Physics Issues and Trade-offs in Magnetic Fusion Power Plants

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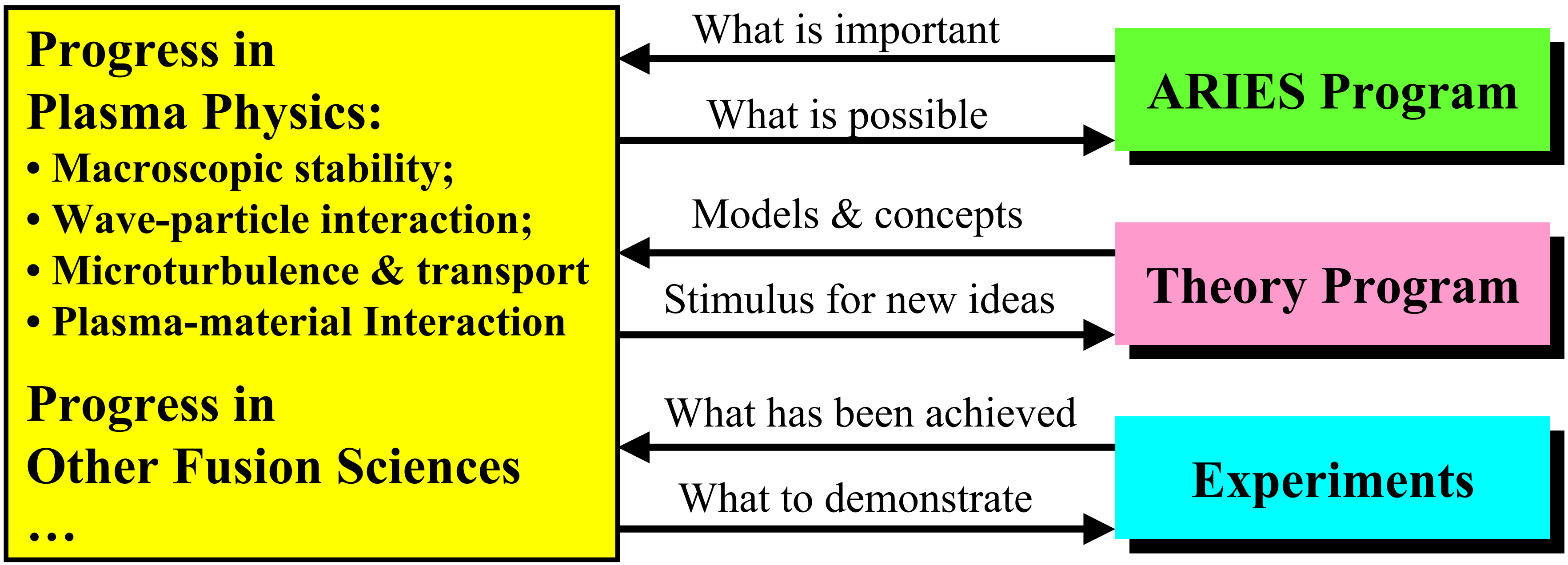
You can download a copy of the paper and the presentation from the ARIES Web Site:
ARIES Web Site: http://aries.ucsd.edu/ARIES/

Analysis of Conceptual Fusion Power Plants Identifies Key R&D Issues and Provides a Vision for Fusion Research



- Trade-off among disciplines and systems usually determine:
  - ✓ The optimum regime of operation;
  - ✓ The most useful dimensionless parameters;
  - ✓ most effective experiments for the moment;
  - ✓ The most cost-effective routes to the evolution of the experimental, scientific and technological program.

