Radiation Resistance Issues for Superconducting Magnets

- Toward SLHC and High Intense Muon Experiments at J-PARC -

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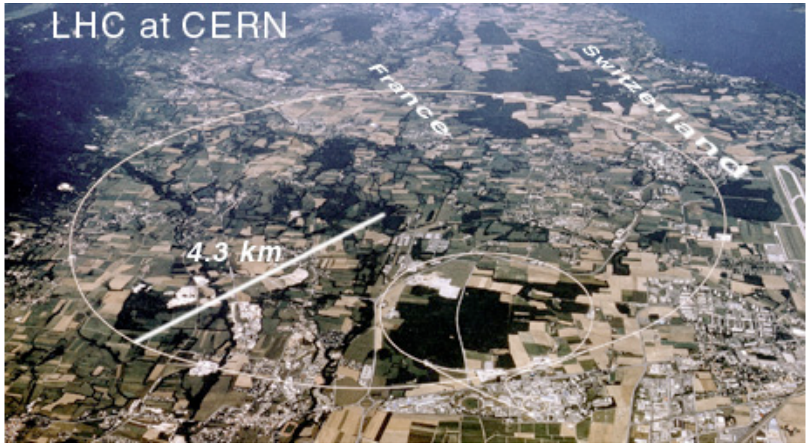
2009.12.15 CSC Seminar at KEK

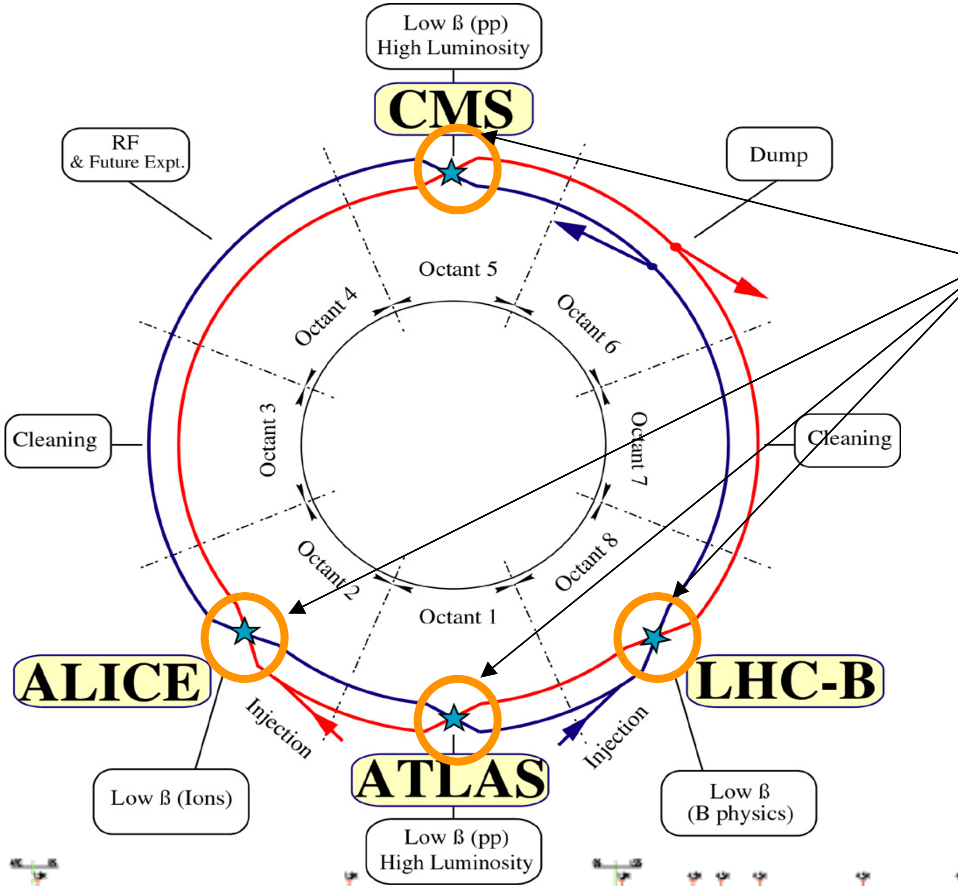
Contents

- Demand of Radiation Resistant SC Magnets
  - SLHC
  - High Intense Muon Experiments
- Guideline of Development
- Property Change of Materials by Irradiation
- Irradiation Test Plan and Present R&D
- Summary

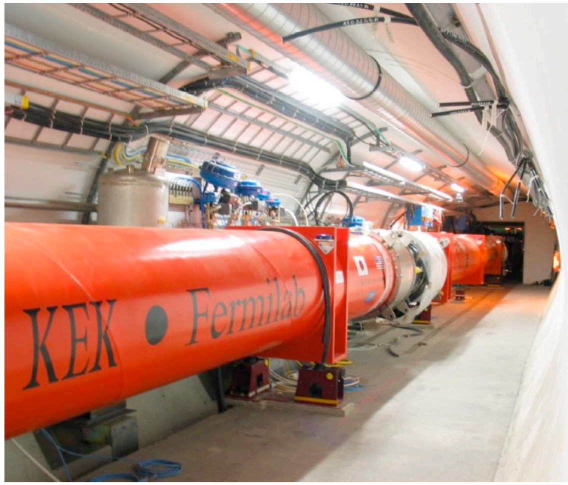
LHC and Experimental Insertions

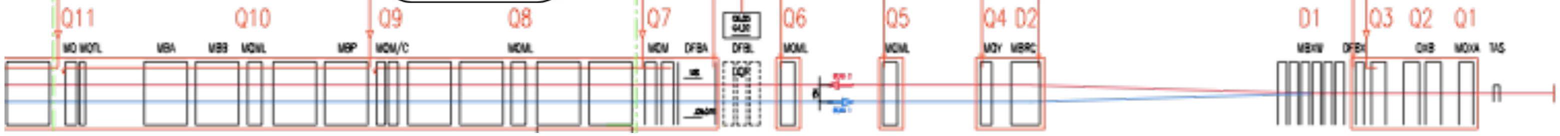
Circumference: 27 km
Injection Energy: 450 GeV (p)
Collision Energy: 7+7 TeV
Peak Luminosity: 10^{34} cm^2/sec





2*4 Experimental Insertions





>> IP

An R&D program to Address Irradiation Effects in Superconductors for LHC Upgrade

L. Bottura, R. Flukiger, A. Ballarino,
F. Liberati, L. Oberli, I. Pong, G. de Rijk

EuCARD workshop on insulator irradiation

CERN, December 2, 2009

Remember : LHC Upgrade
2.5 X « present » values (Phase I)
10 X « present » values (Phase II)
>> SLHC

Data from FLUKA simulations, F. Cerutti, collected by R. Flukiger

Peak fluence - Phase I (2.5 x 10^{34} 1/cm^2s)

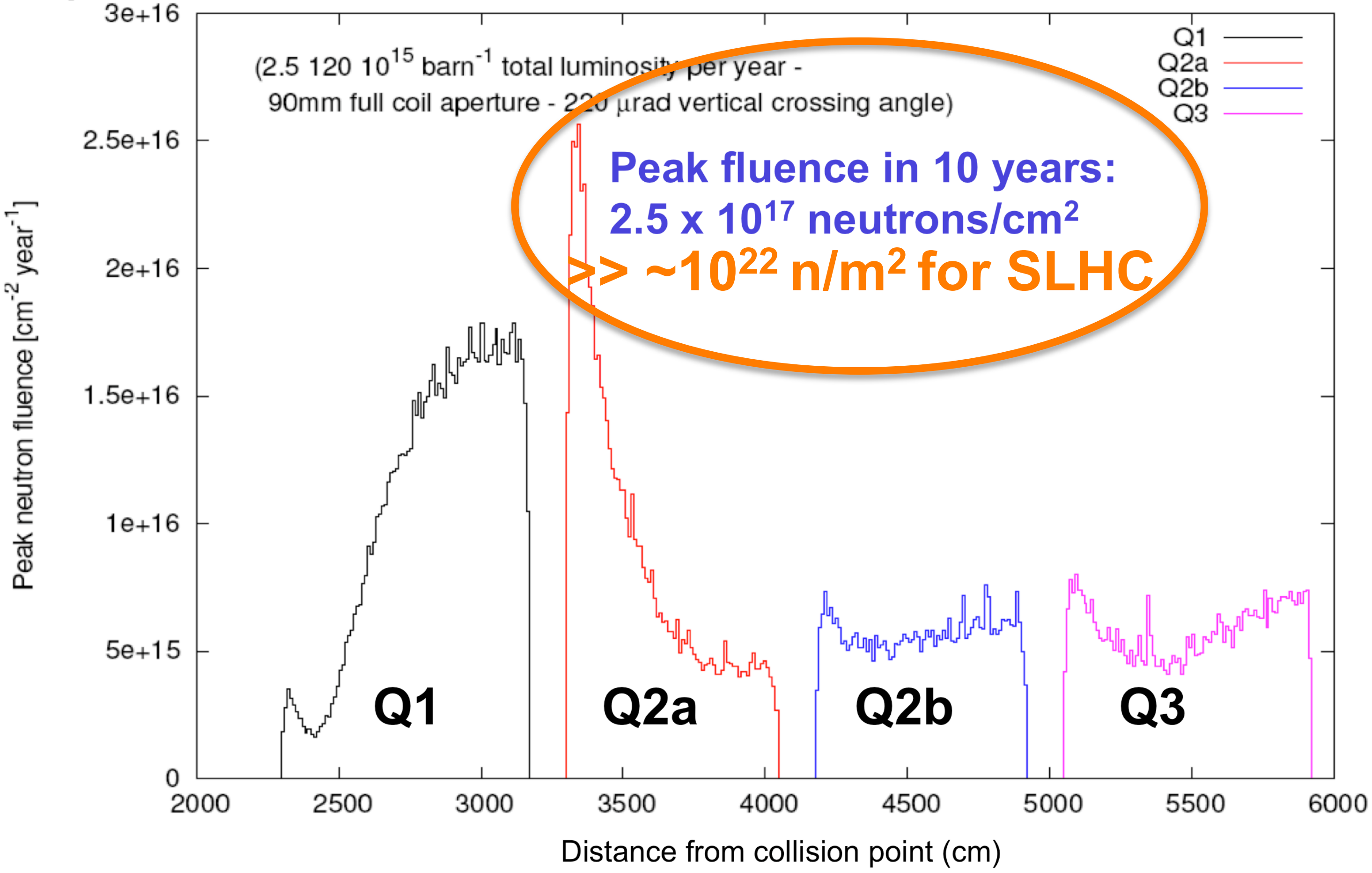
- Radiation spectrum at the IR quads (Q1-Q3)

Neutrons	6%	SC and Cu
Protons	0.15 %	SC and Cu
Photons	87 %	Insulation
Electrons	3.5 %	*negligible effect*
Positrons	2.5 %	
Pions	0.4 %	

- Total fluence in 10 years (200 d/year):
  - neutrons: 2.5 x 10^{17} n/cm^2
  - protons: 6.2 x 10^{15} p/cm^2

Data from FLUKA simulations, F. Cerutti and A. Mereghetti

Radiation map for the IR quads



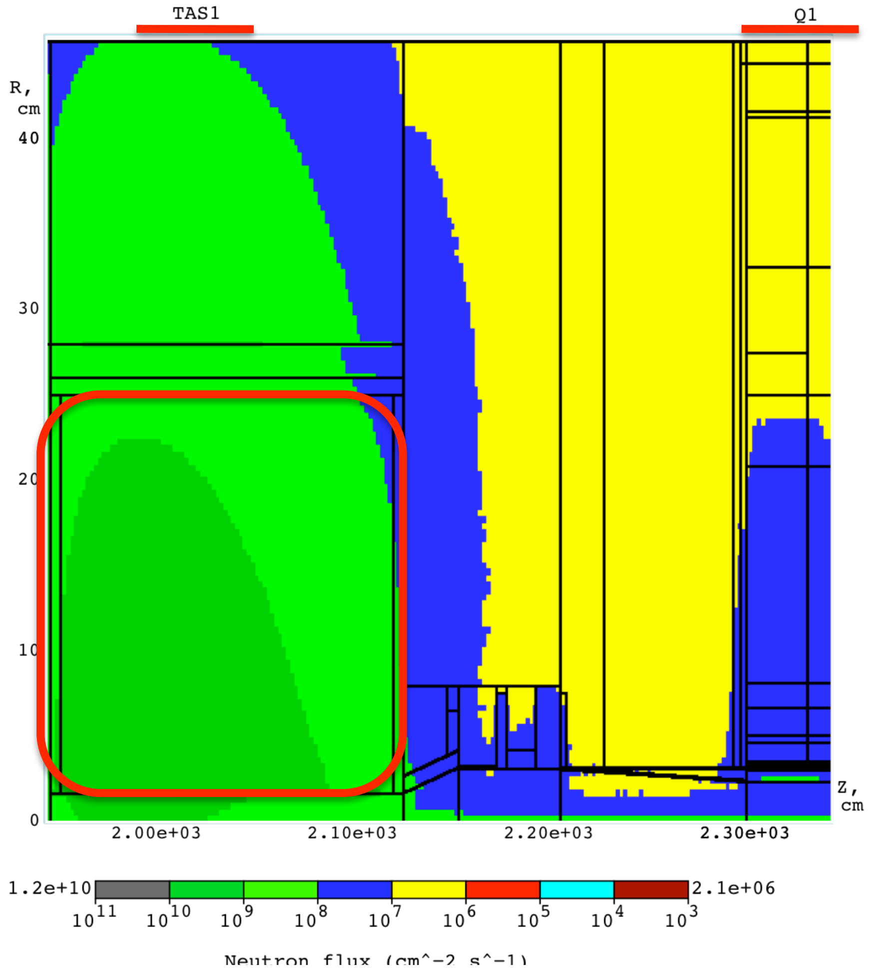
Peak fluence in 10 years:
2.5×10^{17} neutrons/cm^2

>> ~10^{22} n/m^2 for SLHC

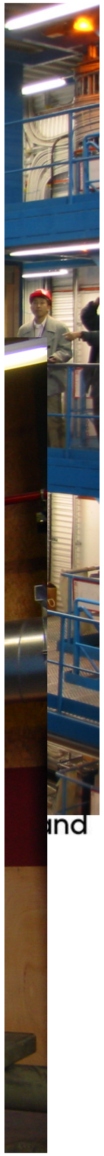
Source of radiation is secondary (& primary?) at IP

Present TAS between IP and IR

*Target Absorber Secondaries: copper



~190W @ Design Luminosity



Figur
(cm⁻

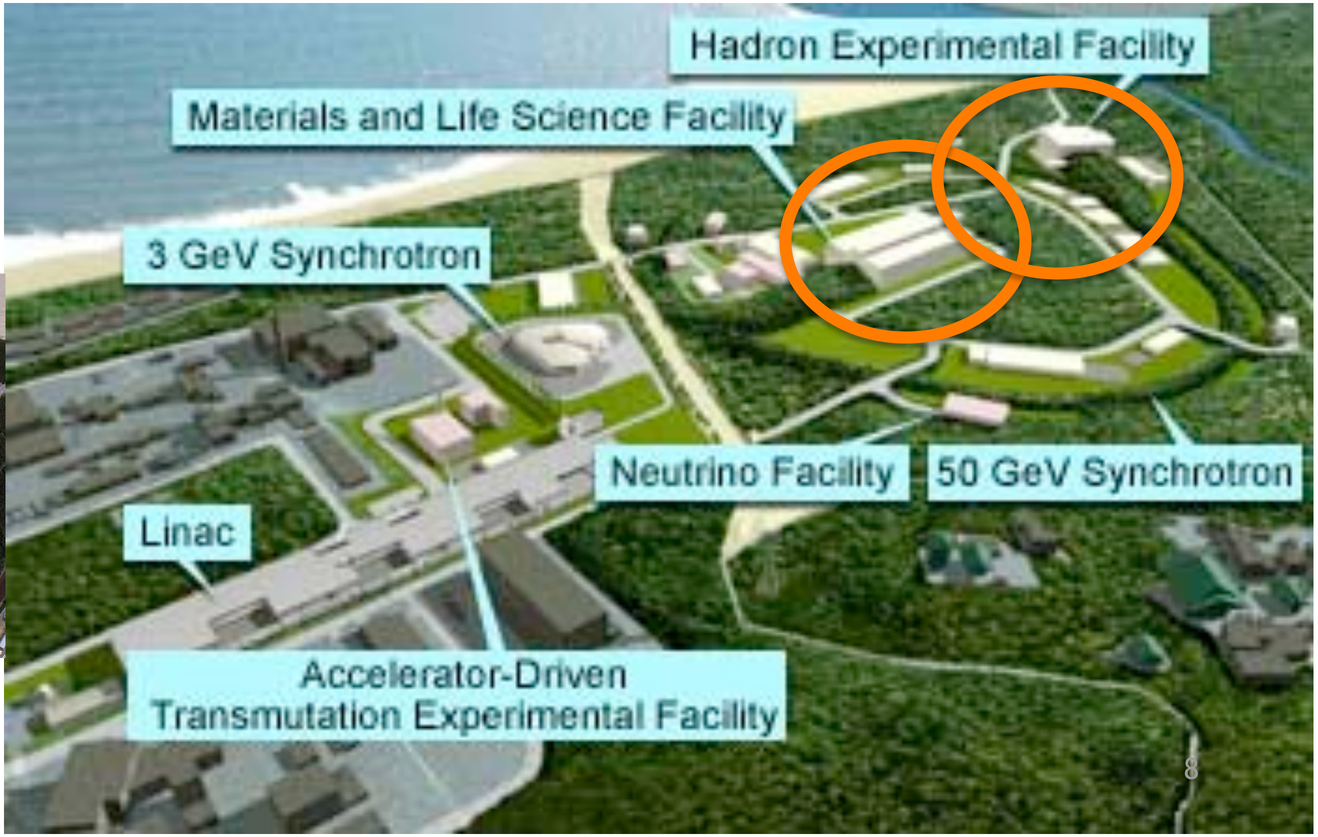
ırs

Big jump of improvement for TAS looks difficult…

>> 10^22 n/m2 in insertion Q magnets in SLHC.

