NSTX-U

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Use of TRANSP for Fast Ion Physics Study and Future Needs

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TRANSP User's Group Meeting

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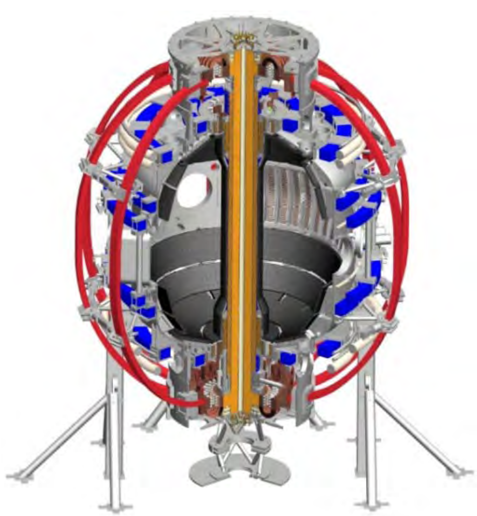

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Outline

- **Introduction**

- **Examples of using TRANSP for fast ion physics**
  - FIDA & FIDA imaging
  - Benchmarking of 3D halo neutral density model
  - Benchmarking of NPA simulator

- **Future needs**
  - 2D background neutral density
  - Fast ion birth profile in scrape-off layer
  - Interaction between fast ions and RF waves
  - Fast ion distribution in constant-of-motion space

Why Need Fast Ion Distribution from TRANSP?

- **Fast ions (FI) are an important source of energy, momentum, and particles.**
  - provide current drive, plasma heating, external torque
  - affect MHD stability, drive instabilities
  - significant FI losses could damage first wall and raise ignition threshold
- **It is challenging to measure full FI distribution.**
  - experiment: f(R, Z, E, pitch) in phase space
  - theory: $f(P_\varphi, \mu, E, v_{sign})$ in constant-of-motion space
- **TRANSP self-consistently calculates f(R, Z, E, pitch) in realistic geometry.**
  - collisional and atomic physics effects, finite Lamar radius effect included.
  - good approximation of realistic FI distribution in quiescent plasmas.
  - ad-hoc FI diffusion model available.
  - reduced models for FI transport are being developed.

TRANSP: provide key inputs for synthetic FI diagnostics;
help understand experimental data;
enable comparisons between experiments and modelings.

FI Distribution has Special Features, but only a Small Portion is Measured by Diagnostics

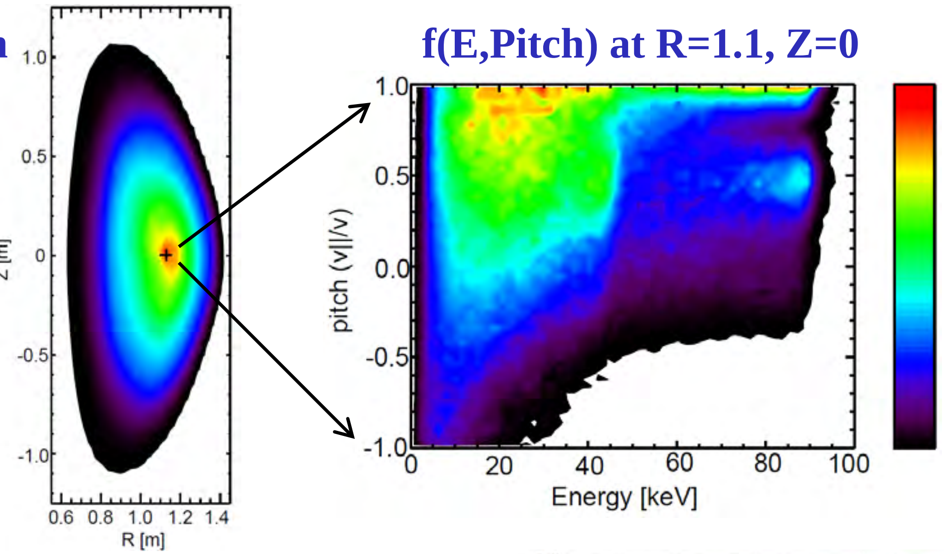
➢**f(R, Z E, pitch)**
- 4-dimensional
- anisotropic
- important for the calculation of current drive, power balance
- crucial for synthetic FI diagnostics

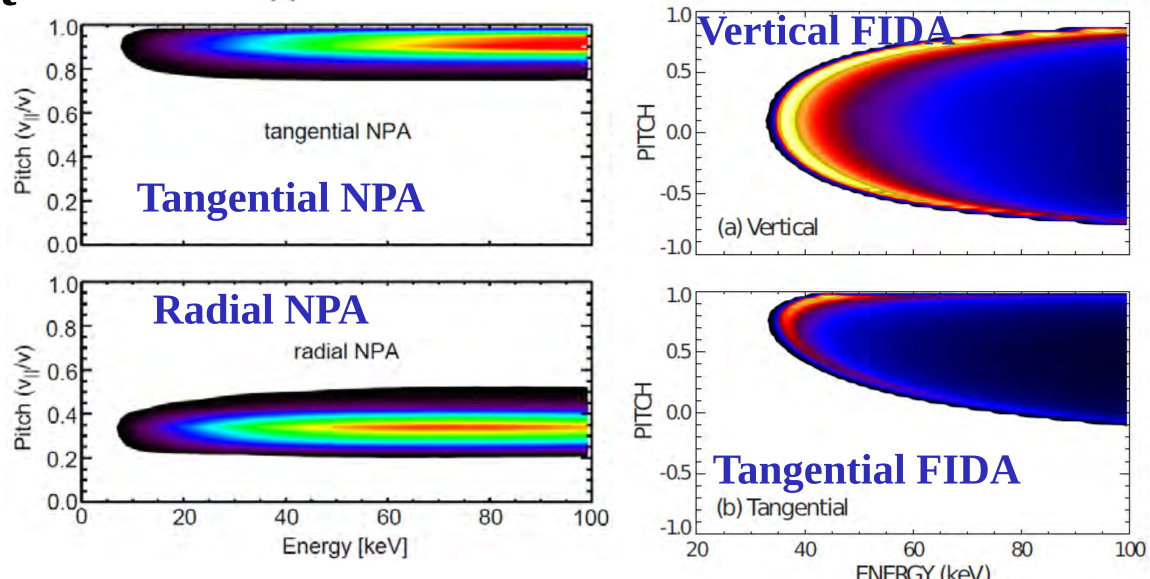
➢**Different FI diagnostics weight f(R, Z, E, pitch) differently**

$$Signal = \iint (\underset{\uparrow}{W} \times f)\,dE\,dPitch$$

weight function

Fast ion density





W (E, Pitch)

