QPS Coil Design

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with contributions from the
Compact Stellarator Coil Group

QPS Physics Validation Review

April 24-25, 2001

PRINCIPAL POINTS

- **Coil development for the “gb4” configuration used the ORNL/PPPL/UTexas suite of design tools. The QPS PVR design was the product of COILOPT optimizations.**
- **The PVR coil set for the “gb4” configuration meets engineering constraints and reproduces fixed-boundary physics.**
- **The PVR poloidal coil (PF) design can provide needed configuration flexibility and Ohmic heating flux if currents in bell jar are minimized.**
- **Improvements are expect for the conceptual design coil set.**

PRINCIPAL QPS COIL DESIGN CRITERIA

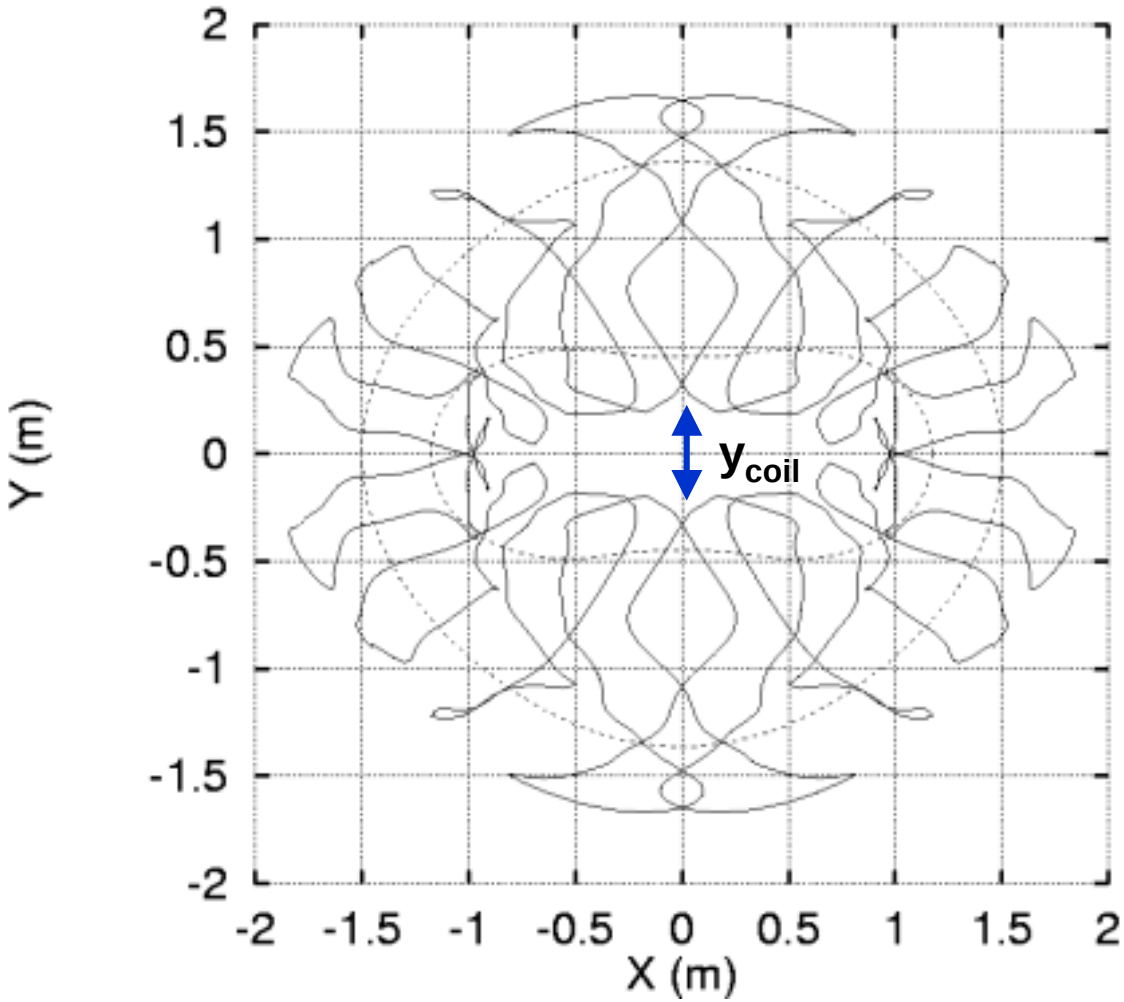
- **Realize QPS physics goals:**
  - **reconstruct reference design parameters.**
- **Coil current density consistent with room temperature:**
  - **$\leq$ 8 kA/cm^2 (by maximizing coil-to-coil, coil-to-plasma spacing)**
- **Minimize N_{coil} / N_{period}:**
  - **reduce total number of coils/coil types (cost, number of power supplies)**
- **Maximize minimum (bend) radius of curvature of coils:**
  - **engineering limits ρ_{min} to > 7 cm for PVR coil cross sections.**

