Physics Studies in Support of ARIES-CS

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Presented by T.K. Mau

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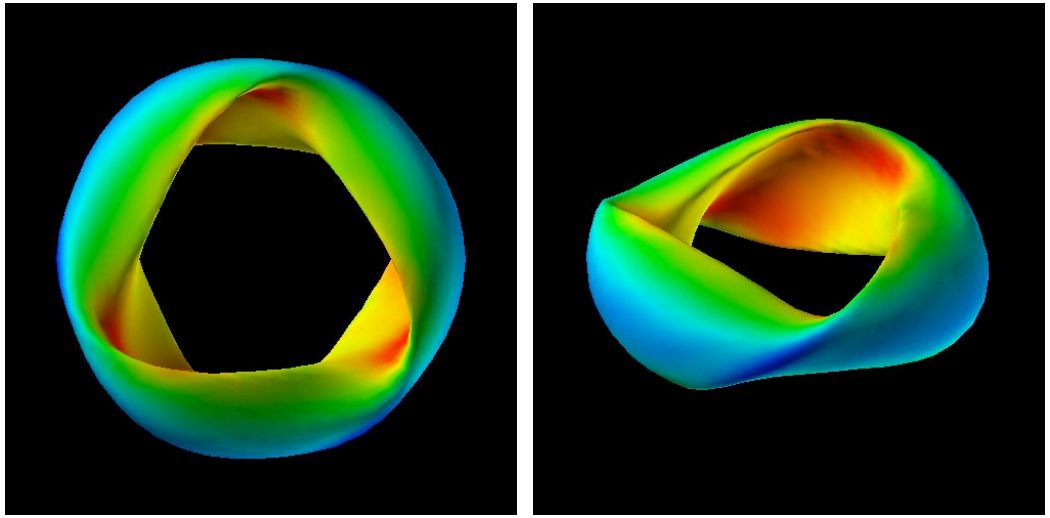
Outline of Discussions

- **Physics basis for the ARIES-CS baseline configuration**
  - **Unique features**
  - **Equilibrium and MHD stability**
  - **Transport and confinement (thermal, alphas)**
  - **Coils**
  - **Divertors**
- **Advanced configurations**
  - **Family in which the baseline configuration is a member**
  - **Extra-low aspect ratio**
  - **Tailored rotational transform**
- **Role of NCSX**
- **Summary/Conclusions**

The ARIES-CS Baseline Configuration

The baseline plasma is a three field-period, aspect ratio 4.5, quasi-axisymmetric configuration with R=7.75 m.



Plane and perspective view of the geometry and |B| of the last closed magnetic surface

Reference parameters for baseline:

R=7.75 m,

<a>=1.72 m,

<n>=3.6·10^{20} m^{-3},

<T>=5.73 keV,

B=5.7 T,

=5%,

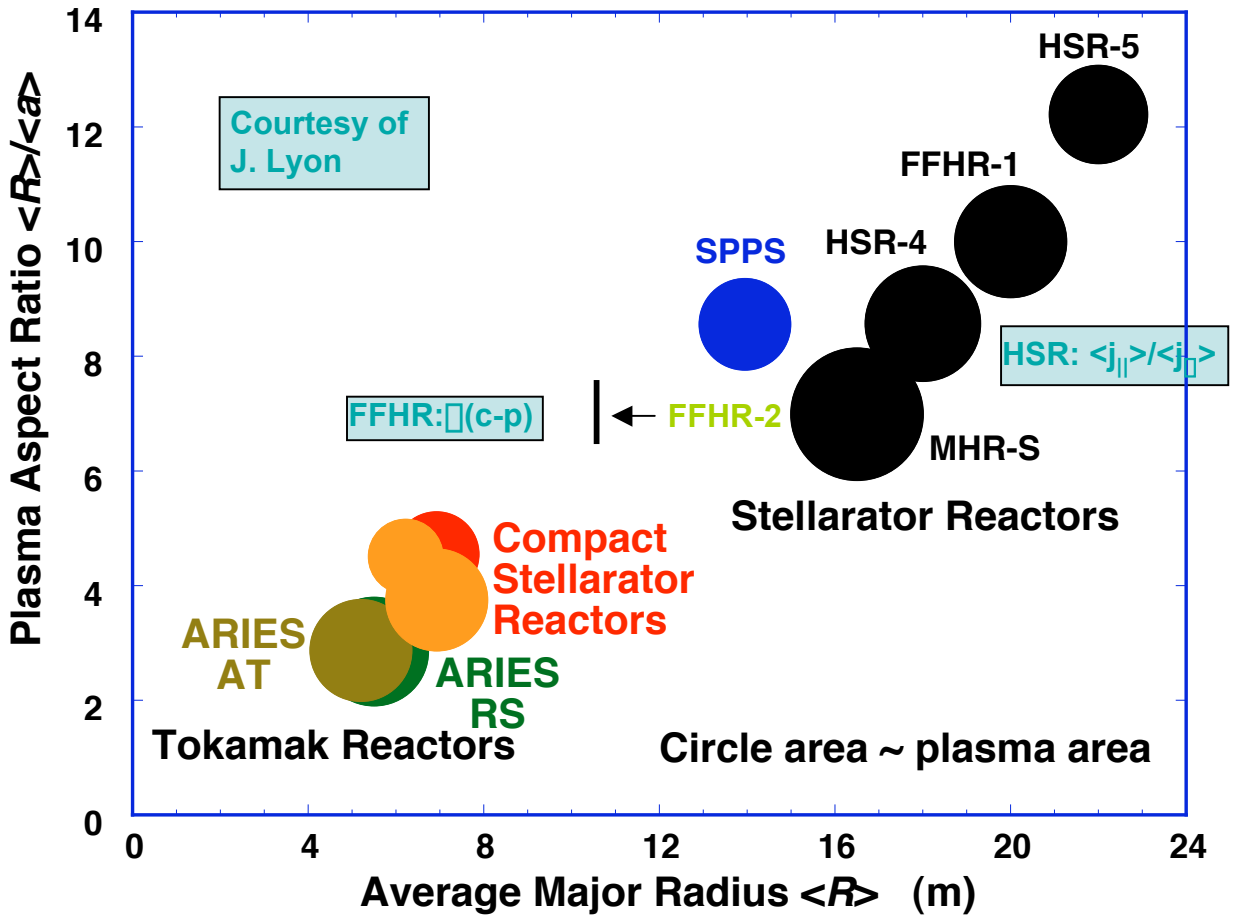
Ip=3.5 MA,

P(fusion)= 2.364 GW,

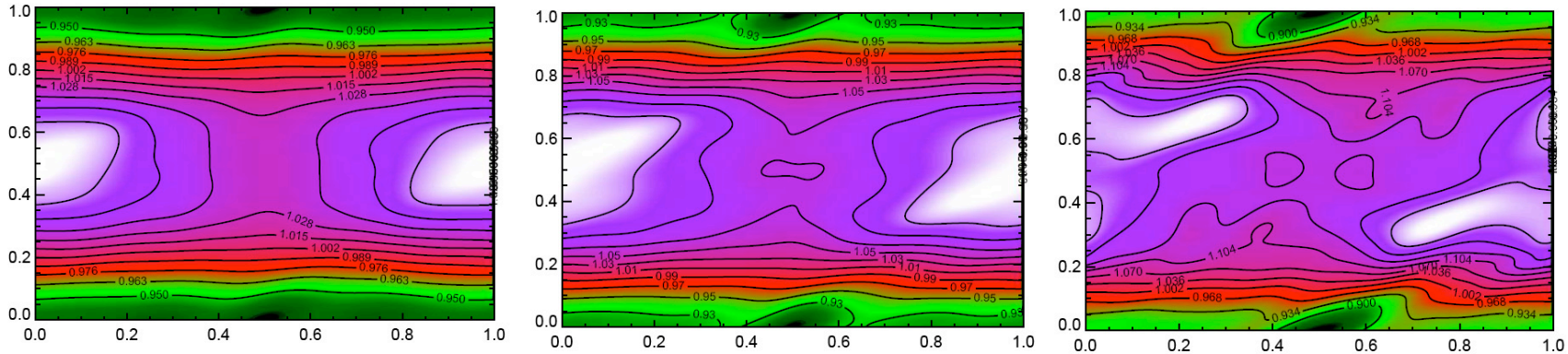
P(electric)= 1 GW

Compactness is a Unique Feature and Goal

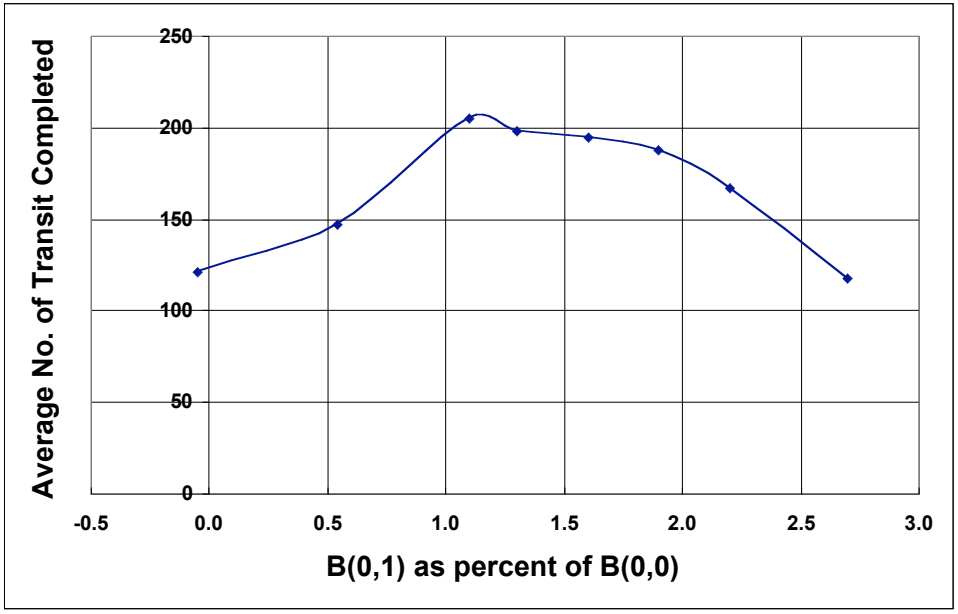
- **Compact reactor system** → **Lower COE**
  ← **QAS, QPS** **QHS?**



The configuration has "good" quasi-axisymmetry, but it also has a "not so small" amount of mirror ($B_{1,0}$) and its side-band helical ($B_{1,1}$) component. The "residues" are specifically introduced to improve confinement of fast ions.

