Benchmark of Collisional-Radiative Models for ITER beams at Alcator C-Mod Tokamak.

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Beam-based plasma diagnostics on ITER need high accuracy and reliability. A valid collisional-radiative (CR) model is required for ITER high energy beams. Excited states and their sublevel populations are found to be essential for some of the beam diagnostics, such MSE and CXRS/BES, and dynamics of beam penetration. Although, an assumption of statistical populations among $m$-states is frequently used, its validity for high beams energies and high magnetic fields is doubtful. In addition, much attention should be paid to accuracies of cross-sections used. An appropriate non-statistical $nkm$-resolved CR model was recently prepared [1]. Here we report an empirical verification of this model in Alcator C-Mod and the short extrapolation to the relevant parameter range for ITER. Experiment was performed on Alcator C-Mod tokamak, which operates in a unique range of parameters, well suited for testing this model for ITER beams. Beam emission spectra were collected for a selected range of plasma parameters. The ratios $\sigma_1/\sigma_0$, $\pi_4/\pi_3$ and $\Sigma\sigma/\Sigma\pi$ were measured and compared to the $n$-resolved statistical population model and $nkm$-resolved non-statistical model. Measured ratios show apparent deviations from statistical model and reasonable agreement with non-statistical model.


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1. Injected neutral beams are extensively used in magnetic fusion research for heating and diagnostic purposes.

2. Beam excited states are critical for beam heating and beam-based diagnostics.

3. The \( n \)-resolved (statistical) models were found to be in relatively good agreement with measured beam attenuation [2, 3] and were able to explain the enhanced CX spectra [4, 5], but they were not able to reliably explain the measured beam spectra [6, 7].

4. A full \( nkm \)-resolved beam CR model is needed with revised \( nkm \)-resolved cross sections.

5. Recently, Marchuk [1] recalculated proton impact excitation cross-sections with the atomic-orbital close-coupling method and the Glauber approximation, which takes into account electric-field-induced ionization from highly excited states. Along with other recommended cross-section they were implemented into NOMAD CR code [8] and predicted a significant deviation from statistical model for ITER beams [9,10].

6. A benchmark of the model in ITER parameter range is needed.

7. Alcator C-Mod tokamak operates in a unique parameter range, which is the optimal test bed for testing the beam penetration models for ITER.

8. Here we present results of comparison of beam emission spectra measured at Alcator C-Mod with two theoretical predictions: \( n \)-resolved model with statistical population among the \( m \)-sublevels [11] and \( nkm \)-resolved model [9].
• BES spectrum was acquired through one of the toroidal core-CXRS channels.
• 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)
• Statistical population model was used for beam n=3 excited state [11]
• Measured spectrum did not agree with simulated spectrum.
• Inadequate population modeling and polarization sensitivity of the collection optic were expected to be the main reasons for the difference.
Diagnostic Neutral Beam on C-Mod*

Beam parameters: \( V \sim \text{up to } 50 \text{ keV}, I \sim \text{up to } 7.5 \text{ A}, \quad \tau \sim \text{up to } 1.5 \text{ sec (modulated)} \)

- Source ions are \( H^+, H_2^+, H_3^+ \) and possibly \( H_2O^+, H_3O^+ \) or \( CH_4^+ \)
- 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
- There are four distinct energy components: \( E, E/2, E/3 \) and (group of \( E/18, E/19, E/20 \))

*Thanks to Robert Granetz and Mo Chung (PSFC)
Beam simulation by ALCBEAM\textsuperscript{13}(v4.5)

- ALCBEAM unifies: ion beam formation, extraction and neutralization processes with beam attenuation and excitation in plasma and neutral gas and beam stopping by the beam limiters and tokamak walls, beam velocity distribution (new features)

“Toroidal optical views”
7 BES fibers, 148 slots* in MSE dissector (shown in purple).

- Min chord separation for system is 1.5 cm
- Polarization preserving MSE optics.
- The beam (green) is injected in the midplane of the tokamak and pivoted by ~7 degrees from the F-port axis.

Red chord – toroidal core-CXRS chord used in 2010

*Thanks to Bob Mumgaard (PSFC)
A high resolution H$_\alpha$ grating is used to resolve the spectra in the vicinity of D$_\alpha$

Andover bandpass filter (6570-6690 Å) separates 3 spectra imaged onto the same row

Blocking bar – to cut D$_\alpha$ line (6530-6600 Å) (otherwise saturated).