A RANGE OF "TARGETS" WERE NEEDED TO MEET PHYSICS AND ENGINEERING CRITERIA

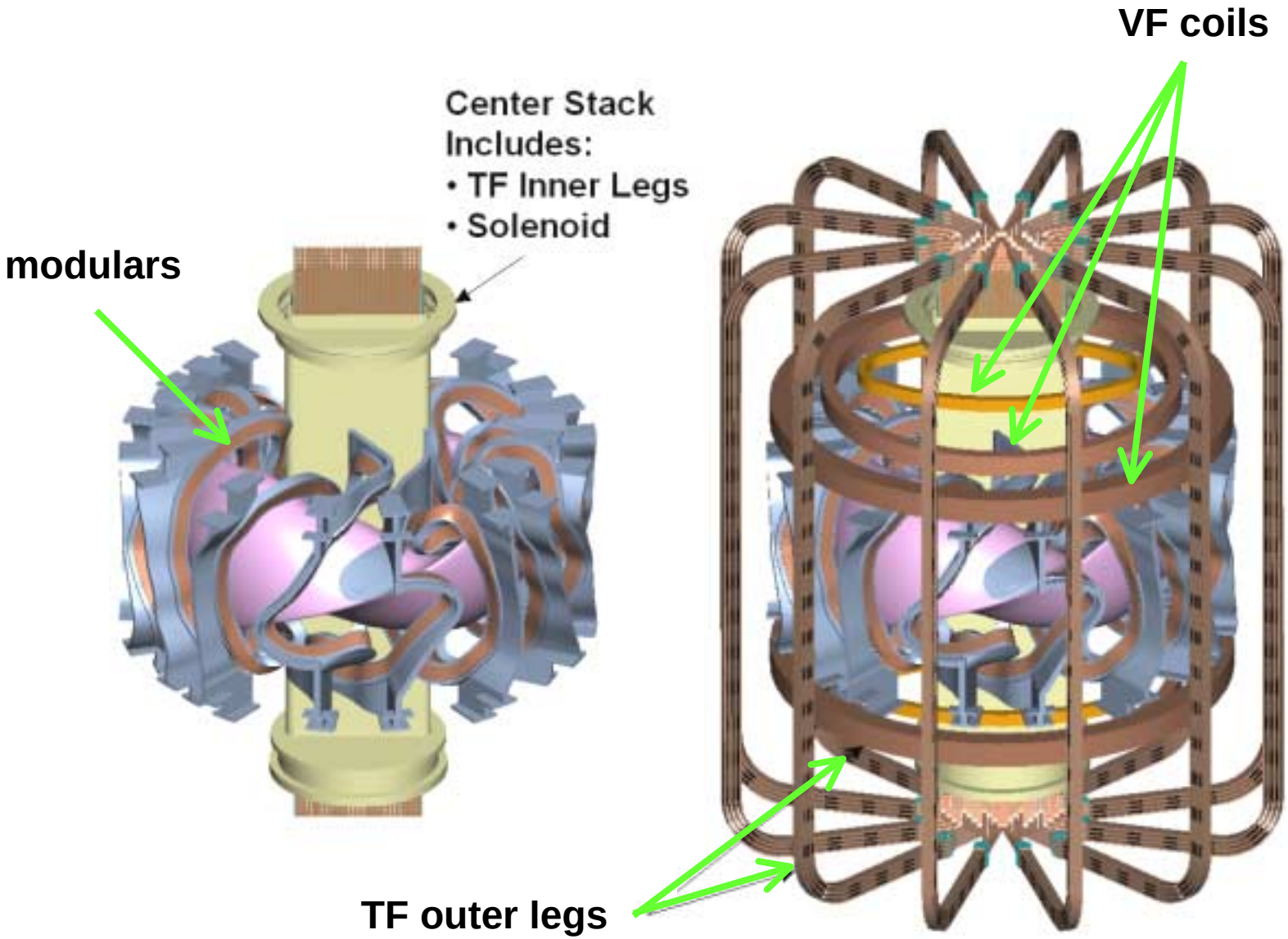
Target	Parameter	Value	Purpose
RMS B_{norm} error on LCFS (%)	δB_{rms}	≤ 2.0	Equilibrium reconstruction
Avg. B_{norm} error on LCFS (%)	δB_{avg}	≤ 1.5	Equilibrium reconstruction
Max. B_{norm} error on LCFS (%)	δB_{max}	≤ 10	Equilibrium reconstruction
Min. coil-coil separation (cm)	$\Delta_{cc,min}$	≥ 11	Min. coil current density
Min. coil-plasma distance (cm)	$\Delta_{cp,min}$	≥ 13	Access, flexibility
Min. radius of curvature (cm)	ρ_{min}	≥ 7	Coil fabrication
Min. $\lvert y_{coil} \rvert$ (cm)	y_{min}	≥ 20	Access for TF, OH

Coil geometry was varied until targets (constraints) were achieved.

QPS COILS: OPTIMIZATION BASED ON SINGLE-FILAMENT REPRESENTATION



THE QPS COIL SET



PRELIMINARY OPTIMIZATIONS WITH ONLY MODULAR COILS SUGGESTED THAT TEN OR ELEVEN COILS/PERIOD HAD SMALL BEND RADII AND HIGH CURRENT DENSITIES

ID	N_c	δB_{avg}(%)	δB_{max}(%)	$\Delta_{cc,min}$(cm)	ρ_{min}(cm)	$\Delta_{cp,min}$(cm)
0205a2	**10**	**2.37**	**15.28**	**8.5**	**5.7**	**12.3**
0129a2	**11**	**1.86**	**15.64**	**7.7**	**5.3**	**11.2**

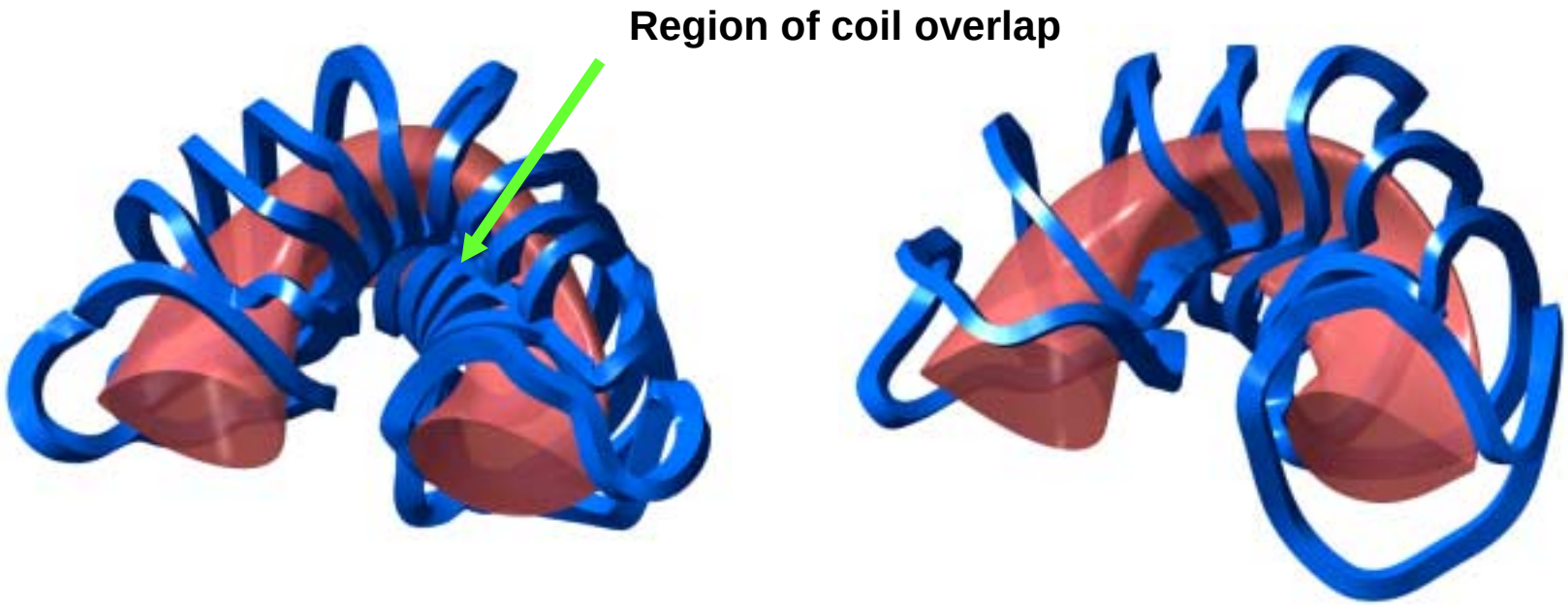
PRELIMINARY OPTIMIZATIONS WITH ONLY MODULAR COILS SUGGESTED THAT EIGHT COILS/PERIOD WITH COILS ON THE SYMMETRY PLANES HAD UNACCEPTABLY HIGH ERRORS

