Plasma Configuration Design of the U.S. National Compact Stellarator Experiment (NCSX)

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I. Introduction.

- Quasi-axisymmetric stellarators.
- Comparison with other stellarators and with tokamaks.

II. A QA configuration and its physics properties.

- Ballooning.
- Kink.
- Vertical stability.
- Confinement.

The NCSX Design is Based on the Quasi-Axisymmetric Approach to Producing Good Drift Trajectories

Two Methods are known for improving drift trajectories:

- Quasi-omnigeneity (W7X, QOS).
- Quasi-symmetry.

Quasi-Symmetry

drift trajectories: Equations in Boozer coordinates depend only on B^2, not on components of $\mathbf{B}$. (Boozer, 1983)

Quasi-symmetric field: $B^2 = B^2(\Psi, \theta - N\phi)$ has helical symmetry or axisymmetry. (Nührenberg & Zille, 1988)

Quasi-axisymmetry: In Boozer coordinates, drift trajectories look same as in axisymmetry. (Nührenberg, Lotz & Gori)

Garabedian: Quasi-axisymmetric configurations naturally emerge in study of increasingly compact quasi-symmetric configurations. Attractive modular coils.

Quasi-Axisymmetric Stellarators

Comparison with W7X and quasi-helical stellarators: Bootstrap Current

quasi-helical stellarators: relatively small compared to tokamak; opposes external transform.

W7X: bootstrap current (as well as Pfirsch-Schlüter current) adjusted to be small.

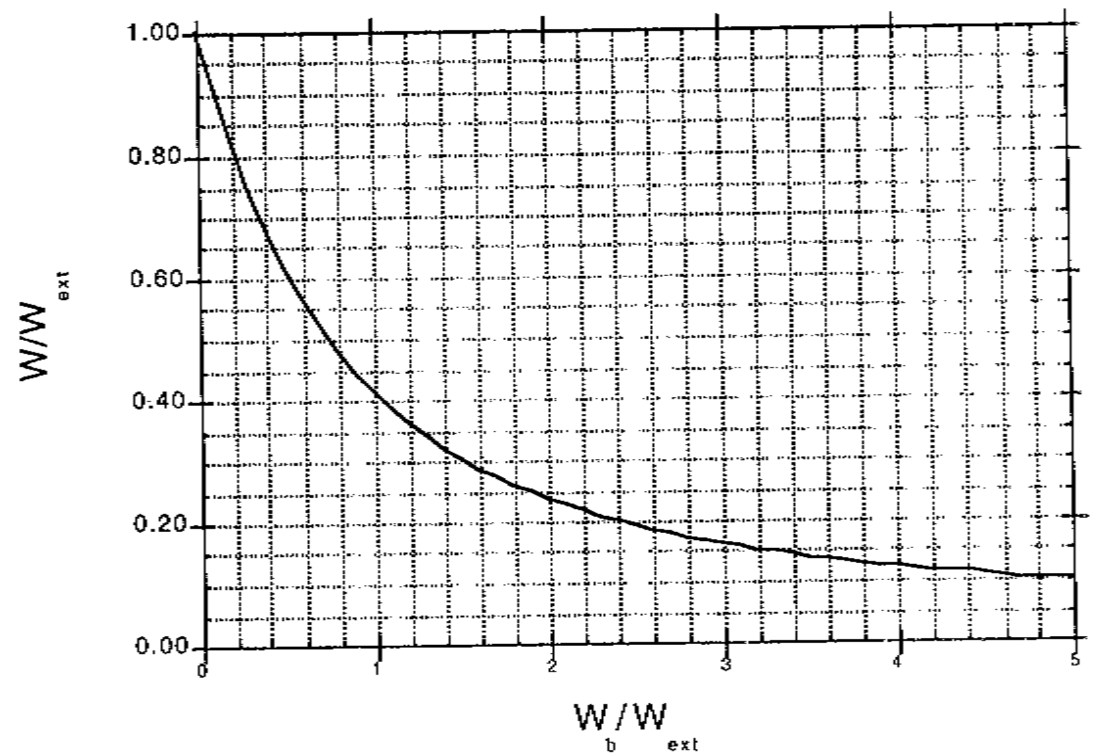
- Changes in equilibrium at finite β small.

q-a stellarator: comparable to tokamak, and in direction which adds to external transform.

- Bootstrap current provides substantial transform, reducing transform required from coils.
- Predicted to give self-healing neoclassical effect on magnetic islands if ι increases outward.
  Improves equilibrium β limit and robustness to field errors.

