Layout

$\tilde{E}$ diagnostic on Pegasus

Abstract	Fluctuation estimates (equations)	Broadening Effects Summary	Throughput requirements & F-P design	Beam summary and requirements
Measurement of $\tilde{E}$ desired	Estimate values & correlation analysis	Broadening Effects-Divergence	Spectrometer concept	Ion source
High-speed line-width measurement (stark spectrum)	Estimates for Pegasus vs NSTX & DIII-D	Broadening Effects - Window effect	Spectrometer code results	Power supplies
System overview (top view machine)	Anticipated mag. field helps ease spectrometer	Spectrometer resolution	APDs	Summary

Abstract

A new diagnostic is being developed to measure $E(r,t)$ fluctuations in the core of high-temperature large-scale magnetically confined fusion plasmas. Fluctuations in the splitting of the π-components of these spectra indicate fluctuations in the local electric field on top of the motional Stark field. The diagnostic approach incorporates two primary components: a diagnostic H^0 beam and a high sampling frequency, high throughput, high spectral resolution spectrometer to observe beam emitted light. A low-divergence ($\Omega \approx 0.5^o$) diagnostic beam designed for motional Stark effect (MSE) measurements on the PBX-M tokamak will be redeployed on the Pegasus Toroidal Experiment. The beam will incorporate an updated vacuum system, remote access controls, and low-ripple power supplies. The power supplies will provide up to 6 mA/cm^2 of full-energy H^0 at the focal plane at 80 keV/amu for pulse lengths up to 50 ms. The beam will be retrofitted with a new ion source based on an in-house washer-stack arc discharge concept in order to maximize the full-energy species fraction in the injected neutral population. A high throughput, high resolution spectrometer is being developed to observe Stark-split hydrogen Balmer line emissions from beam-plasma interactions. The fluctuations and intensity of the emissions are expected to be small, with $\delta E/E_{MSE} \sim 0.1\%$ and intensities $I \approx 3.3 \times 10^{12}$ photons/cm^2-ster-sec. To address this challenge, the spectrometer concept is being optimized to achieve high throughput ($U \approx 0.01$ cm^2-ster, assuming a plasma spot size of 2 cm x 2cm) with étendue-matched optics, while mitigating lens effect broadening introduced by the necessarily large optical elements. Modeling of MSE spectra and broadening effects suggests a spectral resolution requirement of $\Delta\lambda \approx 0.02$ nm. Spatial resolution in the plasma is set by the beam focus and optical sightline geometry, and is designed to be ≈ 2 cm. Polarization spectroscopy of the beam emissions will attenuate the perpendicular σ-components of the spectrum, improving the ability to resolve the π-component separation and easing spectrometer requirements. Detector concepts, such as thermo-electrically cooled avalanche photodiodes and intensified fast CMOS detectors, are being evaluated to provide photon-noise-limited detection at $f_{Ny} \approx 500$ kHz.

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

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

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]

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

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

The measured field is

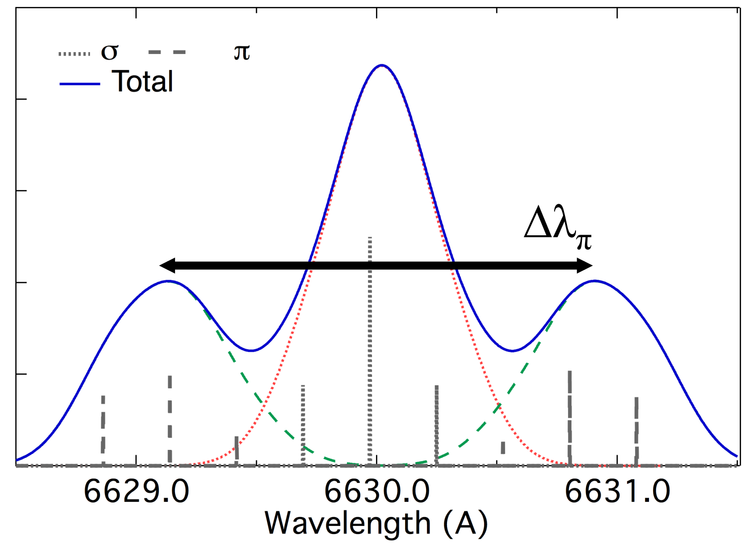
$$\boldsymbol{E}_{tot} = \boldsymbol{E}_{plasma} + \boldsymbol{v}_{beam} \times \boldsymbol{B}$$

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

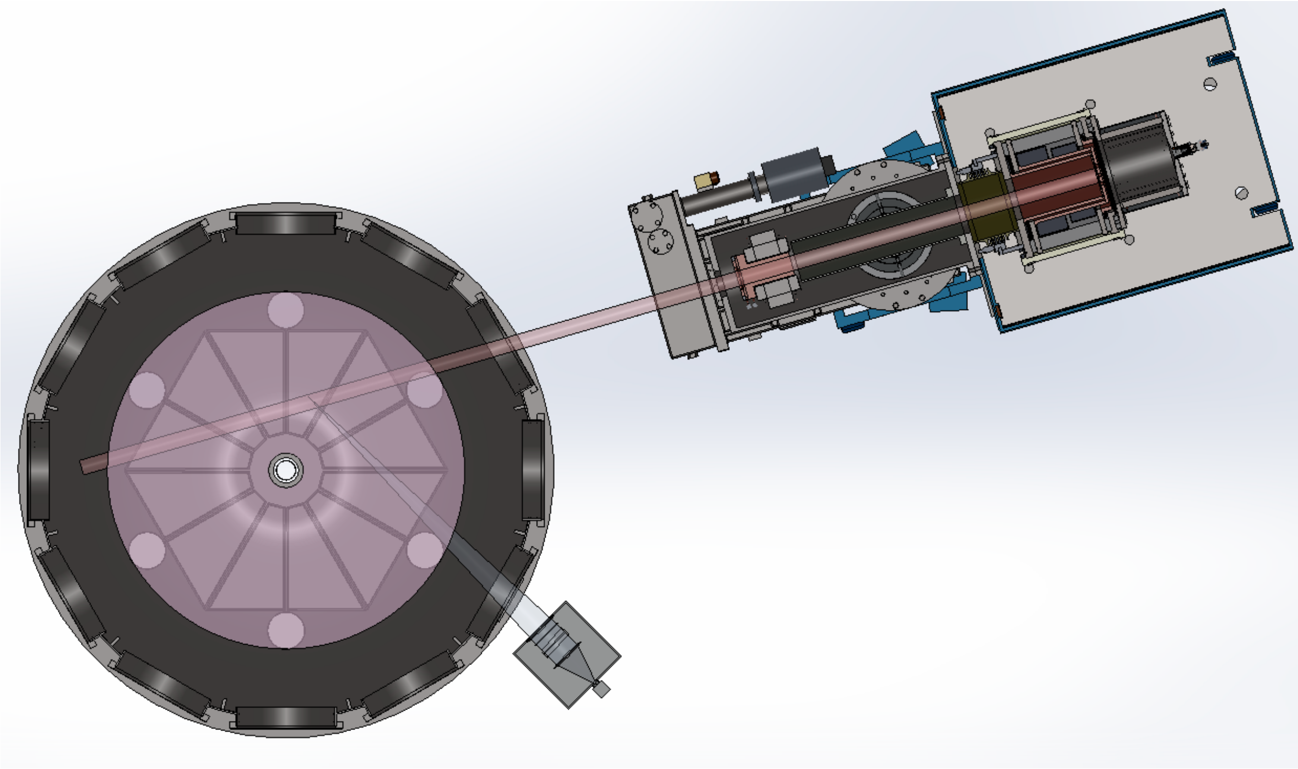


Model MSE spectrum

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).

