BPX-AT

- EXECUTIVE SUMMARY -

D. Meade, W. Reiersen et.al.

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A. BPX-AT Executive Summary

Introduction

BPX-AT is an advanced tokamak optimized to study the critical physics issue for ITER and DEMO - burning plasma physics, especially alpha heating, in advanced tokamak regimes. BPX-AT is the only device proposed in the New Tokamak Initiative that has the capability of resolving advanced tokamak physics issues at reactor relevant plasma conditions that can be extrapolated directly to DEMO. Furthermore, BPX-AT has the capability of exploiting the progress expected during the next decade of fusion research by installing sufficient engineering capability to study thermal stability, disruption control and ash accumulation in ignited ($Q > 25$) plasmas with an advanced tokamak configuration for ~ 50 energy confinement times. BPX-AT is capable of addressing long pulse issues in lower performance ($I_p = 1.9$ MA) advanced tokamak regimes with full current drive and profile control for pulses lengths of > 400 seconds. BPX-AT makes optimum use of existing facilities at the TFTR site and has a cost of $642M (FY92), less than 1/2 of BPX, with first plasma in the year 2000 and full hardware capability in 2001. The funding profile required for BPX-AT fits within the 5% real growth per year fusion funding plan recommended by the SEAB Task Force on Energy Research Priorities (1991).

Background

During the last decade numerous technical review committees [MFAC Panel 3 (1983), MFAC Panel 14 (1986), ERAB(1986), National Research Council(1989) and FPAC(1990)] have thoroughly reviewed the magnetic fusion program and all concluded that burning plasma issues were the next technical issues to be addressed in fusion research, and that a device should be built to address these issues as the next step in the US magnetic fusion program. The demonstration and study of self-heated plasmas is not just the next frontier but the most important step in over 40 years of fusion physics research. The most recent review of the world fusion program by the FPAC[1] led to a plan described in the United States National Energy Strategy (NES)[2] for the development of fusion as an energy source by the mid-21st century. The NES adopted the goal of operating a fusion demonstration plant (DEMO) by the year 2025, and a commercial plant by about 2040. The main elements of the plan are a strong core physics and technology program, D-T experiments on TFTR, burning plasma experiments on the Burning Plasma Experiment (BPX), long pulse burning experiments and technology development on the International Thermonuclear Experimental Reactor (ITER), a materials test facility and a steady-state experiment leading to the DEMO. A key element of the FPAC recommendation and NES was a Burning Plasma

Experiment (BPX) costing approximately $1B, which would address the critical D-T physics issues, i.e., self heating of the plasma by alpha particles and would " greatly reduce the risk that ITER could run into difficulties which would compromise its ETR mission" [1].

The Secretary of Energy Advisory Board (SEAB) Task Force on Energy Research Priorities reviewed (1991) the Energy Research priorities under the constraint of capped Energy Research budgets and recommended that "magnetic fusion program funding must increase at a modest rate (e.g., 5 per cent real growth per year)..." and that this was incompatible with the authorization of the BPX proposed at $1.4B (FY91$). SEAB [3] recommended that:

> "Concept exploration should begin to define a new experiment in the $500M class for the purpose of scientific study of tokamak improvements (e.g. , second stability, steady state, bootstrap current) that could suggest new operating modes for ITER and permit the design of more reactor-desirable follow-ons to ITER."

The Fusion Energy Advisory Committee (FEAC) was charged(1991) to determine the appropriate next step in the absence of BPX and the effect of the loss of BPX on the ITER program. Recently, FEAC [4] reaffirmed the preference for the NES plan for fusion and a " national effort focussed on the physics of burning plasmas" but felt that " it does not appear possible to proceed with the construction of BPX without either diminishing its mission or timeliness, or severely affecting important core programs which remain". The BPX-AT with drastically reduced costs provides a substitute for BPX that can carry out a broader mission than BPX without impacting that core program. Without a BPX-like device, the present plan is to have ITER be the "burning plasma experiment" and to address self heated plasmas for the first time in a huge device whose main mission should be as an Engineering Test Reactor. This high risk approach is like attempting to build a 747 before the Wright brothers demonstrated the basic principles of self-sustained flight at Kitty Hawk. This one-step-does-all plan is without precedence in large technology development programs (e.g., aviation, fission, space, computers, etc.), and dramatically increases the probability of total program failure. Presently there are over 10 deuterium tokamaks operating and addressing overlapping physics issues, which provide the ability to develop solutions to problems using small devices and then to implement these solutions quickly and cost-effectively on larger devices. For example, the success of JET is due to the H-mode discovered on ASDEX 4 years after JET construction began. Since over 10 deuterium tokamaks are needed now, it seems overly optimistic to assume that one large deuterium-tritium device will be sufficient to address much more difficult problems. If burning plasma physics problems arise on ITER, there will be no place to test solutions except on ITER. FEAC [5] together with other ITER parties has concluded that the loss of BPX will cause the duration of the physics phase of ITER to increase from 6 to 10 years in order to carry out the burning plasma physics mission, possibly delaying the 2025 startup of DEMO. Even larger delays will occur if ITER has a major misstep. BPX-AT would have the capability to resolve these critical issues prior to and during the operation of ITER whose annual operating cost is estimated to be $400M and total program cost is likely to be in the 15-20 $B range.

