BEAM PENETRATION - THEORY AND PREDICTIONS*

CONF-771129--2

James A. Rome
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

I. INTRODUCTION

Neutral beam injection has proved to be very successful at heating the moderate sized, moderate density tokamaks of today and is now the prime candidate for heating the next generation of tokamaks. It is thus appropriate to consider the conditions under which injection heating can be applied to the larger, denser tokamaks of the future.

Extrapolation into the future is not immediately obvious because the regime of applicability of injection is about to change. There are at least three reasons for this. (1) Beam penetration is becoming increasingly difficult. In machines like ATC, ORMAK, and TFR, even low (20-30 keV) energy beams might not be fully absorbed in the plasma. But, for DIII, TFTR and ALCATOR-C, even 80 keV beams (H) barely get to the center. (2) Injection power is increasing by orders of magnitude. So far, injection power has only been up to three times greater than the Ohmic heating power. At such a level, signficant heating can be observed but no possible deleterious effects of injection have been observed. With proposed levels of injection at about 10 times the Ohmic heating power, any limit to injection heating should be observable. This can be most easily done on smaller machines like ISX-B because the volume is smaller. (3) Injector efficiency decreases with increasing injector energy. In spite of great improvement in source design (particularly with respect to species yeild), overall injector efficiency drops drastically as the energy is raised to achieve good beam penetration. At some level, this inefficiency becomes intolerable, at least for reactor applications.

*Research sponsored by Department of Energy under contract with Union Carbide Corporation.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SUMMARY

A review of the theory of beam penetration and deposition in tokamaks shows that large neutral energies are required to penetrate reactor plasmas. On the other hand, for good efficiency, positive ion sources must operate below $\sim$ 80 keV (H^+). Thus innovative start-up and heating scenarios are required. Design of an injection system is discussed. Fueling by means of high energy beams appears to be inefficient and may lead to "blow out" or to a lack of central heating.

To shed light on some of these issues, we will first briefly review beam deposition theory and then discuss strategies for injection and some implications of high power injection.

II. BEAM DEPOSITION IN A TOKAMAK

Energetic neutrals (as opposed to ions) are used for injection in order to penetrate the large toroidal magnetic field of the tokamak. Thus, we must first decide where these fast injected neutrals will become ionized.

There are several ionization processes to consider. At low energies (< 30 keV/nucleon), resonant charge exchange with the hydrogen ions is the dominant process. Since this process exchanges a high energy ion for a low energy ion (which can leave the plasma since it becomes a low energy neutral), ions created by charge exchange do not necessarily provide new plasma particles and hence are not a good source of fuel. But, with high power injection at energies below 30 keV, the increase in neutral density may be important and can lead to plasma cooling and increased gas recycling at the walls.

At injection energies over 30 keV/nucleon, ionization by impact on protons (or deutrons) is dominant. Electron impact ionization occurs but is negligible except at very high energies.

Recently, it has been discovered that the injected fast neutrals can charge exchange and/or impact with impurities in the plasma. Since both of these processes seem to go like $Z_j^{1.4}$, they could be dominant in some situations. Adding over all impurity species of density n_j gives an effective enhancement of the proton impact ionization cross-section:

$$\sigma_i \simeq \sigma_{i_{proton}} [n_p + \sum_j n_{zj} Z_j^{1.4}]/n_e \qquad (1)$$

The (non-resonant) charge exchange on impurities cross-section also seems to scale like $Z_j^{1.4}$ but is about 5 times smaller than the impurity impact cross-section.

Since the injected neutrals go in a straight line, we may treat the beam as being composed of many beamlets each of which traverses the plasma on a different straight line path. Along this path, s, the neutral beam density, N_B, decays by

$$N_B(s) = N_B(0) \exp \left\{ -\int_{-\infty}^{s} K(s')n_e(s')ds' \right\} \tag{2}$$

where

$$K = \frac{n_i}{n_e} \langle \sigma_{cx} v_{bi} \rangle + \sigma_i V_b [n_p + \sum_j n_{zj} Z_j^{1.4}]/n_e \tag{3}$$

$N_B(0) I_B$ is the particle source rate of the beamlet of current I_B, v_{bi} is the relative velocity between the beam and the plasma ions, and the averages are over the plasma ion and electron distribtuions.

