Note: Multi-point measurement of $|B|$ in the gas-dynamic trap with a spectral motional Stark effect diagnostic

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An upgraded spectral motional Stark effect diagnostic has been installed on the gas-dynamic trap (GDT) experiment to enable spatially resolved measurement of $|B|$. A new low-noise charge-coupled device detector, combined with enhancements of the diagnostic neutral beam, allows single-shot profile measurements. Previously only single-point motional Stark effect measurements were possible, and detector noise severely limited measurement precision, requiring multi-shot averaging. The plasma pressure profile in GDT is derived from the measured diamagnetic modification of $|B|$ and used to examine the conditions of stable plasma confinement at high plasma pressure.

out by the control PC, and sent to the data acquisition server for analysis.

The S/N of the recorded spectra has improved by approximately a factor of four, sufficient for single-shot analysis. This improvement has been achieved despite the fact that this new CCD detector is divided into eight binned strips, each 128 pixels high. Previously, the original CCD detector was vertically binned the entire height of the detector, resulting in more étendue for the spectrometer system. But the lower noise of new detector, an Apogee Alta U47 with an E2V CCD47-10 back-illuminated sensor, overcomes this disadvantage. The total detector system noise (in electrons) for each spatial channel is approximately one tenth the noise of the single spatial channel of the original detector. (This system noise includes contributions from the dark current integrated during the 20 ms exposure, dark current integrated during the vertical shift time required for on-chip binning, and read-out amplifier noise.) The new back-thinned sensor also has better vertical shift time required for on-chip binning, and read-out noise includes contributions from the dark current integrated during the 20 ms exposure, dark current integrated during the vertical shift time required for on-chip binning, and read-out amplifier noise. The best fit delivered the separation between individual lines, which is proportional to $|B_z|$. The $\sim45^\circ$ between the beam and sightlines increased the difficulty of fitting MSE data. Due to broadening of beam emission lines, no clear separation between the central $\sigma$-peak and two $\pi$-wings was visible on acquired spectra. This makes the fit procedure unstable, if both the parameters of split and broadening are being varied. The estimation for the beam emission line broadening (Gaussian curve

### Table I. Parameters of the diagnostic neutral beam on GDT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original DNB (DINA-F110)</th>
<th>New DNB (DINA-F110)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>40 keV</td>
<td>50 keV</td>
</tr>
<tr>
<td>Beam current (neutral H equivalent)</td>
<td>3.5 A</td>
<td>2.2 A</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>0.2 ms</td>
<td>5 ms</td>
</tr>
<tr>
<td>IOS aperture</td>
<td>80 mm</td>
<td>110 mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>1.3 m</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Beam diameter at focus</td>
<td>4.5 cm</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Current density at focus</td>
<td>0.2 A/cm²</td>
<td>0.4 A/cm²</td>
</tr>
<tr>
<td>Full energy fraction</td>
<td>$&gt;95%$</td>
<td>$\approx80%$</td>
</tr>
</tbody>
</table>

The ion-optical system (IOS) is composed of four electrodes (grids) 110 mm in diameter. The grids have a spherical shape enabling geometrical focusing of the ion beam.

Measuring relatively small modifications of magnetic field with a good accuracy requires precise calibration of the wavelength axis on acquired spectra. The setup of the MSE diagnostic on GDT allows capture of the beam emission spectrum, $H_\alpha$ emission line of the bulk plasma and two emission lines of CII carbon ions at $\lambda_1 = 657.805$ nm and $\lambda_2 = 658.288$ nm on the same CCD image. We used the $H_\alpha$ ($\lambda = 656.28$ nm) and CII ($\lambda = 658.288$ nm) for in situ measurement of the spectrometer dispersion.

If one can neglect the fine structure and other corrections of the same order to the Stark spectrum of beam emission, the spectrum can be fit by the simple formula: $I(\lambda) = C \cdot \Sigma e^{-(\lambda-\lambda_i)^2/2\delta \lambda^2}$, where $\lambda_i$ are nine equidistant $\pi$- and $\sigma$-components and $\delta \lambda$ is the line broadening. The best fit delivered the separation between individual lines, which is proportional to $|B_z|$. The $\sim45^\circ$ between the beam and sightlines increased the difficulty of fitting MSE data. Due to broadening of beam emission lines, no clear separation between the central $\sigma$-peak and two $\pi$-wings was visible on acquired spectra. This makes the fit procedure unstable, if both the parameters of split and broadening are being varied. The estimation for the beam emission line broadening (Gaussian curve

### FIG. 1. (Color online) A schematic view of the new motional Stark effect diagnostic on GDT: 1 – GDT vacuum vessel, 2 – DINA-5M diagnostic beam, 3 – expander volume with differential pump-out, 4 – plasma column cross section, 5 – pneumatic shield covering optics between shots, 6 – vacuum window and ferroelectric liquid crystal (FLC) shutter unit, 7 – assembly of 8 light collecting lenses, 8 – fiber bundle, 9 – Jarrel-Ash 0.5 m spectrometer, 10 – Alta U47 digital CCD detector, 11 – diagnostic server. The eight measurement locations in the plasma correspond to the eight spectra simultaneously recorded on the CCD. The cross section shown is at the fast ion turning point, thus the plasma has a relatively small diameter. The GDT axial magnetic field is perpendicular to the page, so the motional E points upward.

### FIG. 2. (Color online) Sample spectrum acquired in hot-plasma GDT shot. The ion-optical system (IOS) is composed of four electrodes (grids) 110 mm in diameter. The grids have a spherical shape enabling geometrical focusing of the ion beam. The magnetic field in plasma calculated by the beam emission spectrum: $|B_z| = 0.437$ T.
half-width at $e^{-1}$ level) gives $\delta \lambda \approx 0.65$ nm, where the beam particles angular spread makes the major contribution. Instead of fit, the real line broadening is measured directly in calibration shots without magnetic field and plasma. In these shots, the diagnostic beam is fired in the hydrogen cloud puffed by a pulsed gas valve.

In experiment on GDT, the major point of interest in measurements using spectral motional Stark effect diagnostic, is delivery of the so-called relative diamagnetic field reduction $\Delta B/B = (B_{\text{vacuum}} - B_{\text{plasma}})/B_{\text{vacuum}}$. We measured vacuum magnetic field in shots without plasma using local gas puff as a target for the diagnostic beam. The FLC shutter open time was varied in the range of 0.5..1 ms. Exposures less than 0.5 ms did not provide enough S/N for reliable single-shot spectra processing. Exposures longer than 1 ms “smeared” dynamics features of the fast ion equilibrium. Both in gas shots for $|B_{\text{vacuum}}|$ calibration and in hot-plasma shots, we observed an acceptable S/N $\approx 7$ (for central observation lines) of the beam signal. This allowed measurement of the local magnetic field with a relative accuracy of $\approx 3\%$–$5\%$ and final relative accuracy in $\Delta B/B$ of $\approx 10\%$–$15\%$. Figure 2 shows a sample spectrum recorded in a hot-plasma GDT shot. Deuterium neutral beam injection was used for heating, so the bulk plasma contained a fraction of thermal deuterons. This plasma confinement scenario with D-injection was optimized for maximum density of fast ions in the turning point region. Accordingly, the diamagnetic field reduction and the transverse plasma pressure were also maximized.

Figure 3 shows the radial profile of the $\Delta B/B$ quantity measured in this regime with the maximum of $\approx 0.27$. The beam signal level in edge observation lines was not enough for calculation of $|B_{\text{z}}|$ with an acceptable accuracy.

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