Extensions of FIDASIM capabilities: Passive signals, 3D geometry and neutron collimator signals

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I. Motivation and introduction to FIDASIM

II. (a) Cold neutral and passive signal capabilities

II. (b) NSTX-U passive FIDA modelling benchmark and TCV passive NPA signals

III. 3D geometry capabilities and validation with FIDA measurements on LHD

IV. (a) Weight functions produced by FIDASIM and their relevance for Orbit Tomography

IV. (b) Neutron collimator weight functions and benchmark with uniform inputs
Motivation for FIDASIM upgrades

- FIDASIM is internationally used to model FIDA and NPA signals
- Experiments have shown that signals from cold neutrals can be as important as signals from injected neutrals\(^1\)\(^–\)\(^6\)
- 3D capability is needed to study fast ion confinement in stellarators and in tokamaks with ELM-control coils
- Modelling FIDA, NPA and neutron collimator signals in a common framework is favorable for orbit tomography

**Purpose of this work:** Upgrade FIDASIM to treat cold neutral effects, 3D configurations and neutron collimator signals

1. Hao, PPCF 60 (2018) 025026
2. Heidbrink, PPCF 63 (2011) 085007
3. Geiger, PPCF 59 (2017) 115002
5. Bolte, NF 56 (2016) 112023
Fast-ion $D_\alpha$ (FIDA) and Neutral Particle Analyzer (NPA) diagnostics measure the fast-ion distribution.

https://d3denergetic.github.io/FIDASIM/
FIDASIM is a synthetic diagnostic code that simulates FIDA and NPA signals.

- FIDA and NPA measure the fast-ion distribution function.
- Forward modelling predicts FIDA & NPA signals to compare with measurements\(^1\).

Theoretical Fast-ion Distribution

- Charge exchange is modelled, and the FIDA radiance & NPA flux are calculated.
- More required inputs:
  - Plasma profiles
  - Electromagnetic fields
  - Diagnostic geometry

\(^1\)Heidbrink, CCP 717 (2011)
FIDASIM can model the signal produced from multiple light sources

Beam emission (Full, Half, Third)

Bremsstrahlung

DCX and Halo

Cold neutral emission

Active Fast-ion $D_\alpha$ (FIDA)

Passive Fast-ion $D_\alpha$ (p-FIDA)
Passive signals improve understanding on the fast-ion distribution and neutral density profile

<table>
<thead>
<tr>
<th>Active vs. passive signal distinction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Type</td>
</tr>
<tr>
<td>Active</td>
</tr>
<tr>
<td>Passive</td>
</tr>
</tbody>
</table>

- Passive signals must be treated to get valid active FIDA data
- Simulating passive signals provides quantitative information on fast-ion losses that may be a challenge for ITER
- P-FIDA signals are enhanced when fast ions are expelled to the edge by instabilities
- Neutral density profile may be found from a known fast-ion source with passive measurements

1 Bolte, NF 56 (2016) 112023
2 Hao, PPCF 60 (2018) 025026
FIDASIM reads in cold neutral density, calculates their atomic states and predicts passive signals

- FIDASIM accepts 2D and 3D cold neutral density input
  - TRANSP variable \(dn0wd\)

- Atomic state calculations
  - Assume ground state, \(f_1 = 1\), for all cold neutrals
  - Use the local plasma parameters to iteratively solve the collisional radiative model (COLRAD)
  - Once equilibrium is achieved, distribute neutrals throughout the interpolation grid

- Perform passive calculations in a cylindrical grid

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Time evolution of neutral population fluxes for initial condition \(f_1 = 1\) (solid) and \(f_3 = 1\) (dashed). The fluxes are normalized to unity at each time step\(^1\). Equilibrium is achieved quickly in both cases.

\(^1\)Stagner, (Thesis) UCI (2018)
Passive-FIDA signals are comparable in magnitude to active-FIDA signals at NSTX-U

- P-FIDA spectra are measured and simulated on NSTX-U\(^1\)

<table>
<thead>
<tr>
<th>Experimental Parameters(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Species</td>
</tr>
<tr>
<td>(T_e)</td>
</tr>
<tr>
<td>(n_e)</td>
</tr>
<tr>
<td>(n_f)</td>
</tr>
<tr>
<td>(n_n)</td>
</tr>
<tr>
<td>(P_{\text{NBI}})</td>
</tr>
<tr>
<td>(B_T)</td>
</tr>
<tr>
<td>(I_p)</td>
</tr>
</tbody>
</table>

