Neoclassical Transport Properties and Their Limits in NSTX

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Abstract – QP1.023

The low aspect ratio and low toroidal field of NSTX enhance its neoclassical transport properties, but also push the limits of standard neoclassical models. Particle and energy transport, plasma rotation, the radial electric field, and bootstrap current are examined for typical NSTX discharges. Regimes of inward and outward impurity transport driven by a combination of the inductive electric field (Ware pinch), inward transport on the deuterium density gradient, and outward transport on the ion temperature gradient are identified. Orbit losses and atomic physics effects near the plasma boundary lead to modifications in the bootstrap current and impurity transport properties in the H-mode pedestal. Potato orbit effects near the axis, included as a viscosity modification, can enhance the ion energy transport, but are reduced by orbit squeezing. The low aspect ratio and high beta of NSTX plasmas provide a critical test of the limits of neoclassical theory.

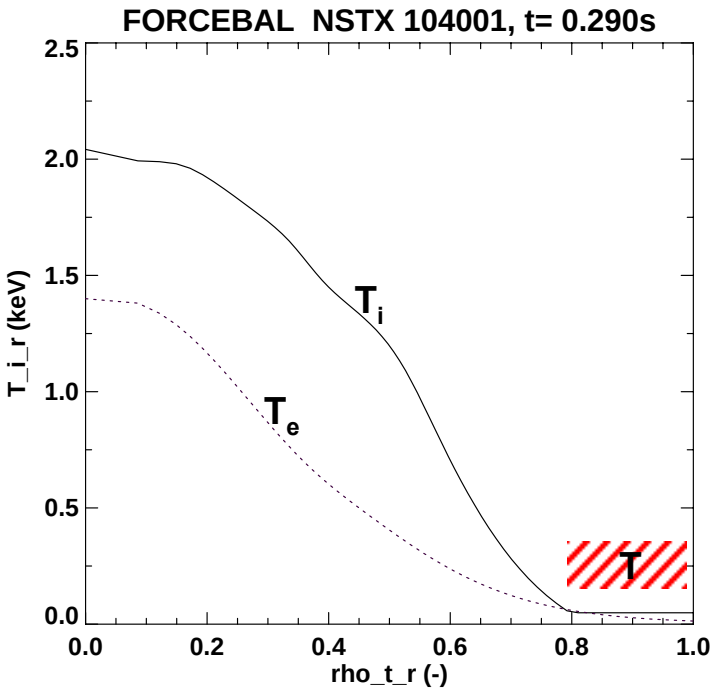
Outline

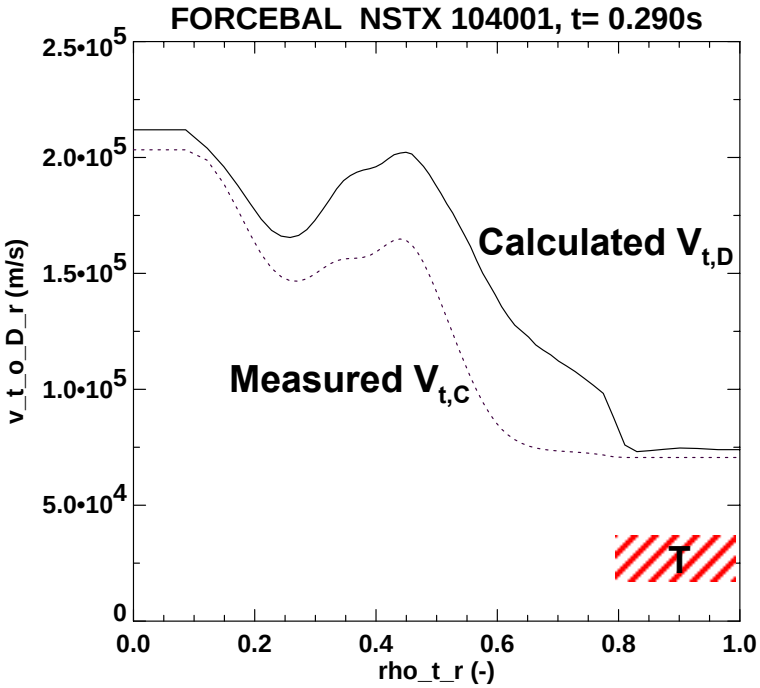
- NCLASS/FORCEBAL installation for NSTX analysis
- Transport properties
  - Particle
  - Energy
  - Bootstrap current
  - Radial electric field
- Limitations of present analyses illustrated for example NSTX plasma (shot #104001)
  - Implications of high rotation velocities in NSTX
  - Implications of $B_p \sim B_t$ in NSTX
  - Potato orbit effects in NSTX
- Summary

