PLASMA SHAPE CONTROL CALCULATIONS FOR BPX DIVERTOR DESIGN[*]

D. J. Strickler and G. H. Neilson
Oak Ridge National Laboratory
P. O. Box 2009, Oak Ridge, TN 37831-8508

S. C. Jardin and N. Pomphrey
Princeton Plasma Physics Laboratory
P. O. Box 451, Princeton, NJ 08543

Abstract

The Burning Plasma Experiment (BPX) divertor is to be capable of withstanding heat loads corresponding to ignited operation and 500 MW of fusion power for a current rise time and flattop lasting several seconds. The poloidal field (PF), diagnostic, and feedback equilibrium control systems must provide precise X-point position control in order to sweep the separatrices across the divertor target surface and optimally distribute the heat loads. A control matrix MHD equilibrium code, BEQ, and the Tokamak Simulation Code (TSC) are used to compute preprogrammed double-null (DN) divertor sweep trajectories that maximize sweep distance while simultaneously satisfying a set of strict constraints: minimum lengths of the field lines between the X-point and strike points, minimum spacing between the inboard plasma edge and the limiter, maximum spacing between the outboard plasma edge and the ICRF antennas, minimum safety factor, and linked poloidal flux. A sequence of DN diverted equilibria and a consistent TSC fiducial discharge simulation are used in evaluating the performance of the BPX divertor shape and possible modifications.

BPX Divertor Magnetics Constraints

BPX physics considerations for the 500-MW, DN diverted plasma discharge require that $\kappa \approx 2$ (plasma elongation measured at the 95% flux surface) and $q \geq 3.2$ during the current flattop (I_p = 11.8 MA, B_t = 9 T). Additional constraints are imposed as general requirements[1] for the magnetic geometry; specifically,

1. the distance along the separatrix flux surface between the X-point and the divertor target surface should be at least (a) 10 cm for the inner strike point (ISP) and (b) 15 cm for the outer strike point (OSP), and
2. at the large major radius side of the plasma, the separatrix flux surface should vary by at most ±1.0 cm from some reference surface parallel to ICRF antennas and extending ±50 cm from the horizontal midplane.

Flexibility in the plasma configuration requires operation in single-null (SN) divertor and limiter modes. Appropriate variations in the equilibrium constraints apply to these alternative modes but are not discussed in this paper.

Equilibrium Model

The control matrix MHD equilibrium code BEQ,[2] with input generated by the Tokamak Simulation Code TSC,[3] is used to compute solutions characterized by fixed plasma radii, current, field, volt-seconds, and profile parameters (β_p, $l_i/2$) at a given set of time points ($4.5\ \mathrm{s} \leq t \leq 13.2\ \mathrm{s}$). Values of the safety factor and the OSP position are also prescribed as functions of time. Plasma current, field, and profile parameters are determined in a preliminary TSC simulation. The BEQ code computes the PF currents controlling the plasma shape, and the poloidal flux distribution on the divertor plates, for use in the optimization of the divertor geometry and sweep scenario and for evaluating the divertor performance .

The reference BPX geometry and PF coil system for this study are shown in Fig. 1. The external PF coil set is referred to as GEM-46,[4] consisting of seven independent coil groups providing the equilibrium vertical field, shaping field, and inductive flux for the diverted plasma.

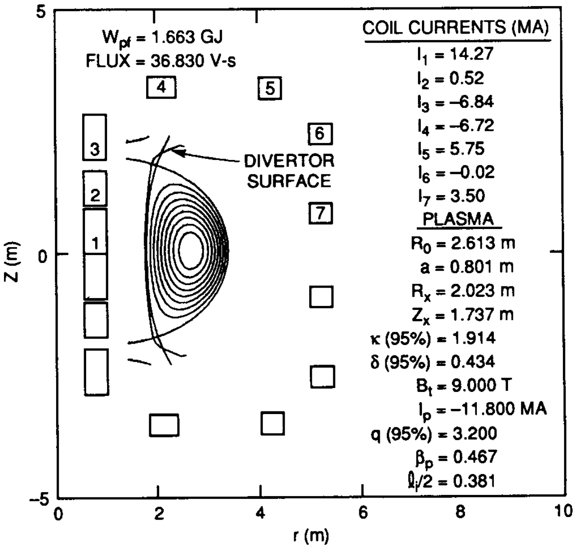

Fig. 1. The BPX poloidal field coil system, limiter and divertor surface geometry, and an end-of-burn equilibrium.

