Exploration of Compact Stellarators as Power Plants:

Initial Results from ARIES-CS Study

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UC San Diego

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Exploration and Optimization of Compact Stellarators as Power Plants -- Motivations

Timeliness:

- Initiation of NCSX and QSX experiments in US; PE experiments in Japan (LHD) and Germany (W7X under construction).
- Progress in our theoretical understanding, new experimental results, and development of a host of sophisticated physics tools.

Benefits:

- Such a study will advance physics and technology of compact stellarator concept and addresses concept attractiveness issues that are best addressed in the context of power plant studies, *e.g.*,
  - ✓ α particle loss
  - ✓ Divertor (location, particle and energy distribution and management)
  - ✓ Practical coil configurations.
- NCSX and QSX plasma/coil configurations are optimized for most flexibility for scientific investigations at PoP scale. Optimum plasma/coil configuration for a power plant (or even a PE experiment) will be different. Identification of such optimum configuration will help define key R&D for compact stellarator research program.

ARIES-Compact Stellarator Program Has Three Phases

<u>FY03/FY04: Exploration of Plasma/coil Configuration and Engineering Options</u>

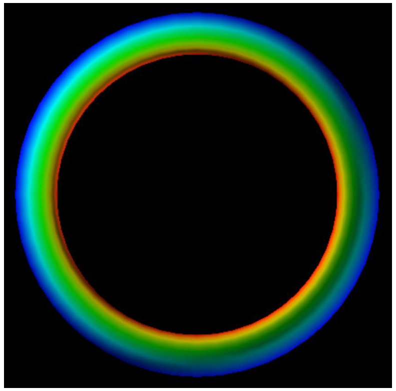
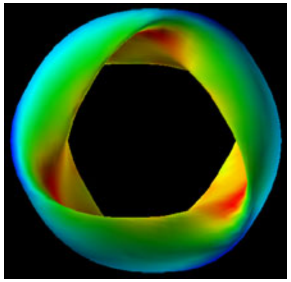
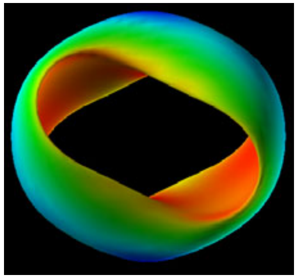
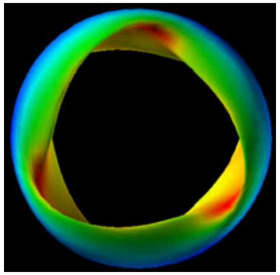
1. Develop physics requirements and modules (power balance, stability, α confinement, divertor, *etc.)*
2. Develop engineering requirements and constraints.
3. Explore attractive coil topologies.

<u>FY04/FY05: Exploration of Configuration Design Space</u>

1. Physics: β, aspect ratio, number of periods, rotational transform, sheer, *etc.*
2. Engineering: configuration optimization, management of space between plasma and coils, etc.
3. Choose one configuration for detailed design.

<u>FY05/FY06: Detailed system design and optimization</u>

We have focused on Quasi-Axisymmetric stellarators that have tokamak transport and stellarator stability

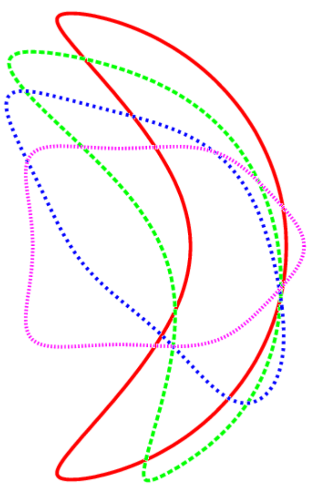





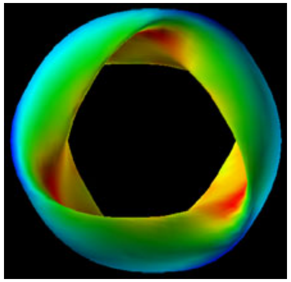
- In 3-D magnetic field topology, particle drift trajectories depend only on the strength of the magnetic field not on the shape of the magnetic flux surfaces. QA stellarators have tokamak-like field topology.
- Stellarators with externally supplied poloidal flux have shown resilience to plasma disruption and exceeded stability limits predicted by linear theories.
- QA can be achieved at lower aspect ratios with smaller number of field periods.
  - ✓ A more compact device (R<10 m),
  - ✓ Bootstrap can be used to our advantage to supplement rotational transform,
  - ✓ Shown to have favorable MHD stability at high β.

Three Classes of QA Configuration have been studied

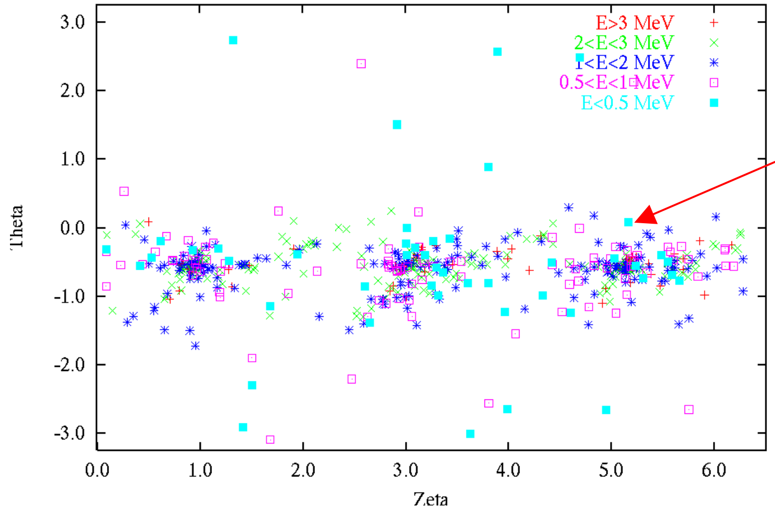
I. NCSX-like configurations

- ✓ Good QA, low effective ripple (<1%), a energy loss ≤15% in 1000 m^3 device.
- ✓ Stable to MHD modes at $\beta \geq 4\%$
- ✓ Coils can be designed with aspect ratio ≤ 6 and are able to yield plasmas that capture all essential physics properties.
- ✓ Resonance perturbation can be minimized.





Footprints of escaping α on LCMS for B5D.
Energy loss ~12% in model calculation.

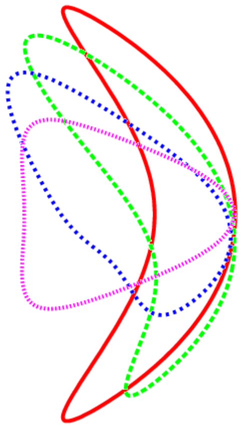


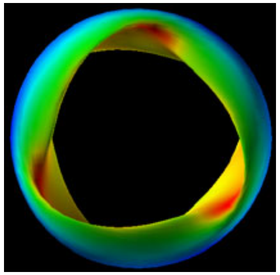
Heat load maybe localized and high (~a few MW/m^2)

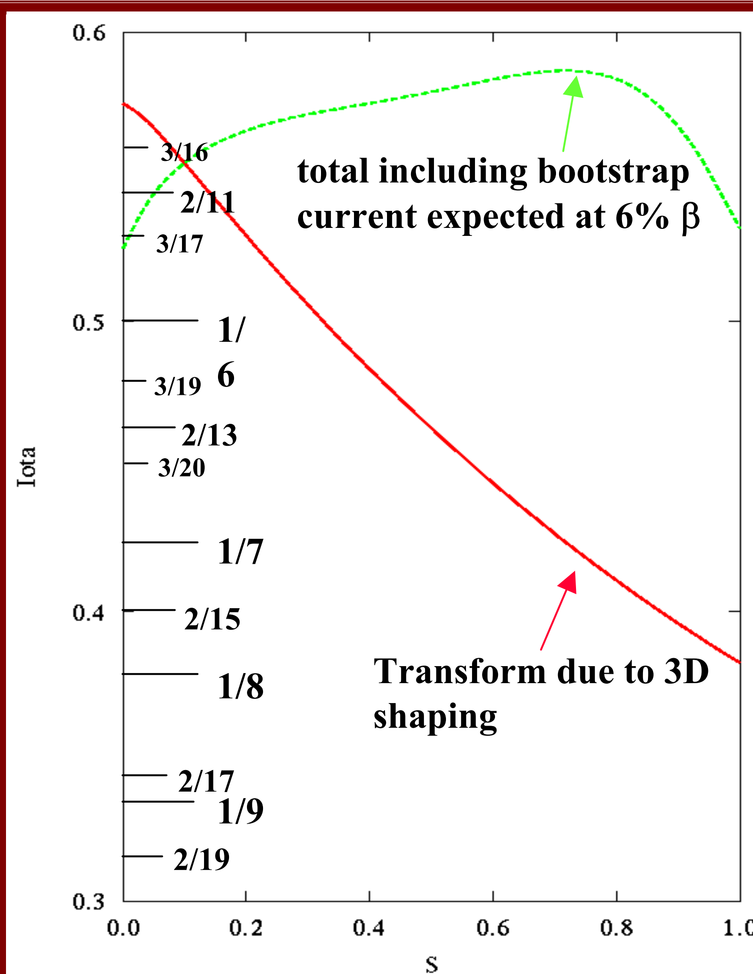
Three Classes of QA Configuration have been studied

II.SNS-QA configurations

- ✓ Newly discovered, aimed particularly at having good flux surface quality.
- ✓ Characterized by strong negative magnetic shear from shaping coils.
- ✓ Have excellent QA and good a confinement characteristic (loss ~10%).
- ✓ Exist in 2 and 3 field periods at various iota range.
- ✓ Inherent deep magnetic well.







