Simulations of Plasma Performance in a Beam-Driven Tokamak
Fusion Reactor with $Q \approx 2-3$

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Abstract

Supershot profiles were used to simulate plasmas in a neutral-beam-driven tokamak reactor designed to achieve fusion energy production with $Q \approx 2-3$. Profiles from a TFTR supershot were scaled to larger radii, density, and electron temperature. The TRANSP code was used to calculate performance of these plasmas. Examples are given of steady-state plasmas with large beam-driven bootstrap currents. The required energy transport rate is comparable to that in TFTR, but the particle transport rate must be less. The PEST code indicates that the plasmas would be MHD stable if the central q_ψ can be controlled.

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The supershot regime, discovered in TFTR,¹ is an efficient plasma configuration for producing thermonuclear fusion energy since the density is concentrated in the region of high temperature. It has been suggested² that it may be possible to scale this regime to a steady-state tokamak fusion reactor achieving fusion energy production with $Q \approx 3$. The proposed operational mode uses high energy D^0 and T^0 neutral beams to fuel and drive current in D/T plasmas, while using the beams and fusion alphas to heat the plasma.

The required neutral beam power is anticipated to be $P_{NB} \approx 150$ MW, which at $Q = 3$, gives the substantial neutron wall loading needed for a fusion test reactor. Proposed uses of the neutrons from such a "Beam-Driven Tokamak Reactor" (BDTR) include developing nuclear-resistant components for use in future engineering test reactors and fusion power reactors, and for making isotopes such as tritium, ^{60}Co , and fissile material.

This paper describes simulations of plasma performance in a BDTR. The TRANSP³ code was used to calculate fueling rates, transport coefficients, current profiles, and neutron production. The PEST code⁴ was used to study the MHD stability. Engineering issues, such as the feasibility of the continuous, high-energy D^0 and T^0 injection, presumably from negative ion sources, are not addressed.

We found that in order to achieve high Q , the plasma must be dense. High density implies that the fusion will be mainly thermonuclear, instead of beam-target or beam-beam. The energy confinement in these simulated plasmas is slightly higher than L-mode. The energy

transport coefficients are estimated to be comparable to the values in TFTR supershots. Thus, if the energy confinement does not degrade in the extrapolations, the energy source from the beams will be sufficient. Also, the currents driven by the beams appear to be sufficiently large for confinement.

Steady-state fueling of the centrally peaked, high-density plasma requires high power and high energy ($\approx 150 - 250$ keV) neutral beams. The diffusion coefficients in the central region must be lower than the supershot values. The diffusion coefficients are expected to decrease with increasing density, plasma current, and toroidal field, so the required values appear feasible.

The scaled-up supershot profiles have a centrally peaked pressure profile, so the MHD stability is determined by the internal kink and ballooning stability. If the pressure is too high, the configuration becomes unstable. This results in an upper limit of Q , which is ≈ 3 with $q_\psi(0)$ above ≈ 1 . In order to improve the MHD stability, noncircular plasma shapes were assumed.

There are several approaches to simulating plasma performance in hypothetical reactors. In the predictive approach, transport coefficients deduced from past plasmas are extrapolated to the new regime. These extrapolations, along with the heating and fueling depositions, are used to predict plasma parameters. In the interpretative approach, plasma profiles from past plasmas are extrapolated to the new regime, and the plasma transport and performance are calculated from the extrapolations. This paper takes the interpretative approach.

TRANSP Simulations. TRANSP is an interpretative code which has been used to analyze discharges from TFTR, PBX, JET, and other tokamaks. The simulations described here are the first uses of TRANSP for reactor simulations.

Several seconds of the steady-state regions of the BDTR discharges were simulated. The profiles for n_e , T_e , and T_i were specified so the energy and particle sources could be computed from the neutral beam injection (NBI) parameters and the assumed particle confinement time ($\tau_p = 0.2$ s). Given the energy and particle capacity of the profiles and the source rates, the energy and particle fluxes could be computed, and with the profile gradients, the diffusivities could be computed.