- TRANSP 1D neutral density output is used in this modelling\(^2\)
- Shapes of measured spectra are in agreement with simulated spectra

\(^1\)Hao, PPCF 60 (2018) 025026
\(^2\)Geiger, PPCF 59 (2017) 115002

2D passive-FIDA modeling done on NSTX\(^1\). Thin and thick line is experiment and simulation, respectively
FIDASIM p-FIDA capability is benchmarked with 2D passive-FIDA modeling done on NSTX

- Plasma, fields, geometry and fast-ion distribution function from the NSTX passive modelling study are reused in this benchmark
- P-FIDA spectra are wavelength integrated between 650.8–654.0 nm
- Good agreement between time series data
In TCV, passive signals can exceed active signals

- TCV is a fairly small tokamak with relatively large orbits and deep neutral penetration

- The calculated passive flux exceeds the active flux for the tangentially viewing compact NPA

- Passive FIDA signals are also large

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2. Geiger, PPCF 59 (2017) 115002
Interpolation grid is extended to 3D by accepting toroidal variable $\phi$

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Interpolation Grid Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>R, Z</td>
</tr>
<tr>
<td>$n_\phi = 1$</td>
<td></td>
</tr>
<tr>
<td>$\phi = 0$</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>R, Z and $\phi$</td>
</tr>
<tr>
<td>$n_\phi &gt; 1$</td>
<td></td>
</tr>
<tr>
<td>$\phi \in [-\pi, \pi)$ or $\phi \in [0, 2\pi)$</td>
<td></td>
</tr>
</tbody>
</table>

- Unless the user provides $\phi$ variable information, FIDASIM will default to an axisymmetric configuration.

- In both cases, the code maps the fields, plasma parameters and fast-ion distribution function onto the interpolation grid.
Diagnostic grids are incorporated into FIDASIM

<table>
<thead>
<tr>
<th>Signal</th>
<th>Diagnostic Grid Name</th>
<th>Coordinate System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active FIDA, BES, DCX, Halo, Cold</td>
<td>Beam</td>
<td>Cartesian</td>
</tr>
<tr>
<td>Active NPA</td>
<td>Beam</td>
<td>Cartesian</td>
</tr>
<tr>
<td>Passive FIDA</td>
<td>Passive neutral</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Passive NPA</td>
<td>Passive neutral</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Neutron Collimator</td>
<td>Neutron</td>
<td>Cylindrical</td>
</tr>
</tbody>
</table>

• Generating diagnostic grids from user defined inputs optimizes the calculations performed by FIDASIM

• Cylindrical diagnostic grids are created as follows
  ○ If the interpolation grid is 3D, then the diagnostic grid is the interpolation grid
  ○ Otherwise, the code will generate a cylindrical grid specific to the geometry of the diagnostic and its intersection with the plasma boundary

• Diagnostic grid settings are written to the output file for the user
FIDA signals predicted by FIDASIM from 3D inputs agree with FIDA measurements on LHD

**Experimental Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>Deuterium</td>
</tr>
<tr>
<td>$T_e$</td>
<td>$\sim 1$ keV</td>
</tr>
<tr>
<td>$n_e$</td>
<td>$\sim 10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>$P_{NB1}$</td>
<td>0.8 MW</td>
</tr>
<tr>
<td>$B_T$</td>
<td>2.75 T (counter)</td>
</tr>
<tr>
<td>$R_{ax}$</td>
<td>360 cm</td>
</tr>
<tr>
<td>$B_q$</td>
<td>100 %</td>
</tr>
<tr>
<td>Gamma</td>
<td>1.354</td>
</tr>
</tbody>
</table>

1Fujiwara, P1 63, IAEA (2019)

**FIDASIM Sensitivity Study**

- Predicted FIDA spectra from scaled inputs are compared with spectra from unmodified inputs

$$\left(\frac{FIDA_{scaled} - FIDA_{baseline}}{FIDA_{baseline}}\right) \times 100\%_{LOS}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Percent difference for $parameter \times (-15%)$</th>
<th>Percent difference for $parameter \times (+15%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$</td>
<td>+1.81%</td>
<td>-2.44%</td>
</tr>
<tr>
<td>$T_e$</td>
<td>-0.81%</td>
<td>+1.17%</td>
</tr>
<tr>
<td>$T_i$</td>
<td>+5.73%</td>
<td>-2.96%</td>
</tr>
<tr>
<td>$Z_{eff}$</td>
<td>+2.87%</td>
<td>-4.60%</td>
</tr>
</tbody>
</table>
Weight functions describe a diagnostic’s sensitivity to phase space