Since ITER will not test the advanced tokamak features identified by ARIES, a separate device is needed to develop the advanced tokamak features that will be incorporated in the DEMO design. In particular, demonstration of self-heated plasmas in an advanced tokamak regime prior to DEMO design, such as the proposed BPX-AT, is required to provide a solid foundation for DEMO.

BPX-AT Description

This white paper describes an upgrade to the TFTR facility based on the BPX design concept, BPX-AT, that will address advanced tokamak and burning plasma issues concurrently. The engineering and costing of BPX-AT is on solid ground due to the several years of BPX design and review. This $642M facility is designed to take advantage of the advances likely to be made during the next decade of confinement research costing over $3B worldwide. Long pulse (~420 s) plasmas with high bootstrap currents and advanced divertors can be studied in the initial configuration ($B_T = 3T$, $I_p = 1.9$ MA) starting in the year 2000 which costs $462M. Additional power, heating systems, and D–T capability would be added within 1 year so that burning plasma physics, especially alpha heating, can be done in conjunction with advanced tokamak features. BPX-AT is projected to attain $Q \sim 5$ using standard confinement assumptions of $C_\tau = 2$, thereby satisfying the minimum requirement to study self heated plasmas. Several tokamaks (TFTR, PBX-M and DIII-D) have already achieved $C_\tau \sim 3.5$ for short pulses ($<\tau_E$) and $q \sim 4$, if these advanced tokamak confinement enhancements required for DEMO can be realized for longer pulses and $q \sim 3$ during the next 10 years, then BPX-AT will ignite ($Q > 25$) at 7.5T with a pulse length of 45 seconds and a fusion power output of ~ 120MW. This regime allows the study of advanced tokamak features (enhanced confinement, high bootstrap current, and second stability) with self heated plasmas for ~ 50 energy confinement times. The total project cost is $642M (FY92$) and the required funding profile fits within the 5 per cent real growth per year fusion funding plan recommended by SEAB.

BPX had a simple, elegant, and mature design and a sound physics design basis. Although BPX-AT is different from BPX due to its smaller size and higher aspect ratio, key elements of the tokamak configuration, structural design criteria, and physics design basis were preserved.

The tokamak (Fig. 1) features self-supporting, BeCu TF coils, wedged in the nose region. The PF solenoid is also constructed with a BeCu alloy and is self-supporting for radial loads. BeCu is a well-characterized material with outstanding strength (σ_y~107ksi) and good electrical conductivity (68% IACS). Minimal additional conductor R&D would be required. Self-supporting designs have the desirable feature that EM loads are reacted internally, avoiding interfaces between systems which are often difficult to quantify and are sensitive to manufacturing tolerances and differential thermal growth. Structural analysis of the TF indicates that the peak stress in the conductor occurs in the nose region and is 68ksi. Stress levels in the TF are within the allowables prescribed in the BPX Structural Design Criteria Document [6]. In fact, the stress levels appear low enough in the outer leg to use OFHC Cu, thereby reducing the conductor material cost and the cost of power supplies.

The TF and external PF coils are adiabatic during a shot with a pre-shot temperature of 80K. At full parameters, joule heating limits the flattop to ~10s. However, at reduced parameters, the rate of joule heating is reduced so pulse lengths can be extended rather dramatically. At 3T, the flattop time can be extended to ~420s which should be ample for the advanced tokamak mission. The time required to cool the coils down to 80K with LN_2 between thermally limited pulses is ~1 hour. Cooldown times would be shorter for pulses which are not thermally limited.

