PPPL PRINCETON PLASMA PHYSICS LABORATORY

Global gyrokinetic study of shaping effects on electromagnetic modes at NSTX aspect ratio

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U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

University of Colorado Boulder

TEXAS The University of Texas at Austin

ECP EXASCALE COMPUTING PROJECT

HBPS High-fidelity Boundary Plasma Simulation

PRINCETON UNIVERSITY

IPP Max-Planck-Institut für Plasmaphysik

NERSC

Outline

- Introduction
- Use of profile-consistent magnetic equilibria
- Benchmarking of an approximation for the inclusion of compressional magnetic perturbation $\delta B_{||}$ effects
- Shaping study based on NSTX EP H-mode discharge #132588
- Conclusion

Introduction

- NSTX discharge #132588 is an Enhanced Pedestal H-mode (EP H-mode) discharge that features:
  - An absence of edge localized modes (ELMs);
  - Significantly improved energy confinement;
  - High plasma β;
  - High plasma shaping.
- We have performed a shaping study based on NSTX EP H-mode discharge #132588.
- Local gyrokinetic simulations of NSTX discharge #132588 have found that $\delta B_{||}$ effects are important, so we include an approximation for $\delta B_{||}$ effects.
- In order to properly take into account finite-pressure effects, we use profile-consistent magnetic equilibria when performing scans over plasma β.

X-point Gyrokinetic Code (XGC)

- The X-point Gyrokinetic Code (XGC) is a total-*f* global electromagnetic (EM) gyrokinetic particle-in-cell (PIC) code.
- It can model magnetically confined plasmas for:
  - Tokamaks (whole plasma volume from the magnetic axis to the material wall);
  - Stellarators (core region).
- Total-*f* EM XGC is unique:
  - Includes realistic divertor and limiter geometry;
  - Allows for non-Maxwellian plasmas;
  - Computes neoclassical and turbulent transport together with self-consistent 3D background and perturbed fields;
  - Uses a nonlinear Fokker-Planck-Landau collision operator;
  - Includes neutral particle recycling, and heat and torque sources.
- For details, see R. Hager, S. Ku, A. Y. Sharma et al., “Electromagnetic total-f algorithm for gyrokinetic particle-in-cell simulations of boundary plasma in XGC”, Phys. Plasmas (submitted).

X-point Gyrokinetic Code (XGC)

- In the work presented here:
  - Only the tokamak δf EM capability is used;
  - Collisions are not included;
  - The SOL is not included.
- For further details, see:
  - A. Y. Sharma *et al.*, "Global gyrokinetic study of shaping effects on electromagnetic modes at NSTX aspect ratio with ad hoc parallel magnetic perturbation effects", Phys. Plasmas (2022).

Use of profile-consistent magnetic equilibria

- We take into account finite-pressure effects by using profile-consistent magnetic equilibria.
  - When scanning over β, the magnetic equilibrium is reconstructed at each value of β such that the magnetic equilibrium pressure is consistent with the input pressure profile.
- We have a convenient workflow for generating these profile-consistent magnetic equilibria for any:
  - Aspect ratio A;
  - Elongation κ;
  - Triangularity δ.
- The present study is limited to up-down symmetric magnetic equilibria.
  - An extension to up-down asymmetric magnetic equilibria should be relatively simple.

Use of profile-consistent magnetic equilibria

Workflow:

1. Compute Fourier coefficients of a boundary from:
   a. Major radius R;
   b. Minor radius a;
   c. Elongation κ;
   d. Triangularity δ.
2. Provide VMEC with
   a. Boundary Fourier coefficients;
   b. Pressure profile;
   c. q profile;
   d. Enclosed magnetic flux.
3. Convert the VMEC output to G EQDSK format using the MConf tool (available at PPPL).
4. Convert from G EQDSK format to EQD format using a simple XGC tool.

