Impurity Poloidal Rotation in DIII-D Under Low Toroidal Field Conditions

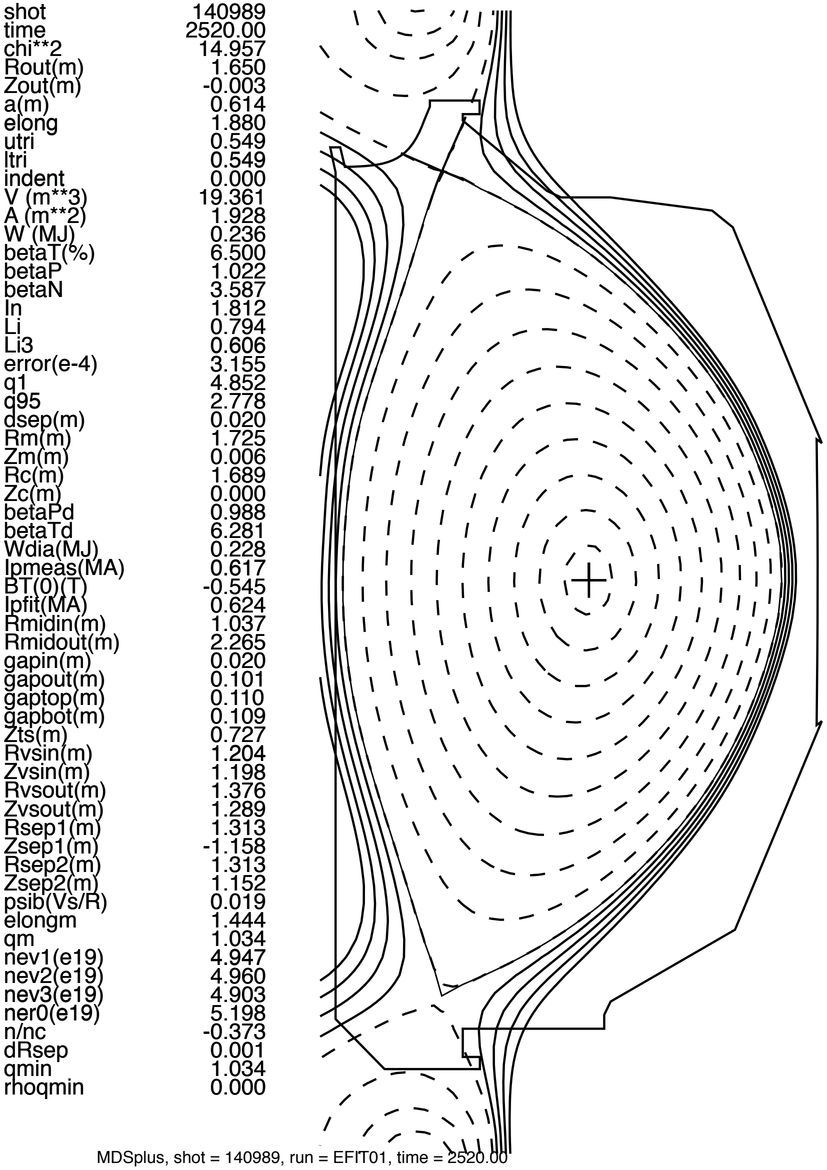
K.H. Burrell[1], W.M. Solomon[2], B.A. Grierson[2], E. Belli[1], R.E. Bell[2], W. Wang[2], G.M. Rewoldt[2]

[1] General Atomics

[2] Princeton Plasma Physics Laboratory

Transport Task Force Meeting
Annapolis, MD

April 15, 2010



```
shot          140989
time          2520.00
chi**2        14.957
Rout(m)       1.650
Zout(m)       -0.003
a(m)          0.614
elong         1.880
utri          0.549
ltri          0.549
indent        0.000
V (m**3)      19.361
A (m**2)      1.928
W (MJ)        0.236
betaT(%)      6.500
betaP         1.022
betaN         3.587
In            1.812
Li            0.794
Li3           0.606
error(e-4)    3.155
q1            4.852
q95           2.778
dsep(m)       0.020
Rm(m)         1.725
Zm(m)         0.006
Rc(m)         1.689
Zc(m)         0.000
betaPd        0.988
betaTd        6.281
Wdia(MJ)      0.228
Ipmeas(MA)    0.617
BT(0)(T)      -0.545
Ipfit(MA)     0.624
Rmidin(m)     1.037
Rmidout(m)    2.265
gapin(m)      0.020
gapout(m)     0.101
gaptop(m)     0.110
gapbot(m)     0.109
Zts(m)        0.727
Rvsin(m)      1.204
Zvsin(m)      1.198
Rvsout(m)     1.376
Zvsout(m)     1.289
Rsep1(m)      1.313
Zsep1(m)      -1.158
Rsep2(m)      1.313
Zsep2(m)      1.152
psib(Vs/R)    0.019
elongm        1.444
qm            1.034
nev1(e19)     4.947
nev2(e19)     4.960
nev3(e19)     4.903
ner0(e19)     5.198
n/nc          -0.373
dRsep         0.001
qmin          1.034
rhoqmin       0.000
```