Goldston

BOOTSTRAP CURRENT SUPPRESSES ISLANDS WHEN $d\iota / dr > 0$



$$W = -W_b + \left(W_{ext}^2 + W_b^2\right)^{1/2} \quad W_b \equiv \frac{2\mu_o R j_b}{mB\iota'} \sim 4\,\iota_b / (m\iota') \sim a$$

Comparison with Other Stellarators (continued)

Aspect Ratio

Stellarator aspect ratios generally >> tokamak aspect ratios.

Quasi-axisymmetric stellarators can have favorable MHD stability and confinement at tokamak-like aspect ratios.

Lower cost development path and reactor?

Axisymmetric component of shaping can be used in QA stellarators to improve ballooning stability, get 2nd stable regime in core.
Strong average shaping believed to provide confinement enhancement in tokamaks.

Rotation possible with quasi-symmetry. Tokamak-like transport barriers?

QA configurations continuously deformable to tokamaks. Provides potential evolutionary path for tokamak to a hybrid between an advanced tokamak and a drift-optimized stellarator.

Quasi-Axisymmetric Stellarators

Comparison with advanced tokamaks:

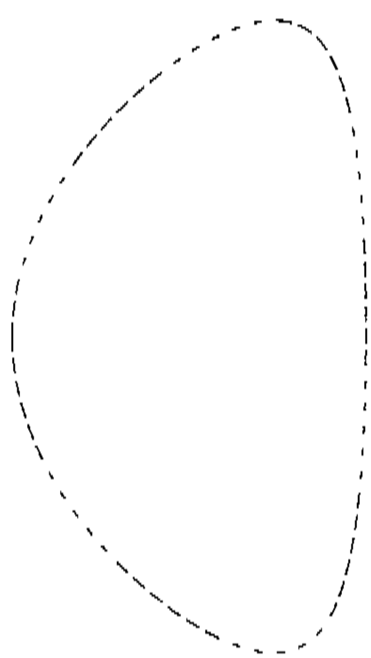
- Externally generated rotational transform eliminates or reduces need for rf current drive.
- External control over transform profile: Can produce monotonically increasing ι (decreasing q).
- Can use nonaxisymmetric field to stabilize external kink and vertical mode, even in absence of conducting wall.
- Disruption suppression.
  - Present day stellarator experiments do not see disruptions in normal operation. (Although they can produce disruptions if they try.)
  - W7A saw suppression of disruptions when fraction of externally generated $\iota > 20\%$.

QA Configuration Design

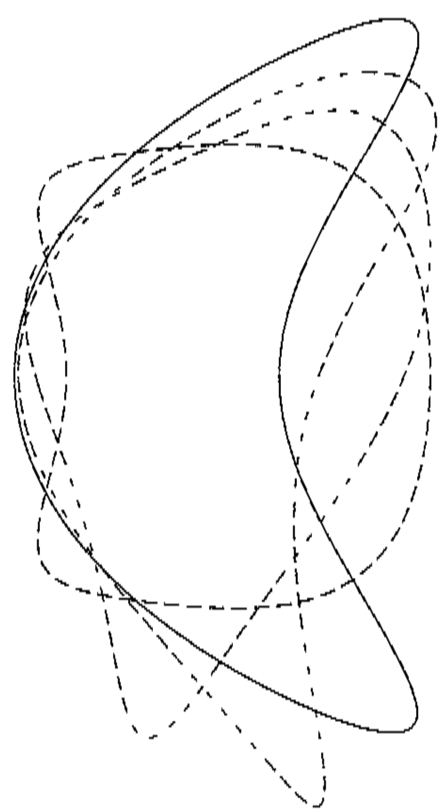
Start with ARIES-RS advanced tokamak equilibrium. Morph to 3D stellarator configuration, retaining quasi-axisymmetry. Aspect ratio constrained by PBX coils.

Retain ARIES bootstrap-like current profile and associated pressure profile.

Aries tokamak β limit $\approx$ 4.5% (with conducting wall). Optimization study performed at $\beta \approx 4\%$.

