Spectral MSE Study on HSX and Non-Statistical Beam Level Populations

C. Ruiz, S.T.A. Kumar, O. Marchuck[1], F.S.B Anderson, D.T. Anderson

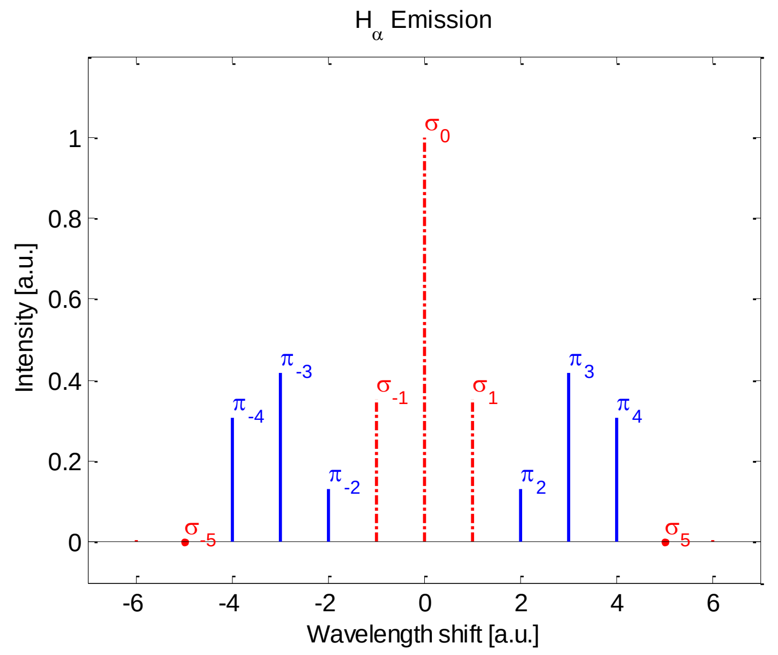
HSX Plasma Laboratory, Univ. of Wisconsin, Madison, USA;
[1]Forschungszentrum Juelich GmbH, Germany

Introduction/Motivation

- A good knowledge of the radial electric field profile is required to understand plasma transport properties.
- A radial electric field results in ExB shear flows, which in turn leads to changes in the particle confinement and a reduction of turbulence.
- Previous measurements of radial electric field using CXRS on HSX have shown discrepancy to the expected Er.
- Perform a measurement of Er using motional stark effect diagnostic.
- Validation of atomic physics codes for the non-statistical population of the atomic energy levels.
- Show a method to measure radial electric field without specific knowledge of the population of the hydrogen atomic sublevels.

Overview/Theory/Background

- A moving particle in an external electric and magnetic field experiences a force. In it's frame of reference the Lorentz electric field is:
  - $\boldsymbol{E}_L = \boldsymbol{v} \times \boldsymbol{B}$
- The total electric field felt by the particle in a plasma is:
  - $\boldsymbol{E}_T = \boldsymbol{E}_r + \boldsymbol{E}_L$
- The radial electric field (E_r) is given by the force balance equation.
  - $E_r = \frac{\nabla P_i}{Z_i e n} + v_\phi B_\theta - v_\theta B_\phi$
- A diagnostic neutral beam injects neutral particles into a plasma that get excited mainly due to collisions.
- According to atomic theory, the energy sublevels of an excited atom in an external electric field will be perturbed. Leading to the well known Stark Effect.
  - $\lambda_s = \frac{3}{2}\frac{e\,a_o}{hc}\lambda^2\, n(n_1 - n_2)\,|\boldsymbol{E}_T|$
- Where n_i is a parabolic quantum number which varies with the formula $n = n_1 + n_2 + |m_l| + 1.$
- Each emitted photon has a given polarization given by:
  - $\Delta_m = 0 \rightarrow \pi$ lines
  - $\Delta_m = \pm 1 \rightarrow \sigma$ lines
- Where $\pi \,\&\, \sigma$ refer to the polarization parallel or perpendicular with respect to the total electric field felt by the neutral atom.
- The total emission intensity for a given atomic transition is:
  - $I = \sum I(\theta) A_{ij}\, N_i$
  - $I_\pi(\theta) = \sin^2\theta$
  - $I_\sigma(\theta) = \frac{1}{2}(1 + \cos^2\theta)$

