INTEGRATED PLASMA AND COIL OPTIMIZATION FOR COMPACT STELLARATORS

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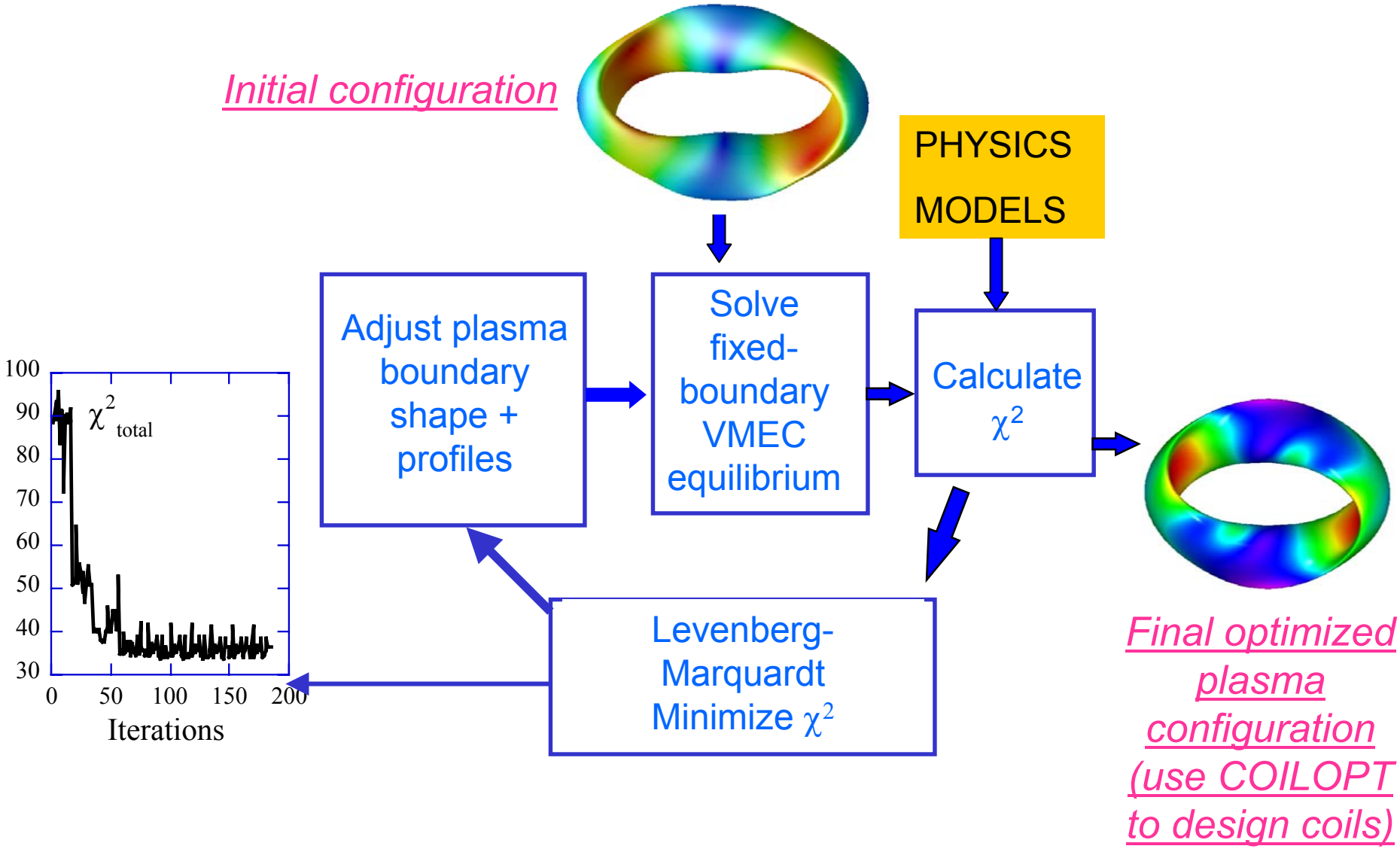
Abstract

The integration of the COILOPT model, based on explicit representations for modular coil geometry, into the stellarator optimization package STELLOPT, provides a unique and important computational tool for the design of compact stellarators. This merged optimization technique has led to conceptual designs for the quasi-axisymmetric National Compact Stellarator Experiment (NCSX) and the Quasi-Poloidal Stellarator (QPS)

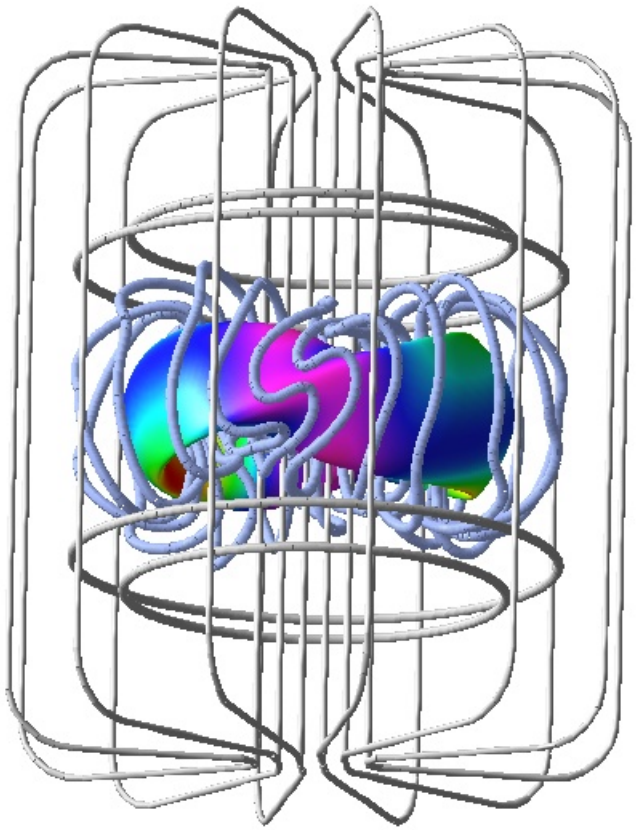
Compact stellarator design is improved by recent numerical tool developments

