# Issues in "Burning Plasma Science"

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(with inputs from many people at PPPL)

Burning Plasma Science Workshop
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- Burning plasma physics issues
- Fusion energy development issues

  => big issue: local burn control in an AT

- Our conclusions
- Alternate path

# Burning Plasma Physics Issues

*assuming here the motivation is largely driven by plasma physics interest, not fusion energy development (i.e. reactor-relevance)*

## General issues:

What are the interesting plasma physics issues which could be studied in a new burning plasma experiment (which could not be studied without one) ?

What would be needed in a burning plasma experiment to study these plasma physics issues ?

Are these plasma physics issues sufficiently interesting to motivate a burning plasma experiment ?

# What are the Interesting Plasma Physics Issues in a BP Experiment ?

1) Alpha particle driven collective instabilities

e.g. for Toroidal Alfven Eigenmode (TAE), EPM, fishbones, etc, especially where there area many modes and possible Alfven turbulence

2) Exploring of a new part of plasma parameter space

e.g. plasmas with low $\rho/a$ at low $\nu$ and high $\beta$
(note that low $\rho/a$ plasmas already accessible)

## Less compelling issues:

- alpha particle heating physics
- single-particle alpha confinement, control, and loss
- plasma turbulence and transport physics
- plasma-wall interaction and He ash transport
- study of a complex non-linearly coupled system

# What is Needed to Study these Plasma Physics Issues in a BP experiment ?

- Theory and/or simulations showing that this physics is interesting and accessible in this particular BP experiment

- High confidence that the machine will reach the required plasma parameters to do this physics

- Excellent diagnostic coverage, e.g. measurement of alpha particle density profile, temperature and q(r) profiles, internal fluctuation amplitudes, etc.

- Sufficient run time in DT to do good physics (e.g. TFTR had ≈100,000 shots over 15 years and 300 shots with significant DT power over 3 years)

# Are These Physics Issues Sufficiently Interesting to Motive a BP Experiment ?

*This is debatable, but it is fairly clear that:*

- A BP experiment would most likely be perceived and judged by the everyone inside and outside the fusion community as a step toward a tokamak reactor, not as a physics experiment

- There are many other equally interesting plasma physics issues (inside and outside fusion) which are much less costly and which do not need a BP experiment (see end of talk)

# Fusion Energy Issues for BP Experiment

*assuming here the motivation is largely driven by fusion reactor relevance, not plasma physics interest*

## General issues:

What are the fusion energy development issues which could be resolved with this BP experiment ?

Will a BP experiment develop generic fusion technology of value to another MFE configuration ?

Is this experiment on a clear path towards a viable fusion reactor (or, should it be)?

# What are Fusion Energy Development Issues Which Could be Resolved ?

1) What is "self-organized" state of a burning plasma ?

e.g. determine whether plasma performance
changes with self-consistent alpha heating ?
Is there some unpredicted new physics ?

2) Can a burning plasma be adequately controlled ?

e.g. determine whether an alpha-heated BP
can be sustained for a reactor-relevant timescale
without He ash buildup, MHD, disruption, etc.

Less compelling issues:

- determining whether or not plasma will "ignite"
- demonstration of large "fusion power" production
- development of tokamak reactor technology

# Will a BP Experiment Develop Generic Technology for an MFE Reactor ?

1) Most technology development does not need DT

   e.g. RF heating, current profile control, fueling, pumping, non-carbon PFCs, etc, could be done without (or in DD phase of) a BP experiment

2) BP exp't doesn't develop much nuclear technology

   e.g. radiation damage small, tritium breeding not needed, but activation (even in DD) will require generic improvements in remote handling

3) Other MFE concepts need science not technology

   e.g. FRC and RFP need stability and current drive physics studies, ST needs size scaling, etc.

