Recent Progress in Development of Low-Aspect-Ratio Quasi-Omnigeneous Stellarators

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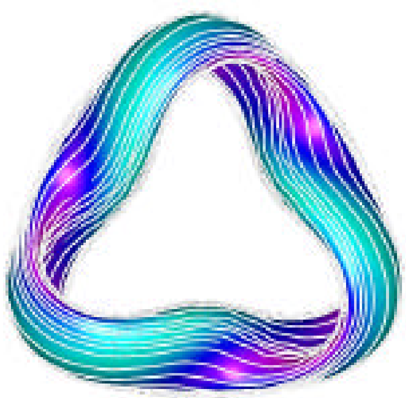
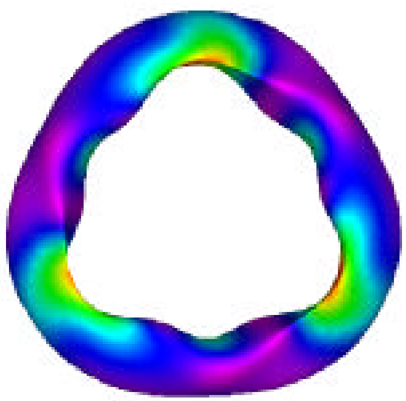
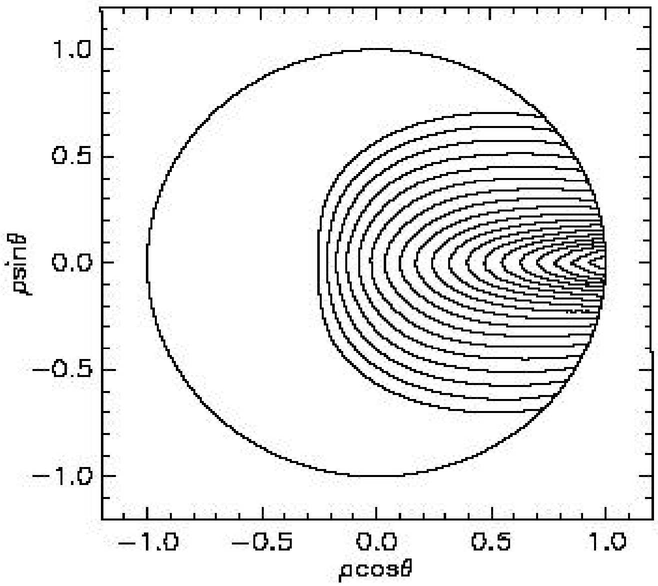
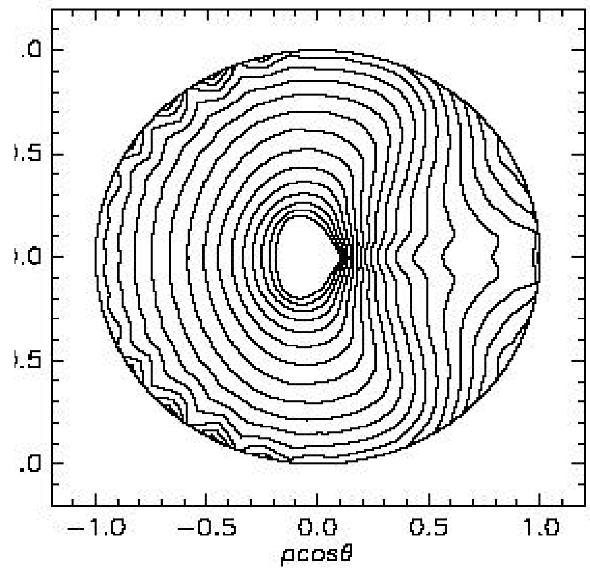