- STELLOPT (stellarator optimization code)
  - Determine plasma shape, pressure and current profiles to target physics parameters
- COILOPT (coil optimization code)
  - Determine coil geometry to best reconstruct plasma shape and satisfy engineering design constraints
- Integrated plasma/coil optimization
  - Include COILOPT coil representation and engineering constraints in free-boundary STELLOPT calculation

Optimization of the plasma configuration - STELLOPT



The coil design process - COILOPT

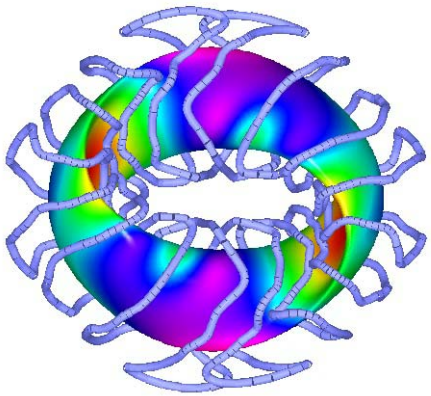


COILOPT varies coefficients in an explicit representation of modular coils on a coil winding surface (CWS) to minimize B-normal (plasma + coils) at plasma boundary.

- Fourier series or cubic B-spline (control point) representation for coil winding law
- incorporates VF, TF coils and currents in optimization
- variable CWS shape (Fourier series) included in optimization
- engineering penalty targets: coil-coil and coil-plasma separation, coil curvature, access, etc.
- Difficult to reconstruct prescribed plasma shape <u>and</u> satisfy coil constraints

Merged STELLOPT / COILOPT solutions target both compact stellarator plasma properties, coil geometry

Initial configuration based on coil representation



Physics and Coil Geometry Models

Adjust modular coil geometry and plasma profiles

Free-Boundary VMEC equilibrium

Calculate χ^2

Final optimized plasma and coil configuration

Levenberg-Marquardt Minimize χ^2

Measures of stability, transport, and coil feasibility used in STELLOPT to optimize compact stellarator plasma configurations

Example	Target	Model/code
Quasi-symmetry, transport	Minimize effective ripple (ε_{eff}), B_{mn}, $n \neq 0$ (QA), $m \neq 0$ (QP)	NEO [1]
Ballooning, Mercier, kink stability	MHD stability at target β = 4% (NCSX), 2% (QPS)	COBRA [2], TERPSICHORE [3]
Coil engineering feasibility	Coil complexity, current density	NESCOIL [4]

1. V.V.Nemov, et al., Phys. Plasmas **6** (1999) 4622.
2. R. Sanchez, et al., J. Comp. Phys. **161** (2000) 589.
3. D. V. Anderson, et al., Int. J. Supercomput. Appl. **4** (1990) 34.
4. P. Merkel, Nucl. Fusion **27** (1987) 867.

