Overview of ARIES Physics Studies

ARIES-I, ARIES-II/IV, ARIES-III [D-^{3}He], Pulsar, ARIES-RS, ARIES-ST, ARIES-AT

presented by

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For the ARIES Physics Team

ARIES Program Review
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UCSD

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General Atomics

Outline

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- **Overview of the ARIES Physics Studies**
- **Some Physics Highlights and Lessons Learned from the ARIES studies**
- **Physics Figures of Merit allow comparison with existing tokamak database**
- **Impact on General R&D**
- **Summary and Conclusions**

- Overview -

Features of The ARIES Studies

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- **Systems Code does not do all the physics analysis**
  - **Detailed MHD and CD analysis performed for each plasma regime**
  - **These detailed results are then incorporated into the systems code**

- **Physics Analysis is performed in enough depth to uncover critical issues and key dependencies**
  - **Some desirable physics features cannot be incorporated simultaneously with others...eg., highest β and highest I_{BS}/I_P**
  - **Some desirable physics regimes are not compatible with engineering constraints...eg., highest plasma κ and δ**

- **These considerations have led to the identification of preferred physics regimes**
  - **ARIES-RS/AT, ARIES-ST**

- Overview -

Physics input in is in 5 key areas

- **Detailed equilibrium and stability analysis***
  - Includes plasma startup, vertical control, etc
- **Detailed bootstrap and current drive analysis***
  - Includes calculation of CD profiles and antenna design
- **Confinement and profiles**
  - "Experimental" profiles, ITER confinement scaling
- **Divertors and heat removal**
  - Compatible with engineering constraints
- **Particle exhaust and fueling**

*these are gone into in the most depth

Comparison of the ARIES designs

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Parameter	FS	SS	PU	RS	ST	AT
Length of burn, τ_B(h)	¥	¥	2.5	¥	¥	¥
Plasma aspect Ratio, A=R/a	4.0	4.0	4.0	4.0	1.60	4.0
Major Radius, R(m)	7.96	6.4	8.68	5.52	3.20	5.2
(κ , δ)	1.8,.7	2.0,.67	1.8,.5	1.9,.77	3.7,.67	2.1.84
Plasma Current, Ip(MA)	12.5	7.7	15.0	11.3	28.4	12.8
Toroidal beta, β(%)	2.0	3.04	2.5	4.98	50.3	9.1
On-axis toroidal field, B_T (T)	8.96	8.37	7.46	7.98	2.0	5.8
Peak field at TF coil, B_{TF} (T)	15.9	15.9	13.1	15.8	7.4	11.1
Cylindrical safety factor, q*	3.77	4.60	2.40	2.37	2.87	2.08
Stability parameter $\varepsilon\beta_p$	0.54	1.21	0.32	0.57	1.01	0.57
Normalized beta, $\beta_N=\beta/(I/aB)$	2.88	5.28	2.7	4.84	7.3	5.45
Ave Ion Temperature, T_i(keV)	14.0	12.0	14.0	18.0	16.0	18.0
Electron density, n_e ($10^{20}/m^3$)	1.31	1.97	1.26	2.11	1.58	2.16
ITER 89P scaling multiplier, H	1.71	2.47	2.37	2.34	2.83	1.97
Bootstrap-current fraction, f_{BC}	.57	.87	.34	.88	.958	.915
CD power to plasma, P_{CD} (MW)	237	199	NA	80	27.6	34.6
CD efficiency, γ_B(10^{20}A/W m^2)	.55	.49	NA	1.61	5.2	4.1
Peak neutron load, I_w (MW/m^2)	2.61	4.7	1.82	5.57	5.5	4.9
Heat flux FOM, P_{TR}/R (MW/m)	71.2	89.0	29.5	76.7	136	29
Recirculating power fraction, ε	.28	.33	.06	.17	.34	.14
Mass power density, kWe/tonne)	36.6	49	22.6	66	55	139
COE (mill/kWeh 1992 $)	100	92	130	75	80	52

Five Distinct Operating Regimes have been explored for Power-Plant potential

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- **ARIES-I . . First Stability**
  - **tradeoff between high-b and high-$I_{BS}/ I_{P,}$**
  - **intermediate elongation is best**
- **ARIES-II/IV . . Second Stability**
  - **showed true benefit of "high q_0" 2nd Stability was to reduce CD requirement, not to increase b**
- **PULSAR . . Pulsed Reactor**
  - **demonstrated that b is limited by ohmic profile constraint**
- **ARIES-RS/AT . . Reversed Shear**
  - **excellent reactor potential for RS comes from both high b and reduced CD requirements**
- **ST (Low-A) . . Normal Conductors**
  - **first self-consistent stability and CD calculation of high-b and high-I_{BS}/ I_{P} Low-A Equilibrium**

Many Critical Issues and dependencies have been uncovered by the Power-Plant Studies

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MHD Regime:

- **tradeoff b for I_{BS}/I_P (and alignment) and hence circulating power**
- **operate at 90% of b-limit to reduce disruption frequency**
- **severe constraints on close-fitting shell and n>0 feedback**
- **effect of ohmic-profiles on stable b in non-CD machine**

Plasma Shaping:

- **plasma elongation limited by control-coil power and conductor location**
- **plasma triangularity restricted by divertor geometry**

Current Drive:

- **need for efficient off-axis CD (other than LHCD)**
- **a-resonance's and absorption taken into account**
- **CD frequency also important for wall-plug efficiency**
- **minimize coverage of RF launchers to avoid affecting tritium breeding**

Divertors:

- **radiated power needed to reduce power to divertor**

Confinement:

- **Standard confinement scalings sufficient for most designs**

- Lessons Learned -

Non-Inductive current drive is very costly !

