CONF-941182--4

PROSPECTS AND STATUS OF LOW-ASPECT-RATIO TOKAMAKS

Y-K. M. Peng
Oak Ridge National Laboratory
P.O. Box 2009-8071
Oak Ridge, Tennessee 37831
(615)576-7476

ABSTRACT

The prospects for the low-aspect-ratio (A) tokamak to fulfill the requirements of viable fusion power plants are considered relative to the present status in data and modeling. Desirable physics and design features for an attractive Blanket Test Facility and power reactors are estimated for low-A tokamaks based on calculations improved with the latest data from small pioneering experiments. While these experiments have confirmed some of the recent predictions for low-A, they also identify the remaining issues that require verification before reliable projections can be made for these deuterium-tritium applications. The results show that the low-A regime of small size, modest field, and high current offers a path complementary to the standard and high A tokamaks in developing the full potential of fusion power.

I. INTRODUCTION

Projections for deuterium-tritium (D-T) applications of low-aspect-ratio ($A \equiv R_0/a$) or spherical tokamaks have been improved based on recent high-temperature data from a number of small pioneering experiments such as Small Tight Aspect Ratio Tokamak (START),[1] Helicity Injected Tokamak (HIT),[2] Current Drive Experiment-Upgrade (CDX-U),[3] and Tokyo Spheromak-3 (TS-3) converted to tokamak.[3,4] These projections indicate that plasmas for A = 1.2 to 1.3 with $(R_0+a) \leq 1.4$ m and I_p = 6 to 10 MA can be driven to steady state[5,6,7] and produce high fusion neutron wall loads W_L around 1 MW/m^2. Such plasmas would permit small nearer-term Blanket Test Facilities (BTF)[6] for testing full-function blanket modules for fusion. For $A \approx 1.2$, plasma properties were calculated[5,8] for future power plants that have the potential capability of complementing the best reactors based on the standard or high A (= 2.5 to 4.5) tokamaks in providing economic power.

In the present paper, the requirements for attractive BTF and reactors, and the desirable plasma and design features projected for low-A are identified in Section II. The status of the low-A experimental data relative to these projections and the research issues are presented in Section III. The paper closes with a discussion in Section IV of low-A development steps that can contribute to realizing the full potential of tokamak fusion power.

II. ECONOMIC FUSION POWER REQUIREMENTS AND LOW-A TOKAMAK FEATURES

A key motivation for lowering A has been to obtain high beta (hence low external field) and good confinement (hence small plasma size). These together would reduce reactor power source size and capital investment.[8] The potential benefit of reducing A was already seen in the limited physics indications a decade ago.[9] However, low-A was not pursued at that time because of uncertainties in the method of plasma production.

Since then standard and high A tokamak research has made great progress in data, interpretation, modeling, and the awareness of requirements for producing economic power. These stringent requirements are listed below in qualitative terms together with the calculated, desirable, low-A tokamak physics and engineering features:

- *Low power source equipment cost* – small plasma size with high beta and good confinement: The magnitude of the plasma shaping factor S ($\equiv I_p q_\psi / aB_{t0}$) has been measured in DIII-D[10] and shown to be a good indicator for the best $\beta\tau_E$ values obtained. Free-boundary magnetohydrodynamic (MHD) equilibria with "natural" elongations without using shaping poloidal field coils (PFCs) are calculated as A is reduced from 2.5 to 1.2. The results are summarized in Table I and Figure 1.

TABLE I. ASPECT RATIO AND q DEPENDENCES OF NATURALLY ELONGATED PLASMAS

Aspect ratio A	**2.5**	**1.4**	**1.2**	**1.2**
Edge safety factor q_ψ	2.7	6.8	17.1	21.8
Axis safety factor q_0	1.0	1.0	1.0	4.7
"Natural" elongation κ	1.0	1.5	2.0	2.3
β_I $(\equiv 2\mu_0\langle p\rangle/B_p^2)^a$	0.8	0.6	0.6	1.1
β_{Nt} $(\equiv\langle\beta_t\rangle aB_{t0}/I_p)$	0.04	0.04	0.04	0.12
$\langle\beta_t\rangle$ $(\equiv 2\mu_0\langle p\rangle/B_{t0}^2)$	0.04	0.12	0.21	0.92
S $(\mathrm{MA{\cdot}m^{-1}{\cdot}T^{-1}})$	2.7	20	89	174
Field utilization I_p/I_{tfc}	0.08	0.42	0.87	1.3
Diverted SOL $\Delta_{div}/\Delta_{SOL}{}^b$	0	−0.6	−0.9	−0.9

