMPONENTS:

- SUPERCONDUCTOR: NbTi, Nb_3Sn, …
- STABILIZER: Cu
- INSULATION: Fibre reinforced plastics (FRP's)
- STRUCTURAL MATERIALS: Stainless steel (not addressed)

RADIATION ENVIRONMENT AT THE MAGNET LOCATION

ITER:

γ-RADIATION:	5×10^{7} Gy
FAST NEUTRONS:	1×10^{22} m^{-2} (E>0.1MeV)

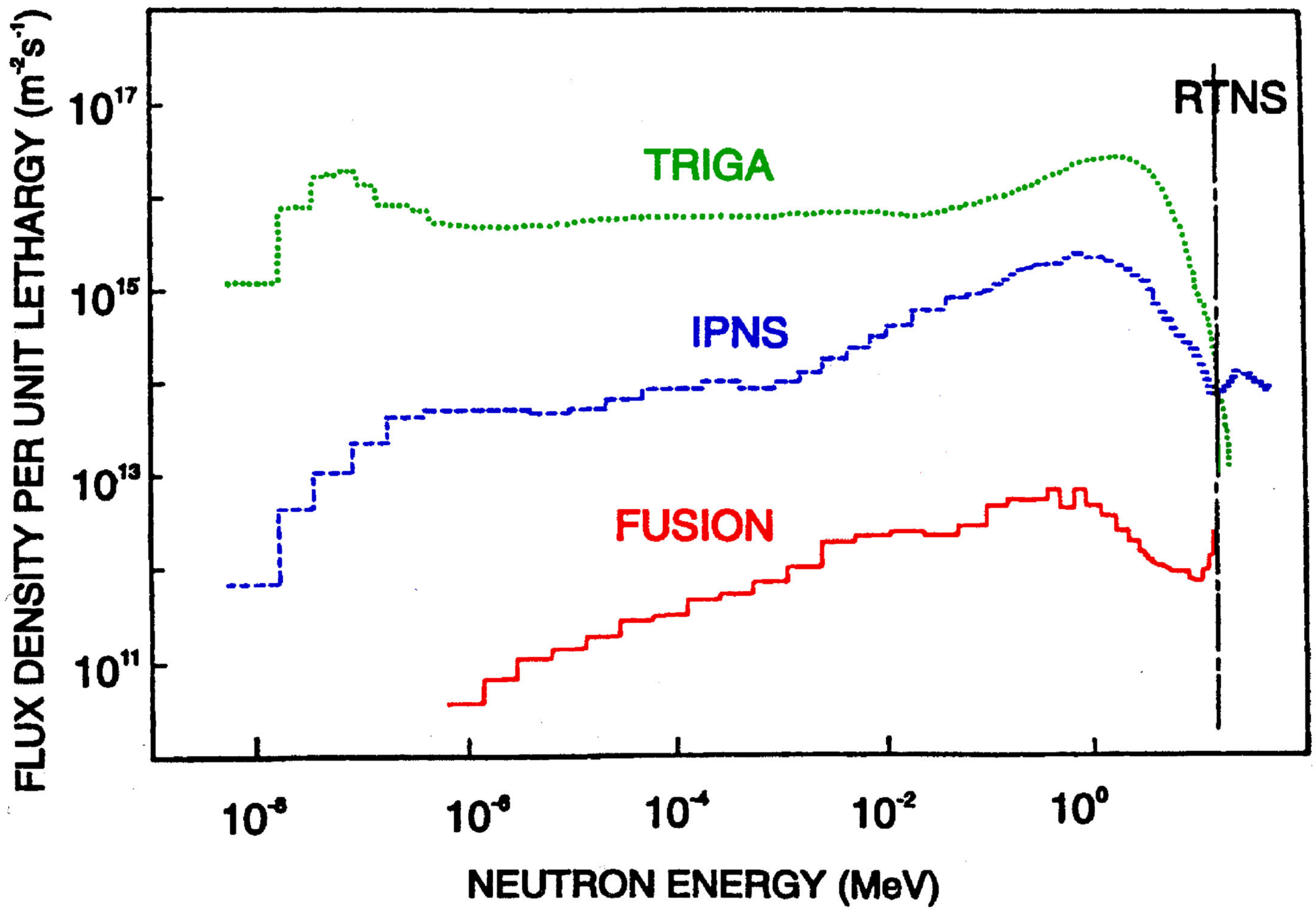
STARFIRE:

γ-RADIATION:	> 10^{8} Gy
FAST NEUTRONS:	2×10^{22} m^{-2} (E>0.1MeV)

OPERATING TEMPERATURE: ~ 4.5 K

THERMAL CYCLES TO ROOM TEMPERATURE (SERVICE WORK)

PULSED OPERATION (FATIGUE)



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

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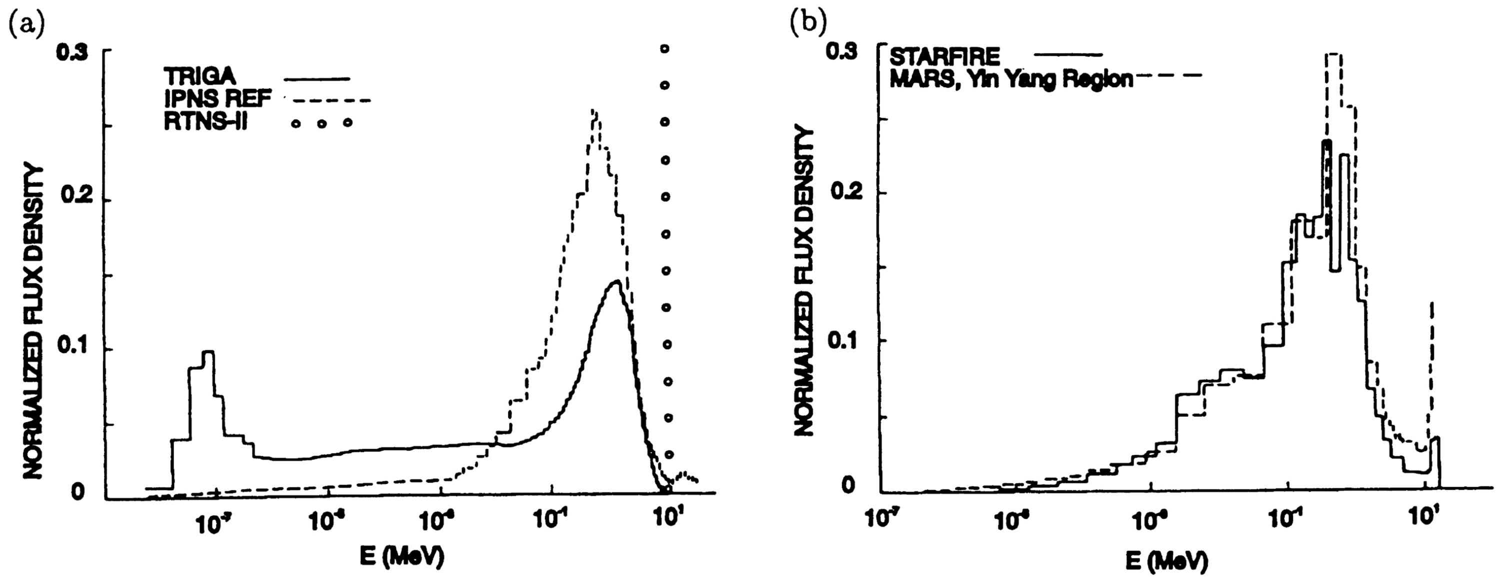
(a)
TRIGA
IPNS REF
RTNS-II
NORMALIZED FLUX DENSITY
0.3
0.2
0.1
0
E (MeV)
(b)
STARFIRE
MARS, Yin Yang Region
NORMALIZED FLUX DENSITY
0.3
0.2
0.1
0
E (MeV)

