Physics Basis for a Tokamak Fusion Power Plant

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Lessons Learned from the Design Studies:

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

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General Atomics

Outline

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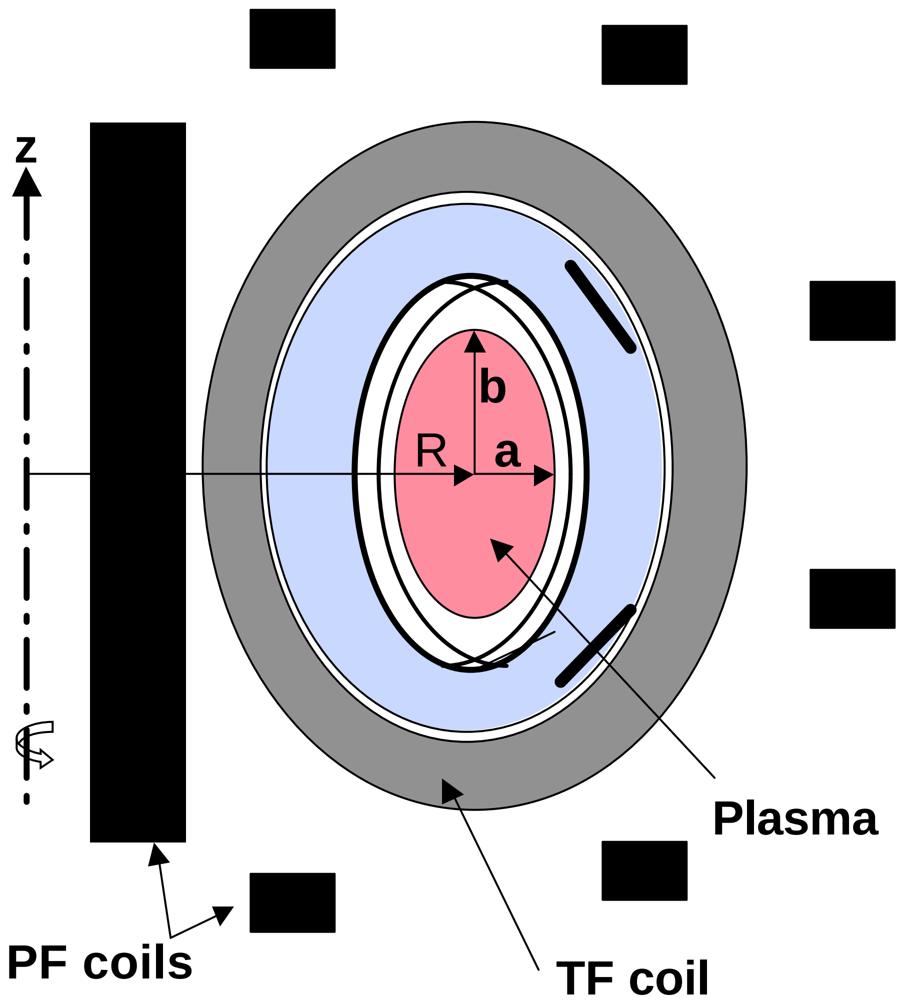
- **Tokamak Basics Affecting Power Plant Design**
- **Overview of the ARIES Designs**
- **Decision tree for a Power Plant Design**
- **Physics Figures of Merit**
- **Summary and Conclusions**

Tokamak Basics



Top Level Design Issues

Plasma Geometry: $A \equiv R/a$, $\kappa \equiv b/a$, δ

Plasma Current: $I_P/(RB_T)$

Plasma Pressure: $\beta = 2\mu\langle p\rangle/B_T^2$

Plasma current distribution J(R,Z)

Plasma density distribution n(R,Z)

How to maintain plasma current

Adequate energy confinement

Plasma Stability and Control

How to fuel plasma

How to remove heat and ash

Basic #1:

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

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MHD Theory

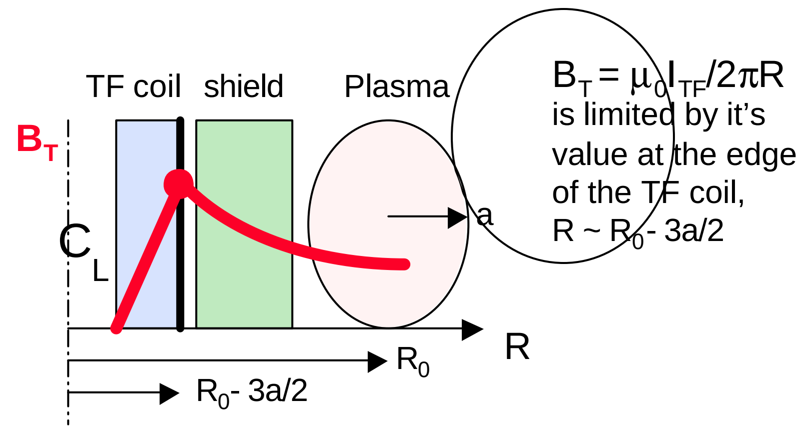
1. Large aspect ratio expansion of MHD perturbed energy δW shows that β enters only as β/ε (reduced MHD)

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



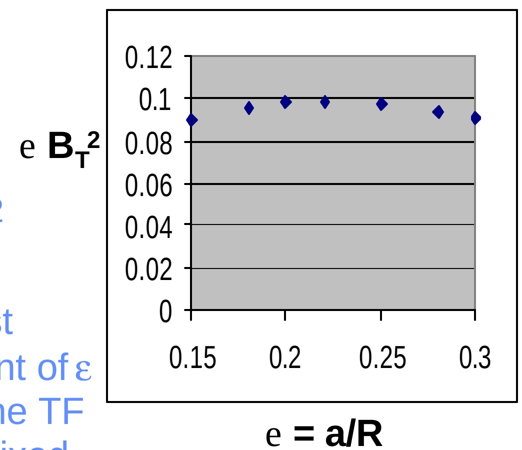
Power Density:

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

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

MHD Figure of merit

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



Basic #2:
Non-Inductive current drive is very costly !

