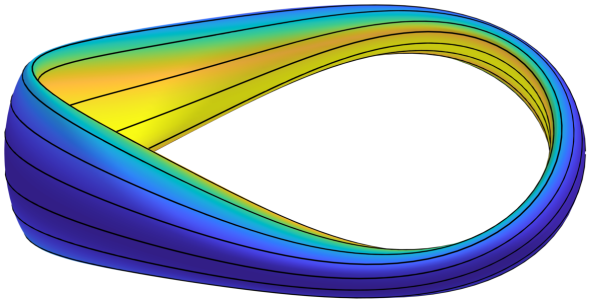
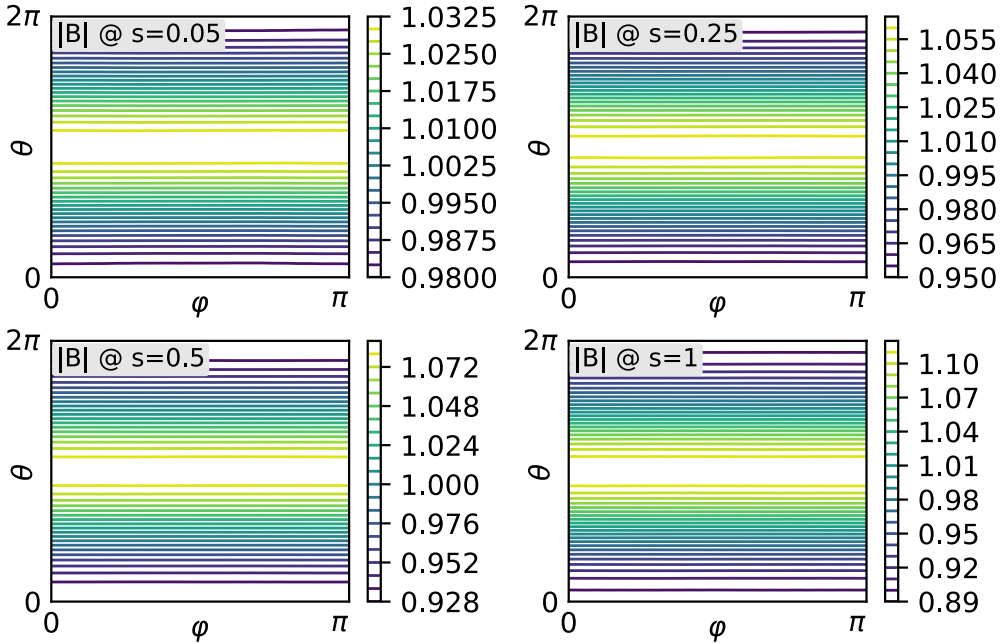
Magnetic fields with excellent quasisymmetry throughout a volume





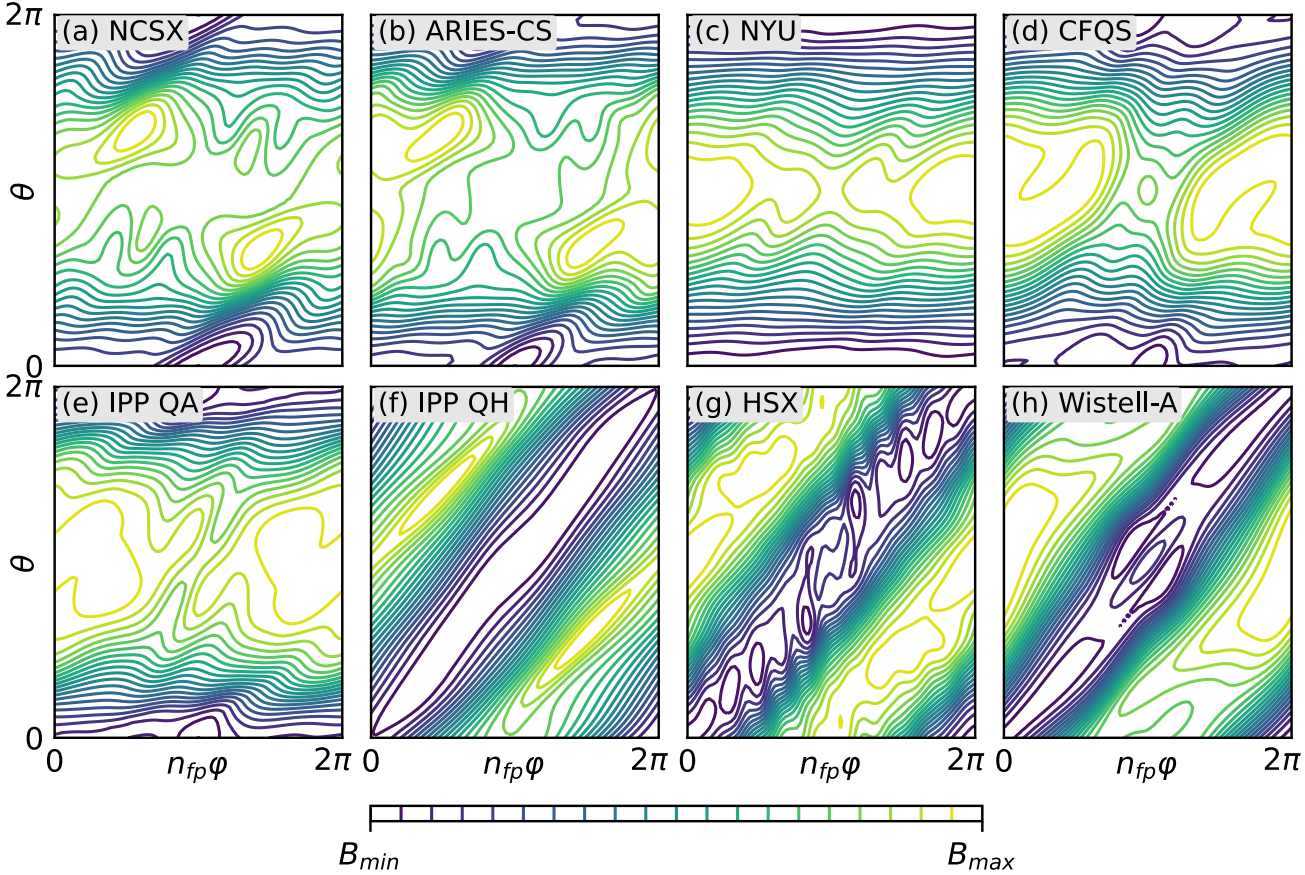
Matt Landreman, University of Maryland

Simons Hour, Aug 5 2021

Thanks to Christopher Albert, Aaron Bader, Joachim Geiger, Per Helander, Sophia Henneberg, Rogerio Jorge, Sam Lazerson, Geoffrey McFadden, Bharat Medasani, Shoichi Okamura, Elizabeth Paul, John Schmitt, Don Spong, Florian Wechsung, Caoxiang Zhu

- Previous quasisymmetric configurations
- New quasisymmetric configurations
- Quasisymmetry $\Longrightarrow$ good confinement
- Next steps

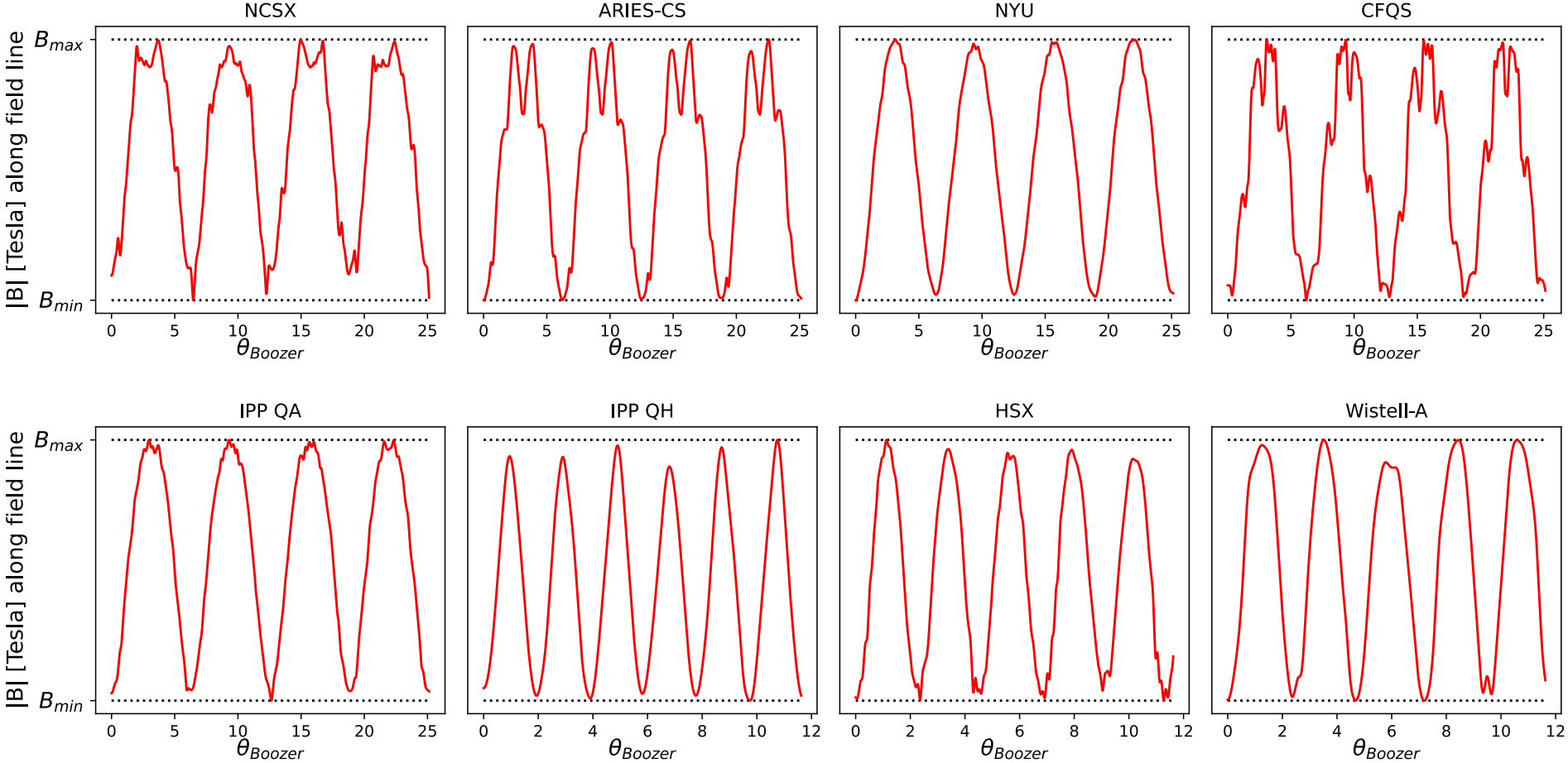
Previous quasisymmetric configurations



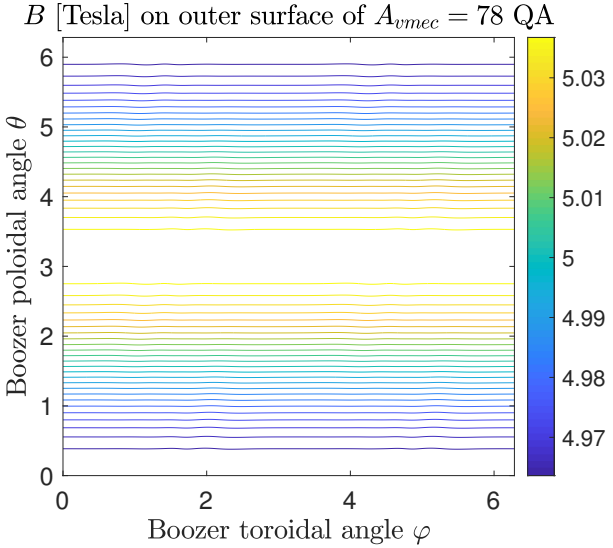
(a) Zarnstorff et al (2001)
(b) Najambadi et al (2008)
(c) Garabedian (2008)
(d) Liu et al (2018)
(e) Henneberg et al (2019)
(f) Nuhrenberg & Zille (1988)
(g) Anderson et al (1995)
(h) Bader et al (2020)