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DAMAGE ENERGY SCALING

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

$\Rightarrow$

$<\sigma(E) . T(E)>$ ....displacement energy cross section

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

SUCCESSFUL SCALING OF T_c AND J_c IN METALLIC SUPERCONDUCTORS

$\Rightarrow$

PREDICTIONS OF PROPERTY CHANGES IN AN UNAVAILABLE NEUTRON SPECTRUM ARE FEASIBLE

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SUPERCONDUCTORS

NbTi – alloy
Nb_3Sn – A15 compound

RADIATION WILL AFFECT THE

- 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 centres: 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 centres

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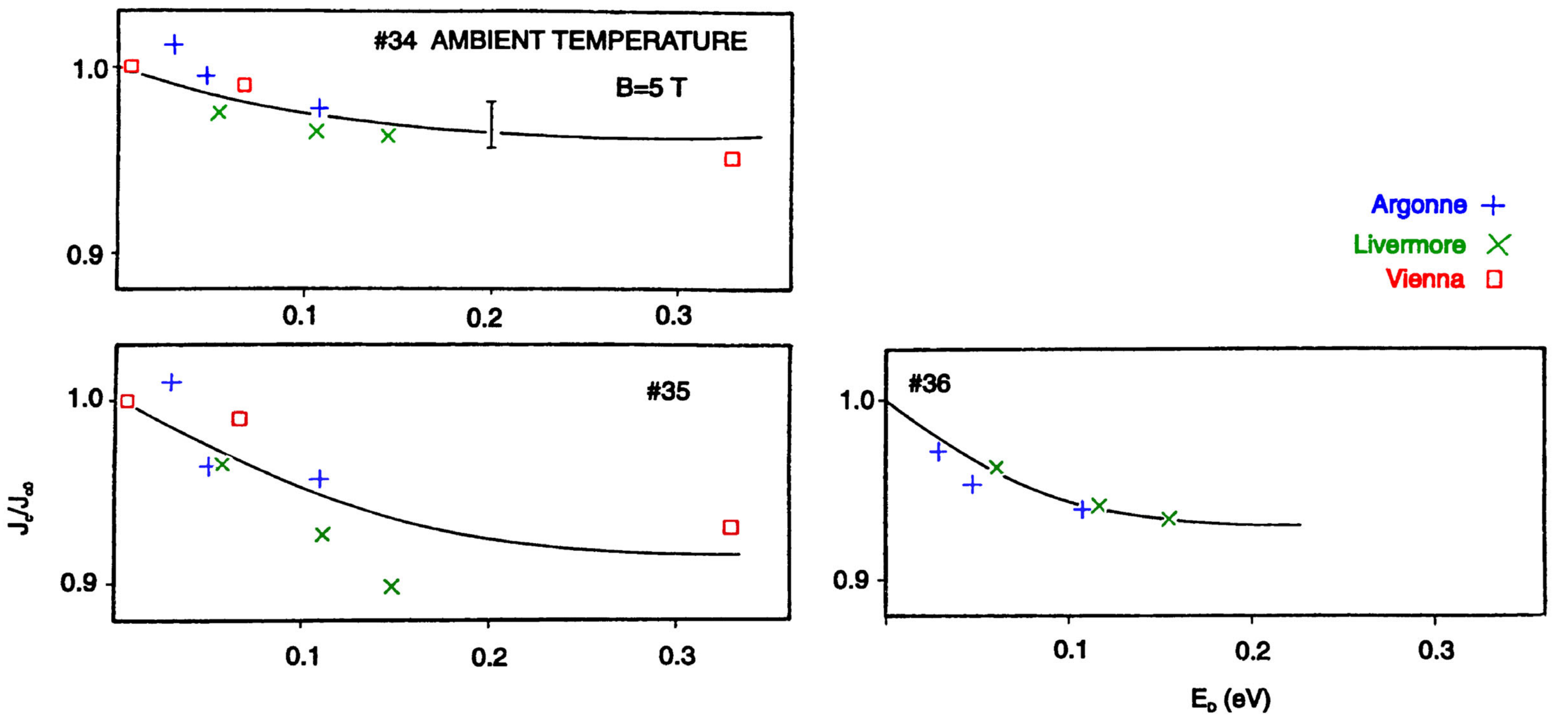

#34 AMBIENT TEMPERATURE
B=5 T
1.0
0.9
0.1
0.2
0.3
#35
J_c/J_∞
#36
E_b (eV)
Argonne
Livermore
Vienna

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Nb_3Sn

- MORE SIGNIFICANT (AND LATER ON DRASTIC EFFECTS) ON T_c - caused by disorder
- SIGNIFICANT ENHANCEMENTS OF 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