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$$I_{CD} = g_{CD} (P_{CD}/n_e R)$$

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)
g_{CD} = CD figure of merit

- **Theoretical calculations show g_{CD} a T_e^n with $0.6 < n < 0.8$**
- **Highest values to date for g_{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, g_{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

Basic #3:

Simple Scalings show Many key Dependencies

$$b_N \equiv b\left(\frac{2p\, a B_T}{5 m_0 I_P}\right) \qquad b_P = b\left(\frac{2p^2 a^2 B^2 (1+k^2)}{m_0^2 I_P^2}\right)$$

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

C_{BS} constant ~ 0.5

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

b_N limited by Troyon Limit (< 3.5)

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

Optimizes at: small e (large A), high b_N, high k

Recent Analysis has concentrated on the Advanced Tokamak with non-monotonic q-profile and current peaked off axis

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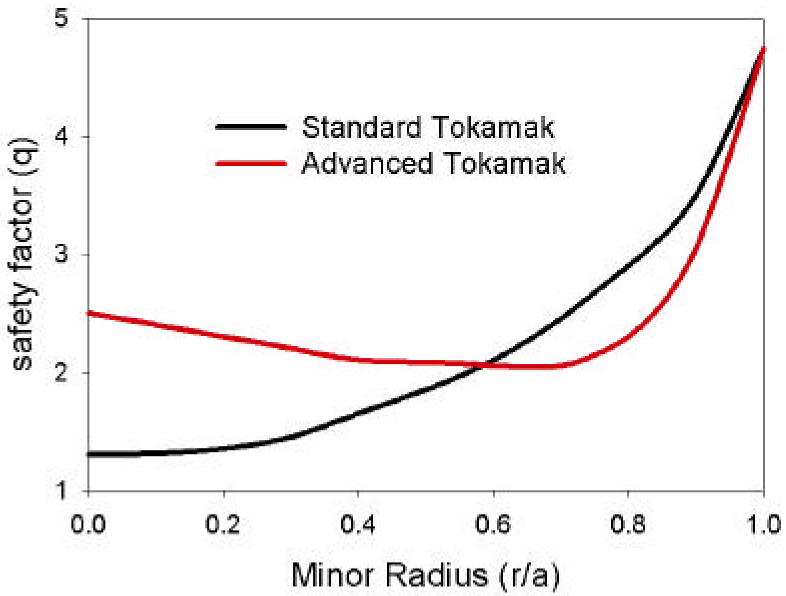
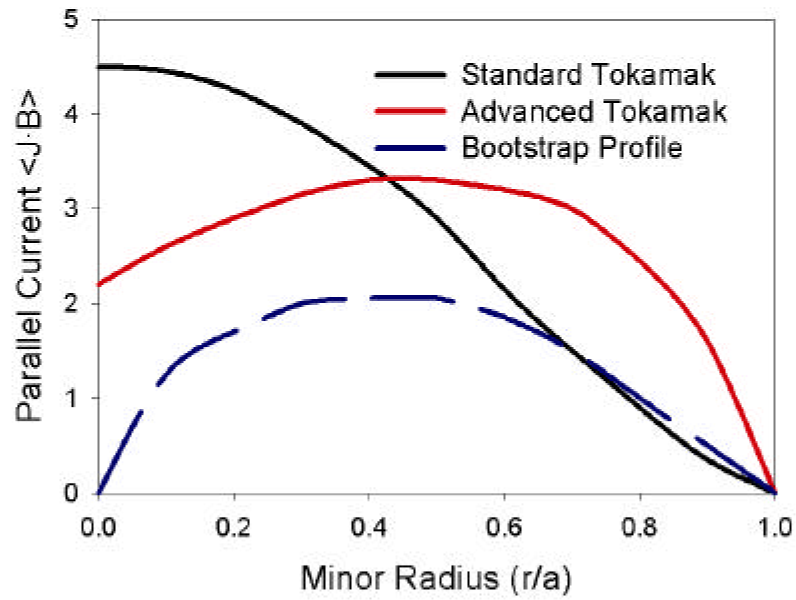
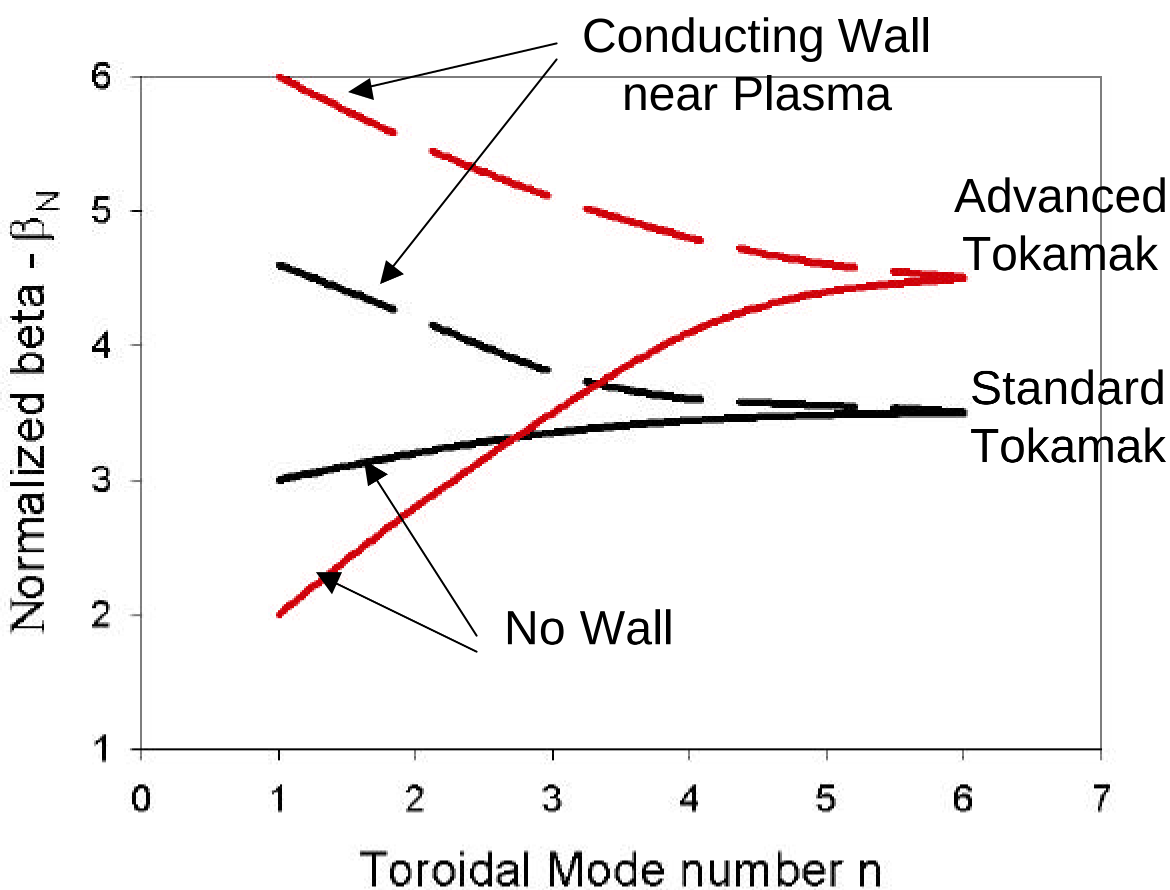




- **Good Stability Properties**
- **Good Energy Confinement**
- **Good Bootstrap Alignment**

Advanced Tokamaks benefit from close-fitting conducting walls much more than do standard Tokamaks.



