NBI Driven Neoclassical Effects

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NBI Forces on Thermal Species Drive Particle and Heat Fluxes and Viscous Heating

- Unbalanced neutral beam injection can influence the interpretation of the particle and ion power balances through:
  - Thermal-NBI friction
  - Viscous heating
  - Thermal-NBI heat friction (needs evaluation)
- The NBI friction and viscous heating effects alone can exceed standard ion neoclassical heat conduction (e.g., works of Stacey, Hinton)
- The NBI heat friction was estimated by Callen in 1974 to have an influence comparable to the NBI friction, and therefore needs to be revisited
- Note that NBI heat friction on electrons a major contributor to the electron shielding current in NBCD
- More thorough quantitative analyses of these NBI effects are suggested when ion turbulence is suppressed:
  - NSTX negative effective ion thermal conductivity with co-NBI
  - Observations of ion thermal conductivity below standard neoclassical in ITBs

Neoclassical Parallel Force Balances with NBI

Hirshman and Sigmar, *Nucl. Fusion* **21** (1981) 1079
Houlberg, Shaing, Hirshman and Zarnstorff, *Phys. Plasmas* **4** (1997) 3230

- **Parallel momentum and heat force balance equations for species j:**

$$\begin{aligned}\langle\vec{B}\cdot\vec{\nabla}\cdot\vec{\Pi}_j\rangle &= \langle\vec{F}_{1,j}\cdot\vec{B}\rangle+\langle\vec{F}^b_{1,j}\cdot\vec{B}\rangle+e_jn_j\langle\vec{E}\cdot\vec{B}\rangle\\ \langle\vec{B}\cdot\vec{\nabla}\cdot\vec{\Theta}_j\rangle &= \langle\vec{F}_{2,j}\cdot\vec{B}\rangle+\langle\vec{F}^b_{2,j}\cdot\vec{B}\rangle\end{aligned}$$

Viscous **Thermal Friction** **Beam Friction** **Ohmic**

- **Classical parallel friction forces between thermal particles:**

$$\begin{aligned}\langle\vec{F}_{\alpha,j}\cdot\vec{B}\rangle &= \sum_k\sum_\beta \ell^{jk}_{\alpha\beta}\hat{u}_{\|\beta,k}\\ \hat{u}_{\|1,j} &\equiv \langle\vec{u}_j\cdot\vec{B}\rangle\\ \hat{u}_{\|2,j} &\equiv \frac{2}{5}\frac{\langle\vec{q}_j\cdot\vec{B}\rangle}{p_j}\end{aligned}$$

Function of parallel flows of all species

- **Neoclassical parallel viscous forces:**

$$\begin{aligned}\langle\vec{B}\cdot\vec{\nabla}\cdot\vec{\Pi}_j\rangle &= \langle B^2\rangle\sum_\beta\hat{\mu}_{1\beta,j}\,\hat{u}_{\theta\beta,j}\\ \langle\vec{B}\cdot\vec{\nabla}\cdot\vec{\Theta}_j\rangle &= \langle B^2\rangle\sum_\beta\hat{\mu}_{2\beta,j}\,\hat{u}_{\theta\beta,j}\\ \hat{u}_{\theta1,j} &\equiv \frac{\langle\vec{u}_j\cdot\vec{\nabla}\theta\rangle}{\langle\vec{B}\cdot\vec{\nabla}B\rangle}\\ \hat{u}_{\theta2,j} &\equiv \frac{2}{5}\frac{1}{p_j}\frac{\langle\vec{q}_j\cdot\vec{\nabla}\theta\rangle}{\langle\vec{B}\cdot\vec{\nabla}B\rangle}\end{aligned}$$

Function of poloidal flows of own species

Neoclassical Particle and Heat Fluxes with NBI

- **The banana plateau fluxes are related to the poloidal flows:**

$$
\begin{aligned}
\Gamma_j^{\mathrm{BP}} &= -\frac{2\pi R B_t}{\Psi' e_j} \sum_\beta \hat{\mu}_{1\beta,j} \left(\hat{u}^{nc}_{\theta\beta,j} + \hat{u}^{b}_{\theta\beta,j} \right) \\
q_j^{\mathrm{BP}} &= -\frac{2\pi R B_t k T_j}{\Psi' e_j} \sum_\beta \hat{\mu}_{2\beta,j} \left(\hat{u}^{nc}_{\theta\beta,j} + \hat{u}^{b}_{\theta\beta,j} \right)
\end{aligned}
$$

  - **Importance relative to standard neoclassical is governed by the ratio of induced poloidal flows**

- **The Pfirsch-Schlüter fluxes are related directly to the forces:**

$$
\begin{aligned}
\Gamma_j^{\mathrm{PS}} &= \frac{2\pi R B_t}{\Psi' e_j} \left[1/\langle B^2 \rangle - \langle B^{-2} \rangle \right] \left[\langle \vec{F}_{1,j} \cdot \vec{B} \rangle + \langle \vec{F}^{b}_{1,j} \cdot \vec{B} \rangle \right] \\
q_j^{\mathrm{PS}} &= \frac{2\pi R B_t k T_j}{\Psi' e_j} \left[1/\langle B^2 \rangle - \langle B^{-2} \rangle \right] \left[\langle \vec{F}_{2,j} \cdot \vec{B} \rangle + \langle \vec{F}^{b}_{2,j} \cdot \vec{B} \rangle \right]
\end{aligned}
$$