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Reasonable Agreement between TRANSP Predictions and FIDA Measurements in MHD-Quiescent Plasma

➢**FIDA (Fast-ion D_α)**

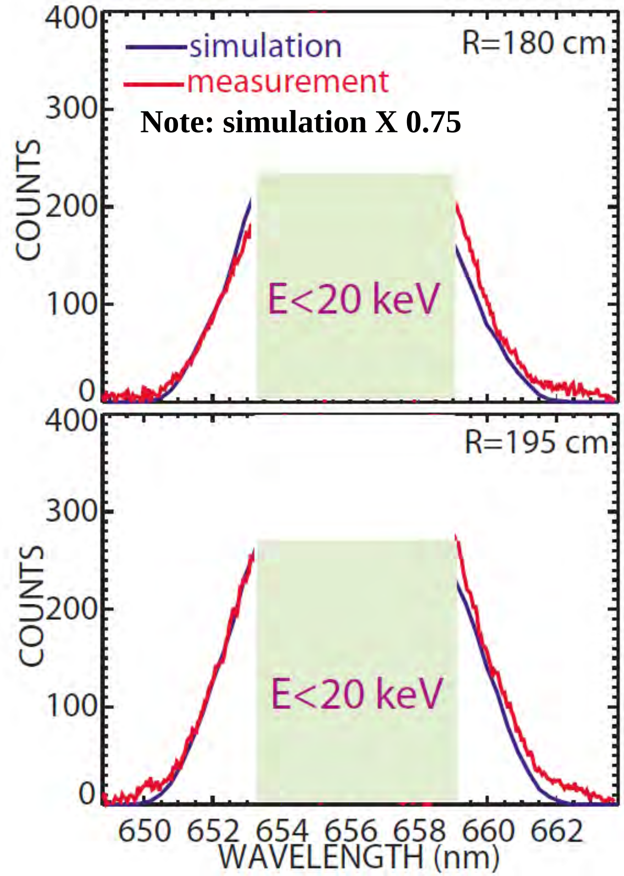
- based on active charge exchange recombination spectroscopy
- measure Doppler shifted D_α light emitted by neutralized fast ions

$$Signal \propto n_{fi} n_{neutral} < \sigma v >$$

➢**Measured spectral shape & magnitude reasonably agree with TRANSP+FIDAsim modeling.**

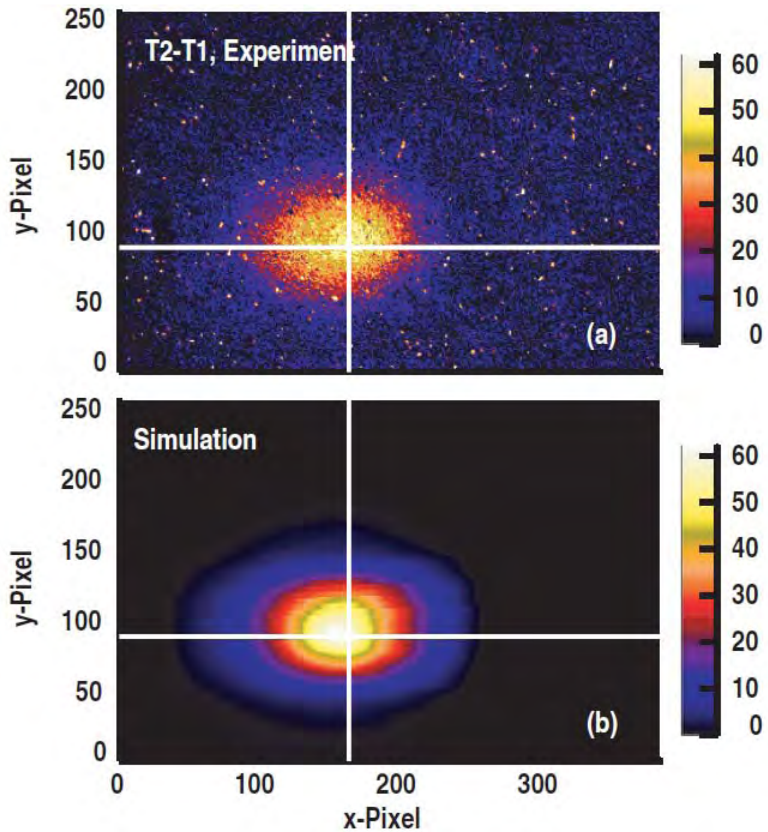
- FIDAsim (synthetic FIDA diagnostic) uses TRANSP's classical fast ion distribution
- prove FIDA diagnostic
- validate Coulomb collision model

