The ARIES-I and Pulsar Designs for a Tokamak Power Plant

ARIES
PULSAR
STARLITE

As determined by the

ARIES Studies

presented by

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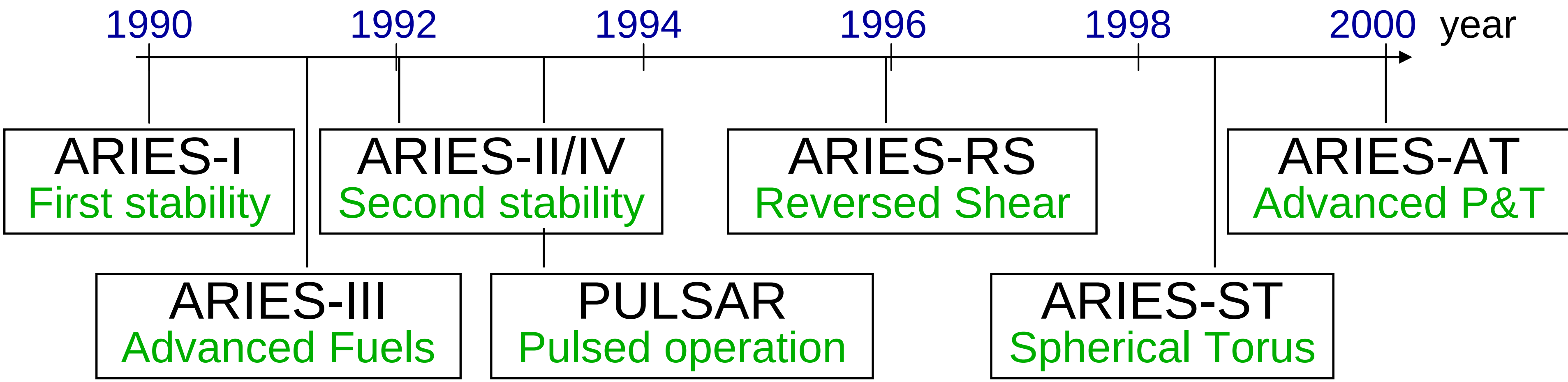
Outline

- **Overview of the ARIES studies**
- **Description of ARIES-I**
- **Description of PULSAR**
- **Relation of ARIES-I and PULSAR to the other ARIES designs**
- **Comparison of ARIES-I and PULSAR**
- **Some of the lessons learned from the studies**
- **Summary and conclusions**

ARIES

- **Advanced Reactor Innovation Evaluation Study**
  - ~ 10 year program to identify and begin evaluation of attractive concepts for a MFE power plant
  - Led by Profs. R. Conn and F. Najmabadi (UCLA/UCSD)
  - Involved over 50 fusion scientists and engineers from about 15 institutions…University, Laboratory, Private sector
- **Documented 7+ tokamak power plant designs**



Philosophy of the ARIES Studies

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A new technology (FUSION) can penetrate the market only if it is significantly better than any existing technology (FISSION)

- Attractive Safety Features
  - Eliminate “N-stamp” requirements
  - Low radioactive inventory
  - Minimal weapons proliferation and security costs
- Attractive Environmental Features
  - Waste disposal advantages – “Class-C” shallow-land burial

The assumption is that if these advantages are factored into the “true cost”, then fusion will have an advantage over fission

The physics and engineering assumptions used in the ARIES designs were sometimes very aggressive in order to get an attractive design:

“Theoretically possible”, not necessarily “experimentally demonstrated”

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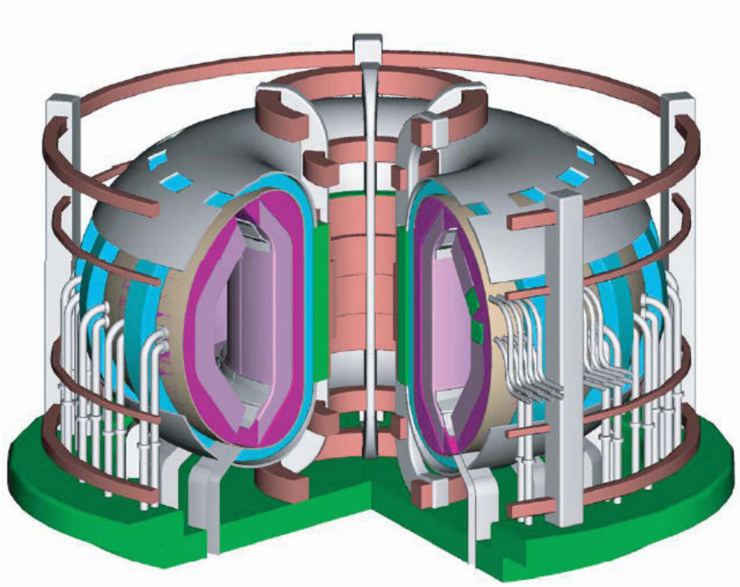
ARIES-I