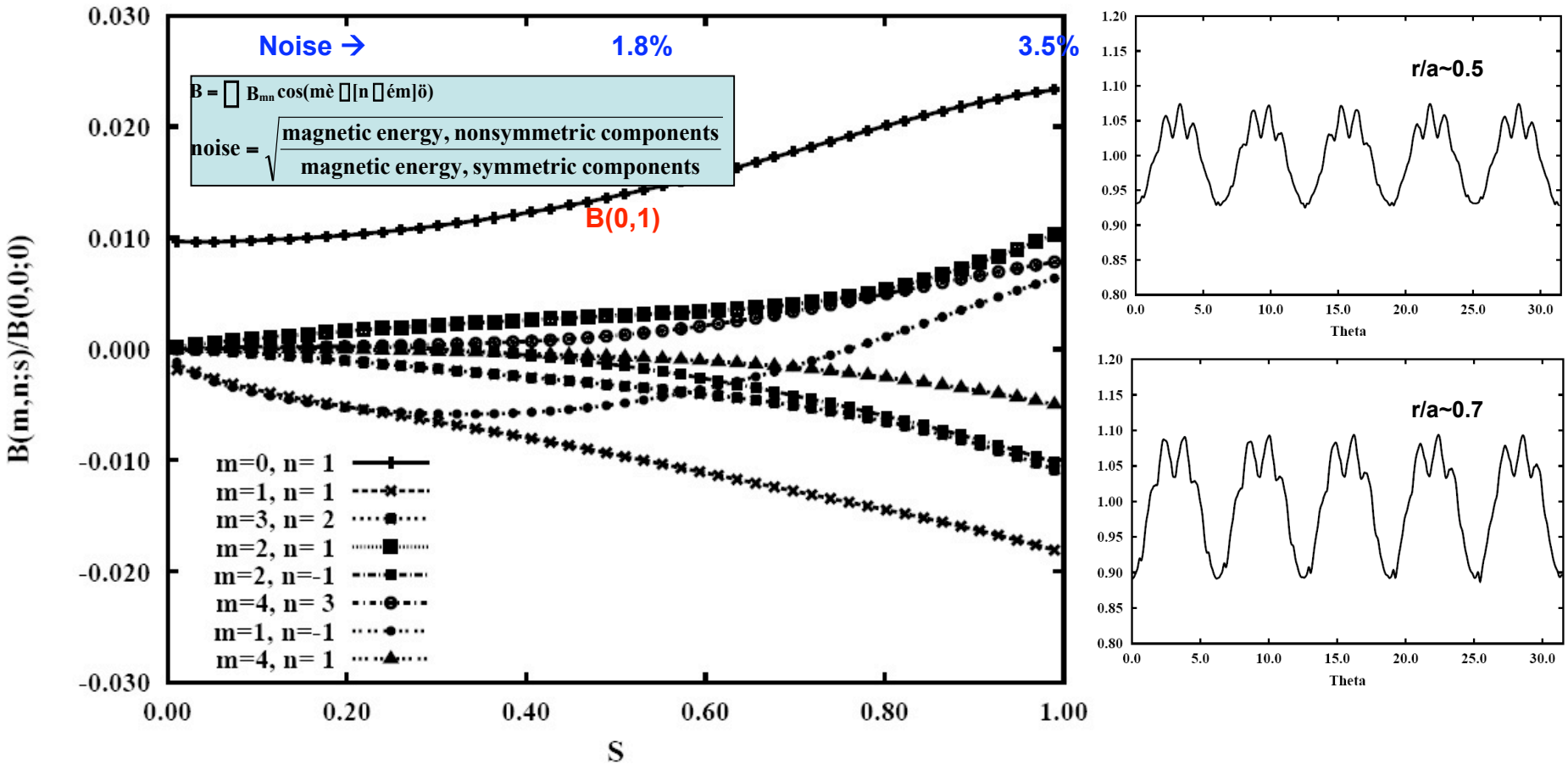


|B| in u-v space on surfaces at r/a~0.5, 0.7 and 1.0

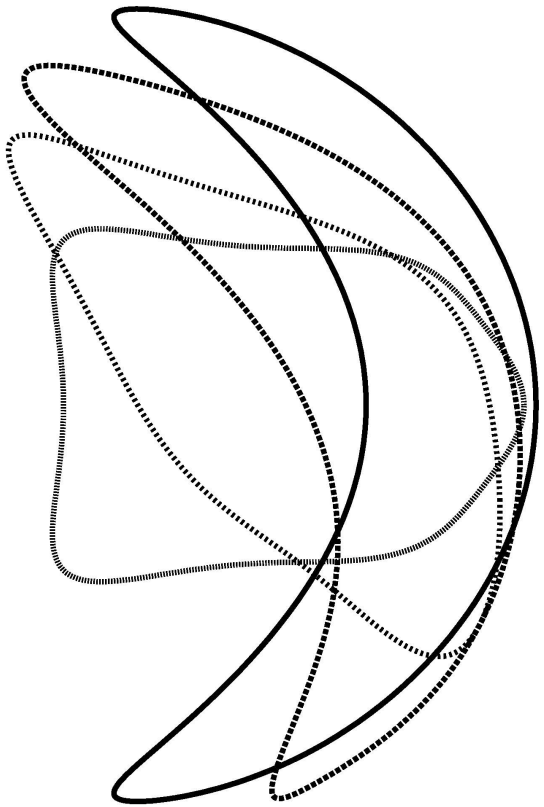


Collisionless orbits improved with ~1-2% B(0,1) as seen in an earlier study. N3AEC, toroidal transit limit=500, R=10 m, B=5.5 T, α born on r/a=0.5.

The 1-2% mirror field helps modify ripple distribution along field lines to reduce the overall ∇B drift loss* without compromising the equilibrium and MHD stability properties.



*H. Mynick, A. Boozer and L. P. Ku, to appear in Phys. Plasmas



Plasma cross section seen in four equally spaced toroidal angles.

The plasma may be described by*

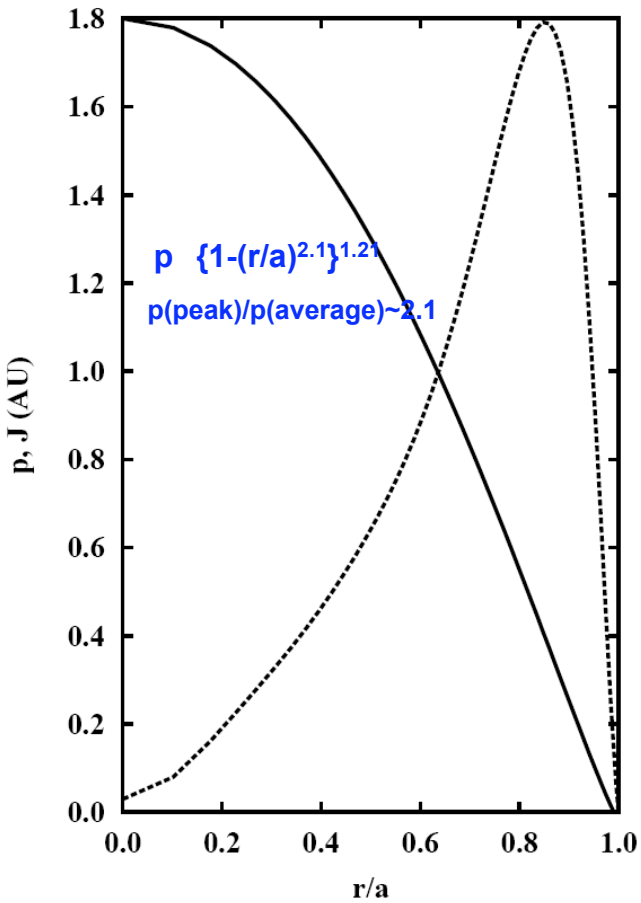
$$r + iz = e^{iu} \sum \alpha_{m,n} e^{-imu+inv}$$

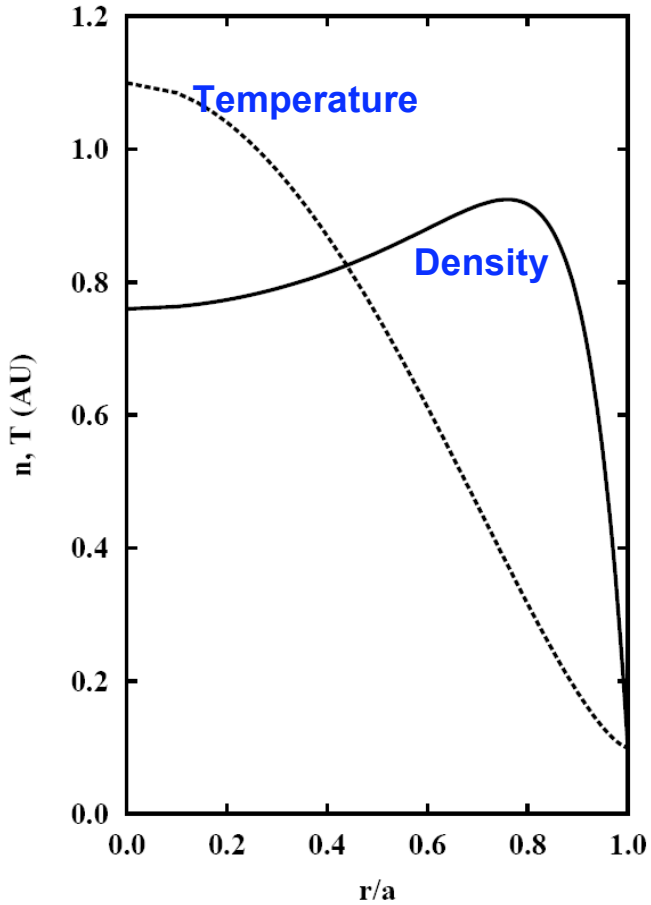
where $\alpha_{2,0}$=-0.25,
$\alpha_{2,1}$=-0.41,
$\alpha_{3,0}$=0.14,
$\alpha_{-1,0}$=0.11, ⇨ α~1.7, β~0.7
$\alpha_{3,1}$=0.15,
$\alpha_{-1,-1}$=0.17,
$\alpha_{0,1}$=0.07,
$\alpha_{3,2}$=0.06,
$\alpha_{4,0}$=-0.06,
with $\alpha_{0,0}$ =1.

