A New Technique for Measuring Local Electric Field Fluctuations in High Temperature Plasmas

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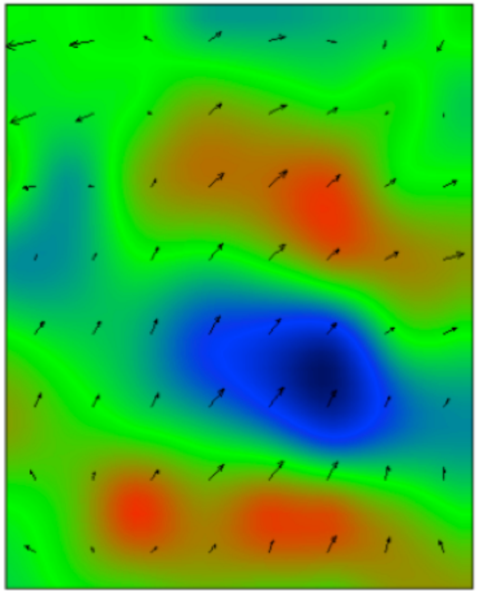
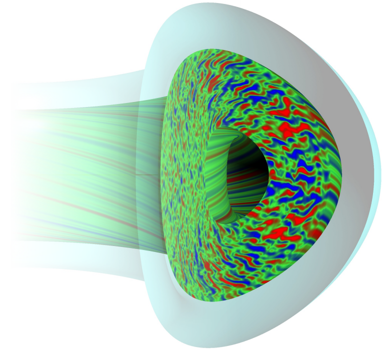
Introduction

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
- Other topics of interest:
  - Nonlinear turbulence dynamics, energy cascades, mode energy transfer, Reynolds Stress: $d\langle \tilde{v}_r \tilde{v}_\theta \rangle / dr$, turbulent particle flux,…
  - Validation of turbulence codes: GYRO, GENE,…



Density perturbations and calculated velocimetry in DIII-D plasma



GYRO turbulence simulation

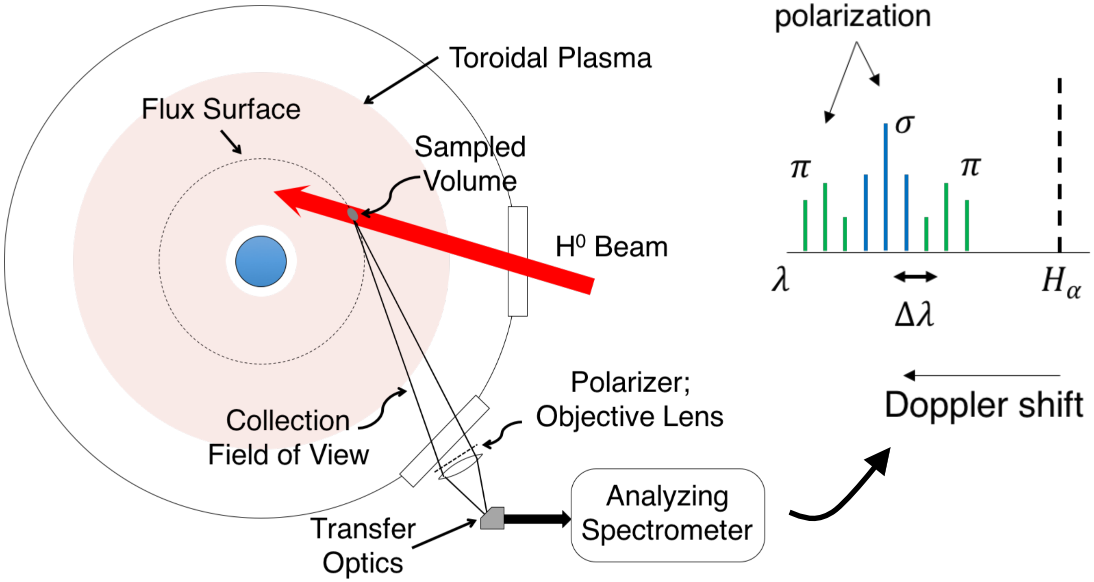
Motional Stark Effect Field Used as Carrier Signal for $\tilde{E}$

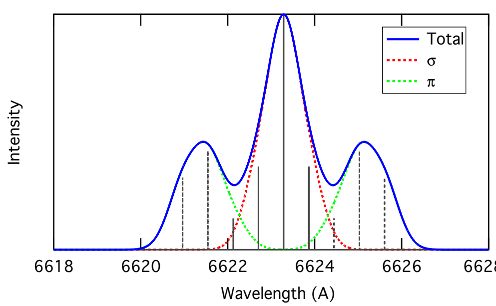
- Motional Stark Effect spectrum provides carrier line broadening for $\tilde{E}$:

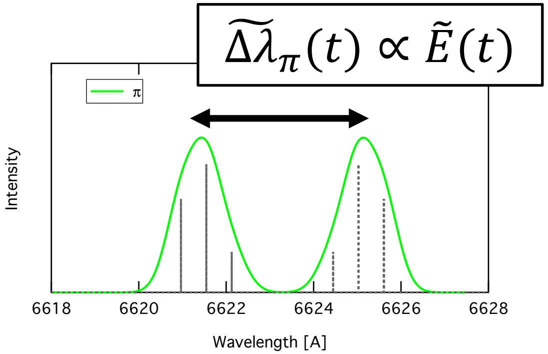
$$\vec{E}_{total} = \vec{v}_b \times \vec{B} + \vec{E}_{plasma}$$

- 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:



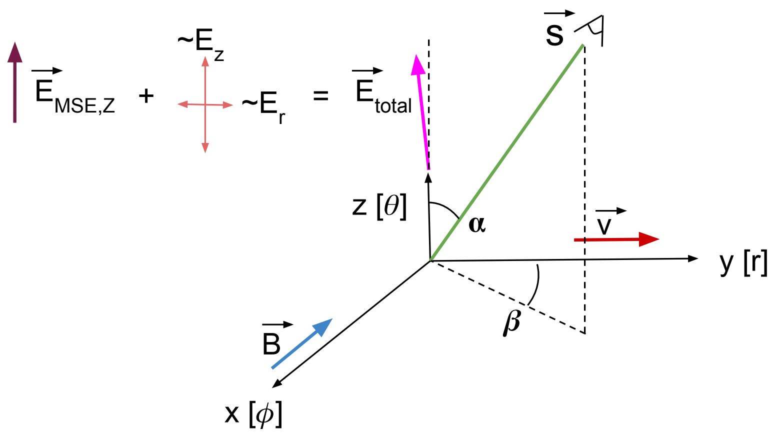


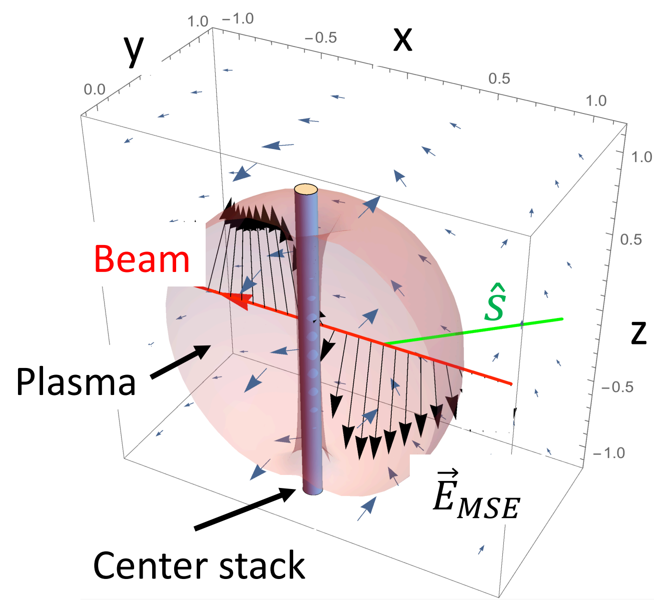


Model Hα Stark Spectrum: 80 keV, 0.5 T

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 3D RMP in plasma edge, $\tilde{B}/B$ has narrow frequency bandwidth
- $\tilde{B}/B$ and $\tilde{E}/E$ distinguishable using different beam energy components

Estimate of $\tilde{E}/E$ in Tokamaks

$\tilde{E}$ Estimated for Tokamaks Using Drift Wave Scaling

- Drift wave turbulence:

$$\frac{\tilde{n}}{n} \approx \frac{e\tilde{\phi}}{T_e}$$

- Long wavelength turbulence peaks at $k_{\perp}\rho_s{\sim}\alpha$, α=0.1-1
    - From BES and other measurements

- $\tilde{E}{\sim}k_{\perp}\tilde{\phi}$ and $\tilde{n}/n \sim 1/k_{\perp}L_n$ where $L_n{\sim}a$ (worst case)

$$\tilde{E} \approx \frac{\tilde{n}}{n}\frac{T_e}{e\rho_s} \approx \frac{T_e}{ea}$$

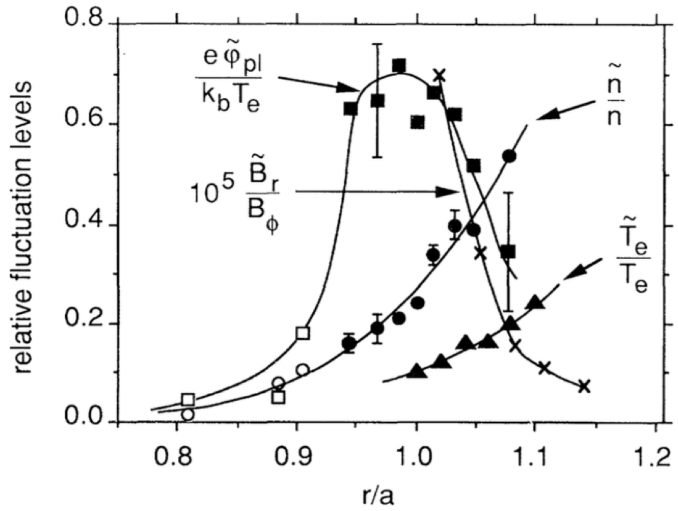
$\tilde{E}/\vec{E}_{MSE}$ in Fusion Grade Plasmas is ~10^{-3}

- Tokamak drift wave turbulence scaling gives $\tilde{E} \approx T_e/ea$

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	$0.7-1\times10^{-3}$

- $\tilde{E}$ turbulence broadband, majority of fluctuation power < 300 kHz
- $\tilde{E}$, $\tilde{n}$ rise from core to edge
- $\tilde{E}/E_{MSE}$ comparable to typical photon noise floor for BES