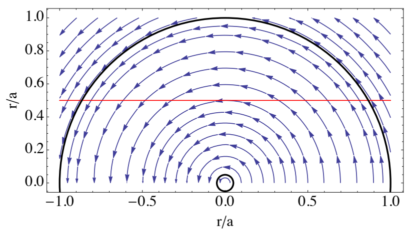
Optimization of beam-spectrometer angle should improve the ability to resolve line-width fluctuations

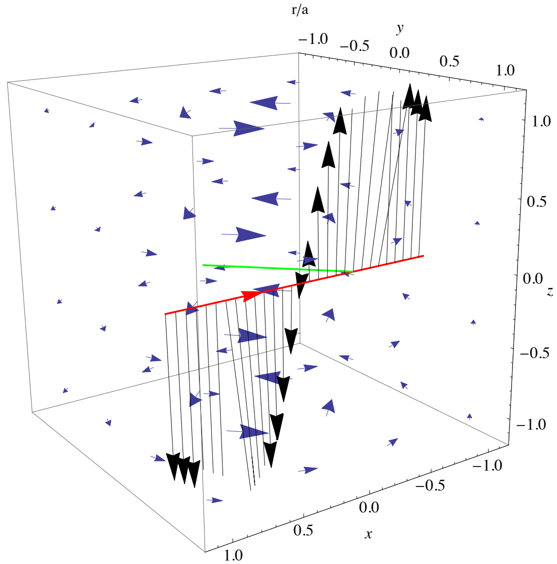


Geometry selection maximizes I_π/I_σ ratio and fluctuation sensitivity

High-resolution polarization spectroscopy can then extract fluctuations in the line splitting

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



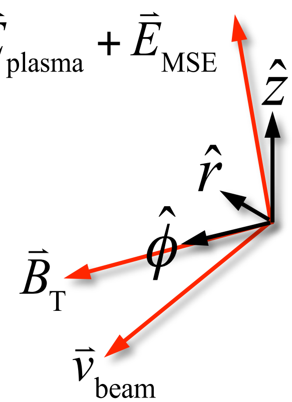


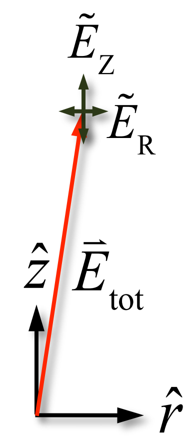
3D modeling illustrates Lorentz field structure (black arrows) for a given beam energy (red arrow) and field (B_T in blue arrows)

Intensity ratio depends on sightline angle (θ) to $\vec{E}$ and upper state population densities (n_π, n_σ)[1]

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

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





Neutral beam injection and viewing angle at midplane provide the best angle for measuring $\tilde{E}_Z$

[1] D. Voslamber, *Rev. Sci. Instrum.* ***66***, *2892 (1995)*

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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)

$$\tilde{E} \approx T_e/ea \approx 500\,\mathrm{V/m}$$

$$E_{\mathrm{MSE}} \approx 5\times10^5\,\mathrm{MV/m} \longrightarrow \tilde{E}/E_{\mathrm{MSE}} \approx 10^{-3}$$

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 ($B_\phi >> B_\theta$)

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

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.

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

Anticipated fluctuations for Pegasus are small:

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

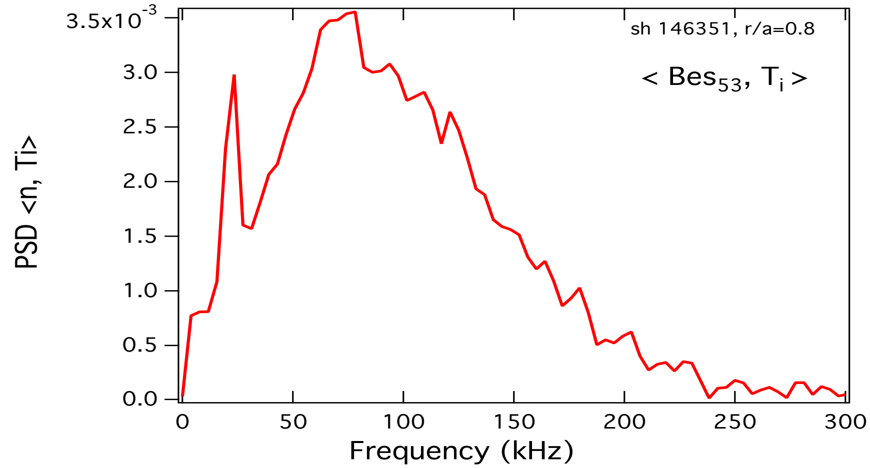
Expected noise floor ~ 10^{-3}

Small fluctuations in T and n have been measured:

$$\tilde{T}_{\mathrm{i}}/T_{\mathrm{i}} \sim 10^{-2} \quad \text{(HF/UF-CHERS)}^{1}$$

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

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



Assuming uncorrelated noise, it should be possible to extract $\langle \tilde{E}\tilde{n} \rangle$ in a similar way:

$$\underbrace{\tilde{S}_{\mathrm{E}}}_{(measured)} = \tilde{E} + \underbrace{\tilde{N}_{\mathrm{E}}}_{(noise)} \qquad \underbrace{\tilde{S}_{\mathrm{BES}}}_{(measured)} = \tilde{n} + \underbrace{\tilde{N}_{\mathrm{BES}}}_{(noise)}$$

$$\langle \tilde{S}_{\mathrm{E}}\tilde{S}_{\mathrm{BES}} \rangle = \langle \tilde{E}\tilde{n} \rangle + \underbrace{\langle \tilde{E}\tilde{N}_{\mathrm{BES}} \rangle + \langle \tilde{N}_{\mathrm{E}}\tilde{n} \rangle + \langle \tilde{N}_{\mathrm{E}}\tilde{N}_{\mathrm{BES}} \rangle}_{Uncorrelated \longrightarrow 0}$$

$$\approx \langle \tilde{E}\tilde{n} \rangle$$

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

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

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

Experiment	T_e(eV)	B(T)	a (m)	$\tilde{E}/E_{MSE}$
Pegasus	100	0.15	0.3	1×10^{-3}
Pegasus–U	300	0.3	0.35	1.4×10^{-3}
NSTX	1000	0.6	0.6	1.3×10^{-3}
DIII-D	2000	2	0.7	0.7×10^{-3}