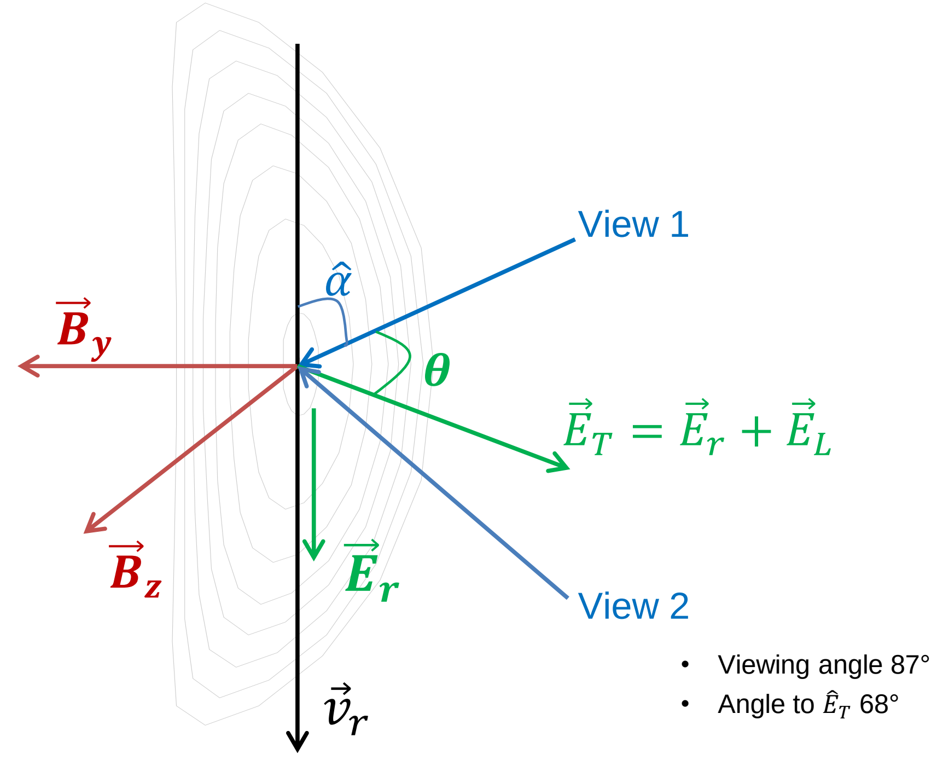


- Notice that the total intensity depends on the atomic transition probability (A_{ij}), the viewing angle (θ), and the total number of excited particles at a specific sublevel (P_i).
- If we take the ratio of two different atomic spectral lines,
  - $I_f = \frac{I_\pi}{I_\sigma} = \frac{2\sin^2\theta}{1+\cos^2\theta}\frac{A_{ij}}{B_{ij}}\frac{P_i}{Q_i}$
- Take the ratio of the π_3/σ_1 transition, for which the atomic sublevel of each of those comes from the same upper level. Then, knowledge of the total number of particles is not required [1].
- The intensity ratio can be solved for the viewing angle:
  - $\cos\theta = \left(\frac{2\,A - I_f}{2\,A + I_f}\right)^{1/2}$
- Now if we project the E_T into the viewing direction with an appropriate coordinate system

$$\boxed{\boldsymbol{E}_T \cdot \widehat{\boldsymbol{\alpha}} = |\boldsymbol{E}_T| \cos\theta = \alpha_1 E_r + v_r\left(\alpha_3 B_y - \alpha_2 B_z\right)}$$

- We can solve for radial electric field if we know the magnetic field components and beam velocity.