➢**Consistent with neutrons and NPA**

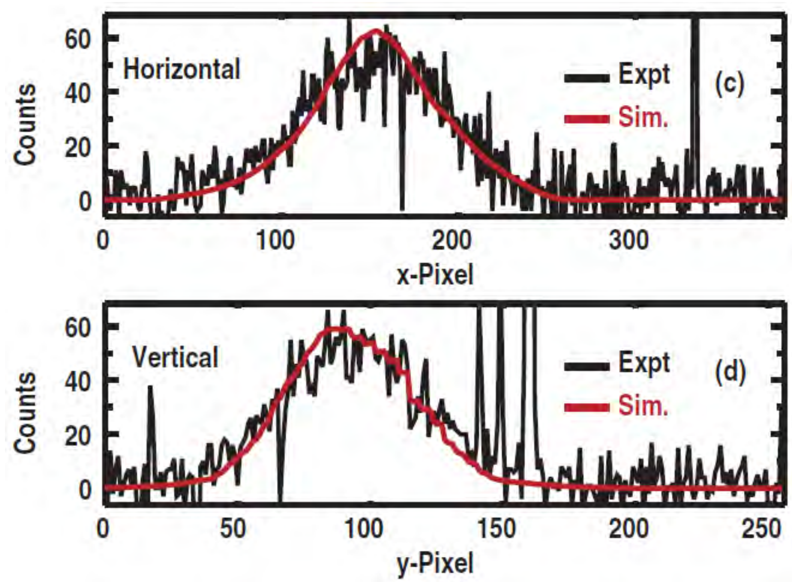


Luo, Phys. Plasmas 14 (2007) 112503

FIDA Image Agrees with Theory in MHD-Quiescent Plasmas



Van Zeeland, PPCF 51(2009) 055001



Note: one normalization in this comparison.

- FIDA Imaging: FIDA + narrowband filter → 2D time-resolved profile
- FIDAsim simulates FIDA image with TRANSP's classical fast ion distribution
- The measured spatial structure & temporal evolution are in excellent agreement with TRANSP+FIDAsim simulations.

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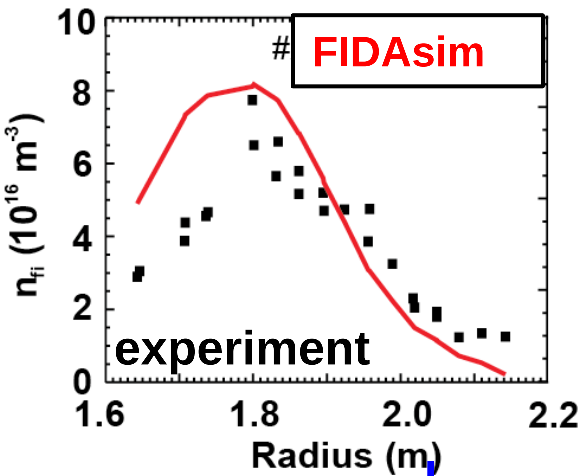
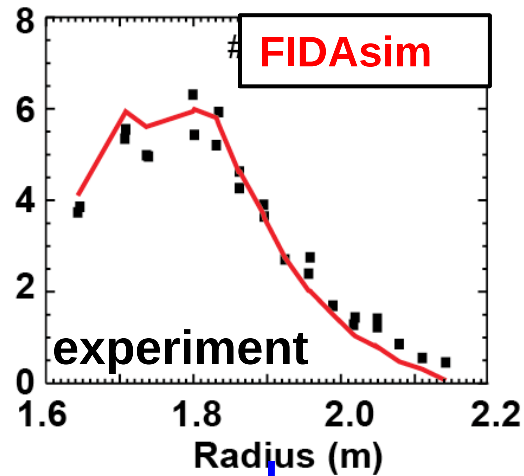
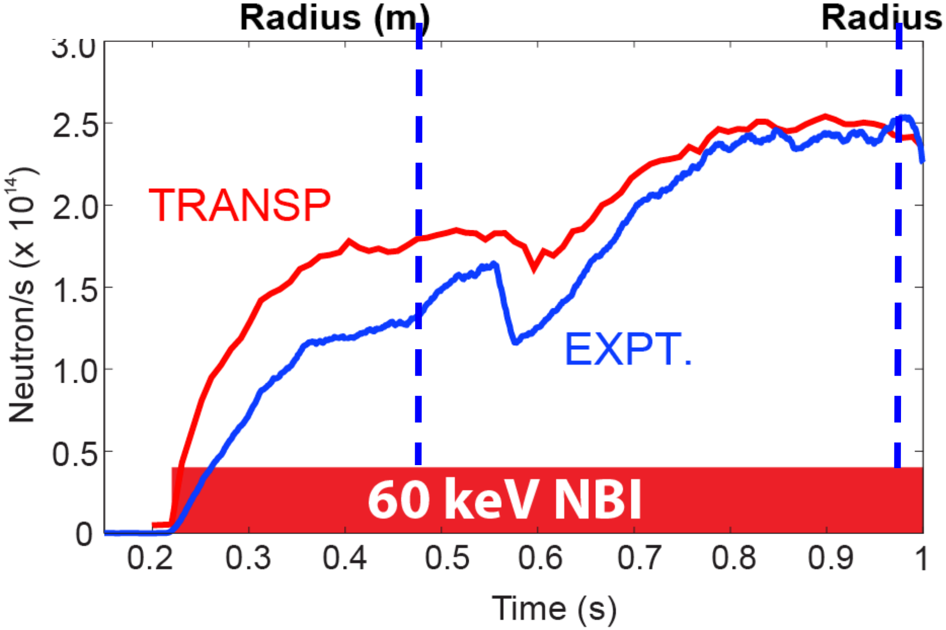
Large Reduction in Core Fast-Ion Density Induced by RSAE Activity

Courtesy of M. Garcia-Munoz

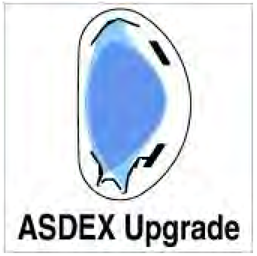
M. Garcia-Munoz, Nucl .Fusion 51 103013, 2011 (2011)







- Large deficit in FIDA emission relative to FIDAsim indicates central depletion of FI density
- After the mode disappears, FIDA profile and neutron return to classical levels