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$$I_{CD} = \gamma_{CD} \, (P_{CD}/n_e R)$$

I_{CD} = Total non-inductively driven current (A)
P_{CD} = Power to plasma by CD system (W)
n_e = average density (in units of $10^{20}/m^3$)
R = major radius (m)
γ_{CD} = CD figure of merit

- **Theoretical calculations show $\gamma_{CD} \propto T_e^n$ with $0.6 < n < 0.8$**
- **Highest values to date for γ_{CD} are 0.45 (JET with ICRF+LH) and 0.34 (JT-60 with LHCD). Note that for a Reactor with I_P=20 MA, $n_e = 1.5 \times 10^{20}$, R = 8 m, $\gamma_{CD} = 0.34$, this gives**

P_{CD} = 700 MW to the plasma.

- **This is unrealistic for a 1000 MW Power plant, since wall plug power is much higher (several efficiencies involved)**

=> most of the plasma current must be self-generated (bootstrap) for a non-inductive reactor

It's b/e (i.e. bR_0/a) that's important for a SC design

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MHD Theory

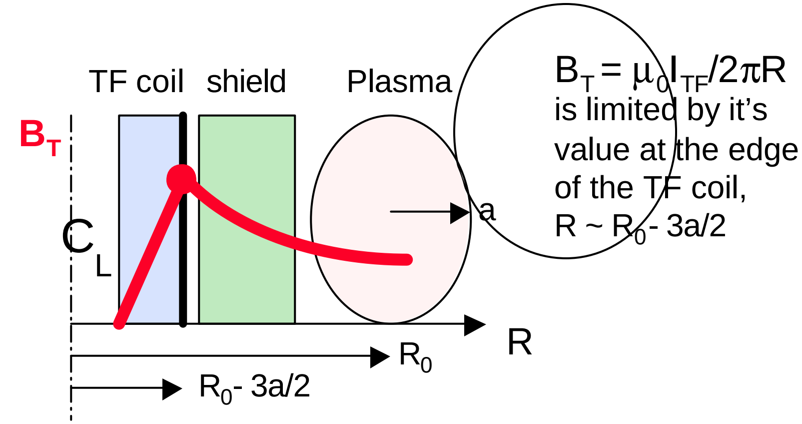
1. Large aspect ratio expansion of MHD perturbed energy δW shows that β enters only as β/ε (reduced MHD)

2. Troyon scaling may be written in dimensionless form as:

$$\beta/\varepsilon < C_T S/(20q^*)$$

Here , the right hand side is independent of ε. C_T = 3.5 is the Troyon coefficient, q* > 2 is the cylindrical safety factor, and $S=(1+\kappa^2)/2$ is the shape factor.

SC Reactors



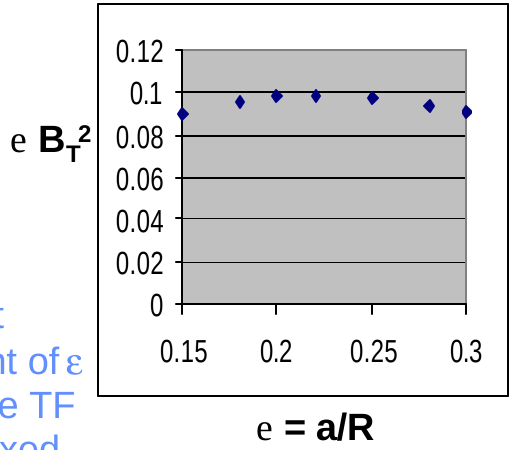
Power Density:

$$P \sim \beta^2 B_T^4$$

$$= (\beta/\varepsilon)^2 (\varepsilon B_T^2)^2$$

MHD Figure of merit

Almost independent of ε for B_T at the TF coil held fixed



- Lessons Learned -

Summary of power-plant options

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	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/AT
PULSAR	**13.0**	**Y**	**N**	**N**	
ARIES-RS/AT	**7.5**	**Y**	**Y**	**Y**	
ARIES-ST	**8.0**	**N**	**Y**	**Y**	

Not yet considered by ARIES

	Projected COE	Super-conducting?	Wall Stabilization?	Current Drive?
ARIES-ST-NW		**N**	**N**	**Y**
ARIES-RS-NW		**Y**	**N**	**Y**
PULSAR+CD		**Y**	**N**	**Partial**

Probably no interest

	Projected COE	Super-conducting?	Wall Stabilization?	Current Drive?
Inductive-Cu		**N**	**N**	**N**
Inductive-SC-AT		**Y**	**Y**	**N**
Inductive-Cu-AT		**N**	**Y**	**N**

