Recent Progress in Configuration Development for Compact Stellarator Reactors

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Overview of Progress Since May

- Made an attempt to understand the impact of coil aspect ratio.

  Today, we'll discuss B_{max} and complexity using NCSX-M50 type coils.

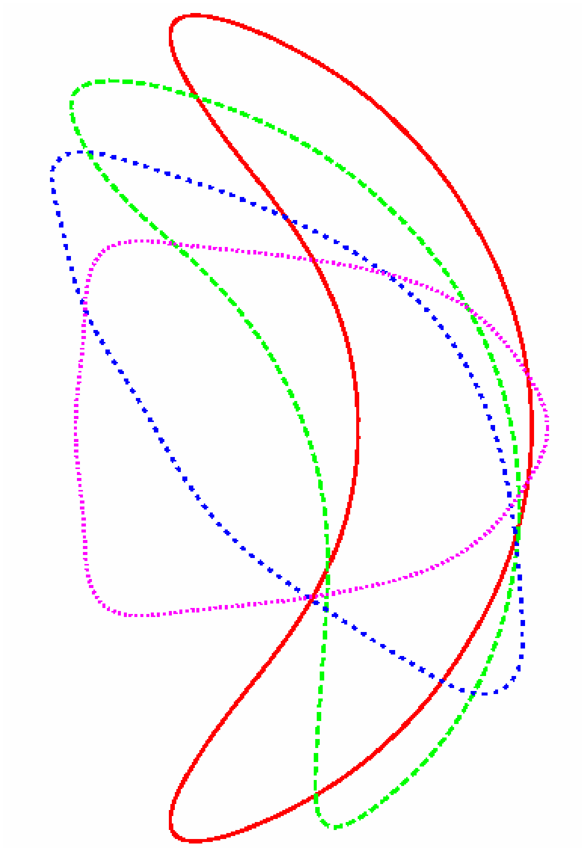
- Made a preliminary inquiry into alternative coil concepts.

  We'll show some possibilities, but ….

- Assembled a package to calculate heat load on first wall due to escaping α particles.

  Today, we'll show results of a limiting case with R=8.3 m, A=4.5, and B=5 T.

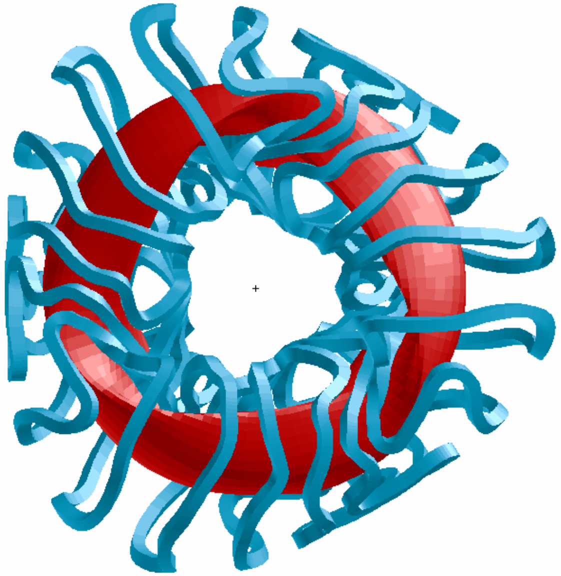
NCSX-like Plasmas and Coils



NCSX-like plasma with A_p=4.5 will ignite at B=6.5 T, R=8.3 m, β=4.1%, producing 2 GW(th) power output, provided that H=3 is used in ISS95 for transport scaling and 10% α loss is assumed.

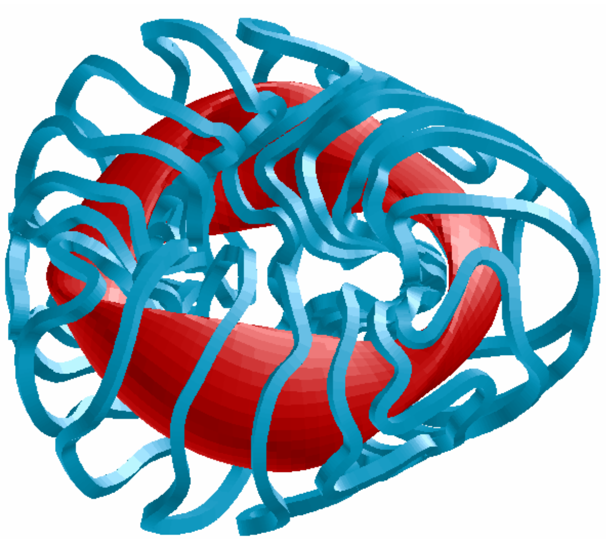
NCSX-like Plasmas and Coils

The coil set previously provided in the working configuration has a coil aspect ratio A_c=6.8, The corresponding minimum coil-plasma separation is 1.2 m. There may not be enough room to accommodate the coil body of a size necessary to reduce the current density and field intensity to acceptable levels.



Δ_{min} (coil-plasma)=1.2 m

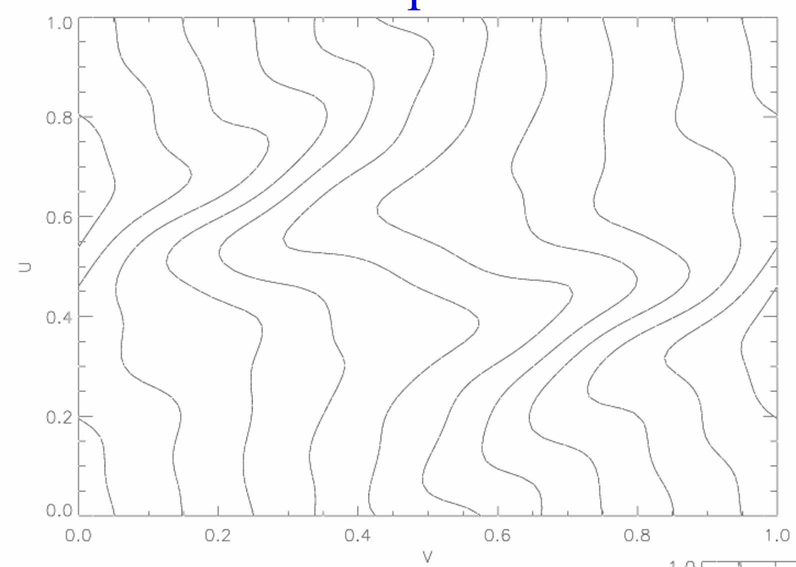
Δ_{min} (coil-coil)=0.88 m



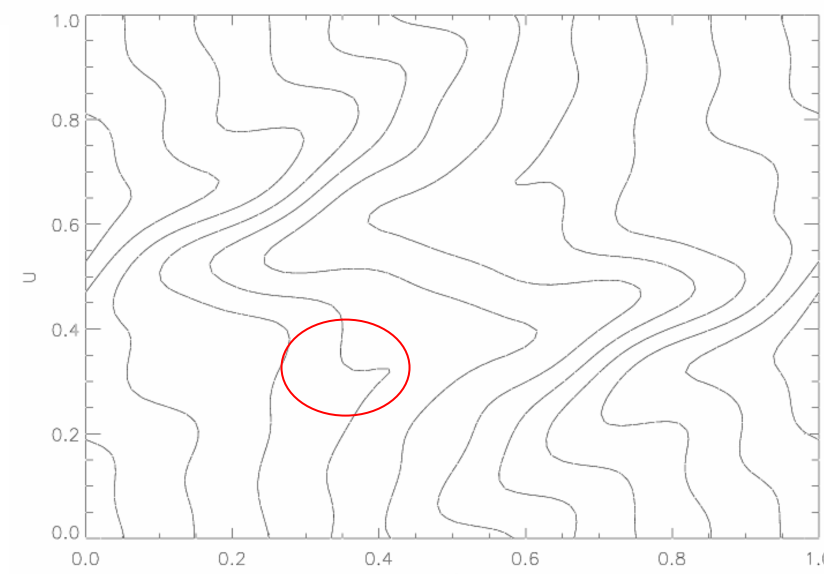
- Since $P_f \propto \beta^2 B^4 R^3 / A^2$ and $I_c \propto RB$, one could reduce B by increasing R. This not only relieves the problem of B_{max} and J_{max} in coils, but also increases Δ_{min}(coil-plasma). Increasing R, however, makes the device less compact and increases cost.

- An alternative is to reduce the coil aspect ratio. But, smaller coil aspect ratio could potentially leads to kinkier coils and also larger B_{max}. We want to find out
  - Is there an "optimum" coil aspect ratio,
  - How B_{max} or R vary with respect to coil aspect ratio.