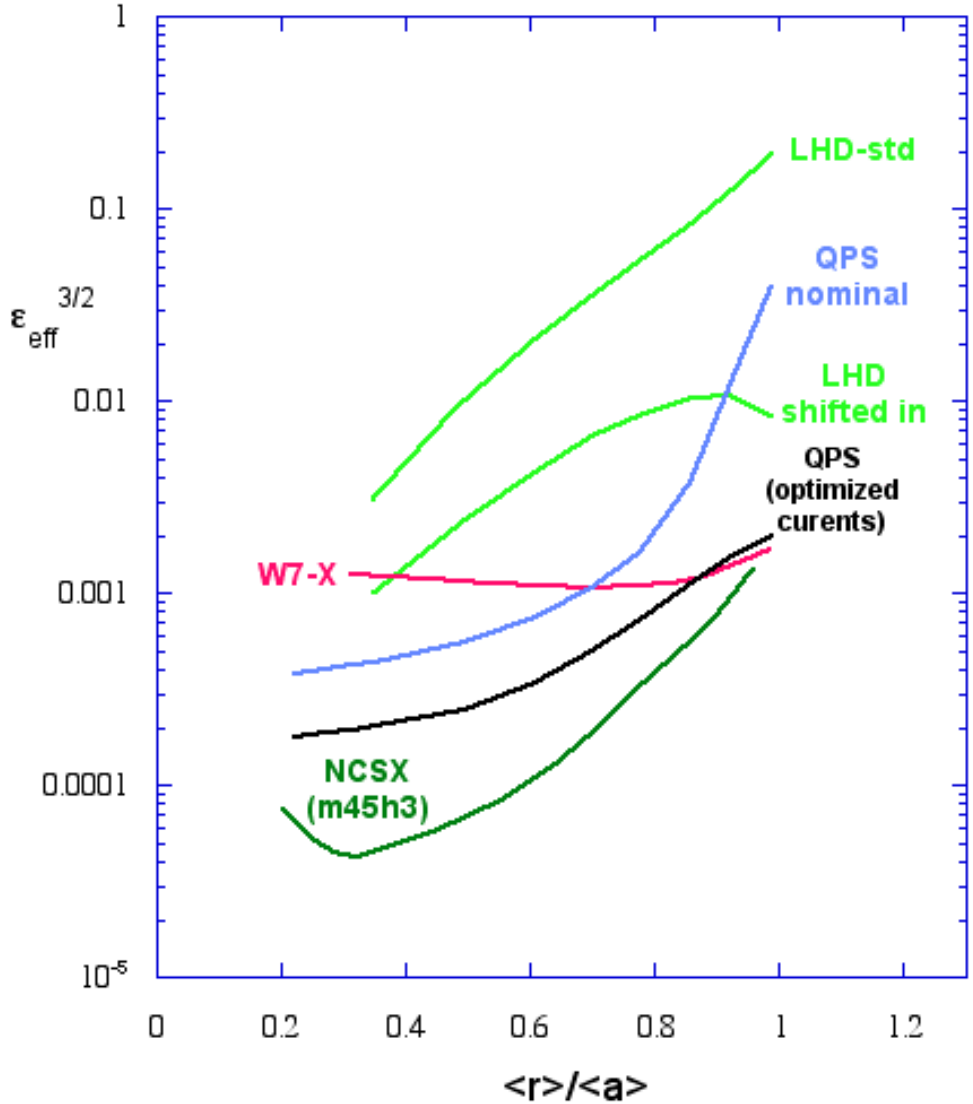
Coil geometry and current density constraints used in COILOPT to insure engineering design feasibility

Example	COILOPT target
Minimum coil-coil separation	≥ 15cm (NCSX) ≥ 9cm (QPS)
Minimum coil-plasma separation	≥ 18cm (NCSX) ≥ 13cm (QPS)
Minimum coil radius of curvature	≥ 10cm (NCSX) ≥ 9cm (QPS)
Access	NBI (NCSX) Space in center for TF, PF (QPS)

Features of NCSX, QPS compact stellarators

Feature	NCSX	QPS
R, a, B, $P_{heating}$	1.4m, 0.33m, 2T, 6-12MW	0.9m, 0.33m, 1T, 1-3MW (ECH, EBW, ICH)
Magnetic Symmetry	Quasi-axisymmetric	Quasi-poloidal
Aspect Ratio, Field Periods, Modular Coils	A = 4.3, N = 3, N_c = 18	A = 2.7, N = 2, N_c =16
Key Physics Issues	Proof-of-principle: High-β stability and confinement	Concept exploration: Low A equilibrium and transport

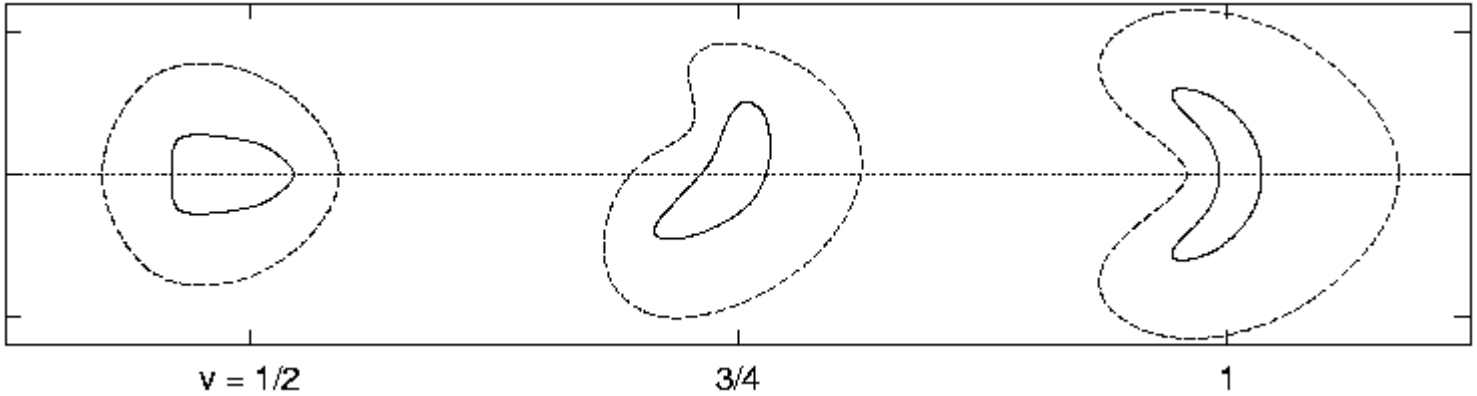
Ripple Transport ($\sim\varepsilon_{eff}^{3/2}$) is Targeted in NCSX, QPS Designs

