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

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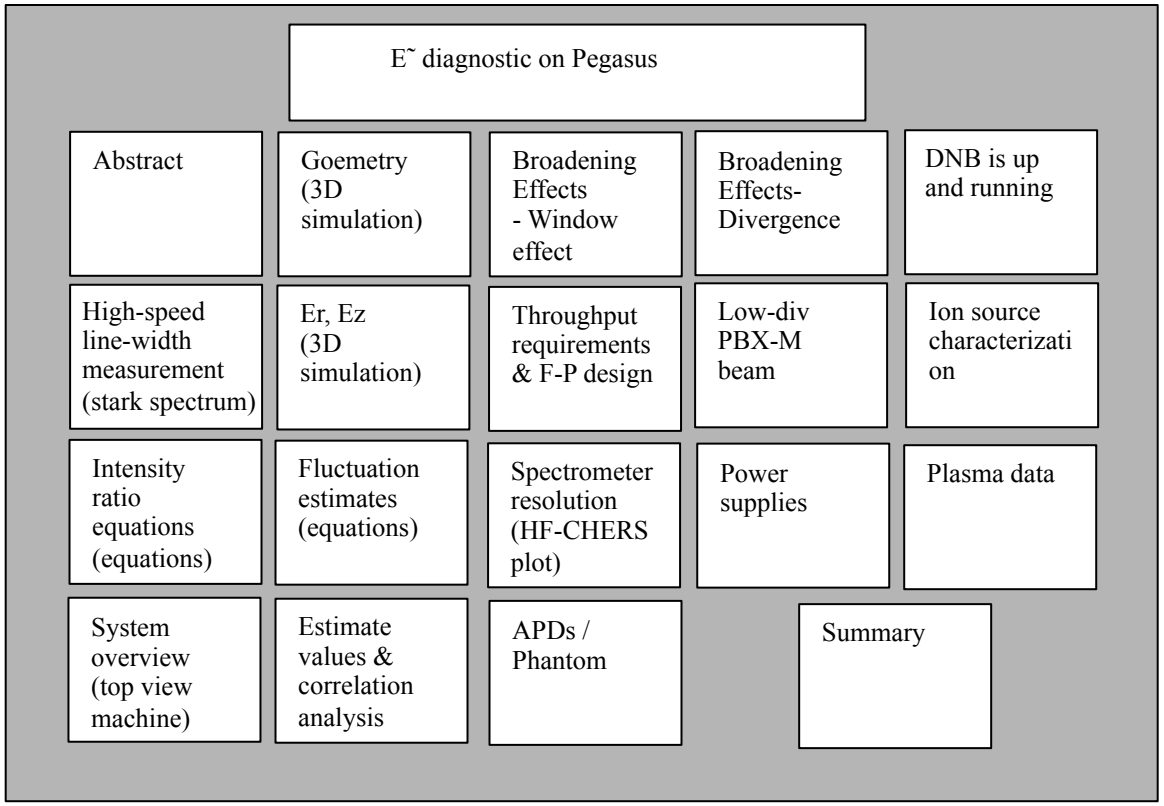
University of Wisconsin-Madison

APS-DPP 2014
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New Orleans, LA



PEGASUS Toroidal Experiment

Layout



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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 $\tilde{E} / E_{MSE} \approx 10^{-3}$
- 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

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Fluctuations in the separation of the π components of the Stark manifold are proportional to fluctuations in the local electric field

Motional Stark effect splits H^0 Balmer-α into π ($\Delta m = 0$; parallel to E_{MSE}) and σ ($\Delta m = \pm 1$; perpendicular) components[1]

The MSE Hamiltonian is[2]

$$H_{St} = -(3/2)n(n_1\text{-}n_2)ea_0E$$

$$\rightarrow \Delta\lambda^{\pi}_{H\alpha}(\text{Å}) = 0.277(\pm 2,\pm 3,\pm 4,\pm 8)E_{tot}\ (\text{MV/m})$$

The measured field is

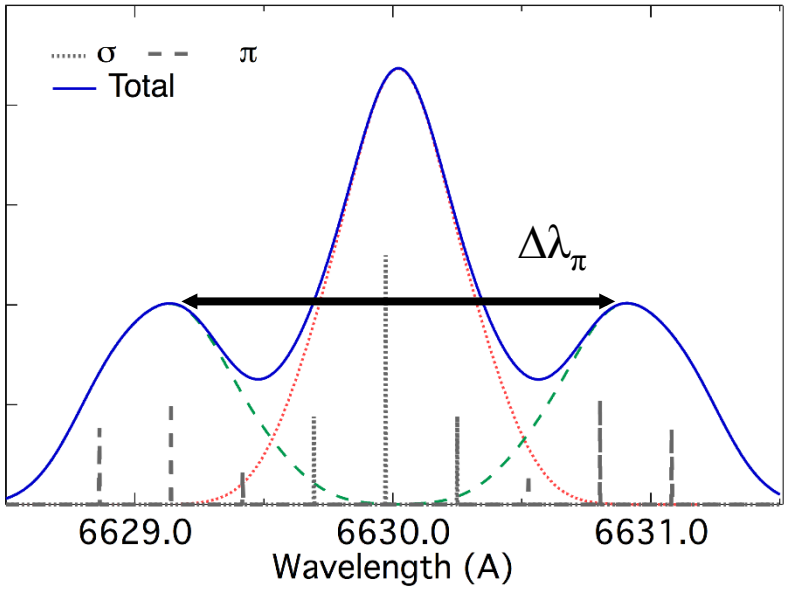
$$\boldsymbol{E}_{tot} = \boldsymbol{E}_{plasma} + \boldsymbol{v}_{beam} \times \boldsymbol{B}$$

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

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

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

δv_{beam} information obtained from Doppler shift



Model MSE spectrum

1 H. A. Bethe & E. E. Salpeter. Quantum Mechanics of One- and Two-Electron Atoms. New York: Dover Publications, Inc., 1957.