$\alpha_{0,1}$=0.04 for NCSX

*L. P. Ku & P. Garabedian, FS&T, 50, 207 (2006)

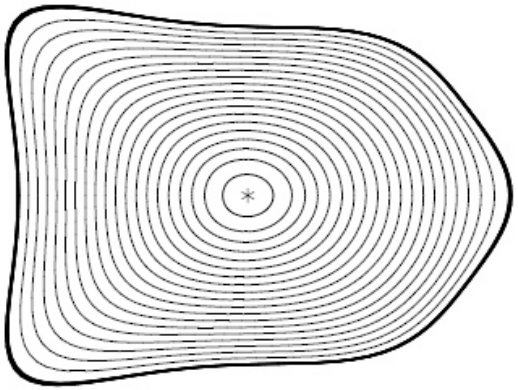
The baseline equilibrium is calculated assuming a peaked pressure profile and shifted current profile derived from ARIES-RS studies to assure favorable MHD stability. A hollow density profile is assumed in the systems code and also in some slowing down calculations with the temperature profile chosen to provide a consistent pressure profile.



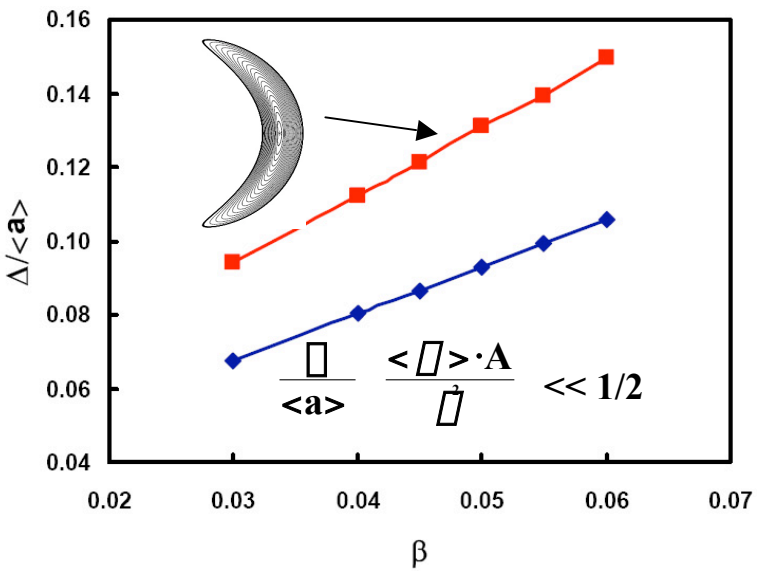


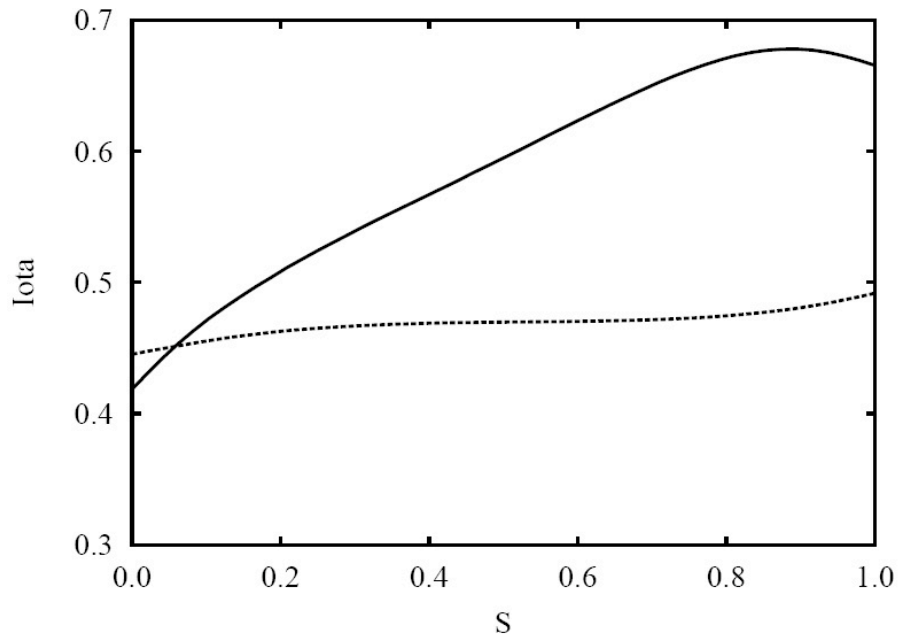
Sensitivities of MHD stability and particle transport to different profiles have been examined in a limited number of cases. In these cases, most favorable characteristics remain unchanged.

Equilibrium calculations indicate small Shafranov shifts at high β thanks to the significant transform from plasma shaping and the small plasma aspect ratio. The rotational transform increases nearly monotonically as the plasma radius increases.



Equilibrium calculated @ 5% β by VMEC*

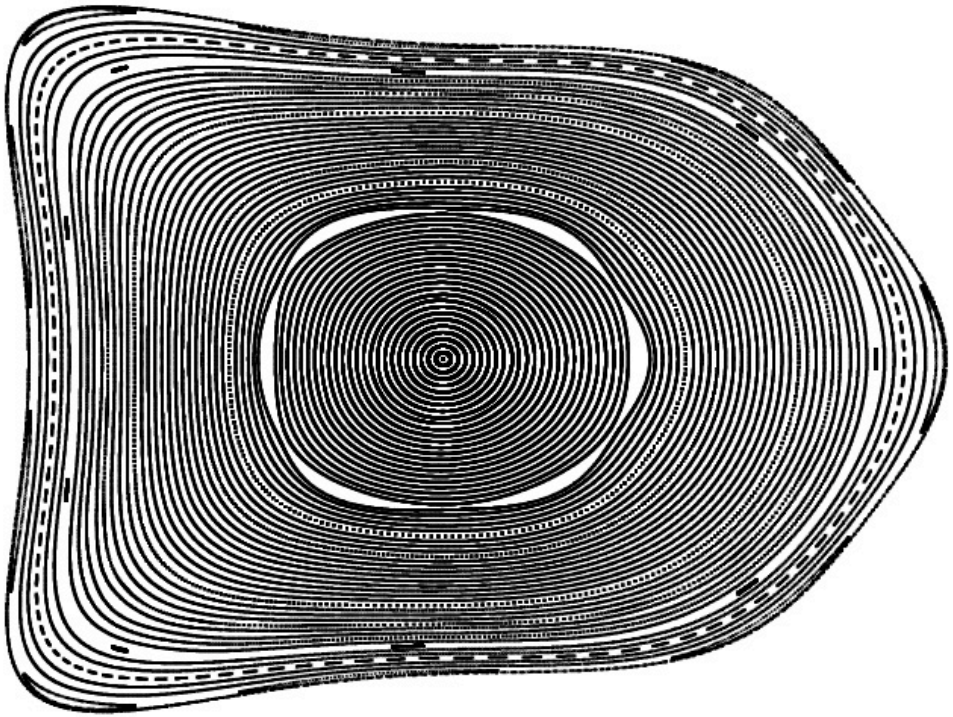




External and finite β total transform

*VMEC—S. P. Hirshman, W. I. van Rij, P. Merkel, Comp. Phys. Commun. 43, 143 (1986)

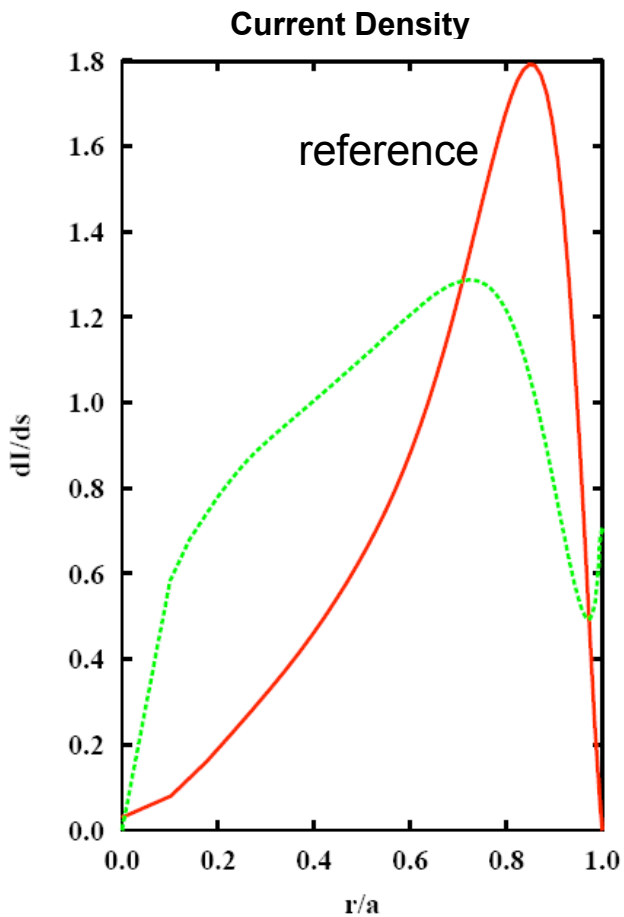
Fixed-boundary equilibrium calculation without presupposition of the existence of nested flux surfaces indicates the configuration has good surface integrity. Islands do exist but the widths are small and so is the potential loss of fluxes.

