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NTV and kinetic MHD research using POCA

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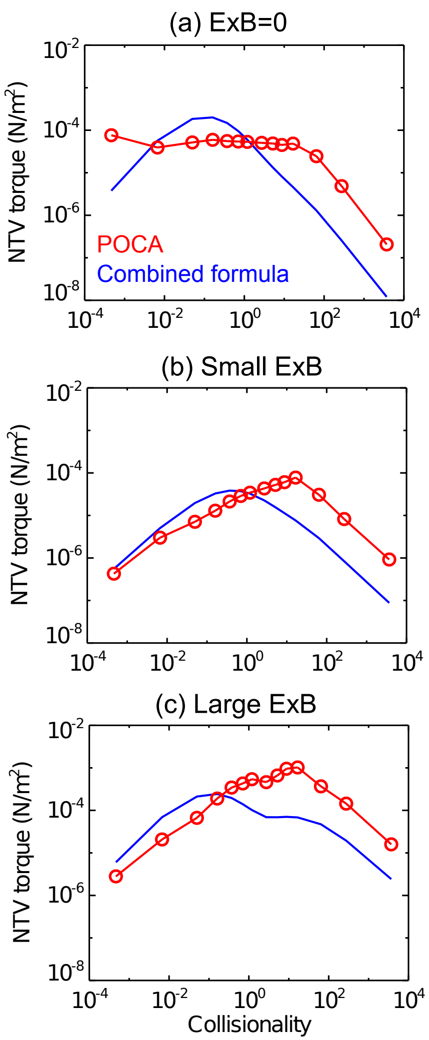
Outline

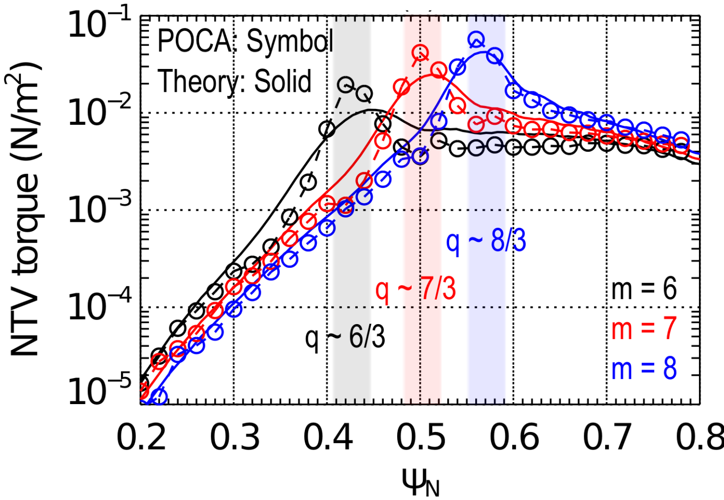
- Validation of NTV physics with particle simulation
- Prediction of magnetic braking in NSTX-U
- Possible application to kinetic potential energy
- Future work

NTV physics has been validated using a guiding-center particle simulation with POCA