# Is This Experiment on a Clear Path Toward a Viable Fusion Reactor ?

*If it is not (or if we don't know), we should say this so that people outside the field are not "confused"*

*If it is, we need to explain our vision of a viable tokamak fusion reactor goal (see below)*

# Tokamak Reactor Visions

*"It is well known from simple power balance arguments that, for a viable steady state tokamak reactor, most of the plasma current must arise from bootstrap current and the magnetic configuration should be that of a relatively high-q, reverse shear plasma..."  ITER PBD, NF Dec. 1999, Ch. 9, p. 2636*

For a "conventional" steady-state tokamak [Jardin]:

- Need I ≈ 20 MA from conventional $\tau_E$ and $\beta$ scalings
- Assume inductive and bootstrap current negligible
- Need $P_{cd} \approx 700$ MW from known CD efficiencies
- Need $E_{cd} \geq 1500$ MWE to drive this current

=> Highly unrealistic for a 1000 MWE reactor !

BP experiment based on "conventional" tokamak (e.g. ITER-EDA in ELMy H-mode) would not be well justified based on fusion energy science, (unless it was aimed at a ohmic pulsed reactor)

# ARIES Tokamak Reactors

[S. Jardin et al, Fusion Eng. and Design 2000, p. 281]

| | FS | PU | RS | SS |
|---|---|---|---|---|
| I (MA) | 12.6 | 15 | 11.3 | 7.7 |
| $\beta_n$ | 2.9 | 2.7 | 4.8 | 5.3 |
| $f_{bs}$(%) | 57 | 34 | 88 | >100 |
| $f_{recirc}$ (%) | 29 | 6 | 17 | 33 |
| COE (rel) | 100 | 130 | 77 | 93 |

- FS and PU have "normal" magnetic shear, PU is pulsed
- RS and SS have reversed magnetic shear => AT modes

