Temporal Dynamics of NSTX NBI+HHFW Discharges using CQL3D-Hybrid-FOW

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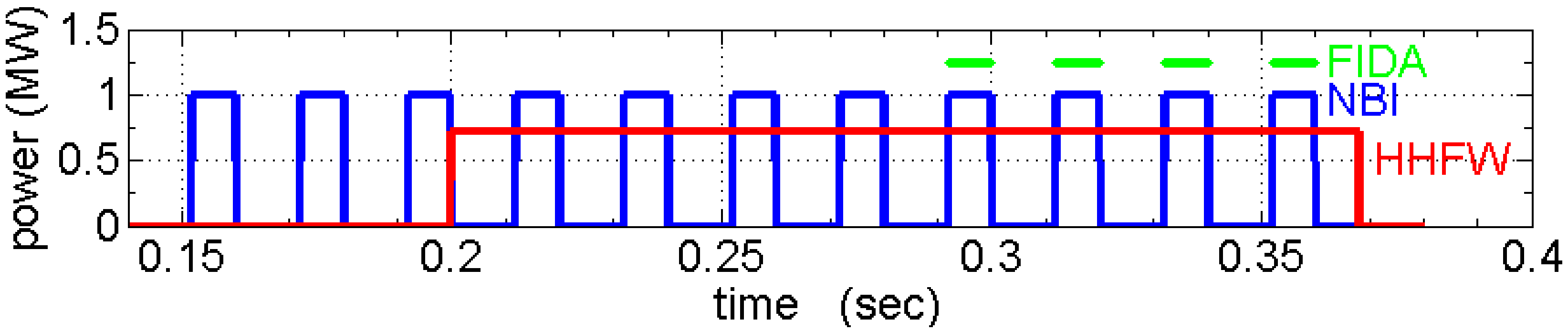
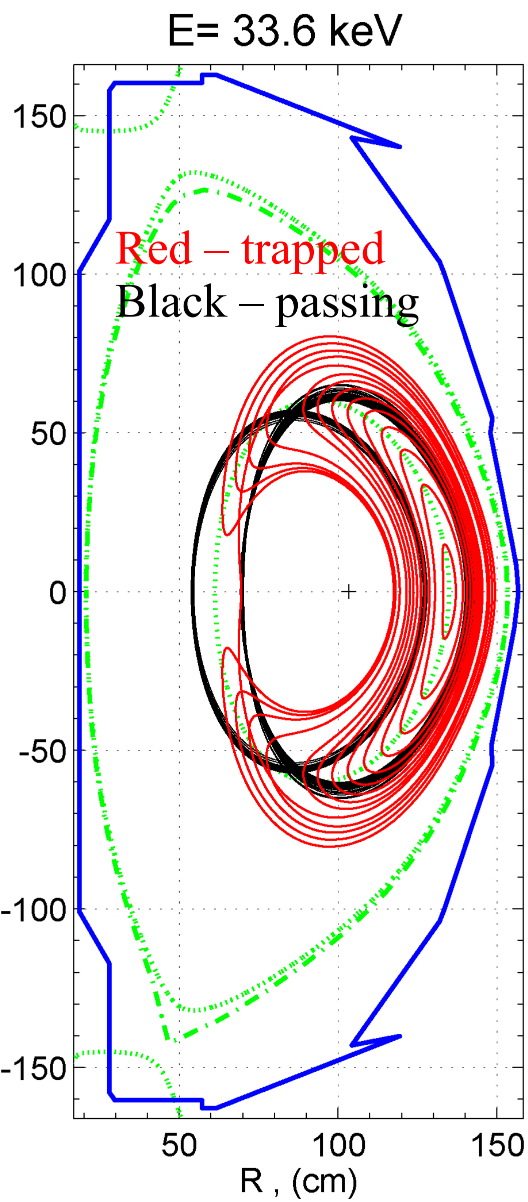
- The Fast Ion Diagnostic FIDA signal resulting from NBI and HHFW injected into NSTX has been simulated with the CQL3D Fokker-Planck + GENRAY codes.
- We report FIDA results from simulations with increasing fidelity to the expt, with ZOW, 1st-order orbit correction, FOW-hybrid.
- The FIDA experiment consists of a 1.0 MW modulated NBI with 0.4 duty factor, 0.020 sec total period (8 msec on, 12 msec off) for 11 periods. HHFW is on for a portion of the NBI beam blips, FIDA avg'd over 4 beam blips, as shown below in this slide.
- Plasma profiles evolve throughout:
  ne0=2.14 ==> 3.67e13, Teo=760 ==> 790, Tio=790 ==> 1190,
  Zeff=2.6 ==> 4.0, V_phi=80e3 ==> 100e3 rad/sec. (makes difference to NBI dep.)
- NBI and HHFW powers as below. FIDA signal obtained from last 4 beam-on periods.



Hybrid-FOW



Distr.function for a given Ψ_{pol} consists of all orbits that have same $<\Psi_{pol}> = \Psi_{pol}$.

