Overview of demands on materials for ITER monitoring, control, and diagnostics

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- For “conventional” nuclear installations: mainly metallic (steels) structural materials
- In marked contrast, fusion systems (ITER, DEMO, PP) will also require functional (insulators) materials:
  - H&CD systems; DC, AC/RF insulation, transmission
  - Diagnostic systems; not only electrical, but also optical transmission
  - Remote handling systems
- The environment of operation can be hostile; high temperature, high voltages, vacuum, and above all a radiation field
- Must take into account the radiation effects on these materials when making a choice for a particular application; i.e. testing required

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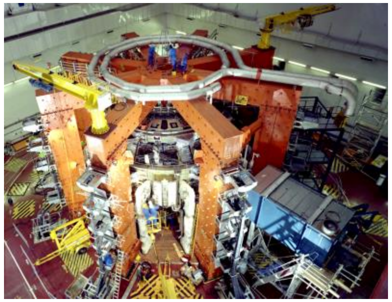
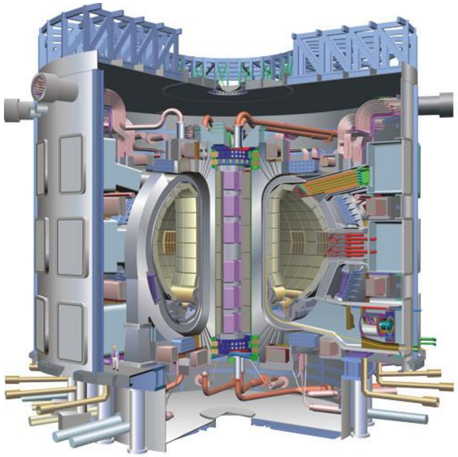
From early plasma devices to ITER, DEMO & PP



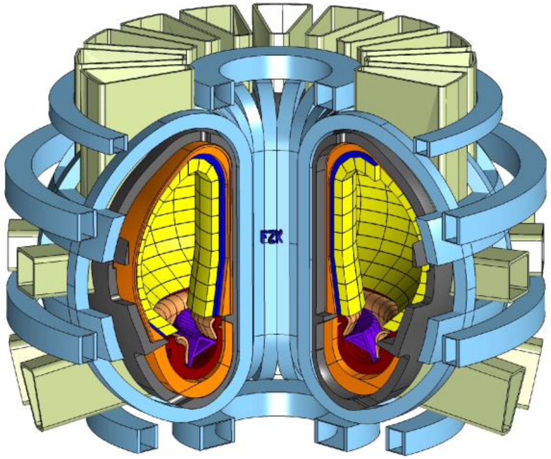
- **Early machines like JET, TFTR ⇒**

Technical challenge related to **machine size, accessibility, and reliability**, but with few radiation problems due to the limited number of DT shots.



- **Near term ITER ⇒**

Completely new range of challenges where **radiation and materials related issues become important**; systems which must work in a radiation field, plus the problem of remote handling and maintenance.



- **Future DEMO and PPs ⇒ ?**

Next step forward to DEMO and subsequent power plants will require a real **quantum jump** in technology and materials development

Final goal ⇒ produce electricity

Candidate materials

- **Structural:**
  SS-316L-IG, RAFM (Eurofer, F82H), ***ODS, V-5Ti, SiC***

- **High heat flux:**
  Be, W, CFC on Cu (CuAl25-IG or DS Cu)

- **Breeder:**
  Liquids; Li, Pb-Li, Solids; Li_2O, Li_4SiO_4, $LiAlO_2$

- **Cooling:**
  H_2O, He, Pb-Li, Li

- **Insulators:**
  Al_2O_3, MgO, BeO, $MgAl_2O_4$, AlN, Si_3N_4, SiO_2, diamond ……

Candidate insulator materials for fusion applications

Refractory oxides in generally highly rad resistant (ionic)

Al_2O_3, MgO, BeO, $MgAl_2O_4$

Nitrides, silicas, carbides (covalent)

AlN, Si_3N_4, SiO_2, diamond, *(SiC & SiC/SiC)*

Also: ***PI, PEEK, Elastomers ……***

Gases for NBI ***SF_6 or dry air (synthetic)***

Required insulators come in all sizes ⇒ testing difficult

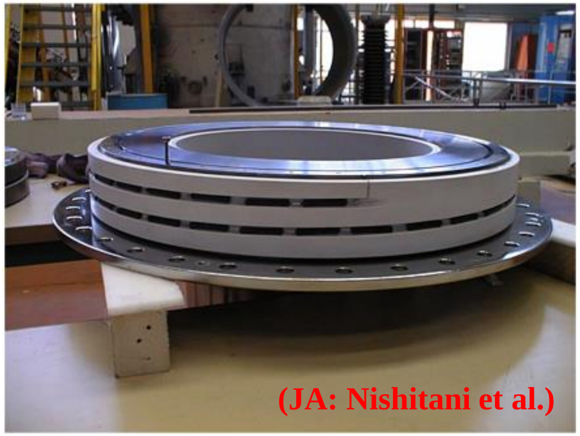
From small almost “COTS”:

Electrical connectors

(EU: Hodgson et al.)

Large diam. ~ 2 m NBI bushings

Difficult to manufacture



(JA: Nishitani et al.)

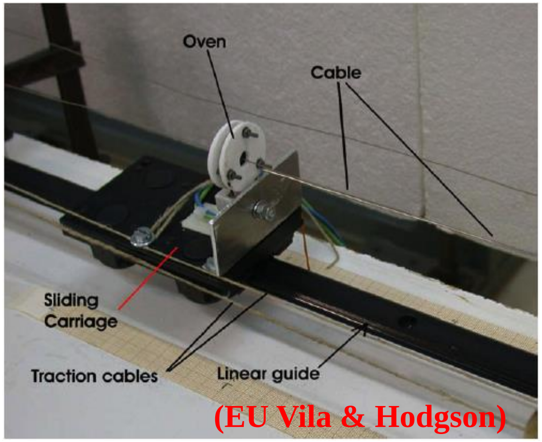
Pressure gauge
alumina feedthroughs

(EU: Haas et al.)

ECRH
diamond windows

(JA: Nishitani et al.)

MI cables
alumina, magnesia ..



(EU Vila & Hodgson)

Relevant operating conditions to be defined:

For the required system:

1. **Select necessary components**
2. **Identify radiation sensitive part/s**
3. **Determine “exact” position in the machine**
4. **Operating conditions and required testing can then be defined ⇒**

Dose rate, dose ***(n & γ flux & fluence)***

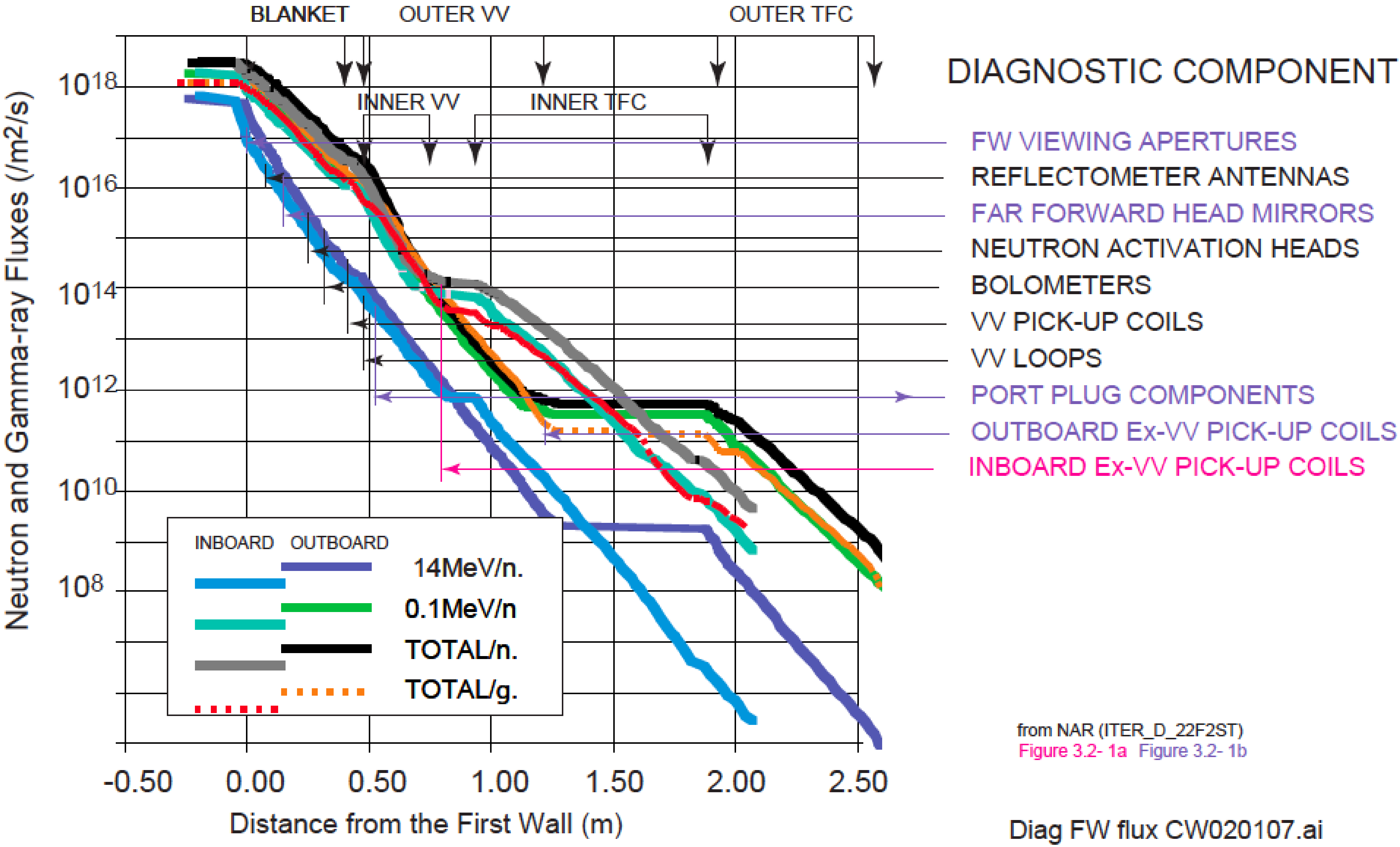
Temperature

Electric fields (DC, AC/RF)

