Plasma Rotation in

[redacted]

Mechanisms have been developed to control/affect plasma rotation

Describing toroidal rotation in tokamaks is a transport problem

Thesis

Outline

Starting point for the calculation is the plasma kinetic equation

(x,v .

$$\frac{f_s}{t} + \overset{r}{v}\#$$

$$d^3\vec{v}\left(1, m_s\vec{v}, \frac{m_s v^2}{2}\right)\left[\frac{\# f_s}{\# t} + \vec{v} \;\; \% f_s + \frac{q_s}{m_s}(\vec{E} + \vec{v} \;\&\; \vec{B}) \;\; \frac{\# f_s}{\# \vec{v}} = C(f_s) + S(f_s)\right]$$

V_s

A number of assumptions are made to make analytic progress

Small gyroradius expansion is used

Transport equations for density and pressure are obtained by flux surface averaging

The different orders of the momentum balance equation refer to different timescales

$$\vec{J}_0 \quad \vec{B}_0 = \# p_0$$

$$= e \quad n_i \, q_i \; E + V_i \quad B \qquad p_i$$

$$\Omega_t \quad V_i \qquad V \quad = \quad \frac{d}{d} + \frac{}{n_i q_i}\frac{dp_i}{d} \quad qV$$

$$V_t \quad \frac{E_r}{B_p} \quad \frac{}{n_i q_i}\frac{dp_i}{dr} + \frac{B_t}{B_p} V_P$$

V

$$\vec{V} = \vec{e} \, \vec{V}\# \qquad + \vec{e}_{\%} \vec{V}\# \quad \% = V \, \frac{\vec{B}}{B} + \vec{V}_{\&}$$

Poloidal flow is obtained from parallel force balance

Viscous damping occurs

After determining the poloidal flow, there is a unique relationship between E_r and the toroidal rotation

$$\Omega \equiv \vec{V} \cdot \nabla\zeta = -\left(\frac{d\Phi}{d\psi} + \frac{1}{n_i q_i}\frac{dp_i}{d\psi} - q\vec{V} \cdot \nabla\theta\right)$$

$$< \vec{B} \quad \# \quad \overleftrightarrow{\ }_i >\%$$

$$V_t \quad \frac{E_r}{B_p} \# \frac{1}{n_i q_i B_P}\frac{dp_i}{dr} + \frac{1.17}{q_i B_p}\frac{dT_i}{dr}$$

Pressure/temperature profiles determined by transport processes

$$\vec{V} = \vec{e}\,\vec{V} \quad + \vec{e}\,\vec{V} \quad = V\frac{\vec{B}}{B} + \vec{V} \qquad \vec{V} = \frac{\vec{B}}{B} \quad \frac{d}{d} + \frac{}{n_s q_s}\frac{dp_s}{d}$$

$$V \quad R\frac{d}{d} + \frac{}{n_i q_i}\frac{dp_i}{d} + \frac{R}{q_i R}\frac{dT_i}{d}$$

Electron parallel momentum balance produces parallel Ohm's law

$$ {}_e e \quad \vec{E} \cdot \vec{B} \qquad \vec{B} \ddagger \quad \ddagger \, \overleftrightarrow{\%}_e \qquad \vec{B} \ddagger \vec{R}_e \qquad \vec{B} \ddagger \vec{S}_e $$

$$ {}_e \quad {}_e \qquad \vec{B} \ddagger \vec{V}_e \ddagger \quad \vec{V}_e \qquad {}_e \, e \quad \vec{B} \ddagger \vec{V}_e \,\&\, \vec{B} $$

$$ \# $$

$$ < \quad \% \;\; \& \quad >= \qquad < \quad > \;\mu \qquad + \mu $$

$$ \dot{E} \;\; \dot{B}_0 \qquad \#_{\|}^{nc} \quad \dot{J} \;\; \dot{B}_0 \qquad \#_{\|} [\;\; \dot{J} \;\; \dot{B}_{BS} \qquad \dot{J} \;\; \dot{B}_{CD} \qquad \dot{J} \;\; \dot{B}_{d\;n} \quad] $$

$$ = \qquad + \frac{{}_{\#}\mu}{\quad} \qquad < \overset{r}{\%} \; r \quad >= \& \frac{{}_{\#}\mu}{\quad} \qquad \frac{}{\quad} \& \qquad {}_{(} < \quad > $$

$$ < \overset{r}{\%} \; r \quad >= \& < \overset{r}{} $$

Parallel Ohm's law is used to describe collisional ambipolar particle flux

$$_s^a = \frac{1}{q_s} < \vec{e} \quad \vec{R}_s > \quad n_0 < \vec{e} \quad \vec{E} > \qquad \vec{R}_e \quad n_e e({}_{\|}\vec{J}_{\|} + \quad \vec{J}) = \quad \vec{R}_i$$