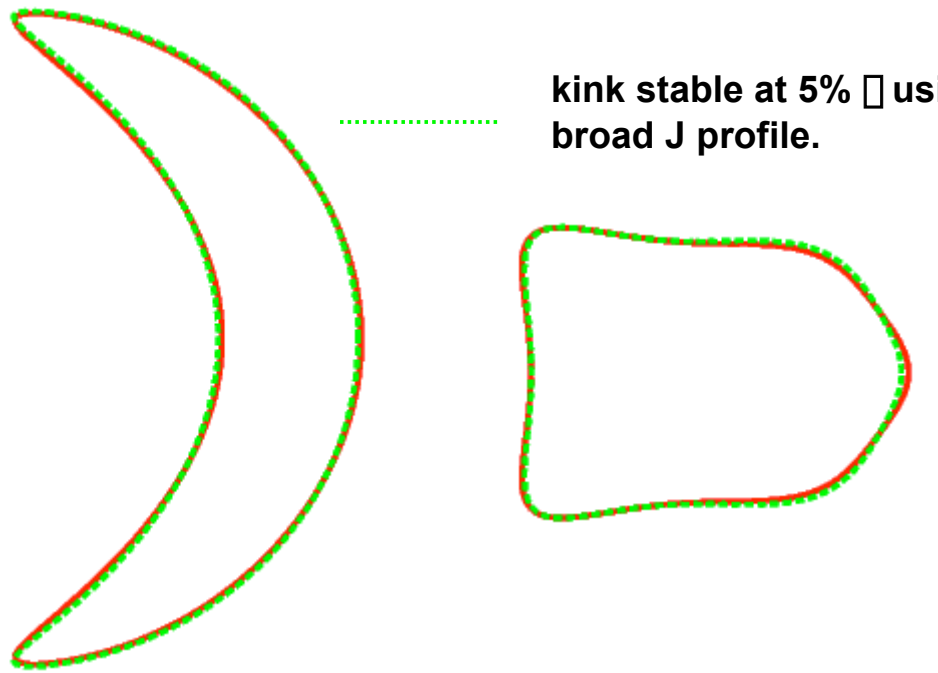


Poincaré plot of an equilibrium at 5% □ by PIES*

*PIES– A. Reiman and H. Greenside, Comp. Phys. Commun. 43, 157 (1986)

The configuration has favorable characteristics for global mode stability. When a broader (than reference) current profile is used in sensitivity studies, a small modification of the plasma shape will suffice to re-stabilize the kink modes at 5% β.

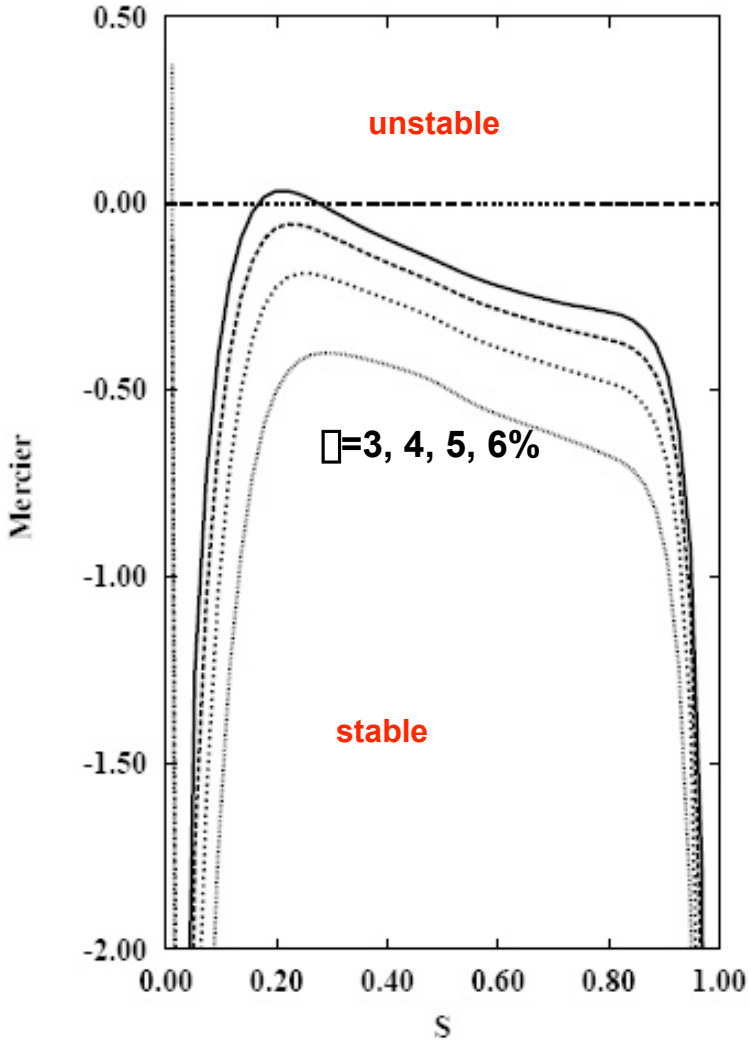


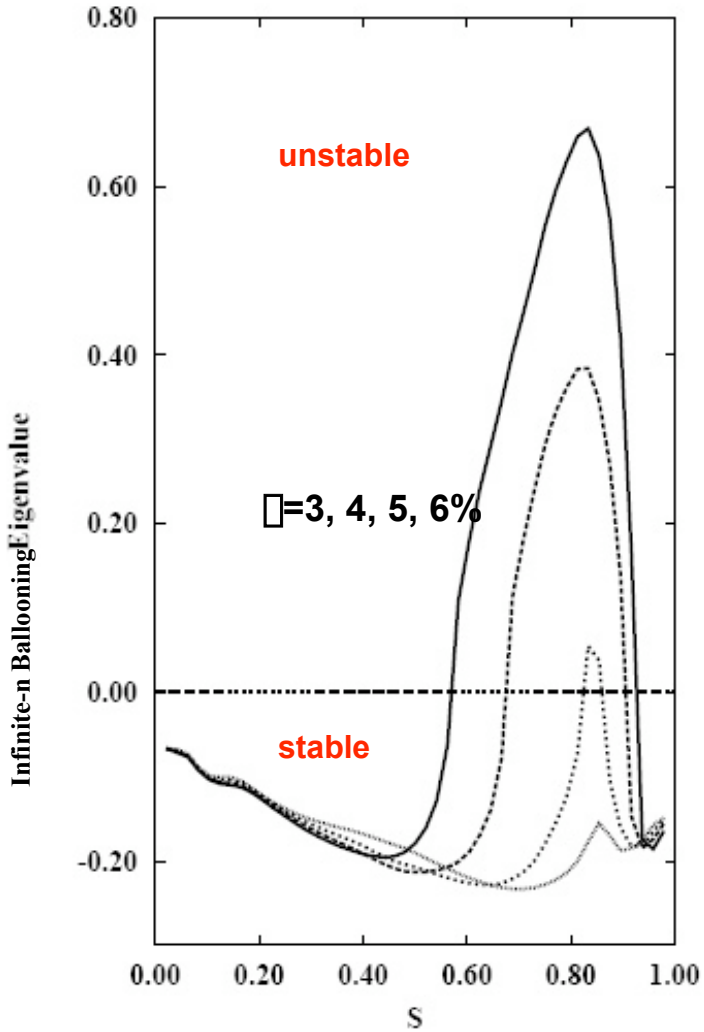


kink stable using the reference J profile.

kink stable at 5% β using a broad J profile.

The configuration has good stability characteristics to the Mercier and ballooning modes (COBRA* calculations).

