A Compact Advanced Burning Plasma Experiment

Dale M. Meade and Robert D. Woolley

Princeton Plasma Physics Laboratory
Princeton, NJ, 08543, USA

1. INTRODUCTION

The achievement of high fusion power gain,Q, in a laboratory plasma is a crucial step in the development of magnetic fusion. A high Q plasma is needed as a test facility to determine the conditions required for ignition, and would enable the study and optimization of a burning plasma. The achievement of an ignited ($Q \geq 10$) plasma will allow these scientific objectives to be achieved while providing a litmus test for the reality of magnetic fusion.

2. PHYSICS OBJECTIVES AND REQUIREMENTS FOR AN ADVANCED BURNING PLASMA PHYSICS EXPERIMENT

The primary physics objectives are:
(1) Determination of the conditions required to achieve high Q energy producing plasmas,
(2) Control of high Q plasmas through modification of plasma profiles and external sources,
(3) Determination of the effects of fast alpha particles on plasma stability,
(4) Sustainment of high Q plasma - high power density exhaust of plasma particles and energy and alpha ash exhaust, some evaluation of alpha heating on bootstrap current profiles, and
(5) Exploration of high Q burning plasma physics in some advanced configurations and operating modes that have the potential for attractive fusion applications.

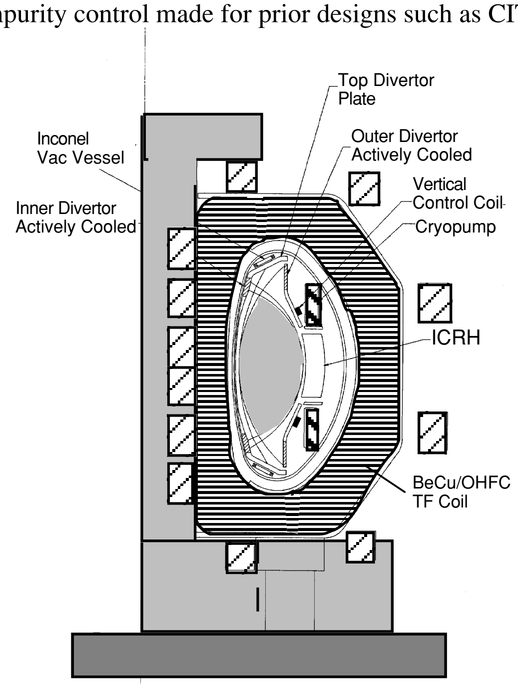
The physics of a burning plasma can be explored if the parameters listed below are attained.

$Q \geq 10$, $P_a/P_{Heat} > 66\%$,	- alpha heating dominant but actively controlled
Burn time $\geq 10\ t_{as}$	- alpha heating, fast alpha effects (e.g., TAE)
$\geq 10\ t_E$	- pressure profile evolution due to alpha heating
$\geq 3\ t_{He}$	- helium ash accumulation
$\geq 3\ t_{cr}(t_{current\ redistribution})$	- evolution of bootstrap current

The initial D-T experiments on TFTR and JET confirmed the single particle confinement requirements for alpha particles and were able to detect weak alpha heating in agreement with expectations [1, 2]. At $Q > 10$, alpha heating will dominate the plasma heating and the effect on energy confinement and pressure profile can be determined. The alpha slowing down time is in the range of 0.1 to 0.5 s for the Burning Plasma experiment to be discussed and is sufficiently short so that the alpha distribution is in equilibrium. The energy confinement time range of 0.6 s is short compared to burn times anticipated. The alpha ash confinement time is expected to range from 4 to 10 t_E or from 3 to 6 s. The normal conductor device under consideration is projected to have burn times of several helium ash transport times. The current redistribution time, t_{cr}, due to alpha heating modifications of the bootstrap current profile is a key issue for advanced burning plasma experiments and is more difficult to satisfy. For baseline physics assumptions and full magnetic fields the typical pulse length corresponds to ~ 1 t_{cr}. Fortunately, as advanced tokamak performance is attained the plasma current and magnetic field can be reduced allowing a very substantial increase in pulse length for normal conductor devices so that pulse lengths of several t_{cr} can be attained.

3. BPX-AT: AN ADVANCED BURNING PLASMA EXPERIMENT

The compact tokamaks (e.g., Ignitor, BPX-AT and CIT) first advocated by Coppi [3] with higher magnetic field and higher plasma densities have advantages with respect to plasma confinement, beta limits, operating density limits, impurities and fast alpha particle limits and are well suited for studying burning plasma physics for the required time scales. Recent results from tokamak confinement experiments, in particular Alcator C-Mod, confirm the high field compact ignition tokamak design assumptions with regard to confinement, ICRF heating, power handling and impurity control made for prior designs such as CIT.



