NSTX-U

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Application of POCA for NTV Analysis and Field Line Tracing in the Non-Axisymmetric Magnetic Perturbations

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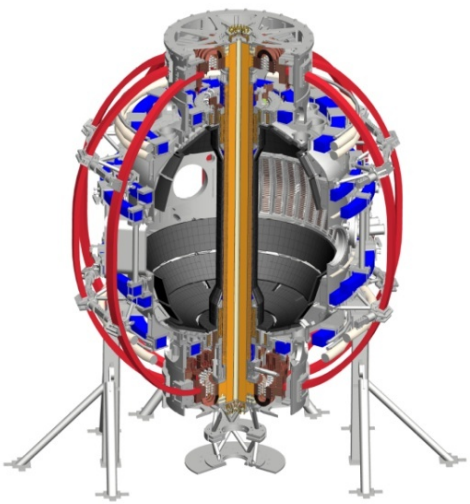

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Background

- Neoclassical Toroidal Viscosity (NTV) plays an important role for control of plasma rotation, stability and performance in perturbed tokamaks
  - Non-axisymmetric magnetic perturbations (NAMPs) can fundamentally change the neoclassical transport by distorting particle orbits on deformed or broken flux surfaces
  - NAMPs drive significant magnetic braking by NTV, thus change plasma rotation impacting on tokamak performance
  - NAMPs are important control elements to actively stabilize locked modes, edge localized modes, and resistive wall modes

- Analytic NTV theories have been successful to show fundamental physics, but lack of quantitative validations
  - $1/\nu$ regime in the high collisionality **[K.C. Shaing, POP (2003)]**, $\nu\_\nu^{1/2}$ regime in the low collisionality **[K.C. Shaing, POP (2008)]**, superbanana plateau regime in the low ExB precession **[K.C. Shaing, PPCF (2009)]**
  - Neoclassical offset rotation in the counter-I_p direction **[A.J. Cole, PRL (2007)]**
  - Approximations by large-aspect-ratio, zero-orbit-width, simplified collision operator, only trapped particles, and/or regime separation
  - Missing physics for rotational resonances

Motivation to δf particle code for NTV calculation

- A δf particle code has been developed to calculate neoclassical transport in perturbed tokamaks
  - Verify basic NTV physics such as quadratic δB dependency, BH resonance, etc
  - Analyze and predict NTV in magnetic braking experiments, using δB spectrum from 3D perturbed equilibrium solver (IPEC)

- Bounce-harmonic (BH) resonance enhancing NTV **[K. Kim, PRL (2013)]**
  - Predicted by **[Linsker and Boozer, PFL (1982)]**, **[H.E. Mynick, NF (1986)]**, and reformulated by **[J.-K. Park, PRL (2009)]**
  - Only mechanism to enhance the NTV in the fast rotating plasma
  - Orbit closing by resonant ExB is a critical physics to explain the BH enhanced NTV, which can be captured only by particle simulation w/o approximations
  - First numerical verification of enhancement mechanism of NTV by BH resonances
  - Recent KSTAR experiments of strong magnetic braking by BH resonances

- New capability for field line tracing considering plasma response
  - Enable field line tracing considering ideal plasma response compared to vacuum field

Outline

- δf guiding-center particle code – POCA
- Applications to validating theories
- Applications to magnetic braking experiments
- Applications to field line tracing
- Summary

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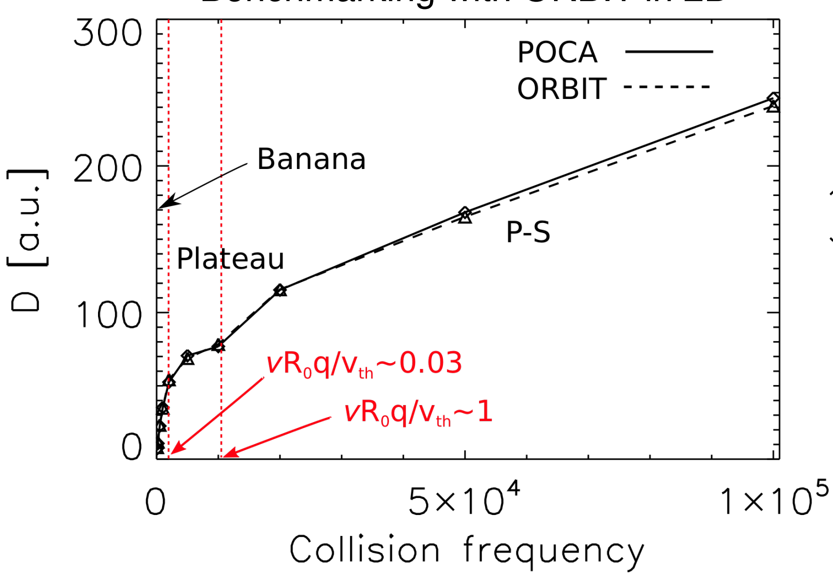
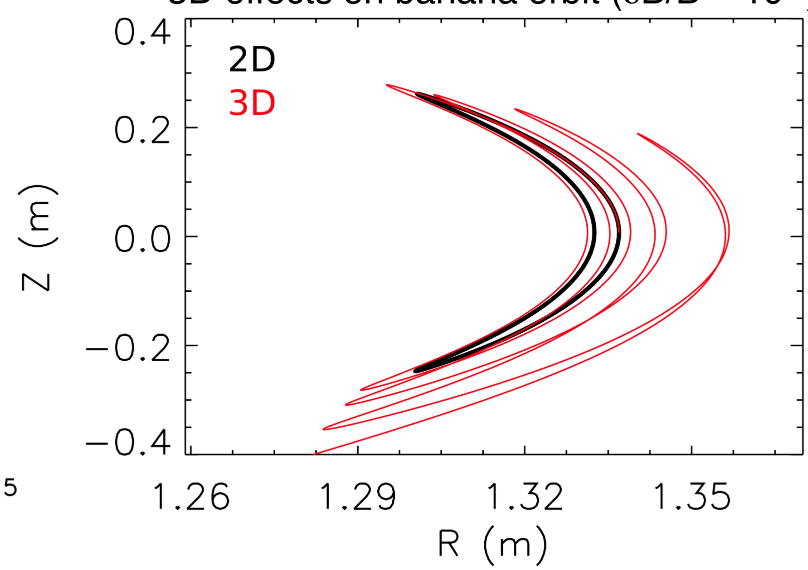
POCA is a drift-kinetic δf particle code for neoclassical transport calculation in NAMPs

- POCA (Particle Orbit Code for Anisotropic pressures) **[K. Kim, POP (2012)]**
  - Follows guiding-center orbit motions on the flux coordinates
  - Solves Fokker-Plank equation with modified pitch-angle scattering collision operator conserving toroidal momentum
  - Calculates local neoclassical quantities: Diffusion, flux, bootstrap current
  - Calculates anisotropic tensor pressure and NTV torque
  - Uses DCON/IPEC type routines and parallelized with MPI
  - Reads 2D equilibrium from 20 equilibrium types and 3D magnetic perturbations from IPEC and analytic model

Benchmarking with ORBIT in 2D



3D effects on banana orbit ($\delta B/B \sim 10^{-2}$)



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

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

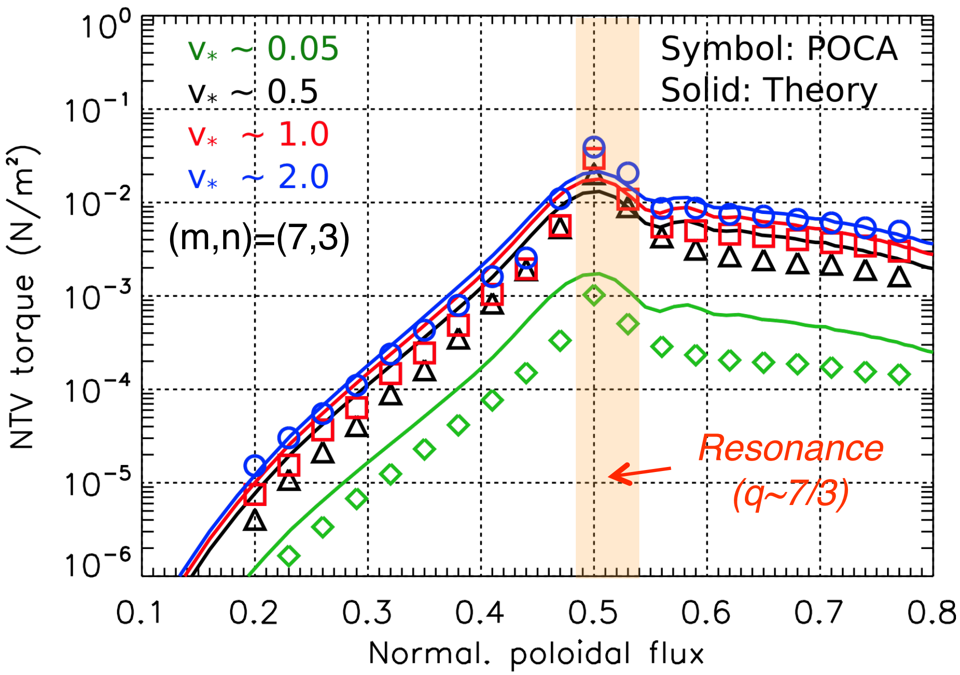
  - Fokker-Planck equation is reduced to $\frac{d\hat{f}}{dt}-C_m(f)=-\vec{v}\cdot\nabla\psi\frac{\partial\ln f_M}{\partial\psi}-\vec{F}\cdot\frac{\partial\ln f_M}{\partial\vec{v}}$

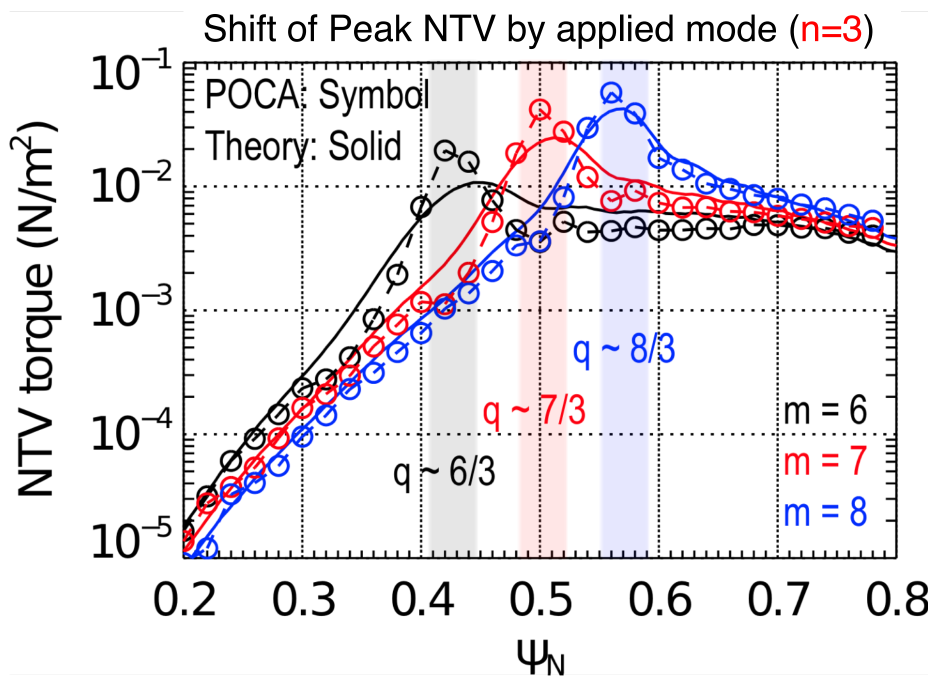
  - Using local Maxwellian, δf can be obtained from

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

Neoclassical Toroidal Viscosity (NTV) is calculated using perturbed pressures and magnetic field spectrum

- NTV calculation was benchmarked with analytic NTV theory
  - POCA calculates NTV torque using magnetic field spectrum decomposed to Fourier series and perturbed pressures $$\delta P = \delta P_\perp + \delta P_\parallel = \int d^3v \left(\frac{1}{2} m v_\perp^2 + m v_\parallel^2 \right) \delta f$$
    [J.D. Williams and A.H. Boozer, POP (2003)]
  - NTV torque is calculated in Boozer coordinates by $$\tau_\phi = \langle \hat{e}_\phi \cdot \nabla \cdot \vec{P} \rangle = \left\langle \frac{\delta P}{B} \frac{\partial B}{\partial \phi} \right\rangle$$
  - Calculated NTV torque shows good agreements with theory, revealing strong resonant features to applied magnetic perturbation **[K. Kim, POP (2012)]**





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Combined NTV theory is a good guide for benchmarking

