The accuracy of the Alcator C-Mod Motional Stark Effect (MSE) diagnostic is limited primarily by partially polarized background light that varies rapidly both in time (1 ms) and space – factor 10 variations are observed between adjacent spatial channels. ITER is likely to operate in a similar regime. Visible Bremsstrahlung, divertor molecular D2 emission, and glowing invessel structures generate unpolarized light that becomes partially polarized upon reflection. Because all three sources are broadband, the background light can be measured in real-time at wavelengths close to the MSE spectrum, thereby allowing the background to be interpolated in wavelength rather than in time. A 10-spatial-channel, 4-wavelength MSE-MSLP system has been developed using polarization polychromators that measure simultaneously the MSE pi- and sigma- lines as well as two nearby wavelengths that were chosen to avoid both the MSE spectrum and all known impurity lines on each sightline. Initial performance evaluation indicates that the background channel measurements faithfully track the background light in the pi- and sigma- lines. The improvement in accuracy of pitch-angle measurements and increased diagnostic flexibility over a wide range of plasma conditions will be reported.
Executive summary

• The Multi-Spectral Line Polarization MSE diagnostic functions as designed.

• It accurately measures the partially-polarized MSE background even in circumstances where the background changes rapidly in time and space:
  • RF turn-on, turn-off
  • L/H transitions
  • $P_{rad}$ and VB spikes
  • Ramp in density

• A few channels at the plasma edge have residual problems during large H → L transitions.

• It provides a much more accurate measurement of the background light than traditional beam modulation.
Recall: Plasma’s unpolarized emission becomes strongly polarized upon reflection from the MSE “view dump”.

- C-Mod’s MSE view dump is an ICRF antenna
- Developed a polarization sensitive camera to image light reflected from antenna
  - Reflection is highly polarized, spatially complex

Any light in the MSE wavelengths can become partially-polarized MSE background

![Diagram showing polarization camera at MSE location, reflected light, and polarization images.](image)
MSE requires surprisingly high signal-to-background, and/or accurate estimates of the background, to achieve reasonable accuracy (e.g. $\Delta \theta = 0.1$ to $0.2^\circ$)

\[ I_s = \text{intensity of polarized emission from beam} \]

\[ I_b = \text{intensity of polarized background} \]

\[ S_b = \frac{I_s}{I_b} \quad \theta = \tan^{-1} \left( \frac{I_{2\Omega_1}}{I_{2\Omega_2}} \right) \]

\[ \Delta \theta = 28.6^\circ \left( \frac{f}{S_b} \right) \sin(2(\theta_s - \theta_b)) \]

\[ \text{e.g. even with } S_b \approx 30, \text{ we need to measure background to 10\% accuracy to get } 0.1^\circ \text{ accuracy on polarization angle!} \]

Imperfect estimation of the partially-polarized background light is the dominant source of error for MSE on C-Mod, and to date, limits its use to moderate-density, L-mode plasmas.
Source #1: Visible Bremsstrahlung is always present and becomes weakly polarized.

- Background is often dominated by visible Bremsstrahlung emission
  - Seen on first pass and reflection
  - Polarization fractions = 0.01-0.1
  - Similar in all sightlines/wavelengths

- Perhaps just correlate with Bremsstrahlung diagnostic and subtract it?

But this is not usually the dominate source.
Source #2: Hot glowing structures from around the machine are seen via reflection.

- Glowing RF antennas, limiters, divertor can dominate MSE polarized background
  - Polarized light post-disruption
  - Structures only visible upon reflection
    - Polarization fractions = 0.3-0.5
- Broadband emission
  - Only visible in a few sightlines at a time
    - Depending on location of source
  - Due to complexity of view dump
  - Varies rapidly in time
Source #3: Quasi-continuum emission from the divertor. Perhaps molecular D2 emission?

- Correlates very well with edge Dα
  - But is not Dα
  - Correlates with stray light from machine protection cameras
  - Correlates with quasi-continuum from divertor spectrometers
- Polarization fractions = 0.1-0.5
- Changes quickly (<ms)
- Polarization angle depends on active divertor
- Similar behavior observed in all sightlines/wavelengths
A multi-year effort has successfully characterized four sources of background light that affects MSE

- **Visible Bremsstrahlung**: ever present, sometimes dominates
  - Small polarization fraction, 0.01 to 0.1
  - Similar in all MSE sightlines and wavelengths

- **Molecular H₂/D₂** – ever present except in helium plasmas, sometimes dominates
  - Moderate/high polarization fraction, 0.1 to 0.5
  - Similar behavior observed in all sightlines / wavelengths
  - Most emission from “active” divertor – polarization angle changes when USN → LSN
  - Can change on millisecond time scale during e.g. L → H mode transitions

- **Glowing invessel structures** – infrequently dominates
  - High polarization fraction, 0.3 – 0.5
  - Glowing RF antennas, limiters, divertor. Also post-disruption
  - Can vary rapidly in time (~10 ms) and space (factor >10 difference in adjacent channels)

- **Emission from runaway relativistic electrons** – seen only during dedicated runaway expts
  - Just a curiosity. Possibly gives info on energy distribution of runaways.
  see: R. A. Tinguely, GO4.00006, Analysis of Runaway Electron Synchrotron Radiation in Alcator C-Mod.
But we can exploit the fact that all three sources of background light are quasi-broadband

• Measure the polarized background light at wavelengths near the MSE $\pi$ and $\sigma$ lines
  
  • In real time (no time interpolation), simultaneously with the $p$ and $s$ measurements.
  
