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

FIDASIM

A Neutral Beam and Fast-ion Diagnostic Modeling Suite

Alvin V. Garcia[1]
Luke Stagner[2]
William W. Heidbrink[1]
Yutaka Fujiwara[3]

[1]University of California, Irvine, USA
[2]Oak Ridge Associated Universities, USA
[3]National Institute for Fusion Science, Japan

This work was supported by the U.S. Department of Energy under DE-FG02-06ER54867 and DE-SC0019253.

Outline

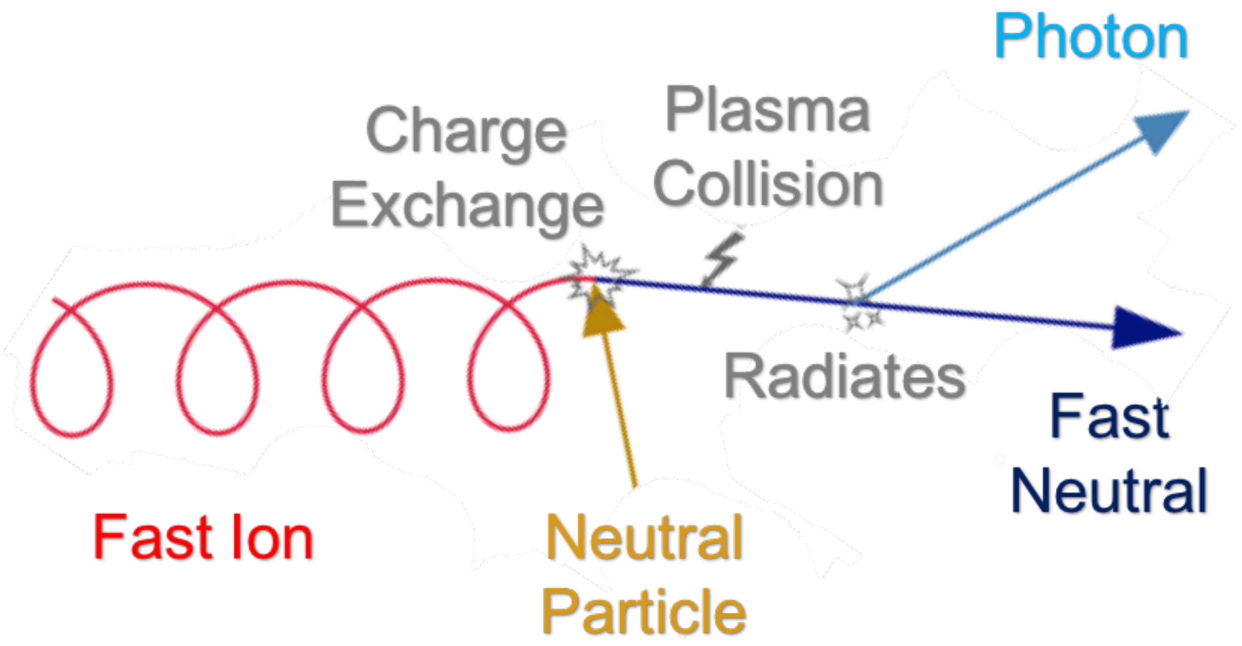
- I. Motivation and introduction to FIDASIM
- II. (a) Cold neutral and passive signal capabilities
- II. (b) NSTX-U passive FIDA modelling benchmark and TCV passive NPA signals
- III. 3D geometry capabilities and validation with FIDA measurements on LHD
- IV. (a) Weight functions produced by FIDASIM 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
[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



FIDA Diagnostic

NPA Diagnostic

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

FIDASIM is a synthetic diagnostic code that simulates FIDA and NPA signals

Theoretical Fast-ion Distribution

- FIDA and NPA measure the fast-ion distribution function
- Forward modelling predicts FIDA & NPA signals to compare with measurements[1]

