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

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On behalf of:

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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 or potential turbulence, $\tilde{\phi}$ or $\tilde{E}$, remains a challenge
  - $\tilde{E}_\theta \times B_\phi \cong \tilde{v}_r$: 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,…

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

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

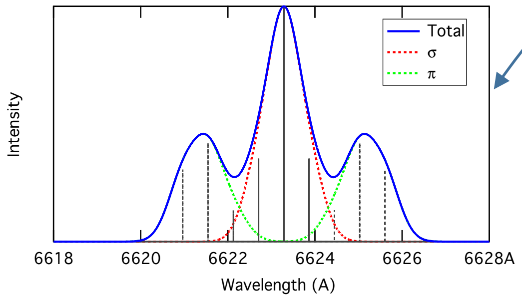
$$\vec{E}_{total} = \vec{v}_b \times \vec{B} + \vec{E}_{plasma}$$

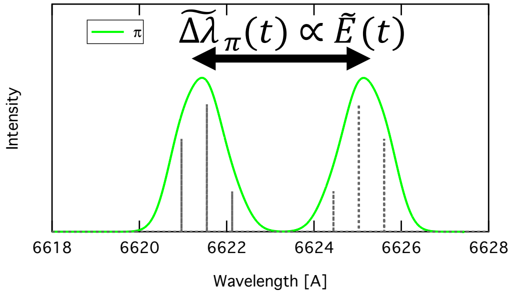
- Measure high-speed variations in π/σ line intensity ratio or in π-components linewidth to derive $\tilde{E}$

- Spatial Heterodyne Spectrometer (SHS) provides flexible analyzer of multiplet spectrum

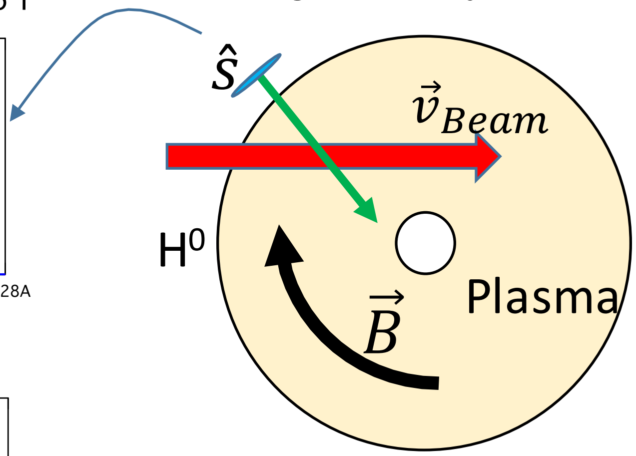
- New CMOS imaging systems provide detection and DAQ

Model Hα Stark Spectrum: 80 keV, 0.5 T





Diagnostic layout:



Tokamak Top Down View

Analysis of Stark Multiplet Allows Measurement of $\vec{\tilde{E}}_{plasma}(t)$

- Midplane beam, sightline: linewidth changes

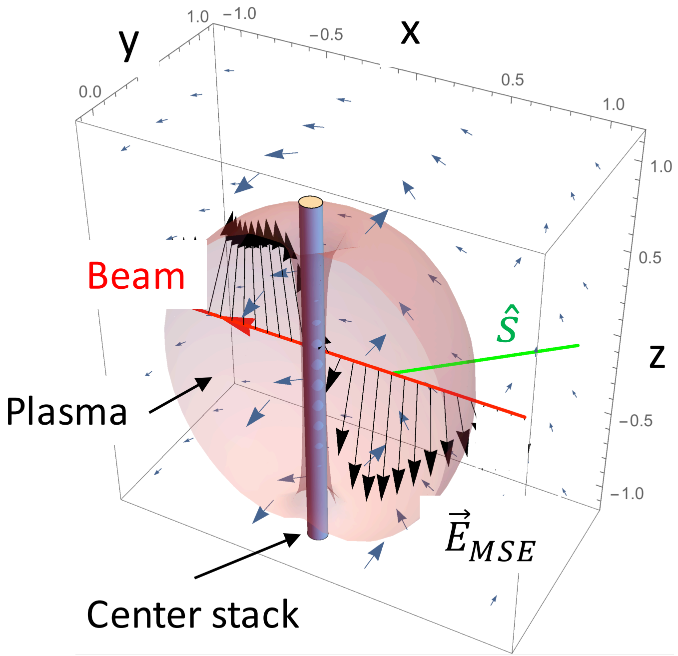
$$\widetilde{\Delta\lambda}_{Stark} \propto \tilde{E}_z$$