- Combined NTV formula reflects fundamental NTV physics [J.-K. Park, PRL (2009)]
  - Bounce-averaged drift-kinetic equation based on BH resonance is analytically solved using Krook collision to connect regimes
  - The combined NTV formula gives the toroidal torque density as

$$\boxed{\left\langle \hat{e}_\phi \cdot \nabla \cdot \vec{\Pi} \right\rangle_l = \frac{\varepsilon^{-1/2} P}{\sqrt{2}\pi^{3/2} R_0} \underbrace{\int_0^1 d\kappa^2 \delta_{\omega,l}^2}_{\delta B^2} \underbrace{\int_0^\infty dx R_{1l}}_{\text{Resonance}} \left[\underbrace{u^\varphi + 2.0\sigma \left| \frac{1}{e} \frac{dT}{d\chi} \right|}_{\omega_{rot}-\omega_{neo}} \right]}$$

$$\delta_{\omega,l}^2 = \sum_{nmm'} \delta_{nmm'}^2 \frac{F_{nml}^{-1/2} F_{nm'l}^{-1/2}}{4K(\kappa)} \qquad F_{nml}^{y} \equiv \int_{-\vartheta_t}^{\vartheta_t} d\vartheta \left(\kappa^2 - \sin^2(\vartheta/2)\right)^y \underbrace{\cos(m - nq \pm l)\vartheta}_{\text{Phase shift of resonant surface by ExB precession}}$$

$$R_{yl} = \frac{1}{2} \frac{n^2\left(1+(l/2)^2\right)\frac{\nu}{2\varepsilon} x \left(x - \frac{5}{2}\right)^y e^{-x}}{\left(\underbrace{l\omega_{l,bounce} - n\omega_{E\times B}}_{\text{Bounce-harmonic resonance}} - \underbrace{n\omega_{\nabla B}}_{\text{Magnetic precession}}\right)^2 + \left(\left(1+(l/2)^2\right)\frac{\nu}{2\varepsilon}\right)^2 x^{-3}}$$

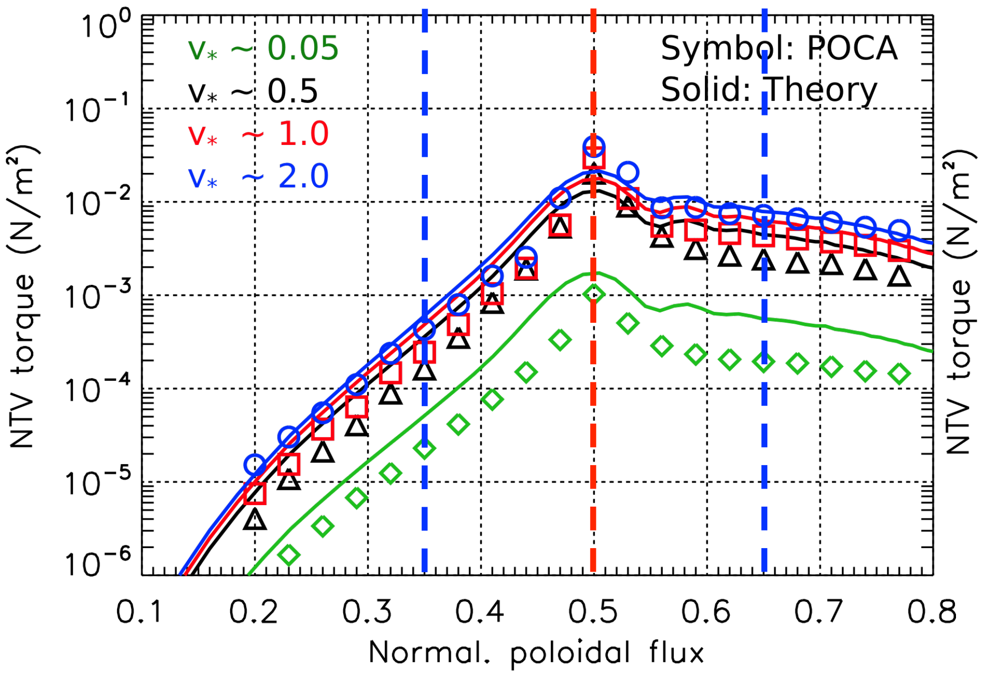
  - Include δB^2 dependency, various resonances between bounce motion, magnetic precession, electric precession, and neoclassical offset rotation

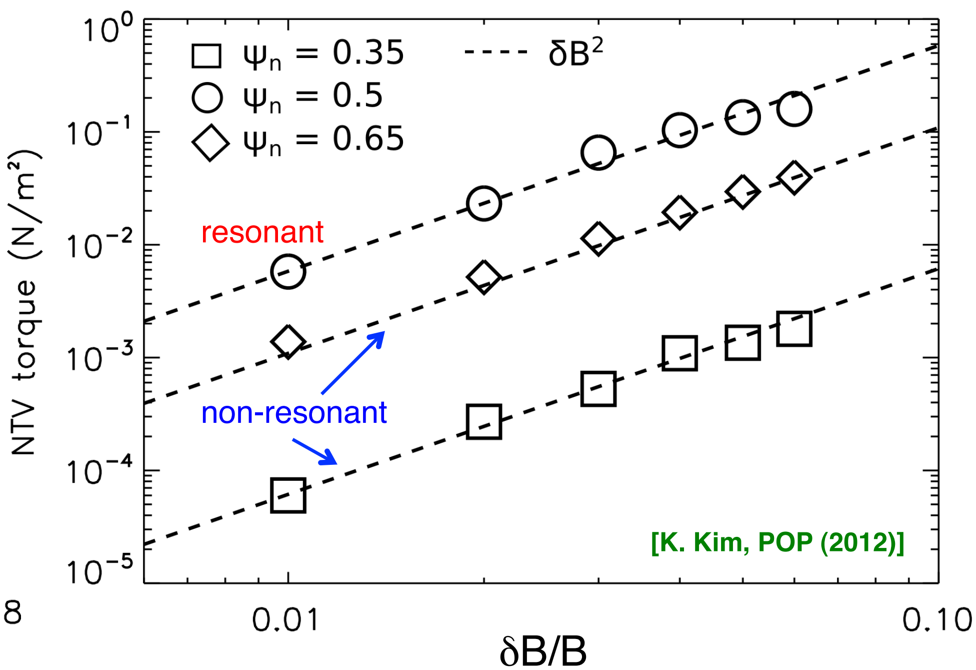
Quadratic δB dependency is the fundamental NTV physics

- Particle simulation confirms the quadratic δB dependency of NTV

$$\left\langle \hat{e}_\phi \cdot \nabla\cdot \vec{\Pi} \right\rangle_l = \frac{\varepsilon^{-1/2} P}{\sqrt{2}\pi^{3/2} R_0} \underbrace{\int_0^1 d\kappa^2 \delta_{\omega,l}^2}_{\delta B^2} \int_0^\infty dx R_{1l} \left[u^\varphi + 2.0\sigma \left| \frac{1}{e}\frac{dT}{d\chi} \right| \right]$$

  - NTVs at both resonant and non-resonant flux surfaces increase as δB increases following $\tau_\phi \sim (\delta B)^2$
  - Useful to particle simulation, enable NTV scaling by δB to improve statistics





New type of closed orbit is formed by rotational resonance

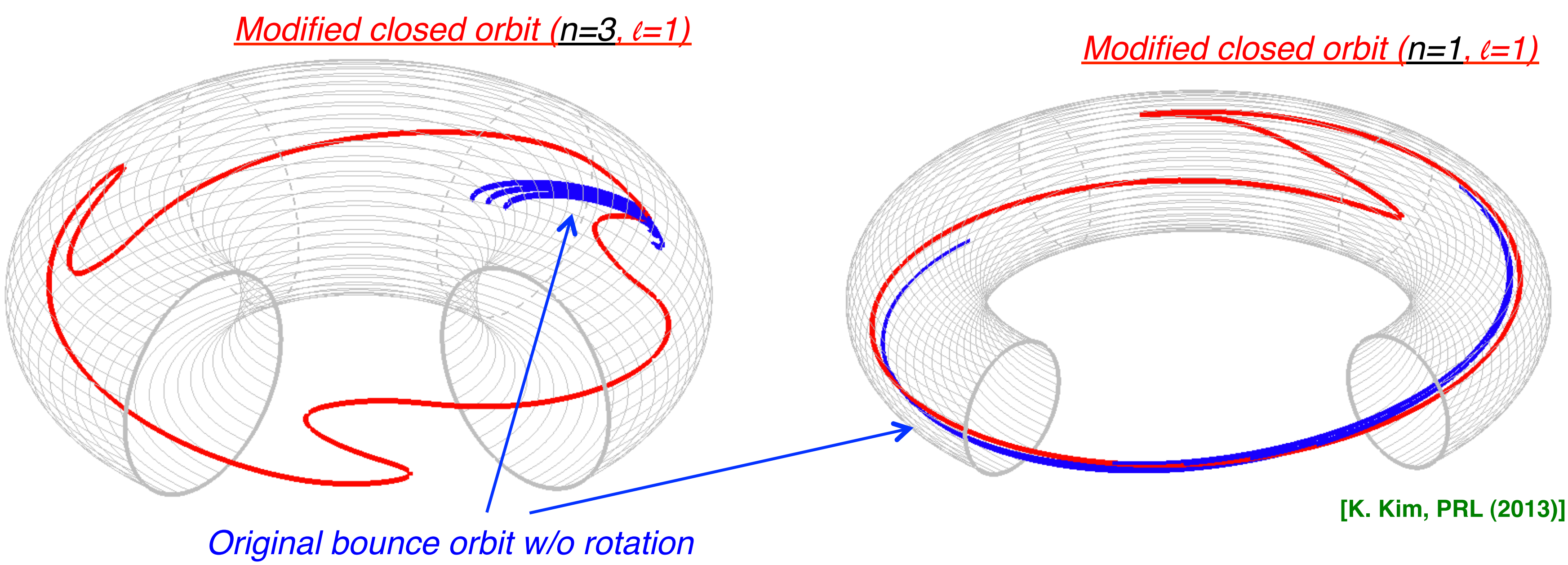
- Parallel/perpendicular ExB drifts can form a closed loop at resonance
  - Resonant field is shifted to follow path of the closed orbit satisfying

$$\text{Resonant field condition}: \quad m - nq \pm l = 0$$

  - Resonance condition is represented by particle's bouncing class ℓ

$$\text{Resonant condition}: \quad l\omega_b \approx n\omega_E$$

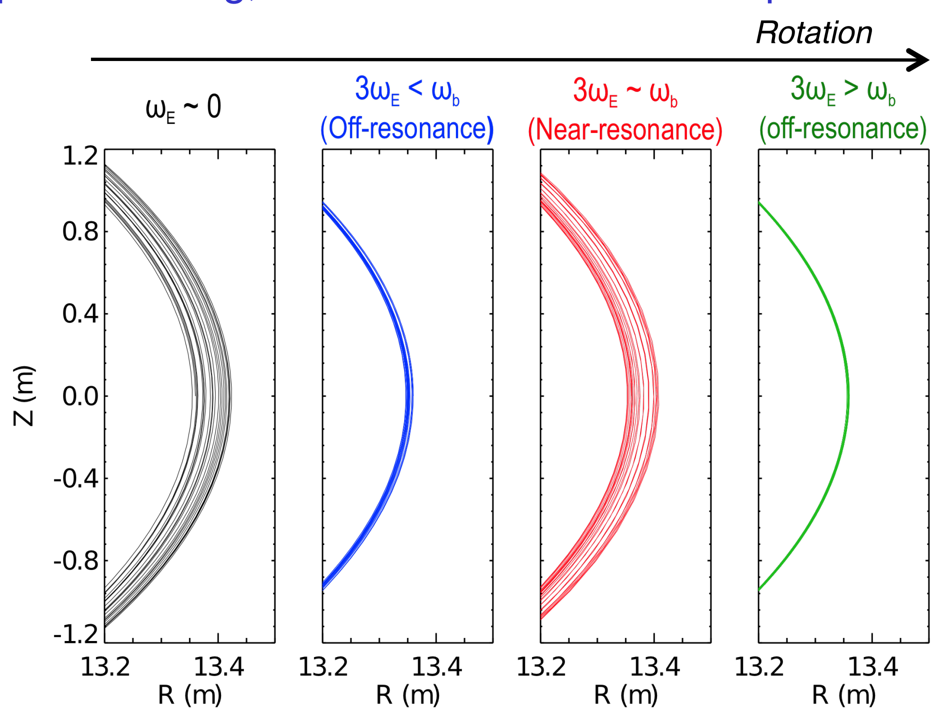
  - Banana orbits can be closed, if ExB is fast enough to reach BH resonant frequency
  - Various closed orbits can exist depending on energy and pitch of particle, magnetic field configuration, and ExB precession



[K. Kim, PRL (2013)]

Rotation scan clarifies transport mechanism by rotational resonances

- BH resonances enhance radial particle transport by closed orbits preventing random phase-mixing
  - Radial drift is large when $\omega_E \sim 0$ as orbits are nearly closed without ExB precession, equivalent to superbanana plateau resonance
  - When ω_E is off-resonant ($3\omega_E \neq \omega_b$), particle drift decreases due to phase-mixing
  - When ExB approaches the first BH resonant frequency ($3\omega_E \sim \omega_b$), modified closed orbit prevents phase-mixing, thus enhances radial transport and NTV



[K. Kim, PRL (2013)]

Peak NTV is found at the resonant ExB precession frequency, verifying BH resonances in NTV

- BH resonance enhanced NTV is confirmed by Er scan
  - Theory indicates bounce-harmonic resonances occur when