Fluctuations in TEXT



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

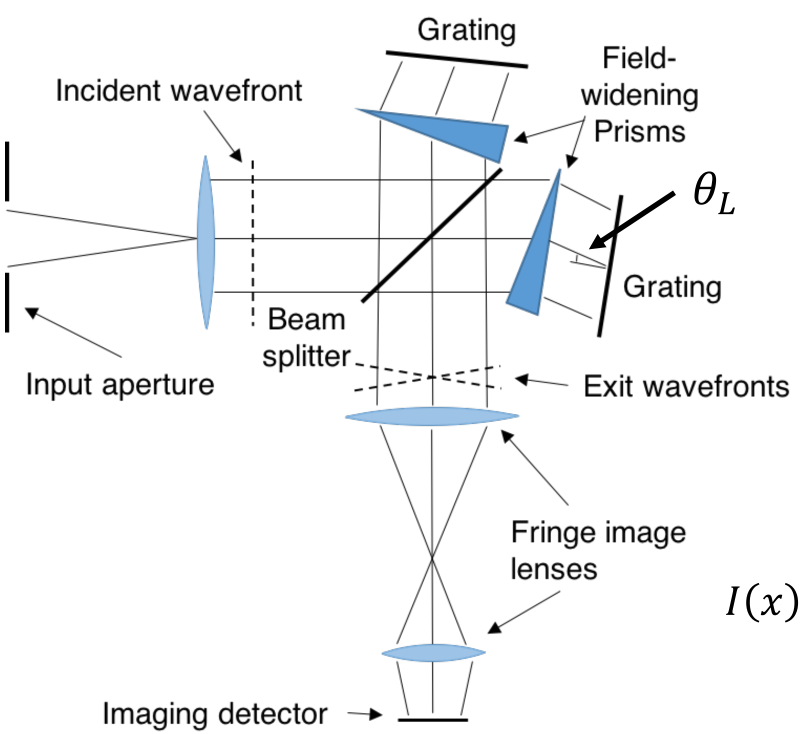
Spectrometer Requirements

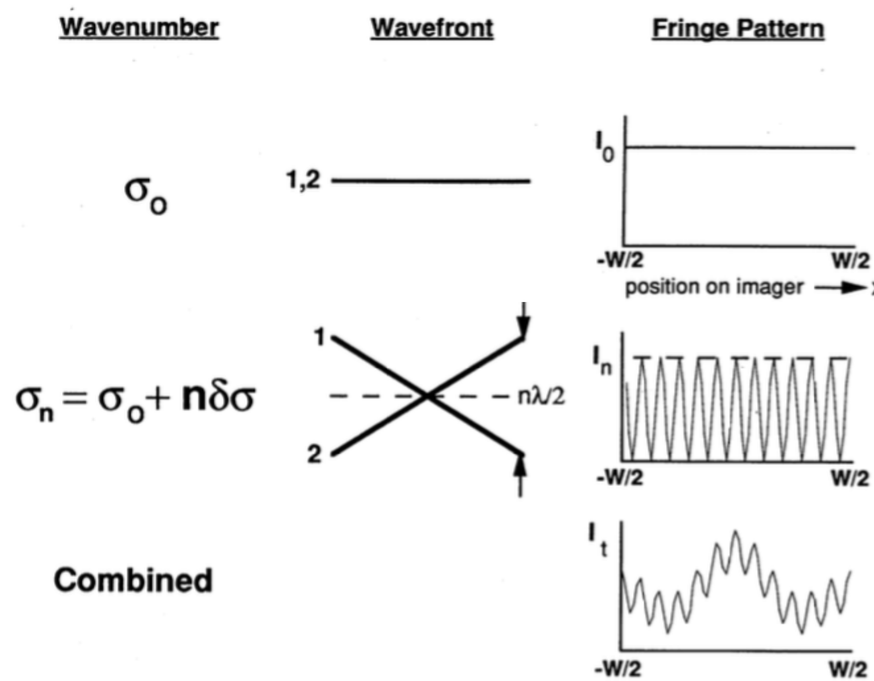
$\Delta\tilde{\lambda}_\pi$ Spectrometer Requirements are Formidable

- Resolution:
  - Need ~8 spectral bins to resolve 2 gaussian-like π components
  - $\Delta\lambda^{\pi}_{H\alpha}\sim 4$ Å giving a spectral resolution of 0.5 Å, $R=\frac{\lambda}{\delta\lambda}\sim 1.3\times10^4$
- Throughput:
  - Matched to collection optics, port availability, U = 0.01 - 0.1 cm^2-str
  - 2 spatial points desired
- Compatible detector system:
  - ~250 kHz time response
- Mitigation of sightline-DNB geometric broadening

Spatial Heterodyne Spectroscopy Meets $\tilde{E}$ Spectrometer Requirements

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





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

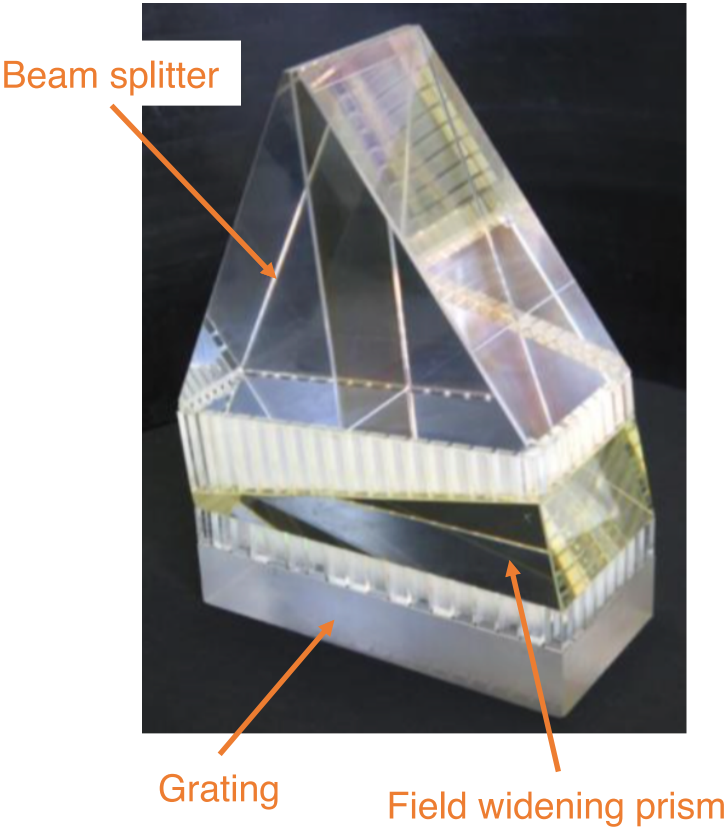
 J. Harlander, R. J. Reynolds, and F. L. Roesler., ApJ, **396,** 1992.

Spatial Heterodyne Spectroscopy Achieves High Resolution and Throughput

- SHS theoretical resolving power:
  - $R = \sigma/\delta\sigma \approx 2W/d$
  - For $\tilde{E}$: Need R~1x10^4
  - For W=50 mm only requires d=1/100 lines/mm
  - Resolution readily achievable with simple coarse gratings, compact size
- SHS throughput comparable to field widened Fourier Transform spectrometer
  - For $\tilde{E}$: need throughput of 0.01-0.1 cm^2str
  - $U = 2\pi\eta A/R$ = 0.0015η cm^2str ; η~1(no field widening) – 100 (field widening)