First-Stability Regime, Steady State Plasma
MHD Stable without a Conducting Wall

- **ARIES-I design was to have “present day” physics (“first stability regime”), aggressive engineering, but keeping safety and environmental advantages**
- **Because RF current drive is relatively inefficient, the fraction of self-generated current (bootstrap current) must be large…68% in ARIES-I**
- **The constraint of “first stability” and high bootstrap current leads to relatively low β = 1.9%, and modest normalized β_N = 3.0,**
- **Since fusion power ~ $\beta^2 B^4$, this is compensated by high B (21 T at coil, 11.3 T at plasma center)***



R=6.75 m, a = 1.5 m,
B_T = 11.3 T, I_P = 10 MA

1 GW net power

*(Redesign, A-1’, has 16 T and 9 T)

Engineering features of the ARIES-I design:

- Advanced superconductor Nb_3Sn alloys toroidal field magnets producing 21 (16) T at magnet and 11.3 (9) T at plasma center
- ARIES-I blanket is He-cooled (at 10 MPa) design with SiC composite structural material, and Li_2ZrO_3 solid tritium breeders with beryllium neutron-multiplier
  - Composites are high strength, high temperature structural materials with very low activation and very low decay afterheat
- An advanced Rankine power conversion cycle as proposed for future coal-burning plants (49% gross efficiency).
- Folded wave-guide launcher made of SiC composite with 0.02 mm Cu coating
- Fusion power core modular for easy maintenance using a vertical lift approach

Major Parameters of ARIES-I

A-1'

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Aspect Ratio	4.5	4.5	High A to decrease I_P and divertor heat loads, and increase f_{BS},
Major Radius (m)	6.75	7.9	Required for power balance
Vertical Elongation κ	1.8	1.8	Minimizes PF energy, vertically stable
Plasma Current (MA)	10.2	10	Provides adequate confinement
Toroidal Field on Axis (T)	11.3	9	At limit of advanced alloy conductor
Toroidal beta	1.9%	1.9%	At first stability limit without wall
Neutron Wall load (MW/m^2)	2.5	2.0	20-MWy/m^2 lifetime
Recirculating Power fraction		0.29	97 MW ICRF CD power,
Net electric power (MW)	1000	1000	Same for all ARIES designs
Net plant efficiency	39%		Advanced Rankine steam power cycle with 49% efficiency

ARIES-I

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

Troyon Limit: $$\beta \le C_T \left(\frac{\mu_0}{40\pi}\right)\left(\frac{I_P}{aB_T}\right)$$ *C_T=3.0*

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=4.5, I_{BS}/I_P=.68, β=1.9%, q_0=1.3

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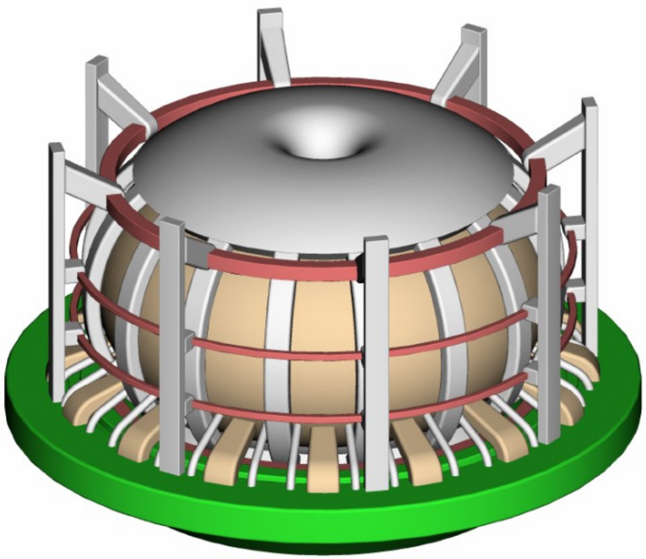
Objectives of the PULSAR study

- **Study the feasibility and potential features of a tokamak with a pulsed mode of plasma operation as a fusion power plant.**
- **Identify trade-offs which lead to the optimal regime of operation.**
- **Identify critical and high-leverage issues unique to a pulsed-plasma tokamak power plant.**
- **Compare steady-state and pulsed tokamak power plants.**



R=8.6 m, a = 2.15 m,
B_T = 7.5 T, I_P = 15 MA

1 GW net power

PULSAR Plasma Regime of Operation

- The loop voltage induced by the "inductive" current-drive system is constant across the plasma:

$$\frac{\partial \vec{B}}{\partial t} = 0 \quad \Rightarrow \quad \nabla \times \vec{E} = 0 \quad \Rightarrow \quad V_L = Const$$

  - Current-density profiles (induced and bootstrap) are determined by *n* and *T* profiles;