The assumed plasma pressure and toroidal magnetic flux profile functions used to evaluate the plasma current density distribution,

$$J_\phi = r dP/d\psi + F(dF/d\psi)/(\mu r), \tag{1}$$

in the equilibrium problem, are given in terms of their derivatives

$$dP/dx = P_0[\exp(-Ax) - \exp(-A)]/[\exp(-A) - 1], \tag{2}$$

$$dF^2/dx = 2\mu R_o^2 P_0(1/\beta_J - 1)[\exp(-Bx) - \exp(-B)]/[\exp(-B) - 1], \tag{3}$$

where x is the normalized poloidal flux and P_0 is adjusted so that the total plasma current, $I_p = \iint J_\phi dr dz$, is fixed at an input value. The resulting equilibrium pressure and current density profiles are characterized by the poloidal beta,

$$\beta_p = 4\int P dV/(\mu R_o I_p^2), \tag{4}$$

---

[*] Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

and the plasma internal inductance,

$$l_i/2 = \int B_p^2 dV/(\mu^2 R_o I_p^2), \tag{5}$$

respectively. The safety factor at the 95% flux surface is

$$q = F/(2\pi)\oint_{x\approx.95} dl/(r^2 B_p). \tag{6}$$

TSC data for the plasma current, volt-seconds, poloidal beta, and internal inductance are given in Fig. 2. In BEQ, a Newton's algorithm is used to solve for the parameters B and β_J, [Eq. 3], together with the elongation of the 95% flux surface, κ, such that the equilibrium values of β_p [Eq. (4)], $l_i/2$ [Eq. (5)], and q [Eq. (6)] match the TSC data. Function values for the Newton's iteration are provided by solving the free-boundary equilibrium subproblem. The equilibrium calculation determines the external PF coil currents necessary for convergence to solutions with prescribed R_o, a, linked flux, κ, and OSP position, using the control matrix algorithm.[2]

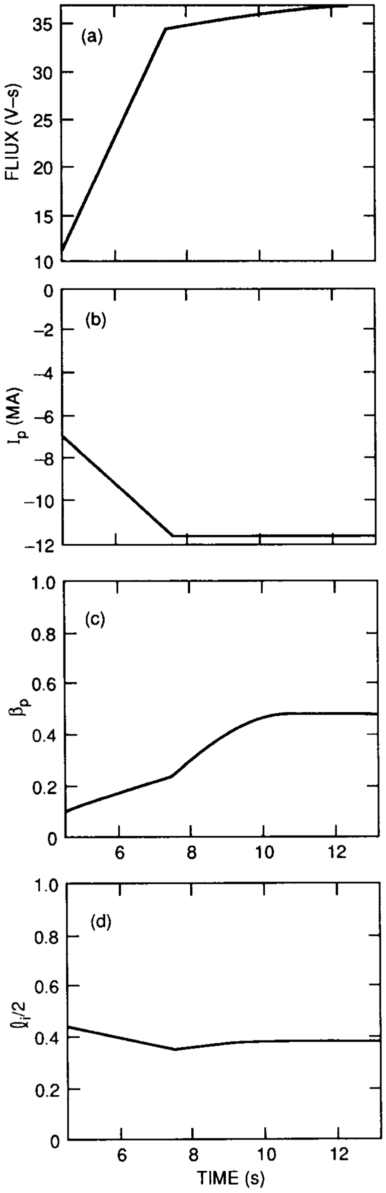

Fig. 2. Time-dependent values of (a) linked flux, (b) plasma current, (c) poloidal beta, and (d) internal inductance are from a TSC fiducial discharge calculation and provide input data for the equilibrium modeling of a divertor sweep.