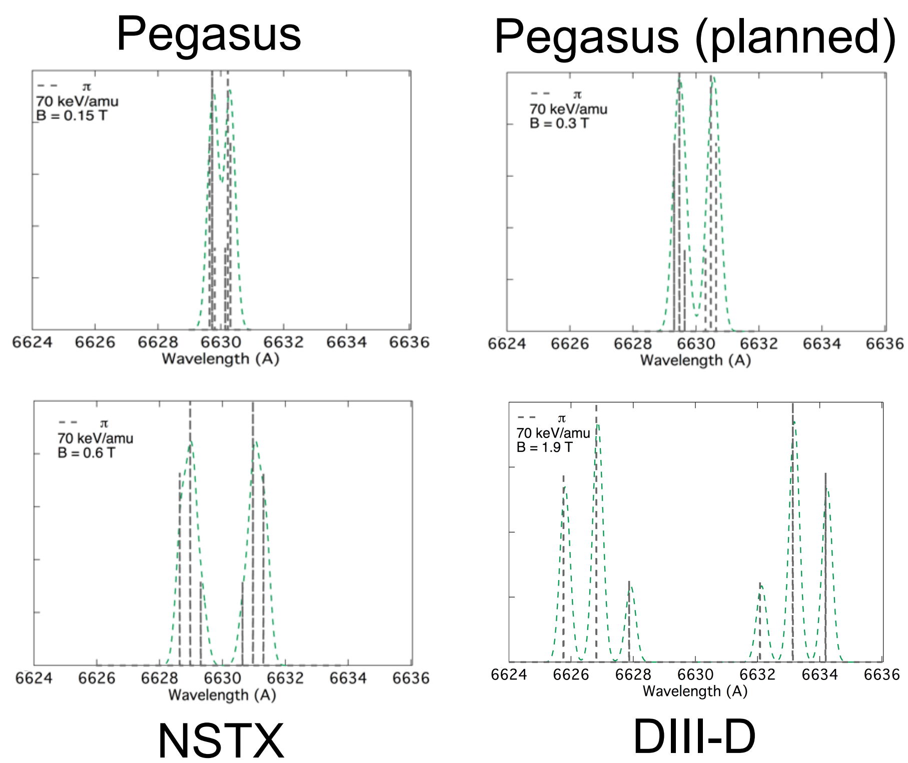
~O(0.1%) for these machines

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

Stronger magnetic fields ease constraints on spectrometer by accentuating Stark splitting

Doubling the magnetic field strength from 0.15T to 0.30T (upgrade planned for Pegasus), increases the motional Stark splitting making the components easier to resolve



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

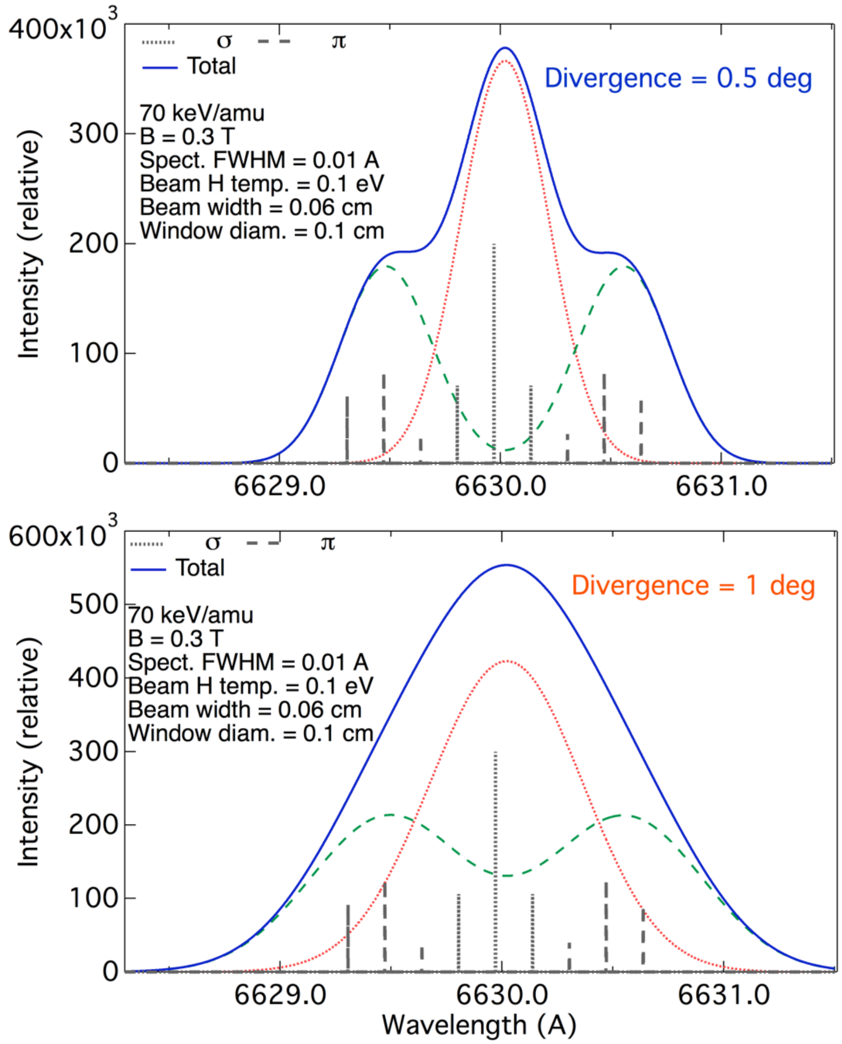
Beam divergence

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

Beam divergence causes variation in Doppler shifts

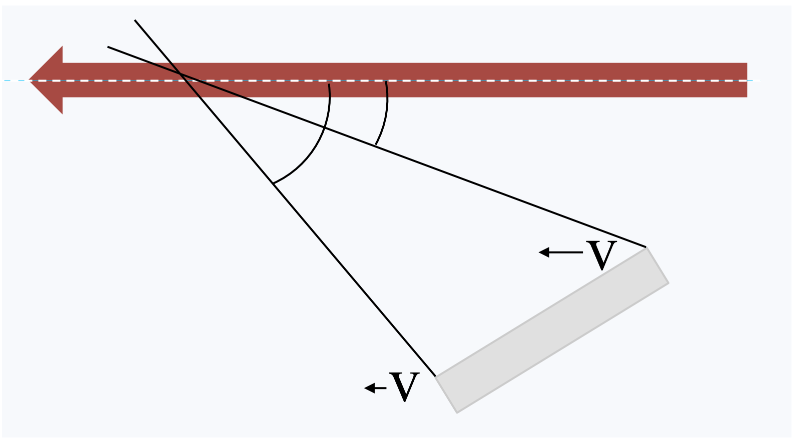
Beam divergence requirement: $\Omega<1°$