Global benchmark of approximate $\delta B_{||}$ effects

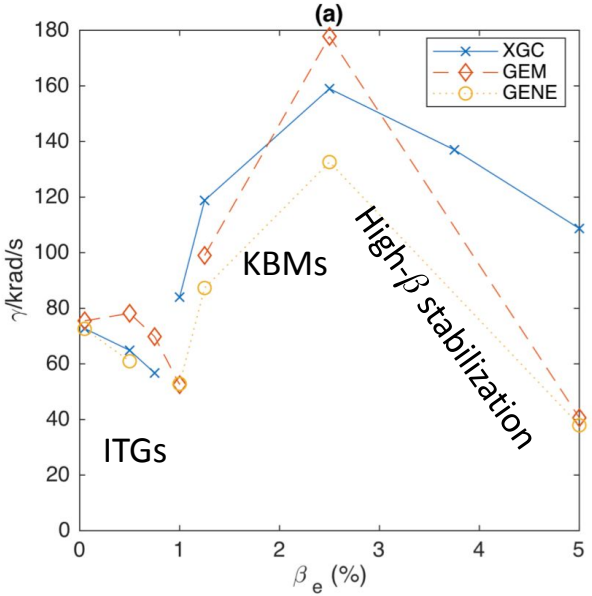
Perturbed EM field model	Numerical implementation	Computational cost	Validity	Common usage
$\delta\phi$, $\delta A_{||}$, $\delta B_{||}$	Relatively complex	Relatively expensive	Always valid	Local simulations
$\delta\phi$, $\delta A_{||}$, $\delta B_{||}$=0	Relatively simple	Relatively cheap	Maybe invalid at: • high β; • low aspect ratio.	Global simulations
$\delta\phi$, $\delta A_{||}$, approximate $\delta B_{||}$ effects	Relatively simple	Relatively cheap	Limited verification with local simulations	Local simulations

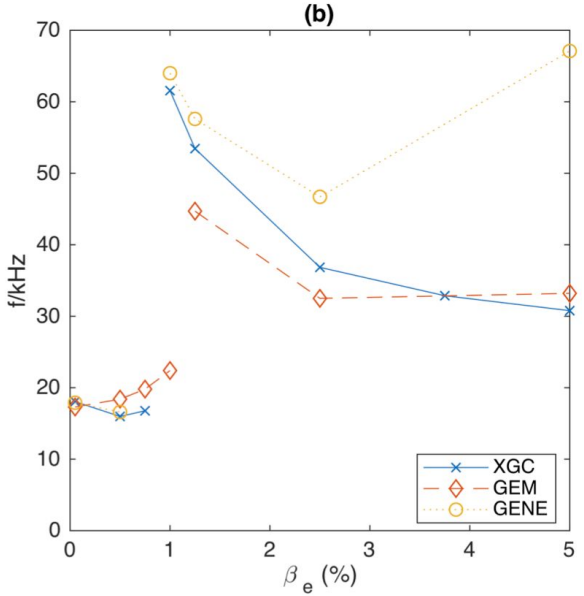
Global benchmark of approximate $\delta B_{||}$ effects

- To lowest order in β and $k_{\perp}\varrho_i$, the inclusion of $\delta B_{||}$ cancels the pressure-dependent part of the ∇B-drift (Joiner, PoP, 2010).
- Thus, a lowest-order approximation for the inclusion of $\delta B_{||}$ effects is to remove the pressure-dependent part of the ∇B-drift.
- This approximation has previously been verified with local gyrokinetic codes.
- We have performed a benchmark of this approximation between the global gyrokinetic code XGC and the global versions of the gyrokinetic codes GEM and GENE.
- The case that is used is based on the Cyclone Base Case (CBC), except that the ratio of the ion gyroradius to tokamak minor radius ϱ^* is approximately 1/50, compared to approximately 1/180 for the CBC, thus, we refer to this case as the Economical Cyclone Base Case (ECBC).
- A single toroidal mode number n=6 is considered, and real electron mass is used.