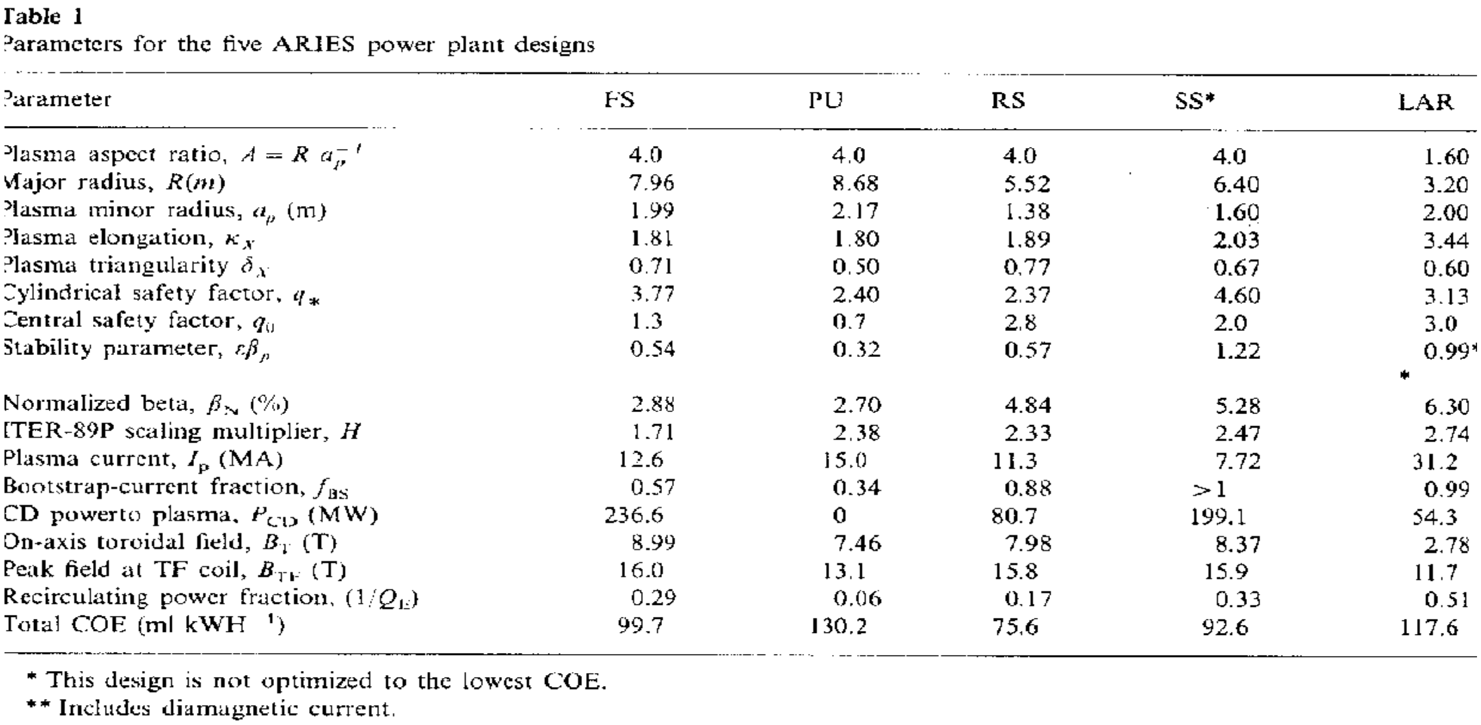


**Table 1**
Parameters for the five ARIES power plant designs

| Parameter | FS | PU | RS | SS* | LAR |
|---|---|---|---|---|---|
| Plasma aspect ratio, $A = R\ a_p^{-1}$ | 4.0 | 4.0 | 4.0 | 4.0 | 1.60 |
| Major radius, $R(m)$ | 7.96 | 8.68 | 5.52 | 6.40 | 3.20 |
| Plasma minor radius, $a_p$ (m) | 1.99 | 2.17 | 1.38 | 1.60 | 2.00 |
| Plasma elongation, $\kappa_X$ | 1.81 | 1.80 | 1.89 | 2.03 | 3.44 |
| Plasma triangularity $\delta_X$ | 0.71 | 0.50 | 0.77 | 0.67 | 0.60 |
| Cylindrical safety factor, $q_*$ | 3.77 | 2.40 | 2.37 | 4.60 | 3.13 |
| Central safety factor, $q_0$ | 1.3 | 0.7 | 2.8 | 2.0 | 3.0 |
| Stability parameter, $\varepsilon\beta_p$ | 0.54 | 0.32 | 0.57 | 1.22 | 0.99** |
| Normalized beta, $\beta_N$ (%) | 2.88 | 2.70 | 4.84 | 5.28 | 6.30 |
| ITER-89P scaling multiplier, $H$ | 1.71 | 2.38 | 2.33 | 2.47 | 2.74 |
| Plasma current, $I_p$ (MA) | 12.6 | 15.0 | 11.3 | 7.72 | 31.2 |
| Bootstrap-current fraction, $f_{BS}$ | 0.57 | 0.34 | 0.88 | >1 | 0.99 |
| CD powerto plasma, $P_{CD}$ (MW) | 236.6 | 0 | 80.7 | 199.1 | 54.3 |
| On-axis toroidal field, $B_T$ (T) | 8.99 | 7.46 | 7.98 | 8.37 | 2.78 |
| Peak field at TF coil, $B_{TF}$ (T) | 16.0 | 13.1 | 15.8 | 15.9 | 11.7 |
| Recirculating power fraction, $(1/Q_E)$ | 0.29 | 0.06 | 0.17 | 0.33 | 0.51 |
| Total COE (ml kWH $^{1}$) | 99.7 | 130.2 | 75.6 | 92.6 | 117.6 |

* This design is not optimized to the lowest COE.
** Includes diamagnetic current.

# Local Burn Control in ATs

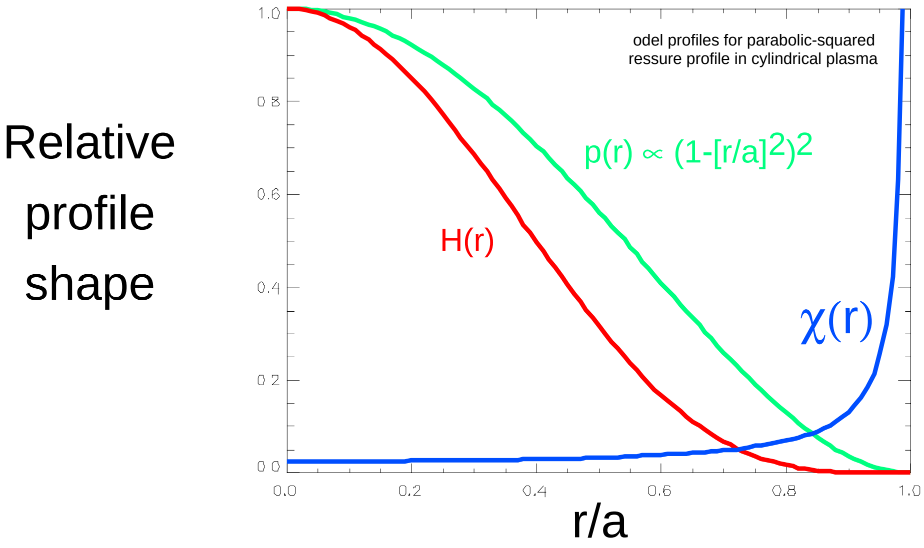
*Are the assumed p(r) and j(r) in an AT reactor consistent with a steady-state burning plasma, i.e. with self-generated alpha heating ?*