ID	N_c	δB_{avg}(%)	δB_{max}(%)	$\Delta_{cc,min}$(cm)	ρ_{min}(cm)	$\Delta_{cp,min}$(cm)
0205b3	**8**	**3.66**	**29.32**	**9.6**	**6.7**	**11.5**
0205a2	10	2.37	15.28	8.5	5.7	12.3
0129a2	11	1.86	15.64	7.7	5.3	11.2

PRELIMINARY OPTIMIZATIONS WITH ONLY MODULAR COILS SUGGESTED THAT EIGHT COILS/PERIOD NOT AT SYMMETRY PLANES COULD MEET TARGETS

ID	N_c	δB_{avg}(%)	δB_{max}(%)	$\Delta_{cc,min}$(cm)	ρ_{min}(cm)	$\Delta_{cp,min}$(cm)
0205b3	8	3.66	29.32	9.6	6.7	11.5
0206a4	**8**	**2.06**	**14.95**	**10.0**	**6.7**	**12.0**
0206a10	**8**	**1.75**	**12.15**	**9.8**	**5.4**	**13.5**
0205a2	10	2.37	15.28	8.5	5.7	12.3
0129a2	11	1.86	15.64	7.7	5.3	11.2

FEWER COILS PROVIDE A MORE OPEN GEOMETRY



11 coils/period **8 coils/period**

AUXILIARY TFs AND A VERTICAL FIELD WERE INCLUDED IN THE "FINAL" COILOPT RUNS

ID	$2*B_{tf}/\langle B_{phi}\rangle$	I_{mod} (kA)	I_{VF} (kA)
0216a1	-.071	366	-201
0213b2	**-.121**	**374**	**-205**
0216a2	-.212	391	-205
0216a3	-.283	403	-208
0216a4	-.071	366	-90
0216a5	-.212	391	-126
0214a1	-.107	372	0

Relative to the 1 T average B_{phi}:

- **An I_{vf} of 200 kA corresponds to about 0.08 T at the centerline.**
- **A $B_{tf}/\langle B_{phi}\rangle$ of 0.12 corresponds to a 6% auxiliary TF (0.06 T).**
- **$2*B_{tf}$ capability is +/- 0.3 T.**

AUXILIARY TFs AND A VERTICAL FIELD CONTRIBUTED TO REDUCED ERRORS FOR THE REFERENCE COIL SET

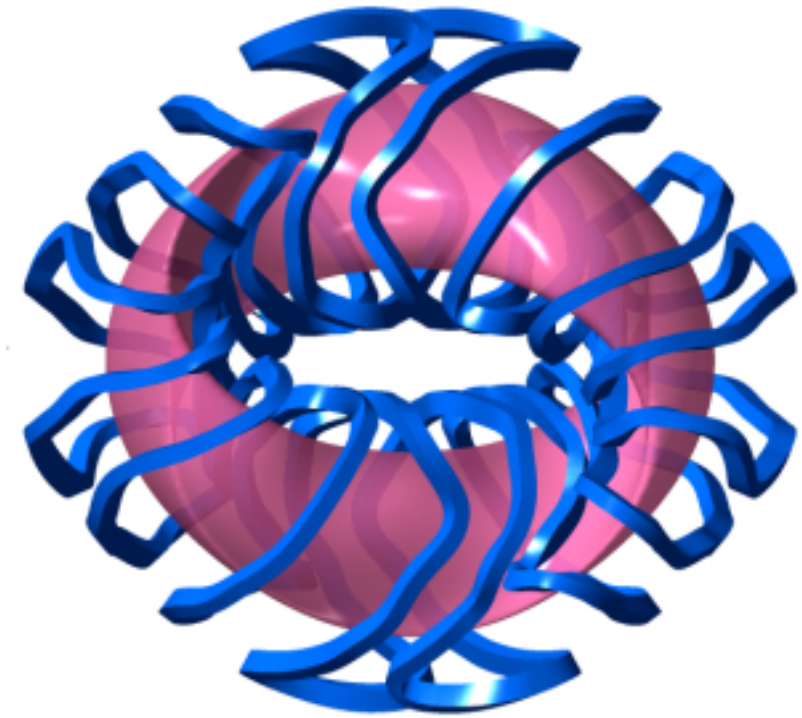
ID	$2*B_{tf}/<B_{phi}>$	I_{mod} (kA)	I_{VF} (kA)	δB_{avg} (%)	δB_{max} (%)
0216a1	-.071	366	-201	1.42	9.52
0213b2	**-.121**	**374**	**-205**	**1.43**	**8.66**
0216a2	**-.212**	**391**	**-205**	**1.38**	**7.03**
0216a3	-.283	403	-208	1.49	7.51
0216a4	-.071	366	-90	1.64	10.22
0216a5	-.212	391	-126	1.44	7.95
0214a1	-.107	372	0	2.03	11.90

lowest error: improvements are possible

THE REFERENCE SELECTION WAS BASED ON ERRORS, $B_{tf} \leq 6\%$, AND GEOMETRY

ID	$2*B_{tf}/\langle B_{phi}\rangle$	I_{mod} (kA)	I_{VF} (kA)	δB_{avg} (%)	δB_{max} (%)	$\Delta_{cc,min}$ (cm)	ρ_{min} (cm)	$\Delta_{cp,min}$ (cm)
0216a1	-.071	366	-201	1.42	9.52	11.5	7.3	13.2
0213b2	**-.121**	**374**	**-205**	**1.43**	**8.66**	**11.4**	**7.2**	**13.4**
0216a2	-.212	391	-205	1.38	7.03	11.6	7.7	13.3
0216a3	-.283	403	-208	1.49	7.51	11.6	6.9	13.4
0216a4	-.071	366	-90	1.64	10.22	10.4	6.6	12.5
0216a5	-.212	391	-126	1.44	7.95	10.7	7.4	13.5
0214a1	-.107	372	0	2.03	11.90	8.6	6.6	12.9

