Detection and application of Doppler and motional Stark features in the DNB emission spectrum in the high magnetic field of the Alcator C-Mod tokamak

I. O. Bespamyatnov\textsuperscript{a}, W. L. Rowan\textsuperscript{a}, K. T. Liao\textsuperscript{a}, R. Mumgaard\textsuperscript{b}, S. Scott\textsuperscript{c} and R. S. Granetz\textsuperscript{b}

\textsuperscript{a}Institute for Fusion Studies, The University of Texas, Austin, TX
\textsuperscript{b}MIT Plasma Science and Fusion Center, Cambridge, MA
\textsuperscript{c}Princeton Plasma Physics Laboratory, Princeton, NJ

bespam@physics.utexas.edu
Abstract

The spectral region in the vicinity of the D\textsubscript{α} line is to be studied with a high resolution spectrometer. This region contains spectral lines emitted by atoms in the diagnostic neutral beam (DNB) and plasma atoms and ions. Spectrally, temporally or spatially isolated emission serves as a measure of the properties of emitting particles and surrounding medium. In this way parameters such as beam energy and density distribution, toroidal and poloidal magnetic fields can be measured. In C-Mod, the main obstacle for application of these techniques is that at high magnetic fields (5-8T) the spectral separation due to motional Stark splitting is similar to the spectral Doppler shifts of lines emitted by DNB atoms of energies E\textsubscript{full} (50 keV), E/2, E/3 and E/16. This results in partial blending of observed spectral lines and consequent masking of Doppler or Stark effect. Therefore a high spectral resolution (~1-2Å) and a complex spectral fitting technique are needed for isolation of different components. Results of this work will be used in the further development of Beam Emission Spectroscopy (BES) system installed at C-Mod and in support for the current Motional Stark Effect (MSE) diagnostic.

Supported by USDoE Awards DE-FG03-96ER54373 and DE-FC02-99-ER54512
Summary and conclusions

1. Spectral region (6560-6680 Å) in the vicinity of the D$_\alpha$ line was studied with a high resolution (~2Å) spectrometer. Spectra collected through some poloidal and toroidal views were analyzed in detail.

2. The spectral region of interest contains red-shifted spectral lines emitted by atoms of the diagnostic neutral beam. If spectrally resolved, these lines provide the data for measurement of the plasma magnetic field (MSE) and beam energy and density distribution (BES).

3. This region is also contaminated by several impurity lines, which may complicate the spectral isolation of the beam emission lines. These impurity lines were identified and their intensities were quantified.

4. In its current state, the system allows for spectral isolation of the two red-shifted $\pi$-components of the full energy component. Current MSE-polarimetry system measures intensity and polarization of the same $\pi$-components.

5. The full energy $\sigma$-components can be identified with less accuracy, because these components are partially blended with beam components emitted by lower energy atoms and contaminated by other spectral features. Some of these features are analyzed elsewhere (see poster TP9.00086: K. Liao).

6. There are several ways to improve the system capability for identification of the beam emission.
   a) Increase density of the beam full energy component.
   b) Decrease spectrometer slit size from 90 to 50 μm. (higher resolution, but lower throughput)
   c) Use physical blocking of D$_\alpha$ instead of broadband filter. (sharper spectral edges)
   d) Use edge poloidal channels to look at blue-shifted beam spectral lines. (less spectral contamination by impurity lines)
   e) Decrease the amount of the carbon impurity in the tokamak (currently the main contaminant in the spectral region of interest).
Beam parameters: $V \sim$ up to 50 keV, $I \sim$ up to 7.5 A, $\tau \sim$ up to 1.5 sec (modulated)

- The source ions are accelerated to different velocities proportional to $m^{-0.5}$
- The ions are neutralized and converted to $H_0$ atoms (about 50% efficiency for full energy component)
- Remaining ions are separated from atomic beam by bending magnet
- Beam atoms are analyzed spectroscopically to infer the beam energy distribution
Beam simulation by ALCBEAM code

Some results of ALCBEAM simulation for shot 1101019028, time: 0.46-0.55 sec
Currently only 19% of the beam atoms have maximum energy (large E/3 component). DNBI ion source was recently changed and beam still need to be conditioned to achieve nominal parameters.
The light is collected by two optical periscopes: 20-channels poloidal periscope (shown in red) and 20-channels toroidal periscope (shown in blue) and transmitted through 30 transfer fibers to holographic imaging spectrograph (Kaiser f/1.8 Holospec).

- Fibers from MSE periscope can also be connected to the spectrometer (2 at a time)
- Spectrograph is set up to accept the light from up to 45 spatial channels and spectrally disperse them onto the CCD detector, while keeping them spatially separated.
Poloidal and Toroidal optical views

• “Poloidal optical views”
  20 chords are mainly poloidal with small toroidal components (18 active shown in red).

• “Toroidal optical views”
  20 chords have toroidal and poloidal components (8 active shown in blue).

• Chord separation for system is 1.2 cm

• The beam (green) is injected in the midplane of the tokamak and pivoted by ~7 degrees from the F-port axis.