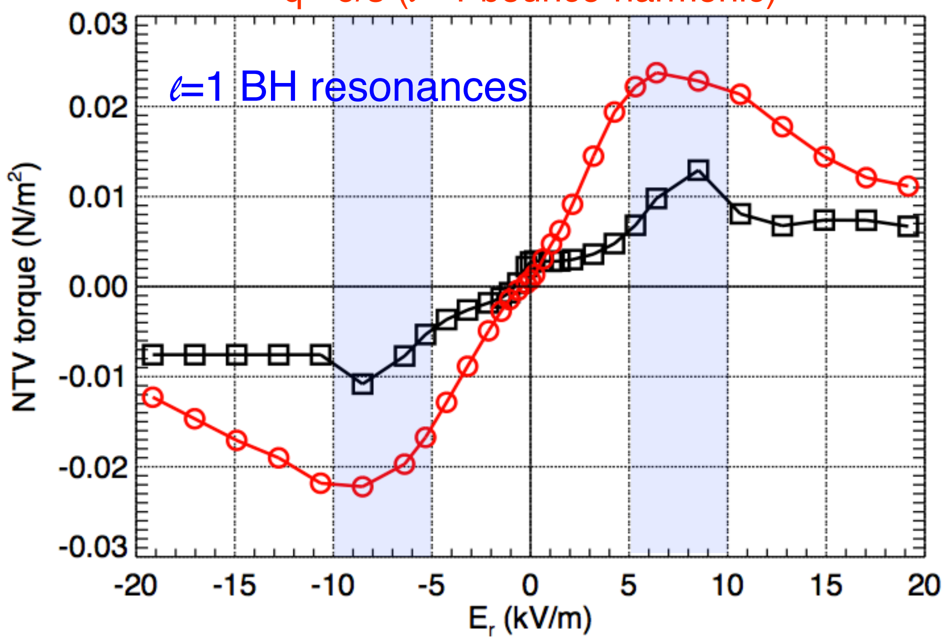
$$l\omega_b - n\omega_E - n\omega_{\nabla B} = 0 \quad \longrightarrow \quad l\omega_b \approx n\omega_E$$

  - Resonance flux surface is shifted to $m - nq \pm l = 0 \quad \longrightarrow \quad q = (m \pm l)/n$
  - Bounce-harmonic resonance by ℓ = 1 class particles with (m=7, n=3) is predicted at

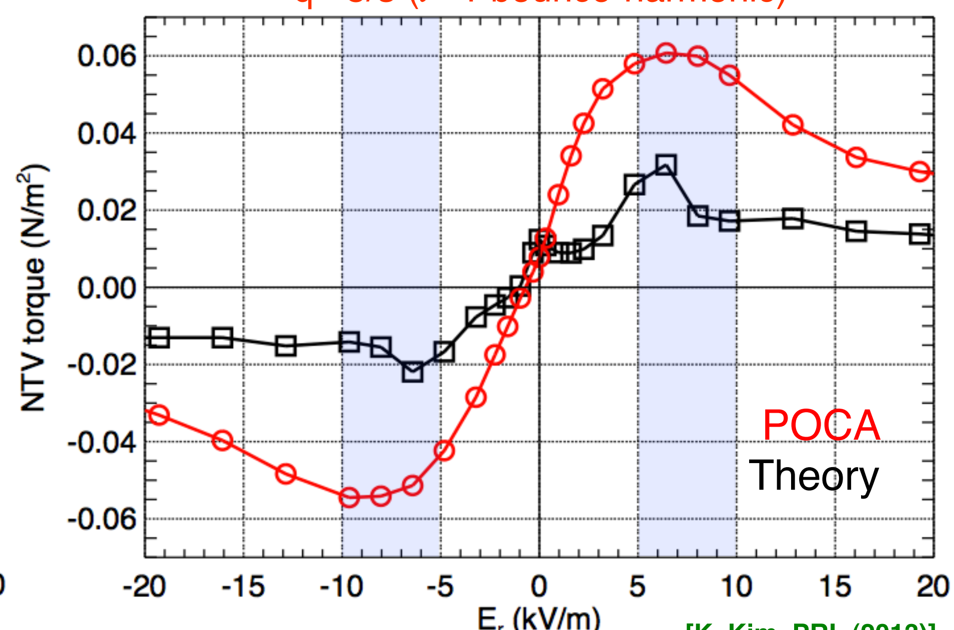
$$\omega_E \approx E_r / RB_p \quad \to \quad E_r \approx \pm 7 \text{ kV/m}$$

  - POCA reproduces strong peak NTV around predicted ExB precession frequency

q= 6/3 (ℓ =1 bounce-harmonic)



q= 8/3 (ℓ =1 bounce-harmonic)

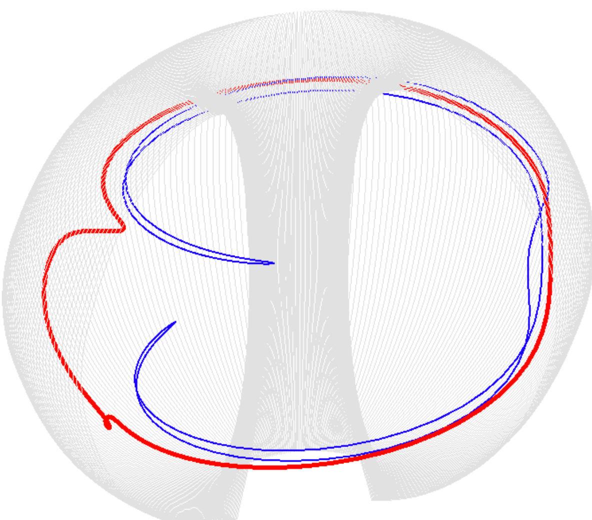


[K. Kim, PRL (2013)]

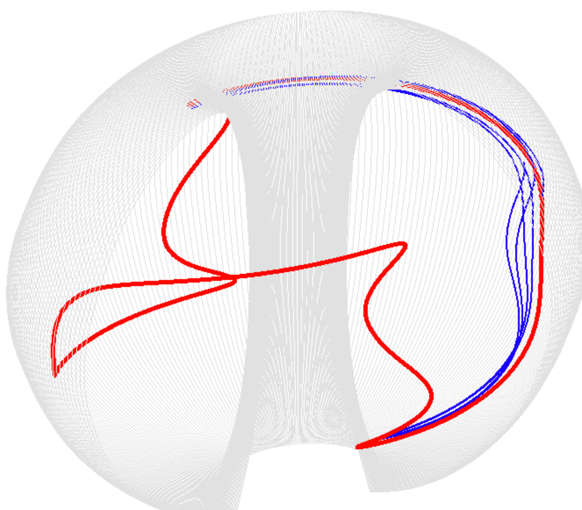
Closed orbits by BH resonances can be found in NSTX

- 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

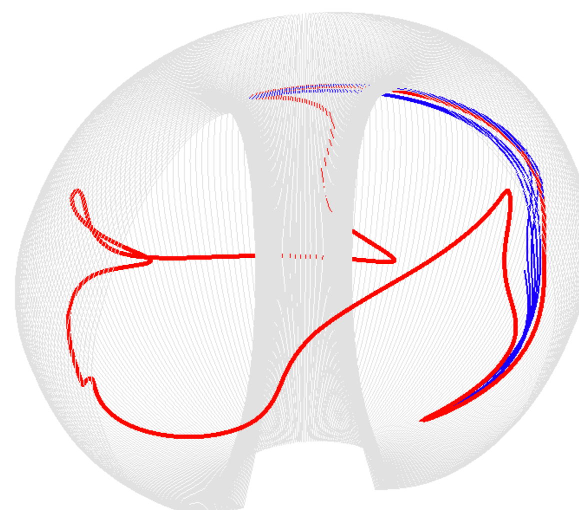
Closed orbit (n=1, ℓ=1)



Closed orbit (n=2, ℓ=1)



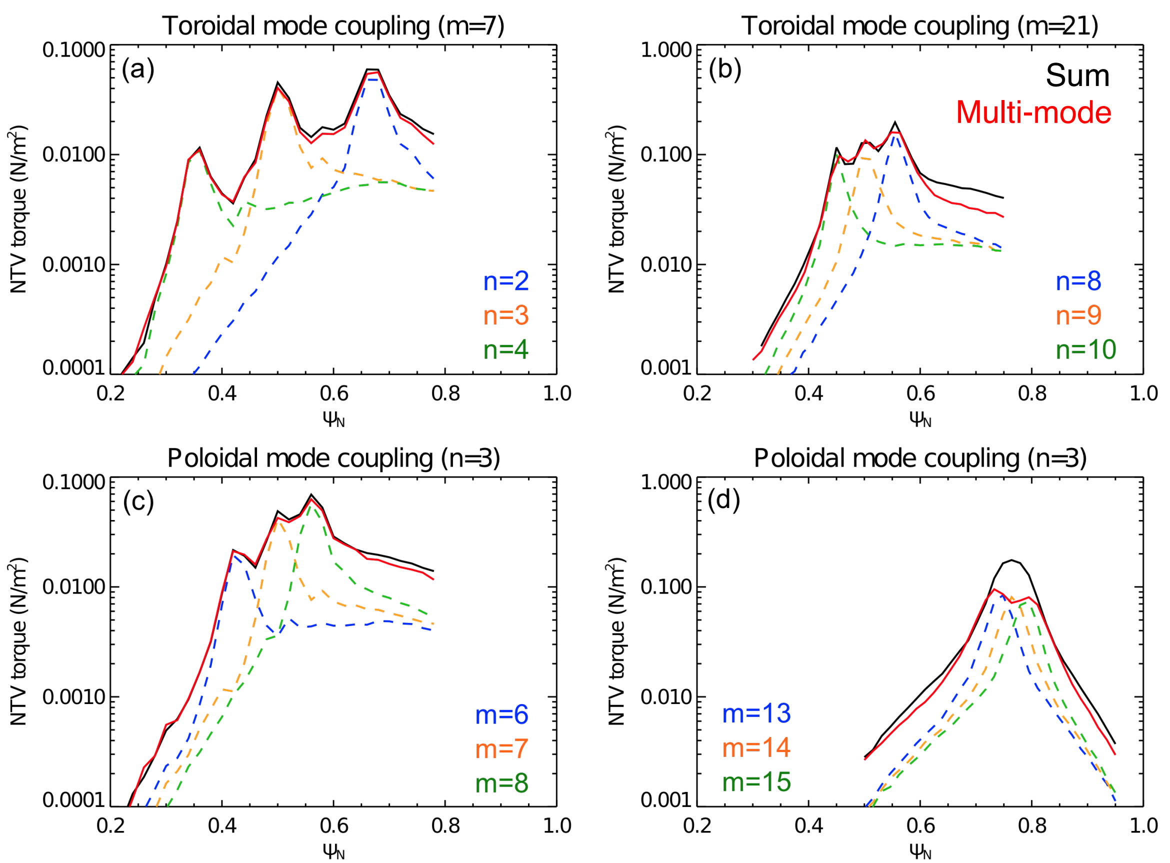
Closed orbit (n=3, ℓ=1)



Original bounce orbits w/o rotation

Mode coupling effect of NTV was tested using analytic δB

- Poloidal modes can be coupled but toroidal mode cannot
  - Three-mode magnetic perturbation applied and compared with linear NTV sum of three single-mode perturbations of the same harmonics
  - Indicate no or weak toroidal mode coupling effect regardless gap
  - Poloidal modes can couple when the gap is small



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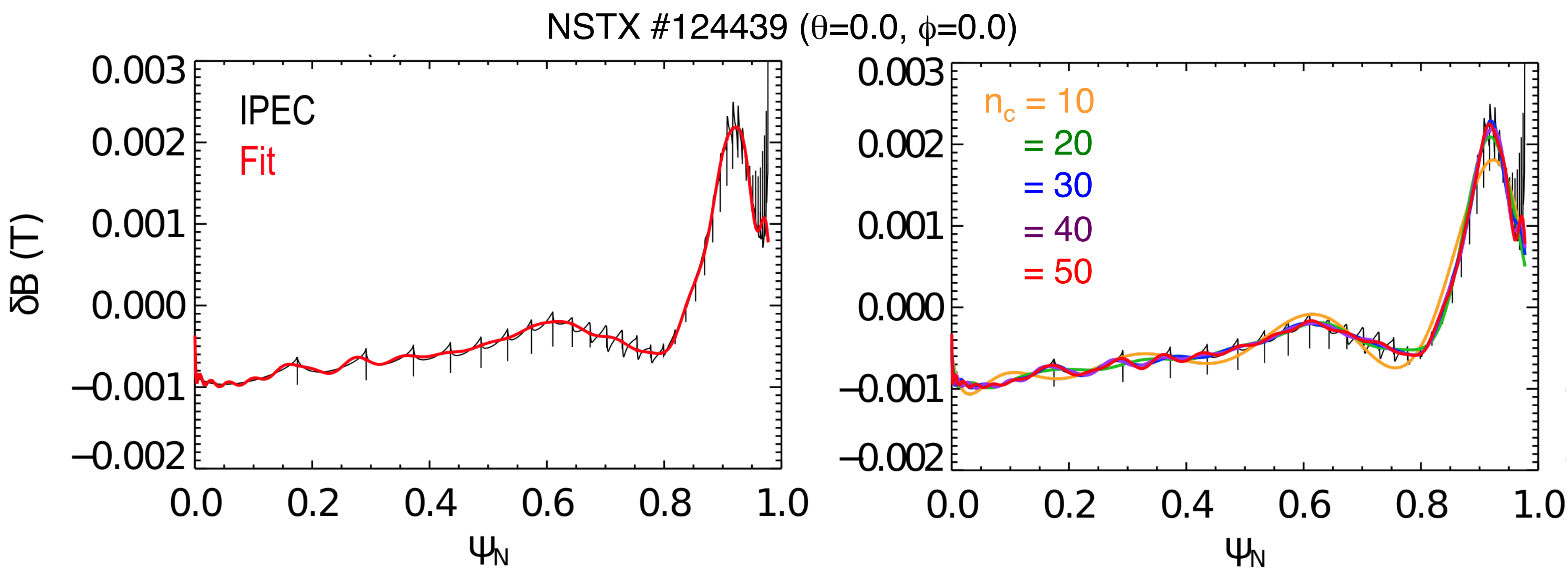
POCA is being actively applied to experimental analysis