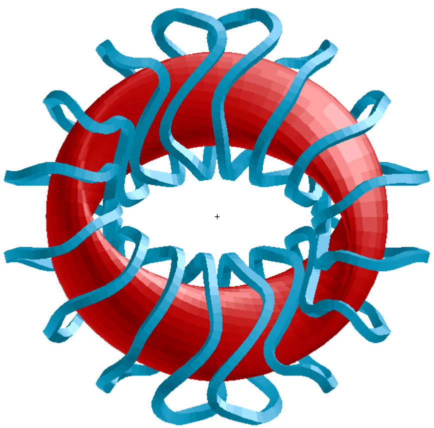
The rotational transform is avoiding low order resonance in regions away from the core at target β, yet superb quasi-axisymmetry is achieved.

Three Classes of QA Configuration have been studied

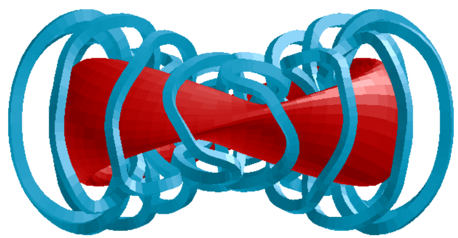
III. MHH2

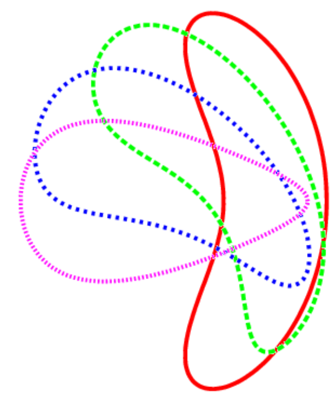
- ✓ Low plasma aspect ratio (A < 3.5) in 2 field period.
- ✓ Simple shape, "clean" coils

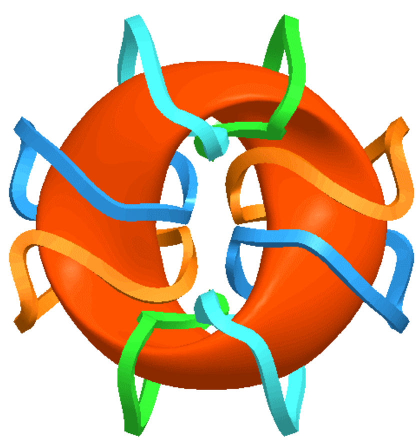
O-II-1.2: Garabedian



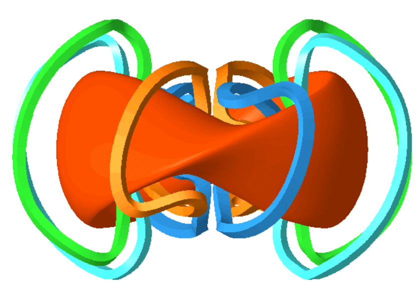
A=3.7 and 16 coils

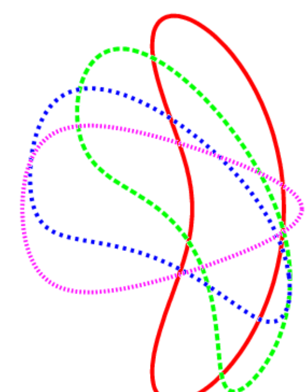




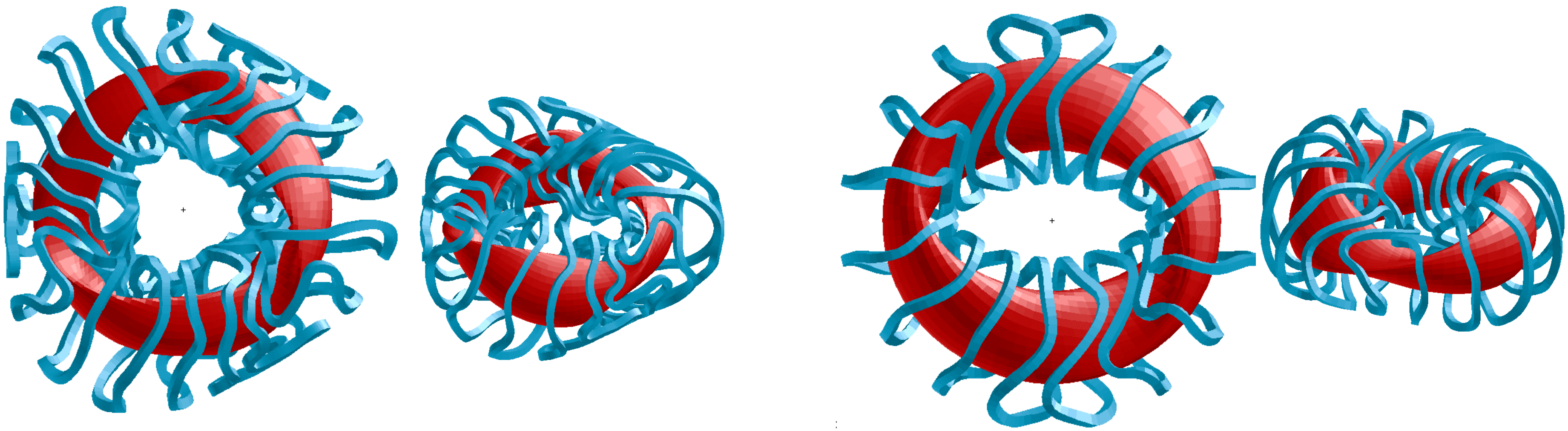


A = 2.7 and 8 coils



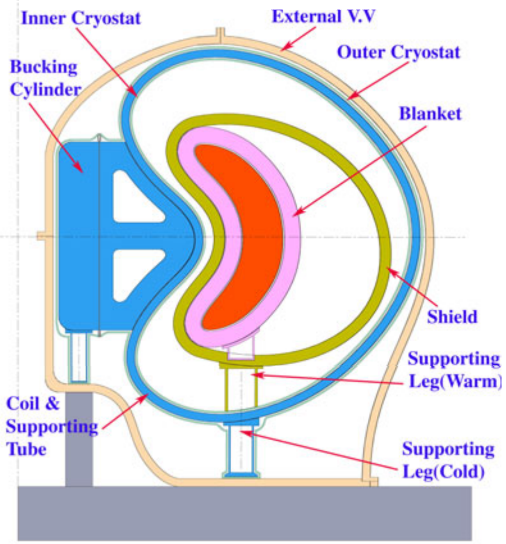


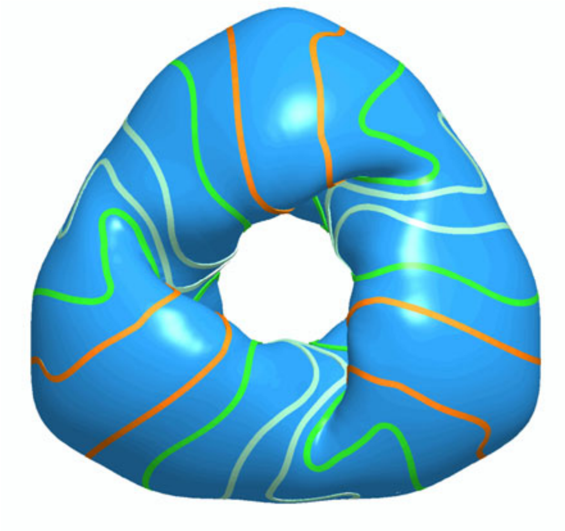
Desirable plasma configuration should be produced by practical coils with low complexity

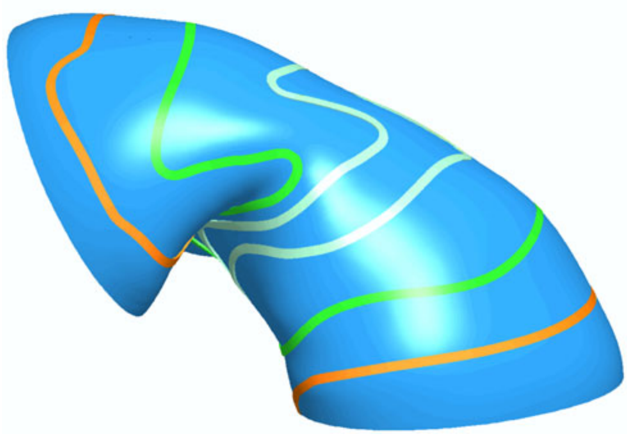


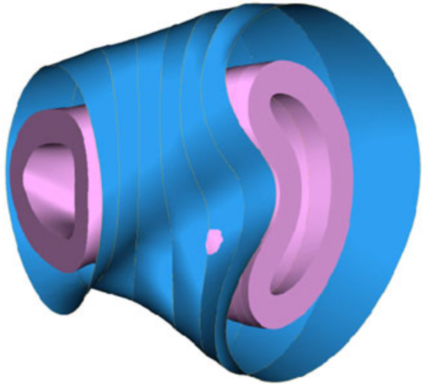
- Complex 3-D geometry introduces sever engineering constraints:
  - ✓ Distance between plasma and coil
  - ✓ Maximum coil bend radius and coil support
  - ✓ Assembly and maintenance (most important)