Divertor Sweep Optimization

Since BPX physics guidelines[1] assume that 80% of the power flow to the divertor goes to the outer divertor target, the OSP position is a critical parameter. For each prescribed OSP position on the divertor plate, the field line length between the X-point and the strike points is maximized, within the requirements for MHD stability, by choosing the plasma elongation κ such that $q = 3.2$. The length of the OSP sweep is optimized by starting near the outboard edge of the divertor surface and sweeping the OSP inward until the distance from X-point to either the ISP or the OSP approaches its minimum value. The paths followed by the X-point, ISP, and OSP are shown in Fig. 3 and 4. Plasma elongation for this sequence of equilibria is initially κ = 1.90 (corresponding to $q = 4.3$) at t=4.5 s, increases to κ = 2.08 ($q = 3.2$) at beginning of flattop (BOFT), and returns to κ = 1.91 ($q = 3.2$) at end of burn (EOB). Since the elongation is growing prior to BOFT, the ISP initially follows an outward trajectory before sweeping inward. During flattop (constant q) the path of the X-point is almost linear (Fig. 4). The resulting sweep distance for the OSP is 39.3 cm during flattop (46.4 cm between t = 4.5 s and EOB). The ISP sweep during flattop is 30.5 cm, and the ISP is at its minimum distance from the divertor surface (10.0 cm) at EOB. The sweep distances and approximate length of the separatrix flux contours between X-point and strike points are shown in Fig. 5. PF coil currents controlling the plasma shape and OSP path are given in Fig. 6.

The radial coordinate of the outer separatrix flux surface at points 0.5 m above the plasma midplane, a measure associated with antenna coupling, is R = 3.346 m at t = 4.5 s, R = 3.357 m at BOFT, and R = 3.337 m at EOB. This variation of 2.0 cm during flattop is the maximum allowed under the requirement to match the antenna shape and is a further indication that the OSP sweep distance is maximum for the divertor geometry.

The divertor surface[5] used for this study (Fig. 3 and 4) is based on a constant safety factor ($q = 3.2$) sequence of equilibria and designed to significantly extend the sweep distance of the OSP over a previous divertor design (Fig. 4).

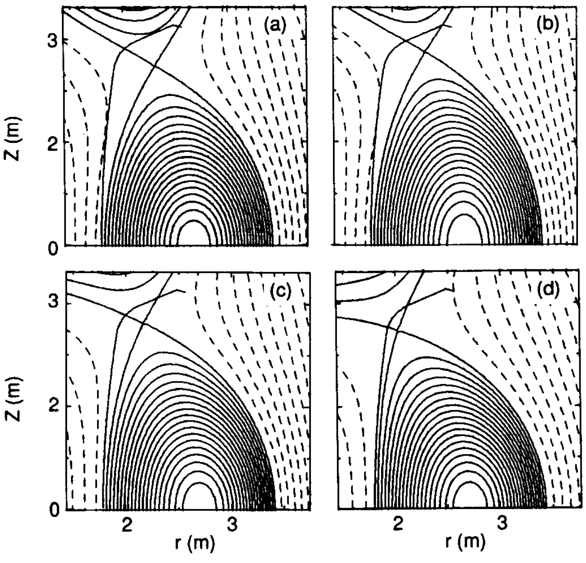

Fig. 3. Equilibrium solutions at (a) t=4.5 s, (b) t=7.5 s (BOFT), (c) t=11.74 s, and (d) t=13.2 s (EOB) show the sweep of the separatrix flux surface across the divertor target surface.

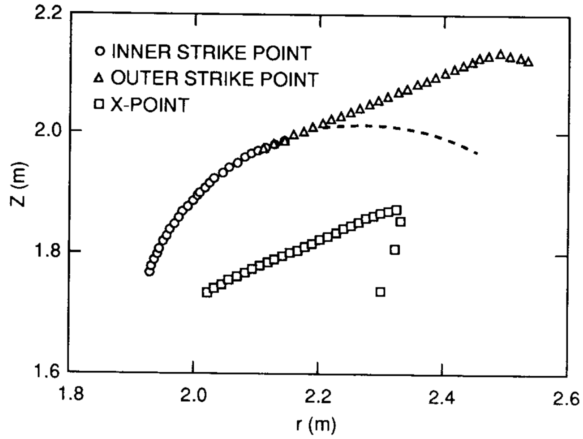

Fig. 4. The trajectory of the X-point, inboard strike point (ISP), and outer strike point (OSP) during the divertor sweep simulation. The previous BPX divertor geometry (dashed line) resulted in a reduced sweep distance.