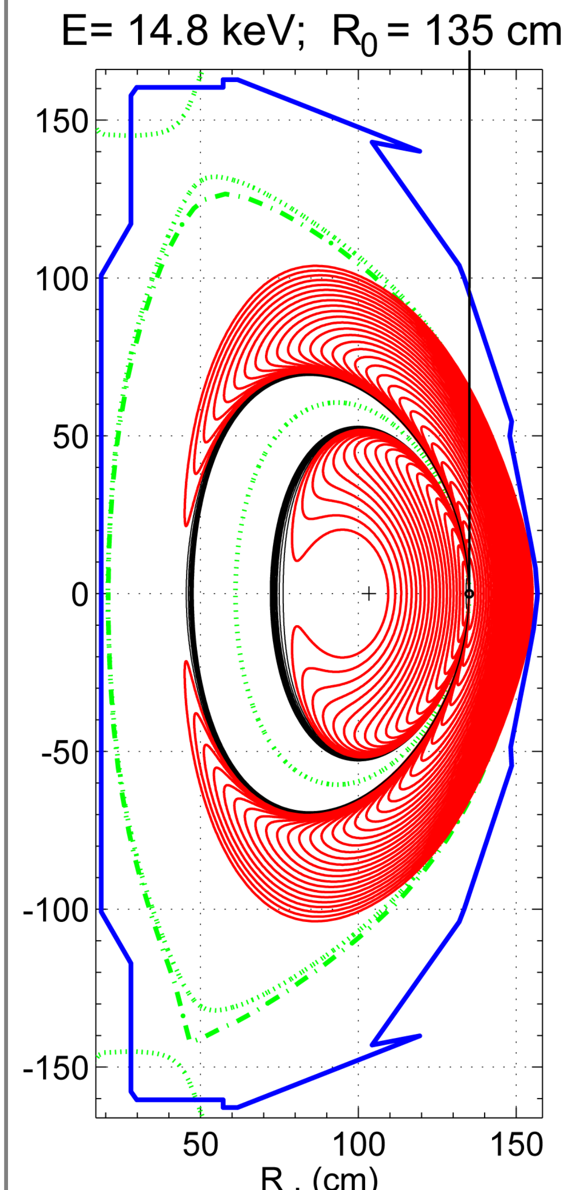
But the local *f* can be reconstructed from solution.

Main Advantage:
Fast (only twice slower than ZOW)

Disadvantages:

- Only partial FOW capabilities (NBI, RF, diagnostics, loss cone).
- Collisions remain ZOW.
- No neoclassical transport (only model transport as in ZOW)

Full-FOW



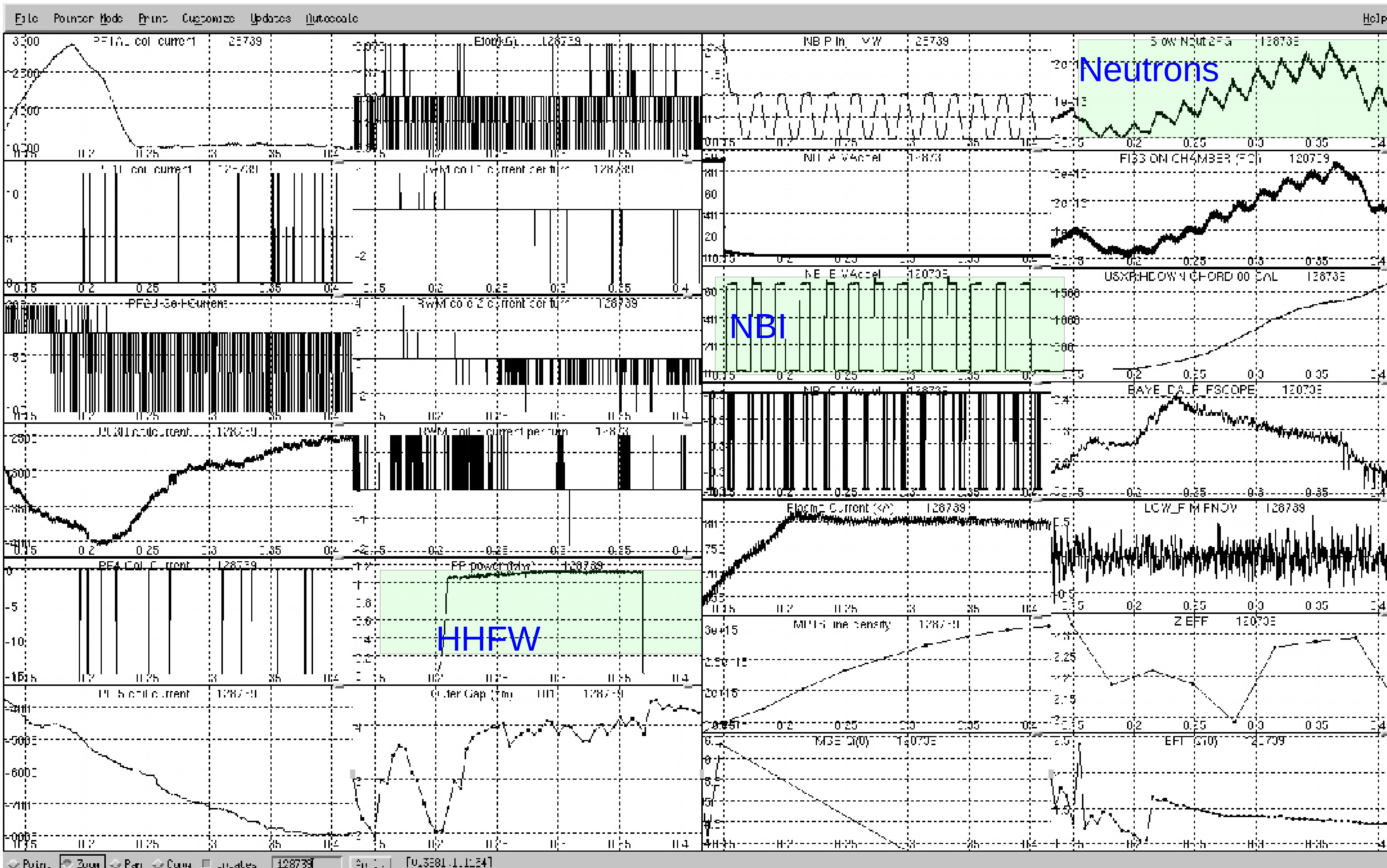
Actual local *f* at a given R_0 at the midplane - made of all orbits that pass through R_0 ("0" refers to points on the midplane).

