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

R. T. Mumgaard

MIT-PSFC Alcator C-Mod

S.D. Scott, R.S. Granetz, S.Shiriawa, R.R. Parker, G.M. Wallace

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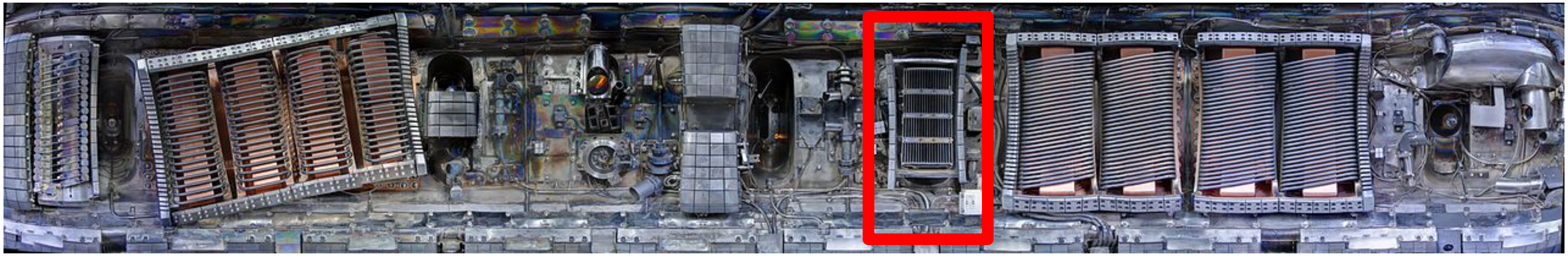
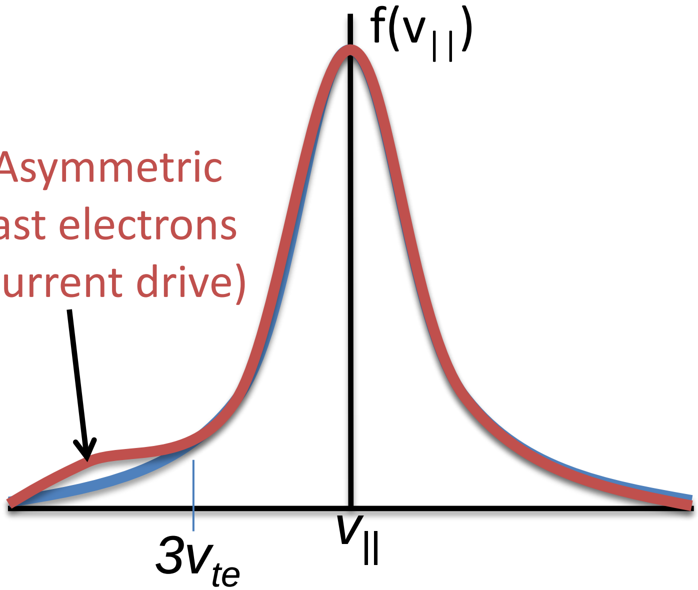
LHCD on Alcator C-Mod: Uniquely at ITER density, frequency and field.



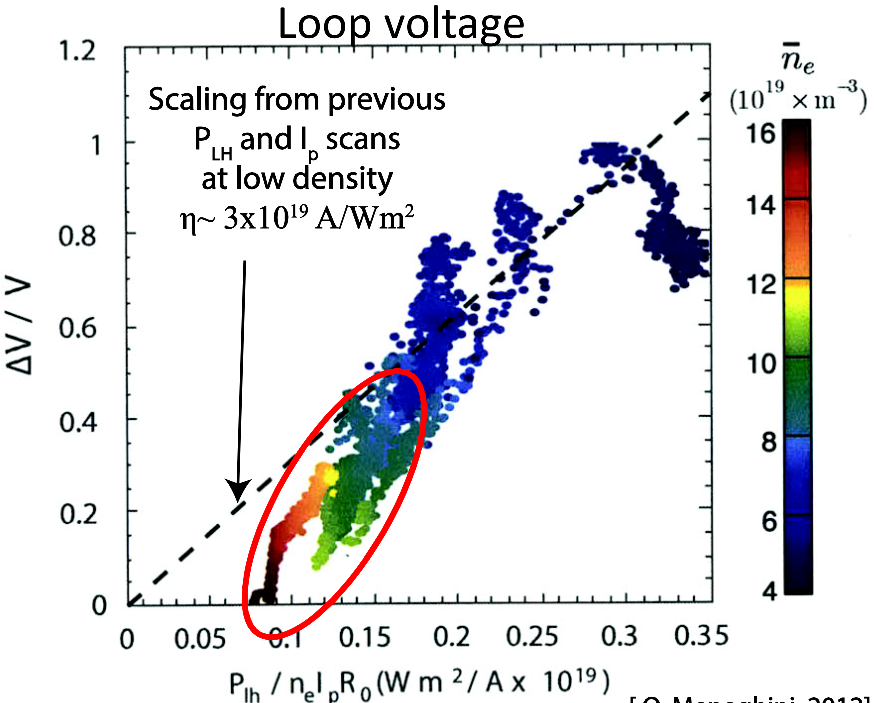
- B_T = 3-8T (ITER: 5T)
- n_e = 0.5-5 x10^{20}m^{-3} (ITER: 0.5-1x10^{20}m^{-3})
- 4.6 GHz (ITER: 5 GHz) P_{source} = 2.5MW
  - Variable phasing: $n_{||}$=1.5-3 (ITER~ 2)
- 16 column launcher couples ~ 1MW
- Up to 1s long pulse (~ 5 x τ_R)
- Completely **non-inductive** current drive demonstrated
- Creation of **Reversed-shear** profiles (q_0 ~ 2) with transport barriers



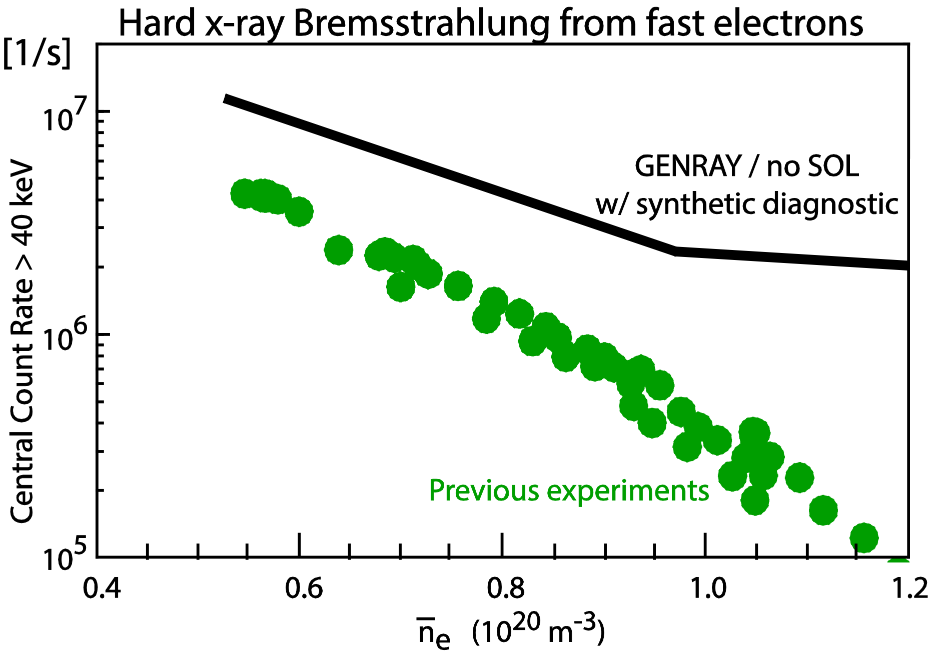
A tool to study current drive physics, benchmark LHCD codes and produce targets for transport and MHD studies

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

- LHCD efficiency:
  $\eta \equiv n_e I_{LH} R_0 / P_{LH}$ $= 2.0 - 3.0 \times 10^{19}$ A/Wm^2 confirmed at low density (< 0.5x 10^{20}m^{-3})
  [P.T. Bonoli, POP 2007]
- However, anomalous large drop in efficiency as density is raised $\bar{n}_e \sim 0.7 \times 10^{20}$ m^{-3}
  - Smaller change in loop voltage than expected, loss of Hard X-ray emission
  - Has since been observed in other experiments



[O. Meneghini 2012]

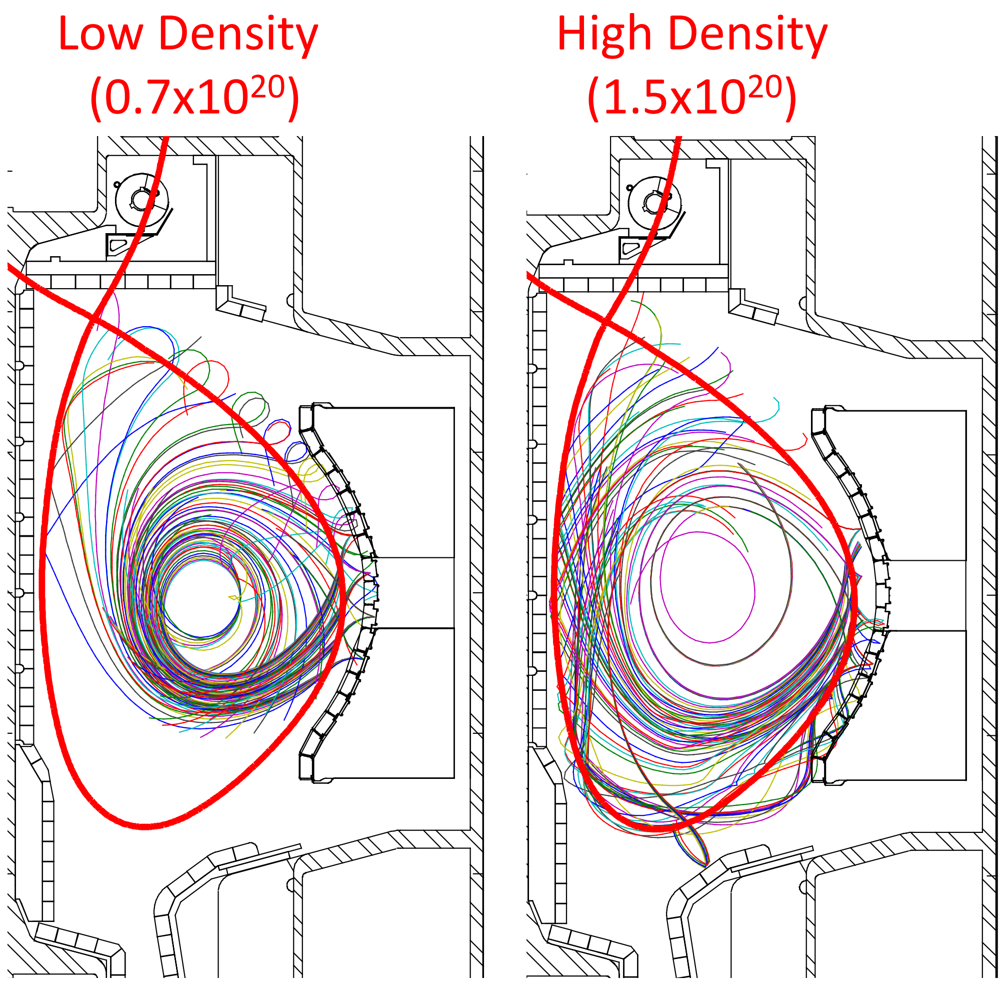


Various explanations put forward for this loss, still an unresolved question.

