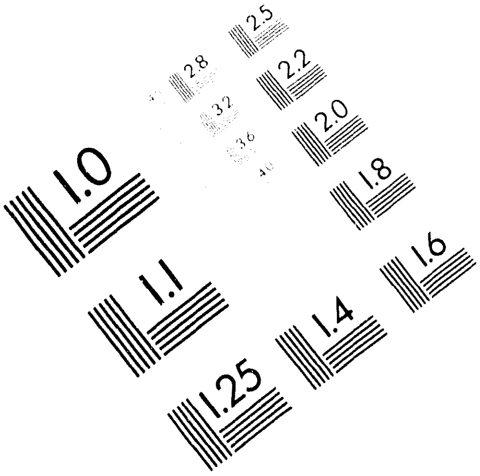

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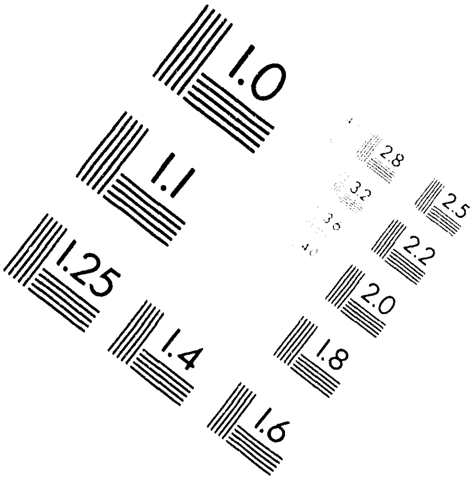

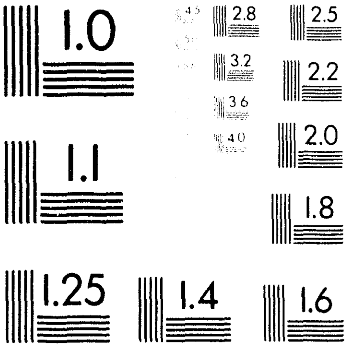

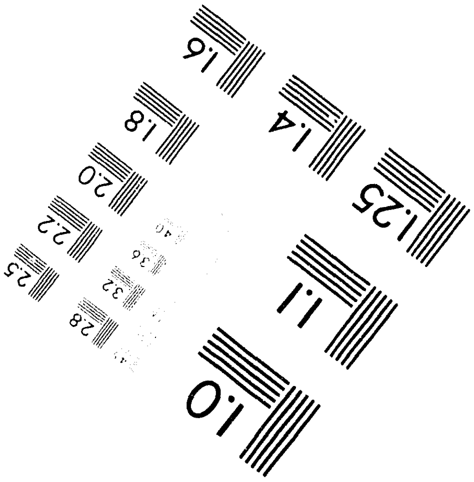

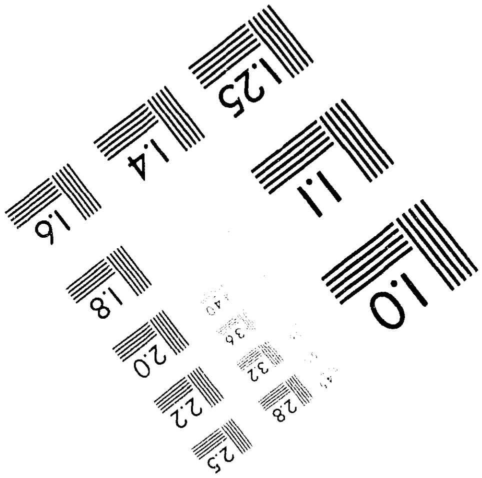

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Motional Stark Effect Upgrades on DIII-D

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Motional Stark Effect Upgrades on DIII-D*

B.W. Rice, D.G. Nilson, D. Wróblewski*
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1 Abstract

The measurement and control of the plasma current density profile (or q profile) is critical to the advanced tokamak program on DIII-D. A complete understanding of the stability and transport properties of advanced operating regimes requires detail poloidal field measurements over the entire plasma radius from the core to the edge. In support of this effort, we have recently completed an upgrade of the existing MSE diagnostic, increasing the number of channels from 8 to 16. A new viewing geometry has been added to the outer edge of the plasma which improves the radial resolution in this region from 10 cm to < 4cm. This view requires the use of a reflector that has been designed to minimize polarization amplitude and phase effects. Vacuum-compatible polarizers have also been added to the instrument for *in-situ* calibration. Future use of the MSE diagnostic for feedback control of the q profile will also be discussed.