Inputs

FIDASIM

A Neutral Beam and Fast-ion Diagnostic Modeling Suite

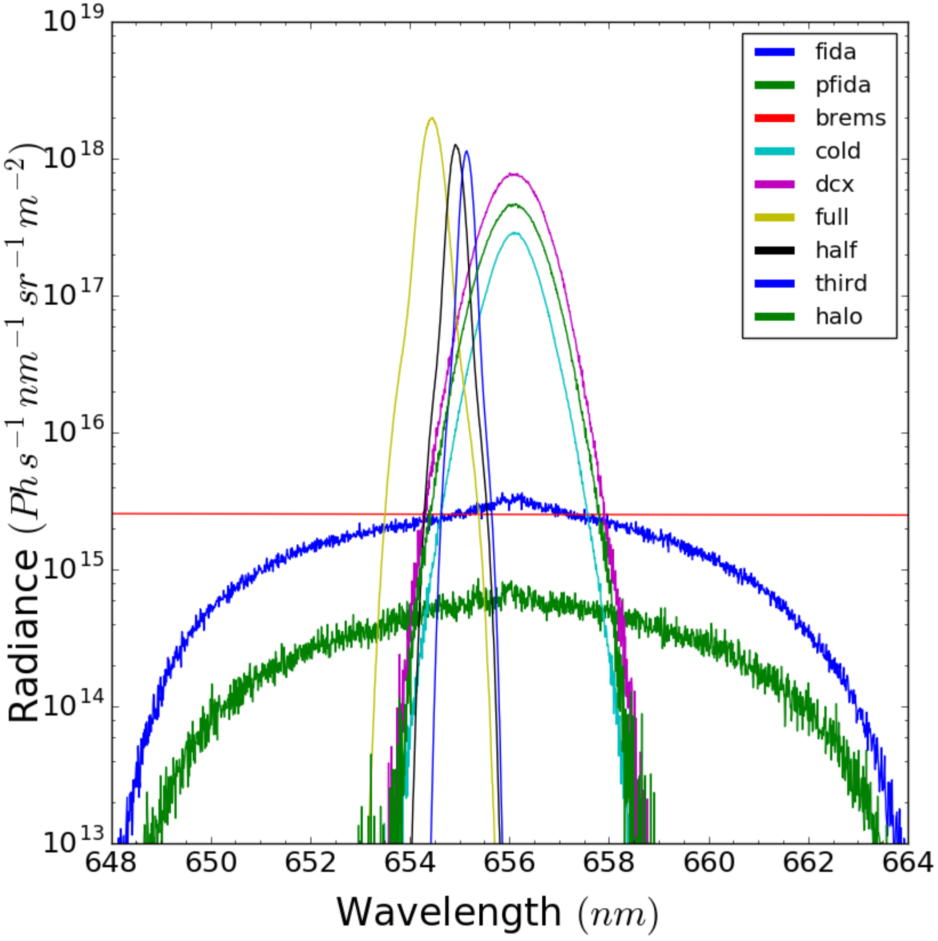
Outputs

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

Experimental Measurements

[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_α (FIDA)

Passive Fast-ion D_α (p-FIDA)

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

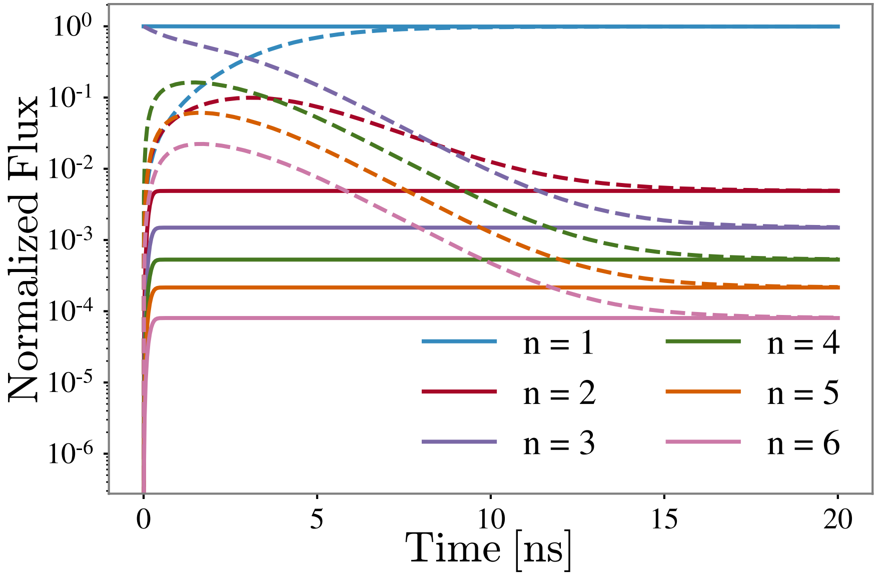
Active vs. passive signal distinction	
Signal Type	Charge exchange source
Active	Injected neutrals
Passive	Cold neutrals