QO Optimization Procedure Improves Confinement of Trapped Particles

Open drift surfaces | **Closed drift surfaces**



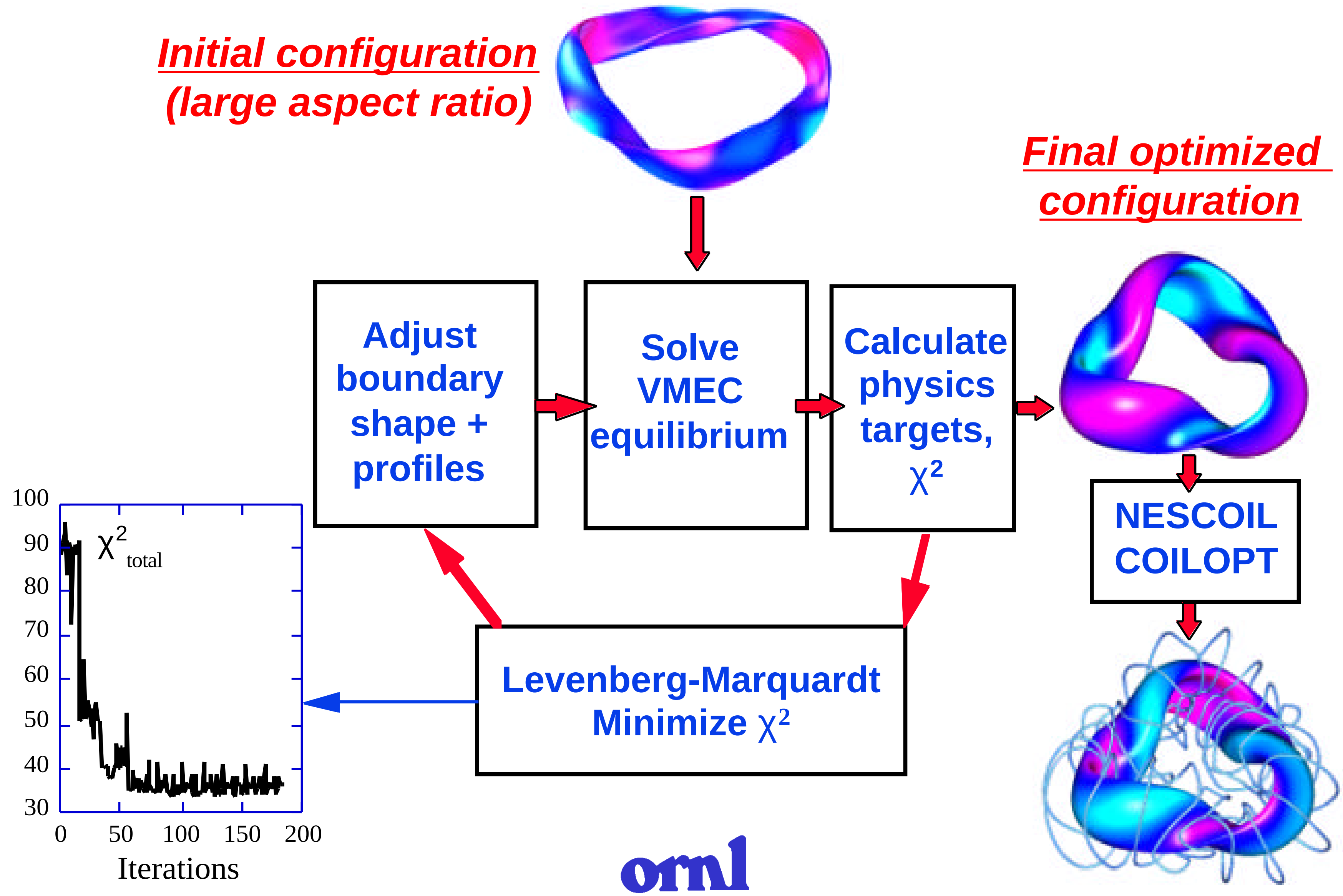


- **Approximate alignment of bounce-averaged drift orbits and magnetic surfaces reduces neoclassical transport**
- **J* $\int v_{||} d\varphi$, approximate second adiabatic invariant; no E_r**

TOPICS

- **Optimization of Low-Aspect-Ratio Quasi-Omnigeneous (QO) Stellarators**
- **Low-Bootstrap-Current Configurations with Stellarator Shear**
- **Higher-Bootstrap-Current Configurations with Tokamak Shear**

Optimization Determines Outer Flux Surface Shape.
Coils to Produce This Shape Are Then “Reverse-Engineered”.

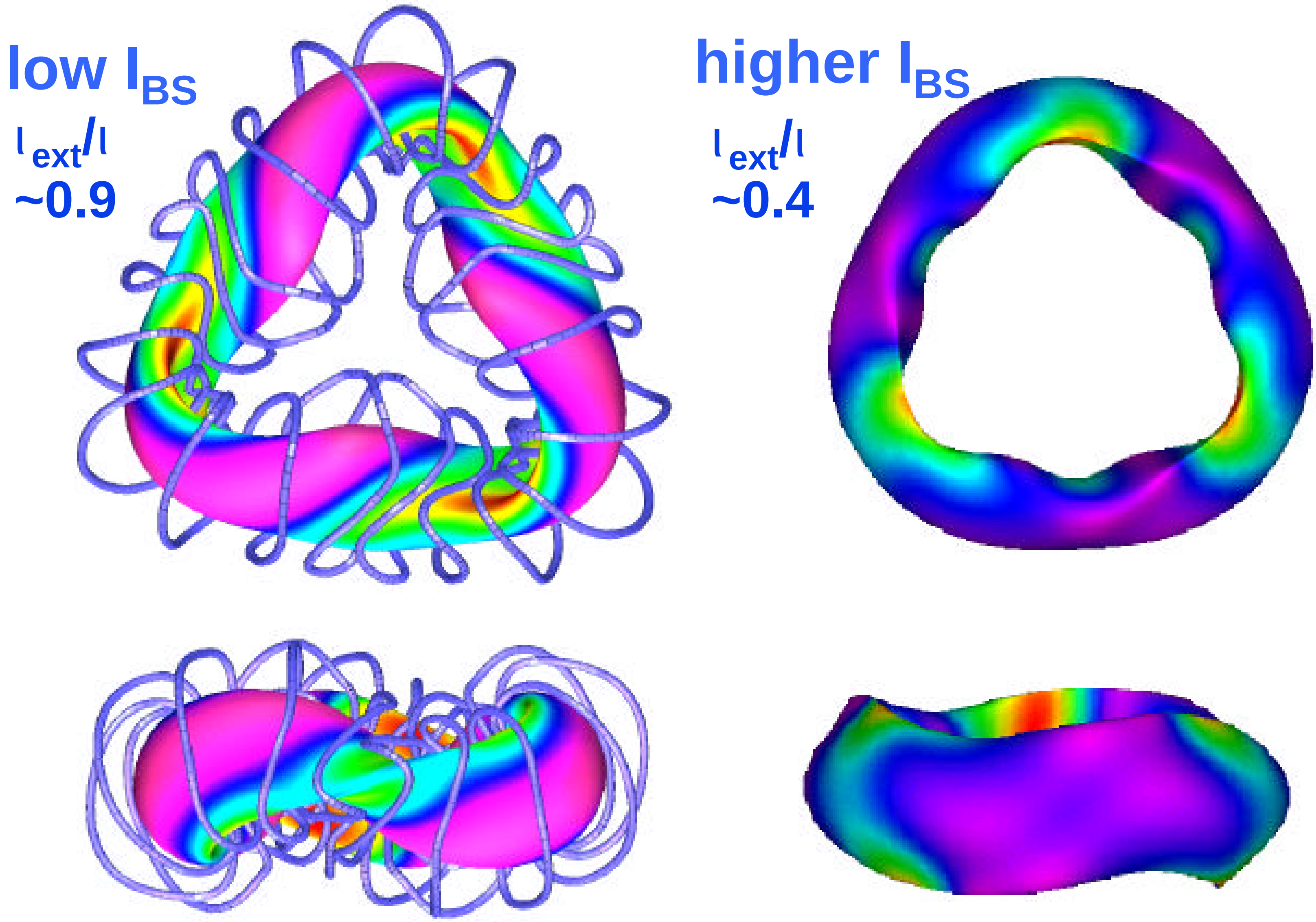


Concept Optimization Process Integrates a Wide Range of Physics Criteria in χ^2

Targets (Physics/Engineering)	Example	
Bounce-average omnigeneity (drift surfaces and flux surfaces aligned)	$B_{min} = B_{min}(\psi)$ $B_{max} = B_{max}(\psi)$ $J^* = J^*(\psi)$	**Transport**
Trapped, passing orbits	Replace J* with J	
Local diffusive transport	D, χ from DKES	
Current profile	monotone increasing $I(\psi)$ **self-consistent I_{BS}**	**Equilibrium**
Limit maximum plasma current	e.g., $I_{max} < 40$ kAmps	
Iota profile	$\iota(\psi) = 0.5$ $(\rho = 0)$ to 0.8 $(\rho = a)$	
Magnetic Well, Mercier	**$V'' < 0$, $D_M > 0$ over cross section**	**Stability**
Ballooning stability	**$\langle\beta\rangle \sim 4\%$**	
Aspect ratio	$R_0/a \approx 3$ to 4	**Geometry**
Limit outer surface curvature	avoid strong elongation/cusps	

