Overview of the ARIES-CS Compact Stellarator Power Plant Study

Farrokh Najmabadi and the ARIES Team
UC San Diego

Japan-US Workshop on Fusion Power Plants and
Related Advanced Technologies with EU participation
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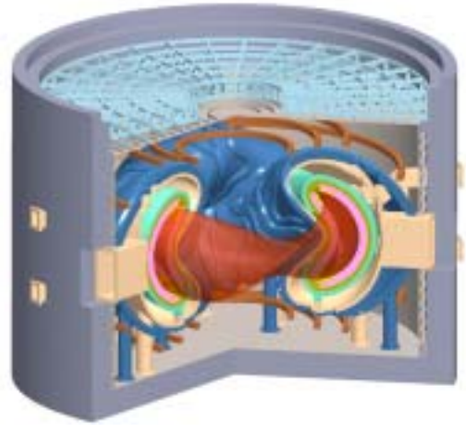

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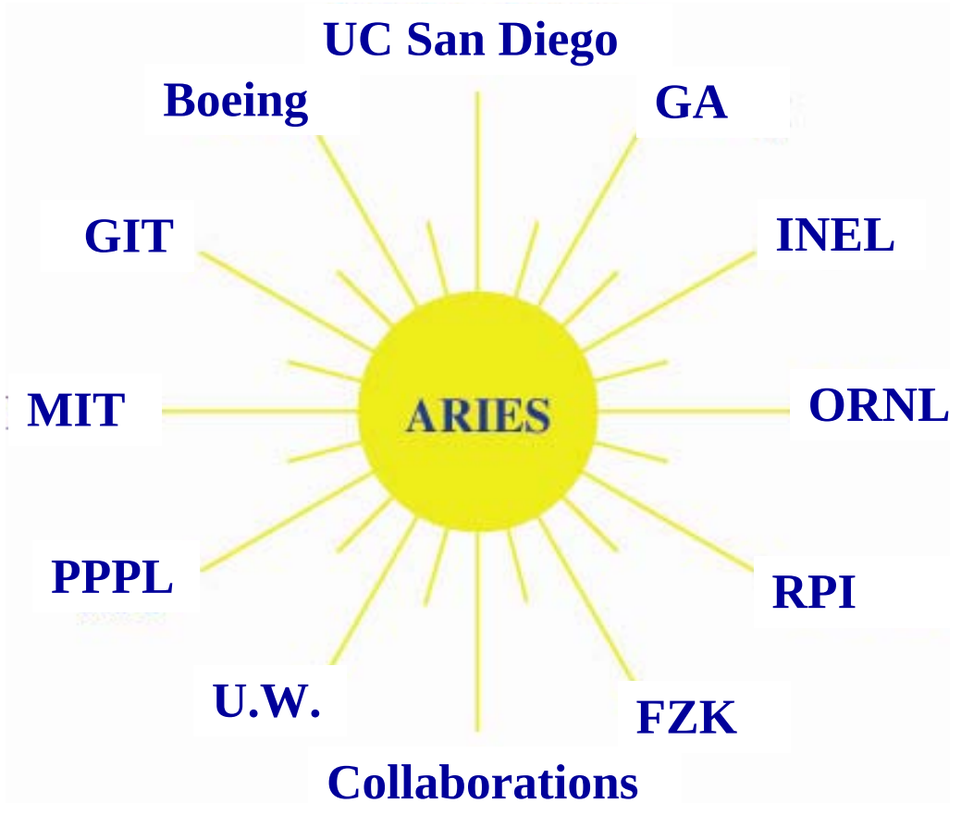


For ARIES Publications, see: http://aries.ucsd.edu/

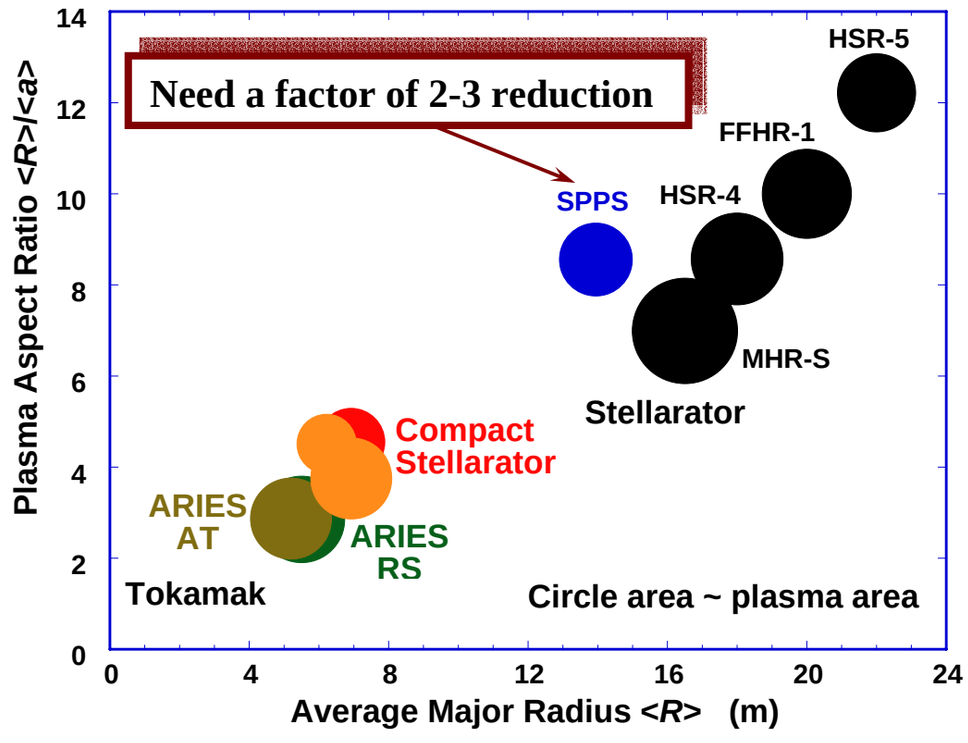
Goals of the ARIES-CS Study

- Can compact stellarator power plants be similar in size to advanced tokamak power plants?
  - ✓ Reduce aspect ratio while maintaining "good" stellarator properties.
  - ✓ Include relevant power plants issues (α particle loss, Divertor, Practical coils).
  - ✓ Identify key areas for R&D (what areas make a big difference)
- Impact of complex shape and geometry
  - ✓ Configuration, assembly, and maintenance drives the design
  - ✓ Complexity-driven constraints (e.g., superconducting magnets)
  - ✓ Complex 3-D analysis (e.g., CAD/MCNP interface for 3-D neutronics)
  - ✓ Manufacturability (feasibility and Cost)
- First design of a compact stellarator power plant
  - ✓ Design is pushed in many areas to uncover difficulties

Goal: Stellarator Power Plants Similar in Size to Tokamak Power Plants

- Multipolar external field -> coils close to the plasma
- First wall/blanket/shield set a minimum plasma/coil distance (~2m)

- A minimum minor radius
- Large aspect ratio leads to large size.



- Approach:
  - ✓ **Physics:** Reduce aspect ratio while maintaining "good" stellarator properties.
  - ✓ **Engineering:** Reduce the required minimum coil-plasma distance.

Physics Optimization Approach

NCSX scale-up

Coils

1) Increase plasma-coil separation
2) Simpler coils

High leverage in sizing.

Physics

1) Confinement of α particle
2) Integrity of equilibrium flux surfaces

Critical to first wall & divertor.

Optimization of NCSX-Like Configurations: Increasing Plasma-Coil Separation

- ✓ A series of coil design with $\mathbf{A_c = \langle R \rangle / \Delta_{min}}$ ranging 6.8 to 5.7 produced.
- ✓ Large increases in B_{max} only for $A_c < 6$.
- ✓ α energy loss is large ~18% .

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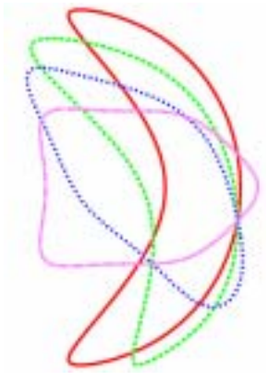


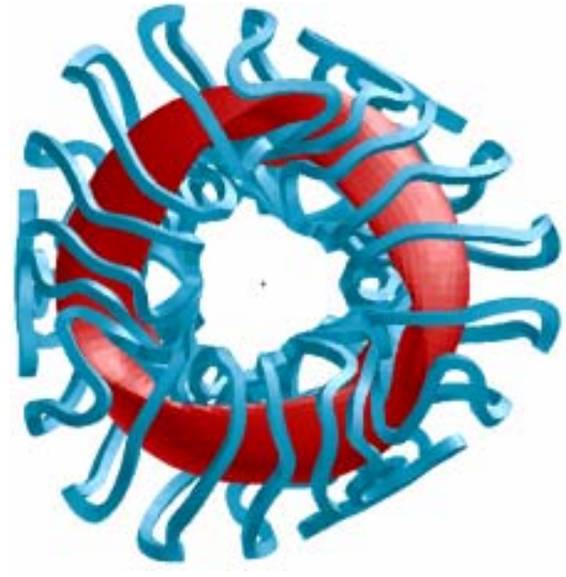
A_c=5.9

For <R> = 8.25m:

Δ_{min}(c-p)=1.4 m

Δ_{min}(c-c)=0.83 m

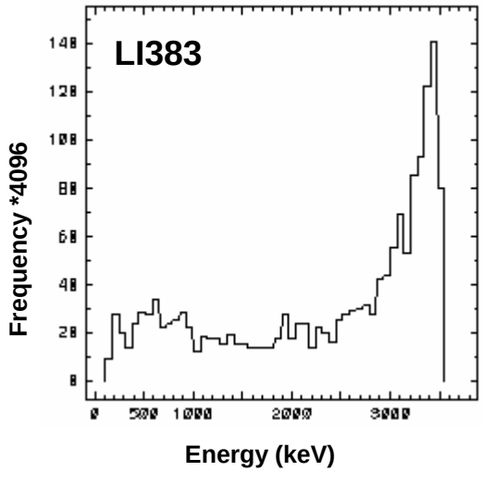
I_{max}=16.4 MA @6.5T

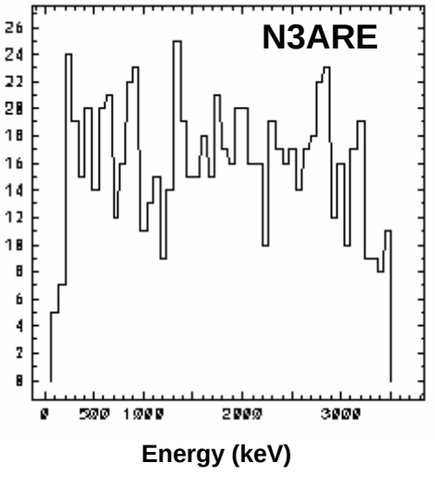


Optimization of NCSX-Like Configurations:
Improving α Confinement & Flux Surface Quality

A bias is introduced in the magnetic spectrum in favor of B(0,1) and B(1,1)

✓ A substantial reduction in α loss (to ~ 3.4%) is achieved.





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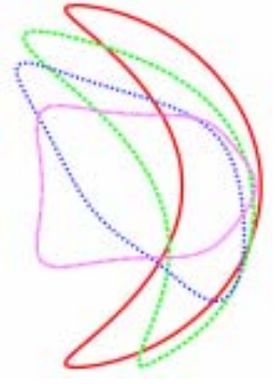


Baseline Configuration

✓ The external kinks and infinite-n ballooning modes are marginally stable at 4% β with no nearby conducting wall.

✓ Rotational transform is similar to NCSX, so the same quality of equilibrium flux surface is expected.

Physics Optimization Approach

NCSX scale-up

Coils
1) Increase plasma-coil separation
2) Simpler coils

High leverage in sizing.

Physics
1) Confinement of α particle
2) Integrity of equilibrium flux surfaces

Critical to first wall & divertor.

Reduce consideration of MHD stability in light of W7AS and LHD results

New classes of QA configurations

MHH2
1) Develop very low aspect ratio geometry
2) Detailed coil design optimization

"Simpler" coils and geometry?

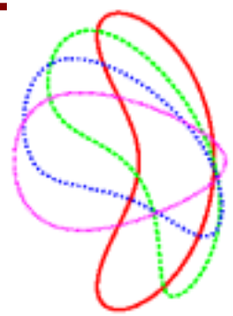
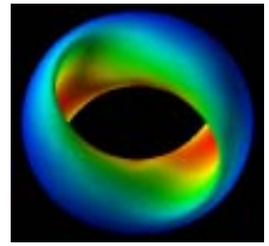
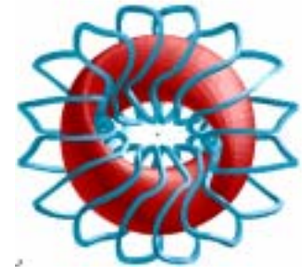
SNS
1) Nearly flat rotational transforms
2) Excellent flux surface quality

How good and robust the flux surfaces one can "design"?

Two New Classes of QA Configurations

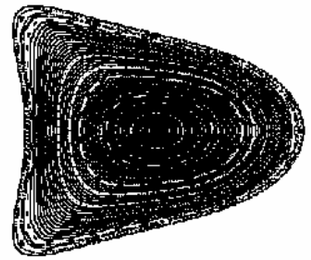
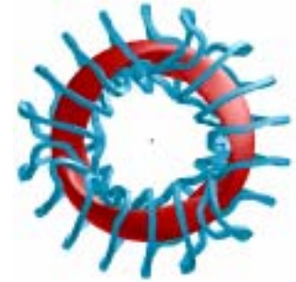
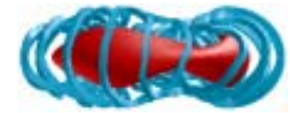
II. MHH2

- ✓ Low plasma aspect ratio (A_p ~ 2.5) in 2 field period.
- ✓ Excellent QA, low effective ripple (<0.8%), low α energy loss (≤ 5%) .

