XII. OPERATIONS PLAN

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The operating program for BPX after the achievement of first plasma may conveniently be divided into a preliminary phase and a burn physics phase, the latter forming the major focus of the project. The preliminary phase includes the development tasks and physics studies necessary to reach the high-Q plasma regime. In this section, we describe the operational plan for the preliminary phase and the early part of the burn physics phase.

In developing this plan, we have aimed at achieving high-Q D-T operation within 3 years from the first plasma operation. To meet this target, it has been necessary to assume that the physics predictions that underly the BPX design will be largely fulfilled during the preliminary phase, so that extensive investigation of fundamental physics issues in the nonignited regime will not be necessary. It must also be pointed out that since some details of the BPX design remain to be determined on the basis of future results from existing and planned experiments [e.g., the provision of electron cyclotron heating (ECH) as well as ion cyclotron resonance frequency (ICRF) auxiliary heating], details of this plan will continue to evolve.

The operation of BPX is subject to several significant constraints, some of which have not been encountered in planning for previous tokamak experiments. The most obvious is the radiation associated with D-T operation and the resulting activation of the structure. The activation levels after a single ignited discharge are sufficiently high to prohibit personnel access inside the central cell surrounding the machine and to restrict all maintenance inside this area to remote-handling techniques. Even operation with deuterium plasmas at high auxiliary heating power results in significant activation levels: running 1000 deuterium plasmas with stored energies of 5 MJ over a 7-month period produces a dose rate of 6 rem/h at the vacuum vessel after a week of cooling down. Thus, the restrictions on access to and maintenance capability for an activated system have substantial bearing on the operations plan throughout the life of the experiment.

The impact of the limited fatigue lifetime of the device must also be considered during all phases of this plan. The magnets are designed for a lifetime of 3000 full-field ($B = 9$ T, $I = 11.8$ MA) plasma shots (excluding commissioning shots), with an allowance for an additional 30 000 shots at half of the full stress, which corresponds to operation at $B \sim 6$ T, $I \sim 8$ MA. The magnet design for BPX is based on conservative engineering practice, so it is anticipated that additional full-field shots will be available beyond the specified lifetime, albeit at a somewhat increased risk of coil failure. However, the goal of the operations plan must be to achieve the primary mission of the project within the specified fatigue lifetime and thus to maximize the utility of the full-field discharges during the early phases of operation. The detailed dependence of the projected fatigue lifetime on stress level may influence the strategy adopted in approaching the burning plasma regime. To conserve the fatigue life, it is desirable that the auxiliary heating scheme be compatible with operation at toroidal fields between the half-stress level $B \sim 6$ T and the full toroidal magnetic field of 9 T. It will be essential to maintain a cumulative log of the usage of the fatigue lifetime and to provide software for predicting the fatigue cost of any planned shot or experiment.

Additional constraints on BPX operation arise from the time required to cool the magnet coils and other subsystems between plasma shots. At full field, the time between shots with the nominal 10-s flattop is specified to be 1 h. Thus, during a two-shift operating day, at most 16 full-parameter shots could be produced. Current large tokamaks produce between about 20 (JET, JT-60) and 80 to 100 (TFTR, DIII-D) shots on a normal operating day. The time required to cool the coils depends on their energy input; thus, from the standpoint of magnet cooling, shots of 10-s pulse length at 6 T can be run at a rate of 2 per hour and half-length shots at this field can be run at 3 to 4 per hour. An increased shot rate for reduced-parameter discharges would be particularly useful in the early phases of operation when newly installed systems are being commissioned. It will be a design goal of the auxiliary heating and other BPX subsystems to be capable of maintaining the repetition rate allowed by the coil cooling time.

In most present tokamaks, major disruptions result in a series of subsequent discharges that are atypical and unsuitable for inclusion in the data set of a planned experiment. Since they could significantly reduce the number of useful shots in BPX, disruptions should be avoided by all means. Fortunately, it has been possible to design BPX to operate safely away from the disruptive limits that have been identified and explored in the present generation of tokamaks. It is expected that "cleanup" shots following a disruption would be taken at reduced parameters to achieve a higher shot rate and avoid wastage of the fatigue life. The success of boron coating of the limiters in TEXTOR and TFTR in reducing the time to recover from disruptions is also encouraging. The elevated temperature of the graphite surfaces facing the plasma and the use of limiter coatings is also expected to improve the reproducibility of discharges in BPX compared to many present tokamaks in which operation is typically not reproducible after an interruption to regular pulsing.