These are typical results for comparitive ideal MHD stability analysis of Advanced Tokamak and Standard Tokamak.

Resistive wall mode stability needs to be taken into account.

Needs to be demonstrated.

ARIES-AT Equilibrium

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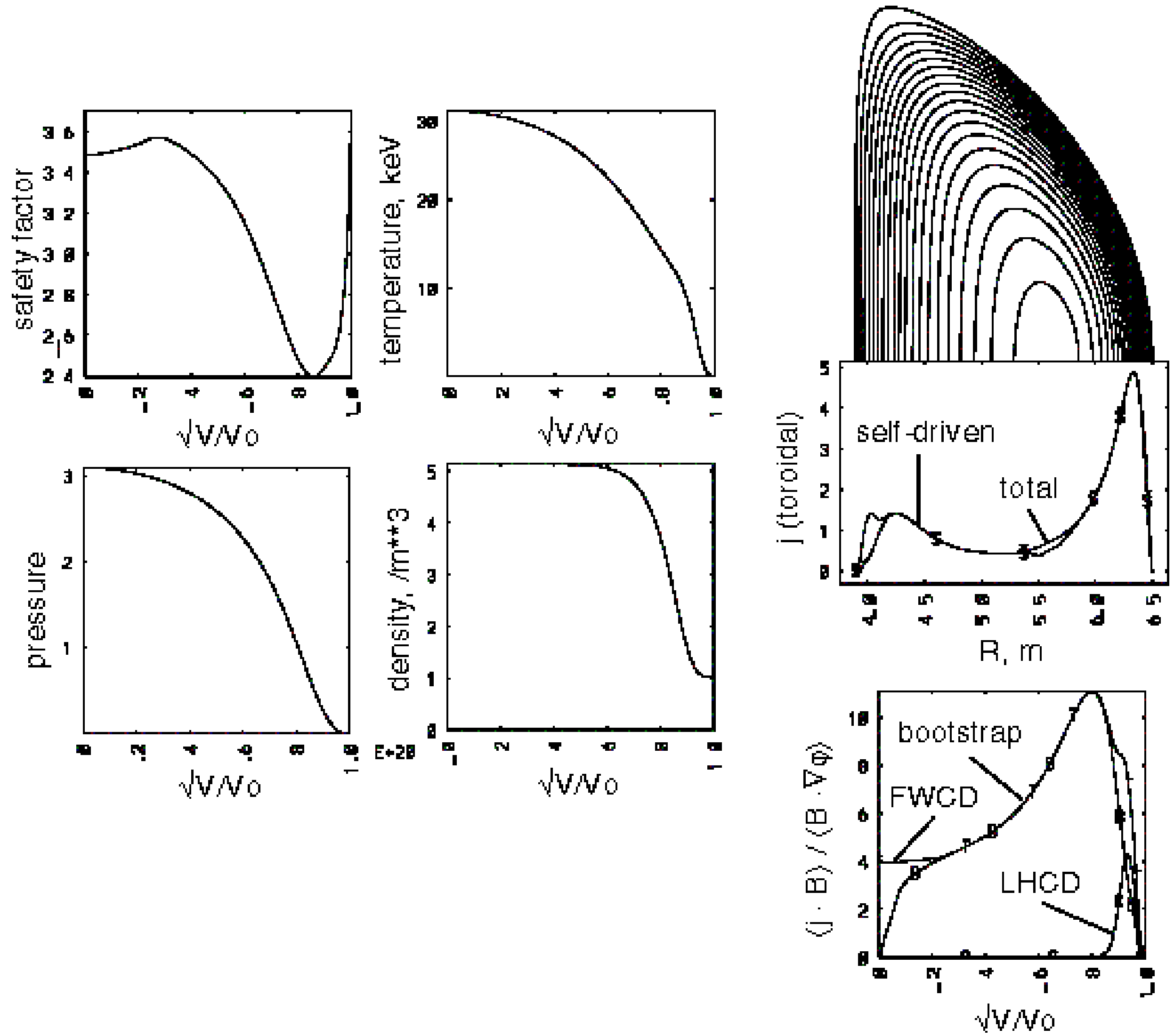

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Target Equilibrium Can be Maintained with RF- and Self-Driven Currents

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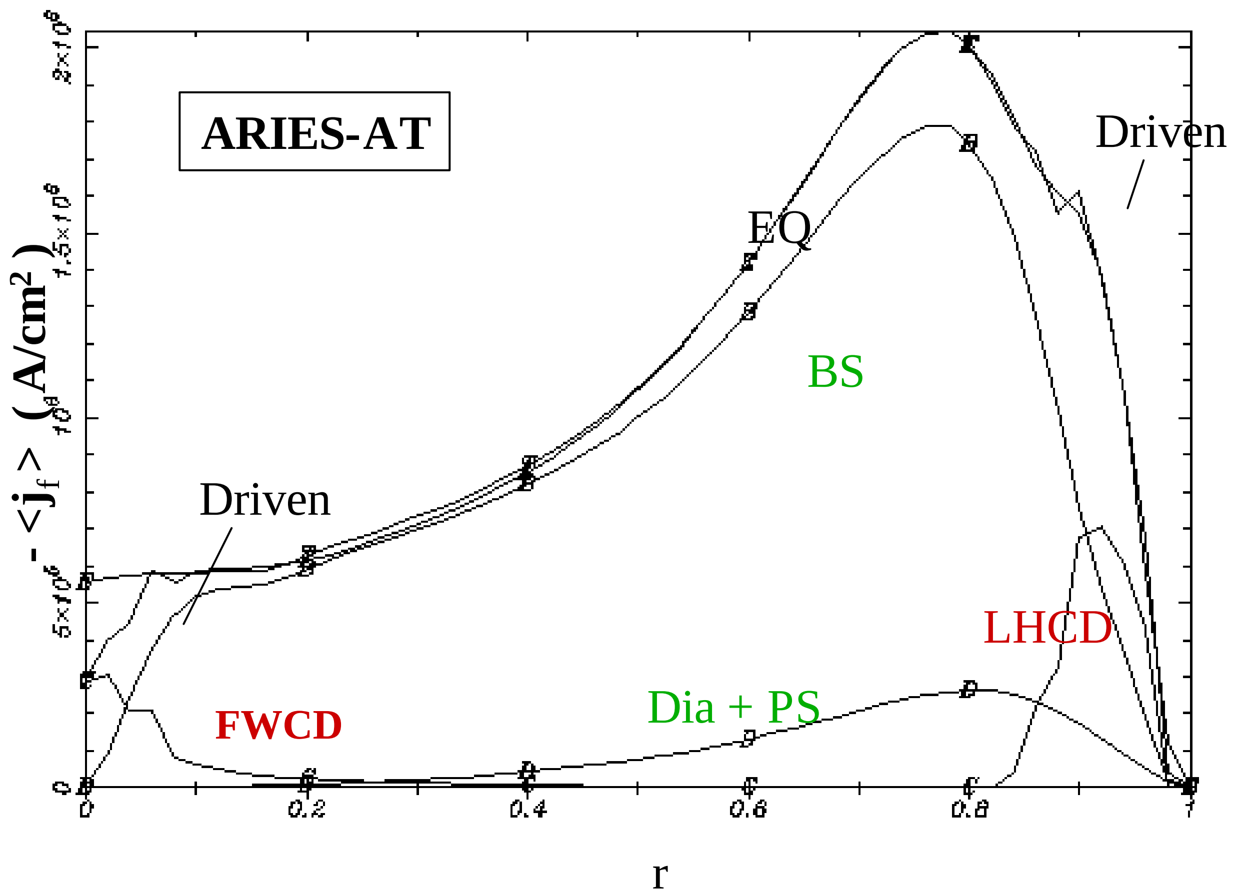
- **2 RF schemes are required to drive the seed currents on ARIES-AT:**
  (I) ICRF fast waves for on-axis drive; (2) LH waves for off-axis drive.



