

LHCD current profile measurements and reactor-relevant MSE techniques on Alcator C-Mod.

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MIT-PSFC Alcator C-Mod

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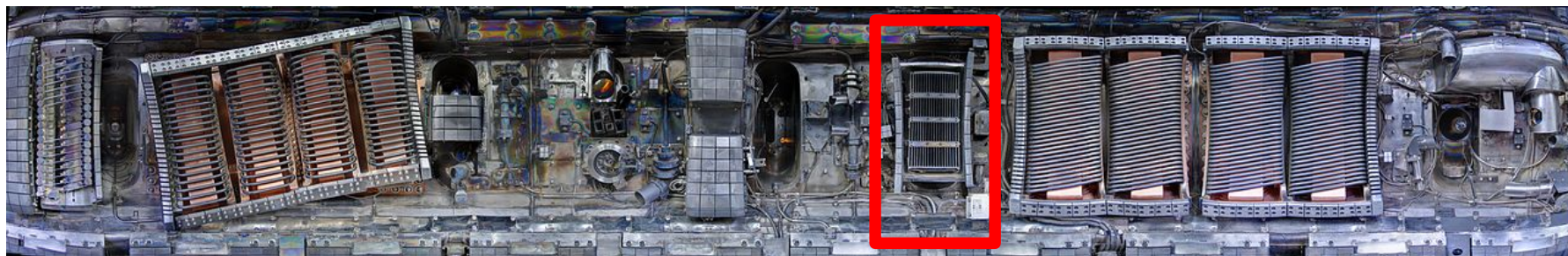
Outline of talk

- Recent results with LHCD on C-Mod enabled by MSE
- Challenges for MSE in next-step devices
 - And in C-Mod for similar reasons
- MSE polarized background subtraction
- C-Mod's experience with MSE in-situ calibration
- Conclusions

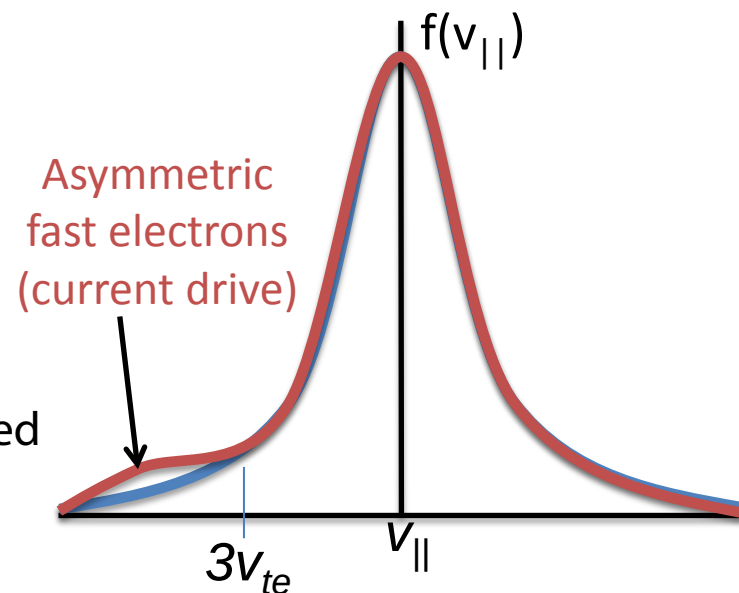
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LHCD on Alcator C-Mod: Uniquely at ITER density, frequency and field.



- $B_T = 3-8T$ (ITER: 5T)
- $n_e = 0.5-5 \times 10^{20} \text{m}^{-3}$ (ITER: $0.5-1 \times 10^{20} \text{m}^{-3}$)
- 4.6 GHz (ITER: 5 GHz) $P_{\text{source}} = 2.5 \text{MW}$
 - Variable phasing: $n_{||} = 1.5-3$ (ITER ~ 2)
- 16 column launcher couples $\sim 1 \text{MW}$
- Up to 1s long pulse ($\sim 5 \times \tau_R$)
- Completely **non-inductive** current drive demonstrated
- Creation of **Reversed-shear** profiles ($q_0 \sim 2$) with transport barriers



A tool to study current drive physics, benchmark LHCD codes and produce targets for transport and MHD studies

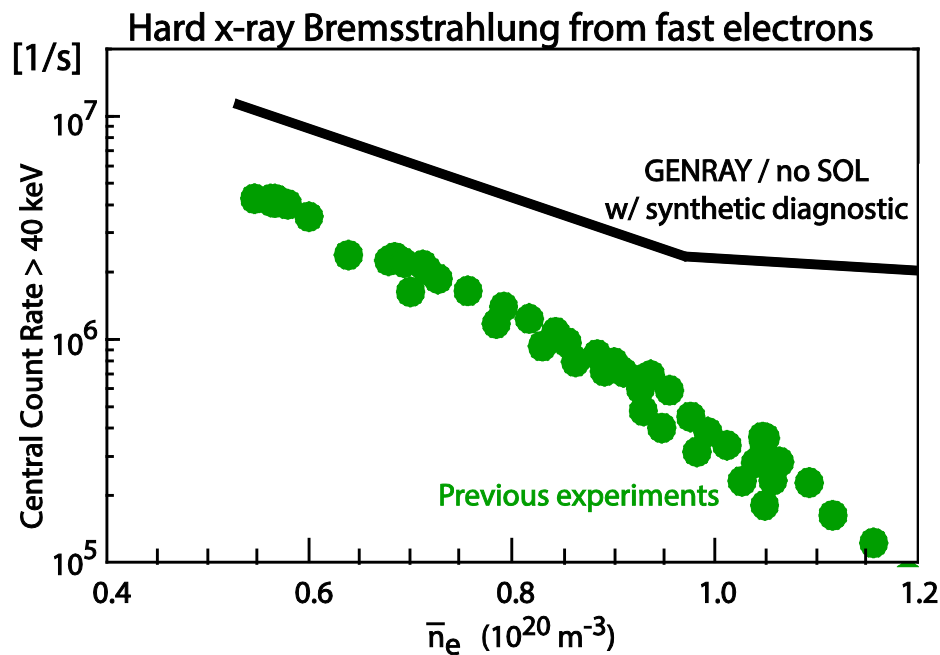
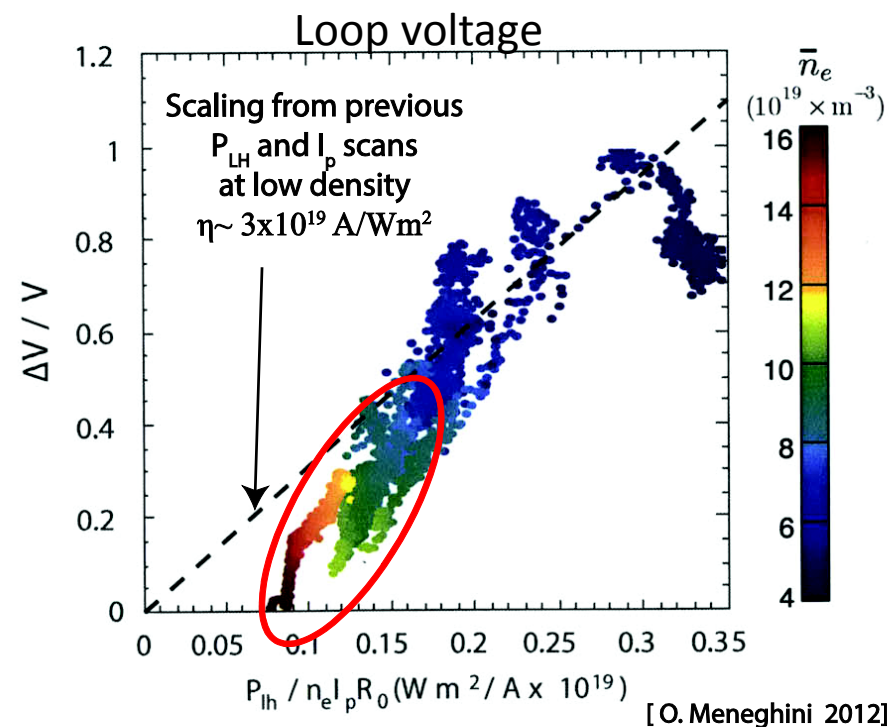
0-D measurements show a decrease in current drive efficiency at increased density.

- LHCD efficiency:

$$\eta \equiv n_e I_{\text{LH}} R_0 / P_{\text{LH}} = 2.0 - 3.0 \times 10^{19} \text{ A/Wm}^2 \text{ confirmed at low density } (< 0.5 \times 10^{20} \text{ m}^{-3})$$

[P.T. Bonoli, POP 2007]

- However, anomalous large drop in efficiency as density is raised $\bar{n}_e \sim 0.7 \times 10^{20} \text{ m}^{-3}$
 - Smaller change in loop voltage than expected, loss of Hard X-ray emission
 - Has since been observed in other experiments

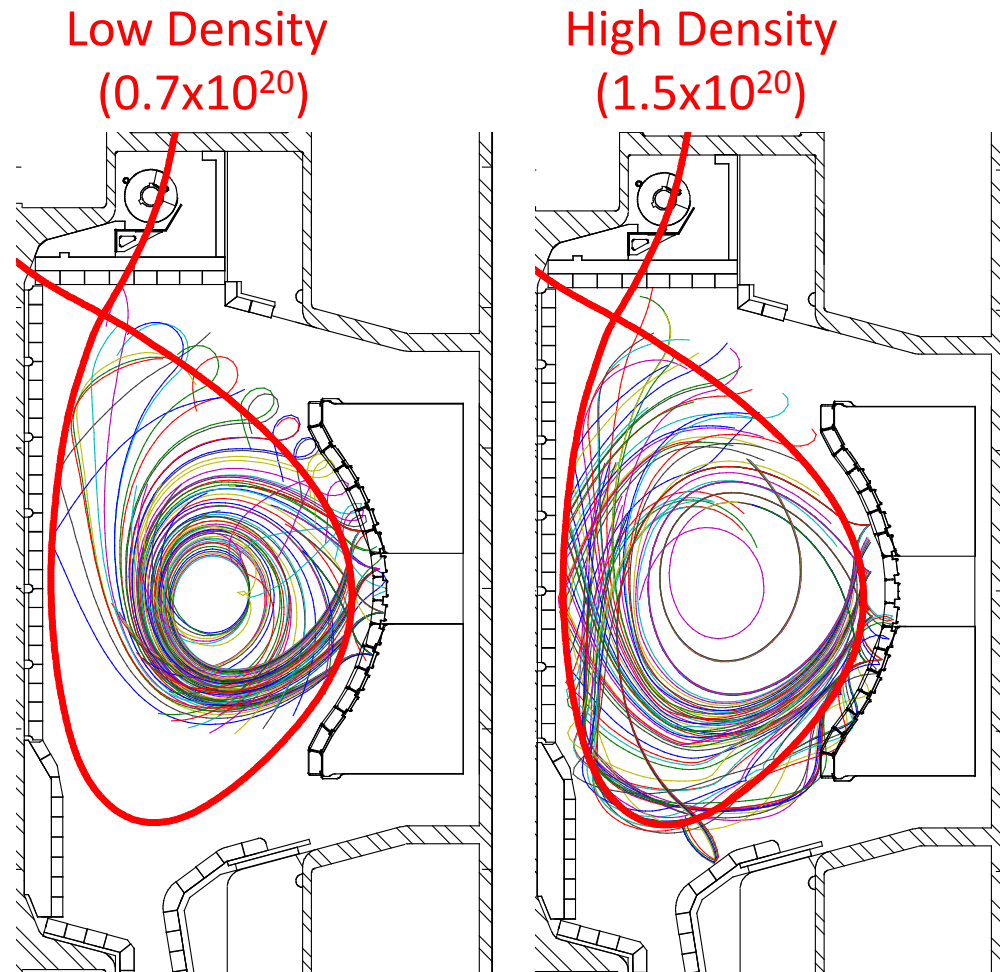


Various explanations put forward for this loss, still an unresolved question.

- Ray tracing simulations show the LH wave makes multiple passes through plasma at high density
 - Spends more time in edge region
- Possible things that could go wrong:
 - Parametric decay instability
 - Collisional absorption in SOL
 - Full-wave effects (interference, diffraction)
- Simulation results with collisional absorption and full-wave effects match 0-D hard X-ray counts

What about 1-D profiles?

- Use MSE

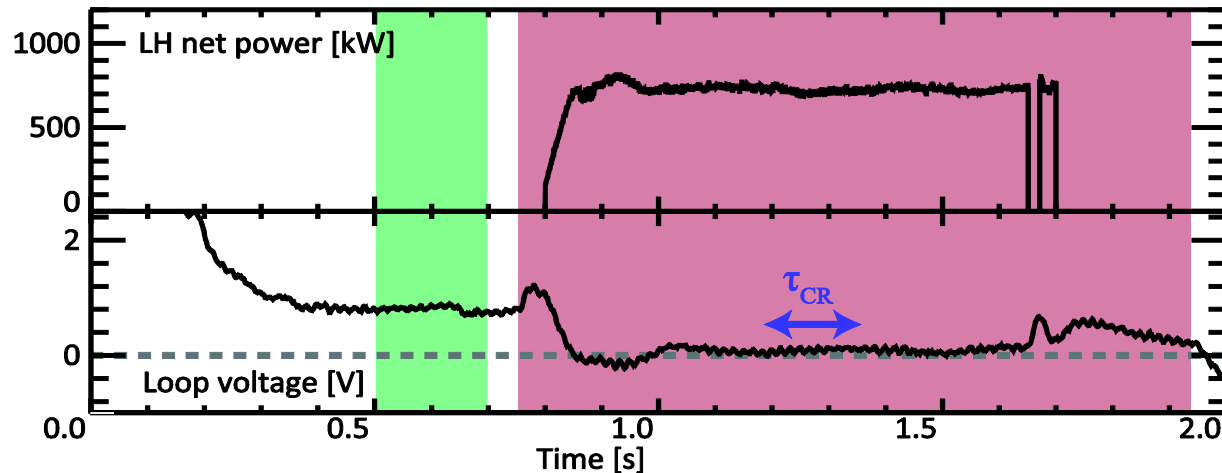


GENRAY/CQL3D simulations with SOL

[G. Wallace NF 2010]

A caveat: Using MSE in this study was difficult for two important reasons.

- 1) MSE polarization angle response drifts on the several minute time scale
 - Extensive tests show no drift within a shot
 - Calibration technique using reconstructions from a reference Ohmic portion of shot
 - Requires nearly the same target discharge and dedicated portions of the discharge

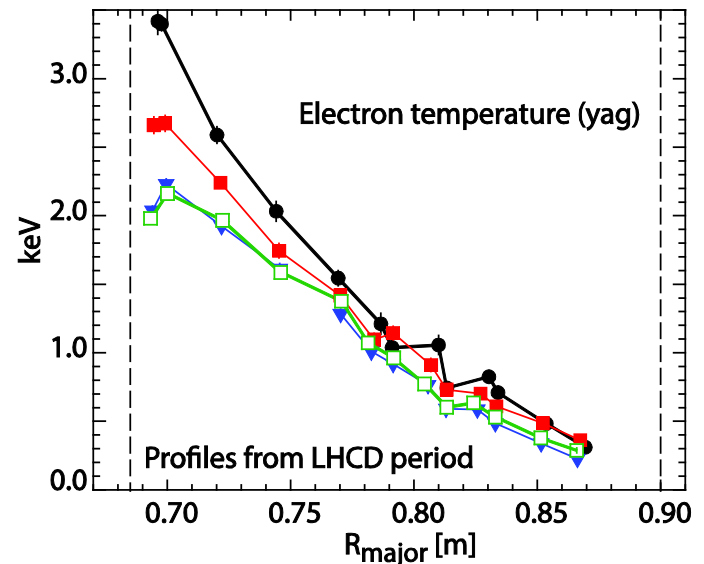
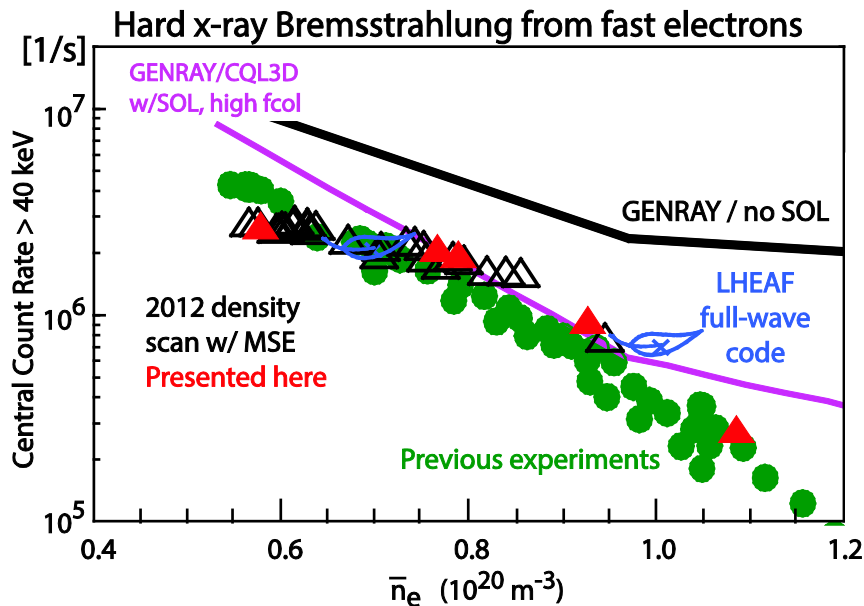
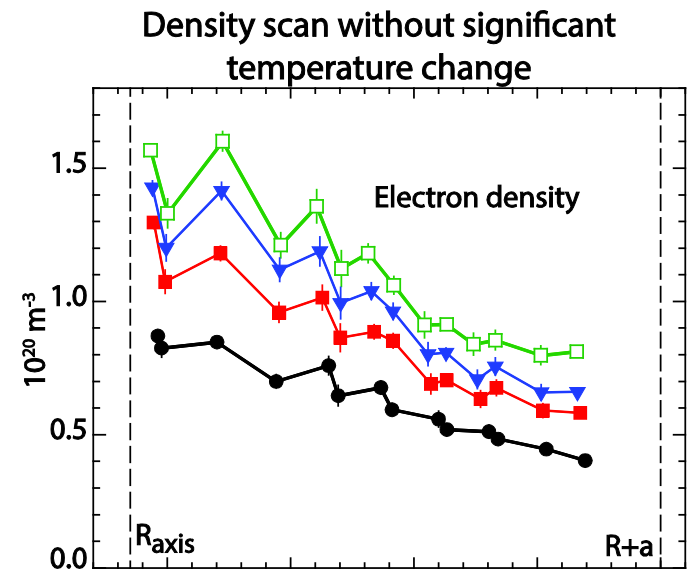
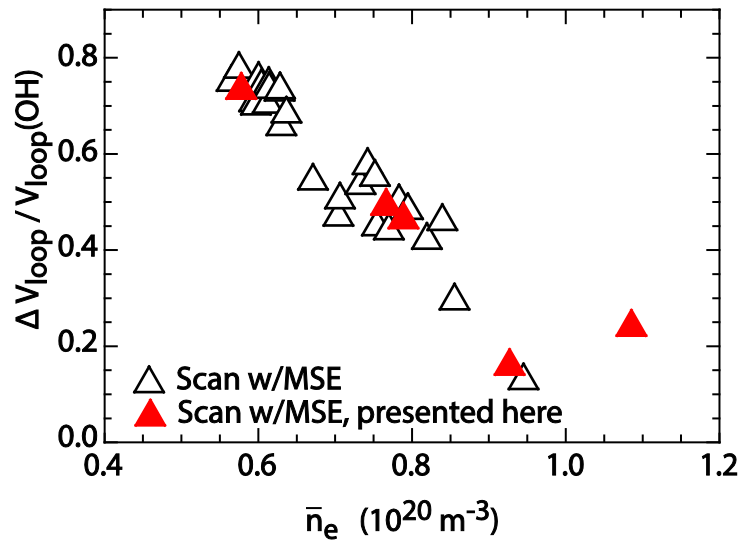


Use KEFIT during Ohmic portion to calibrate MSE

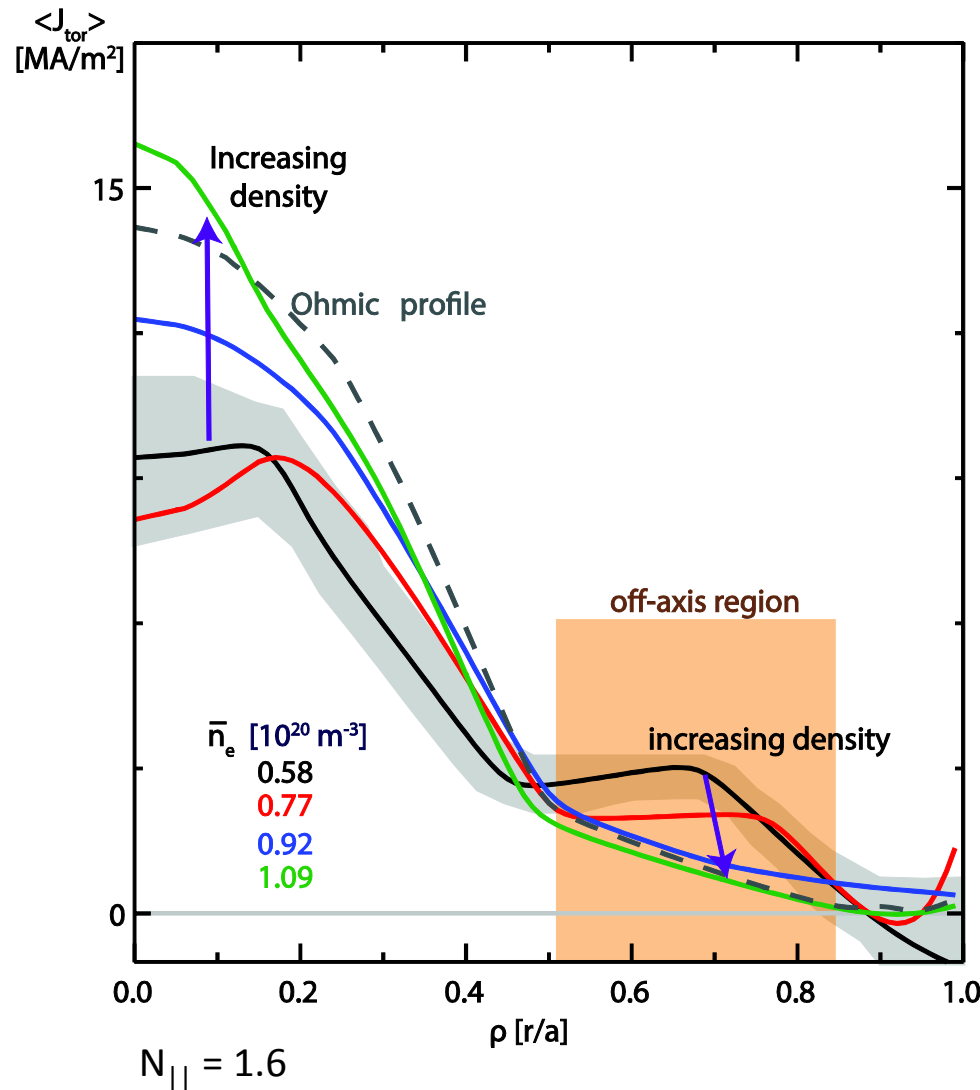
Apply calibration to measure changes in current profile

- 2) Large polarized background limits study to relative low density, quiescent plasmas.

Dedicated experiment to document LH current profiles as a function of density for the first time.

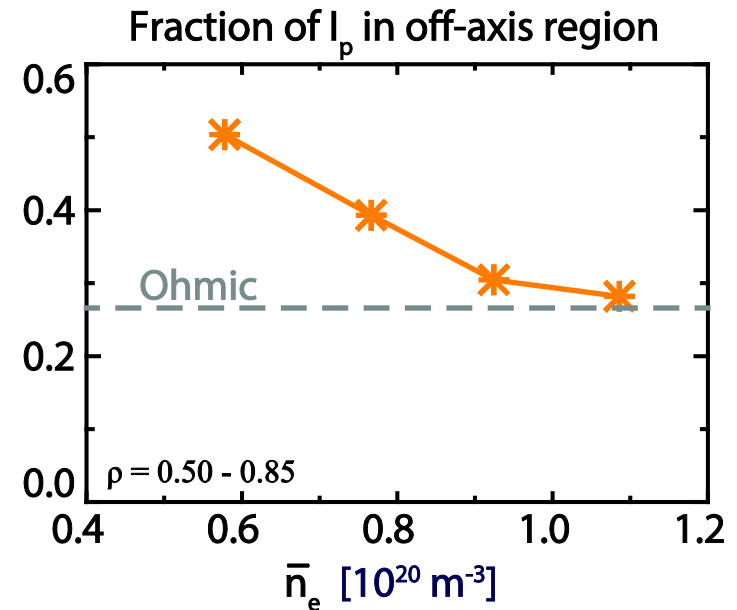


MSE measurements of current profile show off axis current drive disappears as density is raised.

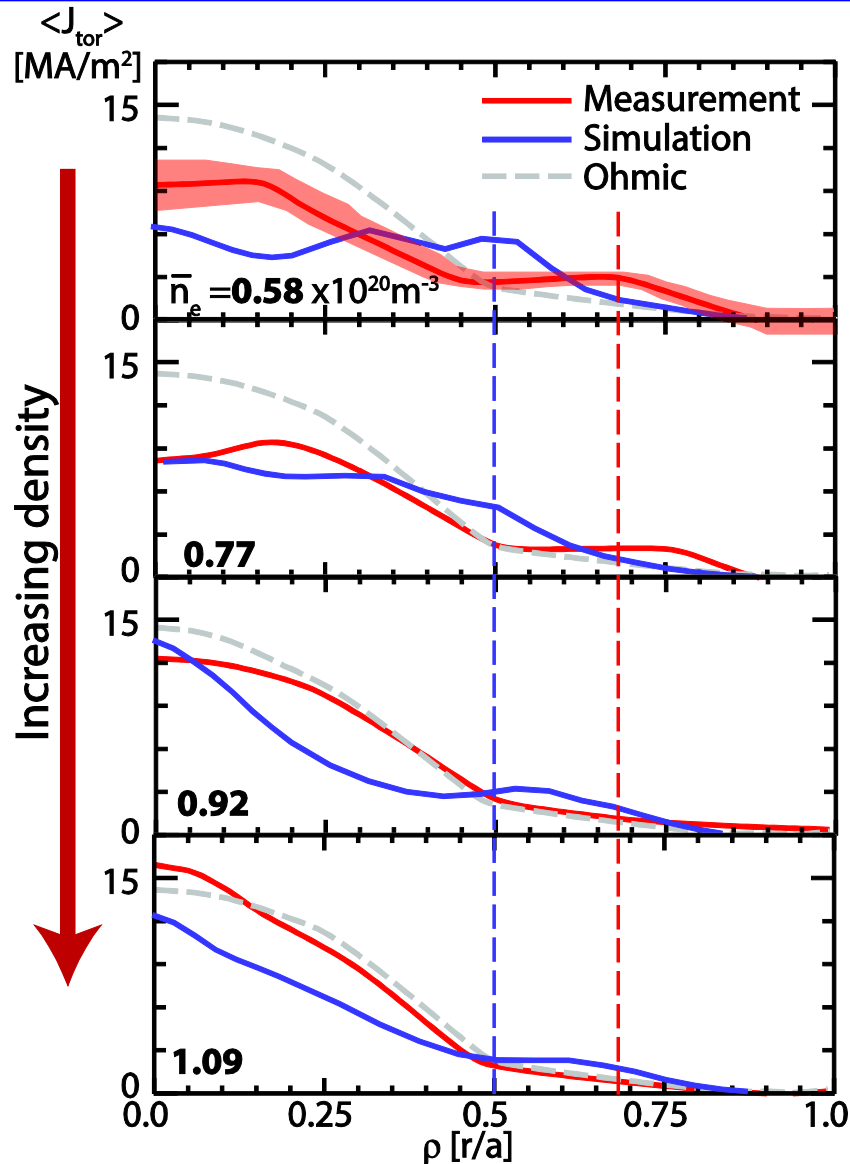


Increasing density:

- Loss of off-axis current drive around $\rho=0.7$
- Moves outward
- More current on-axis (Ohmic)



Measurements show qualitatively disagreement with GENRAY/CQL3D with SOL absorption.



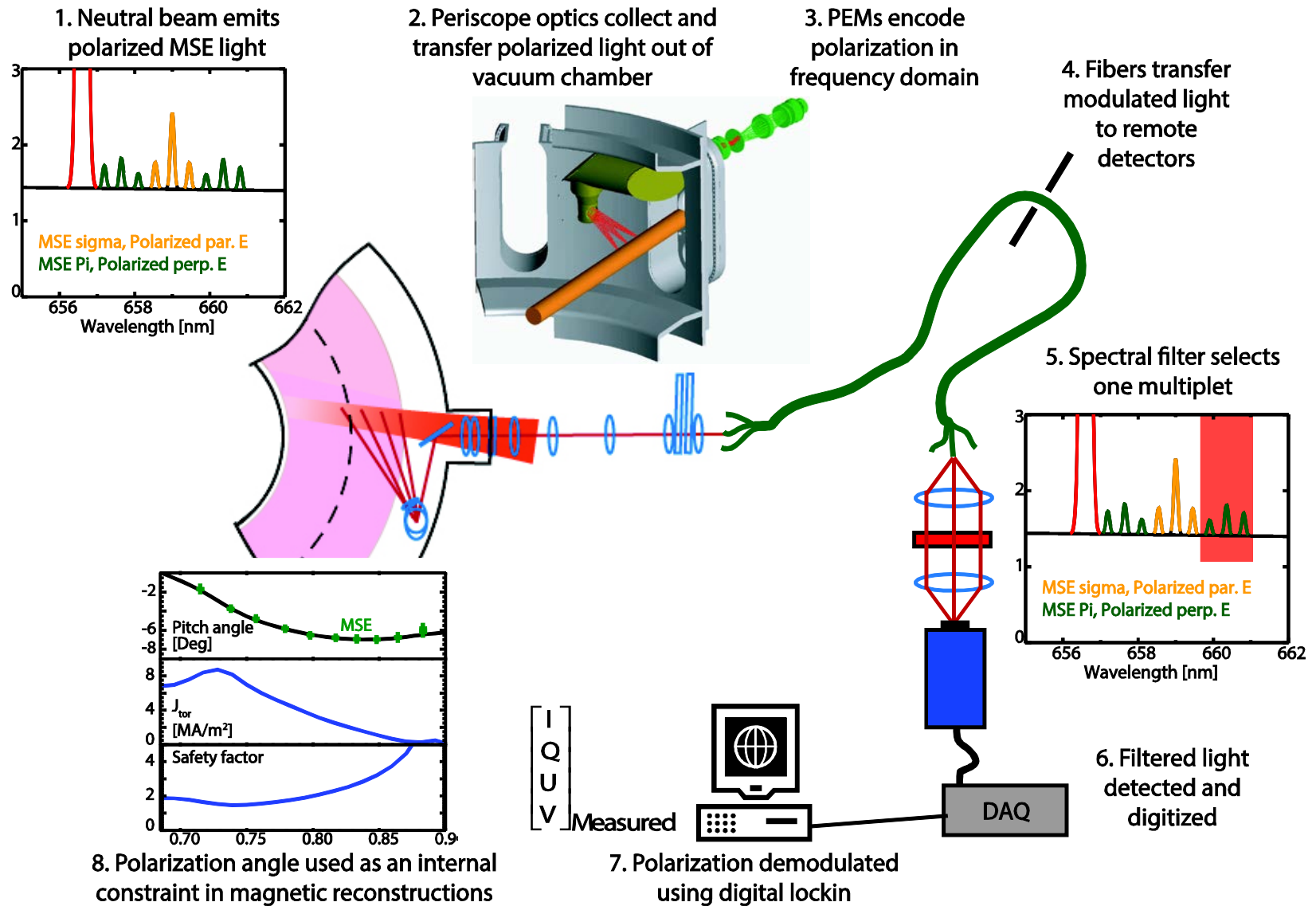
Discharges simulated with GENRAY/CQL3D with collisional absorption in SOL:

- At low density the simulations indicate current drive at $\rho=0.5$
 - Measurements show it further out.
 - Simulations under predict the central current density
- As the density is increased both simulations and measurements show the current moves outward
 - Simulation drastically over predicts the amount of off-axis current
- At high density the simulations still show off axis current drive
 - Measurements show nearly Ohmic profile

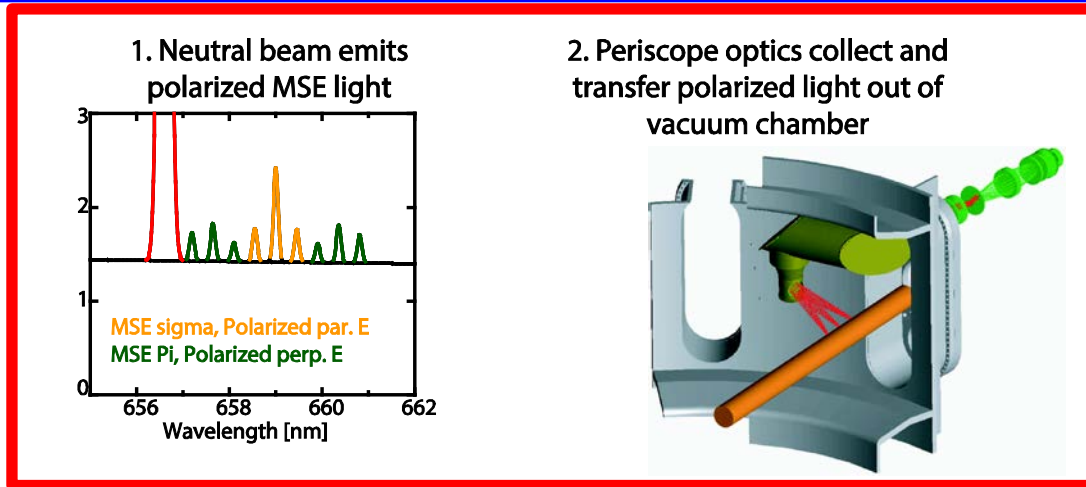
Outline of talk

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 - And in C-Mod for similar reasons
- MSE polarized background subtraction
 - Everything is polarized!
- C-Mod's experience with MSE in-situ calibration
- Conclusions

A reminder of how a MSE-LP system works.



MSE-LP planned for control on next-step devices but there are challenges.



Next step devices will:

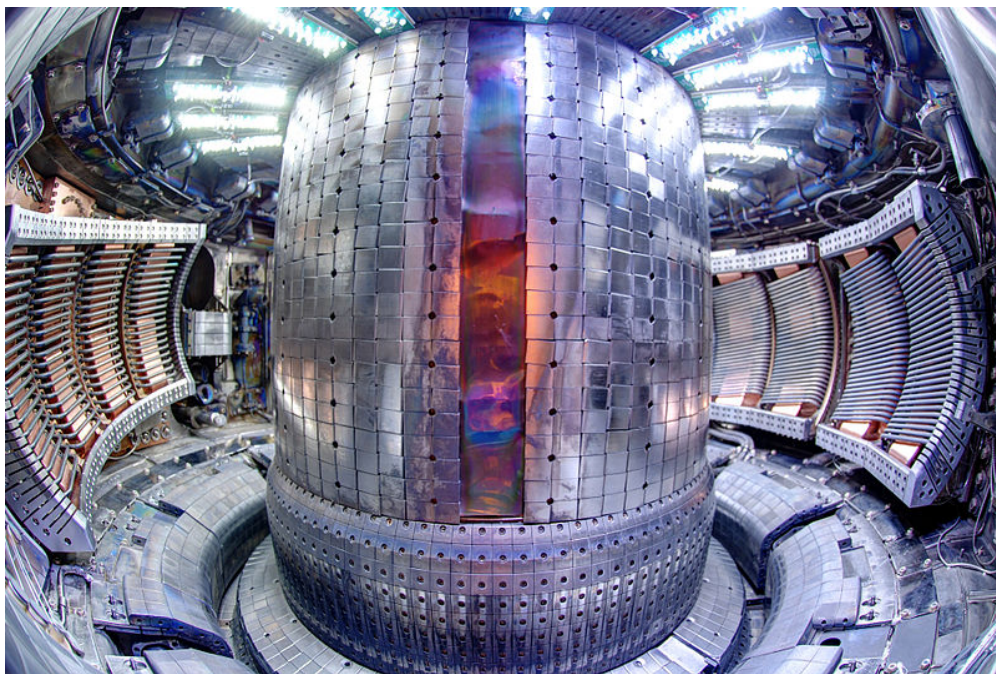
- Have harsher measurement conditions
- Have less diagnostic access
- Have a lower appetite for risk
- Require better diagnostic data
- Demand high diagnostic availability

Two big problems are foreseen for next-step MSE-LP systems

1. The beam is no longer the brightest thing in the view
 - Poor beam penetration with long sightlines through dense plasma
 - Many of other sources of light
2. The polarization preserving periscope is complicated
 - Its polarization properties will change over time due to erosion and deposition on the first mirror
 - Won't be able to calibrate using plasmas and beam-into gas as regularly as we'd like, if at all

C-Mod has tackled versions of these two problems out of necessity

C-Mod MSE: weak beam, high density, no view dump, complicated optics, in a harsh environment.

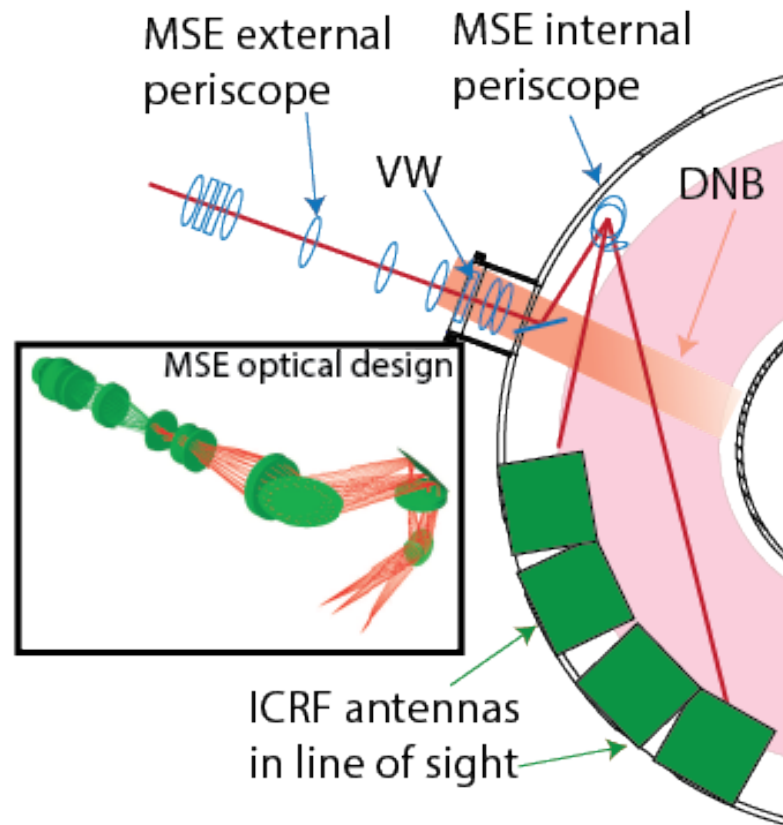


Alcator C-Mod:

Shiny metal PFCs, high power densities

High field: 200g's during disruptions

Cryogenic magnets: Large thermal swings ($>40^{\circ}\text{C}/\text{min}$) and large thermal gradients



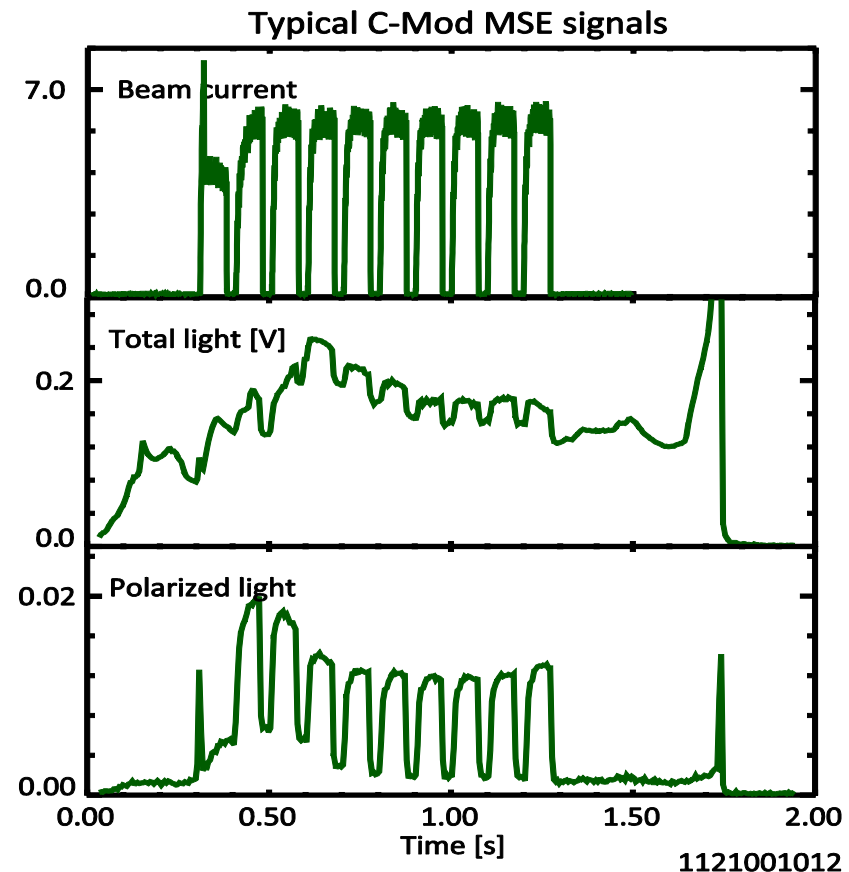
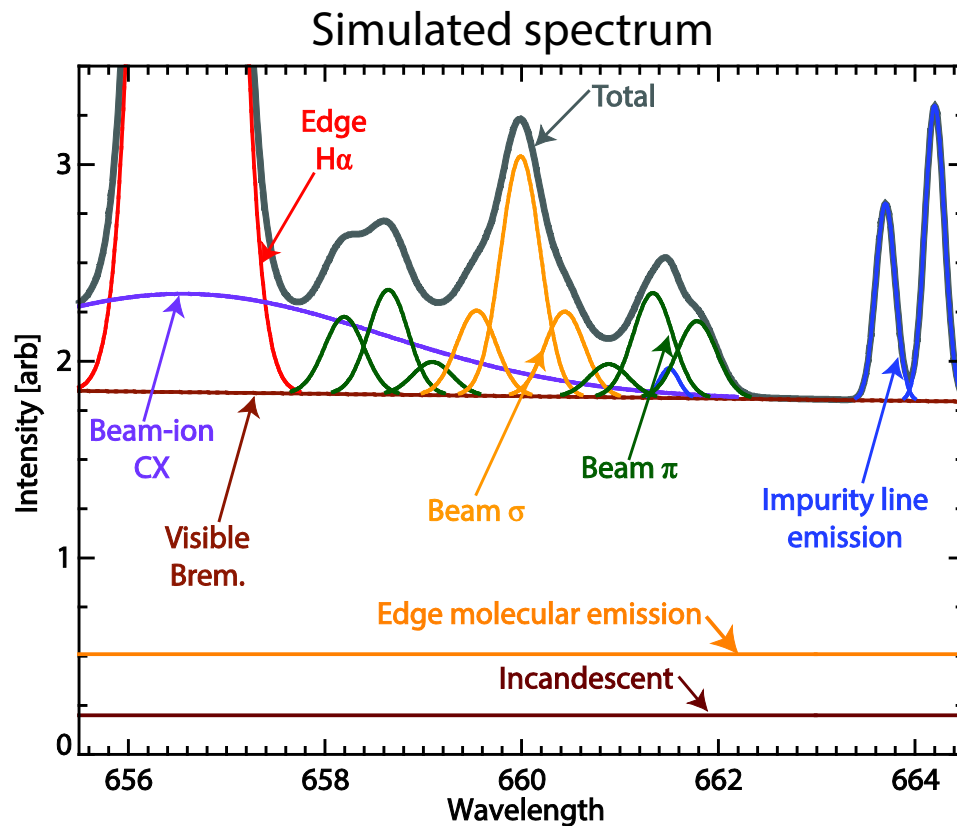
Complicated optics, ICRF view dump

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Weak beam and strong background leads to poor polarized signal/background ratios.

- MSE beam signal is typically same order (or less) than the total plasma emission
 - MSE system observes a weak diagnostic neutral beam
 - C-Mod's high density ($\bar{n}_e$ up to $2 \times 10^{20} \text{ m}^{-3}$) plasmas are very bright
- System collects substantial polarized background light



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Polarized background is a dominate cause of polarization angle uncertainty on C-Mod.

- Not limited by photon statistics
- Similar issues on JET, Tore Supra, JT-60U

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{Beam} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{Measured} - \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{Background}$$

Need to estimate, typically use time-interpolation across beam blips.

$$\tan(2\theta_{Beam}) = \frac{U_{Measured} - U_{Background}}{Q_{Measured} - Q_{Background}}$$

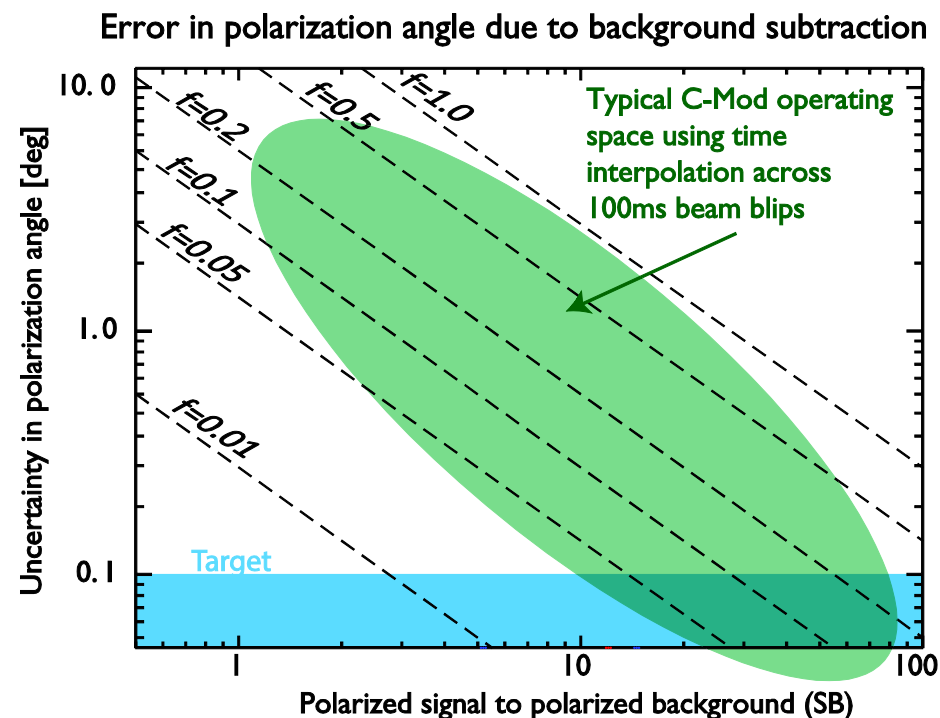
How well you can
Subtract the background:

$$f = \left| \frac{\sqrt{Q^2 + U^2}_{actual} - \sqrt{Q^2 + U^2}_{estimated}}{\sqrt{Q^2 + U^2}_{actual}} \right|$$

- Have only modest control over polarized signal to background (SB)

Need a better estimate of the background Stokes vector than beam blip interpolation

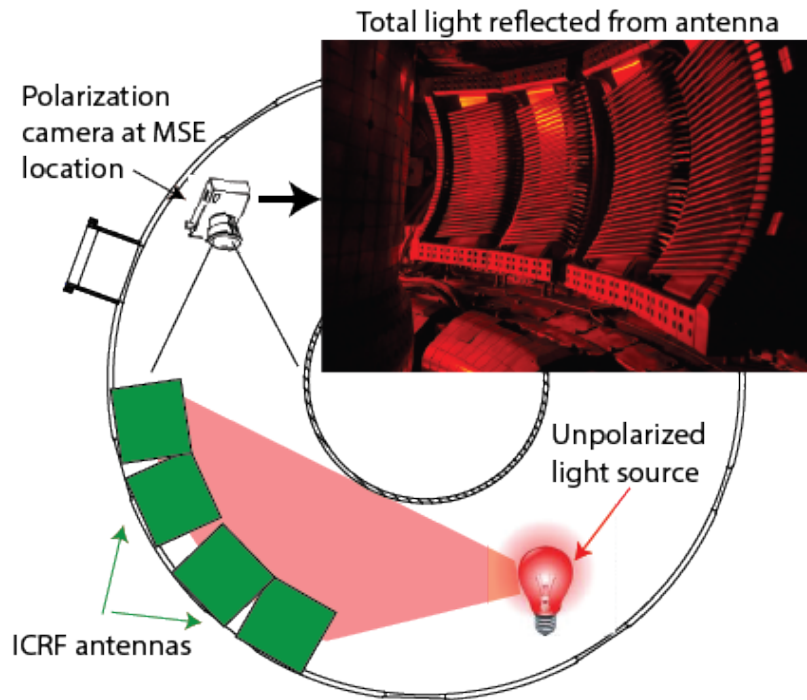
→ Undertake a comprehensive study of polarized light in the tokamak



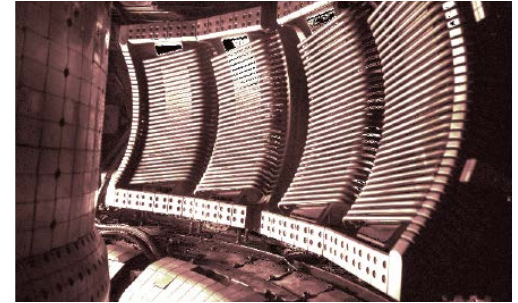
DIII-D, TFTR,
NSTX, MAST
→

Light is substantially polarized upon reflection from 'view dump'

- Developed a polarization sensitive camera to image light reflected from ICRF antenna :
 - Reflected light is complexly and highly polarized
 - Polarization angle depends on location of source
- Any light in the tokamak can be reflected into the MSE sightline, becoming partially polarized



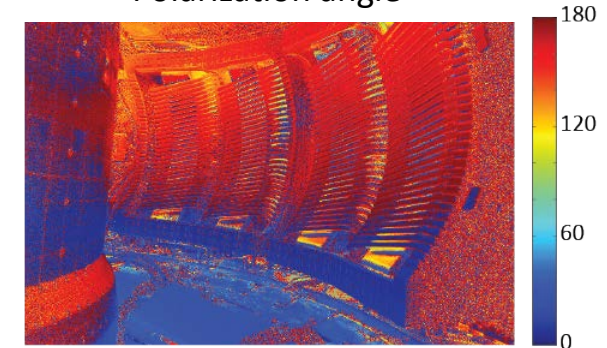
Linearly polarized reflected light



Polarization fraction



Polarization angle

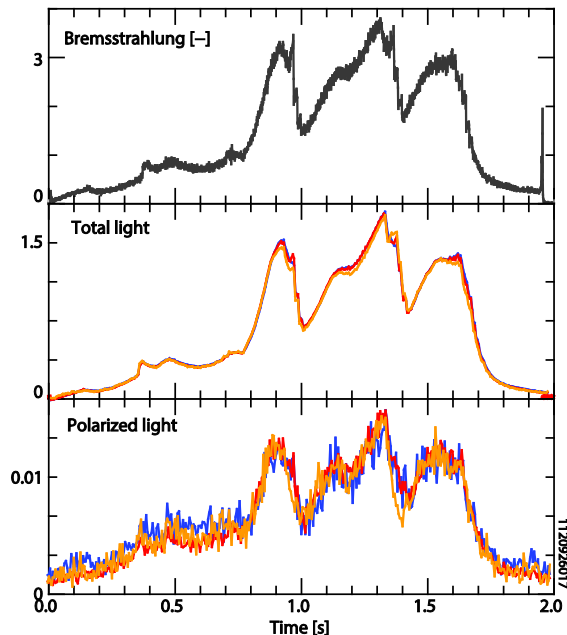


Three primary sources of background light identified.

And they likely get worse on next step devices.

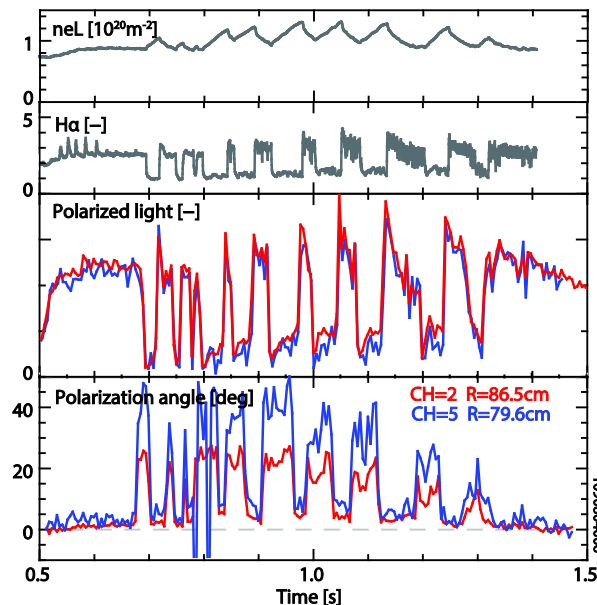
Visible Bremsstrahlung

- Dominates total light
- Seen on first pass and reflection: <5% PF
- Doesn't vary much sightline-sightline
- **Broadband**



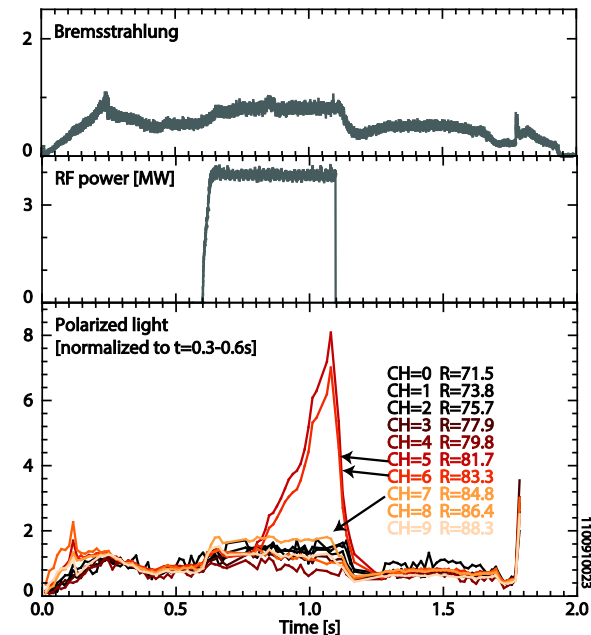
Divertor/edge emission

- Seen mostly upon reflection: <30% PF
- **Changes very quickly**
- Seen in all sightlines
- Polarization angle depends on active divertor
- **Quasi-broadband**



Glowing structures

- Seen only upon reflection: <50% PF
- **Highly sightline dependent**
- Can become dominate source of polarized background
- **Broadband**



The character of polarized background light severely limits strategies for estimating it.

- Composed of multiple independent background sources changing on fast time scales
 - Need real-time measurement
- Need to estimate the background polarization to high accuracy ($\sim 1-5\%$)
 - Use same PEM technique as the MSE measurement
- Spatially complex polarized background
 - Need to measure on the same sightline as MSE
- Few options for increasing polarized signal to polarized background
 - Sources uncontrollable. Beam power fixed. Larger etendue doesn't help.
 - No room for dedicated view dump on C-Mod.
 - Most viable PFCs in future devices won't make good view dumps.
- Ab-initio calculation using ray tracing techniques unlikely to get polarization properties of reflected light accurate enough for compensation

A solution: Measure the polarization at adjacent wavelengths in real time on the same sightline, then wavelength interpolate.

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{\text{Beam}} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{\text{Measured}} - \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{\text{Estimated background}}$$

$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{\text{red of MSE}}$
use wavelength interpolation
 $\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{\text{blue of MSE}}$

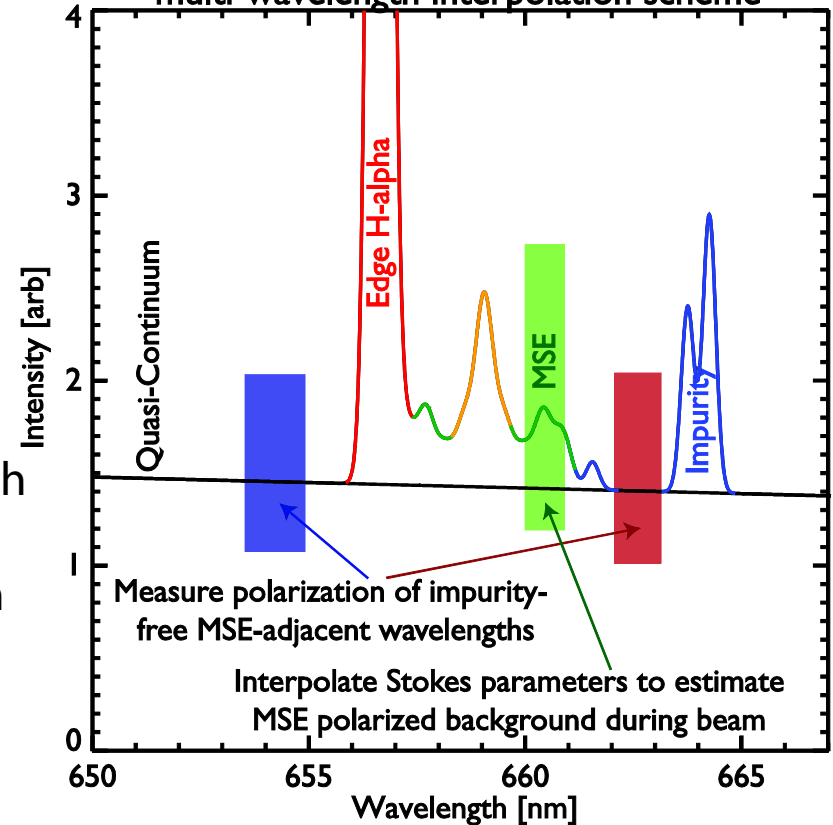
Valid if:

- Sources are quasi-continuum over wavelength range of interpolation
- Polarization mechanism is weakly wavelength dependent

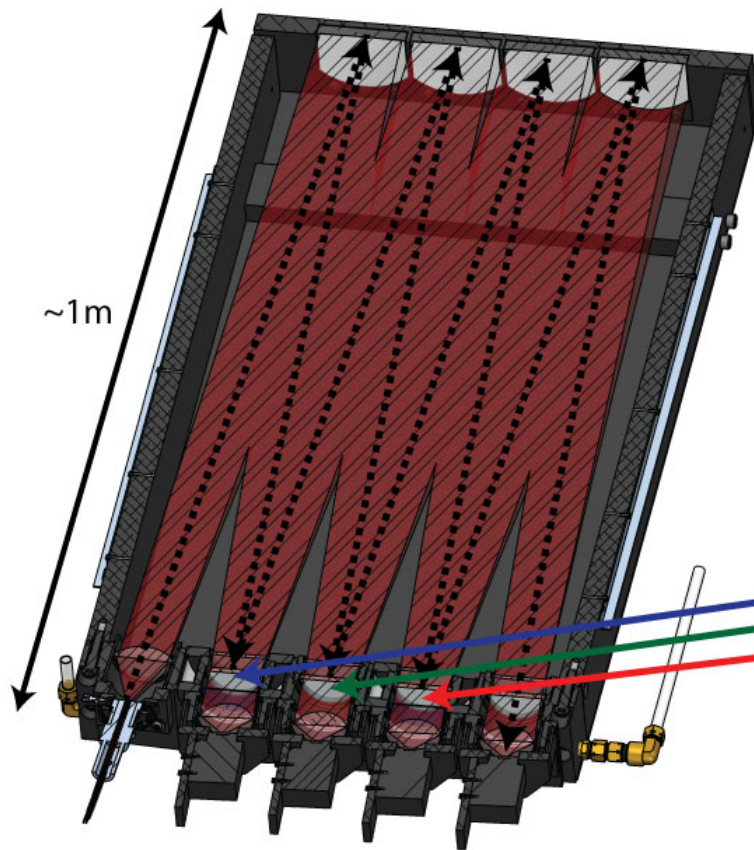
Advantages:

- Requires infrequent beam modulation
- Can provide real-time background estimate
- Requires no changes to the MSE upstream optics.

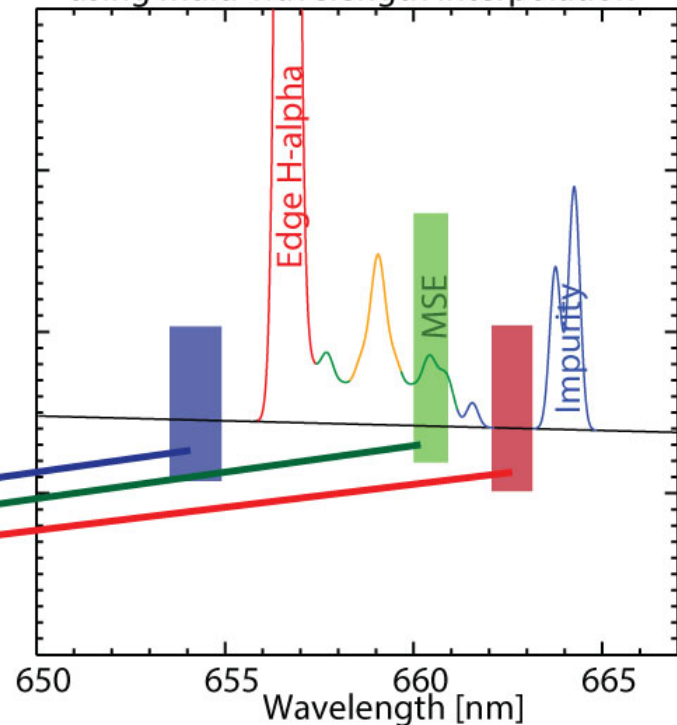
Real-time MSE polarized background subtraction using multi-wavelength interpolation scheme



Use an interference filter based polychromator with APDs to measure the polarization at several wavelengths.



Real-time MSE polarized background subtraction using multi-wavelength interpolation

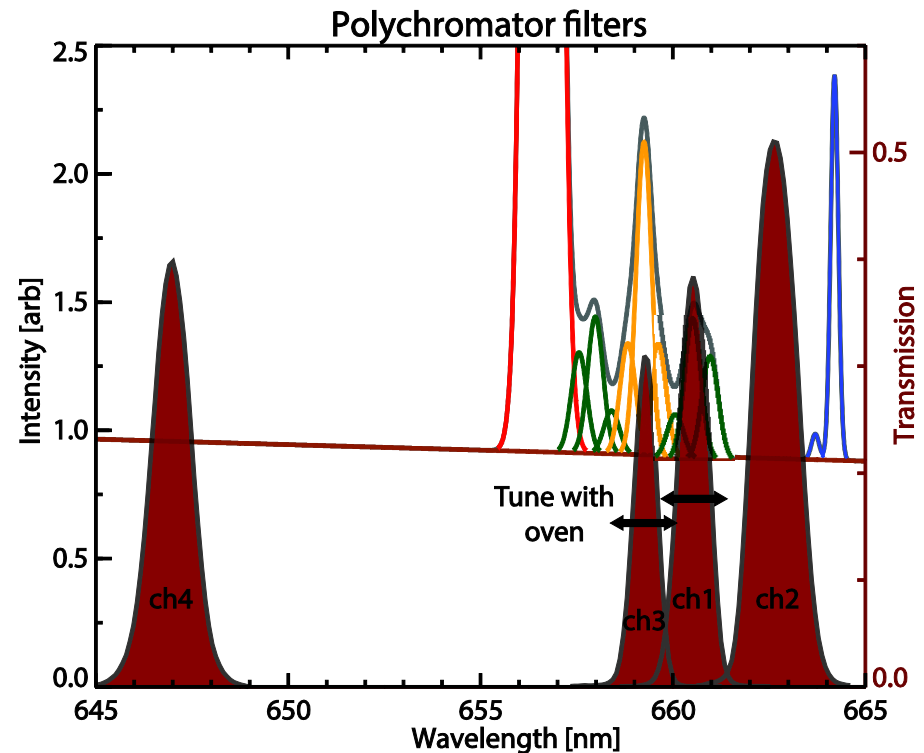


Challenges for a MSE polychromator:

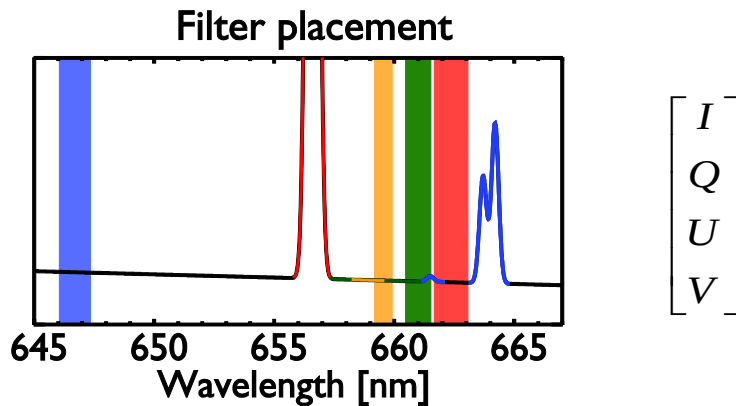
- Close spectral spacing of narrow bandpass filters requires small AOI
- Tune the filter bandpasses shot-shot
- Accommodate a large etendue

Single sightline system constructed and tested last campaign on C-Mod.

- 4 wavelength channels
- High etendue ($9\text{mm}^2\text{sr}$) and transmission (86%-70%)
- Acceptable filter performance with 3deg tilt
- Easy to manufacture and align
- Machine independent

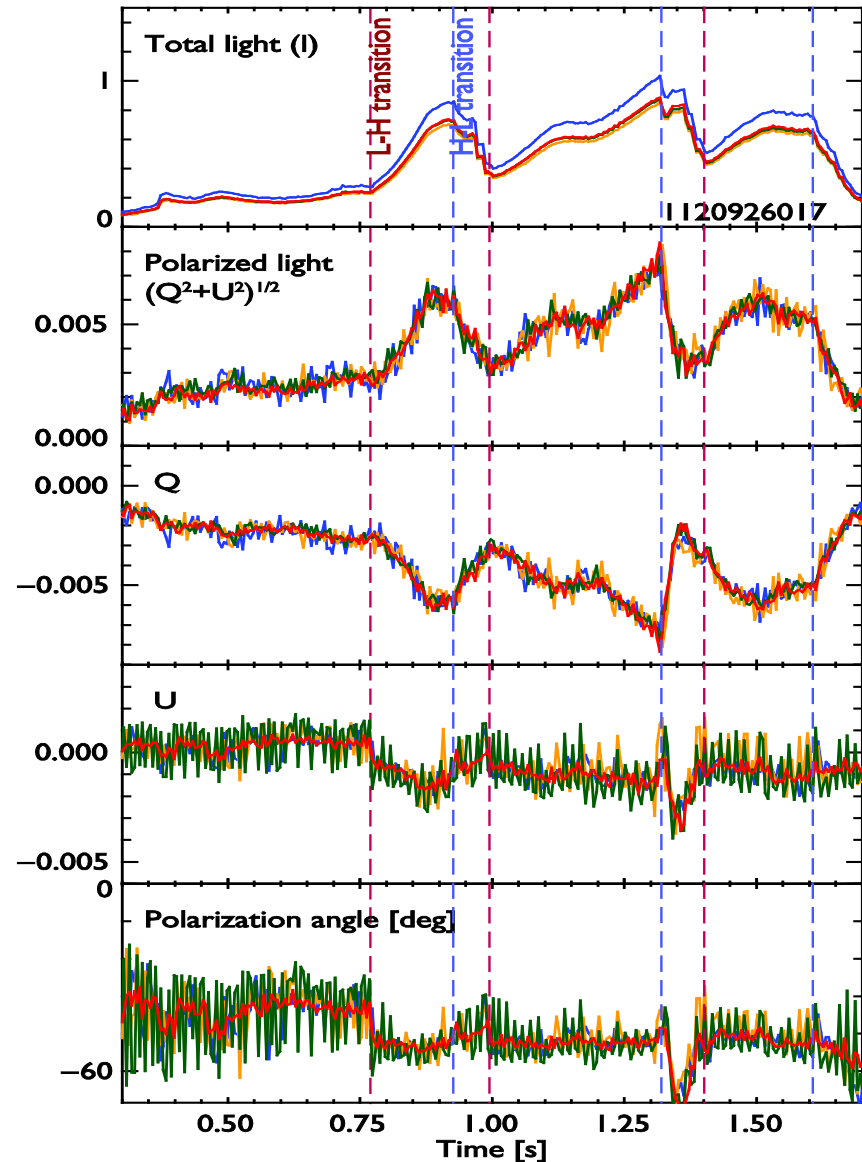


Polarization at adjacent wavelengths highly correlated even as background changes significantly.

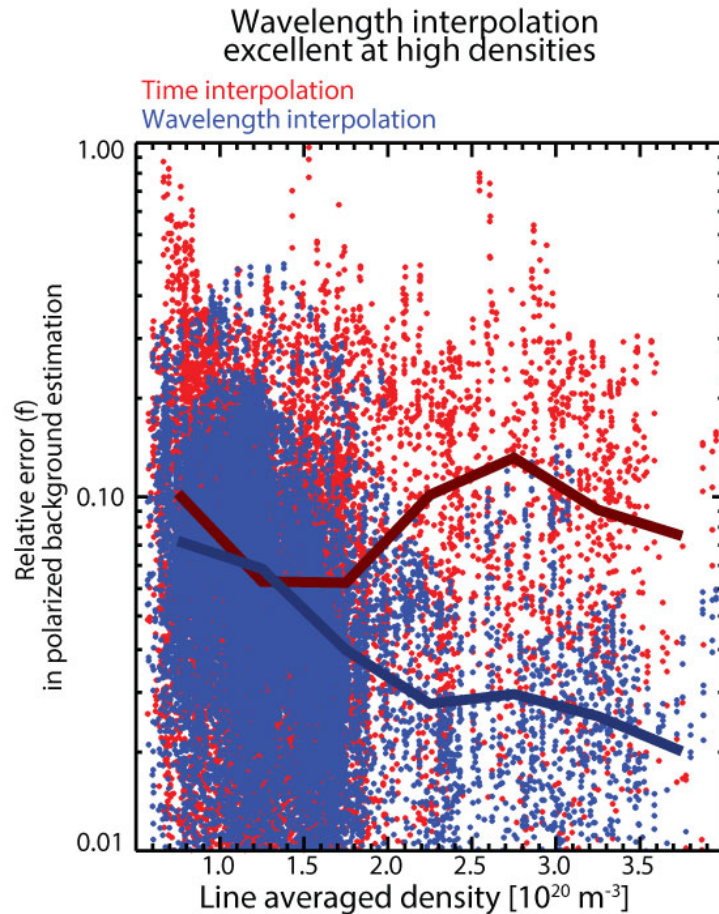


Polarization of the different spectral regions agree

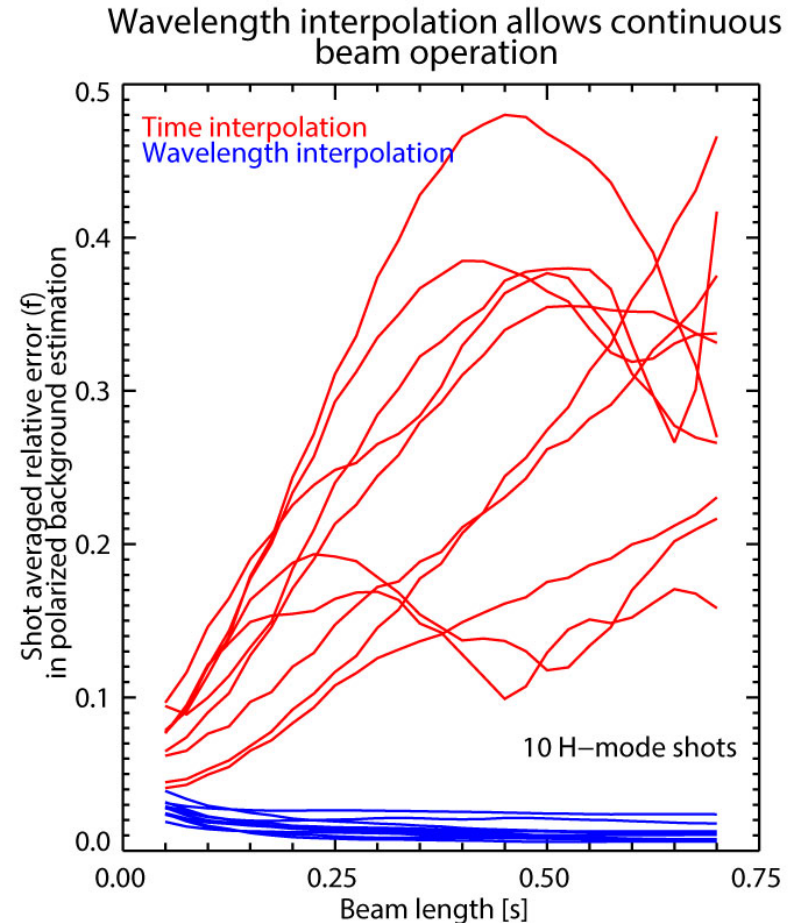
- Follows the transients well across entire discharges
 - Even over plasma transitions when contributions from different sources are changing
- Agreement near the photon statistic limit
- Result independent of MSE sightline
- Works over large wavelength range



System performed 5x better, 10x better at high densities and allows continuous beam operation.

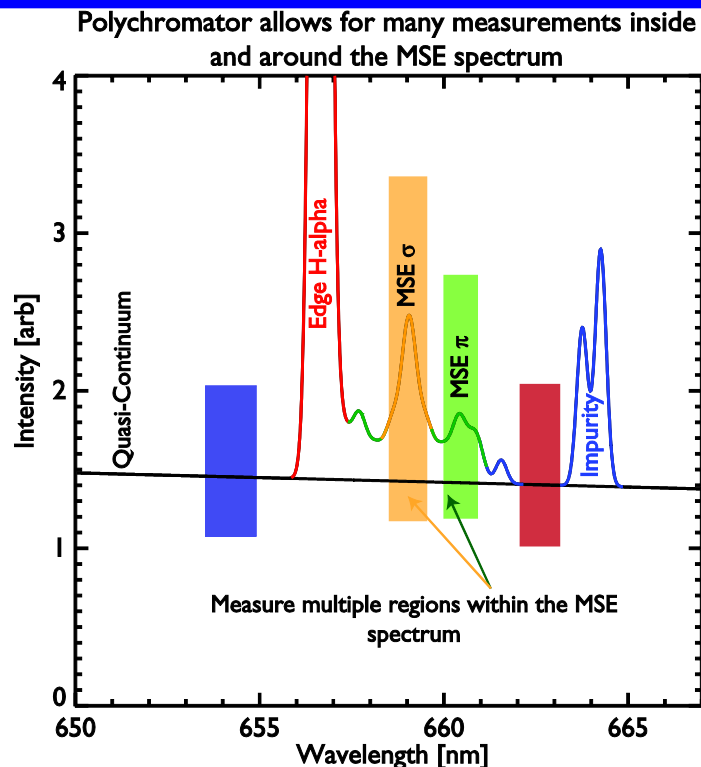


100ms beam length



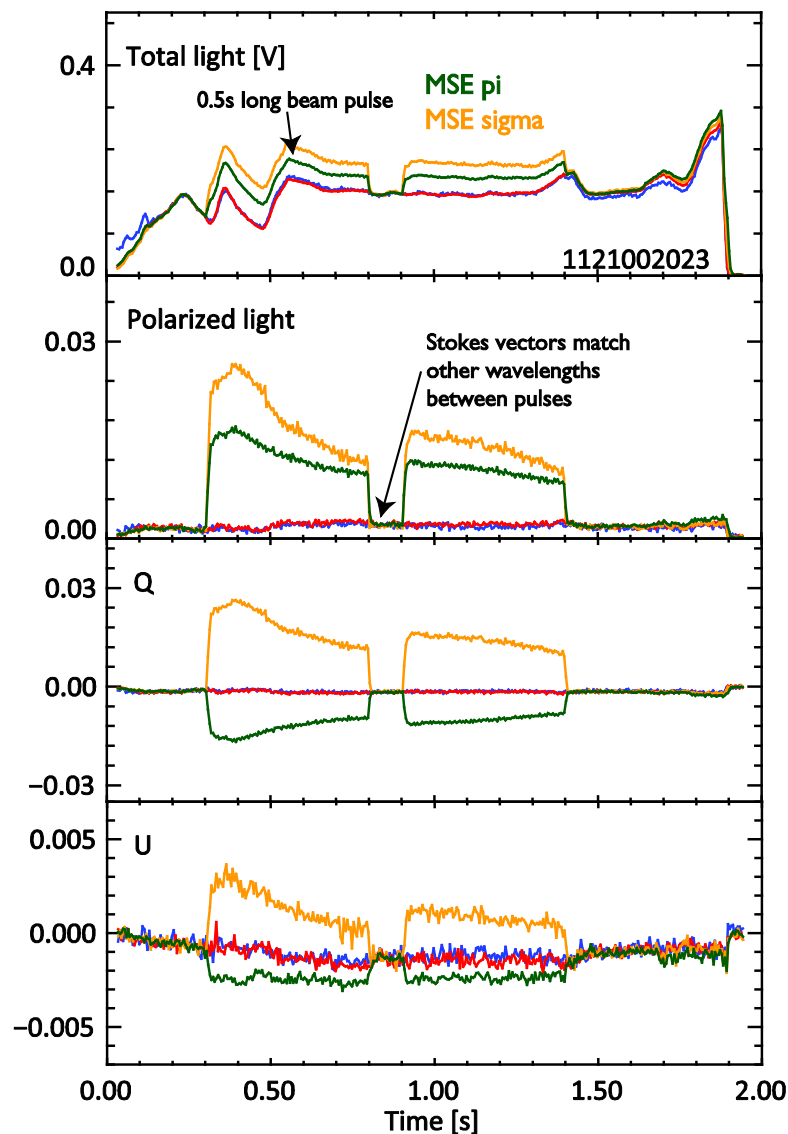
- No effort made in wavelength interpolation system to minimize noise
 - Use wider bandpass, higher transmission filters to decrease sampling noise

System also allows for simultaneous measurement of multiple MSE lines.



- Can increase signal substantially
- Allows for checks of:
 - Atomic physics
 - Calibration

Future upgrade: Convert all sightlines to polarization polychromators

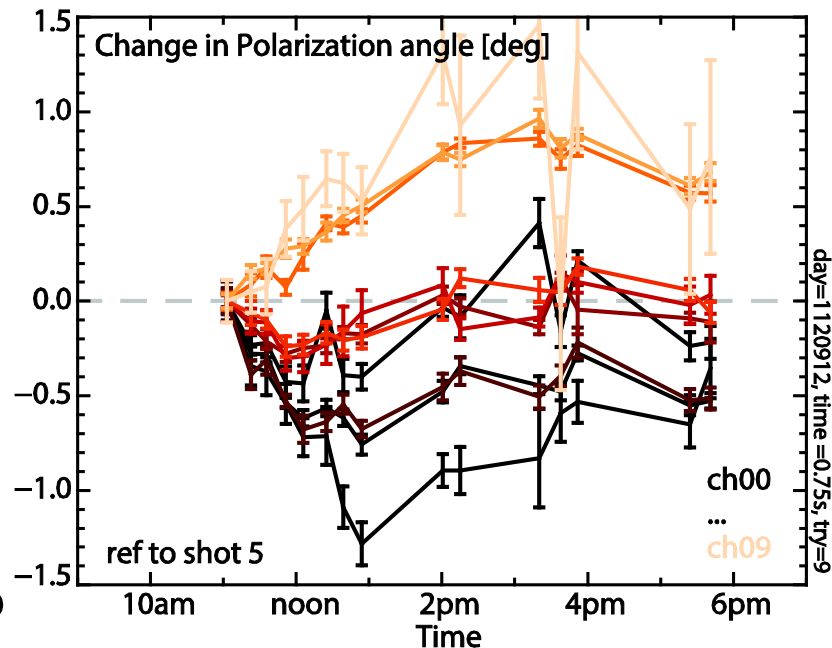
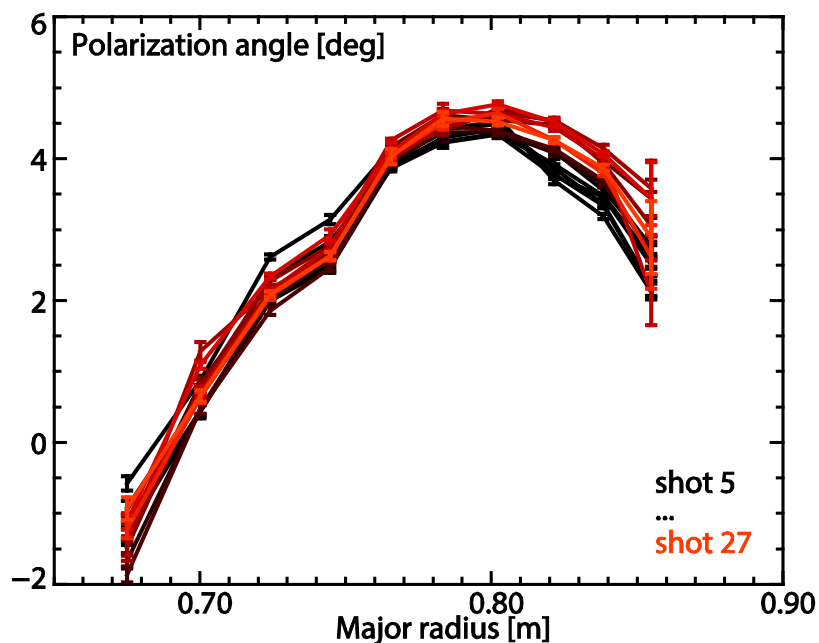


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Observation: the polarization diagnostic response drifts shot-to-shot on C-Mod.

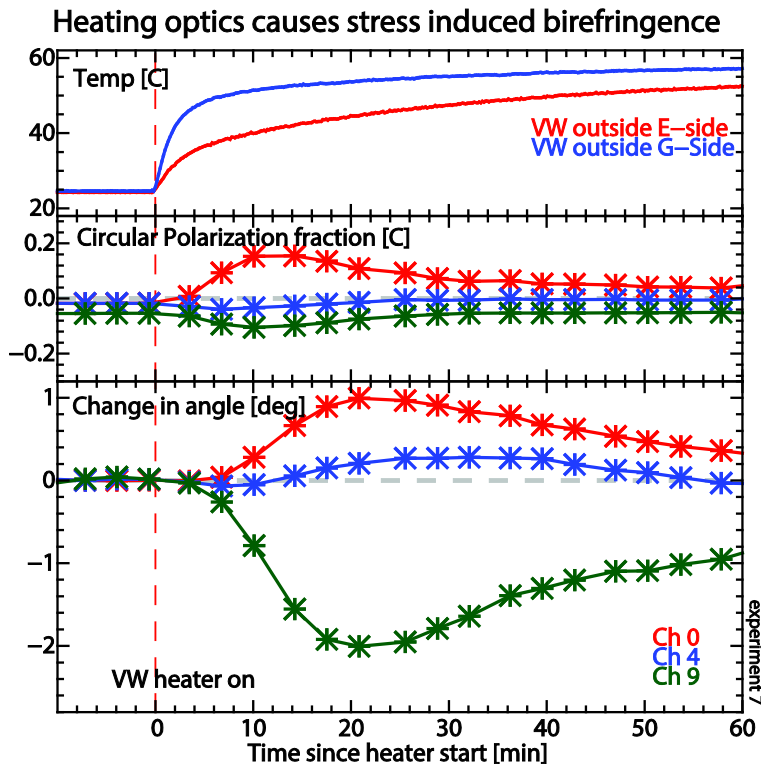
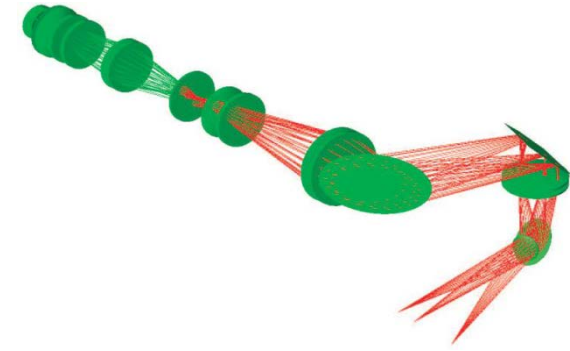
Drift in polarization angles observing the beam in identical plasmas



- Use identical shots to judge reproducibility
 - Polarization angle drifts $\sim 1^\circ$ shot-to-shot across runday
 - Channel dependent (though smoothly)
 - Not repeatable runday-to-runday
 - Changes in circular polarization also apparent

Stress-birefringence is the primary cause of drift. Attempts to stabilize the harsh thermal environment undertaken.

- System's many transmissive optics undergo large thermal gradients
 - Causes stress-induced birefringence, rotating polarization
 - Reproduced during maintenance periods by heating optics
- Thermal isolation of components alleviated problem but didn't eliminate it

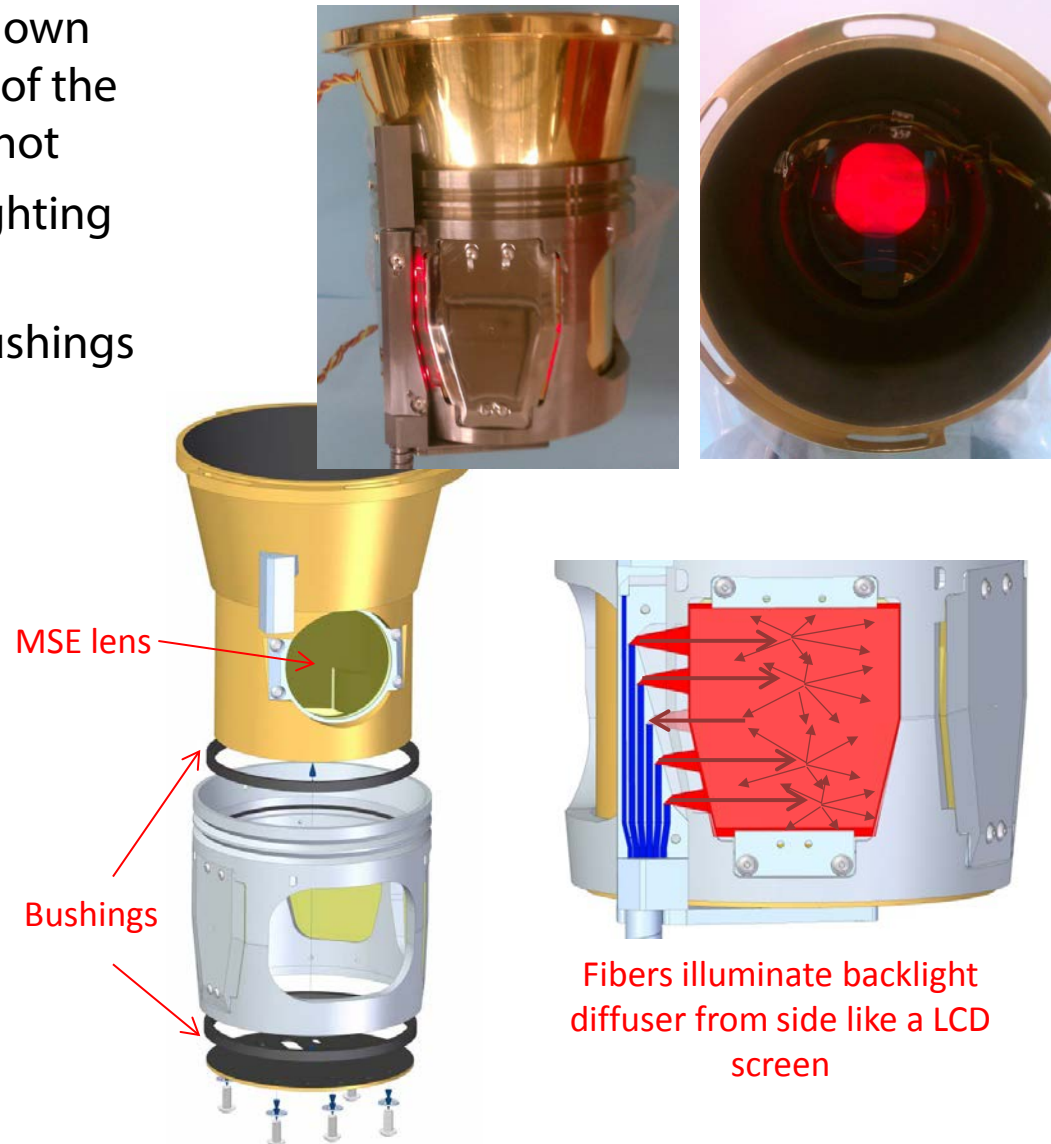


MSE periscope covered with radiative heat shield

Problem analogous to mirror erosion and deposition in next-step devices.
Try in-situ calibration on C-Mod.

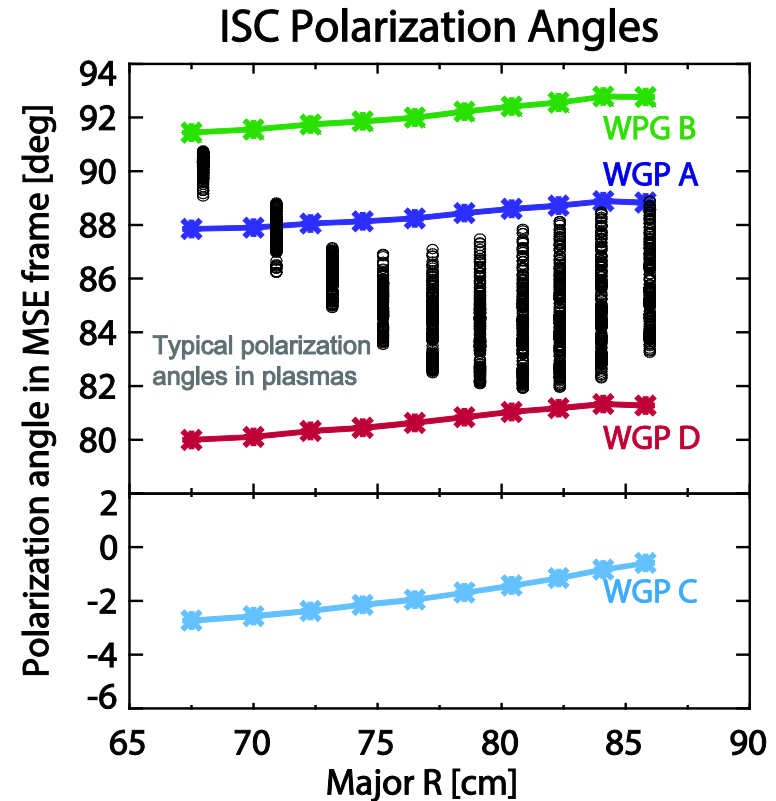
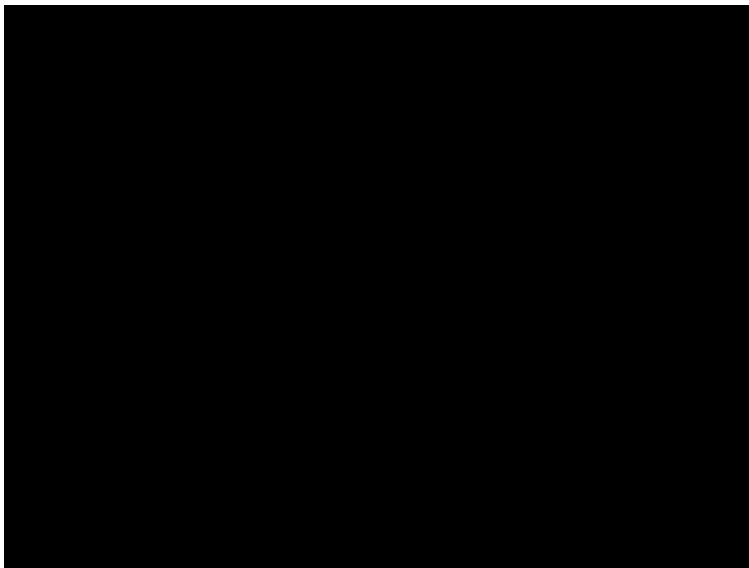
Intershot calibration system (ISC) was developed: Input known polarizations into the diagnostic objective lens.

- 4 wire grid polarizers (WGP) with known absolute angles are rotated in front of the objective lens within seconds of a shot
- WGP are illuminated using a backlighting diffuser and fiber inputs
- System rotates on high precision bushings
 - Mechanically aligned to $<0.05^\circ$



System quickly inputs 4 polarization angles immediately following a discharge, allowing interpolation.