A new smaller slit plate (90 μm slits) was installed in the spectrograph to increase system resolution (~2Å)

*Thanks to Steve Scott (PPPL)
Beam tank $H_\alpha$ spectrum (bi-Gaussian fit)

- Beam $H_\alpha$ spectrum measured in the beam tank is a standard way to determine beam energy distribution.

- A standard positive-ion beam formation model assumes that beam has 3-4 discrete energy components.

- Realistic beams are represented by asymmetric distribution of kinetic energy, with most atoms at some fraction of the maximum energy and a decaying wing toward lower energies formed due to the partial acceleration of the ions.

- Once instrument broadened, each of the components is well approximated by two Gaussians: one at the center wavelength of the component and another one at the slightly shifted wavelength.

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**Energy fractions (by current of extracted ions), %**

- $H^+$: 72%
- $H_2^+$: 6%
- $H_3^+$: 23%
- $H_2O^+$: 19%

**Energy fraction (by density of atoms), %**

- $H\alpha$: 21%
- $H_2^+$: 6%
- $H_3^+$: 48%
- $H_2O^+$: 25%
Selecting C-Mod parameter for testing ITER beams

- Alcator C-Mod tokamak operates in a unique parameter range, which is the optimal test bed for testing the beam penetration models for ITER.
- Alcator C-Mod Ohmic plasma is optimal for comparison.
- A proposed ranges of parameters for ITER baseline discharge are shown below, along with relevant range of C-Mod Ohmic plasmas.
- Six C-Mod Ohmic discharges are selected for benchmark experiment.
- 92 spectral collected from 5 viewing chords cover the selected C-Mod parameter range to a great extend.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER</th>
<th>Alcator C-Mod</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$, pedestal to core, cm$^{-3}$</td>
<td>[0.9-1.35] 10$^{14}$</td>
<td>[0.6-1.36] 10$^{14}$</td>
</tr>
<tr>
<td>$E_{beam}$, keV/amu</td>
<td>100.0 and 500.0</td>
<td>50.0</td>
</tr>
<tr>
<td>$T_e$, pedestal to core, keV</td>
<td>2-15</td>
<td>0.4-2.5</td>
</tr>
<tr>
<td>$T_e/E_{beam}$</td>
<td>[2.0-15.0 and 0.4-3] 10$^{-2}$</td>
<td>[0.8-5] 10$^{-2}$</td>
</tr>
<tr>
<td>$B_{tor}$, T</td>
<td>4.0(outer edge)-5.3T(axis)</td>
<td>4.2(outer edge)-5.57(axis)</td>
</tr>
<tr>
<td>$Z_{eff}$</td>
<td>1.7-2.3 (He:1.7-2%, Be:2%, Ar:0.1-0.3%)</td>
<td>1.5-2.2 (B:1-2%, Ar:0.2%)</td>
</tr>
</tbody>
</table>
**H\textsubscript{\alpha} emission model**

- Linear Stark effect with quadratic correction for energy levels should be used for C-Mod and ITER. Quadratic corrections: for C-Mod – up to 1.5% , for ITER up to 1.5-5%.

\[
E_n = -\frac{R_y}{n^2} + \frac{3}{2} ea_0 E_L \times n \times (n_1 - n_2) - \frac{1}{16} \left(ea_0 E_L\right)^2 \times n^4 \times \left(17n^2 - 3(n_1 - n_2)^2 - 9m + 19\right)
\]

- Zeeman effect is also included as additional 1.5% correction for C-Mod, but may be neglected for ITER (0.15-0.75% effect)

- Linear Stark splitting (15 lines – 9 are significant intensity for this application):

\[\Delta \lambda_{\sigma(\pi)}(\hat{A}) = 0.277 \times (0_{\sigma}, \pm 1_{\sigma}, \pm 2_{\pi}, \pm 3_{\pi}, \pm 4_{\pi}, \pm 5_{\sigma}, \pm 6_{\sigma}, \pm 8_{\pi}) \times |E_L|\left(\frac{MV}{m}\right)\]

- Intensity of a Stark component: 

\[I_{\sigma(\pi)} = \Phi_{\sigma(\pi)}(\Theta) A_{if} P_i T_{\sigma(\pi)} \]

\[P_i – \text{population of the upper level}, \quad T_{\sigma(\pi)} \text{ – transmission of the optics of } \sigma \text{ and } \pi \text{ components}\]