- Midplane beam, off-midplane sightline: Intensity ratio change

$$R = \frac{\sum I_\pi}{\sum I_\sigma} \propto \tilde{E}_R F(\tilde{n})$$

- First emphasis on line width measurement: insensitive to density fluctuations

Example: ST Geometry



$\tilde{E}$ 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}

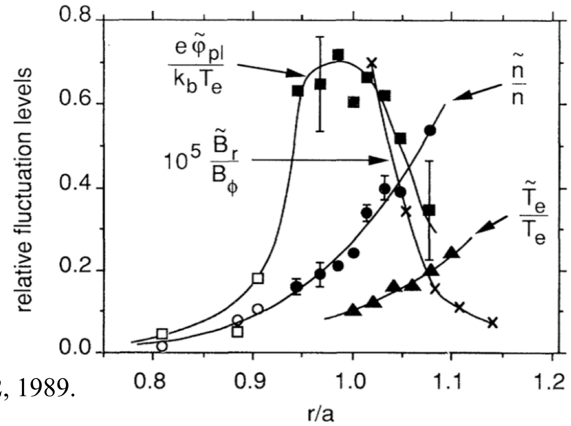
- Tokamak drift wave turbulence scaling gives $\tilde{E} \approx T_e/ea$

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	$0.5 - 1\times10^{-3}$

- $\tilde{E}$, $\tilde{n}$ rise from core to edge

- Comparable to typical photon noise floor for BES

Fluctuations in TEXT



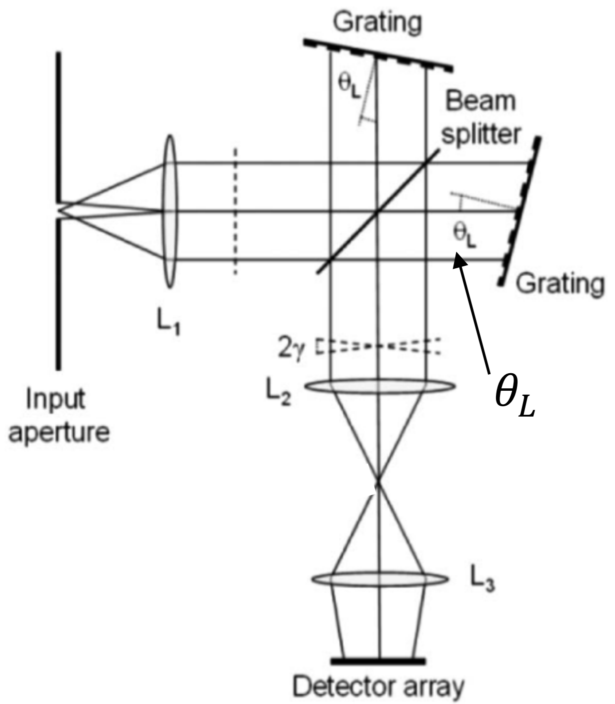
C. P. Ritz, et. al., Phys. Rev. Lett., **62**, 1989.

