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Progress in ITER-Relevant Diagnostic Technologies at JET

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ABSTRACT.
In recent years on JET, technological upgrades in the field of diagnostics have been focused mainly on the measurements of fusion products and plasma wall interactions. Neutron spectrometry has been improved with the installation of a high resolution time-of-flight neutron spectrometer, an upgrade of the Magnetic proton recoil spectrometer and a coherent development strategy for compact spectrometers (NE213 liquid scintillators and diamond detectors). For fast particles, γ-ray spectrometry is being upgraded with the addition of neutron attenuators, based on both pure water and LiH and the installation of better detectors using high-Z scintillator materials. Significant attention has also been devoted to testing radiation hard detectors, ranging from Chemical Vapour Deposited diamond detectors for neutron counting to Si-on-insulator technologies for particle detection and innovative Hall probes for the measurement of steady-state magnetic fields. To improve the diagnostic capability for measuring erosion and redeposition at the first wall, first, very encouraging, results have been obtained with Laser Induced Break-down Spectroscopy. Significant progress has been made with a test programme of mirror materials for ITER.

1. INTRODUCTION

JET, whose present mission consists of developing plasma scenarios and of testing technologies for ITER [1], is a unique environment for the qualification of specific diagnostic solutions for the next step. The plasma parameters and volume, the tritium capability and the first wall material mix are JET specific features that allow relevant testing of measuring techniques and technologies, indispensable for ITER, in reactor relevant conditions.

Recent operation in tritium (TTE) and the development of a new ITER-like RF antenna have provided impetus for the development of new, relevant diagnostic technologies. These new aspects of JET scientific activity have stimulated ITER relevant developments allowing the measurement of **fusion products** [2]. Neutron diagnostic upgrades most relevant to ITER include neutron spectrometry, with the implementation of a new spectrometer based on the Time-of-Flight approach, and improvements to the Magnetic Proton Recoil spectrometer, both aimed at improving the measurement of the 2.45MeV neutron spectra. A systematic comparison between these more traditional high resolution spectrometers and compact ones, based on NE213 liquid scintillators, will be pursued further in future experimental campaigns. Another major area of development has been diagnostics for “burning plasma” including **detection of fast particles and lost alphas**. A new approach to γ-ray detection has allowed the determination of the spatial distribution of both the fusion and the ICRH accelerated alpha particles. For this method to be useful to ITER there is a need to reduce the neutron background. Neutron absorbers, made of demineralised water or LiH, will be tested at JET. Improved electronics with time resolution, signal-to-noise ratio and neutron/gamma discrimination level suitable for ITER is also a priority. In the field of **radiation-hard detectors**, a lot of effort has been devoted to refining the technology of Chemical Vapour Deposition (CVD) diamond detectors, particularly in the direction of extending the applicability of these diodes to measure 2.45MeV neutrons (previously only 14MeV neutrons were detected). Hall probes, with the long term objective of complementing ITER magnetic diagnostics with steady state ex-vessel measurements, were installed during last shutdown and are providing some initial results. New silicon-on-insulator detectors are being developed for the two Neutral Particle Analysers, in order to reduce the noise from the neutron background, a problem that affected the isotopic composition measurements during the TTE campaign.

Another major area of investigation at JET relevant to ITER is the study of **plasma-wall interactions**. This line of research is motivated by the need to operate JET with more ITER like configurations. These are accessible with the new divertor which has a power bearing septum replacement plate. The relevance of these studies to ITER will be further enhanced by the installation in 2008 of a completely new metallic wall [3]. To assess the problems linked with erosion and redeposition at the first wall, an innovative approach using Laser Induced Break-down Spectroscopy has provided encouraging results. This involves ablating the surface layer with a laser pulse and measuring its composition via spectroscopic detection of the emitted radiation. A set of mirror materials was also installed in suitable cassettes and the degradation of their optical properties will be investigated using ellipsometry.

