

Impact of Advanced Technologies on Fusion Power Plant Characteristics: The ARIES-AT Study

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You can download a copy of the paper and the presentation from the ARIES Web Site:
ARIES Web Site: <http://aries.ucsd.edu/PUBLIC>

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- 3) Boeing High Energy Systems,
- 4) General Atomics,
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- 6) Massachusetts Institute of Technology,
- 7) Princeton Plasma Physics Laboratory,
- 8) Rensselaer Polytechnic Institute,
- 9) University of Wisconsin - Madison,
- 10) Forschungszentrum Karlsruhe



Top-Level Requirements for Commercial Fusion Power Plants

➤ **Public Acceptance:**

- No public evacuation plan is required: total dose < 1 rem at site boundary;
- Generated waste can be returned to environment or recycled in less than a few hundred years (not geological time-scale);
- No disturbance of public's day-to-day activities;
- No exposure of workers to a higher risk than other power plants;

➤ **Reliable Power Source:**

- Closed tritium fuel cycle on site;
- Ability to operate at partial load conditions (50% of full power);
- Ability to maintain power core;
- Ability to operate reliably with less than 0.1 major unscheduled shut-down per year.

-
- ## ➤ **Above requirements must be achieved simultaneously and consistent with a competitive life-cycle cost of electricity goal.**

Translation of Requirements to GOALS for Fusion Power Plants

Requirements:

➤ Have an economically competitive life-cycle cost of electricity:

- Low recirculating power;
- High power density;
- High thermal conversion efficiency;
- Less-expensive systems.

} Improvements “saturate”
after a certain limit

➤ Gain Public acceptance by having excellent safety and environmental characteristics:

- Use low-activation and low toxicity materials and care in design.

➤ Have operational reliability and high availability:

- Ease of maintenance, design margins, and extensive R&D.

➤ Acceptable cost of development.

ARIES-AT² Was Launched to Assess the latest Developments in Advanced Tokamak Physics, Technology and Design Concepts

Advanced Tokamak

- High-performance reversed-shear plasma
 - * Build upon ARIES-RS research;
 - * Include latest physics from the R&D program;
 - * Include optimization techniques devised in the ARIES-ST study;
 - * Perform detailed physics analysis to enhance credibility.

Advanced Technology

- High-performance, very-low activation blanket:
 - * High thermal conversion efficiency;
 - * Smallest nuclear boundary.
- High-temperature superconductors:
 - * High-field capability;
 - * Ease of operation.
- Advanced Manufacturing Techniques
- Detailed analysis in support of:
 - * Manufacturing;
 - * Maintainability;
 - * Reliability & availability.

The ARIES-RS Study Set the Goals and Direction of Research for ARIES-AT

	<u>ARIES-RS Performance</u>	<u>ARIES-AT Goals</u>
Economics		
Power Density	Reversed-shear Plasma Radiative divertor Li-V blanket with insulating coatings	Higher performance RS Plasma, SiC composite blanket High T_c superconductors
Efficiency	610°C outlet (including divertor) Low recirculating power	> 1000 °C coolant outlet > 90% bootstrap fraction
Availability	Full-sector maintenance Simple, low-pressure design	Same or better
Manufacturing		Advanced manufacturing techniques
Safety and Environmental attractiveness	Low afterheat V-alloy No Be, no water, Inert atmosphere Radial segmentation of fusion core to minimize waste quantity	SiC Composites Further attempts to minimize waste quantity

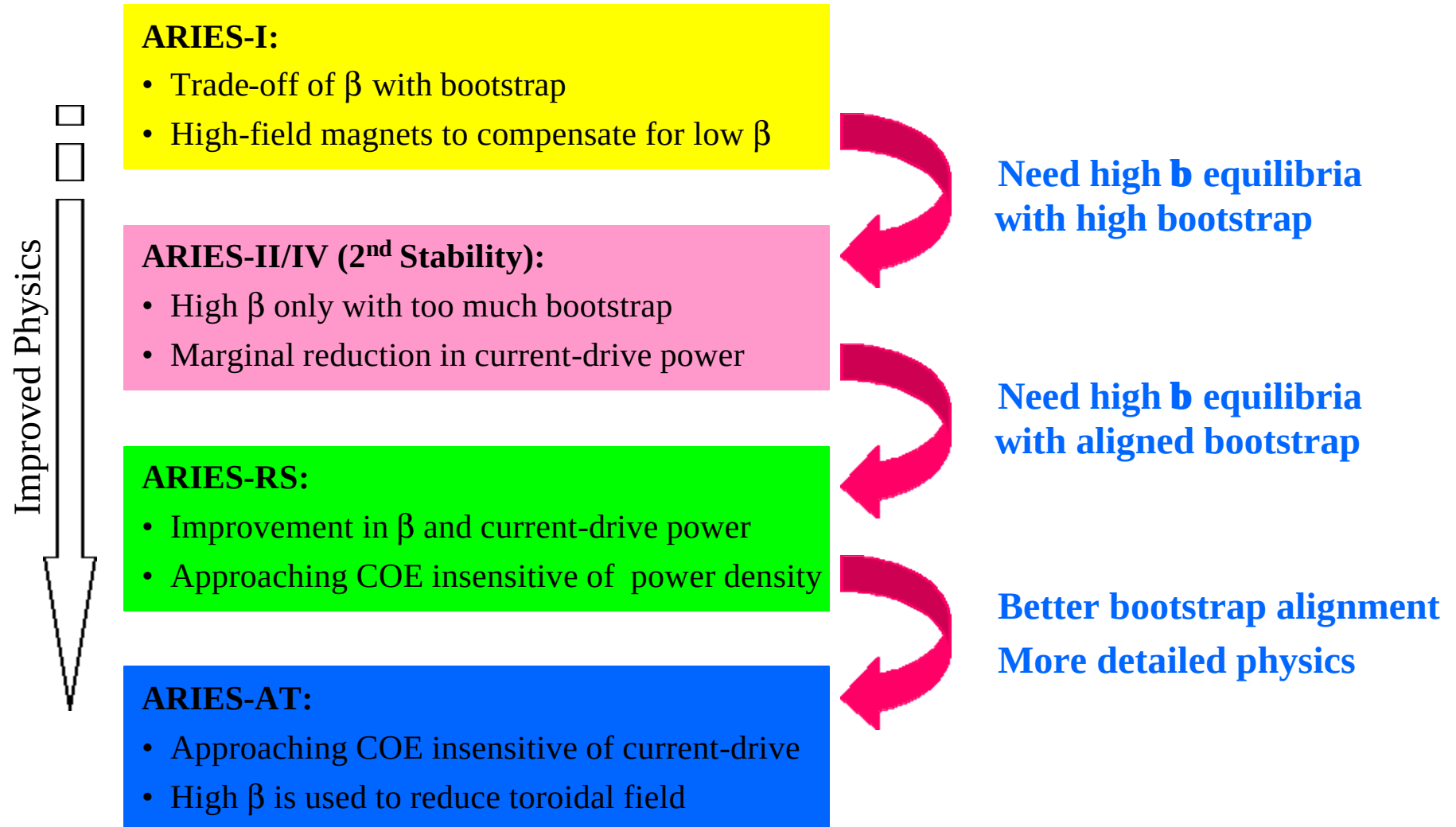
Major Parameters of ARIES-RS and ARIES-AT

	ARIES-RS	ARIES-AT
Aspect ratio	4.0	4.0
Major toroidal radius (m)	5.5	5.2
Plasma minor radius (m)	1.4	1.3
Toroidal β	5%*	9.2%*
Normalized β_N	4.8*	5.4*
Plasma elongation (κ_x)	1.9	2.2
Plasma current	11	13
Peak field at TF coil (T)	16	11.4
Peak/Avg. neutron wall load (MW/m ²)	5.4/4	4.9/3.3
Thermal efficiency	0.46	0.59
Fusion power (MW)	2,170	1,755
Current-drive power to plasma (MW)	81	36
Recirculating power fraction	0.17	0.14
Cost of electricity (c/kWh)	7.5	5.