- 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



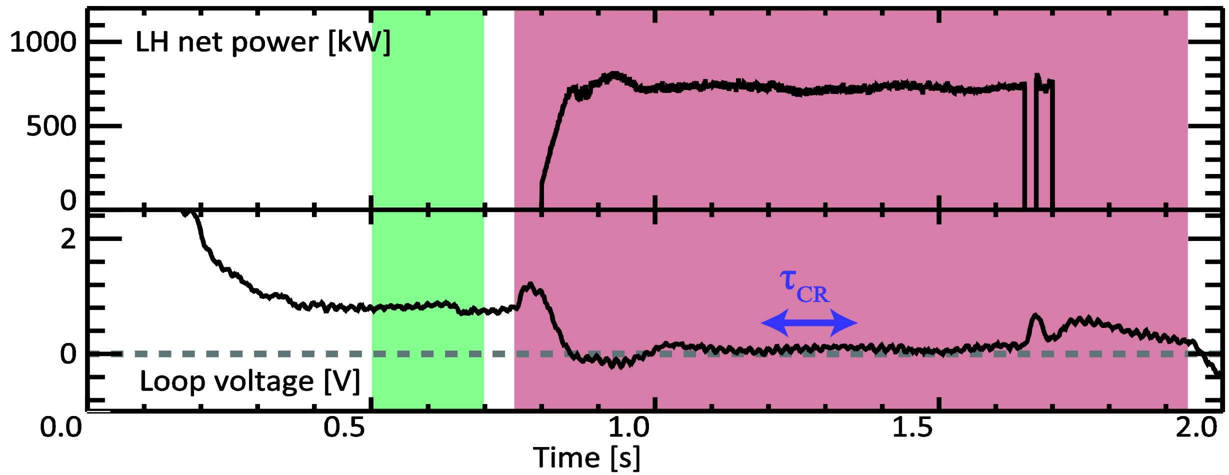
GENRAY/CQL3D simulations with SOL

[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 serveral 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

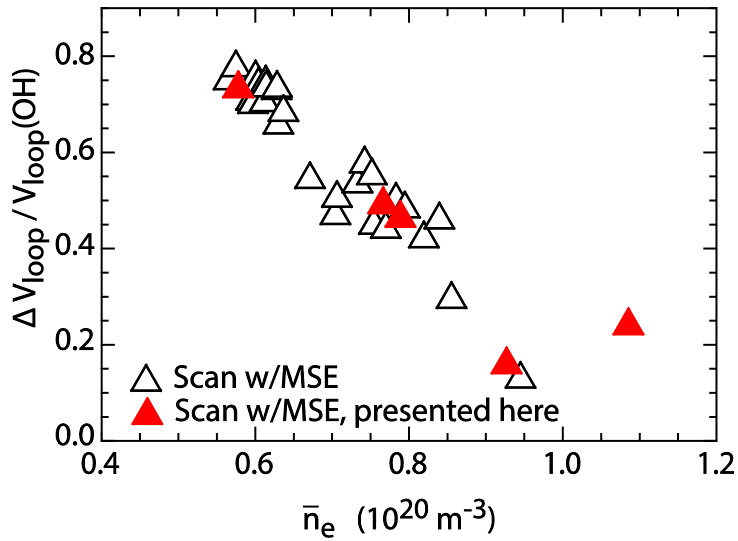


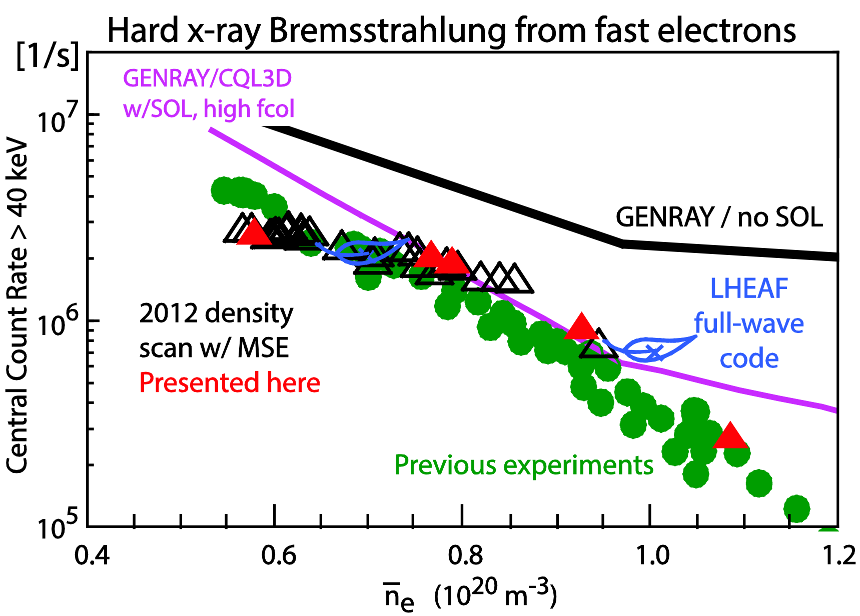
Use KEFIT during Ohmic portion to calibrate MSE

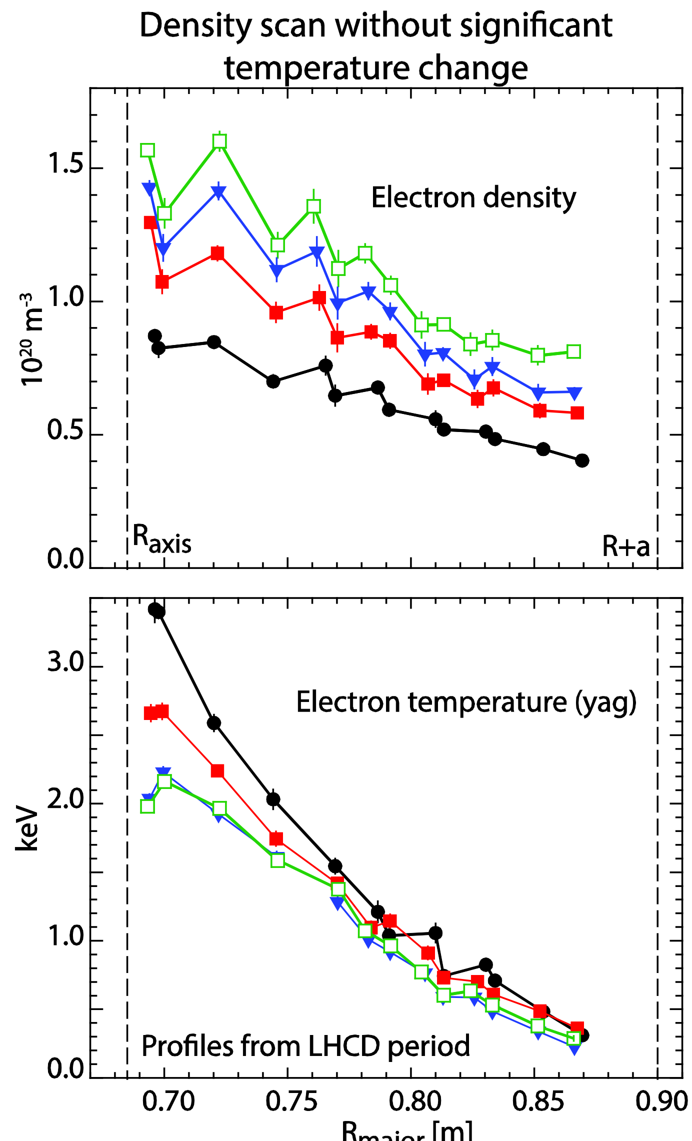
Apply calibration to measure changes in current profile

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

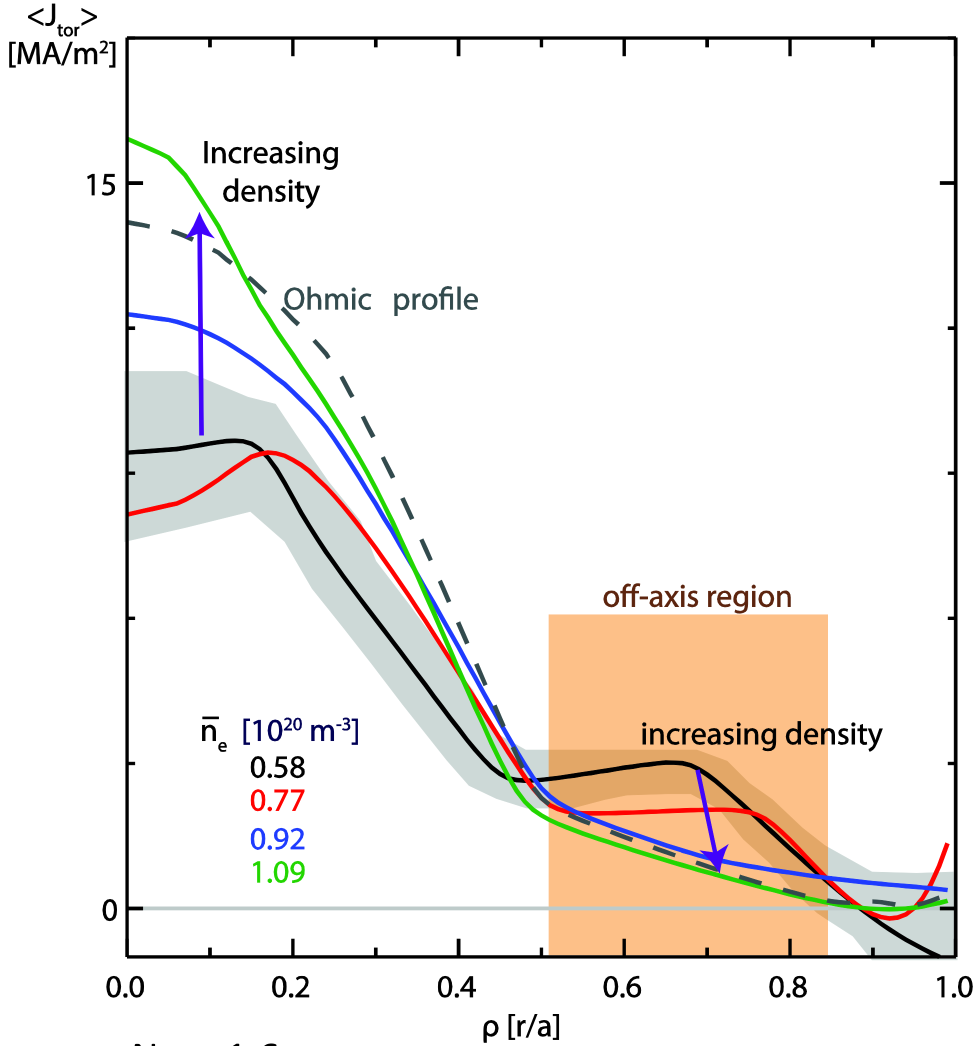
Dedicated experiment to document LH current profiles as a function of density for the first time.







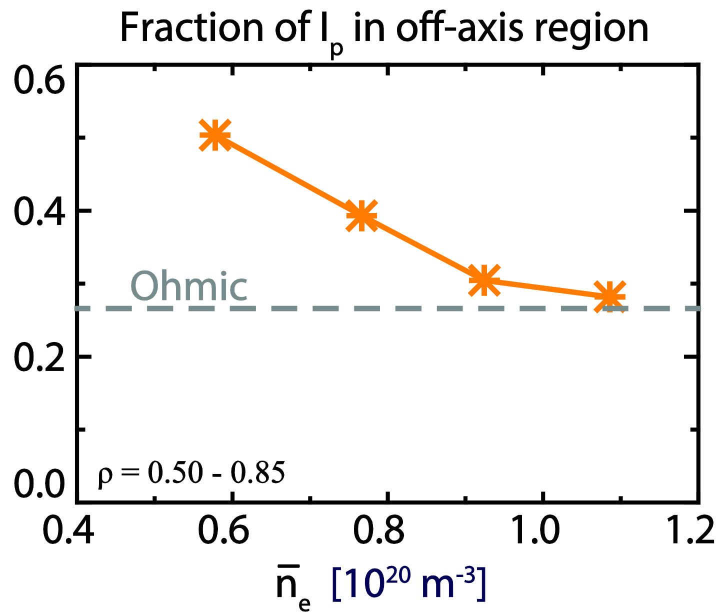
MSE measurements of current profile show off axis current drive disappears as density is raised.