2 H. Y-H. Yuh, PhD Thesis, MIT (1995).

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Potential Use of Fluctuations of π and σ Intensity Ratio

- Intensity ratio function of upper state population density

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

- Intensity ratio fluctuates due to density fluctuations

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

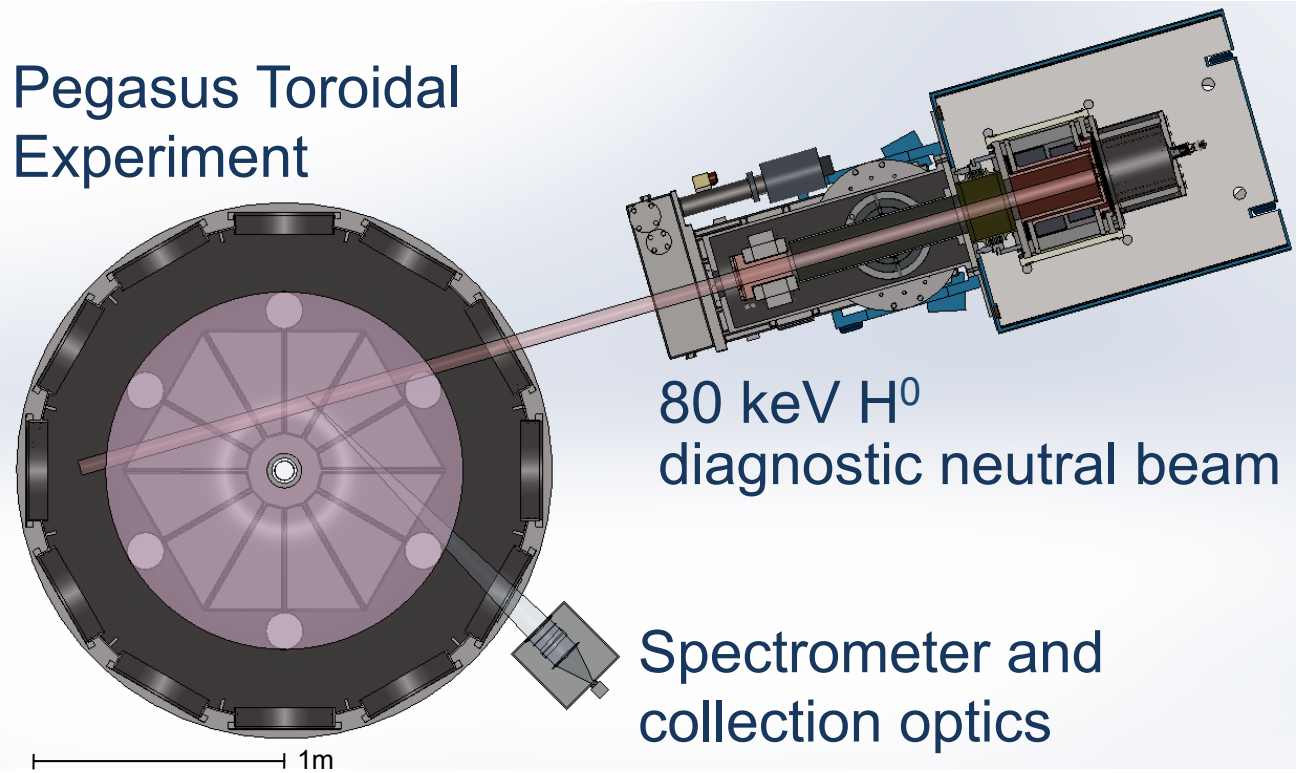
- For electrostatic fluctuations, $\tilde{E}$ term ~2-5 x $\tilde{n}/n$

$$\tilde{R} = R\left[2.7\tilde{\theta} - 0.07\frac{\tilde{n}}{n}\right] \qquad \text{Drift Waves: } \frac{\tilde{n}}{n} \sim \frac{e\tilde{\phi}}{T_e}$$

- 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

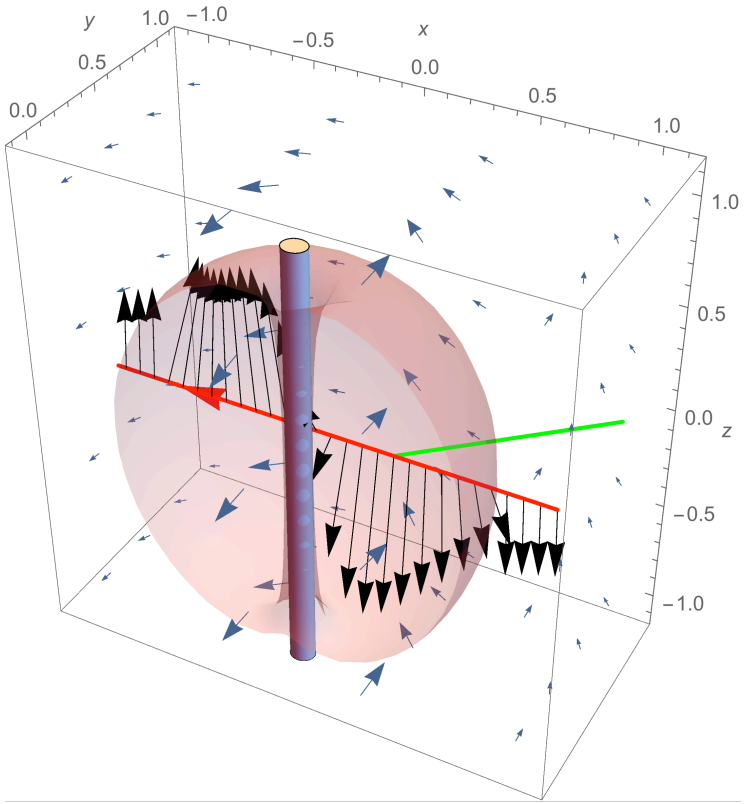


Geometry selection maximizes sensitivity to desired fluctuation component

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

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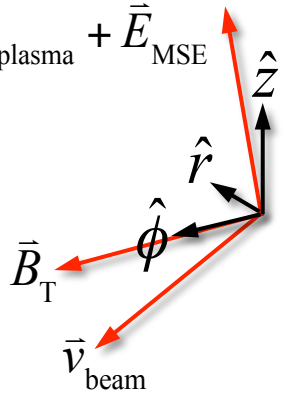
Beam-sightline selection can optimize sensitivity to transport-relevant δE fluctuations



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

$$\vec{E}_{\text{tot}} = \vec{E}_{\text{plasma}} + \vec{E}_{\text{MSE}}$$

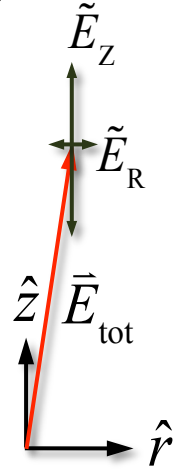
Lorentz field fluctuations subtracted from signal