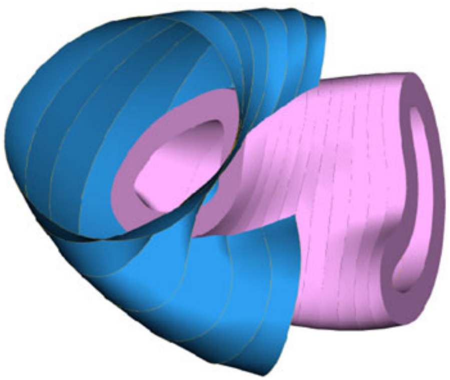
Field-Period Assembly and Maintenance

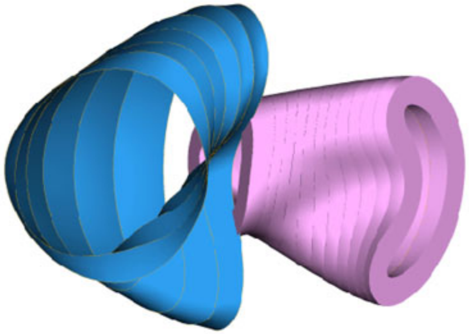




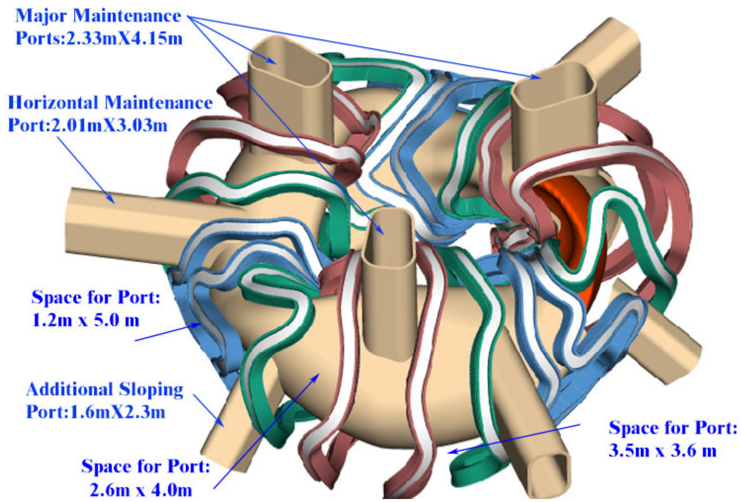


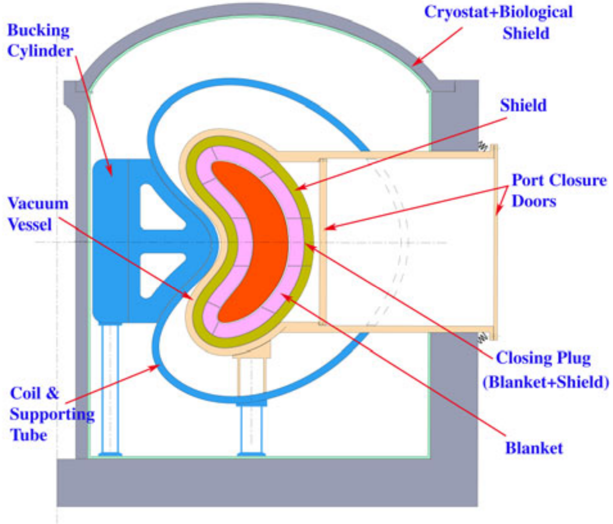


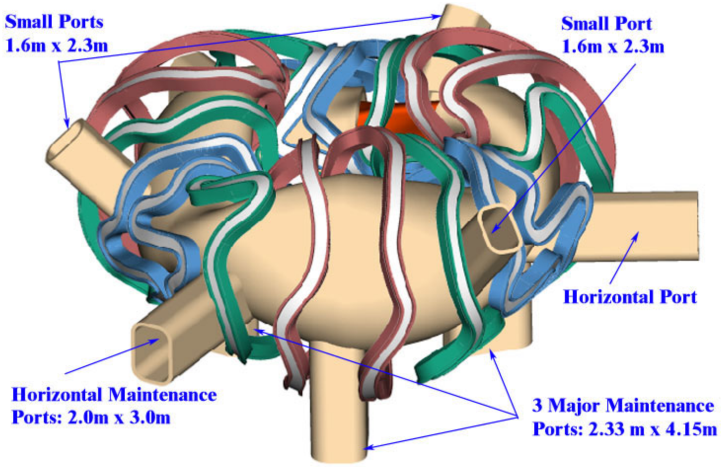




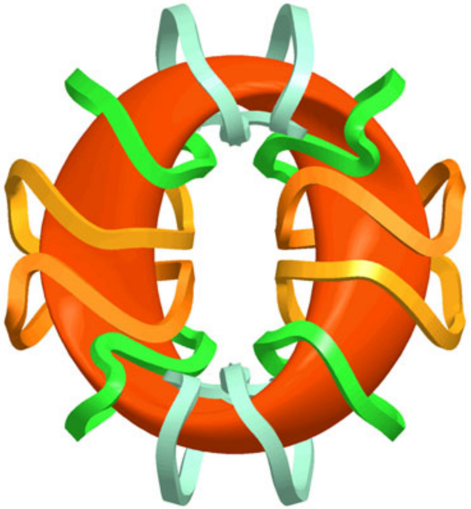
Modular Maintenance through ports



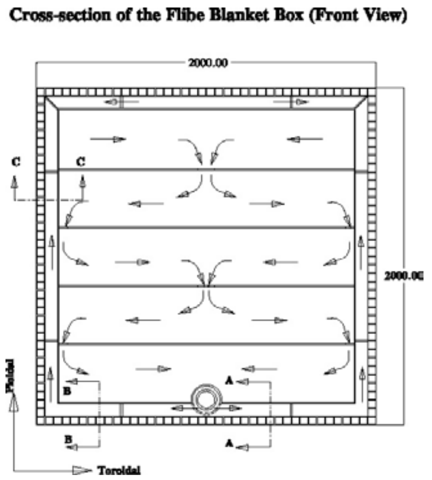




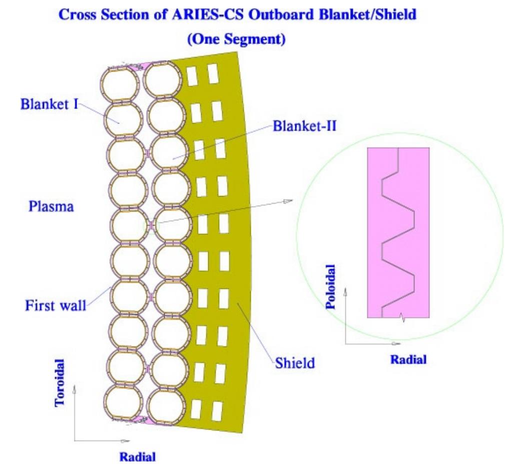
O-II-1.2: Raffray
P-I-31: Wang



Five Blanket Concepts Were Evaluated

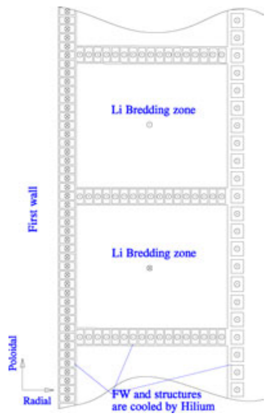


O-II-1.4: Raffray

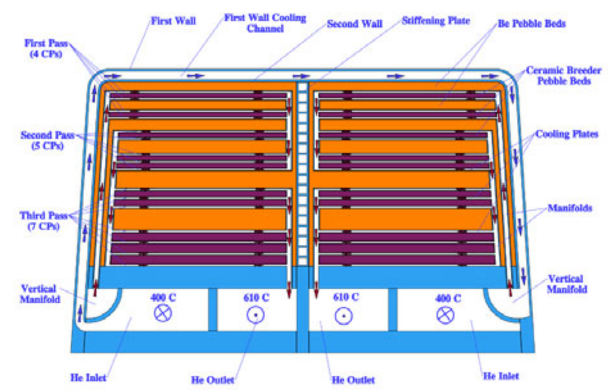


1) Self-cooled FLiBe with ODS Ferritic Steel (Modular maintenance)

2) Self-cooled PbLi with SiC Composites (ARIES-AT type)



