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Passive and Active Corpuscular Diagnostic Techniques for Studying LHD Plasma High-energy Particle Physics

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Abstract

Corpuscular methods are extremely informative particularly in experiments with a magnetically confined plasma devoid of toroidal axial symmetry. Spatially resolved measurements of atomic fluxes emitted by the plasma are required to study physical aspects of various plasma heating mechanisms, fast particle confinement properties and the related subjects. An advanced passive diagnostic has been developed that enables such measurements to be made on LHD. Another method has been proposed that is aimed at achieving essential locality of measurements and simplifying the data interpretation. The method consists in active measurements of hot plasma emitted neutral particles with an injected pellet ablation cloud as an artificially created localized target for the charge-exchange process.

Keywords:

corpuscular diagnostic, neutral particle analysis, charge-exchange, high-energy particle, ion distribution, plasma heating, drift orbit, stellarator/heliotron, Large Helical Device (LHD)

1. Introduction

Two diagnostics are presented, in which the measured fluxes and energy spectra of atoms escaping from the high-temperature plasma provide the information about its ion component. The passive diagnostic proposed in ref. [1] has been successfully implemented and started to operate recently. An active diagnostic fundamentally similar to ref. [2] is being developed. Semiconductor detectors are used for neutral particle energy analysis in both cases.

The scope of experimental studies that can be performed on quasistationary magnetic confinement devices by means of these particle techniques is rather wide. The following areas should be mentioned: the ion distribution function evolution due to different heating mechanisms; fast ion confinement and transport; its influence on the radial electric field, which is a significant factor for plasma microturbulence and general confinement properties. As a matter of fact, these areas are strongly interdependent.

For a fusion reactor modeling, in addition to understanding the heating mechanisms, an important aspect is the ignition condition when the plasma is

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heated by α-particles. Fast particle confinement is also important for reducing the heat load on the walls.

Theoretical models exist of the energetic ion distribution due to ICR and NBI heating on LHD, and of the energetic ion transport (e.g. [3,4]). In ref. [5] a self-consistent model is given of the radial electric field and the fast ion orbits.

The diagnostics (Fig. 5) described below are capable of direct measurements of LHD plasma energetic particle parameters with time and space resolution.

2. Passive Silicon Detector-based Neutral Particle Analyser (SDNPA)

Geometry of experiments: A compact quasilinear horizontal array of six ion-implanted silicon detectors and a vertically movable collimating aperture provide a two-dimensional scan of the non-axisymmetric LHD plasma column. The angle between the sight lines in the horizontal direction is 4.6°. The angular sector observable due to the vertical scan is 14°. The geometry of experiments is shown in Fig. 1(a). The value of the effective plasma radius has been calculated as a function of the distance from the collimating aperture along each viewing chord. The results are shown in Fig. 1(b) for the middle vertical scan position for one sample magnetic configuration.

Several collimating apertures with different areas are available in order to be able to adjust the atomic flux so that it does not exceed the maximum acceptable for the detectors. Since the detectors are sensitive to X-rays, one of the apertures is covered by a 13 μm beryllium foil to measure the X-ray background. It should be subtracted from the measured signals to obtain neutral particle spectra. However, the X-ray spectra by themselves interpreted as bremsstrahlung/recombination contain valuable information about T_e, plasma density and Z_{eff}.

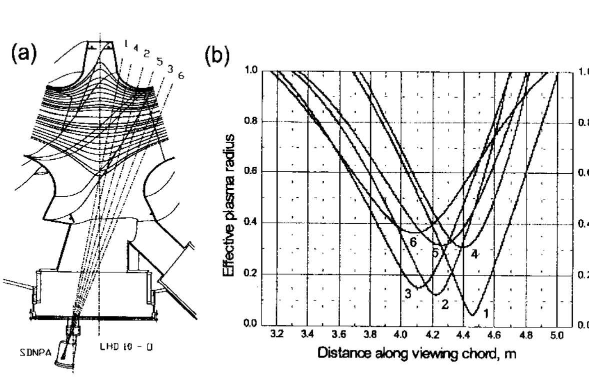

Fig. 1 (a) SDNPA six viewing chords; (b) effective plasma radius vs. distance along the viewing chords at the middle vertical scan position for R = 3.6 m, β = 0.22%.