J-PARC

- Constructed by JAEA and KEK
- Completed 2009
- Proton accelerator complex aiming high beam power:
  3 GeV - 1MW at RCS
  50 GeV - 750 kW at MR
- Material and Life Science: Neutron and Muon >> SuperOmega
- Elementary Particle Physics: Pion, Muon, Neutrinos, etc. >> g-2, COMET



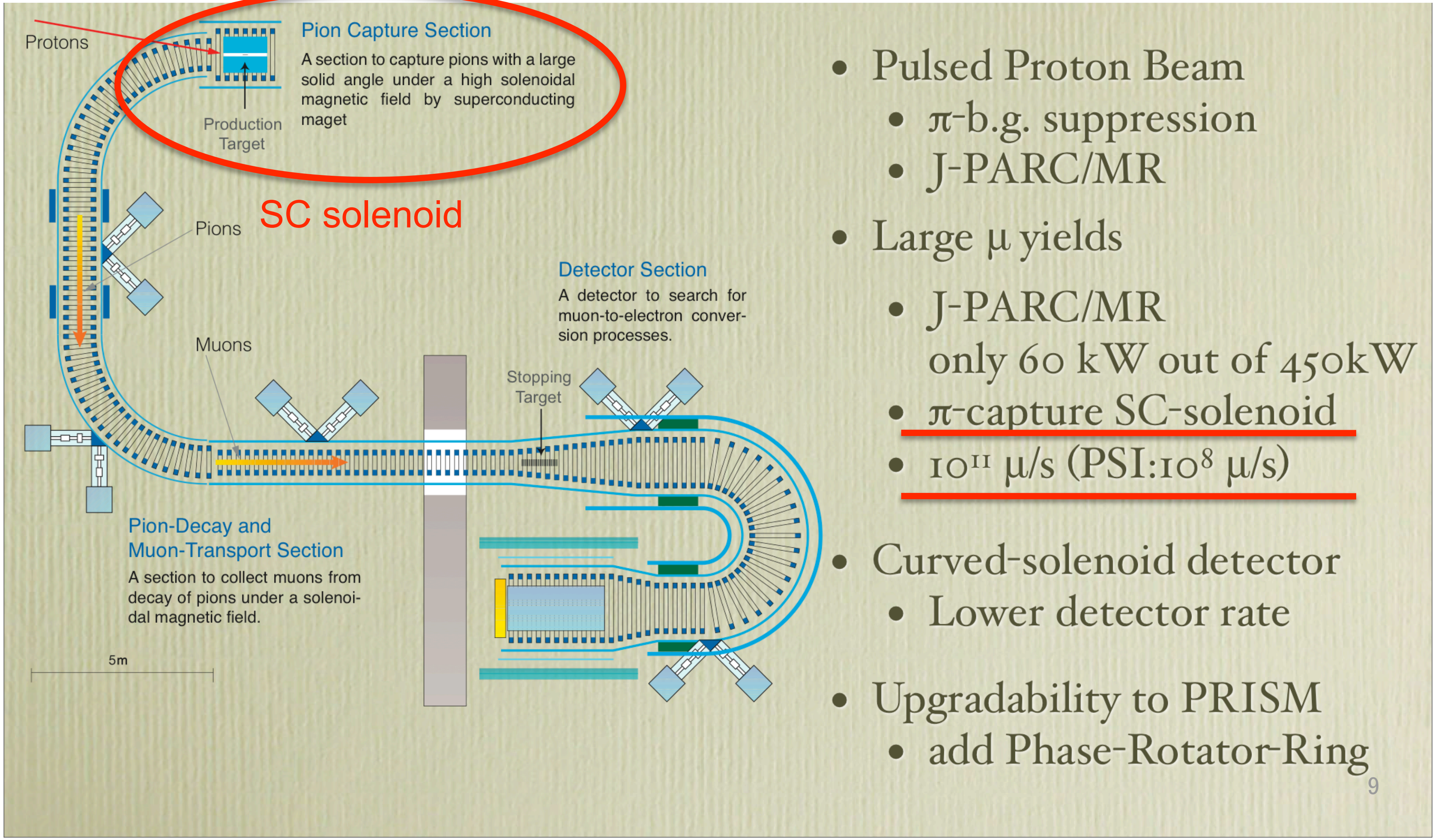
COMET Overview

Search for "μe conversion": $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$

>> forbidden by Standard Model.

>> very sensitive to a new physics beyond S.M.

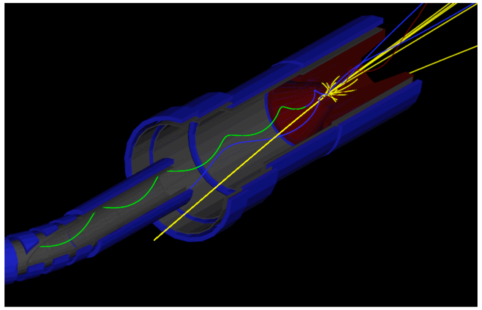
Stage 1 approved by PAC of J-PARC: candidate of flagship experiment



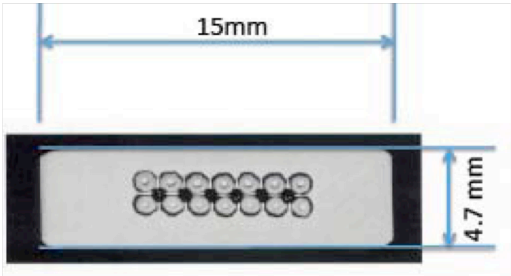
- Pulsed Proton Beam
  - π-b.g. suppression
  - J-PARC/MR
- Large μ yields
  - J-PARC/MR only 60 kW out of 450kW
  - π-capture SC-solenoid
  - 10^{11} μ/s (PSI:10^8 μ/s)
- Curved-solenoid detector
  - Lower detector rate
- Upgradability to PRISM
  - add Phase-Rotator-Ring

COMET Pion Capture SC Solenoid

Tungsten target in the magnet bore >> Radiation shield 300 mm thick
ϕ1000-1300mm, 5T, Al-stabilized NbTi
Indirect pipe cooling



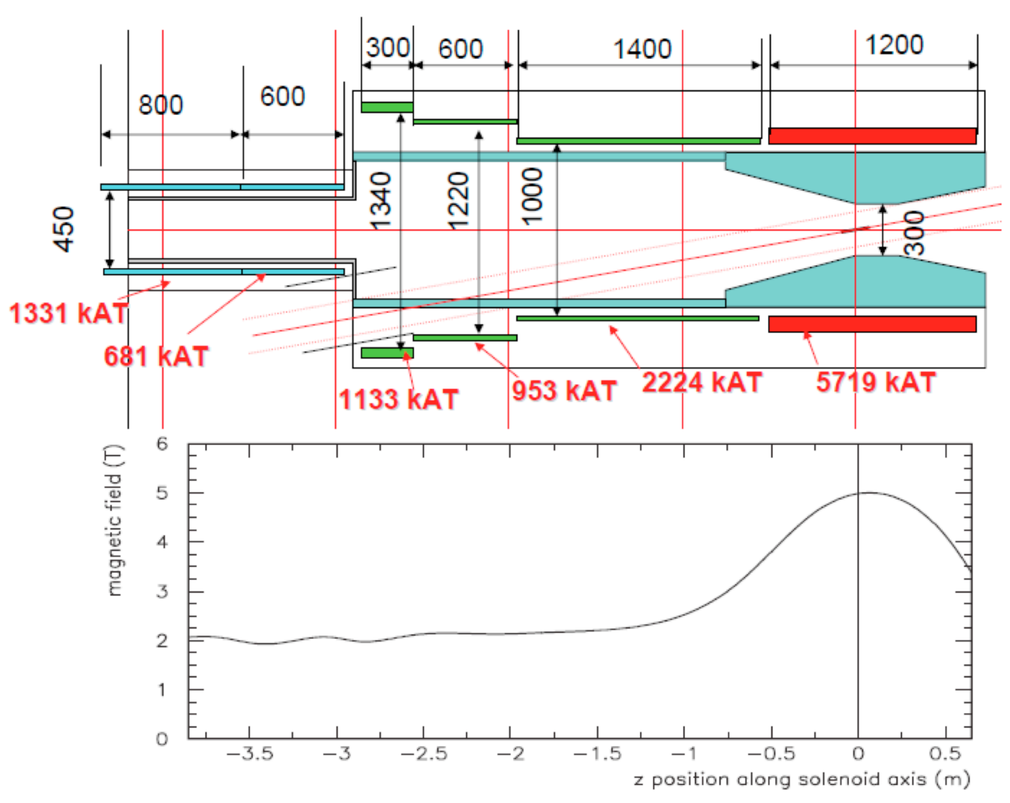
- Al-stabilized superconducting cable
  - to reduce heat load by radiation from target
  - cable dimension: 15mmx4.7mm



Al/Cu/NbTi : 7.3/0.9/1.0

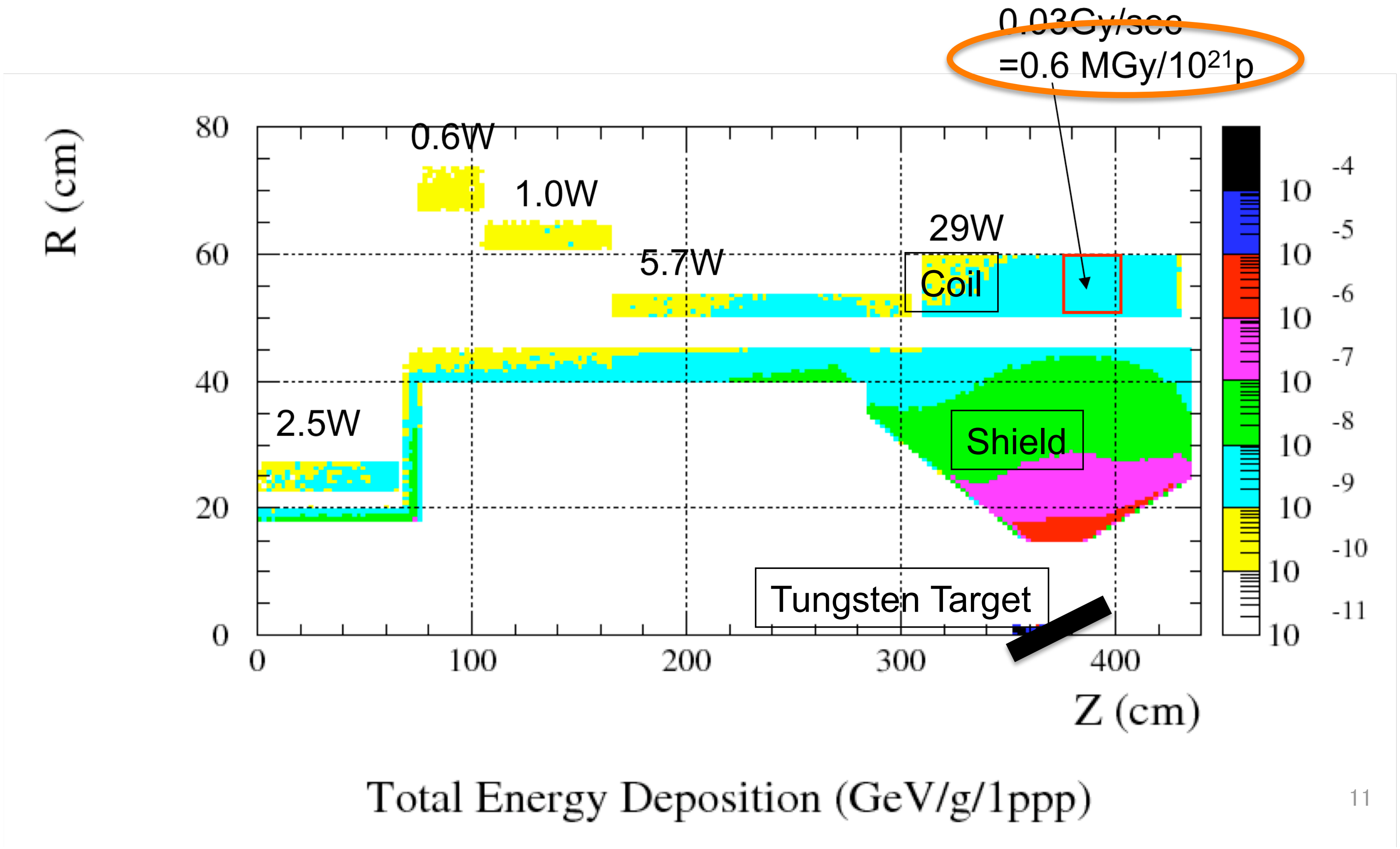
- Coil parameters:

	length (mm)	thickness (mm)	current density (A/mm^2)
Coil1	1200	90 (6 layer)	53.0
Coil2	1400	30 (2 layer)	53.0
Coil3	600	30 (2 layer)	53.0
Coil4	300	60 (4 layer)	62.9



