High β Quasi-poloidally Symmetric Compact Stellarator Configurations

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A detour in the optimization of a compact stellarator

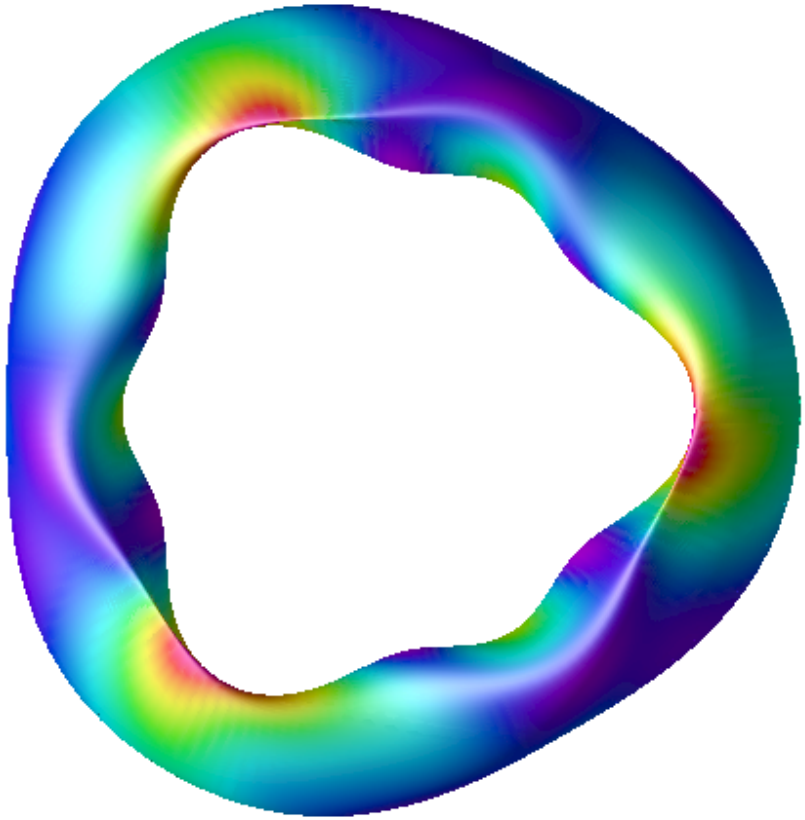
- Using an iterative stellarator optimization code to optimize plasma configurations for…
  - Low aspect ratio, $A < 4$
  - Good confinement by minimizing the deviation of surfaces of constant second adiabatic invariant from flux surfaces
  - Ballooning and Mercier stability
  - $\beta > 2\%$ and …

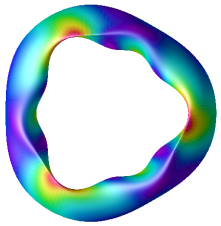
A detour in the optimization of a compact stellarator

- Using an iterative stellarator optimization code to optimize plasma configurations for…
  - Bootstrap current *consistency* and *alignment*
    - Consistency: the neoclassical bootstrap current is calculated from the equilibrium pressure and rotational transform profiles
    - Alignment: the bootstrap current provides nearly 100% of the equilibrium current
- And along the way, we found…

Compact, High-β Stellarator Configurations

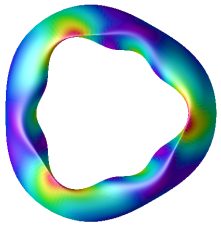
- $A = 3.7$
- $N = 3$
- $\beta = 15\%$
- Tokamak-like rotational transform
- Moderate, bootstrap-aligned current





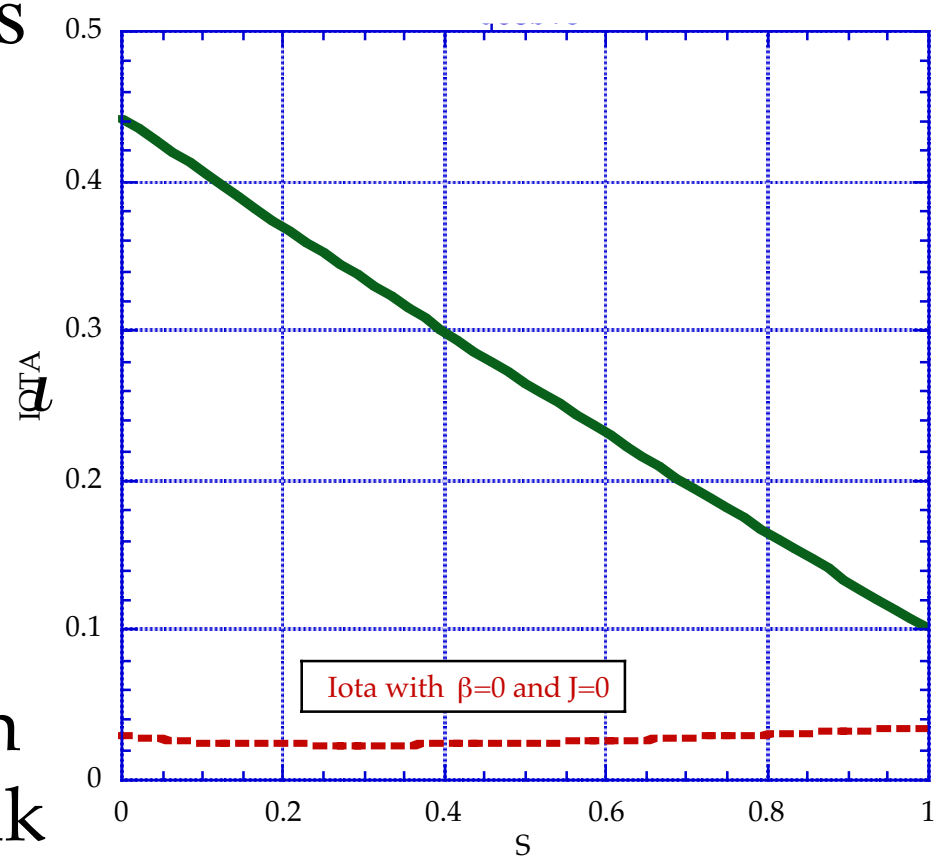
Compact, High-β Stellarator Configurations