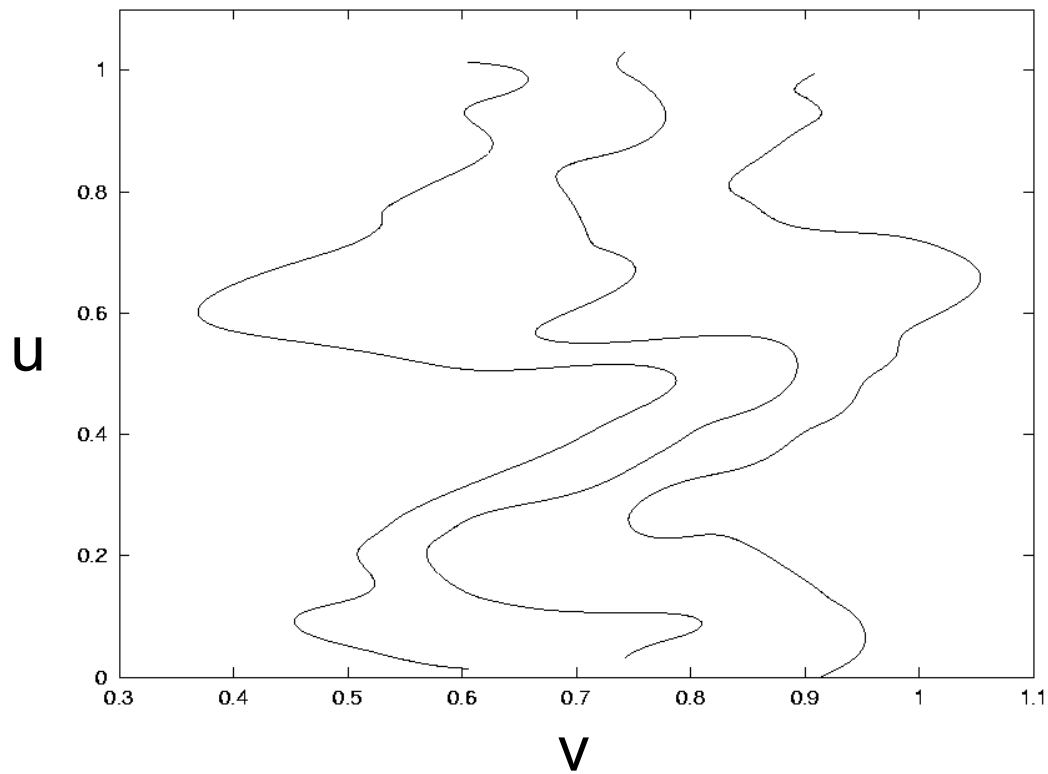


Combined optimization required to achieve both physics and engineering goals in NCSX

Configuration	LI383	M12	M25	M45
$\langle\beta\rangle$ (%)	4.19	4.09	4.05	4.08
$\varepsilon_{eff}^{3/2}$ ($\times 10^4$), center	0.24	0.32	0.41	0.96
f_{NB} (%)	14.5	14.2	13.5	15.5
no. of modular coils		21	18	18
Δ_{min}, coil-coil (cm)		12.8	11.9	16.0
Δ_{min}, coil-plasma (cm)		17.5	19.9	18.7
Δ_{min}, NBI access (cm)			30.9	37.4
min. bend radius (cm)		7.7	9.4	10.5

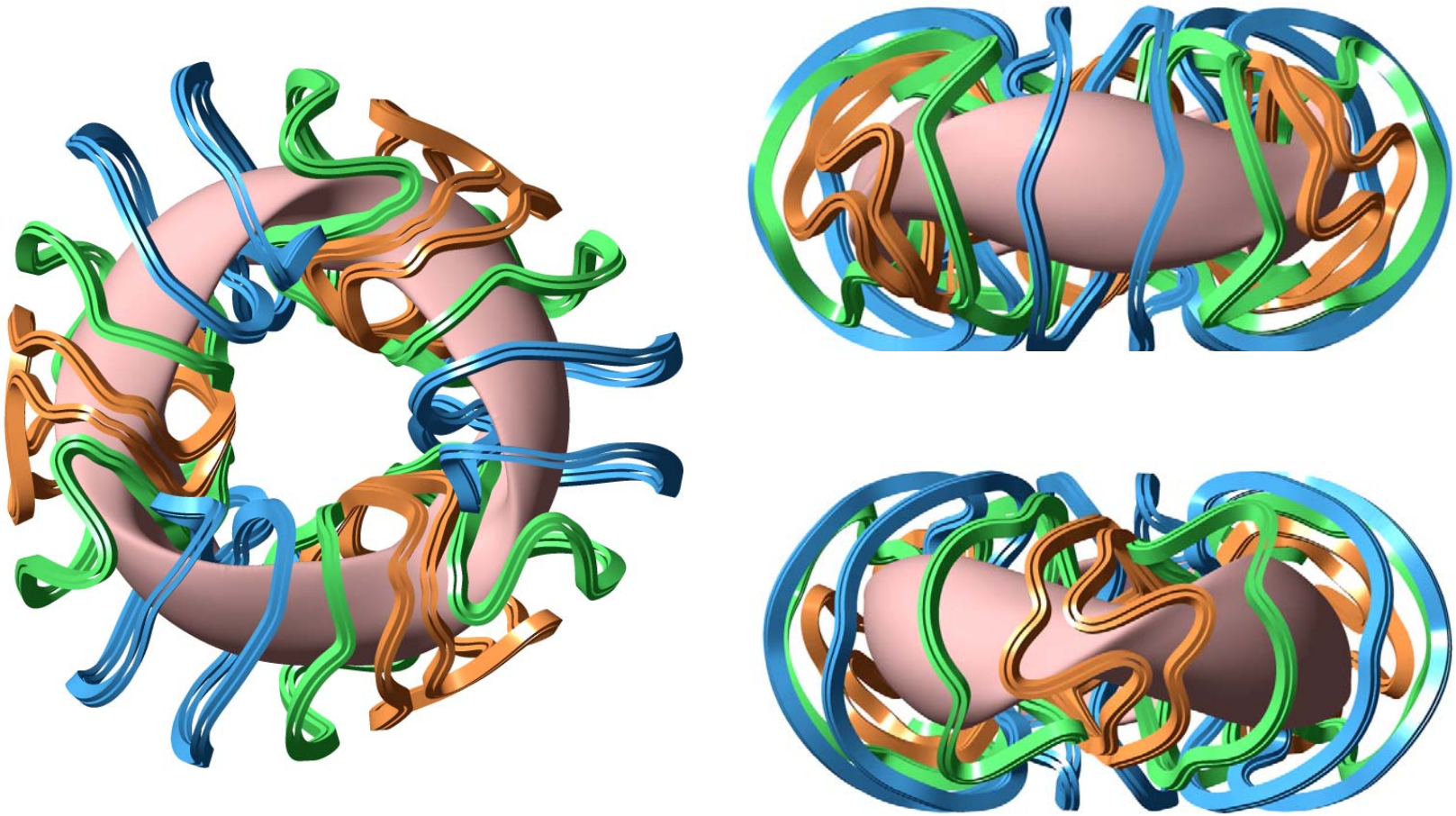
(Numbers in red were inadequate for engineering design)