- 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

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



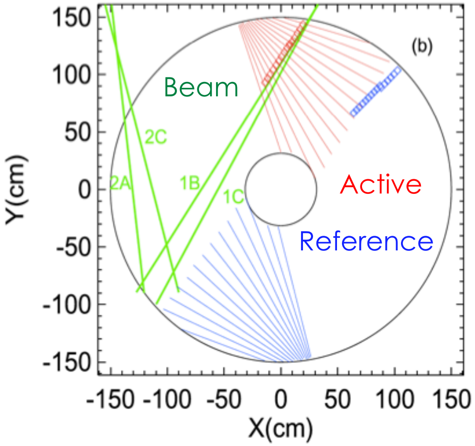
Time evolution of neutral population fluxes for initial condition $f_1 = 1$ (solid) and $f_3 = 1$ (dashed). The fluxes are normalized to unity at each time step[1]. Equilibrium is achieved quickly in both cases

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

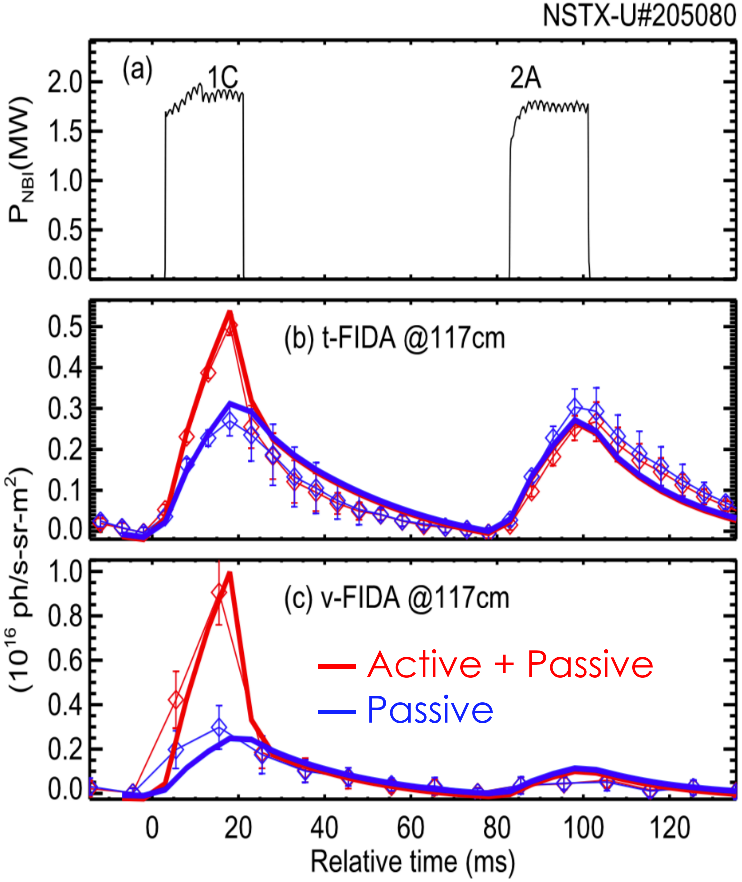
Passive-FIDA signals are comparable in magnitude to active-FIDA signals at NSTX-U

- P-FIDA spectra are measured and simulated on NSTX-U[1]

Experimental Parameters[1]	
Ion Species	Deuterium
T_e	0.6–0.9 keV
n_e	$1.2–1.4 \times 10^{19}$ 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