- Lessons Learned -

Decision Tree for Fusion Power Plant Design

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

YES

ARIES-RS/AT

ARIES-ST

NO

ARIES-I

PULSAR

ARIES-RS-NW

ARIES-ST-NW

PULSAR+CD

Assume wall stabilization of kink-modes turns out to be practical

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

- **90+% Bootstrap Current**
- **wall to stabilize kink modes**
- **maximize b^2B^4 to ballooning**

Copper → **Optimizes at**

1.2 < A < 1.6

ARIES-ST

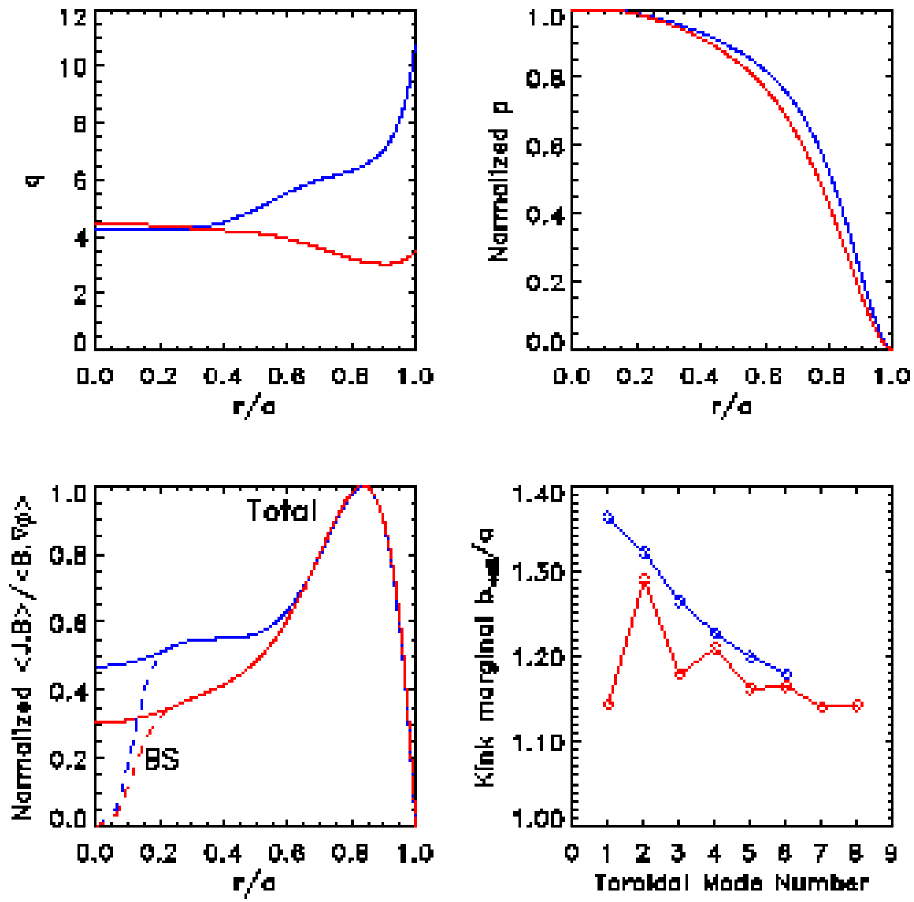
SC → **Optimizes at**

2.5 < A < 5

ARIES-RS/AT

ARIES-ST and ARIES-RS/AT 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 ~ $p^{1/2}$

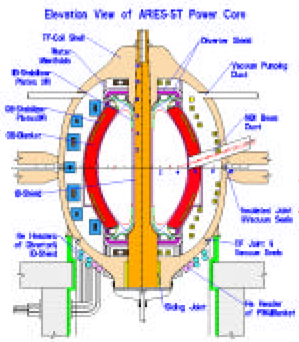
A = 1.6   k = 3.4

b = 56% b_N = 8.2

A = 3.3   k = 2.5

b = 14% b_N = 6

(note: actual ARIES-RS/AT designs less aggressive at A=4.0, κ=1.9/2.1, β_N=4.8/5.4)



Simple scaling relations show ARIES-ST is good aspect ratio for Copper Tokamak:

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Troyon Limit

$$(b/e)(eb_P) \le \left(\frac{b_N}{20}\right)^2 \frac{(1+k^2)}{2}$$

Bootstrap fraction

$$\frac{I_{BS}}{I_P} = 1 = \frac{1}{e^{1/2}}(eb_P)C_{BS}$$

$$b \le e^{1/2} C_{BS} \left(\frac{b_N}{20}\right)^2 \frac{(1+k^2)}{2}$$

Toroidal Field

$$B_0 = B_{MAX}(1-e)$$

Power Dissipated in TF Coil

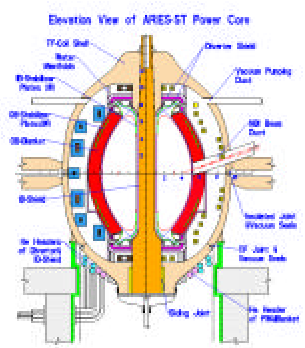
$$P_{TF} \sim \frac{I_{TF}^2\, k\, a\, h}{(R_0 - a)^2} \sim B_{MAX}^2\, k e R$$

Fusion Power

$$P_{Fusion} \sim b^2 B_0^4 V \sim e\, C_{BS}^2 \left(\frac{b_N}{20}\right)^4 \frac{(1+k^2)^2}{4} B_{MAX}^4 (1-e)^4 e^2 R^3 k$$

Engineering Q

$$Q_E \sim \frac{P_{Fusion}}{P_{TF}} \sim C_{BS}^2 \left(\frac{b_N}{20}\right)^4 \frac{(1+k^2)^2}{2} B_{MAX}^2 (1-e)^4 e^2 R^2$$



Physics Parameters should be chosen to optimize Q_E within acceptable limits.