The optimization of the rate of useful shots in BPX will be aided by the provision of a sophisticated real-time control system capable of assessing the state of any discharge and of aborting any shot that does not satisfy predetermined conditions on key parameters. Early termination of unsatisfactory shots will reduce the heating of critical components, minimize wastage of the fatigue life and accumulation of tritium in the vacuum vessel, and also reduce the likelihood of disruptions.

XII.A. SEQUENCE OF EXPERIMENTAL RUNS

The operation phases may be broken down further into a number of experimental runs that will last from a few to many months. It has been assumed that the facility will be available for plasma operation and that the project will be adequately staffed to permit physics experiments for 2 shifts per day, 5 days per week, and for 2 weeks out of 3, on average during the experimental runs. Routine daily maintenance will take place during the third shift. More extensive maintenance and engineering testing time will be scheduled during the third week of the cycle. This pattern is similar to that for TFTR.

During the tritium phase, it is planned to use periods of glow-discharge cleaning in a helium-oxygen mixture to remove tritium from the surface layers of the limiter and divertor plates and prevent the accumulation of an unacceptable tritium inventory in the vacuum vessel (see Chap. IX). Estimates of the rate of tritium buildup on these surfaces based on laboratory data and measurements in TFTR indicate that tritium removal will be required after about 10 days of running in the reference full-parameter conditions. The schedule of 2 weeks of operation followed by 1 week of maintenance is thus compatible with this plan for tritium removal.

This operations plan is designed to take effect upon the achievement of the first plasma in BPX. It has been assumed that at that time

1. The coil systems and power supplies will have been commissioned to their full rated levels.
2. The full diagnostic set will have been installed and tested as far as possible without plasma.
3. The auxiliary heating generators and couplers, including possible upgrades to the present design capability, will have been installed and tested (in vacuum).
4. The remote-handling systems will have been installed in the central cell.

The last requirement is included because it is planned to start using remote-handling techniques during the first shutdown period when the tokamak is not yet activated and manual intervention to correct problems is still possible.

XII.A.1. Run IA: Initial Ohmic Operation (Hydrogen, $B \leq 6$ T); 6 Months

This initial run will be aimed at establishing routine plasma operation at fields up to 6 T and currents to 8 MA. Hydrogen or helium plasmas only will be used to allow full hands-on maintenance during the run. The major tasks to be completed during this period will be

1. commissioning of the plasma control system
2. establishment of techniques for breakdown and current rampup
3. optimization of feedback controls, including those for the shape and the vertical position instability
4. cleanup and conditioning of the first wall
5. initial operation of the pellet fueling system (hydrogen pellets only)
6. operation of the full diagnostic set and data acquisition system
7. establishment of an operating routine, including discharge cleaning procedures, shot interval, shot sequence, etc.

This initial "shakedown" run period will also provide some physics results in the areas of q (safety factor) and density limits, disruption characterization, divertor performance, and confinement in the ohmic plasma. Data on current penetration will be of particular interest because the achievement of full-current operation will require an optimized startup.

The key to this run period, from the standpoint of both operating experience and tokamak conditioning, will be the number of plasma shots. We anticipate limited machine availability during the early part of this run. However, as the power levels and pulse durations will be relatively low at first, an average of 100 shots per week should still be achievable. As operation becomes more established and the availablity increases, this average should be maintained while the field, current and pulse length are increased to the 6-T, 8-MA, 5-s flattop operating point planned for this run. The shakedown period is estimated to require about 2000 pulses over a period of 6 months. The debit from the fatigue lifetime will be essentially zero for this run.

Commissioning of the ECH system, which will have been installed and tested off-line prior to the first plasma, will also begin during this run, although it will not be the pacing activity for operations. Nonintrusive investigations of the coupling to the plasma will be combined with the major activities listed above in ohmically heated discharges.

XII.A.2. Run IB: Initial Auxiliary Heating (hydrogen, $B \approx 6$ T); 4 Months

Once plasma operation at 6 T is reliable, the focus of operations will shift to the auxiliary heating system. The goal of this run is to raise the heating power as far as possible toward the design level to provide a test of the power handling capability and alignment of the divertor before activation of the structure in the deuterium phase of operation. It is planned to use ^{3}He minority coupling in hydrogen plasmas for these tests. In some previous experiments, difficulties have been encountered with this coupling scheme due to a parasitic resonance at the plasma edge of residual deuterium from prior operation. Since no deuterium will have been introduced into BPX at this stage, these difficulties should not occur, but if problems are encountered, ^{4}He majority plasmas will be used. Careful control of the ^{3}He minority density will be required (see Chap. VI).

