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Modeling of charge exchange recombination spectroscopy and inverse problem analysis using Bayesian approach

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Nonlinear wave-particle interactions play a crucial role in determining the heating and transport properties of magnetically confined, low collisional plasmas. Experimental detection of persistent non-Maxwellian velocity-space distributions with real-space structures is still extremely challenging, and validation of the theoretical concept has not been extensively performed. Assuming that the plasma emission spectrum is a good proxy for the velocity distribution function, the detection of wave-particle coupling structures is within reach [1]. Recent hardware [2,3,4] and software [5] developments in phase-space structure detection have made it possible to find a bifurcation in the phase-space structures observed in the LHD, potentially affecting the resonant plasma heating [6].

In this talk, the Bayesian approach is used to systematically solve the inverse problem of plasma diagnostics, i.e. the estimation of the plasma velocity distribution function from the measured emission spectrum. Before doing so, a forward model of charge exchange recombination spectroscopy is developed, accounting for the emission cross-section effect, the Zeeman and fine-structure effects, line integration, the instrumental function of the spectrometer, and others. The diagram of the forward model procedure is given in Fig. 1.

For the Bayesian inference, the posterior distribution that corresponds to the target of the estimation is inferred by the Markov chain Monte Carlo (MCMC) algorithm. As a first step, the ion temperature profile expressed as

$$T_c(\rho;\rho_0,T_0,\alpha) = T_0\left[1-\left(\frac{\rho}{\rho_0}\right)^{\alpha}\right]$$

and parameters α and T_0 are estimated.

Test of the inference is performed using a synthetic data where the true values are known. Thanks to the MCMC process, the true values are successfully obtained with an efficient sampling. Furthermore, the influence of noise on the inference is examined. By tuning a hyperparameter, the estimation uncertainties are determined based on its statistical properties. The optimum hyperparameter is obtained by calculating the Bayesian free energy. This approach enables us to directly estimate the velocity distribution function from the measured emission spectrum, and is expected to accelerate experimental work on nonlinear wave-particle interaction.

References
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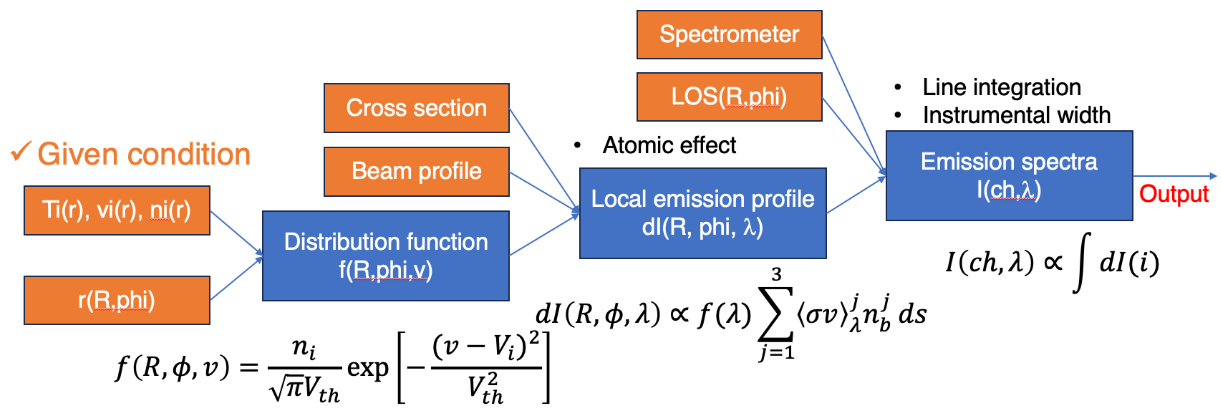

Fig. 1. Schematic of forward model of charge exchange recombination spectroscopy.