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Performance of functional materials and components in a fusion reactor: the issue of radiation effects in ceramics and glass materials for diagnostics

Marc Decreton [a,*], Tatsuo Shikama [b], Eric Hodgson [c]

[a] *Fusion Research Unit, SCK•CEN Belgian Nuclear Research Centre, 200 Boeretang, B-2400 Mol, Belgium*
[b] *Institute for Materials Research, Tohoku University, Sendai, Japan*
[c] *CIEMAT, Madrid, Spain*

Abstract

Reliable plasma diagnostics systems are key elements for an efficient operation of future fusion reactors. They represent a major challenge, as existing systems must be upgraded to the harsh environment of a burning plasma and to the stringent requirements of real-time control actions. Radiation effects bring in this respect specific constraints. The front ends of most of the diagnostics systems are inside the vacuum vessel, and therefore subject to intense neutron and γ radiations. These systems use particular components, such as ceramic insulators, dielectric and optical windows, optical fibres and complete sensor assemblies. Studying radiation effects for these components requires particular attention to the material choice and a specific methodology. The paper makes a review of the research performed worldwide on this subject and discusses the state of the art and the future priorities to be set.

1. Introduction

The diagnostics systems on future burning plasma machines, and in particular on ITER, will play a major role. They will guarantee three major objectives: protect the machine, control predefined operational scenarios and support advanced plasma research. The step towards a long duration burning plasma operation sets new challenging requirements to existing systems [1]: high reliability and repeatability, resistance to harsh environment, long operation periods, remote maintainability. Further design and developments is still needed [2,3]. Part of this work concern the material choice and the study of environment-induced degradation processes. A specific aspect of diagnostic systems is indeed their use of non-metallic materials, usually not so comprehensively characterized in nuclear environments.

Ceramics are of course also applied in other nuclear applications. Areas such as waste processing, space and accelerator instrumentation, fission reactor and reprocessing plants maintenance, have generated plenty of data on radiation damage. The fusion community itself studies ceramic structural components, as well as ceramic solid breeders, neutron multipliers and coatings. These studies however have only a limited impact on the actual information needed to upgrade present diagnostics systems. They either apply to low radiation fluxes and energies, or they do not consider the simultaneous effect of neutrons, γ and heat. They also usually look to only one functional parameter: mechanical strength, optical transmission or insulating properties. The fusion diagnostics requires however a tolerance to the combination of several environmental conditions and the simultaneity of different operational specifications. A vacuum window for instance must keep both transparency and mechanical strength.

These challenging requirements triggered increasing research during the last decade. Involving a collaborative network of key laboratories worldwide, five main

* Corresponding author. Tel.: +32-14 33 34 14; fax: +32-14 32 13 36.
E-mail address: mdecreto@sckcen.be (M. Decreton).

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fields are studied: insulators, including mineral insulated cables; windows, dielectric and optical; optical fibres; complete sensing heads; metallic mirrors. As this paper focuses on ceramics, the review will cover here the four first items of this list.

2. Ceramics in the diagnostics systems

Practically all diagnostics systems [4] share, in one way or another, the use of ceramics.

These materials appear first as *electrical insulation* in coils and probes, cables, bolometer substrates, insulating breaks and feedthroughs. Four degradation mechanisms are here of concern: RIC (radiation flux induced conductivity), RIED (radiation-induced electrical degradation), surface effects, and RIEMF (radiation-induced electromotive force) for cables. But insulators often play also a structural role. Their mechanical embrittlement and tritium retention must also be considered.

Ceramics and glasses are also used as *transmission medium* for optical and electromagnetic diagnostic, allowing sensitive instrumentation to be located remotely. Windows have to transmit signals over a broad spectral range: from radio-frequency in ion cyclotron emissions, micro- and millimetre-waves in electron cyclotron emission and in microwave reflectometers, to infrared, visible or ultraviolet light in LIDAR based Thomson scattering systems, interferometers, polarimeters, thermography and viewing systems. Windows are key components with tough specifications both for signal transmission and for vacuum tightness. One distinguishes dielectric windows (where dielectric loss is the main parameter) from optical ones (where optical absorption and luminescence are important). In both cases, mechanical strength and tritium permeation are crucial. The use of the same materials as *optical fibres* is a particular case with specific constraints.