Mechanical stress

Environment etc.. ***(vacuum, “air”,*** N_2***,*** SF_6***, coolant ..)***

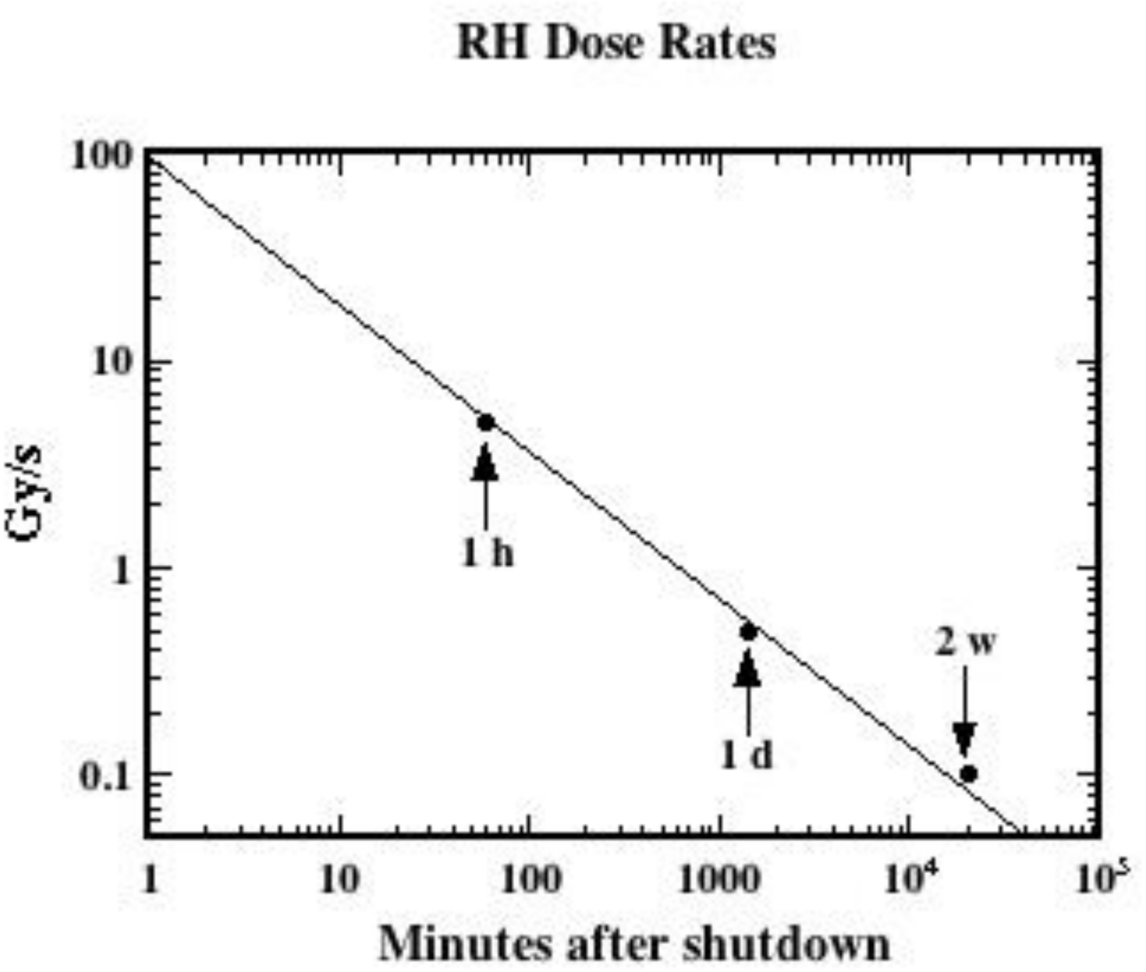
ITER n and γ fluxes



from NAR (ITER_D_22F2ST)
Figure 3.2- 1a Figure 3.2- 1b

Diag FW flux CW020107.ai

Radiation levels for RH rapidly reduce



Radiation levels for insulators

ITER (1st wall ≤ 3 dpa)

Ionizing dose rates < 1 Gy/s to 100s Gy/s

Ionizing doses up to < 10 GGy

Displacement dose rates ≤ 10^{-8} dpa/s

Displacement doses ≤ 0.3 dpa

Temperatures for insulators

Nuclear heating ≥ 1000 s ⇒

Components up to, and even above 200 C (*depends on position*)

Irradiation T very important (aggregation, annealing)

Also at high T between pulses (annealing)

⇒ Many materials/components in vacuum ⇐

1 Gy (Gray) = 1 J/kg *"rule of thumb"* *$10^{25} n/m^2$ => 1 dpa (displacement per atom)*

Properties affected and of concern for fusion devices

Electrical conductivity ♦
Optical absorption and emission ♦
Dielectric loss and permittivity ♦
Thermal conductivity ♦
Mechanical properties ♦ ♠

For example:

Resistance decrease --> Joule heating, breakdown ♦
Optical absorption --> light transmission loss ♦
Materials swell --> distortions ♦ ♠
Become brittle --> break ♦ ♠
Corrode easier --> mirrors, leaks ♦ ♠

♠ ***Stainless steel can withstand many dpa and GGy***
♦ ***But insulators can be modified by*** 10^{-6} ***dpa or a few kGy (see Annex)***

The special case of insulators

Insulators are in general polyatomic materials
Hence response is more complex than in metals --->

2 or more sublattices --> may not tolerate mixing

Hence more types of defects

Defects may have different charge states and mobilities

Displacement rates and thresholds may be different on each sublattice

Interaction between defects on different sublattices

Defects produced in some cases by ionization (radiolysis)

Insulator sensitivity to radiation

Result ===> insulators are far more sensitive to radiation damage than metals

Stainless steel can withstand many dpa and GGy

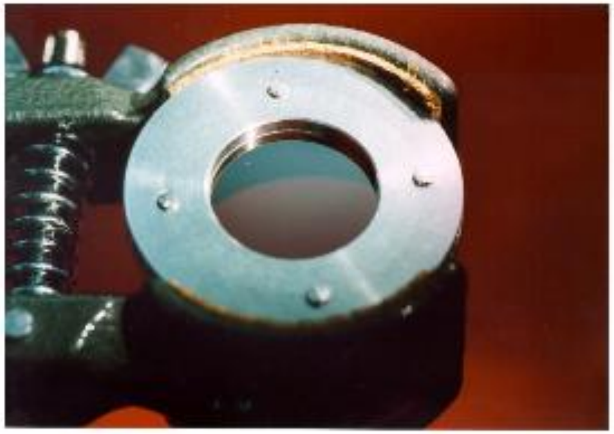
But insulators can be modified by 10^{-6} dpa or a few kGy

Hence problems expected even in ITER

Both dose and dose rate are important

Swelling problems

- **Expect mica to swell 90^o to C plane**



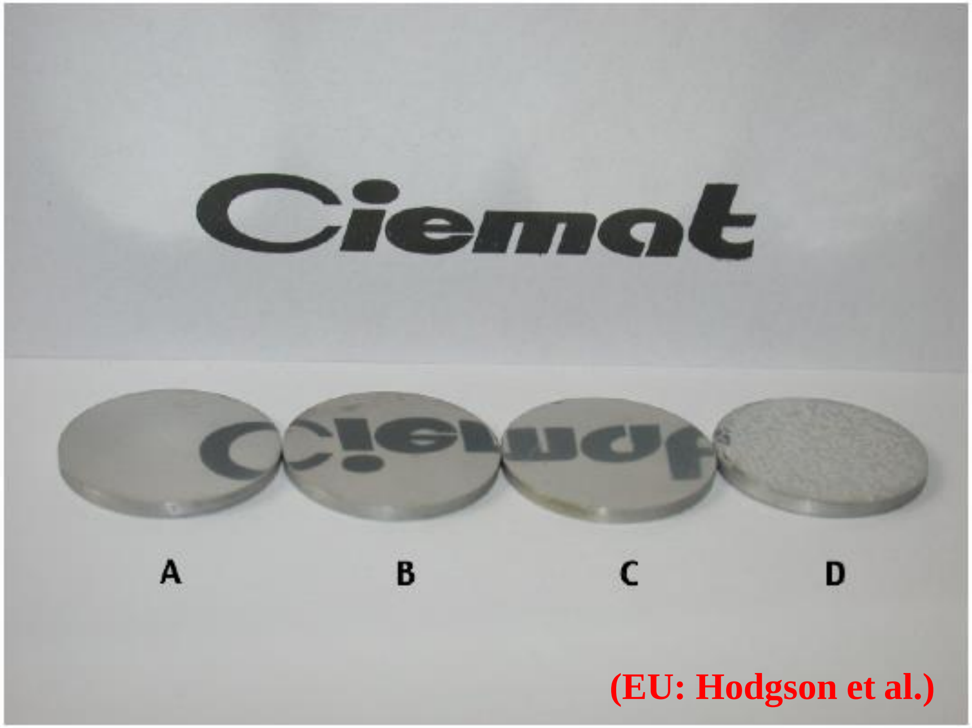
- **Unirradiated mica --->**

- **Irradiated to 10^{-2} dpa ->**
  (FZK data)

(EU: Heidinger et al.)

⇒use SiN as bolometer substrate (and change Au to Pt)

Corrosion is enhanced



(EU: Hodgson et al.)

Figure 1b. Humid air and irradiation effects in Uncoated Aluminium 20 mm diameter disks

A: As received

B: No irradiation and humid air (80% HR)

C: 50 kGy and Nitrogen gas

D: 50 kGy and humid air (80% HR)

Radiation enhanced effects can be serious

Al on Pyrex glass. SiO overcoating

- Mirrors can corrode
- Even with SiO protection
  (related to SiO → SiO_2 swelling)

- Problem for LOCA
  (Loss of coolant accident)

PEEK electrical connector insulation

^{60}Co γ-irradiation 5.5 Gy/s. T = 120 °C

Polyether ether ketone

(EU: Hodgson et al.)

CVD diamond for ECH window. 20 mm in diameter, 1.5 mm in thickness

Neutron irradiation (>1 MeV), T ~100 ° C

unirradiated

1.15×10^{20} n/m^2

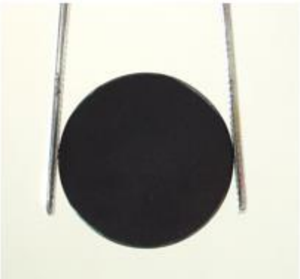
≈ 10^{-5} dpa

Green colour

⇒ C vacancies

1.19×10^{21} n/m^2

≈ 10^{-4} dpa



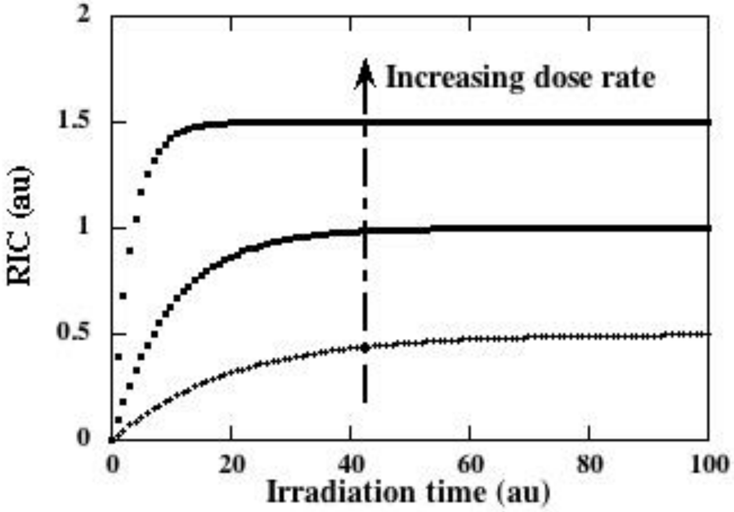
(JA: Nishitani et al.)

