NSTX

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Improvements to the Fast-ion D_α (FIDA) Simulation Code

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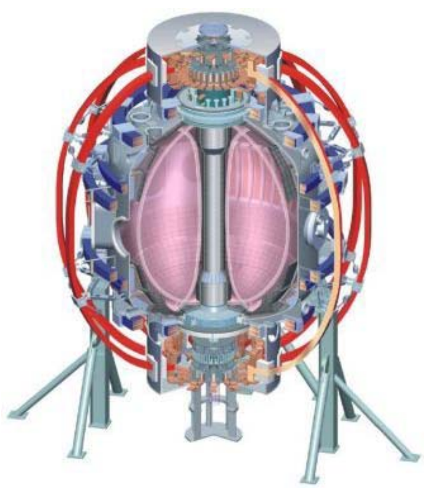

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Abstract

Improvements to a Fast-ion D_α Simulation Code,* Y. Luo, *Tri Alpha Energy*, W. Heidbrink, E. Ruskov, *UC Irvine*, D. Liu, *UW Madison*, M. García-Muñoz, B. Geiger *IPP Garching*, R. Akers, C. Michael *CCFE* – FIDASIM is a code that models fast-ion D_α (FIDA) light that is produced by charge-exchange reactions between fast ions and injected neutral beams in tokamak plasmas. Reactions with both the primary injected neutrals and with the cloud of secondary "halo" neutrals that surround the beam are treated. Accurate calculation of the fraction of neutrals that occupy excited atomic states (the collisional-radiative transition equations) is an important element of the code. Judicious selection of grid size and other parameters facilitate efficient solutions. D_α light from beam emission, direct charge-exchange with protons, and the beam halo are also calculated. For greater speed, conversions to FORTRAN and GPU are underway. FIDASIM has been applied to data from DIII-D, NSTX, ASDEX-U, and MAST.

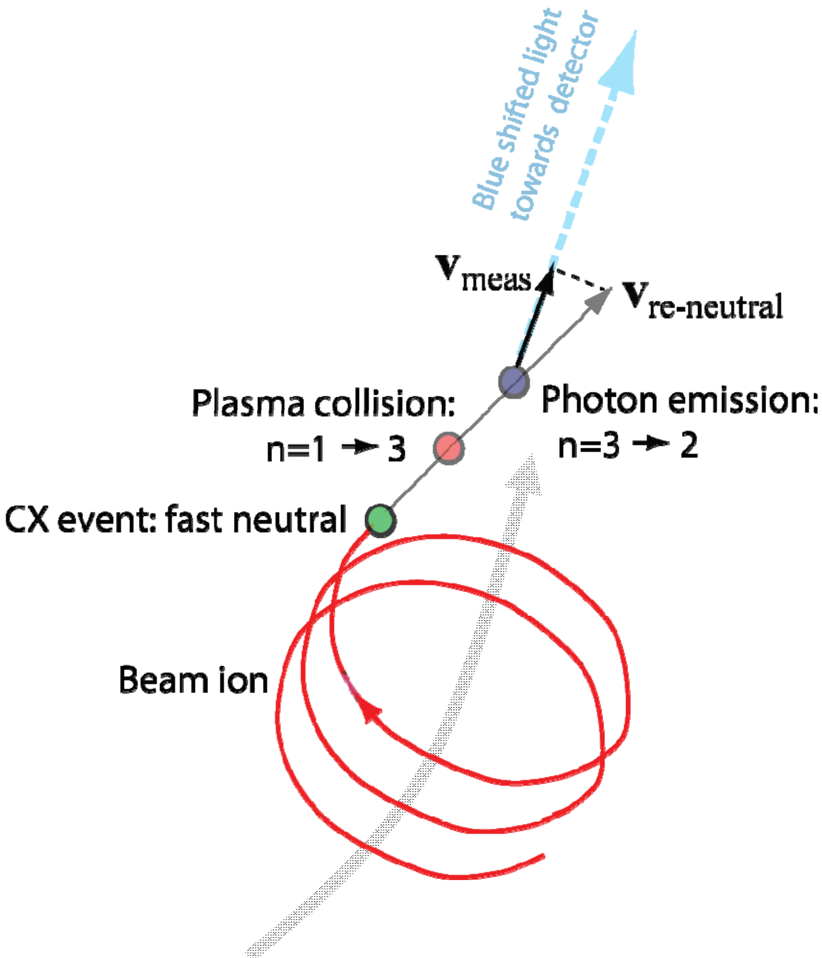
* Supported by the DOE under DE-FG02-06ER54867.

MOTIVATION

- FIDASIM is a 3D code which calculates the Doppler shifted D_α spectrum of fast-ions that underwent CX events with beam or halo neutrals.
- To identify fast-ion anomalies in experiments (redistribution and/or loss) the measured fast-ion profiles have to be compared with code predictions.
- In addition to DIII-D and NSTX, FIDA measurements are available on ASDEX-U and MAST. The code has been extended* to support these 4 machines.
- FIDASIM is written in IDL and is computationally very intensive. Specialized FORTRAN version written for ASDEX-U currently is being adopted for general use.

** W.W.Heidbrink et al, " A Code that simulates Fast-Ion D_α measurements and Neutral Particle Measurements"*
Submitted to Communications in Computational Physics

Beam ions are diagnosed through active charge-exchange D_α spectroscopy (FIDA technique)