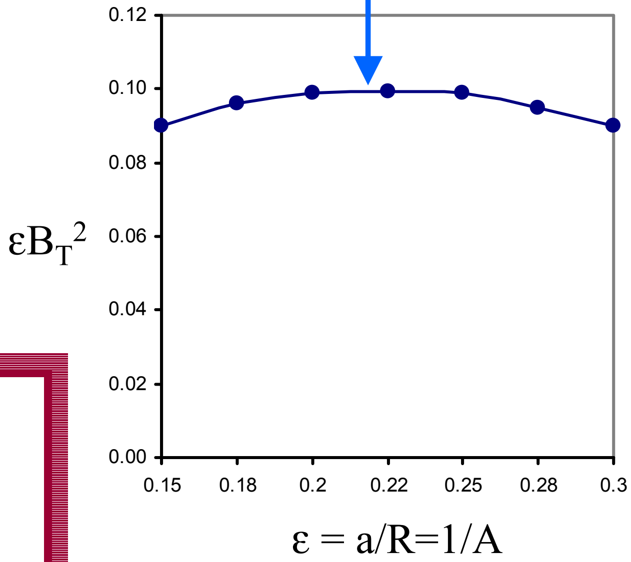
Trade-offs Among Systems Determine Optimum Regimes of Operation

- For Superconducting Tokamaks, it is β/ε (*i.e.*, $\beta R/a$) that is important, not β.

  Fusion power density, $P_f \sim \beta^2 B_T^4 = (\beta/\varepsilon)^2 (\varepsilon B_T^2)^2$

MHD Figure of Merit

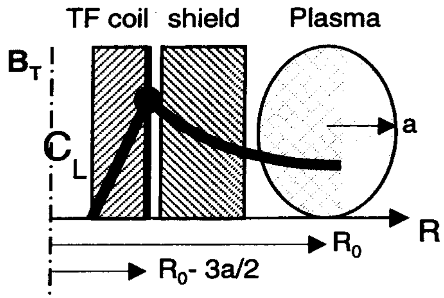
Almost Constant for B_T fixed at the TF coil