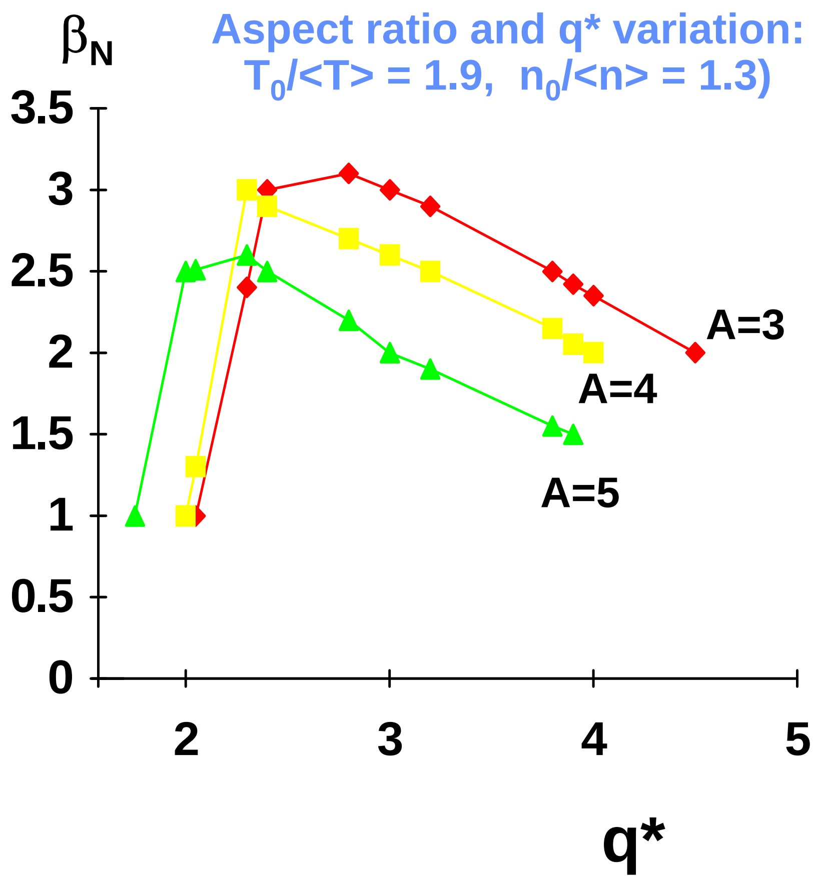
$$\vec{J} = \frac{V_L}{2\pi R \eta(n,T)} + J_{BS}(n,T)$$

  - Pressure profile is *n* x *T*

- Thus, Equilibrium is completely determined from $n(\psi)$, $T(\psi)$, I_P

PULSAR Plasma Regime of Operation(2)

- It follows that the current-density profile cannot be tailored to achieve the highest possible β
  - β_N is limited to $\leq$ 3.0 (for most favorable profiles…broad)
  - Bootstrap fraction is not large (~30% to 40%, maximum)
  - Second stability operation is not possible
- A large scan of stable ohmic equilibrium was made and a fit to the data base was used in the systems analysis



Power Flow in a Pulsed Tokamak

- **Utilities require a minimum electric output for the plant to stay on the grid**
- **Grid requires a slow rate of change in introducing electric power into the grid**
- **Large thermal power equipment such as pumps and heat exchangers cannot operate in a pulsed mode. In particular, the rate of change of temperature in the steam generator is ~ 2^{o}C/min in order to avoid boiling instability and induced stress.**

➔ **Therefore, Steady Electric Output is Required and an Energy storage system is needed.**