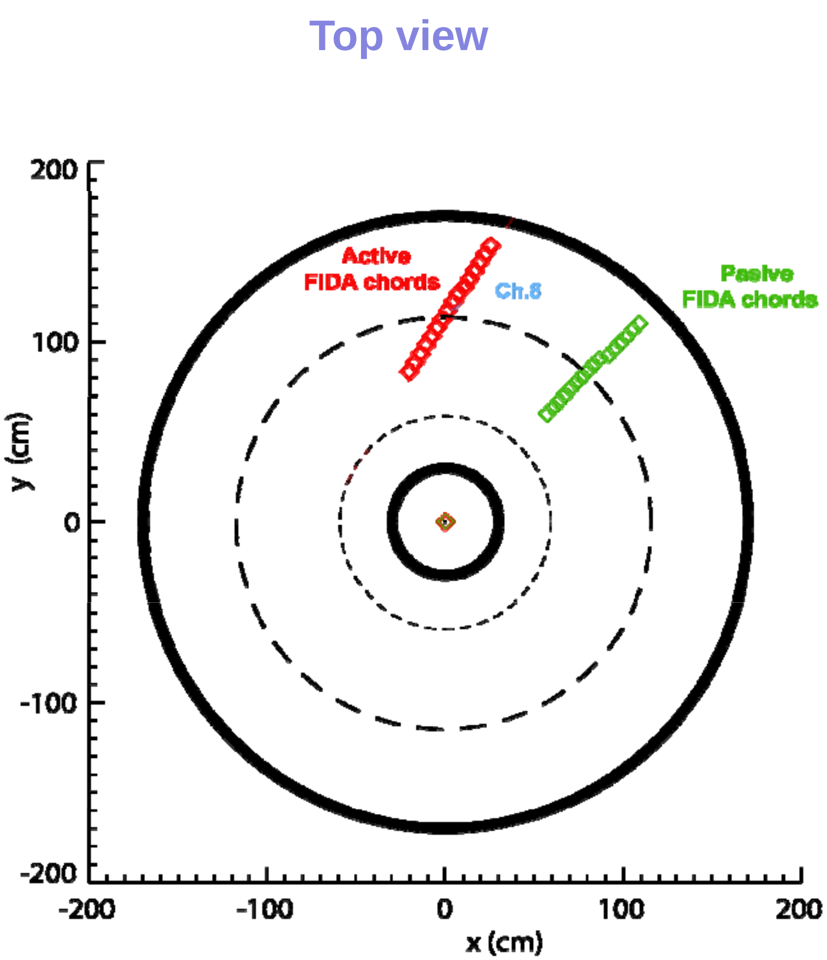


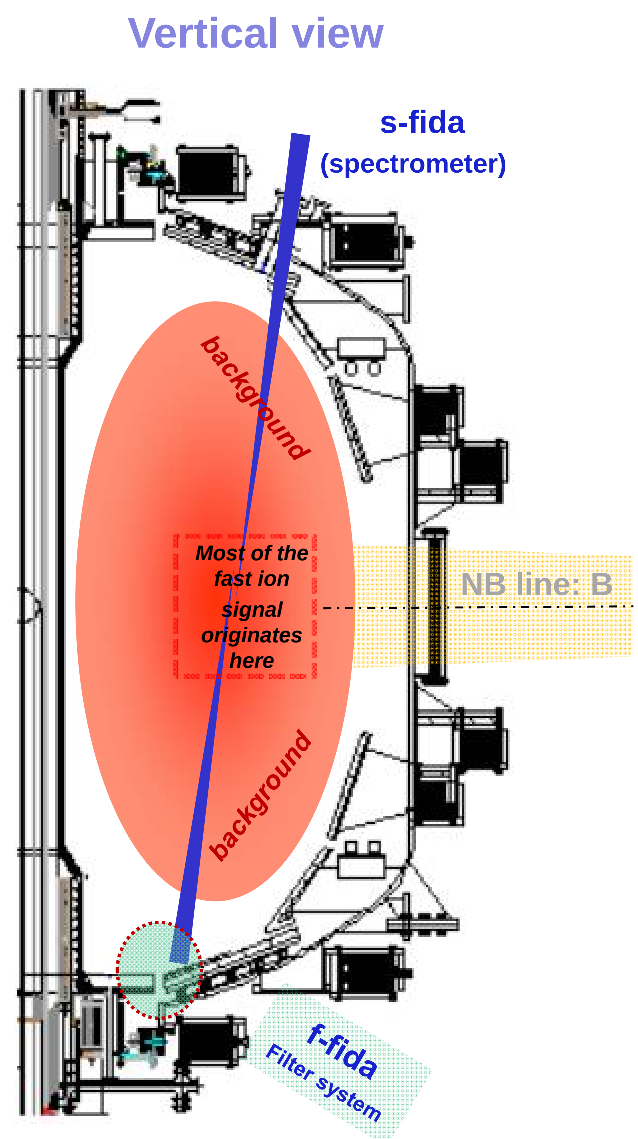
- Photons emitted by re-neutralizing fast ions (interacting with the beam and halo neutrals) have Doppler shifted wavelengths vs. the cold D_α line (λ_0 = 656.1 nm).

- Key is distinguishing fast-ion features from the dominant cold D_α emission. Techniques used include notch filters, beam-modulation and passive channels for background subtraction, and spectral profile fitting.

W.W.Heidbrink , " Fast Ion D_α measurements of the fast-ion distribution function", RSI 81 10D727 (2010)

FIDA diagnostics deployed at NSTX



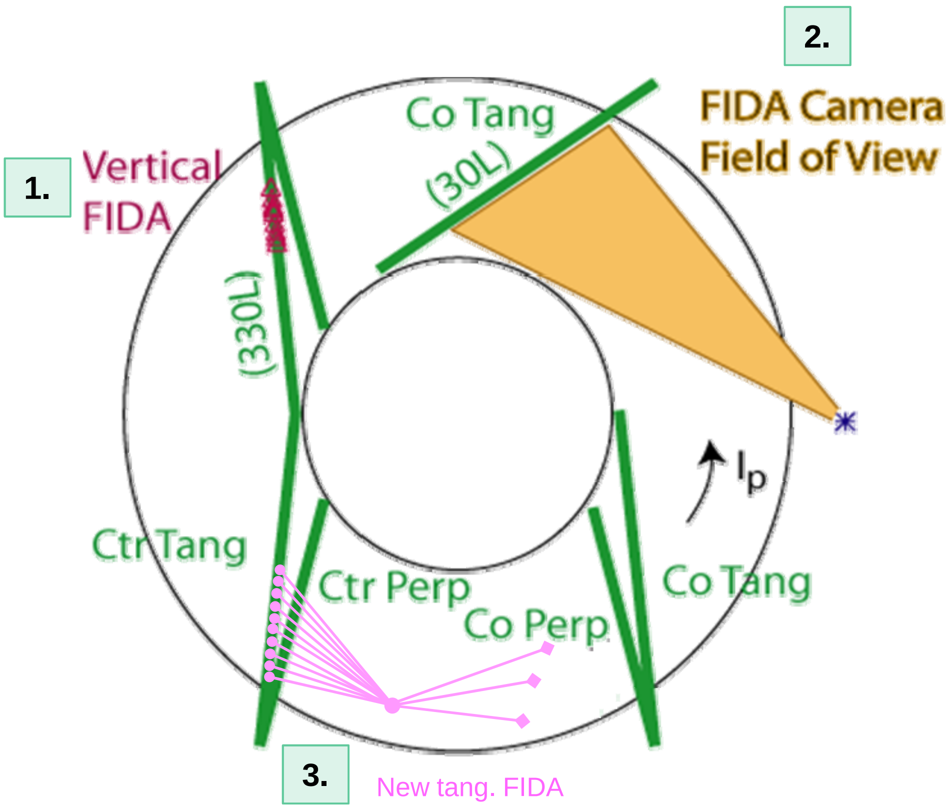


- **Additional tangential FIDA system is under development**

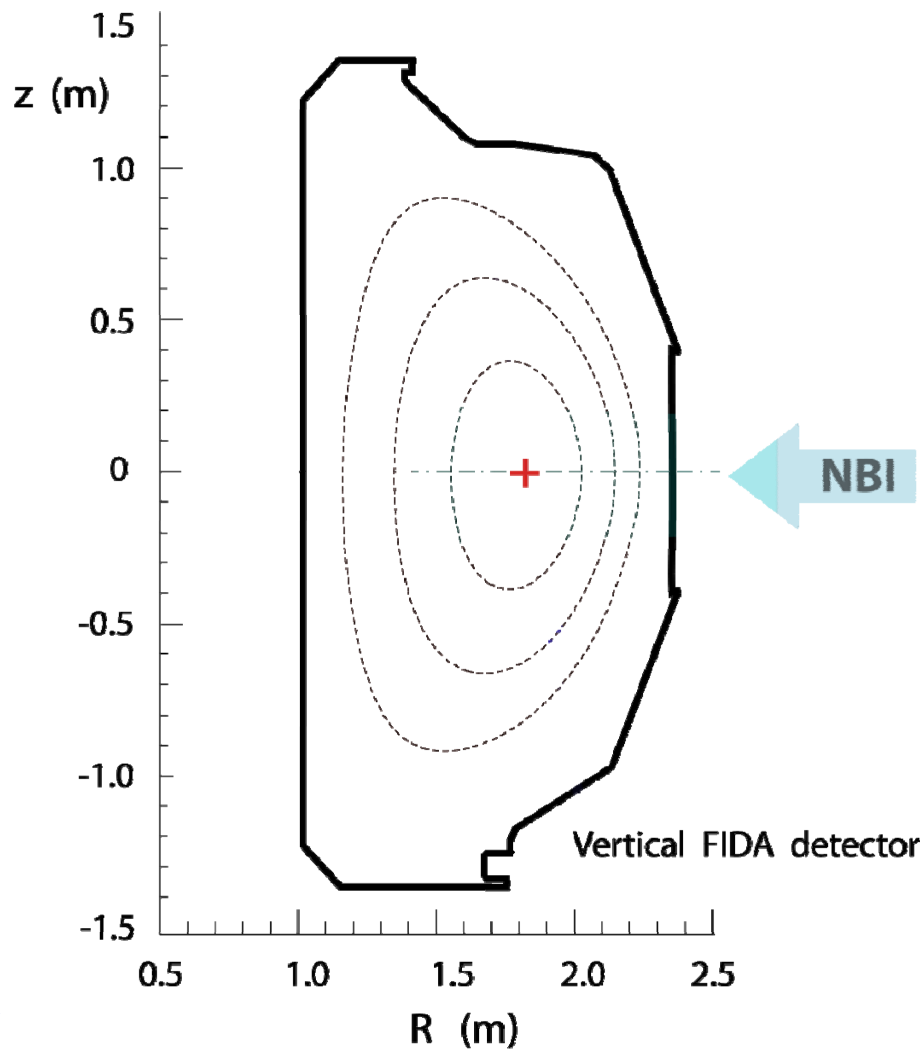
A. Bortolon, " A tangentially-viewing fast-ion diagnostics for NSTX", RSI 81, 10D728 (2010)