Examples showing that modular coils may be more complex for smaller coil aspect ratios



← Ac decreased by ~30%



Method of Study

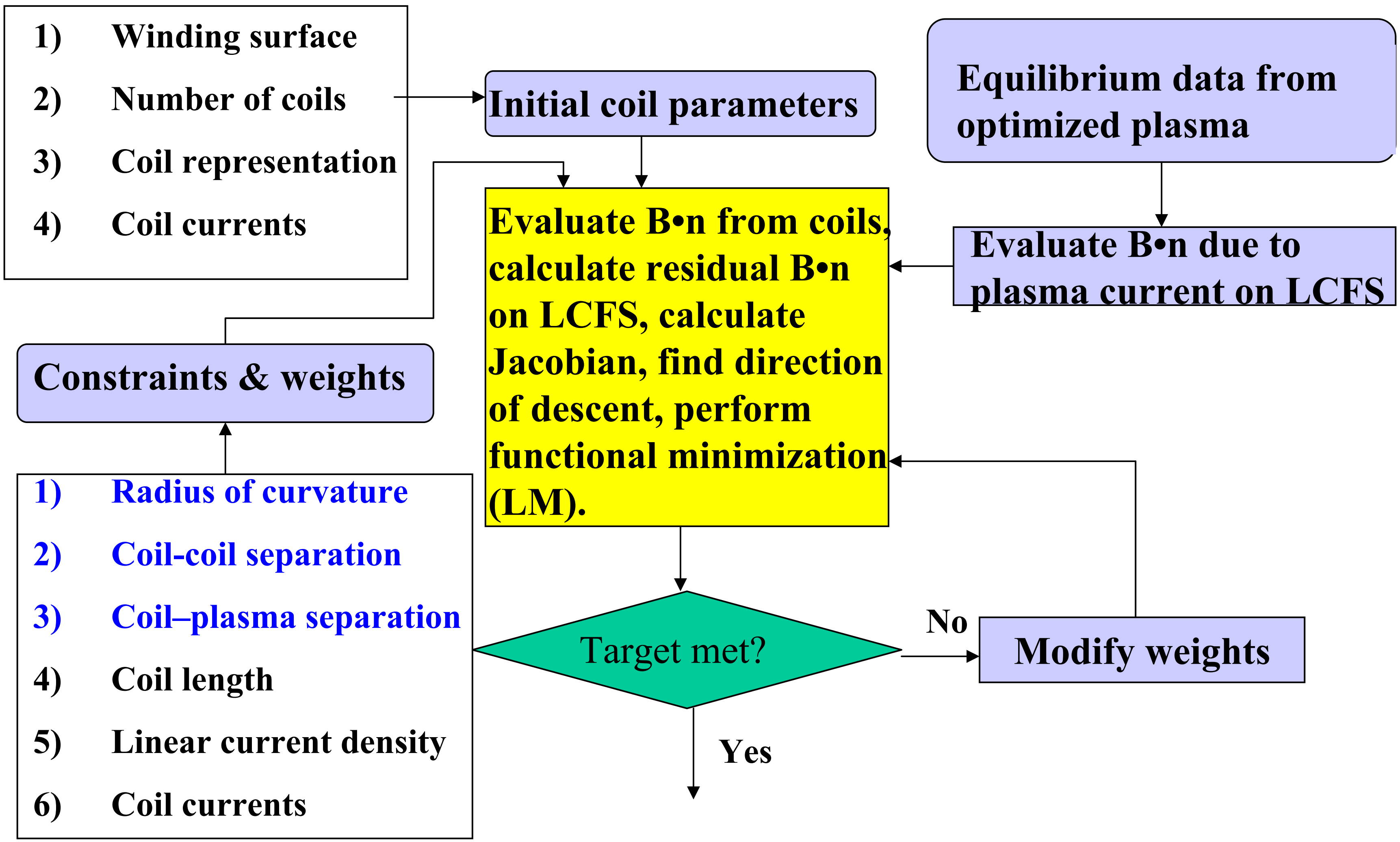
- For coil design, we want, on the last closed magnetic surface,

  B_{norm} (coil) = $-B_{norm}$ (plasma pressure)

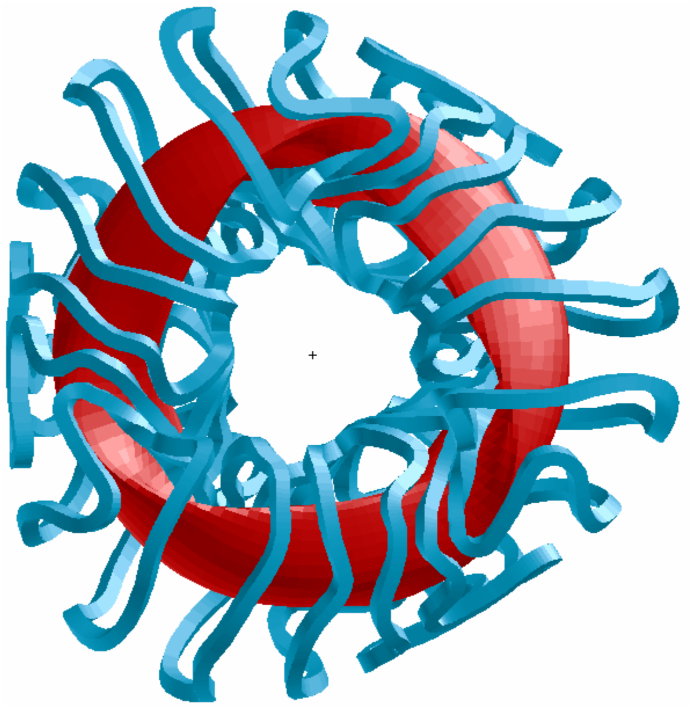
- For discrete coils, we stipulate that, on a computational grid of 64x64:
  - Average $|\{B_{norm}$ (coil)+ B_{norm} (plasma pressure)$\}/ B_{norm}$ (plasma pressure)$| < 0.5\%$
  - Maximum $|\{B_{norm}$ (coil)+ B_{norm} (plasma pressure)$\}/ B_{norm}$ (plasma pressure)$| < 2.0\%$

- We asked for Δ_{min}(coil-plasma)=\{1.2 m, 1.6 m\} for R=8.3 m, subject to an additional constraint Δ_{min}(coil-coil)$\geq$0.85 m.

