Supported by Office of Science

The Motional Stark Effect Diagnostic on NSTX

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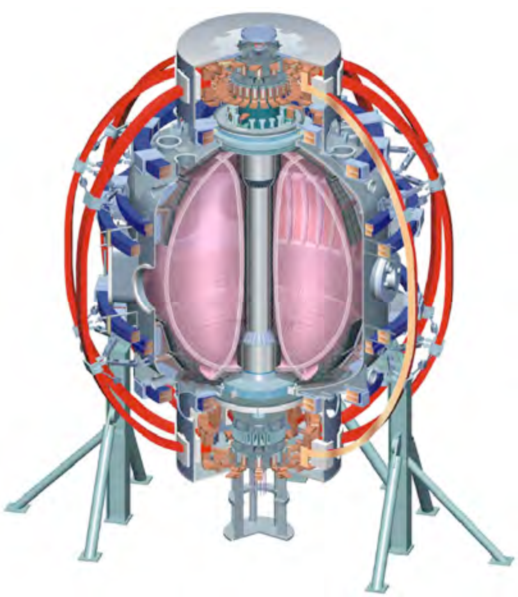

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ABSTRACT

This work describes the implementation and recent results from the MSE-CIF diagnostic on NSTX. Due to the low magnetic field on NSTX the MSE diagnostic requires a new approach for the viewing optics and spectral filter. This has been accomplished with a novel optical design that reduces the geometric Doppler broadening, and a high throughput, high resolution spectral filter to optimize signal-to-noise. This MSE diagnostic presently has 16 of a possible 19 sightlines operating, providing measurements of the magnetic field line pitch from the plasma center to near the outboard edge of the plasma. The system operates well at low magnetic field, >0.3 T, using collisionally induced fluorescence (CIF) from a deuterium heating beam operating at about ~90 keV. MSE data has been obtained in several regimes, including L-mode, H-mode, and reversed shear. The measurements reveal the development of both monotonic and reversed shear q-profiles depending on the discharge evolution. The presence of MHD is found to have a significant effect on the profile evolution and will be discussed.

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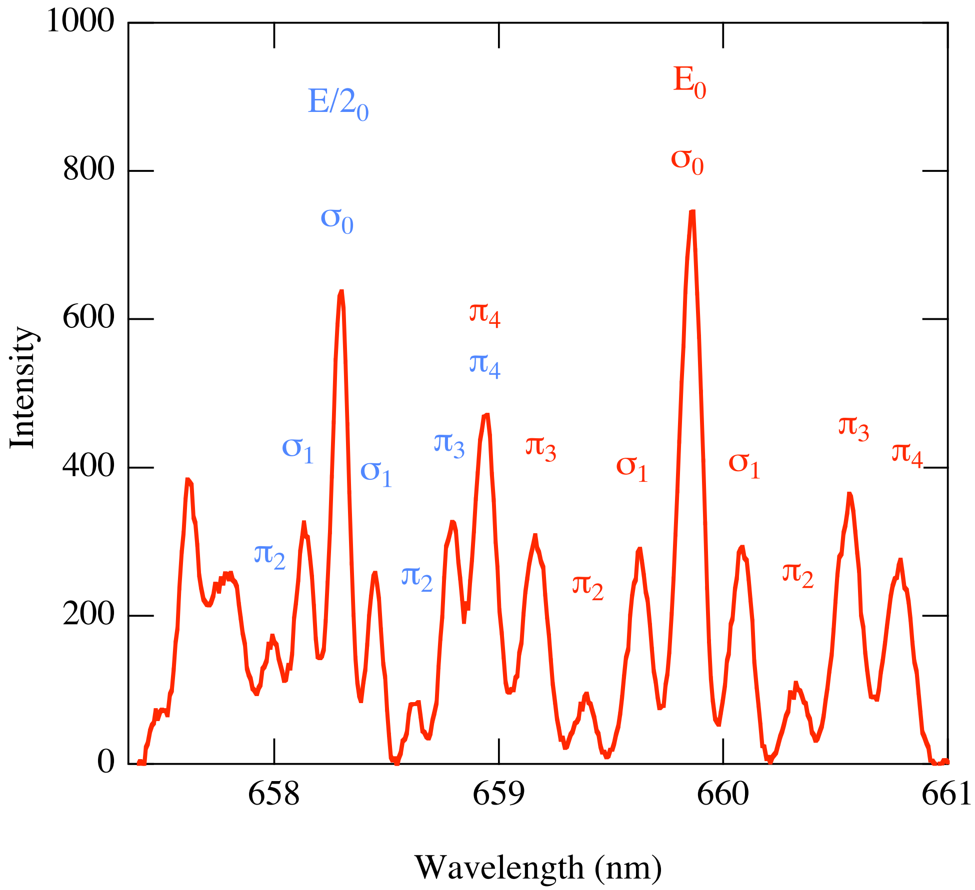
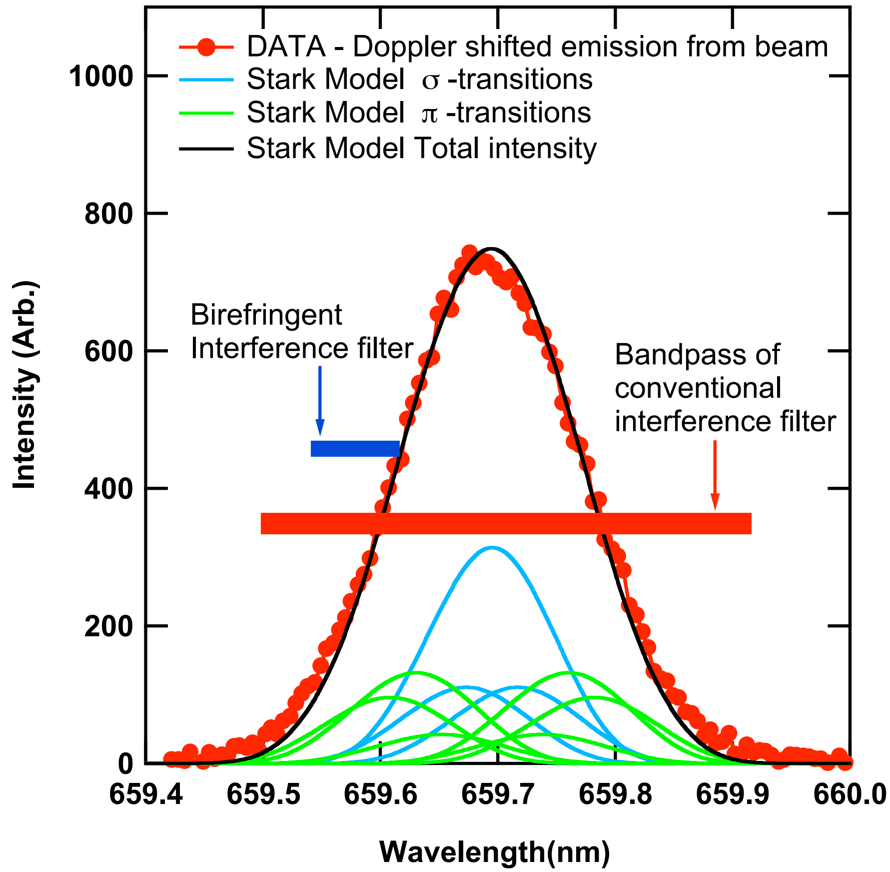
MSE Spectra at High Magnetic



