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Thermal Load on the W7-X Vessel from NBI Losses

M. Drevlak

[2] *Max-Planck-Institut für Plasmaphysik, IPP-EURATOM Association, Germany*

Abstract

For the operation of W7-X, as well as other magnetic confinement devices, it is of great importance to predict whether fast particle losses might be concentrated in certain regions to an extent that the plasma vessel or in-vessel components could be damaged. A first assessment of this issue for W7-X had been carried out by [1].

The ANTS code has been developed for the simulation of plasma processes involving the effects from drift motion and particle collisions. In its current form, the code uses a full-f MC approach. As a first application, the thermal load from NBI losses on the inner vessel of W7-X has been investigated.

In this paper, an overview of the code structure is given, the numerical approach is outlined and first numerical results are presented.

1. Introduction

Neutral beam injection is being considered as a heating source for W7-X. The current design envisions two beamlines consisting of 4 beams each. The complete NBI system would be capable of delivering a total of 8 MW heating power. Using balanced or unbalanced injection, the NBI can be used to drive or compensate a net toroidal plasma current and so adjust the magnetic equilibrium to a desired configuration. The NBI particles are injected at energies of 20keV, 30keV and 60keV.

A first assessment of NBI losses and the resulting load on the vacuum vessel in 'W7-X had been carried out by [1]. In this work, that investigation is repeated with a larger number of particles and using a recent, more accurate representation of the vacuum vessel and in-vessel components, resulting in better spatial resolution.

2. The ANTS code

The ANTS code (plasm**A** simulatio**N** with drif**T** and collision**S**) is a full-f MC code. It was created based on existing code originally written for the ONSET [2] and EXTENDER [3] packages. In particluar, the code is able to use the entire range of coil types available from the ONSET package in order to describe the external magnetic field. Moreover, the same range of classes for the representation of mesh fields is used. In contrast to the approach used by [1], no flux surface representation of the magnetic field is used inside the plasma domain. Instead, a mesh field is used in the entire domain of computation, and the integration of the particle orbits is carried out in cartesian coordinates. This approach provides the greatest flexibility and will facilitate a faithful treatment of magnetic fields with islands. At this stage of development, the code assumes stellarator symmetry for all its fields. Extensions allowing for fully 3d fields have begun.

ANTS reads CAD data using the PISA library written by [7], allowing it to deal with existing descriptions of W7-X available in the ANSYS format.

ANTS can be run with different sets of differential equations describing the drift motion of the particles and, at this point, simulates collisions with an arbitrary number of background plasma components. So far, only Maxwellian background plasmas have been implemented.

3. Equilibrium configuration and plasma profiles

In this work, NBI losses are calculated for two configurations based on a VMEC equilibrium with $\langle\beta\rangle = 2\%$ computed by [4]. It is a free boundary equilibrium with the coils carrying uniform currents. No auxiliary coils are used.

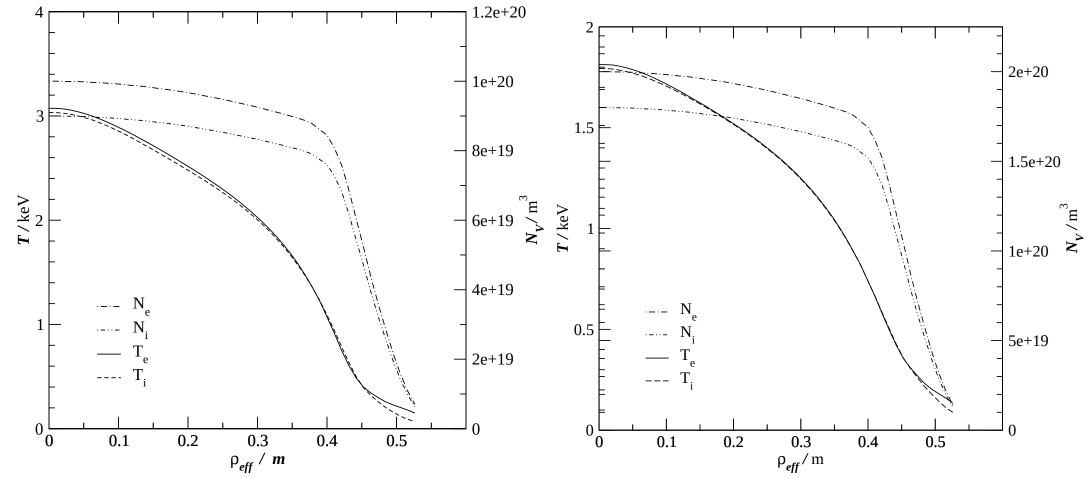

Figure 1: Temperature and number density for electrons and ions for both the low density case (left) and the high density case (right).