- Actuated using cable-in-conduit system immediately following every shot
- Backscatter used as a feedback sensor to determine when system is properly aligned



- Measurement of the 4 WGP's allows the plasma measurements to be corrected
- System is repeatable to $<0.05^\circ$
 - $>6,500$ cycles in C-Mod to date
 - $>18,000$ cycles in vacuum during engineering phase
- Allows checks of pump-down stress, PEM stability, Faraday rotation, lens heating etc.

System tracks the diagnostic drift across the entire run day and campaign revealing trends.

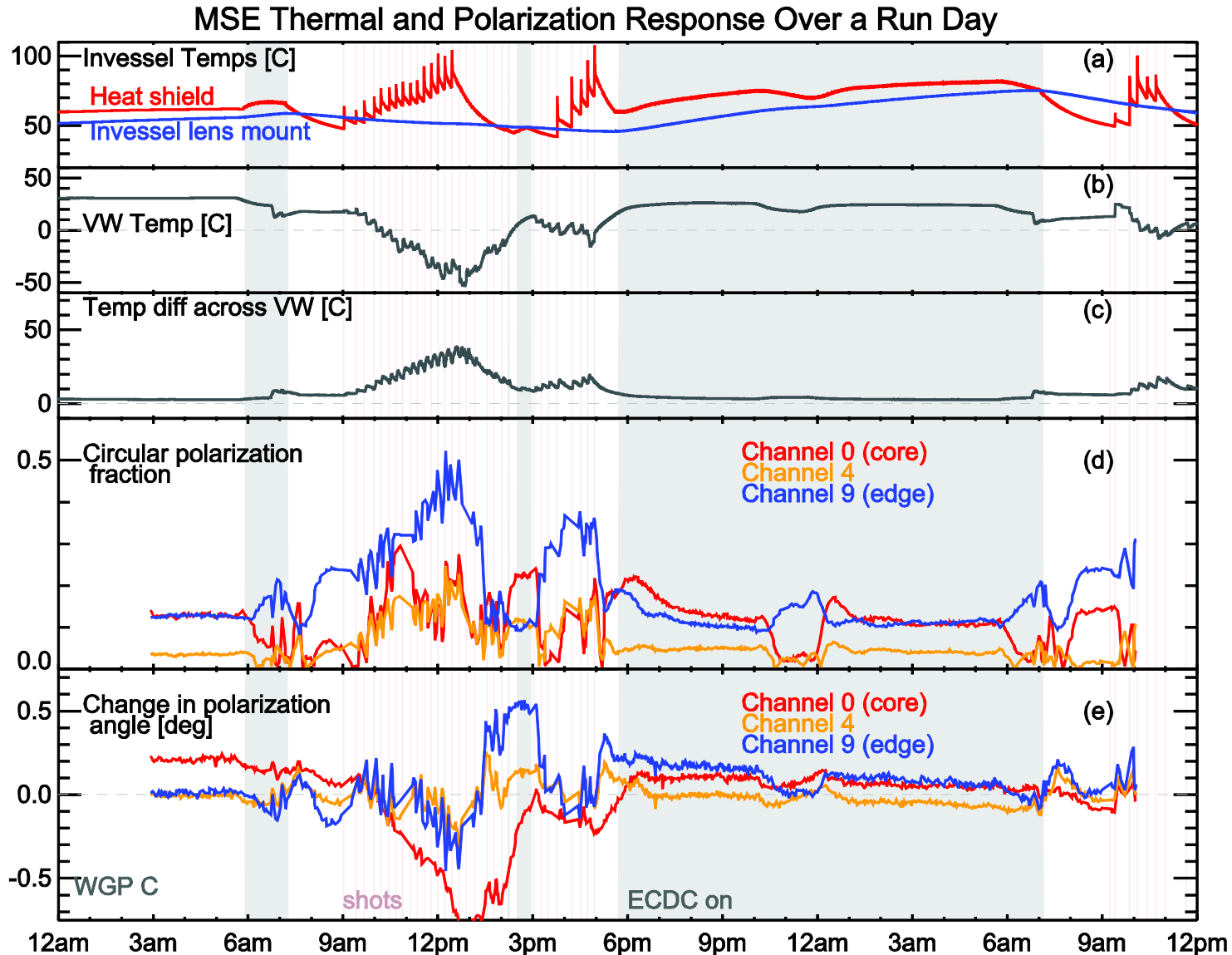
Heat shield protects optics from plasma

...but VW ratchets down in temp

...developing large thermal gradients

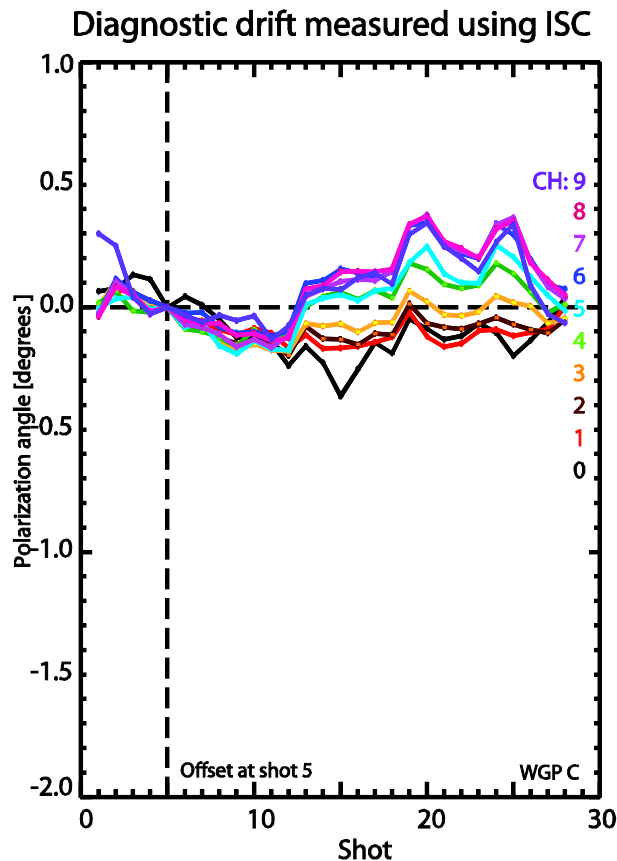
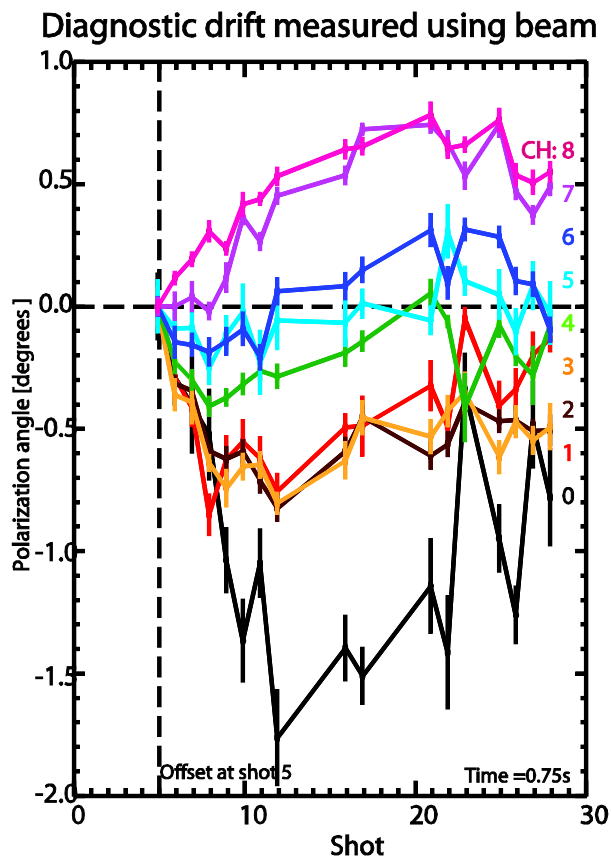
...becomes birefringent

... changing the polarization angle



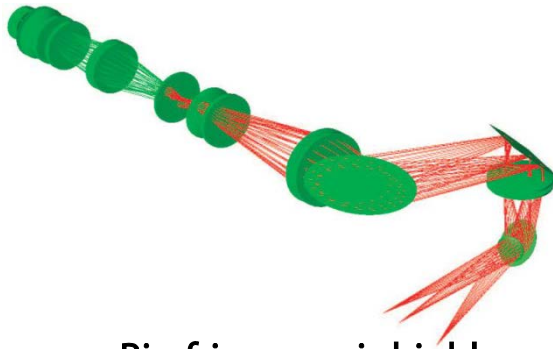
But... The first implementation didn't track the “right” diagnostic drift.

- Use identical plasmas to judge diagnostic drift via beam observations
- Compare to that inferred from the ISC
 - Quantitative and qualitatively different!

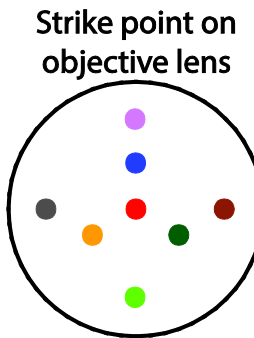
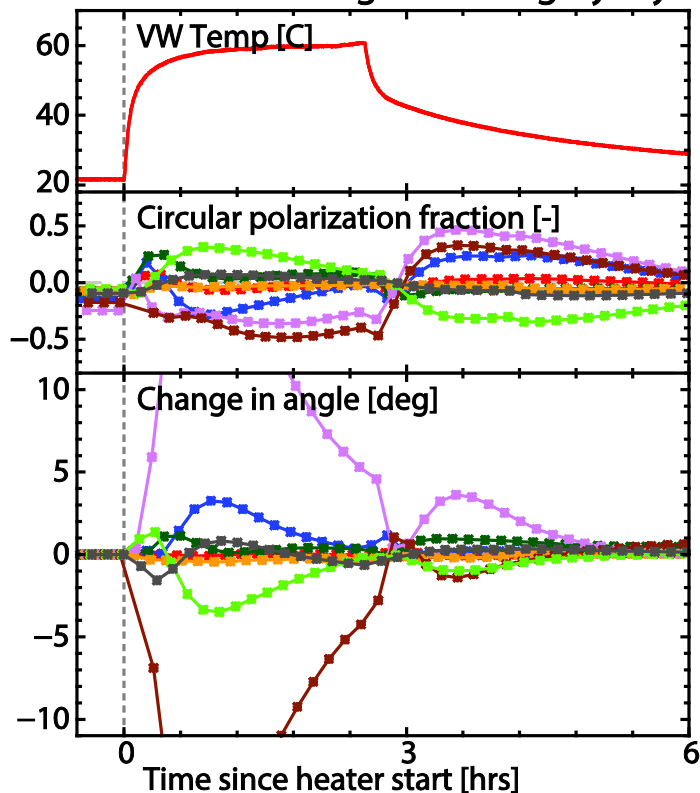


Determined the problem:

Diagnostic response is extremely ray dependent.



Birefringence is highly ray dependent



- Discrepancy reproduced during maintenance period
- Further tests done with ray-tracing source
 - Ray strikes a different portion of the lens with a different stress state
 - Different polarization aberration
- Sightline calibration a weighted average of all the rays

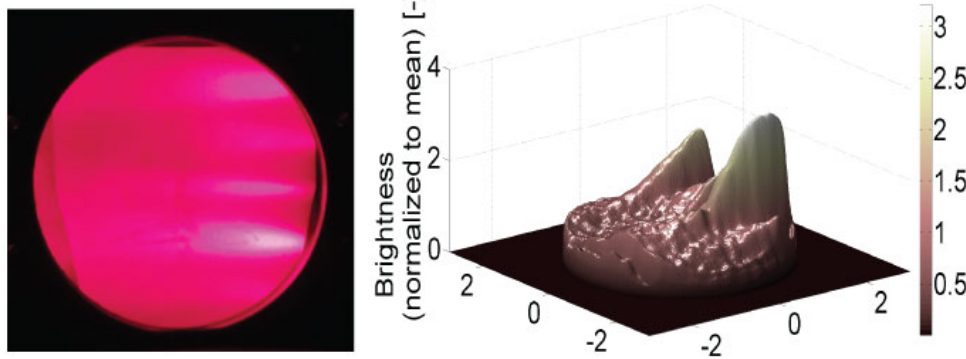
Thus a proper calibration source must match beam illumination (ie uniform)

- Probably important for next-step systems
 - Non-uniform first mirror erosion/deposition

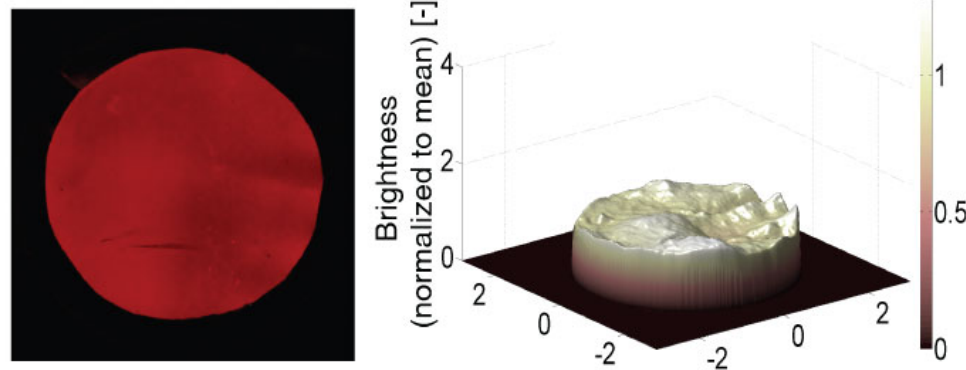
Rebuilt the ISC with uniform illumination.

Bench trials successful, awaiting confirmation in-situ.

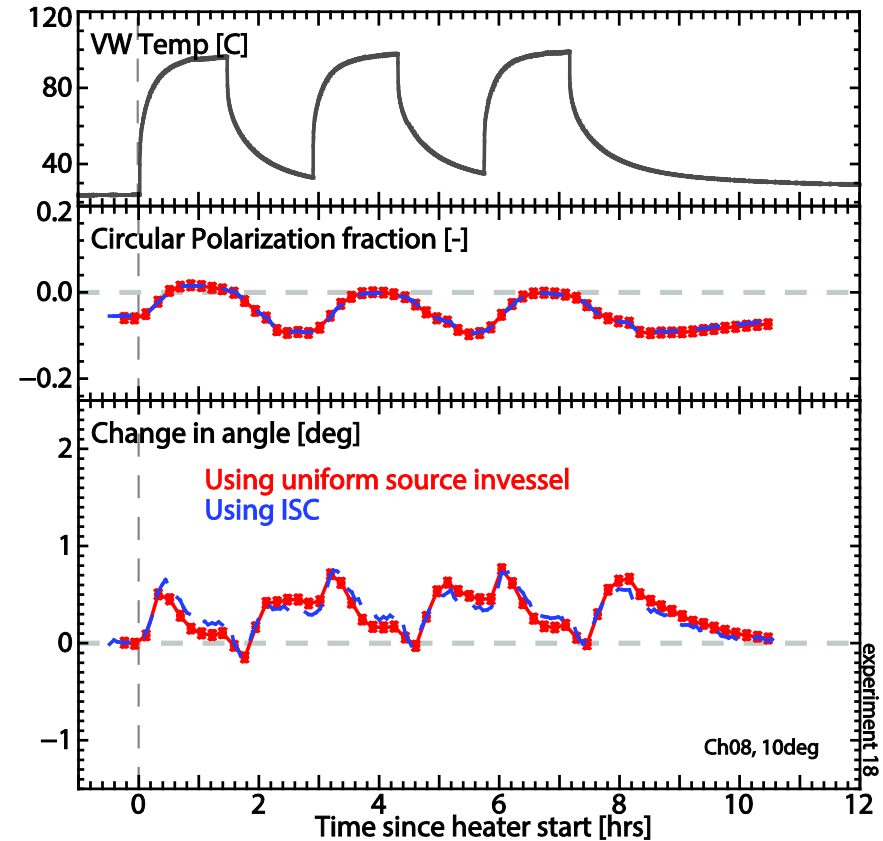
ISC uniformity prior to rebuild



ISC uniformity after rebuild



Rebuilt ISC tracks properly tracks changes in the diagnostic



- Care taken to make ISC source uniform during rebuild
- ISC now tracks birefringence imposed during maintenance periods
 - Comparison with beam-into plasmas soon

Outline of talk

- Recent results with LHCD on C-Mod enabled by MSE
- Challenges for MSE in next-step devices
 - And in C-Mod for similar reasons
- MSE polarized background subtraction
- C-Mod's experience with MSE in-situ calibration
- **Conclusions**

Talk summary

- MSE system on C-Mod is operation and making physics measurements
- LHCD current profile measured for the first time in the density regime where we observe a loss of current drive
- Ray tracing simulations do not reproduce the observed trends
- These measurements were challenging due to calibration drift and background subtraction
- We expect to encounter polarized background and calibration drift in next-step MSE-LP systems
- Background polarization mechanism and sources identified
- Broadband nature allows them to be wavelength interpolated
- Polychromatic fielded, improves situation by 5x-10x in regime where required
- Developed in-situ calibration system to correct for drift from birefringence
- Source uniformity important due to ray-dependence in polarization aberrations
- Awaiting final word with beam-into-plasma

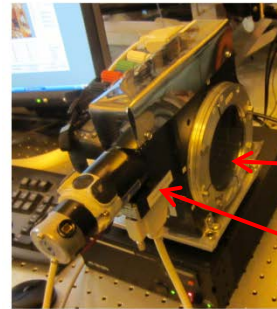
Extra slides

- Polarized background
 - [Polarization camera](#)
 - [Polarized sources](#)
 - [Proof-of-principle](#)
 - [Polychrometer](#)
 - [Polychrometer results](#)
- [Calibration strategies](#)
 - [ISC design](#)
 - [ISC-DNB discrepancy](#)
 - [Other ISC uses](#)
 - [Ray-dependent calibration](#)
 - [ISC-non-uniformity](#)
 - [PEM monitoring](#)
- [View monitoring](#)
- [Filter checks](#)
- [Other diagnostic checks](#)
- [Robotic calibration](#)
- [Thermal isolation](#)
 - [L2](#)
 - [Thermal shield](#)
 - [Vacuum window](#)
 - [Vacuum window results](#)
- [Reconstructions](#)
 - [LHCD raw data](#)
 - [LHCD reconstructions](#)
 - [Comparisons to models](#)
- [Beam stuff](#)

Polarization camera

Developed a polarization imaging camera to photograph polarization upon reflection from tokamak walls

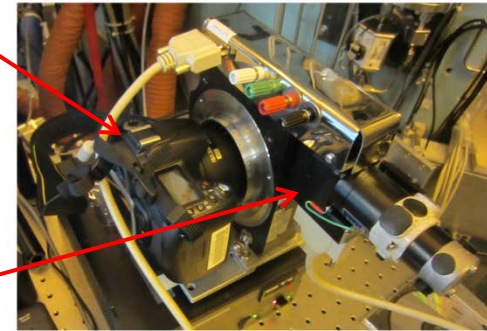
- DSL Camera mounted behind a computer controlled rotating stage with linear polarizer attached
- Take high dynamic range photos of a scene while rotating polarizer
- Fit Malus's $\cos^2$ law to each pixel to determine the polarization properties
- Polarization fraction accuracy $\sim 1\%$



Computer controlled DSLR

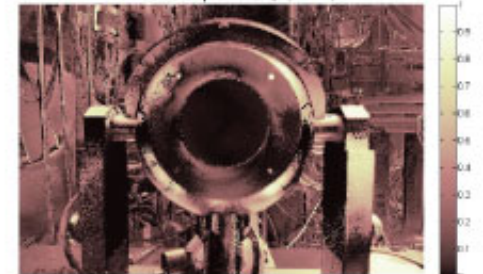
Linear polarizer

Computer controlled rotating stage

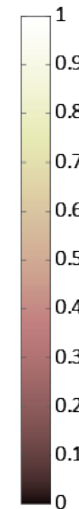
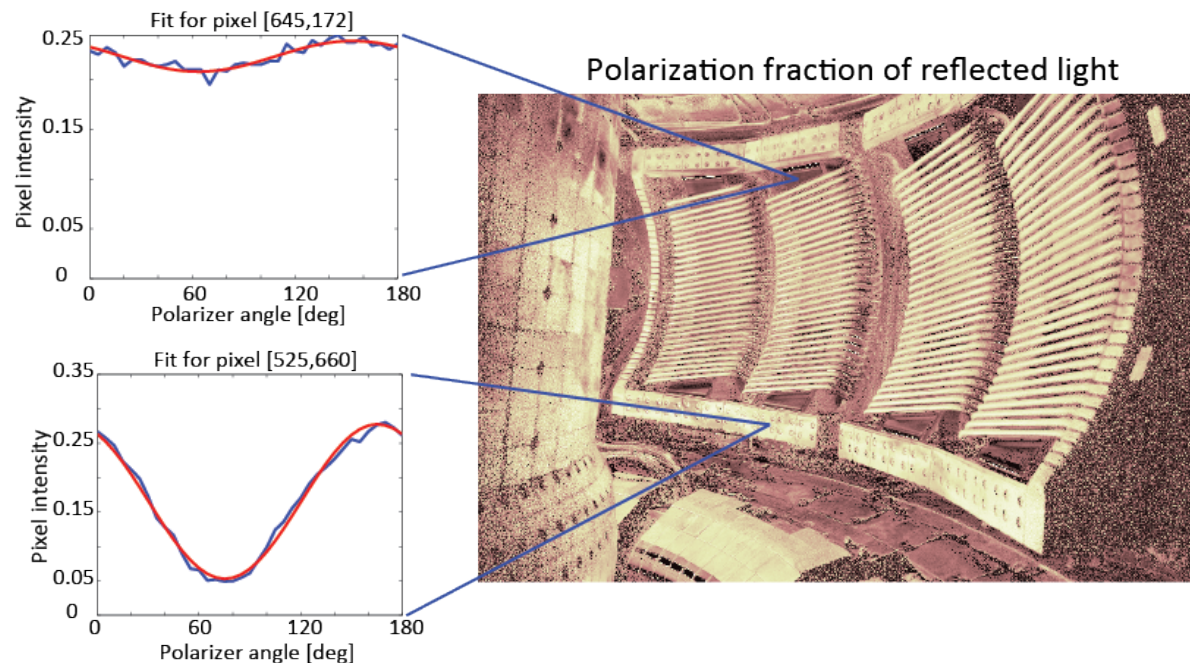


Labsphere used to check technique.
Gives proper polarization fractions.

Labsphere (PF=0)

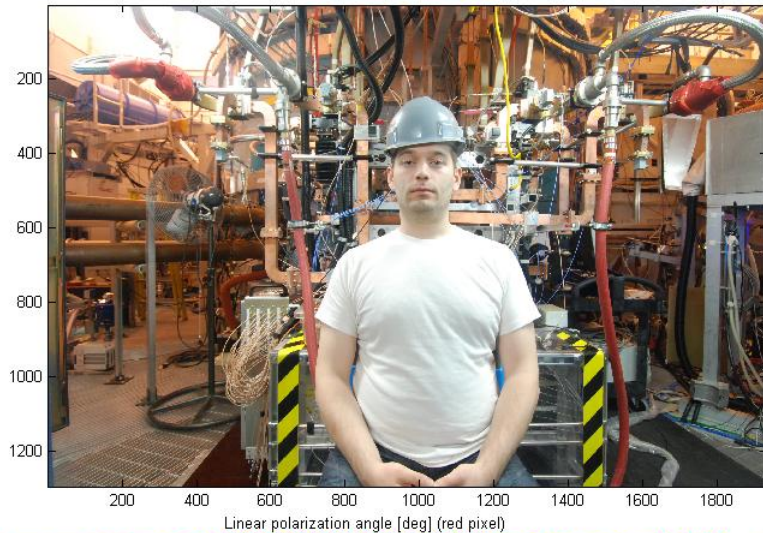


With polarizer in front of Labsphere (PF=1)



Generally the whole world is polarized

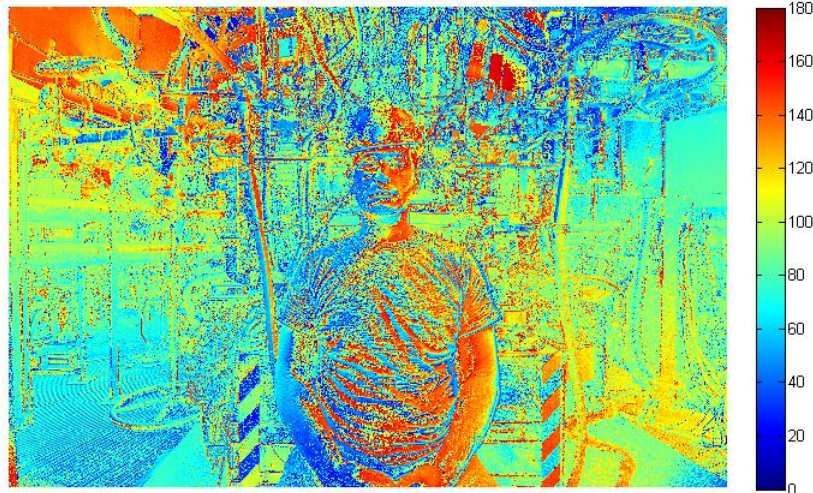
Photo



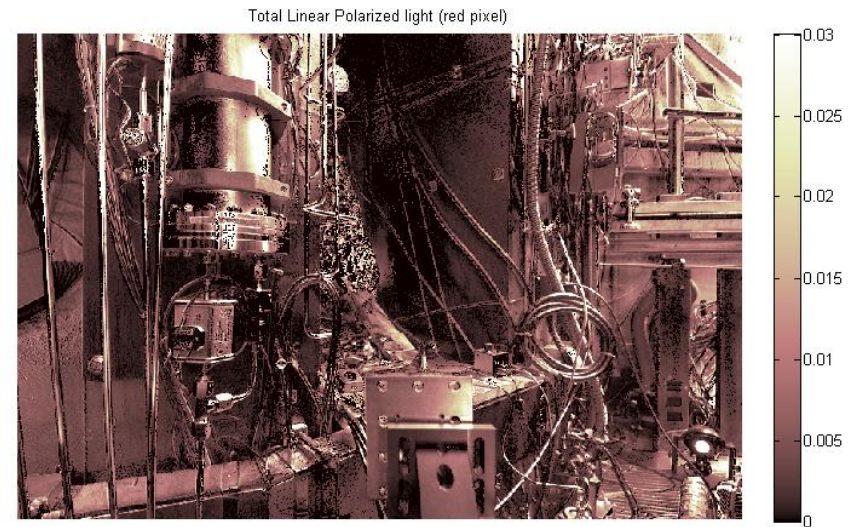
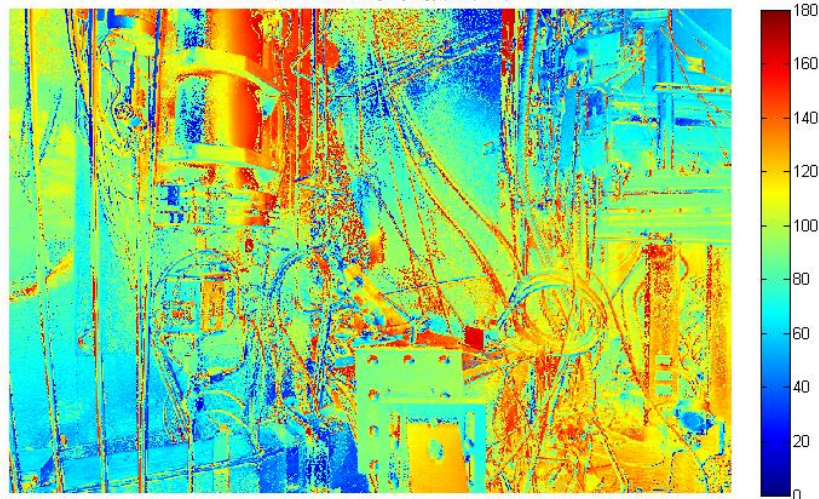
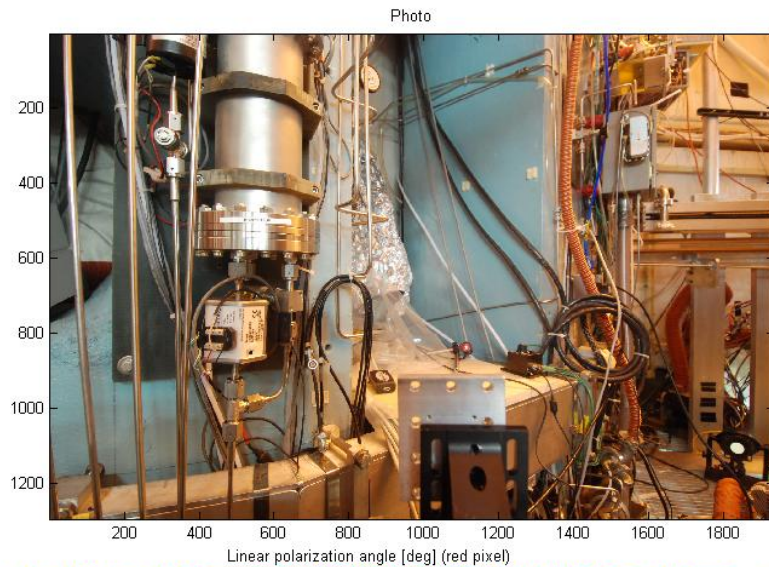
Total Linear Polarized light (red pixel)



Linear Polarization fraction (red pixel)



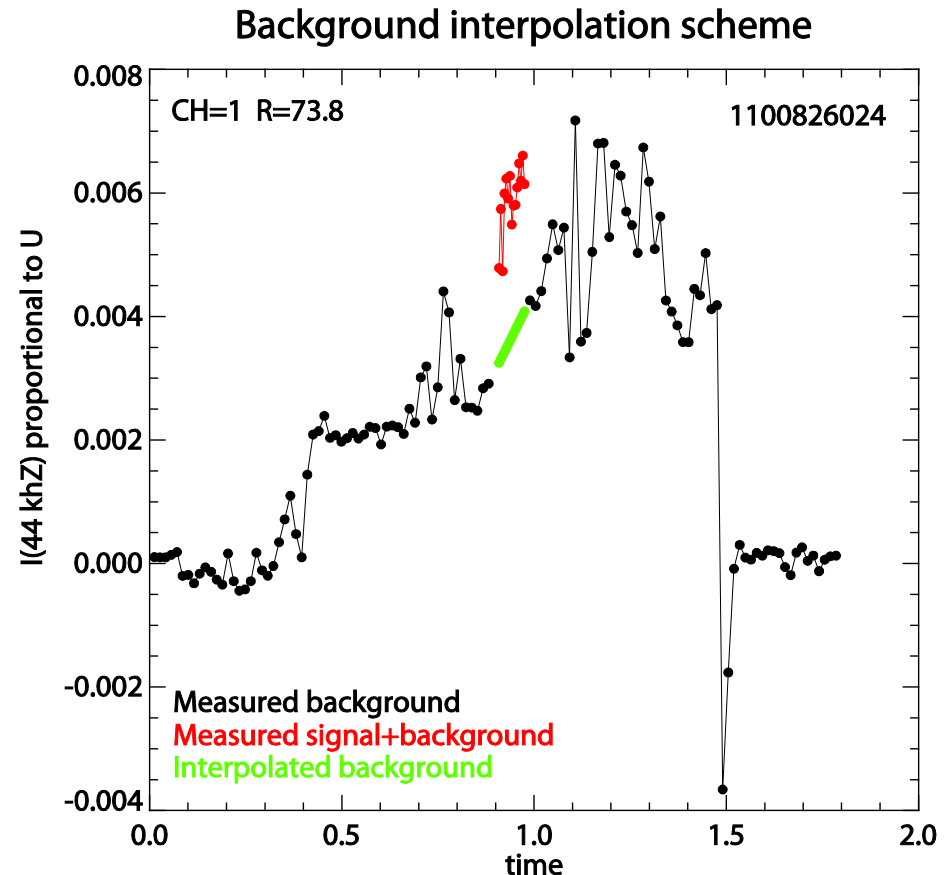
Generally the whole world is polarized



Polarized background

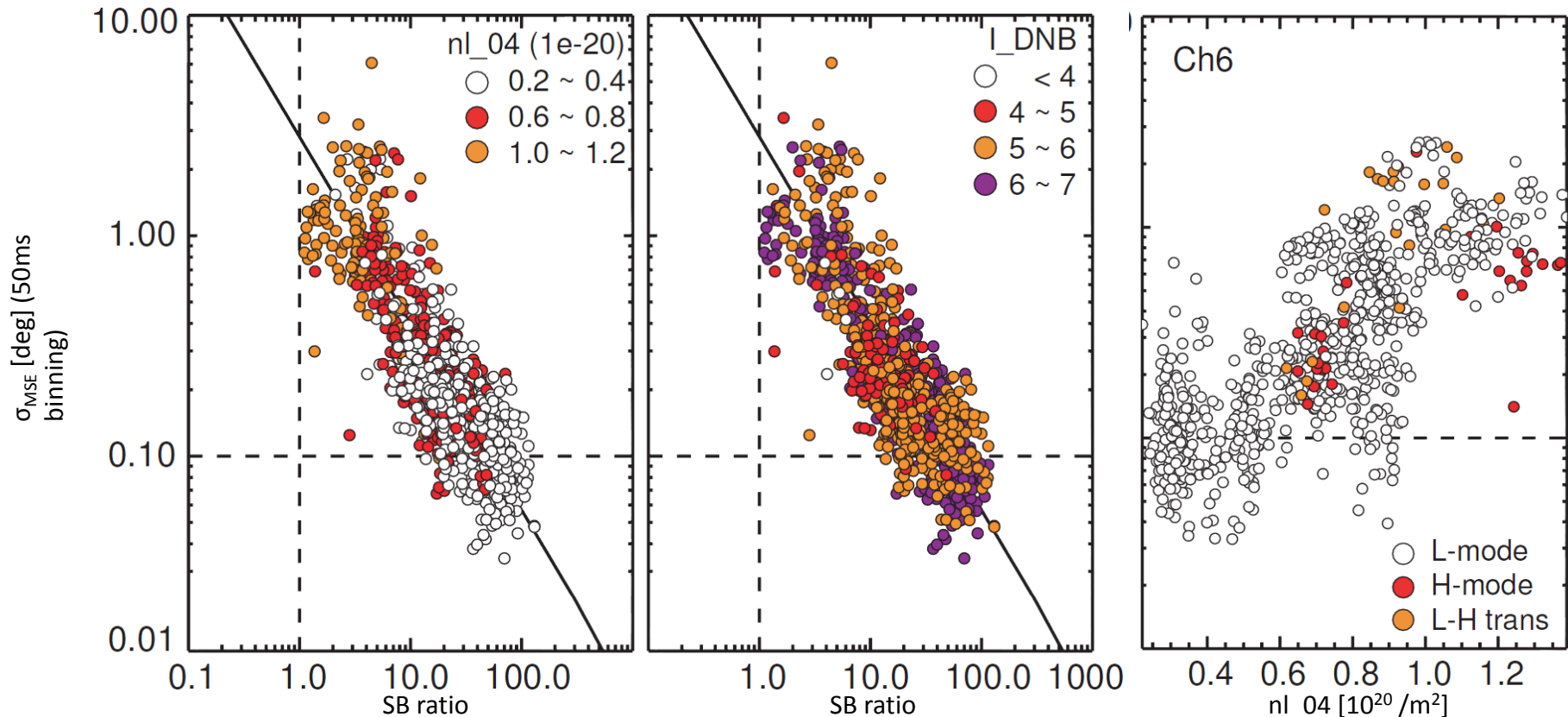
Time interpolation of background light.

- Partially polarized background light is not problematic if it can be subtracted accurately.
- The current method uses beam-on beam-off interpolation.
 - The background Stokes parameters are measured before and after the beam then interpolated and subtracted during the beam.
 - However, the background changes substantially during a beam pulse ($\sim 70\text{ms}$).
 - Data during transient events such as L-H transitions, ICRF or LH turn on, ICRF or LH faults, other interesting physics on $<100\text{ms}$ timescales has high uncertainty.



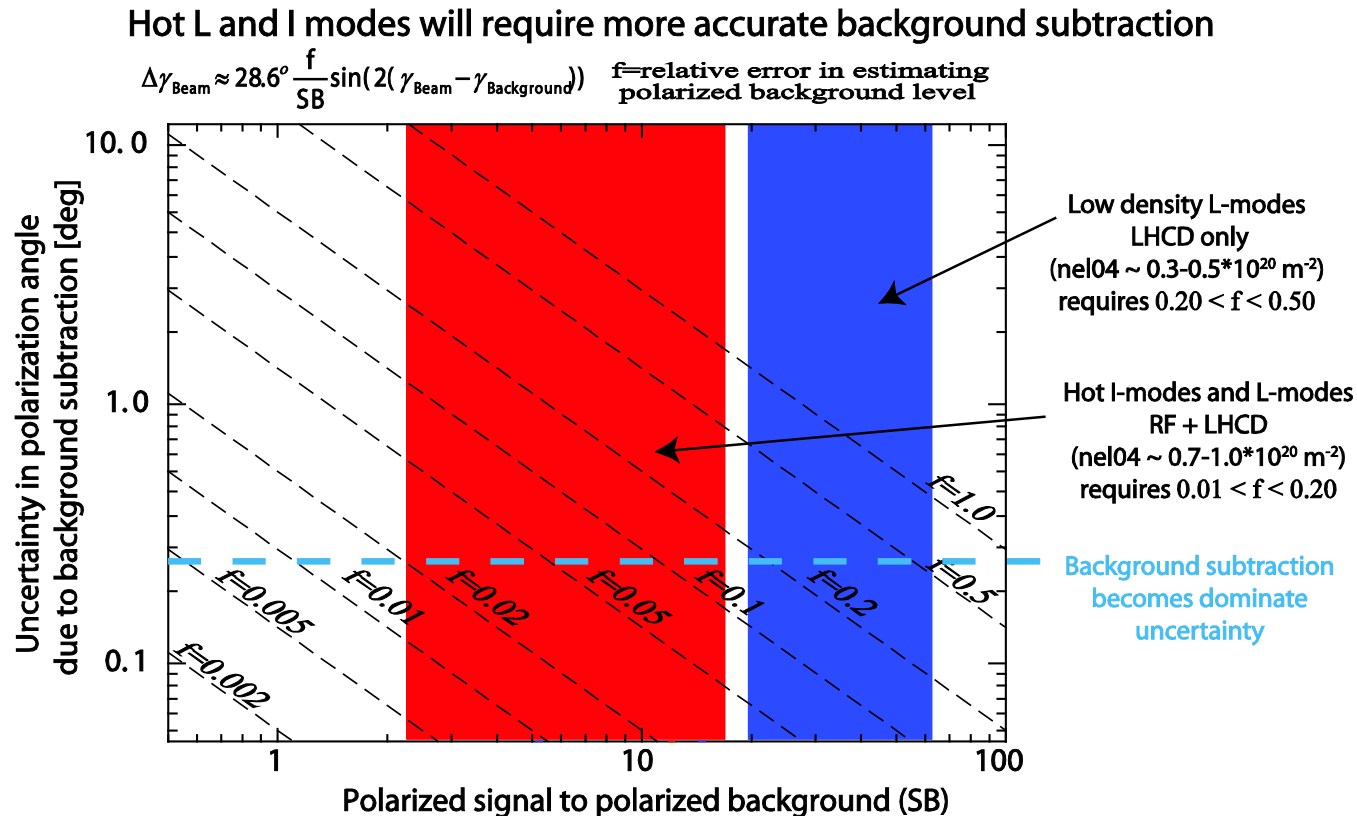
Experimental observations about how the background impacts the measurement

- Low signal due to beam attenuation and/or high background limits densities where MSE can make meaningful measurements to L-modes with $nl_{04} < 0.6$.



Ko thesis

To extend MSE measurement range on C-Mod we will require better background subtraction



- Better background subtraction is required for MSE measurements for RF heated I-modes and L-modes at higher density
 - Need to be able to estimate background at near the 1%-20% level
 - Only need to estimate it at the >20% level in low density LHCD only shots

Antenna materials.

- Generally all the materials introduce polarization.
- Dielectrics have particularly high polarization fractions

Faraday rods:
B4N coated copper

Faraday rods:
TiC coated copper

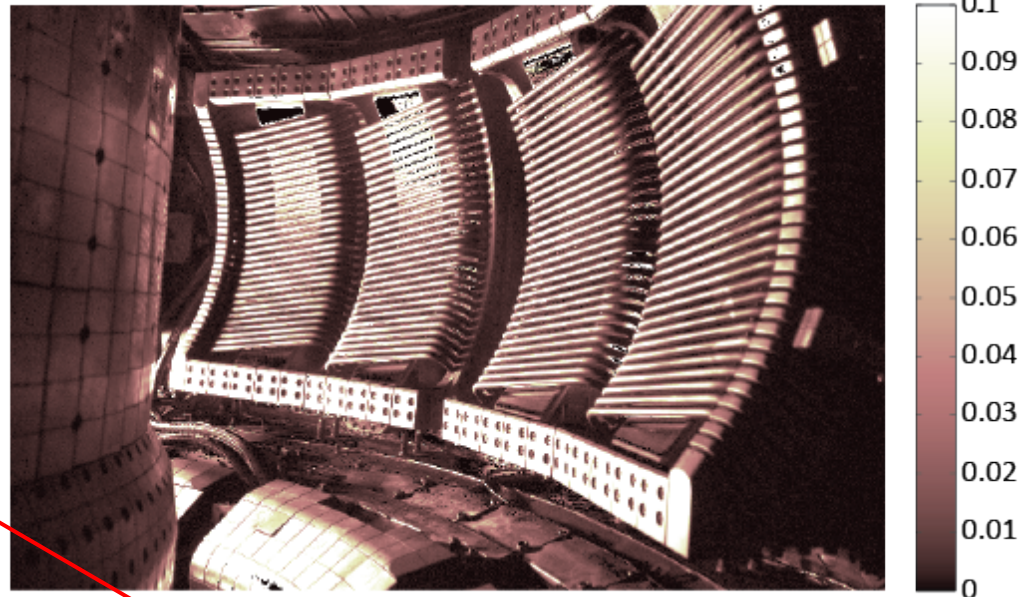
RF straps:
Polished copper

Antenna tiles:
Molybdenum

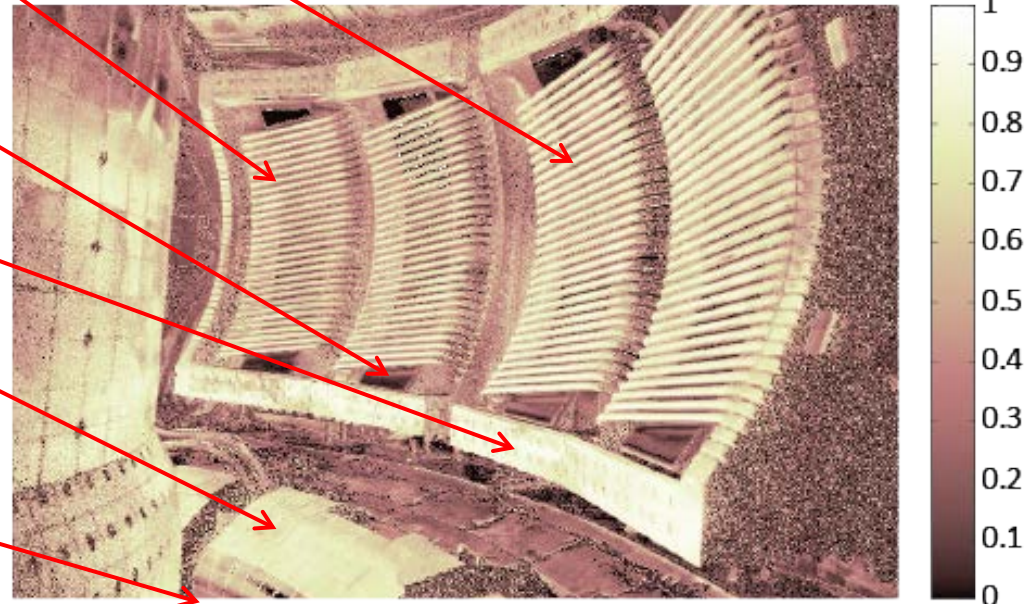
Divertor shelf tiles:
Boron coated Molybdenum

Vertical divertor tiles:
Molybdenum

Linearly polarized light reflected from antenna



Linear polarization fraction of light reflected from antenna

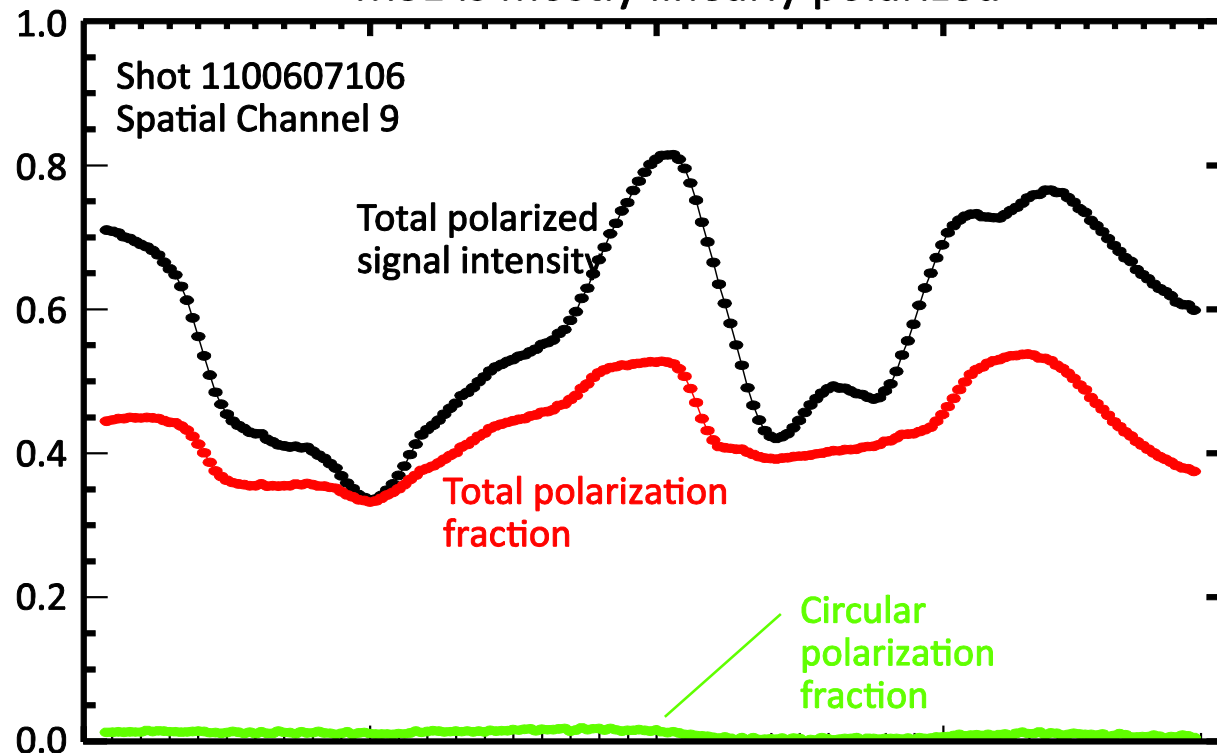


[Return to TOC](#)

Most of the reflected light is linearly polarized, only slight circular polarization.

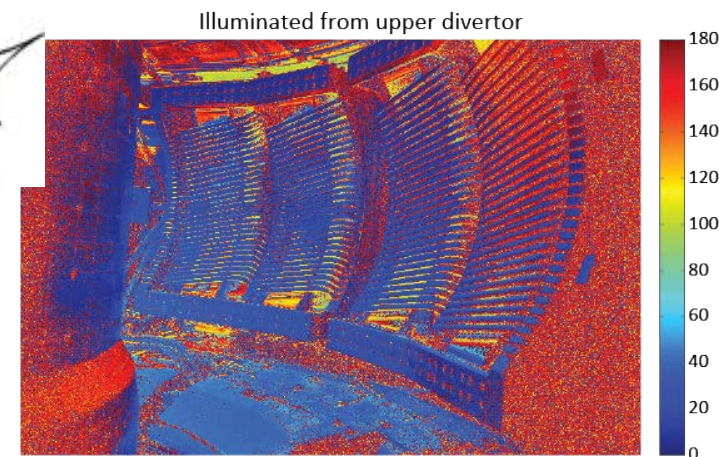
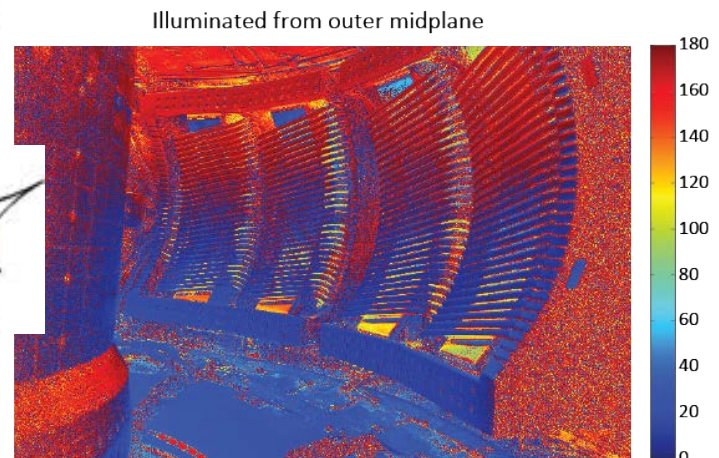
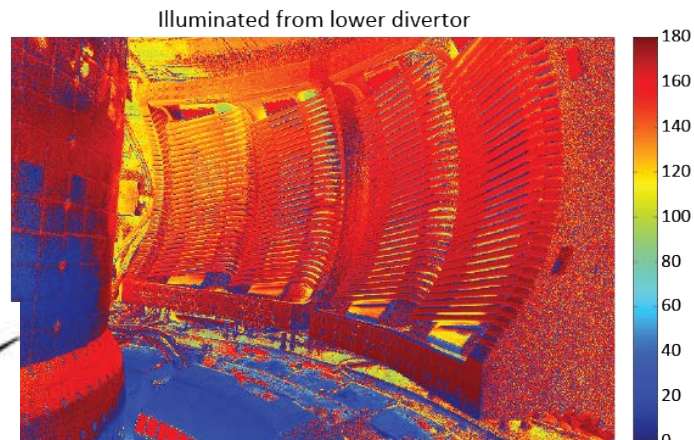
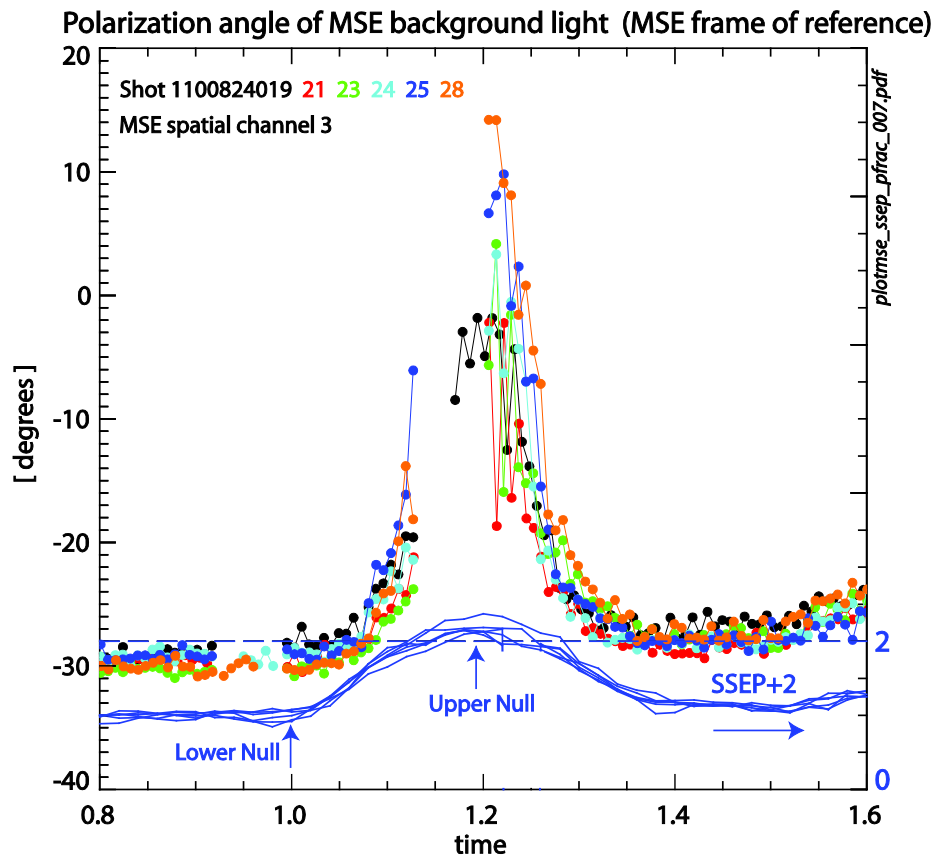
- Unpolarized source taken in vessel and shone onto antenna from outside of MSE view.
 - Waved around while taking MSE data
- MSE used to measure the polarization of the reflected signal. (since it is made for that!)

Light reflected from antenna and detected by
MSE is mostly linearly polarized



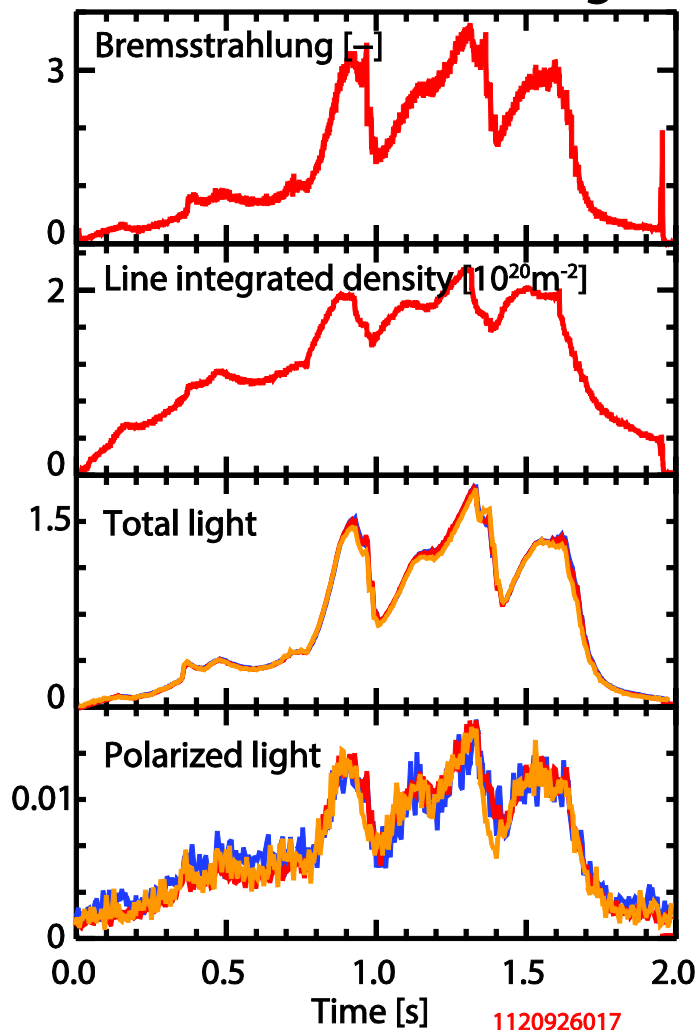
Polarization angle of the light depends on where it was emitted.

- Polarization angle depends on location of source in the poloidal plane.
 - Similar to polarization background changing depending on active divertor



Have identified sources of background light. VB, impurity line emission were expected and found

MSE background often looks
like Bremsstrahlung

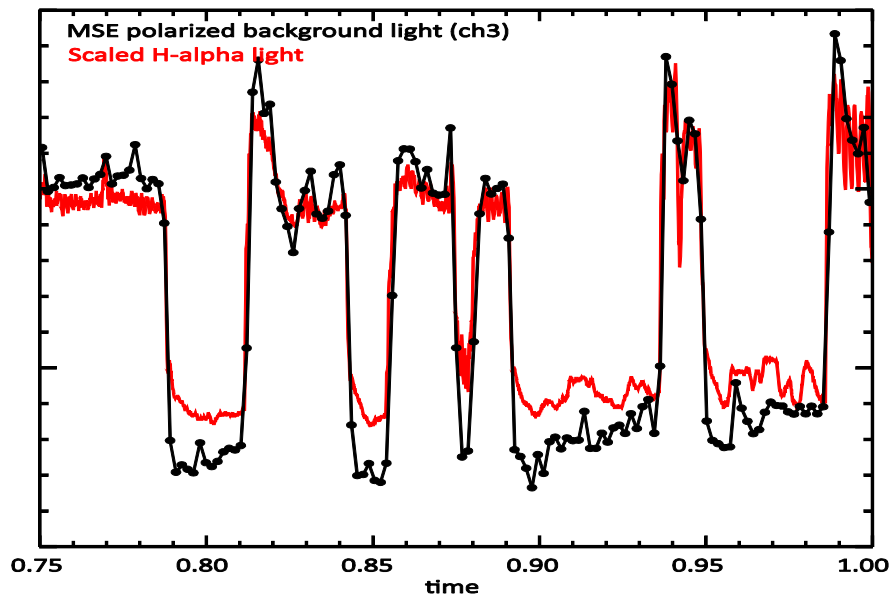


- As one would expect the background is often dominated by visible Bremsstrahlung emission.
 - Seen on first pass and reflection
 - Polarized at $\sim 1\text{-}5\%$ level
- Impurity line emission is polarized in channels spectrally overlapping a puffed impurity line (Ne)
 - Polarization fraction higher $\sim 30\%$
- Can also deduce contributions from other sources which become dominate in certain regimes.
 - Look for correlations in polarization intensity, fraction and angle
 - Many times something other than VB dominates the polarization

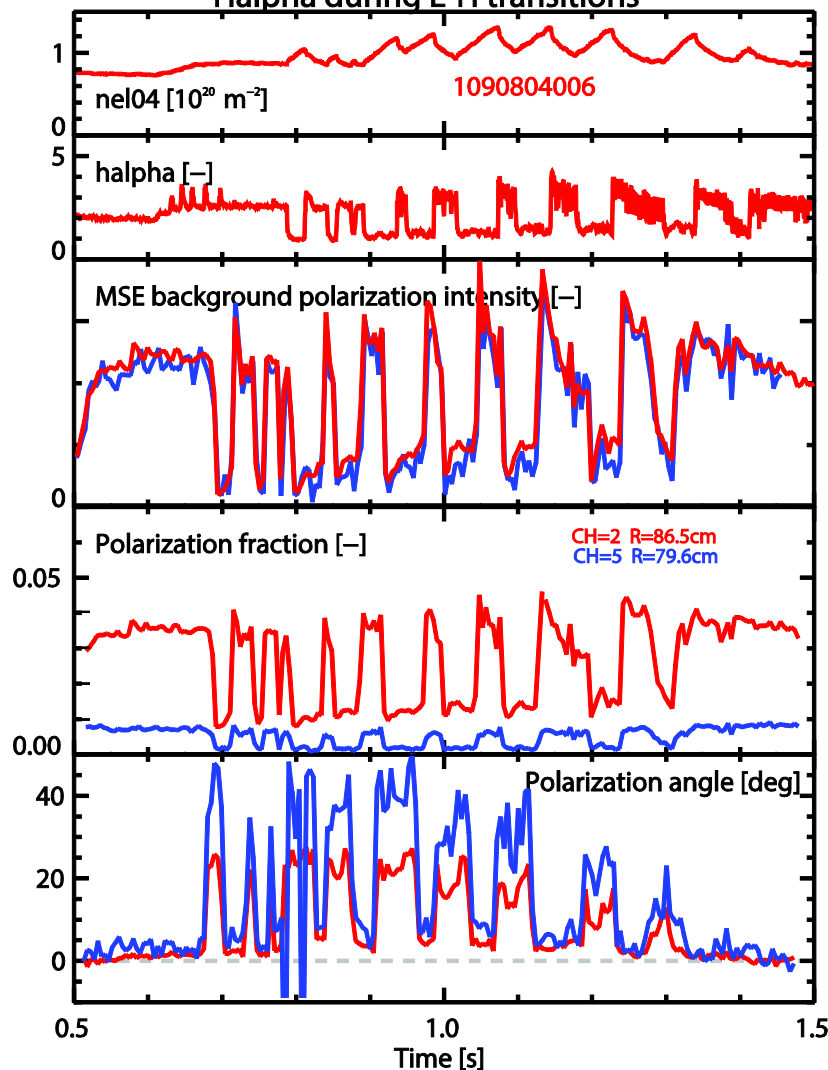
Not expected: Some form of Quasi-continuum edge emission (molecular D2?)

- Correlates very well with edge Dalpha
 - But is not edge Dalpha
- Correlates with stray light imaged from machine protection cameras
- Correlates with quasi-continuum emission observed by divertor visible spectrometers
- Polarization angle depends on active divertor
 - MARFES can cause similar angle changes

MSE polarized background often scales just like edge Halpha



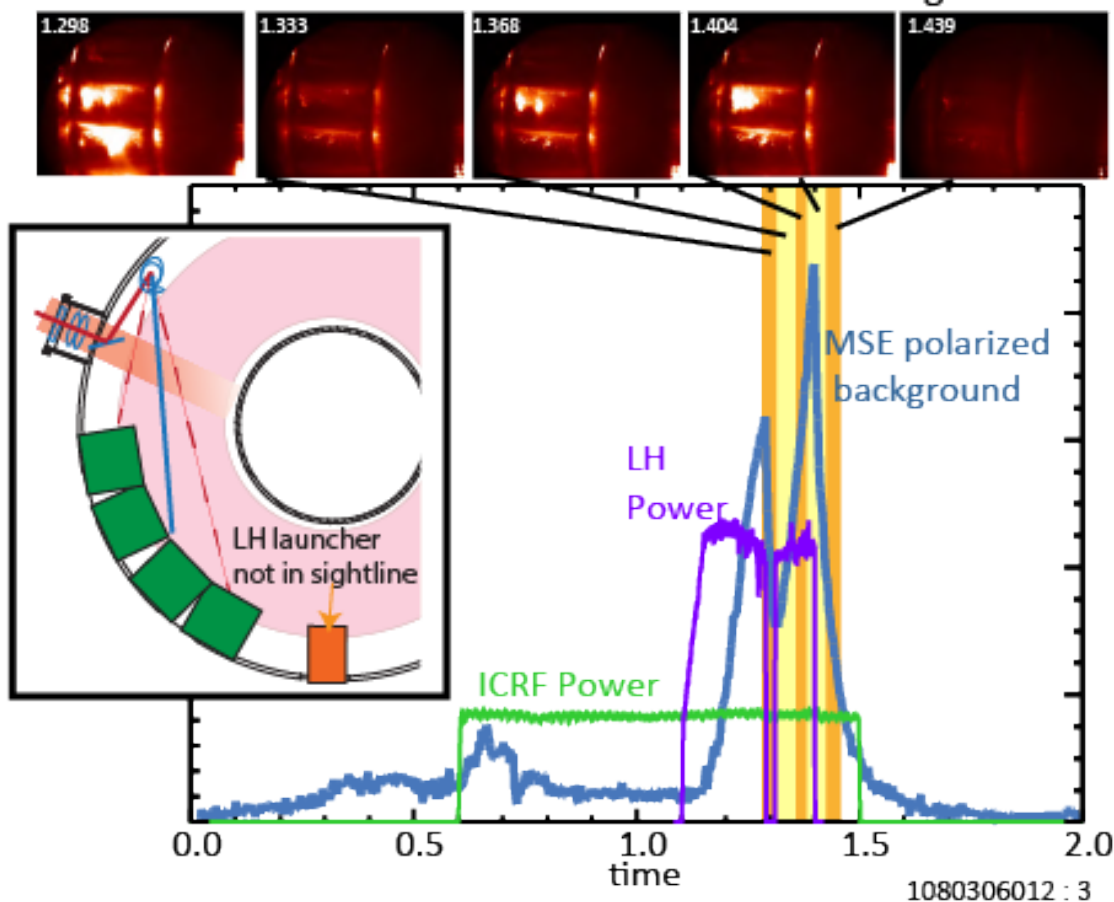
Polarized background correlates with Halpha during L-H transitions



Not expected: Hot glowing structures can dominate the polarized background

- RF antennas, LH launcher, limiters, divertor hot spots can dominate MSE polarized background
 - Structures only visible upon reflection
- Observe polarized light post disruptions, likely from divertor
- Polarization fractions 30%-50%

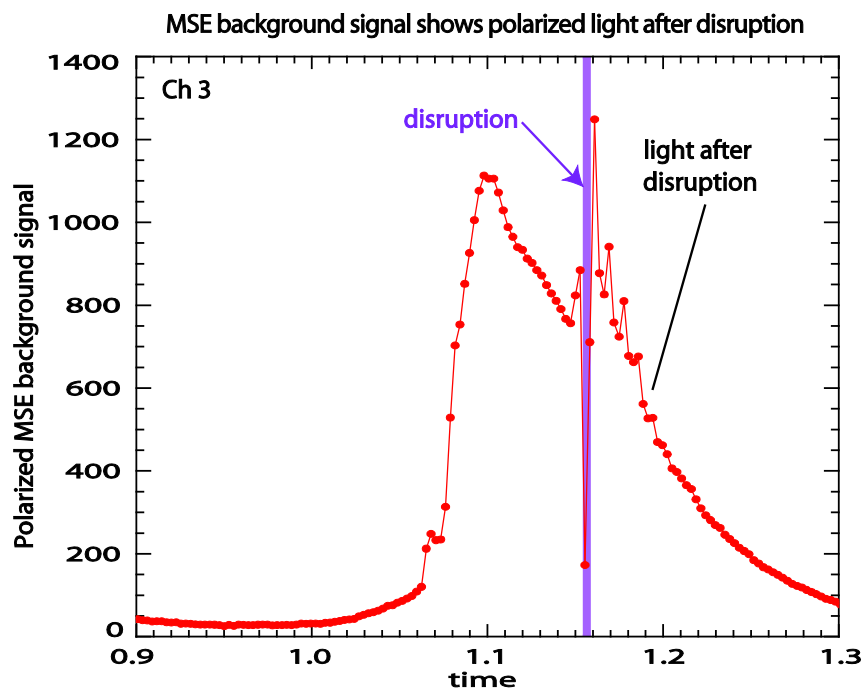
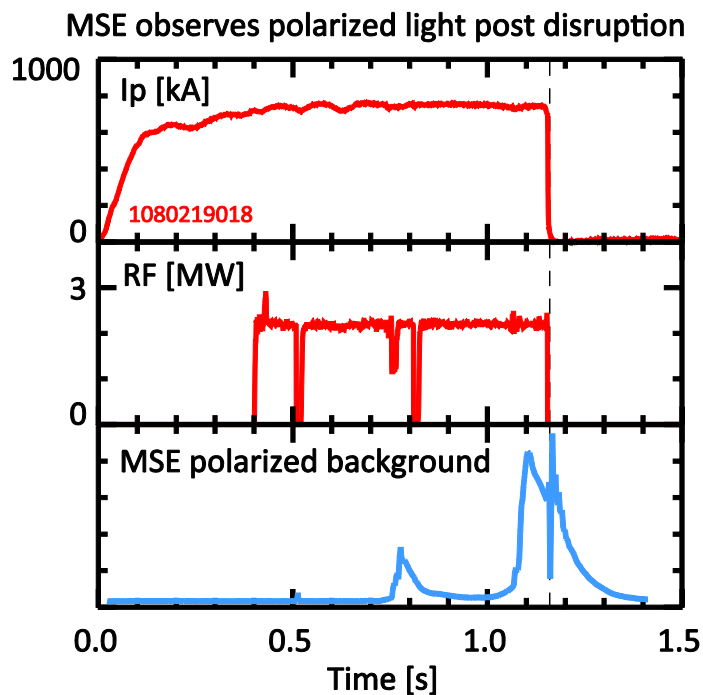
MSE observes polarized light correlating with heating of the LH launcher. The launcher is not in the MSE sightline.



1080306012 : 3

Not expected: Hot glowing structures can dominate the polarized background

- RF antennas, LH launcher, limiters, divertor hot spots can dominate MSE polarized background
 - Structures only visible upon reflection
- Observe polarized light post disruption
- Polarization fractions 30%-50%



Proof of principle experiments

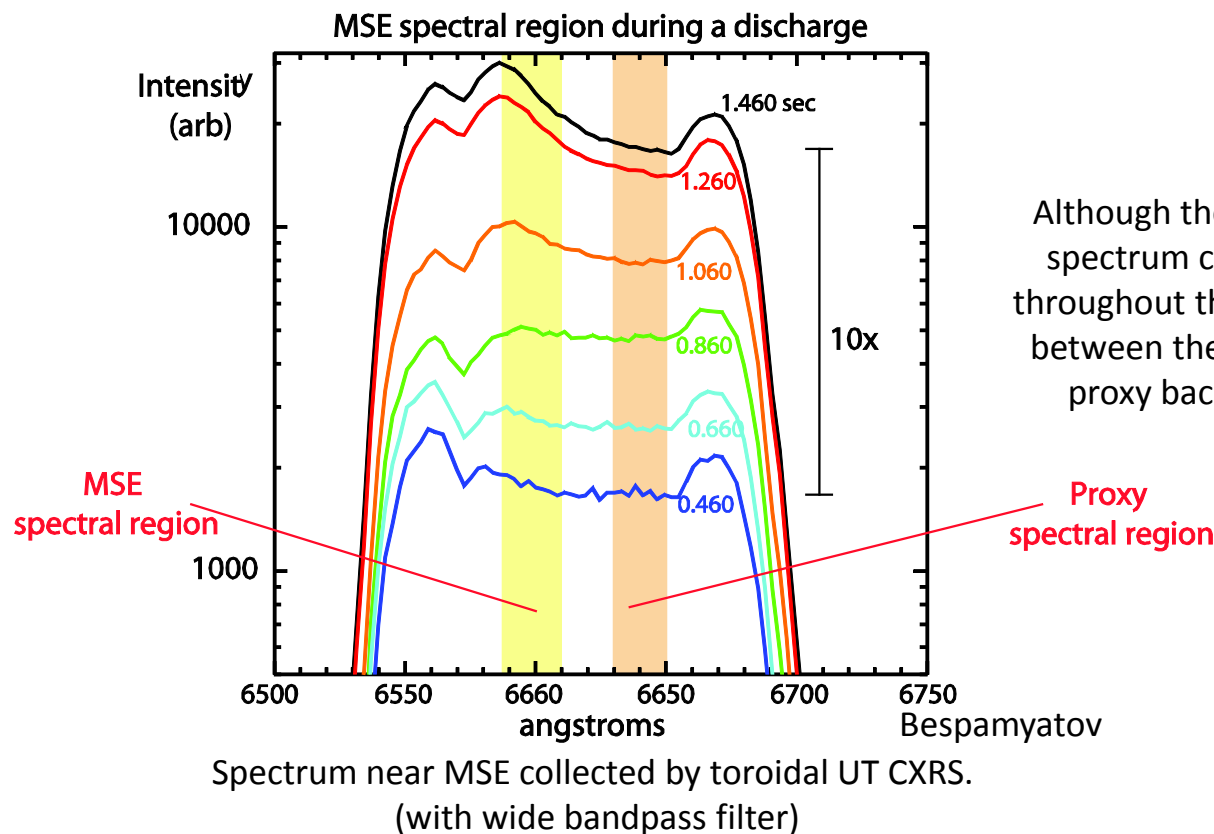
Possibility of a real-time background subtraction method using a proxy wavelength to reduce f .

Hypothesis:

The background light is smoothly varying in wavelength near the MSE spectrum.

The method of polarization is wavelength independent near the MSE spectrum.

Therefore the polarization of the MSE background light can be related to the polarization of light in a nearby wavelength. This relation should vary slowly.

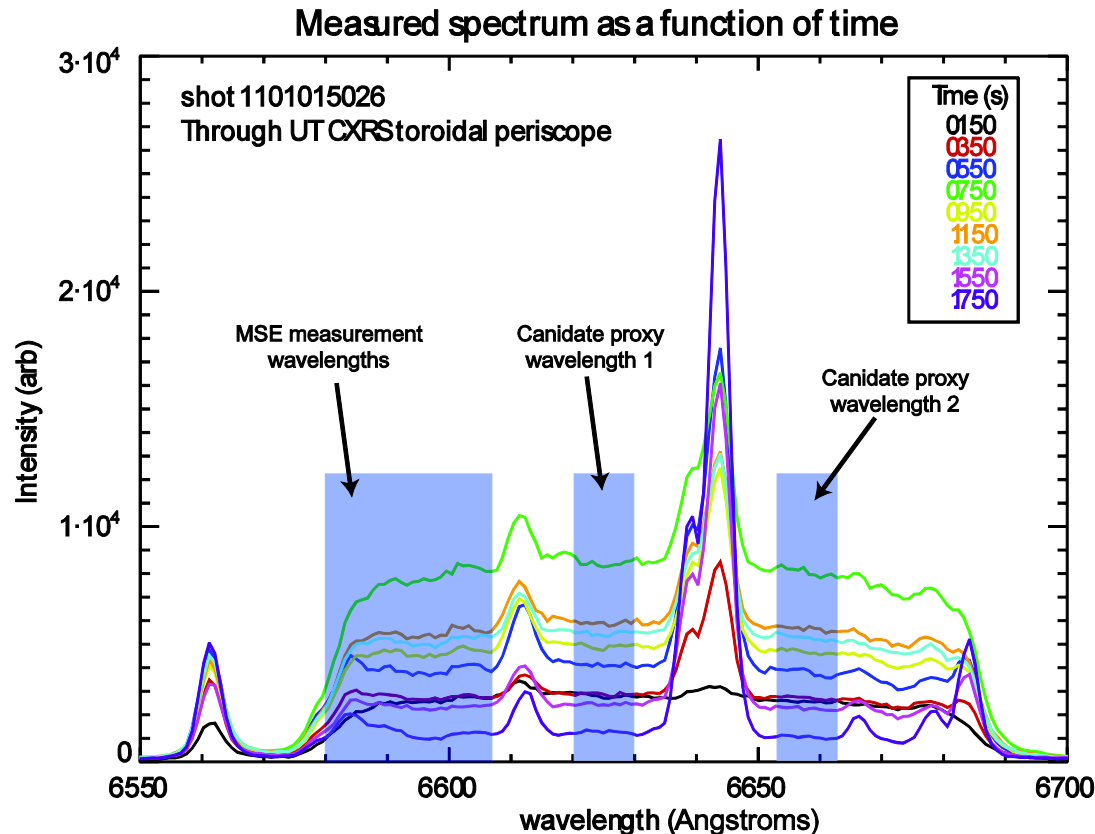


Although the absolute intensity of the spectrum changes by a factor of ~ 10 throughout the shot, the relative change between the MSE background and the proxy background is much slower

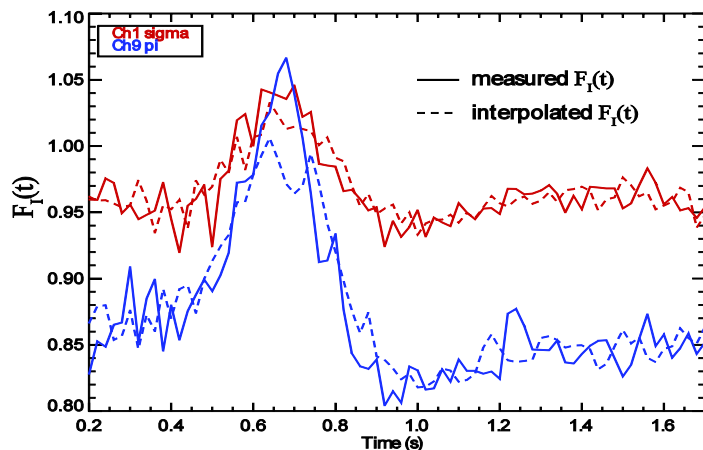
Proof of principle using spectrometer at different wavelengths (but not polarization sensitive)

Key idea: Measure the polarization at multiple wavelengths.
Interpolate in wavelength in-addition-to/instead-of time.

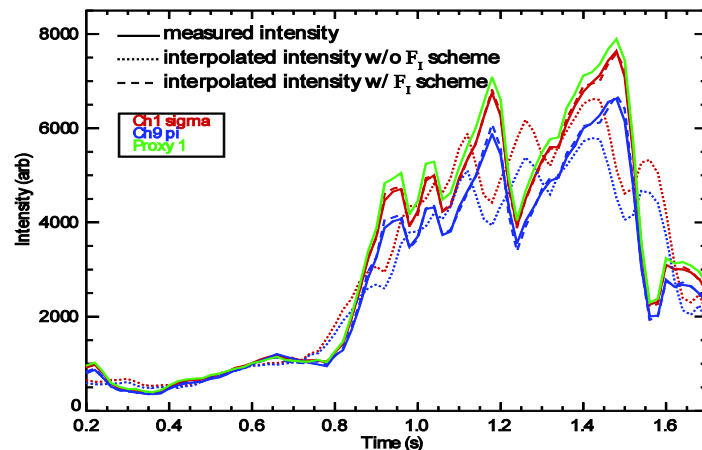
- Use a polychromator to measure polarization along same view cord.



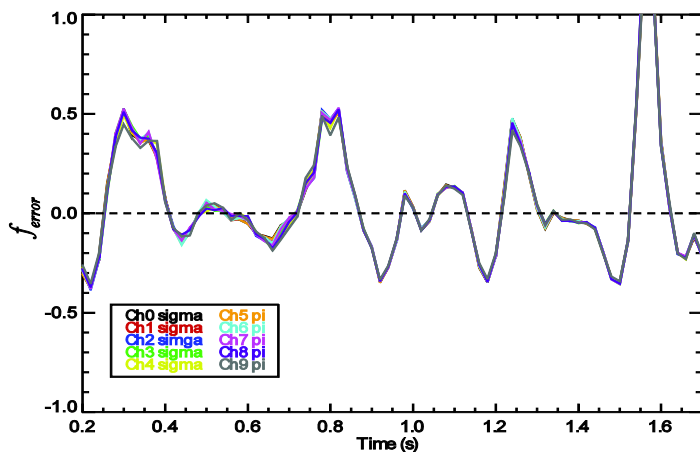
Possibility of a real-time background subtraction method using a proxy wavelength to reduce f .



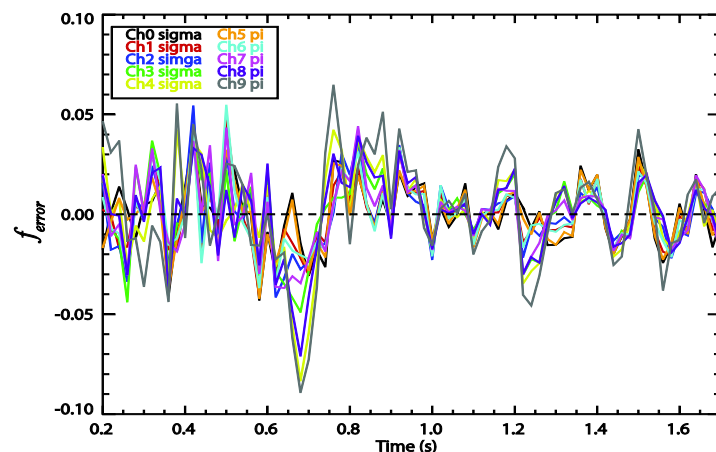
F_I calculated between 2 MSE ch wavelengths and proxy 1 wavelength. Notice how the interpolated F_I follows the actual F_I closely.



Intensity of two MSE channels and the proxy wavelength compared to reconstructions using normal interpolation (dotted) and the F_I scheme (dashed).

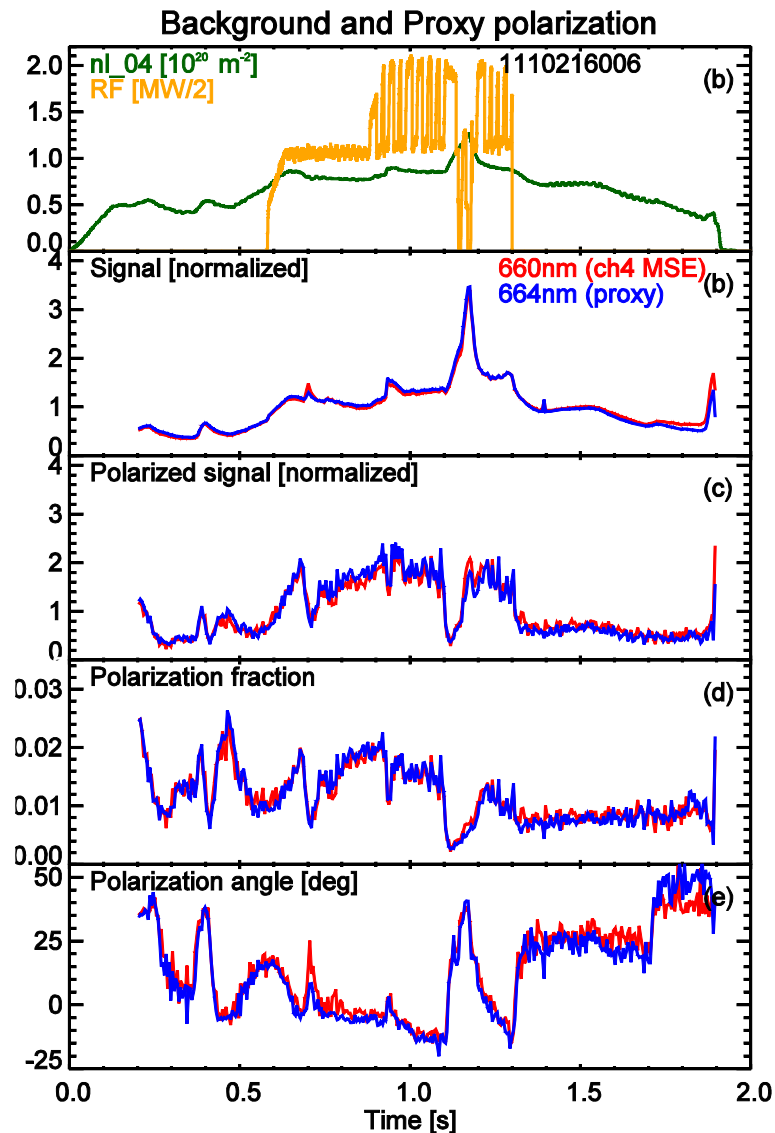


f_{error} between MSE σ wavelengths (ch 0,1,2,3,4), MSE π wavelengths (ch 5,6,7,8,9) assuming no proxy subtraction. Note the scale.

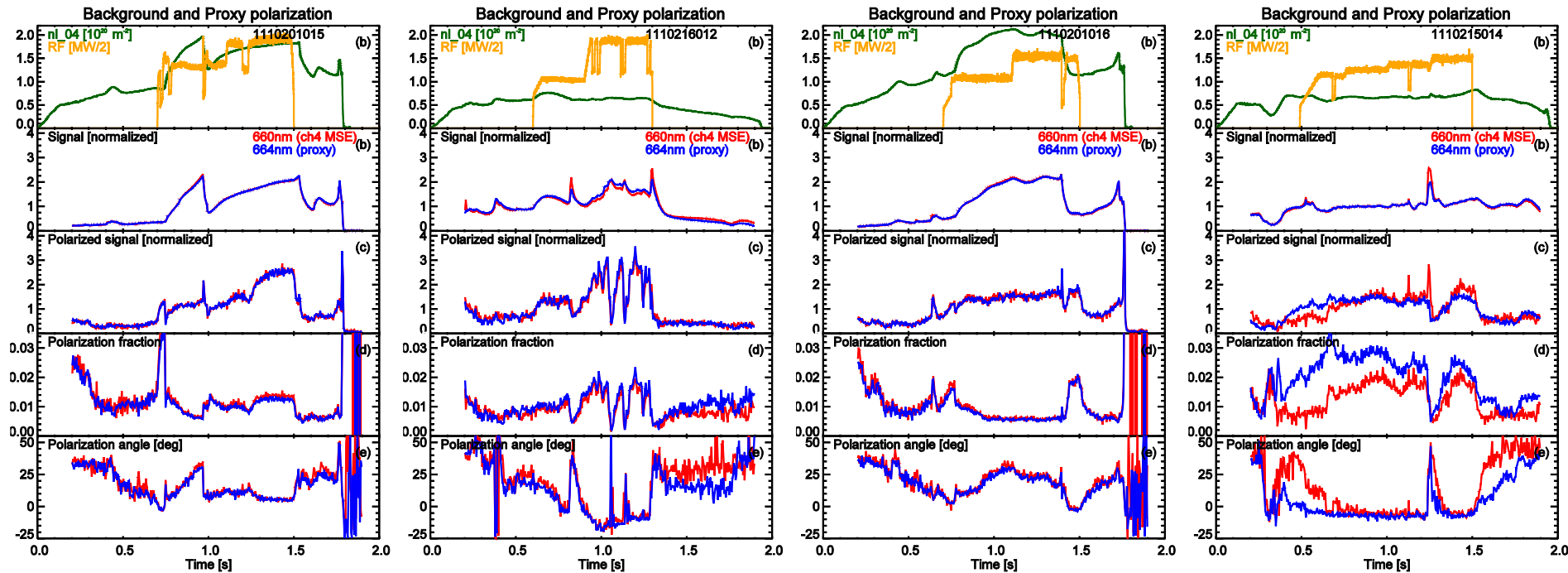


f_{error} between MSE σ wavelengths (ch 0,1,2,3,4), MSE π wavelengths (ch 5,6,7,8,9) and proxy 1 wavelengths.

Proof of principle design by splitting MSE sightline into two filters and detectors.



Proof of principle design by splitting MSE sightline into two filters and detectors.



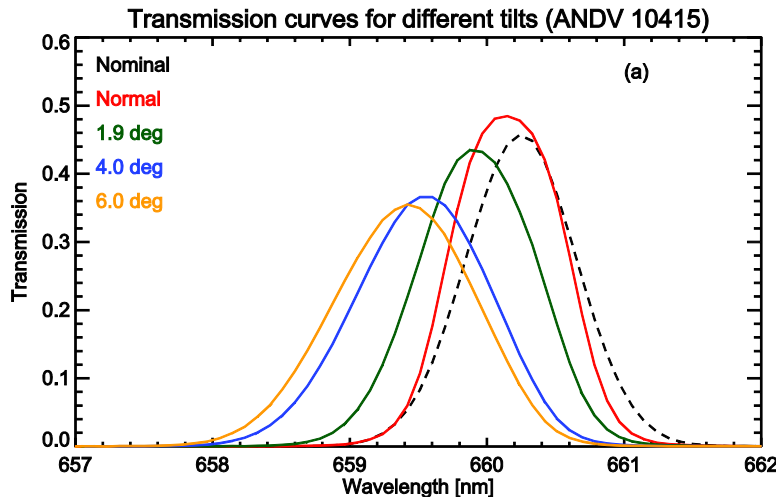
Polychrometer

Optical design completed, components procured.

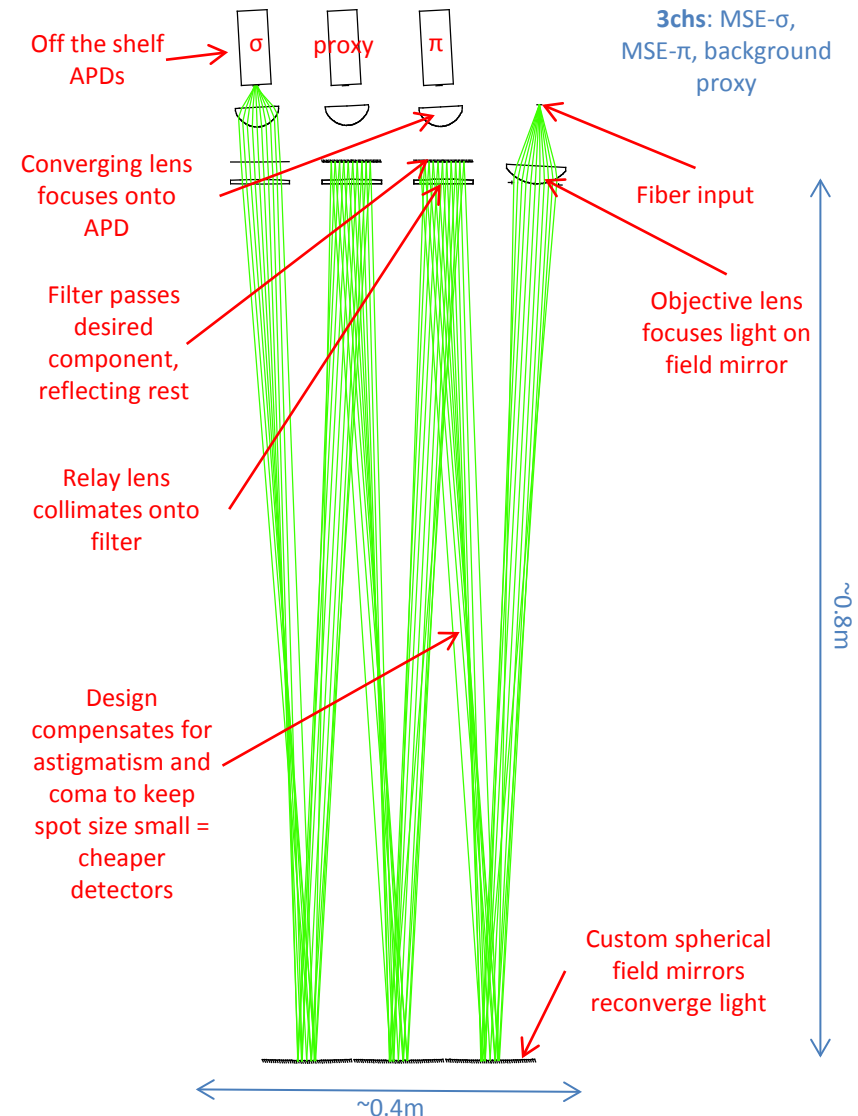
First channel operation 5 weeks out.

