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POSITIVE ION SYSTEMS — STATE OF THE ART AND ULTIMATE POTENTIAL*

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Neutral beams formed by positive ion extraction have proven to be a viable means of heating fusion-like plasmas. State of the art in the Plasma Technology Section at ORNL is depicted in Fig. 1, where positive ion energy per pulse is used as a measure of performance and plotted as a function of time of achievement or expected completion. The PLT or ISX-B ion source has been operated at 40-keV, 60-A, and 0.3-sec pulses with H(D) neutral injected power of 750 kW (∿ 1000 kW) on the PLT device. In the near future these systems will be expanded to 50 keV, 100 A, and 0.5 sec for application on ISX and PDX. Plans have been made to continue the positive ion development in accordance with the requirements for TNS.

A schematic of the PLT or ISX-B ion source is shown in Fig. 2. The extraction plasma is contained by placing permanent magnets arranged about the periphery of a cylindrical anode.[1] The cathode region of the plasma generator serves as an intense source of electrons and feeds the anode plasma. The impedance of the arc is controllable by adjusting the gas feed in the cathode and anode regions and by tuning the coil which surrounds the cathode chamber. High plasma uniformity and arc efficiency are realized,[1,2] and a 70-A current of ions at 35 kV is extracted from a 22-cm grid pattern.

The ion source is coupled to a transport system or beam line with care taken to make the entire system compact, simple, and inexpensive. The injection solid angle is optimized by utilizing the maximum injection orifice and by coupling the

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ion source as tightly as possible to the fusion device. The ion optics are then matched to this injection solid angle. The requirements on the ion optics are kept as conservative as possible to reduce the requirements on critical hardware and thus improve reliability and functionality. Figure 3 depicts the PLT beam line as it was tested and developed on the Medium Energy Test Facility at ORNL. A plasma ion temperature rise of approximately 2 eV per kW of injected power is realized.

The Research and Development program has provided us with several options for focusing and controlling ions. ORMAK optics[3] (1° HWHM) have been improved upon by shaping the extraction apertures (0.6° HWHM). Precel optics, placing a potential between plasma generator anode and plasma grid, provide an improvement of 30% in the beam transmission through a PLT beam transport system. A coated plasma electrode with high precel and large gap provided the best optics yet obtained of 0.33° HWHM at 30 kV.[4] Multistage optics at high energy[5] reveal an improvement of 50% to 70% over ORMAK-type injectors. Care is taken to match the injection requirements to the appropriate optics such that the most reliable and economical system is realized.

A sophisticated monitoring and data analysis system is now available for developmental work on these systems. Figure 4 represents an example of the data taken on a PLT beam line. The power is monitored on each element of the system, and from this information, the ion optics are discernible and the system functionality is easily optimized. Similar data acquisition techniques have been used to measure the beam species in the ion dump region, and then the beam species at the source is calculated from well-known cross sections(see Fig. 5). The atomic yield of 85% is a valuable asset when considering ion optics, neutral beam penetration, and energy recovery schemes. The dominance of the atomic species is evidenced by the species data taken in the ion dump region, as seen in Fig. 6.

The efficiency of neutral beam heating is strongly dependent on beam penetration. Neutral beam energy must be optimally matched to the target or tokamak plasma

density, which in turn presents a problem because the plasma varies by as much as an order of magnitude within a given pulse. It is, therefore, desirable to vary the beam energy. The extraction potential can be dynamically varied; however, the ion optics are strongly dependent on energy and the system efficiency is not preserved. Hydrogen and deuterium could be injected simultaneously into the source in a programmed manner that would allow for a wide range of penetration. However, this method would likely complicate the main thrust of the plasma studies and is therefore not desirable. A third option is possible. The species can be varied within a pulse (say from 50% atomic to 90% atomic), resulting in a variation in beam energy which is characteristic of the half energy for 50% atomic yield and full energy for 90% atomic yield. Exact species proportion is strongly dependent on energy and the type of hydrogen isotope used for heating (see Fig. 7).