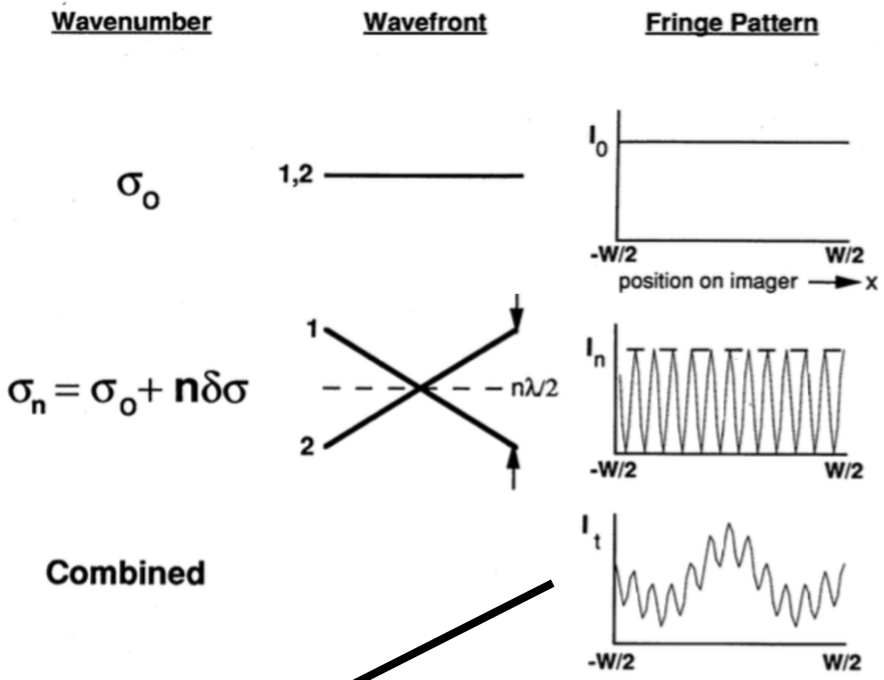
$\Delta\tilde{\lambda}_{\pi}$ Spectrometer Requirements are Formidable

- Resolution:
  - Need ~8 spectral bins to resolve 2 gaussian-like π components
  - $\Delta\lambda_{H\alpha}^{\pi}\sim 4$ Å giving a spectral resolution of 0.5 Å, $R=\frac{\lambda}{\delta\lambda}\sim 1.3\times 10^{4}$
- Throughput:
  - Matched to collection optics, port availability, U = 0.05 - 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





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

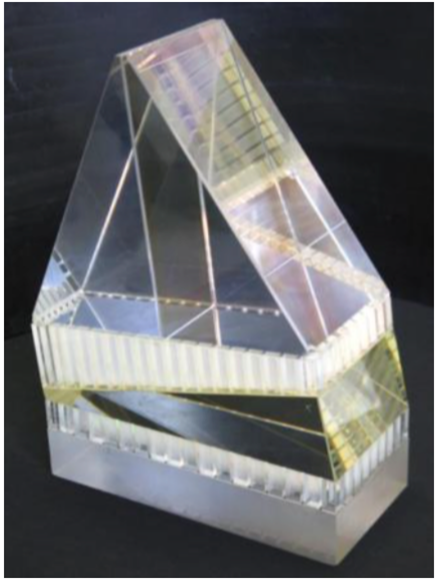
J. Harlander, R. J. Reynolds, and F. L. Roesler., ApJ, **396,** 1992.

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 0.05-0.1 cm^2str
  - $U = 2\pi\eta A/R = 0.0015\eta$ cm^2str ; η~1(no field widening) – 100 (field widening)
    - Required throughput readily achievable in SHS

DASH Interferometer



$R \approx 5x10^4$, $U \approx 0.15$ cm^2str

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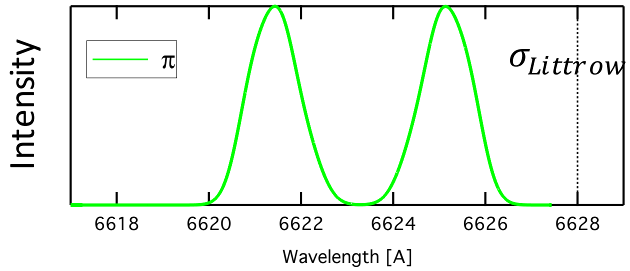
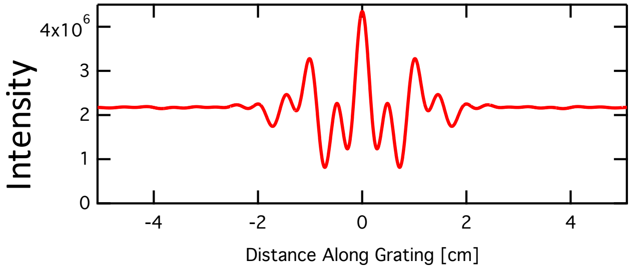
J. M. Harlander, C. R. Englert, D. D. Babcock, and F. L. Roesler, Opt. Express, OE, **18**, 2010.