Strategy for BPX-AT

BPX was sized to achieve Q=5 with 100MW of fusion power provided the energy confinement time was at least 1.45 times the confinement time predicted by ITER89-P scaling. Analysis of H-mode data on various tokamaks indicates that a confinement enhancement of 1.85 is the "center of the error bars" on what can be expected based on current physics understanding and operating techniques. The philosophy for sizing BPX was that the device should be capable of meeting the minimum mission objectives even if confinement were substantially less than predicted for H-mode plasmas. This ultra-conservative posture led to a BPX which was a 2.6m tokamak with an aspect ratio of 3.25 and a total project cost of $1.43B (FY91$). In order to reduce the cost, it is necessary to reduce the size of the device.

For BPX-AT, a more optimistic philosophy (consistent with the SSAT philosophy) was adopted.

It was assumed that when BPX-AT is operated, achieving a confinement enhancement of at least 2 over ITER89-P scaling is a reasonable expectation because of improvements in physics understanding and operating technique derived from operating existing tokamaks during the next 8 years. Thus, the tokamak parameters were reduced from an IA product of 38 for BPX (11.8MA, A=3.25) to 25 for BPX-AT (6.25MA, A=4) with an attendant reduction in size from 2.6m to 2.0m. An expanded list of machine parameters is provided in Table 1.

Once the high performance tokamak is available, the advanced tokamak features are "free". For example:

- long pulses (~ 400 seconds) are available at reduced field (3T);
- ICH heating for D-T operation can be used for advanced tokamak current drive;
- high bootstrap current regimes are accessible;
- second stability regimes (q_0~2, q^*/q_0>2.3) are also accessible;
- advanced divertor concepts can be incorporated.

The experimental program of BPX-AT can be phased so that initial (Phase I) experiments are carried out in hydrogen and deuterium at reduced field with modest heating (15MW ICH, 2MW LHCD), thereby reducing front end costs. The first phase of operation reflects the standard startup procedure and will be spent optimizing the tokamak configuration and plasma performance while validating remote maintenance techniques. Phase I objectives are to demonstrate successful long pulse, current driven operation with adequate:

- power handling capability;
- current profile control;
- bulk density, density profile, and particle control;
- diagnostic capability, and
- remote maintenance capability.

The total number of neutrons produced in Phase I will be budgeted to preserve hands-on maintenance capability until Phase I objectives are met. During this 1 year startup period when the machine is being optimized, power and heating system modifications necessary for Phase II can be installed during shutdown periods.

