Coil Design to Achieve Physics Goals of NCSX

Presented at NCSX PVR by

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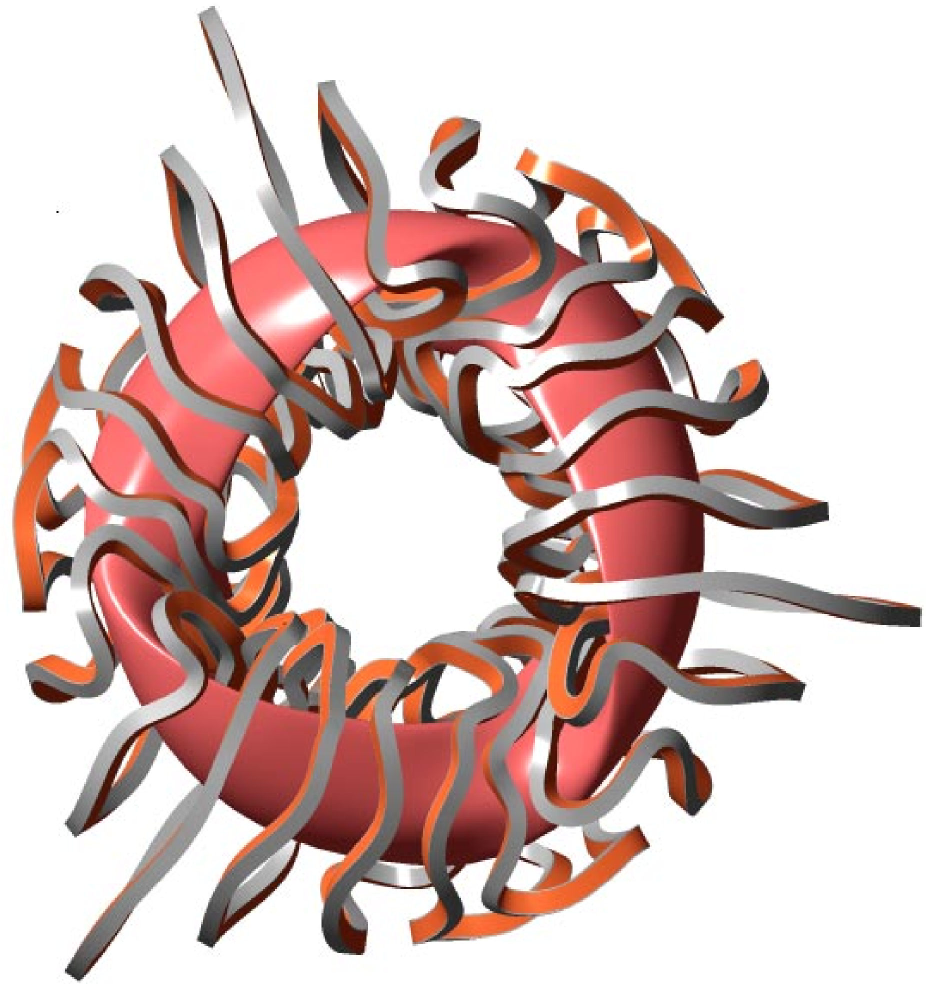
Status of NCSX Modular Coil Design

- Methods have been developed to design practical modular coils that achieve the desired physics properties of NCSX while satisfying realistic engineering criteria necessary for their manufacture, con-struction, and accessibility.
- Modular configuration M1017
  - selected for pre-conceptual design and engineering studies

M1017 Modular Coils

$N_p = 3$

$N_{coils} = 21$



Modular vs Saddle Coils

- **At previous PAC, configurations based on saddle coils were thought to be likely candidates for reference coil configuration**
- **Since then, it was found that modular coils reproduced the desired physics performance of NSCX better than the saddle coils**
- **Decision was made to concentrate efforts on producing best possible modulars for PVR**

NCSX Coil Design Philosophy

- Reverse engineering (J.Nuehrenberg 1980's)
  - Separate physics optimization from coil design
  - Efficient exploration of large parameter space
  - Procedure confirmed (for large A) in HSX* (pg 22)

- Method generalized for low *A*, to include coil design targets in the physics optimization
  - NESCOIL current sheet targets added to other (physics) stellarator optimization targets

