3D Shaping in Tokamaks,
with Particular Application to NHTX

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Tokamak has evolved from axisymmetric device with circular cross-section to strongly shaped axisymmetric device.

Can 3D shaping be used to improve the tokamak?

- 3D coils incorporated in ITER to control ELMS.
- NCSX design study used ARIES RS tokamak design as starting point, adding 3D shaping.

Outline of This Talk

- Vacuum surfaces for startup without transformer.
- ELM mitigation with the same N=5 coils.
- Stabilization of vertical modes using a relatively simple set of saddle coils

Vacuum surfaces can allow startup without transformer.

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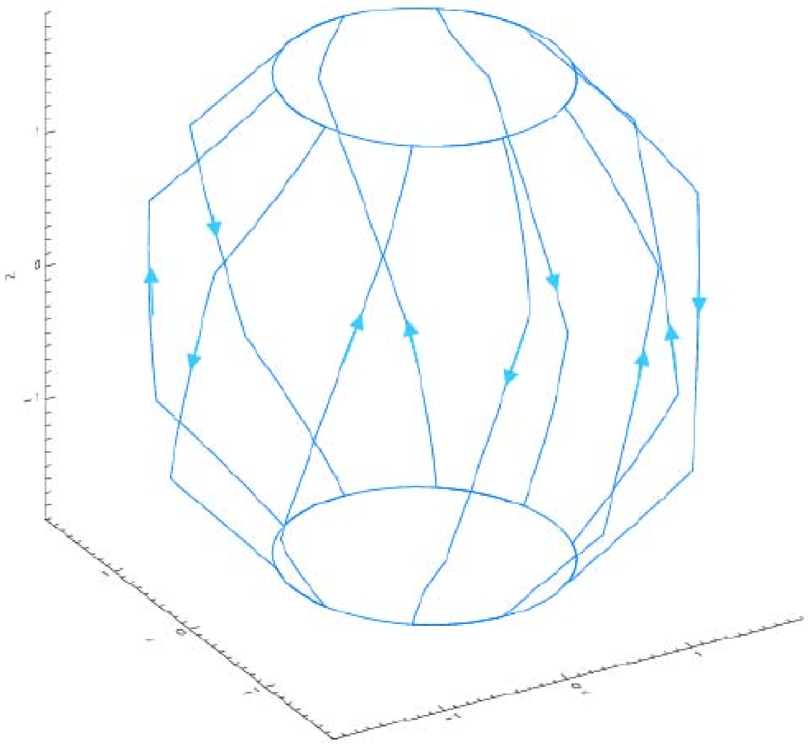
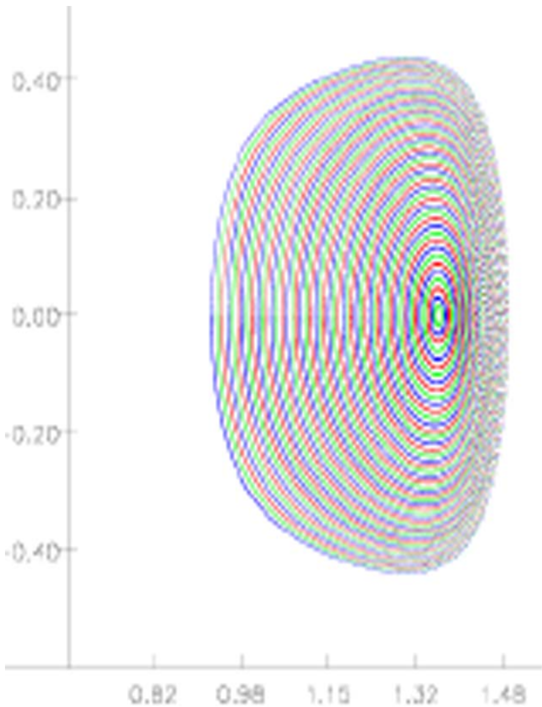


Nonaxisymmetric 5-period coils added to PF coils. (Fits NHTX 10 TF coils.)

- Can produce vacuum flux surfaces with coils that do not penetrate hole in torus. (R. P. Freis, C. W. Hartman, and J. Killeen, Bull. Am. Phys. Soc. 13, 276 (1968); H.P. Furth and C.W. Hartman, Phys. Fluids 11, 408 (1968))
- Produces small rotational transform.
- For startup, need to confine passing electrons. Required transform is small.