Once the fast ions are born, the ions go onto tokamak orbits which are determined by the injection geometry. This process is treated in detail in Ref. 1 for tangentail injection.

The point to make here is that a geometrical peaking of the fast injected ion density can occur because the orbit drift surface area can shrink to zero for certain orbits, called "stagnation orbits." This can be easily seen by regarding tokamak orbits as a competition between $\overline{B} \times \nabla B$ and curvature drifts, and motion along field lines. The two drifts are vertical in a low β tokamak. On the equator, there is a poloidal component of $v_{\parallel}$ which is also vertical and of opposite signs on the two sides of the magnetic axis. Thus, there is some radius for which these two velocities precisely cancel and the orbit shrinks to a circle in the equatorial plane centered on the symmetry axis. All other orbits are toroidal shells with finite surface areas.

The result of this shrinking is that neutrals which are ionized near the stagnation point spread over a smaller area and hence the fast ion density is peaked by this geometric effect. The result of many computer calculations shows that this allows the fast ion density to be centrally peaked (instead of decaying exponentially) for a/λ_o, the ratio of minor radius to mean-free path in the center of the plasma, up to 4.

Figure 1 was developed by H. C. Howe and shows the plasma opacity ($n_e(0)a$) versus energy/nucleor for various values of Z_{eff} under the condition that $a/\lambda_o = 4$ and for a parabolic density profile and for tangential injection. Basically, this graph gives an ideal of how much injection energy is needed for a given plasma.

Perpendicular injection can slightly enhance penetration since the path length to the center of the plasma is shorter. On the other hand, perpendicularly injected particles cannot have stagnation orbits and hence do not benefit as much from the geometric peaking (they can however have very small orbits). Also perpendicularly injected particles can get trapped in the ripples in the toroidal field caused by the descreteness of the coils and drift vertically out of the machine. Thus, practically, if perpendicular injection is used, the injectors are tilted about 12° from the true perpendicular so as to avoid this trapping region.

However, the preceeding "back of the envelope" treatment of injection deposition must be revised for several reasons: The $a/\lambda_o = 4$ criterion is insufficient to assure centrally peaked plasma heating. To do this requires that the deposition profile be more peaked than the plasma density profile. It is becoming increasingly apparent that the highest values of β can be achieved in elongated cross-section plasmas; at high β values, the flux

surfaces also become non-concentric. Finally, with long beam lines becoming common, the beam divergence, focusing and cross-section must be taken into account.

For these reasons, D. Post of Princeton Plasma Physics Laboratory developed a new Monte-Carlo beam deposition code which correctly treats the injector geometry. This code was then modified by R. H. Fowler of ORNL to use numerically generated solutions of the MHD equilibrium equation to correctly treat the plasma geometry. Finally, this code is being coupled into the 1½ D transport code of J. T. Hogan which recomputes the plasma equilibrium during the simulation.

III. INJECTION STRATEGIES

Given that you wish to heat a large, dense tokamak with beams, a quick look at Fig. 1 is v ry discouraging. For example, typical TNS parameters of $n_e(0) = 1 \times 10^{14}$, $a = 1.25$ m yield a marginal penetration energy of 80 keV (H) for $Z_{eff} = 1.5$. Raising the density or Z_{eff} makes penetration impossible for reasonable injection energies. Once the required injection energy goes above 80 keV (H), more complicated injection scenarios must be used.

One example of this is a low density start-up scenario such as proposed for the ORNL TNS.[2] At low densities, beam penetration is no problem; and the central density must then be increased with, say, pellet injection while heating is continued. As β increases, the magnetic axis shifts outward and fusion reactions begin to occur in the central region. A combination of this α-particle heating and the shortened distance to the center may allow the now marginally penetrating beam to be sufficient.

An alternative scenario proposed for JET is the expanding limiter start-up. If the plasma is started with high density but with a small radius, the initial plasma couls be heated with moderate energy beams. Then, cold plasma would be added to the outside and would be heated up by the beams which now no longer penetrate.

