MOTIONAL STARK EFFECT DIAGNOSTIC FOR MULTI-CHORD MEASUREMENTS OF PLASMA BETA IN GDT

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Measurement of plasma magnetic field in magnetic confinement devices by observation of Stark splitting of the diagnostic beam emission line (MSE diagnostic) is the reliable and commonly used approach. The spectral MSE diagnostic developed for the gas dynamic trap (GDT), allows for measurements of $|\mathbf{B}|$ in plasma, which are of significant importance for the study of hot-ion GDT plasma with $\beta \geq 0.4$. Further experimental program for study of anisotropic plasma with high pressure implies higher requirements for the temporal and spatial resolution and precision of measurements using MSE diagnostic. Accordingly, the diagnostic system with enhanced capabilities is projected, comprising neutral beam injector RFX-DNBI and the optical system for single-shot magnetic field spatial profile measurements. H-alpha emission of diagnostic beam atoms recorded from each of eight light collection chord, is digitized by the CCD-based detector and then processed using the quantum mechanical model, which allows β calculation for a wide range of experiment parameters.

I. INTRODUCTION

The Gas-Dynamic Trap (GDT) is a long axially symmetric mirror system with a high mirror ratio (Fig. 1) for confinement of a two-component plasma [1]. The first component is a collisional target plasma with ion and electron temperatures up to 120 eV and density up to 5×10^{19} m^{-3}. The mean free path for scattering of target plasma ions into the loss cone is much less than mirror-to-mirror distance, thus target ion confinement can be modeled as an ideal gas confined in a box with a pinhole leak. The second component is a fast ion population with a mean energy of ≈10 keV and density up to 2×10^{19} m^{-3}, produced by 45° neutral beam injection. The fast ions are confined in the collisionless mirror regime, and their turning point corresponds to a mirror ratio of 2. The critical issue for feasibility of a neutron source based on a gas-dynamic trap is stable confinement of a high density of fast ions with a small angular distribution [2] The axial and radial profiles of plasma pressure (or plasma β) near the fast ion turning points determines the spatial profile of neutron flux in the testing zones of a projected GDT-based neutron source [2]. Profiles of plasma β can be constructed by measuring the profile of the diamagnetic perturbation of the confining axial magnetic field in GDT. The single point motional Stark effect (MSE) diagnostic for measurement of the perturbed magnetic field in GDT is described in Ref. 3. Ref. 4 reports recent results of measurements of plasma β radial profile in the fast ion turning point. Here, we report projected upgrade of the MSE diagnostic aimed to the further study of anisotropic plasma confinement in GDT.

II. MSE DIAGNOSTIC AT GDT AND MOTIVATION FOR UPGRADE

Recent measurements of the radial profile of plasma β in the turning point region have been made with a Motional Stark Effect (MSE) spectroscopic diagnostic temporarily loaned to the Budker Institute by the University of Wisconsin-Madison [3]. This diagnostic utilizes the effect of appearing of the Lorentz electric field $\mathbf{E}=\mathbf{v}\times\mathbf{B}$ in the frame of reference of a fast atom injected transverse to a magnetic field. For a hydrogen atom injected by a diagnostic neutral beam the resulting Stark splitting of hydrogen emission lines is linear in magnetic field. The magnitude of the Stark splitting can be precisely measured with sensitive spectroscopic instrumentation. Since the beam energy, and thus atom velocity, is accurately known, this technique provides a robust method of local magnetic field measurements.

The existing diagnostic is comprised of the neutral beam DINA-5M [5] and the single viewing chord optical system with CCD spectrometer [6]. Accordingly, to measure the spatial profile of magnetic field, a series of shots is required. This is a strong reason to modernize the diagnostic so as to allow for a single-shot profile measurements. Another reason is low signal-to-noise ratio of about 1.5, which characterizes the existing diagnostic. To overcome this problem, an additional averaging over a series of shots in each spatial point is made. In GDT experiments discussed in Ref. 4, the magnetic field was

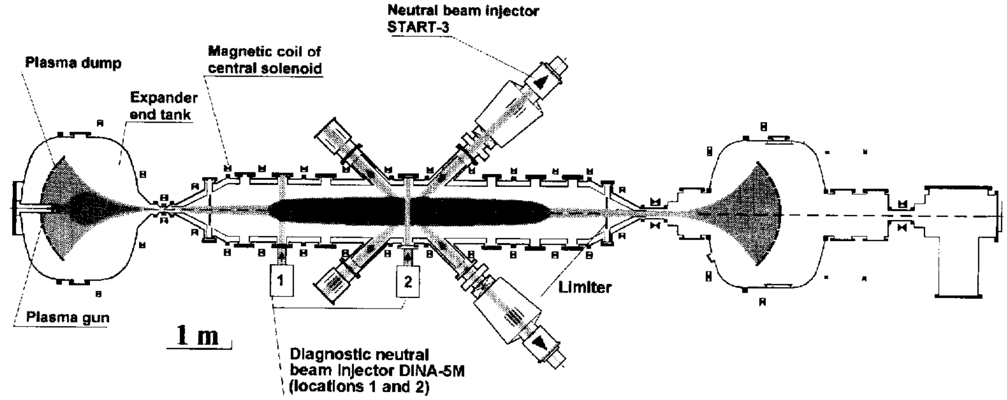

Fig.1 The GDT layout. Location 1 is the fast ion turning point, while 2 is midplane, where MSE measurements are also planned.