The most difficult aspect of this run period to predict is the length of time (number of shots) required to achieve reliable coupling of the full ICRF heating power to the plasma. This time has been quite variable in previous experiments but the trend has been toward more rapid progress in recent experiments. In BPX, the heating of plasma-facing components and the coupler conditioning during the preceding run should promote a rapid progression. The experience from Alcator-C-Mod with ICRF in a configuration similar to BPX will be most valuable. We take a value of 1000 shots to bring the ICRF system to full power. The run will also provide information on the problem of controlling the ICRF coupling to the divertor plasma, although, since only hydrogen or helium plasmas will be used, it is unlikely that an H mode will be achieved during these experiments. The effect of the auxiliary heating on the pellet fueling should also be investigated. This run is estimated to require a period of 4 months. The debit from the fatigue lifetime will be essentially zero for this run also.

XII.A.3. Run IC: Full-Field Plasma Operation (hydrogen, $B \leq 9$ T); 2 Months

The remainder of the hydrogen plasma phase will involve increasing the plasma current to its maximum design value of 11.8 MA, which requires operation at the full toroidal magnetic field, 9 T. Although the magnet systems will have been tested to full fields during the commissioning phase prior to first plasma, the coils and structure will not have been subjected to the same load distribution and transient loads that occur during plasma operation. Since the next period of operation will involve deuterium plasmas, leading to significant activation, it is prudent to test the electrical and mechanical integrity of the tokamak subsystems and to characterize the performance of the divertor at full field. To reach the full plasma current for a useful pulse length, some auxiliary heating using the ^{3}He minority coupling scheme (at higher frequency) will be required. Some full-current disruptions will be performed intentionally to provide the most stringent test of the coil systems and structural and first-wall components. It is anticipated that the shot rate will drop to an average of 80 per week for this run which is estimated to require 2 months. The total debit from the fatigue life of the machine will be limited to the equivalent of 200 full-field shots.

XII.A.4. Shutdown: Remote Maintenance Qualification; 4 Months

Following the completion of the hydrogen phase and the high-field tests, a shutdown for maintenance and installation tasks with a vacuum vessel opening is planned. Based on the results from operation with high power heating, it may be necessary to readjust the alignment of the divertor structure to distribute the plasma heat load more evenly. At this point, hands-on operations within the biological shield will still be possible. However, it is planned to carry out as much of the *maintenance* work as possible using the remote maintenance equipment, to test and qualify this vital system while manual intervention to recover from problems is still possible. "One-off" installation procedures will still be carried out manually. This shutdown is anticipated to require 4 months.

XII.A.5. Run II: Heating and Fueling Physics (deuterium, $B \approx 6$ T); 9 Months

The operational objective of the second major run period will be the full qualification of the auxiliary heating system, the pellet injectors, the divertor and limiters, and the full diagnostic set. The physics objective will be verification of the performance with deuterium plasmas, including parameter space limits, heating, energy and particle confinement, and impurity control. Operation will be routine up to the 6-T, 8-MA level. The ^{3}He minority heating scheme will be used. With deuterium plasmas and high heating power available, the H mode should become accessible. Optimization of the ICH coupling and heating in the H mode will be the initial goal of this run. Control of impurities during the H mode with high-power ICH may be a major issue. Some operation will be conducted at full field and current to test the plasma confinement capabilities in deuterium. Access to the tokamak will become restricted by activation, so routine maintenance will be carried out by remote handling, providing realistic testing of these systems prior to D-T operation. This optimization phase is expected to require about 1000 shots.

The direction and pace of the experimental program for the remainder of this run will depend on the extent to which the relevant physics data base has been established by previous experiments. If the data base is inadequate, it will be necessary to devote time and resources to extending it and conducting operations in unexplored territory. A plan for obtaining the necessary information has been developed and is described in the BPX Physics R & D Plan. Consequently, we assume that major choices between approaches to ignition (for example, between divertor and limiter operation) have already been made and that the activities to be carried out during this phase of operation are those necessary to establish operating procedures and to verify the performance of the chosen approach. We expect that 3000 shots should be sufficient to establish the necessary confidence in all systems to proceed to tritium operation. Thus, this run will take 9 months altogether. The total debit from the fatigue life of the machine will be limited to the equivalent of 100 full-field shots.