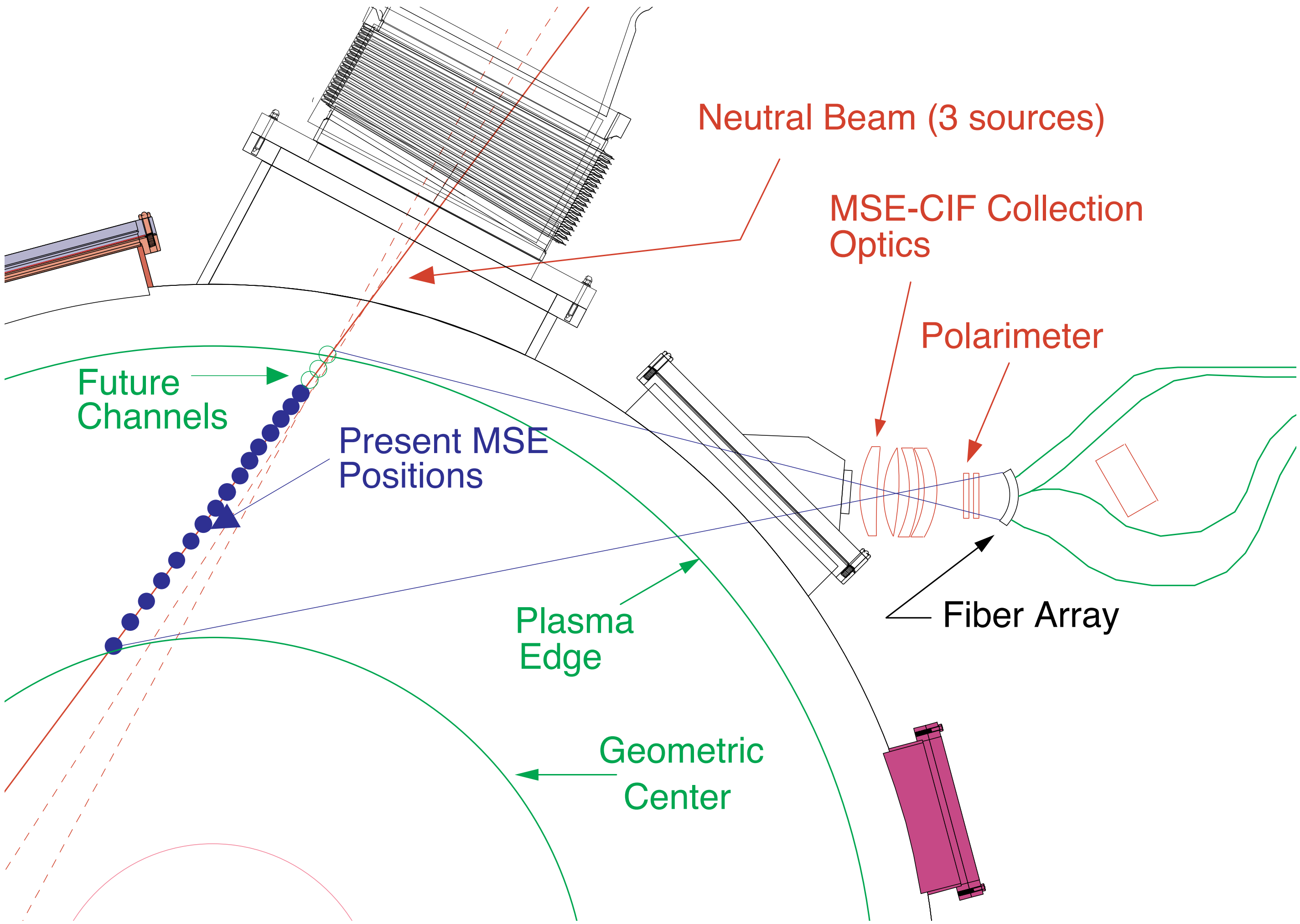
- **E=v x B** electric field ~200 kV/cm at 4.5 T in figure.
- $\Delta m=0(\pm 1)$, $\pi(\sigma)$, are polarized parallel (perpendicular) to the electric field.
- Spectral width is determined by geometric broadening and beam divergence.
- Spectral overlap between π and σ lines reduces polarization fraction and signal-to-noise.

Successful MSE-CIF Polarimetry Measurements at Low Magnetic Field

- At low magnetic field, overlap of Stark multiplet results in low polarization fraction (~2%) with conventional filter.
- Novel birefringent filter with narrow bandpass can isolate a portion of the spectrum resulting in a much better polarization fraction(~40%).
- Allows MSE-CIF measurements at low magnetic field with good time resolution (5-10 ms).



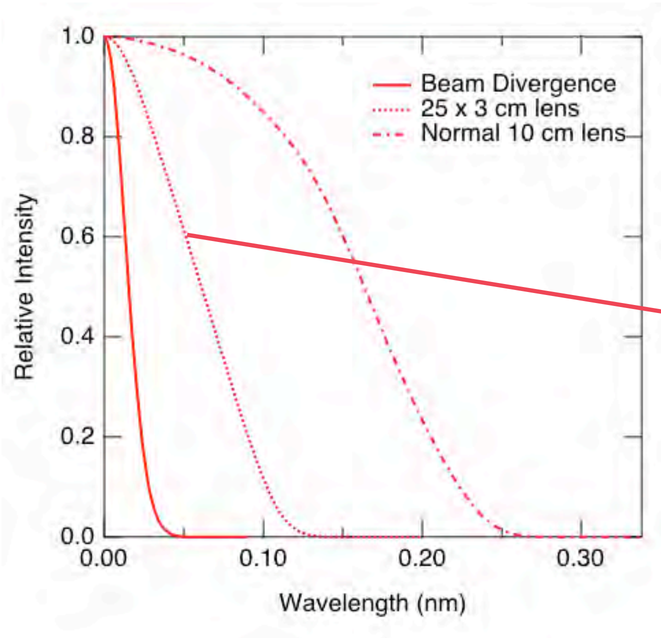
MSE-CIF Layout on NSTX

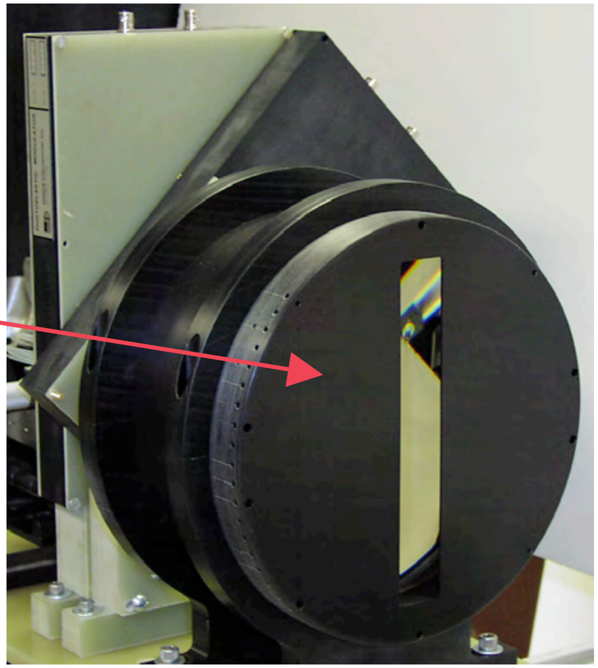


MSE-CIF at Low Magnetic

- Innovations to improve the polarization fraction.
  - ➡ Optimize optics to minimize geometric Doppler broadening.
  - ➡ Development of high resolution, high throughput filter to extend measurements to 0.3 T. Wide field Lyot birefringent filter meets these requirements.