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

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- **ARIES-I . . First Stability**
  - tradeoff between high-β 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 β
- **PULSAR . . Pulsed Reactor**
  - demonstrated that β is limited by ohmic profile constraint
- **ARIES-RS/AT . . Reversed Shear**
  - excellent reactor potential for RS comes from both high β and reduced CD requirements
- **ST (Low-A) . . Normal Conductors**
  - first self-consistent stability and CD calculation of high-β and high-I_{BS}/ I_P Low-A Equilibrium

ARIES-I

First-Stability Regime, Steady State Plasma
MHD Stable with no Conducting Wall

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Troyon Limit:

$$\beta \le C_T \left(\frac{\mu_0}{40\pi} \right) \left(\frac{I_P}{aB_T} \right)$$

C_T=3.2

or,

$$(\beta / \varepsilon)(\varepsilon \beta_P) \le \left(\frac{C_T}{20} \right)^2 \frac{(1+\kappa^2)}{2}$$

Bootstrap fraction:

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

C_{BS}=0.5

it follow that ➔

$$(\beta / \varepsilon) \le \frac{1}{\varepsilon^{1/2} \frac{I_{BS}}{I_P}} C_{BS} \left(\frac{C_T}{20} \right)^2 \frac{(1+\kappa^2)}{2}$$

Bootstrap alignment: *Need to have q_0 > 1 for I_{BS}/I_P > 0.5 to avoid local bootstrap overdrive. This tends to lower C_T*

=> tradeoff between high β and high Bootstrap fraction

A=R/a=4, I_{BS}/I_{BP}=.57, β=2%, q_0=1.3

ARIES-II

Second Stability based on high q_0

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Troyon Limit: $$(b/e)(eb_P) \le \left(\frac{C_T}{20}\right)^2 \frac{(1+k^2)}{2}$$ *C_T=5.8*

- Ramos (MIT) and others found that when q_0 is raised above 2, there is a second stability regime for ballooning modes ….
  - C_T increases from 3.1 (ARIES-I) to 5.8 (ARIES-II)
- However, because of the high q_0, much of of the benefit comes from higher $\varepsilon\beta_P$ (and thus higher I_{BS}/I_P), not higher β/ε
- As we try and increase β further, the edge region becomes unstable…also local bootstrap overdrive becomes a problem
- Nearby conducting walls are needed to stabilize kink modes

$A=R/a=4$, $I_{BS}/I_P=.87$, $\beta=3\%$, $q_0=2.0$

PULSAR

ITER-like design with current driven by OH-coils + Bootstrap current

Troyon Limit: $$\left(b/e\right)\left(eb_P\right) \leq \left(\frac{C_T}{20}\right)^2 \frac{\left(1+k^2\right)}{2}$$ C_T=3.0

Operate at higher I_P (lower β_P) to maximize β/ε

- However, no freedom in current profile…no non-inductive current drive
  - J determined from T and n profiles by stationary constraint

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

- Using this constraint, stability boundaries can be mapped out
  - Depend only on ε, q*, and density and temp. profile form factors

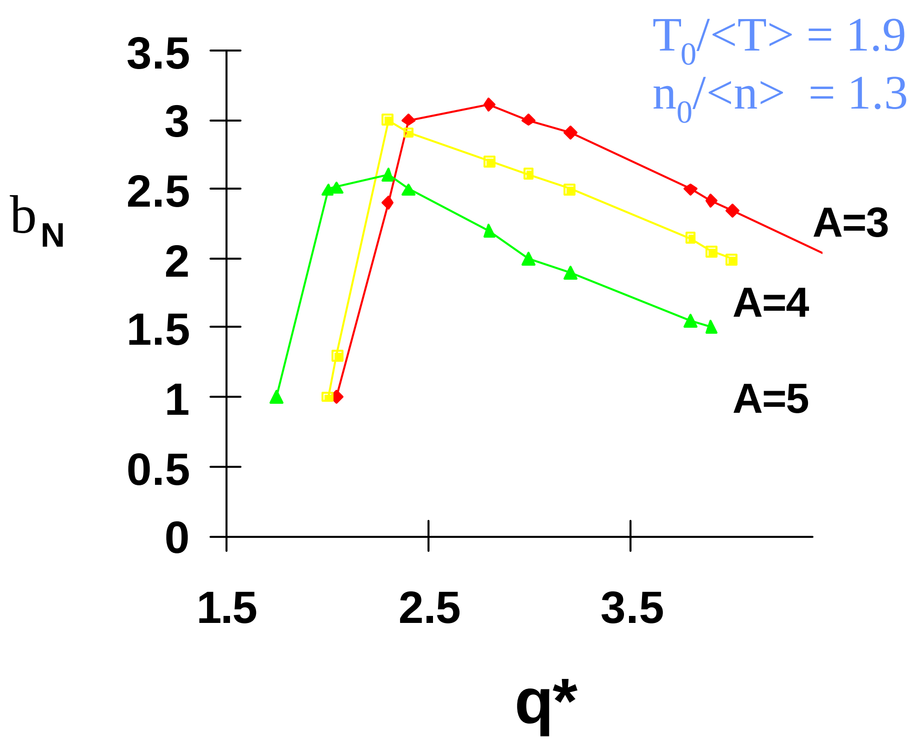
2 HR burn with 2 min OH recharge, during which thermal reservoir is tapped

