EXTENDED NEOCLASSICAL PLASMA ROTATION AND TRANSPORT THEORY

Dr. Cheonho "Leo" Bae

yuri157@gmail.com

Atlanta International School, Atlanta, GA

CONTENTS

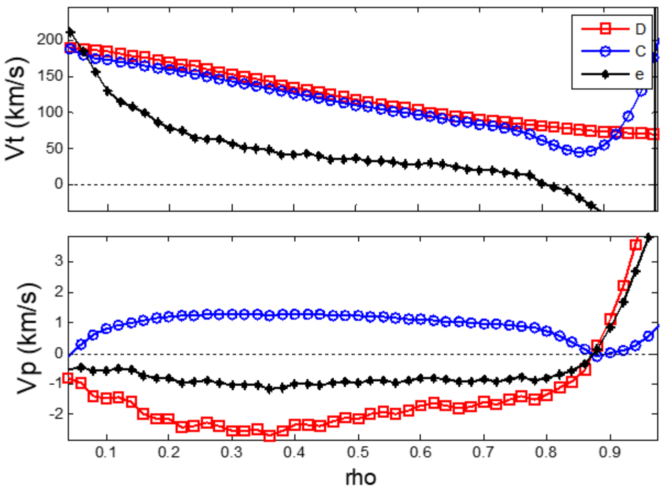
Extended Plasma Rotation Theory(ERT)?

BACKGROUND

- Plasma rotation theories developed by two main approaches
  - Hirshman-Sigmar approach
    - Hirshman and Sigmar, Nuclear Fusion 21 (1981)
    - **Most recent publication:** Houlberg et al., 1998
    - most famous with two (parallel/perpendicular) Momentum Balance Equations(MBE) to calculate neoclassical rotations of multi-ions and Er
  - Stacey-Sigmar approach
    - Stacey and Sigmar, Phys. Fluids 28, 2800(1985)
    - **Most recent publication:** Bae et al., Nuclear Fusion 2013
      - introduced as "Extended Plasma Rotation Theory"
    - Decomposes MBE in three coordinates (radial, poloidal, toroidal)
      - direct comparisons with Vt and Vp measurements possible
      - Radial transport calculations in radial coordinates
  - Others

BACKGROUND

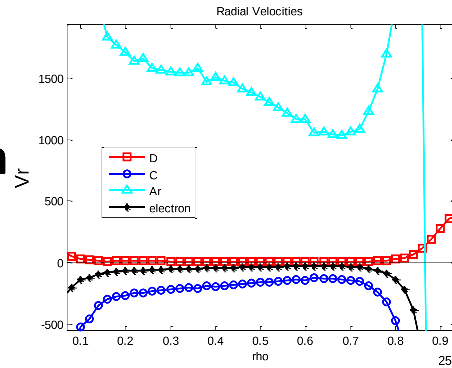
- Neoclassical plasma rotation codes
  - NCLASS
    - based on Hirshman-Sigmar approach
      - Publication: Houlberg et al.,Phys. Plasmas, 4 (1997)
    - calculate neoclassical rotations of multi-ions
    - Embedded in TRANSP
  - GTROTA
    - based on Stacey-Sigmar approach
      - Publication: Bae et al., Comp. Phys. Comm. (2013)
    - Uses D-shaped Miller flux surface geometry
      - Miller et. al., Phys. of Plasmas, 5 (1998)
    - calculates rotation velocities up to four ion species and electron
    - A non-linear iteration code in Matlab
  - Others

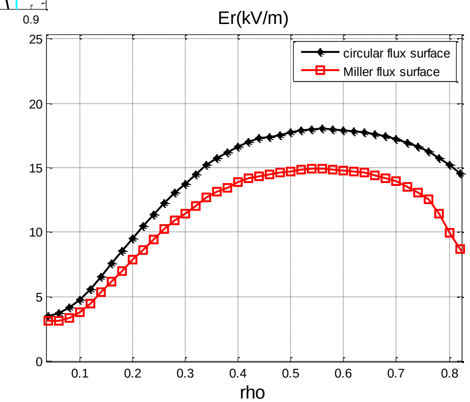


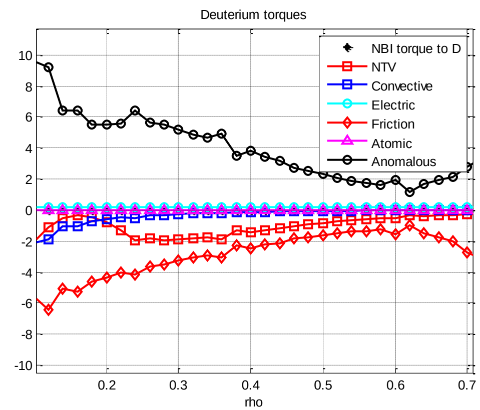
BACKGROUND

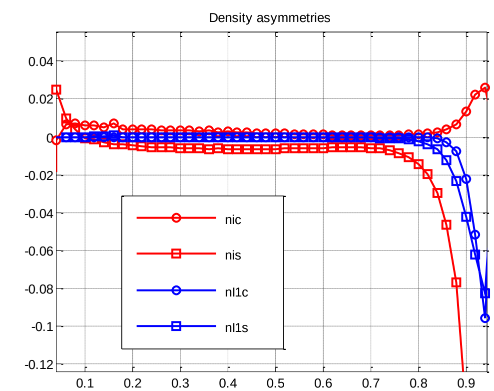
GTROTA major outputs

- **Vt and Vp rotation velocities of 4 ion species and electron** (previous slide)
- **Radial velocity (Vr) and electric field (Er)**
- **All the torques in toroidal angular torque balance**
  - Including viscous torques
- **Poloidal in-out / up-down asymmetries**
  - in density, velocity, and electrostatic potential









- **Vt calculations with DIII-D, KSTAR, and EAST shots agree within 15% of carbon or Ar measurements (CES and XICS measurements) for rho < 0.85**

EXTENDED ROTATION THEORY

- **Based on collisionality-extended Braginskii's closure**
  - **Meaning that it is based on Braginskii's closure but extended for arbitrary collisionality**
    - Details in the next slide
  - **Extension to Mikhailovski-Tsyin's closure in progress** [Plasma Phys 13, 785 (1971)]
    - **For better accuracy in the edge Rotation Study (rho 0.85 to 1.0)**

$$\boxed{-\Omega_a \hat{b}\times\vec{V}_a = \partial_t \vec{V}_a + \vec{V}_a\cdot\nabla\vec{V}_a + \frac{1}{m_a n_a}\nabla\cdot\overleftrightarrow{\pi}_a + \frac{1}{m_a n_a}\nabla p_a - \frac{q_a}{m_a}\vec{E} - \frac{1}{m_a n_a}\vec{C}_a^{10}}$$

$$-\Omega_a\left(\overleftrightarrow{\pi}_a\times\hat{b} - \hat{b}\times\overleftrightarrow{\pi}_a\right) \approx \underbrace{\overbrace{2p_a\overline{\nabla\vec{V}_a}}^{Braginskii} + \frac{4}{5}\overline{\nabla\vec{q}_a}}_{Mikhailovski-Tsypin} + higher\ order\ terms$$

$$\boxed{-\Omega_a\left(\hat{b}\times\vec{q}_a\right) = \frac{5}{2m_a}p_a\nabla T_a + \frac{1}{2}\vec{C}_a^{11} + O(higher)}$$

EXTENDED ROTATION THEORY

▪ Collisionality-extended Braginskii's viscosity representation

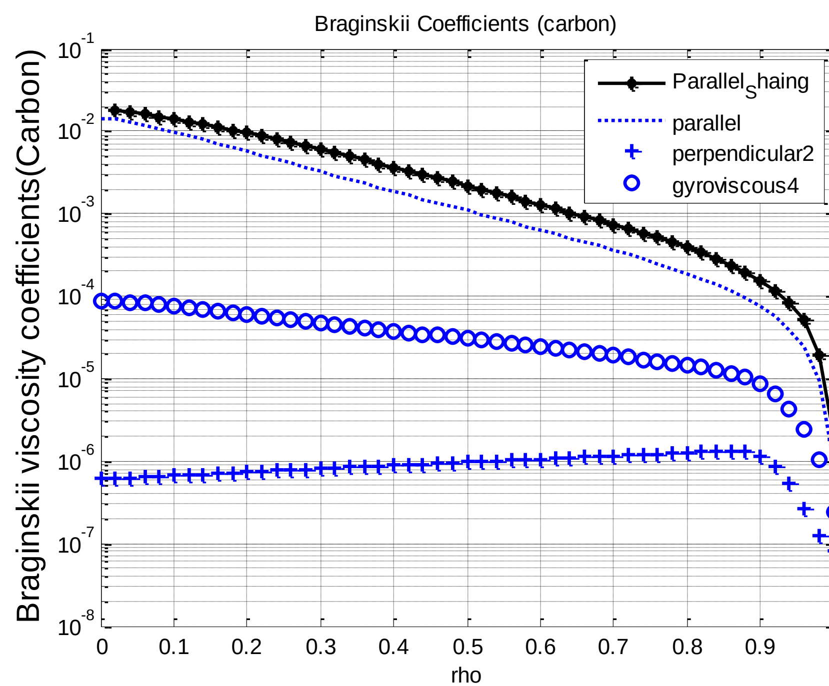
- **Parallel viscosity coefficient extended to low collisionality (trapped particle effect) by Shaing**

  -> Calculations valid for arbitrary collisionality

$$\overbrace{\underbrace{\eta_0 = 0.96 nT\tau}_{\parallel}}^{\text{collisionality dependent}}\ ,\quad \overbrace{\underbrace{\eta_3 = \frac{1}{2}\frac{nT}{\Omega},\ \eta_4 = 2\eta_3}_{gv}}^{\text{independent of collisionality}}\ ,\quad \overbrace{\cancel{\underbrace{\eta_1 = \frac{3}{10}\frac{nT}{\Omega^2\tau},\ \eta_2 = 4\eta_1}_{\perp}}}^{\text{collisionality dependent (but small contribution)}}\ , \quad \Rightarrow \left(\underbrace{\eta_0}_{\parallel} >> \underbrace{\eta_{3,4}}_{gv} >> \underbrace{\eta_{1,2}}_{\perp} \right)$$

- Shaing-banana plateau-PS:

$$\eta_{0j} = \frac{n_j m_j V_{thj} q R_0 \varepsilon^{-3/2} \nu_{jj}^*}{\left(1+\varepsilon^{-3/2}\nu_{jj}^*\right)\left(1+\nu_{jj}^*\right)} \equiv n_j m_j V_{thj} q R f_j$$



EXTENDED ROTATION THEORY

- **Retains all the terms in Toroidal and Poloidal MBE**
  - **Except vanishing ones due to equilibrium and axisymmetry (in grey)**
  - **Includes Reynolds Stress terms (Convective and Atomic torques)**
  - **Atomic term calculated with TRANSP**
  - **No gyroviscous cancellation assumed**
  - **Numerical model becomes extremely non-linear**

Accelerational | Convective | Pressure | Viscous

$$\left\langle R m_a n_a \frac{\partial V_{a\phi}}{\partial t}\right\rangle + \boxed{\left\langle R n_a m_a \left(\vec{V}_a \cdot \nabla\right) V_{a\phi}\right\rangle} + \left\langle R \frac{1}{h_\phi}\frac{\partial p_a}{\partial \phi}\right\rangle \boxed{+ \left\langle R\left(\nabla \cdot \overleftrightarrow{\pi}_a\right)_\phi\right\rangle} =$$

$$\left\langle R n_a e_a \left(-\frac{1}{h_\phi}\frac{\partial \Phi}{\partial \phi} - \frac{\partial A_\phi}{\partial t}\right)\right\rangle + \left\langle R n_a e_a \left(V_{a\psi} B_p - V_{ap} B_\psi\right)\right\rangle + \left\langle R F^1_{a\phi}\right\rangle + \left\langle R S^1_{a\phi}\right\rangle + \boxed{\underbrace{\left(-\left\langle R m_a V_{a\phi} S^0_a\right\rangle\right)}_{-\left\langle R n_j m_j \nu_{atomj} V_{\phi j}\right\rangle}}$$

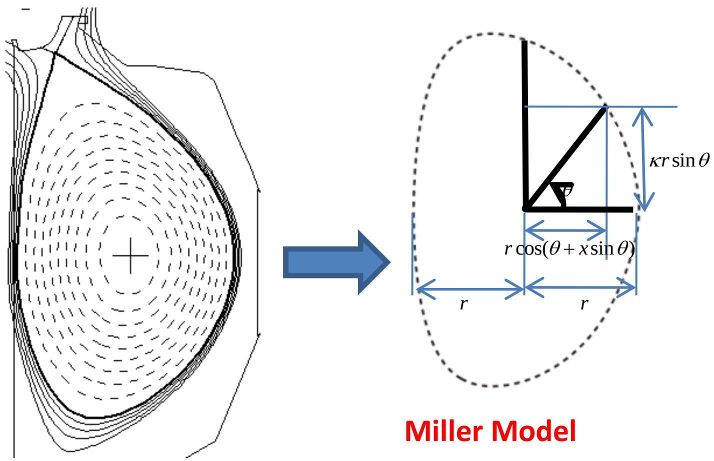
Electric | V cross B | Frictional | External | Atomic

$$\left\langle r m_a n_a \frac{\partial V_{a\theta}}{\partial t}\right\rangle + \left\langle r n_a m_a \left(\vec{V}_a \cdot \nabla\right) V_{a\theta}\right\rangle + \left\langle r \frac{1}{h_\theta}\frac{\partial p_a}{\partial \theta}\right\rangle + \left\langle r\left[\nabla \cdot \overleftrightarrow{\pi}_a\right]_\theta\right\rangle =$$