- 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

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

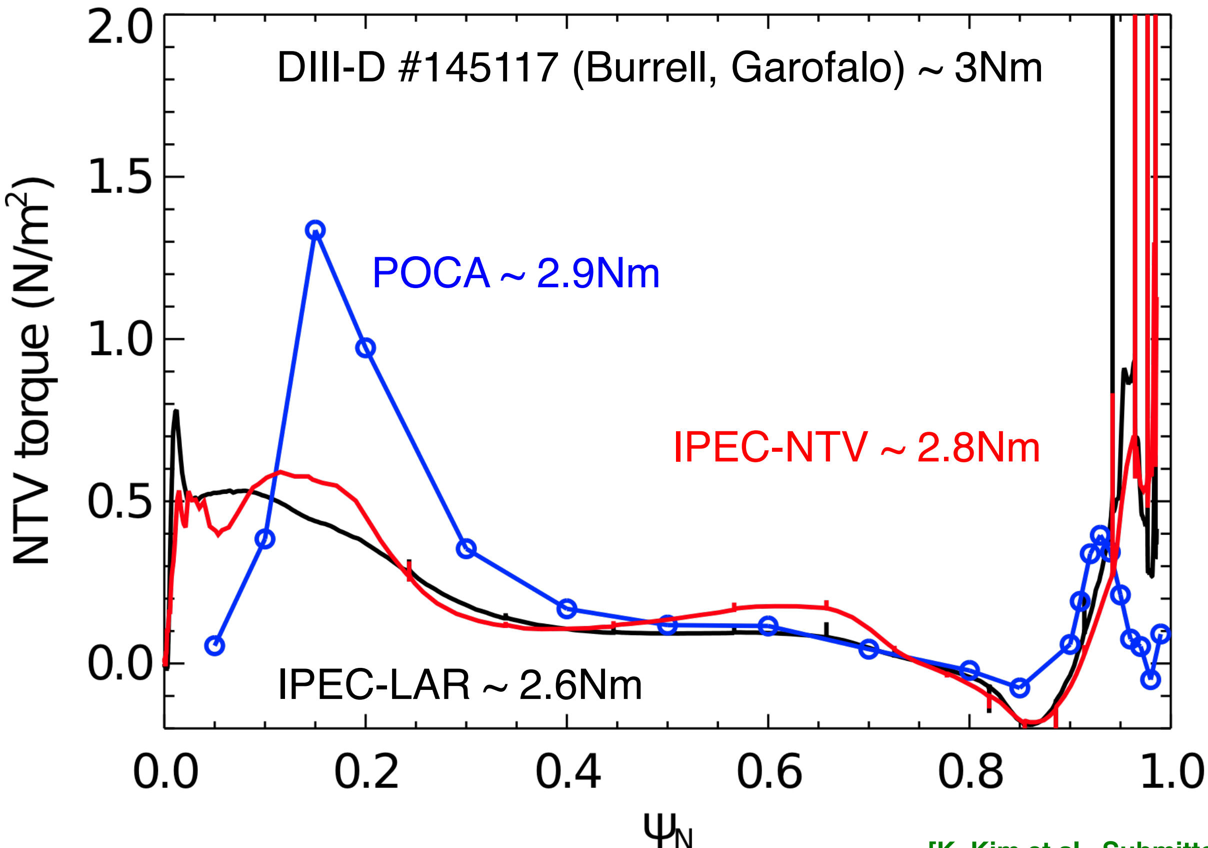
$$\delta B_{mn}(\psi_n) = \sum_m \left[\sum_j^{n_c} a_j \cos\left(j\cos^{-1}(x)\right)\cos\left(m\theta - n\phi\right) + b_j \cos\left(j\cos^{-1}(x)\right)\sin\left(m\theta - n\phi\right) \right] \quad \rightarrow \quad \textit{POCA}$$

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



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

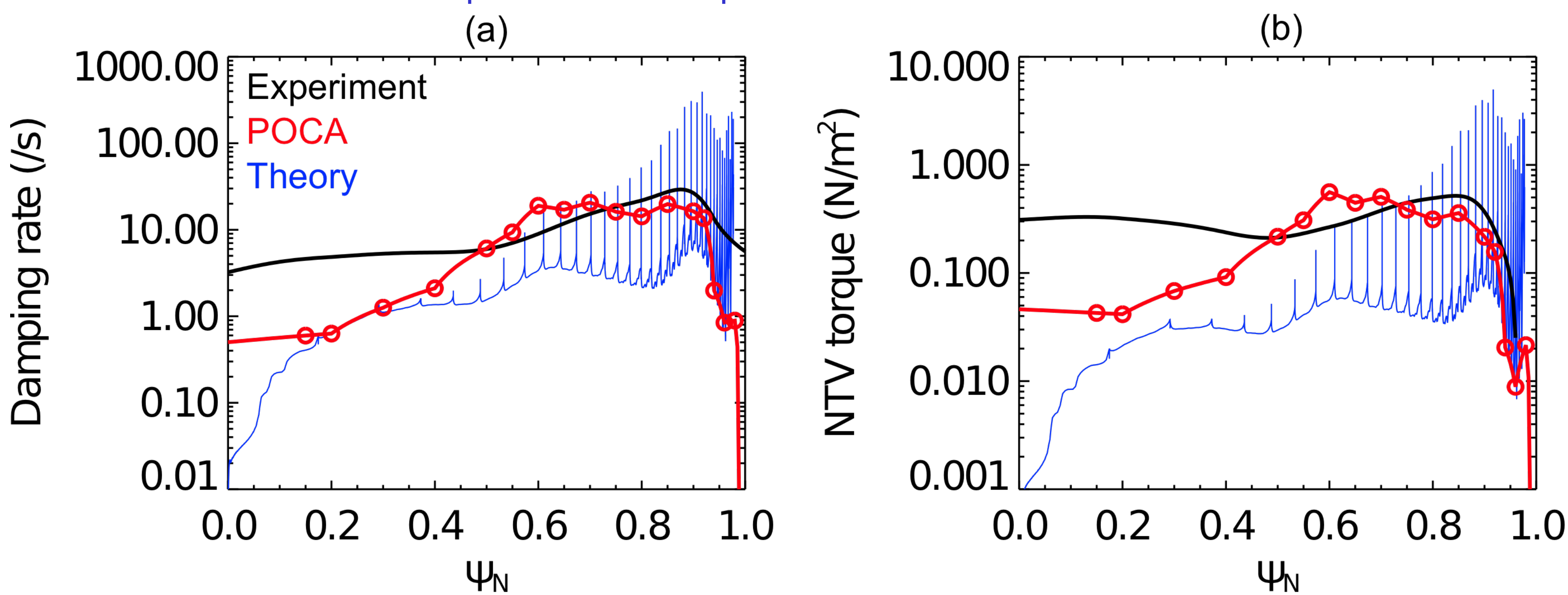
- Application of POCA to DIII-D n=3 magnetic braking (in QH mode experiments) using IPEC δB gives a consistent NTV
  - Consistent with combine NTV formula in profile, and good agreement with measurement in total NTV torque



[K. Kim et al., Submitted to Nucl. Fusion (2012)]

Prediction of NTV in NSTX can be improved with POCA

- Improved agreement with measurement in NSTX n=3 discharge
  - POCA calculates damping rate from NTV / Experiment gives NTV from damping rate
  - Both damping and NTV torque profiles show improved agreements with measurements
  - Combined theory is valid only within an order of magnitude, due to the large aspect-ratio expansion and ignoring finite-orbit-width
  - Total NTV torque agrees well: Exp. ~3.5Nm, POCA ~2.7Nm
  - Room for further improvement in experimental estimation and numerical simulation



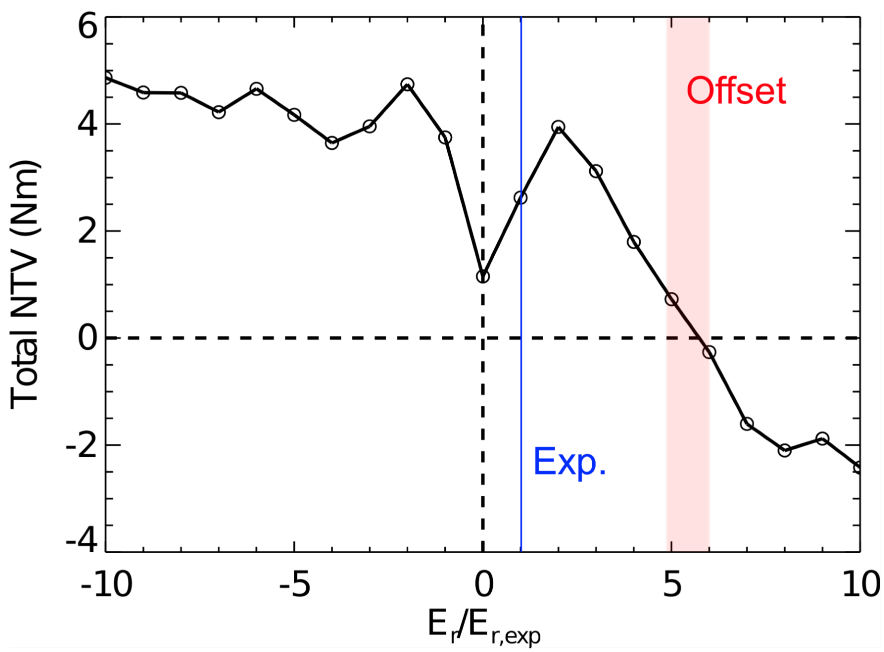
[K. Kim et al., Submitted to Nucl. Fusion (2012)]

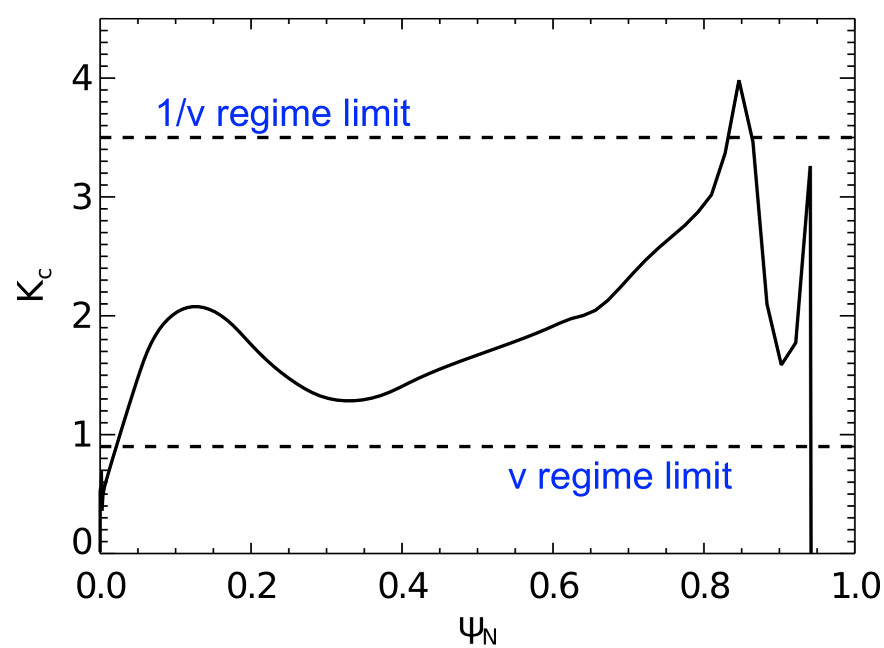
Neoclassical offset can be identified at zero-torque

- Rotation scan predicts neoclassical offset rotation
  - Neoclassical offset can be found approximately, when NTV crosses zero in rotation scan ($E_r/E_{r,exp}$~5)
  - Theoretically, neoclassical offset rotation is predicted by

$$V_{\phi,offset} = K_c \frac{1}{Z_i e B_\theta} \frac{dT_i}{dr} \qquad K_c = \frac{V_{\phi,offset}}{\frac{1}{Z_i e B_\theta}\frac{dT_i}{dr}} \approx 3.5\ (1/\nu\ \text{regime}) \quad \text{or} \quad 0.9\ \ (\nu\ \text{regime})$$

