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FIDASIM

A Neutral Beam and Fast-ion Diagnostic Modeling Suite

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FIDASIM is a synthetic diagnostic code that simulates fast ion D-alpha (FIDA) and neutral particle analyzer (NPA) signals. The code accepts a theoretical fast-ion distribution function as input and predicts the FIDA and NPA spectra. Originally, FIDASIM assumed axisymmetry and included active signals produced only by charge exchange (CX) with injected neutrals. However, passive signals produced by CX with cold neutrals can also be important. For example, passive-FIDA signals of comparable magnitude with active signals were experimentally measured on NSTX-U[1]. Therefore, FIDASIM is improved to predict passive signals for a given edge-cold neutral population. The time series passive spectra output by FIDASIM is successfully cross checked with 2D passive-FIDA modeling done on NSTX-U. The effect of 3D fields on fast ion confinement is an ongoing field of study, e.g. toroidal field ripple, stellerators, etc. Thus, the functionality of FIDASIM is enhanced to simulate signals produced in 3D geometry.

[1]Hao, PPCF 60 (2018) 025026

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Outline

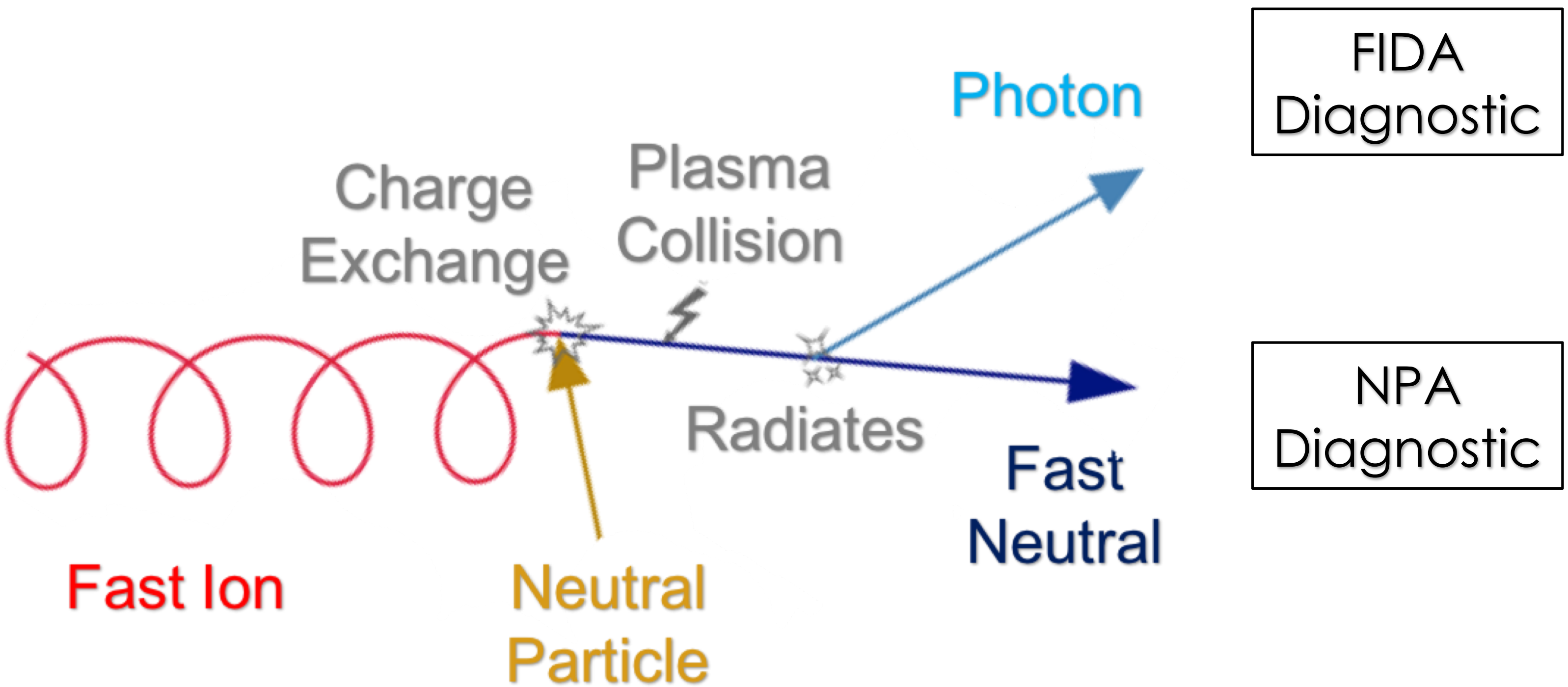
- Motivation and introduction to FIDASIM
- New cold neutral and passive signal capabilities
- Successful NSTX-U passive FIDA modelling benchmark
- New 3D geometry capabilities and preliminary benchmark

Introduction to this work

- FIDASIM is widely used to model FIDA and NPA signals
- Many recent experiments have shown that signals from cold neutrals can be as important as signals from injected neutrals[1][2][3][4][5][6]
- 3D capability is needed to properly treat tokamaks with applied 3D fields, e.g. toroidal field ripple, and stellarators
- Purpose of this work: Upgrade FIDASIM to treat cold neutral and 3D effects

[1]Hao, PPCF 60 (2018) 025026
[2]Heidbrink, PPCF 63 (2011) 085007
[3]Geiger, PPCF 59 (2017) 115002
[4]Heidbrink, PPCF 53 (2011) 085028
[5]Bolte, NF 56 (2016) 112023
[6]Michael C A, PPCF 55 (2013) 095007

