

Exploration of Compact Stellarators as Power Plants:

Initial Results from ARIES-CS Study

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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:

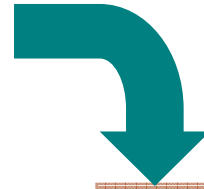
- Such a study will advance physics and technology of compact stellarator concept and addresses concept attractiveness issues that are best addressed in the context of power plant studies, *e.g.*,
 - ✓ α particle loss
 - ✓ Divertor (location, particle and energy distribution and management)
 - ✓ Practical 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

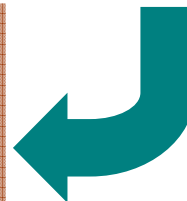
FY03/FY04: Exploration of Plasma/coil Configuration and Engineering Options

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



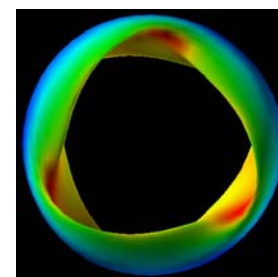
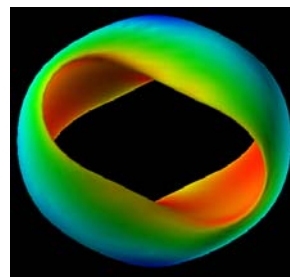
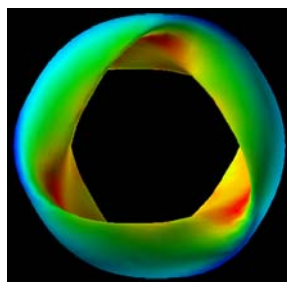
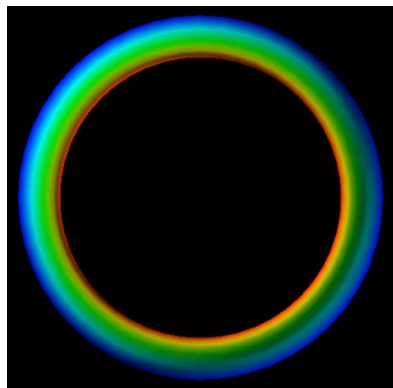
FY04/FY05: Exploration of Configuration Design Space

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



FY05/FY06: Detailed system design and optimization

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

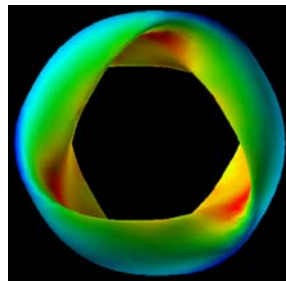
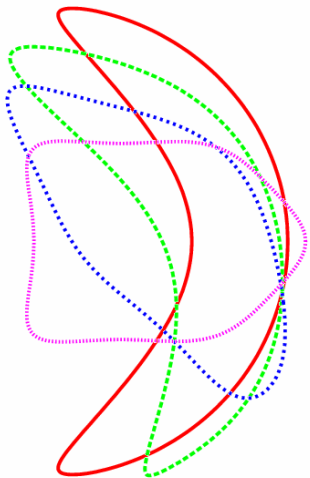


- In 3-D magnetic field topology, particle drift trajectories depend only on the strength of the magnetic field not on the shape of the magnetic flux surfaces. QA stellarators have tokamak-like field topology.
- Stellarators with externally supplied poloidal flux have shown resilience to plasma disruption 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 .