- Designs operate at 90% of maximum theoretical β limit.

Physics Analysis

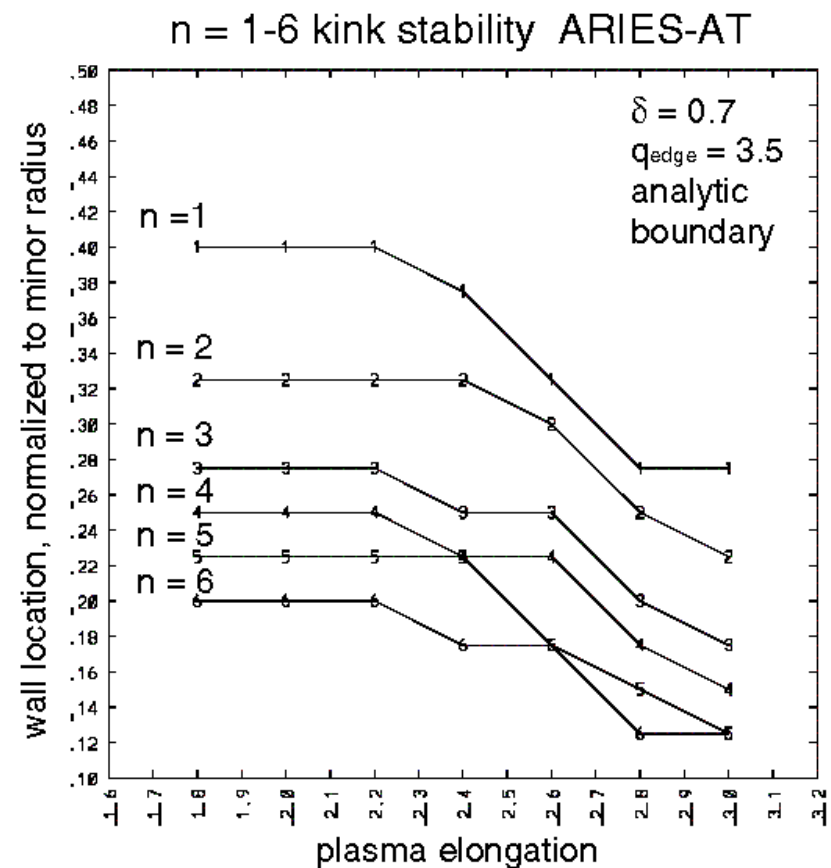
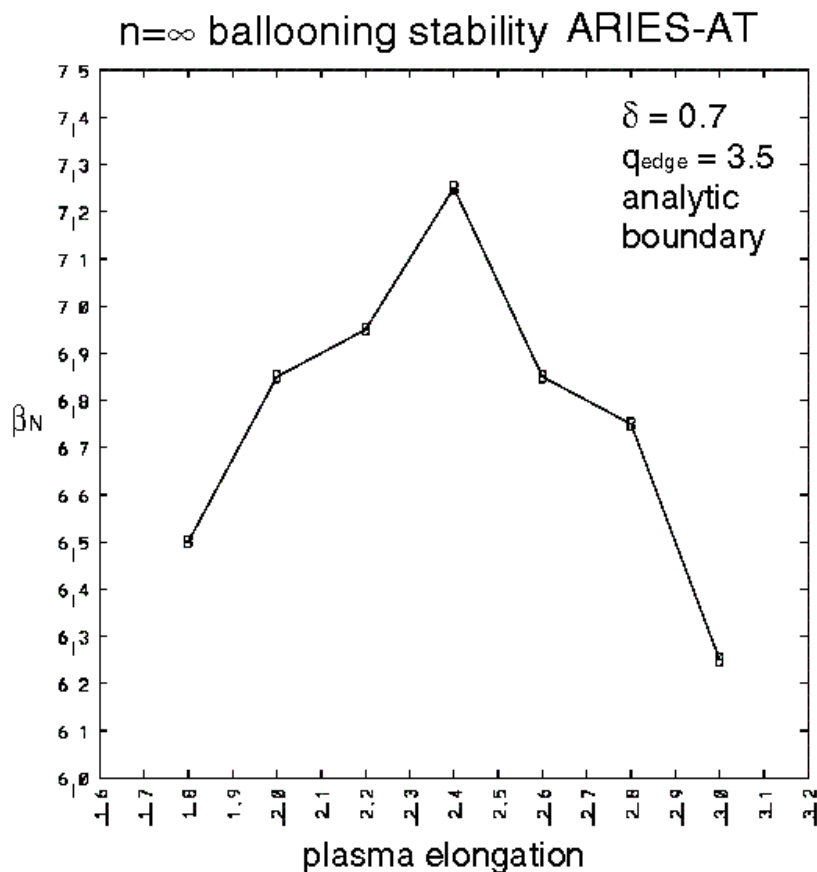
Continuity of ARIES research has led to the progressive refinement of research



ARIES-AT²: Physics Highlights

- Using $> 99\%$ flux surface from free-boundary plasma equilibria rather than 95% flux surface used in ARIES-RS leads to larger elongation and triangularity and higher stable β .
- ARIES-AT blanket allows vertical stabilizing shell closer to the plasma, leading to higher elongation and higher β .
- A kink stability shell ($\tau = 10$ ms), 1cm of tungsten behind the blanket, is utilized to keep the power requirements for $n = 1$ resistive wall mode feedback coil at a modest level.
- We eliminated HHFW current drive and used only lower hybrid for off-axis current drive.
- As a whole, we performed detailed, self-consistent analysis of plasma MHD, current drive, transport, fueling, and divertor.

