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DEVELOPMENT AND TESTING OF THE ORNL/PLT NEUTRAL BEAM LINES FOR THE PRINCETON LARGE TORUS*

W. K. Dagenhart, W. L. Gardner, H. H. Haselton, M. M. Menon, D. E. Schechter, W. L. Stirling, and C. C. Tsai

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

MASTER

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Summary

Four neutral beam lines have been designed, constructed, and tested by the Oak Ridge National Laboratory (ORNL) in cooperation with the Princeton Plasma Physics Laboratory (PPPL) for application on the Princeton Large Torus (PLT) at PPPL. Two neutral beam lines are counterinjectors and two are coinjectors for a total neutral beam power of >3 MW at 40 keV and up to 300 msec. Each beam line utilizes a 40-kV times 60-A modified duoPIGatron[1] ion source with a close-coupled, 1.0-m long gas cell. Species ratios produced by the ion source are 84:13:3:E: E/2:E/3 for H^0 components delivered to the torus. The arc efficiency is <1 kW of arc power per ampere of beam current. Gas efficiency is ∿50% with a total gas throughput of ∿20 T-ℓ/sec including supplemental gas to the gas cell. Two LHe cryocondensation pumps are used, one in the ion source tank with a speed of ∿400,000 ℓ/sec and the other in the drift tube with a speed of ∿20,000 ℓ/sec. The first beam line has been operated on PLT and has delivered 500 kW to the tokamak calorimeter for 150 msec. Initial heating results at 400 kW indicate an increase in T_i, the central ion temperature, from 0.8 keV to ∿1.5 keV.[2]

Introduction

Neutral beam heating of tokamak plasmas has been successfully demonstrated on the Oak Ridge Tokamak (ORMAK) at ORNL, Adiabatic Toroidal Compressor at PPPL, Tokamak Fontenay-aux-Roses at Fontenay-aux-Roses, and Cleo at Culham. For example, T_i was raised from ∿ 0.6 - 1.8 keV on ORMAK with the addition of 360 kW of 30-keV neutrals. As a consequence of these early promising results, neutral beam heating was selected as one of the prime experiments for PLT. The addition of >3MW of neutrals was expected to raise T_i to 4-5 keV. It was expected that each beam line would deliver from 600-900 kW for 300 msec. Initial operation on the ORNL Medium Energy Systems Test Facility (MESTF) has produced neutral beams up to 750 kW at 40 kV for 300 msec. A modified version of this beam line will be used on ISX-B, which has more room to accommodate a larger drift tube differential pumping chamber and has a larger tokamak aperture.[3] This modification will greatly lower the drift tube pressure and hence lower reionization losses and increase transmission of the beam. Modifications of this beam line may also be used in the proposed high power injection experiments on the Poloidal Divertor Experiment (PDX). PDX requirements of 500-msec pulses can easily be met, since at 300 msec the ion source is essentially running at dc parameters. A few of the beam line components would need more cooling for long pulse operation.

Ion Source

The ORNL/PLT neutral beam line employs a modified duoPIGatron ion source, as shown in Fig. 1.[1,4] The extraction grid is 22 cm in diam. and contains 1799 apertures. This source produces 60-A times 40-keV beams for 300 msec with gas efficiency of ∿50%. Gas is fed to the primary low voltage discharge region where electrons are provided by heated oxide coated filaments. This discharge in turn feeds ionizing electrons into the PIG or second anode region to which gas is fed by a second valve. High field samarium-cobalt ceramic permanent magnets are arranged in 20 columns, 15 cm long, to form a line-cusp magnetic field to improve confinement of the PIG volume plasma. This line-cusp field has increased the plasma uniformity so that the current density variation is within ±10% over the 22-cm extraction area.

Filament Lifetime

The mean time before failure of an ion source is largely determined by filament lifetime. This item will become increasingly important on future machines with deuterium/tritium operation where remote maintenance procedures are required. The oxide filaments used on the ORNL modified duoPIGatron are not subjected to direct bombardment by backstreaming electrons and ions and are operated at ∿20 V. During relatively short testing periods, we have had very little trouble with filament failure. One source was run ∿2 months for 45,000 shots before failure; in addition, this source had been subjected to two vacuum failures.