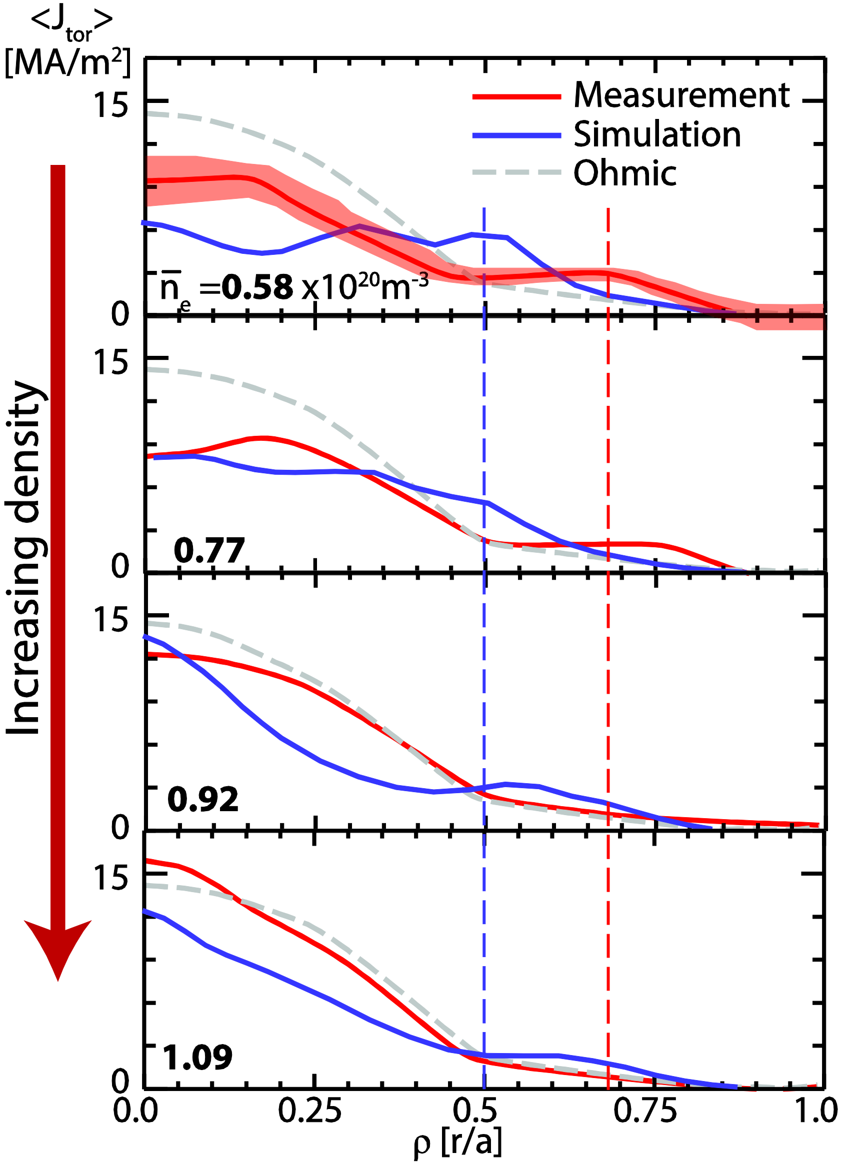
$N_{||} = 1.6$

Increasing density:

- Loss of off-axis current drive around ρ=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 ρ=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

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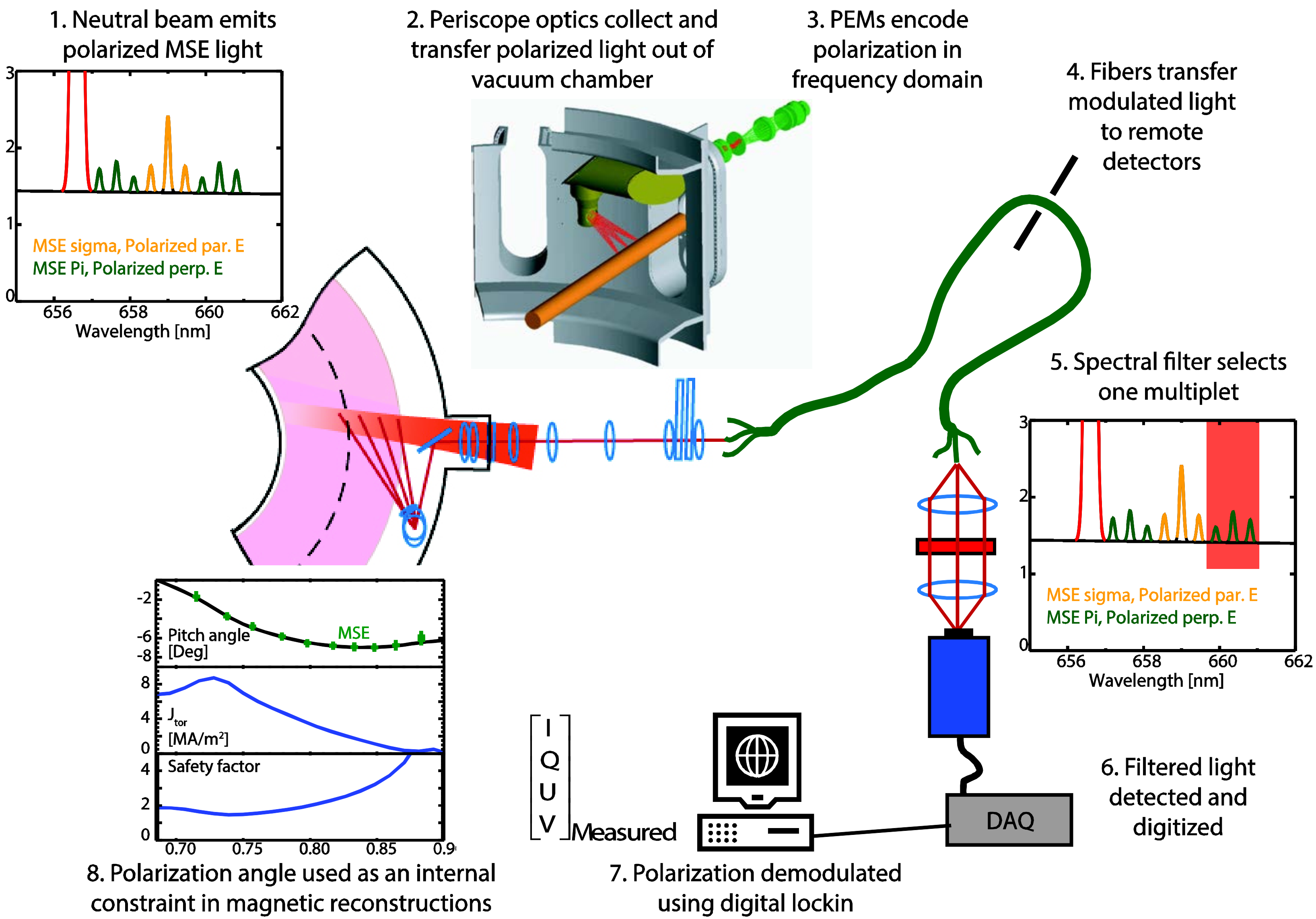
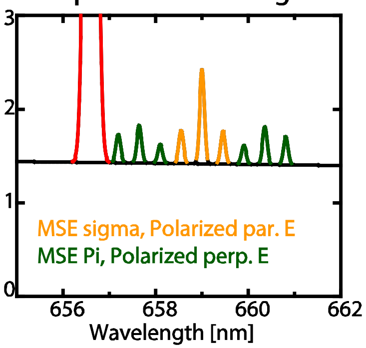
  - And in C-Mod for similar reasons
- MSE polarized background subtraction
  - Everything is polarized!
- C-Mod's experience with MSE in-situ calibration
- Conclusions

A reminder of how a MSE-LP system works.

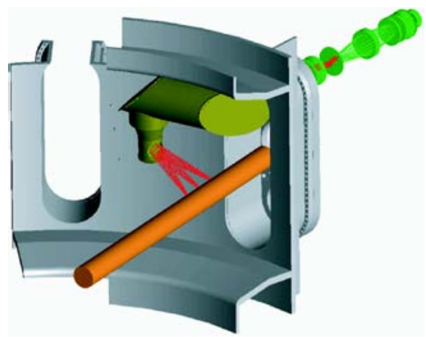


MSE-LP planned for control on next-step devices but there are challenges.

1. Neutral beam emits polarized MSE light



2. Periscope optics collect and transfer polarized light out of vacuum chamber



Next step devices will:

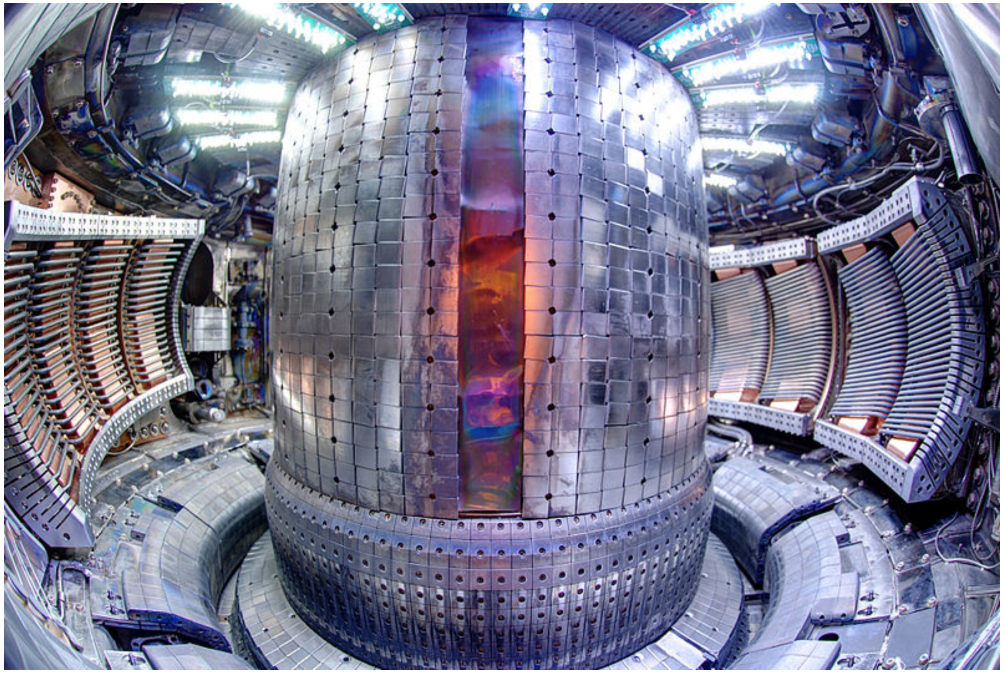
- Have harsher measurement conditions
- Have less diagnostic access
- Have a lower appetite for risk
- Require better diagnostic data
- Demand high diagnostic availability

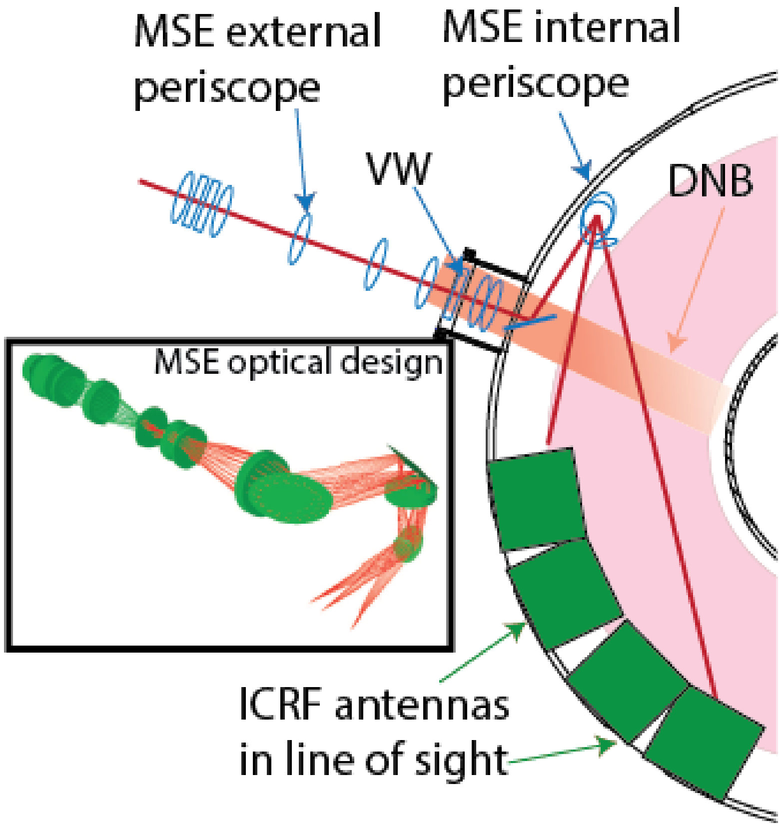
Two big problems are foreseen for next-step MSE-LP systems