Control variables: **shape (40-50 Fourier harmonics R_{mn}, Z_{mn}) for LCFS + profile parameters**

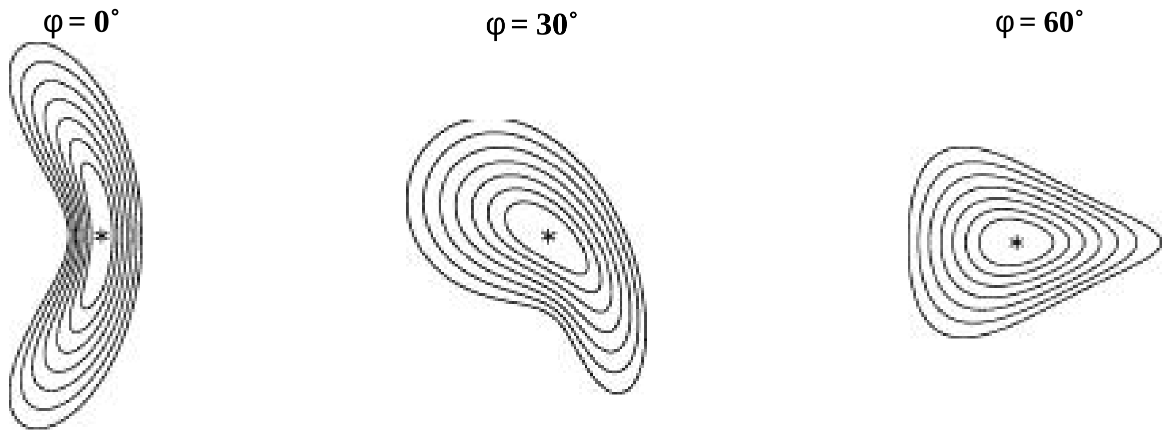
Quasi-Omnigenous Stellarators



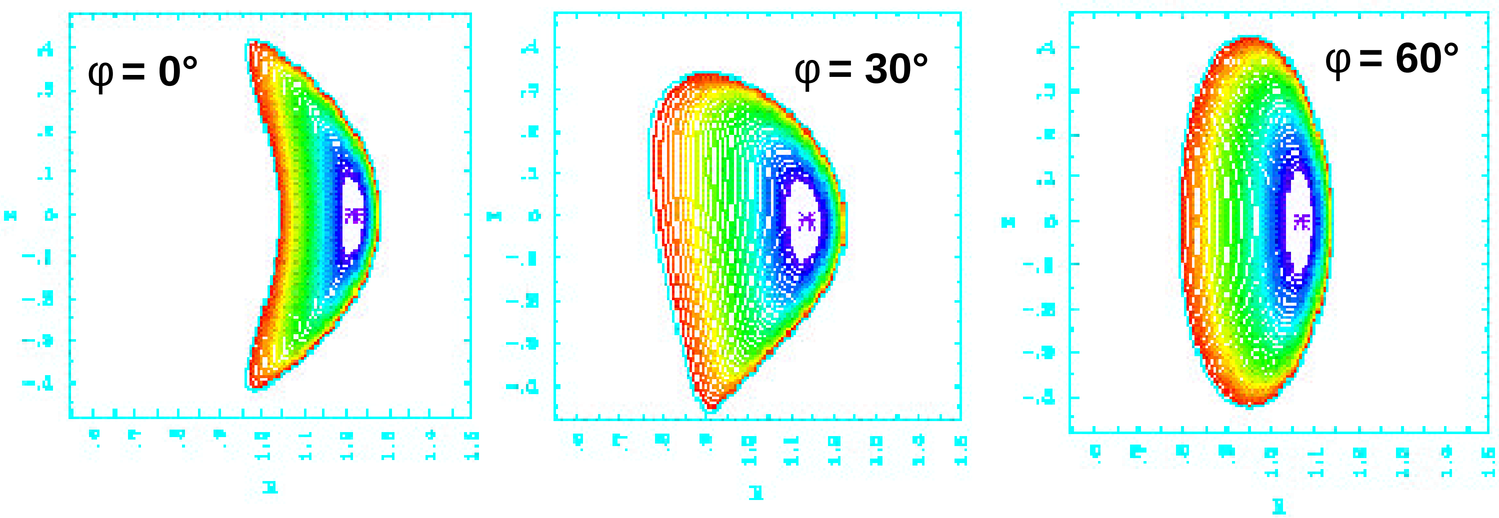
colors indicate contours of constant |B|