The ARIES-AT Equilibrium is the Results of Extensive ideal MHD Stability Analysis – Elongation Scans Show an Optimum Elongation



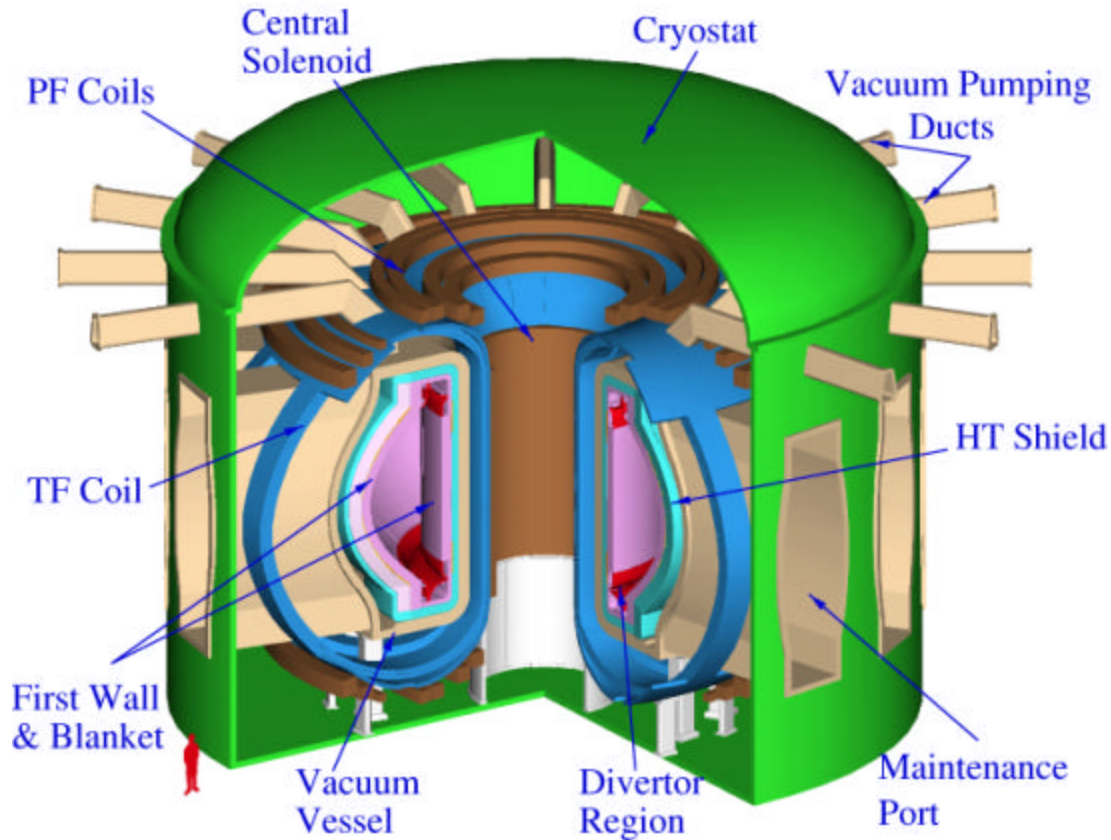
Detailed Physics Modeling Has Been Performed for ARIES-AT

- High accuracy equilibria;
- Large ideal MHD database over profiles, shape and aspect ratio;
- RWM stable with wall/rotation or wall/feedback control;
- NTM stable with LHCD;
- Bootstrap current consistency using advanced bootstrap models;
- External current drive;
- Vertically stable and controllable with modest power (reactive);
- Rough kinetic profile consistency with RS /ITB experiments, as well GLF23 transport code;
- Modest core radiation with radiative SOL/divertor;
- Accessible fueling;
- No ripple losses;
- 0-D consistent startup;

