Quasi-Poloidal Symmetry and DKES Transport Optimizations of High Beta Compact Stellarator Configurations

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Abstract

Recent work on compact stellarators has shown the existence of a class of configurations with high MHD beta limits for both ballooning modes ($\beta > 20\%$) and kink modes ($\beta \sim 11\%$). These configurations are low-field period (M=2-4), tokamak-stellarator hybrids. They have finite bootstrap current which provides the majority of the rotational transform but is only a fraction (1/3-1/5) of that in a comparable tokamak. The magnetic field structure of these configurations exhibits quasi-poloidal symmetry. In this work, these configurations are transport optimized by both enhancing the quasi-poloidal symmetry and using the DKES (Drift Kinetic Equation Solver) transport code as part of a stellarator optimization routine. Targeting enhanced poloidal symmetry does improve neoclassical confinement and also reduces the predicted bootstrap current. However, these effects are often masked by changes in the magnitude of |B| variation as well as changes in the plasma shape. Including DKES in the optimization routine (though transport is often only evaluated on a small number of surfaces due to the computationally intensive nature of DKES) also improves the neoclassical confinement.

I. Introduction

- A class of configurations with high β MHD stability limits
    - Rotational transform primarily from plasma current
    - Better alignment with self-consistent bootstrap current than advanced tokamaks
    - Stable at higher β than comparable tokamak due to lower self-consistent bootstrap current

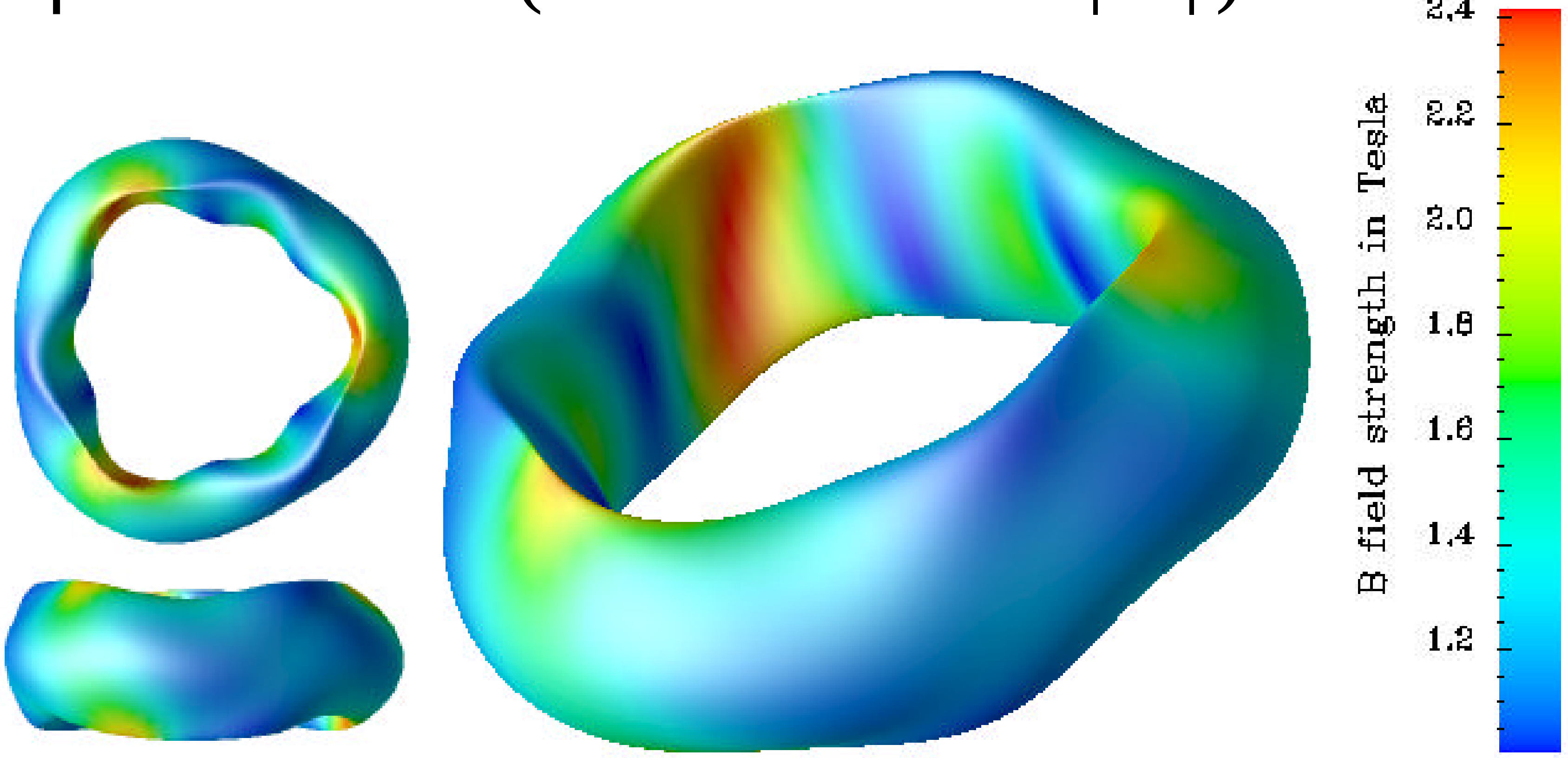
Configuration Properties

- Low aspect ratio: $2 < A < 4$
  - ➢Compact, economically-sized design
- Low number of field periods: N = 2 - 4
  - ➢Relatively simple modular coils
- High β MHD stability limits
  - ➢Ballooning & Mercier stability up to β=23%
  - ➢Vertical/Kink stability up to β =15%
- Confinement which improves with β