Fast-ion D_α (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

Fast-ion Distribution Function

- Forward modelling can be used to predict the FIDA and NPA spectra for comparison with experimental data[1]
- FIDASIM accepts a theoretical fast-ion distribution function

FIDASIM

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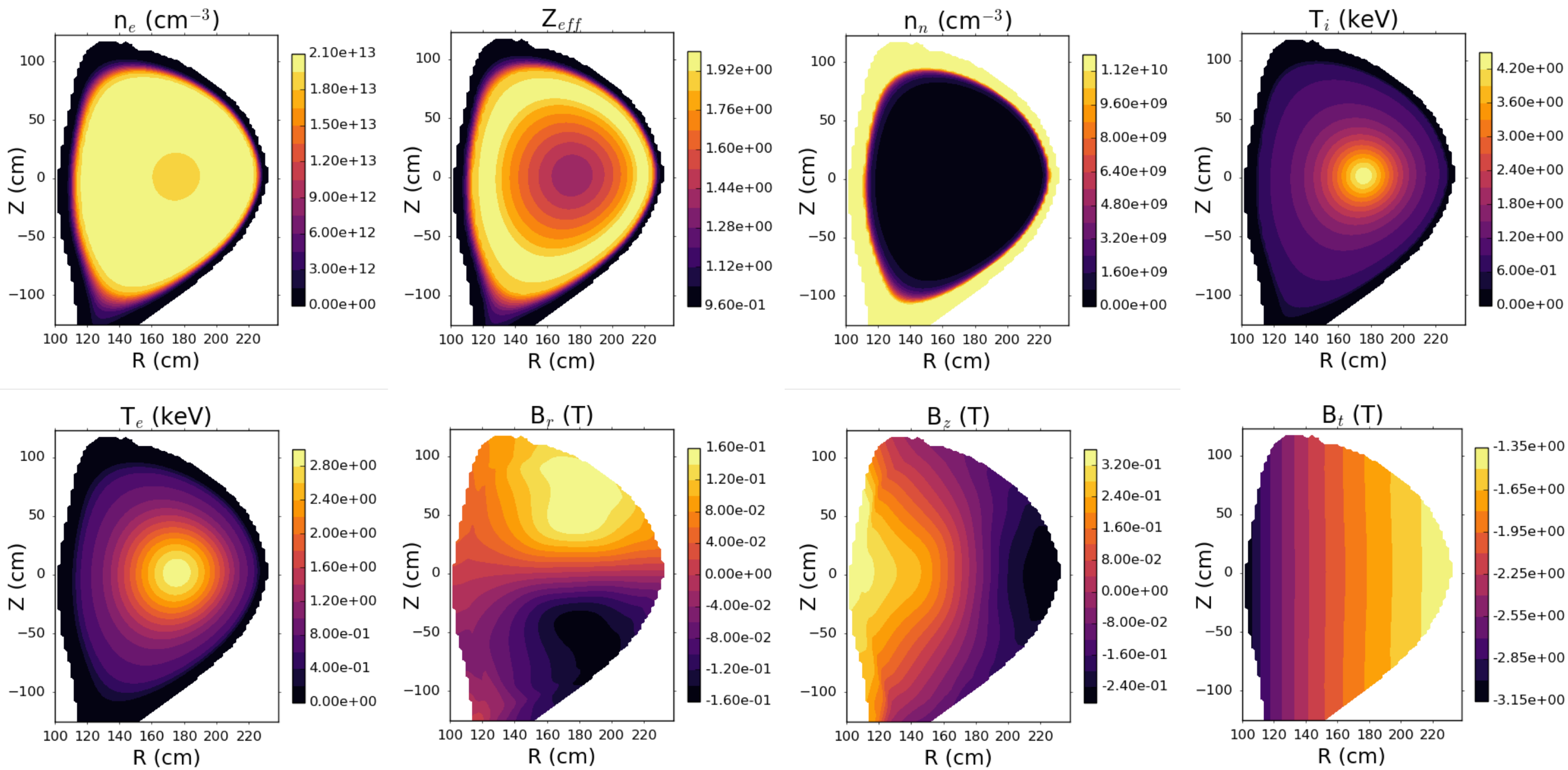
- Charge exchange is modelled, and the FIDA radiance and NPA flux are calculated

[1]Heidbrink, CCP 717 (2011)

Experimental Measurements

FIDASIM requires plasma profiles and electro-magnetic fields as input

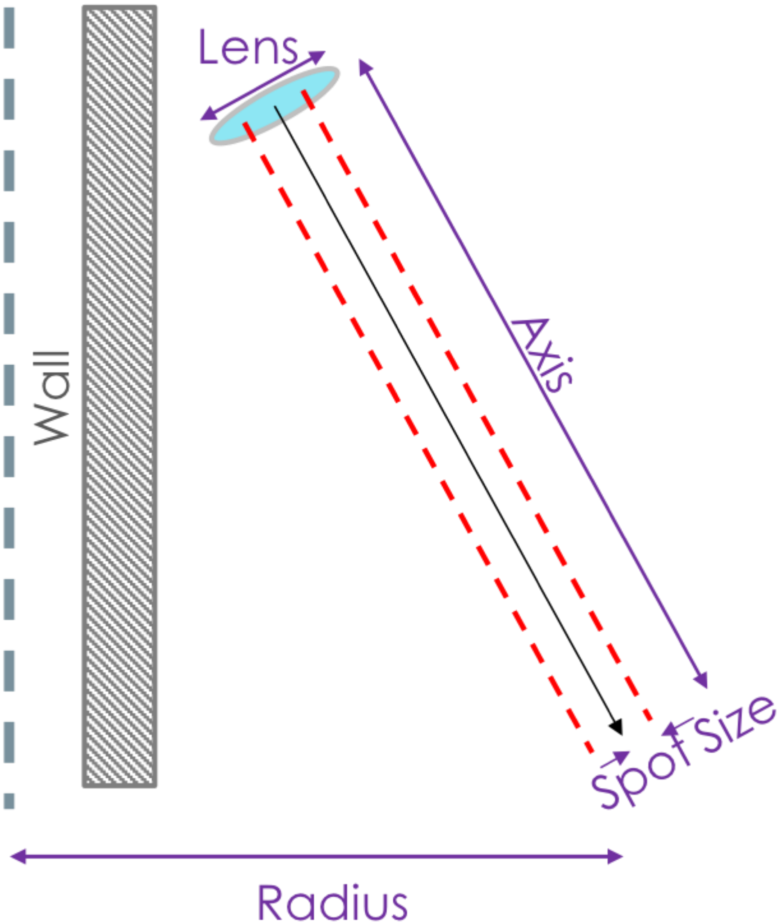



```
plasma = {Ti, Te, Ne, Nn*, Zeff*, Vr, Vt, Vz}
fields = {Br*, Bt*, Bz*, Er*, Et*, Ez*}
```