O-II-5.6: Raffray

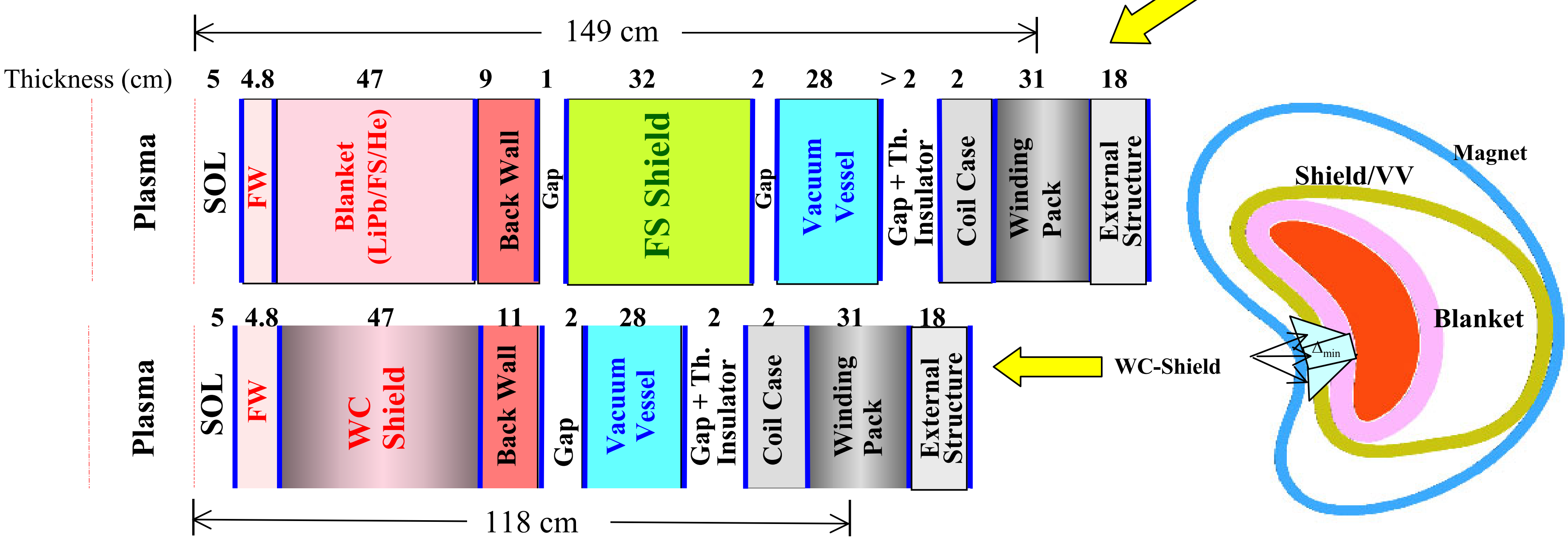


3 & 4) Dual-coolant blankets with He-cooled Ferritic steel structure and self-cooled Li or LiPb breeder (ARIES-ST type)

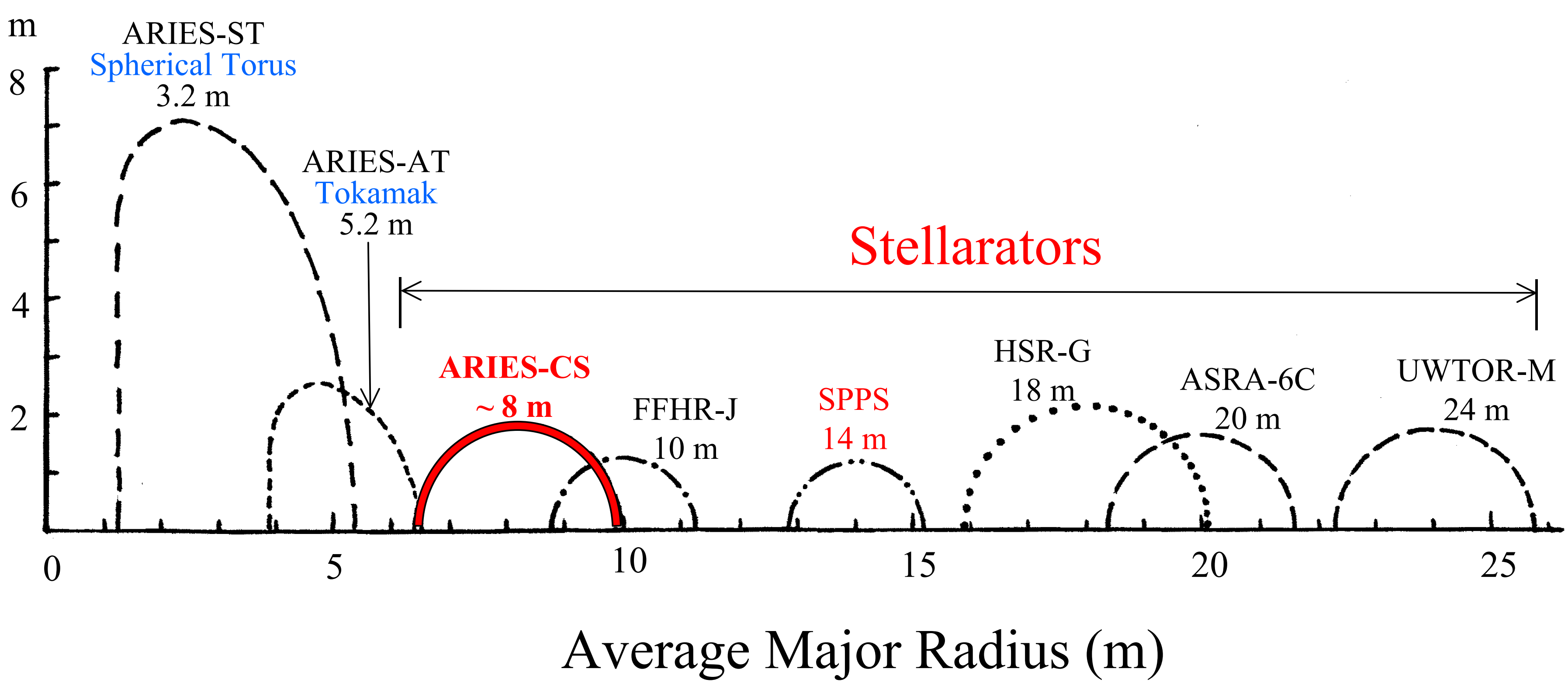
5) He-cooled solid breeder with Ferritic steel structure (Modular maintenance)

Key Parameters of the ARIES-CS Blanket Options

O-II-1.4: El-Guebaly	Flibe/FS/Be	LiPb/SiC	SB/FS/Be	LiPb/FS	Li/FS
Δ_{min}	1.11	1.14	1.29	1.18	1.16
TBR	1.1	1.1	1.1	1.1	1.1
Energy Multiplication (M_n)	1.2	1.1	**1.3**	1.15	1.13
Thermal Efficiency (η_{th})	45%	55-60%	45%	~45%	~45%
FW Lifetime (FPY)	6.5	6	4.4	5	7



Comparison of Power Plant Sizes



O-II-1.3: Lyon

Summary

- The physics basis of QA as candidate of compact stellarator reactors has been assessed. New configurations have been developed, others refined and improved, all aimed at low plasma aspect ratios ($A \leq 6$), hence compact size:
  - ✓ Both 2 and 3 field periods possible.
  - ✓ Progress has been made to reduce loss of a particles to ~10%; this is still higher than desirable.
  - ✓ Stability to linear, ideal MHD modes (kink, ballooning, and Mercier) may be attained in most cases, but at the expense of the reduced QA and increased complexity of plasma shape. Recent experimental results indicated that linear, ideal MHD may be too pessimistic, however.
  - ✓ Assessment of particle/heat loads on in-vessel components are underway.

Summary

- Modular coils are designed to examine the geometric complexity and the constraints of the maximum allowable field, desirable coil-plasma spacing and coil-coil spacing, and other coil parameters.
- Assembly and maintenance is a key issue in configuration optimization:
  - ✓ Field-period assembly and maintenance.
  - ✓ Modular assembly and maintenance through ports.
- Five different blanket concept were evaluated:
  - ✓ Nuclear performance
  - ✓ Affinity with assembly/maintenance scheme (e..g, low-weight modules for modular approach).
  - ✓ Minimum coil-plasma separation.
- Systems level assessment of these options are underway.

This Session:

- **O-II-1.1: Najmabadi et al., "Exploration of of Compact Stellarators as Power Plants, Initial Results from ARIES-CS Study"**
- **O-II-1.2: Garabedian et al., "Reactors with Stellarator Stability and Tokomak Transport"**
- **O-II-1.3: Lyon et al., "Optimization of Stellarator Rector Parameters"**
- **O-II-1.4: Raffray et al., "Attractive Design Approaches for a Compact Stellarator Power Plant"**
- **O-II-1.5: El-Guebaly et al., "Benefits of Radial Build Minimization and Requirements Imposed on ARIES Compact Stellarator Design"**

6. **O-II-5.6: Raffray et al., "Ceramic Breeder Blanket for ARIES-CS" Wed. Afternoon**
7. **P-II-29, El-Guebaly et al., "Initial Activation Assessment for ARIES Compact Stellarator Power Plant" Wed. Afternoon**
8. O-1-3.3: El-Guebaly et al., "Evaluation of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants"
9. P-1-28: M. Wang et al., "Three-dimensional Modeling of Complex Fusion Devices Using CAD-MCNP Interface"
10. P-I-31: Wang et al., " Maintenance Approaches for ARIES-CS Power Core,"

Extra Slides

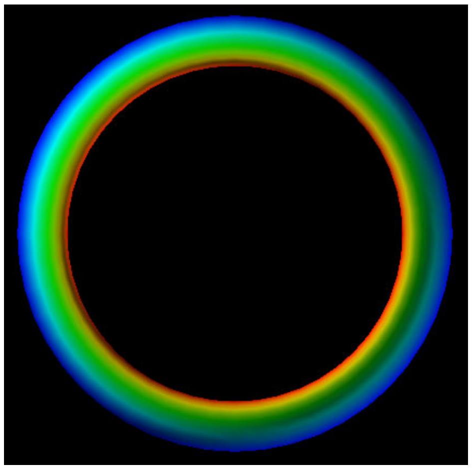
The discovery of quasi-axisymmetric stellarators opens up the possibility of designing fusion reactors that have tokamak transport and stellarator stability.