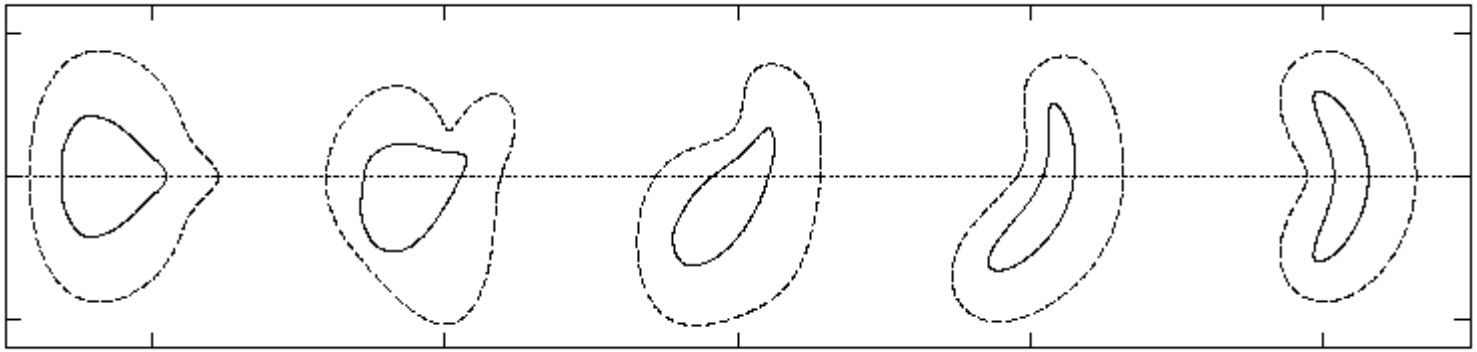
Optimized NCSX plasma and coil winding surface (above), and 3 modular coil types in normalized poloidal (u) and toroidal (v) coordinates (left) for merged optimization M45

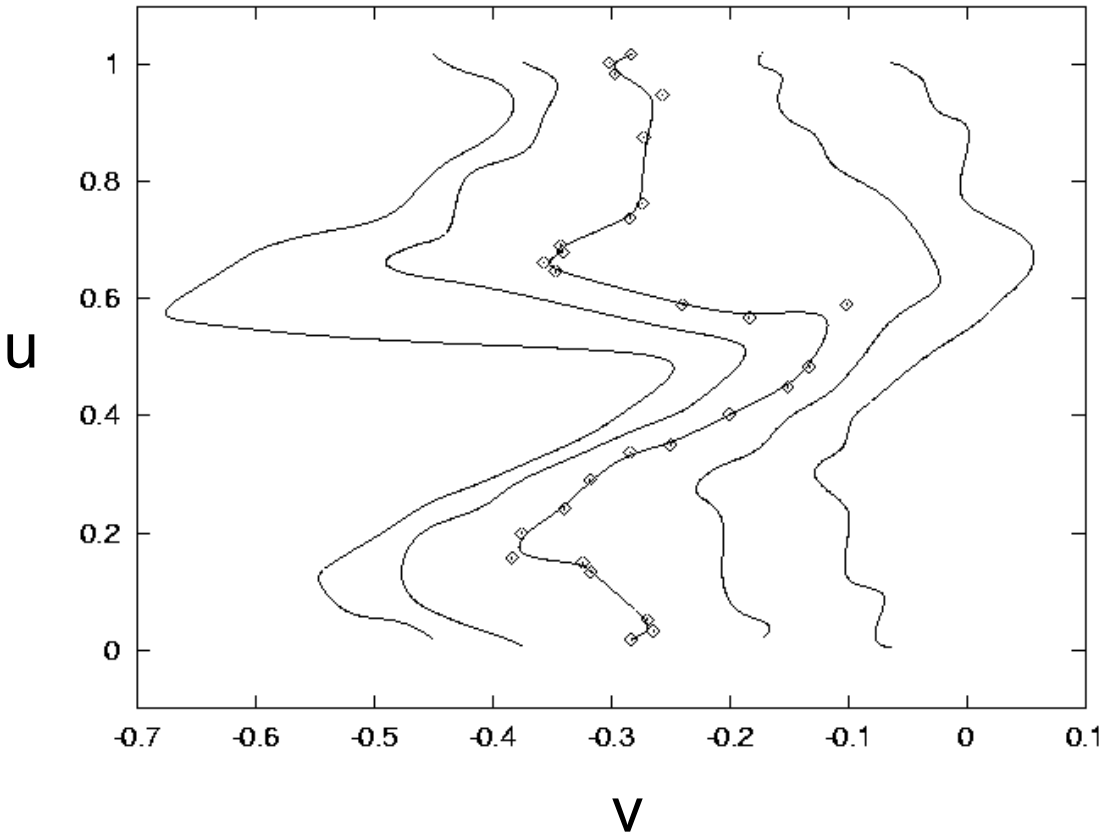
Plasma and modular coils for NCSX configuration M45 satisfy both physics and engineering requirements