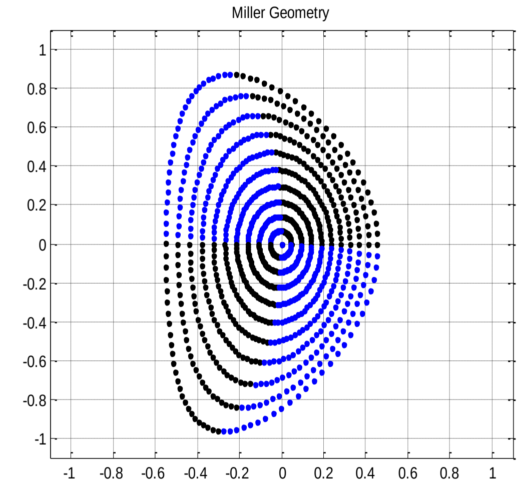
$$\left\langle r\left(-\frac{1}{h_p}\frac{\partial \Phi}{\partial \theta} - \frac{\partial A_\theta}{\partial t}\right)\right\rangle + \left\langle r n_a e_a \left(V_{a\phi} B_r - V_{ar} B_\phi\right)\right\rangle + \left\langle r F^1_{a\theta}\right\rangle + \left\langle r\left(S^1_{a\theta} - m_a V_{a\theta} S^0_a\right)\right\rangle$$

EXTENDED ROTATION THEORY

- **applies D-shaped flux surface geometry using Miller model** [Miller et. al., Phys. of Plasmas, 5 (1998)] **with Shafranov shifts**



Miller Model



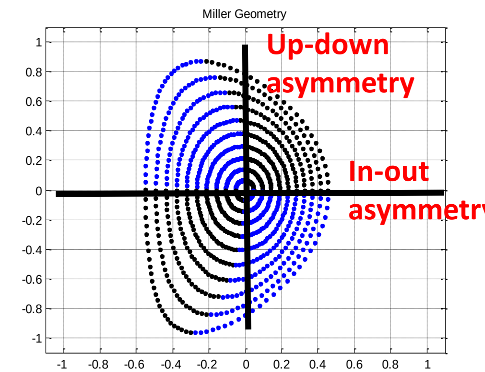
- **Flux surface averages (FSAs) and geometric scale factors(h's) for Miller geometry**
  - **Example: Er formula below shows FSAs and scale factors (h)**

$$\bar{E}_r = -V_{thj}\bar{B}_\theta \left[V_{\theta j}\frac{\left\langle \frac{1}{1+\varepsilon\cos\xi} \right\rangle}{\left\langle \frac{1}{h_r} \right\rangle} - V_{\phi j}\left(1+\frac{\partial R_0(r)}{\partial r}\right)\frac{\left\langle \frac{1}{(1+\varepsilon\cos\xi)}\frac{1}{h_r} \right\rangle}{\left\langle \frac{1}{h_r} \right\rangle} - \frac{1}{V_{thj}}\frac{1}{\bar{n}_j e_j \bar{B}_\theta}\frac{\partial \bar{P}_j}{\partial r} \right]$$

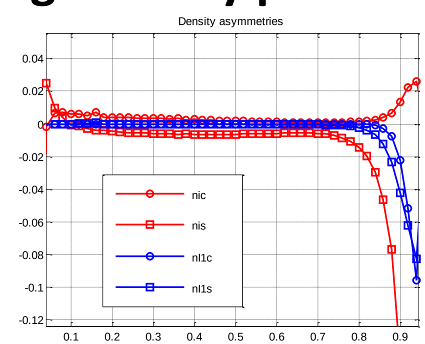
EXTENDED ROTATION THEORY

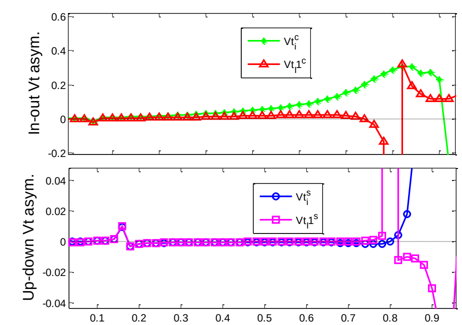
- Includes first-order poloidal perturbations (poloidal asymmetries) in density, velocity, and electrostatic potential
  - **Represented with the 1st order Fourier series**

$$\boxed{X_j(\rho,\phi) \approx \overline{X}_j(\rho)\left[1+\sum_{n=1}^{\infty}\left(\underbrace{X_j^{nc}(\rho)\cos(n\phi)}_{in-out\ asymmetry}+\underbrace{X_j^{ns}(\rho)\sin(n\phi)}_{up-down\ asymmetry}\right)\right]}$$



    - Sine function representing up-down asymmetry
    - Cosine function representing in-out asymmetry
  - **Calculated asymmetries with Miller geometry published in two papers**
    - Bae et al., Nuclear Fusion 2013
    - Bae et al., Phys of Plasmas, 2014
    - A draft under review





  - **Georgia Tech Fusion Research Center has recently developed a code to calculate rotations with 10th order perturbations for accuracy**
    - R. King, MS thesis, Georgia Institute of Technology, May 2019

EXTENDED ROTATION THEORY

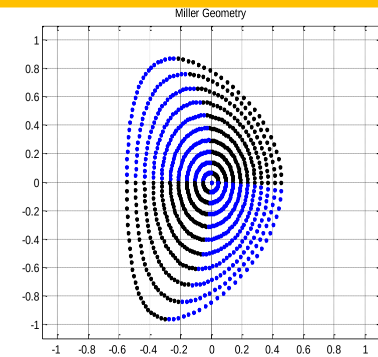
- ## Radial transport of all ion species calculated
  - **Er calculated self-consistently**

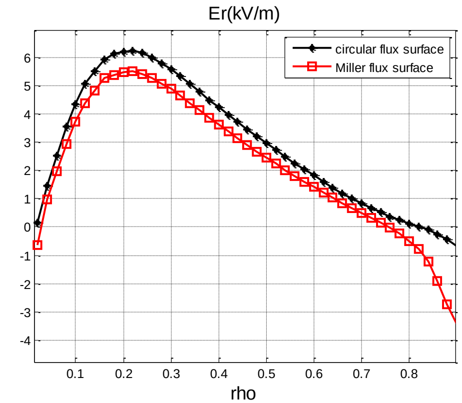
$$\bar{E}_r = -V_{thj}\bar{B}_\theta \left[V_{\theta j}\frac{\left\langle \frac{1}{1+\varepsilon\cos\xi}\right\rangle}{\left\langle \frac{1}{h_r}\right\rangle} - V_{\phi j}\left(1+\frac{\partial R_0(r)}{\partial r}\right)\frac{\left\langle \frac{1}{(1+\varepsilon\cos\xi)}\frac{1}{h_r}\right\rangle}{\left\langle\frac{1}{h_r}\right\rangle} - \frac{1}{V_{thj}}\frac{1}{\bar{n}_j e_j \bar{B}_\theta}\frac{\partial \bar{P}_j}{\partial r}\right]$$

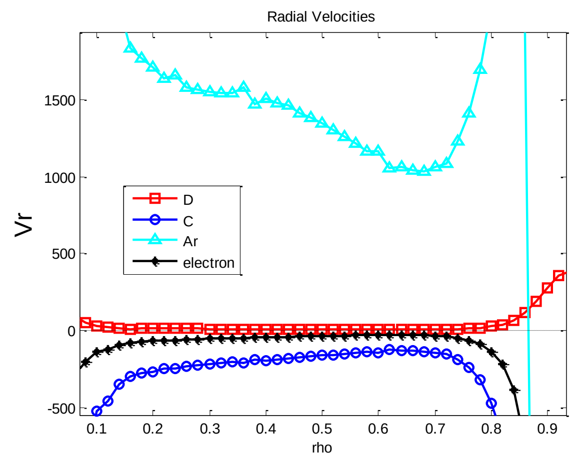
    - **Calculation with Miller flux surfaces published in 2014**
      - Bae et al., Phys of Plasmas, 2014
      - **Difference in Er with Circular vs. Miller model published**

$$\bar{E}_r^{cir} = \frac{1}{\bar{n}_j e_j}\frac{\partial \bar{P}_j}{\partial r} - \left[V_{\theta j}\bar{B}_\phi - V_{\phi j}\bar{B}_\theta\right]$$

  - **Recent investigations on Vr and Radial flux of all ion species**
    - calculated non-self-consistently
    - GTROTA updated to investigate these calculations
    - Collaboration with other researches based on radial diffusivity coefficients (later slides)







MAJOR DEVELOPMENTS

Future directions of ERT and GTROTA (mostly for edge rotation study)

Advises/ideas/recommendations welcomed!

MAJOR DEVELOPMENTS

Extension of ERT to Mikhailovskii-Tsypin's closure

- **Include Heat Equation**
- **Important for edge rotation/transport study**

- Viscosity evolution equation:

$$\boxed{-\Omega_a\left(\hat{b}\times\overleftrightarrow{\pi}_a-\overleftrightarrow{\pi}_a\times\hat{b}\right)=2p_a\overline{\nabla\vec{V}_a}+\frac{4}{5}\overline{\nabla\vec{h}_a}-\overleftrightarrow{C}_a^{20}+higher\ orders}$$

- Heat flow evolution equation:

$$\boxed{-\Omega_a\left(\hat{b}\times\vec{h}_a\right)=\frac{5}{2m_a}p_a\nabla T_a+\frac{1}{2}\vec{C}_a^{11}+higher\ orders}$$

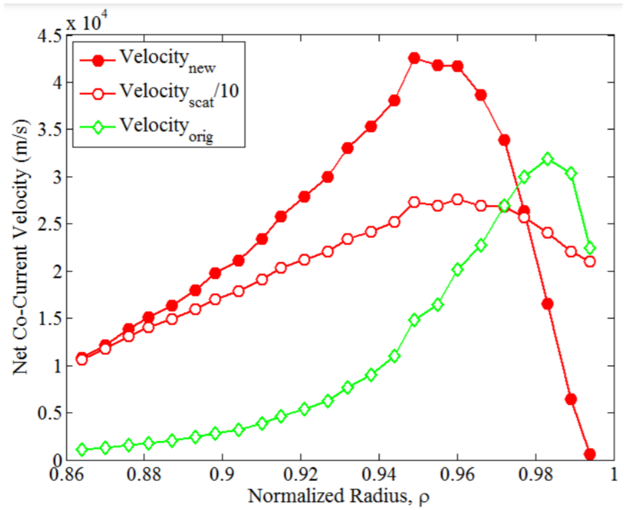
➢ **This development in progress (2016 - ongoing)**

- **1ST order Fourier expansion of temperature being applied**
- **This is next in line for the future development of ERT and GTROTA**
  - doable within a few years to finalize the numerical model and implement it in GTROTA

MAJOR DEVELOPMENTS

To add more edge physics including intrinsic rotation

- **Intrinsic co-current deuterium rotation due to Ion Orbit Loss (IOL)**
  - **Stacey, Phys of Plasmas 25, 122506 (2018)**
    - The predominant IOL of CTR-current ions leaves a predominantly CO-current edge intrinsic rotation



- **This effort shouldn't take long but will need to add other edge rotation mechanisms for higher accuracy**
  - Ideas/suggestions welcomed

MAJOR DEVELOPMENTS

- **Develop an NTV theory based on Stacey-Sigmar approach**
  - **By considering non-axisymmetry in the formalism**
    - **General non-axisymmetric formalism published:** Stacey and Bae, PoP (2015)

$$n_j m_j \left\langle \left[R\left(\vec{V}_j \bullet \nabla\right)\vec{V}_j \right]_\phi \right\rangle + \boxed{\left\langle \left[R\left(\nabla \bullet \overleftrightarrow{\pi}_j\right)\right]_\phi \right\rangle} = \left\langle R n_j e_j E_\phi^A \right\rangle + \left\langle R n_j e_j V_{rj} B_\theta \right\rangle + \left\langle R F_{\phi j} \right\rangle + \left\langle R M_{\phi j} \right\rangle - \left\langle R n_j m_j \nu_{atomj} V_{\phi j} \right\rangle$$

NTV Torque

$$\boxed{\left\langle R\left(\nabla \cdot \overleftrightarrow{\pi}\right)_\phi \right\rangle = \left\langle R^2 \nabla\phi \cdot \left(\nabla \cdot \overleftrightarrow{\pi}\right)\right\rangle = \left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}$$

$$\boxed{\eta_0 \gg \eta_{3,4} \gg \eta_{1,2}}$$
$\parallel \quad gv \quad \perp$

- Dedicated presentation slides in Appendix A

$$\left\langle R\left(\nabla \cdot \overleftrightarrow{\pi}\right)_\phi \right\rangle = \left\langle R^2 \nabla\phi \cdot \left(\nabla \cdot \overleftrightarrow{\pi}\right)\right\rangle = \underbrace{\overbrace{\left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi^0_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}^{\parallel} + \underbrace{\overbrace{\left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi^{34}_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}^{gv} + \overbrace{\cancel{\left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi^{12}_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}}^{\perp}}_{axisymmetric}}_{non-axisymmetric}$$

$$\boxed{\pi^0_{\psi\phi} = -\eta_0 W^0_{\psi\phi}} \qquad W^0_{\psi\phi} = \frac{3}{2} f_\psi f_p H^0 \qquad \boxed{f_\psi \equiv \frac{B_\psi}{B}, \quad f_p \equiv \frac{B_p}{B}, \quad f_\phi \equiv \frac{B_\phi}{B}}$$

MAJOR DEVELOPMENTS

- **Develop an NTV theory based on Stacey-Sigmar approach**
  - **Next step is to develop a numerical model for GTROTA**

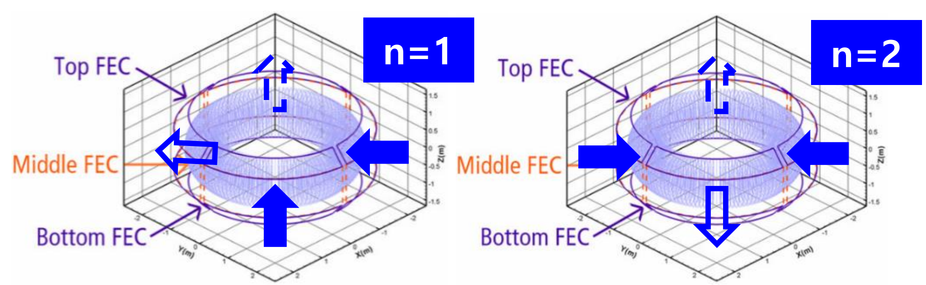
$$\boxed{\pi_{\psi\phi}^{0} = -\eta_0 W_{\psi\phi}^{0}} \qquad W_{\psi\phi}^{0} = \frac{3}{2} f_{\psi} f_{p} H^{0} \qquad \boxed{f_{\psi} \equiv \frac{B_{\psi}}{B},\quad f_{p} \equiv \frac{B_{p}}{B},\quad f_{\phi} \equiv \frac{B_{\phi}}{B}}$$

