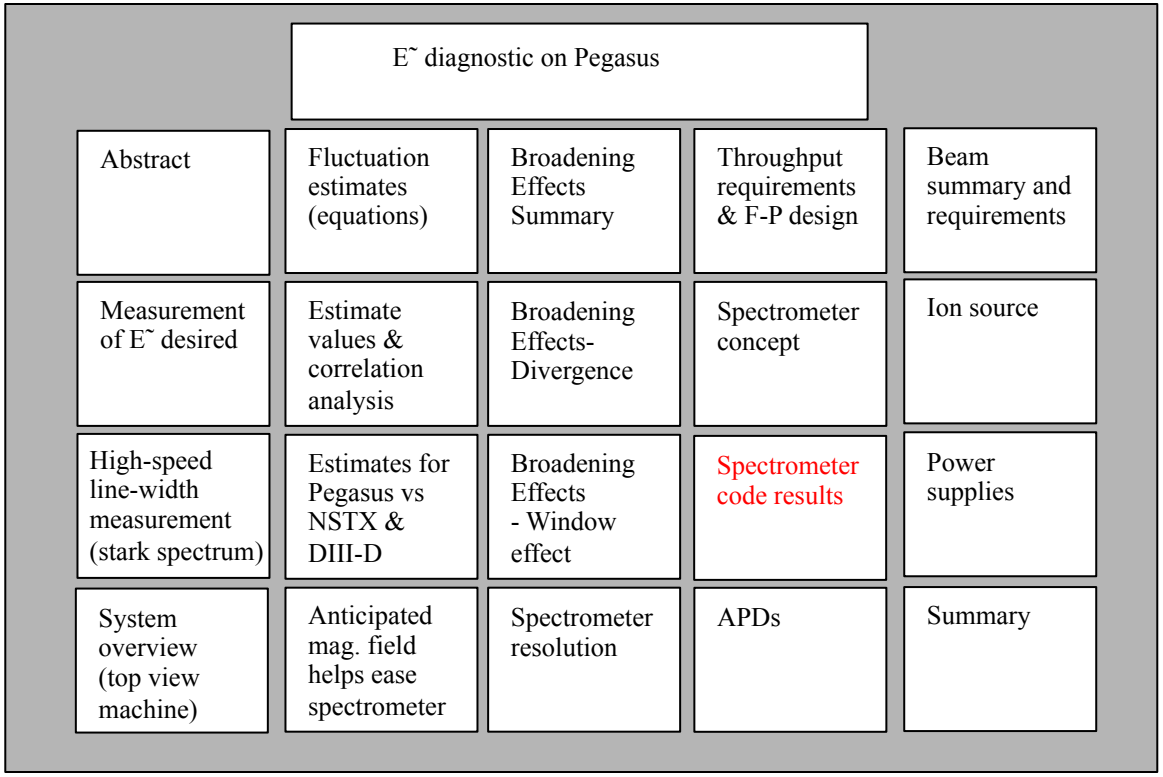
Layout


E˜ diagnostic on Pegasus
Abstract
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Broadening Effects Summary
Throughput requirements & F-P design
Beam summary and requirements
Measurement of E˜ desired
Estimate values & correlation analysis
Broadening Effects- Divergence
Spectrometer concept
Ion source
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Estimates for Pegasus vs NSTX & DIII-D
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Power supplies
System overview (top view machine)
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Summary

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 $\tilde{E}/E_{MSE} \approx 1\times10^{-3}$ in the Pegasus Toroidal Experiment and are comparable to those expected in NSTX and in DIII-D.

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

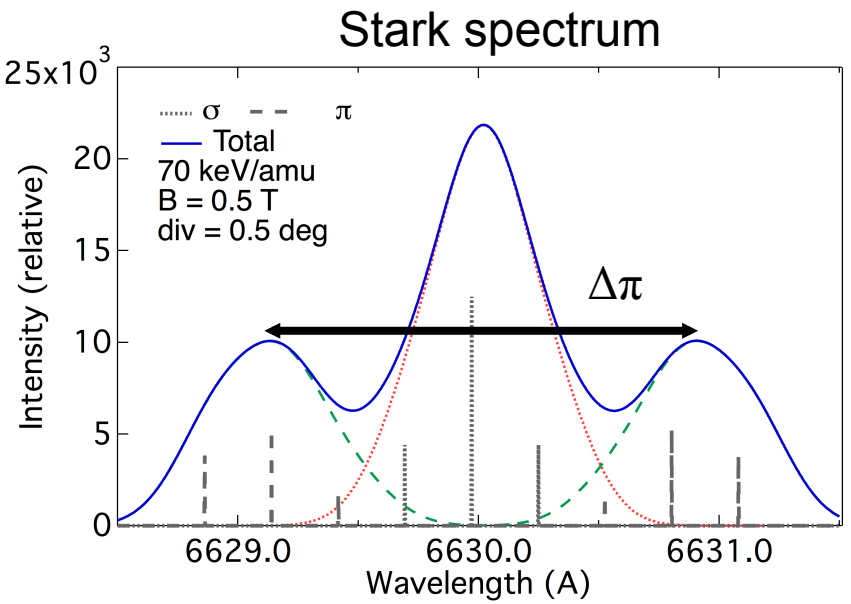
The H Balmer-α line is split by the Motional Stark field induced by neutral beams*