Example SHS:
Monolithic DASH Interferometer

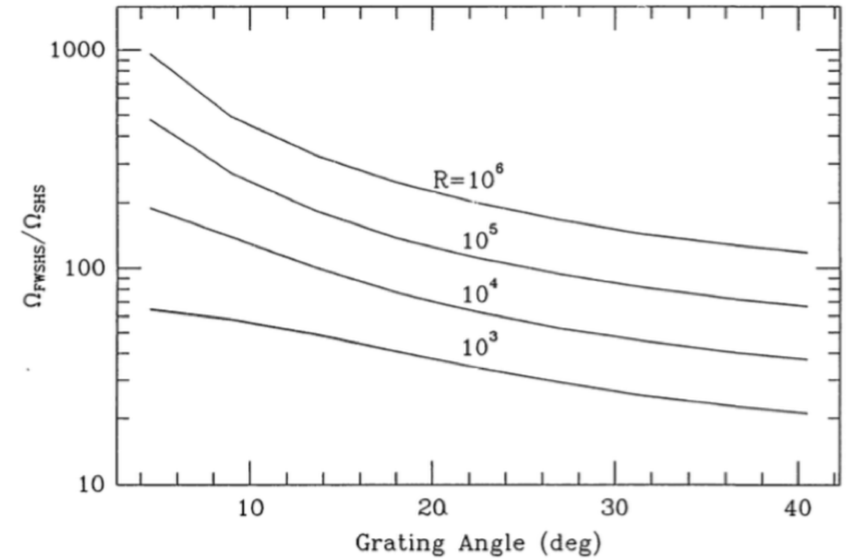
R≈5x10^4, U≈0.15 cm^2str

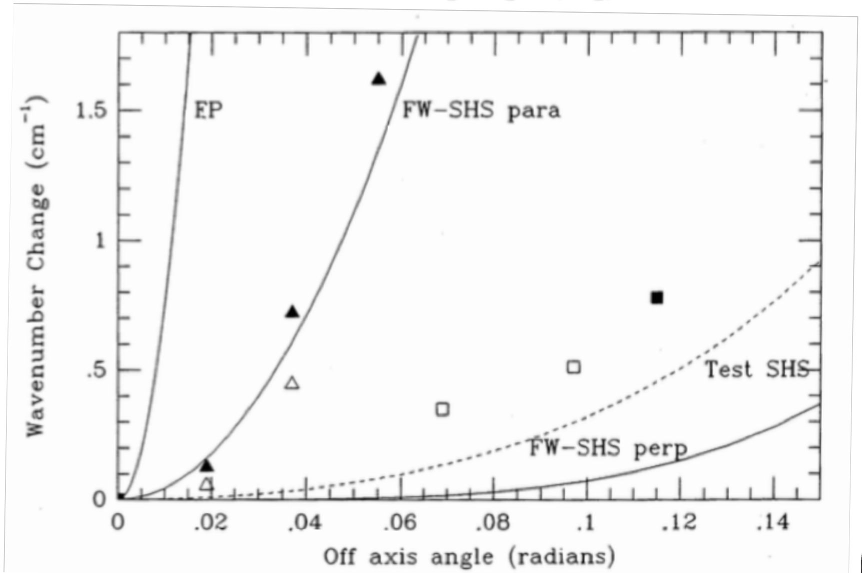


J. M. Harlander, C. R. Englert, D. D. Babcock, and F. L. Roesler, Opt. Express, OE, **18**, 2010.

Field Widening in SHS Increases Throughput, No Moving Parts

- Field widening prisms greatly reduce the path length difference dependence of off-axis ray angle
- Allows for large input angle Ω
- Required throughput (0.1 cm²-str) readily achievable using prisms in SHS
- Prism angle definition:





Interferometer Modeling

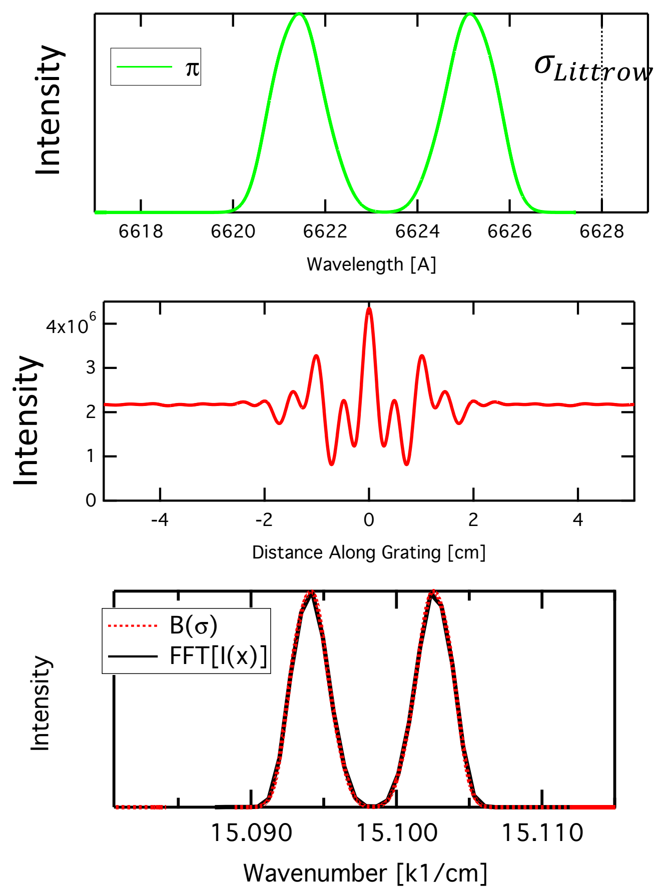
Modeling of Interferogram Used to Explore Spectrometer Design

- Synthetic interferograms generated via modeled π components

- Fourier transform of interferogram $I(x)$ gives $B(\sigma)$

- High speed recording and inversion of $I(x)$ is similar to gaussian fit analysis of $\tilde{T}_i$ and $\tilde{v}$ measurements

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



New CMOS Imaging Technology Provides Turbulence Timescale Measurement

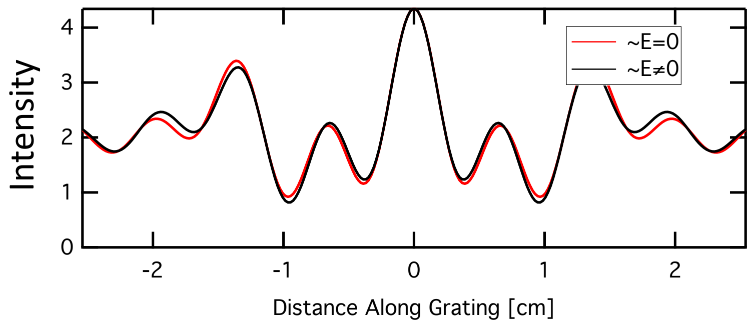
- Flexible, high speed recording of full interferogram at photon noise limit
- Example: Phantom v2512 FAST by Vision Research
  - 500 kHz @ 256 x 80 pixels or 110 x 110 pixels
  - f/1 optics gives U ~ 0.1 $cm^2 str$
  - QE ~ 50% over visible range
  - Integrated DAQ
- Potential for 2 spatial measurements