Global benchmark of approximate $\delta B_{||}$ effects

- Reasonably good agreement between the three codes.
- Stronger disagreement at 5 times the critical β.
  - This is perhaps unsurprising, and may just be a question of convergence.





Shaping study at NSTX aspect ratio

- We have performed a shaping study using:
  - Profile-consistent magnetic equilibria;
  - Approximate compressional magnetic perturbation $\delta B_{||}$ effects;
  - Magnetic geometries that are based on NSTX EP H-mode discharge #132588;
    - Magnetic field strength and *q* profile from NSTX discharge #132588;
  - Plasma profiles that are based on the CBC;
  - A single toroidal mode number *n*=20;
  - Real electron mass.

It would also be interesting to consider other plasma profiles and mode numbers.

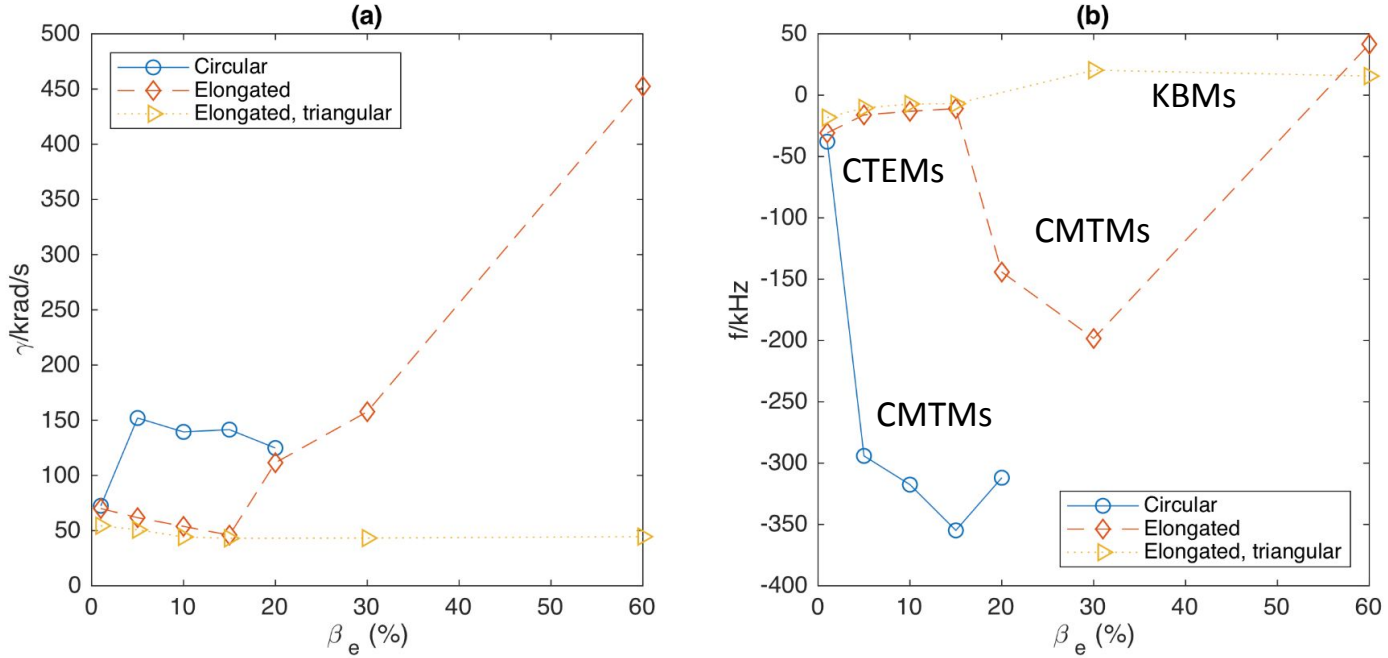
Shaping study at NSTX aspect ratio

We consider the following geometries:

Geometry	Aspect ratio A	Elongation κ	Triangularity δ
Circular	1.4	1.0	0.0
Elongated	1.4	2.2	0.0
Elongated, triangular	1.4	2.2	0.55

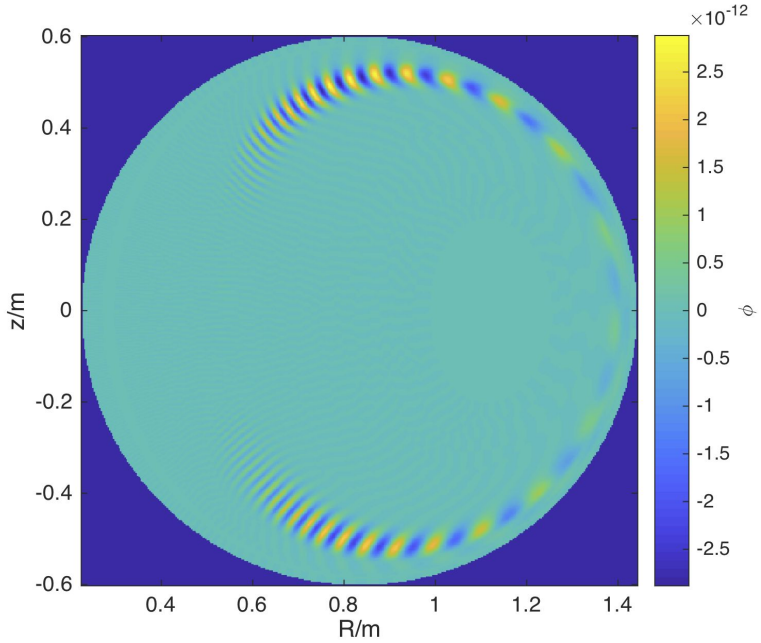
- All of the geometries use an aspect ratio that is identical to that of NSTX discharge #132588.
- The “elongated” and “elongated, triangular” geometries use an elongation κ that is identical to that of NSTX discharge #132588.
- The “elongated, triangular” geometry uses a triangularity δ that is identical to that of NSTX discharge #132588.
- While NSTX discharge #132588 has some up-down asymmetry, all of these geometries exclude up-down asymmetry.

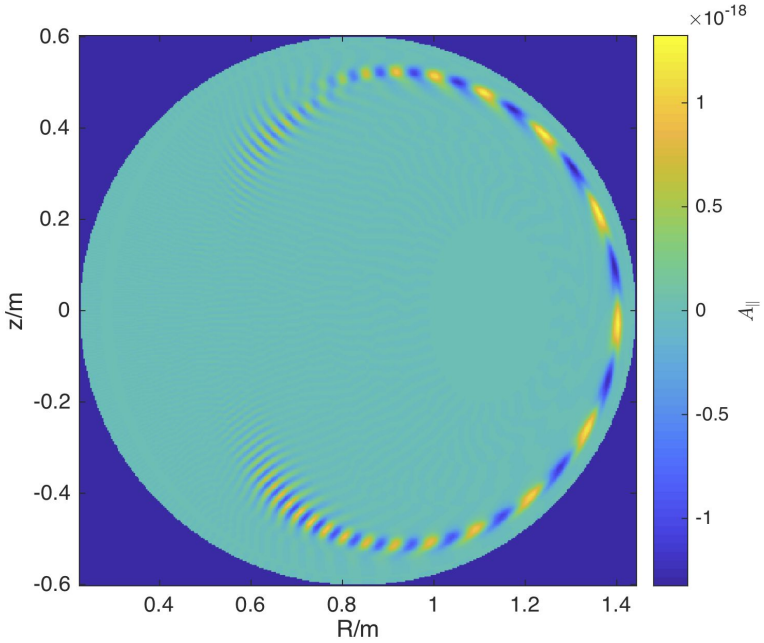
Shaping study at NSTX aspect ratio



- Transitions from collisionless trapped electron modes (CTEMs) to collisionless microtearing modes (CMTMs) to KBMS are observed.
- CMTMs are shifted to higher β, and then suppressed by strong triangularity.
- Strong NSTX shaping makes KBM growth rates as weak as CTEM growth rates.