[a] B_p = edge circumference-average of poloidal field.
[b] assuming $\Delta_{SOL} \sim 0.1a$ for low-A cases.

It is seen that S increases strongly as A is reduced, especially from low (1.4) to very low (1.2) values as κ also increases to about 2. Reducing the plasma internal inductance (as q_0/q_ψ is increased) at very low-A further doubles S and increases κ to 2.3. The average toroidal beta $\langle\beta_t\rangle$ for A = 1.2 can reach high values[7] for the first regime (q_0 = 1.0) and very high values[8] for the second regime (q_0 = 4.7) of stability for ballooning modes.

Assuming the first-regime values, a device with $R_0 \approx 0.8$ m and $B_{t0} \approx 2$ T would permit $I_p \approx 9$ MA and $\langle\beta_t\rangle B_{t0}^2 \sim 100\%\mathrm{T}^2$. This gives a plasma pressure about twice that in the Joint European Torus (JET) for B_{t0} = 3 T and $\langle\beta_t\rangle$ = 5%. Such a plasma would permit an attractive BTF candidate[5,6] that produces the JET-level D-T physics performance of Q ~ 1, while producing fusion powers ~ 20 to 30 MW and $W_L \sim 1\ \mathrm{MW/m^2}$. Estimates of the reactor parameters[8] using a systems code (an ST version of SuperCode[11]) assuming the second-regime indicate $(R_0+a) \approx 5.4$ m and $W_L \approx 6\ \mathrm{MW/m^2}$ for producing 1000 MW in net electricity. The power source equipment cost is estimated to be about one-half of that based on high A advanced tokamak physics. Example parameters for the low-A BTF and reactor are provided in Table II.

- *Reliable operation* – freedom from plasma vertical instability and current-terminating disruptions: The vertical displacement event (VDE) and the subsequent disruption[12] of the plasma current must be eliminated or controlled before a reliable plasma core can be obtained for future tokamak reactors.[13] Early calculations[9] and Figure 1 show that low-A plasmas can be strongly elongated using vertical fields with slightly negative field decay indices. Such low-A plasmas are therefore expected to be vertically stable without requiring feedback control.

