MSE diagnostic on HSX for simultaneous $E_r$ and bootstrap current measurements

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Outline

• Motivation
• Planned diagnostic schemes
• Challenges, expectations
• Conclusions
HSX is a four field period quasi-helically symmetric stellarator

\[ < R > = 1.2 \text{ m} \]
\[ < a > = 0.12 \text{ m} \]
\[ \tau = 1.05-1.12 \]
\[ \mathcal{B}_0 = 1.0 \text{ T} \]
\[ < n_e > \leq 6 \times 10^{18} / \text{m}^3 \]
\[ T_e = 0.5 \text{ to } 2.5 \text{ keV} \]
\[ T_i = 30-60 \text{ eV} \]

- Heating: ECRH 28 GHz, 100 kW (×2)
- No external current drive
Motivation: CHERS measurement does not resolve large $E_r$ predicted near the core

- Reasonable agreement with PENTA predictions for $r/a > 0.2$
- No indication of large positive $E_r$ at the core
- Measurement uncertainty/resolution? PENTA over predicts core $E_r$?

A. Briesemeister et al.
Motivation: Bootstrap current measurements indicate large positive $E_r$ near the core (J. Schmitt et al.)

- Decrease in $I_{BS}$ at 100 kW is in qualitative agreement with PENTA prediction
- A large positive $E_r$ close to the axis reverses $I_{BS}$ near the core

Simultaneous and direct measurements of $E_r$ and bootstrap current near the core is needed
Motivation: Measurement of bootstrap current is crucial for next generation devices

- Bootstrap current can significantly affect magnetic topology and confinement
- Understanding of the bootstrap current and its temporal behaviour is important for island divertor
- Effect of $E_r$ on bootstrap current has been theoretically studied, limited experiments so far

Motional Stark Effect (MSE) diagnostic could measure both $E_r$ and bootstrap current simultaneously.
MSE relies on the ‘motional electric field’ experienced by the neutral beam particles

- Motional electric field, $E_b = \nu_b \times B \sim 2.5\text{MV/m}$ for 30 keV beam into 1 Tesla B

- Beam emission Stark splits into various components (Orthogonally polarized $\sigma$ and $\pi$ components)

- Total 15 components for $H_\alpha$, 9 of which are strong enough to observe

Modeled $H_\alpha$ MSE spectrum
MSE is commonly used for magnetic field measurements - magnitude and the pitch angle

- Stark-split, $\Delta \lambda \propto v_b \times B$ (Spectral analysis)

- Intensity ratio of $\pi$ to $\sigma$ emission gives electric field direction. (Spectral analysis)

- When viewed perpendicular to $E$, $\pi$ & $\sigma$ components are polarized parallel and perpendicular to $E$, respectively. (Polarimetry)
Plasma $E_r$ can significantly affect MSE measurements

- Total electric field: $E_{tot} = E_b + E_r$
- $E_r$ is typically orders of magnitude less than $E_b$
- If $E_r$ vector adds to the smaller components of the $E_b$ vector, relative importance of $E_r$ is larger

Makes MSE a good tool to measure the radial electric field!
Advantages & challenges of MSE on Stellarators

• Vacuum magnetic field is accurately known.
• Beam into vacuum field gives $\Delta \lambda$, calibration.
• Change in Stark emission from the vacuum case gives the required measurements
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Challenge: Pitch angle variation along the sight line within the beam width.
Diagnostic neutral beam on HSX has low divergence, well suited for MSE measurements

- 30 keV, 4A, 3ms Hydrogen neutral beam
- \( \sim \) 80-90% full energy
- Lower radius and divergence than designed (due to a beam limiting aperture tube)
$H_\beta$ emission measurements have been made, Stark splitting observed

- Existing grating does not allow $H_\alpha$ measurement.
- Placed order for new components. Detailed $H_\alpha$ measurements will commence soon.
Spectral method: challenges and plans

- Low density, small sized HSX plasma
- Neutral beam energy levels do not equilibrate
- Most of the MSE simulations assume equilibrated beam
  
Data-fitting allows fine-structure separation. (B field measurements on DIII-D. Pablant et al.)
Spectral method: challenges and plans

- Low density, small sized HSX plasma
- Neutral beam energy levels do not equilibrate
- Most of the MSE simulations assume equilibrated beam
- Beam modeling to get beam energy level population (presently using ALCBEAM from Alcator-C)
- MSE simulation of non-equilibrated beam (NIST)
- Ratio of emission intensities from same upper level. Data-fitting allows fine-structure separation. (B field measurements on DIII-D. Pablant et al.)
Change in polarization of Stark components gives $E_r$

- $E_{tot} = E_b + E_r$

- $E_{tot}$ transformed into a coordinate system where sight line is along the x-axis.

- $\tan \gamma = \frac{E_{new} \cdot \vec{Y}}{E_{new} \cdot \vec{Z}}$

- $\gamma$ is also the direction of polarization of the $\pi$ component of the Stark emission
A dual Photo Elastic Modulator polarimetry system is designed

\[ \tan(2\gamma) = \frac{I(2\Omega_1)}{I(2\Omega_2)} \]

\(I(2\Omega_1)\) and \(I(2\Omega_2)\) - output signals from the lock-in amplifiers
\(\Omega\) - PEM modulation frequency.
Radial electric field can be measured with reasonable accuracy.

Change in polarization angle of the Stark component from its vacuum value as a function of $E_r$. Typical resolution $\sim 0.1^\circ$. 
$\Delta t$ with bootstrap current in HSX is measurable

$\Delta t$ for $I_{BS} = 400A$

VMEC calculation

- Near the core
  $\Delta t \sim 0.006 \Rightarrow \Delta \gamma \sim 0.3667^\circ$

- At mid radius:
  $\Delta t \sim 0.024 \Rightarrow \Delta \gamma \sim 1.3748^\circ$

Changes are well above the typical polarimetry resolution of
$\sim 0.1^\circ$
$E_r$ and bootstrap current effects can be separated

$$\tan \gamma = \frac{E_{\text{new}} \cdot \vec{Y}}{E_{\text{new}} \cdot \vec{Z}} = \frac{[\alpha_1 E_r + \kappa_1 B]}{[\beta_1 E_r + \kappa_2 B]}$$

where $\alpha_1$ and $\beta_1$ depend only on the viewing angle and $\kappa_1$ & $\kappa_2$ depend both on the viewing angle and beam velocity.

Two ways to separate $E_r$ and $B$ effect:

- Measuring emission from two beam energy components (preferred)
- Measuring from two different angles

Simultaneous $E_r$ and bootstrap current measurement is possible
Conclusions

• Direct, localized and simultaneous measurements of $E_r$ and bootstrap current is needed

• Motional Stark Effect is a promising diagnostics, but challenges ahead

• Many advantages over CHERS : direct measurement, no field reversal required, better signal level, no methane doping etc.

• Work on MSE on HSX has been initiated, first results soon

• Useful technique for present and next generation devices