9.73×10^{21} n/m^2

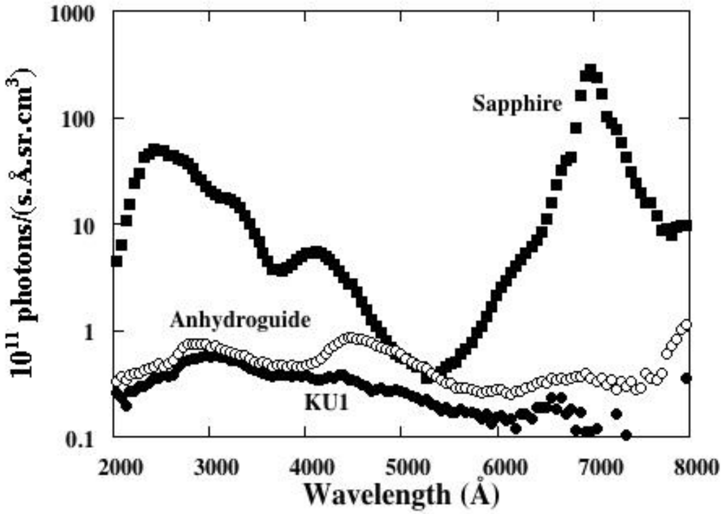
≈ 10^{-3} dpa

Classical examples ("almost" understood): Radiation Induced Conductivity (RIC) and Luminescence (RL)

- **RIC due to excitation of electrons into the conduction band**
- **For a good insulator and MC fusion conditions acceptable**


RIC

- **RL due to recombination and de-excitation processes**
- **Transparent materials suitable for windows, lenses, fibres exist with low RL**


RL

RIC and RL problems from onset of operation (dose rate dependent)

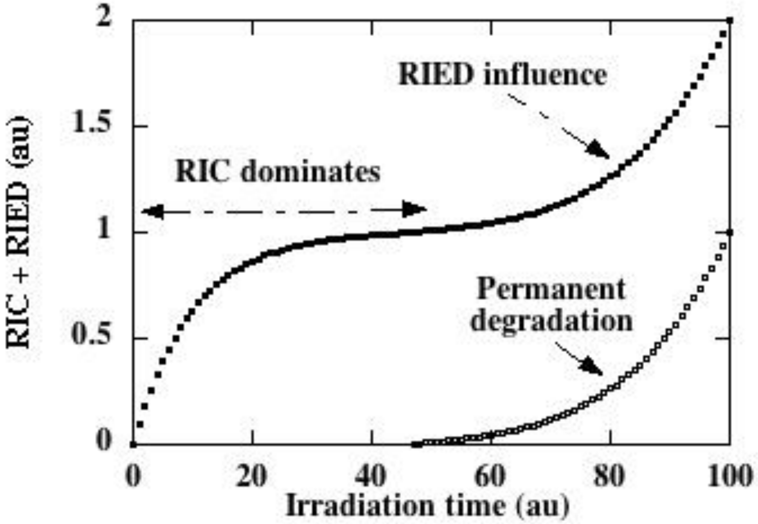
(EU: Hodgson and Moroño)

With irradiation time (dose) RIC and RL change

- **RIC increases due to a permanent degradation of the insulator**

  ⇒ RIED

RIED



- **RL reduces due to defect absorption ⇒**

BUT the window becomes a wall !

Severely limits use of optical fibres

Serious long term problems

(EU: Hodgson et al.)

Degradation of the electrical conductivity

Have to contend with 4 types of degradation

- **RIC ==> Radiation Induced Conductivity**
- **RIED ==> Radiation Induced Electrical Degradation**
- **Surface Degradation**
- **RIEMF ==> Radiation Induced Electro-Motive Force**

Note: conductivity σ (S/m) is inverse of resistivity ρ (Ωm)

Surface Degradation

- Despite the purely academic distinction

  surface and volume degradation just as serious for insulating components

- Two types now recognised ===>
- <u>Surface Contamination</u>
- poor vacuum, sputtering, evaporation

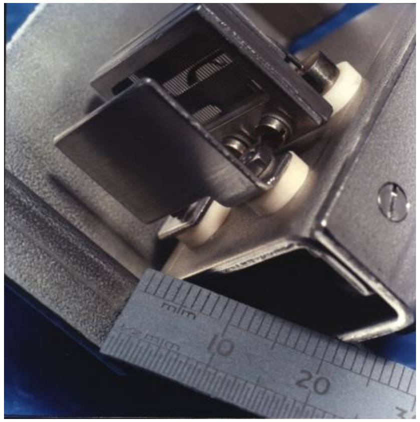
- <u>Real Surface Degradation</u>
- Surface reduction, impurity segregation

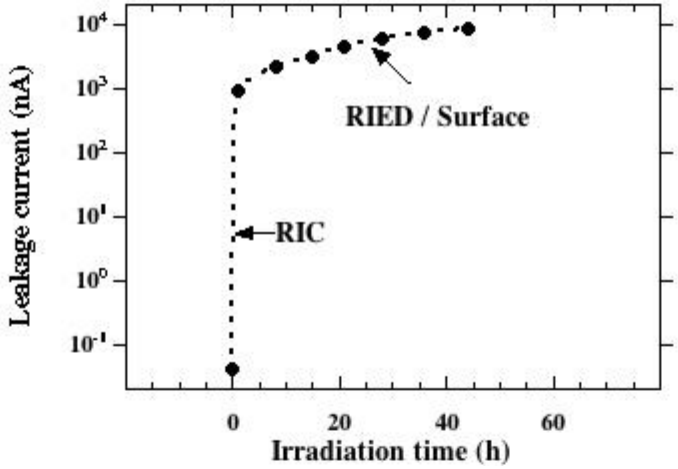
- Can be serious, affected by irradiation environment and ionizing radiation

Surface Degradation for feedthroughs

For simple feedthroughs:

- RIC clearly identified
- Further increased conductivity ?
- RIED or surface



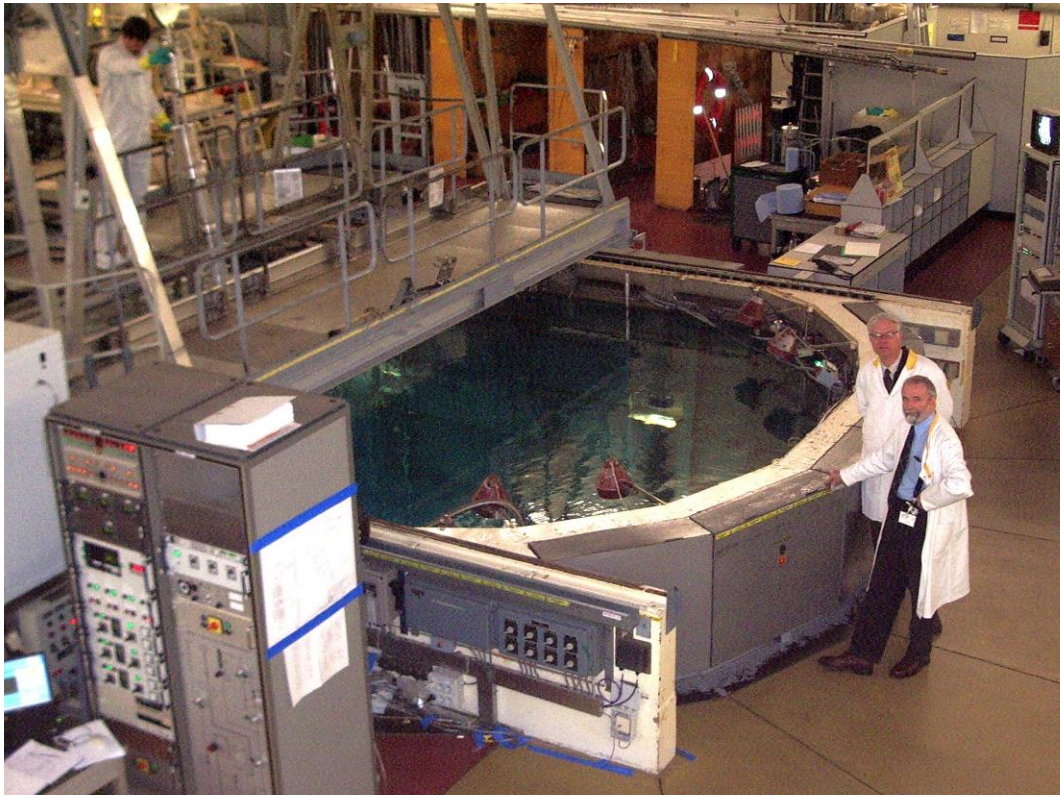


(EU: Hodgson et al.)

Testing must take advantage of existing facilities

Need experimental reactors with in-situ experimental possibilities and expertise (e.g. BR2)

- **Will need to develop / improve the different systems required**
- **Vacuum**
- **Real temperature control**
- **Electrical and optical connections**