MSE Diagnostic with Simultaneous Views



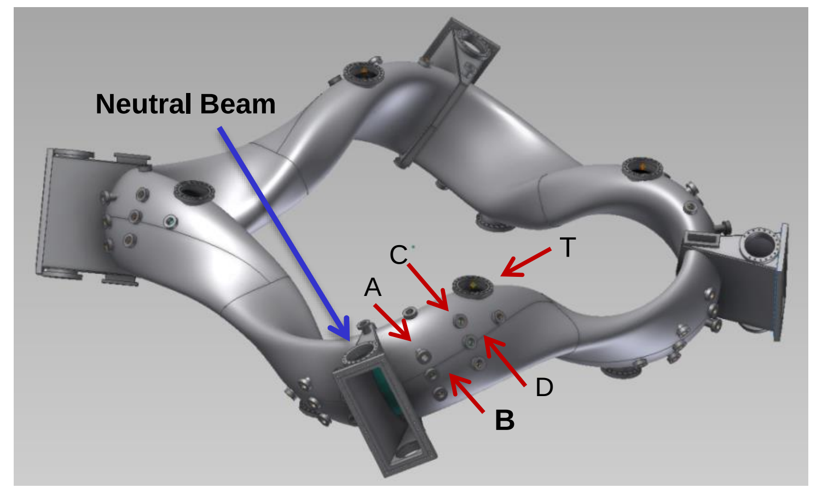
- Viewing angle 87°
- Angle to $\hat{E}_T$ 68°

- Having two views the system of equations for measuring Er and the magnetic field components is complete.
  - $\cos\theta = \frac{\alpha_1 E_r + v_r(\alpha_3 B_y - \alpha_2 B_z)}{\gamma}$
  - $\cos\phi = \frac{\beta_1 E_r + v_r(\beta_3 B_y - \beta_2 B_z)}{\gamma}$
  - $|\boldsymbol{E}_T| = \left(E_r^2 + v_r^2\left(B_y^2 + B_z^2\right)\right)^{1/2}$
- Where $\alpha_i \,\&\, \beta_i$ are the two views directions and γ is the total electric field. The system can be solved analytically.
- After some manipulation we can cast the coupled equations in the form of a general second order equation:
  - $a\,B_y^2 + b\,B_y\,B_z + c\,B_z^2 + d\,B_y + e\,B_z + f = 0$
- Using the resultant method we find an analytical solution to obtain the magnetic field components $B_y \,\&\, B_z$.
- The radial electric field will be given by:

$$\boxed{E_r = \frac{\gamma\cos\theta}{\alpha_1} + \frac{v_r}{\alpha_1}\left(\alpha_2 B_z - \alpha_3 B_y\right)}$$

Feasibility of a Secondary View

- It needs enough Doppler shift to separate from the un-shifted H_α; a good sensitivity of the ratio π/σ is obtained at an angle θ close to 62°

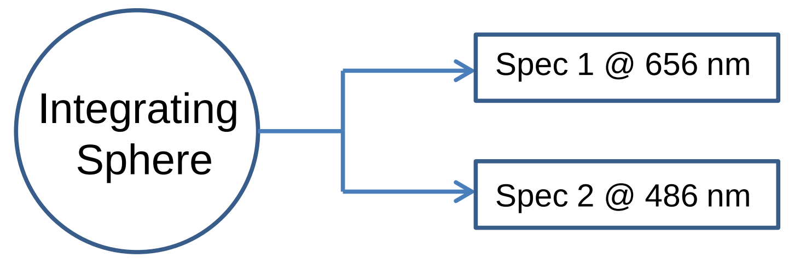


- Four different locations where investigated and the optimal one, location B, has the following parameters:

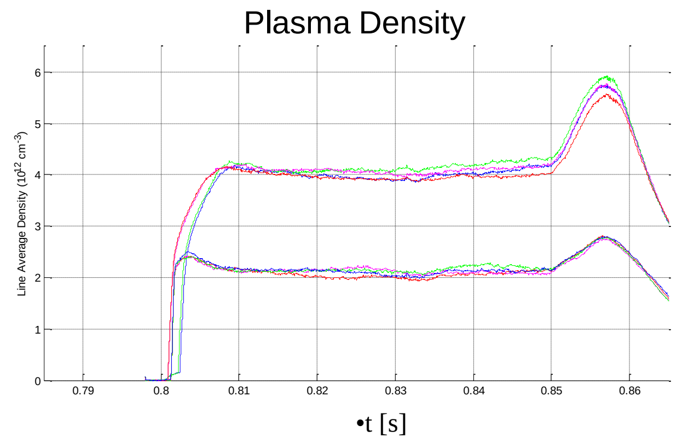
- Doppler shift angle 87°
- Viewing angle 68°