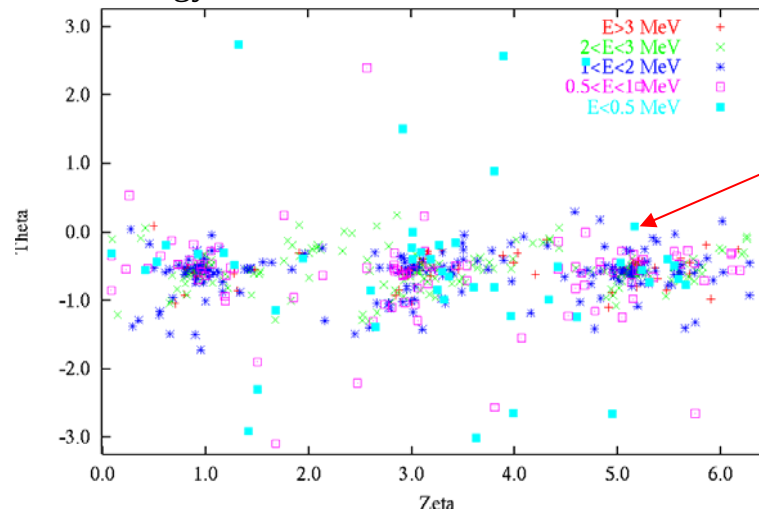
Three Classes of QA Configuration have been studied

I. NCSX-like configurations

- ✓ Good QA, low effective ripple ($<1\%$), a energy loss $\leq 15\%$ in 1000 m³ 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 $\sim 12\%$ in model calculation.

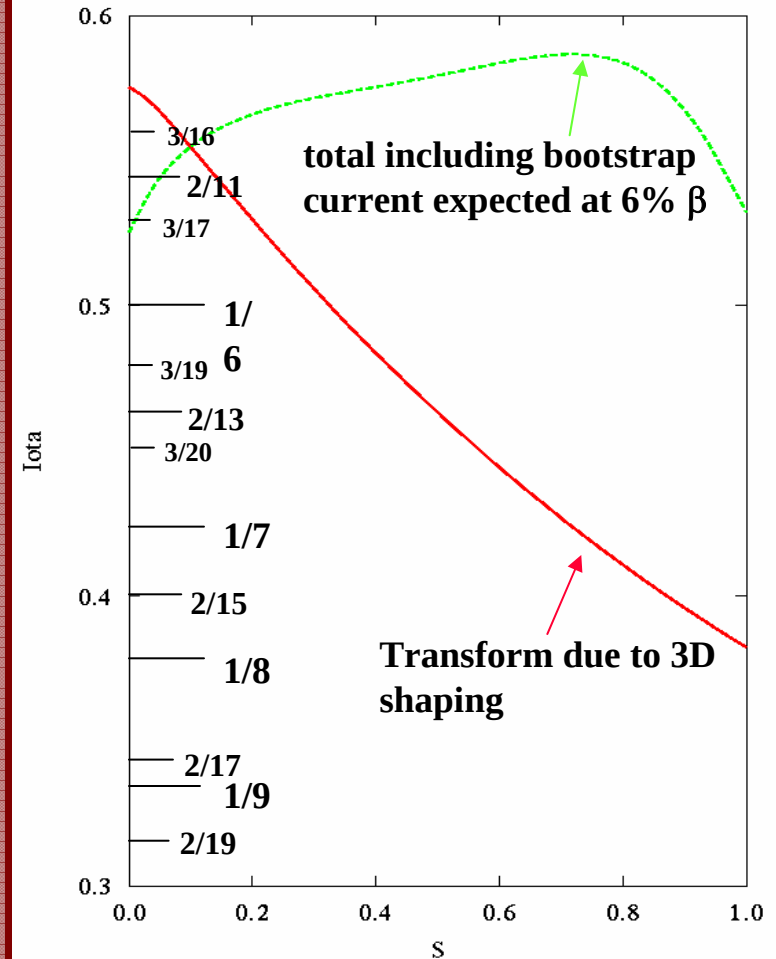
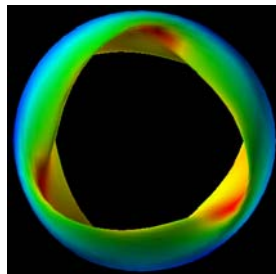
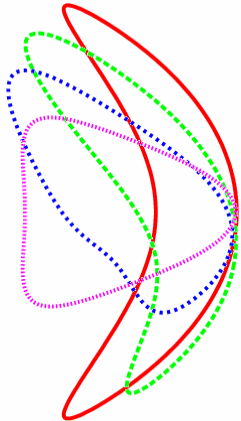


**Heat load
maybe
localized
and high
(~a few
MW/m²)**

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 $\sim 10\%$).
- ✓ Exist in 2 and 3 field periods at various iota range.
- ✓ Inherent deep magnetic well.