Species Measurements

One of the more important characteristics of the ORNL modified duoPIGatron ion source is the high proton yield which it produces. Figure 2 shows a calorimetric scan of the full, half, and third energy ion peaks. This scan was obtained by placing a single 0.6-cm ID inside swirl tube calorimeter in the image region of the deflection magnet, as shown in Fig. 3. The three separated ion species were measured calorimetrically as the magnetic field was scanned; as can be seen, the one-half and one-third energy components are quite low. Figure 4 shows the species ratios as measured at the ion dump. Species ratios of the ions at the ion source and of the neutrals entering the tokamak plasma, also shown, are calculated using known cross sections. The higher proton yield from this source results primarily from the low plasma electron temperature, ∿5 eV, and relatively short mean free path of the ionizing electrons, both of which are related to the use of the line-cusp magnetic field containment in the PIG second anode region. Further experiments are being planned to increase the proton yield and to examine the model proposed to explain the high proton percentage.

Neutral Beam Line

Figure 3 shows a cross section of the beam line and gross dimensions of the major components.[5] The gas cell is 1.0 m long with the first section having a 23-cm ID and the second section, which is 7-cm long, having a 21-cm ID in order to reduce the gas conductance.

The gas cell is fed by a third leak valve near the isolation valve so as to supplement the un-ionized gas from the source and produce a line density of 10^{16}cm^2 for neutralization. The gas cell is magnetically

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shielded by an outer layer of low carbon iron and an inner layer of high permeability steel to reduce the magnetic field below .0002 T.

At 40 keV, the neutral fraction from the gas cell is 60% with the ions being swept out by the bending magnet. The ions are separated by the magnet into the three major components of full, one-half, and one-third energy ions which are dumped onto the three corresponding calorimeters. The average power density on the full energy dump has been measured at ∿5 kW/cm^2.[6] Field clamps limit the extent of the magnet fringing field so that ions are not deflected in the gas cell. The magnet area has operated with pressures up to 10^{-4} torr, and no trouble with space charge blowup has been detected. The magnetic field is 0.15 T for 60-keV D^+ ions.

The neutral beam is collimated at the entrance to the drift tube by four movable, water-cooled, copper defining plates; these plates scrape off the tails of the beam and keep it from bombarding the drift tube walls. The drift tube dimensions were dictated by the space available in the PLT torque frame and space between the toroidal coils. The drift tube penetrates the torque frame, and the small LHe drift tube cryopump lies inside the torque frame between two coils; thus, neither the drift tube nor the drift tube cryopump could be made any larger. The drift tube has a movable V-shaped calorimeter, which is moved into the beam for source conditioning and for cleanup shots between tokamak pulses; the peak power density on this calorimeter is <5 kW/cm^2.

Gas pressure in the drift tube is reduced ∿30% by the drift tube LHe cryocondensation pump; this pump has a speed of ∿20,000 ℓ/sec. The short drift space beyond the cryopump contains the absolute shutoff valve sealed by a Viton O-ring. Metal gaskets were used in the drift tube, and Viton O-rings were used in the rest of the vacuum system. The main ion source tank is pumped by a large LHe cryocondensation pump with a speed of ∿ 400,000 ℓ/sec. Beams with power up to 1 MW have been passed ∿5 cm from the LN_2 chevrons of the drift tube pump, and beams of 2.6 MW have been extracted from the source without any indication of instability from either of these cryopumps. Liquid helium usage is ∿3.5 ℓ/hr and LN_2 usage is ∿10 ℓ/hr for the large pump. Accurate experimental values have not been obtained for the small pump, but they are less. Liquid N_2 level is maintained by an automatic fill system, and LHe is transferred once daily. A small 1500-ℓ/m mechanical pump is used to pump the beam line and source down, and then a 1000-ℓ/sec Sargeant-Welch turbomolecular pump is used before the cryopumps are started. Pressures in the chamber are 10^{-7}-10^{-8} torr with the turbomolecular pump and cryogens. After pulsing H_2, the pressure rises to ∿3 times 10^{-6} torr due to the vapor pressure of H_2 at 4.2 K.