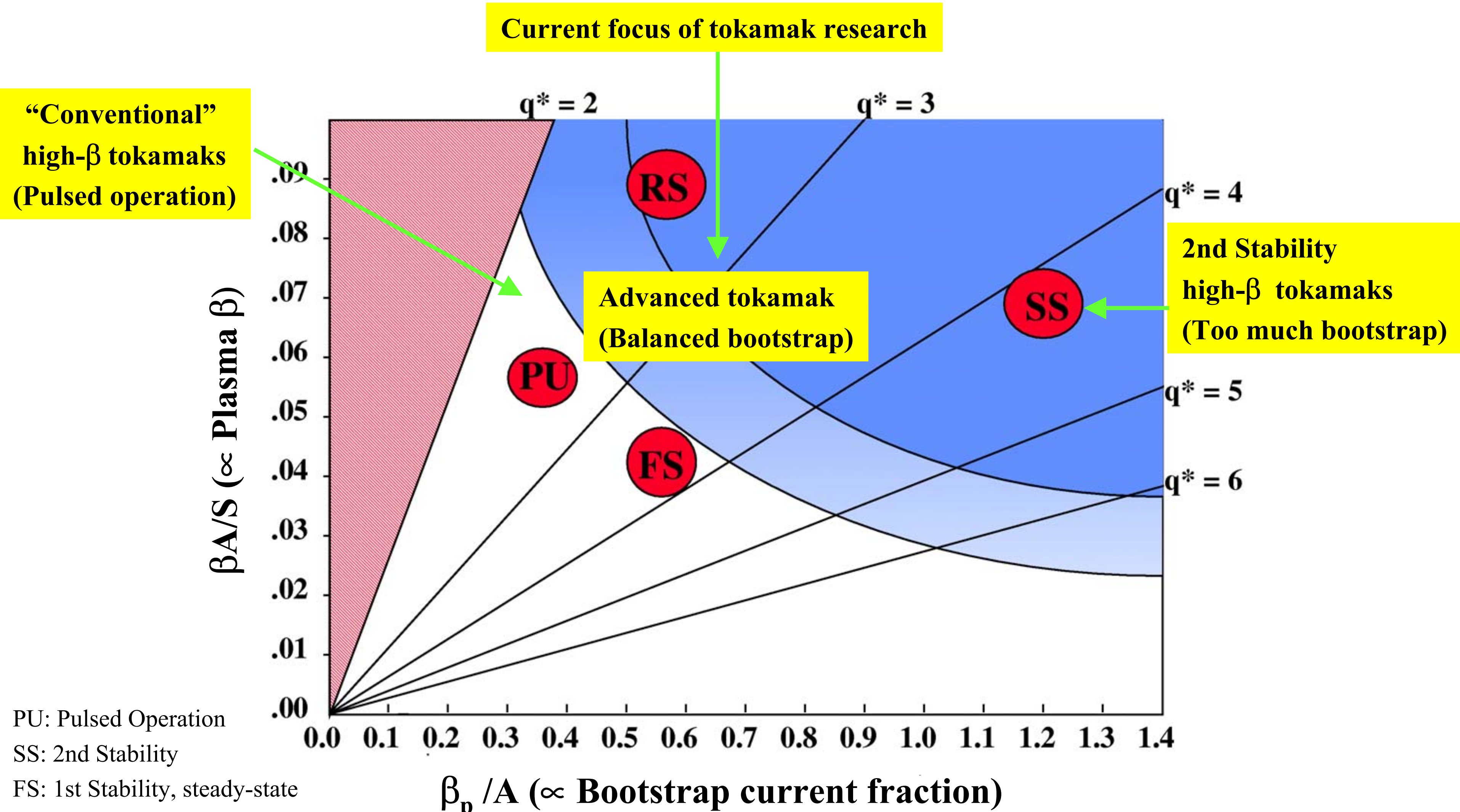
Other Examples

- Trade-off between bootstrap current fraction and β

  $\Rightarrow$ Advanced Tokamak Regime
- Trade-off between vertical stability and plasma shape
- Trade-off between plasma edge condition and plasma facing components capabilities,
- …



Advanced Tokamak Regime Is Based on the Trade-off Between MHD and Bootstrap



PU: Pulsed Operation

SS: 2nd Stability

FS: 1st Stability, steady-state

RS: Reversed-shear

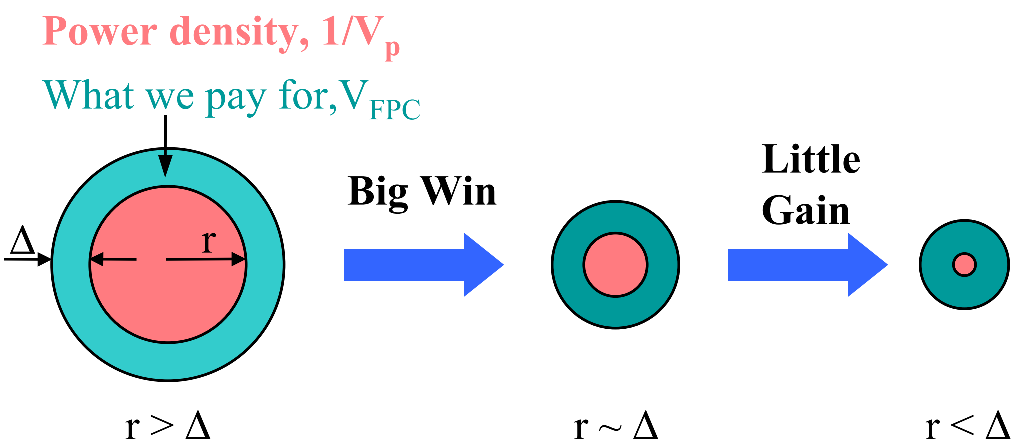
For the same physics and technology basis, steady-state devices outperform pulsed tokamaks

- Physics needs of pulsed and steady-state first stability devices are the same (except non-inductive current-drive physics).