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

$$\vec{E}_{tot} = \vec{E}_{intr} + \vec{v}_b \times \vec{B}$$

Measuring $\widetilde{\Delta\pi}$ provides $\tilde{E}_{intr}$

It is expected that $E_{v\times B(MSE)} >> E_{intr}$



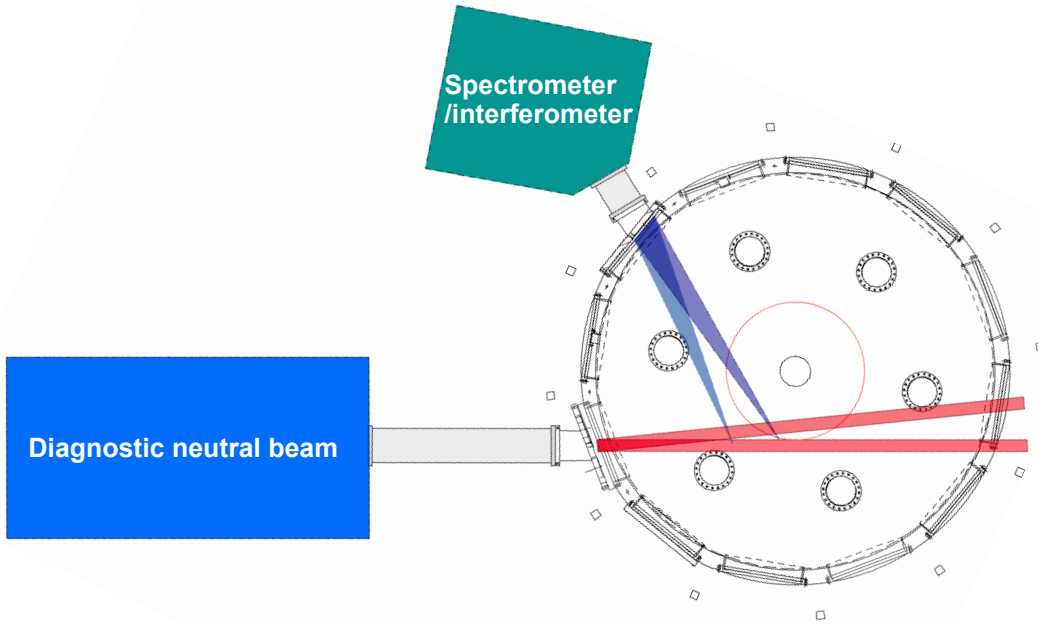
* *G.V. Marr. Plasma Spectroscopy. New York: Elsevier Publishing Co., 1968. Many others.*

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

Selection of beam and observation intersection angle mitigates smearing by the dominant σ component of the Motional Stark spectrum

High-resolution polarization spectroscopy can then extract fluctuations in the line-width splitting of the π components of the spectrum



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:

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

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.

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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:

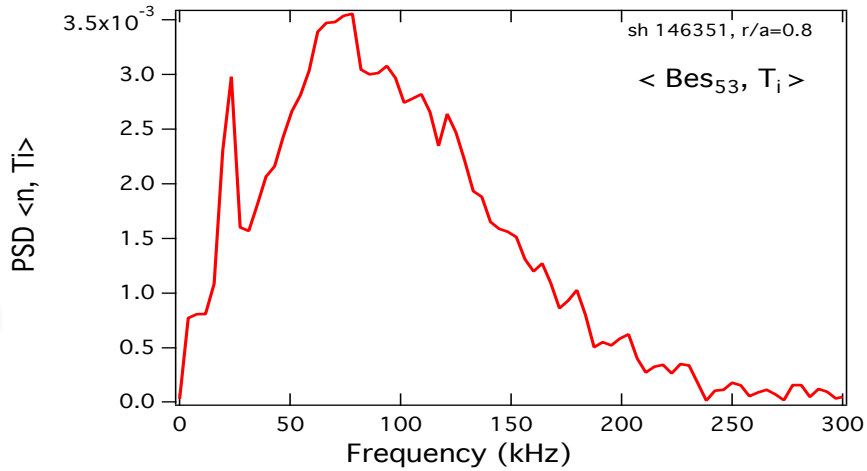
$$\tilde{E}/E_{MSE} \sim 0.10 - 0.15\%$$

Small fluctuations in T and n have been measured:

$$\tilde{T}_i/T_i \sim 2.1\% \text{ (HF/UF-CHERS)}^*$$

$$\tilde{n}/n \sim 1\% \text{ (BES)}^{**}$$

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:

$$\tilde{S}_E = \tilde{E} + \tilde{N}_E \qquad \tilde{S}_{BES} = \tilde{n} + \tilde{N}_{BES}$$

$$\langle \tilde{S}_E \tilde{S}_{BES} \rangle = \langle \tilde{E}\tilde{n} \rangle + \langle \tilde{E}\tilde{N}_{BES} \rangle + \langle \tilde{N}_E \tilde{n} \rangle + \langle \tilde{N}_E \tilde{N}_{BES} \rangle$$