  - **Question is on how to best represent magnetic perturbations**
    - **Up to the 4th order Fourier series being considered but still contemplating**
    - **Ideas being formulated from my experimental experiences at KSTAR**
      - as a team member for the ELM suppression investigation using RMP coils at KSTAR
        - Publication: Jayhyun Kim et al., Nucl. Fusion 57, 022001 (2017)

$$\boxed{\vec{B}_{\text{total}} = \vec{B}_{\text{eq}} + \cancel{\vec{B}_{\text{int}}} + \vec{B}_{\text{RMP}} + \vec{B}_{\text{plasma response}}}$$

n=2 (mid) + n=1 (top/bot)

Port	L	P	D	H	
ϕ	0°	90°	180°	270°	
Top	+	-	-	+	Proxy (n=1 NA field)
Mid	+	-	+	-	Reference (n=2 NA field)
Bot	+	+	-	-	Proxy (n=1 NA field)



MAJOR DEVELOPMENTS

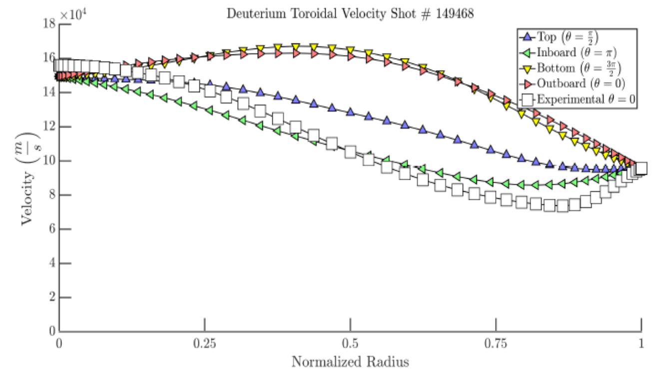
Investigate the converging order of poloidal asymmetries

- **Georgia Tech Fusion Research Center has calculated rotations with poloidal asymmetries up to 10th order**
  - Publication: R. King, MS thesis, Georgia Institute of Technology

$$n = n_0 + \sum \sum a_{ij} J_i(\lambda_{ij}\rho)\cos(j\theta) + b_{ij} J_i(\lambda_{ij}\rho)\sin(j\theta)$$

$$v_t = v_{t0} + \sum \sum a_{ij} J_i(\lambda_{ij}\rho)\cos(j\theta) + b_{ij} J_i(\lambda_{ij}\rho)\sin(j\theta)$$

$$\phi = \phi_0 + \sum \sum a_{ij} J_i(\lambda_{ij}\rho)\cos(j\theta) + b_{ij} J_i(\lambda_{ij}\rho)\sin(j\theta)$$



- **A separate set of codes written with Mathematica and Fortran**
  - Could be a verification opportunity on which order is accurate enough
  - This investigation of the appropriate converging order may take long
- **Two track development approaches with GTROTA**
  - **Accuracy version** (with higher order poloidal asymmetries)
  - **Plasma control version** (for near-real-time calculations of all species)
    - This will have to be collaboration with PCS developers

Ongoing Researches

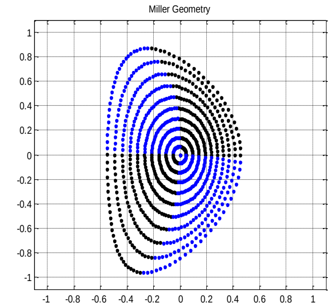
- Publication plans
- Researches under investigation/collaboration

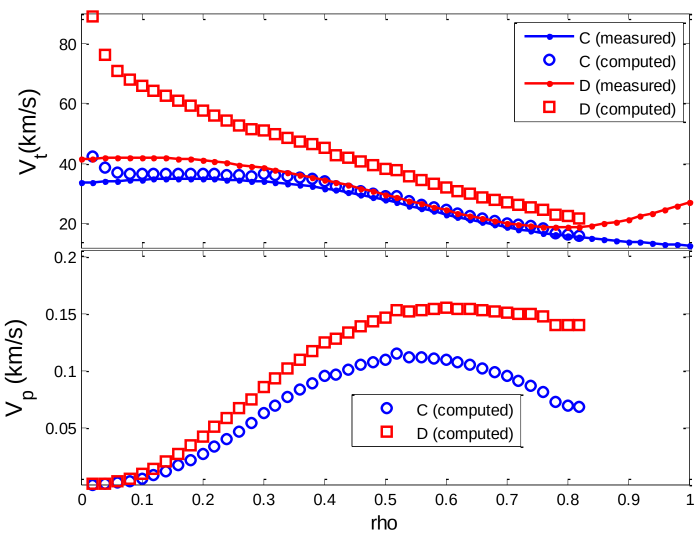
❖ Please note that any research topics discussed in this talk can be considered as collaboration opportunities for others.

Publication Plans

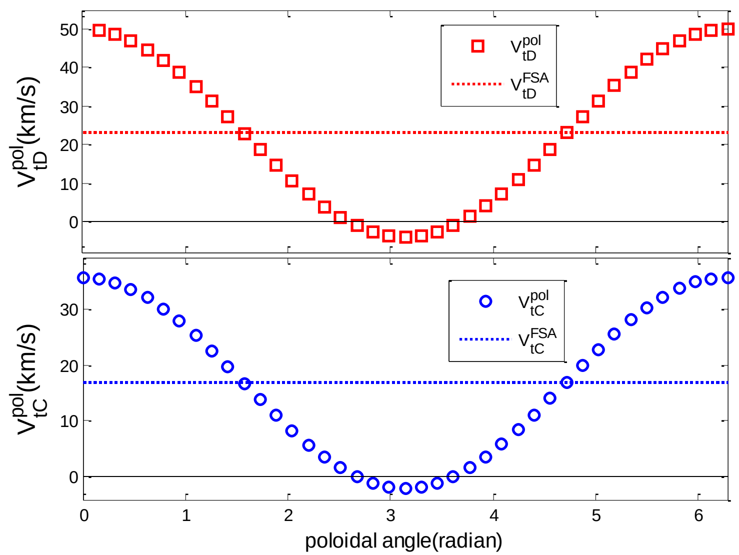
▪ Theory verification with DIII-D deuterium velocity measurements in L-mode (2013-2015)

- **First test opportunity of the theory against deuterium measurements**
  - Deuterium measurement became available from Dr. Brian Grierson
  - Below: DIII-D 145180 (1220ms)
- **Interesting findings on poloidal variation of toroidal velocities**
  - Similar experimental findings with ECEI rotation images analyzed by G.S. Yoon at POSTECH





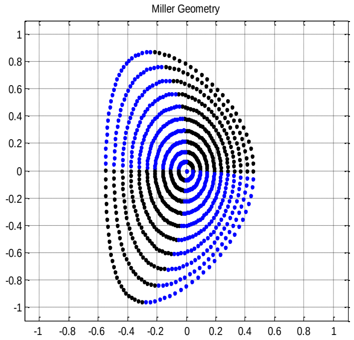
Toroidal velocities (D and C)

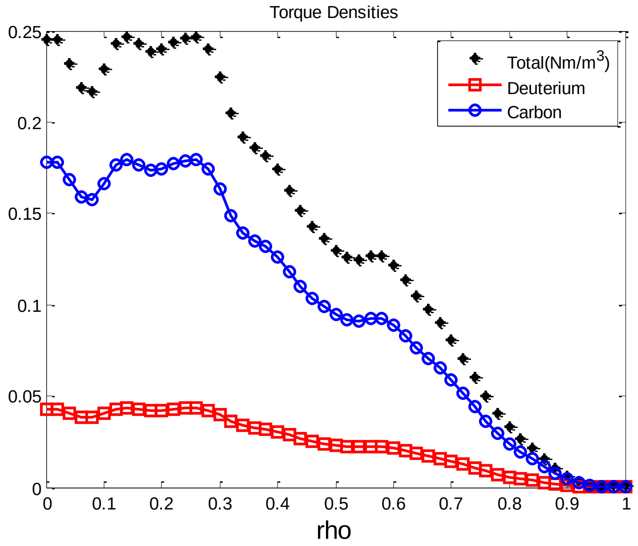


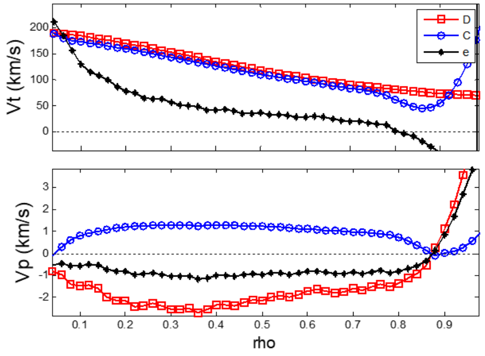
Toroidal velocity asymmetries (D and C) at rho=0.8

Publication Plans

- **EAST and KSTAR H- and L-mode shot analyses (2015-2017)**
  - **Goal was to analyze more L-mode shots and upgrade GTROTA capability to calculate rotations with RF heatings**
    - EAST shots with LHCD and ICRF shots
    - KSTAR L-mode shots
  - **Analyses finalized**
    - Need to extend GTROTA features to add HFS-LFS plotting option
    - Planning to publish with new features available in GTROTA







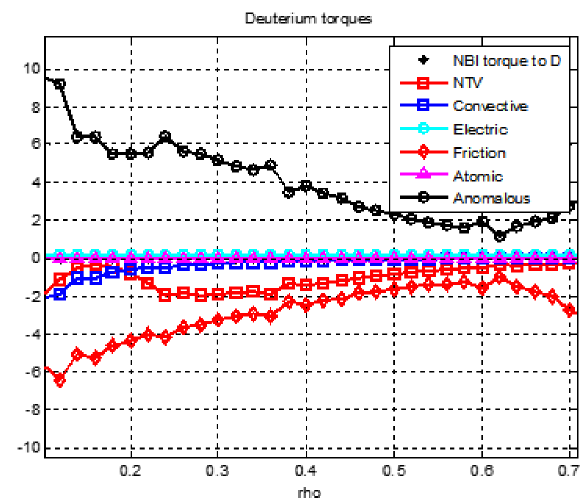
Publication Plans

- **Theoretical investigation of Gyroviscous cancellation validity in Tokama plasmas (2014-2015)**
  - **The well-known gyroviscous cancellation in sheared slab geometry** [Plasma Physics **4**, 1766 (1992)] **has been investigated**
    - **using a systematic perturbative method**
    - **based on the Mikhailovskii-Tsypin's closure relation**
    - **on the large gyrofrequency ordering for flowing plasmas**
  - $O(\delta^1)$ **1st order surviving terms (in colors):**

$$\partial_t \vec{V}_{0\|} + \vec{V}'_{d(1)} \cdot \nabla \vec{V}_{(0)\|} + V_{(0)} \cdot \nabla \vec{V}_{(1)\|} + \frac{1}{m_a n_0} \nabla_\| p_0 = -\Omega_a \left(\hat{b} \times \vec{V}_1 \right)_\| + \frac{q_a}{m_a} \vec{E}_{0\|} + \frac{1}{m_a n_0} \vec{C}^{10}_{0\|}$$

➢ **These are the surviving terms at one order lower than investigated by Chang and Callen** [Plasma Physics **4**, 1766 (1992)]

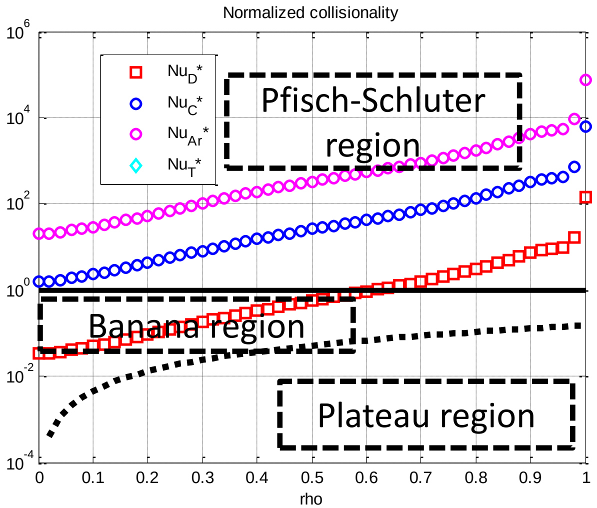
- Submitted for publication but withdrawn for numerical verifications
- Presented at conferences

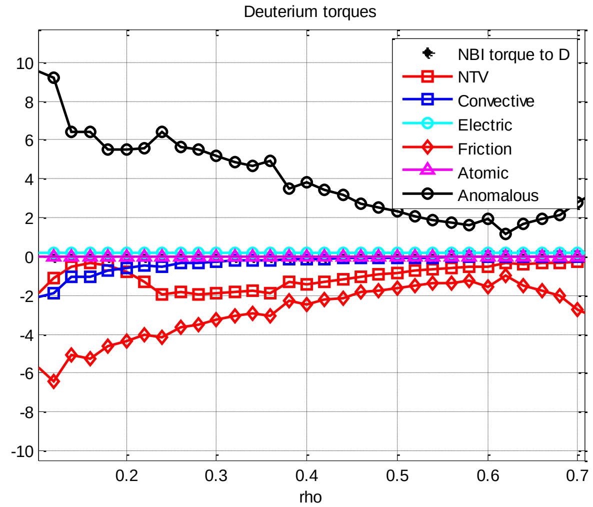


Researches under Investigation/Collaboration

▪ Collisionality effects on rotation and transport

- **Motivated by too many assumptions applied in plasma researches**
  - ERT retains all terms in the MBE (both toroidal and poloidal coordinates)
- **This research is to holistically understand collisionality effects**
  - **within a discharge:** collisionality regimes change and differ for different species
  - **among different discharges:** Different discharges have different regime distributions
- **Q: Can I investigate collisionality effects on various shots and find any consistency on rotation/transport?**
  - Will require analyses of many discharges to answer this question