Neutral beam injection efficiency is limited by the equilibrium fractions of the ions passing through the charge exchange neutralizers. Typical beam penetration requirements are beyond the region in which efficient neutral beams can be produced from positive ions — about 100 keV/nucleon. Energy recovery from the unneutralized portion of the beam leaving the neutralizer will alleviate the low efficiency associated with the high energy acceleration process. Figure 8 shows the typical neutral beam efficiency as a function of beam energy (lower curve). In an idealized situation in which there were no ions or neutral losses and the energy recovery scheme were considered perfect, the efficiency would be 100% (top curve) independent of energy. A more realistic evaluation (central curve) of energy recovery and focusing efficiencies yields a range of improved overall system efficiency that is worthy of investigation. This improvement in efficiency may allow the extrapolation of positive ion extraction for use in the heating of reactor-grade plasmas.

References

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2. C. C. Tsai, W. L. Stirling, and P. M. Ryan, Rev. Sci. Instrum. 48, 651 (1977).
3. R. C. Davis, O. B. Morgan, L. D. Stewart, and W. L. Stirling, Rev. Sci. Instrum. 43, 278 (1972).
4. J. H. Whealton, L. R. Grisham, C. C. Tsai, and W. L. Stirling, J. Appl. Phys., in press.
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THE OAK RIDGE NATIONAL LABORATORY ION SOURCE DEVELOPMENT HAS BEEN PROCEEDING AS AN EXPONENTIAL FUNCTION OF THE EXTRACTED ENERGY.