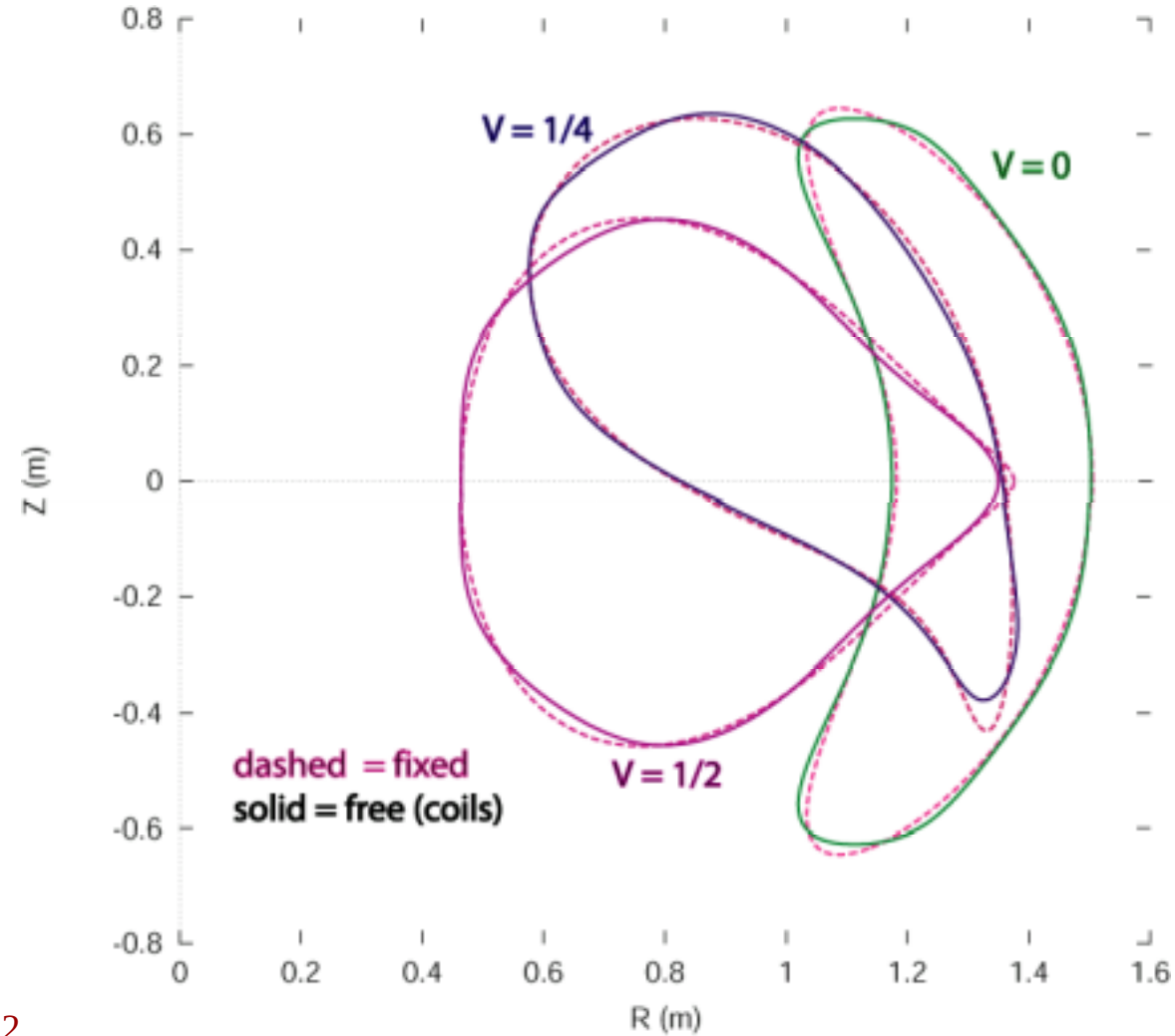
QPS REFERENCE MODULAR COILS (0213b2)



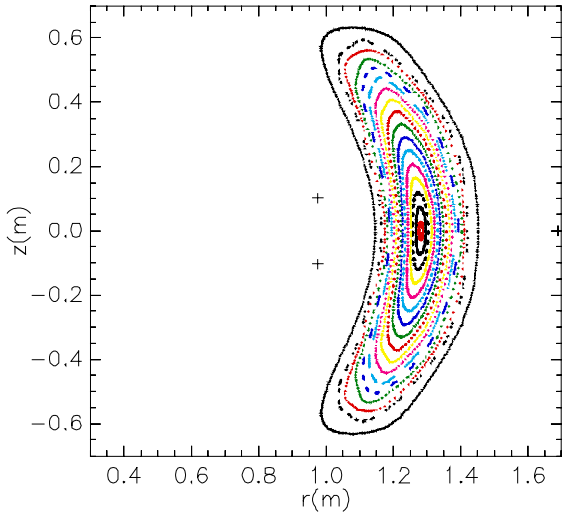
PHYSICS USING FIELDS FROM COILS IS AN ESSENTIAL COMPONENT OF COIL PERFORMANCE

- **Free-boundary VMEC reconstruction/physics (reference):**
  - **compare fixed/free boundary plasma shapes;**
  - **evaluate physics optimization targets;**
    - » **transport, stability properties (Spong)**
  - **evaluate non-targeted physics figures-of-merit;**
    - » **kink, vertical stability (Ware).**
- **Ability to support a range of configurations (Ware, Spong, PVR document).**
- **Flux surface quality:**
  - **field line following for vacuum;**
  - **PIES evaluations, fixed, then free;**
    - » **effort has just been started with only fixed boundary results.**