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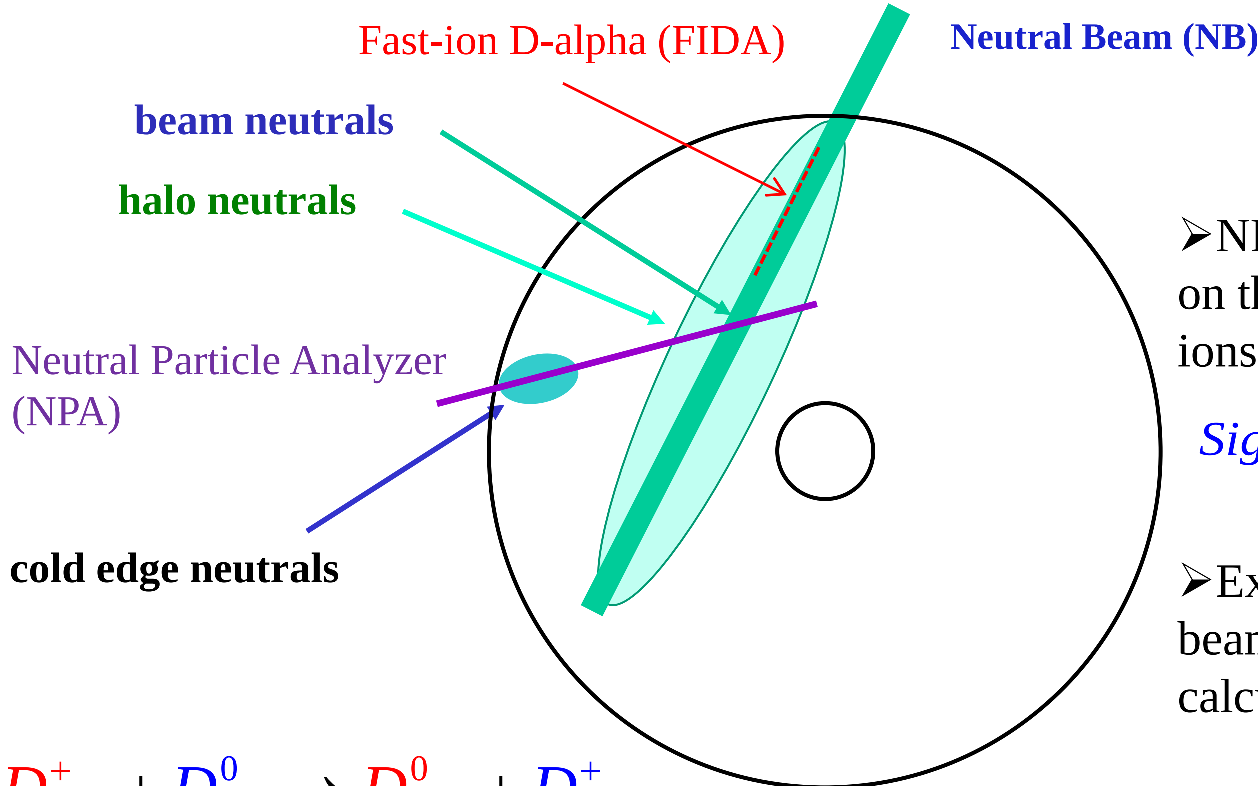
Neutral Density Needs to Be Accurately Modeled In Order to Infer Fast Ion Density



- NPA and FIDA diagnostics rely on the CX reactions between fast ions and neutrals

$$Signal \propto n_{fi} n_{neutral} < \sigma v >$$

- Extensive benchmarking to check beam & halo neutral density calculation in TRANSP.

$$D^+_{fast} + D^0_{NB} \rightarrow D^0_{fast} + D^+_{NB}$$

$$D^+_{bulk} + D^0_{NB} \rightarrow D^0_{halo} + D^+_{NB}$$

$$D^+_{fast} + D^0_{halo} \rightarrow D^0_{fast} + D^+_{bulk}$$

$$D^+_{bulk} + D^0_{halo} \rightarrow D^0_{halo\_high\_generation} + D^+$$

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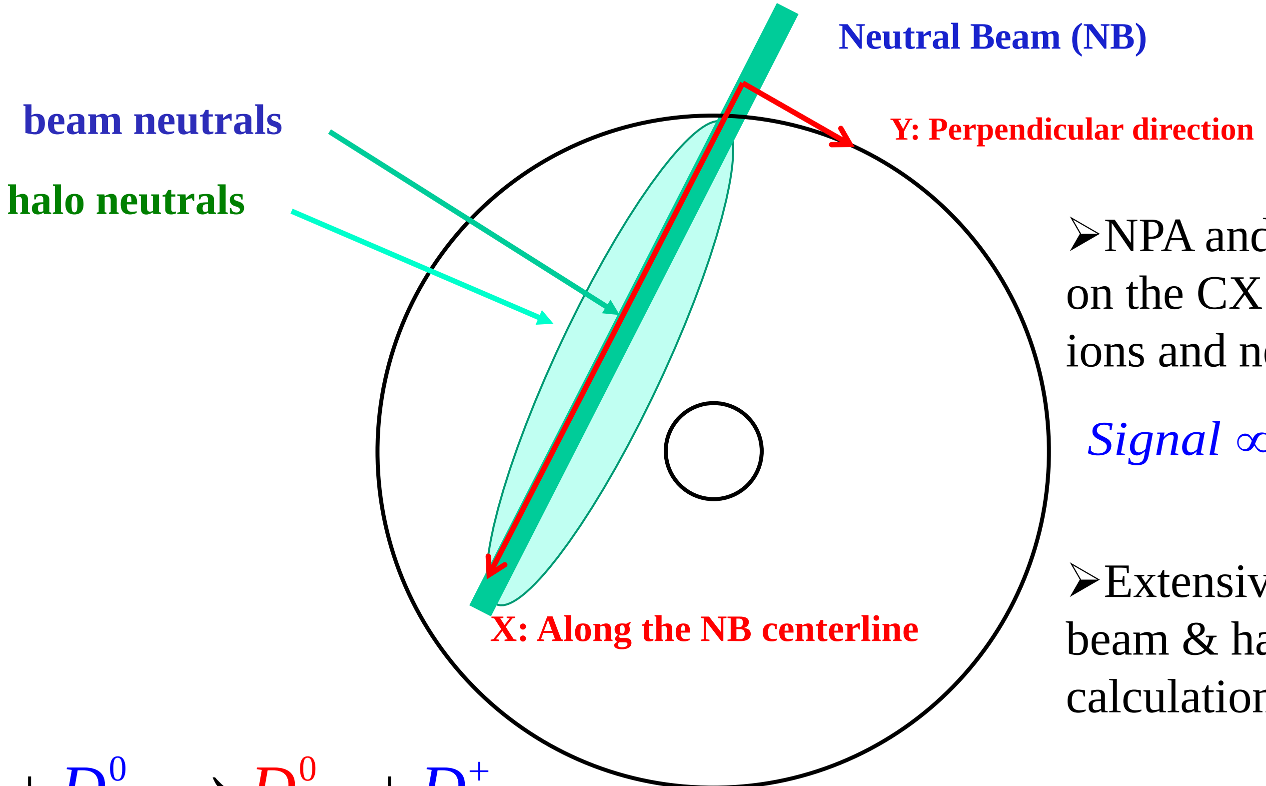