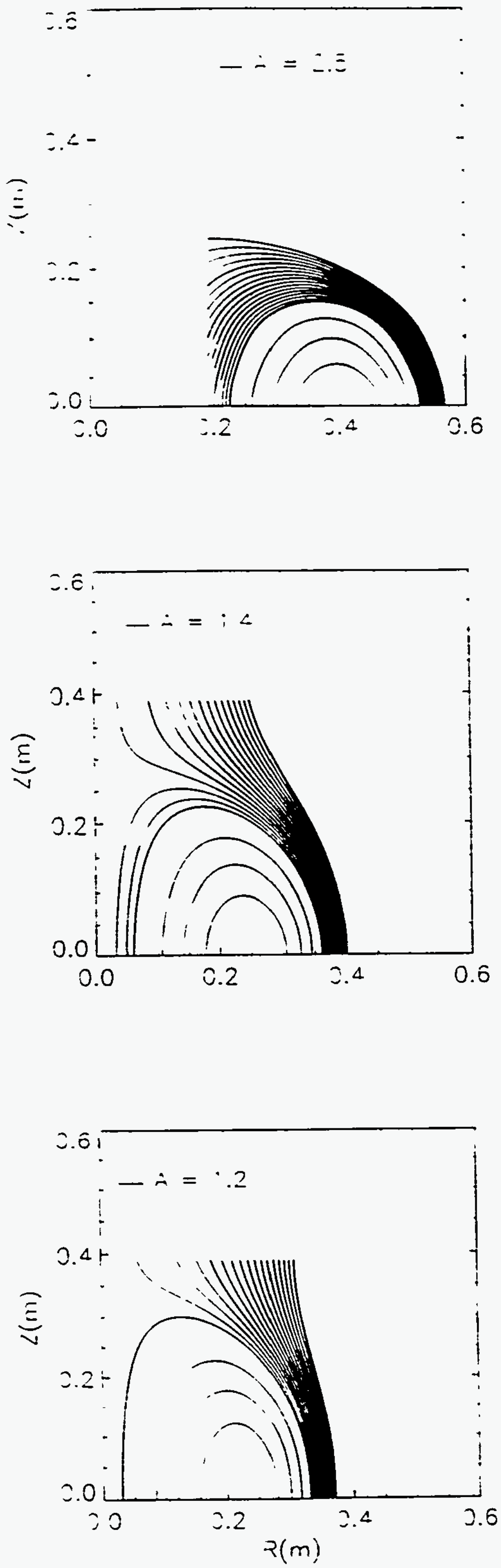

Figure 1. Free-boundary equilibria for A = 2.5, 1.4, and 1.2 using only two pairs of outboard PFCs.

TABLE II. REPRESENTATIVE PARAMETERS FOR LOW-A BTF AND REACTORS

Device Parameters	**BTF**	**Reactor**
Plasma size (R_0+a) (m)	1.4	5.4
Aspect ratio A	1.25	1.2
Toroidal field at R_0 (T)	2.0	2.4
Plasma current I_p (MA)	9.4	43.0
H-factor (ITER-power)	2.5	2.4
Normalized toroidal beta β_{Nt}	3.5	5.8
Average toroidal beta $\langle\beta_t\rangle$	0.24	0.44
Fusion power (MW)	32	2770
Drive power (MW)	19	54
Fusion neutron wall load (MW/m^2)	1.0	6.0

- *Low recirculating power* – large plasma pressure-driven current fraction, low noninductive seed current drive, and low resistive power in normal conducting magnets: Since $I_p/I_{tfc} = S/5q_\psi A$, we find $I_p/I_{tfc} = 3/2$ for the fourth case shown in Table I. The low-A power reactor of Table II would have $I_{tfc} \approx 29$ MA. The resistive power required to drive a steady state toroidal field coil (TFC) with a tapered single-turn copper center leg[13] is estimated to be about 150 MW.[8] Such plasmas were also calculated[8,14] to have the potential for a pressure-driven current fraction up to 90% at the maximum stable beta. Using current drive by MV-level neutral beams, the required power is estimated to be about 50 to 100 MW deposited. The total recirculating power for this power plant is then estimated to about 400 MW. This may seem high. However, since the power core equipment cost is relatively low, the cost of electricity (COE) still becomes about 20%[8] lower than the best reactor COE based on the high A advanced physics tokamak.

- *Sustained power and particle handling, impurity control* – diverted and thick plasma scrape-off layer (SOL) and techniques to disperse exhaust heat over large surface areas: As seen in Figure 1, an increasing fraction of the SOL becomes diverted naturally without using divertor coils as A is reduced toward unity. An MHD instability model[6] has been suggested recently to provide a possible mechanism to maintain a thick SOL in low-A tokamaks. This model suggests that the low-A reactor plasma would have a thick SOL (≈30 cm), about six times that projected for the best high A tokamak reactor. Such a thick SOL would become over 90% diverted for A = 1.2, which would ease the power loading on the inboard limiters that protect the inner leg of the TFC. A divertor channel of about 2 m in length, similar to that assumed in ITER,[15] would be provided for future low-A tokamak reactors.

- *Adequate maintainability* – remotely replaceable reactor power source components permitting scheduled maintenance shutdown in about 3 months biannually: Because of the large S values, relatively small fields are expected for future low-A devices (see Table II). A single-turn center leg for the TFC can become feasible for future D-T-fueled devices.[13] Remote maintenance and replacement of all reactor core components in this case becomes more practical than standard tokamaks with superconducting TFCs. Reactor components that will require regular replacement include the TFC center leg, divertors, first wall, and blankets. The natural divertors permit a simplified PFC configuration, further improving maintainability.