2 Introduction

The measurement of poloidal fields using the motional Stark effect is a well established diagnostic technique that has been implemented on several tokamaks [1, 2, 3]. In brief, the measurement relies upon the splitting of the neutral beam Balmer-α line (D_α) into orthogonally polarized components (σ, π) due to the motional $\mathbf{E} = \mathbf{v} \times \mathbf{B}$ electric field. When viewed in a direction perpendicular to $\mathbf{E}$, the Stark σ and π components are polarized perpendicular and parallel to the direction of the electric field respectively. By measuring the polarization of the Stark σ component, the local pitch angle of the magnetic field B_v/B_t can be deduced.

An 8 channel Motional Stark Effect (MSE) diagnostic has been operational for two years now on DIII-D [1]. The instrument was originally designed for optimum radial resolution of ~ 2 cm in the core, but has poor resolution of ~ 10 cm near the edge. After examining the equilibrium reconstructions for several different J profile shapes relevant to the advanced tokamak program on DIII-D, and performing error analysis using MSE data, we concluded that several improvements to the MSE diagnostic could be made which would benefit our program. These include: 1) improving the radial resolution near the outer edge; 2) increasing the number of measurement chords; and 3) reducing systematic errors through improved calibration techniques. To address these concerns, we have added an additional 8 MSE chords (called edge MSE) to the outside 30 cm of the plasma, using a new viewing geometry that improves the radial resolution in this region.

3 Measurement Geometry

The performance of the MSE diagnostic depends sensitively on the intersection angles between the collection optics line-of-sight, the neutral beam, and the toroidal field. Three criteria must be satisfied for every MSE chord: 1) the optical line-of-sight must be nearly tangent to the toroidal field for optimum radial resolution; 2) the angle between the optics line-of-sight and the neutral beam must be sufficient to give a large enough Doppler shift to clearly separate the full beam energy Stark spectrum from thermal D_α, impurity lines, and the 1/2 and 1/3 beam energy spectra; and 3) the induced $\mathbf{v} \times \mathbf{B}$ electric field must be large enough to provide sufficient separation between the σ and π lines.

The original multichord MSE system on DIII-D had 8 chords ranging from near the vessel center at R=155 cm to near the plasma edge at R=228 cm. Referring to the geometry shown in Fig. 1, the radial resolution is given approximately by δR $(d + w \sin\Omega)/\sin(\Omega + \alpha)$ where d is the optical spot size, and w is the beam width. This function is plotted in Fig. 2 for the existing MSE system (solid line), which shows poor resolution outside of $R \sim 195$ cm. To improve this situation we have added 8 additional chords viewing from a midplane port at a toroidal angle of 45° as shown in Fig. 1. The view from this port is nearly tangent to B_t at the plasma edge, thus giving good radial resolution as shown by the dotted line in Fig. 2. The original MSE chords (now called central) have been realigned towards the plasma core cover the radial range 155 cm $< R <$ 200 cm, while the edge system covers 200 cm $< R <$ 230 cm. This gives a channel spacing of about 4-5 cm, with a resolution for each channel better than 5 cm over the entire measurement range. No chords are located inside of R=155 cm due to excessive beam attenuation.

The maximum angle φ between the optical sightline and the neutral beam is 60° for this view, which is sufficient to separate the 75 keV full-energy Stark spectrum from the 1/2 and 1/3 beam energy spectra. However, there are two strong carbon impurity lines located at 6578 Å and 6583 A which interfere with the 'red-shifted' D_α line (there are no impurity lines in the 'blue-shifted' direction of the central MSE chords). A typical plasma spectrum obtained using the CER spectrometer is shown in Fig. 3 for a deuterium beam energy of 75 keV. This spectra would simulate that of an MSE chord viewing the edge at R = 228 cm from the 45° port. Under these conditions, the full-energy Stark σ line is clearly separated from the CII impurity lines. These impurity lines would, however, interfere with the MSE measurement at beam energies of 65 keV or lower.