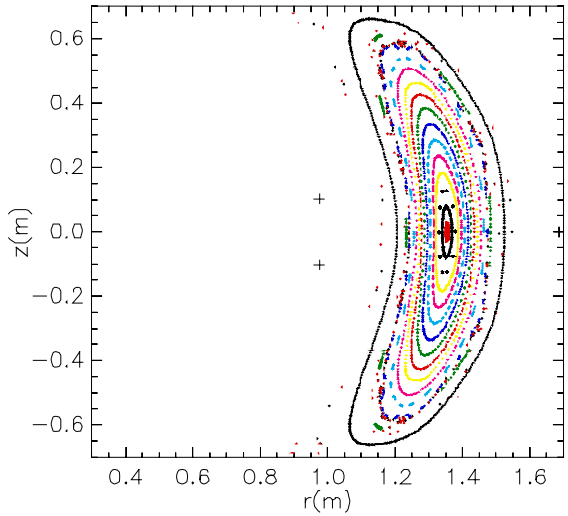
FREE-BOUNDARY EQUILIBRIUM CONFORMS TO FIXED BOUNDARY TARGET



VACUUM SURFACE FROM COIL SET ARE GOOD AND ROBUST TO VF VARIATIONS



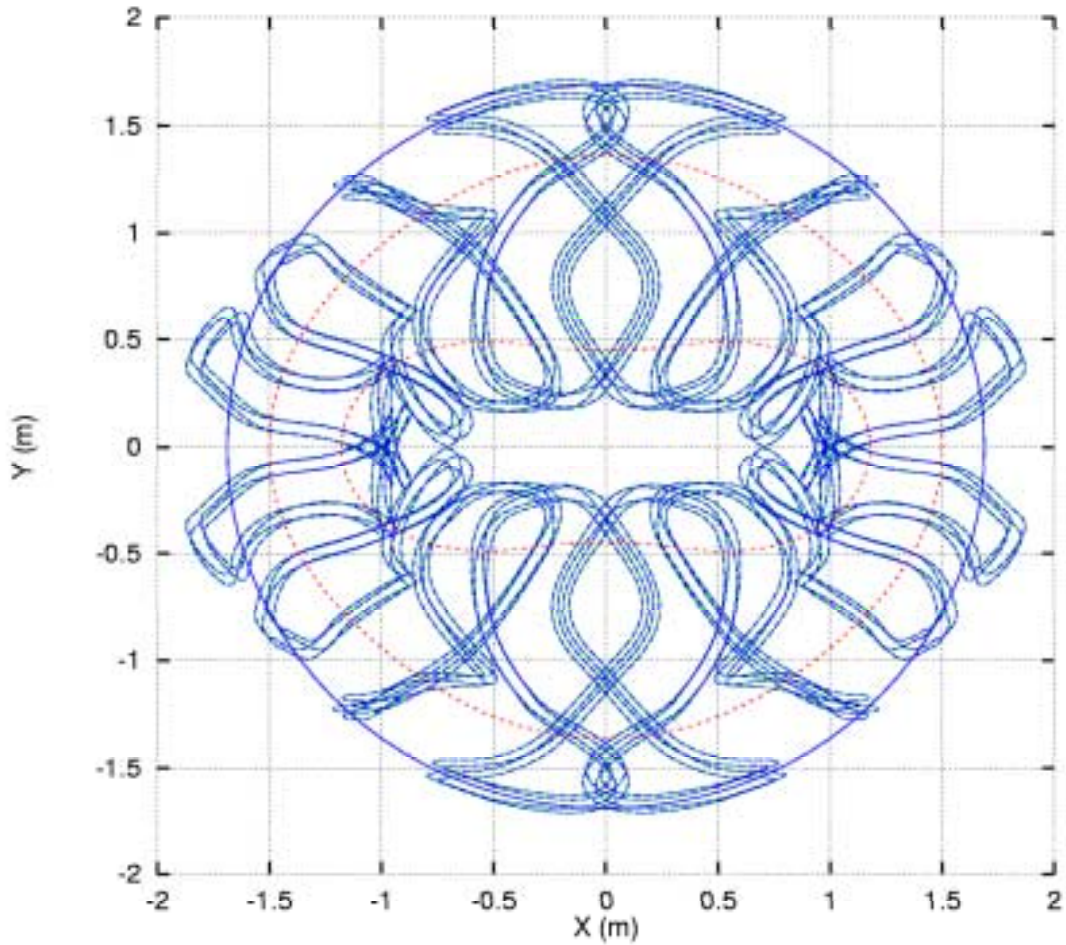
I_{vf} = 204 kA



I_{vf} = 100 kA

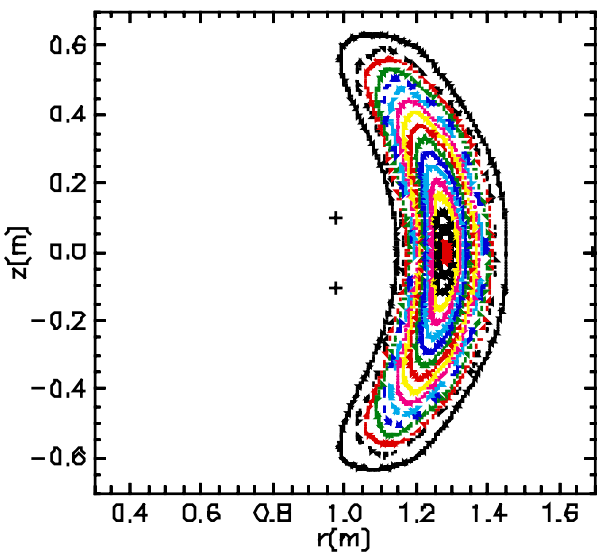
Variations in coil currents for similar configurations have shown good surfaces for a variety of combinations with useful variations in iota. This analysis is planned for the coming year.