3. Environmental conditions

The environmental conditions will depend on the location of the diagnostic system in the machine. A major part of the measurement chains will be put outside the bioshield. But the front end will be installed inside the vessel itself, sometimes close to the first wall (on the blanket backplate or divertor cassettes, in the diagnostic plugs, in the access ports) under strong neutron and gamma fluxes. Substantial heat loads and high neutral particle fluxes will be present at some locations. Large magnetic fluxes and redeposition of evaporated and sputtered material could also cause concern. For ITER [1], near the first wall, the neutron flux will be about 10^{18} n/m^2/s and the γ flux 10^4 Gy/s, with heat fluxes exceeding 10^6 W/m^2. For the whole operation life, this results in the accumulation of 3 dpa and 10^{10} Gy. These levels however quickly decrease when moving away from the plasma. On the backplate already, two orders of magnitudes are lost in neutrons and three in γ. Particle fluxes reach 5×10^{19} atoms/m^2/s at the first wall, but are negligible in most other locations. The temperatures range mostly between 300 and 700 °C. Some electrical components (coils, bolometers) will not avoid the harshest locations. But windows will appear at the back of labyrinths under lower fluxes: e.g. 10^{+14} n/m^2/s for LIDAR windows. Further away, in the cryostat region, radiation levels falls below 10^9 n/m^2/s.

4. Ceramic insulators

Insulating ceramics will be used in feedthroughs, connectors, mechanical supports and general stand-offs, mineral insulated (MI) cables and seals, bolometer substrates and gauge set-ups. An ideal material should keep its geometrical stability (1–5%) and mechanical strength, be high-vacuum compatible, retain electrical conductivity below 10^{-6} S/m, be immune to RIED risk, keep surface effects and tritium diffusion small. MI cables should not generate RIEMF currents incompatible with the measurement requirements. Present data indicate that materials can be found with properties meeting most of these goals, but that attention is still needed for RIED and surface effects in certain extreme conditions and to a well-predictable RIEMF in cables.

4.1. Radiation-induced conductivity (RIC)

RIC, a flux dependent enhancement of the electrical conductivity due to the excitation of electrons from valence to conduction band, will be present in ITER from the on-set of operation. Its magnitude depends in a complex way on ionizing radiation dose rate, temperature, and material impurity content. Although well understood theoretically, it remains difficult to predict in a specific material grade without detailed experimental characterization [5,6]. However, from available data, one can safely say that RIC is sufficiently 'well understood' to allow this type of electrical degradation to be accommodated by the design, and that materials exist which give rise to electrical conductivities $\leqslant 10^{-6}$ S/m for ionizing dose rates of up to 10^4 Gy/s, and temperatures in excess of 300 °C. Possible problems may arise where very low leakage is required, for example in MI cables when high impedance requirements.

4.2. Radiation-induced electrical degradation (RIED)

In contrast to RIC, RIED is a permanent enhancement of the volume electrical conductivity caused by radiation-induced defects in the presence of an electric field. It is a more serious problem, not only from the point of increasing the electrical conductivity beyond that of RIC, but also because this type of degradation is still not fully understood. There is even no general agreement as to whether RIED exists as a real volume degradation, due to the inherent experimental difficulty of separating surface and volume conductivities. Many relevant references can be found in [7] where the importance of electrical field, temperature, total dose, dose rate, radiation source and spectrum, material type, and irradiation environment (vacuum, air, He) is discussed. Available in-reactor results support earlier indications that RIED is a complex phenomenon depending on material type [8]. Recent Japanese reports on aluminium colloid identification for degraded alumina [9] help to confirm earlier results and modelling, where colloid production was suggested as being the RIED cause, and was related to observed gamma alumina formation and material embrittlement [10,11]. Available data have enabled moderately safe operating conditions to be recommended for ceramic insulator use, but further work is clearly required to ensure reliability of selected insulators in ITER and beyond.

4.3. Surface effects

For insulating components, surface degradation may prove to be even more serious than RIC and RIED volume effects. Two types of surface degradation have been examined, a contamination caused by poor vacuum, sputtering, or evaporation [12] and a real surface degradation related to radiation-enhanced surface vacuum reduction and possibly impurity segregation [13]. Both forms are affected by the irradiation environment and ionizing radiation. However the real surface degradation effect is strongly material dependent. It is important to note that this type of degradation occurs in vacuum but not in air or helium. This stresses the extreme importance of a representative irradiation environment for material testing. Most insulating materials in ITER must indeed operate in high vacuum, whereas to date many in-reactor experiments have been performed in helium.

