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FIDA diagnostic modeling using FIDASIM for observation of fast-ion distribution function during neutral injection in the TUMAN-3M tokamak

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The software package was created to generate a complete set of input parameters for modeling in the FIDASIM code with using codes ASTRA/NUBEAM. This code may allow to interpret the measured spectra obtained during experiments with Fast-Ion D-Alpha diagnostics (FIDA), and to isolate the useful FIDA signal from excess radiation. A qualitative comparison of the synthetic and calculated spectra was made, based on the modeling results. The comparison showed similarity in the short-wavelength part of the signal, which may confirm the presence of FIDA radiation in the experimental spectrum.

Keywords: Fast ions, Fast-Ion D-Alpha Diagnostics, Neutral Injection.

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High-energy ions of hydrogen isotopes are present in most current experiments on controlled thermonuclear fusion. Fast ions (FIs) may be produced in tokamak plasma as a result of fusion reactions and plasma heating by neutral-beam injection (NBI) or via radio-frequency heating. Data on the behavior of FIs are important, since their tight confinement is needed to reach high temperatures of core plasma and, consequently, attain thermonuclear fusion. At the same time, FIs may induce build-up of various instabilities, worsening the FI confinement.

The distribution function of FIs should be examined in order to understand their behavior. It is studied with the use of various diagnostics, of which FIDA (Fast-Ion D-Alpha) is an example [1]. FIDA is a spectroscopic diagnostic based on the reaction of charge exchange between deuterium FIs and atoms of an injected beam. FIs capture an electron into an excited quantum state and neutralize. The produced neutral particle has the velocity of an FI and emits line radiation. FIDA radiation originates at the intersection of an atomic beam, the FI localization region, and the direction pattern of an optical instrument, ensuring fine localization of measurements. Other radiation sources detected by the diagnostic are also present in the examined wavelength range: radiation of atoms of the heating beam (the result of their electron-impact excitation), the so-called halo (produced in the process of charge exchange between thermal plasma ions and injected atoms), pFIDA (the result of charge exchange between FIs and background neutral particles), bremsstrahlung radiation, unshifted H_α (D_α) emission lines (the result of electron-impact excitation of cold neutral particles coming from the wall and from the working gas supply system), and impurity lines. This complicates the task of isolating the FIDA signal from the measured spectrum. This diagnostic is currently used widely in numerous experiments throughout the world: DIII-D, ASDEX Upgrade, TCV, MAST, etc. [2,3]. The TUMAN-3M tokamak also belongs to this group of experimental setups.

Experiments on measurement of radiation of charge-exchange atoms were performed at the TUMAN-3M tokamak in different geometries [4]. The FIDA diagnostic at the TUMAN-3M tokamak currently features only one adjustable line of observation. A beam of neutral atoms is injected tangentially to the plasma current with impact parameter $b = 42\,\text{cm}$ (Fig. 1, a). It was determined in preliminary experiments that the optimum geometry is the one with the line of observation being almost perpendicular to the line of injection of neutral particles, since the influence of the Doppler shift of radiation of excited atoms of the injected beam is suppressed in this case. The angle between the line of observation and the FI beam velocity vector is roughly 60°. A beam of hydrogen with an energy up to $22\,\text{keV}$ was injected in experiments into hydrogen plasma. Hydrogen was chosen to be the injected element for the fact that the Doppler shift of hydrogen lines is $\sqrt{2}$ times greater than the corresponding shift of deuterium lines at the same energy. This should facilitate the search for FIDA signals and their interpretation. The obtained experimental spectrum (solid curve in Fig. 2) was used in subsequent studies for comparison with a model one.