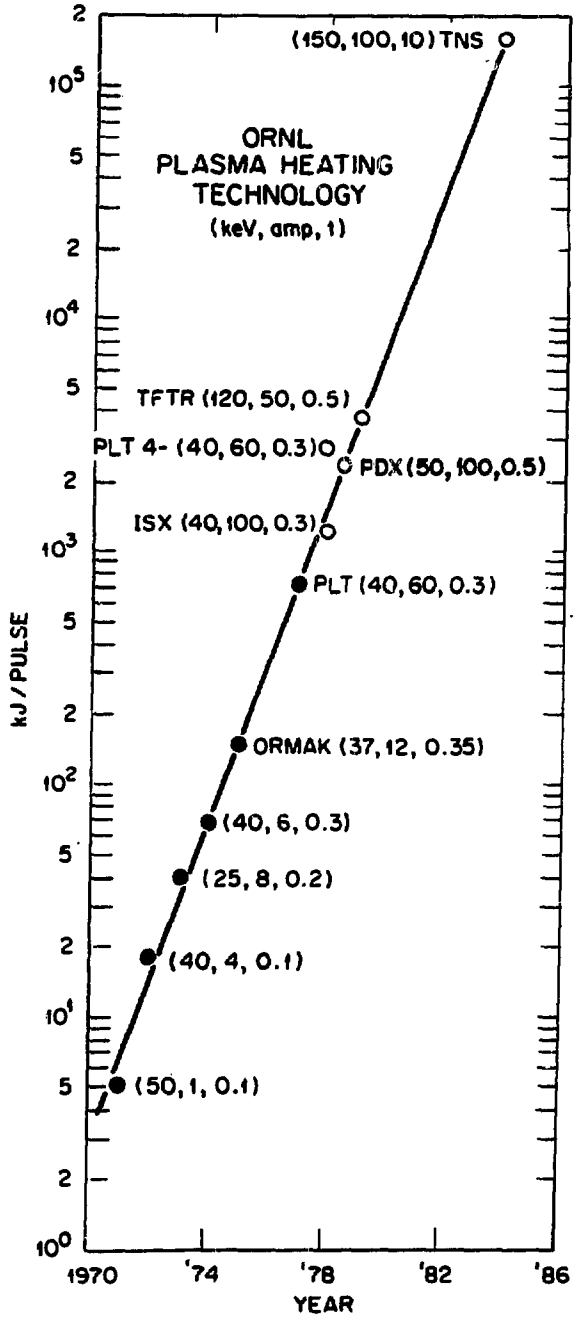
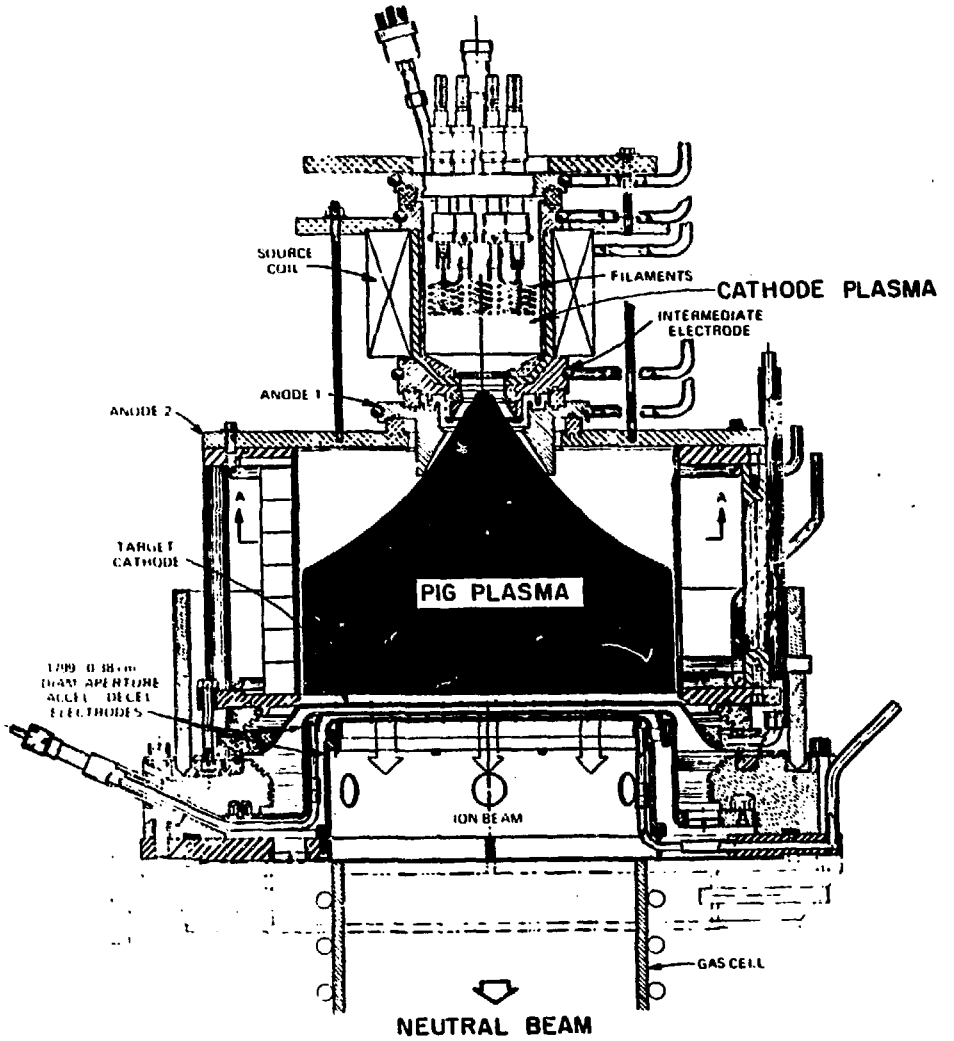
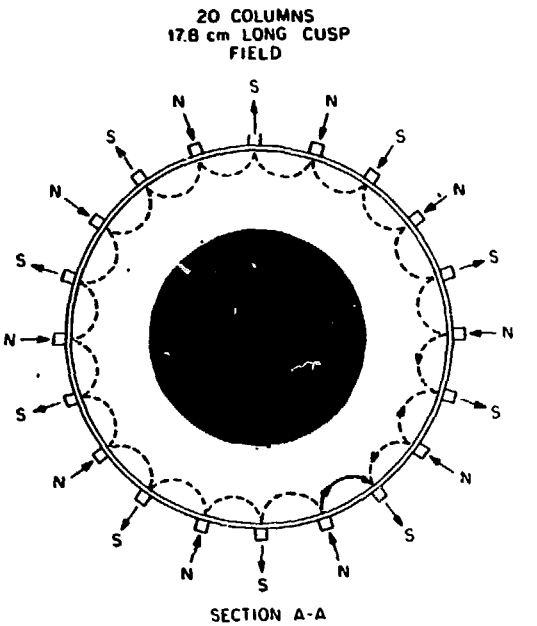