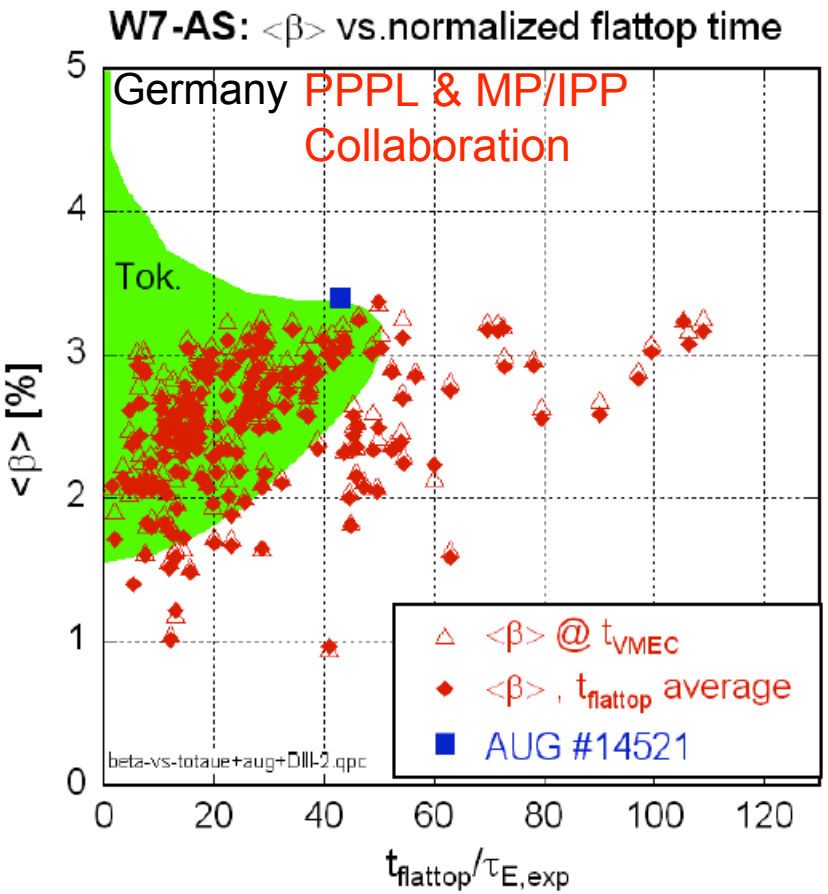


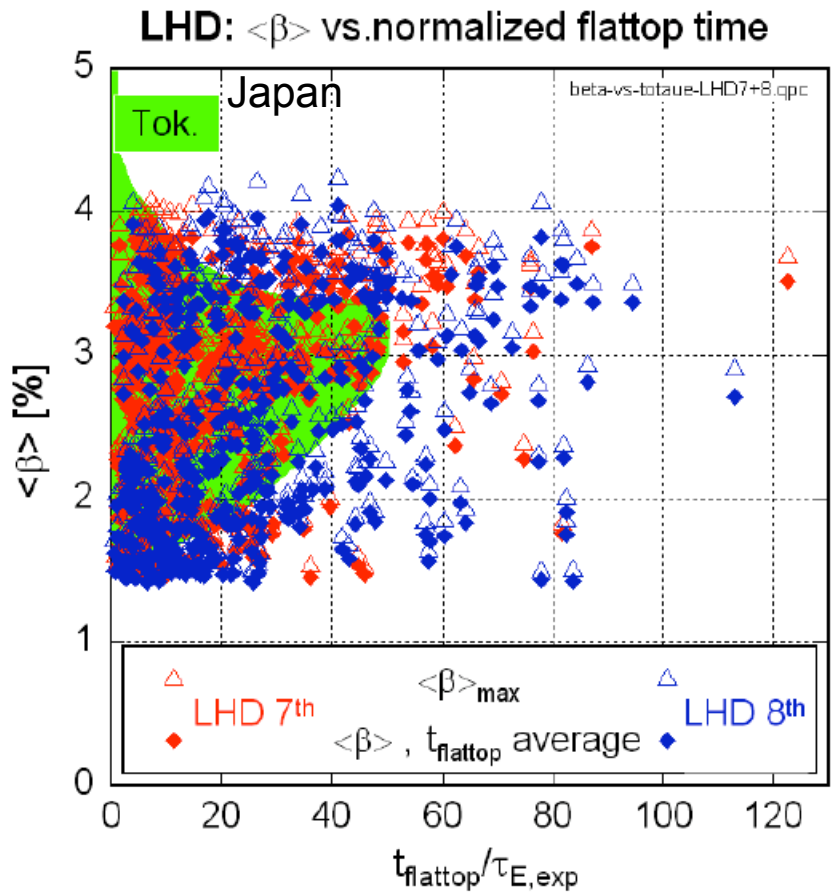


FLR correction typically leads to a higher ballooning limit (~50%). Local pressure flattening also leads to higher limits.

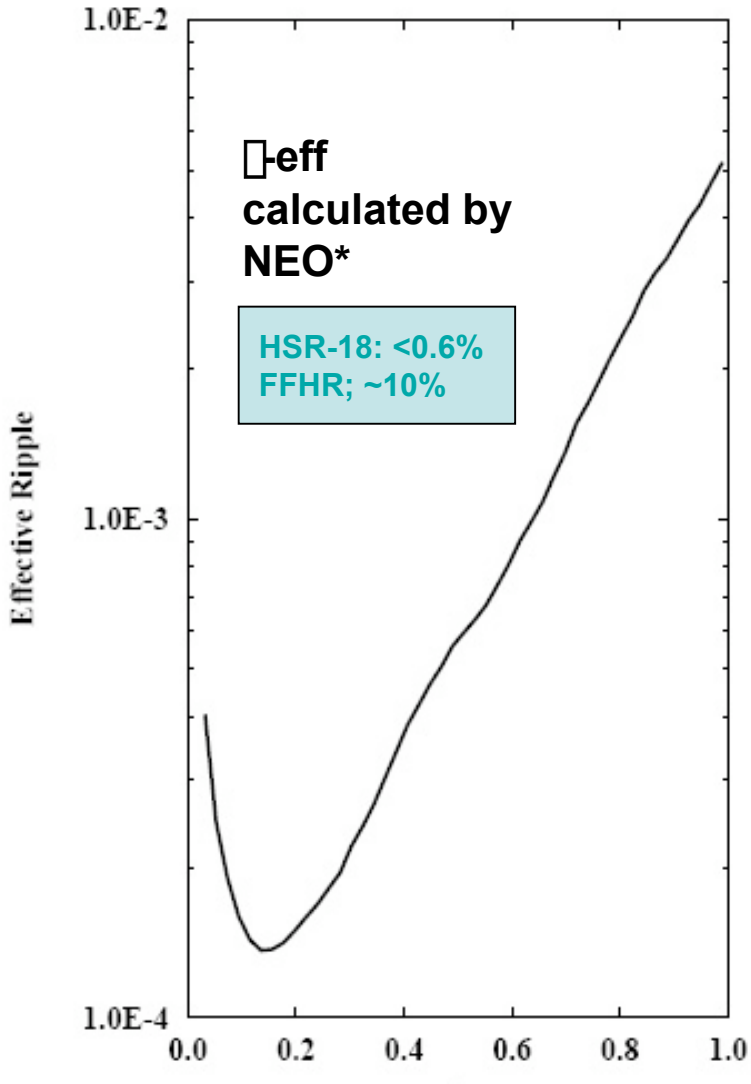
*COBRA—R. Sanchez, S. P. Hirshman, J. C. Whitson, A. Ware, J. Comput. Phys., 161, 589 (2000)

Recent W7AS and LHD Experiments: Steady High-β, Above Linear Limit. (courtesy of M. Zarnstorff)





- **In both cases, well above theoretical stability limit < 2%**
- **Not limited by MHD activity. No disruptions observed. Sustained without CD.**



NEO—V. V. Nemov, S. V. Kasilov, W. Kernbichler and M. F. Heyn, Phys. Plasma, 6(12), 4622 (1999)

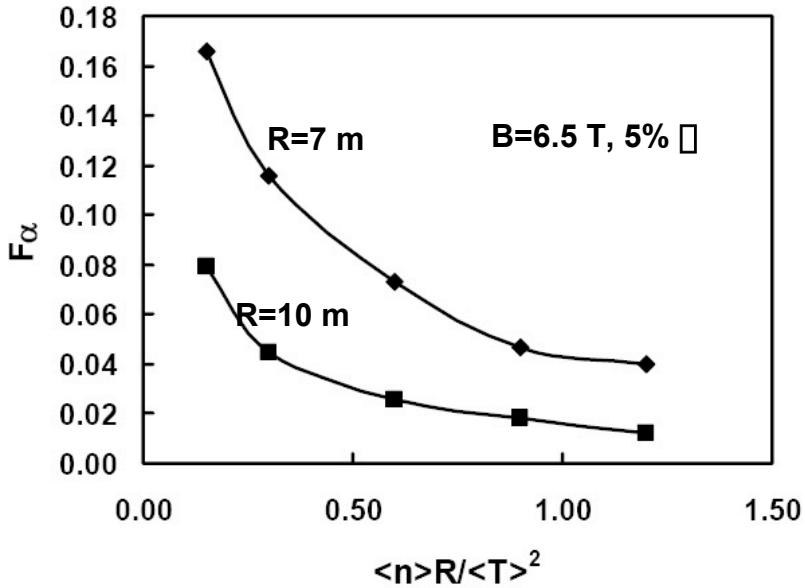
The configuration has very low effective ripple, being everywhere < 0.5%, despite the existence of 1-2% of B(0,1) and B(1,1).

Anomalous transport is expected to dominate the thermal loss. Power balance is achieved with τ_E ~1 s that corresponds to H~1.5 with the ISS-95 scaling:

$$\hat{o}_{iss95} = 0.256 a^{2.21} R^{0.65} P_{MW}^{0.59} n_{20}^{0.51} B^{0.83} e^{0.4}$$

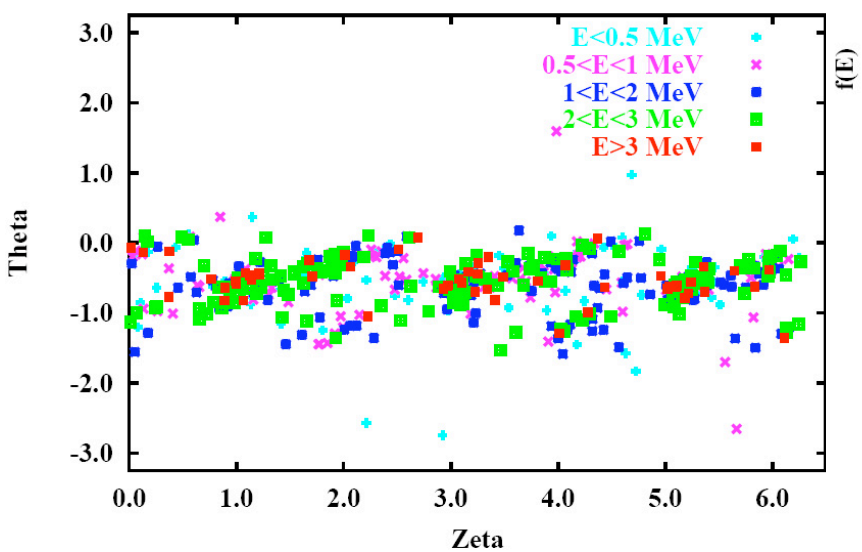
ISS04 has a more favorable scaling.

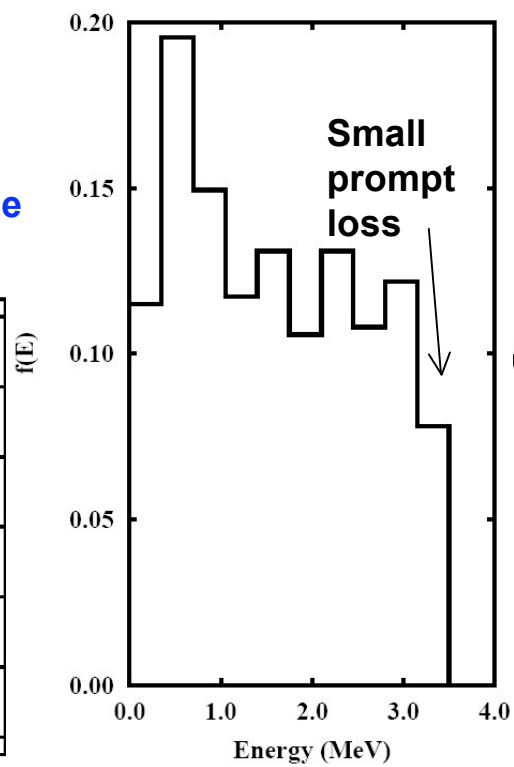
~20 MW auxiliary power is required during startup to reach ignition. Paths of startup have not been studied.

