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Consideration of neutral beam prompt loss in the design of a tokamak helicon antenna

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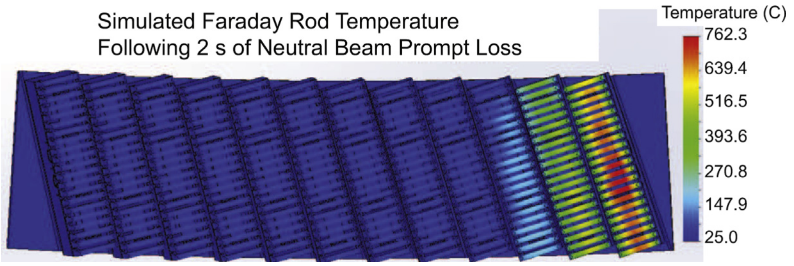
HIGHLIGHTS

- Neutral beam prompt losses place appreciable power on an in-vessel tokamak antenna.
- Simulations predict prompt loss power and inform protective tile design.
- Experiments confirm the validity of the prompt loss simulations.

GRAPHICAL ABSTRACT



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ABSTRACT

Neutral beam prompt losses (injected neutrals that ionize such that their first poloidal transit intersects with the wall) can put appreciable power on the outer wall of tokamaks, and this power may damage the wall or other internal components. These prompt losses are simulated including a protruding helicon antenna installation in the DIII-D tokamak and it is determined that 160 kW of power will impact the antenna during the injection of a particular neutral beam. Protective graphite tiles are designed in response to this modeling and the wall shape of the installed antenna is precisely measured to improve the accuracy of these calculations. Initial experiments confirm that the antenna component temperature increases according to the amount of neutral beam energy injected into the plasma. In this case, only injection of beams that are aimed counter to the plasma current produce an appreciable power load on the outer wall, suggesting that the effect is of little concern for tokamaks featuring only co-current neutral beam injection. Incorporating neutral beam prompt loss considerations into the design of this in-vessel component serves to ensure that adequate protection or cooling is provided.

1. Introduction

A variety of plasma-facing components are challenged to survive the intense radiation and thermal energy environment of the magnetically confined plasmas produced in tokamaks. These range from simple diagnostics to major systems that provide auxiliary heating such as wave injectors. For a potentially large component such as a high power antenna, the proximity to the plasma encourages design that accounts for the nearby magnetic field [1] and rewards such considerations with improved plasma performance [2]. Assessments of potential energetic ion (either charged fusion products or those produced from beam and/or wave heating) losses are separately critical for ITER-like devices because these losses may both reduce the effective plasma heating from neutral beams and damage wall components [3]. Energetic ion orbits are considerably larger than those of the thermal plasma particles, and this can require unique designs for protecting plasma-facing components.

Neutral beams are capable of injecting up to 20 MW of power into the DIII-D tokamak [4,5]. Some of the injected neutrals ionize

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in the plasma such that their resulting orbit takes them directly into a plasma-facing surface. Those prompt loss beam ions can result in $\mathcal{O}(1)\,\mathrm{MW/m^2}$ power loads on the wall. Such power loads were considered during the design of a helicon wave antenna that is proud of the standard wall surface. Analysis of the prompt losses from the neutral beams is used to aid in the design of the helicon antenna, including the design of protective tiles surrounding it.

The value of the helicon antenna is that its injected power is predicted to provide efficient off-axis current drive [6]. Injected from the outer wall, helicon waves will deposit their energy into the plasma before reaching the center. That desirable effect results in off-axis current drive that is an important component in experiments to develop steady state plasma scenarios. The reliability of wave driven off-axis current may be preferable to that sourced from the neutral beams themselves (producing a suitable off-axis neutral beam source is a considerable task [7]). Coupling helicon waves to the plasma requires propagating the wave across the spatial region between the magnetically confined plasma and the antenna. The smaller the distance between the helicon antenna and the confined plasma boundary, the better the injected waves will couple. Efforts to minimize this distance lead to a situation in which the power reaching the helicon antenna due to neutral beam prompt losses is significant.

2. Prototype modeling

DIII-D features a near-continuous wall with cut-outs for diagnostics and access for auxiliary heating. The plasma-facing tiles are composed of graphite. Fig. 1(a) is an engineering drawing cross-section of DIII-D showing a typical plasma (major radius $R_{\mathrm{major}} = 1.7\,\mathrm{m}$ and minor radius $a = 0.7\,\mathrm{m}$) and highlighting the region identified for helicon antenna installation. This antenna installation location was determined based on the availability of diagnostic port access for connection feedthroughs and the existence of a wide viewing region for an infrared camera diagnostic [8]. Predetermining the location of the antenna installation greatly simplified the prompt loss calculations because the new wall shape that incorporates the antenna profile had been set. A photograph of the late-stage installation is given in Fig. 1(b). The center of the antenna is installed at $\phi_{\mathrm{DIII-D}} = 195^\circ$ and the ports just above it and below it are labeled 195R+1 and 195R0, respectively (the naming scheme indicates the toroidal angle location and the fact that these are [R]adial ports located above the midplane [+1] and at the midplane [0]).