In the limit of no external control (i.e. ignition):

- alpha heating power $H_\alpha(r) = c\, p^2(r)$ [approx.]
- radial power balance in steady state:

$$1/r\ d/dr(r\ \chi(r)\ dp/dr) + c\ p^2(r) = 0$$

- For a steady-state p(r) there one possible $\chi(r)$, for example, if $p(r) \propto (1-[r/a]^2)^2$



=> Steady-state with desired profiles is very unlikely without external control of j(r) and/or p(r), since $\chi(p, j, \nabla p, \nabla j\ ...)$ is complicated and unknown

# Issues in Local Burn Control in AT

*Can the required p(r) and j(r) be maintained by active feedback control while maintaining $Q \geq 10$ (or so) in an AT reactor?*

- There are no time-dependent simulations of the ARIES designs which have analyzed this

- There have been a few computer simulations of burn control for the steady-state AT scenario

Some generic problems for AT reactor burn control:

- control power/alpha power $\leq f_{recirc} << 1$
- control power does both CD and heating
- narrow window in p(r) and j(r) for MHD stability
- strong coupling between p(r), j(r), and H(r)
- lack of knowledge of $\chi$ (r) vs. p(r), j(r), etc.
- timescales for p(r) changes faster than j(r)
- need to replace He ash with DT fuel in core
- need for edge power and particle control
- need to maintain fusion power nearly steady
- control failure may lead to plasma disruption !

# Current Profile Equilibrium in Ignited AT

[J. Kesner, Physics Letters A, 1996, p. 303]

- Assumes bootstrap current $\propto \nabla p$ (approx)
- Uses model with $\chi$(r) reduced inside some r*
- Calculates equilibrium alpha H(r) and q(r)
- $q_{min}$ moves toward axis with reduced r*

=> Choice of $\chi$(r) determines H(r) and q(r), so q(r) is not necessarily consistent with MHD stability

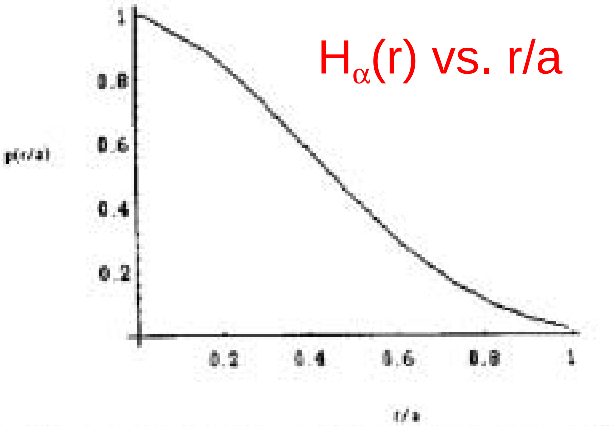

$H_\alpha$(r) vs. r/a

Fig. 4. Equilibrium alpha heating profile for ITER parameters, $B_0 = 6$ T, $a = 3$ m, $R_0 = 8$ m, $n_e(0) = 1 \times 10^{20}$ m$^{-3}$, $T(0) = 15$ keV.