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

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

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

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

Experiment	T_e(eV)	B(T)	a (m)	$\tilde{E}/E_{MSE}$
Pegasus – 1	100	0.15	0.3	1×10^{-3}
Pegasus – 2	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

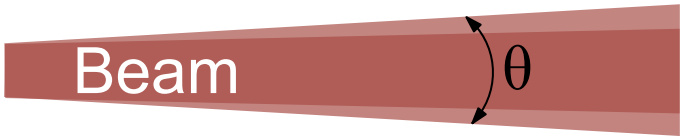
Small signals can be considerably increased by imposing large local E field fluctuations with biased injectors, permitting validation of diagnostic concept at greater signal levels

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

Small line widths necessitate mitigation of smearing by other broadening effects

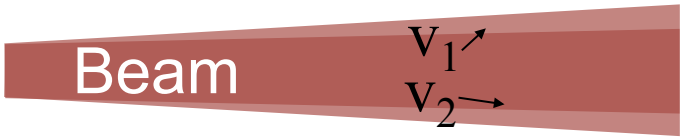
Beam divergence

Finite T_i in the ion source leads to spectral broadening



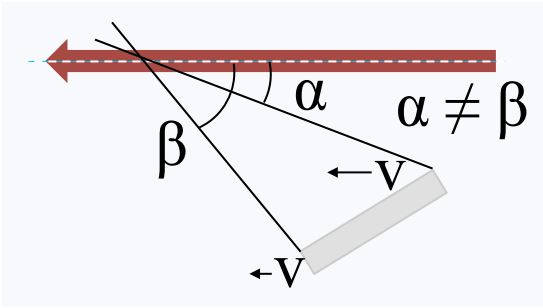
Thermal broadening of beam neutrals

