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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. © *2011 American Institute of Physics*. [doi:10.1063/1.3624742]

One of the leading candidates for development as a volume neutron source or a fusion system using D–He^3 and p–B^{11} schemes, is a device known as the "gas-dynamic trap" (GDT).[2] This magnetic mirror device confines a high-temperature plasma produced by injection of high-power neutral beams. For a magnetically confined plasma of a given temperature, the neutron source strength is strongly dependent upon the magnitude of the confining magnetic field and the plasma pressure. In the GDT experiment at the Budker Institute in Novosibirsk, Russia, initial measurements of plasma pressure confirmed that it reaches very high values.[2] Plasma pressure was experimentally determined by a motional Stark effect (MSE) diagnostic,[3] measuring the diamagnetic modification of |B|. Only single-point motional Stark effect measurements were possible, and detector noise severely limited measurement precision.

The MSE diagnostic relies on the Lorentz electric field $E = v \times B$ that appears 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. In GDT, the magnetic field is typically 0.4–0.5 T, so with a beam velocity of 2.7×10^6 m/s, other effects (Zeeman splitting, fine structure of atom energy levels, and other relativistic corrections) contribute negligibly to line splitting compared to Stark splitting. 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.[4]

The original MSE diagnostic at GDT was composed of a hydrogen neutral beam injector with beam energy of 40 keV and equivalent neutral current of 3.5 A. The spectroscopic instrumentation consisted of a 0.5 m Ebert-Fastie spectrometer with a CCD camera on the exit plane. Obtaining MSE spectra was a time-consuming process, as many spectra were recorded in order to obtain an averaged set with acceptable signal-to-noise. Analysis of the spectra indicated a perpendicular plasma β that exceeds 40% (plasma β is the ratio of plasma pressure to magnetic field energy density). This β value is near the theoretically predicted threshold for pressure-driven plasma instabilities. These initial measurements provided strong motivation to install an improved MSE diagnostic with spatial profile measurement capability. This new diagnostic substantially improves and expands |B| and β measurement capability by implementing new spectral recording instrumentation and upgrading the diagnostic neutral beam (DNB).

The primary enhancement of the spectral recording component of the new MSE diagnostic came from implementation of a modern CCD array detector. This has substantially improved the signal-to-noise ratio, enabling simultaneous recording of eight spatial points from a single GDT plasma discharge. The new CCD detector is mounted on the 0.5 m Ebert-Fastie spectrometer previously used. As shown in Fig. 1, the Stark-split H_α emitted by the hydrogen DNB is collected at ≈45° from the beam direction through a vacuum interface window. The ferroelectric liquid crystal (FLC) shutter serves two purposes. The first is simply as a shutter, to gate integration of the beam emission down to periods of 100 μs, allowing examination of the temporal evolution of plasma parameters on a shot-by-shot basis. The second function is polarization, allowing the σ or π components to be emphasized. After the shutter, the light is focused by eight miniature plano-convex lenses (f = 50 mm, D = 8 mm) onto the inputs of eight fiber bundles. The outputs of these 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. One set of spectra is recorded from each GDT plasma discharge, read

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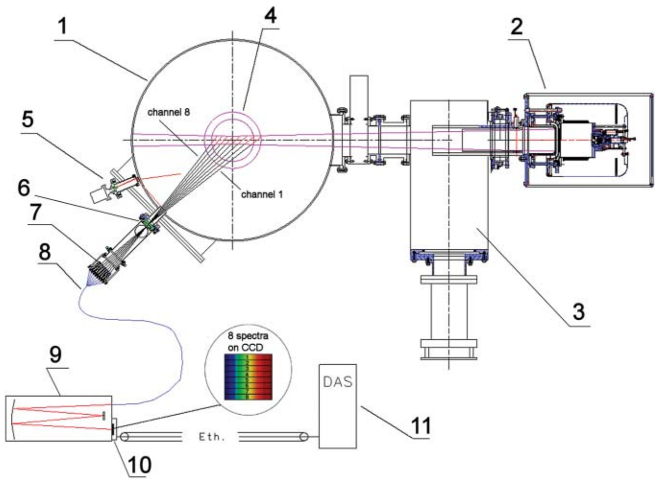

FIG. 1. (Color online) A schematic view of the new motional Stark effect diagnostic on GDT: 1 – GDT vacuum vessel, 2 – DINA-5M diagnostic beam, 3 – expander volume with differential pump-out, 4 – plasma column cross section, 5 – pneumatic shield covering optics between shots, 6 – vacuum window and ferroelectric 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.