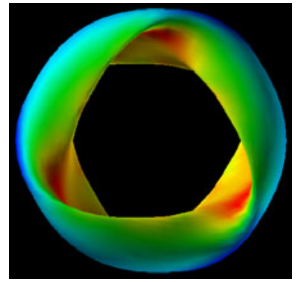
- In 3-D magnetic field topology, particle drift trajectories depend only on the strength of the magnetic field, not on the vector components of the field nor on the shape of the magnetic flux surfaces.
  - QA → tokamak-like field topology → good particle confinement.
- Stellarators with externally supplied poloidal flux have shown resilience to plasma disruption and exceeded stability limits predicted by linear theories.
- QA can be achieved at lower aspect ratios with smaller number of field periods.
  - more compact device (R<10 m),
  - bootstrap can be used to our advantage to supplement rotational transform,
  - shown to have favorable MHD stability at high beta.

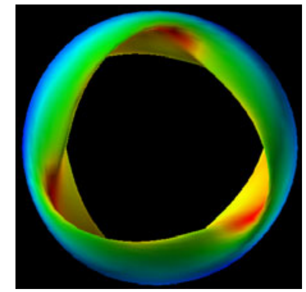
There are many stellarator reactors studied in the past based on a variety of confinement concepts, but all have large sizes. We aim at QA reactors having sizes competitive with advanced tokamaks.

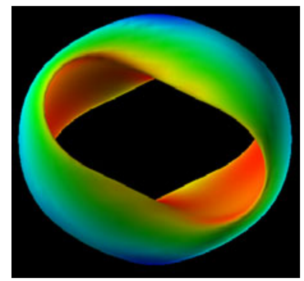
- Helias Reactors based on the concept of W7X (linked mirror, omnigeneous):
  - HSR5/22, 5-field period, A=10, R=22 m, B=5 T, B_{max}=10 T, P_f=3 GW, β~4%.
  - HSR4/18, 4-field period, A=8, R=18 m.
  - HSR3/15, 3-field period, A=6, R=15 m.
  -
- SPPS, Modular Helias-like Heliac (QA)
  - MHH4, 4-field period, A=8.54, R=13.95 m, B=4.94 T, B_{max}=14.5 T.
- Haliotron/Torsatron (classical *l*=2 stellarator)
  - FFHR, 10-field period, A=10, R=10-20 m.

Tokamak-like magnetic field topology can be achieved approximately by three dimensional shaping of the plasma.









- Because we can only find approximate solutions, configurations are not unique.
- The normally over-determined system allows one to impose further constraints, such as MHD stability to the kink or ballooning modes, the shape and magnitude of rotational transform and so on, in the solution.
- Optimization of solution is sought once a set of constraints are defined. The configuration space is immense, however.

Plasma optimization

Plasma boundary represented as Fourier harmonics

Initial "guess", boundary as independent variables

Constraints/weights

1) Select p, J profiles, β, B, FP
2) Iota target
3) MHD stability target (Mercier, ballooning, kink)
4) Transport target (QA, ripple)
5) Coil target (complexity, current density)

ballooning

kink

transport

shape/position

coil complexity

1) Evaluate equilibrium (VMEC, NSTAB), 2) Jacobian calculation, 3) determine direction of descent, 4) perform functional minimization (Levenberg-Marquardt, GA).

Targets met?

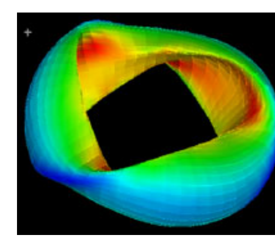
No

Modify weights

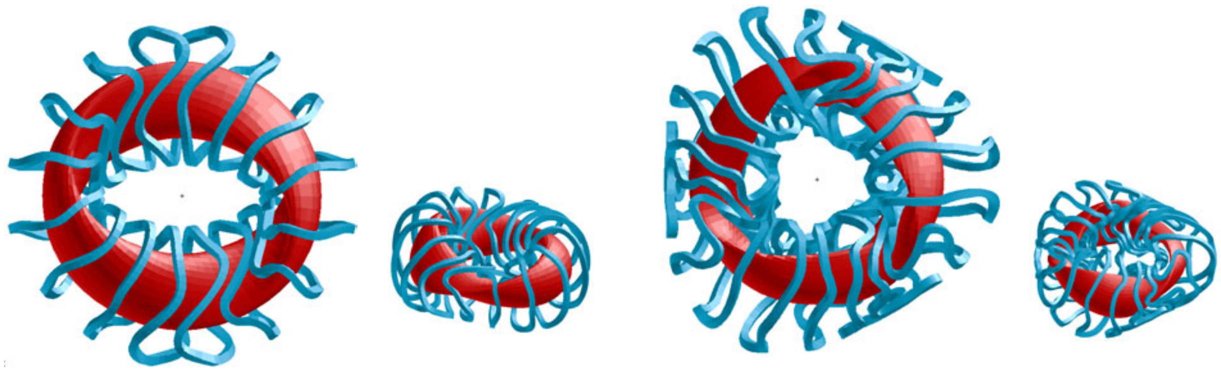
Yes

Islands healing, PIES

Refined calculation and detailed analysis



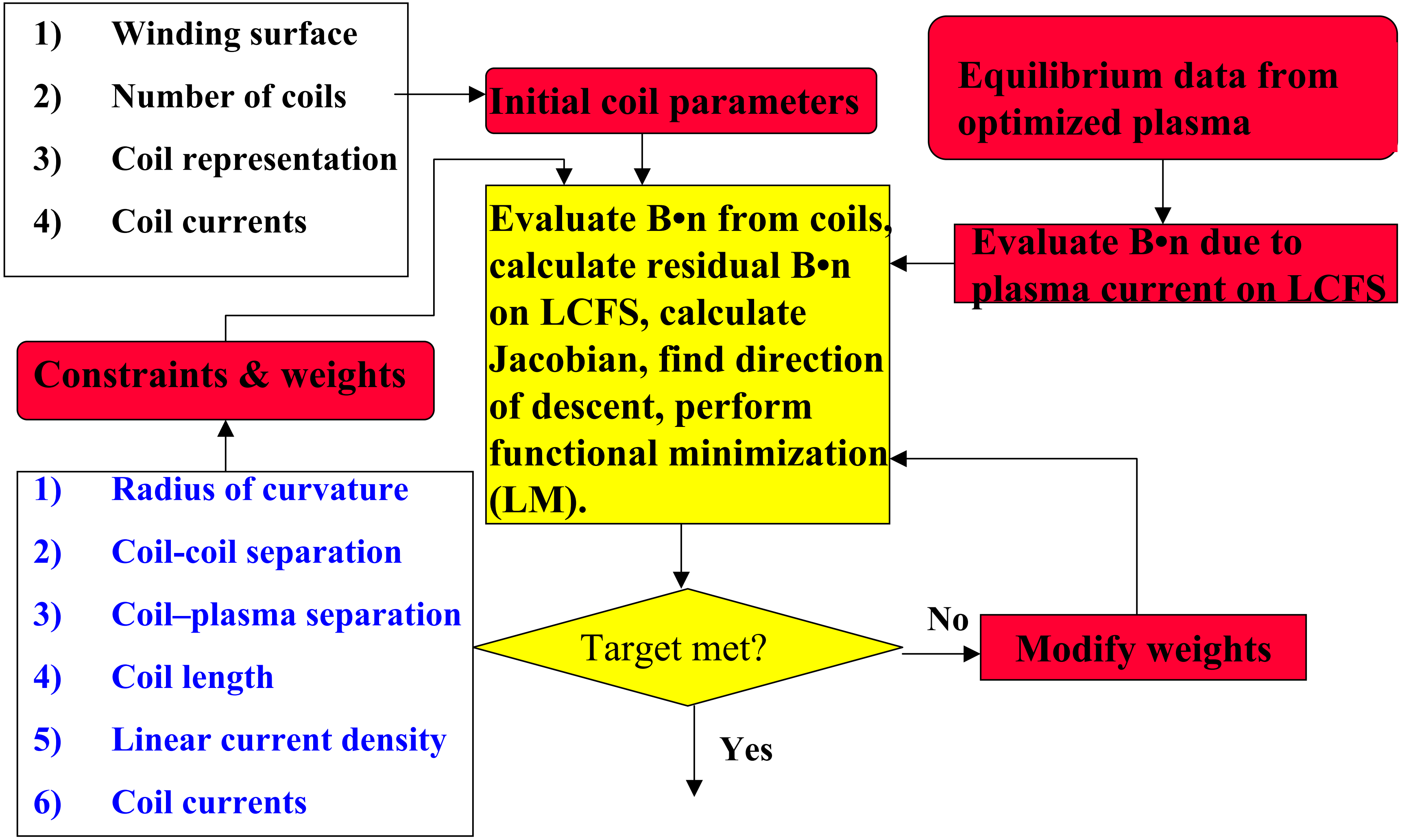
An important element in our effort is to find coils that would produce the desirable plasma with low complexity and good engineering properties.



- 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:
  - 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 try to maximize Δ_{min}(coil-plasma), Δ_{min}(coil-coil) and minimize B_{max}/B_0 to the extent possible.
- Again, optimization process is invoked since there may involve a large number of independent variables (> 100) as well as constraints.

Coil Design and Optimization



We have refined, improved and expand configurations developed in the NCSX project and discovered new classes of configurations as well.

- We have explored configuration space with respect to

  - plasma aspect ratio,
  - number of field periods,
  - rotational transform – both magnitude and shear,
  - vacuum magnetic well depth, linear and non-linear MHD stabilities.