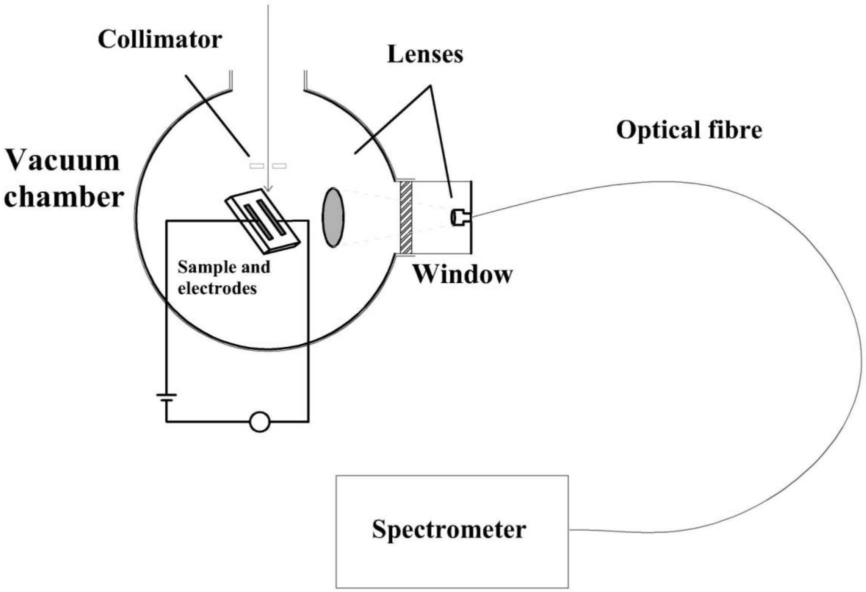


BR2

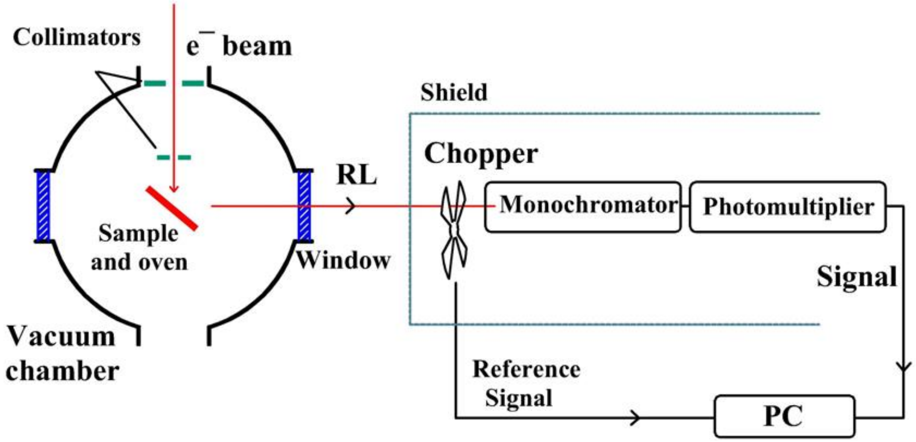
Ion and electron beam accelerators

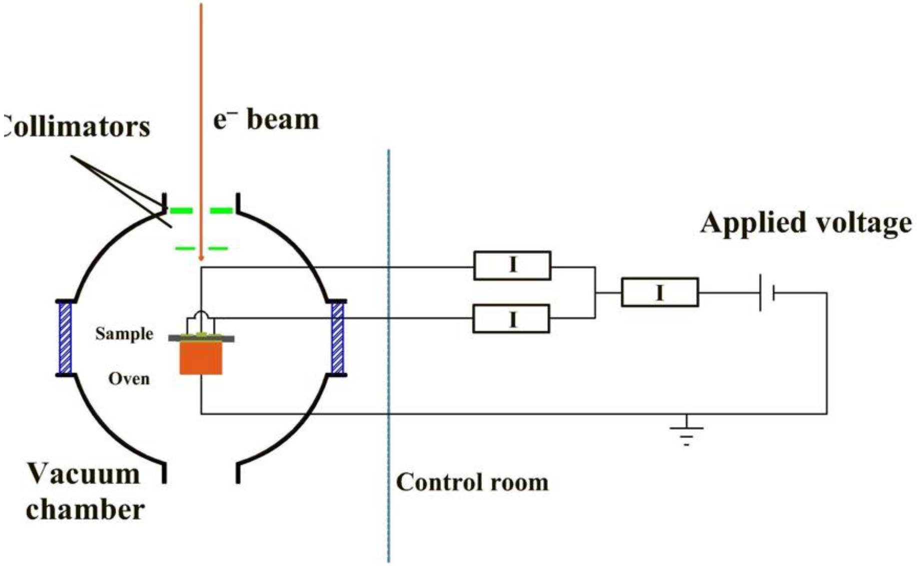
(in vacuum, allow good T control, and provide basic information on radiation effects)

IBIL & σ 1 to 60 keV p, α



RL & σ 0.2 to 2.0 MeV e⁻



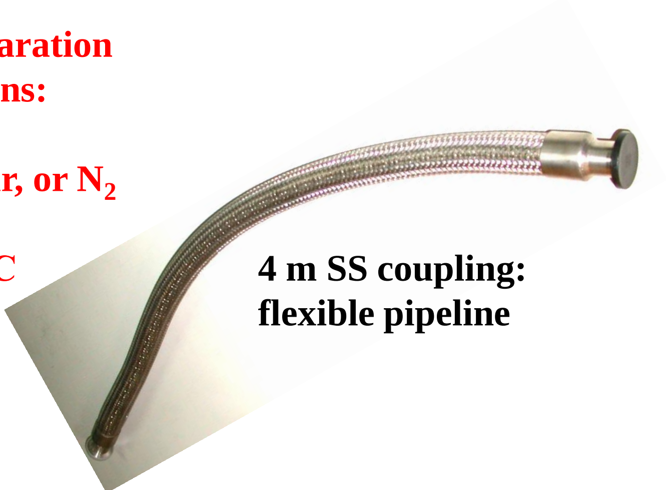


Gamma sources

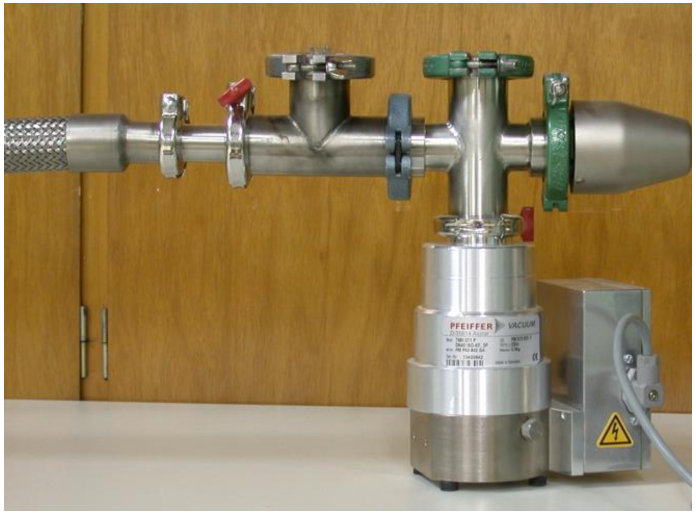
ITER component γ-irradiations

CIEMAT preparation for γ-irradiations:

vacuum, dry air, or N_2
In-situ testing
T ≈ 20 to 250 ºC
≤ 1.5 Gy/s

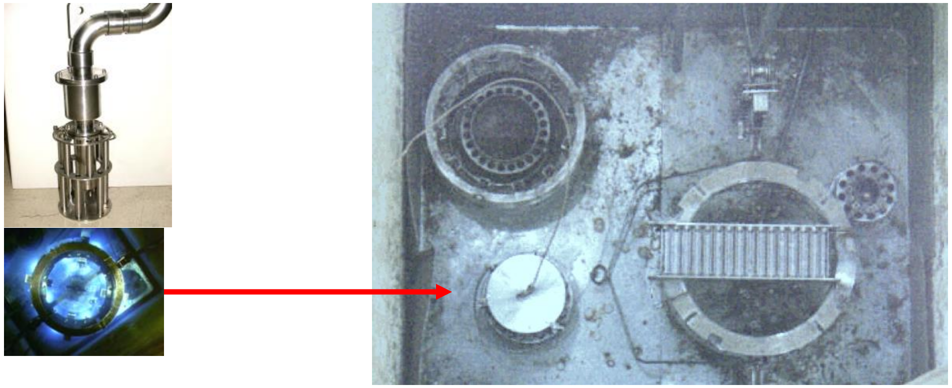


4 m SS coupling:
flexible pipeline



Turbopump < 10^{-7} mbar

Test chamber(s) in “Nayade” pool facility (^{60}Co)
Final vacuum ≈ $3x10^{-5}$ mbar



In situ measurements (F4E-OFC-358)

CIEMAT preparation
for γ-irradiations:
scintilators & lenses
in dry air and N_2
In-situ testing
T ≈ 30 ºC
≤ 1.5 Gy/s

System will allow irradiation and *in situ* measurement of absorption and light emission of scintillators and lenses
In the high radiation region, aluminium light guide tubes will be used rather than optical fibre

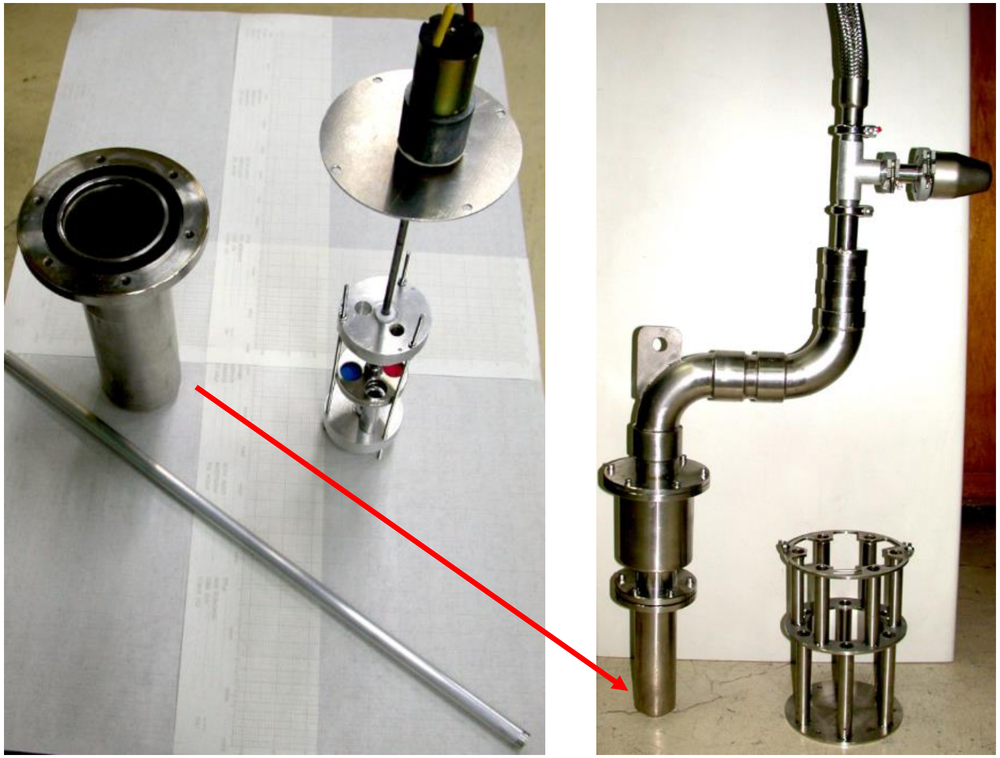
Although component oriented, will provide basic information on radiation effects

Rotating sample holder
Al light guide tube

Detail: 3 sample
+ ref. channel

LEDs

Sample holder and Nayade test chamber



A. Moroño, M. Malo, I. Garcia-Cortes, J. Valle, F. Jimenez, P. Valdivieso, E.R. Hodgson CIEMAT

Conclusions

1. **We will need ceramics/insulators in ITER:**
   Severe limitation to operation, control and safety functions.

2. **For each system/component must identify the radiation sensitive part**

3. **Determine the operating conditions:**
   radiation levels, temperature, vacuum/air, voltage, stress etc.

4. **Check if suitable information is available:**
   considerable data exists in the literature

5. **If in doubt, radiation testing is necessary:**
   In situ testing or PIE ⇒ seek expert advice

Annex and extras

Fusion Relevant Radiation Damage

- ITER will present operational and experimental difficulties and problems not met in present day machines
- Come from the transition **Physics to Technology**
- Not just going from JET scale to ITER - DEMO - PP
- Must remember final aim of programme:

  Fusion power for **Electricity Generation**

- So we need "ignition" ⇒ **neutrons and gammas**
- These produce **Radiation Damage** in the materials
- The most difficult **Long Term Problem** to solve

Displacement Damage

Neutron irradiation displaces atoms / ions from their lattice sites

Produces "displacement damage" in metals and insulators

Cross section generally small (≈ 1 -> 10 barns   1 b = 10^{-24} cm^2)

Measured in "dpa" (displacements per atom)

1 dpa means on average every atom displaced once

Displacement Damage affects ALL materials

At the first wall of ITER or a fusion reactor

we will have approximately;

10^{-6} dpa / s ===> in less than 300 h we have 1 dpa !!

("rule of thumb" 10^{21} n/cm^2 ==> 1 dpa)

Can materials possibly survive such damage ?

Ionizing (gamma) radiation

Gamma radiation absorbed in the materials

Cross section is large ($\leq 10^{5}$ barns)

Measured in Gray (Gy) = 1 J / kg

(old unit: rad, 1 rad = 100 erg / g So 100 rad = 1 Gy)

For gammas: $5\text{x}10^{14}$ gamma/m^2/s ≈ 1 Gy/s
For neutrons: 10^{15} n/m^2/s ≈ 1 Gy/s

Ionizing radiation affects mainly insulators

At the first wall of ITER or a fusion reactor

we will have approximately;

10^4 Gy/s

and for remote handling situations a few Gy/s

(shut down maintenance etc.)