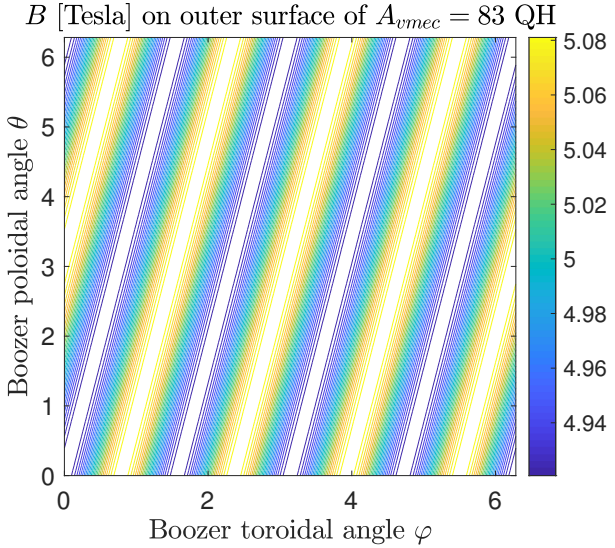
Can we get |B| contours to look truly straight if we optimize for only quasisymmetry?

Previous quasisymmetric configurations (s=0.5)



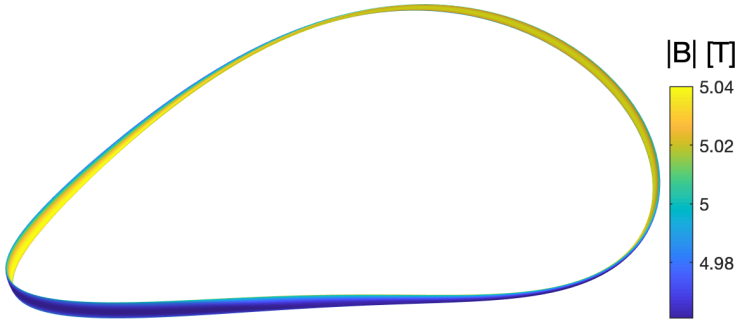
Previous extremely accurate QS was at high aspect ratio

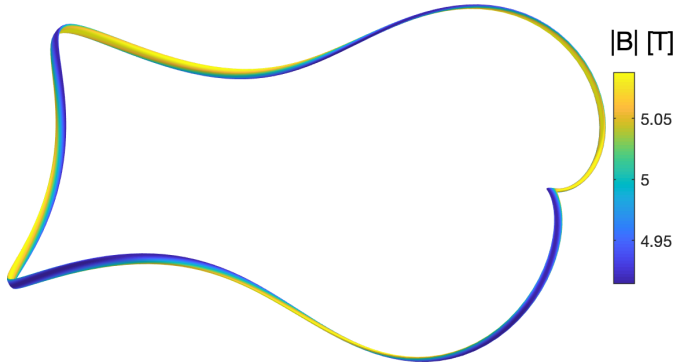




ML & Sengupta (2019)

$B_{m,n}^{asym} < 10^{-5} B_{0,0}$





- Previous quasisymmetric configurations
- New quasisymmetric configurations
- Quasisymmetry $\Longrightarrow$ good confinement
- Next steps

Optimization problem

- Objective functions: $f_{QH} = \left(A - A_*\right)^2 + f_{QS}$ $\quad$ $f_{QA} = \left(A - A_*\right)^2 + \left(\iota_* - \int_0^1 \iota\, ds\right)^2 + f_{QS}$

  Boundary aspect ratio

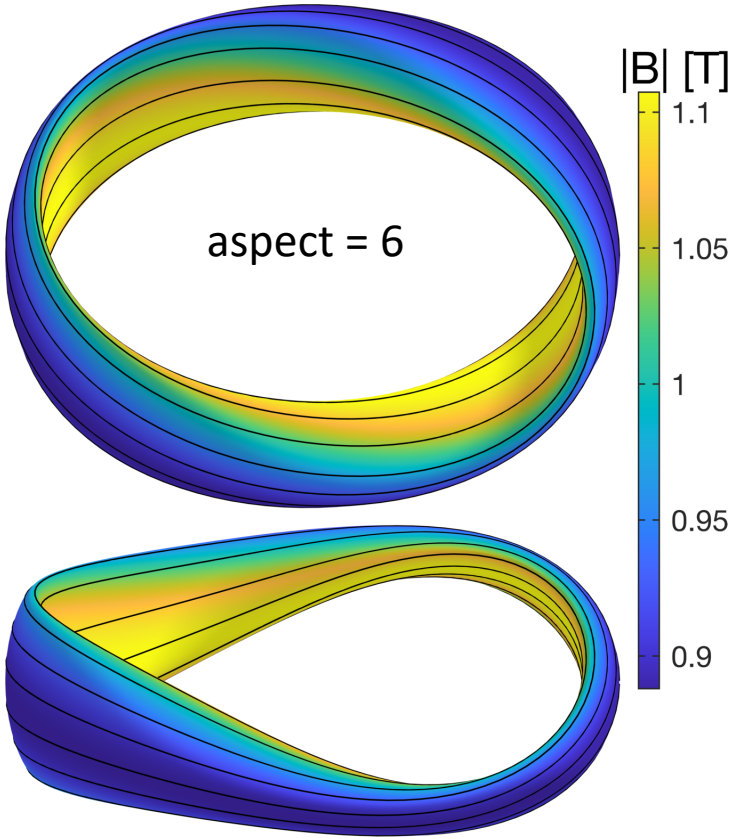
$$f_{QS} = \int d^3x\; w(s)\left(\frac{1}{B^3}\left[\left(N - \iota M\right)\mathbf{B}\times\nabla B\cdot\nabla\psi - \left(MG + NI\right)\mathbf{B}\cdot\nabla B\right]\right)^2$$

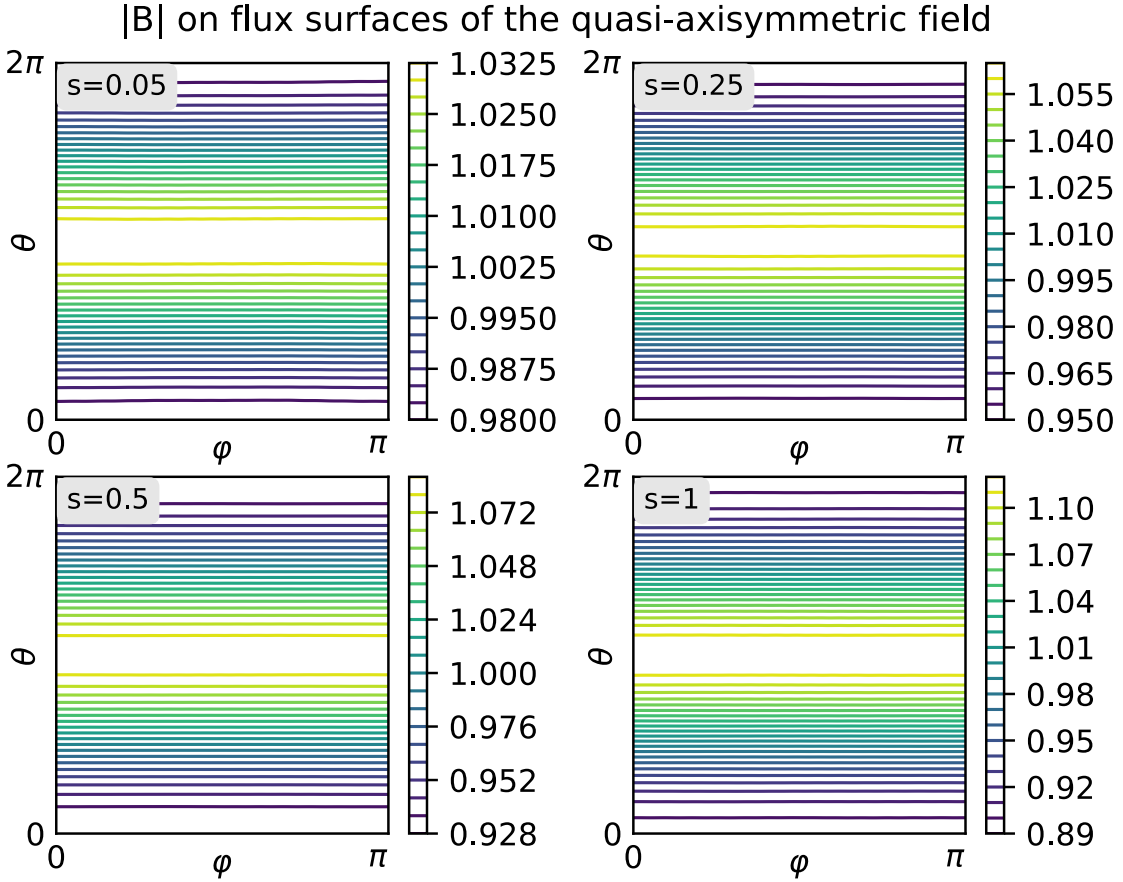
- The usual parameter space: $R_{m,n}$ & $Z_{m,n}$ defining a toroidal boundary

$$R(\theta,\phi) = \sum_{m,n} R_{m,n}\cos\left(m\theta - n\phi\right), \quad Z(\theta,\phi) = \sum_{m,n} Z_{m,n}\sin\left(m\theta - n\phi\right)$$