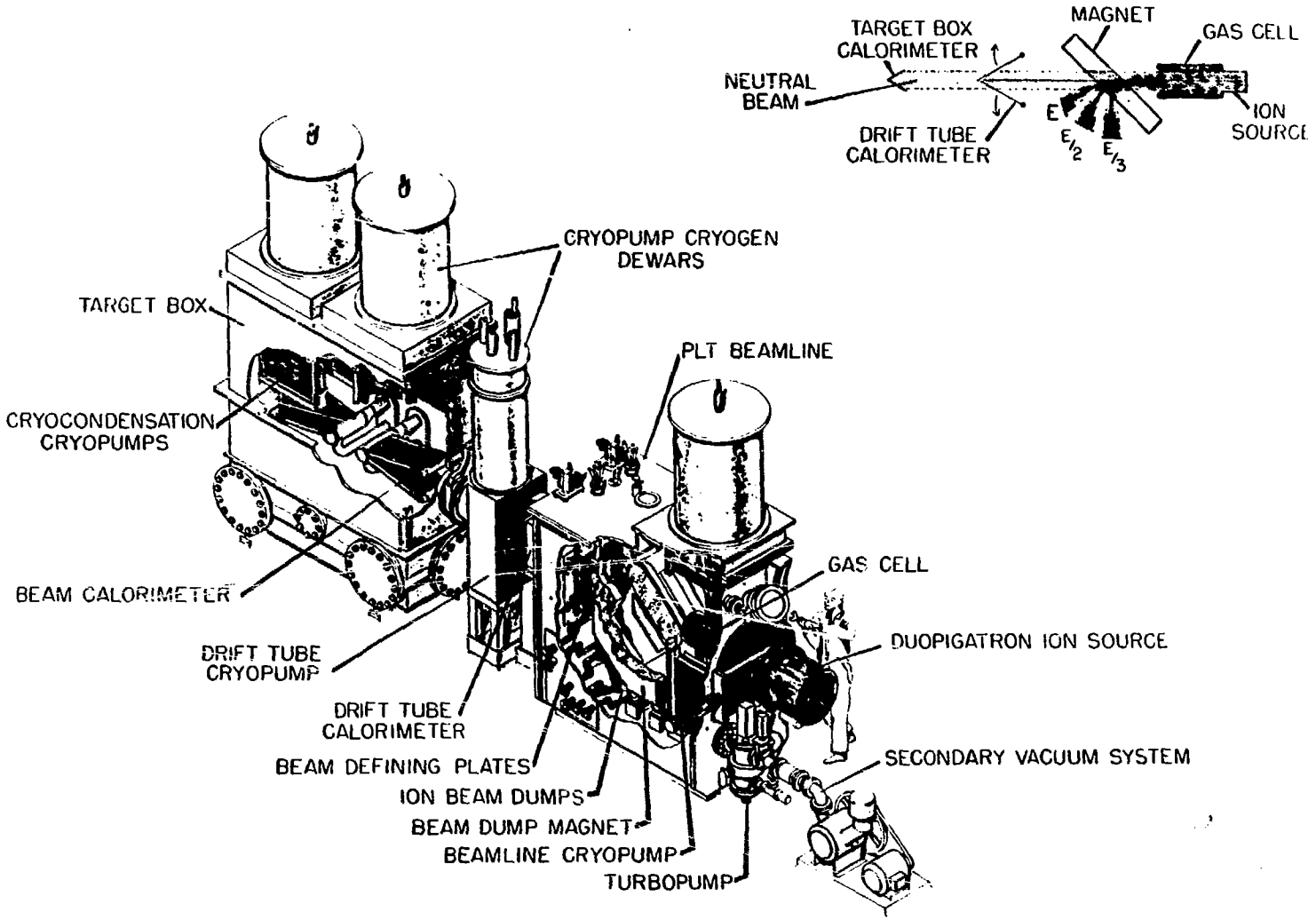
Fig. 1





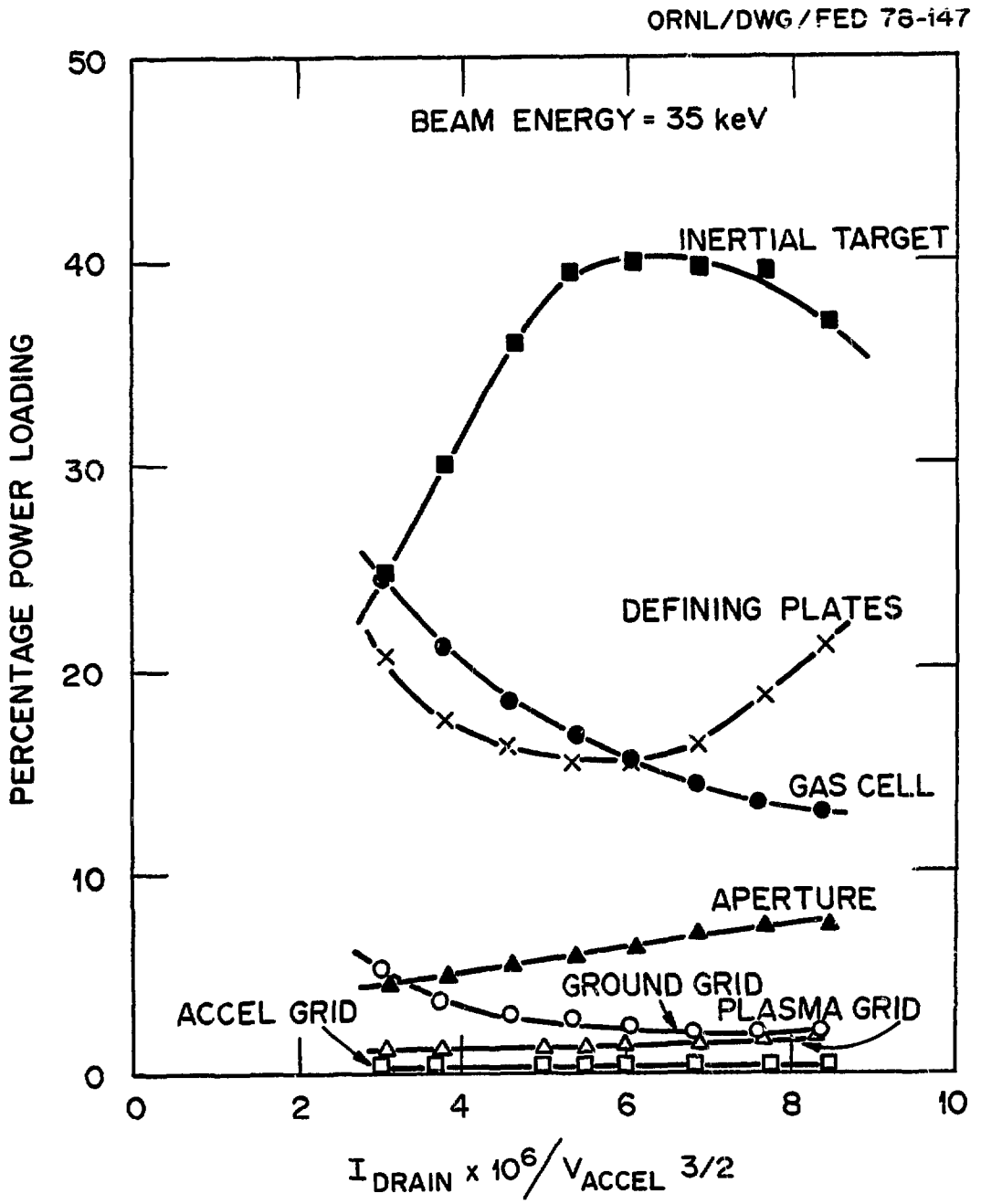
PLT – ISX-B 22 cm Ion Source

Fig. 2



ORNL/PLT BEAMLINE AND ORNL TEST FACILITY TARGET BOX.

