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The influence of neutral beam optimization for DEMO on injector design

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ABSTRACT

The requirements for neutral beam injection (NBI) on DEMO are assessed and the consequences for the design of the injectors discussed. Optimization of current drive requires NBI within a 2 m × 2 m envelope at large tangency radii. This is compatible with beamlines of 20 m length and moderate high voltage stand-off distances between injectors. However, q-profile control will necessitate at least three beamlines of different injector types and may not be compatible with shinethrough. Material irradiation studies show that, with three exceptions, there is no significant design issue for distances greater than 3 m from the tokamak wall.

1. Introduction

Some models of fusion power plant anticipate non-inductive current drive (CD) and plasma control functions for neutral beam injection (NBI), both of which impose demands on the design of the injectors that are different to those on an experimental device. Additional considerations, specific to power plants, such as the impact on the tritium breeding blanket, choice of materials and size of the “nuclear island” (the envelope of the machine subject to irradiation) also impose design constraints. This work investigates the extent of these constraints and the options available for implementation of NBI on a steady state DEMO device. Throughout a major radius of 8.5 m and minor plasma radius of 2.83 m has been assumed, with an average plasma density $10^{20}\,\mathrm{m}^{-3}$. The neutral beams are derived from a negative ion deuterium precursor beam of energy 1.5 MeV, coupled with a photo-neutralizer postulated to give 95% neutralization, the latter having been shown to be necessary to achieve the wall plug efficiency that maximizes the economic viability of a power plant [1].

2. Current drive and plasma control requirements

2.1. Current drive modelling

The efficiency of the CD achieved by NBI was assessed using the code PENCIL [2]. This code, though faster to run than TRANSP [3], omits the ion orbit physics, so is insensitive to beam pitch angle but values of CD efficiency, γ, given by:

$$\gamma = \frac{\langle n_e \rangle R_T I_{CD}}{P} \tag{1}$$

where $\langle n_e \rangle$ is the average plasma density, R_T is the tangency radius of injection, I_{CD} is the driven current and P the injected power are confirmed by TRANSP. Both codes include multi-step processes, i.e. ionization of the beam atoms from excited states. Fig. 1 shows contours of γ for beam injection in the region $6\,\mathrm{m} < R_T < 11\,\mathrm{m}$, $0\,\mathrm{m} < Z < 3\,\mathrm{m}$ where Z is the elevation from the plasma equatorial plane. It is clear that CD efficiency is optimized (where optimization implies $\gamma \geq 0.45$ as used in [4]) for off-axis injection at larger tangency radii and that the optimum injection point for the beam(s) is within an envelope defined by $8.5\,\mathrm{m} \leq R_T \leq 10.5\,\mathrm{m}$ and $0\,\mathrm{m} \leq Z \leq 2.8\,\mathrm{m}$. Using relatively simple geometry it is possible to determine the beamline design requirements to achieve this.

2.2. Plasma control (q-profile) modelling

The requirements for profile control are less well developed, with only a nominal investigation to date [4] indicating stable q-profiles for injection at tangency radii of 9.0 m, 9.5 m and 10 m and $Z = 0$ in the power ratio 8:11:12 respectively. The absolute values of total power depend upon the electron temperature in the plasma and vary from 310 MW for $\langle T_e \rangle = 12$ keV to 146 MW for $\langle T_e \rangle = 18$ keV, although the ratio between the tangential injection positions remains constant [5]. In this study, using TRANSP, the beams were injected at an inclination of 170 mrad to align the beam vector with the local magnetic field. The implications of

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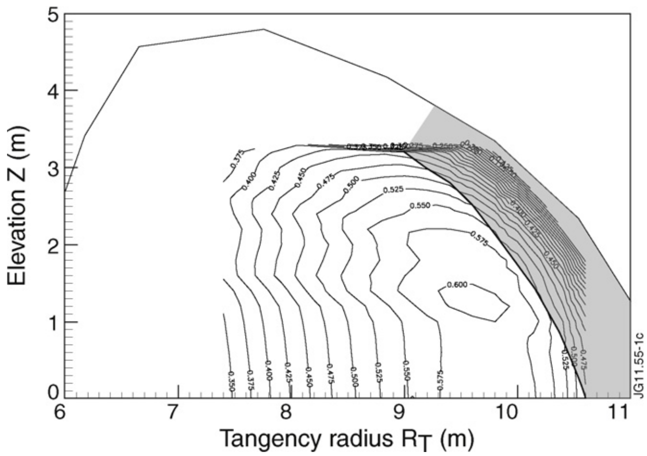

Fig. 1. Contours of current drive efficiency for 1.5 MeV D beam injected at different tangency radii and elevation into average plasma density 0.9×10^{20} m^{-3}, calculated by PENCIL. Injection into the shaded area exceeds the power density limit on the wall due to shinethrough.

this power distribution and inclination angle are investigated in Section 3.