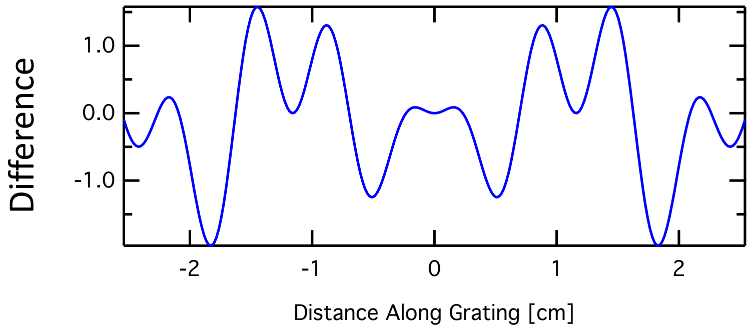
Metric from Simplified Interferogram Scales Linearly with $\tilde{E}$, Requires Less Detector Channels

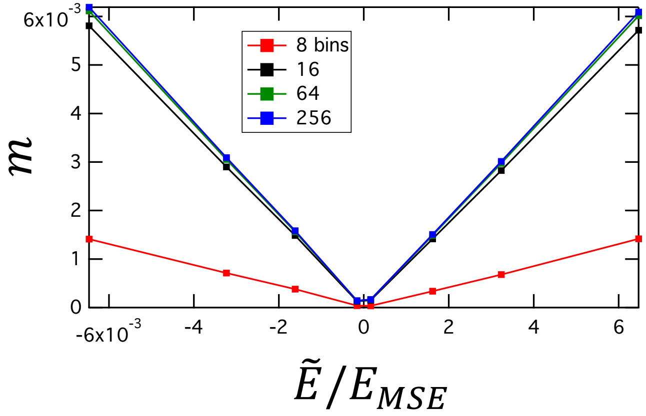
- Want a metric that is proportional to $\tilde{E}$
- Approach: finite number of bins around central fringe region measured to get $\tilde{E}$
- Example metric (m) based on differences in interferogram area from time average area:

$$m = \sqrt{\frac{\sum_j^{N_{bins}} \left(I_{j,\tilde{E}\neq 0} - I_{j,\tilde{E}=0}\right)^2}{\sum_j^{N_{bins}} \left(I_{j,\tilde{E}=0}\right)^2}}$$

- m = $\tilde{E}/E_{MSE}$
- For given case 16 bins are adequate
- Design optimization ongoing, ideally reduce to 3-4 detectors for single spatial point

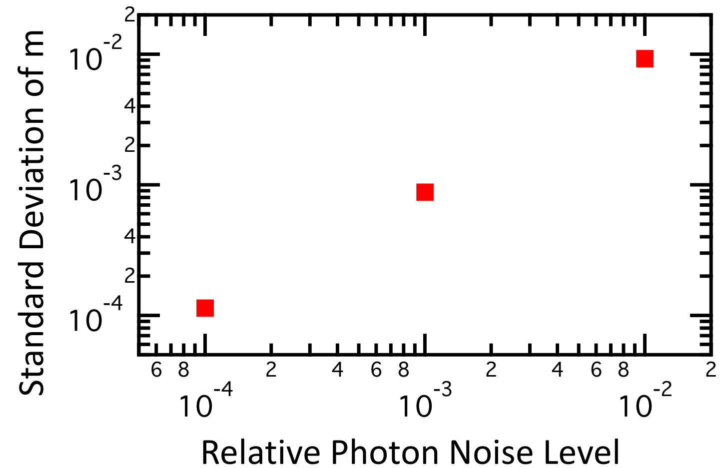




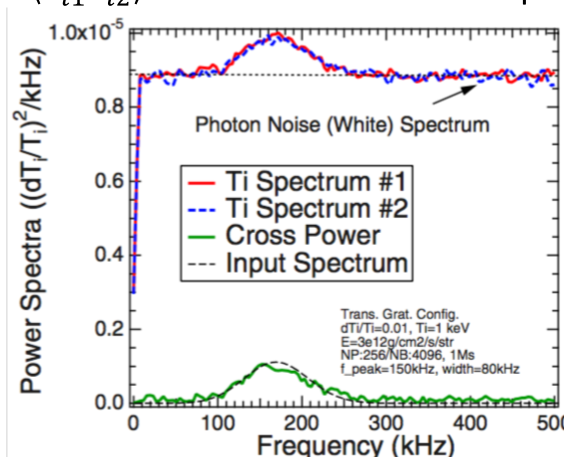


Noise Floor for Multi-bin Metric Equal to Relative Photon Noise Level

- Simulated variation in metric due to photon noise shows relative noise in metric = photon noise level
- Measured photon flux is standard BES signal
  - BES photon noise level ~10^{-3}
- Random photon noise can be suppressed by standard cross correlation techniques
  - Two independent but spatially correlated measurements made simultaneously
  - Example: $\langle \tilde{E}_1 \tilde{E}_2 \rangle$ and $\langle \tilde{E} \tilde{n} \rangle$
- Depending on data record length, can reduce residual noise floor by 10-100x