Plasma Geometry Is Very Different for the Two Types of QO Configurations

Low-I_{BS} , dq/dr < 0; <u>large helical axis excursion</u>, β ~ 4%

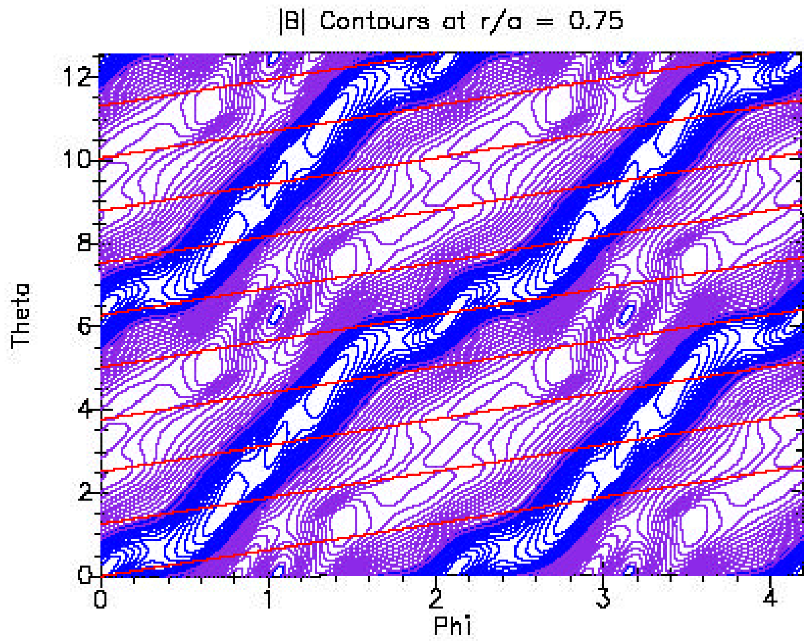


Higher-I_{BS} , dq/dr > 0; <u>nearly planar axis</u>, β ~ 15%

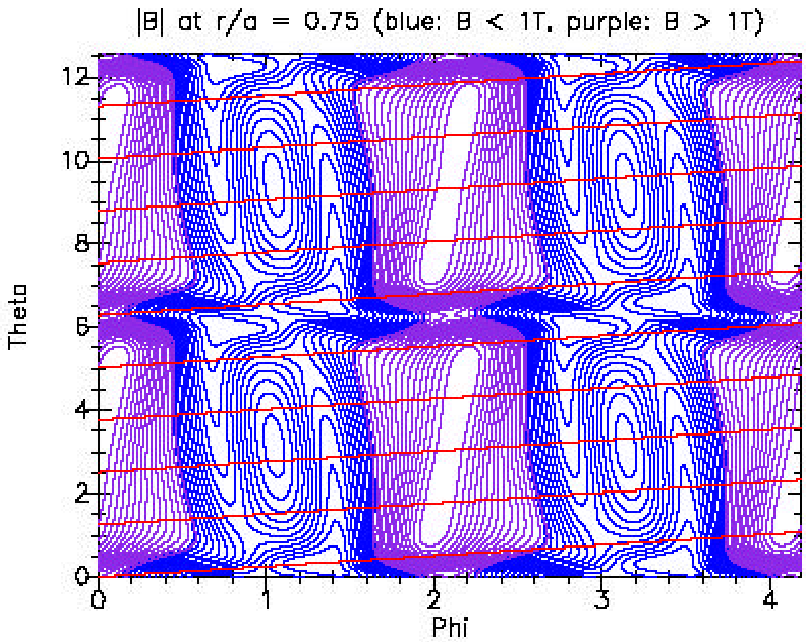


|B| Structure Is Very Different for the Two QO Stellarator Types

earlier near quasi-helical β (= 2%) QO case



recent near quasi-poloidal high β (= 14%) QO case



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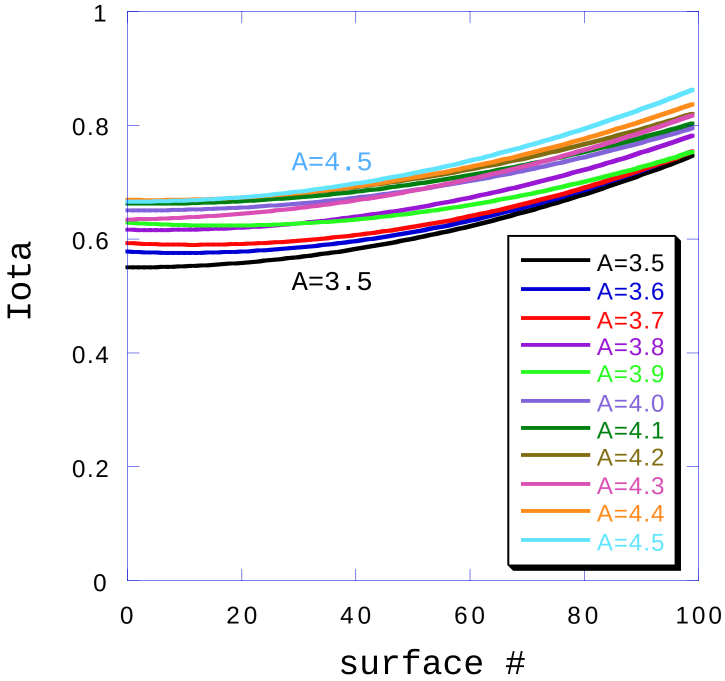
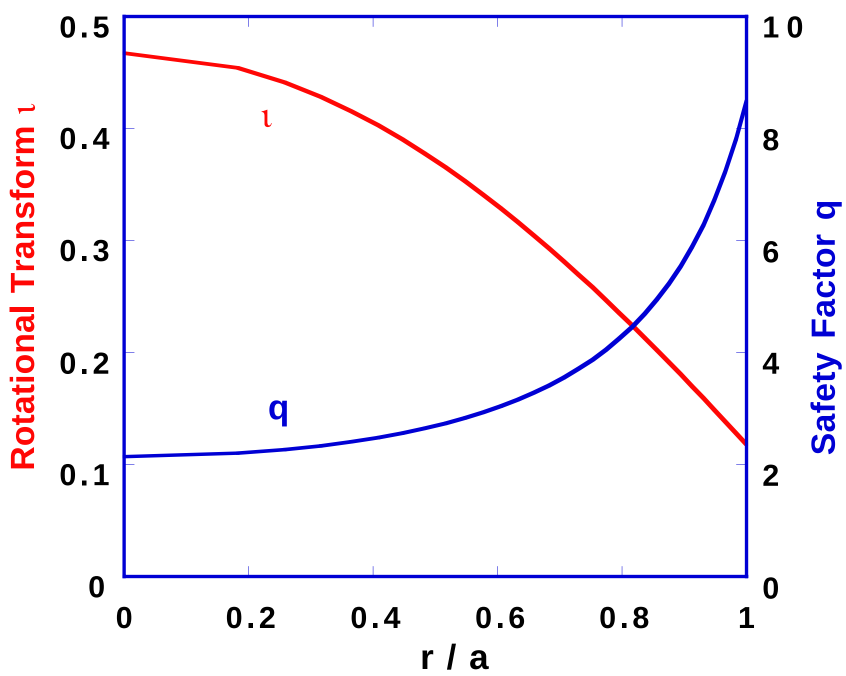
Rotational Transform Profiles Are Very Different for the Two QO Types

