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The diagnosed mobile limiters of the TJ-II stellarator for plasma boundary studies

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Abstract

TJ-II is a medium size (major radius $R = 1.5$ m, average plasma radius $a < 0.25$ m, on axis magnetic field $B = 1$ T) helical axis stellarator. The main characteristic is its magnetic configuration flexibility, due to the separate control of the different magnetic field coils. The two diagnosed mobile limiters are installed to reduce thermal loads on the thin protection plates of the contacting plasma-chamber regions and to study the plasma edge. First diagnostics are a set of thermocouples, Langmuir probes, H_α-detectors and a CCD video camera with different filters (atomic lines of HeI, H_α and near IR) looking at the limiter. A method of passive spectroscopy is proposed to map the electron temperature and density over the whole limiter surface by analysing the emission of helium recycling neutrals. It is expected from previous results of other stellarators, that the boundary magnetic topology will have a strong influence on the plasma–wall interaction. The mobile limiters can control the last closed magnetic surface and diagnose the plasma boundary. A qualitative different plasma edge scenario is foreseen between the limiter and the natural island divertor configuration (rational rotational transform inside the limiter radius). Plasma–wall interaction in TJ-II shows very specific features and the optimisation of the plasma edge topology can influence strongly the core plasma parameters. In particular, impurity screening will be a challenge due to the large power density which will be available in future (up to 2 MW NBI for 0.5 s). A safe operation for future high β-plasmas is also required and the mobile limiters should help to remove a fraction of the conductive/convective power.

Keywords: TJ-II; Limiter; Stellarator

1. Introduction

TJ-II has recently started operation with 250 kW electron cyclotron heating power (ECH) and up to 200 ms pulse duration. Its main objective is to study confinement, transport in low collisionality regimes and plasma stability at high beta (β<4%). A heating power of 2 MW of neutral beam injection (NBI) will be added in about two years. For the first phase up to 800 kW of electron cyclotron heating (ECH) power will be soon available.

A high power density will be achieved in the plasma of about 1 m^3 volume so that plasma–wall interaction control will be a challenge so as to achieve the nominal operation regimes of the machine. The plasma radius of about 15 cm at the limiter (for the largest configurations), will make impurity screening difficult. Particle control will be also an important task, due to the relatively large fuelling rates expected of the future neutral injectors. Although the pulse is relatively short (T <0.5 s), thermal loads can be also locally high, so that surface gas desorption can be important. In addition the problem of plasma–wall interaction is complicated by the change in plasma–wall interaction regions with the different magnetic configurations and also due to the plasma asymmetry typical of stellarators [1].

The principal scope of this paper is to describe the role of the mobile limiters and their diagnostics. The possibility of obtaining two-dimensional electron

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density (n_e) and temperature (T_e) mappings with a new diagnostic is discussed. First experimental results are given and future studies as well as the optimised future limiter design are presented.

2. Experimental set-up

The two mobile limiters are constructed of stainless steel SS-304-LN and are installed in lower machine ports separated 180° toroidally one from each other. They can move 50 cm inside the chamber and can be inclined ±15° from the horizontal plane to accommodate all possible plasma shapes. Fig. 1 shows an image of a limiter inside the torus, where the opposite toroidal limiter can be seen (helicoidally turning one time each of the four periods). The limiter heads, which consist of 10 stainless steel tiles (2 cm poloidally and 9 cm toroidally each), are exponentially shaped in the toroidal direction to homogenise the power density deposition. These limiter heads are provisional and will be replaced by optimised ones for the NBI-phase (see later).

A great effort has been made in diagnosing the limiter with two-dimensional resolution systems (poloidal and radial), since asymmetries characterise the SOL plasma of stellarators, especially if islands are present. Inside the tiles a set of thermoresistive sensors (PT-100) are installed to measure their temperatures and thereby deduce the convective power distribution to the limiters. A set of Langmuir probes have been inserted into the poloidal limiter in order to measure edge plasma parameters. The array is constituted by six group of four pin each on both limiter heads. This distribution of probes gives the time evolution of edge plasma parameters in three different poloidal locations and in six radial location. An H_α array detector looks on both the toroidal and the mobile limiter. A normal or an intensified CCD camera views one of the mobile limiters tangential to the plasma. First, it is a simple tool to check the plasma-limiter distance in a rapid way by inspection of the relative intensity emission from the mobile and the opposite toroidal limiter. Second, with the help of interference filters spectroscopic imaging is possible. The different filters are centred at: H_α (656.3 nm), H_γ (434.0 nm), HeI (667.8, 706.5, and 728.1 nm) and IR (1000 nm). The images are stored in a triggered video recorder and are analysed later with the help of a frame-grabber installed on a PC. With an absolute calibration of the cameras, the hydrogen emission images will be used to study recycling and fuelling to infer particle replacement times, etc. The images with the IR filter can give information on the power deposition profile, although high surface temperatures are necessary and an absolute calibration is necessary and here it will be used only to obtain qualitative information. For example hot spots caused by runaway electrons have been already detected. In the future a commercial IR-thermography camera will also be installed to monitor the temperature of the limiter and the NBI-protections.