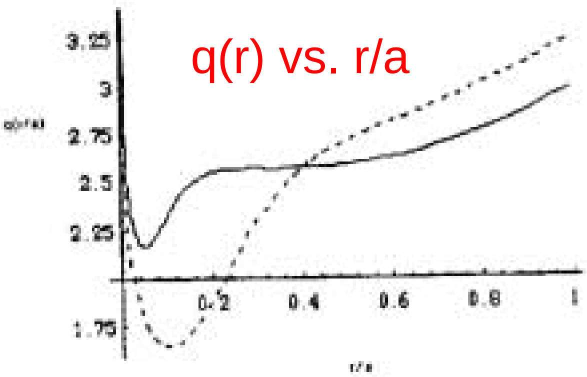

q(r) vs. r/a

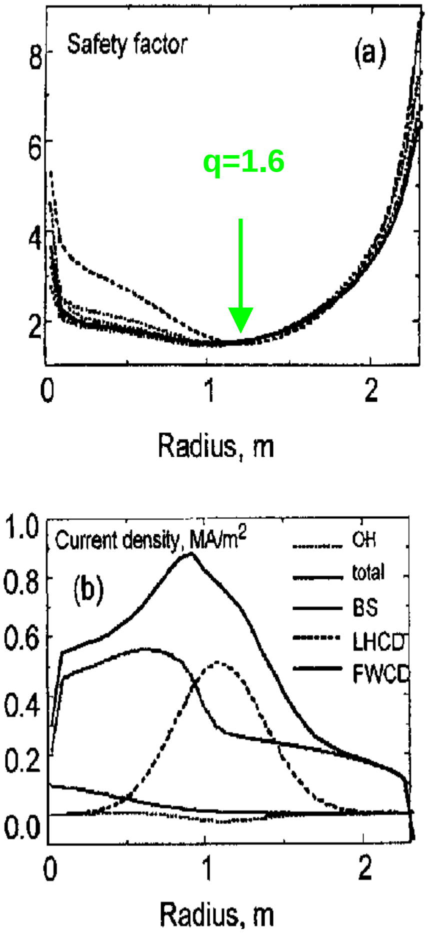
Fig. 5. Equilibrium profiles of the safety factor, $q$, for $r_*/a = 0.30$ (dashed) and 0.18 (solid curve).

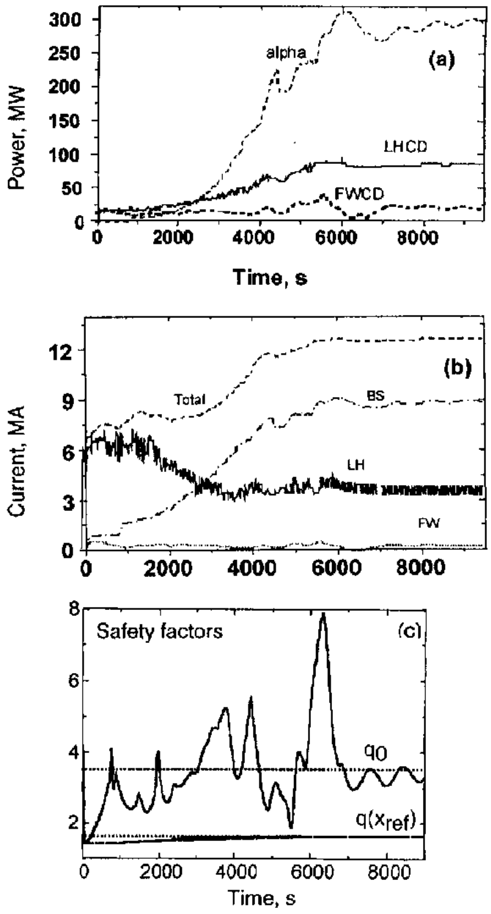
note: this model assumes no external control of q(r) or P(r)

# Current Profile Control in AT BP

[D. Moreau and I. Voitsekhovich, NF 1999, p. 685]

- Based on ITER steady-state advanced scenario
- Models 2-point current profile control with FWCD and LHCD, choosing q(0)=3.5 and q(a/2)=1.6
- Assumes a specific transport model for $\chi(r)$