	BPX-AT	ARIES-RS
R(m)	2	5.5
A	4	4
k	2	1.7
d	0.3›	0.5
B(T)	10	8.0
Ip(MA)	6.25	11.3
Flat top(s)	10	steady
P_{fusion}(MW)	150	2,170

Fig. 1. Cross-sectional View of BPX-AT, an Advanced Burning Plasma Experiment

BPX-AT is a compact Ignitor-like tokamak with physical parameters as shown in Fig. 1. The double null divertor with strong shaping would allow the BPX-AT to explore the same physics operating regimes as envisioned for ARIES-RS, the advanced tokamak reactor. The actively cooled divertor design shown here was initially developed in 1992 when the state of divertor knowledge required that essentially all of the escaping plasma energy be taken on the divertor plate which necessitated a swept separatrix. Recent divertor and radiating mantle experiments have shown that a substantial fraction of the escaping plasma power can be radiated before reaching the divertor plate. These effects have been observed in Alcator C-Mod and are expected to be present in a high density plasma such as BPX-AT. Therefore, the separatrix sweeping capability is no longer needed and the plasma shape can be optimized for MHD stability by increasing the triangularity.

A normal conductor burning plasma device has the advantage of providing high magnetic fields and plasma currents at a reduced size and cost relative to a superconducting system since a neutron shield is not required to protect the toroidal and poloidal coils thereby allowing the major radius to be reduced. A significant cost savings is also realized by using copper alloys and inertially cooled cryogenic technologies. The copper coil systems also allow for stronger and more flexible plasma shaping which is desirable for advanced burning plasma experiments. The design for BPX-AT has BeCu in the inner leg and OHFC for the outer leg of the toroidal field coils. The vacuum vessel material was Inconel 625 and ferritic martensitic steels will be considered in a design update. The BPX-AT cost estimate of $642M (FY92$) is the result of a Conceptual Study during the 1991 New Initiatives Task Force activity and was a detailed cost estimate based on scaling down from the larger size BPX cost estimates.

4. ESTIMATED FUSION PERFORMANCE OF A COMPACT BURNING PLASMA EXPERIMENT

The fusion plasma performance of BPX-AT was estimated using a zero-D model assuming ITER-93H (Elm-free) confinement scaling with alpha heating and fuel depletion due to alpha ash accumulation calculated self-consistently. The plasma profiles were taken to be a flat density profile ($a_n = 0.1$) and modestly peaked temperature profile ($a_T = 1$). The impurity levels were taken to be 3% Be and the alpha ash was assumed to have a confinement time $t_{He} = 5\ t_E$ resulting in Z_{eff} ª 1.5. These assumptions are the same as the modeling assumptions made for the Reduced Cost ITER with the exception that ITER-RC assumes $t_{He} = 10\ t_E$ for the baseline performance mode and $t_{He} = 5\ t_E$ for advanced performance mode. For BPX-AT at Q = 10 increasing t_{He} from 5 to 10 t_E increases the required 93H Elm-free H factor by 10%. Some of these calculations are summarized in Fig. 2 below.

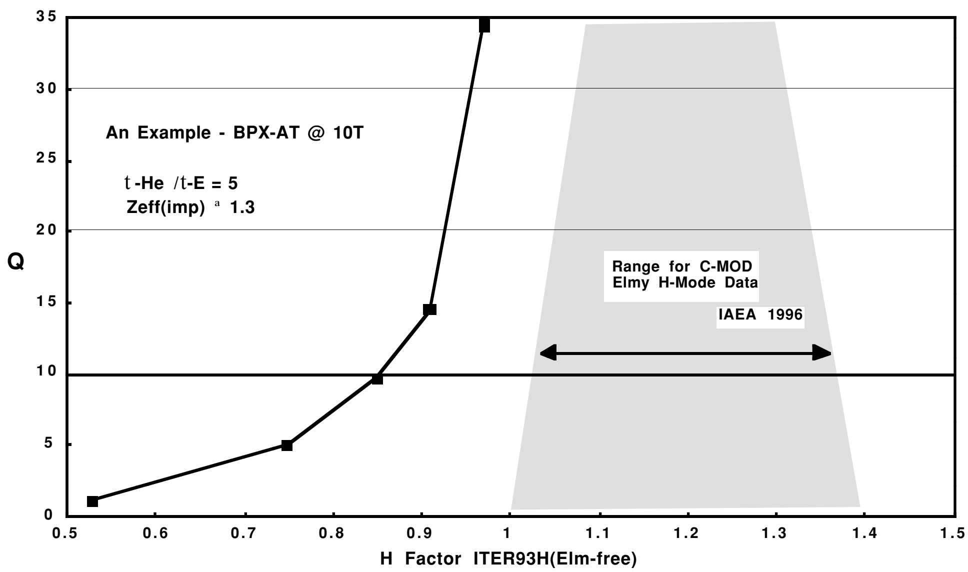


Fig. 2. Fusion power gain for BPX-AT, a compact burning plasma experiment.