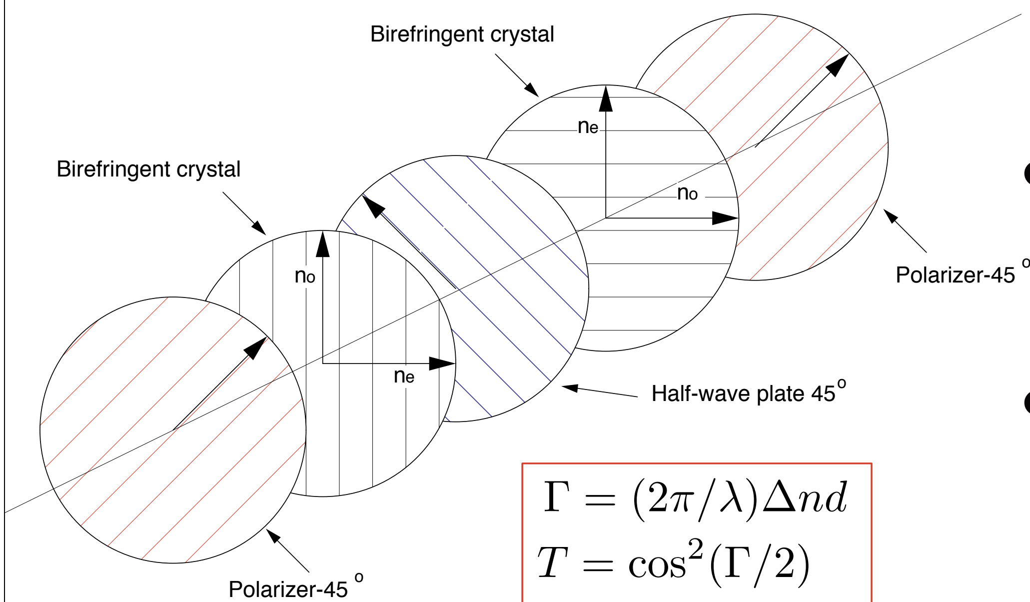
Novel Optics Design





- Novel optics design reduces geometric Doppler broadening.

Wide Field Birefringent Interference Filter(BIF)



$$\Gamma = (2\pi/\lambda)\Delta n d$$
$$T = \cos^2(\Gamma/2)$$

Single Stage Filter

- Single stage of wide field birefringent interference filter (Lyot type).
- Flexible in combining multiple stages to form desired spectral filter.
- Increased luminosity by a factor of 20-1000 relative to other instruments(grating spectrometer, Fabry-Perot, interference filter).

Novel Lyot Birefringent Filter

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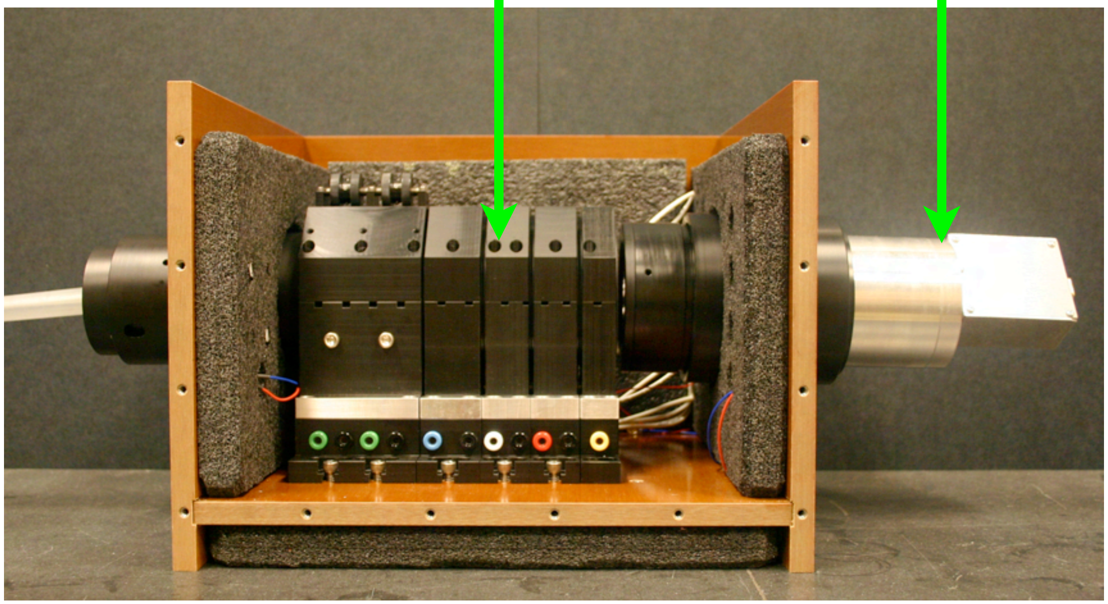
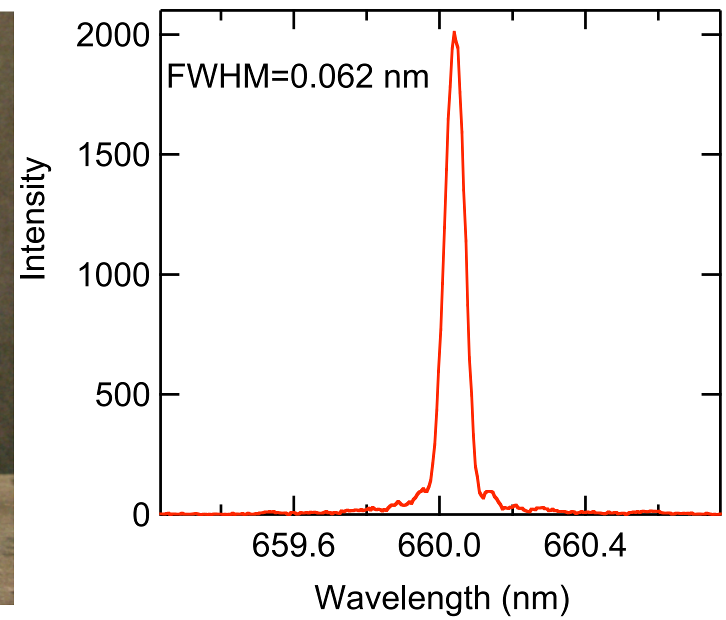
5-stage Filter　　Detector



Filter spectrum



- High throughput, narrow passband filter makes measurements with MSE at low field possible with time resolution of 5-10 ms.
- Modular filter has a 75 mm clear aperture, wide field of view, narrow bandwidth, and is tunable.

BIF has Large Throughput Advantage Over Other Instruments

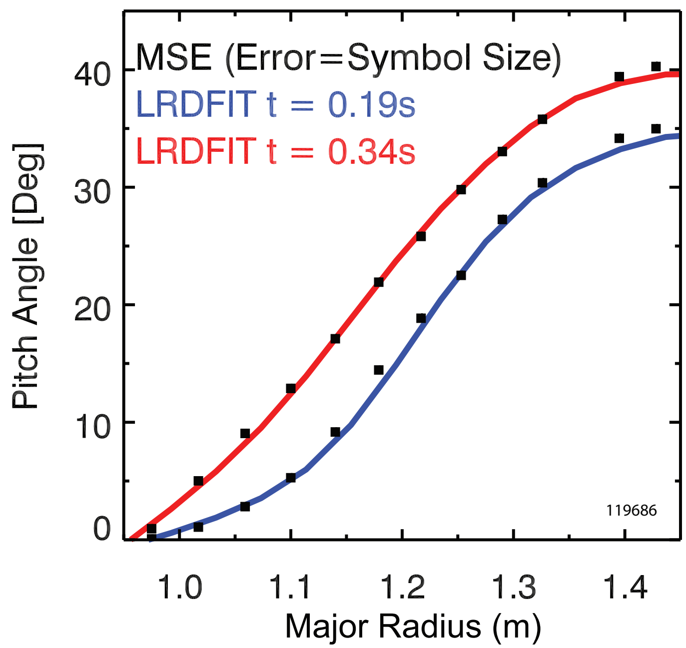
Instrument	Input aperture A(mm^2)	resolution (nm)	f/#	Etendue U(mm^2-sr)	Transmission *t*	Luminosity	Throughput Relative to BIF(NSTX)
BIF(NSTX)	59.7	0.062	1.2	32.6	10%	3.3	1
BIF (achievable)	4560.4	0.17	1.58	1434.8	30%	430.4	130.4
Fabry-Perot	1	0.062	1.2	0.5	25%	0.13	1/25
Grating (reflection)	0.04	0.1	5	10^{-3}	80%	8×10^{-4}	$1/(4\times10^3)$
Grating (transmission)	0.04	0.1	1.8	10^{-2}	80%	8×10^{-5}	1/400

