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Local and Multi - Chord Neutral Particle Diagnostics of Complex 3D Shaped LHD Plasma

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1. Introduction. This paper is a brief overview of neutral particle diagnostics on LHD including the multidirectional passive measurements [1, 2] and the active probing with an impurity pellet injection [2, 3]. Neutral particle analysis (NPA) technique is used on LHD for studies of suprathermal ion tail formation from NBI and ICH, fast ion confinement properties, and also for routine T_i measurements. Spatial and angular resolution is required due to the variety of particle orbit classes and complex 3D field geometry of LHD and many of the modern magnetic plasma confinement devices. The correct NPA data interpretation for a toroidally non-axisymmetrical plasma is considered together with the spatial information retrieval from line-integrated naturally occurring neutral flux observed by a scanning milti-chord passive diagnostic. The development of the active local pellet charge exchange (PCX) diagnostic is described with the emphasis on the most feasible particle energy analyzer type from the viewpoint of the high operating speed requirement. The application of the unique Compact Neutral Particle Analyzer (CNPA) [4] is discussed.

2. Passive NPA in an arbitrary magnetic configuration. A general formulation of neutral particle fluxes from non-axisymmetrical plasma has been proposed for an arbitrary shape of isolines in the diagnostic cross-section [5]. All the relevant plasma parameters are assumed to be functions of the magnetic surface. The flux coordinate $\rho(l) = (\Psi/\Psi_{LCMS})^{1/2}$ along the diagnostic sight line calculated by an MHD equilibrium code such as VMEC determines the kernel of the integral expressing the experimentally obtained energy resolved atomic flux $\Gamma(E) = dN/dE\,dt$ [erg^{-1}s^{-1}] via the sought local atomic birth rate $g(E)$ [erg^{-1}cm^{-3}s^{-1}] within the plasma, which is proportional to the local ion distribution function. The atomic flux attenuation due to secondary charge exchange and ion impact ionization is accounted for. The resultant general working equation is as follows:

$$\Gamma(E,\zeta)=e^{\int\limits_{\rho_{\min}}^{1} Q^{-}(\tilde{\rho},\zeta)\lambda_{mfp}^{-1}(E,\tilde{\rho})d\tilde{\rho}} \int\limits_{\rho_{\min}}^{1} \tilde{g}(E,\rho)\times\left[Q^{+}(\rho,\zeta)e^{-\int\limits_{\rho_{\min}}^{\rho} Q^{+}(\tilde{\rho},\zeta)\lambda_{mfp}^{-1}(E,\tilde{\rho})d\tilde{\rho}} - Q^{-}(\rho,\zeta)e^{-\int\limits_{\rho_{\min}}^{\rho} Q^{-}(\tilde{\rho},\zeta)\lambda_{mfp}^{-1}(E,\tilde{\rho})d\tilde{\rho}} \right] d\rho, \quad (1)$$

where parameter ζ is the vertical plasma scan angle, λ_{mfp} is the mean free path of atoms with respect to ionizing collisions, and $Q^{\pm}(\rho,\zeta)=dl/d\rho$ on the two sight line intervals between the deepest observable point $\rho=\rho_{\min}$ and the LCMS $\rho=1$. The function $\tilde{g}(E,\rho(l))=(\Omega S_a/4\pi)g(E,\rho(l))$ incorporates the geometrical factor depending on the viewing solid angle Ω and the aperture area S_a of the neutral particle analyzer.