In order to carry out these scenarios, it may be necessary to use more flexible injector power supply systems which will ramp up the beam energy during a discharge. If the full-bore, full-density injection energy were to be used just after start-up in the above scenarios much of the beam would go all the way through the plasma and hit the far wall, wasting power and releasing impurities. Also, the density "window" for effective penetration is very narrow, only about a factor of 3-4 increase in the density will go

from a non-absorbed beam to a non-penetrating beam. Since injection seems to be required to attain high density operation in low B-field tokamaks, it seems to be essential that the fast neutral energy be increased as the density builds up.

A further important consideration arises in the selection of an injector system. If penetration of the full energy beam component is marginal, penetration of the half the outside of the plasma which may be deleterious because a thick, cool edge region prevents energetic particles from hitting the wall. Also, energy deposited near the plasma edge leaves faster and is thus less effective in heating the plasma.

ORNL Source 45A into Neutralizer

Energy	Percent Power	Current into Neutralizer	Neutralizer Effic.	Neutral Current	Power Delivered	
80 keV	85%	38.2A	25%	9.6A	717 kw	
40 keV	10%	9.0A	60%	5.4A	216 kw	1.06 Mw total
27 keV	5%	6.75A	70%	4.7A	127 kw	

Berkeley Source 50A into Neutralizer

80 keV	60%	30.0A	25%	7.5A	600 kw	
40 keV	30%	30.0A	60%	18.0A	720 kw	1.60 Mw total
27 keV	10%	15.0A	70%	10.5A	280 kw	

TABLE I

To emphasize this point, consider typical projected performance values for 80 keV ORNL and Berkeley sources (Table 1). Although the ORNL source only delivers 2/3 the power of the Berkeley source, it is better for heating the center of the plasma since it has more power in the high energy component and much less in the two low energy components.

The total beam power/unit volume deposition profiles for tangential injection into the top half of Doublet III are shown for 4 cases in Figures 2 and 3. The innermost point of Fig. 3 is artifically high due to the large (conpared to the beam width) size of the first flux surface. It will be noted that the profiles for the 80 keV Berkeley source and the 50 keV Oak Ridge source are essentially identical and that the only source that is really peaked on axis is the 80 keV Oak Ridge injector. The conclusion from this is that is is essential to have a very high atomic hydrogen fraction in the source in order to heat the center of large dense tokamaks.

VI. FUELING BY NEUTRAL INJECTION

Neutral injection should first be regarded as a source of energy, next, a source of momentum (for tangential injection), and finally as a source of particles. Although beams could be used for fueling, this is not a very energy efficient way to go and may in fact prevent plasma heating.

In order to penetrate a burning reactor, a very high beam energy ($\sim$ 200 keV D) would be required. This large energy per particle would imply a very large number of very high power injectors to supply the desired number of particles. Operation of burning reactors at such high injection energies has been studied by McNally, et al.[3] who showed that with trapped ion losses, the plasma "blows out". Under these conditions, the ion temperature runs away and the density falls towards zero. Also, if the only ions in the plasma are those near the injection energy, a 10% β limit would require densities below $\sim 10^{13}$ cm^{-3}.

In some sense, injection can be regarded as a competition between heating and fueling. Depending upon the models chosen for density transport and recycling at the wall, the plasma density will neither increase or reach a level high enough to shield out future beam particles. Once the beam can no longer penetrate to the center, any further heating must be supplied by α-particles. Thus, there must be a very delicate balance between the beam energy, power, and the particle confinement time to achieve the desired density and temperature at the ignition point before the beam is shielded out of the plasma. For this reason, a divertor may by a very deisrable "knob" to use to control particle flow at the plasma edge.

CONCLUSIONS

For positive ion sources, an upper limit of ∿80 keV (H) exists for reasonable efficiency. Given this constraint, as much current as possible must be concentrated in the H^+ component of the accelerated ions. For large tokamaks, small radius and/or low density start-ups are required to obtain adequate plasma heating. Finally, high energy neutrals do not appear to be suitable for fueling reacting tokamaks.