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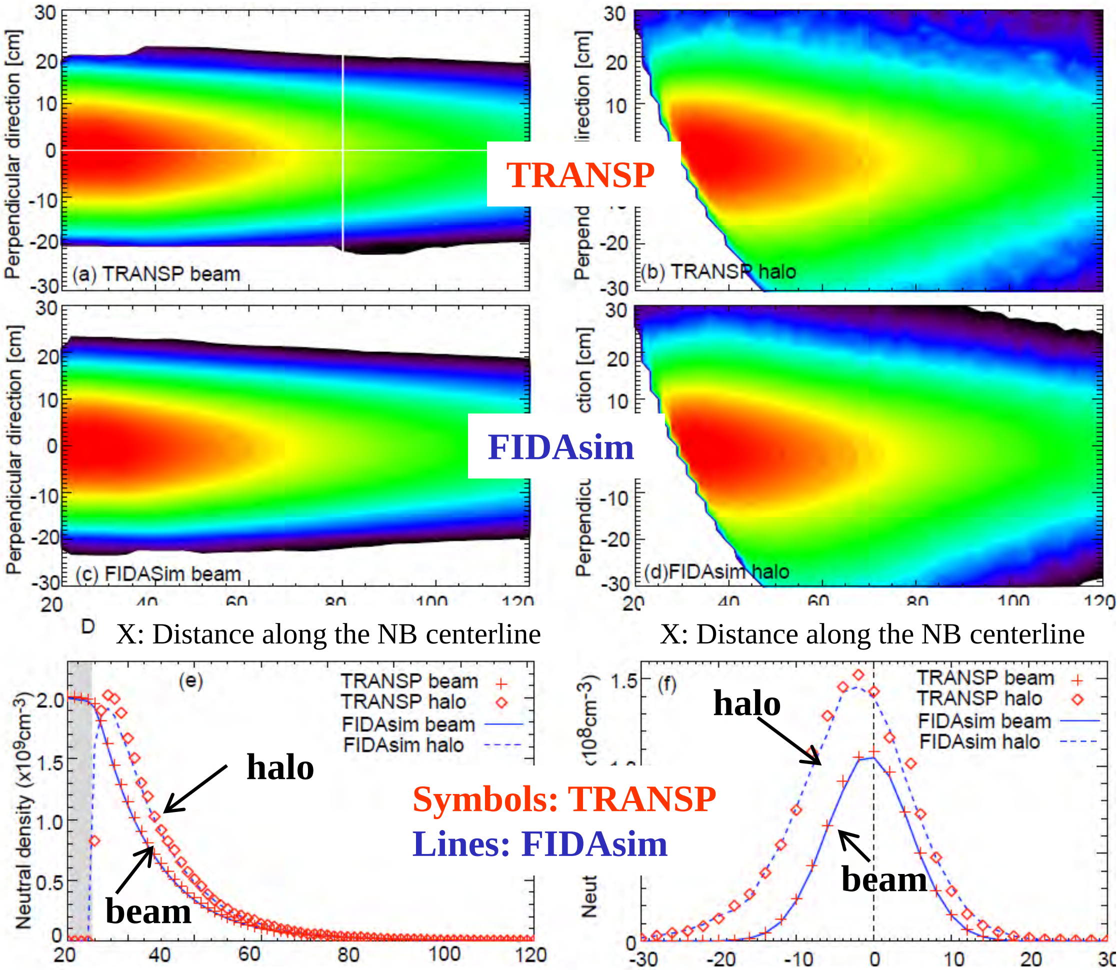
$$D^{+}_{bulk} + D^{0}_{halo} \rightarrow D^{0}_{halo\_high\_generation} + D^{+}$$

Benchmarking of Beam and Halo Neutral Density between TRANSP and FIDAsim

beam neutral **halo** neutral



X: Distance along the NB centerline Y: Perpendicular distance

➢**3D Halo model in TRANSP**
Monte-Carlo method, atomic physics and rotation effects included