4.4. Radiation-induced electromotive force (RIEMF)

Many diagnostic sensors require long sections of radiation exposed transmission cables, or use even the cables themselves as sensing elements in magnetic probes. Radiation generates spurious currents and voltages on such cables, leading to potentially serious perturbations. RIEMF effects, already observed decades ago on fission reactor cables, are caused by radiation-induced currents flowing across the cable insulator. Diagnostic systems requiring the detection of nA currents or μV dc voltages [14,15] will be particularly vulnerable. RIEMF is triggered by charged particles created by gamma (e.g. energetic electrons by Compton interactions) or neutron (recoil protons, β-emitting isotopes) with enough energy to cross the cable insulating material and produce a current between core and sheath. Significant induced voltages can appear at the cable end, and lead to high signal drifts on integrating signal processing units with limited common-mode rejection. Asymmetries in cable properties or environmental conditions (temperature, radiation field) lead to further signal unbalance.

Systematic studies [16] were confirmed by recent in-reactor tests using different materials for the core wires: stainless steel [14], copper [17] or nickel [18]. But the obtained results present often a complex pattern. Strong dependences on cable geometry and material appear. The induced currents vary with time, and in some cases change polarity without remaining proportional to reactor power. Recent analyses [19–21] suggest that additional phenomena must be considered, such as thermoelectric effects due to transmutation or defect generation. Moreover strong thermal effects on the differential voltage for MI cable coils are reported [22].

In order to understand these results, a Monte Carlo modelization was developed. Theoretical [23] and experimental [24] work concentrated on the prediction of induced RIEMF currents. Validation irradiations of coiled and straight MI cables under gamma and neutron environments showed that neutron effects are well modelised, while the strong dependence on the cable environment and its orientation, observed under gamma, requires a larger model basis, involving the cable surroundings and a fine tuning of the energy spectrum. Fig. 1 presents a comparison between stainless steel and

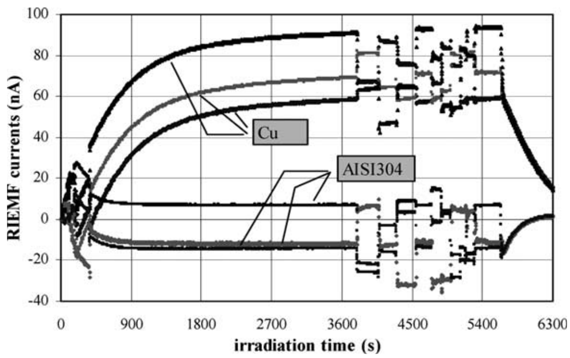

Fig. 1. Observed RIEMF currents in MI cables with Cu and AISI304 core wires irradiated in the BR2 reactor. The difference between the three data sets for each cable type is due to the different azimuthal positions in the irradiation rig. After about one hour (around 3750 s on the graph), the rig is rotated in discrete steps, leading to strong, but internally consistent, instantaneous current variations. After removal of the rig from the reactor core (at 5700 s on the graph), the signals show a sudden change followed by a multiexponential decay.

copper cores, together with the influence of orientation. The observed range (±10 nA for stainless steel, 70–100 nA for copper) is in good agreement with the model. But the differences due to the three azimuthal positions would require a more detailed representation of the cable cross section and the radiation field distribution and orientation.

Further work, mainly on thermal effects, could lead to effective mitigation measures: enhanced internal cable symmetry, use of specific core materials, avoidance of unnecessary asymmetry in the coils surroundings, upgrade of measuring circuits with enhanced tolerance to parasitic effects.

5. Materials for transmission windows

5.1. Optical windows

The optical properties of silica-based windows have been the subject of numerous studies for military, space, accelerator and fission reactor applications. They focused on the radiation-induced absorption (RIA). Present knowledge is nevertheless still pragmatic, with a want for a comprehensive understanding of the actual colour centre dynamics. A direct extrapolation to fusion conditions is therefore difficult, as the following specificities have usually not been taken into account: RIA in UV and in far IR; neutron displacement mechanisms; radiation-induced luminescence (RIL); high power laser beam; surface contamination by erosion dust, or evaporated and sputtered products; recovery phenomena between pulses; mechanical strength. Specific fusion-oriented studies were therefore launched and the following paragraphs review briefly some recent results.