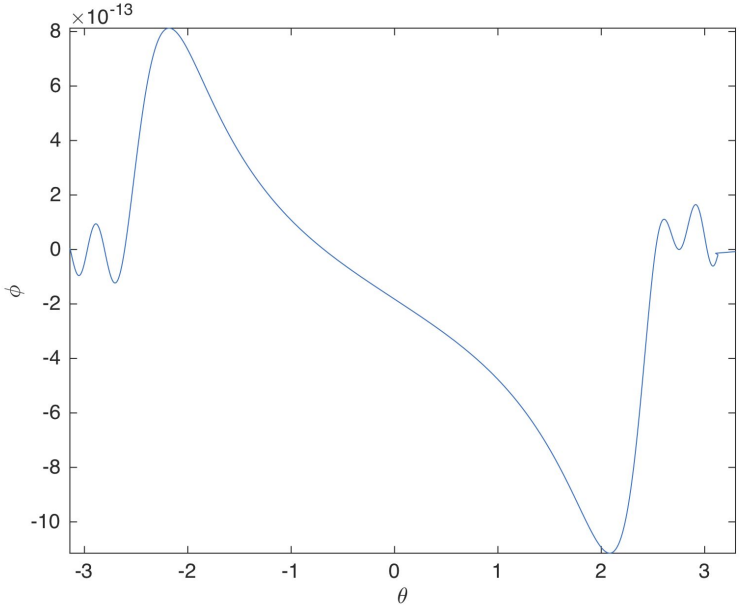
Shaping study at NSTX aspect ratio

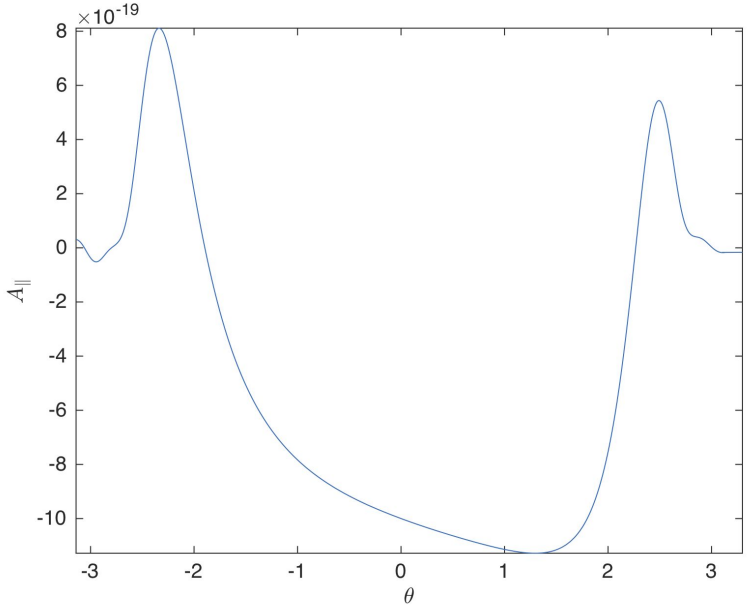




Mode structures for the electrostatic potential ϕ (left) and the parallel magnetic potential $A_{||}$ (right) for the CMTM observed with the "circular" geometry case at β_e=10%.