Test Facility

Figure 5 shows the double ended ORNL MESTF with two ORNL/PLT beam lines in place. Principal elements of the test facility are as follows: the isolated ion source electronics supplies; 60-kV, 60-A at 2-sec (10% duty cycle) high voltage supply, which is shared with an adjacent test facility; beam line control and instrumentation station; PDP-11/40 computer system; LHe cryocondensation pumped target chamber; ORNL/PLT beam lines; and LHe cryostat system. High voltage may be supplied to only one of the ORNL/PLT beam lines or another laboratory at a time. The arc supplies may be used at either end of the facility with or without high voltage. Only one set of arc supplies is available for the MESTF. Testing may be in progress at one facility while maintenance is being performed at the other.

Test Results

Table 1 gives a summary of the beam line peak performance parameters to date.

Table 1. Results from the first three PLT Ion sources (20-cm or 22-cm sources)

40 A - 36 keV - 300 msec	400-kW neutrals
50 A - 40 keV - 300 msec	550-kW neutrals
60 A - 45 keV - 200 msec	700-kW neutrals
70 A - 40 keV - 100 msec	750-kW neutrals

Figure 6 shows that the energy delivered to the target varies with pulse length and that no grid warping or other defocusing is appearing with longer pulses. The droop in the curve is caused by power supply sag with longer pulses. Figure 7 gives the variation of energy delivered to the various beam line components as a function of accel voltage. Power measurements have accounted for ∿90% of the IXV power. Figure 8 gives the variation of power delivered to the target as a function of perveance for various beam current values. Note the stability of the ion source, especially with perveance mismatched. Figure 9 gives the variation of target power with decel voltage.

References

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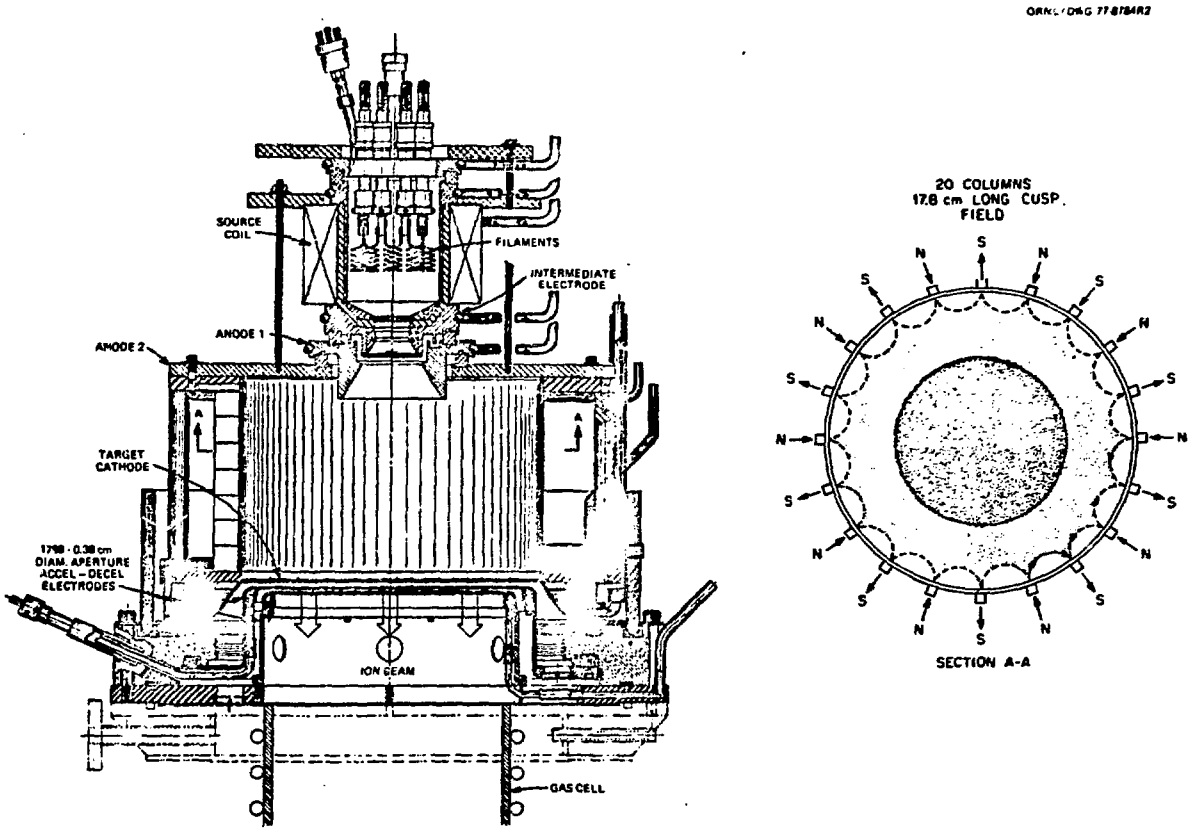