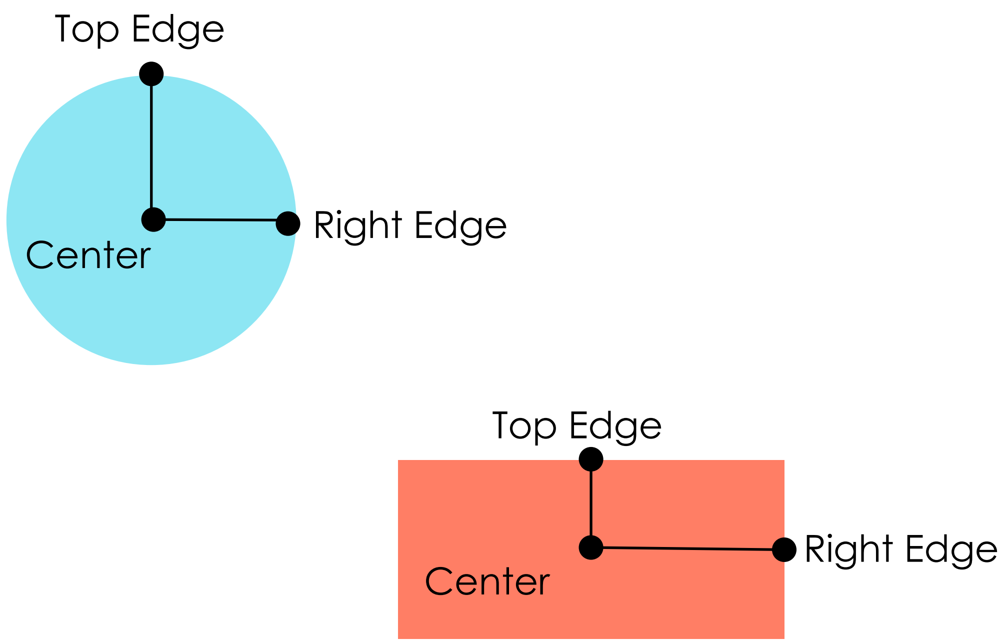
*Inferred

Spectroscopic and NPA geometry are inserted into FIDASIM

- FIDA Diagnostic:
  - Defined by the line of sight



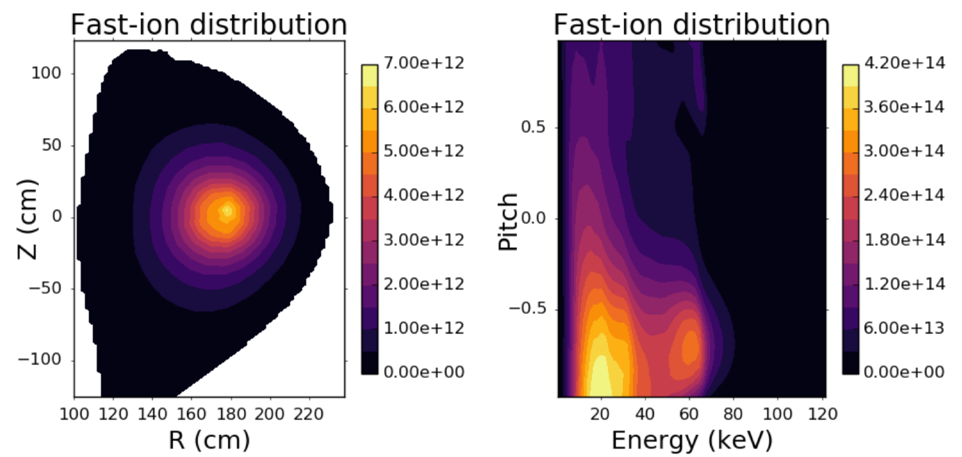
- NPA Diagnostic:
  - Defined by two planes (aperture and detector)
  - Circular or rectangular shapes are acceptable

