Progress on the KSTAR beam emission spectra research

Under the CRP on
Experimental validation of atomic data for motional Stark effect diagnostics

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Scope of the project

Progress on the KSTAR beam emission spectra research

Under the CRP on Experimental validation of atomic data for motional Stark effect diagnostics

• High-precision measurements of beam-emission spectra from KSTAR discharges
• Development of a spectra analysis tool with a modulated interface for atomic data
Outline of the CRP activities

High-resolution spectrum measurements ($\Delta \lambda \leq 0.05$ nm)

- Mirror reflections
- Faraday rotation
- Polarized background
- Multi-ion-source injection

Spectral analysis

Existing (conventional) MSE
- Input for model validation
- Comparison with spectral analyses

Atomic models (NOMAD, ADAS etc)
Outline of the CRP activities

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- Main ion CX (Prelim.)

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Beam penetration (KSTARBEAM, $n_c(r)$)

Main ion CX
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- Main ion CX

Year 3 and beyond (2019 -)
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Origins and characteristics of polarized background light were identified.
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KSTAR now has an addition MSE system to simultaneously measure background.

Collaboration under MIT/PPPL US DoE project
Cross-check for both systems gives reasonable agreements.

- Odd channel fibers to K-MSE
- Even channel fibers to MSE-BP

KSTAR MSE
Since 2015

MSE-Background polychromator (BP)

KSTAR MSE
Single-detector type
(Conventional)

MSE-BP
Since 2019

Pitch Angle (deg)

R (m)

KTRMSE
MSE-BP

t = 2.5 s

1.8 1.9 2.0 2.1 2.2

-10 -8 -6 -4 -2 0 2

thu 19 may 2022, j ko, iaea-crp-neutral, remote (vienna, austria)
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- Main ion CX

High-resolution spectrum measurements ($\Delta \lambda \leq 0.05$ nm)

Spectral analysis

Existing (conventional) MSE
Beam-into-gas calibration that gets around the secondary neutral effects

- Intra-shot pitch angle scan (vacuum field scan) without careful pressure control.
- This limit was addressed in the 2nd IAEA-CRP meeting.

- Intra-shot pressure scan at constant pitch angle profile (vacuum field profile).
- Did this at only a single vacuum-field profile in 2019 → not enough for calibration.
- Multiple vacuum-field profiles in 2020 → too much machine time (5 hrs per MSE).
- Took advantage of a long-pulse machine;
- Extended the pressure scan, utilizing its ‘falling’ phase (and a new vacuum field profile is formed meanwhile).
- Can cover two sets of vacuum field profiles within a shot → run time reduced by a factor of two.
Pressure dependence (2ndary neutrals) is clearly demonstrated.

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- Can cover two sets of vacuum field profiles within a shot → run time reduced by a factor of two.
Faraday effect is dominant. Filter system works fine.

BT: 1.9  2.2  2.5  2.7

MSE polarization angle (deg)
22161, Ch07 (TF only)

pressure (mbar)

2018 data (high p)

2021b2g, Ch19, nbi1b085keV (3rd-order fit)

vacuum pitch (deg)

mse angle - vacuum pol (deg)
Faraday effect is dominant. Filter system works fine.

<table>
<thead>
<tr>
<th>Pressure (mbar)</th>
<th>MSE angle - vacuum pol (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>-2</td>
</tr>
<tr>
<td>90</td>
<td>-1</td>
</tr>
<tr>
<td>92</td>
<td>0</td>
</tr>
<tr>
<td>94</td>
<td>1</td>
</tr>
</tbody>
</table>

**MSE polarization angle (deg)**
- 22161, Ch07 (TF only)

**Pressure (mbar)**
- 10^{-5}
- 10^{-4}
- 10^{-3}
- 10^{-2}

**BT**
- 1.9
- 2.2
- 2.5
- 2.7

**Change in $\pi_3$ (nm)**
- 0.14 nm
- 0.04 nm

**2018 data (high p)**
- 1.8 (90k)
- 2.5 (90k)
- 3.2 (90k)
- 1.8 (85k,clean)
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Year 3 and beyond (2019 -)

