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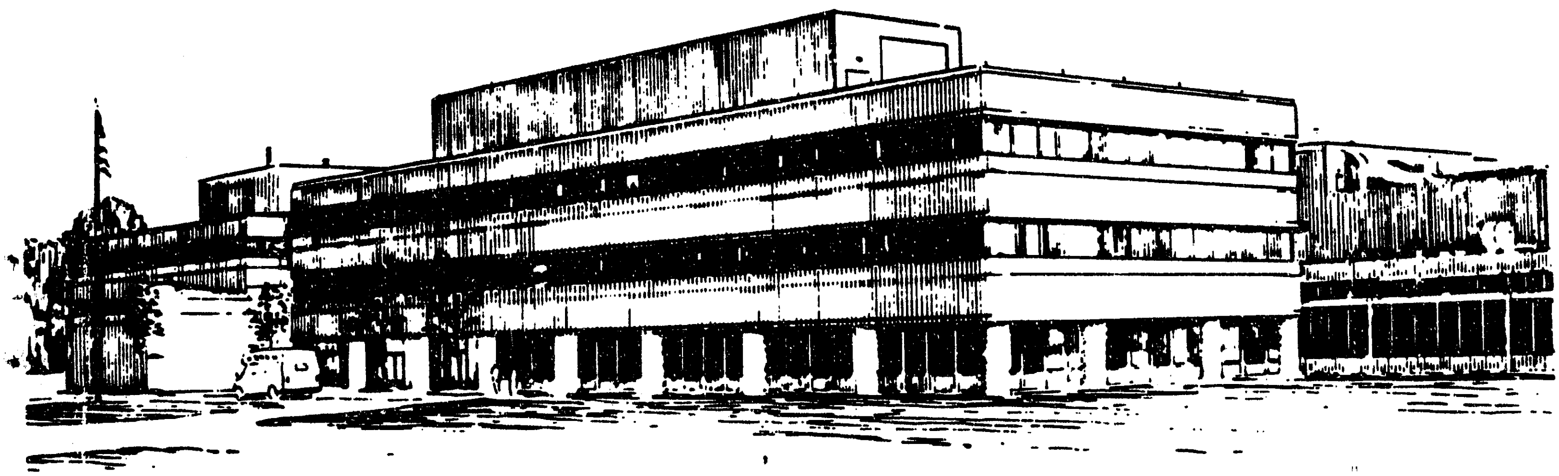

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SIMULATIONS OF BEAM-FUELED SUPERSHOT-LIKE PLASMAS NEAR IGNITION*

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Abstract

Centrally peaked profiles would be advantageous for tokamak reactors since the pressure and the bootstrap current would be peaked in the regions of intense reactivity. We use the TRANSP plasma analysis code to investigate the feasibility of fueling with neutral beam injection. We show that for certain conditions, neutral beams with energies less than 120 keV can penetrate into the cores of plasmas that have a large thermonuclear yield and Q_{DT} ~10. This value of Q_{DT} is too small for an economical reactor if the neutral beam injection is the only fueling source. We give examples for several proposed compact prototype reactor designs.

Introduction

In certain conditions, neutral beam injection (NBI) into plasmas with controlled recycling results in supershots[1]. These are characterized by peaked density profiles and high central ion temperatures. We discuss the potential advantages of NBI fueled supershot-like plasmas in tokamaks operating near ignition. The goal is to investigate the feasibility of these plasmas to aid in the design of future advanced tokamaks.

NBI has been very successful in advancing tokamak plasmas close to ignition conditions. The primary benefits of NBI are heating and particle fueling, but the plasma currents generated by the beam ions are also of considerable interest. The optimal NBI energy E_B for the beam ions depends on the desired role of the NBI. For central particle fueling, E_B should be low to maximize the particle current at fixed injected power P_B, but high enough to penetrate to the core. For heating and current drive, higher E_B is preferable for deepest penetration. With the standard positive ion beam technology, the neutralization efficiency becomes too low for useful power densities if E_B is significantly greater than about 120 keV. Negative ion beam sources would be useful for heating and current drive at very high E_B (500 keV or more), but the fueling rate of NBI is too low be practical. It seems generally accepted that future tokamaks which operate closer to ignition will have to be fueled by means other than NBI since it is argued that the beams with low E_B can not penetrate deeply into the dense plasmas of interest.