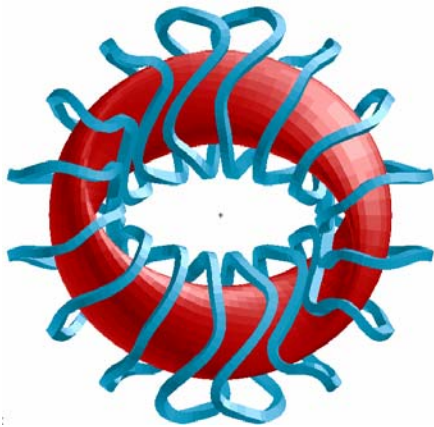
The rotational transform is avoiding low order resonance in regions away from the core at target β , yet superb quasi-axisymmetry is achieved.

Three Classes of QA Configuration have been studied

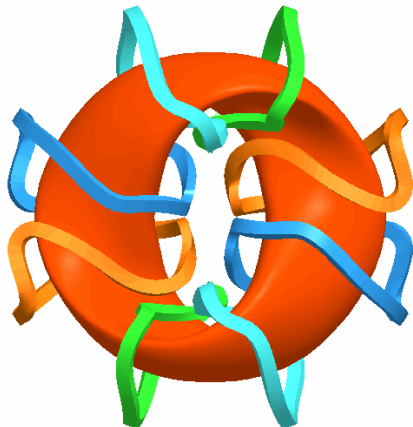
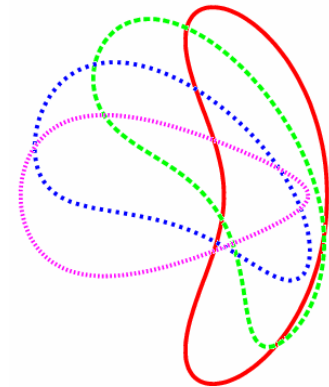
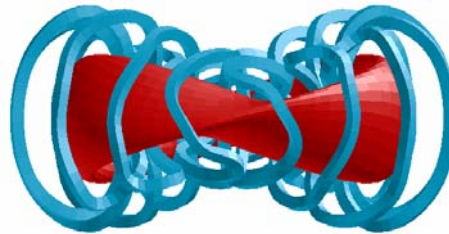
III. MHH2

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

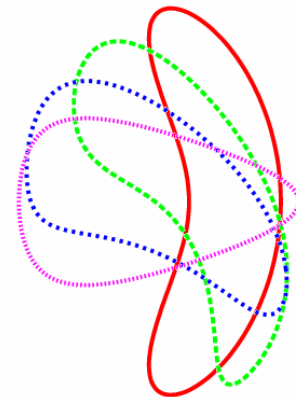
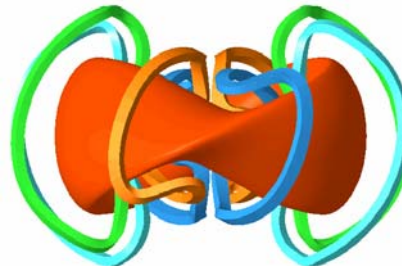
O-II-1.2: Garabedian