Spectral analysis

High-resolution spectrum measurements ($\Delta \lambda \leq 0.05$ nm)

Atomic models (NOMAD, ADAS etc)

Existing (conventional) MSE
- Input for model validation
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Beam penetration (KSTARBEAM, $n_e(r)$)

Main ion CX
Per sightline
MSE signal source: NBI1-A

Filter functions

\[ f_A(\lambda) \]

\[ I_{\pi,A}^A = \int \sum_i \sum_C I_{i\pi}^{A,C} f_A(\lambda) d\lambda \]

\[ I_{\sigma,A}^A = \int \sum_j \sum_C I_{j\sigma}^{A,C} f_A(\lambda) d\lambda \]

\[ I_{\pi,A}^B = \int \sum_i \sum_C I_{i\pi}^{B,C} f_A(\lambda) d\lambda \]

\[ I_{\sigma,A}^B = \int \sum_j \sum_C I_{j\sigma}^{B,C} f_A(\lambda) d\lambda \]

MSE spectra

\[ I_{i\pi}^{S,C}, I_{j\sigma}^{S,C} \]

\[ i = \pm 2, \pm 3, \pm 4 \]

\[ j = 0, \pm 1 \]

\[ S = A \text{ or } B \]

\[ C = \text{ full, half, or third} \]

Filter functions

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\[ I_{\sigma,A}^B = \int \sum_j \sum_C I_{j\sigma}^{B,C} f_A(\lambda) d\lambda \]

Pitch angle profiles

\[ \gamma_A, \gamma_B \]

2nd and 3rd elements of the Stokes vector

\[ Q_A = I_{\pi,A}^A \cos(2\gamma_A) + I_{\sigma,A}^A \cos(2\gamma_A + \pi) + I_{\pi,A}^B \cos(2\gamma_B) + I_{\sigma,A}^B \cos(2\gamma_B + \pi) \]

\[ U_A = I_{\pi,A}^A \sin(2\gamma_A) + I_{\sigma,A}^A \sin(2\gamma_A + \pi) + I_{\pi,A}^B \sin(2\gamma_B) + I_{\sigma,A}^B \sin(2\gamma_B + \pi) \]

\[ \gamma_A^m = 0.5 \tan \left( \frac{U_A}{Q_A} \right) \]

\[ \Delta \gamma_A = \gamma_A - \gamma_A^m \]
As the filter rotates, the peak transmission and width distort.
2021 low and high mse angle profiles

Two reference profiles (low & high)

Low: 40 shots
High: 77 shots
alog10(abs(true angle - measured angle)), NBI1-B as the source

2.2T, Ch02, low & high pitch profiles

Safer regime

Allowed error
alog10(abs(true angle - measured angle)), NBI1-B as the source

1.5T, Ch01, low / high pitch profile
1.5T, Ch12, low / high pitch profile
1.5T, Ch23, low / high pitch profile

2.2T, Ch01, low / high pitch profile
2.2T, Ch12, low / high pitch profile
2.2T, Ch23, low / high pitch profile

2.9T, Ch01, low / high pitch profile
2.9T, Ch12, low / high pitch profile
2.9T, Ch23, low / high pitch profile
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**Year 3 and beyond (2019 -)**
- Beam penetration (KSTARBEAM, $n_c(r)$)
- Main ion CX
KSTAR run time dedicated to atomic data benchmark study during 2020 campaign

Proposed by
O. Marchuk, Yu. Ralchenko, D. R. Schultz, Ph. Mertens

Motivation:
• Deviation of statistical populations in MSE atomic levels and line intensities still observed in many machines (JET, Alcator C-Mod etc).
• No experimental data of MSE intensities in helium plasmas – No predictions and studies available for initial ITER plasmas.