We show that contrary to this belief, for certain plasmas which are close to, or at ignition conditions, D and T neutral beams with $E_B < 120$ keV can penetrate into the core. This offers potential solutions to some of the challenges for ignited plasmas. For instance, the NBI sources of D and T in the plasma core might keep the Z_{eff} low by displacing impurities and the He ash. If the core fueling rate is 10 times the DT fusion rate, and if the He concentration is 10% of the fuel concentration, then the He might be displaced by the NBI ions along with thermal D and T, maintaining a steady state. Also it may prove difficult to replenish the fusing D and T if the inward pinch velocity is small. Pellet injection may be too disruptive for steady state ignition. Also pellets will not penetrate deeply when the electron temperature becomes too high. Unlike pellets, the NBI penetration does not decrease as the electron temperature increases. Unlike gas fueling, the NBI fueling is deep, so edge recycling could be kept low. Other potential uses of NBI are heating for reactor startup, or heating ions to complement the electron heating of the α particles in tokamaks operating close to ignition.

Yet another possible advantage of NBI is that supershot-like profiles with peaked density profiles may be produced. These profiles appear advantageous for several reasons. The region of high density is concentrated in the region of highest temperature, so the pressure and stored energy are used efficiently to maximize the DT fusion rate. The fusion power depends roughly on $\langle n^2T^2 \rangle$ whereas the stored energy depends on $\langle nT \rangle$. MHD stability calculations[2] have shown that the TFTR plasmas with more peaked pressure profiles have increased stability at high $\beta^* \equiv (2\mu/B^2)\sqrt{\langle p^2 \rangle}$. Also long pulse tokamaks will need large non-inductive currents, such as the bootstrap current. With centrally peaked pressure profiles the bootstrap current profile is close to the desired total current. A study of the ignition probability in BPX has shown that peaked profiles can significantly reduce the operating parameters required to achieve a desired fusion performance level relative to those needed with flat profiles.[3] Lastly, supershots might be used for reactor startup, with central ignition[4] in a supershot that later develops into an L-mode or H-mode plasma.

There are disadvantages which may preclude NBI from being of use in commercial reactors. One is the problem of shielding the neutrons since the neutral beams need straight lines of flight into the plasma. Also if an electrical power reactor were fueled continuously and entirely by NBI, economics imposes a lower bound on Q_{DT} and an upper bound on E_B. The Carnot cycle would convert the fusion yield Y_{fus} to electricity with an efficiency η which is typically about 1/3. Some fraction of this electricity, f, would be diverted to the NBI system, and converted to injected power P_B with an efficiency ν which is typically also about 1/3 using positive ion beams. Thus

$$Q_{DT} \equiv \frac{Y_{fus}}{P_B} = \frac{1}{f\nu\eta} \qquad (1)$$

If $\nu\eta \approx 10\%$ and f is less than say 20% to be attractive, then Q_{DT} must be greater than 50. Also, the rate of D and T deposition must be at least as large as the DT fusion rate if NBI is the only fueling source. Each fusion reaction generates 17 MeV of fusion yield, so

$$\frac{Y_{fus}}{17\ \text{MeV}} = \frac{P_B}{f\nu\eta\ 17\ \text{MeV}} < \frac{P_B}{2E_B} \qquad (2)$$

requires E_B < f MeV if $v\eta$ is about 0.1. With f = 0.1, E_B = 100 keV could balance the DT fusion rate. In order for the NBI fueling rate to be much larger than the burnup rate, E_B would have to be too small for penetration. Due to these bounds and potential disadvantages, NBI may be useful only for prototype reactors, or for partial fueling of power reactors, complementing pellet fueling and gas puffing.

Simulations for prototype reactors

We give specific examples of supershot-like profiles in which the central NBI fueling rate is greater than the DT fusion rate. The NBI penetration depends on the plasma profiles and NBI parameters. We studied NBI for the tokamaks in Table I.

