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ORIGINAL RESEARCH

The Beam Profile Calculation for Diagnostic Neutral Beam on HT-7 Tokamak

Lizhen Liang · Chundong Hu

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Abstract A new calculation method is introduced for convergence beam intensity. The program based on this method is prepared for beam intensity distribution and beam power calculation. Taking the HT-7 DNB as a reference, the beam profile calculated by program is similar with that of Gaussian fit of experimental data.

Keywords Diagnostic neutral beam · Beam intensity profile · Extraction grid · Transmission efficiency

Introduction

Diagnostic neutral beam is used as active probe. For magnetically confined plasma, neutral particles travel freely across the confining magnetic field. Thus, it is possible to use neutral particles for plasma diagnostic. Combined with charge exchange recombination spectroscopy (CXRS), plasma rotation velocity, ion temperature, low-Z impurities transmission and so on can be calculated [1, 2].

A typical beamline system, using for neutral beam supply, consists of the ion source, extraction grid, neutralizer, bending magnet, ion dump, high-speed pump and calorimeter [3]. Generally, these elements and the vacuum vessel are named neutral beam injector. In order to operation safely and availably, beam intensity distribution and evolution is a core issue, which decide the power loading on the elements. The calculation for beam intensity distribution is useful for operation decision-making.

L. Liang (✉) · C. Hu
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
e-mail: lzliang@ipp.ac.cn

HT-7 DNB device is a bucket arc discharge ion source with 16 cm diameter extraction area and long-curvature sphere electrode grids. As a result, the beamlets from every aperture in extraction grid steer to a common focus, and the focal distance is 2,568 mm. The calorimeter with 13 thermocouples is located at 1,362 mm downstream. In normal operation, the DNB can produce 6A of extracted beam current in hydrogen at an energy of 50 keV. In this paper we analyze calculation method for convergent neutral beam with one dimensional emitting surface and two dimensional emitting plane, respectively. At the second step, we prepare the calculation program for variation of axial power density, beam intensity profile evolution in HT-7 DNB system. At the same time, the transmission efficiency with the divergence angle and edge of beam are evaluated.

Simulation Method of Beam Intensity for Convergent Neutral Beam

The extraction area with circular apertures in spherical electrode is considered as a reference, and the focal distance is f. The coordinates for this extraction system is shown in Fig. 1. The emitting surface is set in XOY plane, the beam axis is set as Z axis and three axes are in right hand law. The radius of emitting surface is marked as R_0 with a convergence angle θ_0. For any emitting point, we can mark it as $H(r, \varphi, 0)$.

For arc discharge ion source, it is the uniformity distributed source plasma that we expect for ion beam extraction. Consequently, we assume that the beam intensity distribution at the extraction grid has a uniformity distribution in two-dimensional [4–7]. Assuming that the beam-let divergence angle is the same, is constant in space and time, and a beam-let pulled from an aperture has a

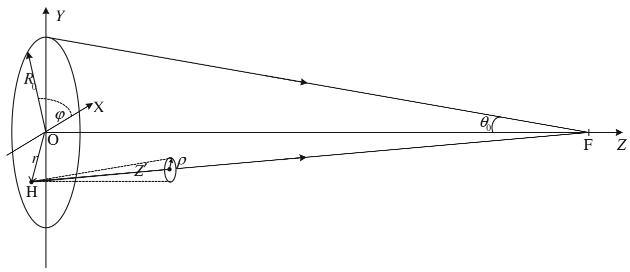


Fig. 1 Coordinate system for convergence neutral beam

Gaussian distribution in two-dimensional for a certain cross-section. The assumption of uniform beam-let divergence is physically inconsistent, but is done to permit a more tractable calculation. Thus, we got the beam intensity distribution formula for a beam-let extracted from a aperture as

$$j(z', \rho) = \frac{i_t}{\pi a^2} e^{-\left(\frac{\rho^2}{a^2}\right)}$$

where, a is the $1/e$ width with the beam divergence angles, i_t is the beam intensity of a beam-let from one aperture, ρ is distance between beam-let axis and the observational point. If the beam transport distance from extraction grid is z', the $1/e$ width is $a = z' \times tg(\beta)$, and β is the beam-let divergence angle. Thus, the beam intensity from H point is determined by variable ρ and z'.