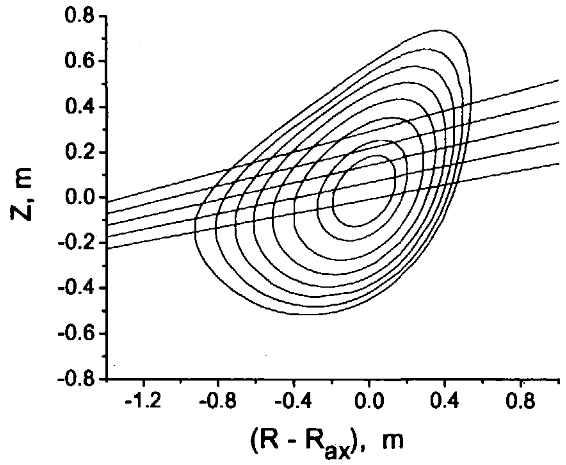

Fig. 1. Magnetic surface structure in one of the vertical cross-sectional planes (#2) and the sight lines at different scan angles (passive NPA).

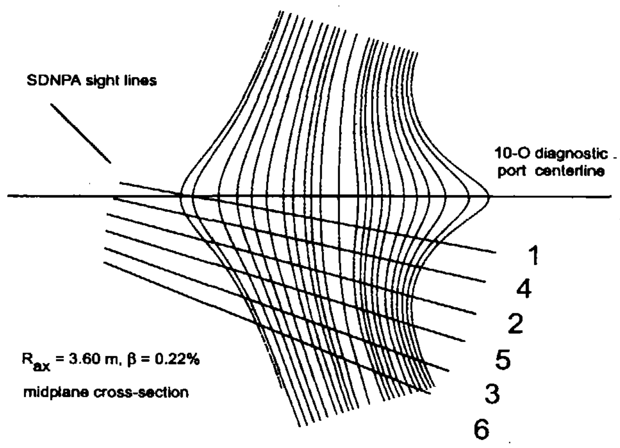

Fig. 2. Horizontal midplane projections of six passive diagnostic sightlines.

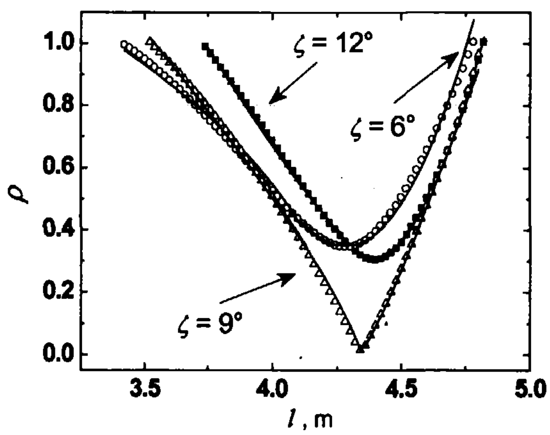

Fig. 3. VMEC data points and uniform polynomial fits $\rho(l)$ (sight line #3).

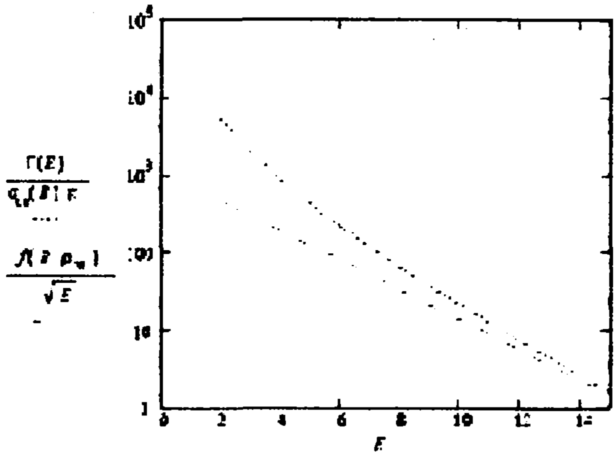

Fig. 4. Measurable (blue) and sought (red) functions of energy numerically simulated for Maxwellian ion distribution function.