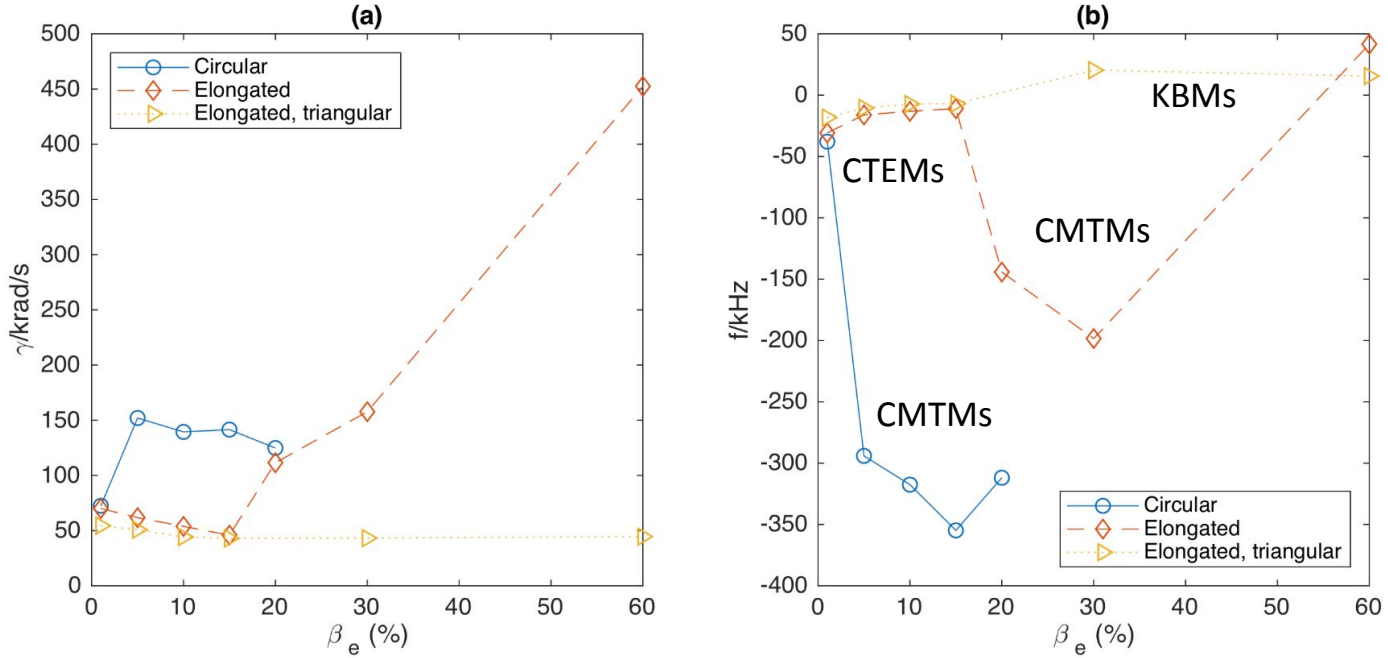
Shaping study at NSTX aspect ratio





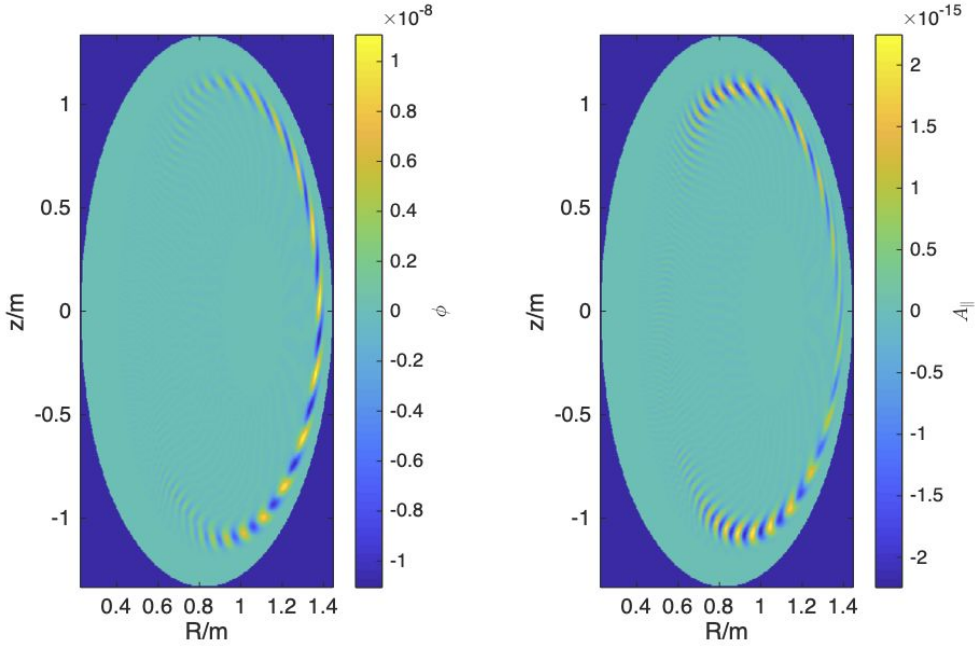
Mode structures along a field line for the electrostatic potential ϕ (left) and the parallel magnetic potential $A_{||}$ (right) showing tearing parity for the CMTM observed with the "circular" geometry case at β_e=10%.