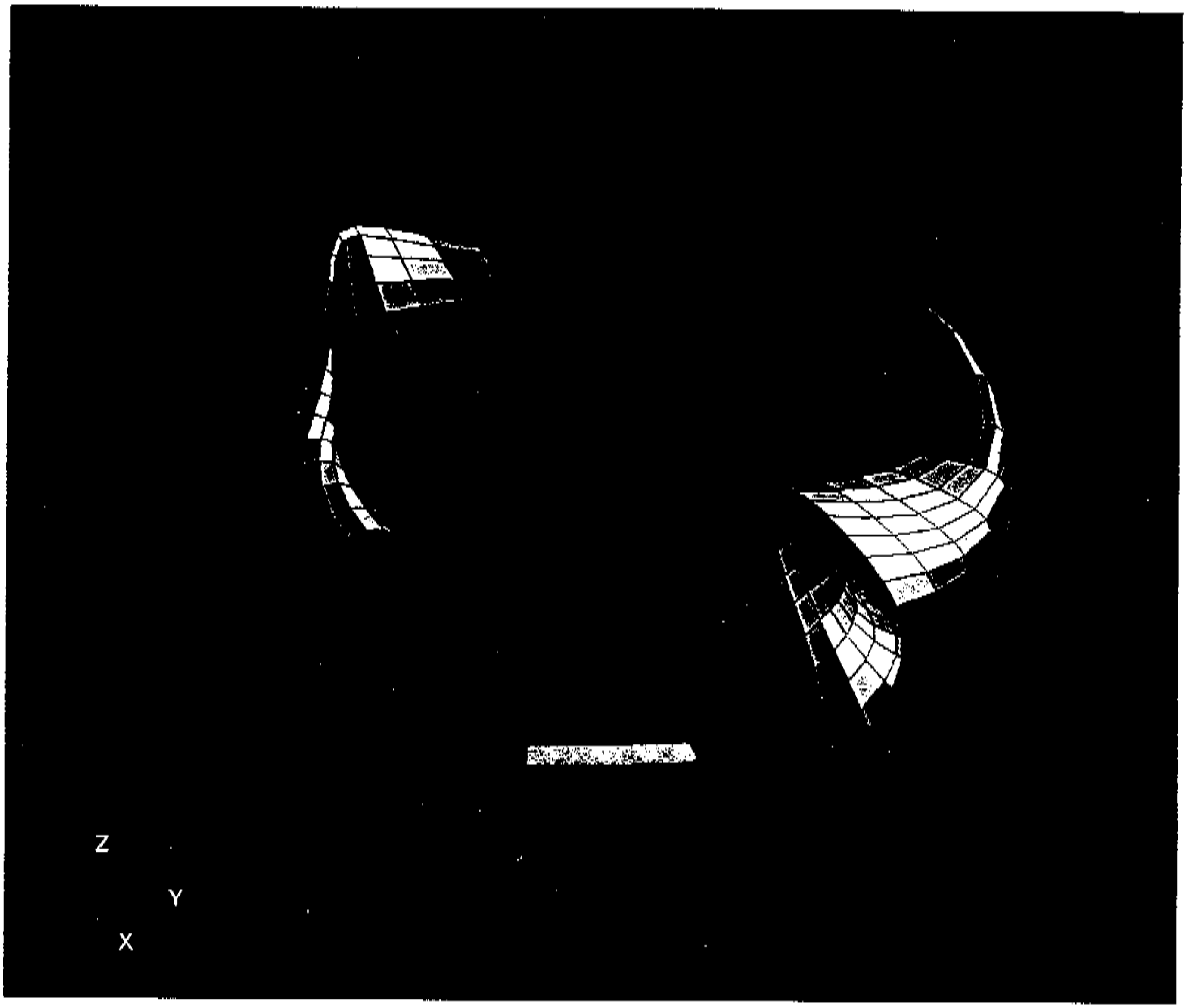


Aries tokamak
starting point

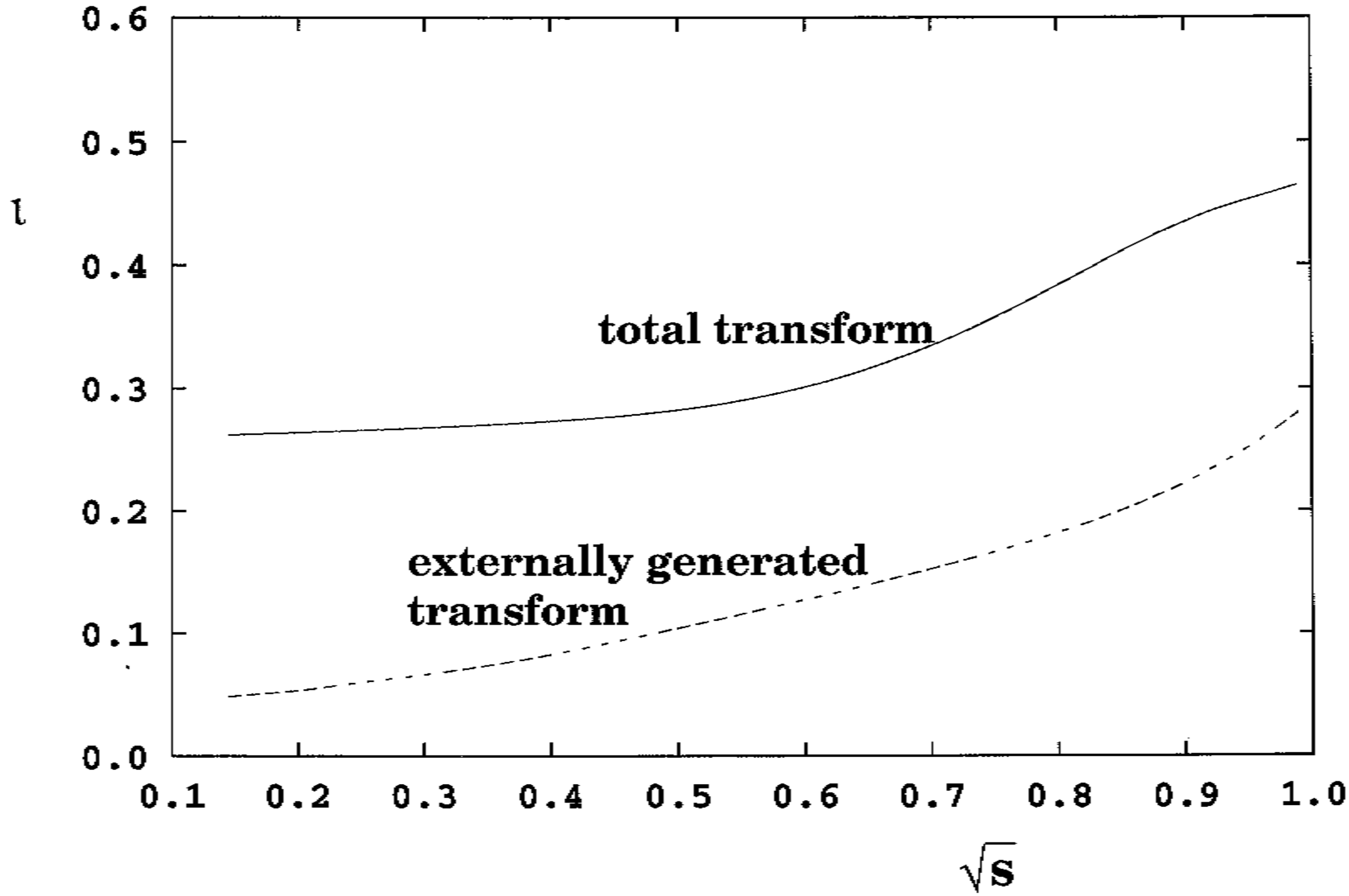


c82 stellarator
configuration

Configuration C82



3 field periods, $R/\langle a \rangle \approx 3.4$



Sign of ι (relative to direction of bootstrap current) gives neoclassical effect that opposes magnetic island formation.

Ballooning Stability

Ballooning β limit an issue for many quasi-symmetric designs, particularly as aspect ratio reduced.

Ballooning limit not yet tested experimentally in stellarators ($\beta \leq 2\%$ in experiments), but:

- Ballooning modes caused disruptions in TFTR.

Ballooning: Our Solution

- Construct quasi-axisymmetric field with large $n = 0$ (axisymmetric) component of ellipticity and triangularity.
- ARIES advanced tokamak studies provide initial guide to stabilizing shape.
- Improved vertical stability allows greater axisymmetric shaping than in tokamak.

Configuration C82 ballooning stable at $\beta \approx 4\%$ with reference profiles.