- *Potential to permit environmentally clean power* – using only low activation materials: Assuming the availability of proper low activation materials for all the torus components, the copper center leg becomes the only remaining source of significant activation in D-T-fueled devices. A copper center leg would be acceptable for devices otherwise using standard materials.

- *Low power required for startup* – easy noninductive current initiation and ramp-up and modest heating to achieve fusion burn: The inboard solenoid must be eliminated to permit very low-A plasmas, rendering noninductive initiation and ramp-up a unique key issue. The auxiliary heating power would be considered modest if it is comparable to the power required for current drive.

These reactor requirements and desirable low-A features are summarized in Table III. Technical advances, such as very high efficiencies for conversion of thermal energy to electricity, low-cost high-field or high-temperature superconducting magnets, and low-cost strong materials are not included because they apply equally to all tokamaks.

III. PRESENT EXPERIMENT AND MODELING STATUS

Low-A tokamak research began about 7 to 8 years ago. The devices since then are summarized in Table IV. Results for high plasma temperatures were first obtained in START,[1] followed possibly by HIT[2] and CDX-U.[3] Data so far have been limited to ohmic plasmas with I_p up to 250 kA (for 5 to 10 ms), R_0 up to 30 cm, and plasma flat-top durations up to 20 ms (for I_p up to 150 kA). The toroidal field B_{t0} applied at the major radius have been up to about 0.5 T. The best data[1] have been characterized by $T_{e0} \le 1$ keV, $n_{e0} \le 2.5\times10^{14}$ cm^{-3}, and $T_{i0} \le 0.2$ keV.

TABLE III. REQUIREMENTS, DESIRABLE FEATURES, STATUS, AND PROJECTIONS FOR LOW-A TOKAMAKS

Requirements for Viable Reactors	Desirable Physics and Design Features	Present Low-A Data	Reactor Projections
Low power source equipment cost	• High $S \equiv I_p q_\psi / aB_{t0}$ (MA·m^{-1}·T^{-1})	20	200
	• High $\langle\beta_t\rangle \equiv 2\mu_0\langle p\rangle/B_{t0}^2$ (%)	2	100
Reliable operation	• Vertical stability for high *b/a*	≤4	≤3
	• Disruption-free operation	Ohmic plasma	High *S*, $\langle\beta_t\rangle$
Low recirculating power	• High self-driven current fraction I_{self}/I_p	0.2	0.95
	• High current drive γ_{CD} (10^{19} m^{-2}A/W)	–*	0.3
	• High toroidal field utilization I_p/I_{tfc}	3	≤3
Sustained power and particle handling, impurity control	• Thick Δ_{SOL} (cm)	3	30
	• Long divertor channel (m)	0.5	2.0
Adequate maintainability	• Demountable jointed TFC	Yes	Single-turn
	• Simple PFC (natural divertor)	Yes	Yes
Potential to permit environmentally clean power	• Can use "advanced" materials, except the copper center leg	Copper TFC	Copper or other material
Low cost for power startup	• Permit easy noninductive current initiation and ramp-up	HI to 250 kA	To several MA
	• Require only modest auxiliary heating	–*	$P_{heating} \le P_{CD}$

* Not yet tested for low-A.

TABLE IV. REPRESENTATIVE PARAMETERS OF RECENT AND PRESENT LOW-A TOKAMAK EXPERIMENTS

Device Name	R_0 (cm)	a (cm)	$A = R_0/a$	I_p (kA)	t_{pulse} (s)	B_{t0} (kG)	T_{e0} (eV)
HSE + rod[16] (FRG, 1987)	7	6	1.1	100	0.06	1.1	20
ROTOMAK + TF[17] (Australia, 1987)	7	6	1.1	3	20	0.2	12
FBX II[18] (Japan, 1990)	47	33	1.4	100	2	5	300
SPHEX Tokamak[19] (UK, 1991)	23	22	1.05	200	0.7	4.5	30
START[1] (UK, 1991)	30	25	1.3	250	40	5	500
TS-3, low-A[3,20] (Japan, 1991)	20	14	1.5	50	2	3	40
TS-3, ultra-low-A[3,20] (Japan, 1993)	20	18	1.05	50	0.1	1.5	20
HIT[2] (USA, 1994)	30	20	1.5	250	10	4.6	100
CDX-U[3] (USA, 1994)	32	20	1.6	50	6	1.0	100

These results in general are very modest relative to the projections desired for future D-T applications. However, several reactor requirements have nevertheless already been confirmed. These are included in Table III and discussed below.