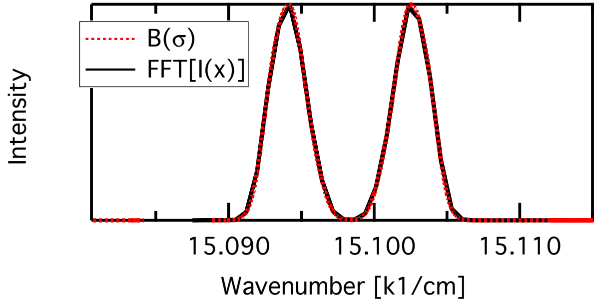
Modeling of Interferogram Used to Explore Spectrometer Design

- 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
  - QE ~ 50% over visible range
  - Integrated DAQ
- Potential for 2 spatial measurements

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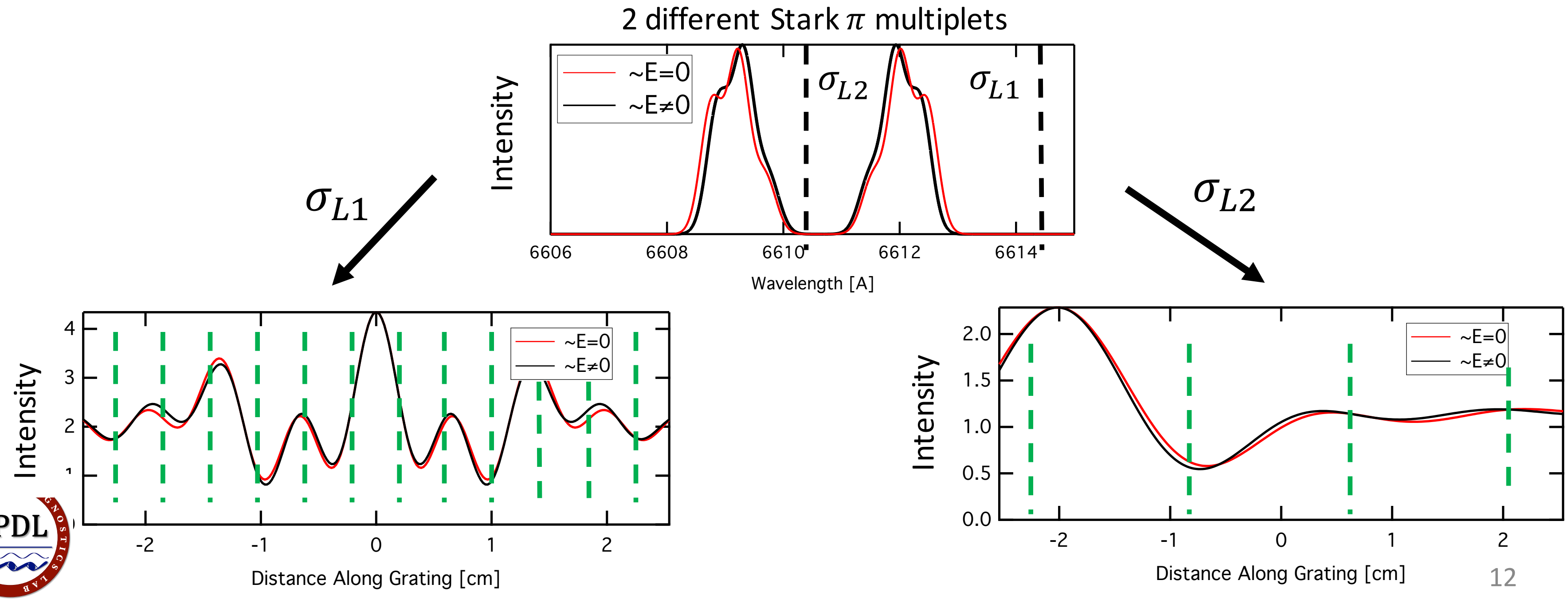
Extracting $\widetilde{\Delta\lambda}$ From Central Fringe Analysis Could Reduce the Number of Detectors