A=R/a=4, I_{BS}/I_P=.34, β=2.5%, q_0=0.8

PULSAR design was purely inductive: 2 hr pulse

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

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



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

Reversed Shear

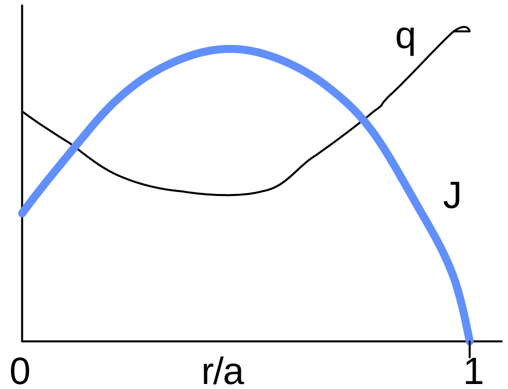
Non-monotonic q-profile with conducting wall to stabilize kink modes

ARIES PULSAR STARLITE

Troyon Limit: $$(\beta/\varepsilon)(\varepsilon\beta_P) \leq \left(\frac{C_T}{20}\right)^2 \frac{(1+\kappa^2)}{2}$$ C_T=5.3

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

- Stable up to C_T = 5.3 (or higher)
- Bootstrap current aligns well with equilibrium current, allowing bootstrap fractions approaching 1.0
- both high β/ε and high I_{BS}/I_P possible simultaneously
- Transport seems to be consistent with profiles required



$$A=R/a=4, \quad I_{BS}/I_{BP}=.88, \quad \beta=5\%, \quad q_0=2.6$$

many questions remain for practical realization

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

Low-A

Copper Magnet machine with wall stabilized kink mode

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Troyon Limit: $$(b/e)(eb_P) \leq \left(\frac{C_T}{20}\right)^2 \frac{(1+k^2)}{2}$$ C_T=7.0

Menard, Miller and others found that at Low-A, ballooning stable configurations exist with C_T= 7.0 and κ=3.4 or greater, and that very good (near 100%) bootstrap alignment is possible

- Also, without SC magnets and their inboard shielding requirements, the degeneracy in ε is broken, and lower A helps in increasing fusion power density
- We have performed an extensive scan of MHD stability space A , q_0, q*, κ, δ
- For most configurations, current drive requirements were excessive (> 400 MW)
- Now concentrated on plasma configurations with very high bootstrap current
- Best so far: A = 1.60, κ = 3.7, q_0 = 3, q* = 3.5

  $\beta = 50\%$ with 96% of current self-driven by bootstrap
- Potential problems:
  - wall stabilization of kink modes
  - profile control to maintain high bootstrap fraction and stable profiles
  - center column power (100s of MW dissipated), lifetime, disposal, etc.

Comparison of the AIRES designs

ARIES PULSAR STARLITE

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, β_N=β/(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

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/AT
PULSAR	**13.0**	**Y**	**N**	**N**	
ARIES-RS/AT	**7.5(5.2)**	**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/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

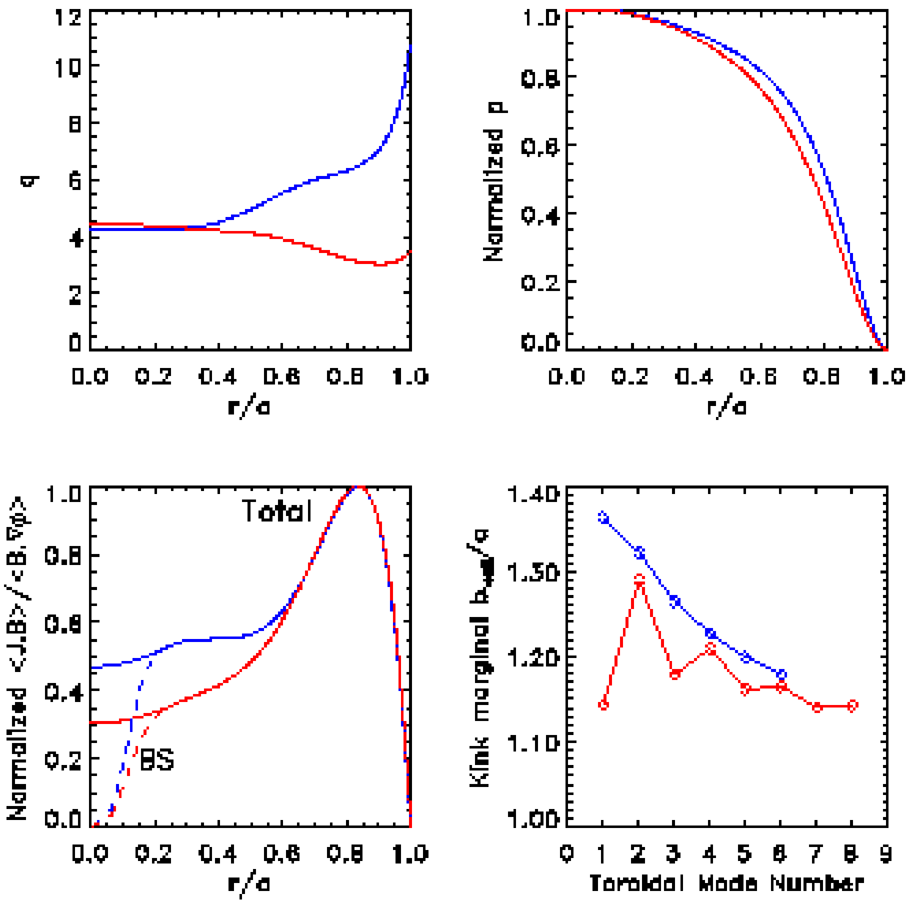
Main difference between ARIES-RS/AT and ARIES-ST is choice of TF conductor

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

Copper	**SC**
Optimizes at	**Optimizes at**
1.2 < A < 1.6	**2.5 < A < 5**
ARIES-ST	**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 ~ $p^{1/2}$