5.1.1. Radiation-induced absorption (RIA)

RIA in silica materials has been widely studied between 400 and 1500 nm [25]. Certain fused silica glasses or quartz have been shown suitable for spectroscopic systems and viewing systems. In this region, silica is essentially affected by ionisation effects (γ). For ITER, two particular rad-hard fused silicas were selected [26,27]: KU1 (high OH) and KS4V (low OH). For IR and visible transmission, sapphire is preferred when possible, as it has a more regular structure with less stable interstitial trapping sites. But being strongly affected by temperature, it must be avoided for applications with large temperature variations. The UV region however has been less studied. Some assessment of KU1 was performed between 200 and 400 nm [27] and showed that RIA is here principally due to oxygen vacancy defects created by radiolysis type displacement mechanisms. A favourable influence of temperature (above 150 °C) was observed, caused by the higher mobility of interstitial oxygen atoms able to fill in the vacancies. Fig. 2 shows typical results in the 200–300 nm region [28]. Fast [29] and 14 MeV [30] neutron tests have confirmed these conclusions, up to 10^{-3} and 10^{-5} dpa respectively, and further work with 14 MeV neutrons is presently ongoing [31].

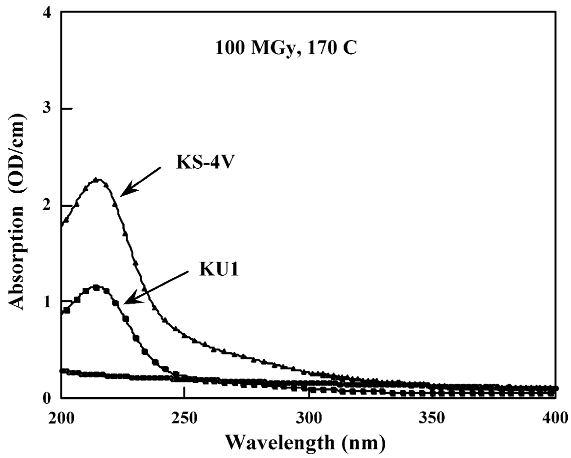

Fig. 2. Optical absorption spectra for KU1 and KS4V gamma irradiated up to 100 MGy.

5.1.2. Radiation-induced luminescence (RIL)

Radioluminescence effects are a major concern in fusion diagnostics. Materials with otherwise superior radiation tolerance, such as sapphire for instance, can be disqualified for prohibitive luminescence [32,33], at least above 100 Gy/s. RIL being essentially due to oxygen vacancies, neutron displacements enhance it. Silica, and in particular KU1, show however a better pattern. In addition to the unavoidable Cerenkov emission, which decreases from the UV as the inverse square of the wavelength, small RIL peaks appear at low wavelengths due to electronic excitation effects, as for instance the 450 nm peak observed in many silicas. Its intensity is proportional to dose rate [34], but fortunately is thermally quenched above 150 °C [28].

5.1.3. Laser-induced damage

The windows used for LIDAR Thomson scattering will be placed away from the first wall, seeing typically a few hundreds of Gy/s and up to 10^{-10} dpa/s. These windows must transmit high power light beams reaching localized power peaks of 10^{+16} W/m^2. Laser-induced damage in glass is a well-studied subject [35], but the fusion environment leads potentially to laser damage enhancement by RIA and surface contamination effects. The former is thermal (laser power absorption), the latter linked to laser-induced surface cracks (electron avalanche effects provoking localized dielectric breakdowns). Fortunately, with KU1, tests conducted under electron irradiation [36] have shown that ionising radiation does not increase enough the electron density in the conduction band to enhance significantly any dielectric breakdown mechanism, while the thermal effect is kept low due to the favourable RIA for KU1 at typical laser wavelengths.

5.1.4. Surface degradation effects

Transmission problems can also be generated by thin contamination layers or surface erosion by particles influx on the vacuum side of the windows. The increased absorption would not only reduce the signal quality, but induce thermal effects under high power light leading eventually to cracks. Preliminary results obtained on KU1 windows [37] show that a rough polishing of the surface has only a minor effect on the signal transmission, but that the deposition of a metal layer would induce significant problems. Care will therefore be taken to design the labyrinths, so as to place the windows in areas where the deposition rate is minimal.

5.1.5. Importance of recovery effects

One of the typical features of fusion machines is their pulsed operation. Although the aim is to reach a quasi-continuous regime, ITER for instance will certainly experience repetitive plasma burn interruptions. This aspect is not always easy to simulate in the usual neutron continuous irradiations, and is even seldom considered in gamma tests. Recovery phenomena are however non-linear and the actual evolution of RIA can depend on the radiation history [38].

5.1.6. Mechanical strength

No significant neutron-induced effects were observed on the mechanical strength of silica material up to 10^{-4} dpa [39]. The strength is actually more dependent on the surface quality of the windows. However, system effects are dominant here, and will be discussed below. It is indeed the window assembly as a whole, and especially the glass–metal joint, that will have to be assessed in this case.