Main Advantage:
Neoclassical radial transport (ion radial transport ~ near neoclassical values in JET and DIIID, and probably ITER)

Disadvantages:

- Factor of 1000 slower than Hybrid-FOW (because of collisional operator, BUT parallelizable with good scaling).
- Complicated bndry conditions.

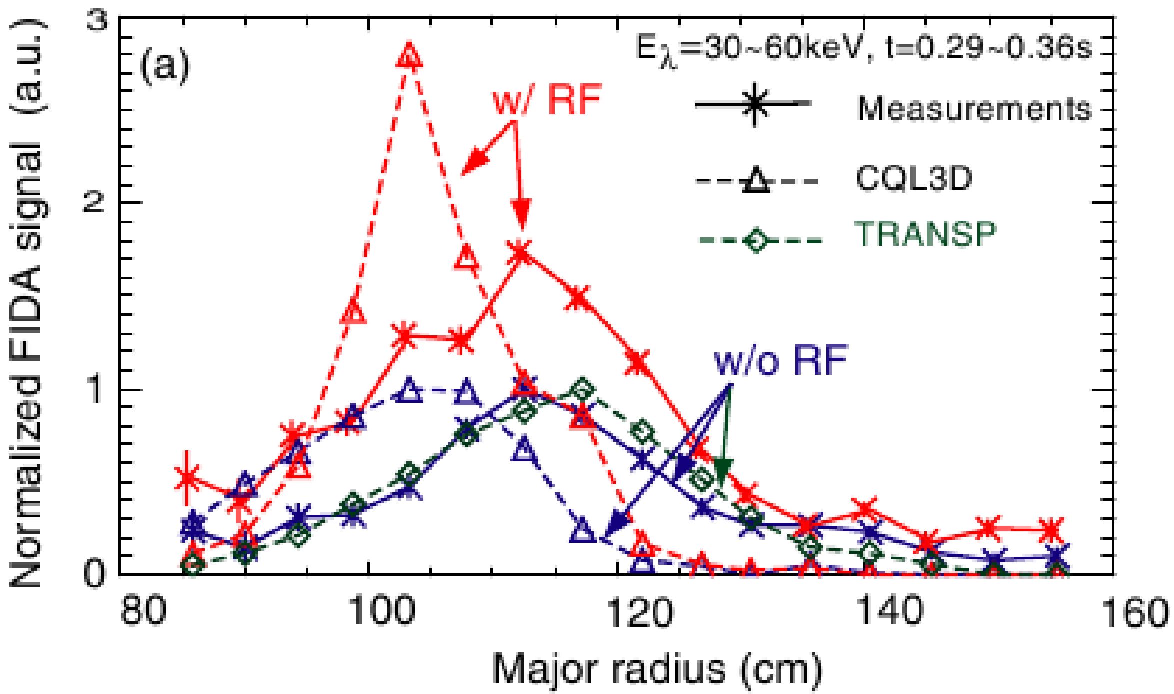
NSTX NBI+HHFW Shot 128739 Summary: Highlighted is HHFW and NBI Power + Neutrons NBI Shot 128742 Has Same NBI, No HHFW



Liu Comparison of CQL3D with FIDA, 2008-2010

- Deyong Liu (w Heidbrink) compared NSTX FIDA results with several simulations, as below.
- TRANSP and ORBIT-RF agreed with experimental FIDA signal radial profile much better than zero-orbit-width (ZOW) CQL3D.
- TRANSP did very well for NBI, but did not have HHFW capabilty.
- CQL3D/FIDA was shifted inwards in minor radius relative to experiment (below).
- Liu et al. and Choi et al. attributed CQL3D problem to ZOW.
- Therefore, began finite-orbit-width extension (FOW) of CQL3D.