The plasma profiles were extrapolated from those of one of the best TFTR supershots (35782) at the time of maximum stored energy. The measured n_e , T_e , and T_i profiles were scaled out in radius and up in magnitude, as shown in Fig. 1. The BDTR parameters assumed are $R = 3.9$ - 4.2 m, $a = 0.95$ - 0.98 m, $I_p = 4.2$ - 5.5 MA, and $B_{TF} = 5$ - 7 T.

In order to improve the MHD stability, a large vertical elongation = 1.6-2.2, and triangularity = 0.25-0.50 were assumed, and for several runs, indentation was assumed. Since the assumed boundary flux surfaces are very noncircular, a new equilibrium module in TRANSP had to be used. This is a modification of the Variational Moments Equilibrium Code (VMEC).⁵ Contour plots of the flux surfaces within the assumed external walls are shown in Fig. 2.

The neutral beam heating and fueling was assumed to consist of D^0 and T^0 beams. Various choices of the beam energies in the range 200-375 keV were studied. If the energies of D^0 and T^0 beams are equal, they can be mixed in the neutral beam sources. This makes the beam systems simpler since the D^0 and T^0 which are recovered from the neutralizers can be reinjected into the sources without having to be separated. The trade-off is that the steady-state D/T mix in the plasma will deviate from the optimal 50/50, because the equal-energy D and T beams have different penetrations. The fueling requirements appear to be crucial. The lower energy appears most promising since the particle current would be larger at fixed NBI power.

Several choices for the tangency radius of the NBI were studied, ranging between 1.0 to 3.9 m, to compare deep and shallow injection. The direction of the injection was varied by choosing some of the sources in the co-direction (parallel to the plasma current) and some in the counter-direction, so that $\text{cofrac} \equiv P_{\text{co}} / (P_{\text{co}} + P_{\text{ctr}})$ ranged from 1/3 to 2/3. The unbalanced NBI ($\text{cofrac} \neq 0.5$) allows large beam-driven currents. The various plasma and BDTR operating parameters are summarized in Table 1.

In order to get high Q, the TFTR supershot density and electron temperature had to be scaled up considerably, but the ion temperature is already high enough. Figure 3 shows that increasing T_i above 35 keV has little effect. The Z_{eff} was assumed, optimistically, to be 1.2. Supershots have Z_{eff} around 2.5, but Z_{eff} tends to decrease with density, so lower Z_{eff} is plausible in a BDTR.

The results of TRANSP runs are summarized and compared with the supershot results in Tables 2-4. Unbalanced injection with cofrac = 1/3 was chosen in order to have a negative beam-driven current countering the large bootstrap current, resulting in relatively broad current and q_ψ profiles which have greater MHD stability. It appears plausible that the assumed neutral beam heating can fuel plasmas with driven currents and $Q \approx 3$. The rest of this paper discusses details of the simulations and their MHD stability.

Energy and particle balance. The particle balance equations solved by TRANSP are

$$\delta n(x)_p / \delta t = v(x)_p + w(x)_p - \nabla \cdot \Gamma_p(x) \quad (1)$$

for each plasma species $p = e, D, T$, or impurity (α , carbon, etc.) where x is the relative flux surface coordinate (r/a for plasmas with circular cross sections). The source rate is separated into a volume source, $v(x)_p$, from beam fueling and charge-exchange loss, and a wall source, $w(x)_p$, from recycling at the divertor or limiter. The volume-integral of Eq.(1) within a flux surface gives

$$\delta N_p(x) / \delta t = V_p + W_p - A(x) \Gamma_p(x) \quad (2)$$

with A = the area of the surface and V and W being the volume integrals of v and w . The recycling source was normalized from Eq.(2) after W was computed using

$$\Gamma_p(a) = N_p / \tau_p$$

with τ_p assumed.

The energy balance equations solved by TRANSP are schematically

$$\delta u_p / \delta t = q_p - \nabla \cdot f_p . \quad (3)$$

Transport coefficients. The phenomenological particle diffusivities are defined and computed from Eq. (2):

$$(V + W)/A = \Gamma_p = -D_p \frac{1}{a} \frac{\delta n_p}{\delta x} .$$

Particle pinch effects, if any, are included in D_p . The heat conductivities are calculated from

$$Q/A = f_p = -n_p \chi_p \frac{1}{a} \frac{\delta T_p}{\delta x} + \frac{3}{2} T_p \Gamma_p , \quad (4)$$

where Q is the volume integral of q .