Fig. 3

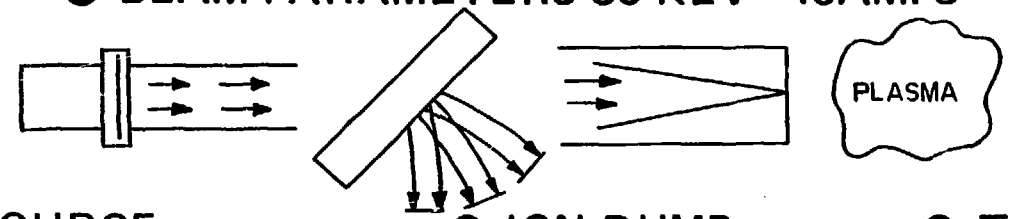


Typical Data From PLT Ion Source and Beam Line

Fig. 4

FROM MEASUREMENTS OF SPECIES IN THE ION DUMP REGION, THE SPECIES EMERGING FROM THE SOURCE AND THE NEUTRAL SPECIES RATIO CAN BE CALCULATED

- BEAM PARAMETERS 30 KEV–40AMPS



ION SOURCE	ION DUMP	TOKAMAK PLASMA
$E(H^+)$ – 85%	$E(H^+)$ – 89%	$E(H^0)$ – 84%
$E(H_2^+)$ – 12%	$E/2(H^+)$ – 10%	$E/2(H^0)$ – 13%
$E(H_3^+)$ – 3%	$E/3(H^+)$ – 1%	$E/3(H^0)$ – 3%

Fig. 5

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THE DEFLECTION MAGNET AND PROBES IN THE ION DUMP PERMITS SPECIES MEASUREMENTS