Small transform suffices to confine passing electrons, allowing transformer-less startup.



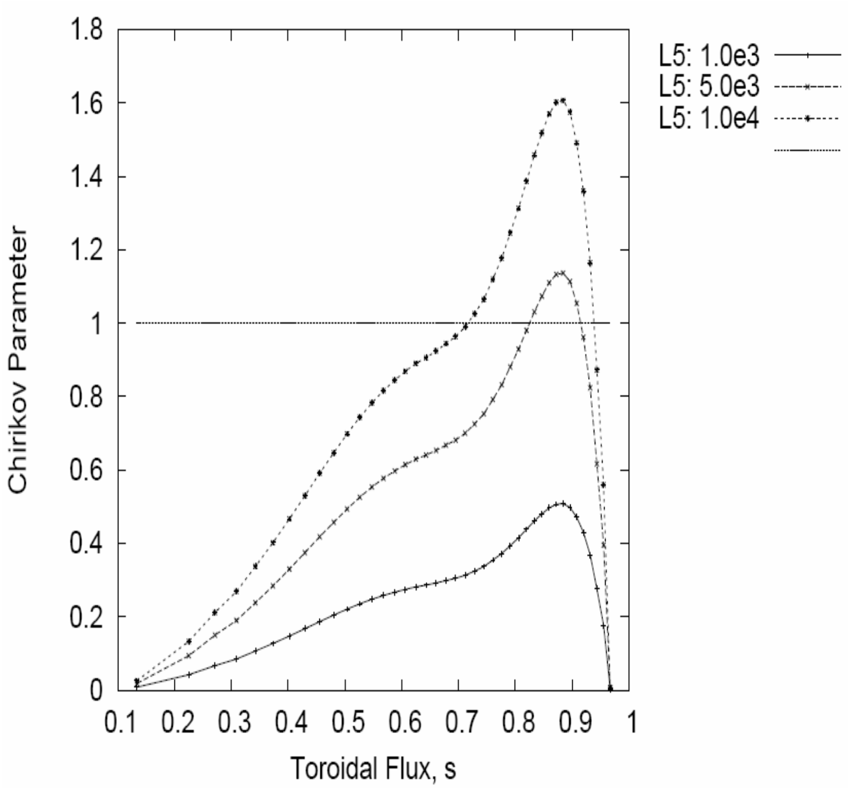
Vacuum flux surfaces.

$\iota_0 = 0.025$

- Confinement of passing electrons requires $\iota > (\rho_e/a)\,A$, where ρ_e is electron gyroradius, a is minor radius, A is aspect ratio.
- 500 kA current in N=5 3D coils needed for ι on axis of .025 at full TF field.
  - Reduce TF field to study on NHTX.
  - For practical application decrease N.
- 100 keV electrons can be confined. Sufficient for startup via LH current drive.

Same coils have been evaluated for ELM mitigation.

N. Pomphrey



Chirikov overlap parameter vs. normalized toroidal flux for three different values of I_{3D}.