Transport results. Examples of the computed densities of the plasma species are shown in Fig. 4. The beam deposition profiles given in Fig. 5 are more peaked for BDTR than TFTR since the beam energy was chosen higher to penetrate the high density BDTR plasmas. The ion source rates are given in Fig. 6. For both TFTR and BDTR the fueling is dominantly due to beams for $r/a < 0.4$ and due to wall recycling for $r/a > 0.6$.

Results for transport coefficients are shown in Figs. 7-8 and compared with the results of supershot 35782. For both the TFTR supershot and BDTR, the dominant energy loss for ions and electrons in the

region near $x = 0.5$ is due to conduction, the $\delta T_p / \delta x$ term in Eq. (4). The heat conductivity for the BDTR is lower than the TFTR values in much of the plasma out to $x = 0.5$, but the effects of alpha heating, estimated below, should make the BDTR values higher.

The particle diffusivities in the inner region ($x < 0.5$) for the BDTR cases are generally lower than the supershot values by a factor of 5-10. With the beam power fixed, as the energy is lowered, the number of particles injected increases, making the particle fueling better and the energy fueling worse.

The computed energy confinement times τ_E^{tot} , which include the thermal and beam confinement, are given in Table 3. They are slightly higher than the Goldston L-mode expression (scaled from $H^0 \rightarrow D^+$ to $D^0/T^0 \rightarrow D^+/T^+$).

Fusion yield. The neutron production profiles are shown in Fig. 9 and the predicted Q values are listed in Table 4. The highest fusion power was 416 MW, giving $Q \approx 2.8$. The fraction of the fusion yield due to thermonuclear reactions is about 73% and the rest is due to beam-target reactions. The beam-beam yield is negligible, in contrast to TFTR supershots, due to the high density assumed.

Alpha effects. Alpha heating was not included in the TRANSP simulations. One of the effects is to increase the energy source, so the beam power could be reduced, leaving the energy source and thermal diffusivities at comparable levels. This effect would increase the thermonuclear contribution to Q by reducing the denominator. Alternatively, the same beam power with higher diffusivities could

generate profiles similar to those assumed, resulting in the same thermonuclear Q. A contrary effect of alpha particles is that they dilute the plasma, so unless their confinement time is short, they would lower Q.

The increase in χ due to alpha heating can be estimated for run 9931 as follows: From Fig. 9, most of the neutron production occurs for $x < 0.2$. The total rate within this surface is 8×10^{19} alphas/cm³/sec. Assuming the alphas deposit their energy within this surface, their contribution to the heating would be 50 MW. The NBI heating of the D and T ions within this surface is 23 MW and the loss by ion-electron coupling is 13 MW. If 1/3 of the alpha energy heats these ions, then the computed χ_{ions} would be higher by a factor of 5. With 2/3 of the alpha energy deposited on the electrons, χ_e would be 2.5 times higher. These values would be close to the values computed by TRANSP in Fig. 7.

Fuel removal. The total volume and wall fueling rates V and W are listed in Table 2. The wall dominates in all cases, as it does in present-day tokamak experiments. The recycling coefficient at the last closed flux surface is defined by

$$R_p = W_p / (A(a) \Gamma_p(a))$$

$$= 1 - V_p \tau_p / (A N_p).$$

This is around 98% for D and T, so a wall pumping efficiency of 2% is required to maintain steady-state, i.e., to remove the beam-injected particles. For comparison, $R_D \approx 0.9$ for 35782.

Ash Removal. The alpha production rate is calculated to $(1-1.6) \times 10^{20}$ /s, so if $\tau_\alpha = \tau_p = 0.2$ s, as assumed, then N_α/N_e will be 0.2%, which is small enough to not dilute the plasma. If τ_p were larger, the wall recycling and R_p would be smaller and N_α/N_e would be larger, and the diffusivity required to achieve the specified density profiles would have to be smaller, and perhaps, less feasible.