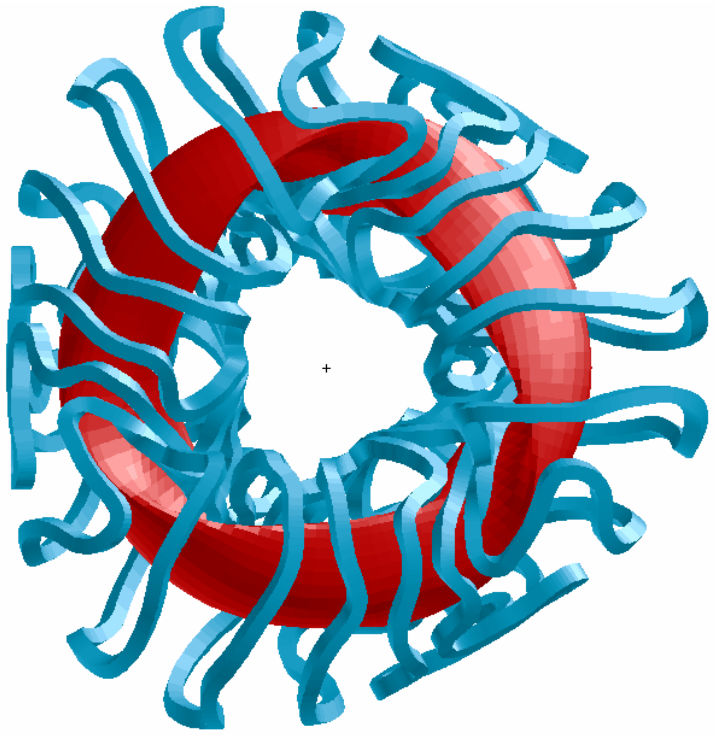
Method of Study



Results and Discussion

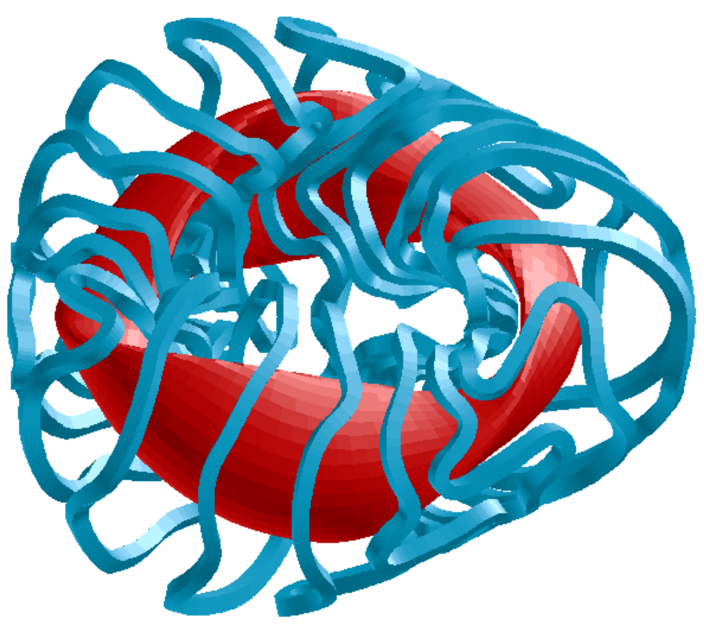


A_c=6.8
Δ_{min}(c-p)=1.2 m
Δ_{min}(c-c)=0.88 m
I_{max}=15.9 MA @6.5T

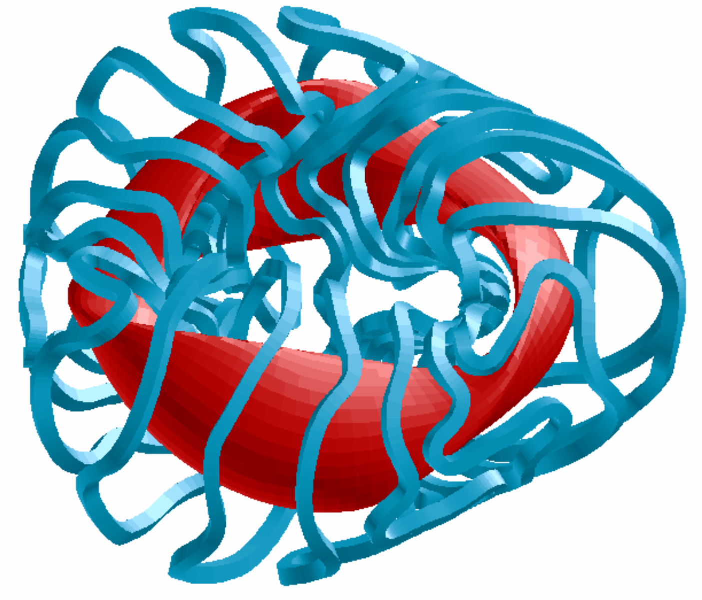


A_c=5.9
Δ_{min}(c-p)=1.4 m
Δ_{min}(c-c)=0.83 m
I_{max}=16.4 MA @6.5T

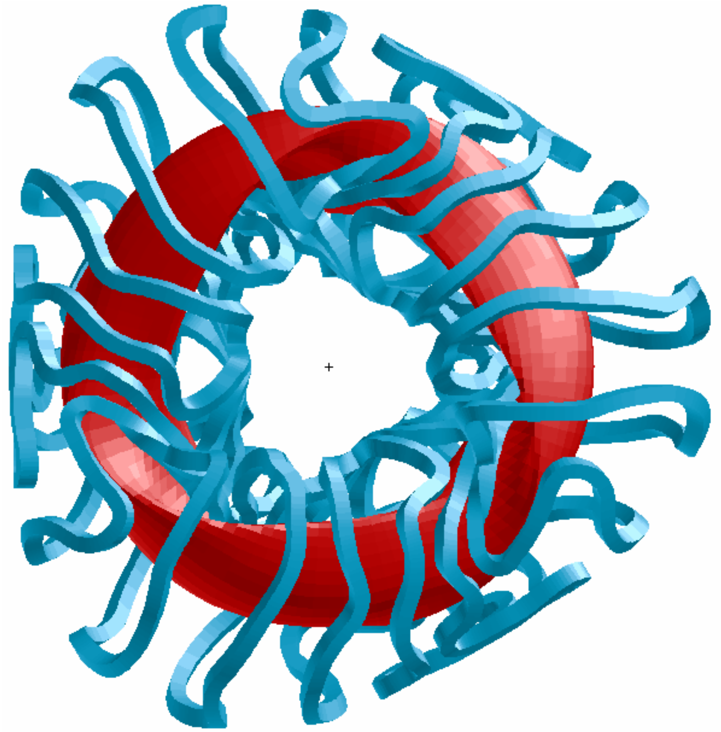
A different view



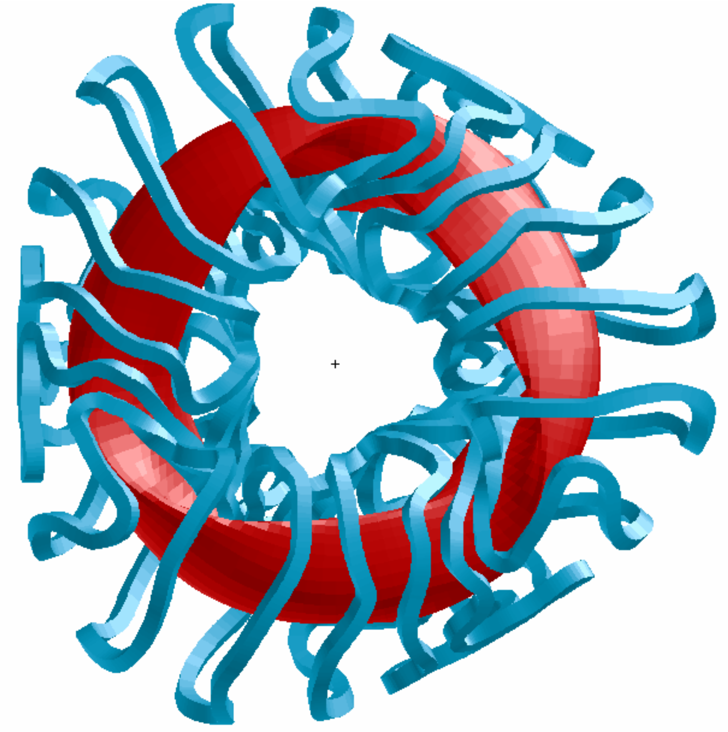
A_c=6.8



A_c=5.9



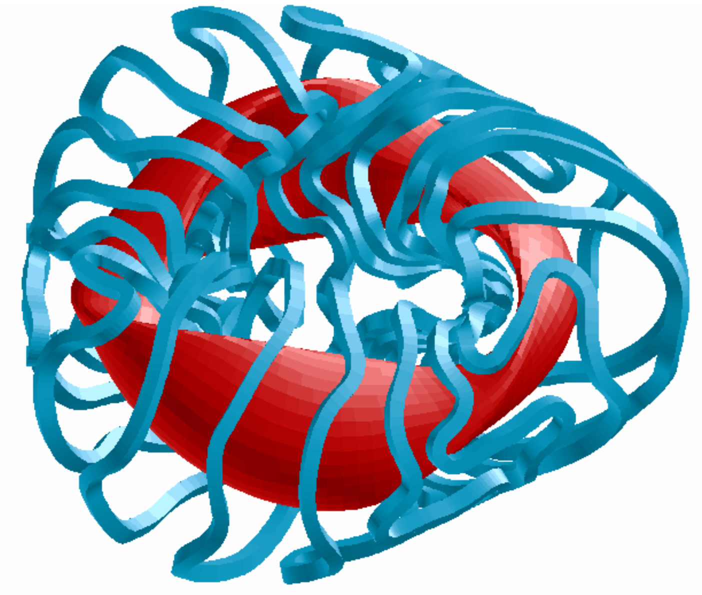
With 1/R



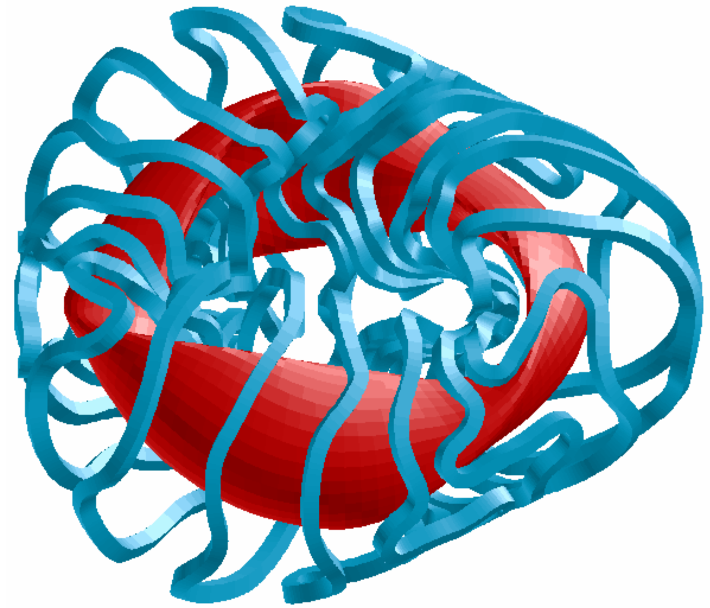
Without 1/R

A_c=5.887
Δ_{min}(c-p)=1.405 m
Δ_{min}(c-c)=0.83 m
I_{max}=16.4 MA @6.5T

A_c=5.926
Δ_{min}(c-p)=1.394 m
Δ_{min}(c-c)=0.83 m
I_{max}=17.6 MA @6.5T

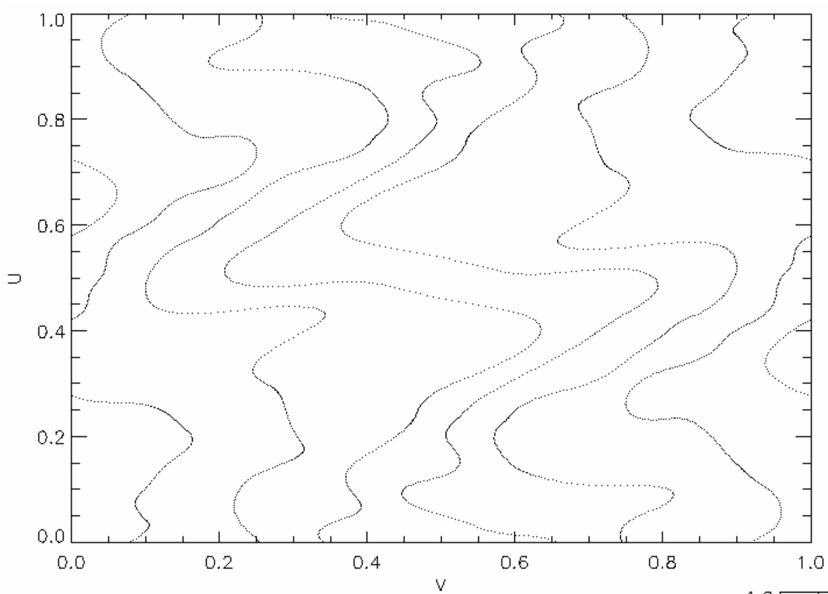


A_c=5.9, with 1/R



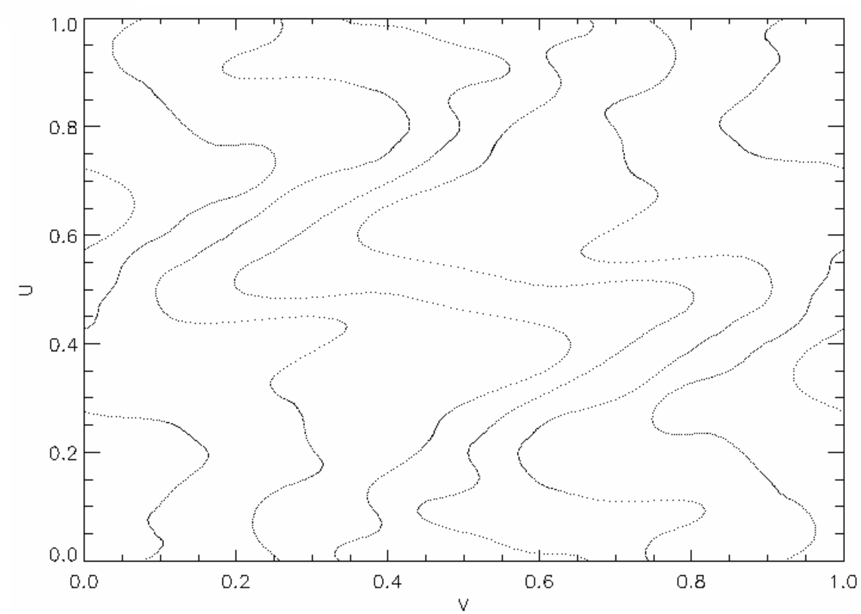
A_c=5.9, without 1/R

Modular coils viewed on the “u-v” plane of the current carrying surface.