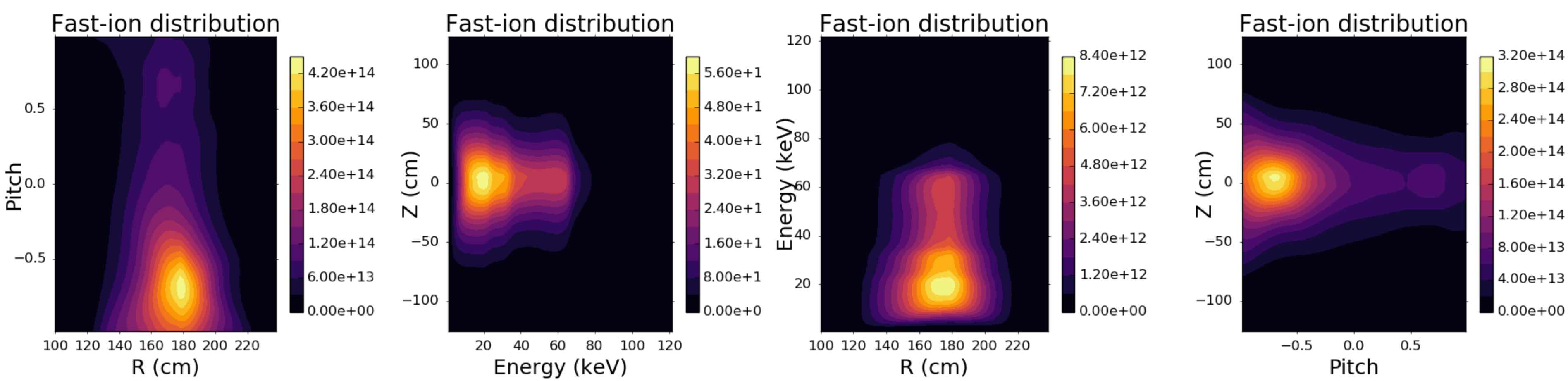


Views are from inside the vessel

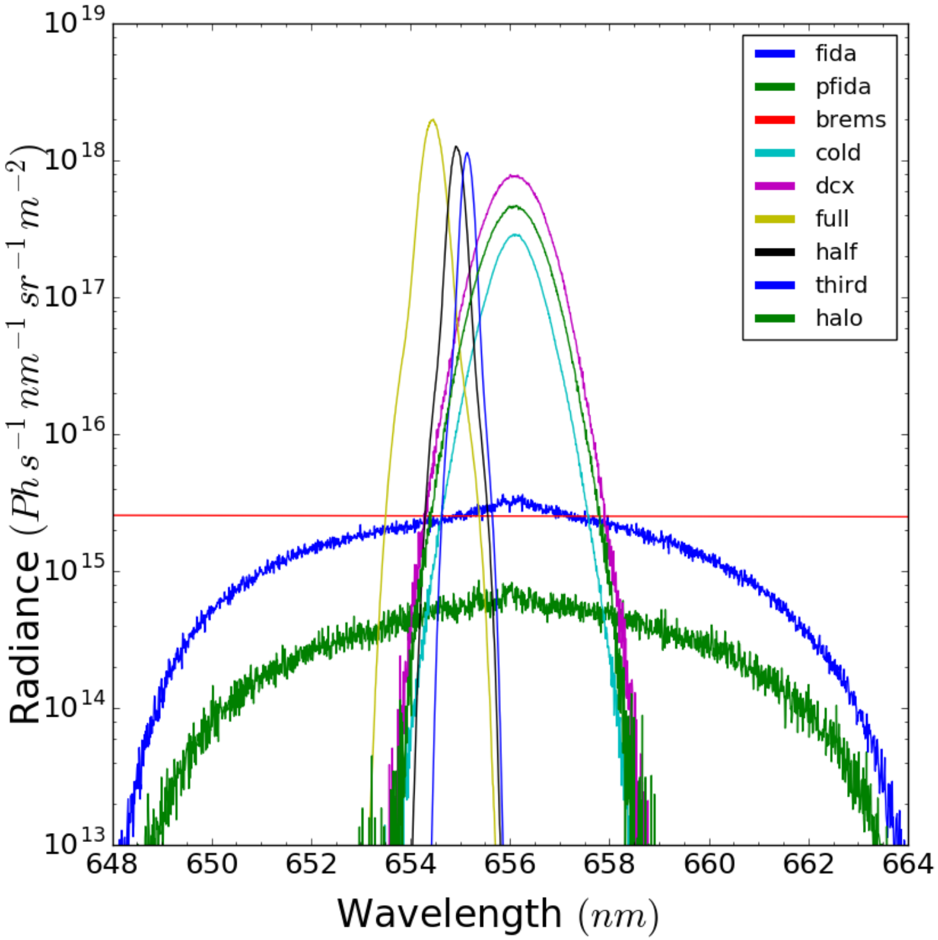
The code accepts several types of theoretical fast-ion distribution functions as input

	Coordinate System
Guiding Center Distribution	$E, p, R, Z\ [, \phi]$
Monte Carlo (Guiding Center)	$E, p, R, Z\ [, \phi]$
Monte Carlo (Full Orbit)	$v_r, v_z, v_\phi, R, Z\ [, \phi]$





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-a (FIDA)

Passive Fast-ion D-a (p-FIDA)

Passive signals improve understanding on the fast-ion distribution and neutral density profile

- ***Active*** diagnostic signals are produced from charge exchange with ***injected*** neutrals, and ***passive*** signals are produced from charge exchange with ***cold*** neutrals
- 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[1]
- P-FIDA signals are enhanced when fast ions are expelled to the edge by instabilities[2]
- Neutral density profile may be found from a known fast-ion source with passive measurements[1]