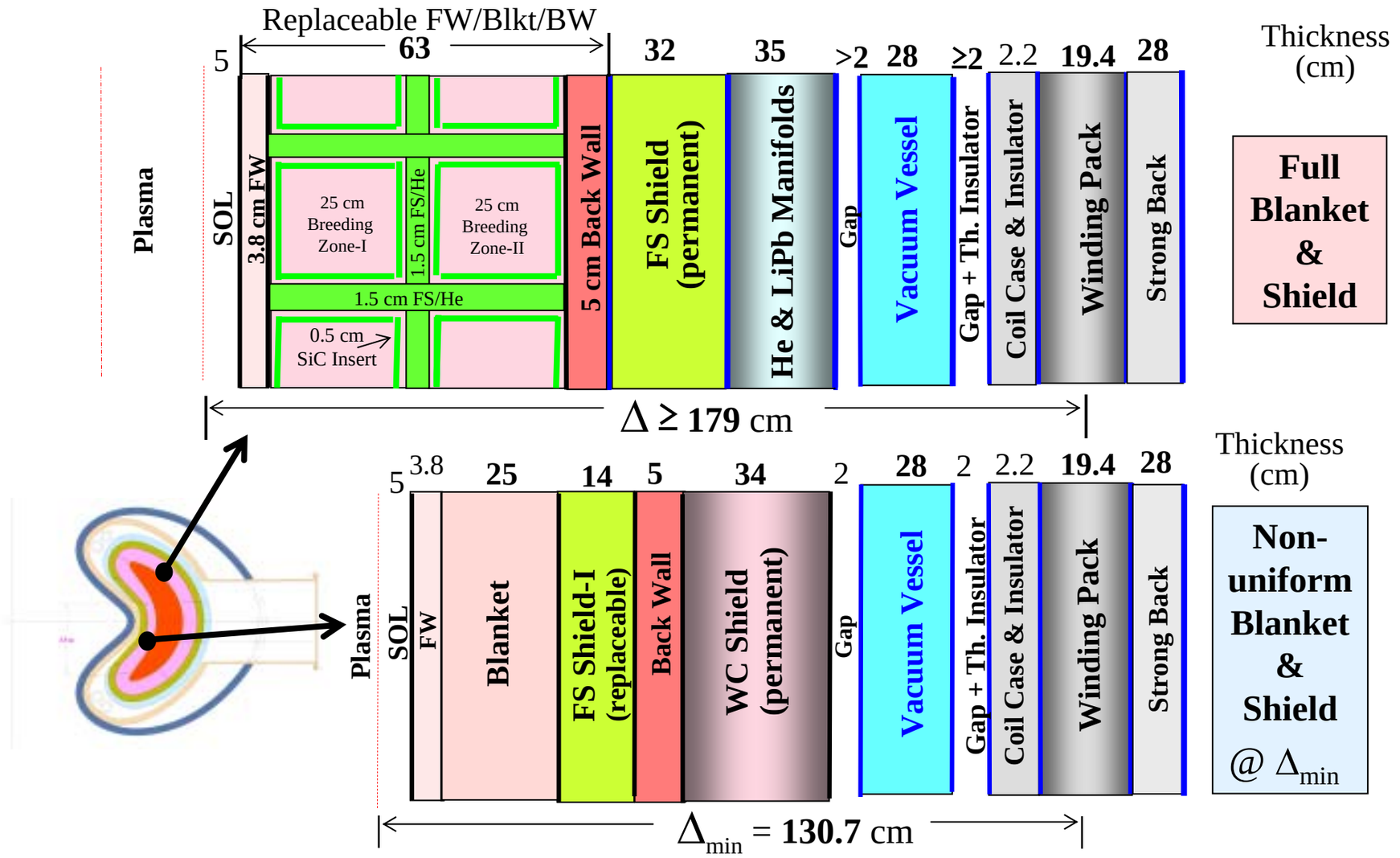




III. SNS

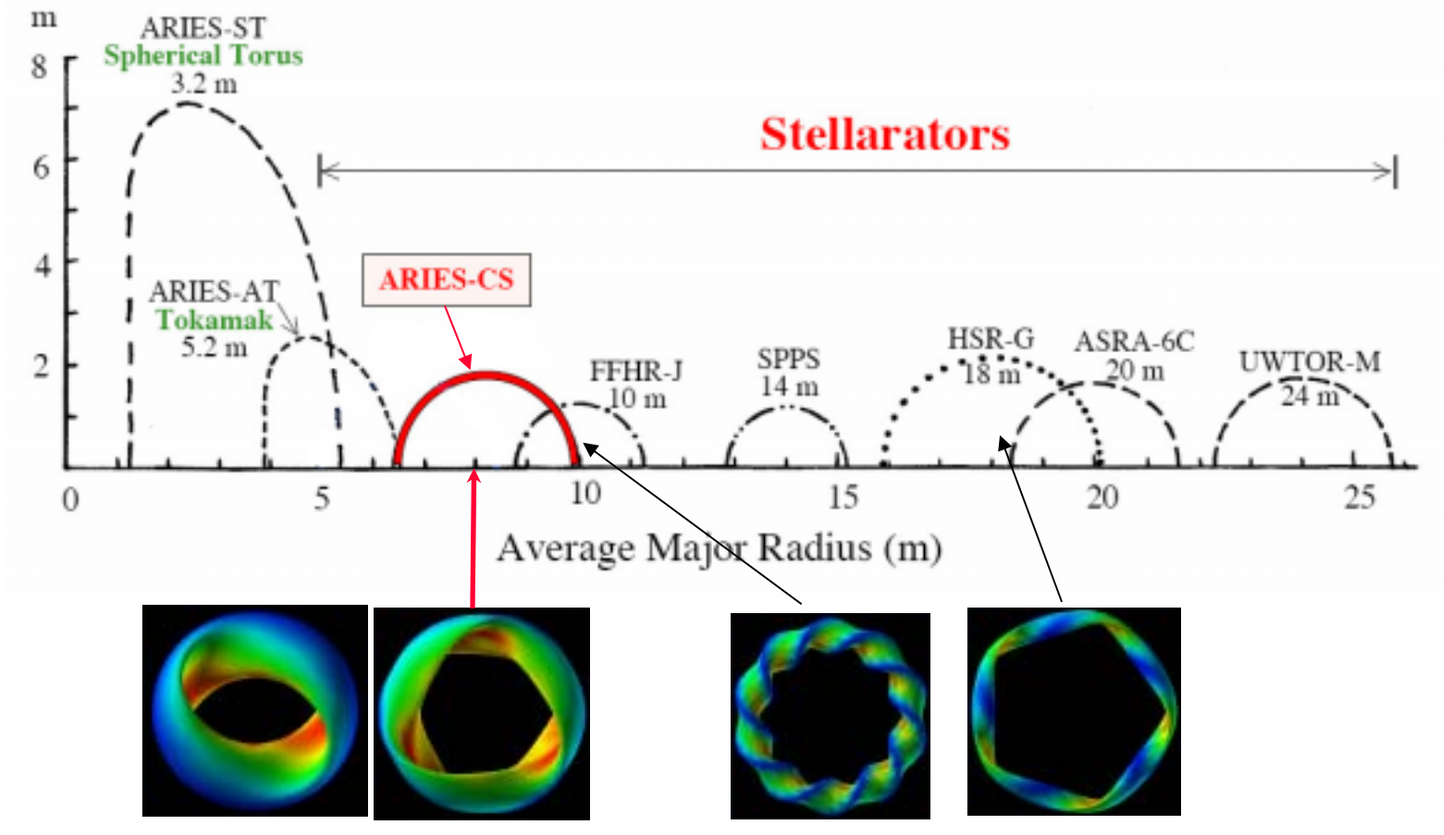
- ✓ A_p ~ 6.0 in 3 field period. Good QA, low ε-eff (< 0.4%), α loss ≤8% .
- ✓ Low shear rotational transform at high β, avoiding low order resonances.

Minimum Coil-plasma Stand-off Can Be Reduced By Using Tapered-Blanket Zones



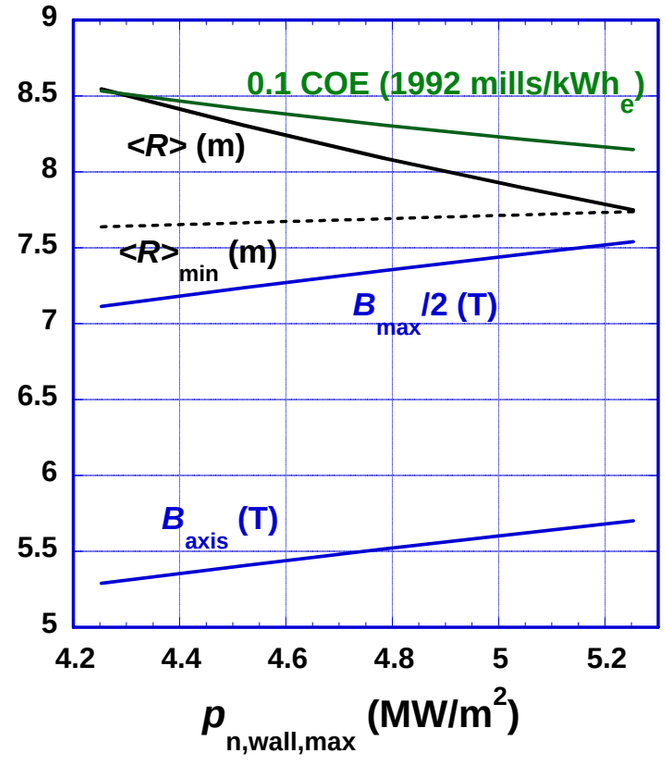
Resulting power plants have similar size as Advanced Tokamak designs



- Trade-off between good stellarator properties (steady-state, no disruption , no feedback stabilization) and complexity of components.
- Complex interaction of Physics/Engineering constraints.

Resulting power plants have similar size as Advanced Tokamak designs

	SPPS	ARIES-CS	ARIES-AT	ARIES-RS
<R>, m	14.0	7.75	5.2	5.5
$\langle B_o \rangle$, T	5.0	5.7	5.9	8.0
<β>	5.0%	5.0%	9.2%	5.0%
FPC Mass, tonnes	21,430	10,962	5,226	12,679
Reactor Plant Equip. (M$)		1,642	900	1,386
Total Direct Cost (M$)		2,633	1,757	2,189



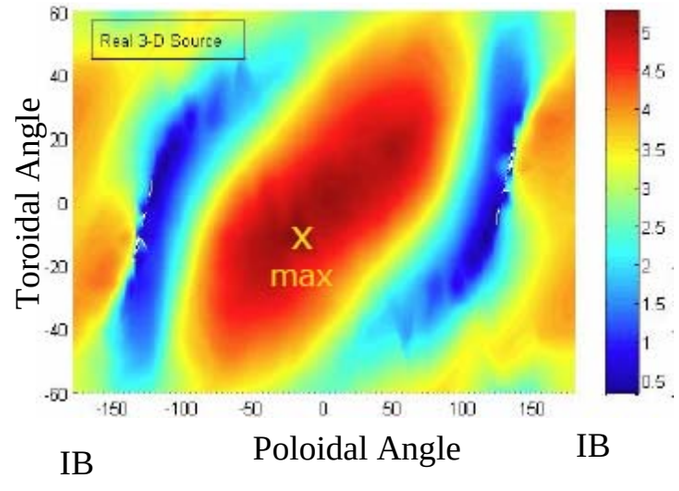
- Major radius can be increased to ease engineering difficulties with a small cost penalty.

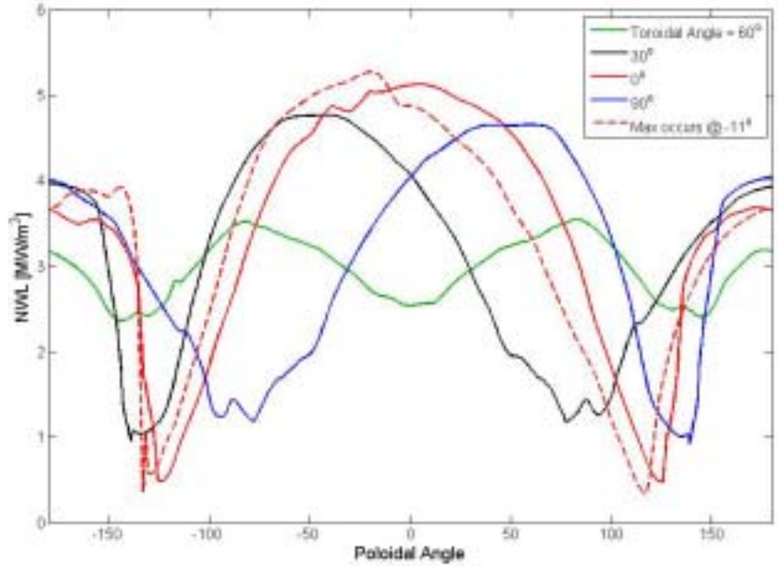
Complex plasma shape and plasma-coil relative position drives many engineering systems

First ever 3-D modeling of complex stellarator geometry for nuclear assessment using CAD/MCNP coupling

- Detailed and complex 3-D analysis is required for the design
  - ✓ Example: Complex plasma shape leads to a large non-uniformity in the loads (e.g., peak to average neutron wall load of 2).