NCLASS/FORCEBAL Installation for NSTX Analysis

- **FORCEBAL installation:**
  - **MDS+ data for EFIT, density and temperature profiles**
  - **Auxiliary file for CHERS rotation data**
  - **IDL graphical procedure for viewing results**
- **TRANSP:**
  - **Older version of NCLASS**
- **Planned upgrades of NCLASS:**
  - **In TRANSP:**
    - » **Newer version of NCLASS**
  - **In FORCEBAL:**
    - » **Potato orbits**
    - » **Ion orbit loss and the L-H transition**
    - » **F90 module with dynamic allocation and optional I/O**

Reference Profiles (Shot #104001, 0.29 s)



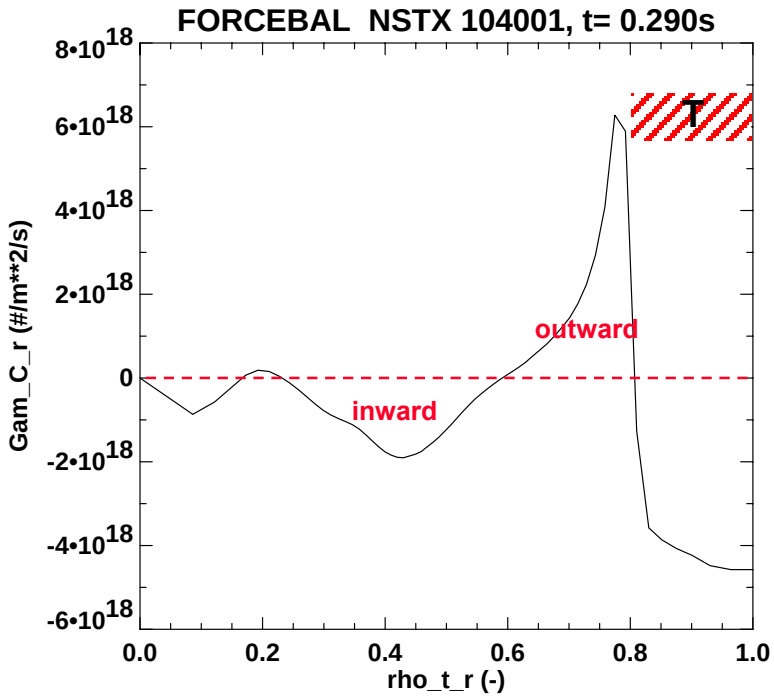


Neoclassical properties calculated from T in shaded region are likely unreliable

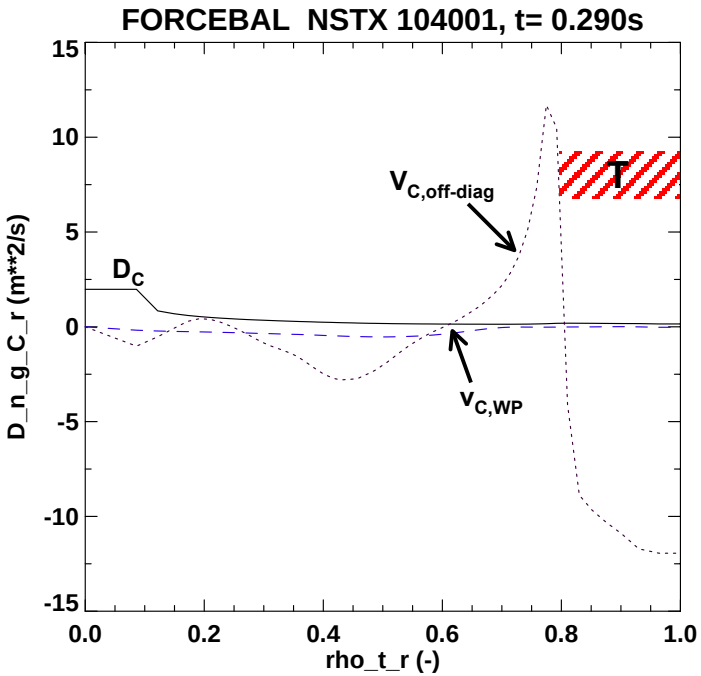
Difference in toroidal rotation expected from species pressure