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$$Q_E \sim \frac{P_{Fusion}}{P_{TF}} \sim \left(\frac{b_N}{20}\right)^4 \frac{\left(1+k^2\right)^2}{2} B_{MAX}^2 (1-e)^4 e^2 R^2$$

Optimizes at : large β_N, large κ, large B_{MAX}, large R

β_N and κ are set by stability limits and their allowable values increase at low $A = \varepsilon^{-1}$

We can approximate MHD stability scalings in the range $1.2 < A < 3$ by:

$$\beta_N \sim (1-\varepsilon)^{-1/2}, \qquad (1+\kappa^2) \sim (1-\varepsilon)^{-1/2}$$

® **Q_E optimizes at intermediate A =** e^{-1} **~ 1.5**

- Lessons Learned -

Reversed Shear such as ARIES-RS/AT is preferred configuration for SC tokamak with stabilizing walls

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Ozeki, Turnbull, Kessel, and others showed non-monotonic q-profile good for several reasons:

- Stable up to C_T = 4.8-5.4 (or higher)

- Bootstrap current aligns well with equilibrium current, allowing bootstrap fractions approaching 1.0

=> **both high b/e and high I_{BS}/I_P possible simultaneously**

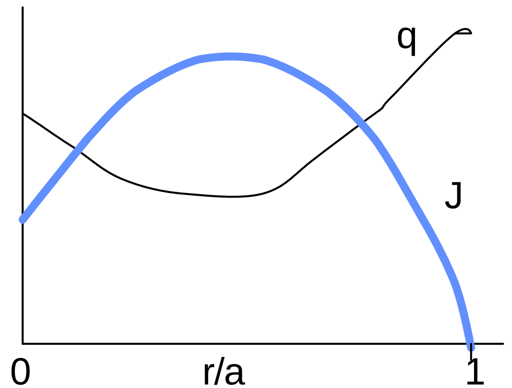
- Transport seems to be consistent with profiles required

$A=R/a=4$, $I_{BS}/I_P=.88\ (.92)$, $\beta=5\%\ (9\%)$

- No strong dependence on Aspect Ratio

many questions remain for practical realization

  - requires wall stabilization of the kink mode
  - can these favorable profiles be maintained ?



Troyon Limit

$$(b/e)(eb_P) \leq \left(\frac{C_T}{20}\right)^2 \frac{(1+k^2)}{2}$$

Decision Tree for Fusion Power Plant Design

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

YES

ARIES-RS/AT

ARIES-ST

NO

ARIES-I

PULSAR

ARIES-RS-NW

ARIES-ST-NW

PULSAR+CD

- Lessons Learned -

Assume <u>wall stabilization</u> of kink-modes is <u>not practical</u>

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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)**

- Lessons Learned -

Comments on the need for wall stabilization

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** b^2B^4
- **low enough recirculating power**

- Lessons Learned -

Pulsed or Steady State?

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Advantages of Pulsed

- **Inductive current drive very efficient in Amps/Watt**
  - » low recirculating power
  - » not constrained to high b_P
- **Heating systems can be optimized for heating to ignition, not CD**