We take the emitting line in the convergence beam as a reference, the coordinate system as shown in Fig. 2. Any point in the observational space can marked as $P(z, \theta')$, the emitting point H can take as $H(0, \theta)$. In this condition, the variable ρ and z' will express as

$$z' = HA + AB = \frac{z}{\cos\theta} + (f - z)(\tan\theta - \tan\theta')\sin\theta$$

$$\rho = BP = (f - z)(\tan\theta - \tan\theta')\cos\theta.$$

The beam intensity from H point emitted beam-let at P point will write as:

$$j(z, \theta, \theta') = \frac{i_t}{\pi a^2} e^{-\left(\frac{((f-z)(\tan\theta - \tan\theta')\cos\theta)^2}{a^2}\right)}$$

where, $1/e$ width is $a = \left\{\frac{z}{\cos\theta} + (f - z)(\tan\theta - \tan\theta')\sin\theta\right\}\tan\beta$. In order to get a beam intensity at P point. We just need to calculate a definitive integral with θ in extraction area from $-\theta_0$ to θ_0. Consequently, the beam intensity at P point could write as:

$$j(z, \theta) = \int_{-\theta_0}^{\theta_0} \frac{i_t}{\pi a^2} e^{-\left(\frac{((f-z)(\tan\theta - \tan\theta')\cos\theta)^2}{a^2}\right)} d\theta'.$$

If the P point and H point is not in the same plane with Z axis, but two planes determined by Z axis and P point, H point respectively have a angle φ. Thus, P point and H point will marked as $P(z, \theta', 0)$, $H(0, \theta, \varphi)$, respectively. In this condition, the variable ρ and z' also satisfy $z' = HA + AB$ and $\rho = BP$, can express as

$$z' = \frac{z}{\cos\theta} + (f - z)(\tan\theta - \tan\theta'\cos\varphi)\sin\theta$$

$$\rho = \sqrt{((f - z)(\tan\theta - \tan\theta'\cos\varphi)\cos\theta)^2 + ((f - z)\tan\theta'\sin\varphi)^2}.$$

The beam intensity at P point will be modified as:

$$j(z, \theta, \theta', \varphi) = \frac{i_t}{\pi a^2} e^{-\left(\frac{(\rho)^2}{a^2}\right)}$$

where, $1/e$ width is $a = \{\frac{z}{\cos\theta} + (f - z)(\tan\theta - \tan\theta'\cos\varphi)\sin\theta\}\tan\beta$. After a definitive integral with θ in extraction area from $-\theta_0$ to θ_0 and a definitive integral with φ in extraction area from 0 to 2π, the beam intensity from all beam-let at P point will be evaluated. But this integration can't be performed easily. So, we prepare the calculation program for above method. For this convergence beam, it is symmetrical for beam axis. Consequently, we can take $\varphi = 0$ as a observational plane. Thus, for different θ' and a determinate Z, the program can calculate the beam profile (Fig. 3).