In order to interpret experimental signals from FIDA diagnostic measurements, expected spectra are modeled numerically with account for all effects producing radiation within the given wavelength range. Modeling was

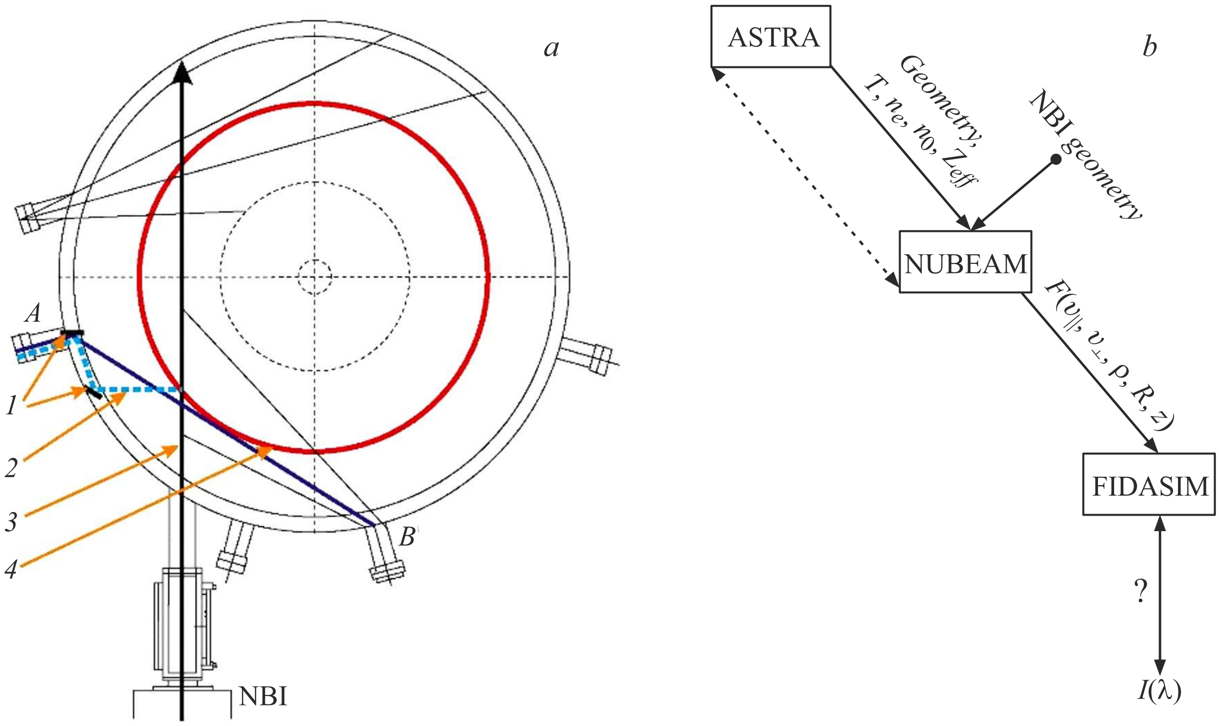

Figure 1. *a* — Geometry of FIDA diagnostic measurements at the TUMAN-3M tokamak. *1* — Periscope with two mirrors; *2* — line of observation, which is perpendicular to injection (dashed line); *3* — NBI line (impact parameter is the distance from the chamber center to the injection line); *4* (circle drawn in bold) — region of localization of the majority of fast ions produced as a result of ionization of atoms of the heating beam. All three lines should intersect at a single point for the diagnostic to be efficient. *b* — Block diagram of FIDA diagnostic modeling (relation between the FIDASIM computation code with ASTRA and NUBEAM codes).

performed with the use of the FIDASIM open-source code [5] that is written in Fortran90 and implements the Monte Carlo method. FIDASIM requires a large array of input data containing the spatial distribution of plasma parameters (electron and ion temperatures, densities of plasma and neutral particles, effective charge, etc.), the FI distribution function, the data on equilibrium in a discharge, the geometry and parameters of neutral injection, the data on lines of observation, etc. When working with FIDASIM, one needs to specify the sources of required input data and their interrelations. The ASTRA [6] and NUBEAM [7] codes were used for this purpose in the present study. The block diagram of synthesis of model diagnostic spectra is presented in Fig. 1, *b*.

