Contributions of Burning Plasma Physics Experiment to Fusion Energy Goals

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Translation of Requirements to GOALS for Fusion Power Plants

- **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.**

Main Contribution of a Burning Plasma Experiment Is to Identify and Demonstrate Optimum Plasma Regime of Operation for Power Plants

- The key is predictive capability!
- A single machine can only explore a region of operation space:
  - Use existing knowledge and power plant studies to identify the most promising design space.
- The collection of ARIES designs form a good basis for experimental plans and progress in a Burning Plasma experiment.
- Focus of talk and optimizations is ~1000-MWe power plants.
  - For a certain regime of operation, a power plant, a burning plasma experiment, and a confinement experiment each optimize in a different set of global parameters (*e.g.*, A, R, …). Focus should be on the regime of operation!

Optimization of Power Plant Plasmas—
First, We Need to Make Fusion Power!

Confinement Time and Transport

- Typically, global confinement is not a major issue in a power plant. All ARIES designs require confinement performance similar to present experiments: H(89P) ~2-3. A better confinement has to be <u>degraded</u>!
- For a burning plasma experiments, good global confinement means we can built a smaller (fusion power) machine. After the machine is operational, confinement better than needed for ignition has to be <u>degraded</u>!
  - A Burning Plasma Experiment should show that a <u>steady</u> fusion burn can be achieved (power and particle control) and fusion power can be controlled within a few percent of its nominal value.
  - Understanding (and manipulating) local transport is critical to optimizing plasma profiles.

Next, We Need to Make Electric Power!

Recirculating Power Should Be Low! Steady-state or Pulsed operation?

- ➢A good comparison: Pulsar pulsed-plasma and ARIES-I first-stability, steady-state.
- ➢**Perception:** The drawback of pulsed-plasma operation is pulsed output power. **(Incorrect)**
  - ∗ Pulsar design included an innovative energy storage system that allowed pulsed-plasma operation while keeping the plant thermal output steady.
- ➢**Perception:** Pulsed-plasma operation does not need any current-drive system. There is more flexibility in choosing plasma parameters. **(Incorrect)**
  - ∗ Pulsed operation has a current-drive system, the PF system. This “current-drive” system is quite expensive (large volt-sec and rapid current ramp). PF system of Pulsar is about 4 times more expensive than ARIES-I.
  - ∗ Because the inductive drive system is expensive, one needs to maximize bootstrap fraction and operate with maximum drive efficiency (high temperature, low impurity concentration, *etc.)*

Þ Physics needs of pulsed and steady-state first stability devices are the same (except non-inductive current-drive physics). Both need to trade-off β with bootstrap!

Optimization of Power Plant Plasmas— Steady-state or Pulsed operation?

- Pulsed-operation: *n* and *T* profiles uniquely determine pressure and current density profile (loop voltage is constant across plasma cross section). Optimum regime is $\beta_N \sim 3$ and bootstrap fraction 30% to 40%.
- Steady-state operation: Current density profile can be tailored: $\beta_N \sim 3.4$ and bootstrap fraction 60% to 75%.
- Higher field in the PF system (larger Vs) and rapid current ramp in a pulsed-plasma system leads to a lower toroidal field strength compared to a steady-state device for the same magnet technology (same conductor and structural material).
  - For the same magnet technology, the steady-state device has a higher fusion power density, it is smaller and cheaper.
- For the same physics and technology basis, a steady-state first-stability device outperforms a pulsed-plasma tokamak.
- Steady-state first-stability operation, entry level to advanced tokamak modes, leads to an acceptable fusion power plant. It should be demonstrated in a burning-plasma experiment.

Optimization of Power Plant Plasmas— Next, Increase Power Density

- Cost of fusion plant decreases with increased power density. For a 1GWe plant, this improvement “saturates” at ~5 MW/m^2 peak wall loading.

➢ A steady-state, first stability device with Nb_3Sn magnet technology has a power density about 1/2 of this goal. Two options are possible:

- ✓ Develop high-field magnets:
  - ∗ ARIES-I pushed the limit for cryogenic superconductor to 19T (1990) .
  - ∗ Advanced STTR-2 proposes high-temperature superconductor to achieve 21 T (2000).
- ✓ High-bootstrap plasma with higher β ⇒ Reversed shear plasma
  - ∗ Added benefit of higher bootstrap fraction,
  - ∗ Resistive wall modes should be stabilized.
  - ∗ ARIES-RS (medium extrapolation): β_N= 4.8, β=5%, P_{cd}=81 MW (achieves ~5 MW/m^2 peak wall loading.)
  - ∗ ARIES-AT (Aggressive): β_N= 5.4, β=9%, P_{cd}=36 MW (high β is used to reduce peak field at magnet)

Continuity of ARIES Research Has Led to the Progressive Refinement of Plasma Optimization

Pulsar (pulsed-tokamak):

- Trade-off of β with bootstrap
- Expensive PF system, under-performing TF

For the same physics & technology basis, steady-state operation is better

ARIES-I (first-stability steady-state):

- Trade-off of β with bootstrap
- High-field magnets to compensate for low β

Need high b equilibria with aligned bootstrap

ARIES-RS (reverse shear):

- Improvement in β and current-drive power
- Approaching COE insensitive of power density