The separation of the σ and π components (proportional to $\mathbf{v} \times \mathbf{B}$) has also been calculated for the edge MSE geometry and is found to be sufficient for toroidal fields of 0.8 T or greater.

4 Edge MSE Design

Details of the light collection optics for the edge MSE instrument are shown in Fig. 4. The design is complicated by the need to have a reflector located close to the plasma surface. A similar problem was encountered on TFTR [3]. A property of all metal reflectors is that the s and p polarizations reflect with different amplitude and phase depending on the angle of incidence [4]. This effect is a serious problem because it can lead to a rotation of the incoming polarization and also polarizes the background plasma light. In principle, if the reflection amplitudes and phase are measured for a given reflector, and the background light level is monitored, then these effects can be corrected [3]. However, these corrections are quite sensitive to reflector surface coatings and may vary during plasma operation.

Two options were investigated for eliminating polarization effects upon reflection: an internally reflecting prism and a multilayer dielectric reflector. The prism has the advantage that the reflectance for the s and p polarizations is 100 percent for all internal reflection angles [4]. Although there is a phase shift, this can be corrected with a coating on the reflecting surface [5]. Because of the large path length through glass, the prism must be manufactured from a zero Verdet constant glass such as Schott SFL6 or SFL56 [6]. Unfortunately, these glasses all exhibit a large thermal expansion coefficient and thermal stress calculations indicate that the prism would be susceptible to stress fractures during baking. Instead we opted for a multilayer dielectric coated reflector [7], consisting of alternating layers of fused silica and tantalum pentoxide deposited on a fused silica substrate. The fused silica substrate offers excellent stability during thermal cycling. Design calculations for angles of incidence between 48° and 68° indicate that the s and p reflection amplitudes are equal to within 1%, with the phase shift between the two polarizations being held to less than 15 degrees. Bench tests of the actual reflector confirmed these specifications. As illustrated in Fig. 4, the reflector is protected from coatings and plasma damage by a carbon tile on one side and a 2mm thick fused silica shield on the viewing side. Thin coatings on the fused silica shield should not affect the polarization because of the near normal angle of incidence.

There are two shutters incorporated into the design. The outer shutter is a carbon shield designed to protect the optics during helium glow wall conditioning between shots. The inside shutter has been fitted with four 2.4 × 3 cm polarizers [8] to be used for calibration. These polarizers are vacuum compatible, consisting of a BK7 substrate with imbedded silver wires. The polarizer shutter can be inserted during plasma operations to provide an *in-situ* offset calibration.

The vacuum window is quite large at 5.5 inches in diameter. Bench measurements indicate that there is a small level of stress birefringence present in the window, but this can be accounted for in the instrument calibration. The three lenses are 11 cm in diameter and combine to give a demagnification of 10. To avoid Faraday rotation effects they are manufactured from Schott SFL6 glass. For each channel, the lenses image onto an array of six 1mm diameter fibers stacked vertically, corresponding to a 1 cm wide by 8 cm high image in the plasma.

The remainder of the edge MSE instrument design external to the vessel (Fig. 5) is is quite similar to the original system described in Ref. [1]. The lenses focus light through two photoelastic modulators (PEM) and a sheet polarizer onto the array of fiber optics. The modulators operate at 20 kHz and 23 kHz. At the fiber output, the light is collimated, passed through a 3 Å bandpass filter, and focused onto a Hamamatsu R636 photomultiplier tube. Two lock-in amplifiers detect the 2nd harmonic of each PEM frequency, which are approximately proportional to the sine and cosine of the polarization pitch angle γ. One notable difference in design compared with the original MSE instrument is that the Wollaston prism used to collect both polarizations as described in [1] has been replaced with a simple sheet polarizer. This reduces the number of photomultipliers to one per channel rather than two and simplifies the entire design. The signal level is maintained by using a total of six fibers to collect a single polarization, rather than three fibers for each polarization as used previously.