FIDA diagnostics deployed at DIII-D

Top view



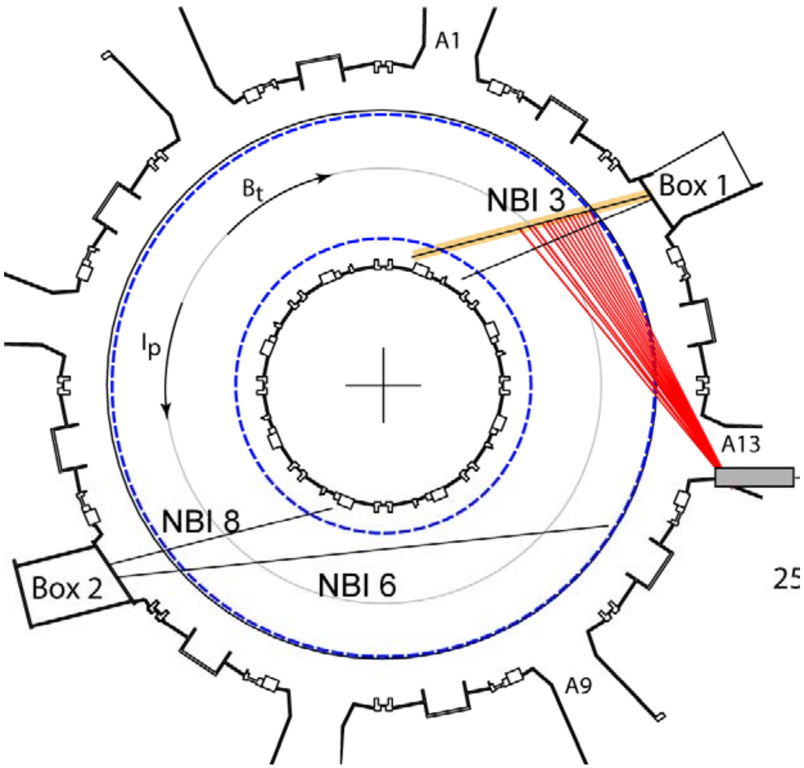
Vertical view



1. *Y. Luo, RSI 75 (2004) 3468*
2. *M. A. Van Zeeland, Plasma Phys. Cont. Fusion 51 (2009) 055001*
3. *C. M. Muscatello, RSI 81 (in press)*

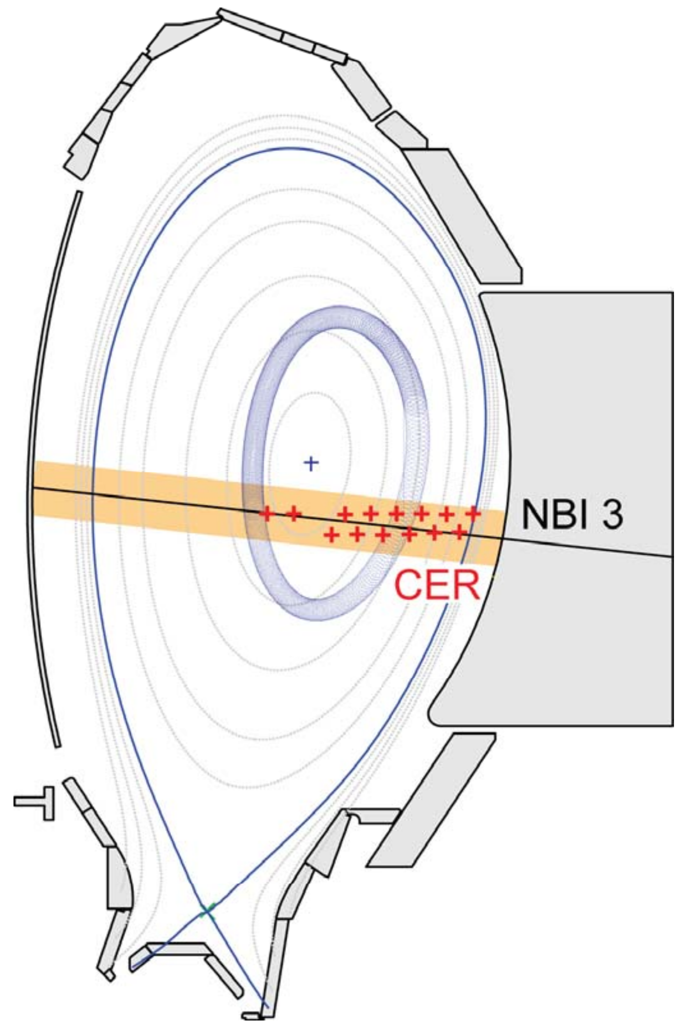
FIDA diagnostics deployed at ASDEX-U

Top view



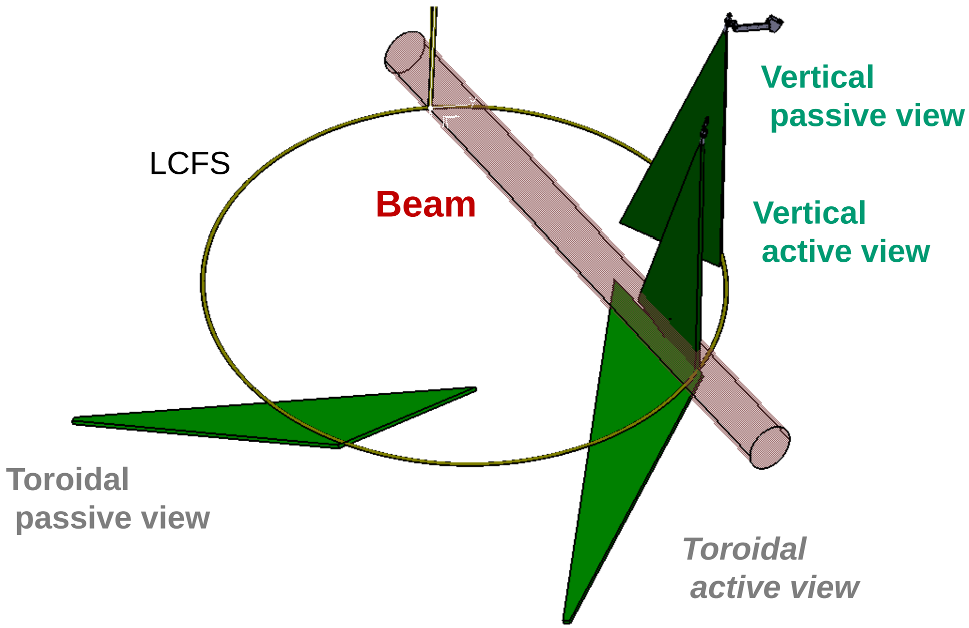
B. Geiger, „Fast-ion D-alpha Measurements at ASDEX-Upgrade", RSI (to be submitted)

Vertical view



FIDA diagnostics deployed at MAST

Isometric view



Plasma column view

- **The system has vertical and toroidal views to be sensitive to passing & trapped fast-ions.**
- **Designed to give fast spectral information:**
  - *24 channels [2 x 12]*
  - *32 fibers/view (approx 2cm between ch)*
  - *0.28ms time resolution*
  - *Expected SNR is ~ 20-30 per channel per pixel*