Plasma Phys. Control. Fusion **52** (2010) 025006 D Liu *et al*



CQL3D Calculation Evolved: ZOW, 1st -order FOW, FOW-Hybrid, FOW

Simulation using NBI power at time-average level, steady-state plasma profiles at average time of FIDA detection. HHFW is at full nominal power, 1.1 MW.

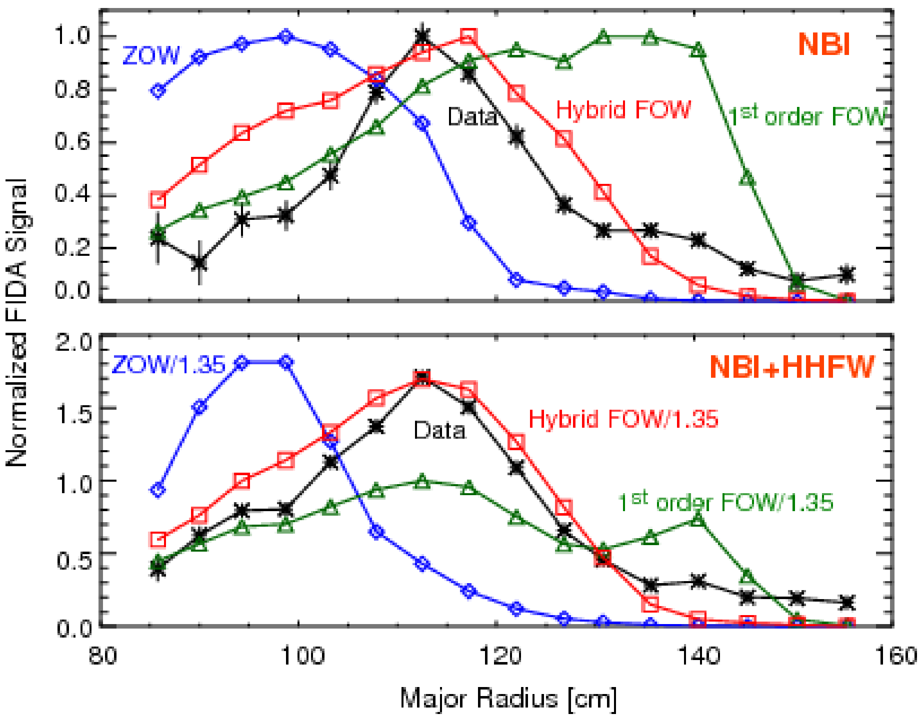
==>

NBI: FIDA/CQL3D calcs normalized to experimental peak. 1St -order orbit correction in CQL3D greatly overestimates R-shift. Hybrid-FOW gets peak close to expt. but width too great.

NBI+HHFW: Simlar problem with 1st -order, Hybrid-FOW good, except 35% too high. Could think just reduce HHFW by usual edge loss amount (35%) but the system is quite nonlinear.

Reducing HHFW by 35% ==> only 17% reduction in peak (not shown).

Next step: Added Modulated Beam.