- Ratios of the lines:

\[
\begin{align*}
I_{\sigma_1} &= \frac{A_{\sigma_1} P_{n_1-n_2=+1}}{A_{\sigma_0} P_{n_1-n_2=0}} \\
I_{\sigma_0} &= \frac{A_{\sigma_0} P_{n_1-n_2=0}}{A_{\sigma_0} P_{n_1-n_2=0}} \\
I_{\pi_4} &= \frac{A_{\pi_4} P_{n_1-n_2=+2}}{A_{\pi_3} P_{n_1-n_2=+1}} \\
I_{\pi_3} &= \frac{A_{\pi_3} P_{n_1-n_2=+1}}{A_{\pi_3} P_{n_1-n_2=+1}}
\end{align*}
\]

\[
I_{\Sigma\sigma} = \left(1 + \cos^2(\Theta)\right) T_{\sigma} \frac{\sum A_{if} P_i}{\sum A_{if} P_i} \\
I_{\Sigma\pi} = \frac{\sum A_{if} P_i}{\sin^2(\Theta)} T_{\pi} \frac{\sum A_{if} P_i}{\sum A_{if} P_i}
\]
Beam-into-gas and broadening effects

- Spectrum measured for beam injected into torus filled with neutral gas is used as a calibration measure.
- Beam energy distribution (bi-Gaussian fit) and broadening mechanisms: instrumental broadening, beam-angular divergence, finite lens and spot size and voltage ripple are identified and used for the beam-into-plasma spectral fit.
- Example below. D$_2$ pressure 1.6 mtorr. No magnetic field is applied.
Beam-into-plasma with magnetic field

- Since C-Mod magnetic field is high, magnitudes of Doppler and Stark shifts are comparable and Stark lines from all 4 energy components are heavily blended.
- However, $\sigma_0, +\sigma_1, \pm\pi_3, \pm\pi_4$ lines of full beam energy component that reside far on the red side of the spectrum and are adequately resolved for definitive study.
- 6-parameter spectral fit:
  - Intensity of each of the Stark component is proportional to the population density of the upper level.
  - Three independent population levels for main energy component were selected as independent parameters for the model.
  - Upper levels for E/2, E/3 Stark lines were set according to the population predicted by $nkm$-resolved model [1].
  - Total intensities of E/2 and E/3 are fit parameters.
  - Total intensity of E/18 component is fixed (from ALCBEAM simulation).

\[
\begin{align*}
1)P_i(E)(\sigma_0, \pm\pi_2), & \quad n_1 - n_2 = 0 \\
2)P_i(E)(\pm\sigma_1, \pm\sigma_5, \pm\pi_3), & \quad n_1 - n_2 = \pm1 \\
3)P_i(E)(\pm\sigma_6, \pm\pi_4, \pm\pi_8), & \quad n_1 - n_2 = \pm2 \\
4)R_{\sigma(\pi)} = \frac{T_\sigma}{T_\pi} & \quad \text{polarization sensitivity} \\
5)I(E/2): \text{intensity of E/2 component} \\
6)I(E/3): \text{intensity of E/3 component}
\end{align*}
\]
Beam-into-plasma with magnetic field (cont)

- Intensities of the lines are extracted from the fits and line ratios $\sigma_1/\sigma_0$, $\pi_4/\pi_3$ and $\Sigma\sigma/\Sigma\pi$ are used for comparison with theoretical predictions.

- Ratio of the sensitivity factors $R_{\sigma(\pi)} = T_\sigma/T_\pi$ is calculated from the fits and was found to be $1.018 \pm 4.6\%$, which is consistent with in-vessel calibrations of the polarization corrected MSE optics.

- Example of one of the fitted spectrum is shown below:
Ratios: $\sigma_1/\sigma_0$, $\pi_4/\pi_3$ and $\Sigma\sigma/\Sigma\pi$

- 92 spectra from 5 viewing chords and 6 plasma shots were analyzed and fit.
- Line ratios were extracted from the fits and compared to theory.