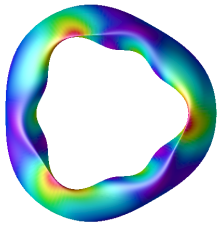
- Compact stellarators
  - low aspect ratio devices (A = 2.5-4)
  - a low number of field periods (N = 2-4)
- A $|B|$ spectrum which exhibits quasi-poloidal symmetry (qps)
  - In Boozer coordinates, $\dfrac{\partial |B|}{\partial \theta_{\mathrm{B}}} \approx 0\,, \quad B_{m \neq 0, n} \approx 0$
  - Results in good neoclassical confinement



Compact, High-β Stellarator Configurations

- Plasma current provides the majority of the rotational transform
  - $\iota(0) \sim 0.4$ to $\iota(a) \sim 0.1$
  - Role of the modular coils is to reduce the bootstrap current
  - $I_{boot} \sim 1/3$ -1/5 that in an equivalent tokamak





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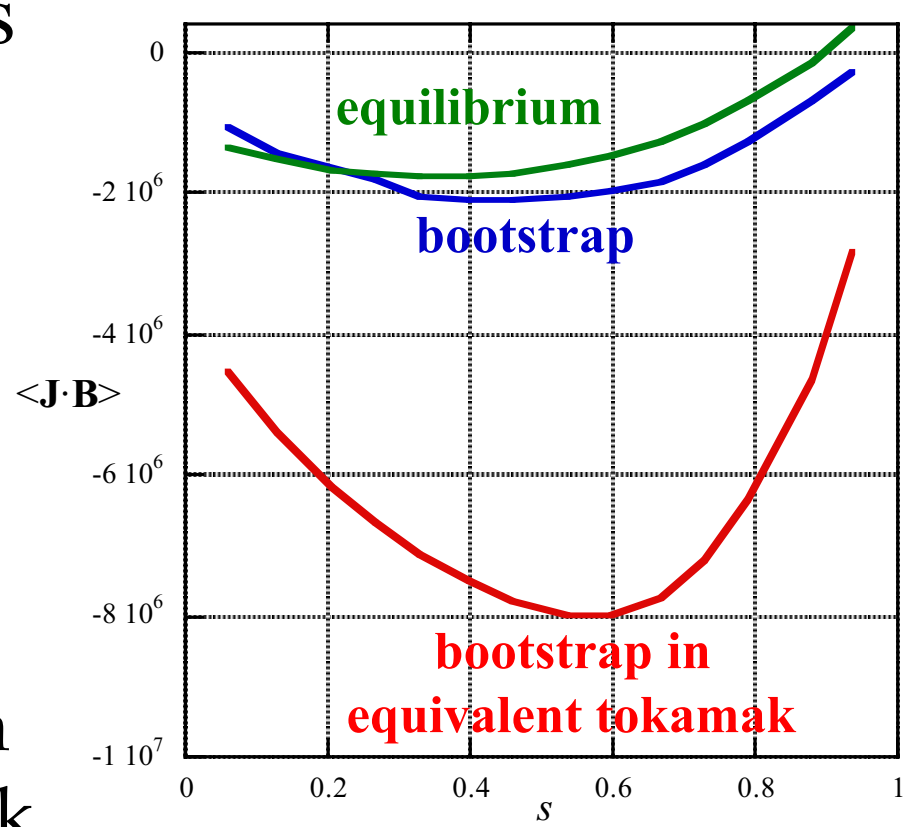
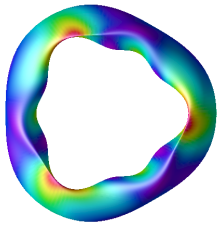
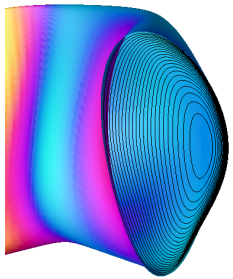