  • With the exactly the same optics & fibers as the $\pi$ and $\sigma$ light.

• Then interpolate in wavelength rather than in time to estimate polarized background emission.
A proposed solution: MSE multi-spectral line polarization (MSE-MSLP).

- Measure the Stokes vectors at wavelengths adjacent to MSE on same sightline
  - Use same PEM technique
- Wavelength interpolate Stokes vectors at each time to estimate MSE background

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

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

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

Valid if sources are indeed quasi-continuum.

Doesn’t require changes to upstream optics, just a detector swap.

Real-time MSE polarized background subtraction using multi-wavelength interpolation.
Passbands for the ‘red’ and ‘blue’ background filters were chosen to avoid lines of known C-Mod impurities.
Designed a high throughput imaging interference filter-based polychromometer for MSE-MSLP.

- Cavity layout allows many spectral channels on same exact sightline, highly photon efficient
- Small AOI required to preserve bandpass filter performance, 3° used

Fiber from existing MSE upstream optics
APDs for each spectral channel
Interchangeable filter ovens allow quick, easy filter changes without need for realignment

Spherical field mirrors
Relay lenses
Interference filters
Condenser lens

~1m
Single sightline prototype was constructed, met the operational requirements.

- Very high throughput: 9mm²sr, filled at NA=0.39
- Acceptable filter performance: ~0.5nm FWHM
  - Thermal tuning with ovens
- Easy to create and maintain cavity alignment
- Water cooling for APD detectors
- Easily replicated, cost effective
- Machine independent
A full 10-channel system was fabricated 2014 - 2015

Cost ~$27k per polychromometer (sightline)
The MSE-MSLP diagnostic is rack-mounted; individual polychromometers can slide open for maintenance.
A ‘typical’ Alcator C-Mod plasma poses challenges for MSE background estimation.

VB emission varies rapidly in time.
Measuring polarized background during beam ‘off’ periods and then interpolating to beam ‘on’ periods is not sufficiently accurate.
During beam ‘off’ periods, we measure the ratio of the MSE π and σ intensity to the two background intensities. During beam ‘on’ periods we multiply this ratio by the measured background intensity to estimate the background intensity experienced by the π and σ channels.
Measured polarized signals in the two background channels typically follow one another very well, confirming that the background light spectrum is broadband and slowly varying in time.
In this noise-only shot, the wavelength-interpolation accurately reproduces the observed background light in the MSE $\pi$-line during ersatz ‘beam-on’ periods.
H --> Lmode transitions are the most challenging phenomena when estimating MSE polarized background: rapid changes in VB emission and Hα.
In this shot, wavelength interpolation accurately estimates the polarized MSE-p background emission even thru H --> L and L --> H transitions.

Caveat: post-facto, discovered imperfect background estimation on sightlines 9 and 10 on this shot, see discussion on upcoming slides. ‘Size’ of transition may matter.
Surprisingly, on a similar-looking H --> Lmode transition, MSE-MSLP provides a less-accurate measurement of the MSE-\(\pi\) background for plasma-edge sightlines in the first few ms following the transition.
During the H→ Lmode transition, both background measurements see a smaller rise in signal than does MSE-π.

The graph shows the signal strength over time for different channels and measurements. The background channels exhibit a smaller rise in signal compared to MSE-π, indicating a spurious net signal at the time of transition. The ratio of VB to Hα intensity changes by a factor of ~2.7 during the transition.
The ‘shortfall’ in background measurement at the H --> L transition is larger at the plasma edge, and absent in the plasma core.
The ‘shortfall’ in measured background light is slightly more pronounced in the MSE $\sigma$-line than in the $\pi$-line.
The ‘shortfall’ is observed on other shots
A single-channel prototype of MSE-MSLP (fabricated 2012 at PSFC) was installed on ASDEX-Upgrade in October. Operational in 1 week.
ITER Relevance

• Several existing MSE diagnostics (DIII-D, NSTX, TFTR) have/had little or no problem with polarized background light.
  • High-current heating beam \(\rightarrow\) intense \(\pi\) and \(\sigma\) light
  • Viewing dumps and/or non-reflective walls.

• Some existing MSE diagnostics (ASDEX-U, JET) have only a modest problem with background light.

• But MSE on ITER will experience the same set of problems that it faces on Alcator C-Mod:
  • Hot walls, potentially glowing
  • Low-current beam (heating beam) \(\rightarrow\) low S/N
  • Lack of viewing dump \(\rightarrow\) reflections leading to polarization
  • High density, long sightline \(\rightarrow\) intense VB & molecular D2

• MSE-MSLP has been adopted for use on ITER MSE system: operational experience on C-Mod will inform design and expected performance.
The future

• Repair the diagnostic neutral beam (December 2015).

• Operate MSE-MSLP during FY16 C-Mod run campaign with DNB and document performance to provide guidance for ITER MSE.

• Find a good home for MSE-MSLP following FY16 campaign.

• Tune algorithms that compute ratio of background signal to MSE $\pi$ and $\sigma$.
  • Can use e.g. $I_{2\Omega2}$, $(I_{2w1}^2+I_{2w2}^2)^{0.5}$, or total signal intensity.
  • Possibly use post-shot data from Intershot Calibration System.
  • Explore whether ‘constant of nature’ ratios are better than time-varying ratios.

• Explore use of measured intensity ratio VB/H$\alpha$ to identify time periods when MSE-MSLP is not sufficiently accurate.