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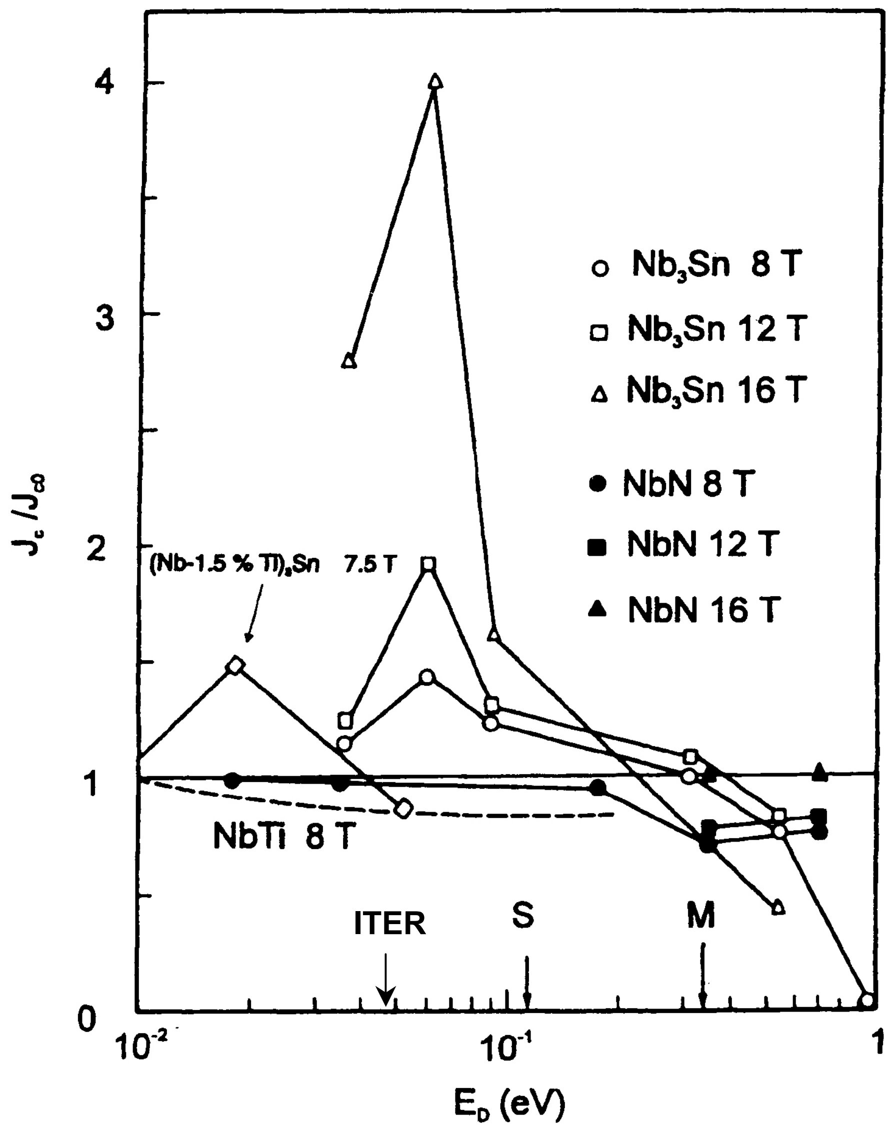
4
3
2
1
0
J_c / J_{c0}
$(Nb-1.5\ \%\ Ti)_3Sn$ 7.5 T
Nb_3Sn 8 T
Nb_3Sn 12 T
Nb_3Sn 16 T
NbN 8 T
NbN 12 T
NbN 16 T
NbTi 8 T
ITER
S
M
10^{-2}
10^{-1}
1
E_D (eV)