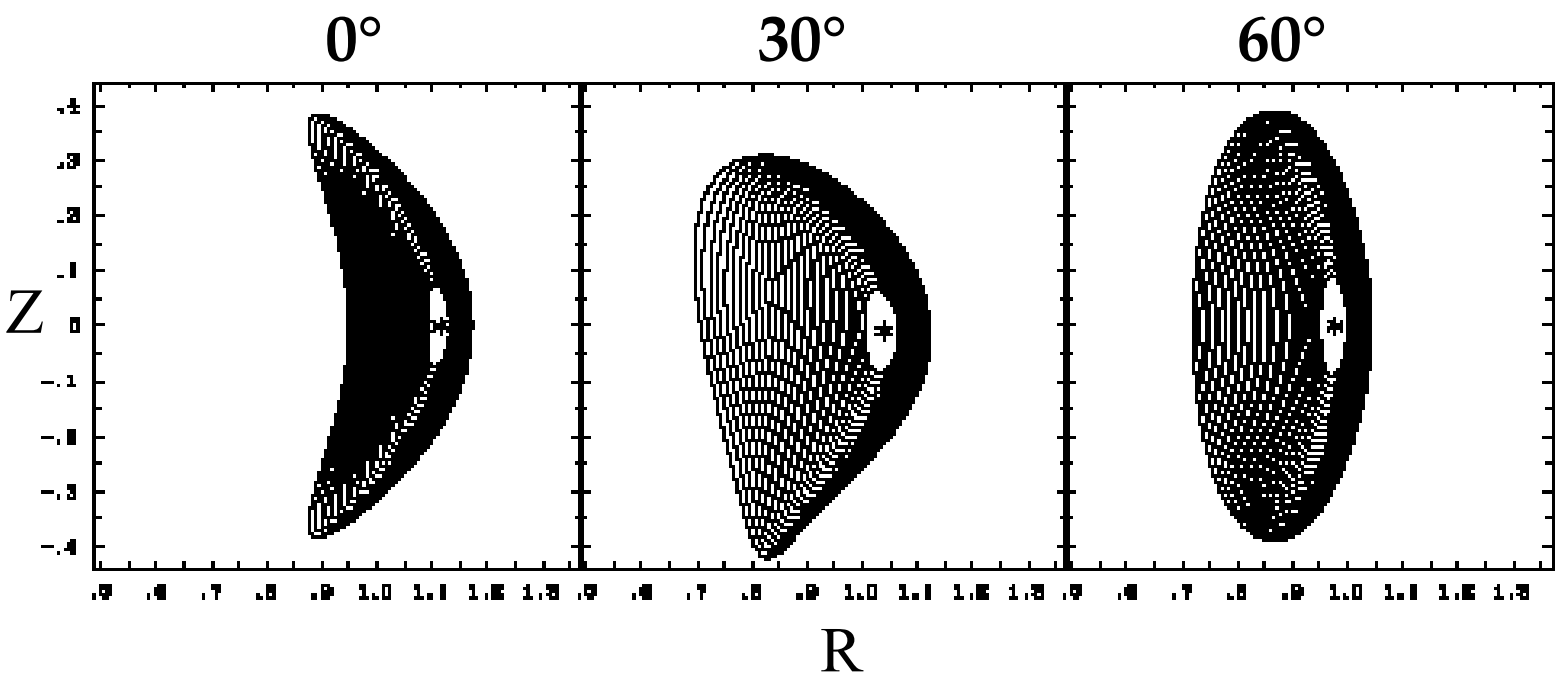
Compact, High-β Stellarator Configurations

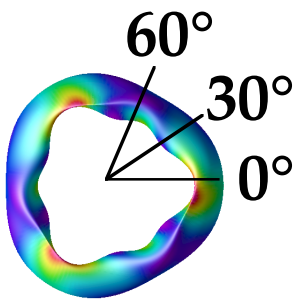
- Strong magnetic wells and high-β MHD stability limits
  - Mercier and ballooning stability, $\beta \sim 23\%$
  - Kink and vertical modes, $\beta \sim 11\%$
- Adequate neoclassical confinement
  - $\tau_{Eneo}/\tau_{ISS95} = 3.6$ in moderate collision frequency regime
  - Neoclassical confinement improves with β

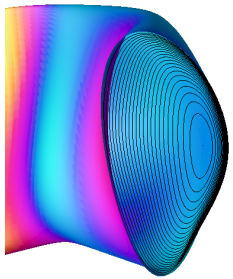


Equilibrium Properties: Flux surface geometry

- Cross sections of magnetic flux surfaces:

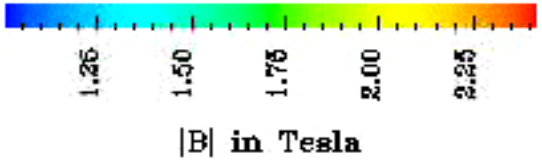


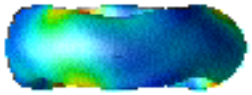


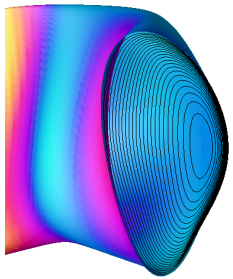


Equilibrium Properties: Flux surface geometry

- Last closed flux surface:

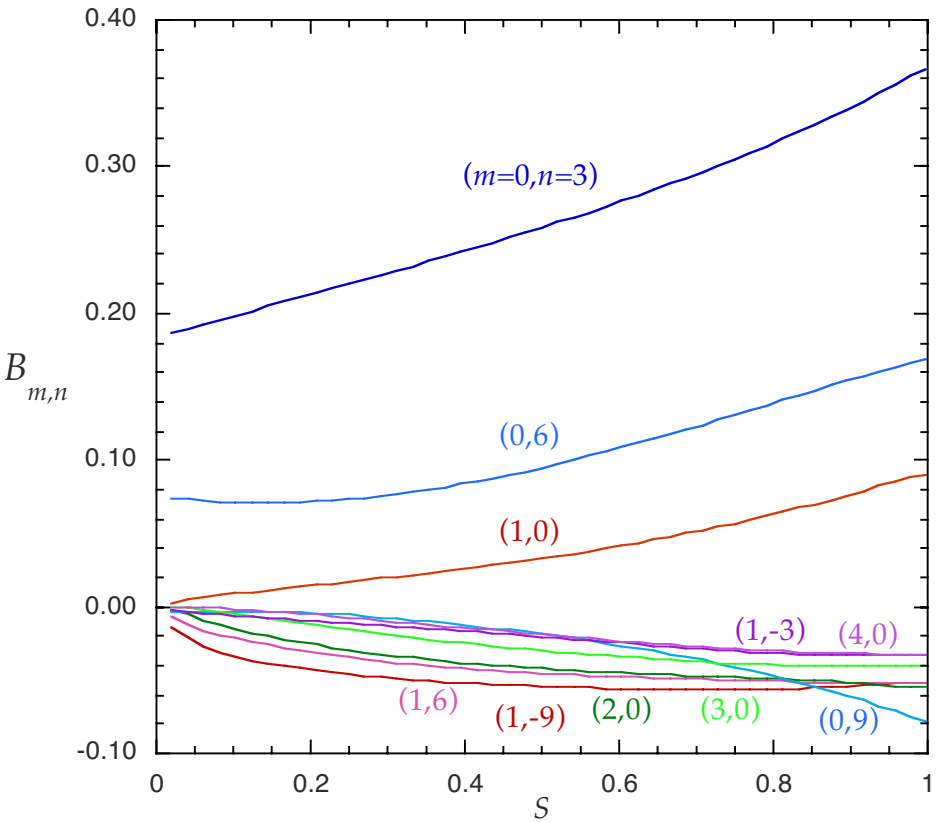


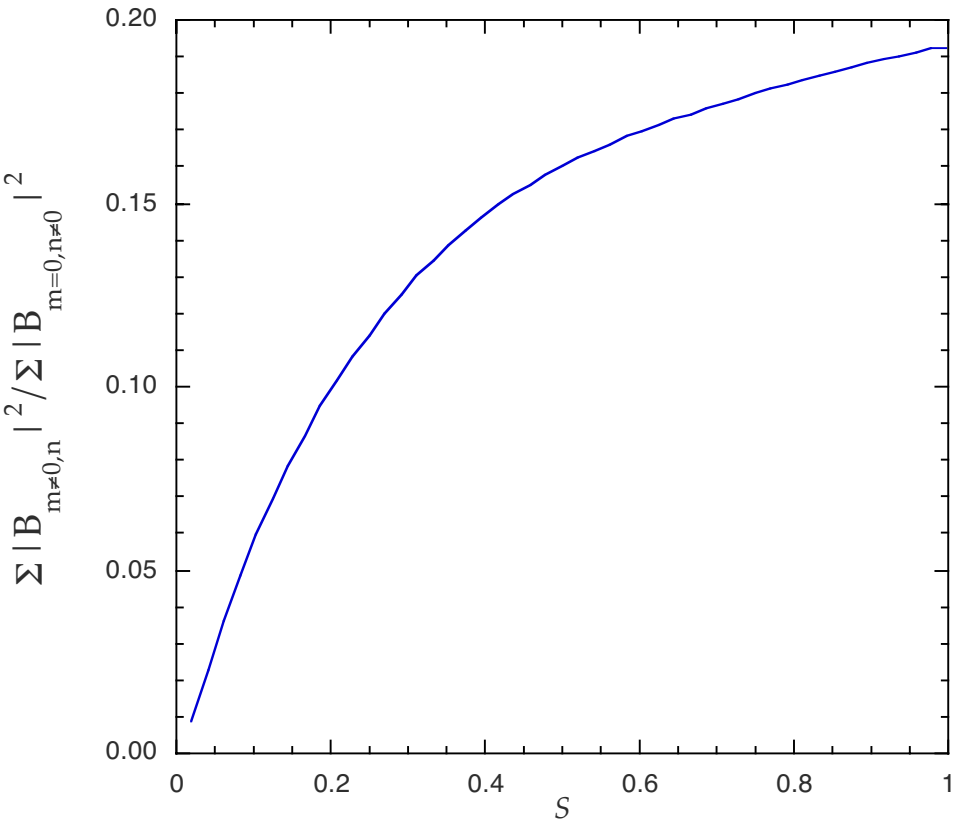


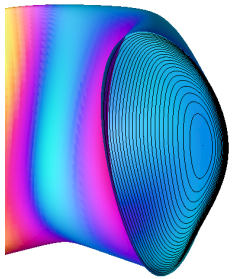


Equilibrium Properties:
High degree of qps in Boozer space

- 10 largest Fourier modes
- Ratio of m≠0 to m=0 modes

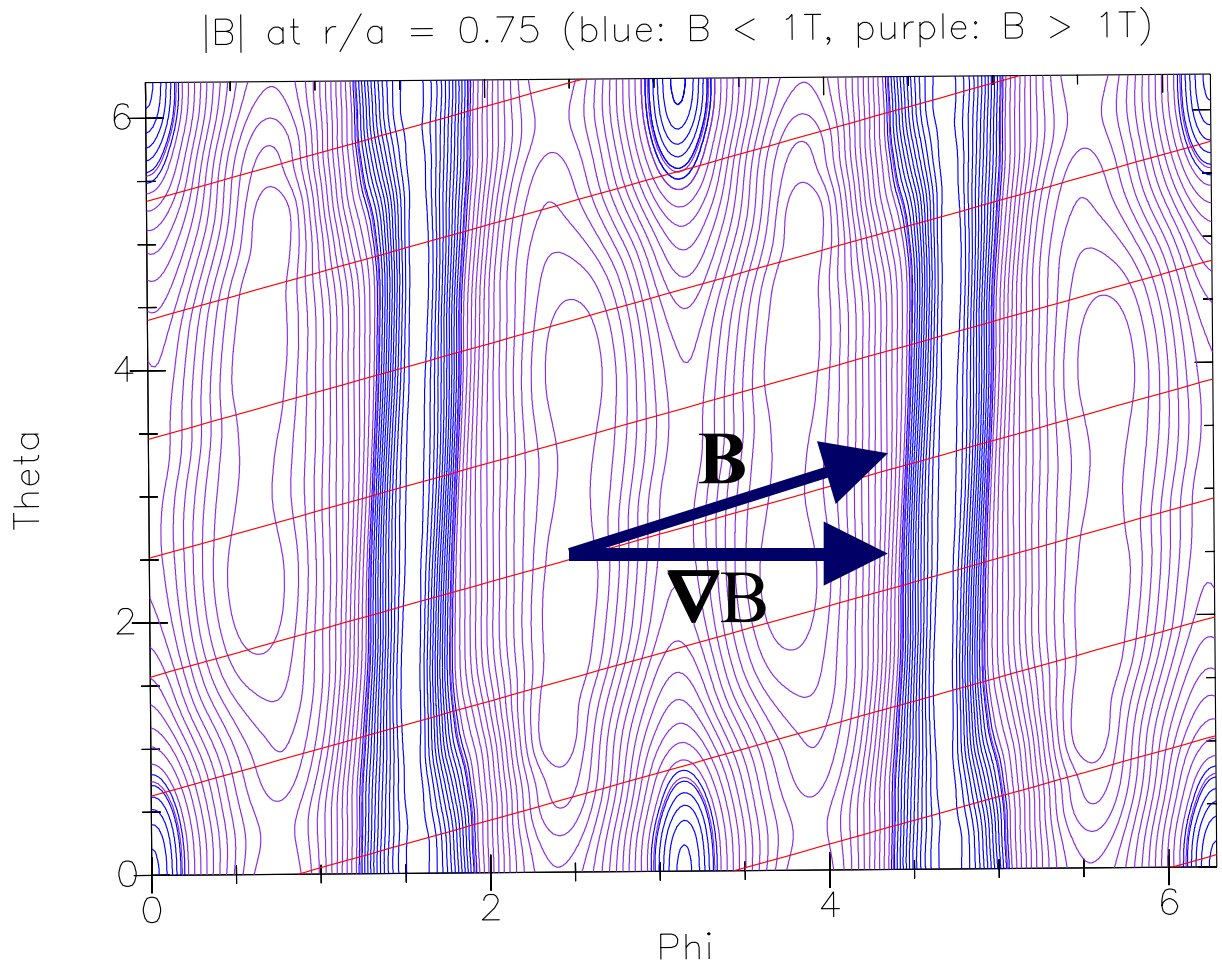


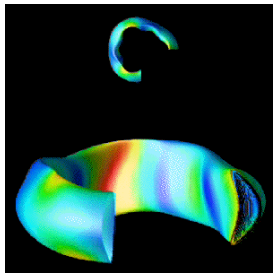