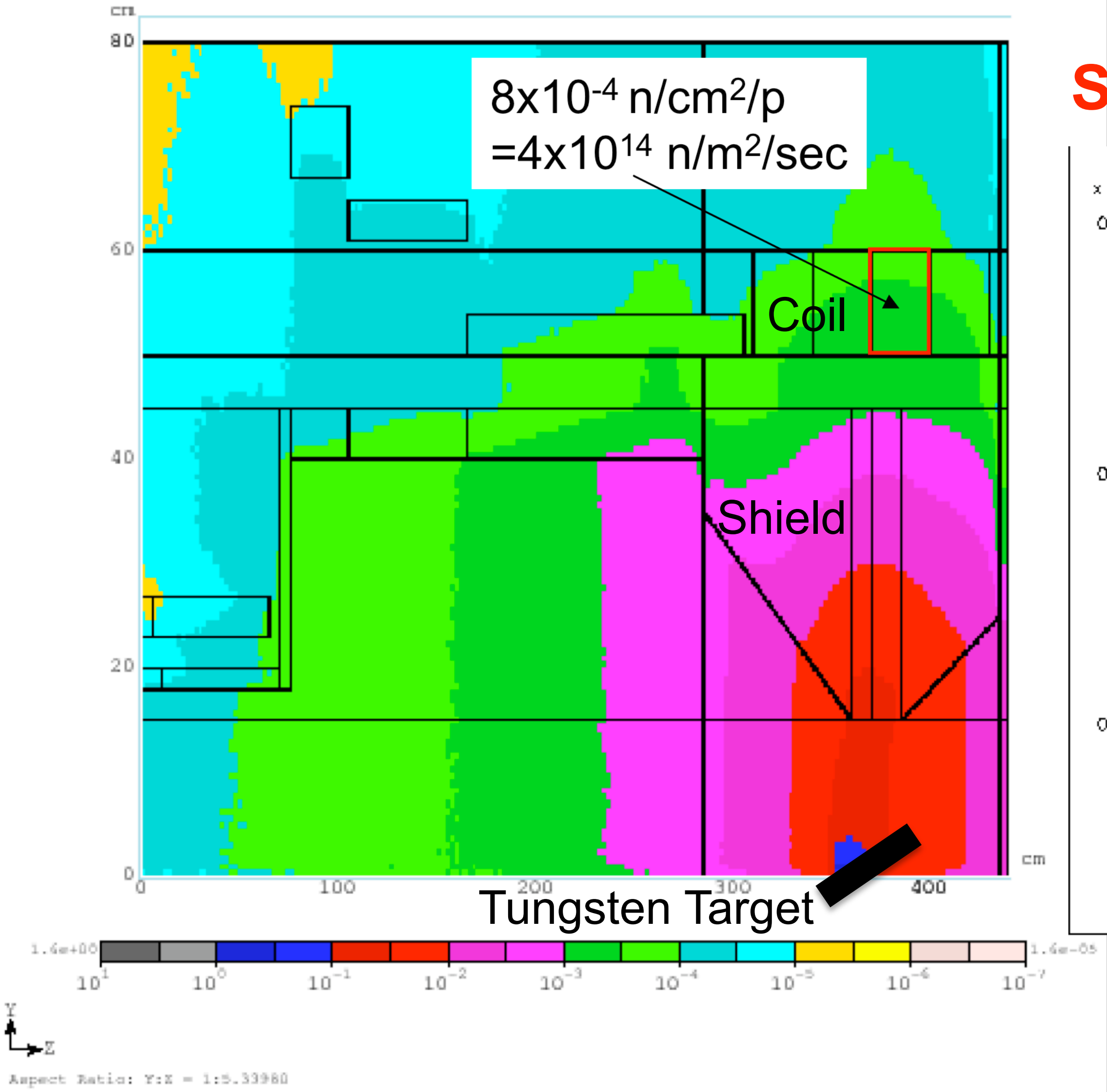
K. Tanaka

Irradiation: Energy deposition



Total Energy Deposition (GeV/g/1ppp)

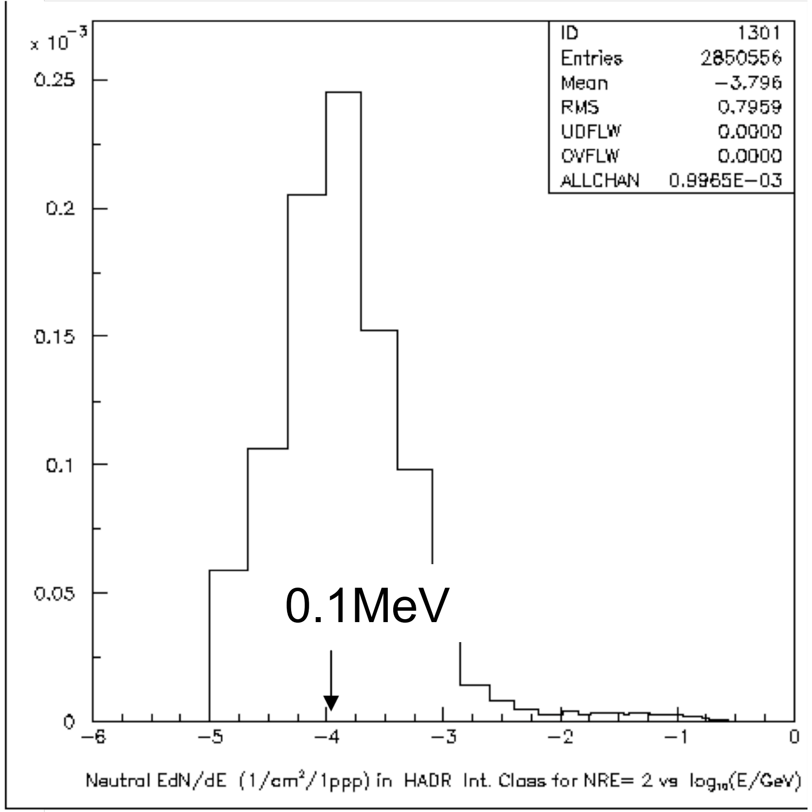
Irradiation: Neutron Fluence



8×10^{-4} n/cm^2/p
$=4\times10^{14}$ n/m^2/sec

~10^{22} n/m^2 for 10^{21} POT

Same order of ITER spec!!



New Demand: Radiation Resistant SC Magnets

- Application:
  - SLHC (>2018)
  - Pion Capture Solenoids: COMET (201x?), g-2, Mu2e
  - Muon Transport: SuperOmega (2010?)
  - Long-term: Muon collider??
- Design Dose Guideline: 10^{22} n/m^2, >10 MGy
  - Similar level as ITER SC magnets!!
- Watch: difference in radiation type, spectrum, environment.

How can we realize the magnet system?

Interaction and Particle Energy

$$p = \frac{\sqrt{((T + m_0c^2)^2 - (m_0c^2)^2)}}{c}$$

$$\lambda = \frac{h}{p}$$

p: Momentum (MeV/c)
T: Kinematic Energy (MeV)
m_0c^2: Rest Mass (MeV)
h: Planck's Constant(=4.1357e-15 eV s)
λ: de Broglie Wave Length (m)

Lattice Constant: ~10^{-10} m >> En ~ 0.025 eV
Nucleus: ~10^{-14} m >> En ~ 10 MeV
Nucleon: ~10^{-15} m >> En ~ 1 GeV
Quark…

- Physics model is energy-dependent: Quark-Gluon String, INC, END…
- Displacement of atom is induced by neutron bombardment beyond ~0.1 MeV.
- But at higher energies, nuclear reaction is more dominant.
- For organic materials, ionization by gamma rays is most influenced.

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R&D for Radiation Resistant SC Magnets

- Simulation for magnet design with acceptable dose
  - MC Codes: MCNPX, Geant4, MARS, PHITS, FLUKA
    - Discrepancy in dose among codes.
    - Uncertainty (factor 2-5 in my impression)
  - Geometry modeling. Suitable setting. Benchmark.
  - Discussion on results of fluence, heat deposition, radioactivity, etc. Feedback to the magnet design with redundancy: enlarging shield, aperture >> COST !!
- Evaluation of Radiation Resistance
  - Choice of appropriate materials.
  - Literature survey and experiment to evaluate the limit.
- Development of Radiation Resistant Materials
  - Cyanate Ester Resin, Ceramic Insulation, etc…

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Elements of SC Magnet

- SC Coil
  - SC: NbTi (or Nb3Sn), MgB2
  - Stabilizer: copper, aluminum
  - Resin: Epoxy, Cyanate Ester
  - Insulator: Polyimide, glass sheet, GFRP, Ceramics
- Mechanical Structure & Cryostat
  - Support: metal, GFRP (w/ Epoxy or CE)
  - MLI: Polyimide w/ Al coating
  - Instrument.: thermometer (Cernox, Pt..), wires, ….
  - Protection: bypass diode, heaters, …..
  - Bus Leads: HTS, copper

Metal, semiconductor, ceramics: influenced mainly by n, p, ions
Organic materials: influenced by gamma rays (e), n (p) (& charged particles)
Composites: gamma rays, n, …..

Irradiation effects are determined by nature of materials, radiation types, energy, ambient gas, temperature.

SC Magnet Operation: mostly around 4K, vacuum or LHe

>> better radiation environment compared with one at RT and in air (oxygen).

Neutron Spectra at Irradiation Facilities

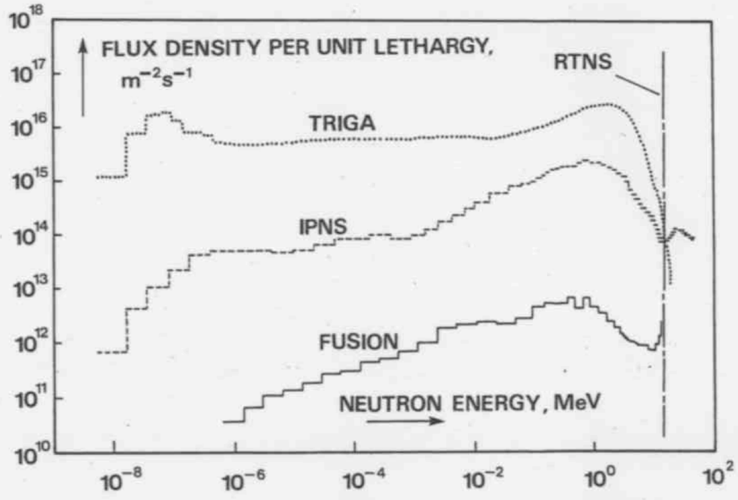


Fig. 1. Neutron flux density distribution for four different neutron sources: fission reactor (TRIGA, Vienna), spallation source (IPNS, Argonne), DT-source (RTNS-II, Livermore), fusion spectrum at the magnet location (STARFIRE).

- Reactor (& SNS) provides both neutrons & gamma rays.
- Those neutron spectra widely range from thermal to MeV.
- DT neutron is rather monochromatic at 14 MeV with negligible gamma-rays.

Gamma-ray Irradiation Facilities

Cs137(0.66MeV) or Co60(1.17, 1.33MeV) gamma ray sources

- In reality, irradiated by a variety of particles with higher energies up to several GeV.
- Difficult to perform irradiation tests with similar radiation environment.

  >> Redundancy must be taken into account.

SC: NbTi (1)

Degradation on Tc: 0.15 K to 0.6 K @up to 10^23/m2

Adv. Cryo. Engineering, 32, p853 (1986)

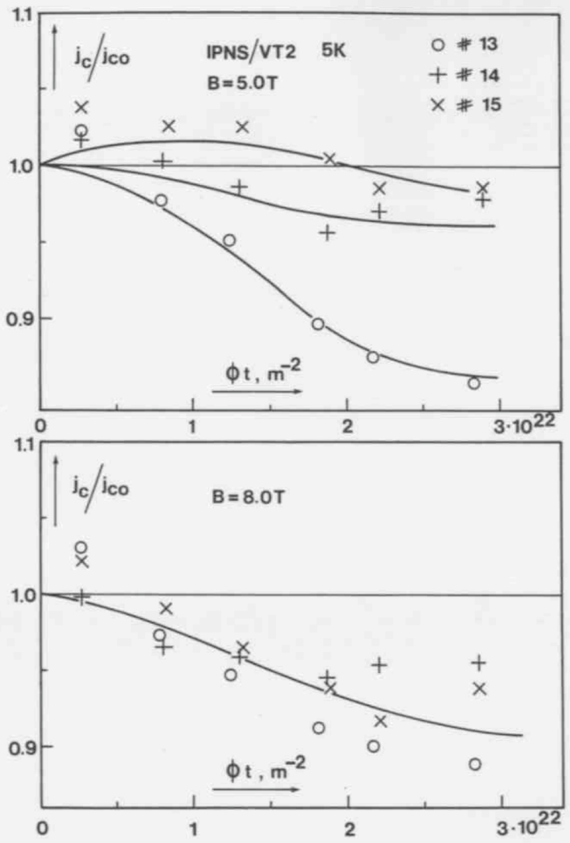
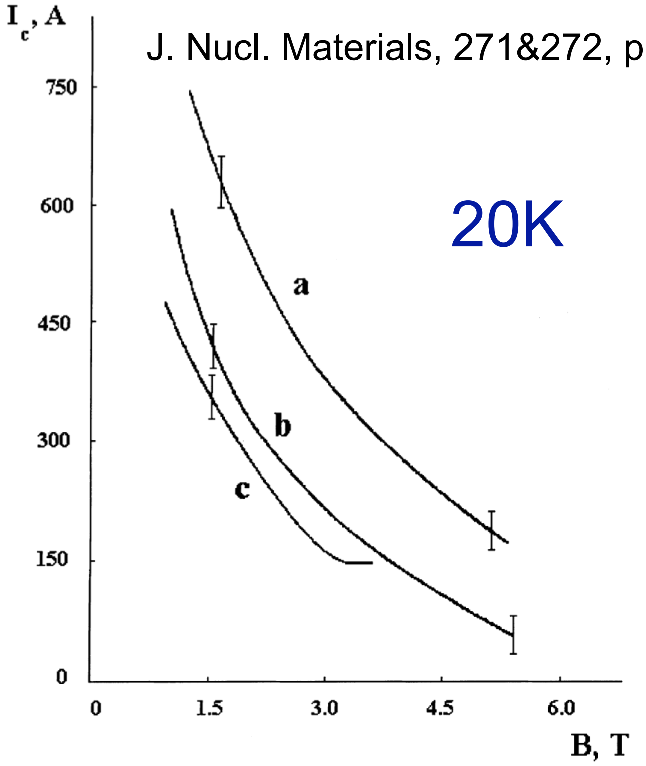


Fig. 2. Change of critical current densities with fast neutron fluence (E >0.1MeV) at 5 and 8 T. #13,14,15: 42,49,54 wt%Ti; annealing temperature: 350°C; final cold work: 71%.

5K

Jc: < 10% reduction up to 10^22/m2

J. Nucl. Materials, 271&272, p505 (1999)



20K

Fig. 2. Dependence of critical current vs magnetic field for 37-core industrial superconducting NbTi wire: (a) before irradiation; (b) after irradiation by the neutron fluence of 8.6×10^{17} cm^{-2}; (c) after irradiation by the neutron fluence of 1.6×10^{18} cm^{-2}.

I: Significant reduction at 5T @ 10^22/m2

SC: NbTi (2)

RT, 77K w/ T.C.

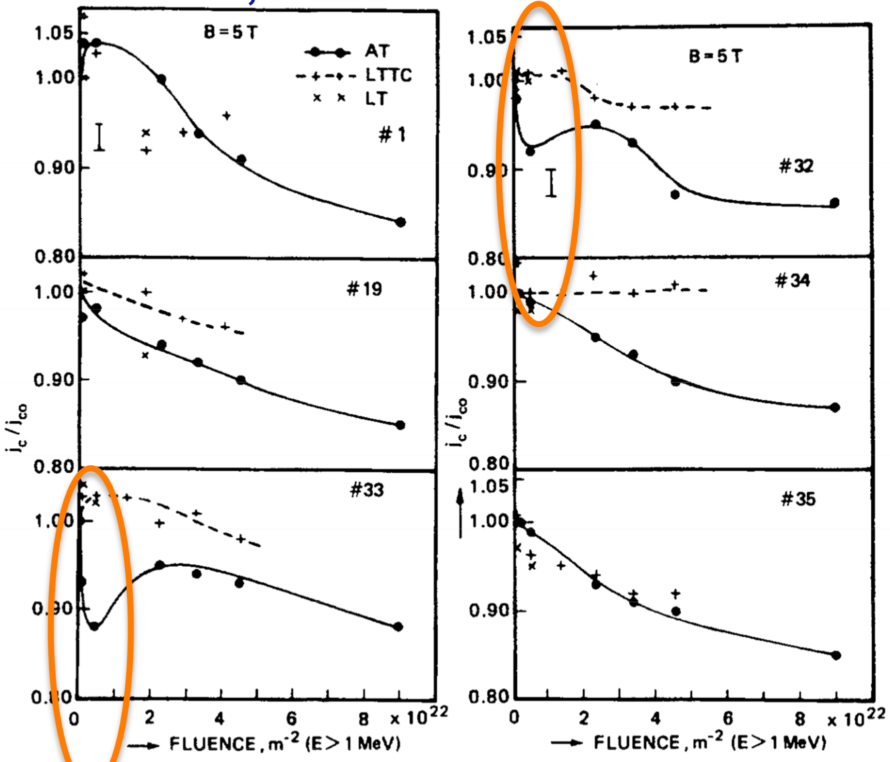


Fig. 11. Changes of critical current densities measured at 5 T with fast neutron fluence. AT, LT: irradiation at ambient temperatu and 77 K, respectively; LTTC: irradiation at 77 K and thermal cycle to room temperature. No. 1: Nb–42 wt% Ti, lowest j_{c0}; Nos. 1 32, 33: Nb–42, 49, 54 wt%Ti, highest j_{c0} of each series; Nos. 34, 35: Nb–49 wt%Ti, Multifilamentary conductors [41].

