Progress Toward a Technique for Measuring Electric Field Fluctuations in Tokamak Core Plasmas

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Abstract

System overview (top view machine)

High-speed line-width measurement (stark spectrum)

Intensity ratio equations (equations)

System overview (top view machine)

Goemetry (3D simulation)

Er, Ez (3D simulation)

Fluctuation estimates (equations)

Estimate values & correlation analysis

Broadening Effects - Window effect

Throughput requirements & F-P design

Spectrometer resolution (HF-CHERS plot)

APDs / Phantom

Broadening Effects - Divergence

Low-div PBX-M beam

Power supplies

Ion source characterization

Plasma data

Summary

E$^*$ diagnostic on Pegasus

DNB is up and running

Fluctuation estimates (equations)

Intensity ratio equations (equations)

System overview (top view machine)

E$^*$ diagnostic on Pegasus
Measurements of E field fluctuations are desired for validating tokamak core turbulence and transport models

- A high-speed, high-throughput polarization spectrometry measurement is being developed to measure local E field fluctuations up to 500 kHz

- Sensitivity to $k \perp \rho_s \approx 0.1 – 1.5$ expected, with $\tilde{E} / E_{\text{MSE}} \approx 10^{-3}$

- A low-divergence diagnostic neutral beam designed for MSE experiments on PBX-M is being optimized for fluctuation measurements and prepared for deployment on the Pegasus Toroidal Experiment
Motional Stark effect splits H$^0$ Balmer-$\alpha$ into $\pi$ ($\Delta m = 0$; parallel to $E_{\text{MSE}}$) and $\sigma$ ($\Delta m = \pm 1$; perpendicular) components$^1$

The MSE Hamiltonian is$^2$

$$H_{\text{St}} = -(3/2)n(n_1-n_2)e a_0 E$$
$$\rightarrow \Delta \lambda_{\text{H}_\alpha} (\text{Å}) = 0.277(\pm 2,\pm 3,\pm 4,\pm 8)E_{\text{tot}} \text{ (MV/m)}$$

The measured field is

$$E_{\text{tot}} = E_{\text{plasma}} + v_{\text{beam}} \times B$$

For 80 keV beam, $B_T = 0.3\text{T}, E_{v \times B} \approx 1 \text{ MV/m}$

If $\delta B \delta E_{\text{plasma}} \sim 0$ and $\delta v_{\text{beam}} \delta E_{\text{plasma}} \sim 0,$

$$\delta(\Delta \lambda_{\pi}) \rightarrow \delta(E_{\text{tot}}) \rightarrow \delta(E_{\text{plasma}})$$

$\delta v_{\text{beam}}$ information obtained from Doppler shift


Potential Use of Fluctuations of \( \pi \) and \( \sigma \) Intensity Ratio

- Intensity ratio function of upper state population density

\[
R = \frac{\sum I_{\pi}}{\sum I_{\sigma}} = \frac{\sin^2 \theta \ n_{\pi}}{1 + \cos^2 \theta \ n_{\sigma}} = F \frac{\sin^2 \theta}{1 + \cos^2 \theta}
\]

- Intensity ratio fluctuates due to density fluctuations

\[
\tilde{R} = R \left[ \frac{\partial \ln F}{\partial \ln n_e} \frac{\tilde{n}_e}{n_e} + 4 \frac{\cos \theta}{(1 + \cos^2 \theta) \sin \theta} \tilde{\theta} \right]
\]

- For electrostatic fluctuations, \( \tilde{E} \) term \( \sim 2-5 \times \tilde{n} / n \)

\[
\tilde{R} = R \left[ 2.7 \tilde{\theta} - 0.07 \frac{\tilde{n}}{n} \right]
\]

Drift Waves: \( \frac{\tilde{n}}{n} \sim \frac{e\phi}{T_e} \)

- Reduce effect of \( \tilde{n} / n \) further by multiple sightlines

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Optimization of beam-spectrometer angle should improve the ability to resolve line-width fluctuations.

Geometry selection maximizes sensitivity to desired fluctuation component.

High-resolution polarization spectroscopy can extract fluctuations in spectral line-widths or component intensity ratios.