Beam and FIDA midplane geometry



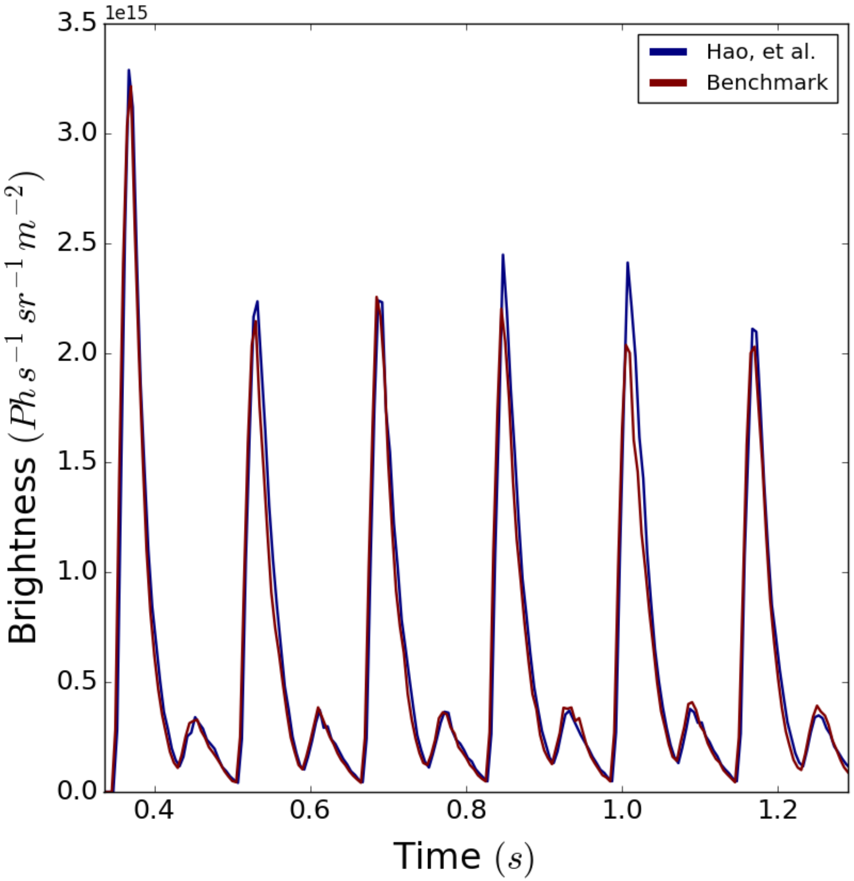
2D passive-FIDA modeling done on NSTX[1]. Thin and thick line is experiment and simulation, respectively

- 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

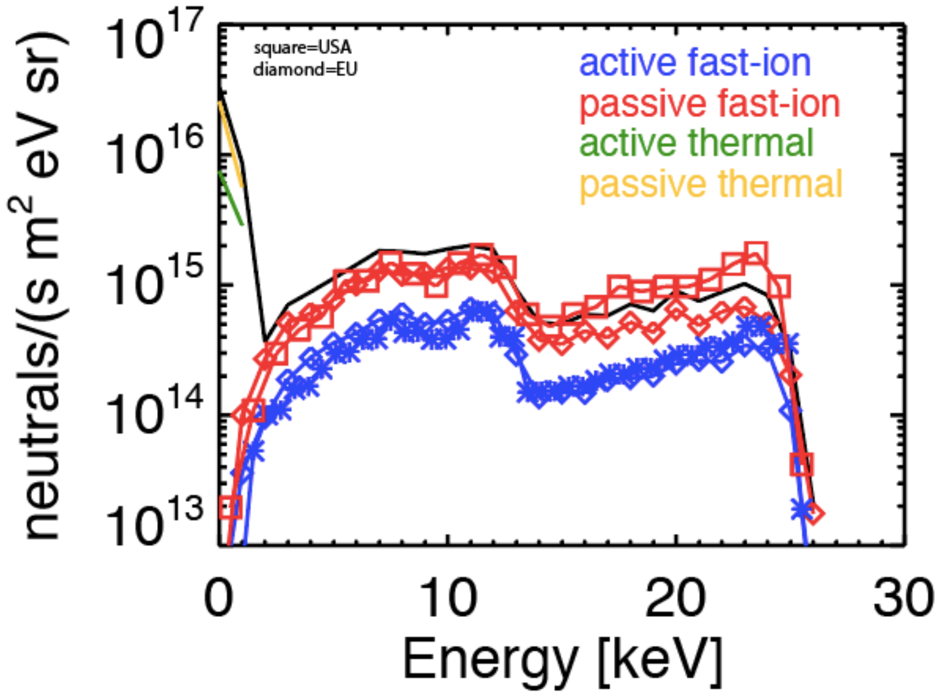
FIDASIM p-FIDA capability is benchmarked with 2D passive-FIDA modeling done on NSTX