J. Nucl. Materials, 108&109, p572 (1982)

RT

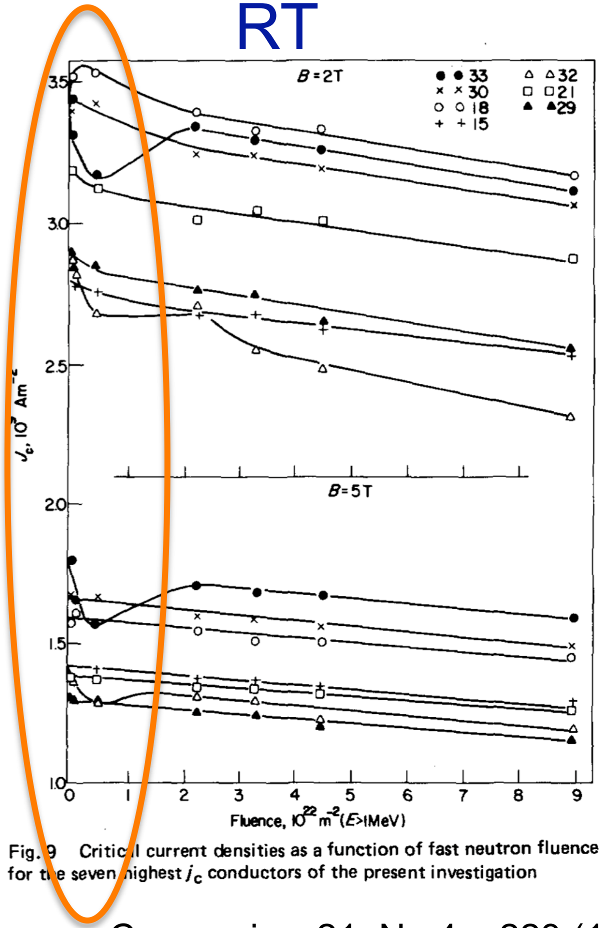


Fig. 9 Critical current densities as a function of fast neutron fluence for the seven highest j_c conductors of the present investigation

Cryogenics, 21, No.4, p223 (1981)

Jc: Drop and recovery observed to 10^22/m2.
10-20% reduction up to 10^23/m2.
Recovery by annealing to RT is observed.

NbTi would be OK up to 10^22/m2.

SC: Nb3Sn

Adv. Cryo. Engineering, 32, p853 (1986)

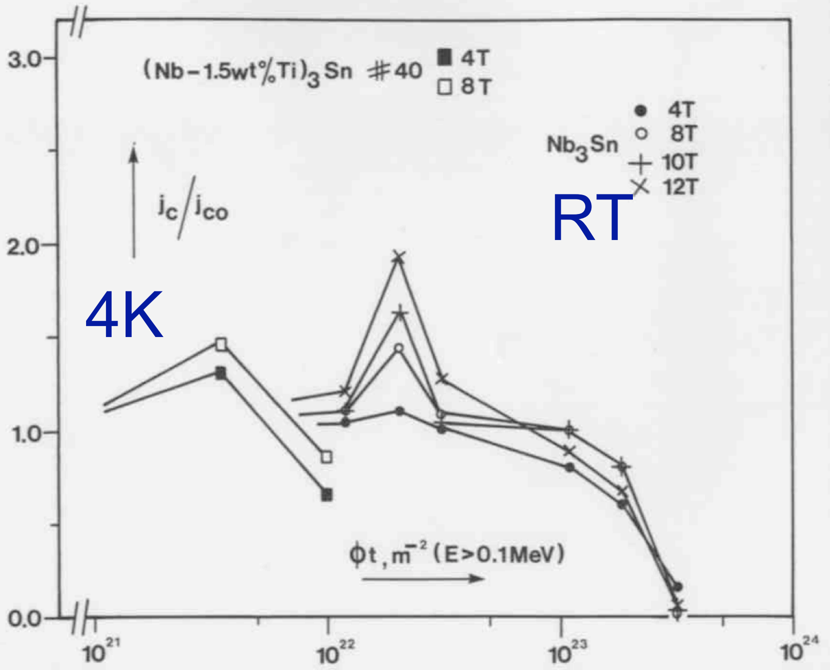
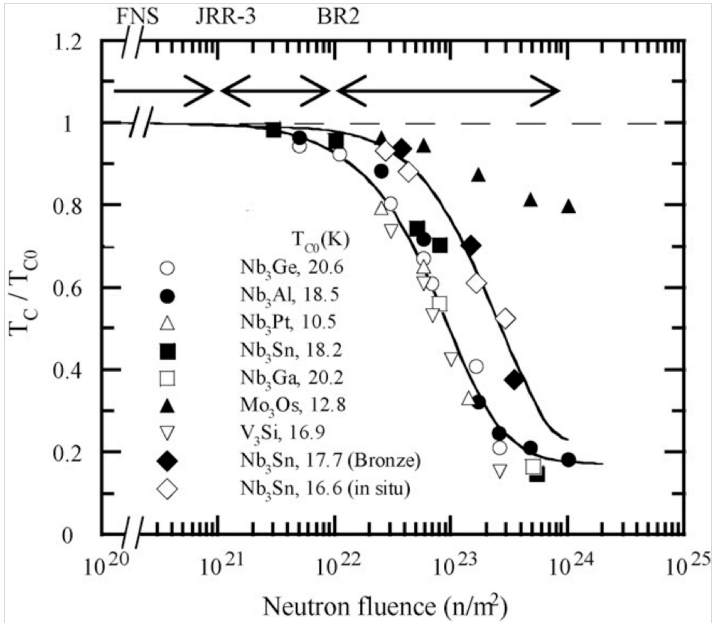


Fig. 6. Change of critical current densities with neutron fluence. The scaling is not completely accurate because of slight differences in damage energy cross sections. Low temperature irradiations on an alloyed conductor are compared to ambient temperature irradiations of pure Nb$_3$Sn[29].

Fusion Eng. Design, 84, p1425 (2009)



Tc: -10% @ 10^22/m2.
-30% @ 10^23/m2.

Jc: Improvement bwn 10^22 and 10^23/m2.
Significant degradation beyond 10^23/m2.

NbSn would be OK up to 10^22/m2 as well.

SC: MgB2

Physica C, 463-465, p211 (2007)

SNS, Irradiated at RT

Natural abundance ratio: B10 19.9%, B11 80.1%

Large neutron capture cross section of B10.

Recent work on B11 enriched MgB2 to improve radiation resistance: B10 < 0.5%.

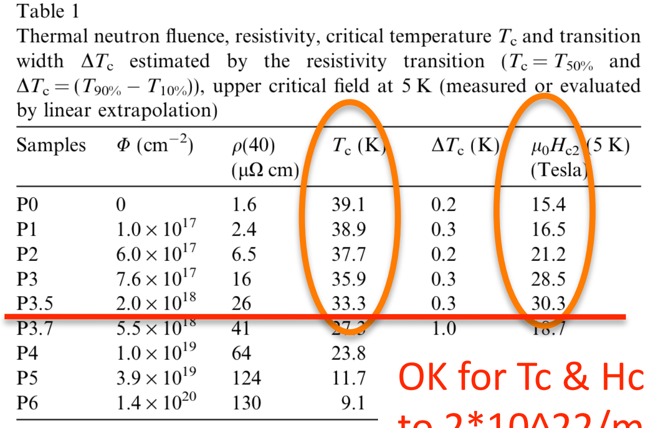


Table 1

Thermal neutron fluence, resistivity, critical temperature T_c and transition width ΔT_c estimated by the resistivity transition ($T_c = T_{50\%}$ and $\Delta T_c = (T_{90\%} - T_{10\%})$), upper critical field at 5 K (measured or evaluated by linear extrapolation)

Samples	Φ (cm^{-2})	$\rho(40)$ (μΩ cm)	T_c (K)	ΔT_c (K)	$\mu_0 H_{c2}$ (5 K) (Tesla)
P0	0	1.6	39.1	0.2	15.4
P1	1.0×10^{17}	2.4	38.9	0.3	16.5
P2	6.0×10^{17}	6.5	37.7	0.2	21.2
P3	7.6×10^{17}	16	35.9	0.3	28.5
P3.5	2.0×10^{18}	26	33.3	0.3	30.3
P3.7	5.5×10^{18}	41	27.3	1.0	18.7
P4	1.0×10^{19}	64	23.8		
P5	3.9×10^{19}	124	11.7		
P6	1.4×10^{20}	130	9.1		

OK for Tc & Hc2 up to 2*10^22/m2

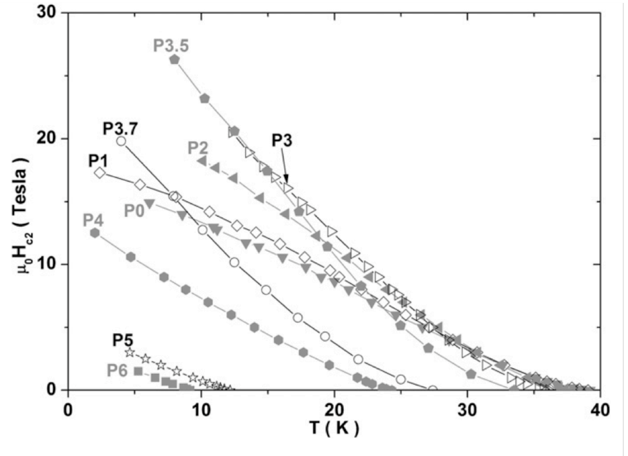


Fig. 1. Upper critical field as a function of temperature estimated at 90% of the resistive transition.

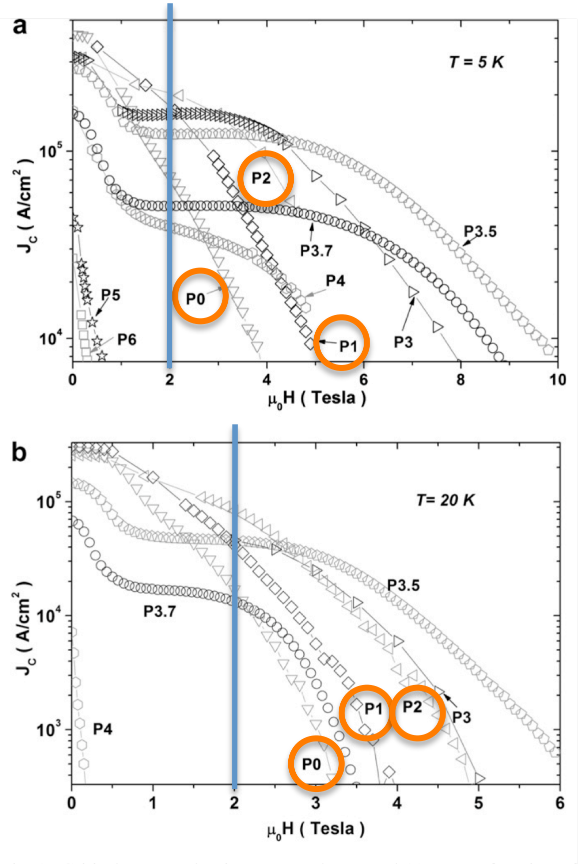


Fig. 2. Critical current density measured at 5 and 20 K as a function of magnetic field.

Jc at higher field improved by irradiation up to 6*10^21/m2.

MgB2 with enriched B11 would be OK up to 10^21/m2.

Availability of production wire should be checked.

Further irradiation tests should be done.

Anneal Effect: Stabilizer - Elec. conductivity-

Irradiated at 4K, and warmed up to RT.

J. Nucl. Materials, 49, p161 (1973&74)

Reactor n
on Al

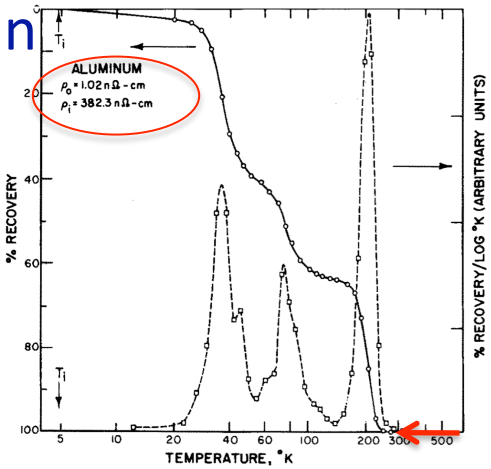


Fig. 3. Recovery and differential recovery versus logarithm of absolute temperature for aluminum irradiated at 4.5 K to 2 × 10^{18} n/cm² of $E > 0.1$ MeV.

Reactor n
on Cu

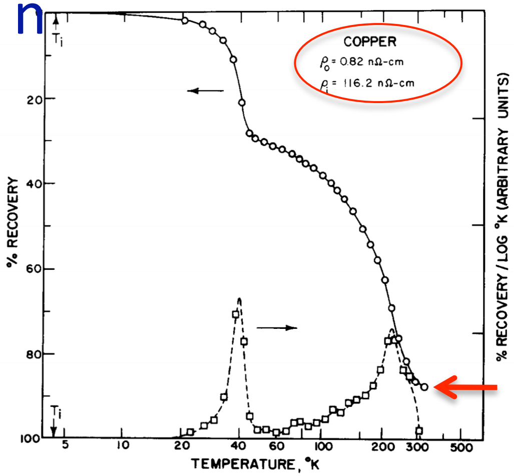


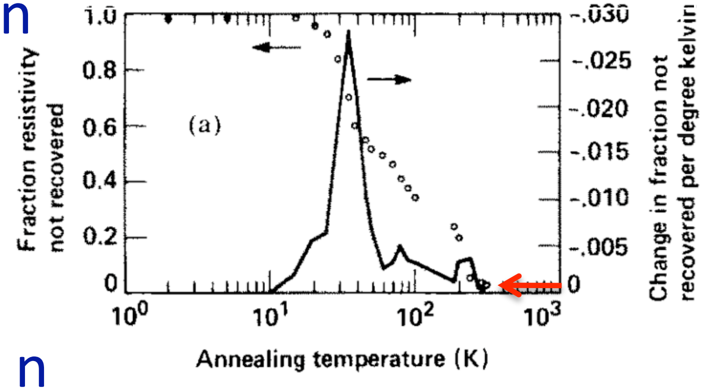
Fig. 5. Recovery and differential recovery versus logarithm of absolute temperature for copper irradiated at 4.5 K to 2 × 10^{18} n/cm² of $E > 0.1$ MeV.

fluence up to 2*10^22/m2.

J. Nucl. Materials, 133&134, p357 (1985)

14MeV n
on Al

r0: 0.386
r-irrad: 0.772
(nΩm)



14MeV n
on Cu

r0: 0.098
r-irrad: 0.191
(nΩm)

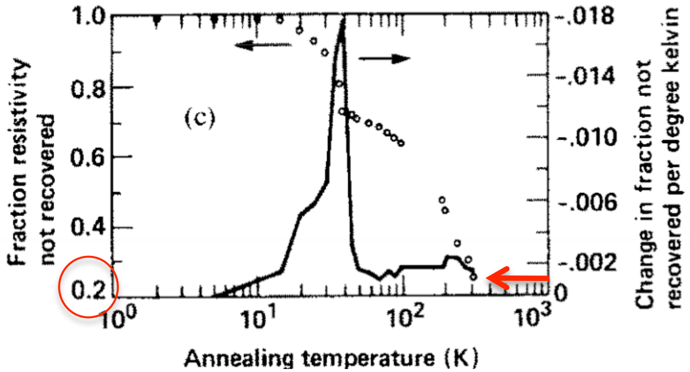


Fig. 2. Post-irradiation, isochronal annealing results for (a) Al, (b) Ni, (c) Cu and (d) Pt. Annealing results below 50 K for Ni and Pt were lost because of warming.