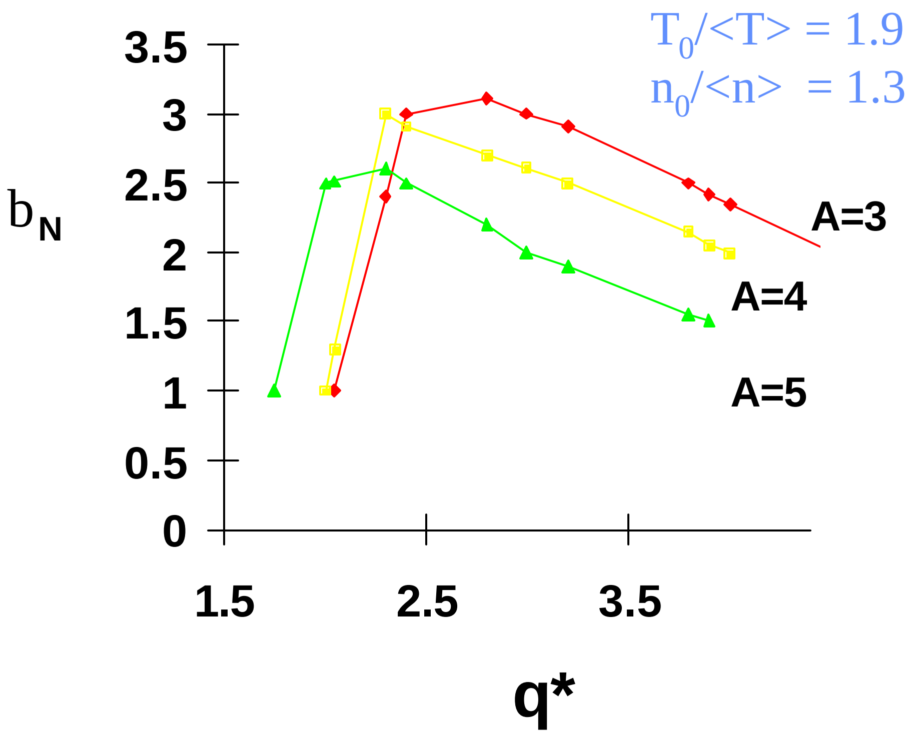
Advantages of Steady State

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

PULSAR design was purely inductive: 2 hr pulse

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

$$\frac{\langle h(J - J_{BS}) \bullet B \rangle}{\langle B \bullet \nabla j \rangle} = \frac{V_L}{2p}$$



Optimizes at higher I_P (lower b_P) than other designs to maximize b/e

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

ie. PULSAR-CD

Physics Figures of Merit Provide Link between Power-Plant Studies and Base Program

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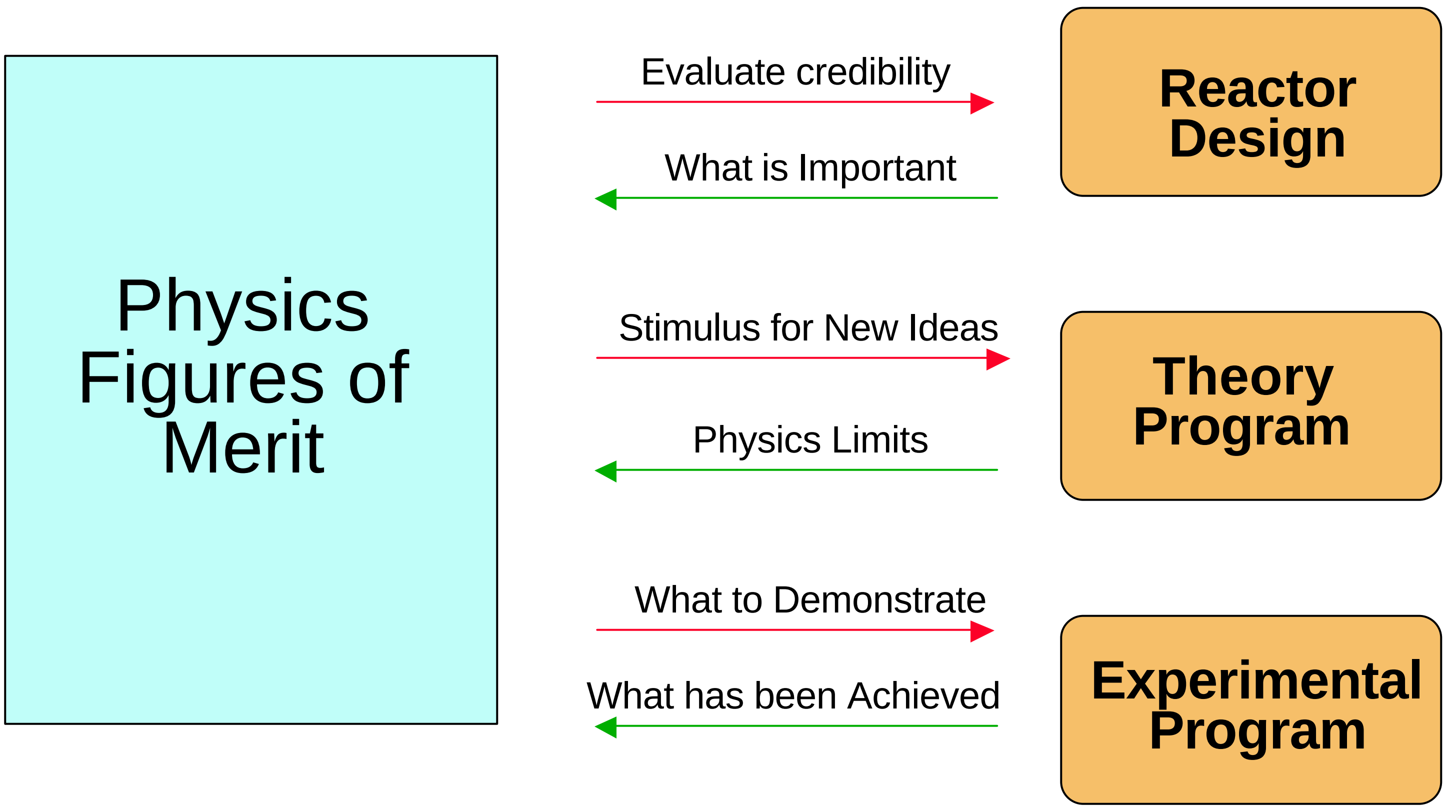