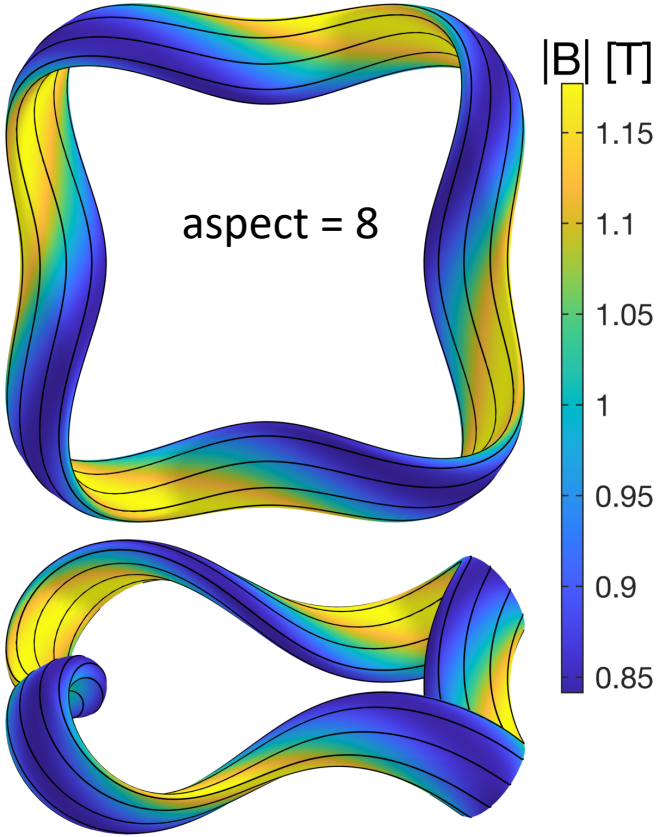
- SIMSOPT with VMEC
- Cold start
- Vacuum fields, to ease confirmation of surface quality
- Algorithm: default for least-squares in scipy (trust region reflective)
- 6 stages: increasing # of modes varied & VMEC mpol/ntor/ns
- Run many optimizations, pick the best
- Low ftol in vmec helps: 1e-15 – 1e-17

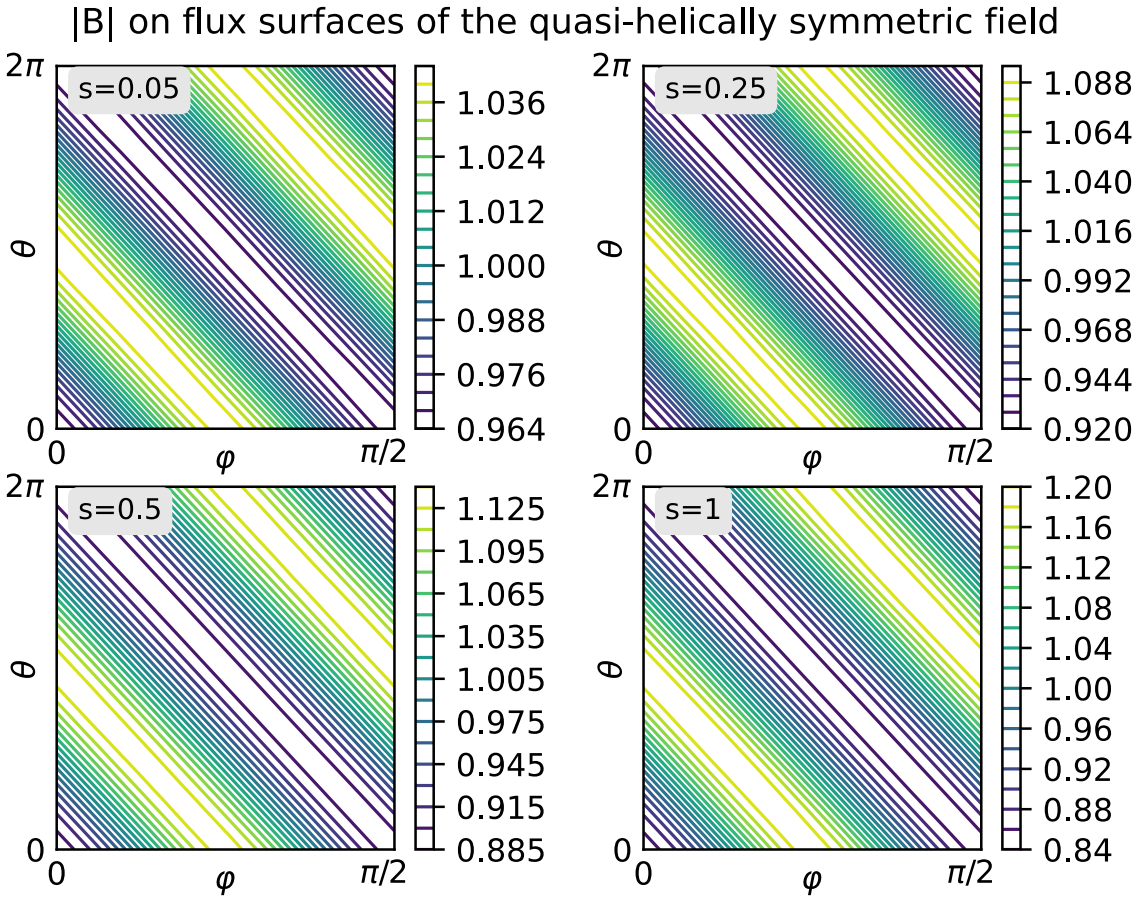
Straight |B| contours are possible for QA