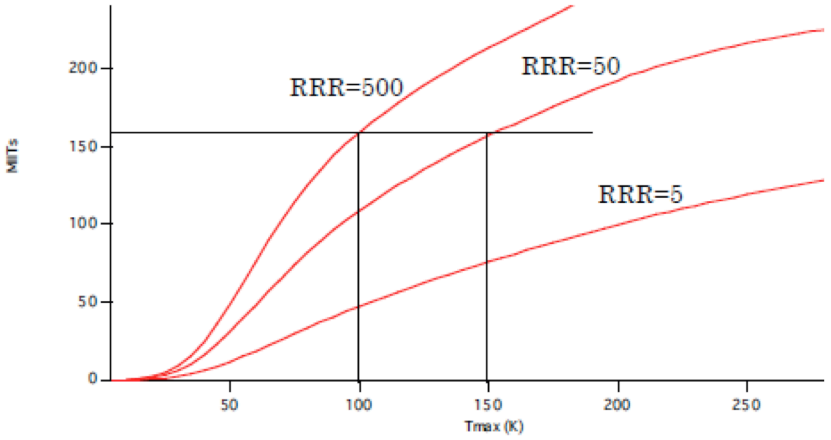
fluence up to 1*10^21/m2.

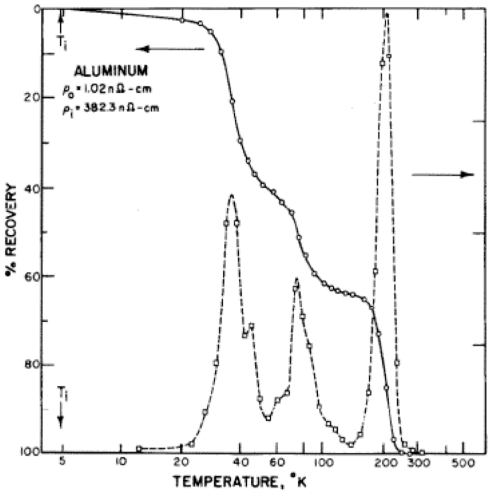
- **Double of electrical conductivity can be observed at 10^21/m2.**
- **Full recovery in Al expected by T.C.**
- **Degradation in Cu will be accumulated even after T.C.**

Why is ρ of Stabilizer Important?

>> very concerned with quench protection.

- MIITs: $\int_{t_{quench}}^{t_{end}} I^2 dt = \int_{T_0}^{T_{\max}} \frac{C_p A}{\rho / A} dT$
- ρ increase ➔ temperature increase





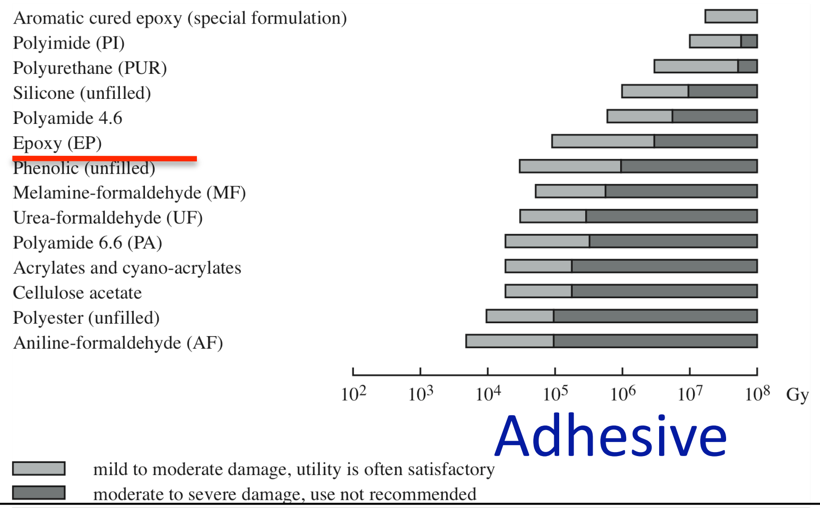
Neutron irradiation test for stabilizers (copper, aluminum) is undoubtedly necessary.

minimum fluence to start of degradation
anneal effect on recovery
R&D of witness sample for the operation

Organic Materials: Overview

CERN Yellow Report, Compilation of radiation damage test data, CERN 98-1 & 2001-06

Table 2: Classification of adhesives according to their radiation resistance



Adhesive

- Polyimide for electrical insulation is OK over 10MGy.
- Our previous work (only w/ γ) shows GFRP (G11) and insulator (GUG) with epoxy-resin could be used in LT environment up to several MGy.

  >> Need to check neutron effects.

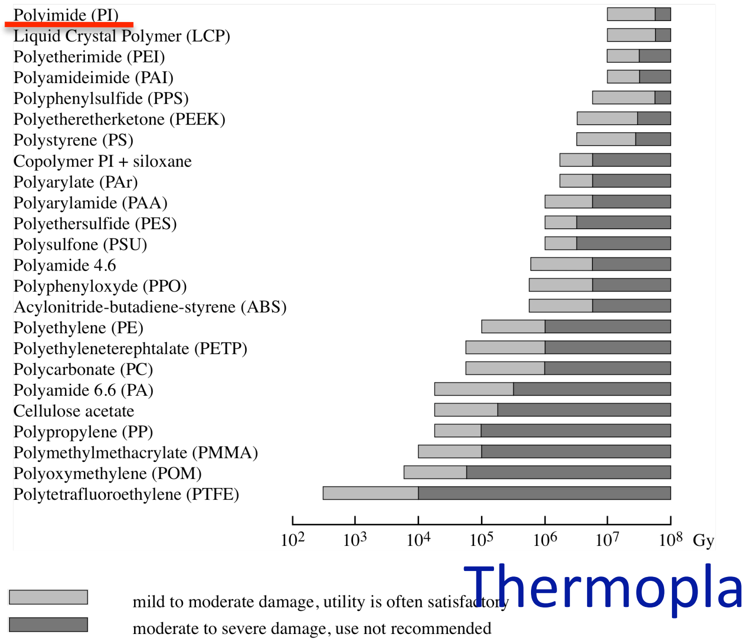
  >> Evaluation tests should be re-considered.

  What purpose? Function? Type of loads?
- As explained later, CE has a better radiation resistance than Epoxy.

  * Note difference is within factors.

Table 2a

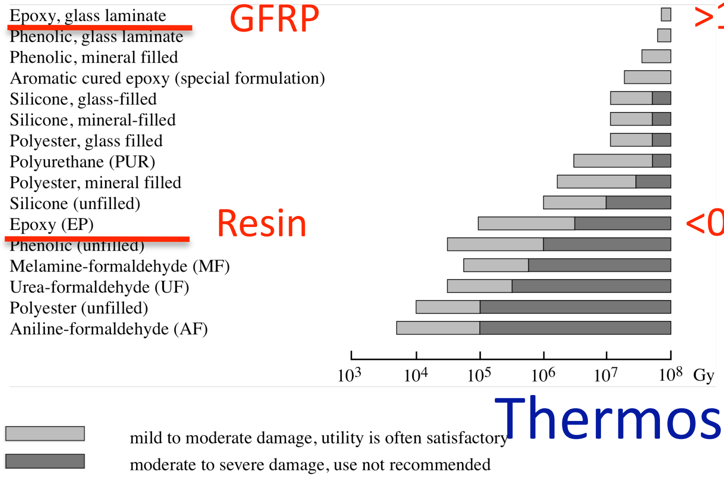
General classification of rigid thermoplastics with respect to their radiation resistance



Thermoplastic

Table 2b

General classification of thermoset resins and composites with respect to their radiation resistence



GFRP

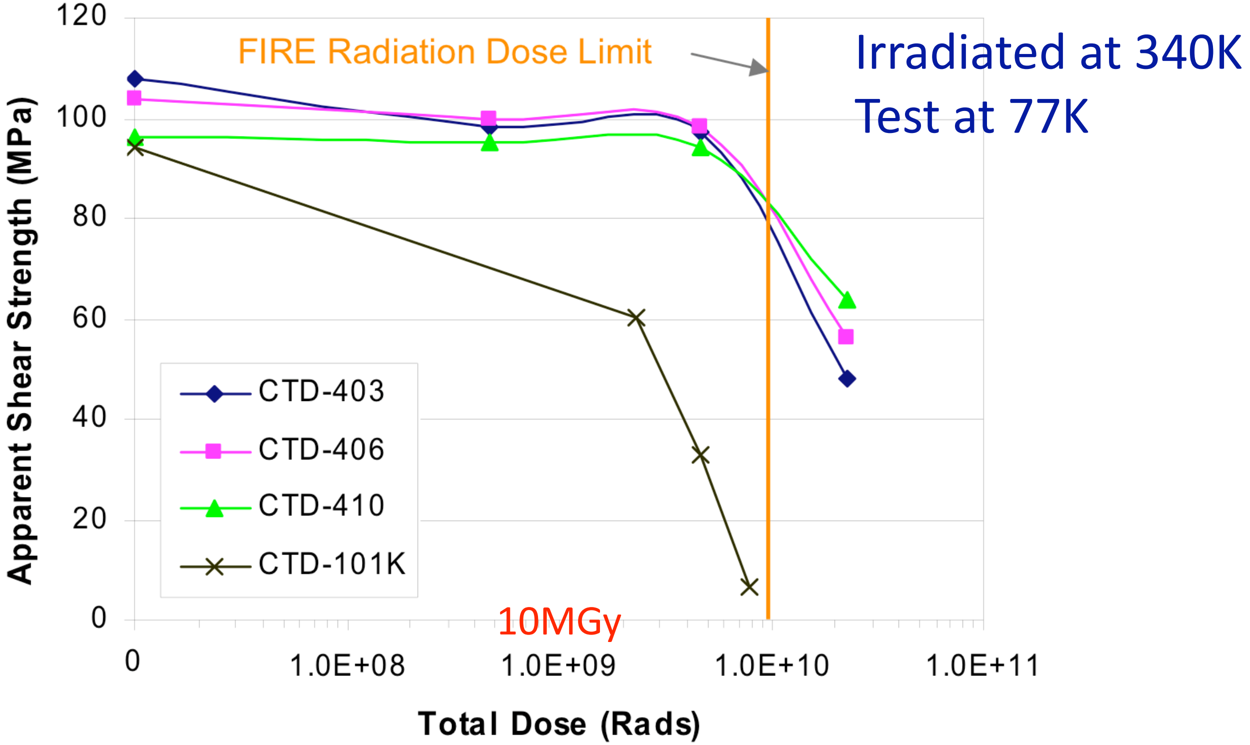
>10MGy

Resin

<0.1MGy

Thermoset

Organic Materials: Epoxy vs. Cyanate Ester



- **Austria TRIGA Reactor Irradiation**
  - **80% gamma, 20% neutron, 340 K**
  - **10^{21} n/m^2 = 4.7 x 10^8 Rads**

Fabian and Hooker et. al., presented at "HHH-AMT, Topical Meeting on Insulation and Impregnation Technologies for Magnets"
Slides available: http://at-hhh-amt.web.cern.ch/AT-HHH-AMT/

Contents

- Demand of Radiation Resistant SC Magnets
  - SLHC
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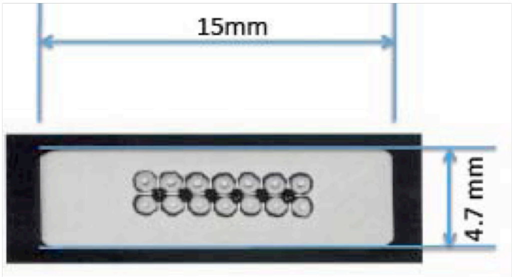
- Property Change of Materials by Irradiation
- Irradiation Test Plan and Present R&D
- Summary

R&D on Al stabilized NbTi conductor

- COMET, Mu2e
- Collaborative work with Hitachi Cable.
- Production of Al stabilized NbTi superconductor for test coil. (>500m)
- Fundamental study on Al stabilizer: doping of different elements, cold-work.
  - >> RRR, Yield Strength, Bonding Strength.
- Property change due to neutron irradiation

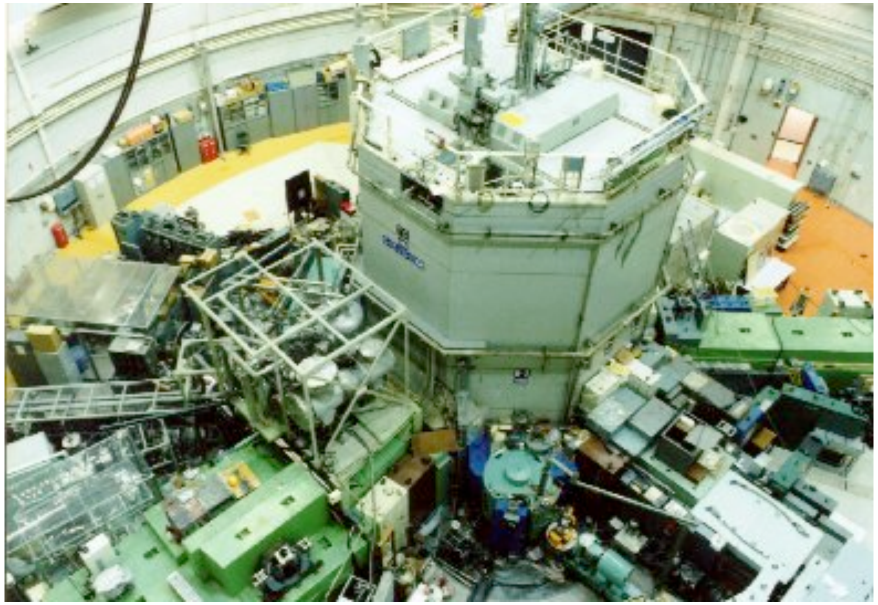
Strand	
Material	NbTi-Cu
Cu/SC ration	0.9
Strand Dia.	1.15 mm
Filament Dia.	27 m
Cu RRR	> 50
SC Cable	
size	2.15 mm x 8.15 mm
# of strands	14
Cable Pitch	87 mm
Ic@4.3K	>14120 A@5T, >11090 A@4T, >8180 A@7T
Al-stabilized Conductor	
Size	4.70 mm x 15.00 mm
Al RRR	>500
Al 0.2% strength	>62 MPa@300K