Physics Figures of Merit

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- **In each of the 5 critical physics areas, we have identified key physics parameters that characterize the physics operating regime**
- **These provide a convenient way to assess present data base and progress towards reactor-grade parameter**

(1) MHD Stability: b/e **and** eb_P

(2) Current Drive: $g_B = n_e I_P R / P_{CD}$ **vs** T_e

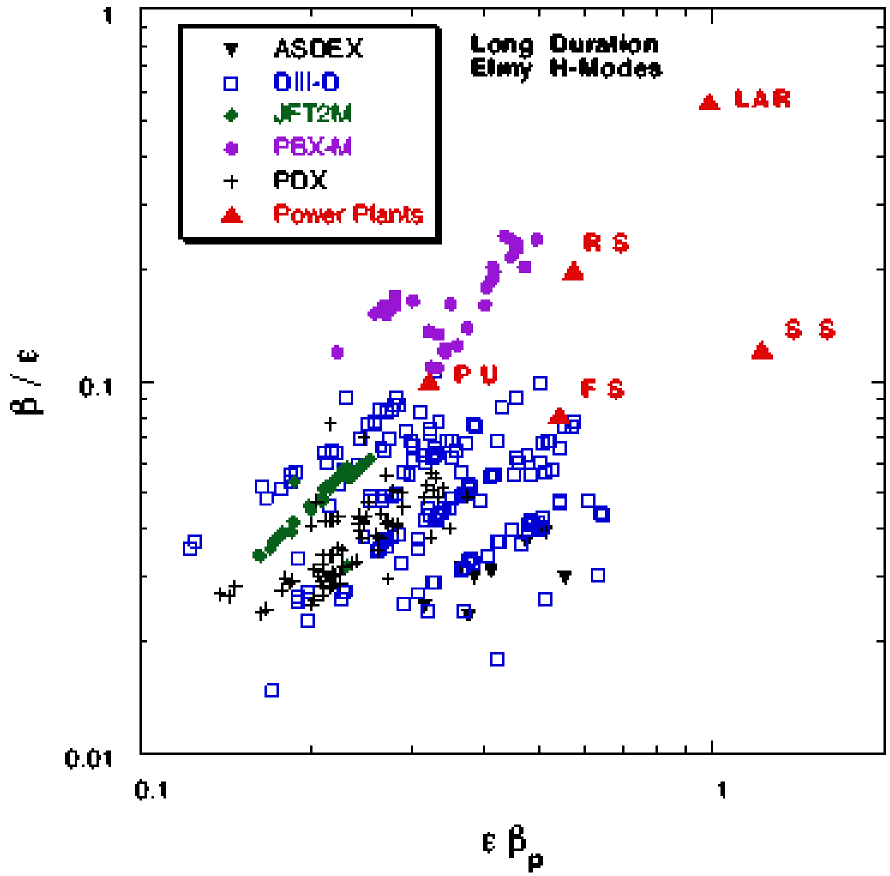
(3) Heat Exhaust: P_{HEAT}/R **vs** f_{RAD}