Experiments

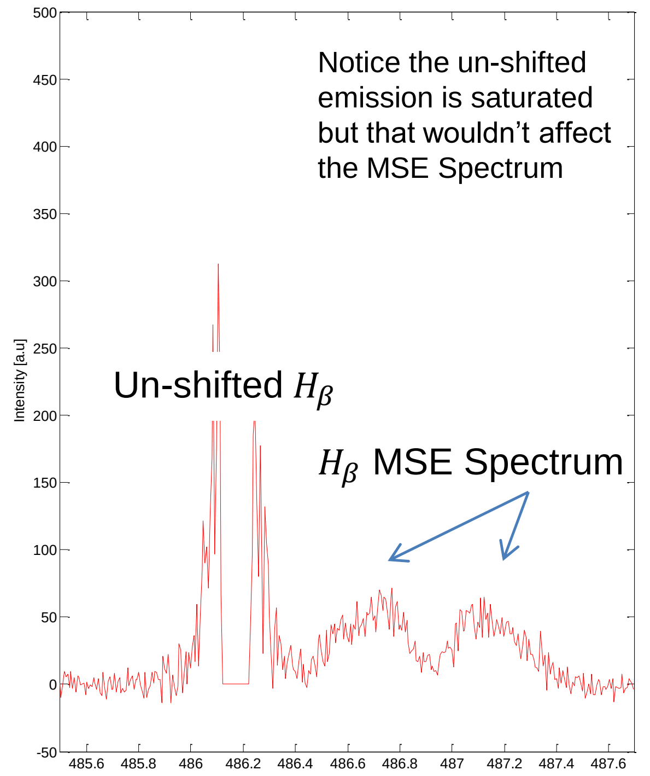
- Two spectrometers with different resolution were used to observe the spectrum at the same radial location.
- An integrating sphere was used to cross calibrate the spectrometers.
- A factor was obtained for different intensities and used on the results shown here.


Integrating Sphere
Spec 1 @ 656 nm
Spec 2 @ 486 nm

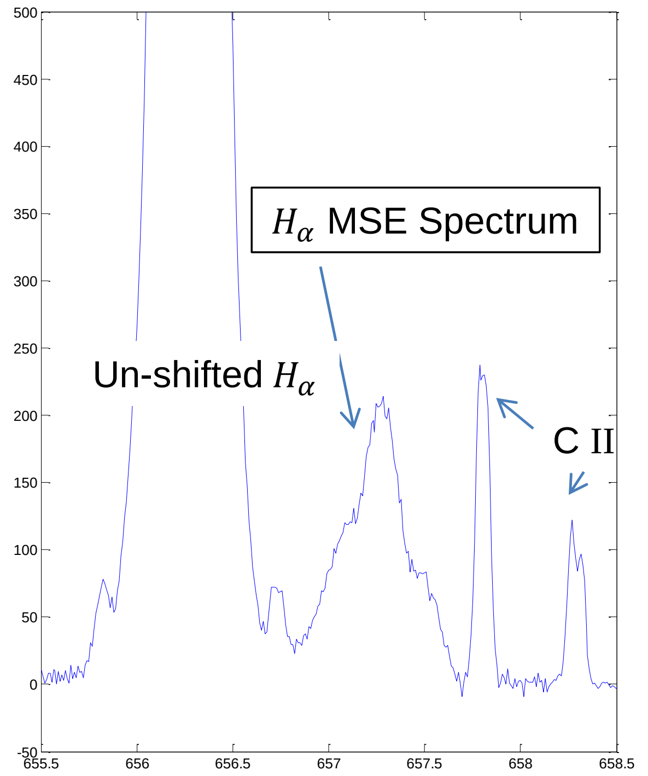
Parameter	Spec 1	Spec 2
Wavelength setting	656	486
CCD Range	9.42	3.16
wl / pxl	0.009 [nm/pixel]	0.006 [nm/pixel]
$\lambda_{\max}$	833	600



- Two line average plasma densities has been investigated. Preliminary results show an increase in the excited population for the higher density case.
- An ensemble of 10 shots and ccd binning is used to produce the spectrum shown here.



Notice the un-shifted emission is saturated but that wouldn't affect the MSE Spectrum



- It can be seen that the H_α signal resembles the simulated data and a larger intensity is observed compared to the H_β signal as expected from atomic theory.