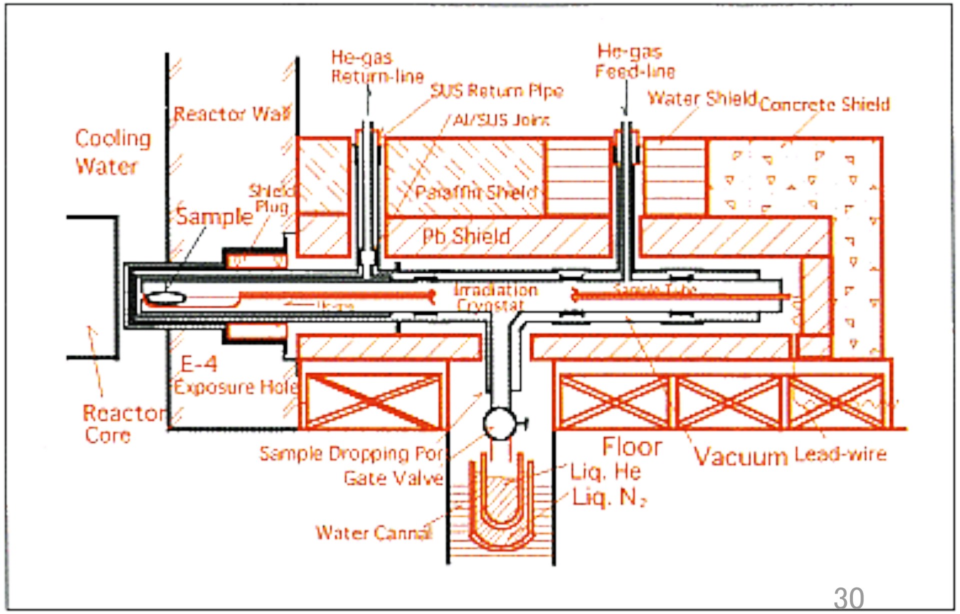


Al/Cu/NbTi : 7.3/0.9/1.0

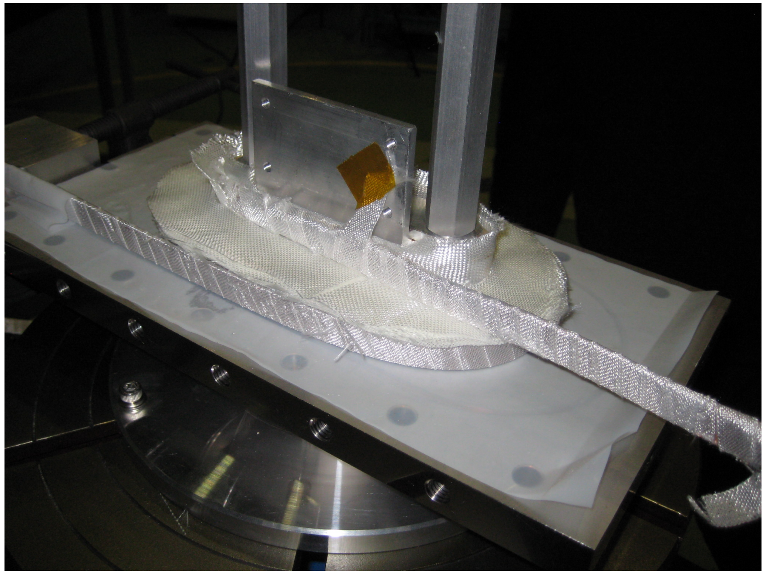
Neutron Irradiation -Plan-

- **Kyoto Univ. Research Reactor (5 MW, 3x10^{13}n/cm²/s for $n_{thermal}$)**
- **Shutdown until spring 2010 for fuel replacement. New operational power is lowered to be 1 MW.**
- **Low temperature irradiation facility available:**
  - **$T_{irrad.}$ from 10 K to 370 K**
  - **Max. fast-neutron flux of 1 x 10^{16} n/m²/s**
- **Sample candidates: Copper (RRR~100), Pure Al (see next slide), others…**
- **In-situ resistance measurement under the irradiation, hopefully up to 10^{22} n/m²**
  - **- Fluence of degradation start**
  - **- Anneal effect on recovery by warm-up to RT**
- **Irradiation test anticipated in fall 2010.**

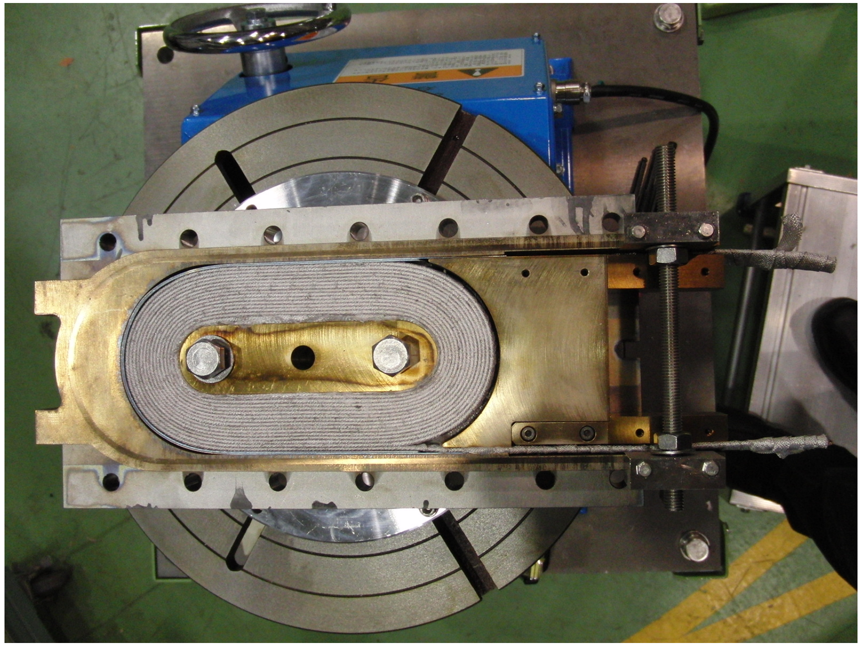


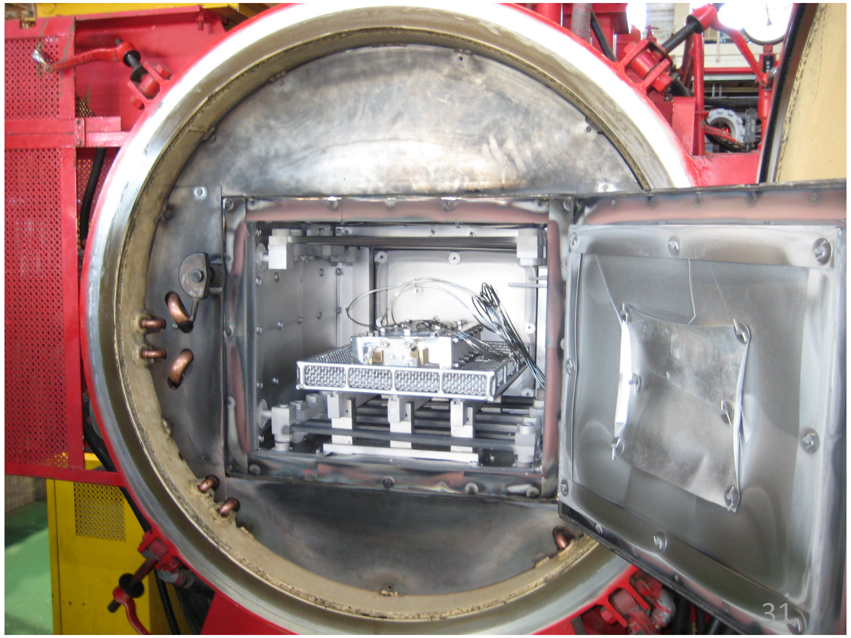


Ceramic Insulation



- A15 type SC wire application: SLHC
- Alumina Insulation Tape, Cloth:
    - Up to 1200 °C
    - t0.125 mm or thinner (0.08 mm?)
- Intrinsically Radiation Resistant ??



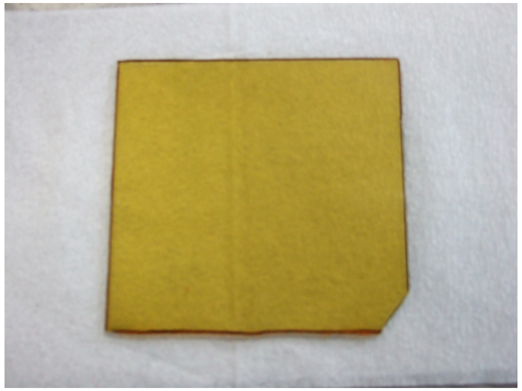


Cyanate Ester Based Resin for Nb3Al Coil Impregnation

- Collaboration for accelerator HFM application (SLHC):
  - Mitsubishi Gas Chemical: provider of Cyanate Ester resin
  - Univ. of Hyogo: evaluation (bonding & mechanical properties)
  - JAEA: gamma-ray irradiation, evaluation (evolved gas)
  - KEK: specification, specimens

- Radiation resistant resin of Cyanate Ester is being developed for the Nb3Al coil impregnation.
- Spec.
  - low viscosity
  - control of solidification
  - mechanical strength

A first resin will be delivered to KEK.



Newly developed CE resins for HF accelerator magnets

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Summary

- Importance of radiation resistance has been risen through development of SC magnets for SLHC and high intense muon experiments such as COMET.
- Tentative design guideline: 10^{22} n/m^2, 10 MGy. (≅ITER spec.)
- Magnet design relies on the MC simulation with taking into account uncertainty and redundancy.
- Based on literature survey and irradiation experiment, appropriate choice of material and property evaluation must be required.
- Thermal cycle to RT may help to recover properties of metal, but not for organic materials.
- Ceramic insulation and Cyanate Ester resin for Nb3Al SC magnet are being developed.
- For COMET pion capture SC solenoid with Al-stabilized NbTi SC, neutron irradiation at cold at KURR is planned in 2010 to mainly evaluate degradation/recovery property of resistivity of stabilizer.

Question: Validity of "Fluence"? Use DPA? Other better index?

Reminder/Excuse

- So far, less experience to construct/operate SC magnets in severe radiation environment.
  - Problem of SC magnets in LHC IR, SRC/BigRIPS, or muon beam line at MLF-J-PARC in near future might be a good lesson…
  - Keep watching!?

- As far as I know, NO SC magnet, even for ITER, has experienced the fluence of 10^{22} n/m^2.
  - Magnet development is NOT trivial at all.

Anneal Effect: SC -Tc&Jc-

Irradiated at LT, and warmed up to RT.

J. Nucl. Materials, 108&109, p572 (1982)

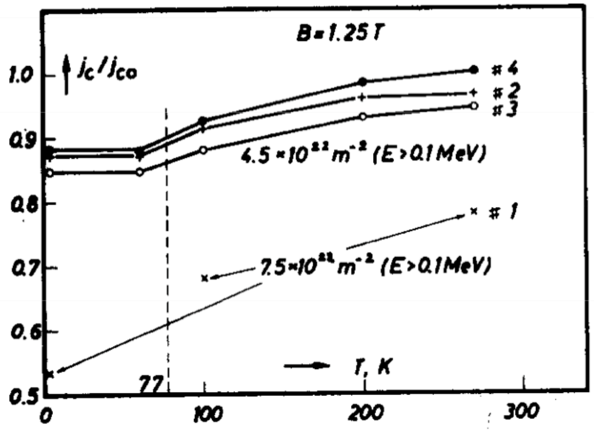


Fig. 9. Recovery of j_c/j_{c0} up to room temperature fc
ent samples of Nb–50 wt% Ti (measured at 4.2 K ar
after [44]. The measurements were made on one filar
1–3: 11 μm filament diameter, No. 4: 21 μm) of mu
tary wires.

NbTi
neutron

NbTi
30GeV proton

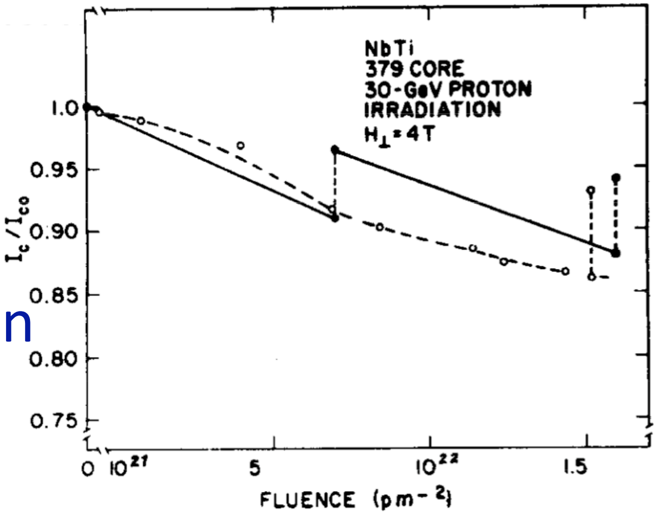


Fig. 10. Changes of critical currents measured at 4 T with proton fluence (Nb–45 wt% Ti, 379 core conductor). ○○○ irradiation at 4.2 K, final anneal at room temperature; … irradiation at 4.2 K, one intermediate and one final anneal to room temperature [33].

For NbTi, some recovery can be expected even after irradiation ~5*10^22/m2.

超伝導・低温工学ハンドブック p487 (1993)

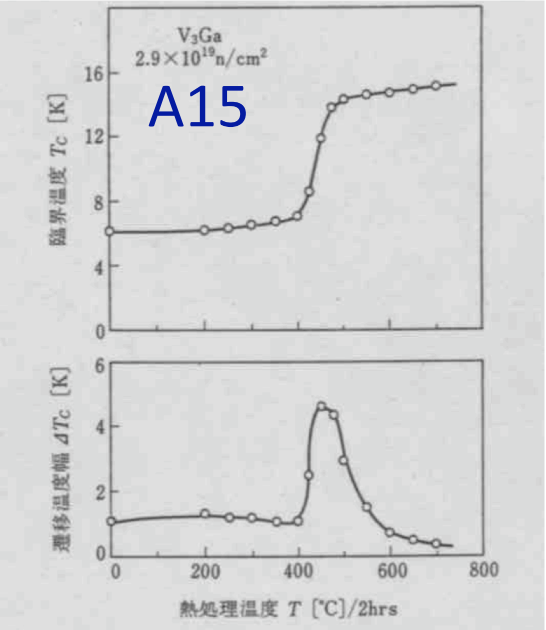
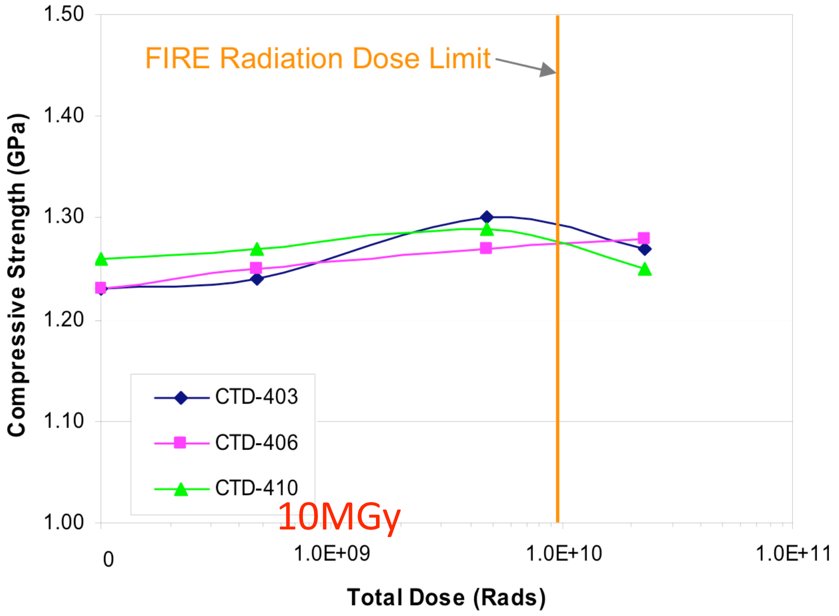


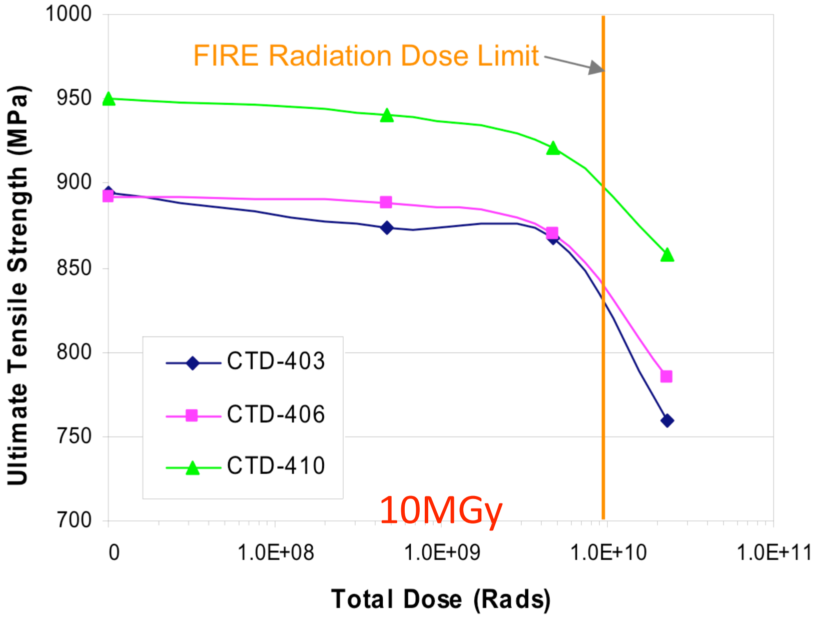
図 3・31　中性子照射した V_3Ga の臨界温度 T_c の熱処理（T〔℃〕，2時間）による回復（ΔT は T_c での常伝導遷移温度幅）［Shiota 1981］

Anneal effect only occurs beyond 400 °C.