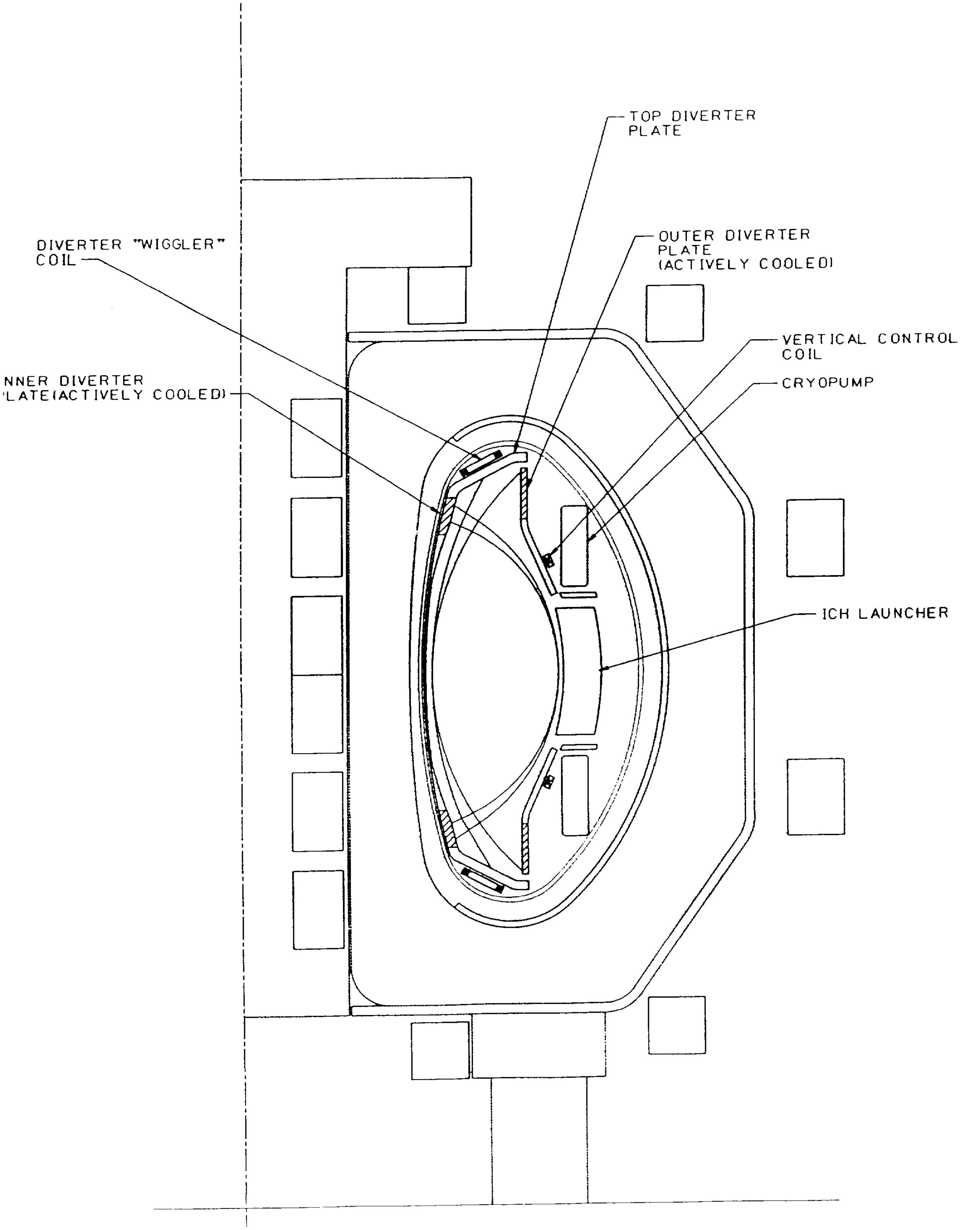


Figure 1 - BPX-AT Elevation View

Table 1 - BPX-AT Parameters

Parameter	Units	BPX-AT	
R	m	2.0	
a	m	0.5	
A		4	
κ_{95}		2	
δ_{95}		0.2-0.3	
B	T	10	
q_{95}		3.3	
I	MA	6.25	
$t_{flattop}$	s	10	
$P_{ICH/FWCD}$	MW	32	to plasma
		40	source power
P_{LHCD}	MW	2	to plasma
C_τ		2	
Q		5	

Phase II objectives will be to:

- confirm and further develop advanced tokamak operating features in D-D with the increased heating and field available, including
    - high bootstrap current,
    - second stability,
    - high beta, and
    - enhanced confinement;
- confirm and further develop advanced tokamak operating regimes in D-T;
- study D-T physics, especially alpha-heating in a DEMO relevant advanced tokamak configuration;
- demonstrate the production of fusion power in excess of 100MW.

Operating Scenarios

The work on SSAT has served to focus thinking on the operating scenarios required for an advanced tokamak. These scenarios include exploring:

- first stability beta limits ($\beta_N \sim 3.5$) with $q \sim 3$;
- high bootstrap fraction ($f_{bs} \sim 0.6$) regimes;
- second-stable regimes with very high bootstrap fraction ($f_{bs} \sim 0.9$).

These scenarios come "free" on BPX-AT. The adiabatic coils, which can provide 10T for 10s, also can provide 3T for ~420s. Parameters for these scenarios are listed in Table 2. These operating points are not isolated but actually represent an envelope defined by power handling/heating limitations, q limits, and β limits.

The advantage of BPX-AT over SSAT as an advanced tokamak is that these scenarios can be replayed *at DEMO-relevant $n\tau T$ and in D-T with alpha physics.* One premise for these scenarios is that they be achieved with "standard" H-mode confinement ($C_\tau \sim 2$). If enhanced confinement ($C_\tau \sim 3.5$) is achieved, even more interesting possibilities develop:

- the high beta operating point has *near-ignition ($Q \sim 25$) conditions* ;
- the high bootstrap operating point has $Q \sim 3$ for $f_{bs} \sim 0.6$;
- the second-stable operating point has $Q \sim 1.4$ for $f_{bs} \sim 0.9$.

Parameters for these enhanced confinement scenarios are listed in Table 3. For studying burning plasma physics, at full parameters with "standard" H-mode confinement ($C_\tau \sim 2$), $Q \sim 5$ is expected. If enhanced confinement ($C_\tau \sim 3.5$) is achieved, ignition can be studied at 7.5T for pulse lengths of ~45s. The fusion power may limited by confinement, available heating, or power handling capability. With a hybrid divertor, heat loads of 60MW (300MW of fusion power with an ignited plasma) can be handled for ~5s. Heat loads of less than 30MW can be handled in steady state.

