ARIES-RS (Reversed Shear) Advanced Tokamak Analysis and Issues

Advanced Tokamak Workshop
General Atomics, 3/9-11/99

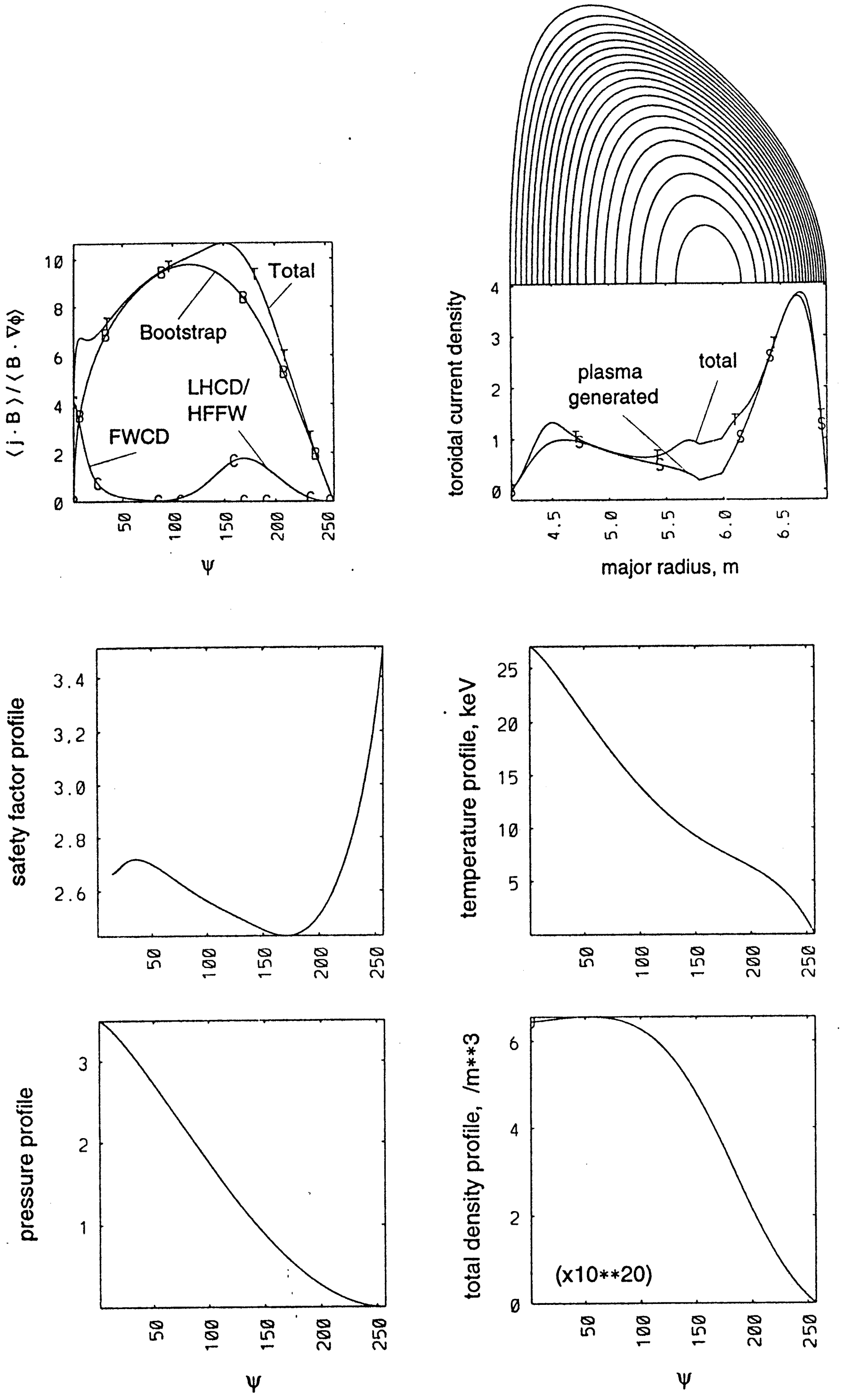
C. Kessel

Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Introduction

- the ARIES-RS study evaluated the reversed shear configuration as a power plant to determine its potential benefits over
  - pulsed/first-stability, (PULSAR)
  - steady-state/first-stability, (ARIES-I)
  - steady-state/second-stability, (ARIES-II)
- the primary benefits of the configuration appear to be
  - high β (with the external kink mode stabilized) —> leading to high fusion power density and small reactor size
  - large bootstrap current and good alignment —> leading to low current drive power and therefore low recirculating power
  - sufficiently good transport that can roughly support the profiles being assumed in the stability and bootstrap calculations —> leading to energy confinement that can easily provide plasma power balance with small auxiliary input power (Q=25-30).