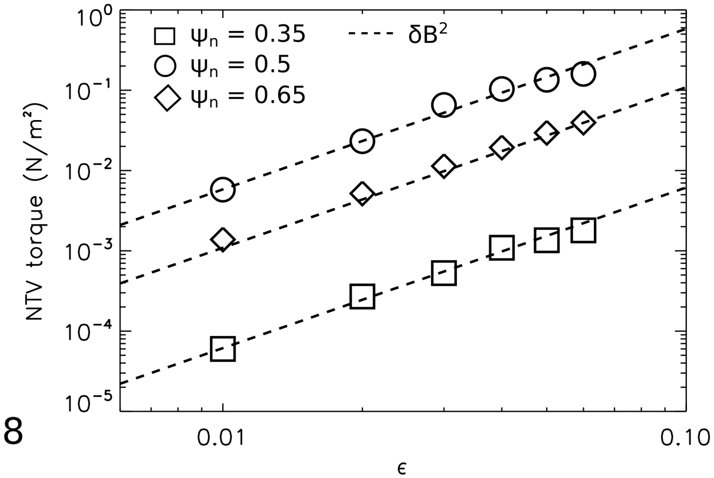
Collisionality dependency



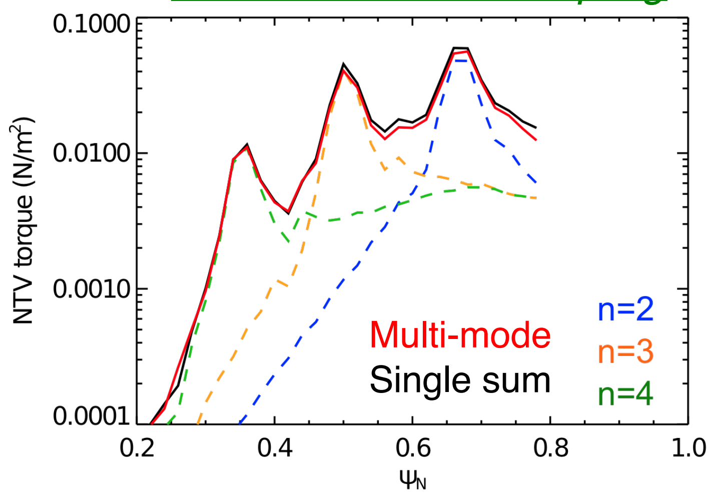
Field resonance



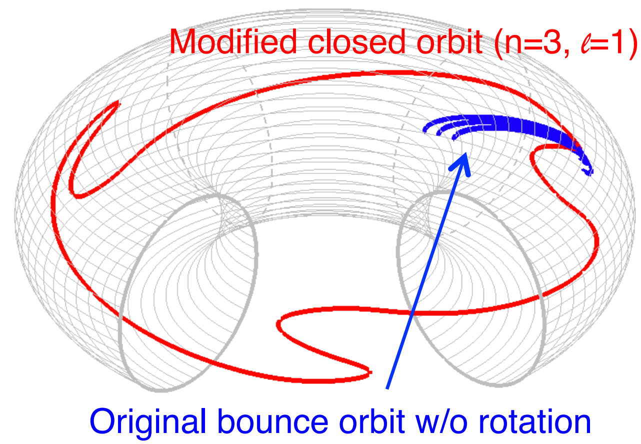
Quadratic δB dependency



Toroidal mode de-coupling

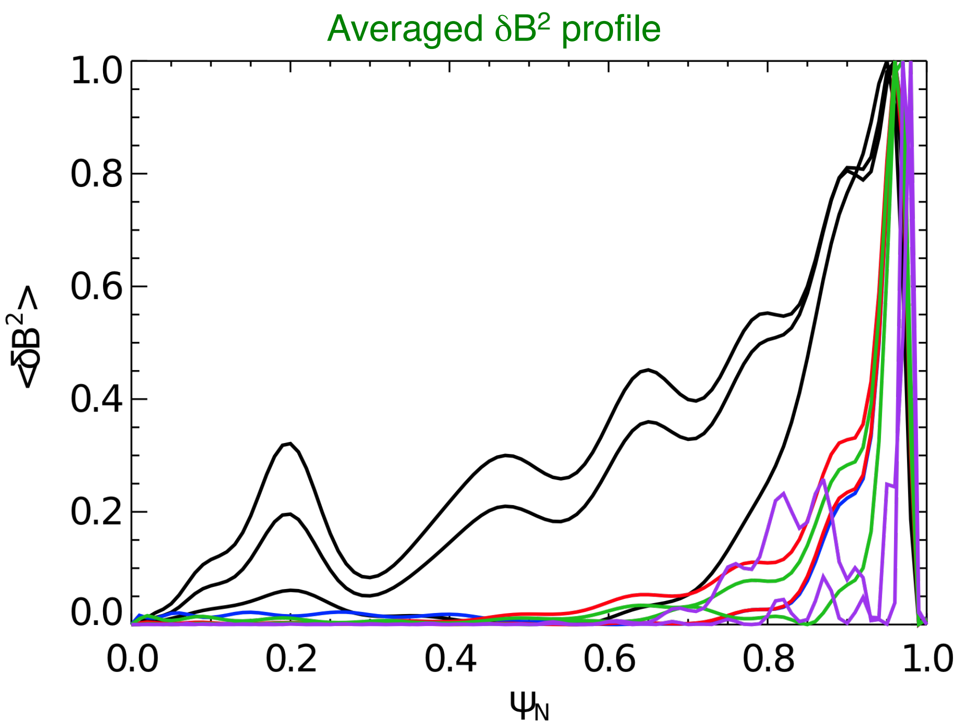


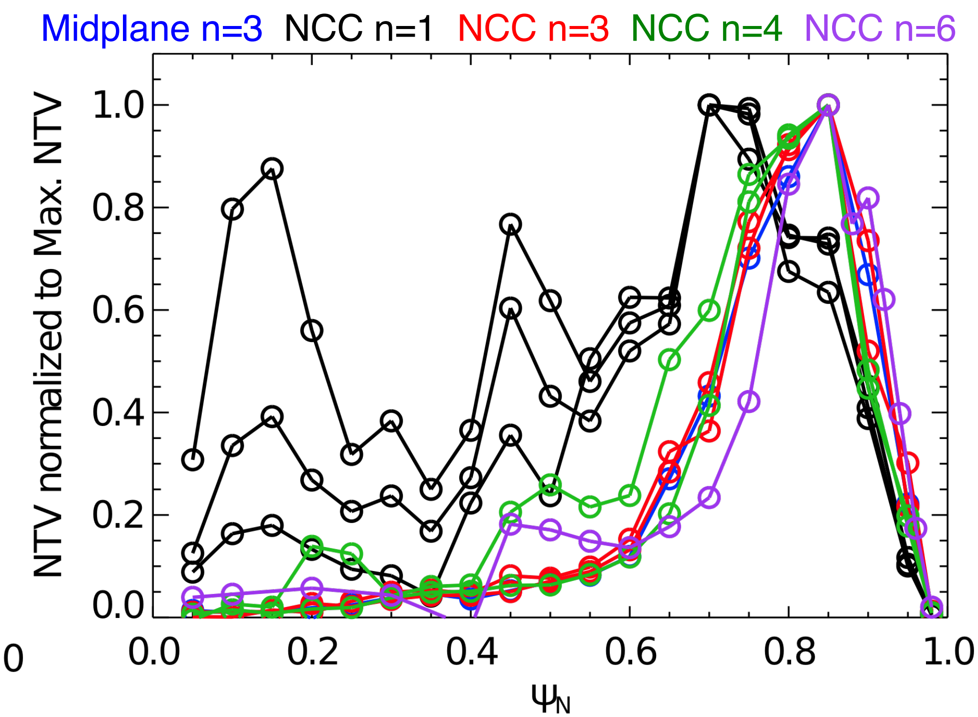
Bounce-harmonic resonance



Various braking profiles can be achieved in NSTX-U

- POCA predicts variability of braking profiles by Midplane and NCC
  - (Full and/or partial) NCC can provide various braking profiles by n=1 ~ 6, depending on phases: Consistent to δB profiles
  - Polynomial degree for fitting δB should be carefully selected in high n (=4,6) cases for better radial resolution in NTV calculations
  - Change target equilibrium and kinetic profiles