MDSplus, shot = 140989, run = EFIT01, time = 2520.00

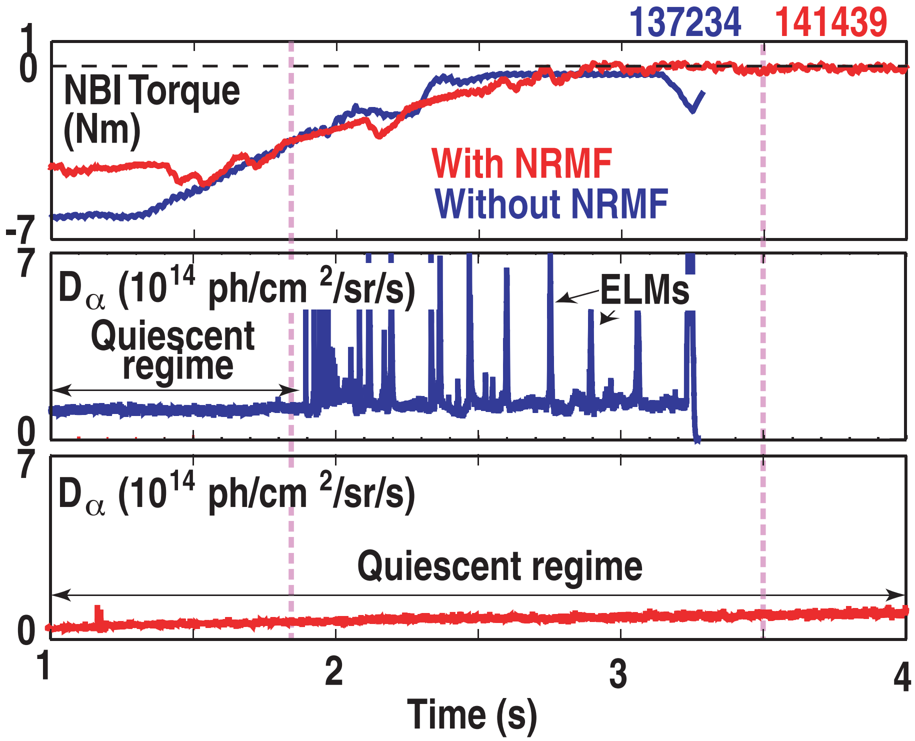
Why Investigate Poloidal Rotation in Tokamaks?

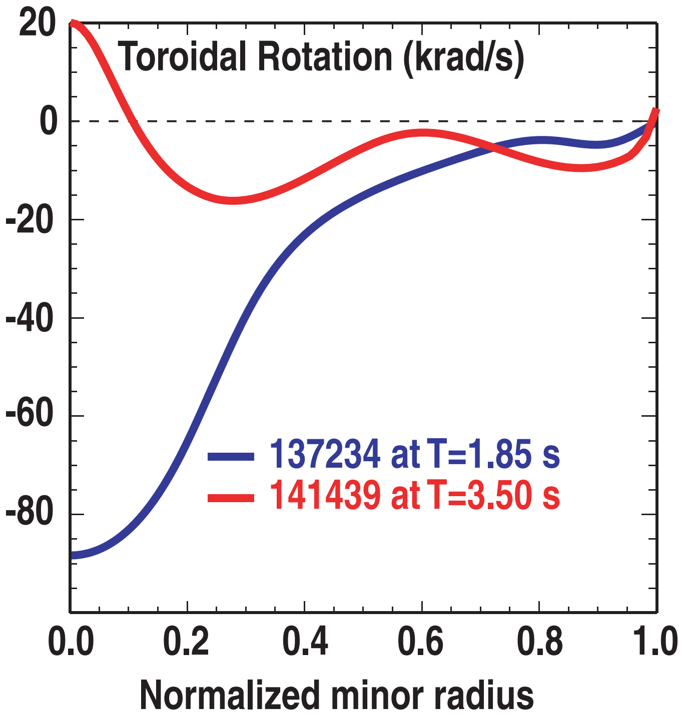
- **Obtaining a predictive understanding of poloidal rotation is an integral part of producing a predictive understanding of rotation in tokamaks**

- **Poloidal rotation is important because it enters into**
  - Changes in E_r when transport barriers form at
    - L to H transition (many machines)
    - RS to ERS transition (TFTR)
    - Core barrier formation (JET)
  - Neoclassical bootstrap current calculation
  - Neoclassical calculation of the offset velocity due to the NTV effects of nonaxisymmetric magnetic fields

Nonzero NTV Offset Velocity Allows QH-mode Operation with No Net NBI Torque Input

- **QH-mode produced with no net NBI torque using nonresonant, n=3 magnetic field perturbations from I-coils plus C-coils**





Previous Comparisons with Neoclassical Theory have Produced Puzzling Results

- **Bootstrap current measurements agree with theory**

- **Offset velocity in nonresonant magnetic braking experiments is in the ballpark of prediction based on neoclassical toroidal viscosity (A. Garofalo et al, PRL, 2008)**
  - NTV offset and poloidal rotation predictions come from same part of theory
  - More exact quantitative comparison requires extension of theory to impurity rotation

- **Measured differences between main ion (helium) and carbon impurity toroidal rotation agree with theory in H-mode plasma edge (J. Kim et al, PRL, 1994)**
  - Shows that differences in poloidal rotation of main ion and carbon agree with theory
  - However, individual poloidal rotation measurements do not agree with theory

Previous Comparisons with Neoclassical Theory have Produced Puzzling Results (continued)

- **Measured carbon poloidal rotation change across RS to ERS transition in TFTR does not agree with neoclassical theory (R.E. Bell et al, PRL, 1998)**
  - Accuracy of poloidal rotation measurement demonstrated by agreement in E_r change across transition calculated from poloidal rotation change and E_r change measured by MSE

- **Measured carbon poloidal rotation in H-mode does not agree with theory in core plasmas in D III-D (W.M. Solomon et al, PoP, 2006) and JET (E. Crombe et al, PRL, 2005)**

- **Recent NSTX carbon poloidal rotation measurements are closer to theory than TFTR, D III-D and JET results but still show some disagreement (R.E. Bell, APS invited, 2009)**