[1]Bolte, NF 56 (2016) 112023
[2]Hao, PPCF 60 (2018) 025026

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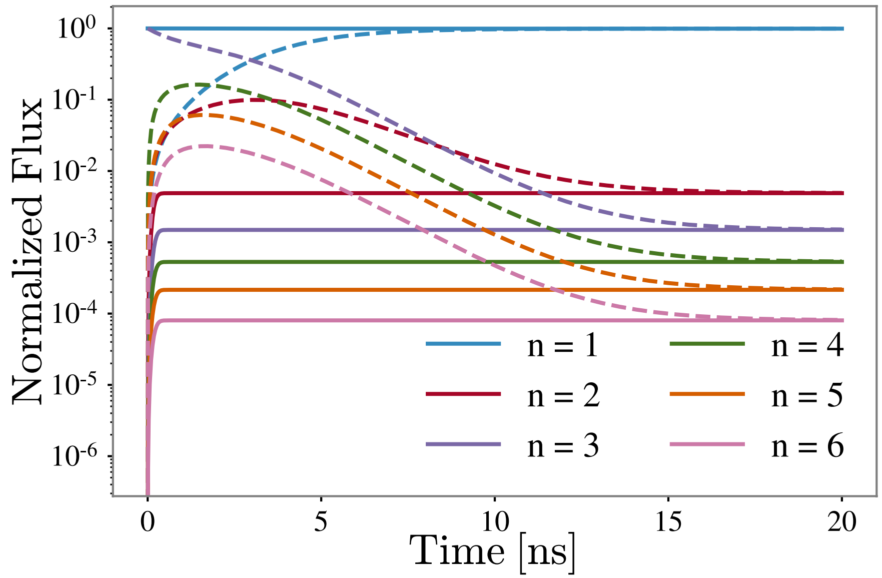
FIDASIM reads in neutral densities, then time-evolves them to simulate passive FIDA signals

- FIDASIM accepts 2D and 3D cold neutral density input
  - TRANSP variable *dn0wd*

- Calculate the cold neutral energy level populations
  - Assume $f_1 = 1$
  - Use the local plasma parameters to time evolve the neutral states by solving the *collisional radiative model* with *COLRAD* until equilibrium is achieved
  - Use the equilibrium population levels to distribute neutrals throughout the grid

- Perform passive calculations

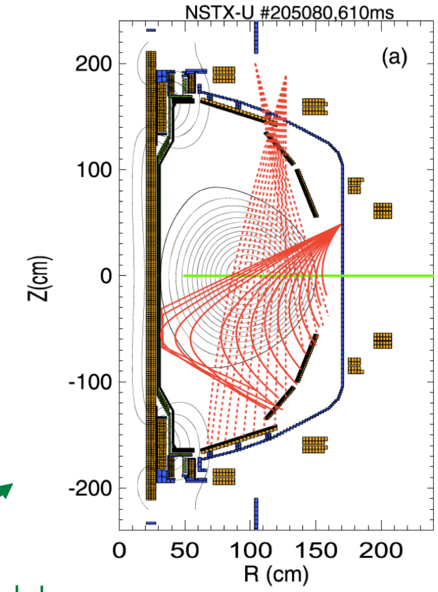


Time evolution of neutral population fluxes for initial condition $f_1 = 1$ (solid) and $f_3 = 1$ (dashed). The fluxes are normalized to unity at each time step[1]. Equilibrium is achieved quickly in both cases.

[1]Stagner, (Thesis) UCI (2018)

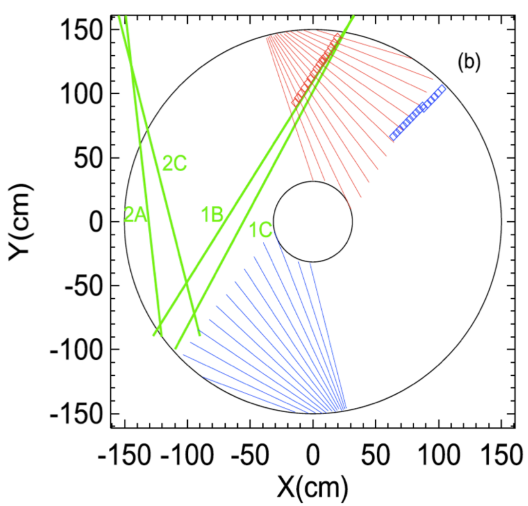
Passive-FIDA signals are comparable to active-FIDA signals at NSTX-U

- Discharges are MHD quiescent, thus, the fast-ion distribution function is calculated by NUBEAM[1]
- 3 fast-ion populations can contribute to passive FIDA signals[1]
  1. **Axisymmetric population that passes through the edge region (calculated by TRANSP)**
  2. Toroidally asymmetric cluster that traverses edge on first orbit
  3. Centrally confined ions that are expelled towards the edge



Plasma Parameters[1]

Ion Species	Deuterium
T_e	0.6–0.9 keV
n_e	1.2–1.4 × 10^{19} m^{-3}
n_f	**10^{10}–10^{11} cm^{-3}**
n_n	**10^{8}–10^{10} cm^{-3}**
P_{NBI}	12 MW
B_T	0.63 T
I_p	0.65 MA