δW_K can be calculated using POCA in NSTX-U

- Perturbed magnetic field is given as

$$\delta B_{mn}(\psi_n) = \sum_m a_{mn}(\psi_n)\cos(m\vartheta - n\varphi) + b_{mn}(\psi_n)\sin(m\vartheta - n\varphi)$$

- POCA calculates NTV by

$$T_\varphi = \left\langle \frac{\delta P}{B}\frac{\partial B}{\partial \varphi} \right\rangle \longrightarrow T_\varphi = \sum_m n\left\langle \frac{\delta P}{B}\left[a_{mn}\sin(m\vartheta - n\varphi) - b_{mn}\cos(m\vartheta - n\varphi)\right]\right\rangle$$

- Kinetic potential energy drives NTV force

$$T_\varphi = 2in\delta W_K$$

[J.-K. Park, POP (2011)]

- δW_K calculation with particle simulation is under test

$$\delta W_K = -\frac{1}{2}\sum_m \left\langle \frac{\delta P}{B}\left[a_{mn}\cos(m\vartheta - n\varphi) + b_{mn}\sin(m\vartheta - n\varphi)\right]\right\rangle$$

Future Work

- Particle simulation will be useful to extensively study NTV transport in NSTX-U
  - Predict broad/steep braking profiles depending on the toroidal mode and coil phase
  - Require detailed study on high toroidal mode for local braking
  - Change target equilibrium and kinetic profiles
- Kinetic potential energy calculation will be tested
  - Compare δW_K with MARS-K, MISK, IPEC-PENT, etc.
  - Physics verification and validation, application to NSTX-U
- Field line tracing with vacuum and ideal plasma response is available

Back up

POCA solves Fokker-Planck equation with guiding-center orbit equations

- Guiding-center motion is described by Hamiltonian equations of motion

[R.B. White, PFL B (1990)]
[M. Sasinowski and A.H. Boozer, POP (1997)]

$$\dot{\theta} = -\frac{2\pi}{q}\frac{1}{g+\iota i}\left\{\frac{q^2B^2}{m}\rho_{\parallel}\left[\rho_{\parallel}\frac{\partial g(\psi)}{\partial\psi} - \iota(\psi)\right] - g(\psi)\left[\left(\frac{q^2\rho_{\parallel}^2B^2}{m} + \mu B\right)\frac{1}{B}\frac{\partial B}{\partial\psi} + q\frac{\partial\Phi}{\partial\psi}\right]\right\}$$

$$\dot{\phi} = -\frac{2\pi}{q}\frac{1}{g+\iota i}\left\{i(\psi)\left[\left(\frac{q^2\rho_{\parallel}^2B^2}{m} + \mu B\right)\frac{1}{B}\frac{\partial B}{\partial\psi} + q\frac{\partial\Phi}{\partial\psi}\right] - \left(\rho_{\parallel}\frac{\partial i(\psi)}{\partial\psi} + 1\right)\frac{q^2B^2}{m}\rho_{\parallel}\right\}$$

$$\dot{\psi} = -\frac{2\pi}{q}\frac{1}{g+\iota i}\left[g(\psi)\left\{\left(\frac{q^2\rho_{\parallel}^2B^2}{m} + \mu B\right)\frac{1}{B}\frac{\partial B}{\partial\theta} + q\frac{\partial\Phi}{\partial\theta}\right\} - i(\psi)\left\{\left(\frac{q^2\rho_{\parallel}^2B^2}{m} + \mu B\right)\frac{1}{B}\frac{\partial B}{\partial\phi} + q\frac{\partial\Phi}{\partial\phi}\right\} - \frac{q}{2\pi}V(t)i(\psi)\right]$$

$$\dot{\rho}_{\parallel} = \frac{2\pi}{q}\frac{1}{g+\iota i}\left[\left(\rho_{\parallel}\frac{\partial g(\psi)}{\partial\psi} - \iota(\psi)\right)\left\{\left(\frac{q^2\rho_{\parallel}^2B^2}{m} + \mu B\right)\frac{1}{B}\frac{\partial B}{\partial\theta} + q\frac{\partial\Phi}{\partial\theta}\right\} - \left(\rho_{\parallel}\frac{\partial i(\psi)}{\partial\psi} + 1\right)\left\{\left(\frac{q^2\rho_{\parallel}^2B^2}{m} + \mu B\right)\frac{1}{B}\frac{\partial B}{\partial\phi} + q\frac{\partial\Phi}{\partial\phi}\right\} - \frac{q}{2\pi}V(t)\left(\rho_{\parallel}\frac{\partial i(\psi)}{\partial\psi} + 1\right)\right]$$

- δf is calculated from Fokker-Planck equation

[M.N Rosenbluth, PFL (1972)]
[M. Sasinowski and A.H. Boozer, POP (1997)]

  – Fokker-Planck equation is written as

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v}\cdot\frac{\partial f}{\partial\vec{x}} + \frac{\vec{F}}{m}\cdot\frac{\partial f}{\partial\vec{v}} = C(f), \quad f = f_M\exp(\hat{f}) \approx f_M(1+\hat{f}) \longrightarrow \frac{d\ln f_M}{dt} + \frac{d\hat{f}}{dt} = C_m(f) \equiv \frac{C(f)}{f}$$