FIDASIM works natively with output files of the TRANSP code. However, its proprietary nature and complexity prevent one from applying it in modeling of discharges at the TUMAN-3M tokamak. The ASTRA transport code is used to model plasma profiles, while the NUBEAM code is used to perform Monte Carlo modeling of the behavior of FIs produced as a result of neutral injection. Plasma profiles (temperature T, electron n_e and neutral n_0 densities, and effective charge Z_{eff}) are first calculated in ASTRA and then transferred to NUBEAM. The model of an atomic injected beam (injection energy and power, fractions of current for components with a full/half energy, impact parameter value, etc.) and the shape of magnetic surfaces are also introduced into NUBEAM. The output parameters of two codes (ASTRA and NUBEAM), namely, the spectral diagnostic geometry and distribution function F, which depends on coordinates z (in the vertical direction), R (along the major radius), and ρ (along the magnetic surface radius) and parallel $v_{\parallel}$ and transverse $v_{\perp}$ components of the velocity of a fast particle, are interrelated, allowing one to obtain a synthetic FIDA spectrum by performing calculations in FIDASIM. The results of modeling are compared with experimental data to determine the accuracy of the FI distribution function that was calculated earlier. In the present study, a basic algorithmic procedure utilizing the direct scheme (ASTRA–NUBEAM–FIDASIM) was compiled.

With interrelations between the key stages of calculation established, a typical discharge was modeled with the ASTRA transport code. Known experimental parameters (chamber geometry, plasma current, toroidal magnetic field, etc.) were introduced into ASTRA, and the same transport code was used to calculate the profiles of variables of interest: density of the neutral component, electron density, and ion and electron temperature (Fig. 3, *a*). The effective

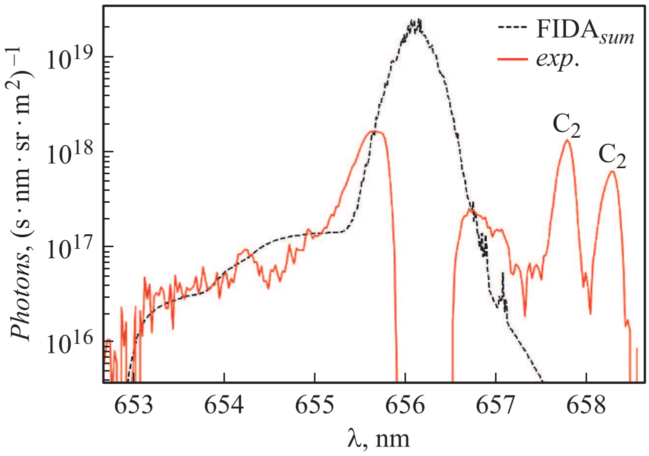

Figure 2. Comparison of spectra obtained in experiments (discharge 22071914) (solid curve) and via modeling with FIDASIM (dashed curve). The typical plasma parameters in experiments are as follows: $B = 0.7-1$ T, $I_p = 130-150$ kA, $n = (0.7-3.5) \cdot 10^{19}\,\mathrm{m}^{-3}$, $E_{\mathrm{NBI}} = 14-30$ keV, and $t_{\mathrm{NBI}} = 20-60$ ms. The emission of unshifted line H_α at the boundary is very bright. A special template filter for radiation suppression, which rejects the central peak of the experimental spectrum, is used in order to prevent saturation of the CCD array at the wavelength of this line.

charge was determined from the conductivity of plasma and was considered to remain constant along the radius and equal to $Z_{eff} = 1.6$. The NUBEAM code, which is designed to model the injection of a beam of neutral atoms into tokamak plasma, was then used to calculate a test FI distribution function depending on the energy, pitch angle, and coordinates of a particle. An example model FI distribution function corresponding to the TUMAN-3M tokamak and two time points (0.3 and 30 ms from the start of injection) is shown in Fig. 3, *b*. It is evident that three peaks observed at the initial moment of time, which correspond to the full energy, one half of it, and a third of the energy, eventually transform into three steps. As FIs get decelerated, the fraction of particles with energies lower than the initial one increases, and the trail of each peak overlaps with preceding peaks. At the same time, the presence of „steps" is indicative of relatively good FI confinement: in the contrary case, when the characteristic confinement time is shorter than the thermalization time, „steps" are replaced by fairly narrow peaks [8,9].