Outline of the FIDASIM Code

Preparatory steps

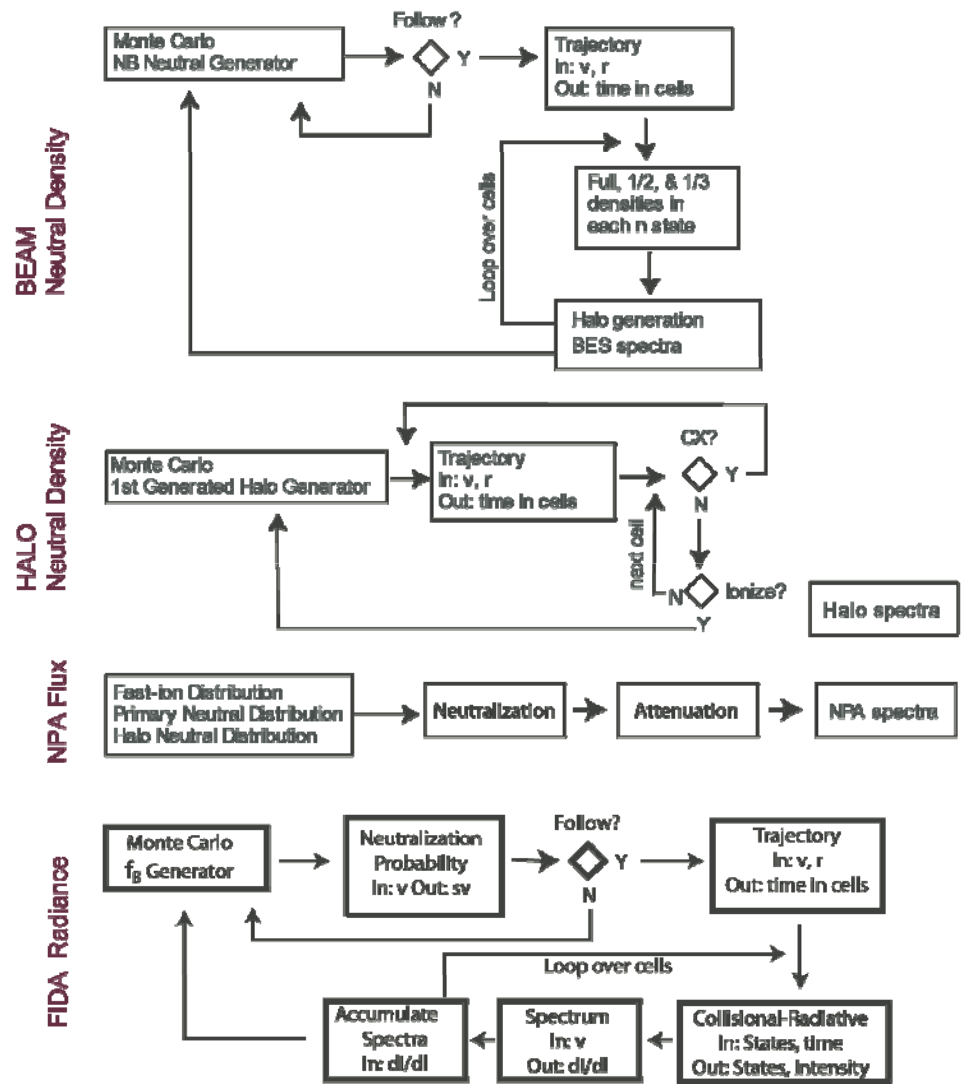
Input Data

Neutral beam geometry
Detector (primary lens) geometry
Equilibrium (G-eqdsk format)
Plasma profiles (N_e, N_{imp}, T_e, T_i, Ω)
Fast-ion Distribution
(from TRANSP, ORBIT-RF or CQL-3D)

Initialization

Create Mesh
Map plasma profiles
E & B Fields
Photon Vectors
Map beam Distribution
Atomic Rates

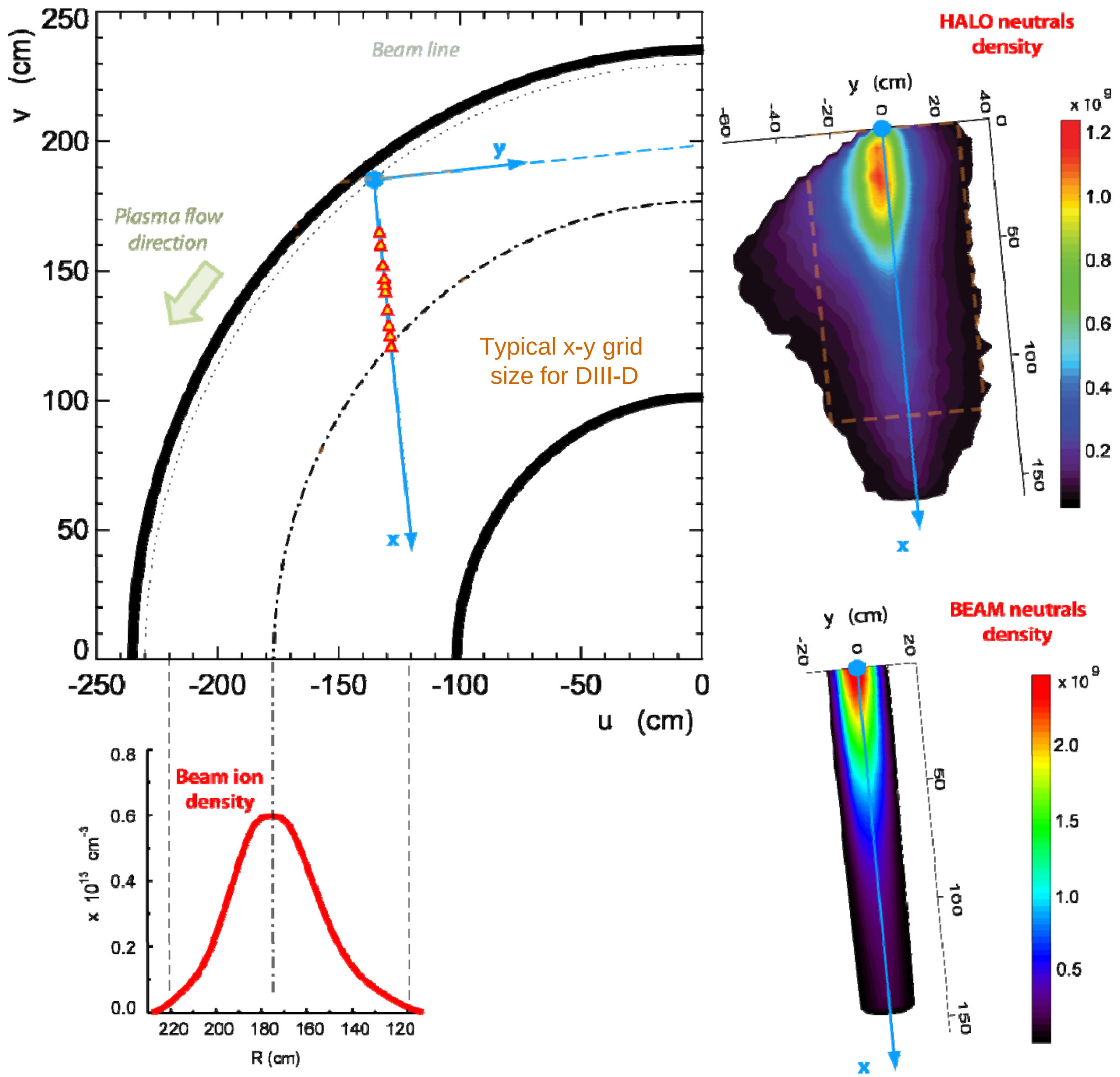
Computational steps



- **Halo and beam neutral densities are functions in real space, velocity space and energy levels with principal quantum number up to n=4**

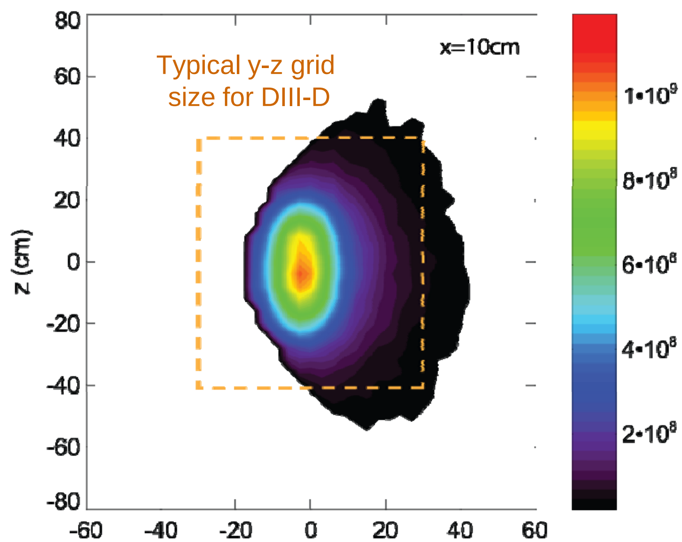
- **They are independent of time, because halos form on a ion-ion collision time scale (~10μs) and FIDASIM models spectra at a particular time instant (i.e. plasma profiles do not change).**