- 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[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 is extended to 3D by accepting toroidal variable ϕ

Inputs	*Interpolation Grid Variables*
2D $n_\phi = 1$ $\phi = 0$	R, Z
3D $n_\phi > 1$ $\phi \in [-\pi, \pi)$ or $\phi \in [0, 2\pi)$	R, Z and ϕ

- Unless the user provides ϕ 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

Signal	*Diagnostic Grid Name*	*Coordinate System*
Active FIDA, BES, DCX, Halo, Cold	Beam	Cartesian
Active NPA	Beam	Cartesian
Passive FIDA	Passive neutral	Cylindrical
Passive NPA	Passive neutral	Cylindrical
Neutron Collimator	Neutron	Cylindrical

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

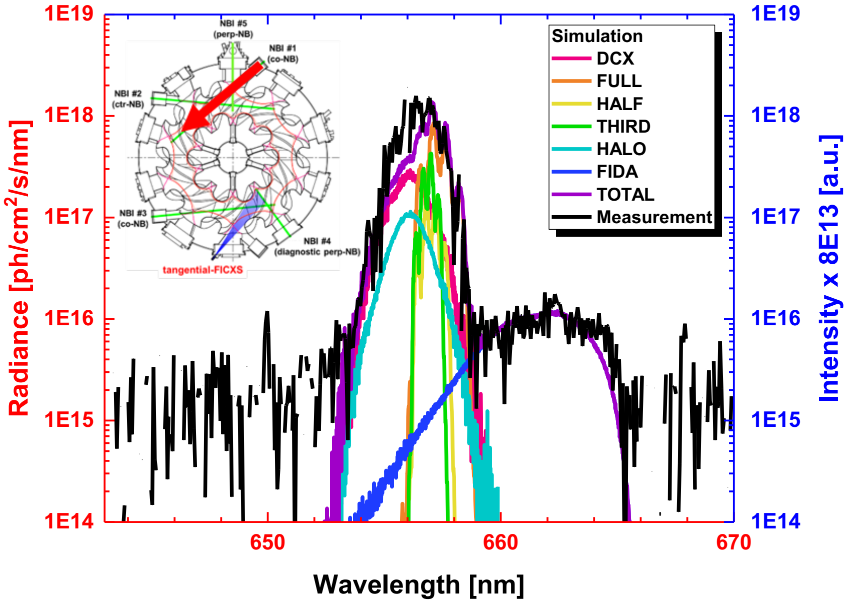
- Cylindrical diagnostic grids are created as follows
  - If the interpolation grid is 3D, then the diagnostic grid is the interpolation grid
  - Otherwise, the code will generate a cylindrical grid specific to the geometry of the diagnostic and its intersection with the plasma boundary

- 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[1]	
Ion species	Deuterium
T_e	~1 keV
n_e	~10^{19} m^{-3}
P_{NB1}	0.8 MW
B_T	2.75 T (counter)
R_{ax}	360 cm
B_q	100 %
Gamma	1.354

[1] Fujiwara, P1 63, IAEA (2019)



FIDA simulations predicted by FIDASIM agree with tangential FIDA measurements during NB1 injection in LHD[1]