Table I Generic tokamaks and supershot-like plasmas with the central NBI fueling rate greater than the fusion rate

tokamak class	R (m)	a (m)	B (T)	I (MA)	$n_e(0)$	$T_e(0)$	Z_{eff}	P_B	b(0)
Small R	1.3	0.47	13	12	8.5	16.5	1.2	8	1
Medium R	3.0	0.69	7	7	3.0	40	1.6	40	12
Large R	7.0	1.1	12	6.5	3.6	47	1.5	50	3.5

The units of n_e, T_e, P_B, and Y_{fus} are $10^{20}/m^3$, keV, and MW. The central burnup fraction b(0) is the ratio of the NBI fueling rate of D to the DT fusion rate.

The small R case is similar to the proposed IGNITOR tokamak.[5] The medium R case is similar to the proposed SSAT,[6] although DT is not planned to play a significant role in this tokamak. The large R case is similar to the ARIES-1 reactor.[7] The plasmas for all three were chosen to have an elongation and triangularity of approximately 1.8 and 0.4 respectively, and a relatively small minor radius which facilitates NBI penetration along the midplane. The plasma boundaries are compared in Figure 1.

The plasma transport for these unexplored plasmas is unknown, so we assumed density and temperature profiles representative of supershots, scaled to give the desired fusion yields. The n_e profile is assumed to have a peaked central region proportional to $\{1-(2x/3)^2\}^{\alpha_n}$ and a broad pedestal proportional to $(1-x^2)$, where α_n is taken to be in the range 2-2.5 to give a peaked central profile, and x is the square-root of the normalized toroidal flux. Its value would be r/a if the flux surfaces were circular. Examples the assumed n_e profiles for the large R case are shown in Figure 2. The electron and ion temperatures are assumed to be equal and to be proportional to $(1-x^2)$.

The TRANSP plasma analysis code was used to calculate steady-state conditions in these plasmas. The simulations calculate the heating profiles of the neutral beams and of the fast α particles[8]. They also predict the neutron emission profiles and the current profiles from the bootstrap and beam driven currents. The predicted α parameters include profiles of the α density, average energy, slowing down time, and β_α. We do not include effects of the He ash. The He concentration must be kept low by some unspecified means to maintain the fusion rate at steady state.

The penetration depends on n_e, T_e, and E_B. We choose $E_B \approx 100$ - 120 keV, with the full and half energy fractions of the TFTR beam lines, and we explored bounds on n_e and α_n. As n_e increases, the beam penetration to the center decreases. This is shown in Figure 3 for the large R tokamak with 25 MW of D and 25 MW of T NBI into the densities shown in Figure 2. The thermal D fueling rates from NBI and wall recycling for the intermediate density case are compared with the DT fusion rate in Figure 4. The thermal T fueling rates are comparable to the thermal D fueling rates. As the density increases, the central fusion rate increases and the central NBI penetration decreases. These cross over at the intermediate density case in Fig. 2. The case with $Q_{DT} = 13$ is summarized in Tables I and II. Plasmas with higher densities could be centrally fueled with greater P_B. The other examples given in the Tables also have predicted central NBI fueling rates equal to the DT fusion rates.

The penetration of the NBI to the core also depends on the peaking of the density profile. We studied variations of the deposition profile on α_n. Figure 5 shows n_e profiles for medium R simulations with $Q_{DT} = 7.2$. The corresponding NBI source profiles of thermal D are shown in Fig. 6. The values of the central source rates increase with increasing α_n. The central source rates are more than an order of magnitude greater than the fusion sink rate.

TRANSP calculates the transport coefficients required by the assumed profiles. These can be compared with those measured in presently operating tokamaks, or with theoretical predictions. Whether of not the transport in the plasmas will be low enough to support the plasmas in steady state remains to be seen. We compare the profiles of the ratios of χ_i / D_e to those measured in one of the best-performing TFTR supershots in Fig 7. The ratios would have to be higher than the measured values since D_e would have to be smaller to support the larger densities. Smaller values of D_e might be expected since the aspect ratio is larger for the simulations. The transport in these advanced tokamaks might be reduced from the rates measured in TFTR for several reasons. Large elongation is expected to increase the ballooning limits, and large aspect ratio is expected to reduce the trapped fraction.

