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JET Experimental Programme and Related Diagnostics Developments

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ABSTRACT.

New diagnostic measurements have driven important steps forward of the JET experimental programme in areas related with H-mode and Advanced Tokamak(AT) physics. As a consequence a programme of diagnostics developments is started. The paper describes the recent new diagnostic measurements and the programme of diagnostics developments on JET. The measurement of the current profile made using MSE(motional stark effect) during strongly reversed shear discharges has shown a large region of low current at centre; the first preliminary measurement of poloidal velocity (made using the CXRS) shows some agreement with the neoclassical calculations; the measurement of the edge density profile made using Li-beam diagnostic and edge LIDAR Thomson Scattering has contributed to ELM physics study; the real time control of the internal transport barriers has improved the steady state capability of AT discharges; a measurement of fast He beam spectroscopy has been carried out, possibly leading to the determination of plasma parameters (Te and Ne) from edge to the pedestal. The diagnostics development programme will give the possibility of contributing to a deeper understanding of i) the link of current profile and the transport properties of the discharges; ii) the pedestal behaviour and the MHD stability (ELMs) properties of the H-mode; iii) fast ion driven MHD; iv) further study and control of tearing modes; v) DT specific themes including the isotopic dependence of the confinement; vi) ITER specific technology to be tested; vii) the possibility of realizing a steady state AT discharge.

1. INTRODUCTION

New measurements are always at the heart of the science development , and this applies also to the fusion experiments. The experimental programme of EFDA-JET is focused on the dynamics of the external (edge) and internal transport barrier characterising the MHD(magnetohydrodynamic), the turbulence and the divertor and wall load behaviour of both regimes. The experiments are mainly pointed to collect informations in discharges useful for ITER. The efforts on the measurements are therefore in the characterisation of the underlying mechanisms preceding and following the formation of transport barriers. In this view essential measurements are:

i) current profile;
ii) pressure profile (i.e. density and temperature) mainly in the transport barrier regions(at the edge for the H-mode);
iii) poloidal and toroidal rotation;
iv) IR measurements of the divertor tiles determining the deposition of power during ELMs(Edge Localized Modes);
v) turbulence.

A quite useful tool for the achievement of steady state internal transport barrier is the real time control. The perspective for the development of diagnostics on JET is mainly related with construction of systems improving the capability in the previous measurements and adding new tools for a specific deuterium-tritium experiment. The present paper reports the new measurements relevant for the advancement of the JET programme and discuss the strategy adopted for the future developments, describing the main technical characteristics of these systems.

2. EFDA-JET EXPERIMENTAL PROGRAMME AND NEW DIAGNOSTIC MEASUREMENTS

The EFDA-JET experimental programme is focusing the activity on the study of H-mode and advanced scenarios . As it is well known both of them are dealing with formation of transport barriers whose dynamics is probably different, but the common feature is that they emerge from the stabilisation of branches of turbulence. The H-mode is characterised by formation of an edge barrier where the sheared flow (EXB) plays an important role. The role of the bootstrap current in the MHD stability of the edge barrier is not clear. Advanced scenarios(AT) are characterised by the formation of an internal transport barrier(ITB). Sheared flow [1] and the current profile play together an important role: in particular the current profile with inverted shear of the q-profile is beneficial for the sustainment of the ITB(which seems to be formed at the position close to the minimum q value where the shear is minimum). In both H-mode and AT-scenarios the measurements of pressure profiles and current profile are needed for further physics understanding. Important additional measurements are the poloidal and toroidal rotation velocities which are useful for the determination of the radial electric field which enters the EXB flow.

In the measurement of current profile, the MSE(motional stark effect) system has demonstrated that during the formation of a reversed shear discharge there is a region of low current in the plasma center.