QPS merged plasma / coil optimization solution (0718) reduced coil complexity in design based on separate STELLOPT and COILOPT optimizations (0411)

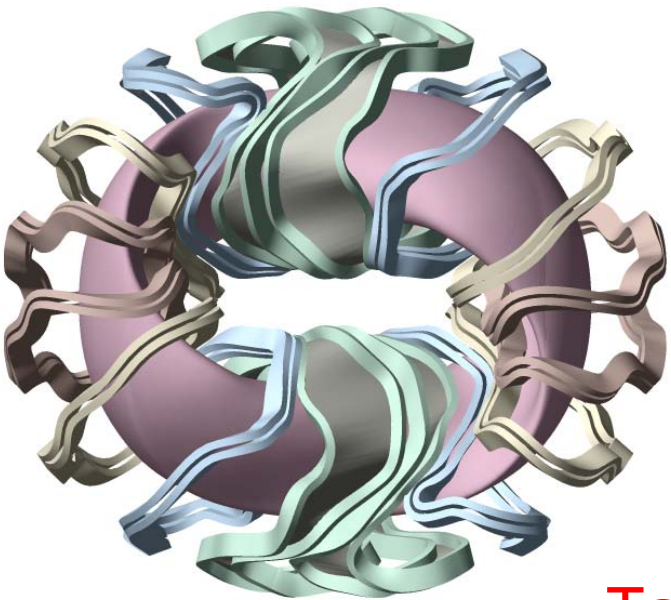
Configuration	0411	0718
$\langle\beta\rangle$ (%)	1.78	1.83
ι (axis)	0.29	0.28
ι (edge)	0.48	0.34
waist, v=0 (cm)	23.3	21.6
ΔY, center (cm)	36.0	36.0
Δ_{min}, coil-coil (cm)	10.1	9.6
Δ_{min}, coil-plasma (cm)	14.6	13.0
min. bend radius (cm)	10.1	9.3