Technical description: The lowest particles' energy that can be measured is about 5 keV taking into account the so-called dead layer consisting of the 500 Å front electrode and the 40 μg/cm^2 aluminium coating eliminating the visible light from the plasma. The maximum measurable energy about 4 MeV is determined mostly by the range of the particles in silicon and the depletion layer thickness which is 300 μm at the standard detector bias voltage of 50 V.

To minimize the thermally dependent leakage current the detectors and the input stages of the preamplifiers are mounted on liquid nitrogen cooled substrates. This results in a noticeably better energy resolution [1] compared to other NPAs using semiconductor detectors. The preamplifiers are located as close as possible to the detectors for noise reduction purposes.

The diagnostic includes a remotely computer controlled precision electromechanical system for vertical plasma scan and aperture selection. A digital data acquisition system with histogramming memory modules builds the detector amplifier pulse height distributions and stores the data. Thus the energy spectra of particles incident on the detectors are obtained.

Physical basis: The general formulae for the quantity measured by the passive diagnostic are as follows:

$$\Gamma(E)\mathrm{d}E = \frac{\Omega S}{4\pi}\int_0^L g(E)\mathrm{d}E\,\mathrm{e}^{-\tau(E,r)}\mathrm{d}r \qquad (1)$$

$$g(E)\mathrm{d}E = \left(n_0\langle\sigma v\rangle_{\mathrm{cx}} + n_{\mathrm{e}}\langle\sigma v\rangle_{\mathrm{rec}}\right)n_{\mathrm{i}}f_{\mathrm{i}}(E,\mathbf{r})\mathrm{d}E \qquad (2)$$

Here $\Gamma(E)\mathrm{d}E$ [s^{-1}] is the measured atomic flux and $g(E)\mathrm{d}E$ [cm^{-3}s^{-1}] is the local differential atom birth rate in the energy range (E, E+dE), Ω is the visible solid angle, S is the analyser's collimating aperture area, the viewing chord is supposed to extend from r = 0 to r = L; n_0 is the density of targets for charge exchange, n_e – electron density, $f_i(E,\mathbf{r})$ – ion distribution function, $\langle\sigma v\rangle_{cx}$ and $\langle\sigma v\rangle_{rec}$ – rates of charge exchange and radiative recombination processes. The Poisson factor $\mathrm{e}^{-\tau(E,r)}$ determines the attenuation of the atomic flux in the plasma.

$$\tau(E,r) = \int_0^r \lambda_{\mathrm{mfp}}^{-1}(E,\zeta)\mathrm{d}\zeta\,, \qquad (3)$$

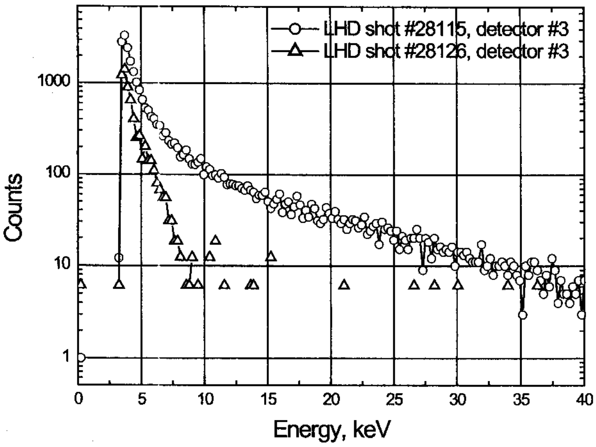

Fig. 2 Total spectrum (circles) and X-ray background (triangles) measured in similar LHD shots (ECRH +NBI heated plasma)

