Reactor Options for Advanced Tokamaks

ARIES
PULSAR
STARLITE

as determined by the

ARIES Studies

(Advanced Reactor Innovation and Evaluation Studies)

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Physics Requirements for Advanced Tokamaks

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General Atomics

Summary of bottom line

- **The most attractive ARIES power-plant designs depend on steady-state wall stabilization of kink modes**

- **If wall-stabilization turns out to be not practical, "advanced tokamak" concepts may still improve existing no-wall designs**

- **improvement may come by increasing β_N, improving CD efficiency, better controlling transport, and/or reducing disruptivity,**

MHD-bootstrap tradeoff: $$(\beta/\varepsilon)(\varepsilon\beta_P) = \left(\frac{\beta_N}{20}\right)^2 \frac{(1+\kappa^2)}{2}$$

- **ARIES-I . . first stability steady state**
  - **tradeoff between high $\beta^2 B^4 \sim (\beta/\varepsilon)^2$ and high $I_{BS}/I_P \sim \varepsilon^{1/2}\beta_P$, at modest β_N and modest κ, and fully steady state**
- **ARIES-II . . second stability with high q_0**
  - **showed the benefit of 2nd stability for <u>conventional q-profiles</u> was to use high β_N to reduce CD requirement, not to increase β/ε**
- **PULSAR . . (ITER-like) pulsed operation with no CD**
  - **maximize β_N subject to "stationary" current profile constraints to obtain highest β/ε ... ($\varepsilon\beta_P$, not a major factor)**
- **ARIES-RS (Starlite) . . reversed shear at A=4**
  - **<u>wall-stabilized reversed shear</u> regime with high β_N and good bootstrap alignment allows both high β/ε and $I_{BS}/I_P \sim 1$**
- **ARIES-ST (Low-A) . . normal conductors**
  - **Increase of both β_N and κ for <u>wall-stabilized low-A</u> equilibrium allows both high-β and $I_{BS}/I_P \sim 1$ to make this competitive**

Summary of power-plant options

	Projected COE	Super-conducting?	Wall Stabilization?	Current Drive?	
ARIES-I	**10.0**	**Y**	**N**	**Y**	
ARIES-II	**9.2**	**Y**	**Y**	**Y**	Superseded by -RS
PULSAR	**13.0**	**Y**	**N**	**N**	
ARIES-RS	**7.5**	**Y**	**Y**	**Y**	
ARIES-ST	**8.0**	**N**	**Y**	**Y**	
Not yet considered by ARIES					
ARIES-ST-NW		**N**	**N**	**Y**	
ARIES-RS-NW		**Y**	**N**	**Y**	
PULSAR+CD		**Y**	**N**	**Partial**	
Probably no interest					
Inductive-Cu		**N**	**N**	**N**	
Inductive-SC-AT		**Y**	**Y**	**N**	
Inductive-Cu-AT		**N**	**Y**	**N**	

Decision Tree for Fusion Power Plant Design

Can wall stabilization of kink modes be made to work in a reactor environment?

YES

ARIES-RS

ARIES-ST

NO

ARIES-I

PULSAR

ARIES-RS-NW

ARIES-ST-NW

PULSAR+CD

Assume <u>wall stabilization</u> of kink-modes turns out to be <u>practical</u>

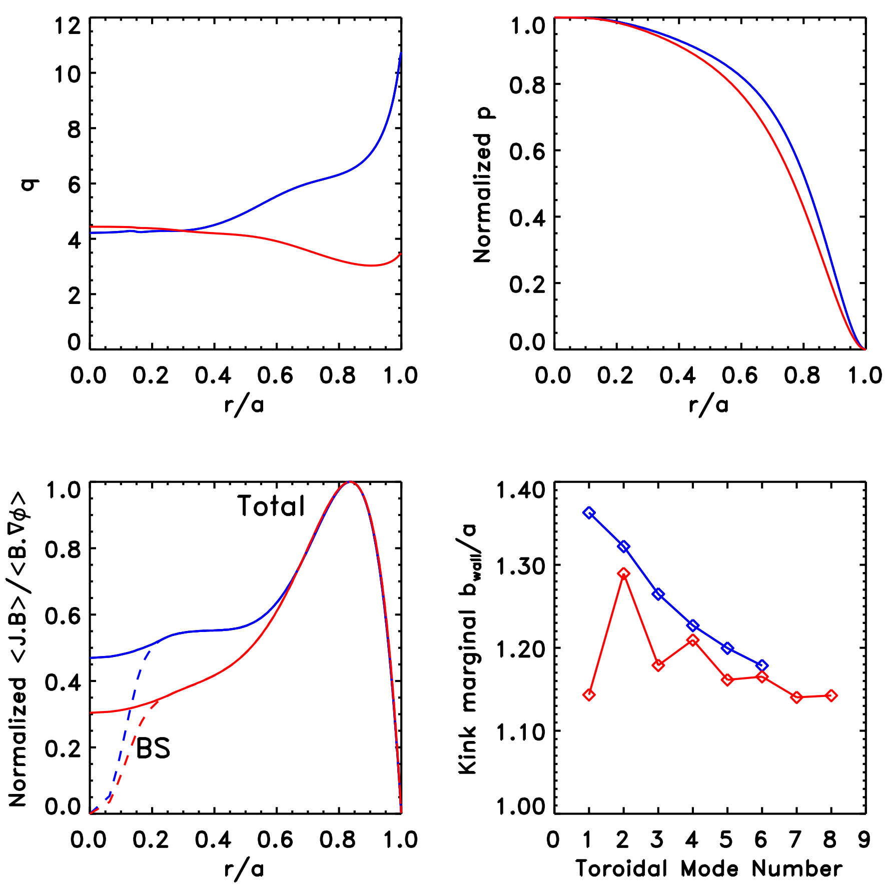
Main difference between ARIES-RS and ARIES-ST is choice of TF conductor