A FOUR-FILAMENT MODEL WAS CONSTRUCTED FROM THE COILOPT SINGLE FILAMENT

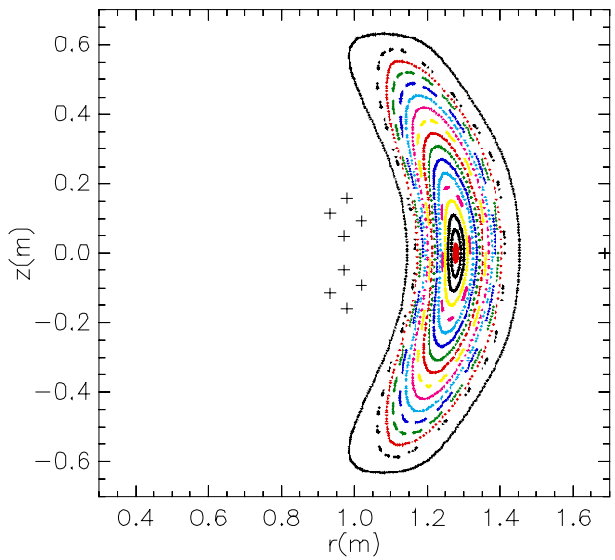


FINITE (FOUR FILAMENT) COILS PROVIDE ESSENTIALLY THE SAME VACUUM SURFACES (AVAC) (V = 0)

filamentary coil



finite coil



PIES ANALYSIS IS UNDERWAY

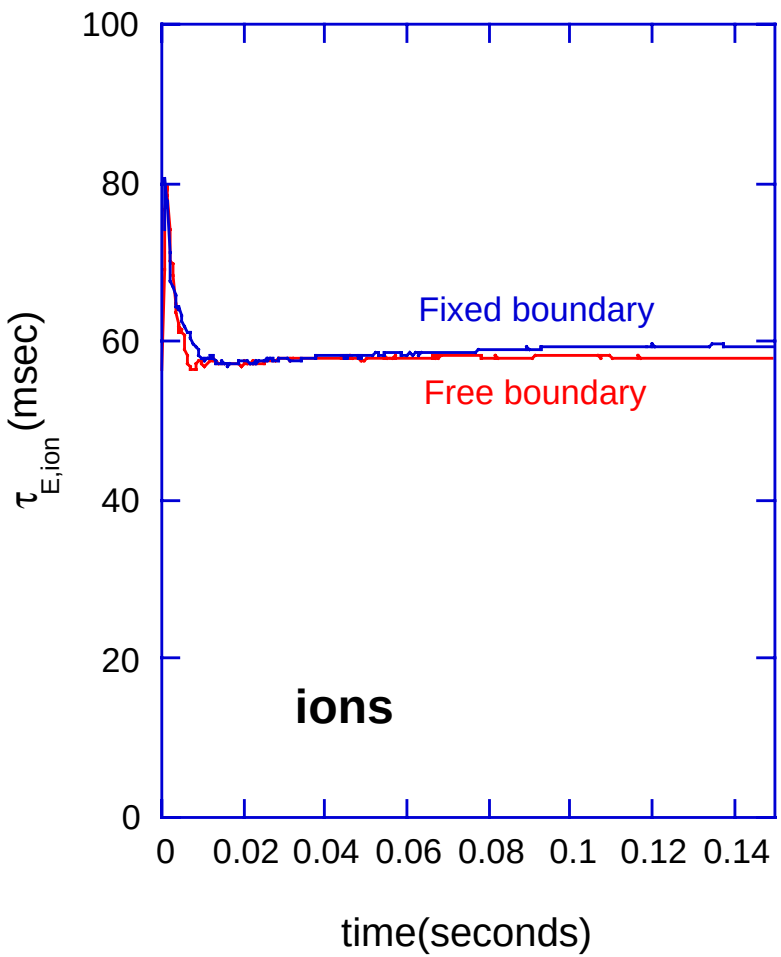
- **Modifications to PIES (larger number of modes, better treatment of the vacuum region) are needed for QPS analysis.**
- **Experience with similar configurations suggest that QPS configurations are relatively robust to flux surface deterioration in free-boundary PIES calculations.**
- **If islands are a problem, the “healing” (PIES + COILOPT) techniques developed for NCSX should be adequate.**

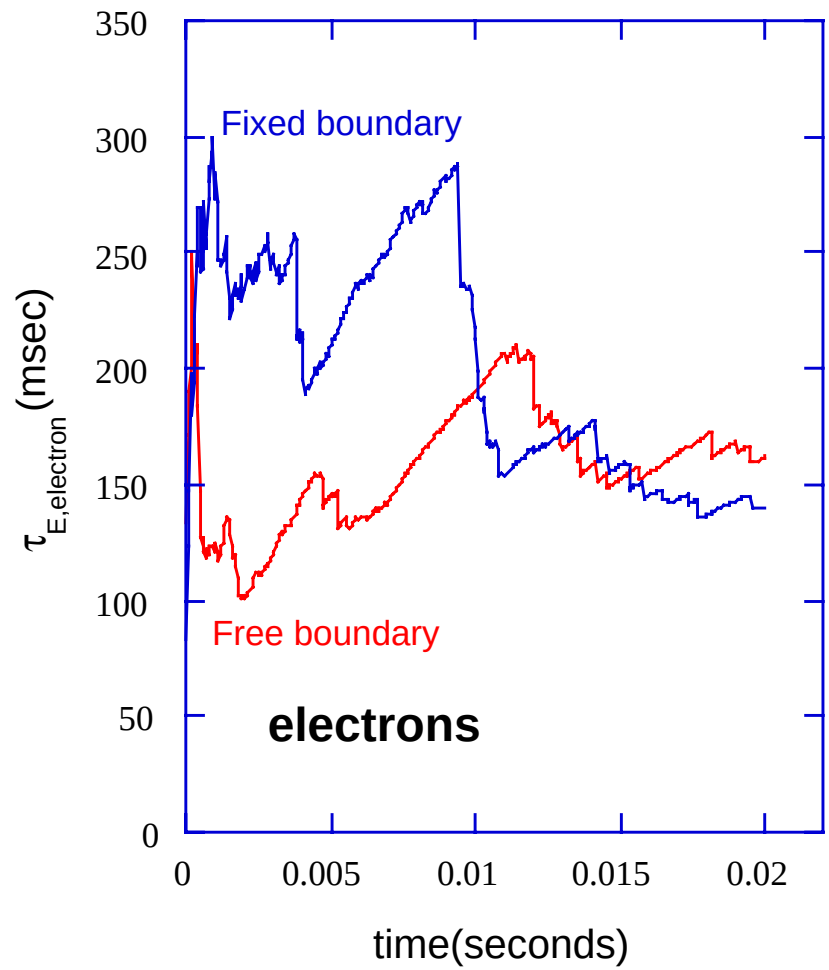
CHI-SQUARE VALUES NORMALIZED TO THE FIXED-BOUNDARY PLASMA INDICATE DESIRED PHYSICS IN THE FREE-BOUNDARY PLASMA

	χ^2 (Balloon)	χ^2 (DKES)	χ^2 (Bootstrap)
Fixed Boundary	**1.0**	**1.0**	**1.0**
Free Boundary	**1.9**	**0.97**	**0.51**

