Abstract
Measurement of $E^-$ desired
High-speed line-width measurement (stark spectrum)
System overview (top view machine)

Fluctuation estimates (equations)
Estimate values & correlation analysis
Estimates for Pegasus vs NSTX & DIII-D
Anticipated mag. field helps ease spectrometer

Broadening Effects
Broadening Effects - Divergence
Broadening Effects - Window effect
Spectrometer resolution

Throughput requirements & F-P design
Spectrometer concept
Spectrometer code results
APDs

Beam summary and requirements
Ion source
Power supplies
Summary

**E$^-$ diagnostic on Pegasus**

*D. S. Thompson, 55th APS-DPP Meeting, Denver CO, November 2013*
Abstract

Accessible methods for measuring $\tilde{E}(r,t)$ in large-scale magnetic confinement experiments are highly desired for validation studies of plasma turbulence models. A new technique based on neutral beam emission spectroscopy is being developed to address this need. Rapid fluctuations in the separation of spectral components of the motionally induced Stark spectrum can reflect fluctuations in the intrinsic electric field of the plasma. Polarization spectroscopy via high-resolution, high-throughput spectrometers that compensate for field-of-view broadening is being developed to isolate and measure these fluctuations. Cross-power correlation analysis between the line-width fluctuations and plasma density fluctuations will be employed to extract the expected small signals. Electric field fluctuations at mid-minor-radius, normalized to an estimated MSE field, are expected to be on the order of $\tilde{E}/E_{MSE} \approx 1 \times 10^{-3}$ in the Pegasus Toroidal Experiment and are comparable to those expected in NSTX and in DIII-D.
A high-speed, high-throughput polarization spectrometry measurement is being developed to measure local E field fluctuations. Expected fluctuations in the intrinsic electric field are small, and correlation analysis techniques are being developed to extract $\tilde{E}$ by using $\tilde{n}$ as a reference carrier wave.
The H Balmer-α line is split by the Motional Stark field induced by neutral beams.

Fluctuations in the π components of the Stark spectrum reflect fluctuations in the intrinsic electric field

\[ \mathbf{E}_{\text{tot}} = \mathbf{E}_{\text{intr}} + \mathbf{v}_b \times \mathbf{B} \]

Measuring \( \Delta \pi \) provides \( \tilde{E}_{\text{intr}} \)

It is expected that \( E_{v \times B(MSE)} \gg E_{\text{intr}} \)

Many others.

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Selection of beam and observation intersection angle mitigates smearing by the dominant $\sigma$ component of the Motional Stark spectrum.

High-resolution polarization spectroscopy can then extract fluctuations in the line-width splitting of the $\pi$ components of the spectrum.

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Tokamak fluctuation scalings provide a course estimate of electric field fluctuation levels

A course estimate of drift wave fluctuation levels can be obtained from scaling relations*

For most tokamaks:

\[
\begin{align*}
\tilde{E} & \sim k_{\perp} \tilde{\phi} \\
\tilde{n}/n & \sim \frac{e\tilde{\phi}}{Te} \sim \frac{1}{k_{\perp} L_n} \\
k_{\perp} \rho_s & \sim \alpha
\end{align*}
\]

\[
\longrightarrow \quad \tilde{E} \approx \frac{\tilde{n} Te}{n e \rho_s \alpha} \quad \longrightarrow \quad \tilde{E} \approx \frac{Te}{eL_n}
\]

Assuming \( L_n \sim a \), electric field fluctuation levels can be estimated by

\[
\tilde{E} \approx \frac{Te}{ea}
\]


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E field fluctuations are expected to be an order of magnitude smaller than fluctuations currently measured.

