AMS APPLIED IN THE RESEARCH FOR
THE FIRST FUSION REACTOR, CONTRACT EURATOM JW11-FT- 1.19

2. THE TOKAMAK

The name Tokamak comes from the Russian word TOroidal'naya KAmera ee MAgnitnaya Katushka (Toroidal Chamber with Magnetic Coils) and it performs the confinement of plasma (T, D, H gas) in order to produce fusion of light nuclei. This is done in the following way: a huge magnet (see Fig.1), called transformer, is charged by increasing the current through its primary windings.

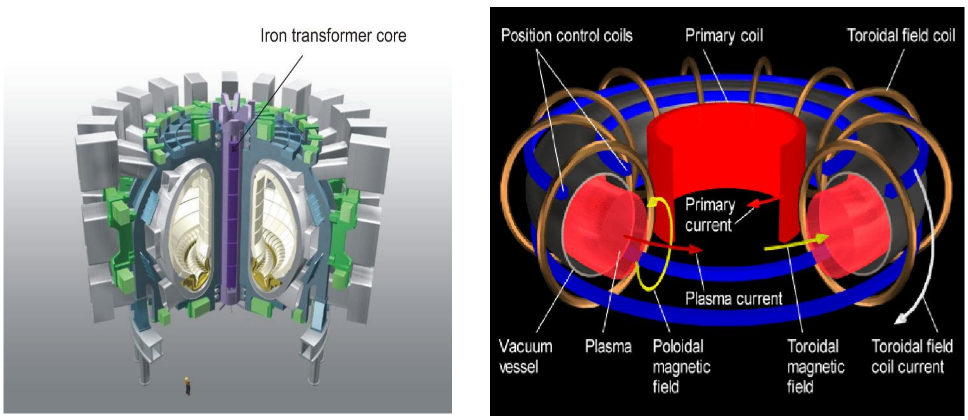

Fig.1: The Tokamak. Left: the ITER concept. The transformer iron core is shown, Right: the different currents and magnetic fields acting on the plasma and producing the confinement (see text).

Then, after pre-filling the vacuum vessel with H, D or/and T gas rapidly some of the atoms will be ionized due cosmic radiation, the transformer will be discharged by ramping down the huge current. The self induction will produce a large electric field gradient around the initial vertical magnetic field (produced by the transformer), which accelerates the few charged particles and these produce further ions, creating the plasma in the Tokamak torus. The described sequence of operations lead to burning plasma and fusion occurs during the duration from tens of seconds up to tens of minutes. It is commonly called fusion discharge. This pulsing regime will also be used in the fusion reactors.

The confinement of plasma is attained in the following way: the plasma current produces its own magnetic field (poloidal) which composed with the toroidal magnetic field (produced by the toroidal coils) will produce twisted magnet lines, forming the confinement magnetic cage and squeezing the ions together. The Energy Confinement Time is a measure of how long the energy in the plasma is retained before being lost from this magnetic cage. It increases rapidly with plasma size and that is why large volumes retain heat much better than small volumes.

However, to sustain the fusion reaction, the Lawson Criterion has to be fulfilled.

At the Tokamak in order to fulfill the triple product magnetic fields are used and isolate the very hot plasmas from the relatively cold vessel walls retaining the energy for as long as possible. Unfortunately, a significant fraction of energy losses in magnetically-confined plasma is due to radiation. On the one side, these energy losses have to be recovered by additional heating and on the other side, one has to protect the walls from the hot core plasma. Thus, it is a twofold problem. A very good confinement and a supplementary heating of the plasma is required.

Let us start with the first requirement: the confinement. If possible the hot plasma should be completely isolated from the walls during the entire confinement time. However, the plasma particles are confined to a certain degree within the volume composed of closed field lines. Those particle that escape this region are called plasma exhaust. The border of the confined region is known as separatrix, while the term Scrape-Off Layer (SOL) designates a narrow region (a few centimeters wide) outside this border (see Fig.2).

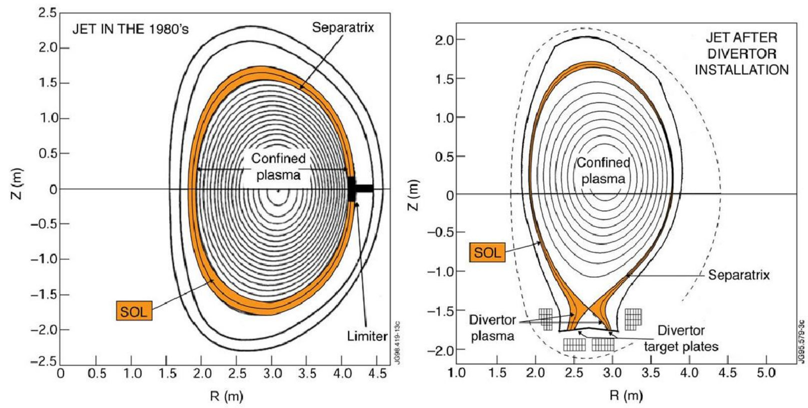

Fig.2: Different regions in confined plasma. At the right: the new confinement obtained after the divertor system was introduced.

About 20 years ago, the Divertor concept [7, 8] was introduced and has since then imposed the modification of the magnetic field lines at the plasma edge, so that the field lines of the SOL are diverted downwards, into a dedicated region, placed at the bottom of the Tokamak vacuum vessel. There the plasma exhaust ends up in collisions with the special target plates (see Fig 2).

The second basic requirement "for fusion" is the supplementary heating of the plasma. Fusion reactions occur at a sufficient rate only at very high temperatures, when the positively charged plasma ions can overcome their natural repulsive forces. For the Deuterium-Tritium reaction to occur over 100 million Kelvin degrees are needed. Currents up to 5 million amperes are induced in the plasma via the transformer and this current inherently heats the plasma, by energizing the plasma electrons and the ions in a particular toroidal direction. A few megawatts of heating power are provided in this way. Other fusion reactions (e.g. D-D, D-He^3) require even higher temperatures obtained by a powerful plasma auxiliary heating system, consisting of the Neutral Beam Injection (NBI) (34 megawatts), the Ion Cyclotron Resonance Heating (ICRH) (10 megawatts) and the Lower Hybrid Current Drive (7 megawatts). Fig.3 shows a top view of the toroidal Tokamak vessel, with the different additional heating systems.

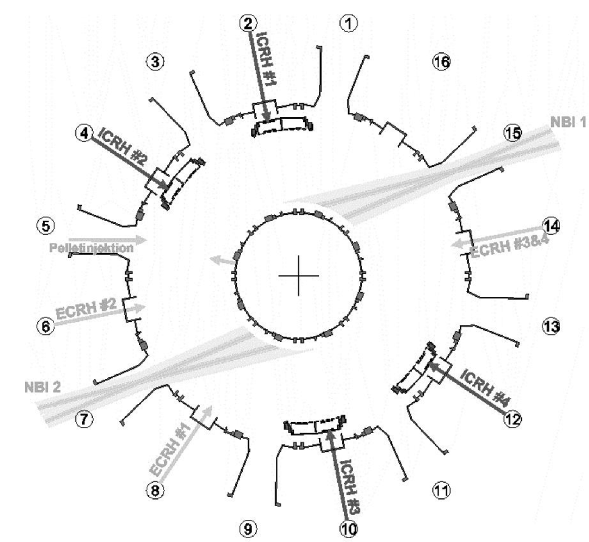

Fig.3: Top view of the Tokamak vessel. It is divided in 16 sectors containing different heating systems, particle injection systems by the NBI and the pelletron. LTS sample were mounted on the internal wall. Plasma is rotating counterclockwise.

The Neutral Beam Injection (NBI) is based on the injection of powerful beams of neutral atoms into ohmically pre-heated plasma [11,12]. These atom beams carry a large uni-directional kinetic energy. In the plasma they lose electrons due to collisions, get ionized, and as a consequence are captured by the magnetic field of the Tokamak. These new ions are much faster then the average plasma particles. In a series of subsequent ion-ion, ion-electron and electron-electron collisions, the group velocity of beam atoms is transferred into an increased mean velocity of the chaotic motion of all plasma particles. The neutral beams are usually formed from atoms of hydrogen isotopes (hydrogen, deuterium or even tritium). Indeed, the beam needs to consist of neutral atoms otherwise it could not penetrate the strong magnetic field that confines the fully ionized plasmas. The energy of the beam must be sufficient to reach the plasma center. If the beam atoms were too slow, they would get ionized immediately at the plasma edge. At the same time, the beam is supposed to have power sufficient to deliver significant amounts of fast atoms into the plasma; otherwise the heating effect would not be noticeable. At large Tokamaks the beam energy is between 80 and 140 keV, corresponding in the case of a deuterium beam to 2800 or 3600 km/s which is approximately five times faster than the mean velocity of the ions in the deuterium plasma.

3.1 DEUTERIUM

The gas fuel introduced in a Tokamak is a mixture of deuterium and tritium gas. The hydrogen isotopes are implanted into the vessel walls with a thermal energy of the plasma (10 up to 20 keV).

Fig.4 presents deuterium DP distributions measured from LTS placed between the protection tiles of the internal wall of the Tokamak. The positions of the LTS were far from the NBI systems. DP spectra are shown together with the unfolded spectrum below. The oscillations that can be seen of the DP distributions are caused by depositions of different materials that occur regularly in the Tokamak vessel (C, W, Be). During the material deposition hydrogen isotopes are captured under or in-between the deposited layers. A sandwich-like structure will be formed on top of the PFC and correspondingly deuterium will also be measured at depth values were it could not penetrate by its thermal energy.

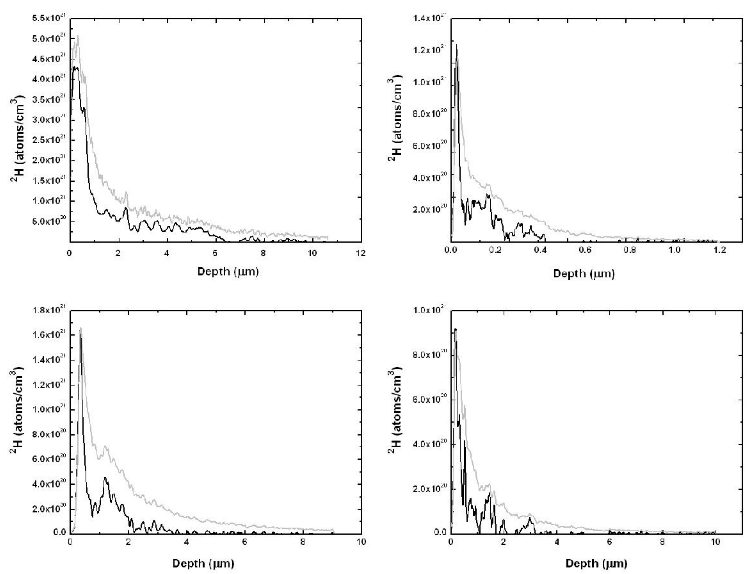

Fig. 4: Deuterium AMS depth distributions measured from LTS. The upper curve represents the initial measured depth distribution and the lower curve represents the

corrected value for the interfering rim effects. Large oscillations are produced by the deuterium trapped under deposition layers

If the LTS are placed in positions close to the NBI systems a second broad peaking of the D depth distribution shows up (Fig.5). The peak corresponds to the penetration range in carbon of the 140 keV neutral Deuterium from the NBI systems and shows that a fraction of the injected particles do not interact with the plasma and is implanted into the opposite wall.

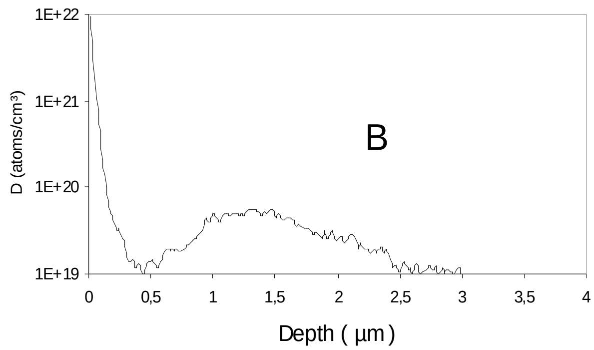

Fig.5: Deuterium depth distribution displaying a broad second maximum of the concentration that corresponds to the penetration in Carbon of energetic atoms (140 keV) produced by the Neutral Beam Injection systems.

A complete toroidal distribution of the accumulated deuterium in the inner wall is shown in Fig.6. The values, expressed in atom/cm^2 by multiplication with the depth value, were calibrated with standards D/C and corrected for the rim effect and background.