- **99% Bootstrap Current**
- **wall to stabilize kink modes**
- **maximize $\beta^2 B^4$ to ballooning**

Copper	SC
Optimizes at	**Optimizes at**
1.2 < A < 1.6	**2.5 < A < 5**
ARIES-ST	**ARIES-RS**

ARIES-ST and ARIES-RS are closely related: Similar optimizations but different A = R/a

ARIES
PULSAR
STARLITE



Optimize pressure profile at f_{BS}=99% to maximize β subject to ballooning stability

n,T ~ $p^{1/2}$

A = 1.6 κ = 3.4

β = 56% β_N = 8.2

A = 3.3 κ = 2.5

β = 14% β_N = 6

(note: actual ARIES-RS design is less aggressive at A=4.0, κ=1.8, β_N=5.5)

Assume wall stabilization of kink-modes is not practical

Main difference between other designs is choice of current drive options, bootstrap fraction and steady state

- **maximize $\beta^2 B^4$ (or β/ε) to ballooning and kink modes**
- **maximize $\gamma_B = n_e I_P R / P_{CD}$ for SS**

pulsed

PULSAR (not AT)

PULSAR+CD

Steady state

ARIES-I

ARIES-RS-NW

ARIES-ST-NW ← too low β_N (low β and I_{BS}/I_P)

Pulsed or Steady State?

Advantages of Pulsed

- **Inductive current drive very efficient in Amps/Watt**
  - » **low recirculating power**
  - » **not constrained to high $\varepsilon\beta_P$ so given β_N will give higher β/ε**
- **Heating systems can be optimized for heating to ignition, not CD**

Advantages of Steady State

- **Continuous operation**
  - » **magnet stresses can be higher(~2)**
  - » **no need for OH coils & their power supplies**
  - » **no need for energy storage**
  - » **possibly fewer disruptions ***
- **Control of current profile**
  - » **high β_N and sawtooth free operation possible ***
  - » **possibility of 2^{ND} stab, rev shear, Low-A operation**

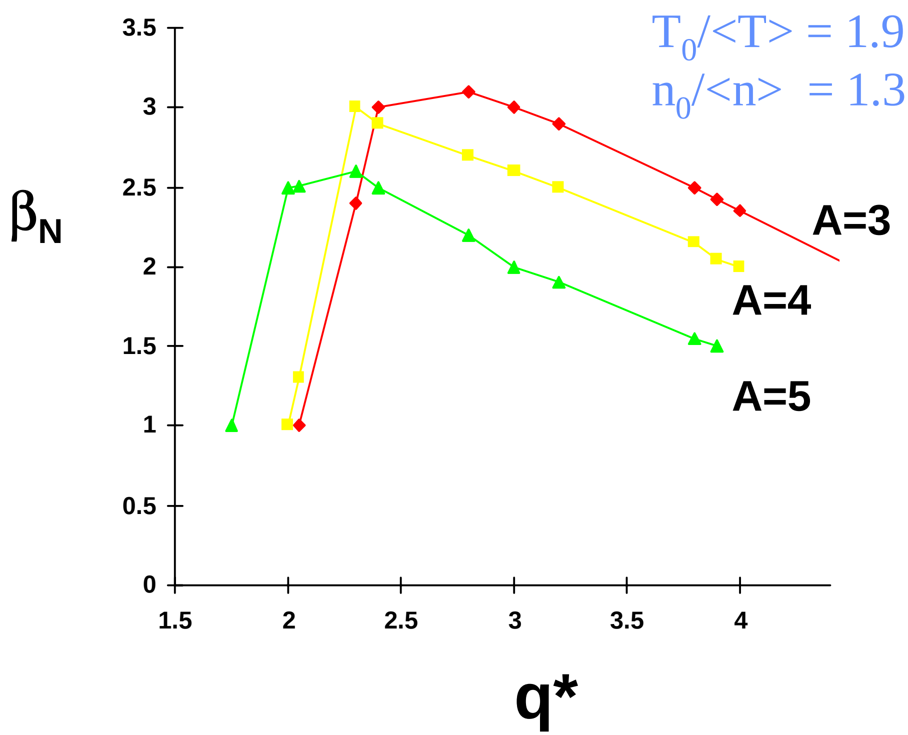
***Pulsed with CD will have some advantages of both**

PULSAR design was purely inductive: 2 hr pulse

ARIES
PULSAR
STARLITE

Current profile determined from T and n profiles by stationary constraint with no CD except bootstrap:

$$\frac{\langle \eta (J - J_{BS}) \bullet B \rangle}{\langle B \bullet \nabla \varphi \rangle} = \frac{V_L}{2\pi}$$



Optimizes at higher I_P (lower β_P) than other designs to maximize β/ε

Optimization <u>with some current drive</u> added has not been done

ie. PULSAR-CD

Summary and Comments

Several "advanced tokamak" options should be considered and prototyped even if wall stabilization of kink modes is not feasible

- **ARIES-I** — **steady state with conventional q profile**
- **ARIES-RS-NW** — **steady state with reversed q-profile**
- **PULSAR + CD** — **pulsed (ITER-like) with CD**

Ultimately, the preferred option will be the one that is:

- **most reliable (ie, disruption and other failure mode free)**
- **has adequate confinement**
- **has high enough fusion power density $\beta^2 B^4$**
- **low enough recirculating power**