Better bootstrap alignment

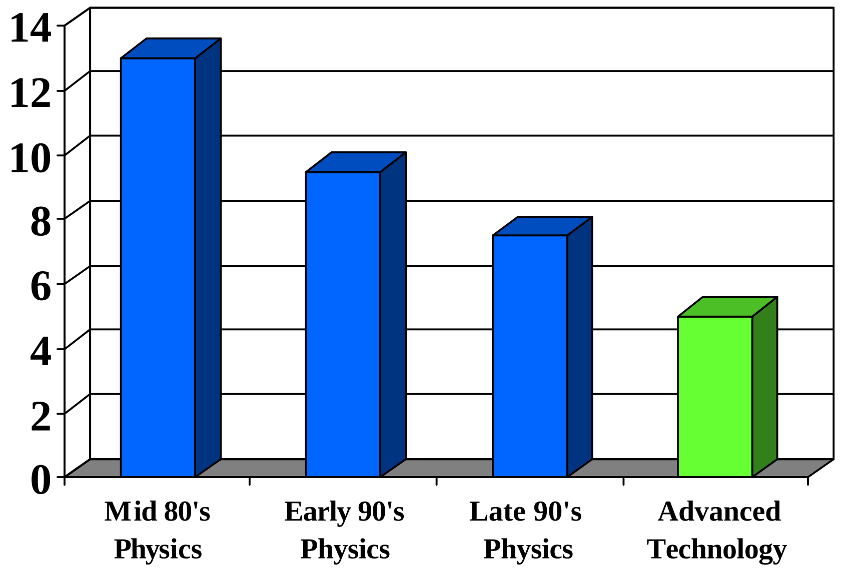
More detailed physics

ARIES-AT (aggressive reverse shear):

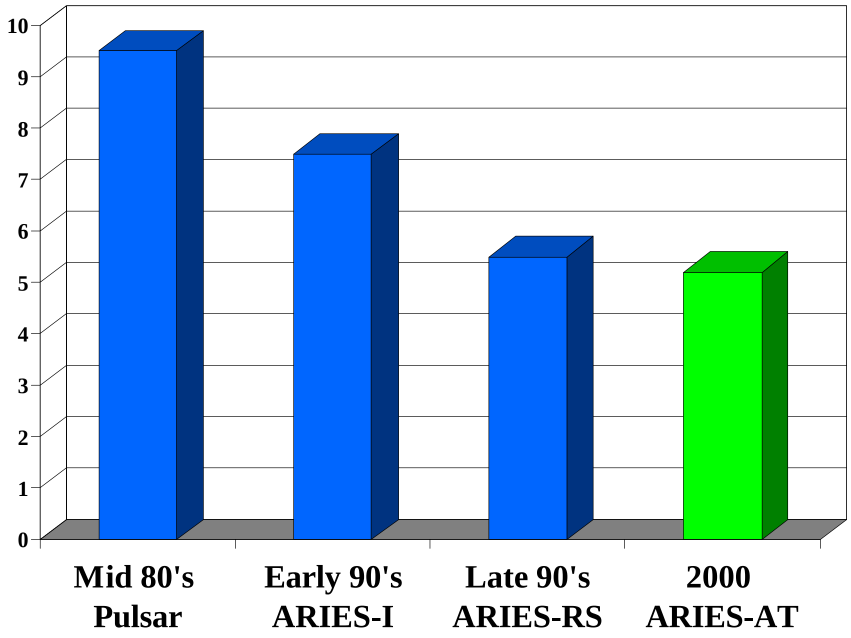
- Approaching COE insensitive of current-drive
- High β is used to reduce toroidal field

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	Fusion Power	1,760 MW
Toroidal β:	9.2%	Net Electric	1,000 MW
Avg. Wall Loading:	3.3 MW/m^2	COE	4.7 c/kWh

ARIES designs Correspond to Experimental Progress in a Burning Plasma Experiment

Pulsar (pulsed-tokamak):

- Trade-off of β with bootstrap
- Expensive PF system, under-performing TF

"Conventional" Pulsed plasma: Explore burn physics

ARIES-I (first-stability steady-state):

- Trade-off of β with bootstrap
- High-field magnets to compensate for low β

Demonstrate steady-state first-stability operation.

ARIES-RS (reverse shear):

- Improvement in β and current-drive power
- Approaching COE insensitive of power density

Explore reversed-shear plasma

a) Higher Q plasmas

b) At steady state

ARIES-AT (aggressive reverse shear):

- Approaching COE insensitive of current-drive
- High β is used to reduce toroidal field

Explore envelopes of steady-state reversed-shear operation

Improved Physics

Optimization of Power Plant Plasmas— Next, Power & Particle Control and Edge Physics

- **Perception:** The best solution is use a radiative mantel to distribute the heat on the first wall uniformly because this leads to lowest heat flux. **(Incorrect)**
  - It is typically easier to cool a divertor plate at 5 MW/m^2 than the inboard first wall at 1 MW/m^2 (because of coolant flow path is longer and space is more limited).
  - H-mode edge requires a radiative mantel and does not lead to the best power and particle control solution (too high a heat flux on the first wall, too much impurities).
  - L-mode edge is much preferred for power and particle control (combined with high-recycling or detached divertor).
  - Current tokamak experiments can make considerable progress in this area.

Summary

- Main contribution of a burning plasma experiment is to identify and demonstrate optimum plasma regime of operation for power plants.
  - Pulsed-plasma operations to explore burn physics.
  - Demonstration of first-stability, steady-state operation as an entry to advanced tokamak modes and an acceptable fusion power plant.
  - Exploration of reversed shear mode for study of higher Q plasma at steady state.
  - Exploration of envelopes of reversed-shear regime.
- Capability to perform technology testing probably adds considerably to the cost of a burning plasma experiment. It is probably more cost-effective to develop fusion technologies separately and test them in a high-fluence follow-up device to the burning-plasma experiment.
  - But we need to do technology development now to be ready for such a follow-up device.