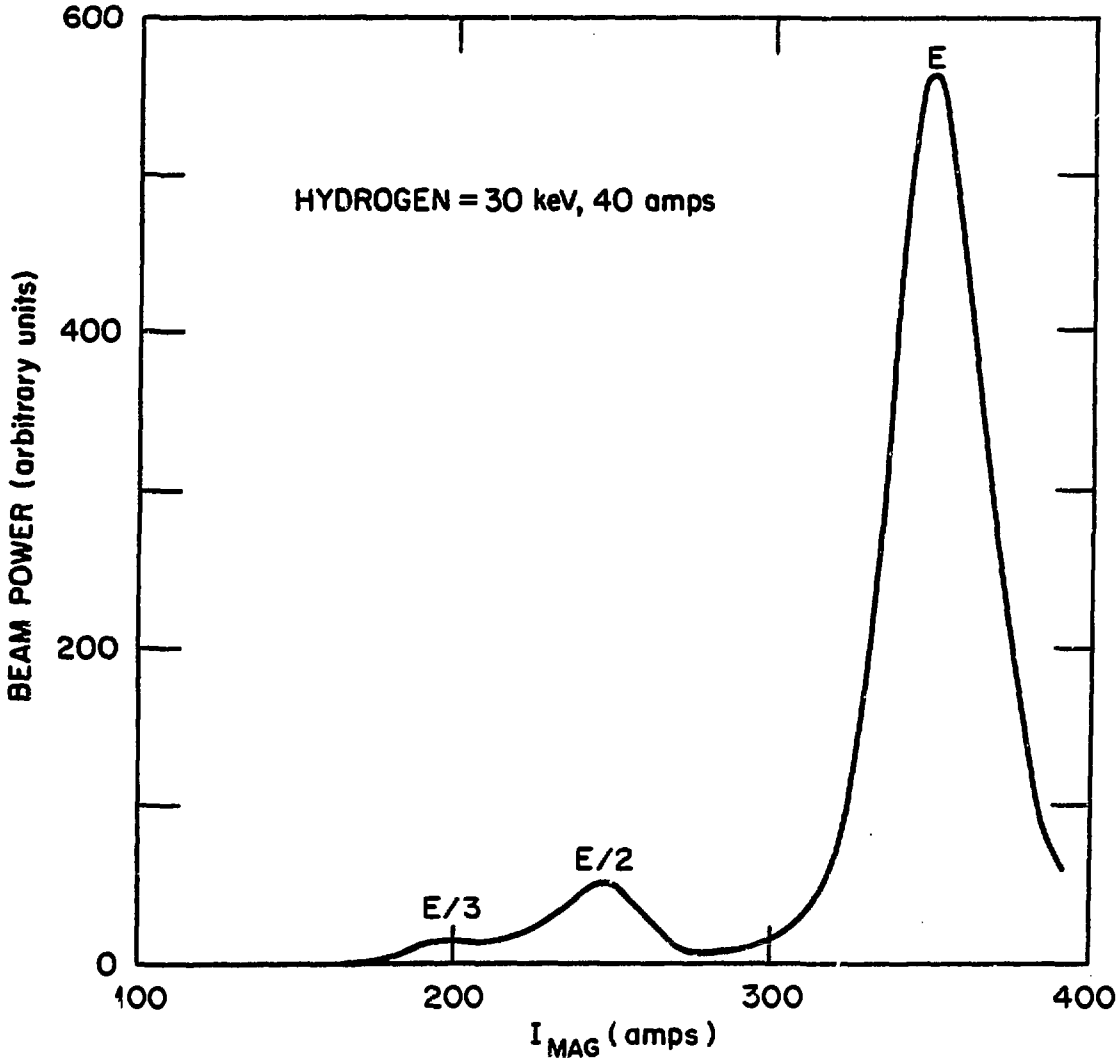

Fig. 6

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CONTROL OF SPECIES YIELD WILL PERMIT CONTROL OF BEAM DEPOSITION WITHIN TOKAMAK.