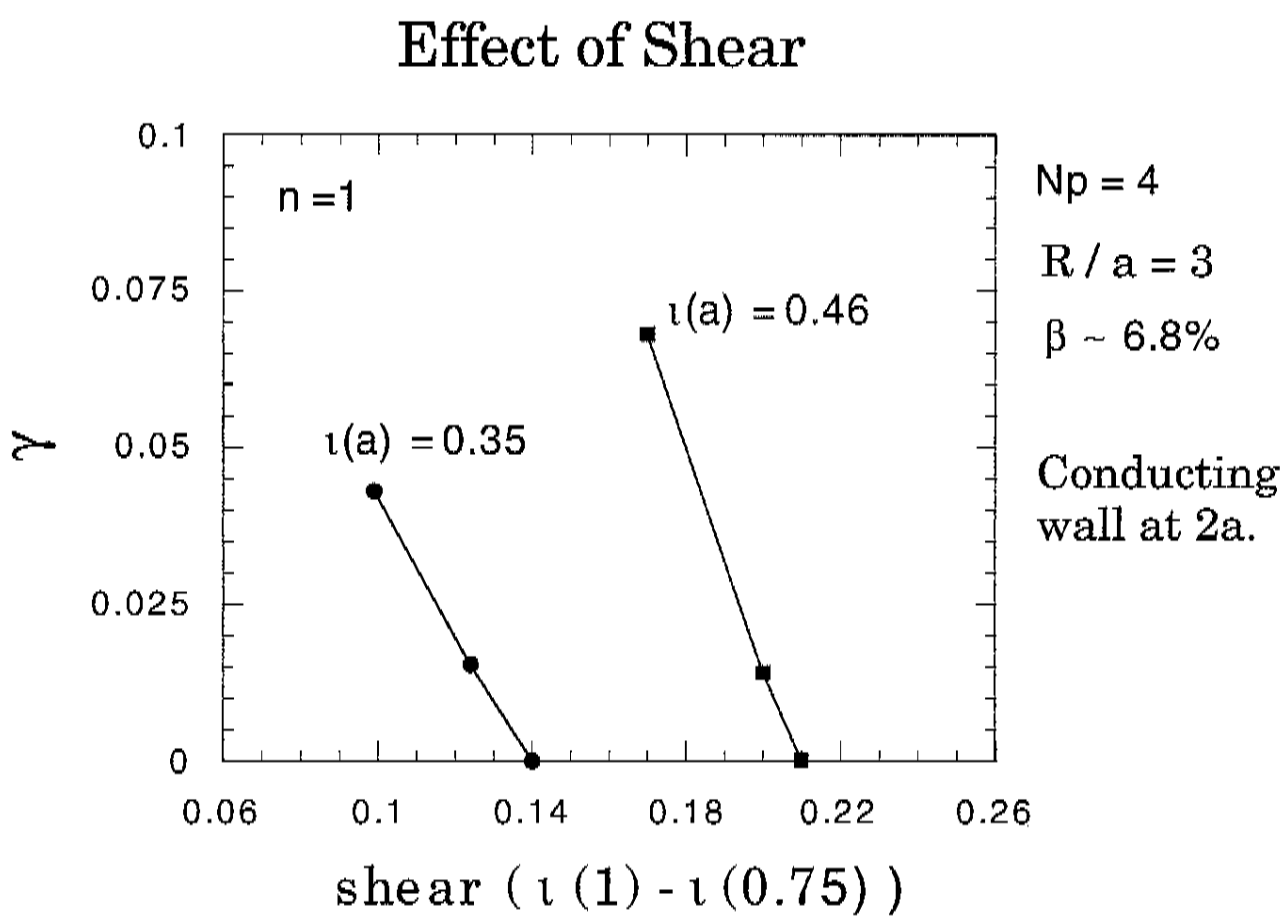
C82 core in 2nd stability regime for ballooning. Can raise β by peaking pressure.

Kink Stability

- External kink a key issue for advanced tokamaks, which rely on stabilization by close fitting conducting wall.
- External kinks not extensively studied in stellarators. Can now be calculated by Terpsichore and CAS3D codes.
- At low collisionality and high β, stellarator bootstrap currents can drive kinks.
- Kink can be driven by Pfirsch-Schlüter current, even for zero net current. (see e.g. Anania and Johnson, 1983)
  Note: Net current **stabilizes** pressure driven external kinks in conventional tokamaks. (Troyon scaling: $\beta_c \propto I/aB$)
- We stabilize external kink in our configuration by a combination of externally generated shear and corrugation of the boundary.

Externally generated shear stabilizes external kink mode, even in absence of conducting wall.

Fu and Cooper. Calculations with Terpsichore code.



- Comparable tokamak has $\beta_c \approx 2.5\%$.
- Advanced tokamaks rely on close-fitting conducting wall to stabilize external kink.