- 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

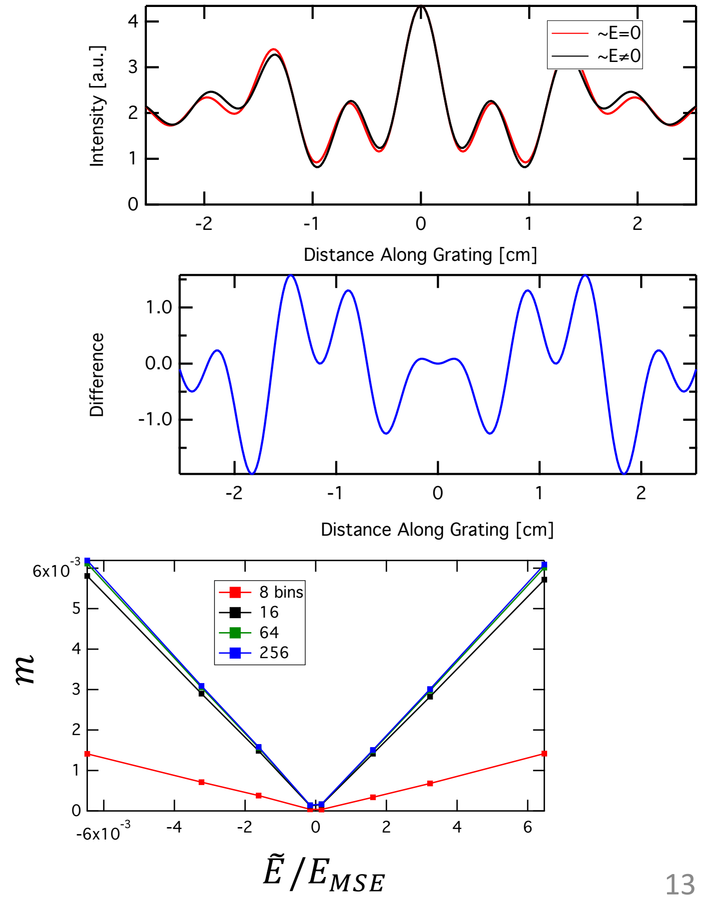


Metric from Simplified Interferogram Scales Linearly with $\tilde{E}$, Requires Less Detector Channels

- Want a metric (m) 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:

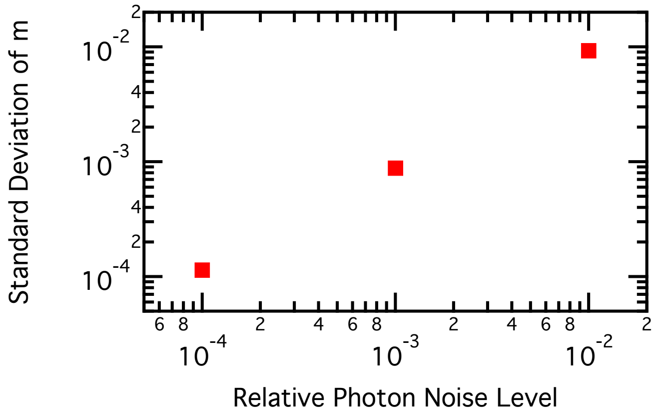
$$m = \sqrt{\frac{\sum_j^{N_{bins}}\left(I_{j,\tilde{E}\neq 0} - I_{j,\tilde{E}=0}\right)^2}{\sum_j^{N_{bins}}\left(I_{j,\tilde{E}=0}\right)^2}}$$