There is a Puzzle in the Theory as Well

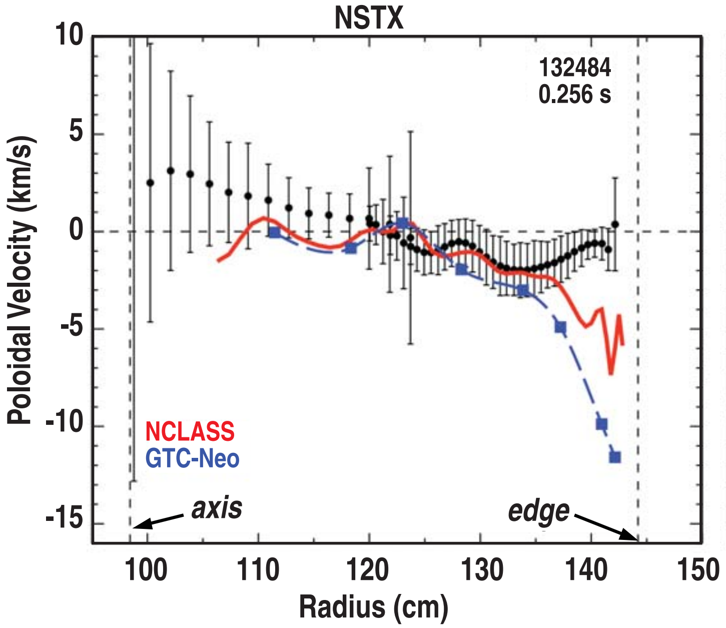
- **Neoclassical theory of poloidal rotation is qualitatively different than the neoclassical theory for cross field transport of particles, angular momentum and energy**
  - Poloidal rotation calculation comes from parallel force balance in first order in gyro-radius (ρ/L)
  - Cross field transport comes from second order portion of theory

- **When neoclassical cross field transport theory fails, we typically ascribe the failure to effects of turbulence**

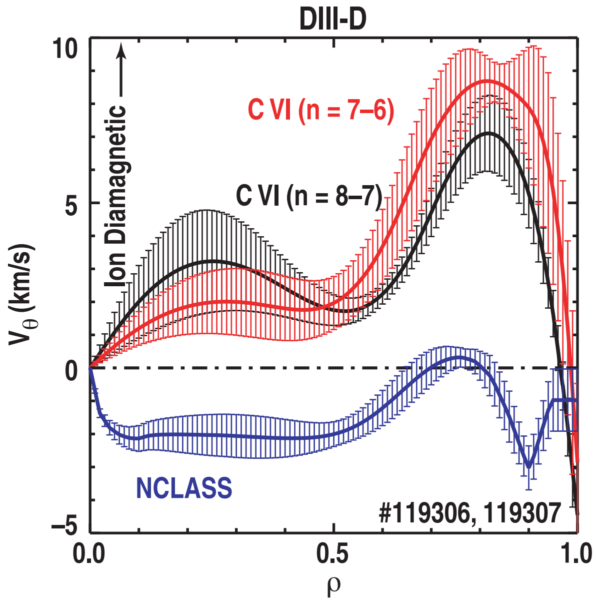
- **Gyrokinetic calculation show that turbulence effects on poloidal rotation are at the 10 to 20% level**
  - R.E. Waltz, et al, Phys. Plasmas 14, 122507 (2007)
  - G. Dif-Pradalier, et al Phys. Rev. Lett. 103, 065002 (2009)

Present Experiment Motivated by Recent NSTX Results

- **The immediate puzzle: NSTX results much closer to neoclassical than previous results in DIII-D, JET and TFTR**



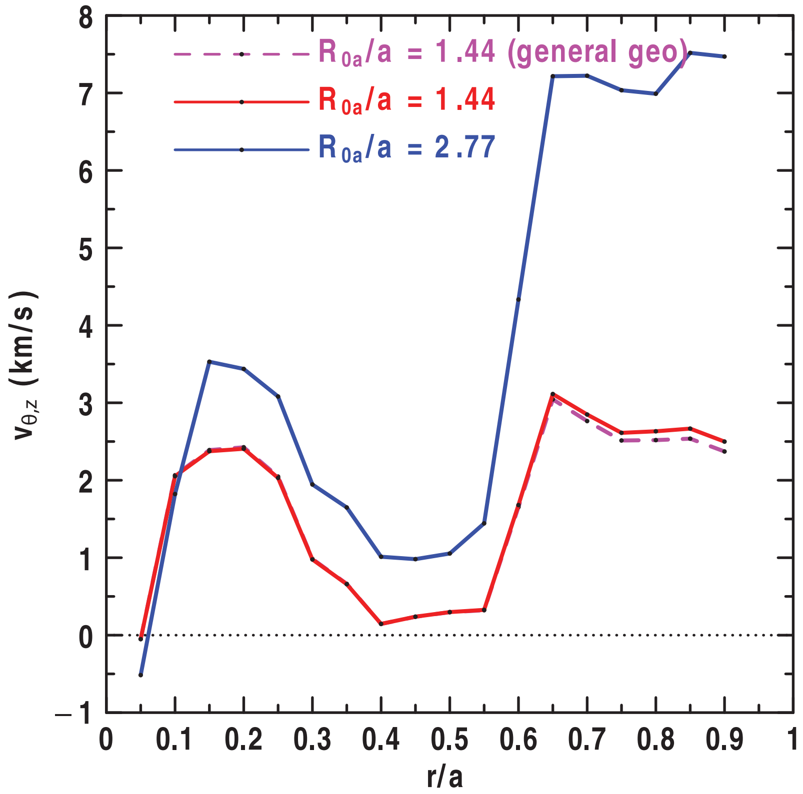
R.E. Bell et al APS 2009



W.M. Solomon et al APS 2005

Experimental Hypothesis: Tighter Aspect Ratio in NSTX Makes Neoclassical Effects Bigger

- If neoclassical effects are bigger at low aspect ratio, then this might force poloidal rotation to be closer to neoclassically predicted value.
- Modelling by E. Belli indicates that aspect ratio affects poloidal rotation
- Test hypothesis by running matched discharges in DIII-D and NSTX