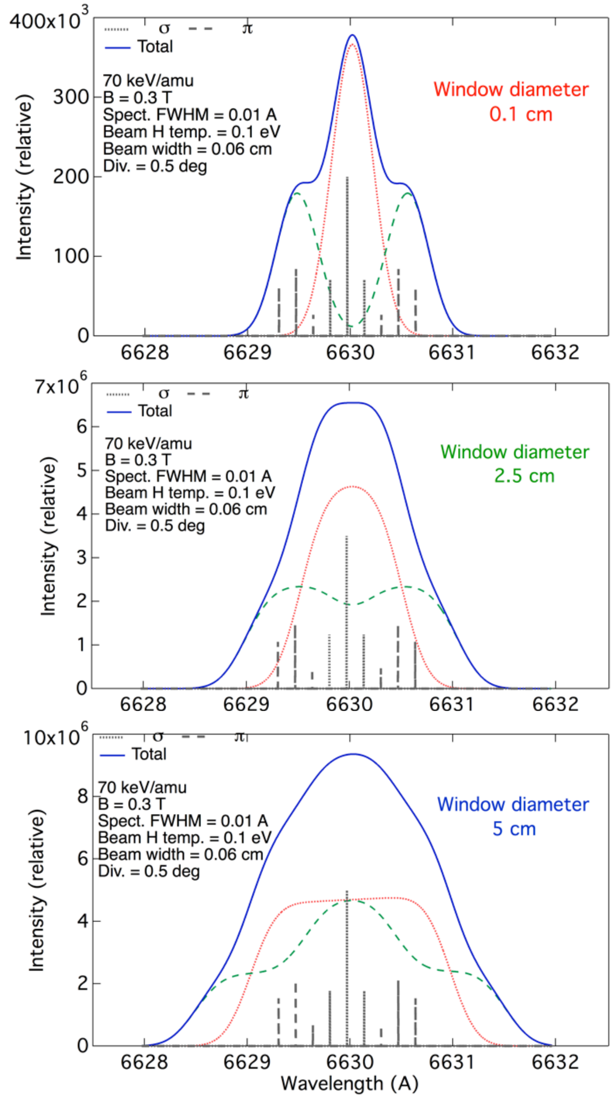
$\Omega \sim 0.5°$ achieved by PBX-M beam*



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

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

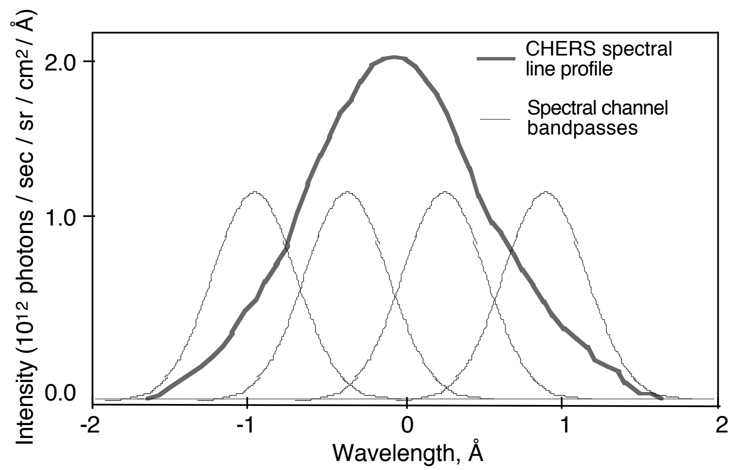
Spectral resolution Δλ ≈ 0.25Å is required to resolve π components of Stark spectrum

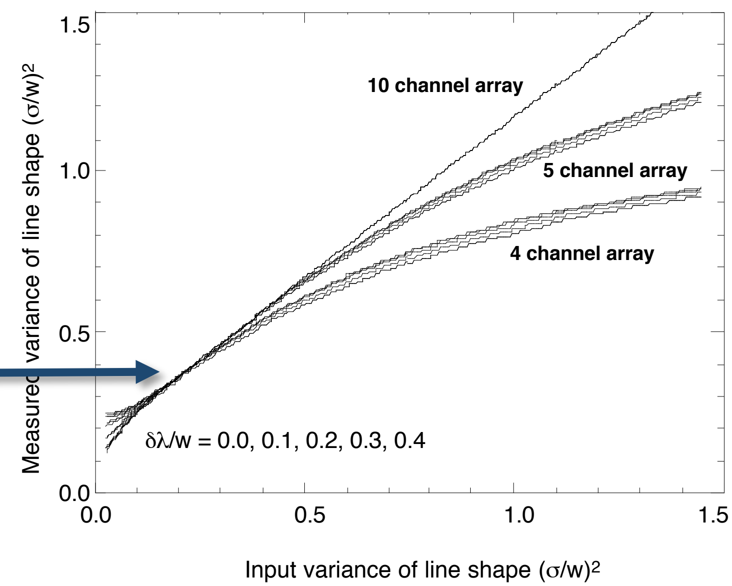
Variance tends toward the real value with increasing number of spectral channels

Total throughput is divided by the number of 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.

Detection system is designed to operate in linear region, as in UF-CHERS





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

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

Piezo-electric control of etalon separation and wedge tilt

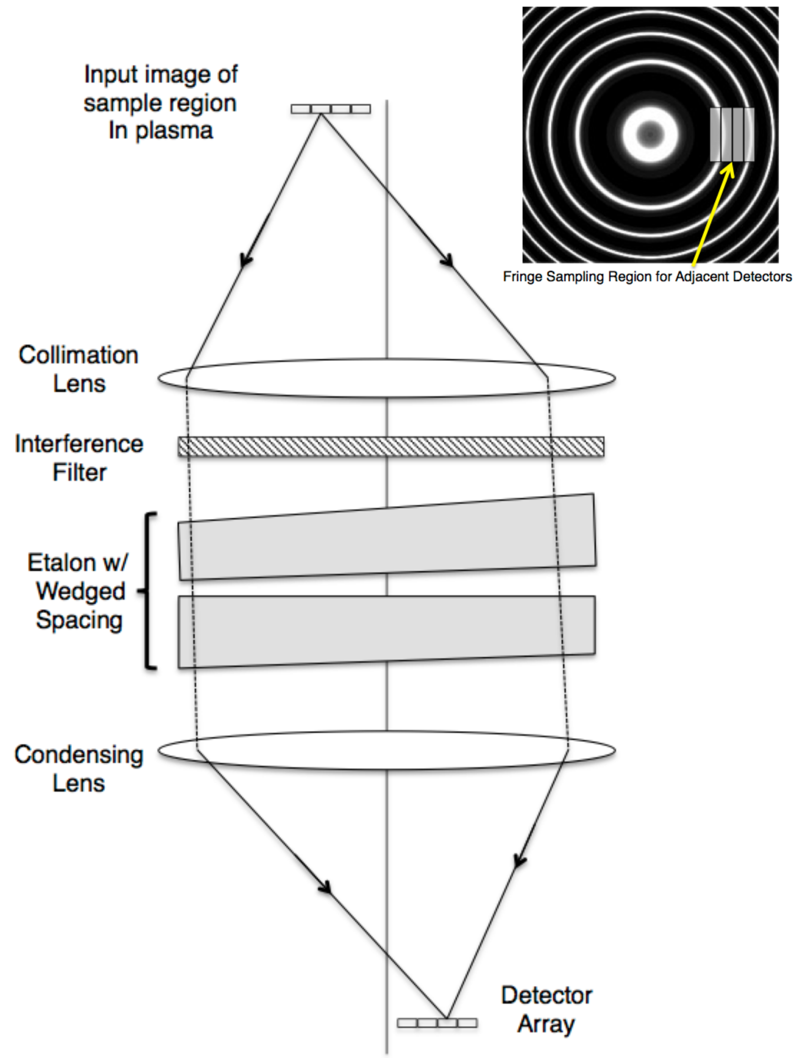
Detectors: Fast, low noise TEC-APD array with frequency-compensated preamplifiers

