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Departamento de Fusión y Física de Partículas Elementales

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22 pp. 7 figs. 24 refs.

Abstract

A diagnostic neutral beam injection system is being developed for the TJ-II stellarator. The principal goal is to increase the signal-to-noise ratio and to provide spatial resolution along the plasma minor radius in Charge Exchange Recombination Spectroscopy and Neutral Particle Analysis diagnostics, while also opening up new opportunities for physics studies. After summarizing the compact diagnostic neutral beam injector system selected as well as the TJ-II vacuum vessel and coil geometry, we address the sensitivity of TJ-II magnetic configurations to the ferromagnetic materials that shield the ion source and neutralizer tubing of the neutral beam injection system using a popular approach in wich the field is approximated via magnetic dipole moments. finally, the scientific and design trade-offs made to minimize the impact are discussed.

Consideraciones sobre el Campo Magnético para el Diseño y Situacion de un Inyector de Haces Neutros de Diagnóstico para el TJ-II

McCarthy, K.J.; López Fraguas, A.; Balbín, R.

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Resumen

Se está desarrollando un sistema de inyección de haces neutros para el «stellarator» TJ-II. El fin principal es aumentar la relación señal-ruido y lograr buena resolución especial en la dirección del radio menor del plasma en los diagnósticos de Espectroscopia de recombinación por intercambio de carga y de Análisis de partículas neutras, con lo que se abren nuevas oportunidades para estudios de física. Tras resumir el sistema de inyección compacto que hemos seleccionado, así como la geometría de la cámara de vacío y de las bobinas del TJ-II, estudiamos la sensibilidad de las configuraciones magnéticas de la máquina a los materiales ferromagnéticos que apantallan la fuente de iones del diagnóstico frente a los campos externos del propio TJ-II usando un conocido método en el que el material ferromagnético se aproxima por dipolos magnéticos. Finalmente se discuten los compromisos entre los requisitos de diseño y de reducción del impacto sobre la máquina.

CLASIFICACIÓN DOE Y DESCRIPTORES

S44; S70
NEUTRAL ATOM BEAM INJECTION; STELLARATORS; FERROMAGENTIC MATERIALS; MAGNETIC ISLANDS; PLASMA DIAGNOSTICS;

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I. Introduction

The TJ-II is a four-period, low magnetic shear, stellarator (*heliac device*) device with an average major radius of 1.5 m and an average minor radius of = 0.22 m whose magnetic configurations are created by a system of external toroidal, poloidal and vertical field coils [1]. It is designed to explore a wide range of rotational transforms ($0.9 = \iota(0)/2\pi = 2.2$) in low negative shear configurations ($\Delta q/q < -6\%$). To date, central electron densities and temperatures up to 1.7×10^{19} m^{-3} and 2 keV respectively have been achieved in plasmas created and maintained by electron cyclotron resonance heating (f = 53.2 GHz tuned to 2nd harmonic, P_{ECRH} = 600 kW, X-mode polarization). More recently, operation of one of two Neutral Beam Injectors (NBI) has commenced [2]. Each NBI will produce a =300 ms pulse of neutral hydrogen accelerated to 40 kV (energy mix ratio 80:10:10) and provide up to 1 MW of additional heating to the TJ-II plasma. The TJ-II is also provided with a large number of modern active and passive diagnostic systems for probing its hot plasma, for example the high-resolution Thomson scattering and Heavy Ion Beam Probe (HIBP) systems, as well as high-resolution visible and vacuum-ultraviolet spectrometers and a neutral particle analysis system [3].