The calculated energy confinement times and bootstrap currents are shown in Table II. The bootstrap current can be a large fraction of the total current.

Table II Calculated energy confinement times and bootstrap currents for the plasmas in Table I

tokamak class	Y_{fus}	Q_{DT}	$q_{MHD}(a)$	τ_E (s)	β_{norm}	I_{boot}(MA)
Small R	100	12	3.5	0.83	0.5	0.8
Medium R	280	7	3.2	0.70	3.1	2.9
Large R	640	13	5.1	1.60	2.2	4.3

Conclusions

Supershot-like plasmas have given high neutron yields in present-day tokamaks. NBI fueling plays a crucial role in creating these plasmas. We argue that NBI fueled supershot-like plasmas have advantages for future advanced tokamaks and prototype reactors. We used the TRANSP code to show examples where the NBI source rates of central D and T are greater than the DT fusion rates.

Figure Captions

Fig. 1 Plasma boundaries used for the TRANSP simulations and the boundary of a typical TFTR supershot. For diverted plasmas the boundaries would specify an outer flux surface such as the 95% surface.

Fig. 2 Examples of electron density profiles used for the TRANSP simulations of the large R cases compared with a TFTR supershot (#55851).

Fig. 3 Profiles of the source rate of thermal deuterium from 25 MW of D NBI corresponding to the three profiles for the large R cases in Figure 2.

Fig. 4 Profiles of source and sink rates of thermal deuterium for the $Q_{DT}=29$ case in Figures 2 and 3. The source rate from NBI is compared with the sink rate due to fusion and an assumed recycling source rate.

Fig. 5 Electron density profiles for the medium R case with α_n varying, keeping $Q_{DT} = 7.2$.

Fig. 6 Profiles of the NBI source rates corresponding to the profiles in Fig. 5.

Fig. 7 Profiles of the ratios of the effective heat and particle conductivity of the thermal ions.

Footnotes

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[a] Columbia University
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Figure 1 Cross sections of plasma boundaries