Dose rate (flux) and dose (fluence) effects

Some of the induced changes will be dose rate dependent

---> problem from on-set of operation

In general not linear

Many effects $\propto$ (dose rate)$^{\delta}$, $\delta \neq 1$

others will be modified by the total dose

---> affect the component or material lifetime

But effect at a given dose depends on dose rate

(1 MGy at 10 Gy/s $\neq$1 MGy at 100 Gy/s *Important for testing to high dose*)

Effects of radiation damage

Displacement damage produces in all materials;

Vacancy + interstitial defects (point defects)
can recombine, remain stable, and
aggregate forming extended defects

Ionization produces in insulators;

changes in electronic charge distribution
enhances defect mobility

(mainly heating in metals)

Transmutation

Nuclear radiation produces transmutation products

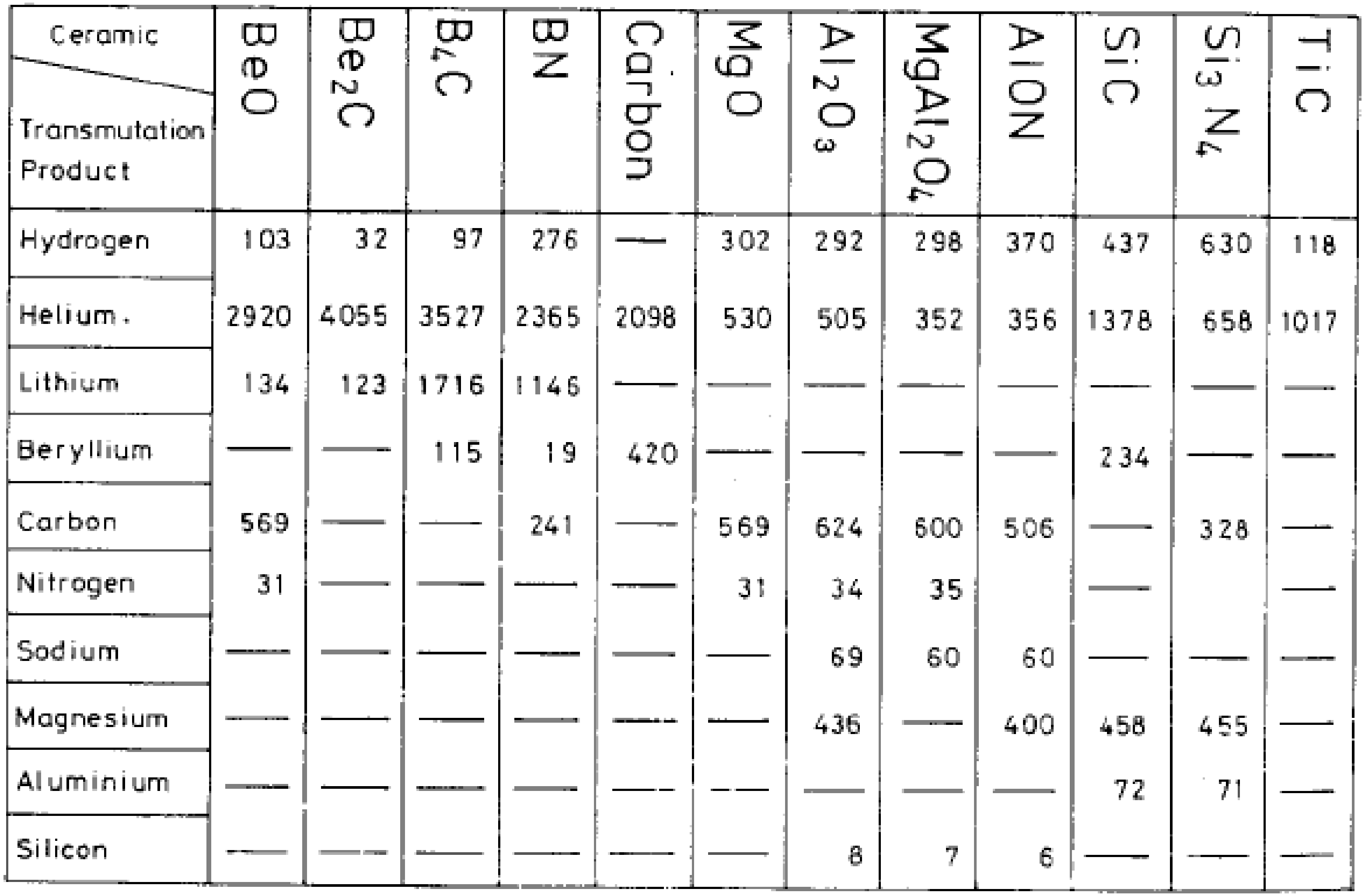
Nuclear reactions (n: α, γ, p)
These lead to impurities in the materials

Can modify properties. (high fluence problem)

In ITER transmutation, except for C, H, and He, not expected to present a serious problem.

BUT beyond ITER yes !

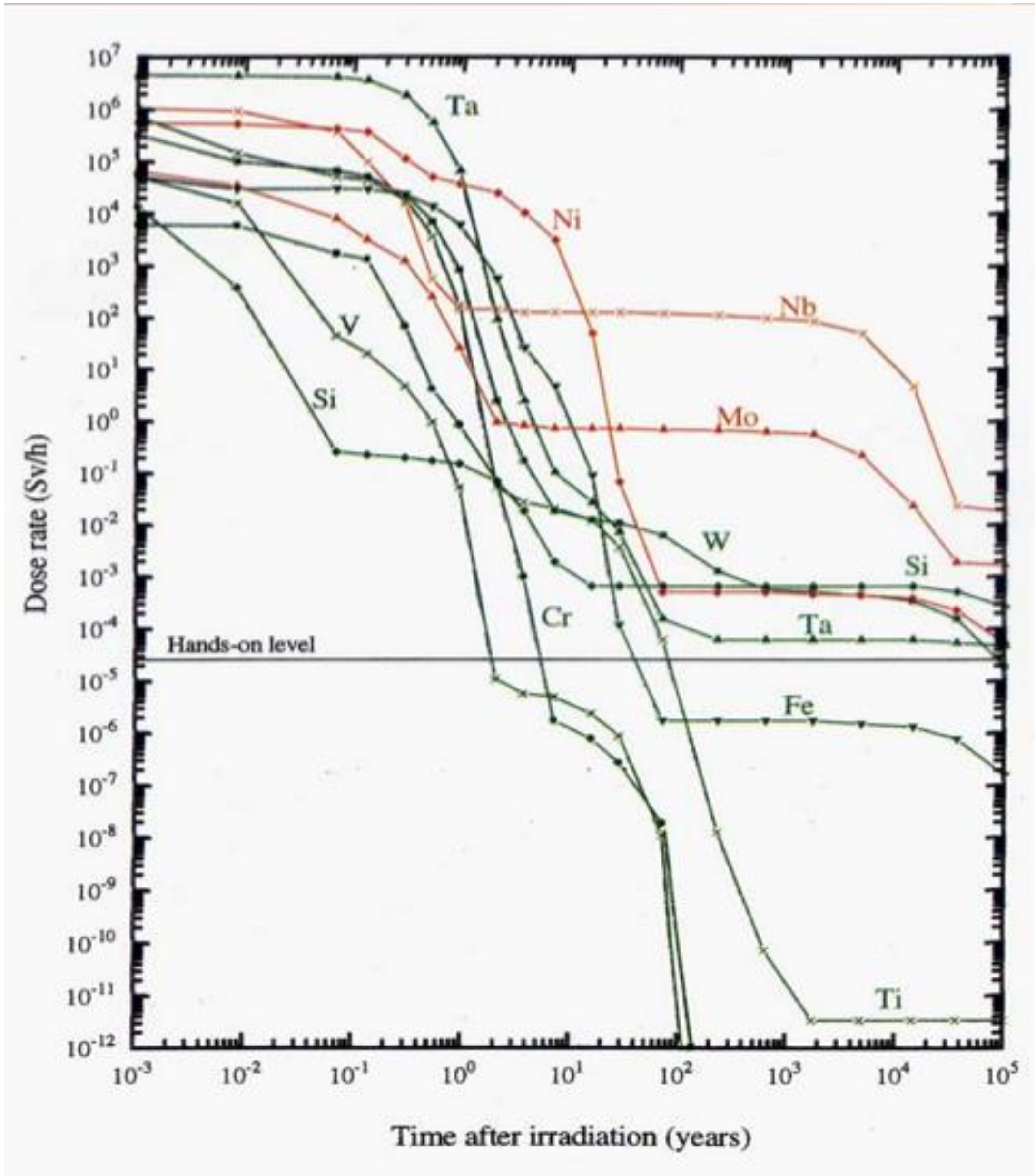
Transmutation
(appm/year at 1 MW/m^2)



Ceramic / Transmutation Product	BeO	Be_2C	B_4C	BN	Carbon	MgO	Al_2O_3	$MgAl_2O_4$	AlON	SiC	Si_3N_4	TiC
⇒ Hydrogen	103	32	97	276	—	302	292	298	370	437	630	118
⇒ Helium	2920	4055	3527	2365	2098	530	505	352	356	1378	658	1017
Lithium	134	123	1716	1146	—	—	—	—	—	—	—	—
Beryllium	—	—	115	19	420	—	—	—	—	234	—	—
⇒ Carbon	569	—	—	241	—	569	624	600	506	—	328	—
Nitrogen	31	—	—	—	—	31	34	35		—		—
⇒ Sodium	—	—	—	—	—	—	69	60	60	—	—	—
Magnesium	—	—	—	—	—	—	436	—	400	458	455	—
Aluminium	—	—	—	—	—	—	—	—	—	72	71	—
Silicon	—	—	—	—	—	—	8	7	6	—	—	—

H, He - swelling. C, (Mg, Na) - electric + dielectric properties

Radioactive decay for different elements



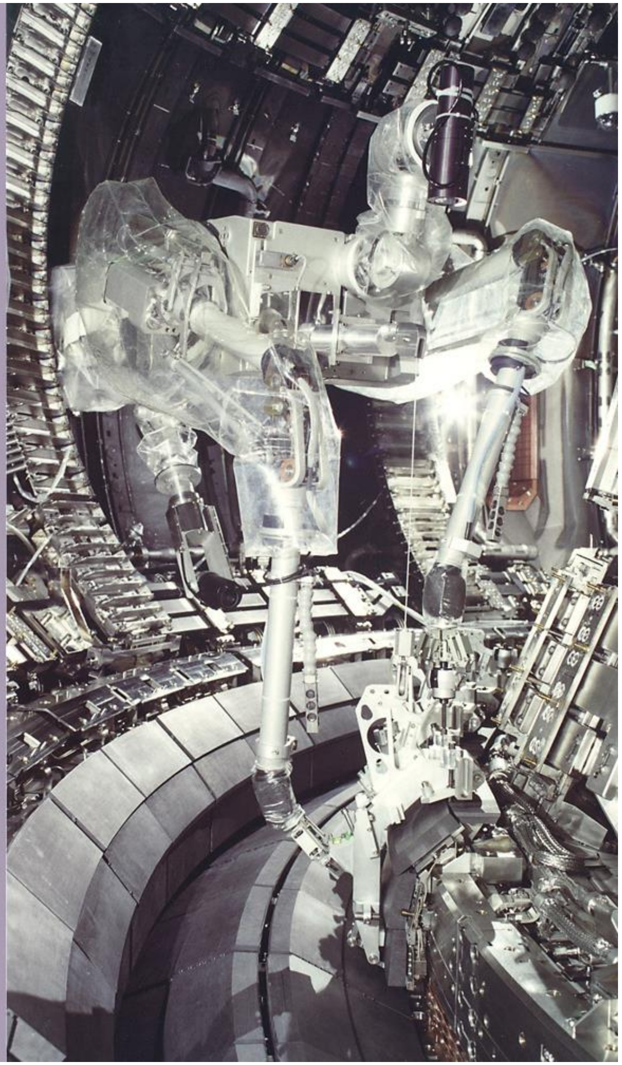
In RA steels change:

Ni --> Mn
Nb --> Ta
Mo --> W/V

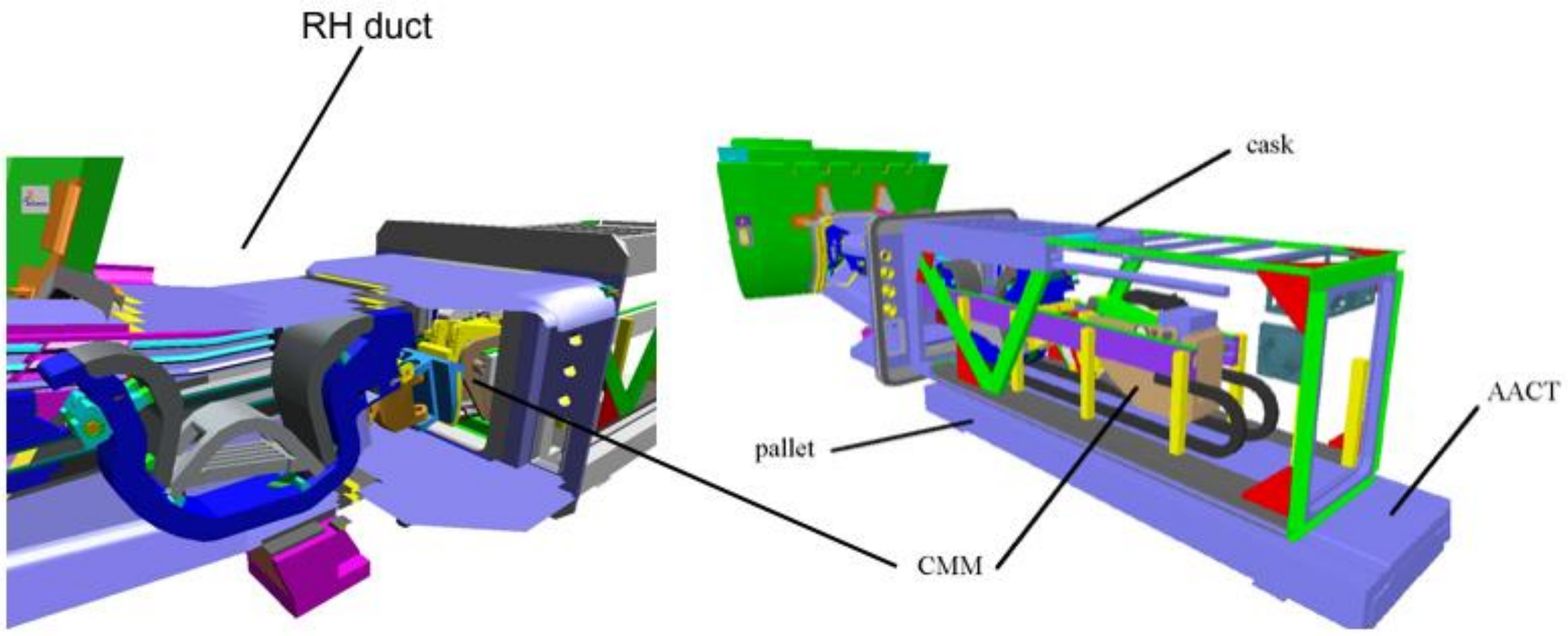
Transmutation leads to residual radioactivity

Need Remote Handling (even in JET)

In ITER RH is mandatory



In ITER RH is mandatory



CMM entering the ITER vacuum vessel duct with a new cassette

- **All maintenance and repairs remotely**
- **Also for 1st wall, NBI** (CMM: Cassette Multifuctional Mover)

Maximum end of life appm transmutation products for alumina in ITER, DEMO, and PP, estimated from 1 MW/m^2 1st wall loading (a wall loading of 0.5 MW/m^2 and 4700 h full power operation has been assumed for ITER) [1, 2].

	H	He	C	N	Na	Mg	Si
ITER	8	14	17	1	2	12	0.2
DEMO	210	363	448	24	50	313	6
PP	394	682	842	46	93	589	11

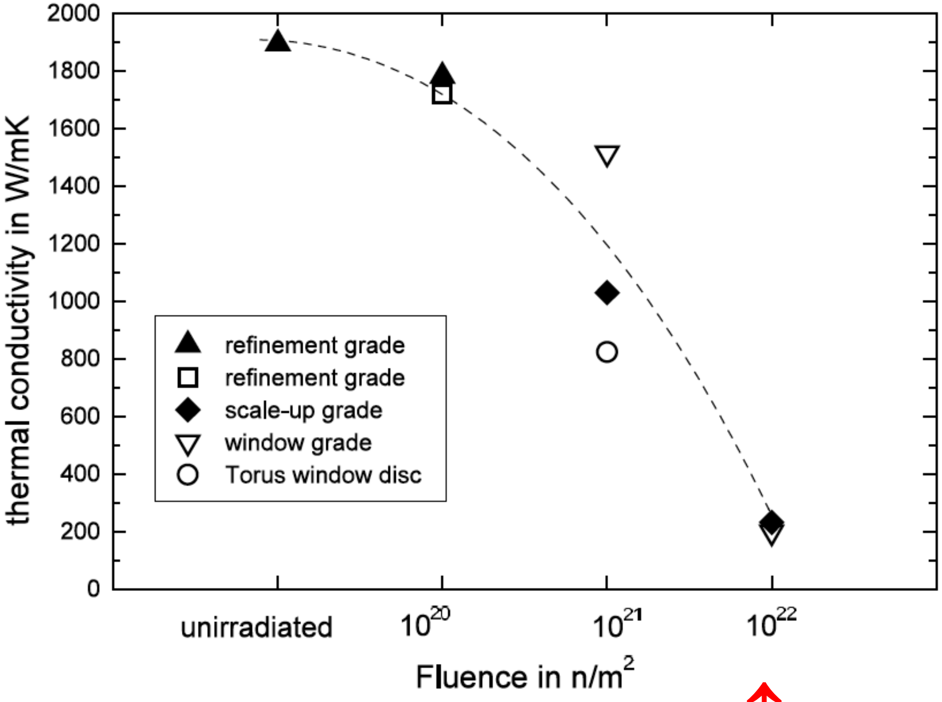
[1] L.H. Rovner and G.R. Hopkins, 1976.

[2] G. Vayakis, E.R. Hodgson, V. Voitsenya, C.I. Walker, 2008.

In addition to H and He, note the large quantities of C, Na, and Mg

Thermal conductivity reduction

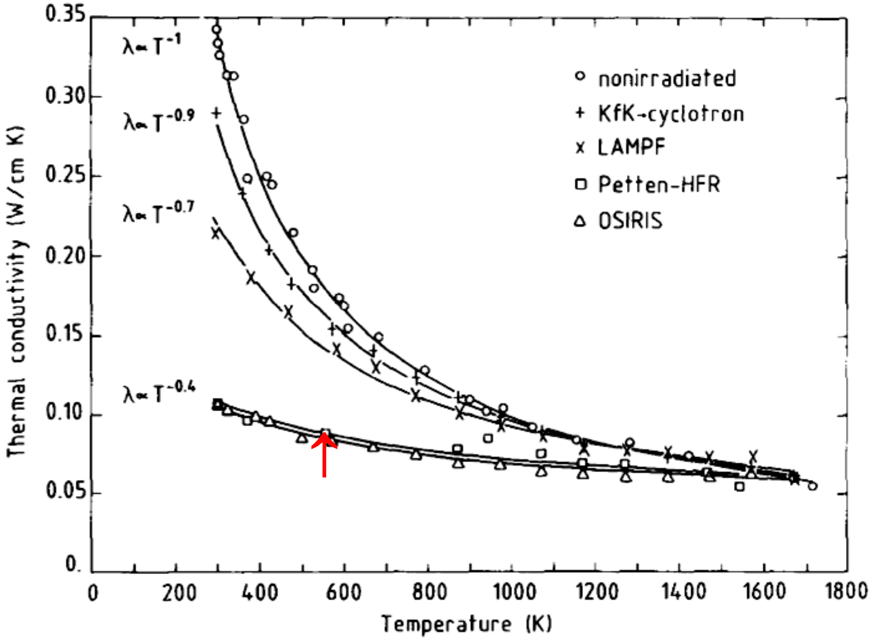
Neutron irradiated window grade CVD diamond



↑

0.001 dpa

995 Alumina



Irradiation conditions

	Fluence (part./cm^2)	Max. energy (MeV)	Irradi-ation temp. (K)	Damage dose (dpa)	
KfK-Cyclotron	1×10^{17}	100	~ 700	≤ 0.001	
LAMPF	5×10^{20}	100	~ 600	0.5	
Petten-HFR	2.8×10^{20}	> 0.1	473	0.4	←
OSIRIS	2.1×10^{21}	> 1	823	5	←

(EU: Heidinger et al.)