Researches under Investigation/Collaboration

Collisionality effects on rotation and transport

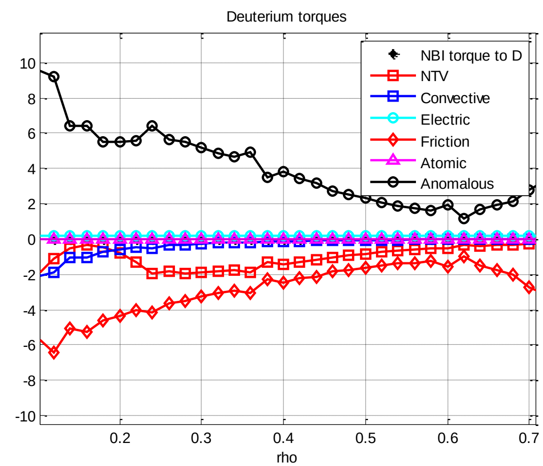
- **However, I can provide my rotation/transport calculations to others so that they can identify right assumptions based on the collisionality and apply appropriate theories**
- Calculations in toroidal angular torques are available in GTROTA

Accelerational Convective Pressure Viscous

$$\left\langle R m_a n_a \frac{\partial V_{a\phi}}{\partial t} \right\rangle + \left\langle R n_a m_a \left(\vec{V}_a \cdot \nabla\right) V_{a\phi} \right\rangle + \left\langle R \frac{1}{h_\phi} \frac{\partial p_a}{\partial \phi} \right\rangle + \left\langle R \left(\nabla \cdot \overleftrightarrow{\pi}_a\right)_\phi \right\rangle =$$

$$\left\langle R n_a e_a \left(-\frac{1}{h_\phi} \frac{\partial \Phi}{\partial \phi} - \frac{\partial A_\phi}{\partial t} \right) \right\rangle + \left\langle R n_a e_a \left(V_{a\psi} B_p - V_{ap} B_\psi \right) \right\rangle + \left\langle R F^1_{a\phi} \right\rangle + \left\langle R S^1_{a\phi} \right\rangle + \underbrace{\left(-\left\langle R m_a V_{a\phi} S^0_a \right\rangle \right)}_{-\left\langle R n_j m_j \nu_{atomj} V_{\phi j} \right\rangle}$$

Electric V cross B Frictional External Atomic



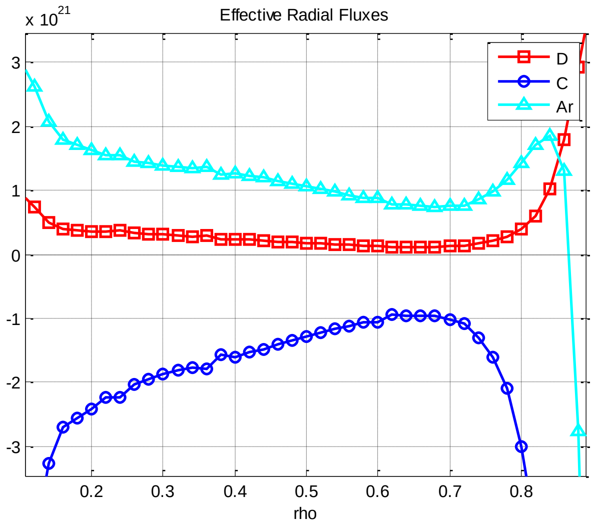
- Plan to do the same code upgrade for poloidal torque balance in the future

$$\left\langle r n_j m_j \left(\vec{V}_j \bullet \nabla\right) \vec{V}_{j\theta} \right\rangle + \left\langle \frac{r}{h_\theta} \frac{\partial p_j}{\partial \theta} \right\rangle + \left\langle r \left(\nabla \bullet \overleftrightarrow{\pi}_j\right)_\theta \right\rangle = \left\langle r F_{\theta j} \right\rangle + \left\langle r n_j e_j E_\theta \right\rangle - \left\langle r n_j e_j V_{rj} B_\phi \right\rangle + \left\langle r S^1_{\theta j} \right\rangle - \left\langle r m_j V_{\theta j} S_j^{\,0} \right\rangle$$

Researches under Investigation/Collaboration

- **A coupled study of ion species rotation and transport**
  - **Motivation is to compare radial transport (Vr and flux) calculations from GTROTA to other calculations based on diffusivity coefficients**
  - **Collaboration with KAIST team on Ar transport study (2015 – 2017)**
    - with density gradient: introduces "Diffusion coefficient (D)"
    - with convective effect: introduces "Convective coefficient (V)"

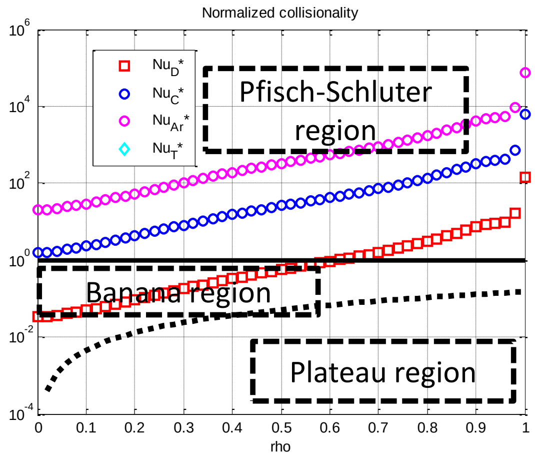
$$\frac{\partial n_a}{\partial t} + \nabla \cdot \underbrace{\left(n_a \vec{V}_a \right)}_{\mathrm{D} fn(n_a) + \mathrm{V} fn\left(\vec{V}_a\right)} = S_a^0$$

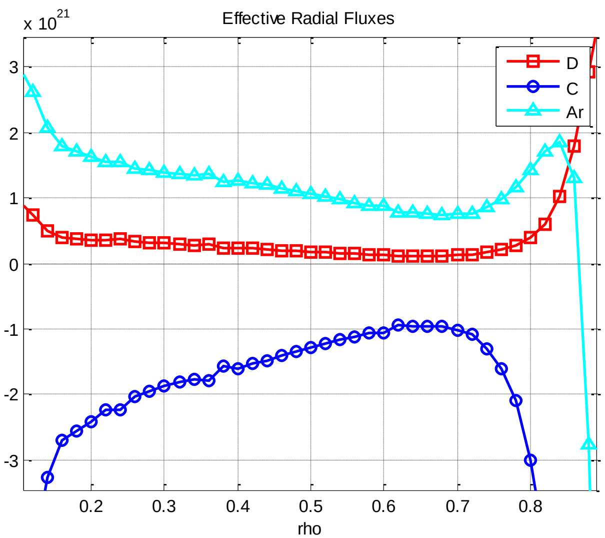


    - KSTAR experiments with Ar injection
    - Analyses delayed due to the temperature measurement accuracy
  - **A dedicated conference slides in Appendix B**

Researches under Investigation/Collaboration

- **A coupled study of ion species rotation and transport**
  - **Motivation: to understand heavy ion (W, Ar, or Ne) transport**
  - **Findings**
    - **Toroidal torque balance different for different ion species**
    - **Radial fluxes of different ion species can be opposite**
      - Probably due to different collisionality regime distributions





- **This research effort is in preliminary stage and need some guidance**
  - **A dedicated talk slides in Appendix B**

CONCLUSIONS

- Theoretical improvement of ERT for the edge rotation study will continue
- Computational code development will continue
- Publications to follow to report the progress and findings to the plasma physics community
- Any questions or collaboration discussions can be emailed to my permanent email below
  - yuri157@gmail.com

- **Thank you for your attention!**
- **Questions and Answers**

Thank you for your attention!

my permanent contact: yuri157@gmail.com

APPENDIX A:
GENERALIZED VISCOUS EFFECTS FOR NON-AXISYMMETRIC TOKAMAK PLASMAS

Cheonho Bae
cbae@nfri.re.kr

National Fusion Research Institute, Daejeon, South Korea

January 2017

KSTAR conference, Muju resort, South Korea

Contents

1. NEOCLASSICAL VISCOUS TORQUES
2. WHERE AM I TODAY?
3. WHERE AM I GOING NEXT?
4. WHAT CAN THIS WORK DO FOR US?
5. QUESTIONS/DISCUSSIONS

NEOCLASSICAL VISCOUS TORQUES

- **Viscous forces in tokamak coordinates**
  - **Toroidal and poloidal momentum balance equations**

$$n_j m_j \left(\vec{V}_j \bullet \nabla\right)\vec{V}_{j\phi} + \left(\nabla \bullet \overleftrightarrow{\pi}_j\right)_\phi = n_j e_j E_\phi^A + n_j e_j V_{rj} B_\theta + F_{\phi j} + M_{\phi j} - n_j m_j \nu_{atomj} V_{\phi j}$$

$$n_j m_j \left(\vec{V}_j \bullet \nabla\right)\vec{V}_{j\theta} + \frac{1}{h_\theta}\frac{\partial p_j}{\partial \theta} + \left(\nabla \bullet \overleftrightarrow{\pi}_j\right)_\theta = F_{\theta j} + n_j e_j E_\theta - n_j e_j V_{rj} B_\phi + S_{\theta j}^1 - m_j V_{\theta j} S_j^{\,0}$$

  - **Viscosity evolution equation**

$$-\Omega_a\left(\overleftrightarrow{\pi}_a \times \hat{b} - \hat{b} \times \overleftrightarrow{\pi}_a\right) = \underbrace{\overbrace{2p_a \overline{\nabla \vec{V}_a}}^{Braginskii} + \frac{4}{5}\overline{\nabla \vec{q}_a}}_{Mikhailovski-Tsypin} + \cancel{\partial_t \overleftrightarrow{\pi}_a + \left(\vec{V}_a \cdot \nabla \overleftrightarrow{\pi}_a + \nabla \cdot \vec{V}_a \overleftrightarrow{\pi}_a\right) + 2\overline{\overleftrightarrow{\pi}_a \cdot \nabla \vec{V}_a} + \nabla \cdot \overleftrightarrow{\sigma}_a - \overleftrightarrow{C}_a^{20}}$$

  - **Braginskii's viscosity representation**

$$\overleftrightarrow{\pi}_{\alpha\beta} = \underbrace{\left(-\eta_0 W_{\alpha\beta}^0\right)}_{\pi_{\alpha\beta}^0} + \underbrace{\left(\eta_3 W_{\alpha\beta}^3 + \eta_4 W_{\alpha\beta}^4\right)}_{\pi_{\alpha\beta}^{34}} \cancel{\underbrace{-\left(\eta_1 W_{\alpha\beta}^1 + \eta_2 W_{\alpha\beta}^2\right)}_{\pi_{\alpha\beta}^{12}}} = \underbrace{\pi_{\alpha\beta}^0}_{\parallel\, viscosity} + \underbrace{\pi_{\alpha\beta}^{34}}_{gyroviscosity} + \cancel{\underbrace{\pi_{\alpha\beta}^{12}}_{\perp\, viscosity}}$$

where

$$\underbrace{\eta_0 = 0.96 nT\tau}_{\parallel} >> \underbrace{\eta_3 = \frac{1}{2}\frac{nT}{\Omega},\ \eta_4 = 2\eta_3}_{gv} >> \underbrace{\eta_1 = \frac{3}{10}\frac{nT}{\Omega^2\tau},\ \eta_2 = 4\eta_1}_{\perp} \Rightarrow \left(\underset{\parallel}{\eta_0} >> \underset{gv}{\eta_{3,4}} >> \underset{\perp}{\eta_{1,2}}\right)$$

- **What do I mean by "Generalized Viscous Effects"?**
  - **Neoclassical Toroidal Viscous (NTV) torque**

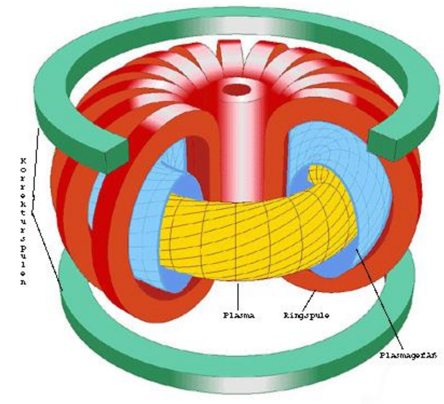
NTV Torque

$$n_j m_j R\left(\vec{V}_j \bullet \nabla\right)\vec{V}_{j\phi} + \boxed{R\left(\nabla \bullet \overleftrightarrow{\pi}_j\right)_\phi} = R n_j e_j E_\phi^A + R n_j e_j V_{rj} B_\theta + R F_{\phi j} + R M_{\phi j} - R n_j m_j \nu_{atomj} V_{\phi j}$$

$$\boxed{R^2 \nabla\phi \cdot \left(\nabla \cdot \overleftrightarrow{\pi}\right) = \frac{1}{R h_p}\frac{\partial\left(R^2 h_p \pi_{\psi\phi}\right)}{\partial l_\psi} + B_p \frac{\partial}{\partial l_p}\left(\frac{R\pi_{p\phi}}{B_p}\right) + \frac{\partial \pi_{\phi\phi}}{\partial l_\phi}}$$

take Flux Surface Average

$$\boxed{\left\langle R^2 \nabla\phi \cdot \left(\nabla \cdot \overleftrightarrow{\pi}\right)\right\rangle = \left\langle \frac{1}{R h_p}\frac{\partial\left(R^2 h_p \pi_{\psi\phi}\right)}{\partial l_\psi}\right\rangle + \cancel{\left\langle B_p \frac{\partial}{\partial l_p}\left(\frac{R\pi_{p\phi}}{B_p}\right)\right\rangle} + \cancel{\left\langle \frac{\partial \pi_{\phi\phi}}{\partial l_\phi}\right\rangle}}$$



  - **Neoclassical Poloidal Viscous (NPV) torque**

NPV Torque

$$r n_j m_j \left(\vec{V}_j \bullet \nabla\right)\vec{V}_{j\theta} + \frac{r}{h_\theta}\frac{\partial p_j}{\partial \theta} + \boxed{r\left(\nabla \bullet \overleftrightarrow{\pi}_j\right)_\theta} = r F_{\theta j} + r n_j e_j E_\theta - r n_j e_j V_{rj} B_\phi + r S_{\theta j}^1 - r m_j V_{\theta j} S_j^0$$

$$\boxed{\left(\nabla \cdot \overleftrightarrow{\pi}\right)_p = \sum_{j=\psi,p,\phi}\left[\frac{1}{h_\psi h_p h_\phi}\frac{\partial}{\partial j}\left(\frac{\left(h_\psi h_p h_\phi\right)\pi_{jp}}{h_j}\right) + \sum_{k=\psi,p,\phi}\Gamma_{pk}^j \pi_{jk}\right]}$$