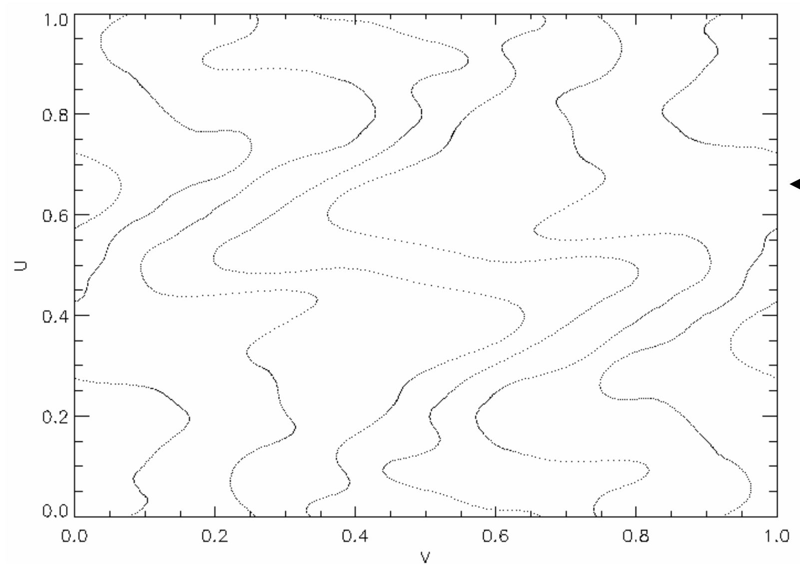


A_c=6.8

A_c=5.9

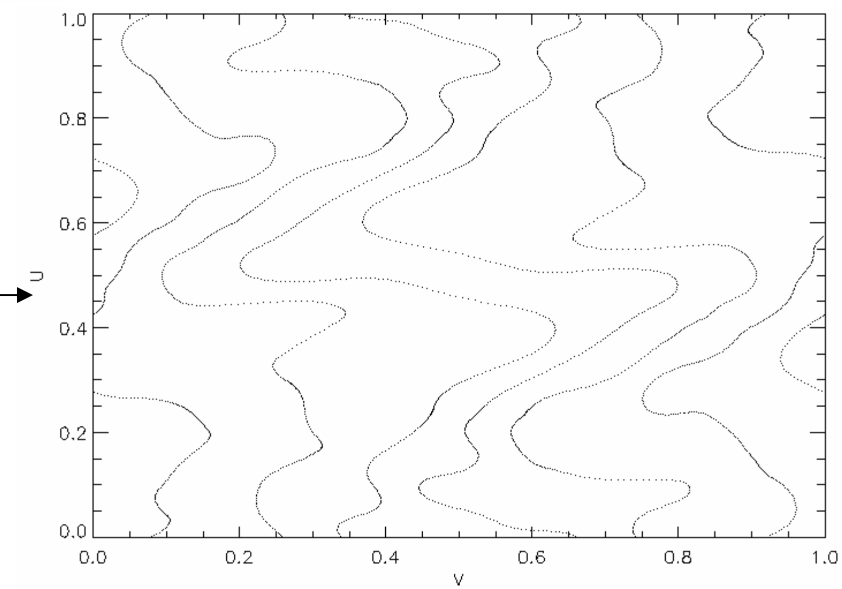


Modular coils viewed on the "u-v" plane of the current carrying surface.

