Progress Towards A New Technique for Measuring Local Electric and Magnetic Field Fluctuations in High Temperature Plasmas

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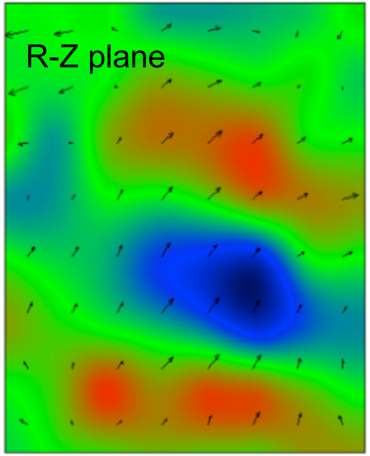
October 26, 2017

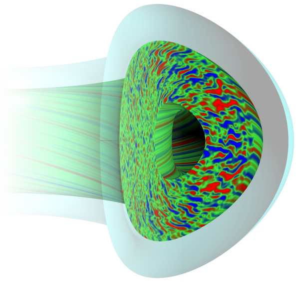
Introduction

Understanding Turbulence in Tokamaks is a Fundamental Challenge for Fusion Energy

- Plasma turbulence in tokamaks results in anomalous transport
  - Cross-field transport >> neoclassical predictions
- Present plasma diagnostics measure key fluctuating parameters $\tilde{n}$, $\tilde{T}_i$, $\tilde{T}_e$, $\tilde{v}$
- Measurement of electrostatic field turbulence ($\tilde{E} \sim k_{\perp}\tilde{\phi}$) remains a challenge, gives $\tilde{v}$
  - $\tilde{E}_\theta \times B_\phi \cong \tilde{v}_r$: turbulent cross-field transport, $\tilde{E}_r \times B_\phi \cong \tilde{v}_\theta$: shear-flow and zonal flow dynamics
- Local magnetic field fluctuation ($\tilde{B}$) measurement also challenging, could provide critical information
  - Local $\tilde{B}$ dynamics during edge harmonic oscillation (EHO)
  - 3D magnetic field perturbation penetration into plasma pedestal



Density perturbations and calculated velocimetry in DIII-D plasma



GYRO turbulence simulation

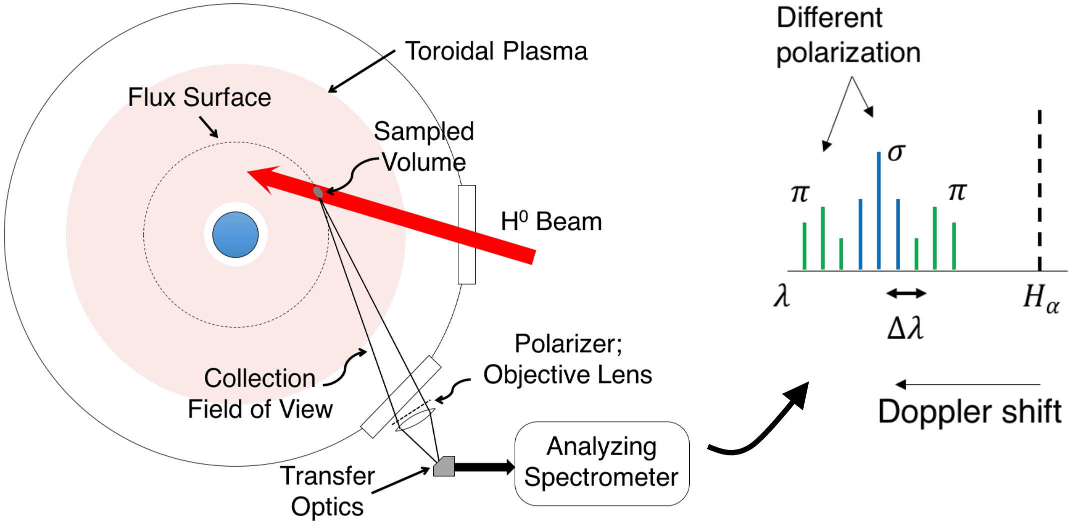
Motional Stark Effect Field Used as Carrier Signal for $\tilde{E}$

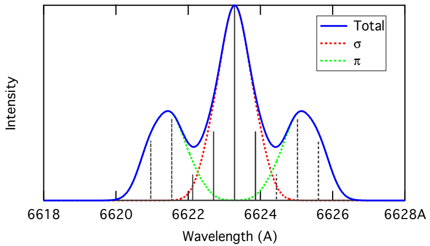
- Motional Stark Effect spectrum provides carrier line broadening for $\tilde{E}$:

$$\vec{E}_{total} = \vec{v}_b \times \vec{B} + \vec{E}_{plasma}$$

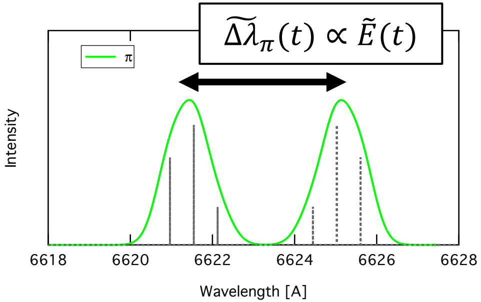
- Measure high-speed variations in π/s line intensity ratio or in π-components linewidth to derive $\tilde{E}$
- Spatial Heterodyne Spectrometer (SHS) provides flexible analyzer of multiplet spectrum
- New CMOS imaging systems provide detection and DAQ

Diagnostic layout:



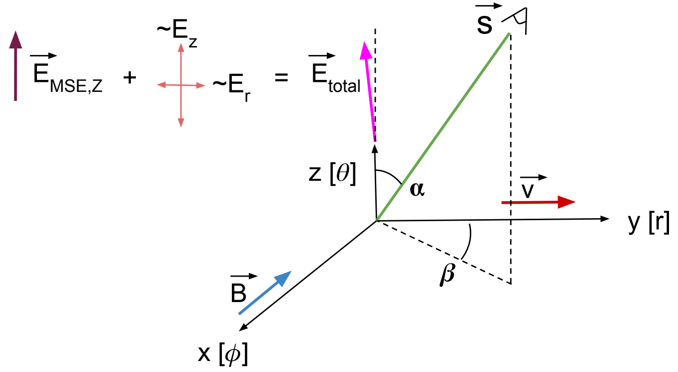


Model Hα Stark Spectrum: 80 keV, 0.5 T

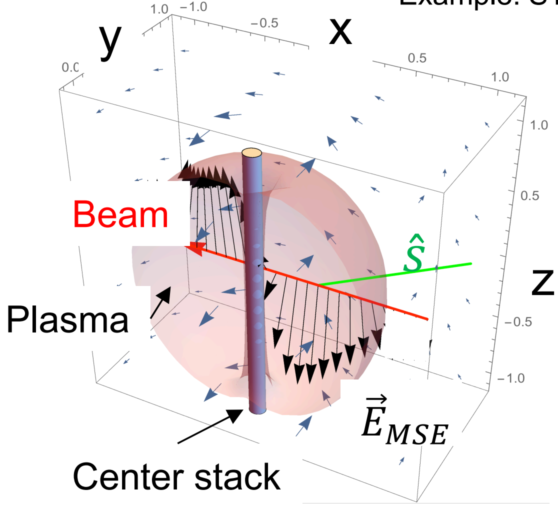


Multiple Techniques Used to Extract Components of $\vec{\tilde{E}}_{plasma}(t)$

- Midplane beam, sightline: linewidth changes
    - Radial beam: $\vec{E}_{MSE}\hat{z}$, $\tilde{E}_z$ doesn't change α
    - $\widetilde{\Delta\lambda}_{Stark} \propto \tilde{E}_z \rightarrow \tilde{v}_r$
- Midplane beam, off-midplane sightline: Intensity ratio change
    - $R = \frac{\sum I_\pi}{\sum I_\sigma} = \frac{\sin^2\alpha}{1+\cos^2\alpha}\left({}^{I_\pi}/_{I_\sigma}\right)(n_e) \equiv \frac{\sin^2\alpha}{1+\cos^2\alpha}F$
    - $\tilde{R} = R\left[\frac{\partial \ln F}{\partial \ln n_e}\frac{\tilde{n}_e}{n_e} + \frac{4\cos\alpha}{(1+\cos^2\alpha)\sin\alpha}\tilde{\alpha}\right]$
    - $\tilde{E}_r \sim \tilde{\alpha} E_{MSE} \rightarrow \tilde{v}_z$
- First emphasis on line width measurement: insensitive to density fluctuations, midplane view



Example: ST Geometry



Local Magnetic Field Fluctuations May be Measurable via Stark Muliplet

- Measurement of local magnetic field fluctuations ($\tilde{B}$) in high temperature plasmas is challenging
  - Provides information on: fast particle modes, island structures, plasma response to 3D RMP for ELM control, high-β turbulence
- Again use MSE field as carrier
- For midplane sightline and radial beam:
  - $\vec{v}_r \times \tilde{B}_\phi = \tilde{E}_z$, $\vec{E}_{MSE}$ is mostly in the $\hat{z}$ direction → $\widetilde{\Delta\lambda}_{Stark} \propto \tilde{B}_\phi$
  - $\vec{v}_r \times \tilde{B}_z = \tilde{E}_r$, changes angle of $\vec{E}_{MSE}$ → measure polarization intensity
- Typically for tokamaks $\tilde{B}/B$ ~ 10^{-5}, 100x smaller than broadband $\tilde{E}/E$
- However for EHO, $\tilde{B}/B$~ 10^{-4}, coherent, low frequency (~10 kHz)
- $\tilde{B}/B$ and $\tilde{E}/E$ may be distinguishable using different beam energy components
  - $\Delta\lambda_1 \propto v_b\tilde{B} + \tilde{E}_{int}$, $\Delta\lambda_2 \propto \frac{1}{2}v_b\tilde{B} + \tilde{E}_{int}$

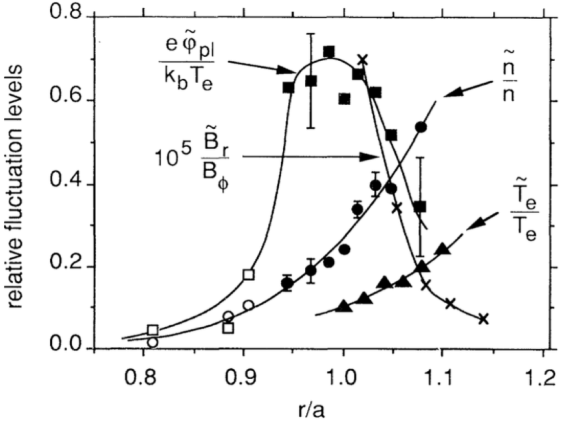
Diagnostic Requirements

$\tilde{E}/\vec{E}_{MSE}$ in Fusion Grade Plasmas is ~10^{-3}

Experiment	$T_{e,0}$ (keV)	B (T)	a (m)	$\tilde{E}/E_{MSE}$
NSTX-U	~2-4 (?)	1	0.6	$1-2\times10^{-3}$
DIII-D	2-5	2	0.7	$0.5-1\times10^{-3}$
Pegasus	~0.3	0.3	0.35	$0.7-1\times10^{-3}$

- Tokamak drift wave turbulence scaling gives $\tilde{E} \propto T_e/a$
- $\tilde{E}$ turbulence broadband, majority of fluctuation power < 300 kHz
- $\tilde{E}$, $\tilde{n}$ rise from core to edge
- $\tilde{E}/E_{MSE}$ at or bellow photon noise floor for BES (typical rms noise ~0.1%)
    - Two independent but spatially correlated measurements (e.g. $\langle\tilde{E}\tilde{n}\rangle$) made simultaneously can suppress incoherent photon noise another ~10x