PULSAR Energy Storage System

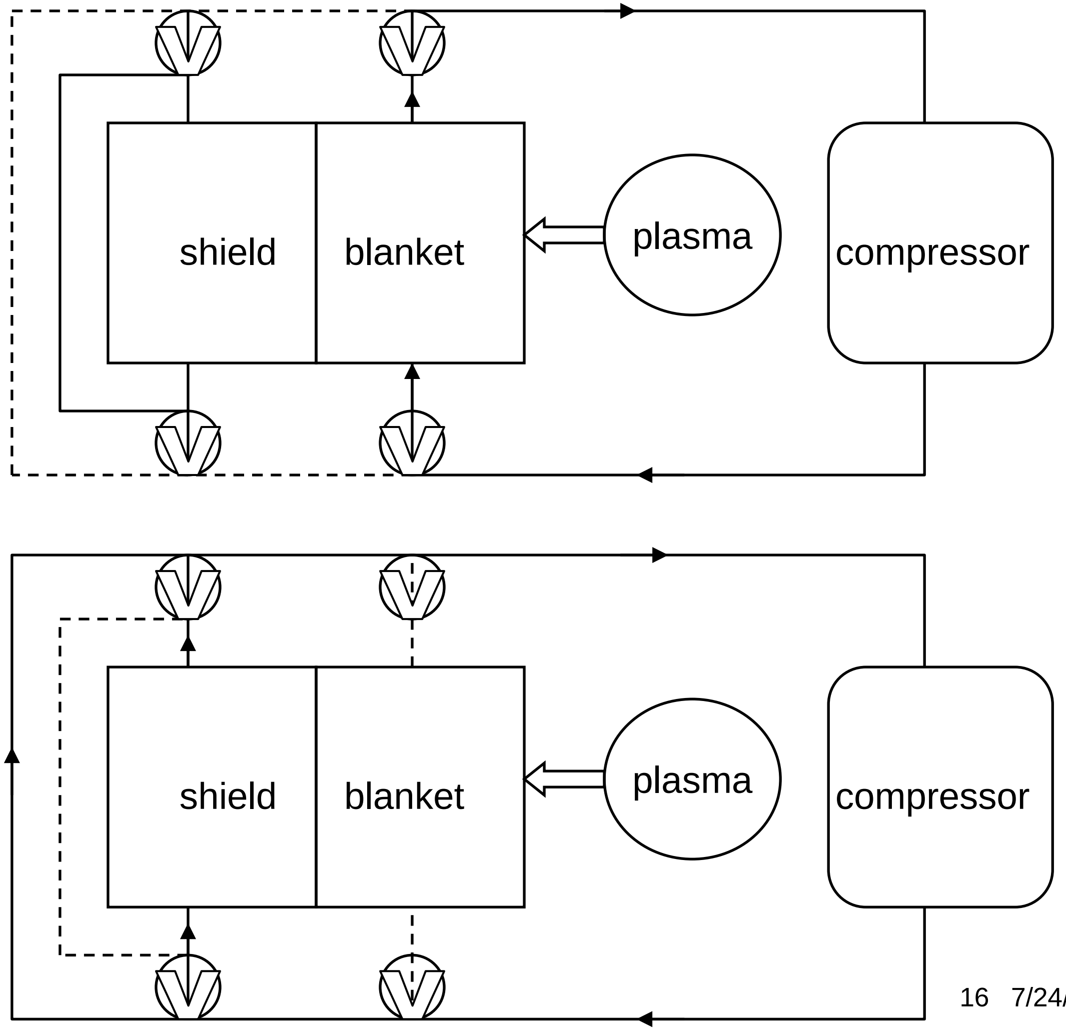
- An external energy storage system which uses the thermal inertia is inherently very large:
  - During the burn, $T_{coolant} > T_{storage}$
  - During the dwell, $T_{coolant} < T_{storage}$
  - But the coolant temperature should not vary much. Therefore, thermal storage system should be very large

- PULSAR uses the outboard shield as the energy storage system and uses direct nuclear heating during the burn to store energy in the shield;
  - This leads to a low cost energy storage system but the dwell time is limited to a few 100's of seconds

Energy is accumulated in outer shield during burn phase, regulated by mass flow control during dwell phase

Burn Phase

Dwell Phase



PULSAR cycle

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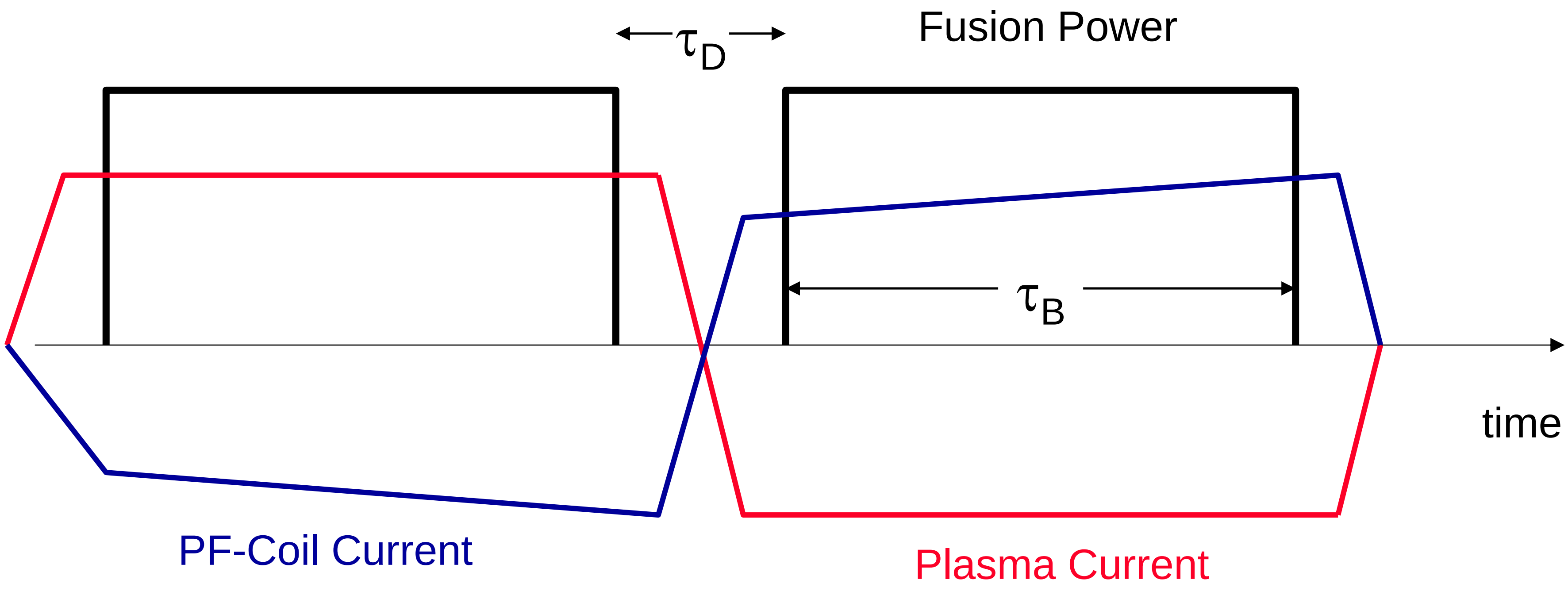