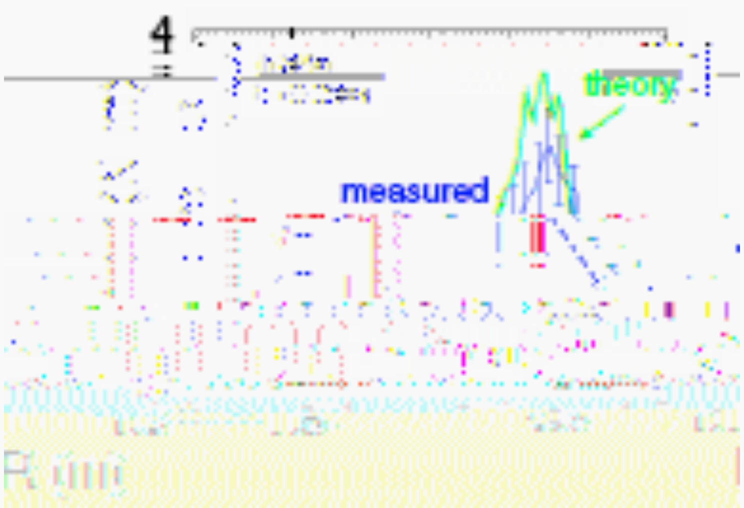
Plasma fluctuations influence particle flux/toroidal momentum balance

3-D magnetic fields produce neoclassical toroidal viscous forces (NTV) throughout the plasma

μ

μ

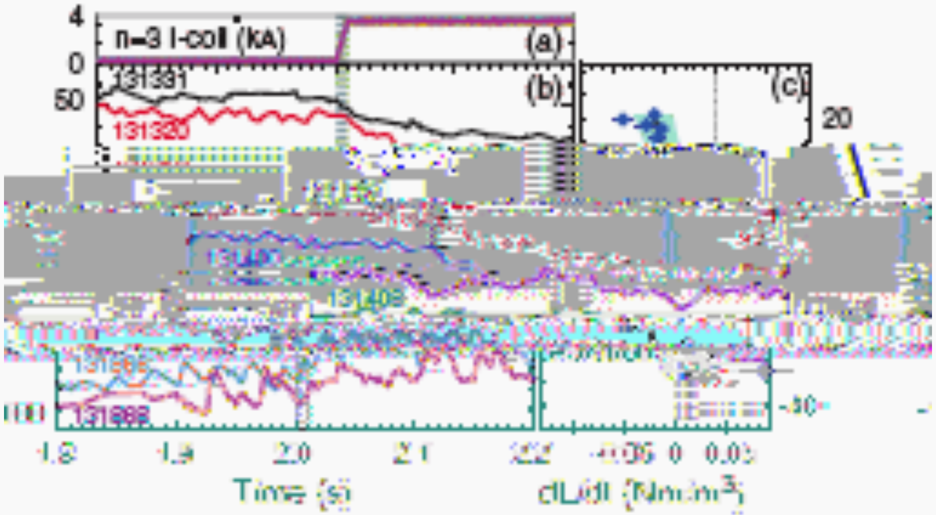
The NTV force is felt throughout the plasma



- Favorable comparison to analytic predictions

- NTV physics has been seen on NSTX, DIII-D, MAST, JET

Experiments on DIII-D have demonstrated the presence of the NTV offset velocity



Initially, slowly rotating
Plasmas sped up to the
Offset NTV velocity when
3-D fields are applied

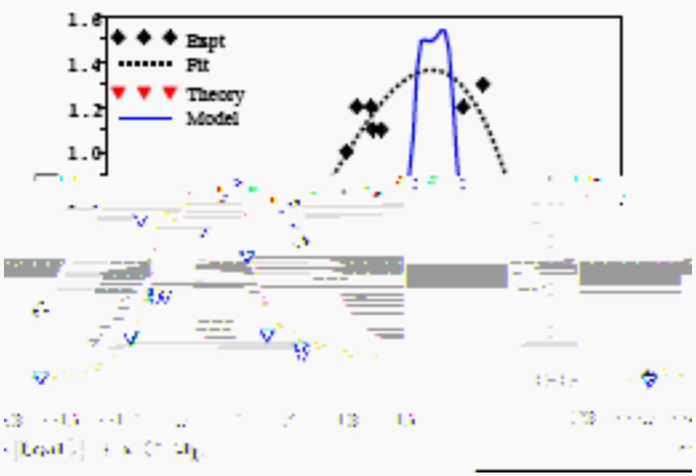
Recent experiments on DIII-D have demonstrated a peak in the NTV force at zero radial electric field

μ

$$_{ti} \quad \frac{n v_{ti} \sqrt{\;\#}}{R \qquad _{\%B} \sqrt{\#} \qquad v \qquad _{E}}$$

Peaks at

Recent experiment on DIII-D Demonstrates peak NTV at



Particle flux has 8 non-ambipolar contributions

Zero radial current produces torque balance relation

$$< \vec{J} \cdot \nabla\psi >= \sum_s q_s \Gamma_s = \sum_s q_s \Gamma_s^{NA}$$

$$\frac{\partial}{\partial t} < \rho_q$$

Toroidal rotation equation includes many different effects

Ω

$$\frac{1}{V'}\frac{}{}(V'L) \quad \# \quad \vec{e} \; \% \& \% \; {}^{NA}_{\|} \quad \# \quad \vec{e} \; \% \& \% \quad (\quad \# \frac{1}{V'} \frac{}{)} (V' \quad) \;) \quad \vec{e} \; \% \tilde{\vec{J}} + \tilde{\vec{B}} \quad \# \dot{)} \; \frac{L}{)} \quad \vec{e} \; \% \; , \vec{S}$$

< r

Toroidal rotation determines radial electric field required for net ambipolar particle flux

Summary

Ω

Summary