For several decades neutral beam injection systems have been widely exploited to study magnetically confined plasmas. Indeed, dedicated low-divergence quasi-stationary neutral beams, often termed Diagnostic Neutral Beam Injectors (DNBI), are now common in most middle and large-scale plasma devices [4]–[6]. Such systems permit localized information to be acquired on several basic plasma parameters by increasing the neutral density along the beam path. For instance, DNBIs are used to measure the bulk majority ion equilibrium and fluctuating velocity, as well as temperature, via Rutherford scattering (RS) [7], to determine impurity ion velocity and temperature by charge exchange recombination spectroscopy (CXRS) [8], to procure magnetic field measurements via motional Stark effect (MSE) [9] and to provide majority ion temperatures by analyzing the energy distribution of escaped charge-exchange neutrals detected by neutral particle analyzers (NPA) [10]. It is now intended to develop a DNBI system for the TJ-II stellarator, fundamentally to increase the signal-to-noise ratio and spatial resolution in NPA and spectroscopy diagnostics [11], [12], but also to further increase the scientific return of this device, for instance to probe plasma flow around magnetic islands [13], [14].

II. Background

Before opting for a dedicated DNBI system for TJ-II, the possibility of using one of its two NBI heating beams was contemplated. However, the large beam diameter, which is comparable to the plasma mean radius, is a major drawback as it complicates localized CXRS measurements. Also, simulations to determine the effect of placing a beam collimator close to the NBI entrance duct showed that the resultant beam would be considerably distorted and that the reduced neutral density levels could not justify such an approach.

After detailed assessment from both scientific and engineering points-of-view [15], the DNBI selected for TJ-II is an upgraded version of the compact DINA-5 injector manufactured by the Budker Institute of Nuclear Physics in Novosibirsk, Russia [16]. It is similar to that provided for the Madison Symmetric Torus (MST) device and also incorporates its specially designed ion focusing grid system [17]. It consists of a cold-cathode arc-discharge plasma generator, a four-electrode multi-aperture ion optical system for beam focusing and an ion neutralization chamber. The main parameters are listed in Table 1. Although this ion optical system can produces a focused beam with a 1/e radius of a few centimeters, this radius increases quickly with increased focal length. Hence it is imperative to minimize focal length in order to maintain a high neutral density and obtain localized active charge-exchange signals.

Ion source type	Arc
Extracted ion current	Up to 4 A
Optimised beam energy (E)	10 - 30 keV
Beam focal length	1.7 m
Initial beam diameter	8 cm
Beam divergence	~0.7°
Beam components (by current)	90% H^+; 5% H_2^+, 5% H_3^+
Disassociation of molecules in neutralizer	100% for H_2^+ and H_3^+
Neutralization efficiency for beam components (E, $E/2$, $E/3$).	0.72; 0.87; 0.88
†Pulse duration	=5 ms

Table 1. Principal parameters of the DNBI selected for TJ-II. †Two single 5 ms long pulses with =50 ms separation can be produced.

The TJ-II has a complicated vacuum-vessel geometry, a bean-shaped plasma cross-section and a fully 3-dimensional plasma structure that spirals around its central coil four times in the poloidal direction during one toroidal passage. Nonetheless, it has excellent diagnostic access (96 large ports in 32 sectors). The DNBI location was dictated by