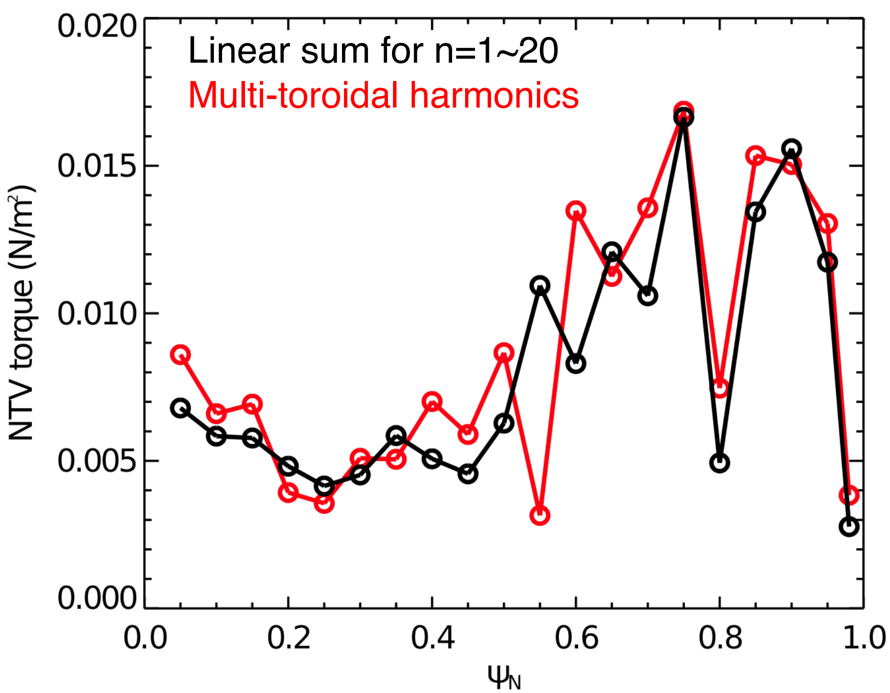
  - Numerically obtained K_c is consistent with theory prediction, indicating the plasma is in the connected regime

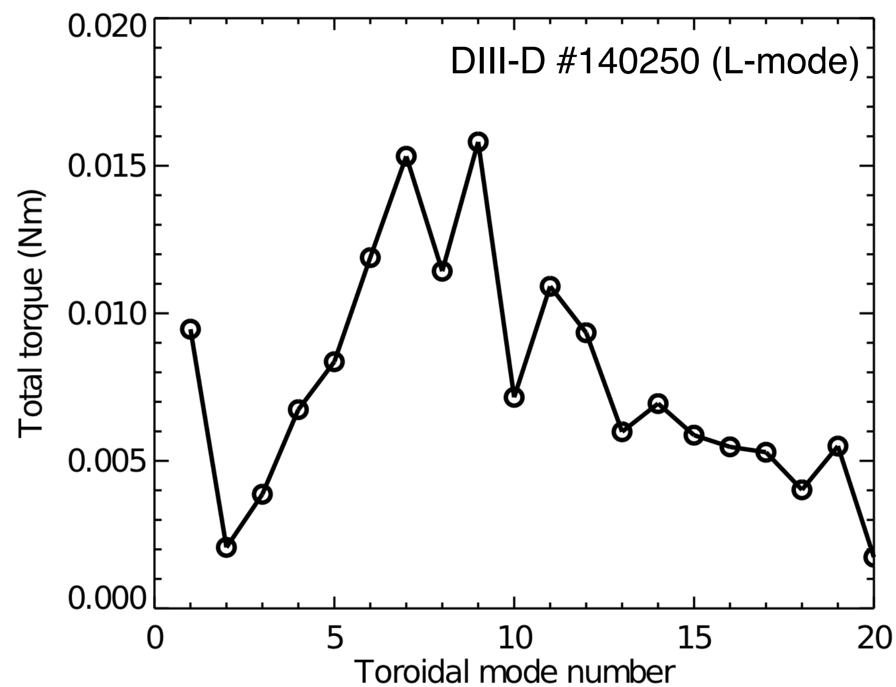




Toroidal mode coupling was tested for TBM mock-up experiment in DIII-D

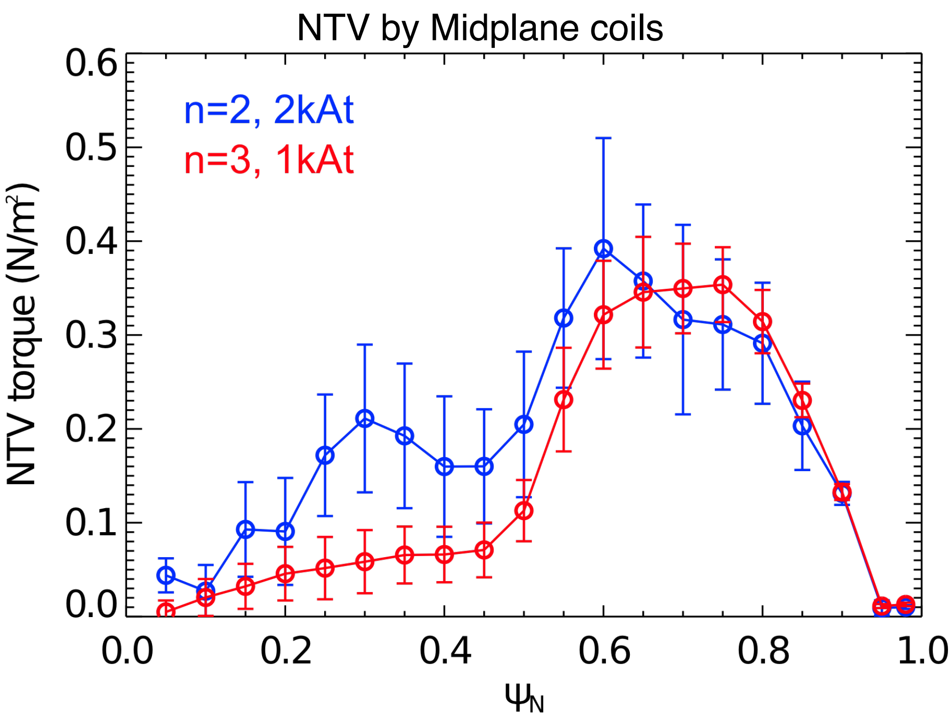
- No (or weak) toroidal coupling was found in TBM case
  - POCA can take multi-toroidal harmonics simultaneously
  - Obtained NTV by multi-modes comparable to linear NTV sum by single modes (~ 0.2 Nm with 10xδB in L-mode), indicating no (weak) toroidal mode coupling
  - Consistent trend with theory for NTV vs. toroidal mode number, but smaller NTV → Weak (no) braking in experiment?
  - High β plasma with visible braking effects will be the next target

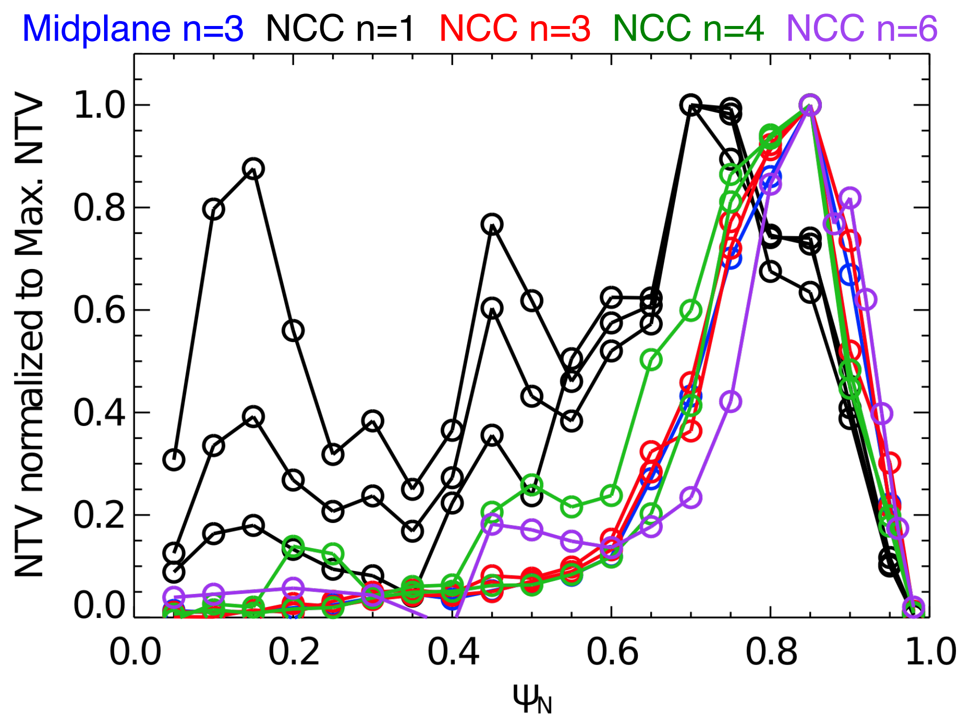




Various Braking Profiles in NSTX and NSTX-U

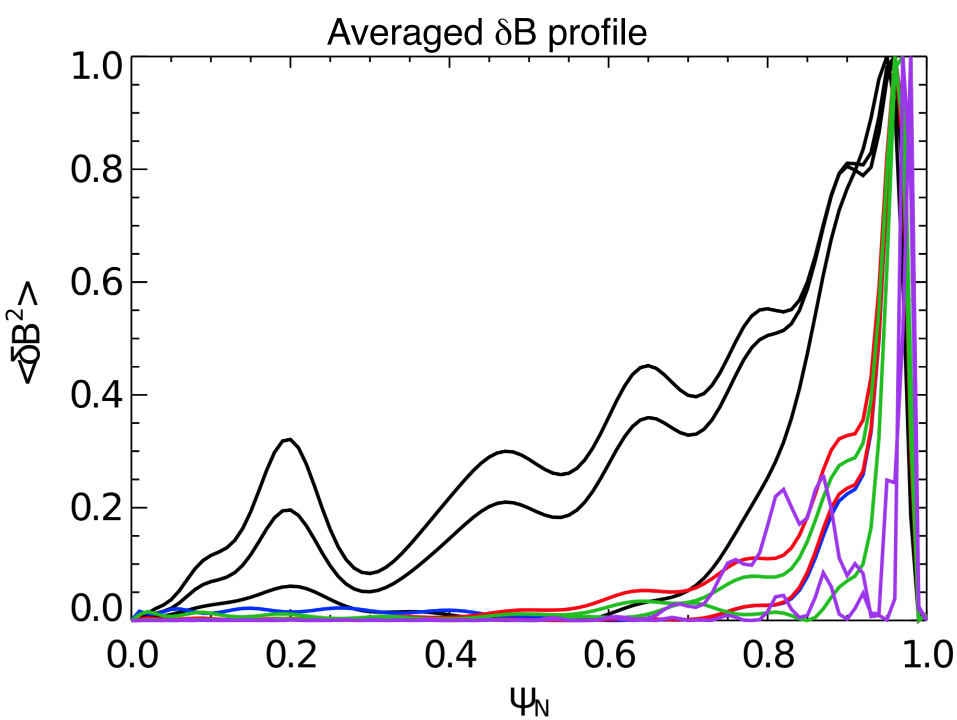
- POCA predicts variability of braking profiles by Midplane and NCC
  - Midplane coils can drive broad (n=2) or peaked (n=3) NTV profiles
  - (Full and/or partial) NCC can provide various braking profiles by n=1 ~ 6, depending on phases

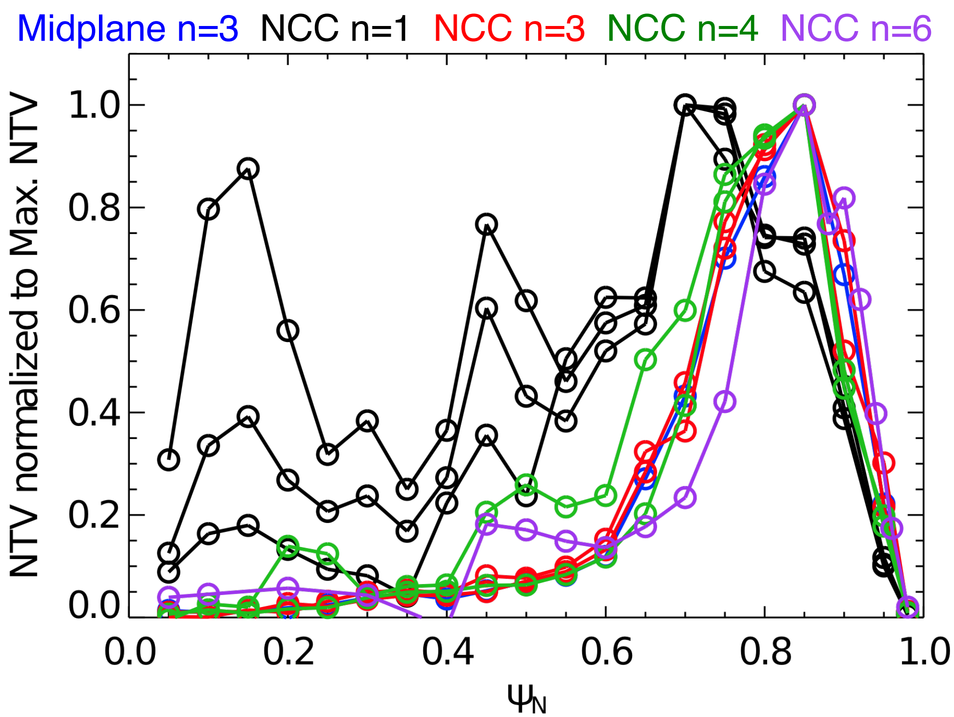




Various Braking Profiles in NSTX and NSTX-U

- POCA predicts variability of braking profiles by Midplane and NCC
  - Midplane coils can drive broad (n=2) or peaked (n=3) NTV profiles
  - (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