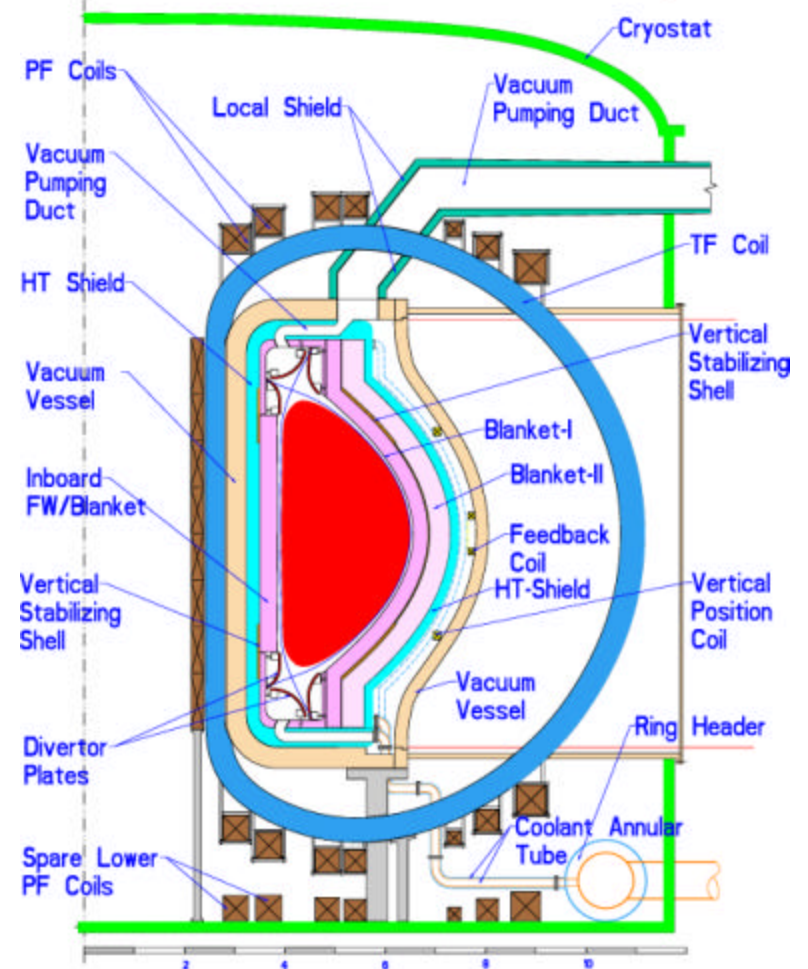
Fusion Technologies

ARIES-AT Fusion Core

Cutaway of the ARIES-AT Fusion Power Core

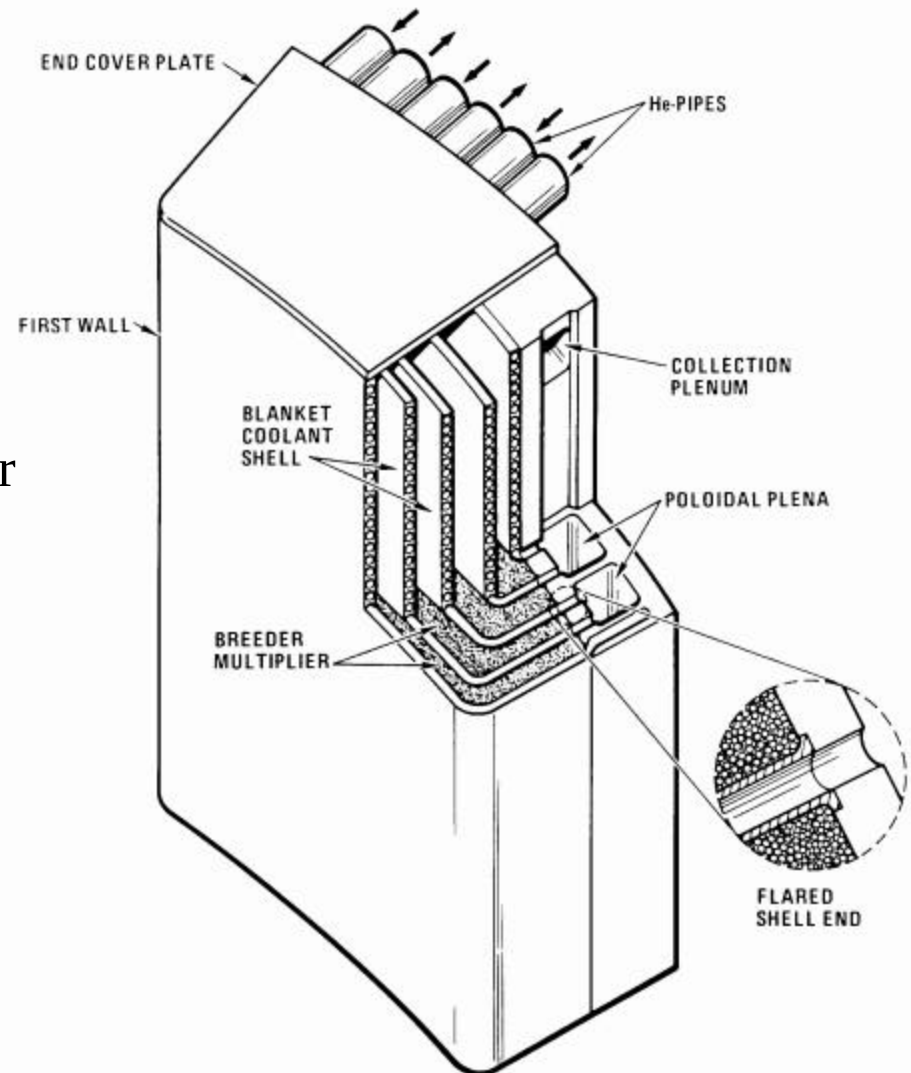


Cross Section of ARIES-AT Power Core Configuration

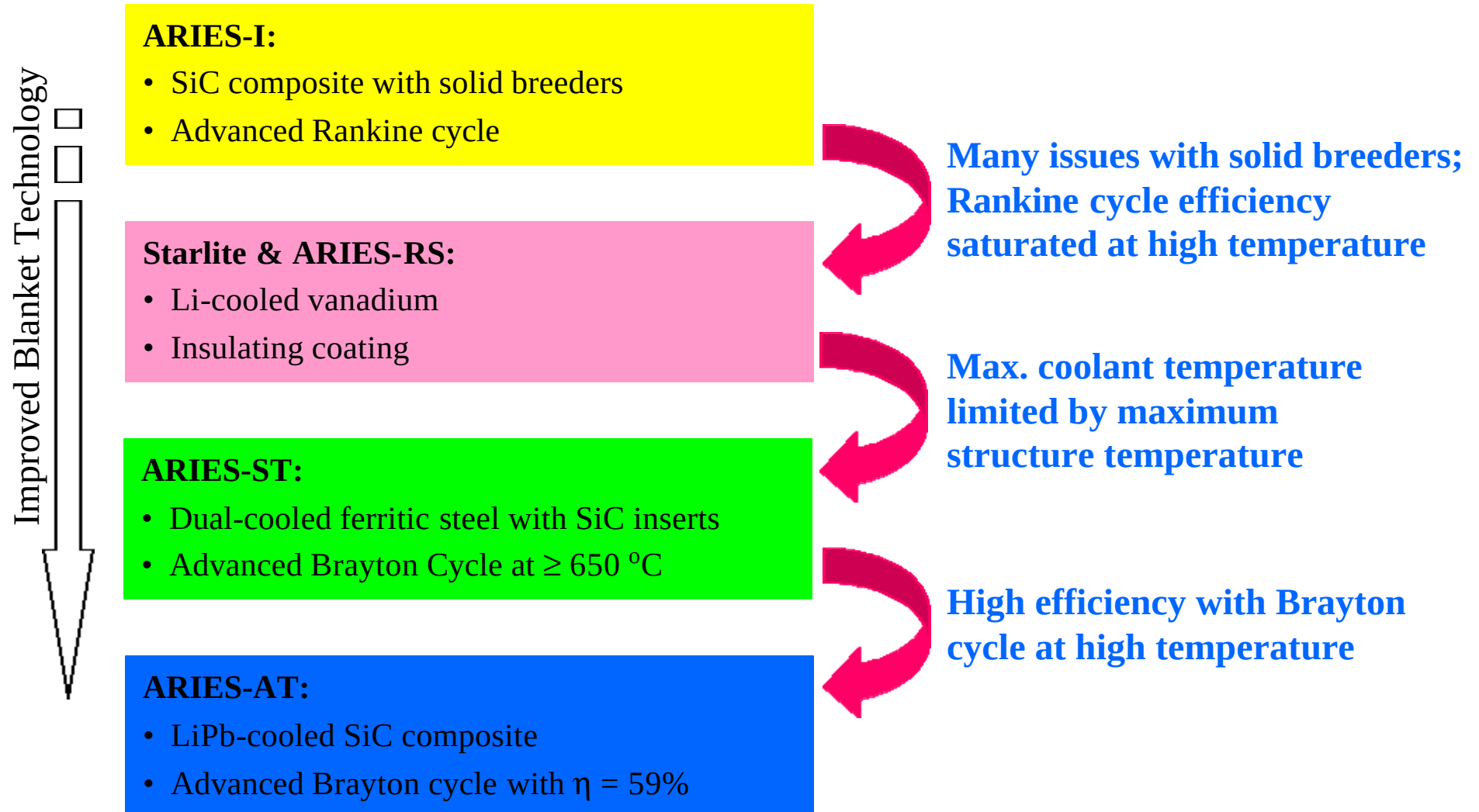


ARIES-I Introduced SiC Composites as A High-Performance Structural Material for Fusion

- Excellent safety & environmental characteristics (very low activation and very low afterheat).
- High performance due to high strength at high temperatures ($>1000^{\circ}\text{C}$).
- Large world-wide program in SiC:
 - * New SiC composite fibers with proper stoichiometry and small O content.
 - * New manufacturing techniques based on polymer infiltration or CVI result in much improved performance and cheaper components.
 - * Recent results show composite thermal conductivity (under irradiation) close to 15 W/mK which was used for ARIES-I.