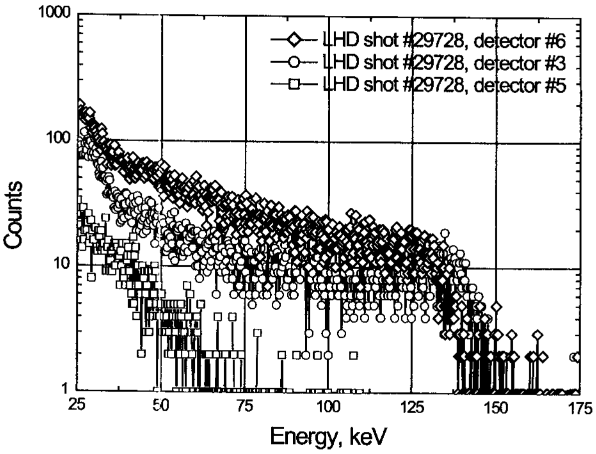

Fig. 3 Neutral particle spectra from NBI heated plasma measured along three different directions.

where the integration is along the direction of sight; λ_{mfp} is the mean free path of an atom with respect to ionizing events, namely the ion impact ionization, the electron impact ionization and the charge-exchange process. The expressions above are basic for the passive NPA data interpretation.

Various practical approaches are possible. For instance, using the known cross-sections of the relevant elementary atomic processes some simplifying assumptions can be made to obtain a working equation for $\Gamma(E)\mathrm{d}E$ that reflects the ion distribution in a less complicated manner. The other routine involves modeling $\Gamma(E)$ using the cross-section data and the independently known plasma parameters. The unknown values are treated as free parameters. In this case the task is to find such free parameters that $\Gamma(E)$ fits the measured atomic spectrum. The latter approach is more powerful and is endowed with more useful information. **Sample initial results:** To illustrate the capabilities of the diagnostic, two examples are given. Figure 2 shows a typical X-ray background spectrum and total energy spectrum measured in similar LHD shots by one of the SDNPA detectors (#3). The X-rays do not strongly affect the measured energetic tails of the neutral particle distribution. On Fig. 3 the neutral particle spectra are shown measured for NBI heated plasma along three different directions, for detectors 6, 3 and 5. The angular separations between these directions are equal. Angular dependence can be clearly seen. The viewing chord of detector 6 is the most tangential one. The plots in Figs. 2 and 3 are in logarithmic scale.

3. Active Neutral Particle Analyser ("pellet charge-exchange", PCX)

Active methods employ measurements of neutral particle flux caused by charge-exchange between plasma ions and atoms of an artificially created target. A collimated neutral beam can be used for this purpose. This method was the first one to make possible measurements of local parameters of the ion component in a hot plasma. Since its invention this technique has been the most progressive and at the same time the most technically complex type of particle diagnostics.

The other more recent idea of a local ion component diagnostic is to use an injected solid pellet ablation cloud as an artificial source of charge-exchange atomic flux that can be measured in a similar way. Such a diagnostic was realized on TFTR for studies of energetic alphas and tritons [2].

LHD is equipped with a diagnostic pellet injector capable of injecting impurity pellets with velocities of the order of 10^2 m/s. A PCX diagnostic is being developed based on the existing injector combined with a natural diamond detector. Such a combination can be a relatively compact and powerful active neutral particle analysis system.

The locality of measurements in this case is determined by the overlap region of the toroidally elongated pellet ablation cloud and the detector's cone of sight. The detector observes the pellet trajectory from behind. The angle between the viewing chord and the injection axis is 2.5° horizontally and 1° vertically. PCX experiment geometry is shown in Fig. 4 (a) and (b). Fig. 5 shows the relative location of the diagnostics.

Suppose that the required spatial resolution l is about 10^{-1} m. A pellet at the velocity v_{pel} of 10^3 m/s would pass this distance in the time T about 10^{-4} s. Let us assume that the total number of counts N needed to build a spectrum is of the order of 10^3–10^4. This would translate into the required count rate $CR = N/T = 10^7$–10^8 s^{-1}. Therefore the analyzer should be able to handle each hit event in the time interval 10–100 ns. If CR_{max} is the maximum acceptable count rate, the number of counts that can be collected $N \leq CR_{max}\, l/v_{pel}$. The operating speed of the analyzer should be high to enable measurements to be made with the desired spatial resolution. Although there is a certain flexibility in v_{pel}, higher CR_{max} is preferable.

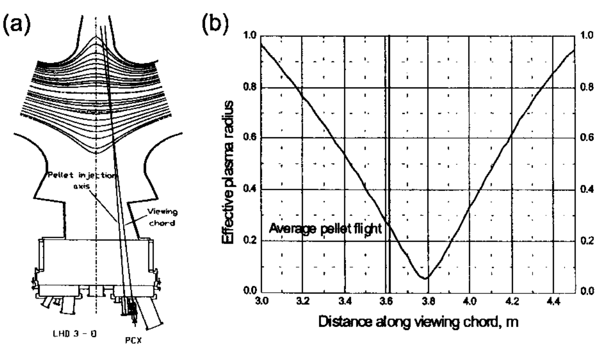

Fig. 4 (a) PCX viewing chord and pellet injection axis; (b) effective plasma radius vs. distance along the viewing chord for $R = 3.6$ m, $\beta = 0.22\%$

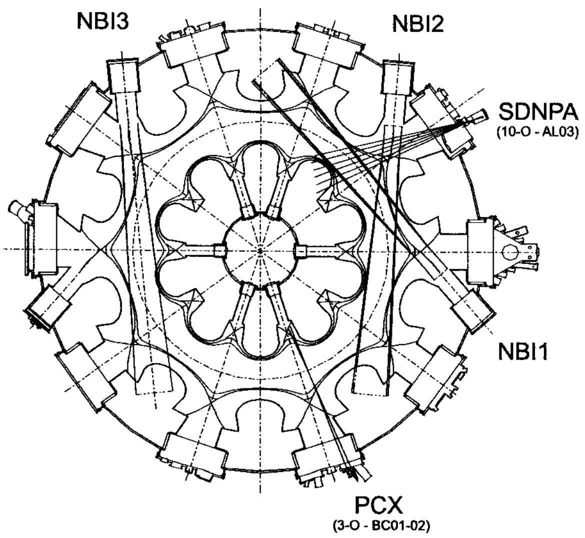

Fig. 5 Relative position of the diagnostics and neutral beam injectors on LHD

If energy losses and scattering of protons in the cloud are negligible and the typical linear size of the cloud L_{cloud} is small compared to the linear scale of spatial variation of the proton distribution function $L_{cloud} < \left(\frac{d \ln f_i(r)}{dr}\right)^{-1}$, then the total emission of atoms H^0 with energy E from the visible area of the pellet ablation cloud per second is given by the formula:

$$\Gamma(E)\mathrm{d}E = F_0(E)\, v_i\, S_{cloud}\, f_i(E)\,\mathrm{d}E, \qquad (4)$$

where $F_0(E)$ is the fraction of the incident protons neutralized by the cloud, $f_i(E)$ is the proton distribution function, v_i is the velocity corresponding to the kinetic energy E, and S_{cloud} is the area of the ablation cloud visible to the detecting element.

The count rate $\frac{\mathrm{d}N_0}{\mathrm{d}E\mathrm{d}t}$ for the atoms with energy E measured by a detecting element of an energy analyser can be calculated as a product of $\Gamma(E)$, the atomic flux attenuation factor and the geometrical coefficient $S_a/4\pi L^2$:

$$\frac{\mathrm{d}N_0}{\mathrm{d}E\,\mathrm{d}t} = F_0(E) \mathrm{v}_i S_{cloud}\, f_i(E)\, \mathrm{e}^{-\tau(E,L)} \frac{S_a}{4\pi L^2}. \qquad (5)$$

Here S_a is the analyser's collimating aperture area, L is the distance between the pellet cloud and the collimator.

A piezoelectrically driven variable width slit is used to adjust the atomic flux to the detector. A fast recording oscilloscope and a set of discriminators are planned to be used to obtain the detector pulse height spectra. Initial measurements are to be made in LHD experiments with this new diagnostic.

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