Figure 1 shows the measurement related with the current hole [2]: the blue line is the measurement of the pitch angle (~Bp/BT) in a discharge without ITB, and the black line is the pitch angle measured in a discharge with ITB created by inverting the q-profile, while the red line shows the measurement of pitch angle in a calibration shot with no-plasma. Comparing the red (calibration with gas) and black lines(measurement in a ITB discharge) a first conclusion could be that in the ITB case the flat region shows that at the center the current is very low. This measurement is new in the sense that for the first time a conclusion on the plasma current profile could be drawn directly from the ‘primary’ measurement of the pitch angle of the MSE system, whithout using the usual procedure of solving the equations of the plasma equilibrium. In this cases an electron transport barrier is observed with steep gradients in T_e. In all these kind of discharges a sawtooth like event is present with $q > 1$ everywhere. Latest report from JET [3] have demonstrated clearly that these events are perturbing MSE channels 14 and 15 (3.319m and 3.272m). These two channels are crucial in the understanding of the current hole as they are at the edge of the flatspot signature, hence reflecting current skin changes at the boundary of the current hole. Using a non perturbative technique that keeps the magnetics data constant before and after the crash allowed to solve numerically the Grad-Shafranov using high order polynomials as basis functions. The results shows clearly that these crashes are playing a fundamental role in the current density redistribution, leading to the decay of the current hole. Moreover, these crashes are possibly preventing the current going negative and clamping it to zero. MHD analysis has shown a burst of broadband magnetic activity during the crashes. First evidence of a direct measurement by MSE at JET, of the plasma radial electric field will be presented at this conference [4]. The technique involves two neutral beam injectors firing sequentially at different energies. The poloidal velocity (v_θ) enters the equation determining the radial electric field which is obtained by the force balance equation . Usually it is calculated using the neoclassical theory, but the measurements are quite rare in the literature. The fig.2 shows the first measurement made on JET. The measurement of v_θ is done using the Charge Exchange Recombination Spectroscopy System.This is a new measurement, and it brings us a substantial agreement with the results of neoclassical theory, taking into account that the estimated error bar on the measurement is $\Delta v_\theta \sim 20$km/s.

In the characterization of the edge profile an important role is played by the density profile . The fig.3a shows the measurement of the edge density profile made using the Thomson Scattering System and the Li-beam [5]. The agreement between these diagnostics is relatively good and it shows the sharp gradient at the edge of an H-mode.This measurement is new in particular because it shows the agreement of two diagnostics and the first measurement of the Li-beam density profile on JET.

The fig.3b shows the measurement of the temperature pedestal in the H-mode discharge: the gradient is clearly seen, and visible with respect to the gradient limit that can be measured. This is the first time the edge gradient is resolved with the edge LIDAR. The reason of this success is a careful design of the plasma shape where the last closed flux surface is optimized to the edge LIDAR line of sight.

For the AT regime all the profiles should be controlled independently. In JET for the **first time** [6] direct control of the current profile has been demonstrated by use of LHCD(Lower Hybrid Current Drive) feedback as actuator, using six chords of the polarimeter for measuring the current profile. The fig.4 shows how the LHCD power keeps fixed the value of q to the reference q-value at half radius versus time, and the Fig.5 shows how the spatial q-profile is kept fixed to the reference(defined by the open circles) using the LHCD: the two figures are related showing the measurement made at the same shot. The main application of this technique is to realize steady state advanced regimes. The control is done in five spatial points for five values of the q-value.

There is an asymmetry in the deposition (of carbon) in the divertor on JET between the inner and outer leg.The evolution of deposition in the inner part of divertor is being now monitored by a novel diagnostic which uses microbalances to measure the layers of deposited material. The calibration of this instrument shows that layers widths of fraction of nanometer could be detected using this technique. The fig.6 shows the first measurement done on JET. The vertical axis is a scale which is proportional to angstroms while the horizontal axis the time is reported: the measurement is taken before the plasma shot to record the reference signal and after to record the deposition. Opening the shutter in between: the measurement is done after the termination of a shot, and after closing down the shutter. The result shows a deposition of 1.3 nm after one shot.

3. JET EXPERIMENTAL PROGRAMME AND DEVELOPMENTS OF NEW DIAGNOSTICS.

The need of refining the spatial resolution of pressure profile and measurements of the plasma current at the edge possibly with high time resolution are needed for a careful understanding of the dynamics of ELMs formation . The same could be said for the measurement of pressure profile in the region of the Internal Transport Barriers. This need has been recognized as high priority for the programme of development of diagnostics. A high spatial resolution(15mm) 'conventional' Thomson Scattering System has been designed for JET [7]. The Fig.5 shows the basic scheme of the system. The laser beam is injected in the equatorial plane and the scattered radiation is collected in the vertical port at 90 degrees scattering angle. The F-number available is F/25(at edge), in this configuration. The detection system is made by filter polychromators with avalanche photodiodes. Using three laser with 1.5J/30Hz of energy each , so having a total input energy of 4.5J, and at a plasma density of 1×10^{19} m^{-3}, a resolution of 15mm is achievable with an average accuracy of 15% in the determination of electron temperature (in the range 0.1-10keV) and of 9% for the electron density. The previous figure assumes that one polychromator is used for measuring three scattering volumes, so the background noise is the sum of these volumes. Presently a collecting window of 200mm of diameter is included into the project.