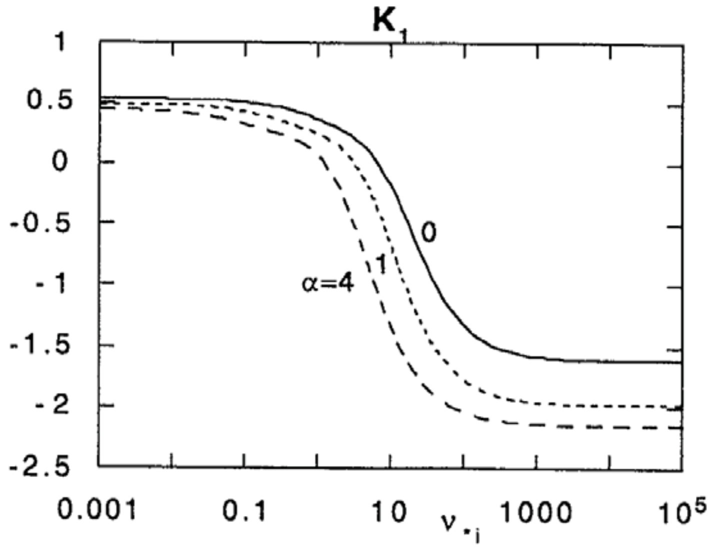


How do we Choose “Matched” Conditions?

$$V_\theta^i = \frac{1}{2} v_{T_i} \rho_i \left(K_1 \frac{1}{L_{T_i}} \right) \frac{BB_t}{\langle B^2 \rangle},$$

$$V_\theta^I = \frac{1}{2} v_{T_i} \rho_i \left[\left(K_1 + \frac{3K_2}{2} \right) \frac{1}{L_{T_i}} - \frac{1}{L_{p_i}} + \frac{Z_i}{Z_I} \frac{T_I}{T_i} \frac{1}{L_{p_I}} \right] \frac{BB_t}{\langle B^2 \rangle}$$

Y.B. Kim et al Phys. Fluids B3, 2050 (1991)



- **Goal is to compare with neoclassical theory, therefore need to consider important parameters in neoclassical theory**
- **Key nondimensional parameters are aspect ratio and $\rho_i(0)/a$**
  - Aspect ratio affects $B_T(0)B_T/\langle B^2 \rangle$
  - For $\nu^* < 0.1$, collisionality dependence is weak
- **Chose to match $\rho_i(0)/a$ by operating at NSTX field (0.5 T) and ion temperature [Ti(0) = 1 keV] in order to minimize effects of gyro-orbit cross section correction on inferred V_{pol}**

Significant Portion of Experimental Plan Completed

- **Develop basic discharge** **DONE**
  - I_P = 0.65 MA, B_T = 0.55 T
  - Balanced double null shape (from 121501)

- **Match density and temperature profiles to high density NSTX case** **DONE**

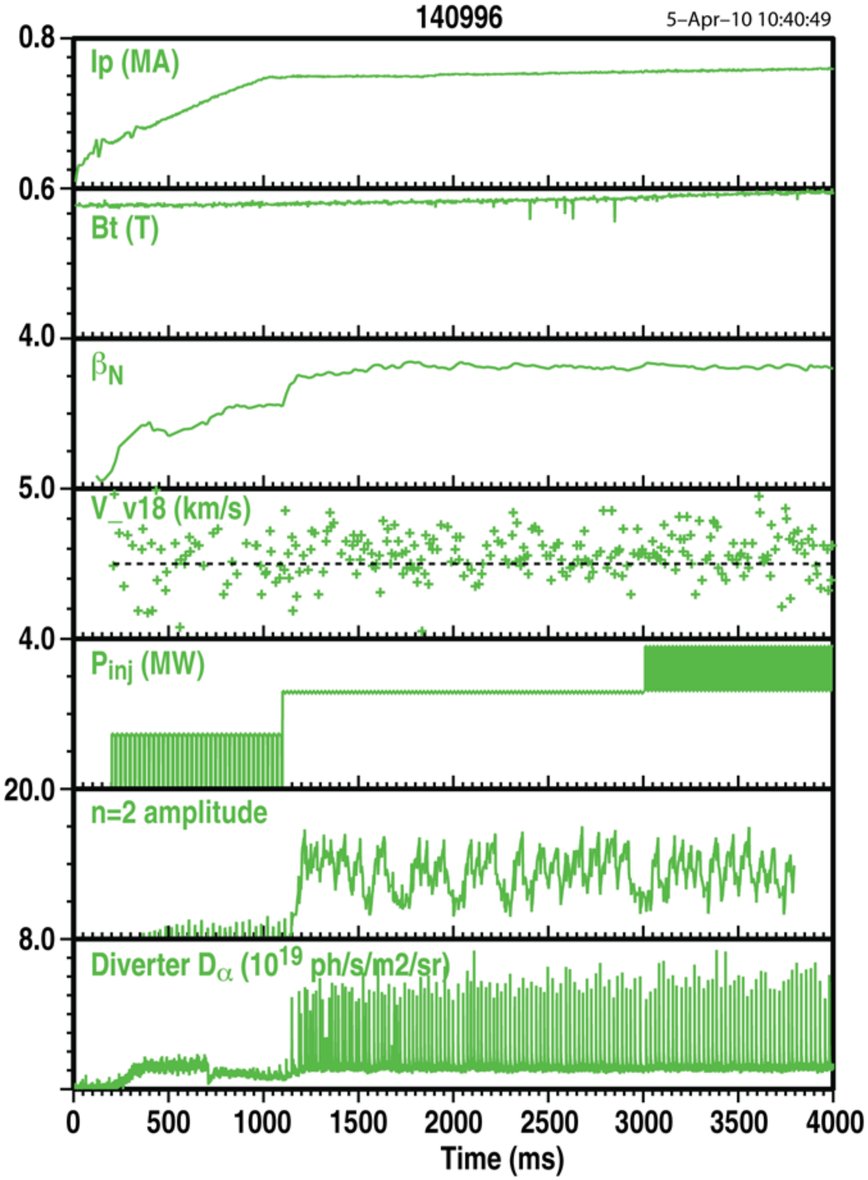
- **Density scan**
  - Find low density locked mode limit and then run 10% above this
  - Obtained density range of 4 to 8 x 10^{19} m^{-3}