Currents. The neoclassical bootstrap current⁵ I_{boot} is relatively small in present-day tokamak experiments,⁶ but the predicted values for BDTR were more than half of the total current I_p . The beam-driven currents were also about half for the runs with $\text{cofrac} = 2/3$. The current driven by the pressure gradient of the thermal plasma $I_{\nabla(P)th}$, which is negligible in present-day tokamak experiments, was up to 8% of I_p . The predicted current driven by the pressure gradient of the beams $I_{\nabla(P)bm}$ is smaller. Relatively small residual Ohmic currents were computed in the simulations. It appears that fine-tuning the plasma and NBI parameters would result in zero j_{Oh} . Computed current profiles are shown and compared in Fig. 10. The $q_\psi(x)$ profiles are given in Fig. 11.

MHD stability. The PEST code was run to study the kink and ballooning stability of several of the TRANSP simulations. The stability depends on the q_ψ and pressure profiles, with the value of $q_\psi(0)$ being particularly sensitive. The values of $q_\psi(0)$ calculated by TRANSP were low, as is typical when the sawtooth model is not invoked. For the PEST calculations, the q_ψ values near the axis were increased, as shown in Fig. 11, keeping the total current fixed. The pressure profiles were scaled to find the instability threshold.

The stability regions for β_{Poloidal} versus $q_{\psi}(0)$ for two cases are plotted in Figs. 12-13. In Fig. 12 for the indented plasma run 9930, the TRANSP result is denoted as point a. If $q_{\psi}(0)$ is increased above 1 to point b, the plasma would be stable to the internal kink, but ballooning unstable. Slight modifications of the pressure profile should make this plasma stable. The stability region for the plasma of run 9931 is sketched in Fig. 13. The internal kink limit extends to higher $q_{\psi}(0)$ in this case, so the value of $q_{\psi}(0)$ would have to be raised to about 1.1 for stability, so this configuration appears more difficult to obtain.

A useful parametrization of the pressure is β^* defined as⁸

$$\beta^* = \frac{2\mu_0}{B_0^2} \left\{ \frac{\int p^2 dv}{V} \right\}^{1/2}$$

The values of $g^* = \beta^* / I_n$ (where $I_n = I_P/a/B_{TF}$) are compared with the TRANSP values in Table 3. For comparison, the Troyon value is $g = 3$, and some supershots with $q_{\psi} \approx 8$ get to $g^* = 4$.

In conclusion, the BDTR plasmas are predicted to achieve $Q \approx 2-3$. This is a factor of ≈ 7 increase above the value expected for current TFTR supershots with a 50%/50% D/T mix. The predictions require that high density supershot profiles can be maintained with the neutral beam injection and recycling providing the fueling. The TFTR supershots were obtained transiently in plasmas with Z_{eff} around 2.5-3 and with approximately balanced injection and circular cross-sections. We do not know whether the supershot profiles will be obtained in the extrapolations to the BDTR.

The energy confinement time does not have to be much larger than the Goldston L-mode expression. Bootstrap and beam-driven currents appear large enough to sustain the total current in steady state. The heat and particle diffusion rates must be lower than those in TFTR supershots. Alpha heating will increase the required energy diffusion rates toward the TFTR supershot values. The diffusion rates in the BDTR plasmas are expected to be lower with the larger density, radius, plasma current, and toroidal field. The cases we studied have approximately four times the electron density, five times the plasma volume, five times the plasma current, and one to two times the toroidal field.

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Table 1

Comparisons of the plasma parameters for the TFTR supershot 35782 with the BDTR simulations

Shot/run	35782	9904	9926	9930	9931
R (m)	2.47	3.9	3.9	4.2	3.9
a (m)	0.81	0.95	0.95	0.98	0.95
elongation	0.97	1.6	2.1	1.7	2.1
triangularity (%)	2.9	25	50	60	50
Volume (m ³)	31	110	135	168	135
P_{NB} (MW)	22	150	150	150	150
E_D (keV)	106	250	250	250	250
E_T (keV)	0	340	375	250	250
cofrac	0.56	2/3	1/3	1/3	1/3
beam tang rad (m)	1.7-2.2	3.9	2.9	2.9	1.0
P_{rad} (MW)	6	60	30	30	30
I_p (MA)	1.2	5.5	5.0	5.0	5.0
B_{TF} (T)	4.7	7.2	7.2	5.9	5.7
$q_\Psi(a)$	6.2	3.8	8.5	10	6.5
$n_e(0)$ ($10^{20}/m^3$)	0.8	2.5	3.3	3.3	3.3
$T_e(0)$ (keV)	8	20	20	20	20
$T_i(0)$ (keV)	26	35	32	32	32
Z_{eff}	2.4	1.2	1.2	1.2	1.2
τ_p (s)	0.07	0.2	0.2	0.2	1.2