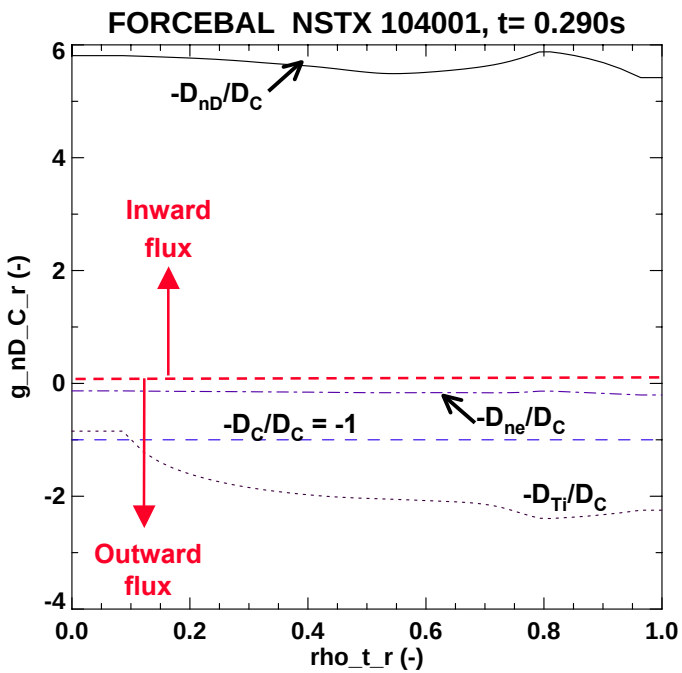
Neoclassical Carbon Flux Shows a 'Barrier'

- **The net radial neoclassical carbon particle flux:**
  - **Is inward in the core**
  - **Shows a region of outward flux in the region 0.4 < ρ < 0.8 that may act to shield the core from edge sources**



Neoclassical Carbon 'Barrier' is Driven by the Strong T_i'





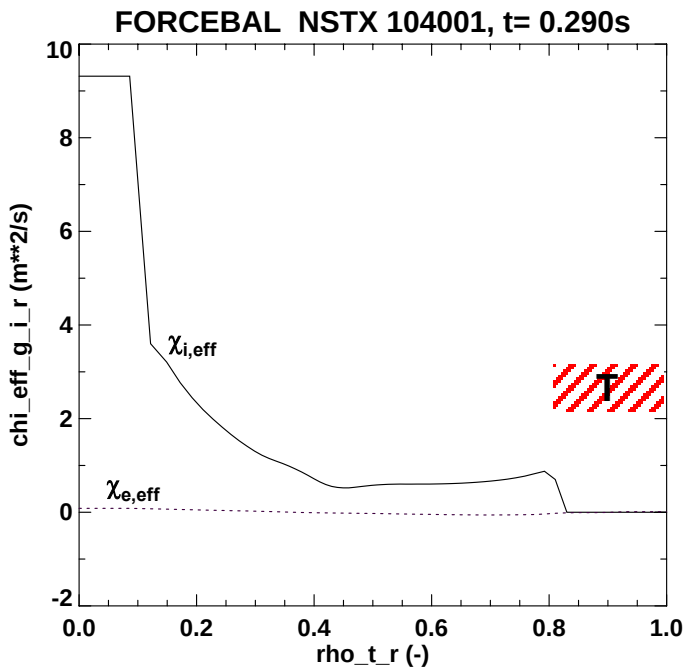
The 'off-diagonal' element (not the Ware pinch or self-diffusion) dominate the radial flux:

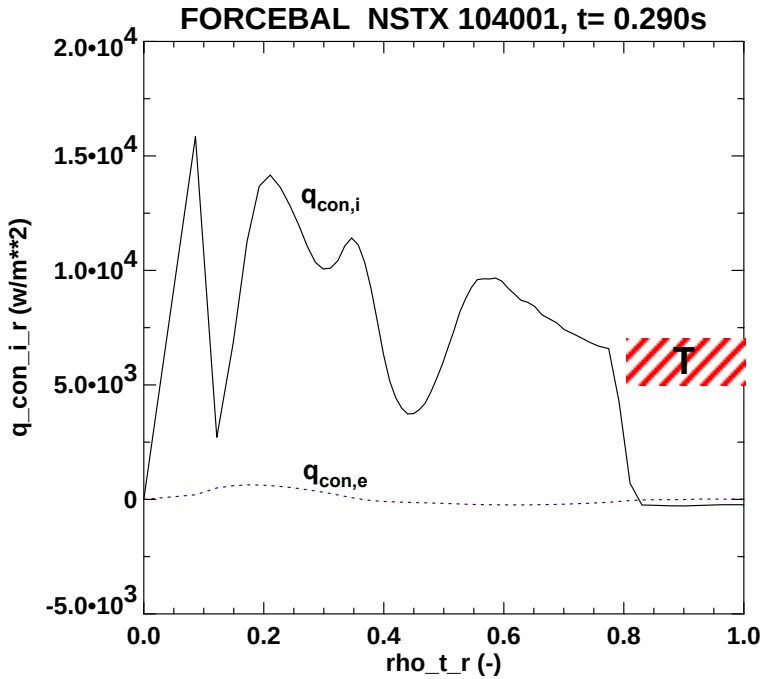
$\Gamma_C = -D_C + n_C(v_{C,WP} + v_{C,off\text{-}diag})$

The 'off-diagonal' components are driven by n_D' (inward) and T_i' (outward), both of which are stronger than self-diffusion, D_C:

$\Gamma_C = -D_C n_C \Sigma_j \, d\ln\alpha_j \, D_j/D_C = D_C n_C \Sigma_j \, g_j \, d\ln\alpha_j$

Neoclassical Conduction Heat Transport





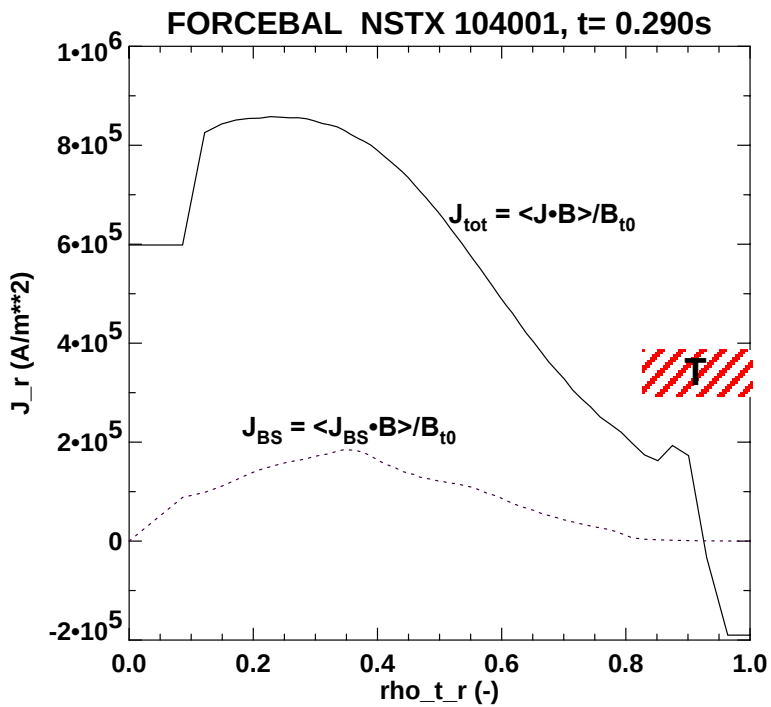
The 'effective' thermal conductivity is smooth and very low at mid-radius:

$\chi_{j,eff} = q_{con,j} / n_j k T_j$'