- 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 ≈ 0.01 cm^2-ster

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

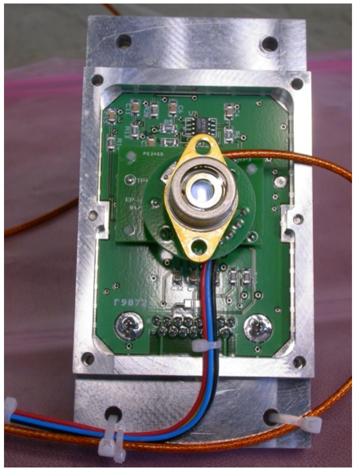
Considering alternative polarization intensity fluctuation approaches

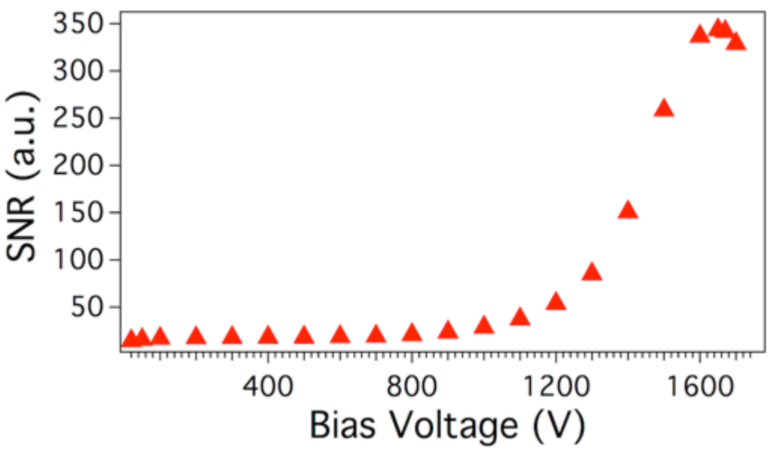


An array of thermo-electrically cooled avalanche photodiodes measures fluctuations

APD detector array like those currently employed by UF-CHERS can be used for $\tilde{E}$ diagnostic

- Thermo-electrically cooled
- Dark current min. @ T ≤ 10 °C
- Optimal SNR ~1650 V_{bias}
- Internal gain ~ 200 V/V
- Frequency-compensated preamplifier
- Effective QE ~ 0.32
- f_{sample} ~ 1MHz → f_{Ny} ~ 500 kHz





Intensified fast CMOS Phantom cameras being considered as a simplified data acquisition system

- QE ~ 0.4-0.5 at λ = 656.3 nm

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

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

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 focal plane: 3-6 mA/cm^2

Beam Divergence: ≥ 0.47°

Species Ratio:

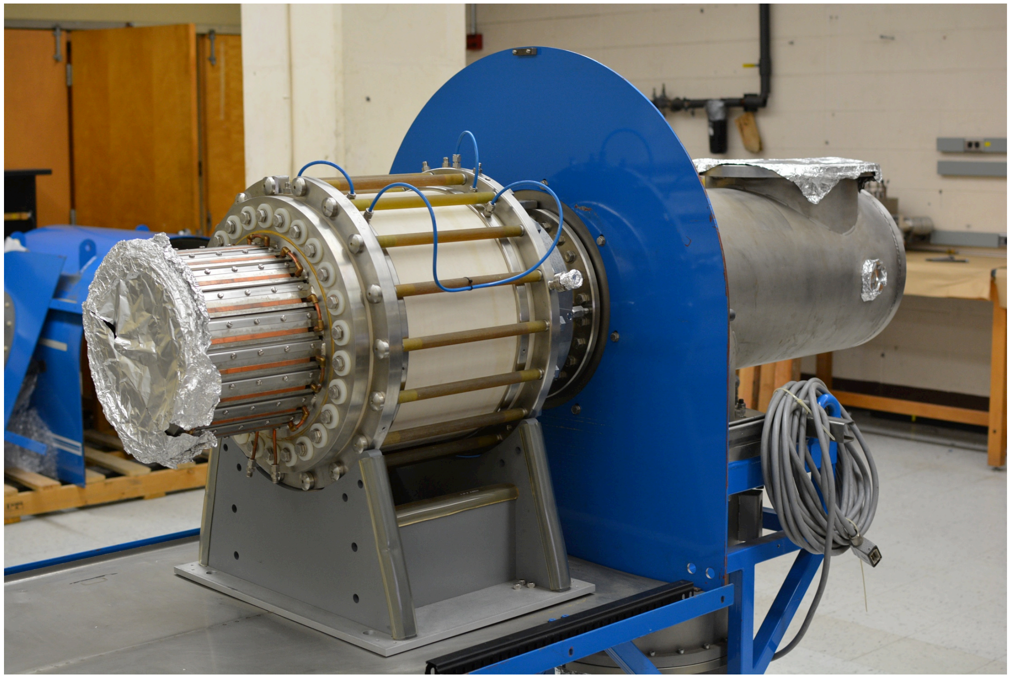
H:H/2:H/3 = 22:35:43 @ 67 kV

Diameter at extraction plane : 8.8 cm

1/e diameter at focal plane: 3.3 cm

Tetrode configuration w/ offset aperture focusing

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



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

Status of DNB refurbishment effort

Vacuum system based on Cryo-Torr 400 High Capacity cryopump backed by Leybold D40 rotary vane pump with molecular sieve and LN2 trap being assembled

DNB isolable from cryopump, foreline, and Pegasus by electrically actuated VAT HV gate valve and Series 012 VATLOCK mini gate valves