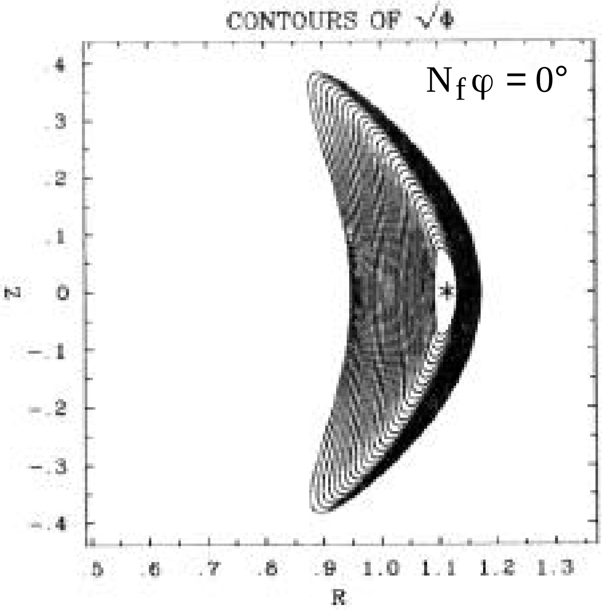
3 Field Period Configuration

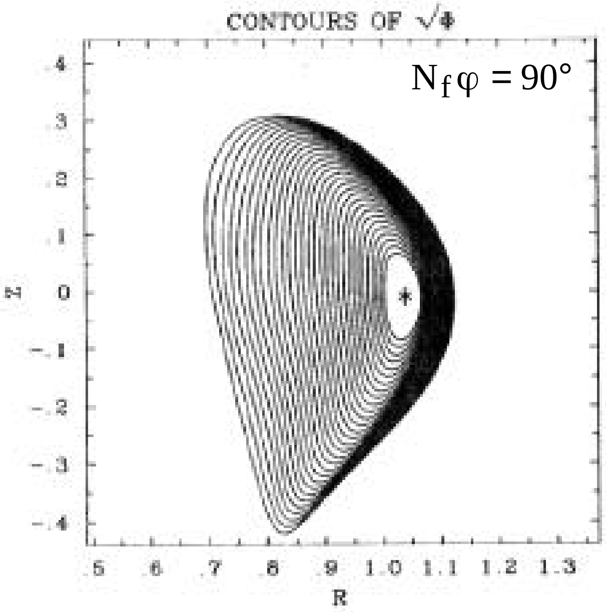
- A = 3.7
- β = 15%

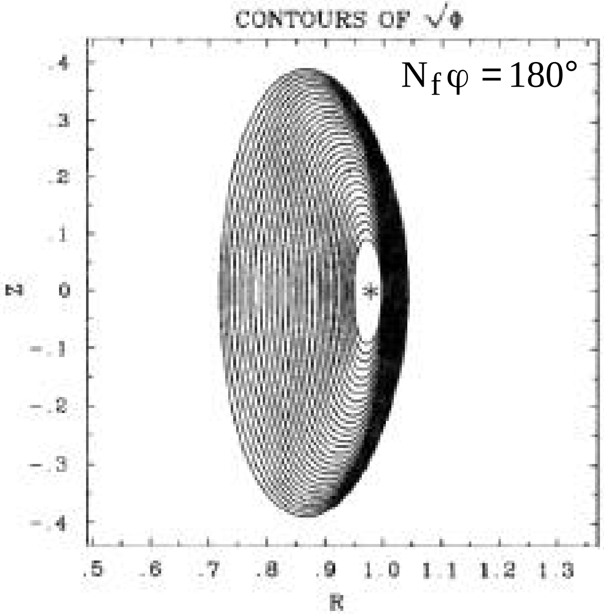
Outer Flux Surface
(color indicates |B|)