2. NEUTRON SPECTROMETRY

One of the most fundamental quantities to measure in a fusion experiment is the total neutron yield [2], since it is the neutrons which provide the net energy output. In present day Tokamaks the escaping neutrons are exploited to derive information about the status of the plasma and to better control it. Neutron Emission Spectroscopy (NES) is particularly useful to diagnose the core fusion process and its fuel ions [4, 5]. With NES the fusion power, the collective motion of the plasma, the fuel ion densities, the ion velocity distribution and hence the effectiveness of different heating schemes (as well as the bulk fuel ion temperature) can be determined. In 1996 a Magnetic Proton Recoil (MPR) neutron spectrometer was installed at JET to detect the 14MeV neutrons. In this diagnostic fusion neutrons are collimated onto a thin plastic foil and scatter on H nuclei. The recoil protons emitted in the forward direction enter the magnetic part of the spec-trometer where they are momentum analysed in the magnetic field and focused onto a focal plane detector, consisting of an array of plastic scintillators coupled to PhotoMultipliers (PM) tubes. The spatial distribution of the recoil protons is measured by the focal plane detectors and this can be related back to the neutron energy distribution at the foil through the spectrometer’s response function. The performance of the system is very good for the 14 MeV neutrons; however the MPR measurements of 2.5MeV neutron spectra were hampered by insufficient background separation. To extend its operational range to include also the 2.5MeV spectrum as well as improving the 14MeV neutron spectroscopy, a MPR upgrade (MPRu) was completed in 2005 [6]. To reduce the background sensitivity of the scintillators, the 32 elements of the new hodoscope consist of two-layered phoswich detectors (Fig.1). The top layer, facing the direction of the incoming protons, is a 0.3mm thick fast scintillating layer in optical contact with a thicker slow scintillating layer. The distinctly different response times of the two layers allow effective Pulse Shape Discrimination (PSD) techniques to be applied, since the 2.5MeV protons are fully stopped in the fast layer and therefore can be distinguished from the background (neutrons and gammas), which predominantly produce emission in both layers. The analogue output of the PM-tubes is processed by custom-built transient recorder cards, which allow a more detailed PSD, hence enhancing the background separation.

To provide detection at optimised rates for 2.45MeV neutrons, it was decided to install another high resolution spectrometer based on the time-of-flight approach. The spectrometer is called TOFOR (Time of Flight For Optimised Rate) and measures the flight time of 2.45MeV scattered neutrons with the help of two sets of plastic scintillator detectors. The first set of scintillators, S1, is placed in the collimated flux of neutrons from the plasma, and the second set, S2, is located on the constant time of flight sphere. A fraction of the neutrons scatter on hydrogen in S1, some of which are detected in S2. The energy of the incoming neutron is uniquely determined by the Time Of Flight (TOF). The final design required careful trade-offs in the geometrical implementation, driven by the TOFOR design objectives of maximum efficiency (ε) and high count rate (C_n). The final TOFOR geometry was determined with the help of extensive GEANT4 neutron transport simulations [7]. It consists of a stack of five S1 scintillators, with 3 PM tubes each, and 32 S2 detectors forming a sort of ring around the instrumental axis on the constant time of flight sphere [8]. The spatial distribution of the S2 flat scintillators, approximating the constant TOF sphere with a radius of R=705mm, was dictated by the requirement of a large solid angle. The final solution should provide nominal performance of $\varepsilon = 0.12$ cm^2 and $\Delta E_n/E_n = 5.8\%$ due to geometrical effects, with a projected count rate of $C_n = 300$kHz for a maximum neutron flux at JET of 3×10^6 n/(cm^2s) on S1. An example of spectra obtained recently with TOFOR is shown in Fig.2.

The activities aimed at developing compact spectrometers for JET and ITER are proceeding quite successfully. The application at JET of liquid scintillator detectors (NE213), well characterized at the Physikalisch-Technische Bundesanstalt (PTB) facilities, has shown that these detectors can be used as high resolution compact neutron spectrometers in fusion research [9, 10, 11]. Progress has been achieved recently with a new calibration technique developed at PTB using the broad energy distribution of the ^{9}Be(p,n) reaction for the experimental determination of the detector response function. This plays a key role in the unfolding methods for the determination of the neutron energy spectra [12]. A well known drawback of organic scintillators is the limitation in processing high count rates, mainly due to the dead time of conventional nuclear electronics. In order to overcome this limit, a prototype Digital Pulse Shape Discriminator (DPSD) has been tested in JET in conjunction with scintillators detectors. The system, developed at ENEA-Frascati, is based on a commercial 200MHz, 14-bit analog to digital transient recorder card, which digitizes the direct output signal from the anode of a photomultiplier [10]. Peak identification, baseline correction, pile-up removal, neutron/g ray separation and pulse height analysis are performed by dedicated software programs. Preliminary irradiation tests of a NE213 detector plus digital acquisition system have already been performed at the PTB facilities [13].