Polychromator design

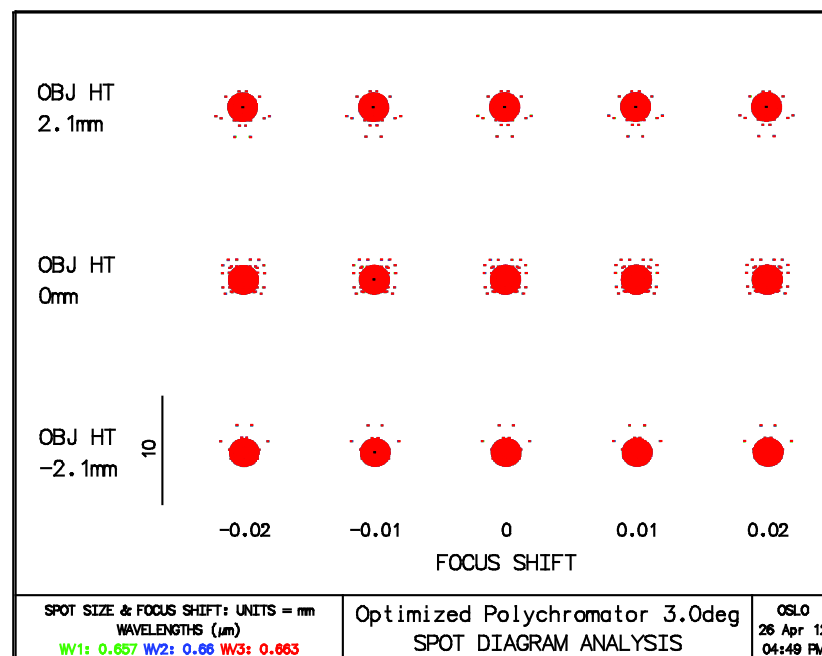
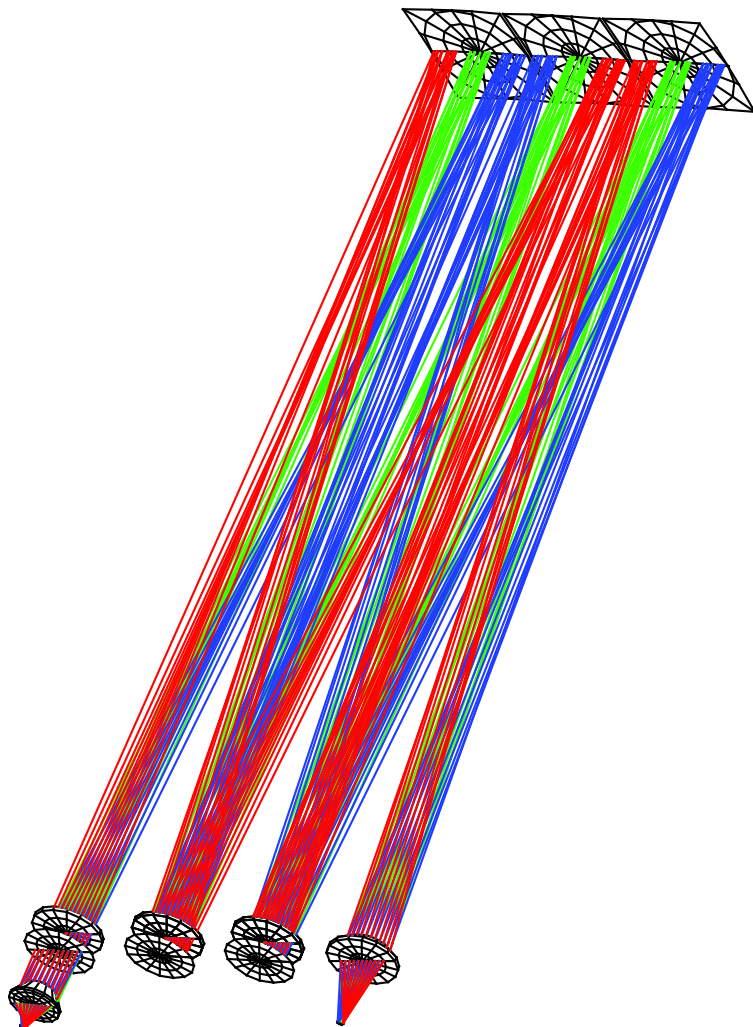
- Minimize off-normal AOI and cone angles
 - Tilt = 3°, cone angle = 2.3°
 - Effect on filter functions measured
- Optical design complete. Lenses, APDs procured
- Custom field mirrors being fabricated
- Mechanical design underway
- Filters for sigma, pi and red side proxy in hand
- Deploy in late June/early July
 - Piggyback runs
 - Does not affect MSE availability



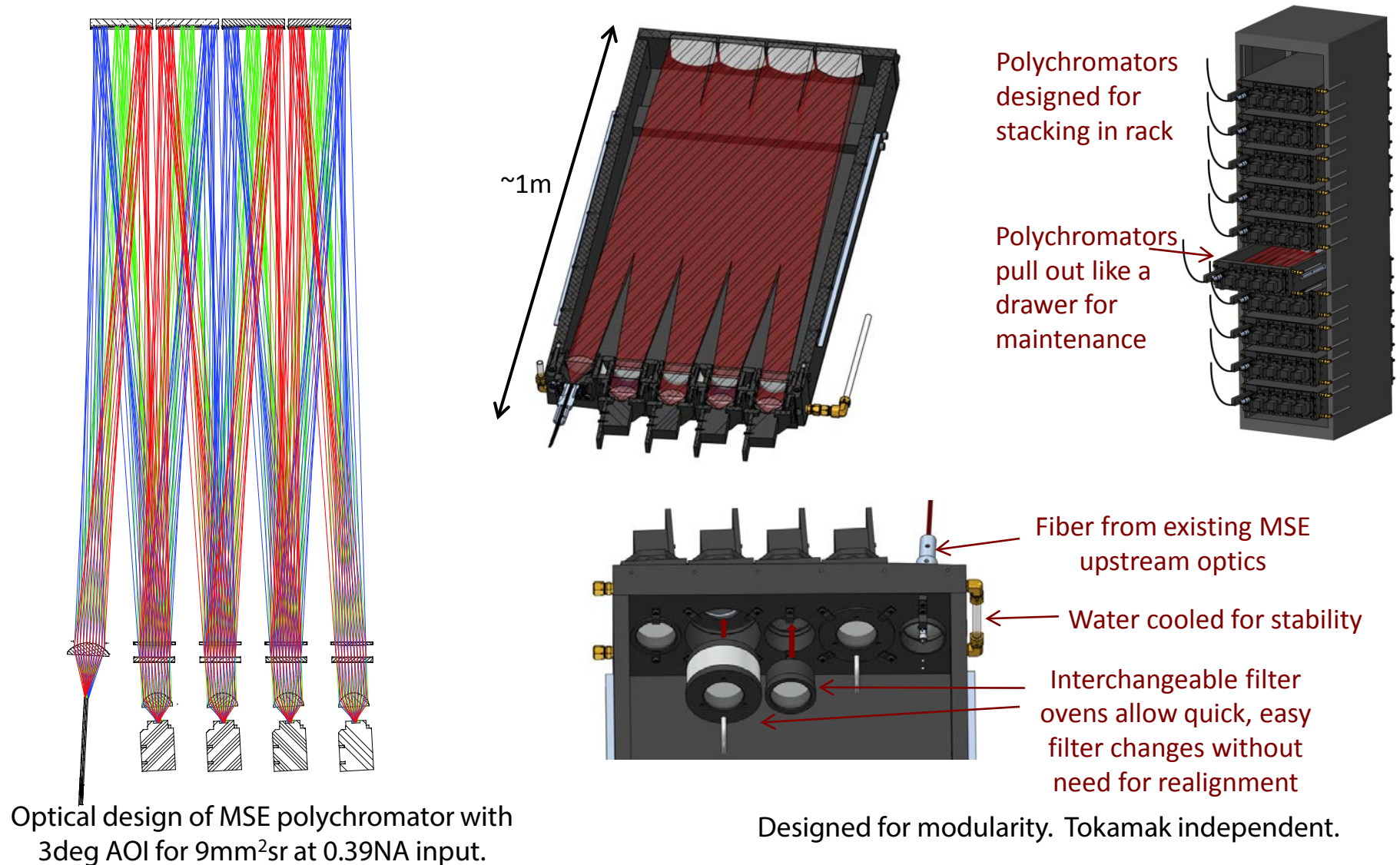
Filter shifts due to tilting measured in situ to inform the allowable tilt angle of background subtraction polychromator



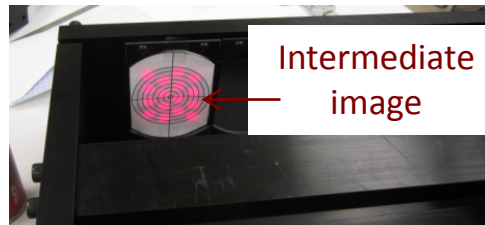
Polychromator optical performance



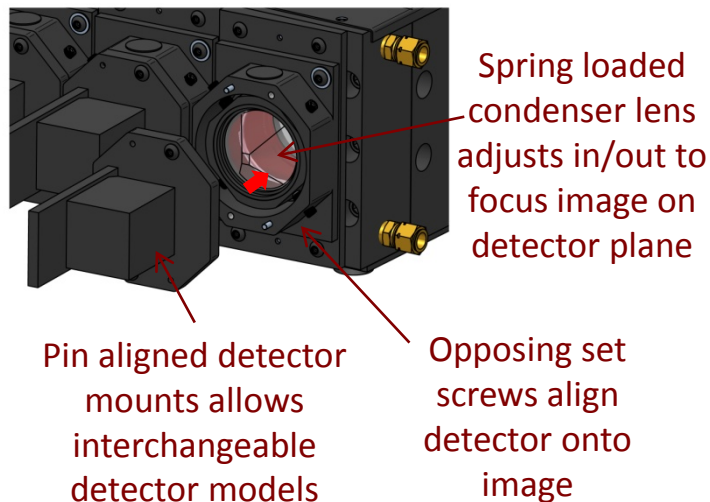
Use an interference filter based polychromator with APDs to measure the polarization at several wavelengths.



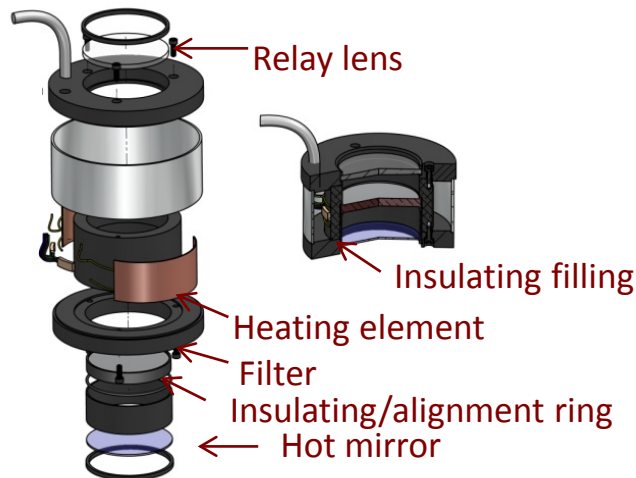
A prototype 4 wavelength polychromator was built and operated during the FY12 campaign.



Single sightline, 4 wavelength polychromator prior to installation in MSE rack

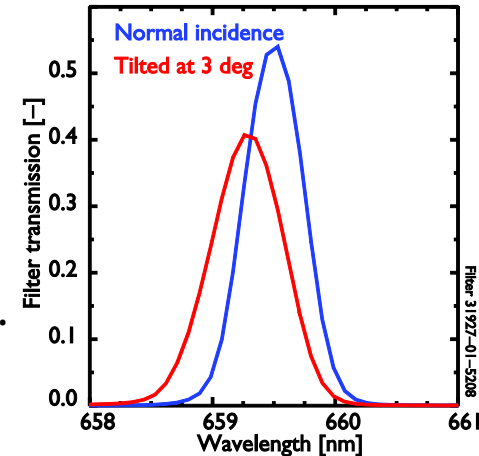


- Good transmission: ~1.2% loss per optical transition (86%, 81%, 76%, 70% ports 1-4 vs 95% in previous 1 detector system)
- ~1.7nm of filter tuning with sub angstrom accuracy using heaters.
- Interchangeable detectors

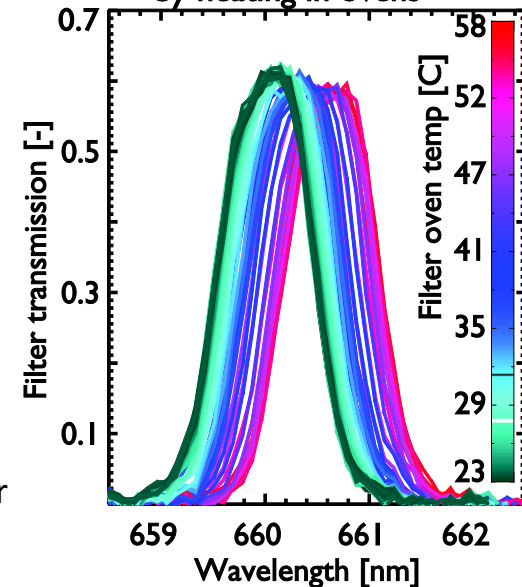


Low cost custom filter ovens tunable from 25C to 120C, allowing ~1.7nm filter bandpass tuning (redshift). 2 sealed ovens per polychromator.

Filter functions measured with tilt in-situ



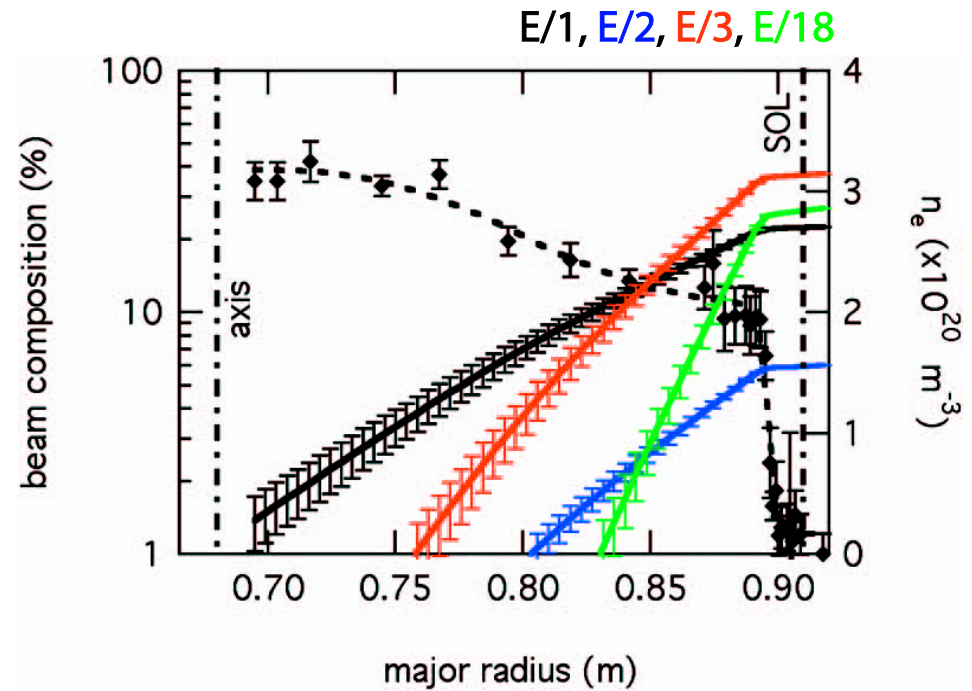
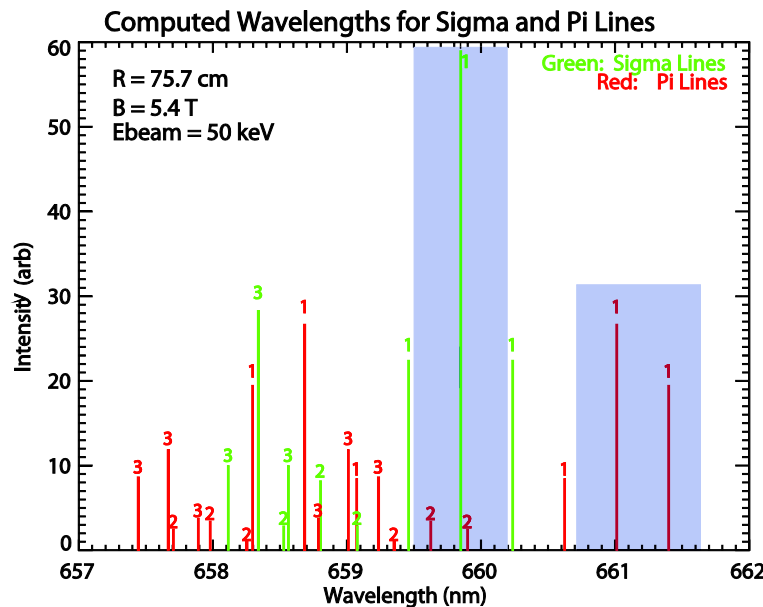
Filter bandpasses tuned by heating in ovens



Extend the system to measure E/1 σ component to increase SB.

Can also add a channel to measure the central σ triplet.

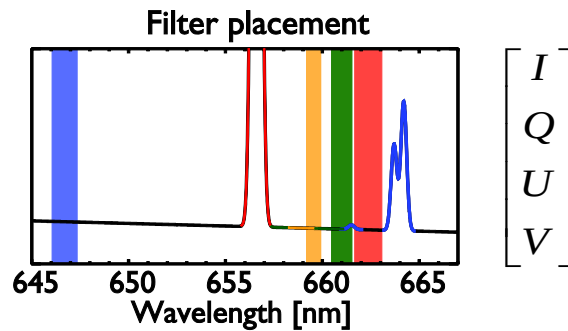
- π - was chosen to avoid contamination from E/2 π - lines. C-Mod's beam has typical density fractions of (0.21, 0.08, 0.45, 0.26) (E/1, E/2, E/3, E/18) (at neutralizer)
- σ and π are polarized perpendicular, therefore contamination leads to net depolarization, not an error in angle.
- The lower energy fractions are attenuated before reaching the core.



Beam component composition and penetration calculated for C-Mod. Bepamyanyov, RSI (2008)

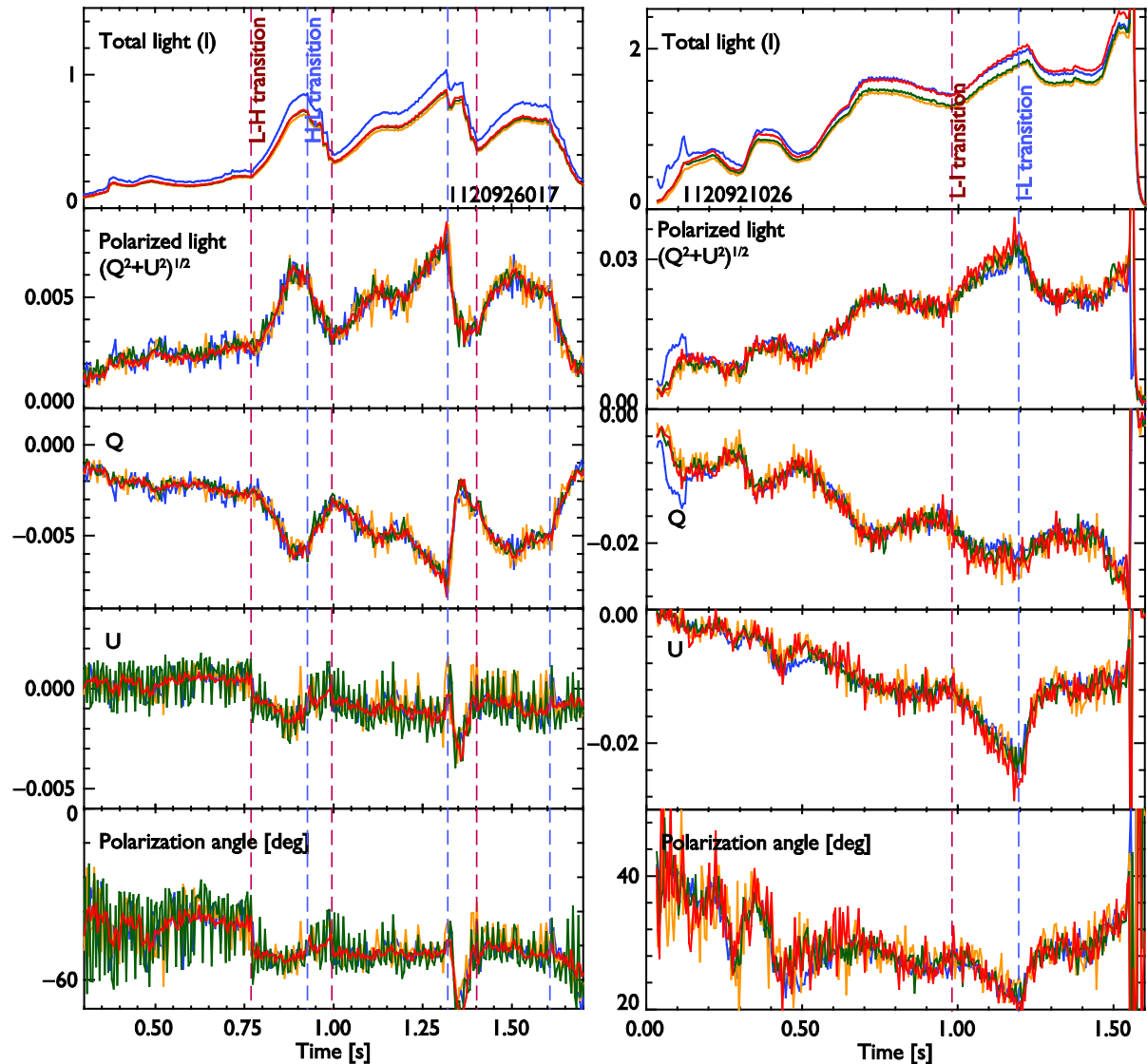
Polychrometer results

Polarization at adjacent wavelengths highly correlated even as background changes significantly.

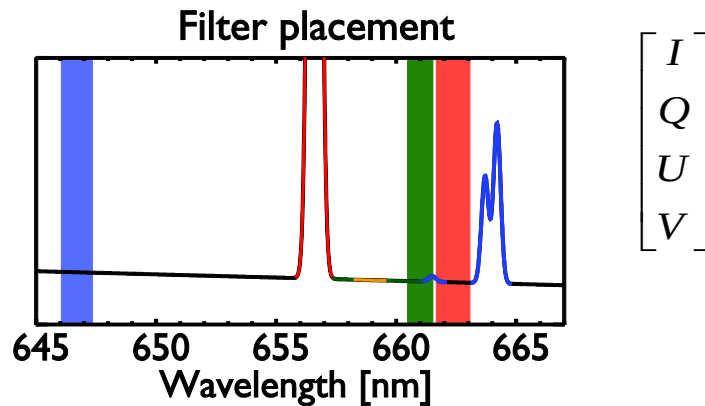


Polarization of the different spectral regions agree

- Over entire discharges
- Over plasma transitions when contributions from different sources are changing
- Result independent of MSE sightline

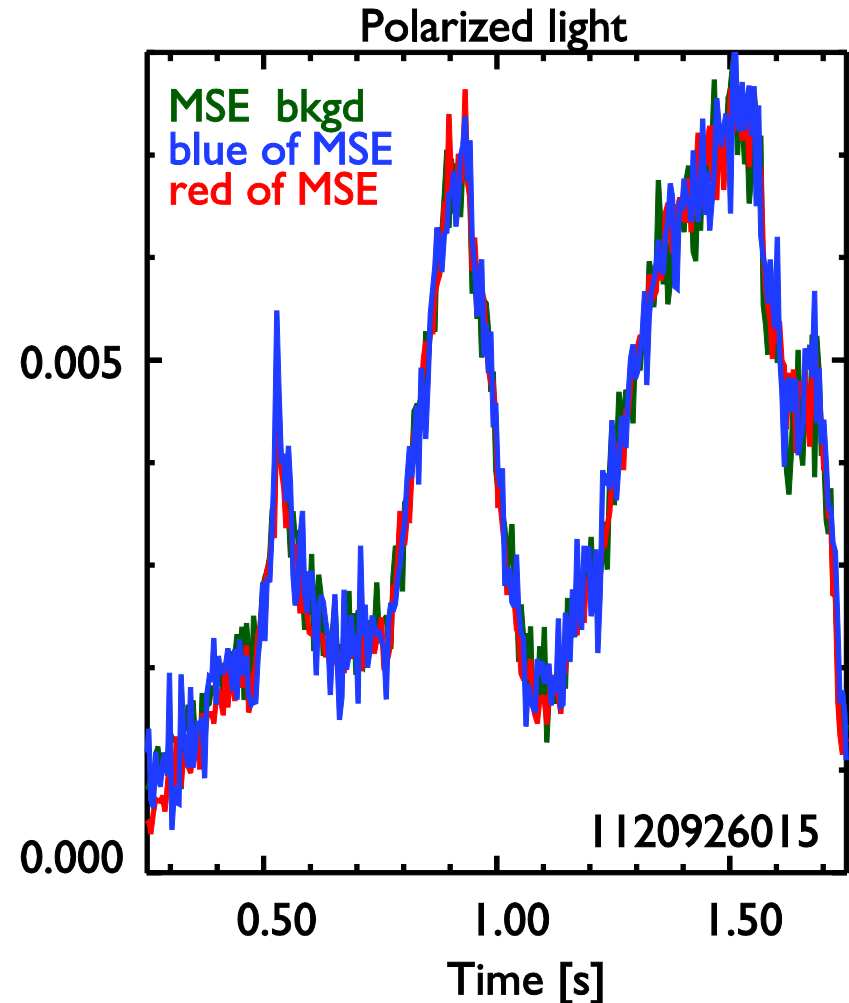


Polarization at adjacent wavelengths highly correlated even as background changes significantly.



Polarization of the different spectral regions agree

- Over entire discharges
- Follows the transients well



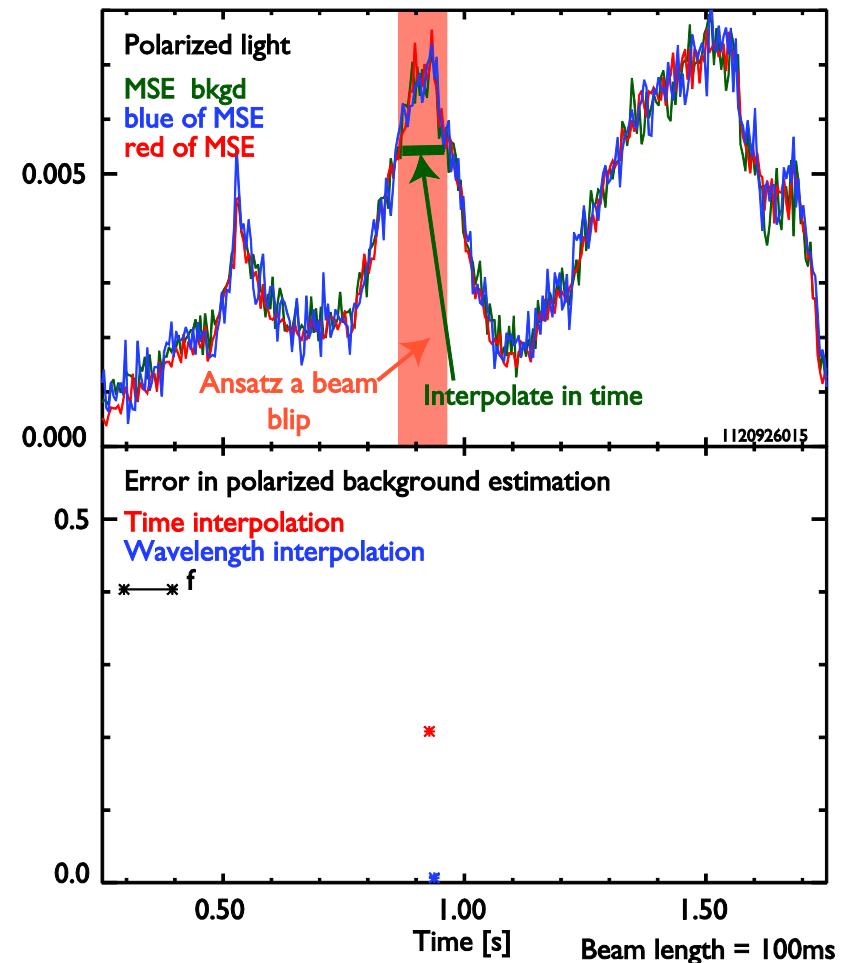
Apply scheme to data: Wavelength interpolation handles plasma transients much better

- To test system using actual (no beam emission) data we ansatz a beam blip and calculate relative error:

$$f = \text{abs} \left(\frac{1}{n_{\text{time points}} \text{ beam length}} \sum \frac{P_{\text{MSE}} - P_{\text{estimate}}}{P_{\text{MSE}}} \right)$$

P_{MSE} = measured polarized MSE background

P_{estimate} = polarized MSE background estimated using time or wavelength interpolation



Ansatz a beam blip and calculate relative error

Apply scheme to data: Wavelength interpolation handles plasma transients much better

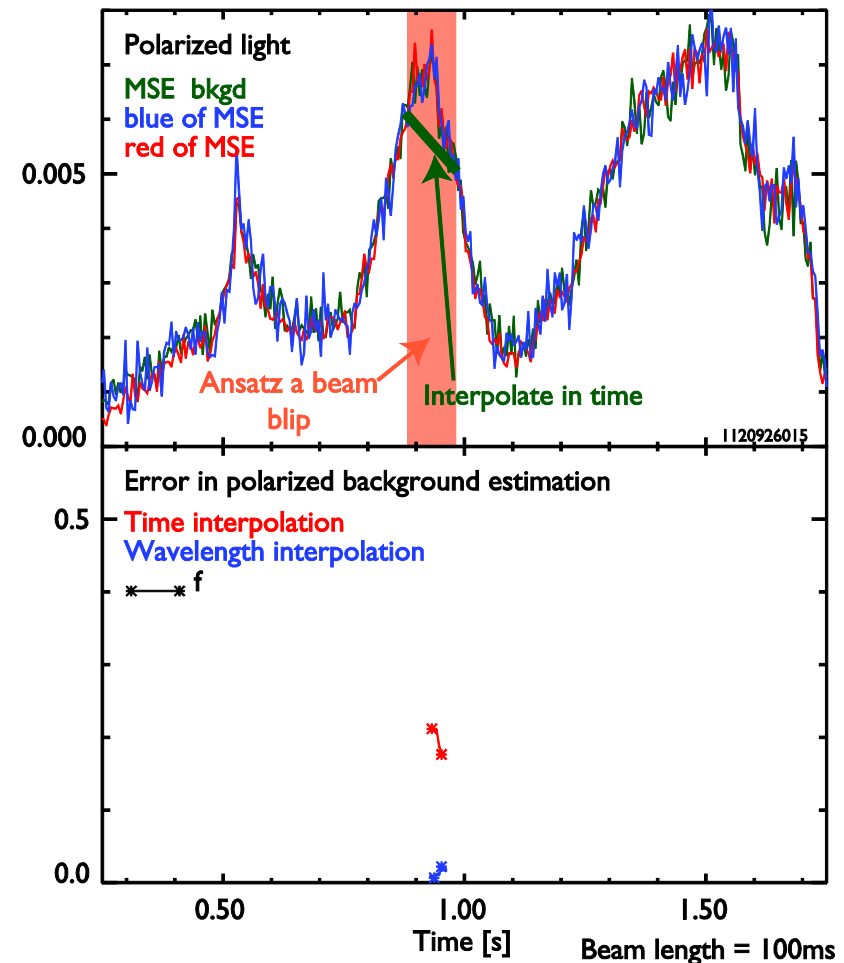
- To test system using actual (no beam emission) data we ansatz a beam blip and calculate relative error:

$$f = \text{abs} \left(\frac{1}{n_{\text{time points}} \text{ beam length}} \sum \frac{P_{\text{MSE}} - P_{\text{estimate}}}{P_{\text{MSE}}} \right)$$

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P_{estimate} = polarized MSE background estimated using time or wavelength interpolation

- Repeat for all possible beam blips



Ansatz a beam blip and calculate relative error

Apply scheme to data: Wavelength interpolation handles plasma transients much better

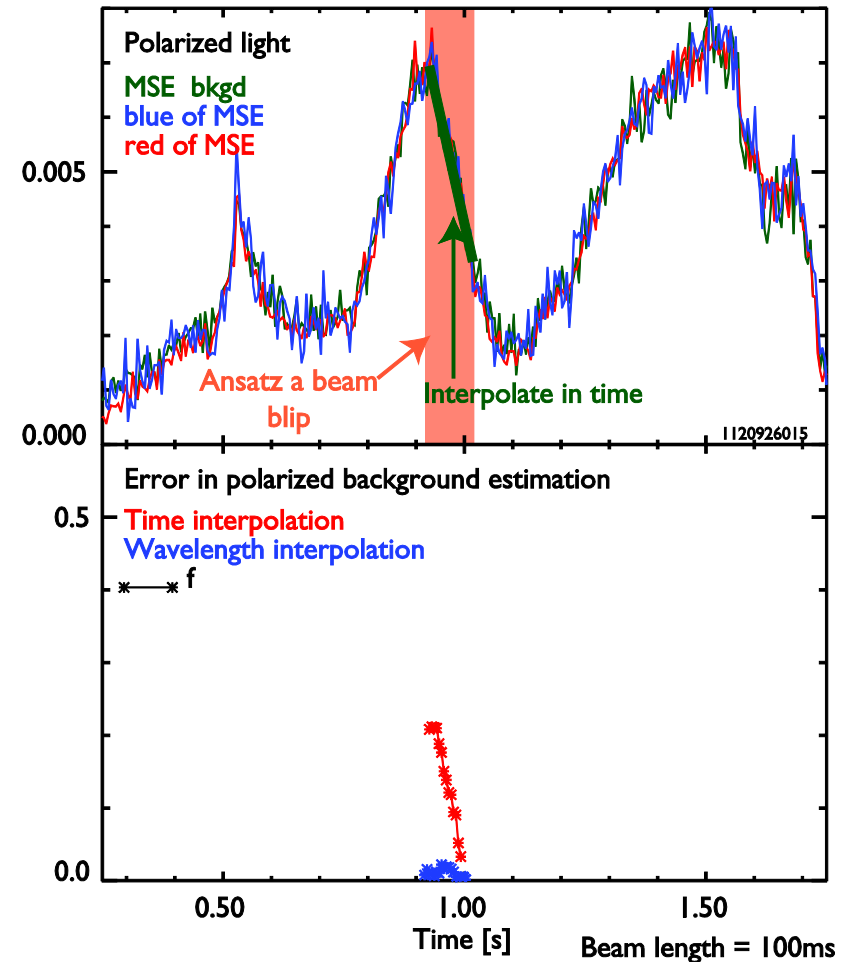
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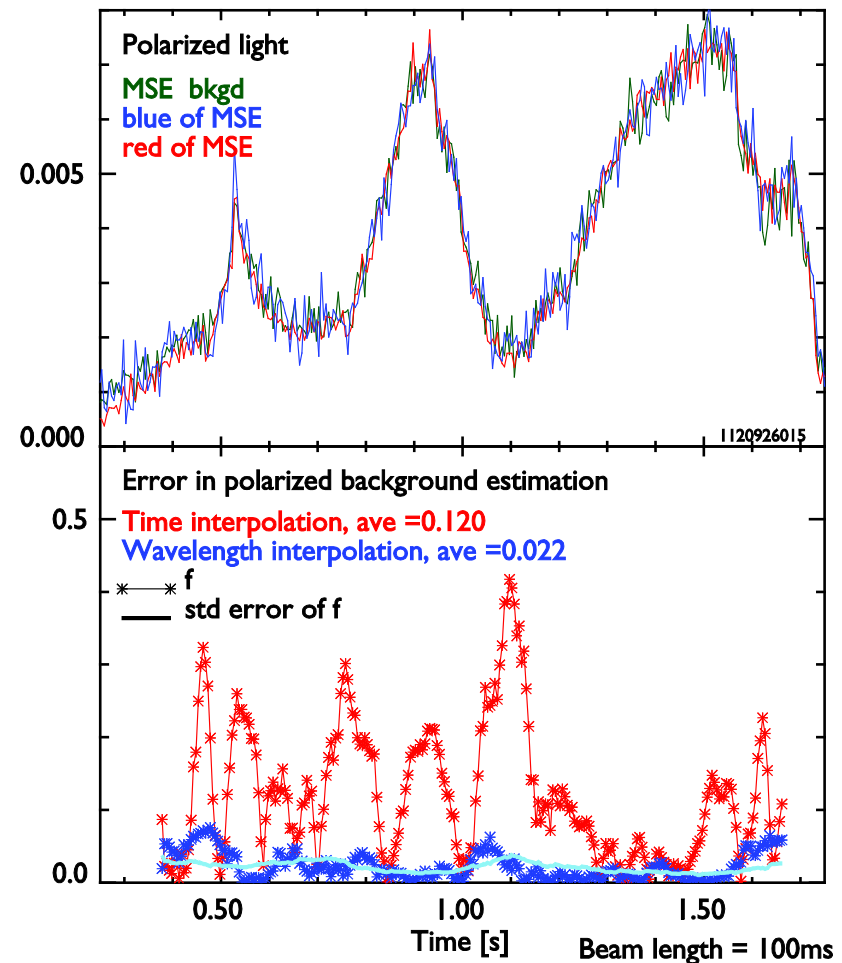
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- Repeat for all possible beam blips

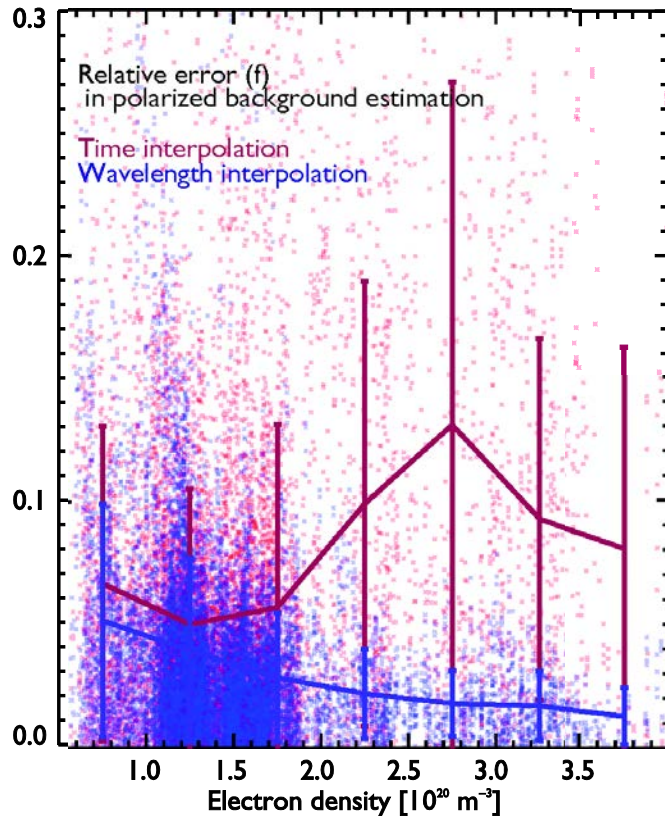
Result (for this shot):

- Wavelength interpolation does 10-50x better during transients
- Averaged over all possible beam pulses wavelength interpolation does 6x better
- Wavelength interpolation performs at the noise limit



System does 5 better overall, 10x better at low signal to background levels.

Wavelength interpolation
excellent at high densities



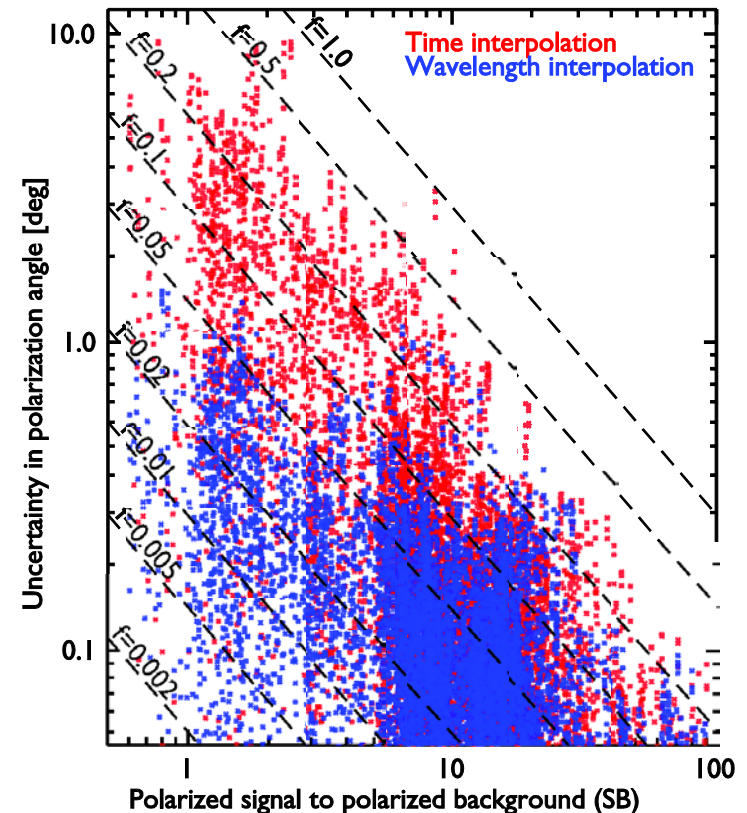
100ms beam length

- No effort made in wavelength interpolation system to minimize noise.
 - Use wider bandpass, higher transmission filters to decrease sampling noise

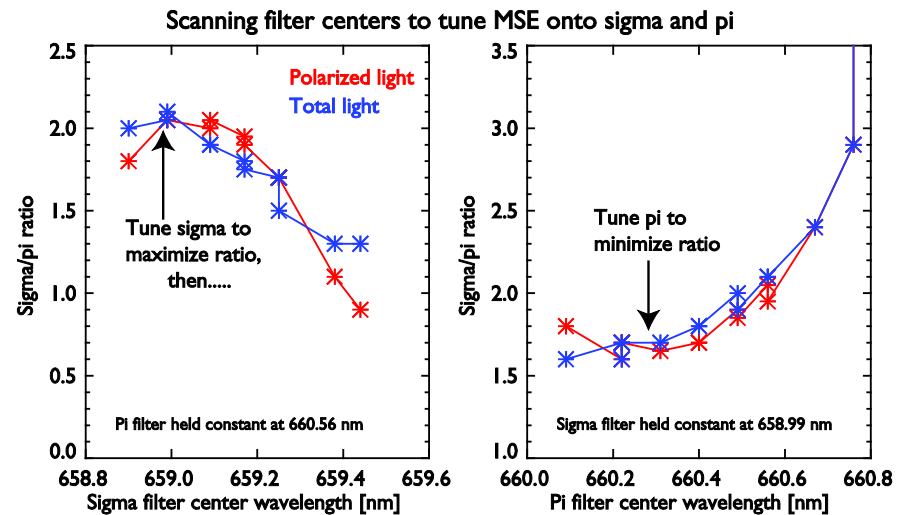
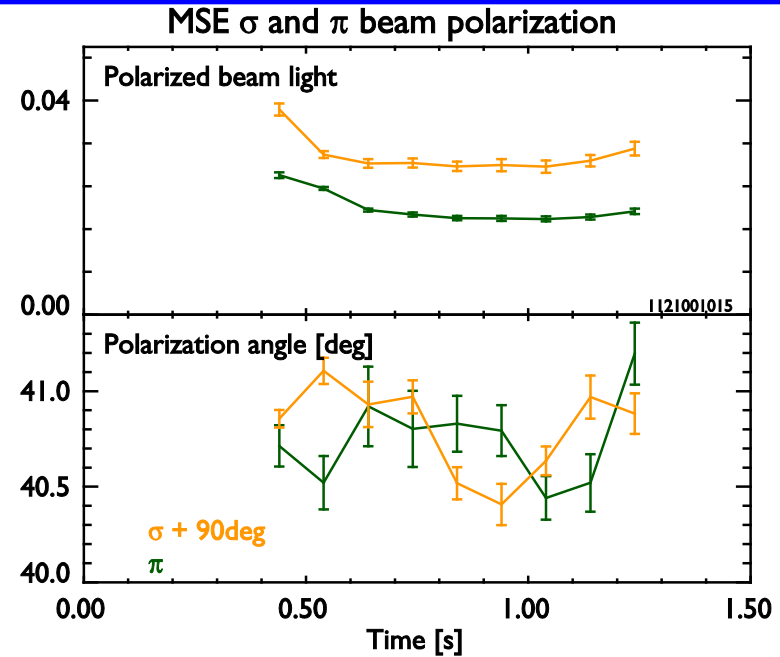
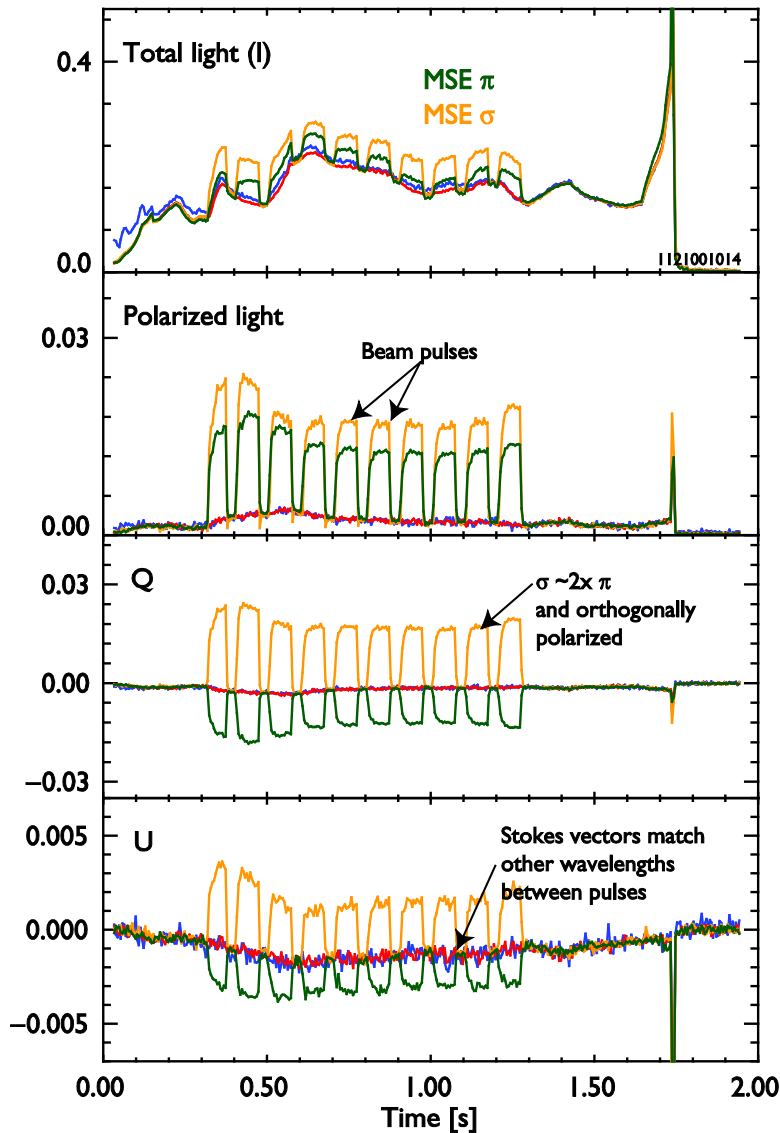
Use an empirical
scaling to map
density to typical
SB.
Calculate resulting
polarization
uncertainty



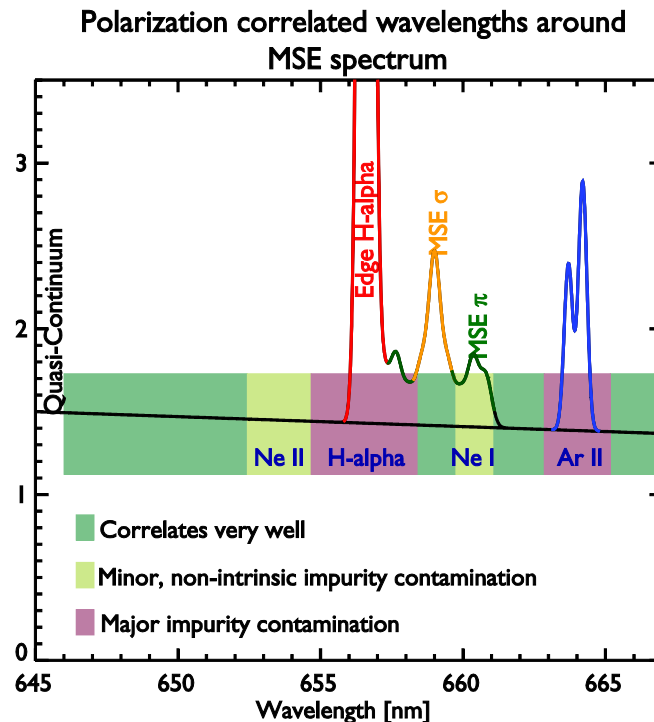
Wavelength interpolation
performs well at low SB



More sigma and pi measurements

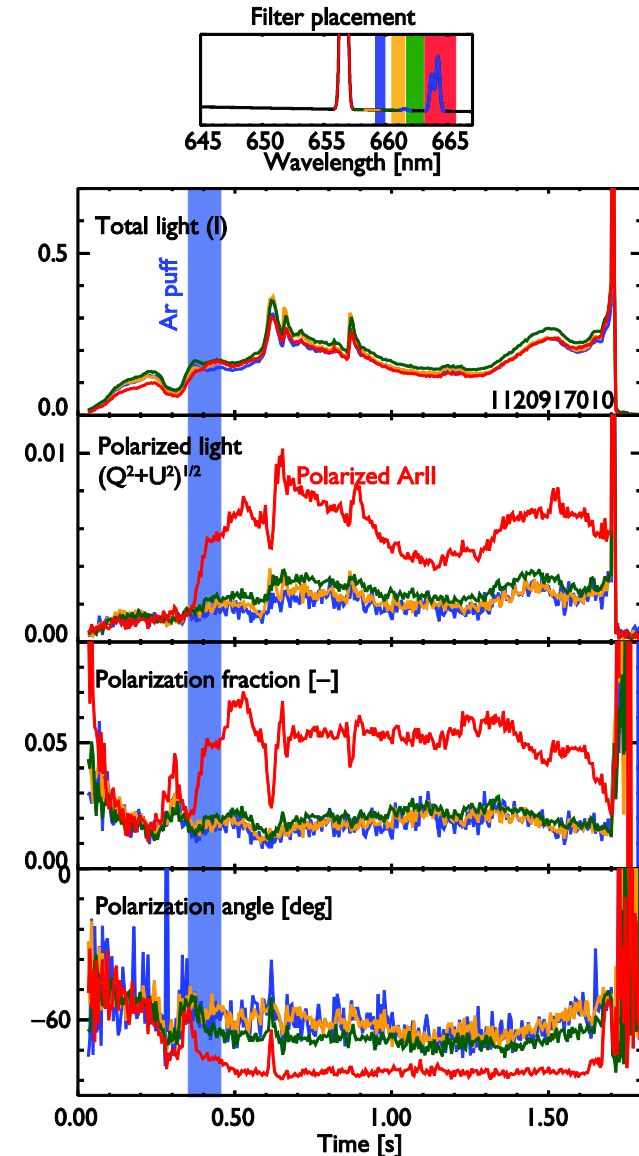


Spectral region around MSE correlates well with MSE background provided impurities are avoided



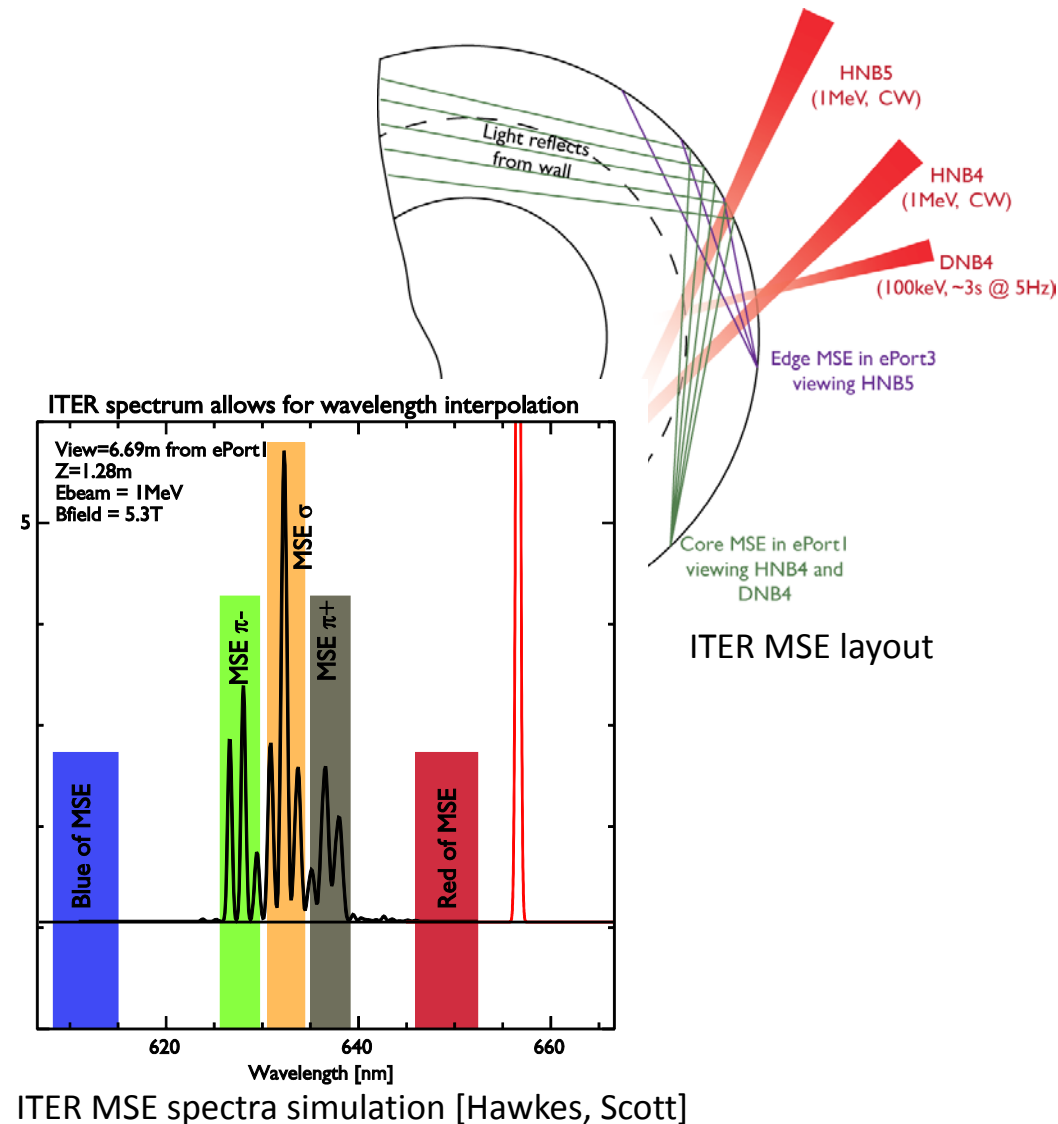
Using various filters the spectral area around MSE was scanned. Much of spectral area correlates well with MSE background

- Areas identified for future use
- Minor impurities require more frequent re-normalization
- Major impurities must be avoided



Similar background subtraction system will likely be required on ITER.

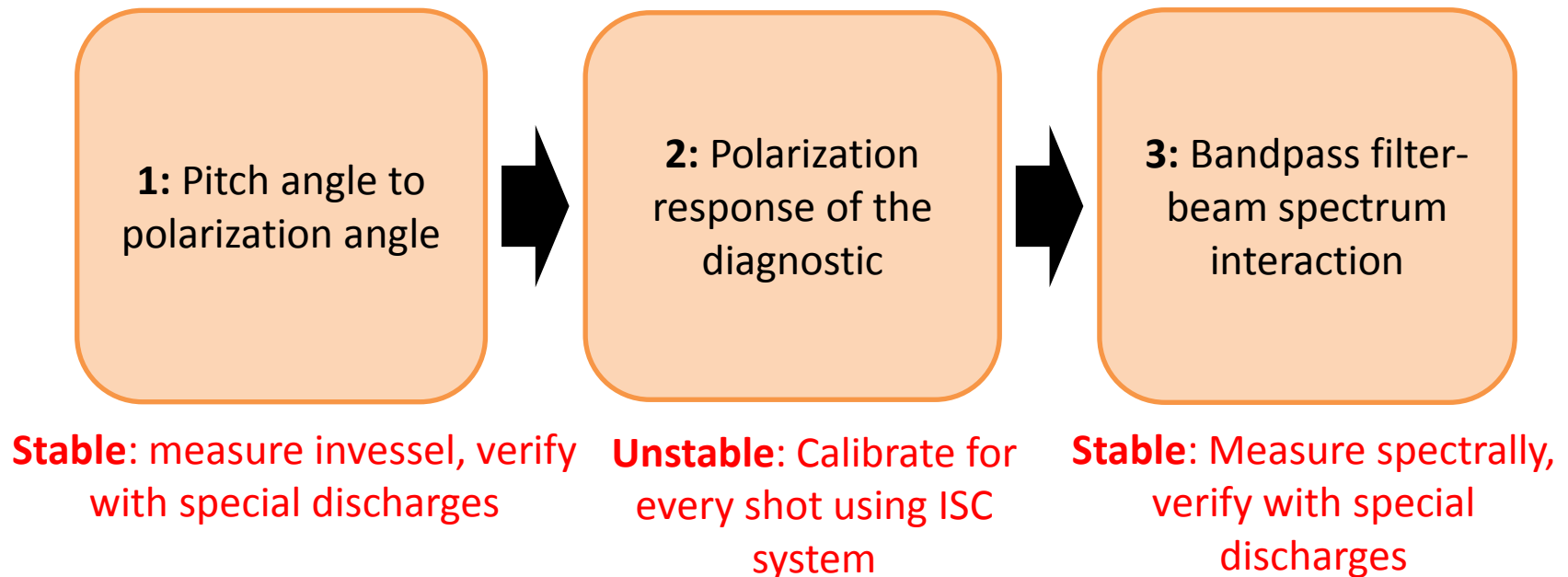
- ITER's MSE system will likely have a polarized signal to background ratio of $<1-10$ due to:
 - Poor beam penetration
 - Reflective metal walls
 - Large, bright plasma
 - Glowing divertor
- Beams will be CW with rare blips off
- However, there are good things:
 - JET studies indicate spectrum is clear of impurities
 - Large Stark shift fully separates the multiplet
 - Negative ion sources only produce full energy
- A good candidate for wavelength interpolation background subtraction



Calibration strategies

New paradigm in calibrating MSE diagnostics. Other institutions interested in results.

- In-situ system tracks the temporally changing component of the calibration.
- Special discharges only need to be performed a few times a campaign, improving diagnostic availability.
- Important as diagnostic access becomes rarer, MSE systems become more complex, environments become harsher and calibration discharges become administratively limited in future devices.



Have a range of calibration options to test the system

Increasing control over input $\longrightarrow$

Can use in vacuum during a shot

Can use in air

Can use in vacuum at any time

Inputs

Polarized light
emitted by beam

Polarized light
emitted by ISC

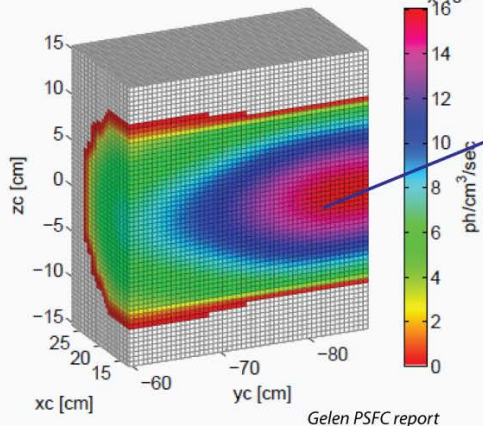
Polarized light
emitted by invessel
calibration system

MSE collection optics

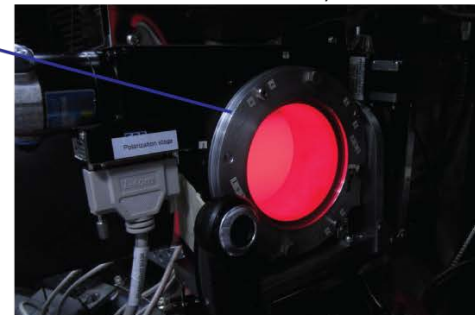
ISC source not quite uniform,
only fills ~80-90% of aperture

How MSE optics see view the ISC

Beam source is very
nearly Lambertian



Invessel source is Lambertian, well controlled

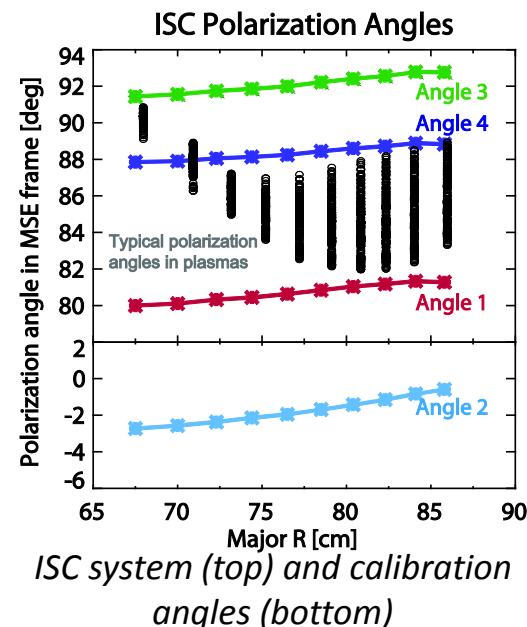


The ISC technique is a new way to calibrate MSE, fielded on C-Mod this campaign.

- Important when constraining magnetic reconstructions:
 - Absolute calibration of pitch angles
 - Accurate estimate of uncertainties
- ISC = (InterShot Calibration), first of a kind system
 - Positions and illuminates 4 calibration sources directly in front of the MSE objective lens
 - Gives diagnostic response to different 4 linear polarizations
 - Operates immediately after the shot
- A new way to calibrate a MSE diagnostic:

MSE calibration techniques

	Beam + fields	Invessel access	ISC
Assumes diagnostic constant over:	Shot-to-shot, runday	campaign	10sec
Uses machine run time	Yes, lots	No	No
Captures Faraday rotation	Yes... for a limited range	No	Yes
Major limitations	Secondary emission (Beam into gas)	Matching beam geometry, illumination	???



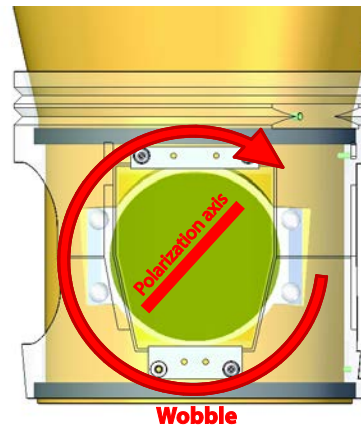
ISC

ISC designed to provide constant angle



Spring aligns WGP in calibrator while still allowing thermal expansion.

Each of 4 WGP's are spring aligned into calibrator, each with a backlight diffuser.



Degrees of freedom (DOF) of WGP controlled by tight tolerances on the running clearances. Choice of materials and bushing thickness ensures critical axial running clearance is constant with changes in bulk temperature. Actuator with feedback system used to control the one free DOF (rotation about z).

Design features:

- Only one moving component (calibrator)
- Calibrator doubles as a shutter for boronization and discharge cleaning
- WGP's kept aligned in calibrator with springs
- Calibrator rotates on precision VESPEL bushings
- Calibrator wobble controlled with tight bushing axial running clearance

- Temperature independent
- Adjusted using shims before installation

Calibrator rotated with stepper motor

- via 3m invessel cable-in-conduit
- 2 Linear vacuum feedthrus
- Potentiometer and load cell feedback

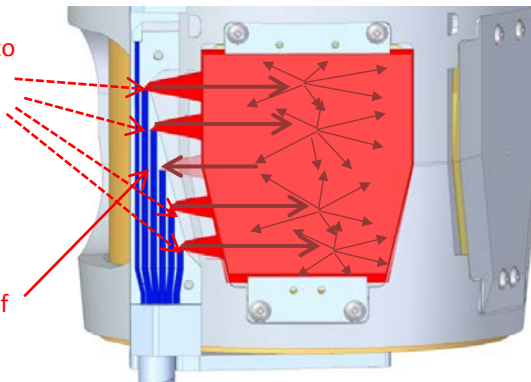
Stationary fiber optics used to illuminate backlight diffuser when a WGP is in front of lens

DOF	Constrained by	Target	Design (20C)
X,Y translation	Diametric clearance	<0.080"	0.010"
Z translation	Axial clearance	<0.080"	0.002"
Rotation about x, y (wobble)	Axial clearance	<0.05 deg	0.03 deg
Rotation about z	Actuator	<1 deg	0.5 deg

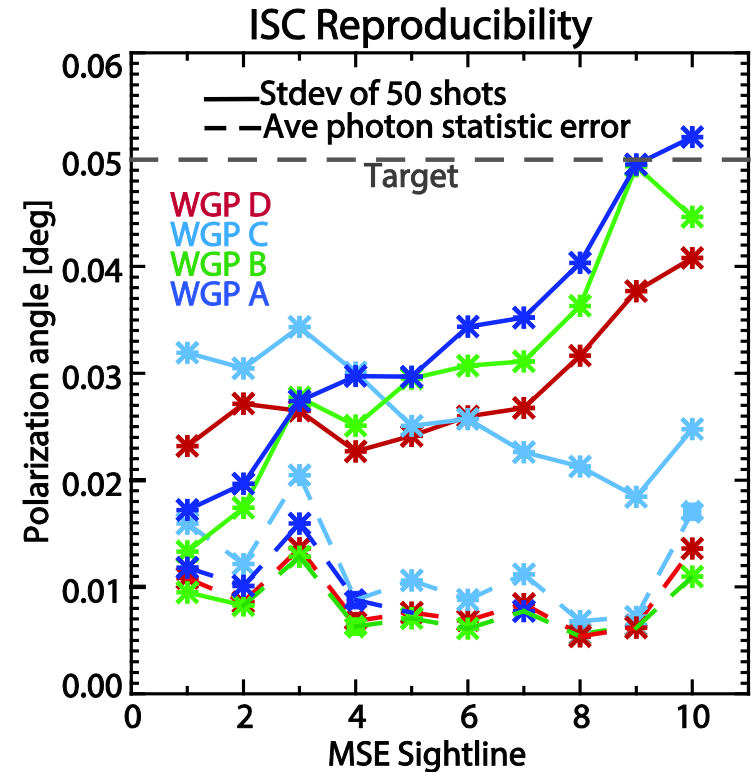
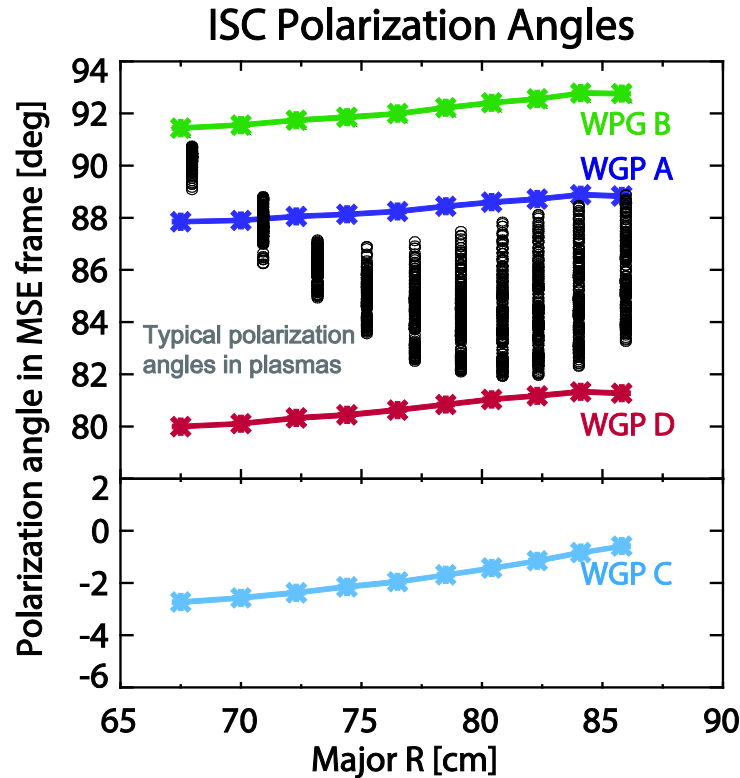
4 sets of fibers input light into the side of the calibrator

When system is properly aligned, light enters and scatters inside the diffuser

Some of the light exits the diffuser, enters the 5th set of fibers and is sensed by the position detector

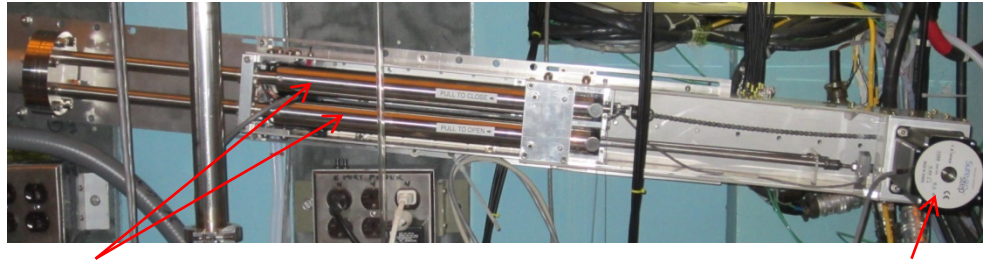


Angles allow for interpolation of diagnostic response. System reliable, repeatable, flexible.

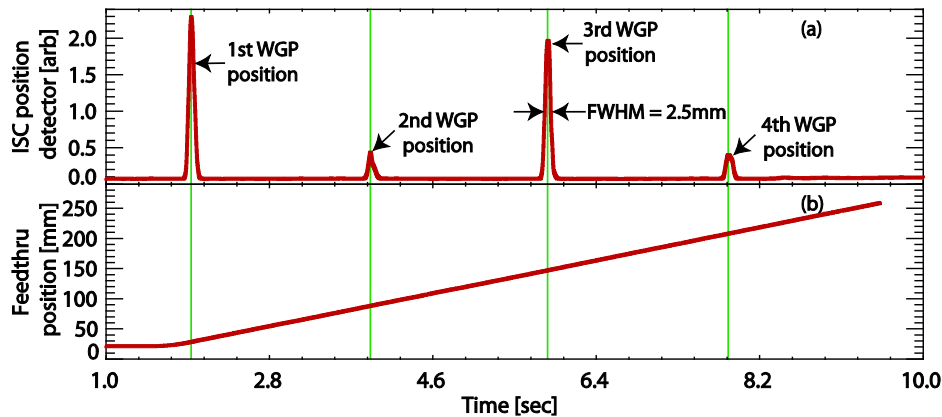


- Measurement of the 4 WGPs allows the plasma measurements to be corrected
- System is repeatable to $<0.05^\circ$
 - $>6,500$ cycles in vacuum to date
 - $>18,000$ cycles in air during engineering phase
- Allows checks of pump-down stress, PEM stability, Faraday rotation, lens heating etc.

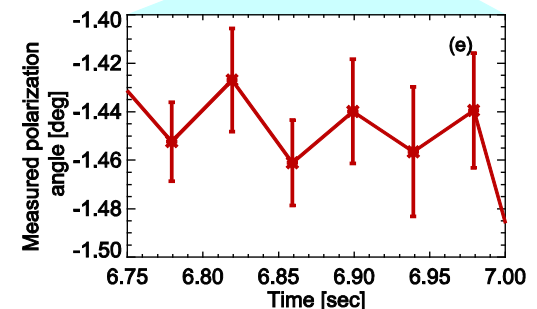
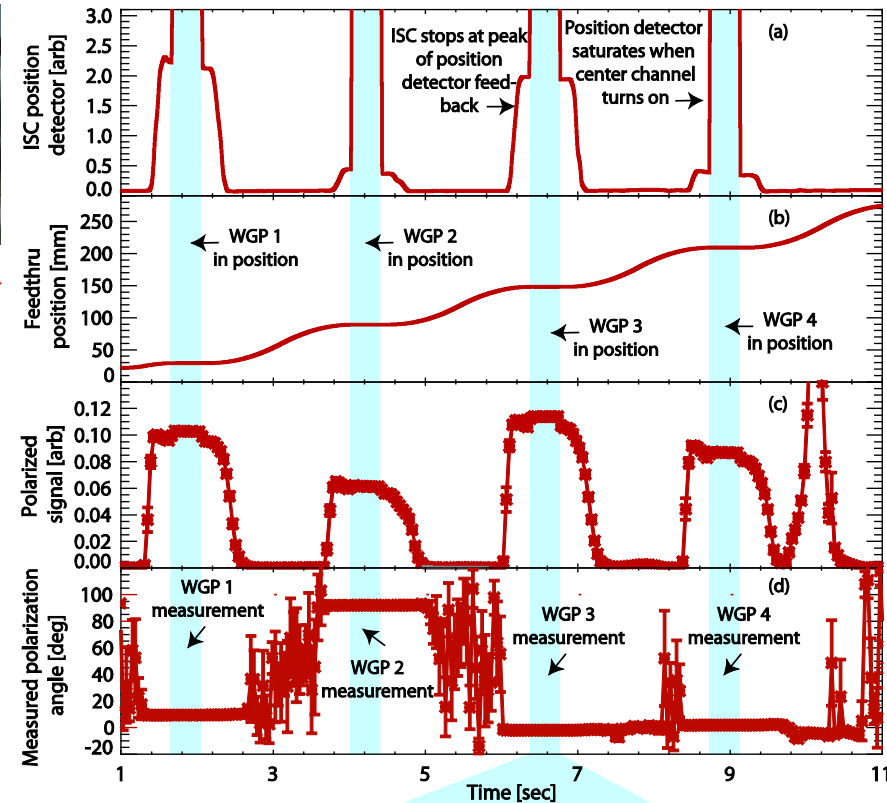
ISC actuated remotely with precision



Feedthrus Push-pull feedthru cable-in-conduit actuation system. Stepper motor



Position feedback from the central fiber/channel (a) as the actuator rotates the calibrator continuously (b). Note the feedback peaks as the light is scattered into and out of the backlight diffuser when the calibrator is in position.



ISC scorecard: Diagnostic does change and it is important to account for it.

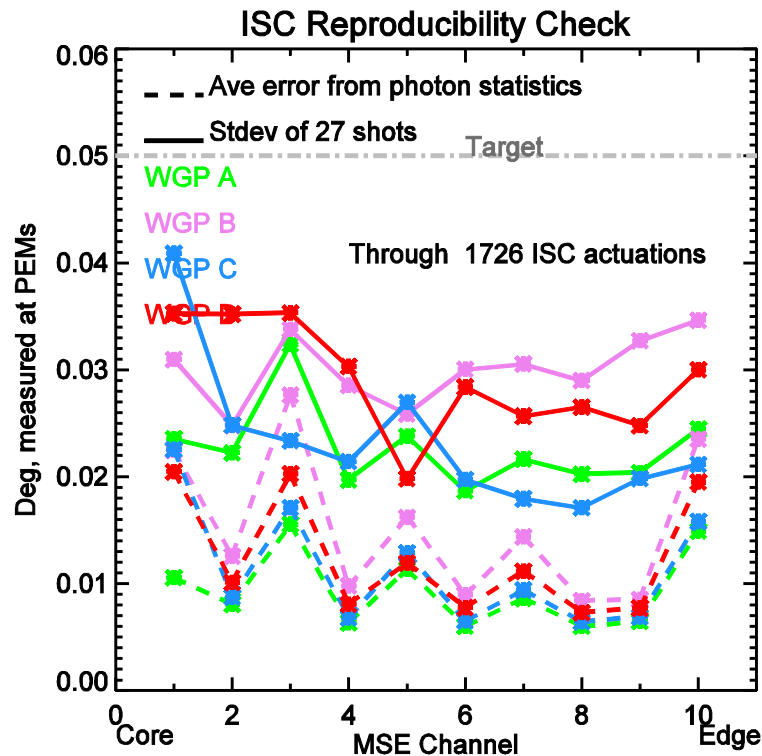
Effect	Change over runday	Change over weeks	Largest change observed	Can ISC correct for it?
VW pump-down stress	NA	NA		Yes
Faraday rotation	0.05°	NA	0.05° on a single shot	Yes
Non uniform illumination	0.05°	NA	NA	Relative changes- Yes, Absolute angle – Maybe
Lens and VW birefringence	0.40°	0.20°	0.90° over runday	Yes
Objective lens heating	< noise level	NA	0.15° on a single shot	w/ post-shot calibration, No w/ pre-shot calibration, Yes
PEM retardance drift	< noise level	0.05°	0.60° over days	Yes
PEM-detector phase shift	< noise level	< noise level	< noise level	Yes
PEM “being bumped” shift	NA	NA	0.20° one time event	Yes

- Changes in polarization angle shot-to-shot and across the runday are typically $\sim < 0.5^\circ$
- Changes across a campaign can be nearly 1.0°
- There are many ways for the diagnostic to change at the 0.1° level
 - ISC corrects for nearly all of them
 - Other calibration techniques cannot

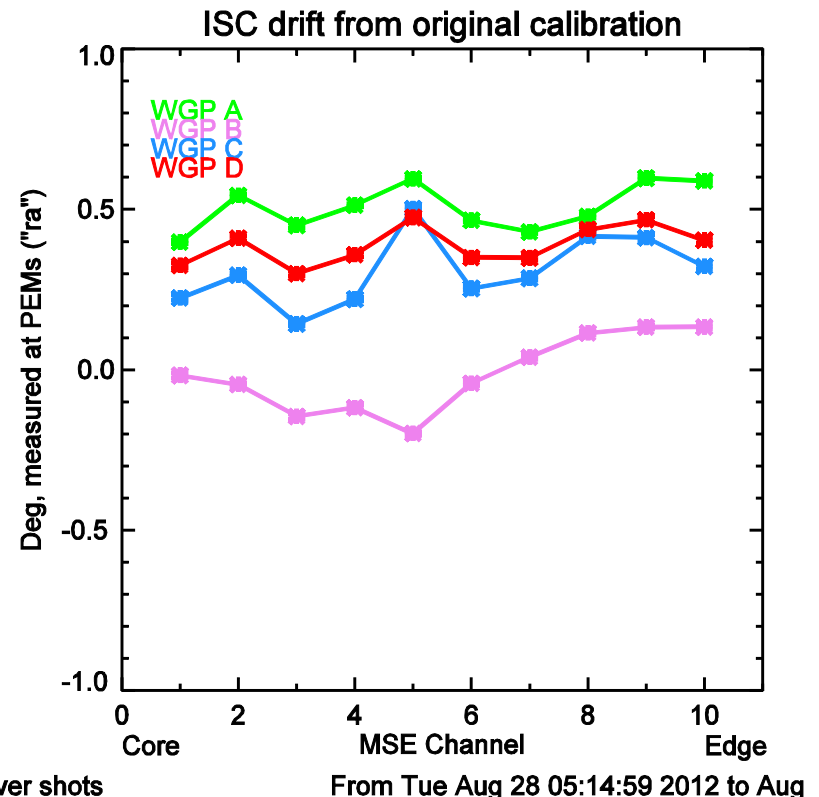
**MSE measurement goal: $< 0.10^\circ$*

ISC continues to be reproducible

- ISC actuates 25+ times early (4am) on Monday mornings when system is thermally stable to monitor reproducibility.
- Has not decreased as campaign has gone forward despite many actuations at temperature in vacuum



Note: calibration drifting over shots

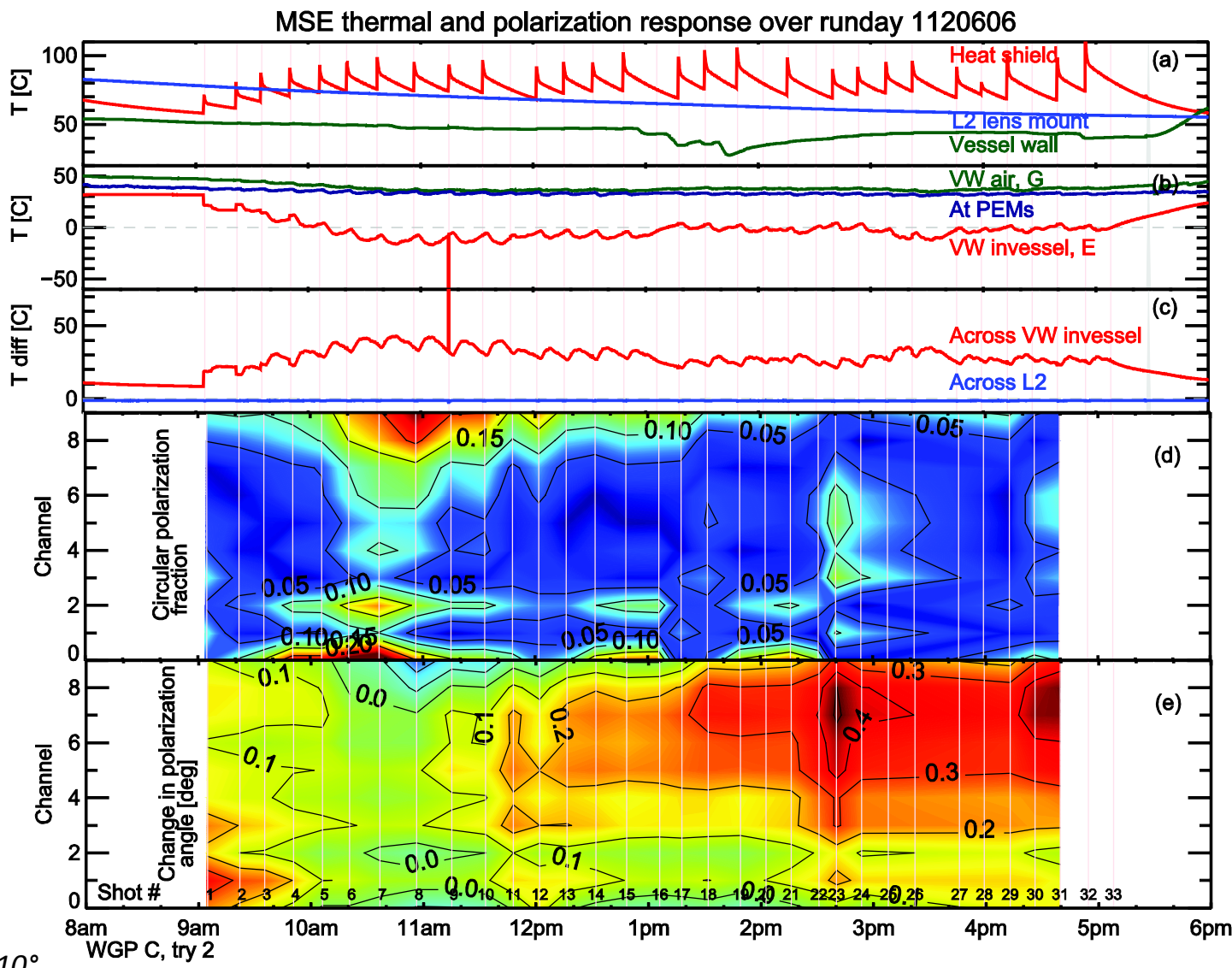


*MSE measurement goal: $<0.10^\circ$

ISC shoots the polarization response of diagnostic changes slowly across the runday at the 0.2° - 1.0° level

- Typical thermal environment:**
- Hot heat shield
 - Lenses slowly cooling
 - Vessel wall and VW fluctuating.
 - Large thermal gradients across VW

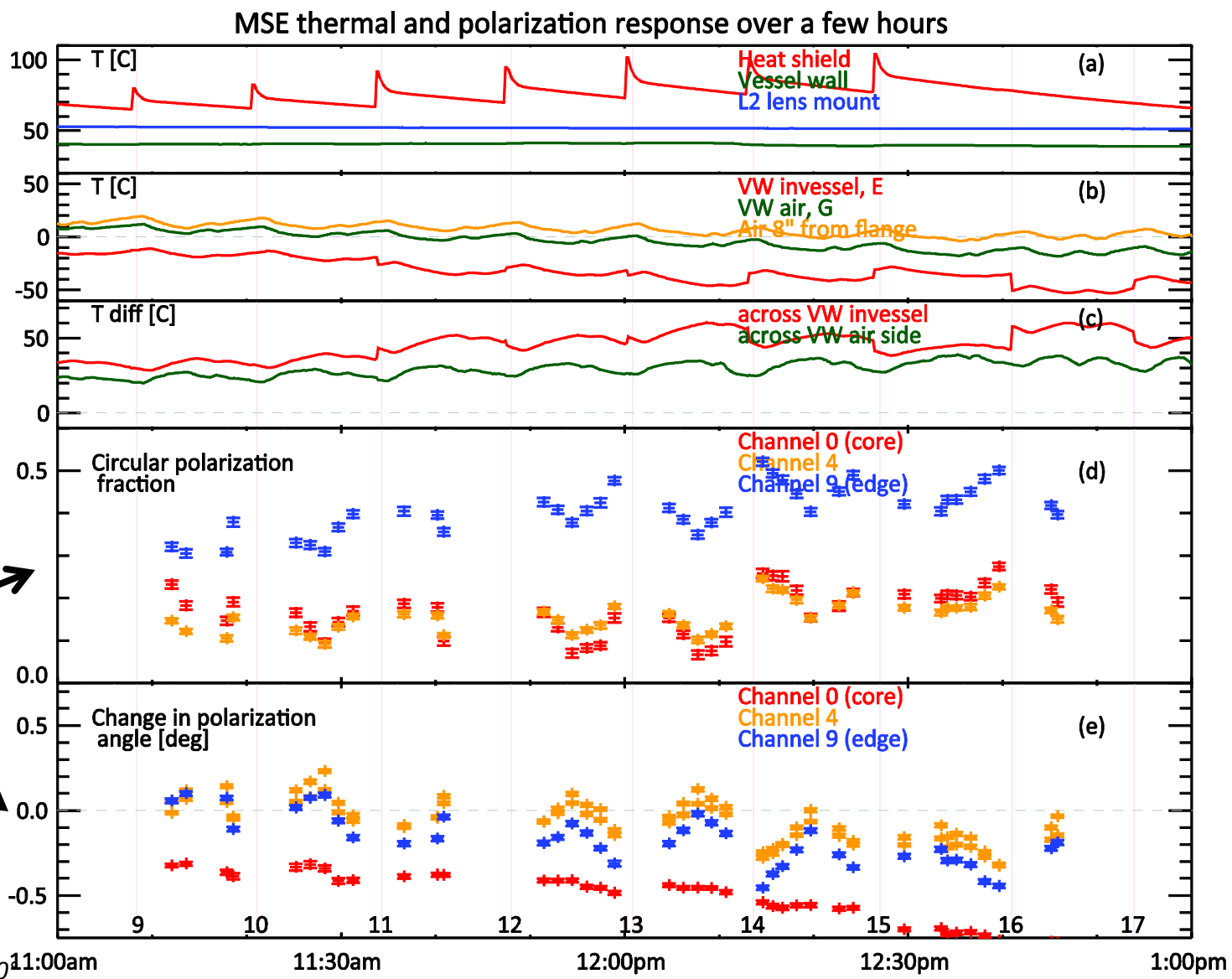
- Typical changes in the polarization:**
- Circular polarization changes from 5% to ~20%
 - Angle changes by ~0.5°



*MSE measurement goal: <0.10°

Calibration changes between shots at a minute time scale

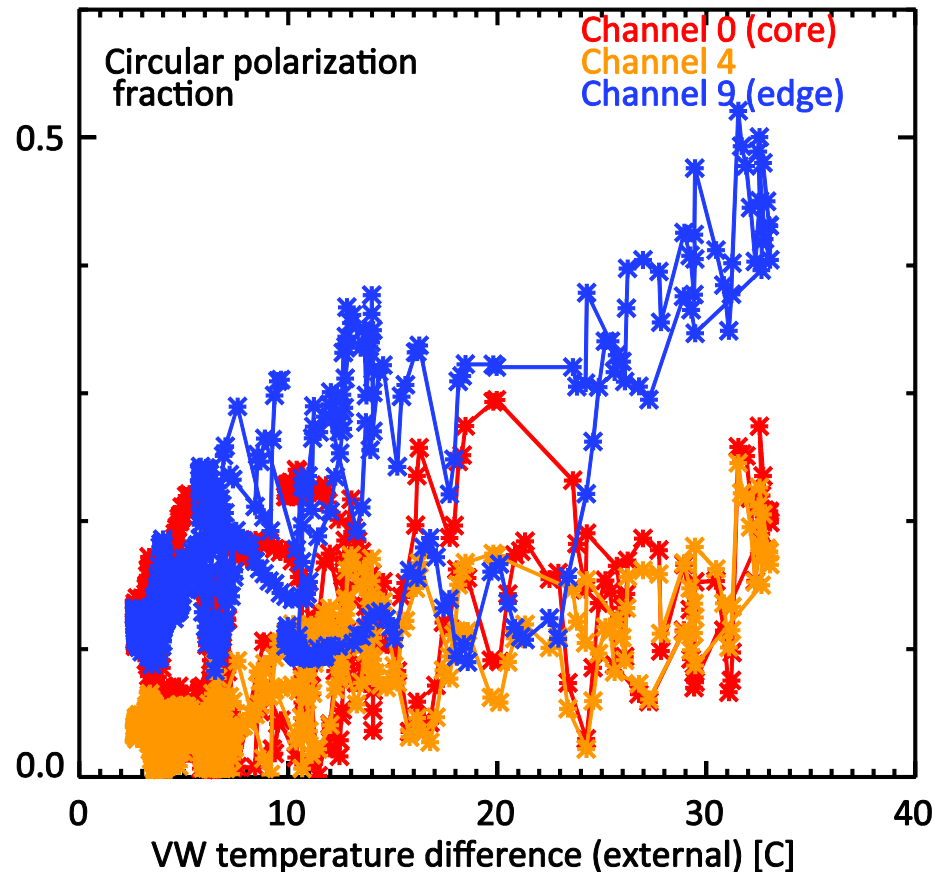
ISC left in one position taking data rapidly.



Response changes minute to minute.

*MSE measurement goal: <0.10

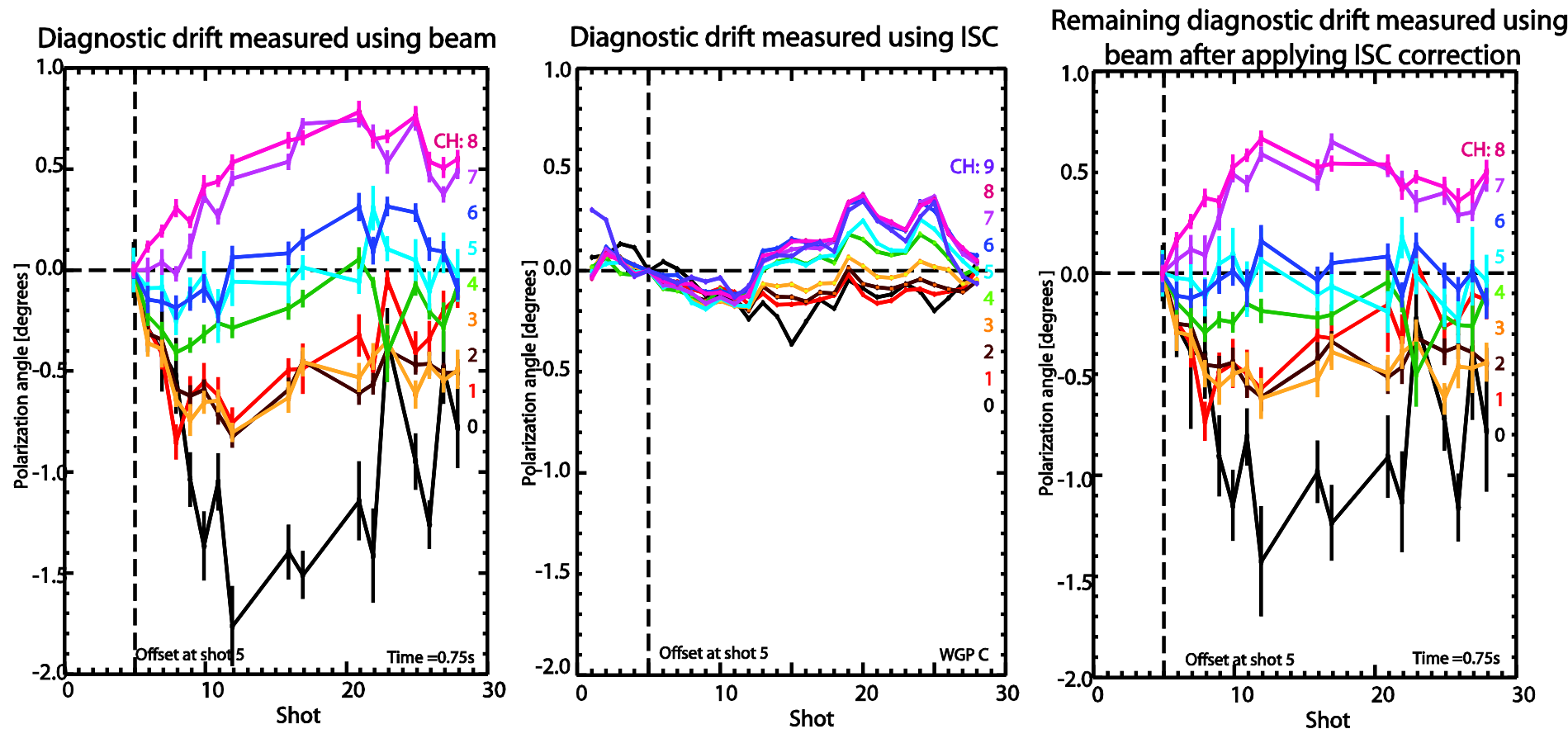
Found diagnostic calibration drifts fast, perhaps related to vacuum window.



Circular polarization (birefringence) correlates with temperature difference across the vacuum window.

ISC-DNB discrepancy

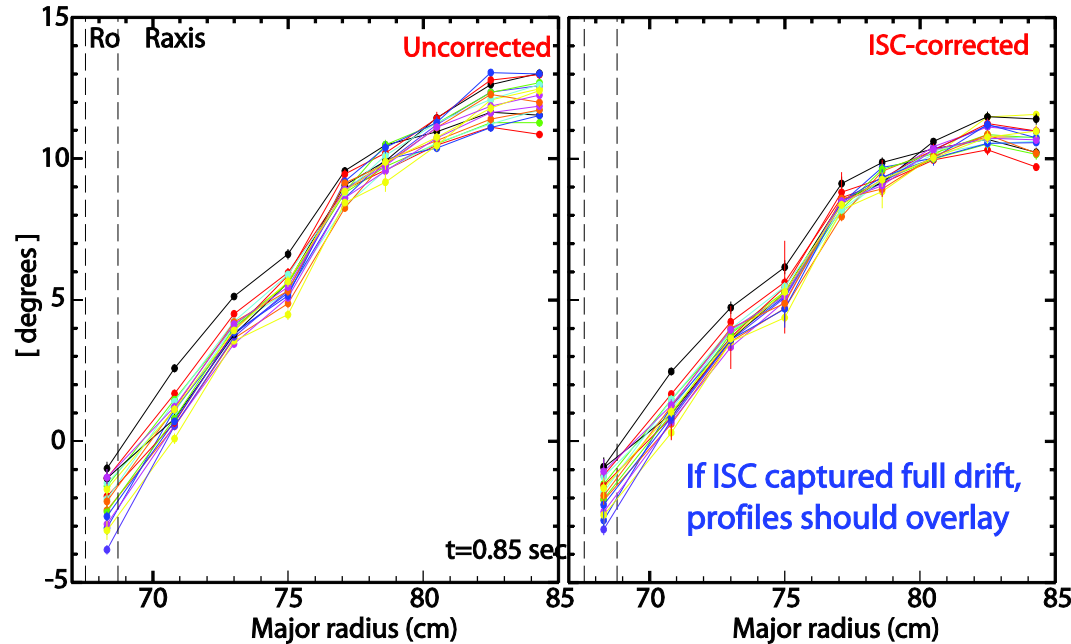
Benchmarking the drift in the diagnostic inferred by the ISC to that inferred from the beam.