- *Low power source equipment cost* – The magnitude of the plasma shaping factor S reached about 20 MA·m^{-1}·T^{-1} in START for A ≈ 1.4, about twice the best S values obtained so far in DIII-D.[10] Vertically stable, very high κ (= 3 to 4) plasmas with hollow current profiles have been seen for short durations immediately following inductive startup in START.[1] Equilibrium modeling of these plasmas have provided confidence that the high S and κ values of Table I are feasible for very low A tokamaks.

Reliable operation – The START plasmas have been found to be vertically stable for natural elongations up to 4.[1] In addition, the ohmic plasma in START has not suffered any current-terminating disruptions for A ≤ 1.8 for about 20,000 shots, though internal MHD activities and reconnection events have been observed regularly.[21] While this is encouraging, the mechanisms for such resilience are not understood at present. Whether this can be maintained for high S high $\langle\beta_t\rangle$ low-A plasmas remains to be tested in collisionless high-temperature plasmas.

- *Low recirculating power* – The fraction of pressure-driven currents in START has been estimated to be up to 0.2 so far. Initial theoretical indications are that the neoclassical model will require adjustment for very low-A, and enhancement for the bootstrap current[22] and reductions in neoclassical ion diffusion coefficient[22] have been suggested. Tests in collisionless plasmas will therefore be required. There are currently no data for current drive in high temperature low-A plasmas. The ability for the plasma to permit high values of I_p/I_{tfc} (up to 4) without tilt or shift instabilities has been verified recently in TS-3 in relatively collisional plasmas.[3,20] Tests in collisionless plasmas will be required before adequate confidence in these issues can be established.

- *Sustained power and particle handling, impurity control* – A thick outboard plasma SOL, about 3 to 5 times the predictions of conventional theory, with relatively high electron temperatures (~50 eV) and large fluctuations has been measured[24] in START. This is so far consistent with the condition of marginal MHD stability for the SOL.[8] Further, the SOL in START is largely (~65%) diverted without using divertor coils. The latter result is consistent with MHD equilibrium calculations.[8] A natural divertor channel of about 0.5 m in length is already available in START. More detailed measurements for high-temperature SOL plasmas in low-A tokamaks will be needed before projections to future large devices can be made with confidence.

- *Adequate maintainability* – All small low-A tokamak experiments so far (see Table IV) have normal conducting TFCs with demountable joints. Experience in START operation and modifications have indicated that such an arrangement is flexible and provides superior accessibility to the plasma chamber. Concepts recently suggested[12,13] for future low-A tokamak reactors have assumed TFCs with a single-turn center leg with minimal or no shielding. Design, construction, and operation of a small BTF would provide valuable experience in remote maintenance of D-T-fueled low-A tokamaks.

- *Potential to permit environmentally clean power* – The activation and damage of unshielded copper in the fusion environment needs to be studied before its advantages and limitations for low-A D-T-fueled tokamaks can be understood. Alternative conductors (to copper) should also be examined.

- *Low power required for startup* – HIT has recently proven the feasibility of initiating low-A plasma currents efficiently for up to 250 kA using axisymmetric coaxial electrodes.[2] This method for plasma startup deserves much study to permit implementation in larger collisionless plasmas with confidence. Other possible options include injections of electron cyclotron (EC) and lower hybrid (LH) waves, which have had some successes in standard tokamaks (up to 100 kA for initiation and up to 2 MA for ramp-up) at low densities. The technique of induction-compression utilized successfully in START[1] can be used if space outboard to the plasma can be made available in future D-T devices.

