The MSE-CIF Diagnostic on NSTX

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NOVA PHOTONICS, INC.

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Abstract

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The adoption of the motional Stark effect (MSE) polarimetry diagnostic is due to its very good temporal and spatial resolution of the q-profile, combined with its exceedingly good accuracy. This has resulted in many important scientific contributions towards our understanding of stability and transport. This work describes the implementation of the MSE-CIF diagnostic on NSTX. Due to the low magnetic field on NSTX the implementation of the MSE diagnostic requires a different approach for the viewing optics and spectral filter. The diagnostic views a heating beam with 8 inch collection optics, imaged onto a fiber array. The optical system is configured to maximize the polarization fraction by reducing the Doppler broadening from the heating beam. This is done with a vertical aperture in front of the collection optics to reduce geometric Doppler broadening. In addition, a wide field Lyot spectral filter with high throughput and high resolution has been developed to achieve thenecessary signal-to-noise. Results with the MSE-CIF diagnostic have been obtained at magnetic fields ≥0.3 Tesla with eight channels providing coverage from the magnetic axis to near the outboard edge. The number of spatial channels can be increased to 19 in the future. Results of various plasmas regimes including L-mode, H-mode, and reversed shear will be presented.

MSE-CIF Status on NSTX

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- 8 MSE channels viewing from the magnetic axis to outboard plasma edge are operational
- Working MSE channels are calibrated using the beam-into-gas technique
- Digital lockins provide in-between shot analysis with typical 10ms time resolution
- Magnetic axis and plasma edge measurements match reconstructed data
- NSTX experiments requiring MSE were able to be carried out

MSE-CIF Layout on NSTX

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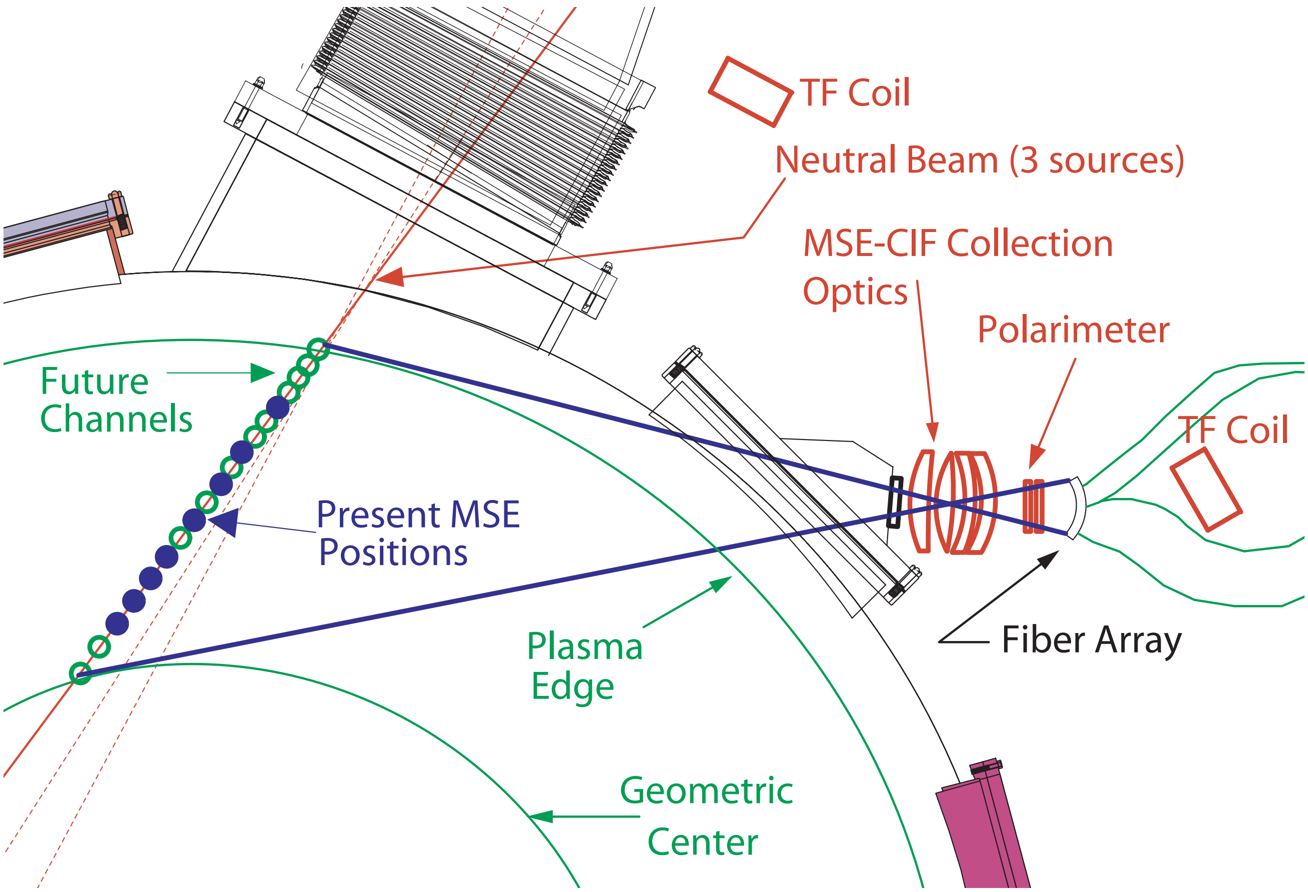

- 8 of 19 possible MSE channels presently view from the magnetic axis to outboard plasma edge
- Tangential sightlines at edge and center provide optimal spatial resolution over a wide field of view

Previous MSE systems operated using a high field Stark multiplet, as shown by TFTR spectra

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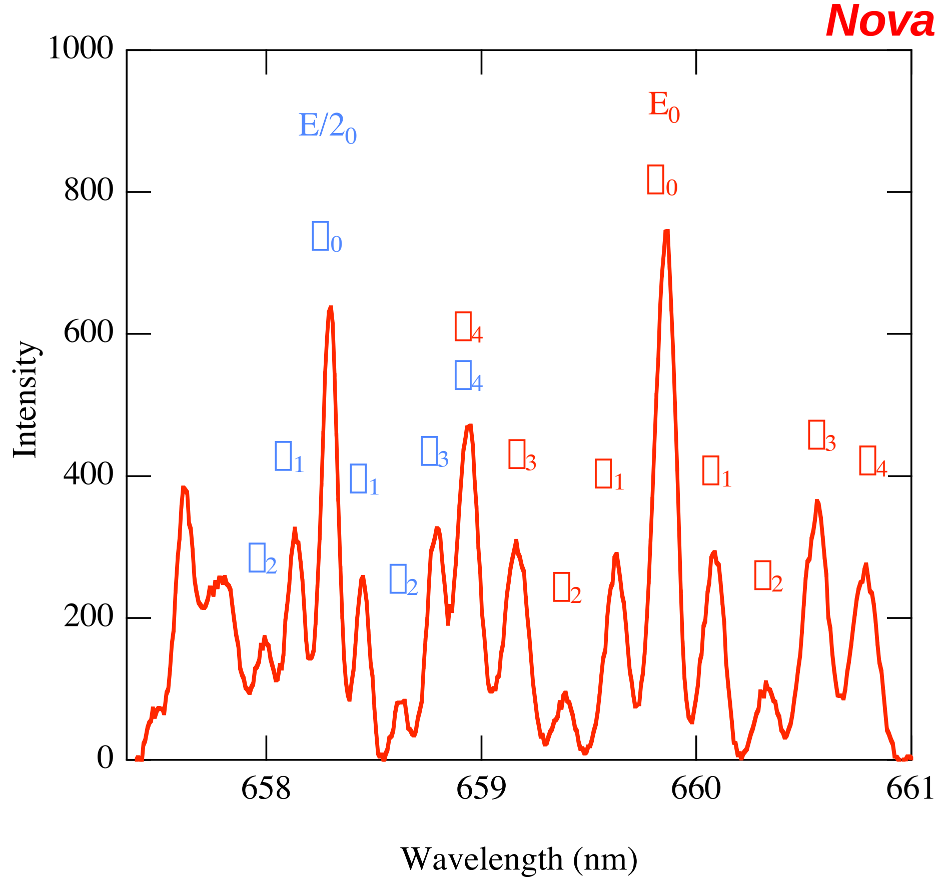

- $\vec{\mathrm{E}} = \vec{\mathrm{v}} \times \vec{\mathrm{B}}$ **electric field is** ~ 200 **kV/cm at 4.5 T, resulting in a spectral splitting.**

- $\boldsymbol{\Delta}\mathbf{m} = \mathbf{0}(\pm\mathbf{1}), \pi(\sigma)$ **component, are polarized parallel (perpendicular) to the electric field.**

- **Spectral linewidth is determined by geometric broadening and beam temperature.**

- **Spectral overlap between** π **and** σ **lines reduces polarization fraction and signal-to-noise.**

NSTX requires MSE to operate at Low Field

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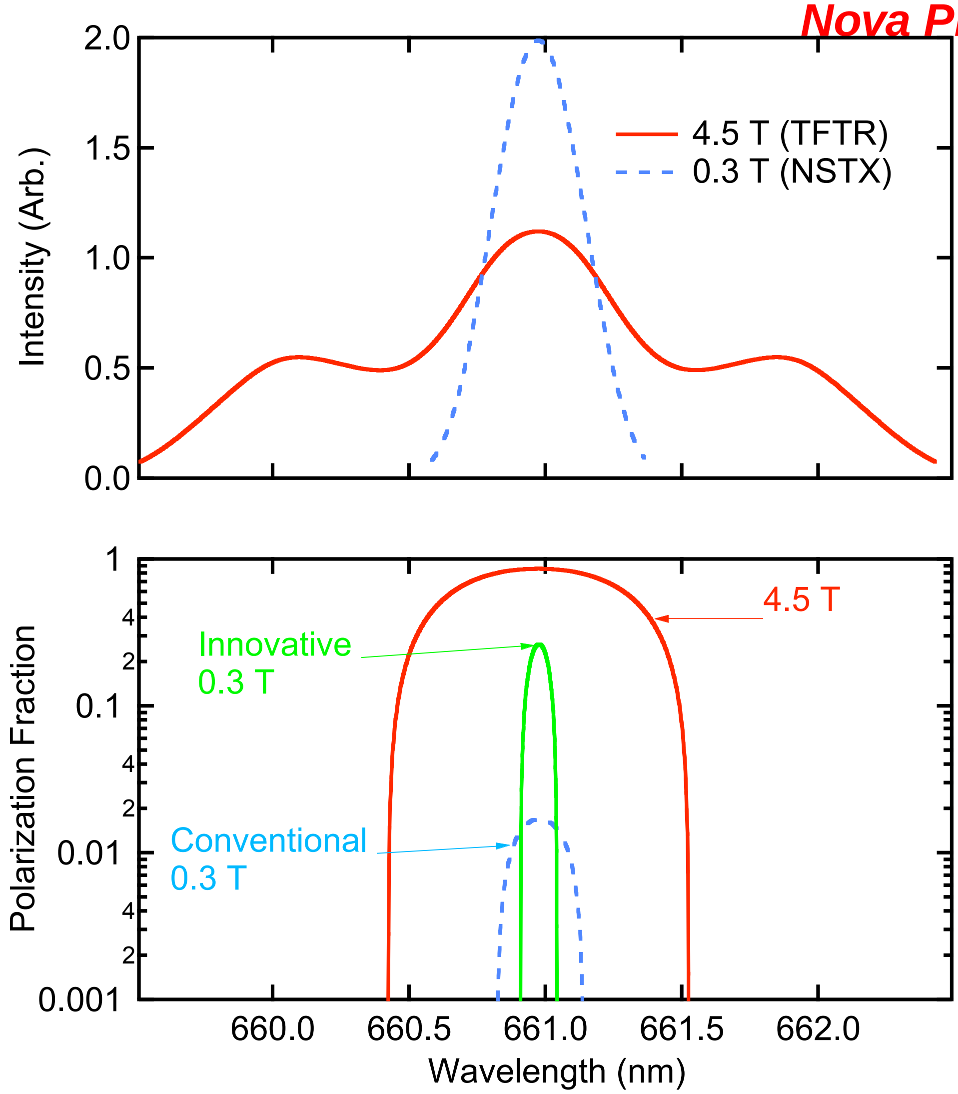

$$P_f = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}$$

$$S/N \propto P_f \sqrt{I}$$

- **Numerical convolution of the MSE spectra including filter, beam, and optics broadening.**
- **Using conventional MSE approach overlap of spectral lines leads to a low($\sim$1%) polarization fraction. This is too low for a measurement.**
- **With improvements in the optics design and filter, the polarization fraction can be raised to $\sim$30% at 0.3 T making a measurement feasible.**

MSE-CIF at Low Magnetic Field

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- **Innovations improve the polarization fraction.**

  1. **Optimize optics to reduce geometric spectral broadening.**
     - **Spectral broadening is from the finite optics and image size. Optimization of the optics can reduce the spectral width.**
  2. **Development of high resolution, high throughput filter to extend measurements to $\sim$0.3 T.**
     - **Wide field Lyot type birefringent filter meets requirements.**

- **Development of MSE-LIF. Further information at Posters BP1.089 and FP1.058.**

Novel Optics Design to Reduce Geometric Doppler Broadening

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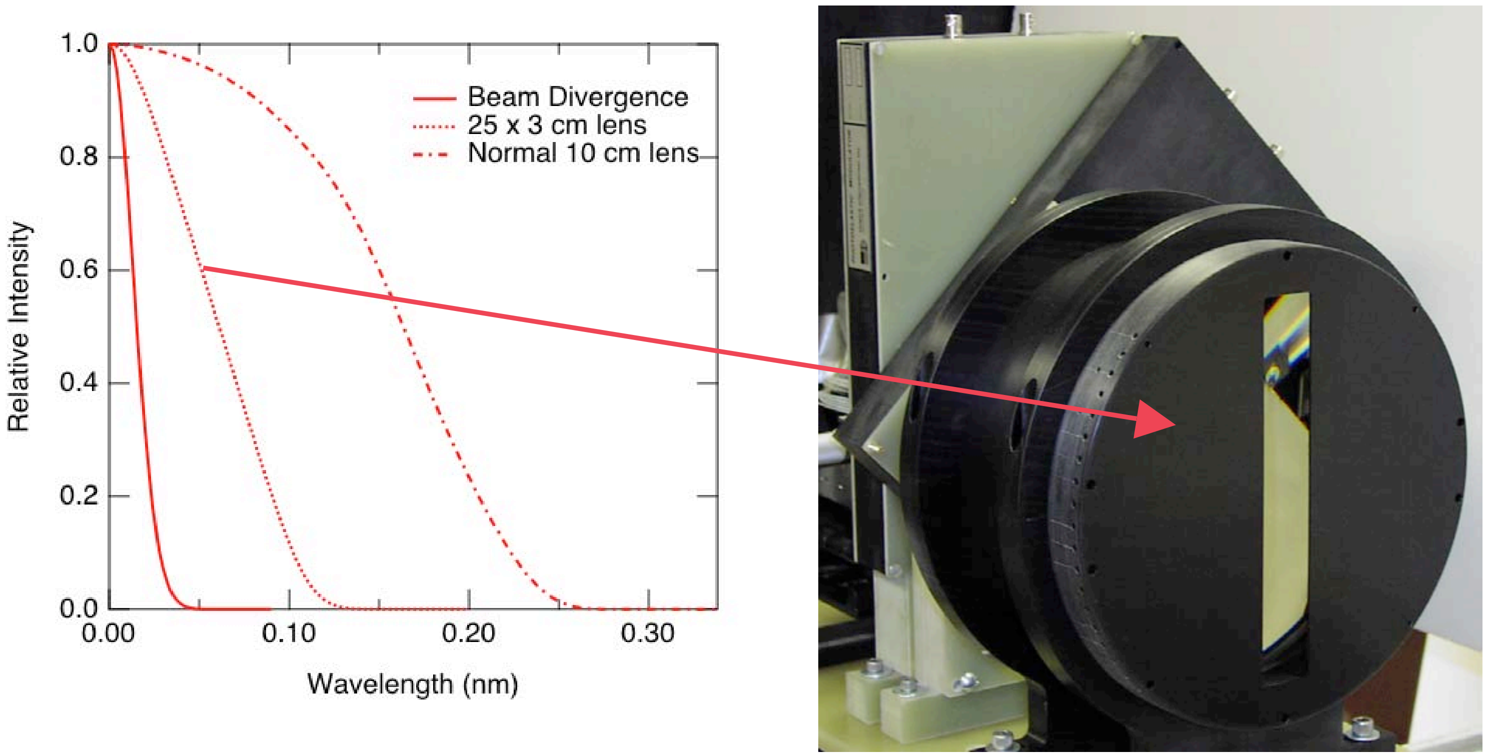

- **Novel optics design, combined with high through-put, high resolution birefringent filter, can increase the polarization fraction to ∼30%.**

High Resolution, High Throughput, Lyot Spectral Filter

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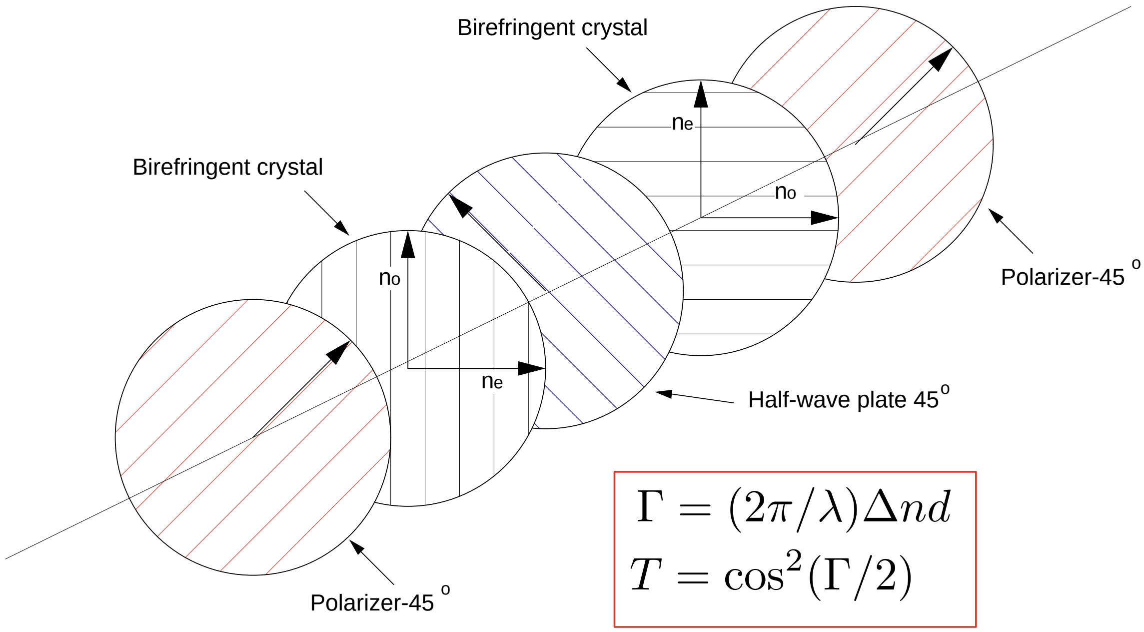

$$\Gamma = (2\pi/\lambda)\Delta n d$$
$$T = \cos^2(\Gamma/2)$$

Single Stage Filter

- **Required resolution and throughput can be satisfied with a wide-field birefringent Lyot type filter.**
- **Flexibility in combining multiple stages to form spectral filter.**
- **Unique feature –** ***electro-optically tunable.***
- **Increased luminosity by a factor of 20-1000 relative to other instruments (grating spectrometer, Fabry-Perot, interference filter).**

Four Stage Filter Transmission

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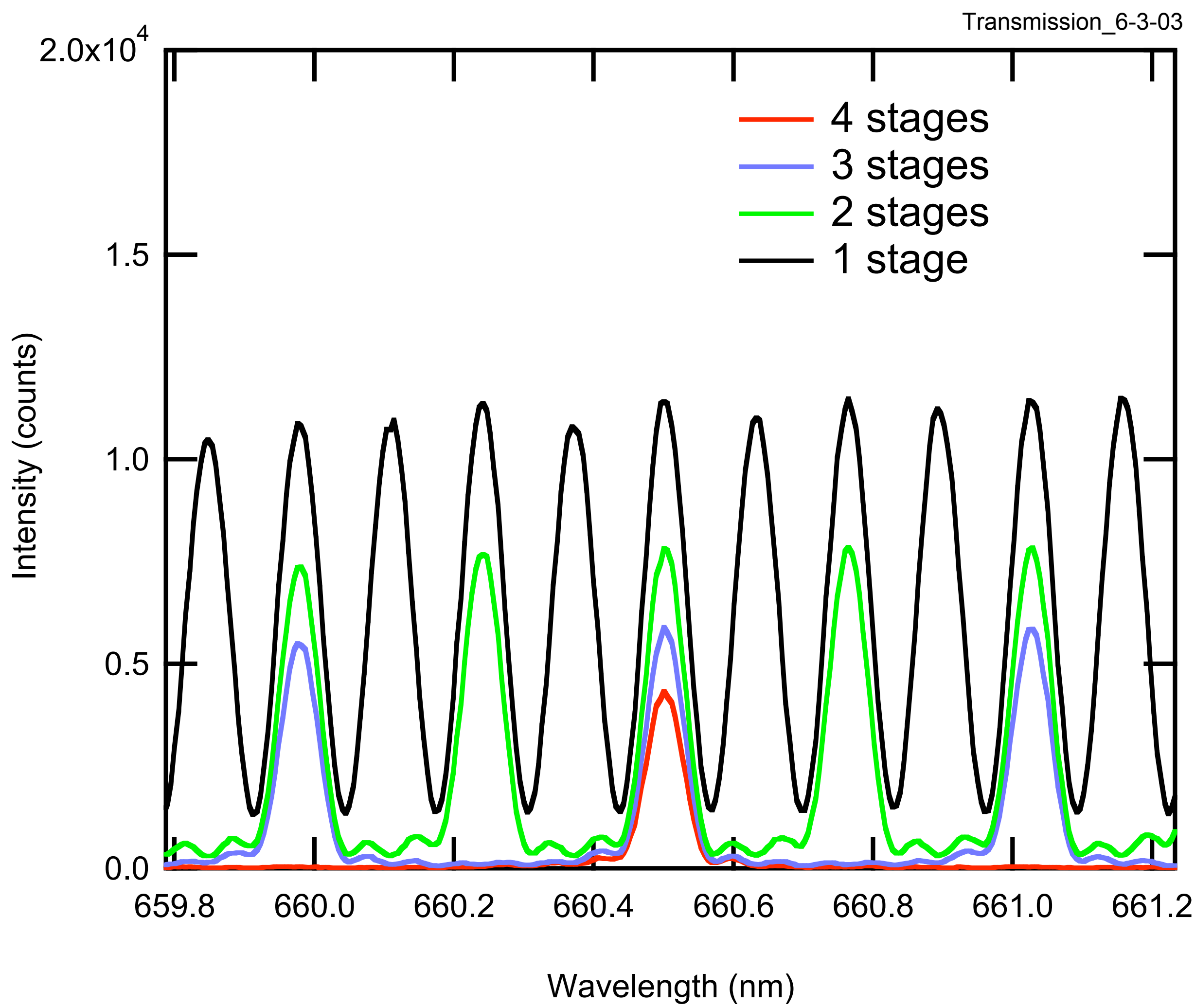

- **Filter data for 4 stage configuration.**
- **Wavelength is tuned electro-optically.**

Birefringent Filter on NSTX

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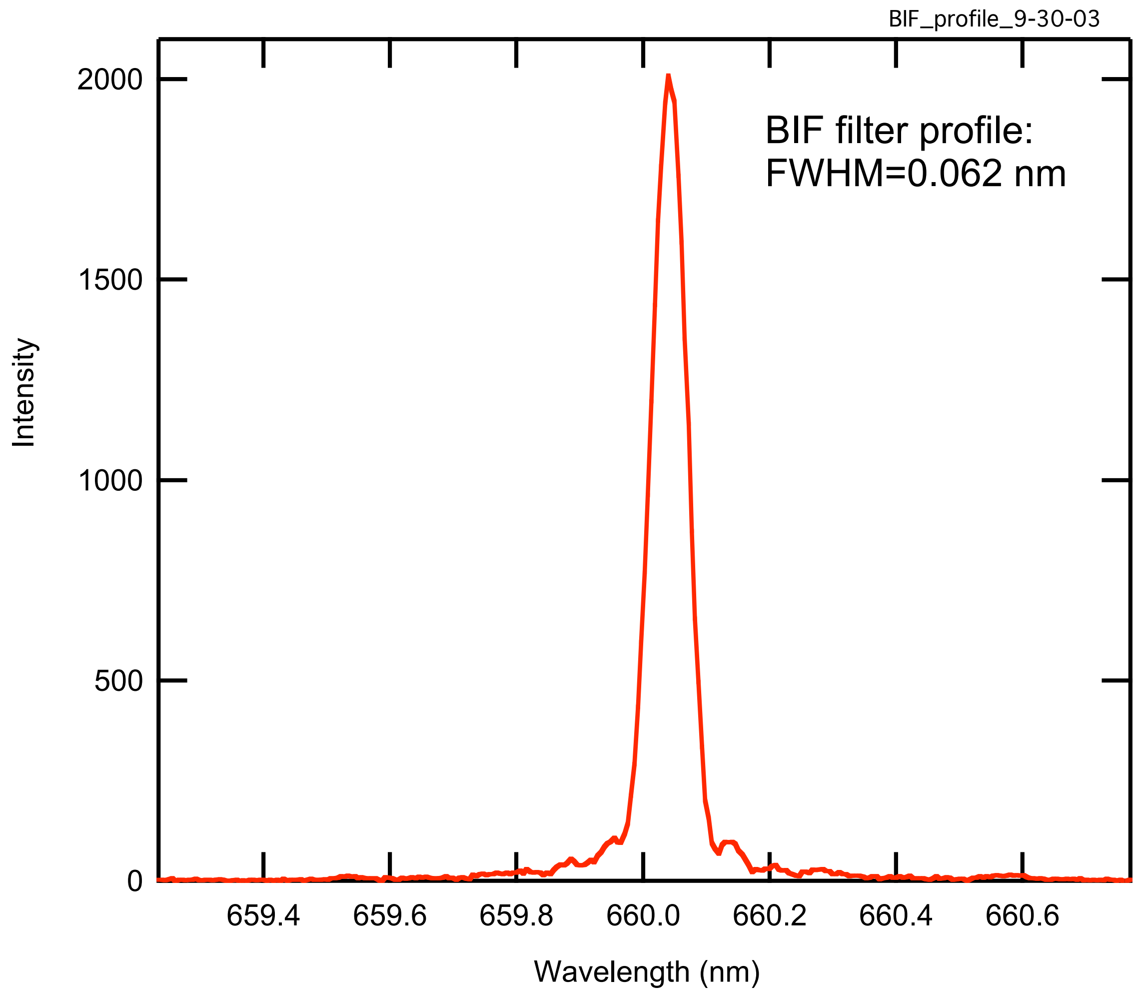

- **Measured transmission of BIF filter.**
- **Five stage filter now used on NSTX.**

Filter and Optics Enclosure

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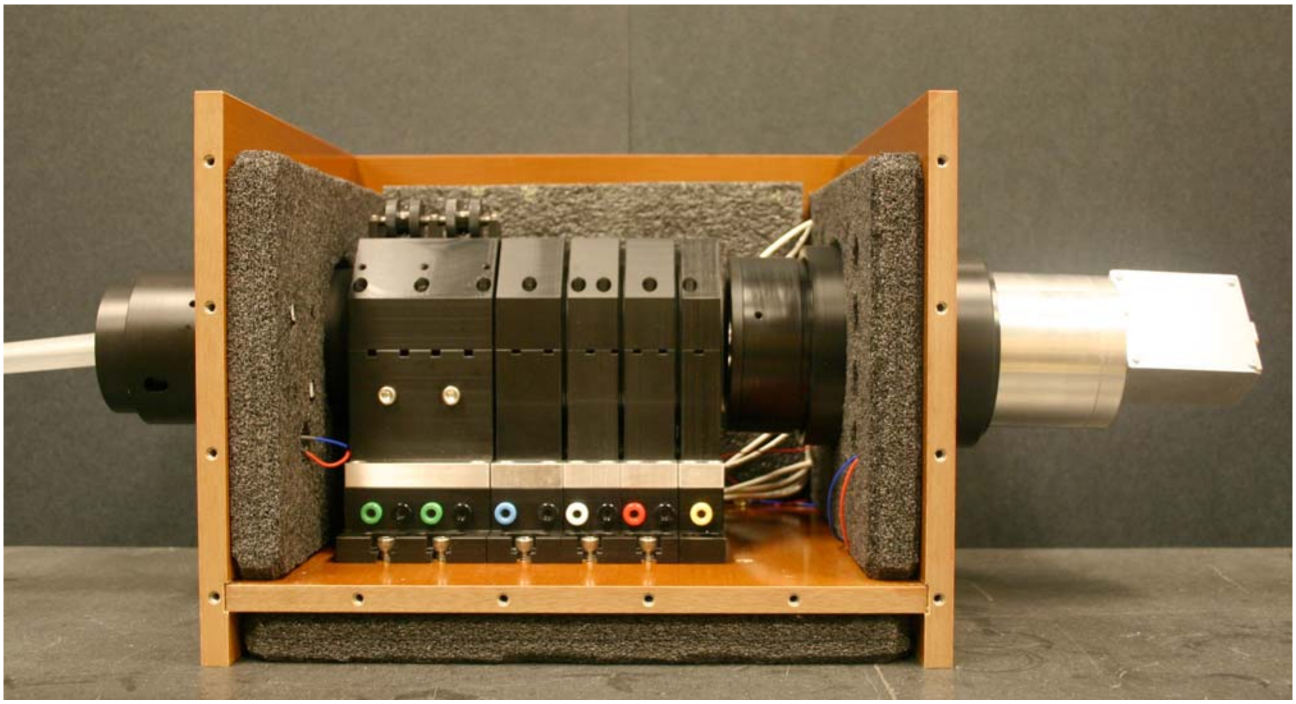

- Enclosure containing Lyot Filter, collimating and focusing optics, APD detector, HV for wavelength tuning, and temperature control
- Compact and modular design allows easy access for maintenance and upgrades
- Achieved a spectral FWHM of 0.062 nm

Birefringent Interference Filter(BIF) has Large Throughput Advantage

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Instrument	input aperture A(mm^2)	$\Delta\lambda$(nm)	f/#	Etendue $U(mm^2 - sr)$	Trans-mission t	Luminosity $U * t$	Relative to BIF
BIF(NSTX)	59.7	0.062	1.2	32.6	10%	3.3	1
Fabry-Perot	1	0.062	1.2	.5	25%	.13	1/25
Grating(ref.)	.04	.1	5.	10^{-3}	80%	8×10^{-4}	$1/(4 \times 10^3)$
Grating(trans)	.04	.1	1.8	10^{-2}	80%	8×10^{-3}	1/400

- **BIF is tunable, but slowly at this time. A rapid tuning version is possible, but some R & D required.**
- **Multi-spectral channel applications:**
  Rapid tuning of BIF makes it more attractive than Fabry-Perot or grating spectrometers, even including disadvantage of single wavelength scanning.

Fiber Optic Holder

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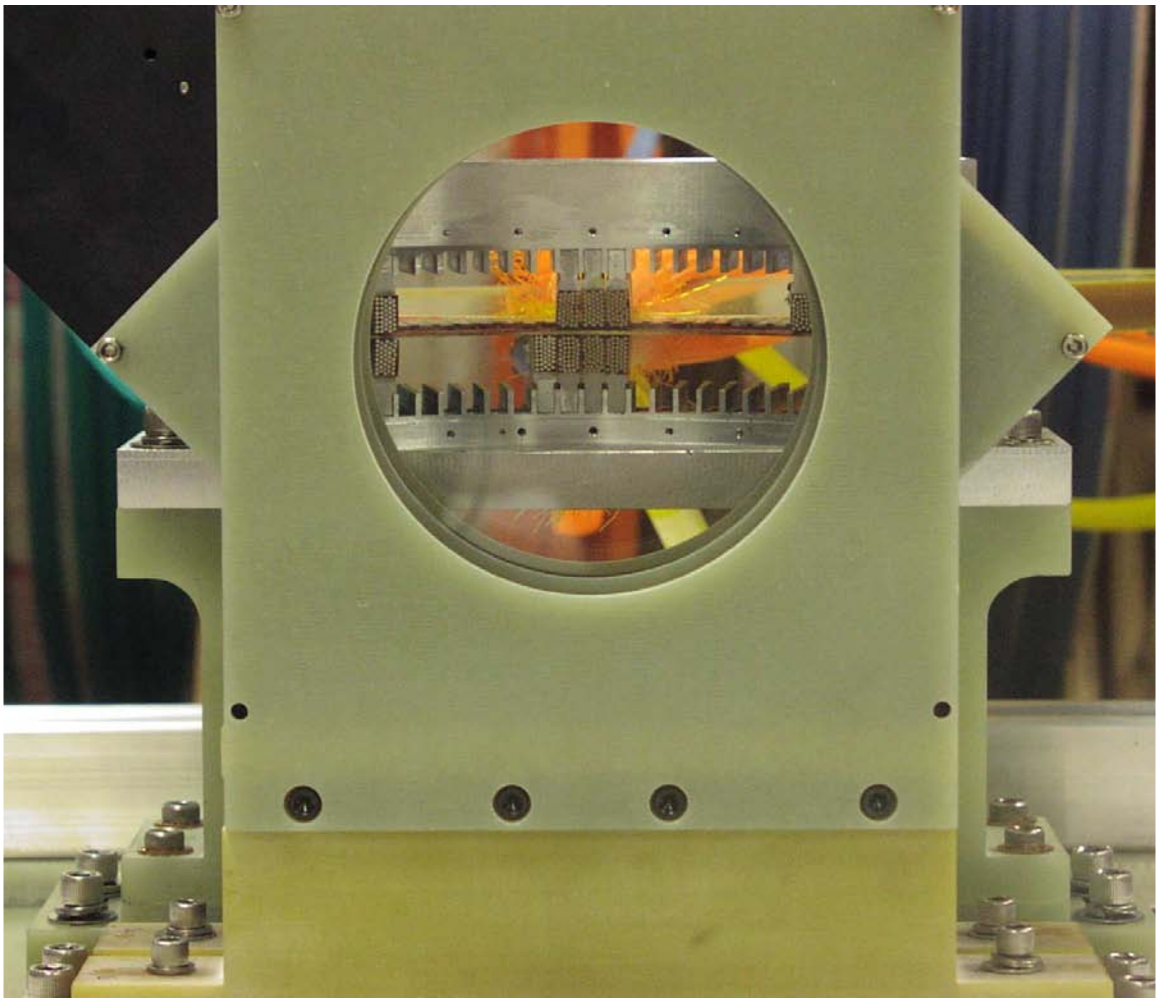

- View of fiber holder with a few fiber ferrules installed.
- Fiber holder is now fully populated and installed on NSTX.

MSE & CHERS Fiber Optic Holder

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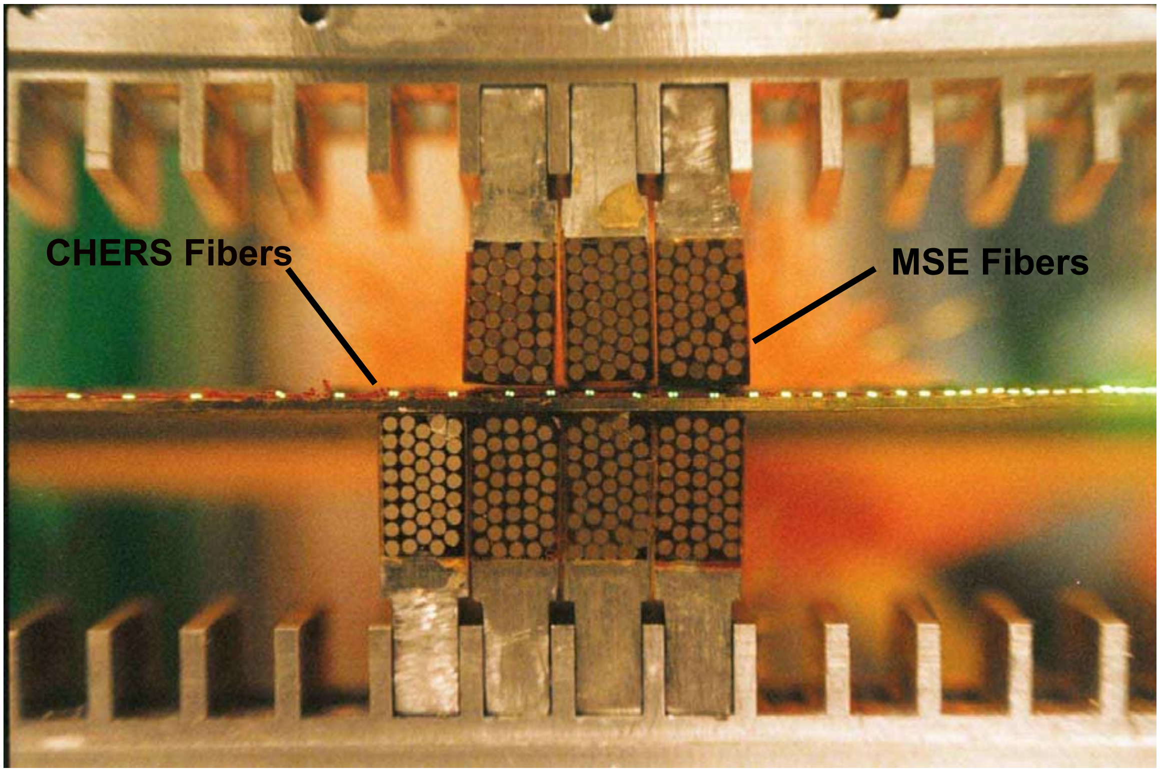

- **View of fiber holder with a few MSE fiber ferrules installed.**
- **CHERS fibers are the small fibers in the mid-plane. Ratio of light collection is about 1000:1.**

Output Fiber Optic Holder

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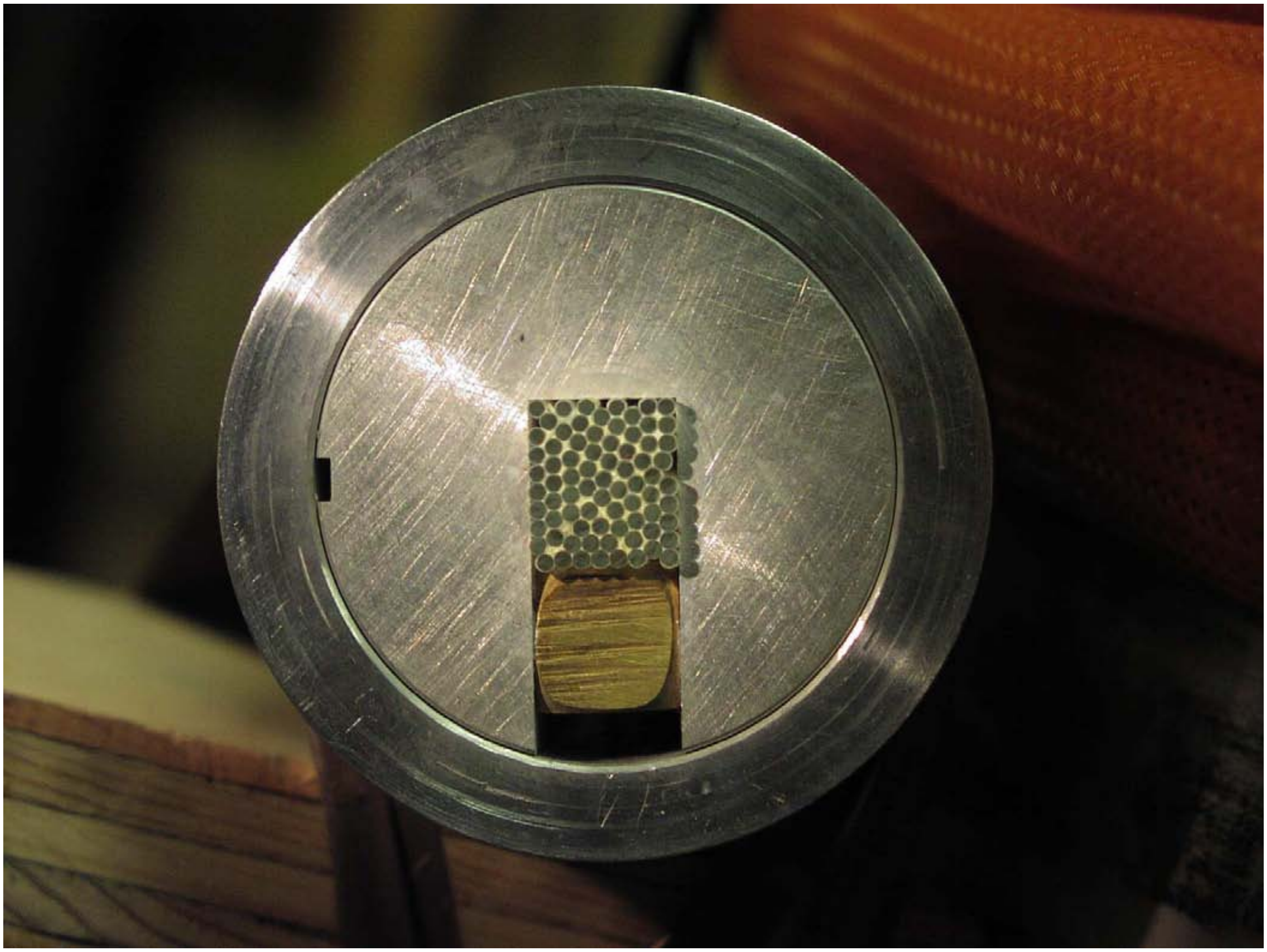

- Fiber optics bundle for a single sight-line.
- 76 $\times$ 1 mm diameter fibers.

Doppler Shifted Beam Emission

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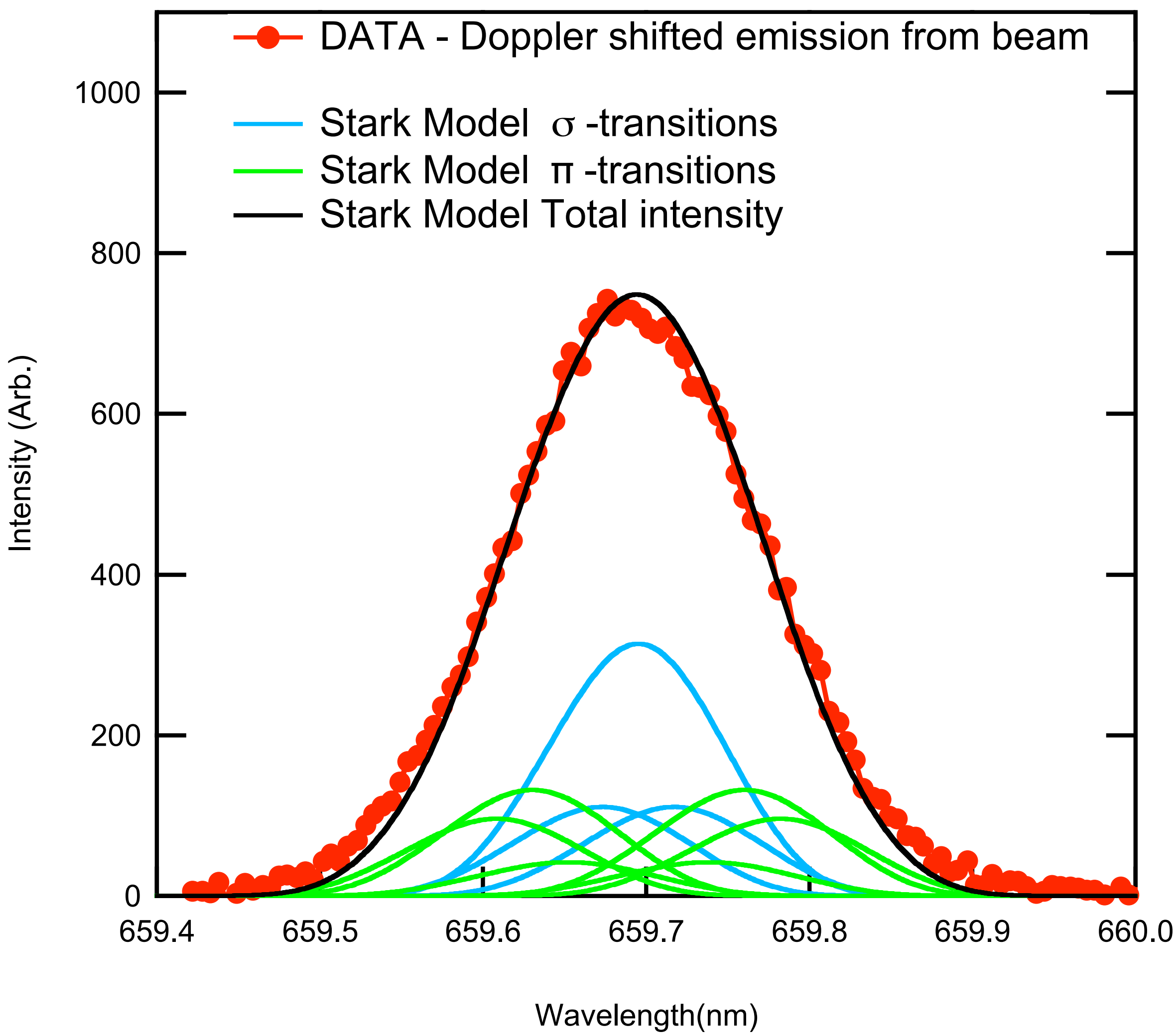

- **"First Light" was observed Jan. 2004.**
- **Spectrometer data from 90 kV deuterium beam at 0.3 T.**
- **Data compares well with model including beam divergence, geometric broadening, and Stark shifts.**

Intensity and Polarization Model

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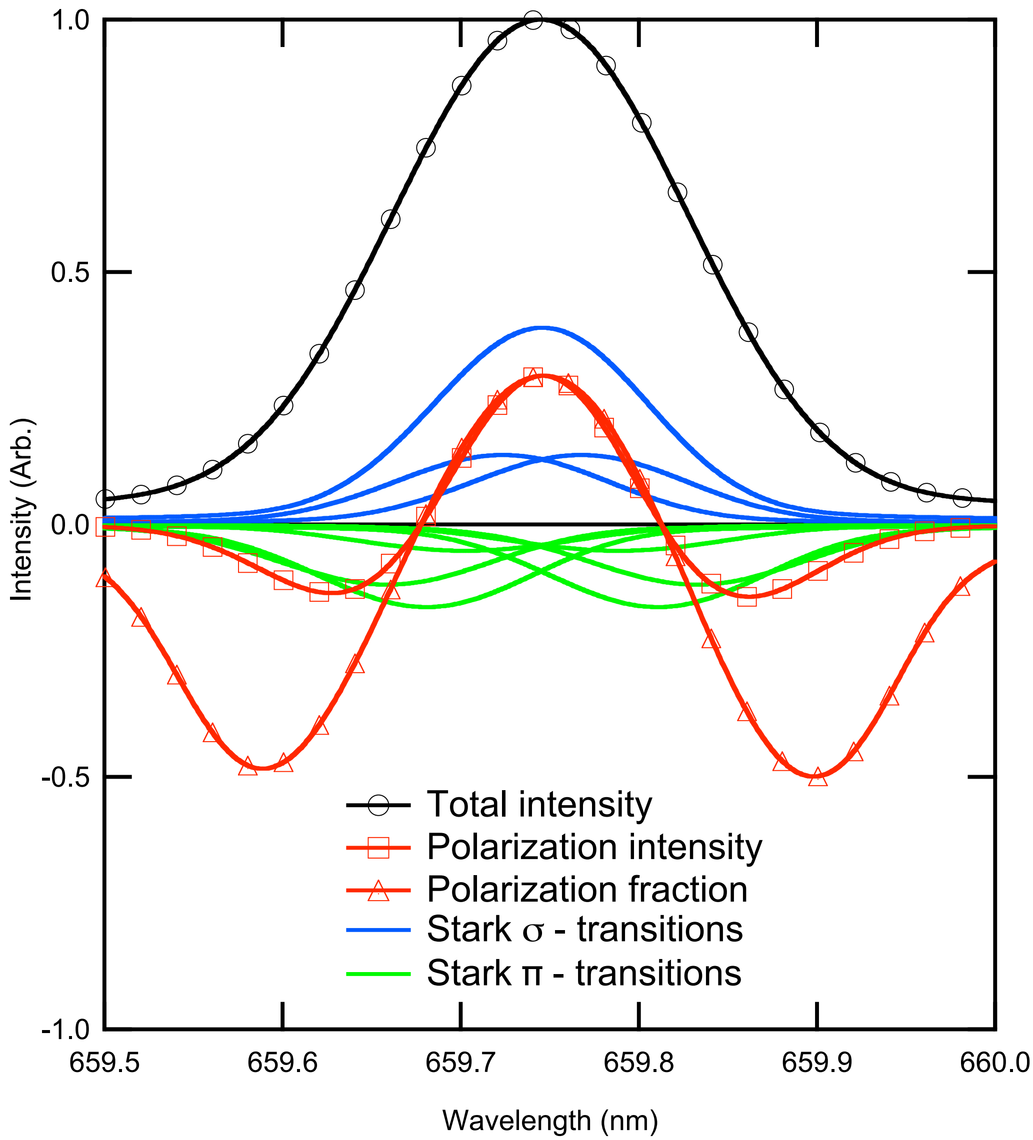

- **Model of intensity and polarization including birefringent filter for 0.3 T.**
- **Obtaining this polarization fraction is key to a successful measurement.**

Polarization Data

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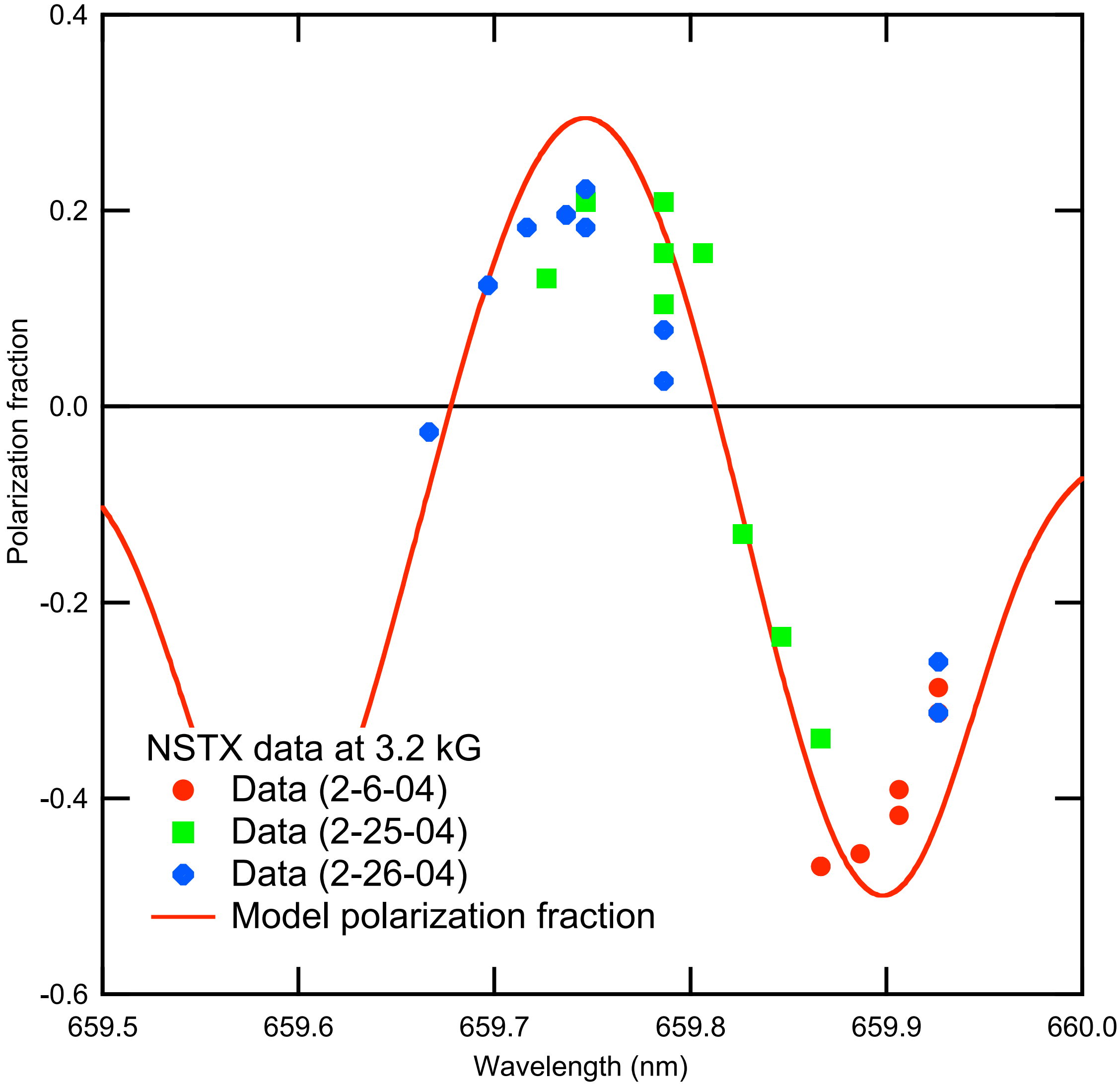

- **Polarization fraction model is consistent with data.**

Primary Calibration performed using Beam into Gas

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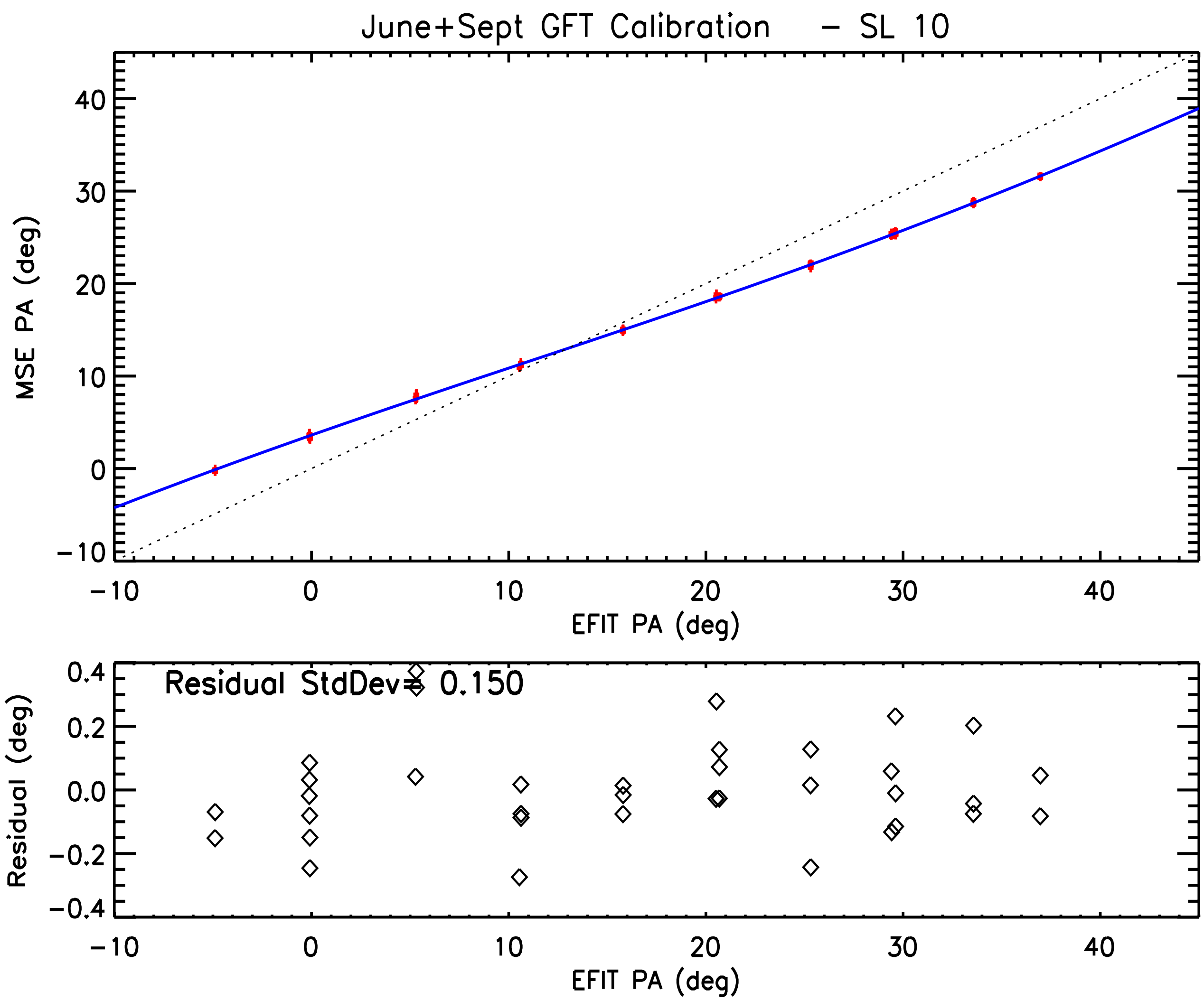
- Measurement during beam into gas-filled torus using a range of pitch fields created using TF and PF coils.
- MSE measurements are calibrated against EFIT vacuum field reconstructions.



MSE Instrumental Response Well Characterized

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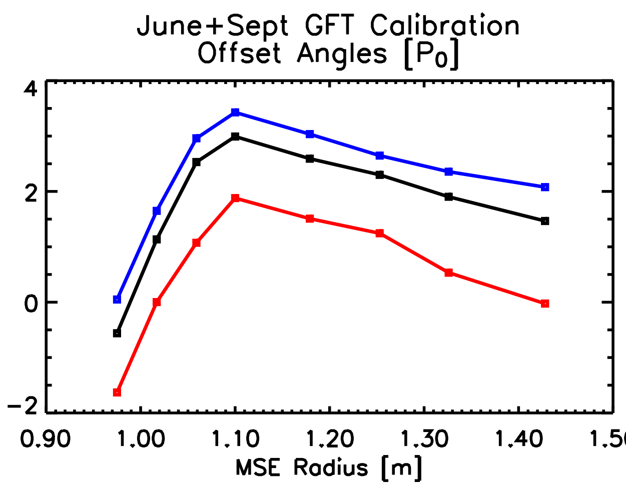
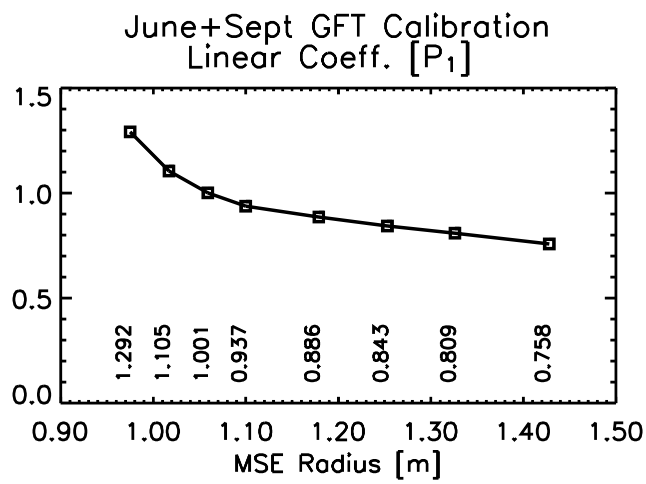
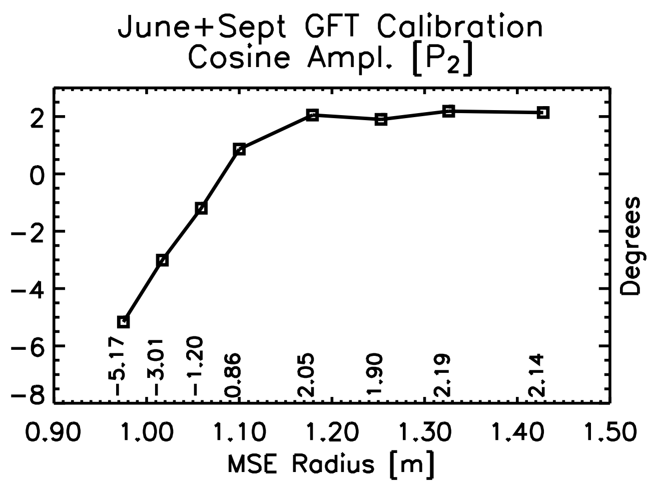
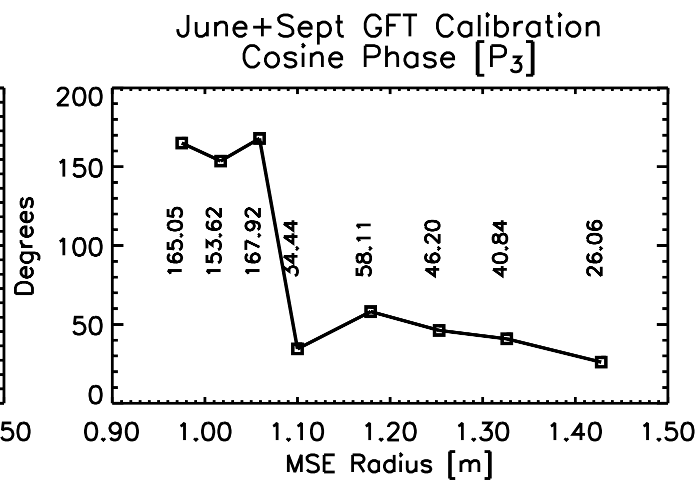
- Sinusoidal component in instrumental response has same functional form as fixed polarizer calibrations, quantitative reconciliation of fitting coefficients is ongoing.
- MSE responses characterized fitted using the functional form:

$$\gamma_{MEAS} = P_0 + P_1 \gamma_{EFIT} + P_2 \cos(\gamma_{EFIT} + P_3)$$









Calibrations at Varying Toroidal fields shows linear Faraday Rotation

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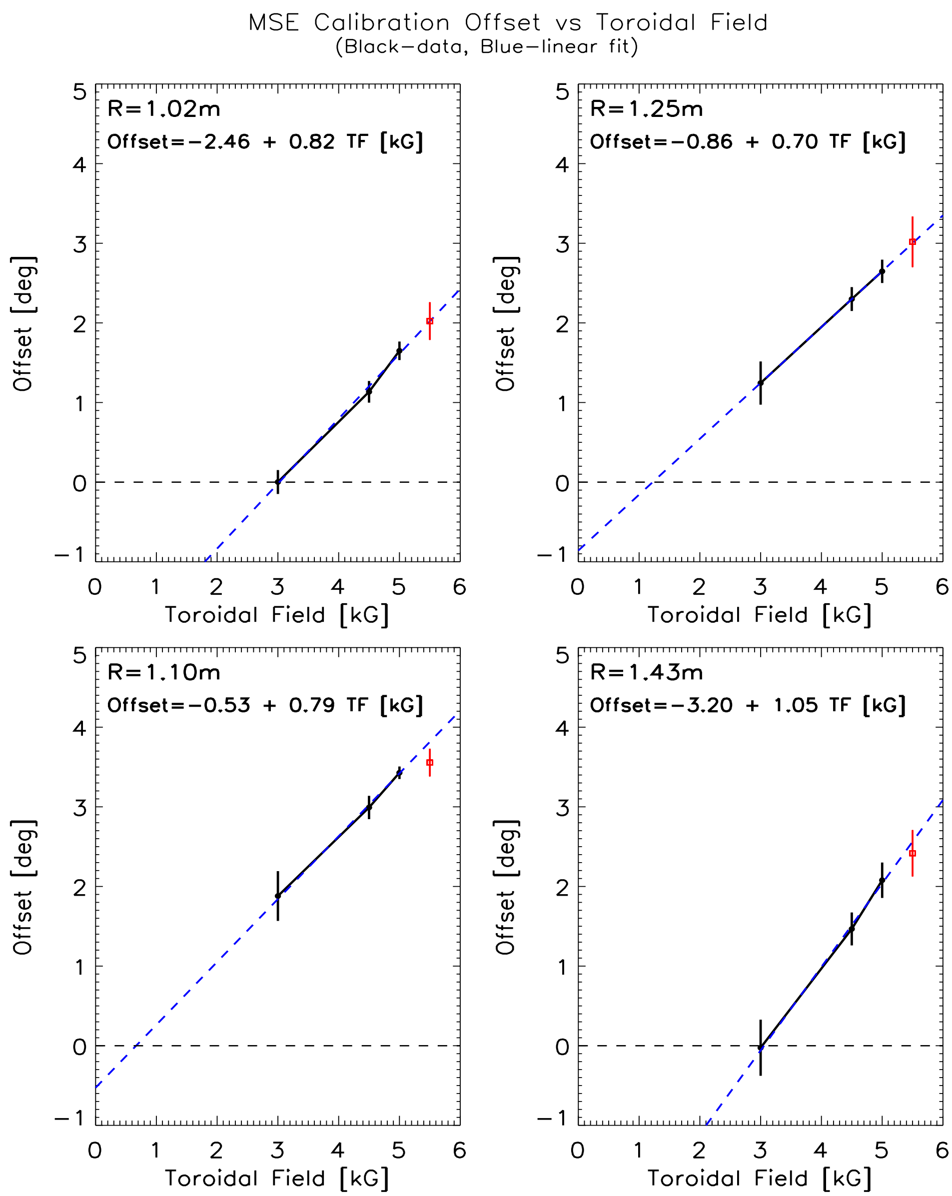
- Coefficients unchanged between June and Sept. calibrations at multiple toroidal fields.
- Optical Faraday rotation can be fitted to a linear function of field as expected.
- Red point shows predicted Faraday rotation data from three shots at 5.5 kG.



Calibrations at Varying Toroidal fields shows linear Faraday Rotation

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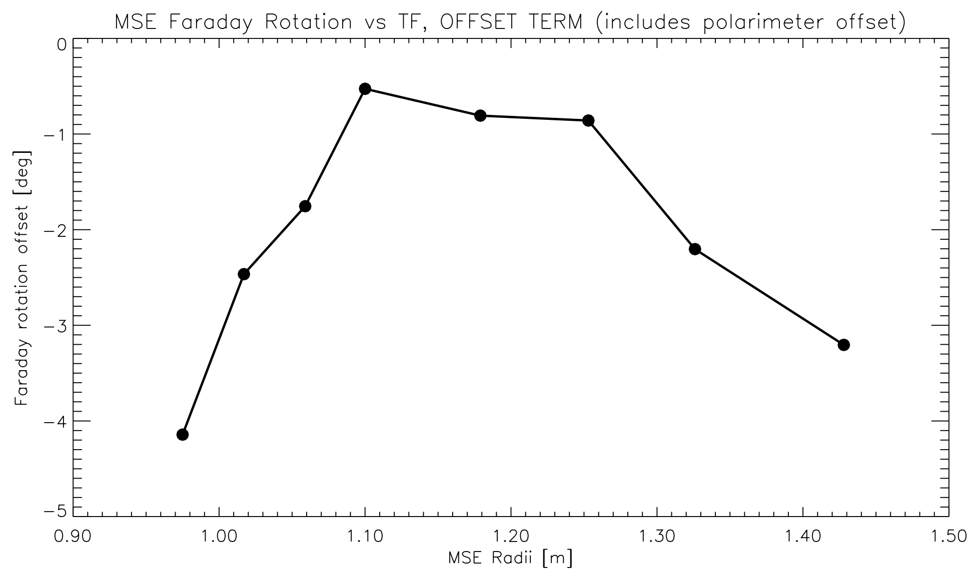
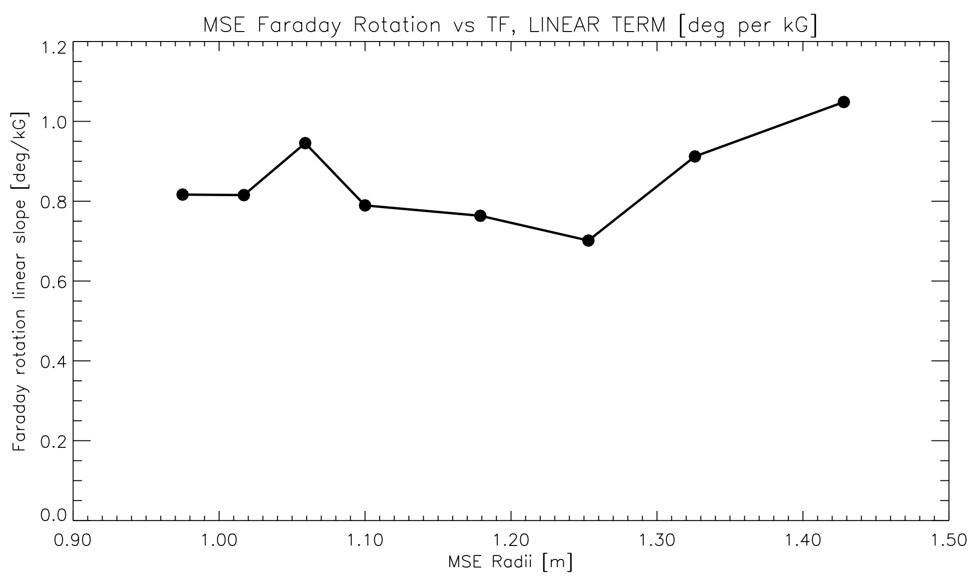
- The fitted linear Faraday rotation coefficients vs. radii is shown.
- MSE optics are positions close to a TF coil, and experiences ripple/fringe fields with complex patterns
- Polarimeter zero offset can be determined from zero crossing of fit.





Magnetic Axis measured by MSE matches reconstructions

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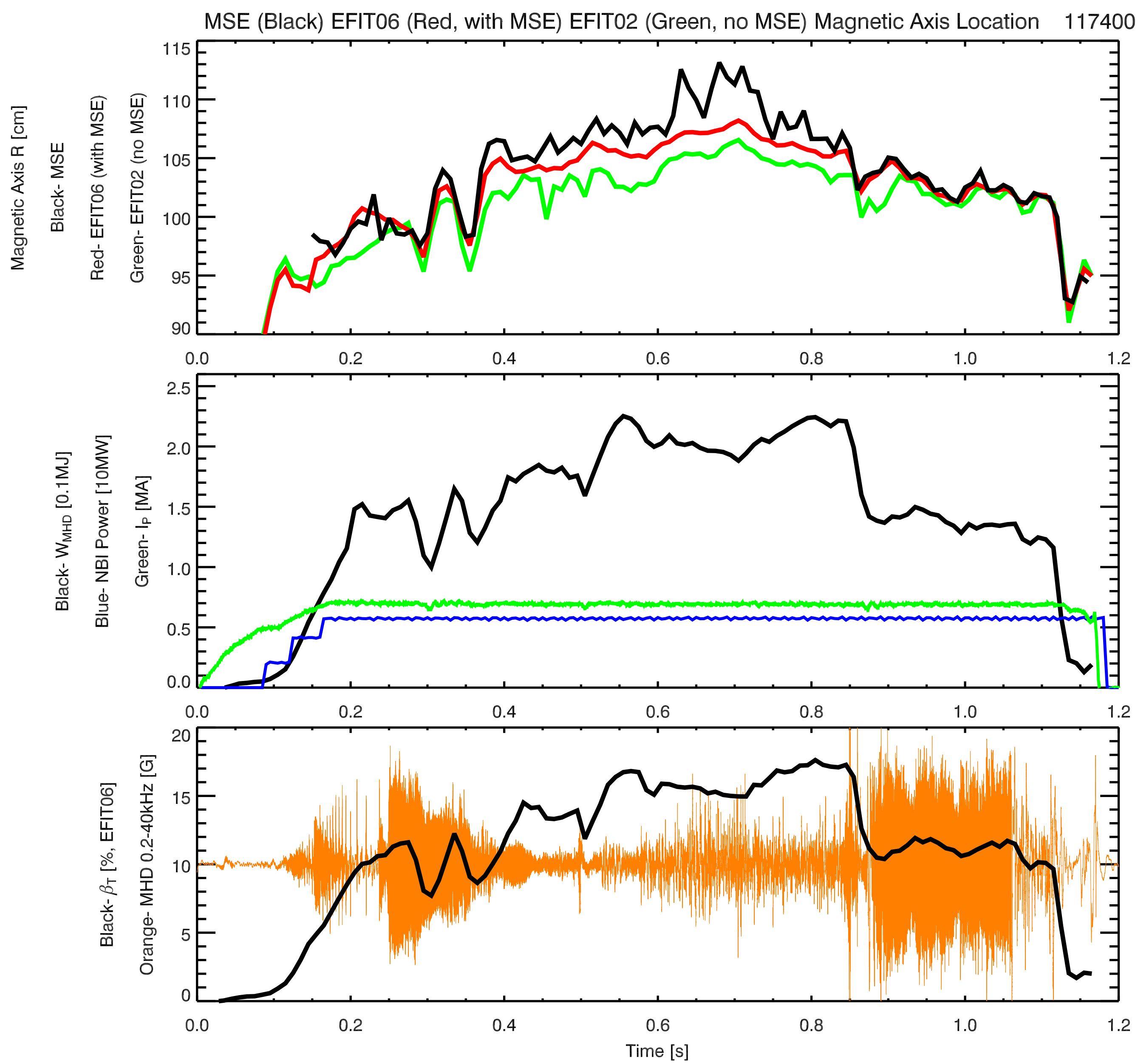
- The zero crossing of MSE pitch angles are mostly consistent with EFIT magnetic axis location, high β plasmas benefit from MSE constraints



NSTX reconstructions using MSE internal constraints

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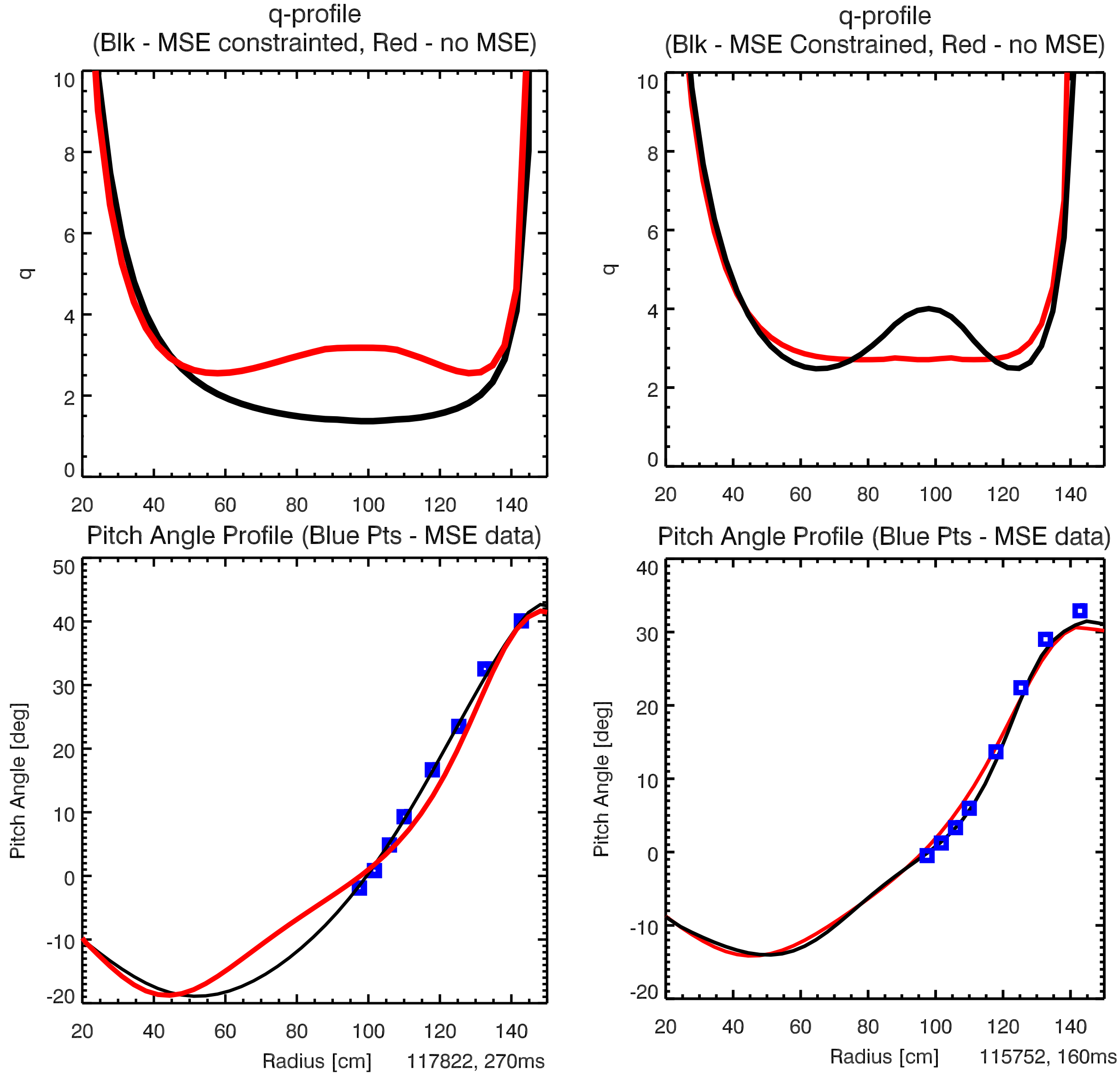
- MSE constrains internal pitch angles in magnetic reconstructions
- Constrained q-profiles to be corrected from monotonic to reversed-shear (and vice-versa)



MSE uses v_ϕ from CHERS for E_r Corrections…

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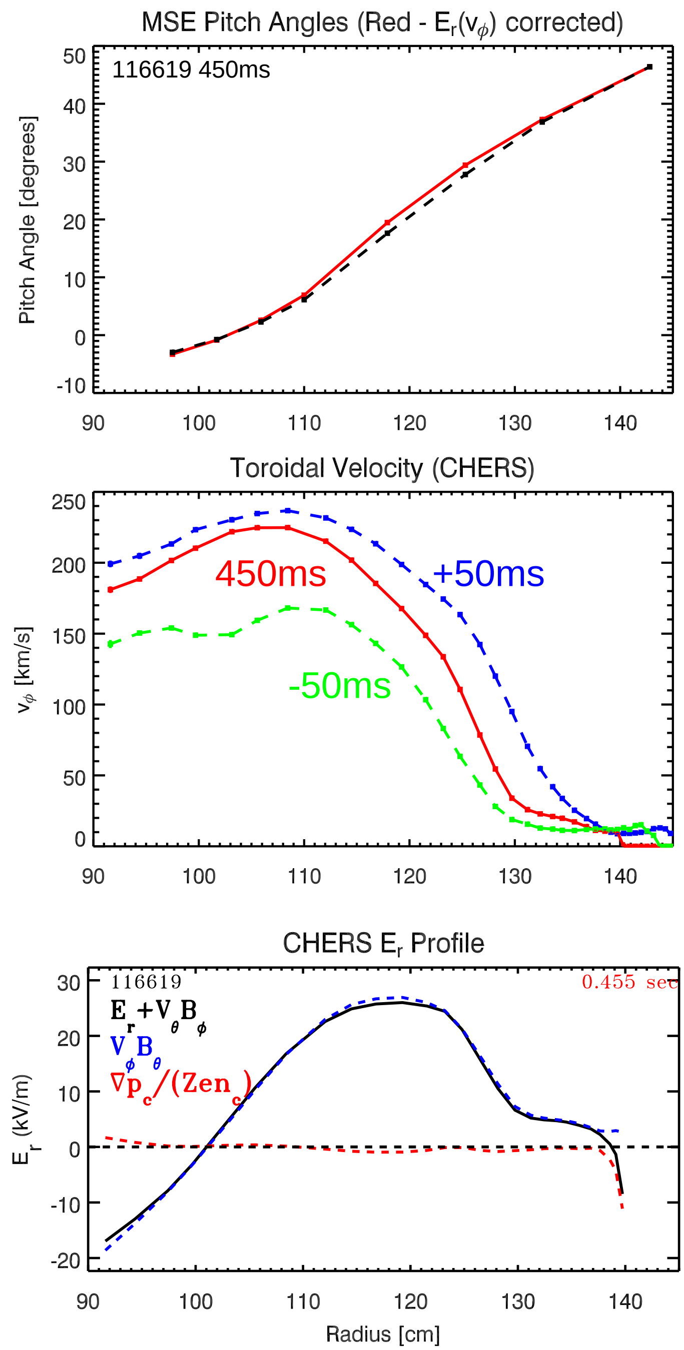
- E_r effects on MSE measurements can arise from v_ϕ, v_θ, ∇p
- Toroidal velocities can affect MSE by up to 10%, and is routinely corrected using v_ϕ CHERS data



but requires v_θ and ∇p for the edge channel in H-mode

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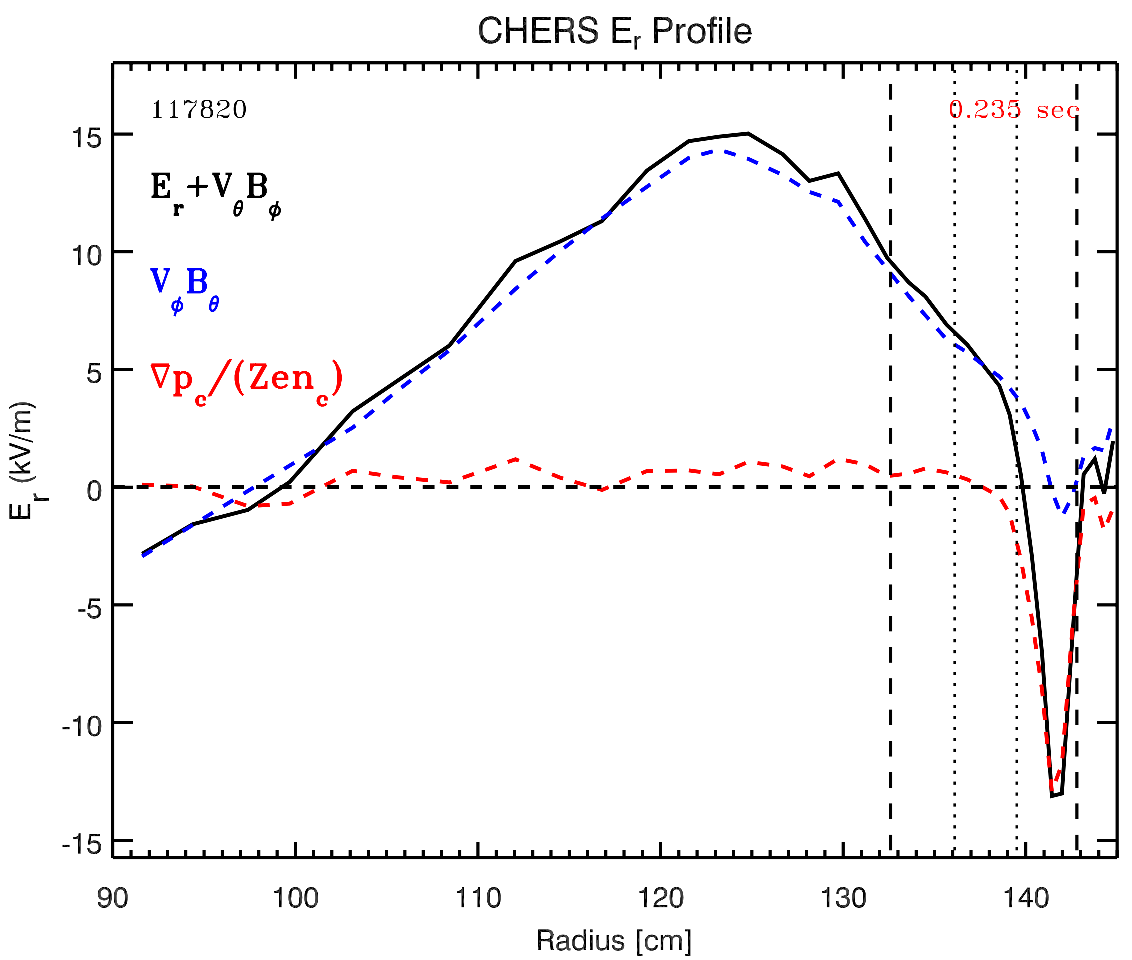
- Edge channel(s) can, in certain plasmas, be affected significantly by v_θ and ∇p, which are not presently used to correct the edge MSE channel
- Edge MSE channel(s) will be corrected using TRANSP Nclass calculations of v_θ or better yet with measured v_θ from the Edge Rotation Diagnostic (R>140cm)
- Estimates indicate approximately a up to 10% effect for the edge channel.



MSE Measurements during HHFW Current Drive

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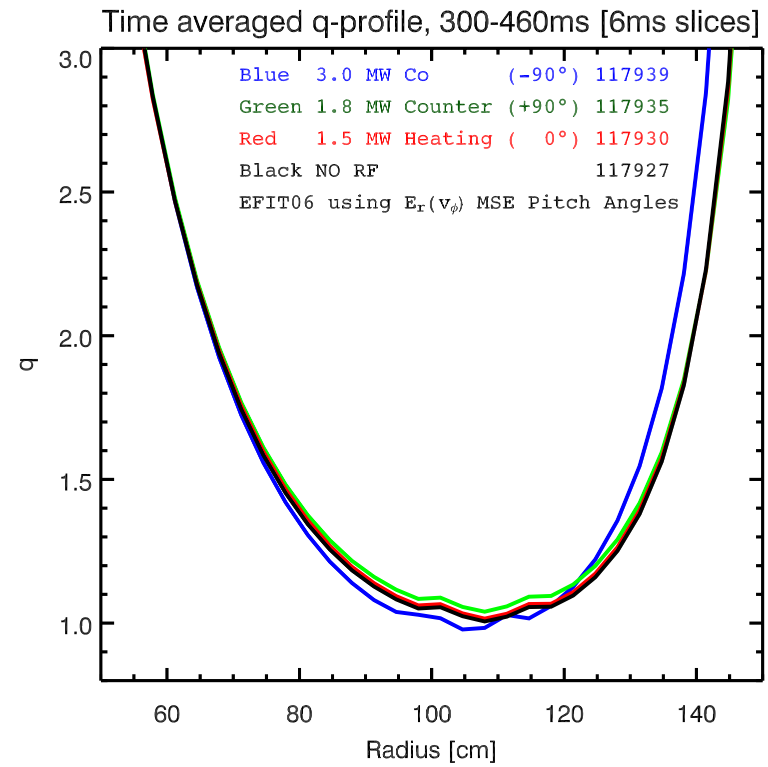
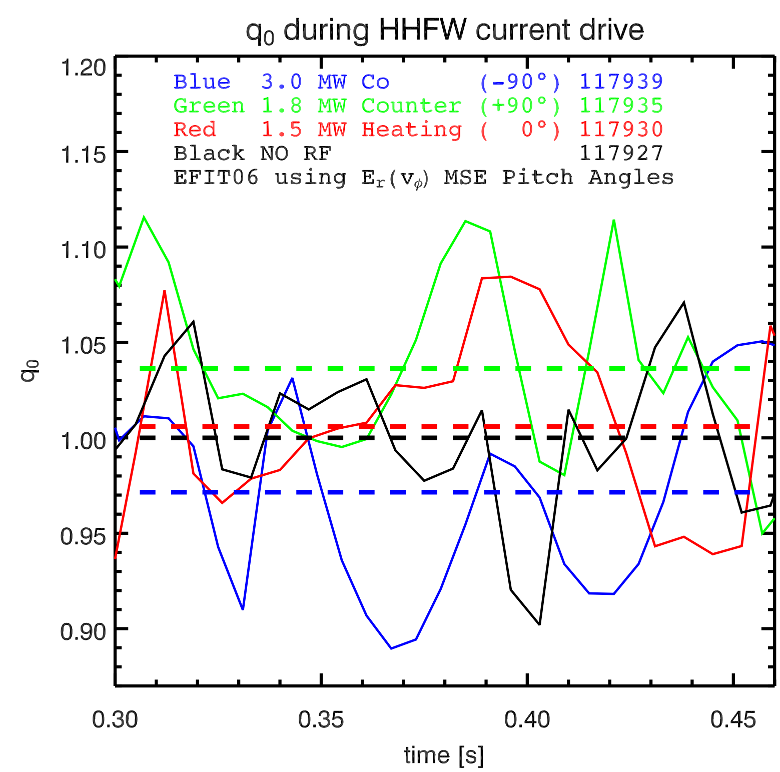
- High Harmonic Fast Wave current drive experiment were carried out using MSE

- MHD activity may have diminished current drive effect

- More shot development of current drive scenarios with NBI needed





Plasma with a Current Hole

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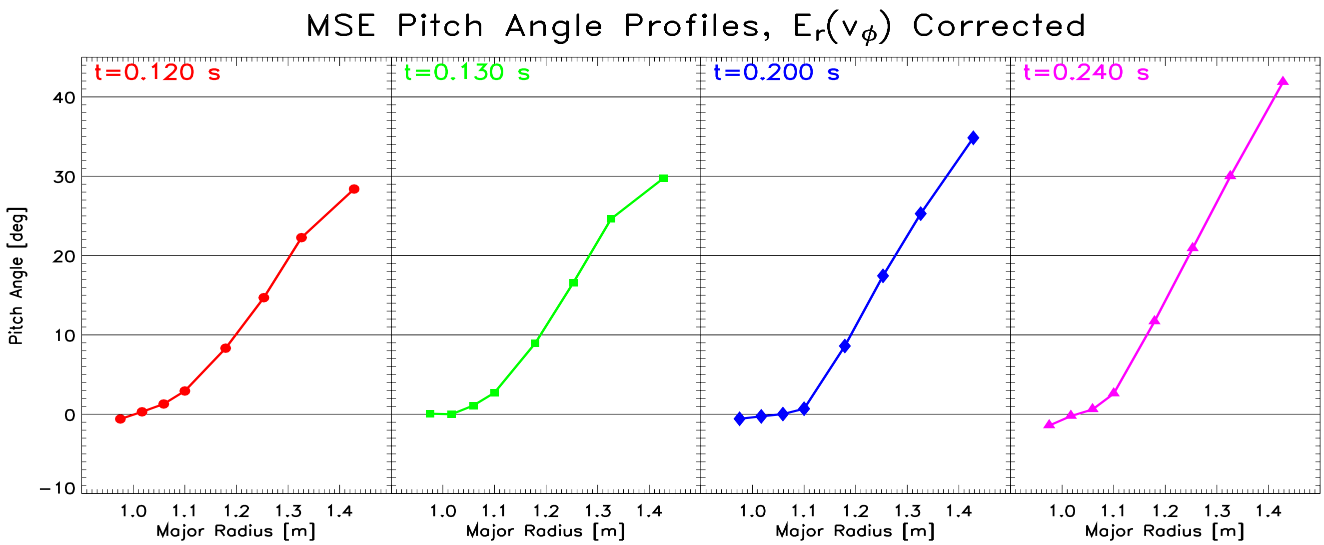
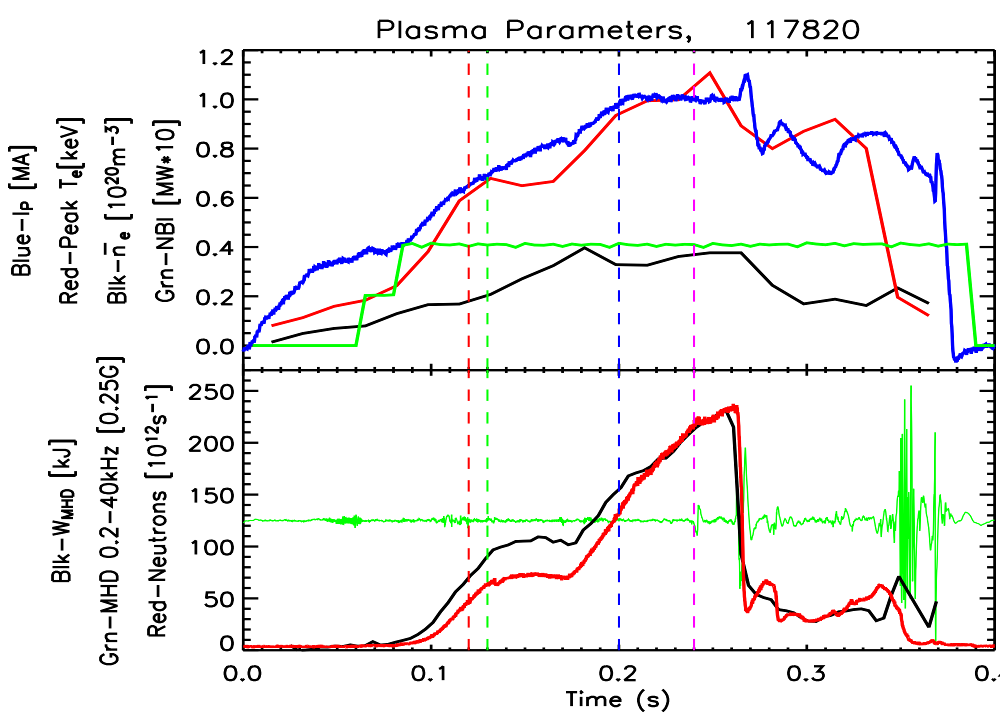
- Shot 117820 produced a high performance, steep edge gradient plasma with an interesting pedestal.
- During the early part of this plasma, MSE measured a "current hole" of substantial maximum size (>12cm), with a period of large q_0 lasting for >100ms.





Summary

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- MSE-CIF on NSTX uses novel sub-Å, high throughput, tunable, birefringent interference filters necessitated by low field.
- MSE had 8 (of possible 19) channels calibrated and routinely operating for the NSTX 2005 run campaign.
- Beam-into-gas calibrations shows predictable and consistent behavior, allowing for significant data reduction.
- Magnetic reconstructions and MSE show decent agreement for typical, monotonic q-profile plasmas. Work is ongoing to improve agreement for reversed-shear and/or high β plasmas
- E_r corrections presently only include the v_ϕ term, edge MSE channel(s) requires the inclusion of v_θ and ∇p terms