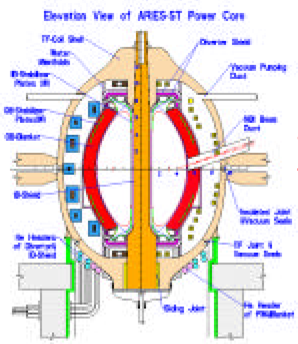
A = 1.6 k **= 3.4**

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

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

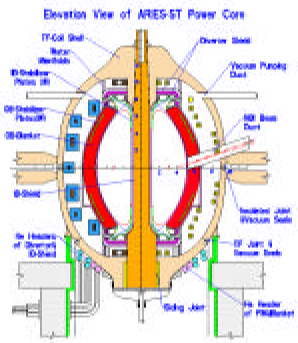
$$b \le e^{1/2} C_{BS} \left(\frac{C_T}{20}\right)^2 \frac{\left(1+k^2\right)}{2}$$

Toroidal Field $$B_0 = B_{MAX}\left(1-e\right)$$

Power Dissipated in TF Coil $$P_{TF} \sim \frac{I_{TF}^2\, k\, a h}{(R_0-a)^2} \sim B_{MAX}^2\, ke\, R$$

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

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



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

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

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**

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 β/ε and high I_{BS}/I_P possible simultaneously**

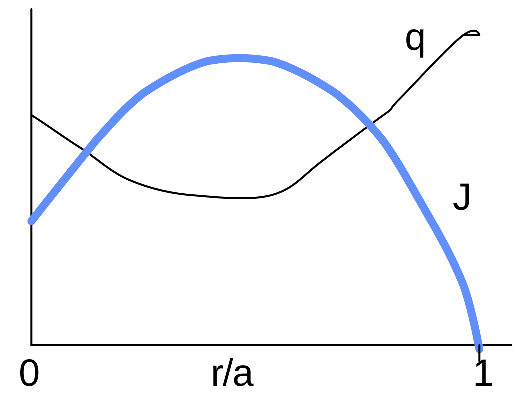
- Transport seems to be consistent with profiles required

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

- 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

$$(\beta/\varepsilon)(\varepsilon\beta_P) \leq \left(\frac{C_T}{20}\right)^2 \frac{(1+\kappa^2)}{2}$$

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**

Assume wall stabilization of kink-modes is not practical

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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)

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 $\propto \beta^2 B^4$
- low enough recirculating power

Pulsed or Steady State?