- The drift in the diagnostic inferred using the beam with repeatable plasmas differs significantly from that inferred using the ISC in magnitude and character.
- There remains up to 1° (in polarization angle) of uncompensated drift.

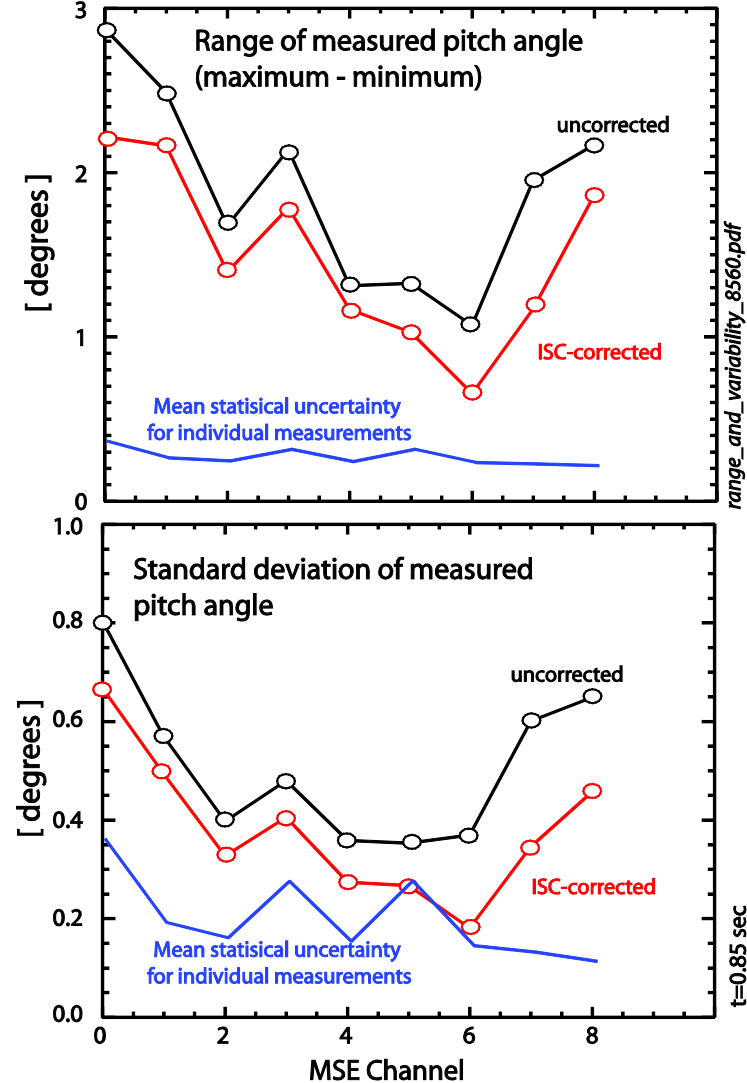
Projecting results into pitch angle are much larger than any uncertainties in plasma or measurement.

Pitch-angle profiles for 1120912 ohmic periods



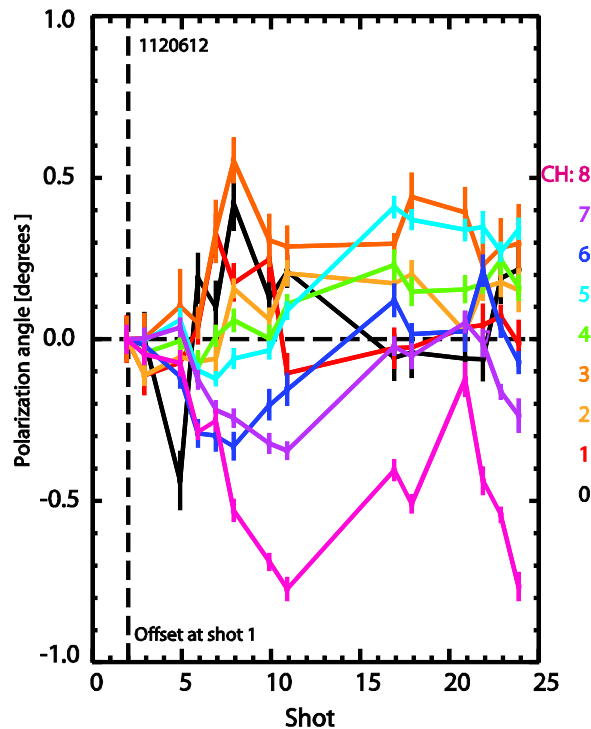
- Large spread in pitch angle profiles is only marginally improved by applying the ISC correction.
- System is performing much worse than the statistical error bars of the individual measurements.
- All ohmic beam pulses within a shot show the same behavior, it is shot to shot drift, not within a shot.
- Remaining drift too large to be real changes in these plasmas (would require $\Delta R_{mag}=2\text{cm}$, $\Delta I_p=120\text{kA}$)

Over 17 shots with beam

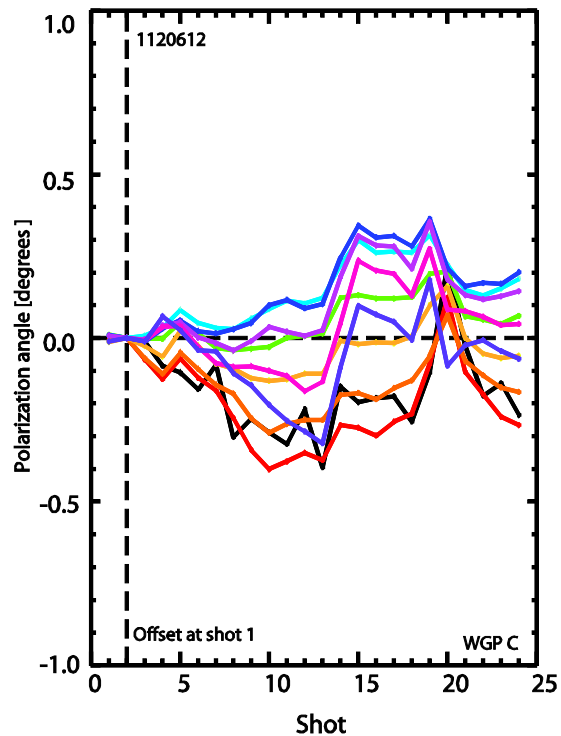


Unfortunately, this isn't the only day that shows this behavior... It is always there.

Diagnostic drift measured using beam

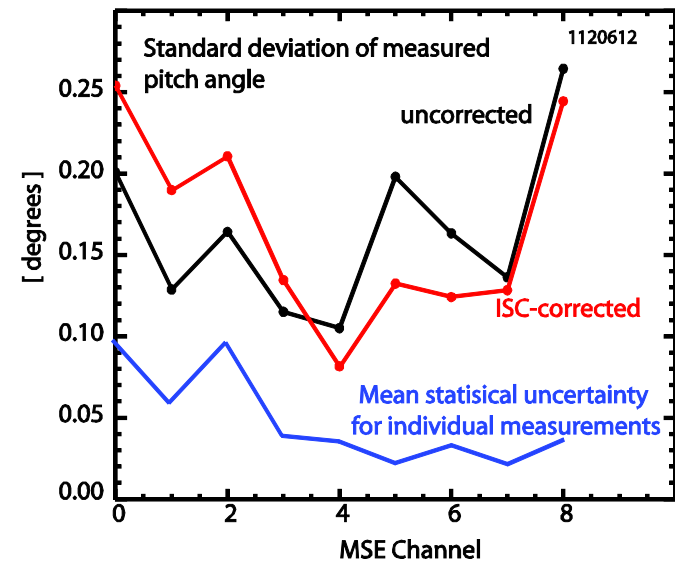
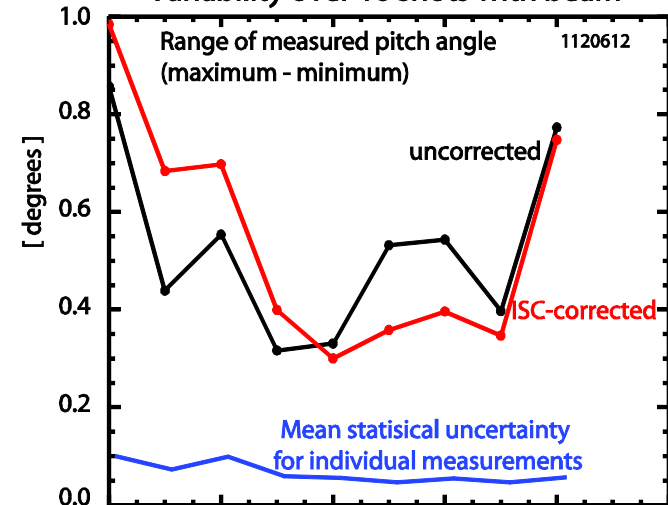


Diagnostic drift measured using ISC

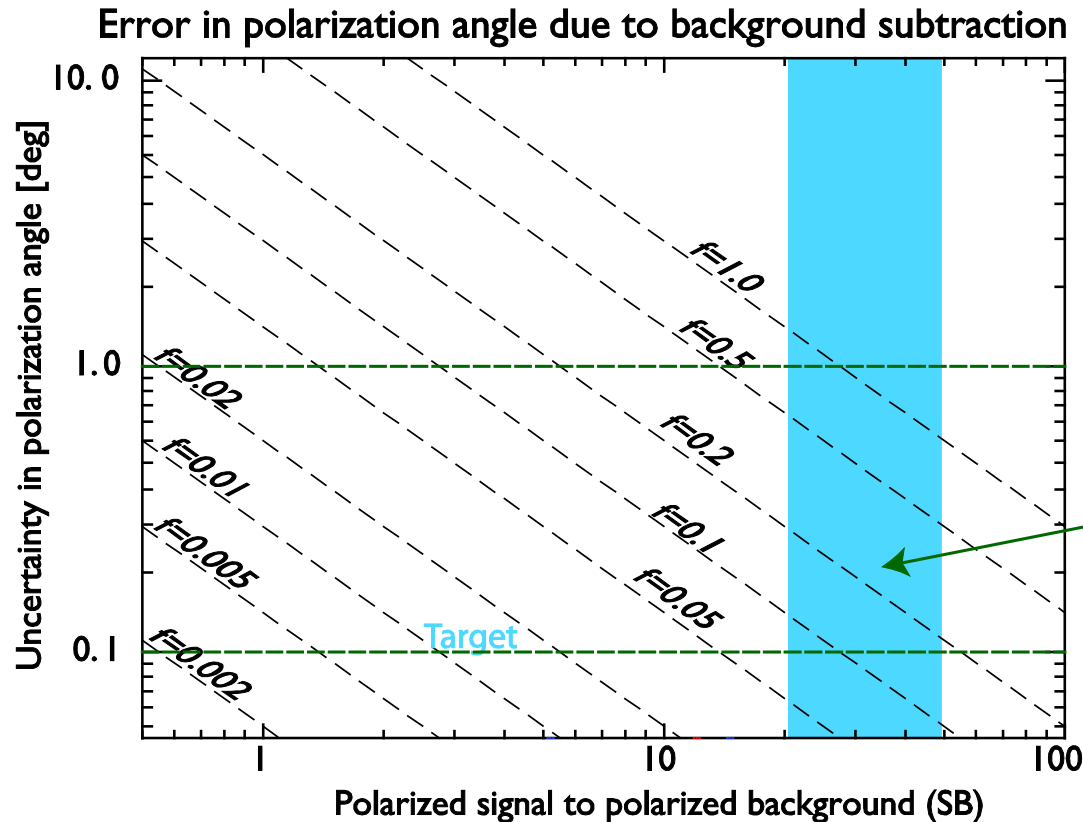


- [Another day with repeatable plasmas](#), again ISC and Beam sources do not agree about the diagnostic drift
- ISC and Beam indicate things are going the opposite way sometimes.

Variability over 16 shots with beam



Polarized background subtraction is not the cause of residual drift on 1120912.



Error in inferred beam polarization angle due to inaccurate background subtraction goes as:

$$\Delta\gamma_{\text{Beam}} \approx 28.6^\circ \frac{f}{SB} \sin(2(\gamma_{\text{Beam}} - \gamma_{\text{Background}}))$$

where:

f = relative error in estimating the polarized background intensity

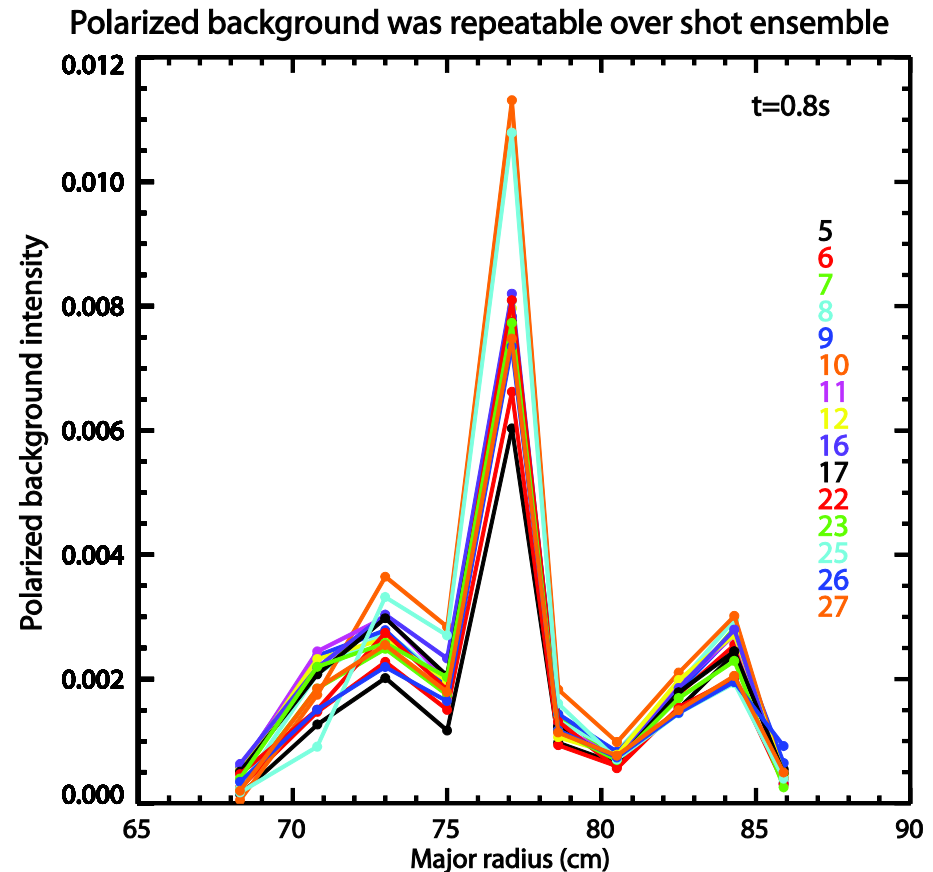
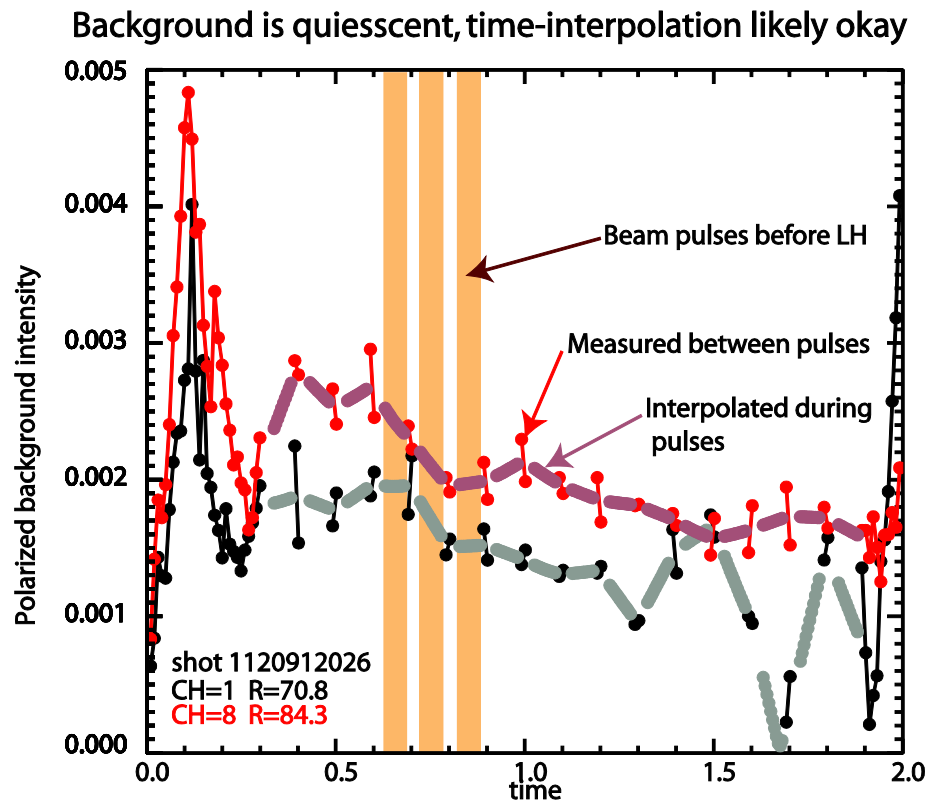
Would have to miss-estimate the background by 100% to produce errors of 1° in polarization angle

*MSE measurement goal: $<0.10^\circ$

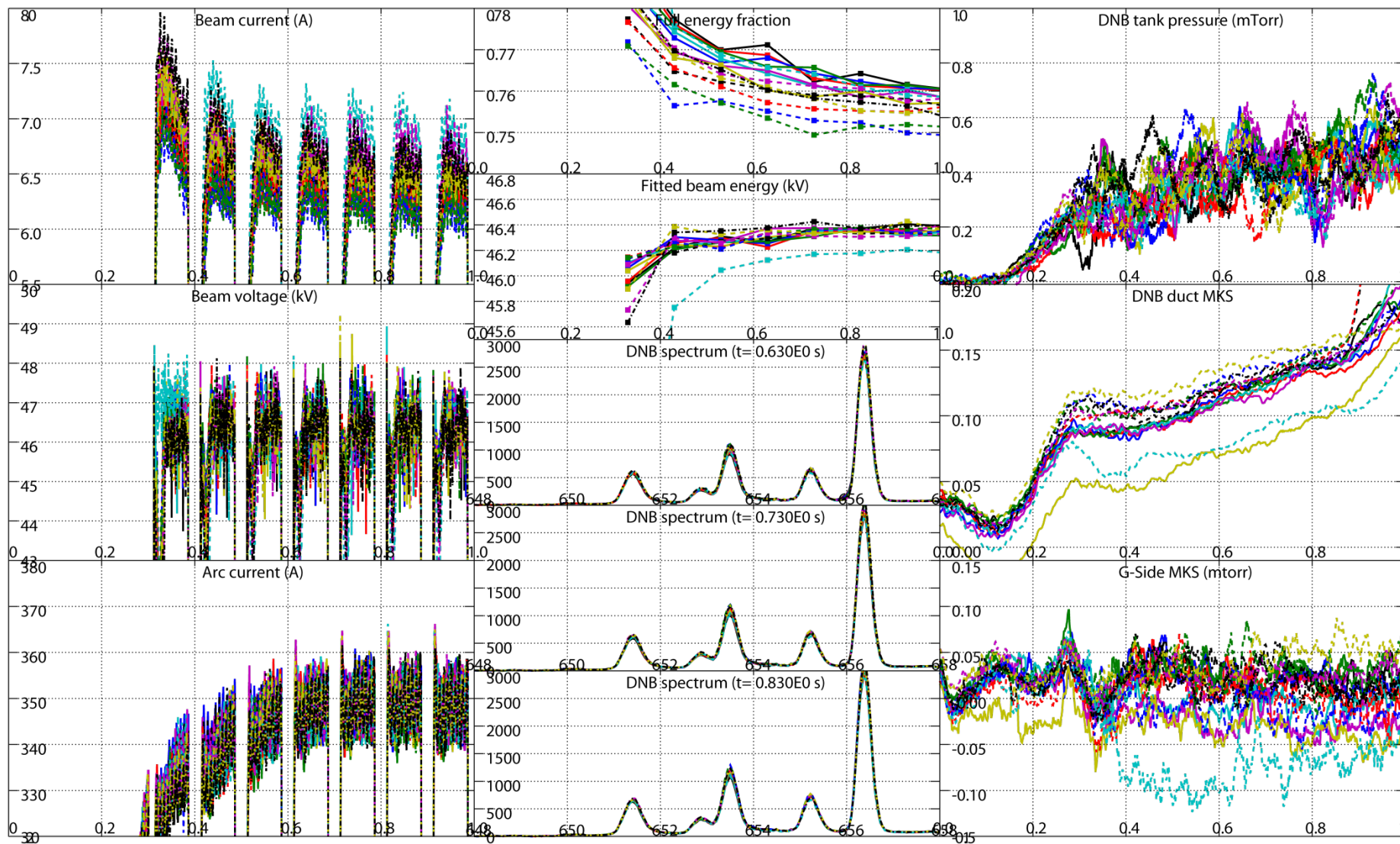
Polarized background subtraction is not the cause of residual drift on 1120912.

Furthermore...

The background was quiet and repeatable.



Beam traces were the same for all shots on 1120912



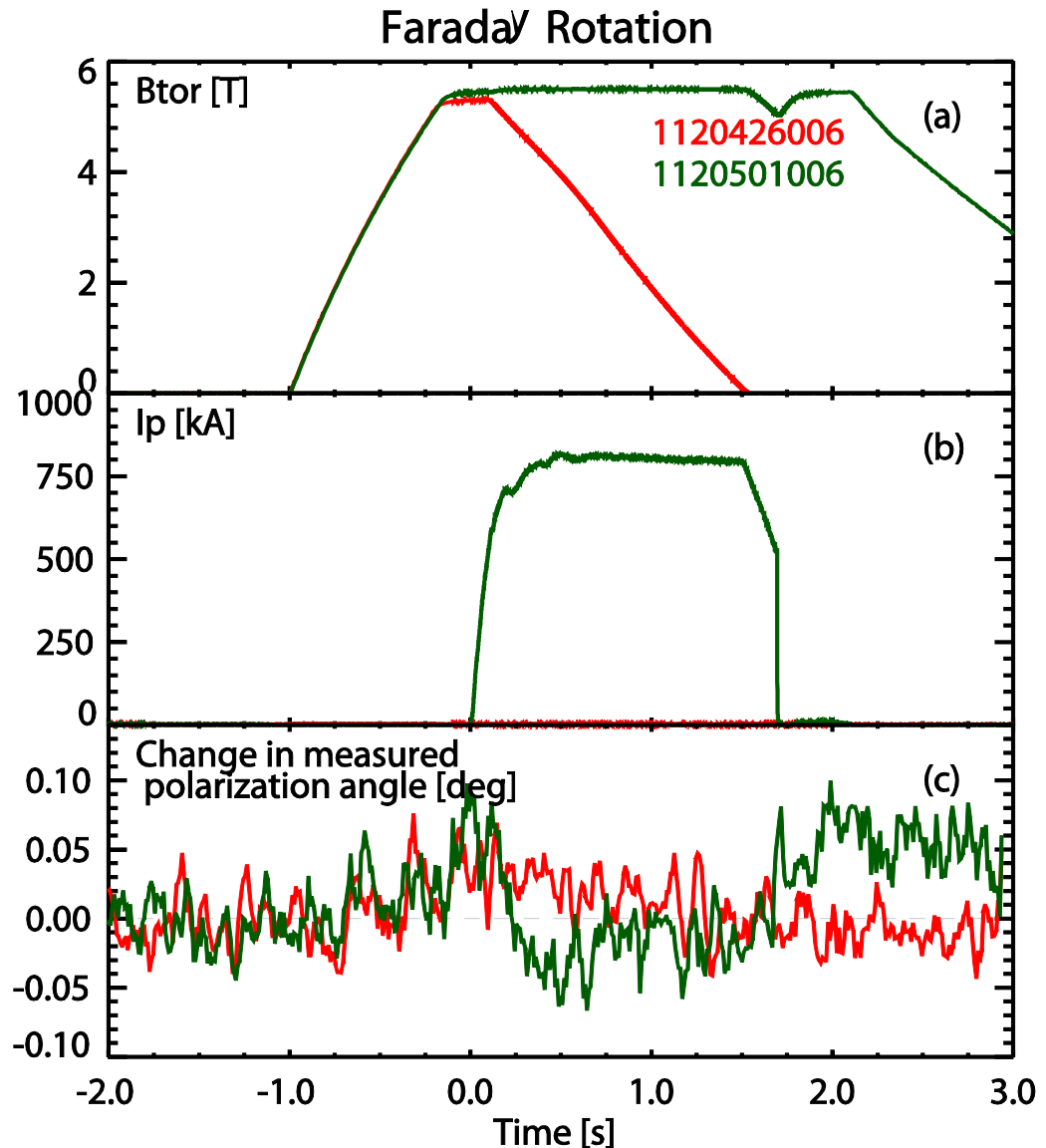
Other uses of the ISC

Faraday rotation is small and behaves correctly

- Faraday rotation measured by keeping ISC stationary through shots.
- Expect and find contributions from Toroidal and poloidal fields.
- Effect has been measured and can be corrected for.
- Will repeat in reverse field.
 - Should switch signs

Faraday rotation:

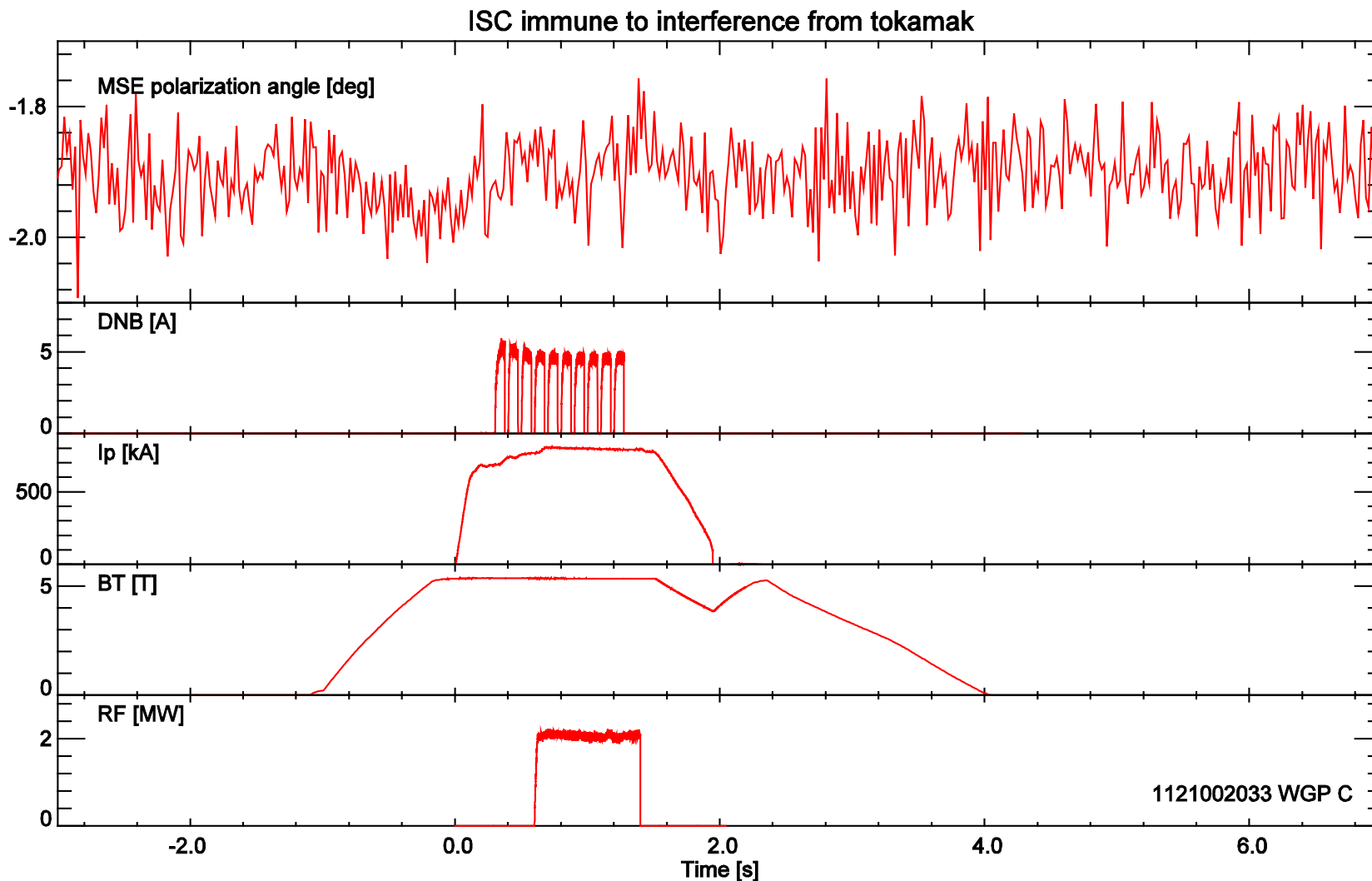
$$\beta = V \int \vec{B} \bullet d\vec{s}$$



*MSE measurement goal: $<0.10^\circ$

Fields, Beam, ICRF, do not affect interfere with the operation of the MSE.

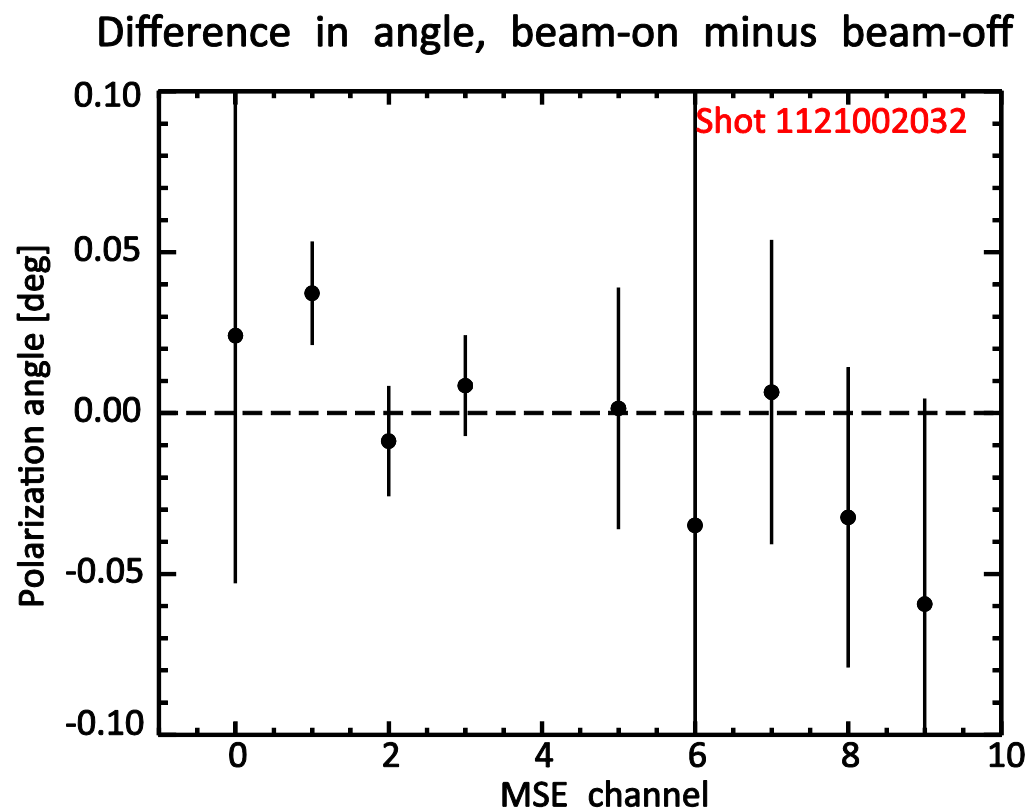
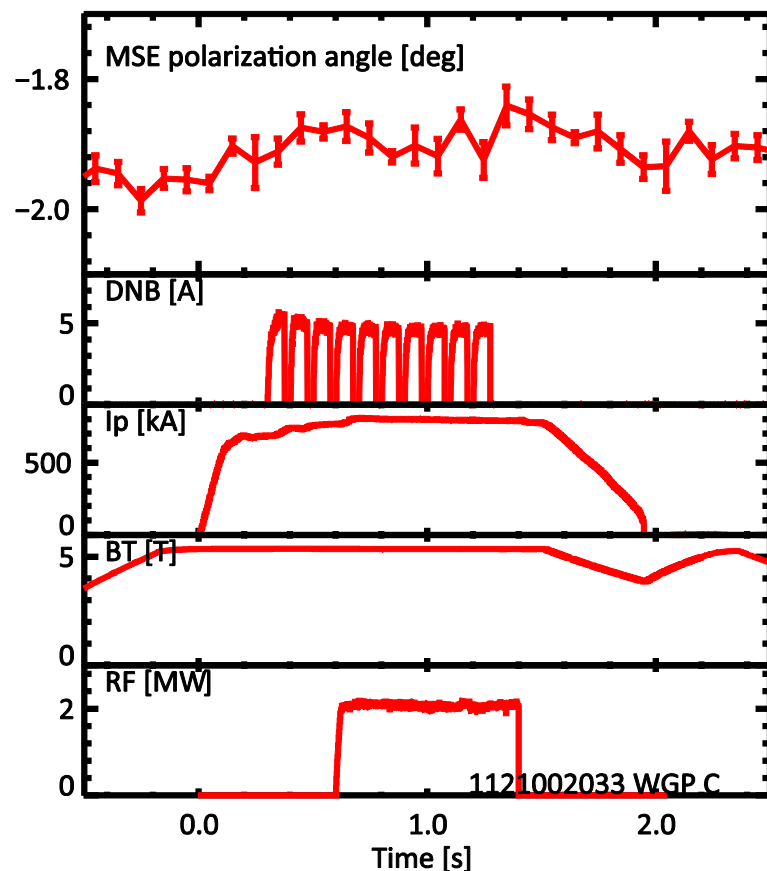
Input constant light from the ISC into the diagnostic objective lens during a C-Mod shot:



The tokamak and beam do not interfere with MSE operation (unlike the diagnostics..)

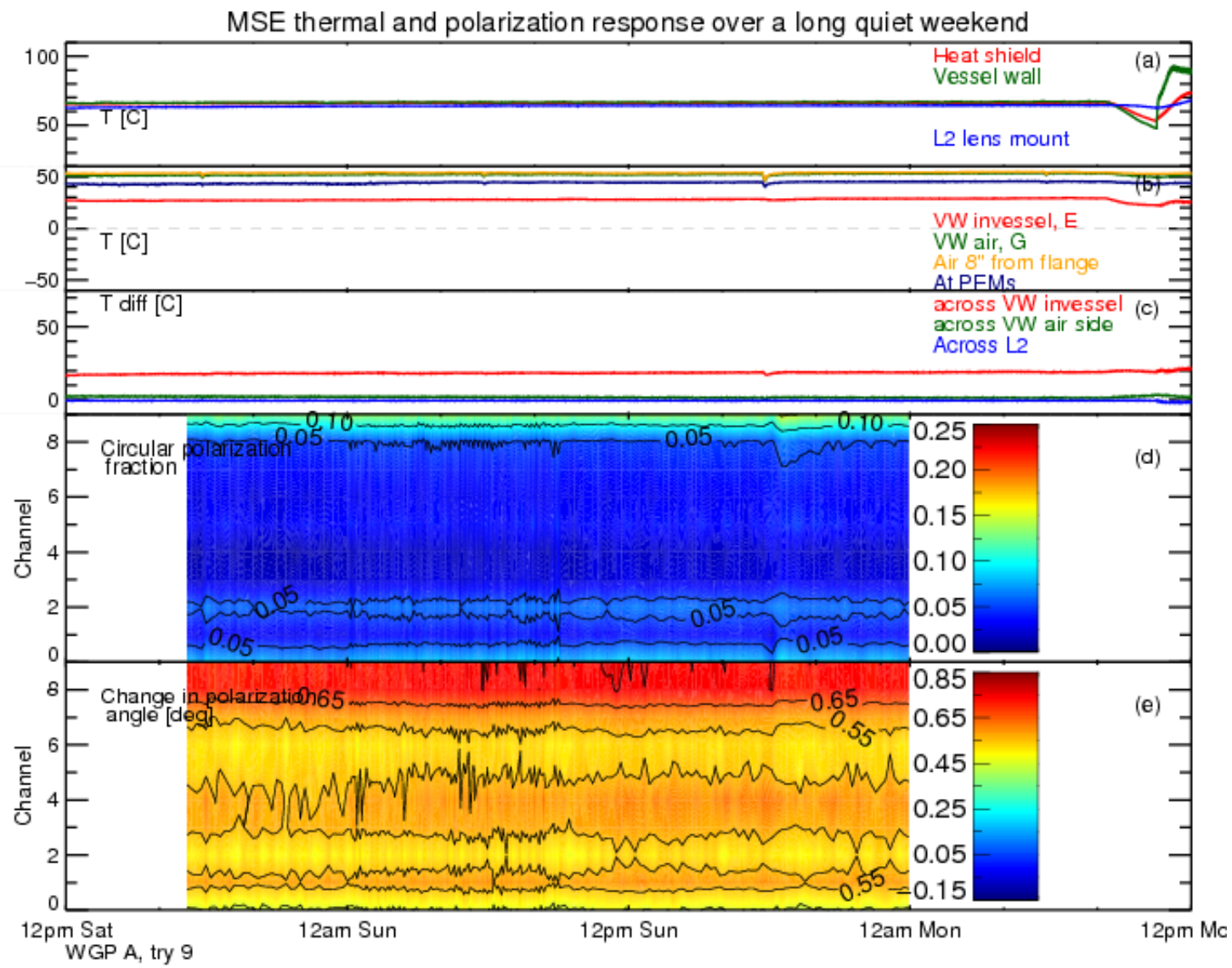
- Observe the ISC during plasma shots w/ beam.
 - The ISC blocks the light from the plasma and beam, thus putting in a constant polarization angle
 - Subtract beam-on and beam-off time points
 - There is no statistical difference

ISC immune to interference from tokamak



**MSE measurement goal: 0.10°*

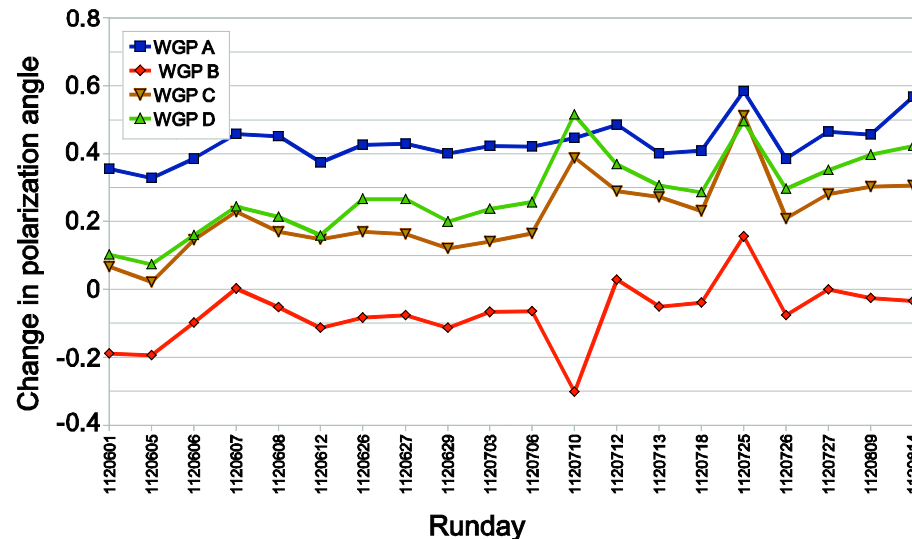
Everything stable over a long weekend when judged by the ISC



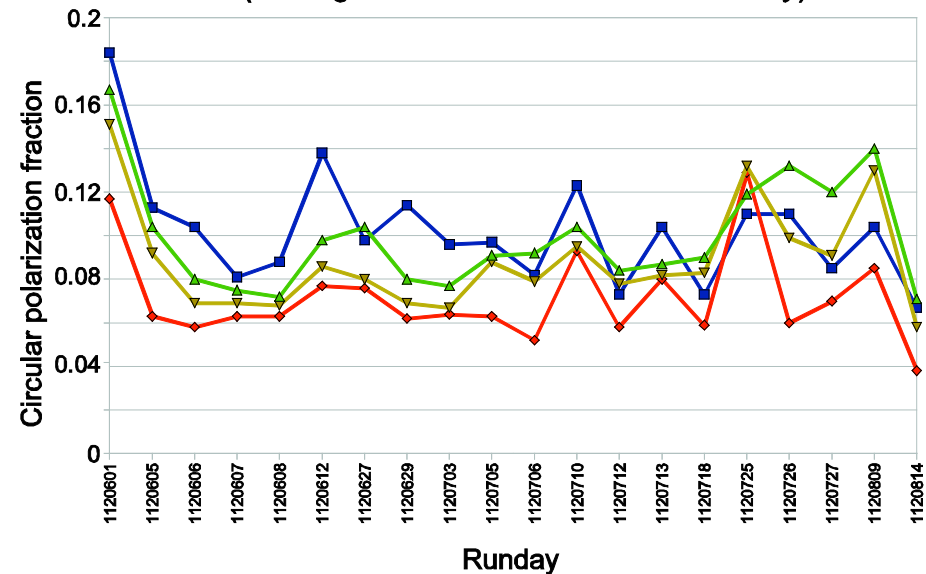
On long timescales the diagnostic changes at the $\sim 0.1^\circ$ - 0.2° level. All 4 polarization sources consistent.

- The calibration has drifted $\sim 0.1^\circ$ - 0.2° over the campaign
 - No “bumps to the PEMs”
- All 4 sources show similar trends
 - No single source has shifted relative to the others
- Circular polarization fraction remains $\sim 10\%$
 - Consistent across all 4 sources

Change in polarization since invessel calibration
(averaged over all chs and over runday)



Circular polarization fraction over campaign
(averaged over all chs and over runday)

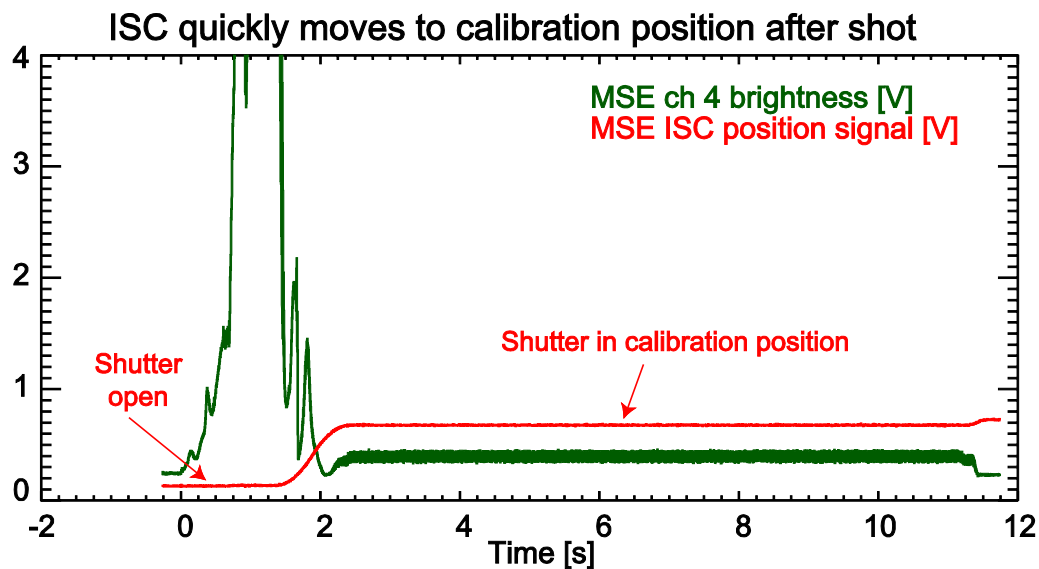


*MSE measurement goal: $< 0.10^\circ$

Plasma heating does not change the diagnostic response significantly within a shot.

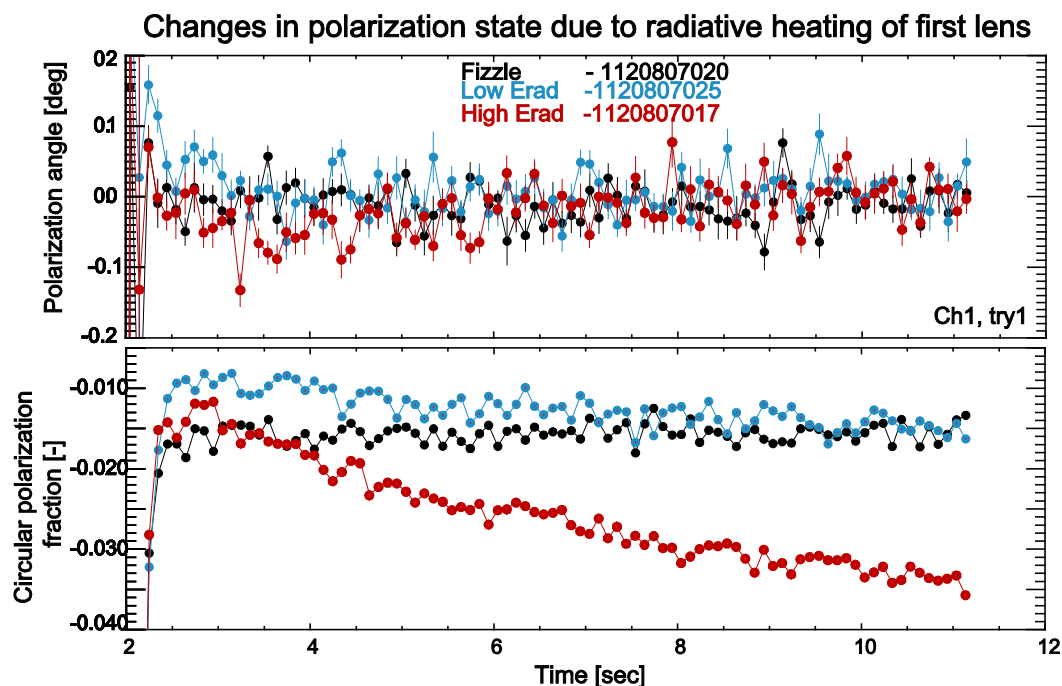
MSE diagnosticians worry that the flash heating of the first lens changes its polarization characteristics during a shot.

- Test this by:
 - Keeping shutter open during plasma
 - Moving quickly ($<0.5\text{s}$) to a calibration position after plasma
 - Observe changes in angle and circular polarization over 10s
 - Repeat for various levels of plasma radiated energy



Plasma heating does not change the diagnostic response significantly within a shot.

- Findings:
 - No changes in polarization angles at moderate to low Erad (where MSE usually operates)
 - Up to 0.10° @ 10s after shot at highest Erad
 - Could be avoided by moving calibration sequence to before shot
 - Extrapolation to high power C-Mod scenarios is worrisome
 - Timescales consistent with heat penetrating lens thickness

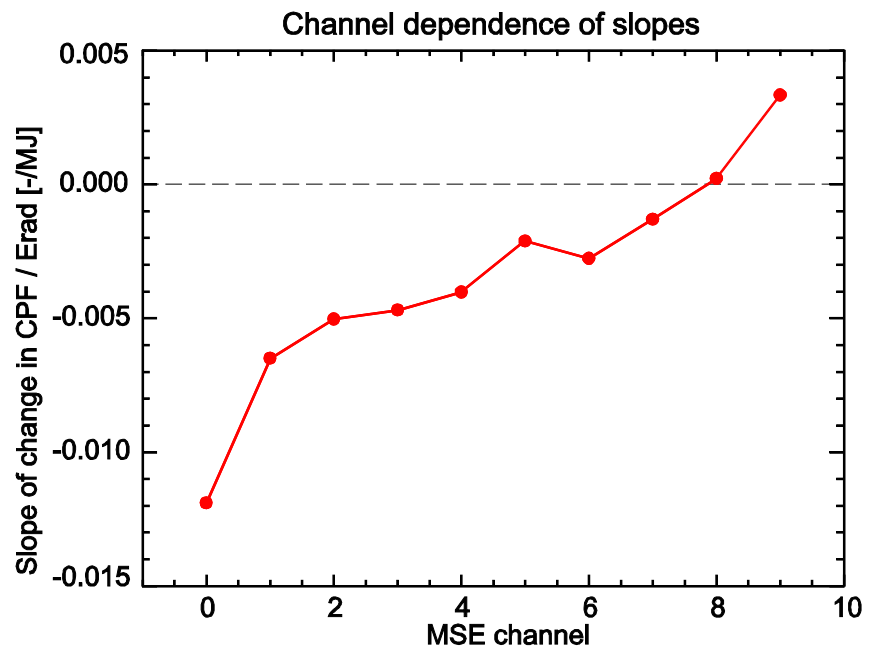
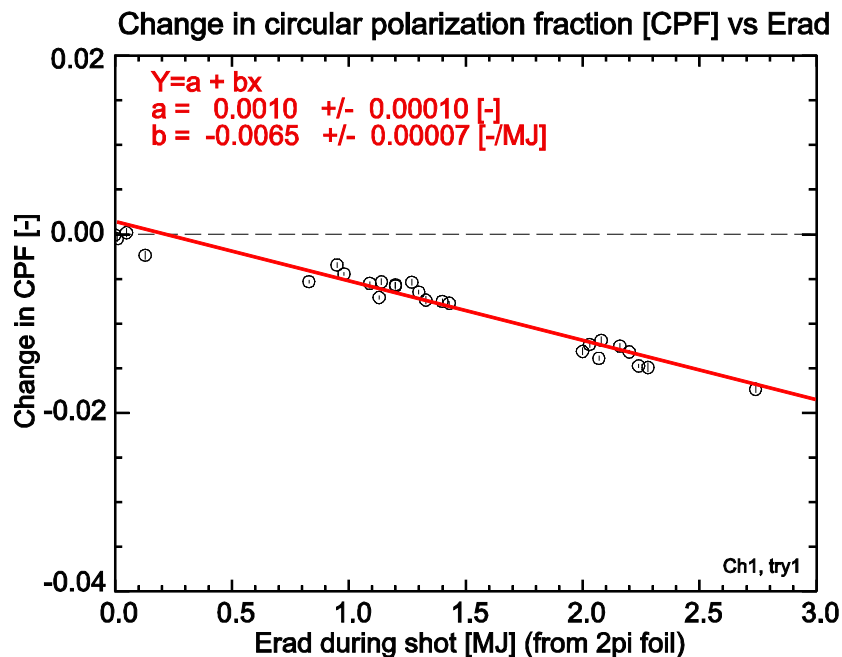


*MSE measurement goal: $<0.10^\circ$

Plasma heating does not change the diagnostic response significantly within a shot.

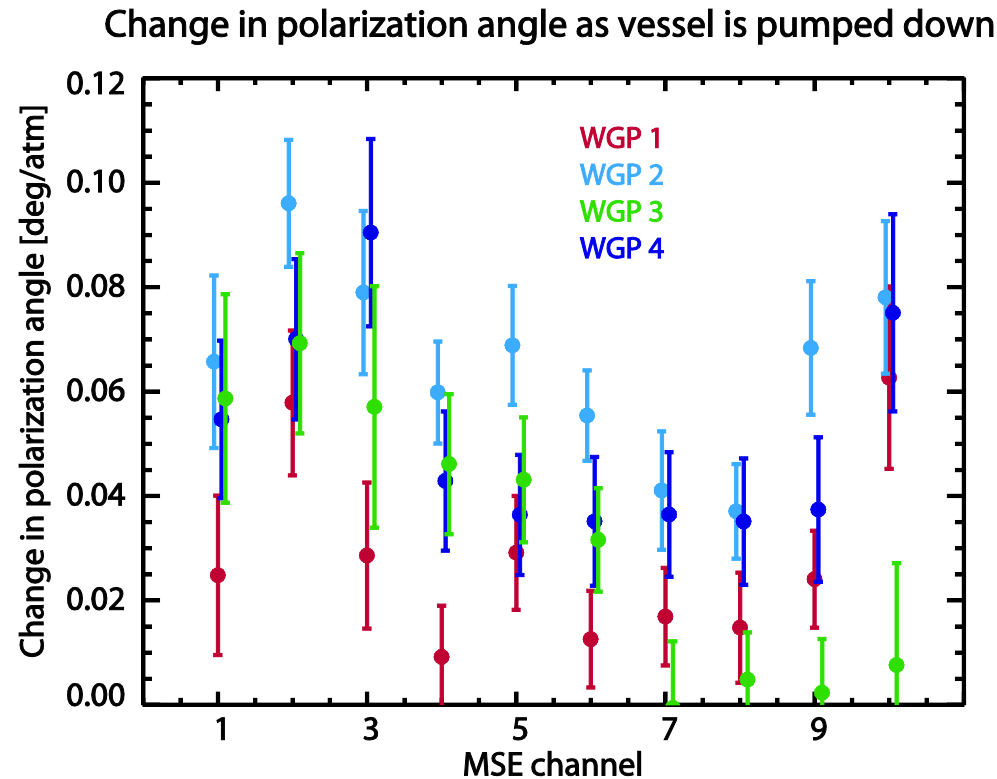
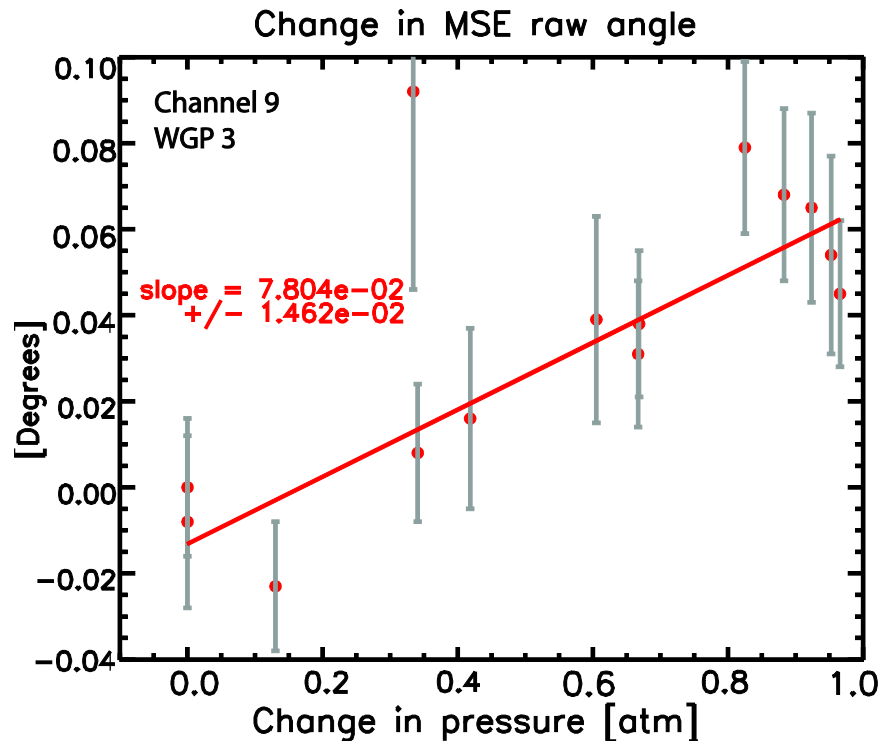
- Findings:

- No changes in polarization angles at moderate to low Erad (where MSE usually operates)
 - Up to 0.10° @ 10s after shot at highest Erad
 - Could be avoided by moving calibration sequence to before shot
 - Extrapolation to high power C-Mod scenarios is worrisome
- Timescales consistent with heat penetrating lens thickness
- Changes in circular polarization fraction scale linearly in Erad
 - Monotonic channel dependence



Pump down not a significant source of polarization change

- ISC kept in constant position as vessel pumped down slowly
- Angle only changes by 0.1°
- Reproducibility needs to be checked

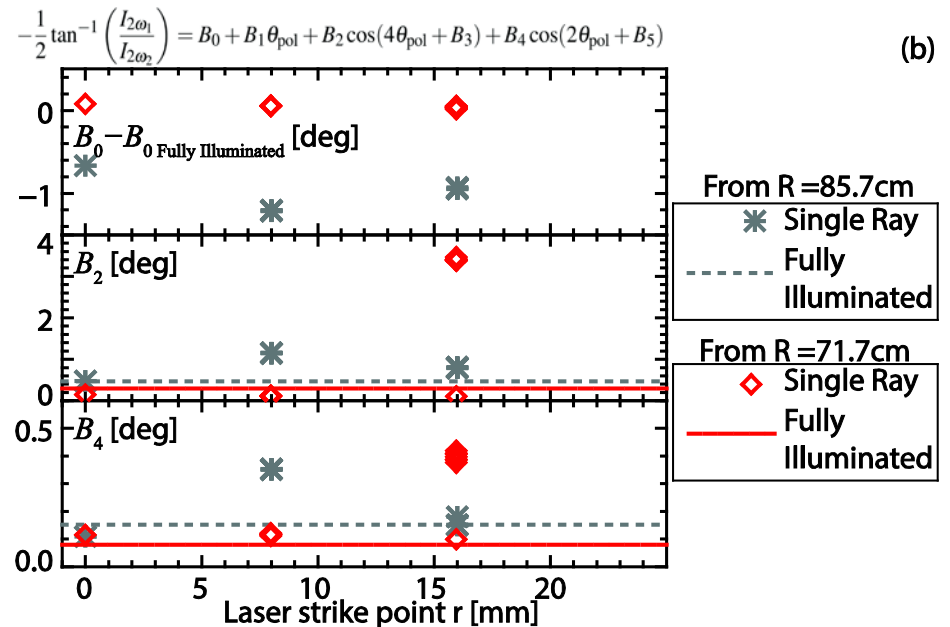
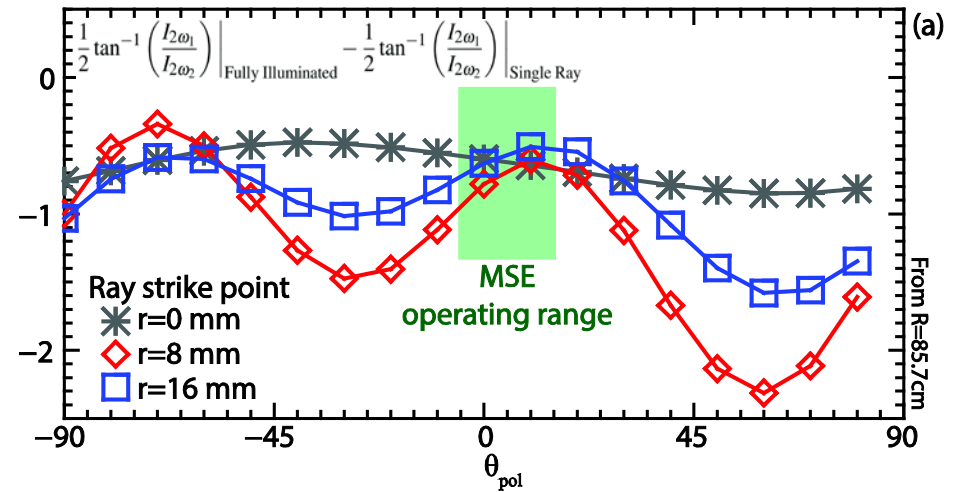
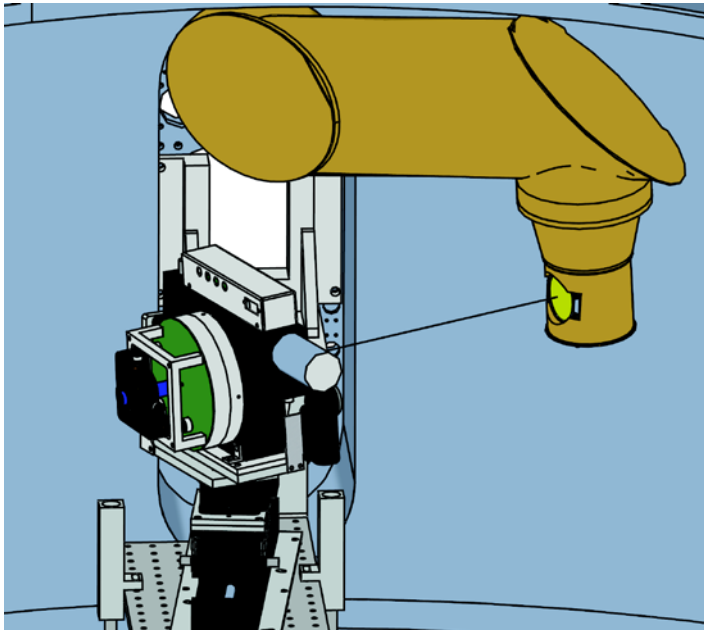


*MSE measurement goal: $<0.10^\circ$

Ray-dependent calibration

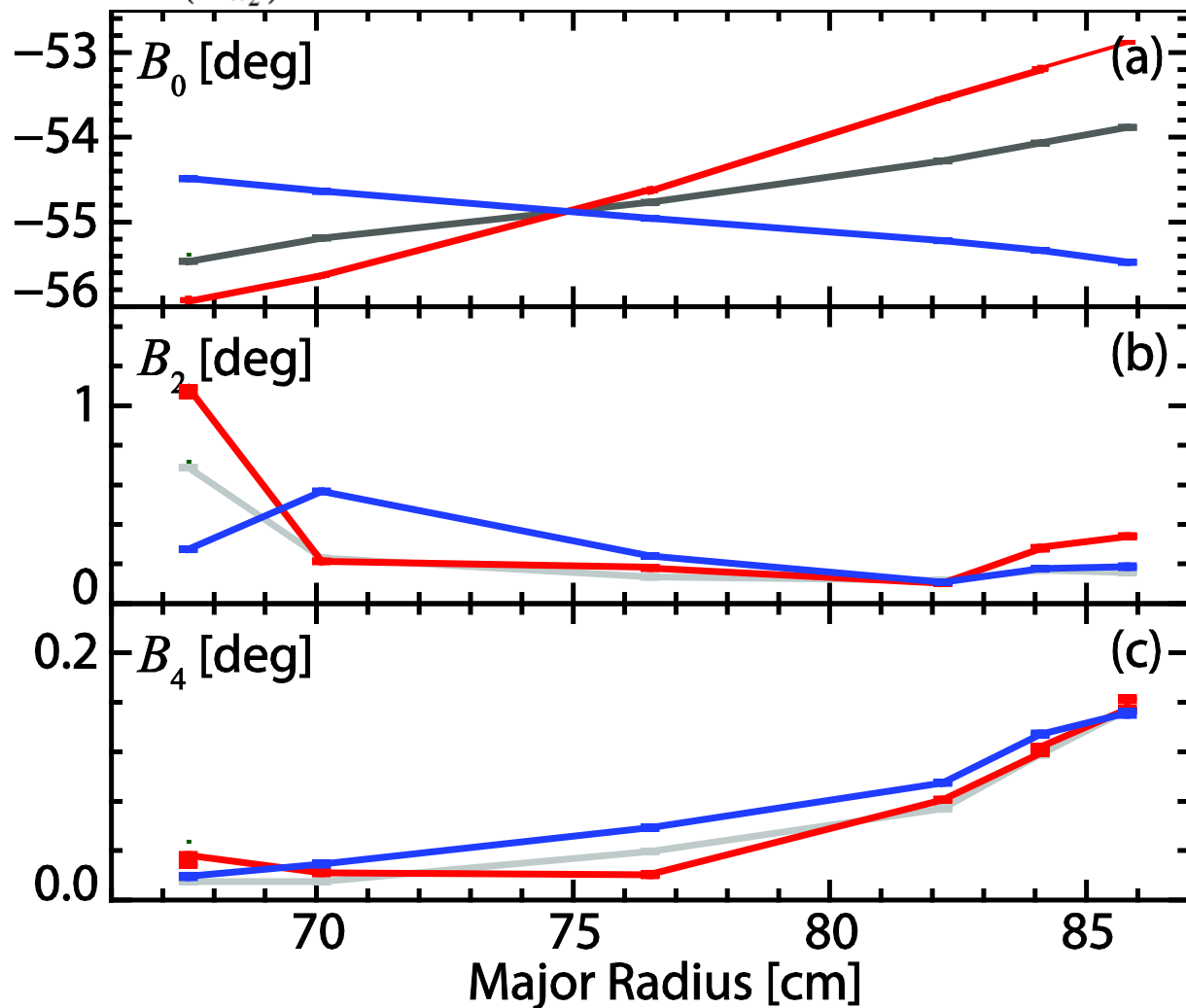
C-Mod's MSE calibration is ray-to-ray dependent!

Laser source traces rays through optical system from object plane



Confirmed with masking the objective lens

$$-\frac{1}{2} \tan^{-1} \left(\frac{I_{2\omega_1}}{I_{2\omega_2}} \right) = B_0 + B_1 \theta_{\text{pol}} + B_2 \cos(4\theta_{\text{pol}} + B_3) + B_4 \cos(2\theta_{\text{pol}} + B_5)$$



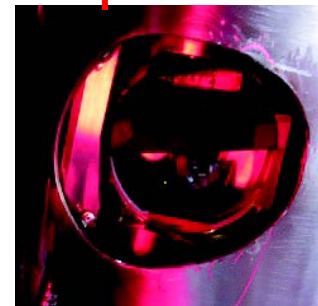
No Mask



Bottom Masked

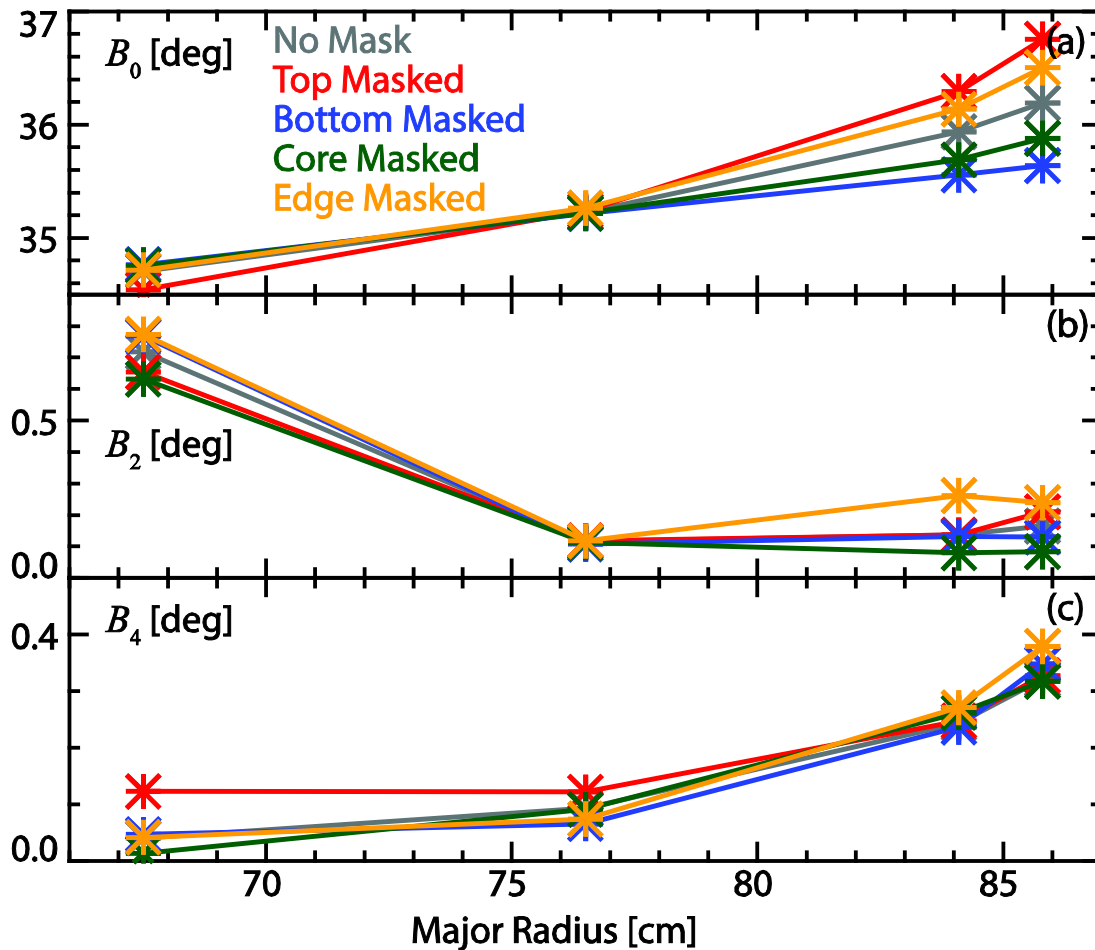


Top Masked

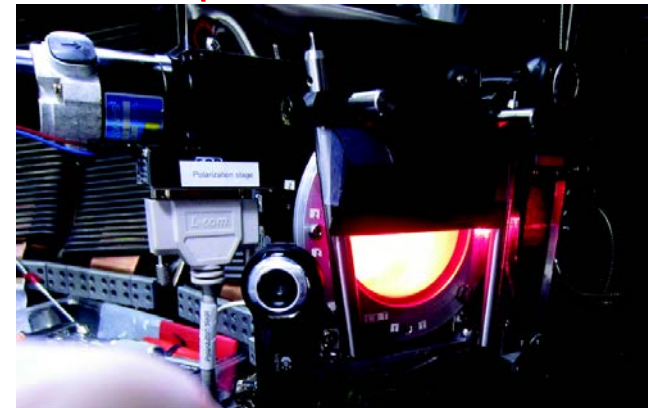


Confirmed by masking the source

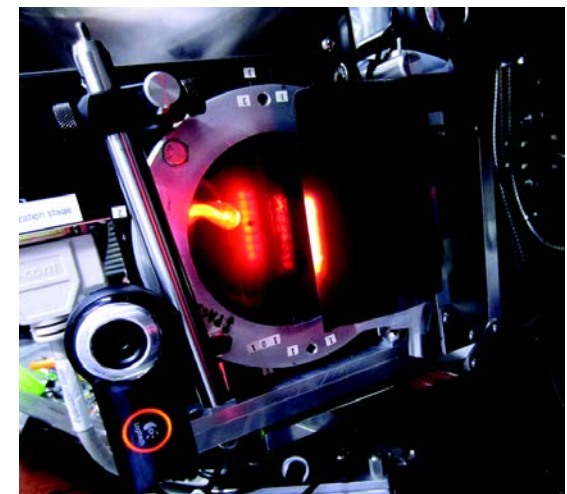
$$-\frac{1}{2} \tan^{-1} \left(\frac{I_{2\omega_1}}{I_{2\omega_2}} \right) = B_0 + B_1 \theta_{\text{pol}} + B_2 \cos(4\theta_{\text{pol}} + B_3) + B_4 \cos(2\theta_{\text{pol}} + B_5)$$



Top (Bottom) Masked

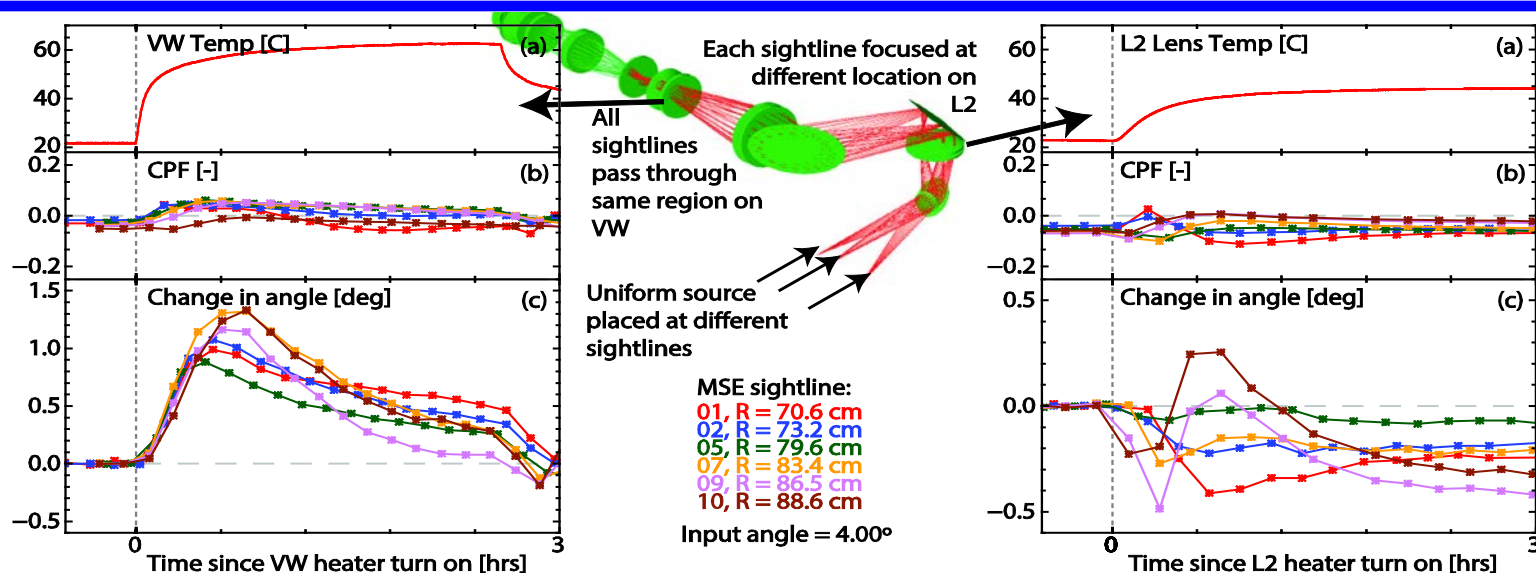


Core (Edge) Masked

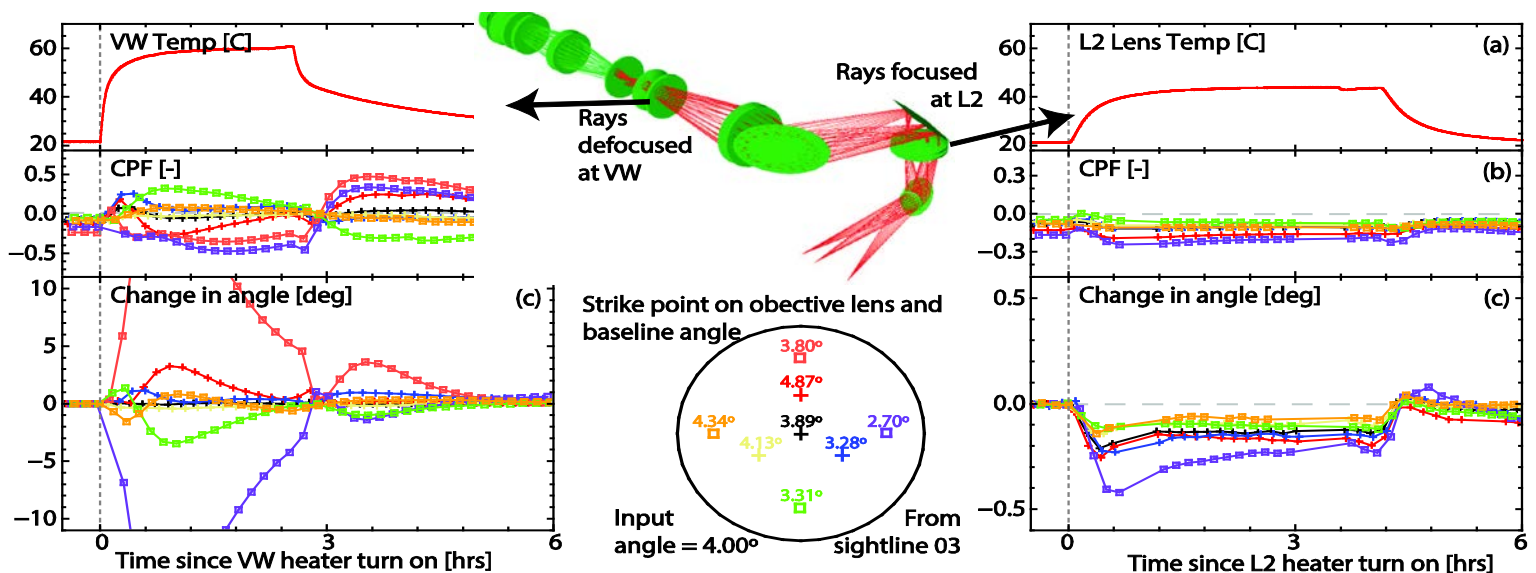


Stress-induced birefringence is REALLY ray-to-ray dependent!

Uniform
source
at different
sightlines



Individual
rays within
a single
sightline



Take aways:

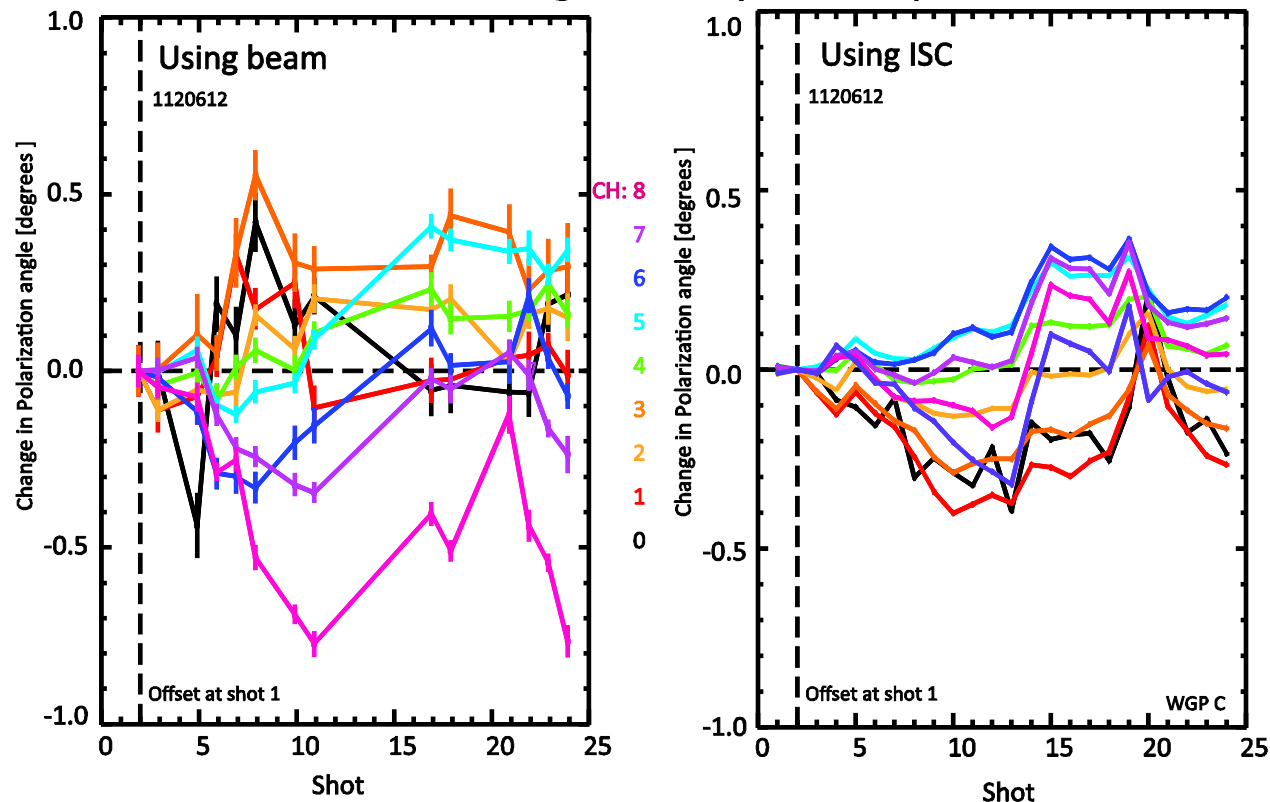
- The 'effective' calibration is really an average over all the rays...
 - You have to be very uniform with your calibration source
 - Especially if you want to track changes to the diagnostic
 - Important for ITER's calibration strategy
 - Mirror coatings behave similar to stress-induced birefringence
 - Likely similar effects on other devices
-
- **Chapter 2 of the thesis (+ some diagnostic verification)**
 - **Systematics in calibration subject of an RSI close to circulation to co-authors**

We think ray-to-ray variability is why the ISC did not properly track changes during C-Mod operation

Despite flawless technical operation, ISC did not properly account for the drift during C-Mod operation..

In fact, it sometimes showed anti-correlated diagnostic changes...

Shot-to-shot drift inferred using beam does not match that inferred using ISC in repeatable plasmas

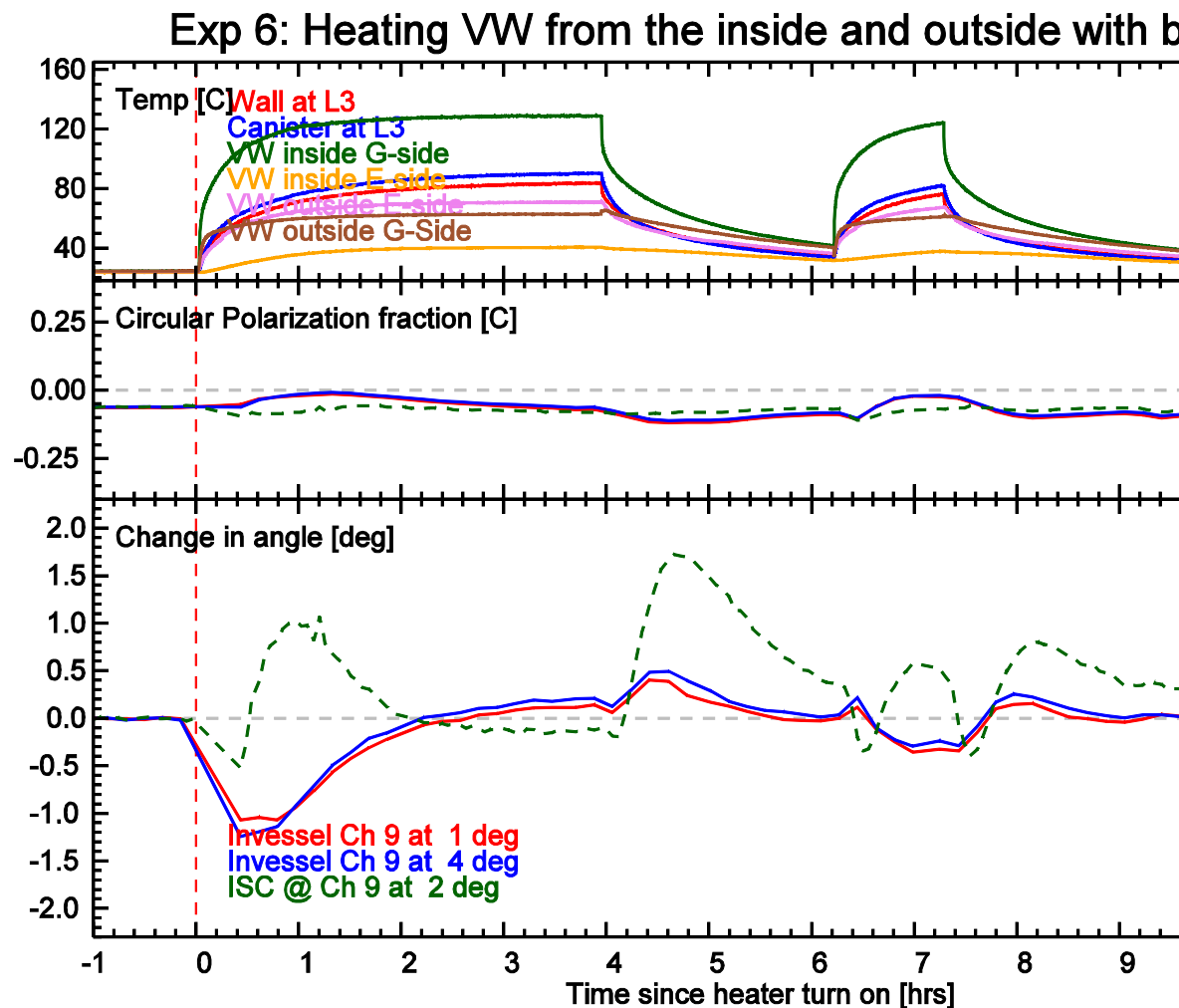
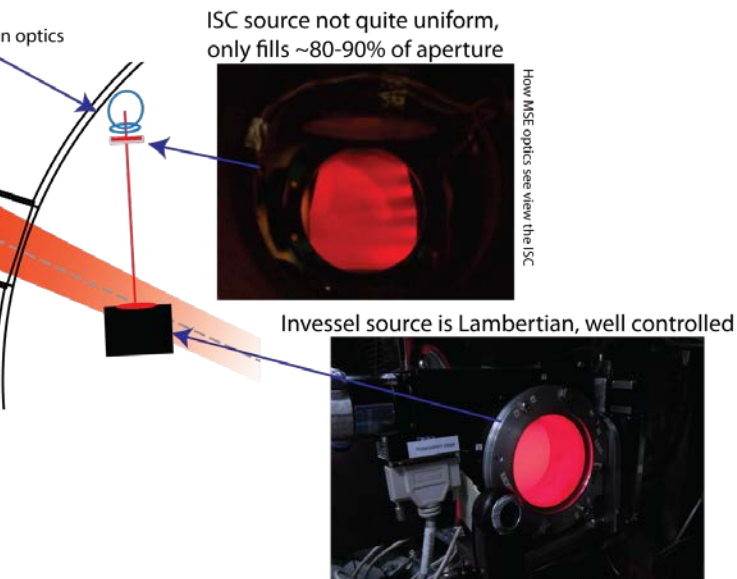


ISC problems reproduced on the bench by heating elements, what could be the problem?...

Experimental setup:

Heat elements (VW, L2)

Simultaneous track diagnostic
response with ISC AND invessel
uniform source



Not cherry-picking a bad case, In fact, the ISC almost NEVER correctly accounted for the drift...

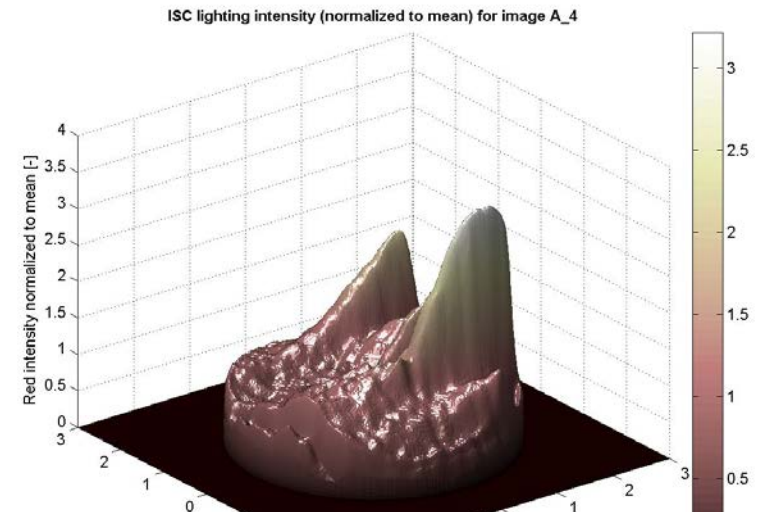
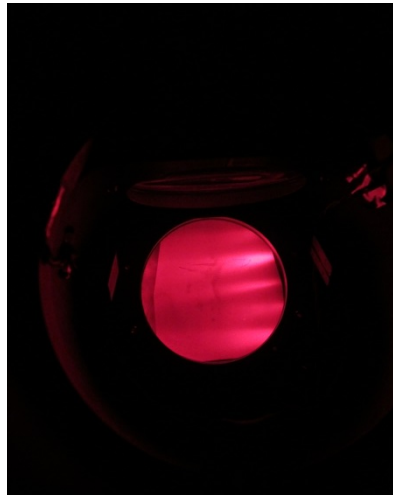
Built a system to measure uniformity. Rebuilt the ISC illumination to make it more uniform.

Prior to rebuild:

Malfunction in LEDs and broken fibers led to large variation in source intensity

$$\text{Max/min} = 3.2/0.16 = 20$$

$$\text{Stdev} = 42\% \text{ of mean}$$

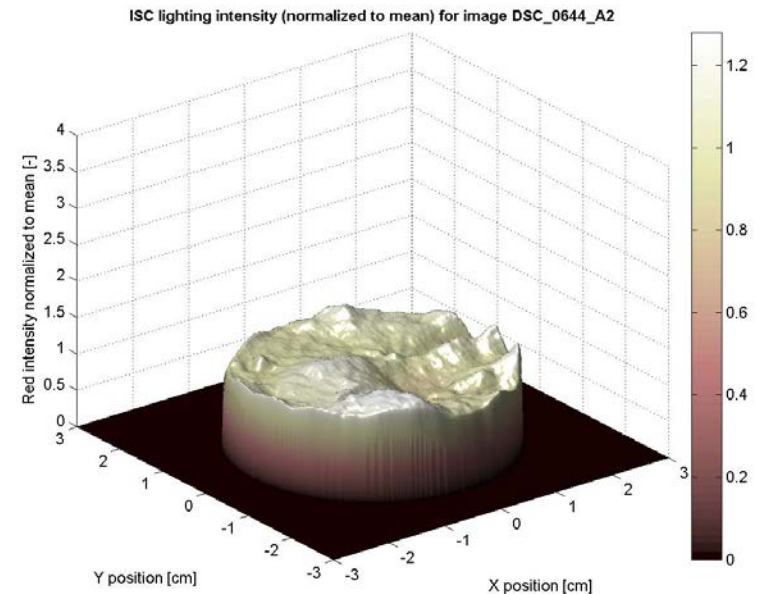


After rebuild:

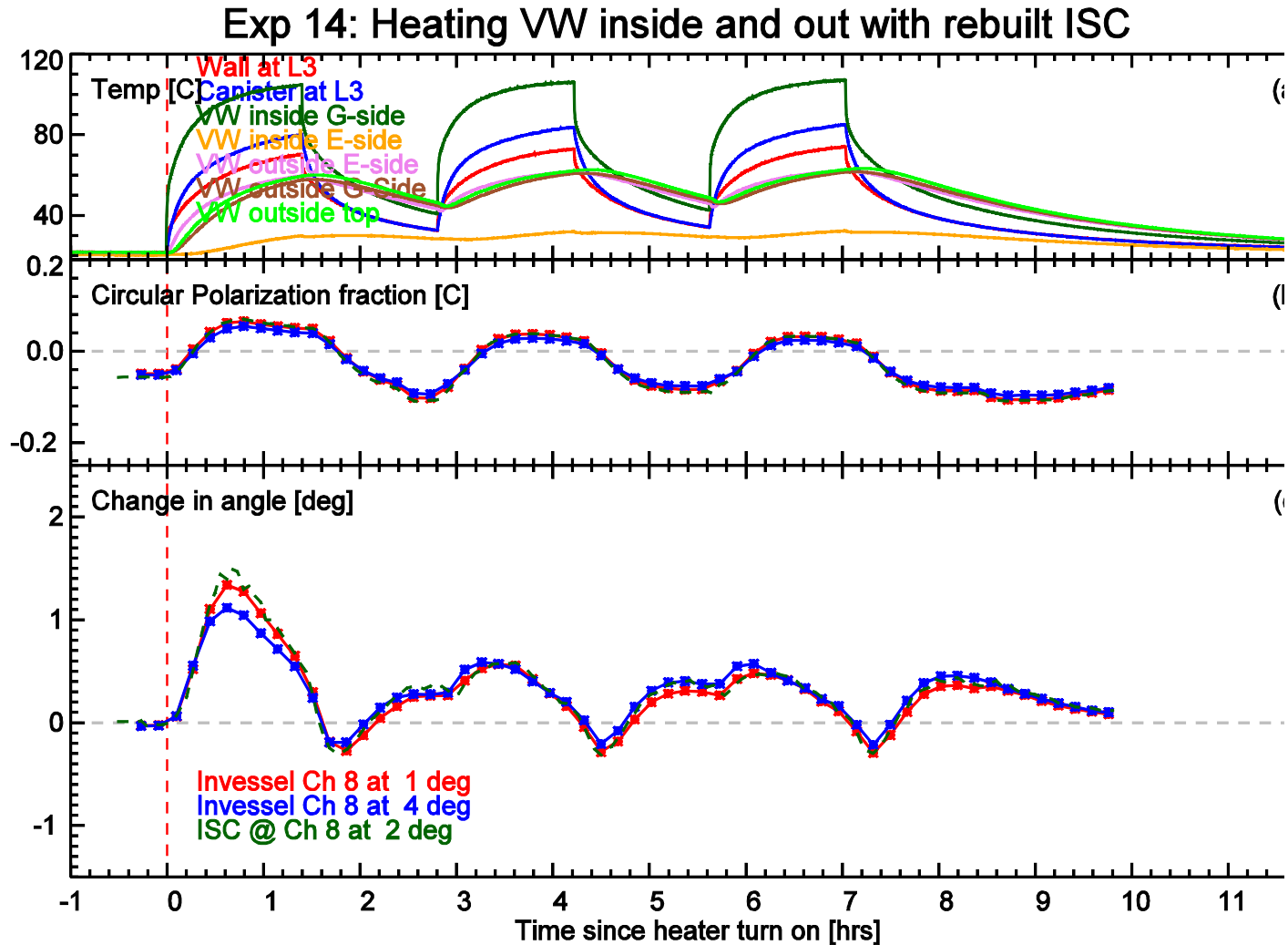
Reconfigured LEDs, repaired fibers, tuned the diffusers via sandblasting, creating a uniform source:

$$\text{Max/min} = 1.2/0.25 = 4.8$$

$$\text{Stdev} = 11\% \text{ of mean}$$



New, more uniform system now tracks changes much better. But need C-Mod for confirmation.