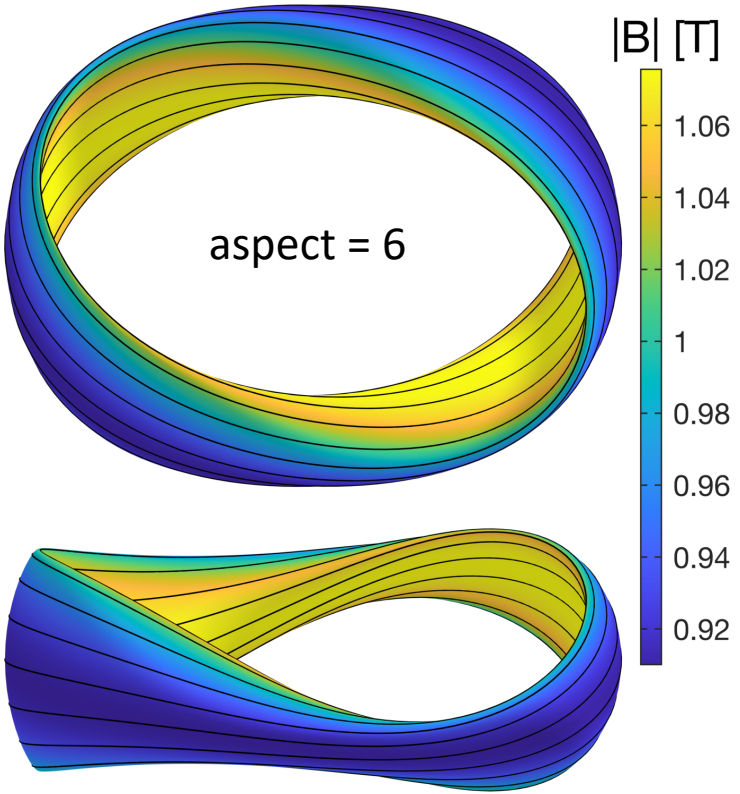


Straight |B| contours are possible for QH

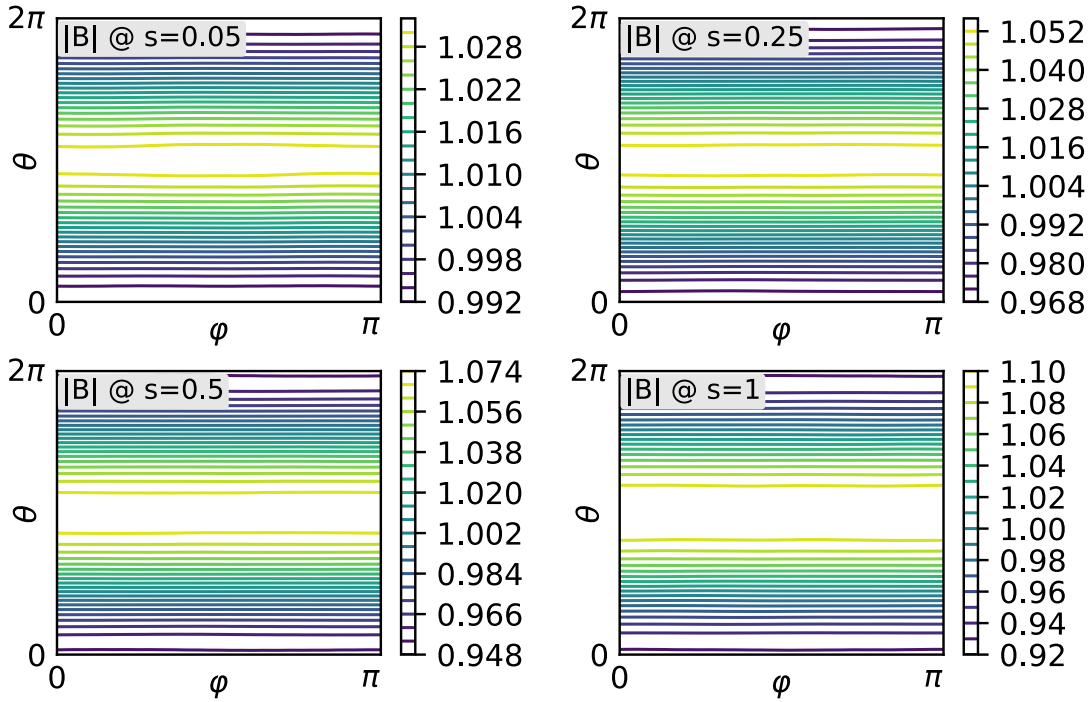




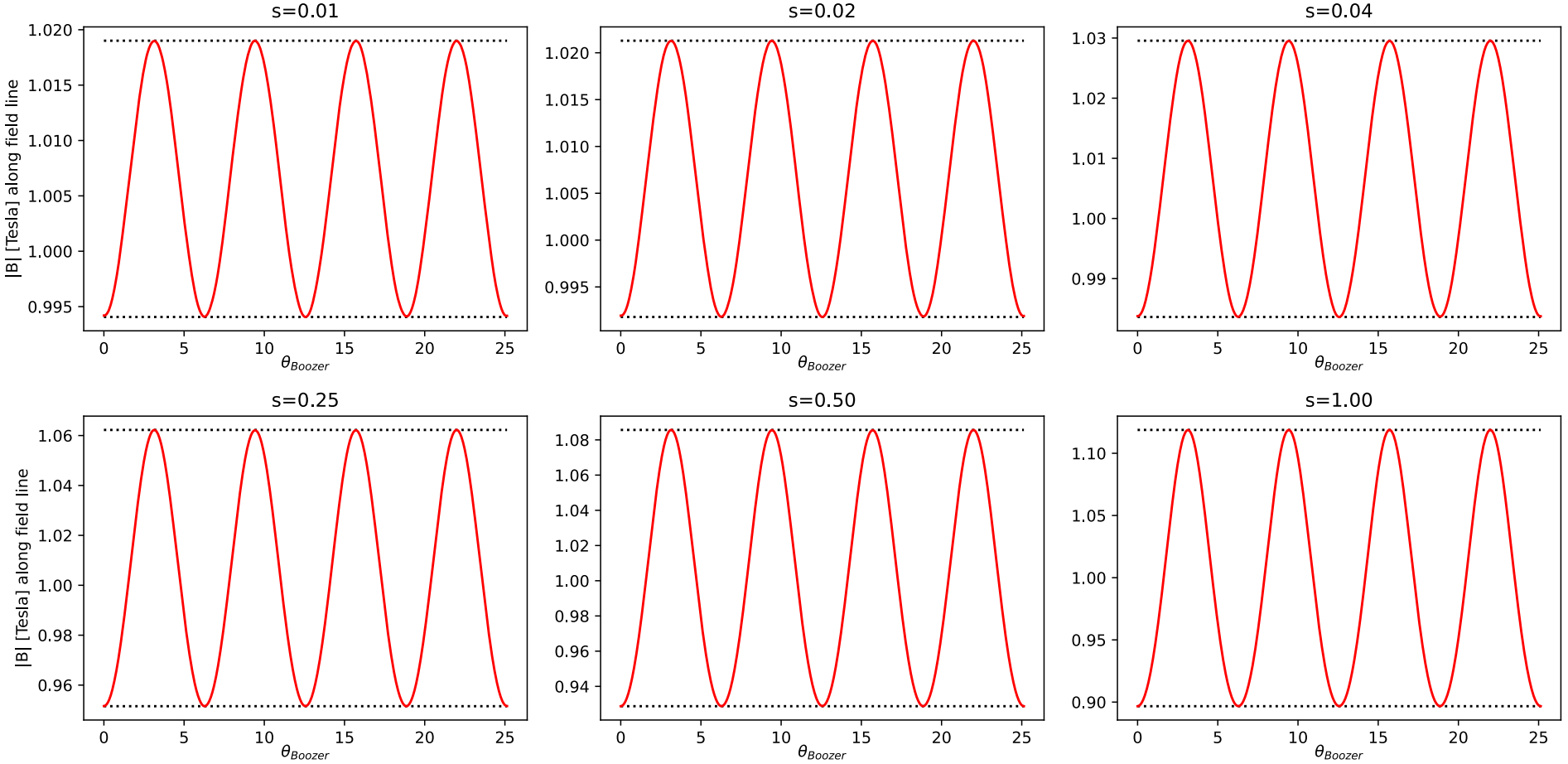
Good symmetry also exists with magnetic well



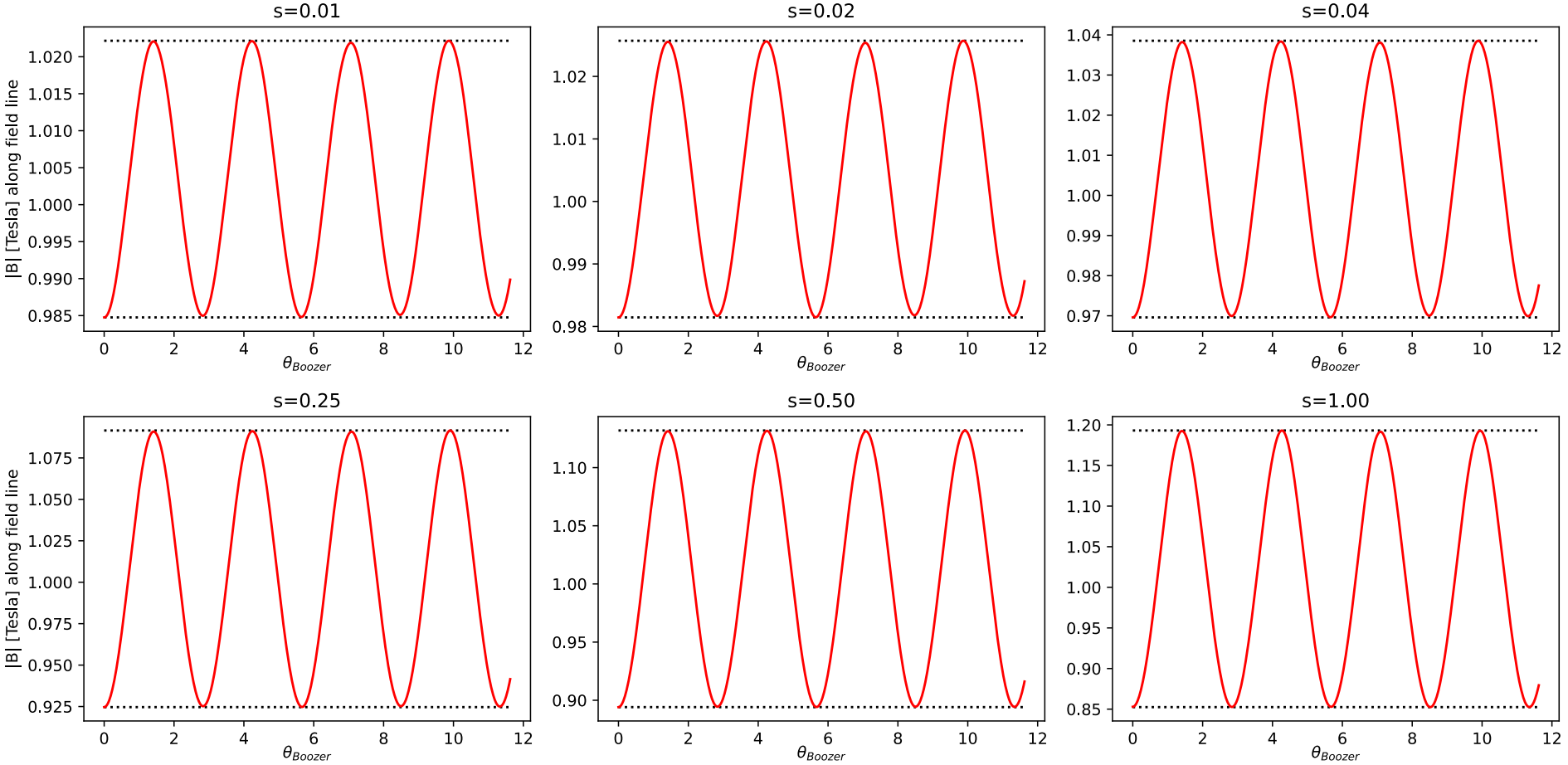
$$\frac{d^2\left(\text{flux surface volume}\right)}{d\left(\text{toroidal flux}\right)^2} < 0 \text{ everywhere}$$