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

Complicated optics, ICRF view dump

High field: 200g's during disruptions

Cryogenic magnets: Large thermal swings (>40C/min) and large thermal gradients

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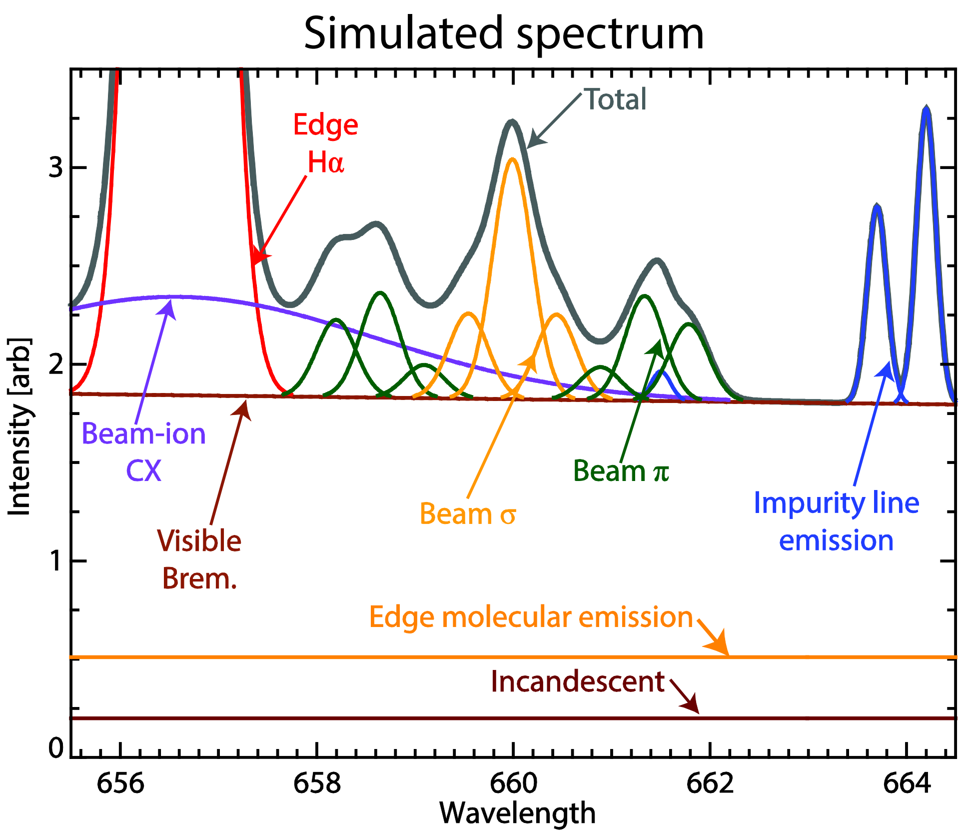
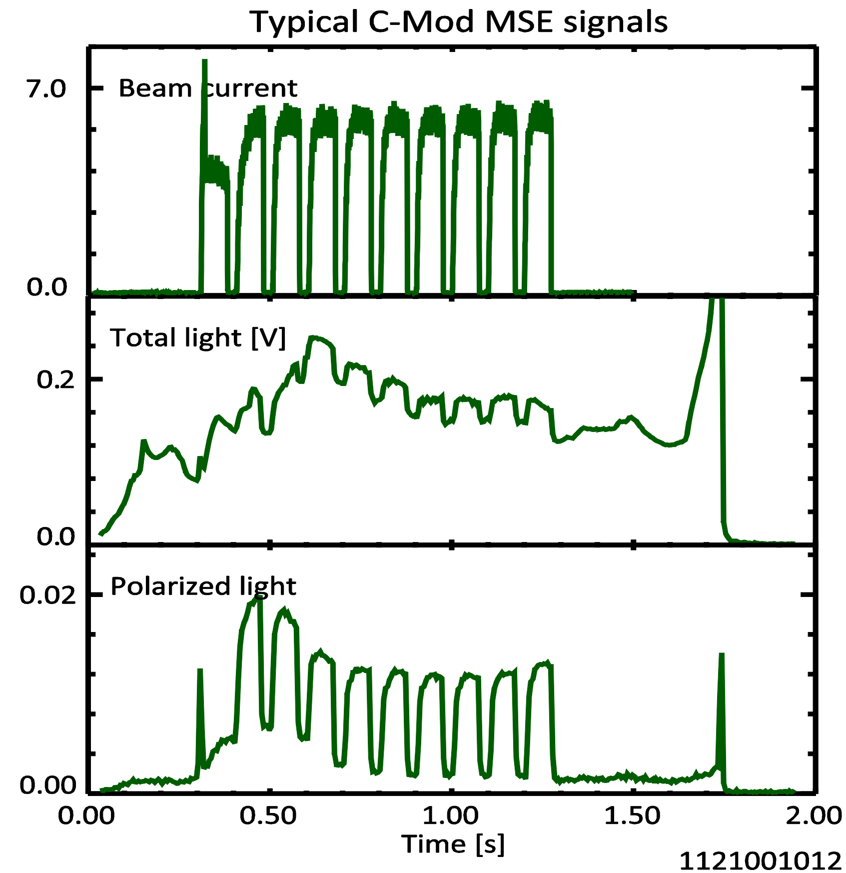
Weak beam and strong background leads to poor polarized signal/background ratios.

- 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 2x 10^{20} m^{-3}) plasmas are very bright
- System collects substantial polarized background light





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

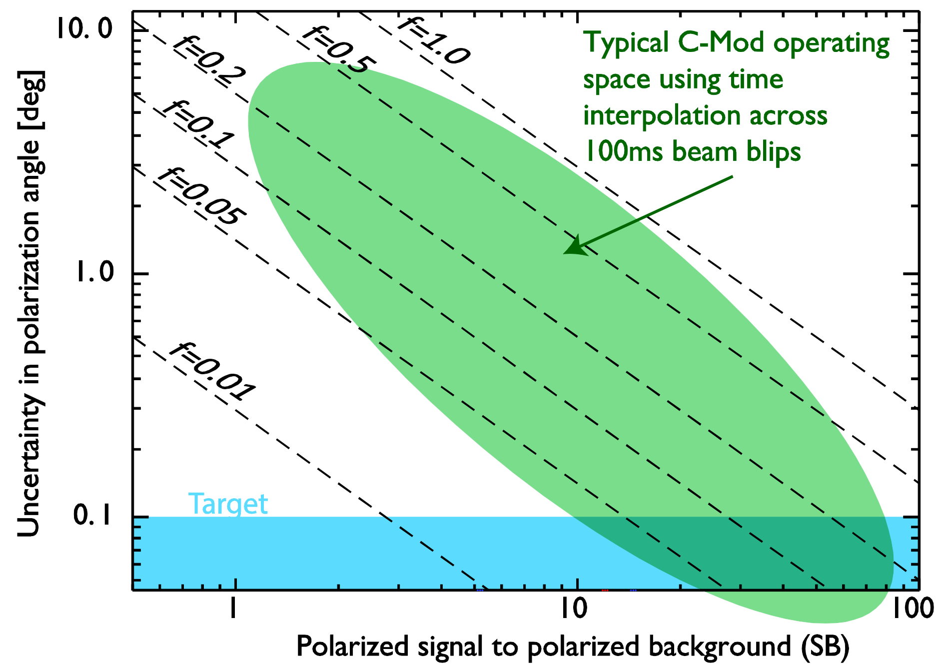
- Not limited by photon statistics
- Similar issues on JET, Tore Supra, JT-60U

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

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

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

Error in polarization angle due to background subtraction



How well you can Subtract the background:

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

DIII-D, TFTR, NSTX, MAST →

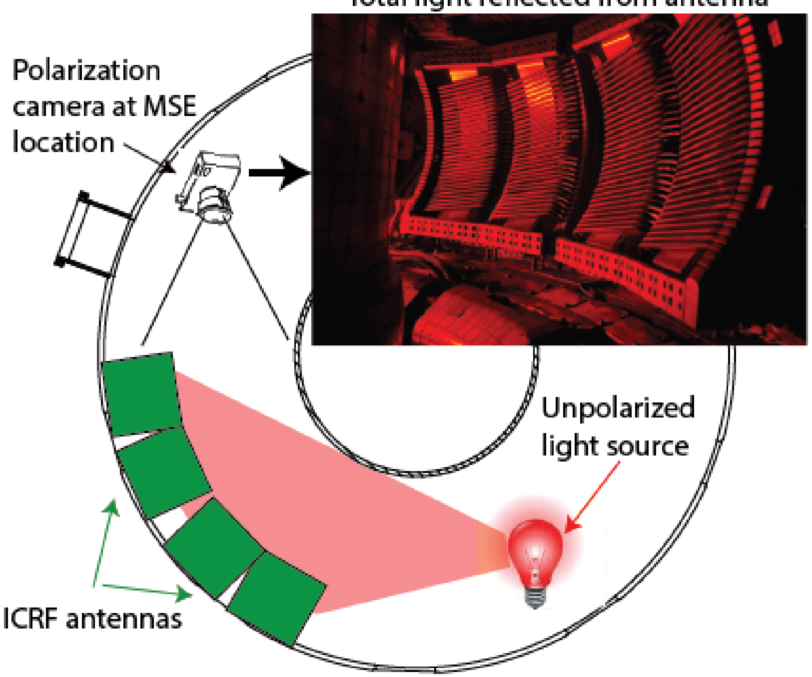
- Have only modest control over polarized signal to background (SB)

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

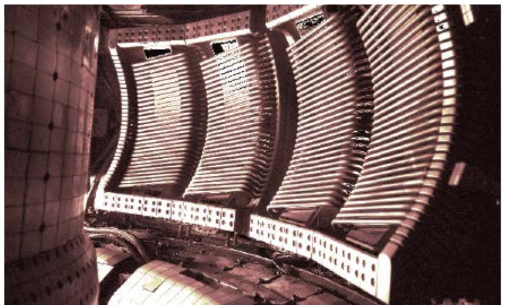
→ Undertake a comprehensive study of polarized light in the tokamak

Light is substantially polarized upon reflection from ‘view dump’

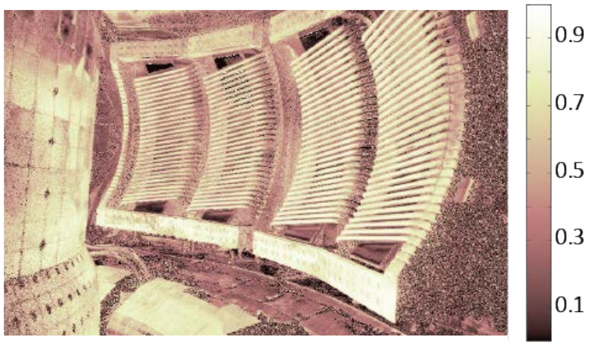
- Developed a polarization sensitive camera to image light reflected from ICRF antenna :
  - Reflected light is complexly and highly polarized
  - Polarization angle depends on location of source
- Any light in the tokamak can be reflected into the MSE sightline, becoming partially polarized



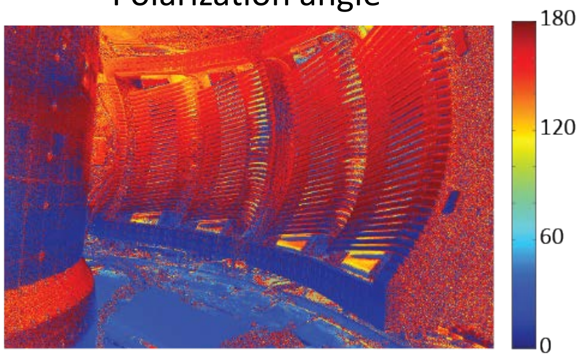
Linearly polarized reflected light



Polarization fraction



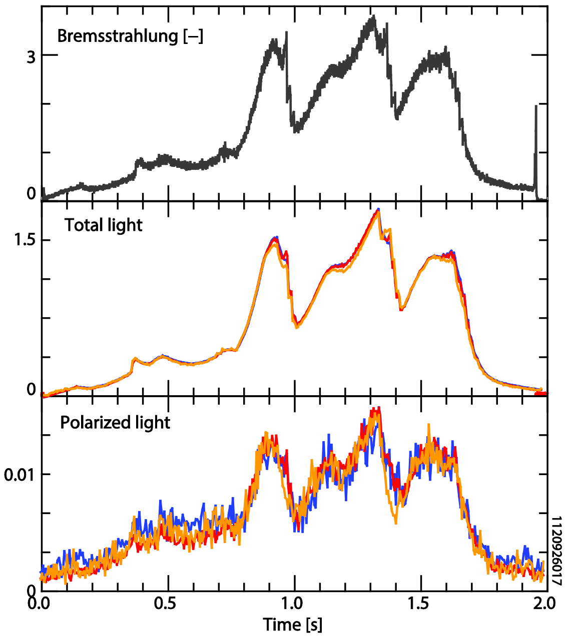
Polarization angle



Three primary sources of background light identified. And they likely get worse on next step devices.

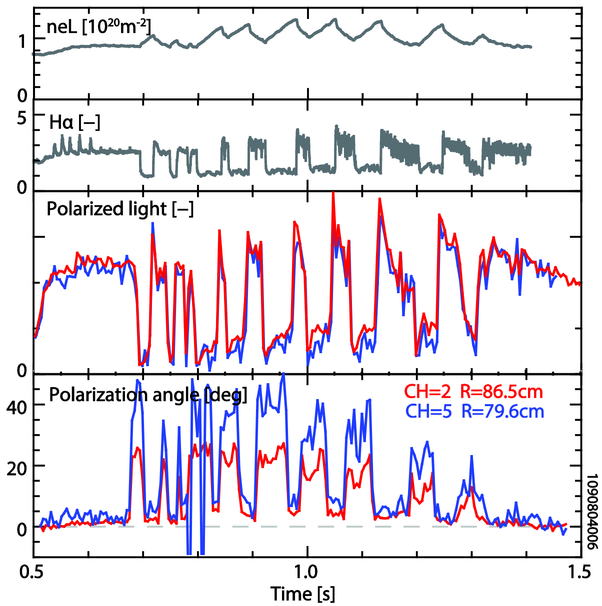
Visible Bremsstrahlung

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



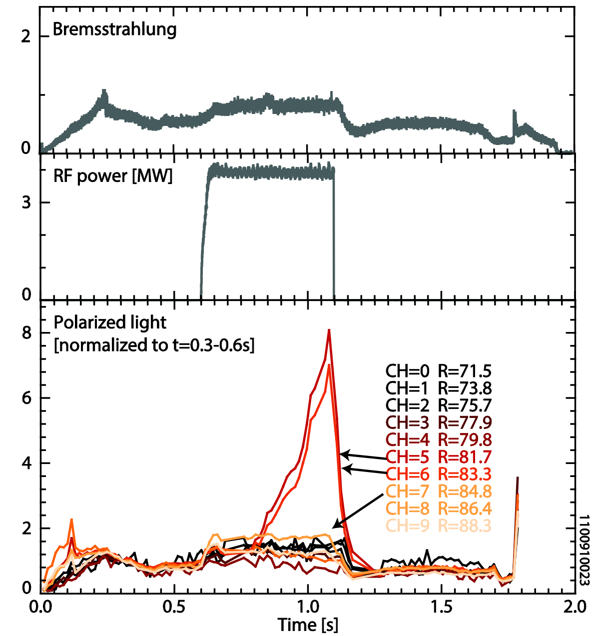
Divertor/edge emission

- 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 (~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-inito 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.

