Status and Plans for Advanced Design Activities

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Electronic copy:  http://aries.ucsd.edu/najmabadi/TALKS/
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ARIES Research Bridges the Science and Energy Missions of the US Fusion Program

- Mission Statement:
  
  Perform advanced integrated design studies of the long-term fusion energy embodiments to identify key R&D directions and provide visions for the program.

- Commercial fusion energy is the most demanding of the program goals, and it provides the toughest standard to judge the usefulness of program elements.

- Knowledge base of fusion power plants involves subtle combinations of physics, technology, and engineering. Extensive systems studies are needed to identify not just the most effective experiments for the moment, but also the most cost-effective routes to the evolution of the experimental, scientific and technological program.
Advanced Design Has Been Investigating the Compact Stellarator Concept

**ARIES Compact Stellarator Program has three phases:**

I. Exploration of plasma/coil configuration and engineering options (FY03/FY04).
II. Exploration of configuration design space (FY04/FY05).
III. Detailed system design and optimization (FY06).

**Recent Results from ARIES Compact Stellarator research**

- 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. Quasi-helical configurations are under study.
- 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.
**Exploration and Optimization of Compact Stellarators as Power Plants -- Motivations**

**Timeliness:**
- Initiation of NCSX and QPS 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.*, 
  - $\alpha$ particle loss
  - Divertor (location, particle and energy distribution and management)
  - Practical coil configurations.
- NCSX and QPS 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.
Three Classes of QA Configuration have been studied

I. NCSX-like configurations

- Good QA, low effective ripple (<1%), a energy loss ≤15% in 1000 m³ device.
- 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.

Footprints of escaping α on LCMS for B5D. Energy loss ~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 ~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 $\beta$, 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

- $A = 3.7$ 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)
# Key Parameters of the ARIES-CS Blanket Options

<table>
<thead>
<tr>
<th></th>
<th>Flibe/FS/Be</th>
<th>LiPb/SiC</th>
<th>SB/FS/Be</th>
<th>LiPb/FS</th>
<th>Li/FS</th>
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<tbody>
<tr>
<td>$\Delta_{\text{min}}$</td>
<td>1.11</td>
<td>1.14</td>
<td>1.29</td>
<td>1.18</td>
<td>1.16</td>
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<tr>
<td>TBR</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
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<tr>
<td>Energy Multiplication ($M_n$)</td>
<td>1.2</td>
<td>1.1</td>
<td>1.3</td>
<td>1.15</td>
<td>1.13</td>
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<tr>
<td>Thermal Efficiency ($\eta_{\text{th}}$)</td>
<td>45%</td>
<td>55-60%</td>
<td>45%</td>
<td>~45%</td>
<td>~45%</td>
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<tr>
<td>FW Lifetime (FPY)</td>
<td>6.5</td>
<td>6</td>
<td>4.4</td>
<td>5</td>
<td>7</td>
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</tbody>
</table>

### Diagram Details

- **Thickness (cm):**
  - Total length: 149 cm
  - Total length: 118 cm

- **Plasma/SOL Diagram:**
  - Blanket (LiPb/FS/He)
  - FS Shield
  - Vacuum Vessel
  - Gap + Th. Insulator
  - Coil Case
  - Winding Pack
  - External Structure

- **Shield/VV Diagram:**
  - WC-Shield
  - Magnet

- **Magnet Diagram:**
  - Blanket

- **Special Points:**
  - $\Delta_{\text{min}}$

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**Legend:**
- FW: First Wall
- SOL: Scrape-off Layer
- WC: Wall Contact
Field-Period Assembly and Maintenance
Modular Maintenance through ports

Layout of 9 Maintenance Ports

- Major Maintenance Port: 2.33 m x 4.15 m
- Horizontal Maintenance Port: 2.01 m x 3.03 m
- Space for Port: 1.2 m x 5.0 m
- Additional Sloping Port: 1.6 m x 2.3 m
- Space for Port: 3.5 m x 3.6 m

Layout of 9 Maintenance Ports

- Small Ports: 1.6 m x 2.3 m
- Horizontal Port
- Horizontal Maintenance Port: 2.0 m x 3.0 m
- 3 Major Maintenance Ports: 2.33 m x 4.15 m
Five Blanket Concepts Were Evaluated

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

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

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)
Comparison of Power Plant Sizes

- ARIES-ST: Spherical Torus, 3.2 m
- ARIES-AT: Tokamak, 5.2 m
- ARIES-CS: ~8 m
- FFHR-J: 10 m
- SPPS: 14 m
- HSR-G: 18 m
- ASRA-6C: 20 m
- UWTOR-M: 24 m

Average Major Radius (m)
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 ≤ 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.
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.

Divertor and First wall Engineering.

Systems level assessment of these options are underway.
An Optimum ARIES-Compact Stellarator Program Plan is a ~$2M/year effort

Possible Scenarios for ARIES Research:

- **$1.35M Level – Configuration Exploration**
  - Limited examination and assessment of concepts. **No integrated assessment.**

- **$1.65M Level – Entry Level for a Power Plant Study**
  - Limited examination of configuration space. Designs will not be fully integrated or self-consistent. Lack of thoroughness will degrade the credibility of the research substantially.

- **$2.0M Level – Comprehensive, integrated, and self-consistent study**
  - Minimum level to support a single, self-consistent design study with thorough examination of configuration space. **Results will be credible and will have lasting impact on R&D.**

- **$2.3M Level – Comprehensive, integrated, and self consistent study and an additional small scale, preparatory study**
  - Such as H production and how fusion can provide transportation fuel (a contributor to all sectors of energy market).