FIDA line of sights & beam sources

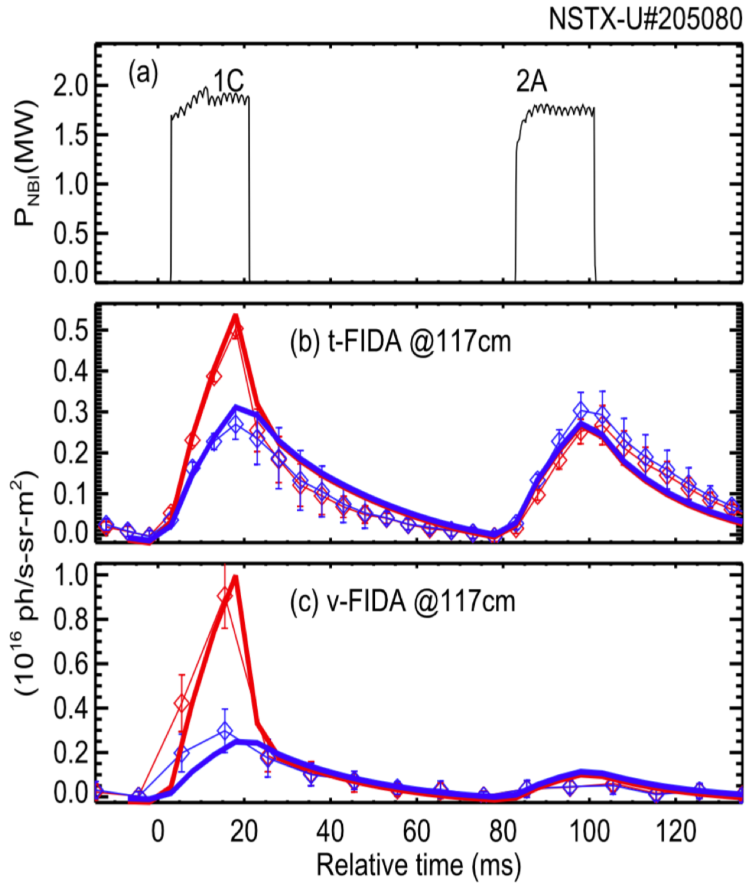
Elevation: Dashed (vertical) solid (tangential)

Midplane:
Squares (vertical)
Solid (tangential)
Red (active)
blue (reference)
Green (beam sources):
1B, **1C**, **2A** and 2C

[1]Hao, PPCF 60 (2018) 025026

Passive-FIDA signals comparable to active-FIDA signals at NSTX-U (cont'd)

- The neutral density profile output from TRANSP only describes 1D injection along flux coordinate ρ. Thus, t-FIDA and v-FIDA are rescaled
- It is clear that the passive signal is comparable in magnitude to the active signal
- The simulation and data are in excellent agreement



Thin and thick curves are experimental and FIDASIM data, respectively. Red curves denote the total signal and blue curves describe only the passive signal.

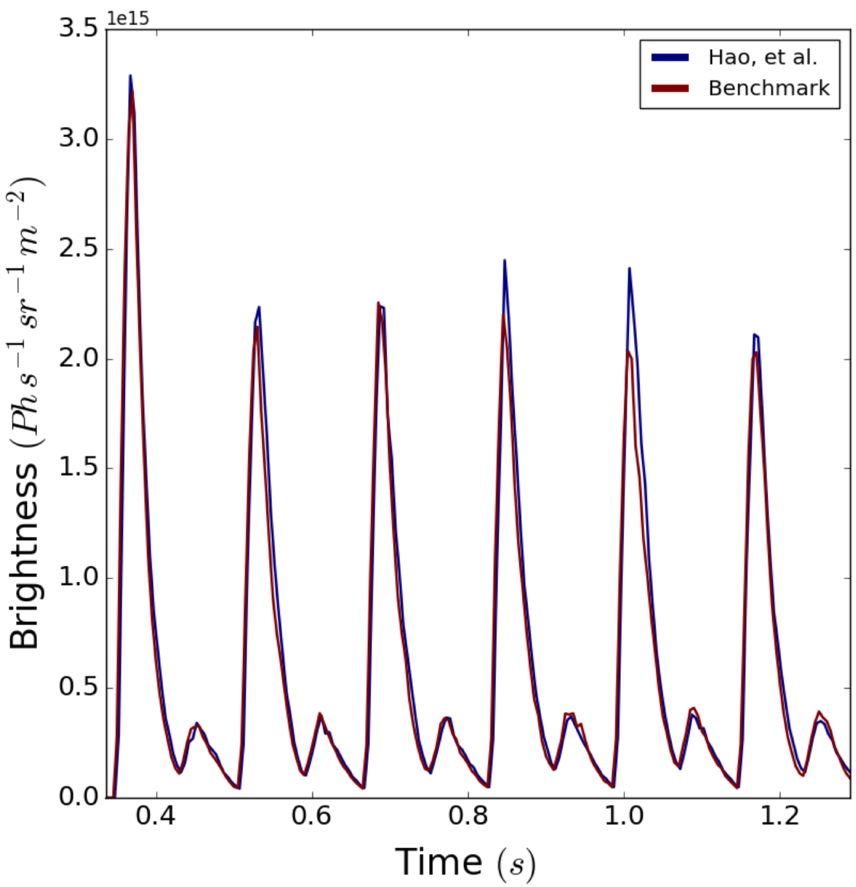
Hao, PPCF 60 (2018) 025026

Successful FIDASIM benchmark with 2D passive-FIDA modeling

- Plasma, fields, geometry and the fast-ion distribution function from the NSTX-U passive modelling are all reused in this FIDASIM benchmark