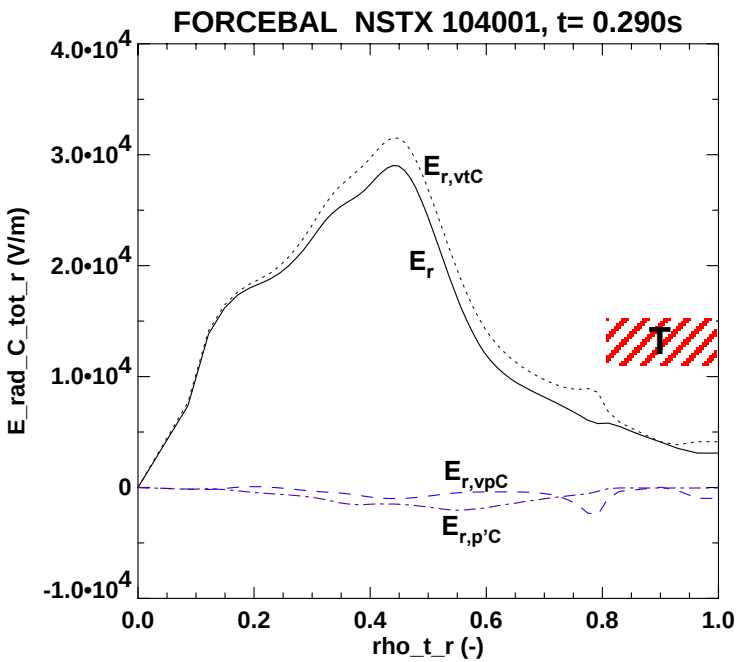
The net thermal ion conduction reflects variations in T_i'

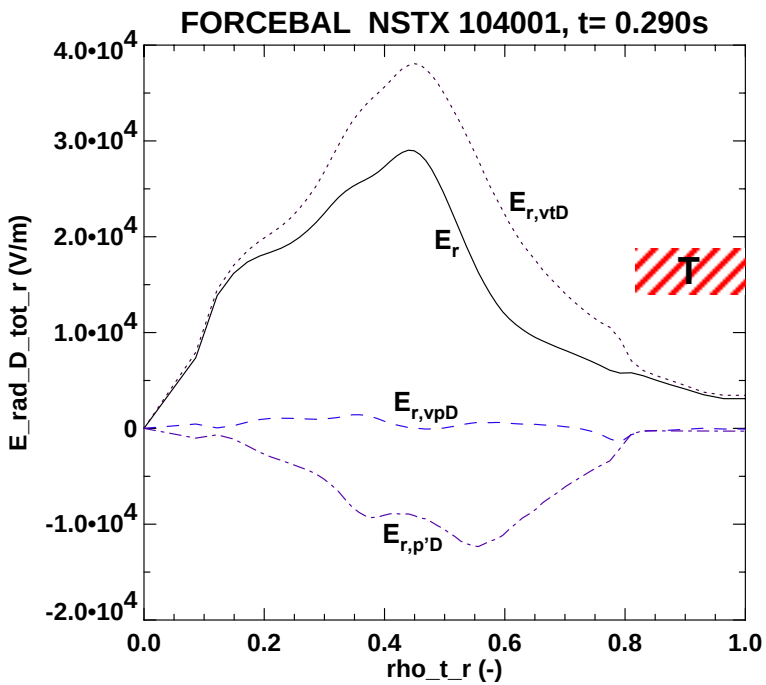
Bootstrap Current is Significant, But Low at Edge

- The bootstrap current:
  - Constitutes about 25% of the total current in this case
  - Is very low in the edge of this plasma because of the low edge temperature (collisional suppression)
  - It should therefore not be affected by edge modifications to neoclassical theory unless higher T edge plasmas are accessed
- Note that the negative edge current comes from the EFIT reconstruction used for this case (not kinetic EFIT)



Toroidal Rotation Dominates C Force Balance, But p' is Also Important in the D Force Balance