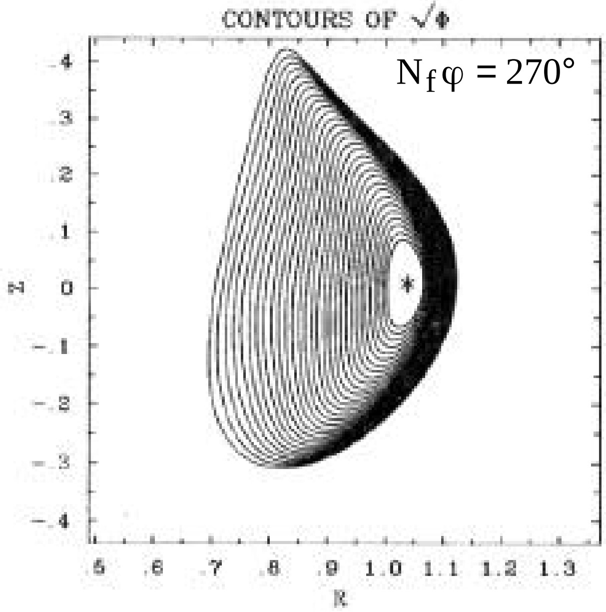


Flux Surfaces

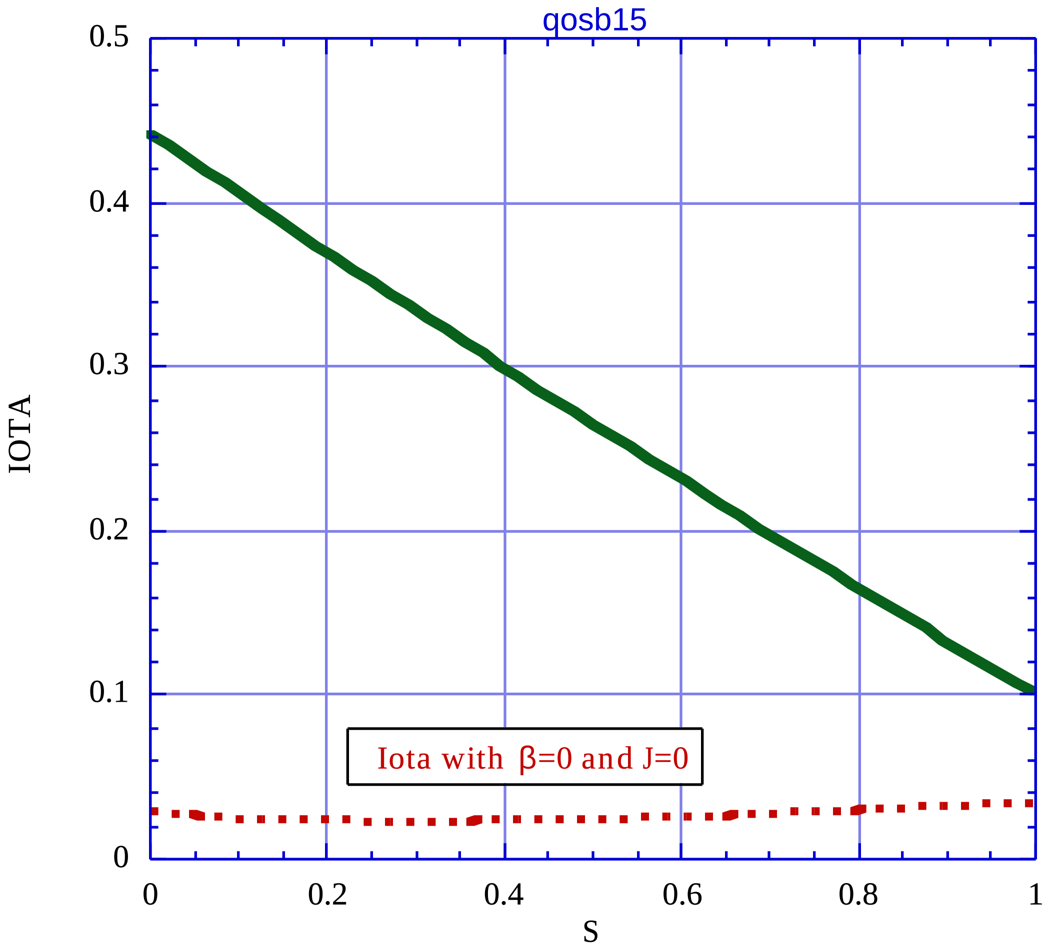






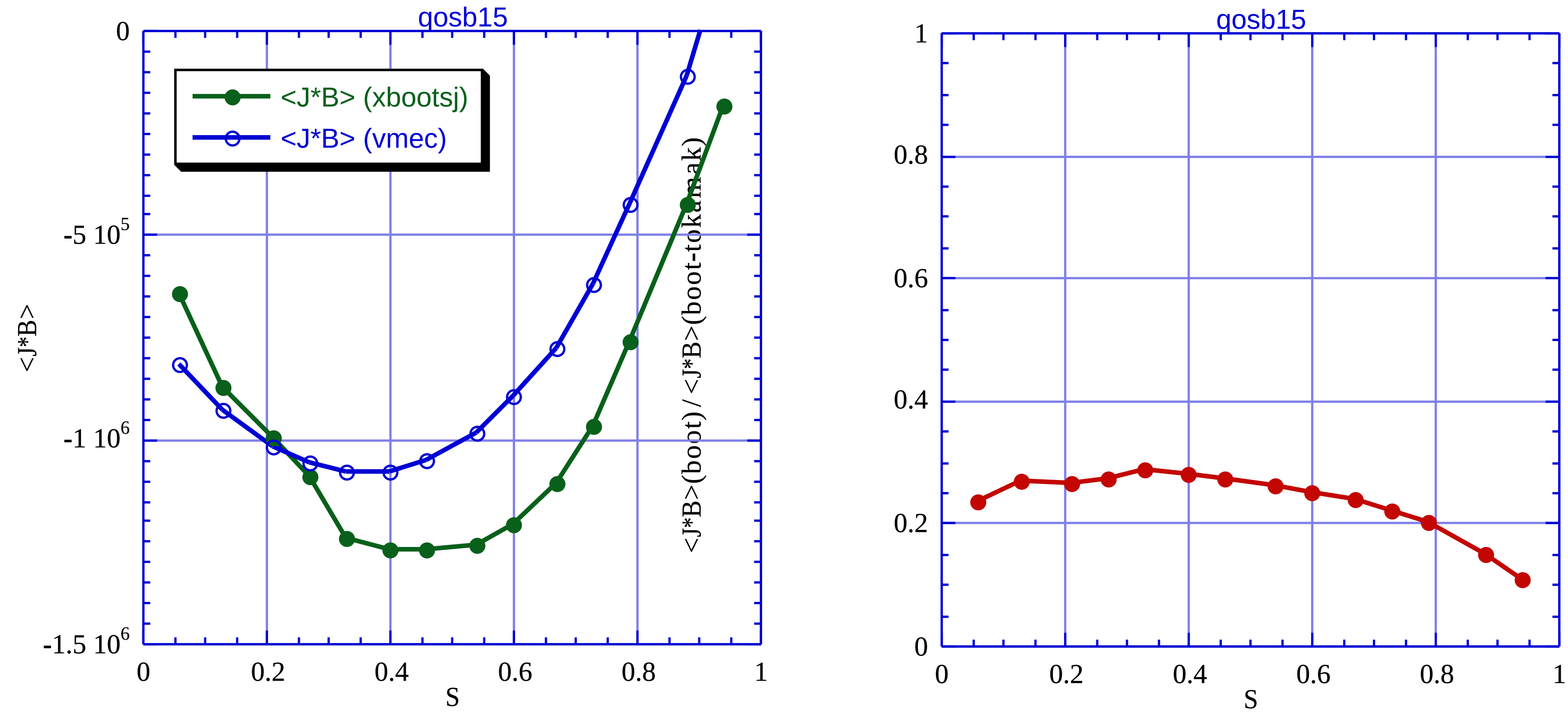


Rotational transform profile is related to the internal plasma current much like in a tokamak



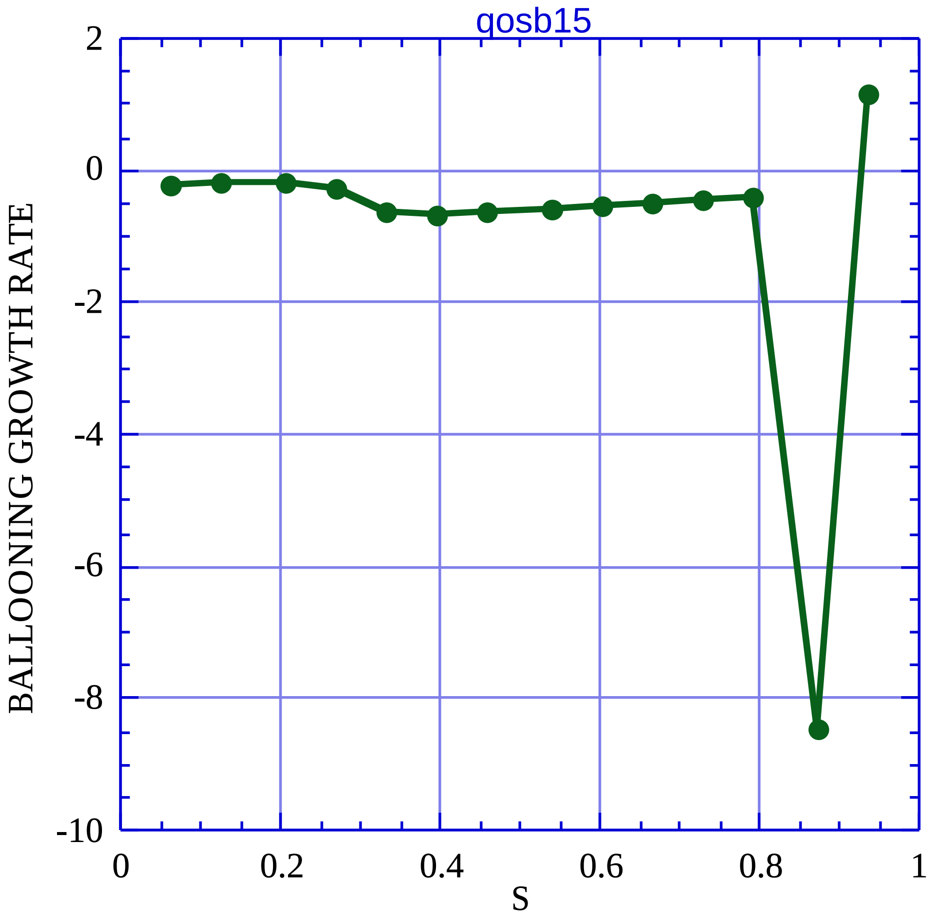
- $\beta = 15\%$
- $\langle |B| \rangle = 1.0\,\mathrm{T}$
- Tor. Cur. = 155 kA

Predicted bootstrap current is in relative alignment with the VMEC current and is a fraction of that in a comparable tokamak



Ballooning stable at all points analyzed except for one point at the edge region

Ballooning stability calculated using the COBRA code.