All elastomer seals replaced

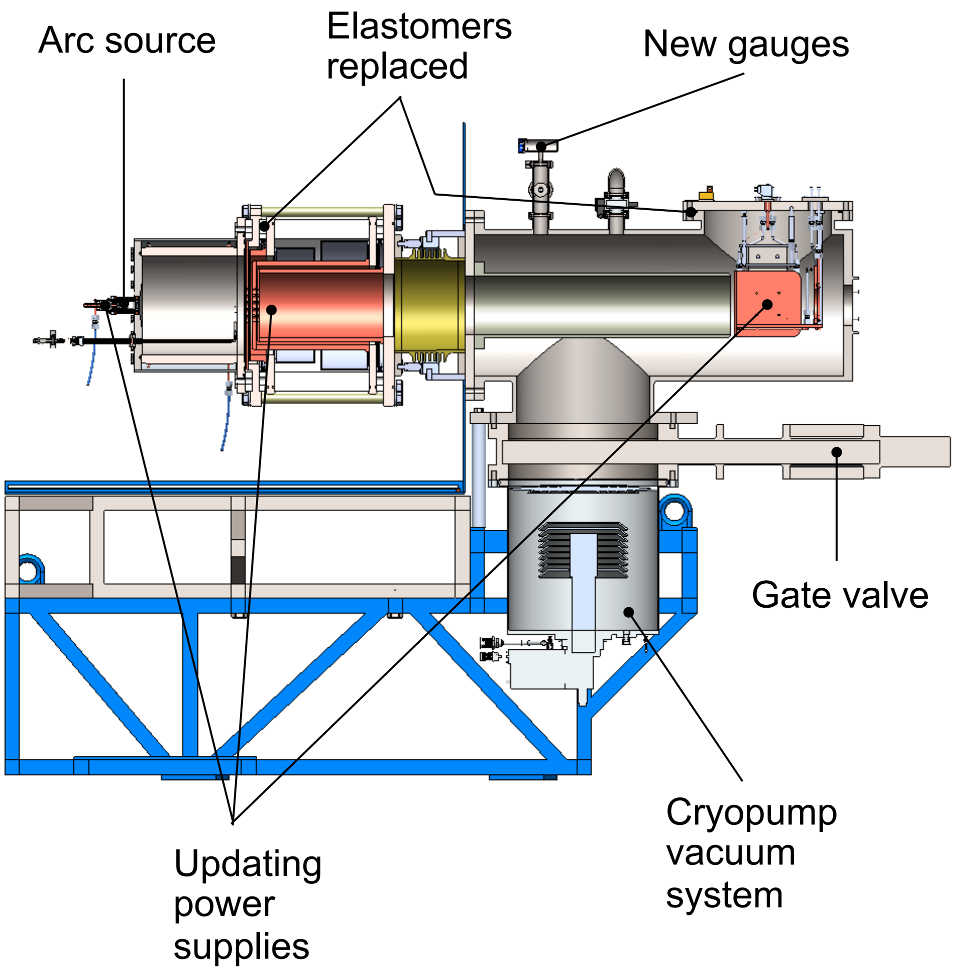
All vacuum gauges replaced and remotely accessible with SRS IGC100 vacuum gauge controller. Presently replacing gas and coolant monitoring

NI LabVIEW software being written to monitor and control all systems remotely

Replacing source to optimize full energy fraction

Modeling resonant converter for high voltage power supply

Communicating with vendors to replace bending magnet and Decel power supplies



The beam will employ technology from Local Helicity Injection as an arc plasma ion source

Washer stack arc sources successfully employed for other diagnostic beams[1-3]

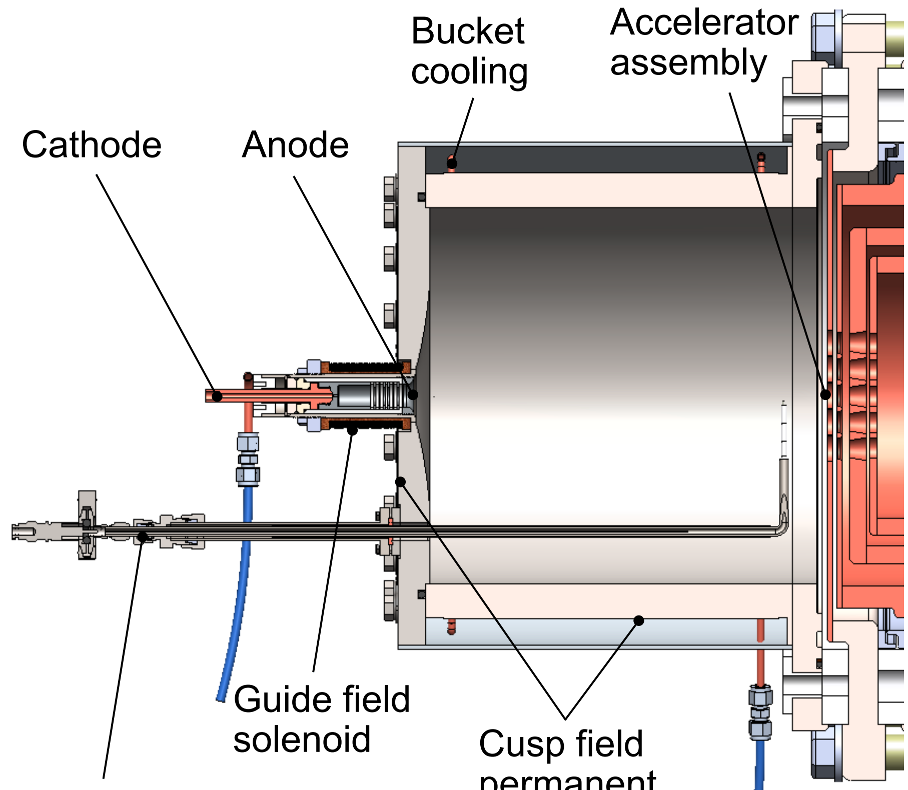
Near 100% ionization of arc plasma provides advantageous species mix for spectroscopy

- Full energy fractions of 80-90% achieved with other arc source diagnostic beams[1-3]

Design does not require an extended burn-in period

- Typical conditioning period for Pegasus arc sources is 10s of shots, with lifetimes of 1000s of shots

Rare earth magnets produce 2kG cusp field at bucket inner surface, ~10%/cm falloff

