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MASTER

DEVELOPMENT OF THE ION SOURCE FOR PDX NEUTRAL BEAM INJECTION

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Summary

The paper describes the development of the ion source for neutral beam injection heating of the PDX plasma. After a brief description of the plasma generator the performance characteristics of the source, with different types of grids, are described. Based on test stand results it is concluded that at least two different versions of the source should be able to meet and even exceed the neutral power and energy requirements expected out of PDX injectors.

Introduction

The plasma heating requirements of the PDX machine call for four ion sources each capable of delivering 1.5 MW of 50 keV neutrals of 500 ms pulse duration. Other specifications for the source include an atomic yield exceeding 80% and a reliability of at least 90%. A complete description of the beam line is given elsewhere. Assuming 50% neutralization efficiency, the above requirements translate to an ion source that can extract about 100 A of primarily atomic species ions, at 50 kV, with a transmission efficiency of 60% in 2 angle (the acceptance angle of the PDX machine). The paper describes the development of the source — an enlarged version of the modified duoPIGatron that has successfully met the injection demands of both PLT and ISX tokamaks. The refinements used to double the power and almost quadruple the energy levels (as compared to PLT/ISX sources) with improved beam optics, are elaborated.

While some geometrical and other losses are inevitable in transporting the beam over long distances (the PDX machine opening of 30 x 34 cm is located 450 cm away from the source), the ion source almost singularly dictates the power transmission efficiency along the beam line. The optical quality of the beam is therefore of prime concern. This in turn is decided by the quality of the plasma and the details of the accelerator geometry . A uniform, dense and quiescent plasma is necessary. The choice of the modified duoPIGatron as the plasma generator is justified elsewhere . The accelerator details are decided by a combination of factors viz, small beam divergence (1.5 HWHM), high current density (0.3 A/cm) and ease of fabrication. All the grids described are curved to provide a focal length of 450 cm. The source performance is evaluated at the Oak Ridge High Power Test Facility which has practically all the features of a beam line.

Plasma Generator

The plasma generator of the PDX ion source is a modified duoPIGatron providing a dense (2 x 10 /cm) plasma, uniform within 5% over the entire 30 cm-diam. extraction surface. It is an enlarged version of the one used in PLT and ISX injectors and is shown in Fig. 1. The second anode is 28 cm long and 42 cm in diameter, with 30 magnets, 23 cm each in length, placed on the outside wall forming a multipole line cusp magnetic field. The intermediate electrode opening into the anode 1 chamber is comprised of four small holes 1.9 cm each in diameter instead of a single hole used in earlier versions. The larger extraction current (100 A) requires significantly larger arc current (about 1400 A) and this in turn demands more filament capacity. Twelve filaments are used each carrying 40 A of heating current. Figure 2 shows the density profiles obtained with the 4-hole intermediate electrode and a similar profile obtained with a single hole version of about the same total area for the opening. The result however should not be interpreted to mean that the single hole intermediate always give a peaked profile. It was possible to obtain fairly uniform profile without sacrificing the density by altering the size of the hole, length of the first anode and size of the axial button. The 4-hole version was, however, selected for all the experiments described below.

Accel Column

The accel column employs a three grid accel decel system. The grids are made of approximately 2-3 mm thick OFHC copper and are actively cooled by demineralized water flowing at the rate of a few hundred cc/s. Grids with either two or three rows of apertures between cooling lines were studied. Reducing the number of rows between cooling lines improves the cooling efficiency at the expense of grid transparency. Similarly use of larger apertures increases the transparency at the expense of current density. The shape of the apertures is a crucial factor in deciding the beamlet optics. Guided by experiments as well as theoretical analysis using powerful computer codes , and bearing in mind the complexity of the fabrication problem, four types of apertures were evaluated. These will be hereafter referred to as type A, B, C, and D and are illustrated in Fig. 3. Note that only the plasma grid had apertures of noncylindrical shapes. The apertures on the other grids were equal to the smaller diameter of the plasma grid aperture. The accel gap was nominally 7 mm and the decel gap about 2 mm.

Characteristics of the Source

Power Deposition

An elegant way of characterizing the source is to plot the power deposition on various elements intercepting the beam, expressed as a percentage of the total drain power, as a function of the perveance (drain current/accel voltage). The percentabe power deposition is relatively insensitive to the exact voltage or current levels enabling the data obtained amenable for simple extrapolations. Moreover the bell shaped curve of transmission efficiency vs perveance is also very useful in maximizing the power reaching the machine. A typical "perveance plot" obtained with type B grids is shown in Fig. 4. Approximately 60% of the total drain power is transmitted to the target subtending 2 to the source. This figure should only improve during actual beamline operation because the gas cell at the test facility was unusually long (200 cm) and narrow (25 cm ID). Another difference at the test facility was that the gas cell started about 100 cm from the exit grid with only a 35 cm-diameter 50 cm-long section closely coupled to the source. Most of the data

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was taken with no gas fed into the gas cell section. Figure 4 also shows the power intercepted by the grids. Around optimum perveance less than 5% of the total power is intercepted by the grids, the middle grid (accel grid) receiving the least. Similar plots were also obtained with the other types of grids and a comparison will be made later. The beam profiles were also measured and the HWHM angles at optimum varried in the range of 1.0 – 1.3 .