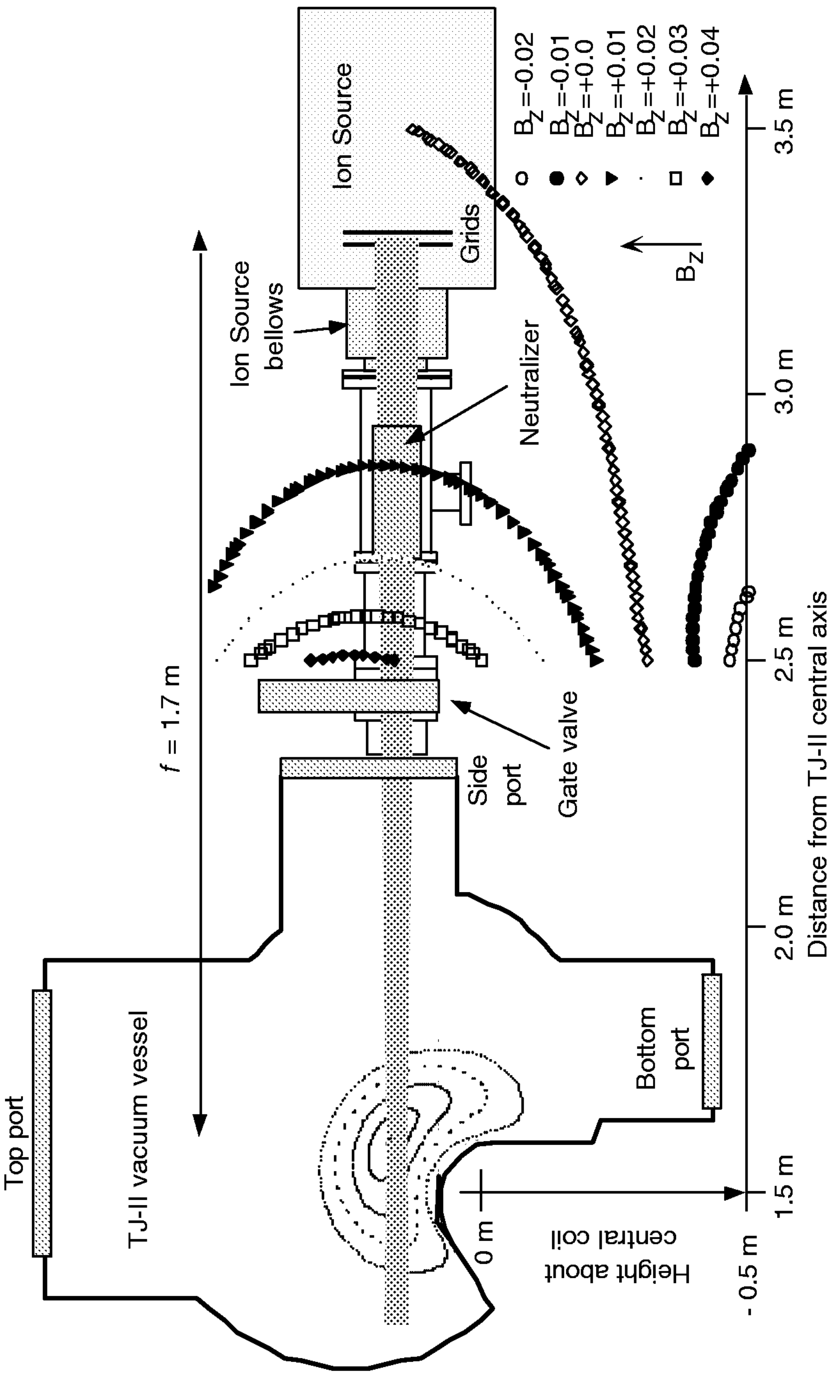


Fig. 1. Diagram of the TJ-II vacuum vessel cross-section and access ports with a magnetic configuration showing the layout of the DNBI ion source, its neutralizer, coupling chamber and beam trajectory (shaded). Contours of constant B_z in the DNBI region are plotted. Of the three B components, *i.e.* Z, *r* and φ, the Z component is the most hazardous for the ion beam and also the most difficult to screen out.