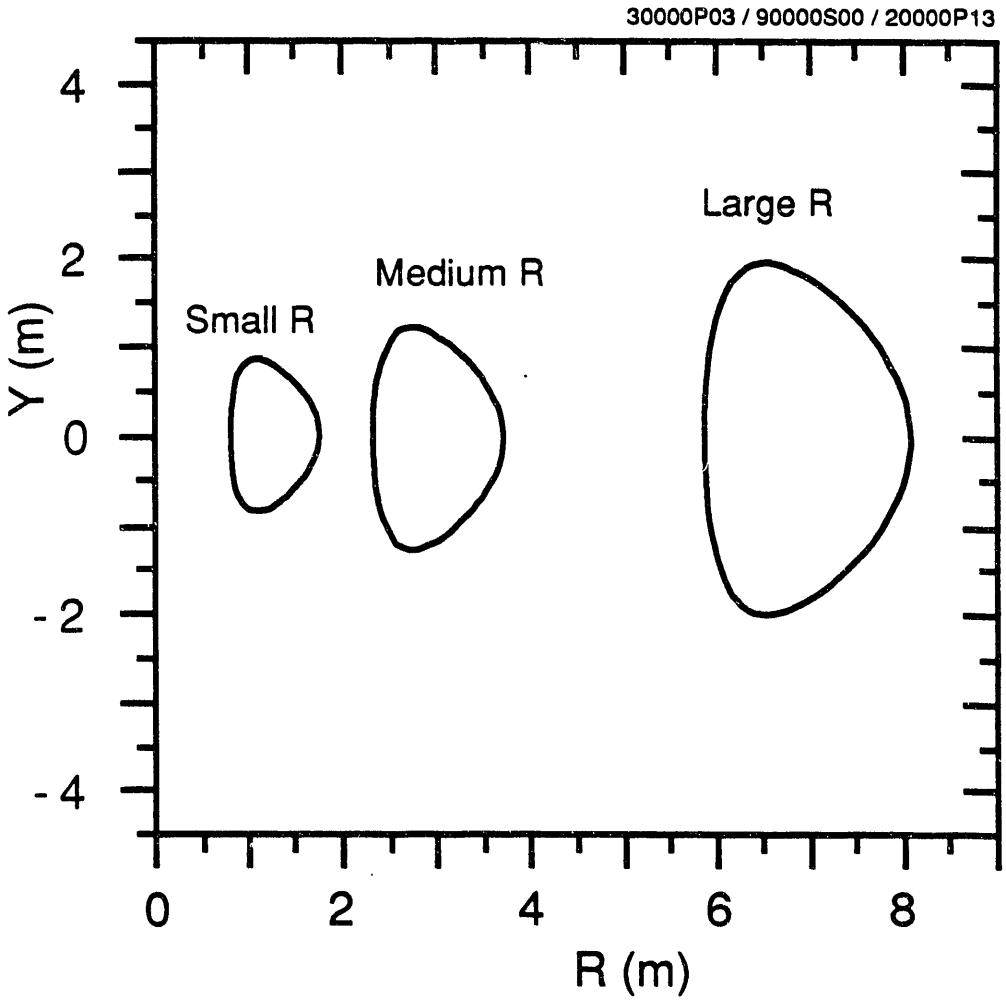


Figure 2 n_e profiles for the large R simulations

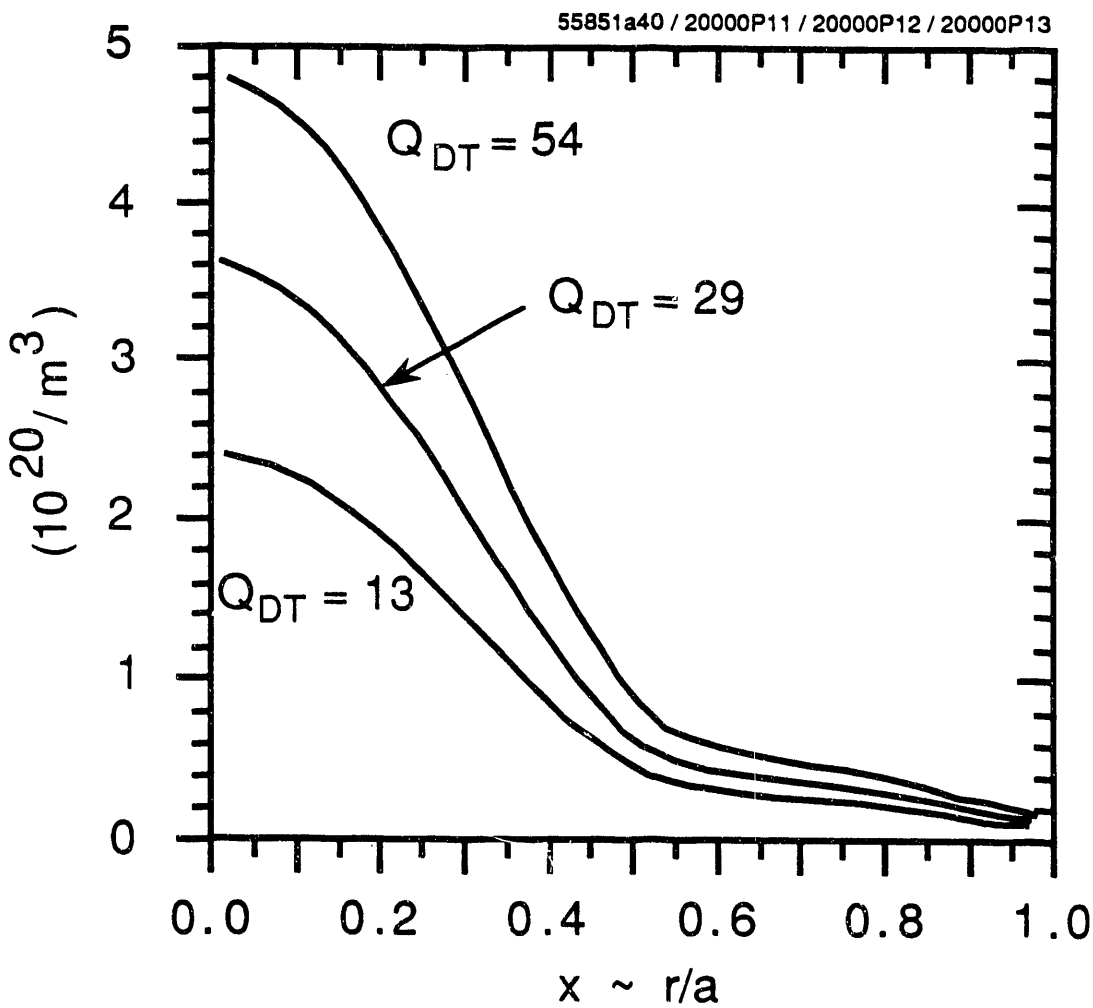


