A study of ion trajectories in the Neutral Beam duct of TJ-II stellarator

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Introduction. A realistic assessment of reionization losses in Neutral Beam ducts is necessary for the correct interpretation of the plasma-beam interaction. The ratio of reionized neutrals can be calculated by beam transport computer codes using a gas target inferred from experimental measurements of residual gas pressure in the duct, and experimental estimates can be made using thermal imaging of the Beam Stop graphite plate [1]. The trajectories of ions born before encountering the last magnetic surface must be evaluated, since the impact areas in the duct or vacuum chamber are a source of gas and impurities and can be subject to potentially high thermal loads. The computer code FAFTRAYN has been written to simulate the reionized ions trajectories in the residual magnetic field of TJ-II. The ion impacts on the duct and vacuum chamber walls are recorded allowing the study of power deposition areas and their dependence on beam parameters or residual gas pressure. The computed power deposition distribution has been compared with the radiation emission maps obtained with bolometer arrays viewing the beam entrance [2], and thermographic images showing the hot spots produced in the vacuum chamber during a beam shot [1].

High reionization signature. The Neutral Beam Injection system (NBI) at TJ-II flexible heliac consists of two tangentially injected hydrogen beams of 34 keV energy, providing a total 1.4 MW power to the plasma [3]. A fraction of the beam power ranging between 10 % (well conditioned duct) to over 50 % (beam blocking case) is lost due to reionization of the neutrals in the duct and beam entrance area. In figure 1, the photograph on the left shows a view of the TJ-II vacuum chamber from the beam#2 duct. Superimposed on the image is a toroidal section of the nested magnetic surfaces at the toroidal sector SB7, and the main lines of sight of the bolometer arrays. The spatial distribution of emitted radiation in NBI plasmas regularly features a pronounced maximum at the central lines, corresponding to area 2 in the figure. Under some circumstances this distribution is radically changed, the maximum shifting to the peripheral area labelled 1 in the figure. This change has been ascribed to the presence of a high level of beam reionization. In order to study the behaviour of reionized ions two kinds of beam shots are performed: shots without magnetic field, in which the

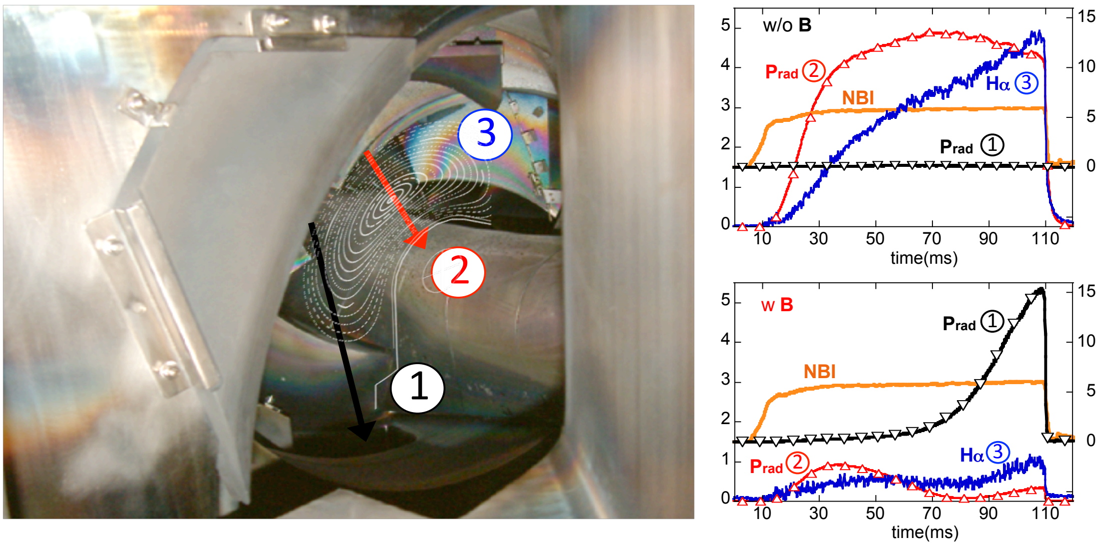

Figure 1. Left: TJ-II vacuum chamber seen from NBI#2 duct. Right: Bolometer signals during beam pulses without (top)/with (bottom) magnetic field.