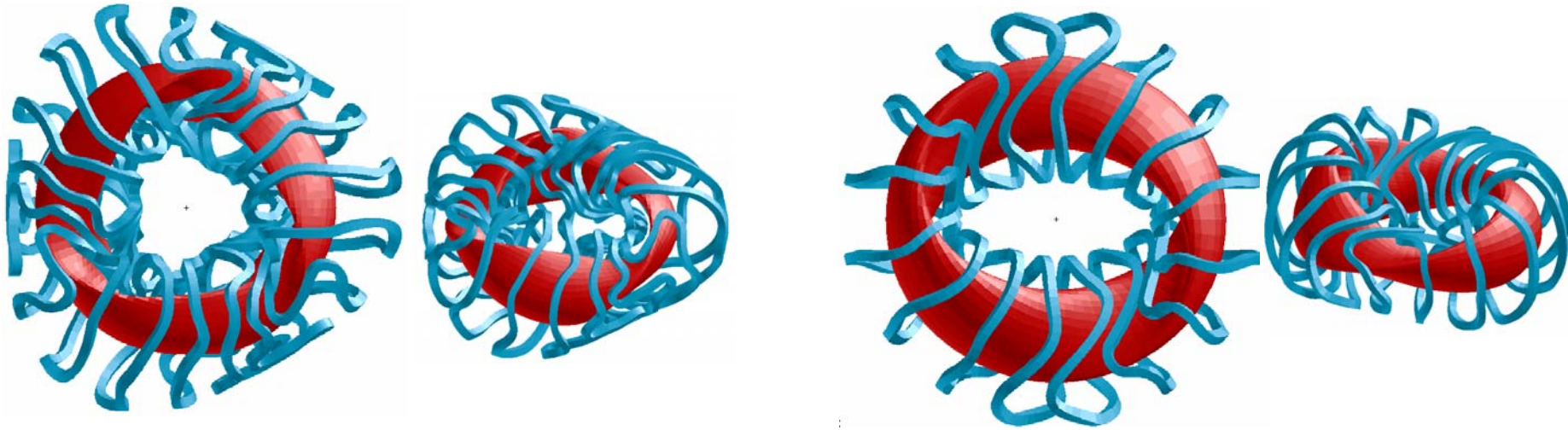
$A=3.7$ and 16 coils



$A = 2.7$ and 8 coils

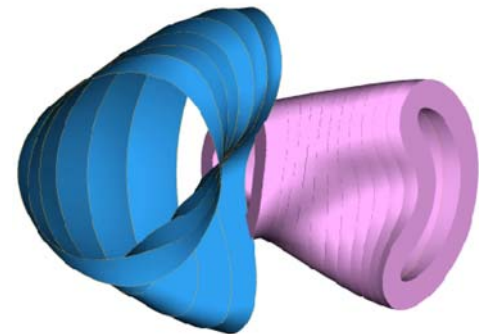
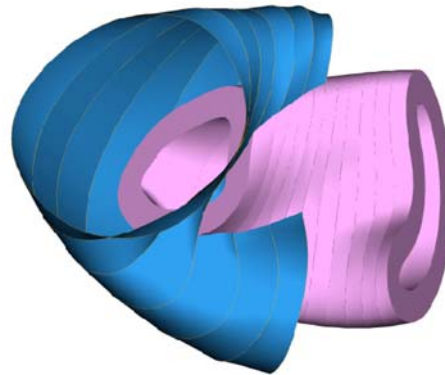
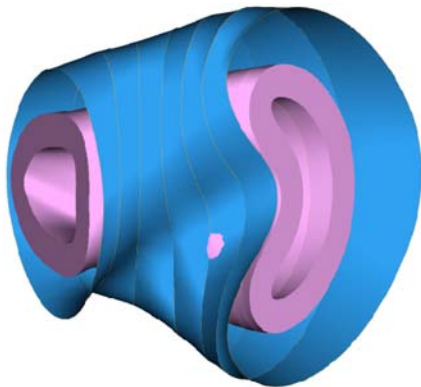
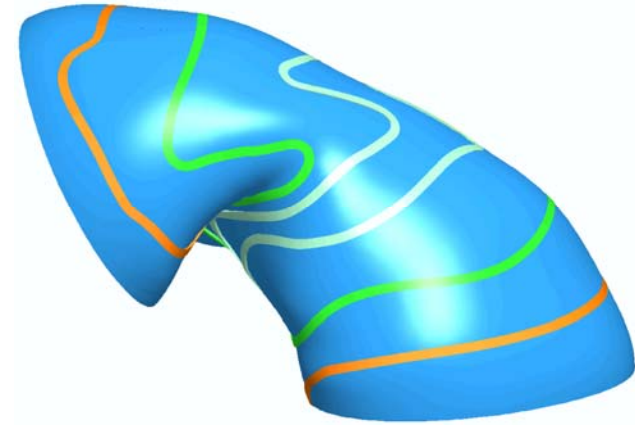
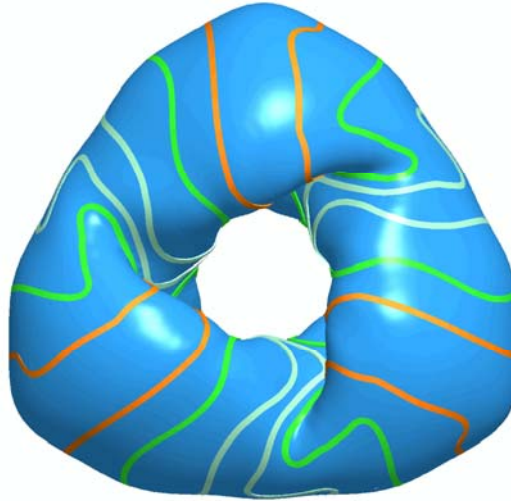
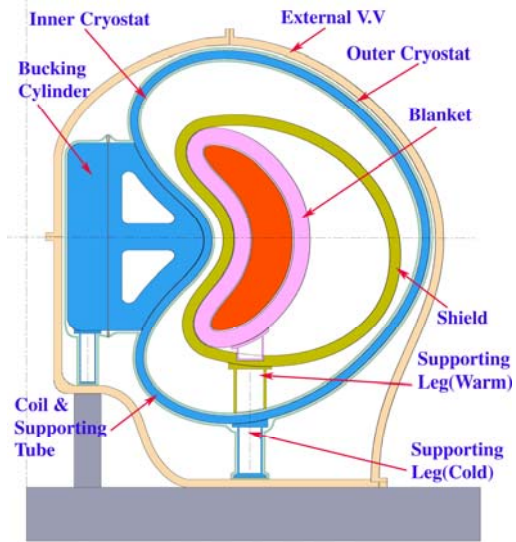