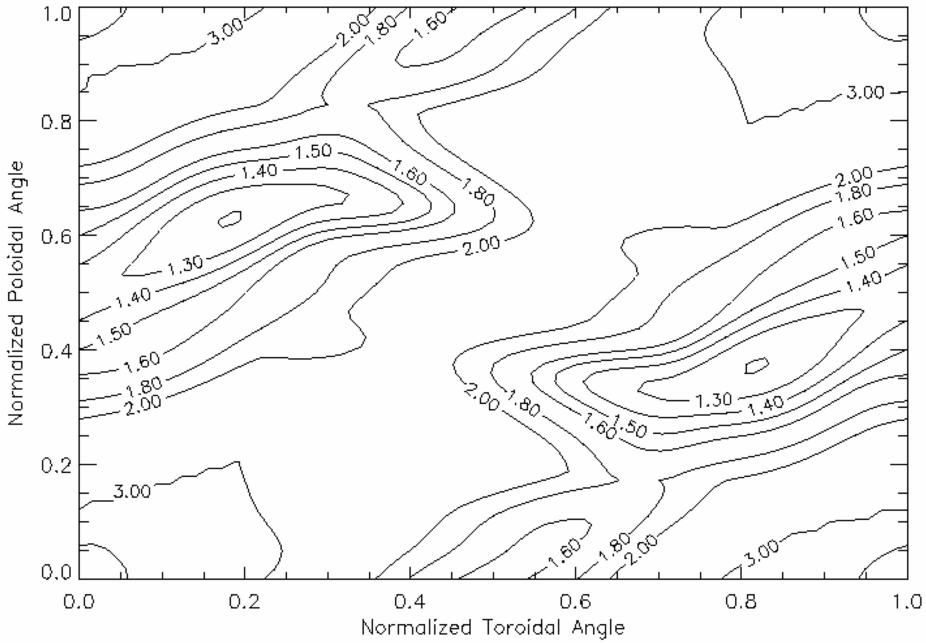


← A_c=5.9, with 1/R

A_c=5.9, without 1/R →

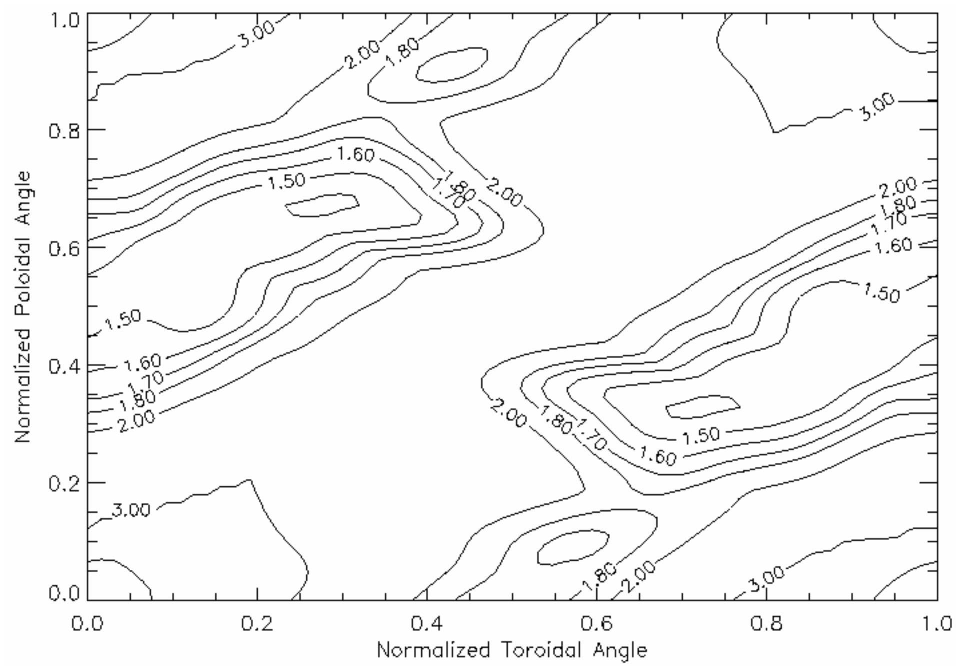


Contours of distance from LCMS to the winding surface. R=8.25 m

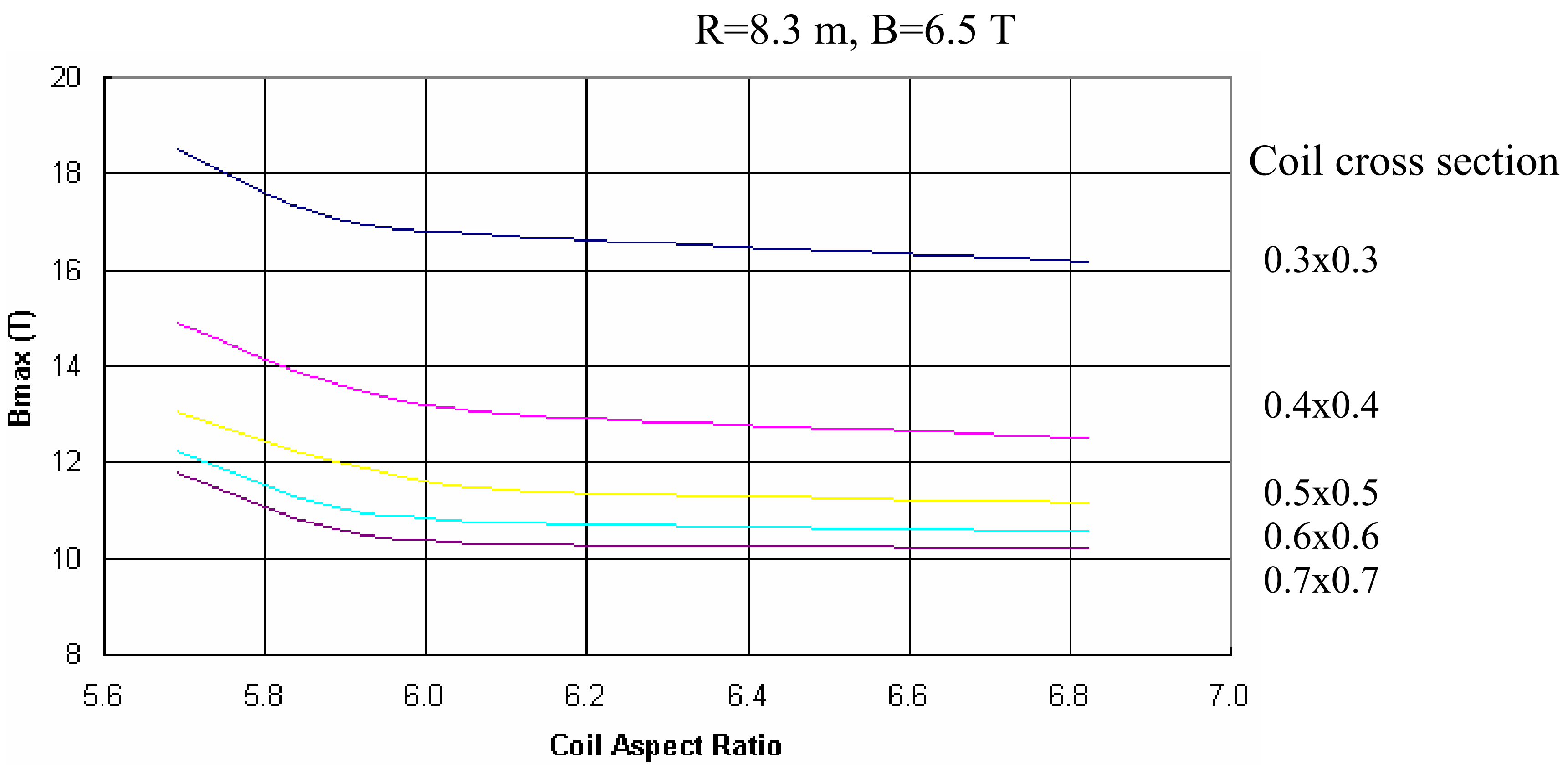


A_c=6.8

A_c=5.9

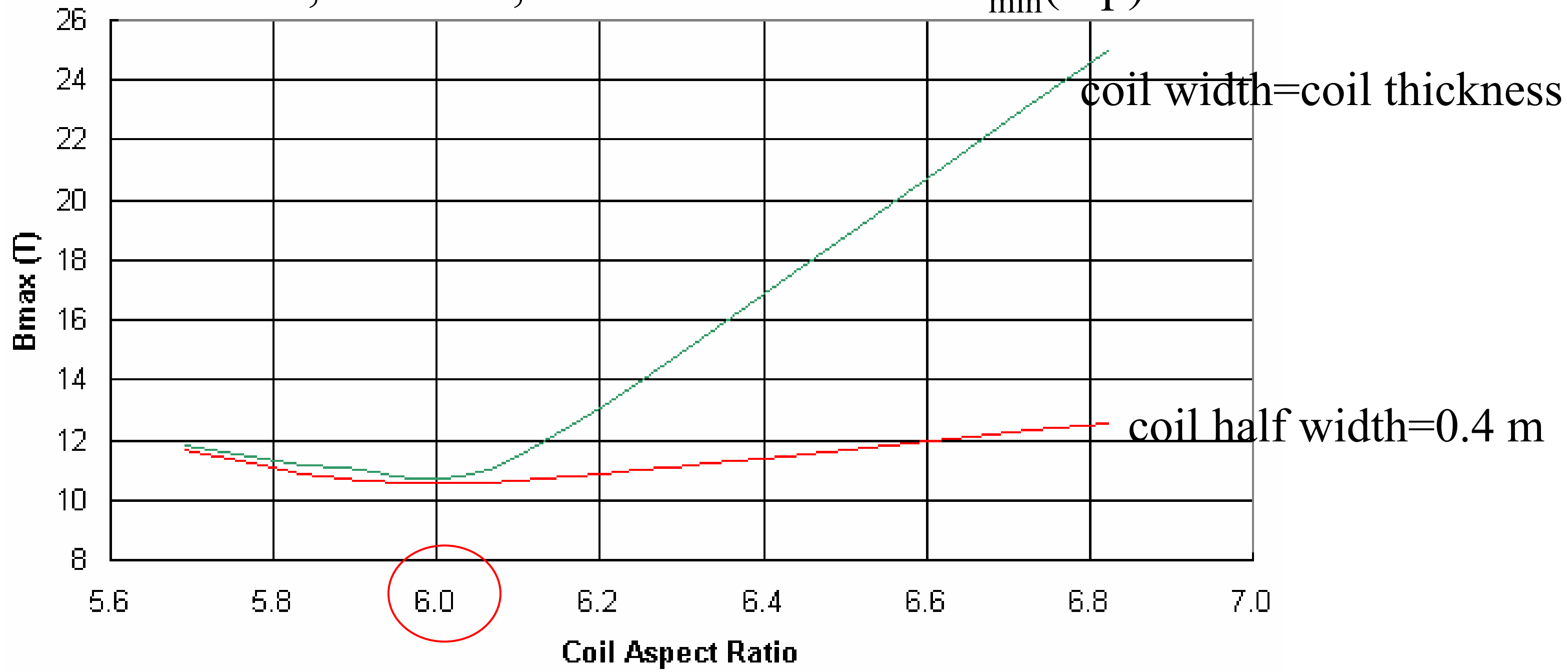


B_{max} increases as A_c decreases, but large increases occur only for A_c<6.

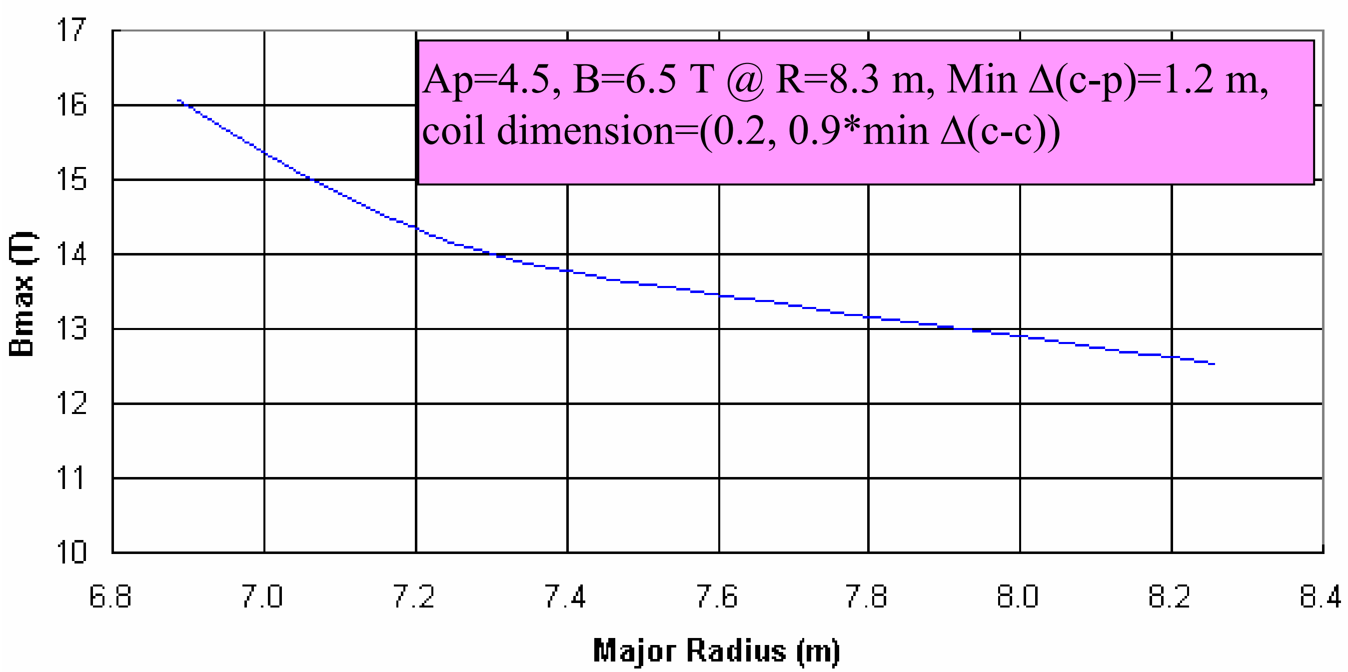


We can take advantage of the increase in Δ_{min}(c-p) as A_c is decreased to increase the coil cross section to reduce J_{max} and B_{max}, but there is a point where further decrease in A_c will no longer be paying off.

R=8.3 m, B=6.5 T, coil half thickness=Δ_{min}(c-p)-1.1 m



For a fixed Δ_{min}(p-c), a smaller Ac could result in a smaller reactor. However, at a fixed β and reactor power B_{max} will increase as Ac decreases. If we keep Δ_{min}(p-c)=1.2 m and assume that 90% of the minimum Δ(c-c) is used for coil width, then for B_{max} < 14 T, R≥ 7.3 m, or A ~ 6.