  - **Importance relative to standard neoclassical governed by the ratio of forces**

- **All of the NBI terms are outward with co-injection, inward with counter-injection (testable by co-/counter-NBI comparisons)**

The Radial Force Balances with NBI

- **Radial force balance equations:**

$$
\begin{aligned}
\langle B^2\rangle \left[\hat{u}^{nc}_{\theta 1,j} + \hat{u}^{b}_{\theta 1,j}\right] &= \left[\hat{u}^{nc}_{\| 1,j} + \hat{u}^{b}_{\| 1,j}\right] + \frac{2\pi R B_t}{\Psi'}\left[\frac{p'_j}{e_j n_j} + \Phi'\right] \\
\langle B^2\rangle \left[\hat{u}^{nc}_{\theta 2,j} + \hat{u}^{b}_{\theta 2,j}\right] &= \left[\hat{u}^{nc}_{\| 2,j} + \hat{u}^{b}_{\| 2,j}\right] + \frac{2\pi R B_t}{\Psi'}\frac{kT'_j}{e_j}
\end{aligned}
$$

- **NBI effects on poloidal rotation should be considered when:**
  - **Determining the radial electric field using the radial force balance with theoretical models for the poloidal rotation**
  - **Comparing measured poloidal rotation with theoretical models**

Viscous Heating with NBI

- **The neoclassical viscous heating is enhanced as the square of the poloidal flow velocities:**

$$
\begin{aligned}
P^{\mathrm{BP}}_{\mu,j} &= \hat{u}_{\theta 1,j}\langle \vec{B}\cdot\vec{\nabla}\cdot\vec{\Pi}_j\rangle \\
&= \left[\hat{u}^{nc}_{\theta 1,j} + \hat{u}^{b}_{\theta 1,j}\right]\langle B^2\rangle \sum_{\beta} \hat{\mu}_{1\beta,j} \left[\hat{u}^{nc}_{\theta\beta,j} + \hat{u}^{b}_{\theta\beta,j}\right]
\end{aligned}
$$

- **In addition to this are heating terms from classical (small) and toroidal viscosity (e.g., Stacey's gyroviscosity, turbulence induced viscosity, …)**
- **Viscous heating is likely important for:**
  - **ITBs with strong pressure gradients**
  - **Strong toroidal rotation**

Summary of NBI Driven Neoclassical Effects

- There is an extensive literature on the theory for NBI driven neoclassical fluxes and viscous heating
- Various of these analyses have shown the effects are comparable to the standard neoclassical effects
- Much of that literature considers individual effects and approximations that can be treated more comprehensively
- These effects should be most visible in experiments with unbalanced NBI when turbulence induced transport is suppressed
  - NSTX cases where negative effective ion thermal conductivity is inferred
  - DIII-D QDB plasmas
  - ITBs
- The primary work for a quantitative study would be to evaluate the parallel NBI friction and heat friction in an NBI package (only the toroidal torque is presently evaluated in TRANSP and other codes)

A Selection of References on NBI Driven Effects

Introductory assessment including momentum and heat flux torques:

- **J.D. Callen, et al, "Neutral beam injection into tokamaks," 5th IAEA, Tokyo (1974), Vol 1, 645**

Momentum torque and viscous heating:

- **S.P. Hirshman, D.J. Sigmar, "Neoclassical transport of impurities in tokamak plasmas," *Nucl. Fusion* 21 (1981) 1079**
- **W.M. Stacey, Jr., "The effects of neutral beam injection on impurity transport in tokamaks," *Phys. Fluids* 27 (1984) 2076**
- **W.M. Stacey, Jr., "Rotation and Impurity Transport in a tokamak plasma with directed neutral-beam injection," *Nucl. Fusion* 25 (1985) 463**
- **W.M. Stacey, Jr., "Convective and viscous fluxes in strongly rotating tokamak plasmas," *Nucl. Fusion* 30 (1990) 2453**
- **W.M. Stacey, Jr., "Poloidal rotation and density asymmetries in a tokamak plasma with strong toroidal rotation," Phys. Fluids B 4 (1992) 3302**
- **F.L. Hinton, Y.-B. Kim, "Effects of neutral beam injection on poloidal rotation and energy transport in tokamaks," Phys. Fluids B 5 (1993) 3012**
- **W.M. Stacey, "Comments on 'Effects of neutral beam injection on poloidal rotation and energy transport in tokamaks,' " *Phys. Fluids* B 5 (1993) 4505**

Momentum and heat flux torques included in formal development of equations (no applications):

- **J.P. Wang, et al, "Momentum and heat friction forces between fast ions and thermal plasma species," *Nucl. Fusion* 34 (1994) 231**
- **W.A. Houlberg, et al, "Bootstrap current and neoclassical transport in tokamaks of arbitrary collisionality and aspect ratio," *Phys. Plasmas* 4 (1997) 3230**