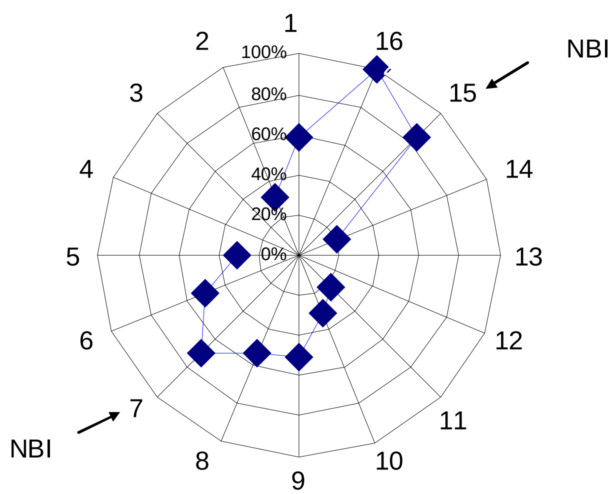

Fig.6: Toroidal distribution of deuterium integrated DP measurements. The depth profiles were integrated up to 2.5 µm depth. The measurements were performed on LTS placed on the inner wall of the vessel.

The two large peaks around sectors 7 and 15 show that part of the neutral deuterium beam is not interacting with the confined plasma. It flies through the plasma and collides with the protection tiles of the inner wall. At these positions the integrated DP spectra exhibit the large peak at 1,5 µm depth as presented in Fig.5. Obviously, the density of the plasma is low and the beam energy is sufficient to reach the plasma center and in a small extend it also escapes on the opposite side. Therefore, it is to be studied by these means when the optimum conditions for energy absorption are matched (plasma density, beam energy and injection direction). However, this “non interactive” fraction was accumulated over a very long time in the many discharge campaigns. AMS is able to measure the exact value if LTS are used in a definite time range.

3.2 TRITIUM

The most efficient fusion reaction is the T-D reaction. Therefore, in each Tokamak deuterium will be present in the gas fuel and, even with lower production yields, energetic tritium (1.01 MeV) will be produced by the DD reaction. This energetic tritium is produced solely in the fusion reaction and it is easy to distinguish it from the tritium in the gas fuel that has about 10 or 20 keV energy and from the tritium injected as a neutral (NBI system) having 140 keV energy. Since the fusion reaction takes predominantly place in the center of the plasma the 1.01 MeV tritium can be used as a fingerprint of the plasma confinement during the fusion discharges. Normally, tritium produced by the fusion reaction is immediately ionized in the plasma magnetic cage and should stay on the rotating trajectories until the end of the discharge duration. However, at the end of the discharge the plasma rotation will be slowed down and the all emerging ions will have moderate energies. AMS-DP based on LTS can easily diagnose the quality of the plasma confinement and also to determine irregularities or malfunctioning in the preservation of the detached plasma and the efficient discharge for fusion. Such applications we presented elsewhere [22], here we want solely to emphasize that in stable fusion conditions the Tritium depth distributions in PFC should not display any peaks at a depth larger than 2 m. It is easy to diagnose campaigns of fusion discharges by using a simple chart indicating the normal or abnormal DP (see Fig.7).

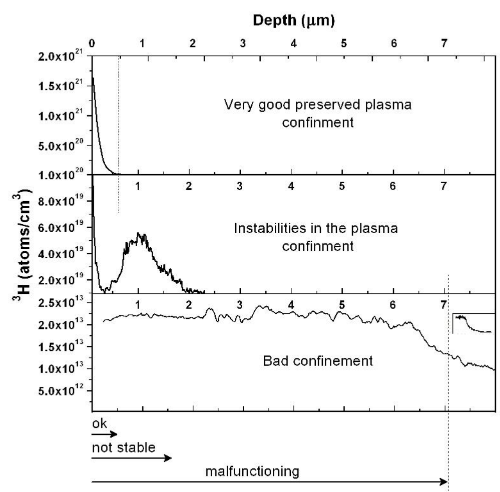

Fig.7 : Diagnose Chart for fusion discharge campaigns in a Tokamak based on tritium DP measurements. The small figure, in the right corner of lowest spectrum, is given to show the entire trend of a DP after discharge campaign with not well confined plasma.

Distributions of integrated tritium DP measured from the several LTS placed on the inner wall, in toroidal geometry, are shown in Fig. 9. The DP distribution drawn by black dots was integrated over a small depth of 0.1 μm that corresponds to the surface of the LTS carbon sample. However, the distribution represented by black squares was integrated over the entire depth of the LTS and give us the bulk inventory of tritium. It is easy to see the two maxima of the implanted tritium at sectors 8 and 16. They are produced by the interaction of the injected 140 keV deuterium beam with the rotating plasma.

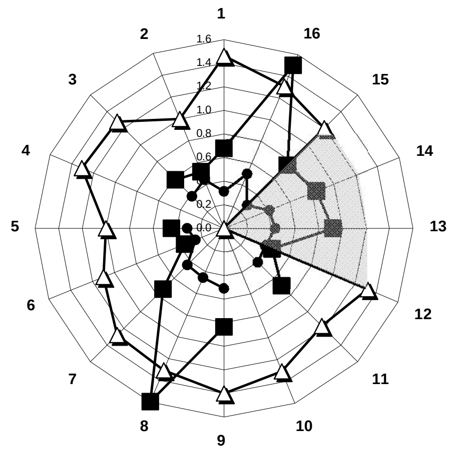

Fig.9: Integrated tritium DP concentrations in toroidal geometry. The squares represent the bulk concentrations and the dots the surface concentration (0.1 µm depth) for the experiment of interference between injected deuterium and fusion produced tritium. The distribution represented by triangles is a surface DP distribution measured during disruption events. The location of disruption is indicated by the shaded region.

Since the LTS are placed on the inner wall and the NBI injection axis is slightly tilted, the interaction area is located at position of the next sector. Therefore, both distribution maxima are shifted with one sector ahead in respect to the position of the NBI sectors. It shows that the interaction removes tritium from the confinement region and disturbs the plasma confinement.

Two divertor geometries are shown in Fig.10. In the first geometry the measurements performed on the divertor flanks showed a symmetric deposition of tritium. For the tilted geometry an important increase of the tritium inventory in the plate no.1 was measured. The exhaust power loading on the divertor is asymmetric possible affecting the ELMs (see above). Measurements were sensitive to the differences of the particle transport downward to the divertor.

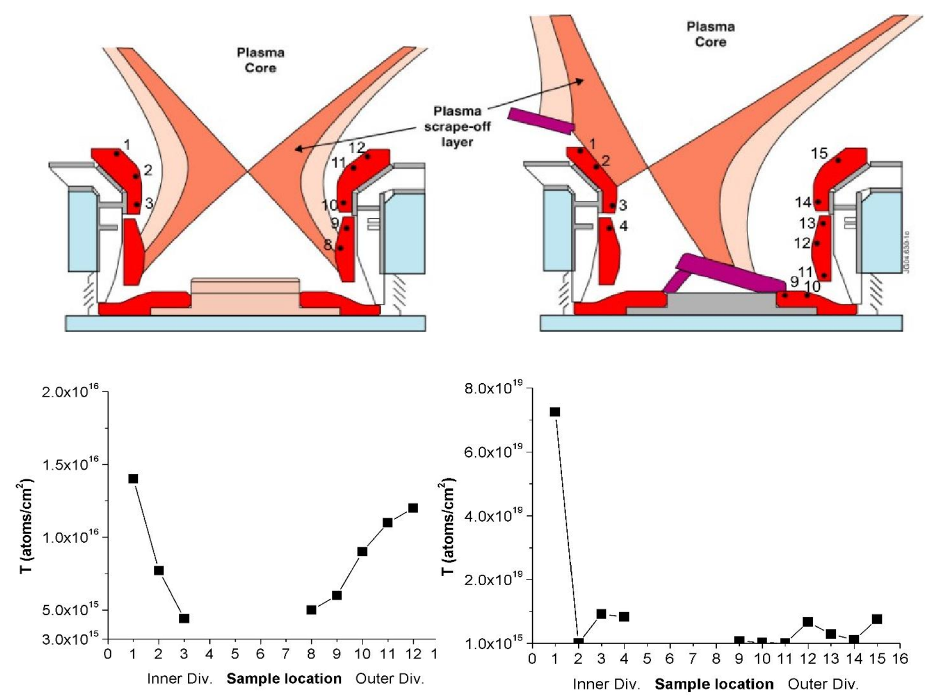

Fig . 10: Tritium integrated AMS DP measured from cuts of protection tiles in different locations of the outer and inner divertor. Two divertor geometries are shown together with the measured tritium inventories in different locations indicated by points in the figure. Lines are drawn to guide the eye.