We conclude:

- The coil design previously provided for the working configuration is not optimal for the point of view of coil aspect ratio.

- For A_p=4.5, NCSX-like plasmas, A_c=6 gives the minimum B_{max} for R=8.3 m and B=6.5 T.

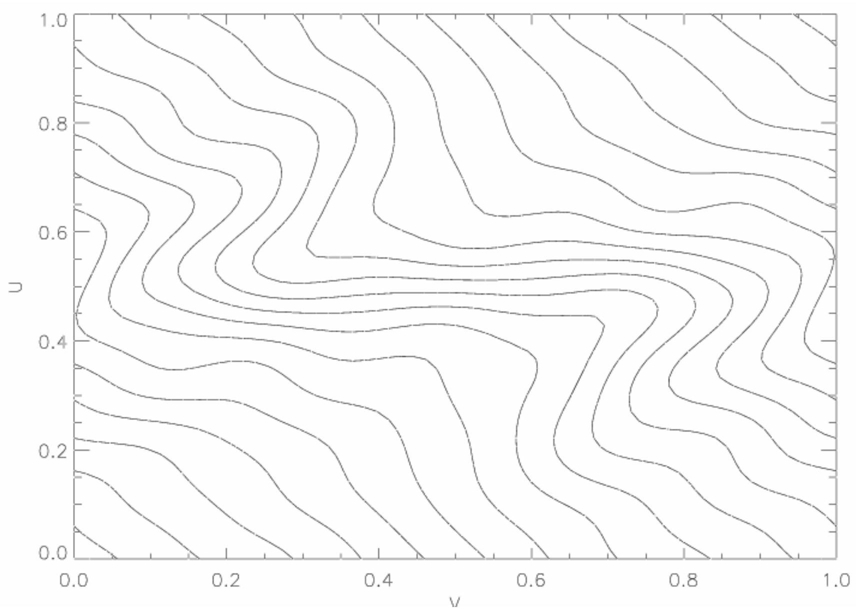
- For a fixed coil to plasma separation of 1.2 m, A_c~6 may also give a minimum sized reactor of ~2 GW(th) at R~7.5 m (sans considerations for confinement, neutron wall load, and tritium breeding – all maybe less favorable). ← need systems study.

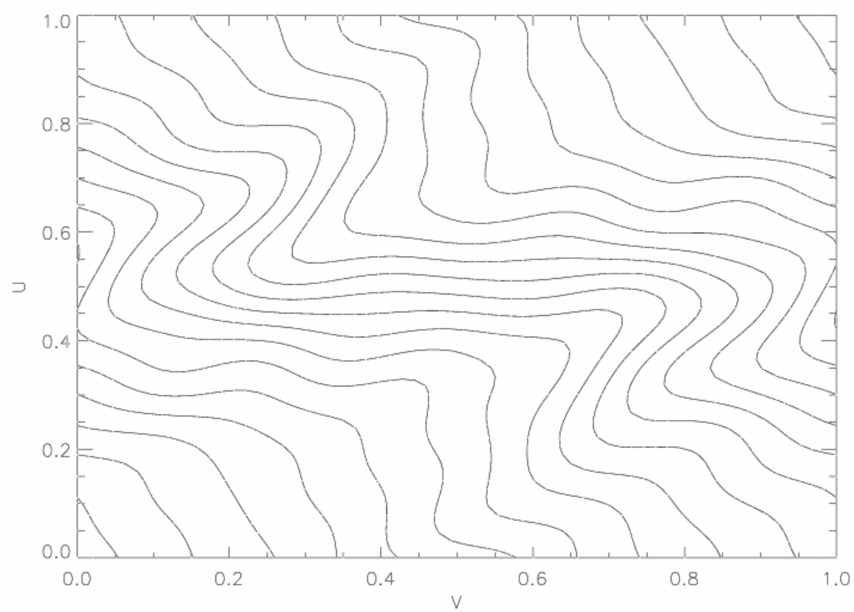
To what extent can the observation be generalized?

Preliminary Study of Coil Options

- 10 coils per period
- 3 field period, A=4.5 plasma (N3AGD)
- Current carrying surface not optimized. Surface follows plasma contour with outboard displacement ~50% larger than inboard.
- Residual errors are high in most cases (max Berr~10-15%).

Helical coils with 1/R background TF: two different relative current strengths.

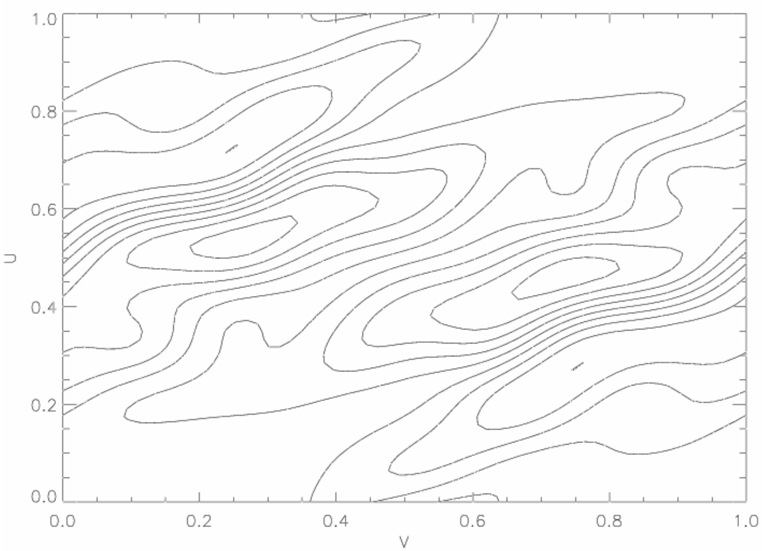




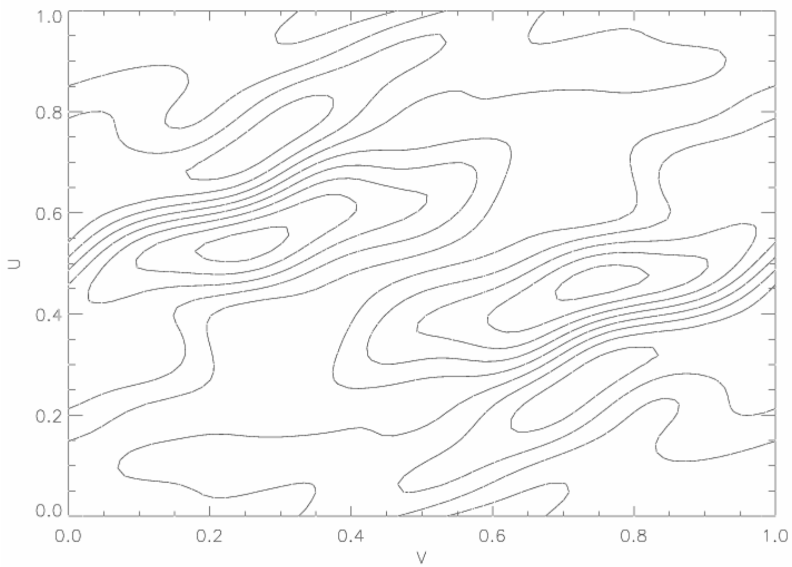
Amenable to sector maintenance concept?

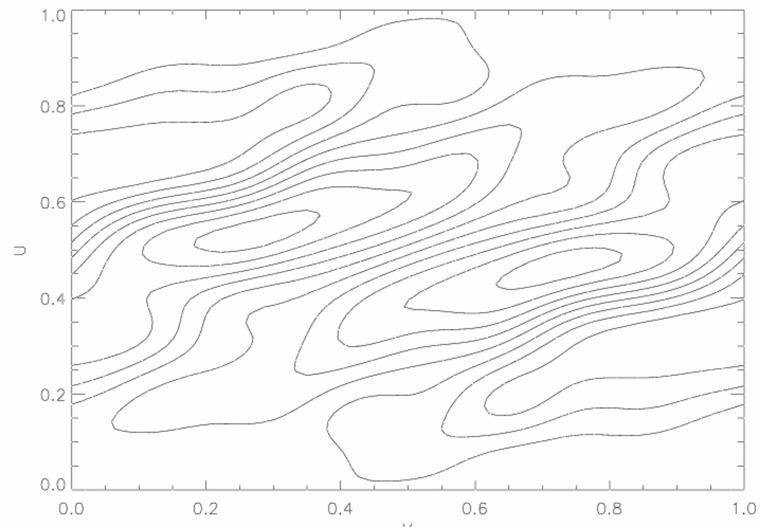
Saddle Coils (amenable to sector maintenance concept?)