Shaping study at NSTX aspect ratio



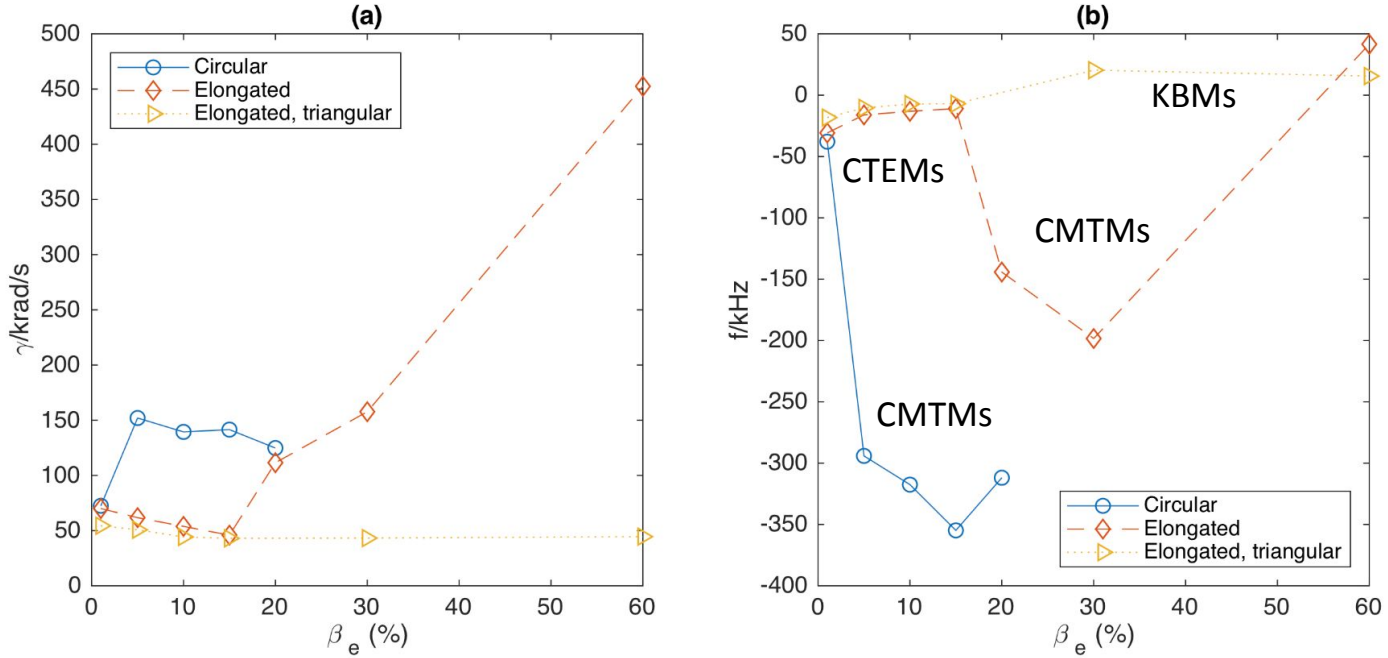
- Transitions from collisionless trapped electron modes (CTEMs) to collisionless microtearing modes (CMTMs) to KBMS are observed.
- CMTMs are shifted to higher β, and then suppressed by strong triangularity.
- Strong NSTX shaping makes KBM growth rates as weak as CTEM growth rates.