Fluctuations in TEXT

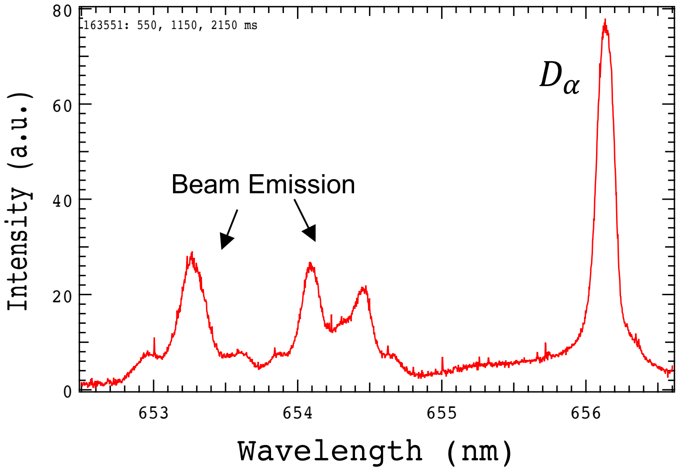


C. P. Ritz, et. al., Phys. Rev. Lett., **62**, 1989.

$\Delta\tilde{\lambda}_{\pi}$ Spectrometer Requirements are Formidable

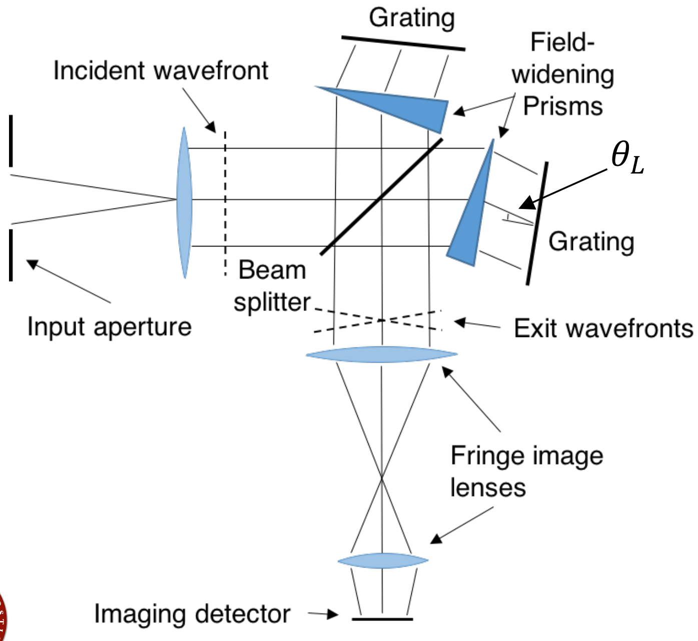
- Resolution:
  - Need ~8 spectral bins to resolve 2 gaussian-like π components
  - $\Delta\lambda^{\pi}_{H\alpha}$~ 6 Å in D3D giving approximate spectral resolution of 0.75 Å, R=$\frac{\lambda}{\delta\lambda}$ ~9000
- Throughput:
  - Matched to collection optics, U = 0.016 cm^2sr per D3D BES spatial point
  - 2 spatial points desired
- Compatible detector system:
  - ~500 kHz time response
- Mitigation of sightline-DNB geometric broadening
  - Spectrometer optics conjugate to plasma collection lens → coherent fiber bundle

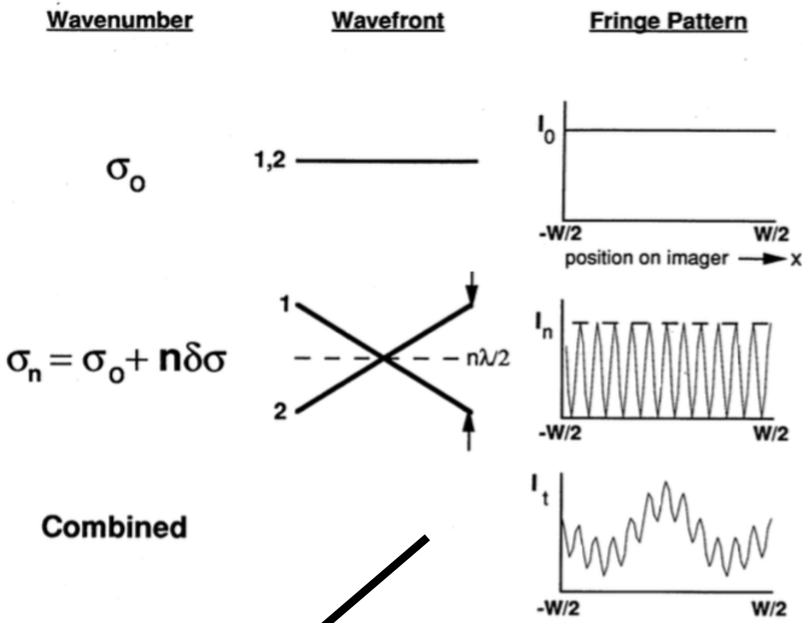
D3D BES Spectrum:



Spatial Heterodyne Spectroscopy Technique Utilized for $\Delta\tilde{\lambda}_{\pi}(t)$ Measurement

- Self scanned, 2 beam interferometer
- Input wavelengths heterodyned around Littrow wavelength
- Field widening prisms increase throughput >10x





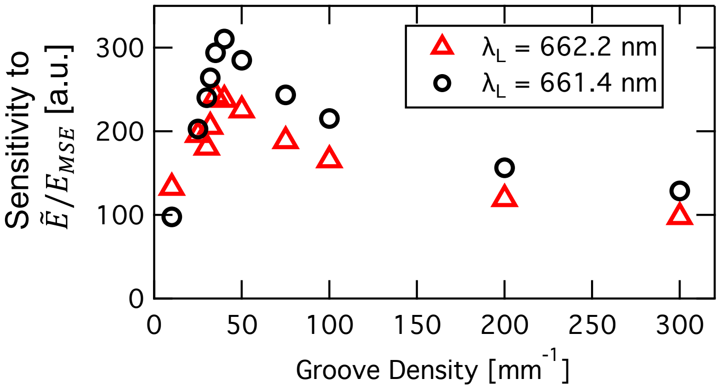
$$I(x) = \int_0^{\sigma} B(\sigma)(1 + \cos[2\pi(4|\sigma - \sigma_0|x \tan\theta_L)])d\sigma$$

J. Harlander, R. J. Reynolds, and F. L. Roesler., ApJ, **396,** 1992.

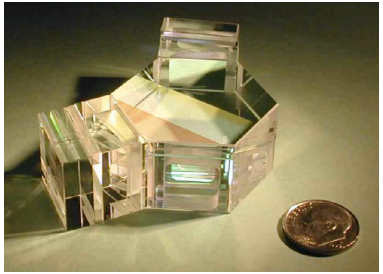
Spatial Heterodyne Spectroscopy Achieves High Resolution and Throughput

- Phase I SHS design points:
  - $R = \sigma/\delta\sigma \approx 2Wd, U = 2\pi\eta A/R$
  - For $\tilde{E}$: Need approximately R~9000
  - Design studies of SHS indicate low groove density grating maximizes sensitivity to $\tilde{E}/E_{MSE}$
  - Phase I parameters: grating width W = 75 mm and 50 g/mm, R~7500 @ ~0.05 cm^2sr
- Future design to utilize field widening prisms
  - Increases U ~100x at the same resolving power
  - Smaller SHS and multiple spatial points

Spectrometer design studies:



Compact monolithic SHS design scales favorably to multiple plasma spatial points:

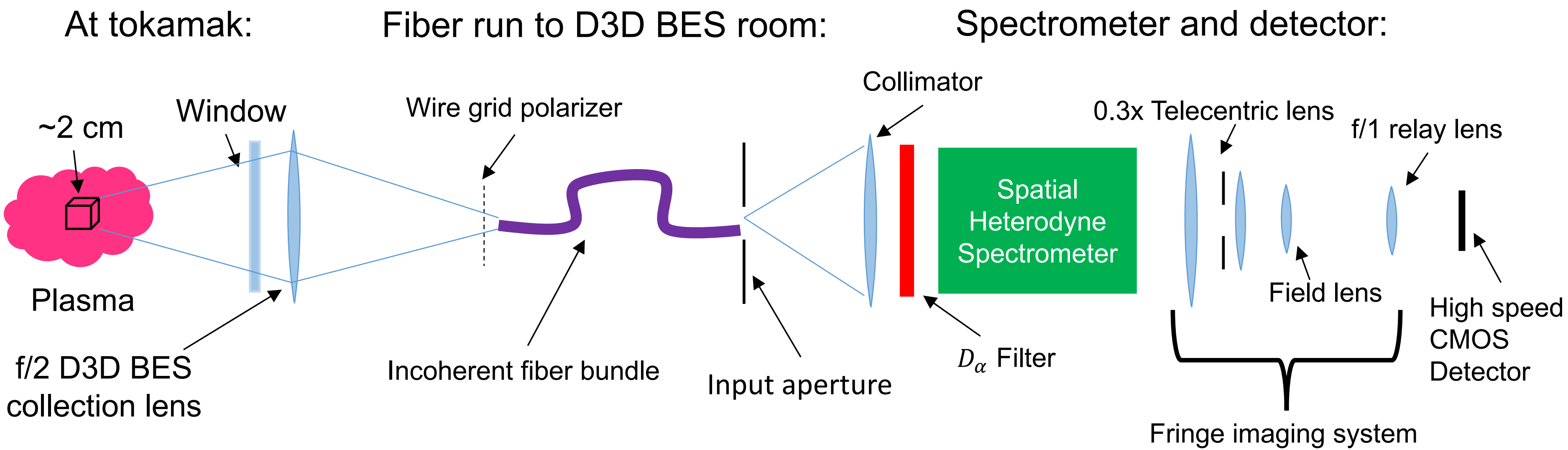


SHIMMER SHS: R≈2.5x10^4, U≈0.1 cm^2sr

Harlander, J. M., Roesler, F. L., Englert, C. R., et al. (2003). Applied Optics, 42(15), 2829–2834.

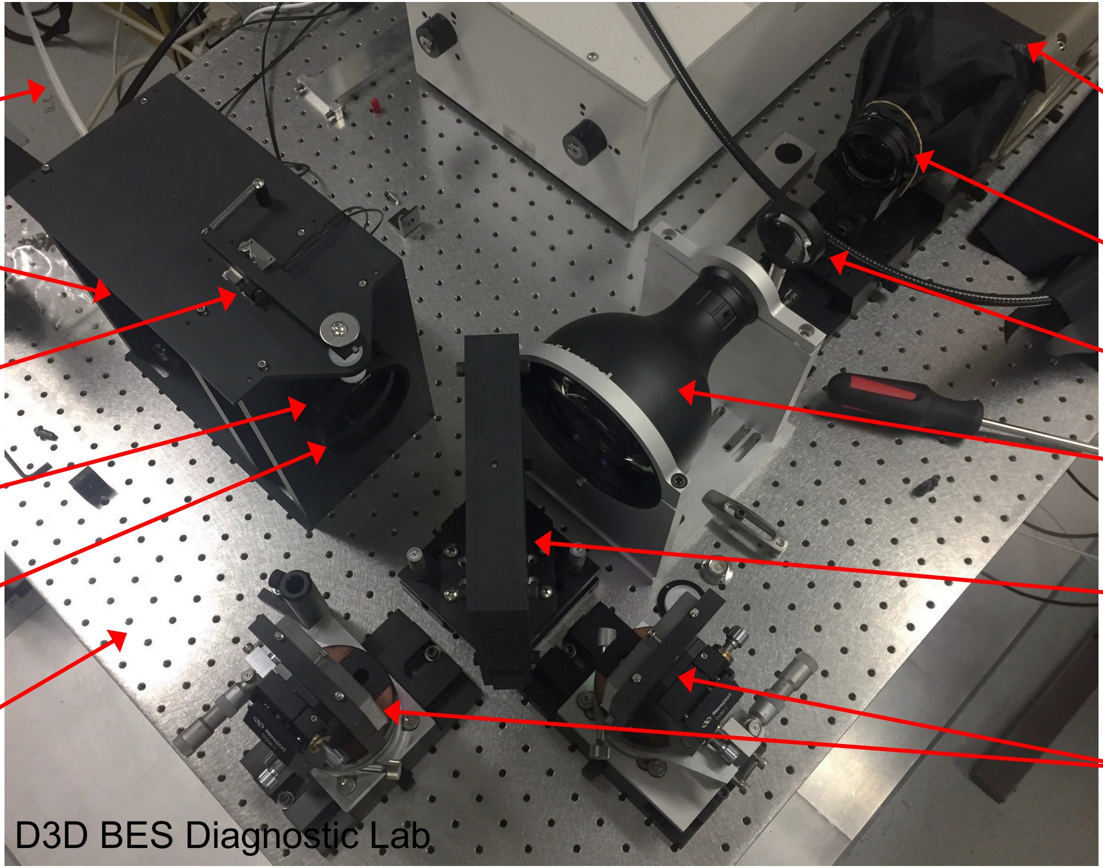
Phase I Progress

Phase I Optical Layout



- Planned full system deployment to D3D for late 2017
- Goal is to validate spectrometer design with measurement of low frequency (~10 kHz) electric or magnetic field turbulence

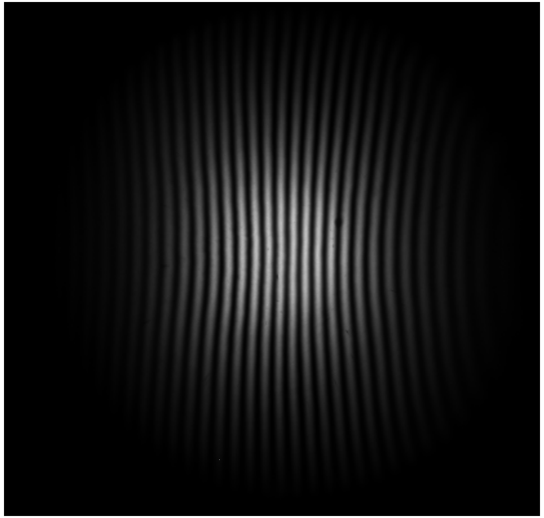
Phase I deployed to D3D for Evaluation in Tokamak Environment