- Plasma physics sets lower limit on dwell time;
    - upper limit set by thermal storage system.
- Burn time determined through trade-off between size of OH system and number of cycles.
    - COE insensitive to burn times between 1 and 4 Hrs

$\tau_D \sim 200$ sec

$\tau_B \sim 9000$ sec

Pulsar Dwell Time Calculation

Current Rampup time	**54 s**
Plasma ignition time,	**53 s**
Plasma de-ignition time	**38 s**
Plasma shutdown time	**54 s**
Total Dwell time:	**200 s**

Burn time, 9000 s

Number of cycles 2,700 / year

PULSAR magnet system

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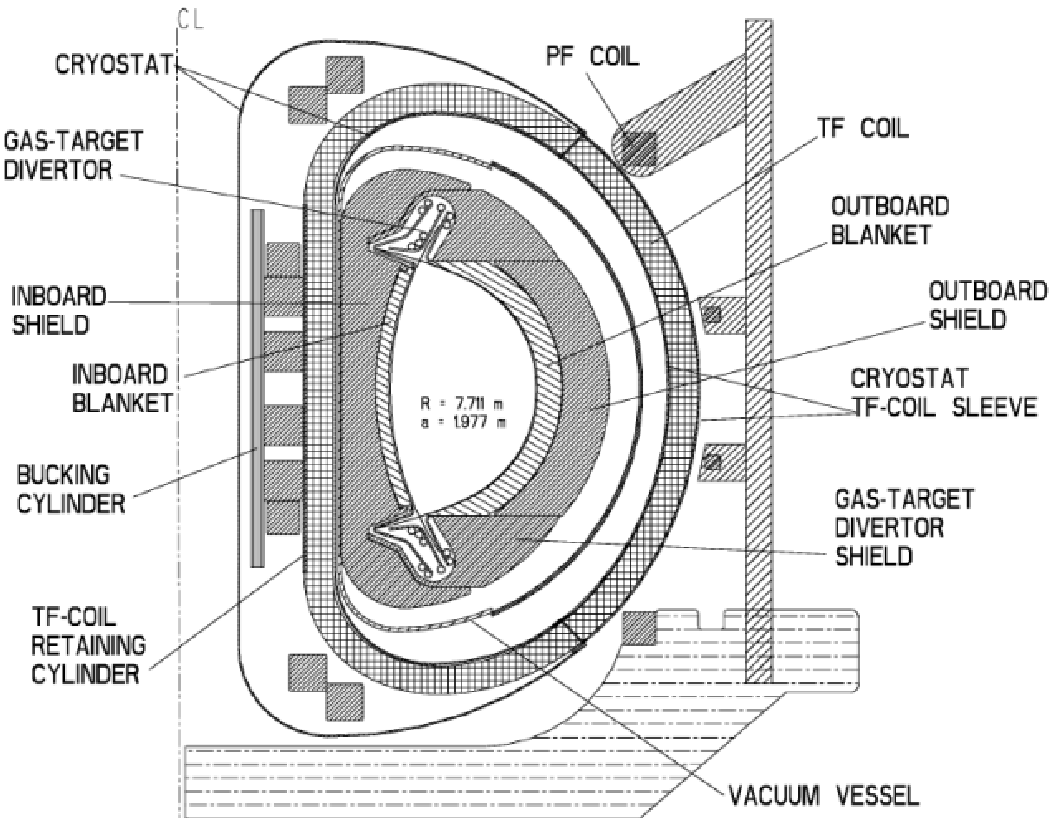
- **The PULSAR TF magnet system is similar to the old ITER design**
- **OH solenoid is located between the TF coil and the bucking cylinder**
- **Shear panels are used between the TF coils**
- **Inner legs of the TF coils are keyed together to support the shear loads**
- **Because of the elaborate key system, the supportable stress in the inner leg of the TF coils is reduced to an equivalent of ~50 MPa for uniformly distributed forces**