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 quantum efficiency than the original detector and operates at a slightly lower temperature of $-27.5\,^{\circ}$C. The new detector system is controlled and read out by the spectroscopy software KESTREL-SPEC.

A small beam diameter at the focal plane and a high beam current fraction at the full injection energy make the DINA-F110 (Ref. 5) diagnostic neutral beam injector the appropriate instrument for application to space-resolved MSE measurements. The parameters of the original DNB as used to make the initial MSE measurements, and parameters of the new DNB, are shown in Table I. The beam energy has been increased to 50 keV to increase the wavelength spread of the motional Stark spectrum, thus enabling more accurate measurement of the splitting of the individual Stark components.

TABLE I. Parameters of the diagnostic neutral beam on GDT.

Parameter	Original DNB (DINA-5M)	New DNB (DINA-F110)
Beam energy	40 keV	50 keV
Beam current (neutral H equivalent)	3.5 A	2.2 A
Pulse duration	0.2 ms	5 ms
IOS aperture	80 mm	110 mm
Focal length	1.3 m	1.8 m
Beam diameter at focus	4.5 cm	2.5 cm
Current density at focus	0.2 A/cm^2	0.4 A/cm^2
Full energy fraction	$>$95%	$\approx$80%

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_α 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_α ($\lambda = 656.28$ 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: $I(\lambda) = C \cdot \Sigma e^{-(\lambda-\lambda_i)^2/\delta\lambda^2}$, where λ_i are nine equidistant π- and σ-components and $\delta\lambda$ is the line broadening. The best fit delivered the separation between individual lines, which is proportional to $|B_z|$. The $\sim$45° 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 σ-peak and two π-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

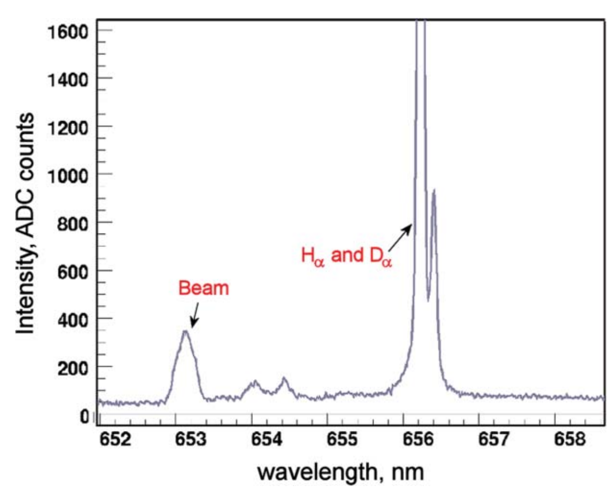

FIG. 2. (Color online) Sample spectrum acquired in hot-plasma GDT shot. Magnetic field in plasma calculated by the beam emission spectrum: $|Bz| = 0.437$ T.

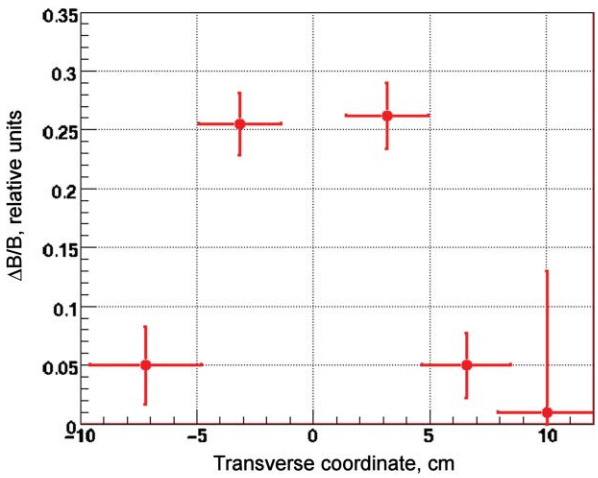

FIG. 3. (Color online) Radial profile of the diamagnetic field reduction ΔB/B in the fast ion turning point.

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 $\Delta B/B = (B_{vacuum} - B_{plasma})/B_{vacuum}$. 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 $|B_{vacuum}|$ calibration and in hot-plasma shots, we observed an acceptable S/N ≈ 7 (for central observation lines) of the beam signal. This allowed measurement of the local magnetic field with a relative accuracy of ≈3%–5% and final relative accuracy in ΔB/B of ≈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 ΔB/B quantity measured in this regime with the maximum of ≈0.27. The beam signal level in edge observation lines was not enough for calculation of $|B_z|$ with an acceptable accuracy.

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