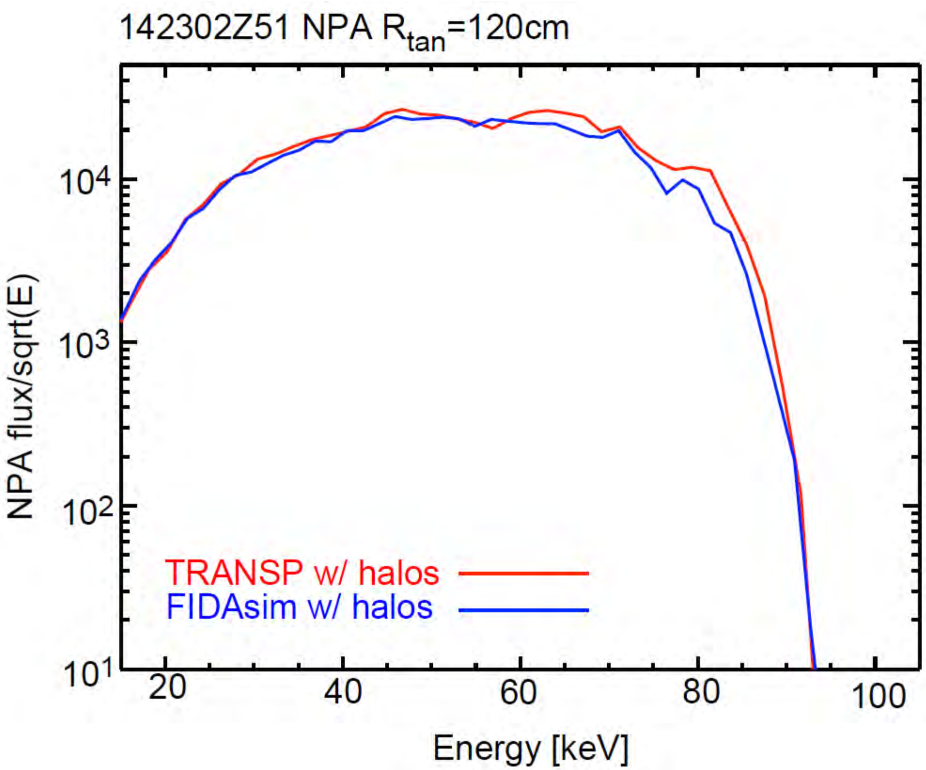
➢**FIDAsim: synthetic FIDA diagnostic**
Output beam and halo neutral density profile in each energy level, NPA, FIDA signals/spectrum

➢**Reasonable agreement between TRANSP and FIDAsim when using the same cross section tables.**

➢**Calculation of beam & halo neutral density is sensitive to cross sections tables.**

Notes: use ADAS ground state cross section tables, consider ground state neutrals only

Benchmarking of NPA simulator in TRANSP and FIDAsim



- **Neutral Particle Analyzer (NPA) simulator**
  - Neutral flux from fast ions that charge exchange with injected neutrals

$$\text{NPA neutral flux} = \int n_{fi} n_{neutral} \sigma_{cx} v_{rel} e^{-\lambda} dl$$

  - Only beam and halo neutrals are considered, edge background neutrals are not included.

- **Agreement between TRANSP and FIDAsim simulated NPA energy spectrum**

Notes: (1) use ADAS ground state cross section tables
(2) consider ground state neutrals only

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  - *Reduced models for fast ion transport*

    (being developed by TRANSP group, not addressed in this talk)

Future Needs I: 2D Background Neutral Density Profile

➢Multiple needs for background neutral density profile.

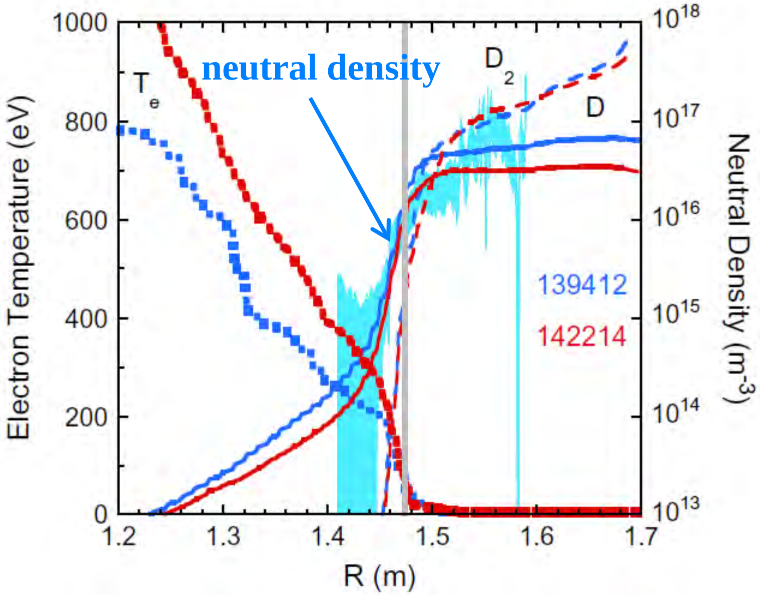
▪fast ion CX losses, NB power deposition

▪interpret and simulate FIDA and NPA passive signals

▪also important for edge physics

➢TRANSP currently uses a simple FRANTIC model, which gives 1D flux surface averaged neutral density profile inside LCFS.

➢D.P. Stotler has used DEGAS 2 Monte Carlo neutral transport code to infer neutral density profile on the midplane from the NSTX Edge Neutral Density Diagnostic (ENDD).



D.P. Stotler et al., J. Nucl. Mater. (2014)

Future Needs II: Fast Ion Birth Profile In Scrape-Off Layer

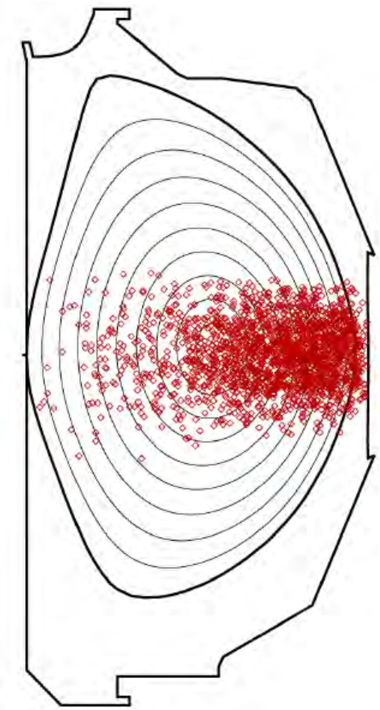
➢FI birth profile in scrape-off layer is needed for

- Effects of 3D fields on fast ions, e.g. prompt loss during RMP
- Passive FIDA and NPA signals, e.g. possibly use FIDA to detect fast ions losses

➢TRANSP currently calculates fast ion birth profile & distribution inside LCFS only.