3. FAST PARTICLE DIAGNOSTICS

At JET one of the major innovative results of the last years in the field of fast particle detection has been the refinement of γ-ray spectroscopy. The positive results obtained during the TTE encouraged further developments. Measurements of fusion-born a-particles in JET TTE discharges [14] with conventional NaI(Tl) and BGO detectors showed the necessity to upgrade the γ-ray diagnostic system in order to improve the energy and temporal resolution of the measurements in high performance DT- and DD-discharges. Recently, a modern data acquisition system (25MHz, 14-bit) for γ-ray diagnostics based on a PCI transient recorder was installed. It allows pulse height analysis of incoming signals at maximum pulse rate of 1MHz, avoiding the effects of pile-up and gain instability, which lead to a distortion of g-ray spectra at high-count rates with fast rate variations [15]. The main limitation for further improving the count rate capabilities with NaI(Tl) and BGO detectors is the rather long scintillation decay-times, of 250ns and 300ns, respectively. It is planned to replace the existing detectors with modern fast high-Z inorganic scintillators such as "BriLanCe" and "LYSO". These new scintillators feature short decay times (16ns and 40ns respectively) and at the same time very high photon yields (relative to NaI(Tl) scintillator). These properties open up the possibility to extend the count rate limit beyond the MHz level, and at the same time to improve the energy resolution for γ-ray spectrometry in the range 2−30MeV.

The feasibility of the γ-ray measurements in fusion related environments depends on the effective suppression of the neutron background. It is also important to avoid carbon-containing materials in the neutron attenuator because inelastic scattering of neutrons leads to unwelcome γ-ray background. A good carbon-free neutron attenuator is water, but 14MeV neutrons can activate this attenuator generating γ-ray background. A more convenient neutron attenuator is 6LiH.which is compact, effective and transparent for γ-rays, and it does not produce interfering g-rays in the high-energy range [16]. It is planned to install, in one of the roof lab collimators, a 30cm long cylinder of 6LiH-attenuator which is expected to reduce the 2.45MeV neutron flux by a factor of about 900. It will be tested for g-ray measurements with the BGO detector at high neutron fluxes in DD-plasmas. The next step will be to implement this neutron attenuating material for a full-scale DT-plasma experiment.

4. RADIATION HARD DETECTORS

Diodes made of Si have been historically used in fusion devices to count neutrons with good time resolution. Their main drawback is the poor radiation hardness, which results in a short and unpredictable useful life. Artificial diamond detectors, manufactured with microwave Chemical Vapour Deposition (CVD) processes, are an alternative technology, already successfully tested at JET. In addition to the higher radiation hardness [17], other advantages of diamond detectors are their low sensitivity to gamma rays, fast response and higher energy resolution. In polycrystalline form the CVD diamond detectors can count the 14MeV neutrons [18] and in monocrystalline form can also be used to perform spectrometry [19]. The latest development in the field consists of covering the diamond surface with a 0.002 mm thick layer of Lithium Fluoride (LiF) 95.62% enriched in 6Li (“LiDia” detector). The LiF layer works as a sort of neutron-to-charged particle converter so these detectors can measure thermalised neutrons. This LiF layer converts neutrons into charged particles through the well-known nuclear reaction: $^{6}Li + n \rightarrow {}^{3}H + {}^{4}He + 4.78MeV$.

The cross section of this reaction exhibits the typical inverse velocity law versus the incident neutron energy. The reaction products, alpha particles and tritons, are thus mainly generated by low energy neutrons with 2.06MeV and 2.73MeV respectively and they are responsible for the main part of the signal detected by JET CVD neutron monitors during DD operation.

Two CVD diamond films are currently installed and operating on JET. One is polycrystalline (CVD1) with an area of about $12mm^2$ and 30mm thick and the second is monocrystalline with an area of about $5mm^2$ area and 20mm thick (CVD2). The neutron detection properties of these two CVD diamond detectors were first characterized at the Frascati Neutron Generator (FNG) [12] and show excellent short and long time detection efficiency stability. A more detailed description of the techniques used to manufacture those detectors can be found in [19, 20]. Both LiDia detectors were then installed inside the JET Torus Hall in two different positions. The set-up of the electronics of CVD1 and CVD2 allows the detection of neutrons in count mode. The minimum measurable neutron rate is determined by counting statistics while pile-up effects fix the maximum rate. The output signals were compared to those obtained with JET total neutron yield monitors (fission chambers). The results of this comparison are very encouraging. Figure 3 shows an example of the temporal response of the count rates recorded with both types of CVD detectors and the total neutron yield measured by the fission chambers during a JET pulse. The higher efficiency shown by CVD1 is consistent with the ratio of the sensitive volumes of the two detectors ($12\times0.002\ mm^3$ CVD1; $5\times0.002\ mm^3$ CVD2).