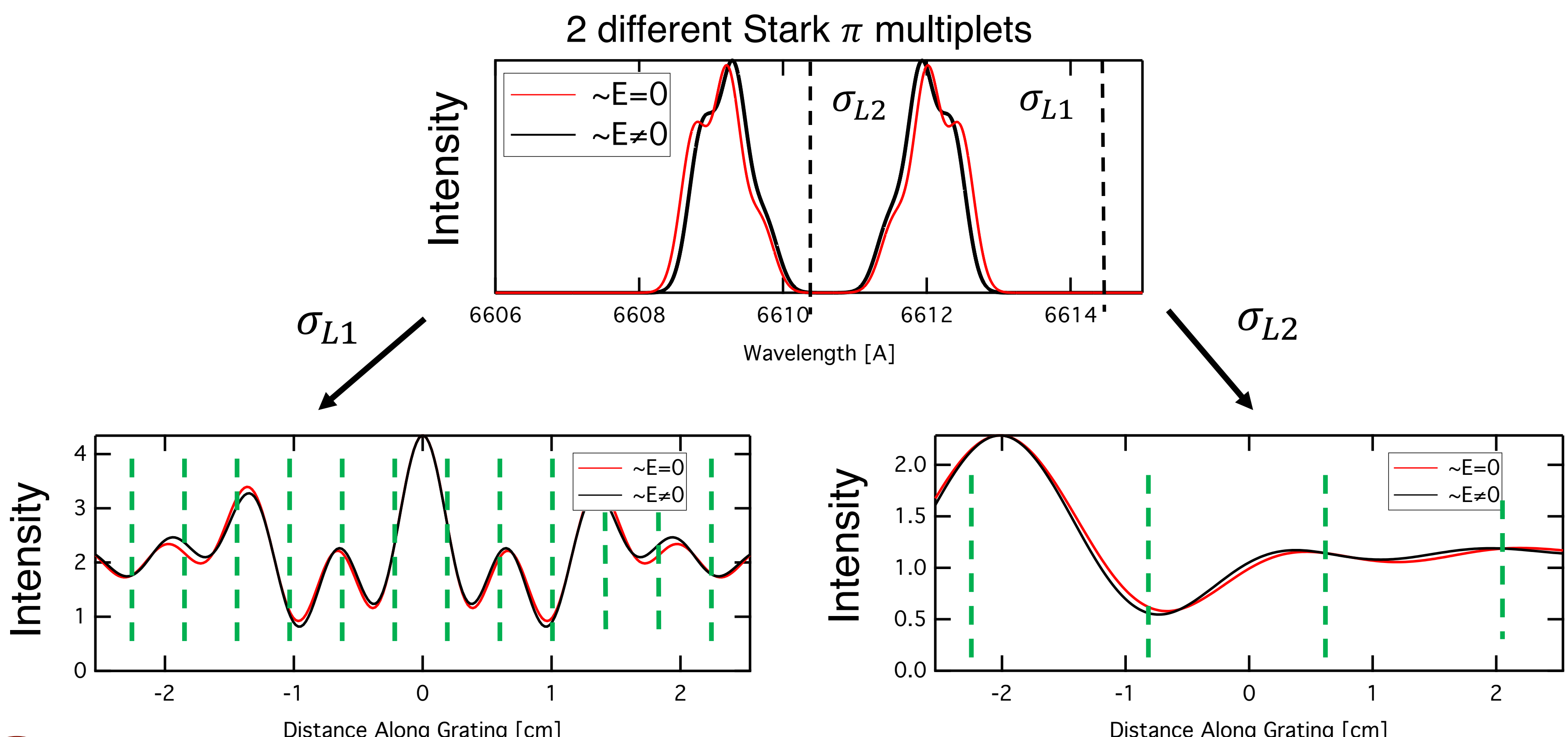
$\langle T_{i1} T_{i2} \rangle$ cross correlation technique



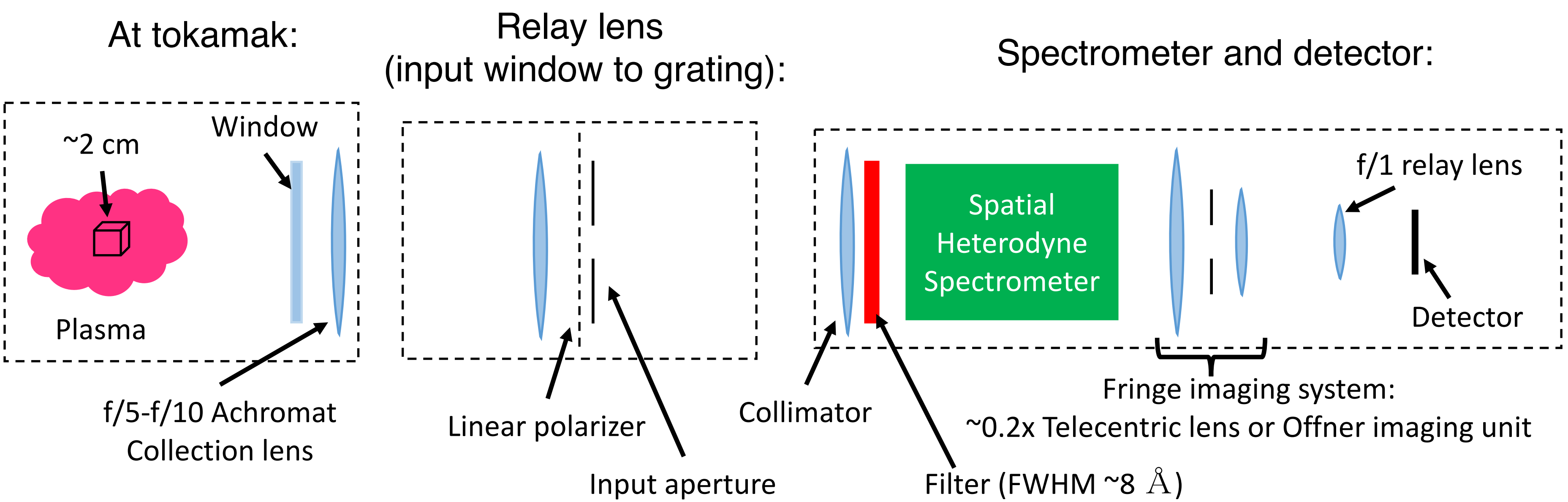
G. R. McKee, D. J. Schlossberg, and M. W. Shafer, Rev. Sci. Instrum., **79**. 2008.