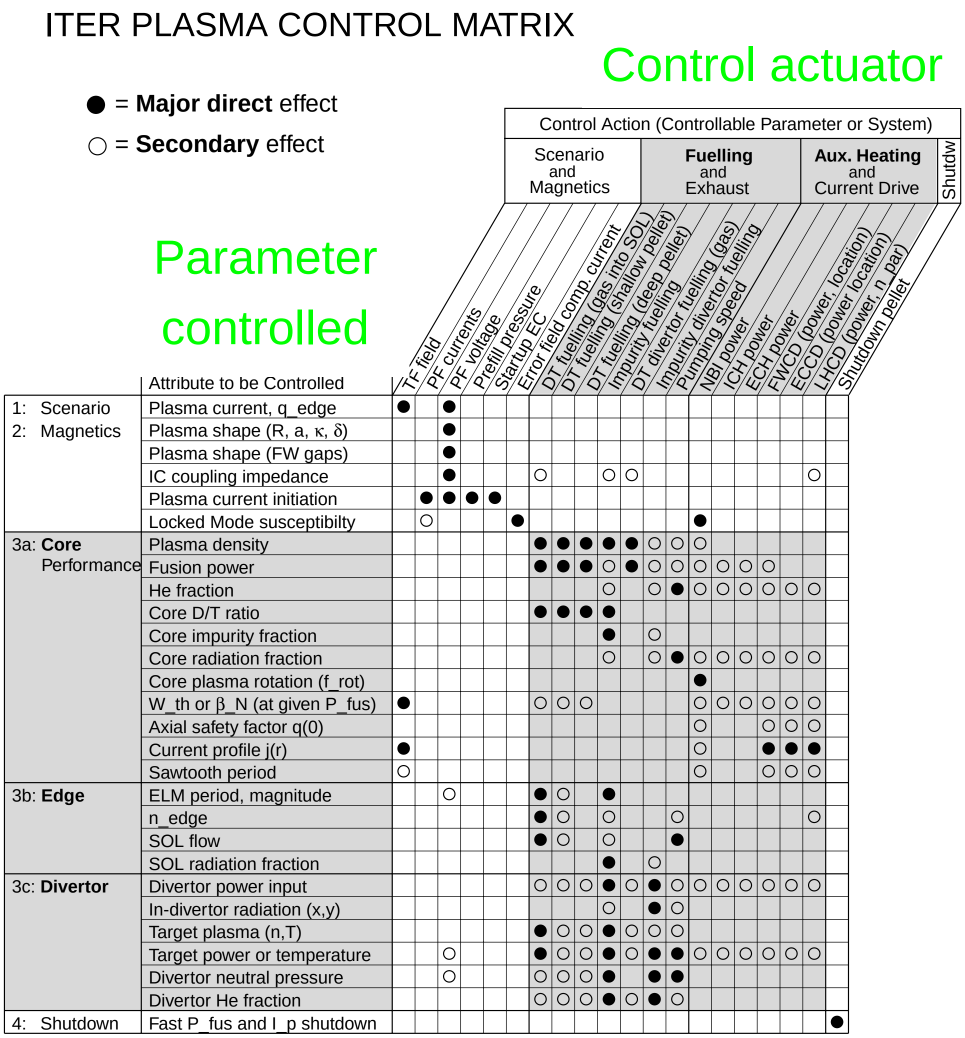


=> Some control of q(r) is achieved !

# General Control Matrix for AT Scenario

[ J.B. Lister et al, NF 2000, p. 1167]

- Need simultaneous control of many parameters, which could lead to stochastic behavior
- Need near-perfect control to avoid disruptions, and intelligent control to minimize power needed