This configuration has good MHD stability properties

- Stable to vertical and kink modes
  - Vertical & kink stability analyzed with the TERPSICHORE code (G. Fu)
- Mercier stable except on a few isolated resonant surfaces

II. Quasi-poloidal Symmetry

- Modification of the |B| Spectrum
  - ➢ Described by Fourier Series:

$$B(\psi,\theta,\zeta) = \sum_{n}\sum_{m} B_{m,n}(\psi)\cos(m\theta - n\zeta)$$

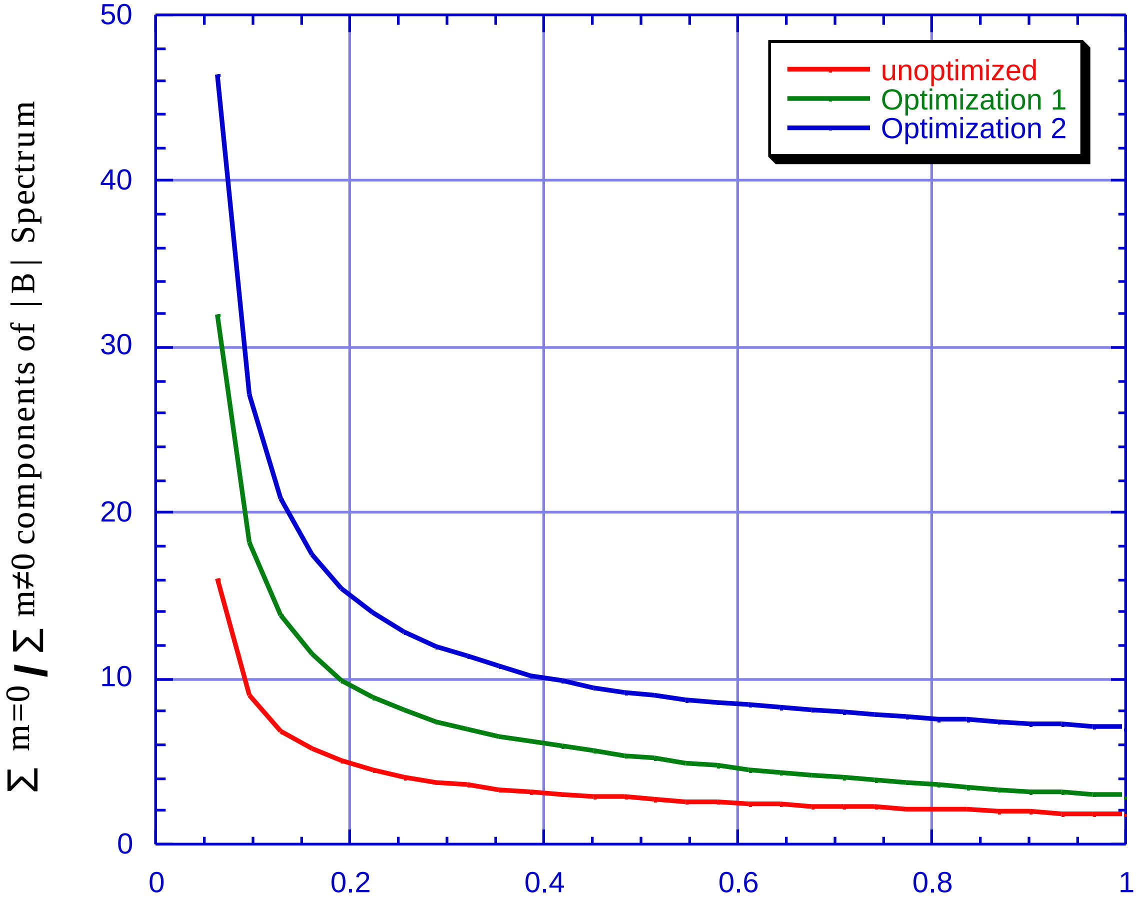
- Poloidal symmetry requires that B is function of ψ and ζ only
  - ➢ |B| has no θ dependence

- Goal:
  - Maximize the ratio:

$$\frac{\sum_{n\neq 0} B_{m=0,n}}{\sum_{m\neq 0}\sum_{n} B_{m,n}}$$

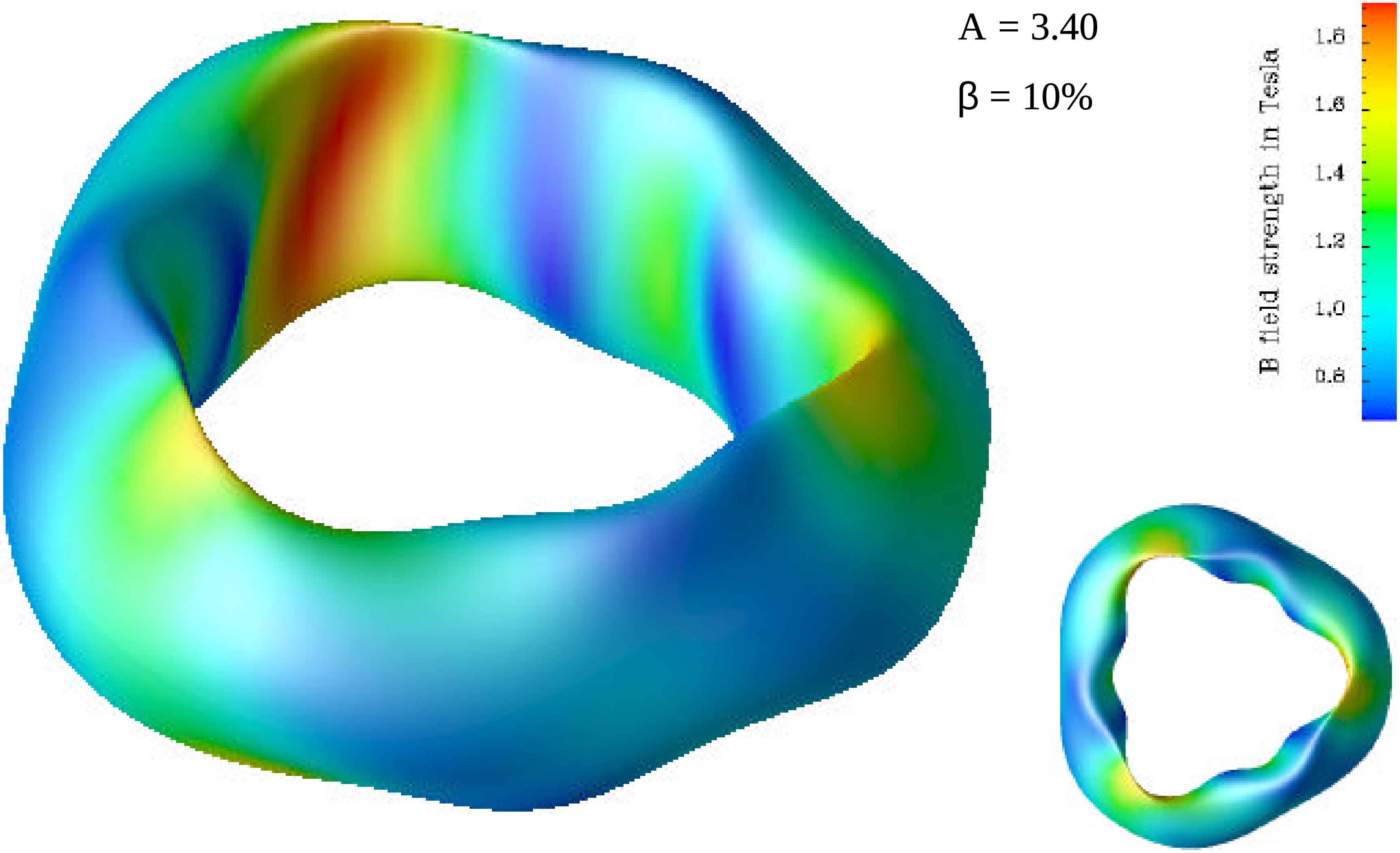
- Method:
  - Target a helicity of (0,1)
  - Other targets: ballooning and Mercier stability, bootstrap current alignment, $A = 3.40$, $\beta = 10\%$