• Spectra collected through chords B11, B5 and B10 (highlighted) are used in this work

• Shot: 1101015023
Fraction of the current associated with each of the extracted species is a measure of the beam performance.

Most of the plasma diagnostics produce improved results as the fraction of neutrals with full energy is increased.

Currently only 19% of the beam atoms have full energy.
A high resolution $H_\alpha$ grating is used to resolve the spectra in the vicinity of $D_\alpha$.

The role of the Andover bandpass filter (6570-6690 Å) is twofold: separate 3 spectra imaged onto the same row, attenuate $D_\alpha$ line (otherwise saturated).

A new smaller slit plate (90 µm slits) was installed in the spectrograph to increase system resolution (~2Å).
Comparison of two spectra collected from one of the toroidal chords which intersects the beam at $R=0.75\text{m}$

Shot: 1101019014, Beam off: $t=[1.17-1.27]$ sec, Beam on: $t=[1.27-1.37]$ sec

- $D_\alpha$ is strongly attenuated by broadband filter.
- Difference between these two spectra is the beam enhanced emission.
Comparison of two spectra collected from one of the toroidal chords B5(R=0.75m)
Shot: 1101019014, Beam off: t=[1.17-1.27] sec, Beam on: t=[1.27-1.37] sec
• Both spectra are reconstructed by dividing out the bandpass filter function.
• Difference between these two spectra is the beam enhanced emission.
• Difference spectrum shows some contribution from beam emission, as well as some beam
  enhancement of the D\(_\alpha\) line.
Averaged spectra among shots with similar beam and plasma conditions: 1101015027, 28, 26, 25

Every beam energy component is Doppler shifted. Vertical lines are the centers of each Zeeman/Stark component. (E: black, E/2: blue, E/3: red, E/16: yellow)

Zeeman and motional Stark splitting effects are applied for every energy component.

All spectral components are aperture and instrument broadened. (Bracco, JOSA, 71, 1318, 1981)

Current resolution is sufficient to resolve only some of the $E_{\text{full}}$ components.

In order to improve the resolution 50 um slits are needed and D-alpha should be isolated by physical block instead of the bandpass filter (see poster TP9.00086: K. Liao).
Impurity lines I

• Shot 1101015023. Poloidal channel B11 (R=0.85 m) (x-axis for plots on the right is the time in units of detector acquired frames)
• The observed line in the vicinity of 6578A. This line has the intensity several time higher than the bremsstrahlung background. About 10% of extra line enhancement due to the beam is also observed. This line can be identified as: C II -6578.05A
• The observed line in the vicinity of 6583A. This line has the intensity several time higher than the bremsstrahlung background. About 15% of extra line enhancement due to the beam is also observed. This line can be identified as: C II -6582.88A
Impurity lines II

• Shot 1101015023. Poloidal channel B11 (R=0.85 m) (x-axis for plots on the right is the time in units of detector acquired frames)
• The observed line in the vicinity of 6592Å. This line has the intensity similar to the level of the bremsstrahlung background. About 5% of beam enhancement is also observed. This line can be identified as: C I - 6591.46Å
• The observed line in the vicinity of 6603Å. This line has the intensity about 25% of the bremsstrahlung background. No consistent beam enhancement is observed. This line (set of lines) can be identified as: C I - 6602.41Å or Ar I - 6604.01Å or Ar I – 6604.85Å
**Impurity lines III**

- **Shot 1101015023. Toroidal channel B10 (R=0.83 m)** (x-axis for plots on the right is the time in units of detector acquired frames)
  - The observed line in the vicinity of 6611A. This line has the intensity about 50% of the bremsstrahlung background. About 10% of beam enhancement is also observed. This line can be identified as C I-6611.35A or N I-6611.40A.
  - The observed line in the vicinity of 6616A. This line has the intensity about 20% of the bremsstrahlung background. No consistent beam enhancement is observed. This line was not identified yet.

---

**Bremsstrahlung**

- **Dα 6561.0A**
- Line @ 6611A
- Line @ 6618A
Impurity lines IV

- Shot 1101015023. Toroidal channel B10 (R=0.83 m) (x-axis for plots on the right is the time in units of detector acquired frames)
- The observed line in the vicinity of 6622A. This line has the intensity about 20% of the bremsstrahlung background. No beam enhancement is observed. This line can be identified as: N I-6622.54A
- The observed line in the vicinity of 6627A. This line has the intensity about 10% of the bremsstrahlung background. No beam enhancement is observed. This line can be identified as: O II -6627.38A
Impurity lines V

• Shot 1101015023. Toroidal channel B10 (R=0.83 m) (x-axis for plots on the right is the time in units of detector acquired frames)
• The observed line in the vicinity of 6532A. This line has the intensity about 8% of the bremsstrahlung background. No beam enhancement is observed. This line can be identified as: Ar I -6632.08A
• The observed lines in the range of 6636-6644A. These lines have the intensity about 50%, 250%, 800% of the bremsstrahlung background. No beam enhancement is observed. These lines can be identified as: Ar II -6636.22A, Ar II -6639.74A, and Ar II -6643.69A
Proposed upgrade to combine CXRS and BES systems