Desirable plasma configuration should be produced by practical coils with low complexity



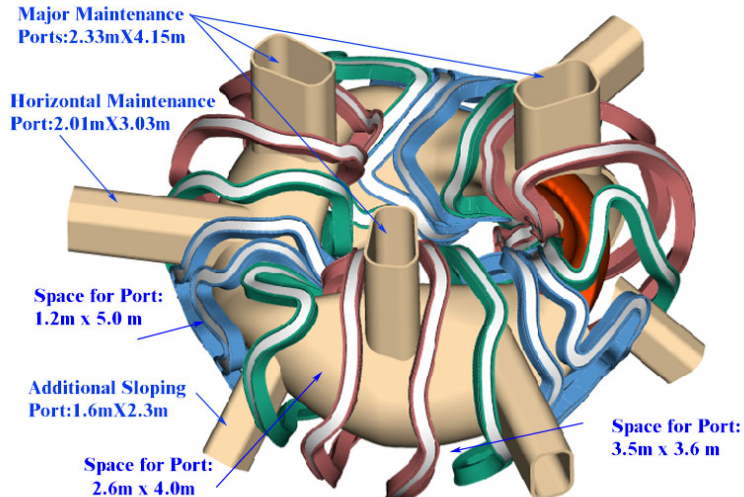
- Complex 3-D geometry introduces severe engineering constraints:
 - ✓ Distance between plasma and coil
 - ✓ Maximum coil bend radius and coil support
 - ✓ Assembly and maintenance (most important)