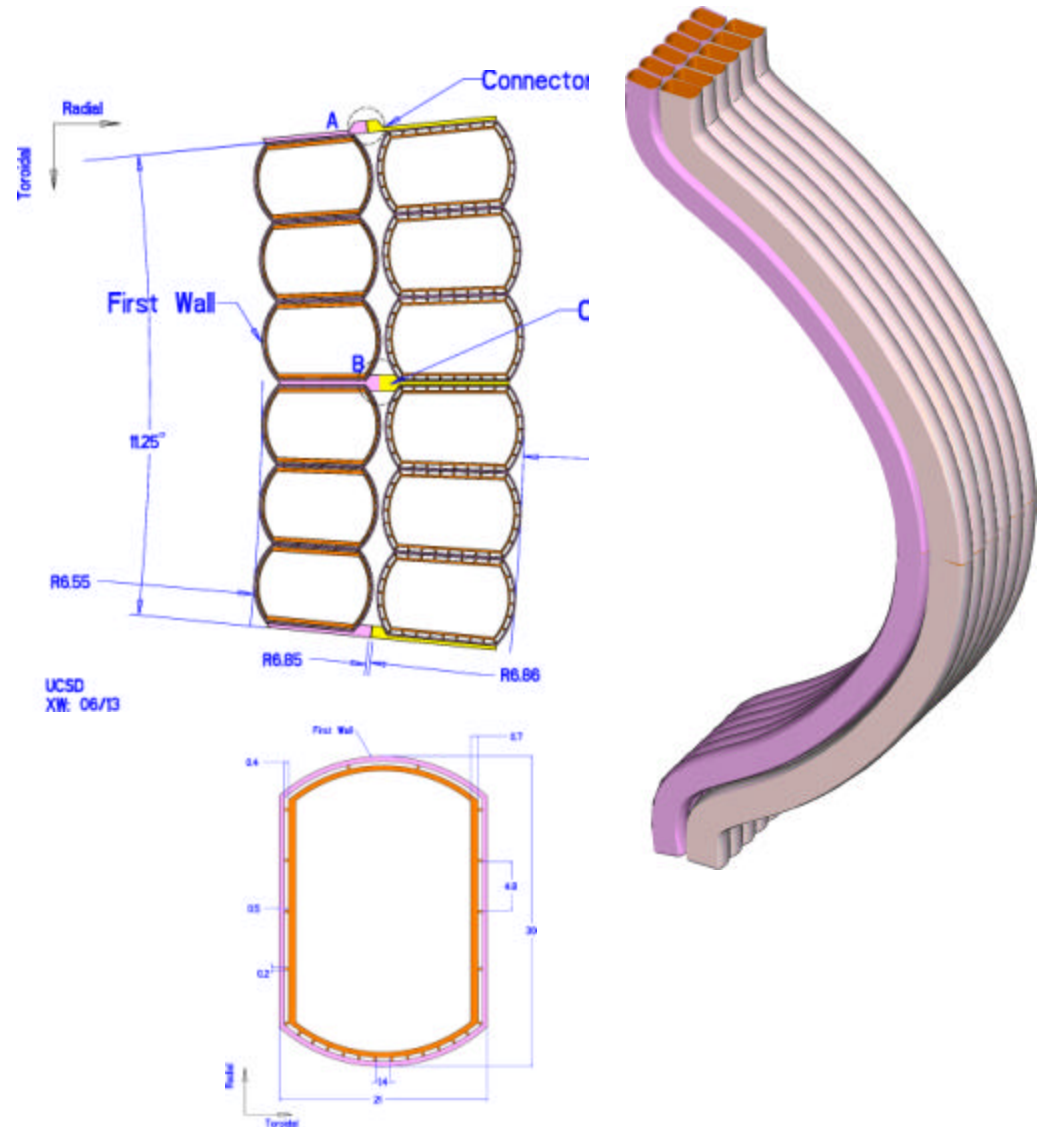
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ARIES-AT²: SiC Composite Blankets

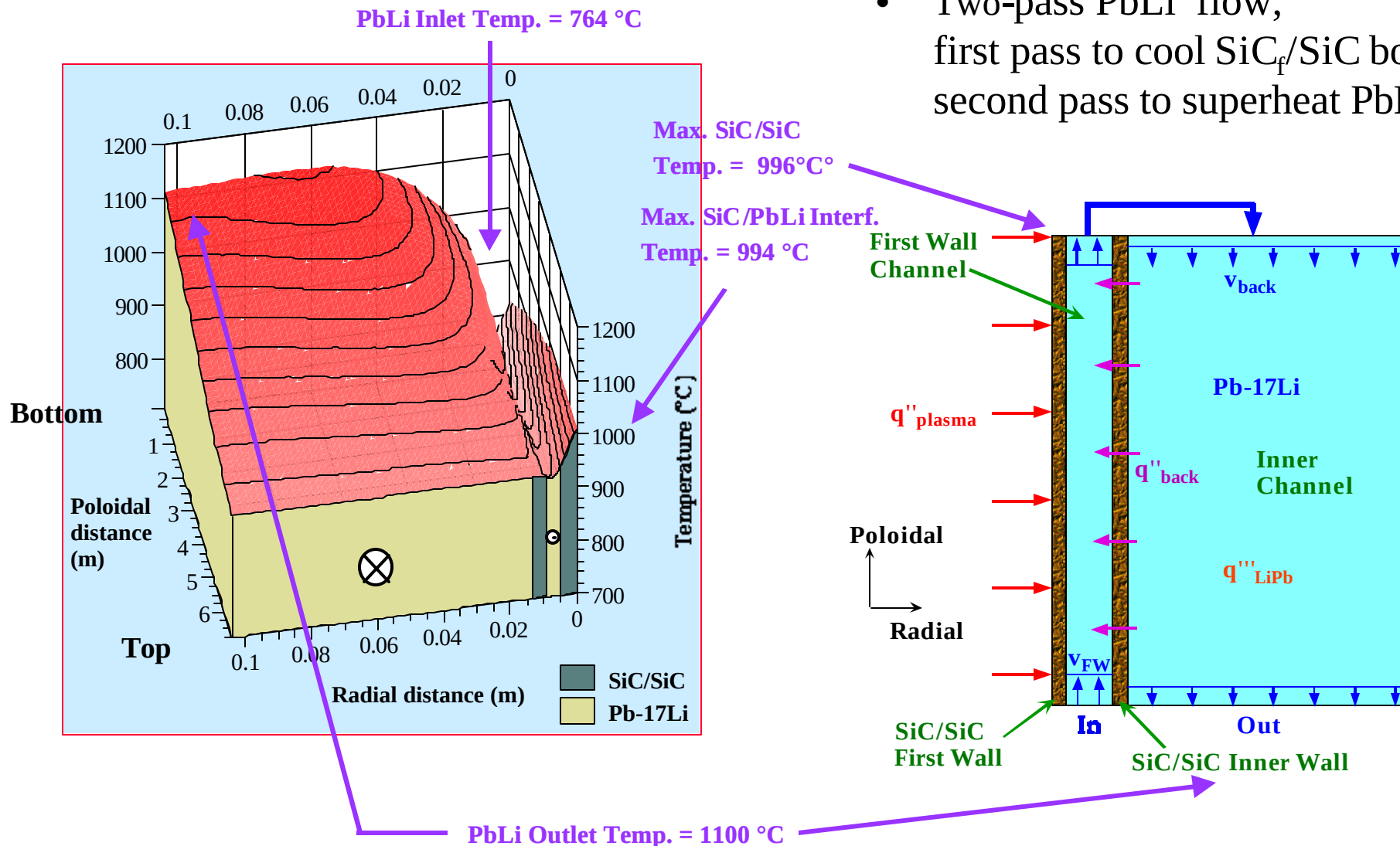
- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature ($\sim 1,100^{\circ}\text{C}$) while keeping SiC structure temperature below $1,000^{\circ}\text{C}$ leading to a high thermal efficiency of $\sim 60\%$.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
- LiPb-cooled SiC composite divertor is capable of 5 MW/m^2 of heat load.