5 Future Work

During the next experimental campaign on DIII-D, we will make the first attempts at feedback control of the on-axis safety factor q_0 using MSE. In preparation for this, we have installed analog fiber optic links to transmit both the $\sin\gamma$ and $\cos\gamma$ lock-in signals to an HP workstation dedicated for feedback control. The workstation will digitize all of the magnetic loop and MSE signals real-time and provide feedback signals to non-inductive current drive sources such as neutral beams or fast wave. Algorithms for calculating parameters such as q_0 directly from the MSE data are being developed.

6 Acknowledgement

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[2] F.M. Levinton, et al, Rev. Sci. Instrum. **61**, 2914 (1990).

[3] F.M. Levinton, Rev. Sci. Instrum. **63**, 5157 (1992).

[4] F.A. Jenkins and H.E. White, *Fundamentals of Optics*, (McGraw-Hill, Inc., New York, 1976).

[5] P. Mauer, J. Opt. Soc. Am. **56**, 1219 (1966).

[6] Schott Glass Technical Information Bulletin No 17 (1985).

[7] Reflector manufactured by Optical Coating Laboratory Inc., Santa Rosa, CA.

[8] Polarizers manufactured by Corning Incorporated, Corning, N.Y.

[illegible] = 3 + 6.6 [illegible]
= 36.4" ✓

7 Figure Captions

1. Overview of the upgraded 16 chord MSE system viewing geometry on DIII-D.
2. Radial resolution versus radial position for the central and edge MSE viewing geometry
3. Red-shifted Stark spectra and CII impurity lines at a beam energy of 75 keV.
4. Edge MSE collection optics.
5. Overview of the edge MSE detection system

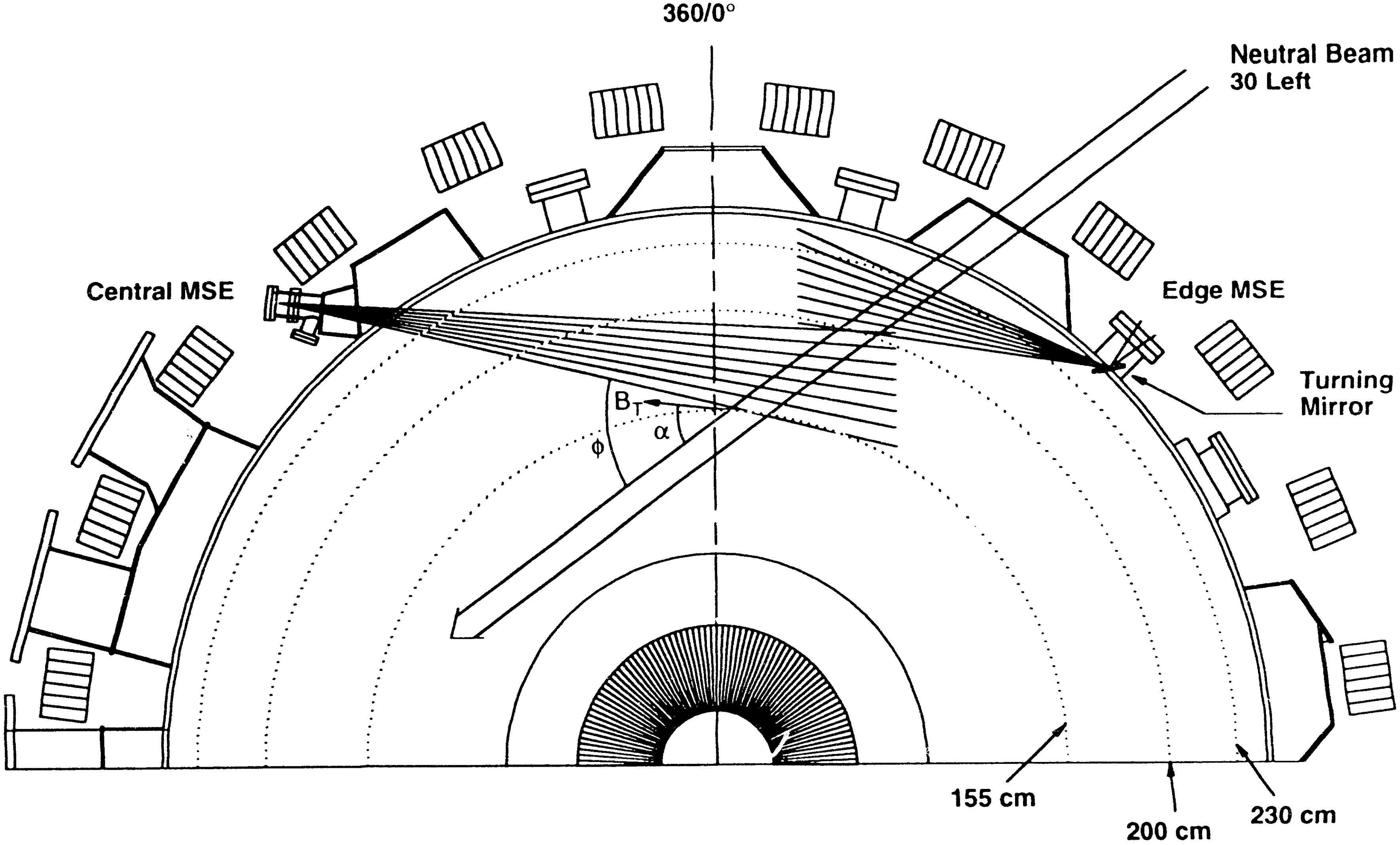
360/0°
Neutral Beam
30 Left
Central MSE
Edge MSE
Turning
Mirror
B_T
α
ϕ
155 cm
200 cm
230 cm