ITER PLASMA CONTROL MATRIX

Control actuator

● = **Major direct** effect

○ = **Secondary** effect

Parameter controlled

| | | Control Action (Controllable Parameter or System) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario and Magnetics | | | | | | **Fuelling** and Exhaust | | | | | | | **Aux. Heating** and Current Drive | | | | | | Shutdw |
| | Attribute to be Controlled | TF field | PF currents | PF voltage | Prefill pressure | Startup EC | Error field comp. current | DT fuelling (gas into SOL) | DT fuelling (shallow pellet) | DT fuelling (deep pellet) | Impurity fuelling | DT divertor fuelling (gas) | Impurity divertor fuelling | Pumping speed | NBI power | ICH power | ECH power | FWCD (power, location) | ECCD (power location) | LHCD (power, n_par) | Shutdown pellet |
| 1: Scenario<br>2: Magnetics | Plasma current, q_edge | ● | | ● | | | | | | | | | | | | | | | | | |
| | Plasma shape (R, a, κ, δ) | | | ● | | | | | | | | | | | | | | | | | |
| | Plasma shape (FW gaps) | | | ● | | | | | | | | | | | | | | | | | |
| | IC coupling impedance | | | ● | | | | ○ | | | ○ | ○ | | | | | | | | ○ | |
| | Plasma current initiation | | ● | ● | ● | ● | | | | | | | | | | | | | | | |
| | Locked Mode susceptibilty | | ○ | | | | ● | | | | | | | | ● | | | | | | |
| 3a: **Core** Performance | Plasma density | | | | | | | ● | ● | ● | ● | ● | ○ | ○ | ○ | | | | | | |
| | Fusion power | | | | | | | ● | ● | ● | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | | | |
| | He fraction | | | | | | | | | | ○ | | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | |
| | Core D/T ratio | | | | | | | ● | ● | ● | ● | | | | | | | | | | |
| | Core impurity fraction | | | | | | | | | | ● | | ○ | | | | | | | | |
| | Core radiation fraction | | | | | | | | | | ○ | | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | |
| | Core plasma rotation (f_rot) | | | | | | | | | | | | | | ● | | | | | | |
| | W_th or β_N (at given P_fus) | ● | | | | | | ○ | ○ | ○ | | | | | ○ | ○ | ○ | ○ | ○ | ○ | |
| | Axial safety factor q(0) | | | | | | | | | | | | | | ○ | | | ○ | ○ | ○ | |
| | Current profile j(r) | ● | | | | | | | | | | | | | ○ | | | ● | ● | ● | |
| | Sawtooth period | ○ | | | | | | | | | | | | | ○ | | | ○ | ○ | ○ | |
| 3b: **Edge** | ELM period, magnitude | | | ○ | | | | ● | ○ | | ● | | | | | | | | | | |
| | n_edge | | | | | | | ● | ○ | | ○ | | | ○ | | | | | | ○ | |
| | SOL flow | | | | | | | ● | ○ | | ○ | | | ● | | | | | | | |
| | SOL radiation fraction | | | | | | | | | | ● | | ○ | | | | | | | | |
| 3c: **Divertor** | Divertor power input | | | | | | | ○ | ○ | ○ | ● | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | |
| | In-divertor radiation (x,y) | | | | | | | | | | ○ | | ● | ○ | | | | | | | |
| | Target plasma (n,T) | | | | | | | ● | ○ | ○ | ● | ○ | ○ | ○ | | | | | | | |
| | Target power or temperature | | | ○ | | | | ● | ○ | ○ | ● | ○ | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | |
| | Divertor neutral pressure | | | ○ | | | | ○ | ○ | ○ | ● | | ● | ● | | | | | | | |
| | Divertor He fraction | | | | | | | ○ | ○ | ○ | ● | ○ | ● | ○ | | | | | | | |
| 4: Shutdown | Fast P_fus and I_p shutdown | | | | | | | | | | | | | | | | | | | | ● |

