Measurement of the passive fast-ion D-alpha (FIDA) emission on the NSTX-U tokamak

G.Z. Hao, W.W. Heidbrink, D. Liu, L. Stagner (UCI)
M. Podesta, A. Bortolon (PPPL)

The 15th IAEA Technical Meeting on the Energetic Particles
Sep. 5-8, 2017
Princeton, USA
Outline

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- summary
FIDA diagnostic measures fast ion density profile through charge-exchange(CX) spectroscopy

- Fast ion exchanges an electron with the neutrals
  - active-FIDA: emission by CX between fast ions and commonly injected neutrals
  - passive-FIDA: FIDA emission related to background neutrals

- FIDA: collect the Doppler-shifted Balmer-alpha light

- Doppler shift of the emitted photon depends on the fast ion velocity
Basic parameters of NSTX-U

- Major/minor Radius $R_0 [m]$: 0.94/0.65
- Aspect Ratio $R_0/a$: $\geq 1.5$
- Plasma current [MA]: $\leq 2$
- Toroidal Field [T]: $\leq 1$
- NBI power [MW]: 12
Active and passive FIDA emissions can be monitored on NSTX-U

FIDA diagnostics:
- Space resolution: ~5 cm, with 16 channels cover 85~150 cm
- Temporal resolution: 10 ms for v-FIDA, 10 or 5 ms for t-FIDA
- Energy resolution: ~10 KeV
- The v/t-FIDA are most sensitive to the trapped and passing particles, respectively

Every line of sight (LOS) intersects the last closed flux surface and can measure p-FIDA light from the edge. While, only the LOS that intersects the injected beam can measure a-FIDA signal.
A brief schematic of FIDA system

- The light collected by the paired views passes through a bandpass filter, grating, filter strip and lenses before it is acquired by CCD camera in 2X16 spectral images.

- Typically, the cold D_alpha line is about a thousand times larger than the FIDA emission.

- Scattering of the D_alpha light by optical instruments can cause the contamination of the FIDA spectral...
Evidence of the existence of scattered light in measured raw signal

- The finite CCD counts are obtained at the boundary pixels of CCD, which is expected to be zero due to the presence of the bandpass filter in the optical system.

- The CCD counts at boundary pixels depend almost linearly on the cold D_alpha intensity summed over several dominant fibers.

- The scattering level is in the order of ~0.1% for the test case carried out on the table. In NSTX-U experiment, the scattering level may be different from this value.

- Singular value decomposition (SVD) method is used to make the scattering correction on the measured raw data.

After scattering correction, both FIDA spectra and spatial profiles get much better agreement with predictions from FIDASIM. This scattering method works reasonably well for most fibers, but fails in a few innermost fibers in some cases because those active and passive views intercept the divertor at different radii.

In the below presented signals, the scattering correction is carried out.
In this study, the typical discharge is a deuterium plasma in a low-confinement mode in a limiter configuration.

In the flat-top phase, the central density $n_e \sim 1.4 \times 10^{19}$, and temperature $T_e \sim 0.9$ keV.

Most results shown below are averaged over 5 cycles.
Model the FIDA signal with FIDASIM

- The a-FIDA simulation is standard: fast-ion distribution from NUBEAM output is sampled and the light produced by CX between fast ions and the injected and halo neutrals is computed.

- The p-FIDA simulation:
  - Axisymmetric populations of fast ions are employed;
  - Toroidally asymmetrical cluster of fast ions is ignored, since the born orbit of fast ion is far less concentrated toroidally than a typical DIII-D case [Bolte NF, 2016];
  - Fast ions expelled to the edge region are ignored, since the typical discharge is MHD-quiescent.
  - Uncertainty in the edge (i.e. background) neutral density is the dominant uncertainty in p-FIDA modelling.

Orbit of an 83 keV fast ion born from the 2A source.
Owing to the large gyro-radius of fast ions in spherical tokamak, fast-ion orbits do traverse the edge, which produces the appreciable p-FIDA signal in theory.

The background neutral density profile is computed by TRANSP code.
The experimental signals agree well with FIDASIM modelling

- The trend of the time evolution of the measured FIDA signals agrees well with the simulated results for both v- and t-FIDA for the chosen fiber (not for all fibers).