Highest Power Levels

The highest voltage, current and energy levels were limited by the maximum ratings of the modulator available at the test stand. While the modulator tubes (X2170) when connected in parallel were capable of providing greater than 100 A, the maximum voltage was limited to 50 kV. Since there is a voltage drop amounting to about 8 kV (tube drop plus power supply sag) under full load, the highest power levels were limited to about 42 kV/110 A. The source with type A grids were operated at this level (Fig. 5) while type B and C grids were able to give 40 kV/100 A and 40 kV/90 A respectively. The sources were also tested to 50 kV levels at reduced beam currents.

Long Pulse Operation

The sources with type A, B and C-type grids were operated under long pulse condition (500 ms) at about 60% of its highest designated capacity. The tests were done at optimum currents (75-80 A) corresponding to 40 kV (due to modulator limitations the test stand not be carried out at 50 kV). A typical pulse obtained with type A grid is shown in Fig. 5. The test was incomplete for type C grids and premature chopping of the beam pulses were observed for pulse lengths exceeding 250 ms. Type A & B grids on the other hand passed the test without showing any deteriorating effects at the higher energy levels. Energy deposition as a function of pulse length for the source with type B grids is shown in Fig. 6. The slight deviation from linearity can very well be explained in terms of change in beam optics as a result of change in current and voltage waveforms. It may, however be noted that these tests were carried out with a non-equilibrium gas cell and the behavior could be different under actual beam line conditions. So far only type A grid was evaluated at the beam line and the problems encountered while extending the pulse length, at full power levels is described elsewhere .

Operation with Precel

It has been reported that pre-accelerating the ions entering the extraction apertures significantly improves the beam optics . This is generally accomplished by connecting a precel supply (100–300 V) between the plasma grid and the second anode or by tying the plasma grid directly to the arc negative terminal. However, unless careful protection measures are employed, these two methods run the risk of damaging the source components due to arcing between the plasma grid and the second anode (the power supply is directly connected across the fault!). Since protection measures were not immediately available the precel effect was studied by tying the plasma grid to the intermediate electrode. A small but definite improvement (5%) in transmission efficiency accompanied by about 10% reduction in optimum perveance was observed with all types of grids. A typical curve showing the effect of precel voltage on power transmission efficiency is shown in Fig. 7. The figure also illustrates the small effect of improving the coupling between the source and gas cell.

Discussion and Conclusions

Table 1 compares the performances of A, B and C-type grids. Only power transmission tests were carried out with type D grid and hence is not included in the table. Type B grids show some definite advantages as is evident from the table viz high transmission efficiency, low grid loading and ability to provide long pulses. Figure 8 compares the performances of type B and D grids. The increased power transmission efficiency of type D is somewhat offset by the reduced optimum perveance. However, the reduced power loading on the ground grid, in the case of type D, should be particularly advantageous for long pulse operation.

Extrapolation of the results obtained with the different grids it should be possible to inject more than 1.5 MW of 50 keV neutrals up to the PDX machine. Because of lower beam divergence and grid loadings type B and D grids are clearly favored.

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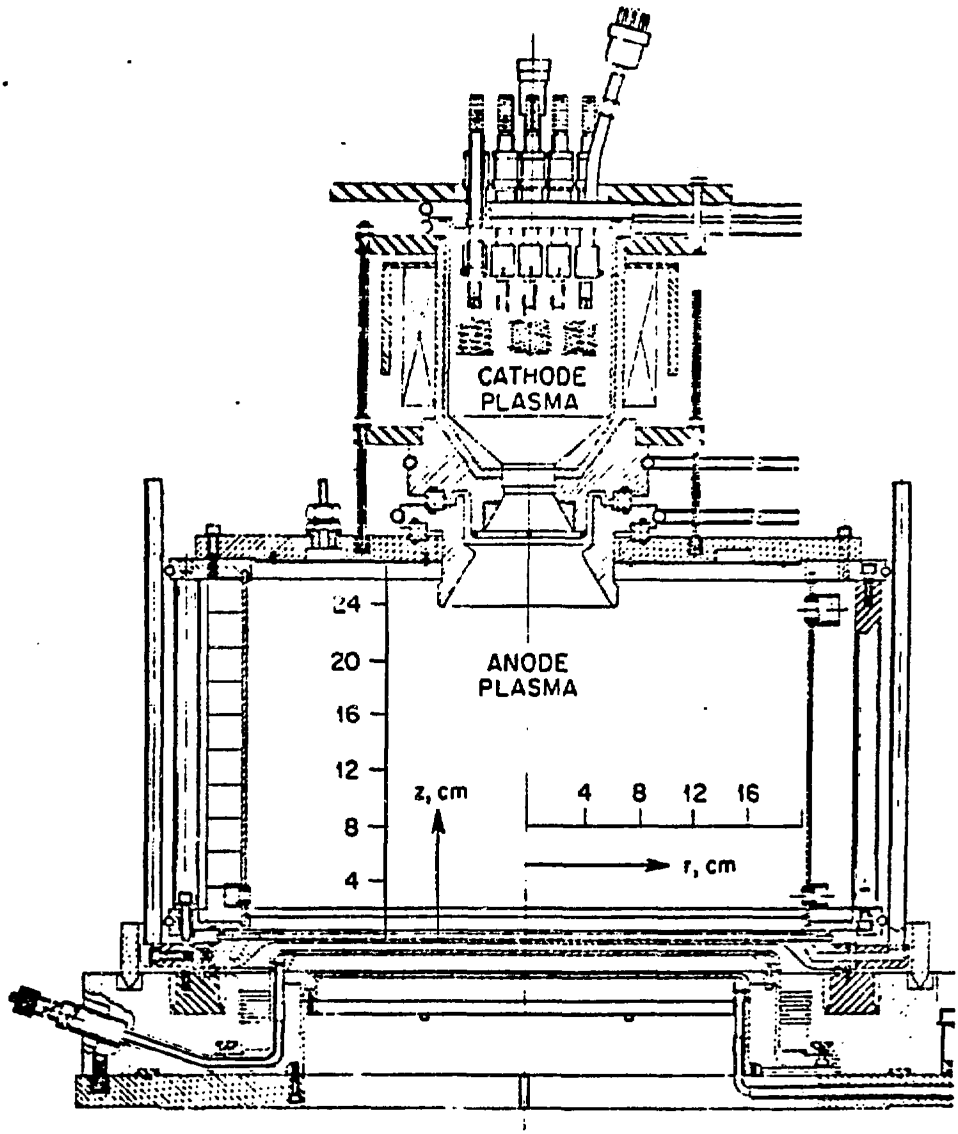