Field-Period Assembly and Maintenance

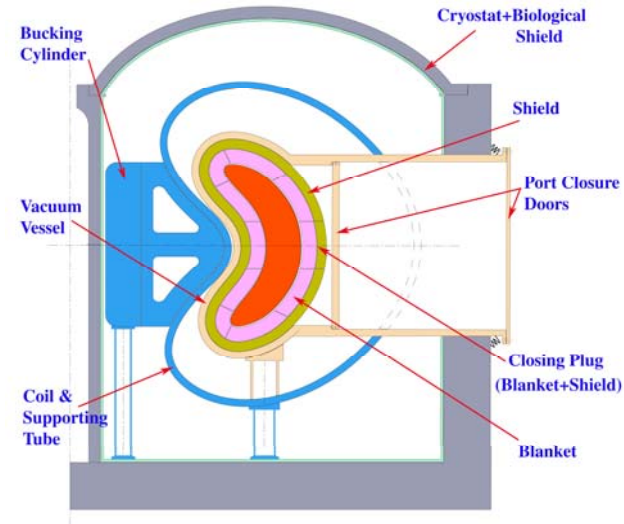
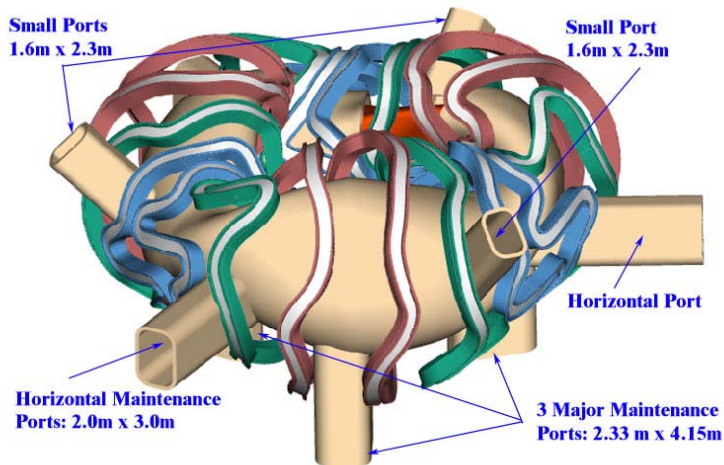


Modular Maintenance through ports

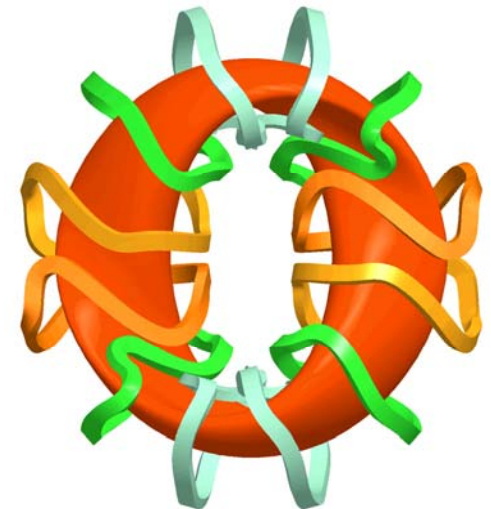
Layout of 9 Maintenance Ports



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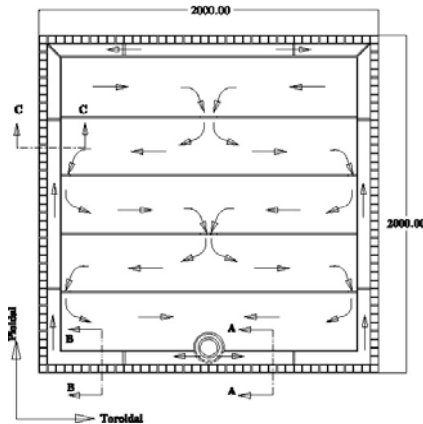


O-II-1.2: Raffray
P-I-31: Wang



Five Blanket Concepts Were Evaluated

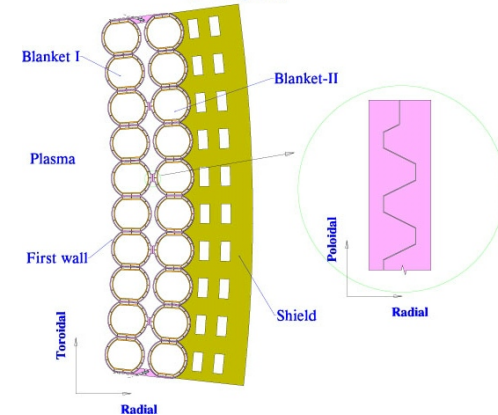
Cross-section of the Flibe Blanket Box (Front View)