NCSX Coil Design Criteria

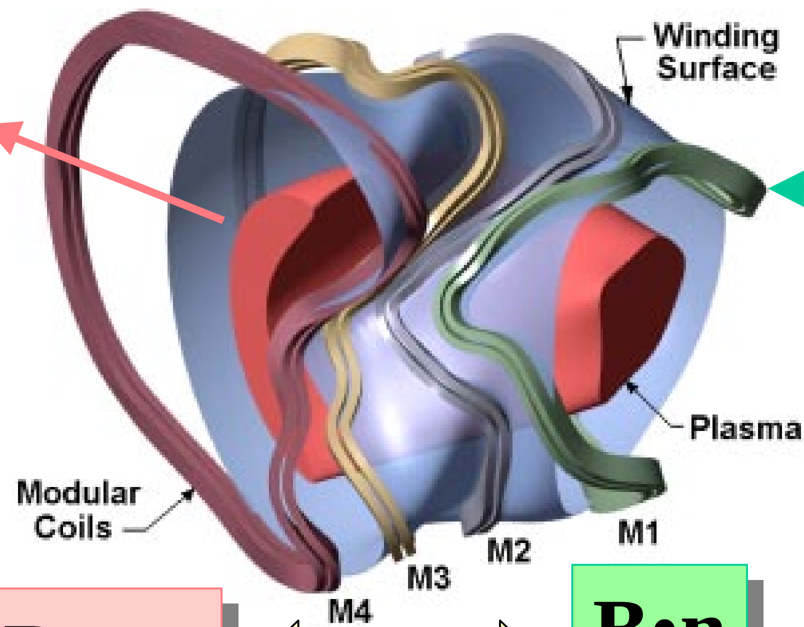
- Realize NCSX Physics Goals
  - Reconstruct reference (S3) design parameters
  - Demonstrate flexibility for startup, intermediate states
- Minimize Coil Current Density
  - Improve accessibility, reduce stresses
  - Achieved by maximizing coil-to-coil spacing

Design Criteria (cont'd)

- Minimize N_{coil} / N_{period}
  - Reduces number of coils (cost) and independent coil types (power supplies)
  - Potential for improved accessibility for NBI, diagnostics
- Maximize (bend) radius of curvature
  - Engineering limits ρ_{min} > 10 cm for NCSX dimensional parameters

Coil Design Process

n
Plasma Surface Normal ($B_{total} \cdot n = 0$)



J_{Coils}
- Filaments on winding surface

J_{Plasma}
From VMEC

B•n
From Plasma (BNORM)

$\Sigma B \bullet n = 0$

B•n
From Coils

L
Inductance Matrix
Biot-Savart

Vary "L" until L• J_{Coils} = B•n(Coils) ≈ -B•n(Plasma)

Coil Design Is A Multi-Step Process

- **Step 1: ΣB_{norm} = 0 on optimized plasma boundary**
  - B^p_{norm} from internal plasma currents
    - BNORM code (Virtual Casing Principle, P. Merkel code)
  - $B^c_{norm} = B \bullet n_S$ from external coils
    - COILOPT code (D. Strickler, L. Berry)
      - varies shape of filamentary coils (and currents)
      - minimize B_{norm} mismatch
      - Matches engineering constraints

Methodology (cont'd)

- Step 2: Free-boundary VMEC Reconstruction
  - Compare fixed/free boundary plasma shapes
    - Approximate criterion
  - Detailed evaluation of optimized physics targets
    - Transport (quasi-axisymmetry), stability (kink, etc.)
  - Evaluation of non-targeted physics figures-of-merit
    - Energetic particle confinement, vertical stability
- Step 3: Free-boundary PIES Evaluation
  - Maximize volume of good surfaces
  - For reference state (full current, β), determine modifications to modulars to "trim-out" resonant B_{normal} components