trajectories of fast particles (neutrals and ions) follow straight lines and strike the walls at the direct beam interception areas, and shots with the full magnetic field (without plasma), in which the ions are deflected from the beam direction, striking the walls at different spots. At the right of figure 1 the signal traces at the top (shot without B field) show enhanced radiation corresponding to the areas labelled as 2 (Central Coils cover) and 3 (graphite Beam Stop). The signal traces at the bottom of figure 1 (shot with full B field) correspond to an extreme case of beam reionization: a strong reduction of radiation coming from the beam direct interception areas 2 and 3, is accompanied by an increase of radiation from the area 1 at the plasma periphery.

Ion trajectory calculation. An ion trajectory code has been written (TRAYN) that follows the trajectories of ions in the residual magnetic field of TJ-II from their birth point in the beam entrance area (beam duct and vacuum vessel before they encounter the last closed magnetic surface) until they hit the wall, either in the duct or in TJ-II vessel. For the main ion energy (34 keV) and the magnetic field range in the duct region (0.01 to 0.25 T), the center-guide approximation is not valid, therefore a finite Larmor radius approach has been implemented. A detailed 3D model of the duct and vacuum vessel has been used in order to locate the potential hot spots and compare the simulation results with images of the infrared camera or radiation maps from the bolometers.

In order to gain insight into the dynamical behavior of the fast particles, a first purely statistical approach has been followed: the ion birth points are uniformly distributed on

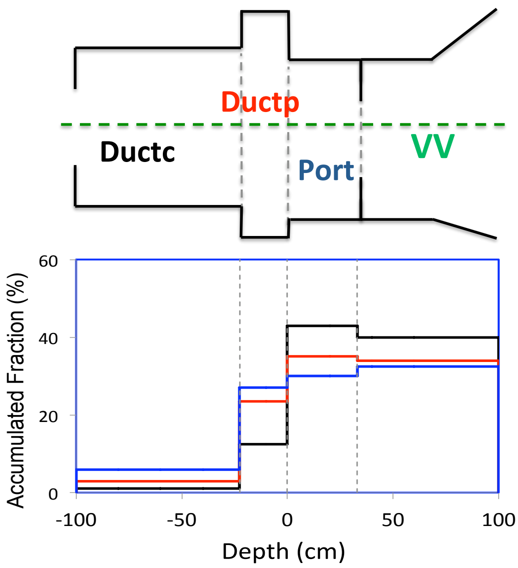

Figure 2: Fraction of accumulated striking points along the beam path for a uniform distribution of birth points, and the three beam energy components: 34 keV (black), 17 keV (red) and 11 keV (blue)

perpendicular planes along the beam axis. The trajectories of 64000 monoenergetic ions are followed until they strike a material surface. The results are summarized in figure 2, where the distribution of striking points is shown along four principal areas: Ductc (cylindrical duct connected to the beam box), Ductp (coupling piece connecting the cylindrical duct and the injection port), Port (connection between duct and vacuum vessel), and VV (stellarator vacuum vessel). The graph presents the accumulated number of impacts in each of the four areas as a fraction of the total number of ions (64000). This approach has been applied to three beam energy values, 34 keV, 17 keV, and 11 keV, corresponding to the three beam energy components that originate as molecular species in the ion source.

One of the main results of the statistical study is that considering all birth points along the duct with equal probability, most of the trajectories die at the port region (> 40%) or inside TJ-II vessel (< 40%) and only a marginal fraction in the first section of the duct. This fraction is higher for the low energy component, since having a larger Larmor radius their trajectory is more likely to end in the first duct sections.