Extracting $\widetilde{\Delta\lambda}$ From Central Fringe Analysis Could Reduce the Number of Detectors

- Full interferogram recording may not be necessary
- Can optimize spectrometer to give fringe pattern of interest without losing light
- $\widetilde{\Delta\lambda}(t)$ then recorded using 3-4 detectors

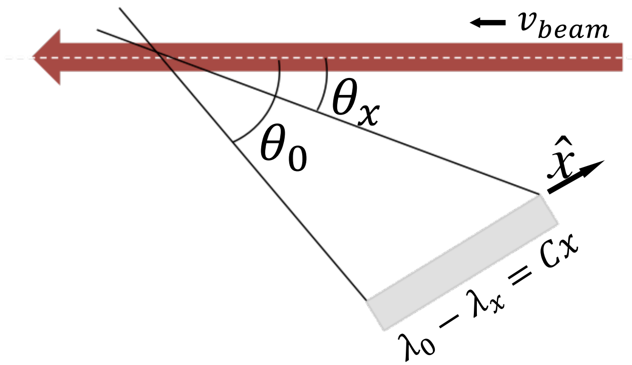


Optics Require Conjugate Imaging, High Throughput

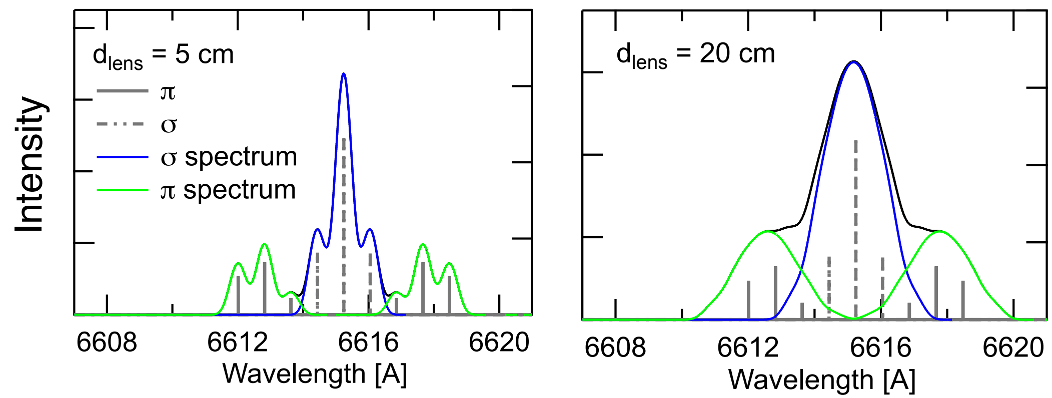


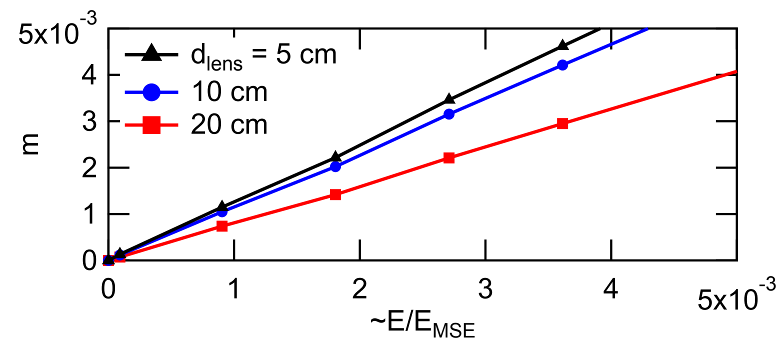
- Fringe image detection requires large depth of field, high throughput, no aberrations
  - Set by maximum path difference between wavefronts and/or coherence length of wavefronts
- Realized with telecentric lens or Offner imaging system and high throughput coupling lens to detector

Geometric Broadening Compensated in SHS, Allows Large Collection Optic



Geometric broadening on DIII-D:





- SHS Fizeau fringe pattern is optically conjugate to input optic
  - λ (phase) shift due to window geometry ~linear across grating

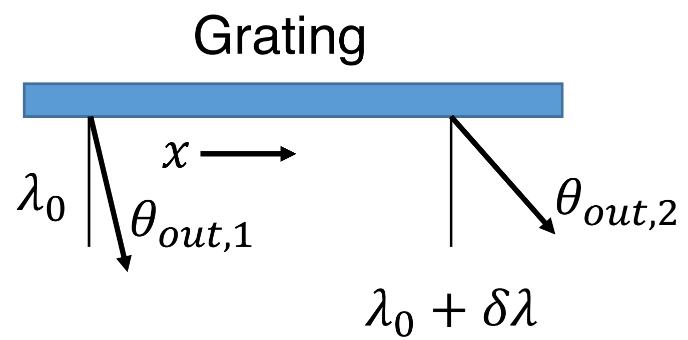
$$\phi_w = 2\pi c x \longrightarrow \phi_{Total} = \phi_G + \phi_w = (8\pi(\sigma - \sigma_L)\tan\theta + \phi_w(x))x$$

  - Convolve $I(x)$ with $\mathcal{F}[\exp(-i\phi_w)]$ in the spectral domain to remove geometric broadening

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

Geometric Broadening can be Actively Compensated For Inside Spectrometer

- Doppler shift across window means that the output angle from the grating is changing across the grating face
- In principle, θ_{out} can be kept constant by varying the grating groove constant in direct opposition to the change in σ due to geometric broadening
- Window effect becomes known linear phase shift across image plane, can be removed
- Similar to Doppler shift compensation in Fabry-Perot spectrometers used to measure planetary wind velocity[1]