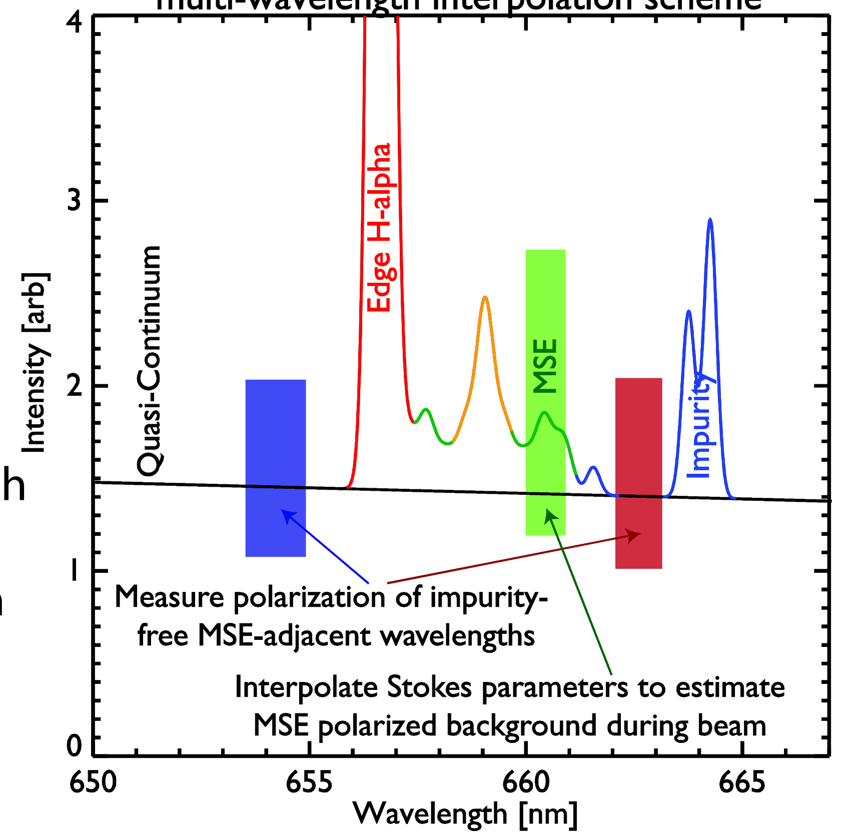
$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{\text{red of MSE}}$$

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

use wavelength interpolation

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

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



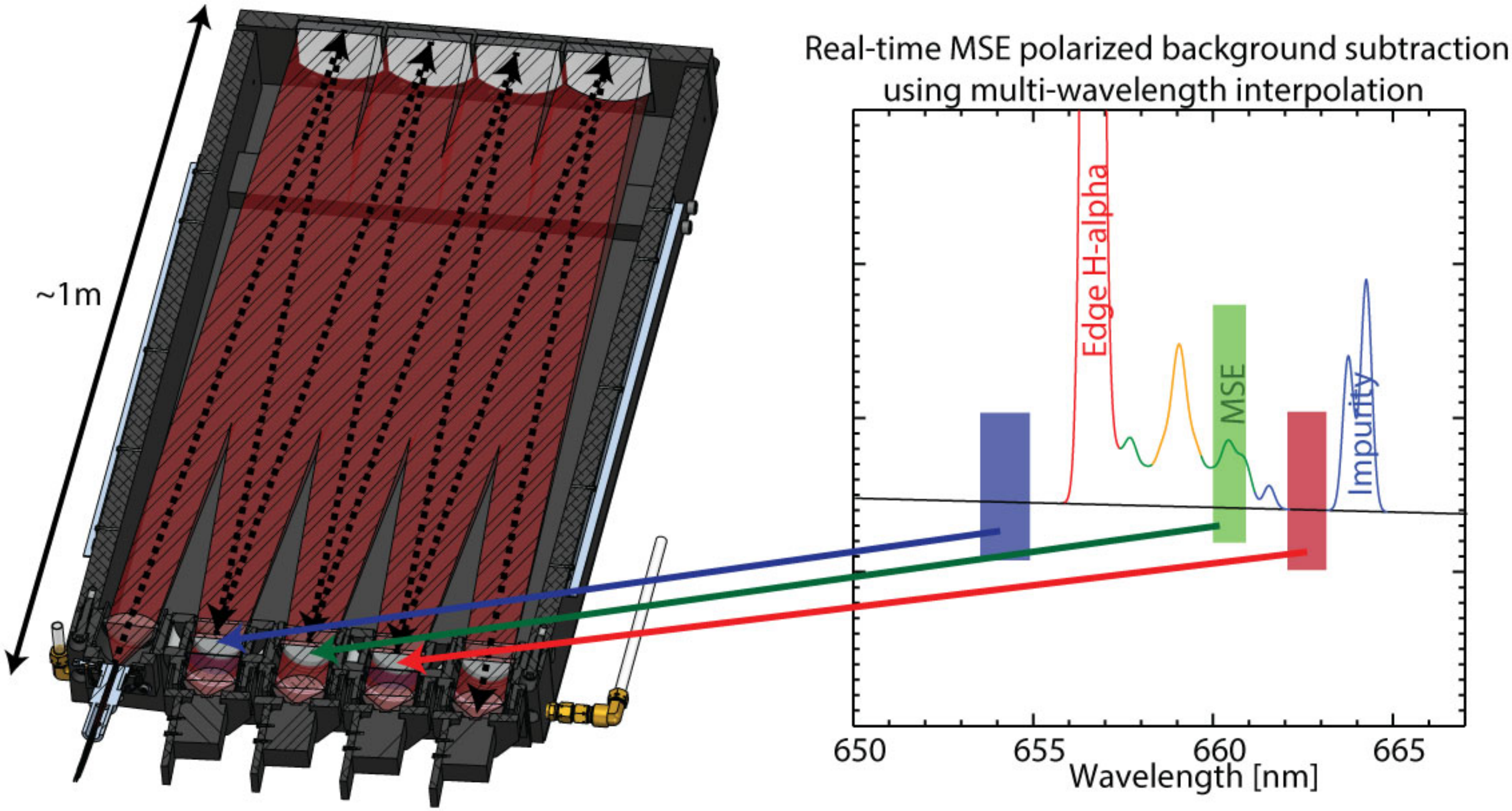
Valid if:

- 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.

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

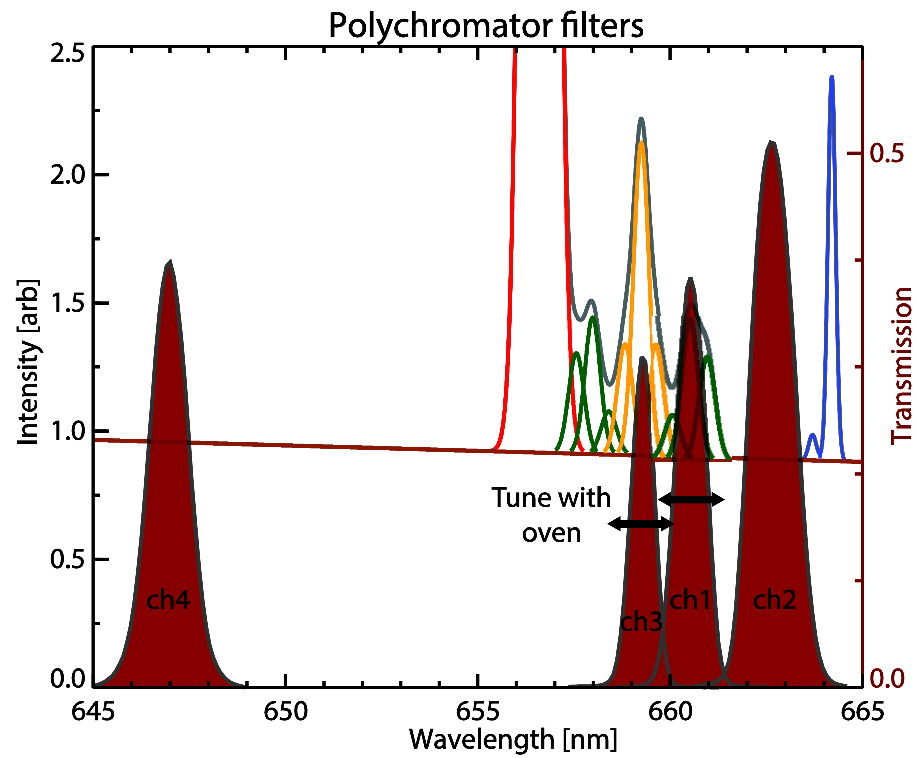


Challenges for a MSE polychromator:

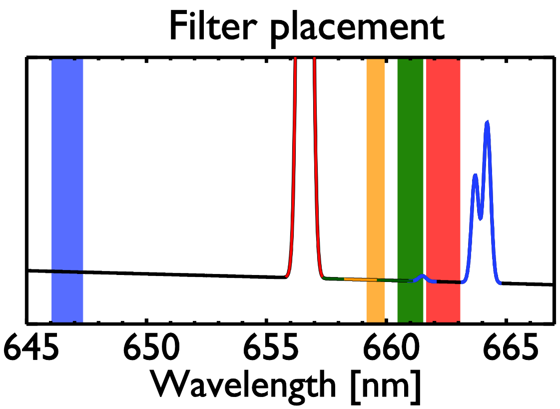
- Close spectral spacing of narrow bandpass filters requires small AOI
- Tune the filter bandpasses shot-shot
- Accommodate a large etendue

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

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



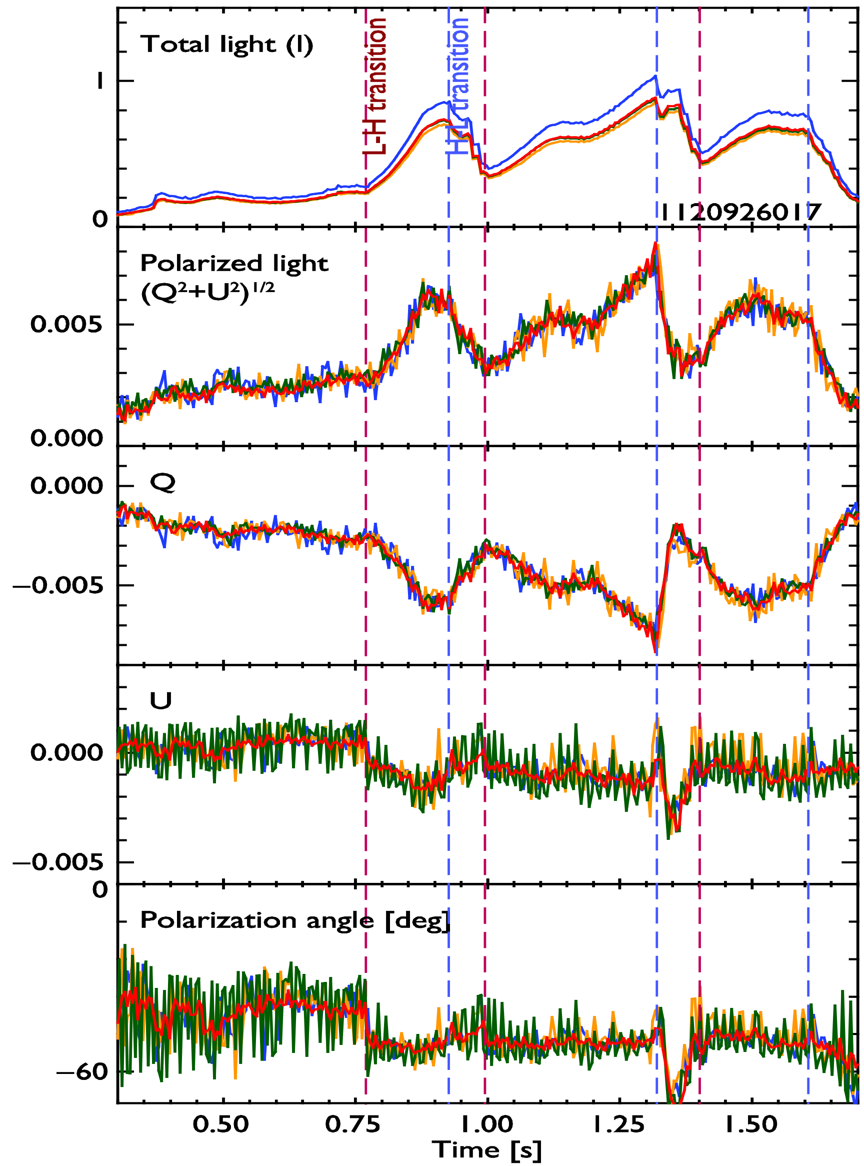
Polarization at adjacent wavelengths highly correlated even as background changes significantly.