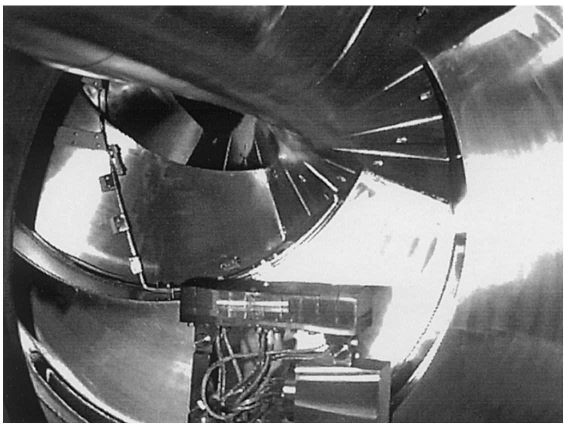

Fig. 1. View of the mobile limiter (bottom) inside the vacuum chamber and the toroidal limiter (top).

A new diagnostic for electron density (n_e) and temperature (T_e) measurement on a limiter with two-dimensional resolution is under development [2]. It is based on the HeI line intensity ratio method as used in the He thermal beam [3], but in this case passive spectroscopy is used in plasmas containing helium. The emission comes from the neutral helium atoms excited in the SOL-plasma, which have previously recycled on the limiter. The method has demonstrated to work well for closed limiter geometry, as in the Tore Supra pumped limiters [2]. Encouraging results were obtained comparing this method with Langmuir probes and a simple theoretical model. Although in the past single channel detectors were used (photomultipliers), here we propose to analyse the emission with the help of video cameras to obtain two-dimensional n_e and T_e distributions. Recently the same method has been also studied to be applied for the divertor of the tokamak de Varennes [4]. The key to the method is to analyse correctly the camera line of view, since in contrast to the active He-beam techniques, here we integrate the emission along the optical chord. A simplified model [2], in which the neutral helium density was assumed to be constant in the emitting region, predicts that with our tangential view most of the emission comes from a region very near to the limiter. This is due to the fact that the radial emission distribution across the SOL is a very strong decreasing function. Therefore a suitable line of view is to look to the limiter head from outside the plasma (without traversing the separatrix), so that the emission is nearly localised at the limiter surface. A correction factor Q can be calculated with the model, which gives the estimated T_e or n_e at the limiter by multiplying it with the chord integrated value T_e^* or n_e^*. For the electron temperature analysis the value of Q was found to vary between $1.2 < Q < 1.6$ for many SOL parameters ($2\ \mathrm{cm} < \lambda_{Te} < 5\ \mathrm{cm}$, $30\ \mathrm{eV} < T_e < 70\ \mathrm{eV}$). If we assume for example a plasma independent value of $Q = 1.4$, the error by integrating the emission would be less than 20%. It should be mentioned that a more detailed analysis is necessary: the helium neutral distribution should be modelled more realistically and the predicted emission profile checked by an experimental perpendicular view of the SOL. This would give a kind of tomographic reconstruction of the emission profile. The method is under the first stage of development and additional theoretical and experimental work is necessary, before obtaining two-dimensional T_e and n_e images.