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



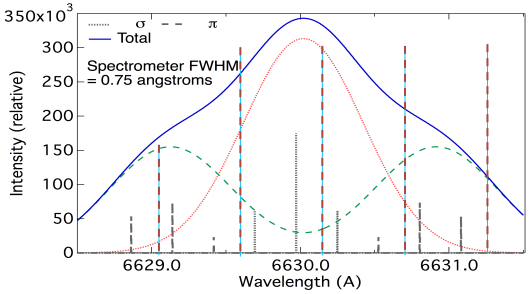
Window effect

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



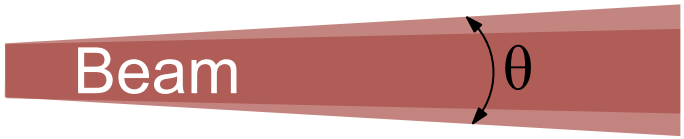
Spectrometer resolution

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

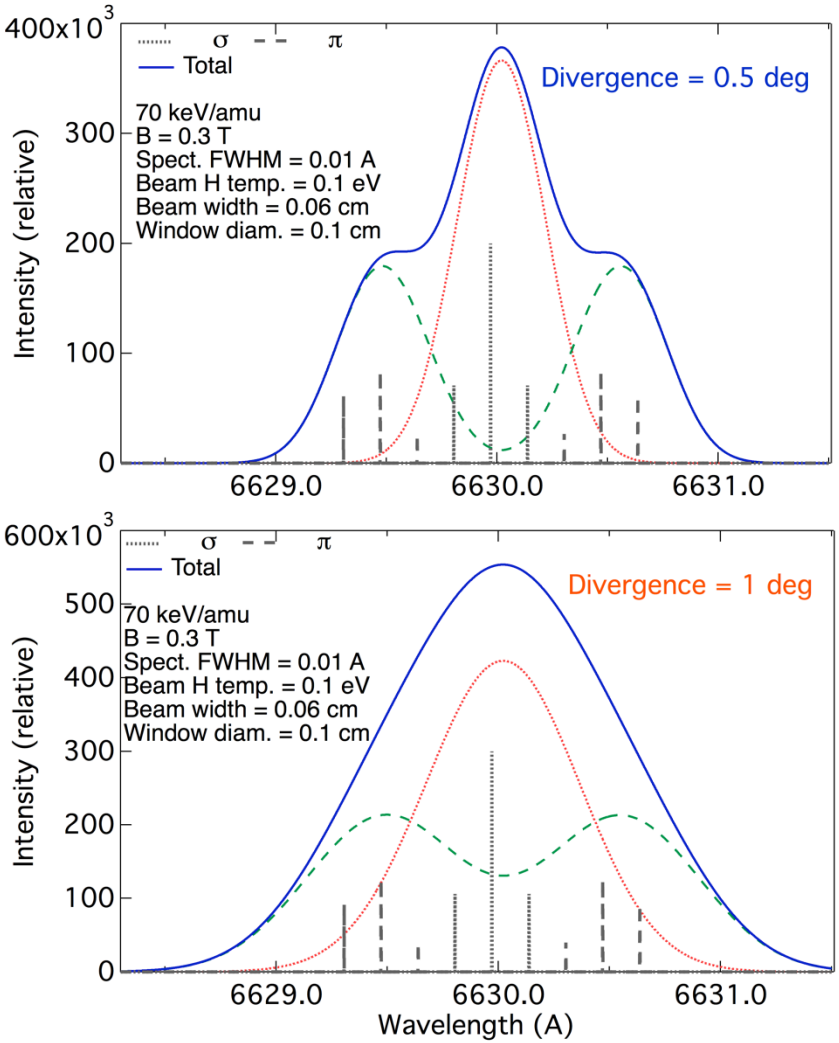


Beam divergence

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

Beam divergence causes variation in Doppler shifts

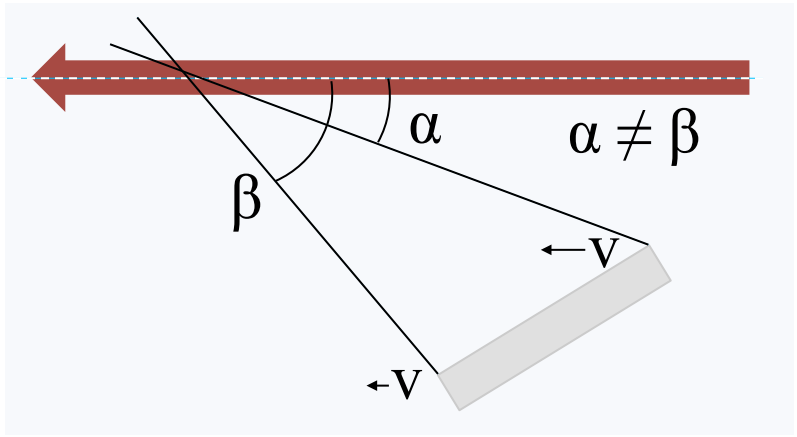
Diagnostic requires low beam divergence ~0.5°, which has been achieved by PBX-M beam*

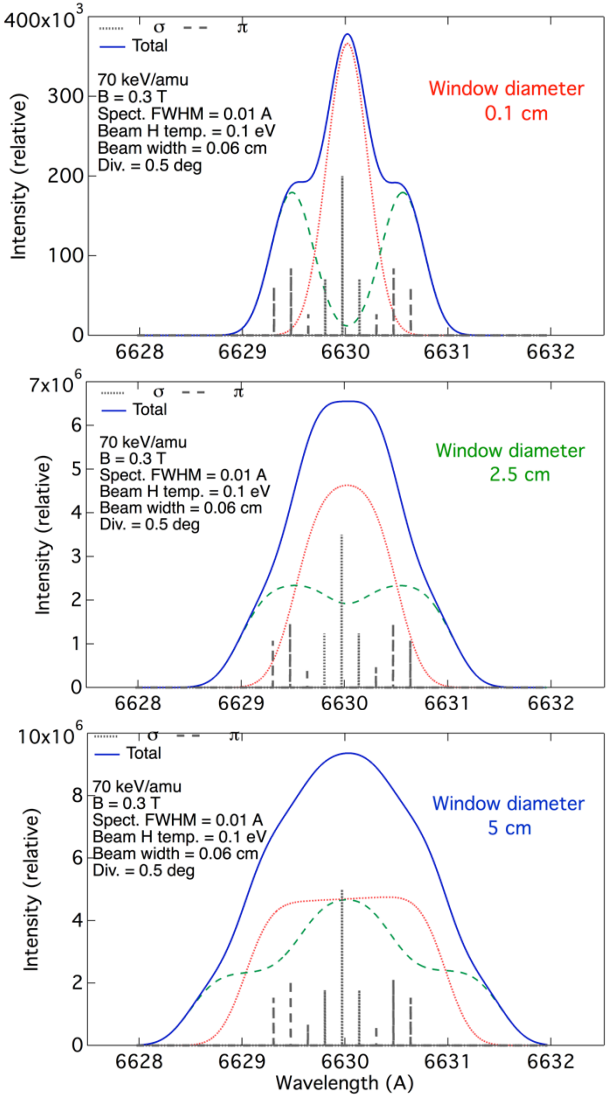


* *Coupland et al., Rev. Sci. Instrum.* ***61****, 472 (1990)*

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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

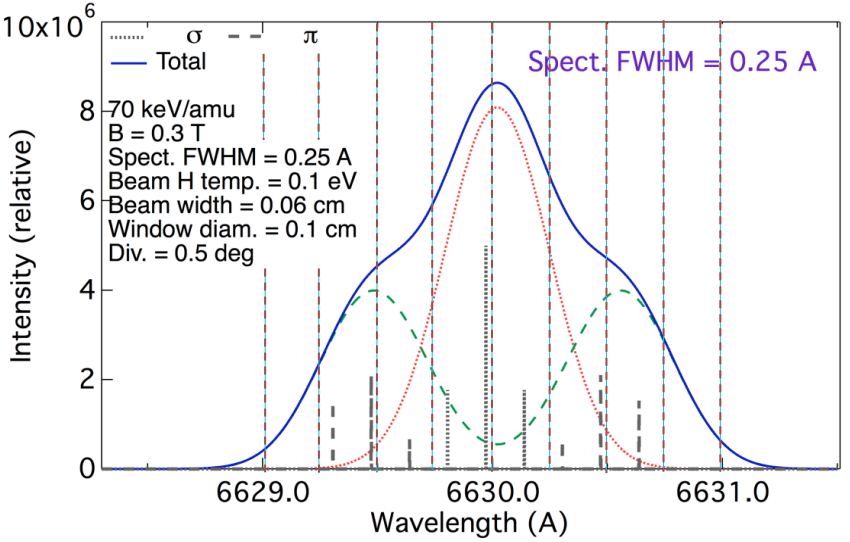
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High spectrometer resolution is required to resolve π components of Stark spectrum