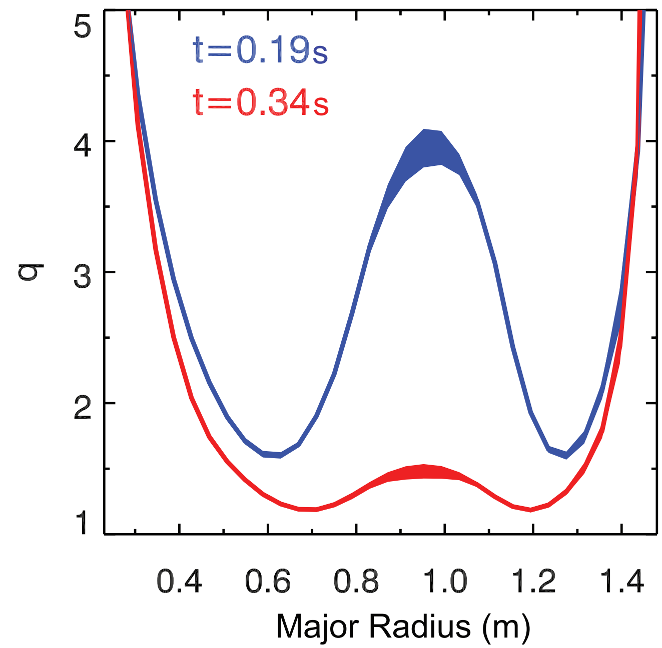
$$U = \pi A(NA)^2 = \pi A/4f^2$$

MSE-CIF Diagnostic Operation

- 16 Channels operational with coverage from geometric center to near outboard edge.
- Upgrade to improve filter transmission by a factor of three is underway.
- Routinely used for physics analysis with LRDFIT equilibrium reconstruction code. (Plan to bring ESC on line later this year).
- MSE data available in over 90% of beam heated discharges.

Equilibrium Reconstruction with MSE

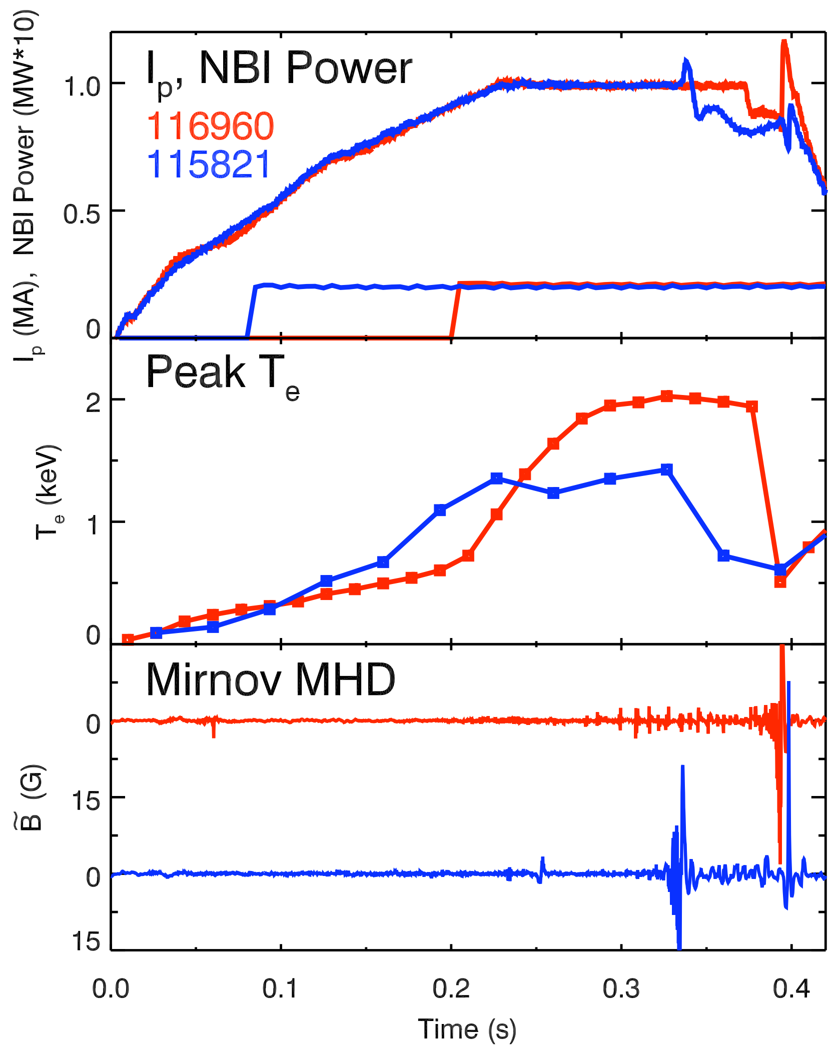




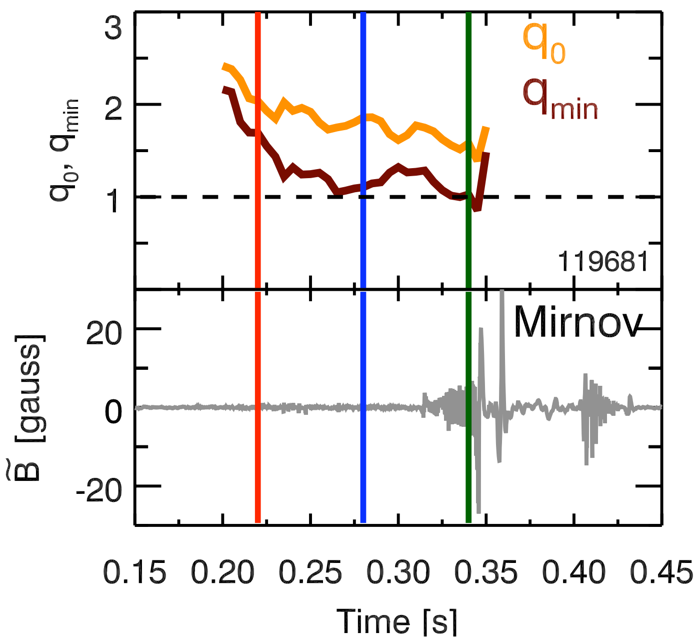
- Use LRDFIT, a free boundary equilibrium reconstruction code (J. Menard). Includes T_e iso-surfaces and toroidal rotation.
- Fits with MSE data have low residuals of ~0.3° in core, but higher at edge.
- E_r correction from V_φ and ∇p included, but not from V_θ presently.
- Variability of LRDFIT reconstruction shown in bands.

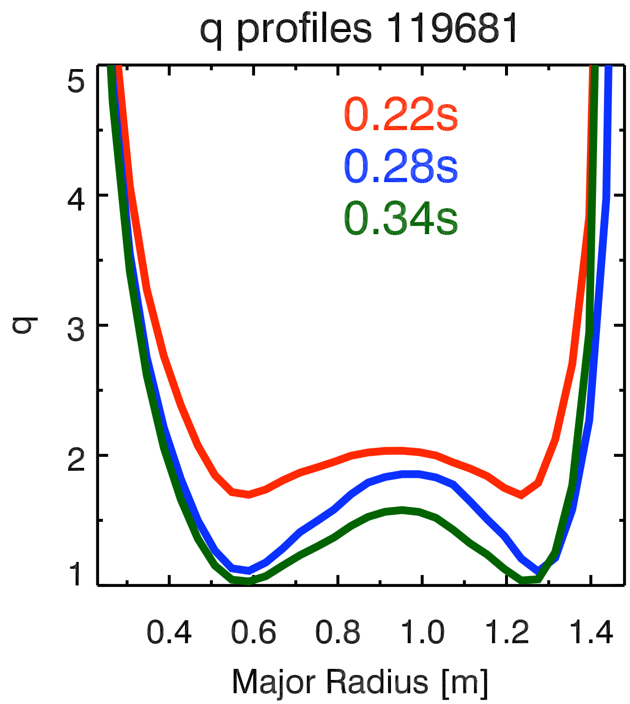
Development of Reversed Shear q-profile

- Varied I_p ramp rate, NBI timing, plasma shaping, growth of major radius, and gas fueling.
- Red curve is RS, blue curve started as RS until MHD event caused redistribution of current to low shear q-profile.