- -> ARIES-RS utilizes the features we normally attribute to advanced tokamak plasmas, and it assumes they are obtained simultaneously in steady-state

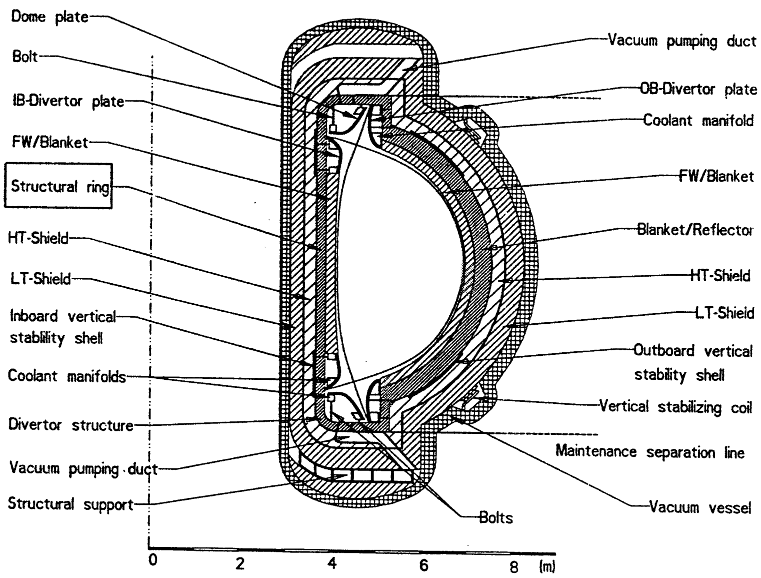


Reference reversed shear plasma configuration

I_p (MA)	11.32
B_T (T)	7.98
R (m)	5.52
a (m)	1.38
κ (95%)	1.70
δ (95%)	0.50
β_p	2.28
β (%)	4.96
β^* (%)	6.18
β_N (%)	4.83
β_N^{max} (%)	5.35
q_0 (axis)	2.80
q_{min} (minimum)	2.49
$\hat{\psi}$ (q_{min})	0.69
q_e (edge)	3.52
I_{bs} (MA)	10.0
$I_{\nabla p}/I_p$	0.91
I_{CD} (MA)	1.15
q_*	2.37
$l_i(3)$	0.42
$n_0/\langle n\rangle$	1.36
$T_0/\langle T\rangle$	1.98
$p_0/\langle p\rangle$	2.20
Kink wall	0.095

Plasma Shape

- ARIES-RS shape parameters are κ_x=1.9, κ_{95}=1.7, δ_x=0.7, δ_{95}=0.5
- the plasma shape is restricted in a power plant by vertical stability/control (κ) and the ability to provide an inboard divertor and adequate neutron shielding to the TF magnet (δ)



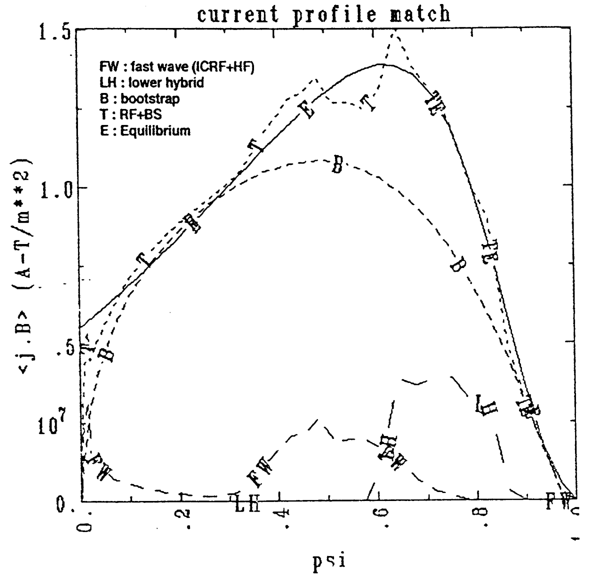
Variation of β with triangularity at $A = 4.0$