Major Parameters of PULSAR

	A-1'	*ARIES PULSAR STARLITE*	
Aspect Ratio	4.0	(4.5)	Optimizes at slightly lower A since f_{BS} does not weigh as heavily
Major Radius (m)	8.5	7.9	Required for power balance
Vertical Elongation κ	1.8	1.8	Minimizes PF energy, vertically stable
Plasma Current (MA)	13	10	Provides adequate confinement
Toroidal Field on Axis (T)	6.7	9	Lower due to cyclic PF induced stresses
Toroidal beta	2.8%	1.9%	First stability limit without wall, lower β_P
Neutron Wall load (MW/m^2)	1.3	2.0	20-MWy/m^2 lifetime
Recirculating Power fraction	0.06	0.29	OH Current Drive is very efficient
Net electric power (MW)	1000	1000	Same for all ARIES designs

PULSAR

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

Troyon Limit: $$(\beta/\varepsilon)(\varepsilon\beta_P) \le \left(\frac{C_T}{20}\right)^2 \frac{(1+\kappa^2)}{2}$$ *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
  - Current profile J determined from T and n profiles by stationary constraint

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

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

9000 s burn with 200 s OH recharge, during which thermal reservoir is tapped

A=R/a=4, I_{BS}/I_P=.34, β=2.8%, q_0=0.8

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Reactor Operating Modes

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	1ST STABILITY REGIME-wall stabilization not required	2ND STABILITY REGIME-wall stabilization of kink modes
STEADY STATE	MODERATE β MODERATE β_p ARIES-I	HIGH β HIGH β_p ARIES RS, AT, ST
PULSED	HIGH β LOW β_p PULSAR	NOT POSSIBLE

Dimensionless Parameter Space
$\beta/\varepsilon \times 2/(1+\kappa^2)$ vs $\varepsilon\,\beta_P$
for Tokamak Reactor Regimes

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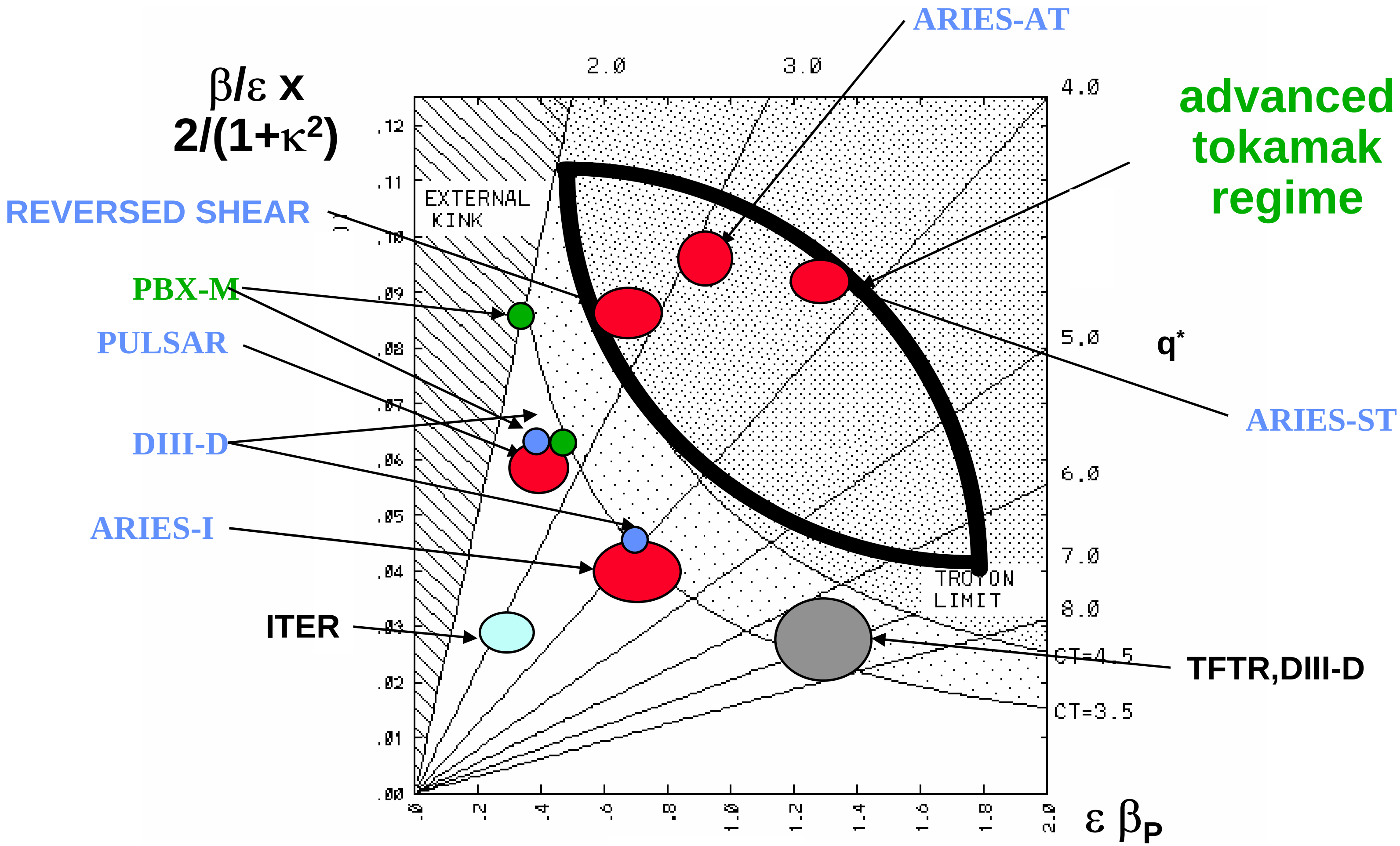