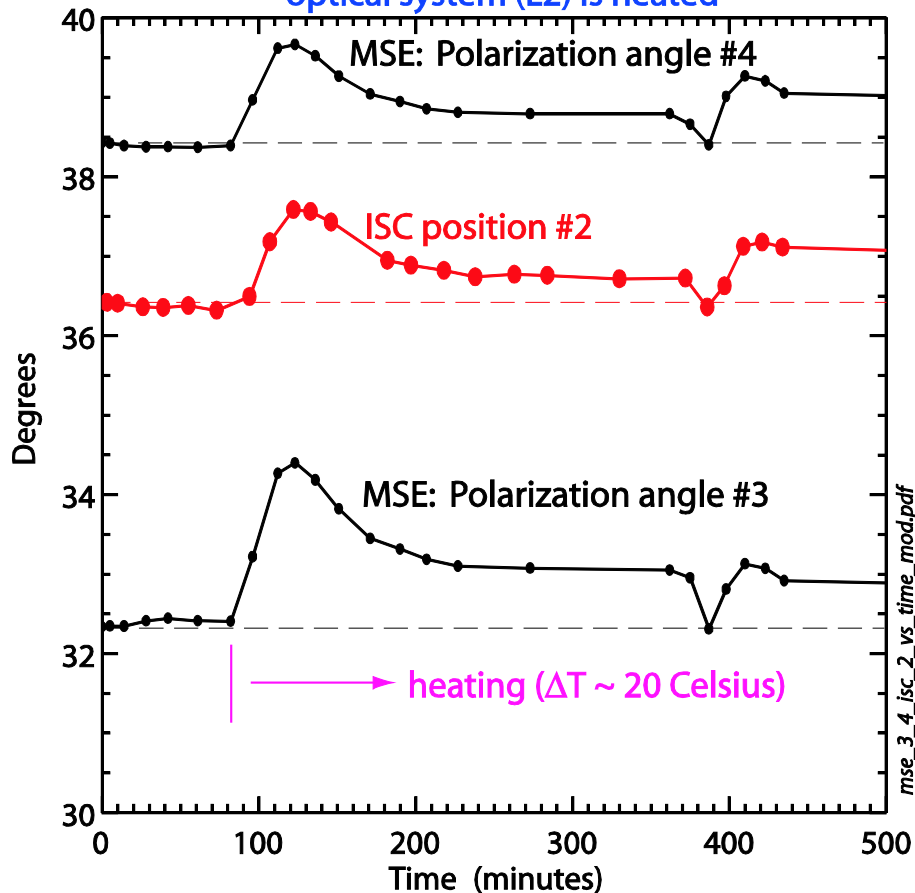


- ISC is Chapter 3 of the thesis
- Subject of an RSI being drafted

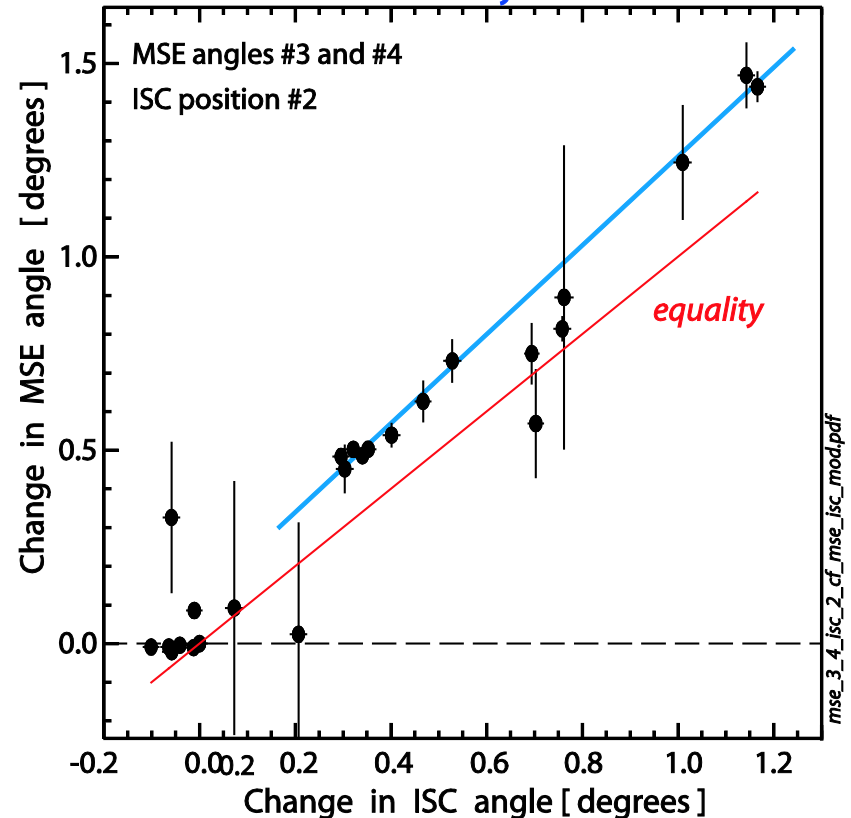
ISC Non-uniformity counter evidence

ISC and invessel source track each other well when lenses are heated invessel.

To assess absolute accuracy of the ISC, compare change in polarization angle measured by MSE to the change measured by the ISC, as one lens in the MSE invessel optical system (L2) is heated



In this heating scan, the ISC system observes only about 80% of the change in angle observed by MSE

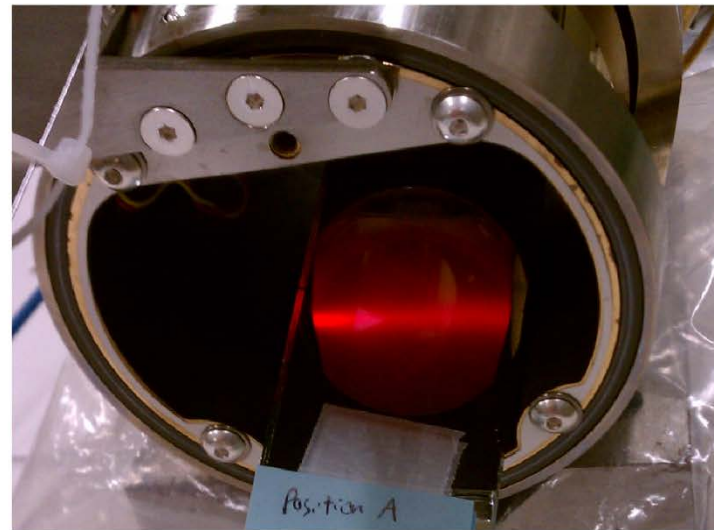
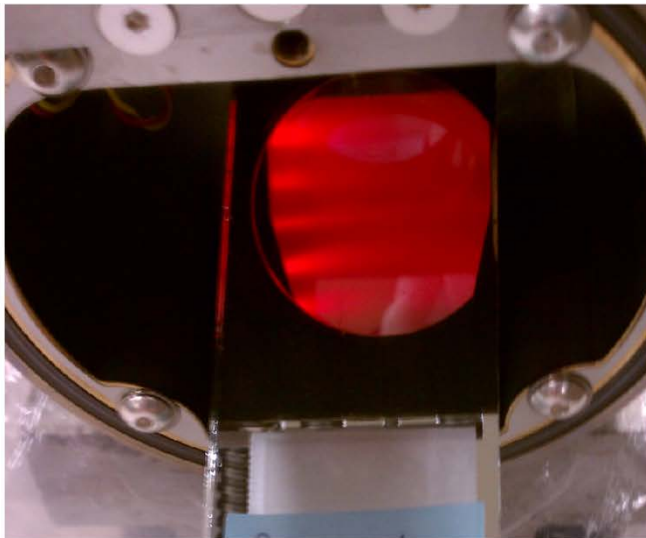


- Similar results obtained for other ISC polarization angles.
- The ISC illumination system fills only $\sim 90\%$ of the MSE objective lens - could this be the cause of the discrepancy?

*MSE measurement goal: $<0.10^\circ$

Changes in diagnostic response properly tracked even with non-uniform illumination

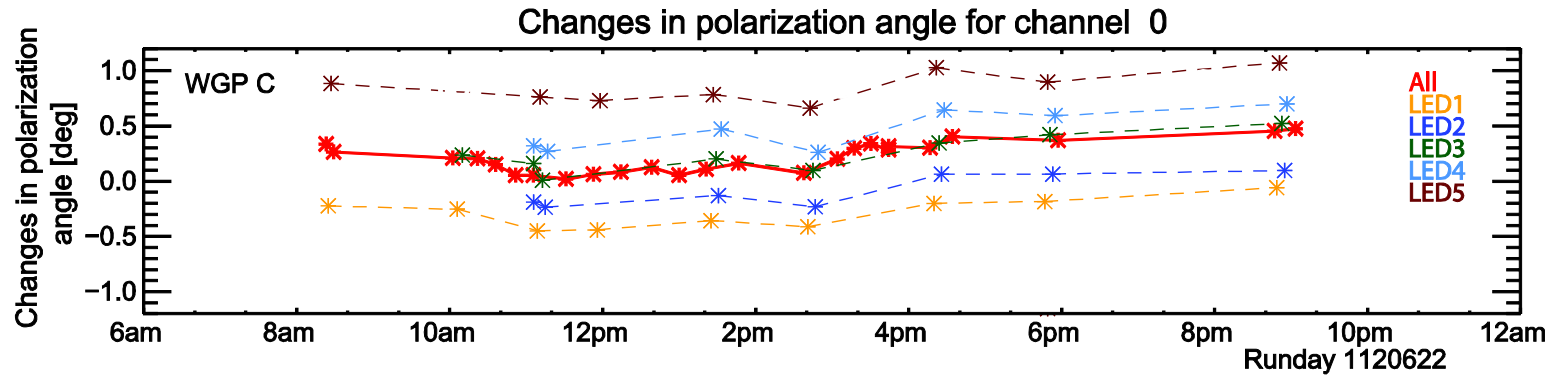
- Each ray that transits the MSE system is affected by it differently
 - Due to AOI effects from mirrors, local stress in lenses, location on PEMs
 - Verified using polarized ray trace and masking invessel
 - Need to have same illumination as beam provides for absolute angle calibration
- **IMPORTANT:** Do all rays see similar **CHANGES** in the diagnostic across the runday?
 - **If not** then illumination from ISC must match beam illumination very closely
 - **If so** then ISC still able to **track changes** in the diagnostic despite non-perfect illumination
- Test this by tracking the diagnostic with using only one of the 5 illumination LEDs at a time



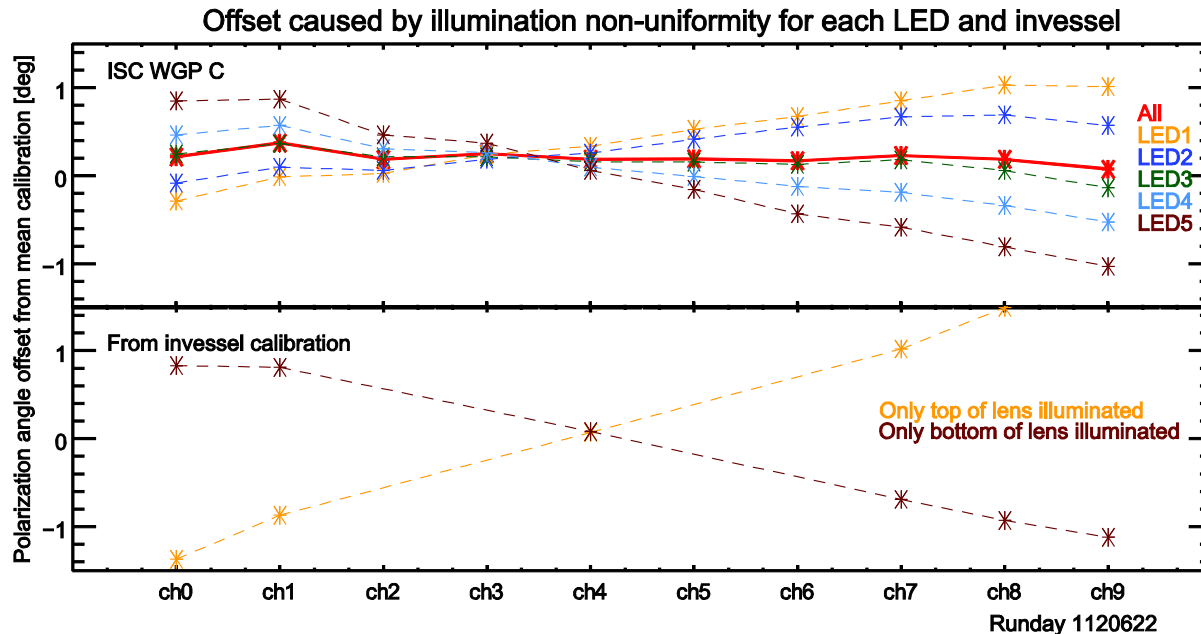
ISC system with full, 5 LED illumination (left) and with only a single LED illuminated (right) as seen from the objective lens

Changes in diagnostic response properly tracked even with non-uniform illumination

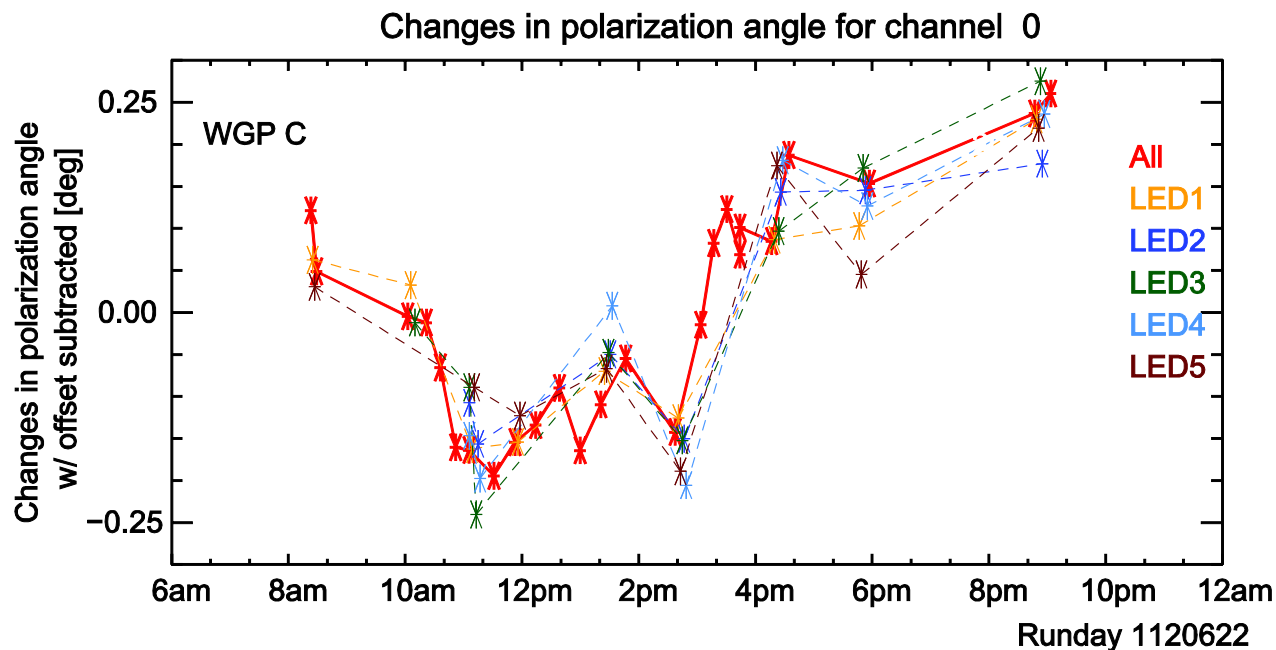
- Track changes in angle using the ISC with only one LED on at a time



- Subtract constant offset due to AOI effects



Changes in diagnostic response properly tracked even with non-uniform illumination



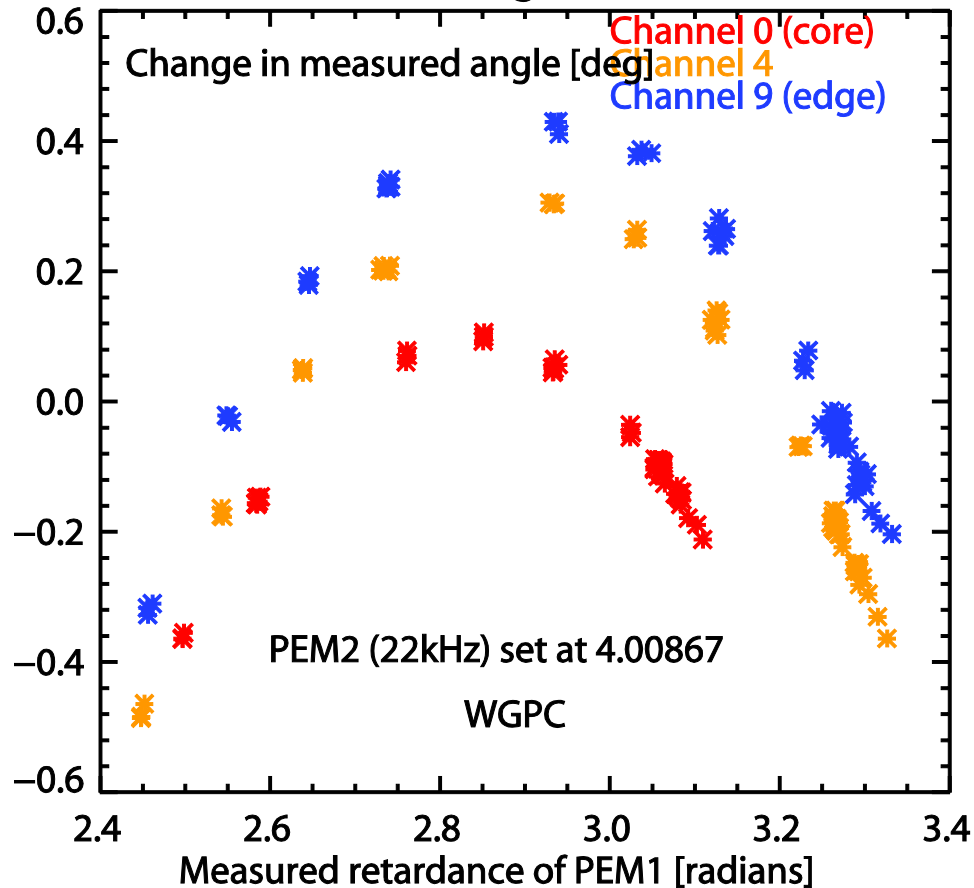
- Different illumination patterns show the same changes in the diagnostic
 - ISC can properly track **CHANGES** despite having non-perfect illumination uniformity
- To get the absolute angle correct the calibration illumination must match the beam illumination to ~20%
- Plasma sweep calibrations/invessel absolute angle calibrations are valid for long time periods by tracking changes with the ISC

*MSE measurement goal: $<0.10^\circ$

PEM monitoring

PEM retardance vs angle behaves correctly

Variation in measured angle vs measured retardance



*MSE measurement goal: $<0.10^\circ$

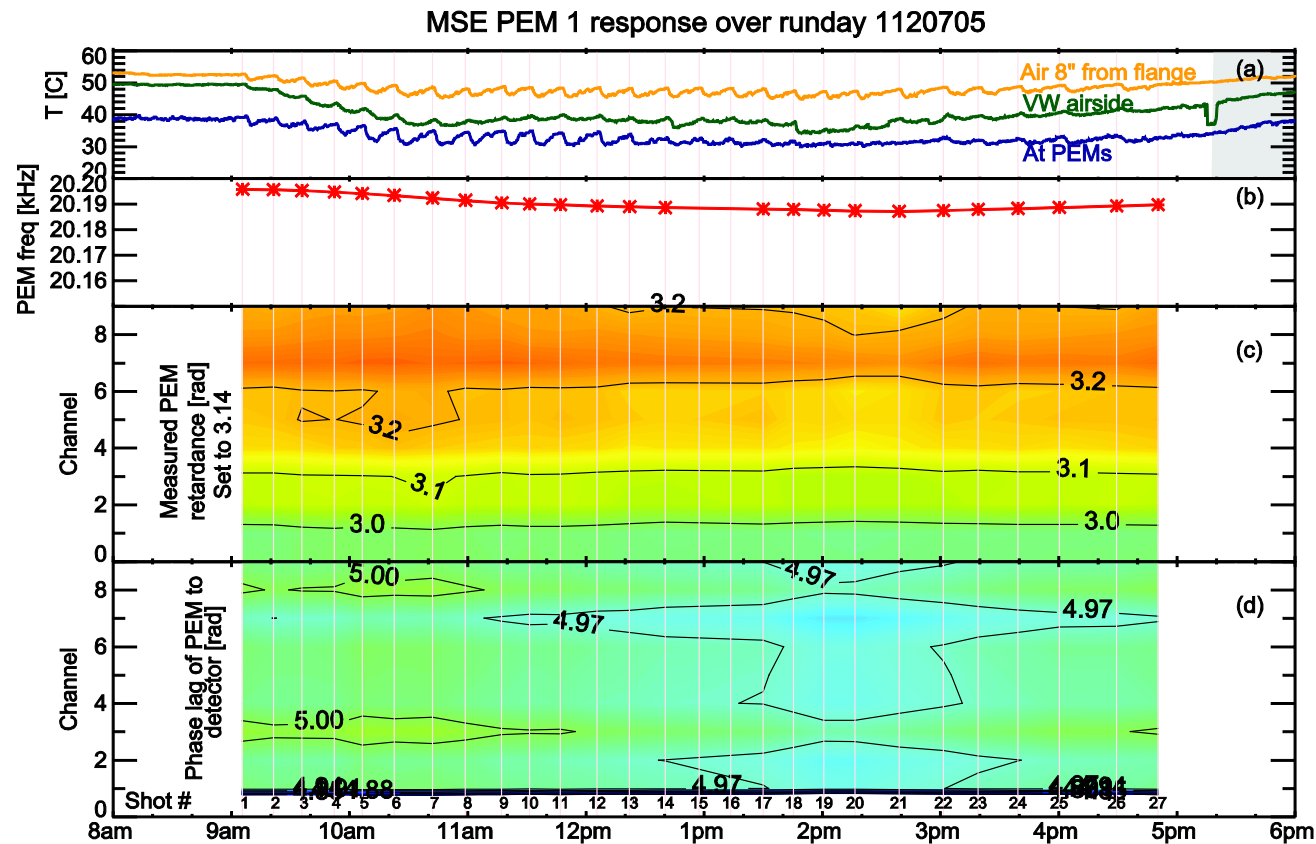
PEMs and phase lags stable for most days

- MSE systems **assume** PEM retardance and the phase between PEM and detector is constant for an entire campaign
 - Complicated electro-optical-mechanical system in a harsh environment
- ISC allows us to test this:
 - PEMs stable during a shot w/ fields, noise etc
 - Stable during a runday, except for every once-in-awhile

Note:
retardance change of 0.3 rad $\sim$
error of 0.1° in polarization
angle

Note:
Change of phase of 0.12 rad $\sim$
error of 0.1° in polarization
angle

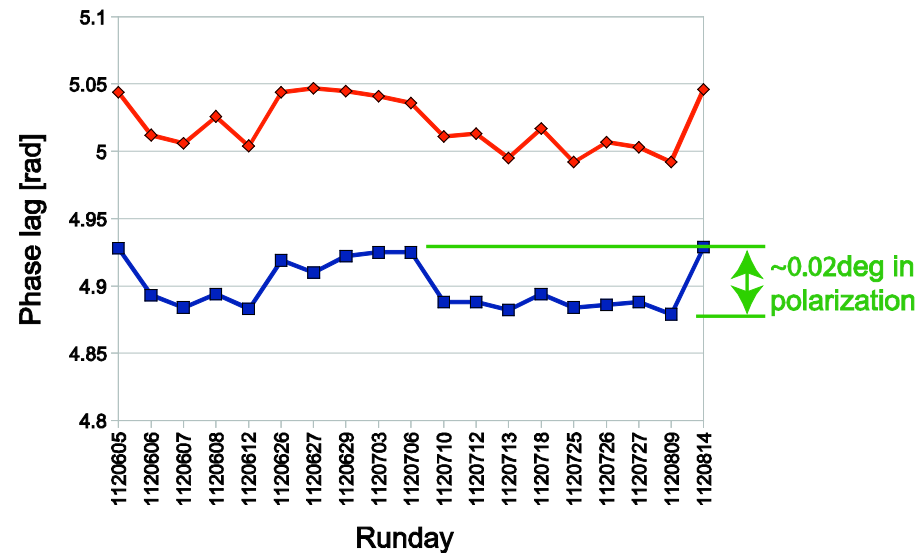
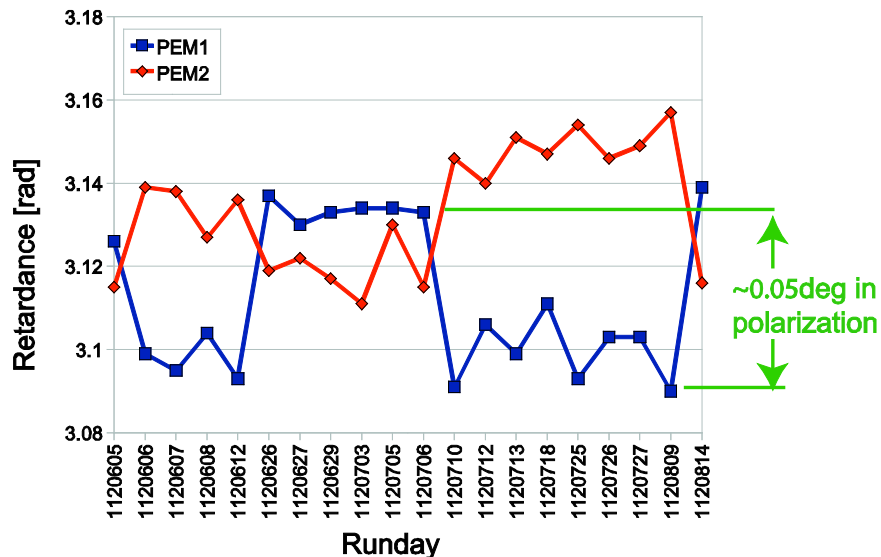
*MSE measurement goal: $<0.10^\circ$



PEMs and phase lags stable for most days

- MSE systems **assume** PEM retardance and the phase between PEM and detector is constant for an entire campaign
 - Complicated electro-optical-mechanical system in a harsh environment
- ISC allows us to test this:
 - PEMs stable during a shot w/ fields, noise etc
 - Stable during a runday, except for every once-in-awhile (those few days in March...)
 - Drifts slightly ($\alpha \sim 0.05^\circ$) across days-weeks

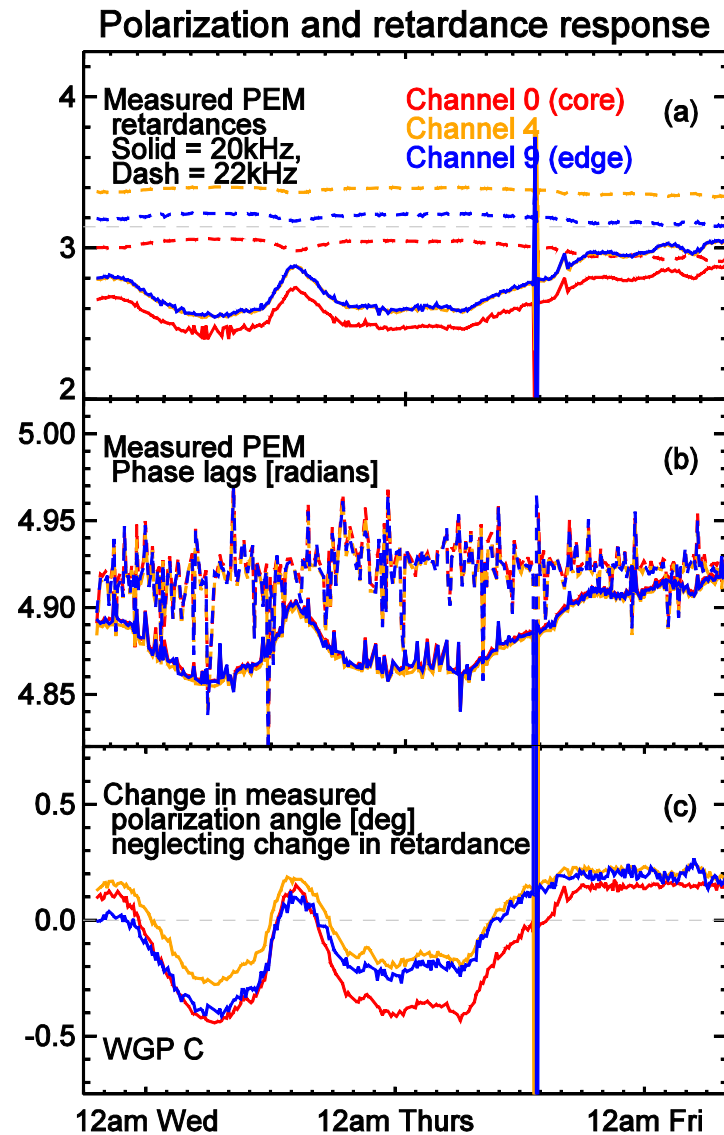
PEM retardance and PEM-detector phase lag stability
(averaged over all chs and over runday)



*MSE measurement goal: $<0.10^\circ$

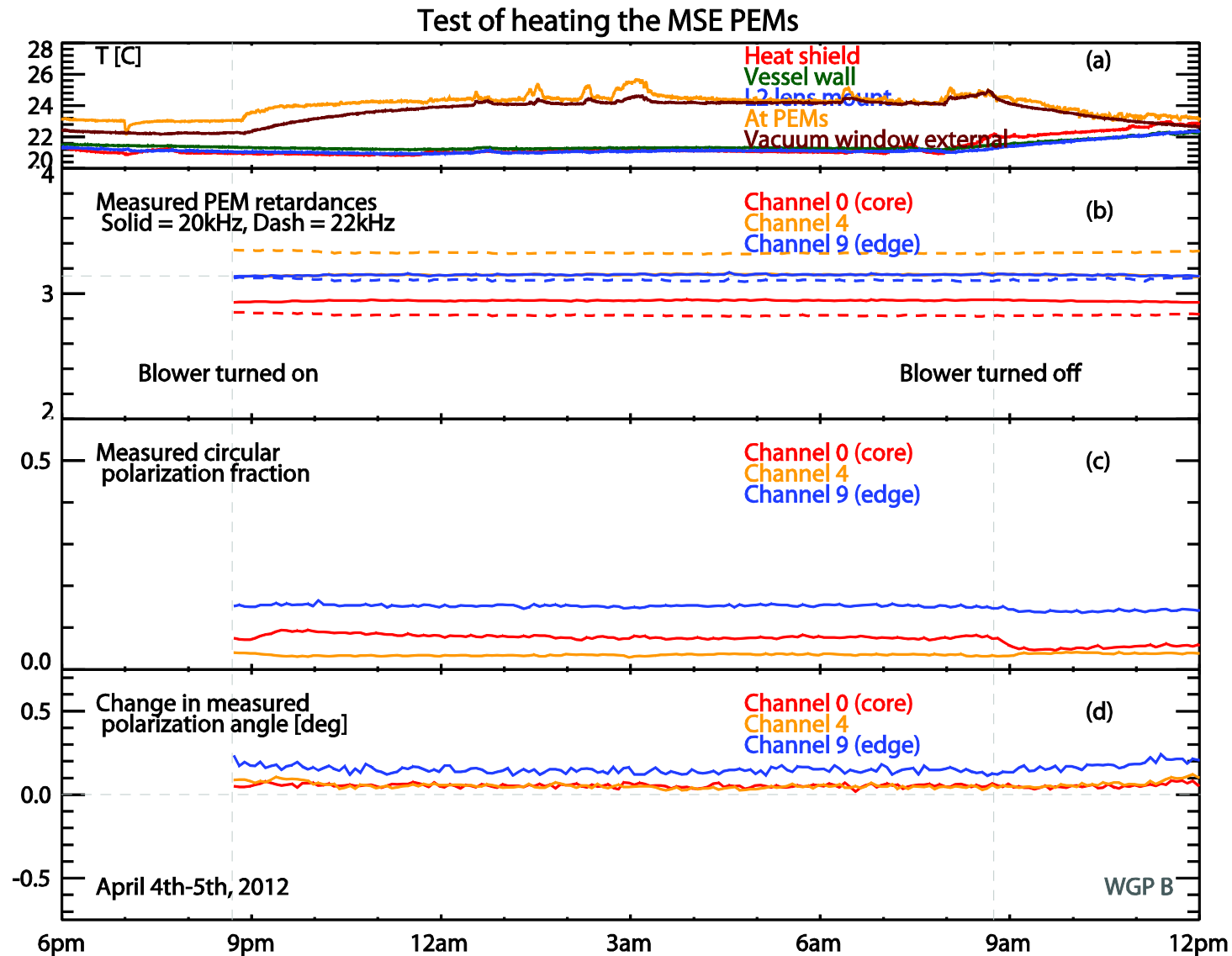
Those days back in March when the PEMs changed

- PEM1 drifted quite a bit over a few days in March.
 - No idea why.



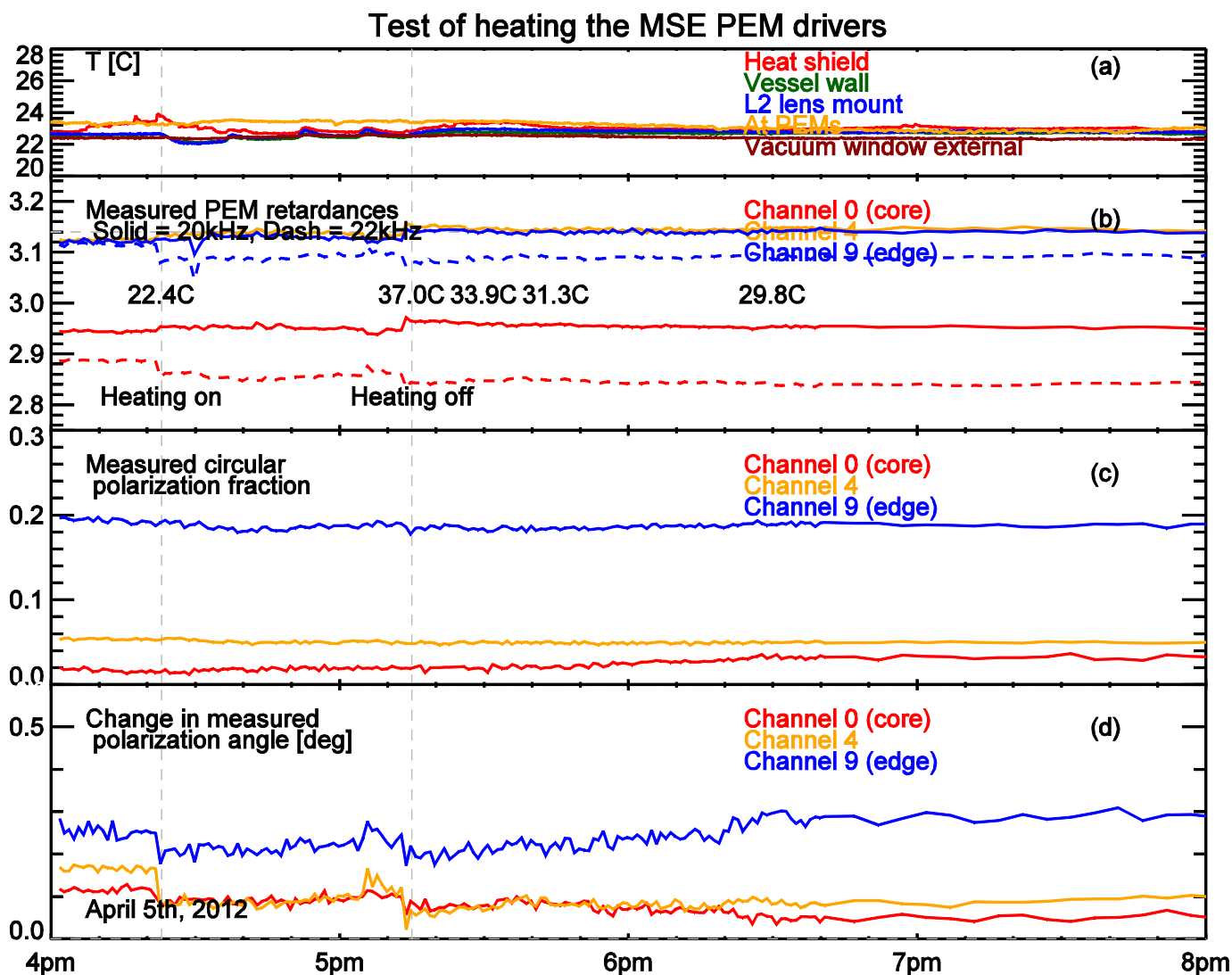
*MSE measurement goal: $<0.10^\circ$

Heating the PEMs to levels they see during the run does not change the resulting angle much



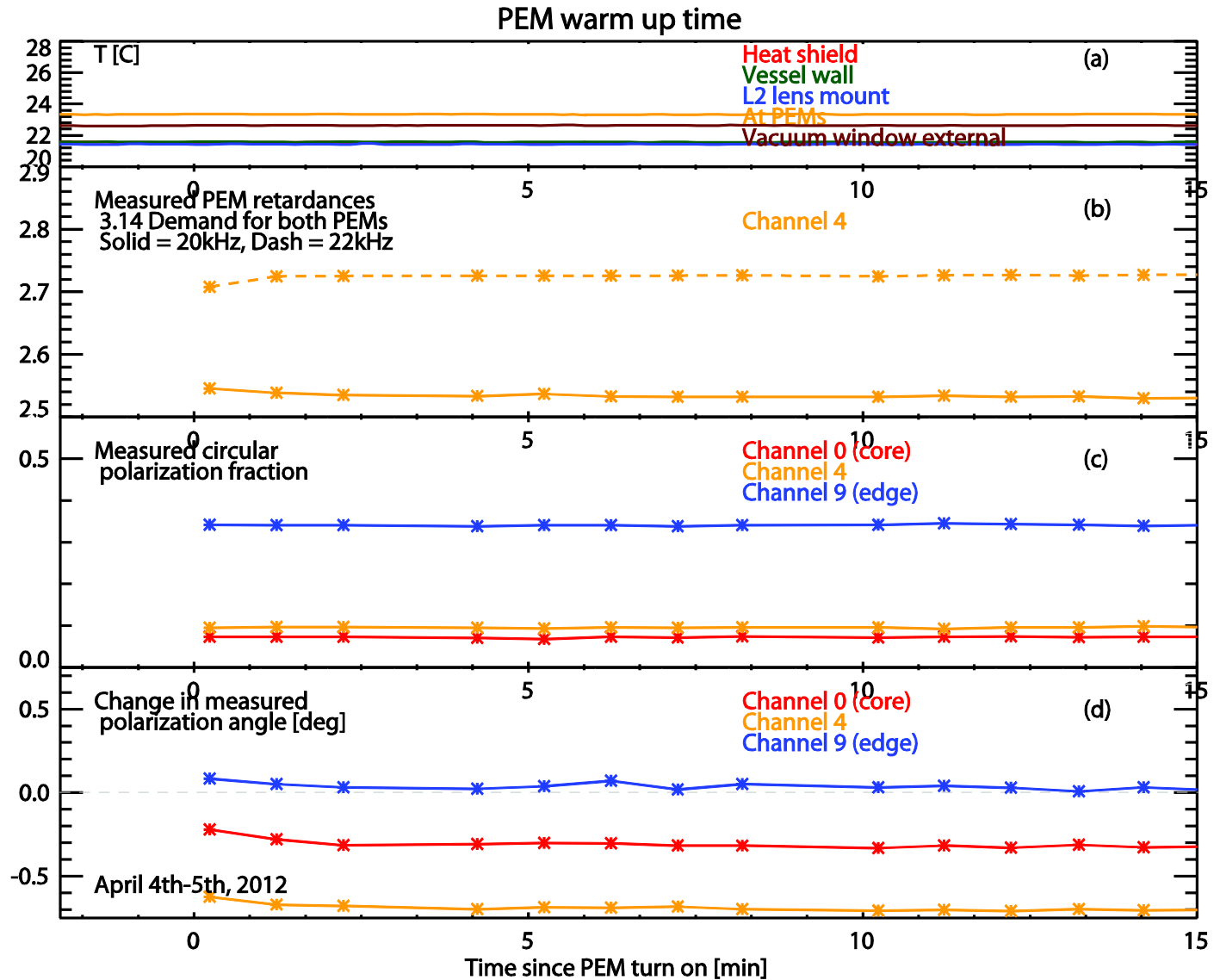
*MSE measurement goal: $<0.10^\circ$

PEMs driver temperature does not affect the retardance or the resulting angle much



*MSE measurement goal: $<0.10^\circ$

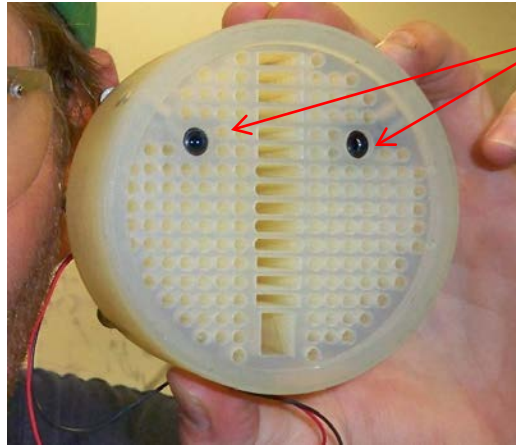
PEMs don't require much time to turn on or change retardance



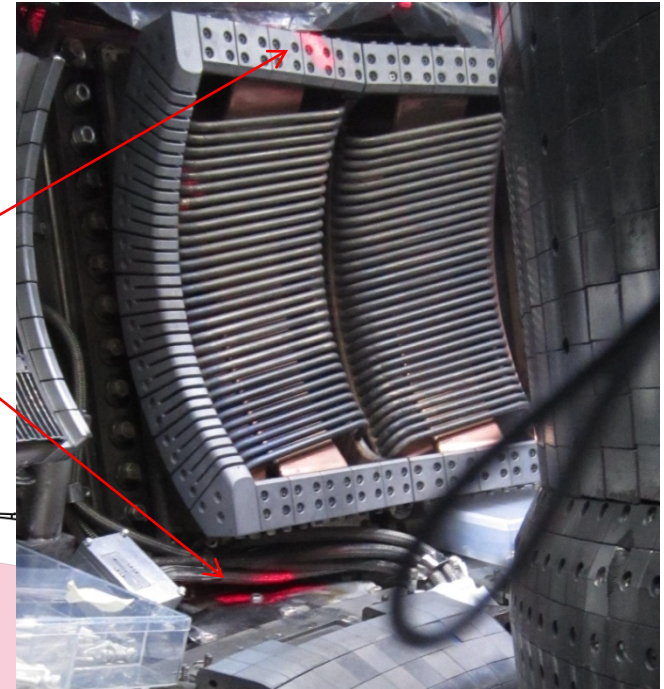
*MSE measurement goal: $<0.10^\circ$

View monitoring

Installed laser tracking system in the diagnostic to track it's view, it doesn't move.



Lasers installed with fibers, traverses whole diagnostic



Strike D-ANT, tracked with DANT camera

MSE dissector lasers

MSE periscope optics

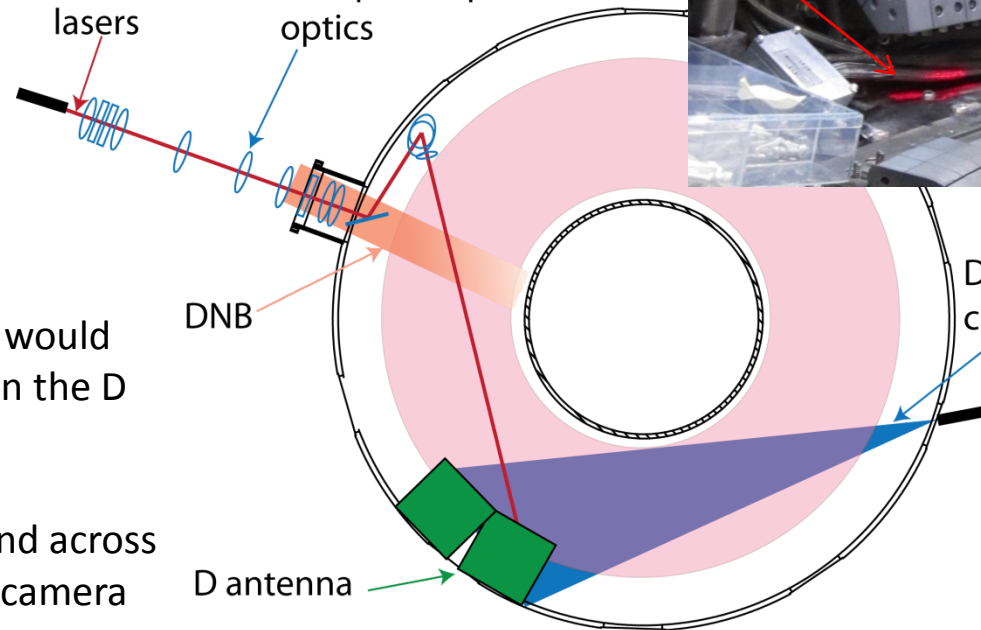
DNB

DANT camera

D antenna

Any movement of the Optics would also move the laser spot on the D antenna.

Track the view shot to shot and across campaign using the DANT camera



Installed laser tracking system in the diagnostic to track it's view, it doesn't move.



Lasers installed with fibers, traverses whole diagnostic

Strike D-ANT, tracked with DANT camera



MSE dissector lasers

MSE periscope optics

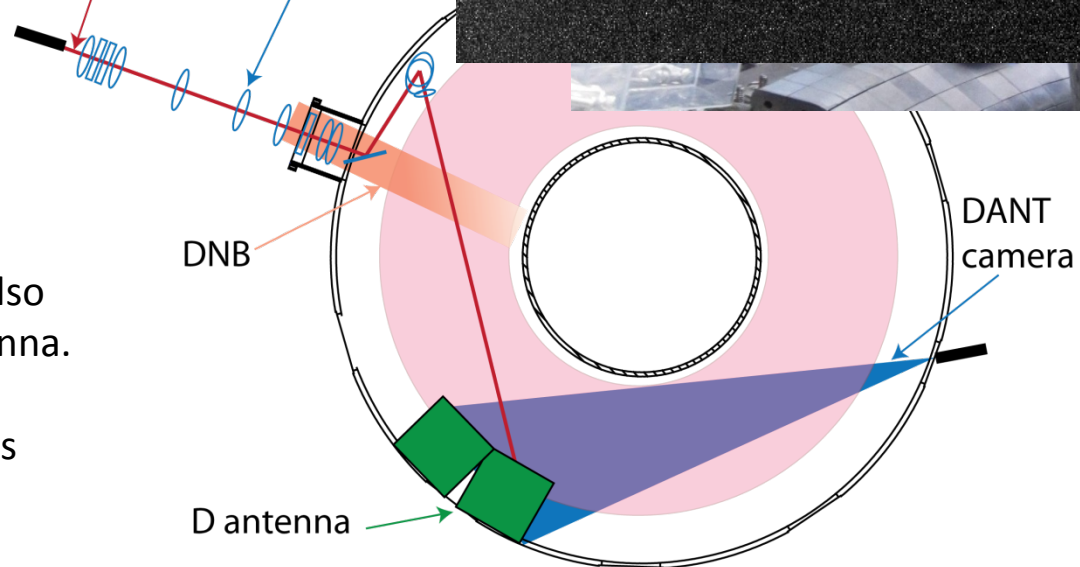
DNB

DANT camera

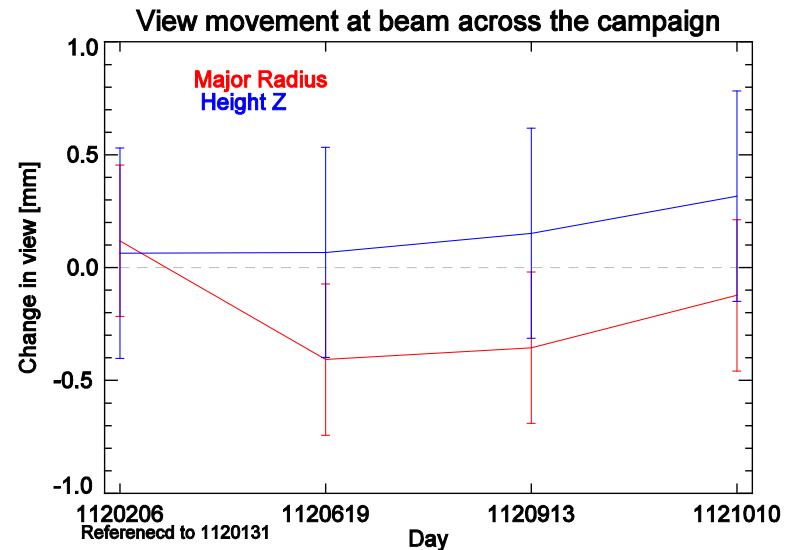
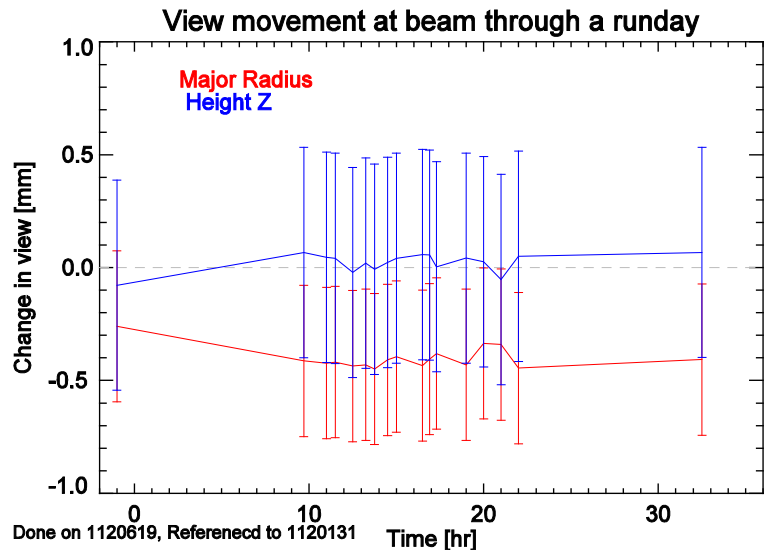
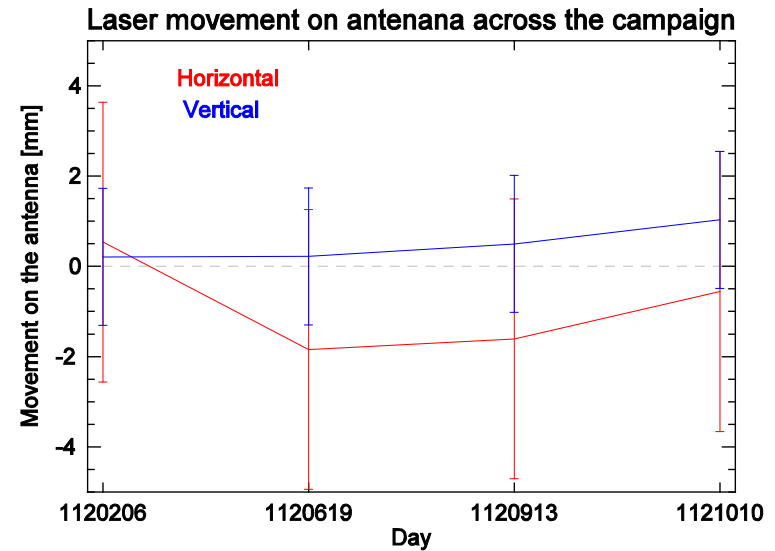
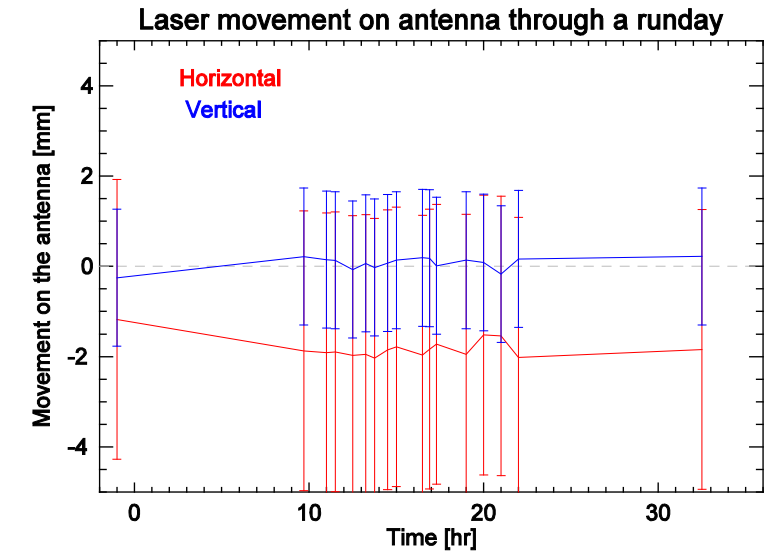
D antenna

Any movement of the optics would also move the laser spot on the D antenna.

Track the view shot to shot and across campaign using the DANT camera



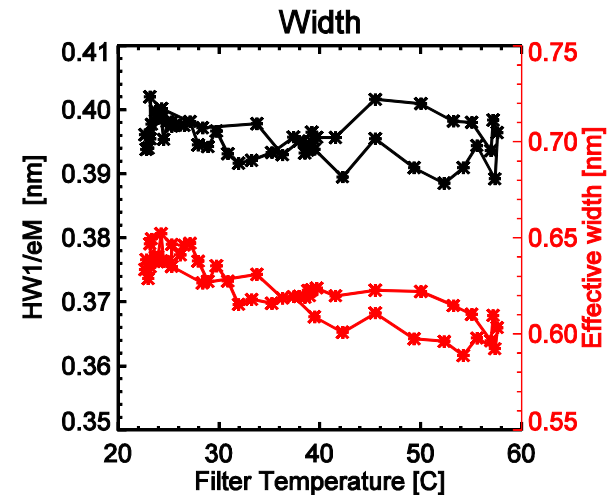
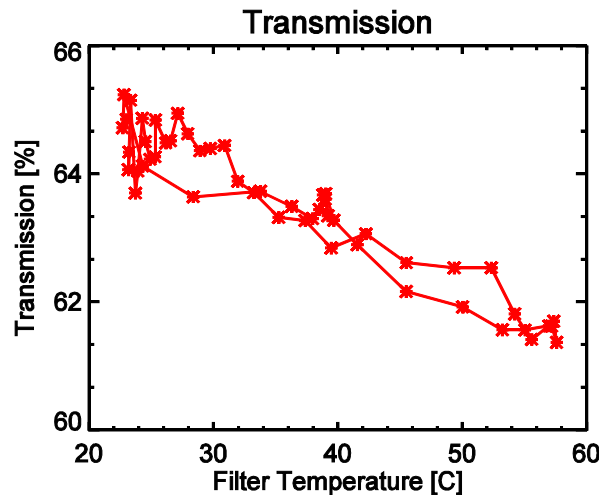
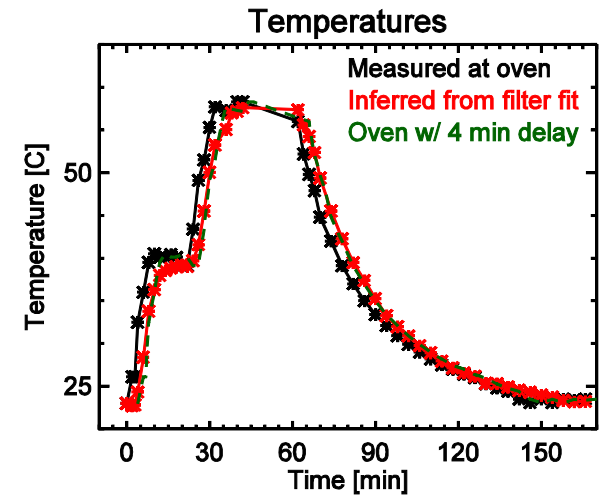
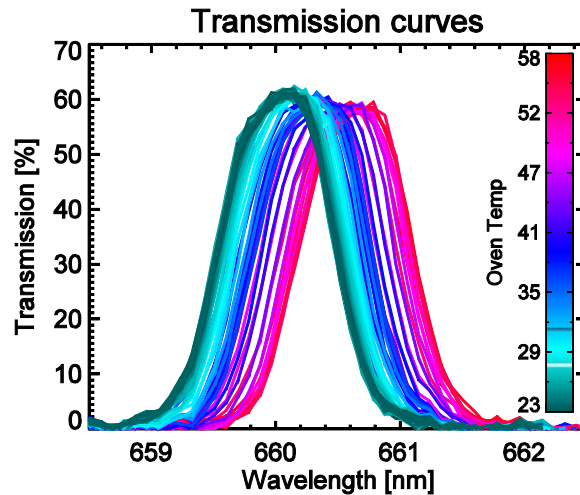
Installed laser tracking system in the diagnostic to track it's view, it doesn't move.



Filter checks

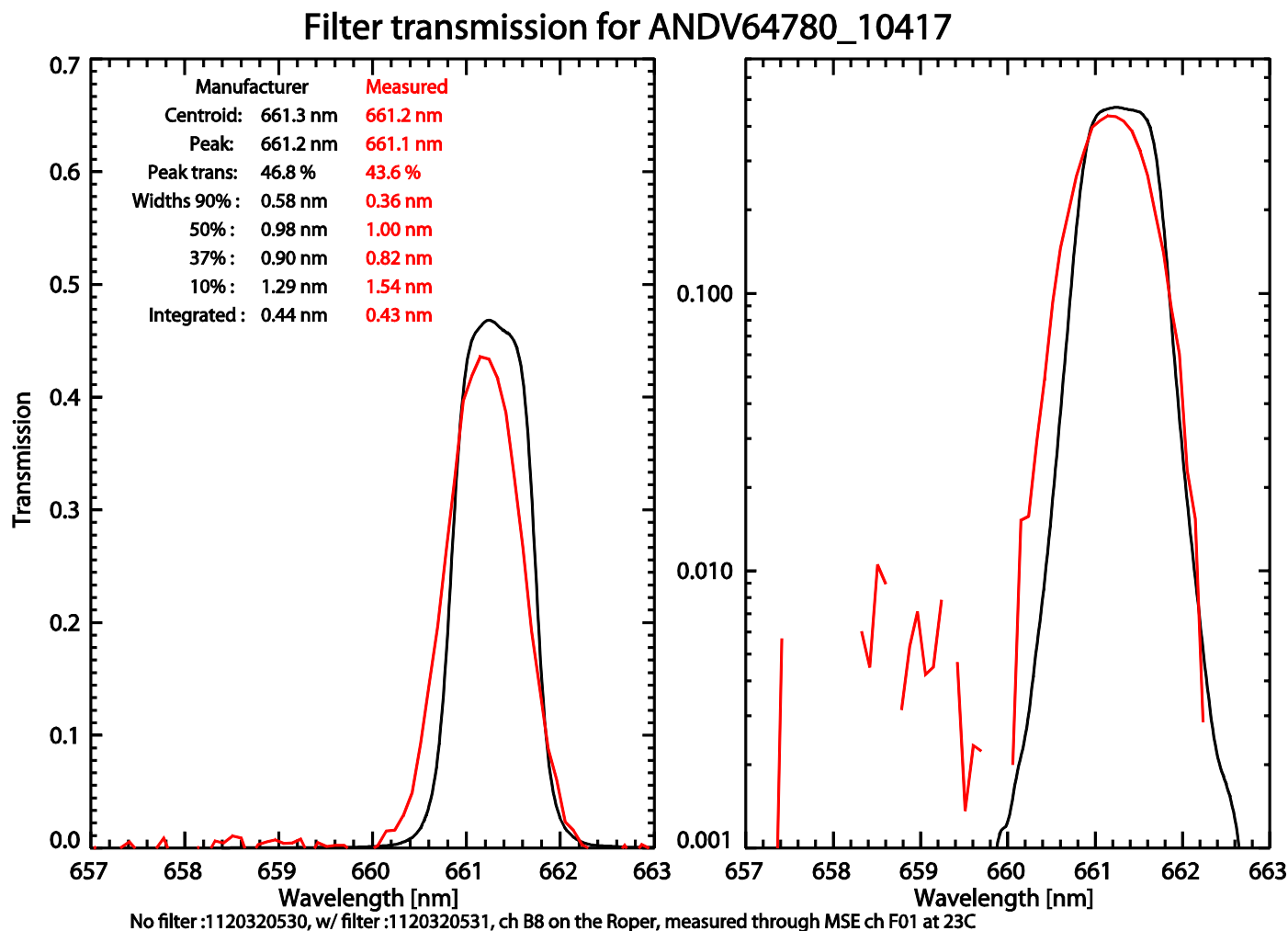
We can accurately tune the filter bandpasses, checked in-situ.

- Used spectrometer with integrating sphere to get full etendue coverage of filter performance.
- Heat filter to steady state and measure change in bandpass to get tuning coefficient ($0.018\text{nm}/^\circ\text{C}$), within 5% of published value.
- Temperature measured dynamically in oven matches temperature inferred from measuring filter. (with 4 minute heat soak delay)
- Sub Å control



Filters have not degraded significantly, nor are they being used improperly.

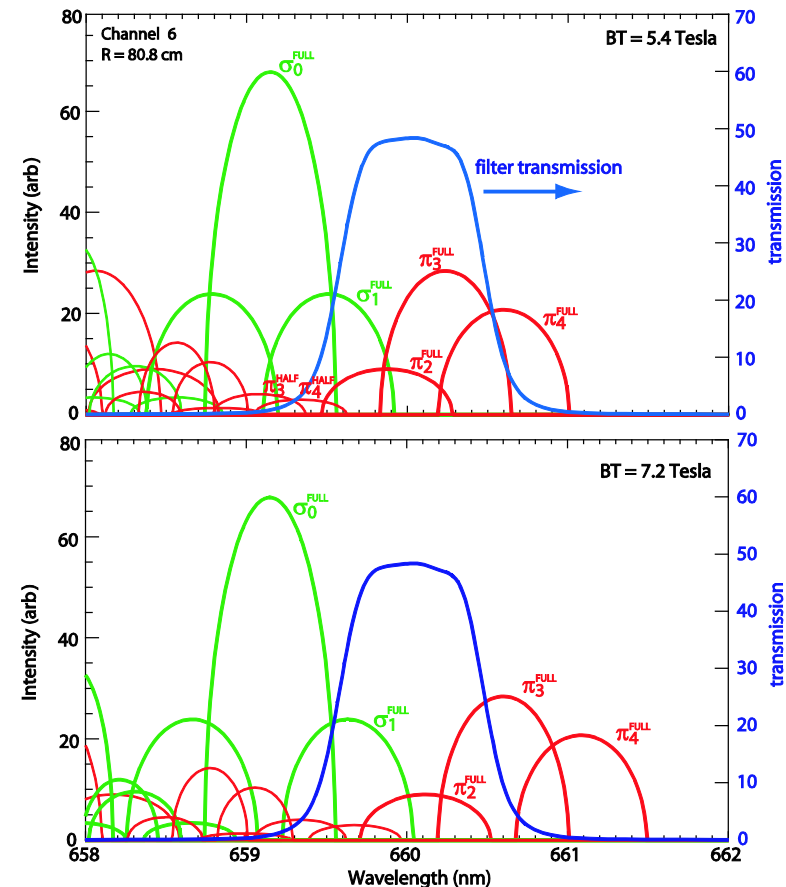
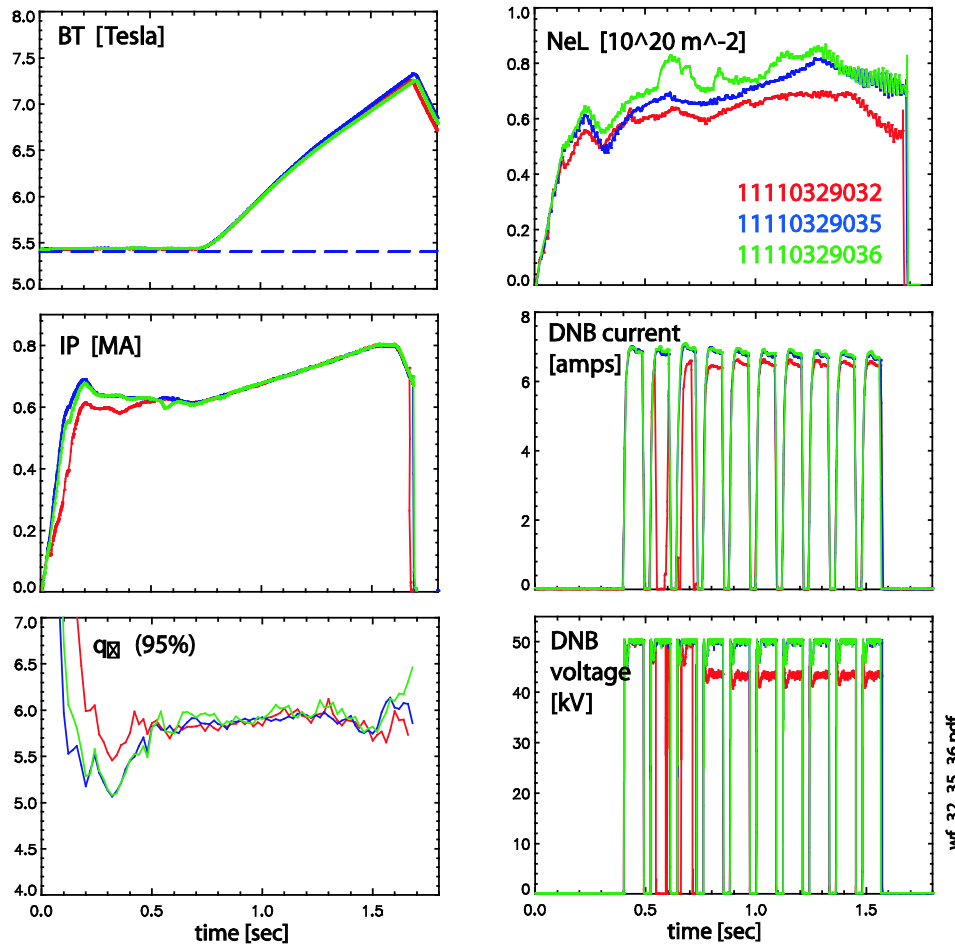
- Used spectrometer with integrating sphere to get full etendue coverage of filter performance. All have been measured, one example here:



Test filter location by scanning toroidal field, thus scanning spectrum past filters.

The toroidal field was ramped up at constant q to move the MSE spectrum past the fixed MSE bandpass filters at constant pitch angle

With an appropriate bandpass filter, an MSE channel can move between a π -dominated spectrum to a σ -dominated spectrum as the toroidal field is ramped during a shot

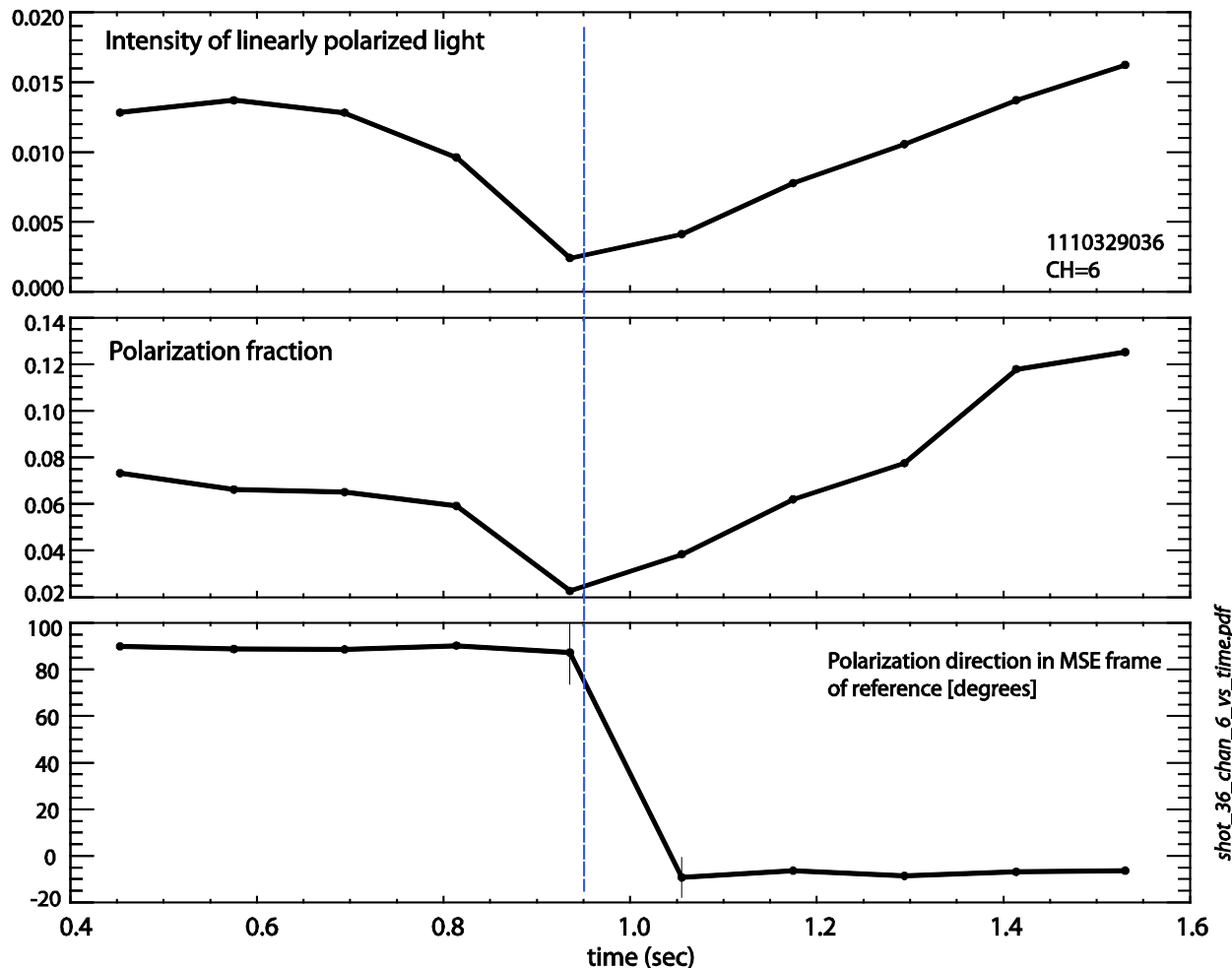


Scott, APS2011

sh_36_ch_6_bt_54_better.p

Test filter location by scanning toroidal field, thus scanning spectrum past filters.

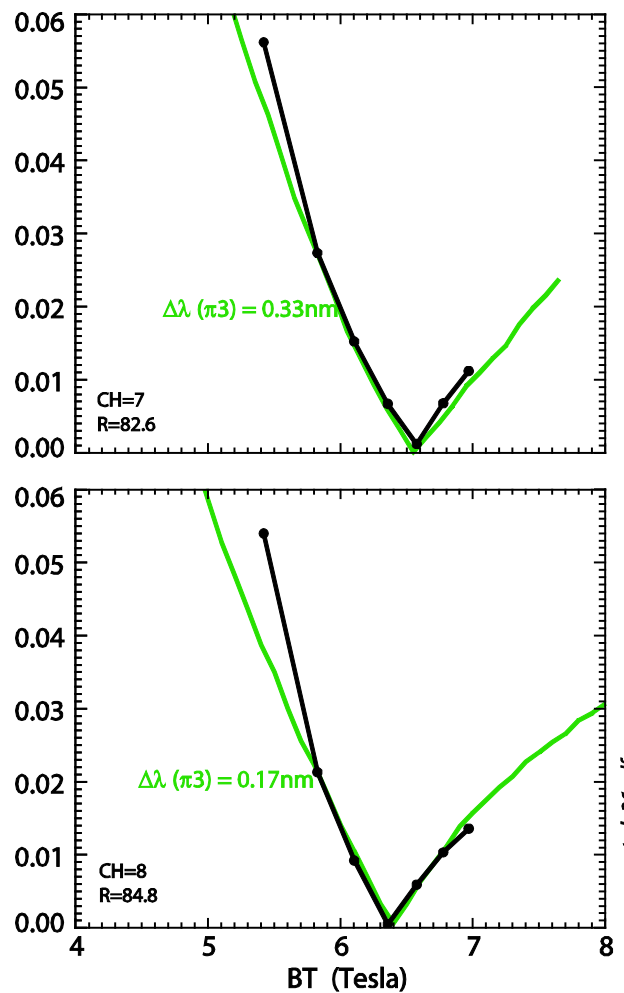
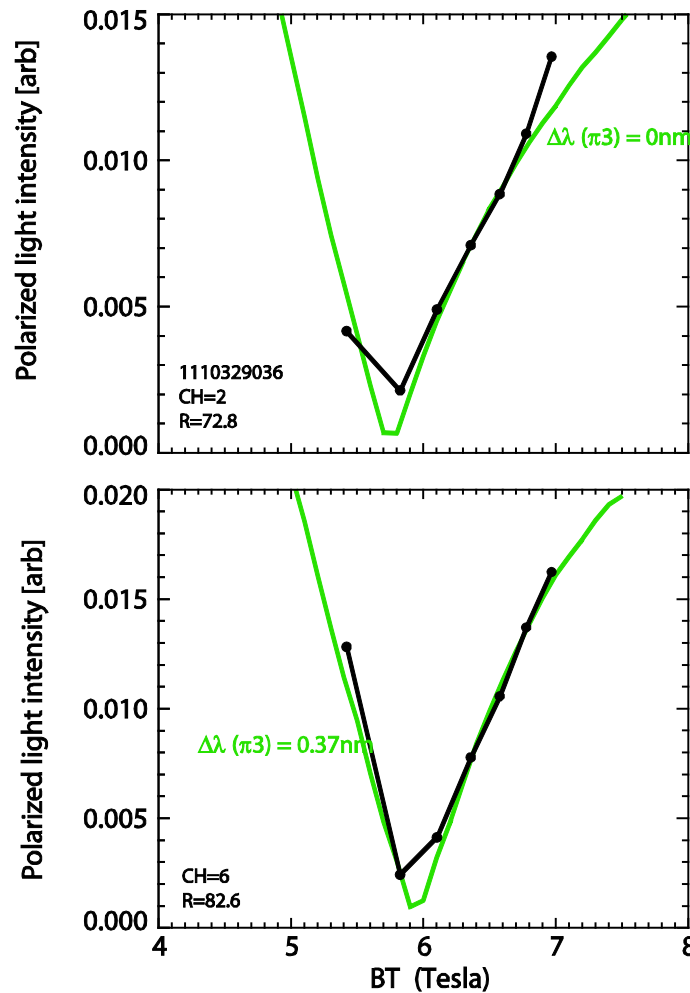
When the σ and π intensities are equal, the net intensity of polarized light and the polarization fraction reach a minimum. The polarization direction changes 90 degrees



Scott,
APS2011

Test filter location by scanning toroidal field, thus scanning spectrum past filters.

The PERF simulations reproduce the minima in observed polarized light intensity quite well when the wavelength is shifted by a few angstroms



Necessary filter shifts

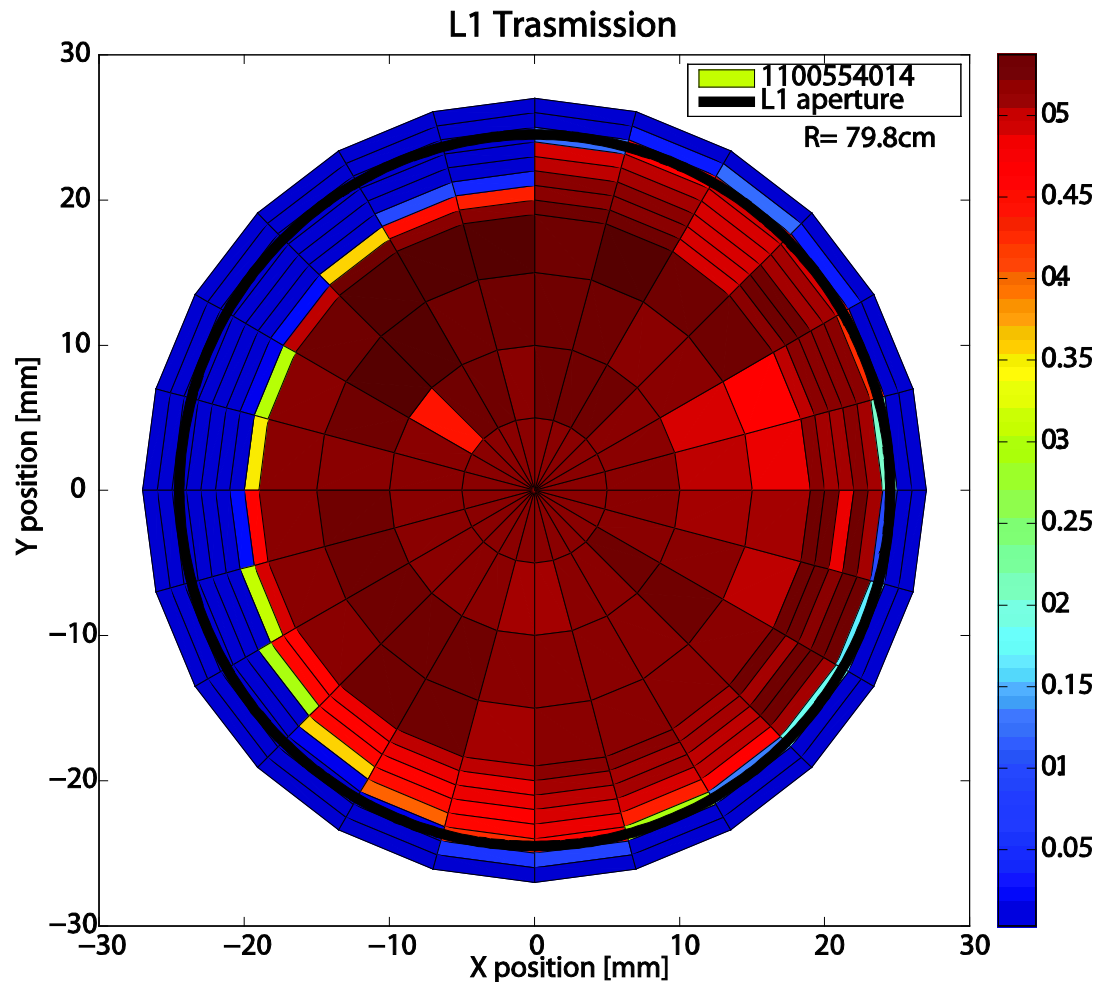
R [cm]	$\Delta\lambda$ (nm)
72.5	0.00 +/- 0.025
76.7	0.39 +/- 0.049
80.8	0.38 +/- 0.012
82.7	0.33 +/- 0.012
84.3	0.17 +/- 0.012
85.8	0.34 +/- 0.049

Scott,
APS2011

Other checks on the diagnostic properties

In vessel system allows ray tracing through the optics. They are not vignetted.

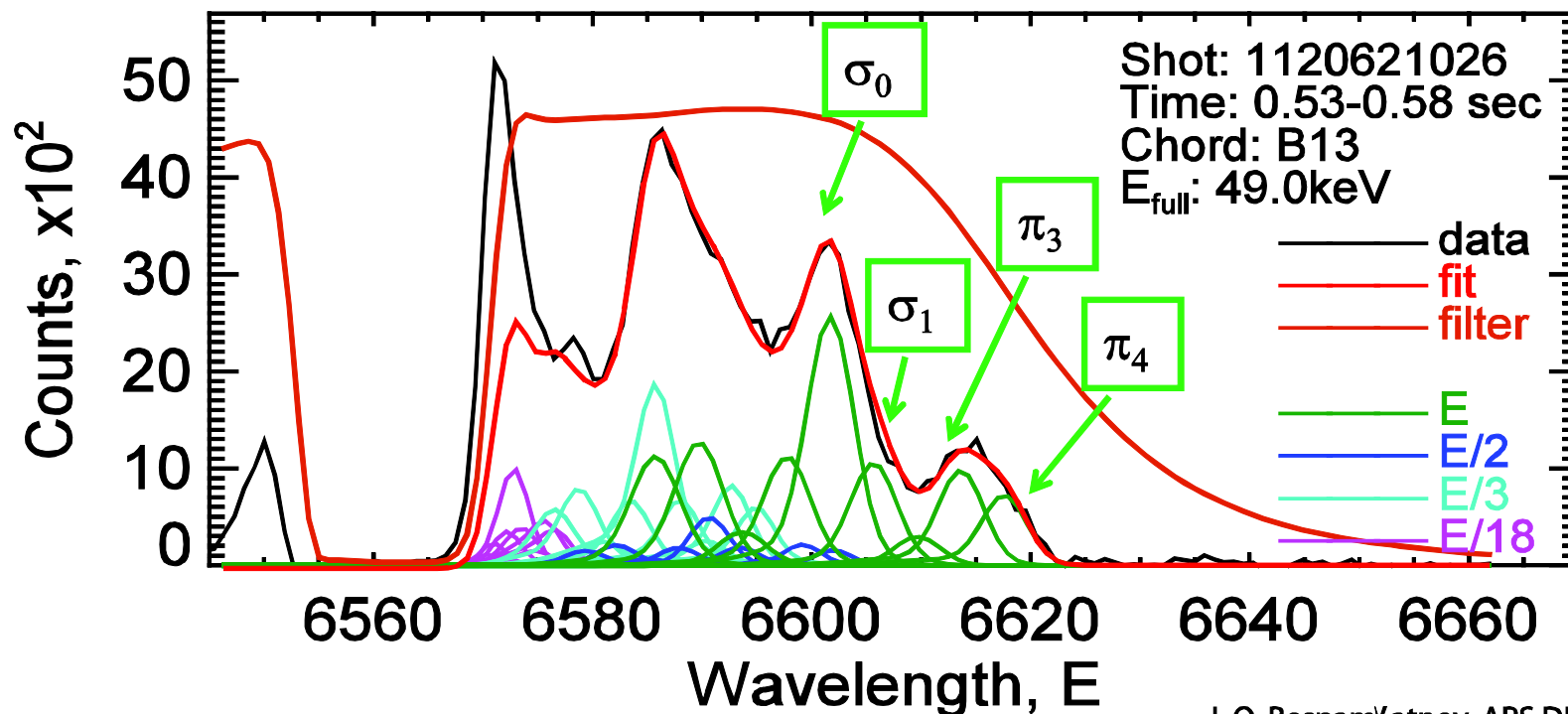
- Laser on calibration robot traces out objective lens aperture automatically
- Detector at image plane (where the fibers go) detects how much laser gets through
- Most channels only slightly vignetted (~20%)
- Largely independent of major radius
- Will be extended to **Polarized** ray trace.



*MSE measurement goal: $<0.10^\circ$

Spectra as measured through MSE optics is well fit by modeling

- Beam emission measured via MSE optics and BES fiber using UT spectrometer and PPPL high resolution grating
- 6 parameter fitting packaged developed by Igor using nkm resolved CR model. [O. Marchuk et al *J. Phys. B: At. Mol. Opt. Phys.* **43** 011002 (2010)]
- Result matches blended MSE spectrum well

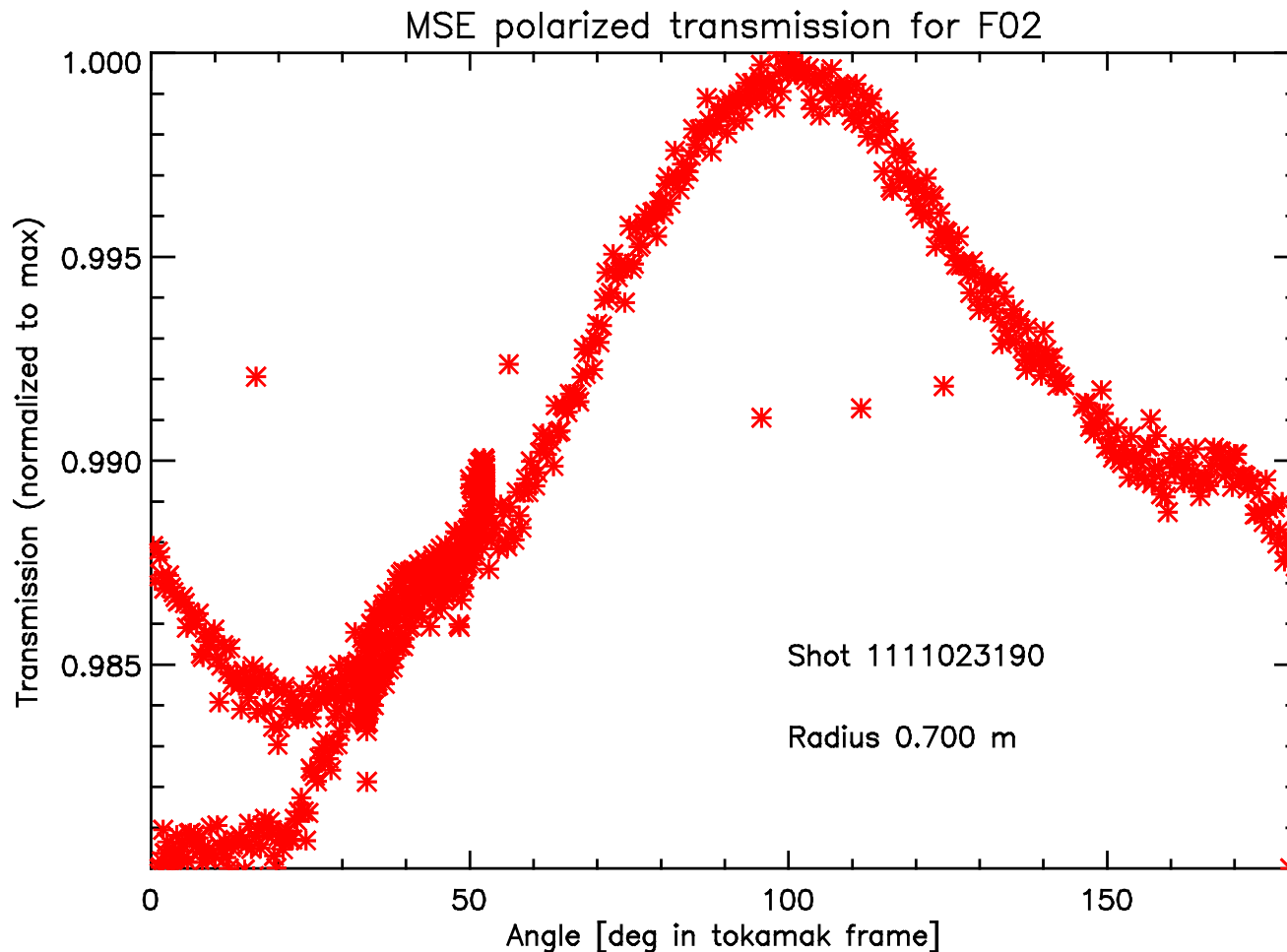


I. O. Bespamvatnov, APS DPP 2012

*MSE measurement goal: $<0.10^\circ$

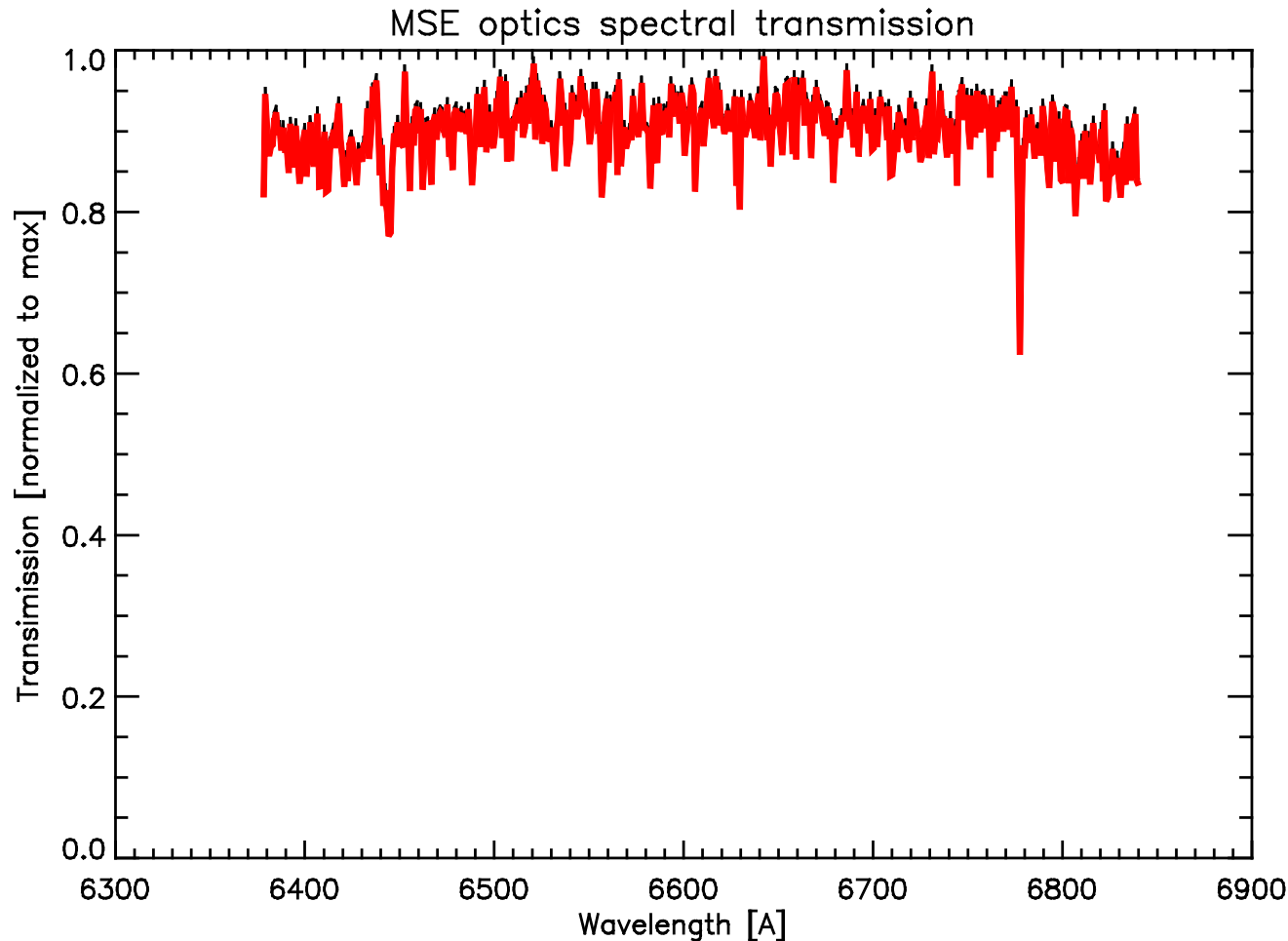
MSE optics have very little polarization dependent transmission

- Use invessel calibration source to rotate a polarizer in front of optics and measure the light throughput.



MSE optics have very little spectral dependent transmission

- Use high resolution spectrometer to measure the spectral transmission curve of the optics using a labsphere as input.