Shaping study at NSTX aspect ratio



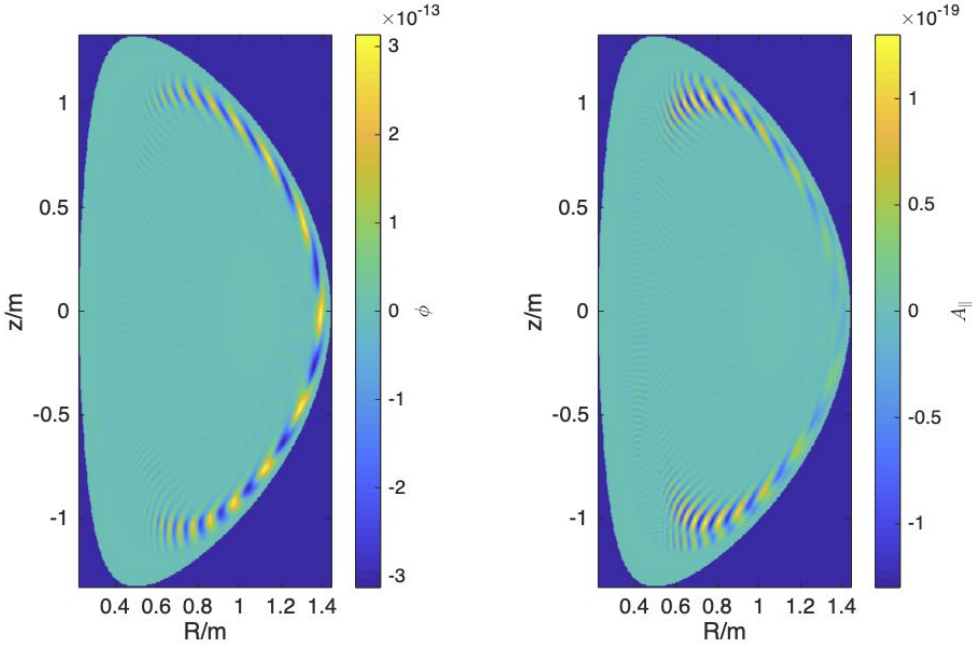
Mode structures for the electrostatic potential ϕ (left) and the parallel magnetic potential $A_{||}$ (right) for the CTEM observed with the "elongated" geometry case at β_e=15%.

Shaping study at NSTX aspect ratio



- Transitions from collisionless trapped electron modes (CTEMs) to collisionless microtearing modes (CMTMs) to KBMS are observed.
- CMTMs are shifted to higher β, and then suppressed by strong triangularity.
- Strong NSTX shaping makes KBM growth rates as weak as CTEM growth rates.

Shaping study at NSTX aspect ratio



Mode structures for the electrostatic potential ϕ (left) and the parallel magnetic potential $A_{||}$ (right) for the KBM observed with the "elongated, triangular" geometry case at β_e=30%.

Conclusion

- A workflow has been developed for performing scans over plasma β using profile-consistent magnetic equilibria with the global gyrokinetic PIC code XGC.
- An approximation for the inclusion of compressional magnetic perturbations $\delta B_{||}$ was benchmarked with the global gyrokinetic code XGC and the global versions of the gyrokinetic codes GEM and GENE.
- The effects of high plasma shaping at NSTX aspect ratio are that there is significant stabilization of CMTMs and KBMs.
  - KBM growth rates are reduced to that of the TEMs.