Fig. 1. The ORNL 22-cm DuoPIGatron Ion Source

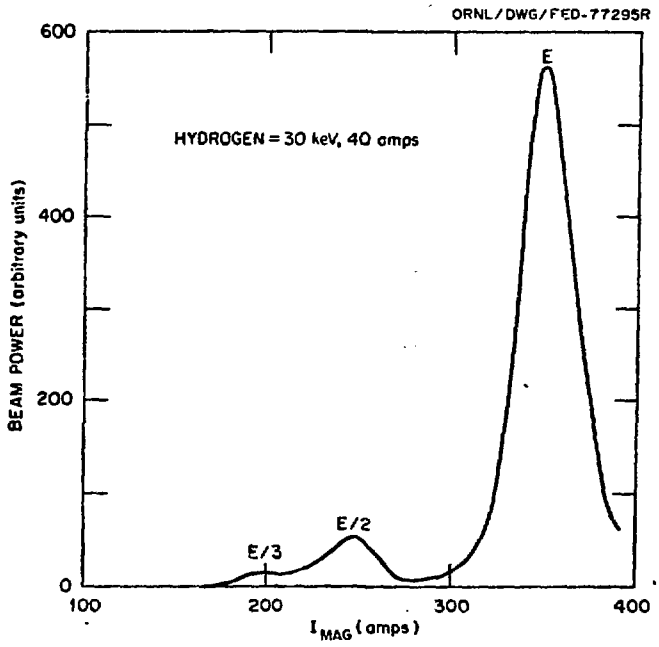

Fig. 2. Calorimetric Scan of the Full, Half, and Third Energy Ion Peaks From the Gas Cell

