Characterization of first wall materials in RFX-mod

A. Canton[1], P. Innocente[1], S. Deambrosis[2], L. Grando[1], E. Miorin[2], M. Siragusa[1], N. Visonà[3]
[1] *Consorzio RFX, Corso Stati Uniti 4 - 35127 Padova, Italy*
[2] *CNR - Institute for Energetics and Interphases, Corso Stati Uniti 4 - 35127 Padova, Italy*
[3] *Università degli Studi di Padova*

Introduction

The hydrogen retention and release properties of the materials devoted to sustain the particle and heat fluxes exiting the plasma strongly affect plasma density control during operation in fusion devices [1]. Carbon has been a very common material for the plasma facing components (PFCs), given its excellent thermal properties and the low radiation losses induced by C impurities. More recently and in reactor perspective, metals (tungsten, molybdenum) are preferred to carbon for their low long lasting tritium retention. From the point of view of density control, the advantage of metals is the low retention and that, even at room temperature, between shots they outgas most of the hydrogen, restoring their absorbing capability.

RFX-mod is a Reversed Field Pinch (RFP) experiment where 0.5s deuterium discharges with plasma current up to 2MA and typical n/n_G in the range 0.1-0.4 are performed. The Inconel 625 vacuum vessel is fully covered by tiles made of polycrystalline graphite (Mersen, PT5890), characterized by a flat central surface (50 mm wide in the poloidal direction) and two flat 10° sloped surfaces (16 mm wide). The plasma-wall interaction (PWI) is not directed at specific locations since there are not limiters, and the average load to the wall at the highest current should be of the order of $1MW/m^2$. Nevertheless local error fields and the macroscopic non-symmetric toroidal deformation of the last closed flux surface, characteristic of the RFP configuration, contribute to localize the PWI giving peak power loads up to $50MW/m^2$. Except for a limited number of shots after wall conditioning, the wall recycling factor R (number of hydrogen atoms exiting the material for each impinging H) is 1 and density depends on input power [2], a common behaviour of all-carbon devices [3]. Density control requires frequent glow discharge (GD) cleaning sessions with high impact on experimental time. The replacement of the graphite wall is under design and in this paper we report on the tests that have been done at RFX-mod with metal and graphitic components.

Tungsten coating on graphite substrate

A full molybdenum or tungsten first wall is not compatible with the mechanical structure of

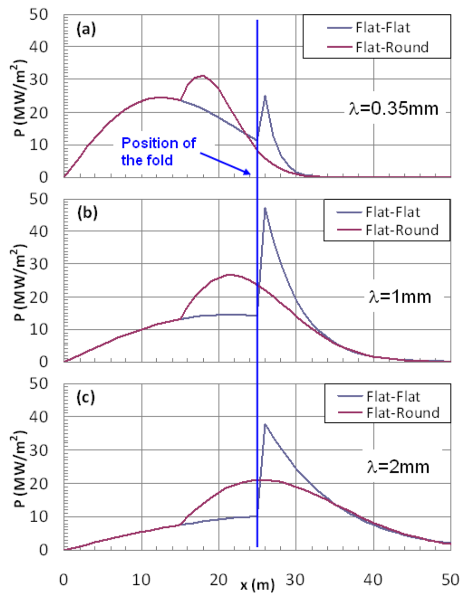

Figure 1: local power deposition for different decay length λ and for old (blu) and new (red) surface shape

RFX-mod, given the much higher weight in comparison to graphite, and a metal interface with plasma can be obtained by PFCs made of graphite coated by thin tungsten layers, as already done in JET [4] and ASDEX Upgrade [5]. In the past years several deposition techniques on samples and tiles have been tested at RFX-mod, but in all the cases the metal film experienced several types of damages, particularly localised at tile edges and where the flat surface folds towards the sloped surfaces [6].

Based on that experience, recently we studied the local power deposition on the tiles surface assuming an exponential decay of power with radial distance from the last closed flux surface and decay length λ, and proposed a modification of the shape with reduced (30 mm wide) flat central surface and connection to edges via rounded surfaces. The effect on the local deposition is illustrated in figure 1 for different values of λ. Except for very short decay length, the new shape contributes to spread the power load. We got a set of tiles coated by the well established CMSII technique [7] with film thickness of 2-3 μm. The thin layer mitigates the differential thermal expansion between film and substrate, one of the reasons of delaminations and following melting. On the other side it does not severely limit the coating life due to plasma sputtering: considering the min/max RFX-mod particle flux, typical edge temperature and pulse length, 2 μm film would be eroded in about $2{\cdot}10^4 \div 2{\cdot}10^5$ discharges. The set included tiles with old and new surface shape and also tiles made of graphite with thermal conductivity 3 times higher than RFX-mod one, in order to quickly dissipate heat and reduce the film temperature. The tiles have been exposed to 100 s of 60-80 kA Tokamak discharges and 100 s of 1.2-1.5 MA RFP discharges, then retrieved and analysed by optical microscope. Thin W film on new shaped tile made by high conductivity graphite is the only one that did not suffer any damage, but during the exposure period only mild PWI has been observed at its location: given the short exposure time with respect to desired lifetime for the new tiles, further tests will be necessary before concluding that this solution can be adopted for the new wall.