Equilibrium Properties:
High degree of qps in Boozer space

- Contours of $|B|$ on a flux surface in Boozer space
  - $\rho = 0.75$ surface is shown
  - Red are field lines
  - Purple (|B| > 1T)
  - Blue (|B| < 1T)

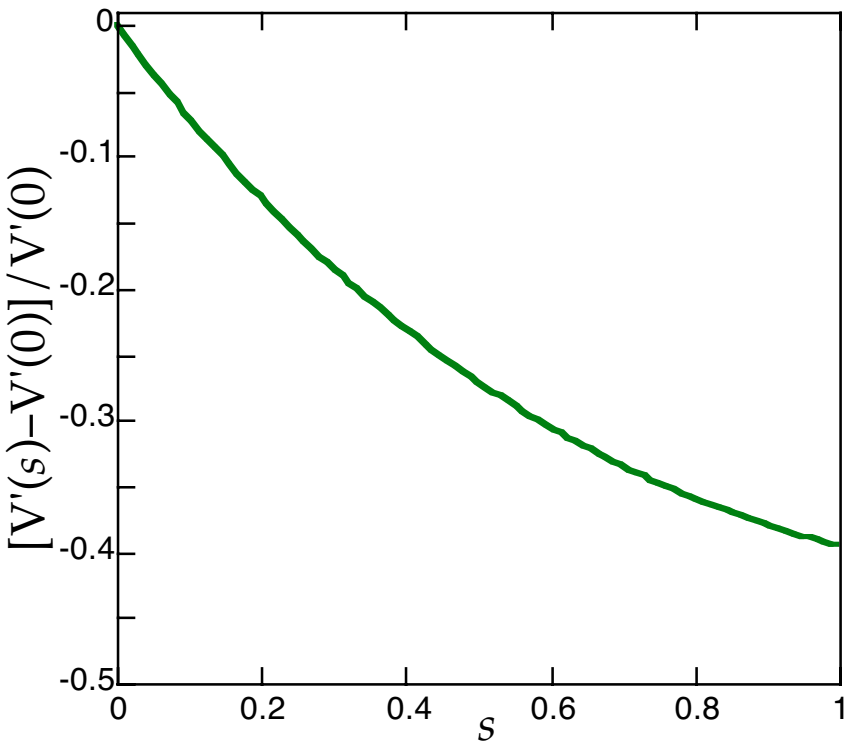




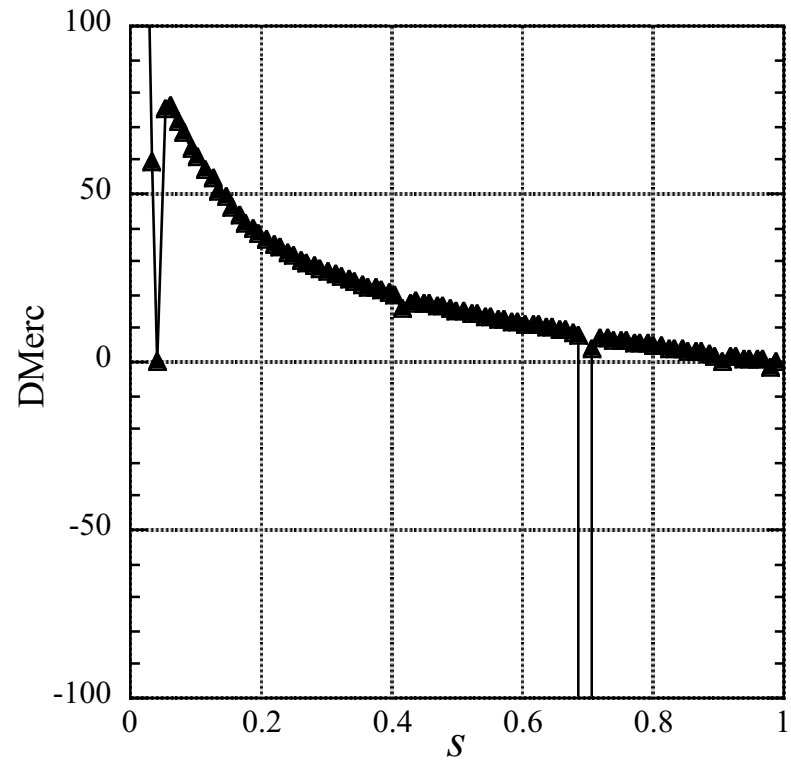
MHD Stability Properties:

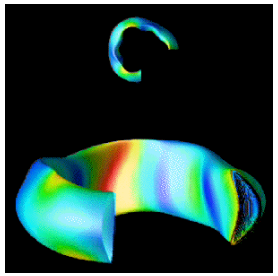
Strong well provides Mercier stability

- Magnetic well



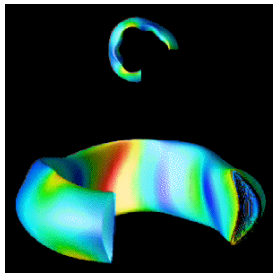
- Mercier factor





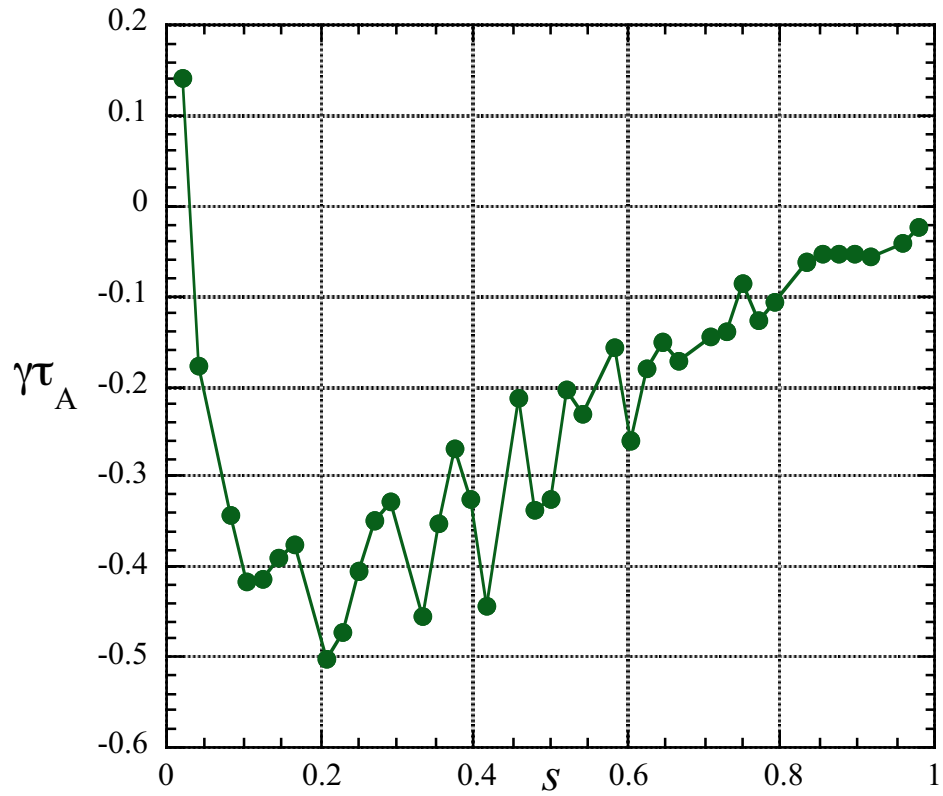
MHD Stability Properties: Ballooning stable at high-β

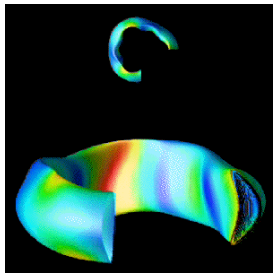
- The finite bootstrap current results in reductions of both the helical curvature & the connection length (relative to standard stellarators)
- Both of these effects contribute to the higher ballooning stability β limits that are observed
- Infinite-n ballooning mode stability was analyzed using the COBRA code