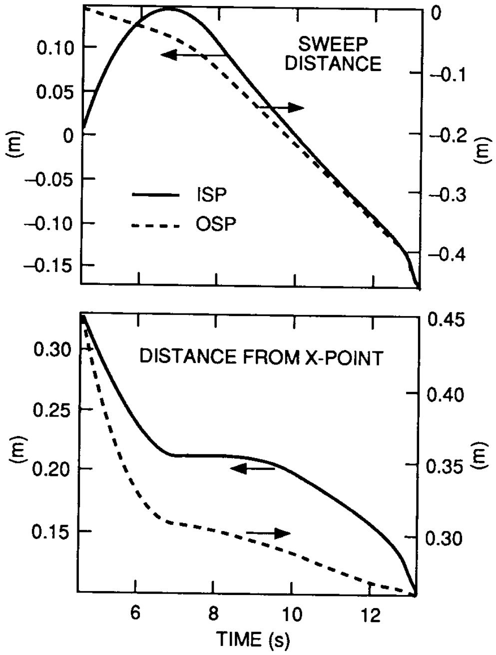

Fig. 5. Divertor sweep distance for the inner and outer strike points, and the distance between the X-point and strike points.

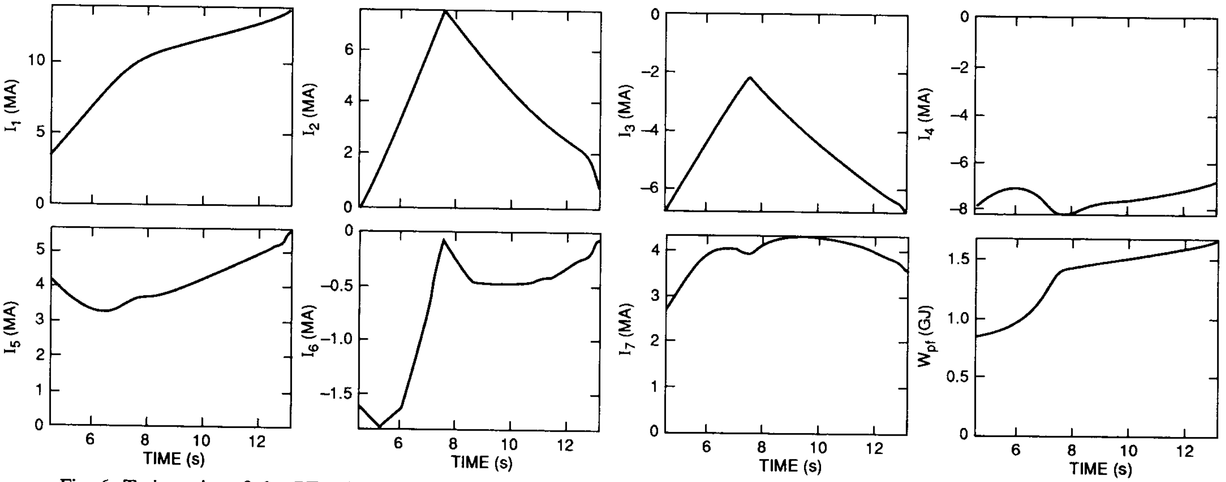

Fig. 6. Trajectories of the PF coil currents controlling the plasma shape and divertor sweep, and the PF stored energy (W_{pf}).

Summary

The equilibrium code BEQ is used to optimize the BPX divertor sweep. A sequence of DN diverted equilibria with constant q during flattop, and a prescribed path of the OSP, demonstrates the feasibility of the BPX divertor surface geometry and maximizes the sweep distance of the OSP subject to limits imposed on distances between X-point and strike points. Plasma profiles and linked flux are consistent with a fiducial discharge simulation using the TSC code.

References

[1] R. J. Goldston et al., "Burning Plasma Experiment Physics Design Description," BPX Report X-910311-PPL-22, March 1991, to be published in Fusion Technology.

[2] D. J. Strickler, Y-K. M. Peng, S. C. Jardin, and N. Pomphrey, "Dependence of CIT PF Coil Currents on Profile and Shape Parameters Using the Control Matrix," Fusion Technol., 19, 1452, 1991.

[3] S. C. Jardin, N. Pomphrey, and J. Delucia, "Dynamic Modeling of Transport and Positional Control of Tokamaks," J. Comput. Phys. 66, 481, 1986.

[4] R. D. Pillsbury (MIT), personal communication.

[5] J. R. Haines (PPPL), personal communication.