Outline

- δf guiding-center particle code – POCA
- Applications to validating theories
- Applications to magnetic braking experiments
- Applications to field line tracing
- Summary

New Capability for Field Line Tracing

- Field line tracing (FLT) routine is now implemented in POCA
  - Use cylindrical coordinates (R, Z, ϕ) including divertor/limiter/wall structures
  - Solves a set of magnetic differential equations

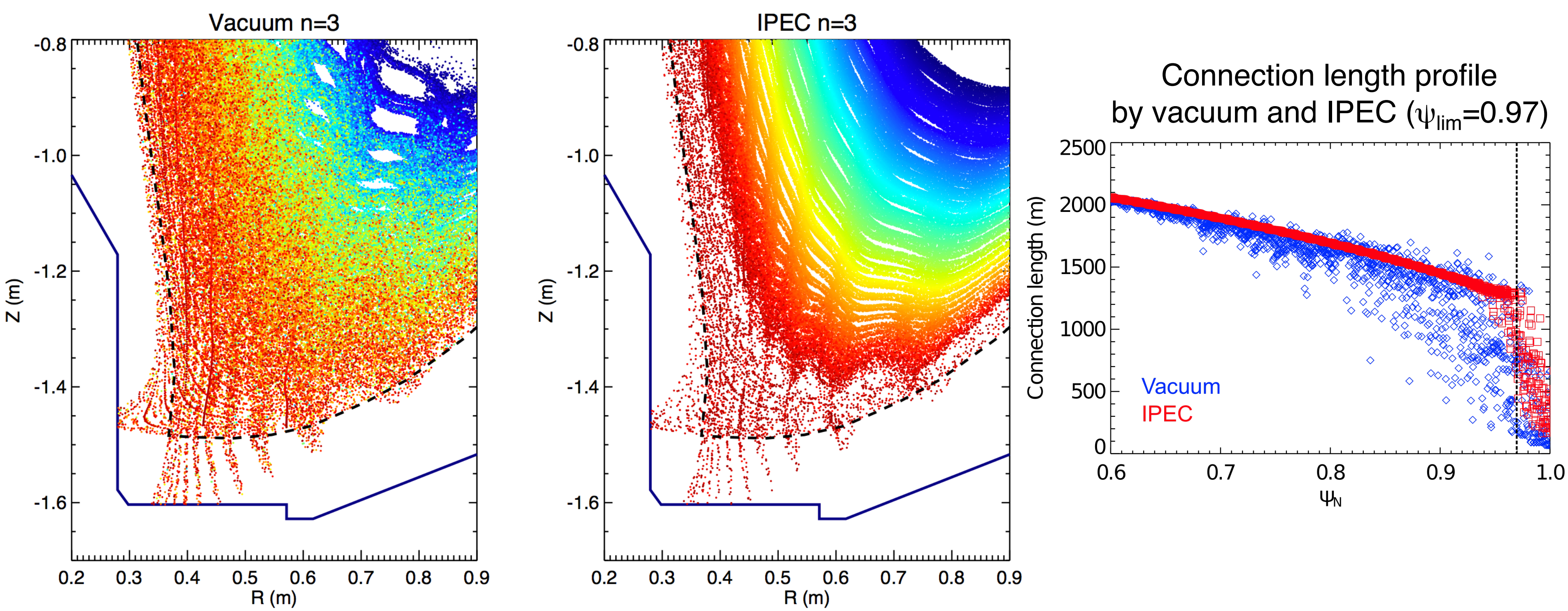
$$\frac{\partial R}{\partial \phi} = \frac{RB_R}{B_\phi} \qquad \frac{\partial Z}{\partial \phi} = \frac{RB_Z}{B_\phi}$$

  - Provide Poincare plot and divertor footprint modified by 3D field
  - Calculate field line connection length and field line loss fraction
  - Benchmarked with NSTX and DIII-D cases (i.e. lobe, divertor footprint, heat flux)
  - Applicable to NSTX-U NCC coil design study

- POCA-FLT has a unique capability via coupling with IPEC
  - Vacuum δB or IPEC δB with ideal plasma response can be taken, which reveals the shielding of resonant field and δB amplification by ideal response
  - Every possible field component can be included for NSTX(-U) with or without plasma response (EFC, PF5EF, TFEF)
  - Multi-toroidal mode can be calculated simultaneously
  - Parallelized for computational efficiency

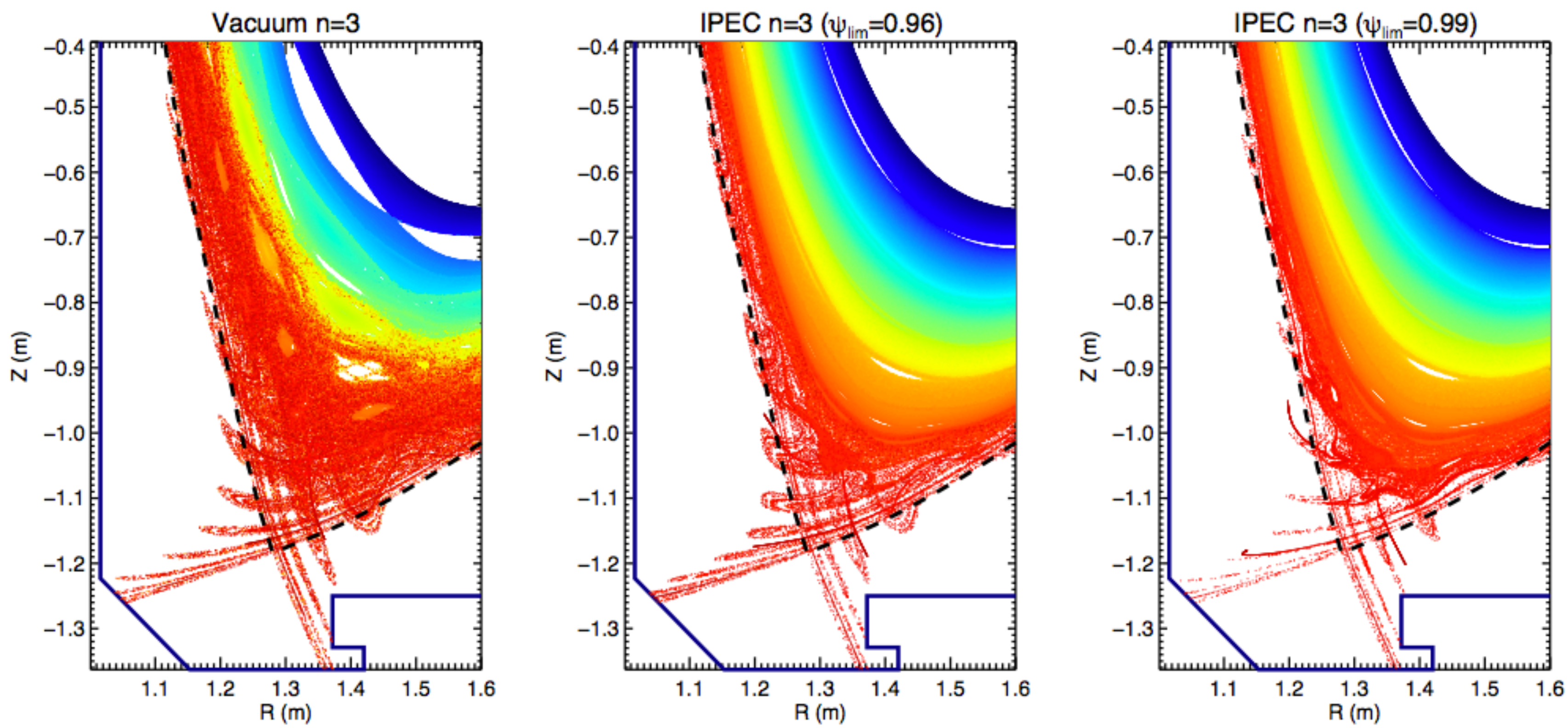
Example 1: NSTX n=3 mode

- Clear lobe structures are found from Poincare plot
  - Similar color indicates the similar initial flux surfaces (core: BLUE → edge: RED)
  - Show field line splitting on the divertor plate
  - Indicates ideal plasma responses shield resonant components, preventing opening of islands and field line loss from inner region (< ψ_n=0.97)
  - Connection length indicates the fundamental feature of stochastic fields



Example 2: DIII-D n=3 mode

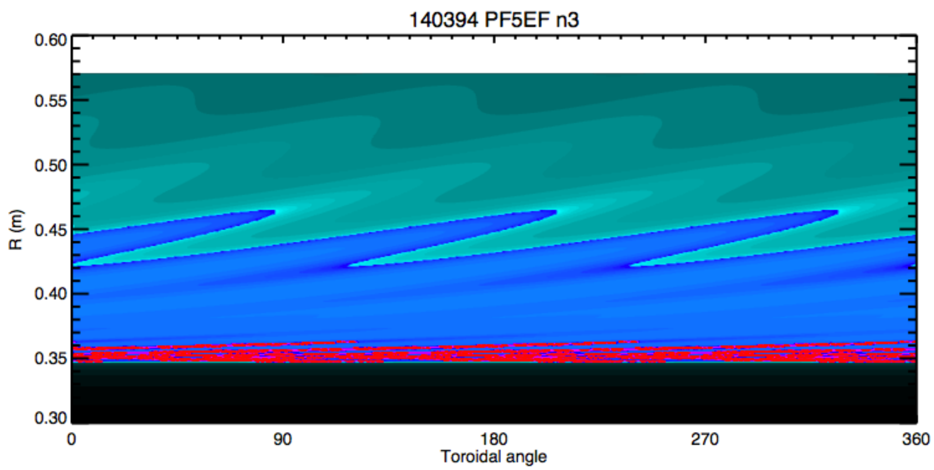
- Similar features by vacuum and plasma response are found
  - Stochastic region changes depending on the boundary for ideal plasma response (ψ_{lim}=0.96, 0.99)
  - Typical lobe structures in DIII-D n=3 are clearly obtained
  - Microscopic structure inside lobe is also captured



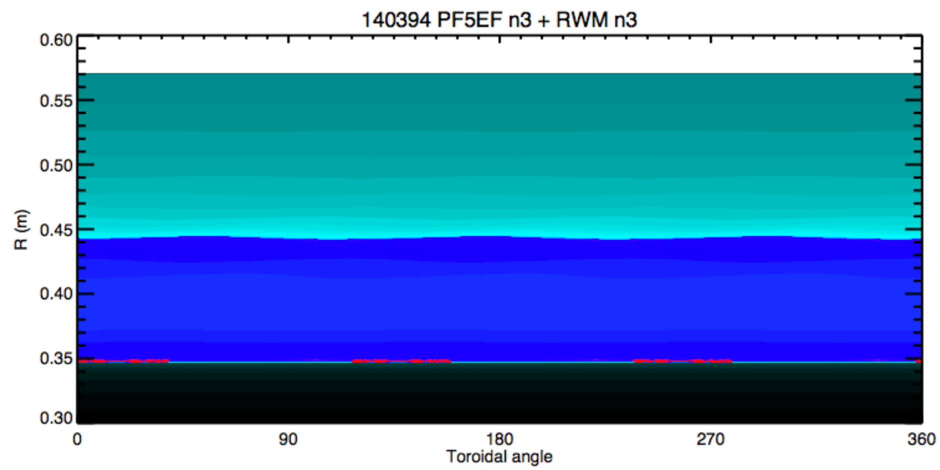
Example 3: n=3 Error Field Correction in NSTX

- Divertor footprint in NSTX EFC discharge shows a clear correction of n=3 error fields from PF5 coil
  - POCA-FLT takes multi-toroidal harmonics using IPEC inputs
    (i.e. n=3 by midplane, PF5 error field, n=1 by midplane, PF5/TF error fields)
  - Intrinsic n=3 error field by PF5 makes clear n=3 pattern
  - When error fields are corrected by midplane coils, split field lines almost disappear, indicating perfect error field correction

Intrinsic error field by PF5 (n=3)