Using the magnetic field from the VMEC solution and assuming an injected NBI power of 4 MW (only one beam line active), two different sets of temperature and particle density for both ions and electrons were used [5] that were computed following the procedure outlined in [6]. The first of these profile sets, referred to as the “low density case”, has a maximum particle density of $\sim 10^{20}/\mathrm{m}^3$ at the magnetic axis. The second, called the “high density case”, has a maximum density of $\sim 2 \times 10^{20}/\mathrm{m}^3$. The density and temperature profiles are shown in Fig. 1.

4. Particle and heat losses

For both the low density and the high density case, a birth distribution of NBI ions was produced. These birth profiles were computed consistently with the plasma profiles and comprise 10^6 particles each.

Low density case

Figure 2: The regions with greatest heat flux, marked by white spheres, are located in the clearances between the coils.

In the low density case, 24.6% of the particles injected are lost, carrying with them 20% of the injected energy. Fig. 2 shows that, as would be expected, the regions with the greatest heat load tend to be located between the coils.

The heat flux density is colour coded, raging from blue (coldest) over red to white for the maximum of the heat flux. The locations with greatest heat flux have been marked with white spheres.

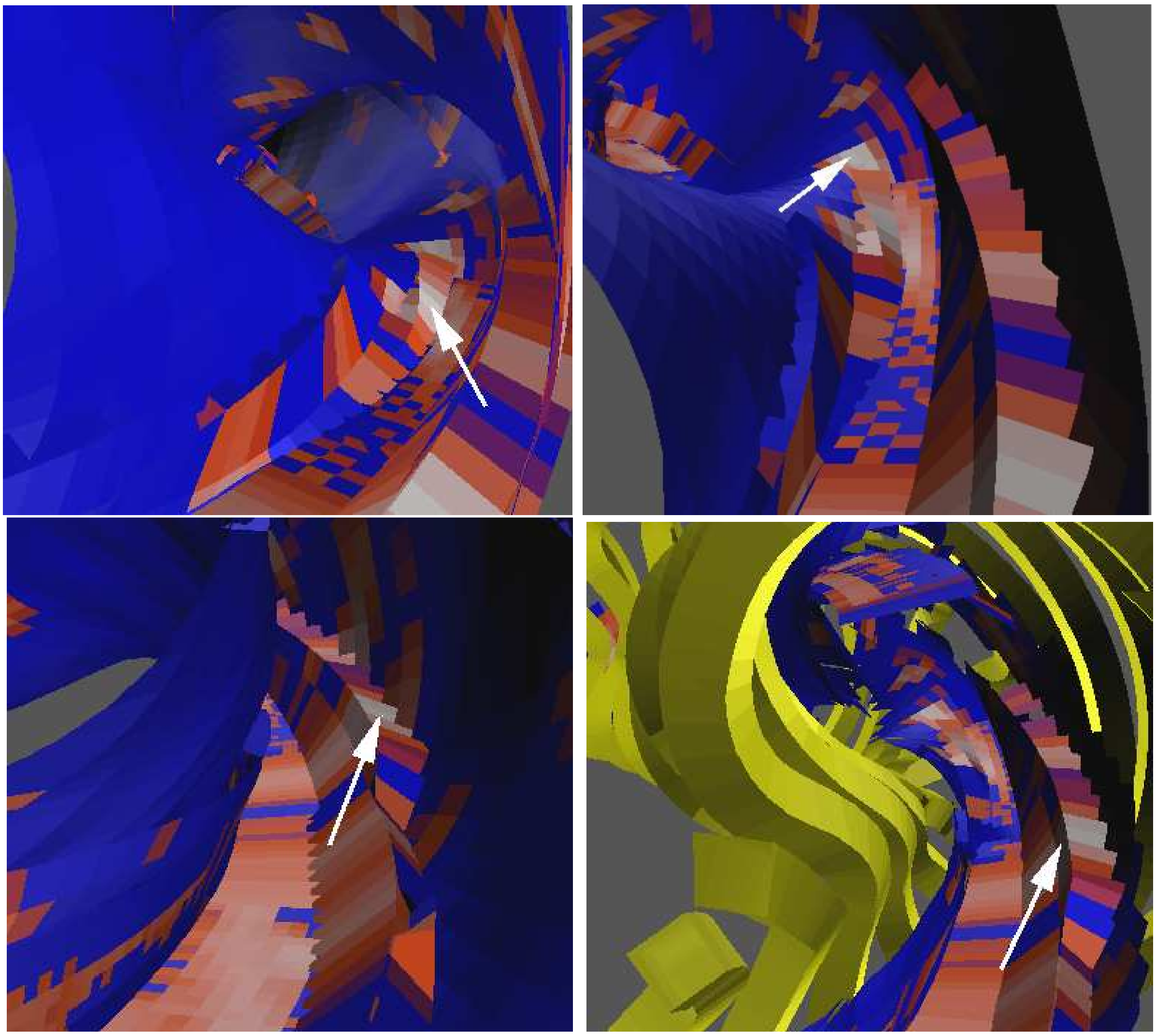

Figure 3: selected locations inside the vacuum vessel exposed to high heat flux from lost NBI particles. Local maxima of the heat flux are denoted by white arrows.

Fig. 3 shows some of the region of the vacuum vessel and in-vessel components exposed to particularly high heat flux. The upper left plot of Fig. 3 shows a region of high heat load located at the edge of the divertor. The heat flux encountered here is $720\,\mathrm{kW/m^2}$. This poses no problem as the divertor is designed to withstand power densities upt to $10\ \mathrm{MW/m^2}$. The upper right plot however exposes a problem. The arrow indicates a location of high heat flux ($624\,\mathrm{kW/m^2}$) on the wall of the vacuum vessel just beyond the divertor. This heat load significantly exceeds the design limit of $100\,\mathrm{kW/m^2}$ and would inflict serious damage to the machine. It needs to be pointed out, though, that the CAD data used in this simulation are not entirely complete. In reality, the W7-X divertor will be furnished with toroidal end plates. These may turn out to absorb a significant