Modelling of influxes from graphite in RFX-mod

An alternative path to control hydrogen influxes from the wall during pulses foresees the use of a C-based material of suitable properties. The parameters that mostly influence the release of particles have been investigated by a code based on the model of Pitcher [3], a self-consistent steady-state model of plasma-wall system in full graphite devices supplied by ohmic power. The model describes plasma by the transport equations and wall by the equations developed in [8]; the interaction of the thermal edge plasma with the wall is described by particle (H and impurities) and power balance, assuming that the only particle source for the plasma is the hydrogen stored in the wall at the beginning of the discharge, and that the input power is in part lost to the wall and in part dissipated by radiation.

In our case, the model has been partly modified neglecting the power lost by radiation, relaxing the condition that graphite is saturated at the beginning of the discharge and splitting the wall in two regions, one being the portion where most of the power is deposited. The ratios of the areas of the two regions S_h/S_w (area of enhanced/area of not-enhanced interaction) and of the particle fluxes from the plasma Γ_h/Γ_w (outflux to the enhanced/to the not-enhanced region) are parameters of the calculations, and are set according to typical experimental observations in RFX-mod: in the runs for this paper S_h/S_w=0.1 and Γ_h/Γ_w=0.5. The model was found to reproduce correctly the experimental dependence of plasma density on input ohmic power, foresees a jump of about 150°C on the wall where enhanced interaction happens (assuming the thermal conductivity of the RFX-mod graphite) and was found to little influence edge plasma temperature, in agreement with experimental observations. The initial concentration C_i of hydrogen in the graphite (ratio of H to C atoms, C_i=0.42 at saturation) was also found to drive the plasma density and at low concentrations the particle flux was proved to come wholly from the region of enhanced interaction. Finally, the thermal conductivity k of graphite, which determines the temperature of the wall, can contribute to lower plasma density in particular at low C_i (figure 2). The picture from the model tells that in RFX-mod we can limit particle influxes from the wall and plasma density, keeping a C-based wall, by: (i) limiting power deposition, in particular avoiding local peaks of load, and this can be done with careful design of the tiles shape as shown in the previous paragraph; (ii) keeping initial hydrogen concentration as low as possible, with effective wall treatment systems; (iii) using

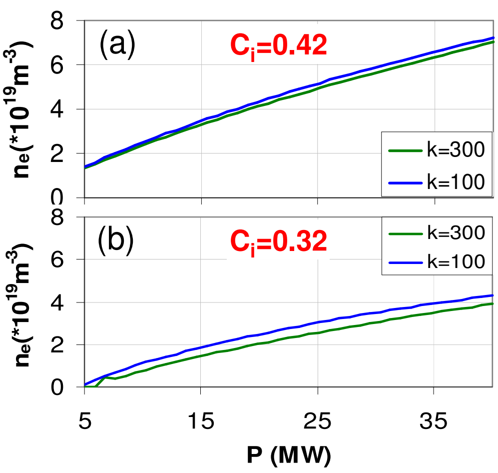

Figure 2: Plasma density as function of input power at graphite saturation (a) and at H concentration 0.32 (b) for different graphite thermal conductivities k

carbon material with high thermal conductivity.

High thermal conductivity graphite

At RFX-mod we tested extruded graphite (EG) as possible candidate material for the new wall. The typical grain size of EG is of the order of hundreds of microns and purity is quite low in commercially available products (hash content ~ 500 ppm). The gross grain of EG leaves visible grooves on the surface, and some grains look poorly adhered to the bulk at microscopic analysis. The mechanical properties are poor with respect to C-based material typically used in nuclear devices (isostatic graphite or CFC), but thermal conductivity is comparable to that of much more expensive CFC. We decided to test this graphite on full scale size, by replacing some of the RFX-mod tiles with new ones made by EG. The aim was to test the survival of the material under load by RFX-mod plasma. In fact, since the area of the new tiles was negligible with respect to the total wall surface, the effect on global particle influxes and plasma density was not detectable, whereas local measurements of H_α radiation were not available at the installation position. After assuring that its mechanical properties were suitable to installation in RFX-mod, we selected FE170 of Tokai Carbon Co. 3 tiles have been exposed to 100 s of 60-80 kA Tokamak discharges and 100 s of 1.2-1.5 MA RFP discharges. The microscopic comparison of sample areas of the tiles before and after exposure did not show any degradation of the material and surface temperature measurements by IR imaging during exposure confirmed the lower T with respect to the surrounding tiles.

Conclusions

Tungsten coated (thickness 2-3 microns) and high thermal conductivity extruded graphite tiles have been exposed to RFX-mod plasmas in order to test a new material for the first wall of the device, that can give lower particle influxes and better plasma density control during operations. The small thickness metal film on high thermal conductivity substrate and proper tile surface shape survived, though tested only at mild power load. The extruded graphite did not deteriorate with exposure, even if some concern comes from purity and grain adhesion, but custom material can be designed in order to minimize these characteristics. Both the solutions are hence interesting even if further tests are necessary to qualify the final solution.

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