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



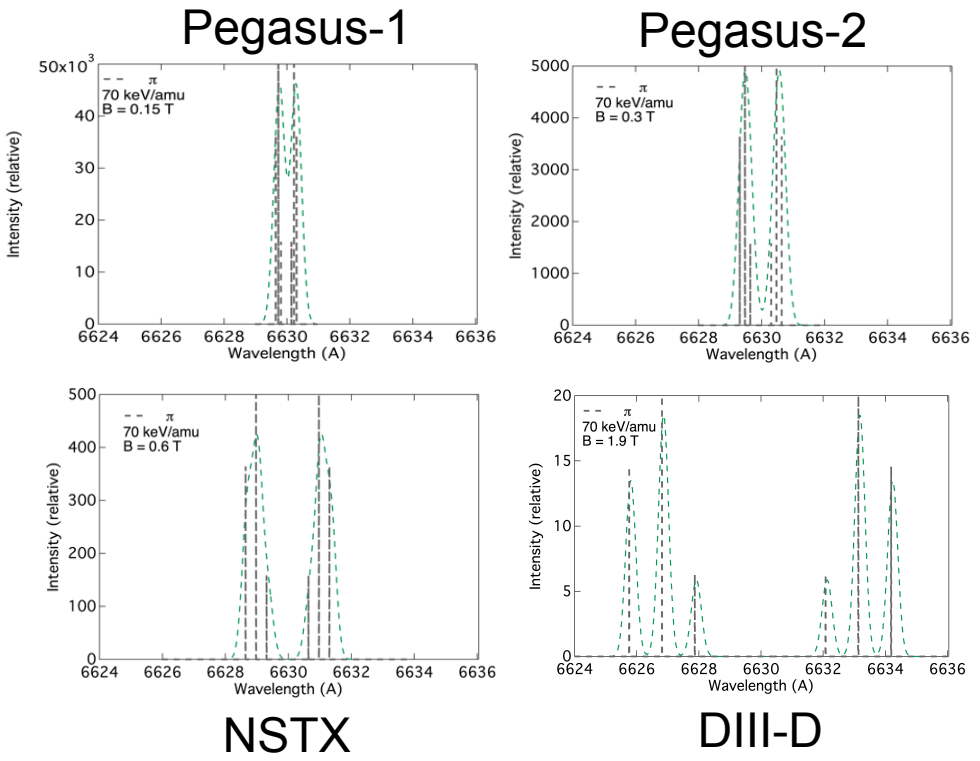
Typical spectra cover 2 Å, suggesting a spectral resolution requirement of 0.25 Å or better for an eight detector array.

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

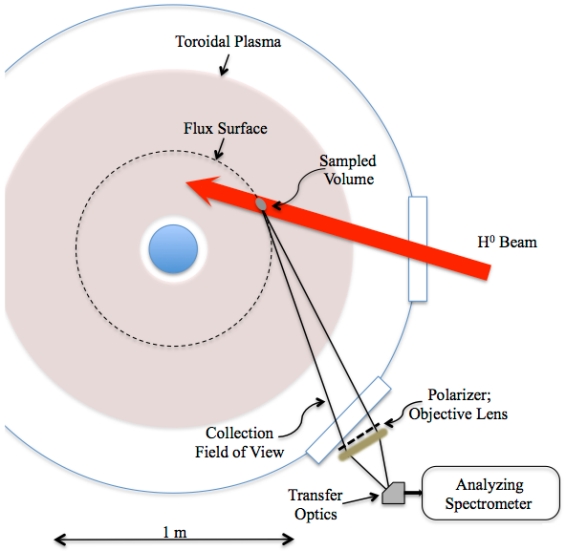
Piezo-electric control of etalon separation and wedge tilt

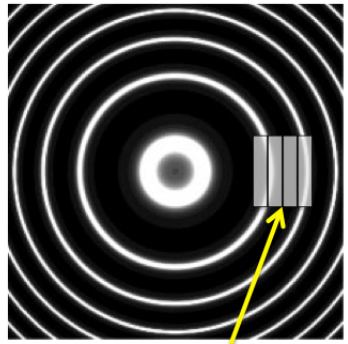
Number spectral channels: 8

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

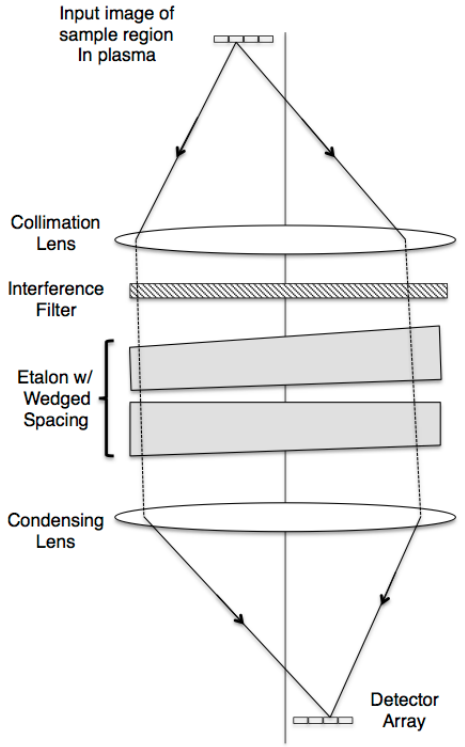
Assuming a 20 cm diameter collection lens and 2 cm spatial resolution, spectral resolution and throughput requirements suggest an etalon with a diameter of ~4 cm is sufficient