Fig. 1

MSE Angle Calc Chart 1

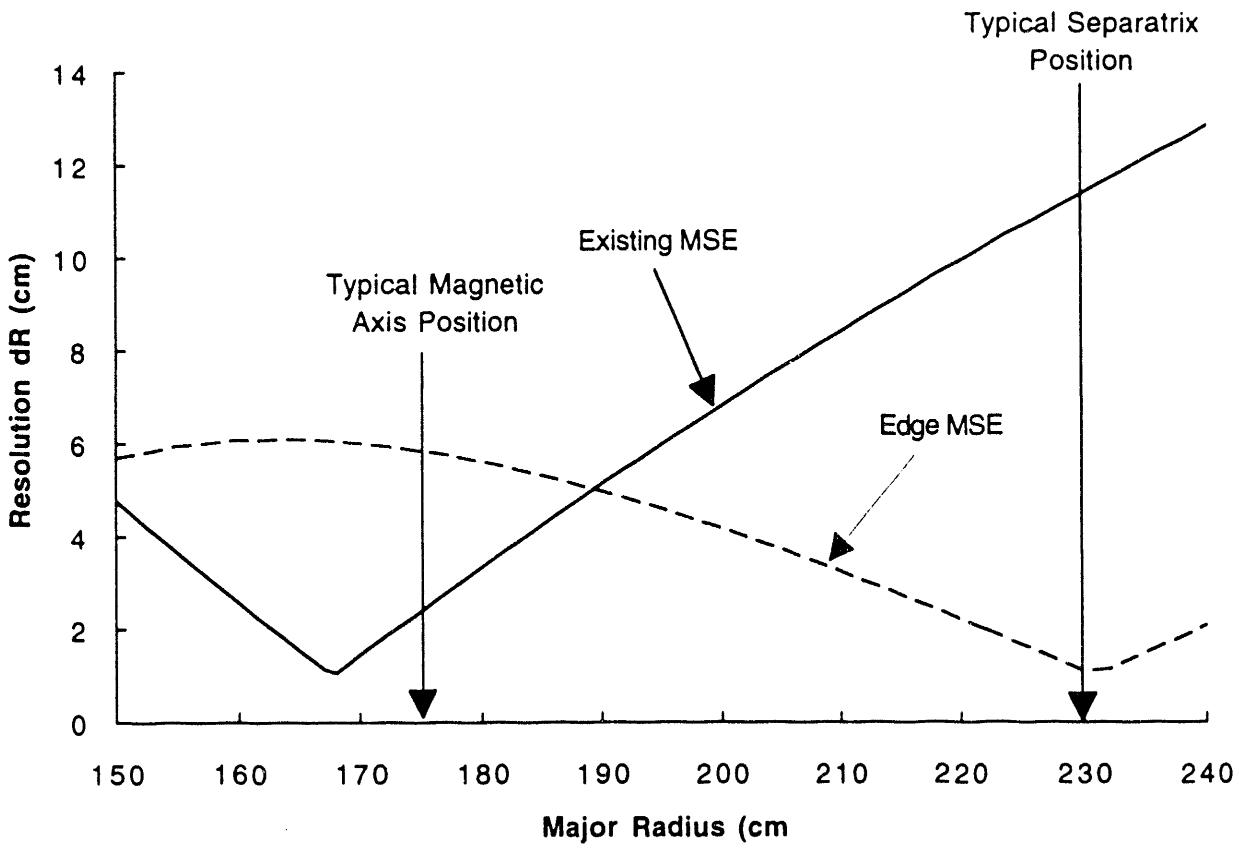

Fig. 2

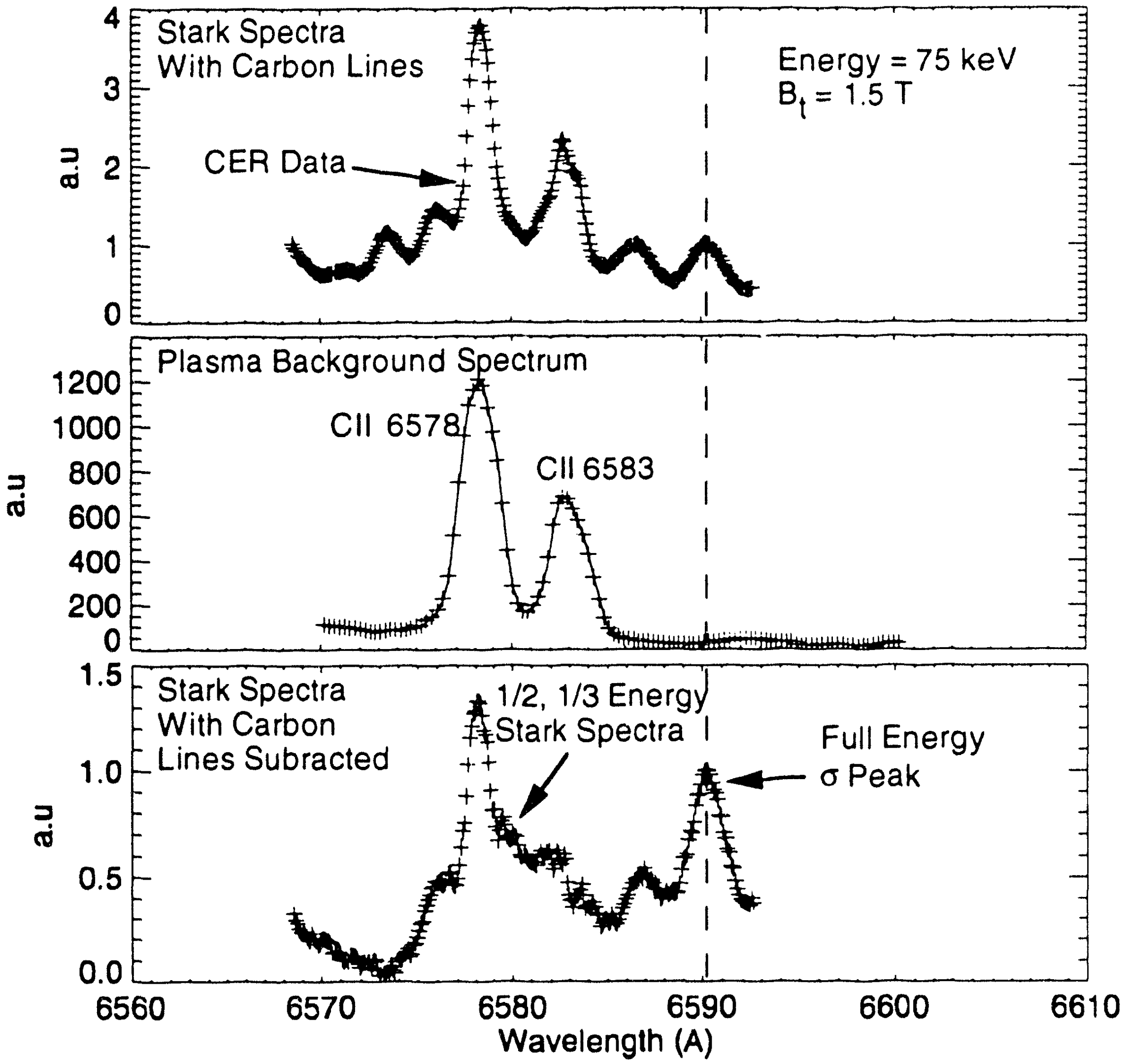
Stark Spectra
With Carbon Lines
Energy = 75 keV
B_t = 1.5 T
CER Data
a.u
4
3
2
1
0
Plasma Background Spectrum
CII 6578
CII 6583
a.u
1200
1000
800
600
400
200
0
Stark Spectra
With Carbon
Lines Subracted
1/2, 1/3 Energy
Stark Spectra
Full Energy
σ Peak
a.u
1.5
1.0
0.5
0.0
6560
6570
6580
6590
6600
6610
Wavelength (A)