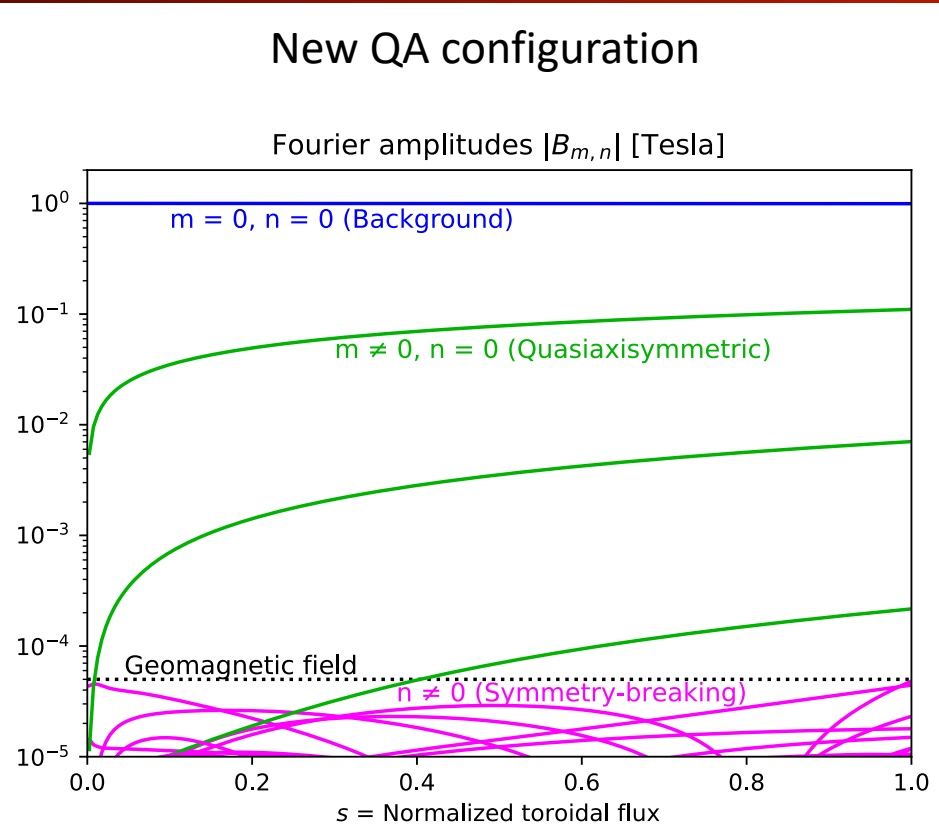
|B| along a field line for new QA

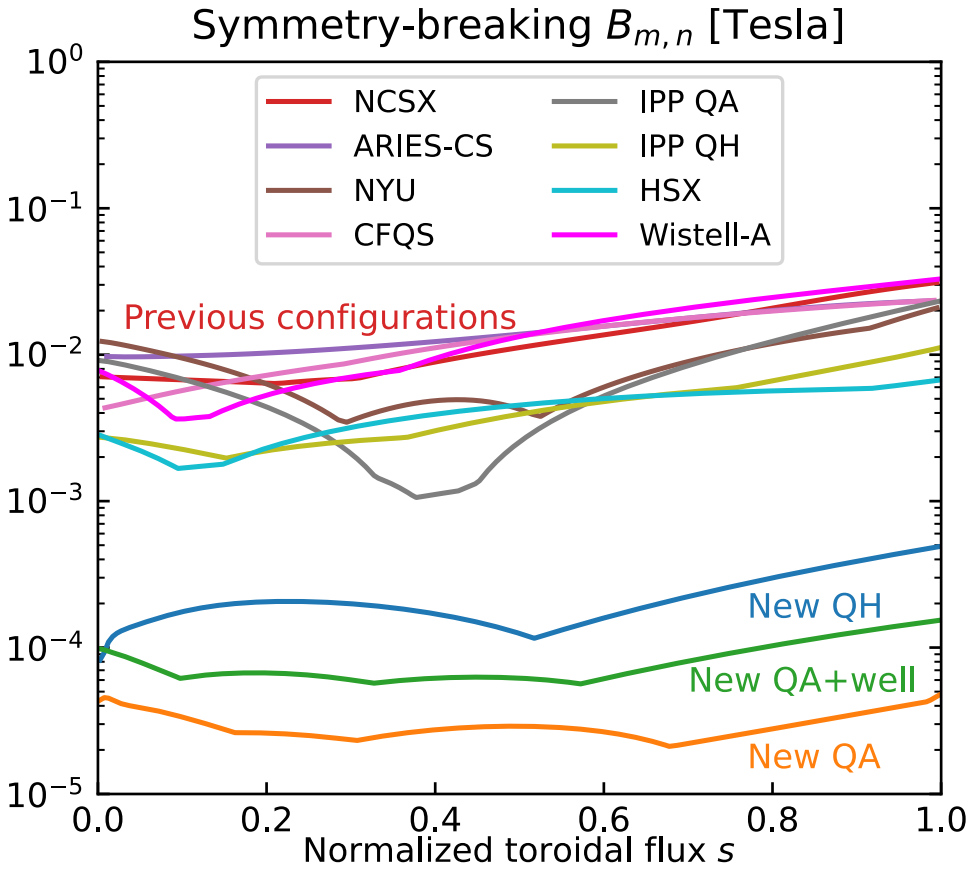


|B| along a field line for new QH

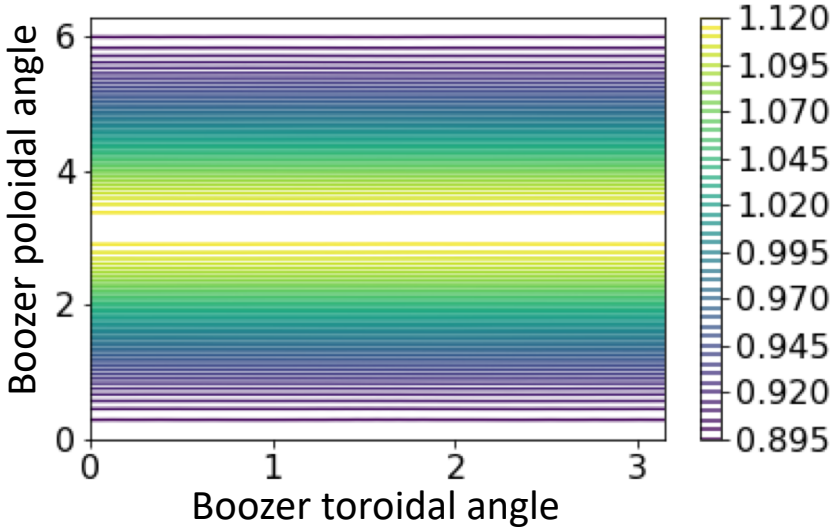


Symmetry-breaking modes can be made extremely small

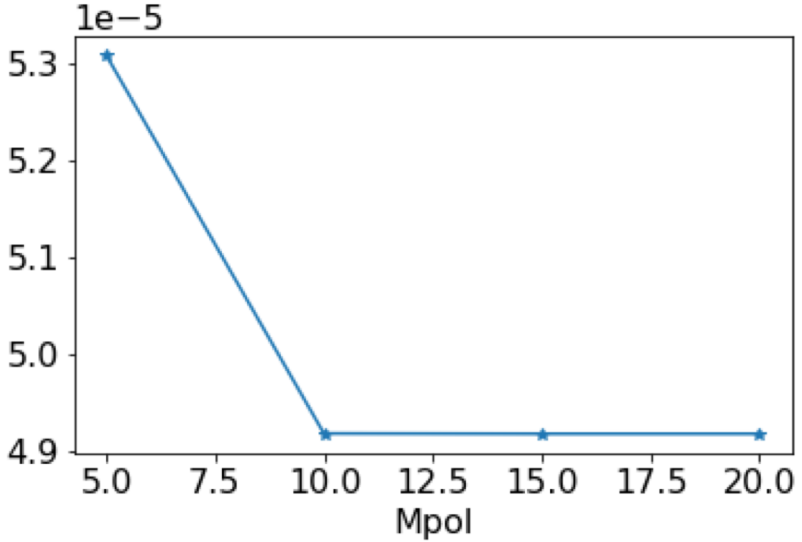




|B| in Boozer coordinates was verified by independent SPEC calculations



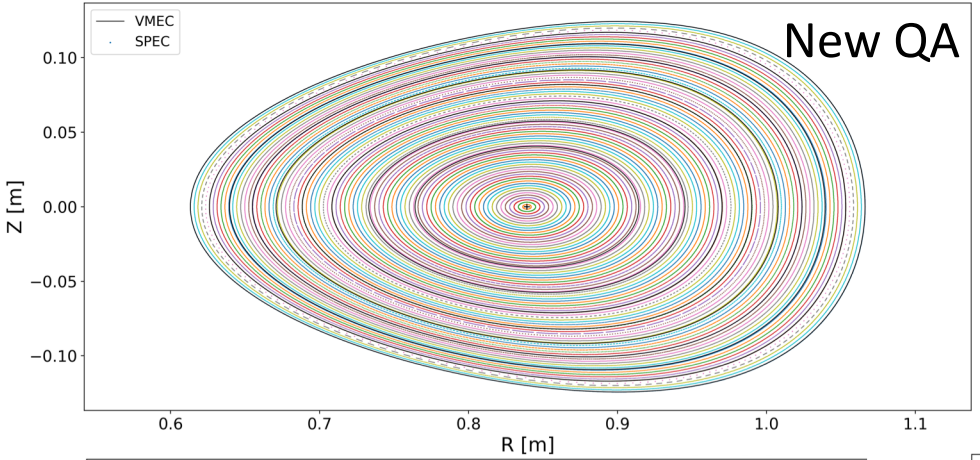
max $|B_{m,n}|$ [Tesla] with n ≠ 0



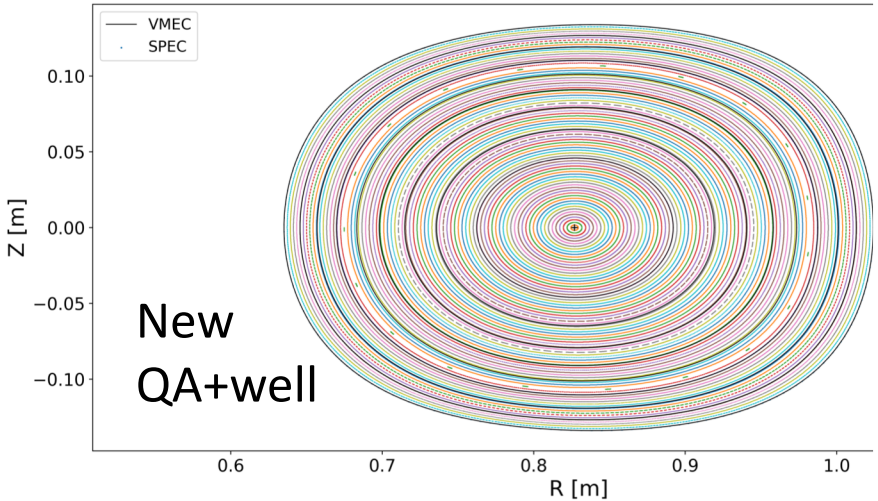
(Ntor = Mpol, Lrad = Mpol + 4)

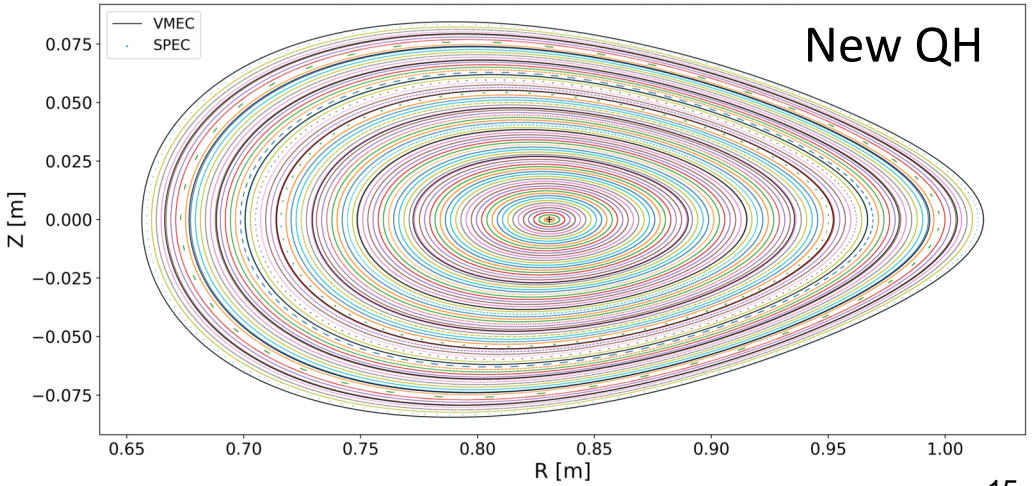
By Elizabeth Paul

SPEC confirms the new QA/QH configurations have no islands or chaos



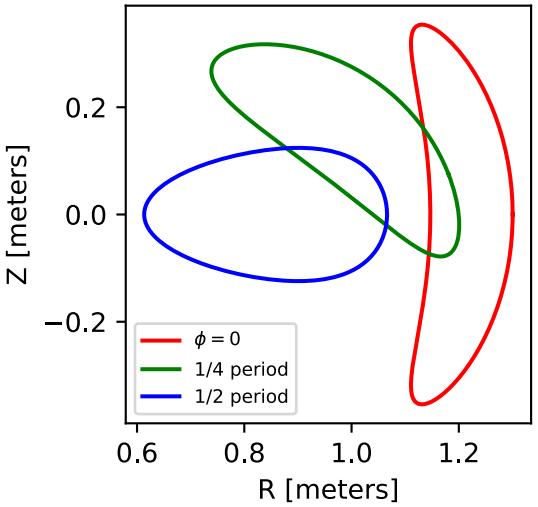
VMEC
SPEC





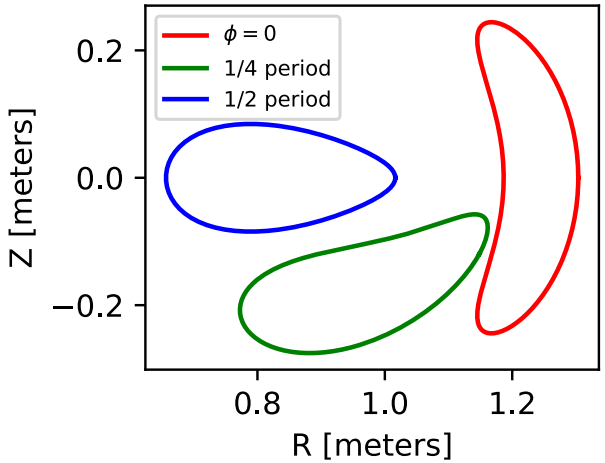
Other characteristics of the configurations

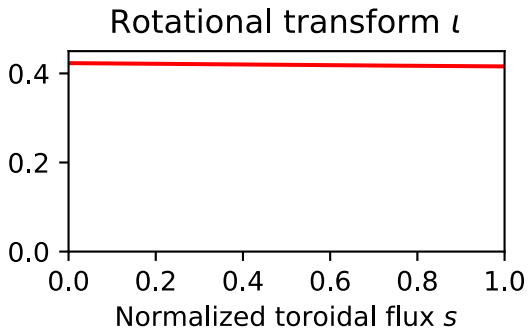
New QA



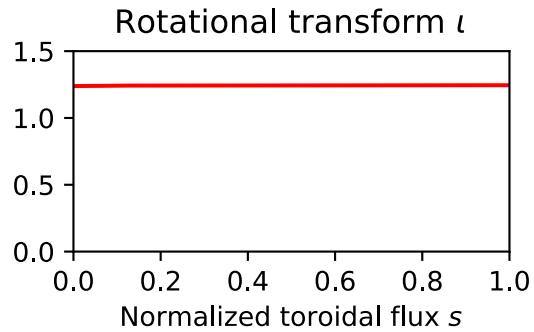
QA & QH both give rise to concave bean shapes, even with no MHD objective.