(4) Energy Confinement: $b t_E/a^2$ **vs** b/e

(5) Helium Ash removal: t_{He}^*/t_E **vs** $b t_E/a^2$

MHD Figure of Merit is b/e vs eb$_{P}$

Need both high fusion power density and high bootstrap current simultaneously



Current Drive Figure of Merit is g_B vs T_e

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$g_B = n_e I_P R / P_{CD}$

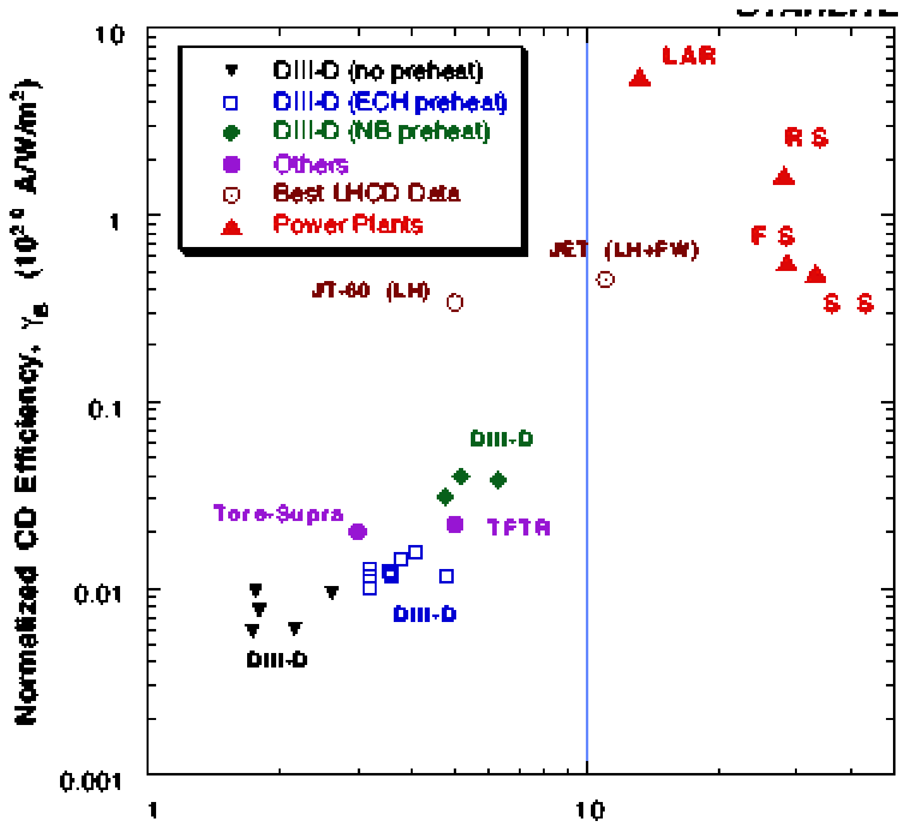
But $I_P = I_{BS} + I_{CD}$,

$= I_{CD}/(1 - f_{BS})$

- * improvement can be made by either operating at high

  $f_{BS} = I_{BS}/I_P$

  or with efficient current drive I_{CD}



Power Handling FOM is P_{HEAT}/R vs f_{RAD}

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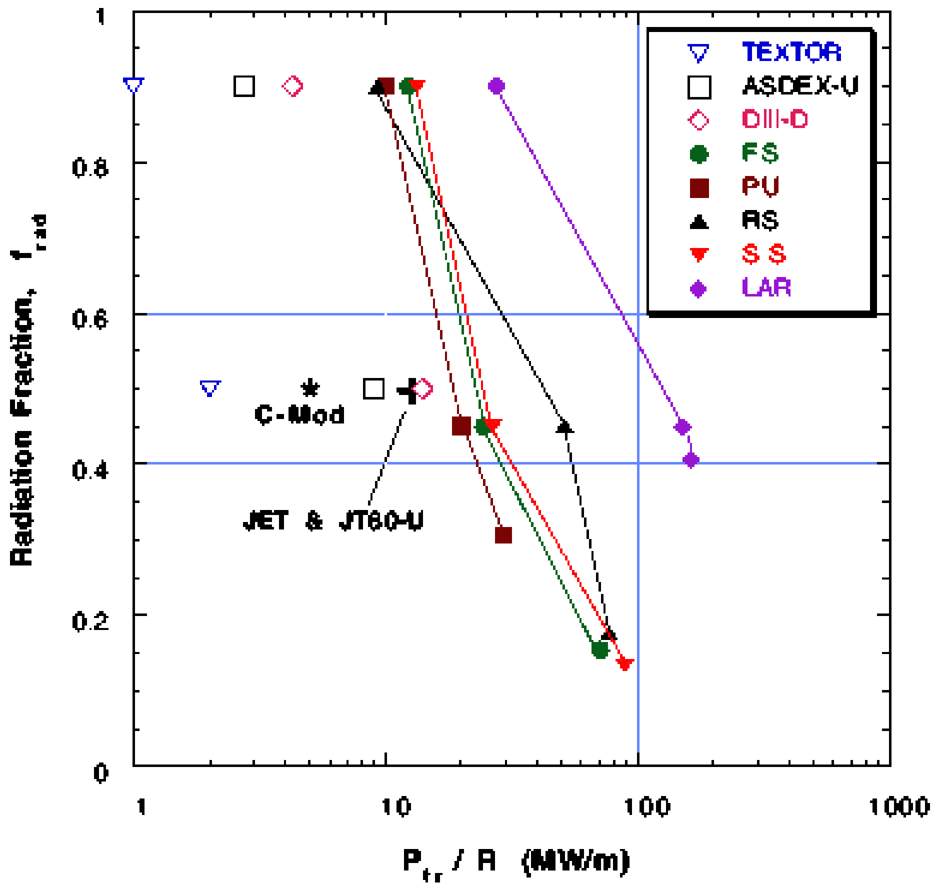
Need to demonstrate high radiation fraction and high power handling capability simultaneously