IV. DISCUSSION

As can be seen in Table III, recent experimental results have confirmed high natural plasma elongation; vertical stability; natural divertor using relatively simple PFCs; and high toroidal field utilization (I_p/I_{tfc}). Jointed demountable TFC has been commonly used. However, there remain many features where substantial progress is needed for economically competitive power plants, and to a lesser degree, for the BTF. These include high shape factor S; order-unity stability beta limits and pressure-driven current fraction; disruption-free operation for high S and high beta; efficient current drive; thick SOL with long divertor channels for high S and high beta; noninductive initiation and ramp-up of high plasma currents; and modest auxiliary heating power for fusion burn. Alternatives to the center leg copper with improved radiation damage and activation properties may require detailed study.

These features need to be tested in collisionless plasmas with I_p at the mega-ampere level, requiring about twice the linear size of the present experiments.[25] Figure 2 plots the plasma currents and the aspect ratios for such experimental tests relative to examples of the present low-A experiments, the standard and high A experiments, and the projected non- D-T and D-T devices.

In the space of the overall plasma size $2(R_0+a)$ and the average fusion neutron wall load we plot in Figure 3 the low-A mega-ampere tests, BTF, and power plant, together with the standard A and advanced physics high A tokamaks (TFTR, JET, ITER, TPX and power plant). It is seen that the low-A tokamak introduces the possibility of using relatively small size plasmas in developing economically competitive fusion power. The utilization of such plasmas, if verified for the collisionless regime, will enhance the full potential of tokamak fusion power.

ACKNOWLEDGMENT

The author is indebted to D. Strickler and J. Galambos who provided some of the calculations presented in this paper. He has benefited much from discussion with A. Sykes, D. Robinson, W. Morris, J Hugill, M. Walsh, R. Goldston, S. Kaye, M. Ono, M Yamada, R. Stambaugh, A. Wootton, R. Blanken, and S. Berk. This work is

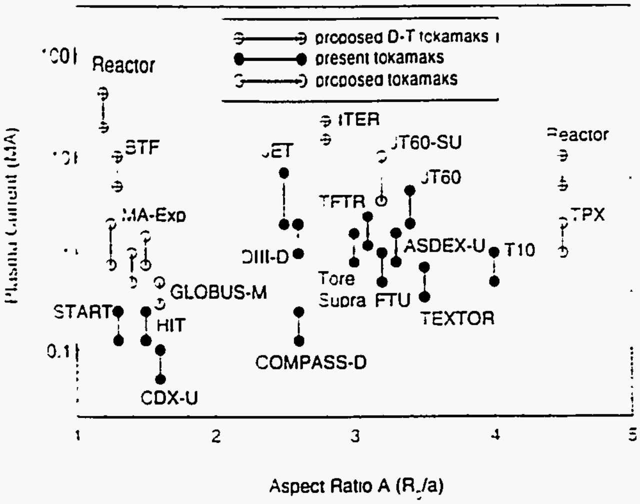

Figure 2. Plasma currents and aspect ratios for present, proposed non-D-T and D-T tokamaks.

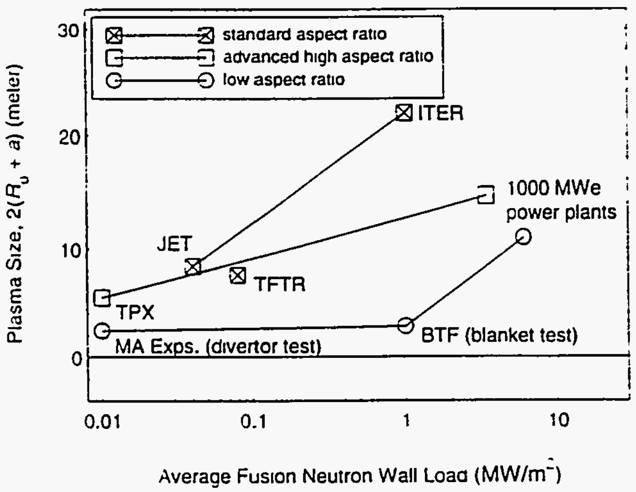

Figure 3. Overall plasma size $2(R_0+a)$ and average neutron wall load for standard aspect ratio, advanced high aspect ratio, and low aspect ratio tokamaks.

sponsored by the U.S. Department of Energy under contract DE-AC05-84OR21400.

REFERENCES

1. Sykes et al. *Nuclear Fusion*, **32**, 694 (1992); A. Sykes *et al.*, *Plasma Phys. and Controlled Fusion*, **35**, 1051 (1993).
2. B. A. Nelson et al., *Phys. Rev. Lett.*, **72**, 3666 (1994); T. R. Jarboe *et al.*, IAEA-CN-60/A-5-II-6-1(R), to appear in *Plasma Phys. Controlled Nuclear Fusion Research 1994*, IAEA, Vienna, 1995.
3. M. Ono et al., *Plasma Physics and Controlled Nuclear Fusion Research 1992*, Vol. 1, p. 693 (IAEA, Vienna, 1993); Y. S. Hwang *et al.* and A. Morita *et al.*, IAEA-CN-60/A-5-II-6-2(R), to appear in *Plasma Phys. Controlled Nuclear Fusion Research 1994*, IAEA, Vienna, 1995.
4. Y. Ono et al., *Phys. Fluids B*, **5**, 3691 (1993).
5. R. Buttery *et al.*, IAEA-CN-60/F-I-3-1(R), to appear in *Plasma Phys. Controlled Nuclear Fusion Research 1994*, IAEA, Vienna, 1995.
6. M. A. Abdou *et al.*, IAEA-CN-60/F-2-II-6-1(R), to appear in *Plasma Phys. Controlled Nuclear Fusion Research 1994*, IAEA, Vienna, 1995.
7. D. C. Robinson, paper I6-02, this conference.
8. Y-K. M. Peng *et al.*, IAEA-CN-60/F-I-3-2(R), to appear in *Plasma Phys. Controlled Nuclear Fusion Research 1994*, IAEA, Vienna, 1995.
9. Y-K. M. Peng, D. J. Strickler, *Nuclear Fusion*, **26**, 576 (1986).
10. E. A. Lazarus et al., IAEA-CN-60/A-I-5-1, to appear in *Plasma Phys. Controlled Nuclear Fusion Research 1994*, IAEA, Vienna, 1995.
11. S. W. Haney et al., *Fusion Technology*, **21**, 1749 (1992).
12. M. A. Pick et al., *Fusion Engineering* (Proc. 14th Symp. San diego, CA, 1991) Vol. 1, 187 (IEEE, New York, 1992).
13. Y-K. M. Peng and J. B. Hicks, *Fusion Technology 1990*, **2**, 1287 (1991).
14. T. C. Hender et al., *Plasma Phys. Controlled Nuclear Fusion Research 1992*, Vol. 3, p. 399, IAEA, Vienna, 1993.
15. P-H. Rebut, "Issue in the Development of Fusion Reactors," paper S-1, this conference.
16. H. Bruhns et al., *Nuclear Fusion*, **27**, 769 (1987).
17. G. A. Collins et al., *Nuclear Fusion*, **28**, 255 (1988).
18. M. Irie et al., *Proc. 17th EPS Conf. Controlled Fusion and Plasma Physics*, Amsterdam, 1990, Part II, p. 245, European Physical Society (1990).
19. K. Browning et al., *Phys. Rev. Lett.*, **68**, 1722 (1992).
20. A. Morita, Ph.D. Thesis, to be published.
21. M. Gryaznevich, et al., *Proc. 20th EPS Conf. Controlled Fusion and Plasma Physics*, Lisbon, Vol. 1, p. 58 (1993).
22. K. C. Shaing, et al., submitted to *Phys. Fluids B*.
23. D. C. Robinson, et al., *Int. Center of Plasma Phys.*, India, Vol. 1, p. 25 (1989).
24. K. Erents et al., paper presented at 21st EPS Conf. Controlled Fusion and Plasma Phys., Montpellier, 1994.
25. Y-K. M. Peng, et al., "Summary of Workshop on Establishing the Physics Basis for Compact Toroidal Reactors, Oak Ridge, July 19–21, 1994, to be published.

DISCLAIMER