Distribution of Neutron wall load



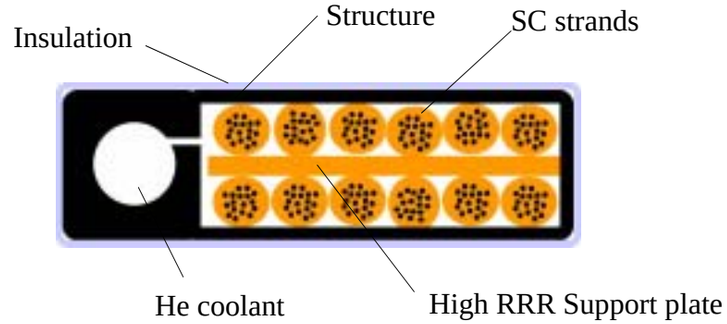


Coil Complexity Impacts the Choice of Superconducting Material

- Strains required during winding process is too large.
  - ✓ NbTi-like (at 4K) ⇒ B < ~7-8 T
  - ✓ NbTi-like (at 2K) ⇒ B < 9 T, problem with temperature margin
  - ✓ Nb_3Sn ⇒ B < 16 T, Conventional technique does not work because of inorganic insulators

Option 1: Inorganic insulation, assembled with magnet prior to winding and capable to withstand the heat treatment process.

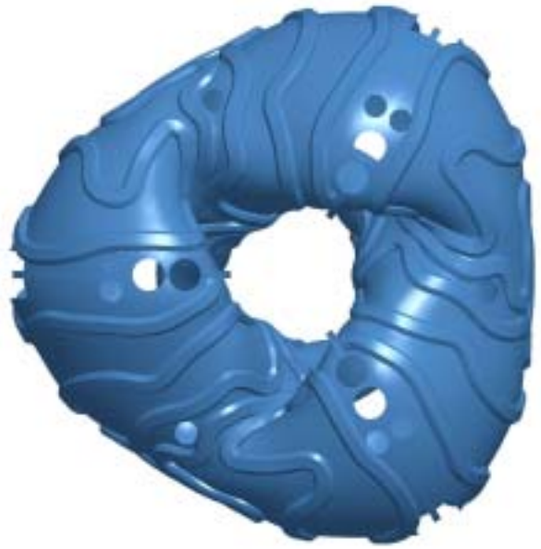
Option 2: conductor with thin cross section to get low strain during winding. (Low conductor current, internal dump).

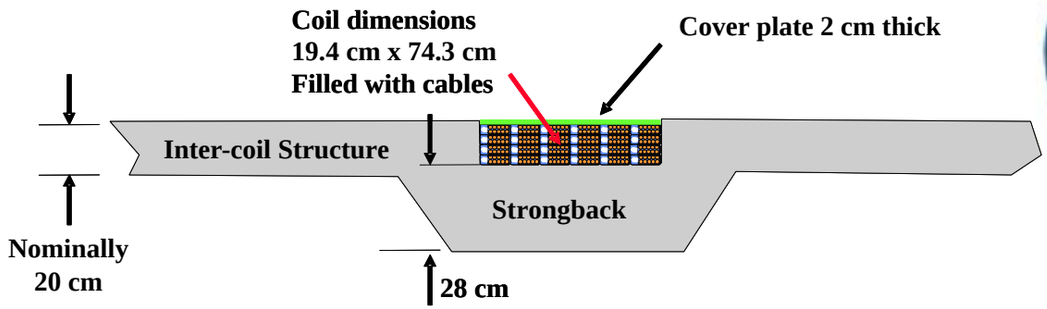


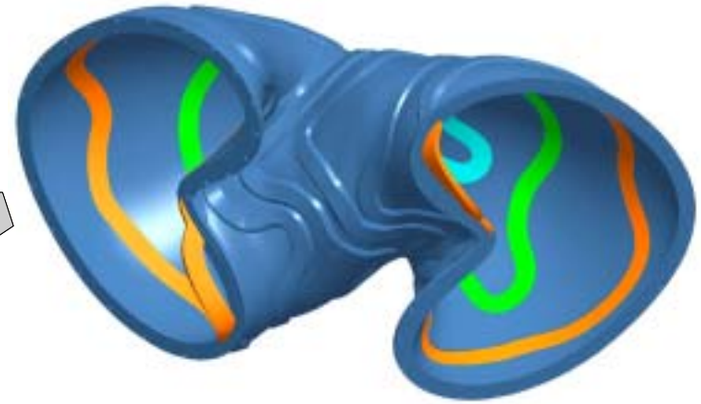
Option 3: HTS (YBCO), Superconductor directly deposited on structure.

Coil Complexity Dictates Choice of Magnet Support Structure

- It appears that a continuous structure is best option for supporting magnetic forces.
- Net force balance between field periods (Can be in three pieces)
- Absence of disruptions reduces demand on coil structure.
- Superconductor coils wound into grooves inside the structure.

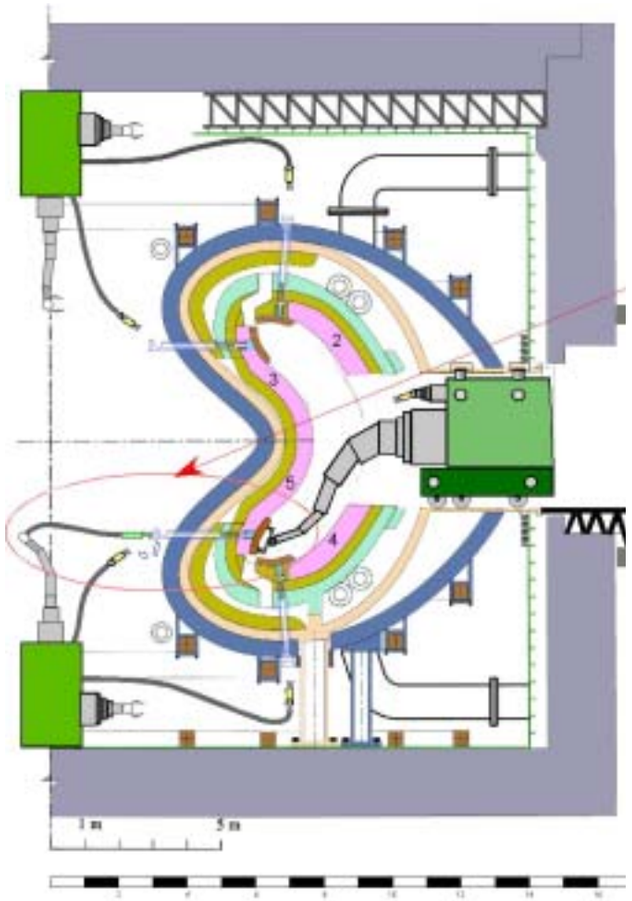


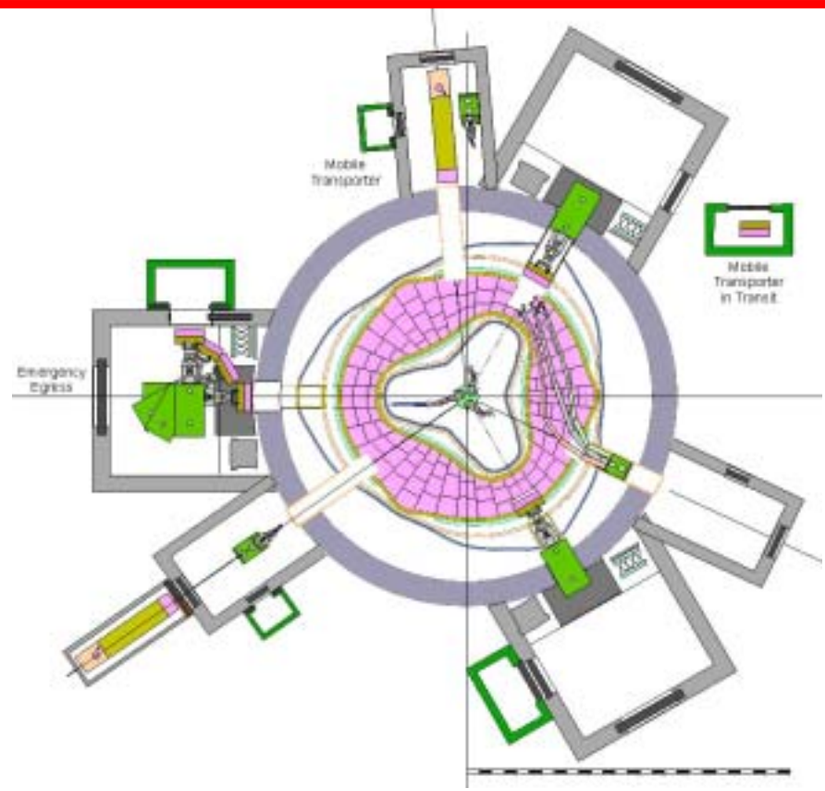




Port Assembly: Components are replaced Through Ports

- Modules removed through three ports using an articulated boom.