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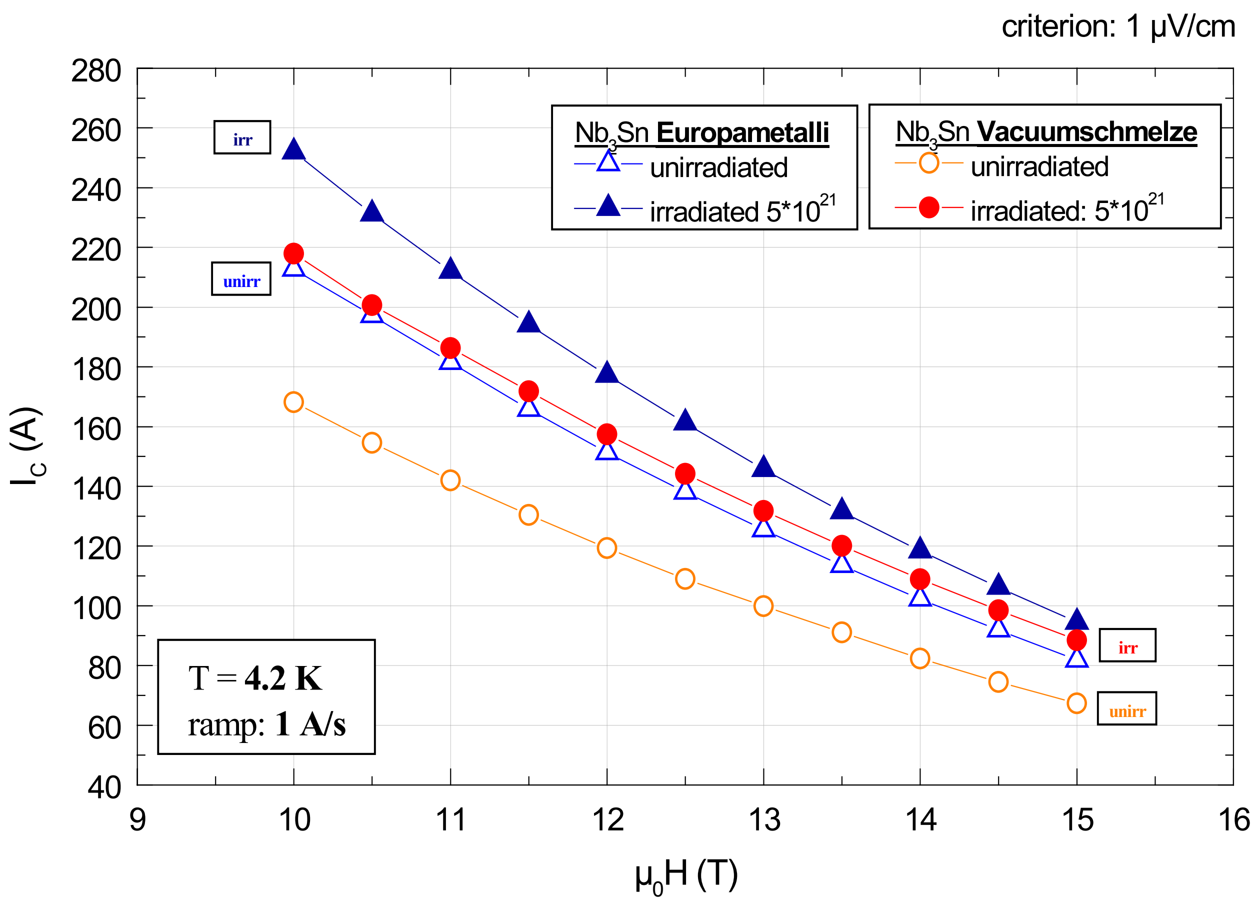
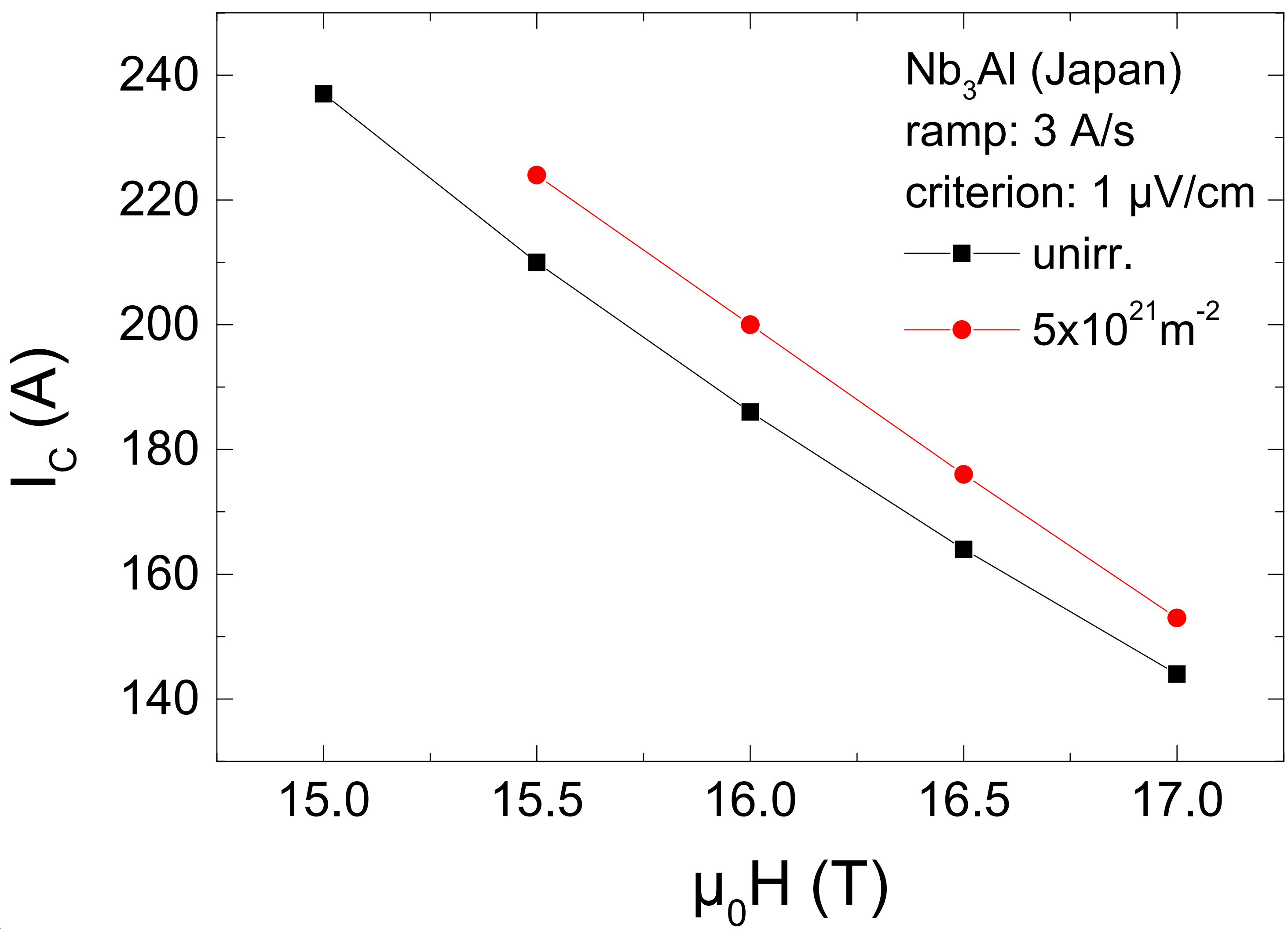
Critical currents of ITER Nb_3Sn wires




Nb3Al (Japan)
ramp: 3 A/s
criterion: 1 μV/cm
unirr.
5x10^21 m^-2
240
220
200
180
160
140
IC (A)
15.0
15.5
16.0
16.5
17.0
μ0H (T)
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STABILIZER

Cu

RRR ~ 100-150 REQUIRED FOR STABILIZING FUNCTION

IRRADIATION:

DEFECTS ACT AS ADDITIONAL SCATTERING CENTRES

$\Rightarrow$

ENHANCE ρ_n

$\Rightarrow$

DECREASE RRR

SUBSTANTIAL MAGNETIC FIELD EFFECT

SUBSTANTIAL TEMPERATURE EFFECT

$\Rightarrow$ ANNEALING

VERY LIMITED AMOUNT OF DATA AVAILABLE

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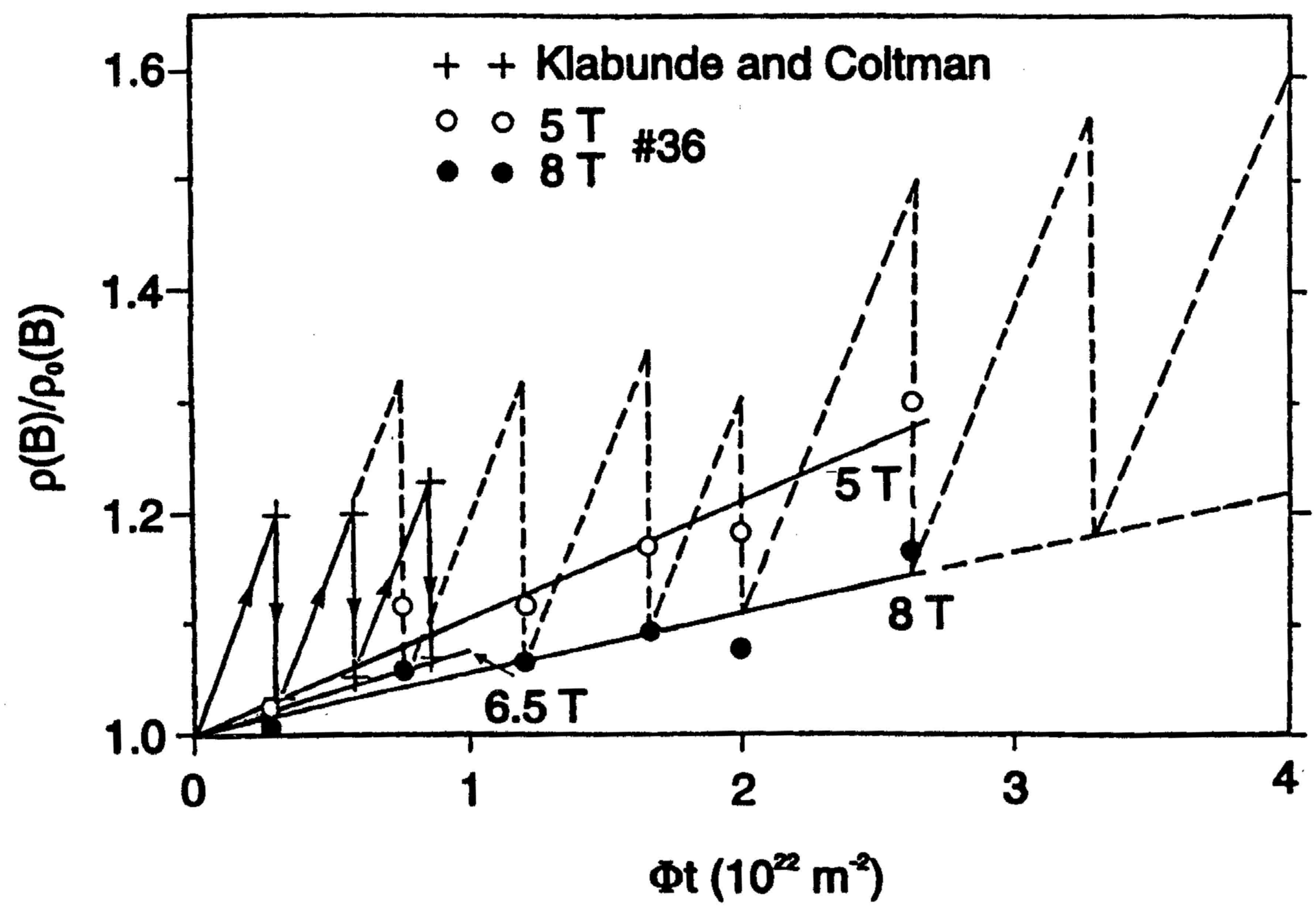

+ + Klabunde and Coltman
o o 5 T
● ● 8 T
#36
1.6
1.4
1.2
1.0
ρ(B)/ρ₀(B)
0
1
2
3
4
Φt (10²² m⁻²)
5 T
8 T
6.5 T

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INSULATORS

ELECTRICAL CONDUCTOR AND WINDING INSULATION

MECHANICAL REINFORCEMENT

MATERIALS:

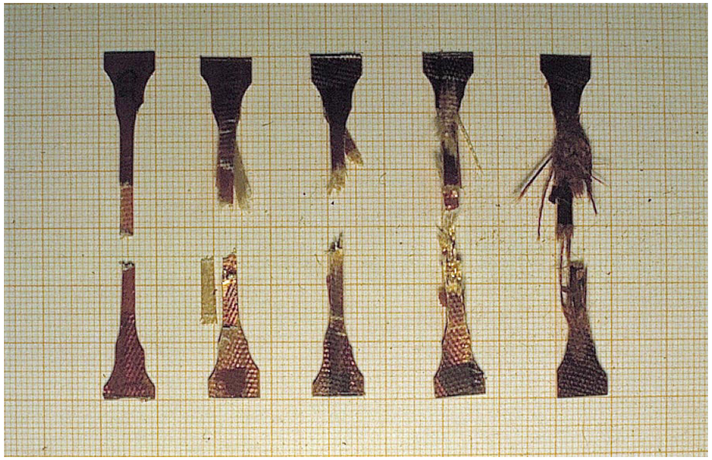
GLASS-FIBRE REINFORCED PLASTICS (SUITABLE FOR VACUUM-IMPREGNATION OF THE COIL)

e.g.

EPOXY - REINFORCED WITH A TWO-DIMENSIONALLY WOVEN GLASS - FABRIC

EARLY RESULTS:

MECHANICAL PROPERTIES ARE MUCH MORE SENSITIVE TO RADIATION EFFECTS



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BASIC STRATEGY

ASSESS INTRINSIC MATERIAL PARAMETERS

- ULTIMATE TENSILE STRENGTH
- SHEAR STRENGTH IN MODE I AND II
- COMPRESSION STRENGTH
- ELASTIC MODULI

EMPLOY FE METHODS FOR ARBITRARY LOAD CONFIGURATIONS

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RADIATION EFFECTS: SCALING PROPERTIES?

IN CONTRAST TO THE SUPERCONDUCTORS:

THE ENTIRE NEUTRON SPECTRUM
+
THE γ-RADIATION
CONTRIBUTE TO THE DAMAGE PRODUCTION

SCALING QUANTITY: ABSORBED ENERGY?

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.

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NEUTRONS:

DIRECTLY DEPOSITED ENERGY BY THE ENTIRE NEUTRON SPECTRUM

GAS PRODUCTION (He, H)

γ-RAYS:

DOSE RATE (in Gy/h) times IRRADIATION TIME

⇒

TOTAL ABSORBED ENERGY (in Gy)

AGAIN: SUCCESSFUL SCALING RESULTS

⇒

PREDICTIONS OF PROPERTY CHANGES IN AN UNAVAILABLE RADIATION ENVIRONMENT ARE FEASIBLE

RESULTS

TENSILE STRENGTH

SHEAR STRENGTH

*INTRA*LAMINAR SHEAR: CRACK PROPAGATION

*INTER*LAMINAR SHEAR

ADDITIONAL PROPERTY CHANGES:

SWELLING
WEIGHT LOSS

PULSED OPERATION:

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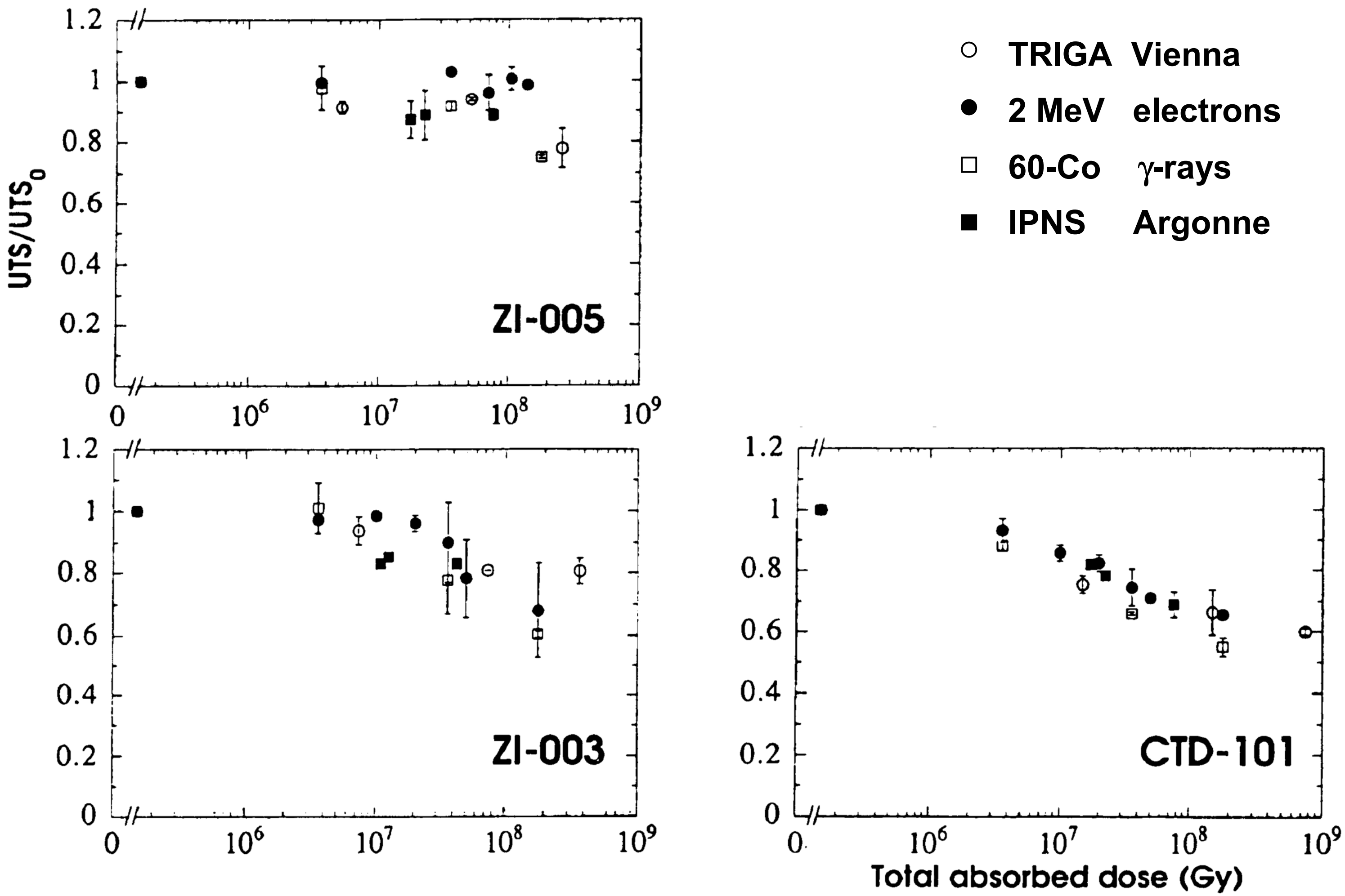

TRIGA Vienna
2 MeV electrons
60-Co γ-rays
IPNS Argonne
UTS/UTS0
ZI-005
ZI-003
CTD-101
0
0.2
0.4
0.6
0.8
1
1.2
0
10^6
10^7
10^8
10^9
Total absorbed dose (Gy)

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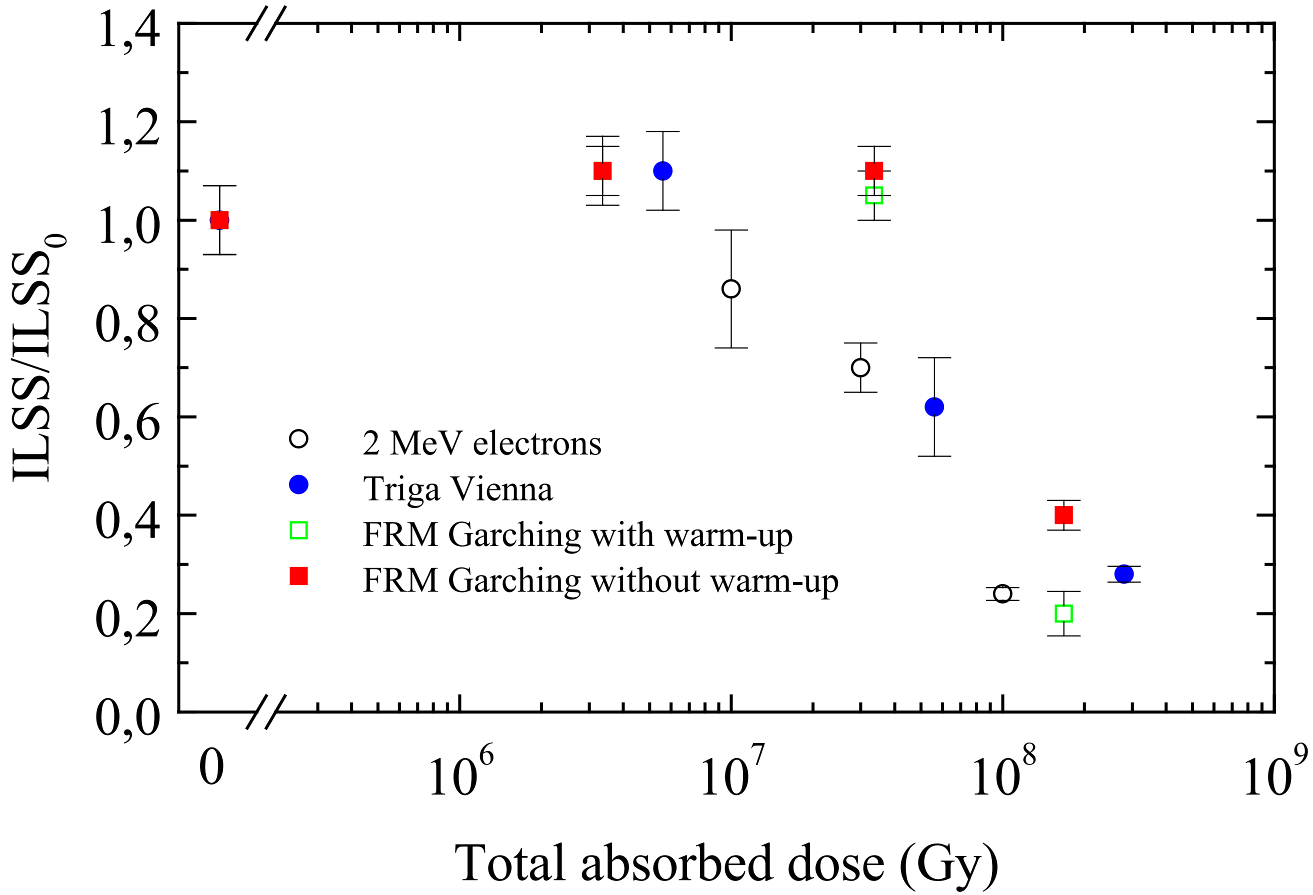