Fig. 1 shows an example of the isoline structure in one of the six vertical cross-sectional planes corresponding to the sight lines (Fig. 2) of the multidirectional passive NPA on LHD. The $\rho(l)$ curves obtained from the MHD equilibrium data are shown in Fig. 3 along with uniform minimax polynomial approximations which are more suitable for computations using (1). Possible approaches to the data interpretation based on this formula were discussed in [5], i.e. kinetic modeling and iterative joining of the numerical model and experimental results by variation of unknown free parameters, such as the ion temperature profile. Fig. 4 illustrates the numerically simulated energy dependence of the experimentally observable σE - corrected atomic flux $\Gamma(E)$ and the Maxwellian exponential factor of the model ion distribution function. In this calculation T_i profile in the form $T_i(\rho) = T_i(0)\left(1-\rho^2\right)^2$ with $T_i(0) = 2.75$ keV was assumed. As it can be seen, $\Gamma(E)$ reflects the core ion parameters well enough only in the upper energy range. Basically, the passive NPA data interpretation in a complex magnetic geometry requires the general approach (1).

3. Active local PCX measurements.

Localized active NPA on LHD by the pellet charge exchange (PCX) method using an impurity pellet injector combined with a natural diamond detector (NDD) as an energy analyzer was described in [2, 3]. Time-resolved spectra of energetic particles neutralized at the pellet ablation cloud moving across the plasma result in radially resolved ion parameter measurements. A solid state detector is an attractive solution, compared to traditional neutral particle analyzers, due to the wide measurable energy range and compactness, which is essential to have a small angle between the sight line and the pellet injection axis so that the pellet cloud remains within the analyzer's viewing cone during the ablation time.

However, the use of solid state detectors in this diagnostic is difficult because of the very high operating speed constraint. As it was demonstrated in [1], the operating count rate should be $C \approx N v_{pel}/\delta l \approx 10^7 \mathrm{s}^{-1}$ for the pellet velocity $v_{pel} \approx 10^3 \mathrm{m/s}$, desired spatial resolution $\delta l \approx 10^{-1} \mathrm{m}$ and the minimum statistically acceptable number of counts per one spectrum $N \approx 10^3$. Traditional pulse height analysis (PHA) techniques normally using pulse shaping amplifiers, peak detecting ADCs and digital histogramming modules cannot provide the operating speed high enough for a good spatial resolution in PCX diagnostics. An alternative approach based on the analysis of digitized preamplifier signals directly without limiting the overall system throughput by subsequent electronics was discussed in [6]. The signals are treated as a piecewise smooth functions of time due to the fast voltage rise following every incoming particle. The spectra are obtained by regularized detection-estimation of signal increments at discontinuity points proportional to the incoming particles' energies. It was shown that the NDD system may be suitable for the uppermost energies above 100 keV.

For the lower part of the energy range of interest a conventional (i.e. with ion separation) compact (169x302x326 mm) neutral particle analyzer (CNPA) is planned [4]. CNPA is a unique charge exchange spectrometer to be used on LHD for the energies in the range 1 - 170 keV for H_0. A high-field-strength (1 T) NdFeB permanent magnet is employed in this analyzer instead of traditional electromagnets and a thin 100 Å diamond-like carbon stripping foil instead of a gas stripping cell. For PCX measurements CNPA appears to be the most suitable energy analyzer type from the viewpoint of the high operating speed and measurement geometry. Its viewing cone allows to use it simultaneously with NDD, which can be located in the CNPA inlet duct. Thus, the possible measurable energies extend from CNPA upper limit to the MeV range.

An array of channel electron multipliers (CEMs) is used for particle detection. The requirement of a high operating speed necessitates the use of CEMs not only in the counting mode but also in the current mode to be able to work with high fluxes and avoid counting statistics difficulties. This implies the application of special measuring electronics and data acquisition. This analyzer can be used in both ways, i.e. in PCX measurements and also as a passive non-perturbing diagnostic. Comparisons and modeling of complementary measurement results from this diagnostic and the multidirectional passive NPA are planned. CNPA is also planned to be used in a combination with the upgraded cryogenic pellet injection system afterwards. In future experiments this analyzer can also be used for active measurements with a diagnostic neutral beam on LHD.

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