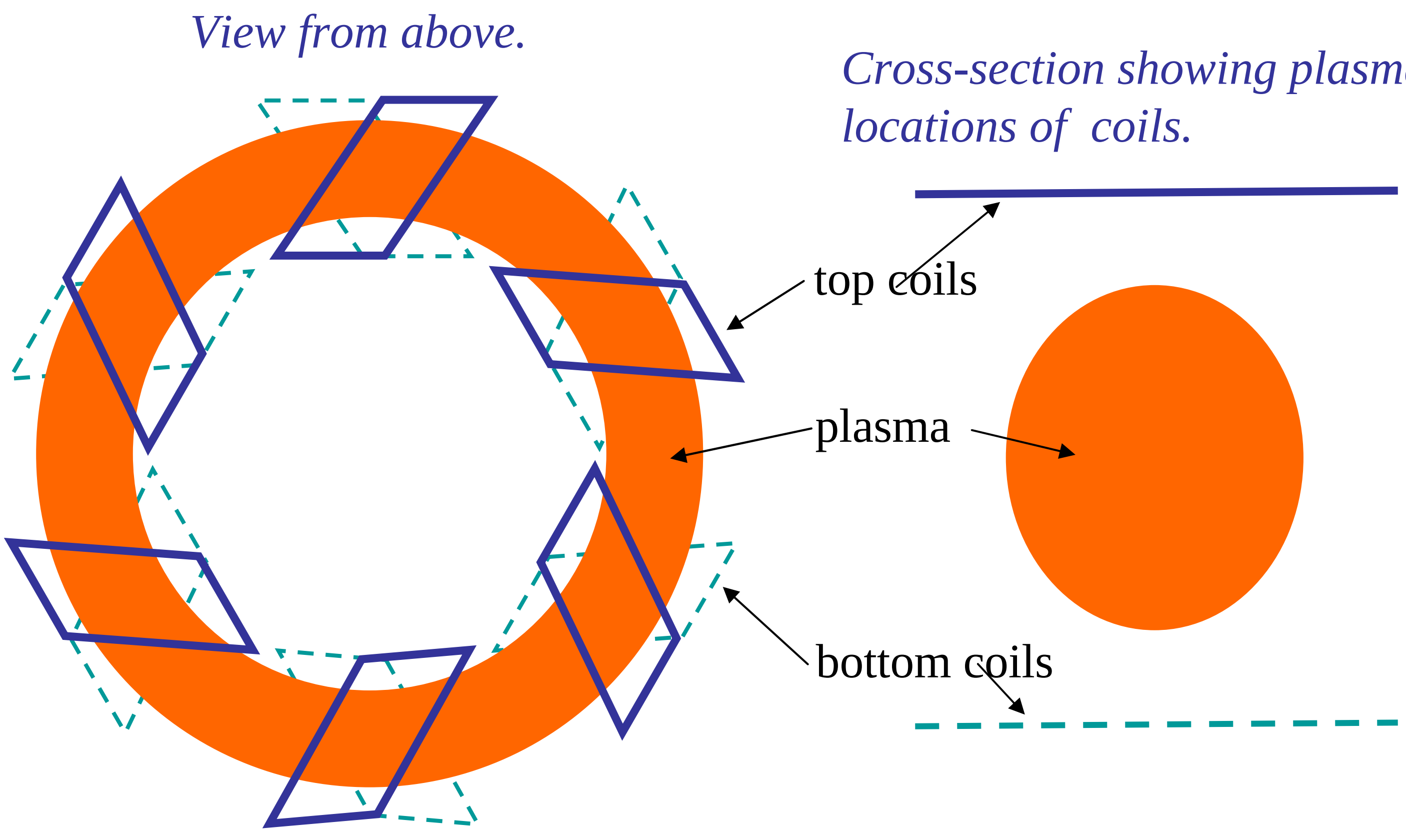
- Calculation superposes 3D vacuum field on axisymmetric equilibrium.
- Island overlap criterion (Chirikov parameter > 1) gives threshold for stochastization in given region.
- For N=5 (5 period) 3D coils with I_{3D}=5.0 kA-turns per coil, get overlap in region near $\rho/a = 0.90$, where $\rho \equiv s^{1/2}a$.

5-period coils for ELM suppression produce little ripple in plasma interior.

- N = 5 field falls off rapidly with distance from coils.
- Estimate effect on neoclassical transport by calculating effective helical ripple using NEO code (Nemov *et al*).
- For I_{3D} = 10.0 kA-turns, efective ripple very small. < 0.05% over entire plasma region. (Compare with NCSX reference equilibrium, where ripple ranges from 0.1% in the core to 1.4% at the edge.)