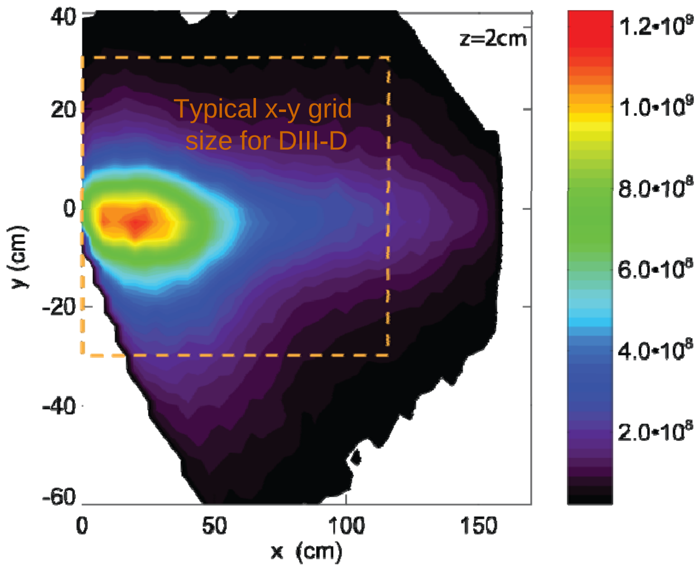
Illustration of FIDASIM calculated Halo and Beam Neutral densities at DIII-D

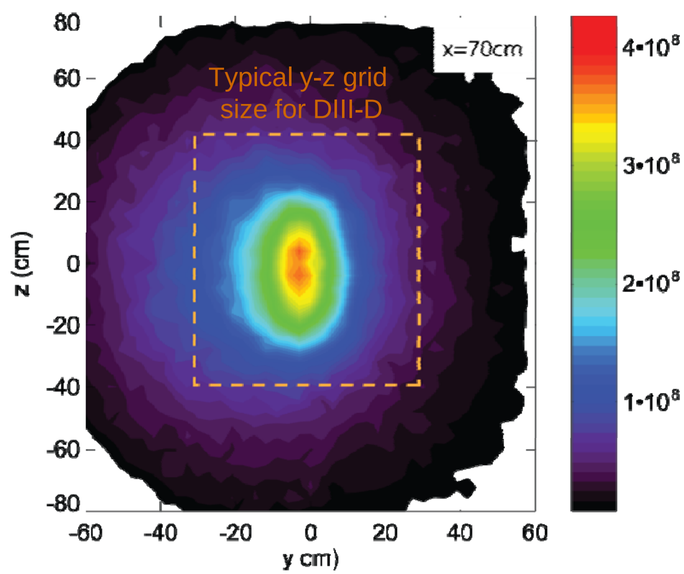


- **Beam neutrals are well collimated along the entire injection line**
- **Beam and Halo neutral densities are comparable in size**

Grid size selection determined by the extent of Halo neutrals

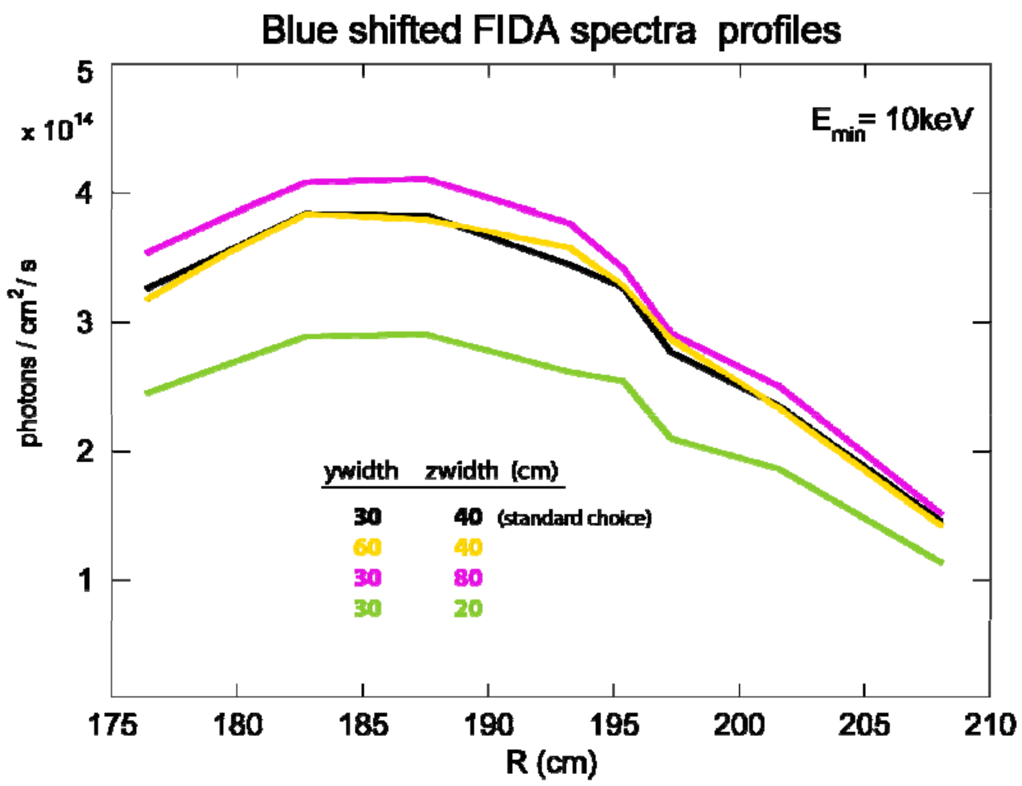






- **Halo neutrals are collimated close to the beam entrance in the vessel, but spread significantly along the beam injection line, both in horizontal, and vertical direction**
- **The computational grid volume is determined by the halo spread size**

Effect of grid size choice on calculated FIDA profiles



- Elongated plasmas have large halo neutral density content in the vertical direction.
- This DIII-D example shows that ~30% lower values for FIDA profiles are calculated when the vertical half-height is reduced to 20cm.

