*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.119 (2006)*

Radiation-hard ceramic materials for Diagnostic and Heating and Current Drive systems for ITER

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Introduction

As a burning plasma experiment, ITER will generate intense nuclear radiation fields of neutrons and γ-rays in the MeV range. The neutron fluence (with $E_n > 0.1$ MeV), is expected to range from 10^{19} m^{-2} (second mirrors at the divertor port) to 10^{24} m^{-2} (bolometers and magnetic coils near the blanket gap) [1]. These irradiation fields will significantly affect diagnostic and Heating and Current Drive (H&CD) systems (see table 1), especially those that will have to operate in-vessel, unless the most suitable ceramic materials are employed or the design of such systems is optimized for the maximum radiation tolerance. The problem facing functional components is considerably more complex than that for the structural metallic materials due to the necessity to maintain intact not only the mechanical, but also the far more sensitive physical properties such as electrical insulation, dielectric loss, optical absorption and emission for windows and optical fibres, and even thermal conductivity.

Effect	Dependency	
Radiation Induced Conductivity (RIC)	ionizing dose rate	Electrical conductivity increases due to the excitation of electrons into the conduction band.
Radiation Induced Electrical Degradation (RIED)	dose, dose rate	Electrical conductivity increases due to radiation and electric field enhanced defect aggregation.
Radiation Induced Absorption (RIA)	dose	Optical absorption increases due to the production of defect-related absorption bands, leading to light transmission loss.
Radiation Induced Luminiscence (RIL)	ionizing dose rate	Light emission due to excitation of defects and impurities.
Dielectric loss	dose, dose rate	Low frequency: increase in DC conductivity. High frequency: polarizing defect losses.
Volume changes	dose	Materials swell, or in some cases shrink; both may cause distortions.
Radiation Enhanced Diffusion (RED)	ionizing dose rate	Enhanced diffusion occurs due to the possible existence of different charge states for defects and impurities. Tritium mobility can be greatly enhanced by ionizing radiation.
Radiation Induced Electromotive Force (RIEMF)	dose, dose rate	Nuclear reactions in mineral insulated cable and surrounding materials induce a voltage between the centre and outer conductors of the cable.
Thermal conductivity decrease	dose	Thermal conductivity decreases due to radiation induced point and extended defects.

Table 1 Main effects of radiation on ceramic materials with their dependency.

An additional complexity is due to the fact that, in the ITER initial phase of operation, radiation flux will be of concern, whereas later on both flux and fluence will play important roles as fluence-dependent radiation damage builds up in the materials and systems. The European Ceramic Irradiation (IRRCER) Programme, implemented under EFDA, supports an extensive research of irradiation effects on ceramic materials and components intended for fusion applications. This programme is focused on the study of the physical and mechanical properties of such materials and components when exposed to different radiation fields (neutron and gamma, as well as electrons, protons, X-rays and photons) of different dose rate (flux) and dose (fluence) in a wide range of different environments (vacuum, controlled atmospheres, temperature ranges, electric and magnetic fields). In this paper, some examples of the results achieved by this EFDA Ceramic Irradiation Programme are presented.

Windows, optical fibres and mirrors

Optical and dielectric properties of windows have been characterized over a wide wavelength range (from the RF to the UV) with different radiation fields (neutrons up to 10^{22} m^{-2}, γ up to 100 MGy, protons up to 6×10^{19} m^{-2}). Fused silica KU-1 and KS-4V, CVD diamond and sapphire windows have emerged as the candidate window materials for ITER diagnostic and H&CD. Neutron irradiation causes RIA in the UV-VIS range but far less in the IR one [2]. In CVD diamond ECRH windows, neutron irradiation reduces the thermal conductivity as shown in figure 1 [3]. In addition, radiation enhanced incorporation of H and D appears to reduce thermal conductivity [4]. Different coatings for protection against corrosion of secondary mirrors are being tested under γ-radiation in the UV range (see figure 2).

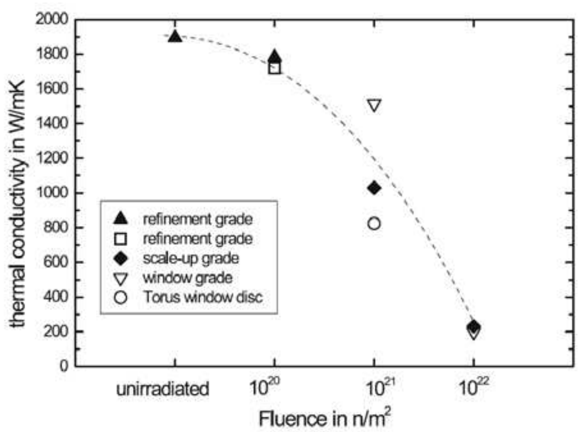

Figure 1. Degradation of thermal conductivity in high grade CVD diamond window due to n irradiation.