Magnetic measurements, which are already quite sophisticated in present day fusion machines, will need significant improvements in the next generation of devices. The two main requirements for magnetic field measurements in future fusion reactors are: a) accurate magnetic field measurements in long-pulse operation (quasi steady state conditions) b) operation reliability with high levels of intense plasma radiation and neutron emission that might lead to spurious signals and/or sensor damage. These constraints cannot probably be met with the present approach of combining traditional inductive measurements, based on pick–up coils and integrators [21]. Even if such coils are used extensively in existing fusion experiments in ITER the discharge duration and the neutron fluence are expected to increase by orders of magnitude, making it very difficult to achieve the required accuracies. A possible solution could be to complement the traditional pick-up coils with suitable galvanomagnetic transducers, namely transducers based on the Hall effect, since they do not have any particular restriction with regard to quasi-stationary and steady-state magnetic field measurements. At JET new Hall probes, together with novel signal processing electronics, are being developed and tested. The main objectives of this line of research are the manufacturing of radiation hard sensors and the refinement of an in-situ periodic recalibration of the sensors (using local coils wounded around the Hall sensors). To achieve sufficient radiation hardness, the approach consists of defect engineering of the semiconductor material in order to compensate the creation of defects in the crystal due to the neutrons, which are responsible of the severe changes that appear on the electric property of the material. Since the radiation-induced defects in InSb semiconductor material with electron-type conductivity act as electron acceptors, the detector is manufactured using a material doped by a specific impurity complex (Sn:Al:Cr) which induce the formation of donors that overcompensate the formation of radiation induced acceptors. For the moment this has been tried using In transmutations into Sn (which acts as donor in InSb) induced by thermal neutrons which are always partially present in the fast neutron flux. The results are under investigation. The residual drifts are meant to be compensated by an in-situ calibration based on local coils, wound around the Hall sensors. Three dimensional detectors have been manufactured (see Fig. 4) and are installed on JET, where they have already provided the first measurements. Similar probes have been tested under irradiation up to the neutron fluence of 1.3×108 n/cm^2 at a temperature of 90º C [22].

Another field in which radiation hard detectors are in great demand, not only for ITER but also for JET, is for the purpose of particle detection. JET Neutral Particle Analyzers showed a quite worrying sensitivity to the neutron background during the Trace Tritium Campaign. The detectors are CsI scintillators, coupled to PM tubes and the limitations were particularly felt in the region of low energy particles, below 1MeV, which is of significant interest to study the effects of the MHD instabilities on fast particle losses. An alternative being pursued at the moment consists of thin Si detectors manufactured on insulating material (the so called Si on insulator technology). This technology allows the detectors to be very thin and therefore reduces dramatically the interactions with the neutrons. The design is at a quite advanced stage and looks very promising.

5. PLASMA-WALL INTERACTIONS: EROSION AND REDEPOSITION

Hydrocarbon redeposition in ITER is a major concern because of the implications for retention of tritium. Hydrogen isotopes are trapped in co-deposited layers created by sputtering of the plasma facing components (C, Be, stainless steel) by the plasma. On JET it has been observed experimentally that heavy deposition takes place at the inner leg of the divertor. Diagnostics based on Laser Induced Break-down Spectroscopy (LIBS) have been tested on plasma facing components extracted from various experiments [23]. The principle of the technique is to ablate the co-deposited layer with a laser pulse and to then analyse spectroscopically the light emitted by the plasma created by the laser-matter interaction. The results obtained in laboratory conditions using TORE-SUPRA and TEXTOR CFC tiles showed promising results, demonstrating that at least on the bench it is possible to discriminate the co-deposited layer from the substrate, to estimate its thickness and to study its composition. This is a consequence of the fact that the laser plasma optical emission spectrum depends directly from the layer composition (C, Fe, Cr and H). In order to test the use of technique under relevant tokamak conditions, the edge JET LIDAR laser (ruby laser: 2J, 300ps pulse duration, 1Hz repetition rate) was used to create a plasma on the surface of an inner leg divertor tile in-situ [24]. Part of the tile under observation had been coated with a Tungsten (W) stripe, which was itself covered with a co-deposited layer formed by the plasma interactions after the tile was installed. Preliminary results show that, after a few laser pulses, the optical signal recorded when ablating the co-deposited layer almost disappeared, indicating that the laser reached the W stripe. These preliminary indications, obtained from limited experiments at JET, demonstrate a proof-of-principle showing that this technique, when implemented in a tokamak environment, should allow the evaluation of the thickness of a co-deposited layer formed on a tungsten surface.