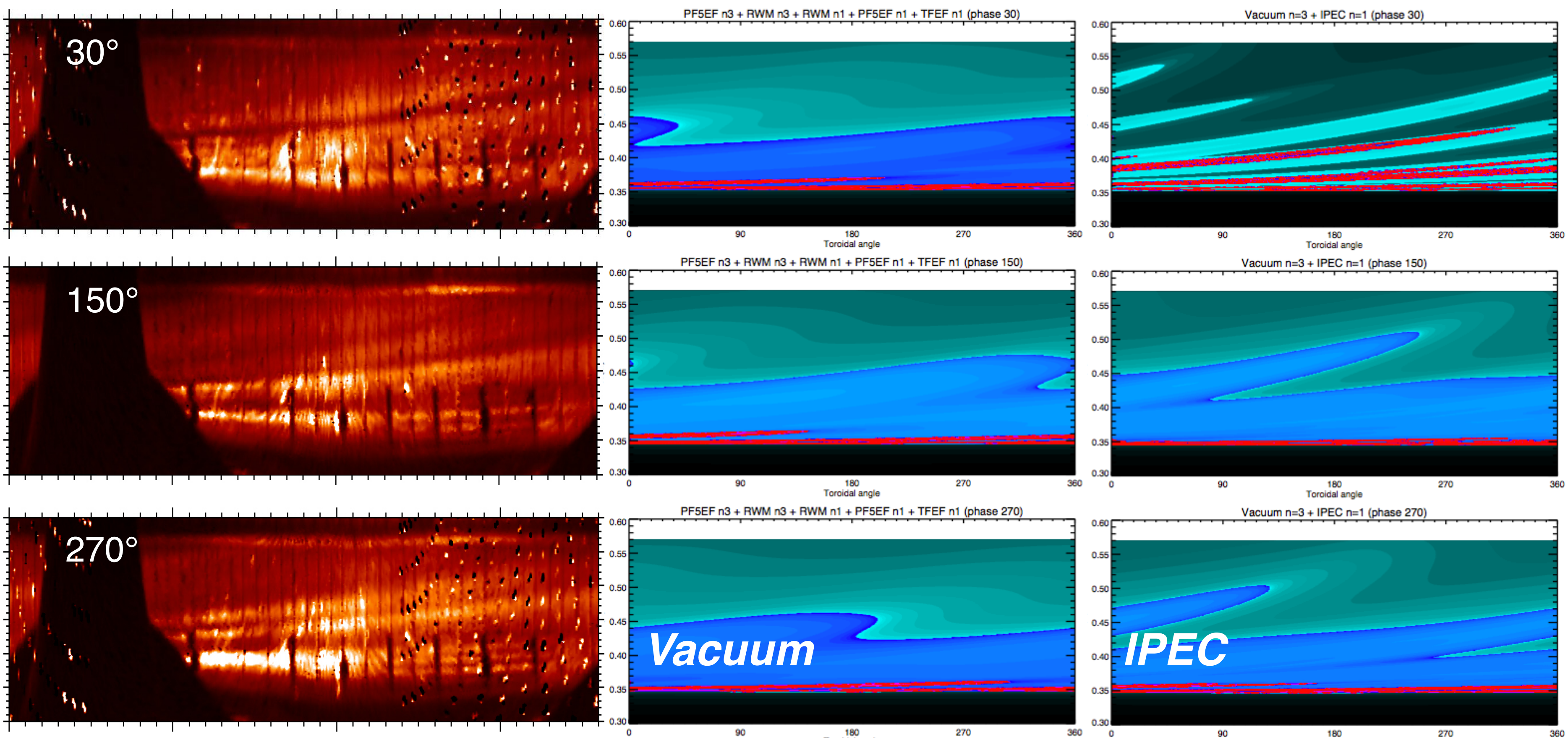


n=3 error field correction

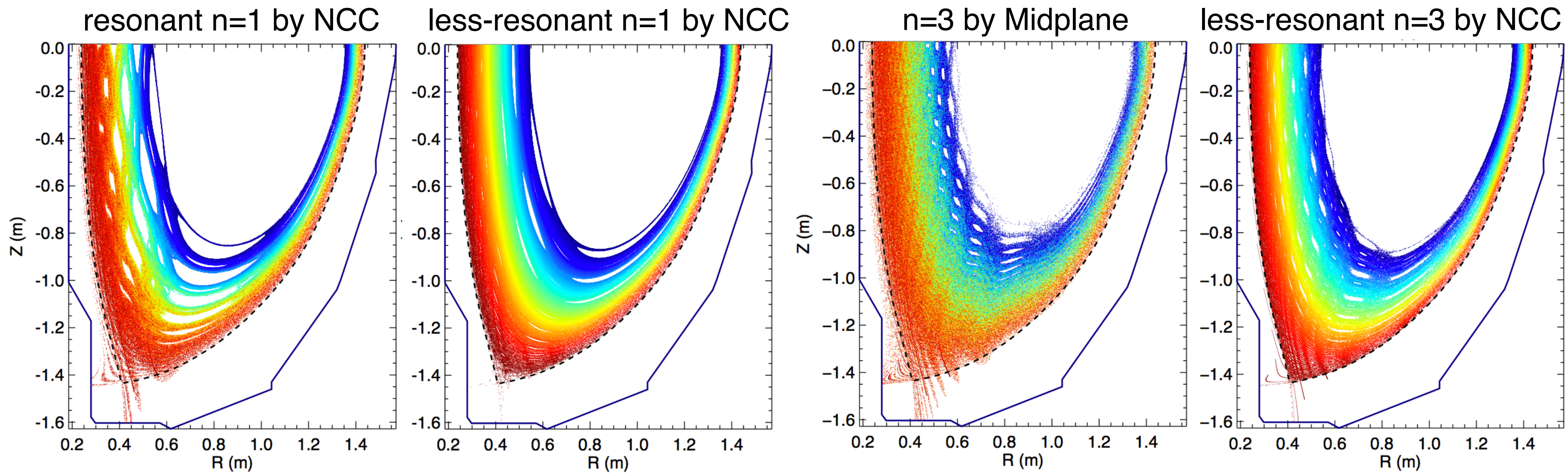


Example 4: POCA-FLT indicates the amplification of n=1 is responsible for the divertor footprint

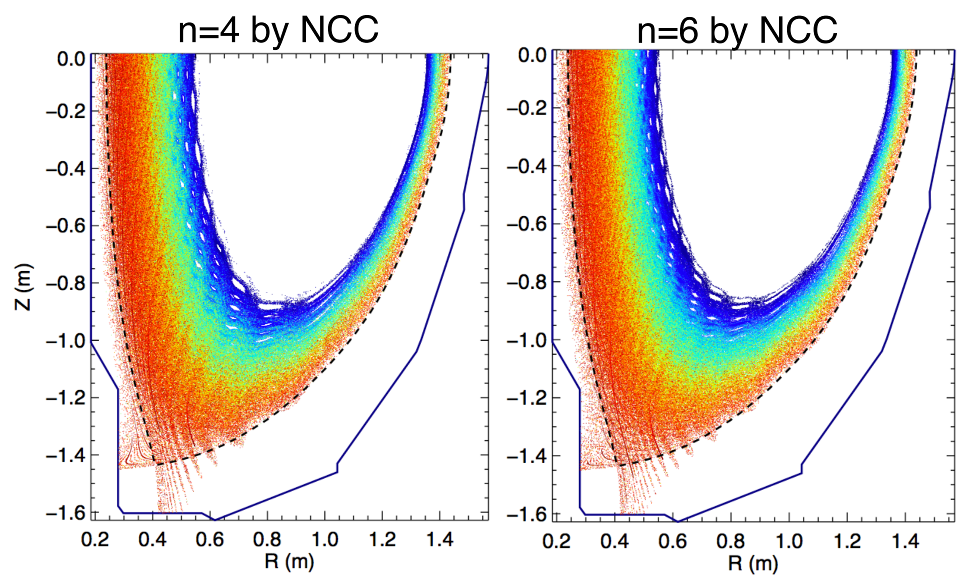
- Additional splitting is generated by amplification of n=1 perturbations
  - Vacuum field cannot explain observed divertor footprint, but n=1 amplifications can do
  - Field amplification by ideal plasma response is well-known, and revealed by FLT
  - Accurate equilibrium required due to sensitivity of n=1 plasma response



Example 5: Field Line Tracing 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



Summary

- POCA is being extensively applied to study NTV physics
  - Verify and validate theories, analyze and predict experiments, investigate new physics

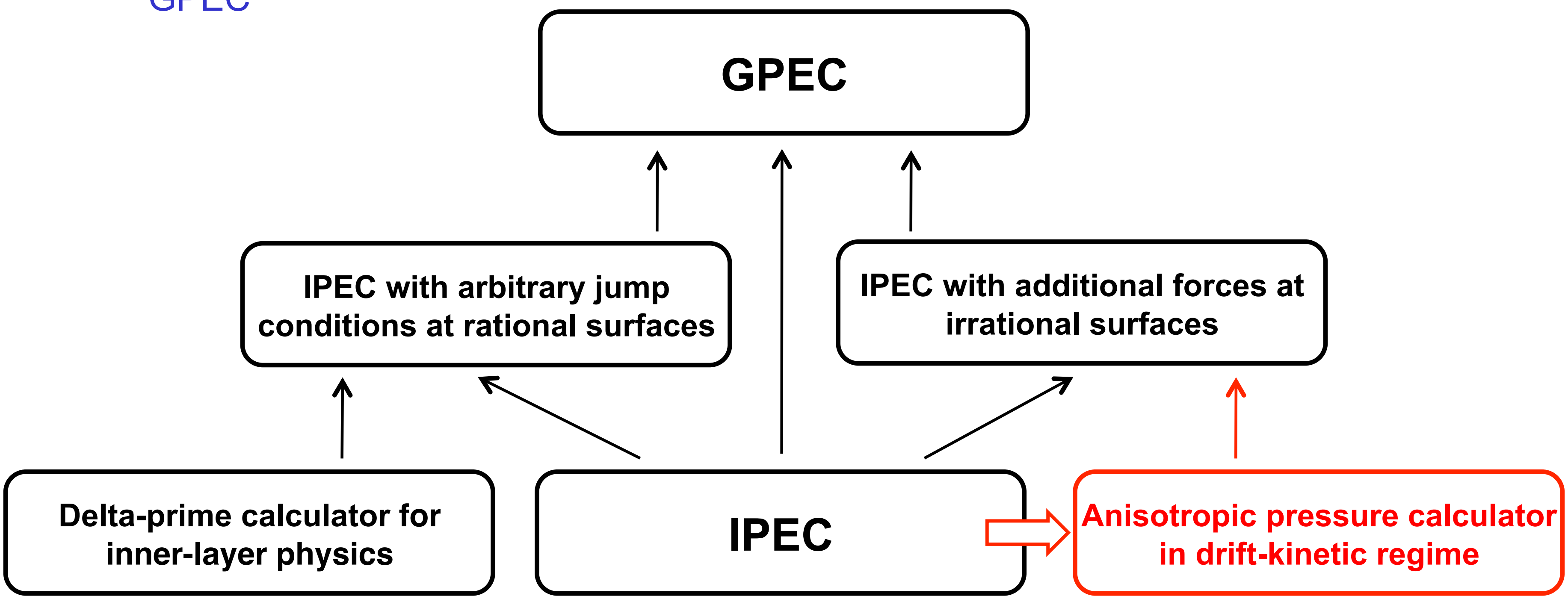
- POCA studies 3D field structures via FLT
  - Well-established method, but unique capability to take 3D field of multi-toroidal harmonics, with or without plasma response

- There are many ongoing and future research topics
  - NTV prediction, analysis and field line tracing for NSTX-U NCC
  - TBM mock-up experiment analysis with high β plasmas in DIII-D
  - Ion/electron orbit tracing to study particle loss by 3D field
  - Calculate δW_k (equivalence of NTV-δW_k)
  - 3D field effects on (ion) bootstrap current

Back up

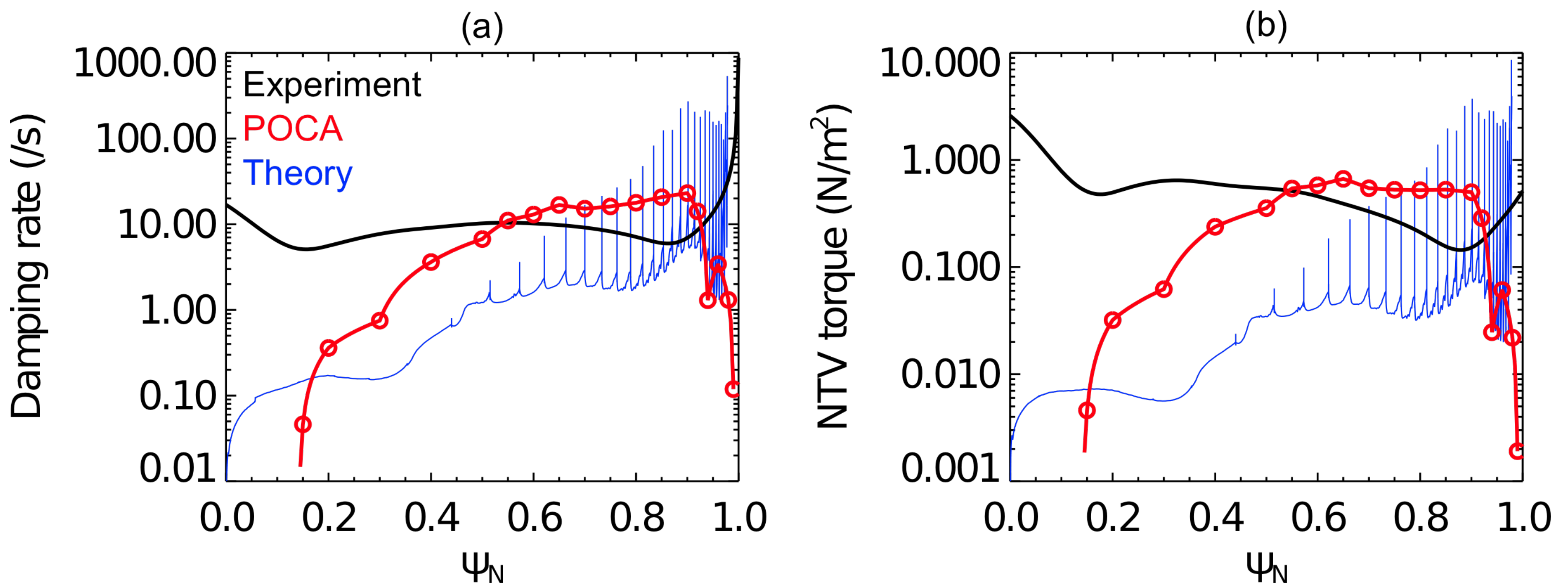
General Perturbed Equilibrium Code (GPEC) is on progress