- The p-FIDA signal depends on the beam injection geometry:
  - For v-FIDA, the p-FIDA light is largest when more perpendicular source (1C) is injected; while, for t-FIDA, the p-FIDA signal is equally large when more tangential source (2A) injects

- For t-FIDA, the p-FIDA light is comparable to a-FIDA signal; p-FIDA contribution to the total signal is larger than that for the v-FIDA when active beam is injected.

Cycle-averaged FIDA signal for (b) t-FIDA and (c) v-FIDA. Red : a-FIDA plus p-FIDA signals; Blue : p-FIDA signal
Curves with and w/o error bars denote experimental and simulated results. Amplitude of simulated results is rescaled to match the measured total photons.
Passive signals are often comparable to active signals

- The p-FIDA signal of t-FIDA is generally comparable to a-FIDA. The passive contribution to the total signal for t-FIDA (when active beam is on) is larger than that for v-FIDA.

- The p-FIDA light of t-FIDA for more perpendicular sources is comparable to that for more tangential beam sources.

- During 2C blips, sawteeth occur, which is likely the reason for the poor agreement between the active and reference view signals of t-FIDA during 2C blips.

Database results from the blip shots. Each sample represents one time slice in the database. Red: active view data; Blue: ref. view data.
The bumps in the spectra related to the non-fully slowed-down distribution (shown in next slide) of fast ions is measured. This features are less prominent on outer fiber (R=117 cm) than on the inner channel (140 cm).

FIDASIM predictions successfully describe the measured bumps in the spectra.

Cycle-averaged spectra of p-FIDA signal measured on the t-FIDA active views during beam-2A on (red) and 2A off (blue) at (a) R=140 cm and (b) 117 cm. (c,d) Difference between the beam-on and the beam-off spectra (red) and the FIDASIM simulation (black).
Non-fully slowed-down distribution of fast ions has local maxima in phase space.
For monitoring passing fast-ion dynamics in time using active beam method, p-FIDA contribution should be subtracted on NSTX-U

- The experimental spectra agree well with simulated results for the inboard beam-source(1C) injection.
- At the $R=140$ cm chord, the a-FIDA emission (black curve in (c)) is almost zero. For both the active and reference views, the measured signals are mainly produced by the passive FIDA emission.
- At the $R=117$ cm, the p-FIDA is comparable to a–FIDA as shown in (f)
- For monitoring passing fast-ion dynamics in time using the active beam method, P-FIDA contribution should be subtracted for inboard beam injection.
The p-FIDA signal is larger at the edge.

P-FIDA increases with major radius in the region \( R > 127 \text{ cm} \).

Experimental radial profiles of integrated p-FIDA signal agree well with FIDASIM prediction.

Integration of the cycle-averaged p-FIDA signal of t-FIDA. Amplitude of simulated results is rescaled to match the measured total photons.
Time-slice method yields larger a-FIDA signal than reference view method due to time-evolving passive contribution.

- Time-slice method ignores the evolution of the p-FIDA emission in the neighbor time slices during beam modulation.
- For the reference view method, the p-FIDA emission is monitored in time and p-FIDA contribution is successfully removed.
- When using time-slice subtraction to determine a-FIDA emission in the presence of time-evolution of p-FIDA signal, care must be taken to correct for the temporal variation of p-FIDA signal.
Summary

- Passive FIDA light makes a relatively large contribution to the total FIDA signal in NSTX-U. Four features of the signals are consistent with the modeling of the p-FIDA light.
  (i) The time evolution of the signals agree well with theory
  (ii) The p-FIDA signals show the expected dependence on beam injection angle
  (iii) The spectra agree with the theoretical prediction for both inboard and outboard beam injection
  (iv) The radial profile agrees with the theory prediction

- The p-FIDA signal is detectable for fast ions in the edge region. The p-FIDA technique may be employed to monitor the fast-ion dynamics in the edge region, as long as the bremsstrahlung emission is not too strong to drown out FIDA emission.

- When p-FIDA light is appreciable and time evolving, a reference view is needed to measure the active FIDA emission.

- For more precise modeling of the p-FIDA emission, a two- or three-dimensional calculation of the edge neutral density is required. This, however, is left for future work.