Development of COILOPT Crucial To Success of this Process

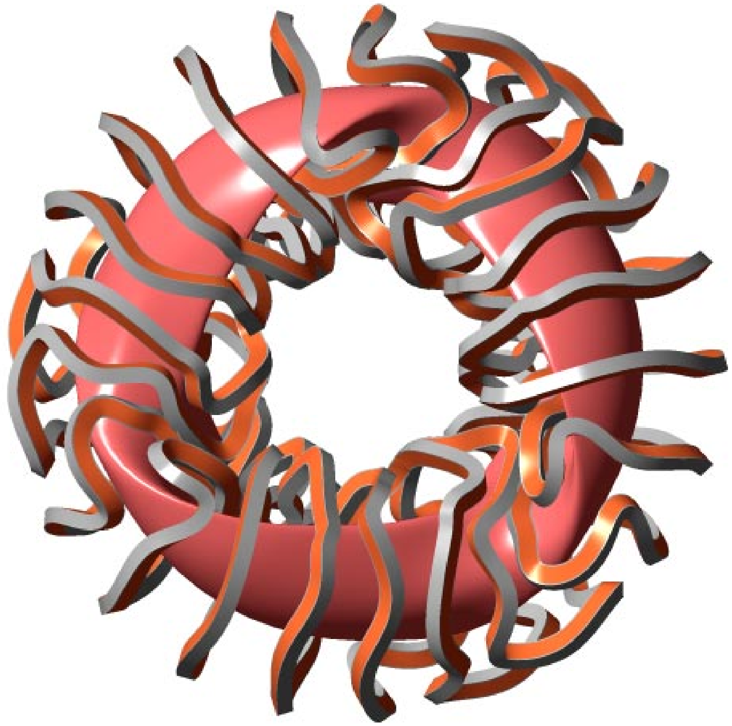
- COILOPT – a flexible coil optimization tool
  - Varies shape (winding law, inductance) of coil filaments within a winding surface
  - Varies winding surface
    - takes advantage of “underdetermined” nature of matching problem: high harmonics of current potential decay rapidly (do not effect plasma shape) but can impact engineering of coils
  - Minimizes B_{normal} mismatch and various engineering criteria, for fixed N_{coil} and predetermined coil symmetry planes (v=0,1/2)

Engineering Properties of M1017 Modulars

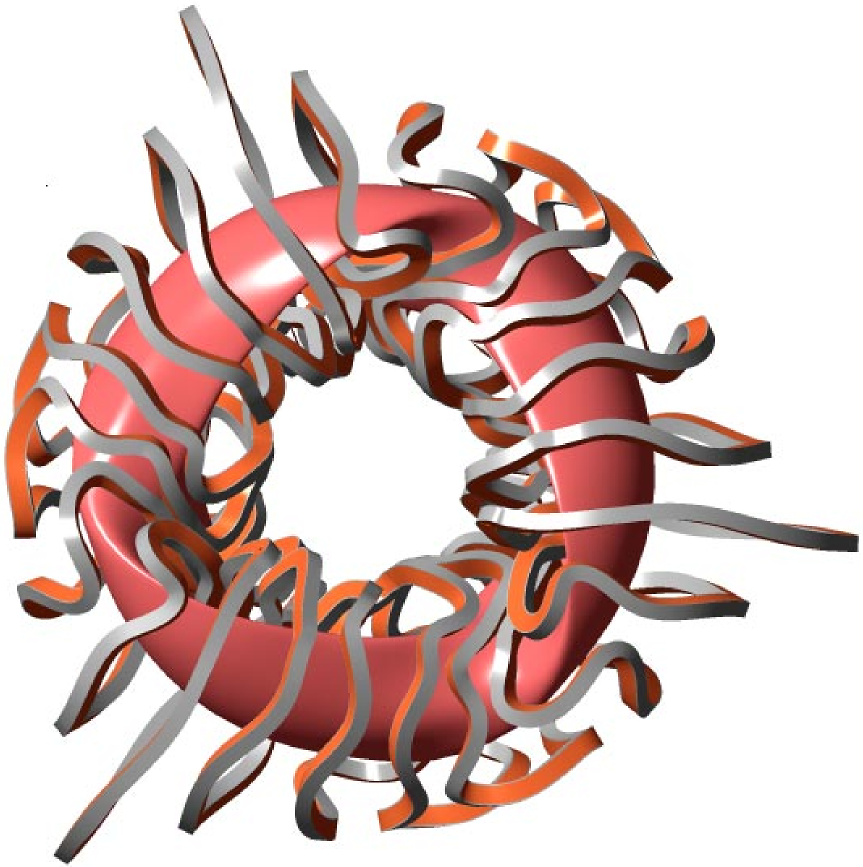
- **M1017 coils evolved from M0907 to satisfy engineering constraints**
- **$N_{coil} / N_{period} = 7$, with a coil at the toroidal symmetry plane v = 0**