Anticipated fluctuations for Pegasus are small:
\[ \tilde{E}/E_{\text{MSE}} \sim 0.10 - 0.15\% \]

Small fluctuations in T and n have been measured:
\[ \tilde{T}_i/T_i \sim 2.1\% \quad (\text{HF/UF-CHERS})^* \]
\[ \tilde{n}/n \sim 1\% \quad (\text{BES})^{**} \]

UF-CHERS correlates \( \tilde{T}_i \) with \( \tilde{n} \) to suppress noise

Assuming uncorrelated noise, it should be possible to extract \( \langle \tilde{E}\tilde{n} \rangle \) in a similar way:
\[
\tilde{S}_E = \tilde{E} + \tilde{N}_E \quad \tilde{S}_{\text{BES}} = \tilde{n} + \tilde{N}_{\text{BES}}
\]
\[
\langle \tilde{S}_E \tilde{S}_{\text{BES}} \rangle = \langle \tilde{E}\tilde{n} \rangle + \langle \tilde{E}\tilde{N}_{\text{BES}} \rangle + \langle \tilde{N}_E \tilde{n} \rangle + \langle \tilde{N}_E \tilde{N}_{\text{BES}} \rangle
\]

New correlation analysis techniques are being developed to extract \( \tilde{E} \) from \( \langle \tilde{E}\tilde{n} \rangle \)

---

Fluctuation level estimates are small, but may be comparable between machines

\[ \sim O(0.1\%) \]

for these machines

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( T_e (\text{eV}) )</th>
<th>( B (\text{T}) )</th>
<th>( a (\text{m}) )</th>
<th>( \frac{\bar{E}}{E_{\text{MSE}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pegasus – 1</td>
<td>100</td>
<td>0.15</td>
<td>0.3</td>
<td>( 1 \times 10^{-3} )</td>
</tr>
<tr>
<td>Pegasus – 2</td>
<td>300</td>
<td>0.3</td>
<td>0.35</td>
<td>( 1.4 \times 10^{-3} )</td>
</tr>
<tr>
<td>NSTX</td>
<td>1000</td>
<td>0.6</td>
<td>0.6</td>
<td>( 1.3 \times 10^{-3} )</td>
</tr>
<tr>
<td>DIII-D</td>
<td>2000</td>
<td>2</td>
<td>0.7</td>
<td>( 0.7 \times 10^{-3} )</td>
</tr>
</tbody>
</table>

Small signals can be considerably increased by imposing large local E field fluctuations with biased injectors, permitting validation of diagnostic concept at greater signal levels

Inferred \( \tilde{\phi} \) can be compared with local probe measurements

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Small line widths necessitate mitigation of smearing by other broadening effects

Beam divergence

Finite $T_i$ in the ion source leads to spectral broadening

Thermal broadening of beam neutrals

Velocity variations along sightline broaden spectrum. This effect is not configurable

Window effect

Light entering window originates from different angles to the beam, which causes Doppler broadening of the spectrum

Spectrometer resolution

An insufficient number of spectral channels results in inability to resolve spectral peaks

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A low-divergence diagnostic beam is desired to reduce divergent broadening.

Beam divergence

Finite $T_i$ in the ion source results in broadening of the emitted beam.

Beam divergence causes variation in Doppler shifts.

Diagnostic requires low beam divergence $\sim 0.5^\circ$, which has been achieved by PBX-M beam*

* Coupland et al., Rev. Sci. Instrum. 61, 472 (1990)

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Doppler-compensated optics are being developed to counter window effect broadening

Larger windows permit greater throughput but resulting Doppler broadening overwhelms line splitting

A spectrometer design that combines Doppler-compensation with high-throughput, high-efficiency optics is desired

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High spectrometer resolution is required to resolve $\pi$ components of Stark spectrum

Experience from UF-CHERS suggests that the minimum number of spectral channels per peak is 4.

In order to resolve a pair of peaks and allow for some beam energy drift, 8 spectral channels are desired.

Total throughput is divided by the number of spectral channels, so it is advantageous to use the minimum number of channels desired for resolution.

Typical spectra cover 2 Å, suggesting a spectral resolution requirement of 0.25 Å or better for an eight detector array.