In ITER many spectroscopy and imaging systems will make use of mirrors inside the vacuum vessel. Unfortunately the environment close to a burning Tokamak plasma can cause significant changes to the optical properties of these mirrors. The most critical issues are: i) re-deposition of materials eroded from the plasma facing components and ii) erosion of the material surface by charge-exchange neutral particles. Therefore, a dedicated programme - First Mirror Test (FMT) - has been started at JET [25] to study these effects with long pulse, ITER-relevant configurations including Be evaporation. An array of cassettes with mirrors has been installed. The cassettes are located in five different locations inside the vacuum vessel. Since both the erosion-deposition patterns and the charge exchange neutral particle emission vary strongly with poloidal location, it is important, for meaningful comparison between samples, that they are placed in equivalent or similar positions. As a consequence, tests of two different materials have been planned for each location. The selected materials are polycrystalline molybdenum and stainless steel, which are presently considered to be strong candidates for ITER mirrors. Mo was chosen because of its hardness, because it is a low sputtering coefficient metal and has high thermal conductivity, which make it a potentially good choice for passively cooled mirrors. Stainless steel is considered to be an adequate substrate for actively cooled mirrors. 32 samples have been installed in JET for testing: 16 made of stainless steel 316L and 16 of Mo-poly. They will be removed during next shutdown and the degradation of their reflectivity will be determined with spectro-photometric techniques.

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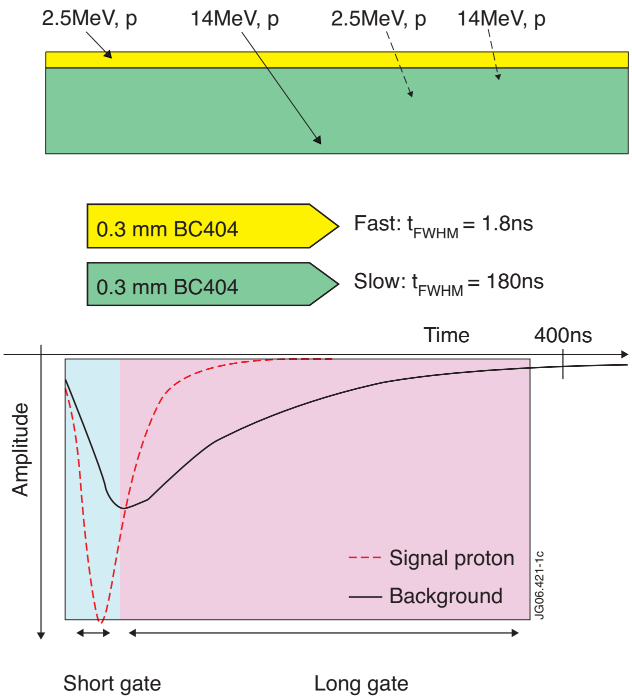

Figure 1: Principle of Phoswich detectors.

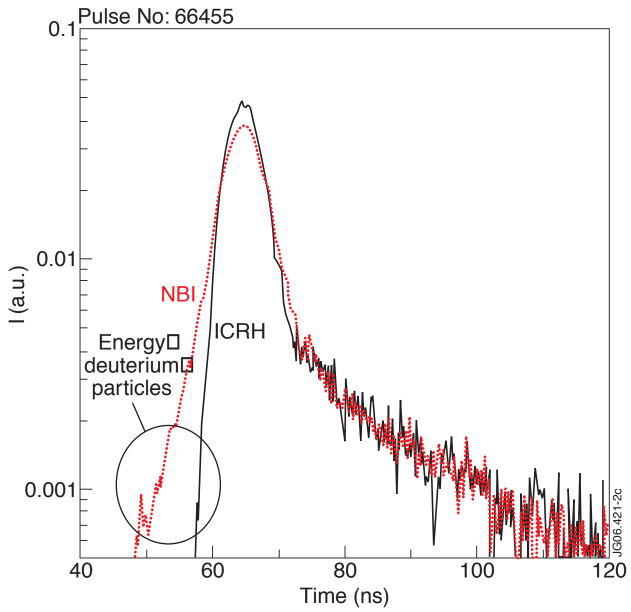

Figure 2: Neutron emission spectra measured with TOFOR from JET discharge #66455 during a phase with NBI (black) and during a phase with ICRH heating (red).