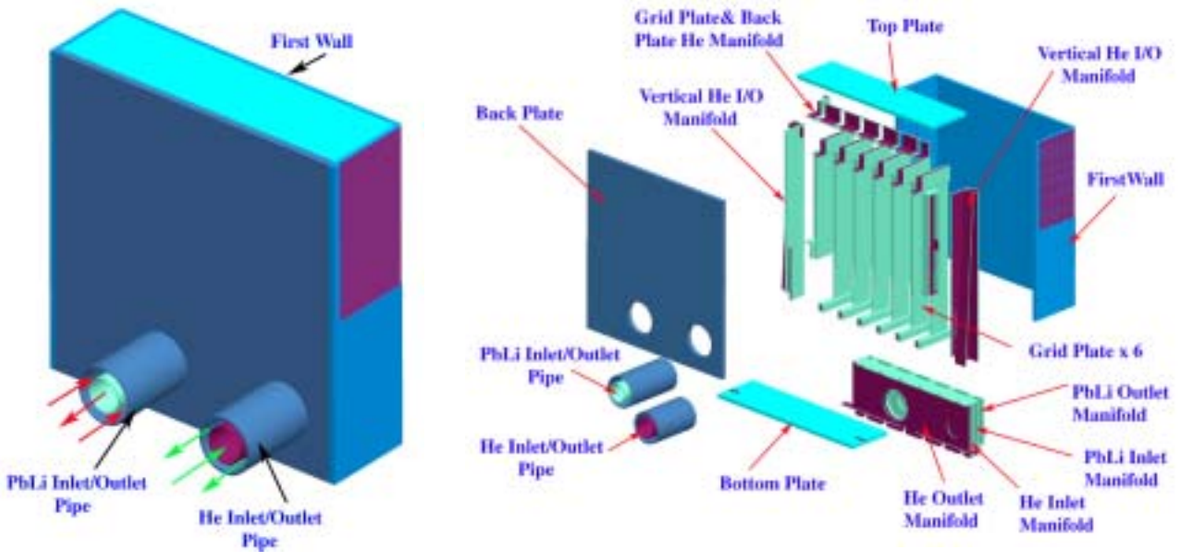


Drawbacks:

- ✓ Coolant manifolds increases plasma-coil distance.
- ✓ Very complex manifolds and joints
- ✓ Large number of connect/disconnects

Blanket Concepts are Optimized for Stellarator Geometry

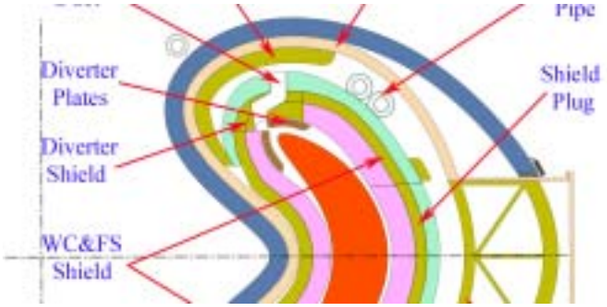
- Dual coolant with a self-cooled PbLi zone and He-cooled RAFS structure
  - ✓ Originally developed for ARIES-ST, further developed by EU (FZK), now is considered as ITER test module
  - ✓ SiC insulator lining PbLi channel for thermal and electrical insulation allows a LiPb outlet temperature higher than RAFS maximum temperature



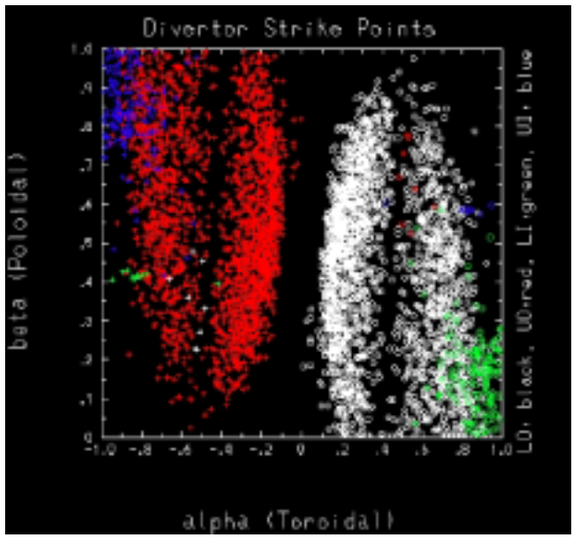
- Self-cooled PbLi with SiC composite structure (a al ARIES-AT)
  - ✓ Higher-risk high-payoff option

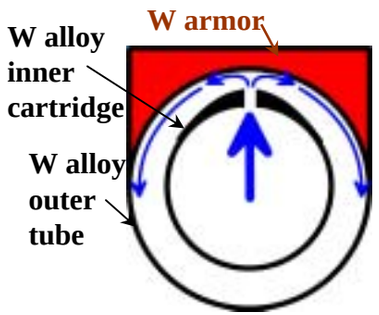
A highly radiative core is needed for divertor operation

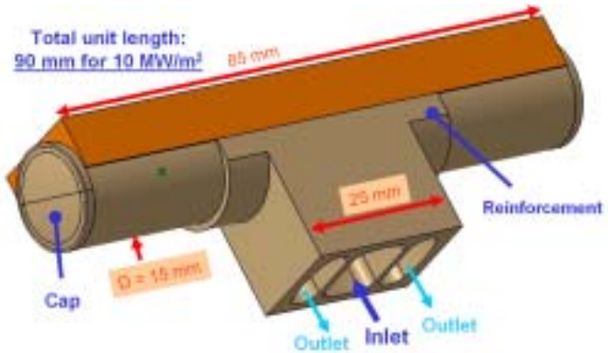
- Heat/particle flux on divertor was computed by following field lines outside LCMS.
  - ✓ Because of 3-D nature of magnetic topology, location & shaping of divertor plates require considerable iterative analysis.



Top and bottom plate location with toroidal coverage from -25° to 25° .







- Divertor module is based on W Cap design (FZK) extended to mid-size (~ 10 cm) with a capability of 10 MW/m^2

Summary of the ARIES-CS Study

Goal 1: Can compact stellarator power plants similar in size to advanced tokamak power plants?

- Reduce aspect ratio while maintaining "good" stellarator properties.
- Include relevant power plants issues (α particle loss, divertor, practical coils).
- Identify key areas for R&D (what areas make a big difference)

Results:

- ✓ Compact stellarator power plants can be similar in size to advanced tokamaks (The best "size" parameter is the mass not the major radius).
- ✓ α particle loss can be reduced substantially (how low is low enough?)
- ✓ A large number of QA configurations, more desirable configurations are possible. In particular, mechanism for β limit is not known. Relaxing criteria for linear MHD stability may lead to configurations with a less complex geometry or coils.

Summary of the ARIES-CS Study

Goal 2: Understand the impact of complex shape and geometry

A. Configuration, assembly, and maintenance drives the design

- ✓ A high degree of integration is required
- ✓ Component replacement through ports appears to be the only viable method.
- ✓ Leads to modules that can be fitted through the port and supported by articulated booms.
- ✓ Large coolant manifold (increase radial build), large number of connects and disconnects, complicated component design for assembly disassembly.

B. Complexity-driven constraints (e.g., superconducting magnets)

- ✓ Options were identified. (e.g., base case for superconducting magnets requires development of inorganic insulators.)

Summary of the ARIES-CS Study

Goal 2: Understand the impact of complex shape and geometry

C. Complex 3-D analysis

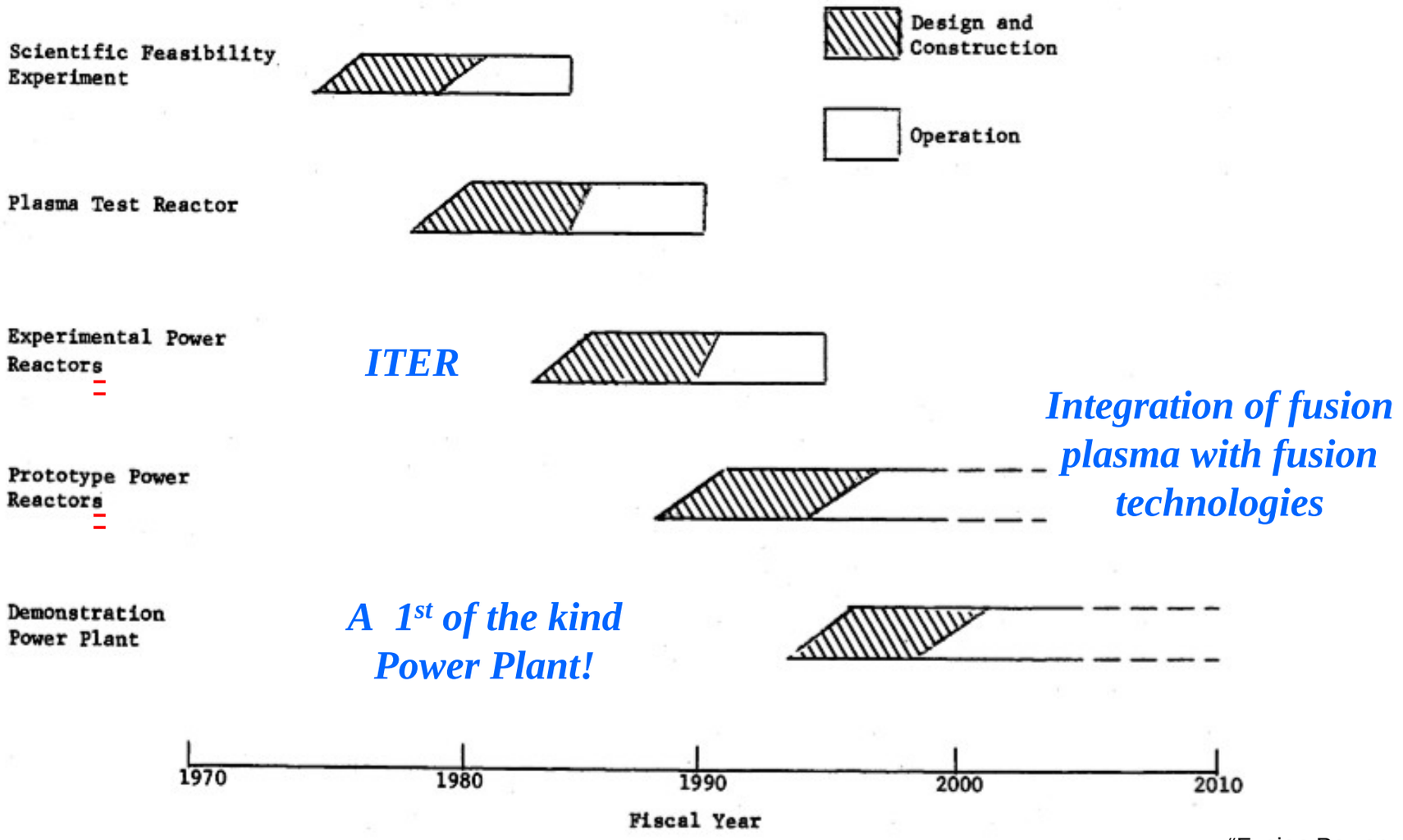
- ✓ 3-D analysis is required for almost all cases (not performed in each case).
- ✓ CAD/MCNP interface for 3-D neutronics, 3-D solid model for magnet support, …

D. Manufacturability (feasibility and Cost)

- ✓ Feasibility of manufacturing of component has been included in the design as much as possible.
- ✓ In a large number of cases, manufacturing is challenging and/or very expensive.