  – Fokker-Planck equation is reduced to $\frac{d\hat{f}}{dt} - C_m(f) = -\vec{v}\cdot\nabla\psi\frac{\partial\ln f_M}{\partial\psi} - \vec{F}\cdot\frac{\partial\ln f_M}{\partial\vec{v}}$

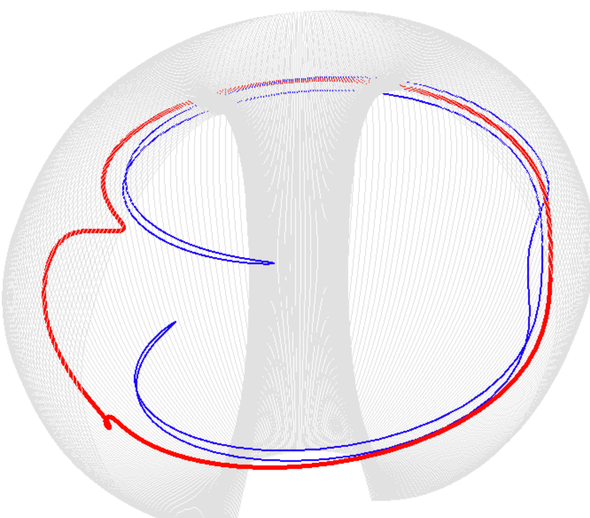
  – Using local Maxwellian, δf can be obtained from

$$f_M = \frac{N}{\left(\sqrt{\pi}v_t\right)^3}\exp\left(-\frac{U-e\Phi}{T}\right) \longrightarrow \Delta\hat{f} = -\left[\frac{1}{n}\frac{\partial n}{\partial\psi} + \left(\frac{3}{2} - \frac{E}{T}\right)\frac{1}{T}\frac{\partial T}{\partial\psi}\right]\Delta\psi - \frac{e}{T}\frac{d\Phi}{d\psi}\Delta\psi + 2\nu\frac{u}{v}\lambda\Delta t$$

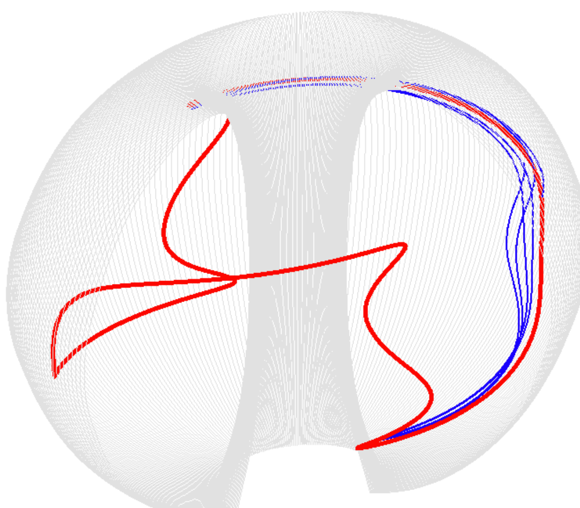
Closed orbits by BH resonances can be found in NSTX

- Bounce-harmonic resonance almost always exist in perturbed tokamaks
  - BH resonance always exist in the finite ExB due to Maxwellian energy distribution, and on every surface due to multi-harmonic magnetic perturbations
  - Modified closed orbits, theoretically predicted and numerically reproduced in the simple configuration, can be also found in the complicated NSTX configuration
  - Identical features in orbit-closing by resonance

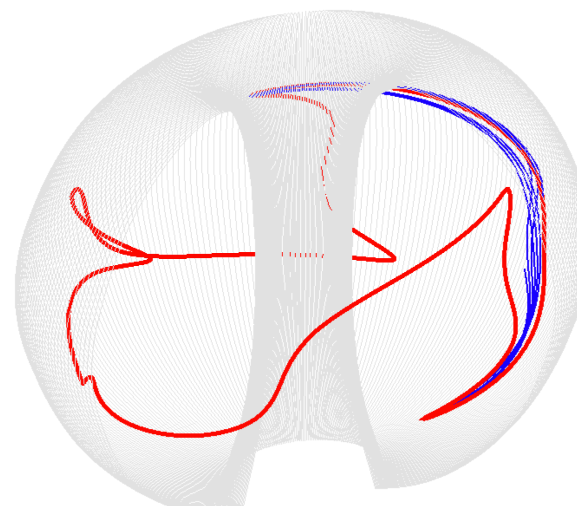
Closed orbit (n=1, ℓ=1)



Closed orbit (n=2, ℓ=1)



Closed orbit (n=3, ℓ=1)