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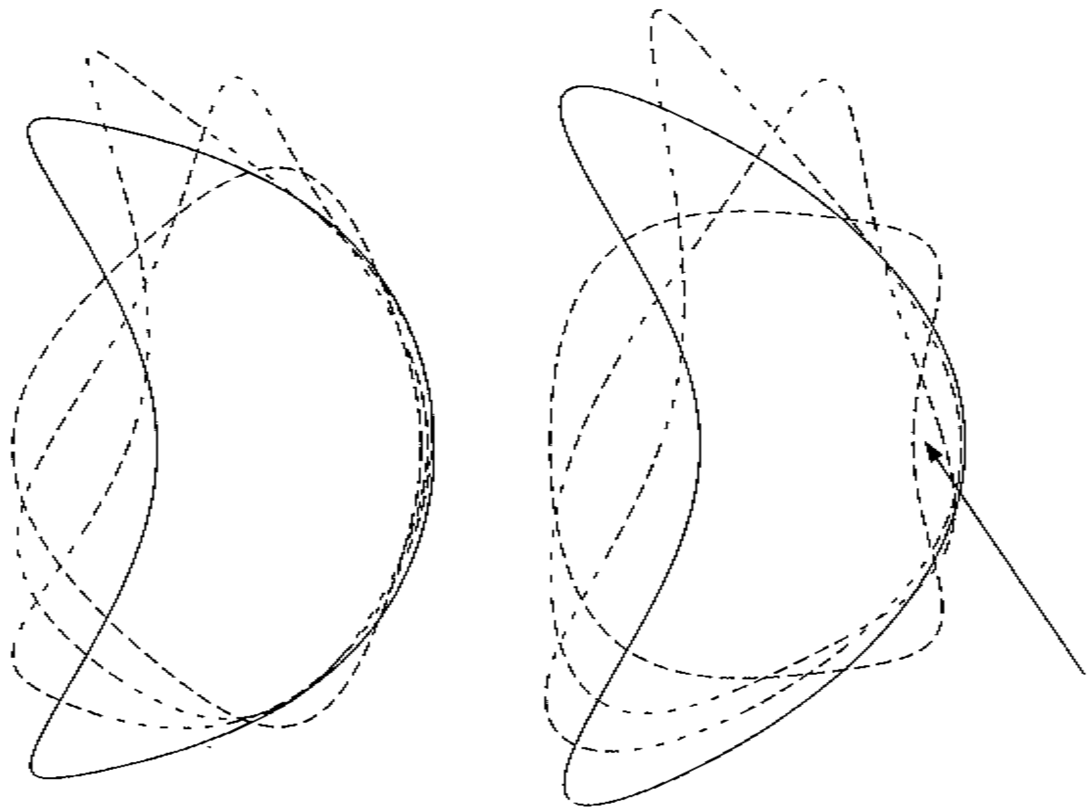
External Kink stabilized without need for wall stabilization by combination of externally generated shear and corrugation of boundary. C82 stable with reference profiles at $\beta \approx 4\%$.



Stabilizing Corrugation with little effect on shear

Indentation controllable with outside pusher coil.

c3 unstabilized

c82 stabilized

ARIES requires conducting wall at 1.3a.

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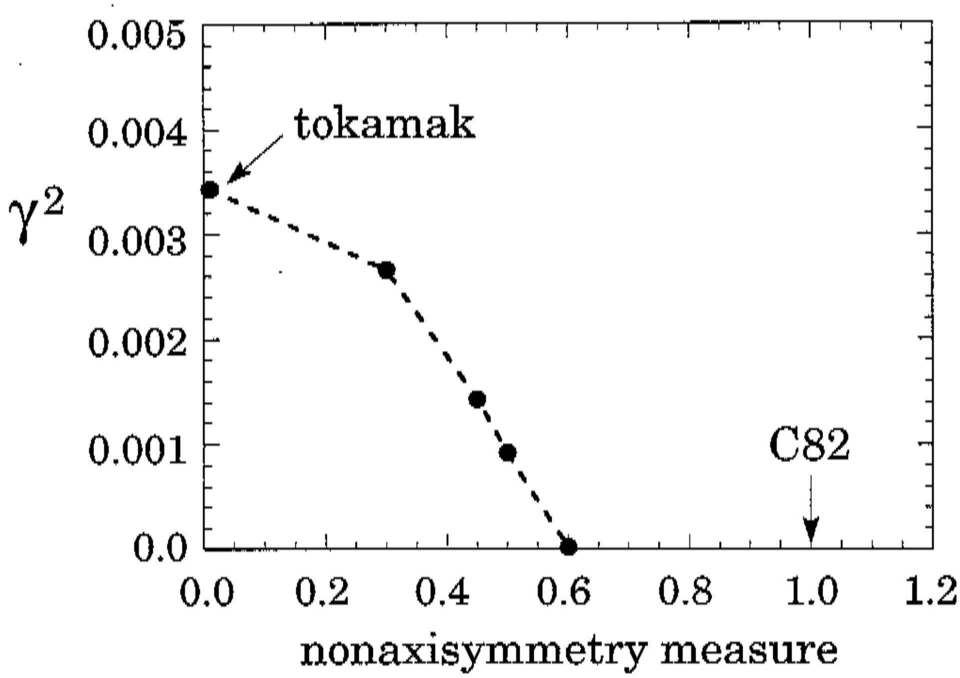
Configuration C82 is robustly stable to the vertical mode. (no conducting wall)