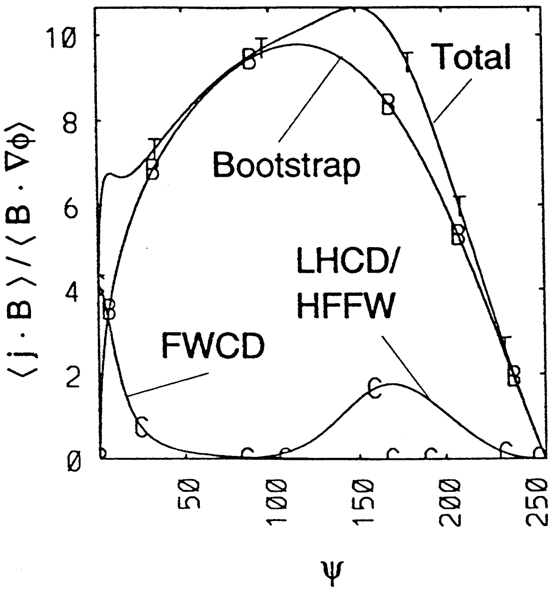
δ	β_N^{max}	β^{max}	q_*	I_p (MA)
0.20	2.15	2.00	2.85	8.95
0.30	3.20	3.13	2.69	9.47
0.40	4.30	4.60	2.48	10.3
0.50	4.85	5.45	2.35	10.8
0.60	5.15	6.25	2.18	11.7

- —> we evaluate the ideal MHD stability with the 95% shape parameters, our β would rise from 4.96% to 5.75% if we had used X-point parameters

Bootstrap Current and External CD

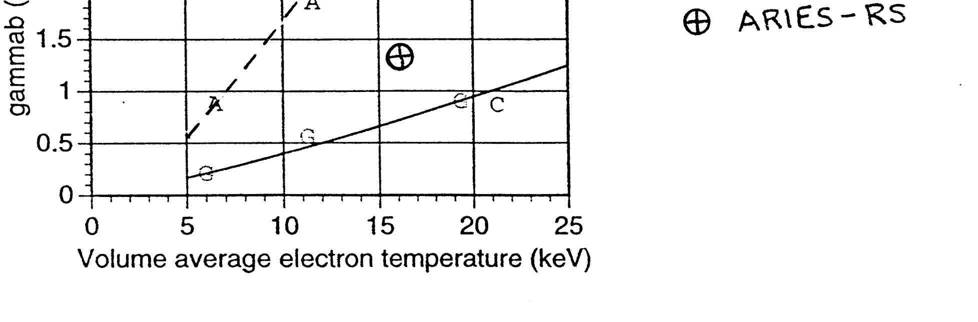
- use collisional Hirshman-Sigmar model for bootstrap calculations and predict the sum of bootstrap, Phirsch-Schluter, and diamagnetic currents to be 91% of the total current
- uses 3 CD systems; ICRF FW (5.5 MW), LH (35 MW), and HFFW (48 MW)
- 3 approaches were taken;
  - ideal MHD stable target plasmas were used in RF calculations to provide best fits
  - self-consistent RF/equilibrium calculations were done, and the resulting configuration checked for ideal MHD stability
  - self-consistent CD/bootstrap equilibria were calculated using the CD profiles from RF calculations, and checked for ideal MHD stability