Original bounce orbits w/o rotation

POCA is being actively applied to experimental analysis

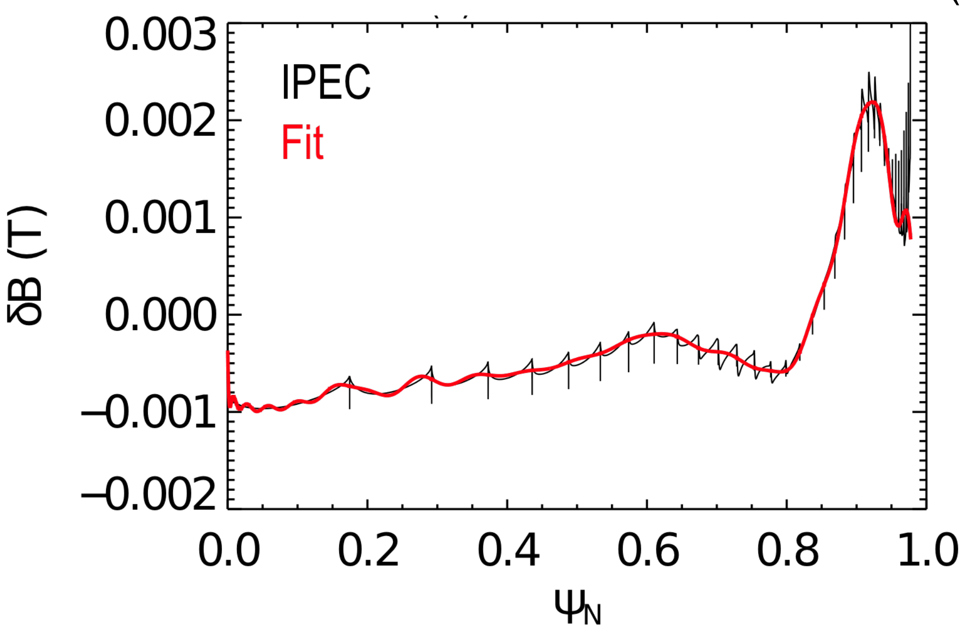
- Perturbed magnetic field spectrum provided by IPEC
  - Original IPEC output contains nonphysical peaks at the rational surfaces
  - Fitting technique (i.e. Chebyshev polynomials) will be used in POCA as

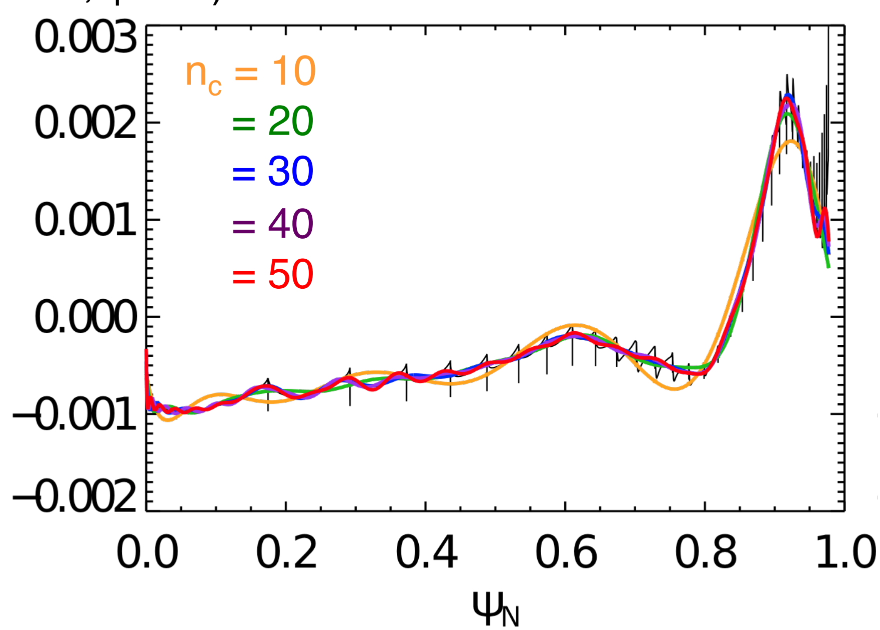
$$\delta B_{mn}(\psi_n) = \sum_m a_{mn}(\psi_n)\cos(m\theta - n\phi) + b_{mn}(\psi_n)\sin(m\theta - n\phi) \quad \leftarrow \quad \textit{IPEC}$$

$$\delta B_{mn}(\psi_n) = \sum_m \left[\sum_j^{n_c} a_j \cos\left(j\cos^{-1}(x)\right)\cos(m\theta - n\phi) + b_j \cos\left(j\cos^{-1}(x)\right)\sin(m\theta - n\phi) \right] \quad \rightarrow \quad \textit{POCA}$$

  - Fitting follows overall features of IPEC δB, and effectively smoothes the peaks

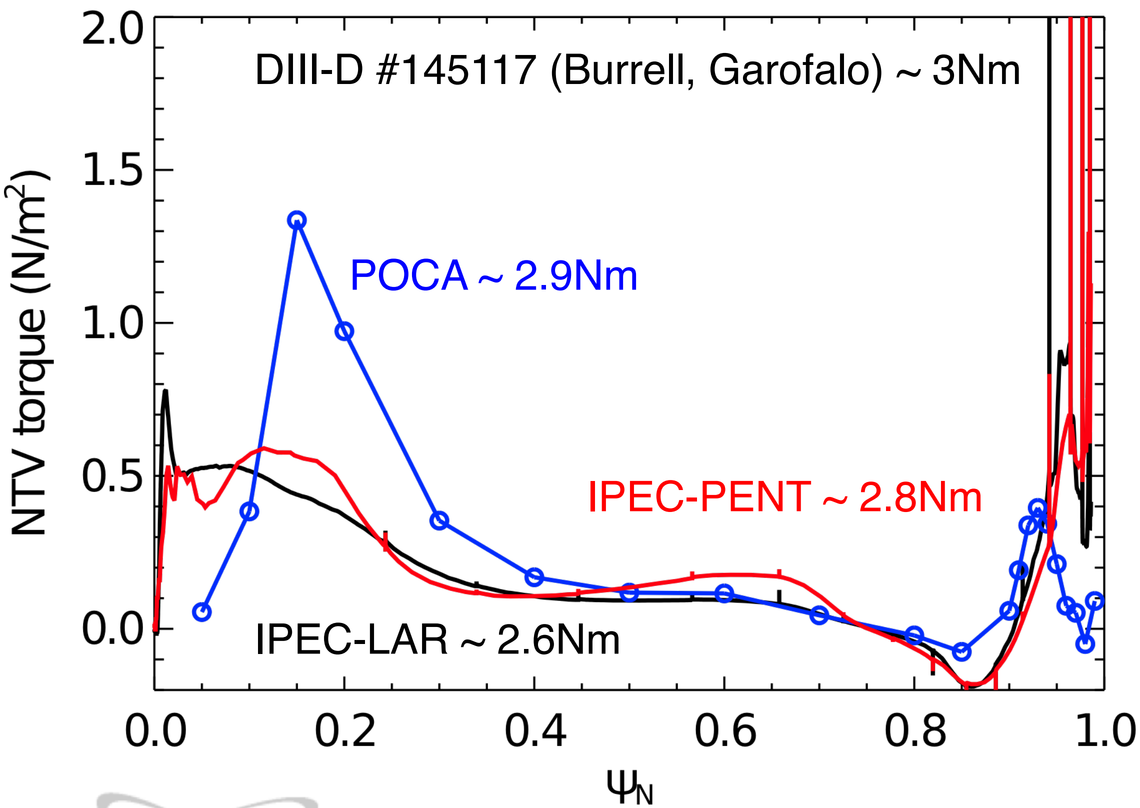
NSTX #124439 (θ=0.0, ϕ=0.0)