- **NBI torque scan to alter rotation**
  - Only small range (45 to 60 km/s) obtained owing to locked modes

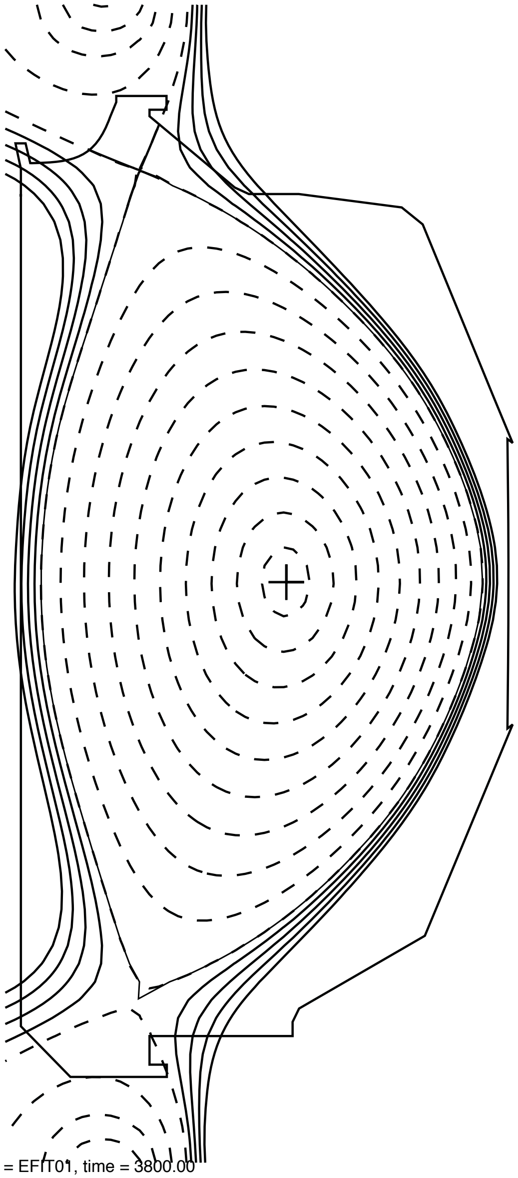
- **C-coil magnetic braking to alter rotation**
  - Range even smaller than torque scan

- **Be sure to get complete documentation at each step**
  done for one case
  - Profiles
  - Fluctuations (BES, PCI)