Multipass input optics may increase performance by a factor of 2-4 but are bulky





Fringe Sampling Region for Adjacent Detectors



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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

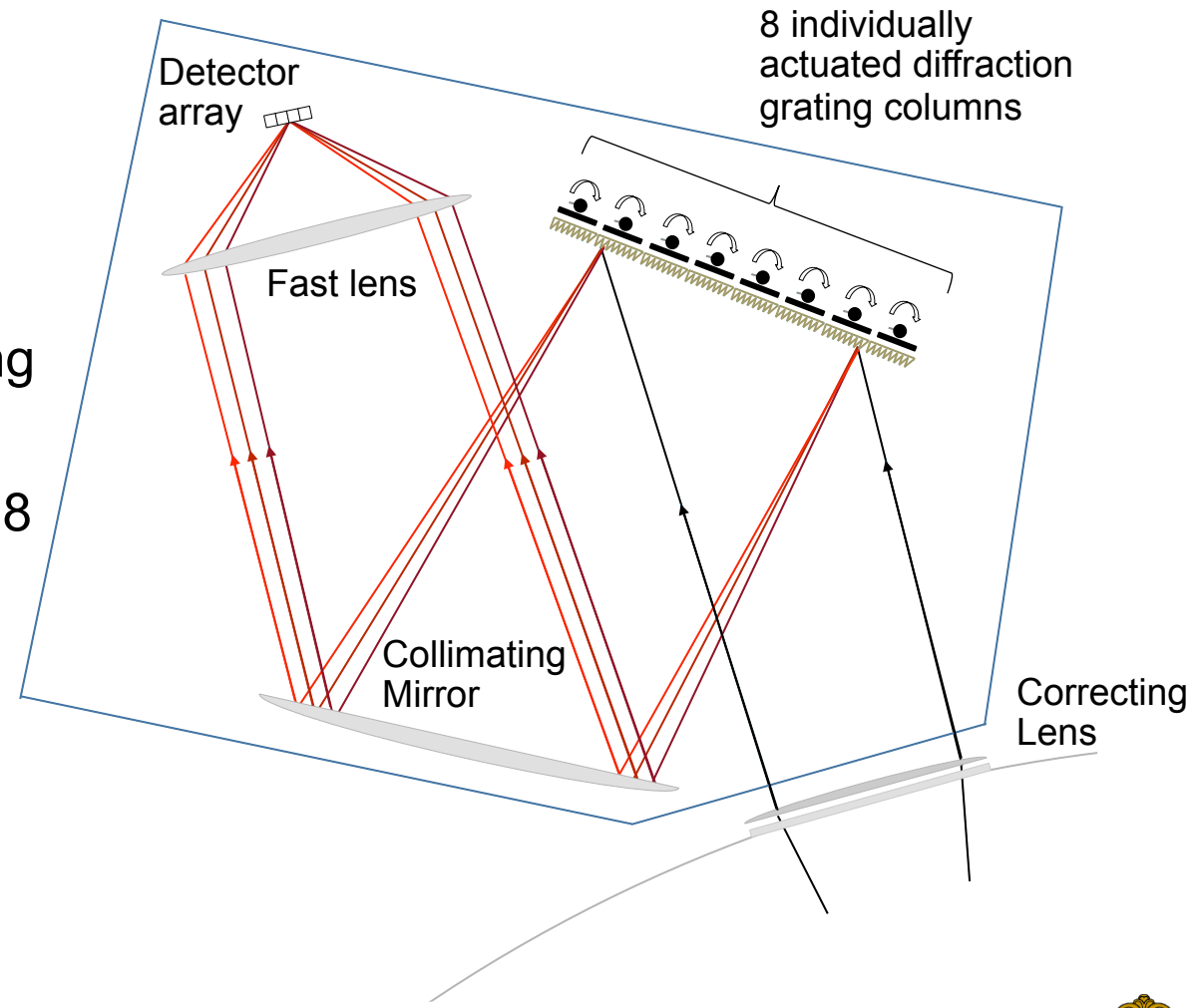
High efficiency diffraction gratings

8 independently tilted grating columns

Number spectral channels: 8

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

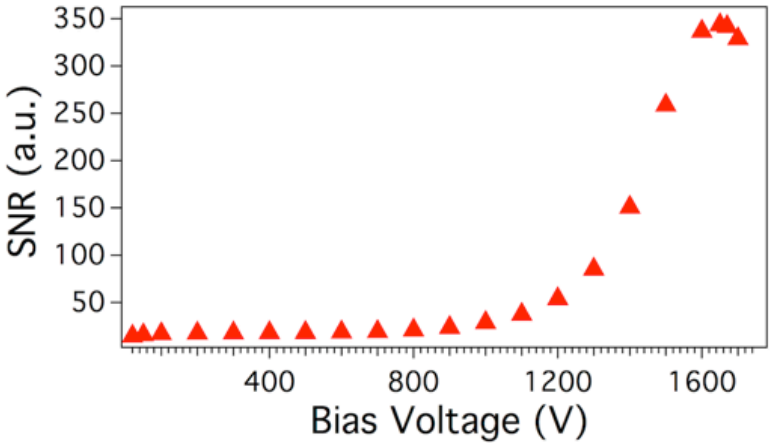
Mosaic components to reduce cost

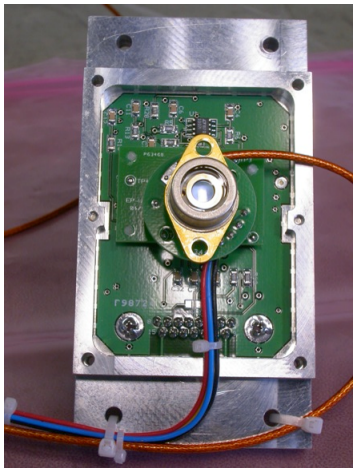