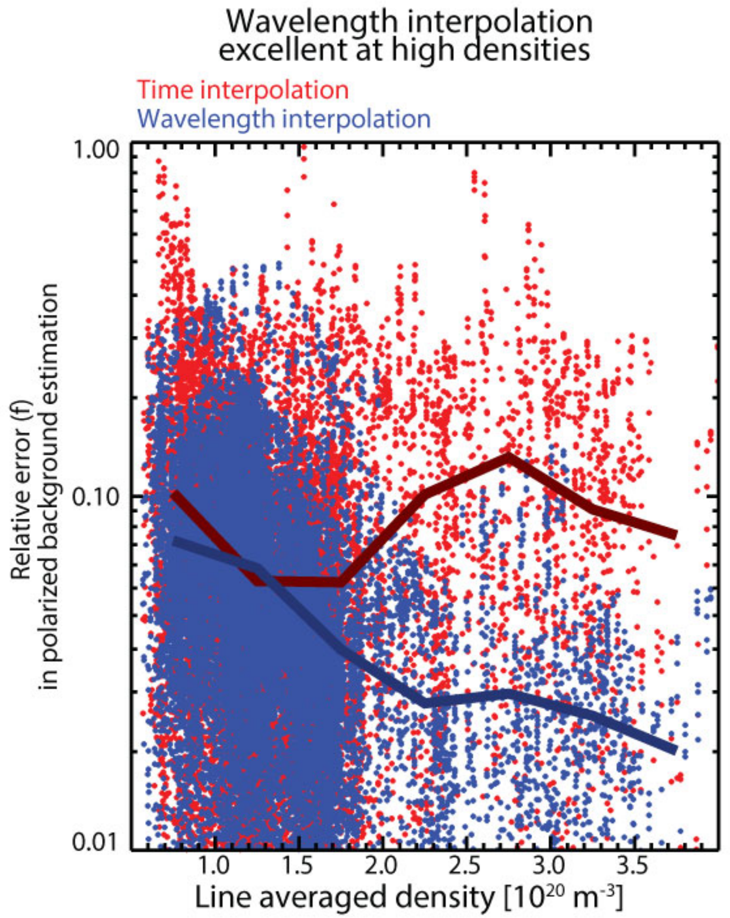
$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

Polarization of the different spectral regions agree

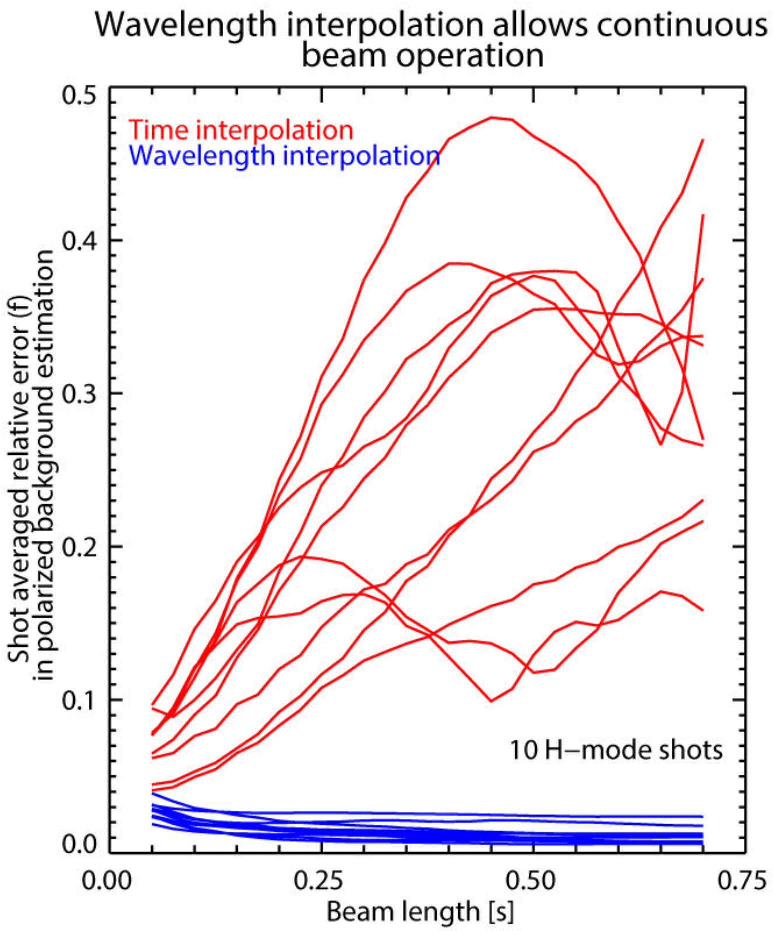
- Follows the transients well across entire discharges
  - Even over plasma transitions when contributions from different sources are changing
- Agreement near the photon statistic limit
- Result independent of MSE sightline
- Works over large wavelength range



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

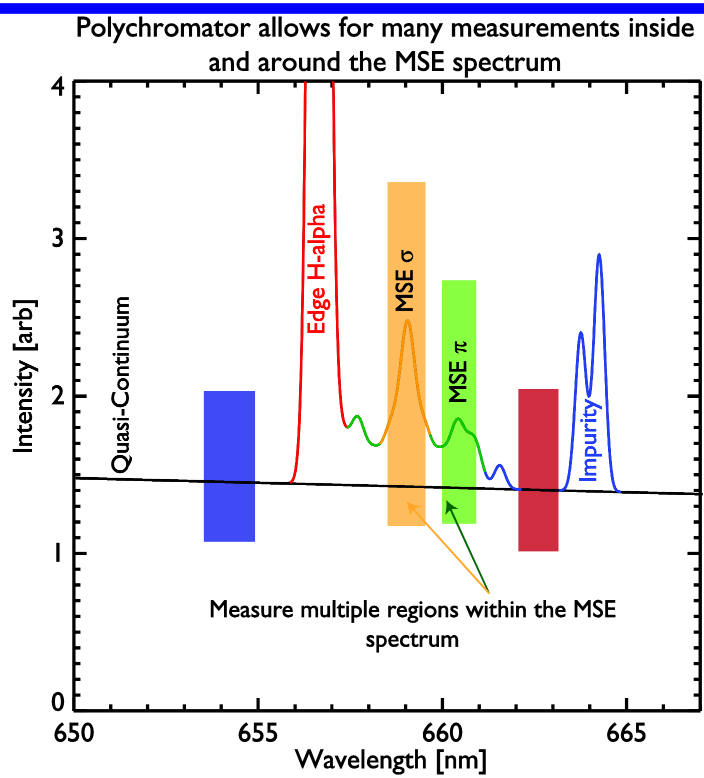


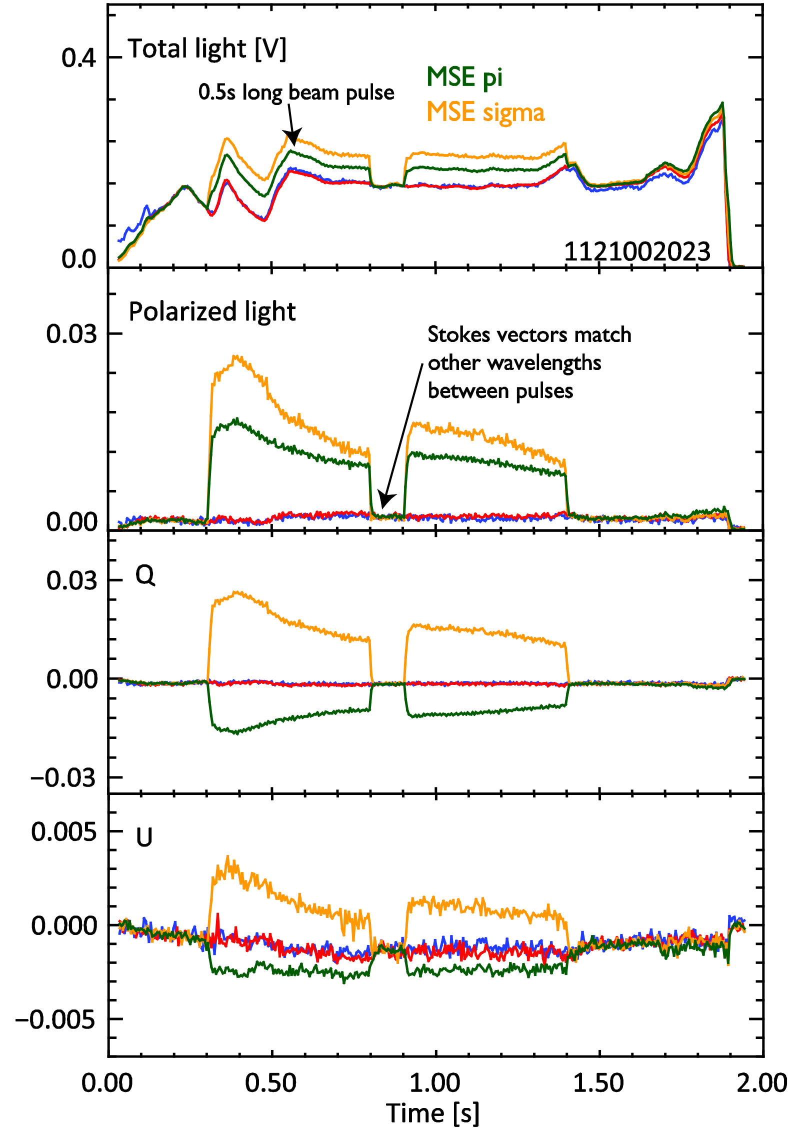
100ms beam length



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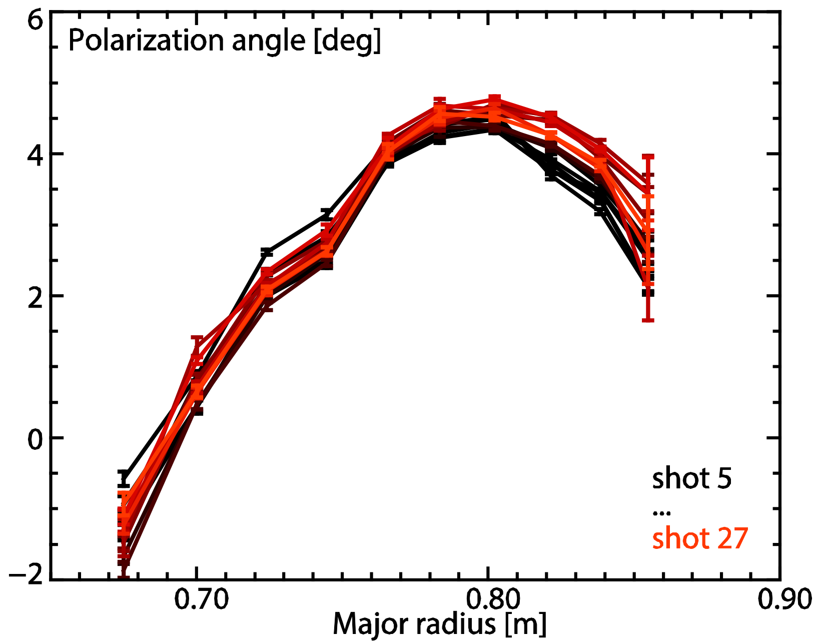
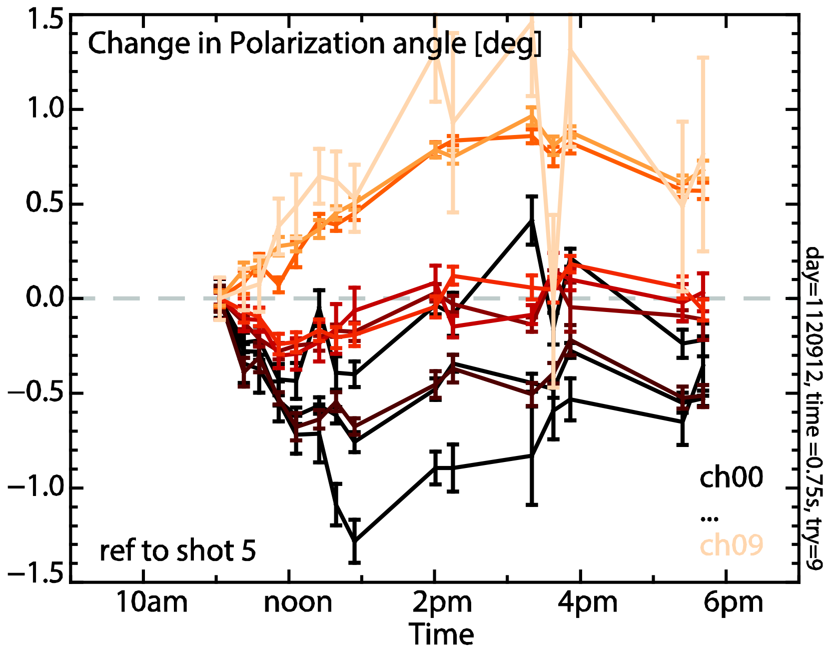
Observation: the polarization diagnostic response drifts shot-to-shot on C-Mod.