XII.A.6. Shutdown: Tritium System Commissioning; 2 Months

Installation and testing of all parts of the tritium handling system outside the central cell will have been completed during the first 2 years of plasma operation. During this shutdown, it will only be necessary to complete the tritium connections to the vacuum vessel and to perform end-to-end tests of the complete system. It may be desirable to remove some diagnostic components that will not be able to function in the high radiation environment of the D-T phase of plasma operation. This shutdown is expected to require 2 months.

XII.A.7. Run IIIA: Initial Tritium Operation (D-T, $B \leq 6$ T); 6 Months

During this run, we will begin D-T operation at fields up to 6 T. This will allow testing of the ICH physics for the fundamental ^{3}He minority and, if the tritium beta is sufficient, the second-harmonic tritium heating schemes. Significant alpha-particle production should occur in these discharges ($Q \leq 2$). This will permit evaluation of prompt losses and single alpha-particle confinement and may give indications of collective alpha-particle effects on MHD activity, pellet ablation, and impurity generation. We anticipate that these studies will require of the order of 1500 reduced-field shots. However, since the initial operation with tritium will inevitably reduce the shot rate, a period of six months has been allowed for these studies. The debit from the fatigue lifetime will be essentially zero for this run.

XII.A.8. Run IIIB: High-Q Studies (D-T, $B \leq 9$ T); 5 Months

The next period of operation represents a transition to the burning plasma phase. At this stage, most of the major tokamak systems necessary for a demonstration of very high Q ($Q > 5$) will have been qualified separately to their full capability. The important exception is the divertor hardware, which only receives its full power and energy loads in an ignited plasma.

The high-Q regime will be approached by increasing the field, current, density, and the auxiliary heating power. The optimum route and the speed of the approach will depend on the details of the operating space and the confinement scaling. Operational considerations during these experiments will include the effects of the alpha-particle heating on pellet fueling and the management of reactivity excursions and heat loads on the divertor and first wall. Physics studies will focus on the collective stability and transport effects of the alpha-particle heating.

We expect that these experiments will subject the machine to severe stresses, as control of the high-Q plasma may be difficult to establish, resulting in large peak heat loads and an increased risk of disruptions. Since it will be necessary to proceed very carefully and possibly to recover from disruptions, the effective shot rate is estimated to drop to 70 per week of operation on average. It is anticipated that about 1000 shots will be run over a 5-month period. Of these shots, about 100 will be at full-field with a larger number at slightly reduced parameters. The total debit from the fatigue life of the machine is expected to be the equivalent of 300 full-field shots.

XII.A.9. Shutdown: Maintenance and Planning; 2 Months

Following the high-Q demonstration, a shutdown of at least 2 months is scheduled. This will provide an opportunity for remote maintenance and repair work that will probably be necessary and allow replacement of diagnostic components nearing the end of their useful life due to radiation exposure. The break will allow the physicists to assimilate and analyze the data from the high-Q demonstration to plan the next series of runs. The engineers will assess the performance of the complete tokamak system operating at its full capability and to make appropriate changes in operating procedures.

XII.A.10. Run IV: Burning-Plasma Physics Studies (D-T, $B \leq 9$ T)

The future operating plan of BPX will depend on the nature of the results and cannot be predicted in any detail. We assume that a reasonable operating schedule will consist of run periods of approximately 6 months duration interspersed with maintenance periods lasting about 2 months. It is to be hoped that the plasma performance will permit much useful data ($Q > 5$) to be obtained at fields that do not significantly contribute to fatigue. The number of equivalent full-field shots could then be limited to about 100 per month, and four such run periods would be possible before the machine fatigue life expires. If the most interesting physics regime is only accessible at full field and current, the usage of the fatigue lifetime may rise to 200 shots per month and the useful life of the machine will be reduced.

While the content of these runs cannot be specified in detail, the physics information desired and the approach can be discussed in general terms. Experiments will be conducted to study plasma transport, stability, and alpha-particle behavior. The operating space in which the heating is dominated by the alpha particles must be fully explored, including effects on density and beta limits, power loading, impurity control, and helium ash buildup. If full ignition is possible, transient behavior should be investigated, including thermal stability and possible methods of burn control. An exhaustive set of parameter scans could easily require in excess of the $\sim$2400 full-field equivalent shots remaining to the device; careful planning based on the actual results will be necessary to maximize the information obtained.