- **Signal** \( S \equiv S = \int dX W(X)F(X) \)
  - \( X \) is phase space
  - \( W \) is the weight function
  - \( F \) is the distribution function

- For example, the expected diagnostic signal in velocity space is\(^1\)
  - \( S = \iint dpdE W(E,p)F(E,p) \)

- \( W \) can be computed with a forward model
  - FIDASIM calculates FIDA and NPA velocity space weight functions
  - Assuming \( F \) is a delta function, \( W \) is the average signal produced by a fast ion with a given energy and pitch\(^2\)

\[
W(E,p) = \frac{1}{2\pi} \int d\gamma dR dZ d\phi S(E,p,\gamma,R,Z,\phi)\delta(\gamma - \gamma_0)\delta(R - R_0)\delta(Z - Z_0)\delta(\phi - \phi_0)
\]

\(^1\)Heidbrink, PPCF 49(9):1457, 2007
Using FIDASIM to calculate weight functions is favorable for Orbit Tomography

- Action-angle formalism is used to derive orbit weights\(^1\)
  - \( W \) is the average signal produced by a fast ion orbit
    \[
    W(E, p_m, R_m) = \frac{1}{4\pi^2 \tau_p} \oint dt dy d\phi S(E, p_m, R_m, X)
    \]
  - Calculating \( W \) for a diagnostic requires loading orbit trajectories into its forward model (FIDASIM)
- Orbit Tomography uses orbit weight functions to infer the full distribution function from experimental data\(^2\)
  - FIDASIM calculates FIDA, NPA and neutron orbit weights
- **Forward modelling and producing weights with FIDASIM eliminates errors made from mistakes in preparing inputs for multiple codes**

\(^1\)Stagner, PoP 24 (2017)

Neutron collimator forward models for beam-target fusion reactions are added to FIDASIM

- For beam-target neutrons, the global production rate is

\[ S = \iiint d\mathbf{r} dp dE \; n_d \langle \sigma v \rangle_\gamma F \]

- Neutron collimator forward model uses NPA probabilistic framework to calculate the geometric factor for an isotopically emitting source\(^1\)

\[ f_{g,i} = \frac{1}{4\pi} \int dx dy \frac{z_i}{\left( (x-x_i)^2 + (y-y_i)^2 + z_i^2 \right)^{3/2}} \]

- Thus, the collimated neutron flux is

\[ S_c = S \; f_g \]

\(^1\text{Stagner, RSI 85.11 (2014) 11D803}\)
Neutron collimator forward model is benchmarked with uniform inputs

- Similar to NPA definitions, the NC diagnostic is defined by an aperture, detector and collimator length
- Uniform and circular emissivity profile is created
- If $D \to \infty$, solid angle
  \[ \Omega = \frac{A}{4\pi r^2} \]
- Expected signals
  - $N = \varepsilon V_{torus} = \varepsilon \frac{(\pi L)^2}{2R}$
  - $N_c = \varepsilon V_{column} \Omega = \varepsilon \frac{A_d^2 L}{4\pi(D+d)^2}$

<table>
<thead>
<tr>
<th>Input Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
</tr>
<tr>
<td>$D$</td>
</tr>
<tr>
<td>$d$</td>
</tr>
<tr>
<td>$r$</td>
</tr>
<tr>
<td>$R$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
</tr>
<tr>
<td>Flux</td>
</tr>
</tbody>
</table>
Conclusion

• Cold neutral and passive signal capabilities are added to FIDASIM

• P-FIDA signals predicted by FIDASIM are successfully benchmarked with passive modelling done on NSTX-U

• FIDASIM can accept fusion configurations with 3D geometry and are successfully benchmarked with FIDA data on LHD

• Weight functions for FIDA, NPA and neutron diagnostics can be calculated by the code

• Forward model for the neutron flux signal is added to FIDASIM and benchmarked with uniform inputs
Future work

- Optimize neutron collimator signals and benchmark with TRANSP

- Incorporate 3 MeV proton weight functions into FIDASIM

- Apply Orbit Tomography to more cases on several fusion devices with multiple diagnostics

- Support FIDASIM user base
Our group is interested in expanding the network of FIDASIM users

- A benchmark between the USA and EU versions of FIDASIM are underway

- New 3D capability is inviting for stellarator scientists to use our code

- Clone the FIDASIM repository

- Find our documentation online
  [https://d3denergetic.github.io/FIDASIM/](https://d3denergetic.github.io/FIDASIM/)

- Have a question about the code? Easily open an issue on GitHub