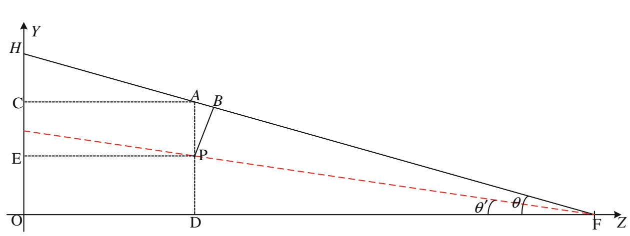


Fig. 2 Coordinate system for convergence neutral beam with emitting line

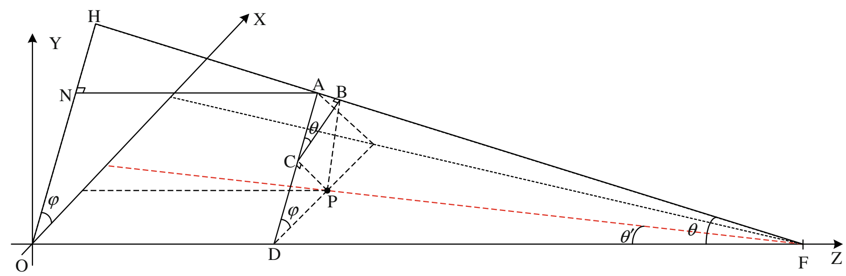
Simulation Results for HT-7 DNB

In HT-7 DNB device, there is a calorimeter with thirteen 2 mm diameter holes crossly distributed and the distance between each two neighboring holes on a same range is 13.5 mm. Behind the hole, thirteen thermocouples are embedded in sample copper respectively for beam intensity measurement [8]. The beam intensity at the thermocouple location can be calculated by

$$P = \frac{2\Delta t}{\pi} \text{ (w/mm)}$$

where, Δt is temperature rise, which is measured using the sample copper. Figures 4 and 5 shown the beam profile at calorimeter. Five starts represent power density obtained by experiment, the dashed is the Gaussian result, the solid line represents calculated results by our calculation

Fig. 3 Coordinate system for convergence neutral beam with emitting plane



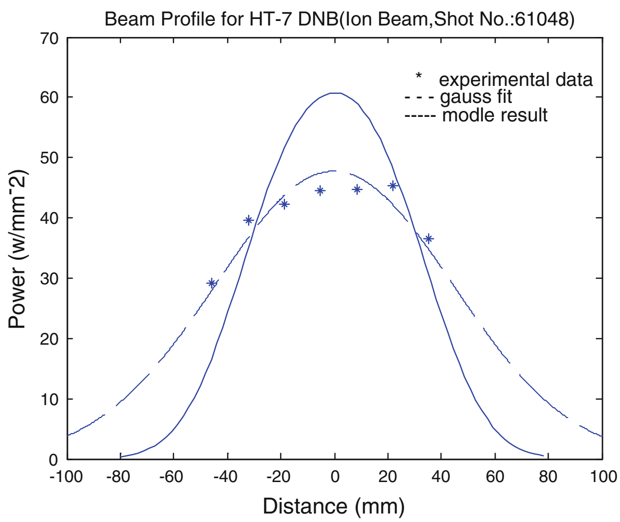


Fig. 4 Simulation result for ion beam

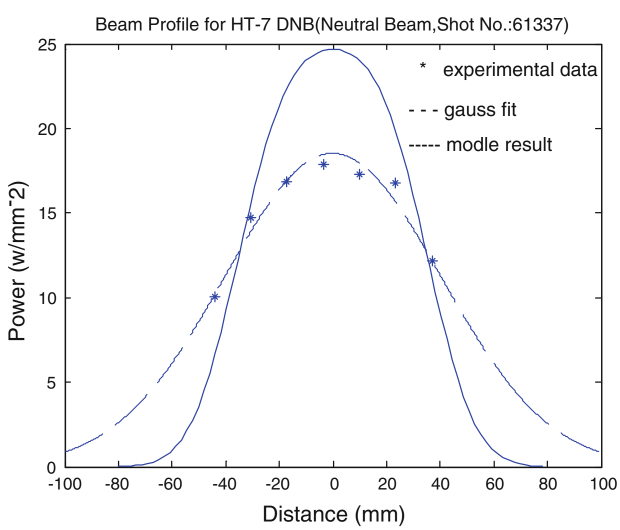


Fig. 5 Simulation result for neutral beam

program with divergence angle evaluated by Gaussian fit. These two shots have the same parameters, but 61,048 shot is an ion beam and 61,337 shot is a neutral beam. During the neutral beam calculation by our program, the neutralization efficiency is taken as 37.2 %, which is obtained by calculation of calorimeter data. The program calculates the beam power, 212.77 and 88.20 kW, which is corresponding with that calculated by calorimeter, 201.46 and 75.14 kW.

Discussion

For convergence neutral beam, approximate calculation method and program of beam intensity have been prepared. It is useful for loading power at the inner elements, this style injector design and so on. But, one thing should be noted. The assumption about identical divergence angle is not appropriate for real system. Besides, it is difficult to confirm space charge effect and the non-uniformity of source plasma as they are time-varying.

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