ID	δB_{avg}(%)	δB_{max}(%)	$\Delta_{cc,min}$(cm)	ρ_{min}(cm)	$\Delta_{cp,min}$(cm)
M0907	0.57	2.55	13.4	11	23.3
M1017	0.61	2.61	14.8	12.3	23.3

M0907 vs M1017 Modulars

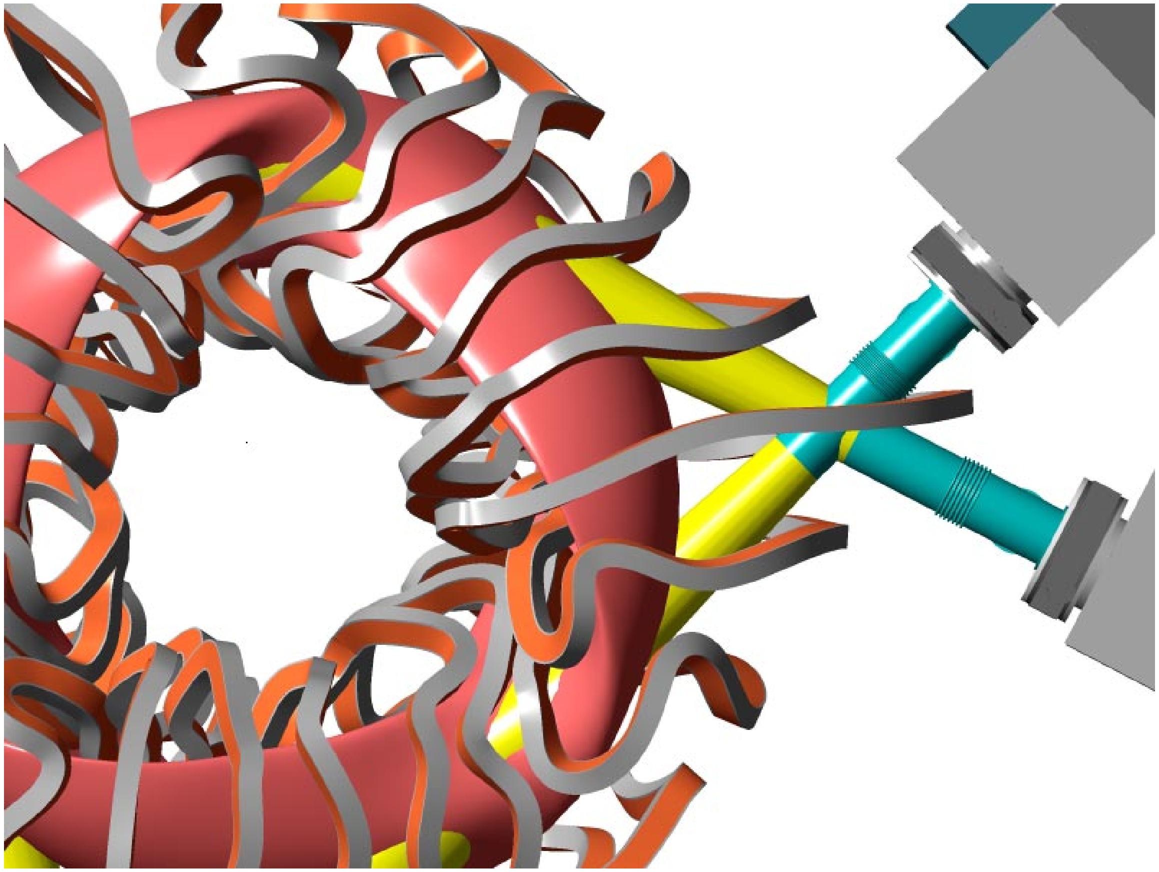


M0907

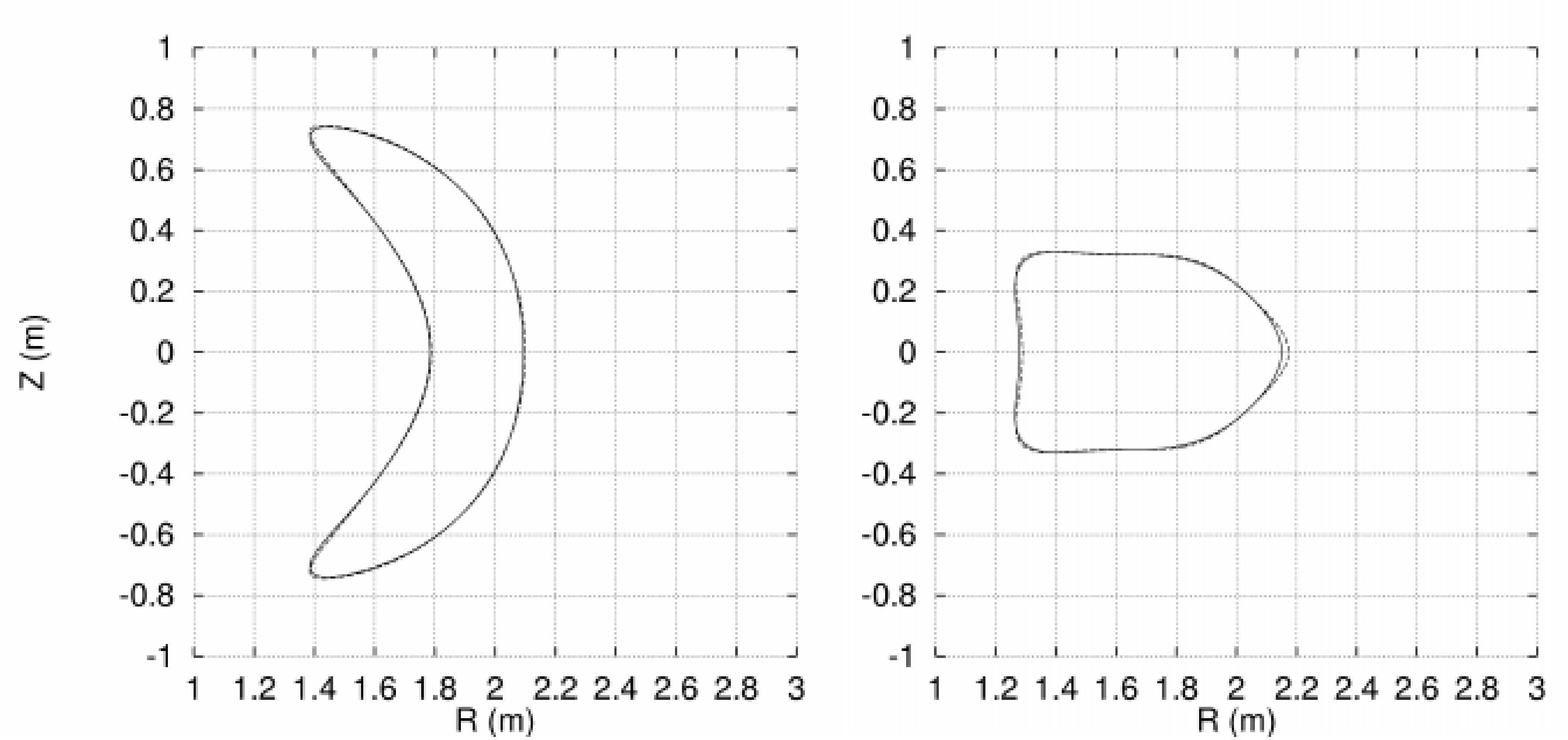


M1017

M1017 Solves NBI Access Problem With Minimal Stray Fields



M1017 Generates High Quality Boundary Reconstruction



Second Optimization of M1017 Coils

- "Exact" boundary agreement is sufficient, but not necessary, to preserve physics
- Improved physics performance obtained by free-boundary optimization varying modular coil currents
  - 4 independent coil types (power supplies)

Vary Coil Currents (2^{nd} Optimization)

	Reference plasma (LI383)	M1017	M1017 (M8)
		(uniform currents)	(variable modular currents)
A	4.36	4.36	4.17
β (%)	4.19	4.15	4.09
R (m)	1.734	1.728	1.726
<a> (m)	0.397	0.396	0.414
ι(0)	0.394	0.406	0.429
ι(a)	0.655	0.651	0.648
λ, Kink (x10^4)	Stable	0.23	Stable
λ, Ballooning, ζ=60	0.91-0.96	0.91-0.96	Stable
$\varepsilon_{eff}^{3/2}$ (x10^4)			
S=0.5	5.6	6.4	7.1
S=0.8	32	30	39
f_{NB} (%), 40KeV NBI, 2T, H	14.4	19.4	15.4