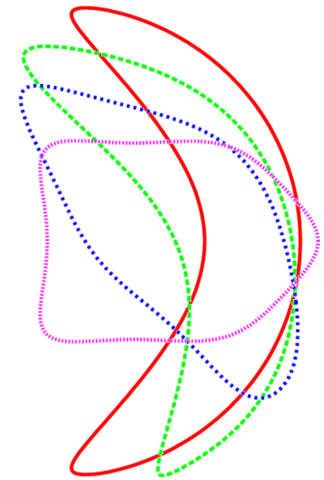
- We have devised ways to minimize the loss of α particles.

- We have investigated ways to mitigate the problem of magnetic islands and methods to improve the flux surface integrity.

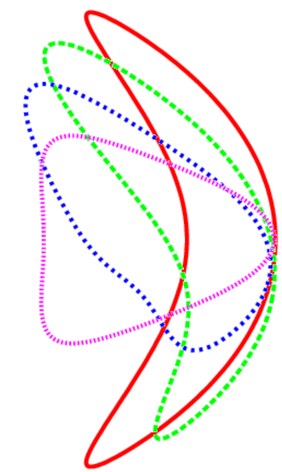
- We have studied coil topology to improve their overall physics and engineering performance.

Three classes of QA configurations have shown promise to be candidates for further reactor studies.

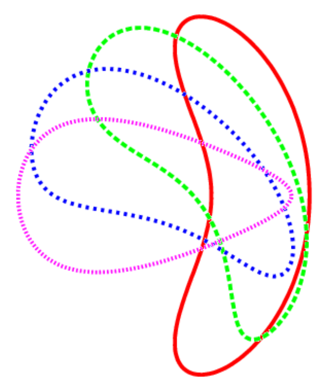
- NCSX-like configurations
  - Good QA, low effective ripple (<1%), α energy loss ≤15% in 1000 m^3 devic
  - Stable to MHD modes at β≥4%
  - Coils can be designed with aspect ratio ≤ 6 and are able to yield plasmas that capture all essential physics properties.
  - Resonance perturbation can be minimized.



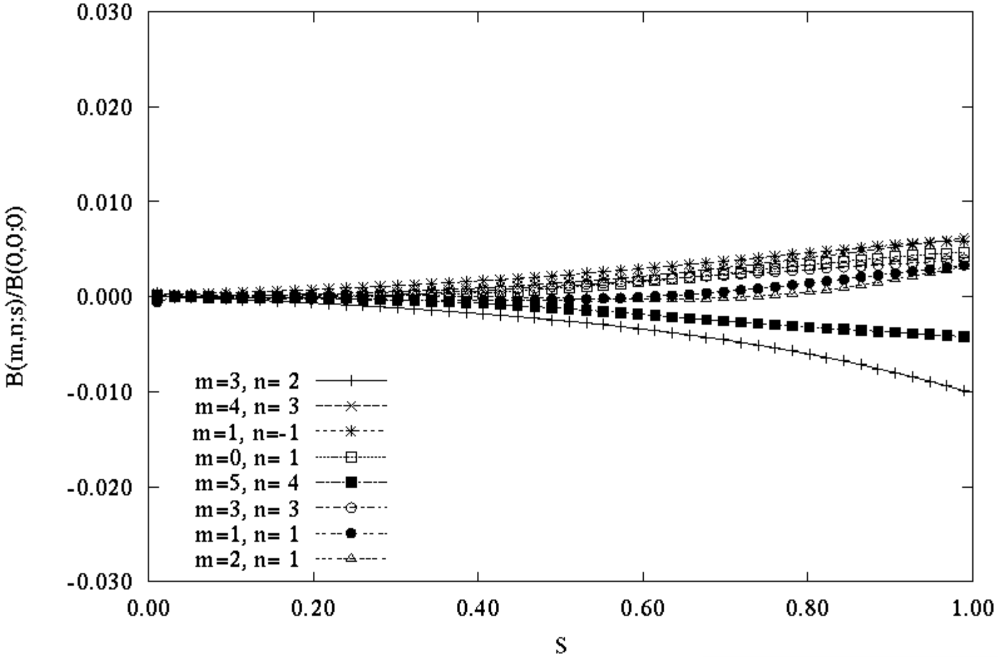
- SNS-QA configurations
  - Newly discovered, aimed particularly at having good flux surface quality.
  - Characterized by strong negative magnetic shear from shaping coils.
  - Have excellent QA and good α confinement characteristic (loss ~10%).
  - Exist in 2 and 3 field periods at various iota range.
  - Inherent deep magnetic well.



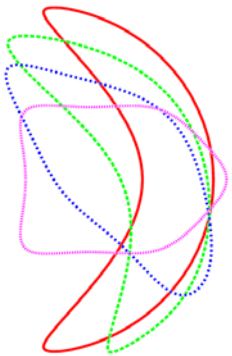
- MHH2
  - Low plasma aspect ratio (A<3.5) in 2 field period.
  - Simple shape, “clean” coils



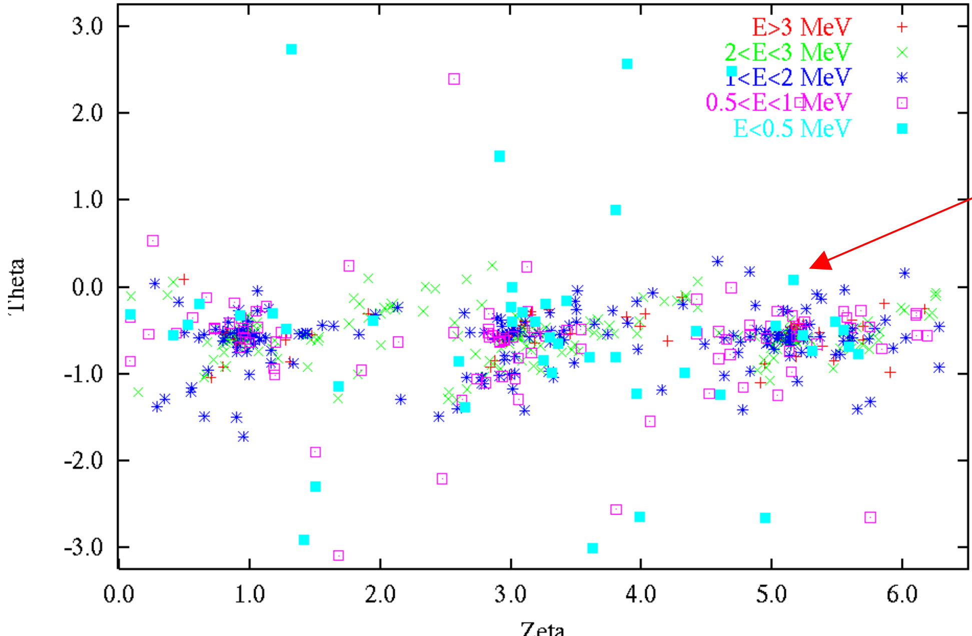
NCSX-like configurations have good quasi-axial symmetry and MHD stability at high β.



Magnetic spectrum of A=6, β=4% NCSX-like B5D configuration, showing the largest residue is <1%.

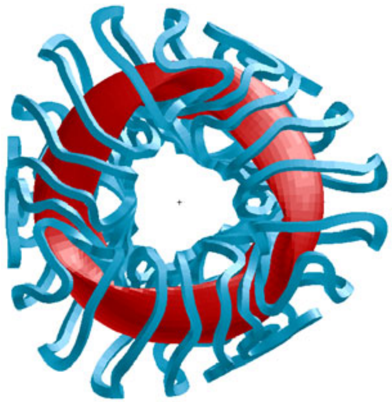


Footprints of escaping α on LCMS for B5D. Energy loss ~12% in model calculation.

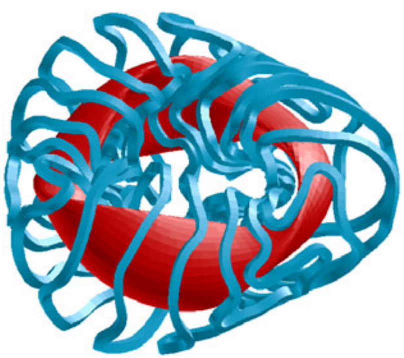


Heat load maybe localized and high (~a few MW/m²)

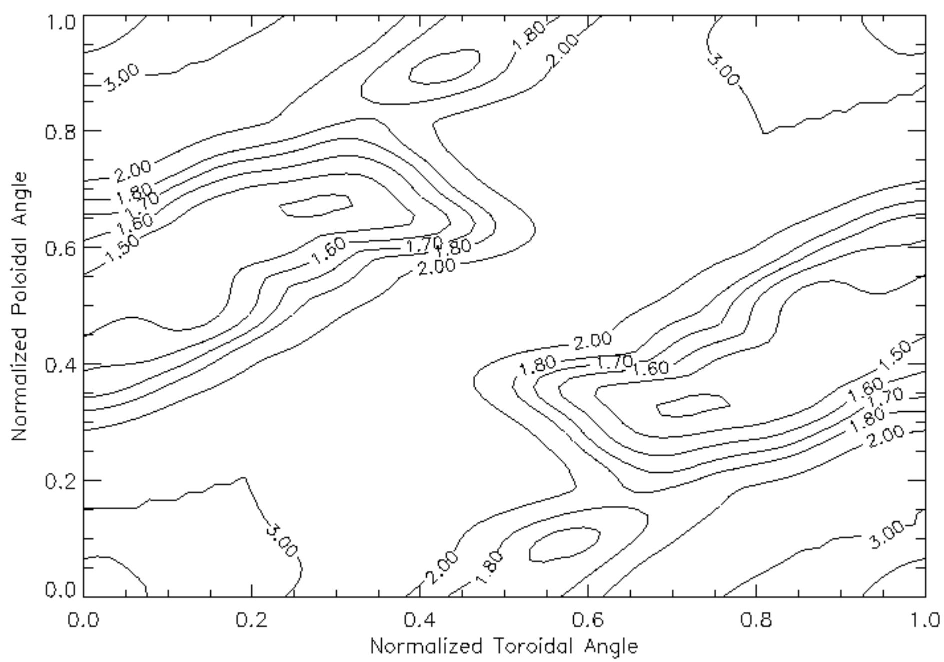
Optimization of modular coils has led to configurations with coil aspect ratios < 6, hence reactors of smaller sizes are realizable.