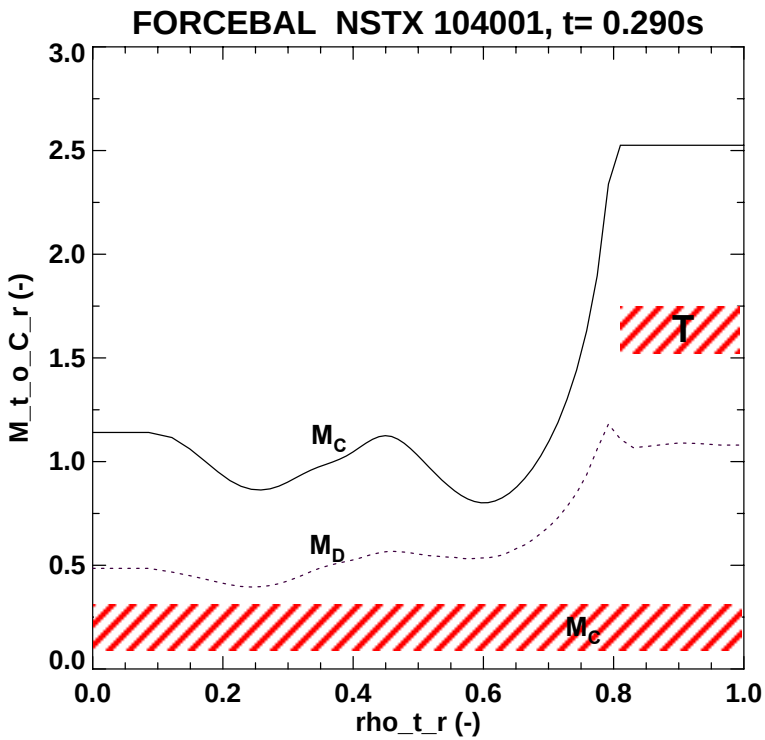


E_r can be well approximated by the measured C toroidal rotation velocity contribution

The D pressure gradient is compensated by a stronger toroidal rotation component

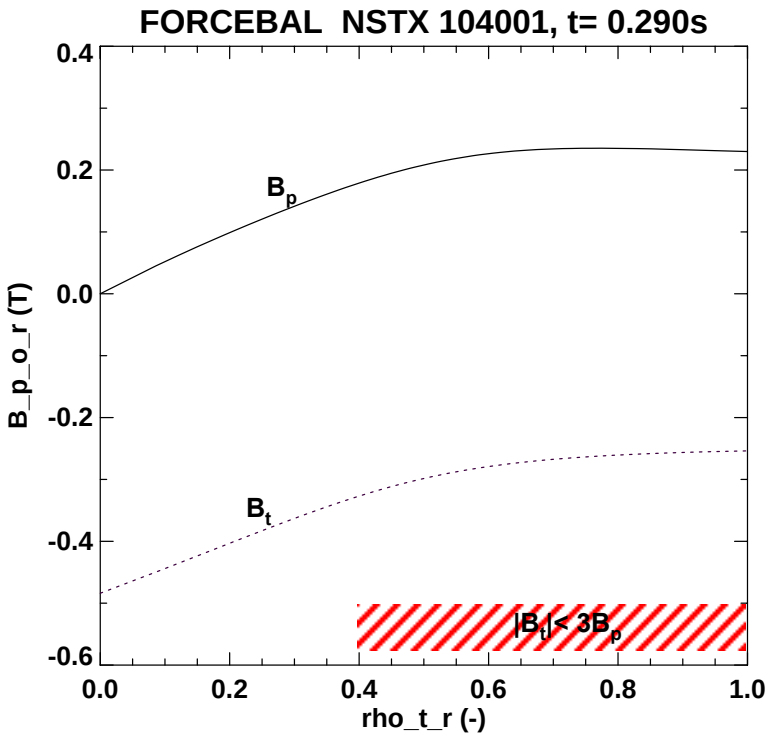
Implications of High Rotation Velocities

- Deuterium rotation velocity:
  - May have to be considered in MHD equilibrium reconstruction
- High impurity toroidal Mach numbers:
  - Densities peak toward outside from centrifugal effects (as seen in JET)
    - Theoretical model to calculate poloidal distribution was developed by M. Romanelli for JET
  - Standard analyses that assume local density is a flux surface quantity are invalid
    - CHERS data must be corrected to obtain impurity profiles, Z_{eff}, transport properties, etc.
    - Lower Z_{eff} reduces Q_{ei}, but probably not enough to explain anomalies in the power balance