Plans to Improve Modular Coils

- **Continue development of less expensive coils with improved access that are easier to fabricate**
  - **Reduce number coils per period**
  - **Reduce maximum J (increase coil-coil spacing)**
  - **Increase radii of curvature where it is tight**
  - **Fit smoother shell to coils**
    - **Present shell design based on coil winding surface is difficult to engineer**
- **Continue to optimize modulars** *together* **with TF/PF coils to improve flexibility and physics preservation**

Improving Modulars (cont'd)

- **Perform analysis of finite thickness coils**
- **Merge Physics Optimization (VMEC, Free-boundary) with COILOPT coil description**
  - **Use current filaments as independent variables to directly optimize physics**
  - **Reverse-engineered coils provide a good "starting point" for this procedure**

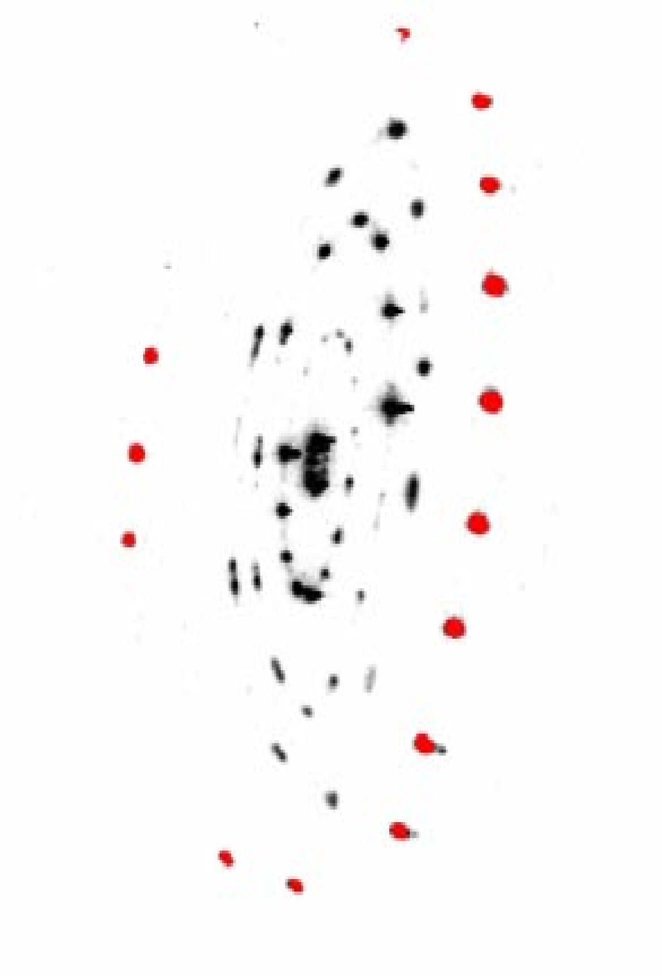
Evolution of Modular Coil Sets

Engineering Property		Original M0907 no NBI access	M1017 NBI access	Remove coil at v=0 plane	Variable I_{mod} added co-TF	Reduce N_{coils}
N_{coils} / Field Period		7	7	7	**7**	6
Symmetry coil, v=0		Y	Y	N	Y	Y
Symmetry coil, v=1/2		N	N	Y	N	Y
NBI access		N	Y	Y	Y	Y
Avg. Field Error	%	0.57	0.61	0.63	0.48	0.59
Max. Field Error	%	2.55	2.61	3.02	1.95	3.06
Min. Coil-Coil Separation	cm	13.4	14.8	15.5	15.6	16.4
Min. Plasma-Coil Separation	cm	23.3	23.3	21.5	21.2	20.9
Min. Radius of Curvature	cm	11	12.5	10.3	9.4	9.3
TF (+=parallel, -=antiparallel)					+	+
I-mod,max/C-C,min	kA/cm	36.4	33	32.9	28.2	33.8
(measure of current density)						

Summary

- A set of modular coils (M1017) has been designed which is capable of reproducing the physics requirements of NCSX over a wide range of operating parameters.
- Work is underway to further improve this coil set.

HSX Confirmation of Reverse Engineering (at $\beta = 0$)



HSX: electron beam mapping of the magnetic surfaces - image shows 4 nested well formed surfaces - outer red dots are reference LEDs. (Magnetic surfaces – not shown – are accurately mapped – see J. Talmadge, IAEA 2000)