Table 2 - Standard Confinement Scenarios in D-D @ 3T

	High Beta	High Bootstrap	2nd Stable
B	3	3	3
n_{20}	.70	.54	.45
T	7.2	6.3	5.8
C_τ	2	2	2
τ	.16	.11	.08
q_{95}	3.1	4.5	6.3
q_0	1	1	2
I_p	1.9	1.3	.91
β_N	3.5	3.5	3.8
f_{bs}	0.4	0.6	0.9
$t_{flattop}$	420	420	420

Table 3 - Enhanced Confinement Scenarios in D-T @ 7.5T

	High Beta	High Bootstrap	2nd Stable
B	7.5	7.5	7.5
n_{20}	3.0	1.4	1.5
T	9.6	13	10
C_τ	3.5	3.5	3.5
τ	0.9	0.7	0.5
q_{95}	3.1	4.5	6.3
q_0	1	1	2
I_p	4.7	3.3	2.3
β_N	3.5	3.5	3.8
f_{bs}	0.4	0.6	0.9
Q	25	3	1.4
P_{fusion}	120	50	30
$t_{flattop}$	45	45	45

Facilities

BPX-AT is to be located in the TFTR test cell. The length and width of the test cell are more than adequate. The height and crane capacity are adequate for all but the heaviest lifts, e.g., PF coils and TF modules. For these lifts, a gantry crane will be used.

The shielding of the TFTR test cell will be increased to maintain the radiation dose at the PPPL site boundary to < 10mR/year. Three factors contribute to the dose at the site boundary - neutrons, activated air in the test cell, and operational releases of tritium, primarily during maintenance. The thickness of the walls and roof of the test cell will be increased to reduce the dose at the site boundary due to neutrons. Close-in shielding, which is integral to the cryostat , is proposed to reduce the level of air activation in the test cell. Also, it has been proposed that there be no negative pressure in the test cell except in the event of a tritium release, thereby reducing the dose at the site boundary due to activated air. The cryostat-shield connected to the TFTR torus tritium cleanup system will also serve as an effective containment boundary for tritium The design objective is to produce ~3 x 10^{23} D-T neutrons (alphas) per year, about 1/3 of the BPX design requirement. Tritium retention in the divertor and limiters will require HeO GDC after ~50 pulses 30 seconds long, but should not be a problem. A closed cycle tritium reprocessing system similar to the one being developed for TFTR will be used. Accident scenarios are the same as TFTR, i.e., 140mR at the site boundary for a worst case 2.5g HTO stack release and 390mR at the site boundary for a beyond worst case 2.5g HTO ground level release.

Cost and Schedule

A phased mission has been proposed for BPX-AT to minimize front end costs without impeding the experimental program. Phase I capabilities are tailored to match present TFTR site capabilities, especially with respect to TF/PF power supplies (74-1kV units), utility power available for long pulse operation (112MW), and stored energy available from the TFTR MG sets (4.5GJ). For BPX-AT, the TF and PF can be powered from the existing utility line along with 15MW (source power) of ICH/FWCD for fields up to 3T. The pulse length at 3T would be limited by heating of the TF and PF coils to ~420s. Operation at higher fields (up to ~5T) would be possible with the pulse length limited by the stored energy of the MG sets, rather than by heating of the TF and PF coils.

For Phase II, the machine capability would be enhanced by:

- upgrading the power from the utility line from 112MW to 425MW;
- upgrading the TF and PF power systems;
- increasing the capacity of the LN2 refrigeration plant;
- increasing the ICH/FWCD source power from 15MW to 40MW;
- upgrading the divertor to handle the additional power;
- adding the capability to operate with tritium.

The cost for BPX-AT was estimated using cost algorithms developed for the New Initiative and the results are shown in Table 4. The Phase I cost is $462M with $249M of the total in the tokamak systems. The biggest single cost element is the TF system at $123M. Phase II costs an additional $181M, mostly in heating system ($56M) and power system ($49M) upgrades.