Outboard blanket & first wall



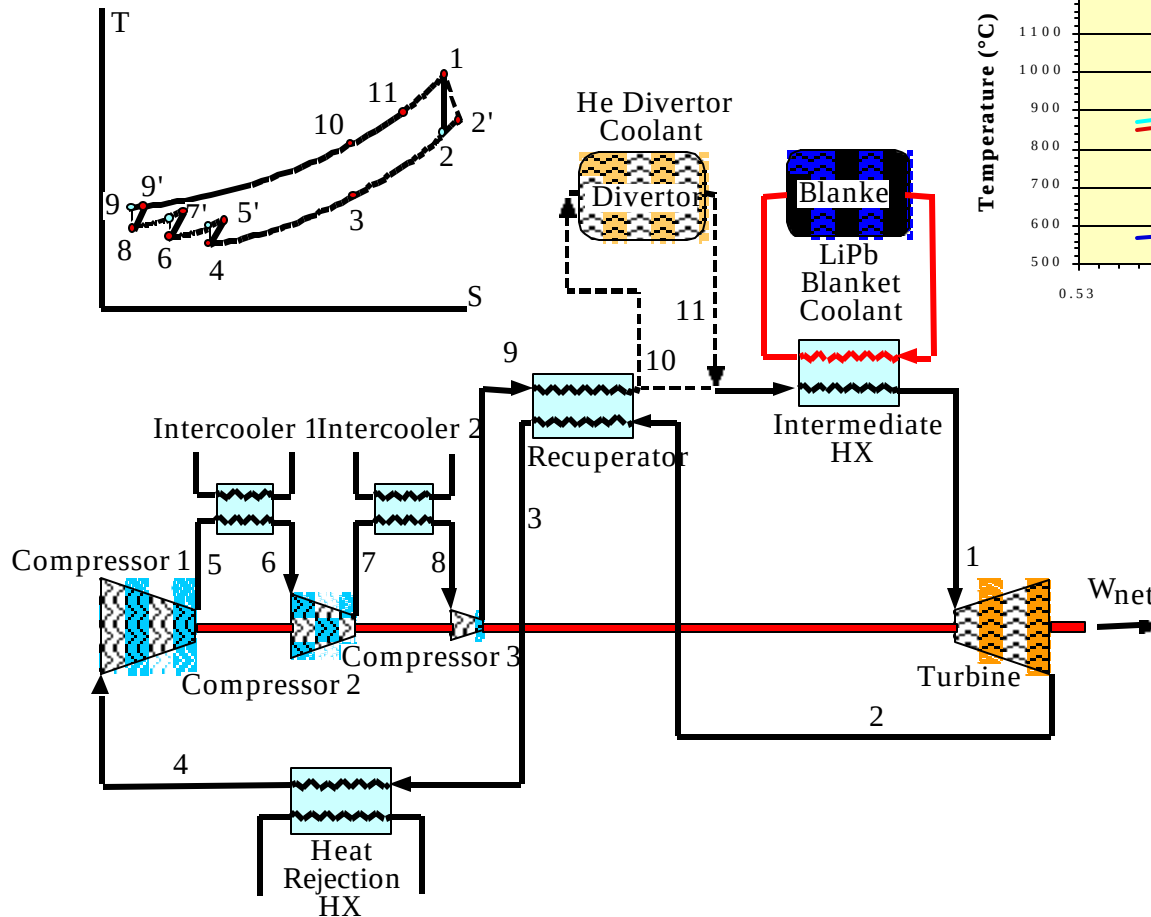
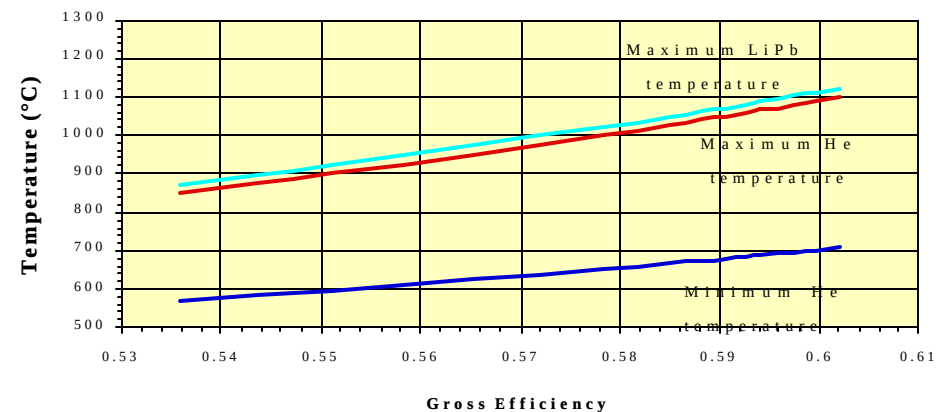
Innovative Design Results in a LiPb Outlet Temperature of 1,100°C While Keeping SiC Temperature Below 1,000°C

- Two-pass PbLi flow, first pass to cool SiC/SiC box second pass to superheat PbLi



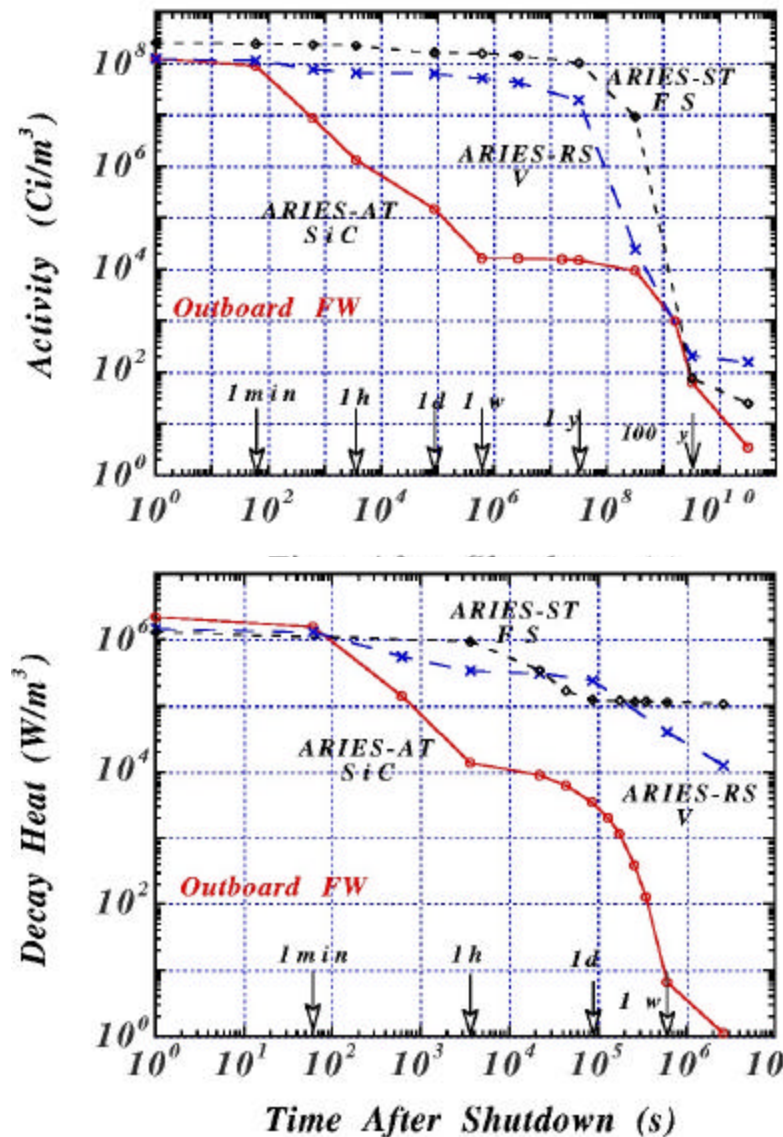
Advanced Brayton Cycle Parameters Based on Present or Near Term Technology Evolved with Expert Input from General Atomics*