Moving to the measurement of the edge current spatial profile, it must be noted that its need is mainly related to the effort of understanding the effect of bootstrap current (as effect of dynamics of ELMs on the edge pressure profile) in the context of the MHD stability of the edge in the H-mode. The nature of the ELMs is not very well characterized, and the scaling of ELMs respect to the various edge parameters is not known accurately. To measure the current edge profile, the MSE system hardly could be used because the spatial resolution required is of the order of 5mm, and the MSE mounted on JET cannot provide this resolution. A method based on the measurement of the ratio of intensities of the π and σ components of the Lorentz Li (2 ^{2}P-2 ^{2}S) triplet is being explored. The intensities $J_\pi(\theta) \sim \sin^2 q$ and $J_\sigma(\theta) \sim 1 + \cos^2 \theta$, where θ is an inclination angle of the line of sight to the total magnetic field vector. So the measurement of the intensity ratio $\xi(\theta) = J_\pi(\theta) / J_\sigma(\theta)$ provides a determination of the direction q of the total magnetic field vector with respect to the line of the sight. In principle two lines of sight must be used for measuring B_z and B_R components of the magnetic field. The intensity ratio method could provide a 10% accuracy in the determination of the poloidal magnetic field at the edge, provided the current of the Li beam is brought to the level of 10mA. The intensity ratio method is different from that used on DIIID (the General Atomic Tokamak) which is based on the traditional Zeeman polarization spectroscopy of the 2S-2P lines of Lithium beam [8].

The important issue of testing samples of candidates of ITER First Mirror [9] (i.e. plasma facing mirrors to be used by various diagnostics) is being addressed in a proposal of mounting samples on JET walls and divertor, for studying the mechanisms of erosion and deposition. Previous studies have clarified that monochristals of Mo, W and SS have to be used as plasma facing mirrors, while

Rhodium coated Cu mirrors can be used for systems like the LIDAR Thomson Scattering which requires a first mirror 2meters far from the plasma, with high quality optical imaging properties. The fig.8 shows a preliminary study of the mirror assembly in the divertor region. The relevance of a test done specifically on JET for ITER is connected to the following arguments: I) the similarity between ITER and JET consists in the fact that in the divertor region the deposition is prevailing respect to the erosion because the temperature of the plasma is below the sputtering threshold(~40eV) in both cases; II) the plasma facing materials and hence the impurities C and Be, are similar in JET and ITER (where W is present in minor part), while for example in ASDEX-U(Axisymmetric Divertor Experiment Upgrade) the dominant impurity would be W; III) due to the JET-ITER similarity of the temperatures in the scrape-off layers, the sputtering-erosion in the main chamber is determined essentially by the particle flux which is estimated of the same order of magnitude.

The in-situ monitoring of the transmission of windows and the characterization of structural changes of the mirror materials under strong neutron fluxes is part of the First Mirror Test on JET. The First Mirror Test is part of the overall system which will be operating on JET related to improve the diagnostics for monitoring the tritium retention on the tile materials, in particular in the divertor region.

The necessity of preparing the diagnostics for a possible (but not yet decided) second Deuterium-Tritium phase of JET has led to the realization of the following diagnostics:

i) Magnetic Proton Recoil Spectrometer upgrade (MPR-U);
ii) Time of flight neutron spectrometer (TOFOR);
iii) lost alphas diagnostics using Faraday Cups and scintillator probe;
iv) test of a scintillator NE213 as a high resolution neutron spectrometer.