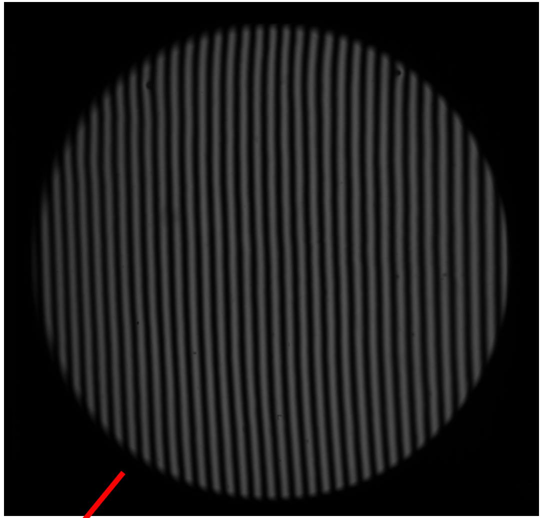
Initial Performance Characterization

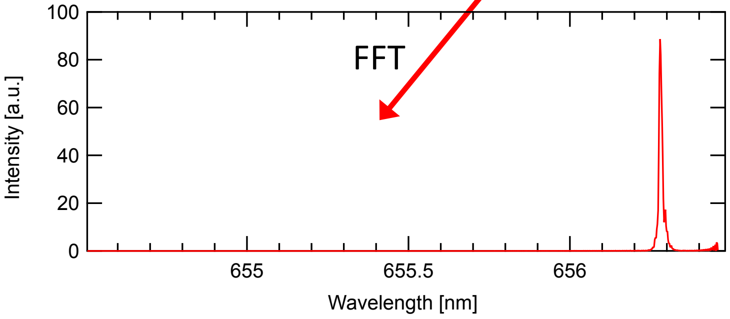
- Single input wavelength leads to single spatial frequency
- Field lens corrects intensity vignetting and fringe distortion due to demagnification lens
- Hydrogen-Deuterium Giessler tube light source to be used for future resolution validation
  - Separation of H_α (656.279 nm) and D_α (656.1 nm) ~ 0.18 nm is close to the desired resolution for the measurement

Without field lens



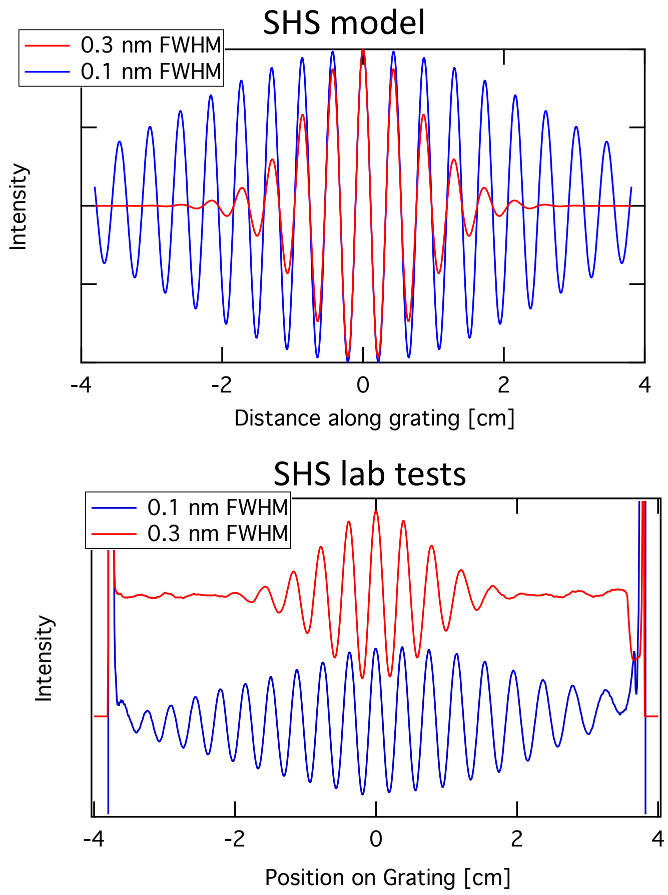
With field lens





Broadband spectral input leads to shrinking of interferogram

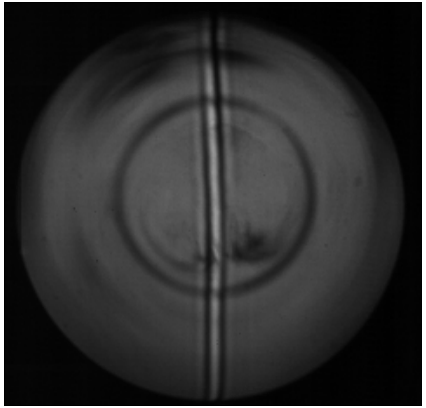
- Variable line width put into SHS using tunable light source
- Spectrally broad input effects inteferogram envelope
  - $I(x) = e^{-wx^2}[1 + \cos(8\pi(\sigma - \sigma_L))x \tan\theta_L]$
  - Multiple broad lines has addition effect
- For fluctuation measurement, desire every pixel in detector to provide meaningful information
  - Design studies of spectrometer sensitivity push groove density down



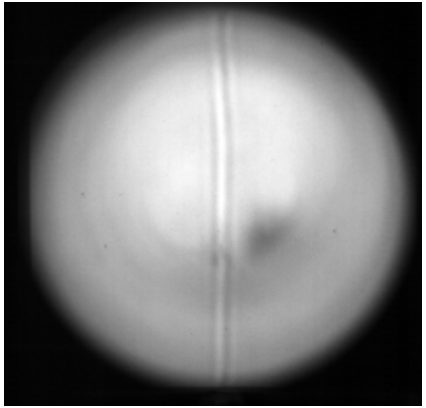
Compensation Plate Needed to Maintain Fringe Contrast, Match Fiber Etendue

- Spectrometer designed to match single fiber etendue
  - U_{BES}=0.016 cm^2sr
  - Full etendue SHS aperture size ~4.5 mm dia. imaged by 75mm dia. f/2 collimator
- Compensation plate required to maintain fringe contrast due to large aperture
- Plate installed in front of 50:50 beam splitter
  - Thickness equal to beam splitter plate, anti-reflection coated, $\lambda/4$ flatness