With 1/R TF



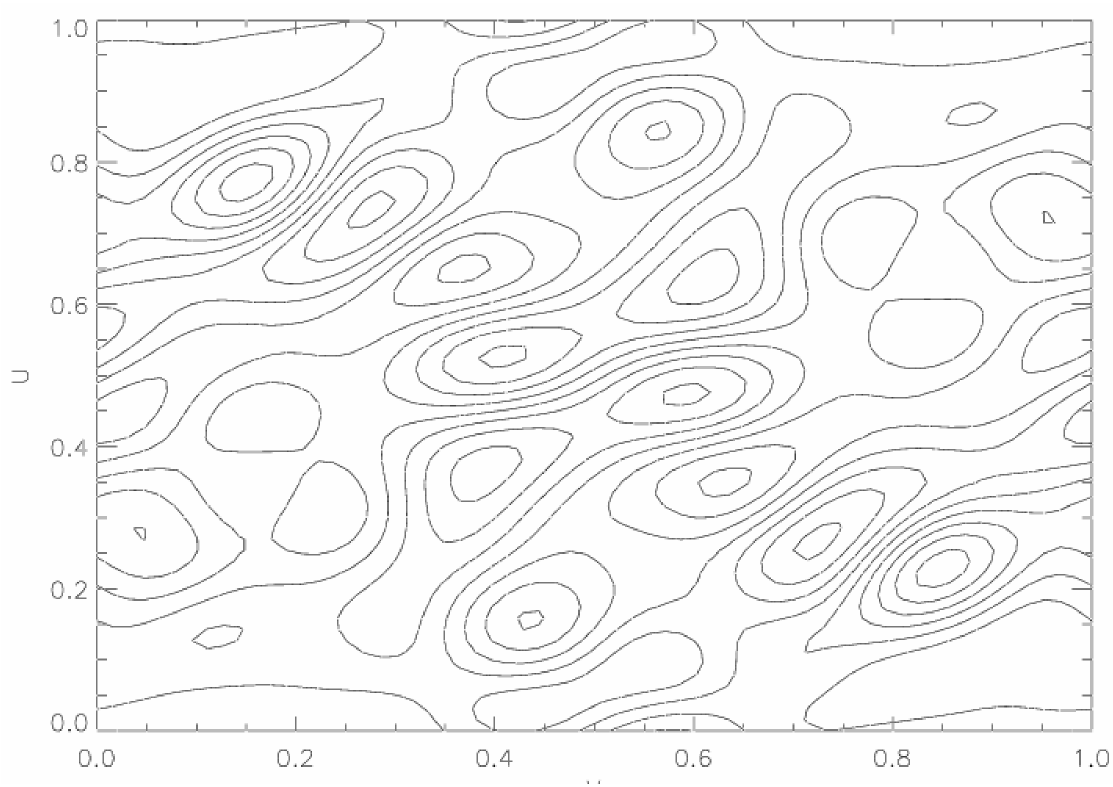
With wavy in-plane TF



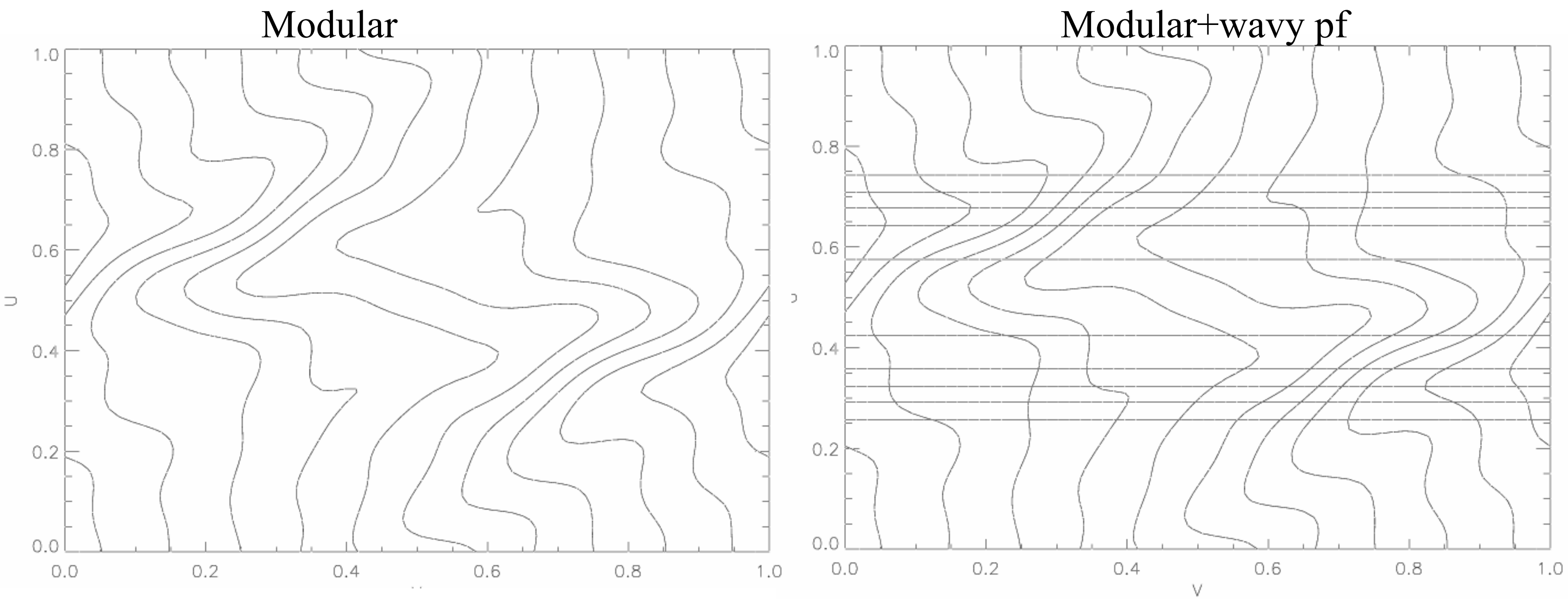


With wavy PF

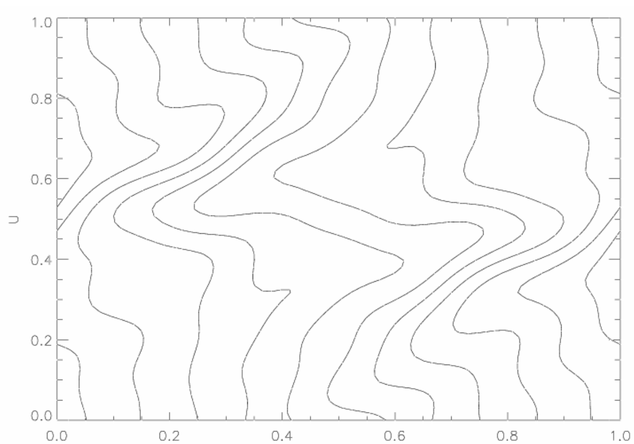
Is there a combination of near planer modular coils and wavy PF such that the saddle loops are short and confined to a single period?

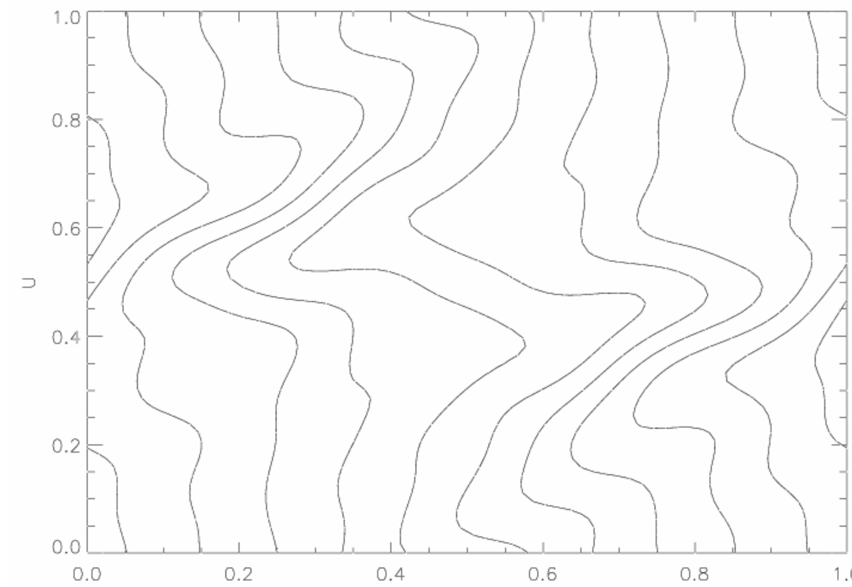


For ease in sector maintenance, we'd like to minimize the toroidal excursion of coils. Can some additional coils help the modular coil design?

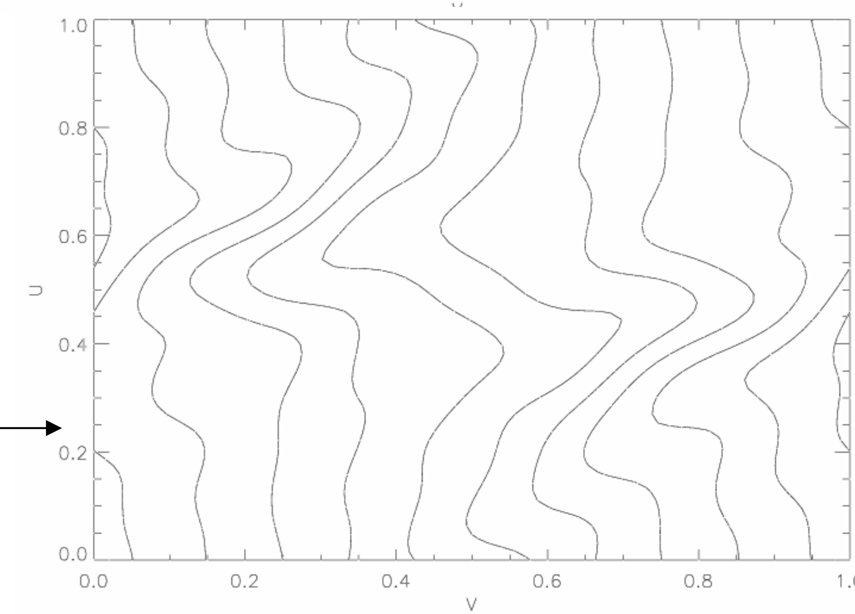


Modular with 1/R planar TF of different currents.





Modular coil current too much?
Can we get error down?