➢M. Van Zeeland has developed a stand-alone model to get fast ion birth profile in plasma and scrape-off layer

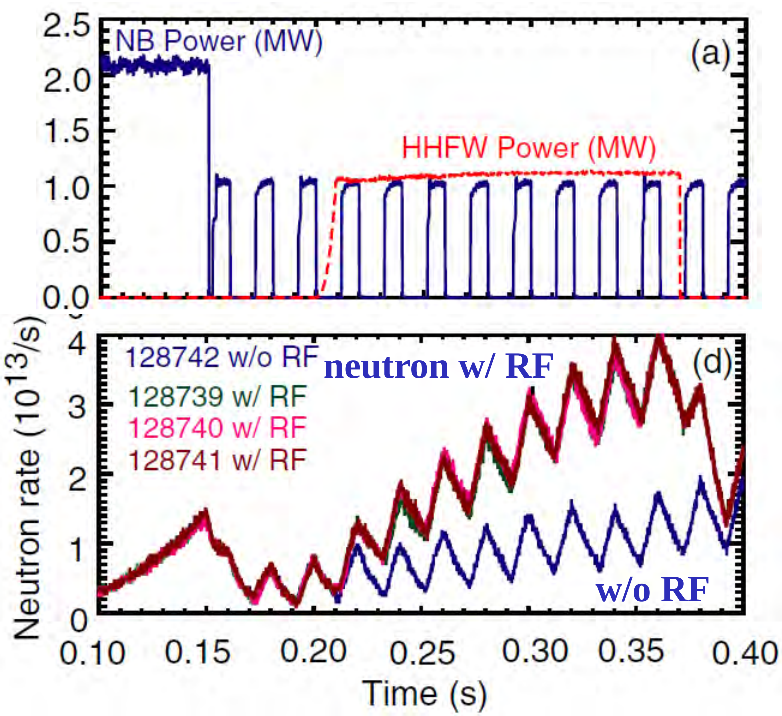
- Code algorithm similar to NUBEAM
- Require plasma profiles extend to scrape-off layer.



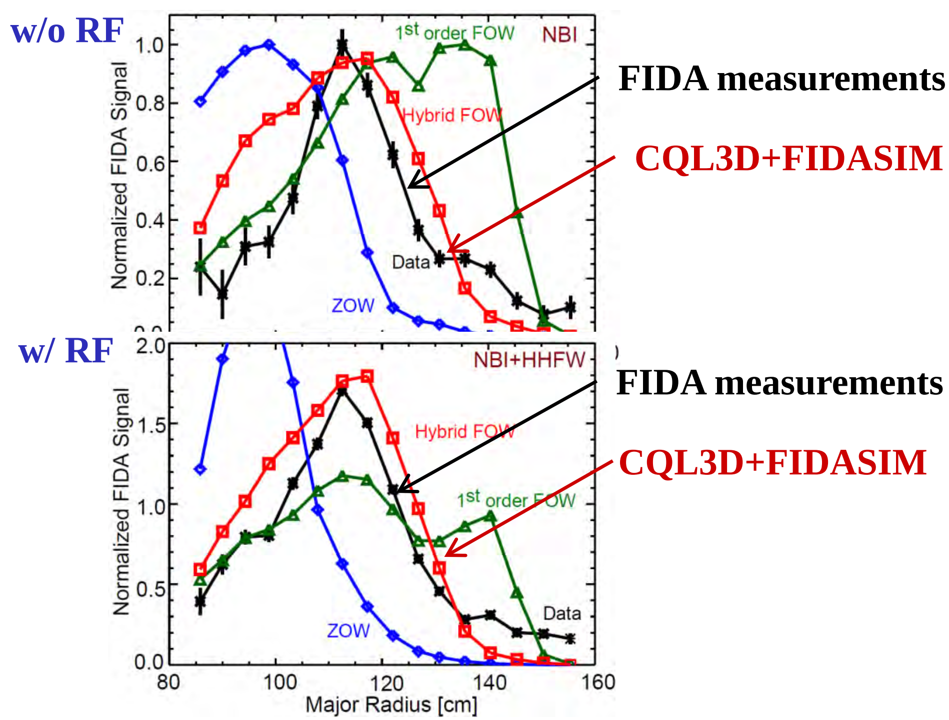
M. Van Zeeland

Future Needs III: Self-Consistently Include the Interaction between Fast Ions and RF Waves

D. Liu et al., PPCF 2010



CQL3D simulations by B. Harvey

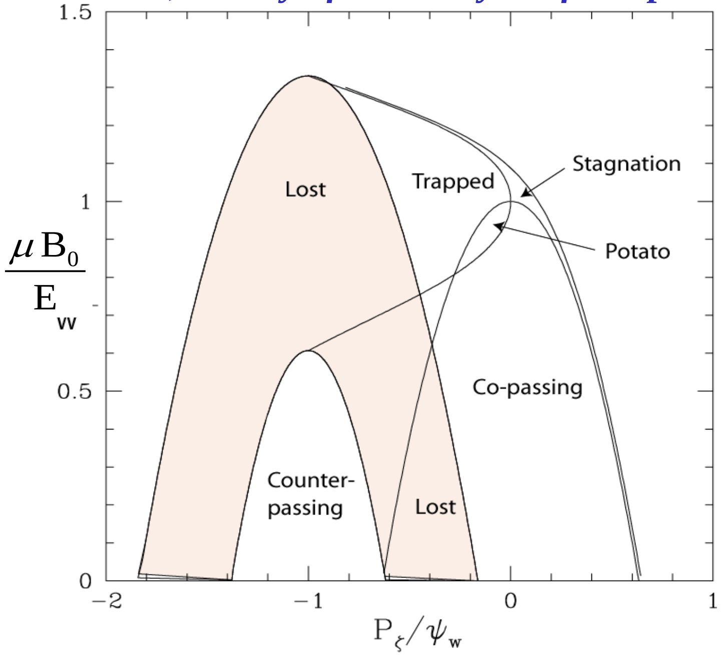


➢Previous experiments and CQL3D modelings show that FIs can be accelerated by RF. When including finite orbit width, modelings reasonably agree with measurements.