Paul Gelen simulated our system with advanced Stokes vector codes. No surprises

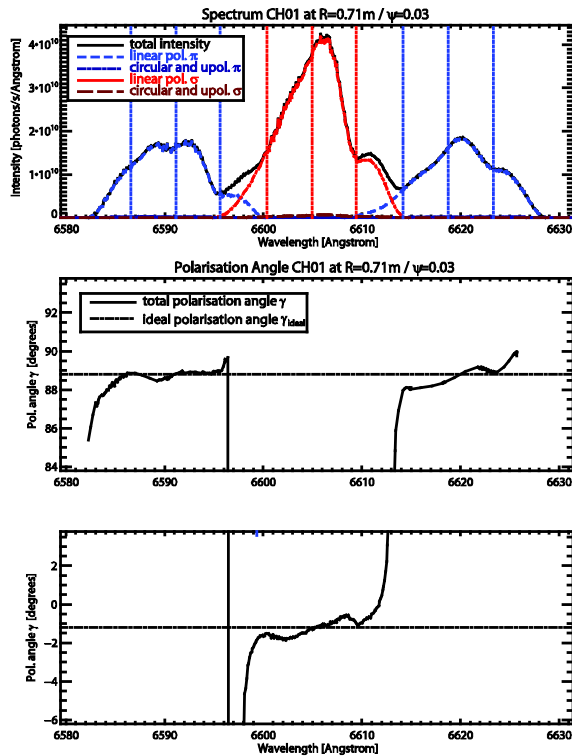


Figure 4.6: Spectrum and polarisation angle of channel 1 of the fully modeled situation.

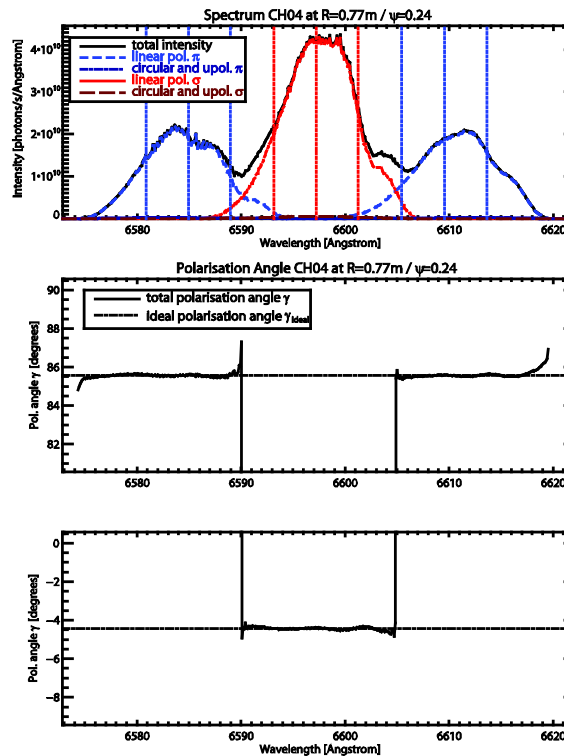


Figure 4.5: Spectrum and polarisation angle of channel 4 of the fully modeled situation.

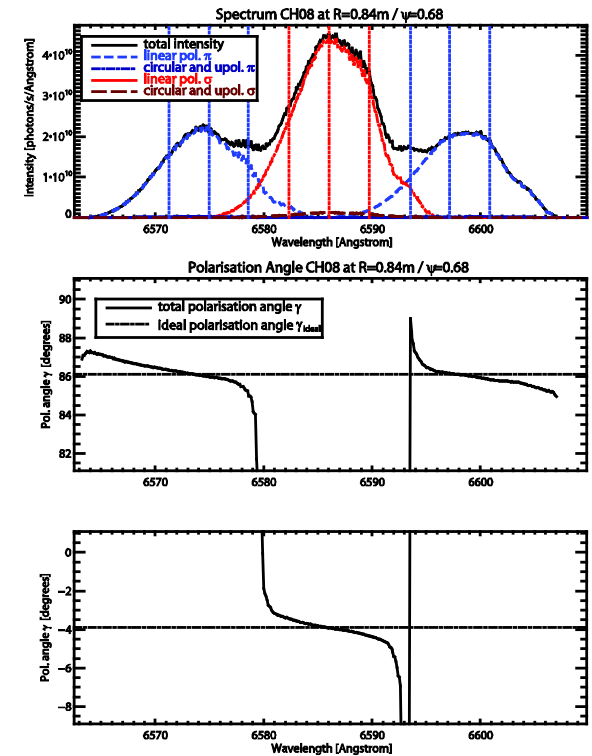


Figure 4.7: Spectrum and polarisation angle of channel 8 of the fully modeled situation.

	Channel 1		Channel 4		Channel 8	
	unfiltered	filtered	unfiltered	filtered	unfiltered	filtered
I [photons/s/ Å]	1.8E+010		2.1E+010		2.1E+010	
I [photons/s]		6.7E+010		7.8E+010		7.9E+010
polarisation angle γ [deg]	88.79	88.77	85.50	85.56	85.93	86.00
$d\gamma/d\lambda$ [deg/Å]	0.26	0.10	-0.01	0.00	-0.11	-0.05
polarisation fraction [%]	99	94	99	92	99	89
S/N [% of maximum]	72	81	75	94	60	89

Gelen PSFC report, 2011

Robotic calibration

MSE calibration on C-Mod

How MSE is calibrated:

- Generate light with known Stokes parameters using polarizer and/or variable retarder.
- Place at a known position along DNB.
- Align k-vector at MSE objective

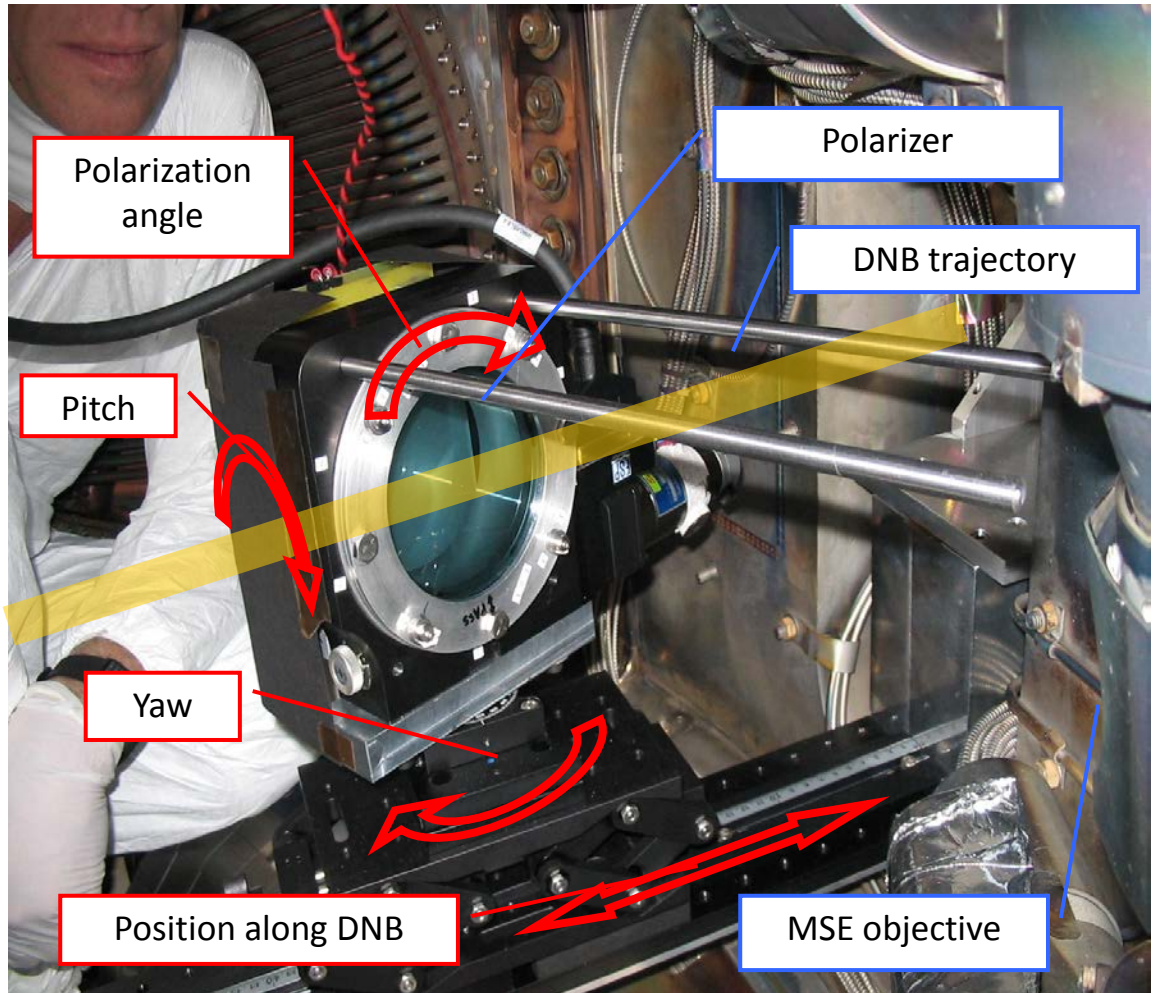
Requires 4 variable DOFs

- Polarization angle relative to the tokamak (ie relative to gravity)
- Position along DNB
- Yaw
- Pitch

DOFs change for each calibration shot

- Typically 36 different polarizations per channel.
- 10 channels.
- Additional repeatability tests.

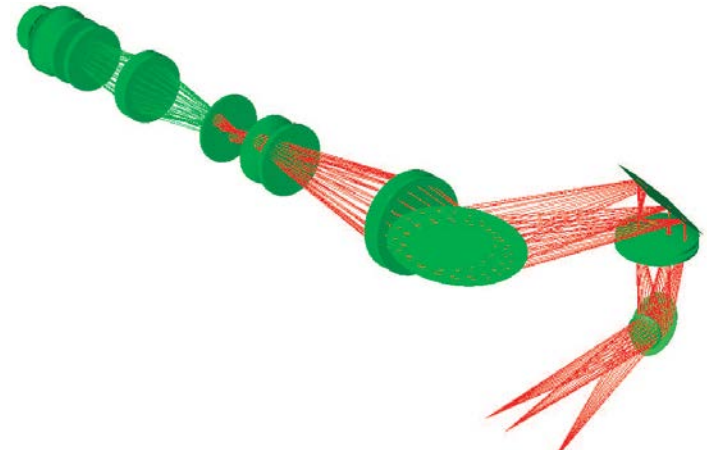
Manual placement makes calibration very time consuming and limits number of tests that can be accomplished during a maintenance period.



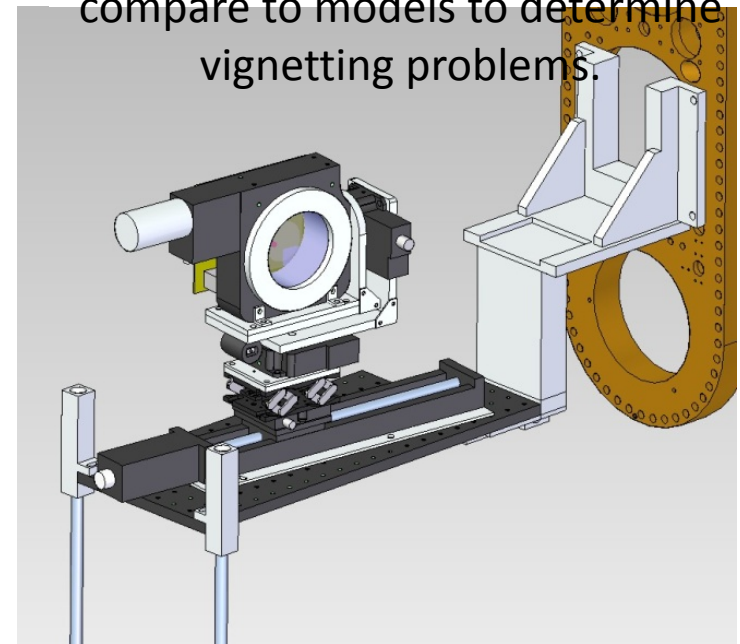
Old C-Mod MSE calibration demonstrating necessary DOFs

Why automate?

1. Streamline MSE calibration
 - Each channel takes >20 minutes of shots
 - Total calibration takes > 3-4 hours
 - Automation does not require repetitive entering and exiting of vessel to adjust for each channel.
2. Programmed to run without supervision (ie overnight), fully remote control.
3. Can operate remotely while other diagnosticians/technicians work in vessel.
4. Can perform an invessel ray tracing to look for vignetting problems.
 - A steady platform with enough DOFs to manipulate a laser from the any field point to any k vector.
 - Repeatable.
 - Results can be reconcile with analytic ray tracing model.
5. Future polarized ray trace calibration to examine dependence of calibration on:
 - PEM angle of incidence
 - Mirror angle of incidence
 - Birefringence averaging.
6. Incorporation of variable retarder to make a full Stokes vector generator to perform a full Mueller matrix calibration using elliptical light.
7. Can continuously calibrate during long term tests.
 - Such as slow heating or cooling of lenses.
8. Synchronized with the C-Mod shot cycle to allow for precise timing and automated data storage.
9. Can be used to calibrate/cross-calibrate other C-Mod beam based diagnostics.



Perform in situ ray tracing to compare to models to determine vignetting problems.

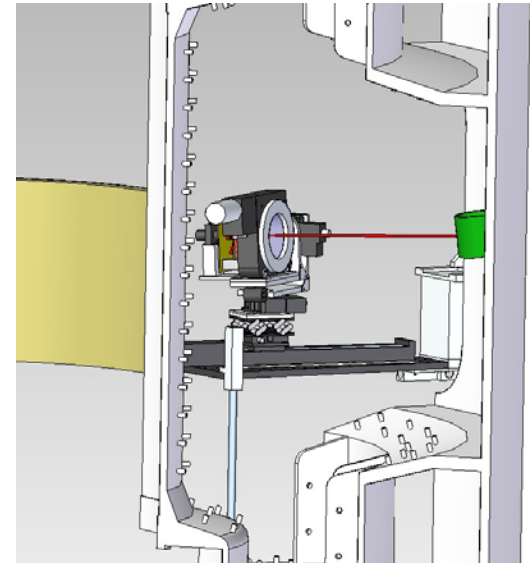


New system design.

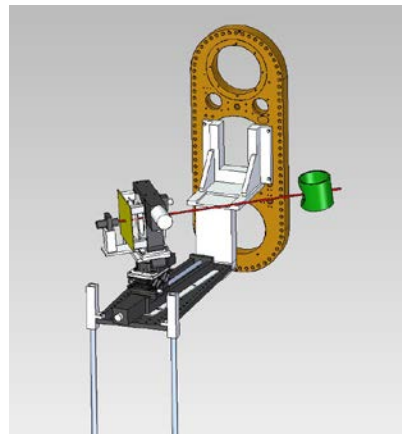
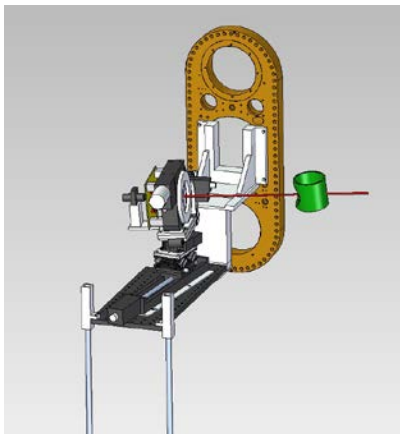
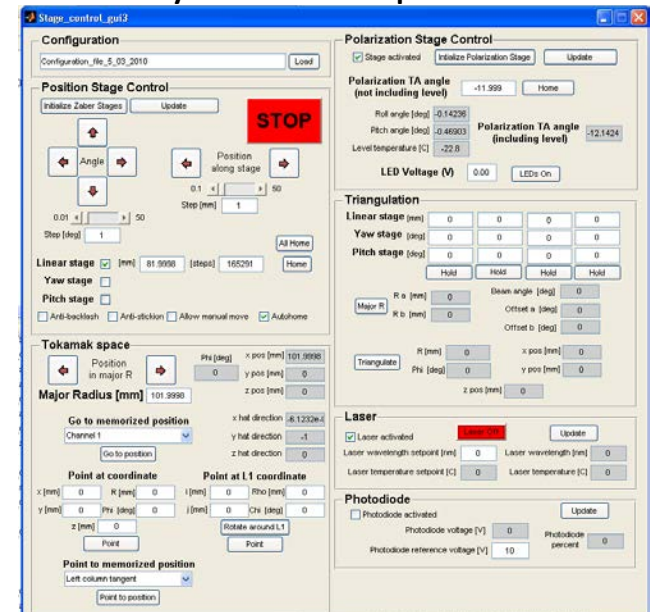
[Return to TOC](#)

New automated calibration system designed.

- Four automated axis:
 - Position along DNB +/- 1mm
 - Pitch +/-0.05°
 - Yaw +/-0.05°
 - Linear polarization angle (with high precision level calibrated wrt gravity) +/-0.02°
- System is easily demountable
 - Maintains alignment along DNB through multiple installations
 - Segmented system with light components to ease installation in vacuum vessel.
 - System can be installed/removed in <10 minutes.
- Multiple light sources
 - Diffuse LEDs with variable radiance.
 - Laser with temperature tuned wavelength. (655nm – 662nm)
- Full control via custom software from outside the vessel.
 - Including multiple web cameras to monitor and record calibration.
- System can also carry and point other tools such as labspheres, point sources, slits etc.
- Assembled from commercially available components.



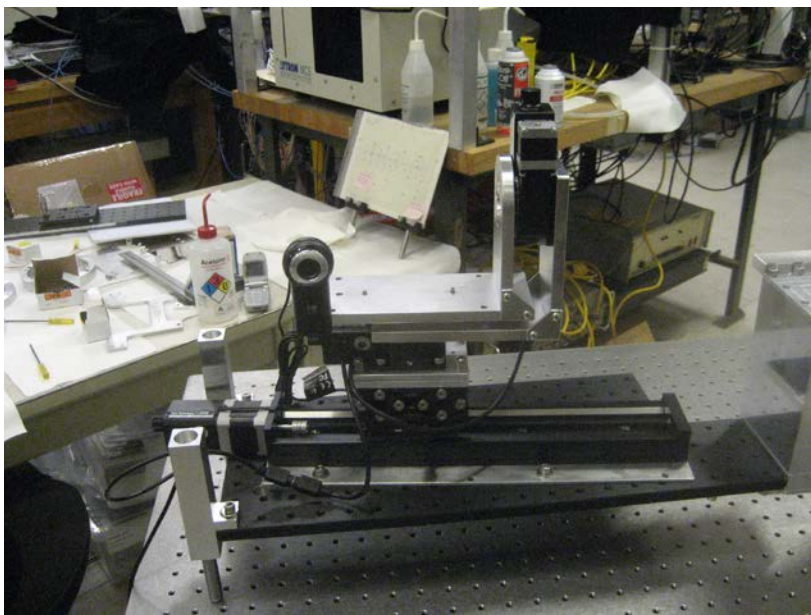
New system with polarization



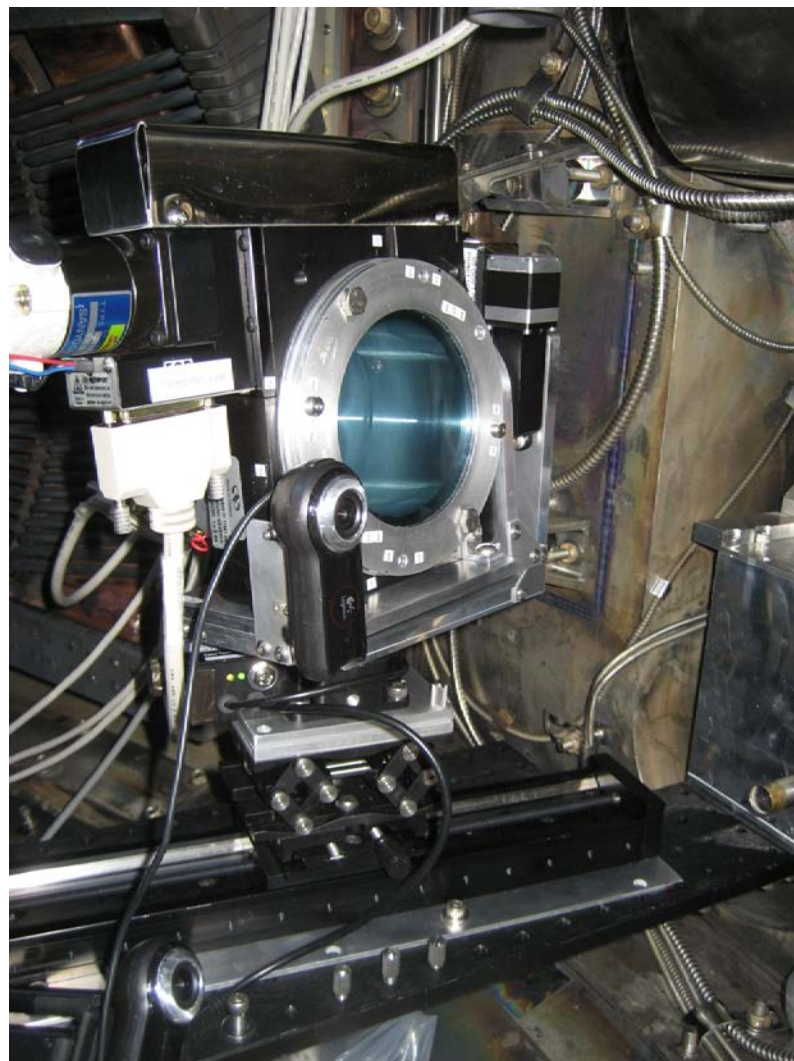
System can calibrate MSE from all field points

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Deployed during the 2010 invessel maintenance period.



Linear, yaw and pitch stages
during assembly.



Full system installed invessel.

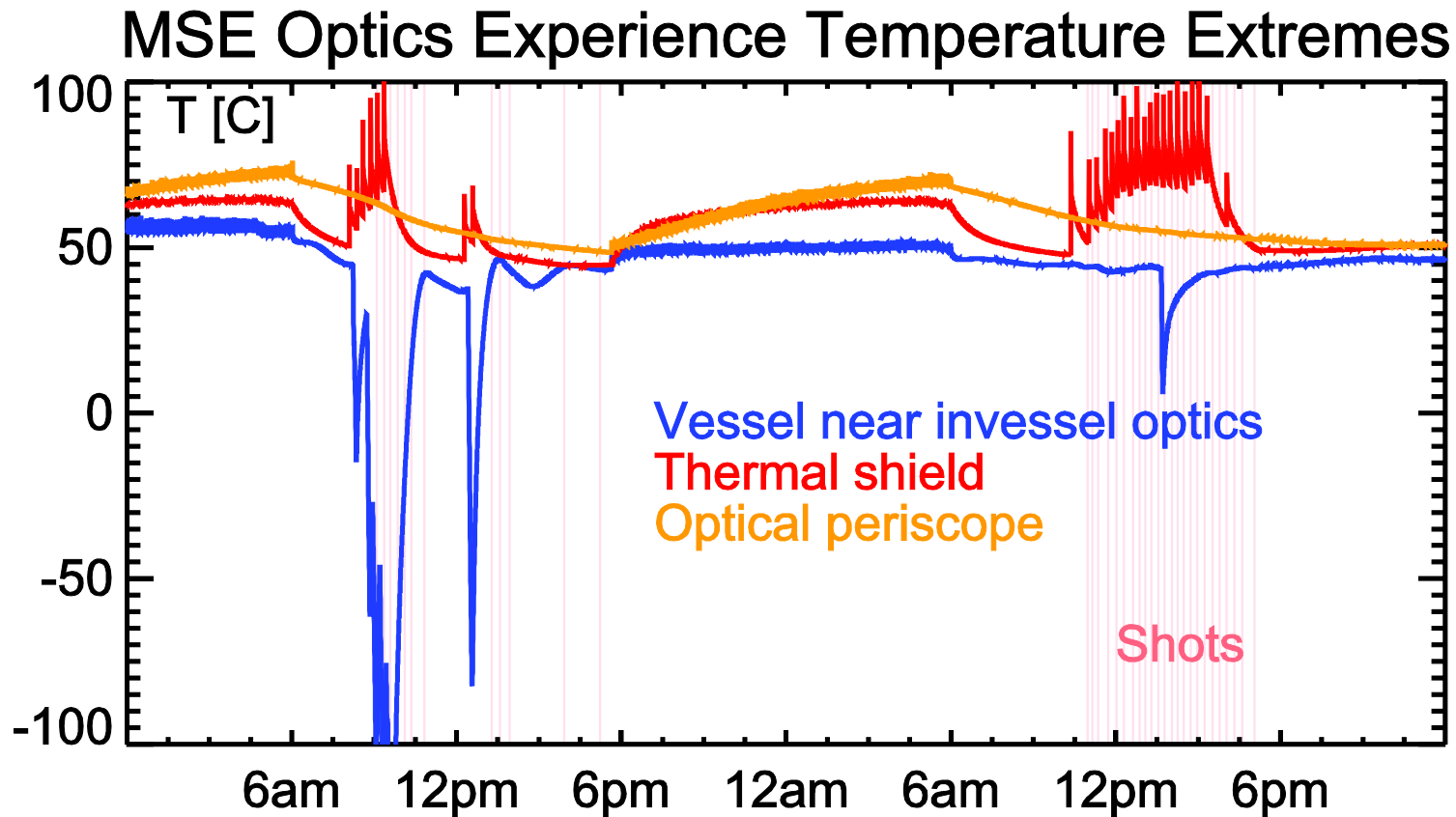
System was used for all calibrations totaling 10650 shots.

- Including scans in many parameters such as APD HV, PEM retardance, source radiance, wavelength etc.
- Data still being worked through.

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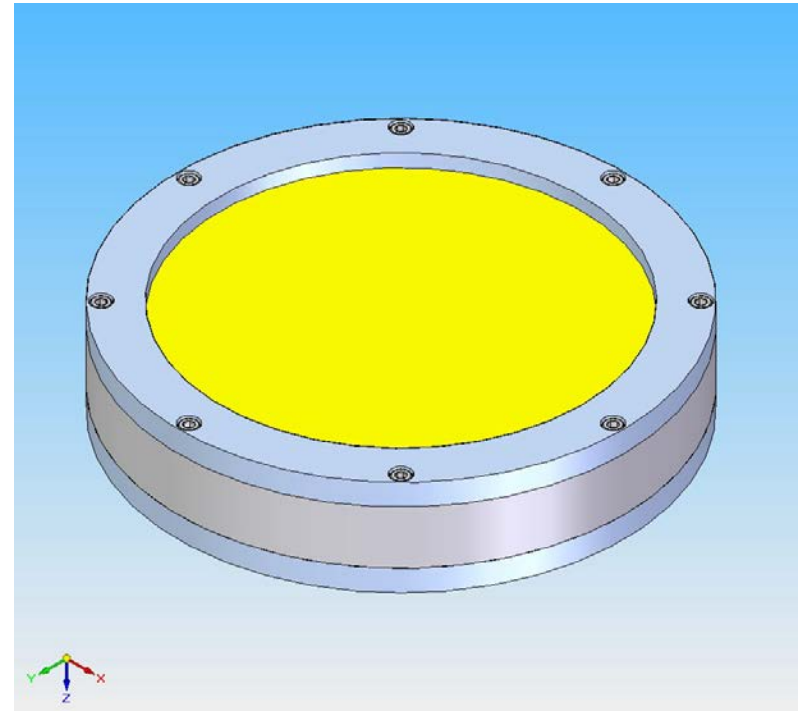
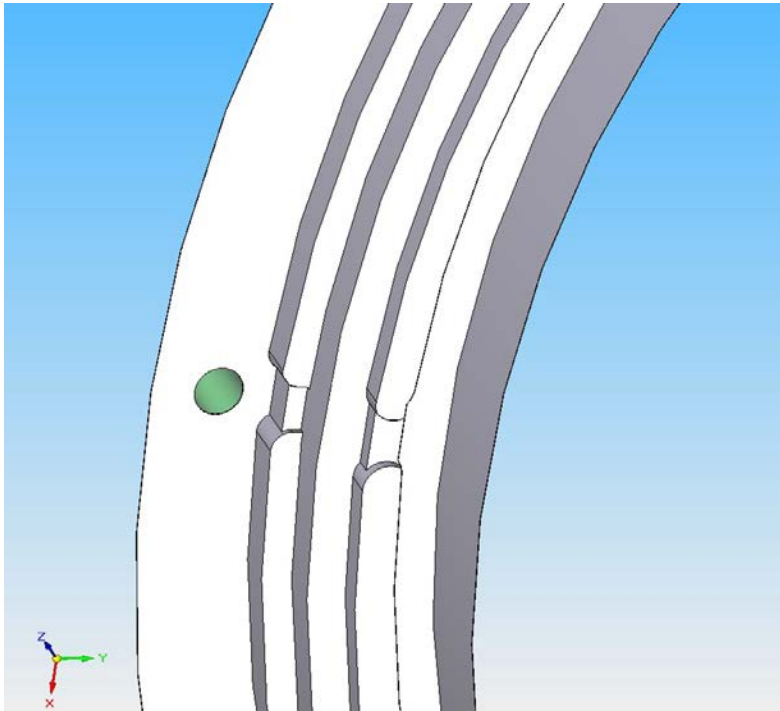
Thermal isolation

The bad thermal environment for MSE



L2 isolation

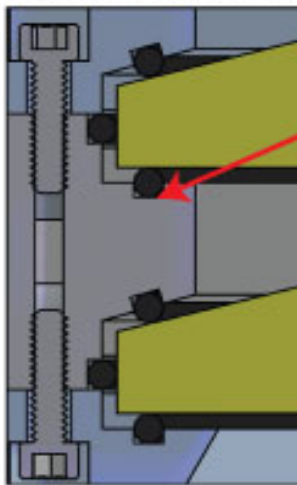
New “sausage” O-ring contact geometry



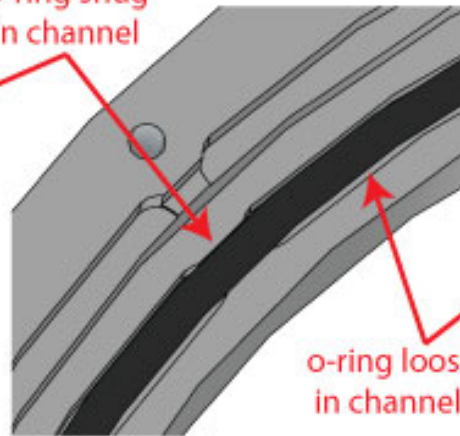
Main Idea: The O-ring acts as a cushion with a variable contact area and spring rate.

- The oversized O-ring gland small has bumps in its bottom and sides, leaving the rest of the O-ring limp during normal operation.
- These bumps create a finite number of spots that the O-ring has contact pressure with the lens, leading to high thermal contact resistance. **The nominal contact area has been decrease by a factor of 8.**
- During a disruption the O-ring deflects into the rest of groove to cushion the lens. Bench tested to 200g's
- Very similar to previous design, requiring no changes to the MSE canister. Uses same pinned mount to canister.
- Consists of middle, top and bottom pieces, machined from Inconel 718.
- Required lens diameter to be ground 4mm.

Small channel portion

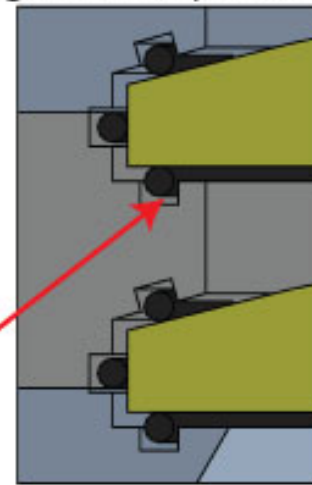


o-ring snug
in channel

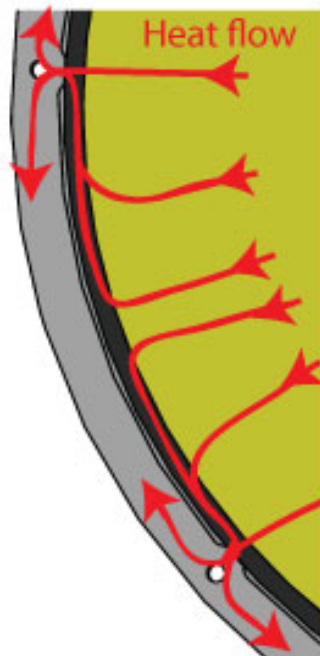


o-ring loose
in channel

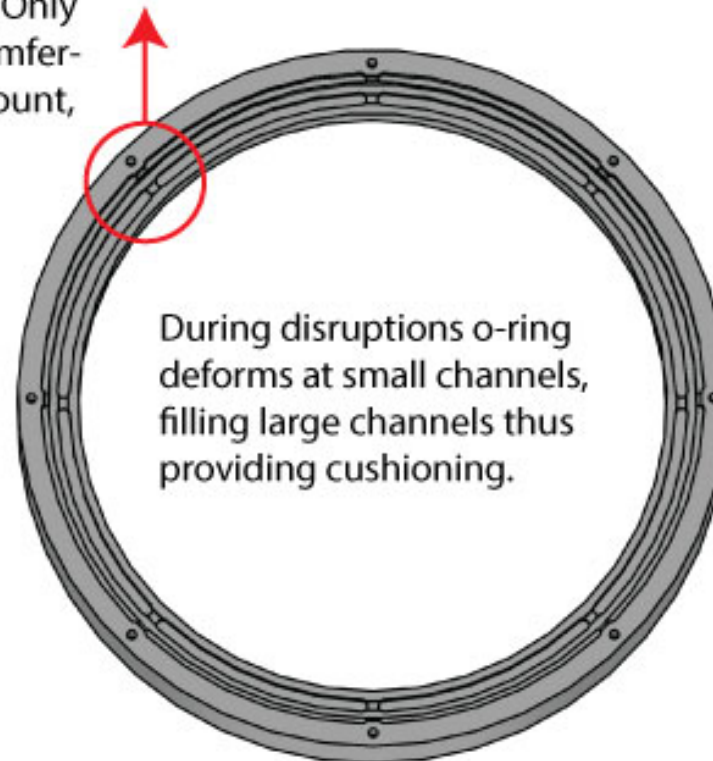
Large channel portion



During normal operation Only 1/22 of each o-ring circumference is in contact with mount, limiting conduction.

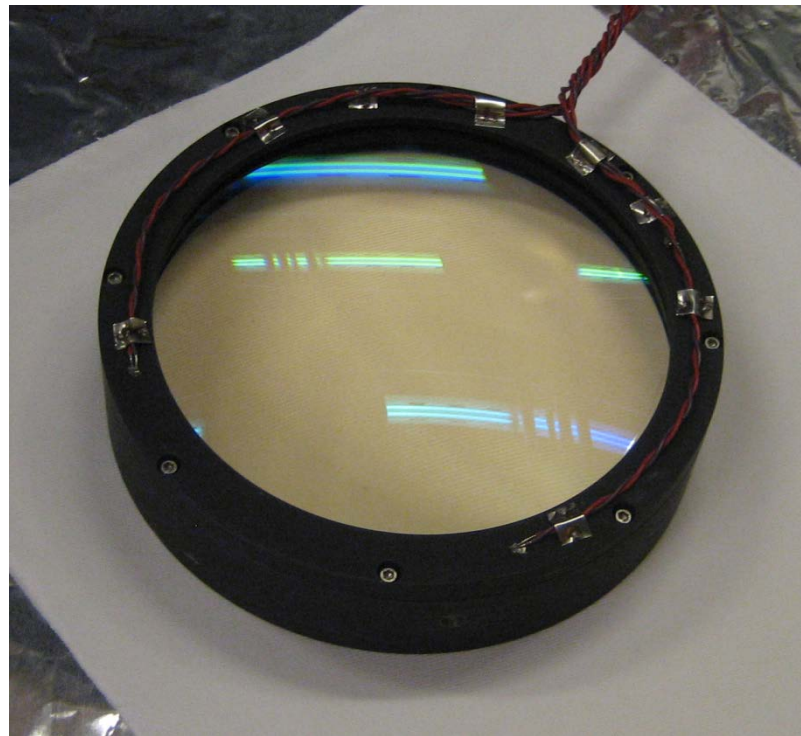


Heat flow



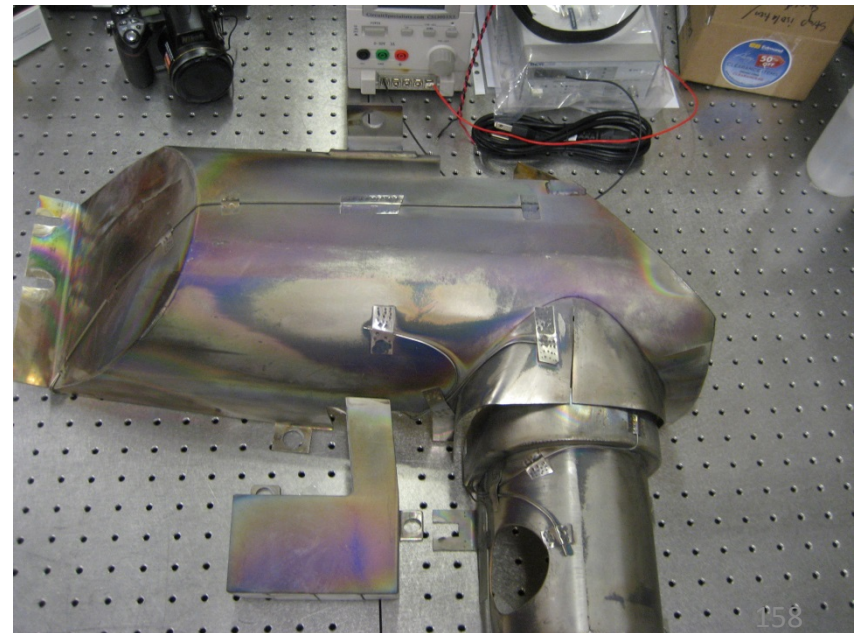
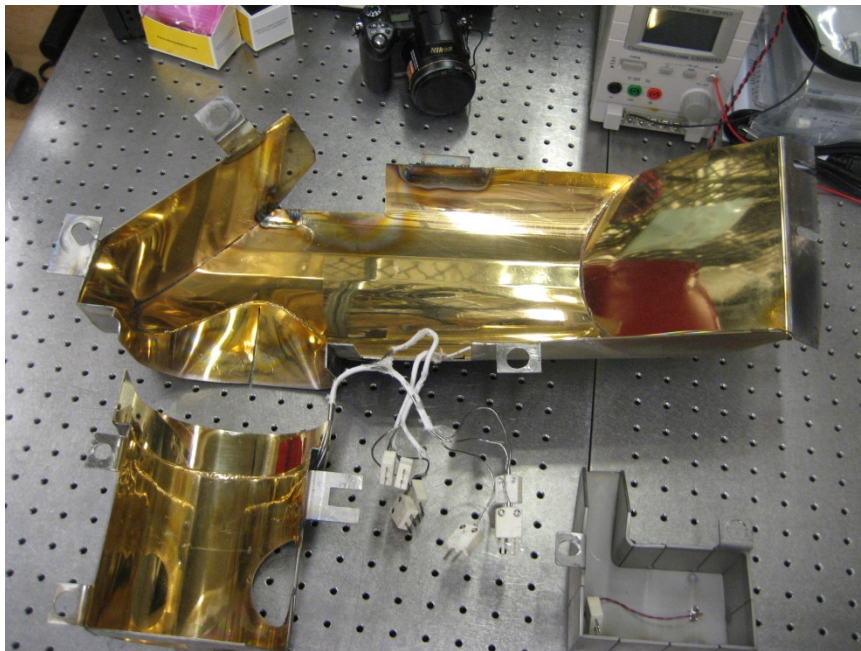
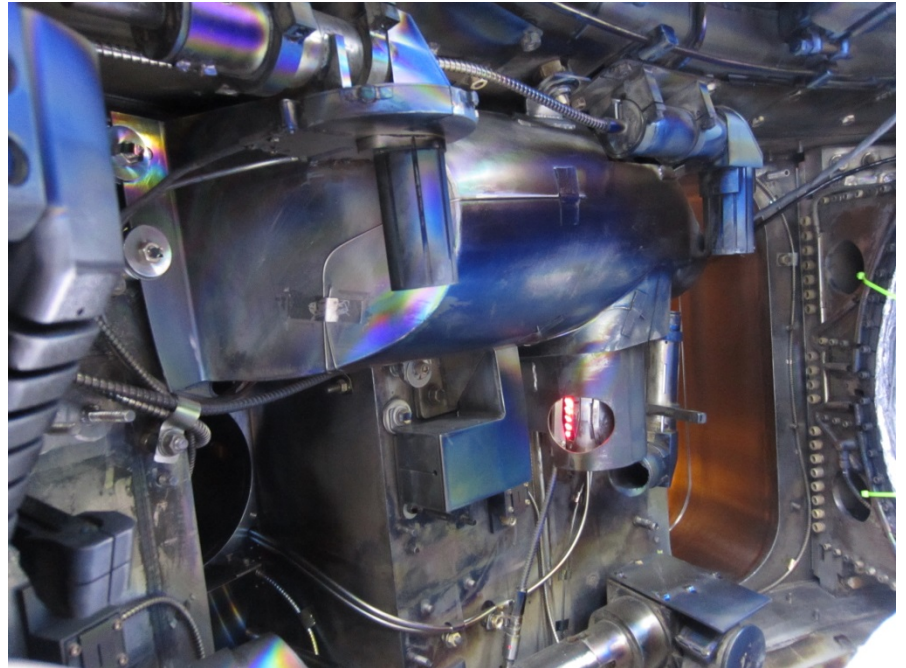
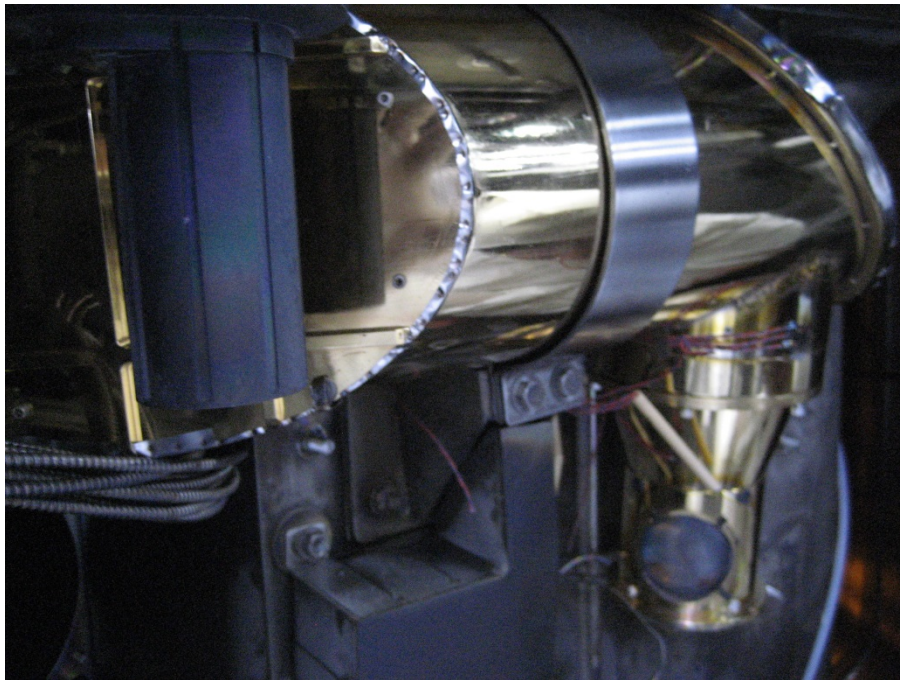
During disruptions o-ring deforms at small channels, filling large channels thus providing cushioning.

“Sausage” O-ring implementation



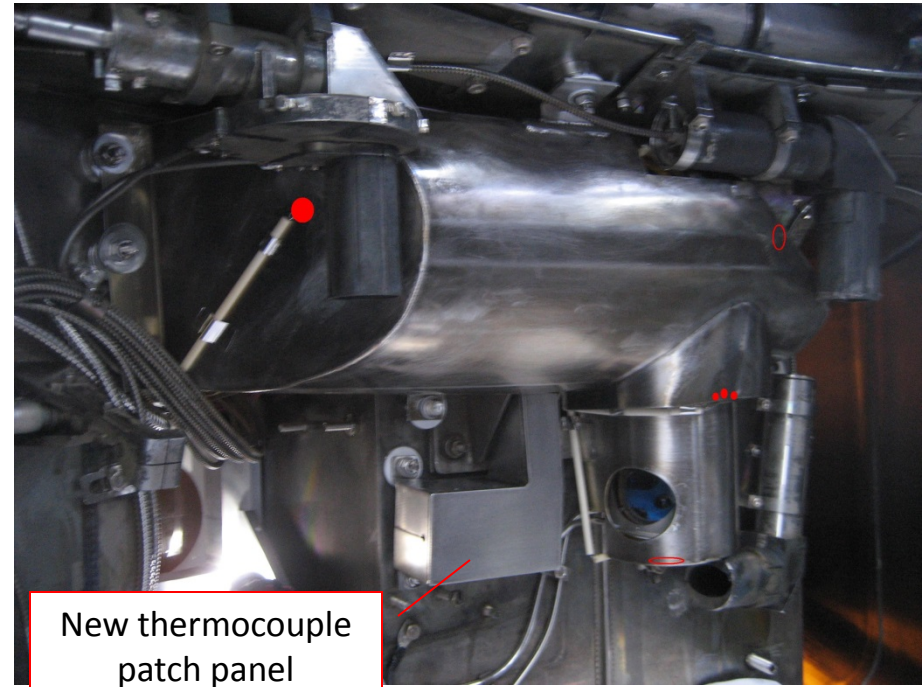
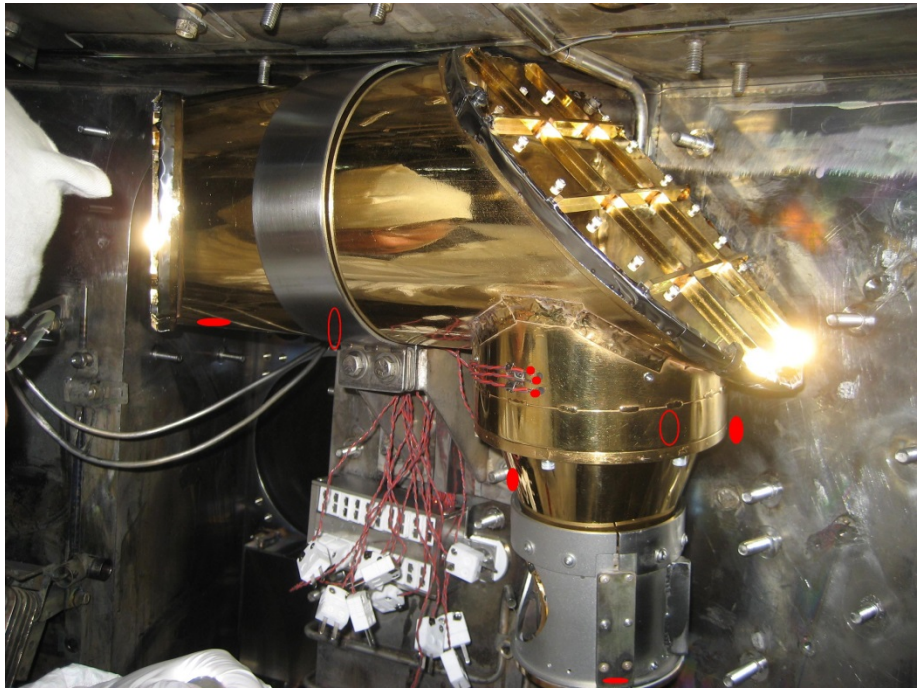
- Mount was fabricated and installed for FY09 campaign.
- Mount was instrumented with 4 thermocouples to monitor the temperature asymmetries of the L2 lens.
- Mount gives an increase thermal isolation in addition to the isolation provided by the shield.

Thermal shield



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Thermocouple locations



To monitor the performance of the thermal upgrades 32 type K thermocouples were installed on the MSE diagnostic.

- High precision system using cold junction compensation and complete type K thermocouple circuitry on each channel for precision absolute temperature
- 20 mounted in vessel to monitor the temperature of the canister (7), thermal shield (6), lens mounts (4), vacuum vessel wal (2) and new thermocouple patch panel (1).
- 12 mounted external to vessel to monitor the two photo elastic modulators and the airside optics.
- Temperature recorded every 10 seconds throughout the run campaign.
- Placement allows for heat flux measurements at L2.
- Can monitor the degradation in performance due to boronization.

Comparison with model and requirements

Thermal property	Previous	Goal	Heat shield model (Ko)	Current	Improvement factor
Maximum Canister slew rate	20°C/hr	1°C/hr	2.5-4°C/hr	4°C	5
Maximum Canister asymmetry	20-30°C	1°C	0.8-1°C	1.5°C	13-20
Canister time constant	0.5 hr	8 hr	-	7.5 hr	15
Maximum L2 mount slew rate	20°C/hr	1.3°C/hr	2.5-4°C/hr	4°C/hr	5
Maximum L2 mount asymmetry	20-30°C	0.34°C	0.8-1°C	0.6°C	33-50

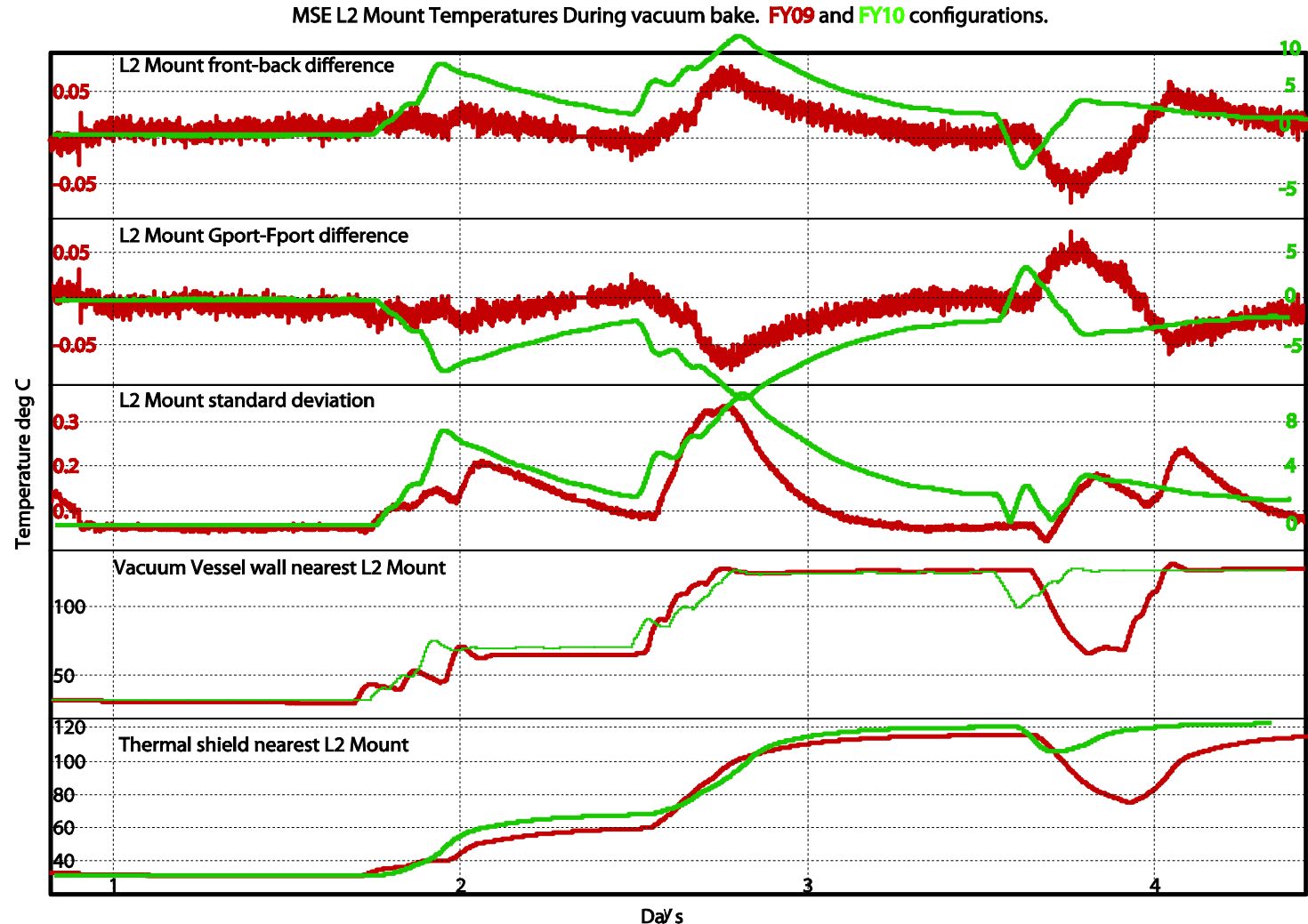
Conclusions of MSE thermal upgrades:

- The thermal upgrades to the MSE system have been implemented. The results as measured by the thermocouple array follow correlate well with the heat shield model presented by Ko.
- The heat shield has significantly lengthened the time response of the MSE system to thermal fluctuations.
- The heat shield has significantly reduced the temperature variations across the L2 mount.
- However, the performance has not reached the level required for pitch angle measurement accuracy of less than 0.1° (in plasma frame) determined experimentally by Ko.
- The improvement in L2 isolation resulting from the redesigned L2 mount remain un-quantified. The mount decreases the contact area between the mount and the lens by a factor of 8.
- Thermal modeling by Ko estimates an increasing the thermal resistance between the L2 and the L2 mount by a factor of 10 would be sufficient to achieve desired temperature symmetry on L2 lens for most plasma shots.
- The temperature data indicates that the stress induced birefringence should be substantially decreased. MSE is awaiting a function shutter for the diagnostic's objective lens and a functioning diagnostic neutral beam on Alcator CMOD to verify this via pitch angle measurements.
- Boronization has not significantly decreased the shield's thermal performance.

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Loss of thermal isolation after FY10 maintenance period.

- Thermal isolation degraded after invessel access. Likely due to tightening of a support strap thus creating a thermally conductive short.
- FY10 L2 lens thermal gradients 10x -100x FY09 L2 lens thermal gradients during a runday.
- Thermal isolation is still better than in 2008.
- Temperature state evolves slowly, ie over hours and not minutes. Thus the absolute calibration is affected by stress-birefringence but most likely not shot to shot.



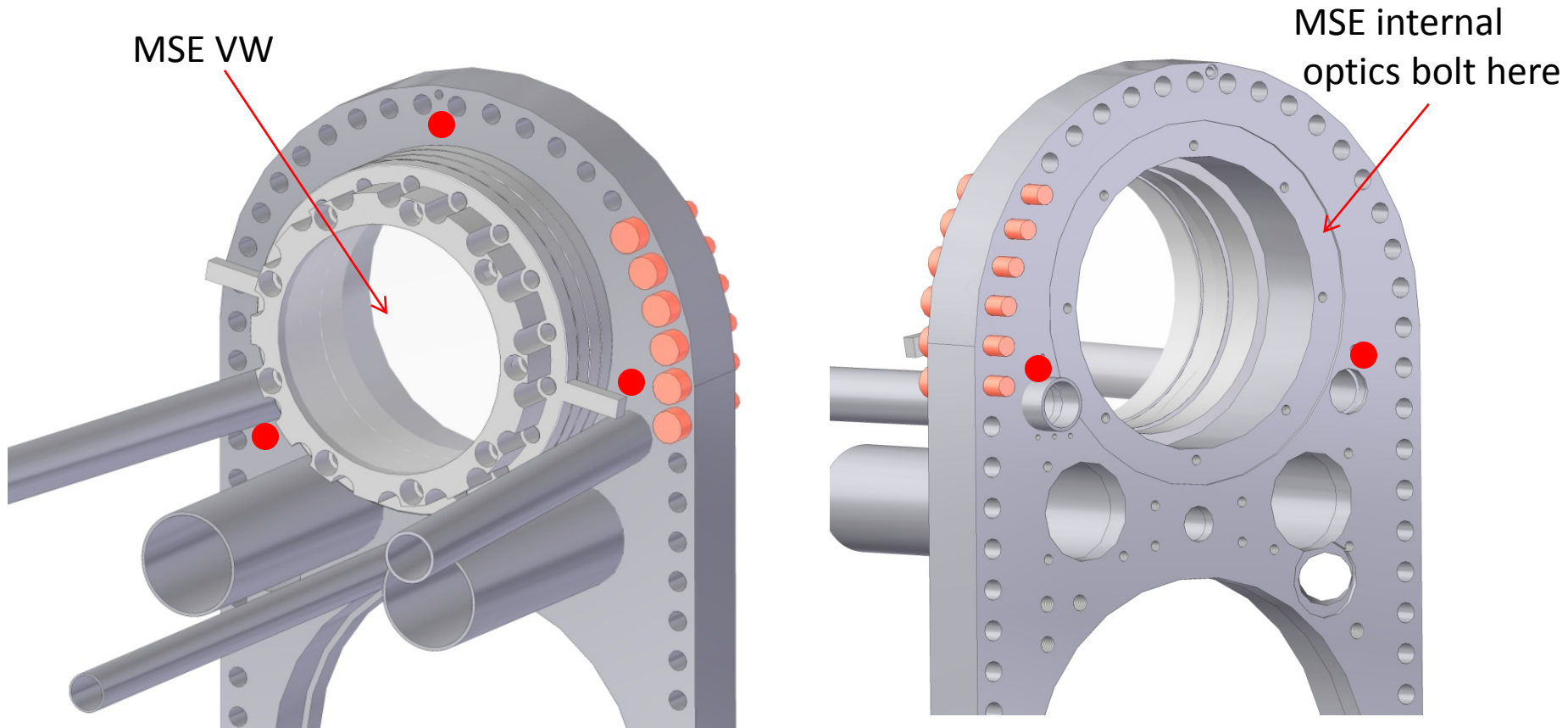
Comparison of thermal isolation during the FY09 and FY10 vacuum vessel bakes. The bakes were nearly identical in these two cases. The vessel wall and thermal shield respond the same between the two years while the L2 lens mount develops much larger gradients in FY10. (Note the difference in scales).

VW thermal isolation

F-port flange has TCs installed on it to monitor temperature of VW

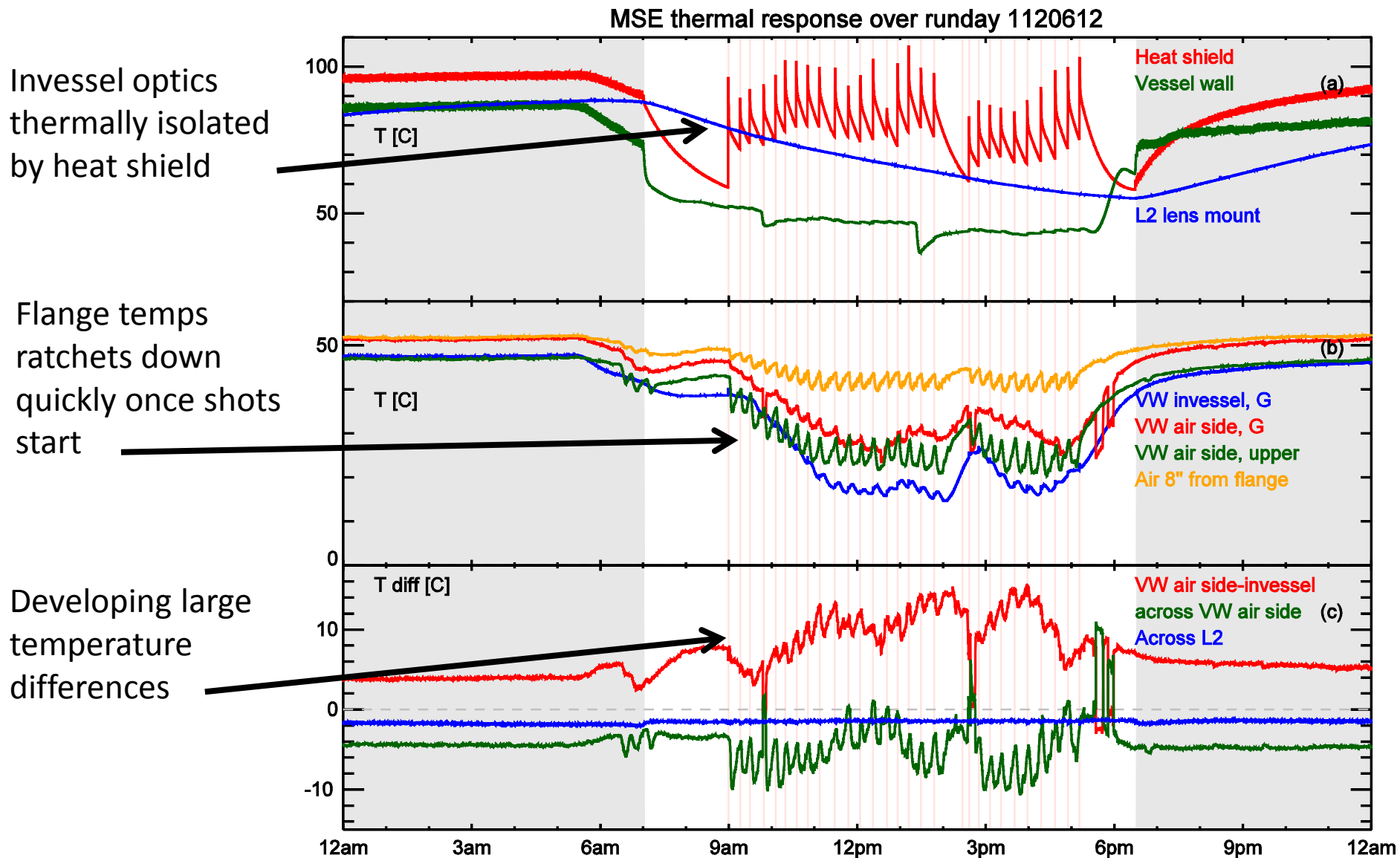
Installed TCs on the inside and outside of F-port flange to track flange temperature

- Motivated by observation of large temperature excursions on the Vessel walls

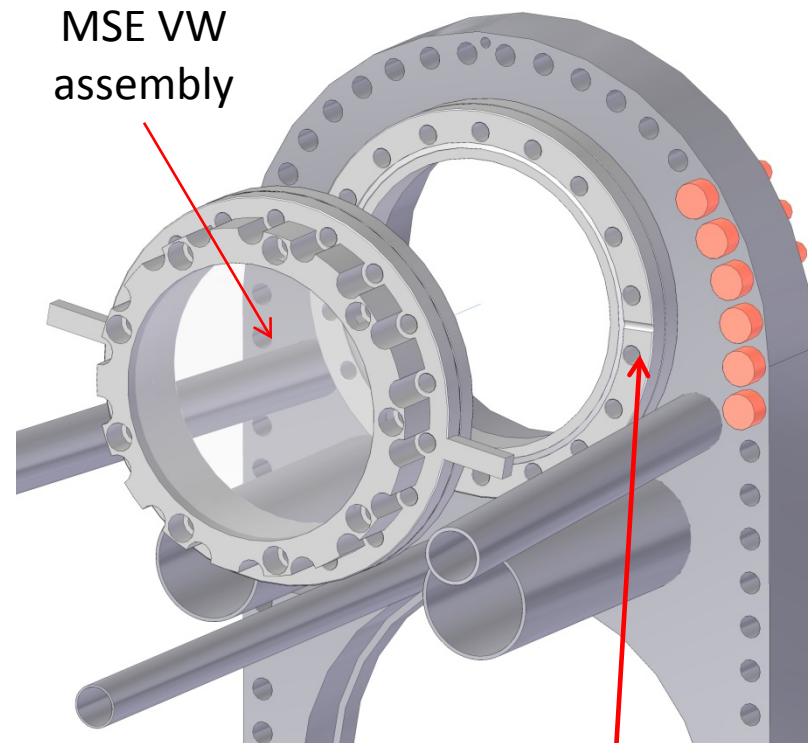
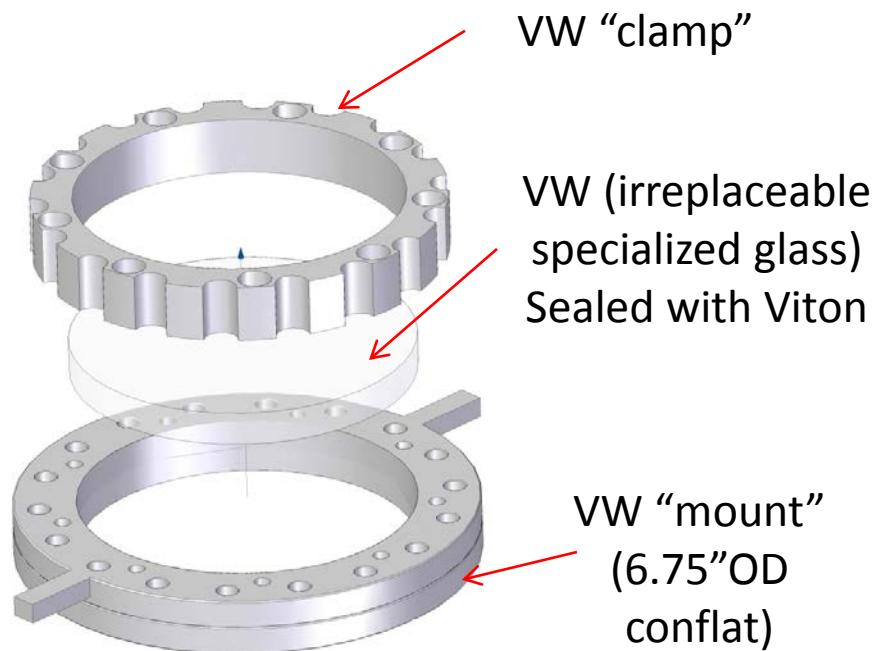


● TCs installed since 2011

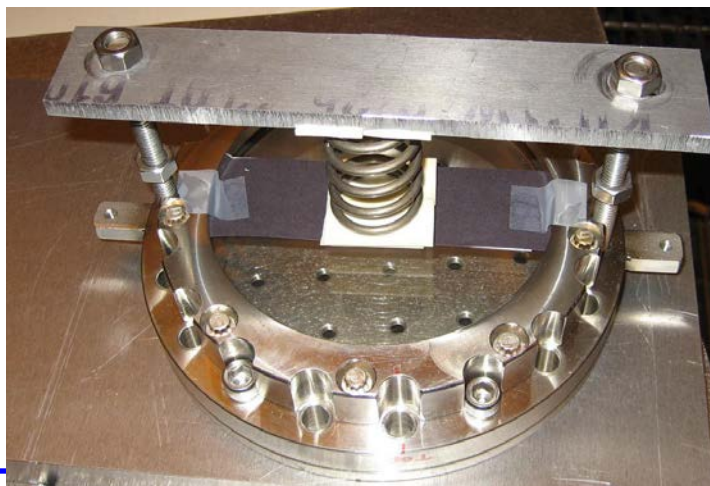
F-port flange temperature swings widely throughout runday. (likely due to magnet cooling leaks)



Overview of MSE VW construction

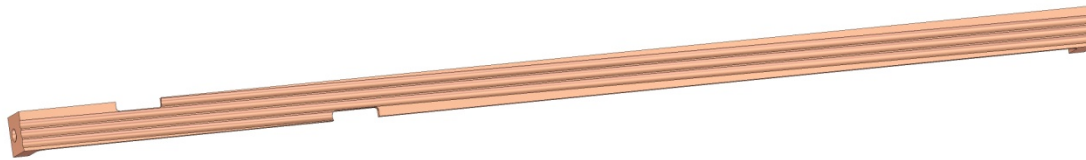


6.75” conflat ring welded to F-
port flange (“VW flange”)

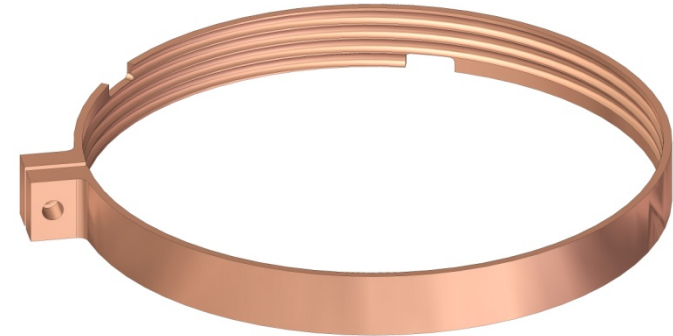


New band design clamps tubing onto flanges, eliminating brazing of tubing

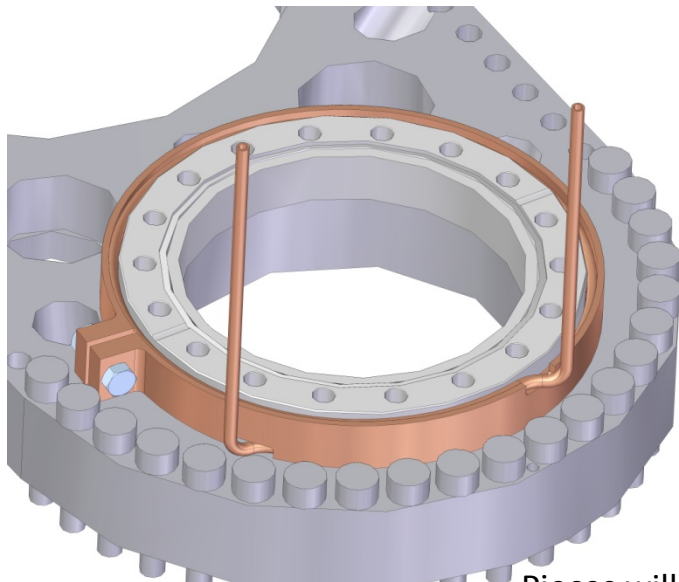
New bands clamp the tubing in place



Grooves machined to hold tubing in place. Piece machined from flat stock and “ears” brazed on.



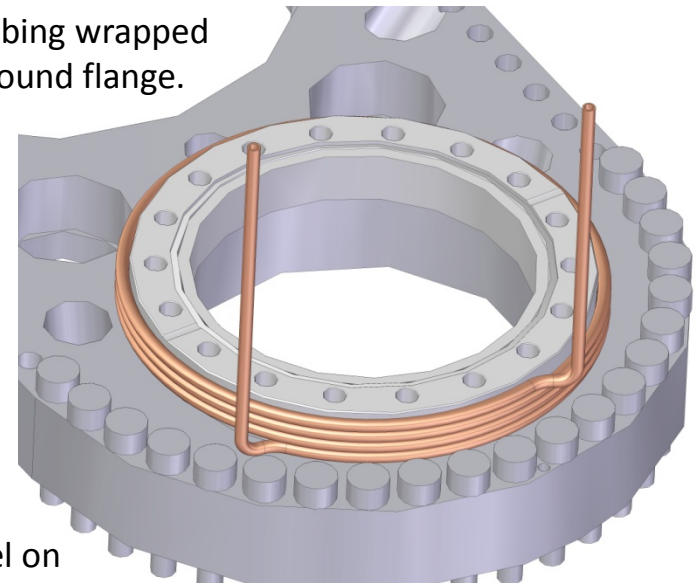
Piece bent into circular form. Grooves form helix on the inside for tubing.



Band clamps tubing in place onto flange tightly. Allows tubing to enter and exit.



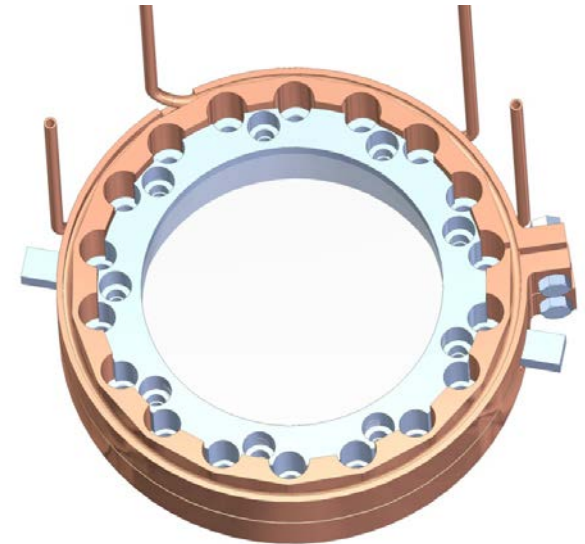
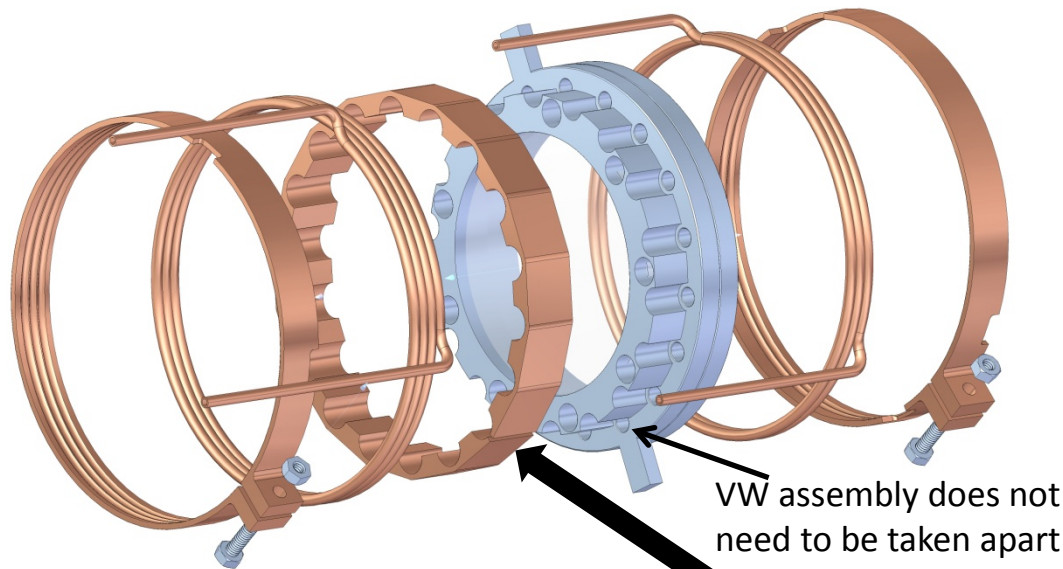
Tubing wrapped around flange.



Pieces will be pre-bent on a mandrel on the bench prior to assembly on F-port

Bands added to VW assembly without requiring disassembly of the VW seal.

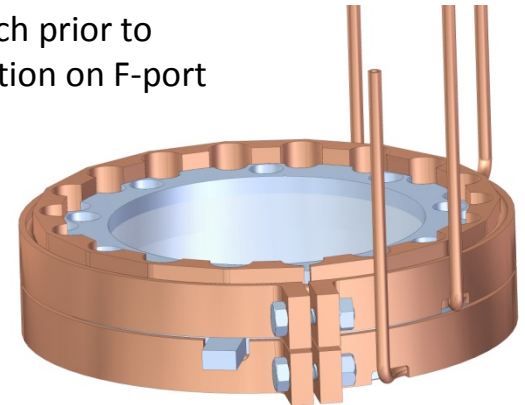
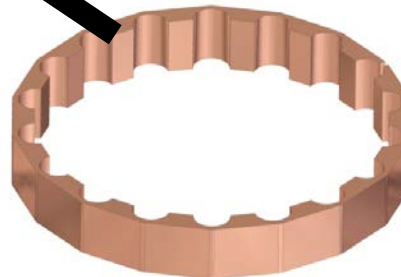
Same tubing concept used on the VW assembly



Assembled and tested on bench prior to installation on F-port flange

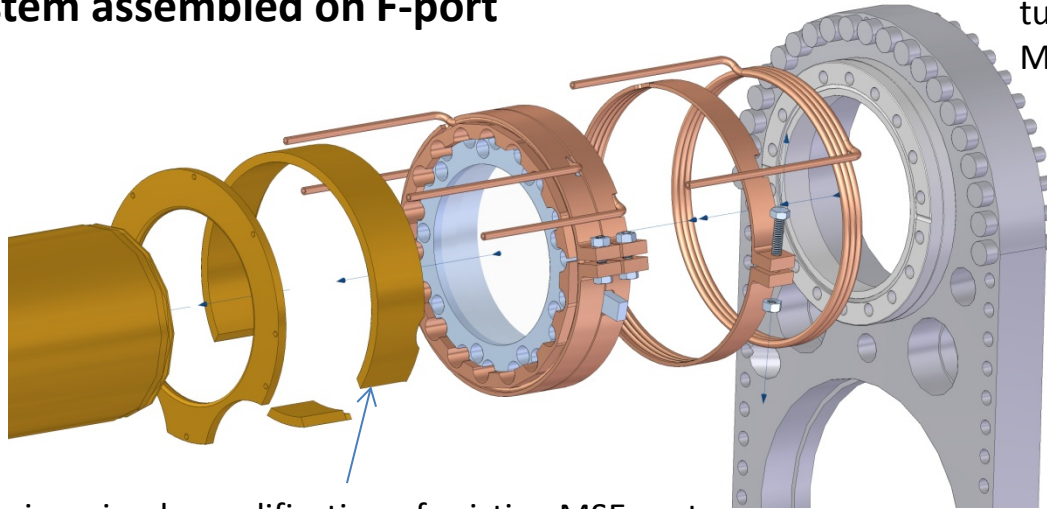


Bolt circle spacer required to allow flange to be bolted in place. This piece is also machined flat and bent into shape.

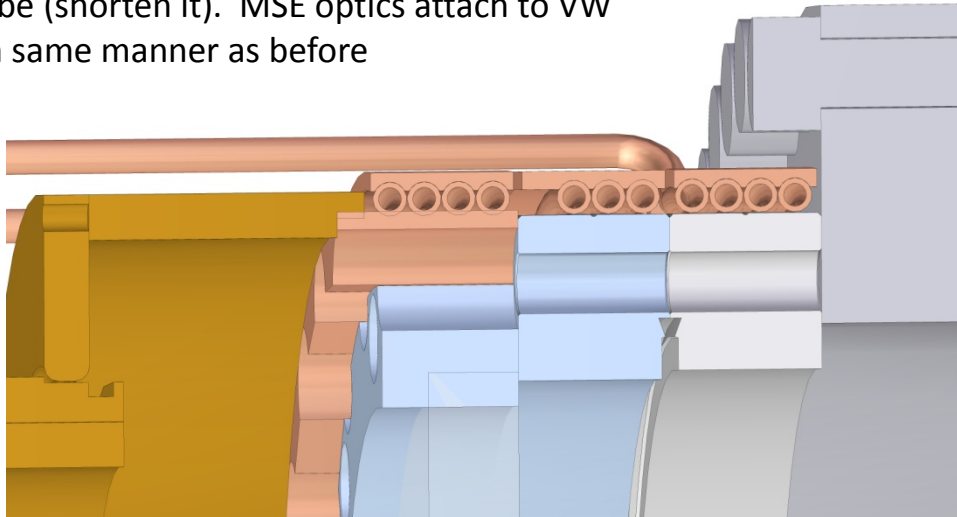


System installed onto the F-port flange in a few easy steps

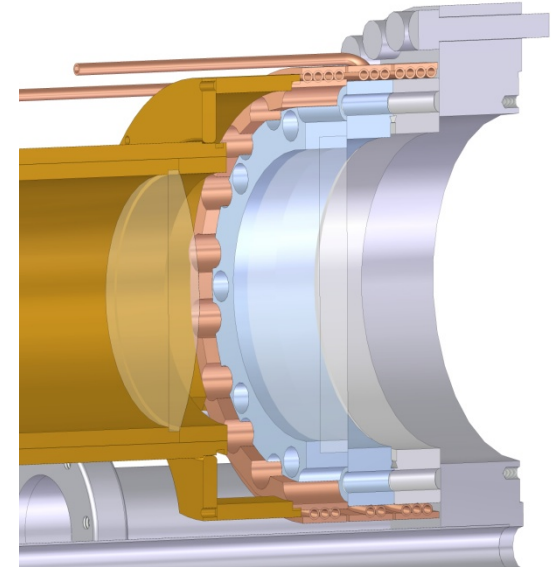
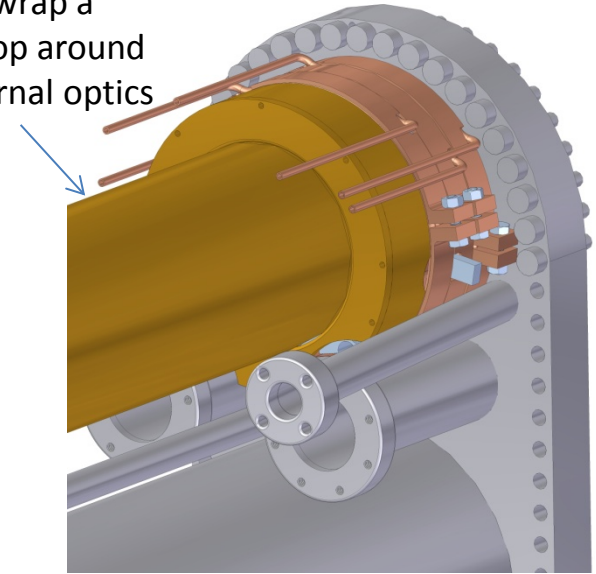
System assembled on F-port



Requires simple modification of existing MSE port cover tube (shorten it). MSE optics attach to VW flange in same manner as before

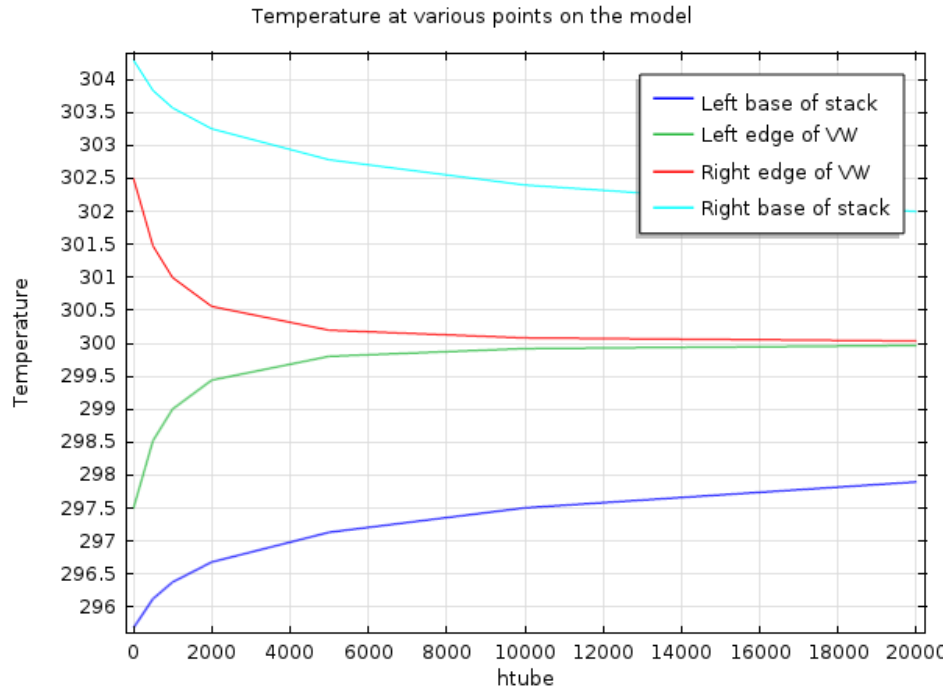


Will also wrap a tubing loop around MSE external optics

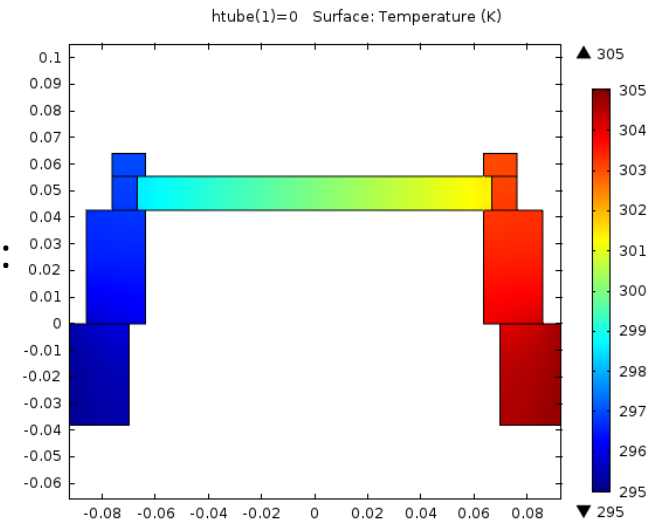


Tuning parameter: Heat transfer coefficient in the tubing.

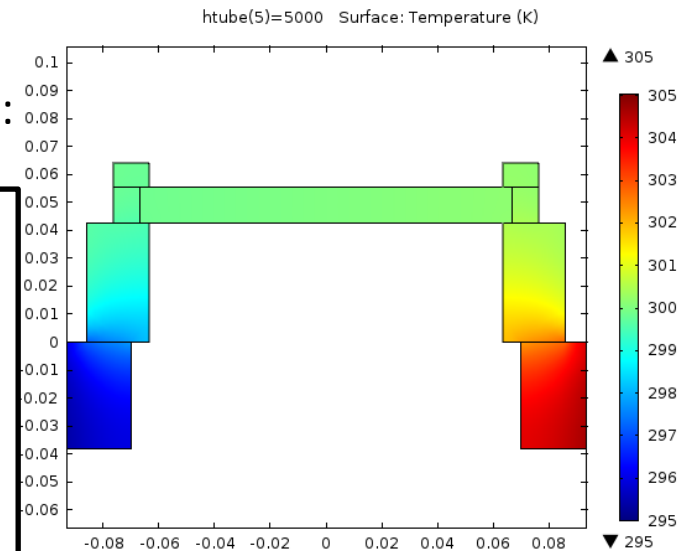
Applying 10C difference across F-port flange (295-305K).
Fluid at average temperature (300K).



No
cooling:



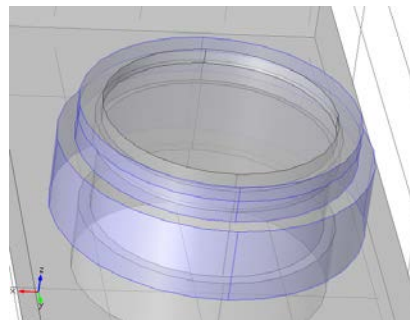
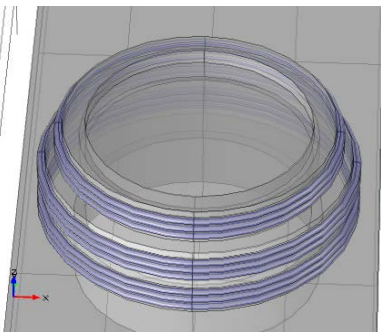
Some
cooling:



Modeling note:



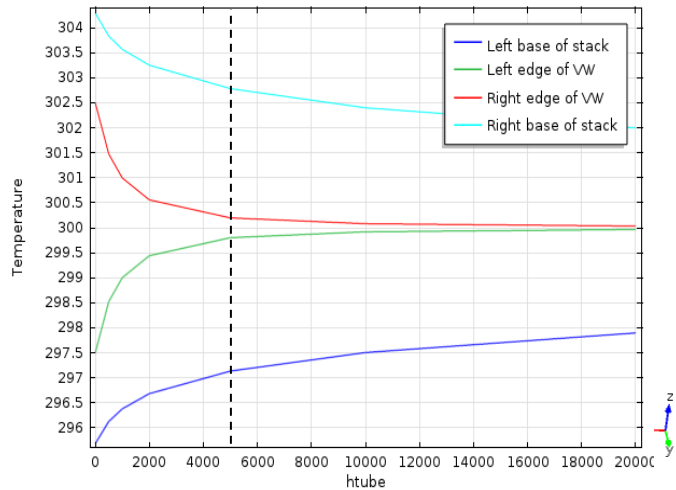
Simplify geometry
to avoid modeling
small tubes, apply
a $h_{\text{effective}}$ to
VW stack OD



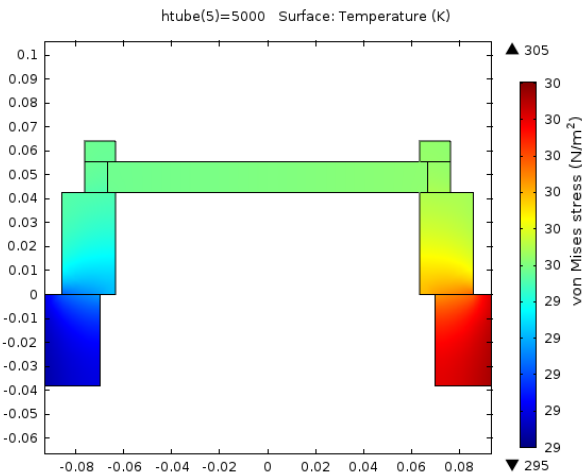
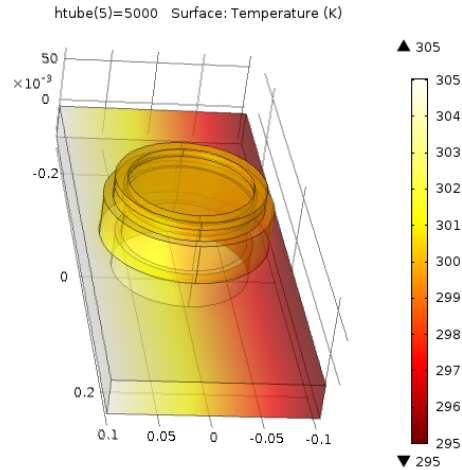
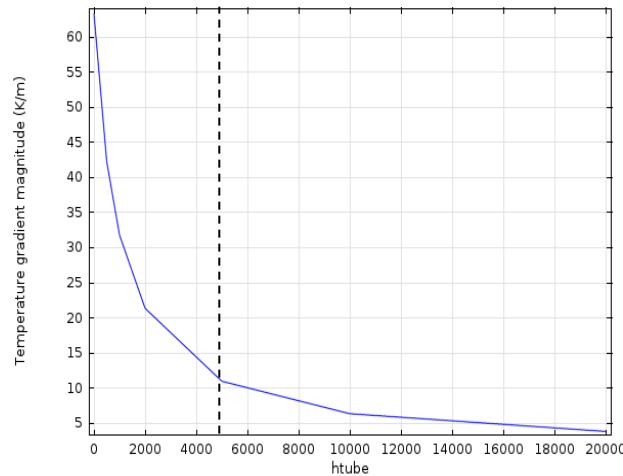
Design point: $h_{\text{tube}} = 5000 \text{ W/m}^2/\text{K}$ provides good equalization around the VW. Diminishing returns higher than that.

Applying 10C difference across F-port flange (295-305K).
Fluid at average temperature (300K).