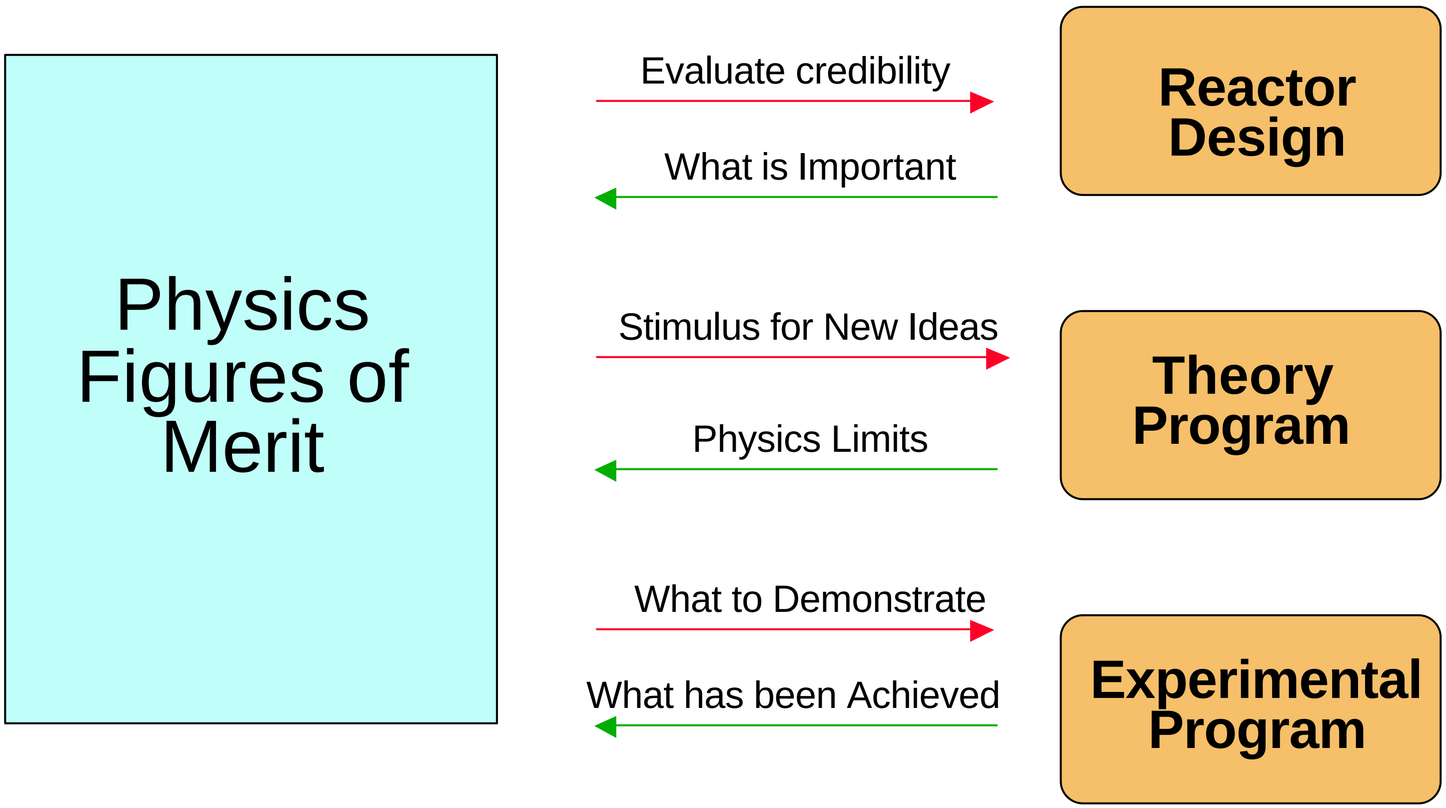
Advantages of Pulsed

- **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**

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



Physics Figures of Merit

- **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: bt_E/a^2 **vs** b/e

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

MHD Figure of Merit is b/e vs eb$_P$

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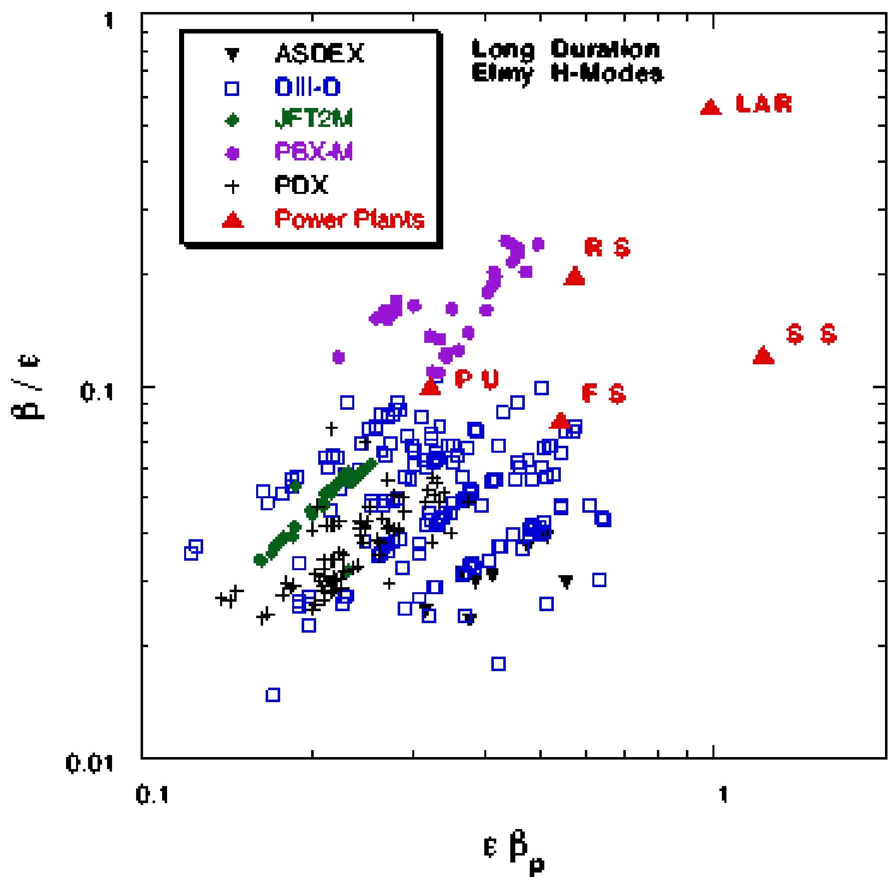
Need both high fusion power density and high bootstrap current simultaneously



Current Drive Figure of Merit is g_B vs T_e

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

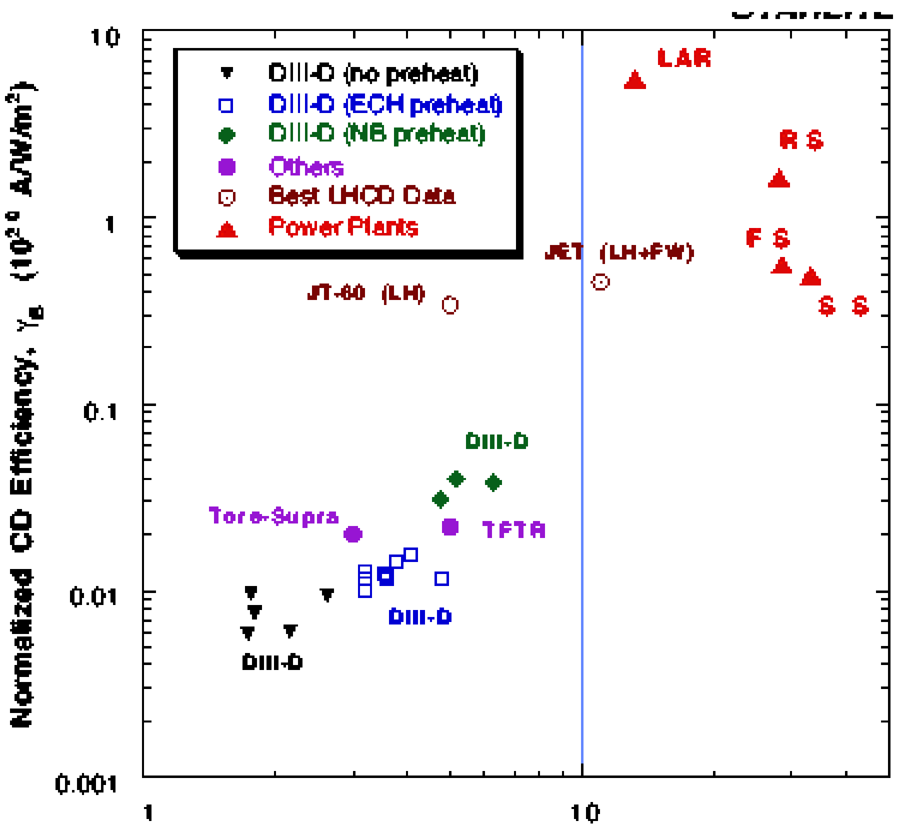
But $I_P = I_{BS} + I_{CD}$,

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

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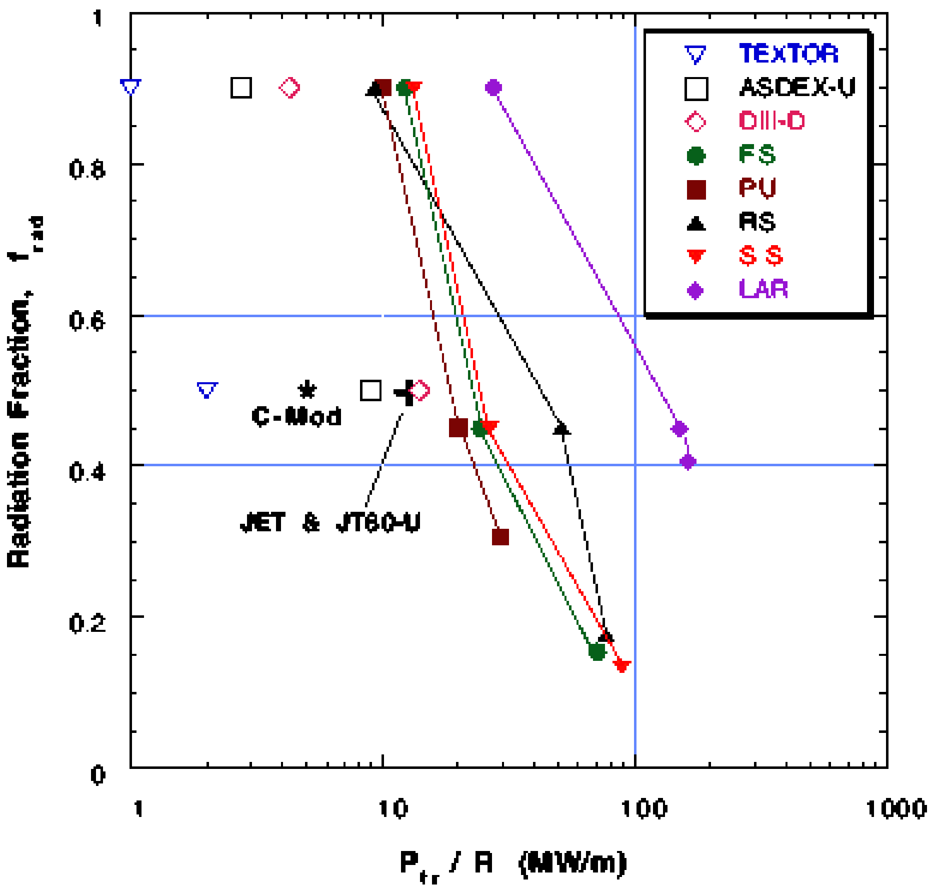
Need to demonstrate high radiation fraction and high power handling capability simultaneously