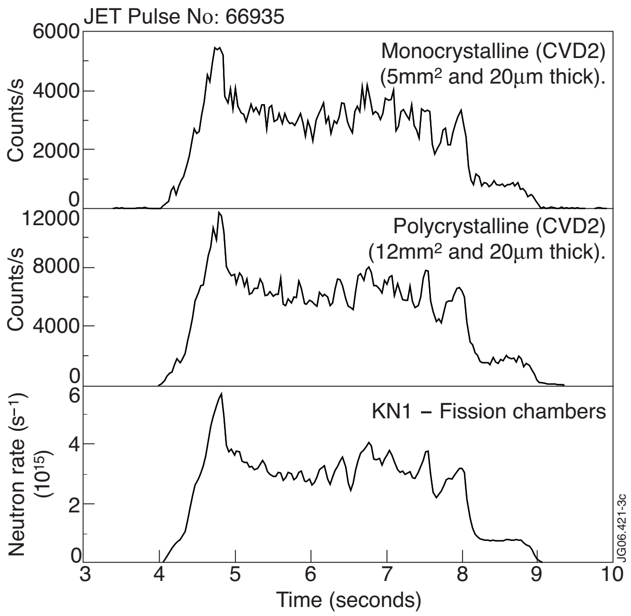

Figure 3: Comparison of time dependent neutron emission measured at JET by fission chambers, and two types of CVD diamond detectors: polycristaline (CVD1) and monocrystalline (CVD2).

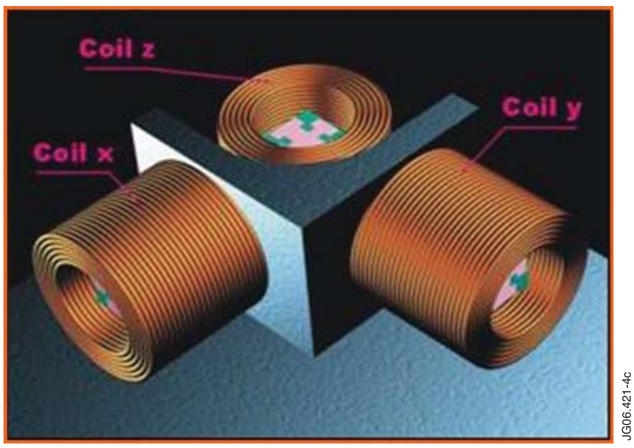

Figure 4: Overview of the three dimensional hard Hall probe assembly, showing the coils wound around the three Hall sensor.

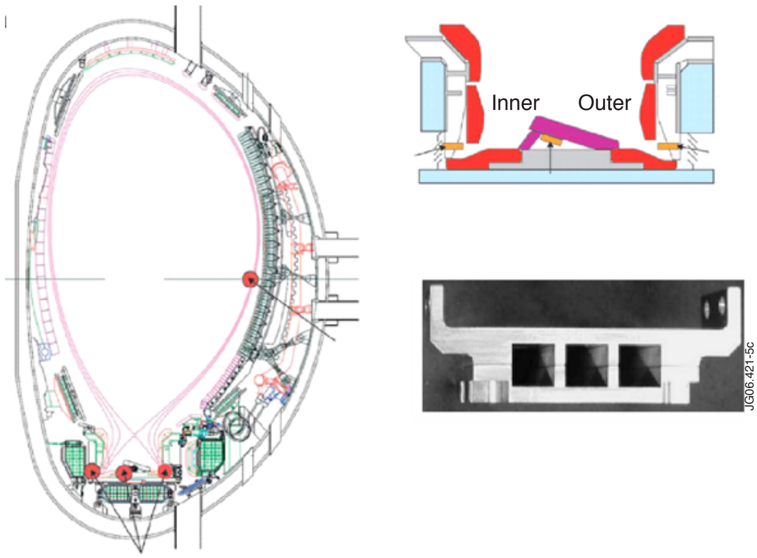

Figure 5: a),b) The locations of the mirror test units inside JET vacuum vessel, c) one of the cassette assembly containing the mirror materials.