Brayton Cycle He Inlet and Outlet Temperatures as a Function of Required Cycle Efficiency



➤ Key improvement is the development of cheap, high-efficiency recuperators.

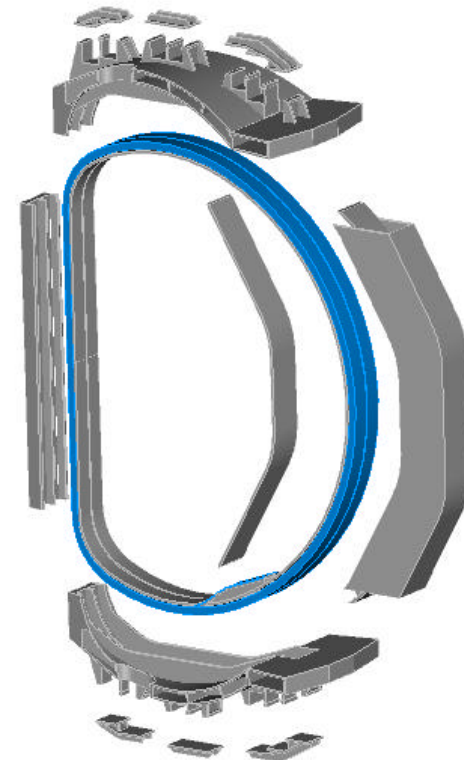
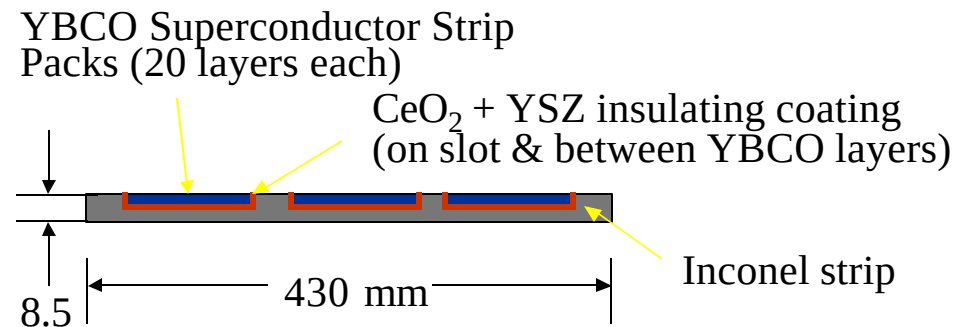
Multi-Dimensional Neutronics Analysis was Performed to Calculate TBR, activities, & Heat Generation Profiles



- Very low activation and afterheat
Lead to excellent safety and environmental characteristics.
- All components qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.
- On-line removal of Po and Hg from LiPb coolant greatly improves the safety aspect of the system and is relatively straight forward.

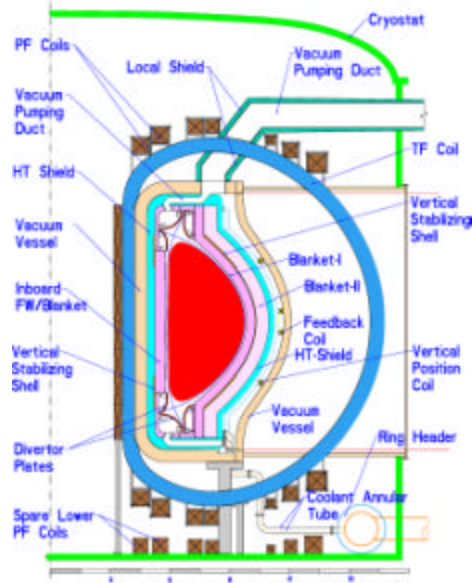
Use of High-Temperature Superconductors Simplifies the Magnet Systems

- HTS does not offer significant superconducting property advantages over low temperature superconductors due to the low field and low overall current density in ARIES-AT
- HTS does offer operational advantages:
 - * Higher temperature operation (even 77K), or dry magnets
 - * Wide tapes deposited directly on the structure (less chance of energy dissipating events)
 - * Reduced magnet protection concerns
- and potential significant cost advantages
Because of ease of fabrication using advanced manufacturing techniques