Fig. 3

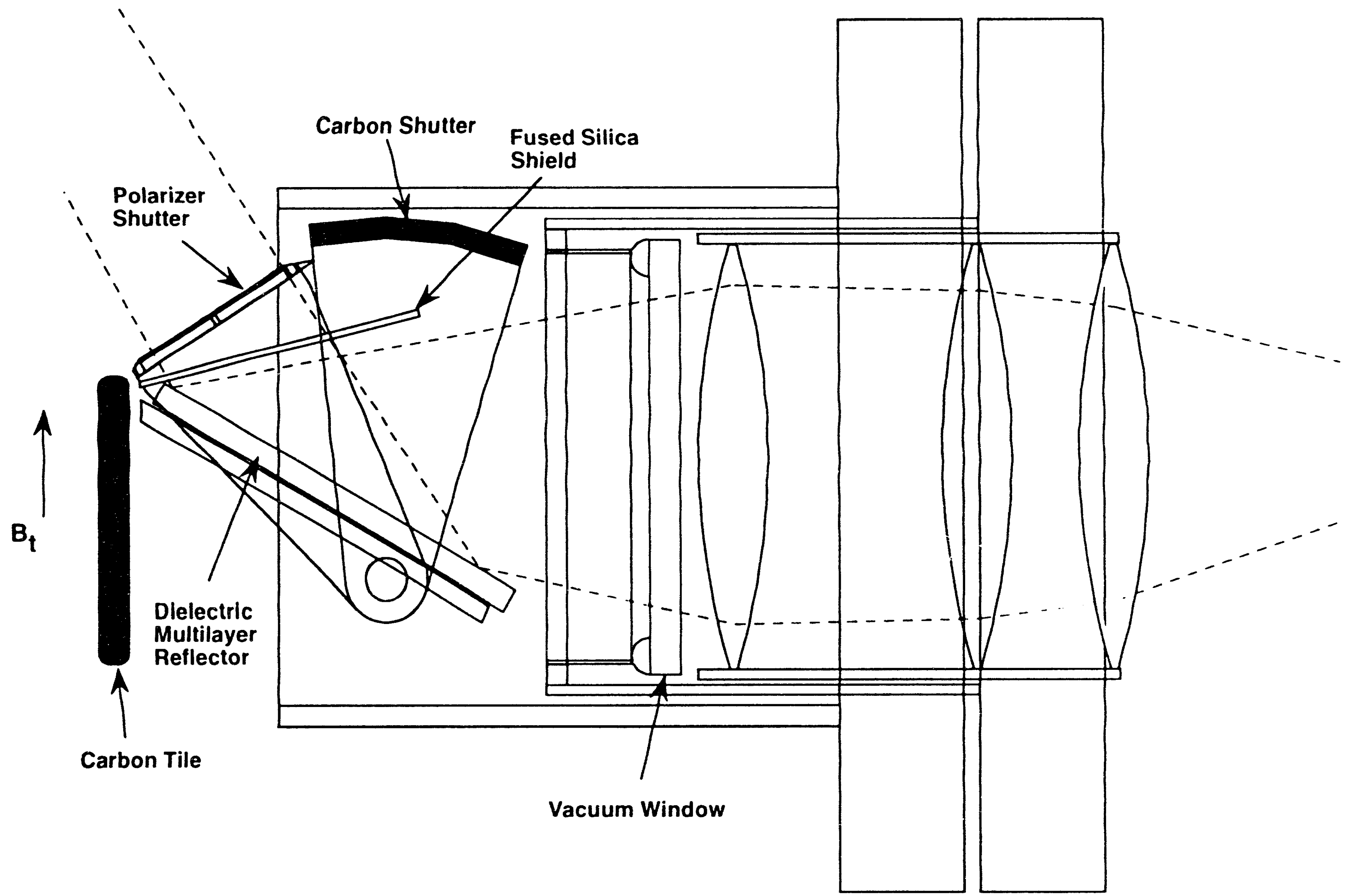
Carbon Shutter
Fused Silica Shield
Polarizer Shutter
B_t
Dielectric Multilayer Reflector
Carbon Tile
Vacuum Window