New QH

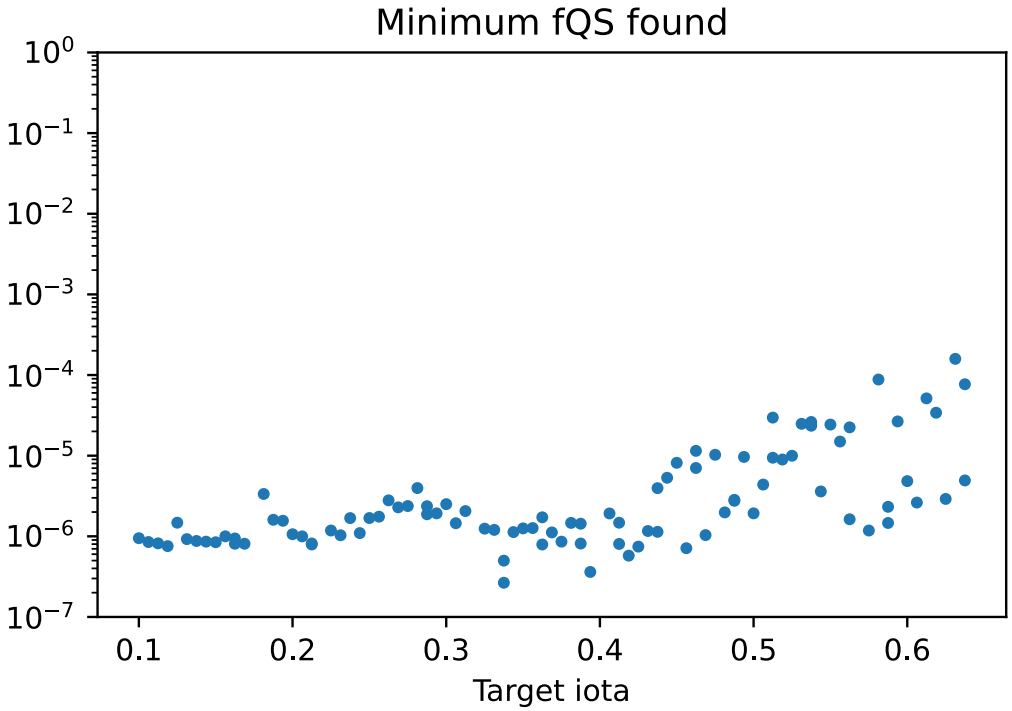




QA & QH both have extremely low shear. Is there a reason?



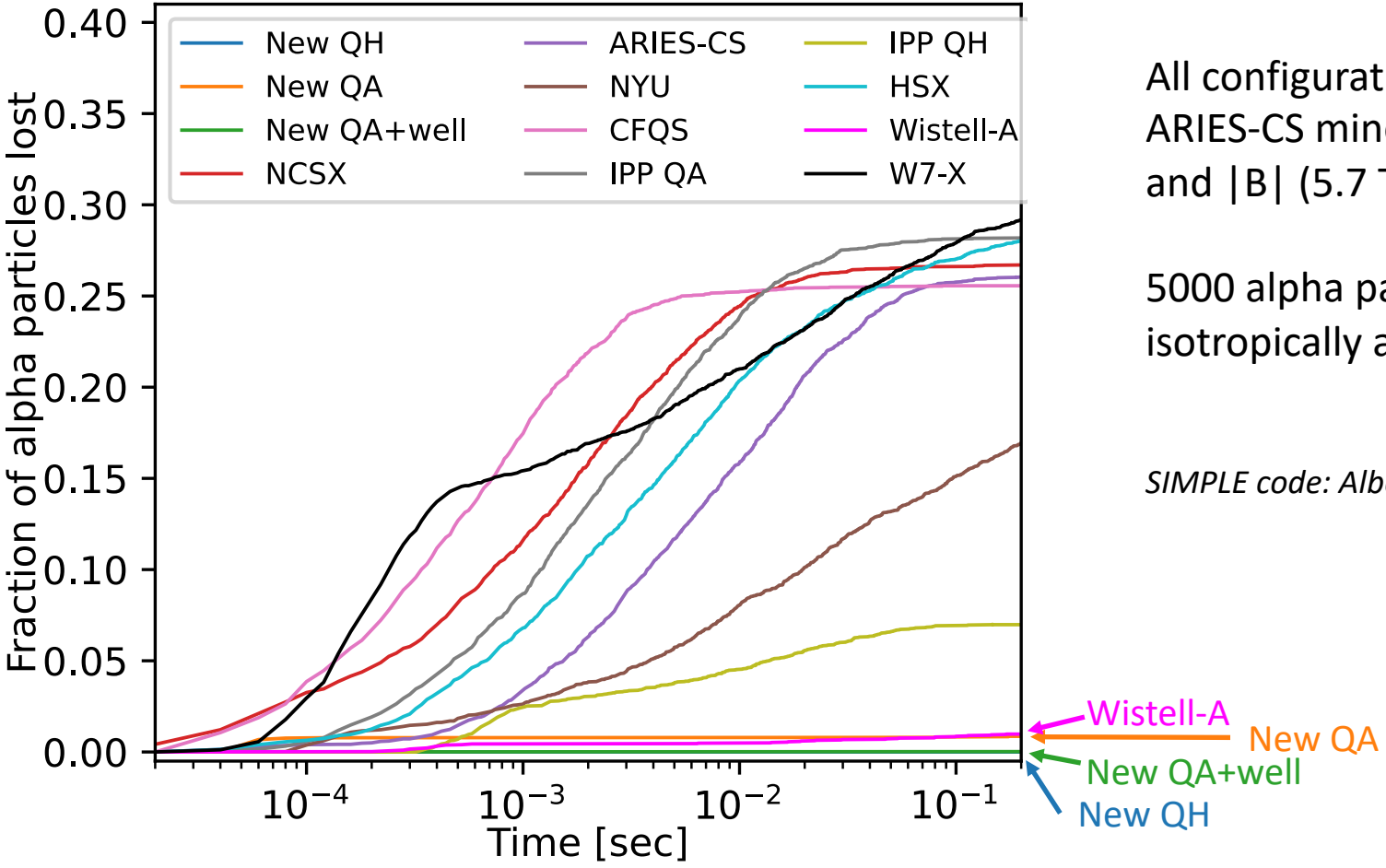
A mystery: Why does QA error not depend more strongly on iota?



- Previous quasisymmetric configurations
- New quasisymmetric configurations
- Quasisymmetry $\Longrightarrow$ good confinement*
- Next steps

*At least if turbulence is neglected

The symmetry yields extremely good confinement of collisionless trajectories

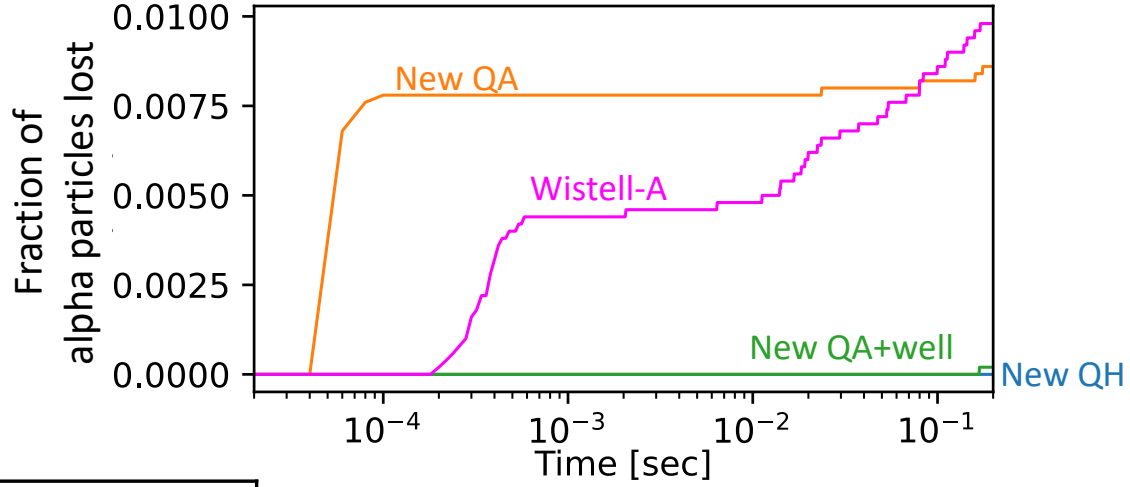


All configurations scaled to ARIES-CS minor radius (1.7 m) and |B| (5.7 T).

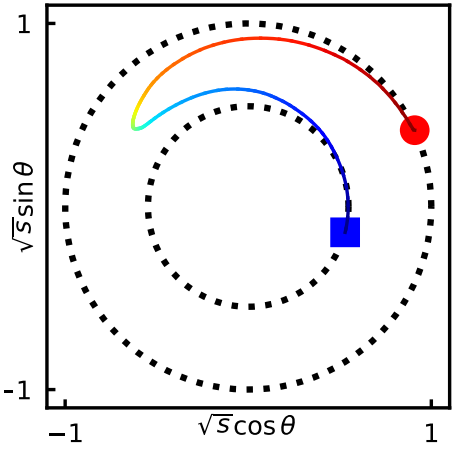
5000 alpha particles initialized isotropically at s=0.3.

SIMPLE code: Albert et al, JCP (2020).

Why does the configuration with best symmetry not have the best trajectory confinement?