The optimizer was able to adjust |B| Spectrum to increase poloidal symmetry



Chi-sq Bmn Contributions	
Unoptimized	17,855
Optimization 1	7,471
Optimization 2	1,835

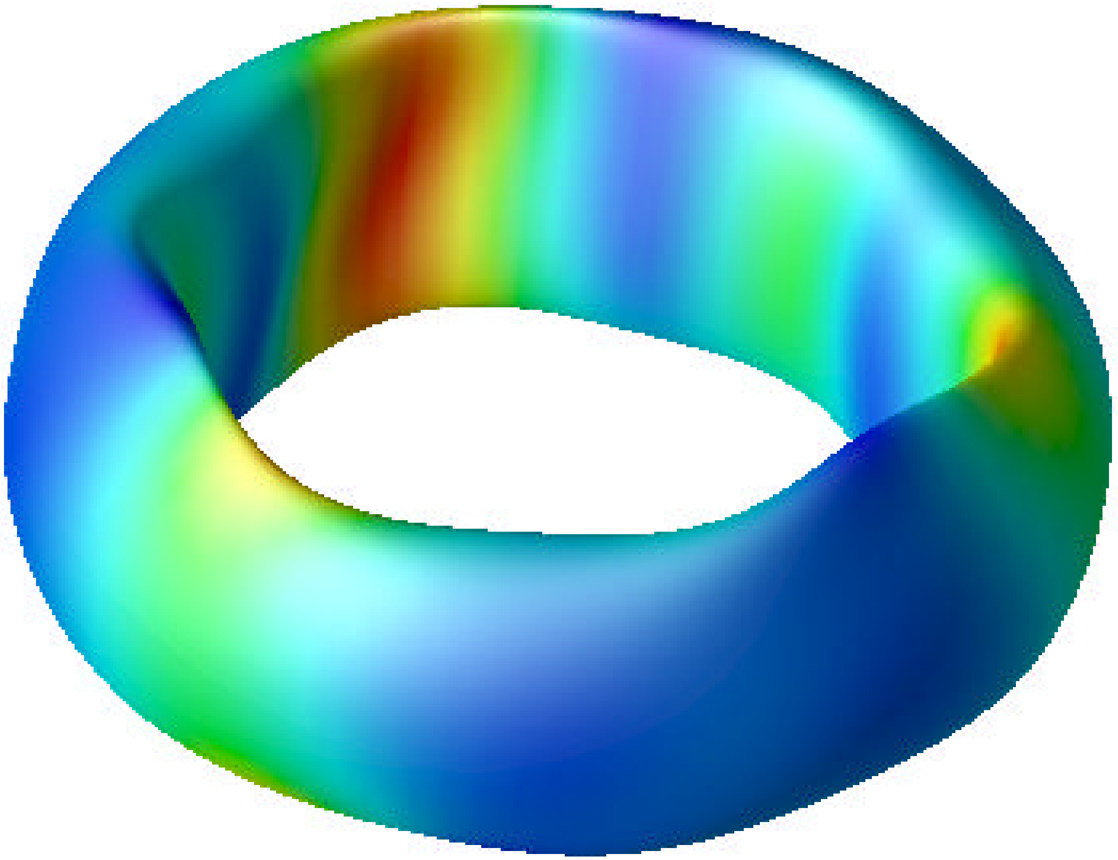
Unoptimized



A = 3.40

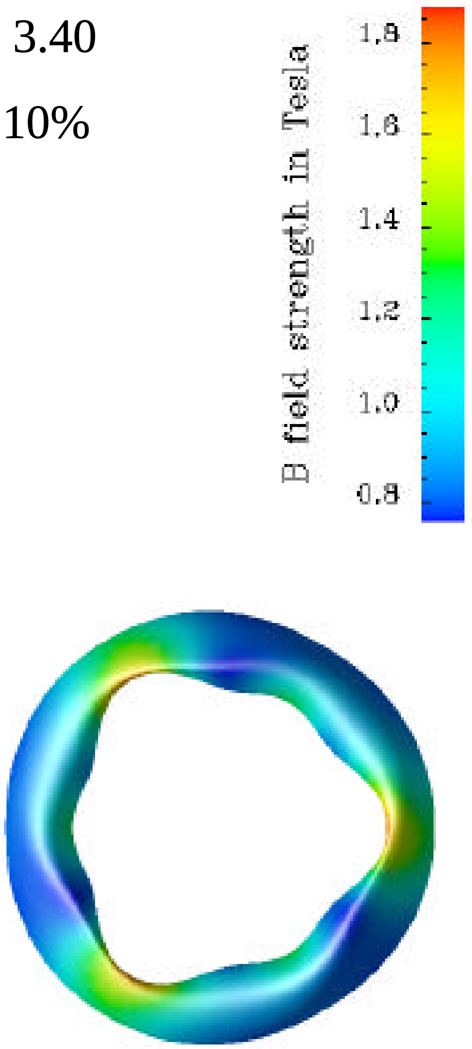
β = 10%

Optimization 1

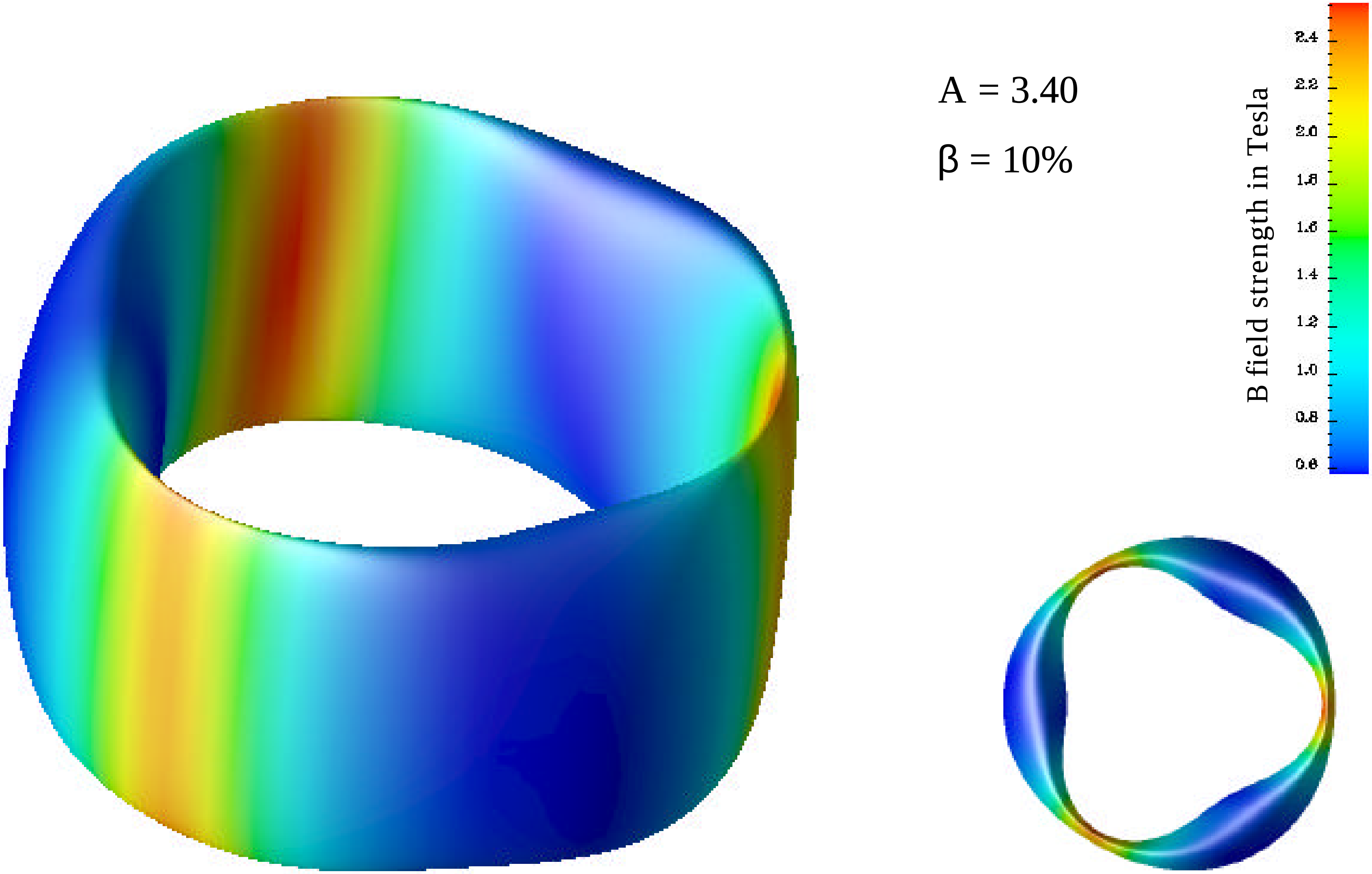


A = 3.40

β = 10%



Optimization 2

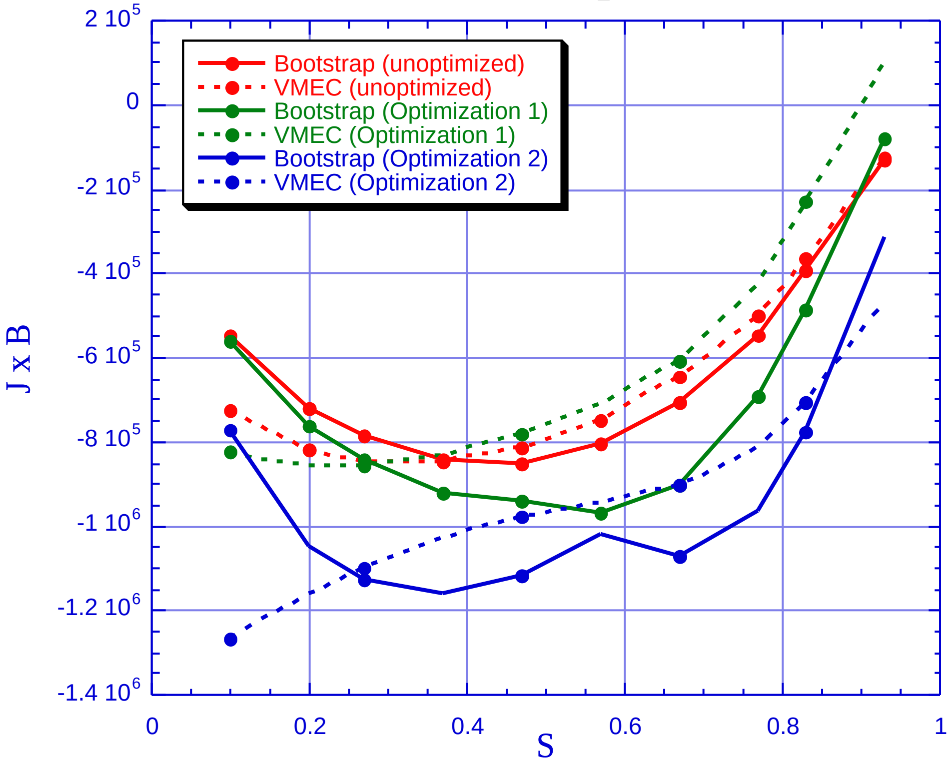


A = 3.40