To get FIDASIM modeling started, a utility program combining all the produced data into resultant files was updated. These files contain data on the magnetic configuration; the temperature and concentration of plasma, magnetic fields, and FI distribution functions interpolated onto this configuration; the geometry of the injected beam of neutral particles and modeling setup parameters; and the fractional energy composition of the beam: E — 44%, $E/2$ — 32%, $E/3$ — 24%. This energy spectrum is close to the one measured based on the Doppler shift of emission of line H_α (D_α) in the case of beam injection into the tokamak chamber filled with a neutral working gas (without a plasma discharge) and in the geometry of observation from the beam „tail" with an AvaSpec-2048 spectrometer. In addition, the geometry of optical spectral FIDA measurements was modeled (this required an accurate calculation of the position and direction of the line of observation), and the corresponding calculation in FIDASIM was performed.

The dashed curve in Fig. 2 represents the calculated spectrum obtained with the use of FIDASIM: the combined detected signal of sources in the given wavelength range of the beam (active FIDA signal, passive FIDA signal, bremsstrahlung radiation, emission of beam atoms, emission of the direct charge exchange and the halo, and emission of cold neutral atoms). The modeled passive FIDA signal turned out to be stronger than the active one. This implies that light is emitted not from a local region along the beam, but from the entire observed volume. This dominance of the passive signal over the active one may be caused by the use of an overstated value of neutral density in calculations. In addition, the orientation of the line of observation, which is directed at a gas feed valve, contributes to an increase in the passive FIDA signal amplitude in experiments. The results of the first comparison of model (dashed curve) and experimental (solid curve) spectra are presented in Fig. 2. It can be seen that experimental and calculated signals agree well in the short-wavelength wing of FIDA radiation. This may be indicative of the presence of emission of fast charge-exchange atoms in the experimental spectrum. The central dip in the experimental spectrum corresponds to the emission of cold neutral atoms that was suppressed by the template filter. Two carbon lines are located to the right of it. The current version of FIDASIM does not allow one to calculate the emission of impurities. It should be noted that FIDASIM calculates both the useful FIDA signal and the level of bremsstrahlung radiation. However, the noise level (constant bias) of the CCD array of the camera in experiments exceeded the bremsstrahlung signal level, making it impossible to compare calculated and experimental spectra quantitatively.

In order to perform a qualitative test of calculations of the FI distribution function, additional calculations of the neutron yield for a discharge with deuterium injection into deuterium plasma and of the FI density based on the obtained distribution function were carried out using the FIDASIM code. The results revealed a satisfactory agreement with experimental fluxes of neutrons and fast neutral atoms measured by charge-exchange atom analyzers ($1.2 \cdot 10^{11}$ neutrons) [10,11]. An example calculated FI density map is shown in Fig. 3, *c*.

As is known, FI confinement may be affected significantly by various kinds of processes, such as the charge exchange with background neutral atoms, instabilities, orbital losses in collisions, etc. In the present study, one probable loss mechanism (the influence of radial electric field E_r