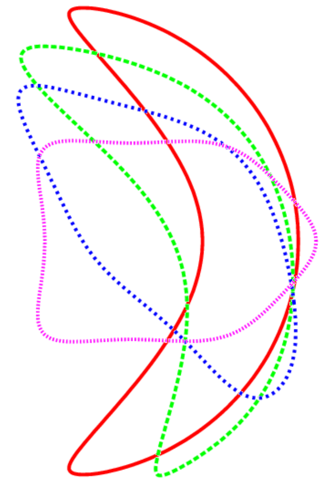
Distance between plasma and coil winding surface shown in one field period for a 3-field period, A=4.5 plasma with R=8.25 m and coils with A_c=6.



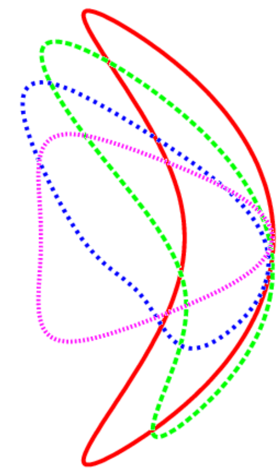
For R=8.25 m
Δ_{min}(c-p)=1.4 m
Δ_{min}(c-c)=0.83 m
I_{max}=16.4 MA @6.5 T
B_{max}/B_0~2 for 0.4 m x 0.4 m conductor



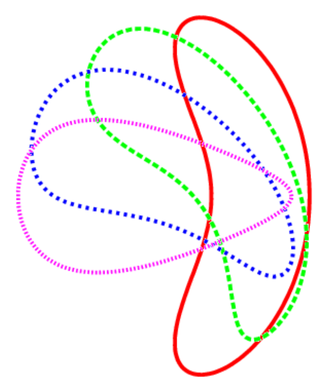
Three classes of QA configurations have shown promise to be candidates for further reactor studies.



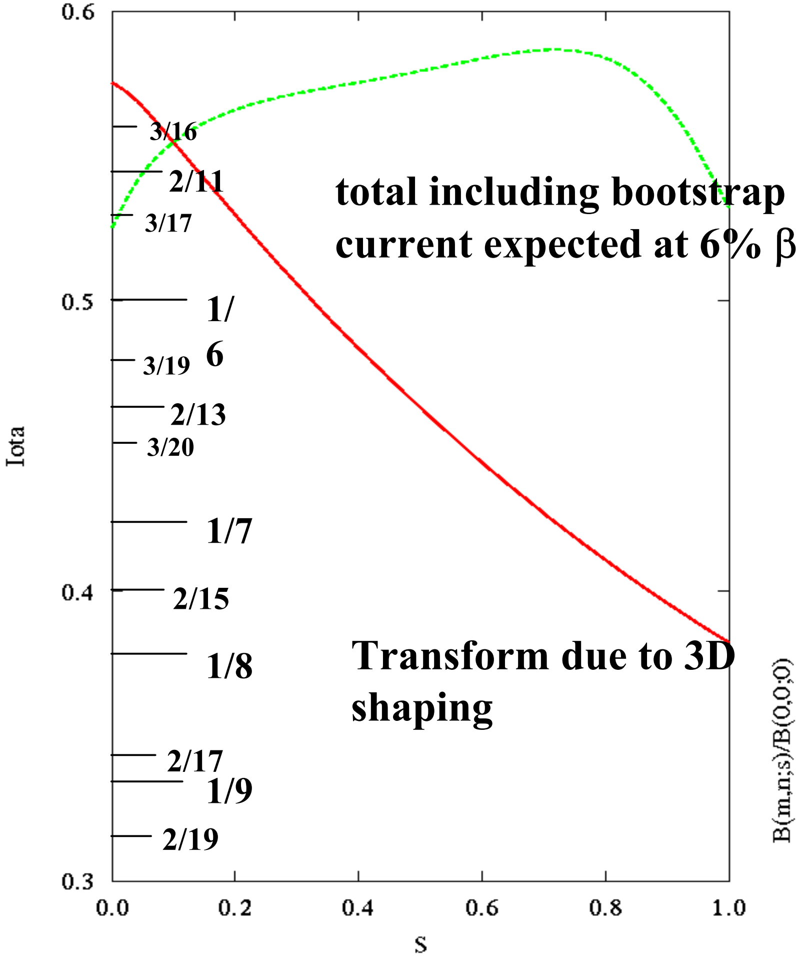
- NCSX-like configurations
  - Good QA, low effective ripple (<1%) and stable to MHD modes to β~5%
  - Loss of α can be limited to ≤15% in 1000 m^3 device at 6.5 T.
  - Coils can be designed with aspect ratio ≤ 6 and are able to yield plasmas that capture all essential physics properties.
  - Resonance perturbation can be minimized.

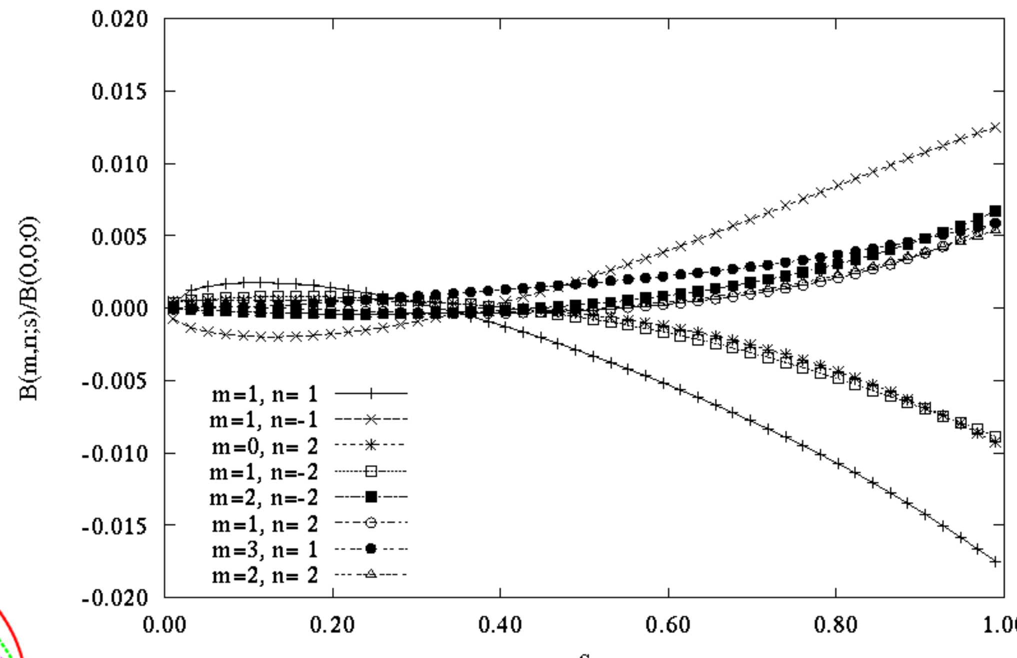


- SNS-QA configurations
  - Aimed particularly at having good flux surface quality.
  - Characterized by strong negative magnetic shear from shaping coils.
  - Have excellent QA and good α confinement characteristic (loss ~10%).
  - Exist in 2 and 3 field periods at various iota range.
  - Inherent deep magnetic well.
- MHH2
  - Low plasma aspect ratio (A<3.5) in 2 field period.
  - Simple shape, "clean" coils

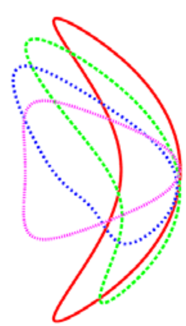


In SNS-QA, the rotational transform may be made to skirt most low order resonance in regions away from the core at target β, yet superb quasi-axisymmetry is achieved.