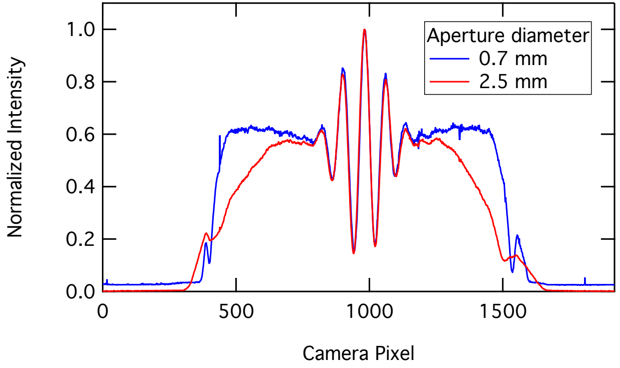
Small aperture



Full aperture



Fringe contrast with compensation plate:



D3D BES Lab vibration environment

- D3D BES lab elevated, thin walls, near HVAC equipment
- Active vibration isolation table nullifies table resonance and vibrations less than 20 Hz
- Further damping of horizontal vibrations may be necessary

SHS central fringe movement due to vibrations

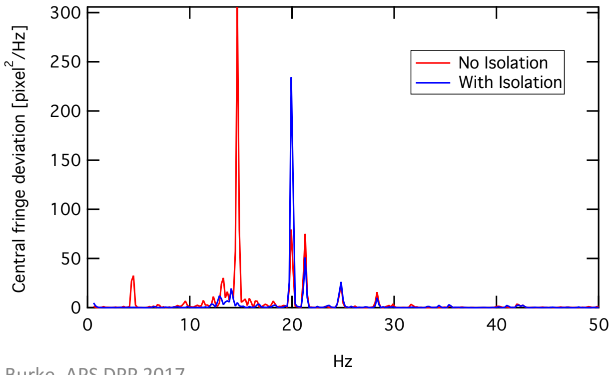
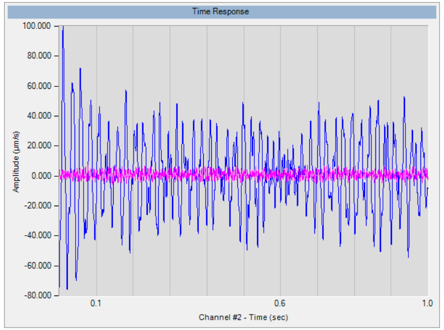


Table sensors: vertical

Time



FFT

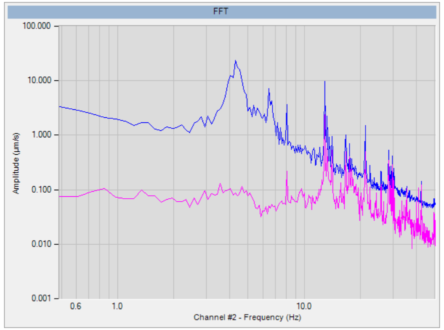
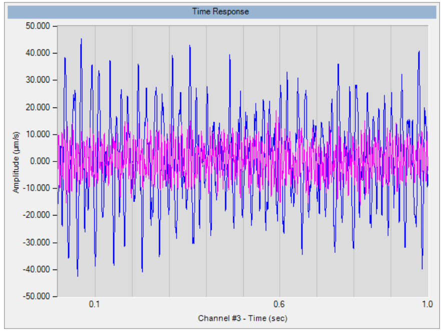
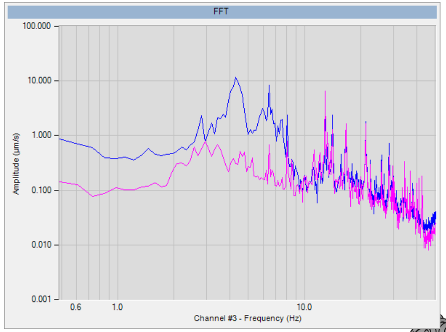


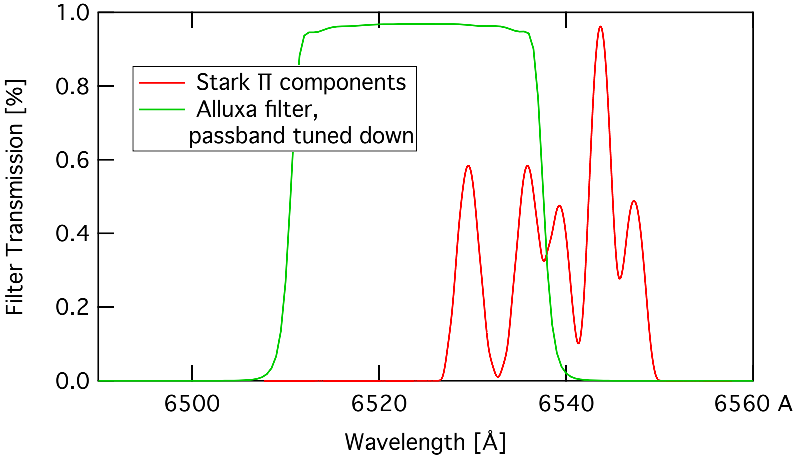
Table sensors: horizontal

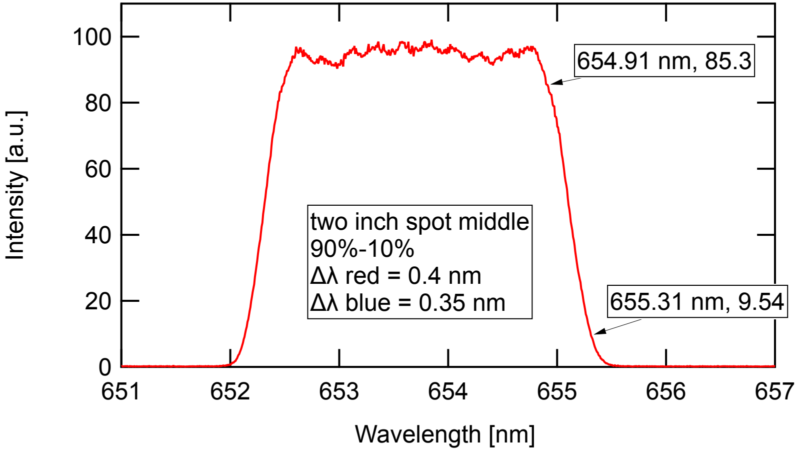




Sharp cutoff D_α filter required to isolate full energy components

- Filter designed by Alluxa
  - 90-10% cutoff <0.25 nm
  - >90% transmission in passband
  - 3 in diameter
- Allows for selection of only full energy beam components (improves sensitivity) or all components (distinguish between $\tilde{B}$ and $\tilde{E}$)
- Movement of passband over large filter area shallows cutoff
  - 0.4 nm 90-10% cutoff useable, misses design point
  - Working with manufacturer on fix