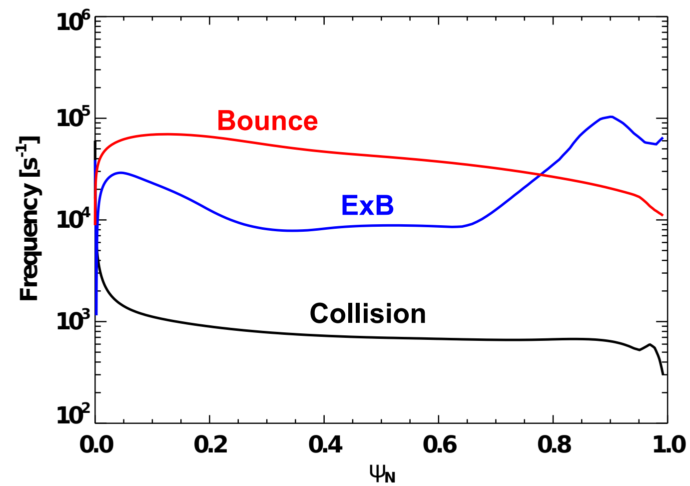


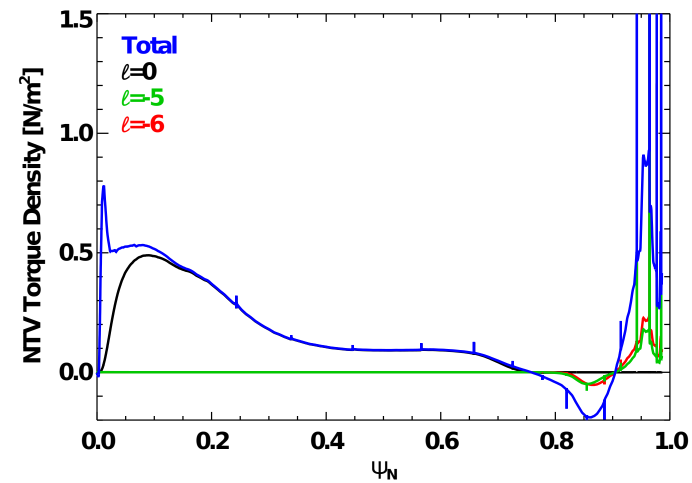


Consistent NTV profile and total NTV was obtained in DIII-D n=3 magnetic braking

- Application of POCA to DIII-D n=3 magnetic braking (in QH mode experiments) using IPEC δB gives a consistent NTV