XII.B. SUMMARY

The operations plan for BPX from first plasma to the main burning plasma experiments has been divided into four major experimental periods, the progression of which is illustrated in Fig. 12.1. The plan has been designed to minimize the use of the fatigue life for verifying that the physics performance required to reach the primary objectives can be achieved. Under this plan, significant activation of the machine will be delayed until after a limited test at full stress levels. Remote maintenance operations will be introduced as early as practicable and exercised during the hydrogen and deuterium plasma phases for routine maintenance, allowing the remote maintenance systems to be thoroughly tested before the introduction of tritium precludes personnel access to the central cell.

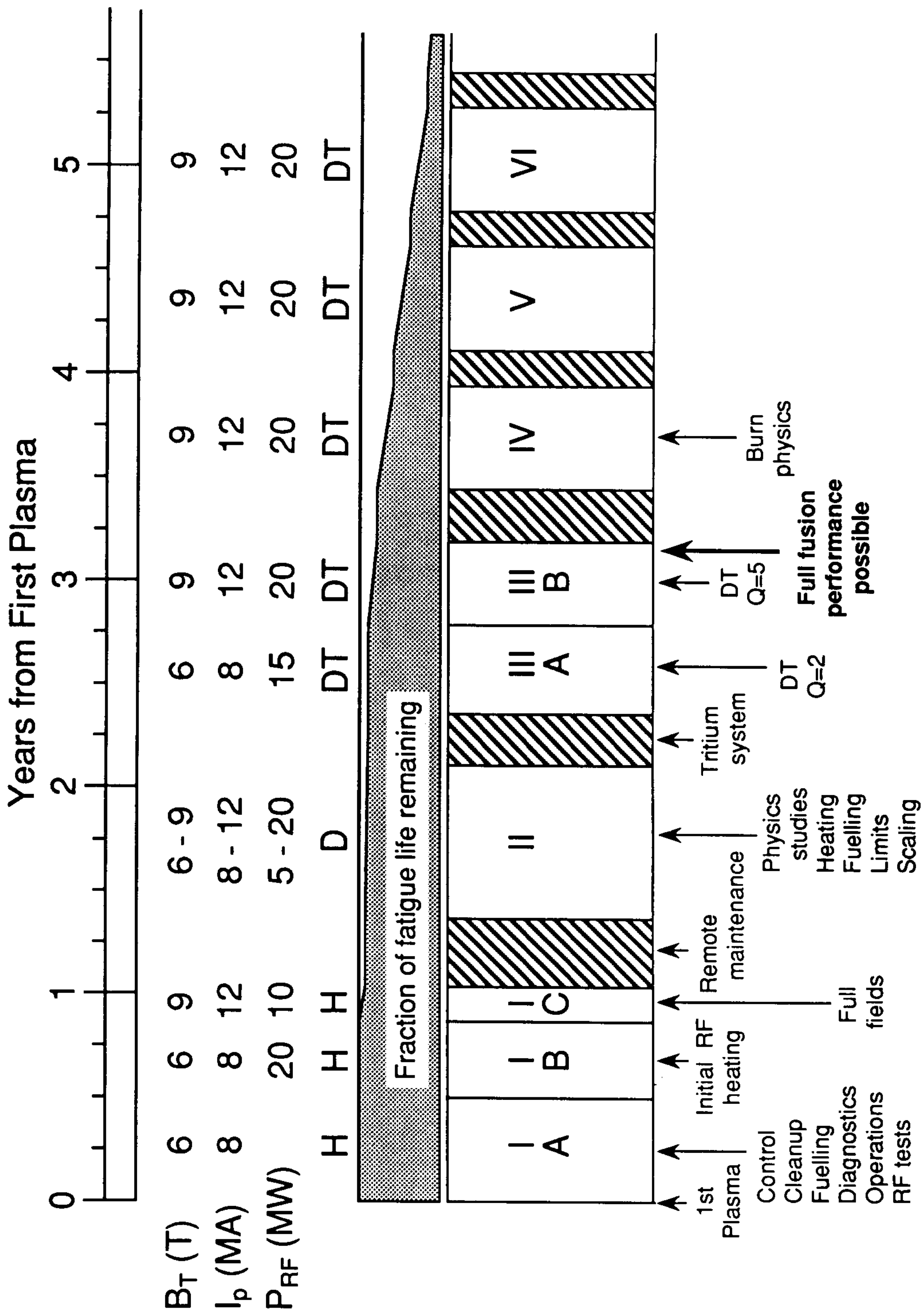

Fig. 12.1. BPX operations plan.