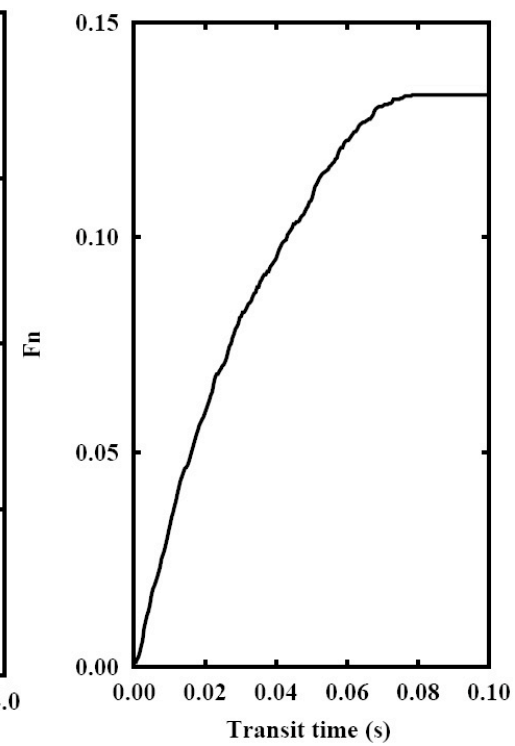


Alpha loss scales approximately with R^2 and B^2 and also scales with collisionality. The density at operating temperature is chosen to provide high collisionality subject to the constraint of Sudo density limit such that the energy loss fraction of alphas is limited to F□ ~ 5%.

Footprint of lost □ in (□,□), lost particle energy distribution and cumulative particle loss versus time for the baseline configuration (ORBIT3D* calculations).

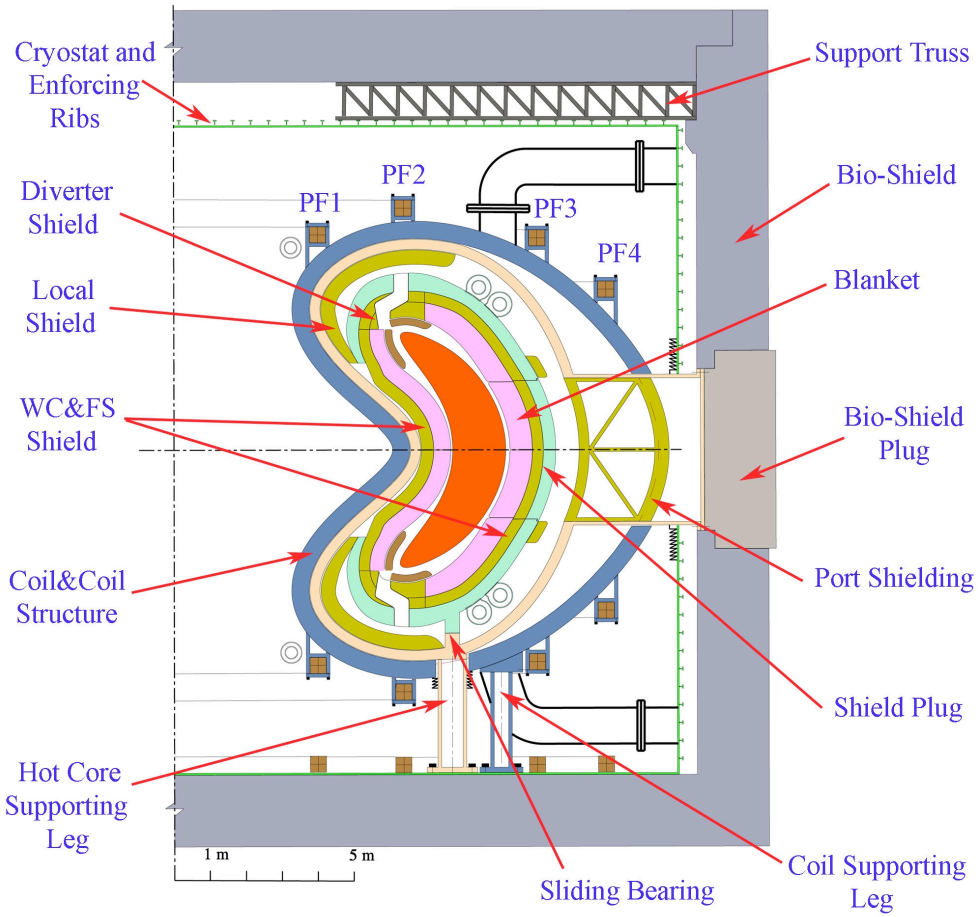




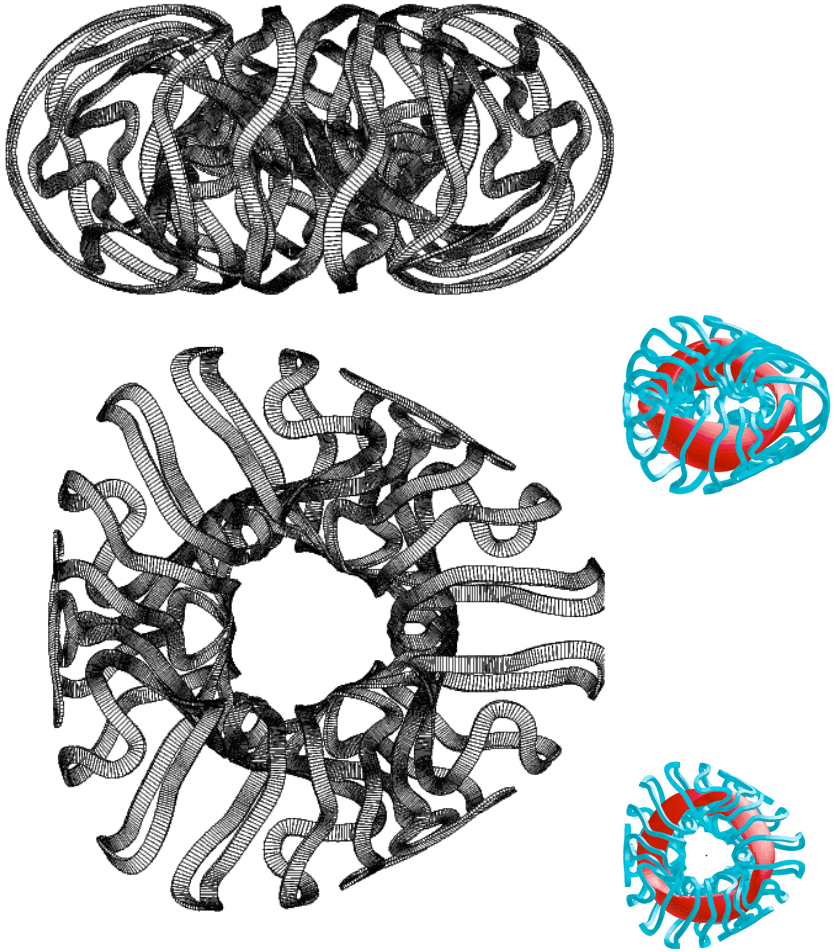


*ORBIT3D—R. B. White and M. S. Chance, Phys. fluids, 27, 2455 (1984)

Modular and PF coils are designed following the NCSX design principles but are optimized to minimize the coil aspect ratio.



Courtesy of Xueren Wang



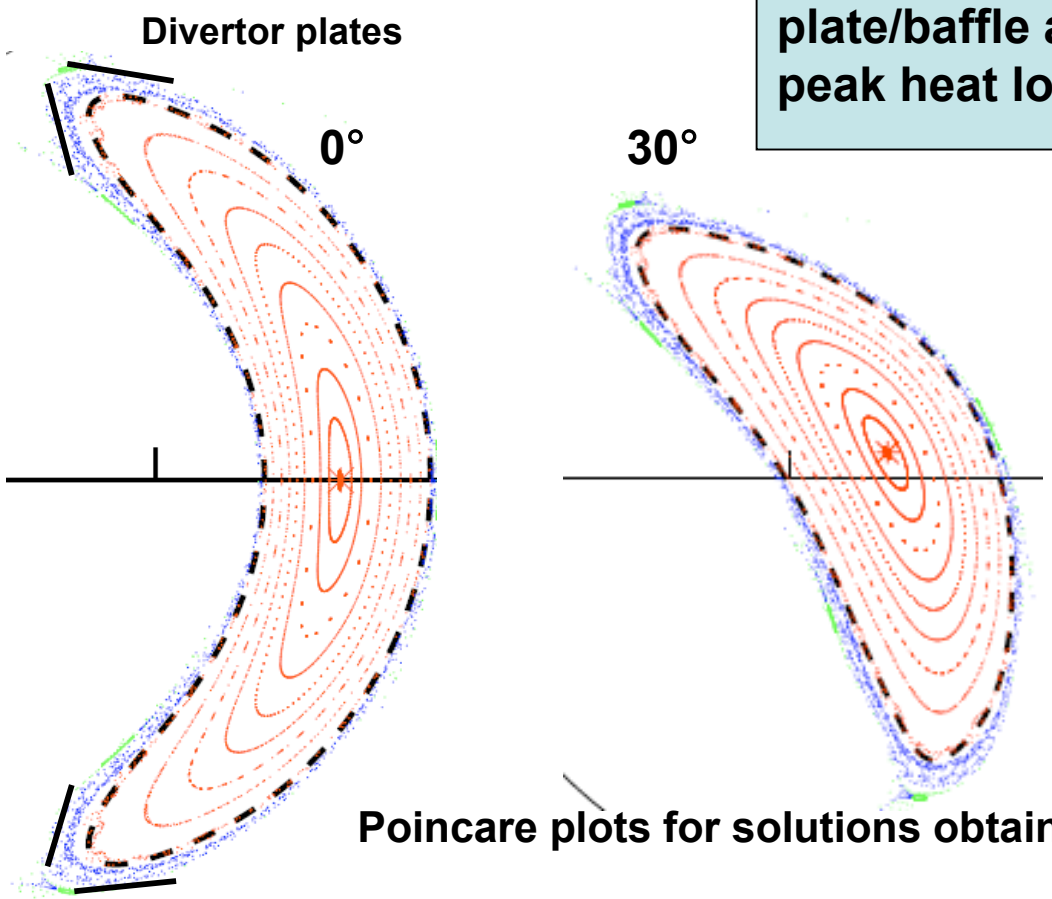
PF coils are designed for startup and equilibrium position control. I(max)< 5 MA.