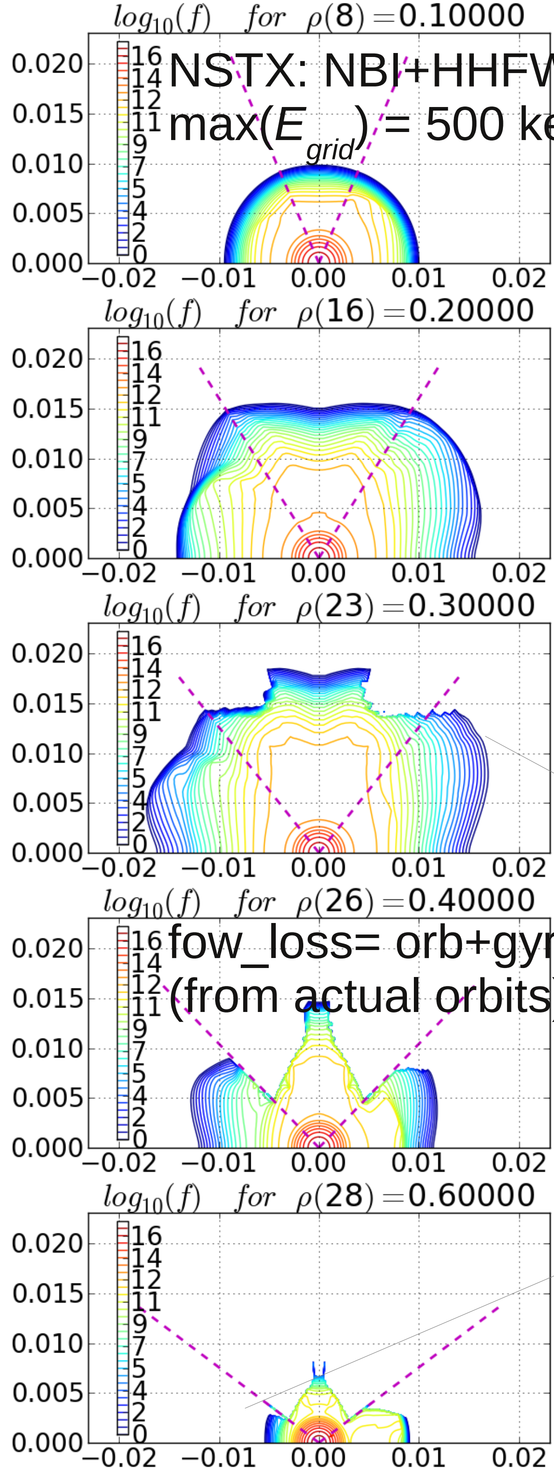
Hybrid-FOW

How to Reconstruct Local Distribution Function – needed for diagnostics

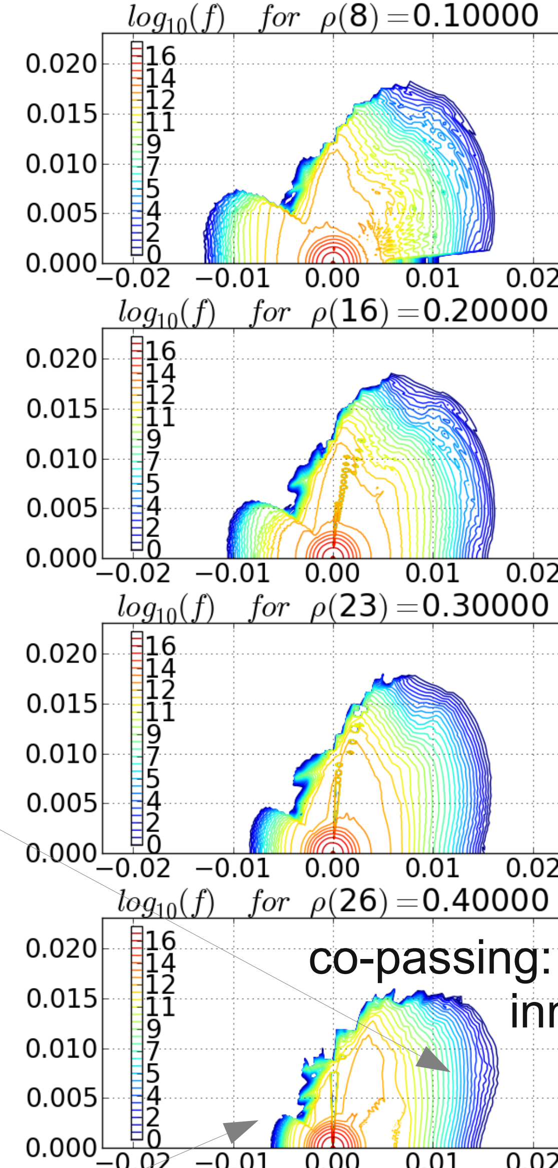
Method: Mapping the COM space of energy, adiabatic invariant and canonical toroidal momentum (E, μ, p_φ) onto the midplane values (u_0, θ_0, R_0) where the grids are defined.

Consider point (R, Z) and an orbit with local (u,θ).
For each such orbit, evaluate (u, μ, p_φ).
Find the nearest (i_u , i_μ , i_{p_φ})-index in the COM table.
Find the value of $<\Psi_{pol}>$ from the COM table – then, determine the two nearest FP'd surfaces; use interpolation to calculate the value of local $f(R, Z, u,\theta)$.

Solution (f_{soln} = f_{BA})



Local f (reconstructed)



co-passing: from inner ρ

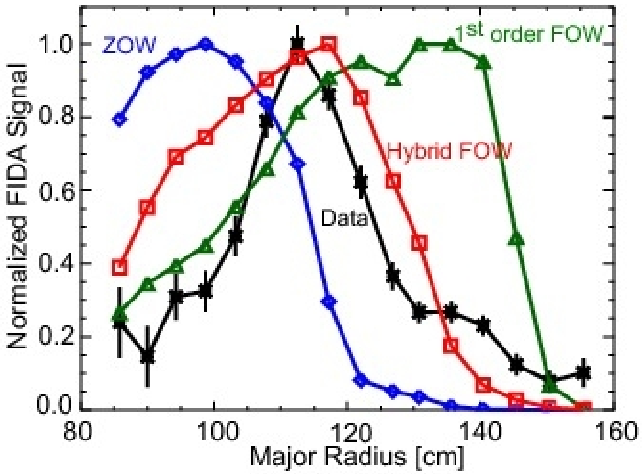
counter-passing: come from larger (outer) ρ

Simulation Fidelity Evolved: Modulated-NBI/HHFW with CQL3D-Hybrid-FOW

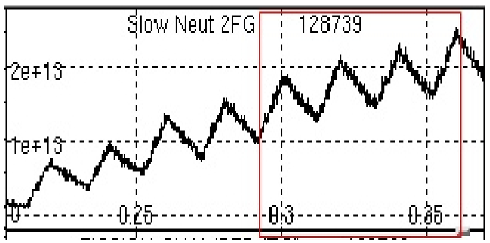
Fixed (time-independent, t~0.325 secs, exptl) background plasma profiles