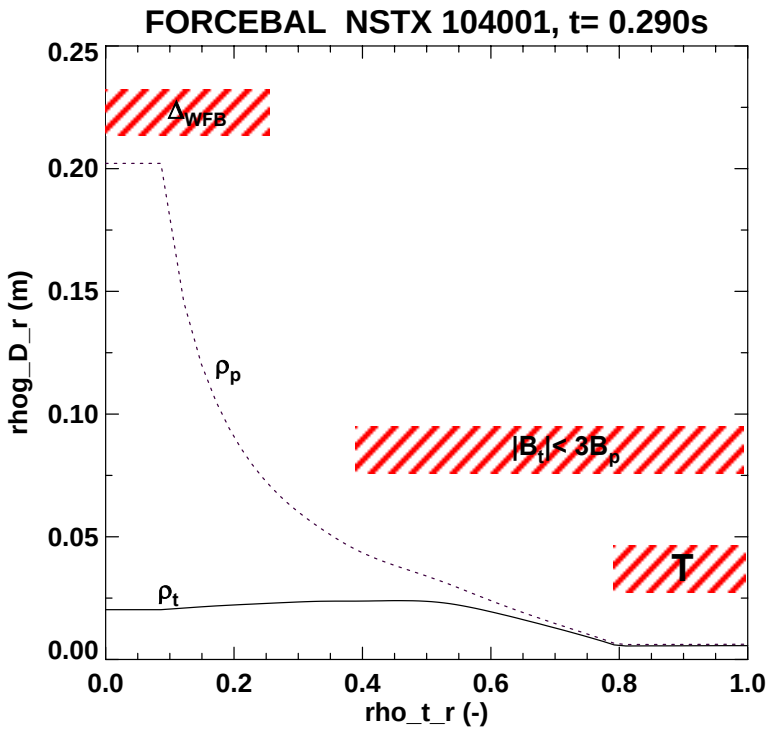
Implications of $B_p \sim B_t$

- Classical and neoclassical transport processes are comparable
- If the L-H transition is driven by orbit losses, the scaling relative to larger A machines would be expected to break
  - We have developed modifications to NCLASS to include ion orbit loss driven L-H transitions (R. Hiwatari, T. Takizuka, K.C. Shaing, W.A. Houlberg, H. Shirai, Y. Ogawa, K. Okano, "Numerical Investigation of Threshold Power by Using L-H Transition Model Based on Ion Orbit Loss," IAEA TCM on H-mode and ITBs, Toki, Sept 2001, to be published in Plasma Phys and Controlled Fusion)
  - Model reproduces B_t, n_e, and I_p scaling of the L-H transition power threshold for standard tokamaks



Potato Orbit Effects

- Width of the 'World's Fattest Banana' (WFB) is 19 cm with $q_0 \sim 1.1$
  - In reversed shear conditions the size grows as $q^{2/3}$
- Potato orbit effects are expected to modify neoclassical transport in the range $0 < \rho < 2\Delta_{WFB}/a$, or $R < 1.35$m, which is most of the core of NSTX
  - NCLASS presently contains an approximate correction for potato orbit effects
  - The theory has been reworked for a more rigorous treatment of the orbits (K.C. Shaing, W.A. Houlberg, P.I. Strand, "Local Potato-Plateau Transport Fluxes and a Unified Plateau Theory," submitted to Phys. Plasmas)
  - We plan to upgrade NCLASS for NSTX applications



Summary

- **FORCEBAL/NCLASS installed for NSTX analysis:**
  - **Interface to EFIT and profile data in MDS+**
  - **Graphical interface to results using IDL**
- **Impurity transport studies should indicate strong off-diagonal effects and perhaps neoclassical 'transport barriers' from T_i' screening as seen in DIII-D and JET**
- **Edge bootstrap current corrections do not yet appear to be important in NSTX because of its low edge temperatures**
- **Extensions to neoclassical theory (as embodied in NCLASS) are dictated by:**
  - **Strong toroidal rotation**
  - **Ion orbit losses at edge for L-H transition studies**
  - **Comparable poloidal and toroidal gyroradii**
  - **Potato orbit effects**