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Stronger magnetic fields ease constraints on spectrometer by accentuating Stark splitting

Doubling the magnetic field strength from 0.15T to 0.30T increases the Motional Stark splitting of the spectral line.

Stronger fields, like those on larger machines, magnify the splitting effect but reduce the intensity.

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Piezo-electric control of etalon separation and wedge tilt

Number spectral channels: 8

Detectors: Fast, low noise, thermo-electrically cooled APD array with frequency-compensated preamplifiers

Assuming a 20 cm diameter collection lens and 2 cm spatial resolution, spectral resolution and throughput requirements suggest an etalon with a diameter of ~4 cm is sufficient

Multipass input optics may increase performance by a factor of 2-4 but are bulky
Large aperture spectrometer concepts that improve etendue and preserve spectral resolution are being studied.

3/4 m Spectrometer

Image space f-number: $N = \frac{f}{2}$

High efficiency diffraction gratings

8 independently tilted grating columns

Number spectral channels: 8

Detectors: Fast, low noise, thermo-electrically cooled APD array with frequency-compensated preamplifiers

Mosaic components to reduce cost

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An array of thermo-electrically cooled avalanche photodiodes measures fluctuations

APD detector array like those currently employed by UF-CHERS* can be used for diagnostic

Thermo-electrically cooled
Dark current min. @ $T \leq 10\, ^\circ\text{C}$
Optimal SNR $\sim 1650 \, V_{\text{bias}}$
Internal gain $\sim 200 \, \text{V/V}$
Frequency-compensated preamplifier
Effective QE $\sim 0.32$
Frequency response $\sim 1\, \text{MHz}$


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Refurbished PBX-M diagnostic neutral beam, designed for MSE, will be deployed on Pegasus

Beam gas: H$^0$
Beam Energy: 60-80 kV
Extracted Ion Current: 2-3 A
Pulse length: 10-20 ms
Focal Length: 400 cm
Full Energy J at focal plane: 3-6 mA/cm$^2$
Beam Divergence: 0.5°
Species Ratio:
\[ \text{H:H/2:H/3} = 22 : 35 : 43 \] @ 67 kV
Diameter at extraction plane: 8.8 cm
1/e diameter at focal plane: 3.3 cm
Offset aperture focusing
Neutralizer target thickness: 200 mTorr-cm,
50% efficiency for 80keV/amu atomic H

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The beam will employ technology from Local Helicity Injection\textsuperscript{1} as an arc plasma ion source.

Washer stack arc sources have been successfully implemented on other diagnostic beams \textsuperscript{2,3,4}

Near 100\% ionization of arc plasma provides advantageous species mix for spectroscopy

E\textsubscript{1} : E\textsubscript{2} : E\textsubscript{3} = 93.6 : 6 : 0.3 achieved at MST\textsuperscript{5}

Design does not require an extended burn-in period

Typical conditioning period for an injector on Pegasus is \textasciitilde50-100 shots, with lifetimes of 100s-1000s of shots

\textsuperscript{1}Perry et al., TP8.00019
\textsuperscript{2}Belchenko et al., Rev. Sci. Instrum. 61, 378 (1990)
\textsuperscript{3}Deichulu et al., Rev. Sci. Instrum. 79, 02C106 (2008)
\textsuperscript{5}Abdrashitov Rev. Sci. Instrum. 72, 594 (2001)

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The diagnostic beam will be powered with up-to-date high-voltage power supplies.

Power supplies designed for 10-20 ms pulse lengths and modifiable energies.

Accel supplies rated for 80kV operation at 5A.

Decel supply can be obtained commercially.

Filters designed to reduce accel grid ripple.

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An electric field fluctuation diagnostic is being developed at the Pegasus Toroidal Experiment.

High-speed polarization spectrometry will be used to infer $E(t)$ from Stark line width fluctuations.

**Near term objectives:**
- Plasma source fabrication and testing
- Refurbish beam
- Complete fabrication of power supplies
- Finalize spectrometer design

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