- P-FIDA spectra are wavelength integrated from 650.8–654.0 nm

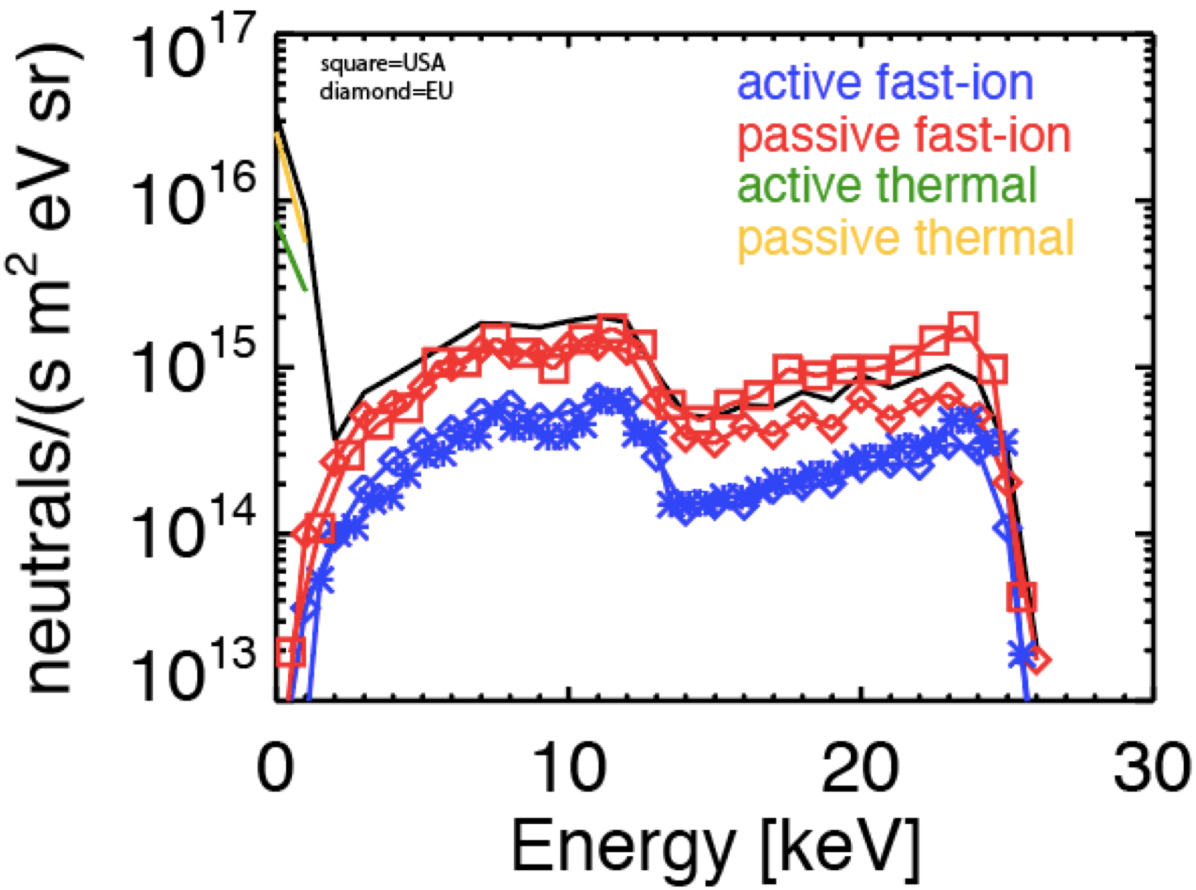
- Both FIDASIM passive signals agree with each other



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[2]

Calculated NPA flux at the compact NPA[1] during beam injection in TCV



[1]Karpushov, RSI 77 (2006) 033504

[2]Geiger, PPCF 59 (2017) 115002

Interpolation grid extended to 3D by taking into account toroidal variable ϕ

- Electromagnetic fields, plasma parameters and the fast-ion distribution function are mapped onto the interpolation grid
- Default settings of FIDASIM are to map the plasma parameters and fields onto the 2D R-Z grid, i.e., assume `nphi` = 1 and `phi` = 0
- If the user inputs any ϕ variable information, the plasma parameters and fields are mapped onto a 3D R-Z-ϕ cylindrical grid

```
grid = {nr, nz, nphi, r, z, phi, r2d, z2d}
```

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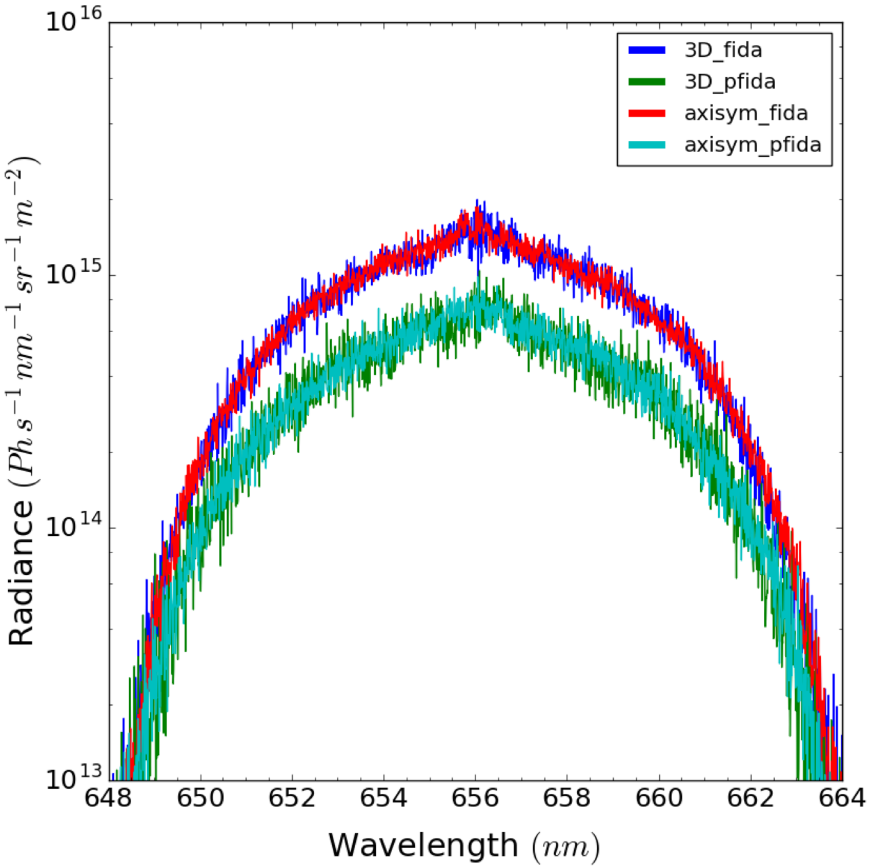
Successful preliminary 3D FIDASIM benchmark with 3D fields and profiles