An array of thermo-electrically cooled avalanche photodiodes measures fluctuations

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

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





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

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:

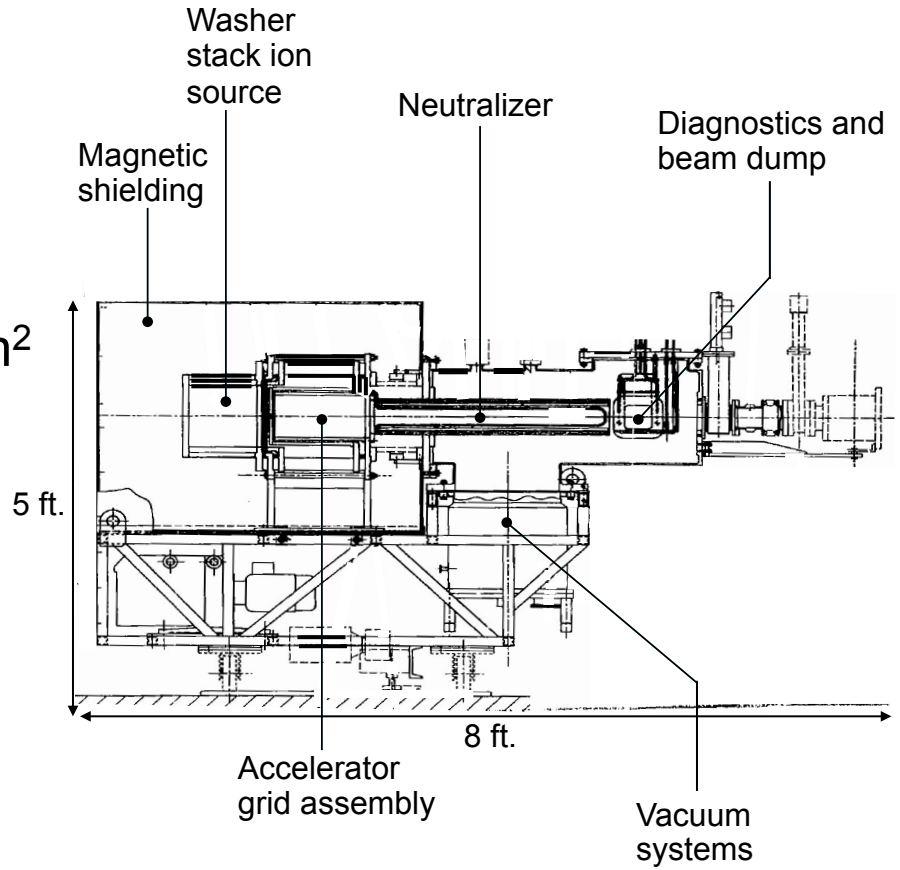
H:H/2:H/3 = 22 : 35 : 43 @ 67 kV

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[1] as an arc plasma ion source

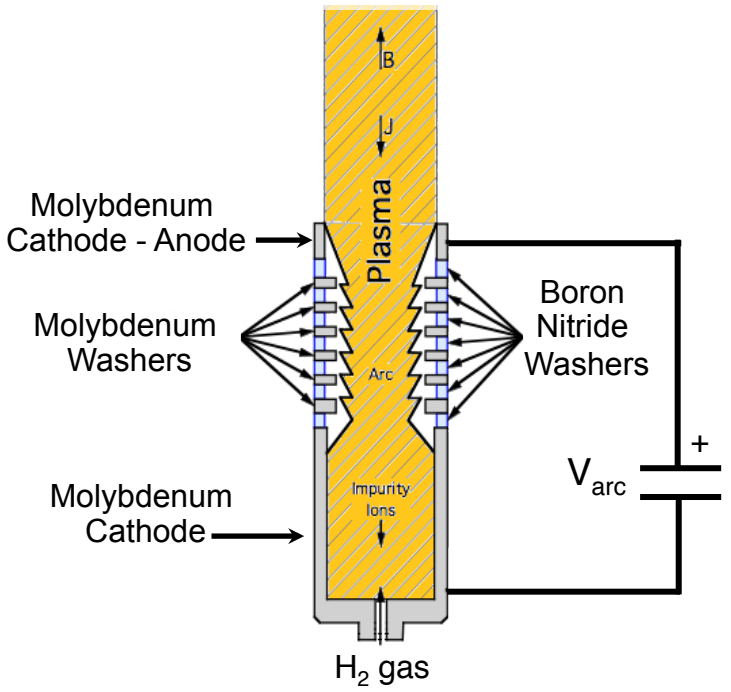
Washer stack arc sources have been successfully implemented on other diagnostic beams [2,3,4]