Pegasus Toroidal Experiment

80 keV H0 diagnostic neutral beam

Spectrometer and collection optics

1m

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MADISON
Beam-sightline selection can optimize sensitivity to transport-relevant $\delta E$ fluctuations

Lorentz field structure (black arrows)
Beam energy (red arrows)
Magnetic field ($B_{\text{total}}$ in blue arrows)
Spectrometer sightline (green line)

Lorentz field fluctuations subtracted from signal

Example: midplane ($\theta_{b-s} \approx \pi / 2$)
beam and sightline maximizes sensitivity to fluctuations in $E_z$

$$\theta \approx \pi / 2 \quad \left| \vec{E} \right| = \sqrt{E_z^2 + E_r^2}$$

$$\frac{\vec{E}_r}{\vec{E}} = \cos \theta \approx 0 \quad \vec{E}_{\text{tot}} \approx \vec{E}_z$$
Geometry and polarimetric approach can be varied to obtain $\delta E_r$, $\nu_r$, $\delta E_z$, and $\nu_z$.

$\tilde{E}_z, \tilde{\nu}_r$ : Line-width method

- Midplane view + spectral width fluctuations
  - Multichannel spectrometer: $\Delta \lambda_{\pi}$

$\tilde{E}_r, \tilde{\nu}_z$ : Insensity ratio method

- View from above/below at angle $\theta$ along beamline
  - High throughput filter to isolate polarized components: $I_{\pi}/I_{\sigma}$

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

A coarse estimate of drift wave fluctuation levels can be obtained from scaling relations\(^1\), \((T_e \sim 150 \text{ eV}, a \sim 0.3 \text{ m}, B \sim 0.15T, 80\text{keV beam})\)

\[
\tilde{E} \approx \frac{T_e}{ea} \approx 500 \text{ V/m}
\]

\[
E_{\text{MSE}} \approx 5 \times 10^5 \text{ MV/m}
\]

\[
\tilde{E} / E_{\text{MSE}} \approx 10^{-3}
\]

Midplane beam injection and sightline nominally most sensitive to vertical field fluctuations

\[
\delta \tilde{E} \approx -k_z \tilde{\phi} \hat{z}
\]

From which radial flux can be estimated \((B_\phi >> B_\theta)\)

\[
\tilde{v}_r \approx \frac{\tilde{E}_z}{B_\phi} \quad \longrightarrow \quad \tilde{\Gamma} \sim \langle \tilde{n} \tilde{v}_r \rangle
\]

\(\Delta r \approx 2 \text{ cm}\) allows resolution of local electric field turbulence at the beam-sightline intersection

Anticipate sensitivity to wavenumber spectral range similar to BES

\[
k_\perp \rho_s \approx 0.1 - 1.5
\]

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

Small fluctuations in $T$ and $n$ have been measured:

$$\frac{\tilde{T}_i}{T_i} \sim 10^{-2} \quad \text{(HF/UF-CHERS)}^1$$
$$\frac{\tilde{n}}{n} \sim 10^{-2} \quad \text{(BES)}^2$$

UF-CHERS correlates $\tilde{T}_i$ with $\tilde{n}$ to extract turbulent signal

Anticipated fluctuations for Pegasus are small:

$$\frac{\tilde{E}}{E_{\text{MSE}}} \sim 10^{-3}$$

Expected noise floor $\sim 10^{-3}$

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Spectral resolution $\Delta \lambda \approx 0.25\text{Å}$ is required to resolve $\pi$ components of Stark spectrum

- Variance tends toward the real value with increasing number of spectral channels
- It is advantageous to use the minimum number of channels desired for resolution
  
  Total throughput is divided by the number of channels
- Typical spectra cover 2 Å, suggesting a spectral resolution requirement of 0.25 Å or better for an eight detector array.
- Detection system is designed to operate in linear region, as in HF-CHERS

Optics are being developed to mitigate geometric Doppler broadening.

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

Optical masking results in unacceptable throughput.

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

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Piezo-electric control of etalon separation and wedge tilt

Detectors: Fast, low noise TEC-APD array with frequency-compensated preamplifiers
   Considering intensified, high-speed CMOS Phantom cameras for simplified data acquisition

For $d_{\text{lens}} = \varnothing 20 \text{ cm}$ and $\Delta r = 2 \text{ cm}$, $d_{\text{etalon}} \approx \varnothing 4 \text{ cm}$ satisfies requirements of $\Delta \lambda = 0.01 \text{ nm}$ and (throughput) $U \approx 0.01 \text{ cm}^2\text{-ster}$

Possible addition of multipass input optics may increase performance by a factor of 2-4
An array of thermo-electrically cooled avalanche photodiodes high speed CMOS detector record spectrometer output

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

Thermo-electrically cooled
Optimal SNR $\sim 1650 \, V_{\text{bias}}$
3 mm$^2$ ster per spectral channel
Frequency-compensated preamplifier
Effective QE $\sim 0.32$
$f_{\text{sample}} \sim 1 \, \text{MHz} \rightarrow f_{\text{Ny}} \sim 500 \, \text{kHz}$