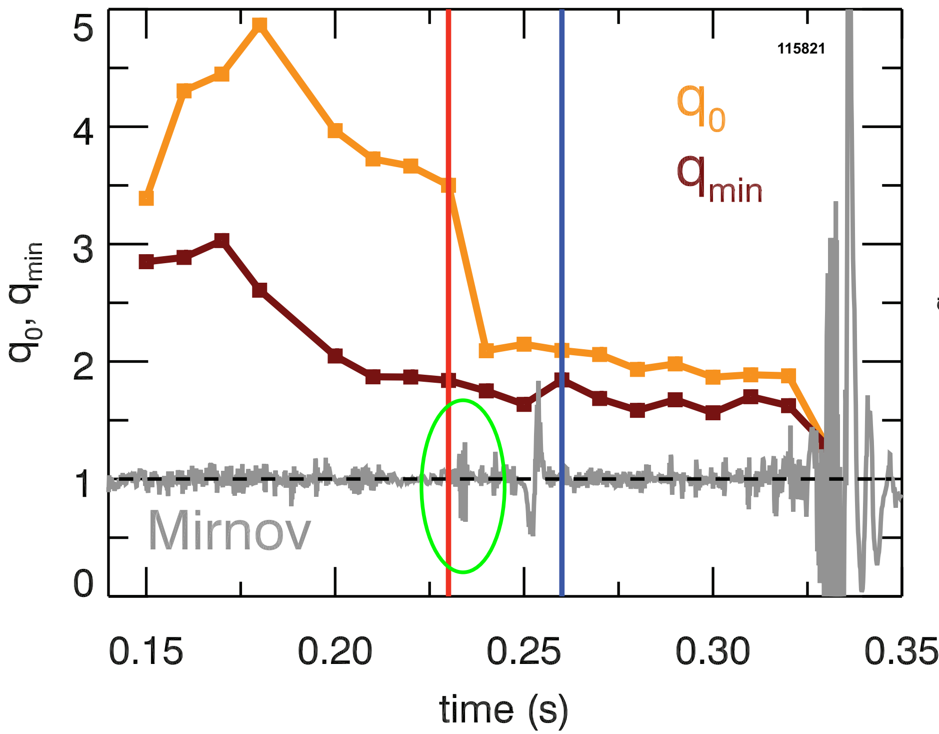
Reversed Shear q-profile Evolution

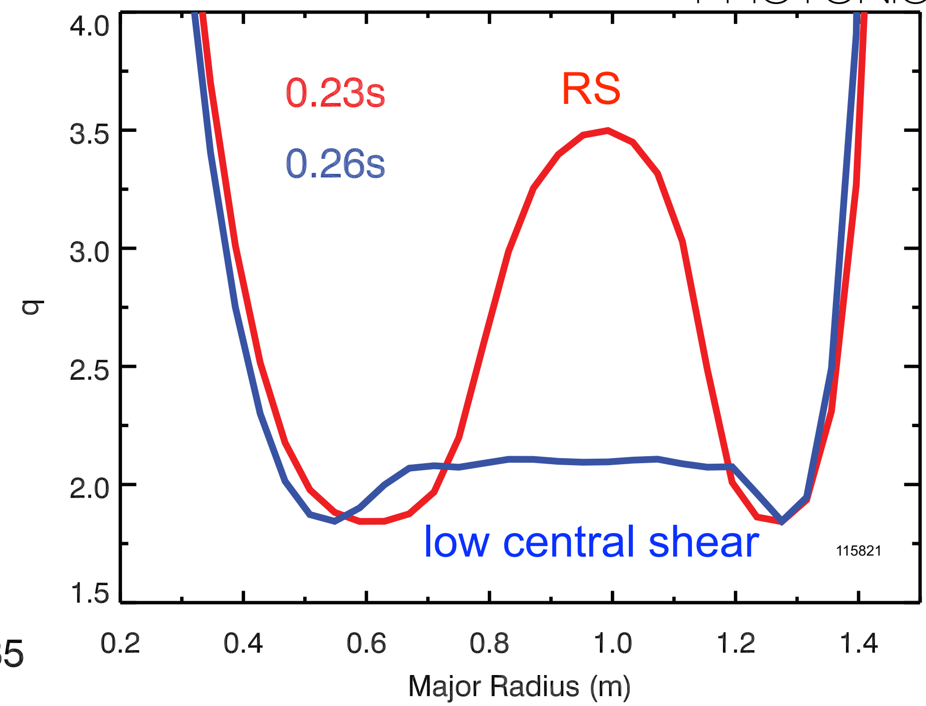




- Beam heating begins at 0.2 s.
- q(0) evolves from ~2. Important to allow both q(0) and q_{min} to drop below 2 before plasma pressure becomes too large.
- As q_{min} approaches 1 an m/n=1/1 MHD mode grows until it locks and the plasma collapses.

Low Shear q-profile After MHD





- MHD (m/n=2/1) event precipitates a large change in q(0).
- Rapid change occurs shortly after q_{min} drops below 2.
- q-profile flattened at q=2.