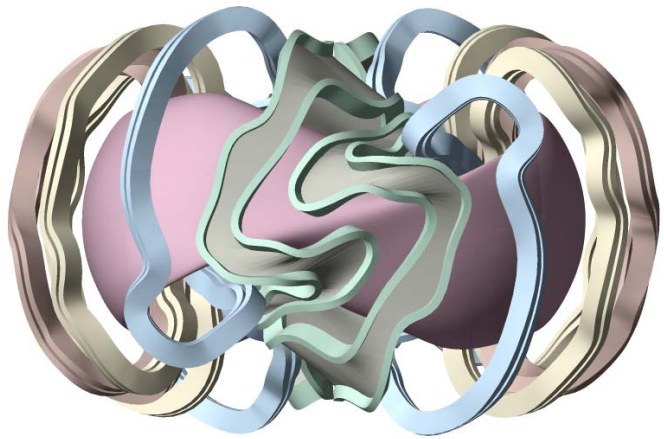




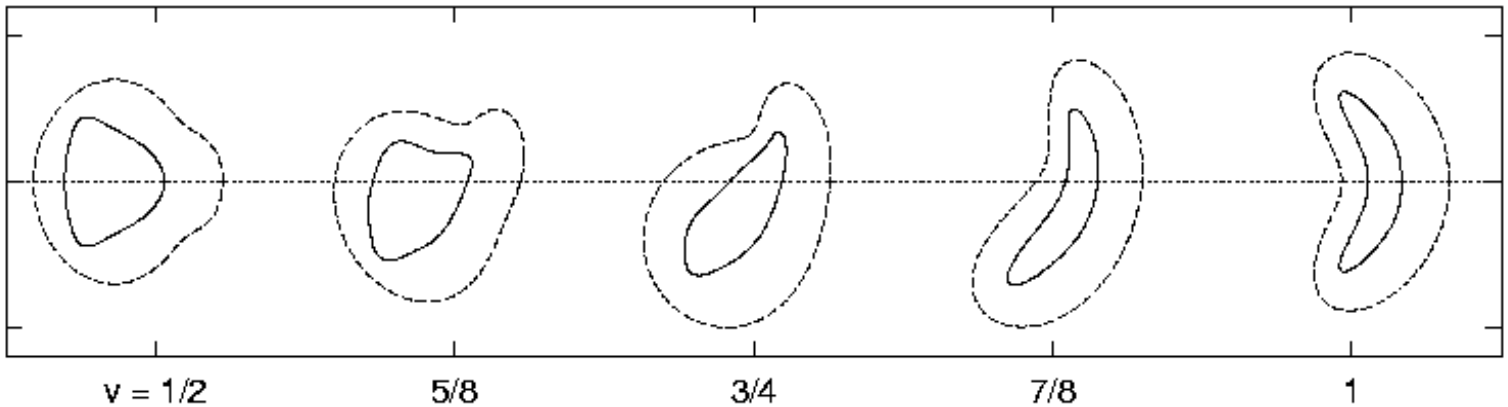
Reconstructed plasma and optimized winding surface (above) resulting from separate plasma and coil optimizations for QPS 0411. Using 41 Fourier modes in the CWS and 28 control points for each coil winding law (left) led to complex coil shapes. Control points for the B-spline series are shown for modular coil 3.

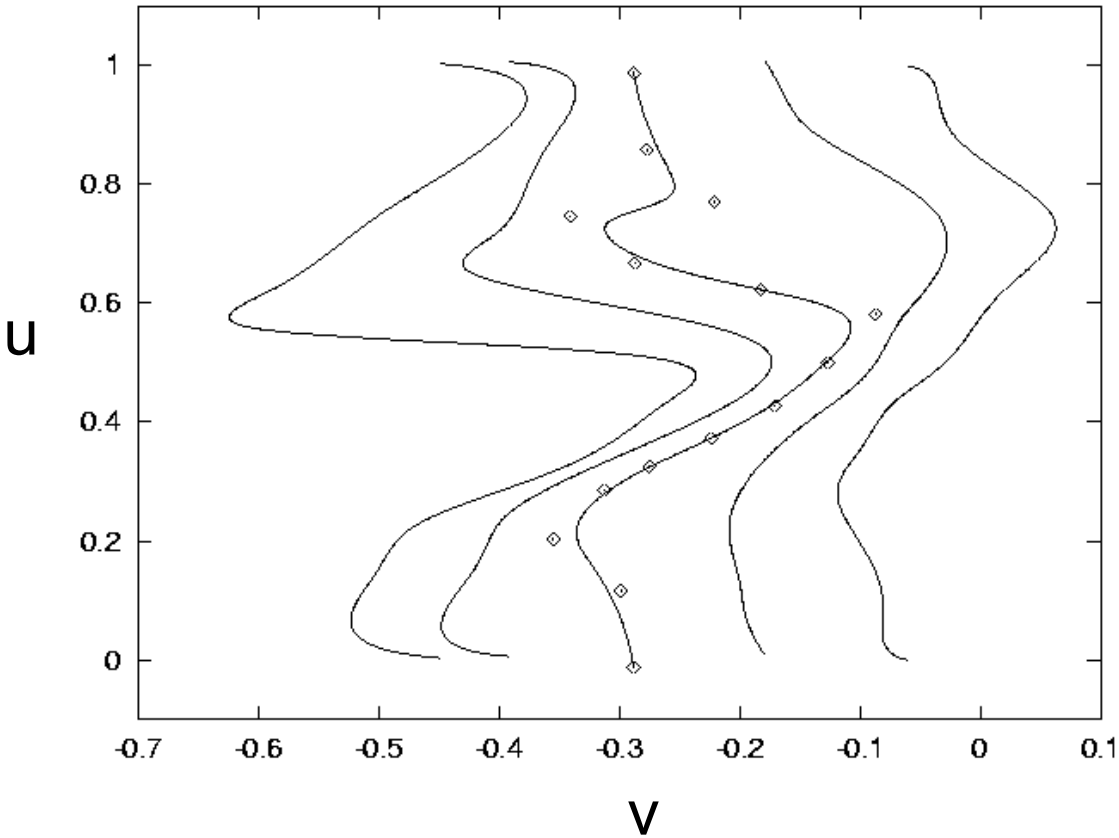
QPS modular coils and reconstructed plasma for configuration 0411, the result of separate STELLOPT and COILOPT optimizations