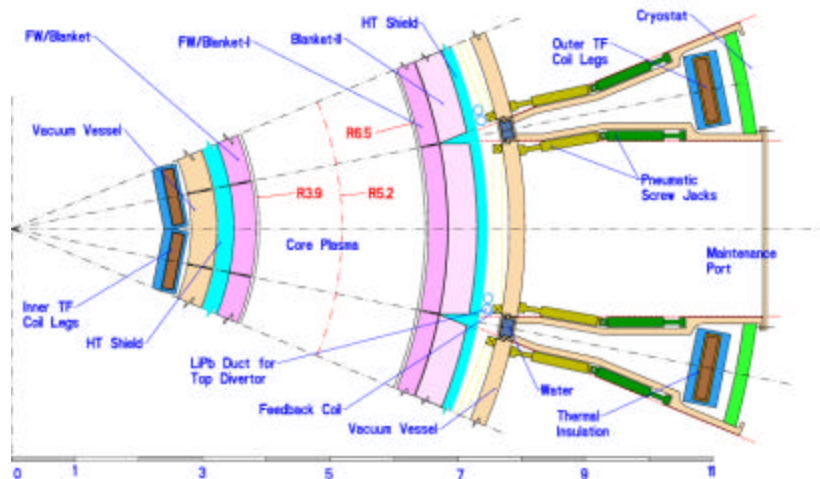


ARIES-AT Also Uses A Full-Sector Maintenance Scheme

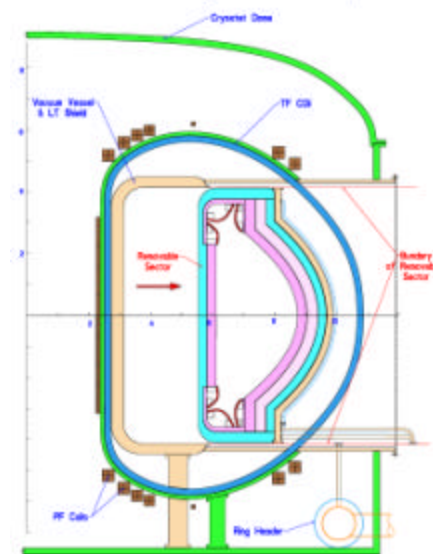
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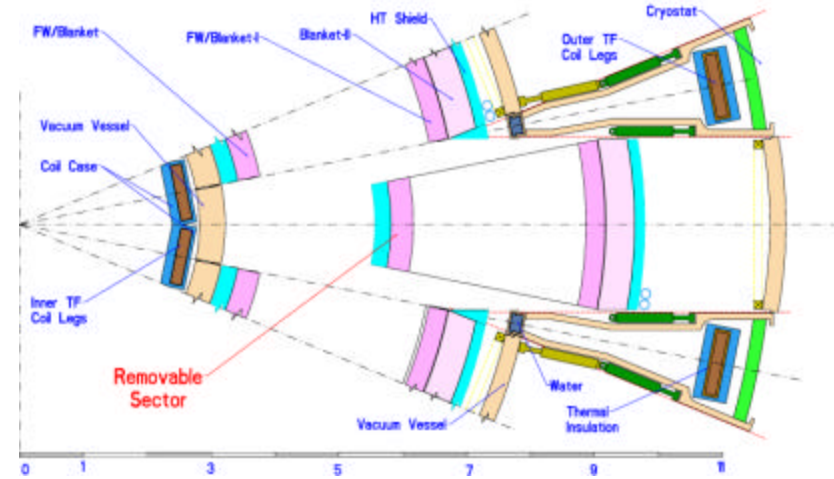
Plan View of ARIES-AT Power Core(1/16 Sector)



Cross-Section of Showing Maintenance Approach



Plan View of Showing the Removable Sector Being Withdrawn



Impact of Advanced Technologies on Fusion Power Plant Characteristics

Technologies

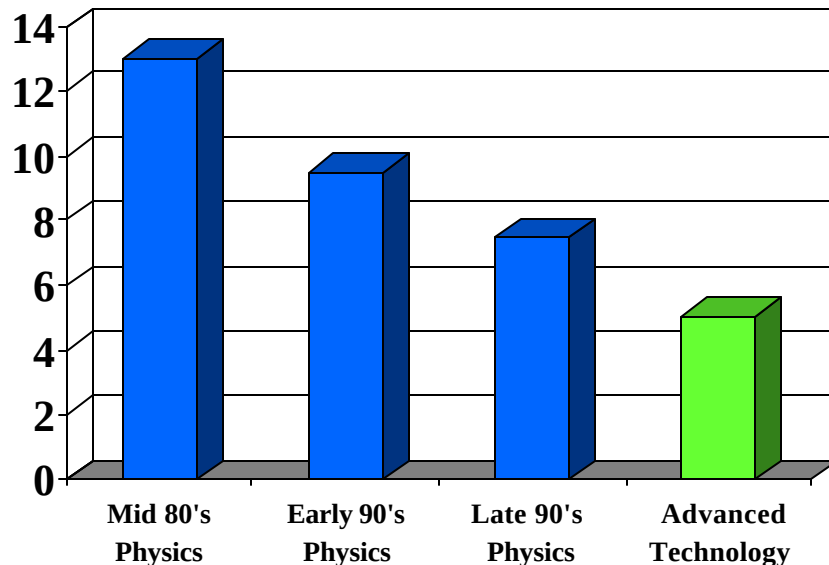
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Impact

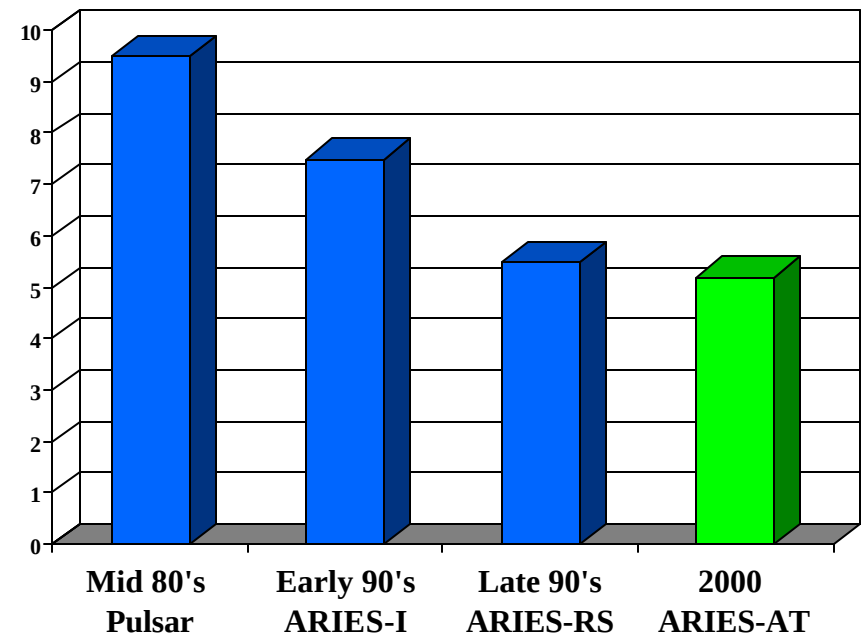
- Dramatic impact on cost and attractiveness of power plant:
 - * Reduces fusion plasma size;
 - * Reduces unit cost and enhanced public acceptance.
- Simpler magnet systems
 - * Not utilized;
 - * Simple conductor, coil, & cryo-plant.
- Utilized for High Tc superconductors.
- High availability of 80-90%
 - * Sector maintenance leads to short schedule down time;
 - * Low-pressure design as well as engineering margins enhance reliability.

Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology

Estimated Cost of Electricity (c/kWh)



Major radius (m)



ARIES-AT parameters:

Major radius: 5.2 m
Toroidal β : 9.2%
Avg. Wall Loading: 3.3 MW/m²

Fusion Power 1,760 MW
Net Electric 1,000 MW
COE 5 c/kWh

ARIES –AT Papers in this Meeting

Advanced Design III- ARIES Special Session

Today 2-5, Grand Ballroom II

- ARIES-AT Blanket and Divertor
- Systems Context of the ARIES-AT Conceptual Fusion Power Plant
- Nuclear Performance Assessment for ARIES-AT Power Plant
- Activation, Decay Heat, & Waste Disposal Analyses for ARIES-AT Power Plant
- Safety and Environmental Results for the ARIES-AT Design

Also see the following papers (presented on Monday):

- “Comparing Maintenance Approaches for Tokamak Fusion Power Plants,” L. Waganer, et al.
- “Loss of Coolant and Loss of Flow Accident Analyses for ARIES-AT Power Plant,” E. Mogahed, et al.
- “An Assessment of the Brayton Cycle for High Performance Power Plant.” Schleicher, et al.

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