  - **Generalized viscous effects**
    - **Work out NTV and NPV torques in non-axisymmetric plasmas**

Flux Surface Averaged NTV torque in non-axisymmetric plasmas

NTV Torque

$$n_j m_j \left\langle \left[R\left(\vec{V}_j \bullet \nabla\right)\vec{V}_j \right]_\phi \right\rangle + \boxed{\left\langle \left[R\left(\nabla \bullet \overleftrightarrow{\pi}_j\right)\right]_\phi \right\rangle} = \left\langle R n_j e_j E_\phi^A \right\rangle + \left\langle R n_j e_j V_{rj} B_\theta \right\rangle + \left\langle R F_{\phi j} \right\rangle + \left\langle R M_{\phi j} \right\rangle - \left\langle R n_j m_j \nu_{atomj} V_{\phi j} \right\rangle$$

$$\boxed{\left\langle R^2 \nabla\phi \cdot \left(\nabla \cdot \overleftrightarrow{\pi}\right)\right\rangle = \left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}$$

$$\boxed{\underset{\parallel}{\eta_0} \gg \underset{gv}{\eta_{3,4}} \gg \underset{\perp}{\eta_{1,2}}}$$

$$\boxed{\left\langle R^2 \nabla\phi \cdot \left(\nabla \cdot \overleftrightarrow{\pi}\right)\right\rangle = \underbrace{\overbrace{\left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi^0_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}^{\parallel} + \underbrace{\overbrace{\left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi^{34}_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}^{gv} + \cancel{\overbrace{\left\langle \frac{1}{Rh_p} \frac{\partial\left(R^2 h_p \pi^{12}_{\psi\phi}\right)}{\partial l_\psi} \right\rangle}^{\perp}}}_{axisymmetric}}_{non-axisymmetric}}$$

$$\pi_{\psi\phi} \approx \pi^0_{\psi\phi} + \pi^{34}_{\psi\phi} = -\eta_0 W^0_{\psi\phi} + \eta_4\left(\frac{1}{2}W^3_{\psi\phi} + W^4_{\psi\phi}\right) - \cancel{\eta_2\left(\frac{1}{4}W^1_{\psi\phi} + W^2_{\psi\phi}\right)}$$

$$W^0_{\psi\phi} = \frac{3}{2} f_\psi f_p H^0$$

$$\boxed{f_\psi \equiv \frac{B_\psi}{B}, \quad f_p \equiv \frac{B_p}{B}, \quad f_\phi \equiv \frac{B_\phi}{B}}$$

$$H^0 = \sum_{\mu,\nu}\left(f_\mu f_\nu - \frac{1}{3}\delta_{\mu\nu}\right) W_{\mu\nu}$$

$$W_{\mu\nu} = \underbrace{\overbrace{\left(\overrightarrow{\nabla \vec{V}}\right)_{\mu\nu}}^{Braginskii} + \left(\frac{2}{5p}\overrightarrow{\nabla \vec{q}}\right)_{\mu\nu}}_{Mikhailovskiii-Tsypin}$$

- Details in Stacey and Bae, PoP (2015)]

WHERE AM I TODAY?

- **Axisymmetric NTV and NPV torques calculated in GTROTA**
  - **NTV represented with gyroviscosity / Braginskii's closure**

$$\left\langle R^2\nabla\phi\cdot\left(\nabla\cdot\overleftrightarrow{\pi}\right)\right\rangle = \underbrace{\overbrace{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{0}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}^{\parallel} + \underbrace{\overbrace{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{34}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}^{gv} + \cancel{\overbrace{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{12}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}^{\perp}}}_{axisymmetric}}_{non\text{–}axisymmetric}$$

$$W_{\mu\nu} = \underbrace{\overbrace{\left(\overline{\nabla\vec{V}}\right)_{\mu\nu}}^{Braginskii} + \left(\frac{2}{5p}\overline{\nabla\vec{q}}\right)_{\mu\nu}}_{valid\ \ for\ high\ collisionality}$$

❖ **Two neoclassical codes that handle gyroviscosity: GTROTA / NEO**

  - **GTROTA based on collisionality-extended Braginskii's viscosity**
    - Parallel viscosity coefficient extended to low collisionality (trapped particle effect) by Shaing

$$\underbrace{\overbrace{\eta_0 = 0.96nT\tau}^{collisionality\ dependent}}_{\parallel}, \quad \underbrace{\overbrace{\eta_3 = \frac{1}{2}\frac{nT}{\Omega},\ \eta_4 = 2\eta_3}^{independent\ of\ collisionality}}_{gv}, \quad \cancel{\underbrace{\overbrace{\eta_1 = \frac{3}{10}\frac{nT}{\Omega^2\tau},\ \eta_2 = 4\eta_1}^{collisionality\ dependent\ (but\ small\ contribution)}}_{\perp}}, \quad \Rightarrow \left(\underbrace{\eta_0}_{\parallel} \gg \underbrace{\eta_{3,4}}_{gv} \gg \underbrace{\eta_{1,2}}_{\perp}\right)$$

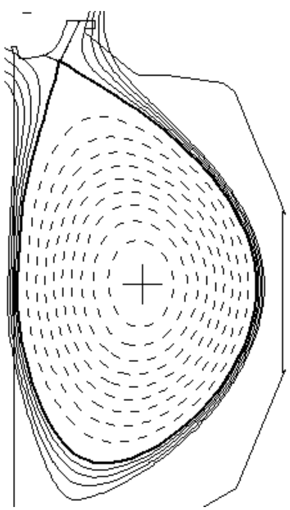
- Shaing-banana plateau-PS:
$$\eta_{0j} = \frac{n_jm_jV_{thj}qR_0\varepsilon^{-3/2}\nu^*_{jj}}{\left(1+\varepsilon^{-3/2}\nu^*_{jj}\right)\left(1+\nu^*_{jj}\right)} \equiv n_jm_jV_{thj}qRf_j$$

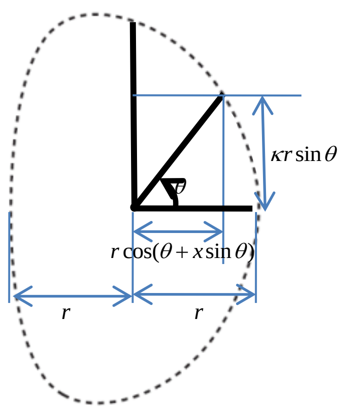
-> **valid for arbitrary collisionality**

- **GTROTA considers first-order poloidal asymmetries in density, velocity, and electrostatic potential**
  - **Rotation calculations with KSTAR #5505-2500ms (H-mode with NBI)**
    [Bae et al., PoP 21, 012504(2014)]
  - **No non-axisymmetric magnetic perturbation in this shot**

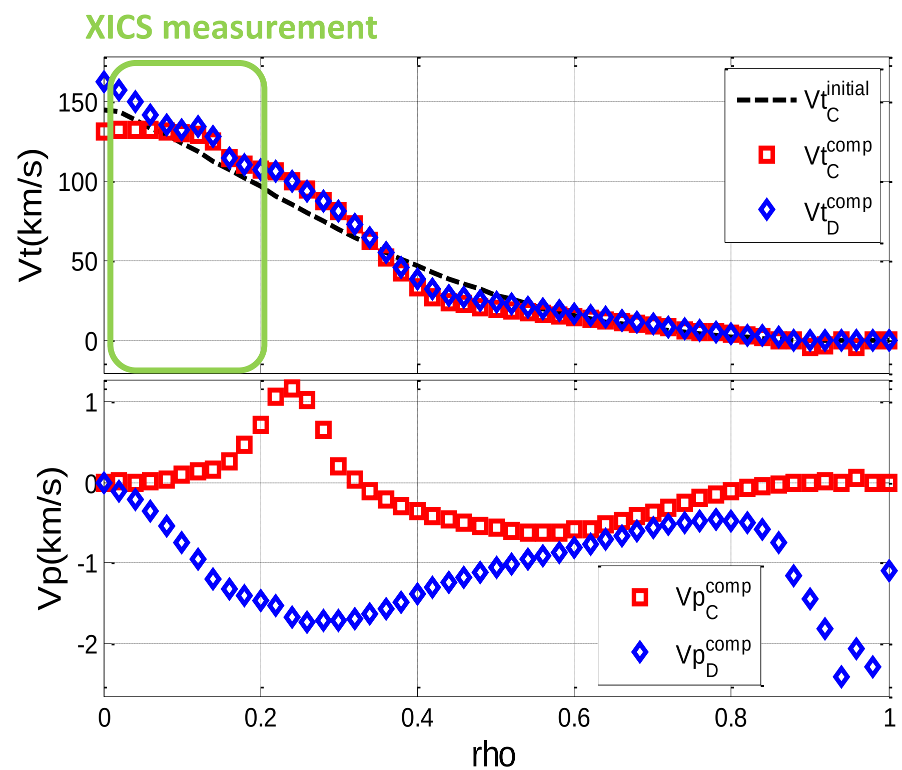
$$\left\langle R^2\nabla\phi\cdot\left(\nabla\cdot\overleftrightarrow{\pi}\right)\right\rangle = \underbrace{\overset{\parallel}{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^0_{\psi\phi}\right)}{\partial l_\psi}\right\rangle} + \underbrace{\overset{gv}{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{34}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}}_{axisymmetric} + \overset{\perp}{\cancel{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{12}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}}}_{non-axisymmetric}$$

$$\pi_{\psi\phi} \approx \pi^0_{\psi\phi} + \pi^{34}_{\psi\phi} = -\eta_0\cancel{W^0_{\psi\phi}} + \eta_4\left(\frac{1}{2}W^3_{\psi\phi} + W^4_{\psi\phi}\right) - \cancel{\eta_2\left(\frac{1}{4}W^1_{\psi\phi} + W^2_{\psi\phi}\right)}$$





Miller Model



WHERE AM I GOING NEXT?

- Generalize to non-axisymmetric NTV and NPV torques
  - Theoretical study published [Stacey and Bae, PoP 2015]
  - Theoretical model development for GTROTA in progress
  - Extend to Mikhailovskii-Tsypin's closure
    - need Heat Flux Density Evolution Equation

$$\left\langle R^2\nabla\phi\cdot\left(\nabla\cdot\overleftrightarrow{\pi}\right)\right\rangle = \underbrace{\overbrace{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^0_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}^{\parallel} + \underbrace{\overbrace{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{34}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}^{gv} + \cancel{\overbrace{\left\langle \frac{1}{Rh_p}\frac{\partial\left(R^2h_p\pi^{12}_{\psi\phi}\right)}{\partial l_\psi}\right\rangle}^{\perp}}}_{axisymmetric}}_{non-axisymmetric}$$

$$W_{\mu\nu} = \overbrace{\left(\overrightarrow{\nabla\vec{V}}\right)_{\mu\nu}}^{Braginskii} + \left(\frac{2}{5p}\overrightarrow{\nabla\vec{q}}\right)_{\mu\nu}$$

$$\pi_{\psi\phi} \approx \pi^0_{\psi\phi} + \pi^{34}_{\psi\phi} = -\eta_0 W^0_{\psi\phi} + \eta_4\left(\frac{1}{2}W^3_{\psi\phi} + W^4_{\psi\phi}\right) \cancel{- \eta_2\left(\frac{1}{4}W^1_{\psi\phi} + W^2_{\psi\phi}\right)}$$

$$-\Omega_a\left(\hat{b}\times\vec{q}_a\right) = \frac{5}{2m_a}p_a\nabla T_a + \frac{1}{2}\vec{C}^{11}_a + O\left(higher\right)$$

$$W^0_{\psi\phi} = \frac{3}{2}f_\psi f_p H^0$$

$$H^0 \equiv \left[\begin{array}{l}
\left(f_\psi f_\psi - \frac{1}{3}\right)\left\{\frac{4}{3}\frac{\partial V_\psi}{\partial l_\psi} - \frac{2}{3}\left(\frac{\partial V_p}{\partial l_p} + \frac{\partial V_\phi}{\partial l_\phi}\right) + 2\left(\frac{1}{h_\psi}\frac{\partial h_\psi}{\partial l_p}V_p + \frac{1}{h_\psi}\frac{\partial h_\psi}{\partial l_\phi}V_\phi\right)\right\} + \\
\left(f_p f_p - \frac{1}{3}\right)\left\{\frac{4}{3}\frac{\partial V_p}{\partial l_p} - \frac{2}{3}\left(\frac{\partial V_\psi}{\partial l_\psi} + \frac{\partial V_\phi}{\partial l_\phi}\right) + 2\left(\frac{1}{h_p}\frac{\partial h_p}{\partial l_\psi}V_\psi + \frac{1}{h_p}\frac{\partial h_p}{\partial l_\phi}V_\phi\right)\right\} + \\
\left(f_\phi f_\phi - \frac{1}{3}\right)\left\{\frac{4}{3}\frac{\partial V_\phi}{\partial l_\phi} - \frac{2}{3}\left(\frac{\partial V_p}{\partial l_p} + \frac{\partial V_\psi}{\partial l_\psi}\right) + 2\left(\frac{1}{h_\phi}\frac{\partial h_\phi}{\partial l_\psi}V_\psi + \frac{1}{h_\phi}\frac{\partial h_\phi}{\partial l_p}V_p\right)\right\} + \\
2f_\psi f_p\left\{\frac{\partial V_\psi}{\partial l_p} + \frac{\partial V_p}{\partial l_\psi} - \left(\frac{1}{h_p}\frac{\partial h_p}{\partial l_\psi}V_p + \frac{1}{h_\psi}\frac{\partial h_\psi}{\partial l_p}V_\psi\right)\right\} + \\
2f_p f_\phi\left\{\frac{\partial V_\phi}{\partial l_p} + \frac{\partial V_p}{\partial l_\phi} - \left(\frac{1}{h_p}\frac{\partial h_p}{\partial l_\phi}V_p + \frac{1}{h_\phi}\frac{\partial h_\phi}{\partial l_p}V_\phi\right)\right\} + \\
2f_\psi f_\phi\left\{\frac{\partial V_\phi}{\partial l_\psi} + \frac{\partial V_\psi}{\partial l_\phi} - \left(\frac{1}{h_\psi}\frac{\partial h_\psi}{\partial l_\phi}V_\psi + \frac{1}{h_\phi}\frac{\partial h_\phi}{\partial l_\psi}V_\phi\right)\right\}
\end{array}\right]$$

WHAT CAN THIS WORK DO FOR US?