- 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



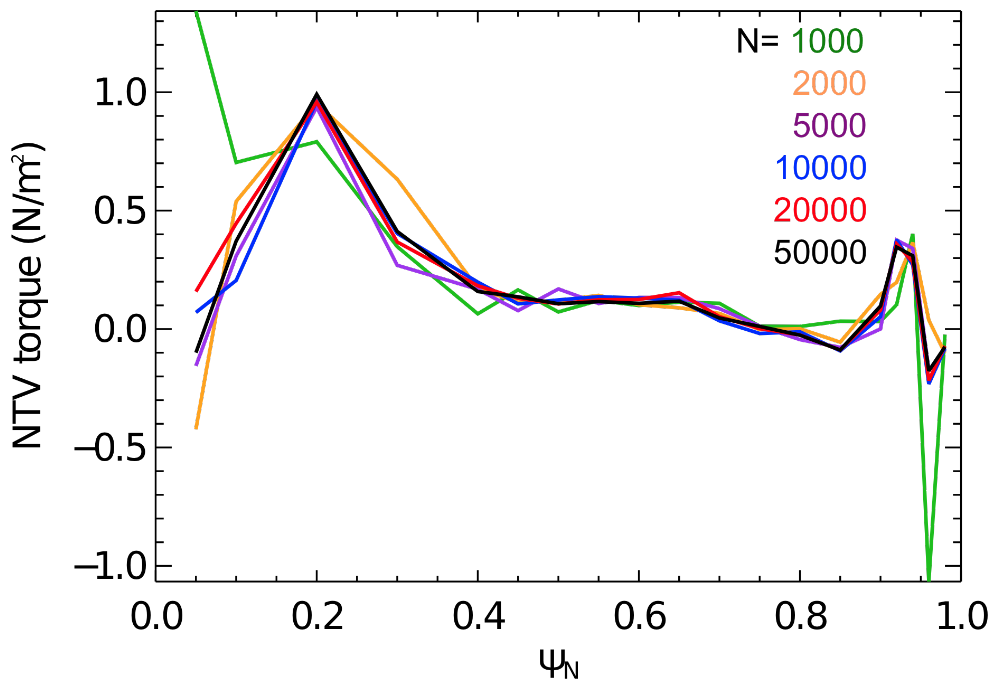
POCA improved a prediction on NTV in NSTX -2

- NTV is calculated for NSTX error field correction experiment
  - Selected discharge 132729 is a case of I_{EFC}=750A, which produced a strong magnetic braking (I_p=1.1MA, B_{T0}=0.55 T) [S.P. Gerhardt, PPCF (2010)]
  - Discrepancies are found in damping and NTV profiles: POCA predicts weaker NTV at inner and edge region and stronger NTV elsewhere
  - Total NTV torque still agrees well: Experiment 5.1 Nm / POCA 3.5 Nm (#132729)
  - Even though large discrepancies with measurement, POCA and theory show a similar profile shape; Check would be necessary for interpretation of measurements



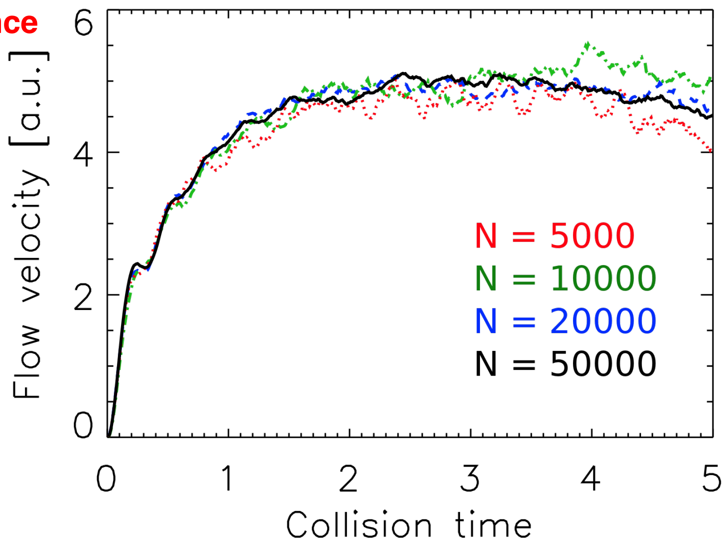
POCA shows a good convergence even in experiment

- Convergence has been tested by scanning test particle number
  - δf particle simulation is acceptable, but still needs improvement for efficiency
  - $N=10^3 \sim 5\text{x}10^5$ have been tested for DIII-D #145117
  - Good agreements with N over $\sim 5\text{x}10^3$ have been found, indicating the computational efficiency can be improved using small number of test particles
  - Most time-consuming part is an interpolation of magnetic field, which will be considered for future upgrade

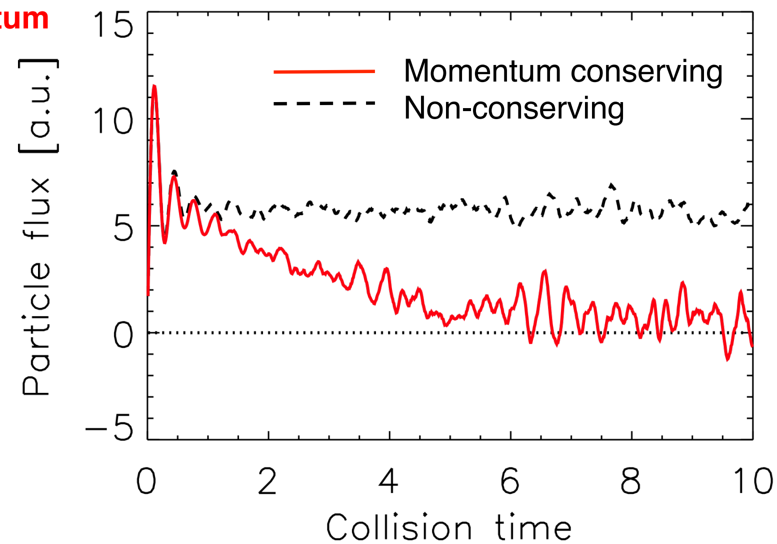


POCA has been successfully benchmarked in Axisymmetry

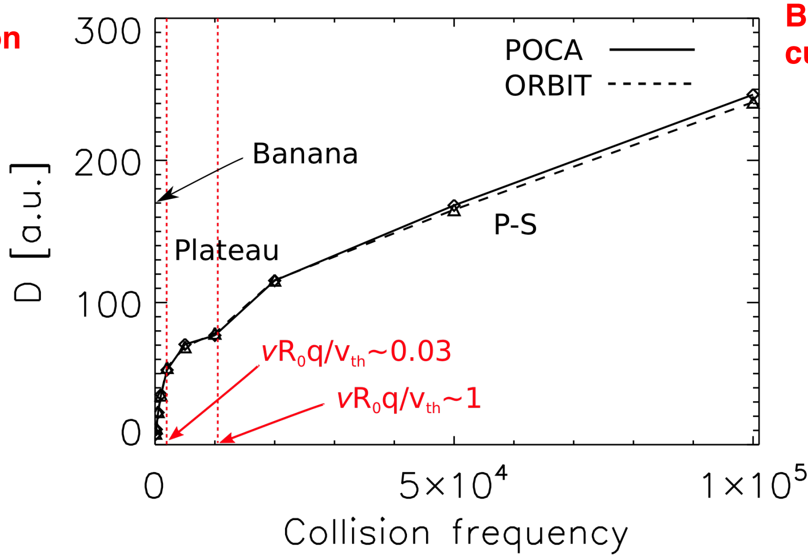
Convergence



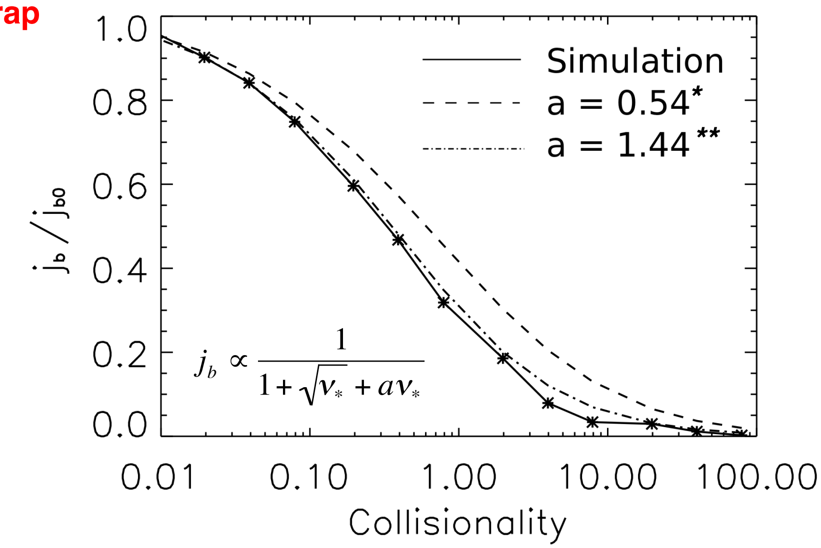
Momentum



Diffusion



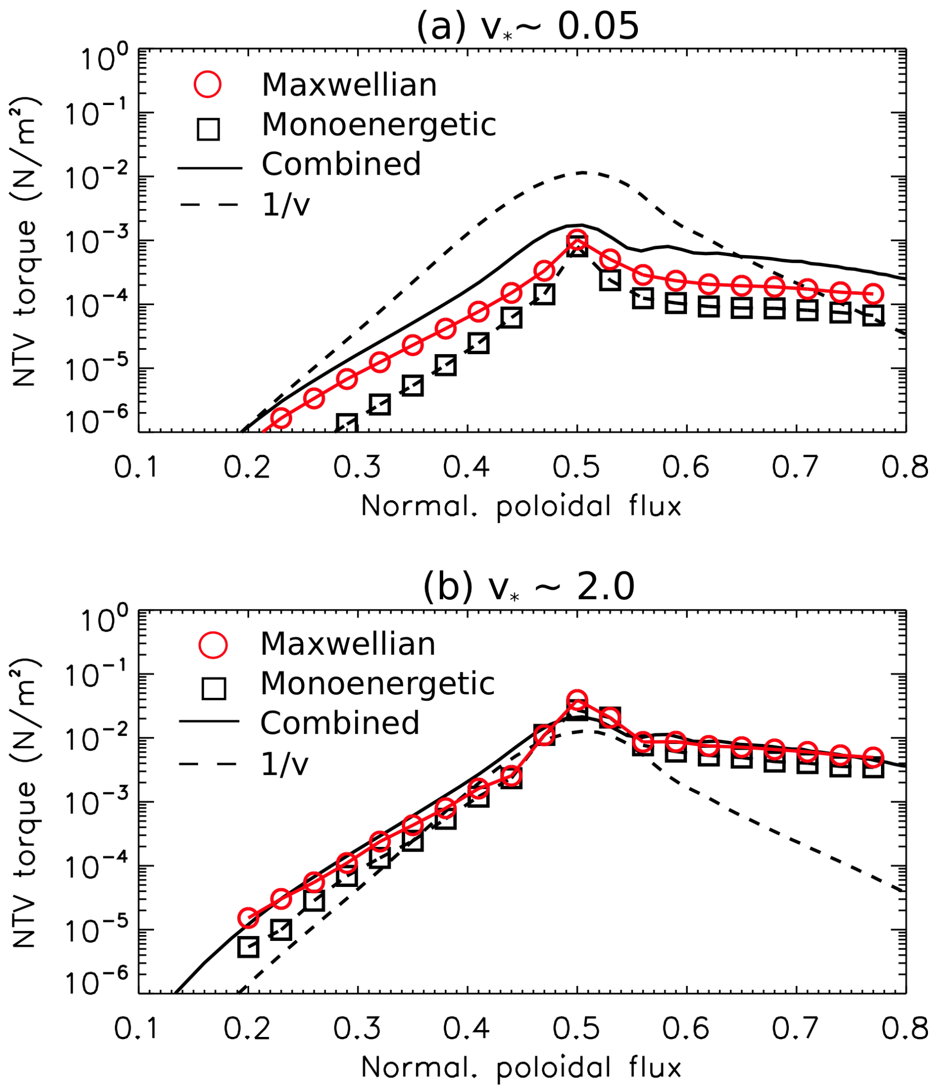
Bootstrap current



[R.B. White and M.S. Chance, Phys. Fluids B 27, 2455 (1984)]

*[F.L. Hinton and M.N. Rosenbluth, Phys. Fluids 16, 836 (1973)]
**[M. Sasinowski and A.H. Boozer, Phys. Plasmas 2, 610 (1995)]

POCA was compared with 1/ν theory



- NTV approaches 1/ν regime as collisionality increases
  - 1/ν formula indicates stronger resonance but weaker non-resonance
  - Magnetic precession and regime overlapping by Maxwellian energy distribution in POCA and combined formula cause broader NTV profiles than 1/ν formula
- High energy particle impacts on NTV
  - High energy particles in the Maxwellian tails strongly impact at the non-resonant flux surfaces
  - In the high collisionality, collisions are found to become more dominant than the high energy particle effects

Bounce-harmonic resonance has been found for KSTAR

- Strong NTV was predicted in a particular level of high rotation, due to the 1st bounce-harmonic resonance, and found in KSTAR