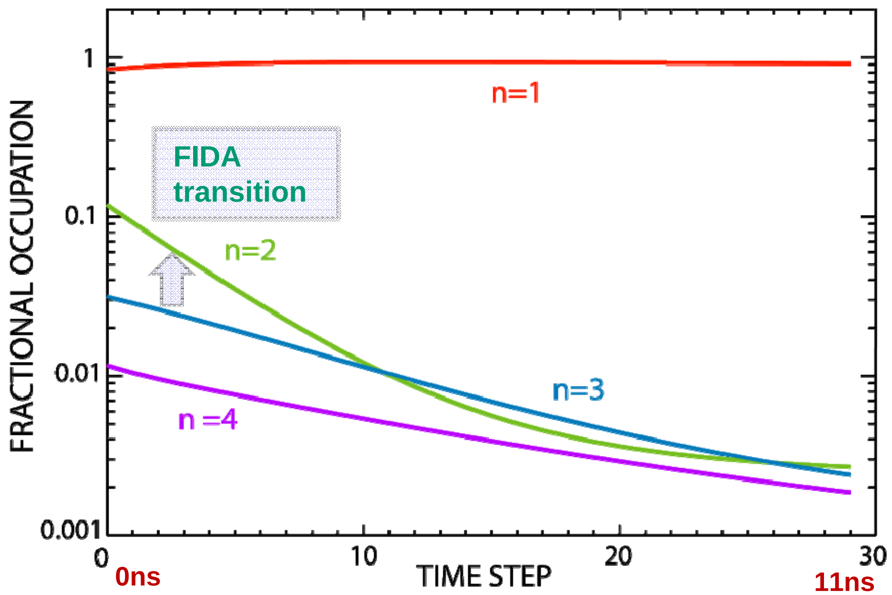
FIDASIM Verification: Atomic Physics

Collisional-radiative model COLRAD is at the code core

$$\frac{dN_j}{dt} = \sum_k N_k M_{kj}$$

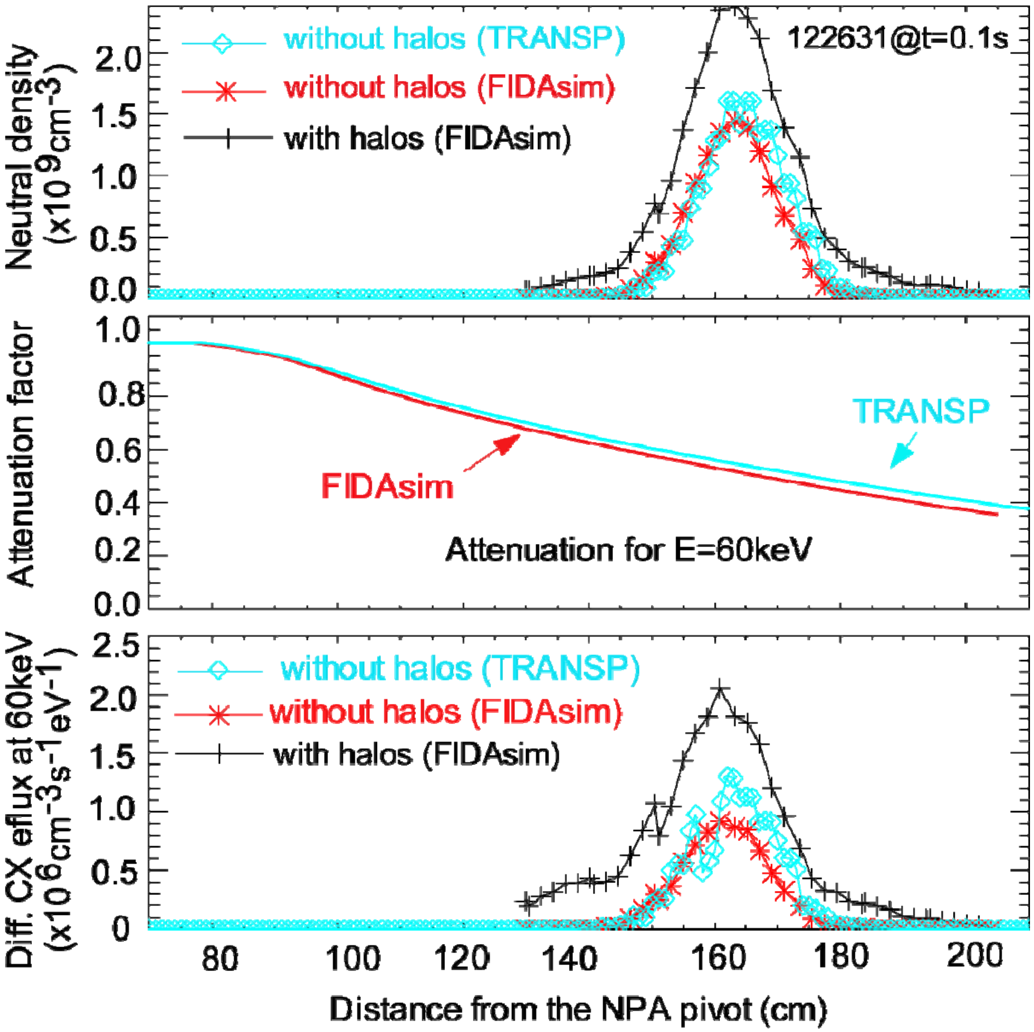
- COLRAD is called each time a neutral enters a new grid cell
- ADAS cross sections and reactivities are used
- Initial neutralization probability for CX between fast ions and neutrals considers only states n=1-4, but COLRAD includes levels up to n=7
- These are the most time consuming calculations in the code (~ 30 %)
- Matrix elements M_{kj} are within few % agreement with Hutchinson, *Plasm Phys.Controlled Fusion **44** (2002) 71*

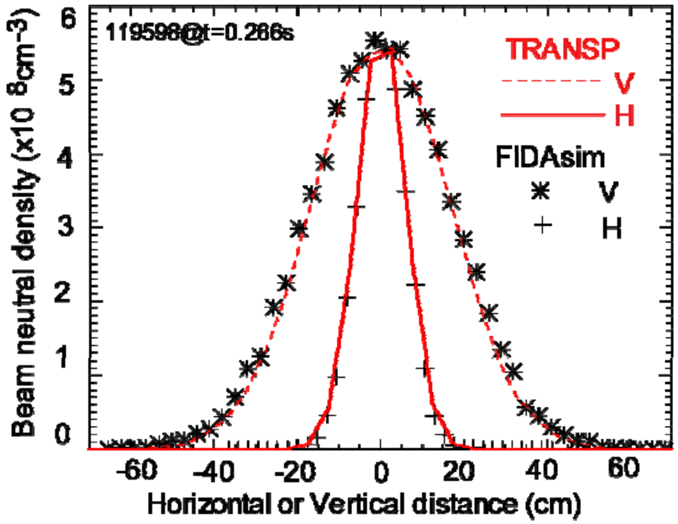
Energy level occupancy after Fast-ion neutralization



- Occupations of n > 1 levels is very low, but σ_{CX} are large, so initial occupation fractions for n=2, n=3 and n=4 are ~ 10%, 3% and 1%

FIDASIM Verification:
Beam Deposition in a NSTX plasma

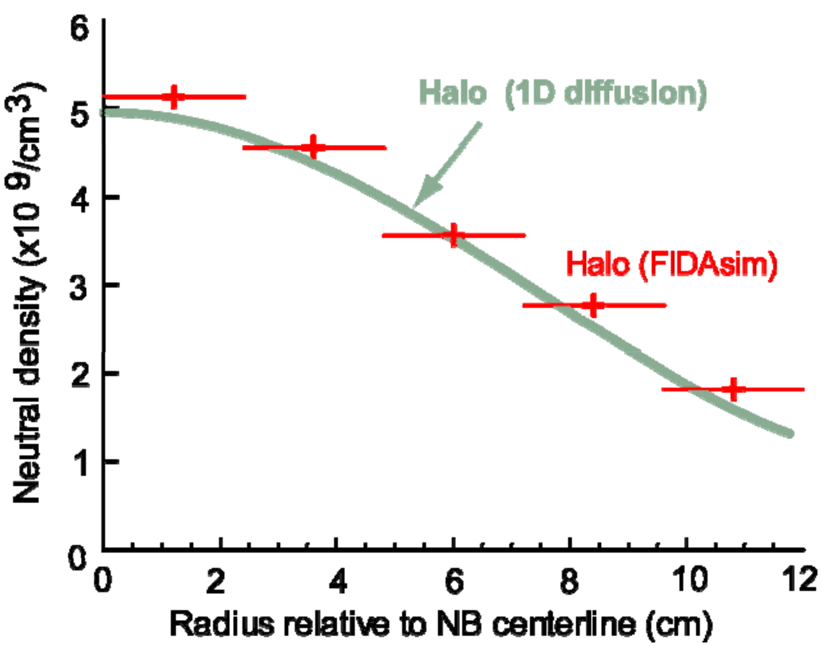




- **TRANSP & FIDAsim beam neutral density profiles in horizontal (H) and vertical (V) direction are in agreement**

- **TRANSP & FIDASIM NPA calculations agree when halo neutrals are neglected.** **(TRANSP currently doesn't have a halo model)**