- **Rotation and transport predictions of deuterium for non-axisymmetric plasmas**
  - Generalized viscous contribution to rotation and transport

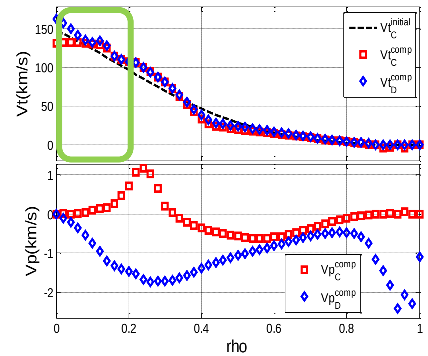
$$\left\langle n_j m_j \left[R\left(\vec{V}_j \cdot \nabla\right)\vec{V}_j \right]_\phi \right\rangle + \boxed{\left\langle \left[R\left(\nabla \cdot \overleftrightarrow{\pi}_j\right) \right]_\phi \right\rangle} = \left\langle R n_j e_j E_\phi^A \right\rangle + \left\langle R n_j e_j V_{rj} B_\theta \right\rangle + \left\langle RF_{\phi j} \right\rangle + \left\langle RM_{\phi j} \right\rangle - \left\langle R n_j m_j \nu_{atomj} V_{\phi j} \right\rangle$$

$$\left\langle r n_j m_j \left(\vec{V}_j \cdot \nabla\right)\vec{V}_{j\theta} \right\rangle + \left\langle \frac{r}{h_\theta}\frac{\partial p_j}{\partial \theta} \right\rangle + \boxed{\left\langle r\left(\nabla \cdot \overleftrightarrow{\pi}_j\right)_\theta \right\rangle} = \left\langle rF_{\theta j} \right\rangle + \left\langle r n_j e_j E_\theta \right\rangle - \left\langle r n_j e_j V_{rj} B_\phi \right\rangle + \left\langle r S_{\theta j}^1 \right\rangle - \left\langle r m_j V_{\theta j} S_j^0 \right\rangle$$

$\boxed{\vec{\Gamma}_j = n_j \vec{V}_j}$ $\boxed{\overleftrightarrow{M}_j}$ $\boxed{\vec{q}_j}$

KSTAR #5505

XICS measurement



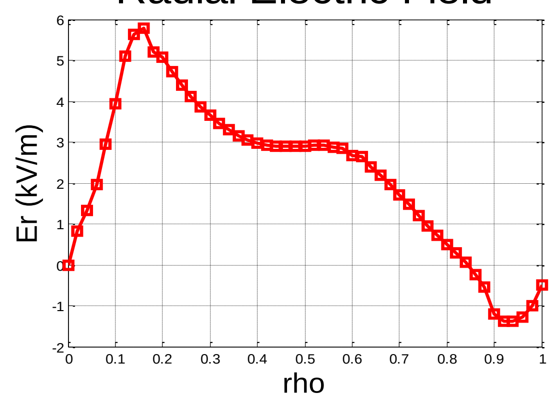
  - Increase accuracy in Er calculation

$$\bar{E}_r = -V_{thj}\bar{B}_\theta \left[V_{\theta j}\frac{\left\langle \frac{1}{1+\varepsilon\cos\xi} \right\rangle}{\left\langle \frac{1}{h_r} \right\rangle} - V_{\phi j}\left(1+\frac{\partial R_0(r)}{\partial r}\right)\frac{\left\langle \frac{1}{(1+\varepsilon\cos\xi)}\frac{1}{h_r} \right\rangle}{\left\langle \frac{1}{h_r} \right\rangle} - \frac{1}{V_{thj}}\frac{1}{\bar{n}_j e_j \bar{B}_\theta}\frac{\partial \bar{P}_j}{\partial r} \right]$$

$$\bar{E}_r^{cir} = \frac{1}{\bar{n}_j e_j}\frac{\partial \bar{P}_j}{\partial r} - \left[V_{\theta j}\bar{B}_\phi - V_{\phi j}\bar{B}_\theta \right]$$

KSTAR #5505

Radial Electric Field



Thank you for your attention!
Questions/Comments

APPENDIX B:

A COUPLED STUDY OF PLASMA ROTATION AND TRANSPORT

: COMPARISON OF TOROIDAL TORQUE CONTRIBUTIONS IN AXISYMMETRIC TOKAMAK PLASMAS

Cheonho Bae[1,2,*], Jayhyun Kim[1], Minjun J Choi[1], Laurent Terzolo[1], Tongnyeol Rhee[1], Hyun Seok Kim[1], Sang Gon Lee[1,2], Youngjae Ma[1]

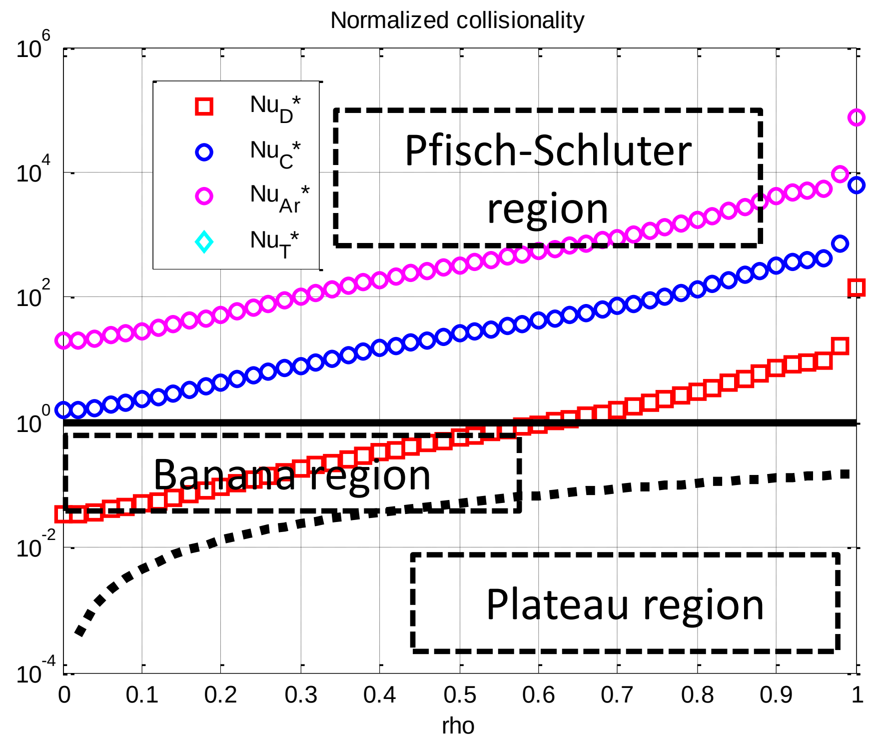
* cbae@nfri.re.kr / yuri157@gmail.com

1. National Fusion Research Institute, Daejeon, South Korea
2. University of Science and Technology, Daejeon, South Korea

11 July 2017
Sapporo, Japan

INTRODUCTION

- **Practical questions!!!**
  1. **How are the rotation & transport differ for different ion species?**
     - **considering their collisionalities differ significantly**
  2. **Can we predict deuterium rotation & transport from the impurity measurements?**
     - **Most transport studies done with impurities**
  3. **Which physical term(s) in the angular momentum(or torque) balance equation have the largest contributions to rotation & transport?**



$$\left\langle Rm_a n_a \frac{\partial V_{a\phi}}{\partial t}\right\rangle + \left\langle Rn_a m_a \left(\vec{V}_a \bullet \nabla\right) V_{a\phi}\right\rangle + \left\langle R\frac{1}{h_\phi}\frac{\partial p_a}{\partial \phi}\right\rangle + \left\langle R\left(\nabla \bullet \overleftrightarrow{\pi}_a\right)_\phi\right\rangle = \left\langle Rn_a e_a \left(-\frac{1}{h_\phi}\frac{\partial \Phi}{\partial \phi} - \frac{\partial A_\phi}{\partial t}\right)\right\rangle + \left\langle Rn_a e_a \left(V_{ar}B_\theta - V_{a\theta}B_r\right)\right\rangle + \left\langle RF^1_{a\phi}\right\rangle + \left\langle RS^1_{a\phi}\right\rangle - \left\langle Rm_a V_{a\phi} S^0_a\right\rangle$$

- **A coupled study of plasma rotation & transport to answer these questions!**

INTRODUCTION

- Most common "particle (or flux)" transport study of today
  - is based on the continuity equation

$$\boxed{\frac{\partial n_a}{\partial t} + \underbrace{\nabla\cdot\left(n_a \vec{V}_a\right)}_{\mathrm{D}fn(n_a)+\mathrm{V}fn\left(\vec{V}_a\right)} = S_a^0}$$

  - closes this equation with approximated physical effects
    - with density gradient: introduces "Diffusion coefficient (D)"
    - with convective effect: introduces "Convective coefficient (V)"
  - We use this model to study individual ion transport
    - by injecting a specific impurities (Ar, Ne, W, etc.)
    - measure fluxes to determine D, V, and effective Vr
    - require dedicated injection systems and diagnostics
    - but still study transport of only one impurity
- Q: can't we just solve the momentum balance equation(MBE) to get Vr?
  - as we do in plasma rotation study

$$n_a m_a \frac{\partial \vec{V}_a}{\partial t} + n_a m_a \left(\vec{V}_a \bullet \nabla\right)\vec{V}_a + \nabla p_a + \nabla \bullet \overleftrightarrow{\pi}_a = n_a e_a \left(\vec{E} + \vec{V}_a \times \vec{B}\right) + \vec{F}_a^1 + \left(\vec{S}^1 - m_a \vec{V}_a S^0\right)$$

INTRODUCTION

- **Plasma rotation study solves MBE to get velocities (mostly Vt and Vp)**

$$n_a m_a \frac{\partial \vec{V}_a}{\partial t} + n_a m_a \left(\vec{V}_a \bullet \nabla\right)\vec{V}_a + \nabla P_a + \nabla \bullet \overleftrightarrow{\pi}_a = n_a e_a \left(\vec{E} + \vec{V}_a \times \vec{B}\right) + \vec{F}_a^1 + \left(\vec{S}^1 - m_a \vec{V}_a S^0\right)$$

  - **if Vr can also be calculated, two studies can be coupled**
- **Plasma rotation theories are developed by two main approaches**
  - **NCLASS (based on Hirshman-Sigmar approach) [Houlberg et. al., 1998]**
    - **most famous with two (parallel and perpendicular) MBEs to calculate neoclassical rotations of multi-ions**
    - **but no further development to couple it with particle/heat transport**
  - **GTROTA (based on Stacey-Sigmar approach) [Bae et. al., Comp. Phys. Comm. 2013]**
    - **introduced as "Extended Plasma Rotation Theory (EPRT)" [Bae et. el., NF 2013]**
    - **takes MBE in three coordinates (radial, poloidal, toroidal)**
      - **direct comparison with Vt and Vp measurements possible**
      - **Vr specifically appears in the toroidal torque balance (next slide)**
- **Q: can I extend EPRT/GTROTA to find Vr/radial fluxes for most generalized tokamak plasmas(both axisymmetric and non-axisymmetric)?**

CURRENT STATUS OF EPRT/GTROTA

- Retains all the terms in the MBEs and in three coordinates
- Velocity calculation models for Vt and Vp
  - Toroidal direction: toroidal torque balance (Flux Surface Averaged)
    - Vr appears in this equation => Effective Vr (later slide)

$$\left\langle Rm_a n_a \frac{\partial V_{a\phi}}{\partial t} \right\rangle + \left\langle Rn_a m_a \left(\vec{V}_a \bullet \nabla\right) V_{a\phi} \right\rangle + \left\langle R \frac{1}{h_\phi} \frac{\partial p_a}{\partial \phi} \right\rangle + \left\langle R\left(\nabla \bullet \overset{\leftrightarrow}{\pi}_a\right)_\phi \right\rangle =$$
$$\left\langle Rn_a e_a \left(-\frac{1}{h_\phi} \frac{\partial \Phi}{\partial \phi} - \frac{\partial A_\phi}{\partial t} \right) \right\rangle + \left\langle Rn_a e_a \left(V_{ar} B_\theta - V_{a\theta} B_r \right) \right\rangle + \left\langle RF^1_{a\phi} \right\rangle + \left\langle RS^1_{a\phi} \right\rangle - \left\langle Rm_a V_{a\phi} S^0_a \right\rangle$$

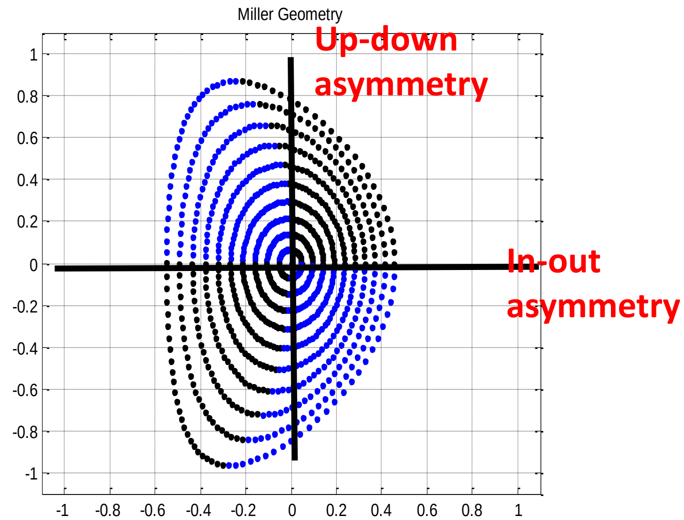
  - Poloidal direction: poloidal torque balance (Flux Surface Averaged)