Fig. 4

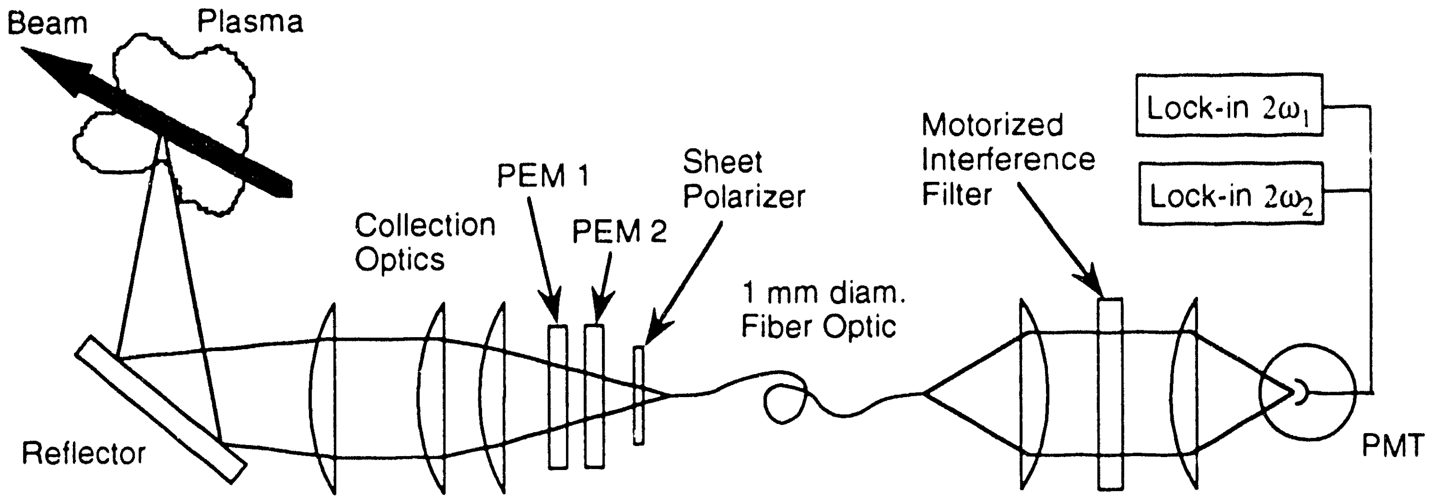
Beam
Plasma
Reflector
Collection Optics
PEM 1
PEM 2
Sheet Polarizer
1 mm diam. Fiber Optic
Motorized Interference Filter
Lock-in $2\omega_1$
Lock-in $2\omega_2$
PMT

Fig. 5

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