Low-I_{BS} QO cases



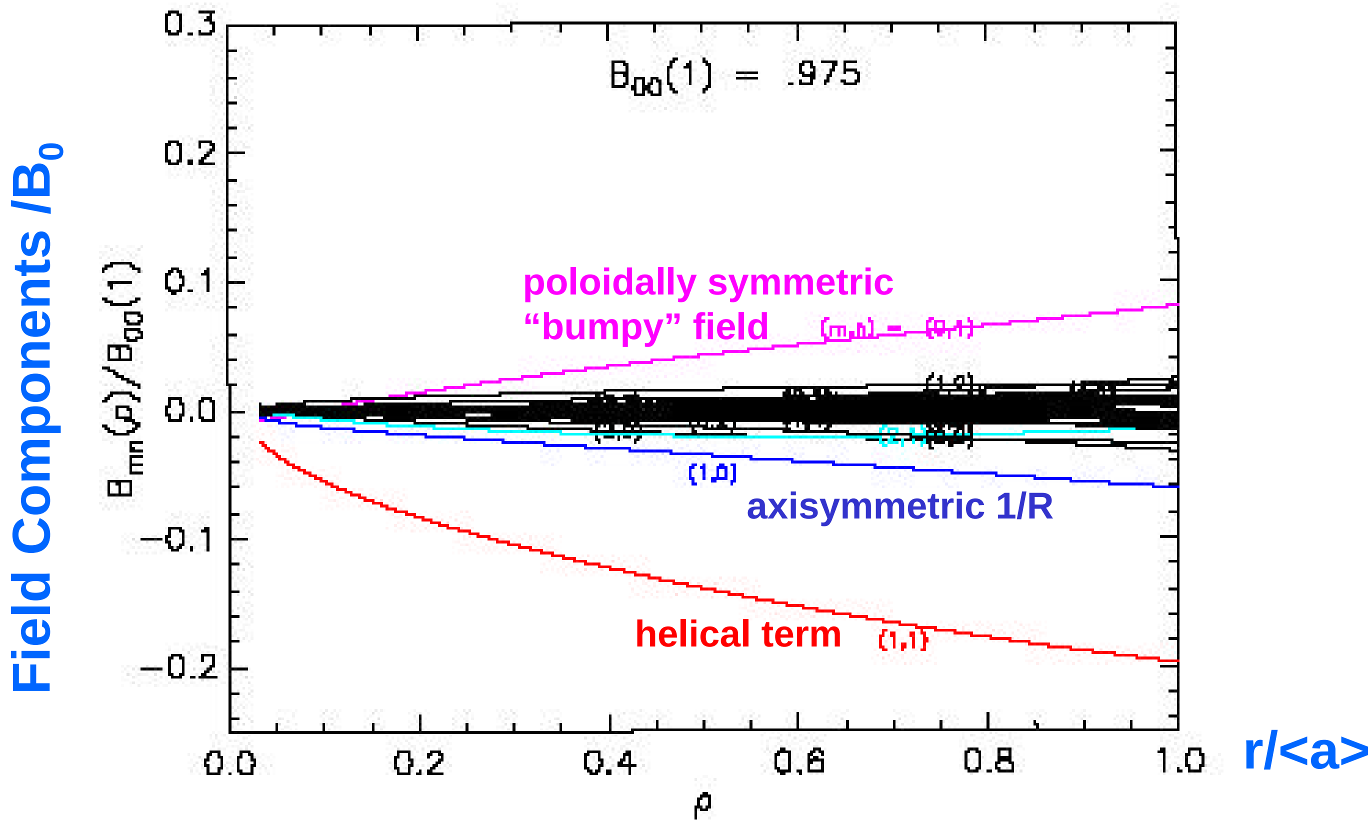
Higher-I_{BS} QO cases



Features of Low-I_{BS} QO Stellarators

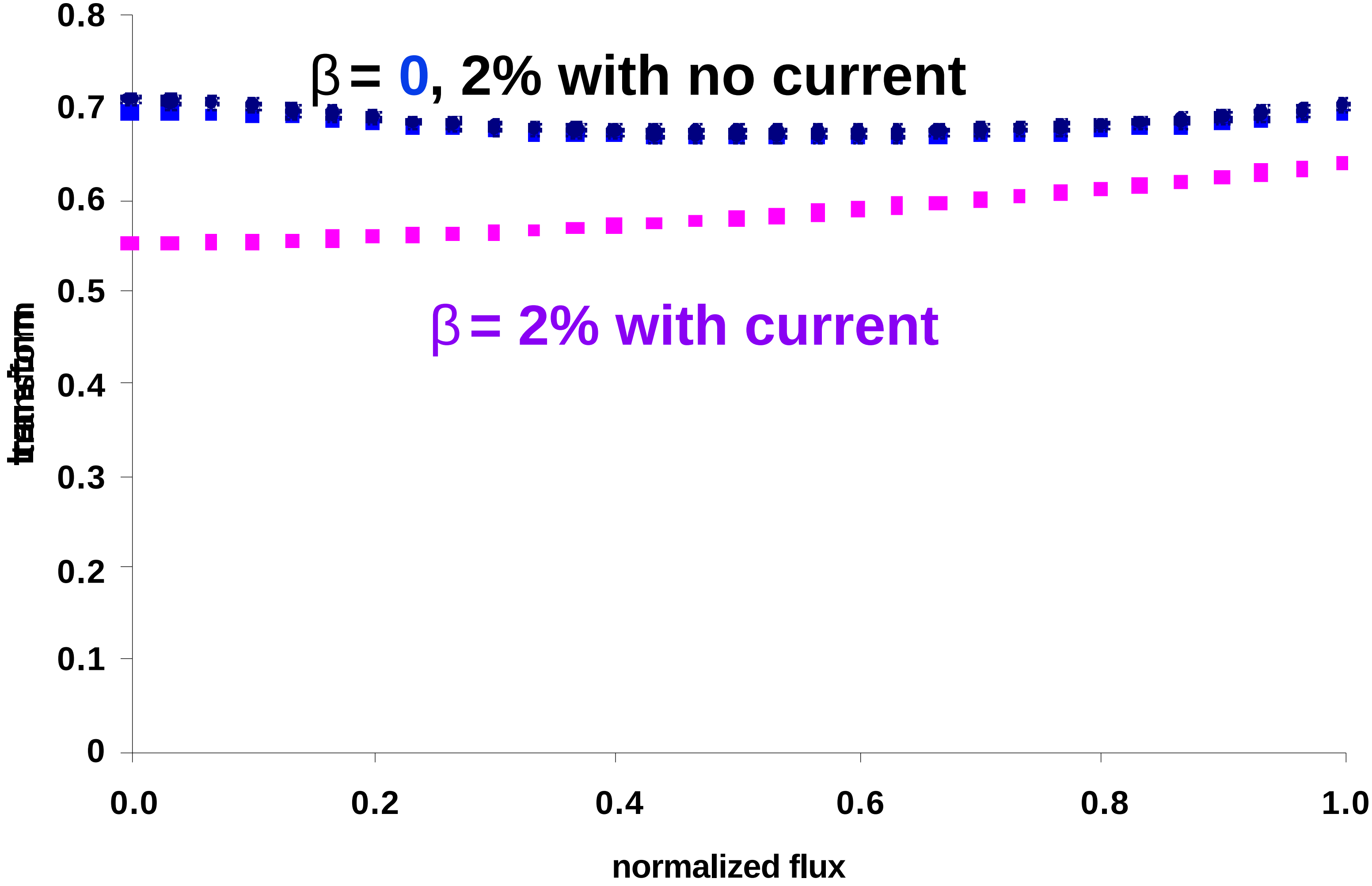
- **Stellarator-like shear (d*q*/dr < 0)**
  - typically $\iota(0) = 0.55\text{-}0.68$, $\iota(a) = 0.74\text{-}0.87$
- **Bootstrap current ~1/10 current in a tokamak**
  - configuration insensitive to increasing beta
  - robust against current-driven modes (external kinks), vertical instabilities, and disruptions
- **Ballooning stability limit 3-4% in reactor range**
  - Mercier stable across the plasma cross section
  - magnetic well and stellarator shear out to plasma edge
  - limits testable in small-medium size experiments
- **More thoroughly studied up to this point**
  - modular coil concept developed
  - preliminary exploration of engineering design issues