FIDASIM Verification:
Halo neutrals calculation



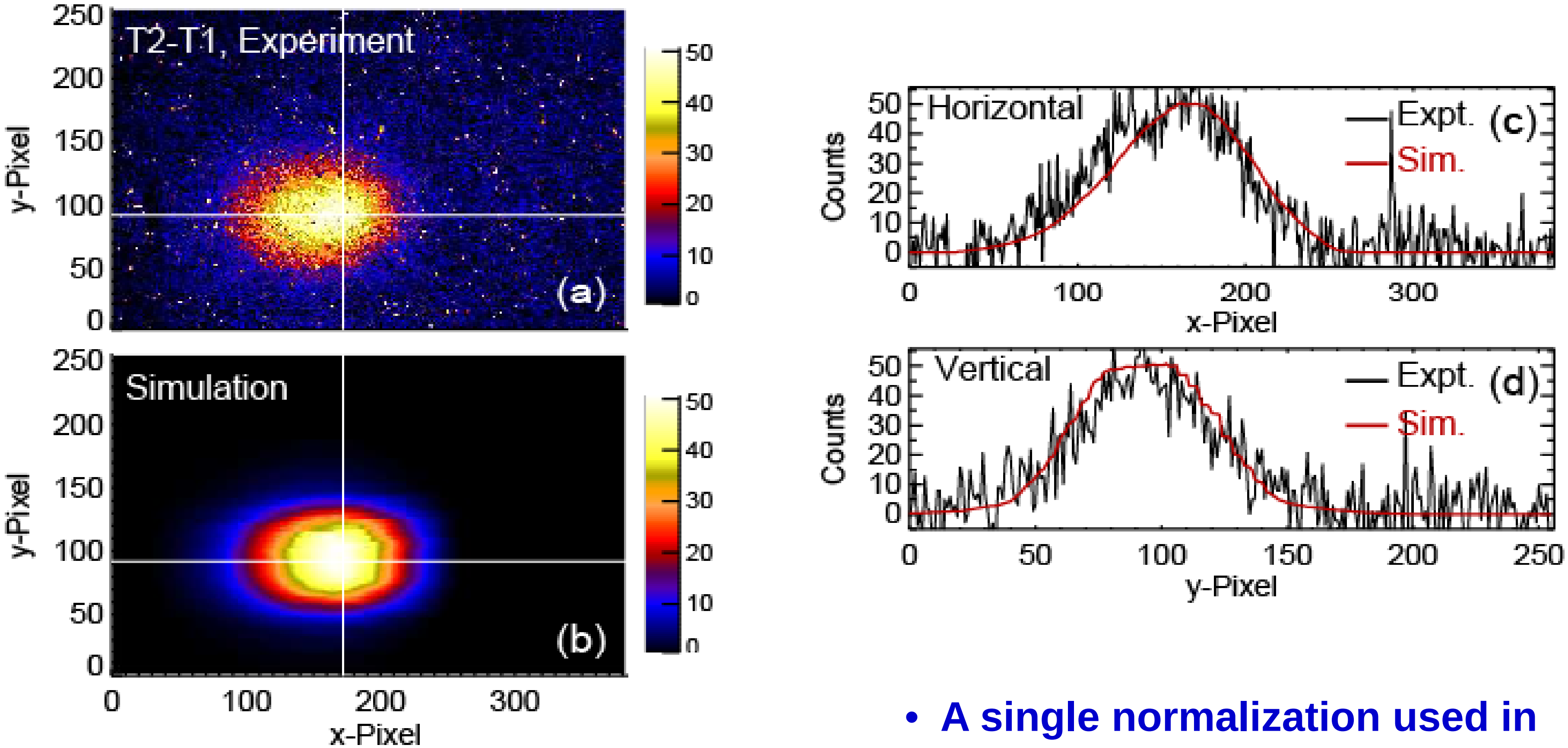
- **Simplified 1-D diffusion model used:**
  - **uniform plasma**
  - **circular beam footprint**
  - **const.rate of halo neutrals creation**
  - **halo neutrals diffuse only radially**

- **The beam footprint is divided into many regions in which the plasma parameters are constant.**

- **Analytical 1-D solution is obtained for each region, then halo densities in all regions are summed and compared with the FIDASIM calculation.**

- **Good agreement between FIDASIM and the 1-D model is achieved.**

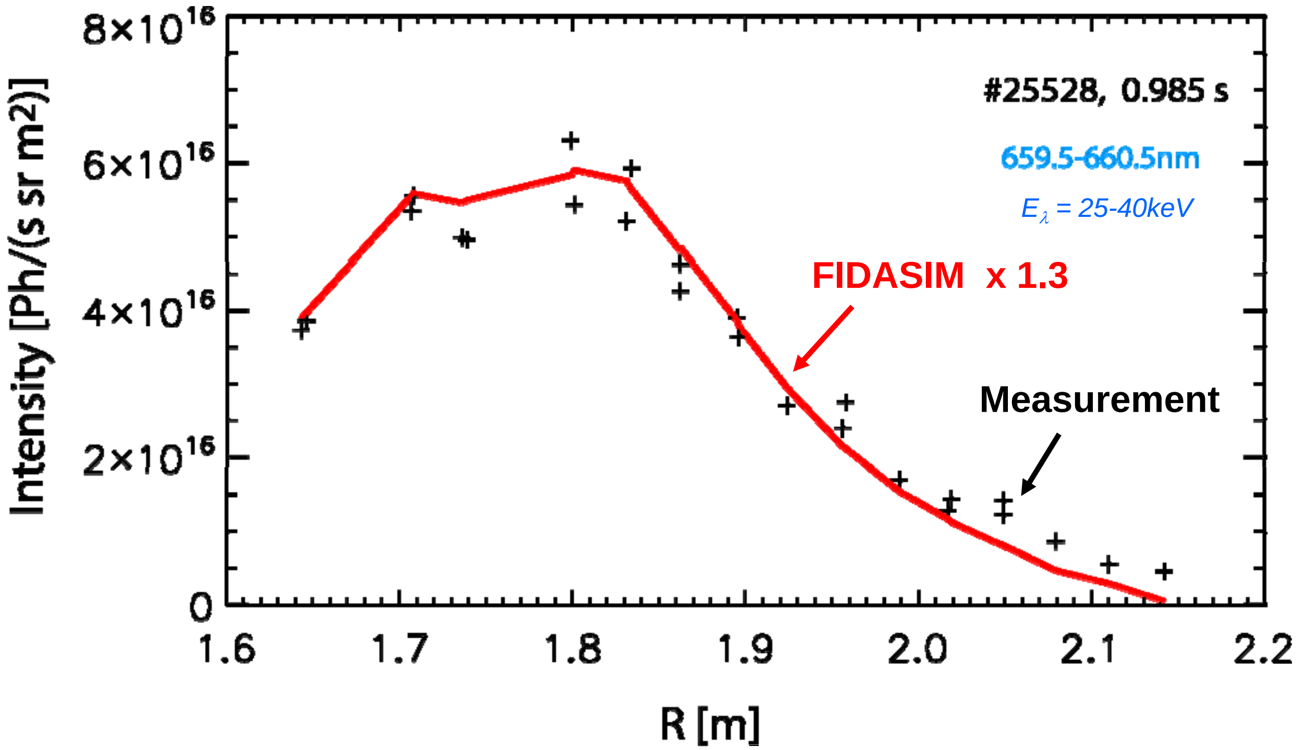
FIDASIM validation: imaging at DIII-D agrees with modeling



Van Zeeland, PPCF 51(2009) 055001.

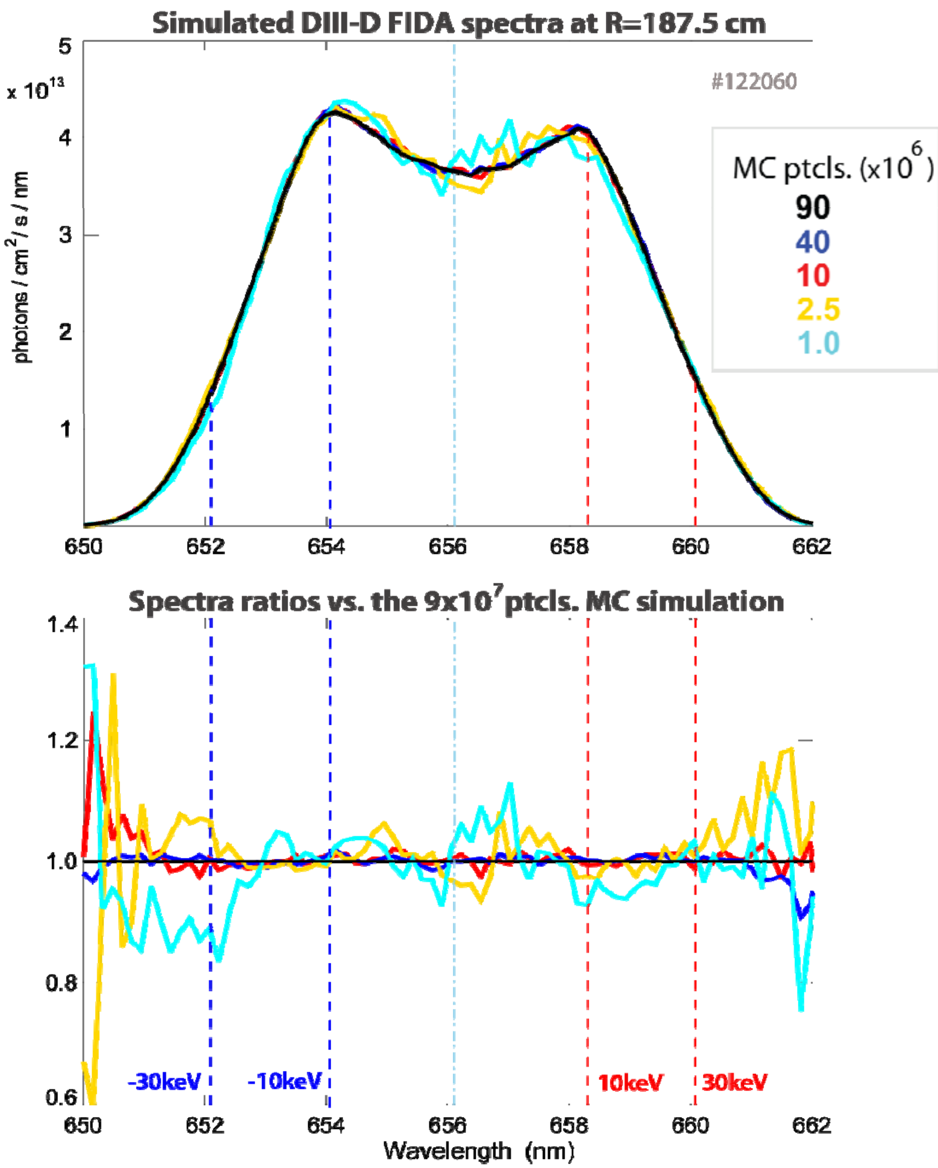
- **A single normalization used in this comparison**