Both the AIRES-I and PULSAR operating modes have demonstrated stationary high performance on DIII-D

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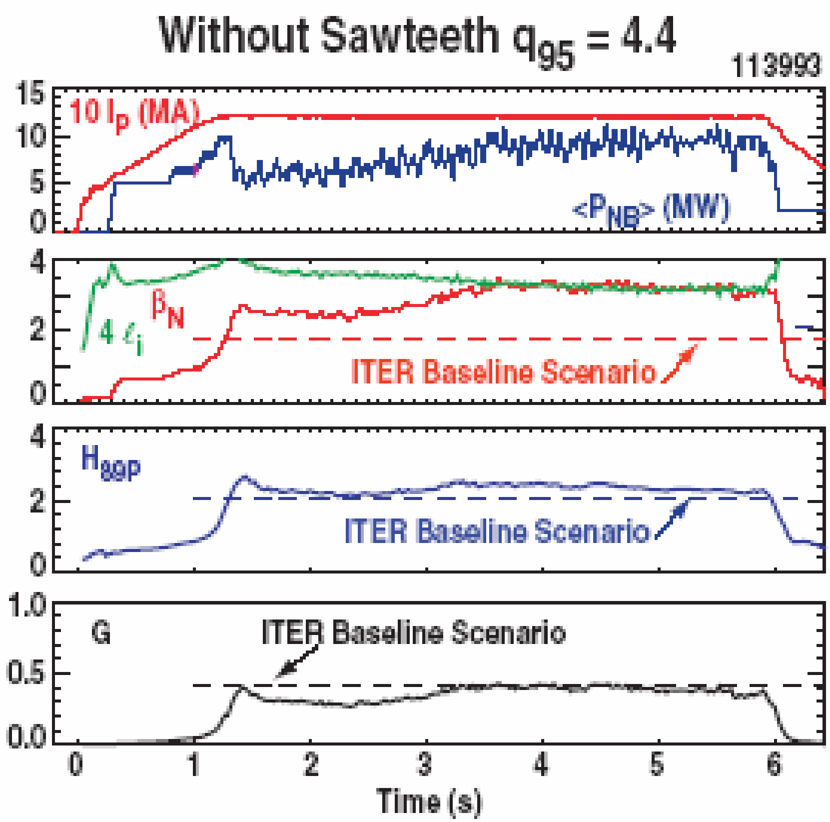
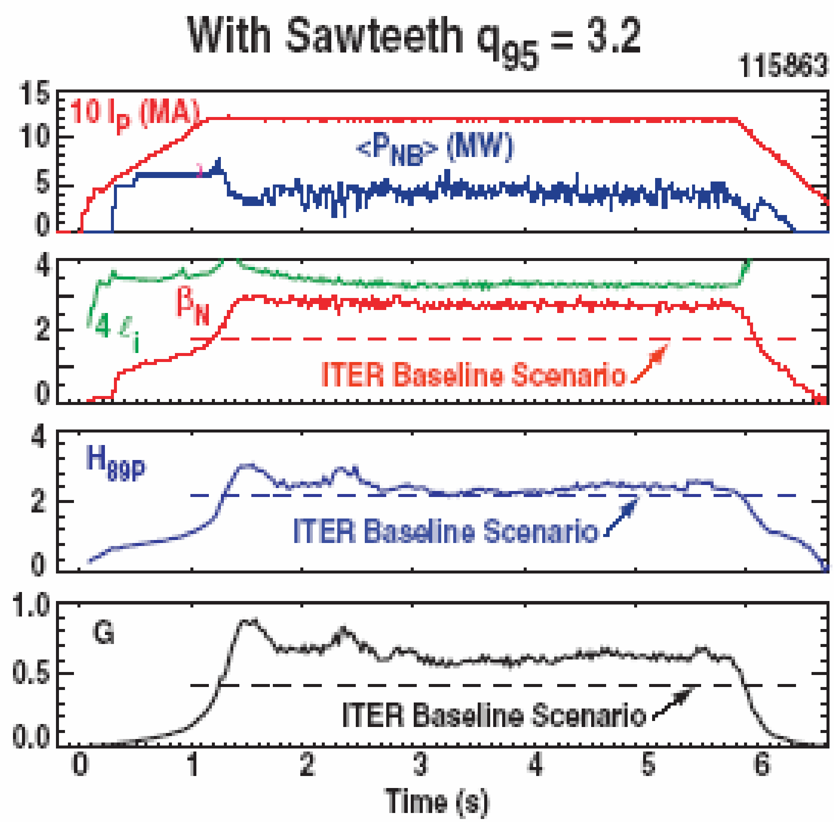
ARIES-I like