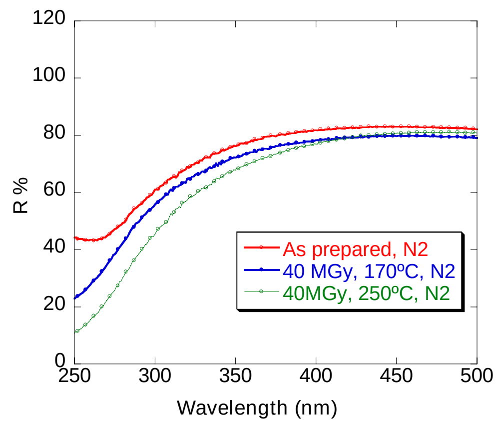

Figure 2. Degradation of reflectivity for Al_2O_3 overcoated Al mirrors.

Unloaded and H loaded optical fibres from KU-1, KS-4V and STU silica with 200 and 600 µm diameter cores have been irradiated with gammas up to 6 MGy, and in-reactor up to 2 GGy and neutron fluence 1×10^{23} m^{-2}: the advantage of H loading in reducing RIA below 750 nm is clearly observed as shown in figure 3 [5]. The possibility of in-situ H reloading, as well as photobleaching and in-situ annealing of the absorption is being investigated. Collaboration between the EU and the Russian Federation is on-going for the development and delivery of H-loaded fibres with a core diameter up to 600 µm.

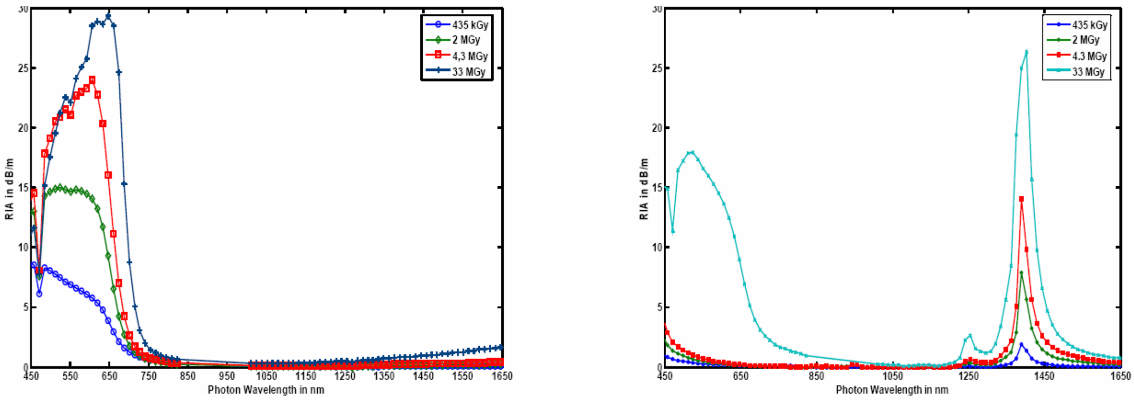

Figure 3 RIA effect due to γ-radiation of standard STU fibres (left) and of H-loaded STU fibres (right).

Bolometers

Standard resistive bolometers, with Au meander resistors and absorber on mica substrates, will suffer significant radiation damage in ITER due to transmutation and swelling [6]. Alternative alumina and AlN substrates with Pt (figure 4) have been tested: in-reactor resistance measurements of the Pt indicated little variation due to neutron irradiation (< 2 %) for a fluence up to 10^{22} m^{-2} in vacuum (< 10^{-3} mbar). From 350 to 500 °C the only change was due to the bolometer temperature, as observed during heating tests carried out before irradiation. Post-irradiation inspection showed no visible degradation of the substrate and of the meander. Instabilities in substrate resistance and contact problems were experienced during irradiation. Post-irradiation inspection after 10^{23} m^{-2} neutron fluence showed no visible degradation of the substrate meander [7]. A complete resistive bolometer prototype with SiN substrate and Pt meanders and absorber (figure 4) has been manufactured and tested. Ionizing radiation tests indicate good performance and in-reactor tests will be performed in 2006.