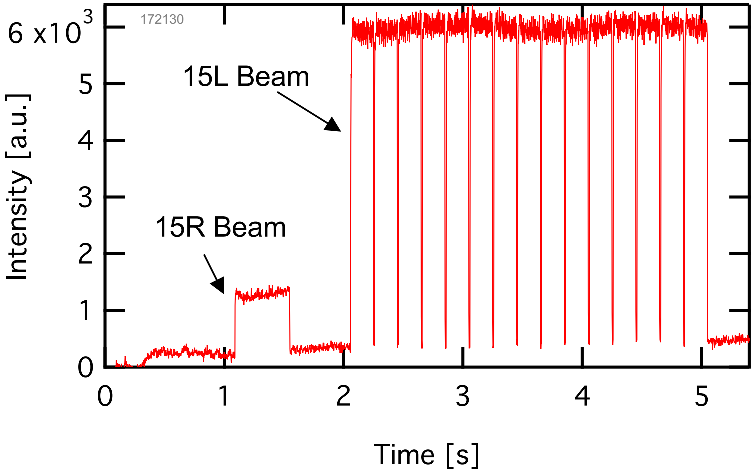


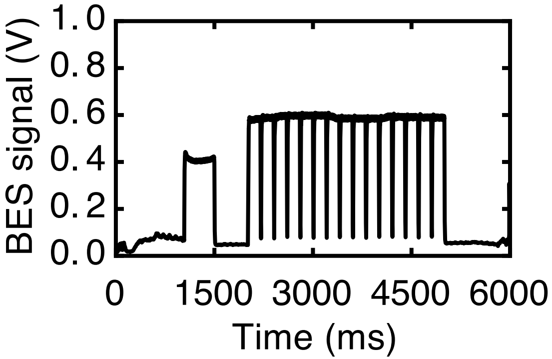


First Light Into Phase I SHS

- First light into SHS using fiber channel next to BES fiber array
  - D3D run for two days in July
- Observed 150L beam modulation
- SHS noise level estimated to be ~0.5%
  - $\sim 4\times10^{7}$ photo-e$^-$ in 2 ms → 2×10^{4} photo-e$^-$/μs
  - At 300 kHz BW, $\frac{d\tilde{N}}{dt} = \sqrt{2\frac{dN}{dt}BW}$ gives $d\tilde{N}/dt$ = 346 or ~0.5% rms noise
- RMS noise level likely to improve with filter and compensation plate fix

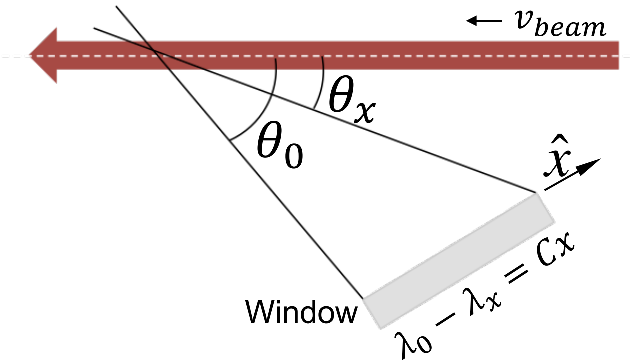
SHS central fringe intensity:



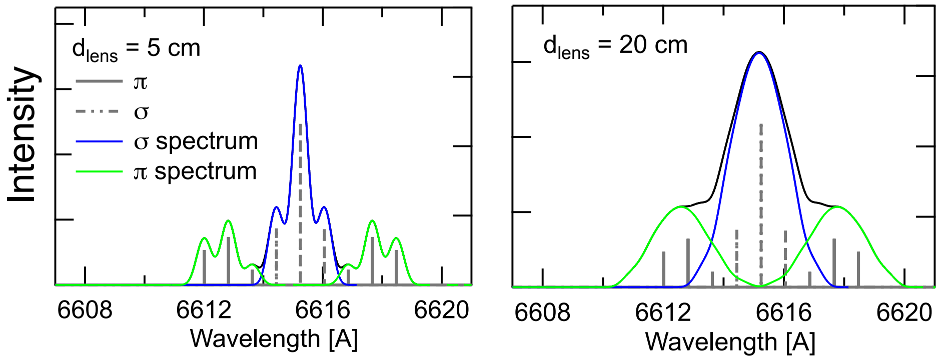


Geometric Broadening Compensation

Geometric Broadening Limits Diagnostic Sensitivity to $\tilde{E}$

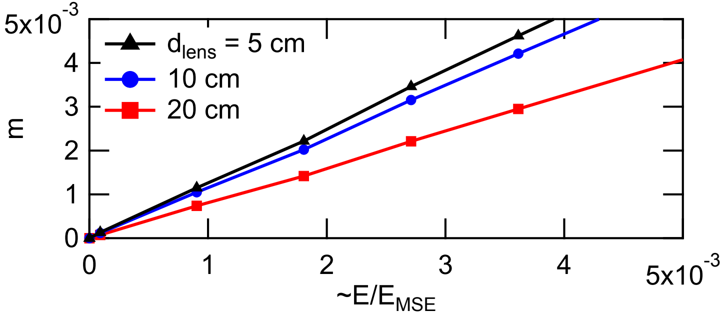


Geometric broadening on DIII-D:

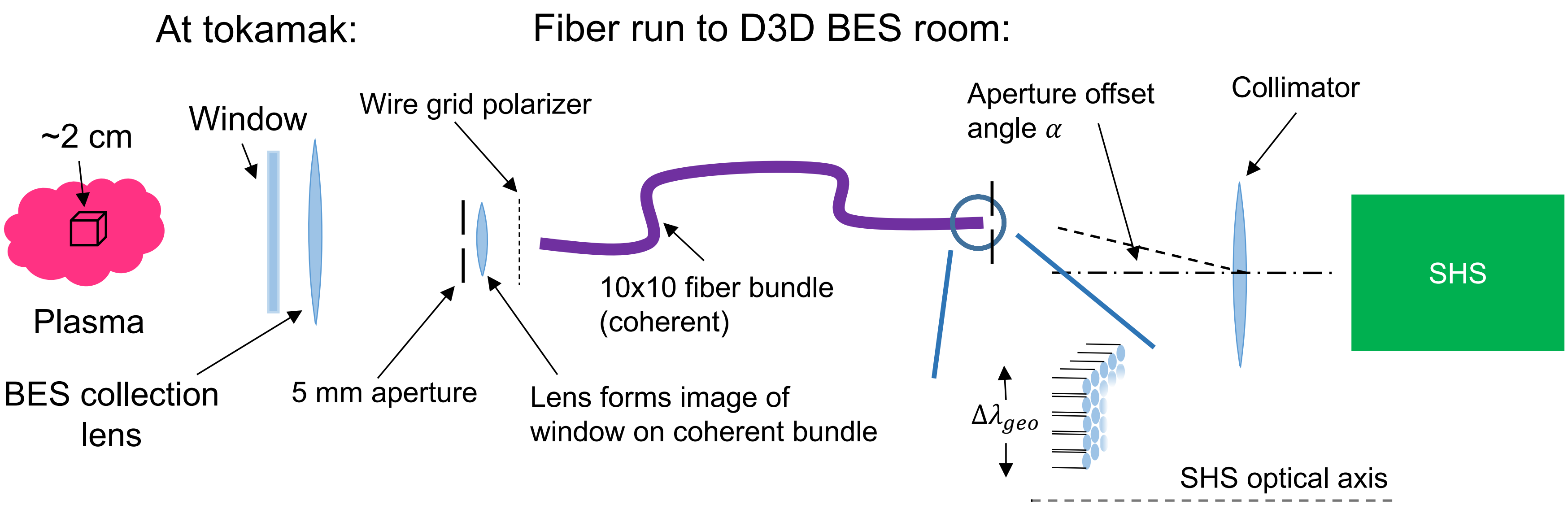


- λ shift due to beam-collection optic viewing geometry is linear across window
  - Shift of ~0.3 nm (~7.5 cm^{-1}) across window
- Can be removed numerically or physically in spectrometer
- Both removal techniques require collection optic be imaged to a place inside spectrometer

Sensitivity to $\tilde{E}/E_{MSE}$ at different window sizes:



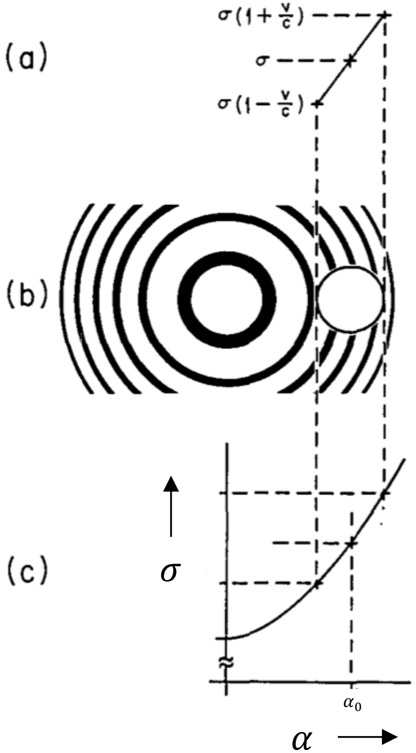
Collection Window Conjugate to Input Aperture Required to Remove Geometric Broadening



- 5 mm aperture size sets plasma collection volume (~2 cm)
- Fore optics image the plasma to the 5 mm aperture while imaging the BES collection lens to a ~10x10 coherent fiber bundle of approximately the same size as the current BES fiber bundles (~4.5 mm diameter) → reduce geometric broadening by ~10x

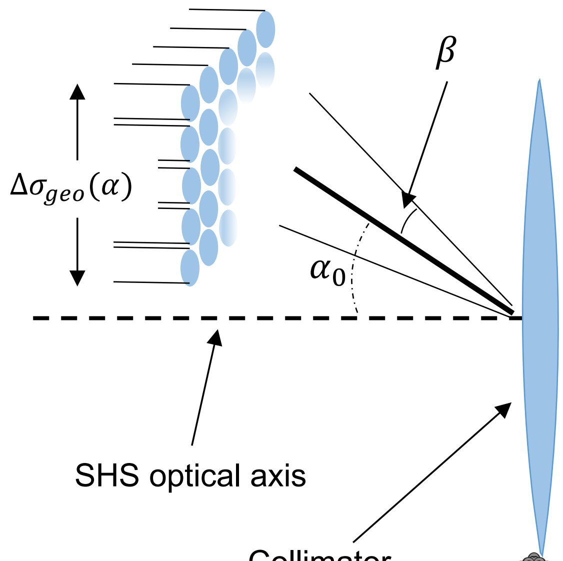
Geometric Broadening Compensation Achieved by Offsetting SHS Aperture

- Shift in real wavelength across BES collection lens can be negated by offsetting aperture (standard practice in atmospheric wind Fabry-Perot spectrometers see Trauger *et al.*)
- At spectrometer, window image rotated 90° so that $\Delta\sigma_{geo}$ is perpendicular to dispersion plane ($\Delta\sigma_{geo}(\alpha)$, where α is angle off dispersion plane)
- Grating equation off-axis has groove spacing (a) change proportional to α, $\sigma a \cos\alpha\,(\sin\theta_{in} + \sin\theta_{out}) = m$
- Solving for wavenumber shift while keeping OPD phase constant:
  - $\delta(\Delta\sigma) = \frac{\Delta\sigma_0}{cos^2(\theta_L)} \tan\alpha_0\,\delta(\alpha)$
  - $\delta(\alpha)$ becomes the field of view of the spectrometer β



J. T. Trauger., Appl. Opt., **11**, 1972.

Doppler compensation concept in SHS:



Summary: Moving Towards Diagnostic For $\tilde{E}$ and $\tilde{B}$ in High Temperature Magnetically Confined Plasmas Using Spatial Heterodyne Spectroscopy

- $\tilde{E}$ measurements appear feasible using high speed measurements of motional stark multiplet
  - Horizontal view gives $\tilde{E}_z$, off midplane gives $\tilde{E}_R$
  - $\tilde{B}$ measurement also possible using Stark multiplet
- Phase I SHS design completed, near deployment for first fluctuation data
  - First light through phase I SHS allowed testing of integrated system in tokamak environment
  - Need for improved filter transmission, compensation plate → changes in progress
- Next steps:
  - Validate technique with low frequency (~10 kHz) $\tilde{E}$ or $\tilde{B}$ measurement at D3D
  - Design Phase 2 spectrometer with geometric broadening compensation, run single coherent fiber bundle to D3D BES diagnostic lab

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