Approach:
• Utilizing the KSTAR’s capability to measure high-resolution MSE spectra, obtain good-quality MSE spectra in helium and D plasmas.
• Comparison with polarimetric MSE results

KSTAR run time dedicated to atomic data benchmark study during 2020 campaign

- 3 out of 25 conventional MSE channels connected to spectrometer (Core / Mid-minor / Edge).
- One shot with density scan at 3.5T, 90 keV deuterium beam (Originally 4 shots given).
- No Te & ne measurements! (Apology to Sascha)
Spectral fit on MSE emission to infer vertical field at KSTAR

• Multi-Gaussian fit model on full energy component of MSE spectrum includes:
  – Asymmetry around $\sigma_0$ dependent of channel position.
  – Free parameters with constraints: relative intensities of MSE multiplets, Stark splitting, line broadening.
  – Fixed parameters: $B_t$, beam energy, viewing angle.
  – Linear background (including FIDA).
  – ‘Forward’ initialization

• Inferred $B_v$’s are compared with that from polarimetric MSE.
Spectral fit on MSE emission to infer vertical field at KSTAR at two ne values

25279, C2, 3.00-3.35s  
Goodness-of-fit: 16.7  
Bz = 0.0547 +/- 0.0082T

25279, C2, 7.00-7.35s  
Goodness-of-fit: 14.9  
Bz = 0.0691 +/- 0.0104T

25279, C15, 3.00-3.35s  
Goodness-of-fit: 32.2  
Bz = 0.2972 +/- 0.0059T

25279, C15, 7.00-7.35s  
Goodness-of-fit: 32.6  
Bz = 0.3138 +/- 0.0063T

25279, C23, 3.00-3.35s  
Goodness-of-fit: 19.4  
Bz = 0.2773 +/- 0.0055T

25279, C23, 7.00-7.35s  
Goodness-of-fit: 14.5  
Bz = 0.2616 +/- 0.0052T

ne = 1.8e19/m^3  
ne = 3.5e19/m^3

Measurement  
Total fit  
σ  
π  
Background
Reasonable agreement between polarimetric and spectral MSE’s

- Bv’s inferred from spectral MSE are overplotted with those from polarimetric MSE
- With slight offsets, Bv’s from spectral MSE exhibit similar sensitivity as those from polarimetric MSE over two different Bv profiles.

Next steps:
- Stabilize (automate) establishing initial conditions.
- Increase the number of ‘spectral’ channels.
- Apply and test more various plasma discharges (ITB etc).
- Cases of multiple ion-source injections? Will be very challenging.

Zoletnik et al. Nucl. Fusion, To be submitted
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Year 3 and beyond (2019 -)

Beam penetration (KSTARBEAM, $n_e(r)$)

Main ion CX
Last time, we mentioned the observation of main-ion CX components.
...which qualitatively broaden during high confinement regimes
Multi-Gaussian fit for main-ion CX interpretation done in addition to MSE fits

Thermal D_α & H_α
Main-ion D_α & H_α
FIDA + Background
Total fit
Experimental data

18739, F4, C20, 1.00-1.35s, 93/-3/0V, 2175mm
Ti = 0.364483 +/- 0.00682312 keV
Vi = 37.5817 +/- 0.547588 km
rcs = 18.112

18739, F6, C20, 2.00-2.35s, 100/-3/0V, 2175mm
Ti = 1.6819 +/- 0.028656 keV
Vi = 166.311 +/- 1.49847 km
rcs = 15.524

18739, F7, C20, 2.50-2.85s, 78/-3/0V, 2175mm
Ti = 0.137170 +/- 0.00138970 keV
Vi = 8.00000 +/- -0.000000 km
rcs = 30.030
Multi-Gaussian fit for main-ion CX interpretation done in addition to MSE fits.

18739, F4, C1, 1.00-1.35s, 93/-3/0V, 1748mm

Ti = 0.843571 +/- 0.00867041 keV
Vi = 50.5295 +/- 1.62785 km
rcs = 5.5560

18739, F6, C1, 2.00-2.35s, 100/-3/0V, 1748mm

Ti = 1.44941 +/- 0.108304 keV
Vi = 126.451 +/- 4.20845 km
rcs = 4.7311

18739, F7, C1, 2.50-2.85s, 78/-3/0V, 1748mm

Ti = 0.778592 +/- 0.00631016 keV
Vi = 35.9013 +/- 0.737629 km
rcs = 11.825

Bt = 1.79 T
Multi-Gaussian fit for main-ion CX interpretation done in addition to MSE fits.