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

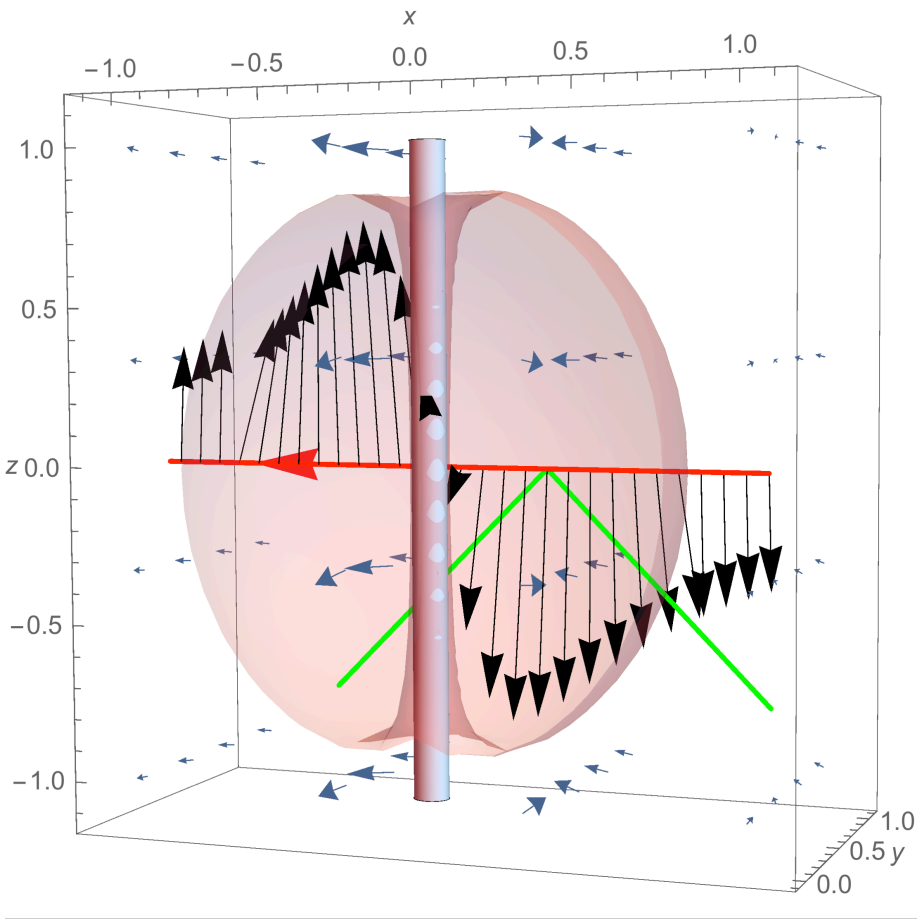
$$\theta \approx \pi/2 \qquad \left|\vec{E}\right| = \sqrt{E_z^2 + E_r^2}$$

$$\frac{\vec{E}_r}{\vec{E}} = \cos\theta \sim 0 \qquad \tilde{E}_{tot} \approx \tilde{E}_z$$



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Geometry and polarimetric approach can be varied to obtain δE_r, v_r, δE_z, and v_z



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

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

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

- View from above/below at angle θ along beamline
  - High throughput filter to isolate polarized components: I_π/I_σ

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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 ~ 150 eV, a ~ 0.3 m, B ~ 0.15T, 80keV beam)

$$\left.\begin{aligned}\tilde{E} &\approx T_e/ea \approx 500\,\mathrm{V/m} \\ E_{\mathrm{MSE}} &\approx 5\times10^5\,\mathrm{MV/m}\end{aligned}\right\} \longrightarrow \tilde{E}/E_{\mathrm{MSE}} \approx 10^{-3}$$

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

$$\delta\vec{E} \approx -k_z\tilde{\phi}\hat{z}$$

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

$$\tilde{v}_r \approx \frac{\tilde{E}_z}{B_\phi} \longrightarrow \tilde{\Gamma} \sim \left\langle \tilde{n}\tilde{v}_r \right\rangle$$

Δr ≈ 2 cm allows resolution of local electric field turbulence at the beam-sightline intersection

Anticipate sensitivity to wavenumber spectral range similar to BES

$$k_\perp \rho_s \approx 0.1 - 1.5$$

[1] *Wesson, J. Tokamaks. Oxford, UK: Clarendon Press, 2004.*

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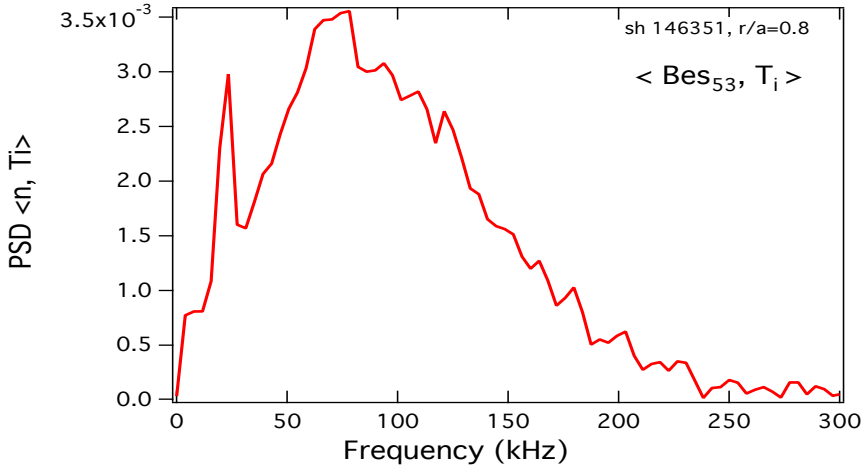
E field fluctuations are expected to be an order of magnitude smaller than fluctuations currently measured

Small fluctuations in T and n have been measured:

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

$$\tilde{n}/n \sim 10^{-2} \quad \text{(BES)}^2$$

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



Anticipated fluctuations for Pegasus are small:

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

Expected noise floor ~ 10^{-3}

[1] *H.T. Evensen et al., Rev. Sci. Instrum.* ***66****, 845 (1995)*

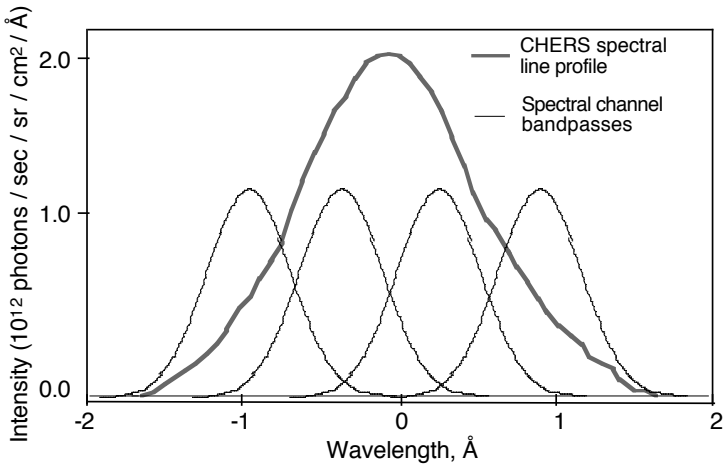
[2] *R.J. Fonck et al., Phys. Rev. Letts* ***70****, 3736 (1993)*

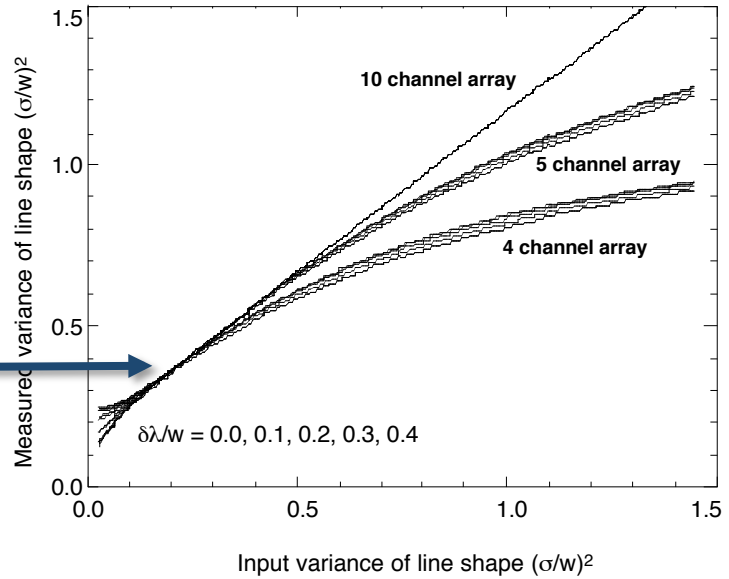
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Spectral resolution $\Delta\lambda \approx 0.25$Å is required to resolve π components of Stark spectrum

- 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

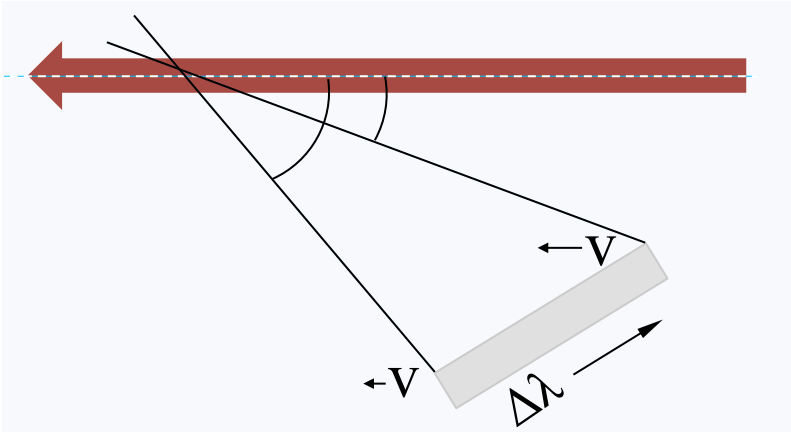


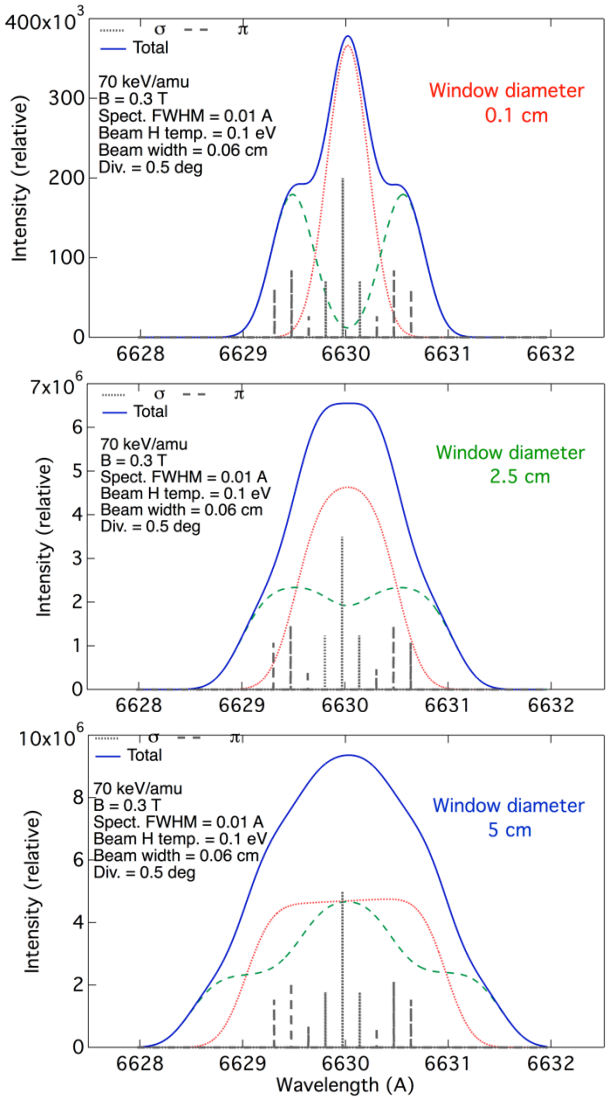


H. Evensen, PhD Thesis, UW-Madison (1996)

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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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Fabry-Perot design with high-throughput wedge-spaced etalon mitigates window effect