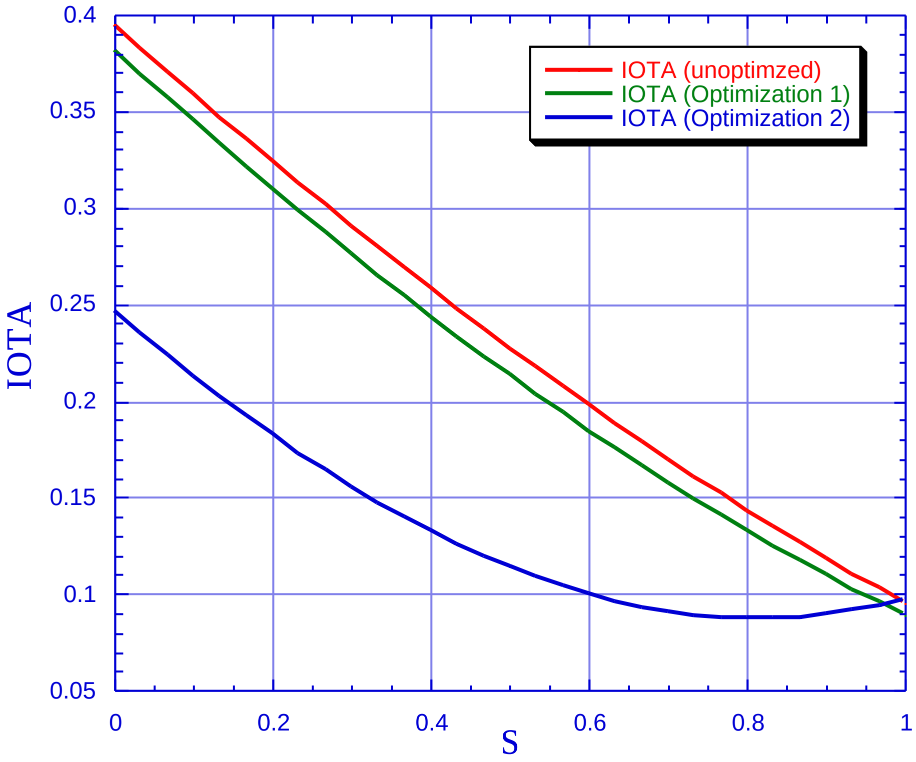
β = 10%

Optimization of |B| spectrum did affect the <J*B> and iota profiles

The amount of field alignment increased with optimization

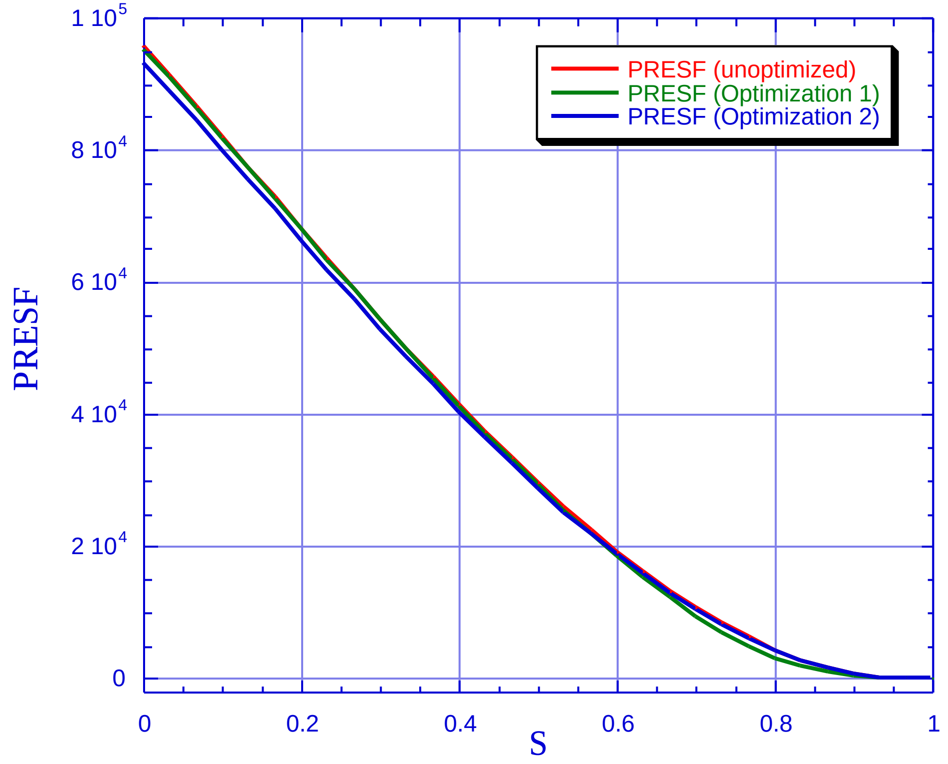


The iota profile of Optimization 2 is lower

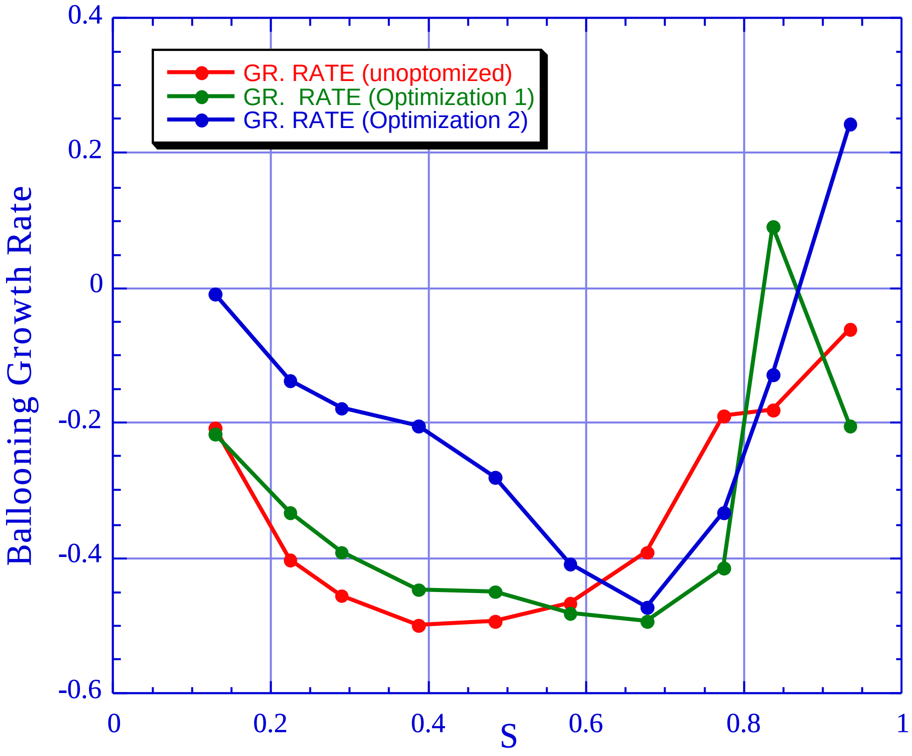


Optimization of |B| spectrum had little affect on pressure and ballooning stability

The pressure profiles remain relatively unchanged by the optimization



The optimized cases each had one surface ballooning unstable.



Optimization of |B| spectrum increased ellipticity & variation of |B| on a flux surface

- Axis-symmetric ellipticity increased during the optimization:

Unoptimized	2.14
Optimization 1	2.74
Optimization 2	4.59

- Optimization 2 is approaching a toroidally linked mirror configuration
  - ➢Large variation of |B| on the outer surface