A more realistic approach should consider a geometrical model of the neutral beam as made up by a number (80000) of neutrals following straight trajectories with a Gaussian angular distribution (1/e divergence 1.3°), and a given ion energy mix (55% of full E, 25% of E/2 and 20% of E/3 components). The Montecarlo code FAFNER performs such simulation [4], following the neutrals inside the 3 D model of the duct and VV until they are reionized through collisions with gas molecules. The trajectories of the ions in the residual magnetic field are then handed over to the code TRAYN.

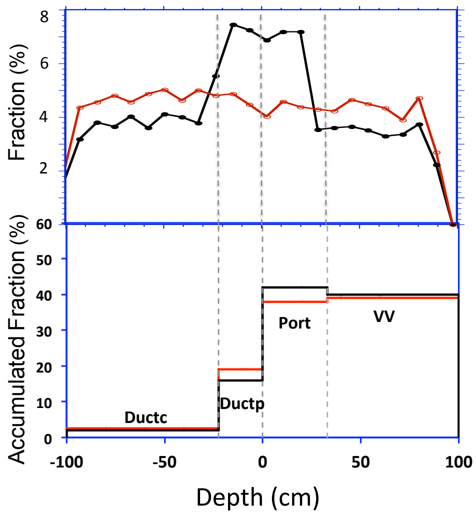

Figure3. Top: Ion birth distribution for a flat (red line) and peaked (black line) pressure profiles. Bottom: Accumulated fraction of striking points at the four principal areas.

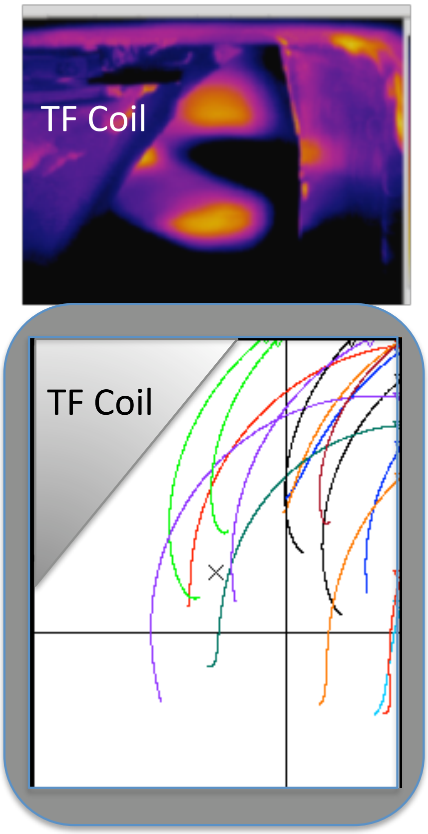

Figure 4: Comparison between a thermal image of the port area (Top) in a high reionization scenario, and a projection of calculated ion trajectories on the port plane

In the approach of the merged code FAFTRAYN, the ion birth points have a distribution that depends on the residual gas pressure profile along the duct, which in turn is a product of the local gas re-emission sources. In order to study the sensitivity of the ion trajectories (and therefore the hot spot locations) to the pressure distribution, two different cases have been considered: a flat profile, and a profile with a pronounced maximum at the Ductp and Port areas. Figure 3 Top presents the ion birth distributions corresponding to those two cases; the ion fractions are normalized to match the same total reionization fraction (31%). Although the birth profiles differ significantly, the striking points (Fig. 3 bottom) show similar distributions except that the port and VV areas have enhanced deposition rates for the peaked pressure case.

Comparison with experiment. This relative insensitivity to the pressure profile has been confirmed by bolometer signals as well as by thermographic images. According to FAFTRAYN calculations the ion impacts in the vacuum chamber tend to accumulate in certain areas like the side port of sector SB7. The radiation pattern detected by the bolometer arrays in that sector (Fig. 1) shifts accordingly. Thermographic images of the port region in a range of reionization scenarios show high temperature areas on the top and right duct walls. In figure 4 a thermal image of the port area is compared with FAFTRAYN calculations showing a projection on the injection port plane of the trajectories of ions born in the Ductp region: 70% of the ions hit the right hand wall and 30% die on the upper wall of the last duct section.

References

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