Double-Null Plasma Run to Match NSTX

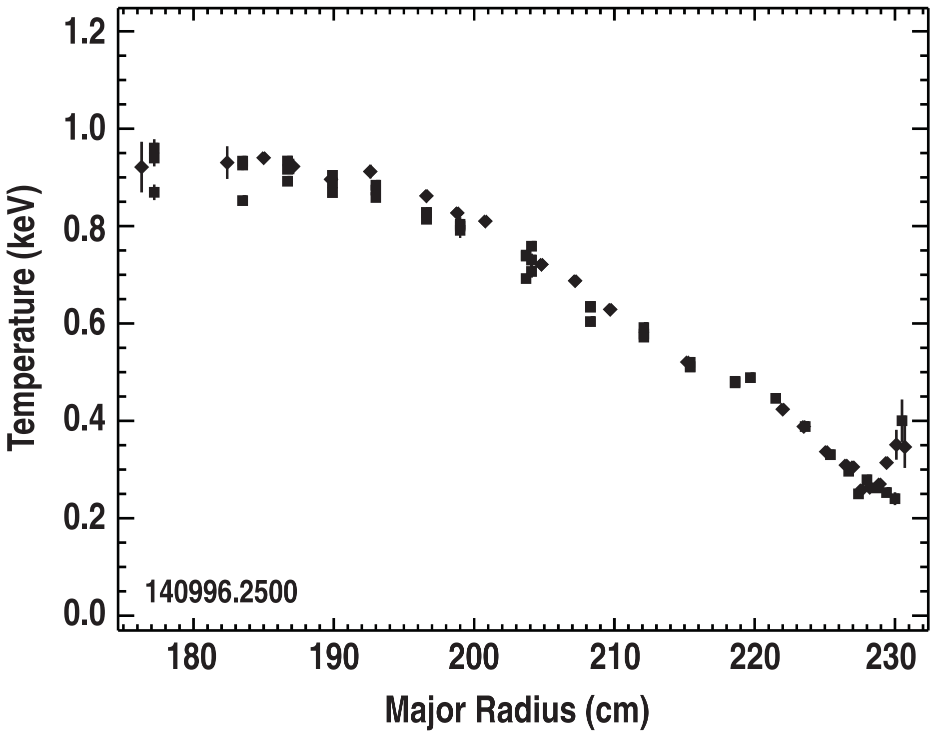


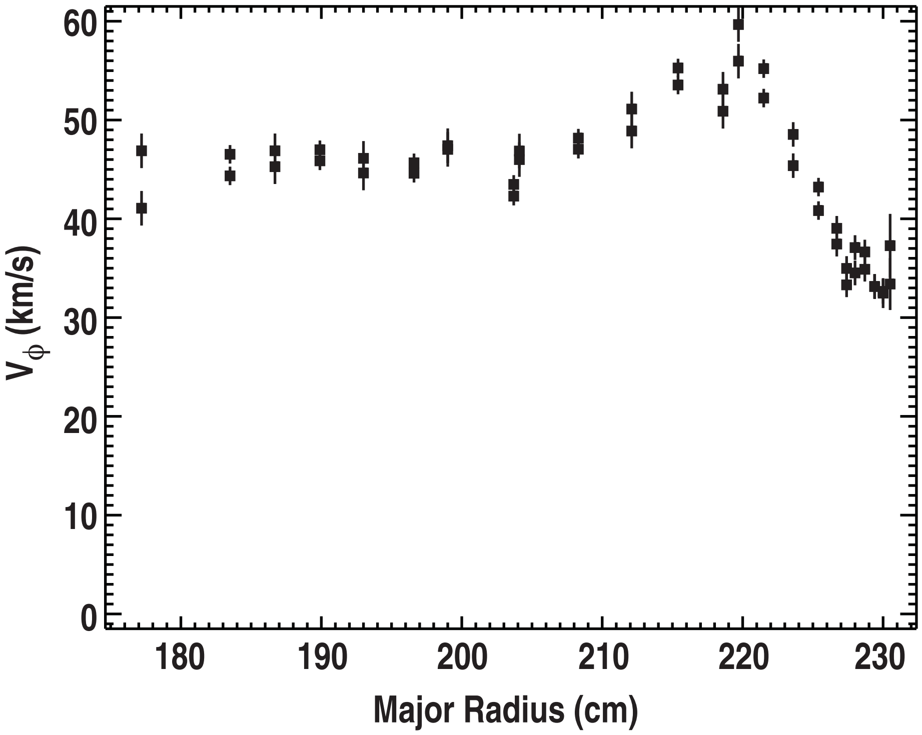
```
shot            140996
time           3800.00
chi**2          16.031
Rout(m)          1.683
Zout(m)         -0.002
a(m)             0.611
elong            1.873
utri             0.553
ltri             0.559
indent           0.000
V (m**3)        19.330
A (m**2)         1.889
W (MJ)           0.235
betaT(%)         5.898
betaP            0.935
betaN            3.277
In               1.800
Li               0.828
Li3              0.628
error(e-4)       5.489
q1               4.924
q95              2.657
dsep(m)          0.056
Rm(m)            1.751
Zm(m)            0.004
Rc(m)            1.711
Zc(m)           -0.000
betaPd           0.922
betaTd           5.817
Wdia(MJ)         0.232
Ipmeas(MA)       0.637
BT(0)(T)        -0.584
Ipfit(MA)        0.647
Rmidin(m)        1.072
Rmidout(m)       2.294
gapin(m)         0.056
gapout(m)        0.071
gaptop(m)        0.141
gapbot(m)        0.107
Zts(m)           0.745
Rvsin(m)         1.205
Zvsin(m)         1.199
Rvsout(m)        1.400
Zvsout(m)        1.269
Rsep1(m)         1.341
Zsep1(m)        -1.147
Rsep2(m)         1.345
Zsep2(m)         1.142
psib(Vs/R)      -0.131
elongm           1.432
qm               1.016
nev1(e19)        4.705
nev2(e19)        4.769
nev3(e19)        4.578
ner0(e19)        4.775
n/nc            -0.368
dRsep            0.001
qmin             1.016
rhoqmin          0.000
```



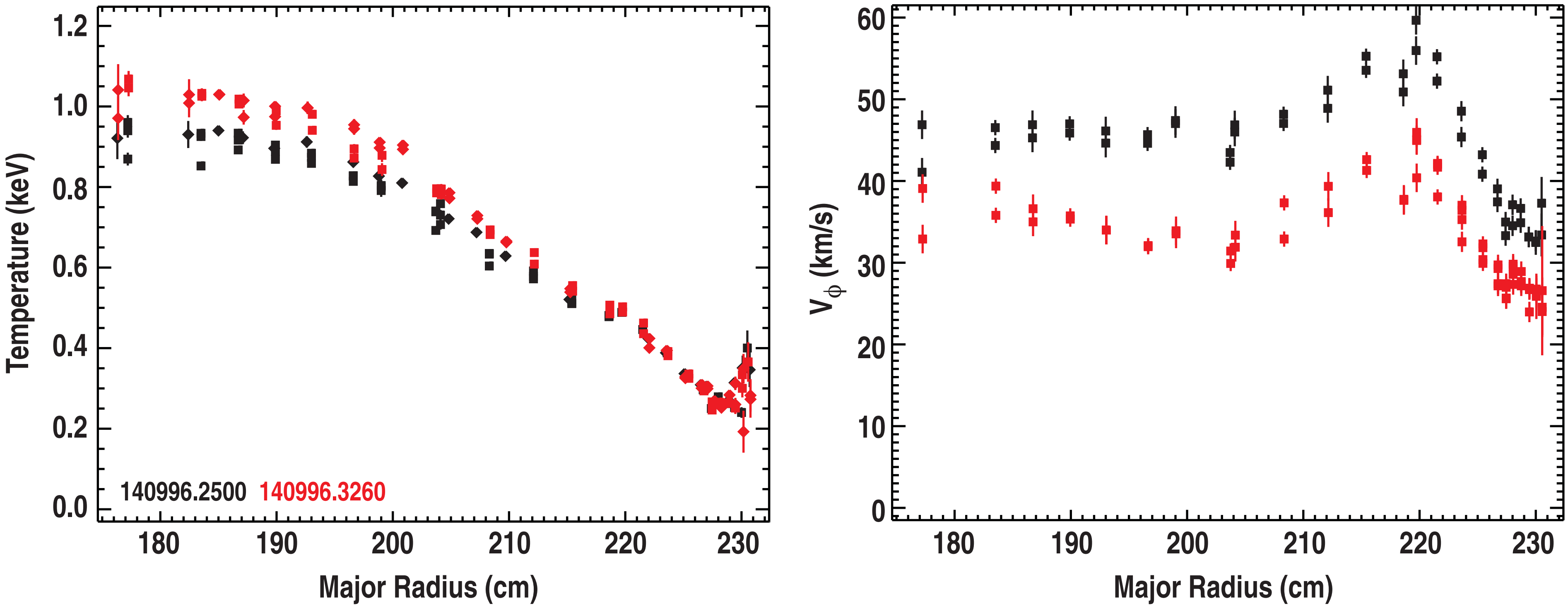
MDSplus, shot = 140996, run = EFIT01, time = 3800.00