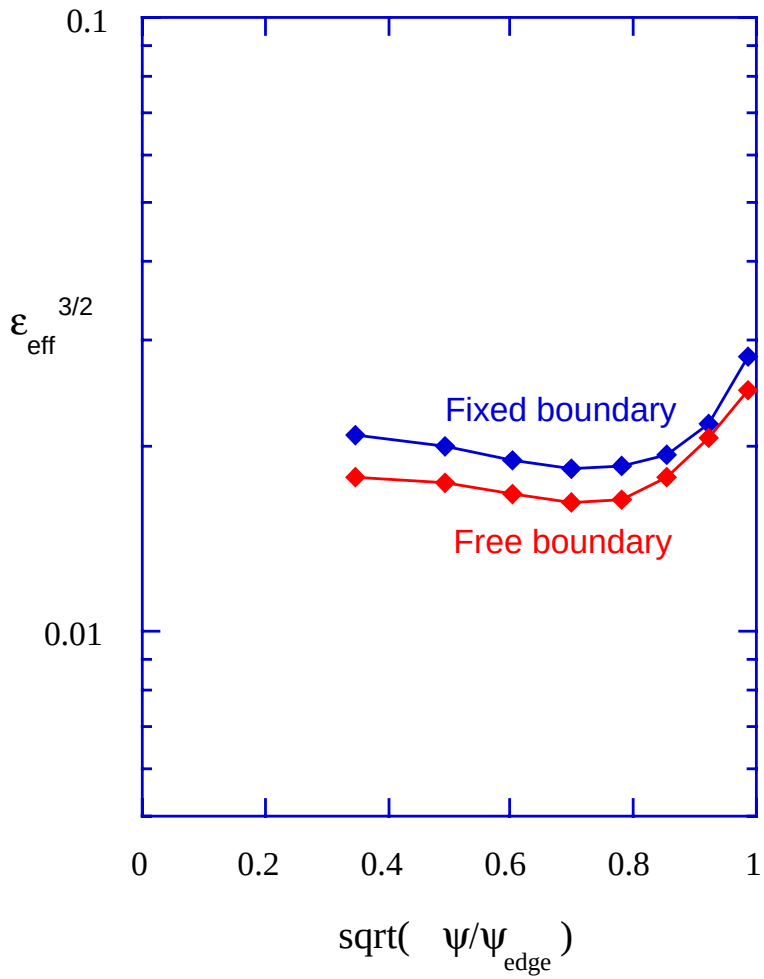
Both equilibria used a nominal, unoptimized pressure profile. Ballooning modes for both configurations were stabilized with small profile changes (Ware).

MONTE CARLO TRANSPORT ESTIMATES ARE NEARLY THE SAME FOR THE FIXED/FREE BOUNDARY EQUILIBRIA





NEO CODE ESTIMATES ALSO SUGGEST COMPARABLE FIXED/FREE CONFINEMENT FOR ALL FLUX SURFACES



THE POLOIDAL COIL SYSTEM MUST MEET THREE NEEDS

- **Supplement the auxiliary TF and modular coils to reproduce the reference configuration.**
- **Provide sufficient flexibility to study physics issues:**
  - **vary iota, shear, shape.**
- **Induce OH currents.**

THE COIL SYSTEM MUST PROVIDE SUFFICIENT FLEXIBILITY TO ADDRESS PHYSICS ISSUES

- **OH current is a principal tool for investigating physics:**
  - **low collisionality $1/\nu$ transport is decreased with I_{OH}.**
- **Reduced shear (line bending) of OH profiles reduces ballooning stability.**
- **Unbalancing of modular currents produced significant variations in vacuum iota for past QPS configurations, this analysis has just been started for the gb4 coil set.**
- **Vertical field variations are possible but did not make significant differences in physics (see PVR document).**

Further studies (with N. Pomphrey, R. Hatcher) are planned to explore device capability.

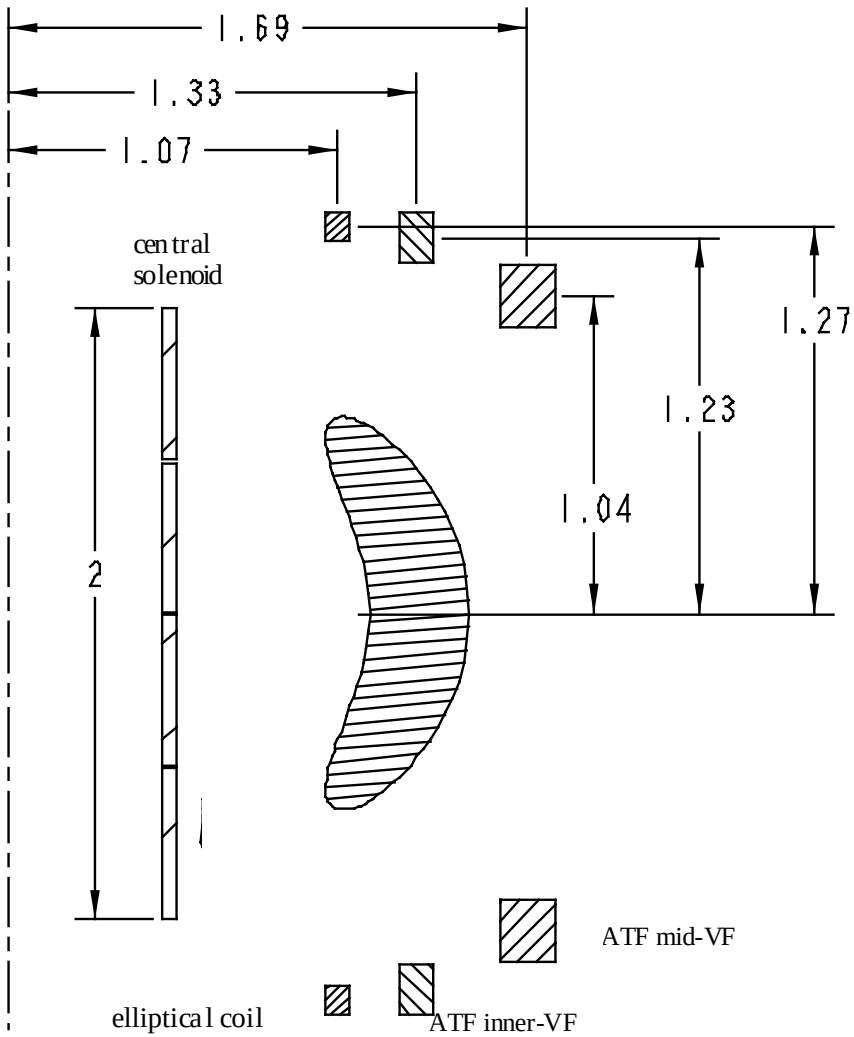
OH FLUX REQUIREMENTS ARE DRIVEN BY *LI* AND *Vt*