From ITER to
an attractive final product

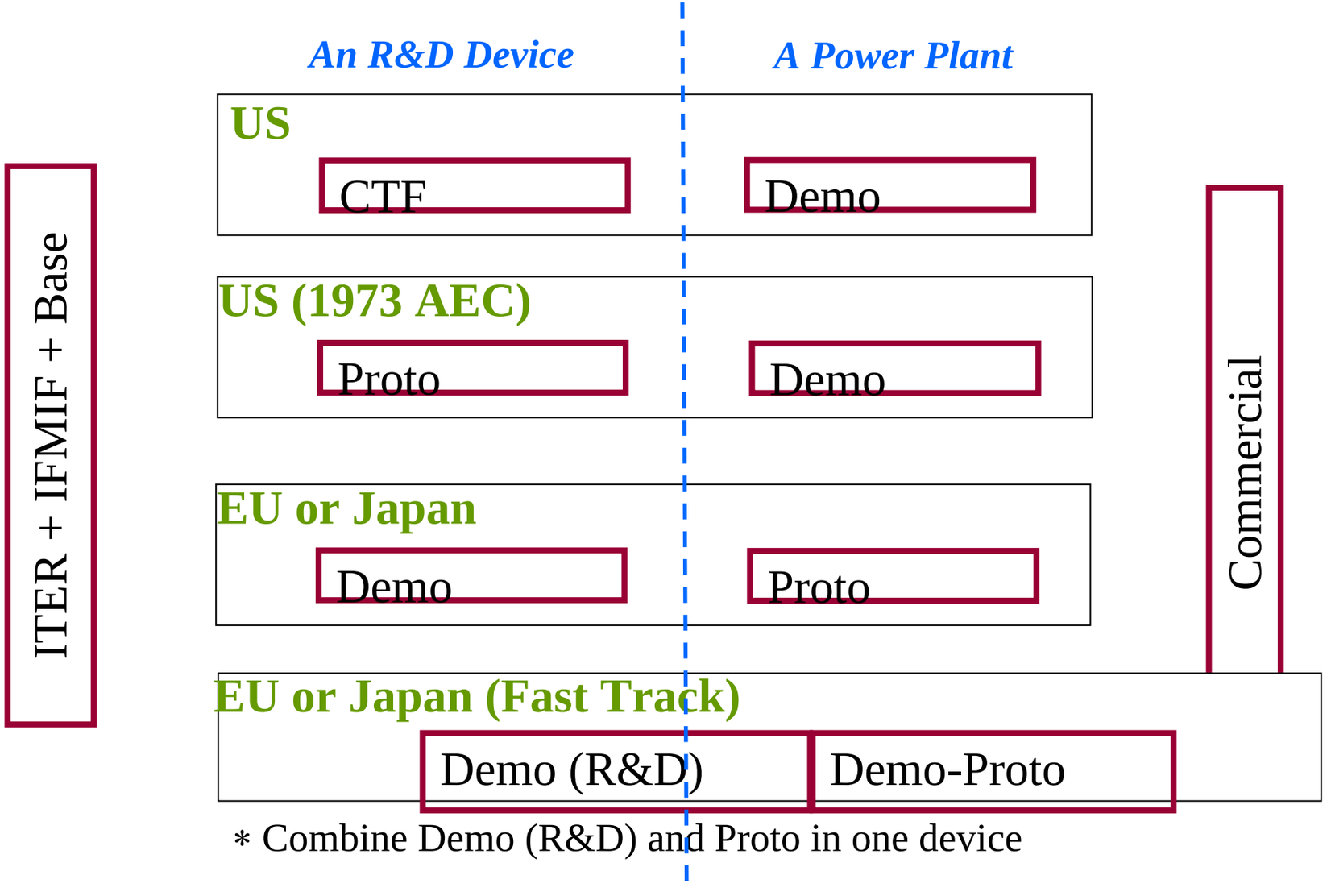
Plans for the Next ARIES Study



Projected Fusion-Reactor Development Program
Wash-1267, July 1973

"Fusion Power: Research and Development Requirements." Division of Controlled Thermonuclear Research (AEC).

World-wide Development Scenarios use similar names for devices with different missions!



∗ Combine Demo (R&D) and Proto in one device

In the ITER area,
we need to develop
a 5,000 ft view

A holistic or integrated optimization approach should drive the development path.

Traditional Approach: Ask each scientific area (i.e., plasma, blanket, …)

- What are the remaining major R&D areas?
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (e.g., fission reactors)? What other major facilities are needed?

Holistic Approach: <u>Fusion energy development should be guided by the requirements for an attractive fusion energy source</u>

- What are the remaining major R&D areas?
  - ✓ What it the impact of this R&D on the attractiveness of the final product.
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (i.e., fission reactors)? What other major facilities are needed?
  - ✓ Should we attempt to replicate power plant conditions in a scaled device or Optimize facility performance relative to scaled objectives

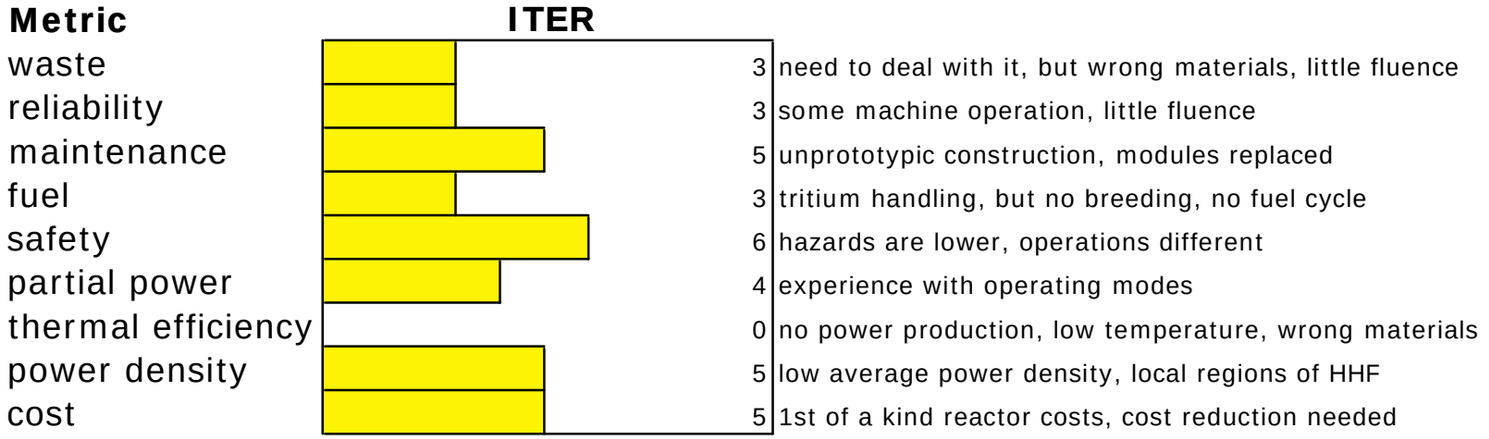
Elements of the Case for Fusion Power Were Developed through Interaction with Representatives of U.S. Electric Utilities and Energy Industry