Effect of Quasi-poloidal Symmetry on neoclassical ion confinement

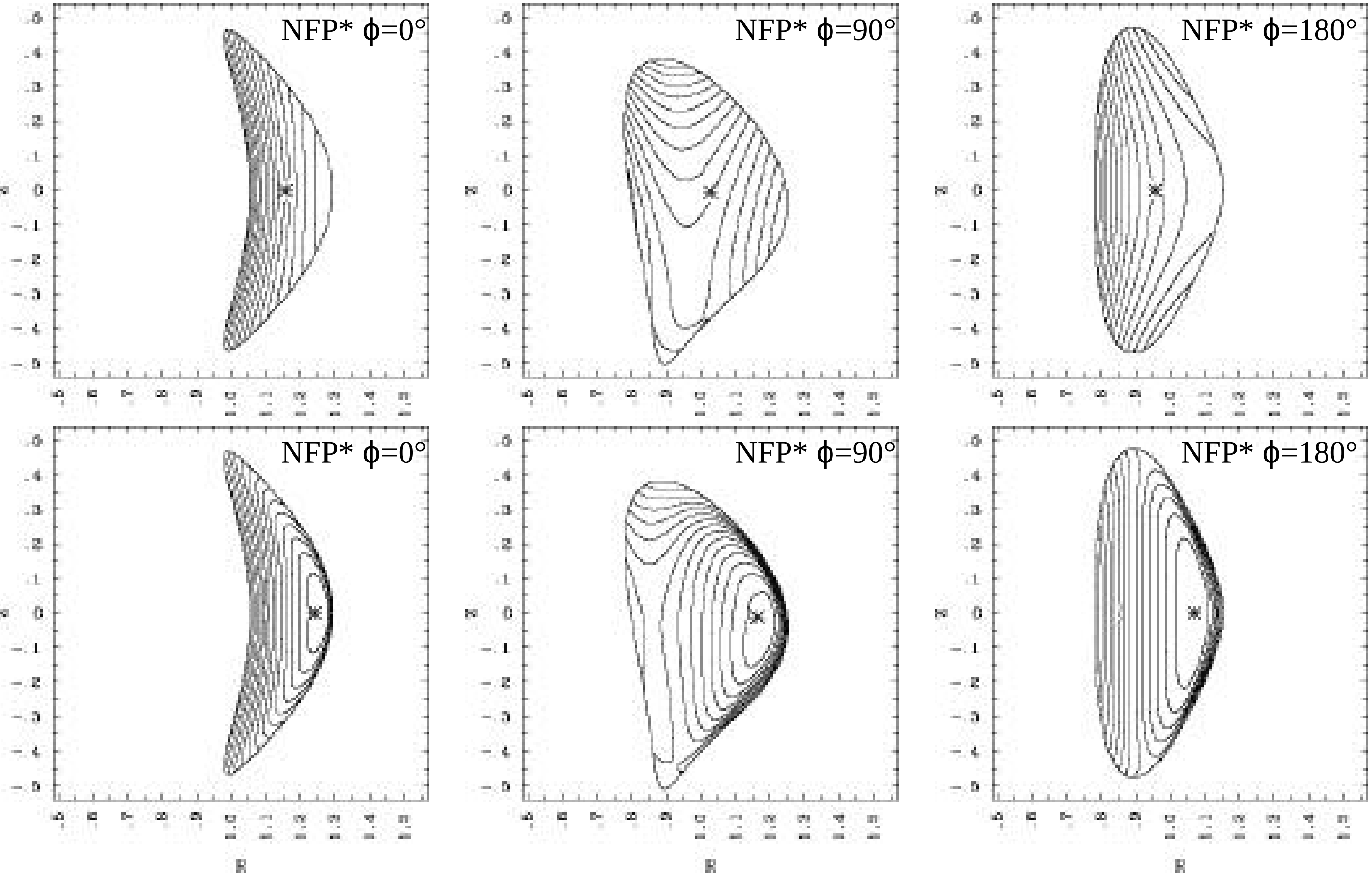
	A	β	τ_{neo}^{*}
Unoptimized	3.40	10%	17.3 ms
Optimization1	3.40	10%	21.4 ms
Optimization2	3.40	10%	13.4 ms

III. Neoclassical Confinement

- Neoclassical confinement improves with increasing β
- As β increases, the surfaces of constant |B| become closed, more in alignment with the flux surfaces
- Optimizing for confinement using the DKES transport code

Alignment of |B| surfaces with flux surfaces improves at higher β

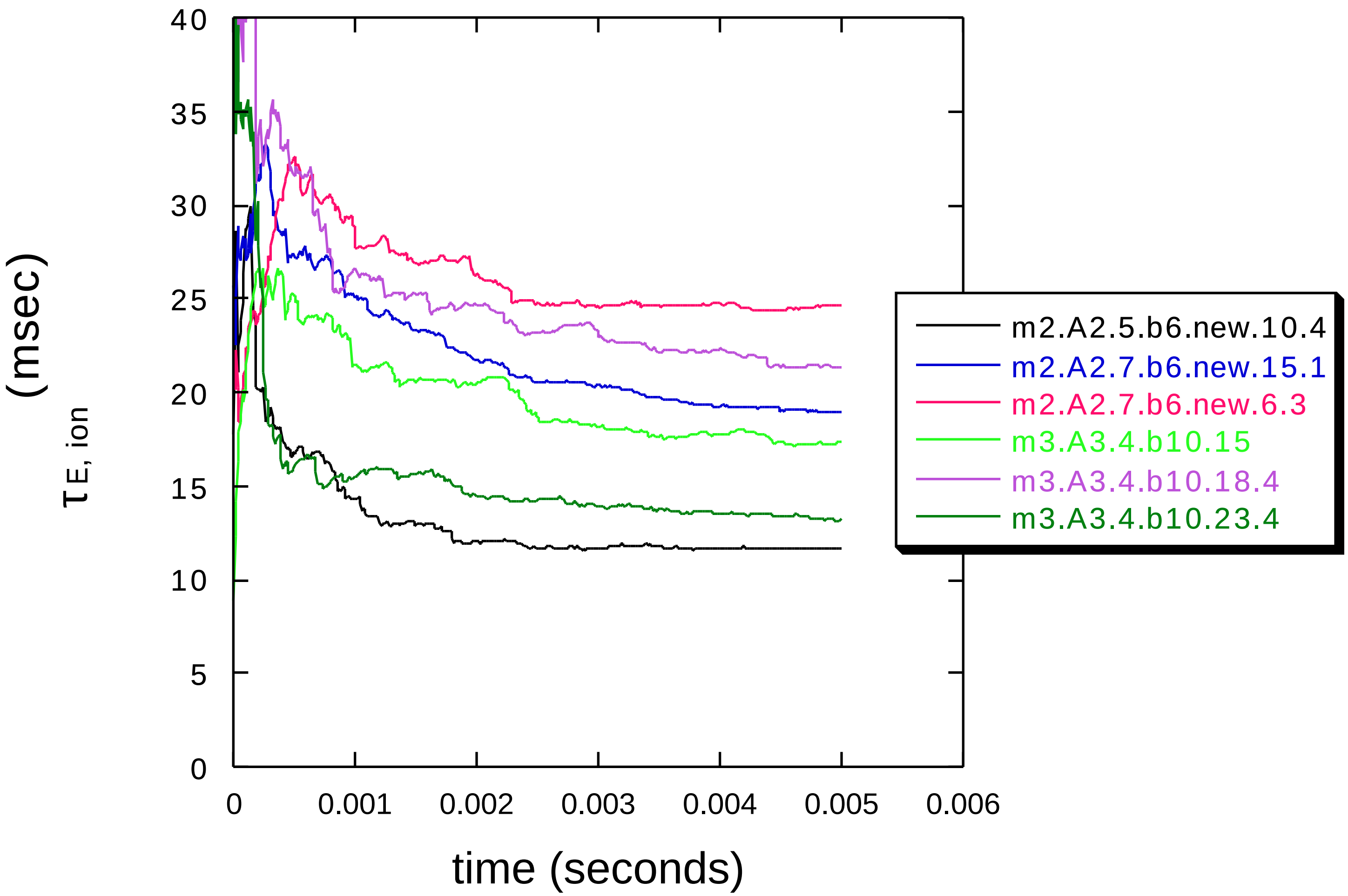
Surfaces of constant |B| at β =0% and β =23%



β=0%:

β=23%:

Neoclassical ion confinement times for the cases shown in this poster



Conclusions

- Compact, high β, MHD stable hybrid configurations
  - Stable at higher β than comparable tokamak due to lower self-consistent bootstrap current
- Targeting quasi-poloidal symmetry initially improved confinement but then degraded it due to thin cross sections.
  - Need to target lower ellipticity (work in progress).