Organic Materials: Cyanate Ester

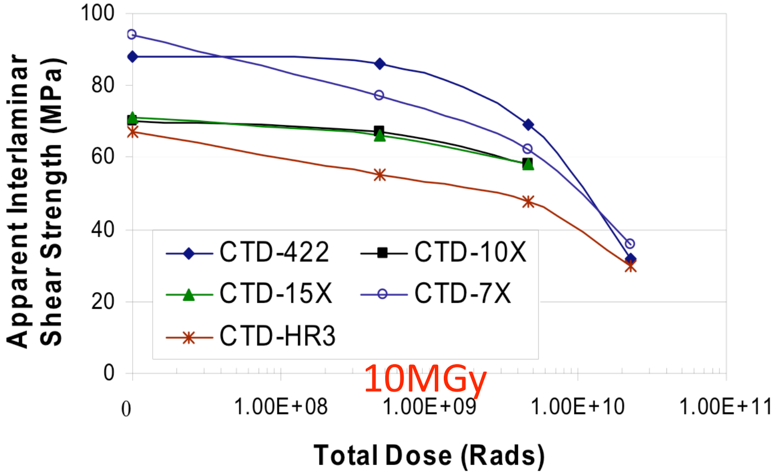
Irradiated at 340K
Test at 77K

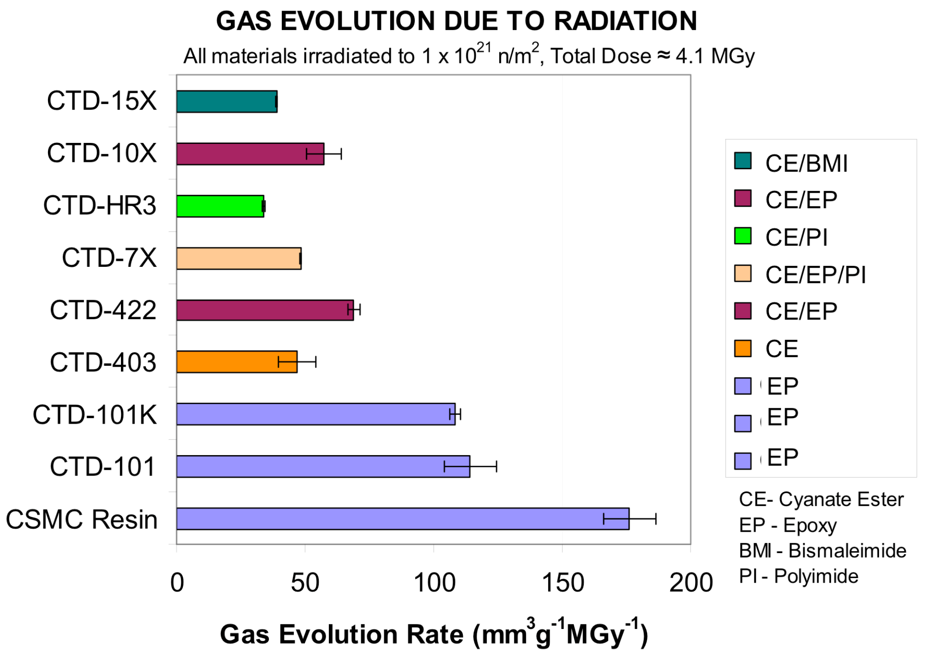




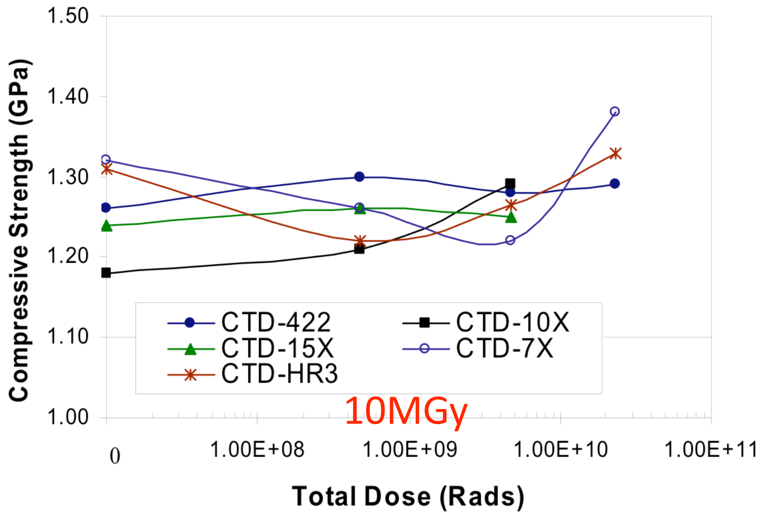
Organic Materials: Cyanate Ester

- **CTD-422 (CE/Epoxy, VPI)**
- **CTD-10X (CE/Epoxy/BMI, hot-melt prepreg)**
- **CTD-15X (CE/BMI, hot-melt prepreg)**
- **CTD-7X (CE/BMI, HPL)**
- **CTD-HRBX3 (CE/BMI, HPL)**

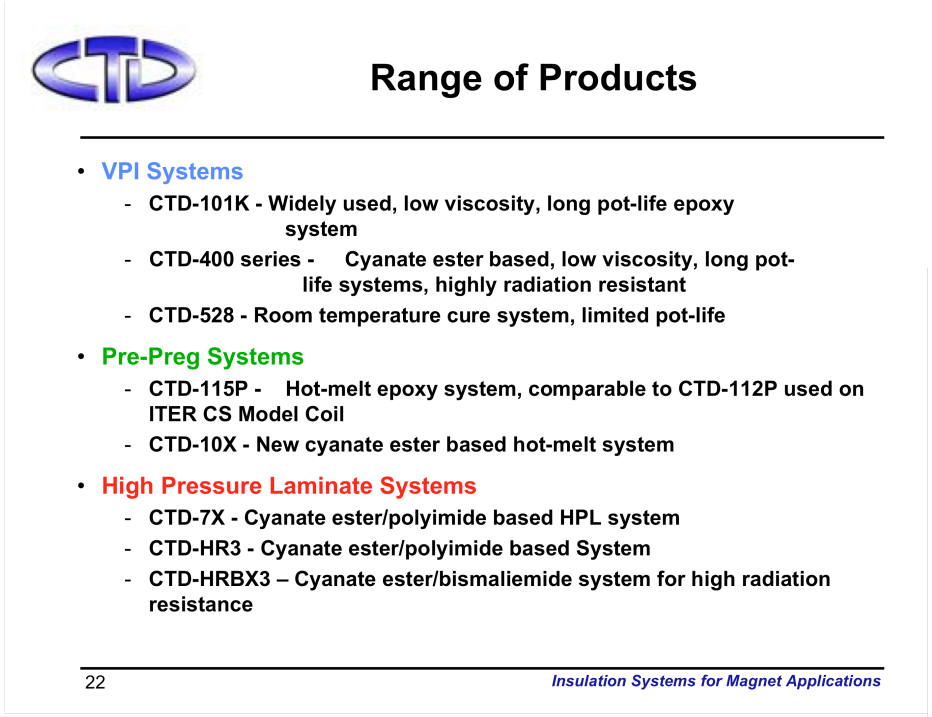




Irradiation and gas evolution testing performed by the Atomic Institute of the Austrian Universities, Vienna, Austria



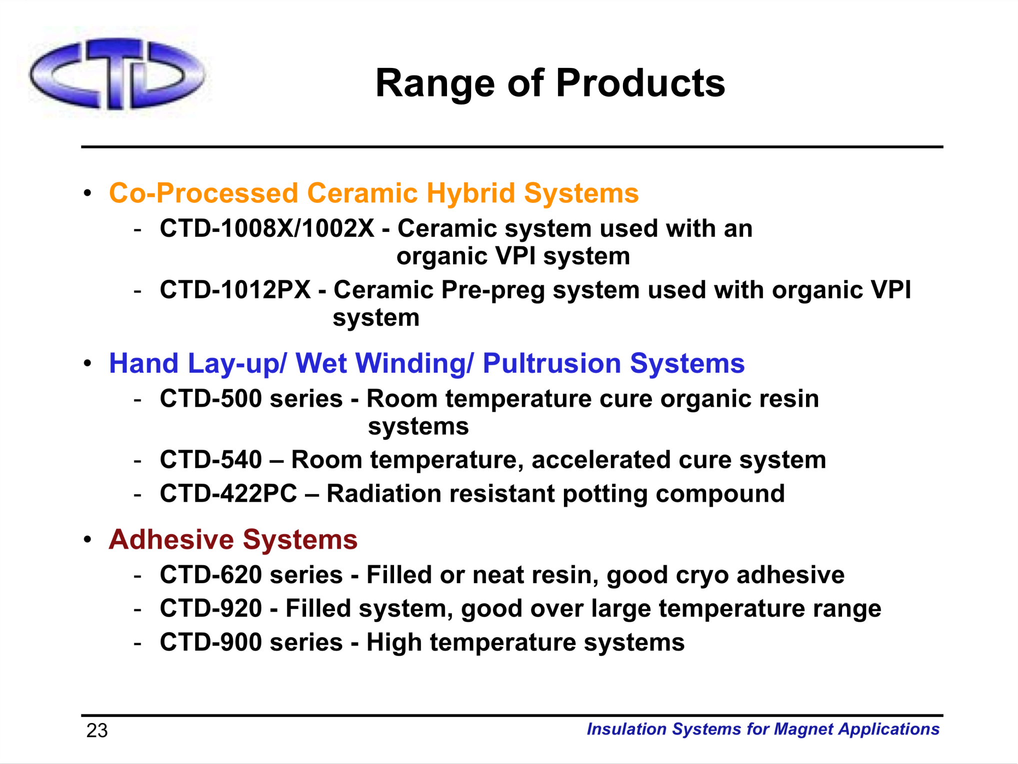
Availability of CE at CTD



Range of Products

- VPI Systems
  - CTD-101K - Widely used, low viscosity, long pot-life epoxy system
  - CTD-400 series - Cyanate ester based, low viscosity, long pot-life systems, highly radiation resistant
  - CTD-528 - Room temperature cure system, limited pot-life
- Pre-Preg Systems
  - CTD-115P - Hot-melt epoxy system, comparable to CTD-112P used on ITER CS Model Coil
  - CTD-10X - New cyanate ester based hot-melt system
- High Pressure Laminate Systems
  - CTD-7X - Cyanate ester/polyimide based HPL system
  - CTD-HR3 - Cyanate ester/polyimide based System
  - CTD-HRBX3 – Cyanate ester/bismaliemide system for high radiation resistance

22 *Insulation Systems for Magnet Applications*



Range of Products

- Co-Processed Ceramic Hybrid Systems
  - CTD-1008X/1002X - Ceramic system used with an organic VPI system
  - CTD-1012PX - Ceramic Pre-preg system used with organic VPI system
- Hand Lay-up/ Wet Winding/ Pultrusion Systems
  - CTD-500 series - Room temperature cure organic resin systems
  - CTD-540 – Room temperature, accelerated cure system
  - CTD-422PC – Radiation resistant potting compound
- Adhesive Systems
  - CTD-620 series - Filled or neat resin, good cryo adhesive
  - CTD-920 - Filled system, good over large temperature range
  - CTD-900 series - High temperature systems

23 *Insulation Systems for Magnet Applications*

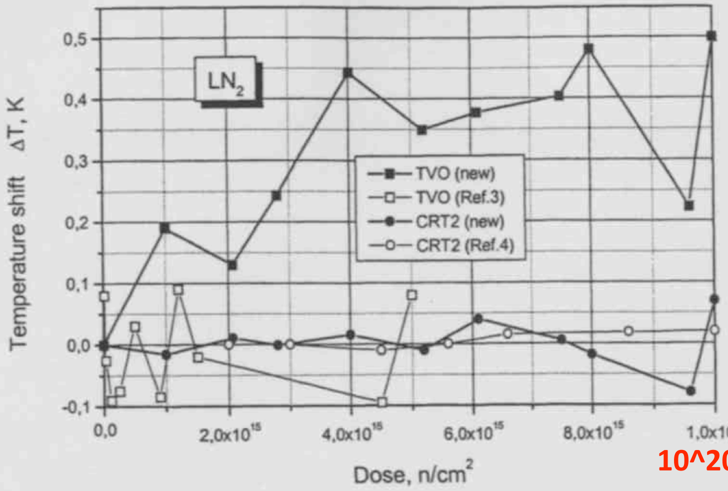
- A variety of CE products is available at CTD, but more expensive.
- KEK has started a collaborative work with MGC on CE development.

  >> Need R&D and evaluation of radiation resistance for a while.

Thermometers: CR

Important role to check soundness of the magnet system.

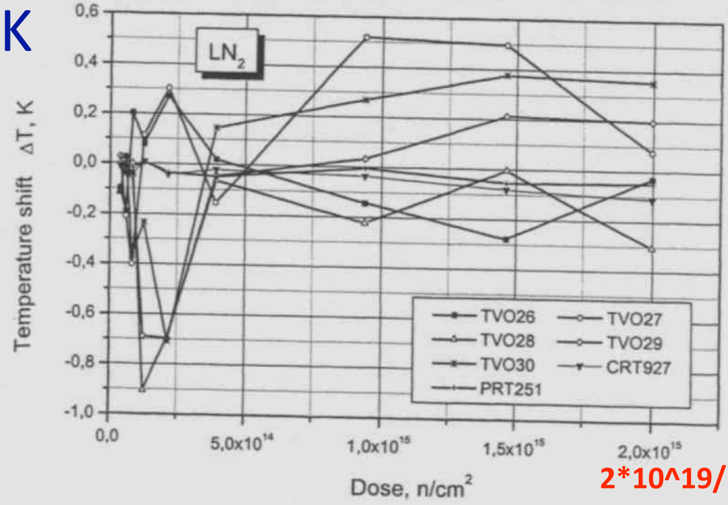
77K



10^20/m2

FIGURE 1. Temperature shift due to neutron irradiation in LN$_2$ at flux of about 10^{10} n/(cm^{2}s) versus the dose for TVO and CRT-2 sensors (D_γ = 85 kGy).

77K



2*10^19/m2

FIGURE 4. Temperature shift due to neutron irradiation in LN$_2$ at flux of about 6×10^9 n/(cm^{2}s) versus the total dose for TVO, PRT-4M and CRT-2 sensors (D_γ = 20 kGy).

Post Irrad.