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

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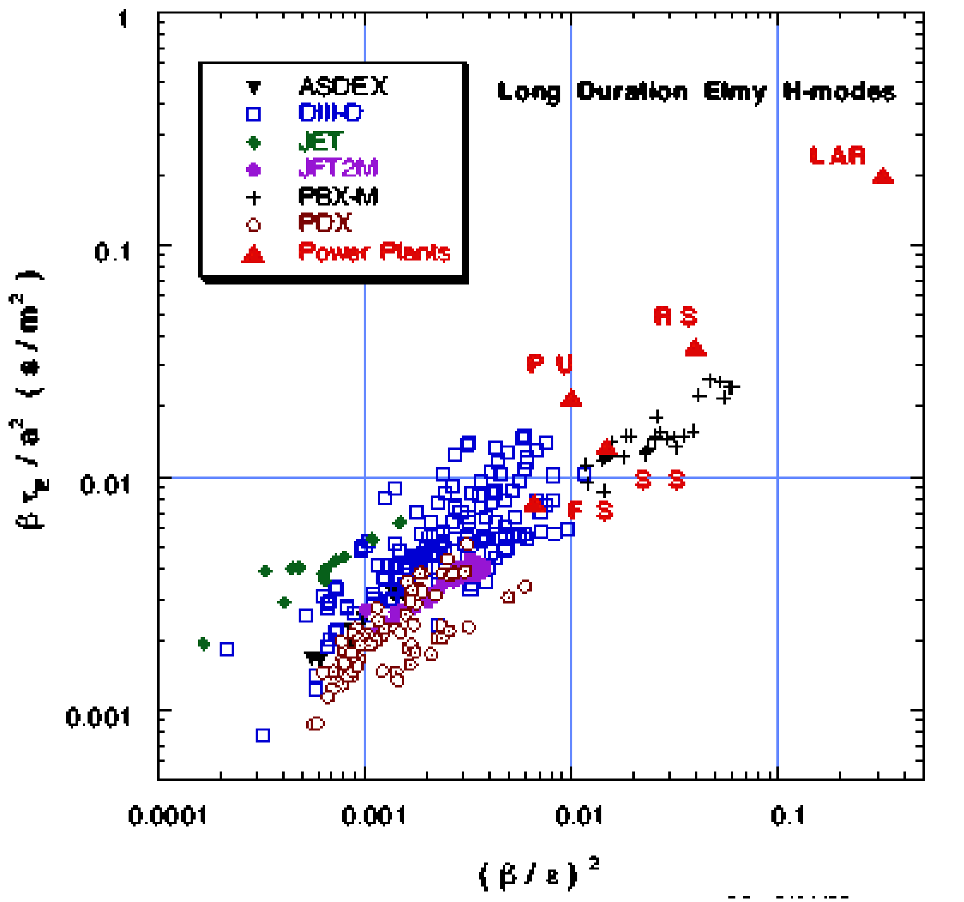
Note:

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

This is just $nT\tau$ 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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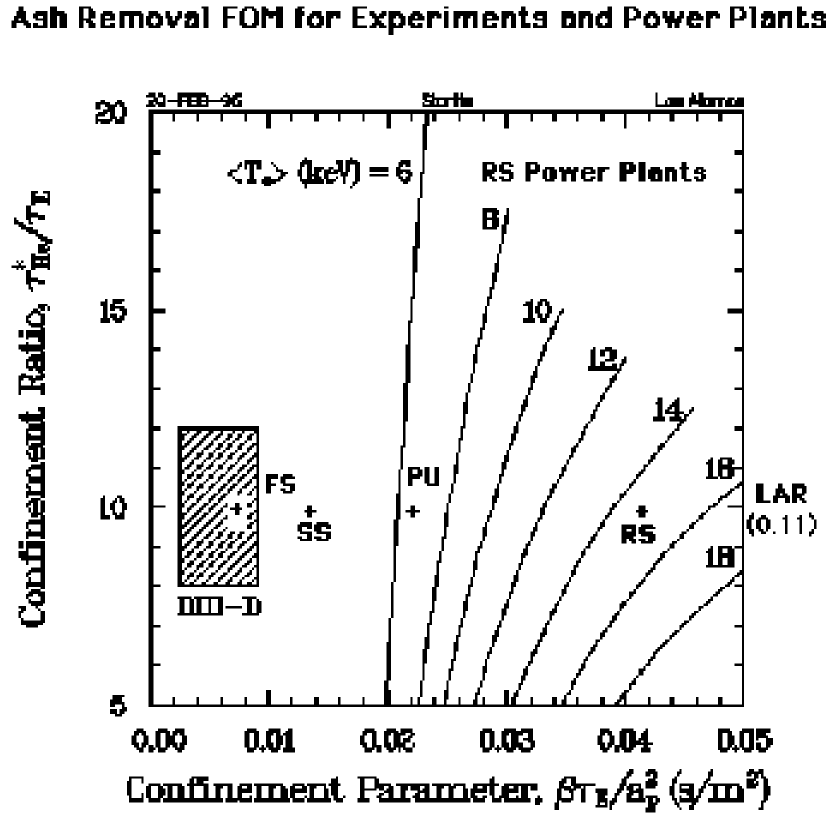
Need adequate helium ash removal and good energy confinement performance simultaneously



Some Physics Highlights of the ARIES studies

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MHD Regime:

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

Summary and Comments

- **This ARIES 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**