Low B_T Plasma has Low Ion Temperature and Toroidal Rotation



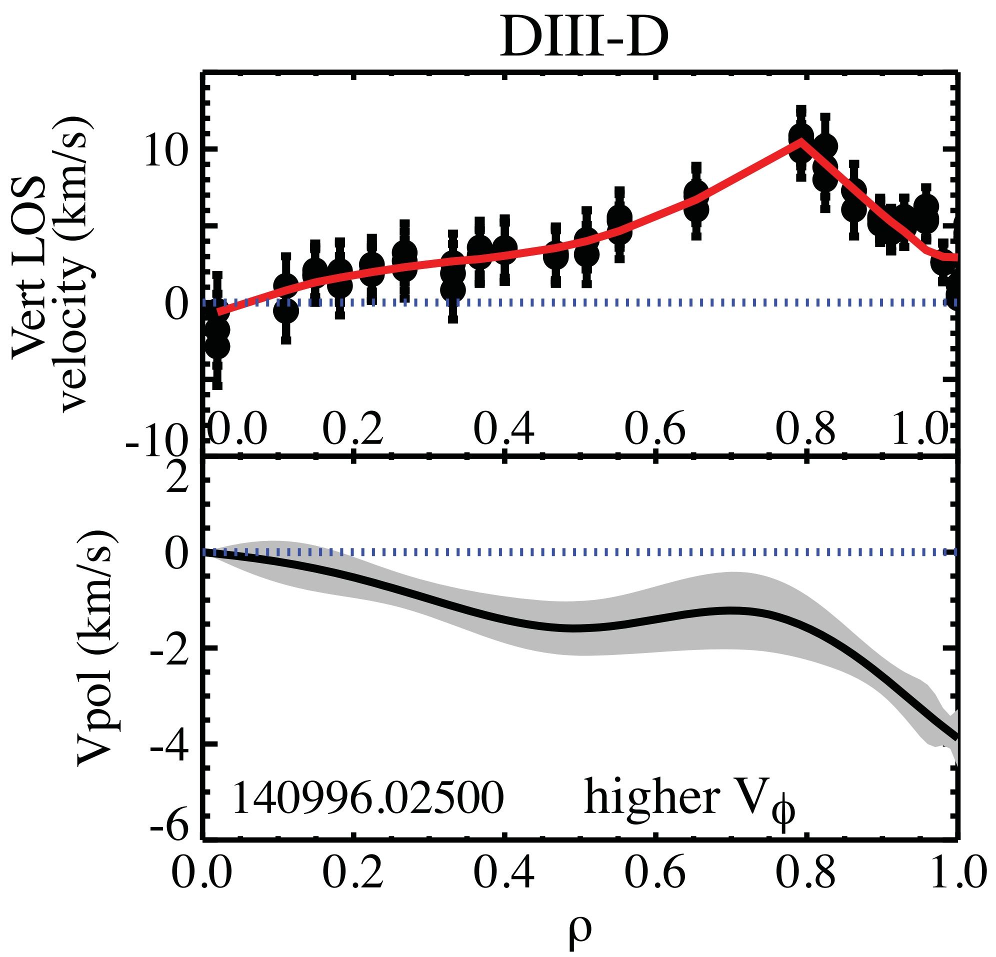


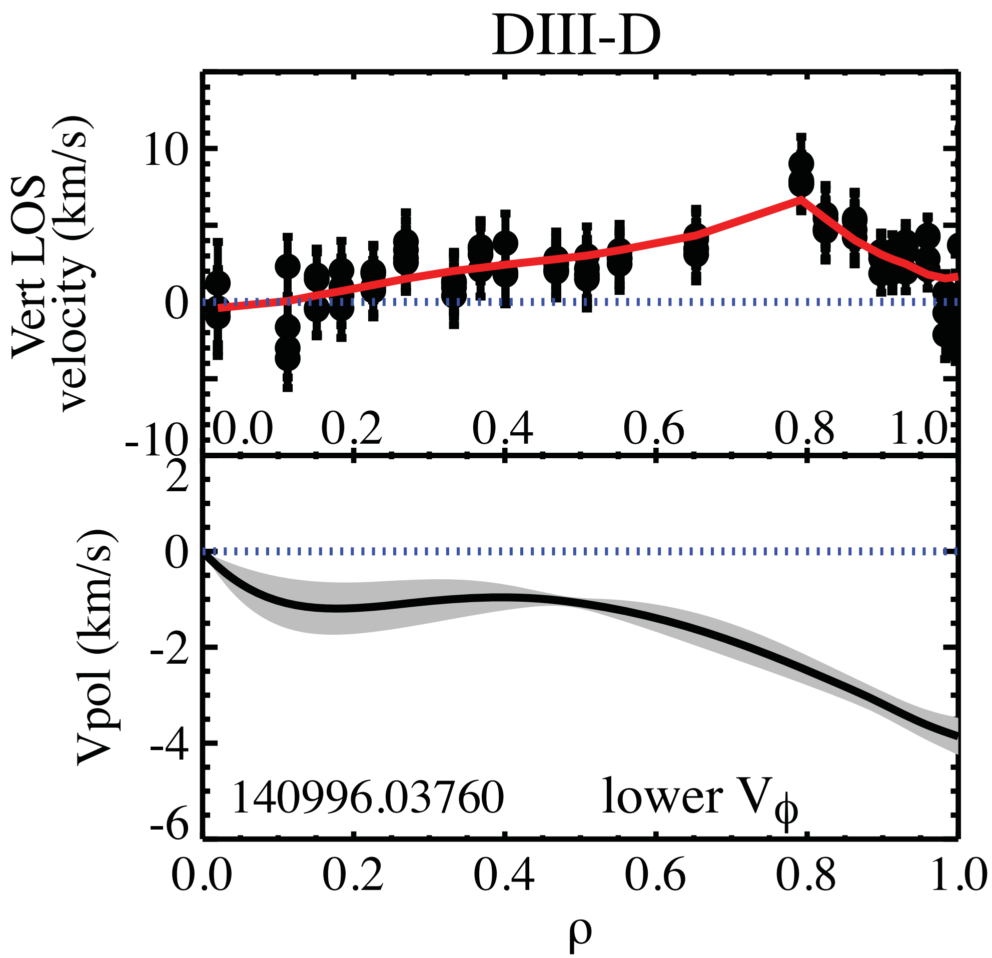
Low B_T Plasma has Low Ion Temperature and Toroidal Rotation