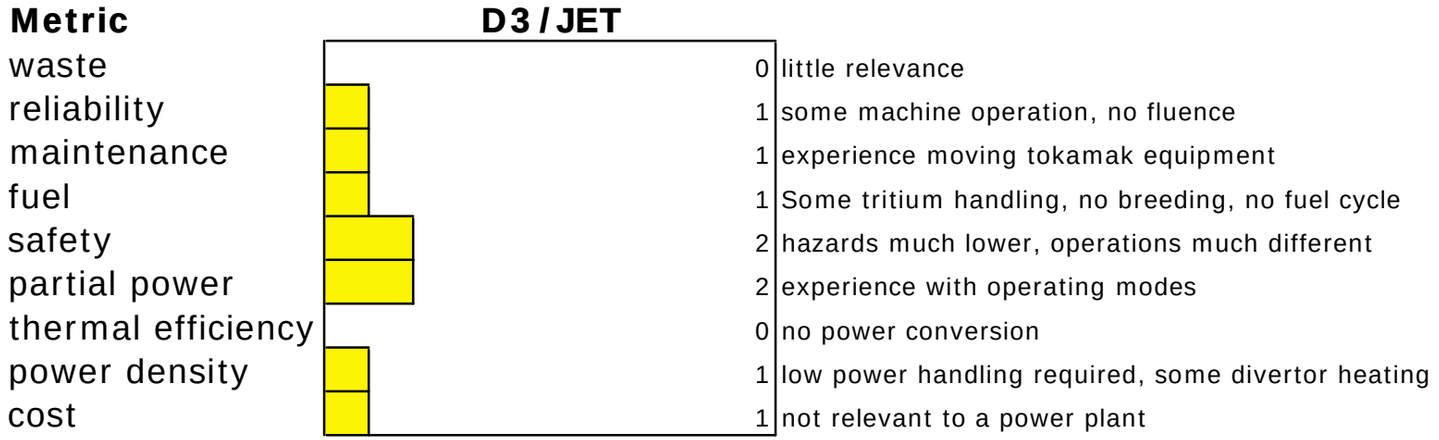
- **Have an economically competitive life-cycle cost of electricity**
- **Gain Public acceptance by having excellent safety and environmental characteristics**
  - ✓ No disturbance of public's day-to-day activities
  - ✓ No local or global atmospheric impact
  - ✓ No need for evacuation plan
  - ✓ No high-level waste
  - ✓ Ease of licensing
- **Reliable, available, and stable as an electrical power source**
  - ✓ Have operational reliability and high availability
  - ✓ Closed, on-site fuel cycle
  - ✓ High fuel availability
  - ✓ Capable of partial load operation
  - ✓ Available in a range of unit sizes

Low-activation material

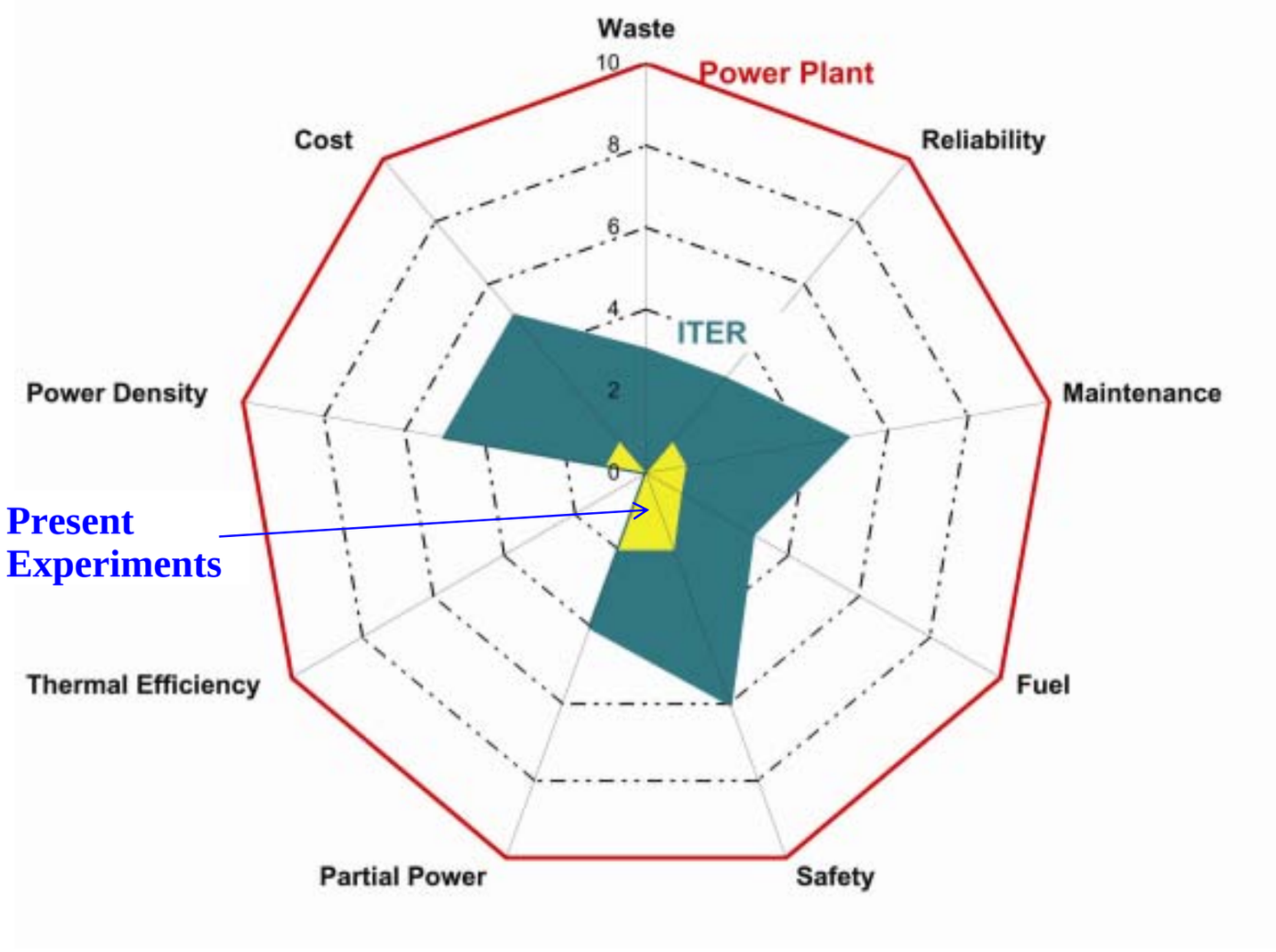
Fusion physics & technology

Existing facilities fail to address essential features of a fusion energy source





ITER is a major step forward but there is a long road ahead.



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ARIES studies emphasize holistic R&D needs and their design implications

Traditional approach	Concurrent engineering/physics
Plasma	Power control
Blankets	Power and particle management
Divertors	Fuel management
Magnets	Maintenance
Vacuum vessel	Safety
	Waste
	Cost

- This approach has many benefits (see below)

Examples of holistic issues for Fusion Power

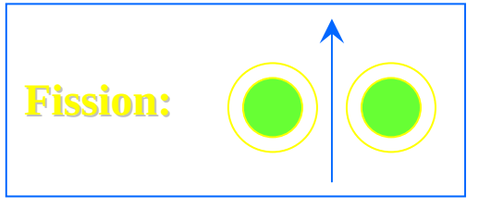
- Power & Particle management: Demonstrate extraction of power core high-grade heat, divertor power and particle handling, nuclear performance of ancillary equipment.

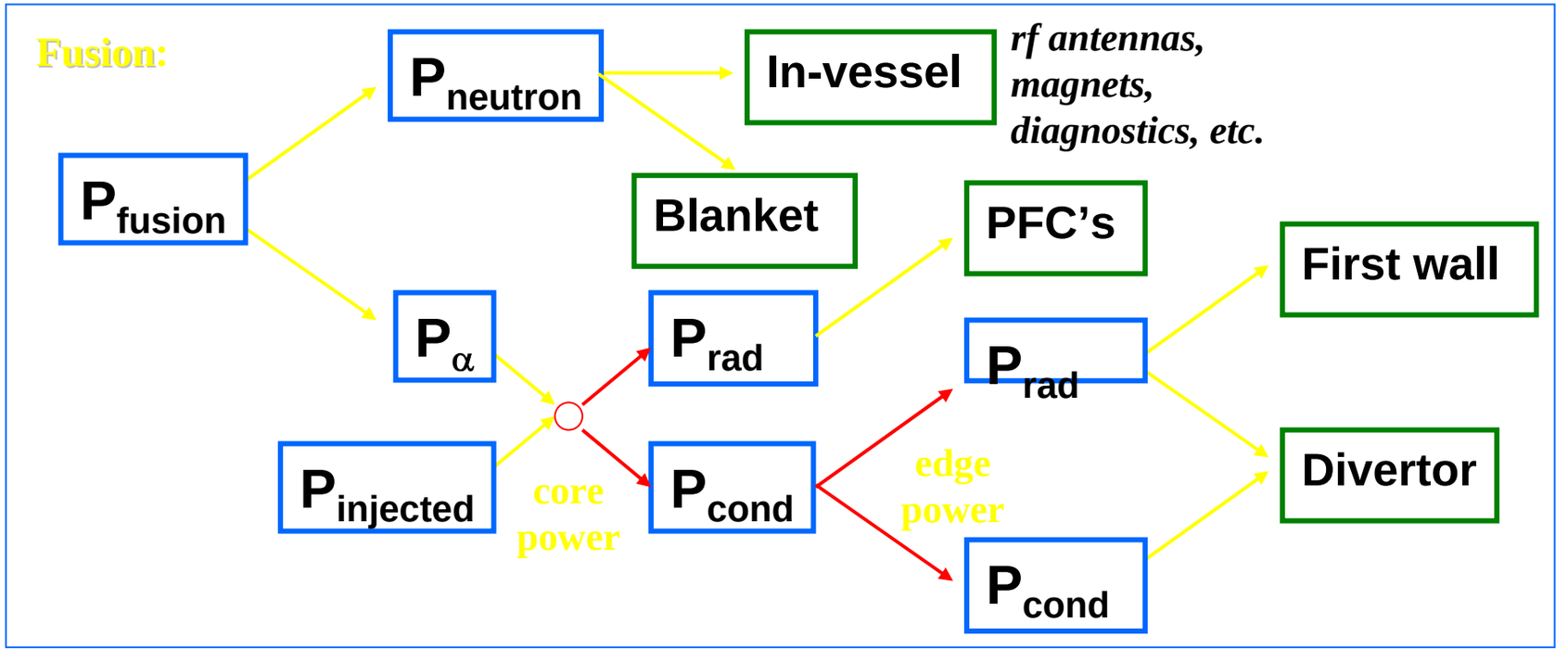
- Fuel management: Demonstrate “birth to death” tritium management in a closed loop with self-sufficient breeding and full accountability of tritium inventory.