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

E1 : E2 : E3 = 93.6 : 6 : 0.3 achieved at MST[5]

Design does not require an extended burn-in period

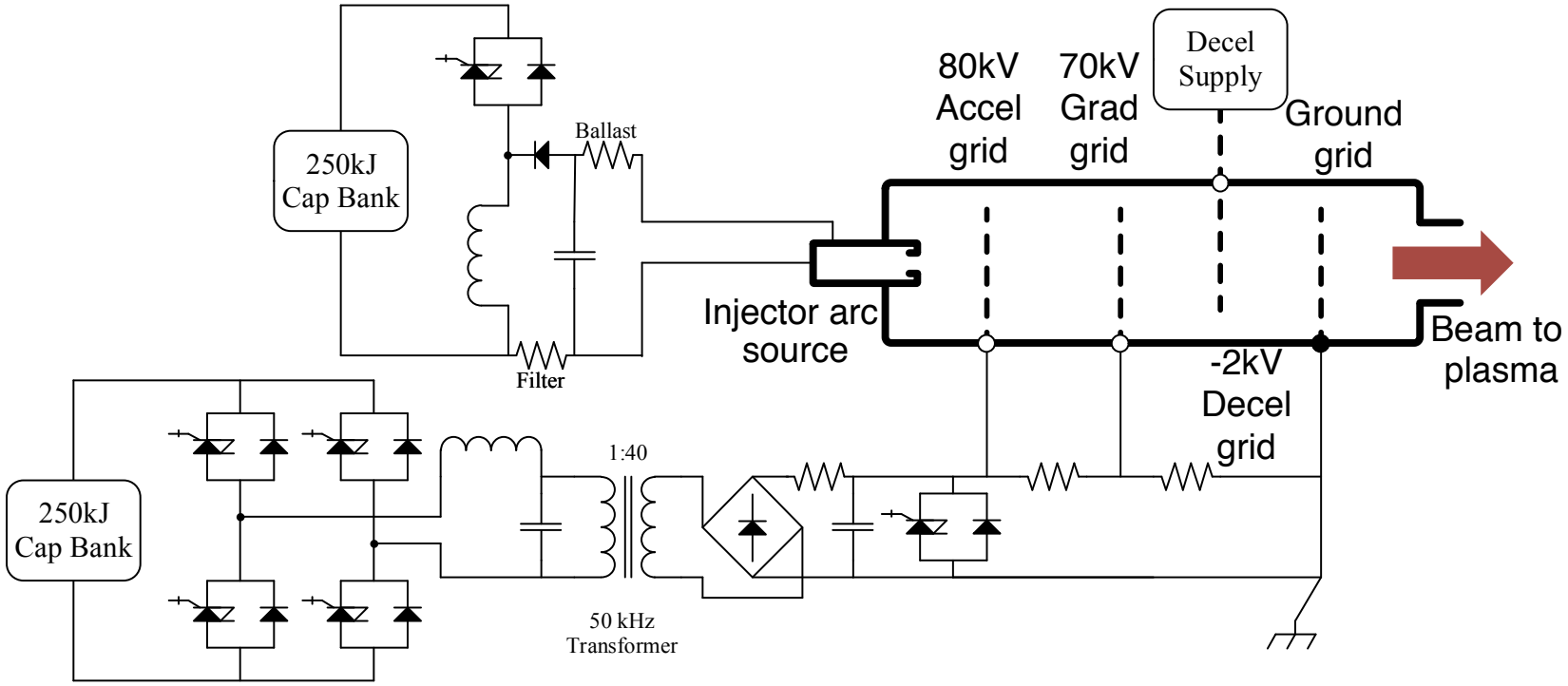
Typical conditioning period for an injector on Pegasus is ~50-100 shots, with lifetimes of 100s-1000s of shots



[1] *Perry et al., TP8.00019*
[2] *Belchenko et al., Rev. Sci. Instrum.* ***61****, 378 (1990)*
[3] *Deichuli et al., Rev. Sci. Instrum.* ***79****, 02C106 (2008)*
[4] *Asai et al., Rev. Sci. Instrum.* ***79****, 063502 (2008)*
[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

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 line width fluctuations

Near term objectives:

- Plasma source fabrication and testing
- Refurbish beam
- Complete fabrication of power supplies
- Finalize spectrometer design

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