considerations such as occupancy [3], NBI shadow, orientation of the magnetic configuration about the central axis, and availability of suitable diagnostic ports. As a result a side port, in a sector where the plasma is accessible from the top, side and bottom ports (see Fig. 1) and where the port/plasma center distances are minimized, *i.e.* ~0.65 to 0.7 m (the side port is radially located at 2.2 m from the TJ-II central axis), was selected. Furthermore, this port was chosen as spectroscopy was deemed to have priority and, with a horizontal beam, multiple fiber-optic channels can be positioned in the top and bottom ports to view the beam interactions from opposing directions. However, soft-iron screens, whose purpose is to reduce stray magnetic fields to tolerable values, cover both the ion source and neutralization chamber. The concern here arises from the fact that stellarator devices are sensitive to field errors arising from coil misshaping, or misalignment, as well as from magnetic materials placed close to the machine. Errors that are large enough can distort vacuum magnetic surfaces thereby impairing the predicted plasma confinement. For these reasons, ferromagnetic materials should be withdrawn to safe distances from the plasma. Also, these issues are becoming of increasing concern in tokamaks [18]. As a rule, in the TJ-II only materials with relative magnetic permeability μ_r, = 1.01 are permitted within =3 m of its central axis and with μ_r = 1.03 within the region =5 m. Materials that supersede these values, such as magnetic screens, require special consideration. As these materials can be withdrawn to relatively large distances, the magnetic field produced by them can be approximated by the dipole term, and this can be modeled as additional coils that are included in the vacuum field calculations. Hence, the intention is to determine an ion-source to plasma-center separation, with some margin of safety, where their impact on magnetic configurations is minimized, *e.g.* no large non-natural islands arise as consequence of magnetic shields.

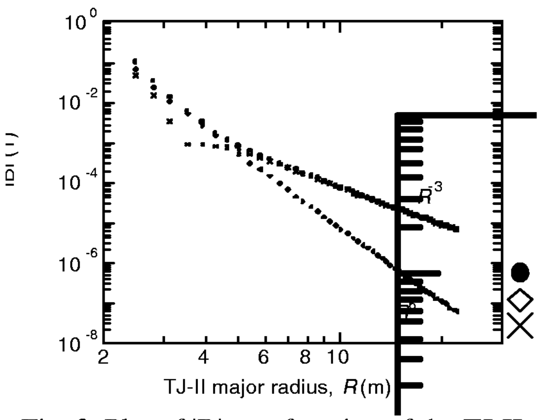


Fig. 2. Plot of |B| as a function of the TJ-II major radius. The central (CC) coil contribution is plotted as filled circles, the vertical field (VF) coil as x´s, and the toroidal field (TF) coil as diamonds.)

III. Shielding study

The TJ-II produces a stray field around itself whose typical radial dependence is shown in Fig. 2. The toroidal field (TF) coils produce a high-order multi-polar field with an R^{-6} dependence, where R is the radial distance from the TJ-II central axis [1]. The other coils, *i.e.* the central coil (CC), the helical field coil (HX), and the vertical field coils (VF), produce a dipolar field with an R^{-3} dependence. For large separations, the dipolar component is the significant one, and an effective dipolar moment can be defined to characterize the stray fields. At smaller distances, both components can be significant. With such dependence, the influence of the TJ-II field on nearby magnetic materials can be reduced to an acceptable level by simply increasing the separation between such material and the TJ-II. Otherwise, if a material reacts with the magnetizing field in a linear, or similar, way, *i.e.*, if it does not exhibit saturation or hysteresis, then the magnetization behaves in accordance with the same power laws while the back-effect on the magnetic configuration behaves as a function of distance from the TJ-II raised to a higher exponent. Non-linear materials are more complicated. Nonetheless the problem of a spherical shell of large permeability immersed in a uniform magnetic field can be solved analytically, its magnetic dipole moment being proportional to the external field [19]. For other non-spherical shapes an effective dipole moment, also proportional to the external field, can approximate the far-field component.

From these considerations, the effect of the ferromagnetic materials used for shielding the DNBI ion source and neutraliser on TJ-II magnetic configurations can be estimated by considering a set of magnetic dipoles defined as circular coils that approximate their far-fields. These coils are included in the standard TJ-II vacuum configuration calculations made with a field-line integration code. A comparison of the configuration properties for the cases with no shielding materials and with magnetic materials located at different distances from