5.2. Dielectric windows

Some of the windows are used for electromagnetic waves. These so-called dielectric windows, used for instance in ECE-based systems, have specific requirements: low dielectric losses, good heat transfer, and mechanical stability. For the high power ECRH system sapphire was first considered, but had to be cryogenically cooled to keep the required performance [40]. CVD diamond (carbon vapour deposition on single crystal silicon) is now considered as the best candidate material, as it ensures the specifications at room temperature with lower temperature and frequency dependencies [41]. It shows superior mechanical strength with small influence on surface finishing. These values were confirmed under neutrons (0.5 dpa at 380 °C) [42]. Silica (e.g. KS4V and KU1) on the other hand showed very large frequency dependency of the dielectric losses, although remaining at an acceptable level ($<10^{-4}$ at 140 GHz) up to 10^{-3} dpa [43]. Although the reduction of strength at this fluence level was irrelevant for ECE applications, a large influence of surface roughness could impair their safe application in case of strong surface deposition and erosion.

6. Optical fibres

Optical plasma diagnostic systems need complex paths, combining mirrors, lenses and windows, to bring the light signals out of the vessel. Optical fibres are particularly attractive to reduce this complexity, at least for part of the length. The applicability of fibre technology was already demonstrated a decade ago on TFTR [44] and JET [45]. The upgrade to a burning plasma machine such as ITER needs however more attention to the problem of radiation effects.

Compared to windows, these effects are enhanced due to the longer optical length, but compared to similar fibre applications in other nuclear areas, the fibre length exposed here to radiation is much shorter.

Numerous data have been generated on the radiation tolerance of fibre links in areas such as fission reactors, accelerators, space or military equipments [46,47]. However, most of these evaluations were limited to communication links, to the RIA in the near infra-red and to gamma fields. As suitable fibres could be developed for these applications, rad-hard communications links can also be envisaged for fusion machines [48]. Diagnostics however require a broader evaluation: higher total doses and dose rates, displacement effects by neutrons, luminescence, use in the visible, UV, and far infra-red parts of the spectrum.

The key parameters affecting the radiation resistance are the fibre composition (dopants, OH-content, impurities, cladding type), the preform and fibre fabrication (preform deposition process, drawing speed, temperature), the fibre preconditioning (pre-irradiation, annealing, hydrogen-loading), as well as the operation conditions (irradiation sequences, temperature, optical power). This explains the great disparities observed on the irradiation behaviour of apparently identical fibres.

Pure silica fibres, using the same KU1 or KS4V glasses already selected for the windows, have been tested in representative in-reactor experiments [49,50]. International round-robin evaluations were performed, where they were compared with fluorine-doped alternatives [51,52]. Additional comparison under pulsed reactor conditions have been performed [53], and hydrogen-loading was evaluated as a RIA-reducing technique. All results confirmed the low RIA values at wavelengths above 700 nm, but indicated important absorption and luminescence effects below this wavelength, especially under neutrons.

The effect of OH, F and H_2 content is still a subject of debate. Fluorine-doped fibres are attractive with an RIA, around 400–600 nm, lower than 10 dB/m at 10^{-5} dpa, but this jumps to 40 dB/m at 10^{-2} dpa. There is a large sensitivity to microbending [54] leading to sudden drops of transmission. A high OH content is on the other hand favourable under neutron tests [51], especially under pulsed environments [53].

The positive role of H_2-loading is known for several years and is due to the passivation effect of hydrogen on the NBOHC colour centres (630 nm) which are converted to hydroxyls [55]. In-reactor experiments [56] confirmed a definite improvement in RIA, but with a decreasing advantage above 10^{-3} dpa. Moreover, the H_2-loading of large core (600 μm) metal-coated fibres is still a technological issue.

The rate of RIA increase is fortunately temperature dependent, so that operation at higher temperature (200–400 °C) should be considered. Successful tests were conducted on TFTR and JET [57] under low fluence, but were corroborated by in reactor measurements up to 10^{-4} dpa [58], and even under 14 MeV flux [59]. The dynamic competition between temperature recovery and displacement damage produces however complex behaviours, leading sometimes to large data scatters and non-linear responses [60].