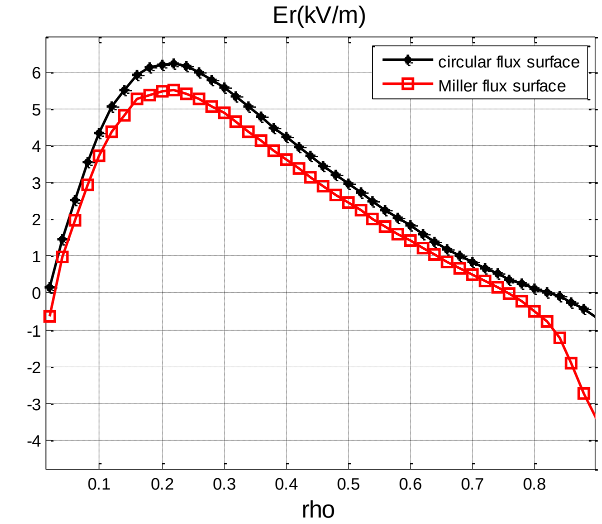
$$\left\langle rm_a n_a \frac{\partial V_{a\theta}}{\partial t} \right\rangle + \left\langle rn_a m_a \left(\vec{V}_a \bullet \nabla\right) V_{a\theta} \right\rangle + \left\langle r \frac{1}{h_\theta} \frac{\partial p_a}{\partial \theta} \right\rangle + \left\langle r\left[\nabla \bullet \overset{\leftrightarrow}{\pi}_a\right]_\theta \right\rangle =$$
$$\left\langle r\left(-\frac{1}{h_p} \frac{\partial \Phi}{\partial \theta} - \frac{\partial A_\theta}{\partial t} \right) \right\rangle + \left\langle rn_a e_a \left(V_{a\phi} B_r - V_{ar} B_\phi \right) \right\rangle + \left\langle rF^1_{a\theta} \right\rangle + \left\langle r\left(S^1_{a\theta} - m_a V_{a\theta} S^0_a \right) \right\rangle$$

  - Radial direction: radial MBE
    - Provides coupling relations with the continuity equation
    - Used to calculate 1st order poloidal variations (aka poloidal asymmetries)
      - in density, velocity, and electrostatic potential [Bae et. Al., PoP 2014]

CURRENT STATUS OF EPRT/GTROTA

- Other EPRT/GTROTA features
  - Uses Miller flux surface geometry
    - for higher accuracy in velocities(Vt, Vp, Vr), momentum/particle transport, and Er calculations





  - All plasma parameters (Vt, Vp, Vr, Er, etc.) self-consistently iterated
    - Maximizes the advantages of plasma fluid equations
  - Calculates Er, Vt, Vp, Vr, and poloidal asymmetries of up to four ion species & electron
    - Simulation of multi-ion plasmas possible (eg., D-T plasma with Tungsten)

CURRENT STATUS OF EPRT/GTROTA

- Current GTROTA handles axisymmetric plasmas only
  - Non-axisymmetric theory available [Stacey and Bae, PoP 2015] but not in GTROTA
- Today, calculated Effective Vr in axisymmetric plasmas
  - defined to represent all anomalous terms (2nd order and higher / turbulence inclusive)
  - Assuming most anomalous transports are in radial direction

Accelerational   Convective   Pressure   Viscous (NTV)

$$\left\langle Rm_a n_a \frac{\partial V_{a\phi}}{\partial t} \right\rangle + \left\langle Rn_a m_a \left(\vec{V}_a \bullet \nabla\right) V_{a\phi} \right\rangle + \left\langle R \frac{1}{h_\phi} \frac{\partial p_a}{\partial \phi} \right\rangle + \left\langle R \left(\nabla \bullet \overleftrightarrow{\pi}_a\right)_\phi \right\rangle =$$

$$\left\langle Rn_a e_a \left(-\frac{1}{h_\phi} \frac{\partial \Phi}{\partial \phi} - \frac{\partial A_\phi}{\partial t} \right) \right\rangle + \left\langle Rn_a e_a \left(V_{ar} B_\theta - V_{a\theta p} B_r \right) \right\rangle + \left\langle RF^1_{a\phi} \right\rangle + \left\langle RS^1_{a\phi} \right\rangle - \left\langle Rm_a V_{a\phi} S^0_a \right\rangle$$

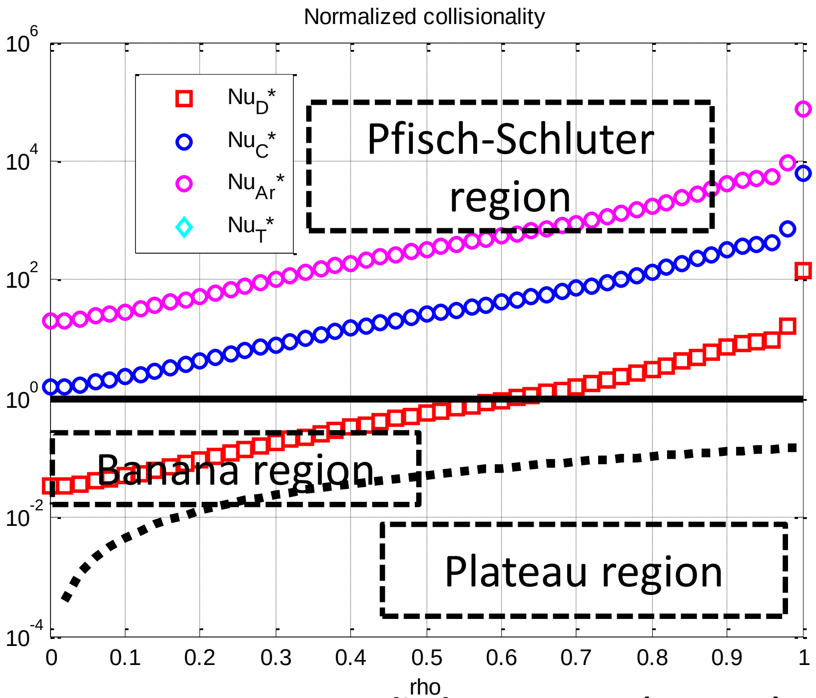
Electric   V cross B   Frictional   External   Atomic

"Anomalous (Effective Vr cross B)"

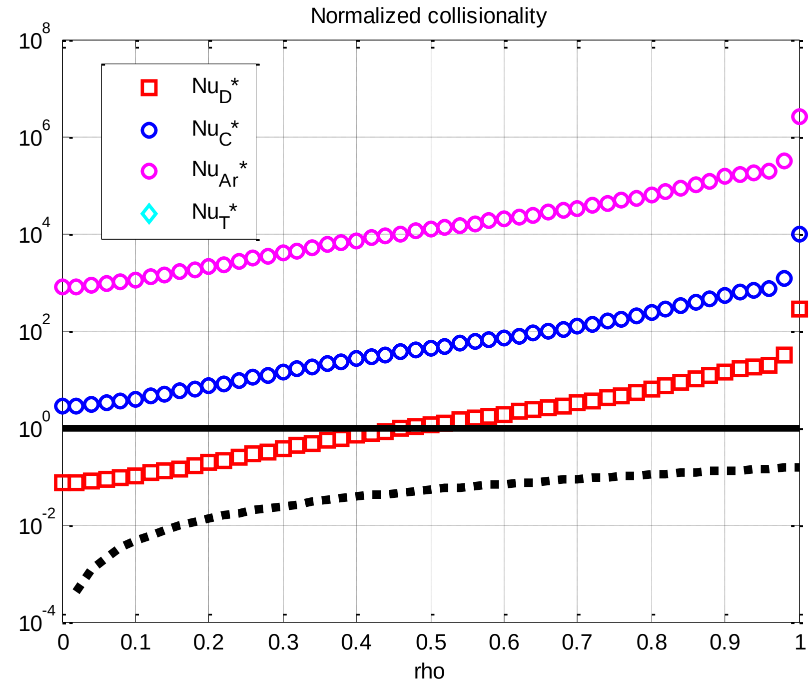
$$\underbrace{\left\langle Rn_a e_a V^{eff}_{ar} B_\theta \right\rangle}_{Rn_a e_a B_\theta \left(V^{eff}_r\right)} = grey\ terms + \underbrace{blue\ terms}_{\text{Reynols stress}}$$

DISCHARGES ANALYZED

- **Four KSTAR discharges analyzed**
  - **Two H-modes with Ar rotation measured (#5505-2500ms / #5953-2500ms)**
  - **Two L-modes with Carbon rotation measured (#13728-4500ms / 13728-4950ms)**
- **One simulation with Tungsten**
  - **Based on #5505-2500ms**



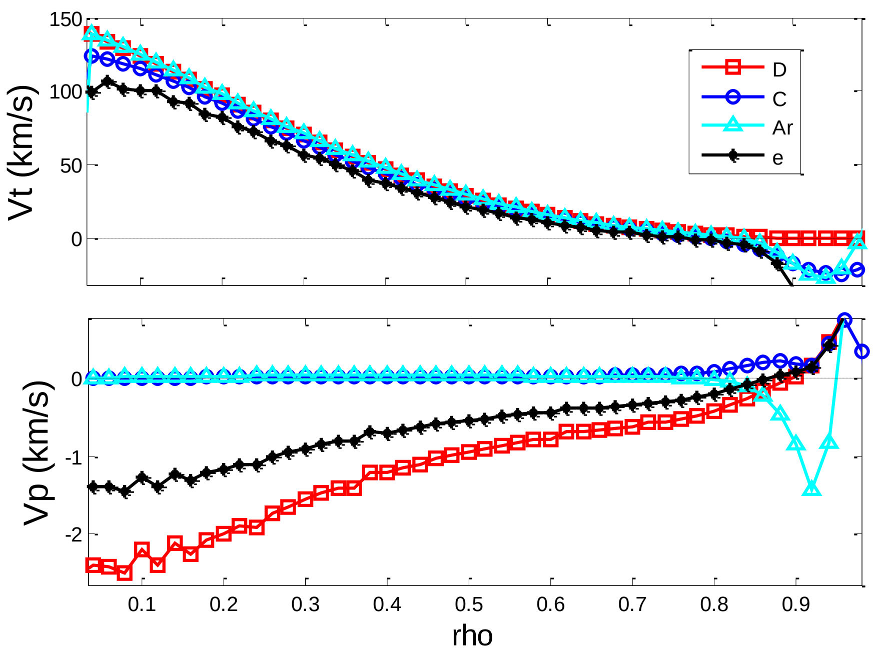
KSTAR discharge #5505 (2500ms)

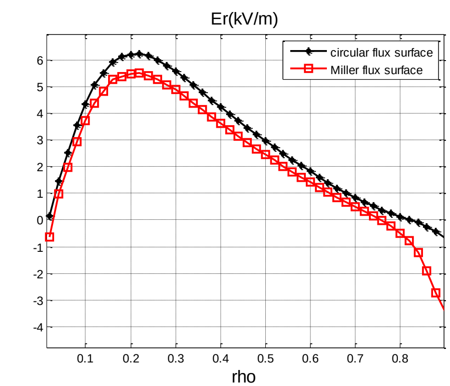


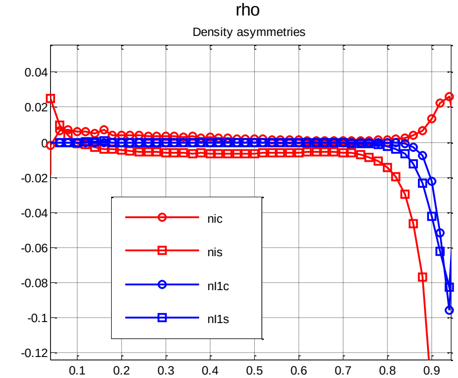
KSTAR discharge #5505 (2500ms) with Ar replace with W

ANALYSIS RESULTS

- **Rotation, poloidal asymmetries, & Er (KSTAR #5505-2500ms)**
  - **Vp and Vt of all ions/electrons calculated**
  - **Vt very close to each other and stays within 10% of the measurement [Bae et. et., NF 2013 / Bae et. al., PoP 2014]**
    - **Er self-consistently(iteratively) calculated**
    - **Poloidal asymmetries (of density, velocity, and electrostatic potential) calculated** (density asymmetry only shown in this slide)