- Safety: Demonstrate public and worker safety of the integral facility, capturing system to system interactions.

- Plant operations: Establish the operability of a fusion energy facility, including plasma control, reliability of components, inspectability and maintainability of a power plant relevant tokamak.

<u>Power & particle management</u>: Demonstrate extraction of power core high-grade heat, divertor power and particle handling, nuclear performance of ancillary equipment.

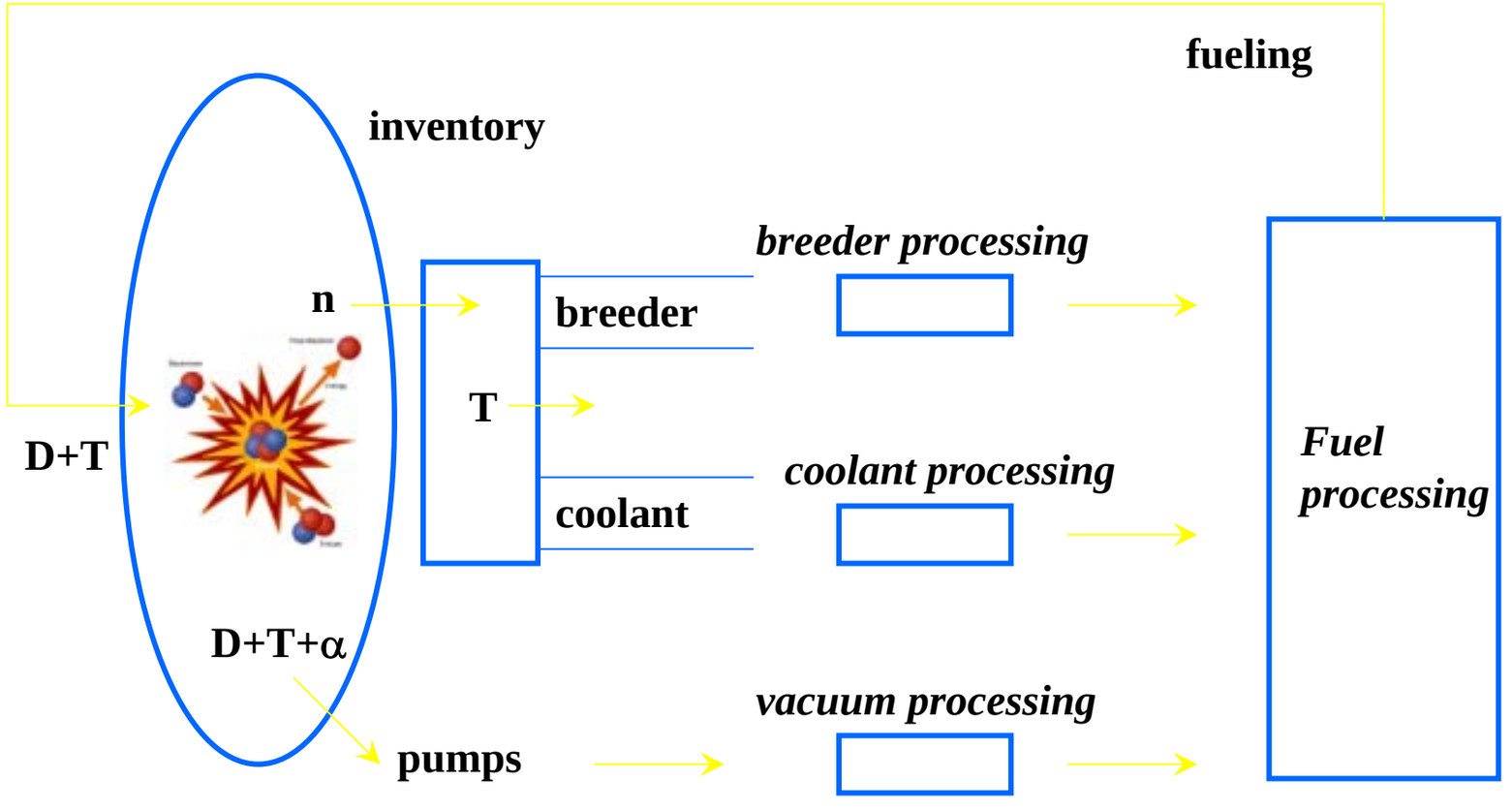




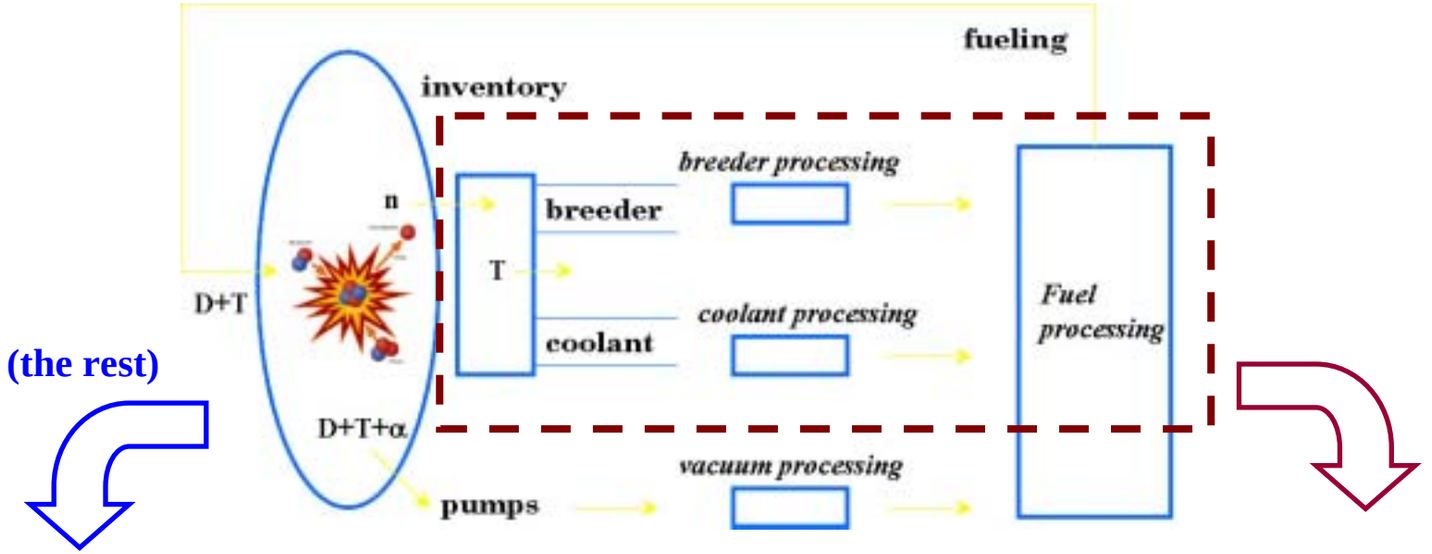
A holistic approach to Power and Particle Management

- Does not allow problem cannot be solved by transferring to another system:
  - ✓ A 100% radiating plasma transfers the problem from divertor to the first wall.
- Allows Prioritization of R&D:
  - ✓ Systems code can be used to find power plant cost (or any other metric) as a function of divertor power handling. This leads to a "benefit" metric that can be compared to other R&D areas, for example increasing plasma β. We can then answer: should we focus on power flow or improving plasma β.
  - ✓ Most technologies for current experiments & ITER are NOT transferable to a power plant. Is this an optimum approach?
- Solution may come from other areas:
  - ✓ Low recirculating power
  - ✓ A higher blanket thermal efficiency reducing input fusion power
- This particular area may have a profound impact on next-step facilities.

Fuel management: Demonstrate "birth to death" tritium management in a closed loop with self-sufficient breeding and full accountability of tritium inventory.



Fuel Management divides naturally along physical boundaries



- ITER provides most of the required data.
- Issues include minimizing T inventory and T accountability

- Can be done in a fission facility.
- Demonstrate in-situ control of breeding rate (too much breeding is bad).
- Demonstrate T can be extracted from breeder in a timely manner (minimum inventory).

For the next three years, ARIES program will examine fusion development scenarios

- What are the remaining major R&D areas?
  - ✓ What are the data base needed to field a commercial power plant (e.g., licensing, operation, reliability, etc.)?
  - ✓ What it the impact of this R&D on the attractiveness of the final product.
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (i.e., fission reactors)? What other major facilities are needed?
  - ✓ Break the systems along physics boundaries (instead of scientific disciplines).
- What other major facilities are needed (CTF, Fast track, etc.)
  - ✓ What are the possible embodiments for CTF and what are the their cost/performance attributes.
- We should consider the needs of next-step facilities in the R&D in current facilities as well as initiating R&D needed to ensure maximum utilization of those facilities.

Any Questions?