Both MPR-U and TOFOR are in the class of the Neutron Emission Spectroscopy (NES) diagnostics [10] which can provide large number of measurement related with 2.5MeV neutron (produced in DD reactions) as well as"u4MeV neutrons(DT reactions). The NES has been used for measuring ion temperature as well as intensity and temperature of fast ion tails driven by heating RF. An advanced function of NES could be the measurement of plasma rotation, the alpha-knock-on neutrons which could be used for measuring the alpha particle tails, and the isotopic ratio nD/nT in the plasma core. The physics objective of the fast ion loss (“Lost Alpha”) diagnostic is to measure the loss distribution of DD charged fusion products (1MeV tritons, 3MeV protons, and 800keV ^{3}He ions), 3.5MeV DT alpha particles, and ICH(Ion Cyclotron Heating) tail ions to the walls. The aim is to measure the lost fast ion distribution as a function of time, poloidal position, energy, and pitch angle of the particle. The main physics focus of this diagnostic is expected to be the mechanisms of loss of ICH tail ions and the mechanism of fast ion loss during MHD activity. The reason of using the NE213 scintillator as neutron spectrometer [11] is based on the possibility of measuring with enough accuracy the response function of the scintillator using neutron sources. The neutron spectrum is then obtained applying the technique of unfolding. This means that the integral equation linking the measured spectrum N(E) and the ‘theoretical’ one Φ(E) is inverted using the scintillator measured response function given as matrix(R):$\Phi(E) = R^{-1}$ N. Such type of technique requires the measurement of the matrix R, the response function, and accurate knowledge of the pulse height response of the electronics and photomultipliers.The response function is measured using neutron sources, while the pulse height response of the electronics and photomultipliers could be measured using standard sources.

CONCLUSIONS

The main new diagnostic measurements relevant for the JET experimental programme have been reviewed : MSE measurement of current hole in reversed shear discharged , poloidal rotation as well as real time control of q-profile and deposition measurements. The programme of development of new diagnostics includes a High Resolution Thomson Scattering system, a Li-beam based measurement of edge current profile, and a test of the ITER first mirror samples. A set of diagnostics dedicated also to a possible DT phase of JET includes Neutron Emission Spectroscopy , lost alphas and a liquid scintillator spectrometer.

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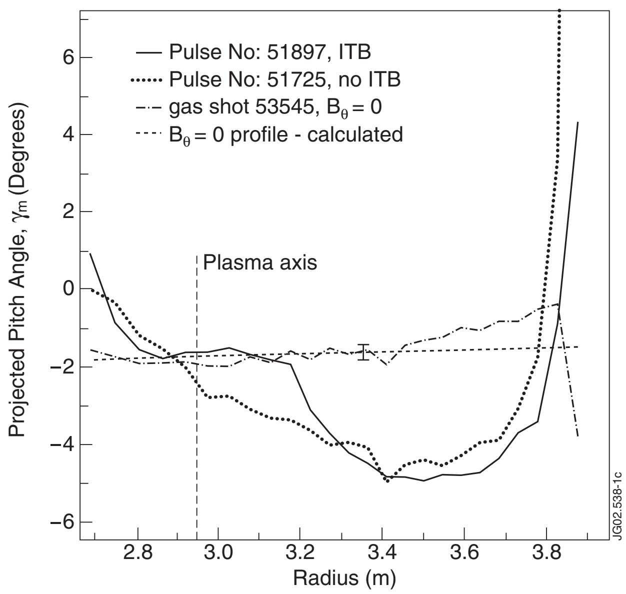


Figurte 1: Formation of the 'current hole' at the plasma center

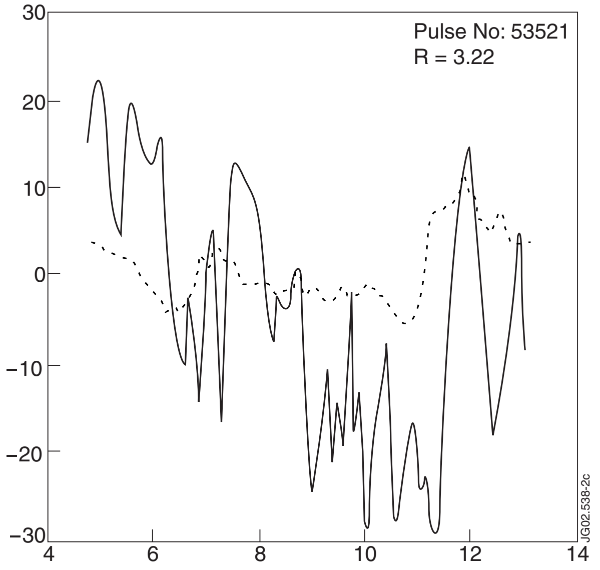


Figure 2: Poloidal velocity (vq) versus time at R = 3.22m (continuous trace), neoclassical calculations(dotted trace). The estimated error bar Δv_θ is of the order of 20km/s.