- 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

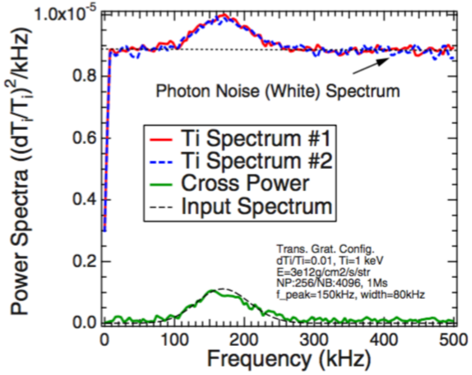


Noise Floor for Multi-bin Metric Equal to Relative Photon Noise Level

- 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

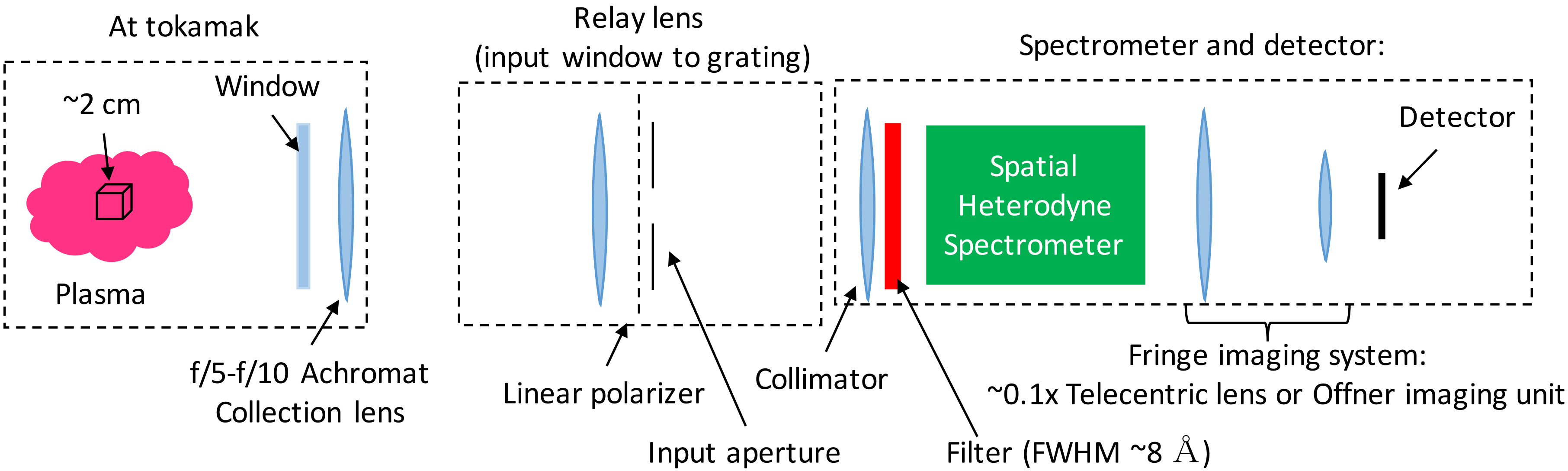


$\langle T_{i1} T_{i2} \rangle$ cross correlation technique



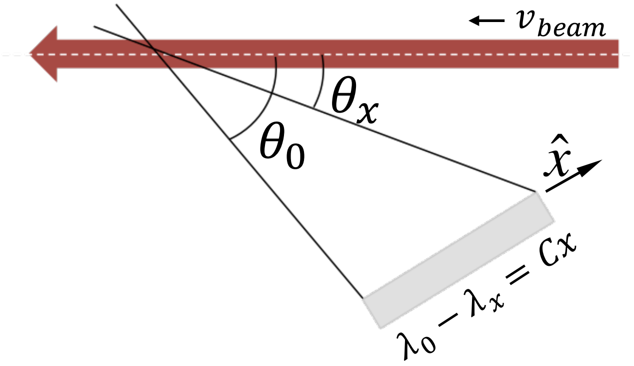
G. R. McKee, D. J. Schlossberg, and M. W. Shafer, Rev. Sci. Instrum., **79**. 2008.

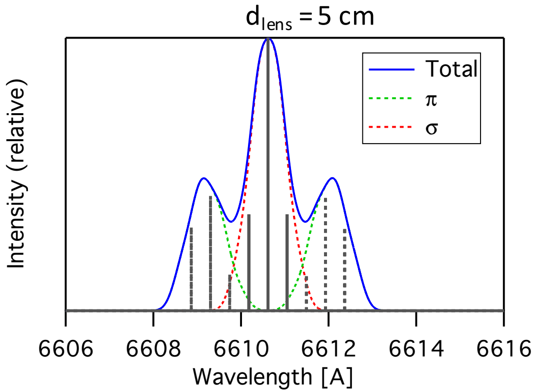
Optics Require Conjugate Imaging, High Throughput