- Rather challenging fit because the beam-off thermal components are included.
- Cross-section distortion and halo not included.
- Impurity-based CX data can be used as initial conditions.
- Full-channel measurements planned to confirm pedestal structures etc.
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Carbon density profiles obtained for the first time in KSTAR

- Last time, a brief introduction was made on the application of the ALCBEAM* code to KSTAR
- ALCBEAM has been modified (and renamed as KSTARBEAM) for the KSTAR beam configs.

$$n_C = \frac{4\pi \epsilon_{CX}^\lambda}{\sum_k \sum_j <\sigma_v>_{j,k} \int n_{b,j,k}(l)dl}$$

$\epsilon_{CX}^\lambda$: the charge exchange brightness at wavelength $\lambda$

$j$: beam energy components ($E, E/2, E/3$)

$k$: beam atoms excited levels

$<\sigma_v>_{j,k}$: the effective cross-section rate (from ADAS)

$dl$: the path length of diagnostic’s line of sight through the beam

$$n_{b,j}(z) = n_{b,j}(0) \exp \left(- \int (n_e(z)\sigma_{S,j}) dz \right)$$

$z$: distance along the beam trajectory

$n_{b,j}(0)$: the initial neutral beam density at the plasma boundary

$\sigma_{S,j}$: the effective beam stopping cross-section

J K Lee et al. AIP Advanced, 2022
Impurity accumulation during ELM-free phase has been observed

- KSTAR plasmas can suppress edge-localized mode (ELM) by applying the resonant magnetic perturbation.
- Carbon density profiles confirm the impurity accumulation during ELM-free while electrons are pumped out.

J K Lee et al. AIP Advanced, 2022
Future plans

- Retry the MSE spectrum measurements in 2022 KSTAR campaign with Te and ne measurements, and narrow slits (lots of nlm-resolved data!) – Dedicated run time allocated in July
- Apply the main-ion CX fit to recent (and upcoming) high-Ti KSTAR plasmas
- Reliable initialization in the MSE and main-ion CX fits
- Extend the spectral MSE to various advanced operation regimes (ITB etc) and the multi-ion-source injection cases and compare it with polarimetric MSE
- Revist the spectrum measurements from the gas with the beam and the field (for atomic physics data collections)
- Utilization of (Comparison with) NOMAD
Shot plan*: 7 shots with NB1A, NB2B, SMBI

• Ref: #29449**
  ✓ Obtained by J W Juhn in 2021
  ✓ 0.7 MA with SMBI, NB1A/B = 80/85 keV
  ✓ Record high $f_{GW}$ & ne (80% & 8.5e19)

• Initial modifications
  ✓ NB1A = 90 keV
  ✓ NB2B replaces NB1B to avoid beam spectral overlap
  ✓ Keep the fueling scheme

• MSE and other hardware
  ✓ MSE 3 channels to spectrometer/CCD
  ✓ Te and ne profiles necessary (TS, ECE)
  ✓ SMBI

• Shot 1: Re-achieve #29449
• Shot 2 / 3: NB1A = 90 keV / 60 keV
• Shot 4 / 5: NB1A = 90 keV / 60 keV with Ar 1%
  (Challenge to even higher $f_{GW}$)
• Shot 6: Ip = 1 MA, NB1A = 90 keV
• Shot 7: Ip = 1 MA, NB1A = 90 keV, Bt = 3.5T

**Alternative in case of no SMBI: #28844 (NB1A/B/C, NB2C, $f_{GW}$ = 74%)

• Expectations if successful:
  ✓ Obtain unique atomic physics data (main purpose)
  ✓ Obtain dataset for spectral MSE for ITER application
  ✓ Pursue record ne/$n_{GW}$ in KSTAR
SMBI Injection Test (#29449)

From 2021 KSTAR Summary
by J W Juhn
0.7 MA Discharge (#28844)

From 2021 KSTAR Summary by J W Juhn

$F_{GW} = 0.74$

Slice & Stack Cartoon
Toroidal Plasma

CH. #1
#2
#3
#4
#5

Peak Density Check
$1.09 \times 10$

$R = [1.78, 1.91]$
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