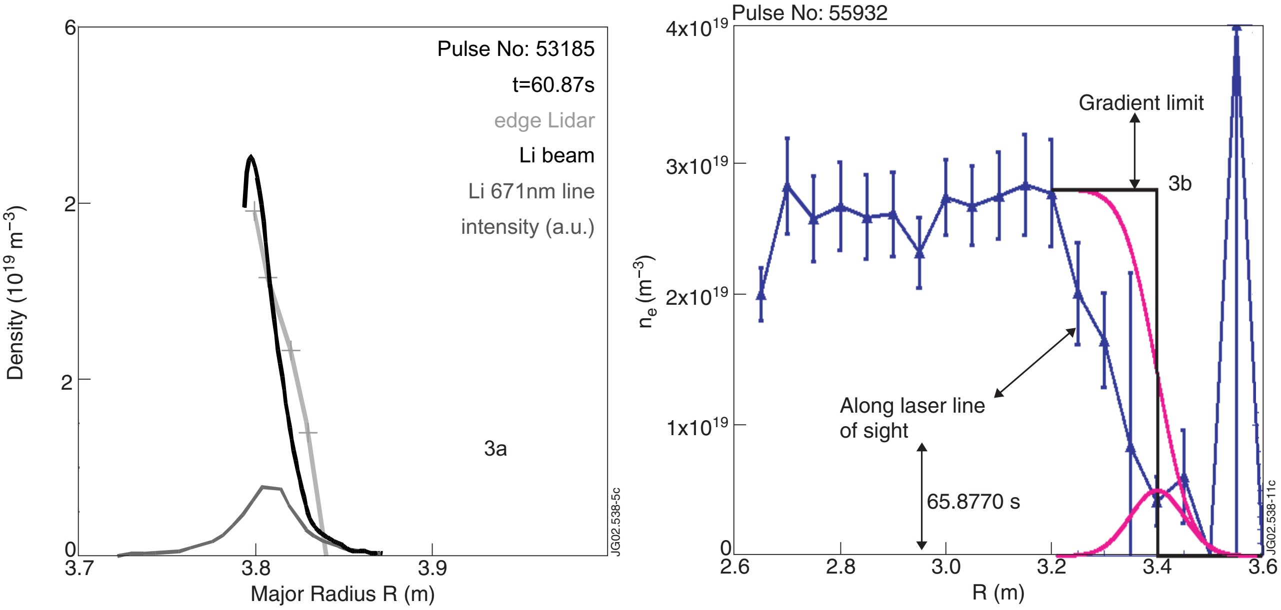


Figure 3: a)Density profile at edge measured by the edge LIDAR Thomson Scattering and Li-beam spectroscopy; b) edge temperature profile measured by edge LIDAR Thomson Scattering showing the 'pedestal' of H-mode.

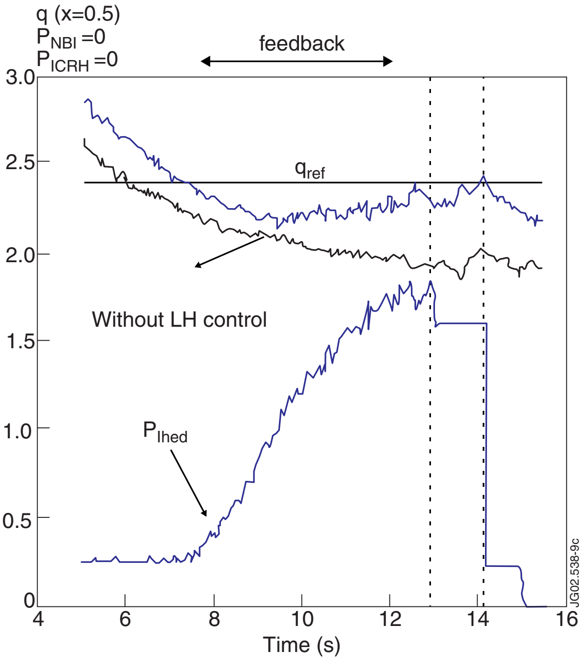


Figure 4: Feedback control of q-profile using LHCD(Lower Hybrid Current Drive): the blue traces show the evolution of the value of q at half radius during LHCD feedback . The measurement of q is done using 6 chords of polarimeter.