Lost trajectories in the new QA look like this:

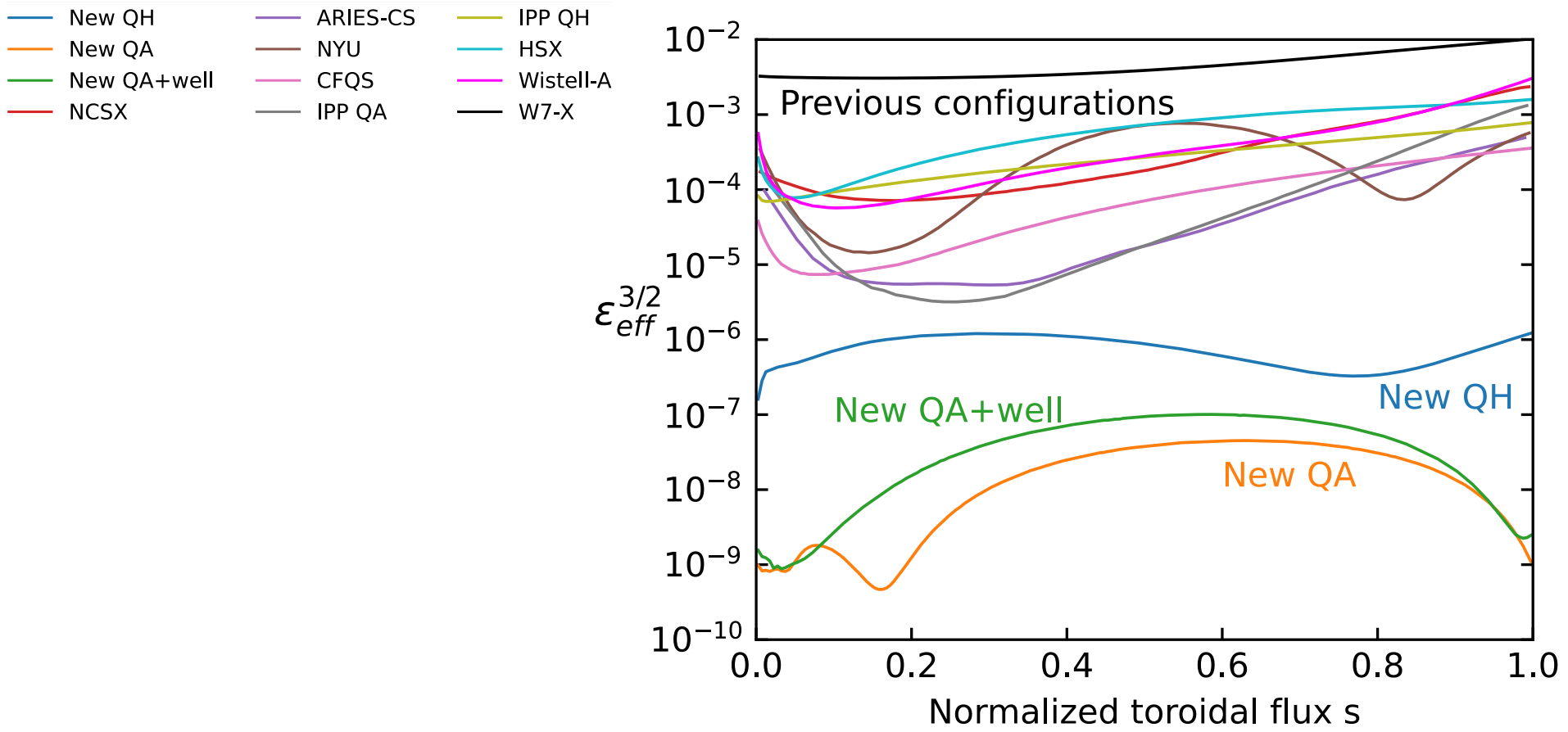


Width of banana orbit $\Delta s \approx \left| \frac{mvR\sqrt{2r\bar{\eta}}}{(\iota - N)\psi_{edge} Ze} \right| \propto \frac{1}{|\iota - N|}$

$\bar{\eta}$ definition: $B \approx B_0\left[1 + r\bar{\eta}\cos(\theta - N\varphi)\right]$ where $r = \sqrt{2\psi / B_0}$

For fixed minor radius, $\frac{\Delta s_{QA}}{\Delta s_{QH}} \sim 4$

The symmetry also yields extremely low collisional transport for a thermal plasma



- Previous quasisymmetric configurations
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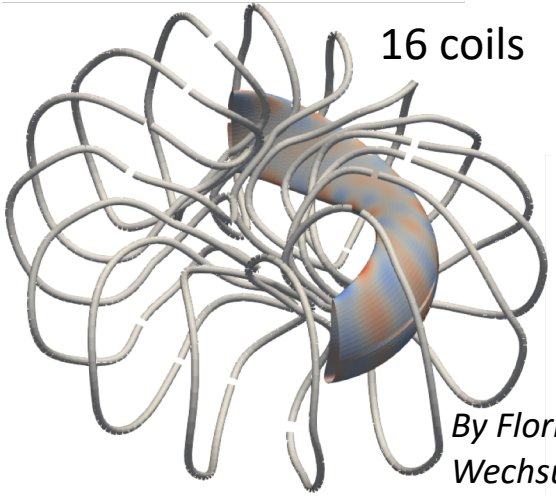
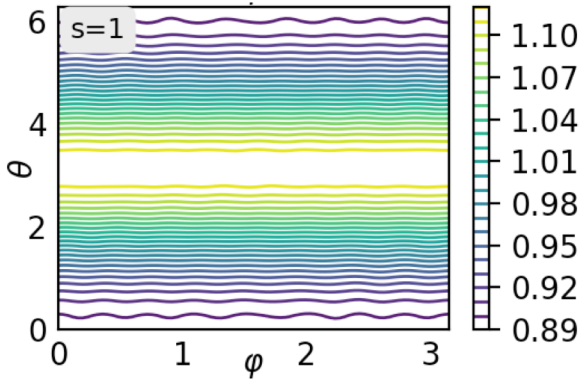
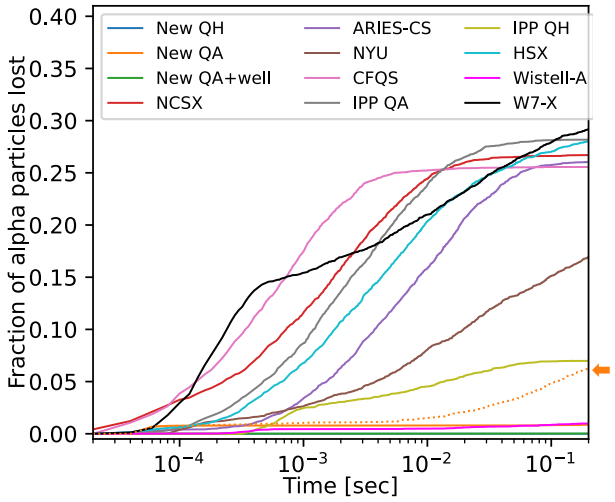
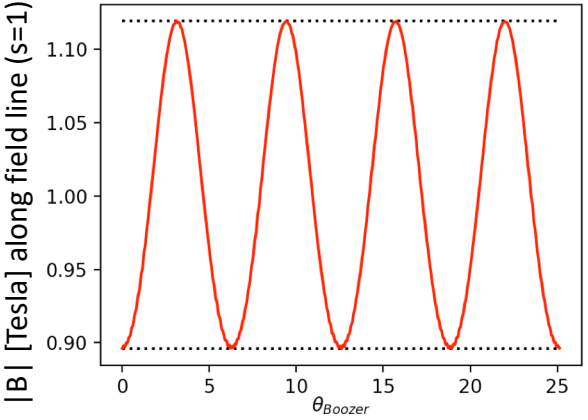
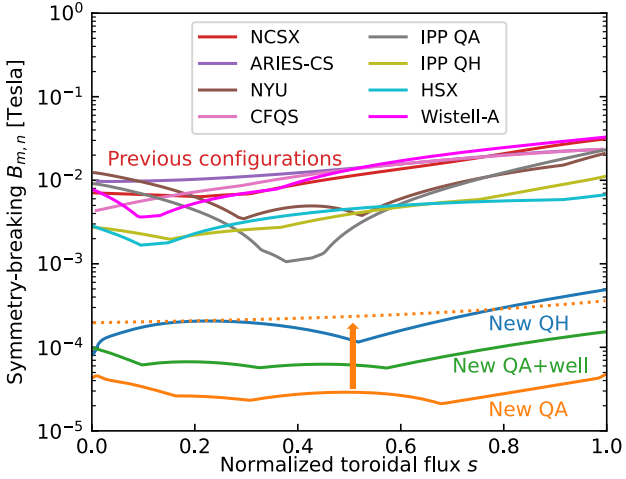
First quick attempt at coils for the QA

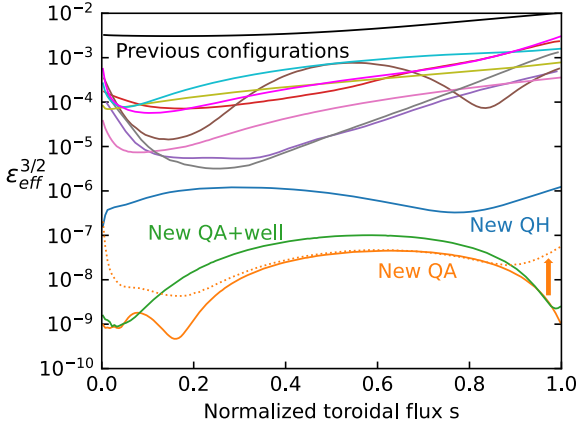




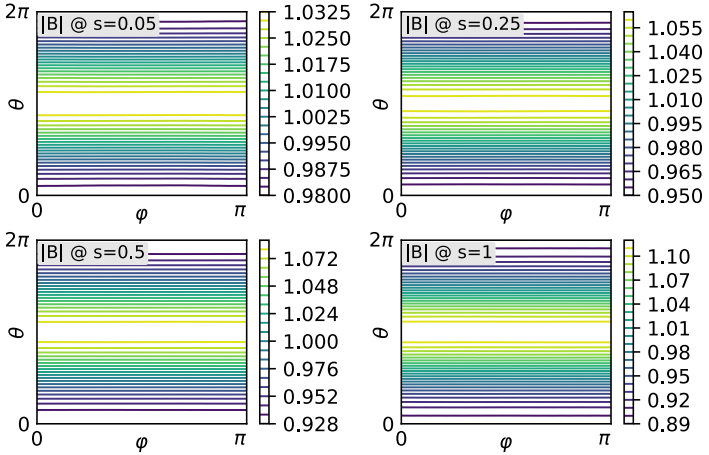


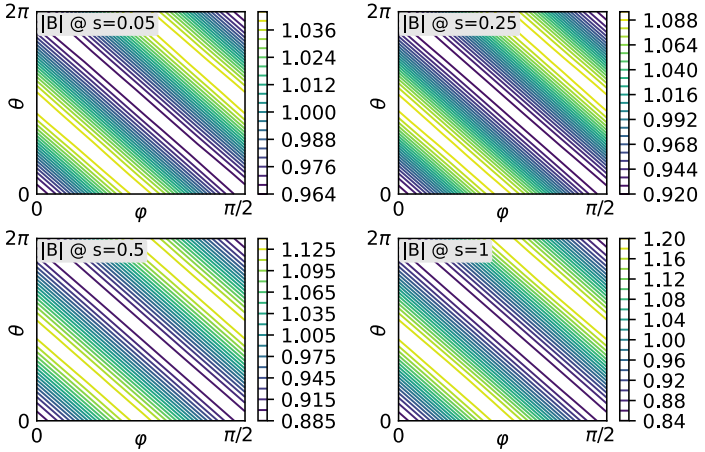






Conclusion: Quasisymmetry can be achieved throughout substantial volumes to high precision