typically 0.4-0.5 T, so with a beam velocity of 2.7×10^6 m/s, other effects contributing to emission line splitting (Zeeman splitting, fine structure of atom energy levels, and other relativistic corrections) are small compared to Stark splitting. However, for planned low-field measurements (≈0.2 T) the noted effects are significant thus requesting to develop an advanced model [7] for experimental spectra processing.

III. PROJECTED MSE DIAGNOSTIC AT GDT

The layout of projected MSE diagnostic is shown in Fig. 2. The energetic hydrogen atoms from the diagnostic injector RFX-DNBI [8] move horizontally through the plasma volume and emit statistically mixed radiation due to excitation by collisions with plasma particles. Eight observation chords are used to collect the beam radiation, which then is recorded and digitized by the CCD spectrometer (see Fig. 2). Fig. 3 shows the layout of the RFX-DNBI neutral beam injector recently developed in the Budker INP for application in such particular fields as motional Stark measurements and active charge-exchange recombination spectroscopy (or CHERS for short) in medium-size devices for magnetic plasma confinement. The injection energy is increased up to 50 keV in comparison with 40 keV of DINA-5M allowing to obtain a more clear separation of MSE spectrum components [3,7]. The main operational characteristics of this injector are listed in Table 1. As a result of several engineering enhancements introduced into the injector design, the angular divergence of the neutral beam is reduced to about 0.5° [8]. Together with higher beam velocity, this

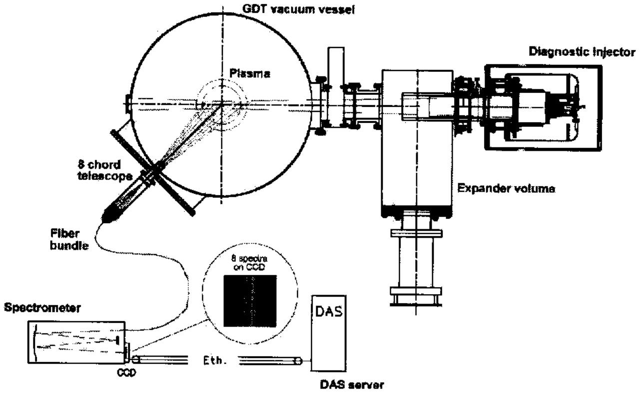

Fig. 2 The layout of the projected 8 chord MSE diagnostic for GDT.

TABLE 1

Element	*Value*
Type of ion optic system (IOS)	Focusing
IOS diameter	110 mm
Injection energy	50 keV
Beam current	5 atom Amperes
Beam radius in the focus	2 cm
Percentage of full energy component	87 %

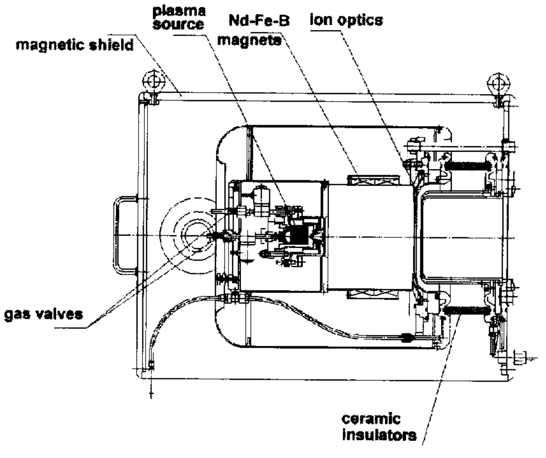

Fig. 3 The layout of the RFX-DNBI diagnostic neutral beam injector

characteristic is important for projected experiments since it allows to reduce broadening of Stark spectrum components [3].

The registration system of the upgraded MSE diagnostic is comprised of eight separate light collection telescopes (Fig. 2), optical shutter and the 0.5 m Ebert-Fastie spectrometer with the digital CCD detector. Recorded and digitized signal from the CCD is transmitted to the main GDT data storage for further processing and calculation of β. Comparing to the single-chord instrumentation reported previously in Ref. 3, we plan to use the Apogee Alta E47+ CCD detector. The outputs of eight fiber bundles are stacked vertically along the entrance slit of the spectrometer. The spectrometer disperses the light horizontally, but preserves this vertical mapping. Thus the CCD detector records eight separate motional Stark spectra, corresponding to the eight spatial measurement points in the plasma. According to the estimates made, the signal-to-noise ratio for each channel will be increased up to 7-10 mostly due to the better performance of the Apogee Alta detector.