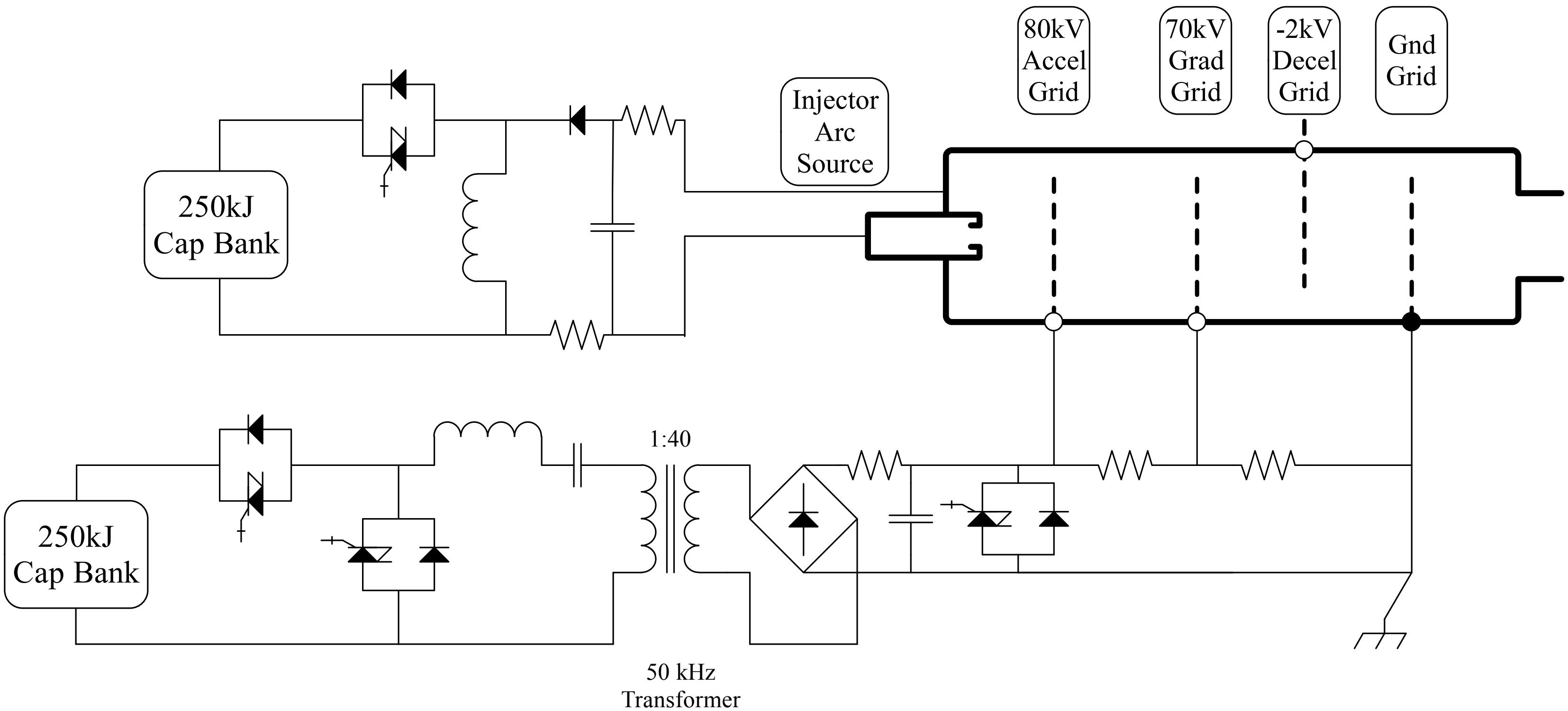


Arc parameters: $n_e \approx 10^{22}$ m^{-3}, $T_e \approx 10$ eV

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

[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)*

New power supplies minimize ripple and voltage droop



- Power supplies designed for 100 ms and modifiable energies
- Accel supplies rated for 80kV operation at 5A
- Decel supply to be obtained commercially
- Filters minimize ripple

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

High-speed polarization spectrometry will be used to infer $\tilde{E}(t)$ from Stark split line width fluctuations

Near term objectives:

- Optical modeling of Fabry-Pérot concept
- Achieve vacuum in beam vessel
- Finalize and test new DNB ion source

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

Backups →

Large aperture spectrometer concepts that improve etendue and preserve spectral resolution are being studied