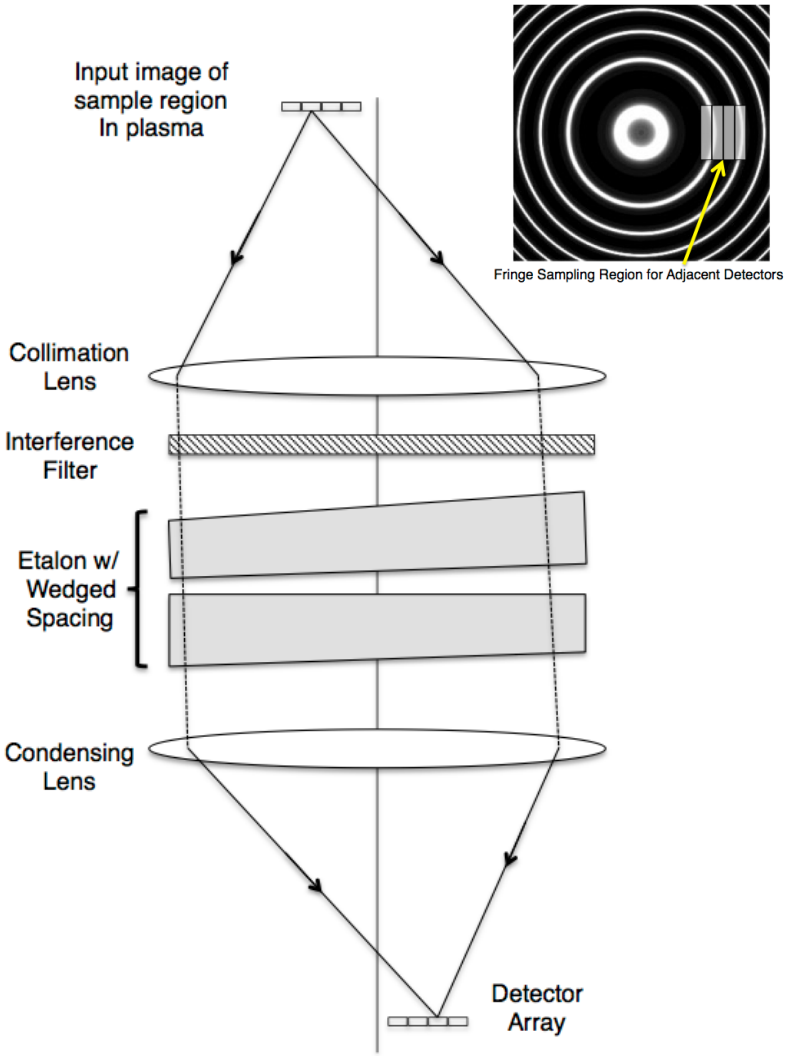
Piezo-electric control of etalon separation and wedge tilt

Detectors: Fast, low noise TEC-APD array with frequency-compensated preamplifiers

Considering intensified, high-speed CMOS Phantom cameras for simplified data acquisition

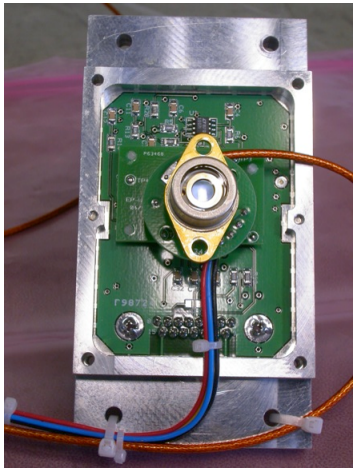
For d_{lens} = Ø20 cm and Δr = 2 cm, d_{etalon} ≈ Ø4 cm satisfies requirements of $\Delta\lambda$ = 0.01 nm and (throughput) $U \approx 0.01$ cm^2-ster

Possible addition of multipass input optics may increase performance by a factor of 2-4



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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 $\tilde{E}$ diagnostic

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

I.U. Uzun-Kaymak et al., Rev. Sci. Instrum. 83, 10D526 (2012)

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

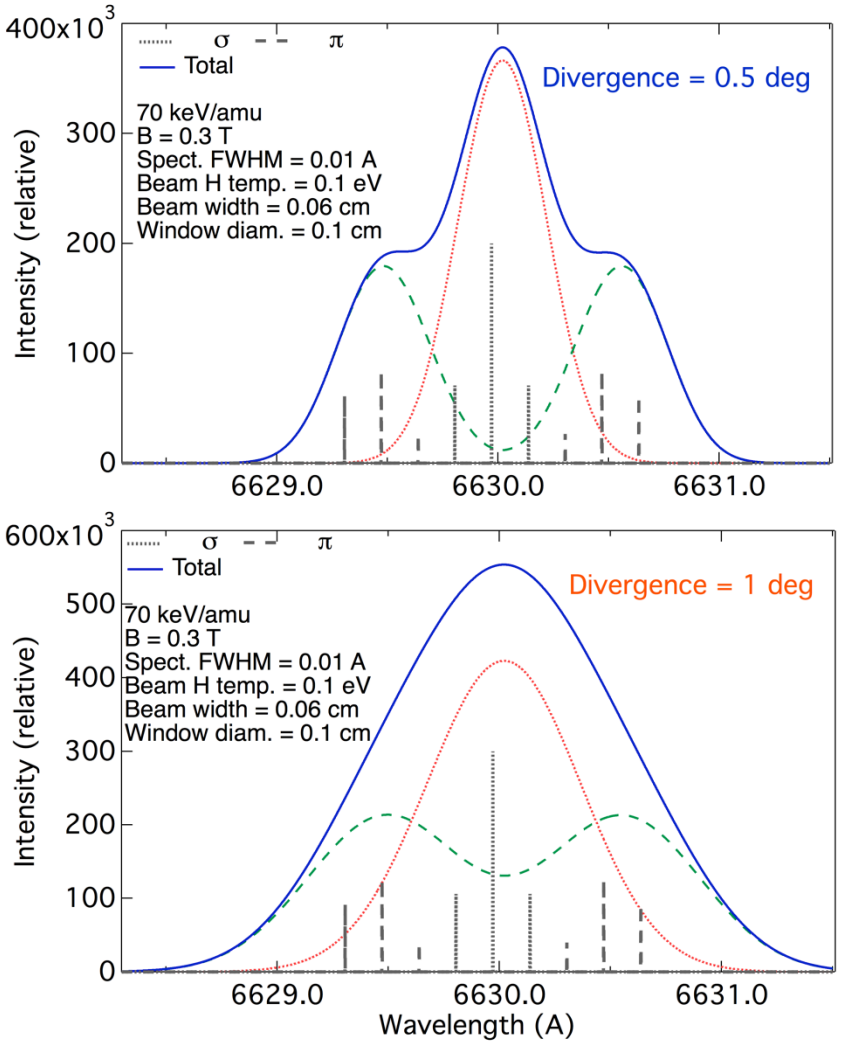
Beam divergence

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

Beam divergence causes variation in Doppler shifts

Beam divergence requirement: $\Omega < 1°$

$\Omega \sim 0.5°$ 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: ≥ 0.47°