➢TRANSP currently has RF and NUBEAM modules, but it does not self-consistently include the interactions between RF waves and fast ions.

Future Needs IV: Output FI Distribution in Constants-Of-Motion Space as well as in Phase Space

Roscoe White, Theory of toroidally confined plasmas



Complex fast ion orbits can be described with constants of motion.

E: Energy

μ: magnetic moment

$P_\varphi \equiv e\psi + mV_\varphi R$: toroidal angular momentum

damping term

driving term

➢f(P_φ, μ, E) gradients are source of free energy $\gamma_{\text{fishbone}} \propto w\frac{\partial f}{\partial E} - n\frac{\partial f}{\partial P_\varphi}$ *L. Chen PRL 1984*

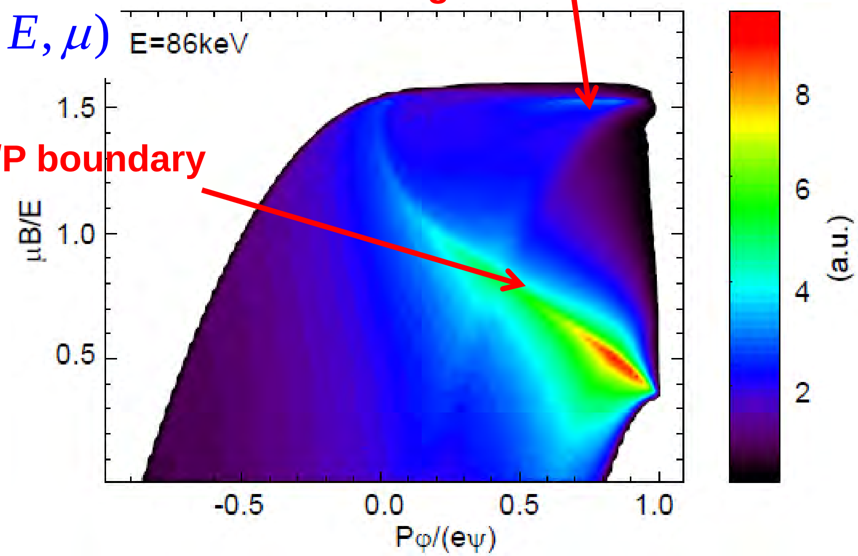
➢Quantitative modeling requires an accurate description of f, especially the gradients.

➢f(P_φ, μ, E) & f(R, Z, E, Pitch) will facilitate modeling & comparison with experiments.

Future Needs IV: Output FI Distribution in Constants-Of-Motion Space as well as in Phase Space (cont'd)

D. Liu APS 2012

$J(P_\phi, E, \mu)$

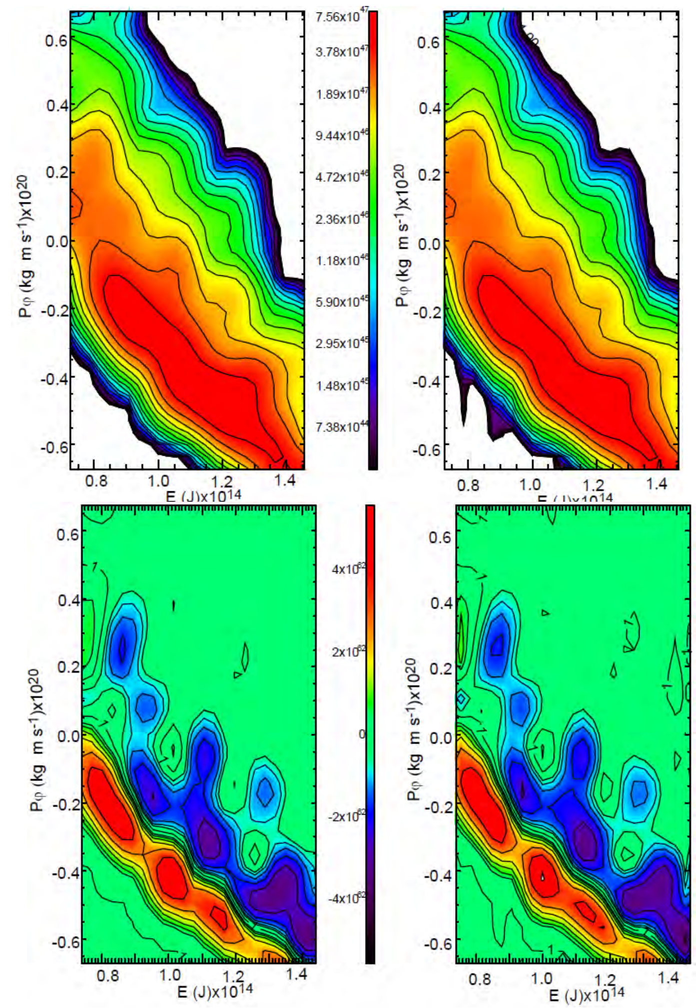


Raw data from TRANSP

$f(P_\phi, E, \mu)\,|_{\mu=2.058e-14}$

cubic B-spline fit

$\frac{\partial f}{\partial E}$



➢ J. A. Breslau & D. Liu successfully transferred f(R, Z, E, Pitch) to f(P_φ, μ, E) for one TRANSP run

▪Transformation Jacobian J(P_φ, μ, E) is accurately calculated with iterated Monte-Carlo method

▪f(P_φ, μ, E) needs to be smooth in P_φ and E, not necessarily in μ.

▪ Need to include electric potential related with rotation, and 1st order correction to μ.

Summary

- **TRANSPSP is a powerful tool for fast ion physics study in terms of understanding experimental data and theoretical modeling.**
- **Need to expand TRANSP capability in the following areas**
  - 2D background neutral density
  - fast ion birth profile in scrape-off layer
  - interaction between fast ions and RF waves
  - fast ion distribution in f(R, Z, E, Pitch) and f(P_{φ}, μ, E)
  - improving reduced models for fast ion transport