FIDASIM Sensitivity Study

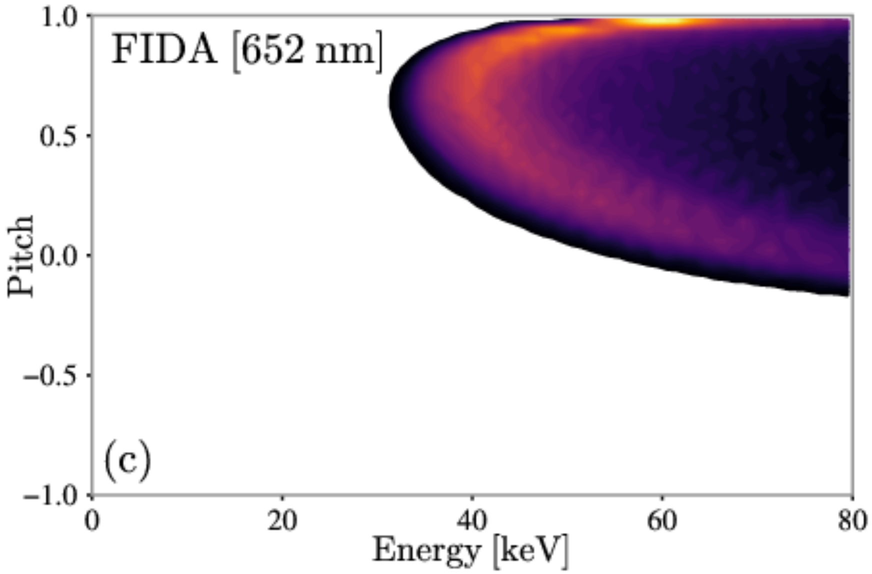
- Predicted FIDA spectra from scaled inputs are compared with spectra from unmodified inputs

$$\left\langle \frac{FIDA_{scaled} - FIDA_{baseline}}{FIDA_{baseline}} \times 100\% \right\rangle_{LOS}$$

FIDASIM response in FIDA signal to uniform scaling of inputs		
$parameter$	Percent difference for $parameter \times (-15\%)$	Percent difference for $parameter \times (+15\%)$
n_e	+1.81%	–2.44%
T_e	–0.81%	+1.17%
T_i	+5.73%	–2.96%
Z_{eff}	+2.87%	–4.60%

Weight functions describe a diagnostic's sensitivity to phase space

- $Signal \equiv S = \int d\boldsymbol{X}\, W(\boldsymbol{X})F(\boldsymbol{X})$
    - $\boldsymbol{X}$ is phase space
    - W is the weight function
    - F is the distribution function
- For example, the expected diagnostic signal in velocity space is[1]
    - $S = \iint dp dE\, W(E,p)F(E,p)$
- 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]



Representative FIDA velocity space weight function for FIDA diagnostic at DIII-D. FIDA weight functions depend on wavelength[2]

[1] Heidbrink, PPCF 49(9):1457, 2007
[2] Stagner, (Thesis) UCI (2018)

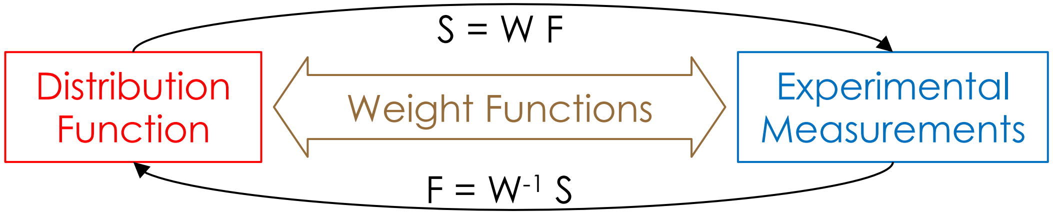
$$W(E,p) = \frac{1}{2\pi}\int d\gamma dR dZ d\phi\, S(E,p,\gamma,R,Z,\phi)\delta(\gamma-\gamma_0)\delta(R-R_0)\delta(Z-Z_0)\delta(\phi-\phi_0)$$

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*

$$W(E,p_m,R_m) = \frac{1}{4\pi^2\tau_p}\iiint dt\,d\gamma\,d\phi\; S(E,p_m,R_m,\boldsymbol{X})$$

    - 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]