1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
ILSS/ILSS$_0$
0
10^6
10^7
10^8
10^9
Total absorbed dose (Gy)
2 MeV electrons
Triga Vienna
FRM Garching with warm-up
FRM Garching without warm-up

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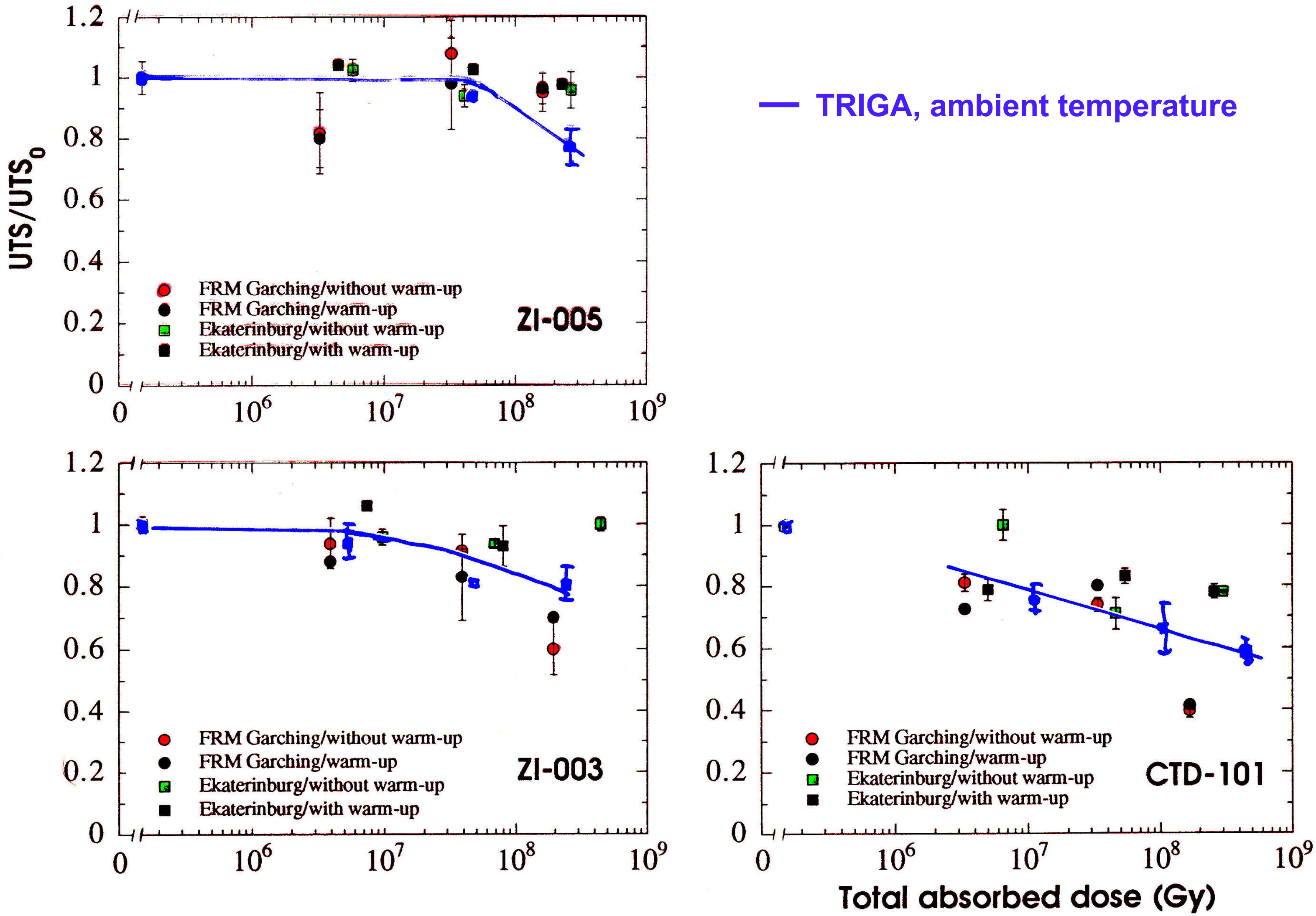

TRIGA, ambient temperature
UTS/UTS$_0$
1.2
1
0.8
0.6
0.4
0.2
0
0
10^6
10^7
10^8
10^9
FRM Garching/without warm-up
FRM Garching/warm-up
Ekaterinburg/without warm-up
Ekaterinburg/with warm-up
ZI-005
ZI-003
CTD-101
Total absorbed dose (Gy)