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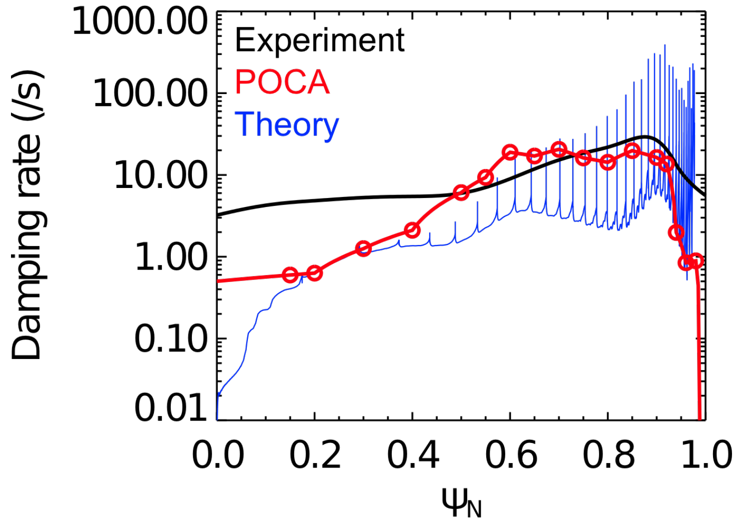
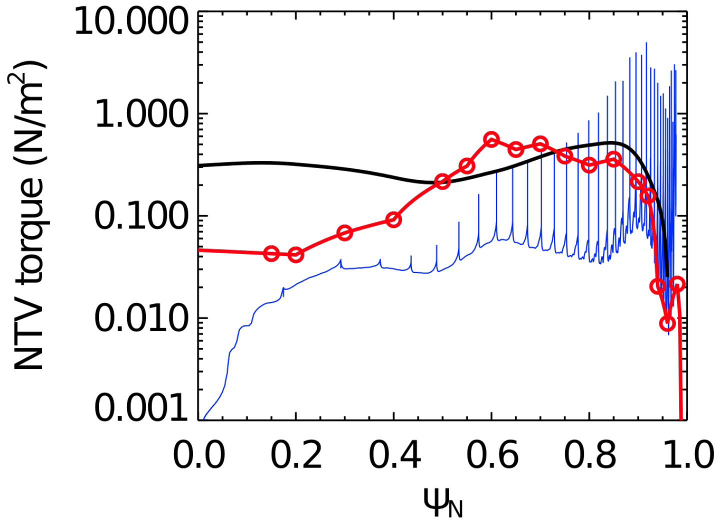
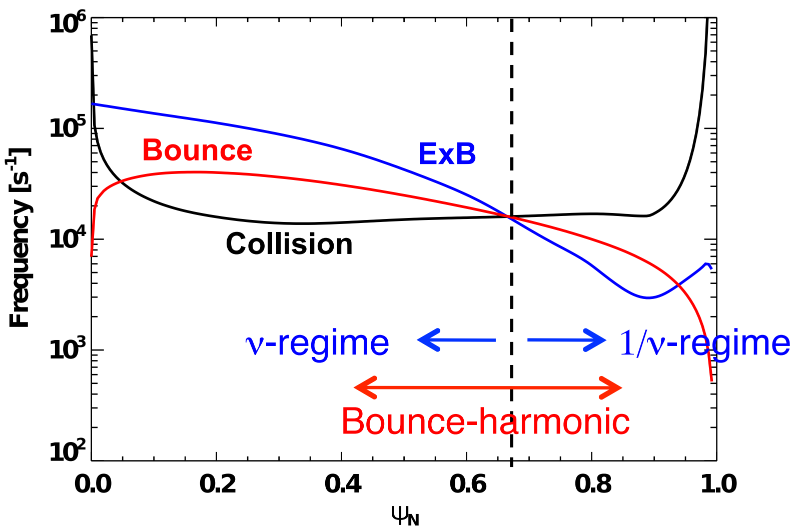
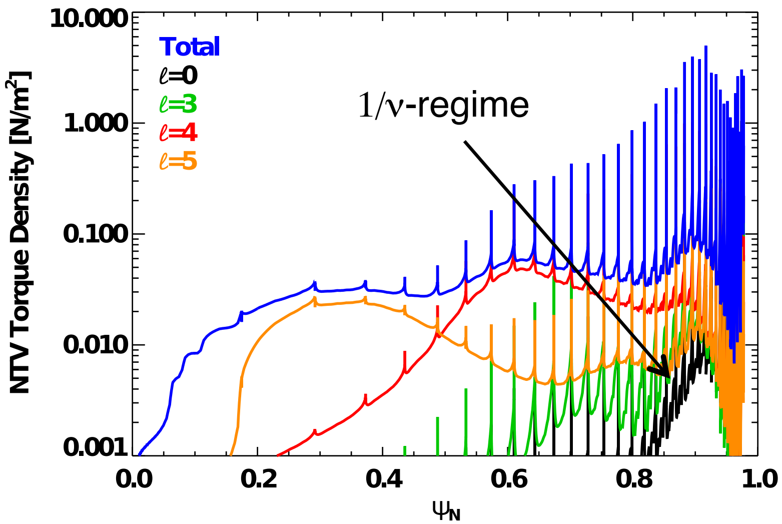
Prediction of NTV in NSTX can be improved with POCA