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

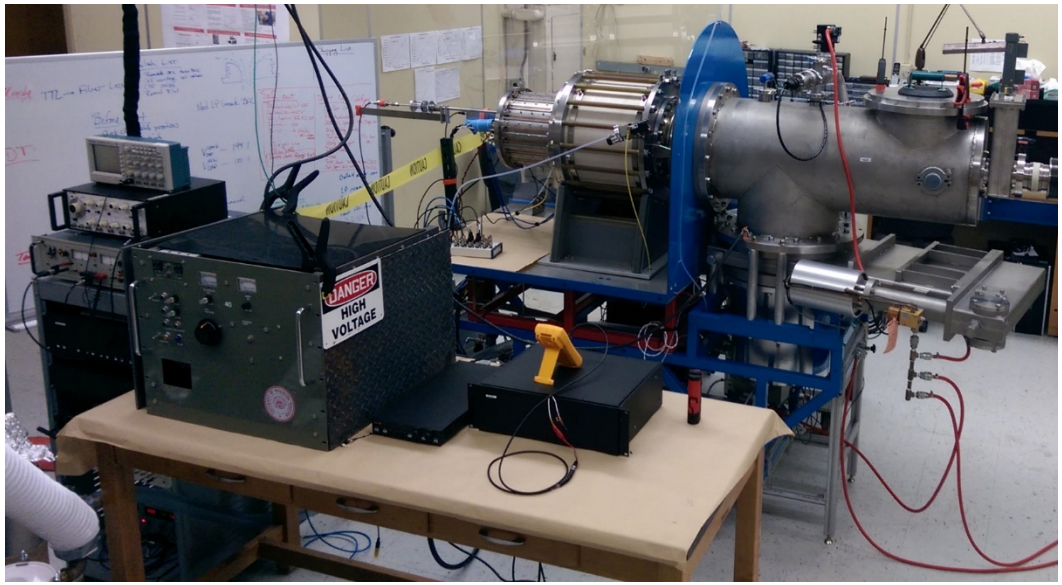
Species Ratio: E:E/2:E/3 = 22:35:43

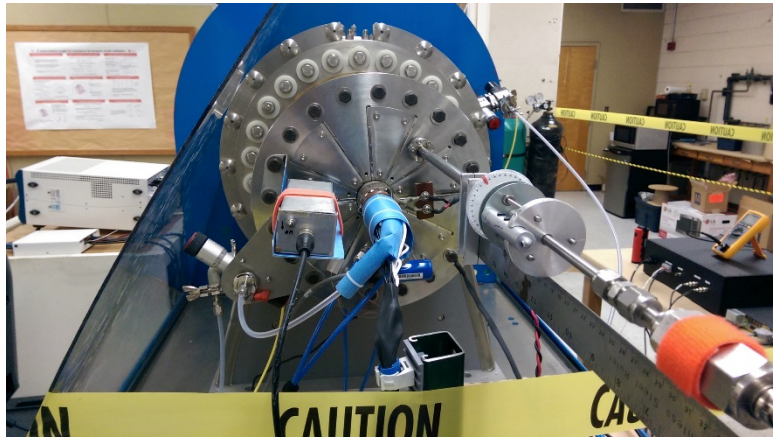
Diameter at extraction plane : 8.8 cm

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

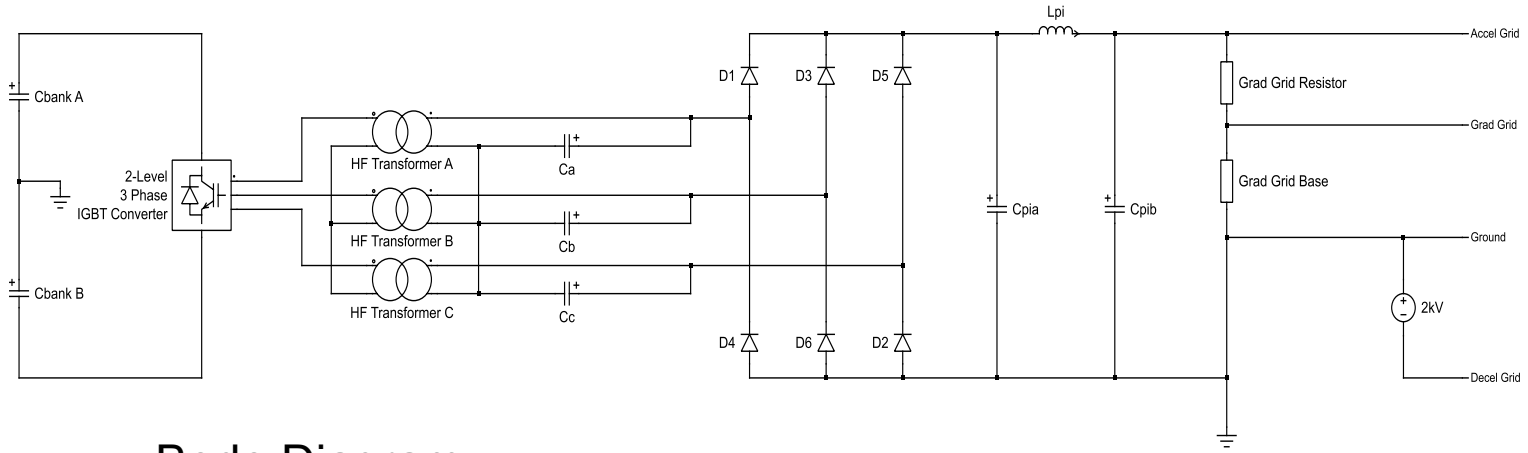


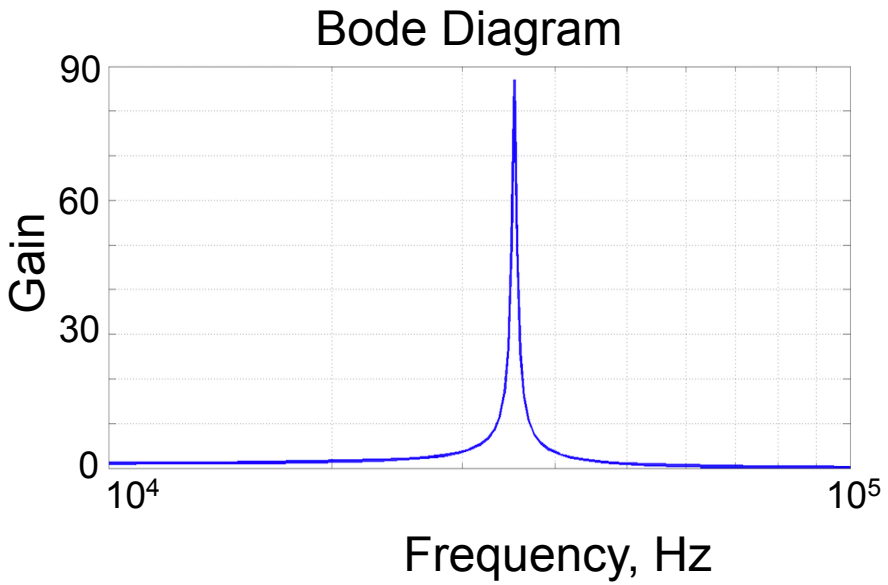


J.R. Coupland et al, Rev. of Sci. Instrum. ***61****, 472 (1990)*
I.L.S. Gray et al, IEEE ***1****, 149 (1989)*

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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