Drift in polarization angles observing the beam in identical plasmas

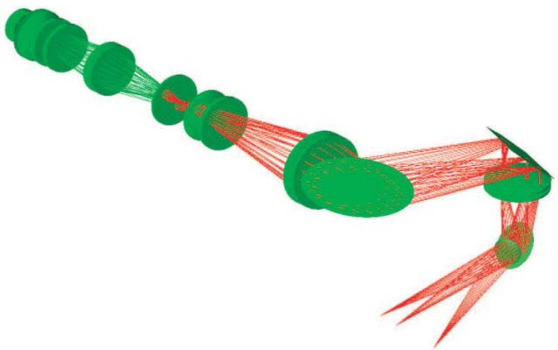




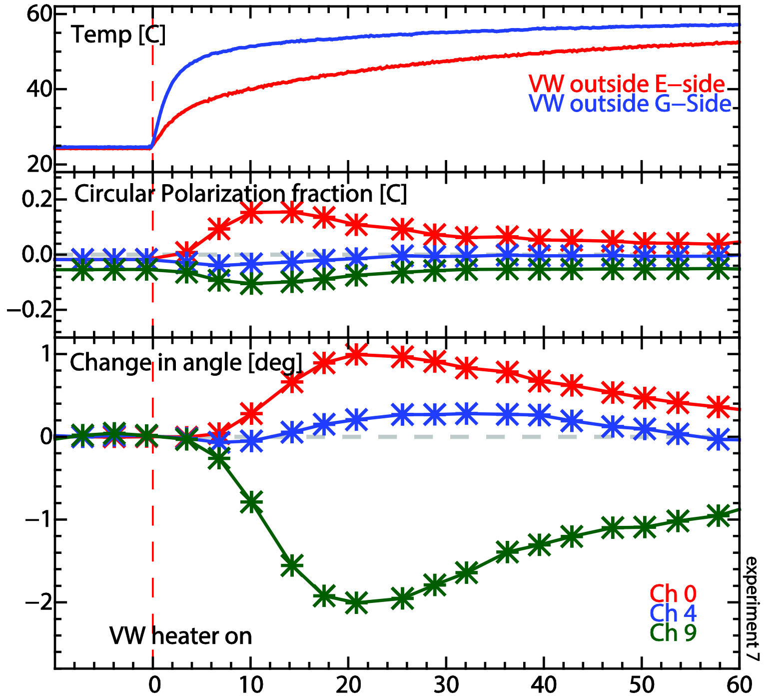
- Use identical shots to judge reproducibility
  - Polarization angle drifts ~1° shot-to-shot across runday
  - Channel dependent (though smoothly)
  - Not repeatable runday-to-runday
  - Changes in circular polarization also apparent

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



Heating optics causes stress induced birefringence



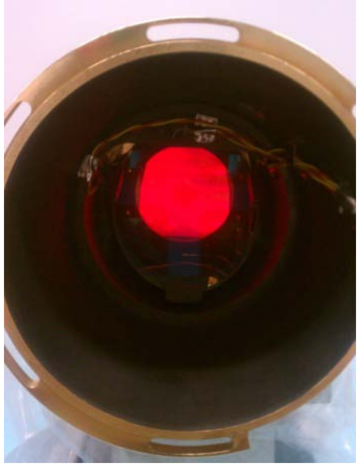
MSE periscope covered with radiative heat shield

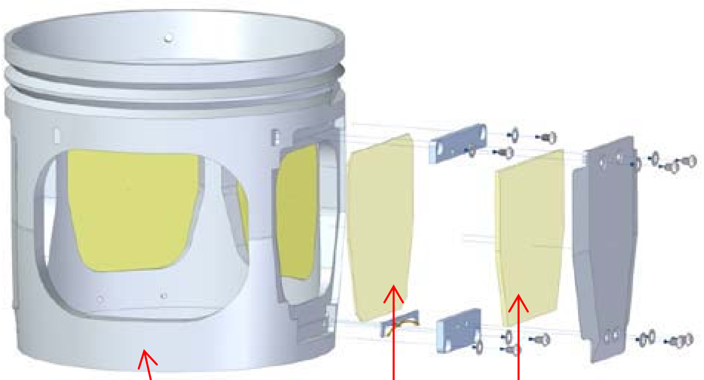
Problem analogous to mirror erosion and deposition in next-step devices.

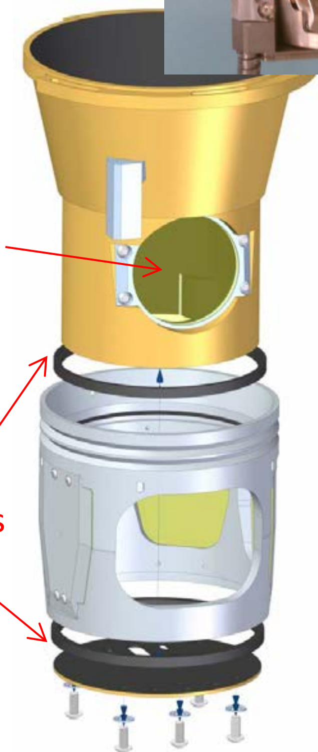
Try in-situ calibration on C-Mod.

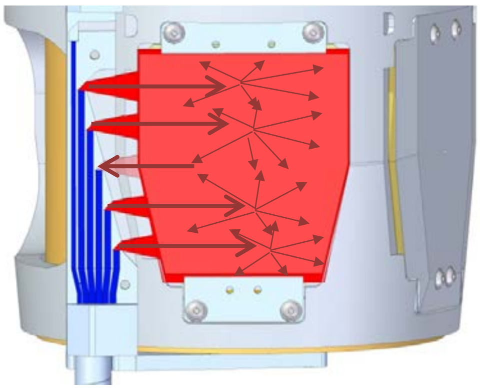
Intershot calibration system (ISC) was developed: Input known polarizations into the diagnostic objective lens.

- 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°



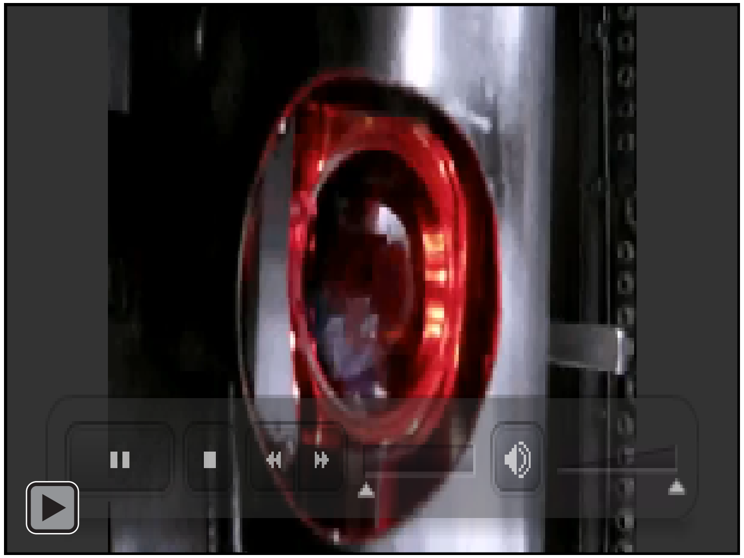


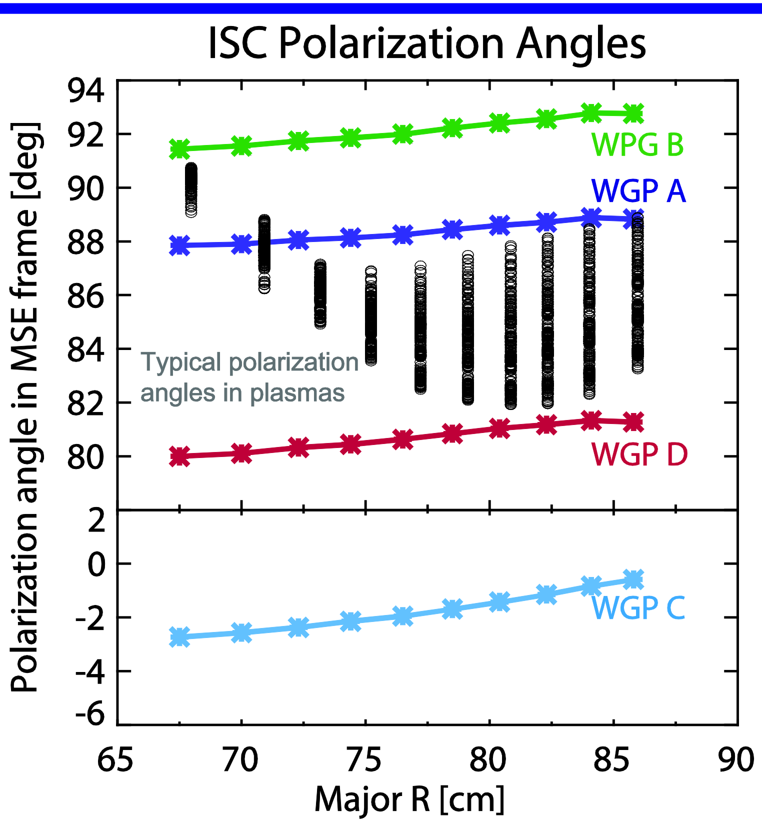




System quickly inputs 4 polarization angles immediately following a discharge, allowing interpolation.

- 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 WGPs allows the plasma measurements to be corrected
- System is repeatable to <0.05°
    - >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 runday and campaign revealing trends.