3/4 m Spectrometer

Image space f-number:
N = f/2

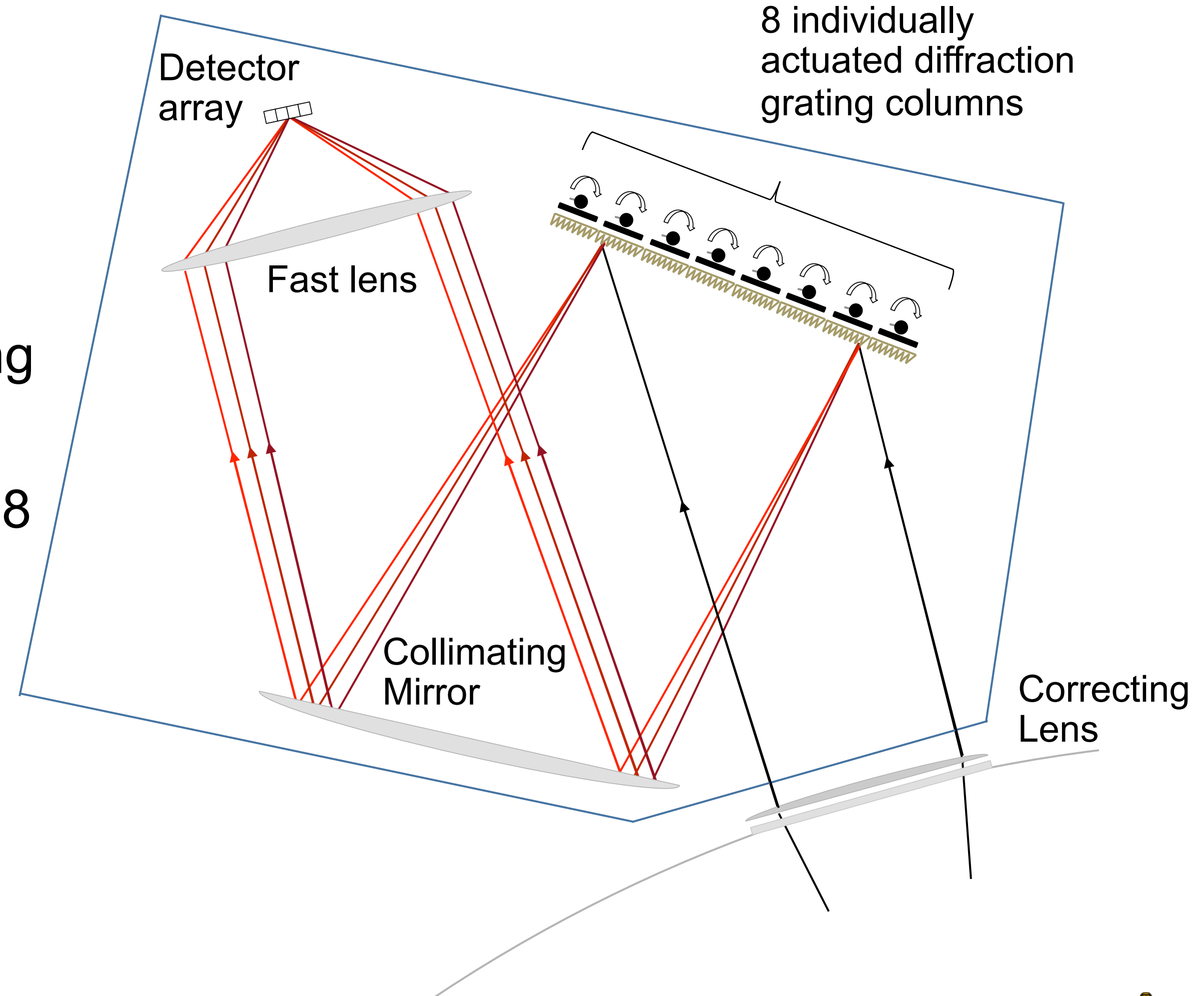
High efficiency diffraction gratings

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



D. S. Thompson, 20th HTPD, Atlanta, GA, June 2014

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

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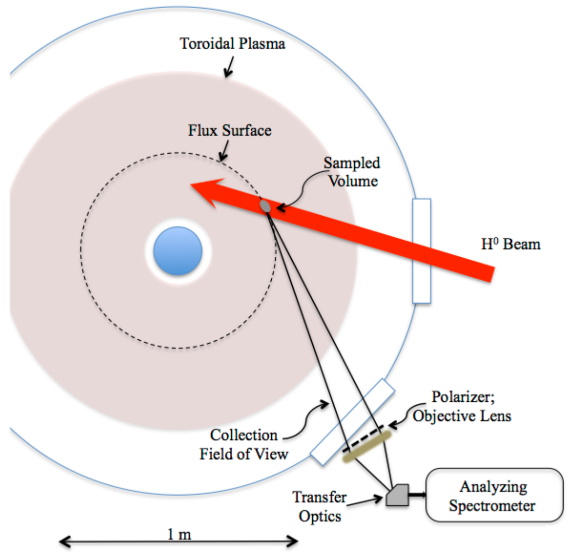
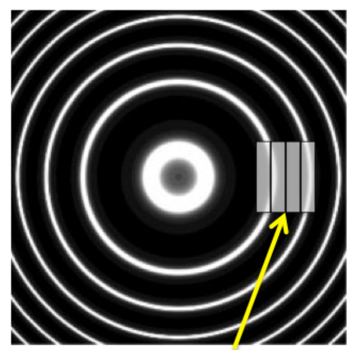
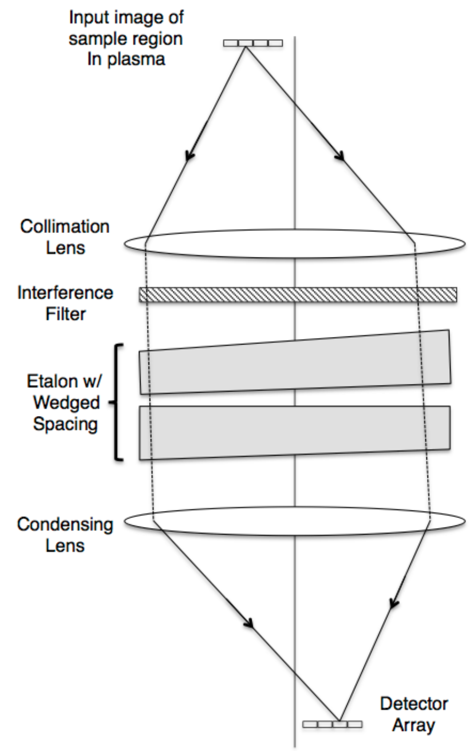



Fringe Sampling Region for Adjacent Detectors



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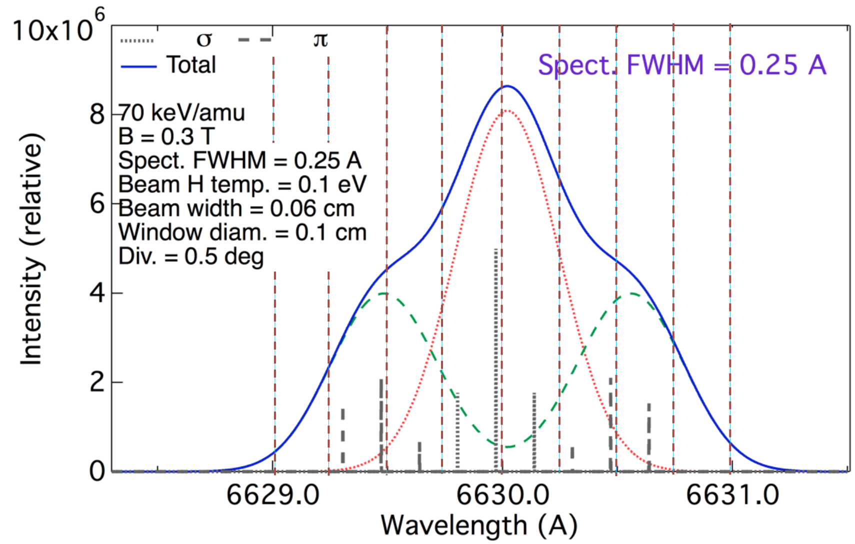
High spectrometer resolution is required to resolve π components of Stark spectrum

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

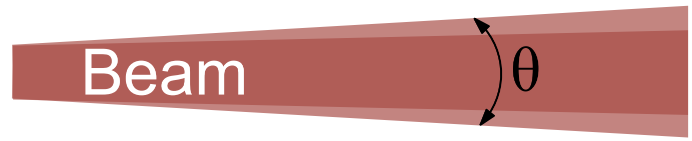


Typical spectra cover 2 Å, suggesting a spectral resolution requirement of 0.25 Å or better for an eight detector array.

Small line widths necessitate mitigation of smearing by other broadening effects

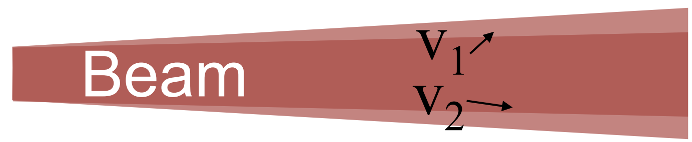
Beam divergence

Finite T_i in the ion source leads to spectral broadening



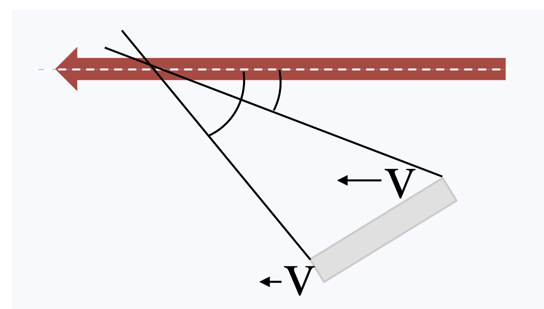
Thermal broadening of beam neutrals

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



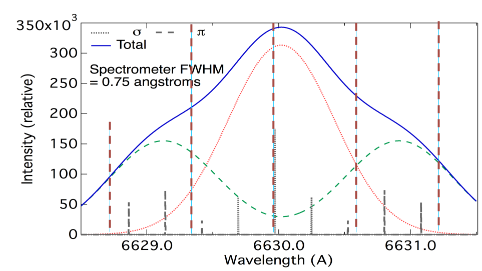
Geometric Doppler broadening

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



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:

$$\left.\begin{aligned} \tilde{E} &\sim k_\perp \tilde{\phi} \\ \tilde{n}/n &\sim \frac{e\tilde{\phi}}{T_e} \sim \frac{1}{k_\perp L_n} \\ k_\perp \rho_s &\sim \alpha \end{aligned}\right\} \quad \longrightarrow \quad \tilde{E} \approx \frac{\tilde{n}}{n}\frac{T_e}{e\rho_s}\alpha \quad \longrightarrow \quad \tilde{E} \approx \frac{T_e}{eL_n}$$

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

$$\tilde{E} \approx \frac{T_e}{ea}$$

*Wesson. Tokamaks. Oxford, UK: Clarendon Press, 2004.