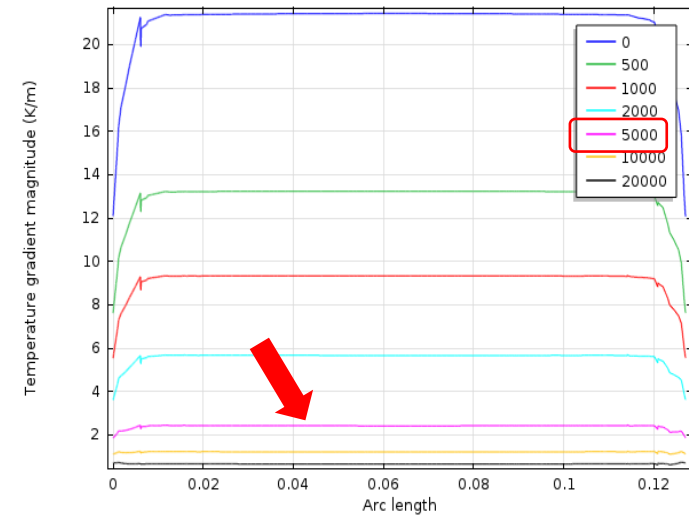
Temperature at various points on the model



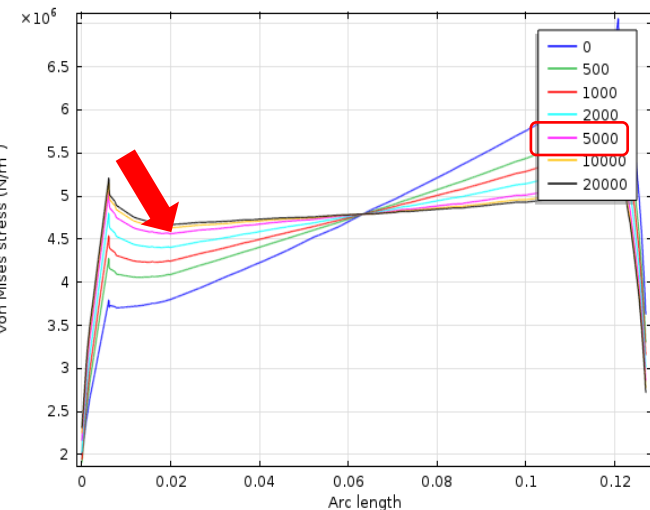
Max temp gradient in the VW



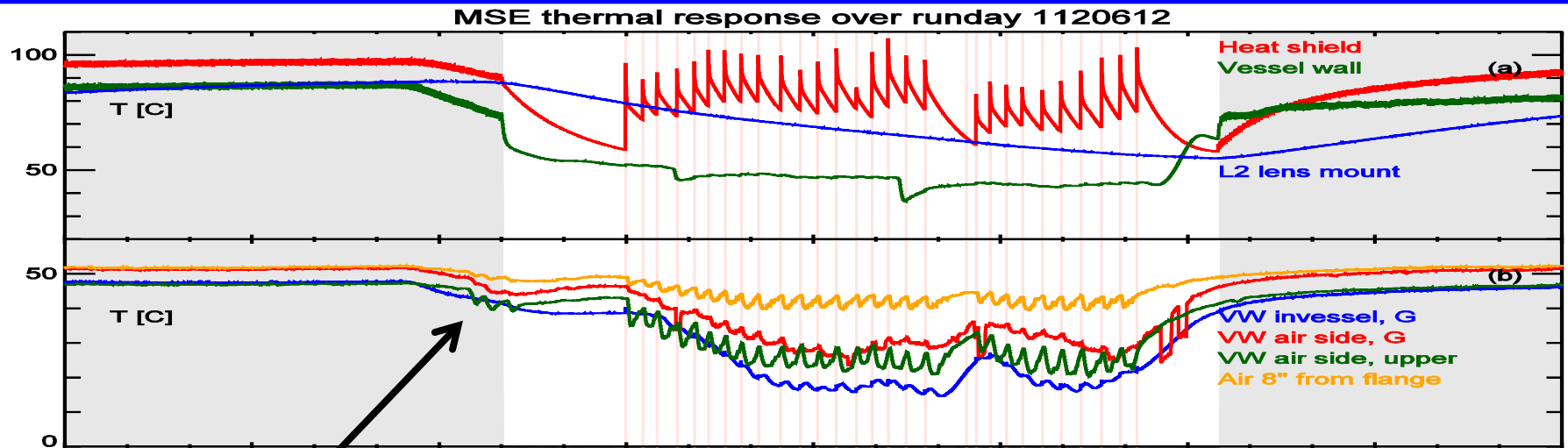
Temperature gradient through VW center at various h_{tubes}



Line Graph: von Mises stress (N/m^2)

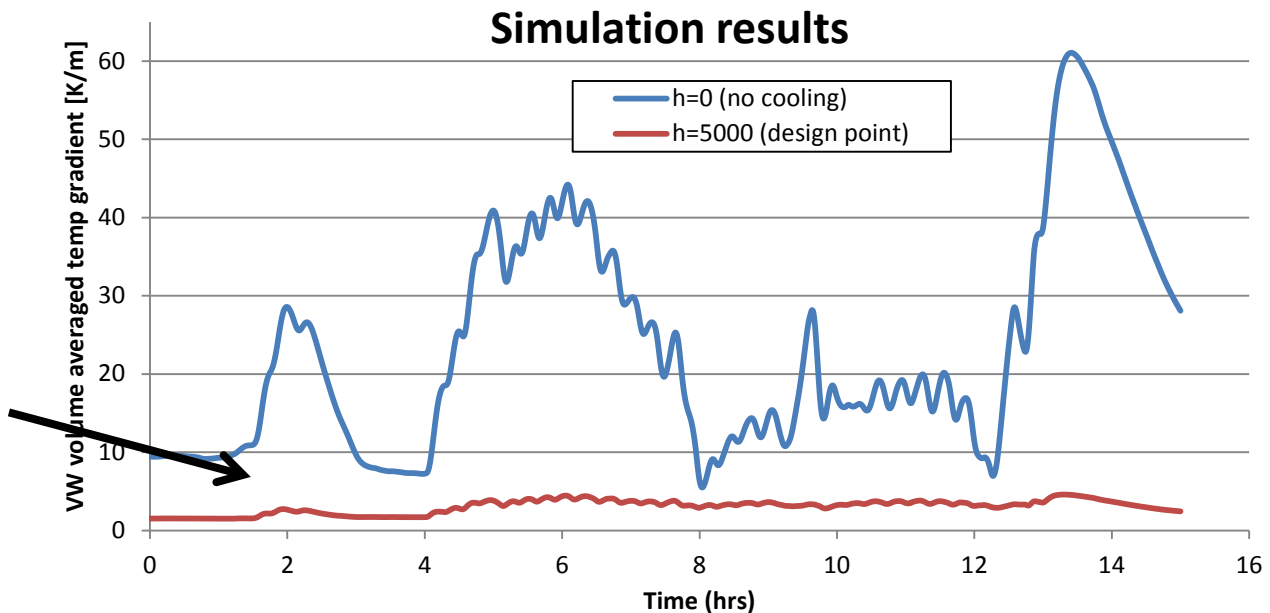


FEM analysis predicts drastic improvement across the runday.

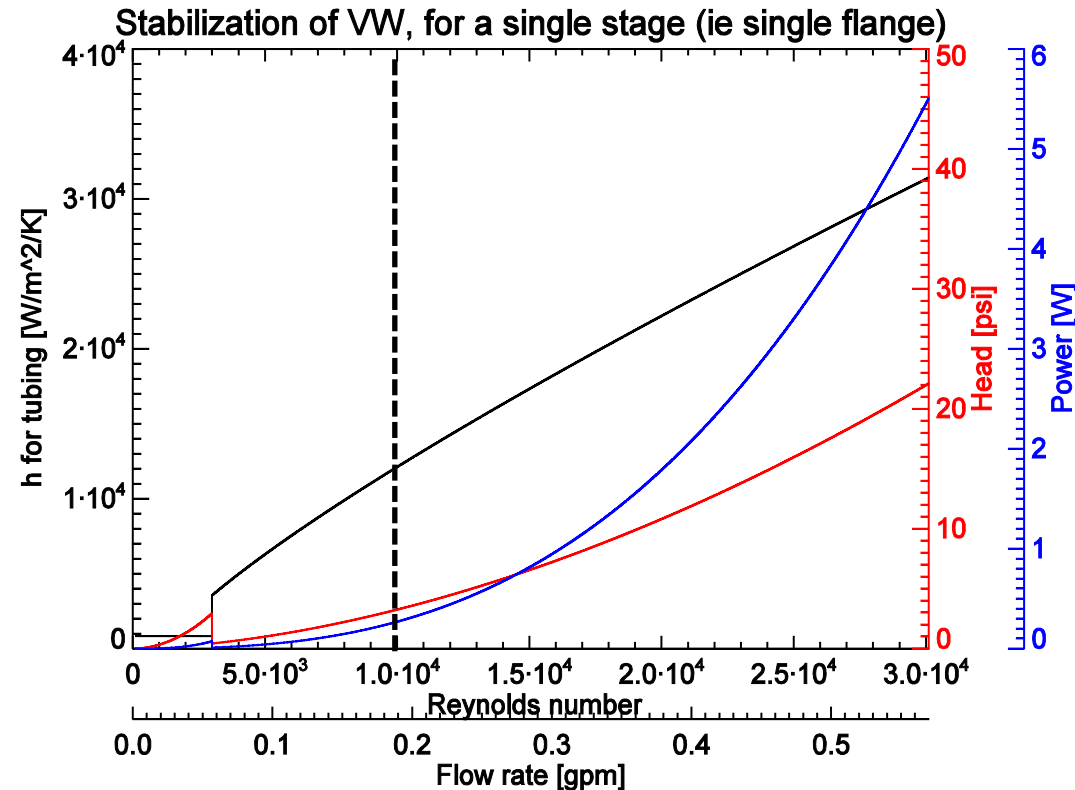


Feed measured VW
temps into FEM
simulation

Simulation results
show a drastic
improvement in
temperature
gradient with VW
heating system.



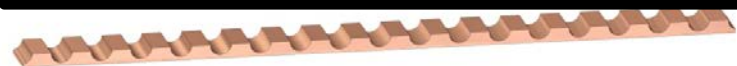
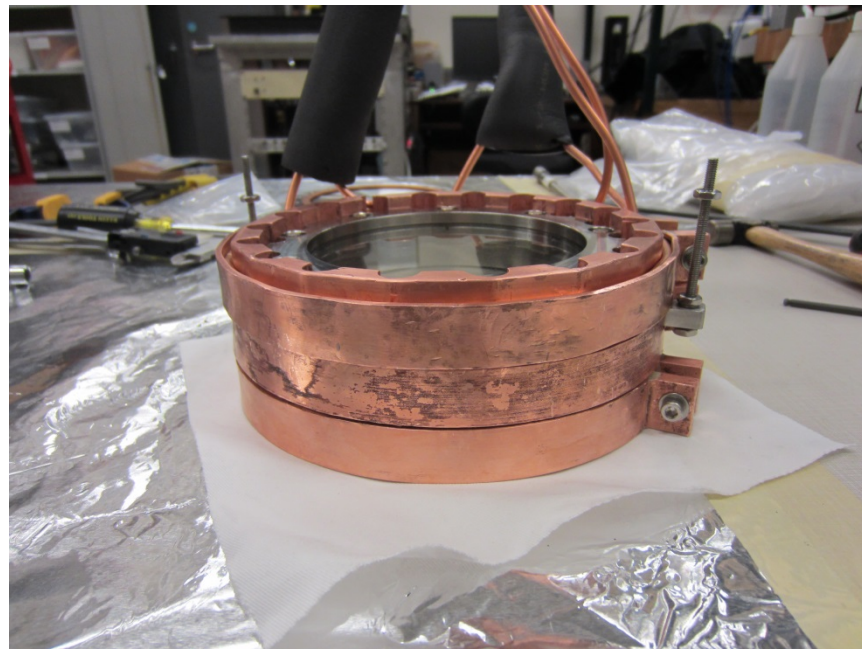
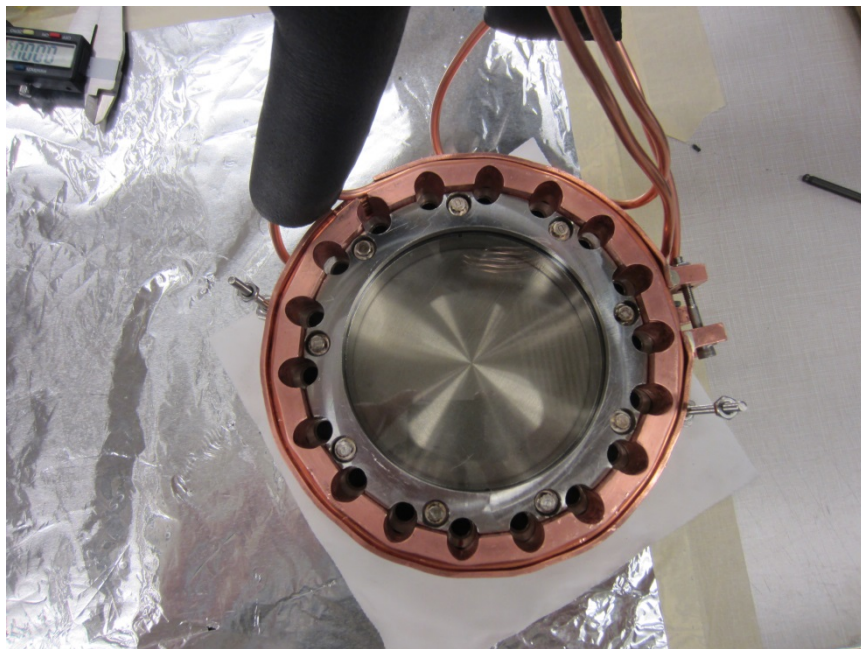
Next step: Specifying the flow conditions to achieve required convection coefficient in the tubing



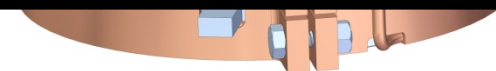
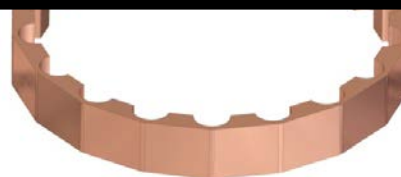
- Use a factor of safety of 2
- Using empirical heat transfer correlation:
 - Convective heat transfer: $h=1e4$ W/m²/K in 3/16" OD tube with 60C water
 - Nusselt number: $Nu = 58$
 - Reynolds number: $Re = 1e4$ (fully turbulent flow in smooth pipe)
 - Velocity through tube = 1.5 m/s
 - Volume flow rate = 0.2 gal/min (per tube x 4 tubes = 0.8gal/min)
 - Pressure drop = 1.8 psi/meter (~4m of 3/16" tubing per flange = 6.4psi)
 - Simulations using runday temperatures show 225W of convection heating required to maintain VW temperature against conduction from F-port flange.

VW thermal stabilization properly assembled onto VW flanges.

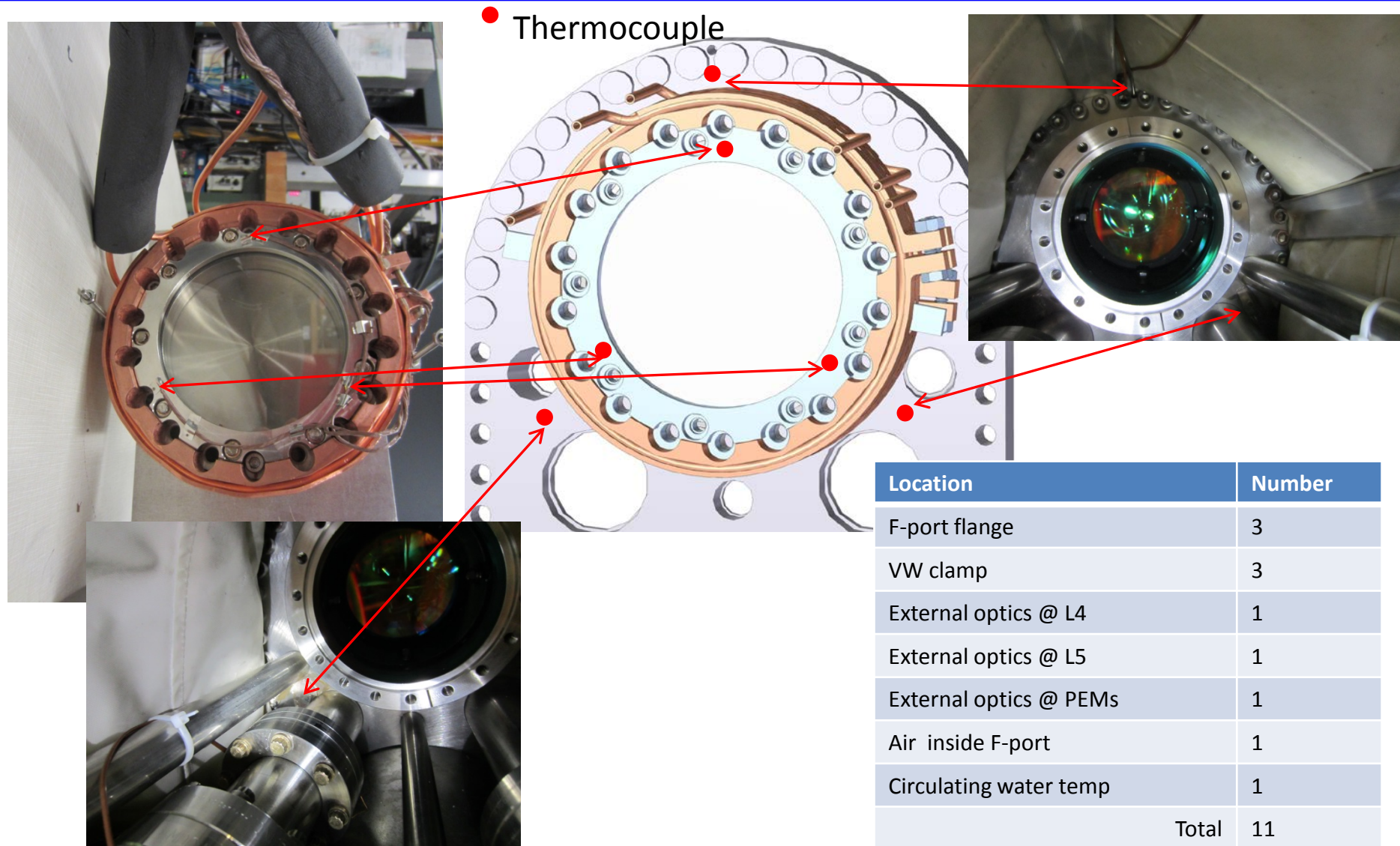
Same tubing concept used on the VW assembly



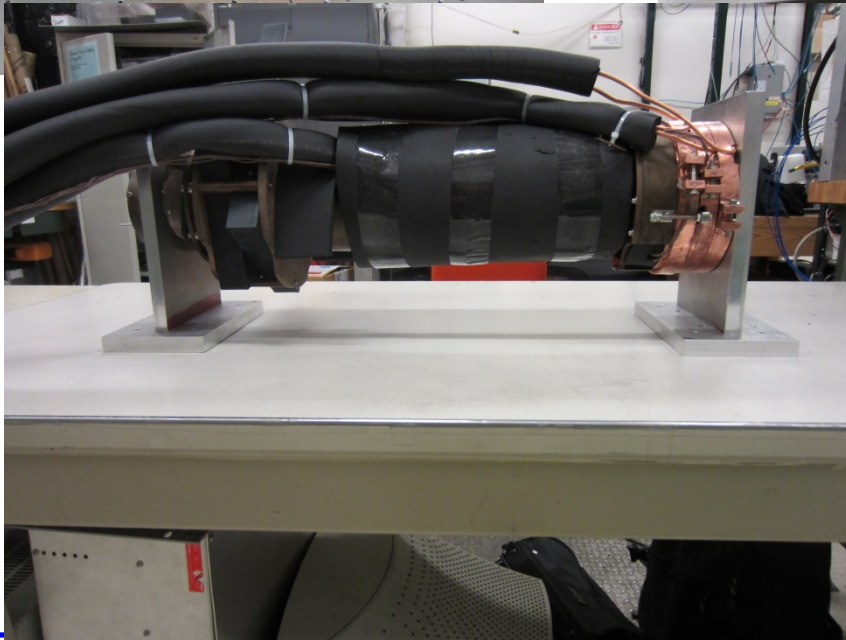
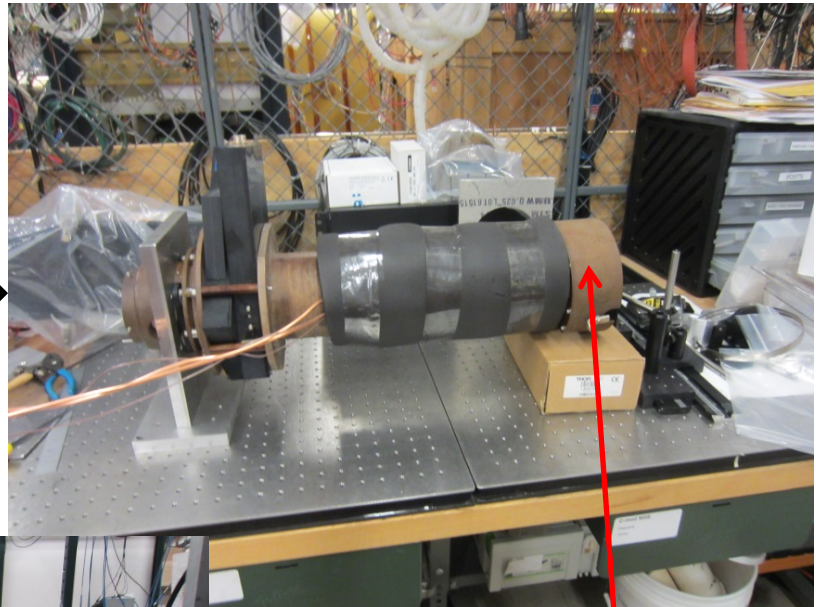
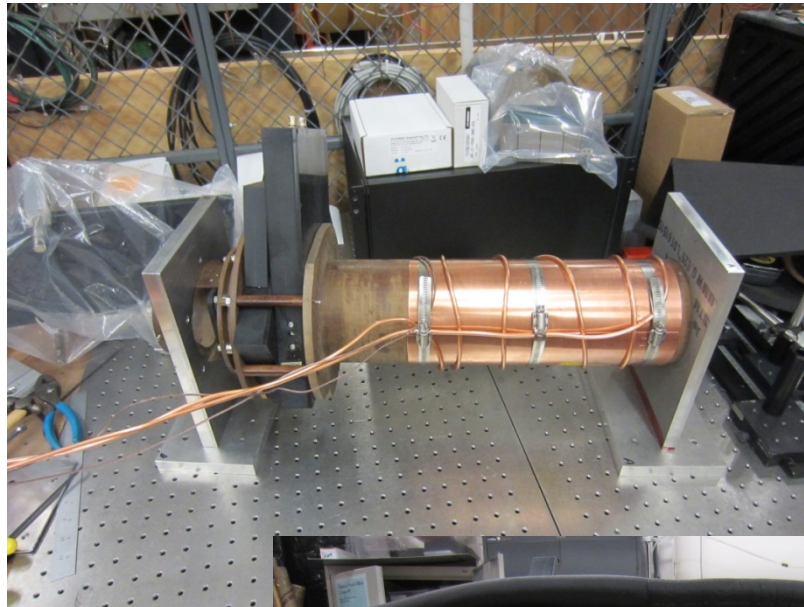
Bolt circle spacer required to allow flange to be bolted in place. This piece is also machined flat and bent into shape.



Measurement TCs added to Flange and VW assembly

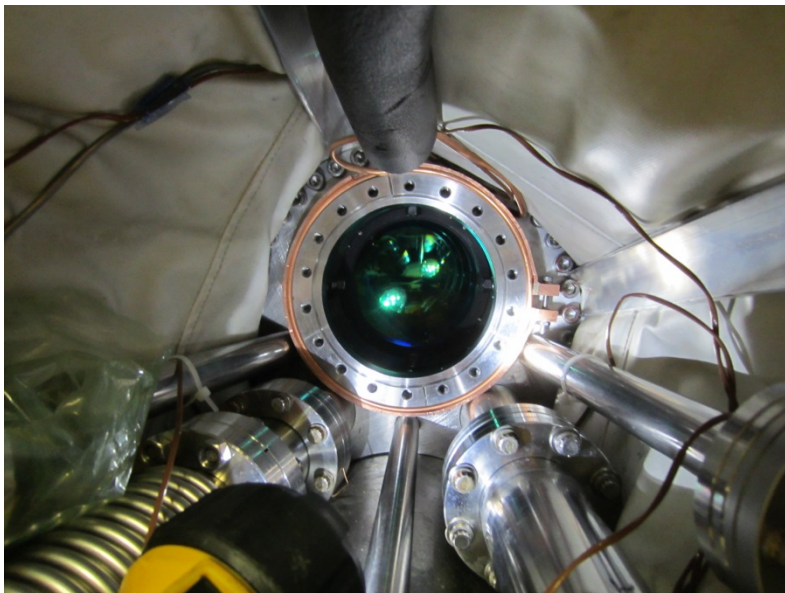


External optics also stabilized with copper sheeting, insulation and TCs:

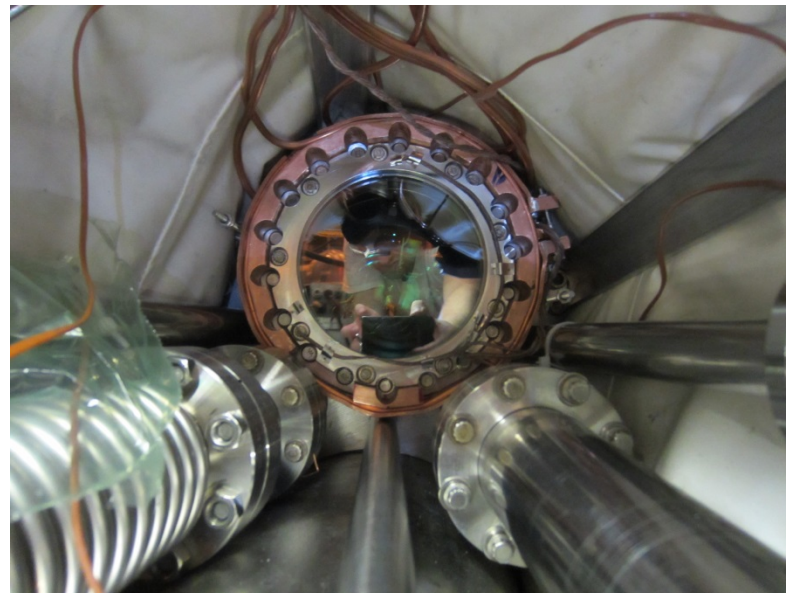


External optics mount
full of insulation,
creating seal to VW.

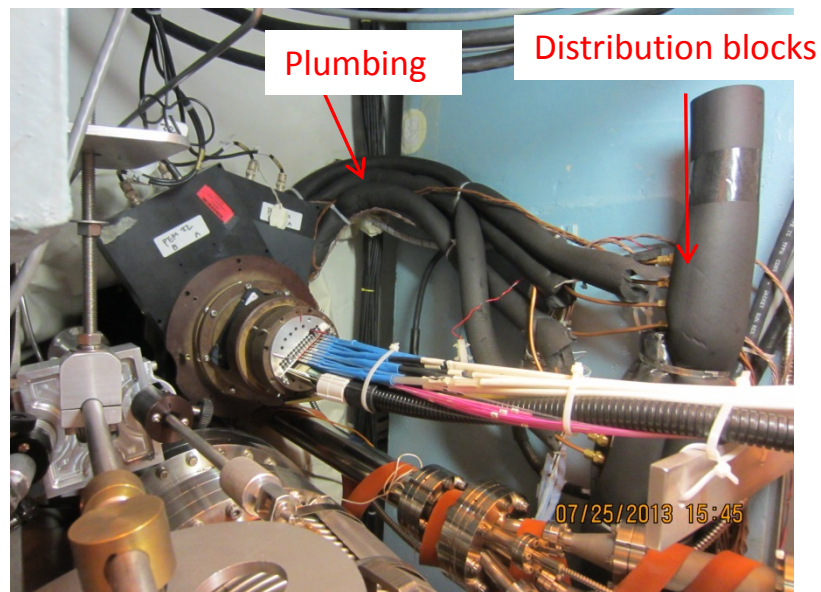
Entire optical train
insulated with
convection from pump



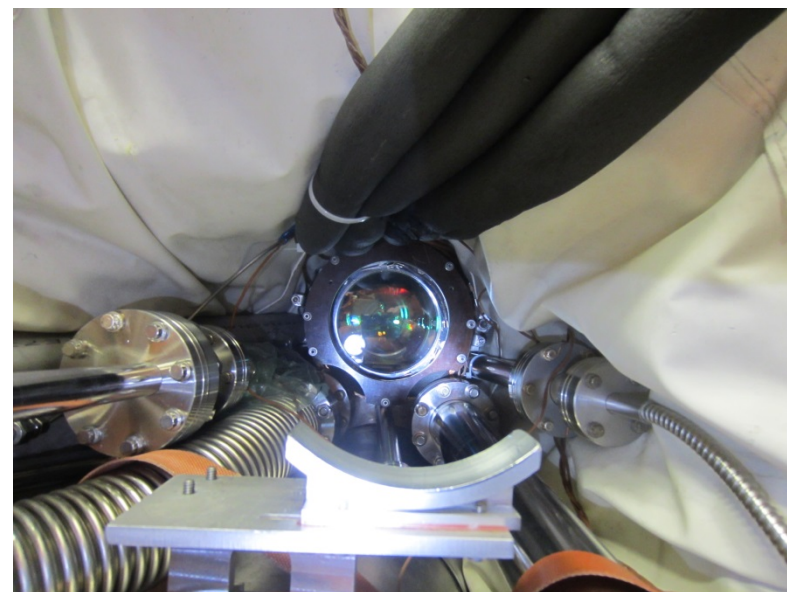
VW flange band installed



VW assembly installed



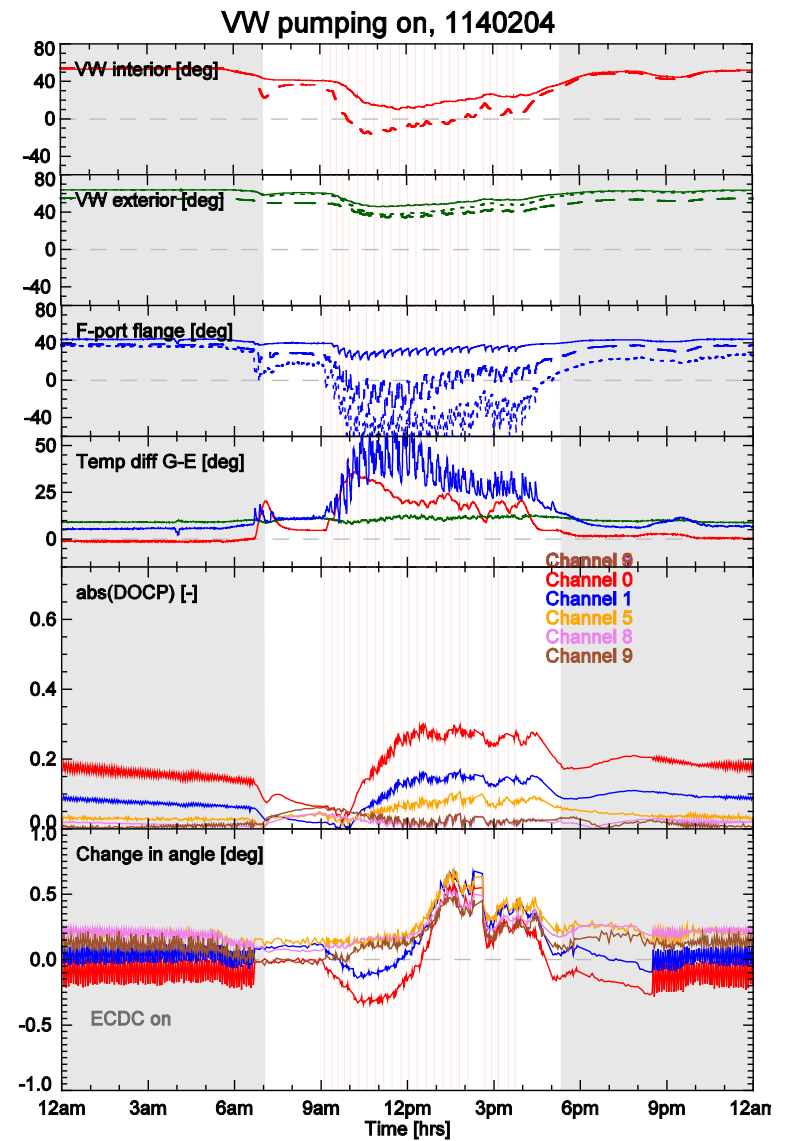
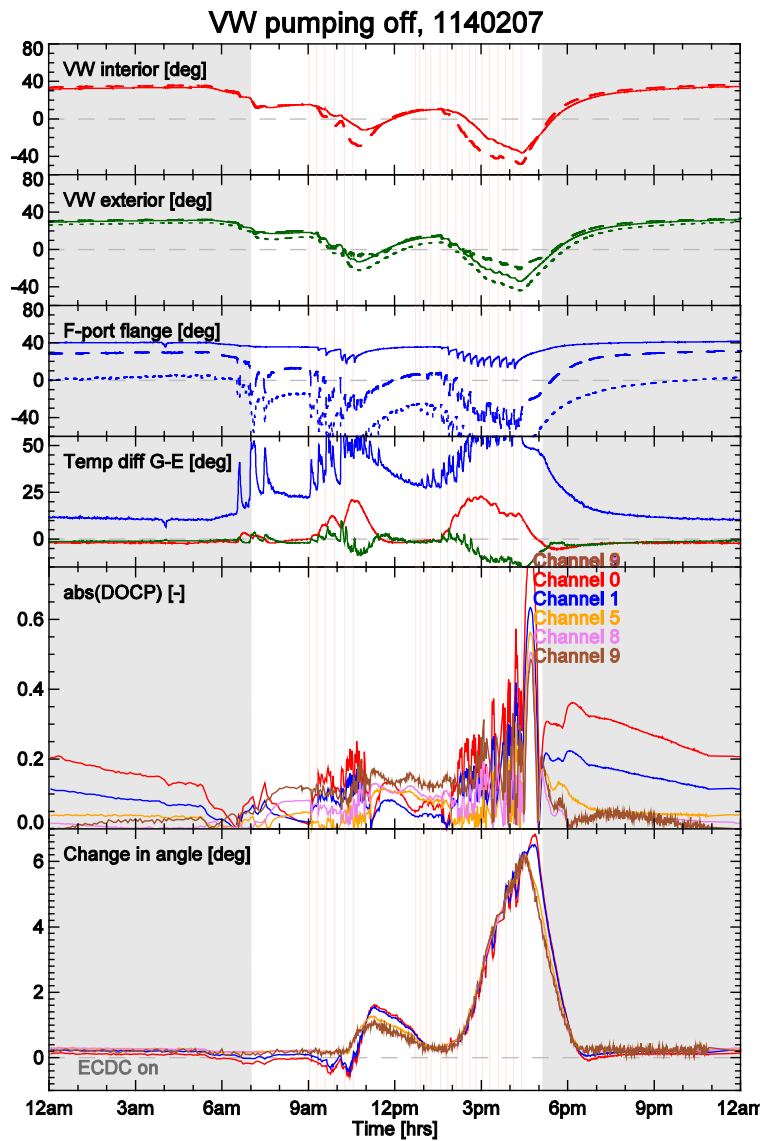
External optics installed, plumbing added



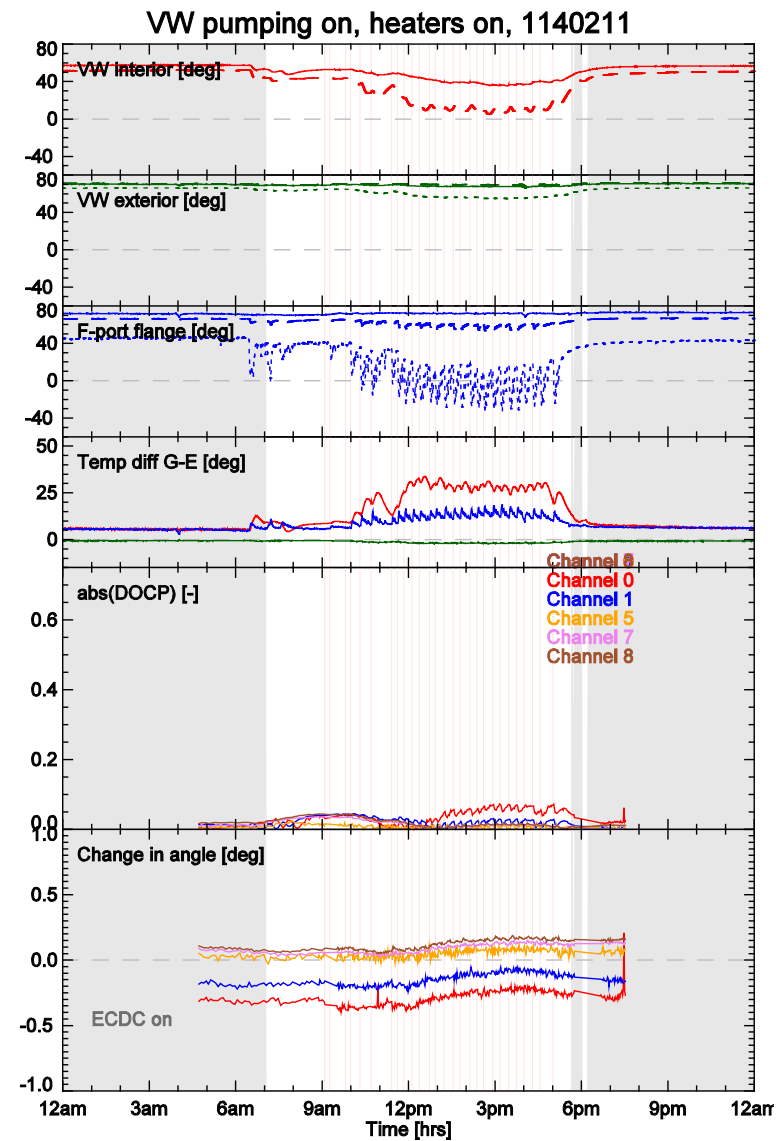
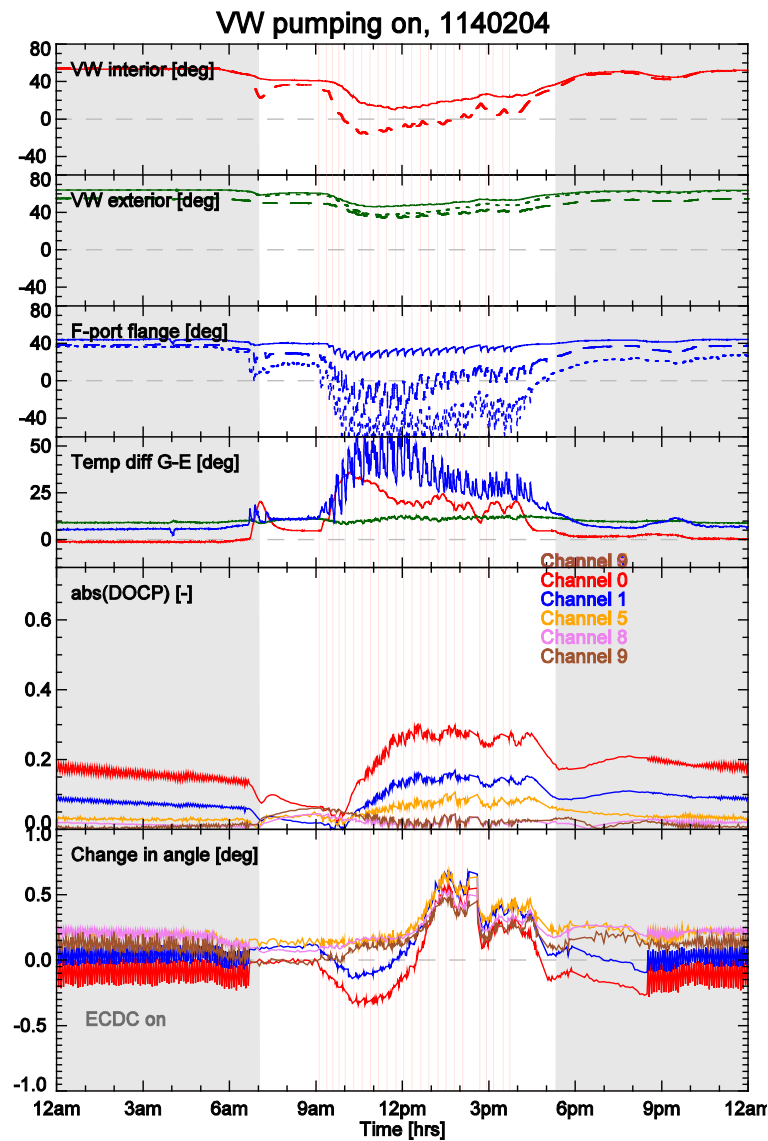
External optics mount installed

VW results

VW system improves things



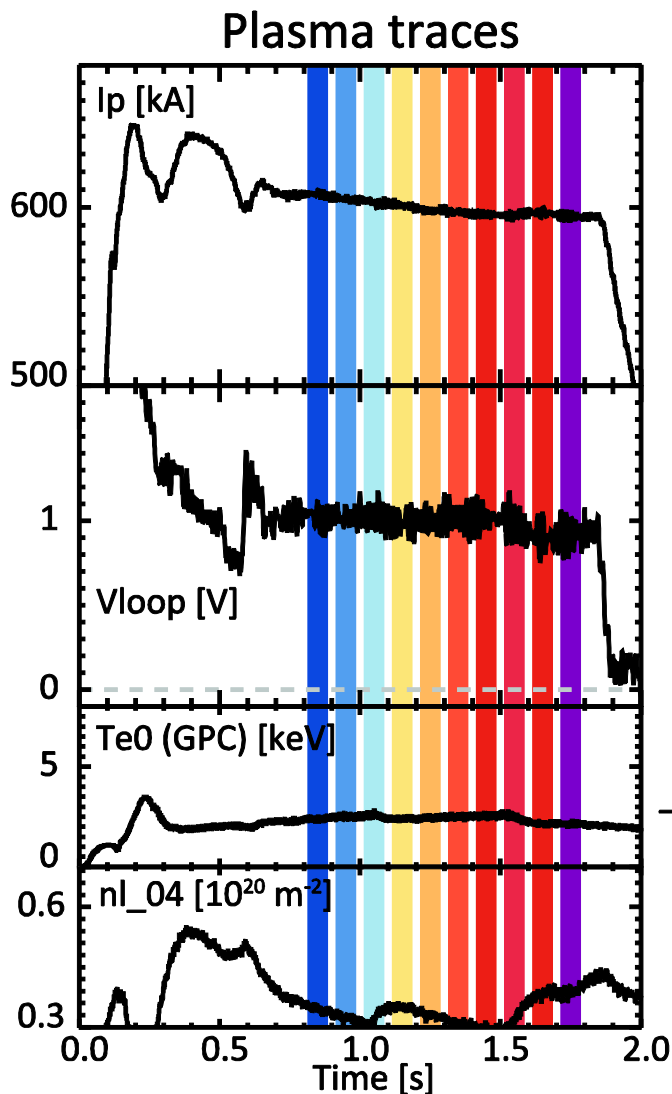
VW system + C-Mod thermal control improves things even more



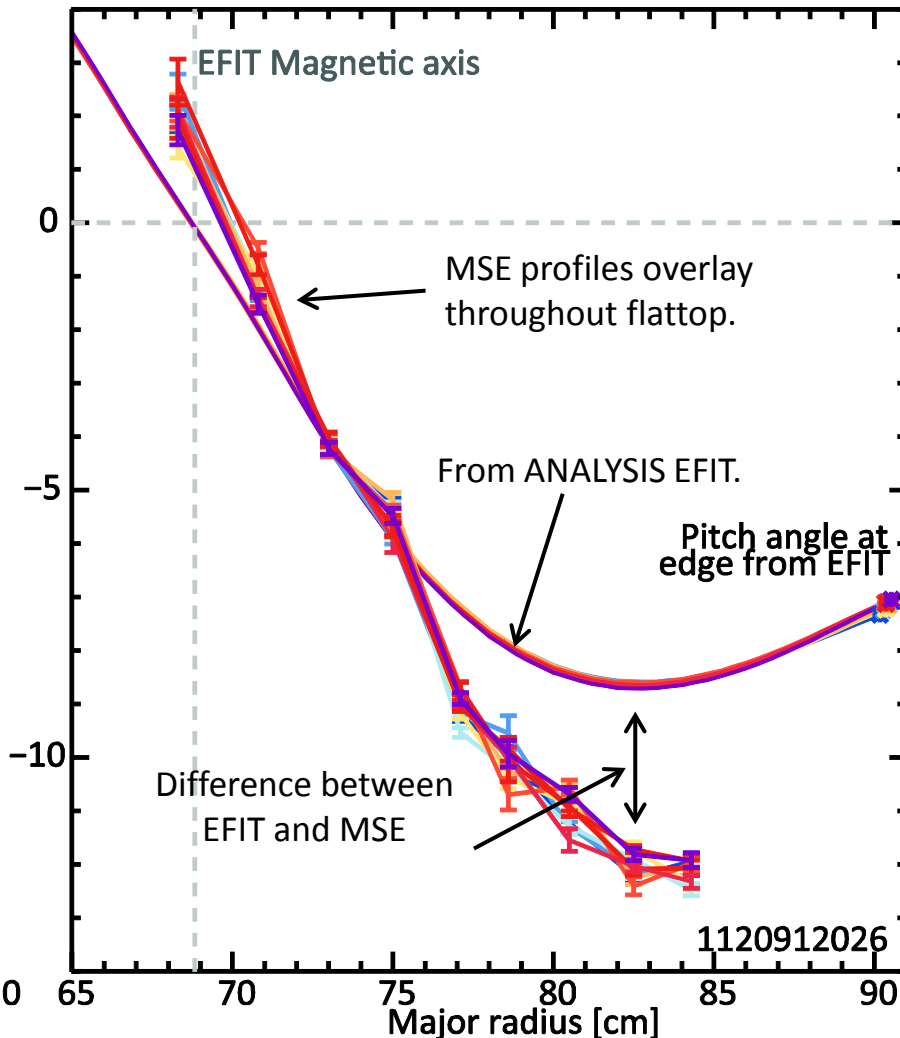
Plasma checks

The diagnostic measures constant pitch angles with constant plasmas. Good.

- MSE measures constant pitch angles in Ohmic shots with constant current



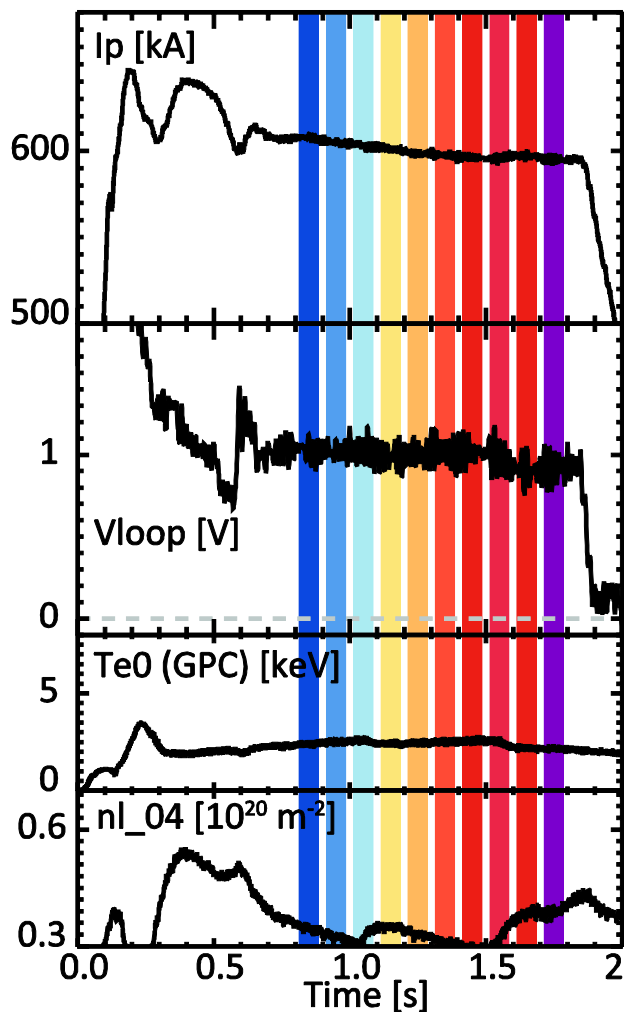
Pitch angle profiles measured by MSE



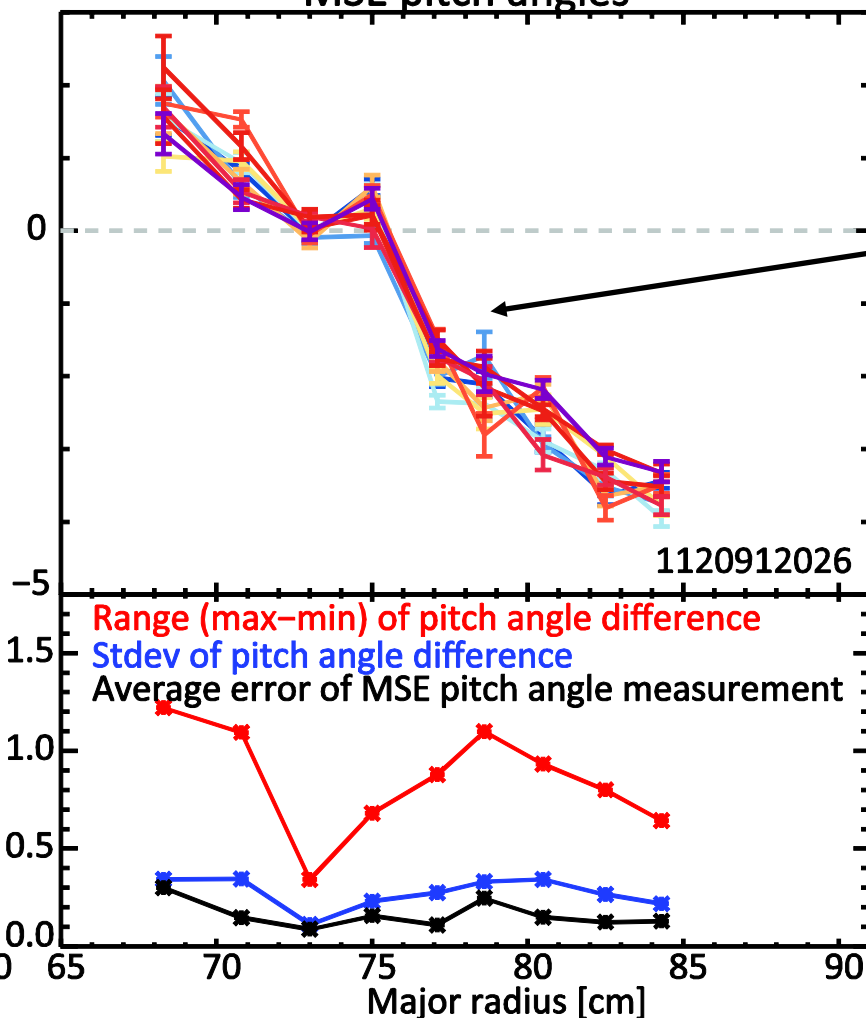
[More Ohmic](#)

The diagnostic measures constant pitch angles with constant plasmas. Good.

Plasma traces



Difference between ANALYSIS EFIT and MSE pitch angles

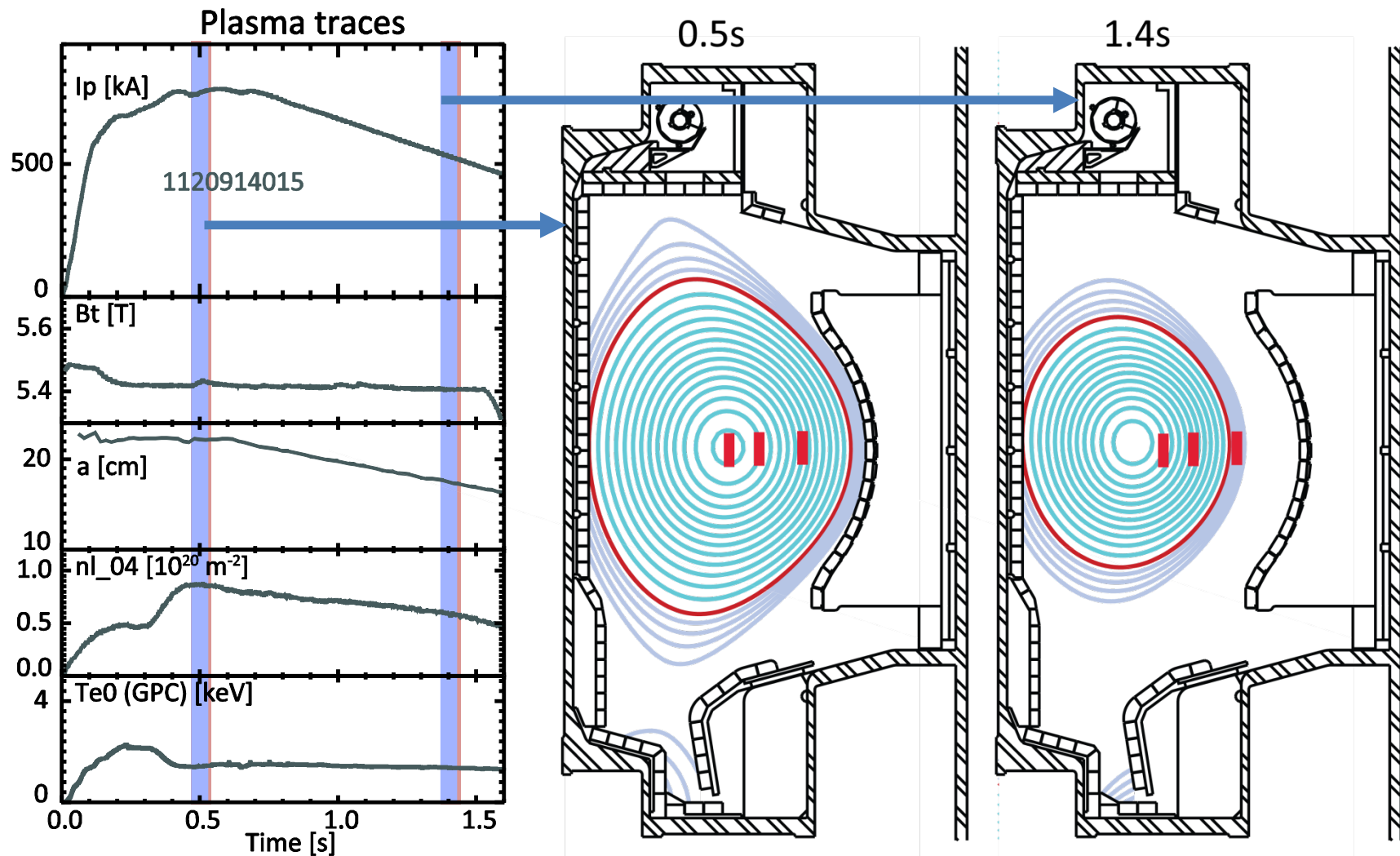


Channel offset is constant within a shot

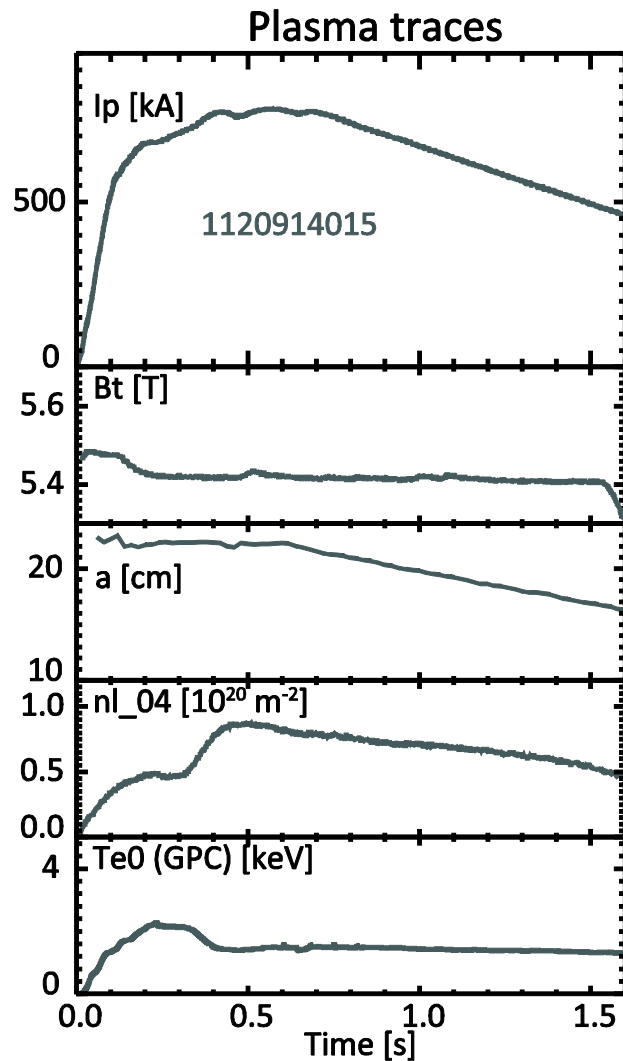
Standard deviation of timeslices is only slight larger than statistical error of individual measurements

[More Ohmic](#)

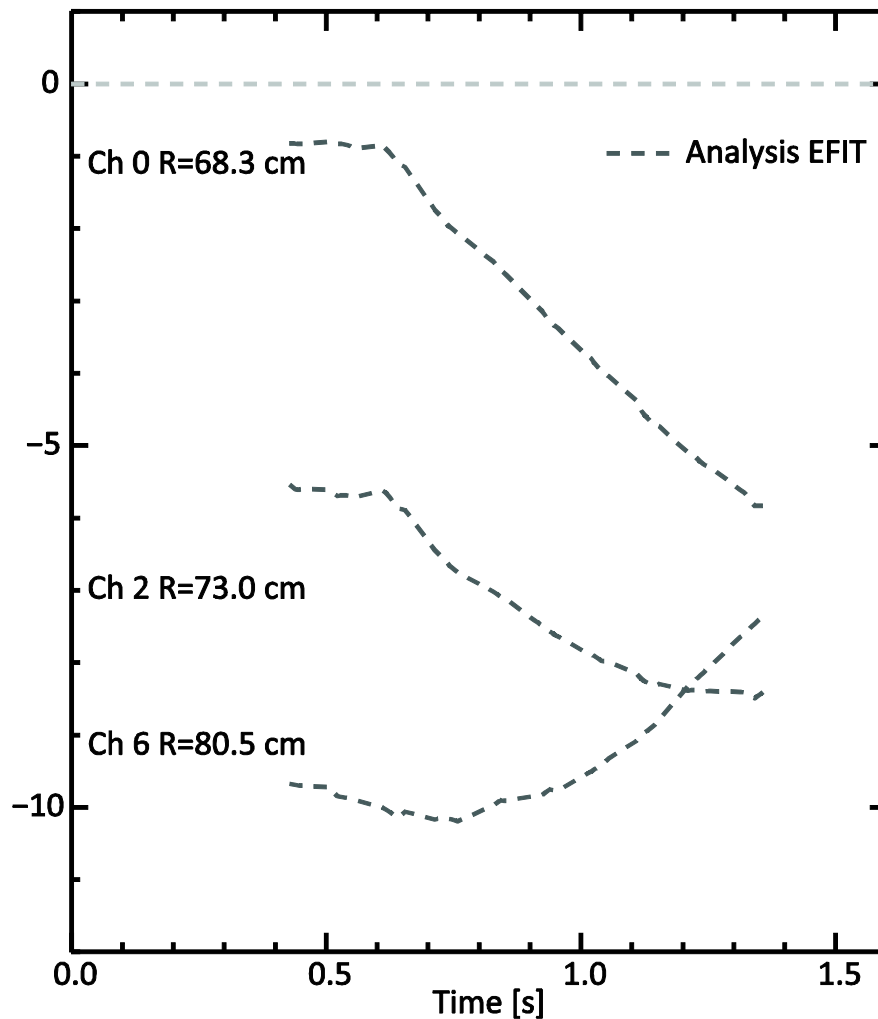
Use plasma outer gap sweeps to see if MSE measures the correct current profile dynamics.



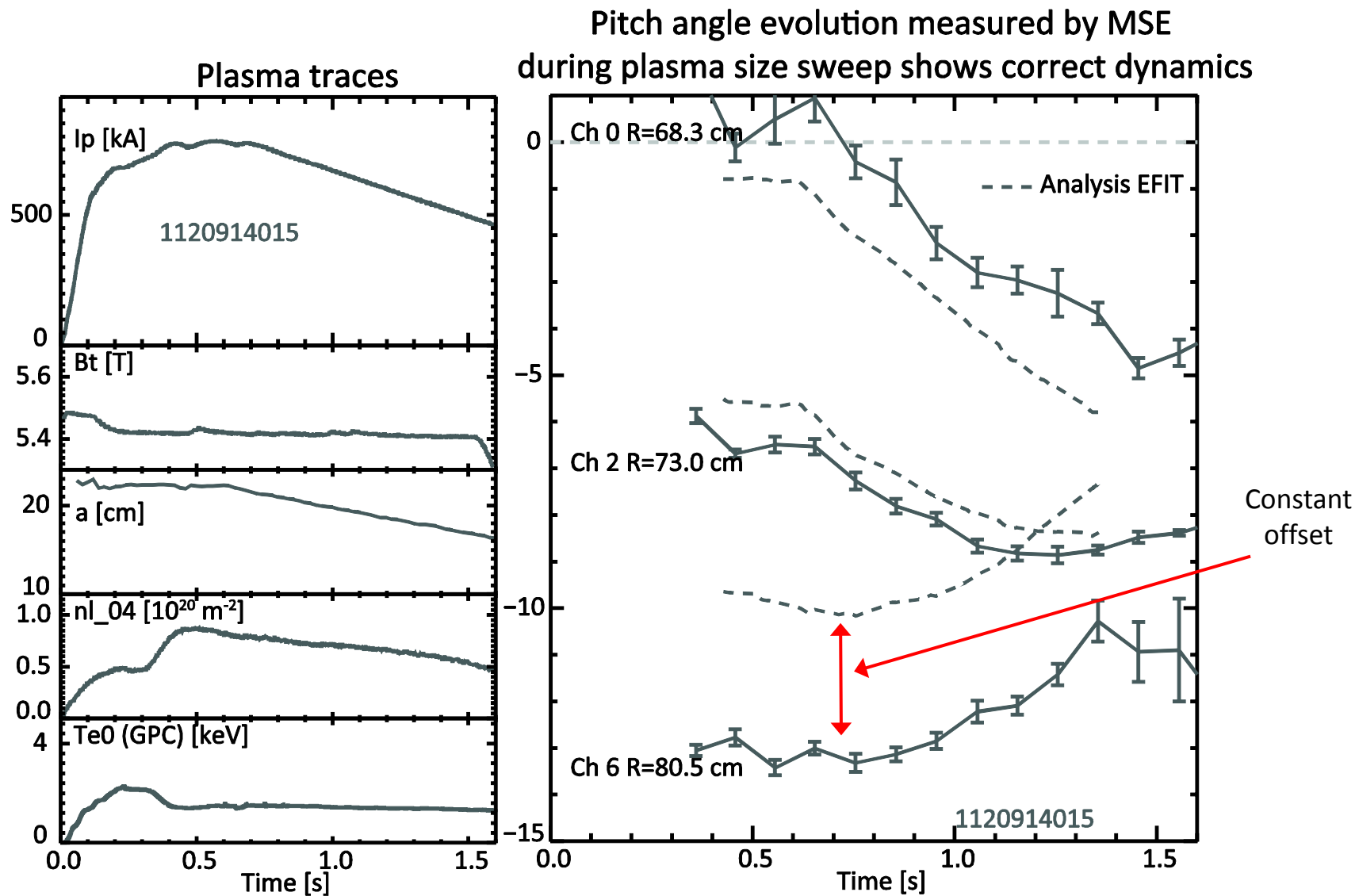
Use plasma outer gap sweeps to see if MSE measures the correct current profile dynamics.



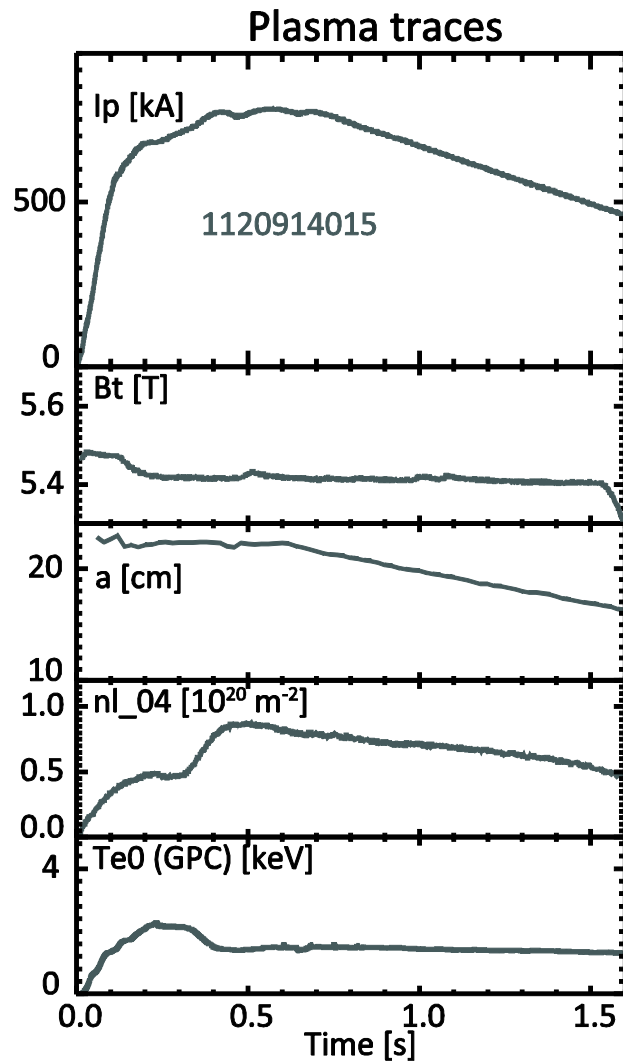
Pitch angle evolution measured by MSE during plasma size sweep shows correct dynamics



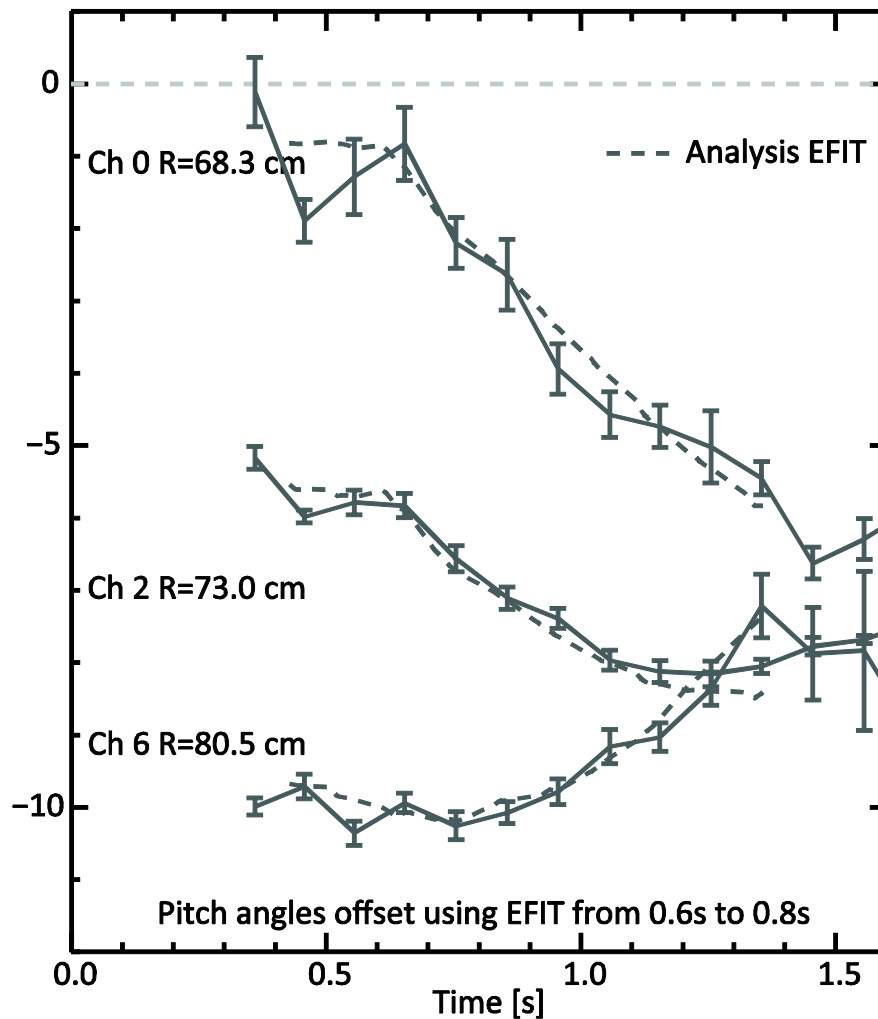
Use plasma outer gap sweeps to see if MSE measures the correct current profile dynamics. It does.



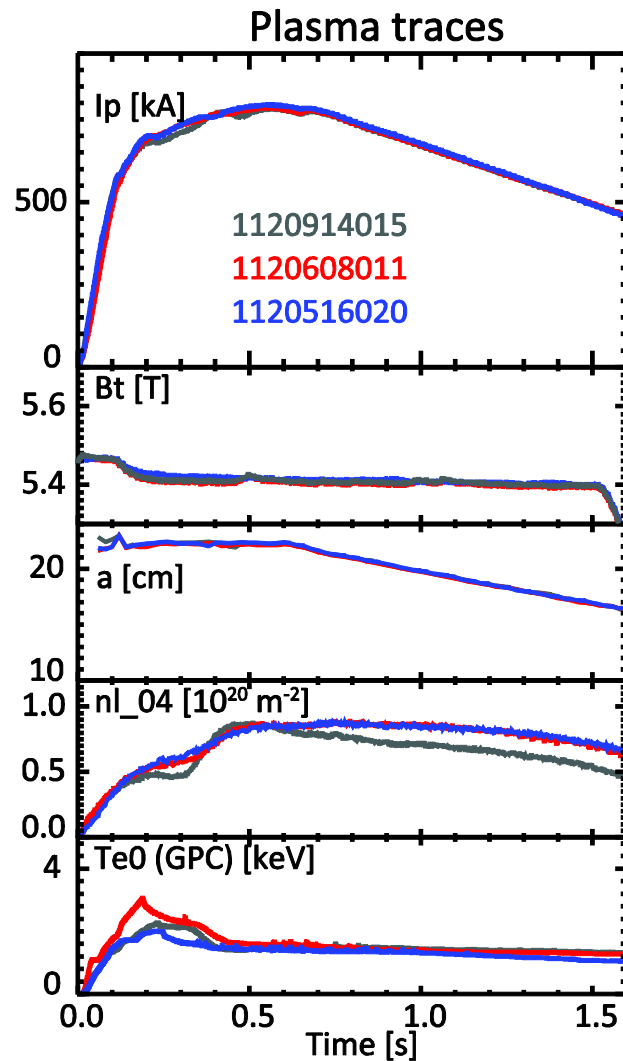
Use plasma outer gap sweeps to see if MSE measures the correct current profile dynamics. It does.



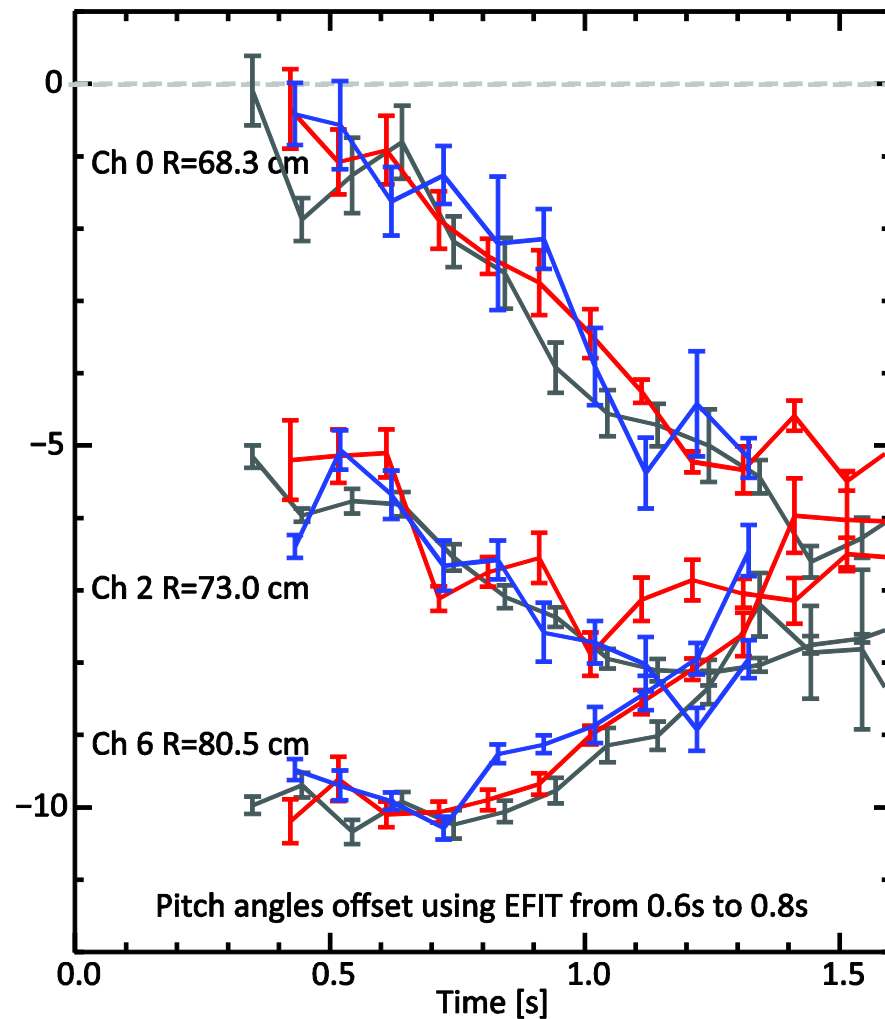
Pitch angle evolution measured by MSE during plasma size sweep shows correct dynamics



Multiple sweeps across the campaign shows the diagnostic measures dynamics reliably



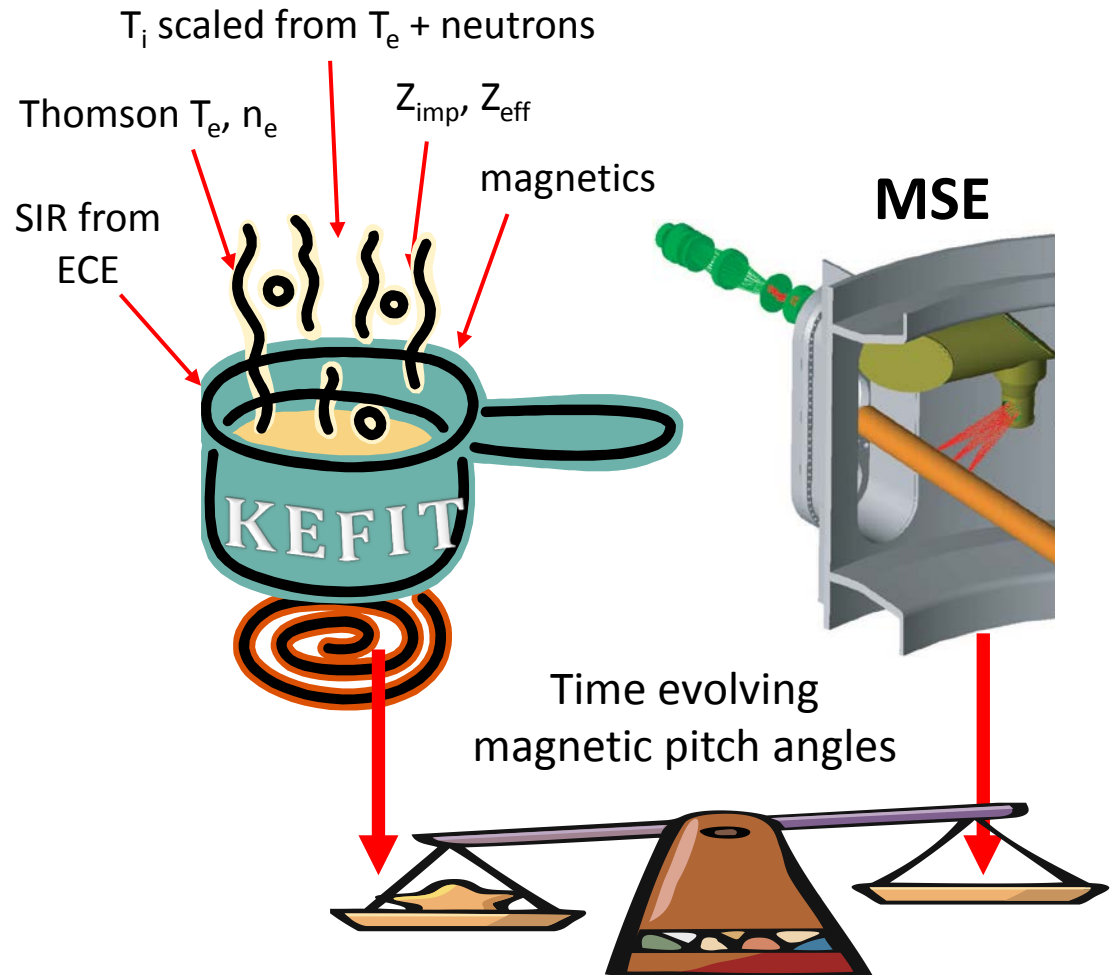
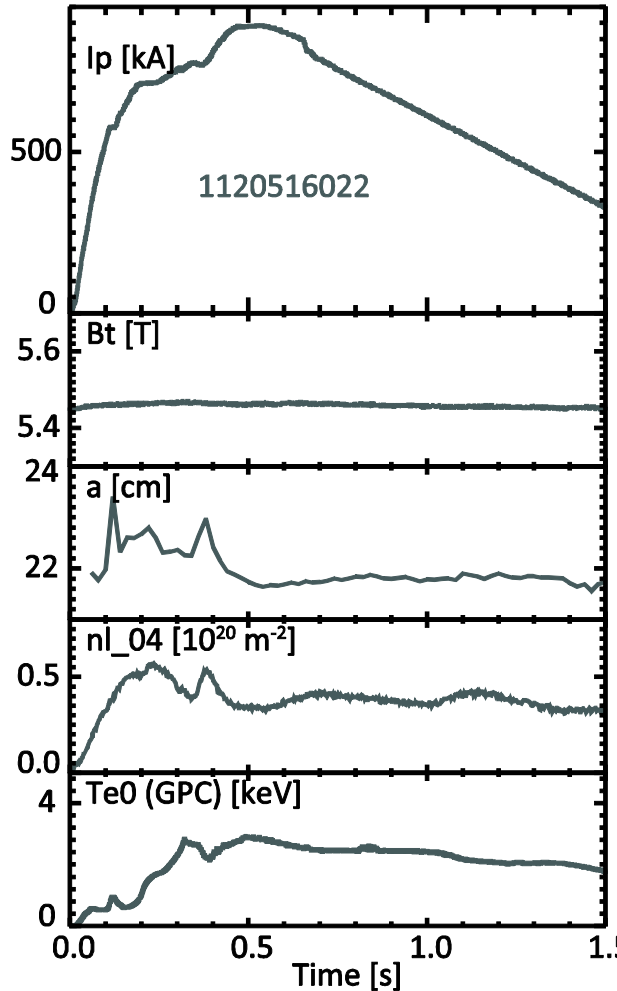
Pitch angle evolution measured by MSE for nearly identical plasma sweep shots



Use current scans to determine that the diagnostic is linear.

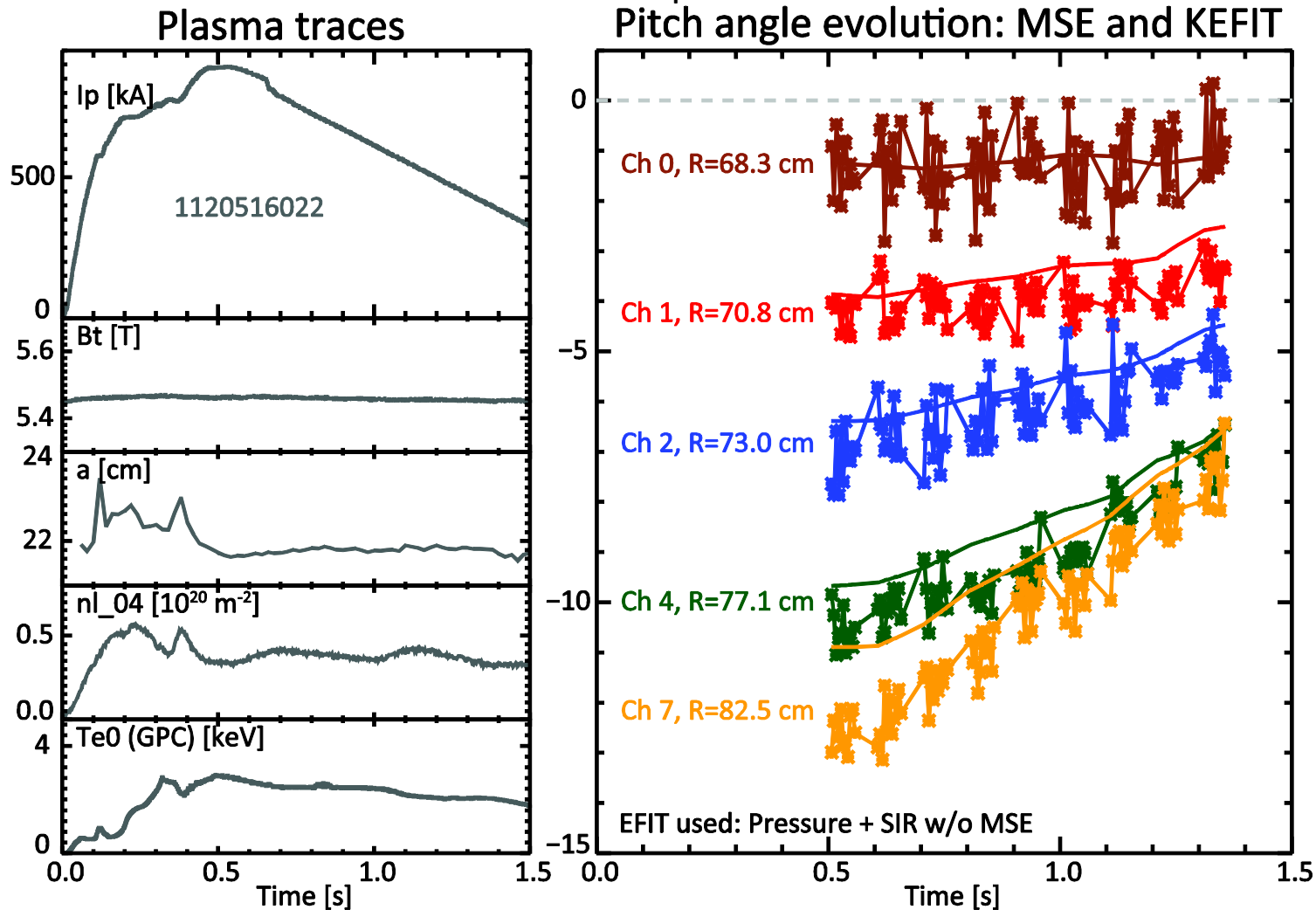
- Ramp plasma current at constant parameters. Reconstruct with EFIT and compare to MSE
- Use best non-MSE EFIT we have: Kinetic profiles + SIR constraint

Plasma traces



Use current scans to determine that the diagnostic is linear.

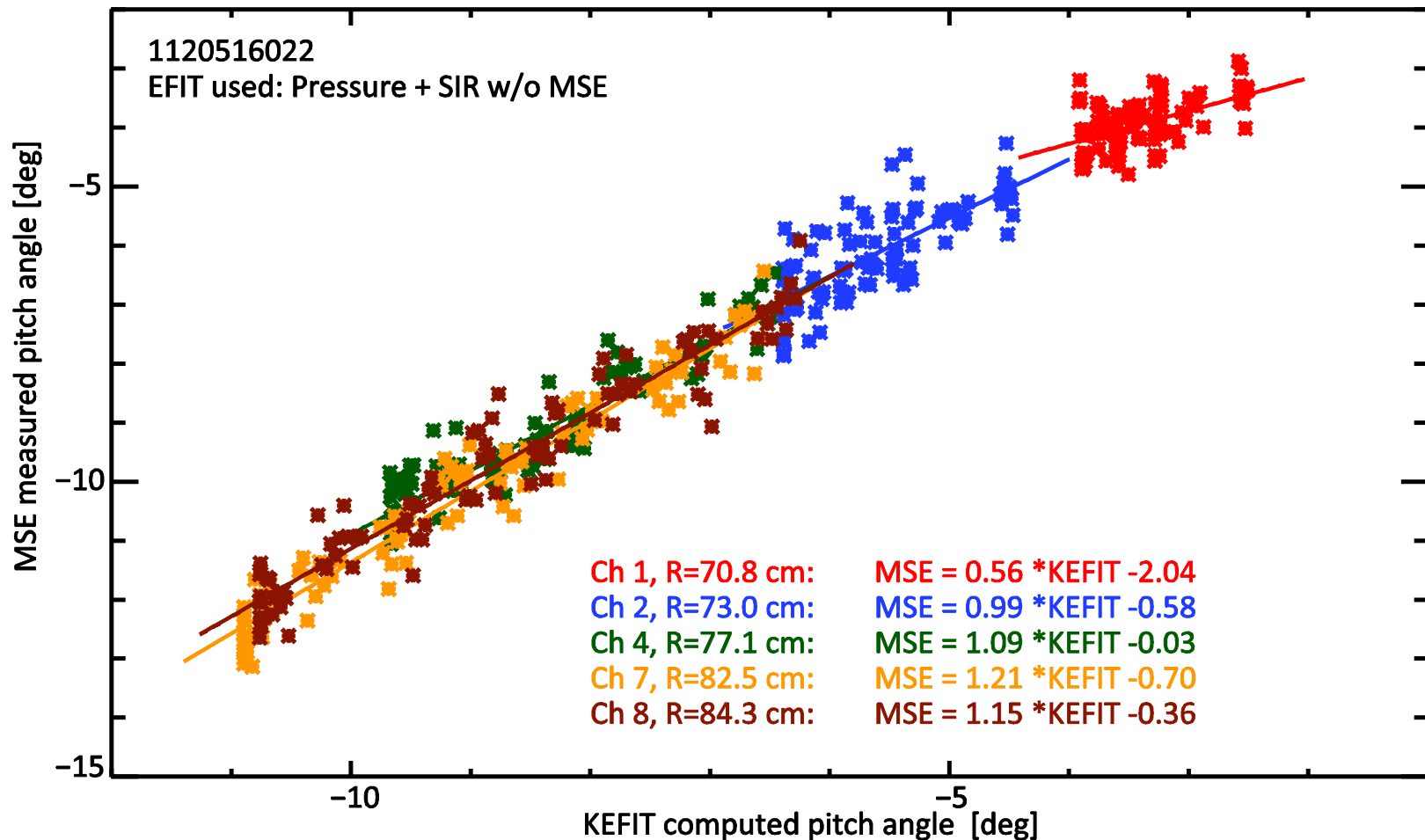
- Ramp plasma current at constant parameters. Reconstruct with KEFIT and compare to MSE
- Use best non-MSE EFIT we have: Kinetic profiles + SIR constraint



Use current scans to determine that the diagnostic is linear.

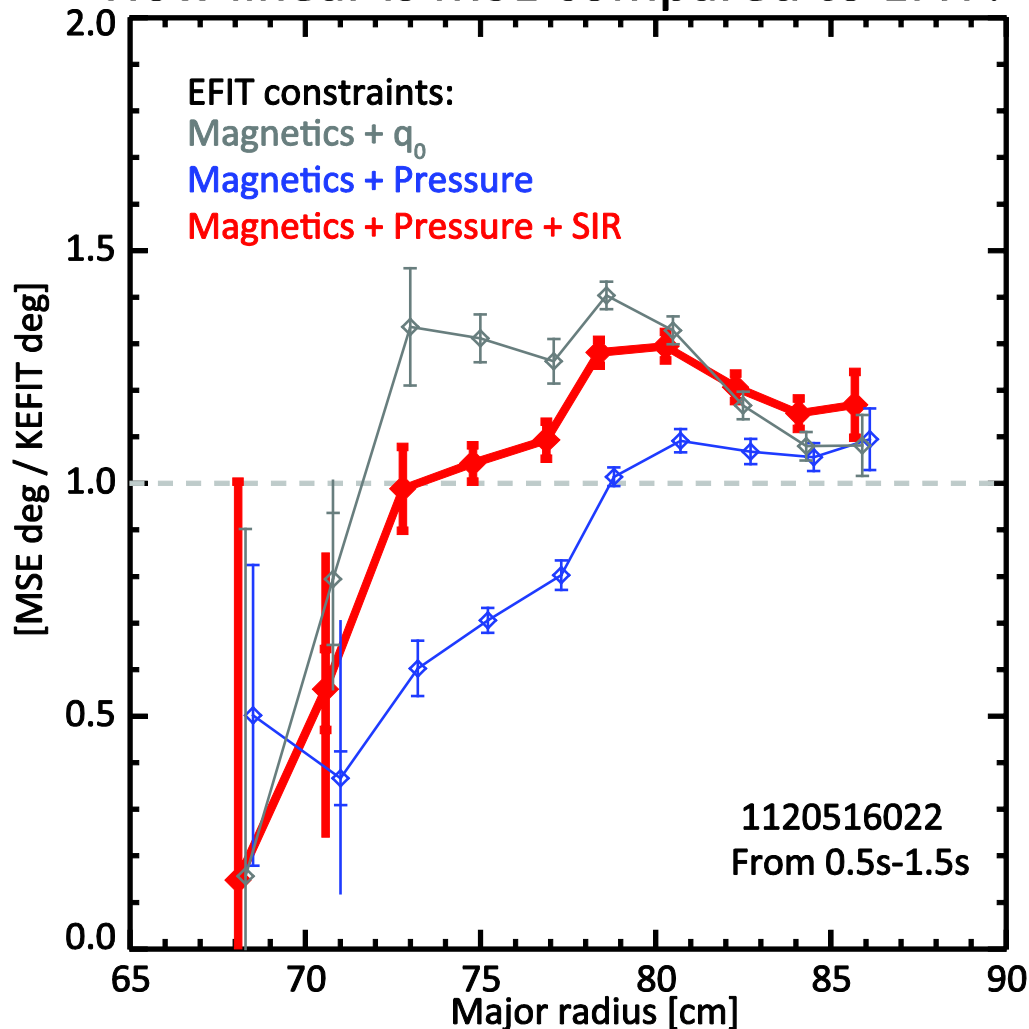
- Plot the measured pitch angle vs the KEFIT computed pitch angle for the scan
 - Fit a line $y=ax+b$

Comparison of MSE measured pitch angles to KEFIT during current scan



Use current scans to determine that the diagnostic is linear.

How linear is MSE compared to EFIT?

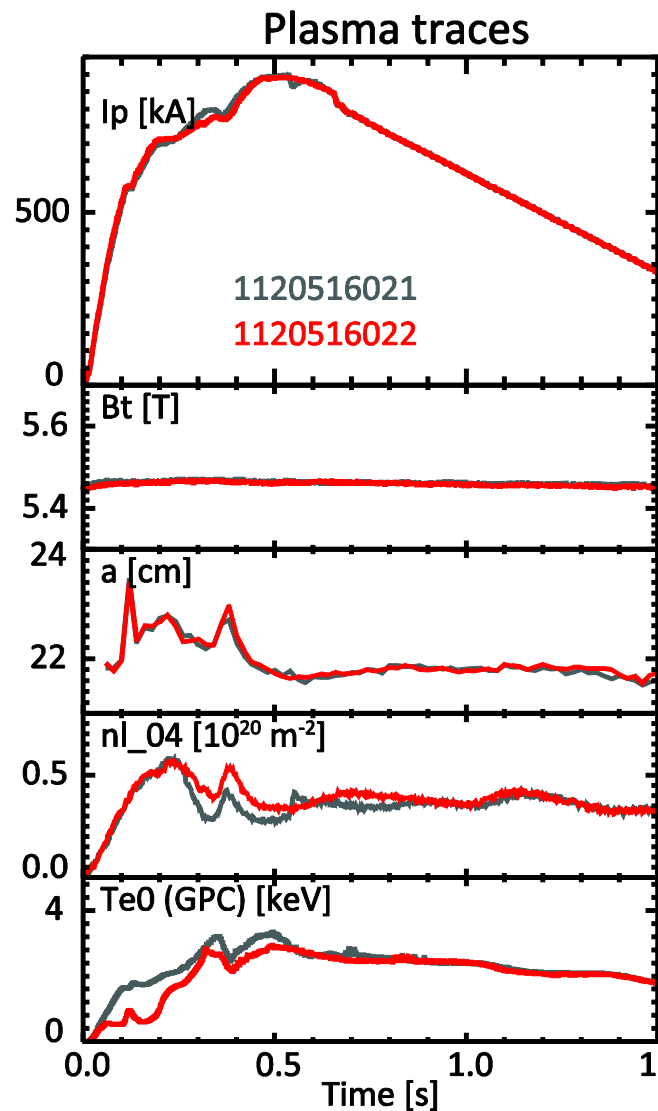


Diagnostic appears to be within ~10-20% of linear

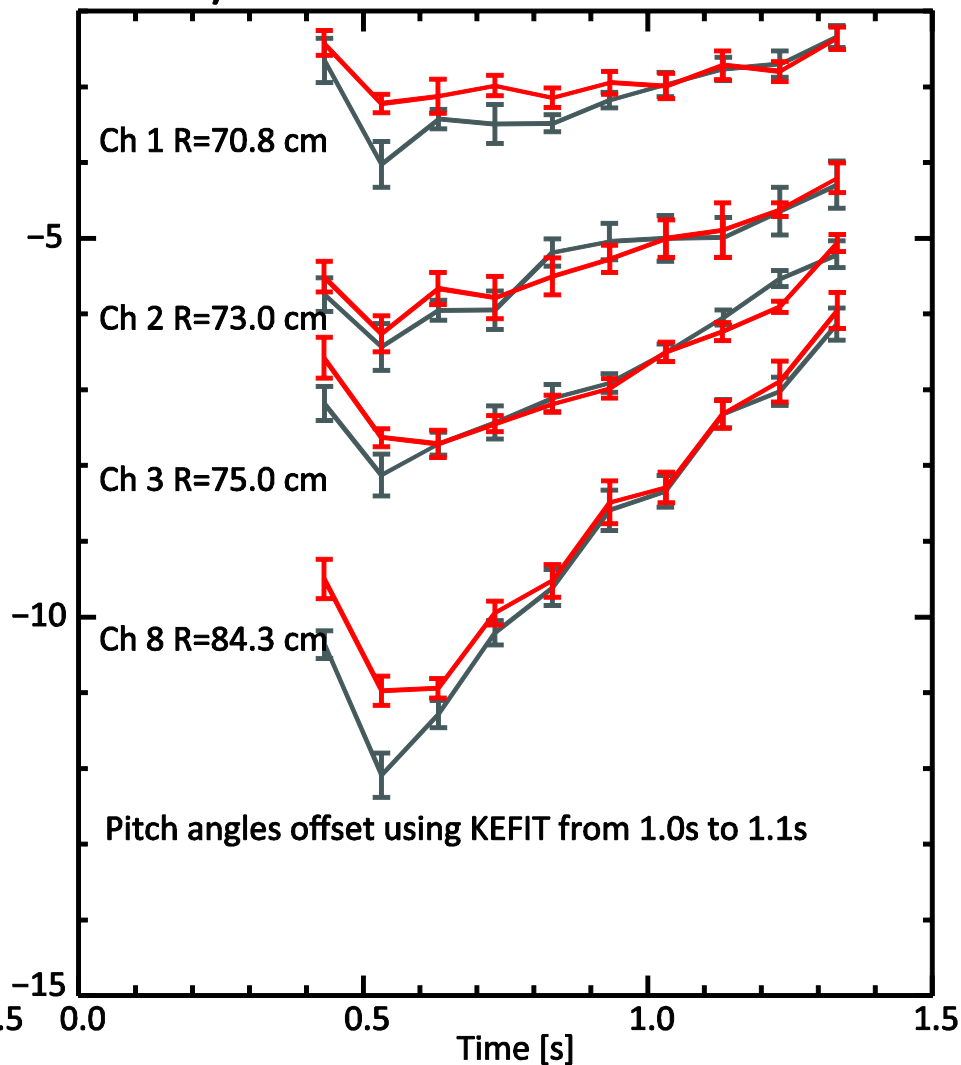
- Particularly in the important mid radius region where the largest changes are observed during LHCD
- Inner channels are harder to judge
 - Smaller scan in pitch angle
 - Less confidence in EFIT
 - Tried to do current scan at small size but disrupted
- Similar to experiment done in '07 which also found linearity in the outer channels

Geometric projection

Use nearly identical shots with large changes in current profile to judge diagnostic repeatability



Pitch angle evolution measured by MSE for nearly identical current scans at fixed size



LHCD raw measurements

Advanced tokamak scenerios: Control everything, all at once, with reactor relevant tools and physic understanding.