3. First experimental results

TJ-II has only operated a few days. Plasmas were produced and heated by microwaves at 53.2 GHz with 200 kW and 100 ms duration. Average electron densities up to $1.4 \times 10^{19}\ \mathrm{m}^{-3}$ where obtained with central electron temperatures of about 200 eV for the first plasmas, giving an energy confinement time of the order of 1 ms. Plasma parameters were improved significantly in the next campaign with larger plasmas and lower radiation losses [5]. Although a more detailed presentation of the first plasma edge results with the limiter diagnostics will be presented in future, a brief summary is given here. A first result is the good agreement between the theoretical limiter position, as deduced from Poincaré-plots, and the experimental one for many different magnetic configurations. This was deduced by comparing the H_α-emission from the mobile and toroidal limiters with the tangential camera when the limiters where inserted into the plasma. Fig. 2 shows typical H_α-images with mobile limiters inserted (a) and retracted (b) (same view as Fig. 1). The saturation currents obtained with the outermost limiter Langmuir probes were similar than those obtained with a reciprocating probe in the separatrix position. The absolute value of about $10^{19}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$ is a typical flux value on the separatrix of low density plasmas. The SOL flux decay length with a toroidal limiter configuration is $\lambda = 15$ mm, as deduced from ion saturation current profiles. The electron temperature at the separatrix is typically 15–30 eV and the electron density $3\text{–}10 \times 10^{17}\ \mathrm{m}^{-3}$. When only the toroidal limiter is in contact with the plasma, the plasma–wall interaction seems to be very asymmetric (along one of the four periods of the machine) [Fig. 2(b)]. This is in agreement with the magnetic surface calculations, the separatrix-toroidal limiter distance varying in certain configurations to more than 25 mm toroidally. Since the flux scrape-off decay length, which is a characteristic measure of the interaction depth, is of the order of 15 mm, a toroidally asymmetric interaction is foreseen.

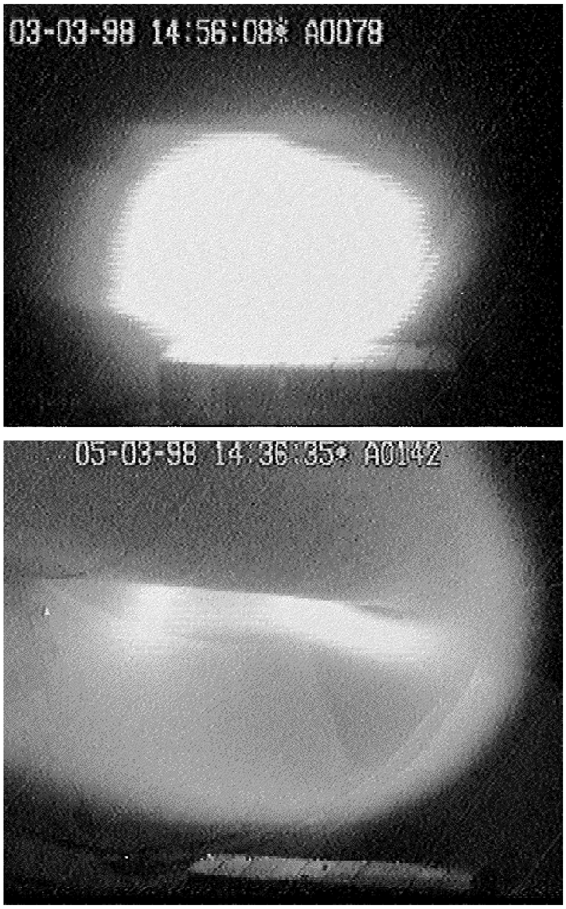

Fig. 2. H_α-images of the plasma with the mobile limiter inserted (top) and retracted (bottom) with the toroidally asymmetric interaction.

4. Future objectives

The mobile limiters should be an important tool for this objective and a new limiter head design is under development for the NBI-phase, corresponding with an all carbon first wall. The high power density which will be injected in the machine, up to $2\ \mathrm{MW\ m}^{-3}$, will make this task difficult and the mobile limiters should help to find the most correct operation scenario. Especially attractive for impurity screening (probably the most important problem) would be the use of the natural island boundary surrounding the well confined core plasma. Although the edge plasma density can be higher than $10^{19}\ \mathrm{m}^{-3}$, the screening island-type plasma thickness is limited by the toroidal limiter to be <30 mm. In this case the mobile limiters should be positioned to avoid the island–vacuum chamber interaction, as predicted by Poincaré-plots. The principal problem when introducing the mobile limiters is that the SOL width necessary to decouple the toroidal limiter is inversely proportional to the plasma radius. This is especially negative if this distance is an important fraction of the plasma radius, as is the case in TJ-II.