High-speed Phantom cameras by Vision Research are being evaluated as a compact and streamlined alternative

Full frame: 25 kHz
1280 X 64 Pixels: 500 kHz
8 mm$^2$ ster per spectral channel
QE = 50% over visible range
Turn key operations
Potential to add image intensifier to increase gain


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A low-divergence diagnostic beam is required to reduce divergence broadening

Beam divergence

Finite $T_i$ in the plasma source results in broadening of the emitted beam

Beam divergence causes variation in Doppler shifts

Beam divergence requirement: $\Omega < 1^\circ$

$\Omega \sim 0.5^\circ$ achieved by PBX-M beam*

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

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Refurbished PBX-M diagnostic neutral beam, designed for MSE, is being prepared for deployment on Pegasus.

Beam Divergence: $\geq 0.47^\circ$

Beam gas: $H^0$

Beam Energy: 60-80 kV

Extracted Ion Current: 2-3 A

Pulse length: 100 ms

Focal Length: 400 cm

Full-energy $J$ at focus: 3-6 mA/cm$^2$

Species Ratio: $E:E/2:E/3 = 22:35:43$

Diameter at extraction plane: 8.8 cm

1/e diameter at focal plane: 3.3 cm

Tetrode configuration with offset aperture focusing

Neutralizer target thickness: 200 mTorr-cm, 50% efficiency for 80keV/amu atomic hydrogen

J.R. Coupland et al, Rev. of Sci. Instrum. 61, 472 (1990)
I.L.S. Gray et al, IEEE 1, 149 (1989)

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3-phase transformer-based power supply provides isolated power with ripple frequencies above turbulence

Power supplies designed for 100 ms and modifiable energies

Accel grid supplies rated for 80kV operation at 5A with low stored energy

Off-the-shelf suppression grid supply

Ripple frequency selectable > 250 kHz
Diagnostic beam with operational new source is preparing for high voltage power supply

- Baseline pressures of $6 \times 10^{-7}$ torr achieved before conditioning
- All gauges and gate valves pneumatically controlled to allow high voltage operation
- NI FPGA and DAQ unit with LabVIEW software monitor system remotely and provide real-time process control
- HV power supply components in bid process
- Arc source and diagnostics operational
- Source characterization in progress

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Near 100% ionization of arc plasma provides advantageous species mix for spectroscopy. Full energy fractions of 80-90% achieved with other arc source diagnostic beams\(^1^3\).

Design does not require an extended burn-in period. Conditioning for Pegasus arc sources requires 10s of shots, with lifetimes of 1000s of shots.

Operational high-voltage diagnostics:

- 120 kHz \(I_{\text{ARC}}\) & \(V_{\text{ARC}}\)
- 500 kHz single swept Langmuir probe
- Calibrated Rogowski coil
- Photodiode
- Pirani gauge

Neutral pressure in bucket: 1-20 mtorr

Arc parameters: \(n_e \approx 10^{22} \text{ m}^{-3}\), \(T_e \approx 10\ \text{eV}\)

\[
\frac{V_{\text{bucket}}}{V_{\text{arc}}} \approx 2000
\]

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\(^1\) Deichuli et al, Rev. Sci. Instrum. 79, 02C106 (2008)
Mapping of operational space of plasma source underway to match grid perveance requirements

$\mathbf{j}_{\text{plasma}} = n_e e v_B$ ; $\mathbf{j}_{\text{ext}} = I_{\text{ext}} / A_{\text{ext}}$

Extracted current: 1-3 A → 34.7 – 104 mA/cm²
Grid extraction area: 19 x 1.52 cm² = 28.8 cm²

$$n_e = \frac{I_e^*}{e A} \sqrt{\frac{2 \pi m_e}{T_e}}$$ (*)

$$v_B = \sqrt{\frac{T_e}{m_i}}$$

Langmuir probe analysis: $T_e \approx 3.6$ eV,
$$n_e \approx 6.4 \times 10^{17} \text{ m}^{-3}$$

Density required to match $j_{\text{ext}}$: $3.7 \times 10^{17} \text{ m}^{-3}$

Quasi-stable period ~ 8 ms

Probe sampling in shaded region

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Measurements of E field fluctuations are desired for testing tokamak core turbulence and transport models

A high-speed, high-throughput polarization spectrometry measurement is being developed to measure local E field fluctuations

Mid-plane beam-sightline geometry advantages line-width measurements sensitive to $E_z$, $v_r$ fluctuations with $k_\perp \rho_s \approx 0.1-1.5$

A low-divergence diagnostic neutral beam to be used in these measurements has been retrofitted with a species-mix optimizing plasma source and will soon have high-voltage power

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