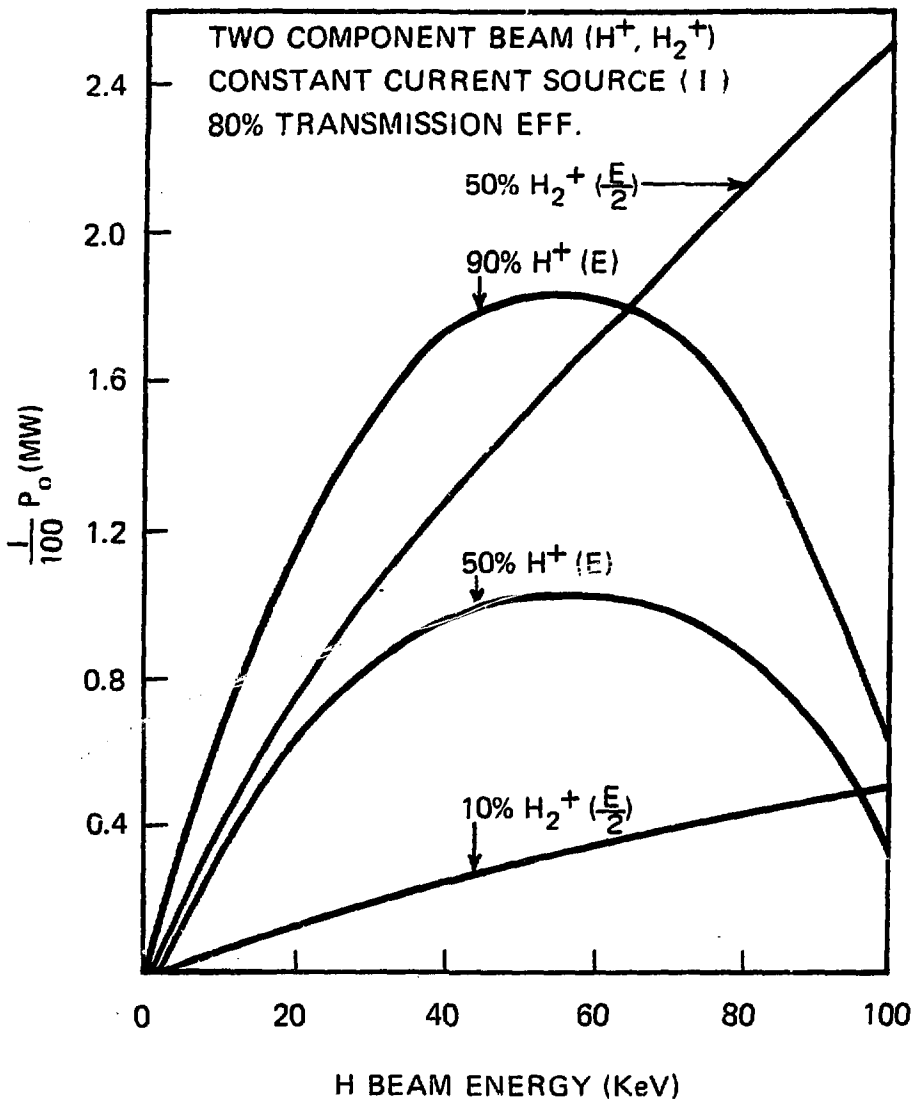

Fig. 7

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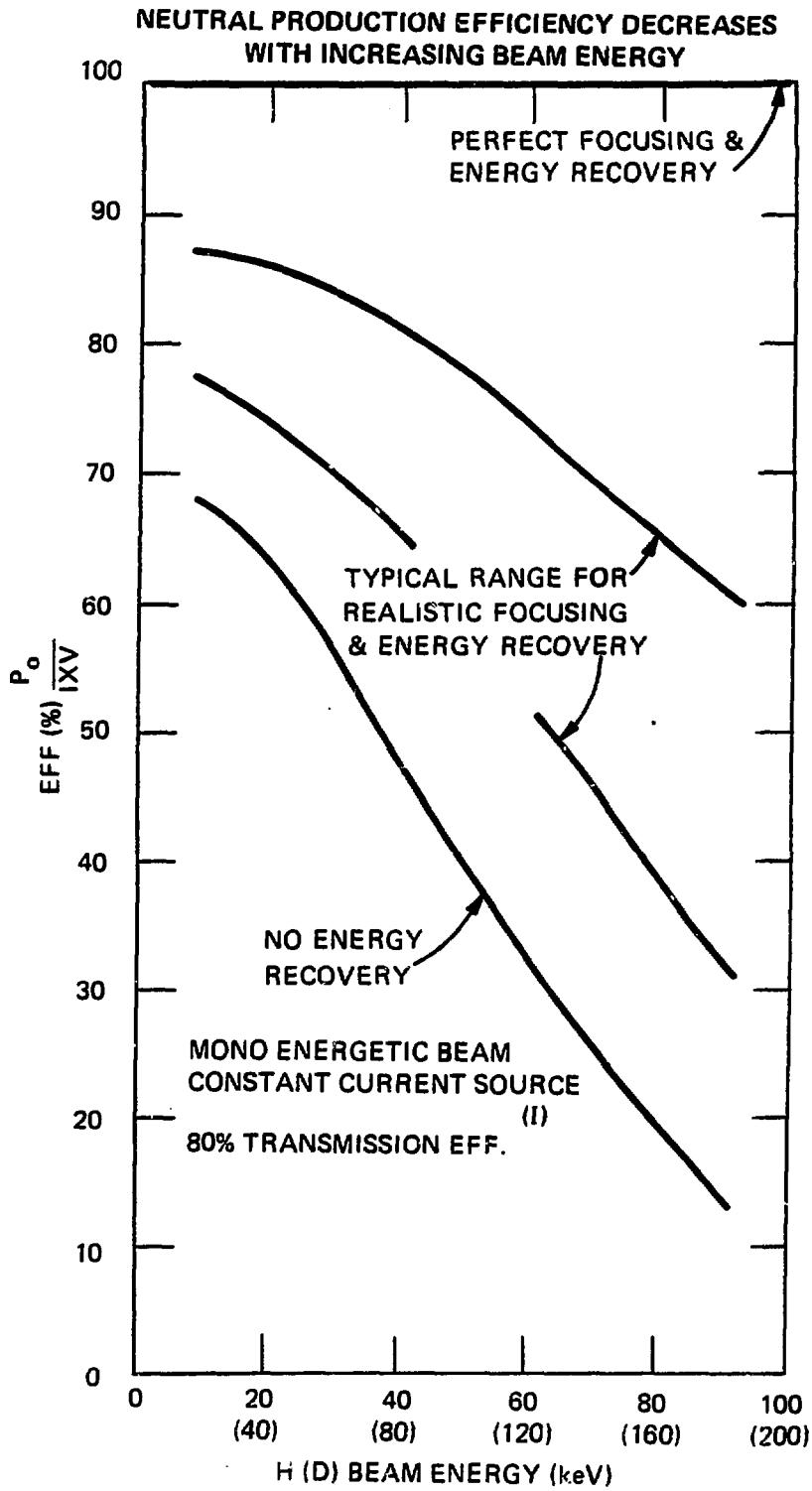

Fig. 8