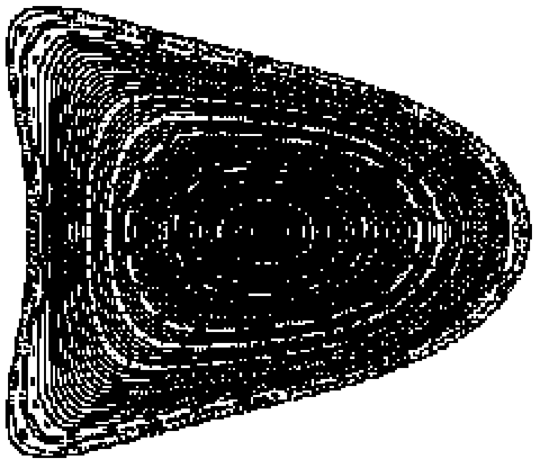


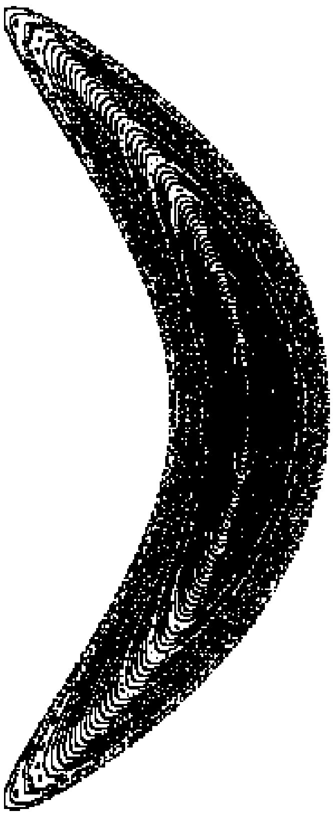


NF=3, A=6.0, ι_{ext}(avg)=0.48, $d\iota_{ext}/ds$=-0.2 @ β=0.0%



A case having excellent flux surface quality has been identified at 6% β.





Poincare plot of KJC167 at 6% β based on PIES calculations.

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  - Loss of α can be limited to ≤15% in 1000 m^3 device at 6.5 T.
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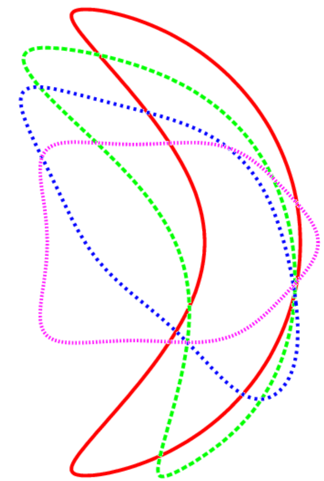

- SNS-QA configurations
  - Newly discovered, aimed particularly at having good flux surface quality.
  - Characterized by strong negative magnetic shear from shaping coils.
  - Have excellent QA and good α confinement characteristic (loss ~10%).
  - Exist in 2 and 3 field periods at various iota range.
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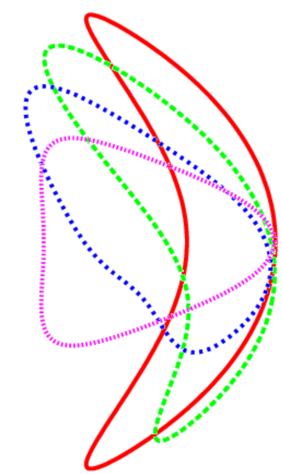

- MHH2
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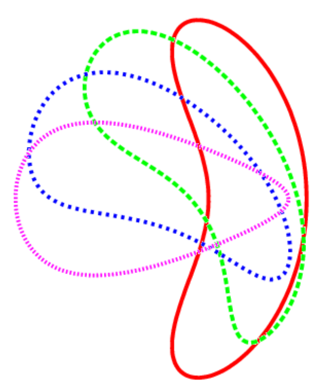
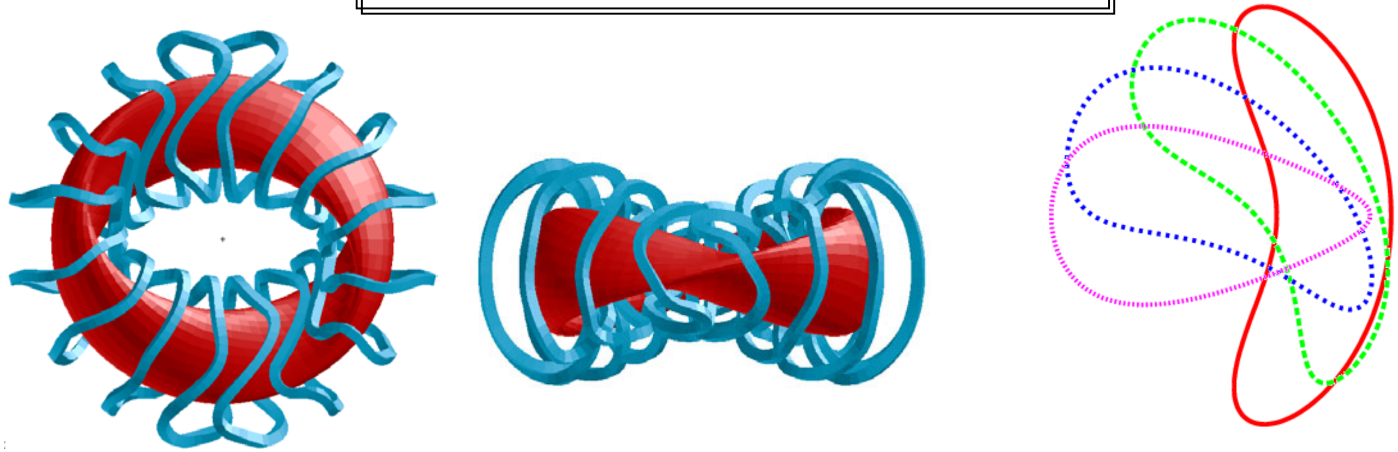
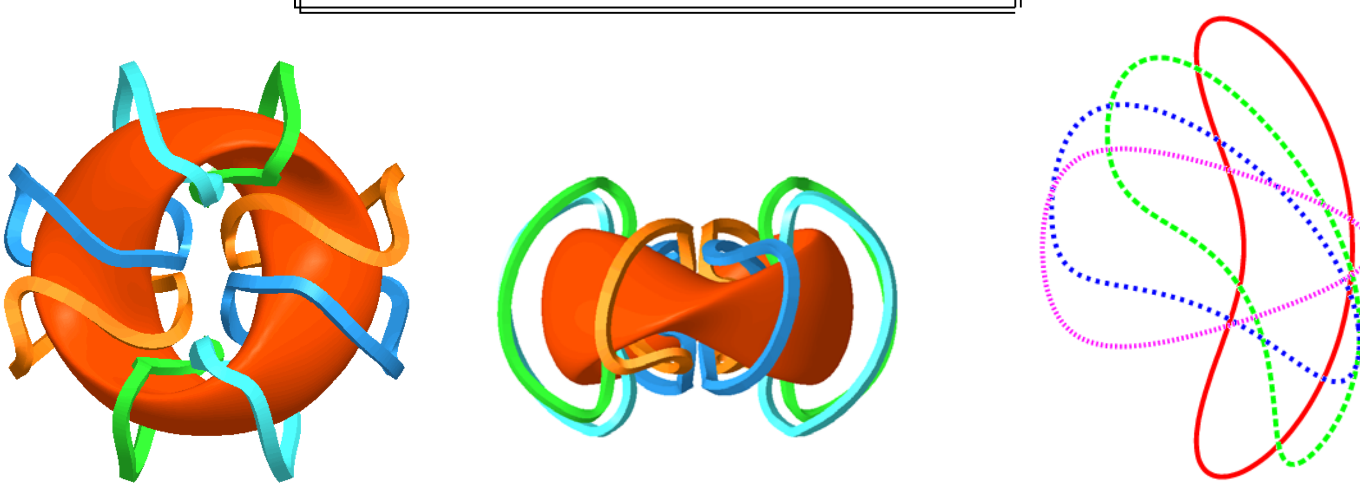


MHH2 with A=3.7 and 16 coils



MHH2 with A=2.7 and 8 coils



Summary

- The physics basis of QA as candidate of compact stellarator reactors has been assessed. New configurations have been developed, others refined and improved, all aimed at low plasma aspect ratios, hence compact sizes at a given fusion power.

  – Configurations with excellent QA have been found with $A \leq 6$. Configurations with both 2 and 3 field periods possible.
  – Progress has been made to reduce loss of α particles. Losses ~10% have been achieved; this is still higher than desirable, however.
  – Numerical calculations using codes based on linear, ideal MHD theories show stability to the kink, ballooning, and Mercier modes may be attained in most cases, but at the expense of the reduced QA and increased complexity of plasma shape. Recent experimental results indicated that linear, ideal MHD may be too pessimistic, however.

- Modular coils are designed to examine the geometric complexity and the constraints of the maximum allowable field, desirable coil-plasma spacing and coil-coil spacing, and other coil parameters.

  – Adequate space found for blanket/shield, although in some cases ingenuity needed in designs.
  – Field on axis ~7 T may be feasible.
  – Strong incentive to simplify coils for maintenance without compromising the fundamental requirement to yield plasmas with all the essential quality.

….. And beyond

- Codes and numerical issues and configuration robustness
  - Development of configurations relies on numerical calculations.
  - There are assumptions/approximations, numerical errors etc.
  - How robust a configuration is? How we can make it more robust?

Existence of nested flux surfaces, number of Fourier modes, convergence, etc. Codes for equilibrium and stability calculations (NSTAB, VMEC, …)

- Data base and adequacy of physics basis
  - There are no data yet for QA devices.
  - Data from other types of stellarators are encouraging, especially with respect to MHD stability (experiments exceed prediction based on linear theory).
  - How we should extrapolate the available data in designing reactors years away?

- Have we sample enough configuration space? Are there attractive regions missed?
  - It takes a tremendous resources to survey the landscape. We only manage to sail a little farther ashore.

- How about other symmetries?
  - Do other symmetries necessarily conflict with "compactness"? Can we take advantage of other symmetry approach?