Fig. 1. The PDX prototype ion source

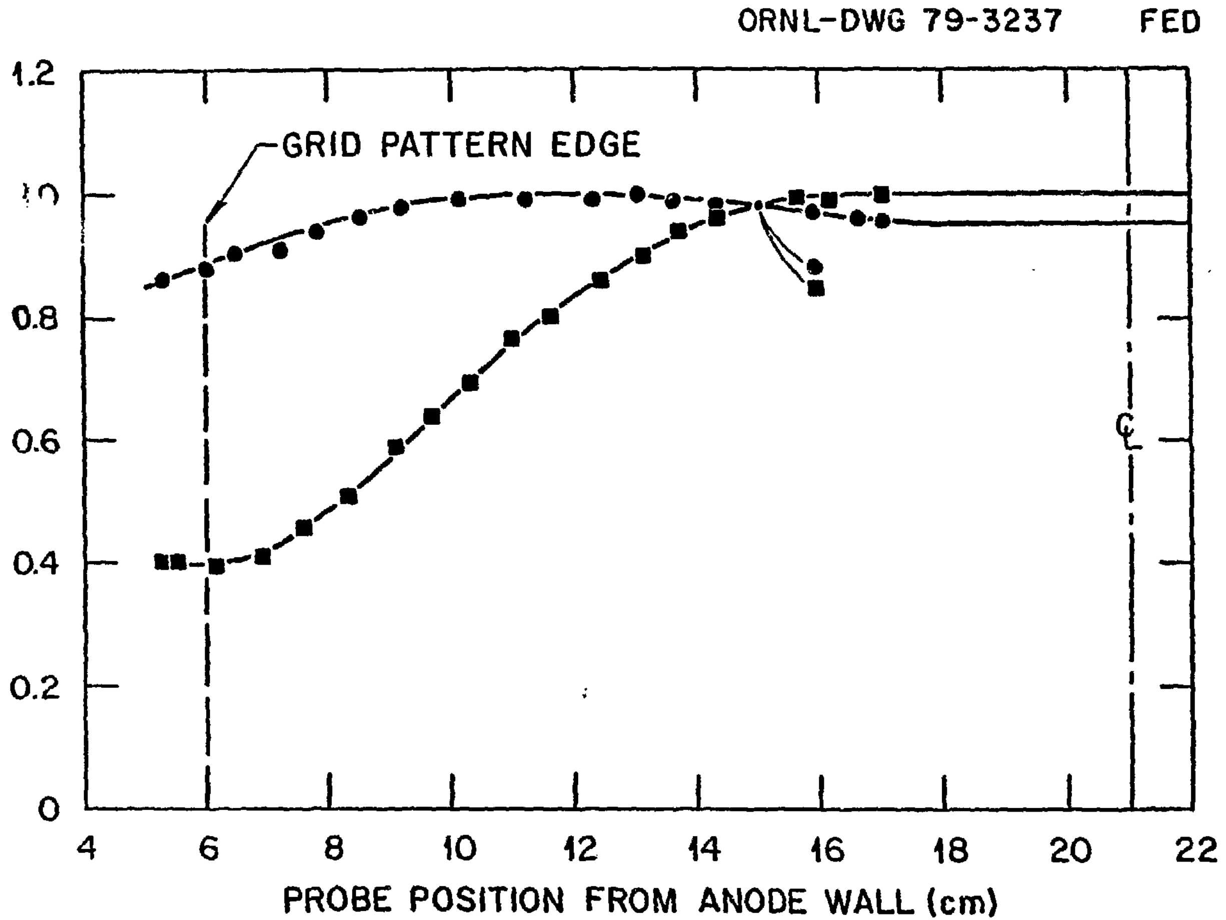


Fig. 2. Plasma density profiles (● 4-hole IE, ■ single hole IE).

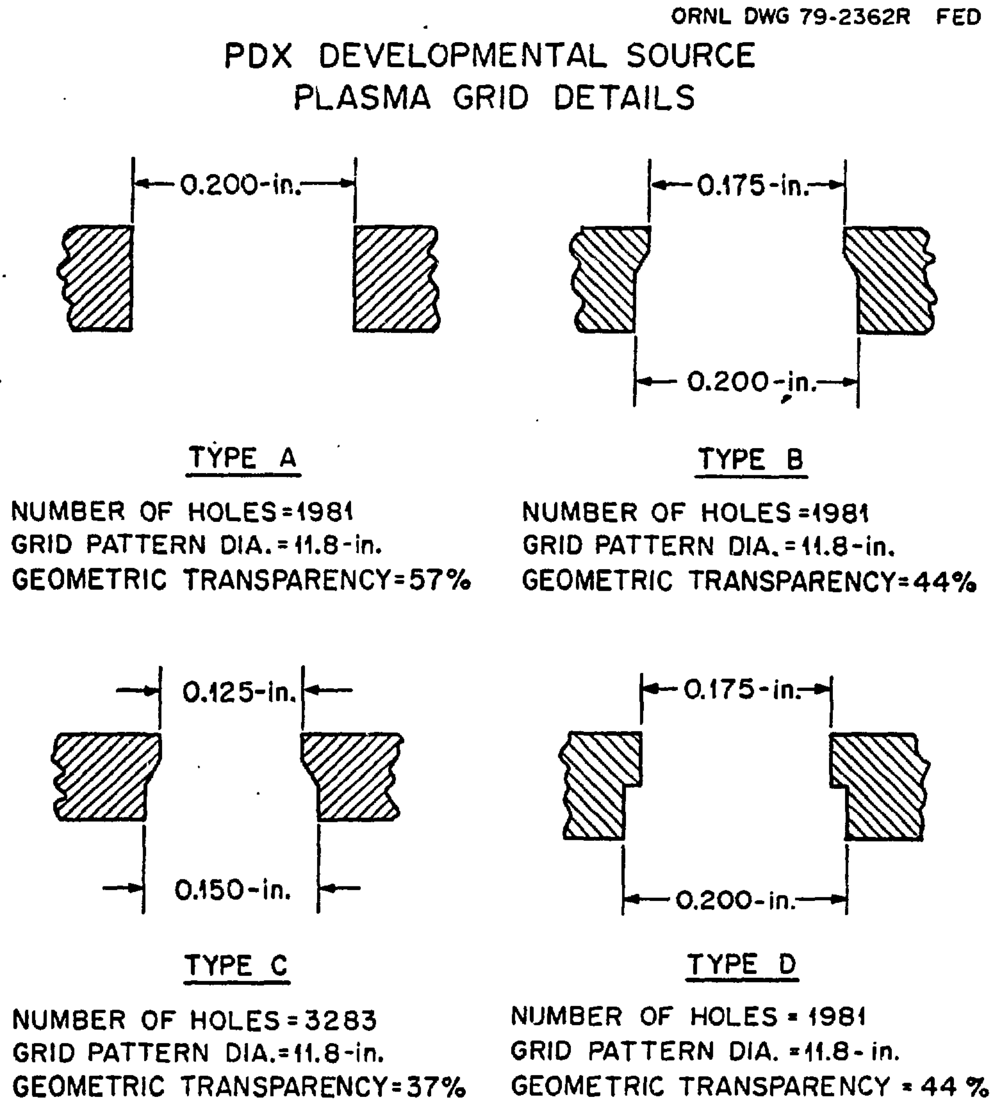
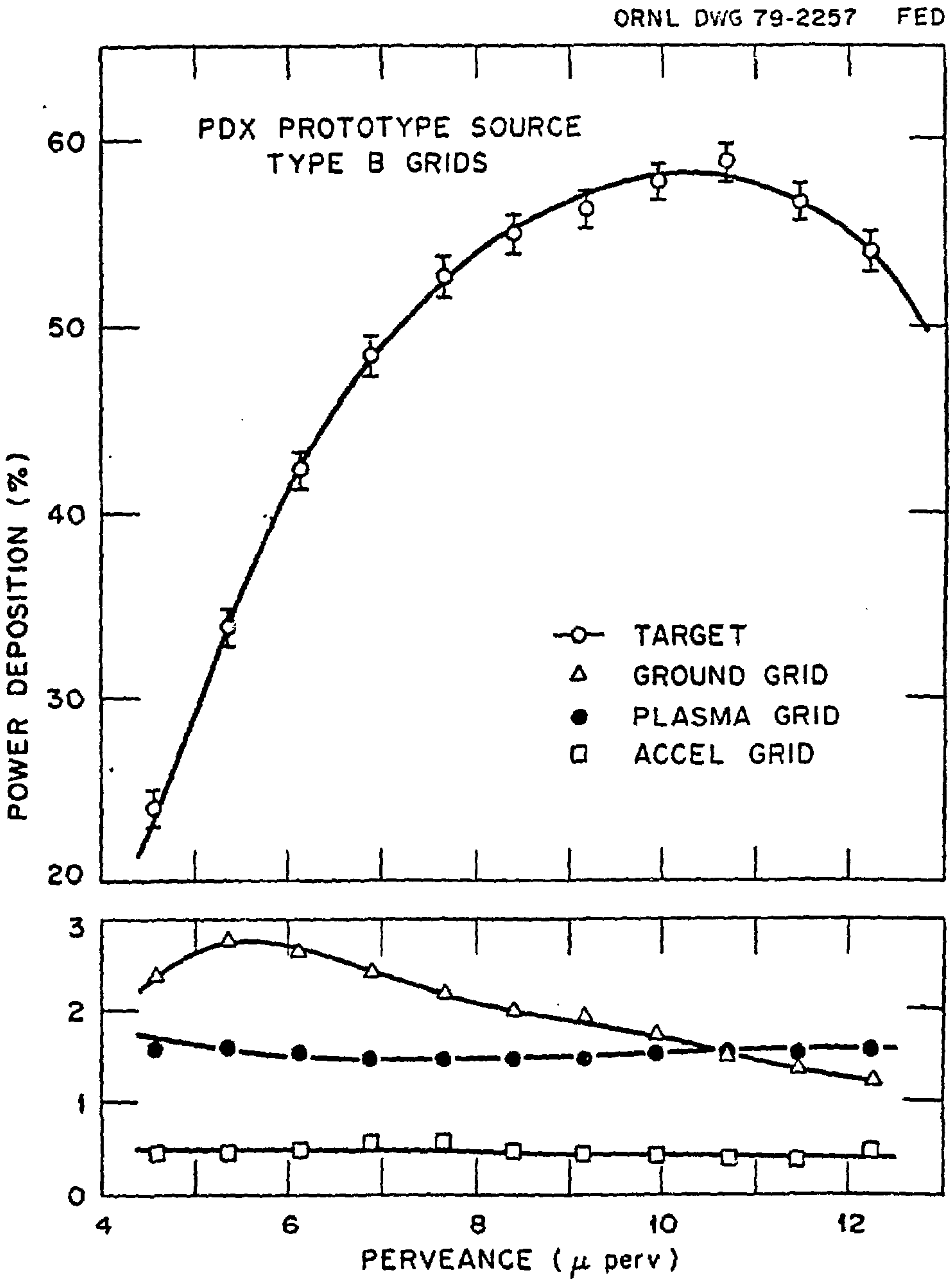


Fig. 3. Details of the various types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PDX PROTOTYPE SOURCE
TYPE B GRIDS
TARGET
GROUND GRID
PLASMA GRID
ACCEL GRID
POWER DEPOSITION (%)
PERVEANCE (μ perv)
60
50
40
30
20
3
2
1
0
4
6
8
10
12

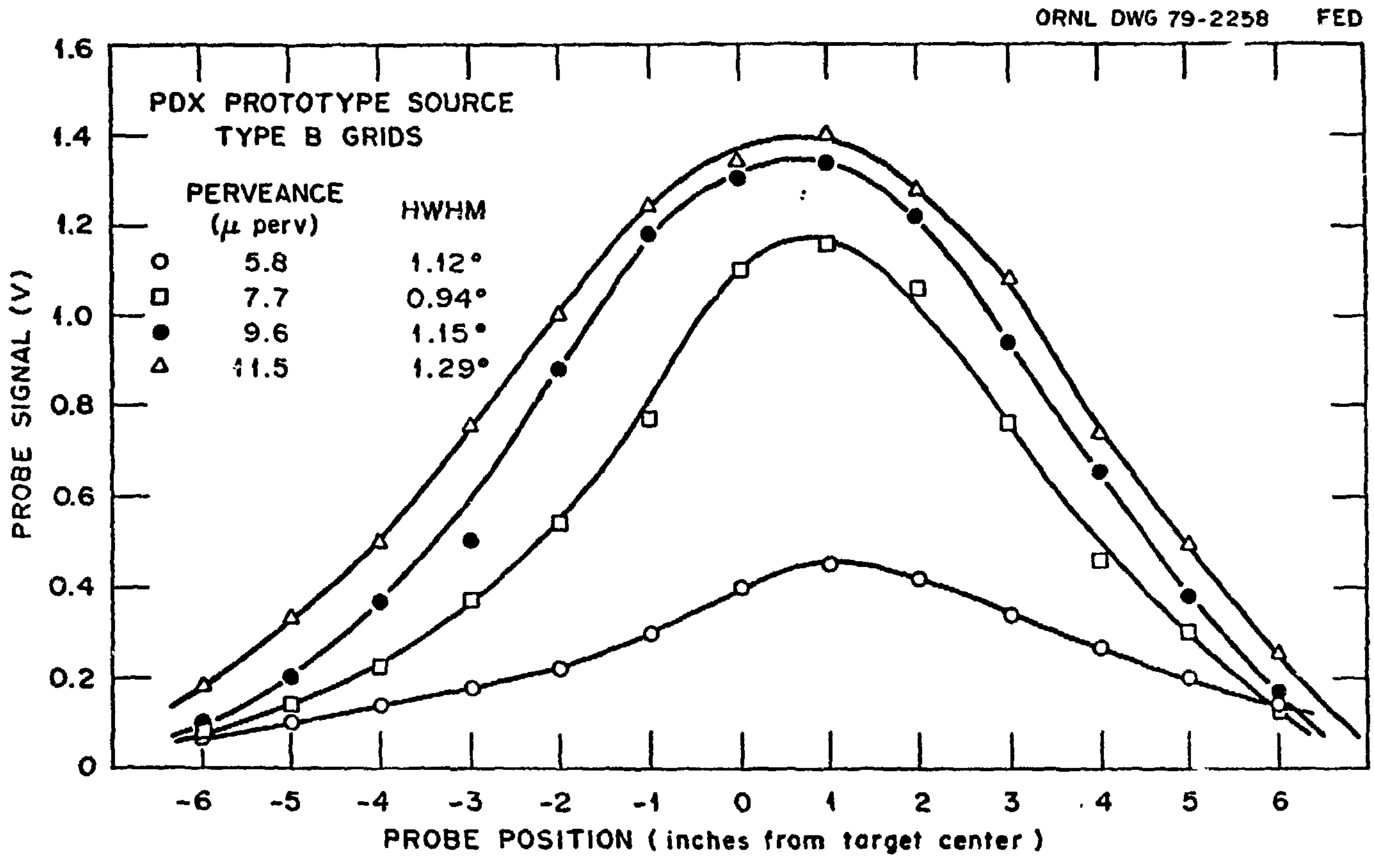

Fig. 5. Power density profiles of the beam.

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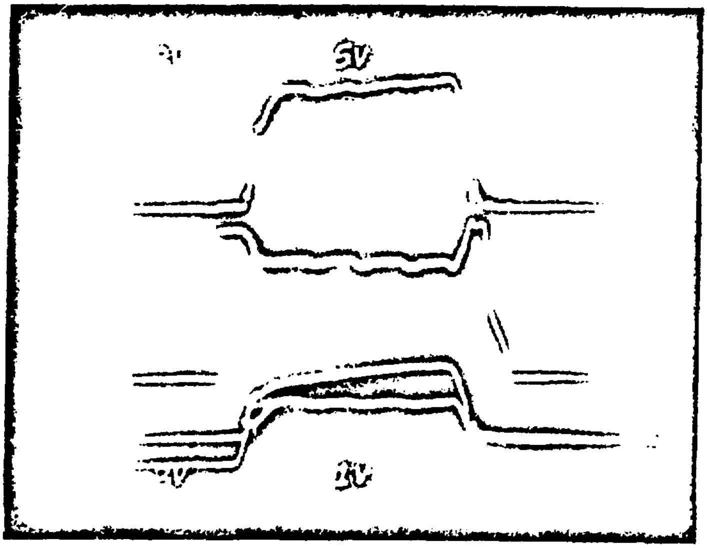


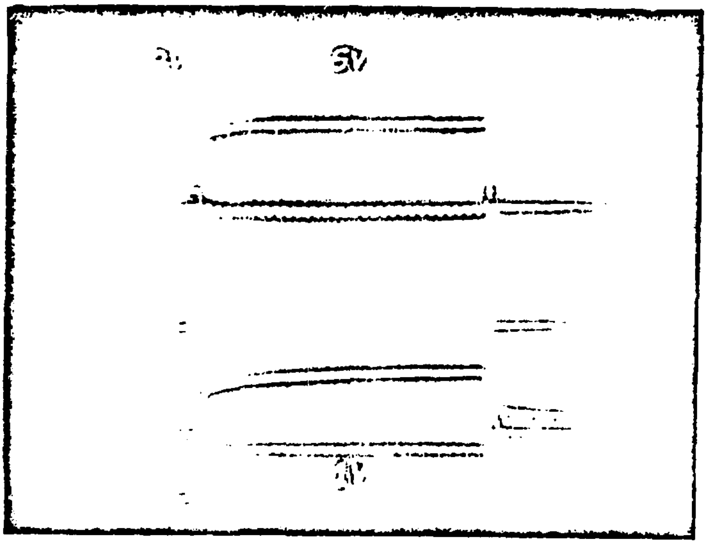
I_{BEAM} 50A/DIV

H.V. 20 kV/DIV

I 1000 A/DIV

V 100 V/DIV

41 kV/110 A/0.075 sec BEAM



I 50 A/DIV

H.V. 20 kV/DIV

I 1000 A/DIV

V 100 V/DIV

41 kV/75 A/0.5 sec BEAM

Fig. 5 Actual wave forms

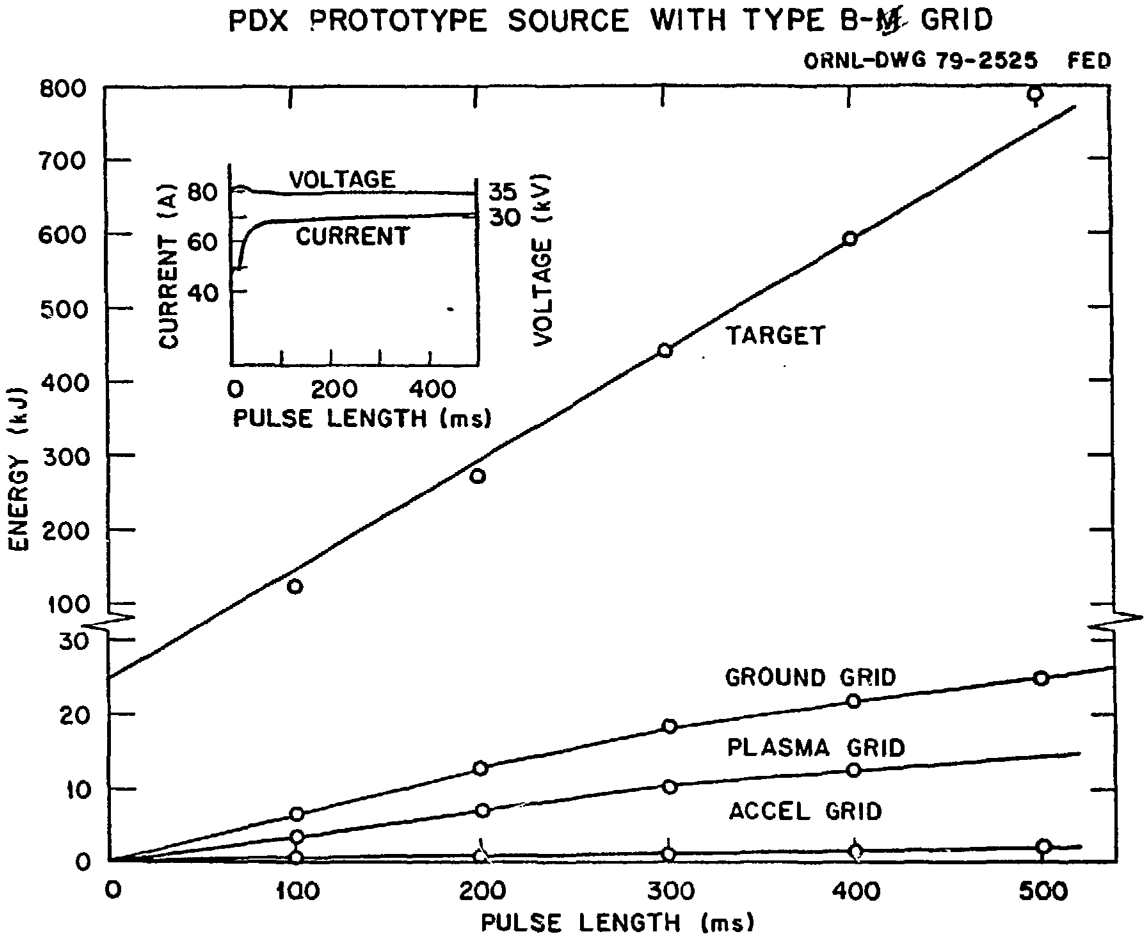


Fig. 7. Energy deposition vs. pulse length.

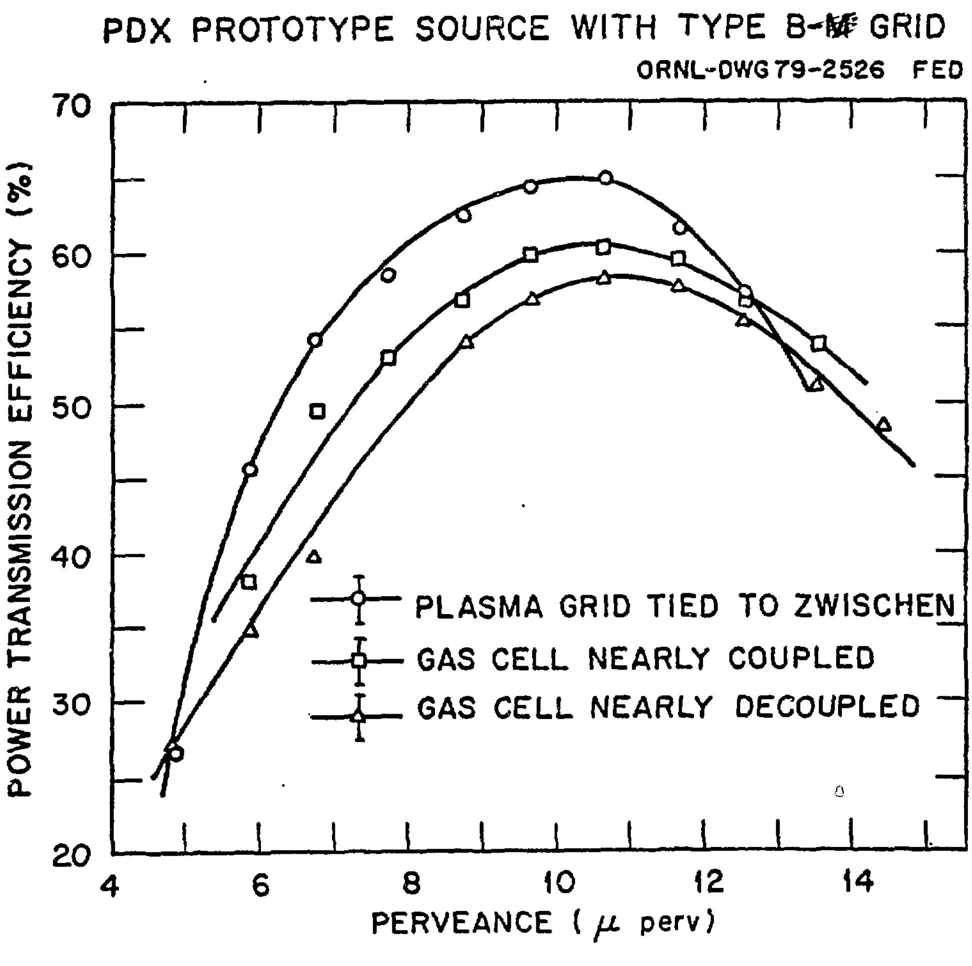


Fig. 8. Effect of precel voltage and gas cell coupling on power transmission.

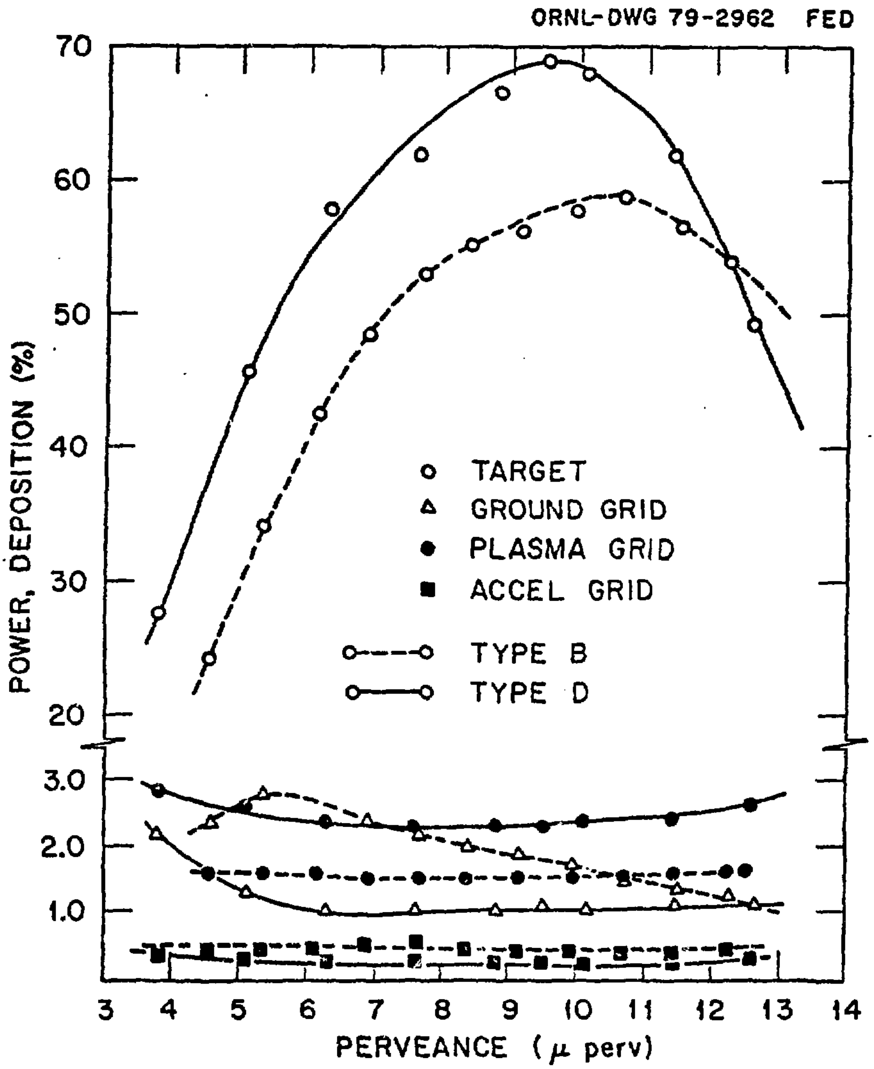


Fig. 9. Comparison of the performance of type B and D grids.

TABLE 1. COMPARISON OF TYPE A, B, and C GRIDS

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PDX DEVELOPMENTAL SOURCE
(TEST STAND RESULTS*)

QUANTITY	TYPE 'A' GRID	TYPE 'B' GRID	TYPE 'C' GRID
BEAM CURRENT	110 A @ 42 kV/100 ms	100 A @ 40 kV/100 ms	90 A @ 40 kV/100 ms
BEAM ENERGY	50 kV @ 25 A/100 ms 47 kV @ 75 A/100 ms	50 kV @ 25 A/100 ms 46 kV @ 75 A/100 ms	48 kV @ 25 A NOT YET TESTED
BEAM PULSE LENGTH	500 ms @ 41 kV/80 A	500 ms @ 40 kV/75 A	NOT YET TESTED
CURRENT DENSITY	0.27 A/cm^2 @ 41 kV	0.33 A/cm^2 @ 40 kV	0.35 A/cm^2 @ 40 kV
BEAM TRANSMISSION (2° TARGET 4.2 M AWAY)	55%	60%	60%
OPTIMUM PERVEANCE†	10 μ perv.	10 μ perv.	10 μ perv.
PLASMA GRID LOADING†	1.9%	1.4%	1.6%
ACCEL GRID LOADING†	0.5%	0.4%	0.6%
GROUND GRID LOADING†	2.7%	1.6%	2.9%

*WITH DECOUPLED NON-EQUILIBRIUM GAS CELL
†UNDER OPTIMUM CONDITIONS