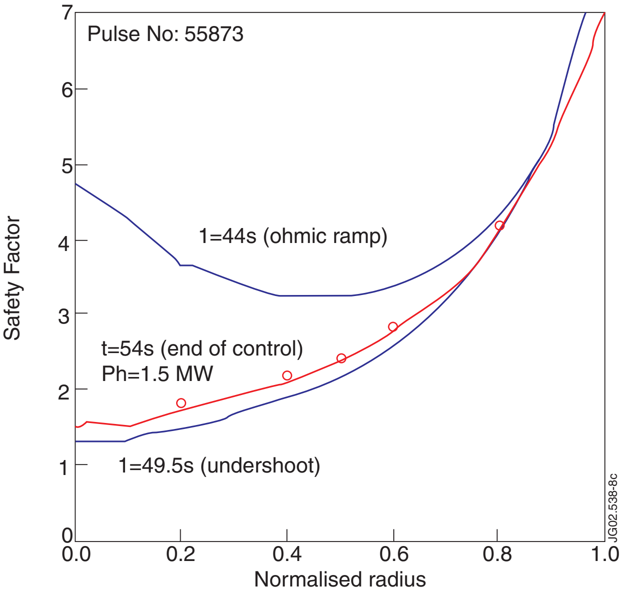


Figure 5: Evolution of the current profile during the action of the LHCD in feedback: the q-profile measured at 4s corresponds the ohmic phase in the fig.4, while the q-profile measured at 9.5 s corresponds to P_{LHCD} = 1MW (see in fig.4).

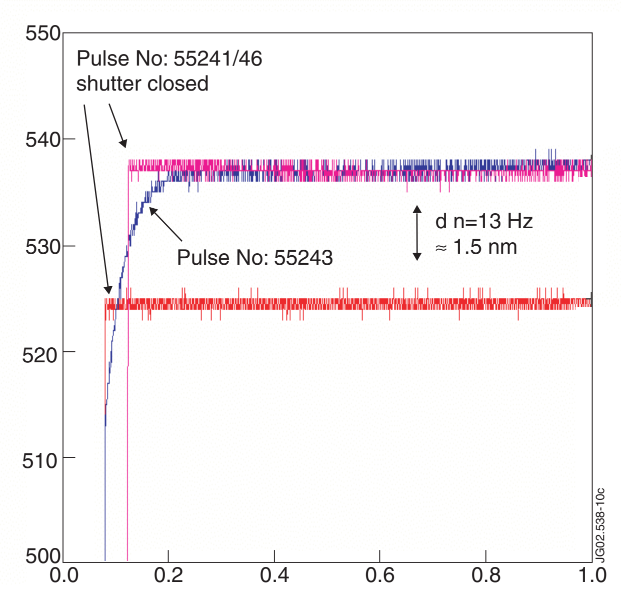


Figure 6: Traces show measurement of Quartz MicroBalance: i) red trace measurement with shutter closed; ii) blue trace measurement with shutter open; iii) pink trace measurement with shutter closed.The layer width measured in the shot 55243 is 1.5nm.