The cost of BPX-AT is compared to BPX in Table 4. Substantial cost reductions have been achieved by:

- reducing the major radius from 2.6m to 2.0m ($400M);
- maximizing use of existing TFTR assets;
    - reusing TFTR/FMIT transmitters for ICH/FWCD ($14M),
    - locating the tokamak in TFTR test cell ($85M),
    - reusing TFTR diagnostics where possible ($8M),
- better utilizing the ICH transmitters by using one transmitter per strap instead of two ($30M);
- reducing the diagnostics complement ($40M);
- developing a lower stress TF coil design which permits the use of OHFC copper in the outer leg and saves on TF coil and power system costs ($30M);
- adopting a minimum cost approach to RM, using prototypes for actual maintenance rather than just for development and training ($85M);

Table 4 - A Comparison of BPX and BPX-AT Costs

WBS		BPX (FY92$)	BPX-AT (FY92$)
1	Tokamak Systems	472	249
11	Plasma Facing Components	58	39
12	Vacuum Vessel	48	15
13	TF	218	123
14	PF	110	40
15	Cryostat	14	11
16	Tokamak Support Structure	4	3
17	Tokamak Assembly	20	18
2	Aux Heating & Current Drive	85	84
23	ICH/FWCD	85	74
24	LHCD	0	10
3	Fueling & Vacuum Systems	72	49
31	Fuel Storage & Delivery	4	3
32	Pellet Injection	16	12
33	Rad Monitoring & Tritium Cleanup	20	14
34	Vacuum Pumping Systems	32	20
4	Power Systems	242	59
5	Maintenance Systems	168	41
6	Data Systems	110	56
61	Central I&C	22	12
62	Plasma Diagnostics	89	43
7	Facilities	180	61
71	Buildings, Mods & Site Improvements	166	24
72	Cryogenic Equipment	11	33
73	Water Cooling	2	1
74	Radiation Shielding	1	3
8	Preparations for Operations	67	13
9	Project Support	95	29
	Total	1490	642

• accepting a higher level of risk by;

- scaling back management, systems engineering, and project physics ($20M),
- limiting R&D to bare essentials ($60M),

• limiting pre-op staff buildup and training ($50M);
• excluding costs not related to the construction project from the project cost estimate, e.g. Program Physics ($25M).

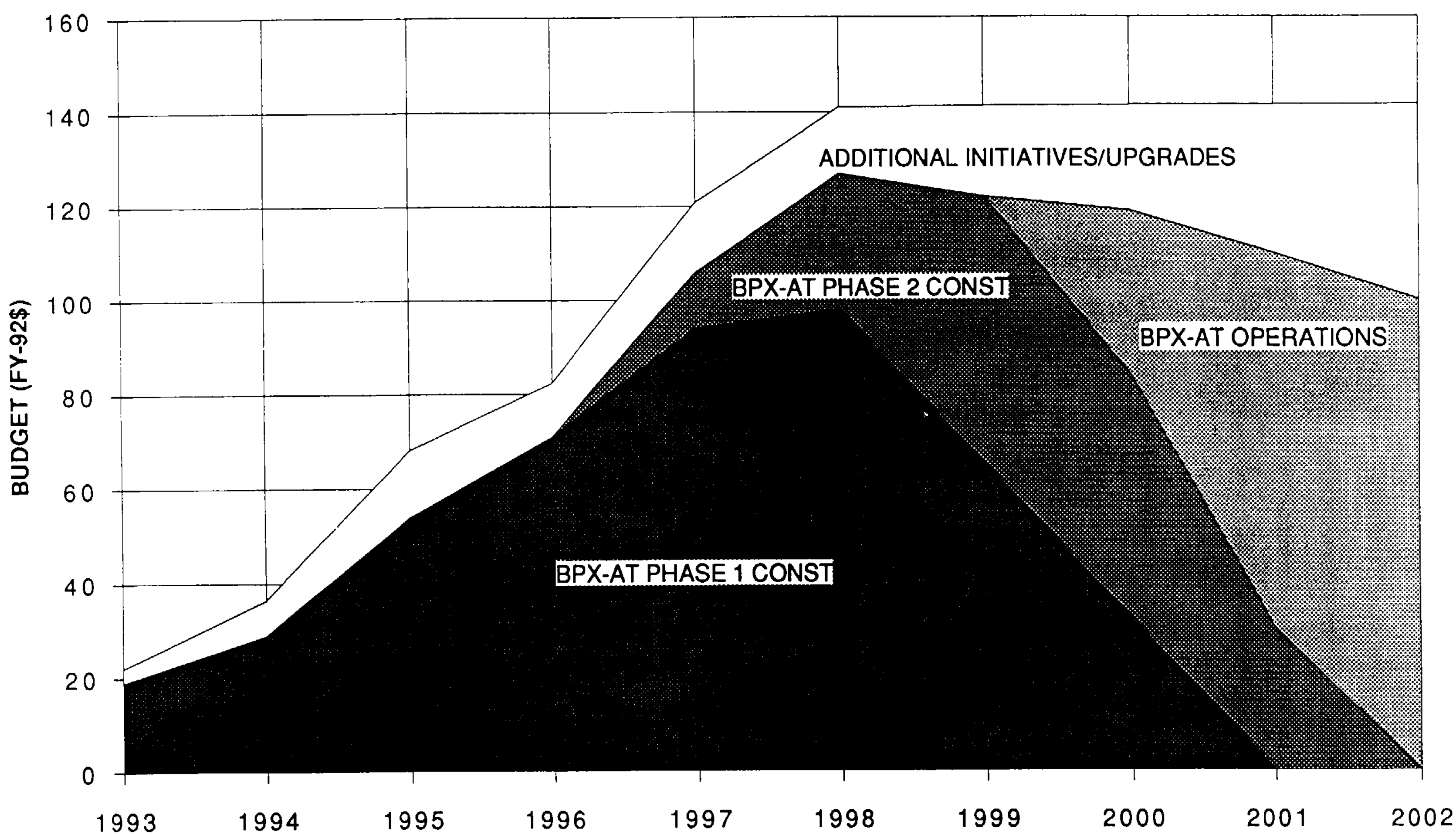
Several features on BPX-AT actually increased costs relative to BPX. These features include 2MW of LHCD ($10M), 32MW of ICH/FWCD delivered to the plasma instead of 20MW ($30M), and a closed-loop LN2 refrigeration plant ($22M). A resource loaded schedule is not available for BPX-AT. However, the BPX-AT schedule should be similar and somewhat shorter than the BPX schedule. For BPX, there were two critical paths – the TF coils and facilities. Since the TFTR test cell is being used, the TF coils are the only critical path. With design-only funding in FY94, a late-2000 first plasma date with full hardware capability 1 year later is reasonable, if funding is available.