The RIL on the other hand is a particularly misleading effect in most diagnostic systems, as it is uncorrelated with the plasma emission. Some fibres have specific luminescence peaks, but the Cerenkov light is dominant for silica fibres. Contrary to RIL in windows, the RIL measurement results here from the emitted light and its absorption over the fibre length. As the Cerenkov effect decreases with increasing wavelength, and that the absorption goes the other way, the RIL results presents usually an apparent peak [61].

Fig. 3 shows typical results [62], where higher RIL values were indeed observed for the H_2-loaded fibre (KU1H2G), as well as for the higher temperature, a consequence of the lower RIA due to H_2-loading and higher temperature.

7. System effects

The choice of a suitable material and the understanding of the degradation process do not solve usually the whole problem. Typical diagnostic front-end components combine indeed different materials to fulfil operational needs, contradicting sometimes environmental resistance requirements. Making a resistant system is often finding an optimum compromise. It is therefore very important to get at the end an assessment of the whole assembly. This step was only taken very recently and should be pursued.

7.1. Window assembly

Windows act as vacuum and tritium barriers, and must not only insure a good transmission, but keep their mechanical strength and low tritium permeability. The question relates to the whole window assembly, and in particular to the ceramics–metal joint. Microcracking for instance caused by radiation-induced segregation and sub-critical crack growth lead to enhanced tritium diffusion and leaks [63]. Studies are on-going on the thermal and mechanical resistance of different window materials and assembly methods (e.g. gold-bonded quartz, bronze-brazed sapphire, welded borosilicate) [64]. They need to be validated under radiation and high temperature.

7.2. Bolometer

Bolometers will be placed inside the vacuum vessel in very demanding locations. On ITER they would accumulate at least 0.1 dpa. A reference JET design uses a mica substrate and a gold conductive strip as temperature sensor. In reactor tests [21] confirmed the good

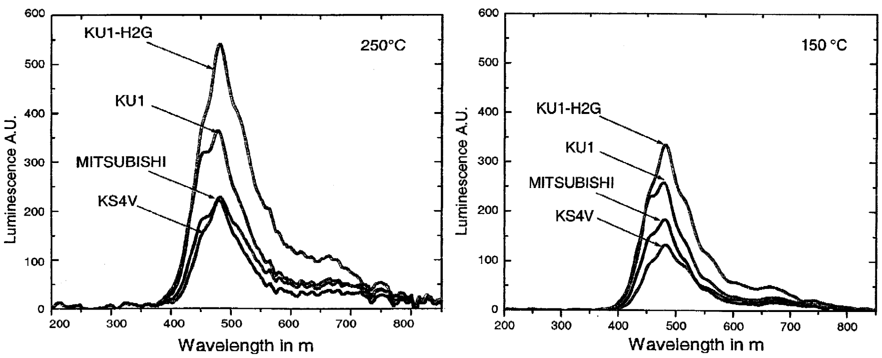

Fig. 3. RIL results for different rad-hard fibres at two temperatures.

tolerance of mica, but showed a large increase of the strip resistance (caused by transmutation), as well as gold-to-mica adhesion problems. Alternative designs are under study [65], using platinum on alumina, aluminium or silicon nitride. This would allow achieving higher temperatures with insignificant metal transmutation and substrate swelling, as well as better metal-to-ceramics adhesion. Other designs based on IR imaging of the foil surface avoid any metal strip and allow array mapping on one single foil. This is claimed to be rad-hard [66], but must still be designed for in-vessel installation.

7.3. Pressure gauge

Pressure gauges are used to monitor neutral gases, and specific sensor design work was conducted for ASDEX, using a hot filament and electrodes assembly with insulated feedthroughs. An assessment under radiation (0.1 dpa), vacuum and high temperature (450 °C) was performed recently [67] on a complete rad-hard mock-up and showed that neither the resistance of the feedthroughs nor the other cause of possible degradation (ionisation of residual gas, RIEMF effects) were sufficiently high to preclude a correct operation.

8. Conclusion and future priorities

Taking as a reference the progress status about environmental effects on diagnostic systems made in 2000 [68], one clearly observes a significant progress in the identification of suitable materials for most of the front end sensors [3]. This does not however imply that complete hardened front-end assemblies are off-the-shelf yet. Further efforts should indeed be focused in particular on the following priorities:

- understanding the parasitic signals on cables, especially the thermal effects;
- assessing the RIED limits in representative conditions;
- developing complete leak-tight window assemblies;
- evaluating the effect of eroded metal contamination on windows;
- proving the achievability of H_2-loading for thick metal-coated optical fibres;
- modelling the radiation effects;
- making existing data available in a comprehensive database.

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