FIDASIM validated in a MHD quiescent ASDEX-U plasma



- Excellent agreement between measured fast-ion density profiles and those predicted by TRANSP in MHD quiescent plasmas

FIDASIM modeling requires large number of Monte-Carlo particles

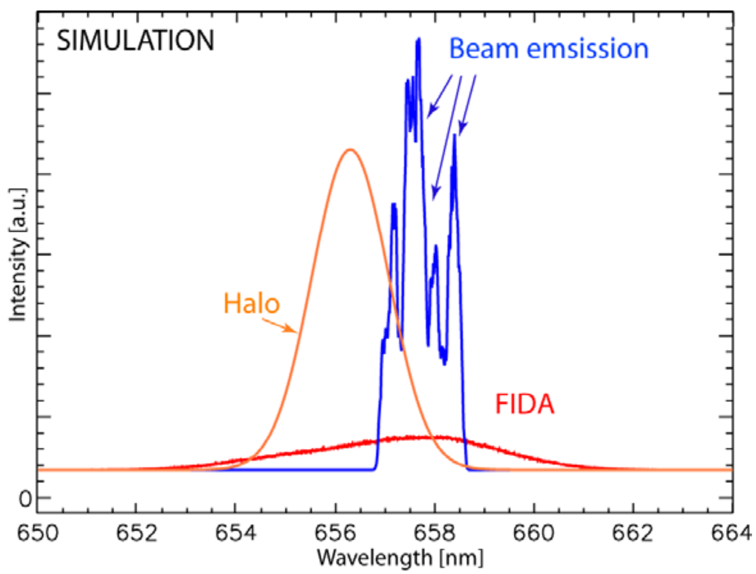


- Need 10^7 MC ptcls. to limit MC noise within 5% for spectra with E_λ < 30keV
- They take 25-30h wall time on a single CPU machine
- Execution time depends on the plasma volume modeled and the choice of grid size
- Need more MC particles if higher ends of the Doppler shifted lines are of interest (i.e. higher E_λ)

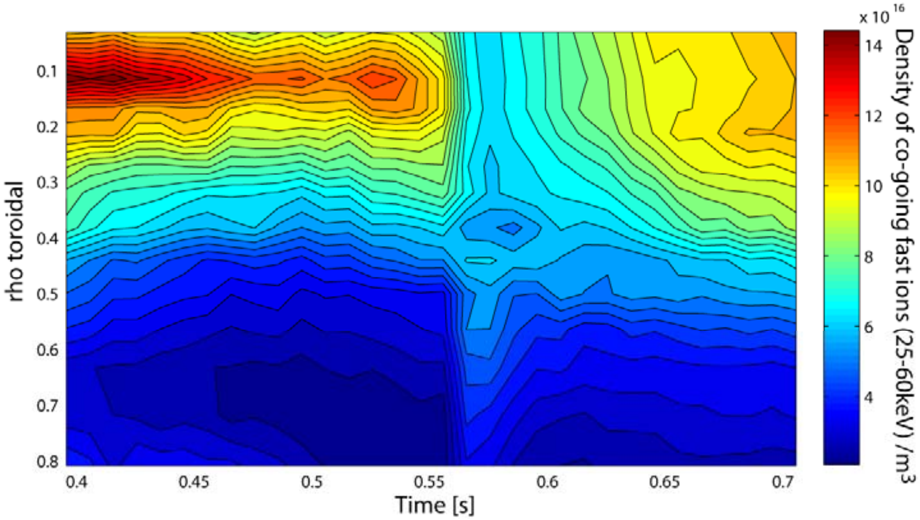
FIDASIM F90 version developed at ASDEX-U

- **Inputs are collected by IDL routines (geometry, kinetic profiles, equilibrium)**
- **Main calculation performed by Fortran 90 Output: Halo, Beam and FIDA emission**
- **15 minutes for a whole FIDASIM run (ray server with 2.33 GHz, 5x10^6 MC ptcls.)**

Simulated FIDA spectrum for a tangential view



Redistribution of fast ions (30 radial profiles) observed during a sawtooth like crash



B. Geiger et al. to be submitted to PPCF

LOCUST-GPU: An ambitious fast-ion GPU based modeling tool

GPGPU particle tracking platform being developed at CCFE – based upon CUDA and openMP technology.

Aim: Develop a platform that can accurately predict all necessary fast ion diagnostic signals for a given NBI heated plasma + fast ion MHD model, in low density plasma, ~non-adiabatic (low field) limit:

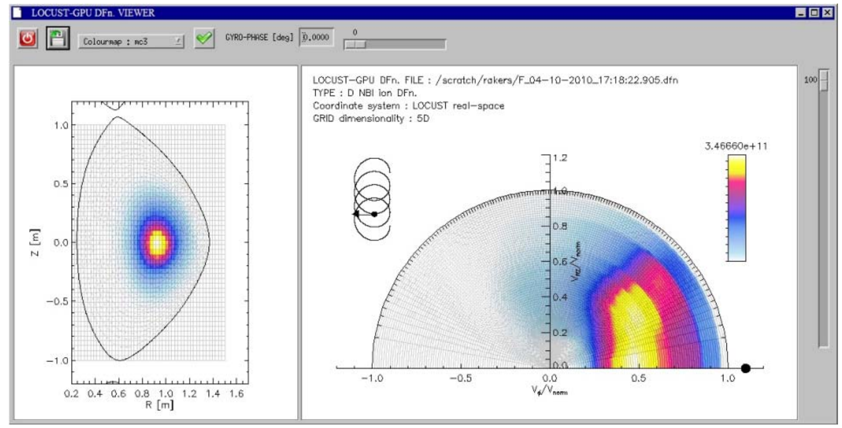
- FIDA
- NPA (almost complete)
- Neutron spectra (complete)
- DD fusion p/T camera imaging (complete)

Fast ion distributions need to be smooth and high resolution as “gradients” are required for MHD modelling (HAGIS).

Challenges:

- minimization of branch divergence,
- maximization of stride-1 global memory access and use of shared memory
- restriction to single precision
- numerical orbit drift for low levels of Goosing

Work has up until now concentrated on charge particle tracking.



The LOCUST-GPU DFn. VIEWER: Interactive tool for interrogating the 5D fast ion distribution

One GTX480 Fermi card delivers a ~50x speed up over a single Nehalem hyperthread – (~4 cards per workstation)

Work on COLRAD_GPU has started. ADAS development team have compiled all necessary rate and cross section coefficients and the solver has been prototyped.

Work now started on n-state resolved primary beam neutral distribution solver.

CONCLUSIONS

- FIDASIM is a 3D MC code with a comprehensive atomic physics model for calculating the Doppler shifted D_α spectrum and NPA particle flux.
- Many aspects of the code have been verified, and validated experimentally in conventional tokamaks.
- FIDASIM predictions have not yet been confirmed in a spherical tokamak (NSTX) and the NPA model has not yet been validated.
- Work on code speed-up with F90 is under way.
- FIDA modeling is being integrated in LOCUST-GPU.