Modular coil winding pack: 0.194 m x 0.743 m I(max)~13.5 MA, B(max)~15 T, R/□(C-P)~5.9, R/□(C-C)~10.

HSR: 10 T (NbTi)
FFHR: 13 T

Field topology outside LCMS is similar to that of NCSX with a natural flux expansion at tips of the crescent shaped section. Divertor plates are being developed in this region with sufficiently long connection lengths for the field lines, maximum field line intersections with plates and minimum heat load peaking factor.

plate/baffle area <15% A(1st wall)
peak heat load ≤ 10 MW/m²

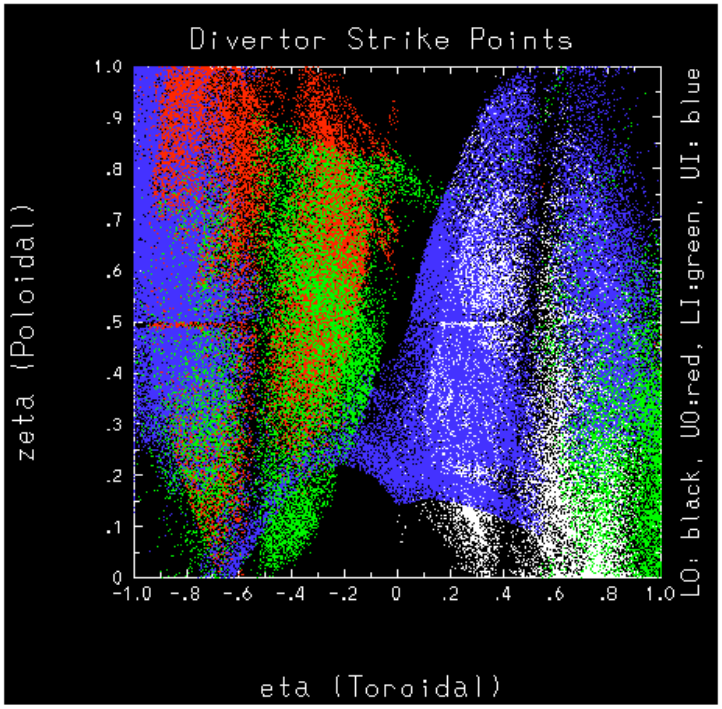


Poincare plots for solutions obtained by MFBE/GOURDON*.

E. Strumberger, Nucl. Fusion 37, 19, 1997.

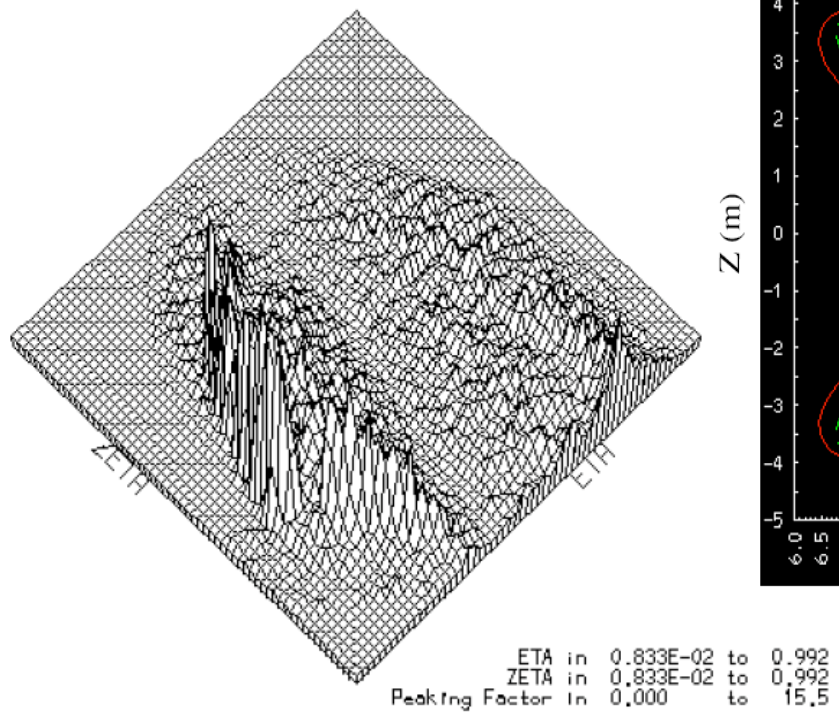
We have arrived at a divertor design (4 plates/period) at ~0.20 m offset from LCMS and with 50° toroidal and 20° poloidal extent, where the plates/baffles provide ~10% surface coverage and intersect ≥97% of combined thermal and alpha particle heat flux. The 'thermal" field lines have an average connection length of ~220 m, leading to adequate upstream to target temperature separations (≥300 eV) at high separatrix densities (~$5 \cdot 10^{19}$ m^{-3}) and good radiated power fraction in SOL and divertors (>50%).

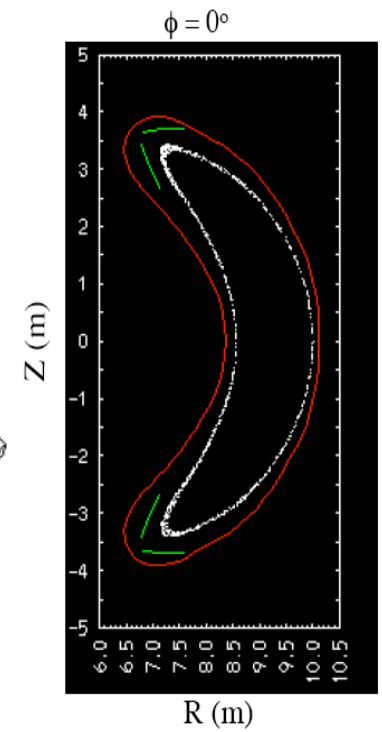
However, not all plates satisfy the peak heat load limit of 10 MW/m^2.



Field line strike points on divertor plates, for both thermal and alpha particles.

$w(i,j)_{max}/w(avg)$~15





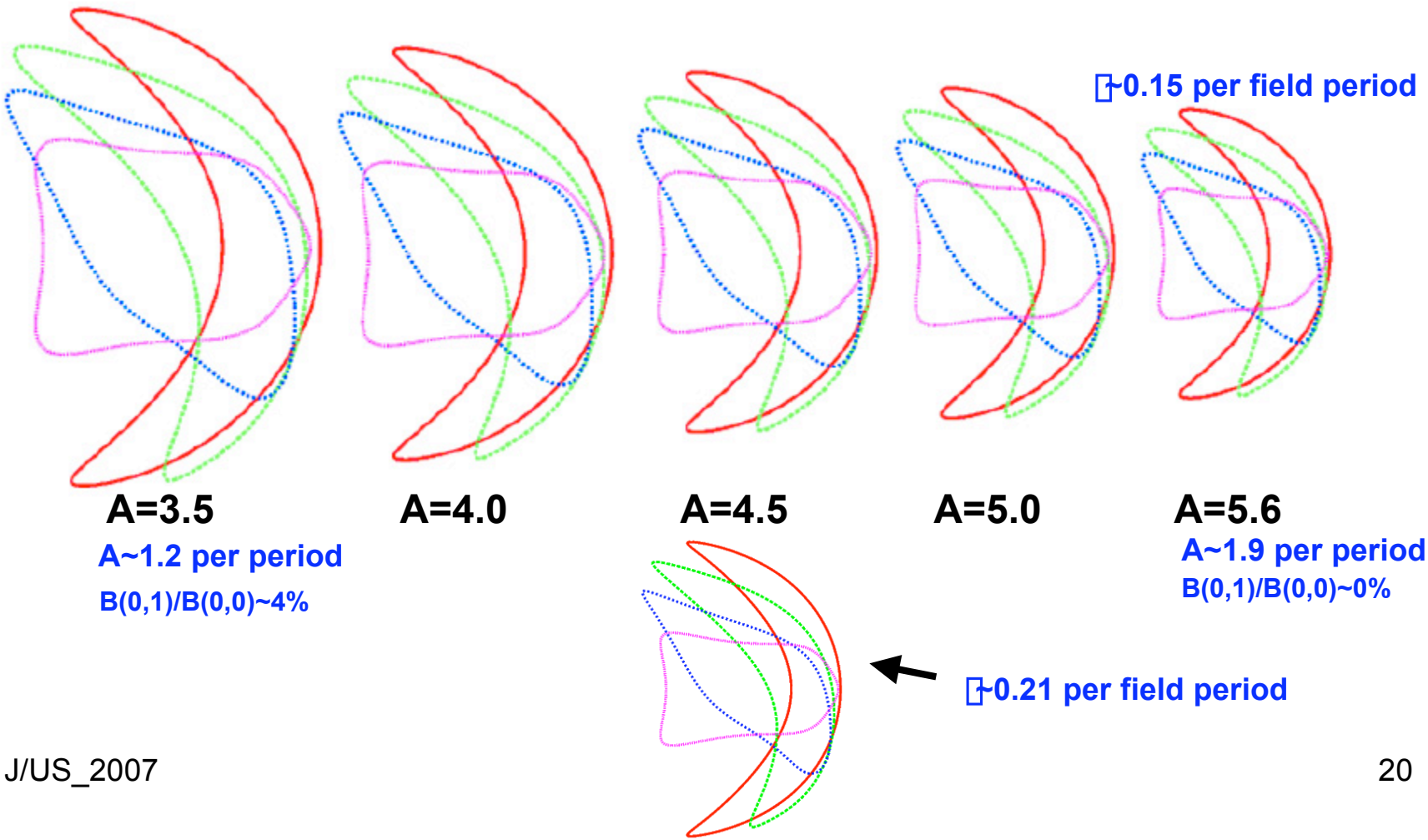
Heat load profile for lower OB half-plate