The existing confinement data base from all tokamaks is centered about an ITER93(Elm-free) H factor of ª 0.85 while the confinement data from Alcator C-Mod, a prototype for the compact ignition tokamaks, has ITER93(Elm-free) H factors of ª 1.2 [4]. The ITER-EDA is projected to ignite for ITER93(Elm-free) H factors of ª 0.85. A somewhat lower field and plasma current such as BPX-AT is projected to achieve $Q \geq 10$ ITER93(Elm-free) H factors of ª 0.85 and would ignite at ITER93(Elm-free) H factors less than those achieved in Alcator C-Mod.

BPX-AT, has copper alloy coils that are precooled by LN to 77 ∞K. The pulse length is determined by the adiabatic temperature rise of the conductor/structure thermal mass during the pulse. A small reduction in the peak coil current allows the pulse length to be increased dramatically. For example, reduction of the magnetic field in BPX-AT from 10 T to 7 T allows the magnetic field flat top to be extended from 12 s to 56 s. This feature of Ignitor-like compact tokamaks can be used to advantage for studying advanced tokamak regimes where improved confinement and b allow the plasma current and magnetic field to be reduced as shown in the example below for BPX-AT (Fig. 3). In order to exploit this capability the initial design would need to incorporate or allow upgrades for active cooling of internal divertor components (as in BPX-AT) and techniques to pump helium ash during the pulse.

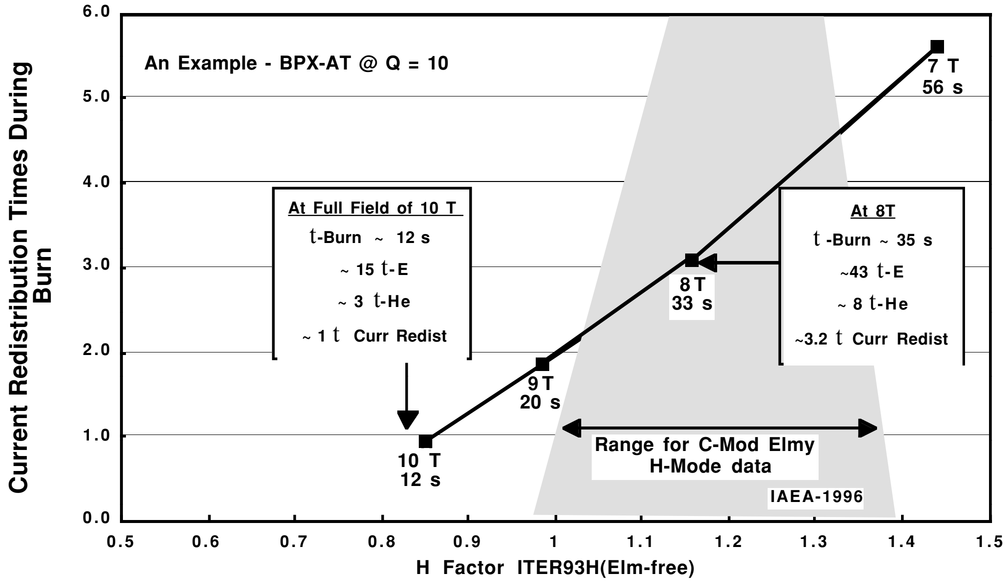


Fig. 3 Capability of an inertially cooled Ignitor-like tokamak to produce pulses with long burn (magnetic field flat top) times that would allow several plasma current redistribution times for studying advanced modes.

An important point is that the Ignitor-like compact tokamaks can explore a broad range of experimental operating space by density variations and by reduction in the magnetic field/plasma current since they have large margins with regard to density, MHD beta and TAE limits. It can be shown that Ignitor-like compact tokamaks can scan the same general range of alpha-driven toroidal Alfvén eigen (TAE) mode instability parameter space as the ITER-EDA device.

5. SUMMARY

The compact high field Ignitor-like tokamak utilizing cryogenic copper alloy conductors is a potential pathway to access Q ≥ 10 conditions and address burning plasma physics with a facility costing £$1B. In addition, evaluation of burning plasma physics in an advanced configuration for up to several skin times is possible.

6. REFERENCES

[1] Taylor, G., et al, Physical Review Letters, 76, 2722-2725, (1996)
[2] Gibson, A. J., et al, Physics of Plasmas, 5, 1839- 1849, (1998)
[3] Coppi, B., Comments on Plasma Physics and Controlled Fusion, 3, 47-62, (1977)
[4] Hutchinson, I. H., et al, Proceedings of the 16th International Atomic Energy Agency Fusion Energy Conference (Montreal), 1, 155-165, (1996)

This work supported by U. S. Department of Energy Contract No. DE-AC02-76CH03073.