Figure 3 Varation of NBI fueling rate with n_e

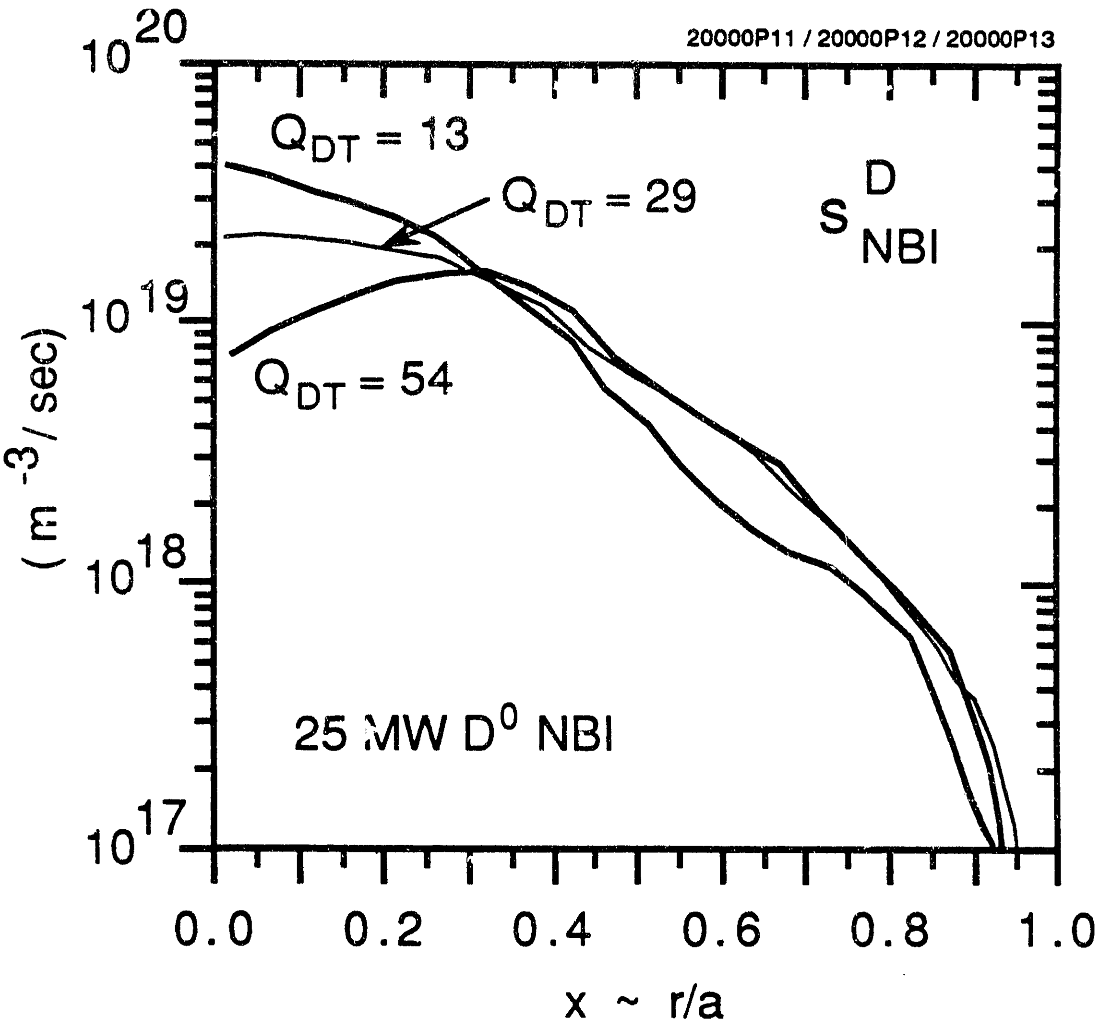
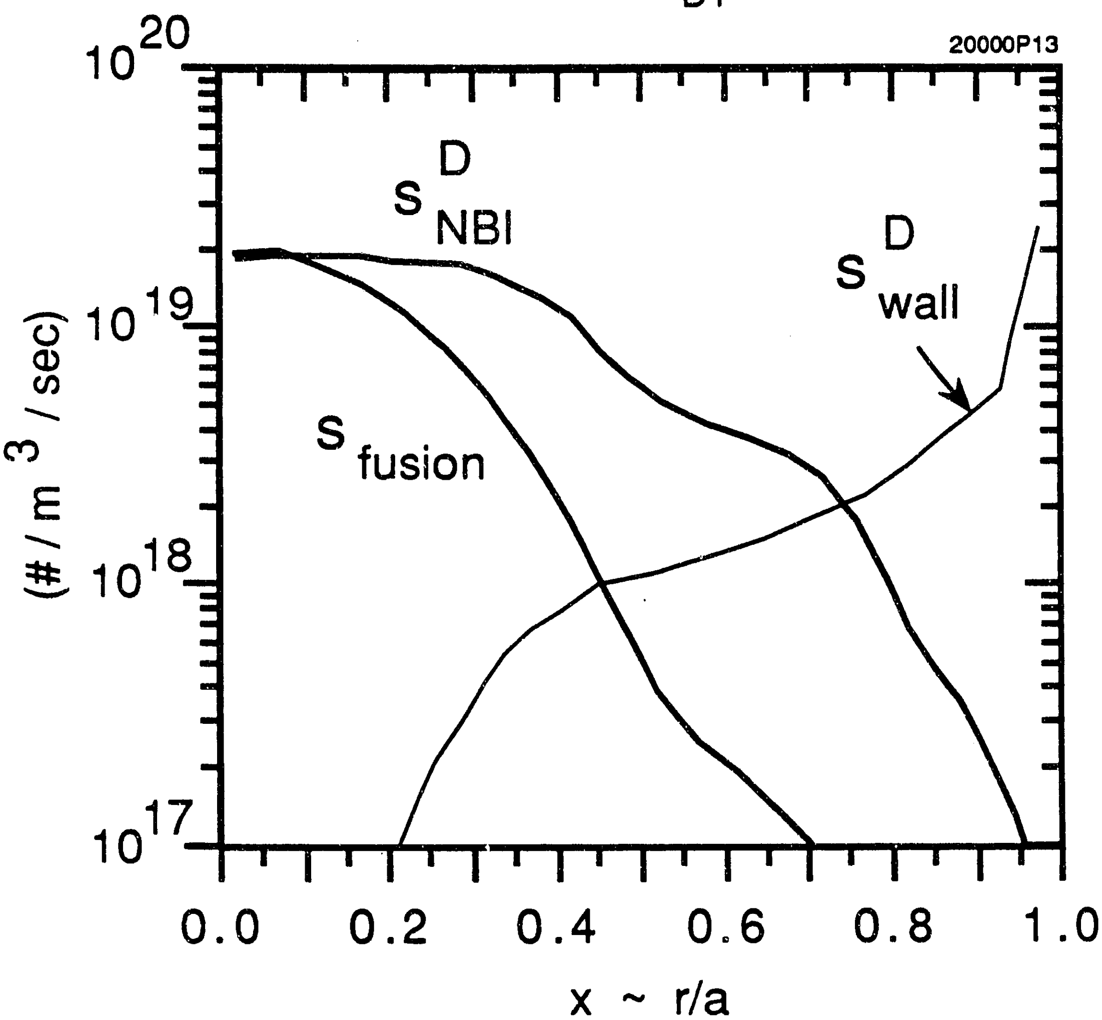


Figure 4 Fueling and burnup

Y = 1430 MW, Q_{DT} = 29



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