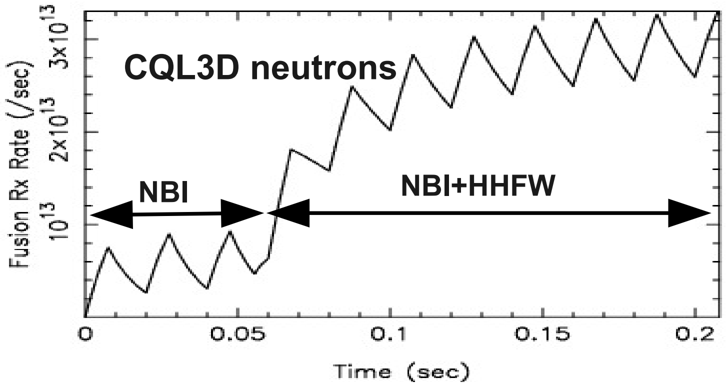
FOW=Finite-Orbit-Width
ZOW=Zero-Orbit-Width

FIDA, NBI ONLY



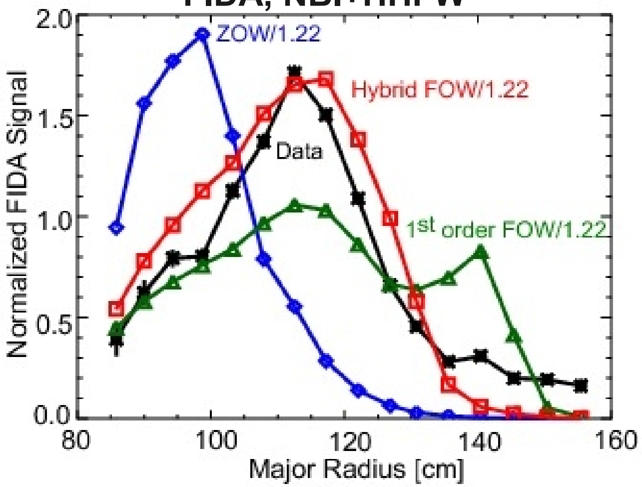
NSTX Neutrons NBI+HHFW



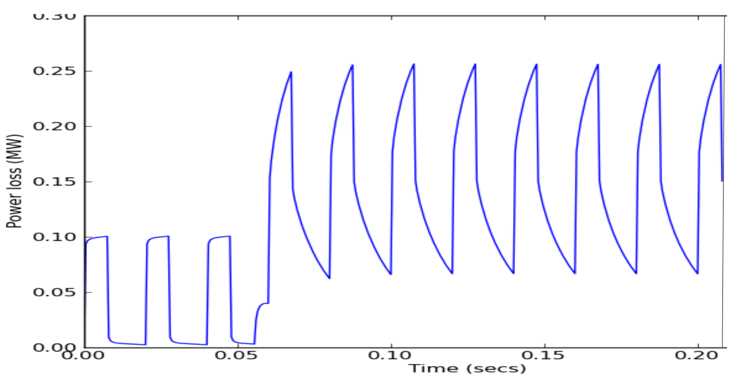


- **Modltd NBI 1.1MW, HHFW 0.71MW**
- **Normalize NBI FIDA to expt**
- **FOW-Hybrid (GC orbits) NBI a little broader than expt**
- **NBI+HHFW FIDA better match, with power reduction 0.65+22% more**
- **Calc'd neutrons ~20% high for NBI only, ~40% high for NBI+HHFW**
- **FI losses markedly increased with HHFW**
- **Modeling plans:** **time-dep background plasma + full FOW neoclassical code**