	Pulsar	**ARIES-I'**
Current-drive system	PF System Very expensive but efficient	Non-inductive drive Expensive & inefficient
Recirculating Power	Low	High
Optimum Plasma Regime	High Bootstrap, High A, Low I	High Bootstrap, High A, Low I
Current profile Control	No, 30%-40% bootstrap fraction $\beta_N \sim 3$, $\beta \sim 2.1\%$	Yes, 65-%-75% bootstrap fraction $\beta_N \sim 3.3$, $\beta \sim 1.9\%$
Toroidal-Field Strength	Lower because of interaction with PF (B ~ 14 T on coil)	Higher (B ~ 16 T on coil)
Power Density	Low	Medium
Size and Cost	High (> 9 m major radius)	Medium (~ 8 m major radius)

Directions for Improvement

Increase Power Density



- ✓ Improvement “saturates” at ~5 MW/m^2 peak wall loading (for a 1GWe plant).
- ✓ A steady-state, first stability device with Nb_3Sn technology has a power density about 1/3 of this goal.

Decrease Recirculating Power Fraction

- ✓ Improvement “saturates” about Q ~ 40.
- ✓ A steady-state, first stability device with Nb_3Sn Tech. has a recirculating fraction about 1/2 of this goal.

High-Field Magnets

- ✓ ARIES-I with 19 T at the coil (cryogenic).
- ✓ Advanced SSTR-2 with 21 T at the coil (HTS).

High bootstrap, High β

- ✓ 2^{nd} Stability: ARIES-II/IV
- ✓ Reverse-shear: ARIES-RS, ARIES-AT, A-SSRT2

Reverse Shear Plasmas Lead to Attractive Tokamak Power Plants

First Stability Regime

- Does Not need wall stabilization (Resistive-wall modes)
- Limited bootstrap current fraction (< 65%), limited β_N= 3.2 and β=2%,
- **ARIES-I:** Optimizes at high A and low I and high magnetic field. H-mode confinement

Reverse Shear Regime

- Requires wall stabilization (Resistive-wall modes)
- Excellent match between bootstrap & equilibrium current profile at high β.
- Internal transport barrier
- **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 extrapolation): β_N= 5.4, β=9%, P_{cd}=36 MW (high β is used to reduce peak field at magnet)