Poloidal Rotation Similar to that in NSTX

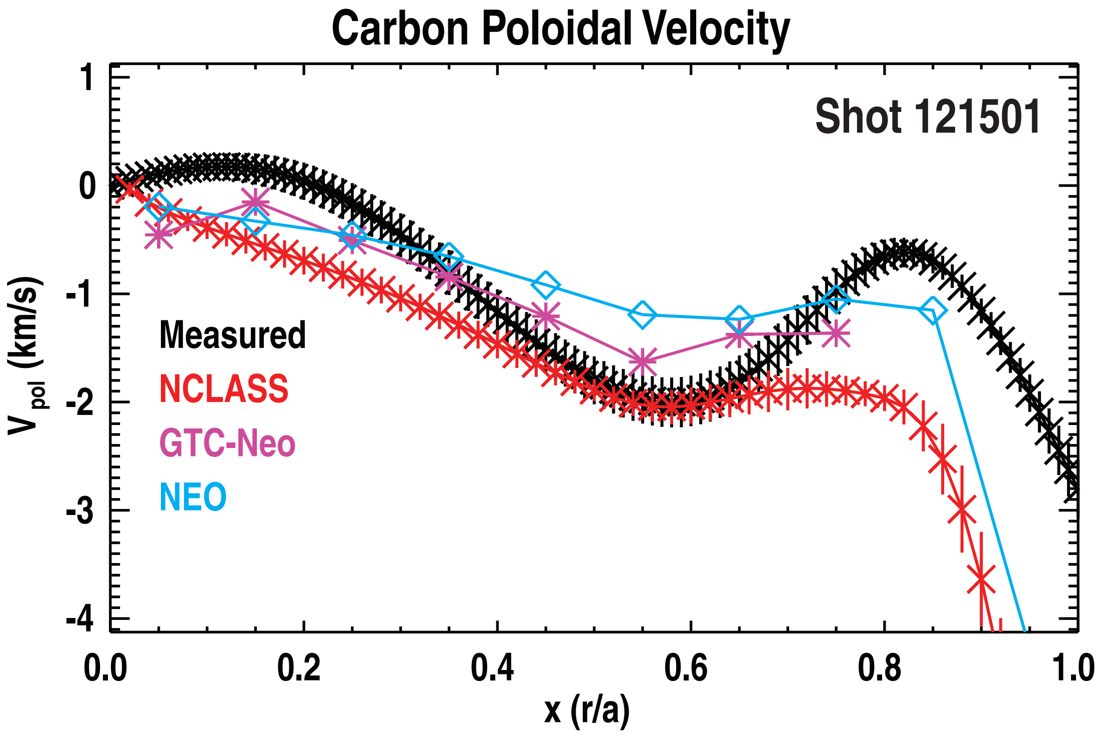
- Analysis of V_{pol} gives values in same range as NSTX
- Little change in V_{pol} with V_ϕ





Neoclassical Poloidal Rotation is Quite Close to Measured for Shot 121501

- **Analysis of 2010 data awaits Thomson scattering recalibration**
- **Have made comparison for shot 121501 from 2005**
  - Plasma conditions don't match NSTX as well as 2010 data, especially Zeff
- **Used measured profiles as input to neoclassical calculation**



Conclusions

- **Still have much more data analysis to do**
- **Preliminary conclusion is that aspect ratio does not explain the major difference between the older TFTR, DIII-D and JET data when these are compared to the recent lower field NSTX and DIII-D results**
- **There must be some other factor**
  - Ion temperature?
  - Orbit squeezing effect associated with core barriers in older shots?

The isothermal case; effect of orbit squeezing

If the temperature gradient is zero, the above expressions simplify:

$$u_\parallel \simeq -\frac{IT_i}{m_i\Omega_i}\frac{N'}{N}\frac{1}{D} \quad \text{where } D \simeq 1 + \frac{I}{\Omega_i}\frac{\partial u_\parallel}{\partial \psi} \tag{24}$$

Therefore, the poloidal flow velocity is

$$u_p \simeq \frac{I^2 T_i B_p}{m_i \Omega_i^2 B}\left(\frac{\partial}{\partial\psi}\ln n_i + \frac{e_i}{T_i}\frac{\partial\Phi}{\partial\psi}\right)\frac{\partial u_\parallel}{\partial\psi} \tag{25}$$

If, in addition, $|(\partial^2/\partial\psi^2)\ln n_i| \ll (e_i/T_i)|\partial^2\Phi/\partial\psi^2|$, then

$$u_p \simeq \frac{IT_iB_p}{m_i\Omega_iB}\left(\frac{\partial}{\partial\psi}\ln n_i + \frac{e_i}{T_i}\frac{\partial\Phi}{\partial\psi}\right)\left(1 - \frac{1}{D}\right) \tag{26}$$

where

$$D \simeq 1 - \frac{cI^2}{\Omega_i B}\frac{\partial^2\Phi}{\partial\psi^2} \tag{27}$$

which may be recognized as the orbit-squeezing factor.