The Low-I_{BS} QO-Optimized Magnetic Field Has Several Spatial Components

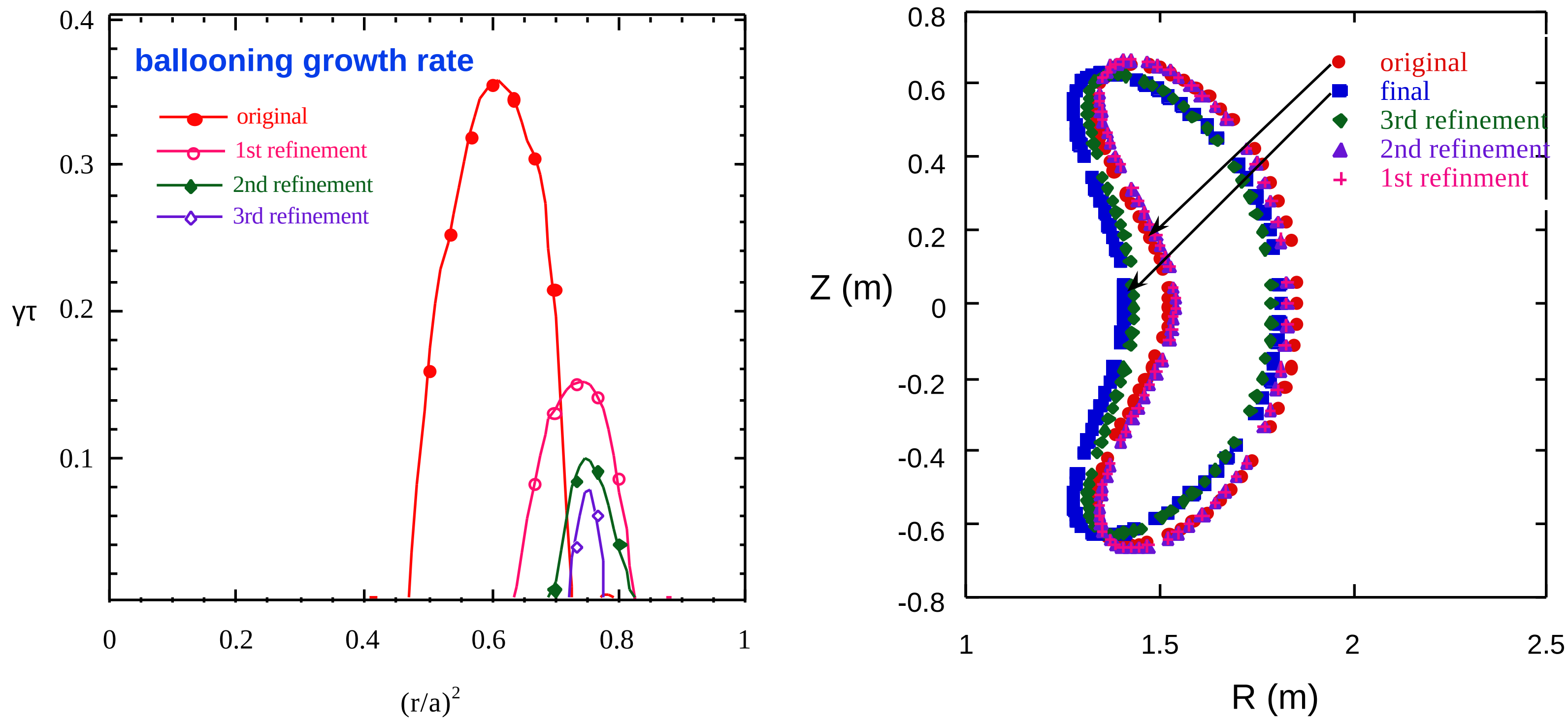


- Dominant helical shaping term produces higher rotational transform
- Small axisymmetric 1/R term reduces toroidal curvature drift
- Radially varying mirror “bumpy” term produces poloidal grad-B drift

Bootstrap Current Contributes ≈10% of the Net Transform Based on Equilibrium Calculations



Shape Optimization Produces Higher-β Configurations



- **Original low-I_{BS} configuration, ballooning unstable at β = 3%, was stabilized by small plasma boundary shape changes**
- **Pressure profile modification raises stable β to 4%**