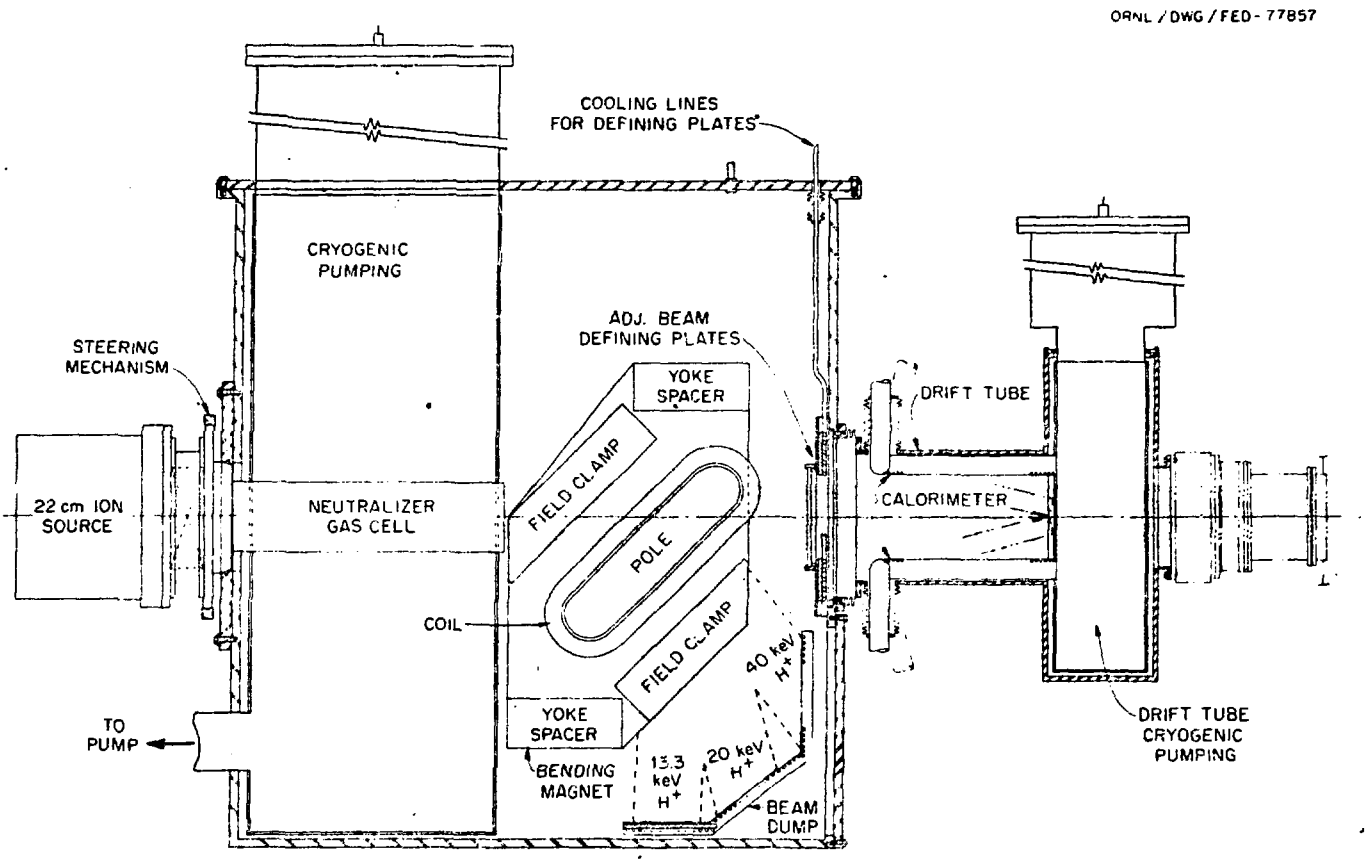

Fig. 3. The ORNL/PLT Neutral Beamline Schematic

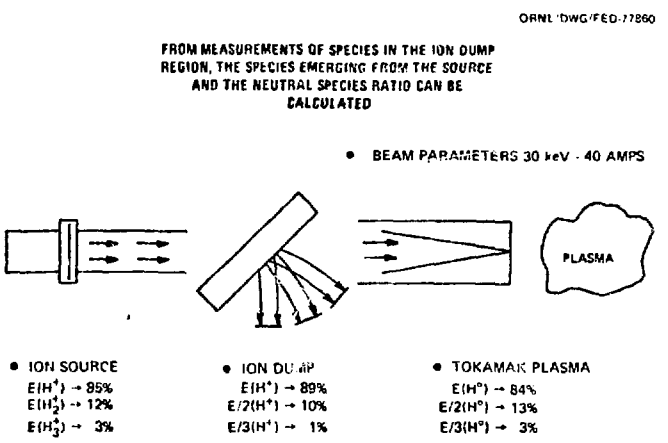

Fig. 4. Measured and Calculated Species Ratios Flowchart

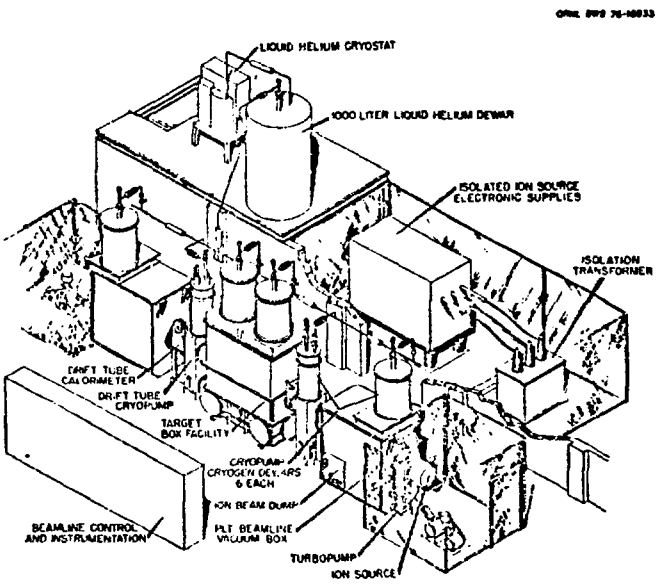

Fig. 5. The ORNL Medium Energy Systems Test Facility