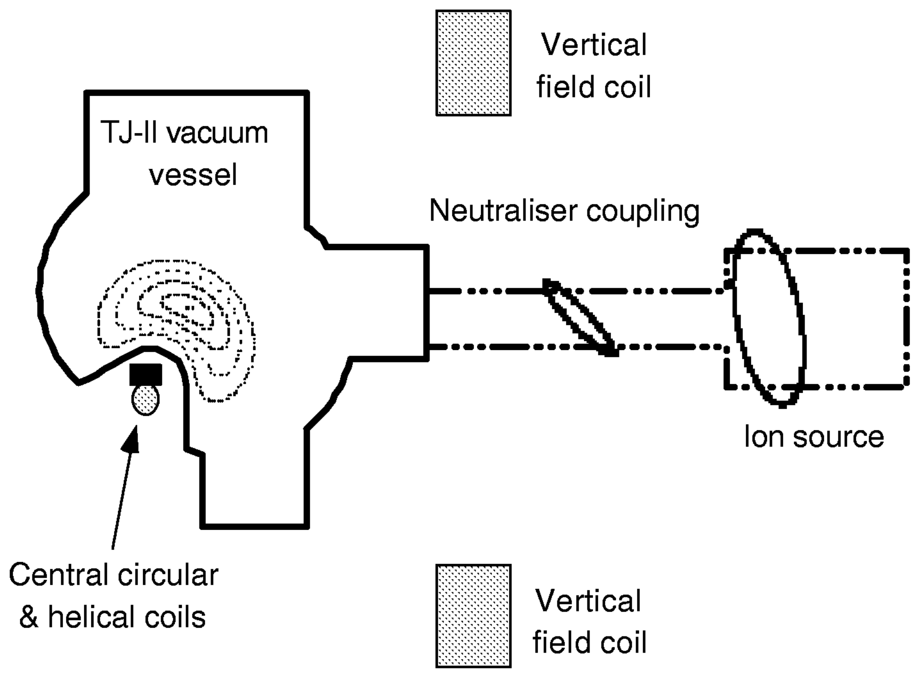


FIG. 3. Schematic cross-section of the TJ-II vacuum chamber and the DNBI showing the relative positions of the TJ-II coils. The toroidal field coils are not shown, as they are located above and below the page [1,2]. The circles represent the locations of the effective dipole moments of the magnetized DNBI screens considered.

the TJ-II central axis provides an evaluation of the minimum safe ion-source to plasma-center separation.

As the onset of large magnetic islands at rational values of $\iota/2\pi$ is considered to be the most harmful influence of field errors, two vacuum configurations have been selected. These are the 100_36_61 and 100_40_63 configurations[1], which are similar in shape and plasma volume [20], [21]. The lowest order $\iota/2\pi$ rational values are 3/2 (non-natural value) for 100_36_61 and 8/5 (natural value) for 100_40_63 (the standard TJ-II magnetic configuration). In order to simplify the task, the shielding was grouped into two masses, *i.e.* the ion source (~41 kg) and the neutralization chamber (~4.4 kg), which, for modeling purposes, were considered as two spherical shells of infinite permeability located at appropriate positions. See Fig. 3. The radius of the shell is defined such that the sphere has the same surface area as that of the shielding, thereby permitting the effective dipole moment for an external magnetic field B_0 to be given by