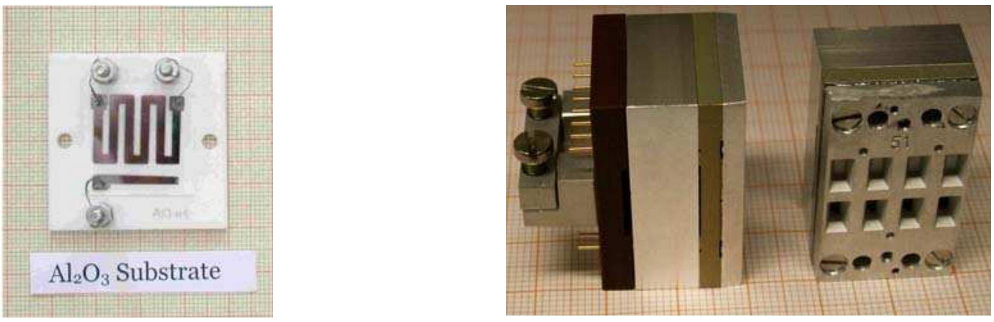

Figure 4. Left: sample of sputtered Pt deposited on alumina insulation successfully tested for γ and n irradiation. Right: a prototype bolometer with Pt - SiN meander-substrate to be irradiated in a neutron field.

Capacitive bolometers [8] are considered an alternative option to resistive bolometers. Antiferroelectric (AFE) and ferroelectric (FE) films 0.2 – 1.3 μm thick have been irradiated for neutron fluences up to 5×10^{22} m^{-2} and 1 MeV γ-rays up to 70 MGy [9]. The AFE films (PZ type) are the most resistant to irradiation with changes less than 5 % in the dielectric permittivity in the 25 – 350 °C range and at different frequencies (figure 5).

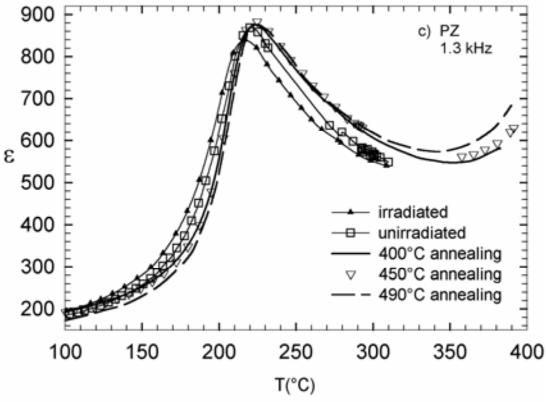

Figure 5. Dielectric constant of a PZ-type AFE thin film intended for a capacitive bolometer.

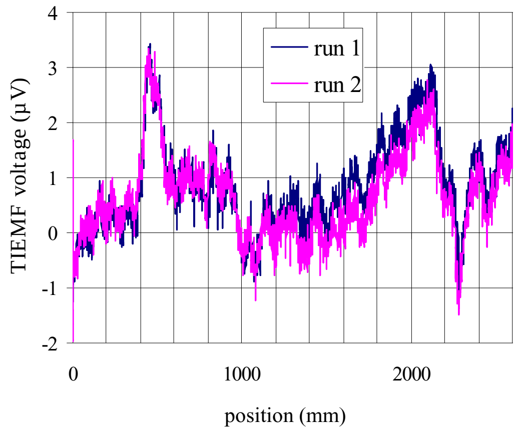

Figure 6. TIEMF in MI cable heated to 300 °C.

Mineral insulated cable for magnetic coils and other diagnostic systems

MI cables have been tested for RIEMF and thermally induced voltages (TIEMF) [10, 11]. RIEMF is mainly due to prompt and delayed neutron induced beta reactions and can be reduced with the proper choice of core and sheath material. On the other hand TIEMF is more difficult to tackle. Small temperature gradients can generate 10's of μV along the central conductor and is associated with non-homogeneities of the Seebeck coefficient along the cables (figure 6). The combined effect of RIEMF and TIEMF has been investigated, in the range 200 - 400 °C and with a neutron fluence of 2.5×10^{24} m^{-2}: the Seebeck coefficient was found to depend on fluence due to neutron induced transmutation. Hall probes have been successfully neutron irradiated at low temperature to a fluence of 10^{22} m^{-2}. Development of Hall probes capable to meet the ITER requirement of 200 °C is ongoing [12]. Finally, extensive screening of thermocouples has identified "N" and "C" types as the best candidates for ITER with negligible RIEMF and transmutation effects [13].

This work, supported by the European Communities, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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