Current Density Fills in and Flattens near q=2

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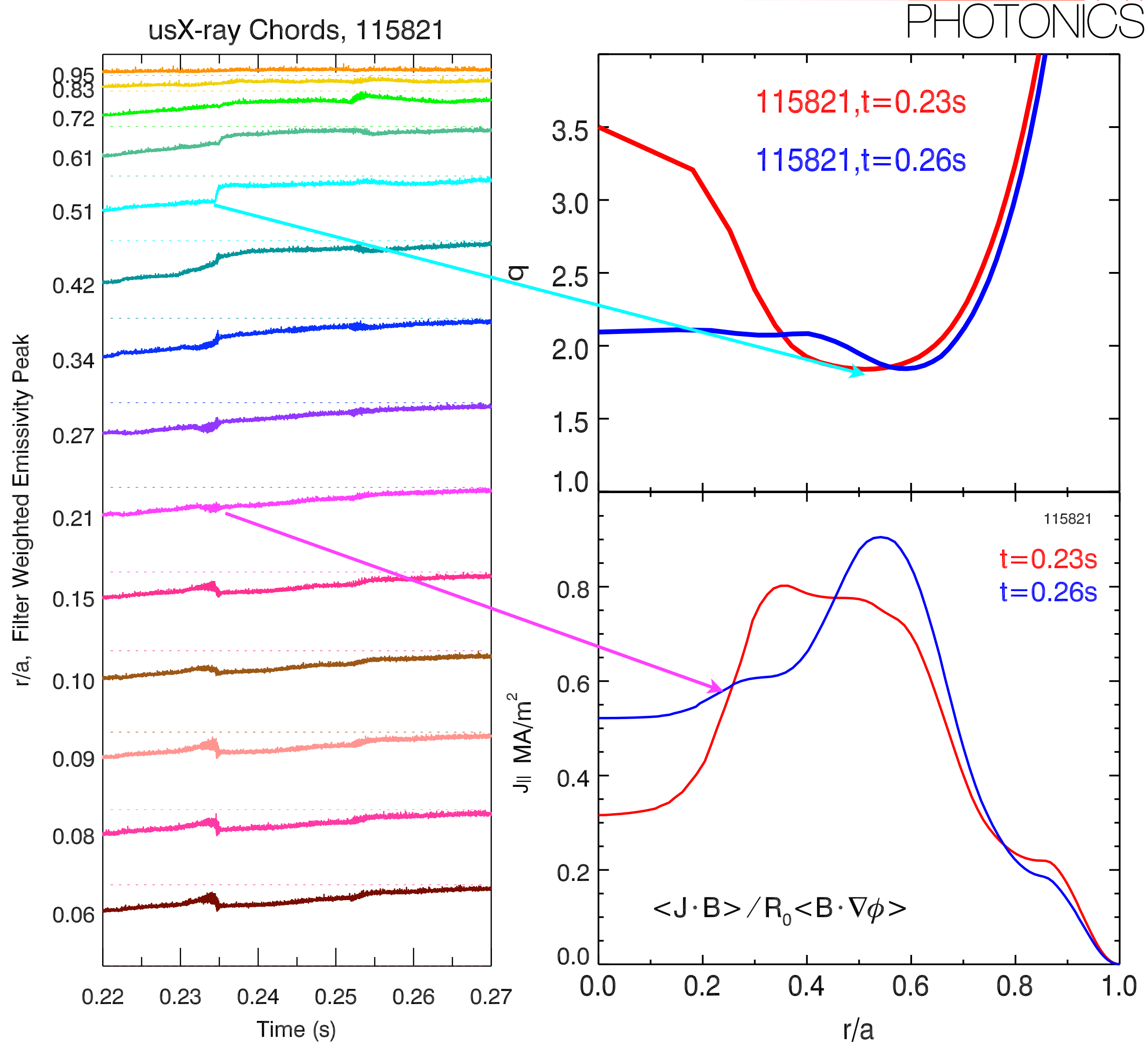
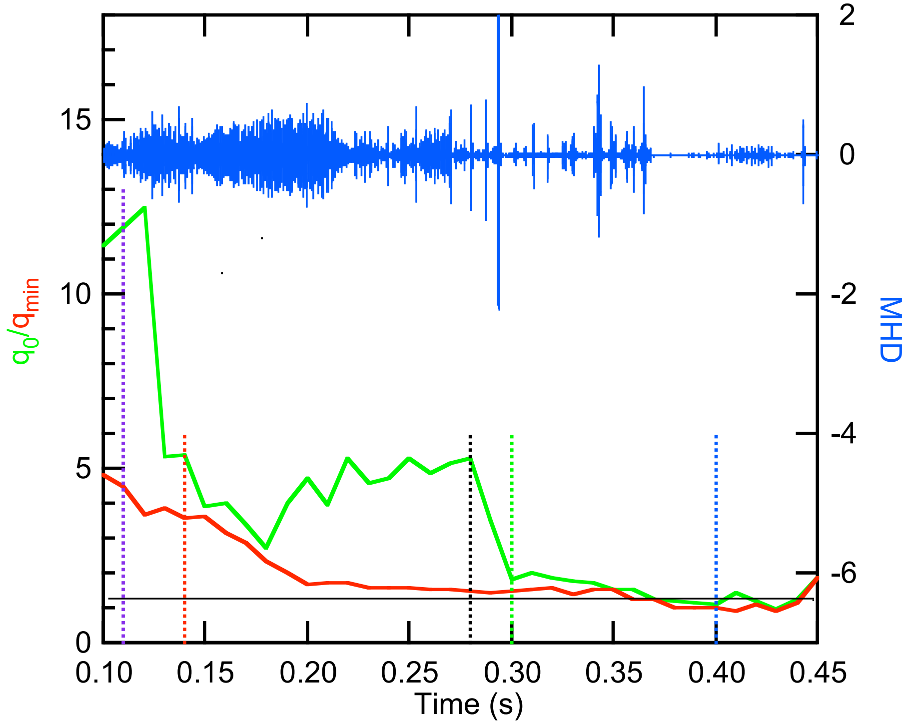
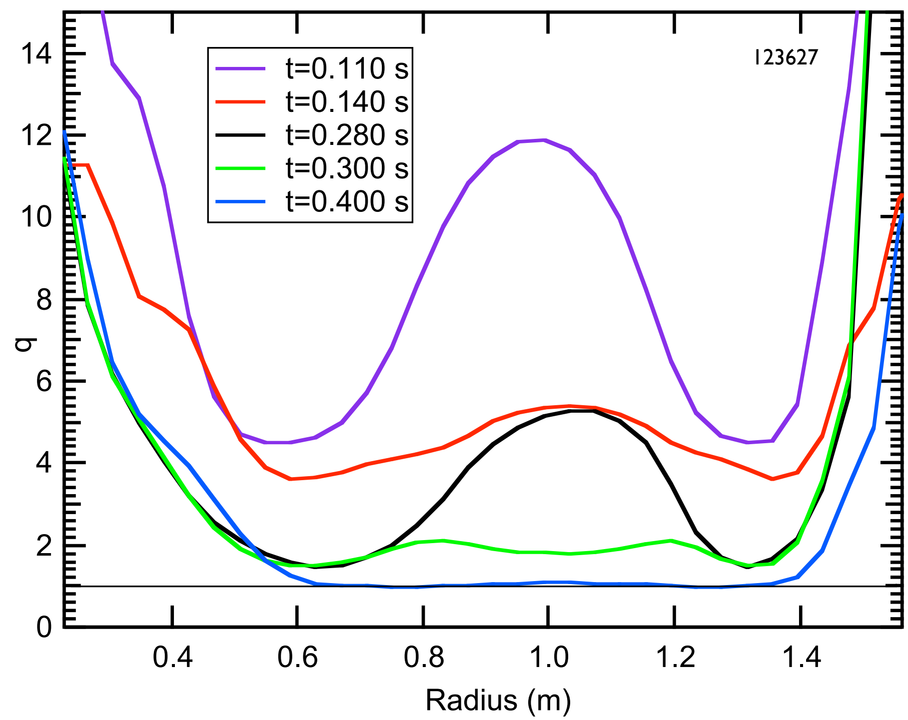
- Soft x-ray data mapped to minor radius using equilibrium and peak of calculated x-ray emission location.
- X-ray data shows sawtooth-like MHD occurs from the q_{min} radius to the magnetic axis.
- Mode analysis confirms m/n=2/1



