§59. Development of New Analytical Method for Energetic Particle Confinement Using CXNPA Diagnostics

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A new experimental technique to investigate the particle confinement of energetic ions during their slowing-down process is developed for charge exchange neutral particle diagnostics. The method is based on the maximum entropy and the maximum likelihood method and is used for the neutral beam short pulse experiment.

Figure 1 shows the concept of the analytical method on NPA-signals for an ideal NB-blip experiment. In this figure, the NB is injected instantly at \( t=0 \) and the waveform of the NPA at injection energy \( E_0 \) can be expressed by the delta function \( (\delta(t)) \). Since the NB particles are ionized all over along their injection path and the NPA is line-integrated measurement, energetic particles produced by the beam experience various slowing-down times depending on their locations in a plasma before they are measured by the NPA. If we neglect the energy diffusion during the slowing-down process, the waveform by the energetic particle at the energy of \( E_i \) circulating on the location of \( p \) can be expressed as \( w(p)\delta(t-x) \), where \( \delta(t-x) \) expresses the characteristic time of energy slowing-down from the injection energy \( E_0 \) to the energy of \( E_i \) and \( w(p) \) is a spatial distribution of the energetic particle along the NPA sight line. In usual plasma parameters, the energy slowing-down times monotonically increasing as it goes to the center from the edge. Therefore, if we looked at a certain energy channel of the NPA during the blip experiment, the temporal behavior of the signal at the channel simply expresses the spatial distribution of energetic particles on its sight line. The ratio \( w(p)/w(\phi) \) gives us the information of confinement ratio for the energetic particle during its slowing-down process from the energy of \( E_0 \) to \( E_i \).

In the actual case, the things are more complicated since the injection pulse width is finite. Suppose, the wave form of the NPA at the injection energy is expressed by \( \psi(t) \). Introducing a response function \( R(t) = \psi(t)/\alpha \), the contribution of energetic particles on the location of \( \rho \) to the waveform of the NPA at the energy \( (E_i) \) can be expressed by \( w(p)R(t-x) \), where \( \psi(t) \) is the maximum response function at the location of \( NPA \) signals for an ideal NB-blip experiment. To evaluate the \( w(p) \), we need to deconvolute the integral of Eq.(1). To treat the deconvolution numerically, we need to convert the waveform \( \psi(t) \), \( R(t) \), and \( w(p) \) to series of discrete numbers. Dividing the region \( \{ \text{kin} \} \) into \( n \)-regions, the Eq.(1) becomes:

\[
\psi'_i(t) = \sum_{j=1}^{n} \int_{t_j-\Delta t/2}^{t_j+\Delta t/2} w_p(\tau(t))R_0(t-\tau) d\tau
\]

where \( R(t) = \delta(t-x) \) and \( w_p(\tau) \) can be written as:

\[
R(t) = \delta(t-x) \quad \text{and} \quad w_p(\tau) = \frac{w_p(t)}{\Delta t/2}
\]

Figure 1 shows a schematic drawing of measured energetic neutral flux for the ideal NB-blip experiment. The thick-dashed lines express the energy slowing-down curves at various locations in the plasma. The triangle symbols express groups of energetic particles circulating around certain plasma locations with delta-function like waveforms. The thick-solid line expresses the waveforms of the NPA at energies of interests (100-keV and 50-keV, in the figure).

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\[
\psi'_i(t) = \int_{t_0}^{\infty} w_p(\tau)R_0(t-\tau) d\tau
\]

where \( \tau_{\text{min}} \) and \( \tau_{\text{max}} \) are the minimum and the maximum of \( \tau \) on the NPA sight line. To evaluate the \( w(p) \), we need to deconvolute the integral of Eq.(1). To treat the deconvolution numerically, we need to convert the waveform \( \psi(t) \), \( R(t) \), and \( w(p) \) to series of discrete numbers. Dividing the region \( \{ \text{kin} \} \) into \( n \)-regions, the Eq.(1) becomes:

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Fig.1 Schematic drawing of measured energetic neutral flux for the ideal NB-blip experiment. The thick-dashed lines express the energy slowing-down curves at various locations in the plasma. The triangle symbols express groups of energetic particles circulating around certain plasma locations with delta-function like waveforms. The thick-solid line expresses the waveforms of the NPA at energies of interests (100-keV and 50-keV, in the figure).

We have to note that the \( R \) is an irregular matrix of \( n \times m \), where \( m \) denotes the number of the scaler time bins in the time range of our interest.

In the field of neutron spectroscopy, the problem like Eq.(2)' is known as an 'an unfolding problem of pulse height spectra of scintillation detector'. Itoh had showed a numerical method of solving the problem like Eq(2)' using the maximum entropy method and maximum likelihood method under the Poisson statistics[1]. Applying his method to our problem, we obtain following equation:

\[
p_{ij} = \sum_{k=1}^{m} R_{jk} \left( c_{ik}/c_{ij} \right) - 1 = 0,
\]

where \( \left( c_{ik}/c_{ij} \right) = \left( c_{i}/Z \right) \sum_{j=1}^{m} R_{jk} \exp(y_{ij}) \), \( c_{i} = \sum_{k=1}^{m} c_{ik} \), \( p_{ij} = \exp(y_{ij}) \), \( Z = \sum_{j=1}^{m} \exp(y_{ij}) \), \( w_{ij} = c_{ij}/Z \), and \( y_{ij} \) are fitting parameters. We will determine the value of \( y_{ij} \) numerically by using Newton’s method, so that they will satisfy the Eq.(3). Detailed equations for numerical coding of the Newton’s method and the error estimation are derived in Ref.1.

Reference