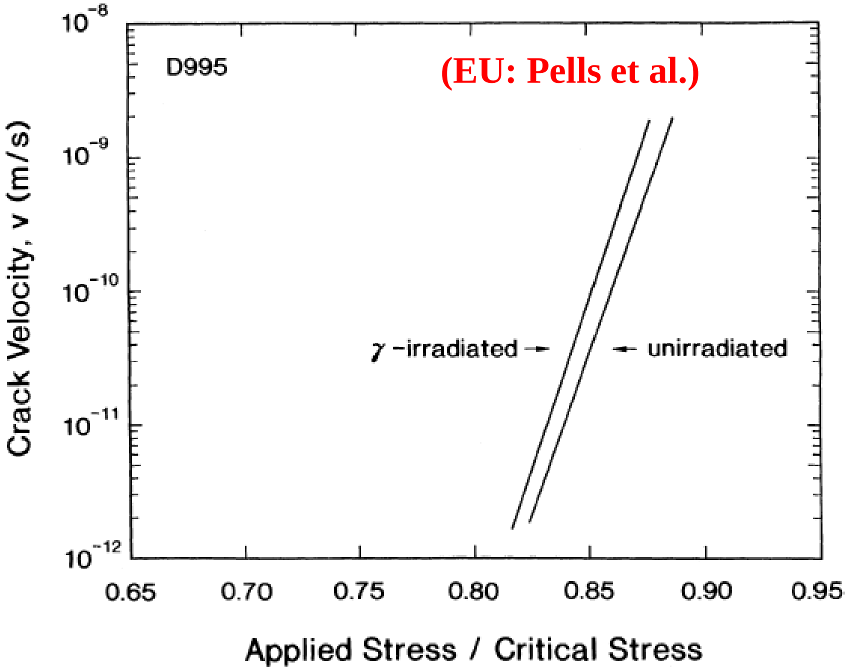
(EU: Rohde & Schulz)

Radiation enhanced effects on mechanical properties

Sub-Critical Crack Growth modified by γ radiation alone

995 alumina ⇒

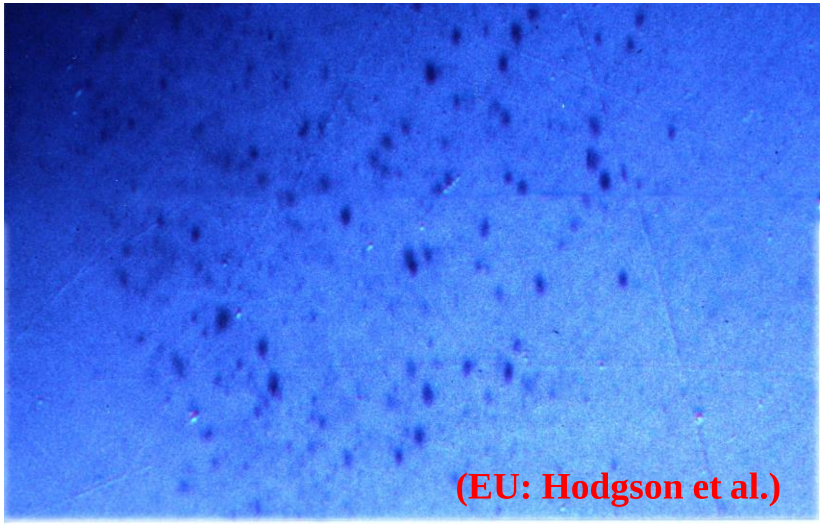
x4 increase in crack velocity
decrease in time-to-fracture
(Even at 1.5 Gy/s, < 1 MGy)



(EU: Pells et al.)

RIED embrittlement and swelling induced by:
***Radiation and E-field* ⇒**

- **At very low doses**
- **MGy and ≤ 10^{-4} dpa**



(EU: Hodgson et al.)

TIEMF in MI cables

- Voltage generation along central conductor

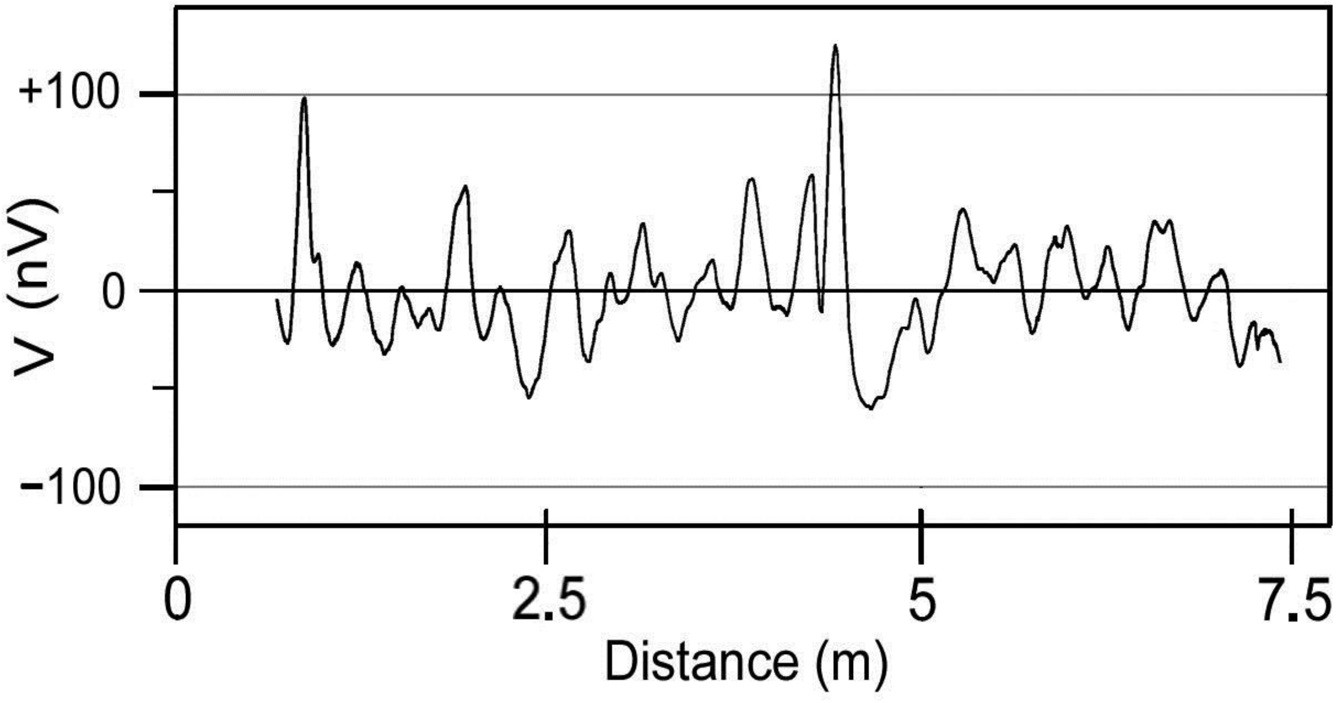
- Depends on radiation and temperature gradient along conductor
- Experimentally difficult to separate Rad. and T effects
- More problematic than RIEMF

- TIEMF has now been studied in detail
- EMF (V) α T. No annealing up to 550 C

- Probably due to damage to wire during production

Typical TIEMF

100s to 1000s of nV for Cu cored cables and 50C temperature difference

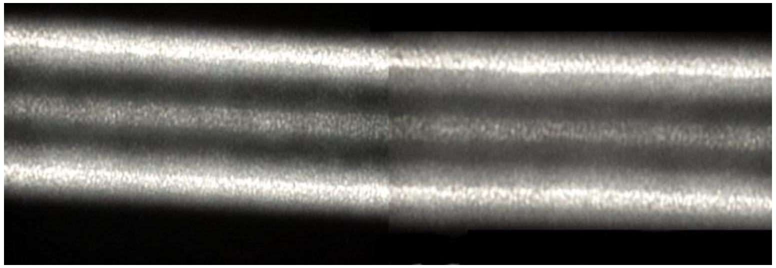


(EU Vila & Hodgson)

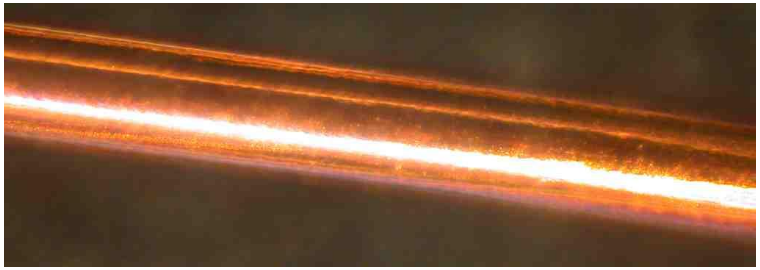
MI cable problem

Severe damage to Cu wire, also encrusted silica - *manufacturing problem*

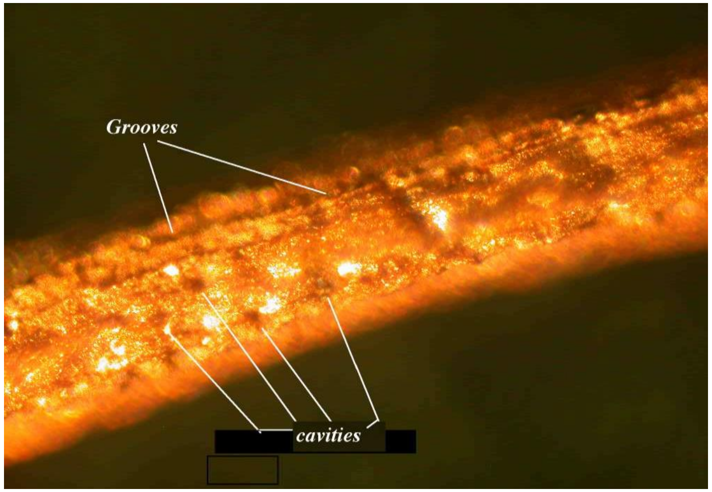
X-ray microphotograph



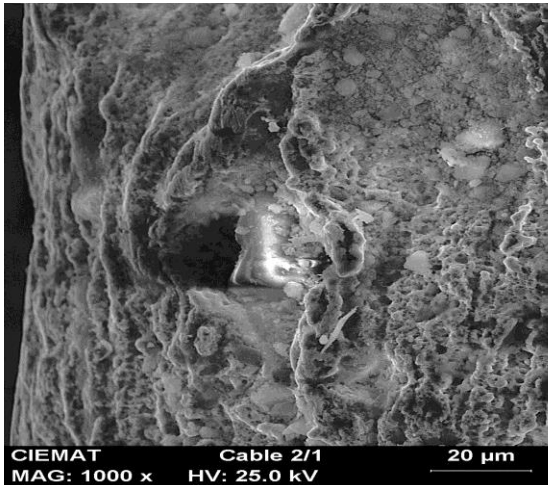
Equivalent Cu wire is “perfect”