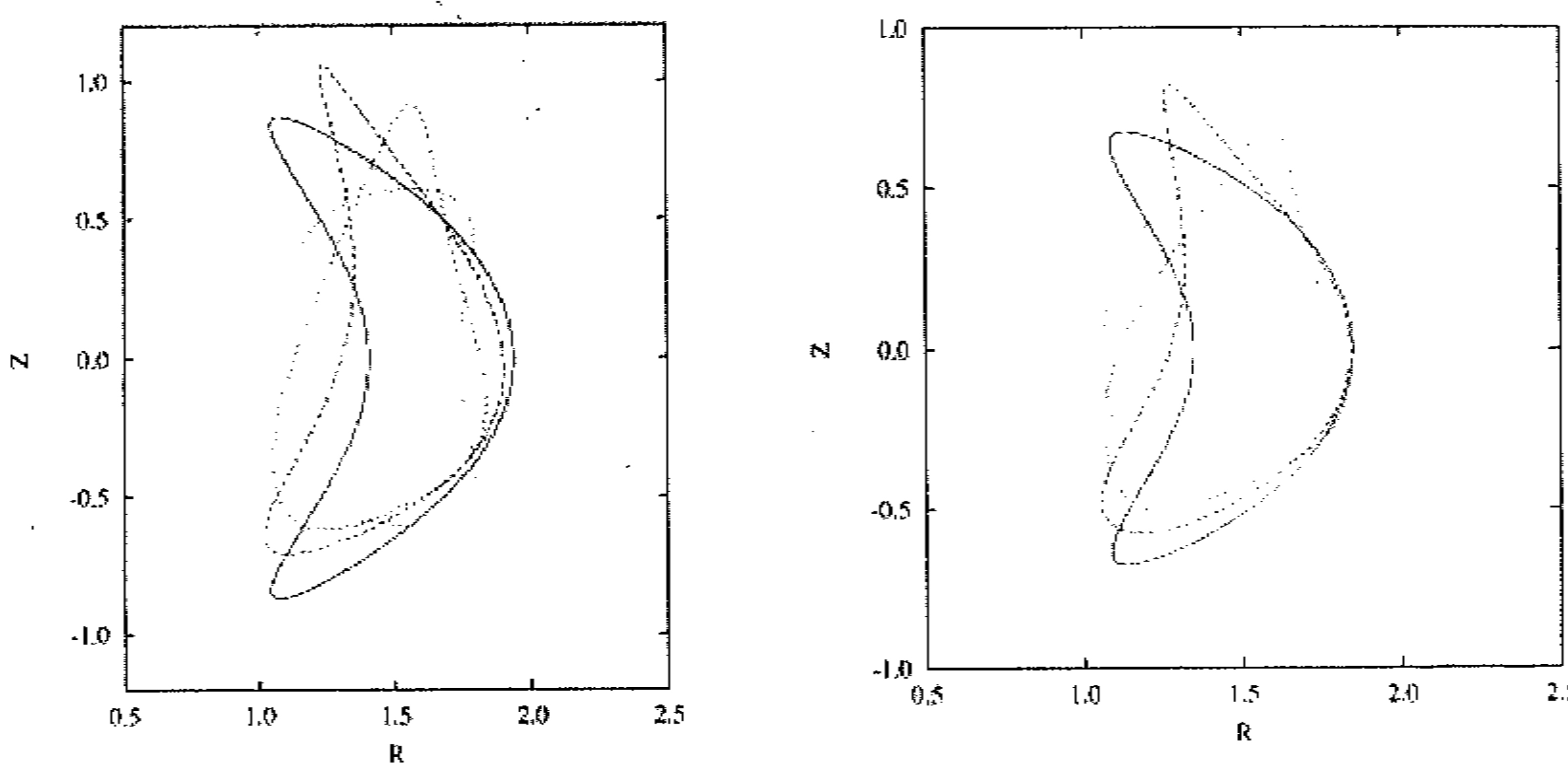
Vertical Stability for a Series of Configurations Interpolated Between C82 and a Tokamak



May be able to further improve design by going to higher elongation.