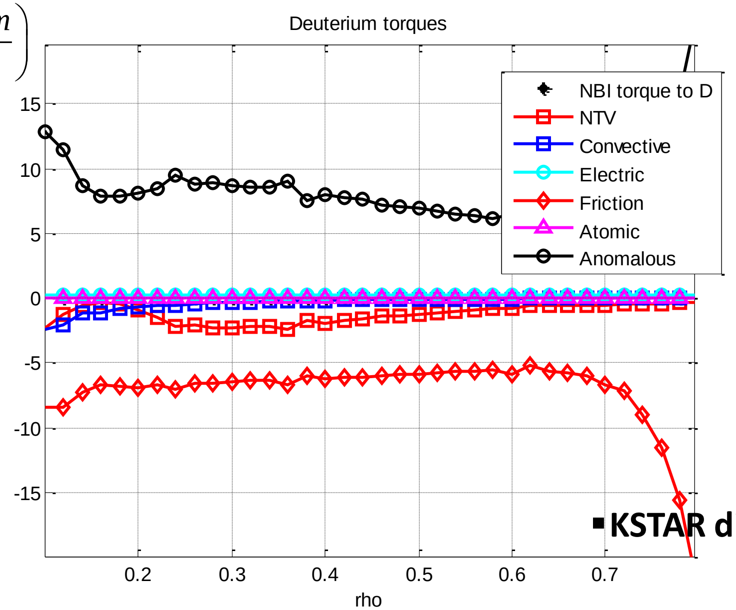


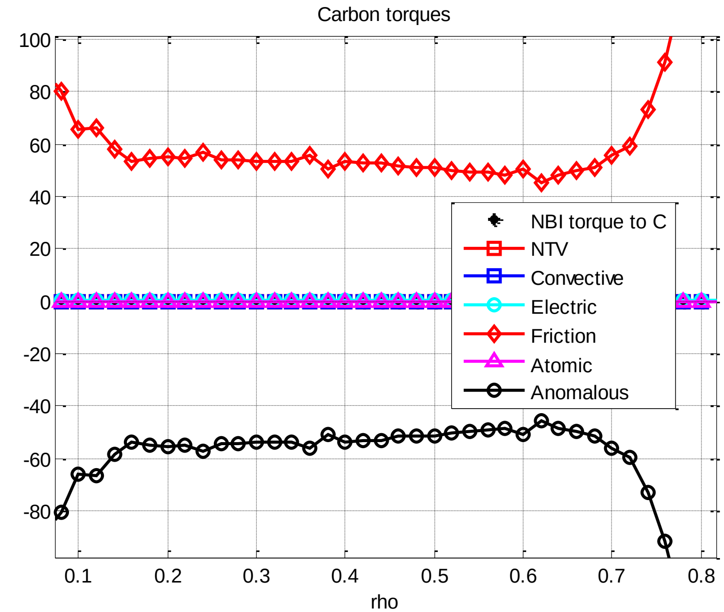
- **KSTAR discharge #5505 (2500ms)**

TOROIDAL TORQUE COMPARISONS

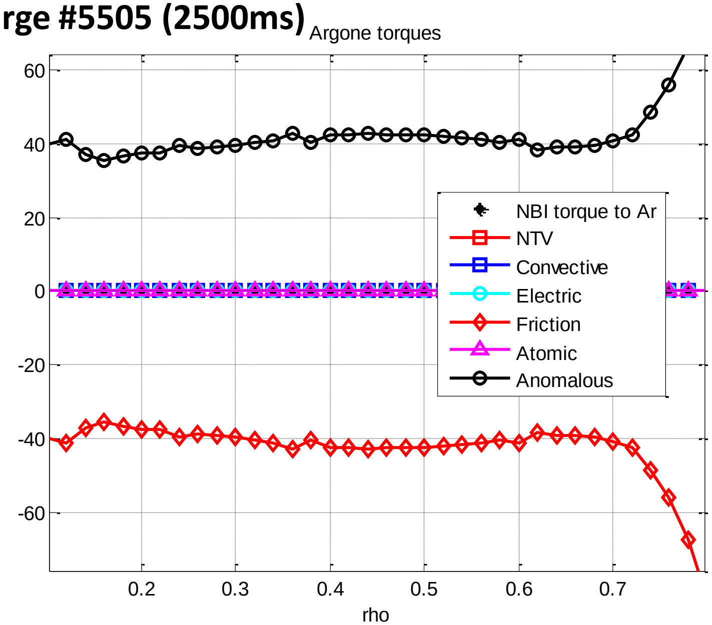
- **Toroidal torque densities**

$$\left(units : \frac{N \cdot m}{m^3} \right)$$





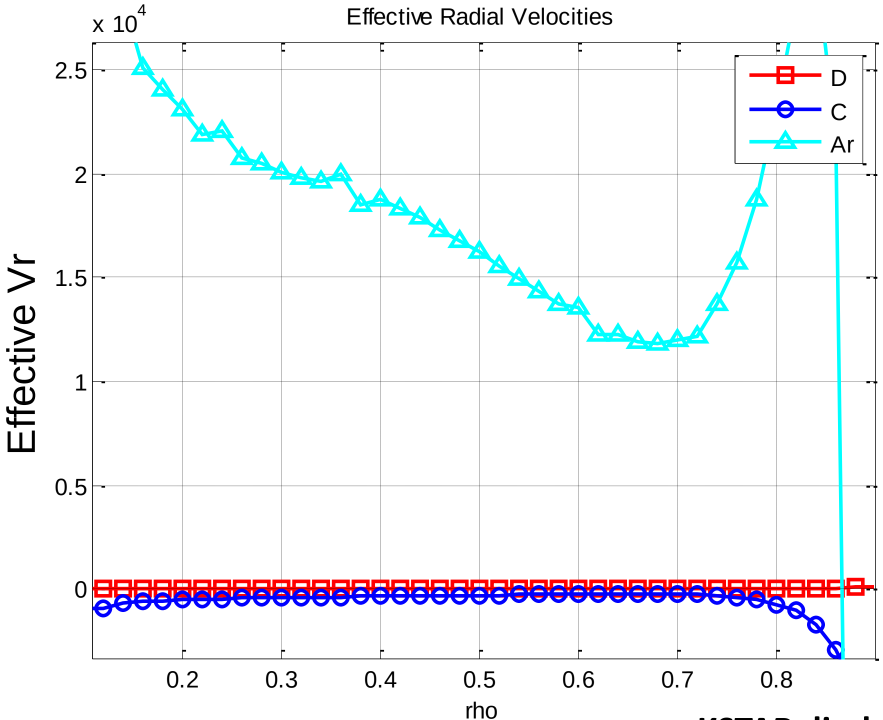
- **KSTAR discharge #5505 (2500ms)**

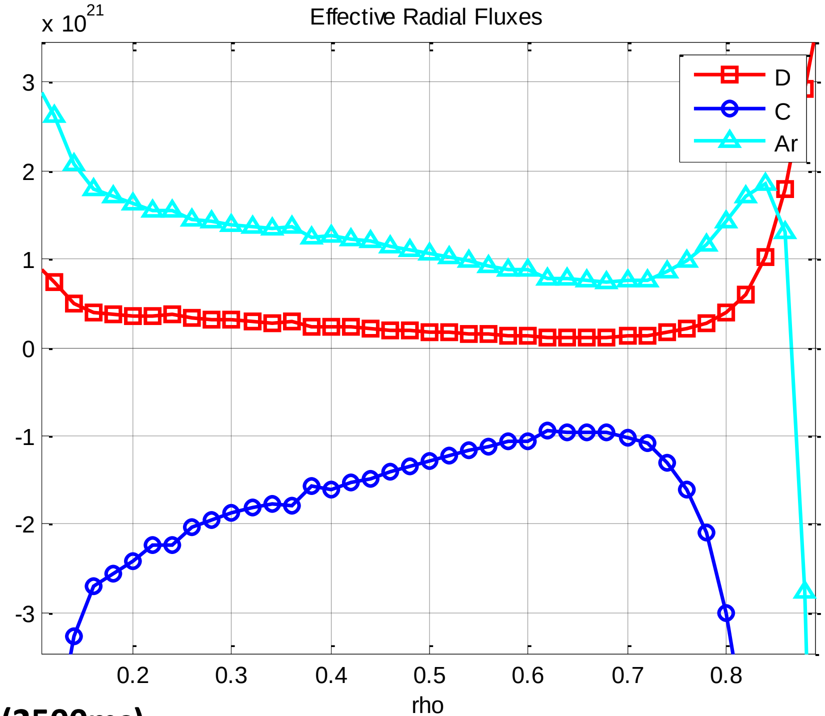


- **Findings**
  - torque balance mostly maintained by **friction and anomalous ("Effective Vr cross B")**
    - especially for the impurities
  - Different balancing relations for different ion species
    - **Q: Is "collisionality" most dominant effect in the rotation and transport of different ion species?**

TOROIDAL TORQUE COMPARISONS

- **Effective Vr / radial fluxes**





- **KSTAR discharge #5505 (2500ms)**

- **Findings**
  - **Effective Vr & radial fluxes larger for impurities**
  - **Impurity fluxes in opposite directions**
    - **Q: Do all the impurities always accumulate in the core?**
    - **Q: What physical mechanism determines these directions? Collisionality?**

FUTURE OPPORTUNITIES

- **Theoretical model development (in progress)**
  - develop a separate Vr subsystem
  - develop numerical models for non-axisymmetric plasmas [Stacey and Bae, PoP 2015]
  - include 1st order toroidal variations (in Bt and others)
- **Numerical code development**
  - Code in non-axisymmetric theories
  - compare all the poloidal torque density terms

$$\left\langle rm_a n_a \frac{\partial V_{ap}}{\partial t}\right\rangle + \left\langle rn_a m_a \left(\vec{V}_a \bullet \nabla\right) V_{ap}\right\rangle + \left\langle r \frac{1}{h_p}\frac{\partial p_a}{\partial p}\right\rangle + \left\langle r\left[\nabla \bullet \overleftrightarrow{\pi}_a\right]_p\right\rangle =$$
$$\left\langle r\left(-\frac{1}{h_p}\frac{\partial \Phi}{\partial p} - \frac{\partial A_p}{\partial t}\right)\right\rangle + \left\langle rn_a e_a \left(V_{a\phi} B_\psi - V_{a\psi} B_\phi\right)\right\rangle + \left\langle rF^1_{ap}\right\rangle + \left\langle r\left(S^1_{ap} - m_a V_{ap} S^0_a\right)\right\rangle$$

- **Simulations/analysis of modern tokamaks**
  - Analyze KSTAR discharges with ITBs
  - Various modes/devices: DIII-D, KSTAR, EAST, etc.
  - W transport simulations
  - ITER-relevant simulations (ITER shapes / D-T fusion / etc.)
  - Collisionality effect simulations
- **open to comments and ideas!**

Thank you for your attention!

Additional slides with more details…
1. Simulation with Tungsten
2. L-mode discharge analysis results
3. Extended Plasma Rotation theory

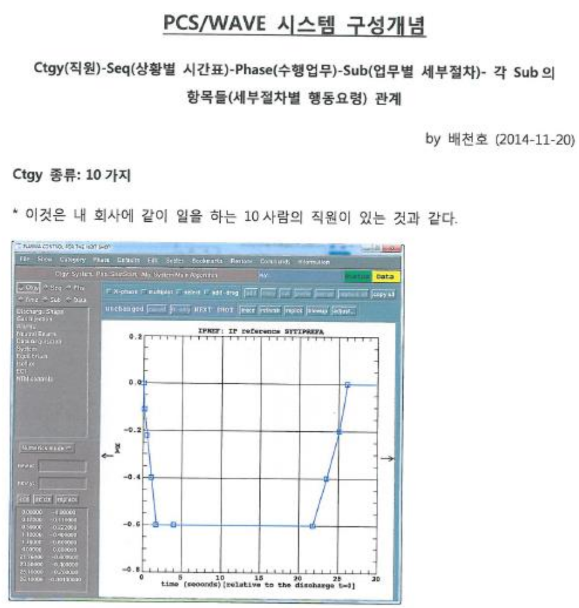
my permanent contact: yuri157@gmail.com

APPENDIX C:

EXPERIMENTAL EXPERIENCES WITH KSTAR

KSTAR CAMPAIGN EXPERIENCES

- **CPO/APO experiences [2013-1017]**
  - **Served as CPO/APO for five consecutive KSTAR annual campaigns**
  - **Develop CPO/APO training manual and checklist**

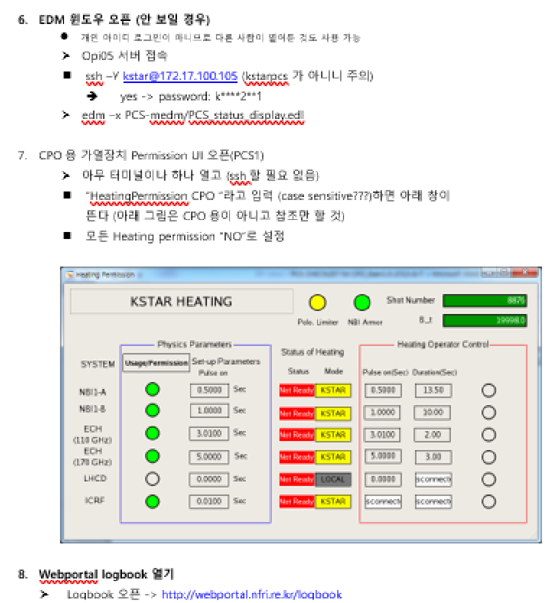

PCS/WAVE 시스템 구성개념

Ctgy(직원)-Seq(상황별 시간표)-Phase(수행업무)-Sub(업무별 세부절차)- 각 Sub 의 항목들(세부절차별 행동요령) 관계

by 배천호 (2014-11-20)

Ctgy 종류: 10 가지

* 이것은 내 회사에 같이 일을 하는 10 사람의 직원이 있는 것과 같다.


6. EDM 윈도우 오픈 (안 보일 경우)
- 개인 아이디 로그인이 아니므로 다른 사람이 열어둔 것도 사용 가능
- Opi05 서버 접속
- ssh –Y kstar@172.17.100.105 (kstarpcs 가 아니니 주의)
  - yes -> password: k****2**1
- edm –x PCS-medm/PCS_status_display.edl

7. CPO 용 가열장치 Permission UI 오픈(PCS1)
- 아무 터미널이나 하나 열고 (ssh 할 필요 없음)
- "HeatingPermission CPO "라고 입력 (case sensitive???)하면 아래 창이 뜬다 (아래 그림은 CPO 용이 아니고 참조만 할 것)
- 모든 Heating permission "NO"로 설정

8. Webportal logbook 열기
- Logbook 오픈 -> http://webportal.nfri.re.kr/logbook

- **KSTAR campaign & PAC coordinator [2013-2014]**
- **Rotation/Transport study shots**
  - **KSTAR shots with CES/XICS/ECEI diagnostics collected**

PUBLICATIONS ON EXPERIMENTS

- H.H. Lee et al., ***Tearing modes induced by perpendicular electron cyclotron resonance heating in the KSTAR tokamak***, Nucl. Fusion 54(2014), 103008
- Jayhyun Kim et al., ***Suppression of edge localized mode crashes by multi-spectral non-axisymmetric fields in the KSTAR***, Nucl. Fusion 57, 022001 (2017)
  - Type-I ELM crash suppression reproduced both consistent and inconsistent suppression performances when compared to the DIII-D results
  - indicates a dependency of ELM suppression on the heating level and the associated kink-like plasma responses
  - dominant and malign kink-like plasma responses over the benign gap filling effects

n=2 (mid) + n=1 (top/bot)

Port	L	P	D	H	
ϕ	0°	90°	180°	270°	
Top	+	-	-	+	➡ Proxy (n=1 NA field)
Mid	+	-	+	-	⇨ Reference (n=2 NA field)
Bot	+	+	-	-	➡ Proxy (n=1 NA field)

$$\vec{B}_{\text{total}} = \vec{B}_{\text{eq}} + \cancel{\vec{B}_{\text{int}}} + \vec{B}_{\text{RMP}} + \vec{B}_{\text{pr}}$$

$$\vec{B}_{\text{pr}} = \vec{B}_{\text{pr}}^{\text{lin}} + \vec{B}_{\text{pr}}^{\text{nl}}$$