- Bounce-harmonic resonances can dominate NTV transport



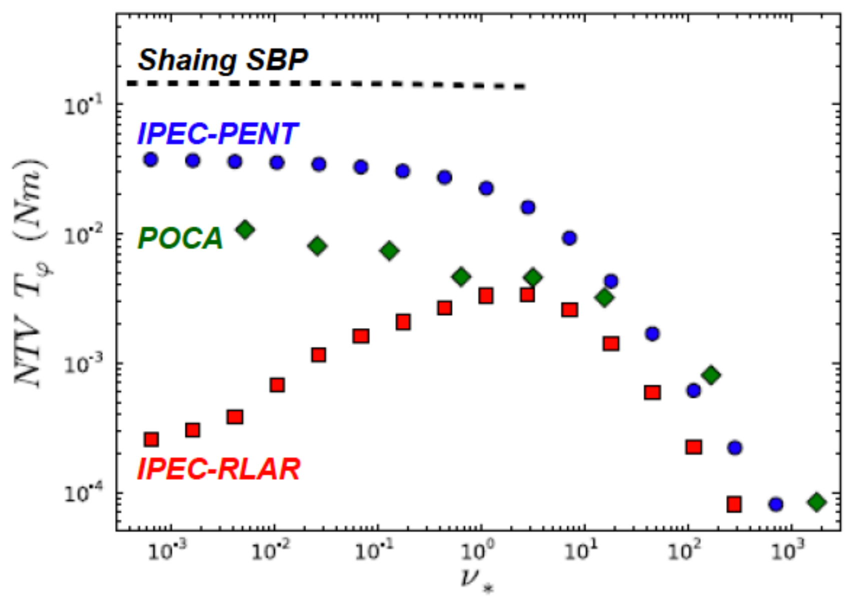






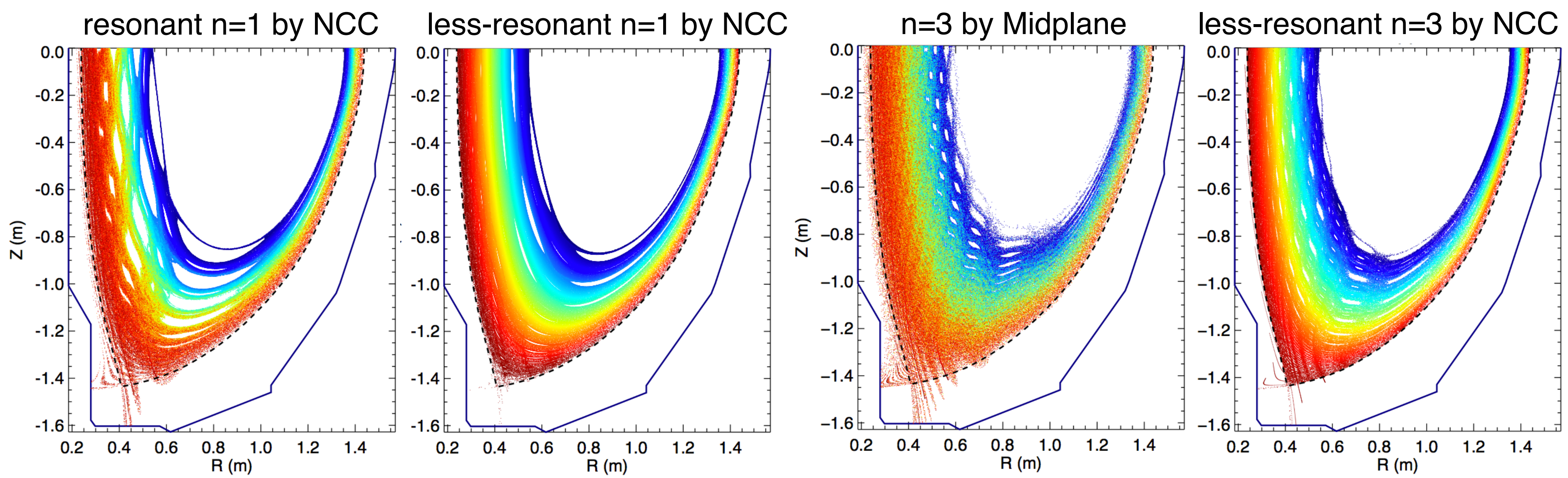
Semi-analytic numerical routines in IPEC have been compared to POCA

- IPEC previously used a reduced large-aspect-ratio NTV formulation with approximated collision operator : IPEC-RLAR
- Now new formulation and implementation for NTV with general geometry have been completed : IPEC-PENT
- Computational cost : IPEC-RLAR < IPEC-PENT < POCA
- Accuracy : POCA > IPEC-PENT > IPEC-RLAR (unacceptable for SBP)

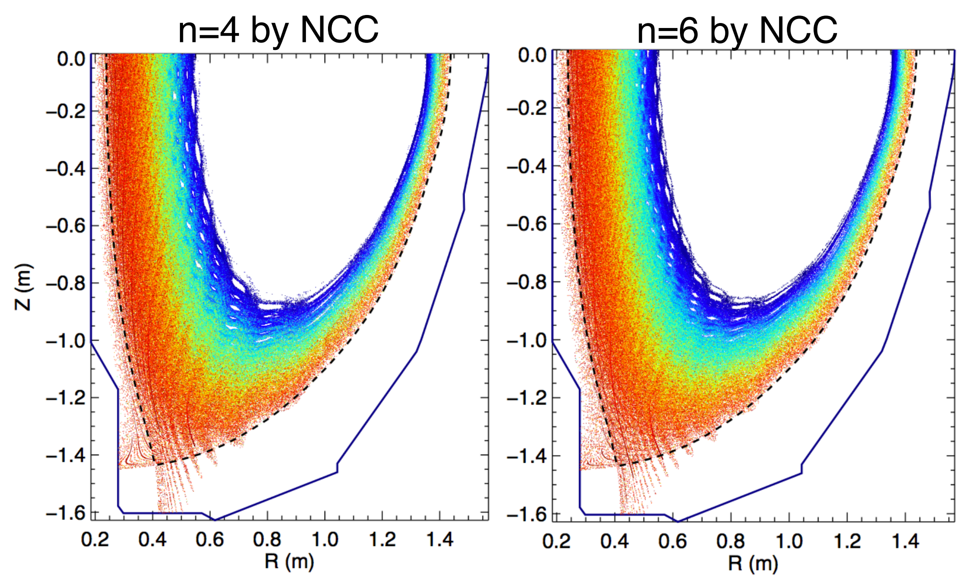


[Logan, To be submitted to POP (2013)]

Field Line Tracing Simulations for NCC



- POCA-FLT supports capability of NCC to produce various 3D field characteristics
  - POCA-FLT predicts modifications of vacuum stochastic layers for n=1~6
  - NCC can provide resonant or less-resonant fields depending on the phase but similar NTV braking profile
  - Higher toroidal mode supplies stronger field splitting on the target



General Perturbed Equilibrium Code (GPEC) is on progress

- Perturbed equilibrium codes are efficient to study 3D field physics in tokamaks with non-axisymmetric perturbations
  - IPEC solves ideal force balance with ideal constraints
  - GPEC will solve non-ideal force balance with arbitrary jump conditions, which will be matched with inner-layer solver
  - POCA will use 3D perturbations from IPEC, and provide anisotropic pressure tensor to GPEC