Issues Considered in Configuration Optimization

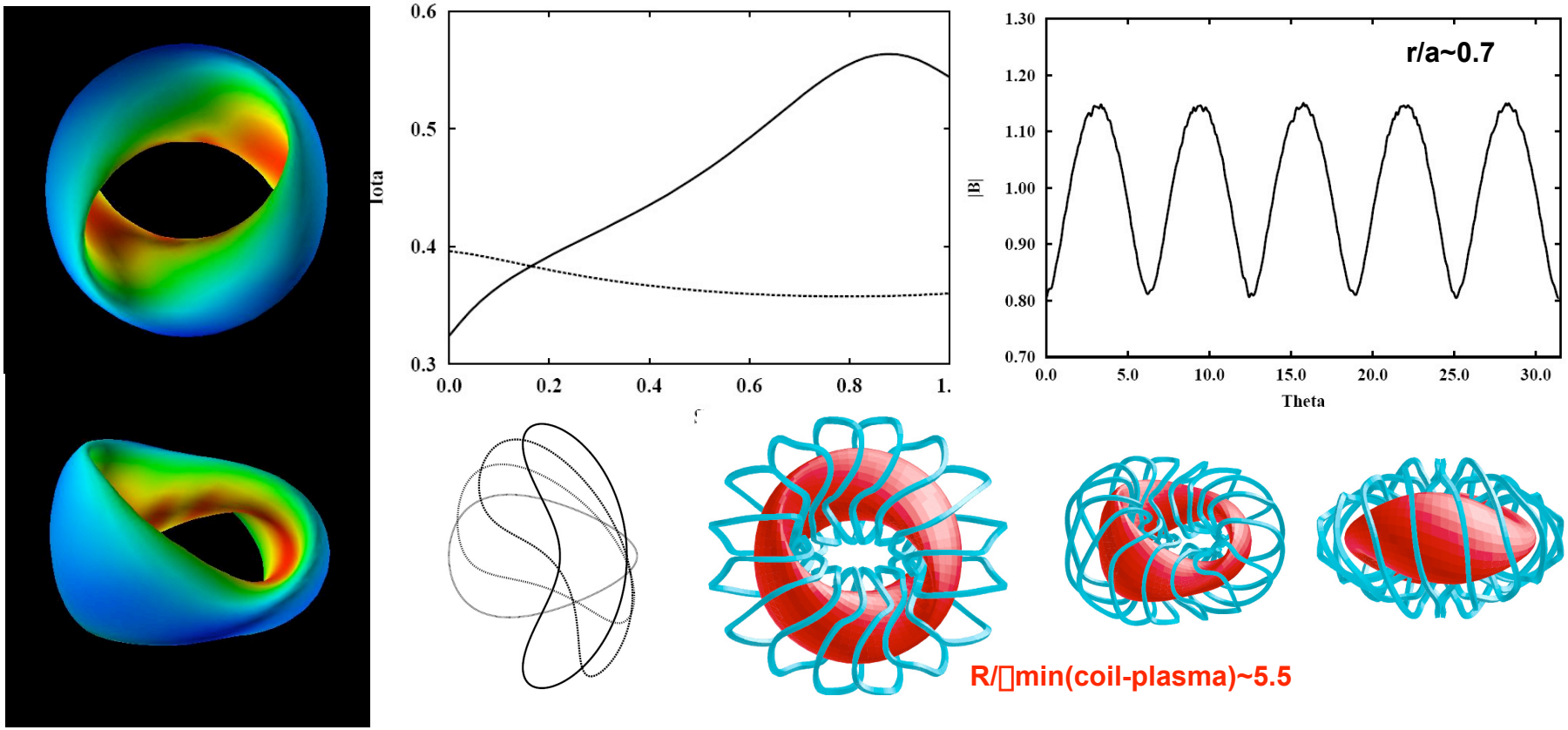
- **Issues important to experiments and QA reactors:**
  - **MHD stability**
  - **thermal confinement**
- **Critical considerations specific to QA reactors:**
  - **confinement of alpha particles**
  - **flux surface integrity**
  - **divertor heat load**
  - **space for blanket/shielding**
  - **maximum field in superconductors**
  - **coils for ease of machine maintenance**

The Advanced and Other Interesting Configurations

The baseline configuration has the characteristic mirror and helical components in the magnetic spectrum for reducing □ power loss fraction. Configurations with this unique feature spans a wide range of aspect ratios and rotational transforms.



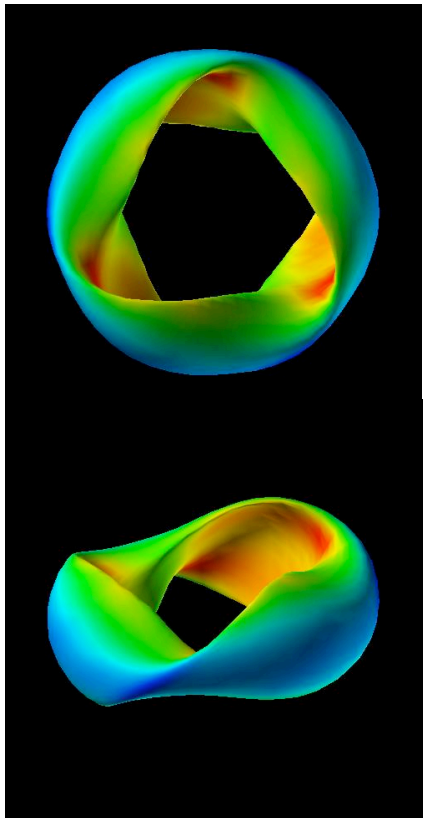
It appears that the lower end of the aspect ratio to maintain good quasi-axisymmetry is ~1.2 per field period, leading to the possibility of designing configurations with A as small as 2.5 for two field-period machines. Here is an example of the MHH2 family (MHH2-K14) chosen for its "gentle" shape. MHD stability and flux surface quality need more studies.

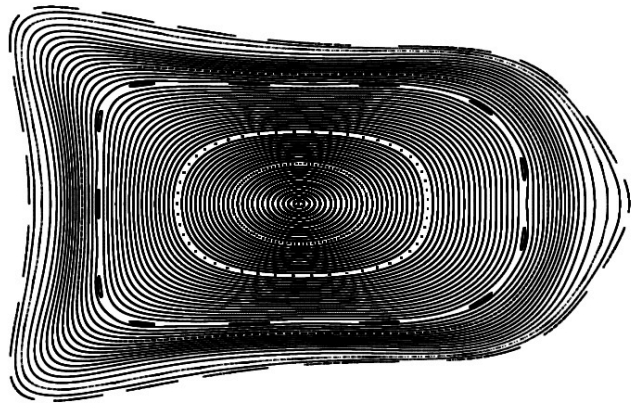


*P. Garabedian & L. P. Ku, FS&T, 47, 400 (2005)

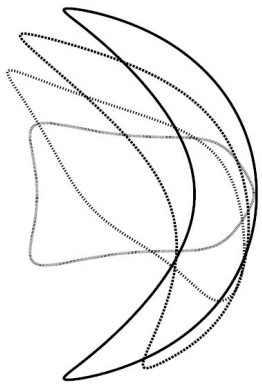
*L. P. Ku, Proc. 21st IEEE/NPSS Symposium on Fusion Engineering, Knoxville, TN, Sept. 26-29 (2005).

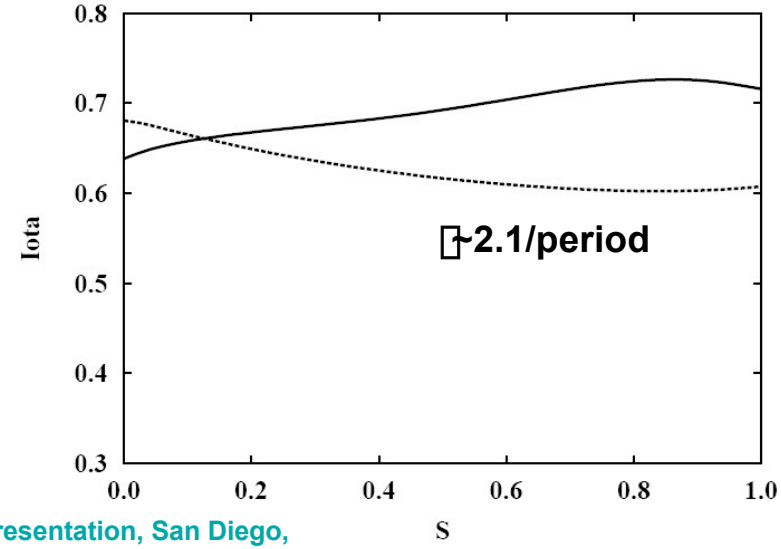
We have also developed the "SNS" family of configurations whose rotational transform profiles are specifically designed to minimize the effects of resonance on the surface integrity. There are members in the family of the baseline configuration that also have similar properties. Here is an example with A~4.5 in which the iota profile lies in a region without low order resonances at 5% β. Coils with good physics and engineering properties need to be designed.





Equilibrium at 5% β calcuated by the PIES code, showing the excellent flux surface integrity





L.P. Ku, ARIES-CS project meeting presentation, San Diego, June 14 (2006).

NCSX experiment will provide necessary physics data base for design improvement.

- **Design involves tradeoffs. Experimental data will help to quantify :**
  - **Rotational transform from coils and self-generated bootstrap current (how much of each?)**
  - **Bootstrap current affected by levels of non-axisymmetric residues (how sensitive?)**
  - **3D plasma shaping to stabilize instabilities (how strong?)**
  - **Quasi-axisymmetry to reduce ripple transport, alpha losses, flow damping (how low must ripple be?)**
  - **Role of non-axisymmetric residues in ripple transport (good/bad? which one? how much?)**
  - **Power and particle exhaust via a divertor (what topology?)**
  - **R/a (how low?) and β (how high?)**

Summary and Conclusion

- **The ARIES-CS baseline configuration meets requirements of MHD stability and particle confinement for high β operations.**

- **Divertors have been developed for particle and power handling; however, an optimized design that satisfy all requirements remains a major topic for future research.**

- **The baseline coils have sufficient space for blanket/shielding so that reactors of R≤8 m to yield 1 GW electric power is achievable. Coil to coil spacing is also sufficient for the implementation of port maintenance scheme.**

- **Our physics studies have uncovered a rich landscape of potentially attractive QA configurations. Related efforts in coil design and system trade-offs may further improve our reactor design .**

- **The experimental results of NCSX should provide a physics data base using which the uncertainties of the present-day design will be reduced and improved design criteria established.**