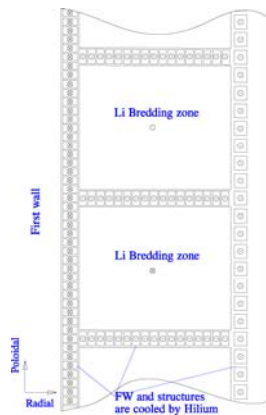
O-II-1.4: Raffray

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

Cross Section of ARIES-CS Outboard Blanket/Shield
(One Segment)

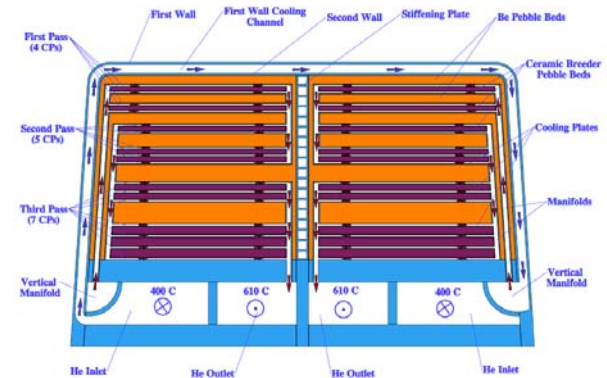


2) Self-cooled PbLi with SiC
Composites (ARIES-AT type)