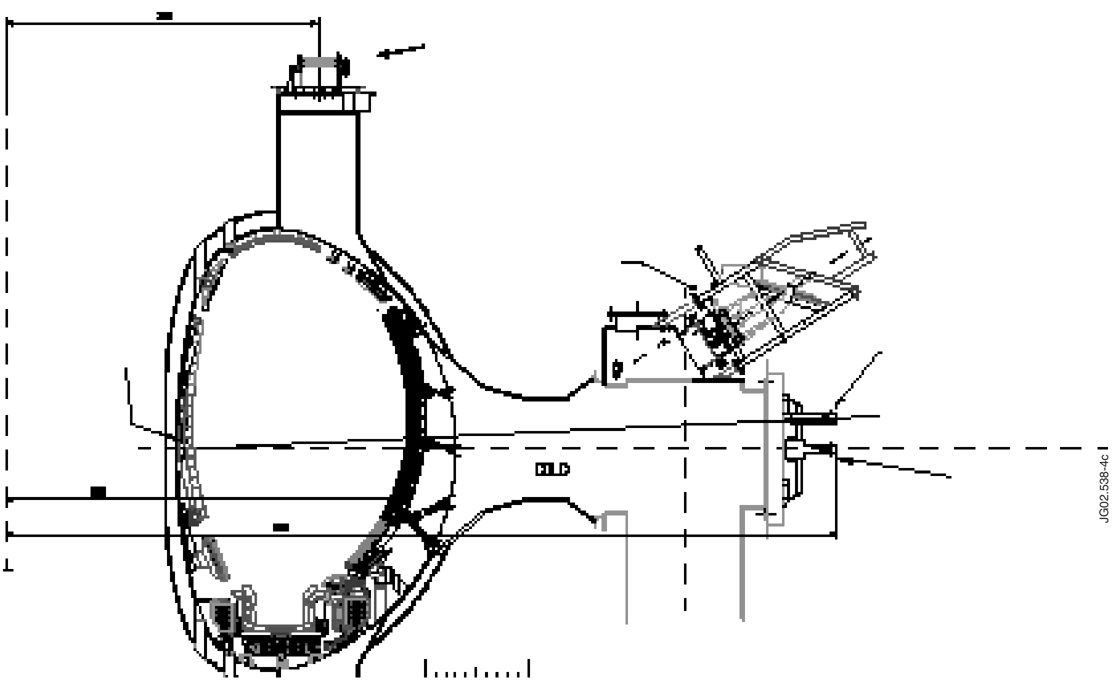
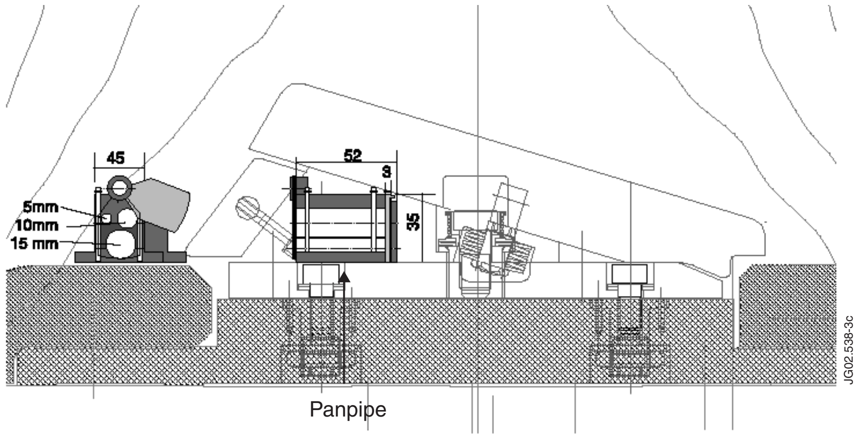
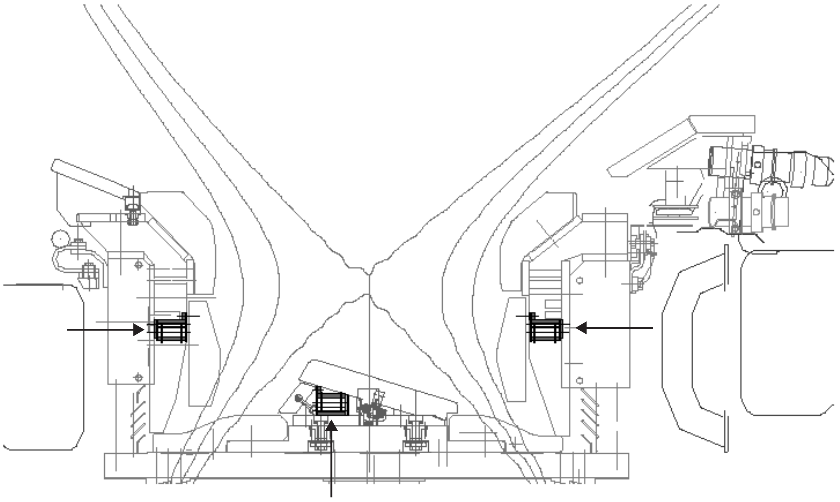


Figure 7: Scheme of the High Resolution Thomson Scattering System.



Schematic of Panpipe Mirror Sample Carrier



Distribution of Panpipe Mirror Sample Carriers in the Divertor

Figure 8: Location of mirrors into the divertor: the panpipe is the assembly of the mirrors.