**Figure 1.** Diagram of the influence matrix between actuators and parameters to be controlled.

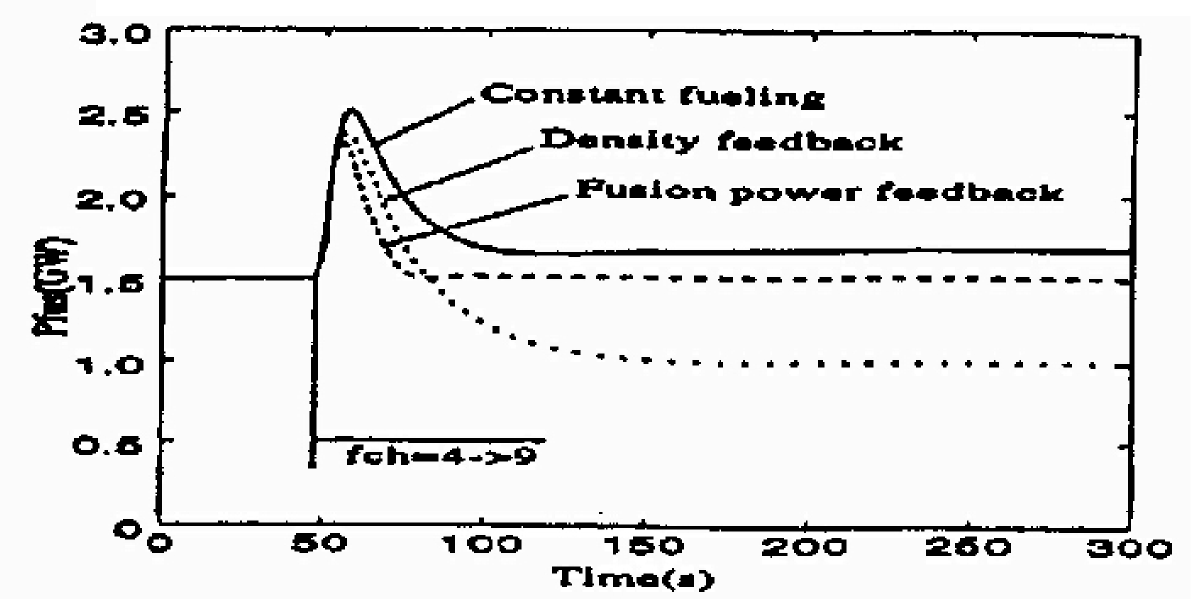
# Control of Conventional Tokamak

[J.-F. Wang et al, Fusion Technology 32, 1997, p. 590]

- Models burn control for ITER-EDA-type plasma
- Global $\chi$ decrease causes fast rise in $P_{fusion}$
- Ash buildup caused slow drop in fusion power
- Feedback via fueling is too slow to control rise

=> Feedback control of conventional burning tokamaks is also difficult

Fusion power vs. time after fast x 2 decrease in $\chi$



# Potential Non-AT Tokamak Reactors

*e.g. like ARIES-I (steady-state) or PULSAR (pulsed)*

## General issues:

*Does the relative simplicity and feasibility of the non-AT reactor designs outweigh their potentially slightly higher projected cost of electricity ?*

*Is there a realistic path from the ITER-EDA design (≈ \$10B cost, COE = ∞) to an attractive reactor (≈ \$2-3B cost, COE ≤ \$0.1/kW-hr) ?*

*If so, what is the next logical next step in our program (e.g. ITER-EDA?)*

# Our Conclusions (sz and dd)

- Plasma physics issues alone (without a specific fusion energy goal) do not provide a sufficient motivation for a new $B-class BP experiment

- Fusion energy development issues are best addressed in a BP experiment which is on a well-defined path toward a viable reactor
    - AT reactors have serious control problems which should be evaluated in any next-step experiment aimed at such a reactor
    - Failure of such control in an BP experiment (e.g. disruptions on every shot) could have negative consequences for fusion research

- Pulsed conventional designs (e.g. PULSAR) may have the best chance of evolving into a viable tokamak fusion reactor

# Alternate Path

1) Develop tokamak physics in non-burning plasmas
   - Study fast particles instabilities w/ NBI, ICRF...
   - Understand $\chi$(p,j,..) - is there a general result ?
   - Understand non-linear consequences of MHD
   - Develop stronger and more efficient j(r) control
   - Try to develop external transport profile control
   - Develop new ideas to reach Q >> 1 and then test them at Q ≥ 1 on JET(DT), KSTAR, etc.

2. Improve our confidence in tokamak reactor designs
   - Do time-dependent simulation of ARIES options
   - Use simulations to develop control requirements
   - Define (diagnostic + actuator + software) needs
   - Validate in DD, then test in a BP experiment

3. Develop alternate MFE concepts in DD plasmas
   - Greater external control (e.g. stellarators ?)
   - Strongly self-organizing (e.g. RFP ?)
   - More "headroom" at high beta (e.g. ST ?)
   - Simpler geometry or engineering (e.g. FRC ?)
   - First test at proof-of-principal stage without BP