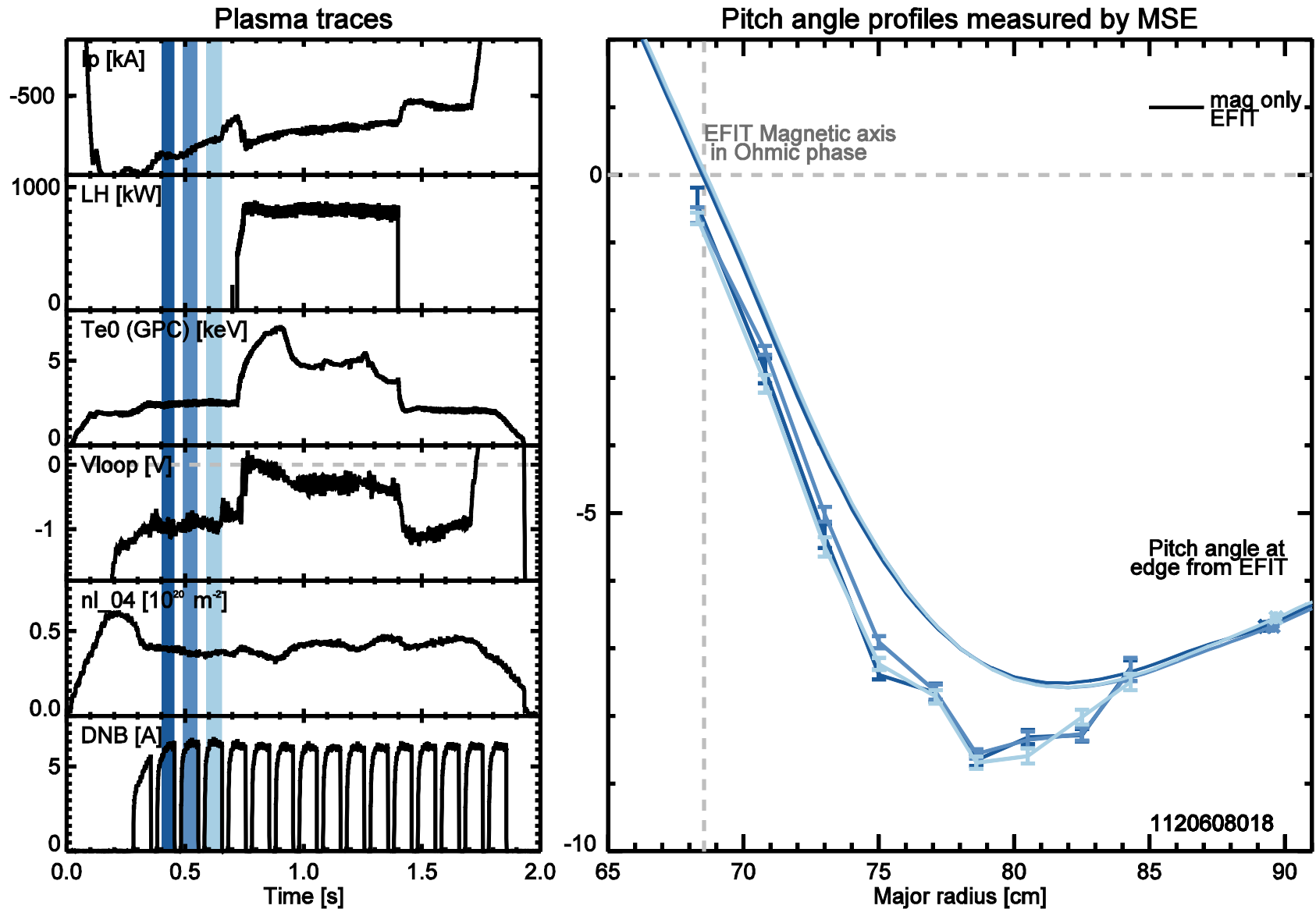
C-Mod is uniquely equipped to study many aspects relevant to advanced tokamak scenarios, particularly the physics of Lower Hybrid Current Drive (LHCD)

Devices with LHCD

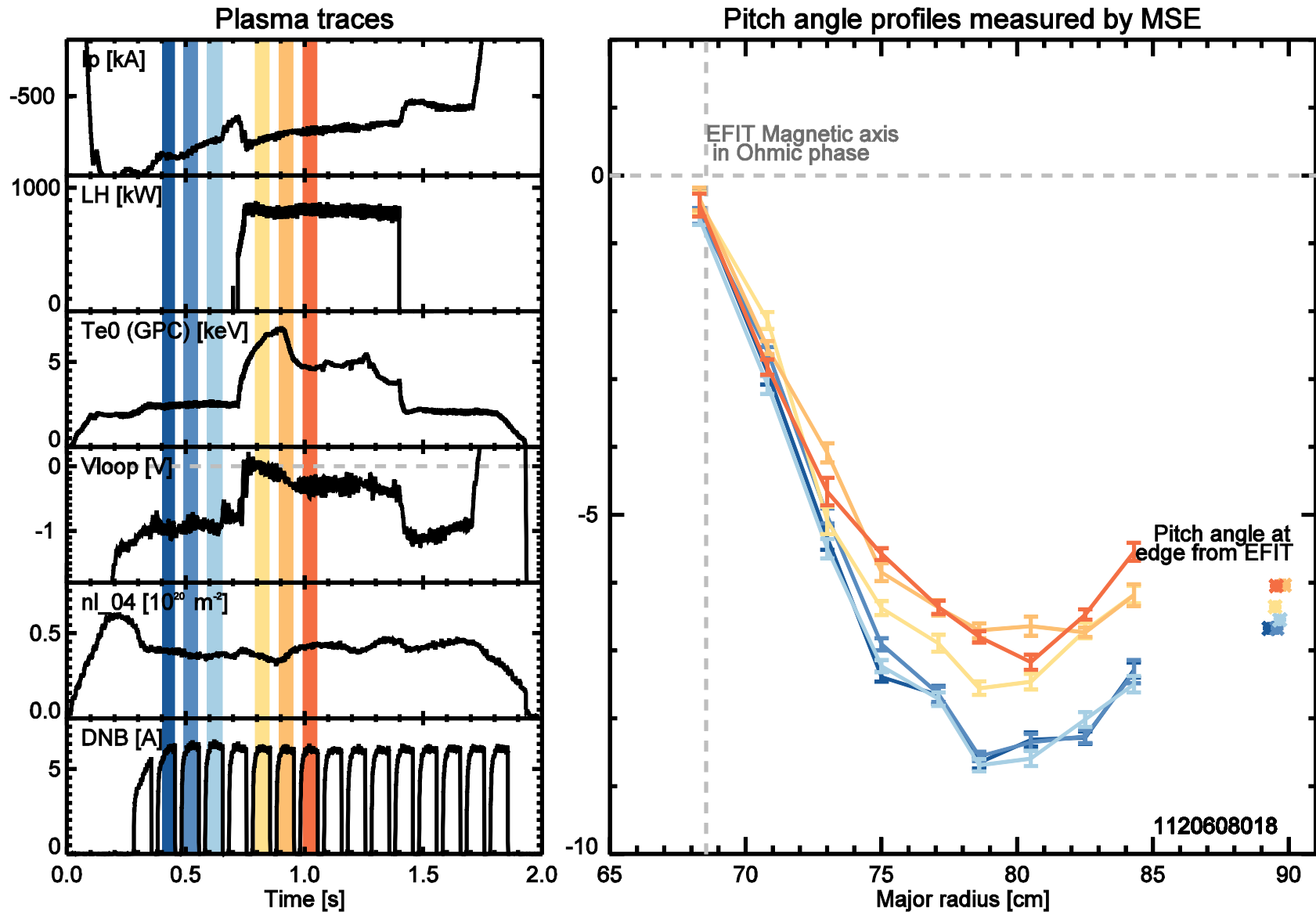
Parameter important for doing LHCD and AT physics	C-Mod	FTU	Tore Supra	KSTAR	EAST
Diverted	Y	N	N	Y	Y
Reactor field	Y	Y	N	N	N
Reactor LH frequency	Y	Y	N	Y	Y
Reactor density	Y	Y	N	N	N
Reactor Temperature	N	N	N	N	N
Magnetic geometry diagnostics	Y	N	Y	N	N

Today I'll take about work on enabling MSE to continue measurements into advanced tokamak regimes on C-Mod and other devices.

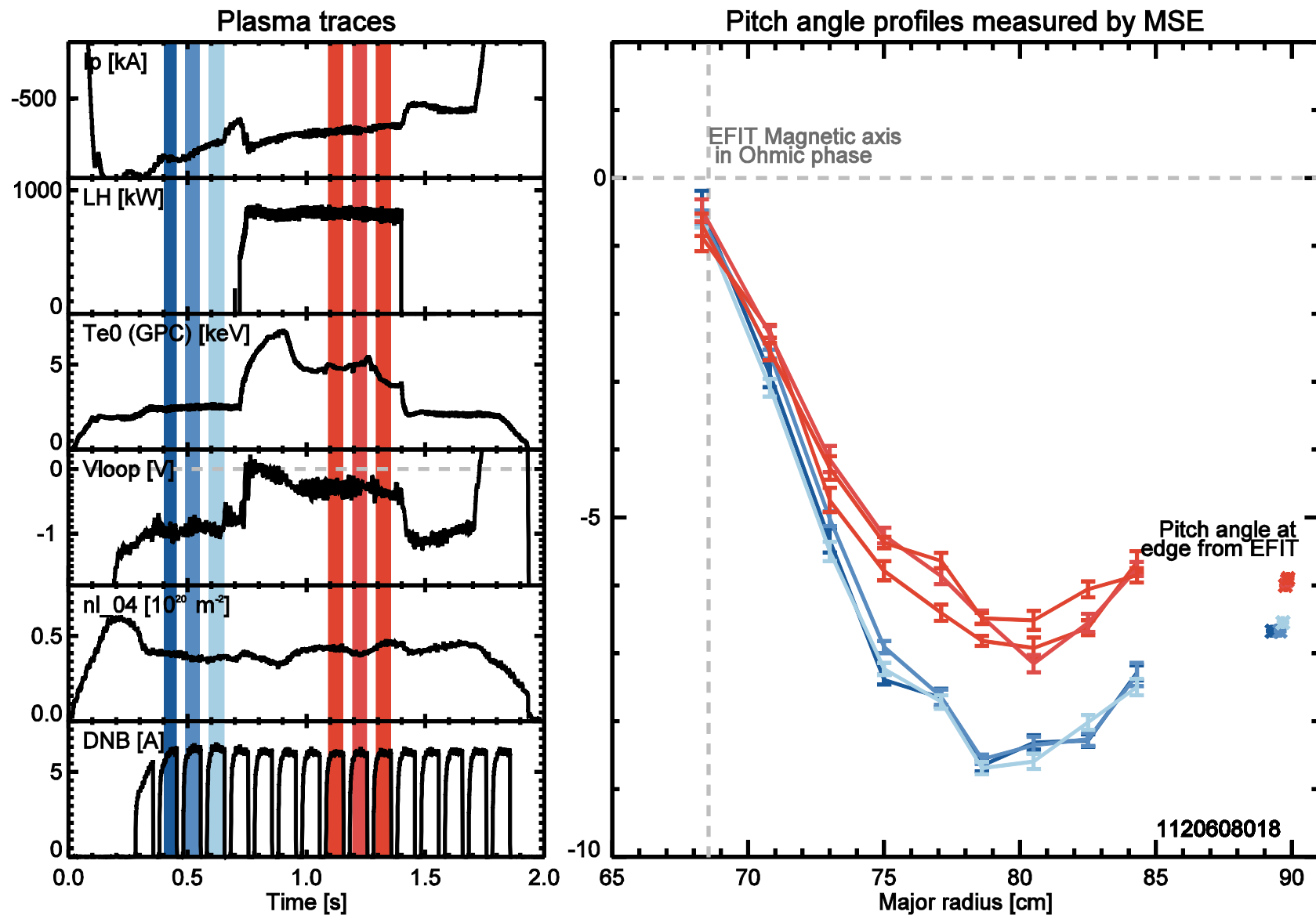
LHCD dynamics: Pre LH Ohmic period



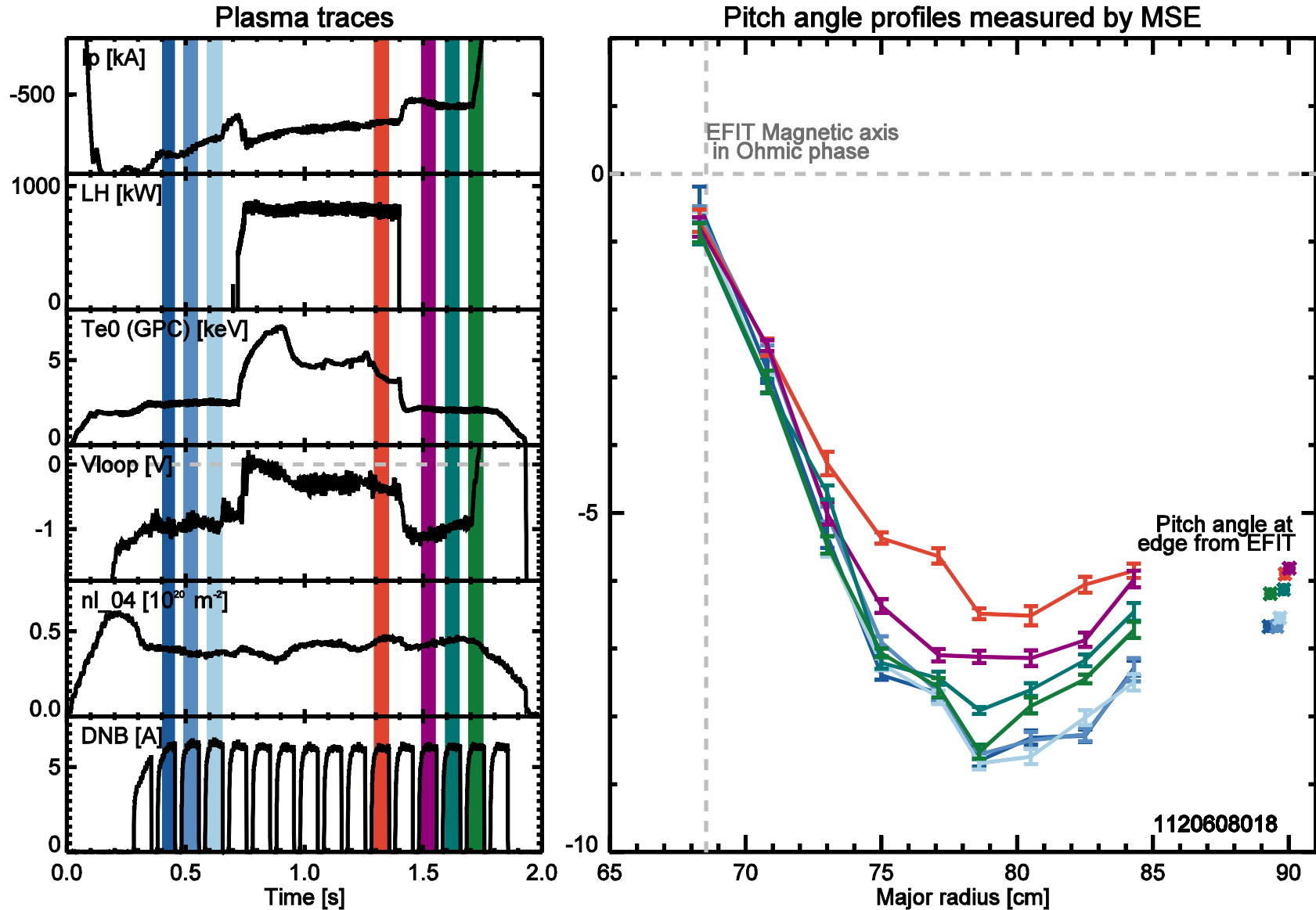
LHCD dynamics: LH turns on and profile evolves



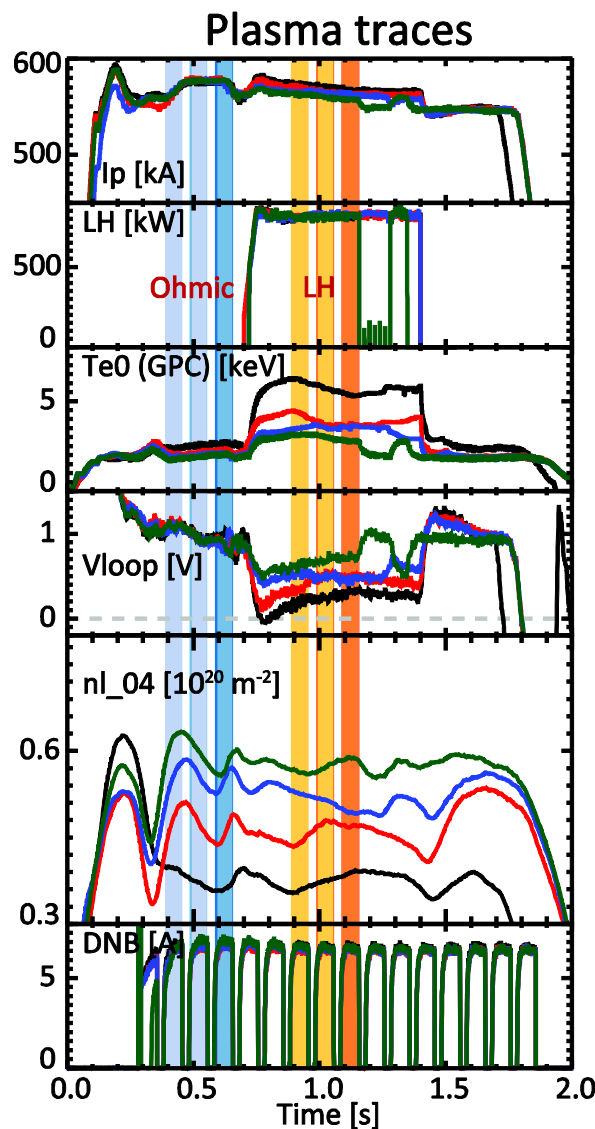
LHCD dynamics: Profile stabilizes at new equilibrium



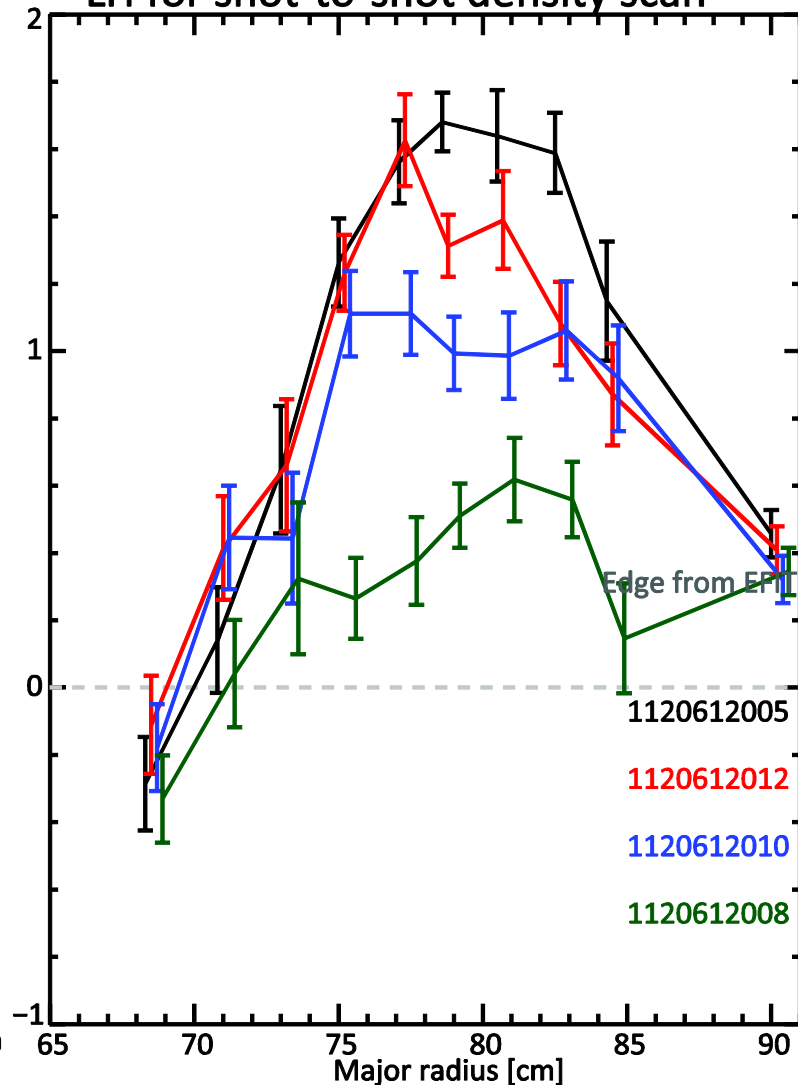
LHCD dynamics: LH turns off and profile revolves back to Ohmic



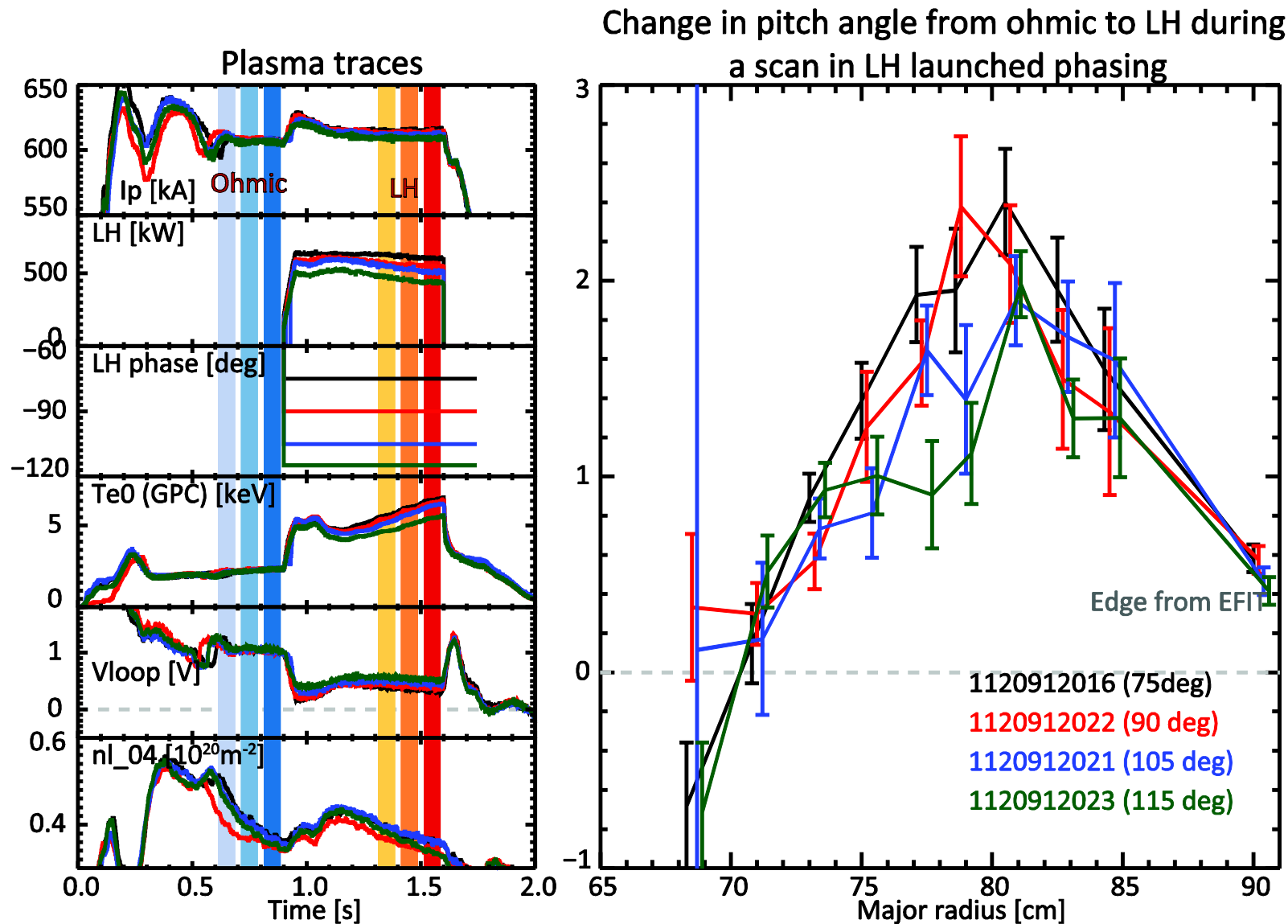
Change in pitch angle profiles from LHCD as a function of density



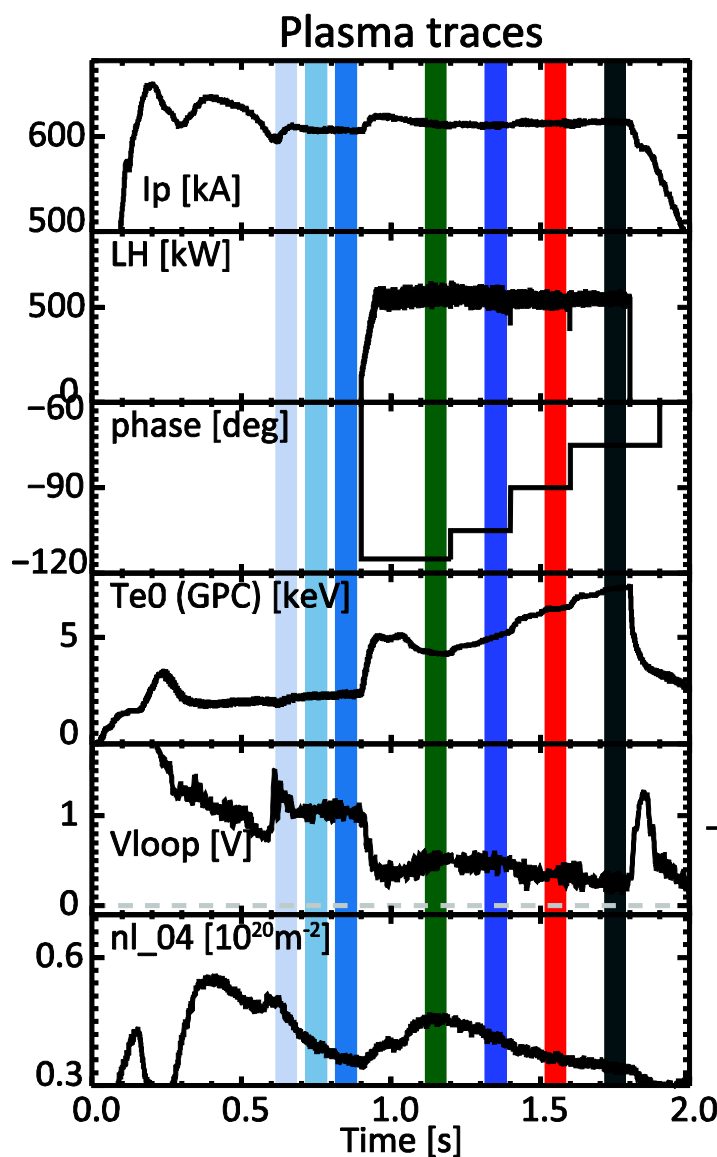
Change in pitch angle from ohmic to LH for shot-to-shot density scan



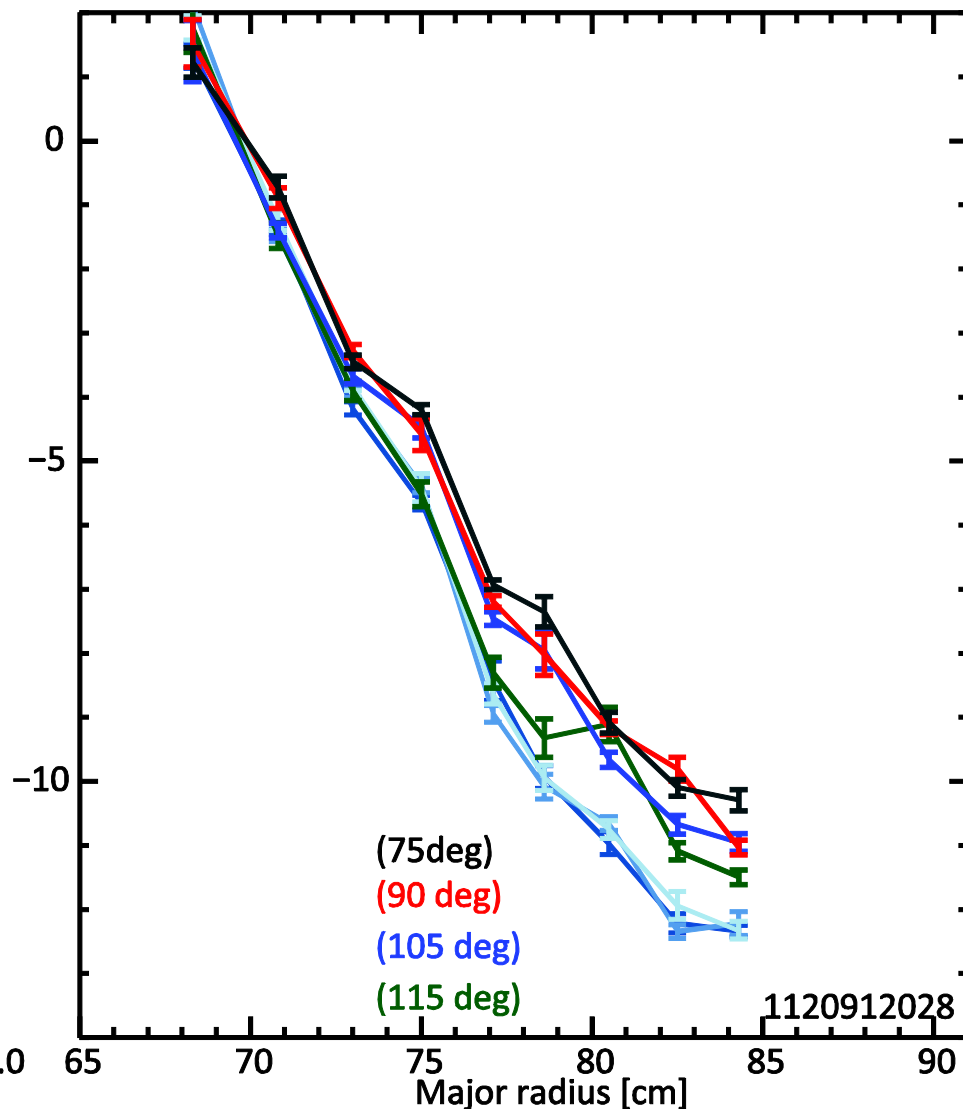
Change in pitch angle profiles from LHCD as a function of launched LH phase



Change in pitch angle profiles from LHCD as a function of launched LH phase



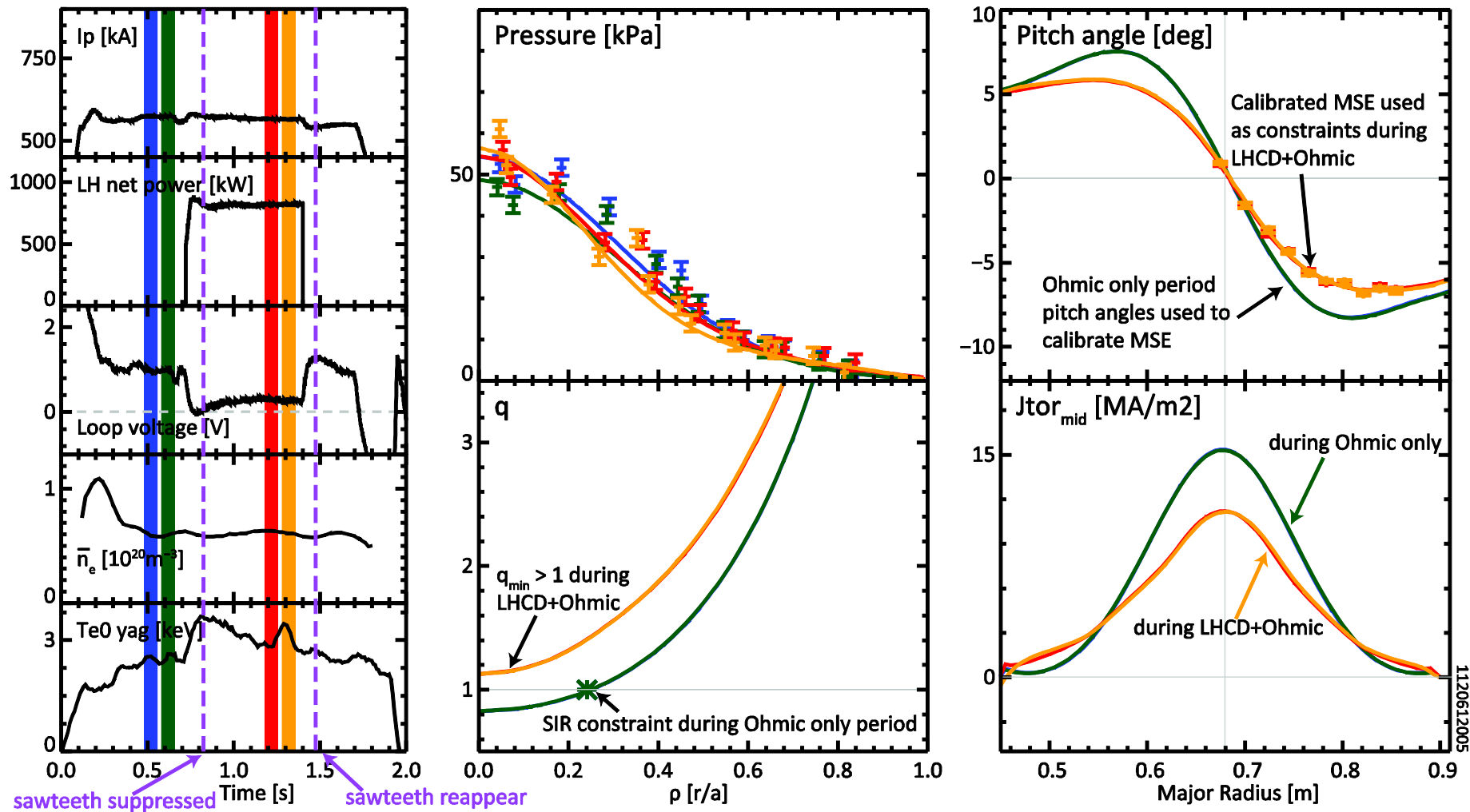
Pitch profile during a within-shot LH phase scan



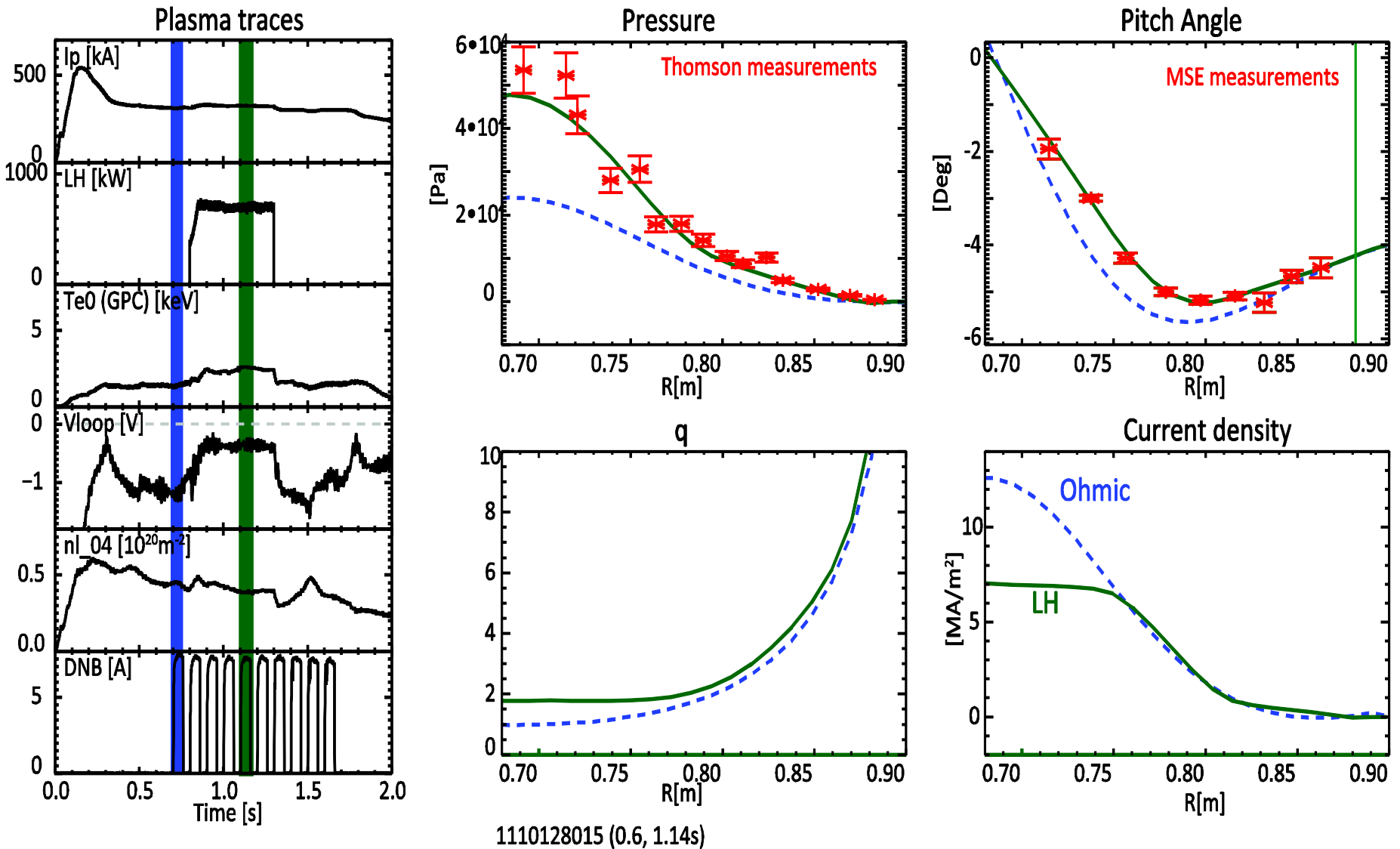
LHCD reconstructions

Reconstruction methodology: Intra-shot constraint

Reconstructions of plasmas with LHCD using within-shot calibration of MSE

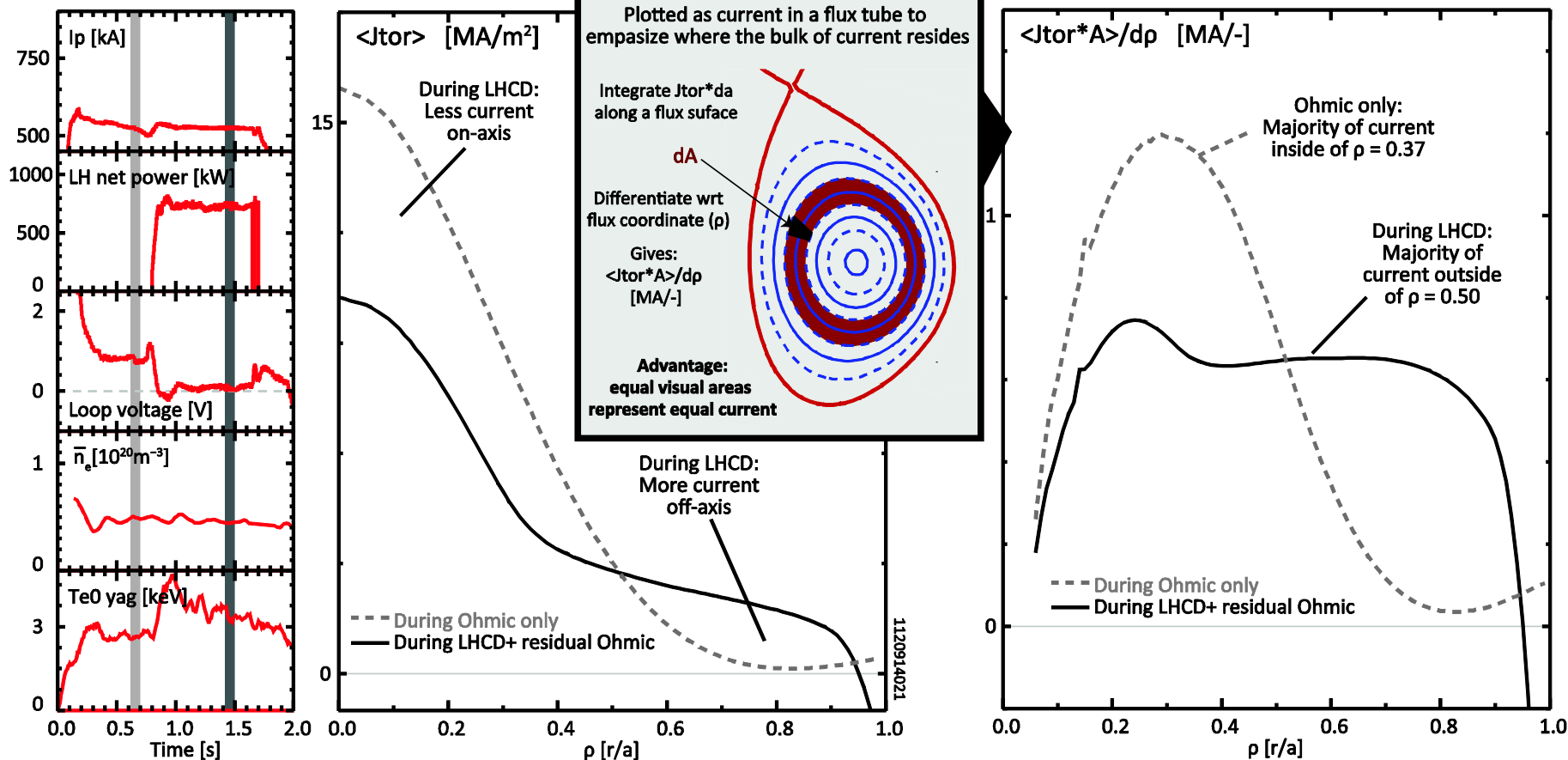


Example of reconstructed data: 1110128 for John Rice



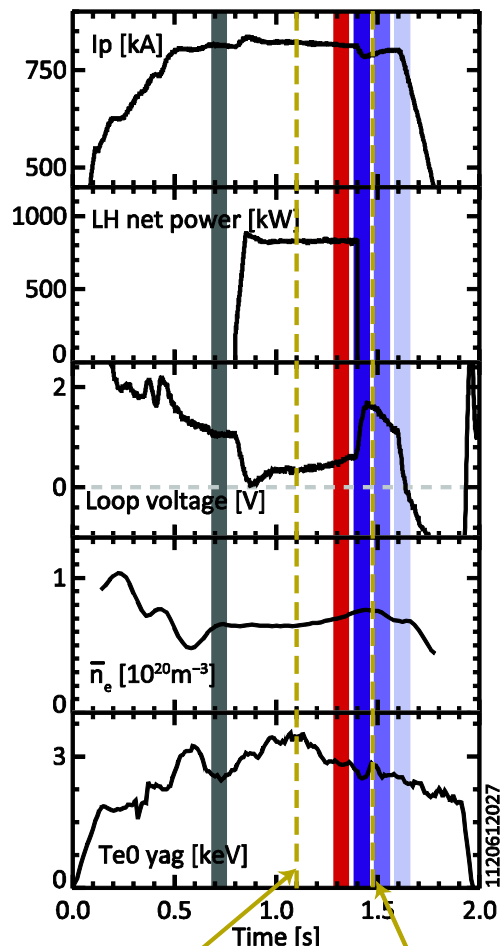
A better way of plotting current density

MSE-KEFIT constrained reconstructions show application of LHCD broadens the current profile

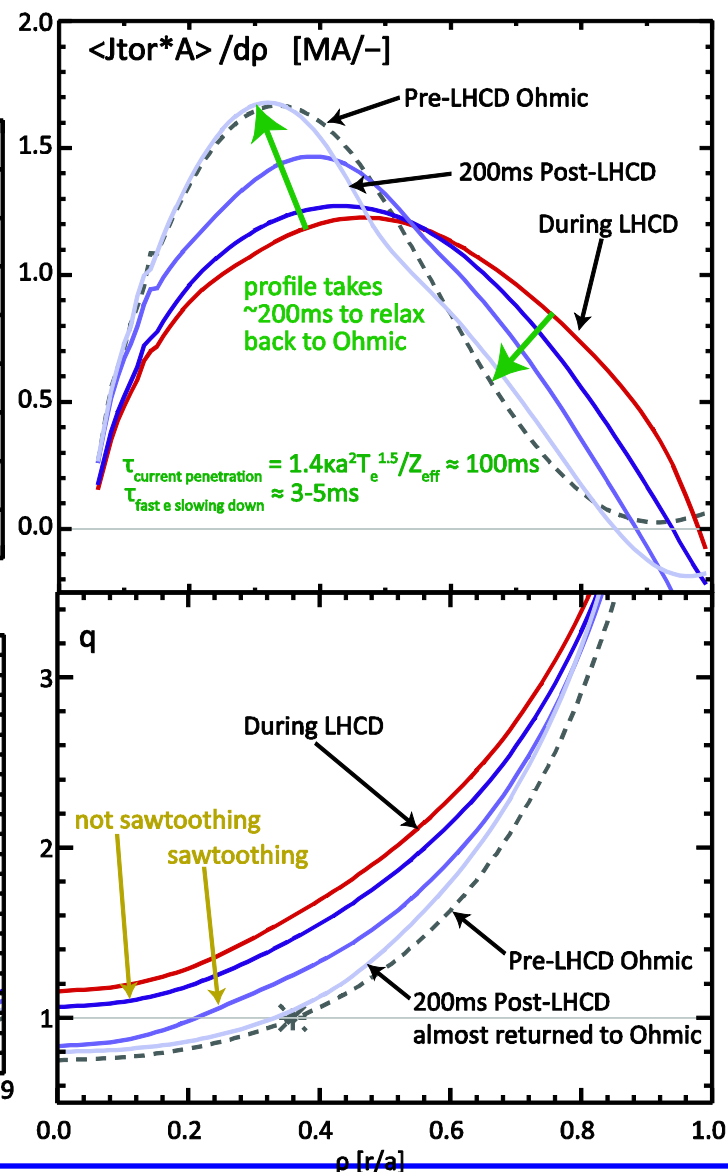
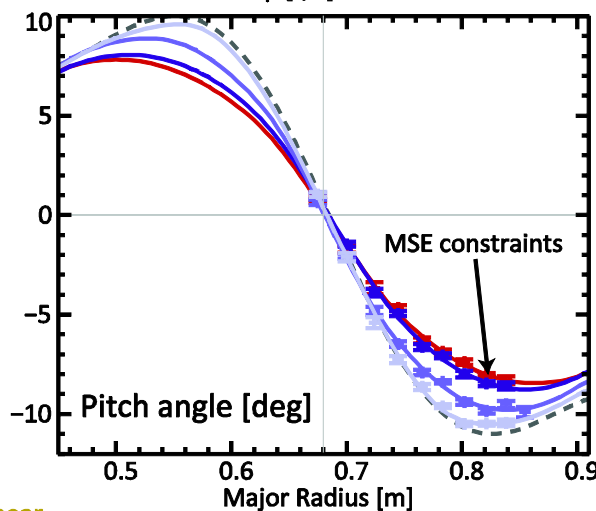
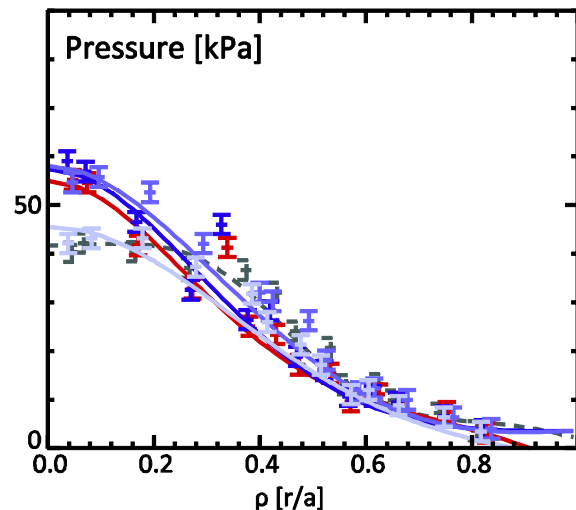


Reconstructions as LHCD is turned off

Reconstructed current profile after LHCD termination evolves on current penetration timescale



Sawteeth suppressed Sawteeth reappear



Decomposing the current density into components

For preliminary analysis of mixed LHCD+Ohmic, decompose the current contributions into three components:

$$\underbrace{J_{tot}}_{\text{From reconstruction}} \Big|_{RF} = \underbrace{\sigma_{Spitz} E_{DC}}_{\text{Residual Ohmic during RF Scaled from Ohmic only period:}} + \underbrace{\sigma_{rf}(J_{rf}, \sigma_{Spitz}) E_{DC}}_{\text{"Driven LHCD" in this paper}} + \underbrace{J_{rf}}_{\text{RF fast electrons interacting with remaining electric field. Calculated to be small using [9], consistent with [10]}}$$

From reconstruction

Residual Ohmic during RF Scaled from Ohmic only period:

$$\sigma_{Spitz} E_{DC} \Big|_{RF} \cong J_{tot} \Big|_{Ohmic} \left(\frac{V_{loop_{RF}}}{V_{loop_{Ohmic}}} \right) \left(\frac{T_{e_{RF}}}{T_{e_{Ohmic}}} \right)^{3/2}$$

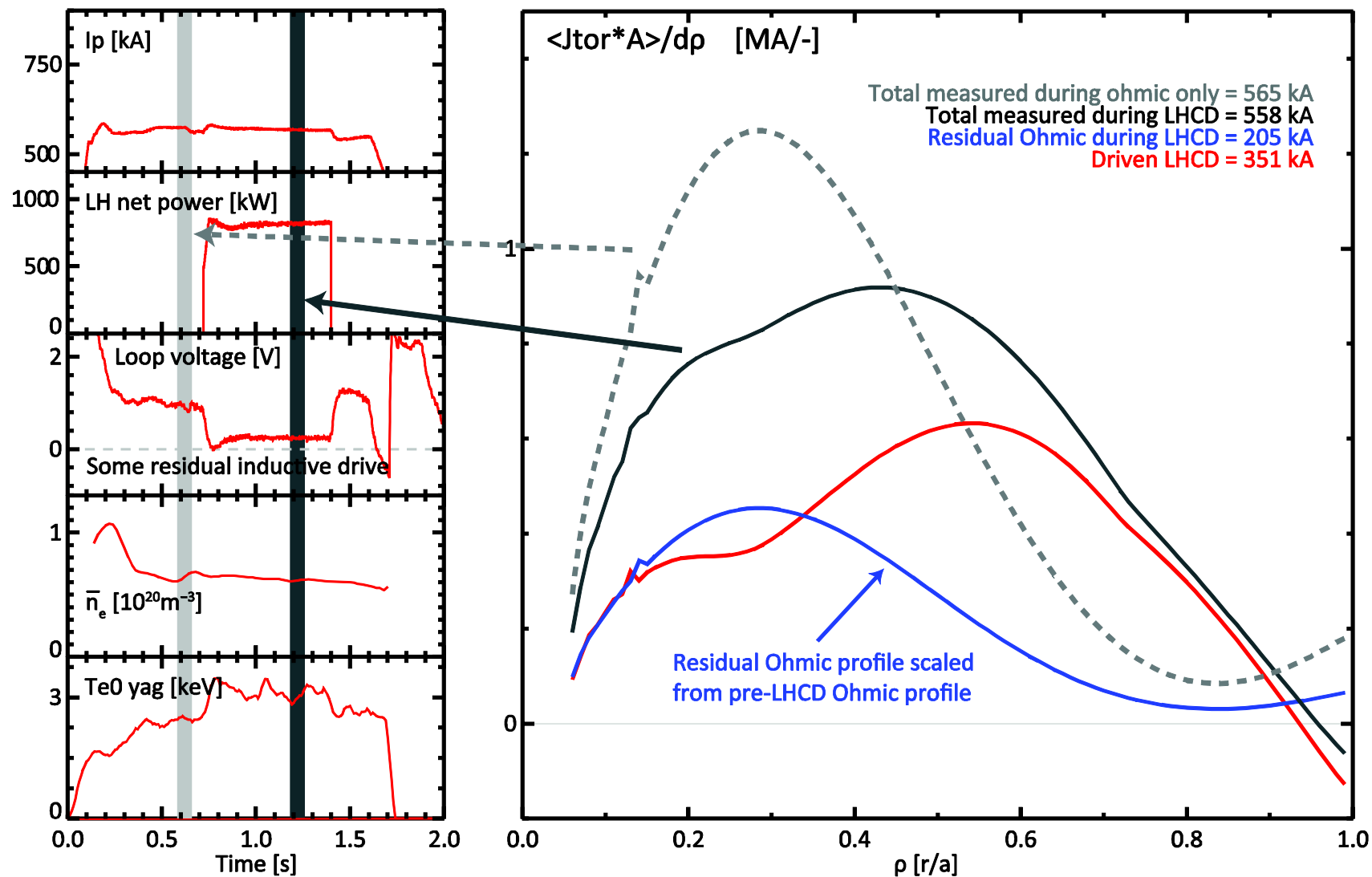
RF fast electrons interacting with remaining electric field. Calculated to be small using [9], consistent with [10]

Assumptions involved in this preliminary analysis:

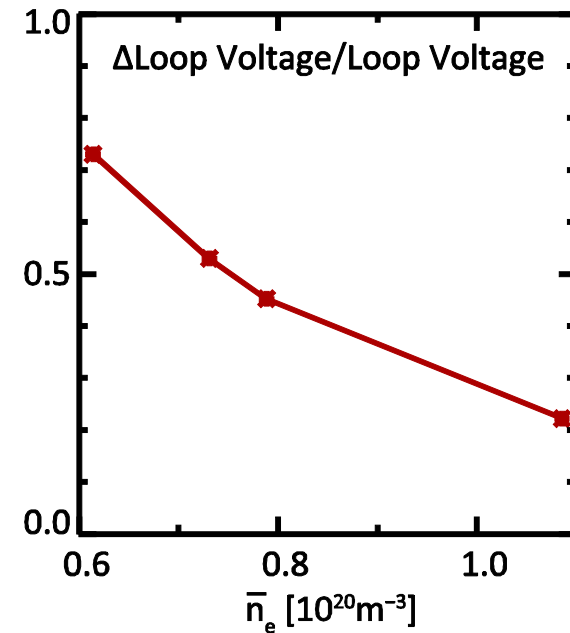
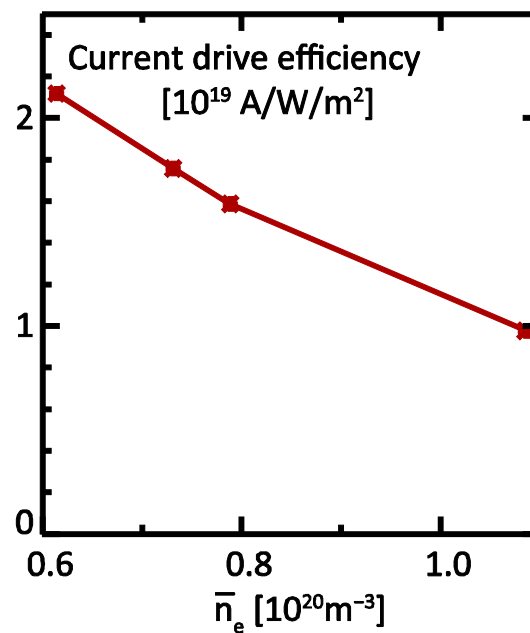
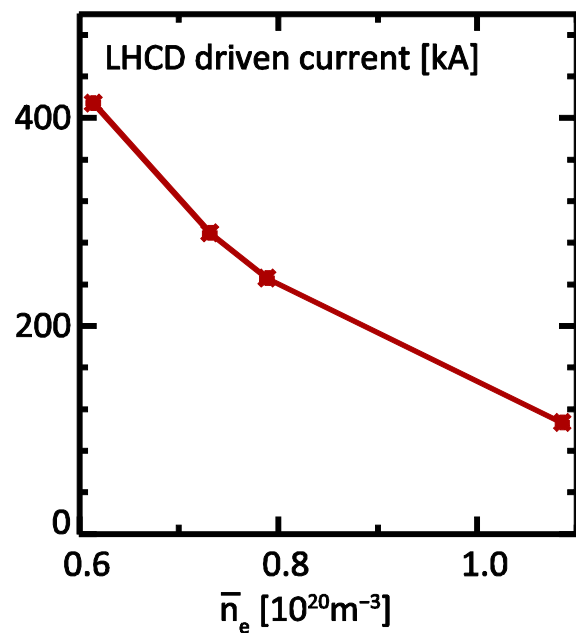
- DC electric field profile the same in Ohmic and LHCD (but with different magnitude)
- Temperature, density, Z_{eff} profiles are the same during Ohmic and LHCD periods
- Z_{eff} constant

Decomposing the current density into components

Decomposing the current profile into residual ohmic and LH driven components

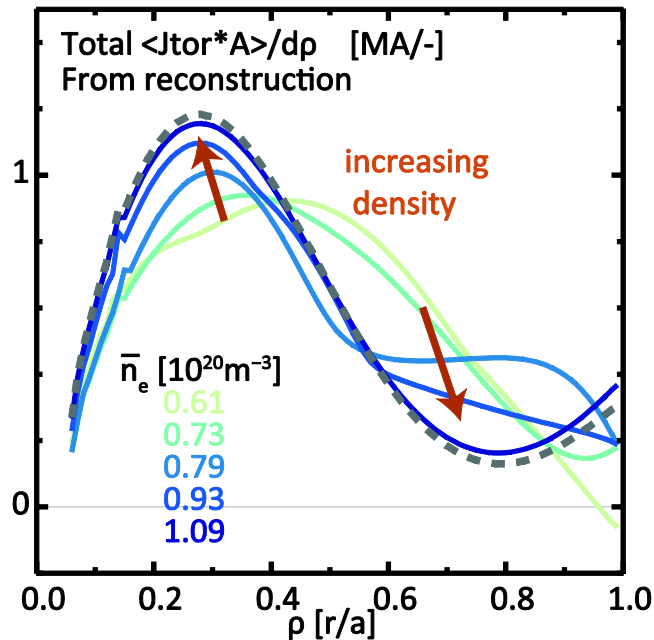


Global parameters vs density



Reconstructions vs density

MSE-KEFIT reconstructions show current profile density dependence

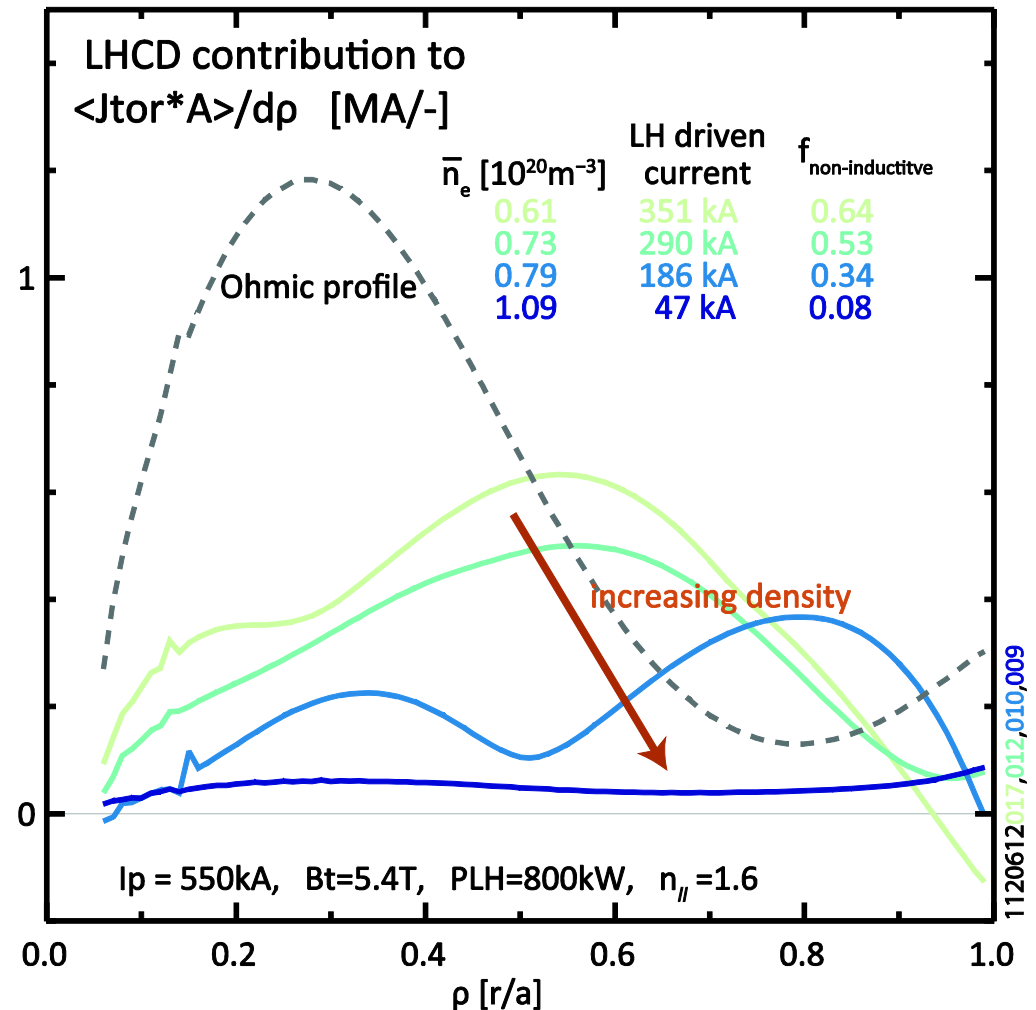


Deconstruct
current profile
into
components



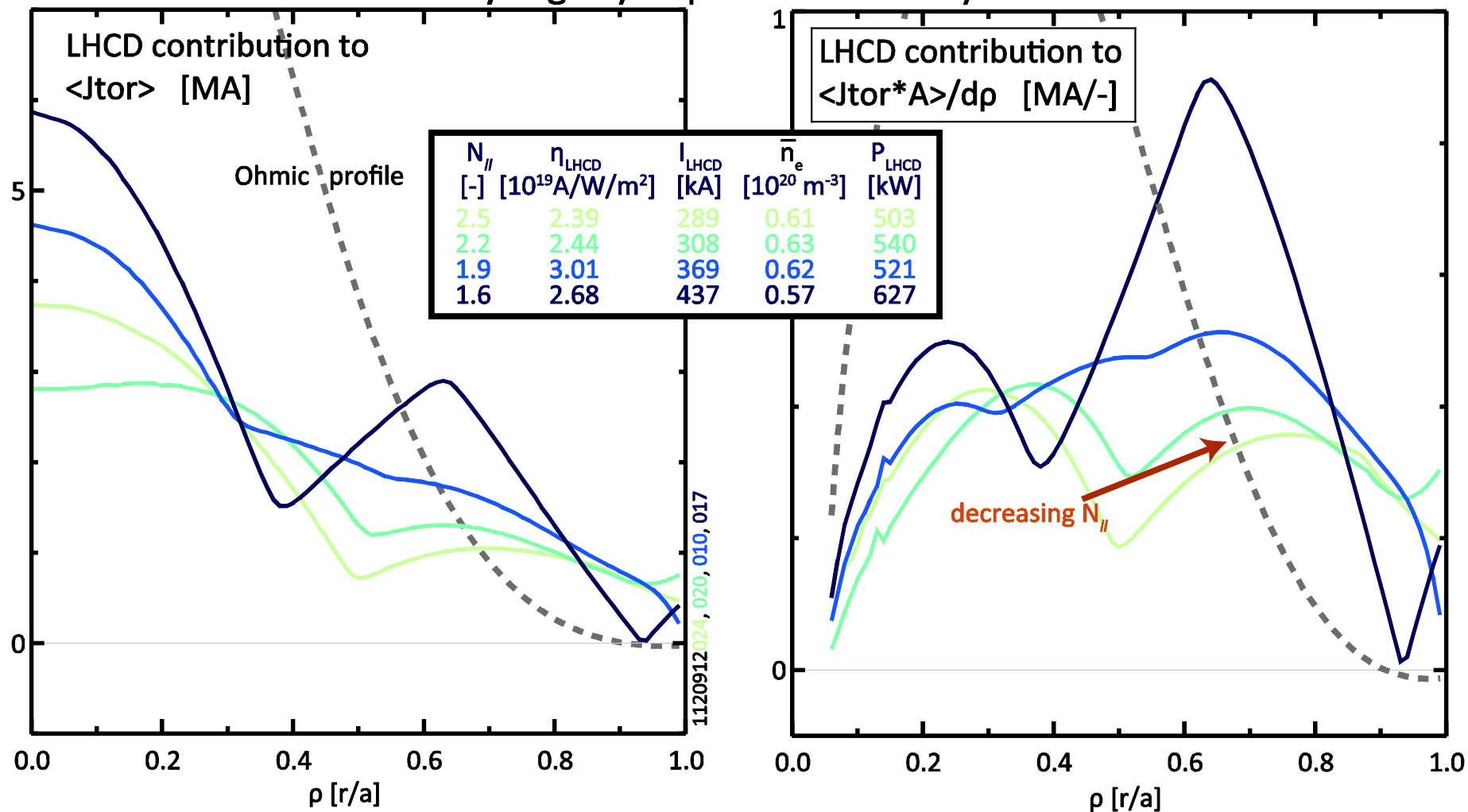
Driven current may shift outward as
density is increased

Further analysis required including determining measurement uncertainty



Reconstructions vs $N_{||}$

Decreasing $N_{||}$ moves current drive outward slightly
but only slightly improves efficiency



LHCD comparison to models

So far our comparison at low densities looks similar to previous comparison (single shot)

Meneghini and Shiraiwa:

$n_{\text{ebar}} = 0.48$
 $I_p = 800\text{kA}$,
900 kW

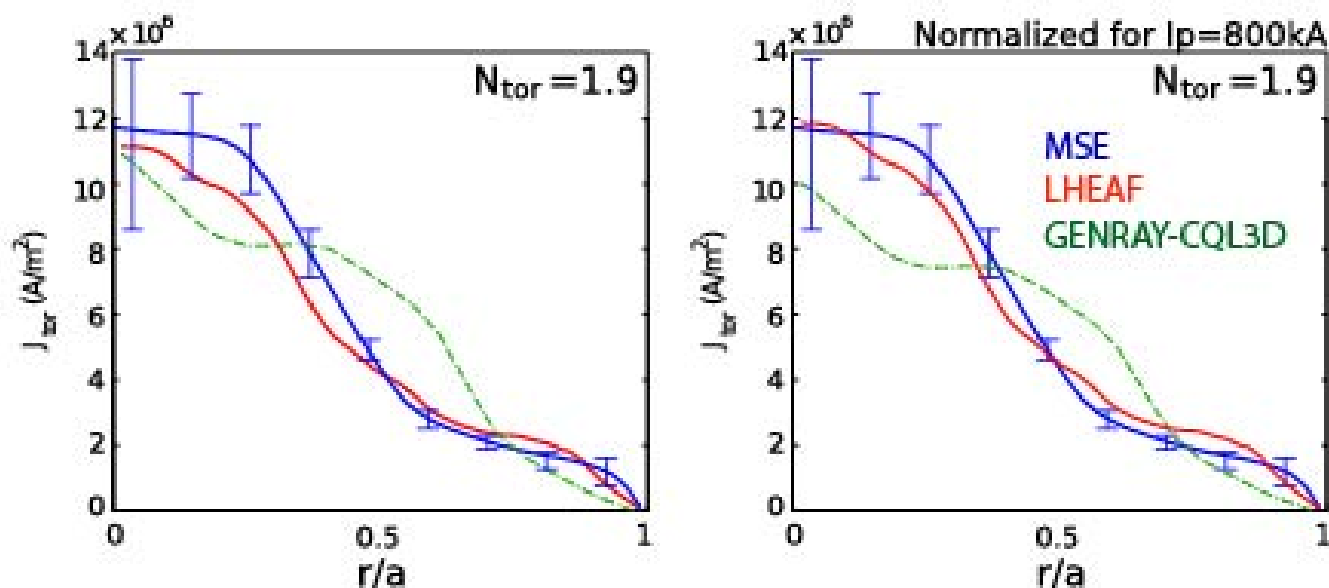


Figure 6-19: (Left) The toroidal current profile evaluated by full wave code LHEAF analysis (red) and kinetic-MSE constrained EFIT (blue) on the low field side mid-plane. The green line is the current profile calculated by the GENRAY/CQL3D ray-tracing/Fokker-Planck code. The error bars of experimental profile include statistical errors of the pitch angle measurements ($\pm 0.1^\circ$ (in the core region) and $\pm 0.2^\circ$ (in the edge region)) and pressure measurements ($\pm 10\%$), and systematical errors associated with the pitch angle calibration technique [115]. (Right) Same as left, but the current profiles are normalized to have the same total current.

Hard X-Rays: Schmith found broad profiles, peaks at $\rho \sim 0.7$

Schmidt's inverted HXR dependence:

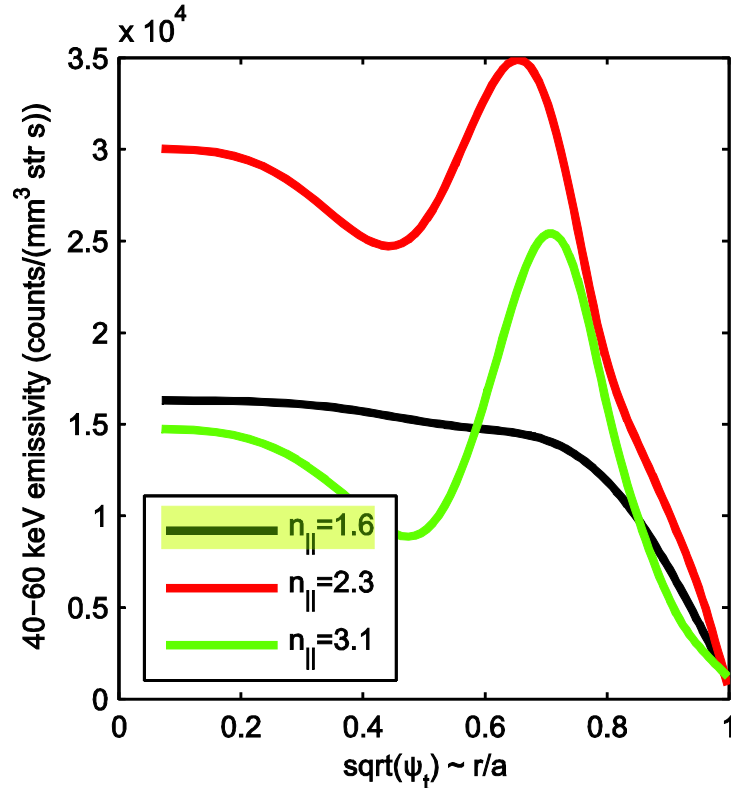


Figure 6-14: Inverted HXR spectra from discharges with 3 different launched $n_{||}$: 1.6, 2.3, and 3.1. Plasma parameters for this experiment were $B=5.4$ T, $T_{e0}=2.3$ keV, $\bar{n}_e = 9 \times 10^{19} \text{ m}^{-3}$, and $I_p=800$ kA. Peak coupled power in these experiments was approximately 455 kW ($n_{||}=1.6$), 415 kW ($n_{||}=2.3$), and 370 kW ($n_{||}=3.1$).

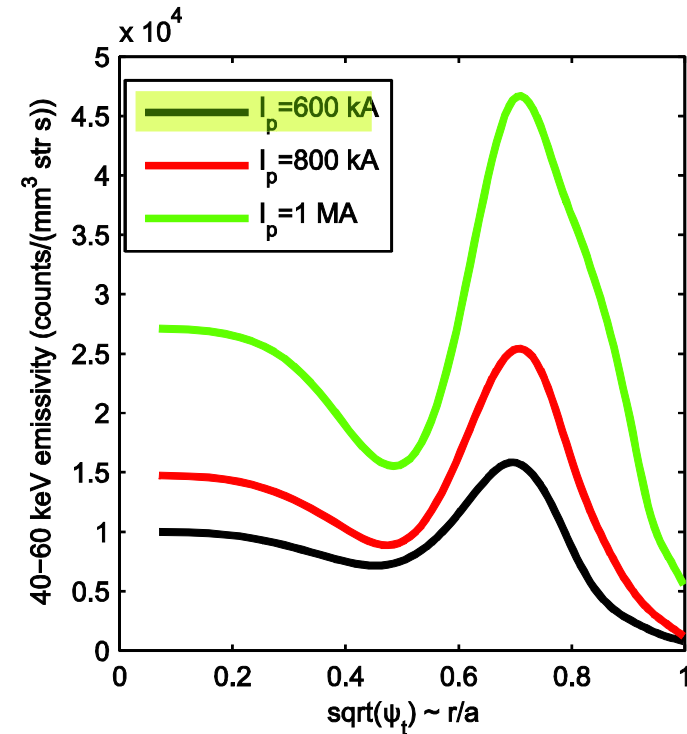


Figure 6-15: Inverted HXR spectra from discharges with 3 different plasma currents: 600 kA, 800 kA, and 1 MA. Plasma parameters for this experiment were $B=5.4$ T, $\bar{n}_e = 9 \times 10^{19} \text{ m}^{-3}$, T_{e0} for the 600 kA, 800 kA, and 1 MA discharges was 1.9, 2.3, and 2.1 keV respectively. As the current increased from 600 kA to 1 MA, the loop voltage increased from 0.8 to 1.1 V. The launched $n_{||}=3.1$ for these discharges. Peak coupled power in these experiments was approximately 360 kW (600 kA), 370 kW (800 kA), and 350 kW (1 MA).

Hard X-Rays: Schmidt found that GENRAY-CQL3D profiles agree with meas. at high $n_{||}$ but not low...

$n_{ebar} = 0.9$
 $I_p = 800kA$,
 Low power

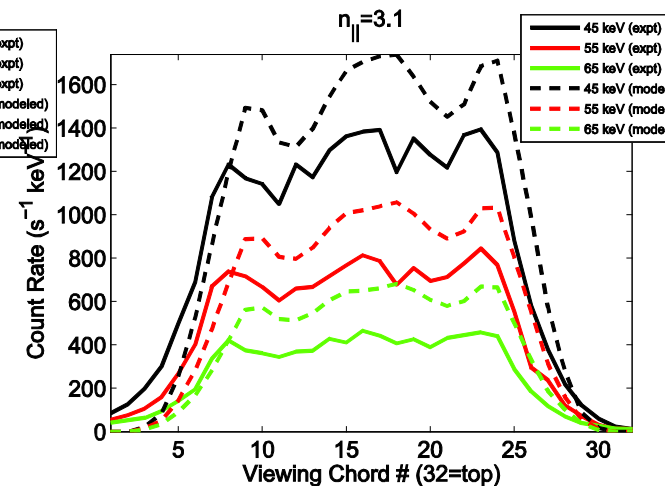
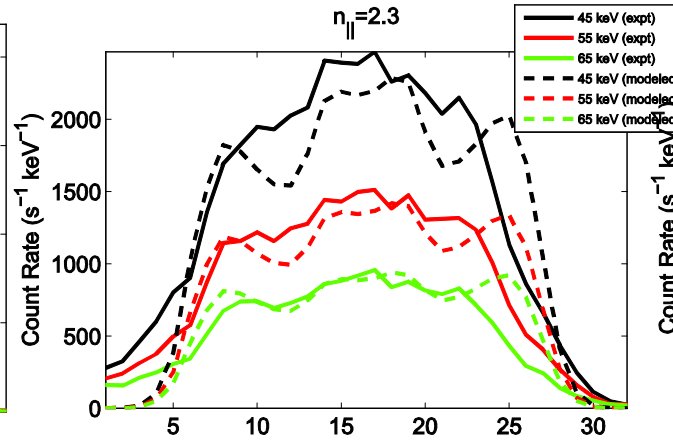
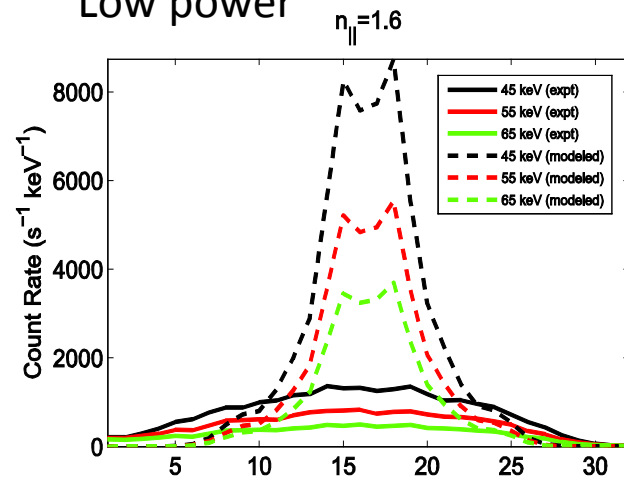


Figure 6-16: Modeled and measured HXR profiles for $n_{||}=1.6$ (60° phasing) LH modulation. A fast electron diffusivity of $0.01v_{||}/(v_{th}\gamma^3)$ m²/s was used.

Figure 6-17: Modeled and measured HXR profiles for $n_{||}=2.3$ (90° phasing) LH modulation. A fast electron diffusivity of $0.01v_{||}/(v_{th}\gamma^3)$ m²/s was used.

Figure 6-18: Modeled and measured HXR profiles for $n_{||}=3.1$ (120° phasing) LH modulation. The simulated HXR profiles mimic the fairly flat central region of the profiles as well as the side peaks. The simulated profiles are very similar in width to the experimental profiles, though they appear to be shifted slightly towards the center of the plasma (closer to chord 32). A fast electron diffusivity of $0.01v_{||}/(v_{th}\gamma^3)$ m²/s was used.

Low $n_{||}$ = simulation too narrow...

Looks kinda like MSE results: MSE says current further out than simulation..

Need to compare measured HXR profile and Jtor profile to simulated profiles...

GENRAY-CQL3D predicts strong scaling with $n_{||}$, MSE doesn't appear to see that..

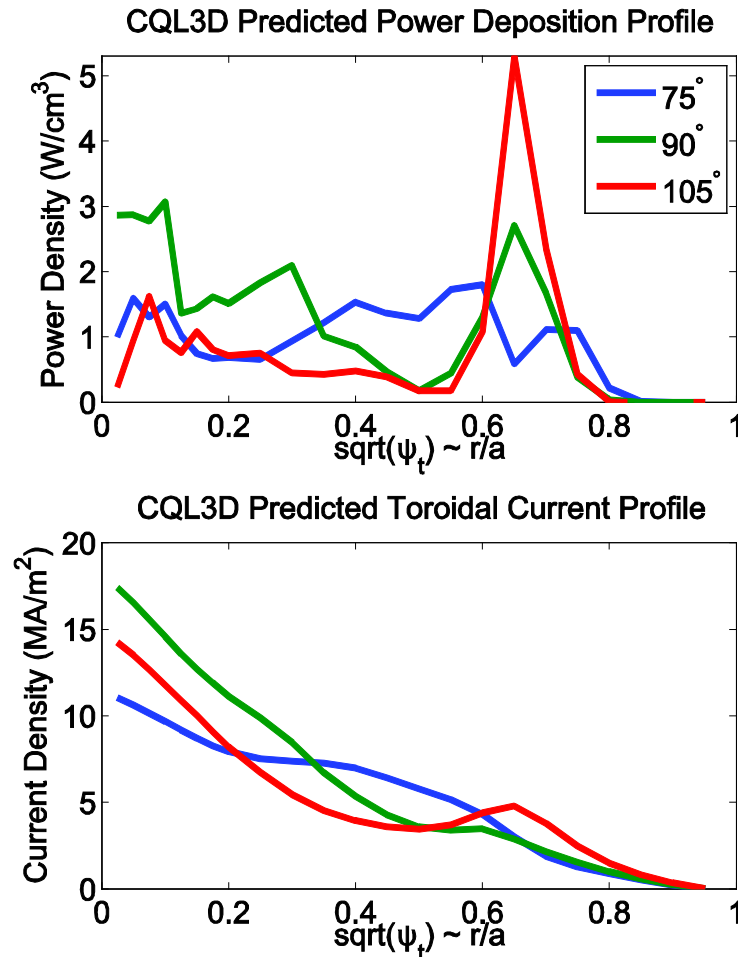
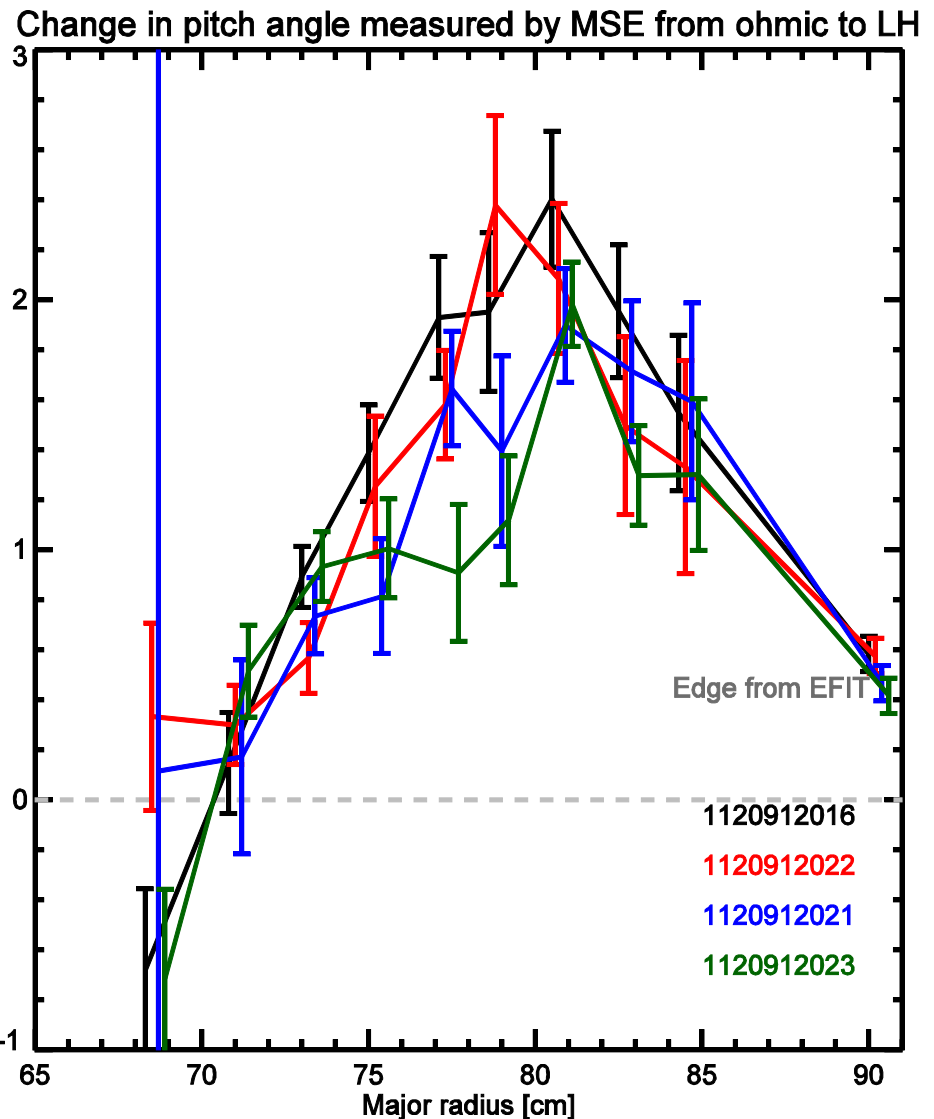
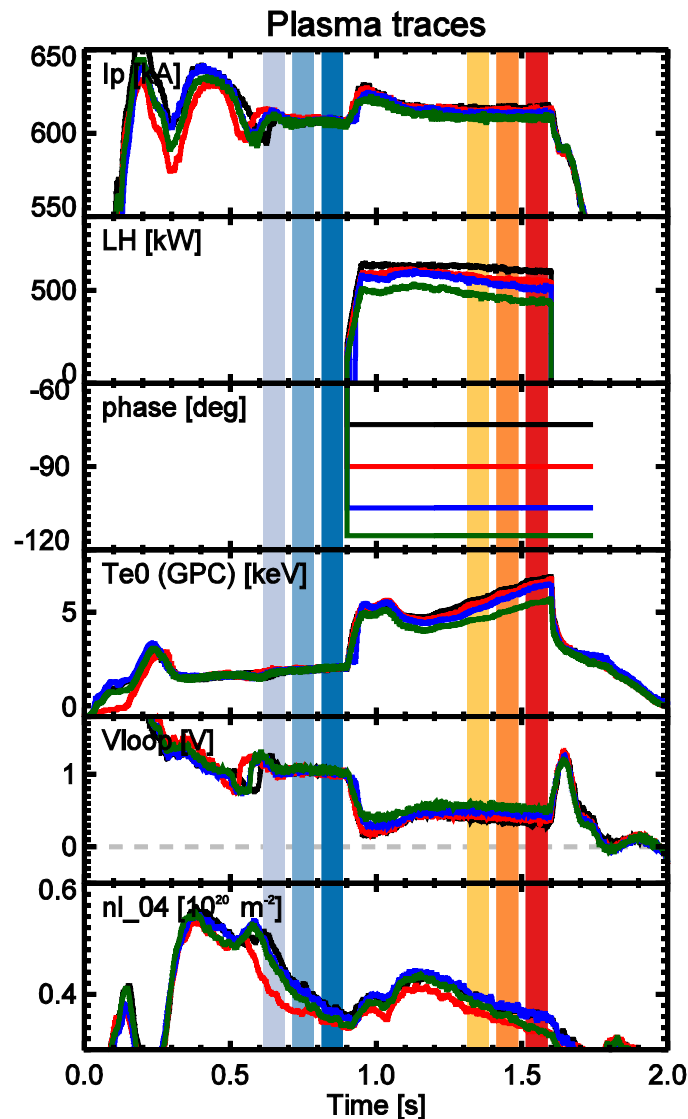


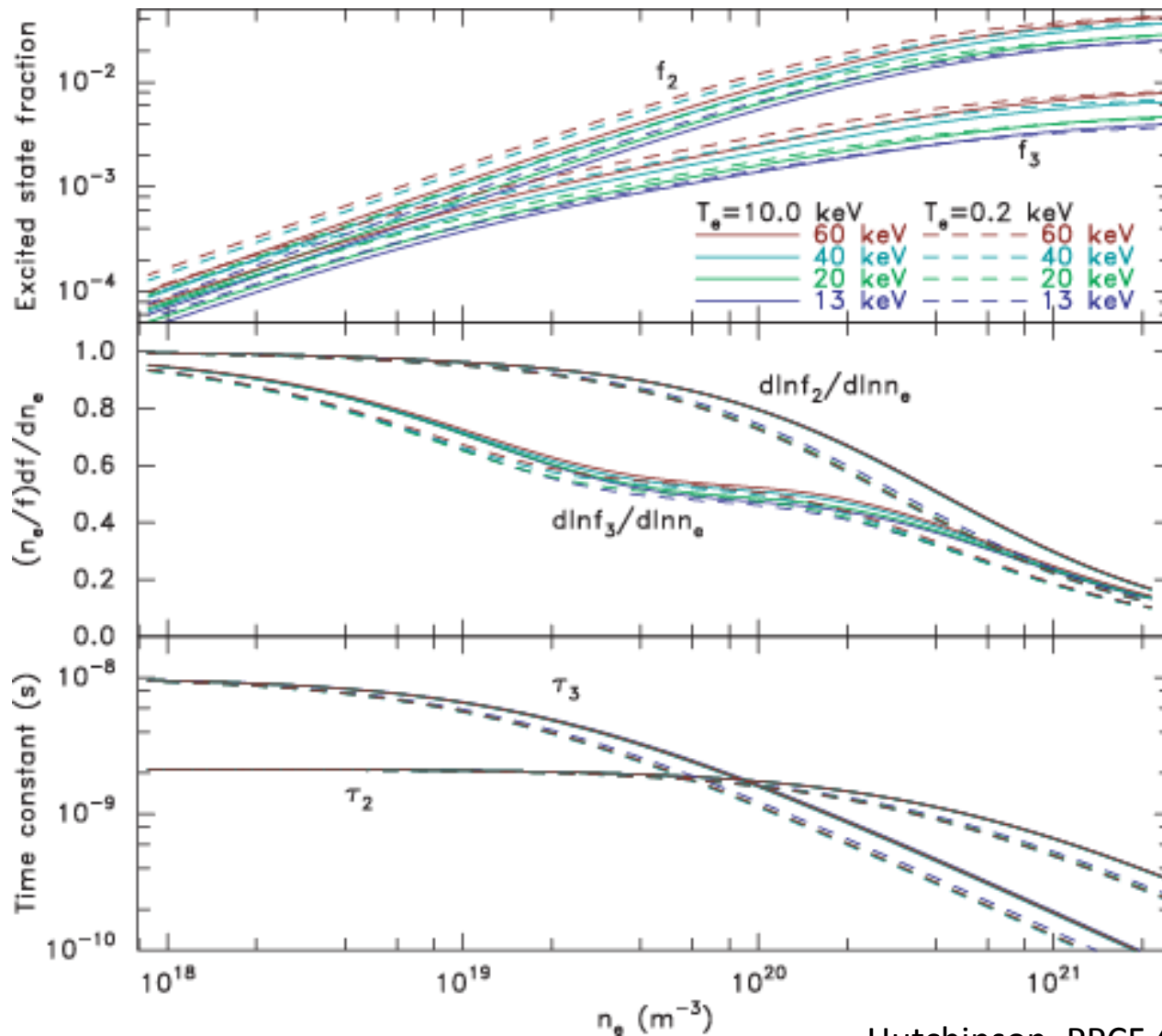
Figure 5-7: Modeled power deposition and current profiles for 3 LH phasings to compare with MSE measurements under similar plasma conditions. In these simulations, $\bar{n}_e = 5 \times 10^{19} \text{ m}^{-3}$, $P_{\text{LH}} = 900 \text{ kW}$, $B = 6 \text{ T}$ and $I_p = 800 \text{ kA}$. Simulations are shown for 75° ($n_{||} = 1.9$), 90° ($n_{||} = 2.3$), and 105° ($n_{||} = 2.7$) phasings.

GENRAY-CQL3D predicts strong scaling with $n||$, MSE doesn't appear to see that..



Beam stuff

Fraction in excited states linearly dependent on density and largely independent of other factors



Hutchinson, PPCF **44** (2002)