The absence of poloidal curvature in the actual limiter heads should be avoided in the next design, since field line integration codes and a simple diffusion model predict a very low interception of the limiter with the outermost magnetic surfaces, producing very large connection lengths, $L_c = 50$ m (assuming no interaction with the toroidal limiter), in contrast with the toroidal limiter configuration ($L_c = 2$ m). This would cause an important increase in the characteristic SOL decay lengths λ, typically a factor of up to 5 when inserting completely the mobile limiters. Since λ would be typically the minimum distance necessary to introduce the mobile with respect to the toroidal limiter to produce the desired interaction, an increase in λ would mean a corresponding decrease in plasma radius. This would mean for example that a flux decay length of about $\lambda = 15$ mm in the toroidal limiter configuration (as has been measured by Langmuir probes), would increase in the mobile limiter configuration to up to $\lambda \approx 60$ mm, which would be the minimum distance to produce a toroidal limiter decoupling. This would reduce the plasma radius by 25% or more, which is prohibitively high. A poloidal limiter shape adapted as good as possible to all plasma configurations would be much more effective in intercepting the magnetic field lines. The field line trajectory code predicts a reduction of a factor of 5 in the connection length with respect to the actual design. Preliminary estimations give a good compromise between the mobile limiter efficiency (producing a flux decay length of about $\lambda = 30$ mm) and a relative small plasma radius decrease (15%). As limiter material, carbon (probably graphite) is selected not only to reduce high Z impurities, but also to increase the heat extraction capability of the limiters without risk of overheating. With this design an important fraction of the input power (50%) can be removed with the mobile limiters. A thermodynamic code predicts no overheating of the limiter surface without refrigeration (pulse duration <0.5 s and 10 min between discharges). The use of carbon is also compatible with conditioning techniques for wall pumping, such as boronization and intensive He glow discharge.

In addition to the optimised carbon head which will be soon manufactured, a preliminary design for an experimental pumped limiter has been also made. The same carbon head can be used, but a plenum just behind it containing an in situ constructed Titanium-getter pump would be added to the limiter body. This is only a preliminary design and its detailed design and construction will depend on the need of such a facility for particle control in the NBI-phase. A throat would prevent neutrals to escape to the plasma, which would be specially effective with a high density edge. In a divertor configuration, the boundary islands would enter the limiter throat and intersect the neutraliser near the titanium pumps. For example Poincaré plots of configurations with $\iota/2\pi = 2$ predict two thin large islands outside the separatrix, which can be largely intersected by the future mobile limiters (Fig. 3). Large active pumping capabilities can be achieved with such a design and density control can be significantly improved for the NBI-phase. Experiments in this area can also contribute to stellarator divertor studies.

5. Conclusions

Two mobile diagnosed limiters have been installed for the initial operation of TJ-II. They will be an important tool to characterise the complex stellarator plasma boundary. A special effort has been therefore made to install diagnostics with two-dimensional resolution. First results are reported here for the first plasmas, but will be presented with more detail in a future work.

For the high power operation phase in about two years, plasma–wall interaction should be optimised to avoid problems of power, particle and impurity control

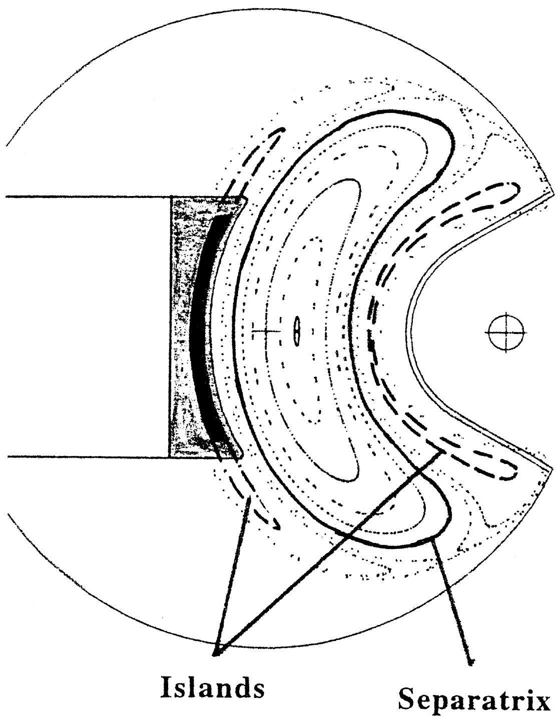

Fig. 3. Natural island divertor configuration with pumped limiter (conceptual design).

that can limit the operation regimes at high power density. The mobile limiters will be important to study and optimise edge plasma parameters and to absorb an important fraction of the convective/conductive power. Therefore a new design of the limiter heads is necessary, as has been shown here. Calculations show that the mobile limiters should have a poloidal shape to increase their efficiency and be of carbon to avoid high Z impurities and to absorb a large fraction of power without overheating.

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