PULSAR like



M Wade, June 2004

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Comparison Chart between PULSAR and ARIES-I'

Physics assumptions of the two first stability devices are the same (except non-inductive current-drive physics).

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	PULSAR	ARIES-I'
Current-drive system	PF system very expensive, but efficient, separate system for heating	Non-inductive drive Expensive & inefficient, used also for heating
Recirculating power	Low	High
Optimum Plasma Regime	Moderate Bootstrap, High A, Low I	High Bootstrap, Higher A, Lower I
Current Profile Control	No, 30%-40% bootstrap fraction β_N~ 3, $\beta \sim 2.8\%$	Yes, 65-%-75% bootstrap fraction β_N~ 3.3, $\beta \sim 1.9\%$
Toroidal-field Strength	Lower because of interaction with cycling 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
Energy Storage	Yes, Shield	No need
Disruptions	More frequent	fewer

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Lesson # 1:
It's β/ε (i.e. $\beta R_0/a$) that's important, not β !

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MHD Theory

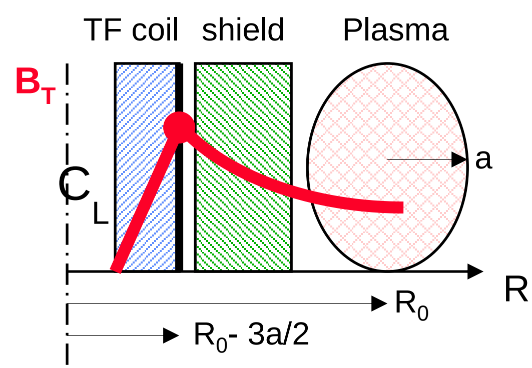
1. Large aspect ratio expansion of MHD perturbed energy δW shows that β enters only as β/ε (reduced MHD)

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



$B_T = \mu_0 I_{TF}/2\pi R$ is limited by it's value at the edge of the TF coil, $R \sim R_0$- 3a/2

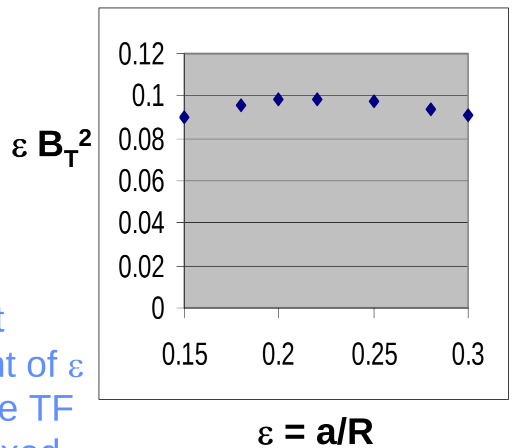
Power Density:

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

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

MHD Figure of merit

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



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

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

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 x 10^{20}, R = 8 m, γ_{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**

Many Critical Issues and dependencies have been uncovered by 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
  - has implications for ITER

Plasma Shaping:

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

Current Drive:

- need for efficient off-axis CD (other than LHCD)
- 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

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Summary

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- Both the ARIES-I and PULSAR designs are very close to the achieved physics data base
- Both steady-state and pulsed power plants tend to optimize at larger aspect ratio and low currents
- Even though the plasma β is larger in a pulsed tokamak, the fusion power density (wall loading,etc) would be lower because the magnetic field at the coil would be lower
- A major innovation of the PULSAR study is the low-cost thermal storage system using the outboard shield
- Much more engineering data is needed to assess the impact of fatigue on the design of the blanket and shield of a pulsed-plasma power plant.
- The magnet system and fusion power core are much more complex in a pulsed-plasma tokamak, but there is no CD system
- Assuming the same availability and unit costs, PULSAR is about 25% more expensive than a comparable ARIES-I class device
- These designs provide an important backup if the more aggressive “Advanced Tokamak” designs prove impractical