$$\sin(\theta_{out}(x)) = \frac{md}{\sigma(x)} - \sin\theta_L$$

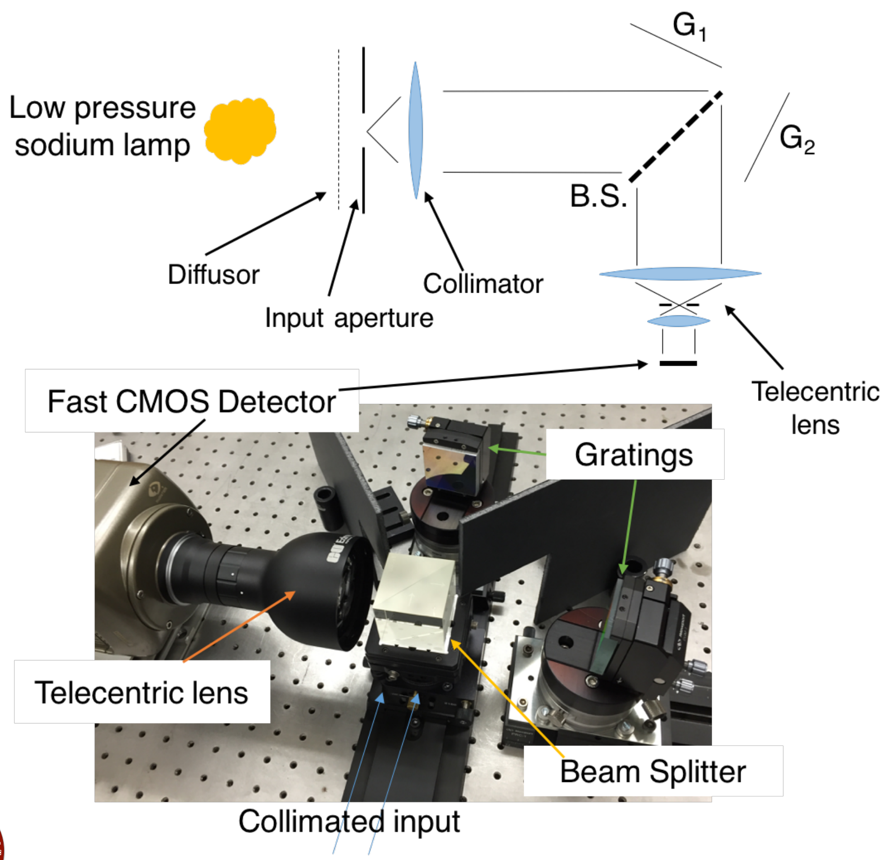
$$\sin(\theta_{out}(x)) = \frac{md(x)}{\sigma(x)} - \sin(\theta_L(x))$$

1: J. T. Trauger and F. L. Roesler, **Appl. Opt.,** vol. 11, 1972.

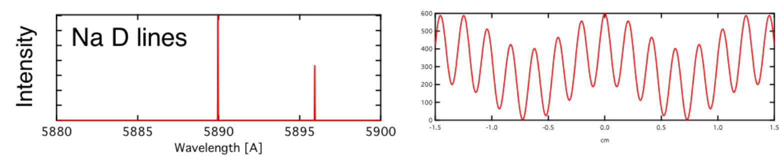
Flexible Modular SHS System Developed for First Tests

- Initial testing done using Na doublet, manipulation of interferogram explored

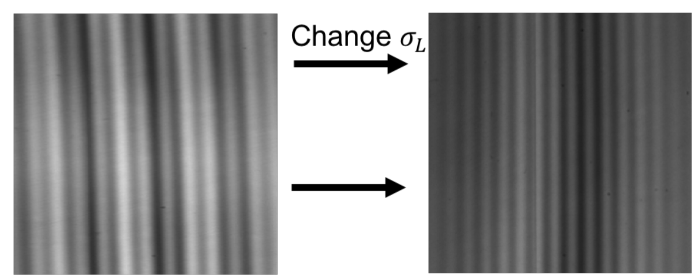
- Fabrication and testing of second SHS underway, to be deployed on Pegasus for initial validation using large amplitude, low frequency, $\tilde{B}$ and $\tilde{E}$ generated by helicity injectors



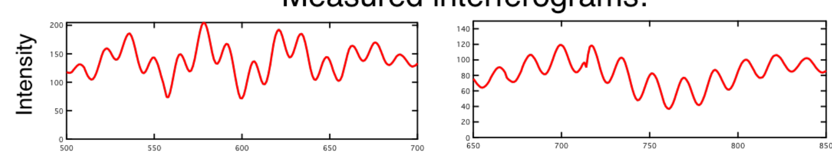
Sodium doublet modeled interferogram:



Sodium doublet in prototype SHS:



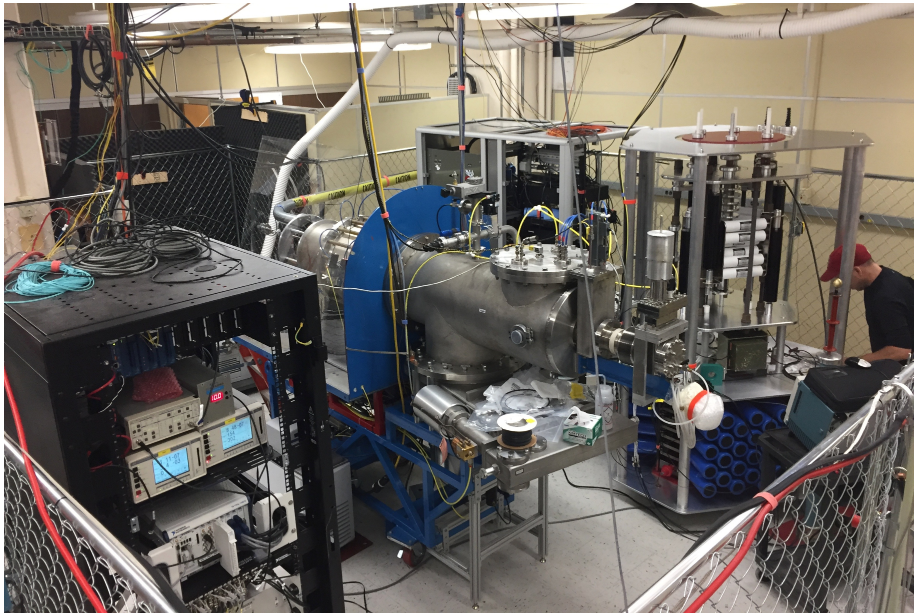
Measured interferograms:



$\tilde{E}$ Diagnostic Requires Low Divergence, High Full Energy Fraction DNB

- H^0 DNB on loan from PPPL
  - Full-energy J at focus: 3-6 mA/cm^{2*}
  - Diameter ~ 9cm
- Features favorable for measurement
  - Low divergence: ≤ 0.47°
    - Mitigates Divergence line broadening
  - High E_b ~ 60 – 80 keV
    - Maximizes MSE broadening
  - 90-95% ionization at full beam energy
    - Ensures maximum signal for diagnostic

DNB refurbishment lab



See M. Bakkens Poster

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

- $\tilde{E}$ 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
- SHS provides flexible, compact, spectrometer concept
  - Full spectrum measurement available
  - Subsampling interferogram may support multiple spatial channels with simple discrete detectors like BES
- Next steps:
  - Commission low divergence, 80 keV/amu DNB
  - Deploy beam to Pegasus for preliminary measurements of large amplitude, low frequency $\tilde{B}$ and $\tilde{E}$