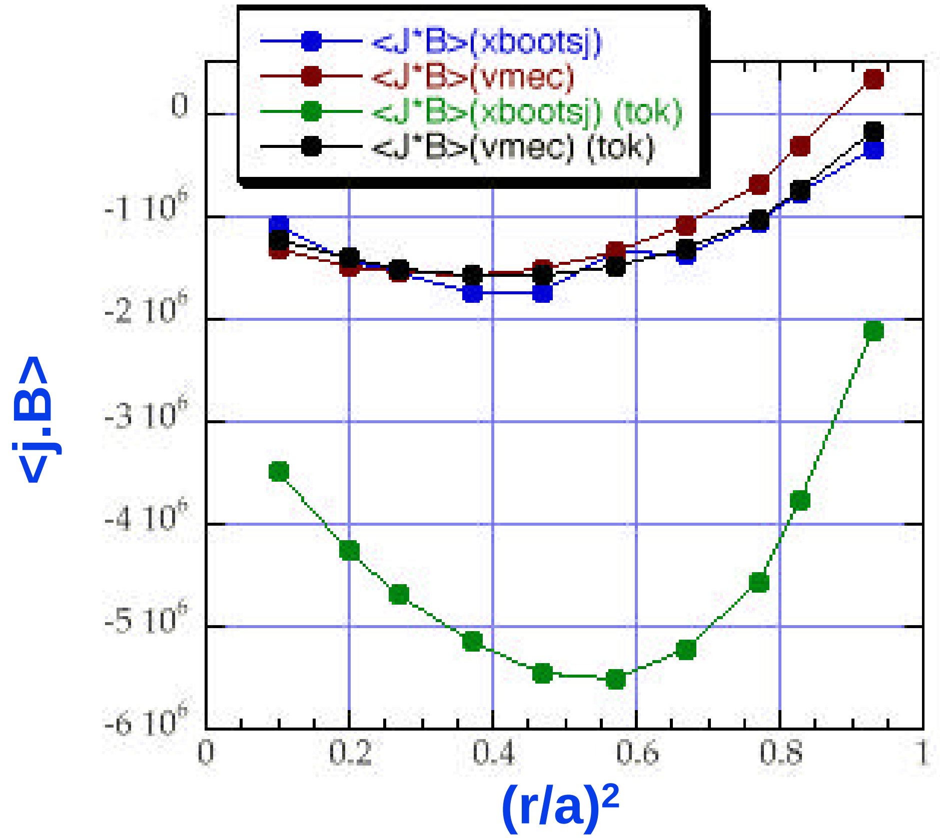
Reference QOS Properties

- **3 field periods, R/<a> = 3.6; global magnetic well**
- **$\iota(0) = 0.56$, $\iota(a) = 0.65$ (monotonic)**
- **Good vacuum flux surfaces; little change with β**
- **Bootstrap current < 1/10 current in similar tokamak**
- **Shaped plasma surface gives ballooning β limit 3-4%**
- **Good neoclassical transport ($\tau_{E,neo} \approx$ 3-5 $\times$ τ_E^{ISS95}) from 3-D Monte Carlo loss rate calculation**
- **Confinement of ICRF-generated tails better than CHS**
- **7 modular coils per period -- changing current in corner coils ±50% changes R/<a> from 2.9 to 4.6**

Higher-I_{BS} QO Stellarator Features

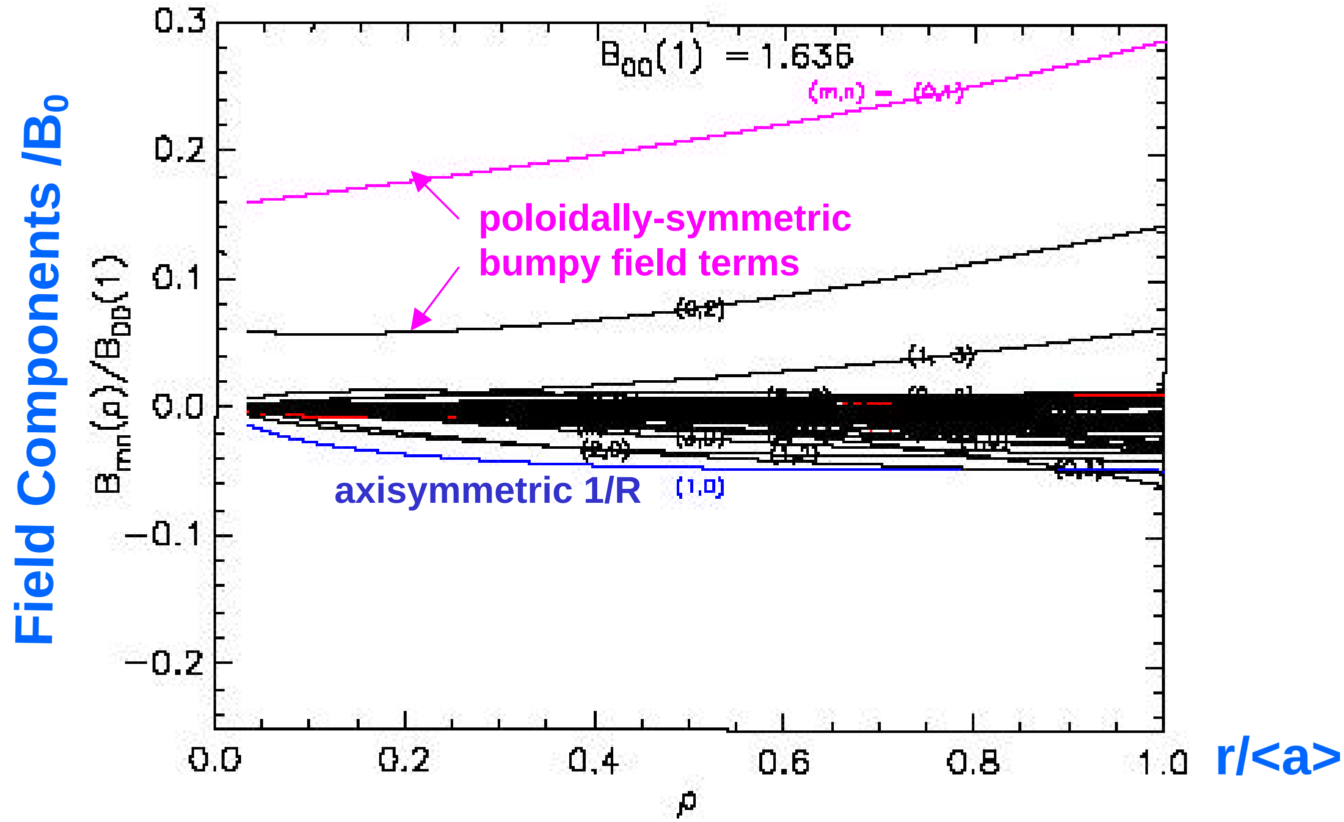
- **Tokamak-like shear (dq/dr > 0)**
  - $\iota(0) \approx 0.47$ ($q > 2$) and $\iota(a) = 0.12$ ($q \approx 8$)
- **Bootstrap current ≈1/4 that of equivalent tokamak**
  - ≈40% of the edge transform comes from the coils
- **Stable at β up to 19%** more attractive for reactor?
  - smoother corners lead to high ballooning beta limits
  - stable to Mercier modes and internal kinks
  - smaller j and j near edge higher external kink limit?
- **Less helical axis excursion**
  - simpler modular coils easier fabrication, lower cost?
- **More mirror-like |B| variation on a flux surface**
  - larger plasma-coil separation possible? smaller reactor
- **Transport ~2x higher than best lower-I_{BS} QO case, but still ~1.6 better than ISS95 stellarator scaling**