2.3. Shinethrough modelling

In addition to the positional requirements imposed by CD and q-profile control, the magnitude of the un-ionized fraction of the neutral beam that impinges on the tokamak inner wall, known as “shinethrough”, needs to be considered. This is a function of the plasma density integrated along the beam path length and can also be calculated by PENCIL or TRANSP. Contours of surviving beam fraction are shown in Fig. 2, the shinethrough equivalent of Fig. 1. Over most of the optimum CD area the shinethrough is fractions of a percentage point (0.001–0.1%). However for $R_T > 9.0$ m the shinethrough fraction becomes significant at elevations inside the $\gamma = 0.45$ contour (for values of Z from 3.0 m to 0 m as R_T increases). The tolerable fraction will depend on the beam power density and the allowable power loading on the tokamak wall, nominally set to 2 MW/m^2 for all sources of power [6].

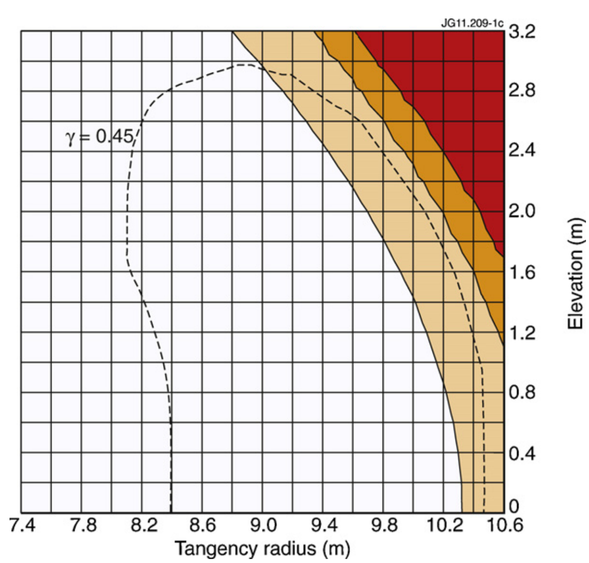

Fig. 2. Contours of beam shinethrough calculated by PENCIL for plasma parameters as in Fig. 1. ○ (0.001–0.1)%, ● (0.1–1.0)%, ● (1–10)%, ● (10–100)%. The broken line indicates the $\gamma = 0.45$ contour.

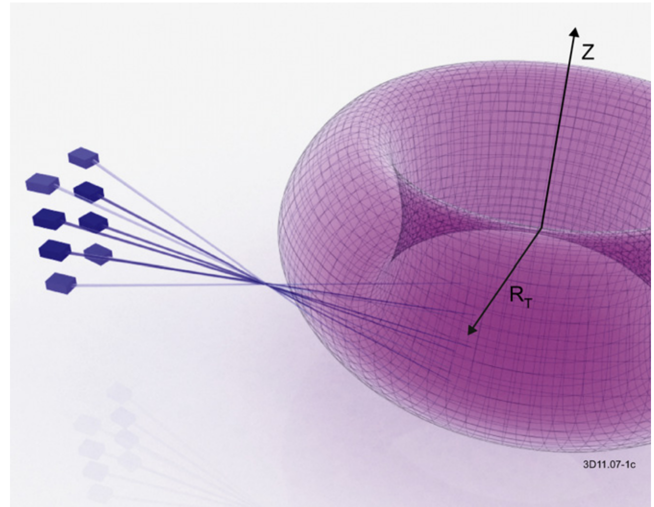

Fig. 3. Schematic of example injector configurations and beamline layout. The upper and lower pairs of injectors correspond to outer tiers possible with small injector sizes.

3. Beamline design options

An example configuration of injectors and beamline layout is shown in Fig. 3 where the upper and lower injectors correspond to the outer tiers possible with small injectors. To examine beamline design options that will fulfill the CD requirements in Section 2 the following assumptions were adopted:

(i) multiple injectors are mounted symmetrically about the vertical and horizontal axes on a single beamline
(ii) the beam axes intersect at the duct entry point, where the beamline joins the tokamak first wall
(iii) the proximity of two adjacent injectors is determined by the high voltage separation, d, given by clump theory [7] as:

$$d = \left(\frac{V}{k}\right)^2 \quad (2)$$

where $V = 1.5$ MV and $k = 1.423$ MV/m$^{1/2}$. The centre-to-centre separation of the injectors is then obtained from the sum of d and the size of the injector structure.

With the injector separation fixed, the angle of inclination to the beamline axes is determined by the beamline length, z. The calculation of the beam centre position and beam size is conducted in two frames of reference: along the axis of the beamline for the beam centre position and along the beam axis for the beam size.

3.1. Minimizing the nuclear island

In seeking to minimize the nuclear island it is necessary to consider the beamline length and the cross sectional area occupied by the injectors. The former is determined by the CD efficiency and q-profile requirements and the neutron flux along the beamline. The latter is determined by the “stacking efficiency” of multiple injectors of different geometries.

3.1.1. Injector stacking

To compare the stacking efficiency of different injector geometries we define the ratio A as the area occupied by the extraction apertures in the plasma grid to that occupied by the injector as a whole, including high voltage hold-off gaps and support structure. In each case the supporting structure is assumed to extend a constant distance of 0.15 m around the perimeter and the high voltage