MHD Stability Properties: Ballooning stable at high-β

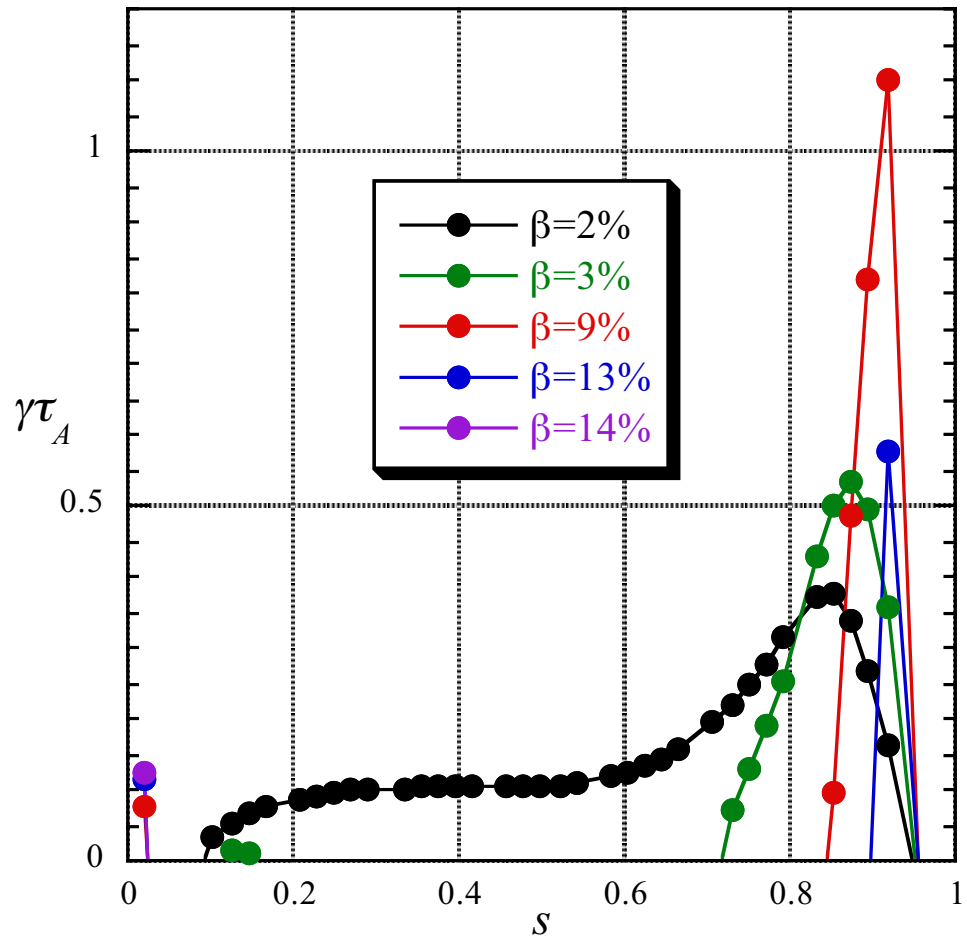
- Ballooning stable & bootstrap consistent cases have been obtained for $2\% < \beta < 23\%$
- Ballooning stability of the $\beta = 15\%$ case is shown at right

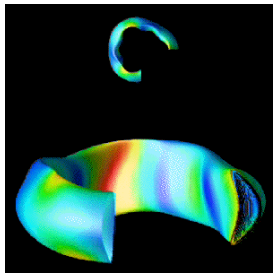




MHD Stability Properties: Ballooning stable at high-β

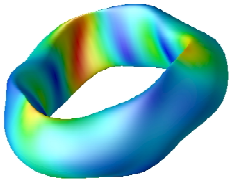
- Evidence of 2nd stability regime
  - Plasma becomes unstable as pressure is decreased for a fixed shape & current
  - Stable plasmas at all $\beta < 23\%$ with small shape/profile changes





MHD Stability Properties: Kink and vertical mode stability

- Stability to kink (n=1) and vertical (n=0) modes tested using TERPSICHORE
  - At β=15%, stable to vertical mode, weakly unstable to kink mode with a growth rate of $\gamma\tau_A \sim 2\times10^{-2}$
  - Scaling β to ~11% (with same shape and iota) completely stabilized the kink mode
  - At this value of β, the Troyon factor is $\beta_N = 19$, significantly larger than $\beta_N \sim 3$ for kink stability in an equivalent tokamak with no wall stabilization



Transport Properties:
Adequate neoclassical confinement

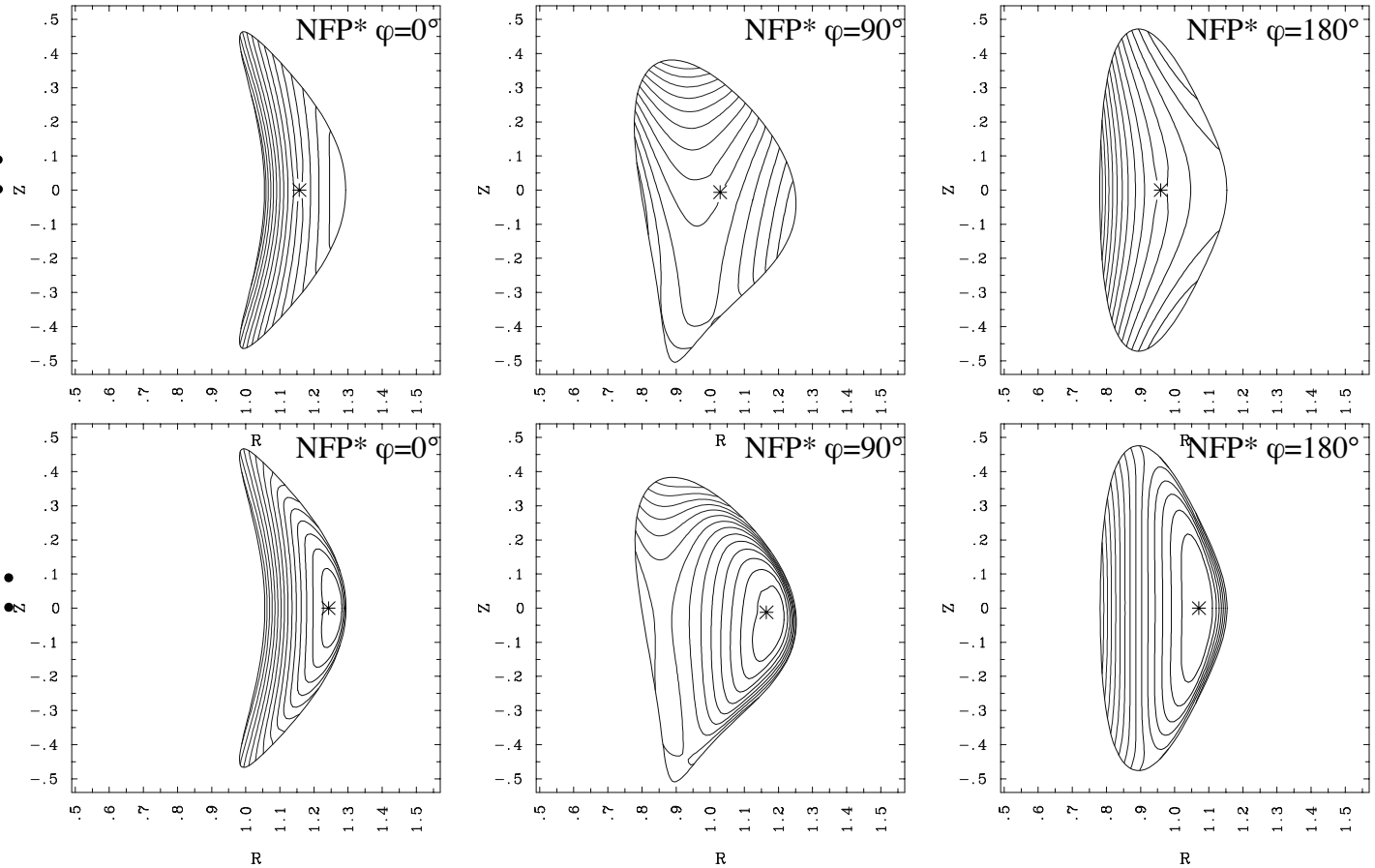
- Neoclassical confinement tested using a Monte Carlo code with $\langle B \rangle$=1 T, $\langle R \rangle$=0.86 m
  - Low collision frequency, hot electron plasma
    τ_{Eneo} = 14 ms & τ_{Eneo}/τ_{ISS95} = 1.4
  - Moderate collision frequency, with $T_e = T_i$
    τ_{Eneo} = 58 ms & τ_{Eneo}/τ_{ISS95} = 3.6
- Recent optimizations using the NEO code have resulted in a factor of ~2 improvement in confinement times