Analysis of the spectrum obtained from the CCD in a GDT shot is performed using the quantum mechanical model, which considers also Zeeman splitting, fine structure of hydrogen atom energy levels and Lamb shift besides the motional Stark splitting. The detailed description of the model can be found in Ref. 7. Spectrum simulation is made for the actual geometry of MSE measurements in GDT plasma as it is shown in Fig. 4. Note that polarisation direction e2 corresponds to the recorded beam signal. Introducing a finite broadening of each line of the H_α multiplet, we simulate the observed spectrum. Fig. 5 shows the example of simulation of this kind. Parameters of calculation are the following: atom energy 40 keV, magnetic field 0.2 T, angle between the beam velocity and the observation line 22.5°. They reflect conditions of planned MSE measurements in the GDT midplane. Fine structure splitting is significant here leading to the deviation from symmetry of the spectra in Fig. 5.

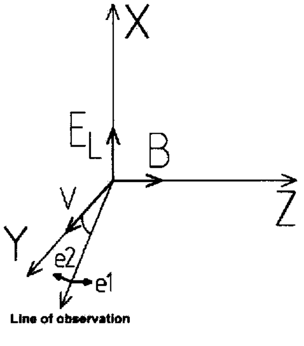

Fig. 4 Geometry used for the spectrum modeling (it repeats the measurement geometry). B is the magnetic field directed along Z axis, V is the beam velocity, E_L is the Lorenz electric field, vectors e1 and e2 show two independent directions of light polarisation (e2 reflects the observed one).

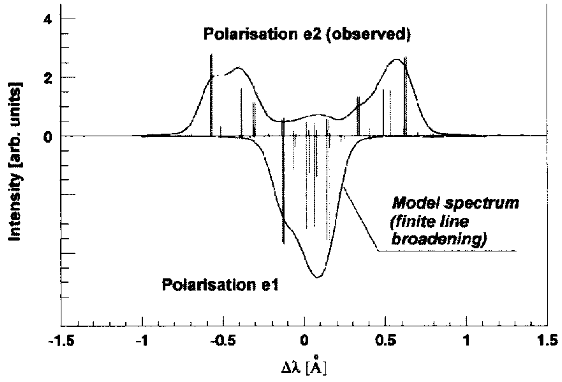

Fig. 5 The simulated H_α spectrum pattern. Calculation parameters are: atom energy 40 keV, magnetic field 0.2 T, angle between the beam and the observation line 22.5°. Lines with two polarisation directions are shown (see Fig. 4), where e2 corresponds to the observed beam emission. Lines e1 are shown drawn in the negative direction of Y axis for convenience. The curve shows profile of a real spectrum with a finite line broadening.

III. SUMMARY

The projected MSE diagnostic for the GDT mirror system provides the capability to measure the radial profile of magnetic field on a single-shot basis. Several improvements introduced into the design of upgraded diagnostic injector, allow to increase the beam energy and current density. The signal-to-noise ratio is expected to be about 7-10 for an individual spatial channel of the diagnostic. Precise calculation of plasma magnetic field is provided by the quantum mechanical model of the H-alpha spectrum.

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REFERENCES

[1] Mirnov V.V. and Ryutov D.D., *Sov. Tech. Phys. Lett.*, **5**, 279 (1979).

[2] V.V. Maximov, A.V. Anikeev, P.A. Bagryansky, A.A. Ivanov, A.A. Lizunov, S.V. Murakhtin,

K. Noack, and V.V. Prikhodko, *Nuclear Fusion*, **44**, 542-547 (2004).

[3] P.A. Bagryansky, P.P. Deichuli, D.J. Den Hartog, A.A. Ivanov, G. Fiksel, S.A. Korepanov, A.A. Lizunov, S.V. Murakhtin, and V.Ya. Savkin, *Rev. of Sci. Instrum.* **74**, 1592 (2003).

[4] A.A. Ivanov, A.V. Anikeev, P.A. Bagryansky, P.P. Deichuli, D.J. Den Hartog, G. Fiksel, S.A. Korepanov, A.A. Lizunov, V.V. Maximov, S.V. Murakhtin, K. Noack, and V.Ya. Savkin, *Phys. Rev. Lett.* **90**, 105002 (2003).

[5] S.A. Korepanov, P.A. Bagryansky, et.al., *Trans. Fusion Technol.*, **35**, 345 (1999)

[6] D.J. Den Hartog and D.J. Holly, *Rev. Sci. Instrum.*, **68**, 1038 (1997)

[7] G. Fiksel, D.J. Den Hartog et. al., *BINP preprint #2003-29*, Novosibirsk (2003).

[8] S.A. Korepanov, G.F. Abdrashitov, D. Beals, et al. *Rev. Sci. Instrum.*, **75**, (2004).