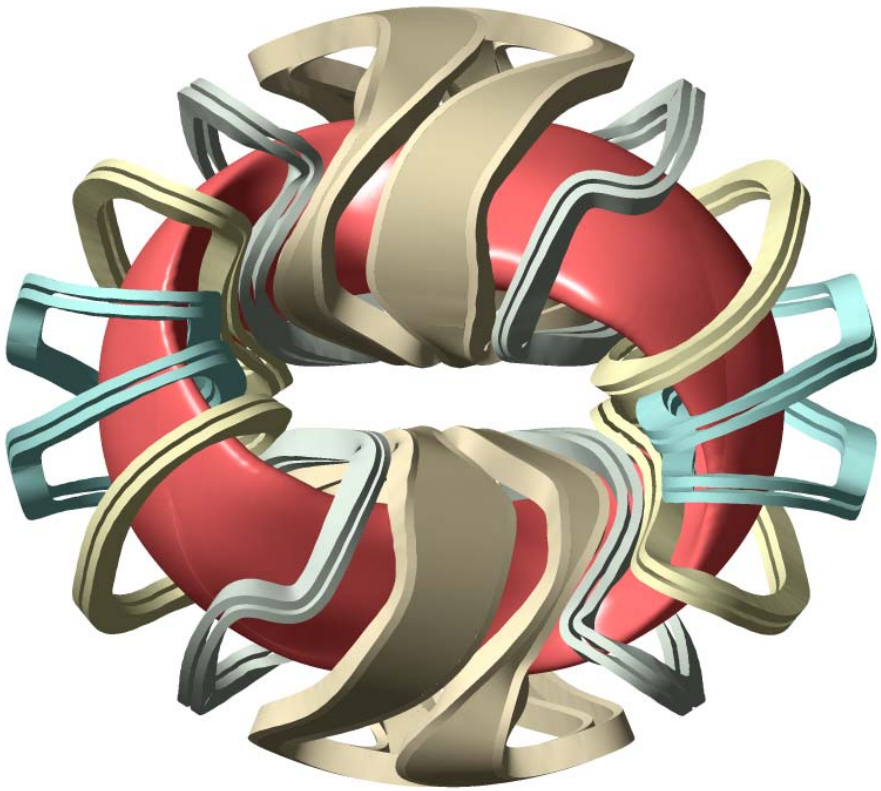
Targeting prescribed plasma shape from fixed-boundary STELLOPT analysis led to complex coil shapes.

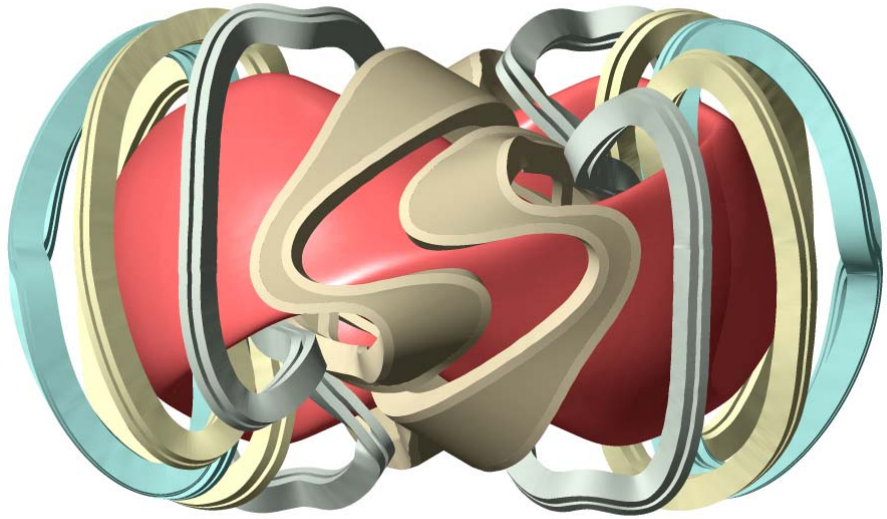


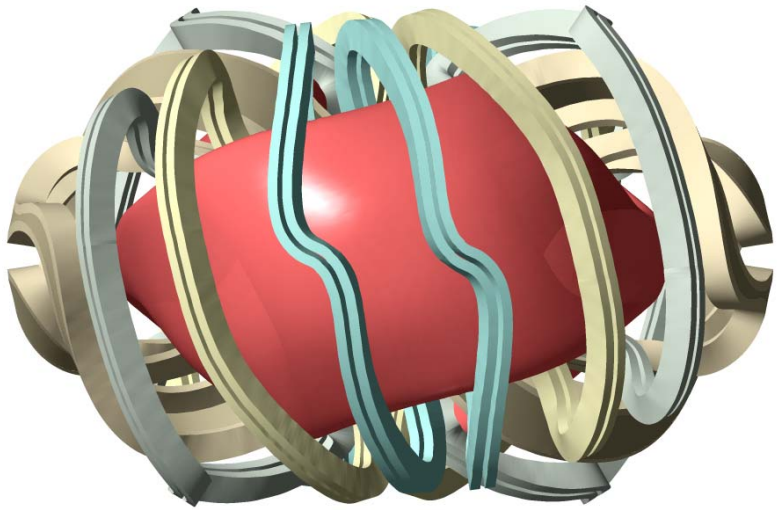


Plasma and optimized coil winding surface (above) for QPS merged optimization 0718. Using 23 CWS Fourier modes and 15 control points in the spline representation of the winding law for each modular coil (left) produced less complex coil shapes while achieving physics goals.

Integrated plasma / coil optimization 0718 led to QPS modular coils with improved manufacturing properties







Summary

The integration of the COILOPT modular coil representation and coil geometry constraints with the stellarator optimization code STELLOPT provides a self-consistent analysis to ensure that physics and coil engineering criteria are simultaneously satisfied. This computational design tool is implemented after the separate plasma and coil optimizations have identified a good initial configuration. The merged optimization technique has been used successfully in the design of the NCSX and QPS compact stellarators.