Transport Properties: Alignment of $|B|$ surfaces with flux surfaces improves with β

- Surfaces of constant $|B|$ at $\beta = 0\%$ and 23%

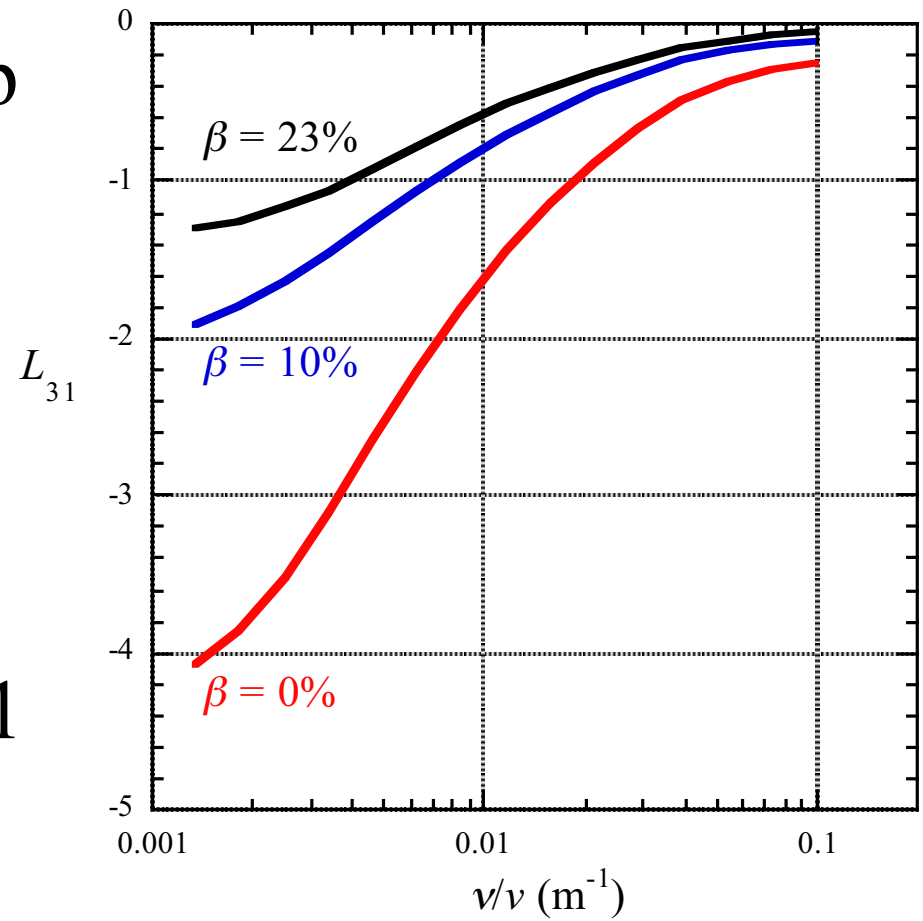
β=0%:

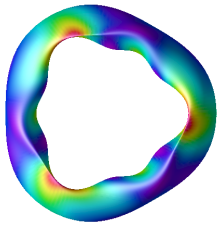
β=23%:



Transport Properties:
Configurational invariance

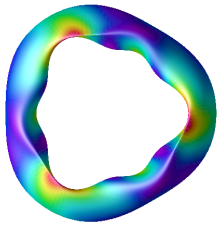
- Decrease in bootstrap current transport coefficient as β increases leads to configurational invariance
- DKES results for L31 at different beta





Conclusions

- Compact stellarator configurations with
  - MHD stability β limits of ~ 11%
  - infinite-n ballooning stability limits of $\beta < 23\%$
  - a low number of field periods (N = 2-4)
  - a quasi-poloidal symmetric $|B|$ in Boozer space
  - good neoclassical confinement
  - tokamak-like rotational transform, $\iota(0)$~0.4 to $\iota(a)$~0.1
  - a bootstrap current which is 1/3 -1/5 that in an equivalent tokamak



Ongoing Work

- Use transport codes to improve neoclassical confinement in these configurations
- Examine the effect of an edge pressure pedestal on MHD stability
- Explore link between the QPS reference configuration & the high-β configurations