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

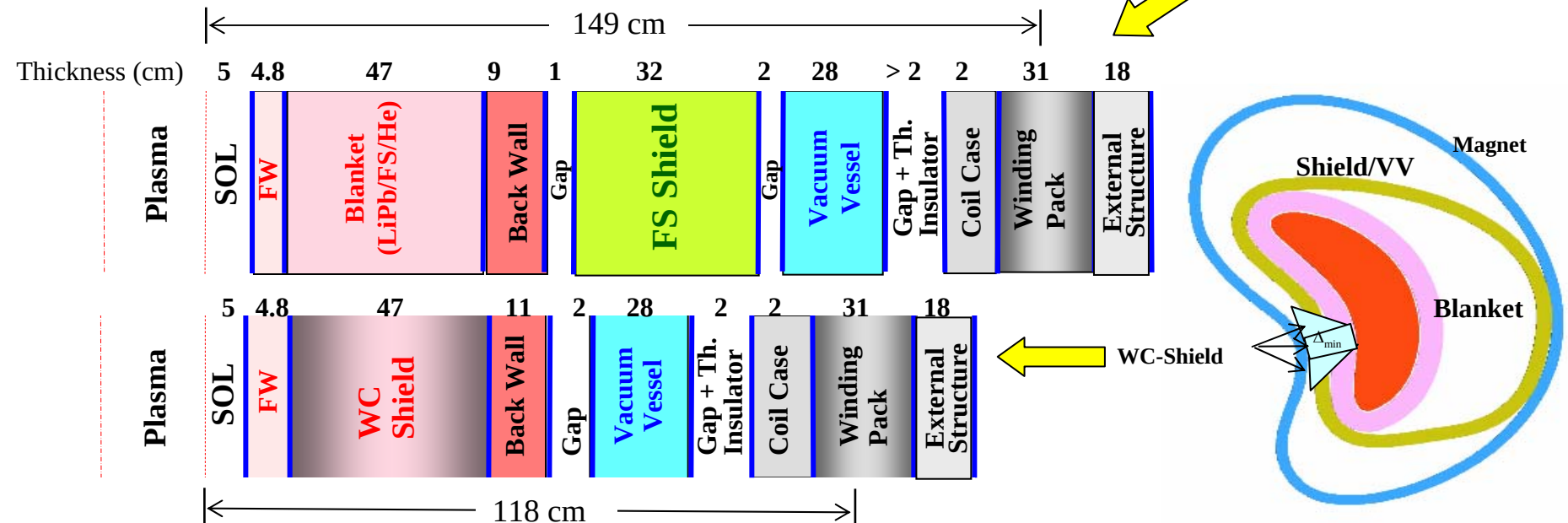
LiPb/SiC

SB/FS/Be

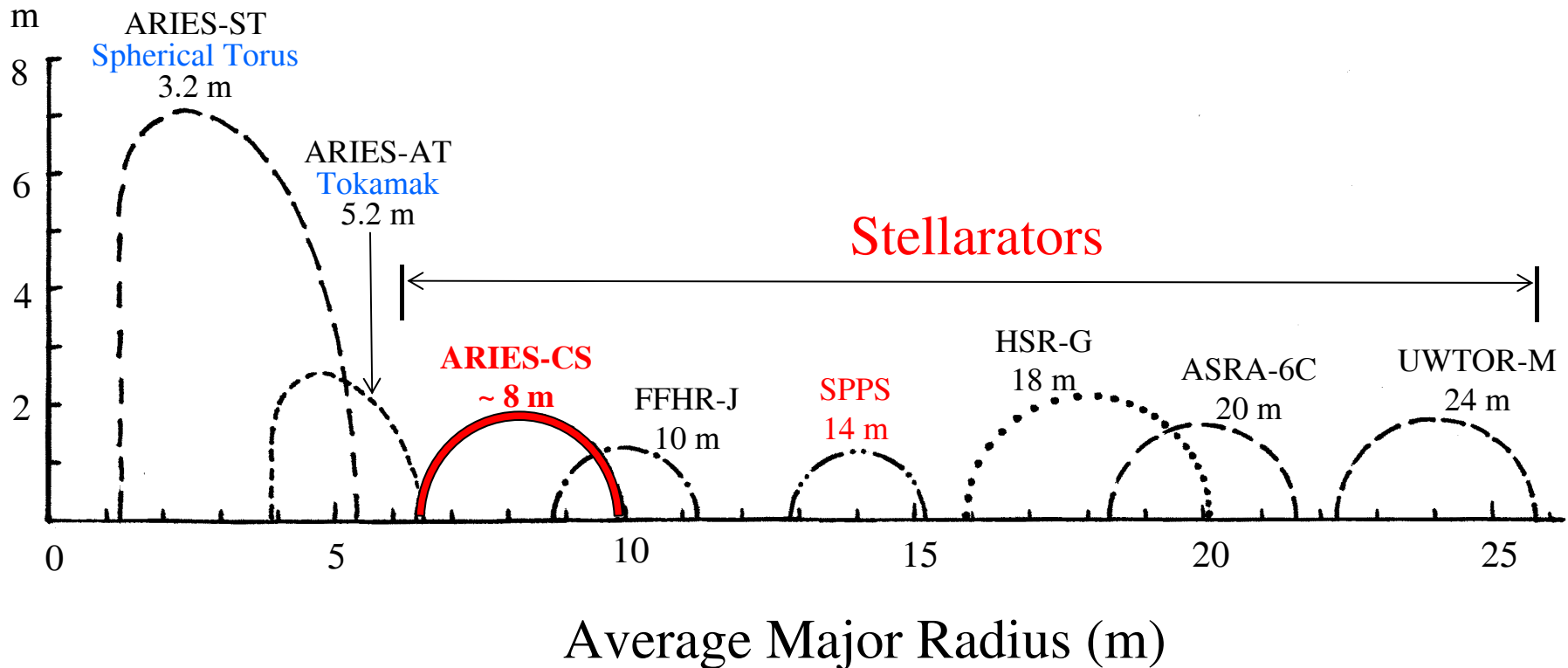
LiPb/FS

Li/FS

$\Delta_{\min}$	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



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 particles to $\sim 10\%$; 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 concepts 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 Compact Stellarators as Power Plants, Initial Results from ARIES-CS Study”**
- **O-II-1.2: Garabedian et al., “Reactors with Stellarator Stability and Tokamak 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,”