- **INDUCTANCE**
  - **internal: with uniform current, l_i = 0.32**
  - **external: (Hirshman and Neilson) l_{ext} = 0.72**
  - **total: 1.03 μH => (L ≈ 1-1.5 μH)* 50-75 kA => *LI* ≈ 0.1 Vs.**
- **RESISTANCE**
  - **R_p ≈ 1- 10 μΩ => 0.1-1.0 V for 100 kA and *t* = 0.1 to 1.0 s for 0.1 Vs.**

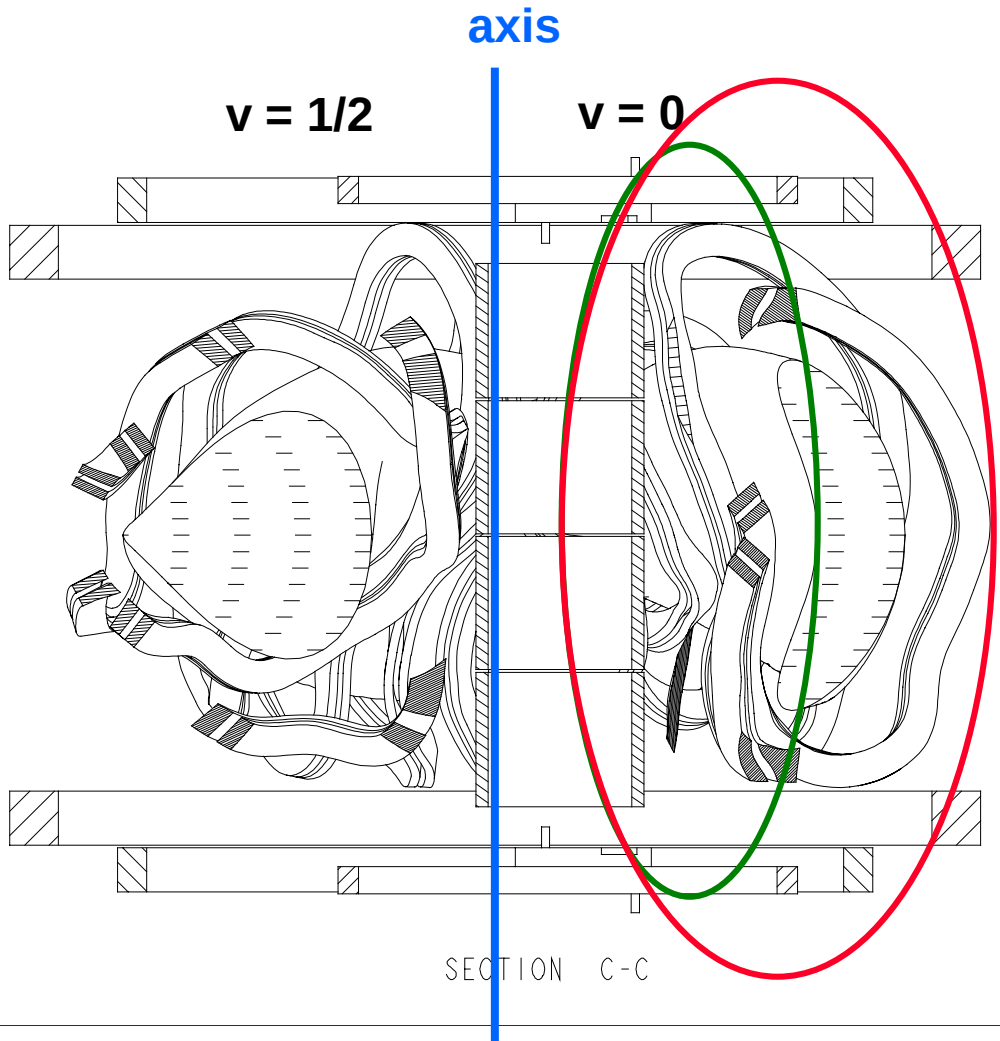
A flux capability of 0.2 Vs is adequate.

- **A 2-m high central solenoid with a race-track cross-section and a two-way flux swing of 0.3 Vs is specified for the PVR.**

PF SET ANALYSES ARE BASED ON A FIVE-COIL SET (distances in meters)



THE FULL PF SET IS NEEDED TO CANCEL THE FLUX FROM THE SOLENOID THAT DOES NOT LINK THE PLASMA



- **Errors from a similar 4-m solenoid are ≈ 0.5%.**
- **Small currents, ≤ 10 kA (5% of the nominal equilibrium currents) in the inner-VF and mid-VF coils reduced the errors to ≈ 0.05%.**
- **This suggests that there is sufficient flexibility in the PF coil set to keep OH error at acceptable levels.**

TANK RESISTANCE AND MUTUALS TO PF COILS DICTATE CHANGING ALUMINUM CYLINDER TO STAINLESS

μ Henries	PF 1/2	PF5	Tank	Plasma
solenoid	0.41	0.09	0.045	0.085
PF5 ATF mid	0.09	14.34	4.14	1.16
tank	0.085	4.14	3.18	0.68
Plasma	0.17	1.16	0.68	1.44

- **ATF mid-VF coil is strongly coupled to the tank.**
- **Aluminum L/R ≈ 0.75 s, > experimental times.**
- **Stainless L/R ≈ 0.01 s.**
- **Working decision: replace existing Al-tank cylinder with stainless component (Nelson).**

COIL ANALYSIS PLANS

- **Optimize modulars with multifilament representation.**
- **Continue PIES analysis with “healing” (as needed).**
- **Develop “circuit” model for shaping and OH. Details are under development, but needs to account for current evolution in the equilibrium and interactions with structure.**
- **Error field analysis from leads and structures.**

SUMMARY

- **Coil set (0213b2) reproduces desired physics and meets engineering constraints.**
- **Preliminary analysis indicates that the PVR PF coil set has the needed equilibrium flexibility and volt-seconds.**
- **Improvements to COILOPT and refined PF analysis will support a successful conceptual design.**