NSTX

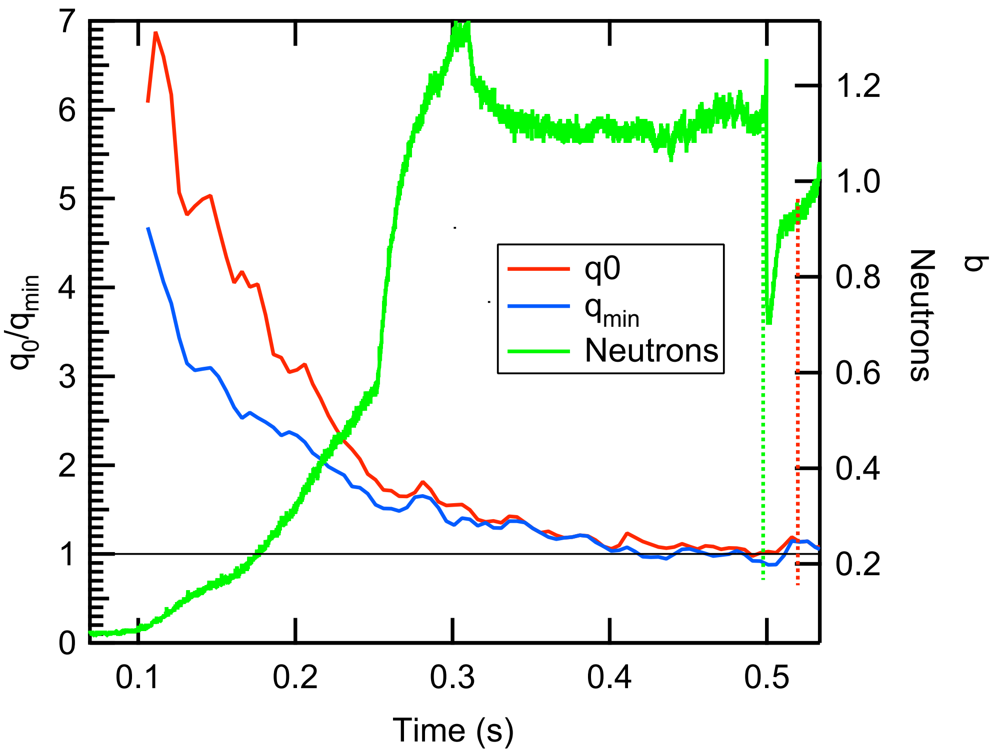
MHD Causes Current Redistribution

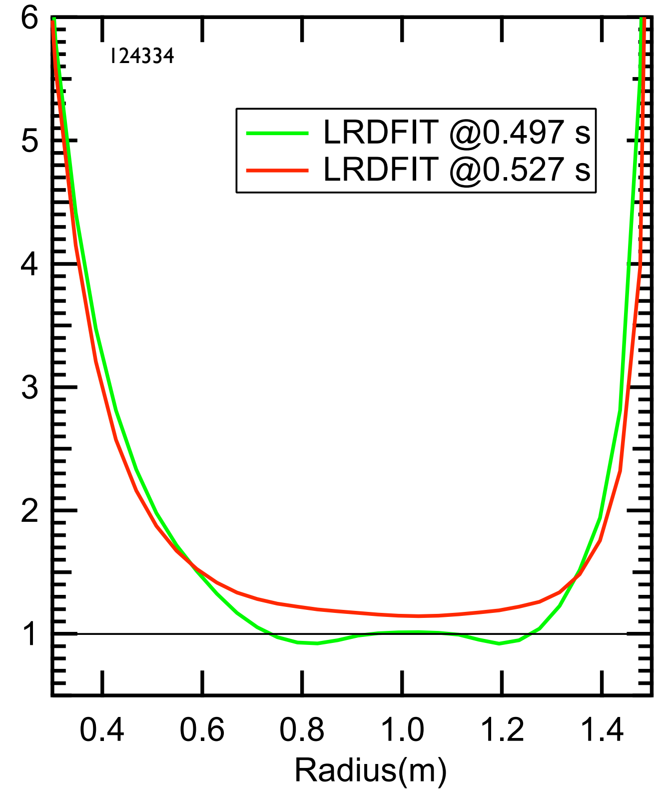




NSTX

Sawtooth like Event with Reversed Shear Raises q(0) above 1.





Fluctuations Observed in MSE Measurements

$$
\begin{aligned}
I &= I_0(1+\alpha\sin(\omega t))(1+\frac{1}{\sqrt{2}}J_0(\pi)\{\cos[2(\gamma+\tilde{\gamma}\sin(\omega t))]+\sin[2(\gamma+\tilde{\gamma}\sin(\omega t))]\} \\
&\quad +\sqrt{2}J_2(\pi)\{\cos[2(\gamma+\tilde{\gamma}\sin(\omega t))]\cos(2\Omega_1 t)+\sin[2(\gamma+\tilde{\gamma}\sin(\omega t))]\cos(2\Omega_2 t)\} \\
&\quad +2\sqrt{2}J_1^2(\pi)\sin(\Omega_1 t)\sin(\Omega_2 t)\cos[2(\gamma+\tilde{\gamma}\sin(\omega t))]+...
\end{aligned}
$$

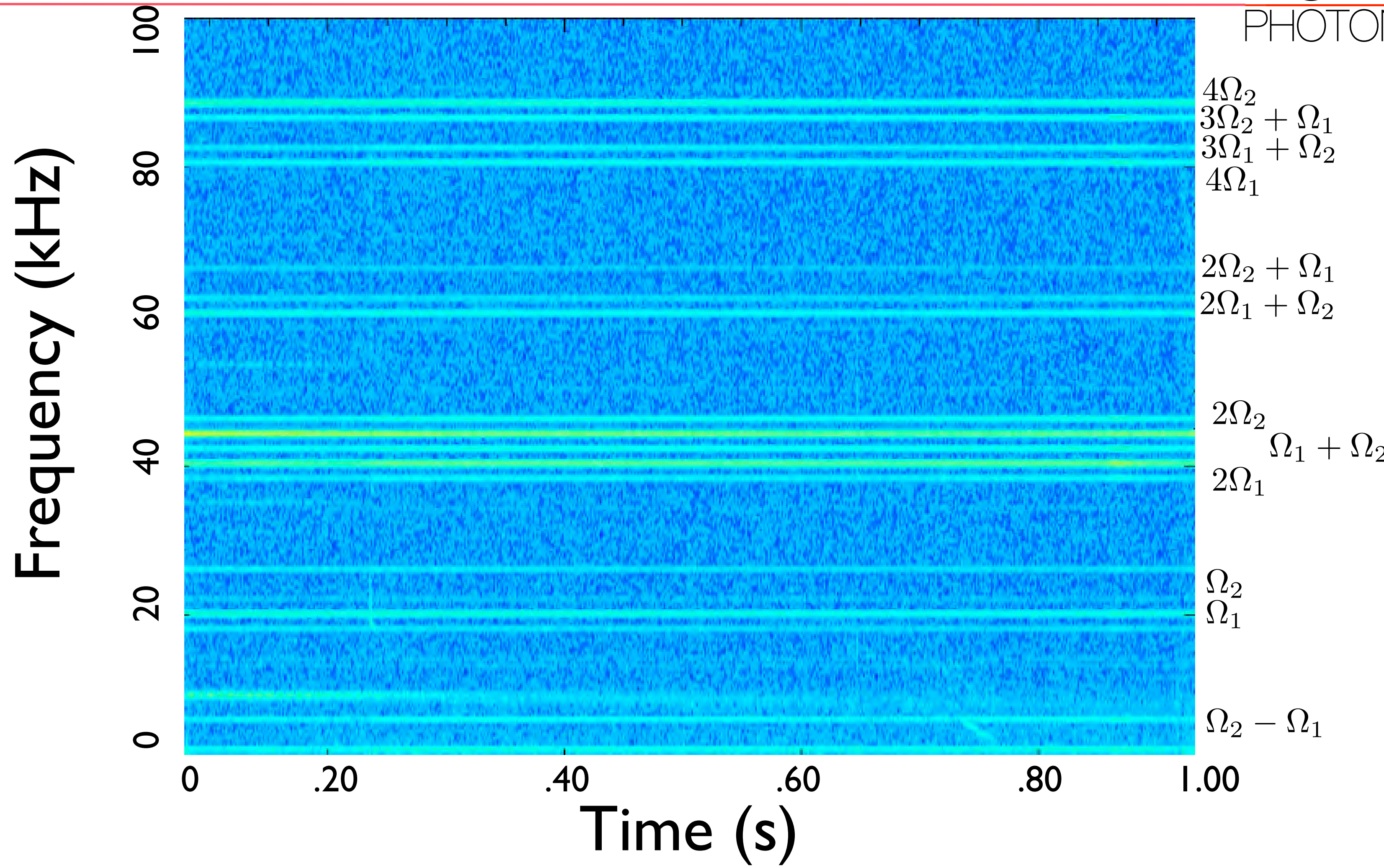
- Polarimeter equation with fluctuating density ($\alpha\sin(\omega t)$) and magnetic ($\tilde{\gamma}\sin(\omega t)$) perturbation.
- Polarimeter has two photoelastic modulators (PEM's) modulated at Ω_1 and Ω_2 .

Fluctuations Observed in MSE Data

$$
\begin{aligned}
I \quad = \quad & I_0(1 + \frac{J_0(\pi)}{\sqrt{2}}\{\cos(2\gamma) + \sin 2(\gamma)\} \\
& + \sin(\omega t)\left(\alpha\frac{J_0(\pi)}{\sqrt{2}}\{\sin(2\gamma) + \cos(2\gamma)\} + \alpha + \sqrt{2}J_0(\pi)\tilde{\gamma}\{\cos(2\gamma) - \sin(2\gamma)\}\right) \\
& - \cos(2\Omega_1 t)\sqrt{2}J_2(\pi)\cos(2\gamma) \\
& - \cos(2\Omega_2 t)\sqrt{2}J_2(\pi)\sin(2\gamma) \\
& + \{\sin((2\Omega_1 - \omega)t) - \sin((2\Omega_1 + \omega)t)\}\left[\frac{J_2(\pi)}{\sqrt{2}}\left\{2\tilde{\gamma}\sin(2\gamma) - \alpha\cos(2\gamma)\right\}\right] \\
& - \{\sin((2\Omega_2 - \omega)t) - \sin((2\Omega_2 + \omega)t)\}\left[\frac{J_2(\pi)}{\sqrt{2}}\left\{2\tilde{\gamma}\cos(2\gamma) + \alpha\sin(2\gamma)\right\}\right] \\
& + \ldots
\end{aligned}
$$

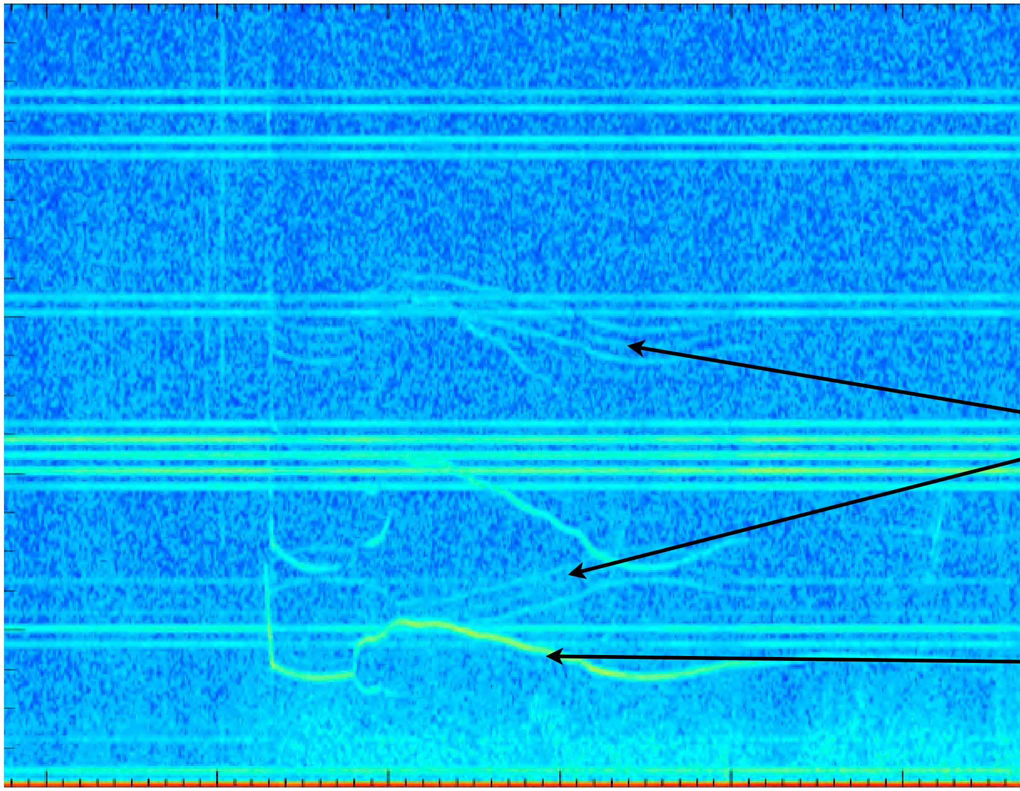
- Expansion of polarimeter equation shows sideband frequency distribution of fluctuations.

MSE Power Spectra



- No apparent fluctuations besides polarimeter frequencies (20 and 22 kHz) from photoelastic modulators.

MSE Spectra with Fluctuations

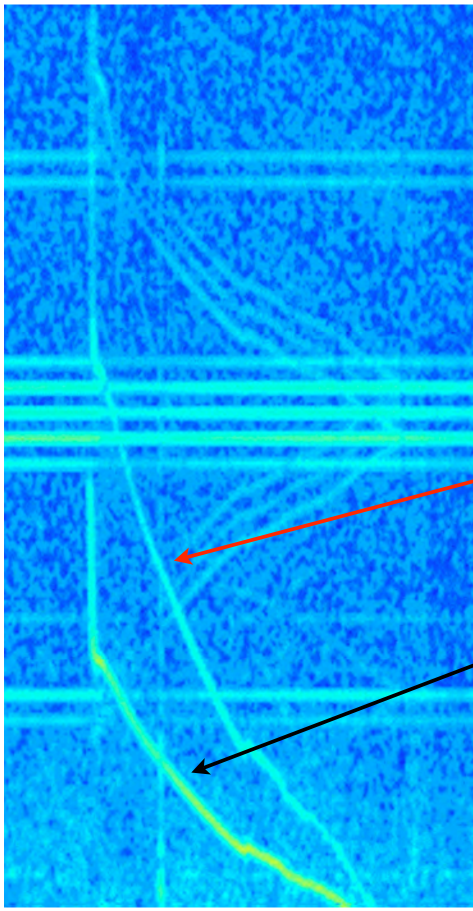


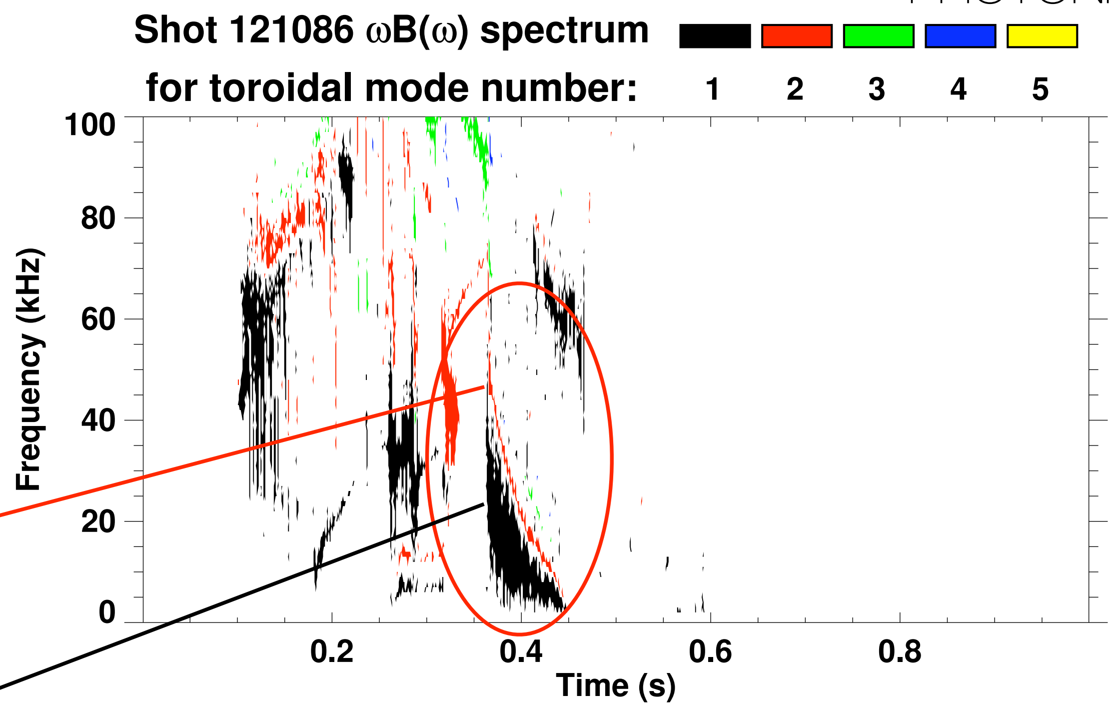
Side bands at

$2\Omega_{1,2} \pm \omega, \Omega_1 + \Omega_2 \pm \omega$

Fundamental at ω

Coherent MHD Mode





- Coherent MHD mode observed on both MSE and mirnov.
- MSE may be able to obtain spatial localization and eigenfunction of mode.

Summary

- The MSE-CIF diagnostic on NSTX presently has 16 channels operational with 19 available for future upgrades. Novel tunable birefringent interference filter design working well. Makes MSE measurements possible at low magnetic field.
- Discharges with a wide range of magnetic shear have been developed.
- MHD can have a strong effect on the current profile evolution.
- Sawtooth reconnection is observed to raise q(0).
- Coherent magnetic/density fluctuations have been observed with high throughput MSE system.