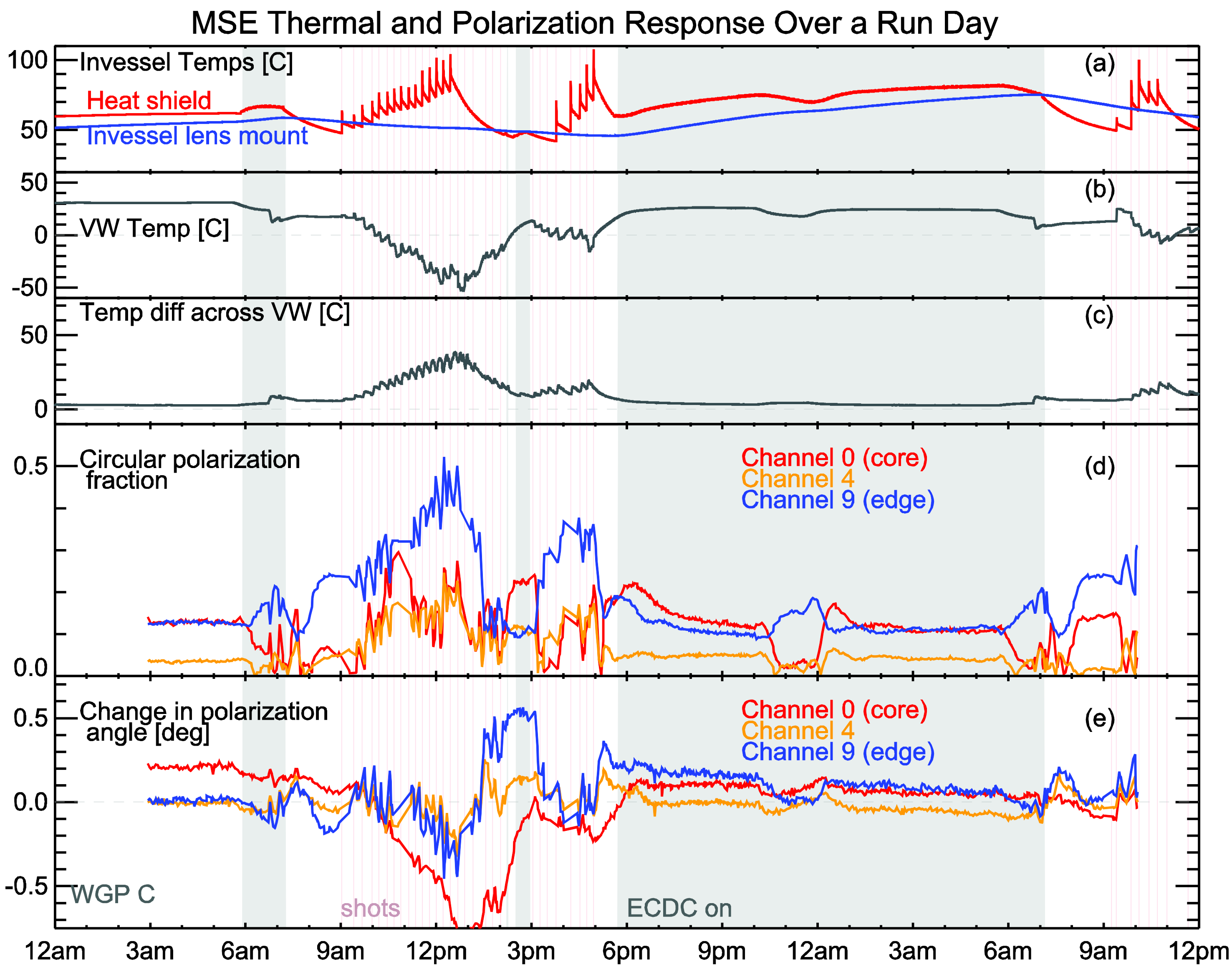
Heat shield protects optics from plasma

...but VW ratchets down in temp

...developing large thermal gradients

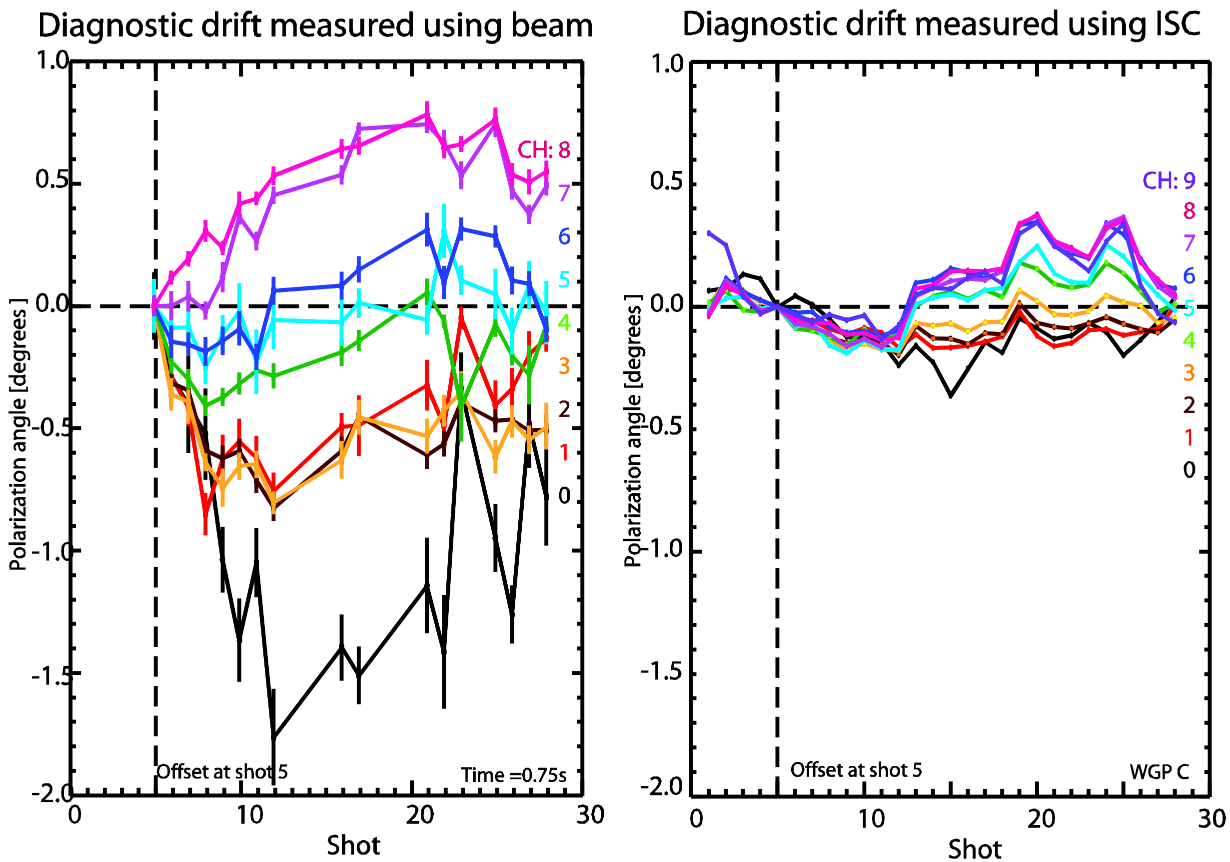
...becomes birefringent

... changing the polarization angle

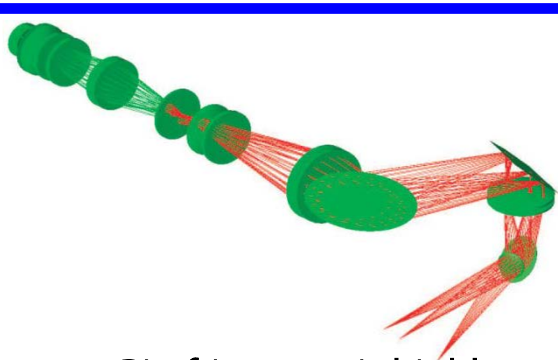


But… The first implementation didn't track the "right" diagnostic drift.

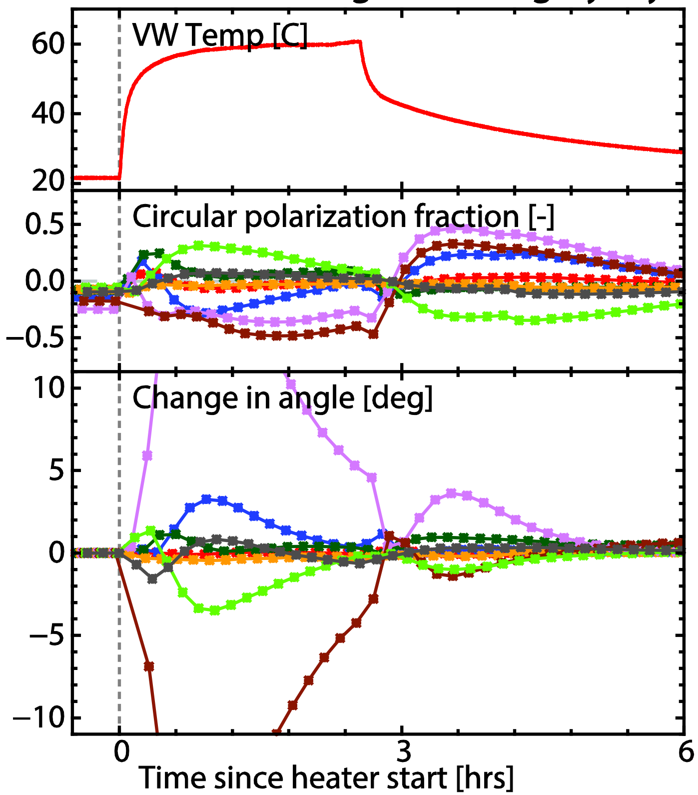
- Use identical plasmas to judge diagnostic drift via beam observations
- Compare to that inferred from the ISC
  - Quantitative and qualitatively different!



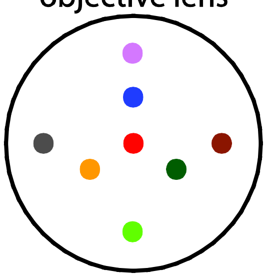
Determined the problem:
Diagnostic response is extremely ray dependent.



Birefringence is highly ray dependent



Strike point on objective lens



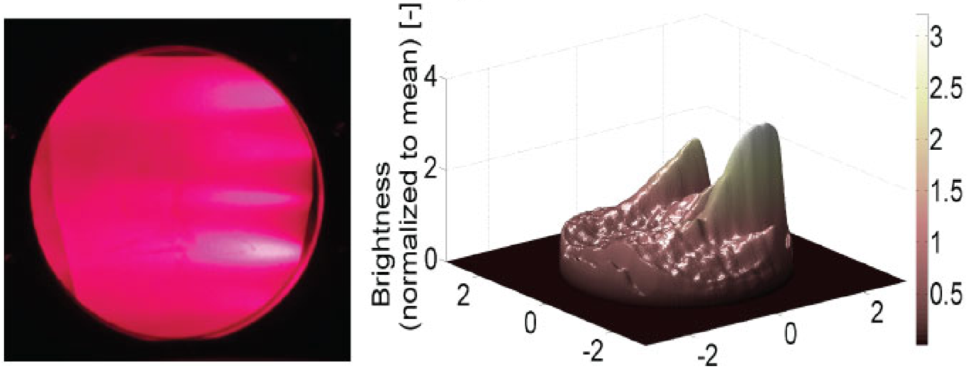
- Discrepancy reproduced during maintenance period
- Further tests done with ray-tracing source
  - Ray strikes a different portion of the lens with a different stress state
  - Different polarization aberration
- Sightline calibration a weighted average of all the rays

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

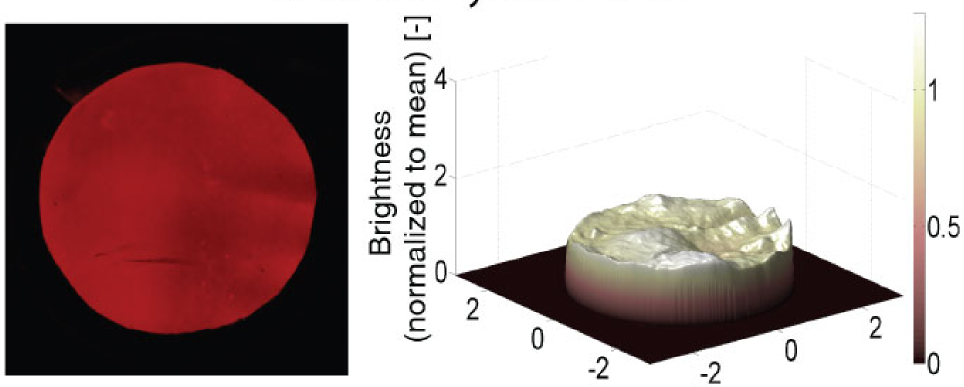
- Probably important for next-step systems
  - Non-uniform first mirror erosion/deposition

Rebuilt the ISC with uniform illumination. Bench trials successful, awaiting confirmation in-situ.

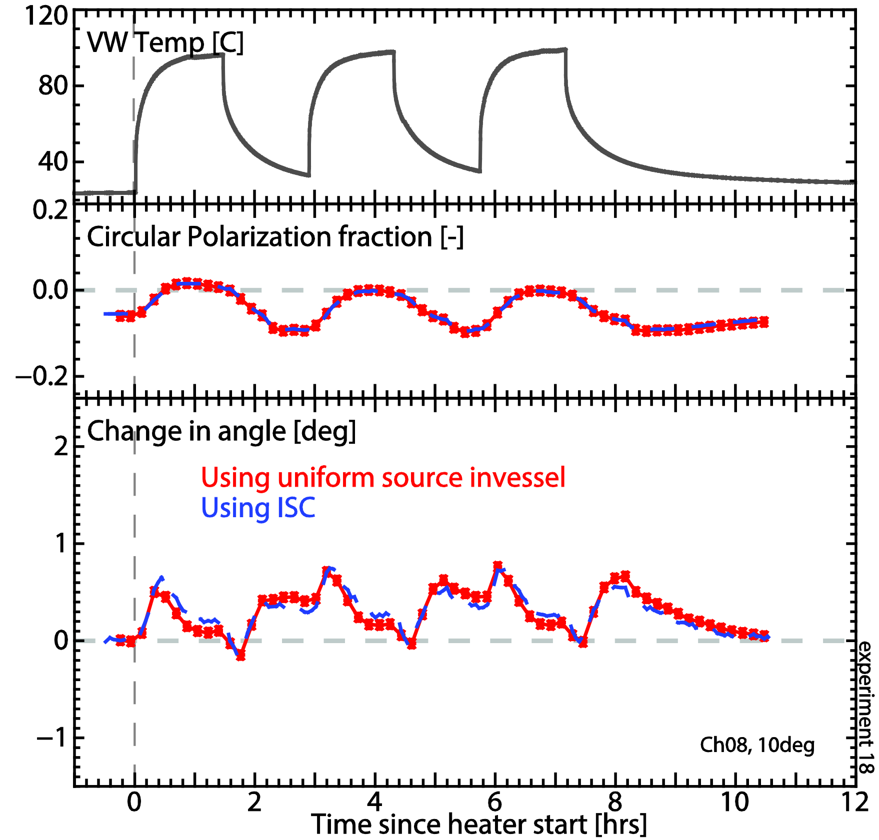
ISC uniformity prior to rebuild



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