- A new integrated CXRS/BES approach is proposed for C-Mod
- A multi-channel optical splitter spatially separates the BES emission of the beam atoms (Balmer-D_α at 6561.0 Å) from the CXRS emission of the B^4+ ions
- Two high resolution (~0.1 nm) high throughput holographic imaging spectrographs (Kaiser Holospec f/1.8) and two high speed, low noise CCD cameras - (Princeton Instruments Micromax and Photometrix Cascade II:512) (512 x 512 pixels) will be used to spectrally analyze the CXRS and BES emissions from all 42 optical channels.
Use of the beam emission to facilitate the CXRS analysis

Charge Exchange Recombination Spectroscopy (CXRS) radiance:

\[
L_{k}^{\text{CXRS}} = \int \varepsilon(n \rightarrow n'') \, dl = \frac{1}{4\pi} N_{k}(B^{5+}) \sum_{j=1}^{M} \left( \int N_{bj} \, dl \right) \times q_{j}^{\text{CXRS}}(n \rightarrow n'')
\]

Beam Emission Spectroscopy (BES) radiance:

\[
L_{k}^{\text{BES}} = \frac{1}{G_{k} \times A_{k}^{\text{BES}}} \int \frac{N_{ki}^{\text{CXRS}}}{K_{k}^{\text{CXRS}}(\lambda_{i}) \times \Delta t} \, di
\]

\[
L_{k}^{\text{BES}} (E_{j}) = \int \varepsilon^{\text{BES}}(E_{j}) \, dl = \frac{1}{4\pi} n_{e,k} \cdot \left( \int N_{bj} \, dl \right) \cdot q_{j}^{\text{BES}}(E_{j}, n_{e}, T_{i}, Z_{eff})
\]

\[
N_{k}(B^{5+}, He^{2+}) = \frac{n_{e} \times \left( \int \frac{N_{ki}^{\text{CXRS}}(E_{j})}{K_{k}^{\text{CXRS}}(\lambda_{i})} \, di \right)}{\sum_{j=1}^{M} \left( \int \frac{N_{ki}^{\text{BES}}(E_{j})}{K_{k}^{\text{BES}}(\lambda_{i})} \, di \right) \times \frac{q_{j}^{\text{CXRS}}(n \rightarrow n'')}{q_{j}^{\text{BES}}(E_{j}, n_{e}, T_{i}, Z_{eff})}}
\]

where \( N_{ki} \) [counts / pxl] is the number of CXRS photons detected in a given detector’s pixel \( i \) from a viewing channel \( k \)

\( K_{k}(\lambda_{i}) \) [counts / J] is the instrument response of the pixel \( i \) to the 1 J of radiant energy of wavelength \( \lambda_{i} \) collected by channel \( k \)

\( q_{j}^{\text{BES}}(E_{j}, n_{e}, T_{i}, Z_{eff}) \) is the rate coefficient of BES emission by beam atoms of energy \( E_{j} \)

\( q_{j}^{\text{CXRS}}(n \rightarrow n'') \) is the rate coefficient of impurity CXRS emission associated with beam energy component \( E_{j} \)

- The integrated analysis is simplified and its accuracy improved by the fact that the viewing geometry is the same for both systems (geometrical factors \( G_{k} \) are cancelled out)

1. Spectral region (6560-6680 Å) in the vicinity of the D\textsubscript{α} line was studied with a high resolution (~2Å) spectrometer. Spectra collected through some poloidal and toroidal views were analyzed in detail.

2. The spectral region of interest contains red-shifted spectral lines emitted by atoms of the diagnostic neutral beam. If spectrally resolved, these lines provide the data for measurement of the plasma magnetic field (MSE) and beam energy and density distribution (BES).

3. This region is also contaminated by several impurity lines, which may complicate the spectral isolation of the beam emission lines. These impurity lines were identified and their intensities were quantified.

4. In its current state, the system allows for spectral isolation of the two red-shifted π-components of the full energy component. Current MSE-polarimetry system measures intensity and polarization of the same π-components.

5. The full energy σ-components can be identified with less accuracy, because these components are partially blended with beam components emitted by lower energy atoms and contaminated by other spectral features. Some of these features are analyzed elsewhere (see poster TP9.00086: K. Liao)

6. There are several ways to improve the system capability for identification of the beam emission.
   a) Increase density of the beam full energy component.
   b) Decrease spectrometer slit size from 90 to 50 μm. (higher resolution, but lower throughput)
   c) Use physical blocking of D\textsubscript{α} instead of broadband filter. (sharper spectral edges)
   d) Use edge poloidal channels to look at blue-shifted beam spectral lines. (less spectral contamination by impurity lines)
   e) Decrease the amount of the carbon impurity in the tokamak (currently the main contaminant in the spectral region of interest)