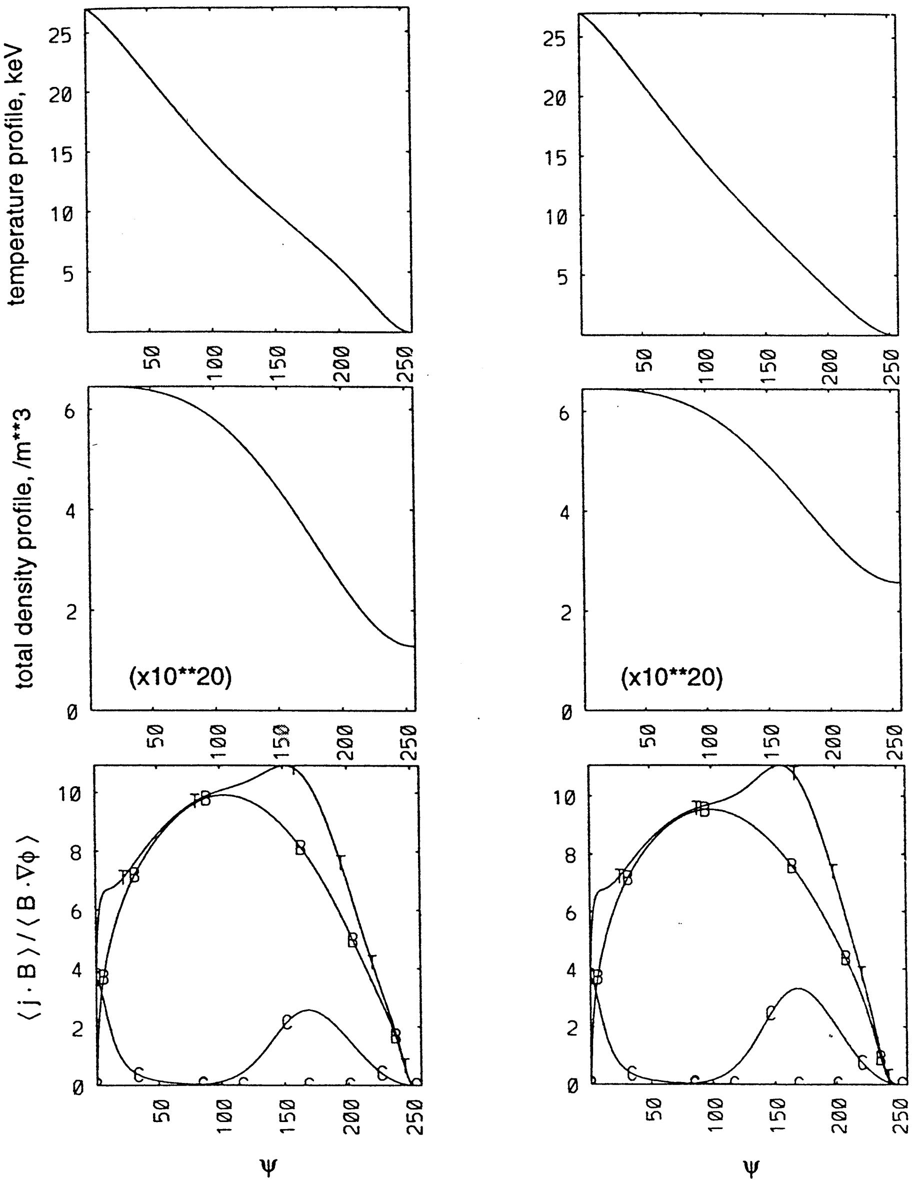


Bootstrap Current and External CD, cont'd

- we rejected 100% bootstrap current solutions because they would require precise density and temperature profiles, and chose to make the off-axis CD a critical requirement for control of r(q_{min})
- we tried to address the robustness of the configuration by scanning
  - the magnitude of temperature and density combination, and found that our bootstrap current contribution was nearly constant
  - temperature and density profiles, and found we could require as much as twice the CD we were providing, or as little as one third
  - the impact of finite edge density required for divertor operation, and found that up to 40% edge density was possible, requiring 40% more current drive, and no loss of β.



Bootstrap Current and External CD, cont'd



- –> the use of the collisionless bootstrap formulation can eliminate the need for off-axis current drive
- –> finite edge temperature consistent with H-mode may relieve off-axis CD requirements

Equilibrium and Ideal MHD Stability

- the maximum β used for ARIES-RS is 90% of the maximum β determined from ideal MHD stability
- for ideal MHD stability scans the current profile was prescribed by

$$\frac{\langle j \cdot B \rangle}{\langle B \cdot \nabla\phi \rangle} = j_o(1-\hat{\psi}) + j_1 \frac{d^2 \hat{\psi}^a (1-\hat{\psi})^b}{(\hat{\psi}-\hat{\psi}_o) + d^2} \tag{1}$$

-
  - $q_o - q_{min} > 0.3$
  - $q_o < 3.0$
  - $q_{min} > 2.0$
  - $r(q_{min})$ maximized, subject to $q_{edge} \geq 3.5$ and a wall distance of 0.3a
- the pressure profile was given by

$$p = p_o(1-\hat{\psi}^{\alpha})^2 \tag{2}$$

Variation of β with pressure profile exponent

α	β_N^{max}	β^{max}	$f_{\nabla p}$	I_{CD} (MA)
1.20[a]	5.77	5.95	0.78	2.28
1.30	5.35	5.54	0.89	1.20
1.40	5.00	5.17	0.89	1.19
1.50[b]	4.64	4.80	0.87	1.37
1.60[b]	4.36	4.50	0.87	1.36

[a] Bootstrap limited, $f_{\nabla p}$ and I_{CD} correspond to $\beta_N = 4.6$ and $\beta = 4.74$.

[b] $T(\psi)$ and $n(\psi)$ do not obey transport constraints.