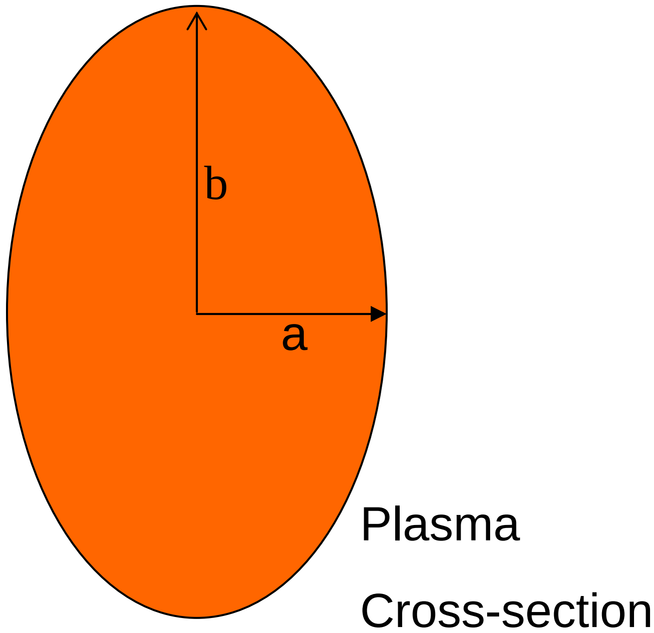
Vertical mode in tokamaks can be passively stabilized by relatively simple set of nonaxisymmetric coils.

A. Reiman, Phys. Rev. Lett. **99** (2007)



Analytical stability calculation for large aspect ratio plasma with uniform current. (Numerical calculations are starting.)

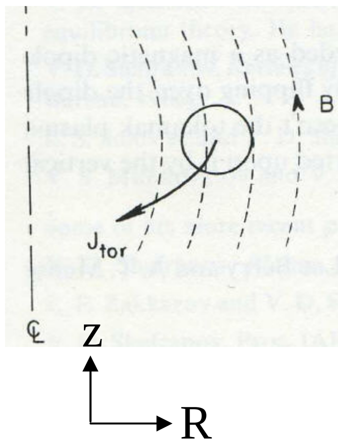
Stabilization of vertical mode allows greater elongation, relaxing important constraint on tokamak design.

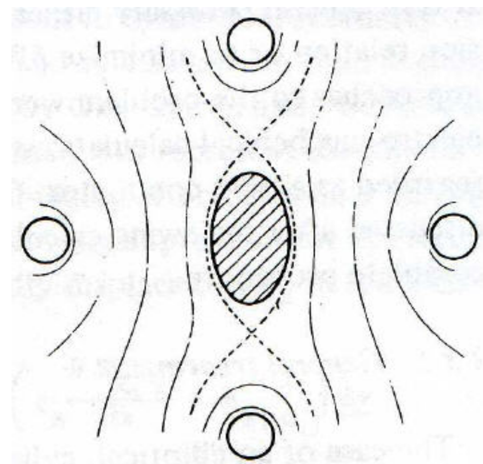


Vertical elongation = b/a $\equiv \kappa$

- Troyon scaling predicts increase in β limit for ballooning and kink modes with elongation for fixed q: $\beta = CI/aB$, $I \propto (1 + \kappa^2) / (2\kappa)$ for ellipse.
- Global confinement scaling laws find that confinement improves with vertical elongation, $\tau \sim I\ \kappa^{0.5}$
- Strong increase in 3D field with decreasing distance from coil suggests nonlinear stabilization of VDEs for linearly unstable configurations.

Physical mechanism of stabilization can be understood by considering motion of current carrying ring in quadrupole field.





- Force on displaced ring determined by $J_{tor} \partial B_R / \partial z$
- Quadrupole component of field exerts pressure that controls ellipticity through $\partial B_z / \partial R$
- For axisymmetric vacuum field, sign of $\partial B_z / \partial R$ determines sign of $\partial B_R / \partial z$
- $\partial B_R / \partial z$ destabilizing for field that increases vertical elongation.
- Nonaxisymmetric coils modify averaged field, decoupling $\partial B_R / \partial z$ from $\partial B_z / \partial R$, allowing stabilization of vertically elongated plasma.

Conclusions

- Nonaxisymmetric coils that do not link the plasma can produce vacuum flux surfaces to aid non-inductive startup. Can test in NHTX with N=5 coil, reduced TF field.
- Coils with N = 5 and modest current can induce stochasticity in outer region of plasma (for ELM suppression) while producing little ripple in plasma interior.
- Vertical mode in tokamaks can be stabilized by relatively simple set of nonaxisymmetric coils placed above and below the torus (analytical calculation).
  - Numerical calculations are beginning.
  - Will want to decrease associated ripple by modifying field to satisfy quasi-axisymmetry.