Eight distinct neutral beams in DIII-D are each capable of injecting up to 2.5 MW into the plasma. These beams are named according to their toroidal angle location and whether they exist in the left or right side of the housing (two beams per housing, e.g., 210L is located at $\phi_{\mathrm{DIII-D}} = 210^\circ$ in the left side of the housing). Prompt losses are determined based on modeling of the neutral deposition and the resulting ion trajectories. The deposition (i.e., the ionization profile) is calculated using a Monte Carlo method that includes the three-dimensional geometry of the beams and the atomic cross-section data for ionization probabilities from ADAS [9,10]. Radial profiles of plasma parameters are provided as measured (e.g., magnetic equilibria from EFIT reconstructions [11], ion density and temperature from charge exchange recombination spectroscopy [12], and electron density and temperature from Thomson scattering [13]). This provides a data set of ions specifying their full location and velocity vector, and that data is used as the initialization for a gyrocenter calculation of their trajectory. Deposition results from this modeling are shown in Fig. 2 for shot 158,527 ($B_t = 1.25\,\mathrm{T}$ and $I_p = 0.7\,\mathrm{MA}$). Fig. 2(a) and (b) shows the deposition as a projection in the Rz-plane. One important capability of the deposition code is that it includes ionization in the scrape-off layer, which, even though the number of neutrals ionizing outside the confined plasma is generally small, has still been found to be a contributing factor in measurements of lost beam ions [14]. The solid white line in Fig. 2(b) is the separatrix and any deposition outside of this represents scrape-off layer ionization. Fig. 2(c) and (d) provides a top-view of the deposition to highlight the distinct toroidal dependence. While this deposition is calculated in three dimensions, the magnetic equilibrium and plasma profiles are all input as axisymmetric properties.

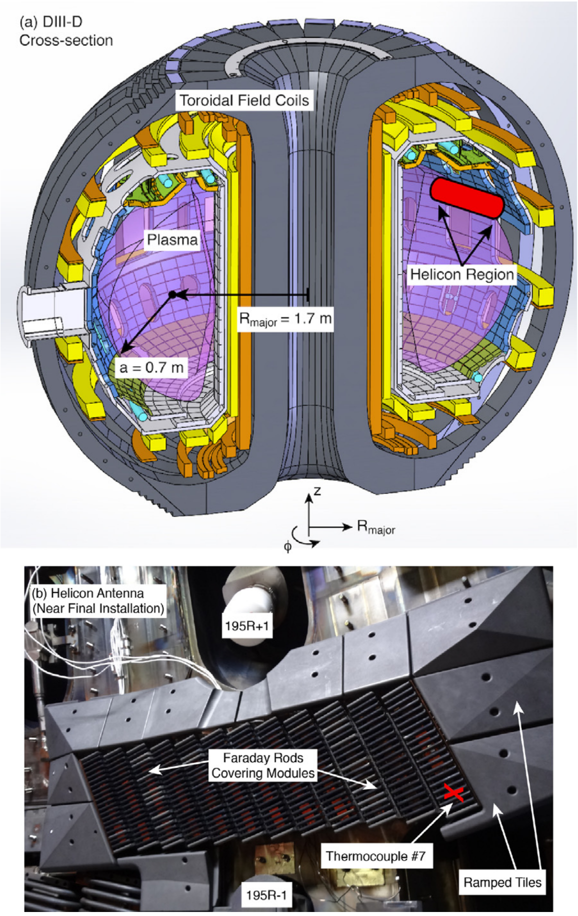

Fig. 1. (a) Engineering drawing of the DIII-D tokamak with a highlight of the helicon antenna installation location slightly above the midplane. (b) Photograph of the helicon antenna as the installation process nears completion with the modules covered by Faraday shields (rods made from titanium–zirconium–molybdenum [TZM] coated with B_4C).

The deposition profile provides the initialization information necessary to calculate the resulting beam ion orbit: initial position (R_{major}, ϕ, z), and initial velocity vector (v_R, v_ϕ, v_z) known from the injection vector of the neutral. The magnetic equilibrium is known separately. Example orbits from Fig. 3 serve to describe the matter at hand, namely that some injected neutrals ionize such that their orbit very quickly connects to the outer wall. Fig. 3 includes two neutrals that ionize with nearly the same properties except that one begins with a velocity vector parallel to the plasma current (black trace) and the other begins with a velocity anti-parallel to the plasma current (red trace). These two arbitrary example orbits show that counter-I_p injected neutrals feature orbits that begin on the inner leg of their banana trajectory whereas co-I_p injected neutrals begin on the outer leg. Counter-injected neutral beams are therefore capable of losing considerably more ions to the outer wall than a similarly built beam that injects along the direction of the plasma current. Whether an injected neutral eventually strikes the helicon antenna is dependent on the plasma parameters and