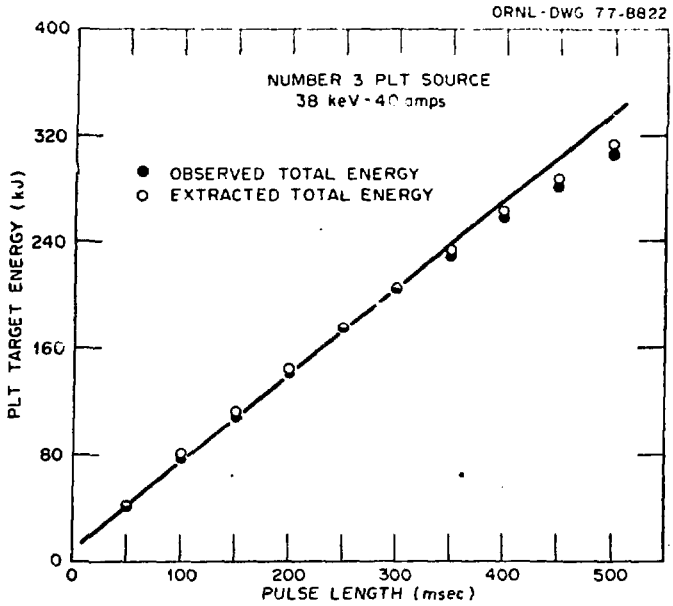

Fig. 6. Target Energy Versus Pulse Length

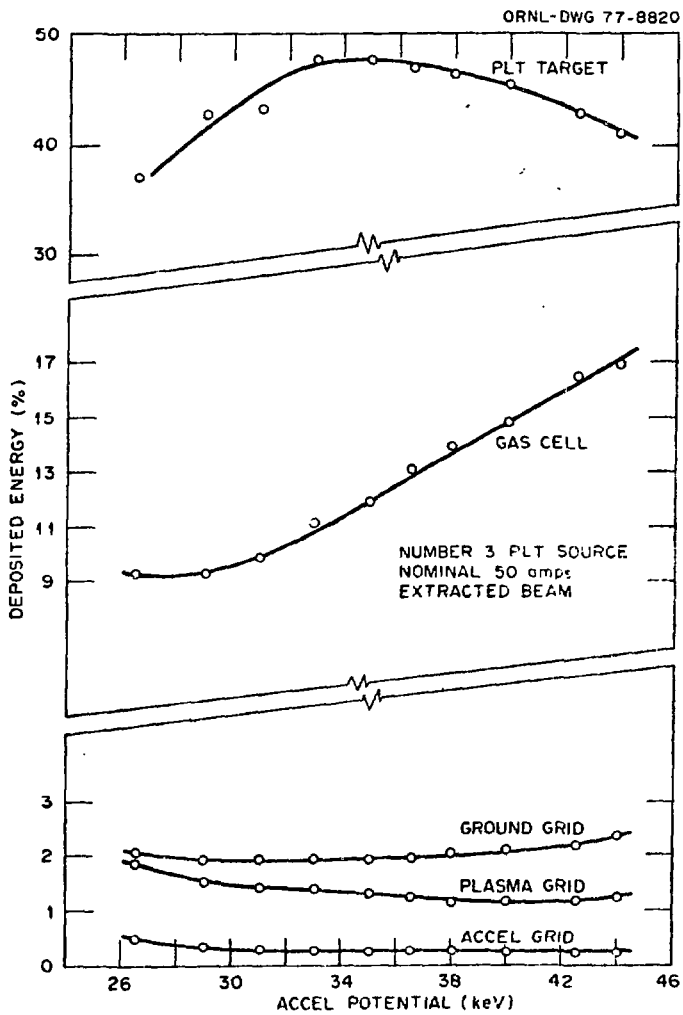

Fig. 7. Variation of the Percentage of Extracted Beam Energy Deposited on Various Beam Components Versus Accel Voltage