$\beta = 15\%$ QO Configuration Has 1/4 the Bootstrap Current of Equivalent Tokamak



- QO case has self-consistent bootstrap current
- I_{BS} 4x larger in an equivalent tokamak; large opposing driven current needed for self-consistent equilibrium

The Higher-I_{BS} QO-Optimized Magnetic Field Has Different Spatial Components



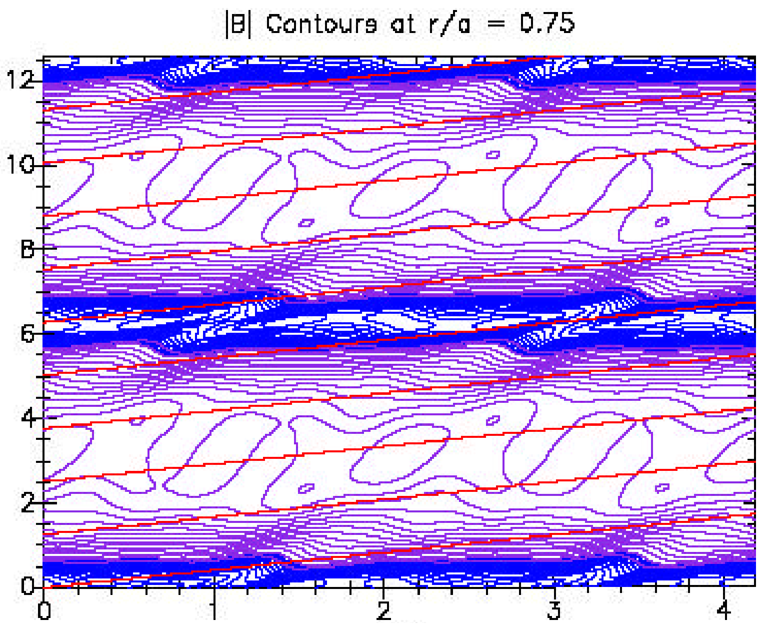
- Dominant poloidally-symmetric terms >5 times larger
- Small axisymmetric 1/R term reduces toroidal curvature drift
- Helically-symmetric terms >20 times smaller

SUMMARY

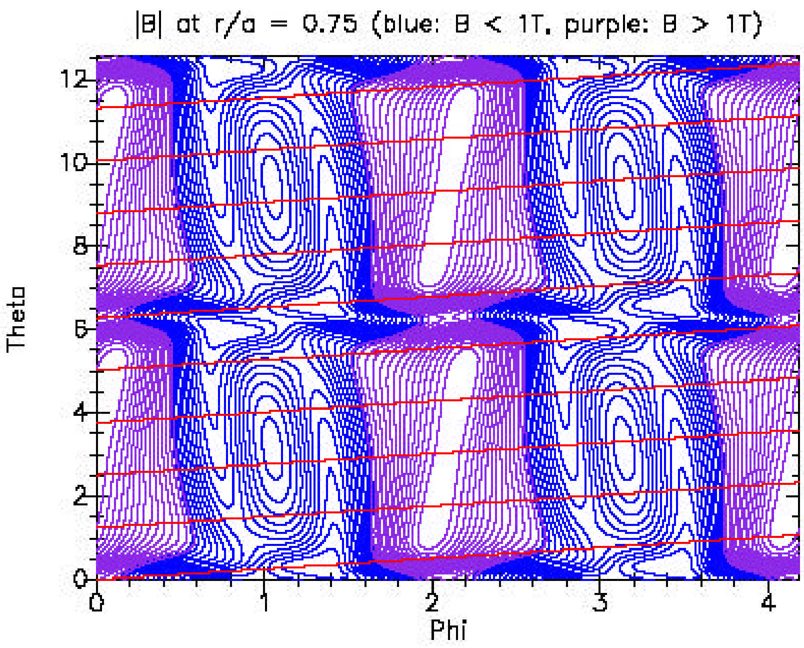
- **Configuration optimization tools are well developed**
  - **3-D equilibrium; self-consistent bootstrap current; coil design**
  - **ballooning, kink, and Mercier stability**
  - **neoclassical transport, energetic orbit confinement**
- **Progress has been made in optimization of the low-I_{BS} QO approach ($R/<a> = 3.6$)**
  - **bootstrap current << current in tokamak for same size and È**
  - **good neoclassical transport ($\tau_{E,neo} \approx$ 3-5 $\times$ $\tau_{E,ISS95}$), $\iota \approx$ 0.7**
  - **ballooning optimization achieves $\beta \approx$ 3-4%**
- **Work has started on a higher-β QO configuration**
  - **ballooning stable up to $\beta \approx$ 19%; also kink stable at $\beta \approx$ 15%**
  - **configuration may allow simpler modular coils and smaller reactor**
  - **neoclassical confinement still needs to be improved**

|B| Structure Is Very Different for QA and QO Stellarators

Quasi-axisymmetric QA case



recent near quasi-poloidal high β (= 14%) QO case



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