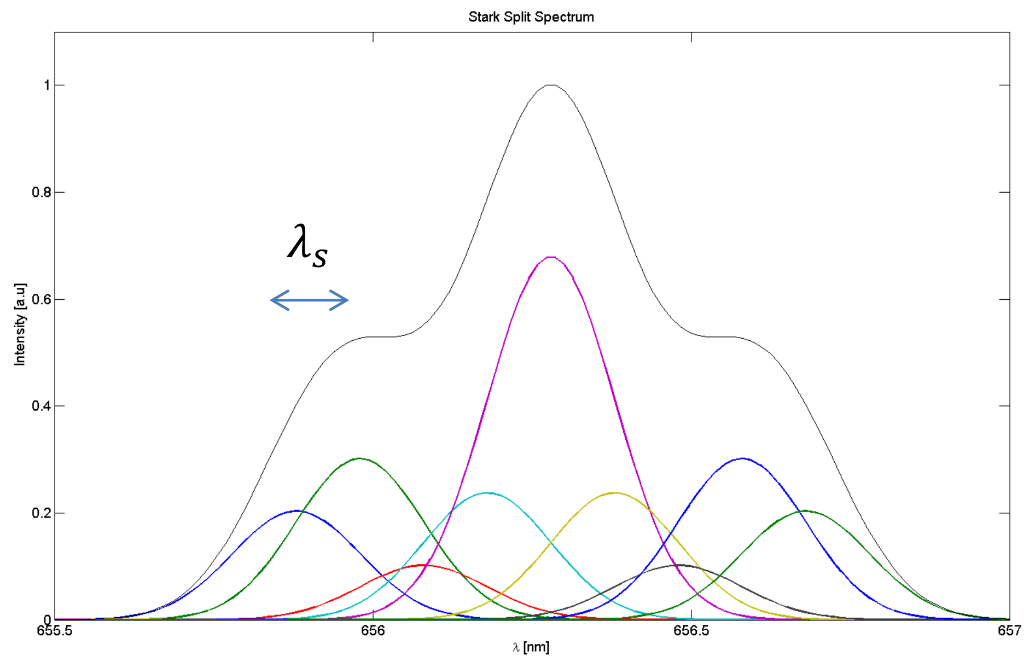
Simulation for HSX Plasmas

- The diagnostic neutral beam and plasma parameters influence the motional stark effect diagnostic. Our DNB and HSX plasma parameters are shown here:

HSX Parameter	Value
B field	~ 1 Tesla
E_L	~ 2.4 MV/m
E_r	~ 35 KV/m
E_r/E_L	~ 1%

DNB Parameter	Value
Beam Energy	28.14 keV
Energy Components	~ 90% H^+ Monoenergetic
Beam Ions	H⁺
Beam pulse duration	3 ms

- Notice that the radial electric field is only ~%1 percent of the total electric field experienced by the neutral atom.



- This simulated MSE spectrum shows that the individual components are not completely resolved to really discriminate one to another, i.e. π_3/σ_1.

Summary and Proposed Work

- A method for measuring the radial electric field without knowledge of the number of excited particles and two simultaneous views has been shown.
- Physical access to simultaneous viewing locations has been investigated.
- Simulation of MSE spectrum for HSX plasmas has been investigated and shows good agreement with results.
- Measurements show a larger population of H_α as expected from atomic theory.
- The performed spectrometers cross calibration provides a basis for comparing results.
- Improvement of the spectrum signal and removal of artifacts is in progress.
- Validation of atomic physics codes for the non-statistical population of the atomic energy levels is in progress.
- Although measurement of radial electric field seems unfeasible at the moment careful investigation of all the possibilities is in progress.

References / Acknowledgements

- Thanks to Dr. N. Pablant for the support and communication for the realization of this work.
- Thanks to the HSX group, my supervisor and colleagues who operate the HSX machine.

[1] N. Pablant, Measurements of the internal magnetic field on DIII-D using intensity and spacing of the motional Stark multiplet, Review of Scientific Instruments 79 (2008)

56th Annual Meeting of the Division of Plasma Physics, October 27 - 31, New Orleans, Louisiana

This work supported by US DOE Grant DE-FG02-93ER54222