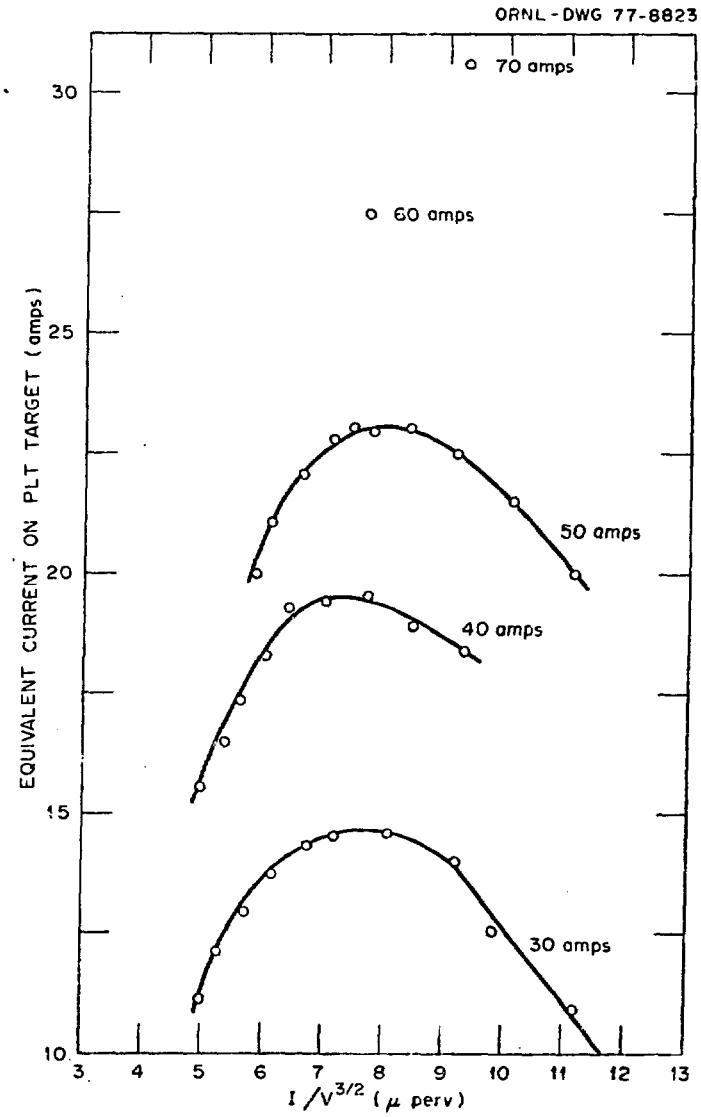

Fig. 8. Variation Target Equivalent Current Versus Perveance

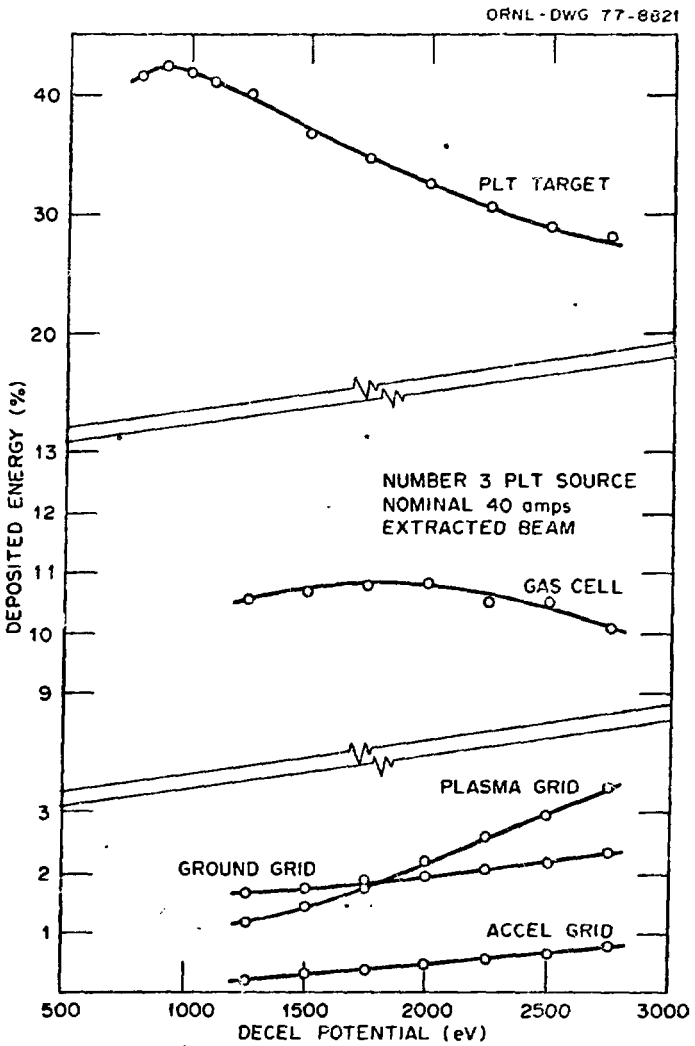

Fig. 9. Variation of the Percentage of Extracted Beam Energy Deposited on Various Beam Components Versus Decel Voltage