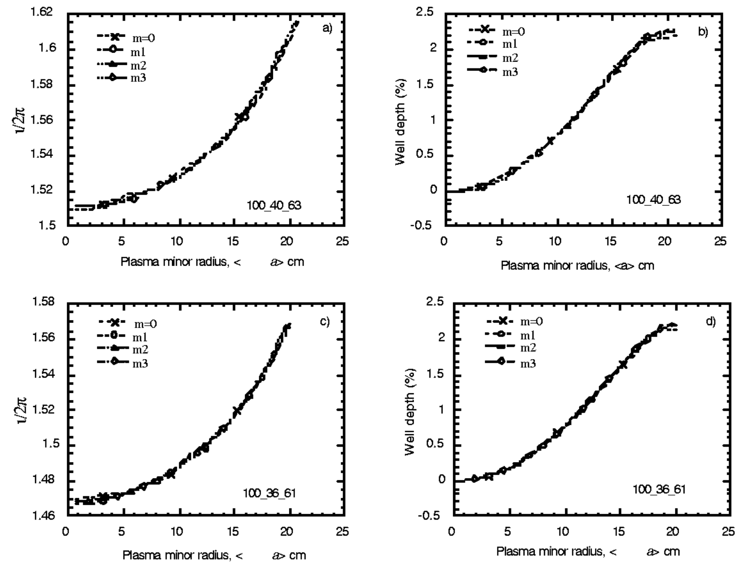
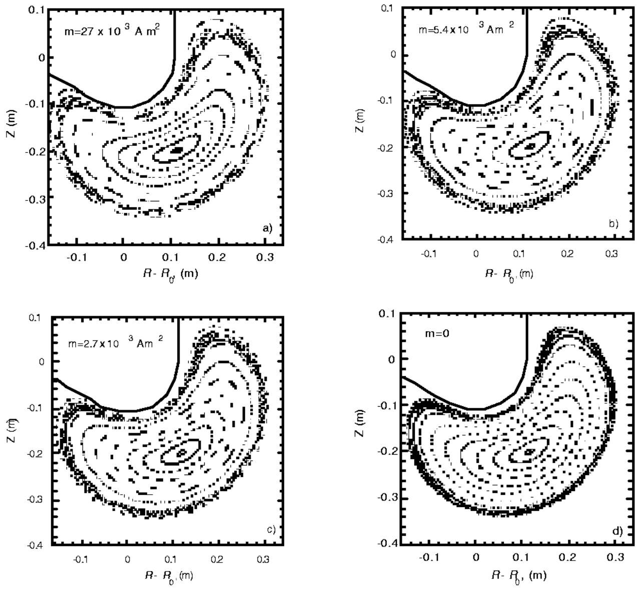


Fig. 4. a) Rotational transform and b) magnetic well plasma profiles, across the plasma minor radius <*a*>, for the TJ-II configuration 100_40_63 with various DNBI focusing grids to plasma center distances. These are for 1.0 m ($m1 = 27 \times 10^3$ A m^2), 1.4 m ($m2 = 5.4 \times 10^3$ A m^2), 1.7m ($m3 = 2.7 \times 10^3$ A m^2) and infinity (no screening material). Here, *m* is the magnetic dipole moment. Figures 4 c) and d) are for configuration 100_36_61 under the same conditions.

$$m = 4\pi / \mu_0 \times B_0 \times R^3 \quad \text{(SI units)} \qquad (1),$$

[1] The TJ-II flexible heliac has a wide range of magnetic configurations that can be accessed by varying the currents in its external coils. There are four coils whose currents can be varied independently; these are I_{CC}, the central circular coil current, I_{HX}, the helical coil current, I_{TF}, the toroidal field coils current, which are fed in series, and I_{VF}, the vertical field coil current. However, during plasma operation with ECRH, the condition of electron cyclotron resonance for |B| restricts the independence of these four current sets. For this I_{TF} is determined once the remaining currents have been defined, while the current set (I_{CC}, I_{HX}, I_{VF}) defines the TJ-II configuration. Moreover, the three numbers that define the configuration are the integer values closest to these currents (in kA) multiplied by 10, *i.e.* in the order CC_HX_VF. For example, the configuration with currents I_{CC} = 9.98 kA, I_{HX} = 3.19 kA, I_{VF} = 5.99 kA, and I_{TF} = 27.28 kA is labelled 100_32_60.

where b is the outer radius of the spherical shell [19]. The finite value of the magnetic permeability and the ferromagnetic material thickness introduce some small corrections.