fraction of the particles striking the vacuum vessel. The lower left plot shows another hot spot located on a baffle plate absorbing a power density of $608\,\mathrm{kW/m^2}$ and the lower right a hot spot receiving $280\,\mathrm{kW/m^2}$. Both locations are designed to tolerate a heat flux density of 1 MW/m^2. The hot spots shown in the two upper figures are located near the triangular cross section, whereas the lower plots show hot spots near the bean shaped cross section.

As would be expected, the pattern of hot spots repeats periodically around the torus.

High density case

Due to greater collisionality, the total power lost is lower than in the low density case. 10% of the energy injected and 13.7% of the particles are lost. The deposition pattern is very similar to the one seen in the low density case. The greatest heat flux is delivered to the divertor close to the triangular cross section of the device with a power density of 424 kW/m^2. The unprotected region adjacent to the divertor at this cross section is exposed to a maximum of 324 kW/m^2.

5. Conclusions

The first results obtained with the ANTS code indicate that the heat load on vessel components in the NBI scenario investigated mostly remains within design limits. So far, however, one exception has been discovered on an unprotected area of the vacuum vessel right next to the end of the divertor. This spot is exposed to heat fluxes of up to 624MW/m^3. Further calculations must be carried out in order to find out if this hot spot is eliminated by the introduction of the toroidal divertor end plates or if the phenomenon persists.

Regarding the scenario investigated, it should be pointed out that the NBI power assumed here is well below the maximum available NBI power of 8 MW envisaged in the design of W7-X. Moreover, the heat fluxes quoted in this work only refer to NBI losses. They combine with the regular losses from the main plasma.

Further investigation is required in order to establish if motion of the hot spots due to the evolution of the magnetic configuration has any influence on the power delivered to affected regions, or if NBI operation needs to be restricted to suitable operational regimes of the device. Moreover, work needs to be done in order to verify if coverage of the machine by the divertor is adequate or if that coverage has to be extended. Finally, possible motion of the hot spots due to varying injection angles deserves attention.

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