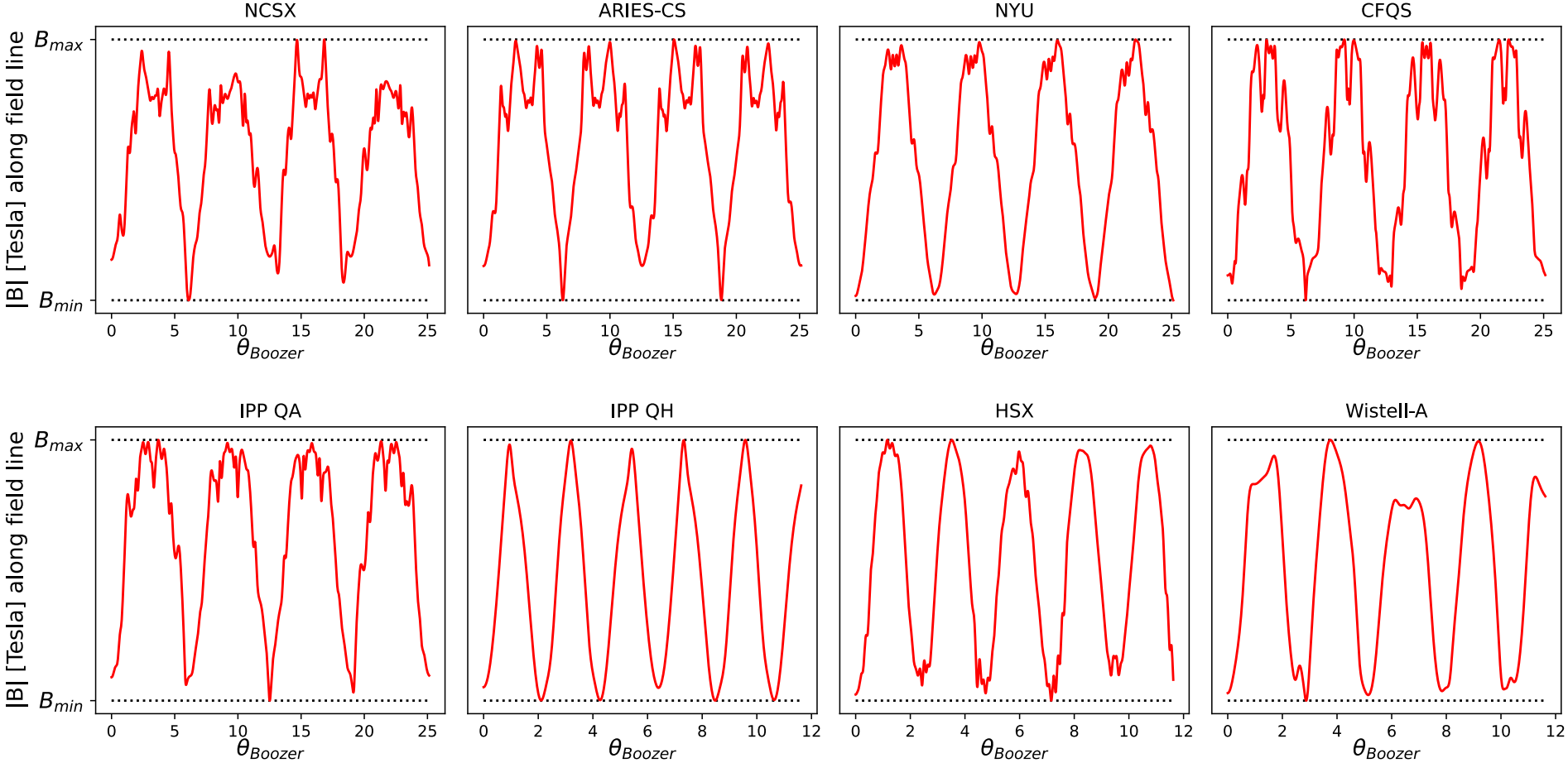


Many questions:

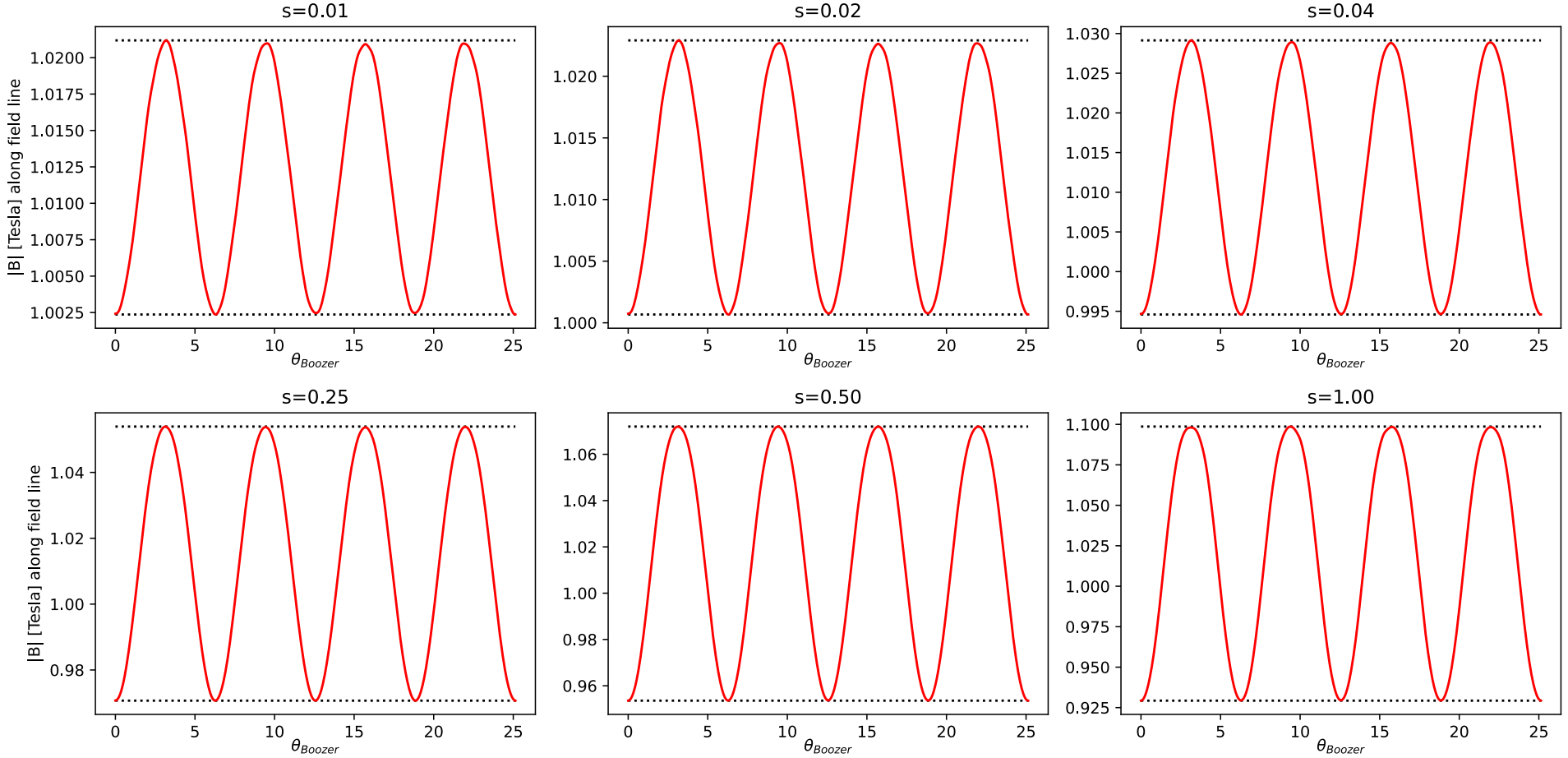
- How well can these configurations be produced with practical magnets?
- Do similar solutions exist with substantial plasma pressure & bootstrap current?
- How close can you come to this confinement with additional MHD stability constraints?
- What are the trade-offs for symmetry vs aspect ratio, iota, well depth?
- How precisely can you attain omnigenity with poloidally closed B contours?

Extra slides

Previous quasisymmetric configurations (s=1)

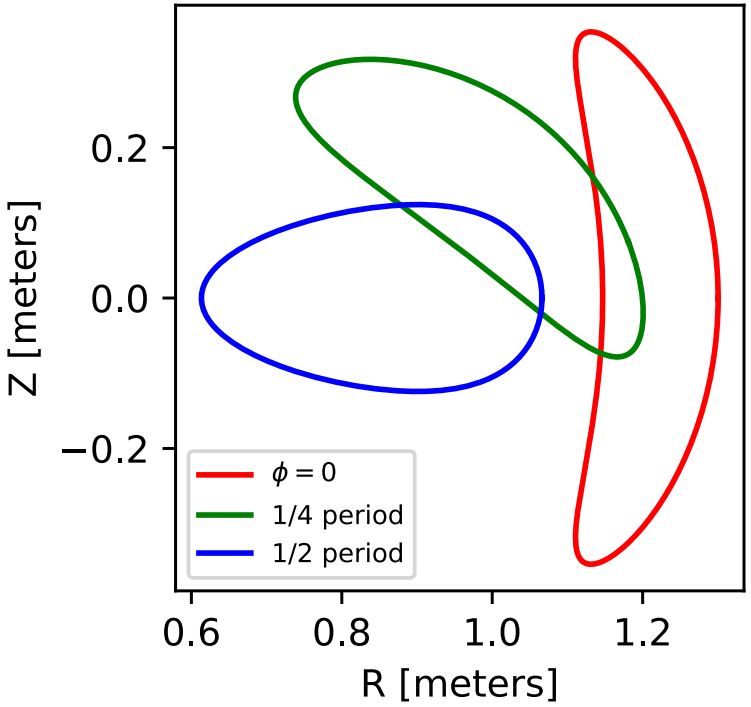


|B| along a field line for new QA with magnetic well



Including magnetic well in the QA increases enlongation

No magnetic well target



With magnetic well target