The cost profile for BPX-AT is given below:

$M FY'92	FY'93	FY'04	FY'95	FY'96	FY'97	FY'98	FY'99	FY'00	FY'01	FY'02
Phase 1	19	29	54	71	94	98	65	32		
Phase 2					12	29	57	52	30	
Operation								35	80	100

This cost profile allows BPX-AT to be built without impacting the core program as shown in Figure 2. The upper envelope in Figure 2 was determined by assuming the SEAB budget recommendation of 5% real growth per year for the fusion budget and then subtracting the core program, TFTR and ITER design/base budgets. The budgets for 1993 to 1997 are those given by the OFE, budgets for 1997 to 2001 assume constant real budgets for the core program and ITER and the planned shutdown and decommissioning of TFTR. The ITER construction budget is assumed to be a special initiative. In this scenario ~$36M is available for additional initiatives/upgrades from 1993 through 1997 and ~$92M available from 1998 through 2000.

Figure 2 BPX-AT FUNDING PROFILE



Conclusions

BPX-AT will address advanced tokamak and burning plasma issues concurrently. Long pulse (~420s) plasmas with high bootstrap currents and advanced divertors can be studied in the initial configuration starting in 2000 which costs $462M. Additional power, heating systems, and D–T capability would be installed during the next year so that burning plasma physics, especially alpha heating, can be done in conjunction with advanced tokamak features. BPX-AT can attain Q~5 using "standard" confinement assumptions of $C_\tau = 2$. If the advanced tokamak confinement enhancements required for DEMO, i.e. $C_\tau \sim 3.5$, can be realized, then BPX-AT will ignite with B~7.5T and a pulse length of 45 seconds. The total project cost is $642M (FY92$) and the funding profile fits within the fusion funding plan recommended by SEAB. If the BPX-AT device were adopted and built on the proposed schedule, the main features of the NES could be maintained, and burning plasma experience on BPX-AT could shorten the ITER phase by 4 years, saving $1.7B (FY91), while providing a unique combination of burning plasma and advanced tokamak physics that would be needed for DEMO design.

The TFTR D-T experiments in 1993-4 should revive interest and enthusiasm for magnetic fusion in the U.S.. BPX-AT is the ideal vehicle for the next natural step after TFTR/JET, the study of burning plasma issues in a DEMO relevant configuration while providing critical operational support for ITER.

Acknowledgements

The technical work described here is a tribute to the skill and dedication of national CIT/BPX team.