- 3D fields and plasma with no toroidal variation are prepared for the case `nphi` = 5 ; `phi` ∈ $[4\pi/3, 5\pi/3]$
- The same inputs are prepared for a second FIDASIM run with `nphi` = 1 ; `phi` = 0
- "Flat top" distribution function and diagnostic geometry are kept constant for both runs
- As expected, both runs match identically



Conclusion

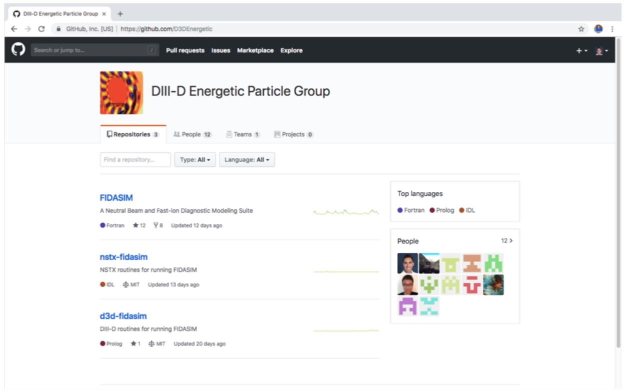
- Passive FIDA & NPA signals are now incorporated into FIDASIM
- Passive signals produced by FIDASIM agree very well with passive modelling done on NSTX-U[1]
- FIDASIM can accept fusion configurations with 3D geometry

[1]Hao, PPCF 60 (2018) 025026

Updated source code and documentation

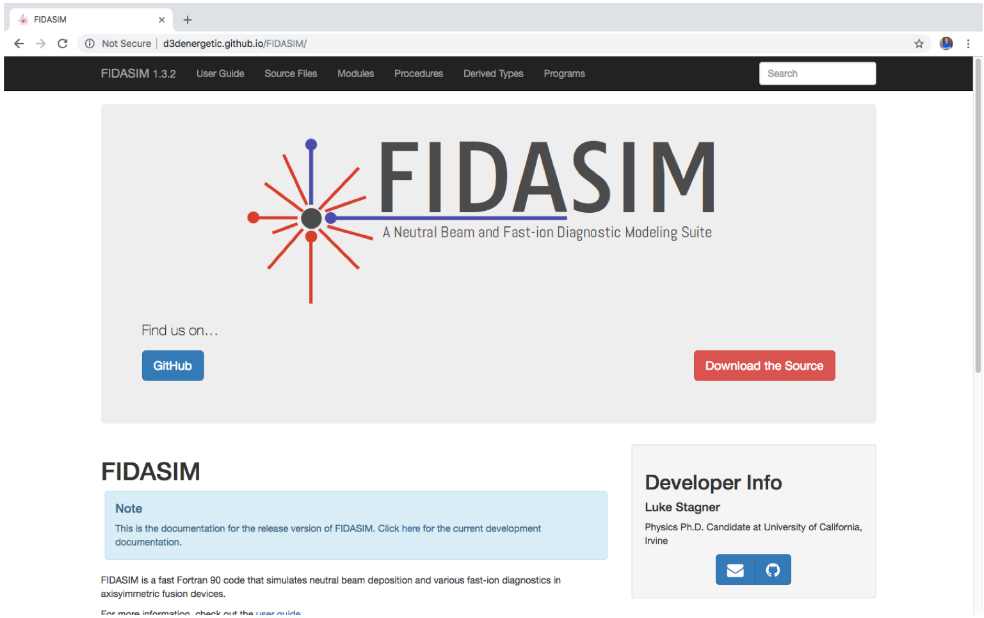
- FIDASIM is version controlled with git
- The source code and issue tracker can be found on GitHub

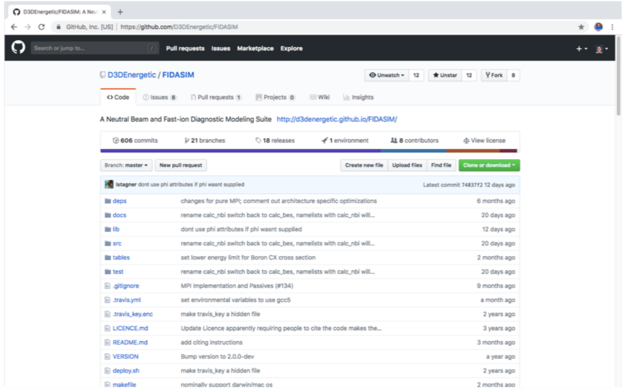
https://github.com/D3DEnergetic/FIDASIM



- Documentation can be found at

https://d3denergetic.github.io/FIDASIM/





Our group is interested in expanding the network of FIDASIM users

- A benchmark between the USA and EU versions of FIDASIM are underway
- Creating a new remote repository for the diagnostic geometry at the Joint European Torus (JET)
- Add a charged fusion product forward model to FIDASIM in relation to our Mega Ampere Spherical Tokamak Upgrade (MAST-U) collaboration
- Stellarator scientists are welcome to clone our FIDASIM repository and use the new 3D capabilities
- FIDASIM 2.0 entering final phases of development