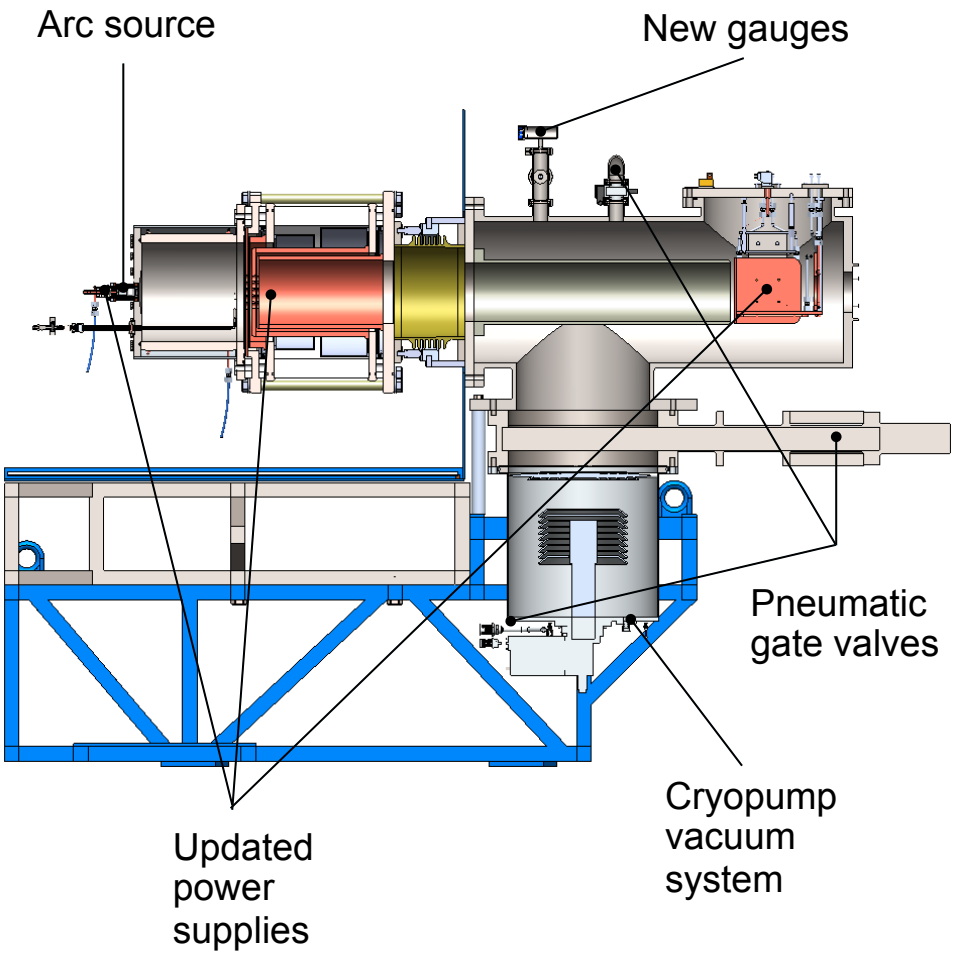
Ripple frequency selectable > 250 kHz

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Diagnostic beam with operational new source is preparing for high voltage power supply

- Baseline pressures of 6 x 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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Species mix optimizing washer stack arc source and accompanying diagnostics operational

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:

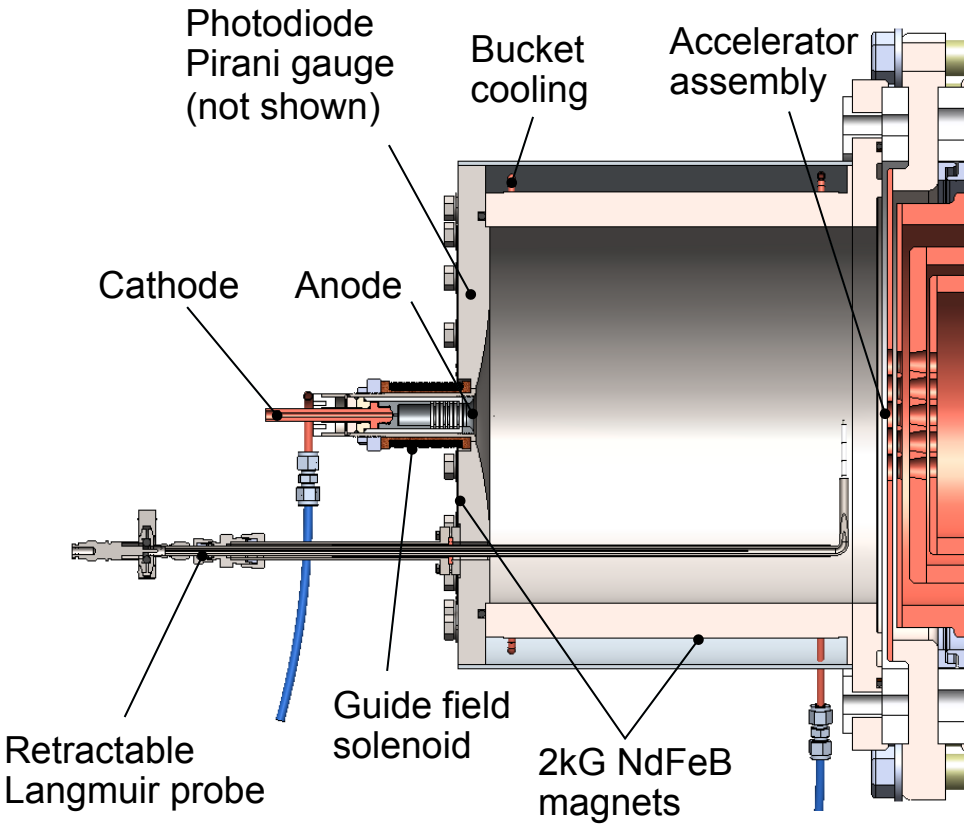
120 kHz I_{ARC} & V_{ARC}

500 kHz single swept Langmuir probe

Calibrated Rogowski coil

Photodiode

Pirani gauge



Neutral pressure in bucket: 1-20 mtorr

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

$V_{bucket}/V_{arc} \approx 2000$

[1] Deichuli et al, Rev. Sci. Instrum. **79**, 02C106 (2008)
[2] Abdrashitov, et al, Rev. Sci. Instrum. **72**, 594 (2001)
[3] Korepanov, et al, Rev. Sci. Instrum. 75, 1829 (2004)

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Mapping of operational space of plasma source underway to match grid perveance requirements

$$j_{\text{plasma}} = n_e e v_B \rightarrow j_{\text{ext}} = I_{\text{ext}}/A_{\text{ext}}$$

Extracted current: 1-3 A → 34.7 – 104 mA/cm^2

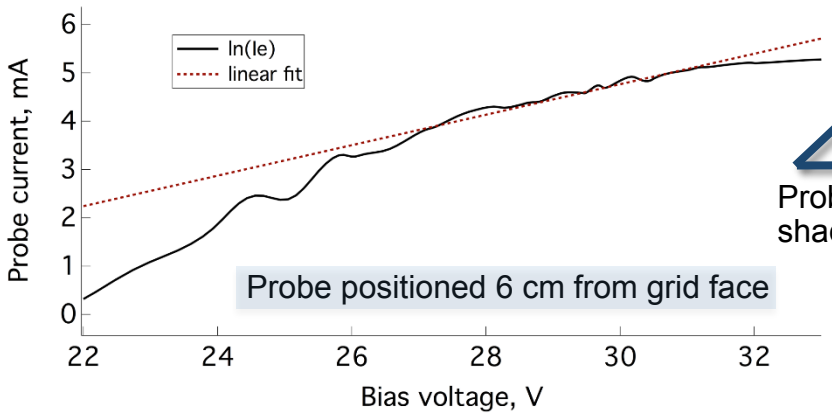
Grid extraction area: 19 x 1.52 cm^2 = 28.8 cm^2

$$n_e = \frac{I_e^*}{eA}\sqrt{\frac{2\pi m_e}{T_e}} \quad (*) \qquad v_B = \sqrt{T_e / m_i}$$

Langmuir probe analysis: $T_e \approx 3.6$ eV,

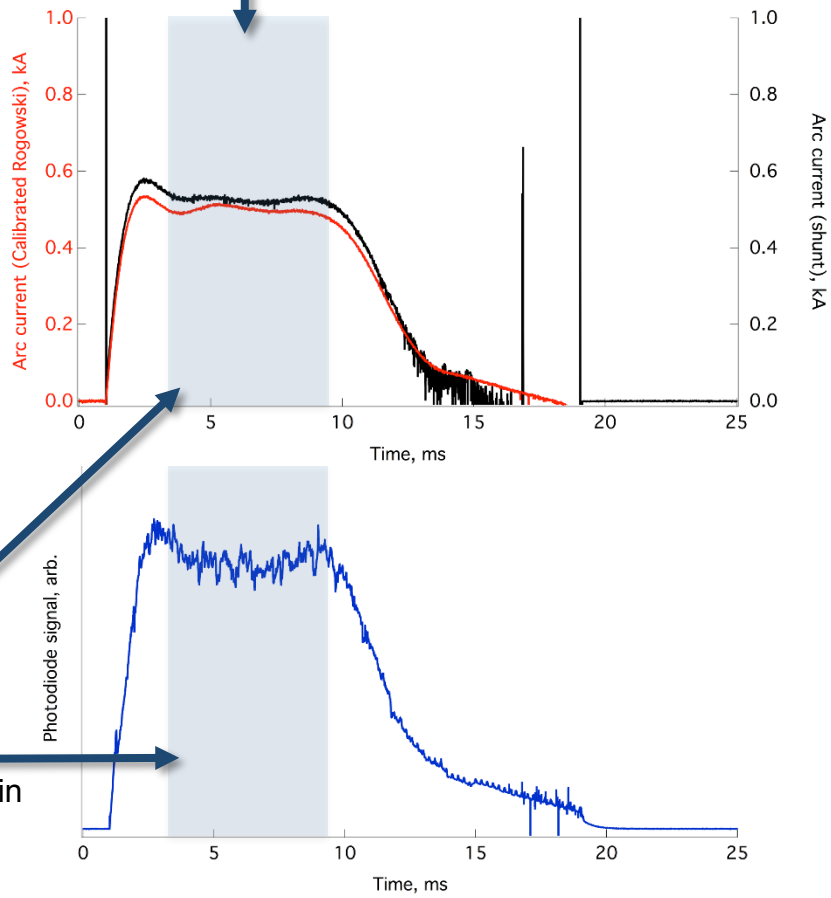
$n_e \approx 6.4 \times 10^{17}$ m^{-3}

Density required to match j_{ext}: 3.7×10^{17} m^{-3}



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Quasi-stable period ~ 8 ms



* *N. Hershkowitz. "How Langmuir Probes Work." Plasma Diagnostics, 113-183. Academic Press, 1989.*

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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 $k_\perp \rho_s \approx 0.1\text{-}1.5$

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

This research is supported by DOE Grant Number DE-FG02-89ER53296