Optical microscopy of core
⇒ extreme surface damage



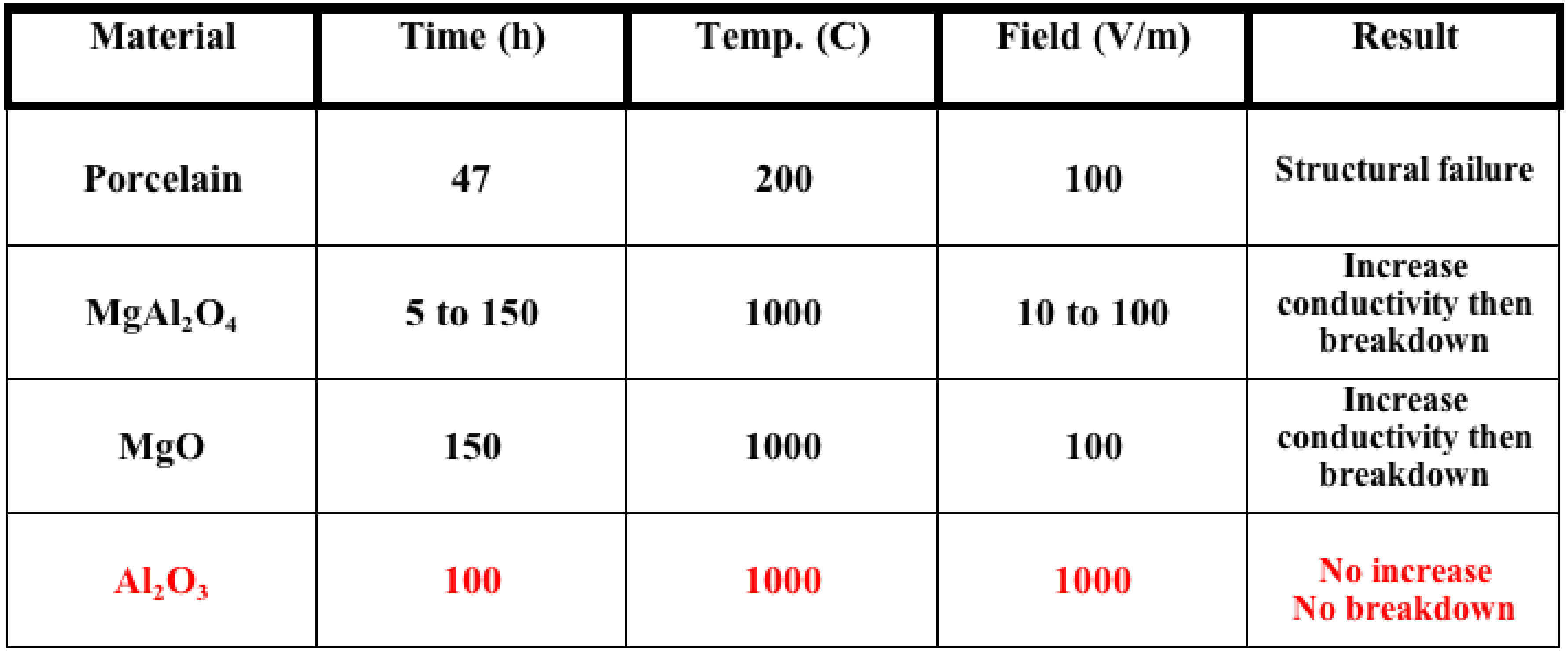
SEM of damaged Cu core
⇒ incrusted silica grains



For “RITES” Cu is better. BUT for TIEMF SS to avoid damage

(EU: Vila & Hodgson)

Electrical behaviour for “well known” insulators

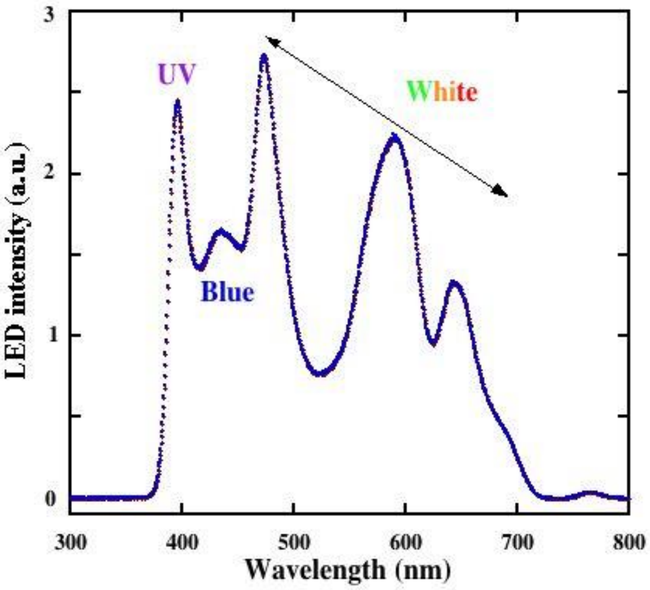


Material	Time (h)	Temp. (C)	Field (V/m)	Result
Porcelain	47	200	100	Structural failure
$MgAl_2O_4$	5 to 150	1000	10 to 100	Increase conductivity then breakdown
MgO	150	1000	100	Increase conductivity then breakdown
Al_2O_3	100	1000	1000	No increase No breakdown

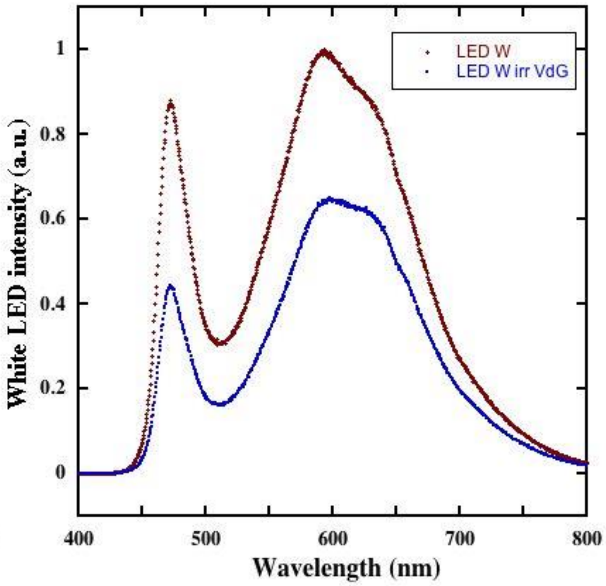
F4E-OFC-358 *(CIEMAT 5)*

System will use LEDs for *in situ* measurement of absorption in scintillators and lenses

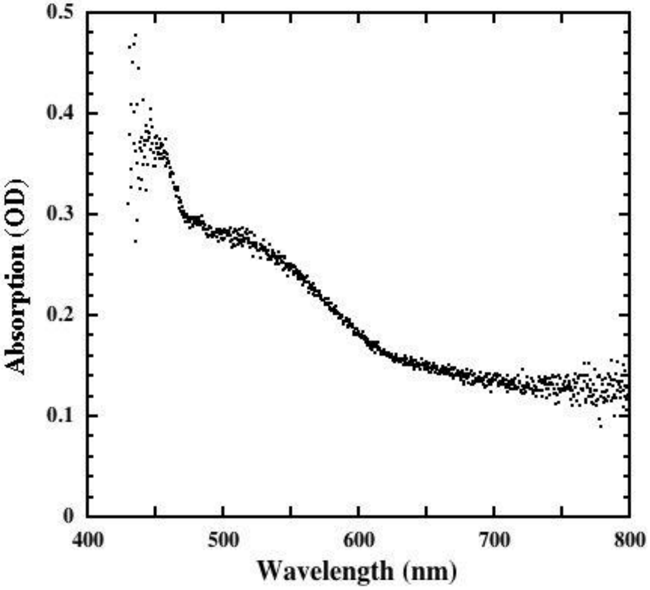
To cover the required range, 3 LEDs will be used: UV, Blue, and White



LEDs suffer radiation damage initially due to absorption in the plastic capsule



This absorption can be observed from the initial and final emissions The experimental reference channel allows compensation for this



A. Moroño, M. Malo, I. Garcia-Cortes, J. Valle, F. Jimenez, P. Valdivieso, E.R. Hodgson CIEMAT

F4E-OFC-358 *(CIEMAT 1)*

July 2013: F4E framework service contract on radiation testing for ITER prototype components and systems awarded to SCK•CEN and CIEMAT

LOT2 (to start 2016): gamma irradiation tests on components required for diagnostics, H&CD, and RH. Will include some of the following:

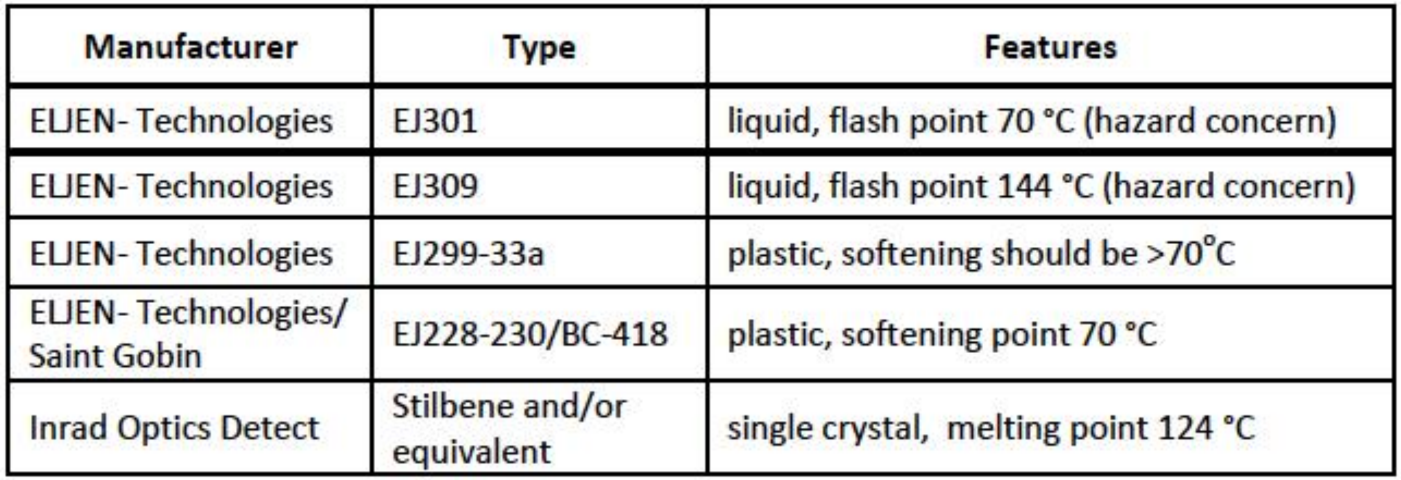
Inductive magnetic coils and steady state magnetic sensors
Pressure gauges, Bolometers, Neutron and gamma-ray detectors
Electrical cables, looms, conduit, joint, feedthroughs and connectors.
Photonic devices (waveguide, fibre, bulk optic, scintillator, mirrors, optical coating, window, integration sphere, polarizer, connector, joint-splice, index gel)
Actuators and mechanical shutter mechanisms. Microelectromechanical systems
Electronics and optoelectronic devices (laser, light emitting diode, charge coupled device, photomultiplier tube, photodetector). Sensors and calibration systems
Thin-films and coatings. Adhesives, Seals. Electrical actuators Hydraulic components (actuators, seal, fittings and valves). Grease-less bearings. Power supplies. Position sensors (resolvers, proximity).Piezoelectric devices. Sensors (temperature, pressure) Electronic circuits for sensor read-out, data transmission and (de)multiplexing of signals, as well as local control functions. Power and I&C cables with associated remote handling compatible connectors and feedthroughs. Cameras and illumination tools. Optoelectronic, photonic , microelectromechanical devices, ... etc..

F4E-OFC-358 *(CIEMAT 2)*

CIEMAT (Research Centre for Energy, Environment, and Technology)

Over the years different experimental systems have been developed in the beam lines of a 2 MV Van de Graaff electron accelerator and a 60 keV ion implanter, as well as for a ^{60}Co gamma pool irradiation facility.
These allow one to study ***in situ*** numerous radiation enhanced and induced effects such as electrical, optical, and diffusion properties in relevant fusion insulating materials.

For this contract the ^{60}Co facilty will be used to examine the following scintillators, as well as lenses:



Manufacturer	Type	Features
ELJEN- Technologies	EJ301	liquid, flash point 70 °C (hazard concern)
ELJEN- Technologies	EJ309	liquid, flash point 144 °C (hazard concern)
ELJEN- Technologies	EJ299-33a	plastic, softening should be >70°C
ELJEN- Technologies/ Saint Gobin	EJ228-230/BC-418	plastic, softening point 70 °C
Inrad Optics Detect	Stilbene and/or equivalent	single crystal, melting point 124 °C

Although the tests are component oriented, they can also provide basic information on radiation effects in the materials