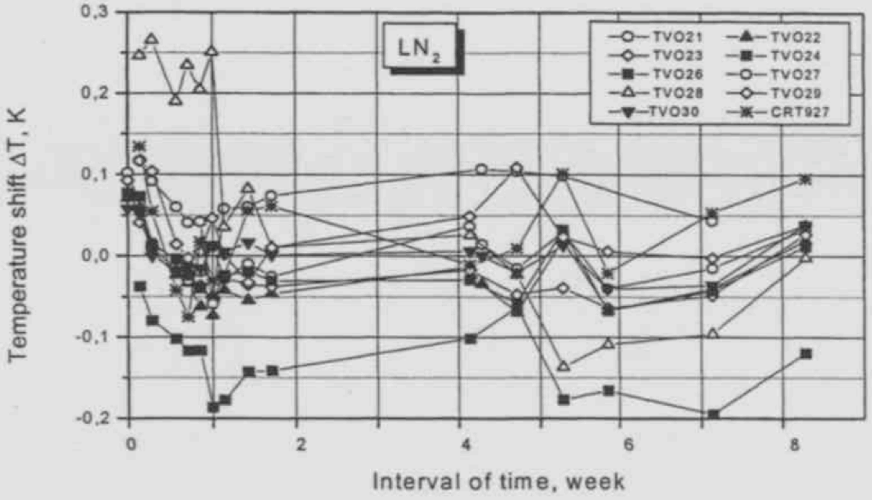


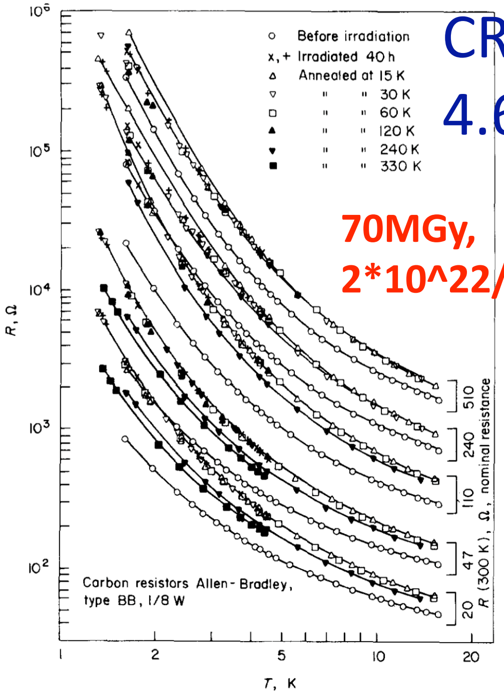
FIGURE 7. Post irradiation behavior of the sensors at 77.3 K after both radiation treatments.

- Data available up to 10^20/m2.
- Conventional CRTs (not TVO: Russian) varies within 0.1 K at 10^20/m2.

Adv. Cryo. Engineering, 47, p1700 (2002)

Thermometers: CR, Cernox, Others

Cryogenics, 17, No.1, p44 (1977)



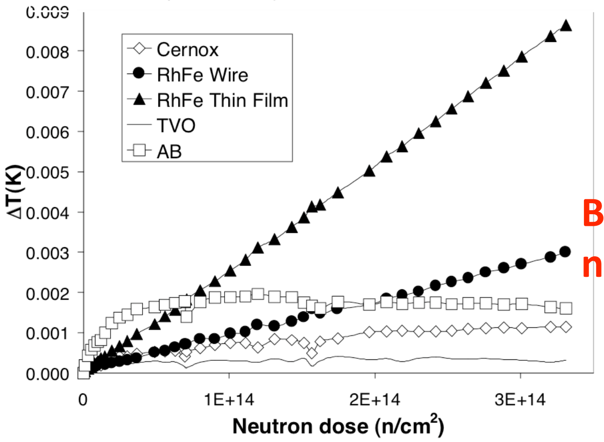
CR,
4.6K

70MGy,
2*10^22/m2

Fig. 2 Influence of reactor irradiation at 4.6 K and of subsequent annealing treatments on the $R(T)$ characteristics of five different Allen-Bradley carbon resistors

Ÿ**Reading drift during irradiation at 4K is 1-2 K.**
>> Serious problem for conduction-cooling magnets.
Ÿ**Some recovery due to anneal effect observed.**
>> Calibration method should be established for the hard radiation environment.

LHC Project Report, 209, CERN (1998)



Cernox,
1.6K

Be-D(20MeV) n source

Figure 3 Error on temperature measurement on some sensors during irradiation (Tbath=1.8 K)

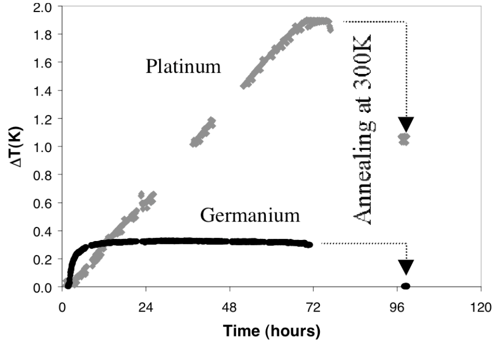


Figure 4 Irradiation-induced error on temperature read-out for Pt and Ge (T=1.8 K, dose=6 10^{14} n.cm^{-2})

Ÿ**Dedicated for LHC environment.**
Ÿ**Irradiated up to 10^19/m2.**
>> All are OK.

Location of thermometers should be carefully chosen with respect to neutron dose.
In-situ calibration procedure may needs to be developed.

Bypass Diode

Irradiated by 450GeV proton (SPS)

LHC Project Report, 688, CERN (2004)

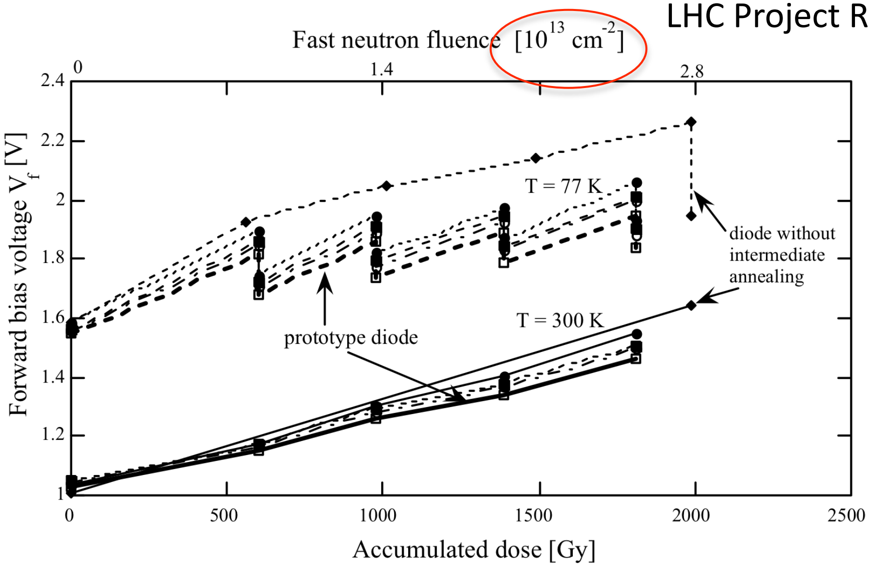


FIGURE 3. Forward bias voltage V_f at forward current I_f = 12 kA versus accumulated dose at 77 K and 300 K for one prototype- and 3 series diodes with intermediate warm up. For comparison is also shown one diode without intermediate annealing.

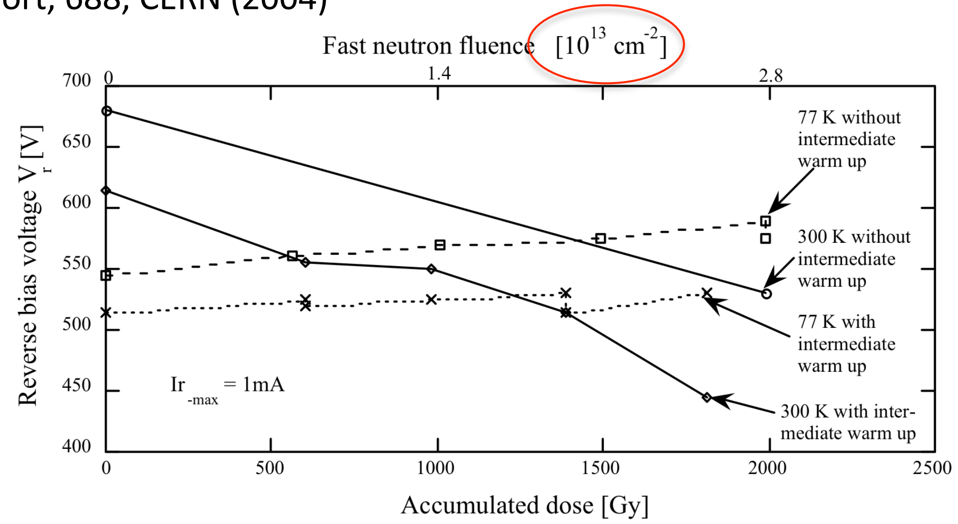


FIGURE 5. Typical reverse bias voltage V_r (I_r = 1mA) at 77 K and 300 K versus accumulated dose of one diode with intermediate warm up to 300 K and one diode without intermediate warm up to 300 K.

Bypass diode for the quench protection is the most sensitive element against the hadronic irradiation.

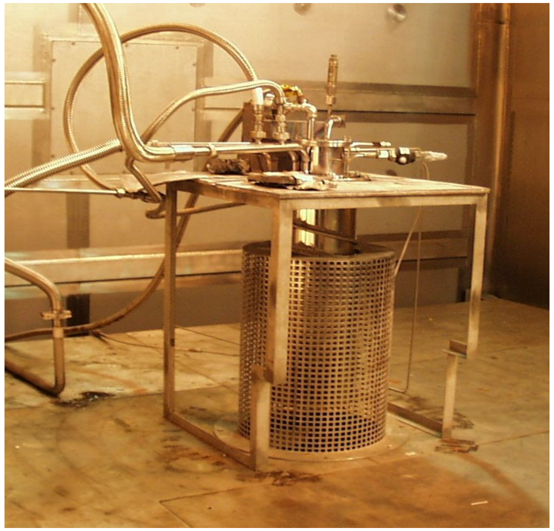
Its characteristic change would result in higher temperature rise or other serious damage of the magnet in case of quench.

Radiation resistance depends on diodes.

Diode should be located as far as possible from the target and shielded.

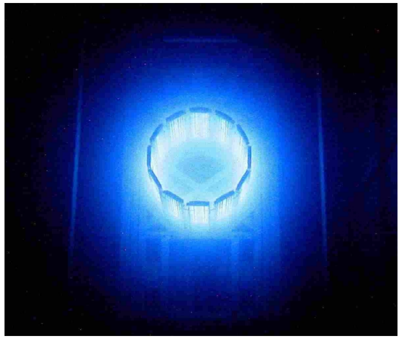
Replacement work should be taken into account.

Gamma-ray Irradiation

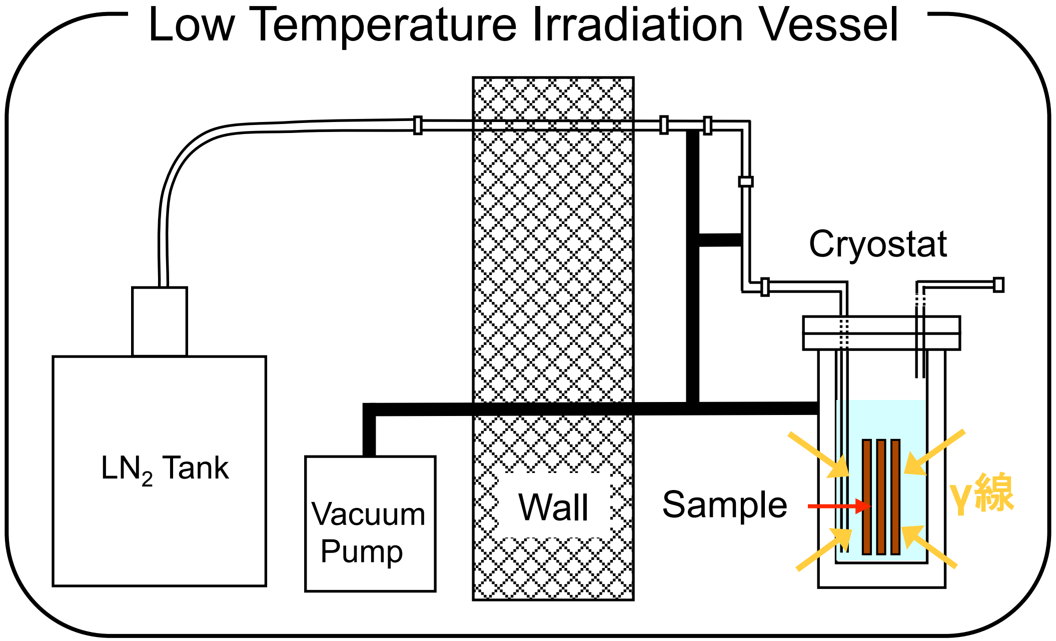


原研高崎Co-60γ線照射用
液体窒素クライオスタット

線源プールで
見られるチェ
レンコフ光



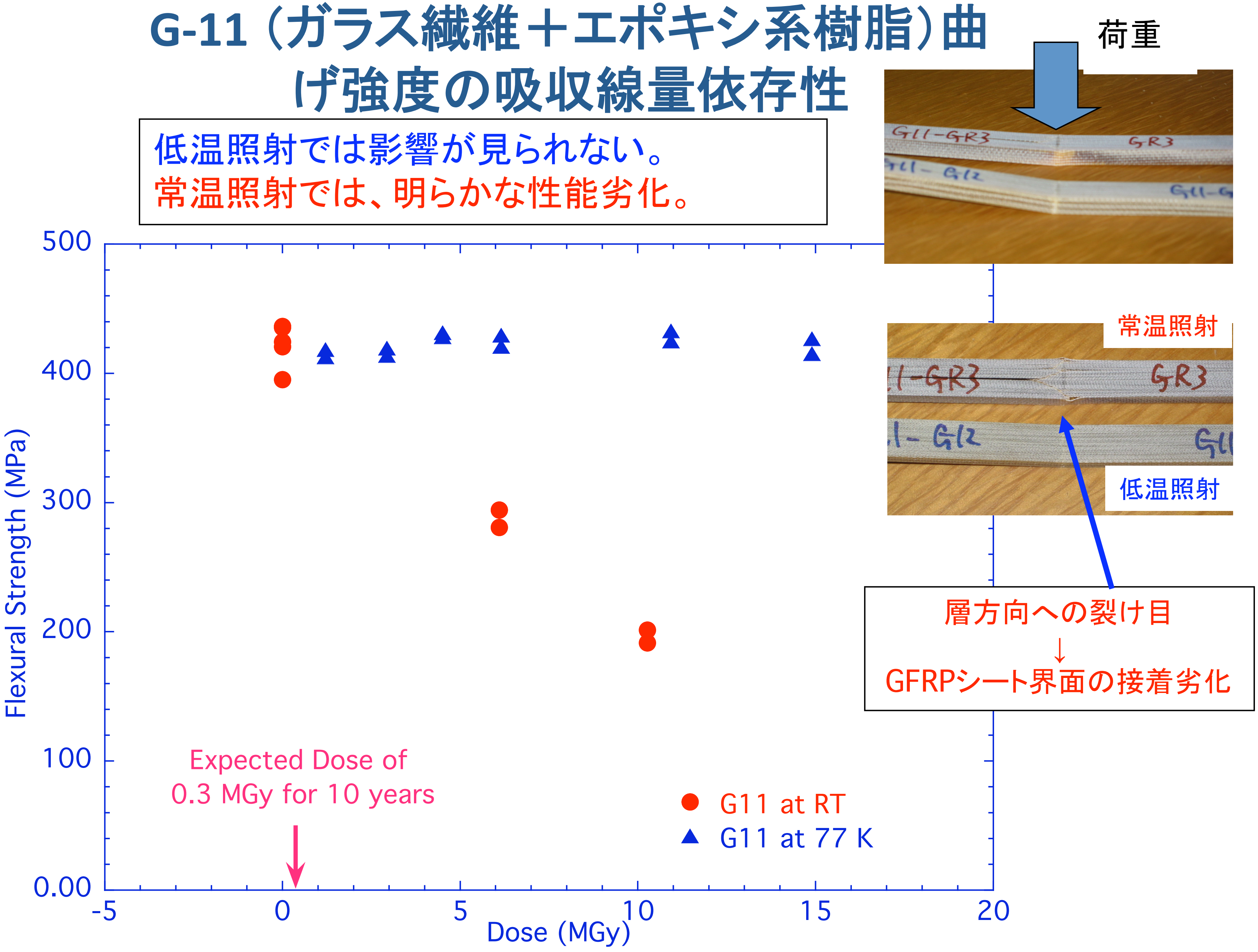
ガラスチューブ（真空）内に装
填された有機材料



試料照射前に、アラニン線
量計を用いて空間線量率
を較正

G-11（ガラス繊維＋エポキシ系樹脂）曲げ強度の吸収線量依存性

低温照射では影響が見られない。
常温照射では、明らかな性能劣化。



層方向への裂け目
↓
GFRPシート界面の接着劣化