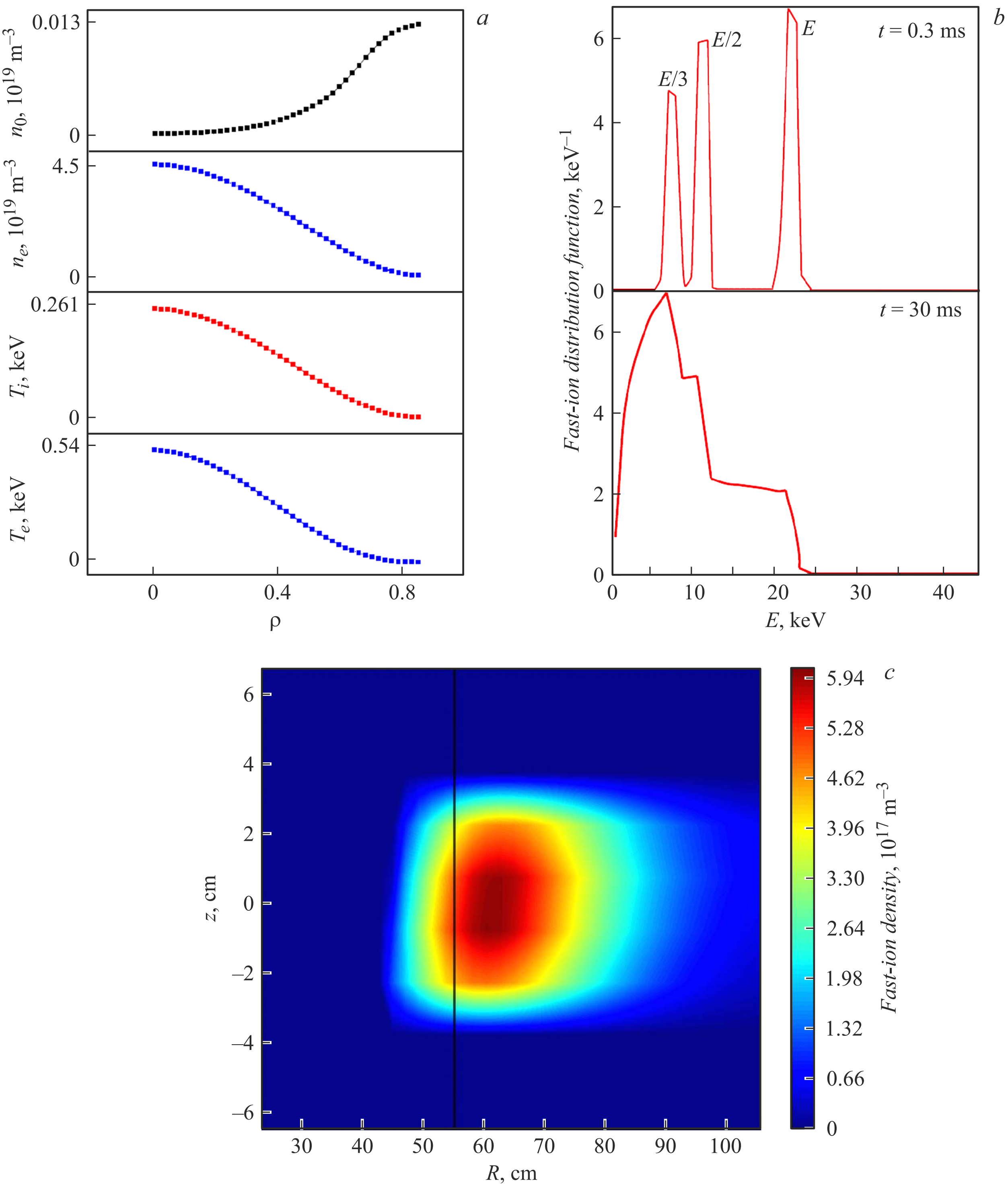

Figure 3. Input parameters of the diagnostic that are needed to calculate a spectrum. *a* — Profiles of plasma parameters calculated with the ASTRA code (from top to bottom: density of background neutral particles, electron density, ion temperature, and electron temperature). *b* — Typical FI distribution function calculated with the NUBEAM code at time points of 0.3 and 30 ms. *c* — FI density estimate calculated with the FIDASIM code. The major radius is plotted on the abscissa axis, and the vertical shift of produced FIs is plotted on the ordinate axis. The color gradient represents FI density. The black vertical line denotes the center of the chamber. The density of fast particles reaches its maximum in the region with $R \approx 59$ cm. A color version of the figure is provided in the online version of the paper.

produced in the periphery of a filament in an L–H transition or in the central part of plasma under injection heating [12]) is considered. However, the effect of an L–H transition and associated field E_r on the spectrum and intensity of the FIDA signal at the TUMAN-3M tokamak was found to be insignificant, which may be attributed to the fact that most FIs are localized near the center of plasma. In order to verify this assumption, FI trajectories were modeled with and without peripheral radial electric field $E_r = -3\,\text{kV/m}$ (typical of the H mode at the TUMAN-3M tokamak). As expected, the introduction of such a field leads to slight distortion of just the trajectories of strongly trapped ions that approach the plasma boundary. These ions should not exert any significant influence on the FIDA signal.

Thus, it may be concluded that the developed software package provides a satisfactory qualitative description of FIDA signals recorded at the TUMAN-3M tokamak. The sensitivity of recording equipment needs to be increased (so that the signal of bremsstrahlung radiation from plasma exceeds the level of noise of the CCD array of the camera) in order to perform a quantitative comparison in the future. A CCD array with a better signal-to-noise ratio (e.g., a cooled array) will be used for this purpose.

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Conflict of interest

The authors declare that they have no conflict of interest.

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