- In order to display the dependences of line ratios on magnetic field ($B_T$) and effective charge ($Z_{\text{eff}}$), we present $nkm$-resolved calculations for three cases: $(E=49\text{keV}, T_e=1.5\text{keV}, B_T=4\text{T}, Z_{\text{eff}}=1.0)$, $(E=49\text{keV}, T_e=1.5\text{keV}, B_T=6\text{T}, Z_{\text{eff}}=1.0)$, $(E=49\text{keV}, T_e=1.5\text{keV}, B_T=5\text{T}, Z_{\text{eff}}=2.0)$.
The measured line ratios show apparent deviation from $n$-resolved (statistical) model [11] and reasonable agreement with $nkm$-resolved model [9].

However, $\sigma_1/\sigma_0$, and $\Sigma \sigma/\Sigma \pi$ ratios show some apparent deviations from $nkm$-resolved model [9] for lower densities.
Extrapolation to ITER beams

- Differences of $\sigma_1/\sigma_0$, $\pi_4/\pi_3$ and $\Sigma\sigma/\Sigma\pi$ ratios from both $n$-resolved and $nkm$-resolved predictions are presented in the Table.
- Results are extrapolated to the ITER 100 keV/amu and 500 keV/amu ITER beams, assuming that line ratios scale according to $E_{\text{beam}}$ scaling of Marchuk $nkm$-resolved model predictions for ITER beams[9].

<table>
<thead>
<tr>
<th>Deviations from a model: $(A_{\text{exp}}-A_{\text{model}})/A_{\text{exp}}$ for $n_e=[0.6,1.0,1.3] \times 10^{20}\text{m}^{-3}$</th>
<th>Alcator C-Mod. 50 keV/amu</th>
<th>ITER prediction: 100 keV/amu beam</th>
<th>ITER prediction: 500 keV/amu beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A=\Sigma\sigma/\Sigma\pi$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-resolved (statistical)</td>
<td>-23%, -14%, -10%</td>
<td>-25%, -16%, -12%</td>
<td>-38%, -26%, 21%</td>
</tr>
<tr>
<td>nkm-resolved</td>
<td>-7%, -2%, -0.5%</td>
<td>-7%, -2%, -0.5%</td>
<td>-7%, -2%, -0.5%</td>
</tr>
<tr>
<td>$A=\sigma_1/\sigma_0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-resolved (statistical)</td>
<td>26%, 15%, 11%</td>
<td>31%, 21%, 17%</td>
<td>41%, 30%, 26%</td>
</tr>
<tr>
<td>nkm-resolved</td>
<td>14%, 6%, 3%</td>
<td>14%, 6%, 3%</td>
<td>14%, 6%, 3%</td>
</tr>
<tr>
<td>$A=\pi_4/\pi_3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-resolved (statistical)</td>
<td>16%, 13%, 10%</td>
<td>14%, 10%, 8%</td>
<td>20%, 16%, 14%</td>
</tr>
<tr>
<td>nkm-resolved</td>
<td>2.5%, 1.5%, 0.5%</td>
<td>2.5%, 1.5%, 0.5%</td>
<td>2.5%, 1.5%, 0.5%</td>
</tr>
</tbody>
</table>
Summary and conclusions

1. Beam penetration and emission models are being revised for ITER beams.
2. After reevaluation and critical assessment of available cross-sections a new \( nkm \)-resolved CR model was developed [1]. The model predicted large deviations of \( \sigma_1/\sigma_0 \), \( \pi_4/\pi_3 \) and \( \Sigma\sigma/\Sigma\pi \) for ITER beams [9,10].
3. To benchmark this model for ITER parameter range the experiment was performed on Alcator C-Mod tokamak.
4. Measured ratios show apparent deviation from \( n \)-resolved (statistical) model [11] and reasonable agreement with \( nkm \)-resolved model [9].
5. \( \sigma_1/\sigma_0 \), and \( \Sigma\sigma/\Sigma\pi \) ratios show some apparent deviations from \( nkm \)-resolved model for lower densities.
6. Measured difference between experiment and conventional \( n \)-resolved (statistical) model was extrapolated to 100 keV/amu and 500 keV/amu ITER beams and found to be:
   - 100 keV/amu: \( \Sigma\sigma/\Sigma\pi : 12-25\% \), \( \sigma_1/\sigma_0 : 17-31\% \), \( \pi_4/\pi_3 : 8-14\% \)
   - 500 keV/amu: \( \Sigma\sigma/\Sigma\pi : 21-38\% \), \( \sigma_1/\sigma_0 : 26-41\% \), \( \pi_4/\pi_3 : 14-20\% \)
   This deviations are even larger than \( nkm \)-resolved model [9,10] predicts:
References

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