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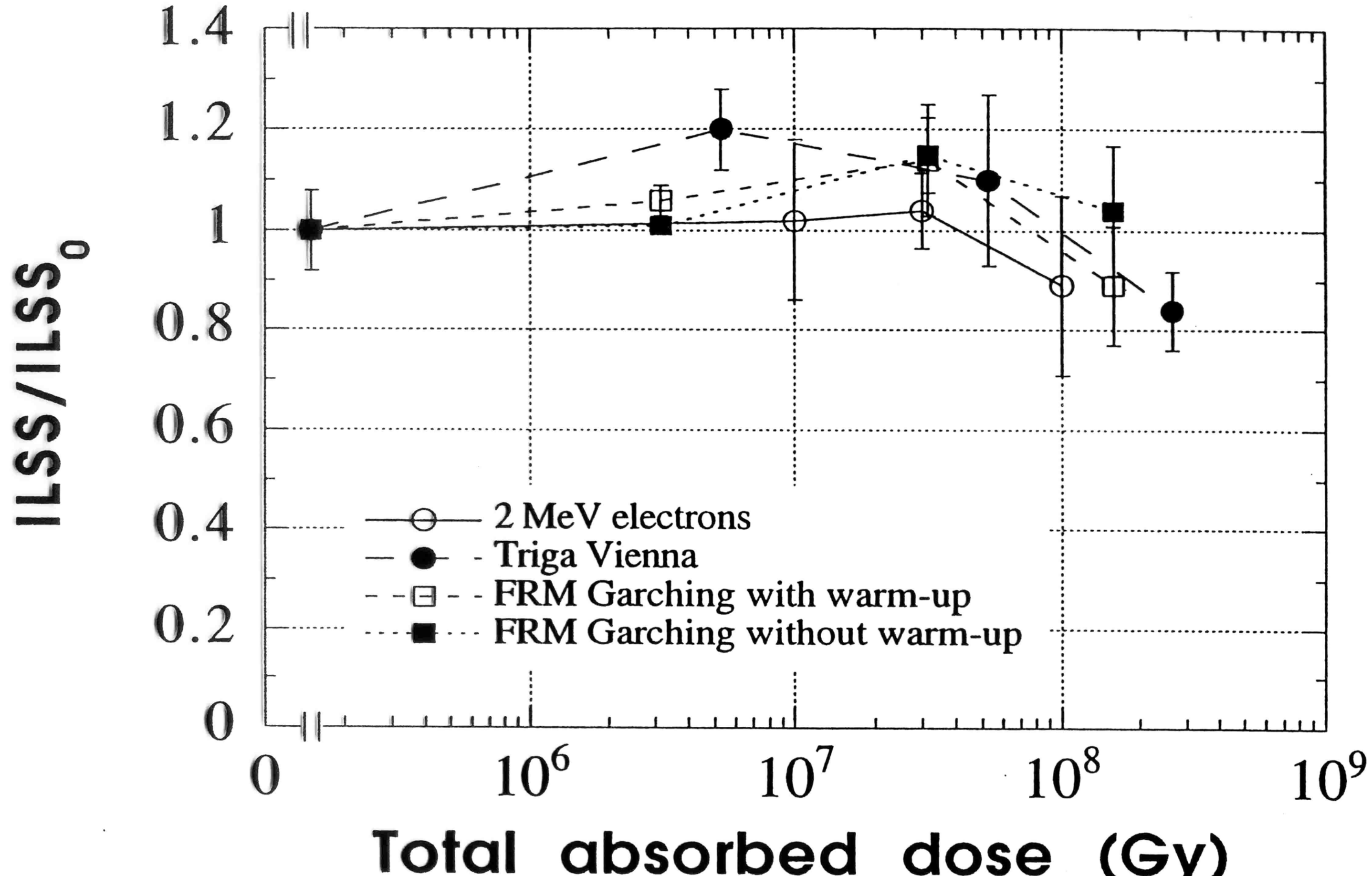
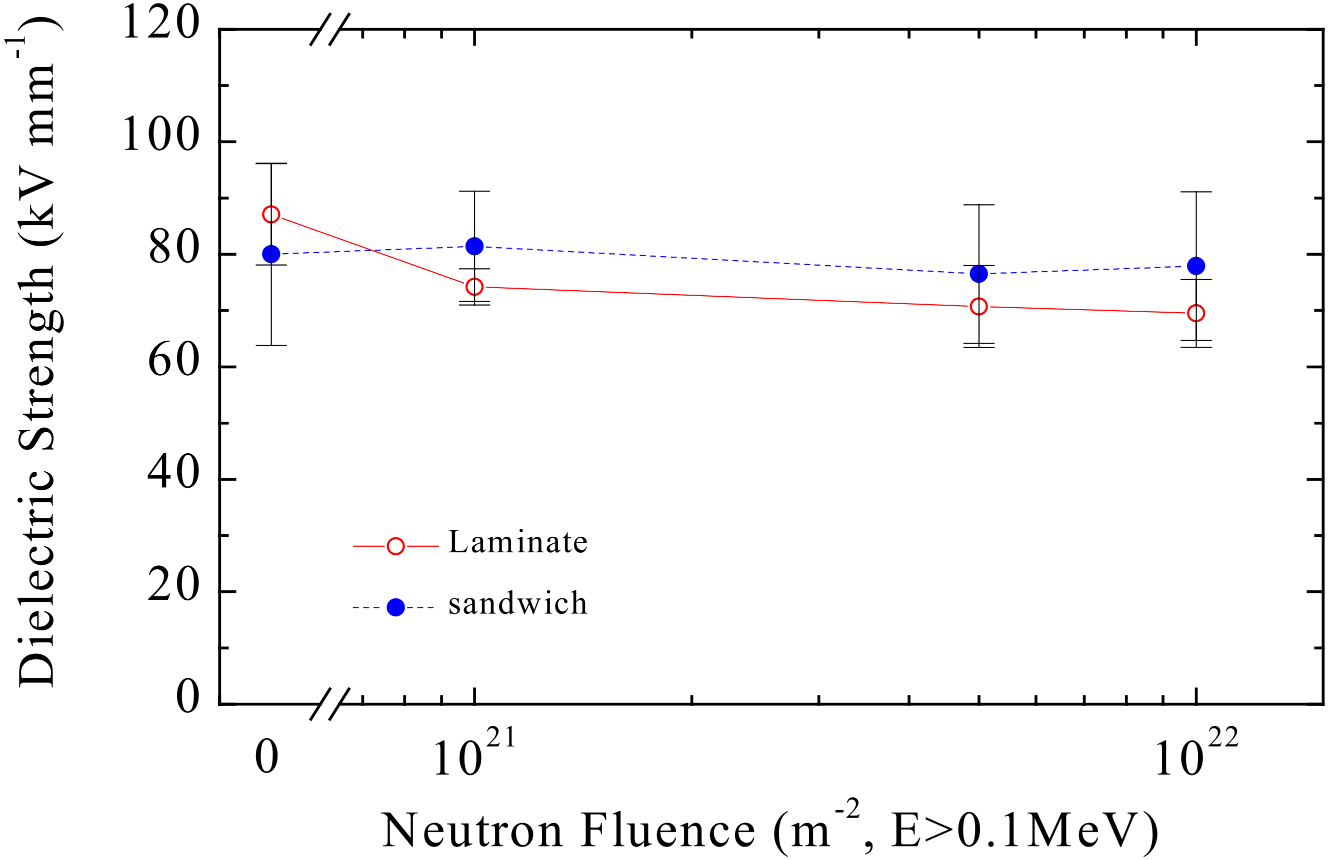
CTD-220P
Bismaleimide/S-glass




120
100
80
60
40
20
0
Dielectric Strength (kV mm-1)
Laminate
sandwich
0
10^21
10^22
Neutron Fluence (m-2, E>0.1MeV)