Nonetheless, when setting b = 0.3 m, μ_r = 10^4 and a screen thickness of ~0.02 m for the ion source, the estimated error is less than 0.2%. However, the effect of field gradients and the actual shape of the screening may be more important. As it is quite complicated to evaluate them accurately, the approximation made was to use a 15-20% overestimate of the magnetic field induced by the TJ-II coils at the shield center. As outlined above, a means of estimating the effect of the magnetic materials on TJ-II configurations is to employ additional coils with appropriate magnetic dipole moments. For this a circular coil with a magnetic dipole close to that estimated for an appropriate spherical screen was located at the ion source with its axis directed along the magnetic field vector at that position. This was repeated for the neutralizer tubing shielding. In this way, modified magnetic surfaces as well as iota and magnetic well profiles for different TJ-II magnetic configurations could be calculated. Figure 4 shows the resultant transform and well profiles for four cases. The first is for a DNBI with no screening material, while the following three are for increasing distances between the ion source focusing grid and the plasma center. The distances selected were 1.0, 1.4, and 1.7 m. Larger separations were not considered as it was judged that the beam diameter and current density at focus would become unacceptable. Now, it is apparent from Fig. 4 that the magnetic shield has a minor influence on the rotational transform and magnetic well profiles. It can be concluded that only rational transforms already present in the configuration need to be considered and that no significant impact on Magnetohydrodynamic (MHD) stability, which is dependent on magnetic well, is to be expected. In contrast, the modeling shows that the influence of shielding on magnetic islands, which arise at low-order rational values of iota, ι, can be significant.[2] For instance, natural islands, *i.e.* ι/2π = n/m, such as the 8/5 in the 100_40_63 configuration are barely affected, see Fig. 5, but low-order non-natural islands, such as the 3/2 in the 100_36_61 configuration, can be strongly influenced by the shielding material. See Fig. 6. Hence, it is only at large separations, where the residual TJ-II field is =0.01 T, that such magnetic islands are similar in size to those occurring when no shielding is present. Note, the 3/2 value in 100_36_61 arises because the perturbation breaks the natural 12/8 rational value in accordance with the 4 times periodicity of the TJ-II. Hence, large non-natural islands can occur in other configurations with similar natural rational values. Using this argument the magnetic shielding should be withdrawn to a safe distance.

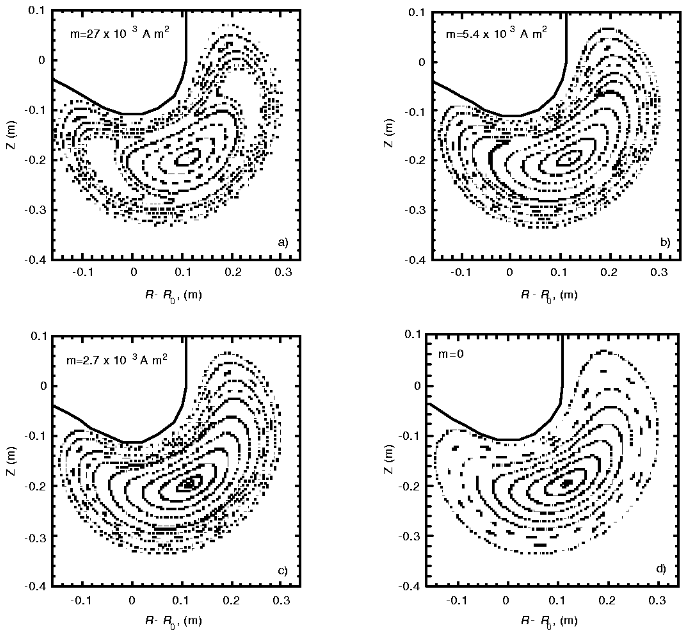


Fig. 6. Magnetic flux surfaces for the 100_36_61 magnetic configuration which contains the ι/2π = 3/2 rational value. The *m* (magnetic dipole) values considered in Fig. 4 are shown. These are a) 1.0 m ($m = 27 \times 10^3$ A m^2), b) 1.4 m ($m = 5.4 \times 10^3$ A m^2), c) 1.7m ($m = 2.7 \times 10^3$ A m^2) and d) infinity (no screening material).