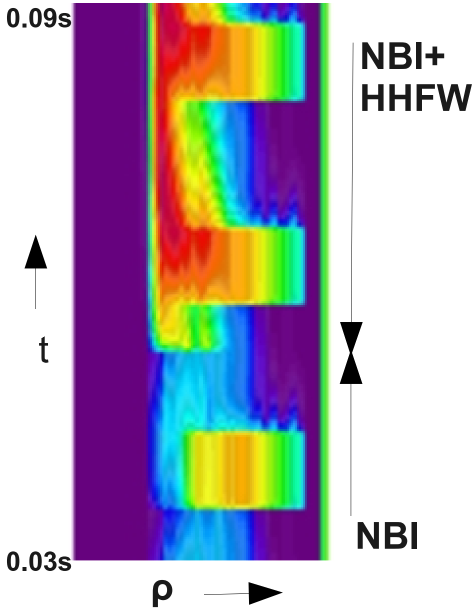
FIDA, NBI+HHFW



FI Pwr Lost to Plasma Edge



FI loss vs radius, t

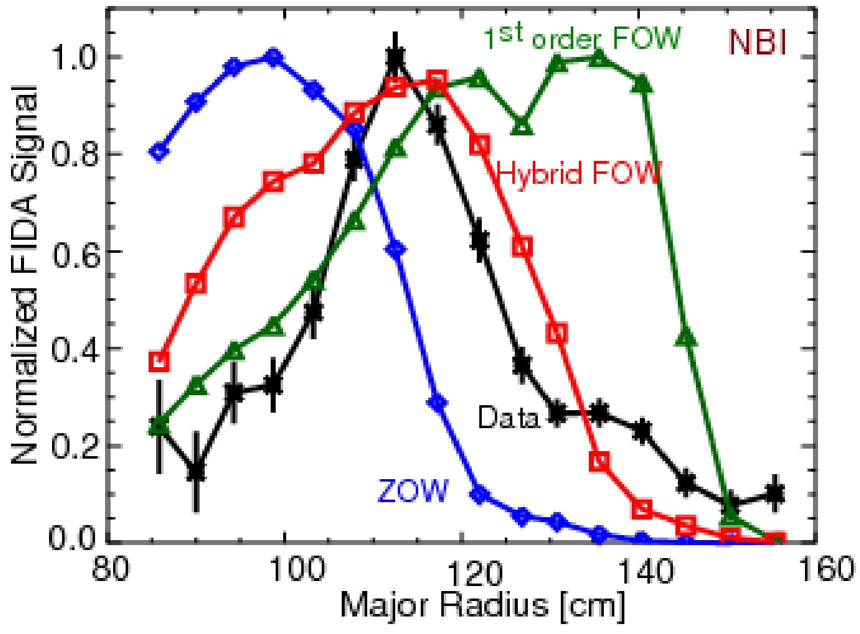


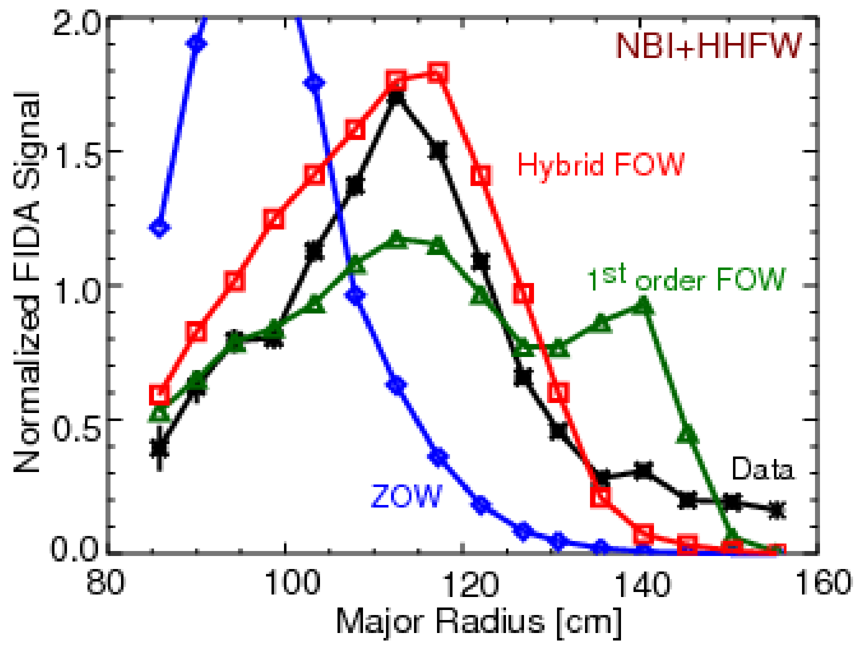
Result: HHFW+NBI still too large, after canonical 35% reduction.

Time-Dependent Background Plasma (profile set from TRANSP)

Spline-time-dependent profiles added to CQL3D. Using TRANSP/exptl profiles.
==> Now, good agreement with HHFW peak (adjusted only for canonical 35 % edge loss.
Provides additional confirmation of 35% edge losses.

Agreement in original Liu paper between NUBEAM and experiment suggests inaccuracy in NFREYA Monte Carlo neutral beam deposition module in CQL3D.
Next step: Use NUBEAM birth points in CQL3D (to be provided by Deyong Liu).