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Table 2

Comparisons of results of the TRANSP simulations for the TFTR
supershot 35782 with BDTR simulations

shot/run	35782	9904	9926	9930	9931
I_{boot} (MA)	0.60	2.8	4.5	4.3	4.3
I_{beam} (MA)	0.24	2.7	-0.2	-0.2	0.0
$I_{\nabla(P)th}$ (MA)	0.0	0.3	0.4	0.7	0.7
$I_{\nabla(P)bm}$ (MA)	0.0	0.0	0.1	0.1	0.0
I_{Ohmic} (MA)	0.56	-0.3	0.2	0.0	0.0
V ($10^{22}/s$)	0.1	0.3	0.3	0.4	0.3
W ($10^{22}/s$)	0.7	3.0	5.0	5.3	5.0
N_D/N_e (%)	61	53	49	45	44
N_T/N_e (%)	0	33	47	42	43
N_{beam}/N_e (%)	20	9	3	2	2
U_{total} (MJ)	3.8	72	72	65	69
U_{ions} (MJ)	1.4	34	30	26	30
U_{el} (MJ)	0.8	17	25	26	25
$U_{\perp}$ (MJ)	1.0	13	11	9	12
$U_{\parallel}$ (MJ)	0.7	8	6	4	2

Table 3

Comparisons of beta and energy transport

shot/run	35782	9904	9926	9930	9931
β_T^{eq} (%)	0.9	2.4	1.7	1.85	2.6
β_p^{eq}	1.85	1.6	3.3	2.9	3.2
I_n	1.23	0.80	0.73	0.85	0.92
g^*	3.4	3.4	3.6	4.0	5.5
χ_i/χ_{CH}	35	120	75	450	75
τ_E^{tot} (s)	0.22	0.50	0.46	0.50	0.50
$\tau_{\text{L-mode}}$ (s)	0.06	0.38	0.34	0.35	0.42

Table 4

Comparisons of fusion yields predicted by the TRANSP simulations. The supershot yield listed is a TRANSP simulation of a D-T plasma with the D-D parameters and full energy NBI (#8795).

shot/run	8795	9904	9926	9930	9931
Fusion yield (MW)	7.8	236	403	361	416
thermal fraction	0.31	0.61	0.72	0.71	0.73
beam-thermal fr	0.58	0.35	0.27	0.28	0.27
beam-beam fr	0.12	0.02	0.01	0.01	0.01
Q	0.35	1.57	2.69	2.41	2.78

Figure captions

Fig. 1 Measured profiles from the TFTR supershot 35782 with the major radius scaled by 1.17 and shifted out 1 m. a) electron density scaled by 4.5, b) electron temperature scaled by 2, and c) ion temperature scaled by 1.36.

Fig. 2 Flux contours and the vacuum vessel wall assumed for plasmas with elongation a) 1.6 and b) 2.2.

Fig. 3 D->T fusion yield versus temperature.

Fig. 4 Plasma and beam density profiles.

Fig. 5 Beam deposition profiles.

Fig. 6 Ion source rate profiles from volume and wall fueling.

Fig. 7 Energy conductivities.

Fig. 8 Particle diffusivities.

Fig. 9 Neutron production profiles.

Fig. 10 Current profiles.

Fig. 11 q_ψ profile computed in run #9931 and the fit used for the PEST analysis.

Fig. 12 MHD stability region for the plasma conditions of run #9930 with the pressure scaled. The points indicate PEST runs.

Fig. 13 MHD stability region for the plasma conditions of run #9931 with the pressure scaled. The points indicate PEST runs.

Fig. 1

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Fig. 2

FIG. 3

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Fig. 4

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Fig. 5

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Fig. 6

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Fig. 7

Fig. 8

Fig. 9

Fig. 11

Fig. 12

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FIG. 13

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