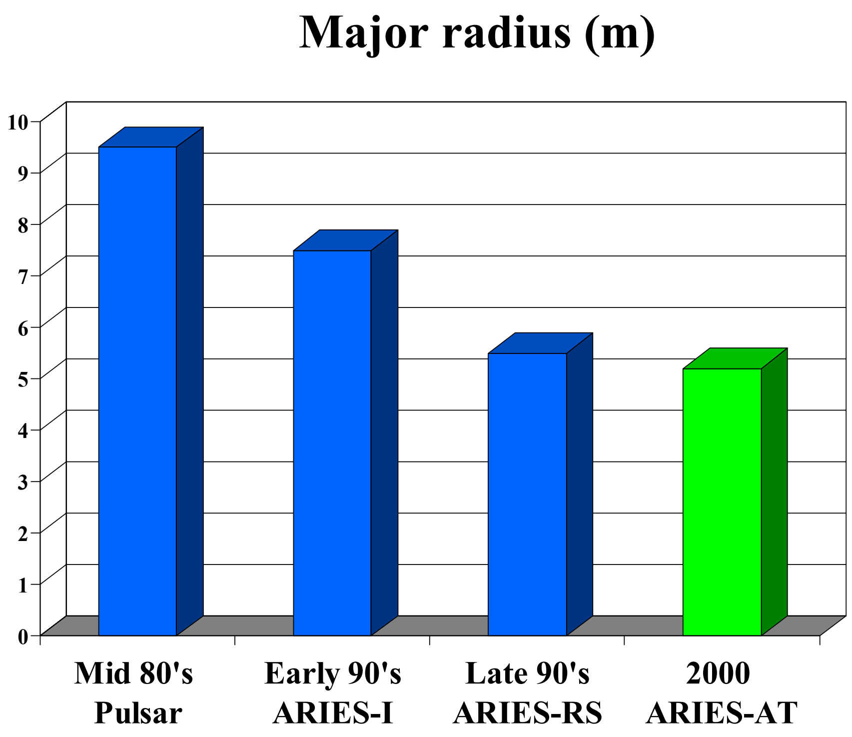
Evolution of ARIES Designs

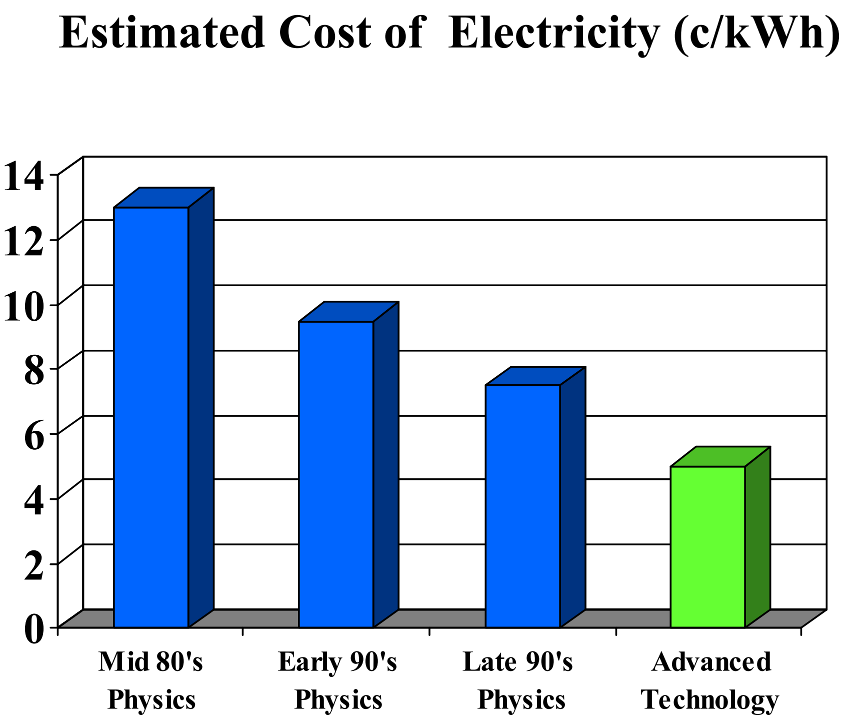
	1st Stability, Nb_3Sn Tech.	High-Field Option	Reverse Shear Option	
	ARIES-I'	ARIES-I	ARIES-RS	ARIES-AT
Major radius (m)	8.0	6.75	5.5	5.2
β (β_N)	2% (2.9)	2% (3.0)	5% (4.8)	9.2% (5.4)
Peak field (T)	16	19	16	11.5
Avg. Wall Load (MW/m^2)	1.5	2.5	4	3.3
Current-driver power (MW)	237	202	81	36
Recirculating Power Fraction	0.29	0.28	0.17	0.14
Thermal efficiency	0.46	0.49	0.46	0.59
Cost of Electricity (c/kWh)	10	8.2	7.5	5

Approaching COE insensitive of power density

Approaching COE insensitive of current drive

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





Approaching COE insensitive of power density

High Thermal Efficiency

High β is used to lower magnetic field

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 <u>steady-state</u> first-stability operation.

ARIES-RS (reverse shear):
- Improvement in β and current-drive power
- Approaching COE insensitive of current drive

Explore reversed-shear plasma
a) Higher Q plasmas
b) At steady state

ARIES-AT (aggressive reverse shear):
- Approaching COE insensitive of power density
- High β is used to reduce toroidal field

Explore envelopes of steady-state reversed-shear operation

Improved Physics

Conclusions

- Progress in fusion sciences in the last decade is impressive.
- Visions for fusion power systems provide essential guidance to R&D directions of the program. They indicate that fusion can achieve its potential as a safe, clean, and economically attractive power source.
- Next-step burning plasma experiment(s) will provide essential plasma physics necessary for fusion power.
- A strong base program in parallel with burning plasma experiments is necessary:
    - ✓ Smaller experiments focus on high pay-off, high risk issues.
    - ✓ Progress in other fusion sciences lag behind plasma physics.