Energy Confinement FOM is $\beta\tau_E/a^2$ vs β/ε

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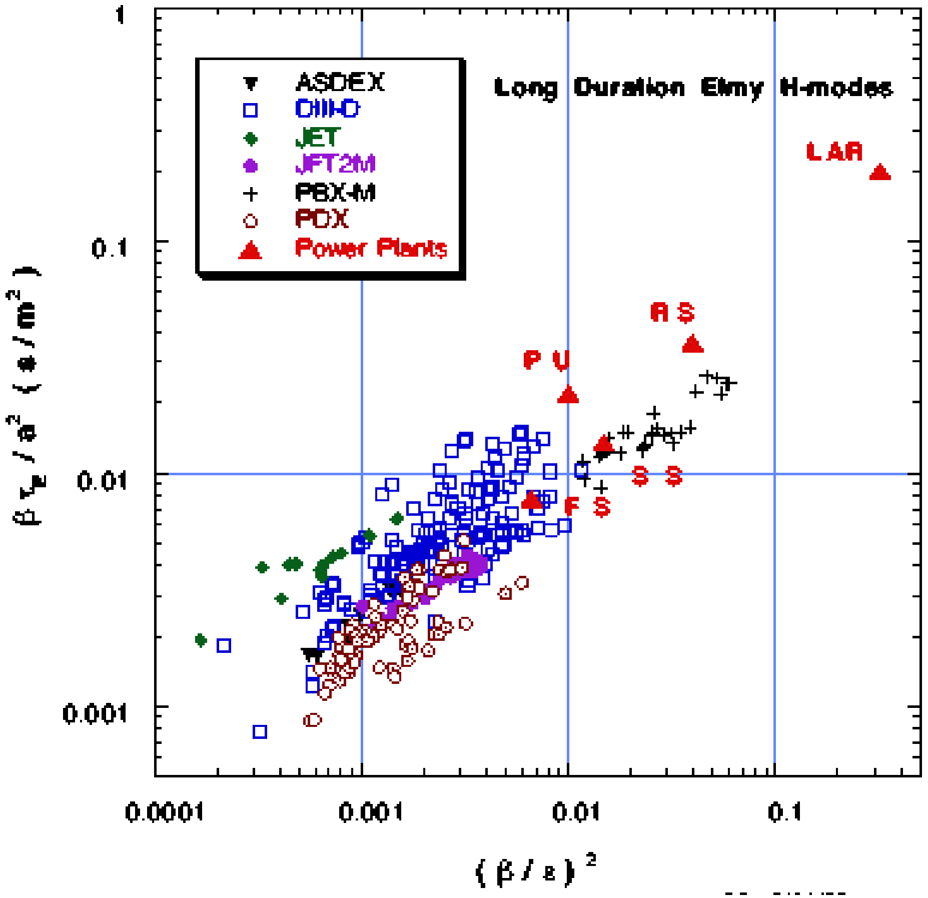
Note:

$\beta\tau_E/a^2 \propto (H_{89P}/q^*)^2$

This is just nTτ with the major dimensional parameters factored out, or the ITER L-mode scaling parameter with the dominant dependence on the current removed.



Helium Ash removal: τ_{He}^*/τ_E vs $\beta\tau_E/a^2$

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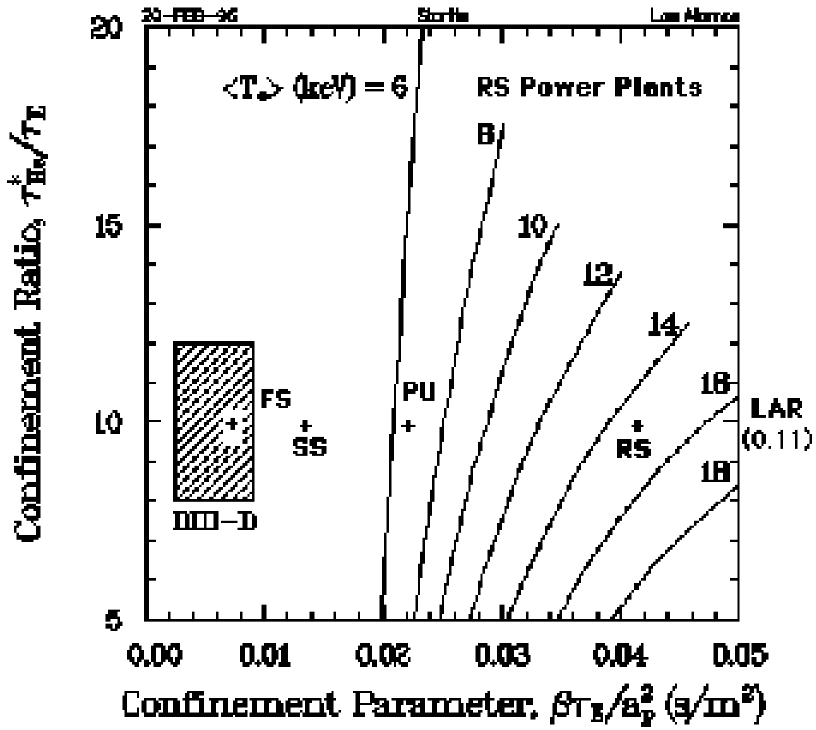
Need adequate helium ash removal and good energy confinement performance simultaneously

Ash Removal FOM for Experiments and Power Plants



Impact on R&D

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- **The ARIES Physics studies have been published in refereed journals**
  - **Fusion Eng. Des 38: “Physics Basis for a reversed shear tokamak power plant”, (1997)**
  - **Fusion Eng. Des (submitted) “Physics basis for a spherical torus fusion power plant”,**
  - **Fusion Eng. Des (to appear 2000) “Physics basis for a tokamak fusion power plant”**
- **These Power Plant Studies have had a considerable effect on the base program**
  - **TPX & KSTAR design influenced significantly by ARIES**
  - **Reversed shear experiments motivated by Reactor potential (FED article referenced in several DIII reports and pub.)**
  - **NSTX and NCSX designs influenced by these studies**
  - **Motivation for ITER and FIRE Advanced Physics Modes**

Summary and Comments

- **This program has produced optimized power plant designs consistent with detailed physics analysis**
- **Many important dependencies have been identified between physics regimes and engineering constraints**
- **Methods proposed for meeting these constraints have had a significant influence on the base program and on program planning**
- **Physics Figure of Merit activity provides an assessment of how close we are to having a prototype of a reactor-grade tokamak**
- **These studies provides a useful forum for new physics ideas to meet engineering constraints**