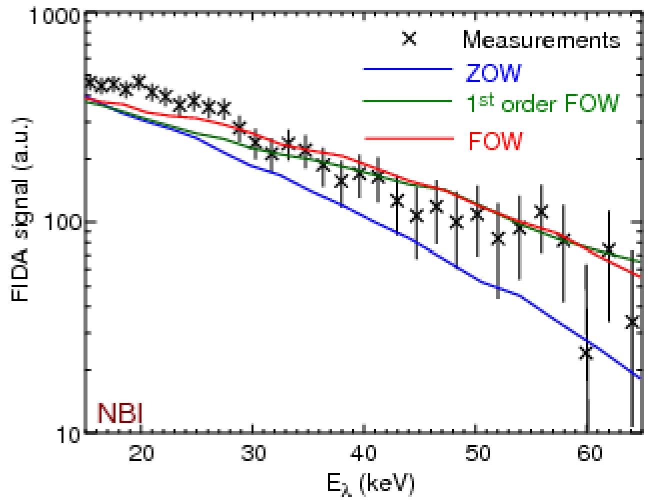


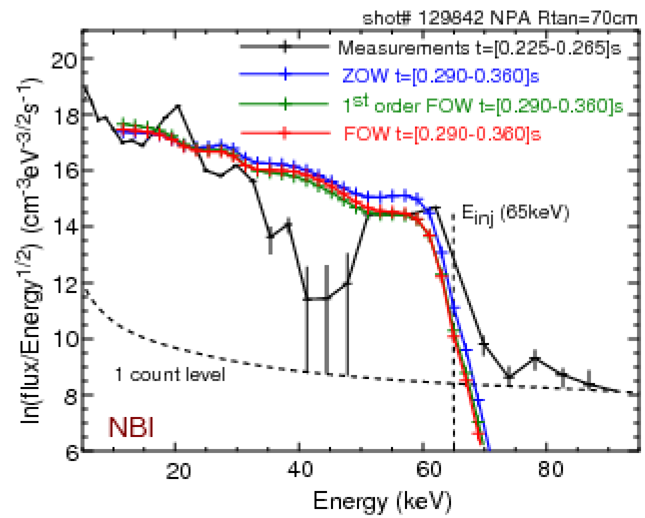
GOOD AGREEMENT OF SIMULATED AND EXPERIMENTAL ENERGY SPECTRA FOR FIDA AND NPA

FIDA

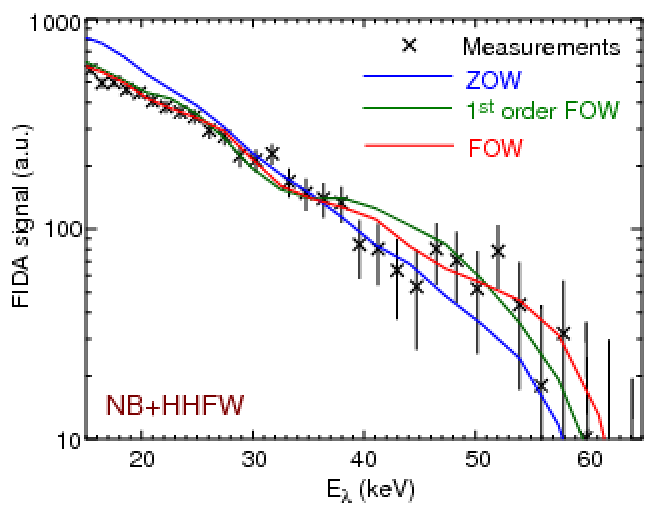
NPA

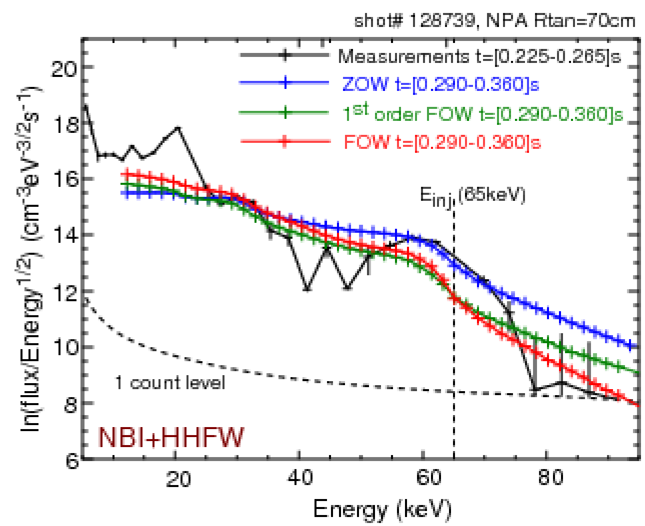
NBI





NBI+HHFW





CQL3D distributions + FIDA/NPA spectra (Deyong Liu)

CONCLUSIONS

- Successive refinement of CQL3D, particularly addition of FOW-HYBRID gives quite accurate FI distributions for NSTX FIDA.
  This is determined from both spatial and energy spectra, and also for NPA.
  We hope that the full FOW neoclassical simulation in CQL3D will result in improved agreement of FIDA toward the plasma periphery.
- HHFW substantially increases fast ion orbit losses, above those for NBI, due to scattering for ions into the loss regions. We will examine this in greater detail.
- Neutron rates are in general accord between simulation and experiment (per Deyong Liu and simulation of experimental signals).
- We have independent agreement with the general assumption of 35% losses of HHFW power near the plasma edge.
- Computer time for the simulations was up to 20 cpu hours (single core) for 20 msec time-dependent, modulated beam simulation. (50 radii, 416 times steps, 180x250 θ x v).
  CQL3D is MPI'd over flux surfaces, which scales well when no radial transport.
  (Parallelized big matrix solver with radial transport is work in progress.)
- We expect that use of NUBEAM FI starting points, rather than from older (1985) NFREYA (internal to CQL3D) will reduce the width of the NBI and NBI+HHFW deposition, providing yet more accurate estimates for FIDA.