S = W F

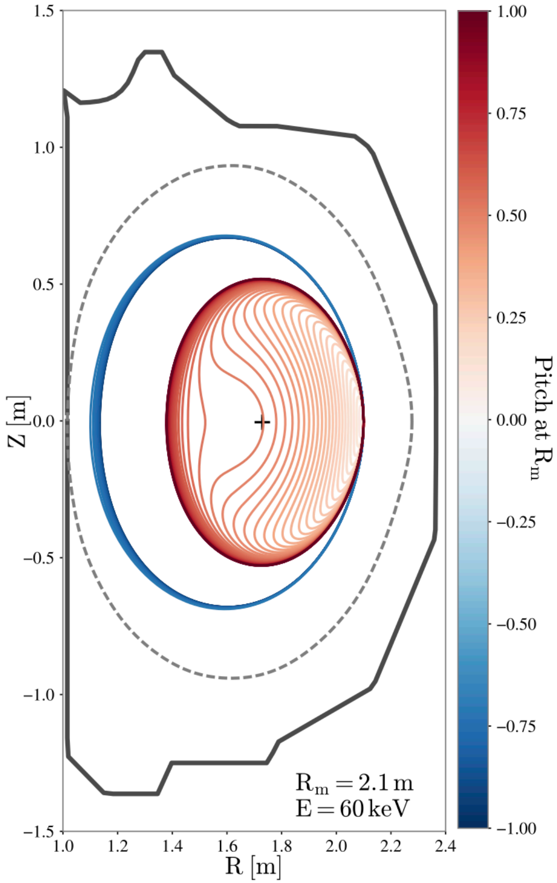
Distribution Function

Weight Functions

Experimental Measurements

$F = W^{-1} S$

    - 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***



Orbit trajectories created from a DIII-D plasma at constant energy and R_m plotted in orbit space[2]

[1] Stagner, PoP 24 (2017)

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

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

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

$$S = \iiint d\mathbf{r}dpdE\, n_d \,\langle \sigma v \rangle_\gamma \, F$$

- Neutron collimator forward model uses NPA probabilistic framework to calculate the geometric factor for an isotopically emitting source[1]

$$f_{g,i} = \frac{1}{4\pi} \iint dxdy \frac{z_i}{\left((x - x_i)^2 + (y - y_i)^2 + {z_i}^2\right)^{3/2}}$$

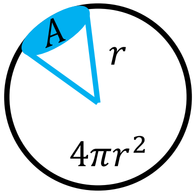
- Thus, the collimated neutron flux is

$$S_c = S\, f_g$$

[1] Stagner, RSI 85.11 (2014) 11D803

Neutron collimator forward model is benchmarked with uniform inputs

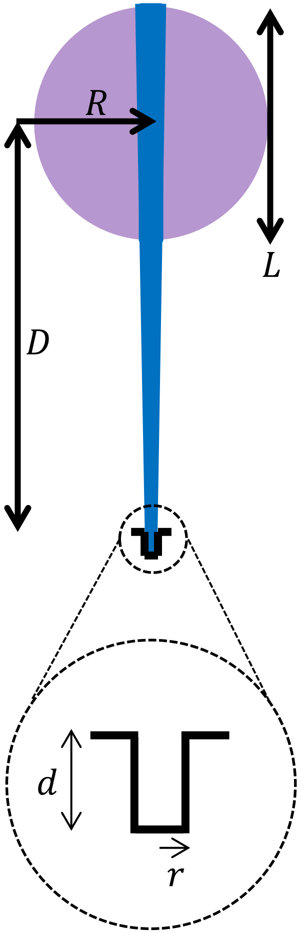
- Similar to NPA definitions, the NC diagnostic is defined by an aperture, detector and collimator length
- Uniform and circular emissivity profile is created
- If $D \to \infty$, solid angle
  - $\Omega = \frac{A}{4\pi r^2}$



- Expected signals
  - $N = \epsilon V_{torus} = \epsilon \frac{(\pi L)^2}{2R}$
  - $N_c = \epsilon V_{column}\,\Omega = \epsilon \frac{{A_d}^2 L}{4\pi(D+d)^2}$

Input Parameters	
L	119.7 cm
D	10^3 cm
d	10^5 cm
r	1 cm
R	170 cm

Results	
Rate	$\frac{\lvert S - N\rvert}{S}\times 100\% = 1.3\%$
Flux	$\frac{\lvert S_c - N_c\rvert}{S_c}\times 100\% \cong 1\%$



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
  https://github.com/D3DEnergetic/FIDASIM

- Find our documentation online
  https://d3denergetic.github.io/FIDASIM/

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