IV. Solutions for the perturbation problem

The drawback of moving the DNBI away from the TJ-II is to increase the distance to the plasma center, and hence its focal length. This is undesirable because of the need to maximize the neutral current density at focus, while also minimizing the beam diameter. In the MST device, the focal length of its DNBI, which is also a DINA-5F, is 1.3 m, which

[2] In a torus, a magnetic field line, when followed the long way around, will either close upon itself after a finite number of transits *n* or continue indefinitely to ergodically cover a surface or volume [22]. Field lines that close upon themselves lie on toroidal magnetic surfaces, called rational magnetic surfaces. Magnetic islands can arise in magnetic traps close to these rational magnetic surfaces. These surfaces are defined by the rotational transformation angle, iota, ι = *n*/*m* (where *n* and *m* are integers). In this case, the perturbating magnetic field contains harmonics of the form cos(*n*φ - *m*θ), where φ and θ are the angle variables along the major and minor circumferences of the torus. The magnetic islands twist their way around the plasma and have their own set of nested flux surfaces and local magnetic axis. The whole structure of each island closes upon itself after continuing around the torus one or more times. Each island can further subdivide into smaller islands, and the smaller islands into finer islands, and so on.

results in a neutral current density of several hundred equivalent milliamperes per cm^2. Note that both beam parameters are dependent on focal length, the focus generally being set to be at or near the plasma center. In Ref. [23], J. Mlynar describes a code to simulate the propagation of the numerous beamlets that form a neutral beam. This code provides an estimate of the beam-width and current density at focus, where the beam is Gaussian-like, given ion source characteristics such as accelerating grid diameter, beam divergence and focus length. This code was used here to estimate DNBI beam characteristics at focus for a range of focal lengths. See Fig. 7.

Several designs had been contemplated, for instance, mounting the DNBI on a horizontal translation system that would allow it to be withdrawn to a suitable distance when sensitive magnetic configurations are under study. However, such a system would require a bellows system and a complicated structure. A reduction in the amount of shielding material used was also contemplated. However, an analysis based on contours of constant B about the DNBI for the three components, i.e. Z, *r*, φ, (see Fig. 1), showed that while the *r* and φ components can be screened out easily, the Z component is more hazardous and difficult to screen out and a screen reduction cannot be contemplated. Instead, a simple solution has been considered. It is to use shielding that is easy and quick to mount, when the DNBI is needed, and to remove when it is not required or when sensitive configurations are to be accessed. Although this will have some impact on the configurations that can be investigated a reduction in the shielding mass could minimize this.

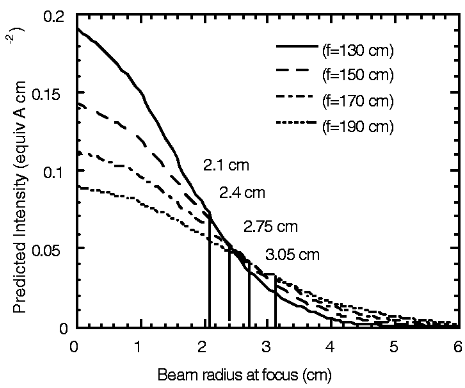


Fig. 7. DNBI neutral beam profiles at focus for several acceleration grid to plasma center lengths, *f*. The vertical lines shown represent the radii for1/e intensity.

V. Conclusions

The TJ-II stellarator device is to be equipped with a compact DNBI system. A study has been made here on the impact of the shielding used for its key components and a possible solution, albeit with some drawbacks, has been devised. Although it has shown that, for the scheme proposed, the equivalent neutral current density and beam size achievable must be compromised to some extend, because of the unavoidable need to remove the ion source to a distance where its magnetic shielding does not perturb sensitive magnetic configurations, enhanced diagnostic systems, such as the upgraded spectroscopic systems implemented on the TCV tokamak, can be availed of to compensate for such drawbacks and to obtain signal and signal-to-noise levels suitable for the studies proposed [24].

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