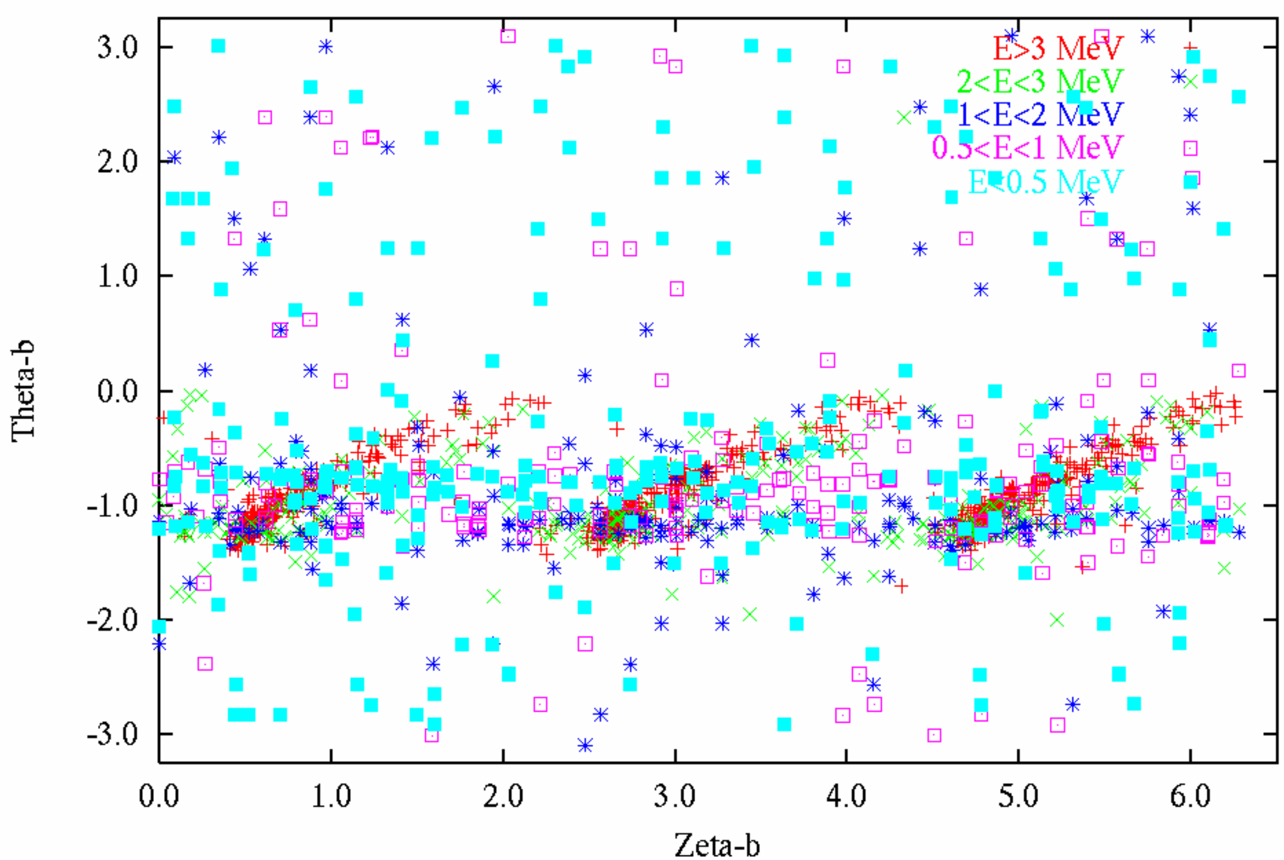
Heat load on the first wall due to escaping α

- In the May project meeting, we showed some configurations with improved α loss. The loss, nevertheless, is still not negligible.

- From engineering point of view there is a need to examine the impact of the heat load due to the escaping particles.

- We use the A=4.5, R=8.3, B=5.3 T working configuration, in which minimization of α loss was not considered, to calculate heat load on the first wall as the initial guide to assess its impact.

Footprint of lost α's in A=4.5, R=8.3 m, B=5.3 T, NCSX-like configuration



Define an α energy loss factor, L(i,j), at (i,j) on the u-v plane of the first wall to be

$$L(i,j) = \left[\frac{\sum_k E_{i,j}^k}{n E_\alpha} \right] \Big/ \frac{A_{i,j}}{\sum_{i,j} A_{i,j}}$$

where,

$E_{i,j}^k$ Is the energy of the k^{th} lost particle at (i,j) defined by a local differential area $A_{i,j}$, and n is the total number of α particles.

then,

α energy (power) flux at (i,j) = L(i,j) • P_α/A,

where P_α is the total α power and A is the first wall area.

For the working configuration, if we assume that the first wall is very close to the last closed flux surface of the plasma, then

P_α = 400 MW for 2 GW thermal power, and

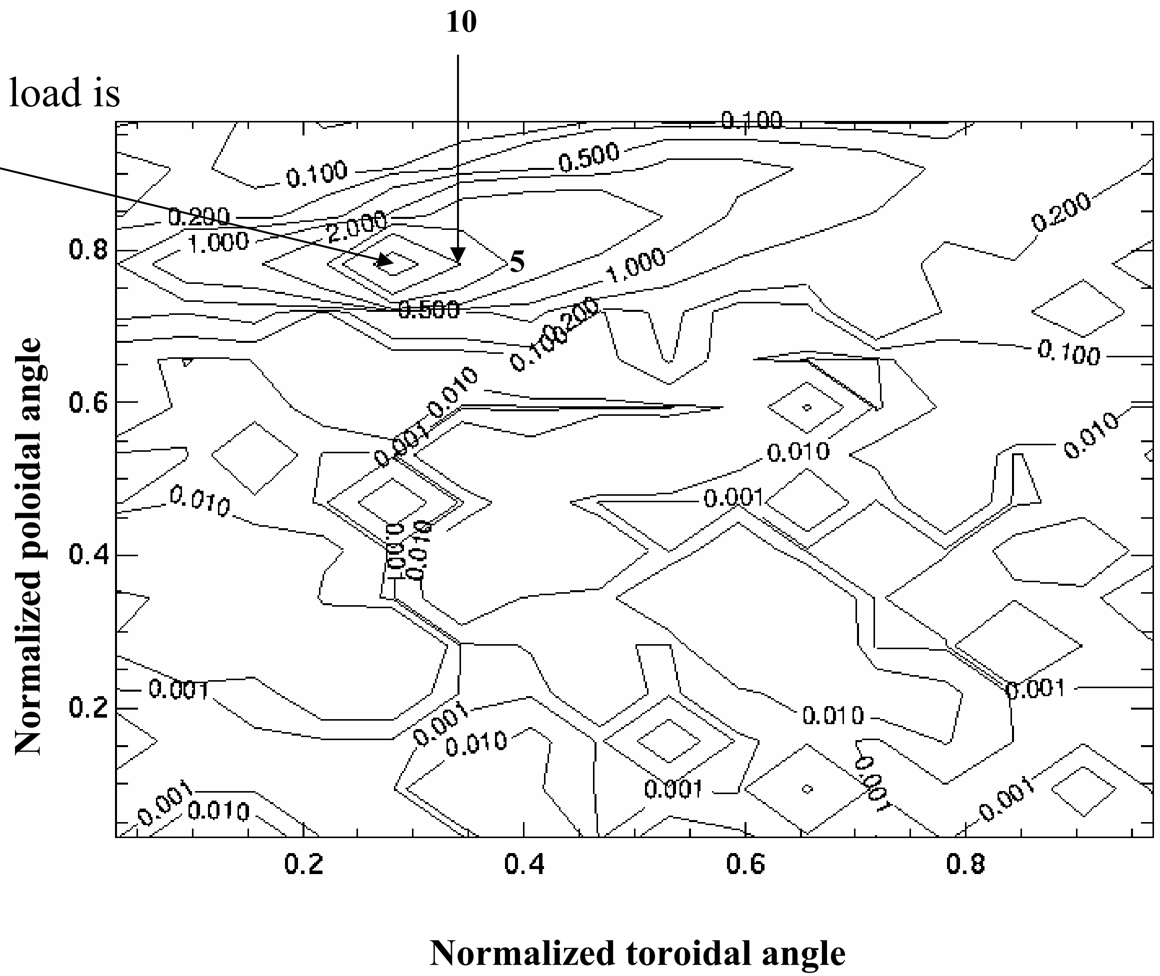
A~ 800 m^2.

Contours of α energy loss factor for R=8.3 m, B=5.3 T, A=4.5 NCSX-like configuration.

For 2 GW(th), the peak load is ~ 15 MW/m^2

Note: given plasma core radiation fraction~30% => P(brems)~0.1-0.2 MW/m^2

Finite orbit effects?



Review of Reactor Configuration Development - FY03

- In October 2002, we reviewed the configuration optimization for NCSX and identified critical areas where issues have not been adequately addressed for reactor development.
  - The review helped us define the initial scope of work for the CS efforts.
- Our primary goal is to study each issue separately to find ways to understand the problems and to devise method to solve the problems.
  - Ultimately, we want to integrate the new understanding into a coherent, self-consistent development of a CS configuration.

- Essential preparation tasks discussed in October:
  - Develop effective figures of merit for optimizing α confinement. **[Jan]**
  - Explore configuration space for attractive reactor regimes (compactness, good quasi-symmetry, low α loss, robust MHD stability at high β, simple coils) **[May (limited scope); continuing effort]**
  - Find means to maximize Δ–min and understand the effects of Bmax on the design of coils. **[Sept]**
  - Develop measures for flux surface quality and understand equilibrium beta limits.
  - Find means to incorporate measures of COE in the configuration optimization.

Issues and Plans

- Issues remain to be addressed for the present repertoire of configurations:
  - Existence of good flux surfaces
  - The impact of higher β
  - Trade-off among B, β, A, R in cost and systems space
  - Integration of separate studies into a consistent and coherent design.
- Develop/study configurations with relaxed MHD stability constraints.