- bootstrap current alignment constraint
  - $\langle j \cdot B \rangle_{bs} \leq \langle j \cdot B \rangle_{eq}$
  - $T(\psi)$ and $n(\psi)$ must satisfy rough transport constraint that dominant gradients fall inside or at $r(q_{min})$

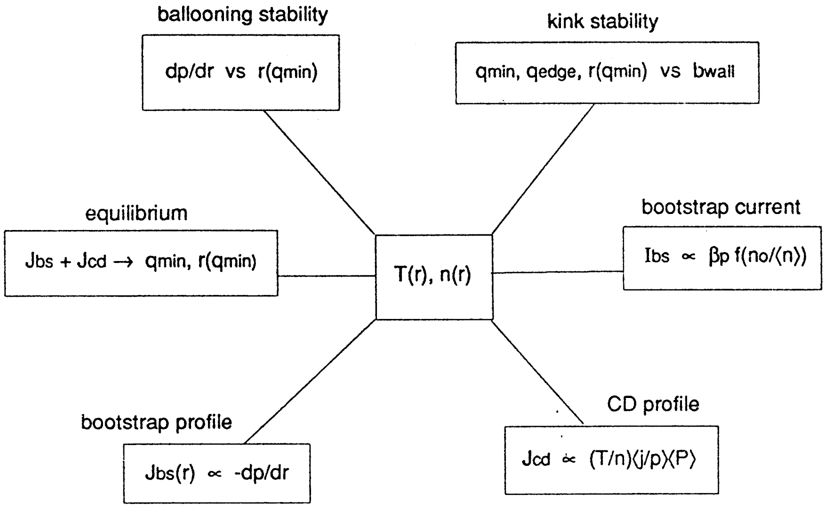
Equilibrium and Ideal MHD Stability, cont'd

- we assume that a conducting shell and plasma rotation will stabilize the low-n kink mode
  - conducting shell assumed at 0.3a for almost all analysis, and β limiting mode was always n=3
  - stability analysis indicated that a wall only on the outboard extending poloidally from -85^o to +85^o was sufficient
  - the design of the vanadium structure/liquid lithium blanket showed that a 2 cm shell would be at 0.1a, and satisfied the criteria developed by Bondeson and Ward
  - it turned out that we could not take advantage of a wall closer that 0.25a, since we could not raise the ballooning limit without making the bootstrap current shift toward the axis
  - in hindsight, letting $r(q_{min})$ shift further out and letting q_{edge} drop below 3.5, may have allowed higher β, but the CD implications are unclear
  - plasma rotation speed requirements were predicted to be 2-6 $\times\ 10^5$ m/s, while CD rotation speeds are $\approx 10^4$ m/s

- -> the stabilization of the low-n kink modes is critical to high β tokamak operation, since no second stable region exists for kink modes
- -> no analysis of neoclassical tearing modes was done

Plasma Transport

- no energy or particle transport analysis was done, only a rough constraint that the temperature and density profiles have their dominant gradients inside or at r(q_{min})
- the profiles used in ARIES-RS provide kinetic stability to toroidal drift-type modes



- –> is it possible that we can figure out how to make the reversed shear transport barrier leak, the same way we found ELM's to cause the H-mode to leak
- –> it is interesting that our predictive capability for ideal MHD stability, bootstrap current, and RFCD are at a better level than our ability to predict the plasma temperature and density that underlies all of them

Other Analysis and Issues

- radiated power from the plasma and the divertor solution
  - 20% radiated power from plasma core ($\approx$ 100 MW)
  - 80% into SOL, utilized a radiating divertor with neon impurity ($\approx$ 400 MW), where some power is also radiated in the SOL
  - Z_{eff} was 2.0
  - $n_{edge}/n_o = 0.2$
  - neon enrichment in the divertor of between 2-8 was assumed
  - mantle radiation required higher Z_{eff} and n_{edge}/n_o greater than 0.4 that adversely affected the CD, MHD stability, and power balance
- analysis was done to demonstrate that we could deposit a pellet inside the $r(q_{min})$ for fueling
- the assumed effective particle confinement time was 10 times
- the energy confinement time corresponded to an ITER-89P multiplier of 2.3
- the plasma was expected to have an H-mode edge with low amplitude/high frequency ELM's

ARIES-RS Implications for Advanced Tokamaks

- the simultaneous achievement of
  - effective stabilization of low-n external kink modes by a conducting wall/rotation or a feedback control system
  - operation near the ideal MHD β-limit
  - 100% non-inductive plasma current with large bootstrap current fraction
  - significant plasma shaping, but not extreme
  - global energy and particle confinement times that are not extreme
  - temperature and density profiles (and therefore pressure) that can support good ideal MHD stability and bootstrap current alignment
  - effective means for power and particle handling between the core plasma, the SOL, and the divertor
  - all in STEADY STATE

- –> to do all these simultanesouly requires feedback control of several subsystems that interact