Ku

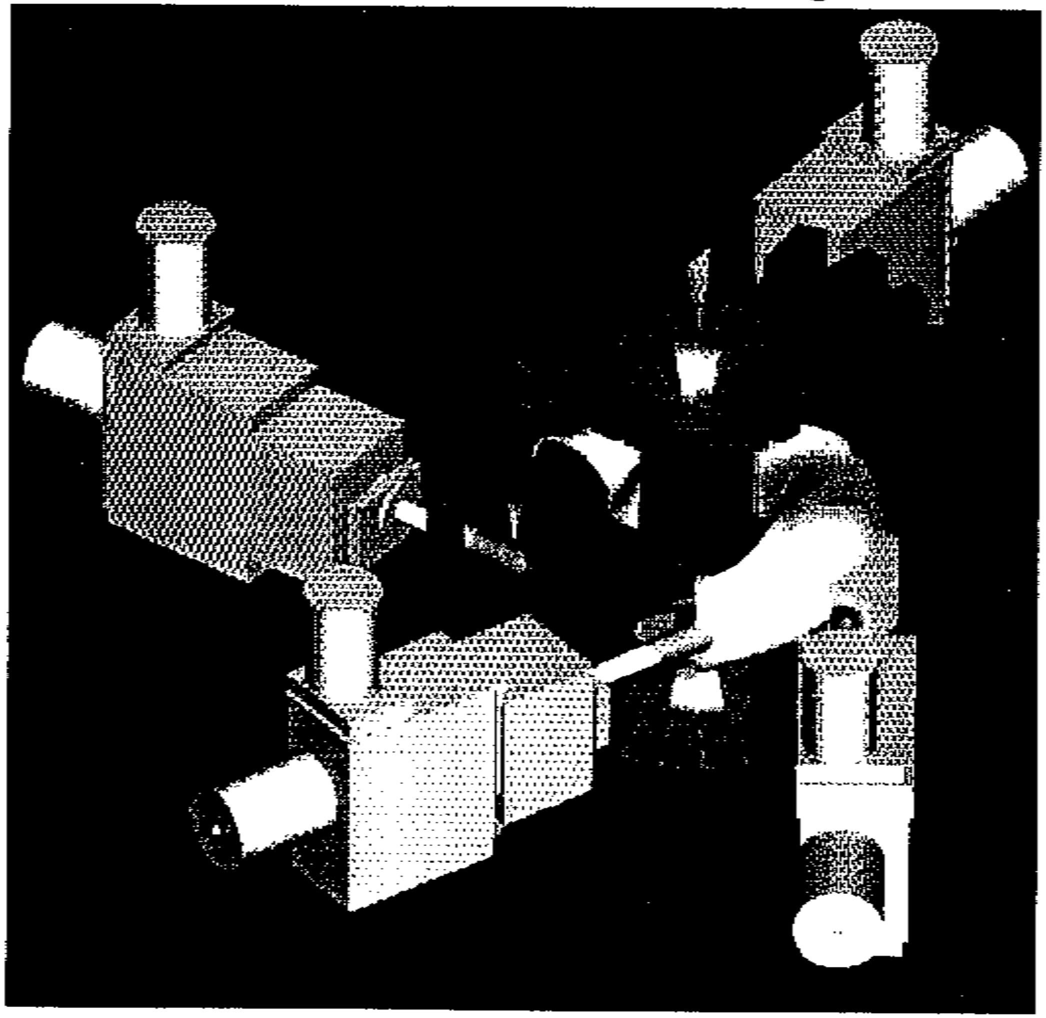
QAS3_ES3: A Configuration with κ=2.5, δ=0.7, and stability β ~5%



090299-LPK

GTC gyrokinetic code: $\tau_{E\,neo} \approx 90$ ms at $B = 1.2$ T. (Mynick & Li

The NCSX Construction Cost Will Be Reduced By Re-Using PBX-M Magnets and Neutral Beams



Machine Parameters

- R=1.45 m, ⟨a⟩=0.42 m
- B≤2 T / ~0.5 s
- I ≤ 330 kA

Plasma Heating:

- NBI: 6 MW
- ICRF: 6 MW available

Estimate: To reach $\beta = 4\%$ require ~5.5 MW NBI at $B = 1.2$ T. (Zarnstorff)

- Also re-use existing diagnostics, power supplies, C-site infrastructure at PPPL.

Conclusions

MHD stabilization opens up new, previously unexplored regime in configuration design space.

- Quasi-axisymmetry provides good neoclassical confinement, possibility of tokamak-like transport barriers.
- Perturbed bootstrap current effects oppose magnetic island formation.
- Ballooning stabilized by axisymmetric shaping. Core in 2nd stability regime.
- Kink stabilized, without conducting wall, by combination of externally generated shear and corrugation of boundary.
- Vertical mode is robustly stable with wall at infinity in kink stabilized configuration.

A proposed experiment would study transport, 3D MHD stabilization, potential advantages and disadvantages of bootstrap current, disruption suppression near the β limit.