References

[1] Fusion Policy Advisory Committee, Final Report, September, 1991

[2] National Energy Strategy, February, 1991

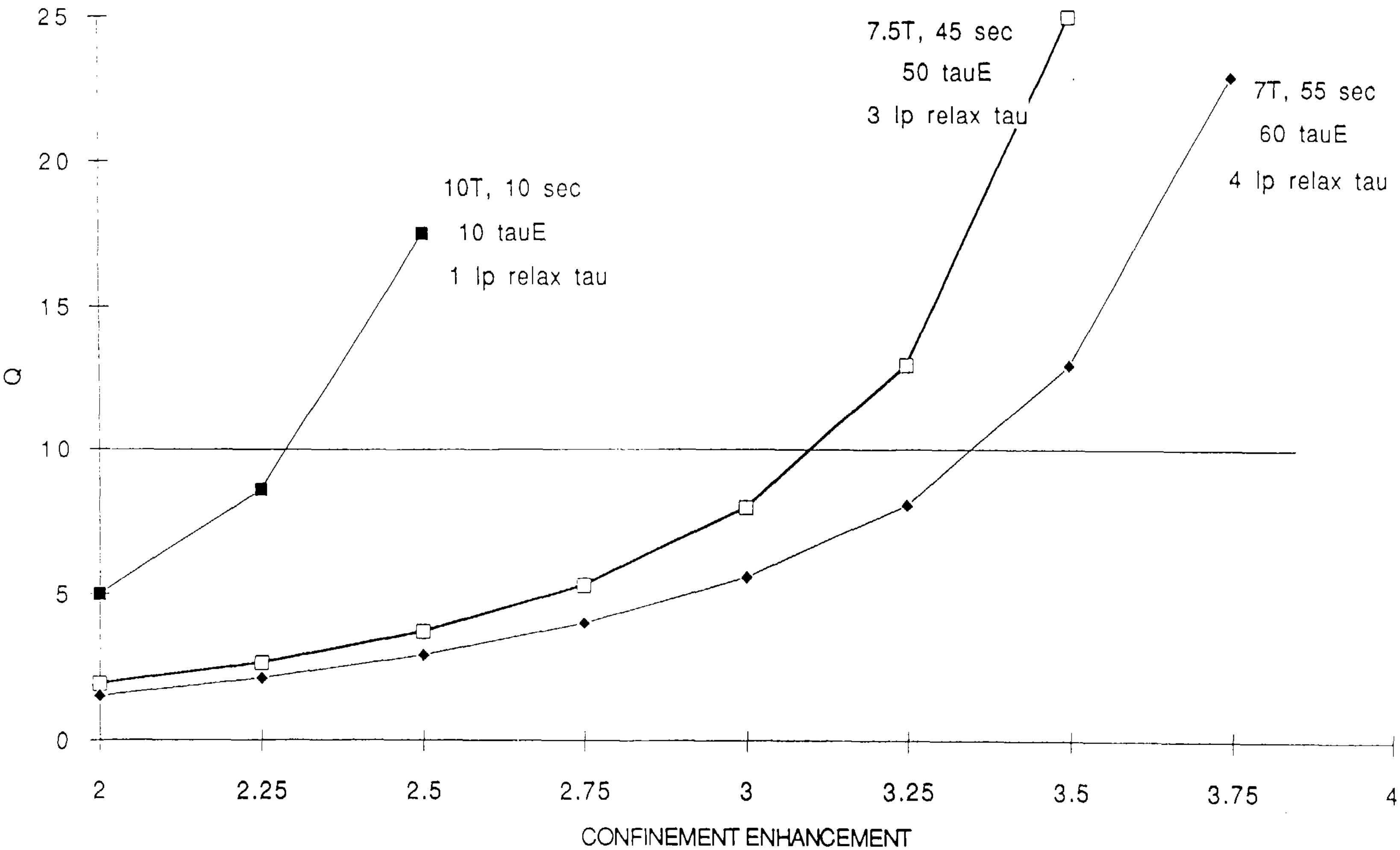
[3] SEAB Task Force on Energy Research Priorities, Letter Report, November, 1991

[4] Fusion Energy Advisory Committee, Letter Report, October, 1991

[5] Fusion Energy Advisory Committee, Letter Report, February, 1992

[6] BPX Magnet Structural Design Criteria, F-910208-PPL-03, Rev. 0

BPX-AT CAN ADDRESS THERMAL STABILITY AND CURRENT PROFILE RELAXATION DURING STRONG ALPHA HEATING WITH ADVANCED TOKAMAK CONFINEMENT ENHANCEMENT



SIMULTANEOUS CONTROL OF THE PLASMA EDGE, CURRENT AND DENSITY PROFILES OVER THE NEXT TWO DECADES OF CONFINEMENT RESEARCH SHOULD CONTINUE PROGRESS OF THE LAST DECADE.