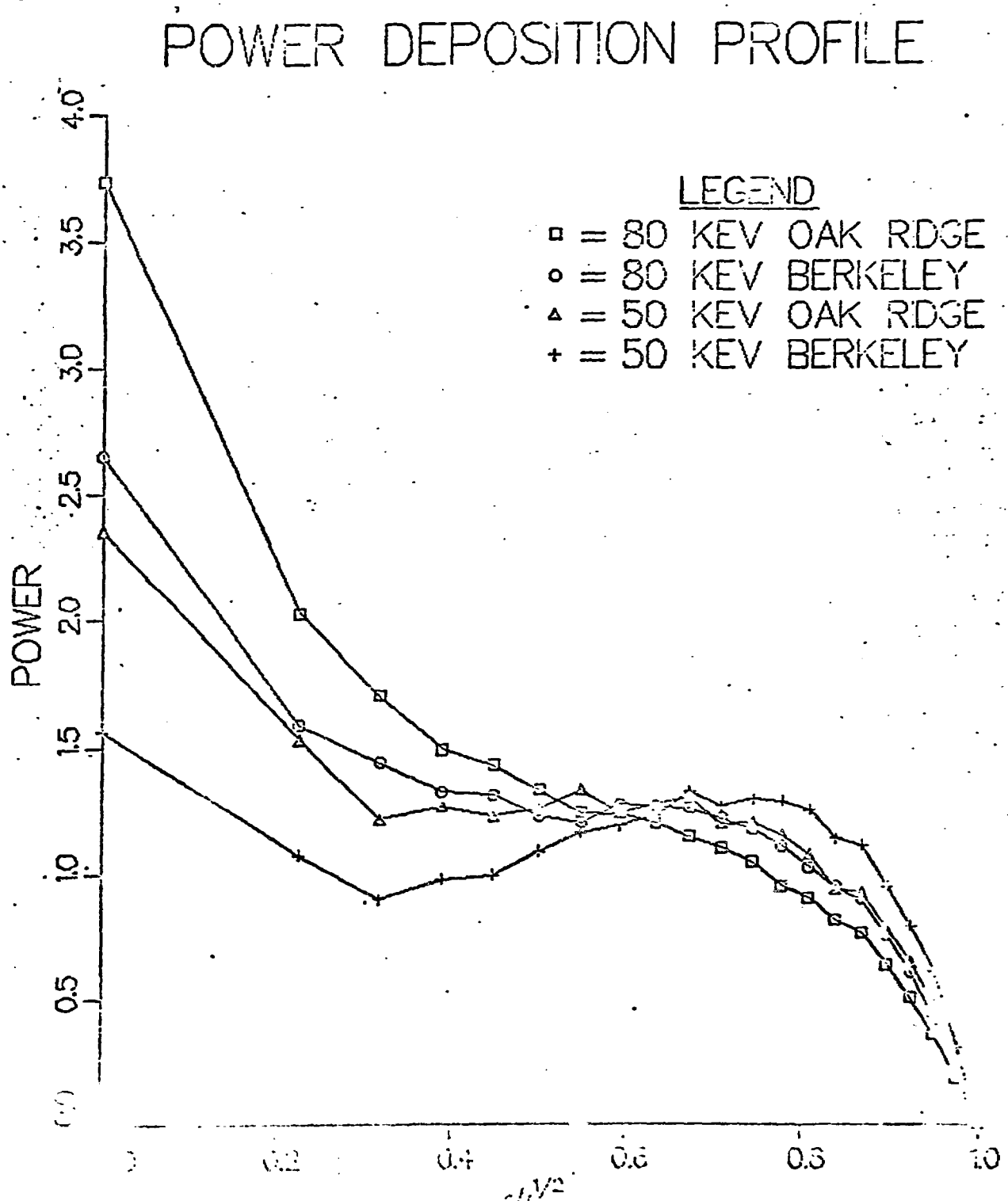

Figure 3: Beam deposition in Doublet III for the parameters of Table 1.

REFERENCES

1. J. A. Rome, J. D. Callen and J. F. Clarke, Nuclear Fusion 14, (1974) 141.

2. J. A. Rome, Y-K. M. Peng and J. A. Holmes, ORNL/TM-5931 (July 1977).

3. J. R. McNally, Jr., J. F. Clarke, R. H. Fowler, T. Hiraoka, R. D. Sharp and D. Steiner, IAEA-CN-331G1-3, "Plasma Physics and Controlled Nuclear Fusion and Research," Vol. III (1974), Tokyo meeting.