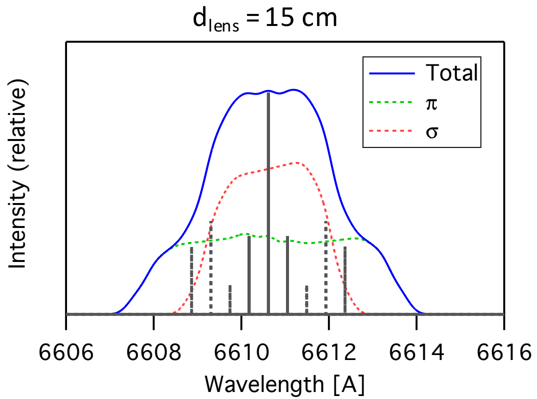


- Fringe image detection requires large depth of field, high throughput, no aberrations
  - Set by maximum path difference between wavefronts and/or coherence length of wavefronts
- Realized with telecentric lens or Offner imaging system

Geometric Broadening Compensated in SHS, Allows Large Collection Optic







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

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

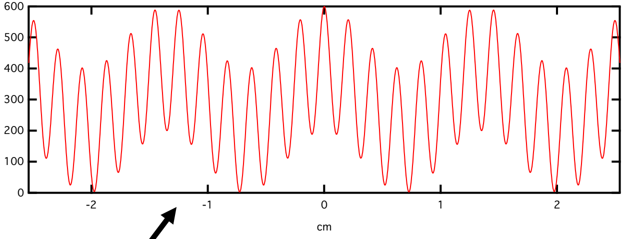
  - Convolve $I(x)$ with $\mathcal{F}[\exp(-i\phi_w)]$ in the spectral domain to remove geometric broadening
  - Chirped gratings, d(x), could actively remove geometric broadening inside spectrometer

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

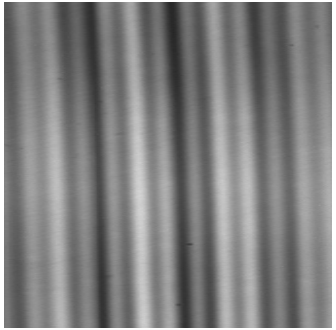
Flexible Modular SHS System Developed for First Tests

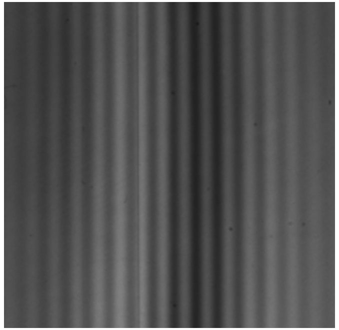
Sodium Doublet: $\Delta\lambda \sim 6$ A

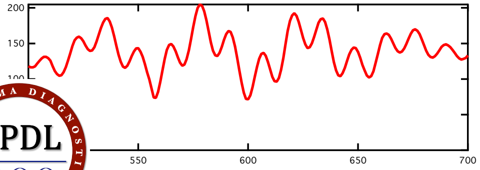
Interferogram model:

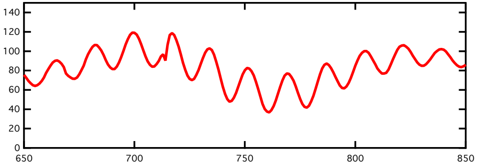


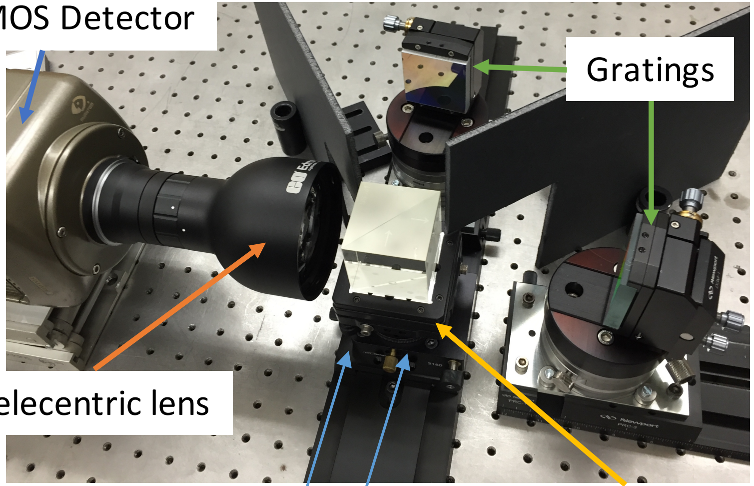
Change θ_L









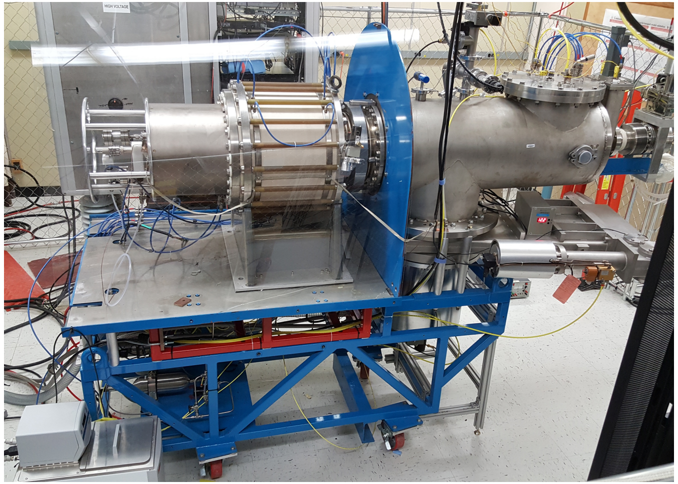


$\tilde{E}$ Diagnostic Requires Low Divergence, High Full Energy Fraction DNB

- 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

Low divergence , high energy DNB



See M. Bakkens Poster #1

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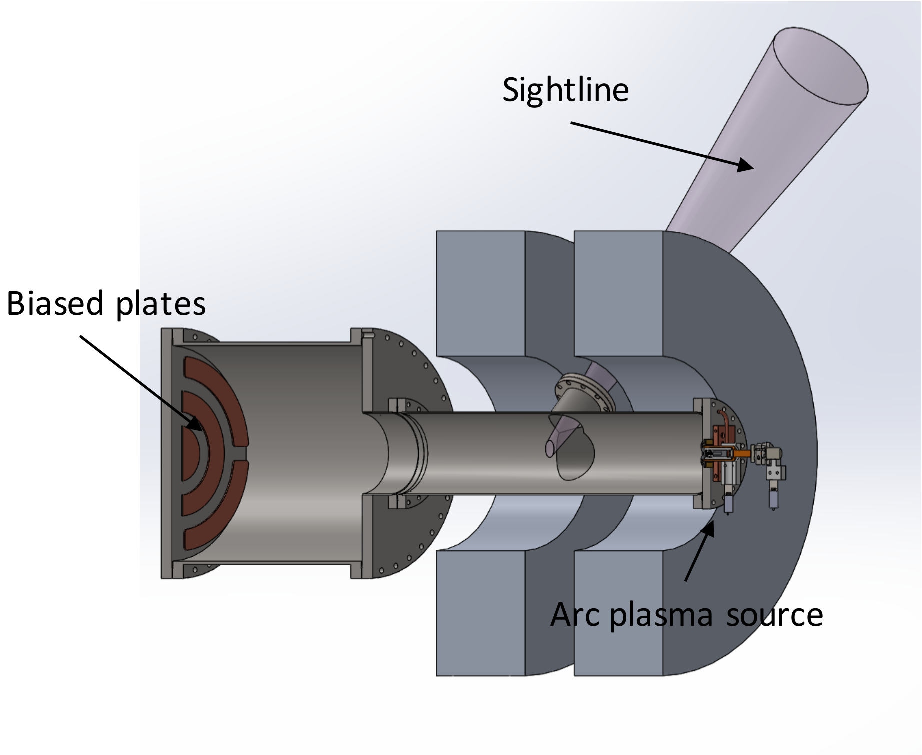
Summary: Moving Towards Diagnostic For $\tilde{E}$ in High Temperature Magnetically Confined Plasmas

- $\tilde{E}$ measurements appear feasible using high speed measurements of motional stark multiplet
  - Horizontal view gives $\tilde{E}_z$, Off midplane gives $\tilde{E}_R$

- 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 DNB
  - Deploy plasma target station to emulate edge tokamak plasma conditions, $n_e > 1\times10^{19}$ m^{-3}
  - Validate diagnostic using imposed electric field fluctautions on target plasma

Validation Test Stand



$\tilde{E}$ Test Stand: