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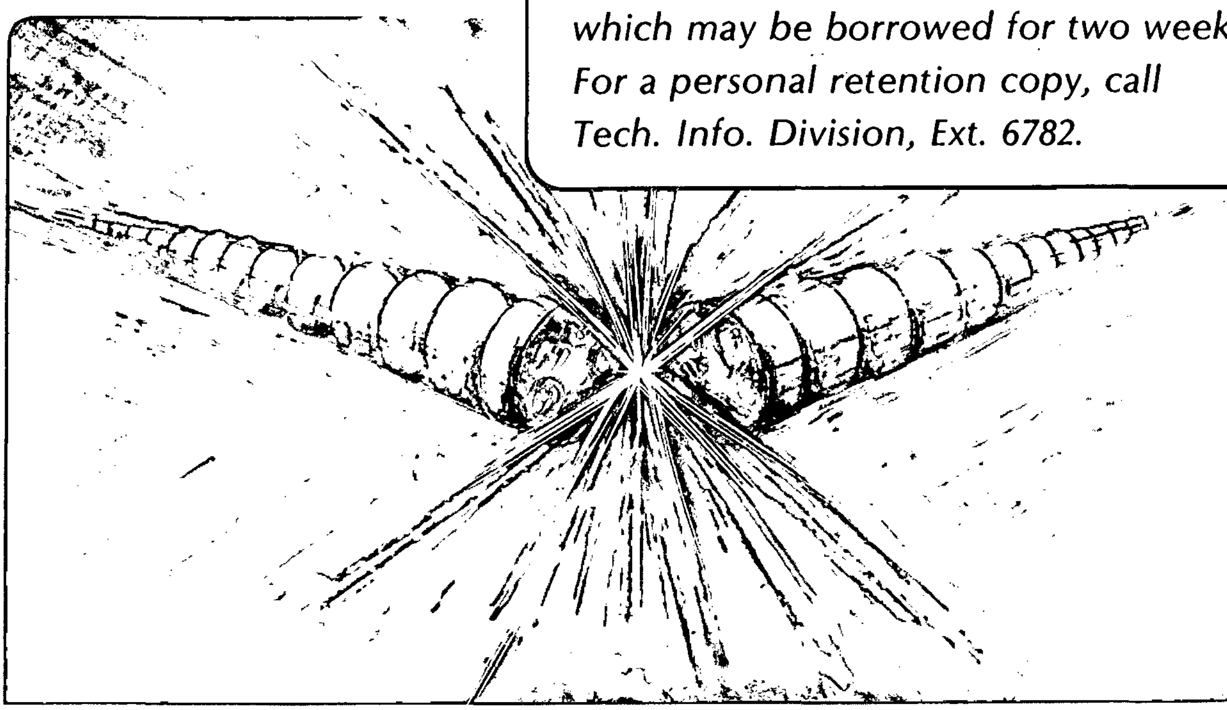

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CALCULATIONS OF GAS DENSITY IN A CLOSELY-PACKED MULTI-CHANNEL ELECTROSTATIC QUADRUPOLE (MESQ) ARRAY*

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Abstract

As a part of our program for developing new accelerators for high-energy negative ion neutral beamlines, we have studied the pumping properties of a MESQ array such as might be interposed between the ion-source/ pre-accelerator and a MESQ accelerator. The studies were performed using a two-and-a-half dimensional Monte Carlo code under the assumption of molecular flow, with pumping to be provided by cryopanels on either side of the array. The basic unit treated by the code was a unit cell which could be translated laterally or longitudinally to reproduce the full array. We have studied the behavior of the system as a function of electrode geometry, array size, and cryopanel position. It was found necessary to insert lateral baffles periodically to prevent downstream migration of the gas in the region between the outer edge of the MESQ array and the cryopanels.

I. Introduction

One of the principal methods for heating a magnetically confined plasma in a fusion device is by the injection into the plasma of multimegawatt beams of neutral hydrogen or deuterium atoms. These beams are produced by accelerating charged particles, produced by multi-ampere ion sources, to

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energies in the range of tens to hundreds of keV and then neutralizing them. For energies in the range of 20 to 150 keV the ions are accelerated in a relatively short electrode structure (similar to a Pierce gun) consisting of one or two high-gradient gaps. As one goes to higher energies, sparkdown considerations argue in favor of a longer structure involving either R-F[1] or low-gradient dc[2] acceleration. In either case, control of the beam over the longer acceleration path, is achieved through the use of alternating-gradient (A-G) focussing.

Negative ions are preferable to positive ions for the production of high energy neutral beams; the greater neutralization efficiency achievable with the former (at higher energies) outweighs the relative ease of ion production of the latter. However, premature neutralization of the beam ions, due to collision with residual gas atoms either during or prior to acceleration, can cause excessive beam loss or deposition of stray beam power in unwanted places. It is therefore necessary in the case of long path accelerators to provide a means whereby the copious quantities of gas emitted from the ion source can be removed prior to the point at which the beam enters the accelerator. A common scheme for accomplishing this involves interposing a low energy beam transport (LEBT) section between the ion source and the main accelerator (a Pierce-gun-like preaccelerator located immediately after the ion source, is necessary for injection into the LEBT) which provides sufficient focussing to transport the beam and yet is sufficiently open to permit adequate pumping. Such structures are usually sufficiently inhomogeneous and anisotropic that it is quite difficult to assess their pumping performance analytically in any but the most approximate way.

The present paper reports on the pumping performance of a proposed LEBT designed to serve as an interface between a multi-aperture ion source and a multi-channel electrostatic quadrupole (MESQ) accelerator, described in more detail in the following section. The basic "philosophy" of the calculations was to take a "standard" geometry which provided satisfactory electrical performance, and vary the geometry to enable us to assess the merits of trading off focussing capability against pumping performance. The pumping performance was evaluated using a so-called two-and-a-half-dimensional Monte Carlo calculation (i.e. one which assumes infinite periodicity in one of the transverse dimensions). A description of the LEBT array and the basic calculation scheme is described in Sect. II. Investigation of the systematic behavior of the structure as a function of its various parameters is described in Sect. III. Evaluation of the results is given in Sect. IV.

II. LEBT Structure and Monte Carlo Code

The LEBT configuration shown in Fig. 1 has a periodic array of focussing and defocussing electrodes which create a series of electrostatic quadrupole fields to provide strong focussing of the beam. This configuration is compatible with a two-dimensional array of beamlets and electrodes (see Fig. 1c). In order to provide strong pumping of the center regions we envision an array which has a high aspect ratio between the height and the width of the array of beamlets, with cryo-pumping along each vertical side of the LEBT. For simplicity in the calculation we assume the array extends infinitely in the vertical direction.

In the code we make the usual assumptions for Monte Carlo calculations of molecular gas flow.[3] The basic unit of the code is the unit cell which can be translated laterally or longitudinally to reproduce the entire structure. Fig. 2 shows the simplest structure, namely the one which has just five cells in the horizontal direction and is only one stage long.

The top and bottom boundaries of the cell are treated as specularly reflecting surfaces, thereby simulating an infinite structure in the vertical direction. The cryopanels are assumed to have a reflection coefficient of 75%.

As may be seen from Fig. 2, the central cell (or cells, in the case of the wider structure) carry the equivalent of one full beamlet of current, although in fact the current corresponds to half of one beamlet plus one fourth of two others. (The outer two cells are necessary to provide the correct electric fields for the beamlets in the interior cells.) We have nonetheless decided to adopt the somewhat imprecise shorthand description of referring to a structure which is N cells wide as being N-4 beam channels wide.

From the position and the direction cosines of a molecule in a cell, the distance to each type of surface (i.e. side wall, top wall, electrode face, etc.) is computed and the molecule is transferred to the point of intersection of its trajectory with the <u>nearest</u> of the surfaces, i.e. the first one which the molecule encounters along its trajectory. If the surface is solid, the direction cosines for the subsequent trajectory are selected randomly from a cosine distribution normal to the surface; if the surface is an interface with a neighboring horizontal cell, the cell index number (longitudinal or lateral) is changed appropriately, and the subsequent trajectory is simply an extension of the original, i.e., the direction cosines are left unchanged.

At the downstream end of the final stage, we introduced the somewhat artificial boundary condition that the beamlet aperture be totally absorbing. This generally resulted in an artificial dropoff in pressure in the final few stages, and consequently the pressure calculated for these stages are omitted from the plotted results; statements in the text referring to final stage pressure refer to extrapolated pressures, which are higher than the calculated ones.

For the calculation of gas density in a given cell, the code computes STL(I,J), the sum of the lengths of every trajectory in that cell. The gas density in a cell is then

$$n(I,J) = STL(I,J)\ 1/4n_0\ A/(N\ V)$$

where n_0 is the gas density at the entrance to the LEBT, A is sum of the beamlet aperture areas in the entrance (or any other) stage, V is the volume of a cell and N is the total number of molecules used in the calculation. We somewhat arbitrarily set $n_0 = 3.22 \times 10^{13}\ cm^{-3}$. While this is the gas density measured within the LBL negative ion source[4], the impedance of the source exit apertures and preaccelerator are expected to lower the pressure at the LEBT entrance by at least a factor of three. However, since this number corresponds to 1 millitorr, it permits one readily to "renormalize" the pressure data. The molecules are assumed to be at room temperature throughout, since molecules scattering off the cryopanels should make several bounces off the electrode structure before reaching the area of the beamlets.

Because the alternate electrode support plates are at electrical potentials which differ by tens of kilovolts (see Fig. 1), it is impermissable in practice for the cryopanels to be immediately adjacent to the plates; therefore the code permits the cryopanels to be offset by an arbitrary distance, with the upstream and downstream ends of the cryopanel space treated as diffusely reflecting surfaces. As we shall show, this greatly increases the gas flow outside the LEBT structure, thereby raising the pressure at the exit end to unacceptable levels. Hence the computer code also permits the periodic placement of baffles, oriented parallel to the support plates and extending from the plates to the cryopanels, in order to restrict the downstream flow of gas outside the electrode structure.

III. Results of Calculations

In studying the systematic behavior of the structure, a "standard" cell geometry was adopted, based on the current-carrying requirements of the quadrupole, and the structure parameters were then varied about these standard values. The standard cell was 3.6 cm long and 3.8 cm wide and 1.9 cm high, with a beamlet aperture of .95 cm radius. The quadrupole electrodes were also .95 cm in radius. The length of the electrodes was generally expressed in terms of the "fill-factor" F, the percentage of the full cell length; the percentage overlap of the electrodes is simply 2F - 100. For the standard geometry we chose F = 60% (20% overlap), which corresponded to an electrode length of 2.16 cm. Because it facilitated making qualitative comparisons, most systematic studies were made with the cryopanels flush with the outside of the electrode structure.

a) <u>Aspect ratio of overall structure</u>. One of the design goals for the accelerator array was that it be able to carry a total current of 10 A. Calculations showed the maximum current per beamlet to be on the order of 100 mA, thereby requiring a 100 beamlet array. In addition to the pumping requirements, considerations of the beam neutralizer design (not discussed here) argued in favor of an array with a large aspect ratio (height to width). On the other hand, too narrow an array would result in an excessively elongated ion source. Hence initial calculations were done to ascertain what the effect of the array width was on the pumping properties, and what an acceptable upper limit on the width might be.

Fig. 3 shows the calculated longitudinal variation of particle density in the central channel(s) of the "standard" MESQ array for structures ranging from one to six beamlets wide. Here, as in subsequent figures, we adopt the practice of including "error bars" to show the statistical uncertainty associated with the individual calculated points. Because these uncertainties exhibit a regular systematic behavior, increasing as the pressure decreases, including error bars on all points would unnecessarily clutter the figure, and hence only occasional error bars are displayed. Moreover, here, as in subsequent figures, the smooth curves are not fitted, but merely drawn to guide the eye.

From Fig. 3 one sees that, at least in the early stages, the pressure falls approximately exponentially. The result is in qualitative agreement with a two-dimensional diffusion model which Hamilton and Willman[5] have used in calculating the pressure distribution in a similar structure. As expected, the pressure fall-off decreases with increasing number of channels. For a structure with a single beam channel (total width five channels; see Sect. II) the final stage pressure shows a drop of about three orders of magnitude within ten stages, whereas for a six-beam-channel-wide structure, it drops by about two orders of magnitude in twenty stages. Also shown in the figure is a comparison of pumping performance in terms of the integrated particle (line) density in the central cell. The transverse pressure distribution (not shown) shows the expected peaking in the central channels; however, for structures with five or fewer beam channels, the variation in line density from outermost to innermost channel is less than the change resulting from the addition (or subtraction) of a single beam channel.

b) Effect of Electrode Overlap. Using the four-beam-channel-wide structure, we looked at the effect of varying electrode length from F = 50% (no overlap) to F = 80% (60% overlap). As seen from Fig. 4, the pressure at the downstream end varies by less than a factor of three over the range of cases considered. The variation in integrated line density is considerably less than that, i.e., only about 20%.

c) Variation with Electrode Radius. For the two-beam-channel structure with F = 60%, the electrode radii were varied from .95 cm (essentially tangent to the beam aperture) to .38 cm. The results (not shown here) were quite similar to those of Section IIIb. The improved pumping performance obtained with the optically marginal electrodes gave an improvement of about a factor of three in downstream pressure, and a reduction of about 20% in integrated line density.

d) Realistic Cryopanel Configuration. As alluded to earlier, systematic studies were made with the cryopanels in the flush-mounted position, since the resulting quasi-exponential pressure distributions greatly facilitated comparisons of different electrode geometries. Having completed such comparisons, we then turned our attention to the question of more realistic cryopanel configurations. The six-cell-wide structure is the one used in all the cryopanel calculations.

The effects of moving the cryopanels from the flush-mounted position to distances of 5, 10, and 40 cm from the edge of the LEBT are shown in Fig. 5. The resulting deterioration in pumping performance is immediately apparent, the downstream pressure increasing between one and two orders of magnitude. Note that with the cryopanels pulled back, the pressure in the early stages actually improves, due to the increased cryopanel area available to those stages. Hence the particle line density increases only slightly and, for these tests, no longer serves as a useful figure of merit.

The deterioration in pumping performance is clearly due to the particles being able to migrate readily downstream once they are outside the electrode structure. In seeking to remedy this difficulty, we made use of the fact that every other electrode support plate in the LEBT is at the same potential (see Fig. 1b), which in practice could be the same as that of the cryopanel. Hence one can periodically insert baffles, parallel to the support plates and extending from the plates to the cryopanels, in order to restrict this gas flow.

The efficacy of the remedy is readily apparent from Fig. 6. Baffles inserted every six stages reduce the downstream pressure by 1 1/2 orders of magnitude; inserted every four stages, they bring the pressure to within roughly a factor of two of that obtained with flush-mounted cryopanels, producing better than three orders of magnitude reduction in the final stage pressure. Finally we note the "scalloping" in the pressure distribution caused by the increased rate of pressure drop in the stages immediately downstream of the baffles.

IV. Discussion of Results

The two basic vacuum requirements on the LEBT are that it be able to pump away enough gas so that the pressure in the main accelerator following it be less than 10^{-6} Torr, and that the integral line density of the gas within it be less than roughly $1.5 \times 10^{14}/cm^2$. These figures are based on what are felt to be conservative estimates of acceptable beam losses in the respective sections of the neutral beam line.

In comparing these numbers with the results obtained in Sect. III, one should recall that the calculations assumed an input pressure of 1 mtorr, whereas in the actual system the pressure is likely to be roughly 0.3 mtorr. This would result in a reduction in both the computed line density and downstream pressure by a factor of three. Under this condition we would require that the LEBT effect at least a 2.5 order of magnitude drop in the final stage pressure, and have an integrated line density of gas less than 4.6×10^{14} when the inlet pressure is 1 m torr.

As may be seen from Fig. 6, a structure six cells wide, using the standard cell geometry and 6 cells wide, with realistic cryopanel geometry plus baffling, easily meets both requirements. This means that, for example, were it desirable to increase the electrode overlap from F = 60% to F = 80% to improve the beam optics, this would still leave the pumping performance more than adequate. Similarly, should one choose to reduce the aspect ratio of the overall structure by increasing the width by one or two channels, this would also be possible.

In summary, the Monte Carlo calculations provide a convenient tool for evaluating the pumping performance of a periodic three-dimensional structure such as an MESQ. For the simplest cryopanel configuration (flush with the ESQ structure) they yield results similar to those of an analytic two-dimensional calculation. However, the present calculations permit evaluation of more realistic cryopanel configurations in which the pressure distribution is not treatable in a simple analytic way. The results show that under relatively conservative assumptions, an ESQ structure with realistically configured cryopanels should be more than adequate to pump away the gas emitted by a negative ion source of the LBL type, and therefore to serve as an effective interface between such an ion source and a multi-channel array accelerator such as an ESQ.

V. Acknowledgements

We would like to thank W.F. Steele for generously providing advice and assistance in our computer calculations. This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF-00098.

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5. Gordon W. Hamilton and Peter A. Willman, "Two Dimensional Gas Flow in an Electrode Assembly, UCID-18568, April 1980 (unpublished).

Figure Captions

Fig. 1 a) End view of a single ESQ cell; the correspondence between focussing (F) and defocussing (D) and electrode polarity is for a negative ion beam. b) Three-stage ESQ beam transport channel. c) End view showing how the single channel ESQ can be expanded into an MESQ array.

Fig. 2 Geometry of single stage of ESQ used in Monte Carlo calculations (upper figure shows top view; lower figure, end view) showing unit cell. Structure contains only a single beam-carrying cell and is therefore five cells wide (see text).

Fig. 3 Longitudinal pressure distribution in a 20 stage MESQ, for different numbers of beam channels.

Fig. 4 Longitudinal pressure distribution in a 20 stage MESQ, for varying degrees of electrode overlap.

Fig. 5 Effect on longitudinal pressure distribution in six-cell-wide MESQ, as cryopanels are moved from being mounted flush against outside of electrode array to being separated from array edge by 40 cm.

Fig. 6 Effect on longitudinal pressure distribution shown in Fig. 5 when transverse baffles are inserted, extending from the edges of the electrode support plates to the cryopanels. The case of the flush-mounted cryopanel geometry is included to demonstrate the efficacy of the baffles in restoring pumping performance.

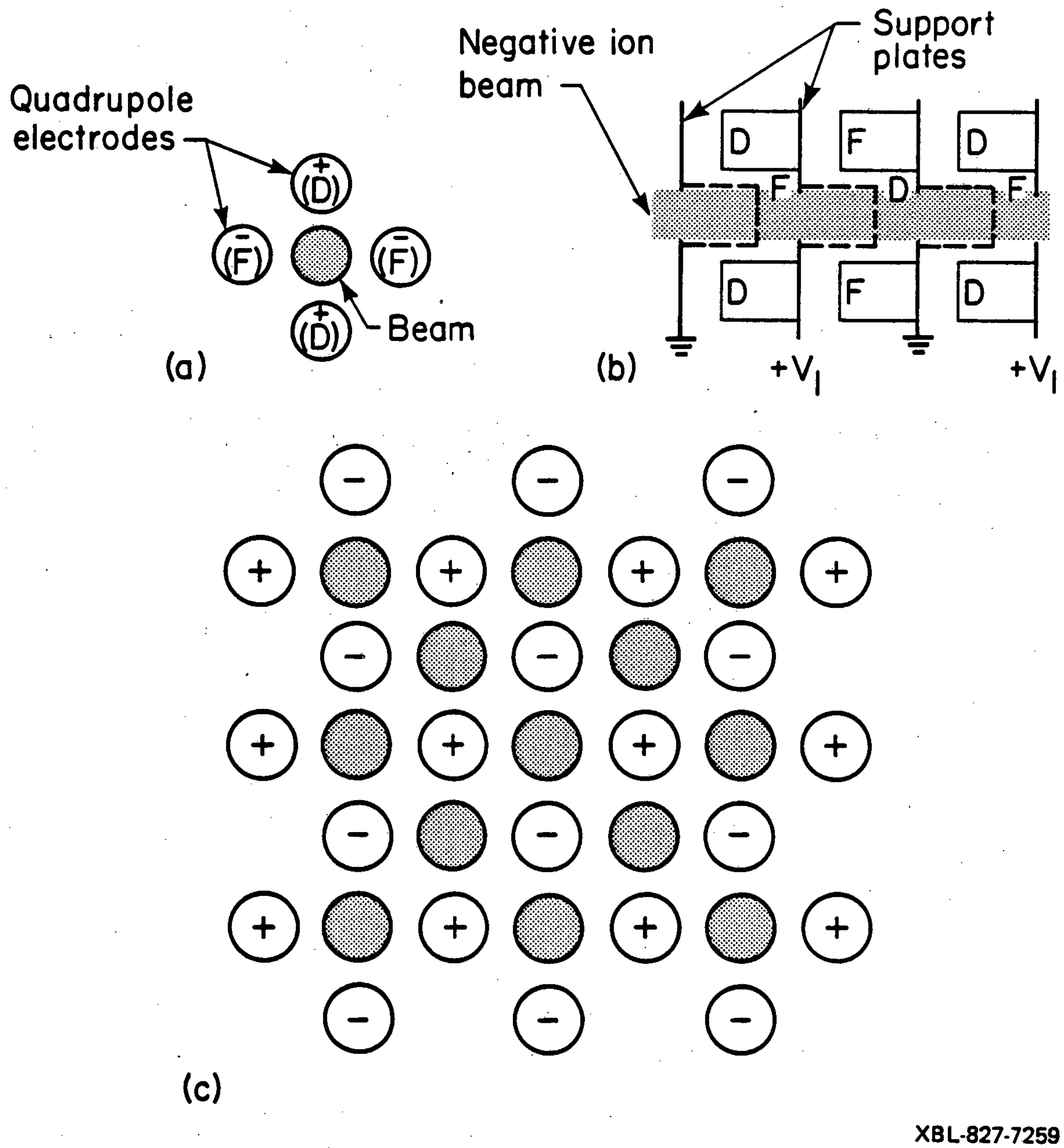
Quadrupole electrodes
+
(D)
−
(F)
−
(F)
+
(D)
Beam
(a)
Negative ion beam
Support plates
D
F
D
F
D
F
D
F
D
+V
+V
(b)
−
+
(c)
XBL-827-7259

Fig. 1

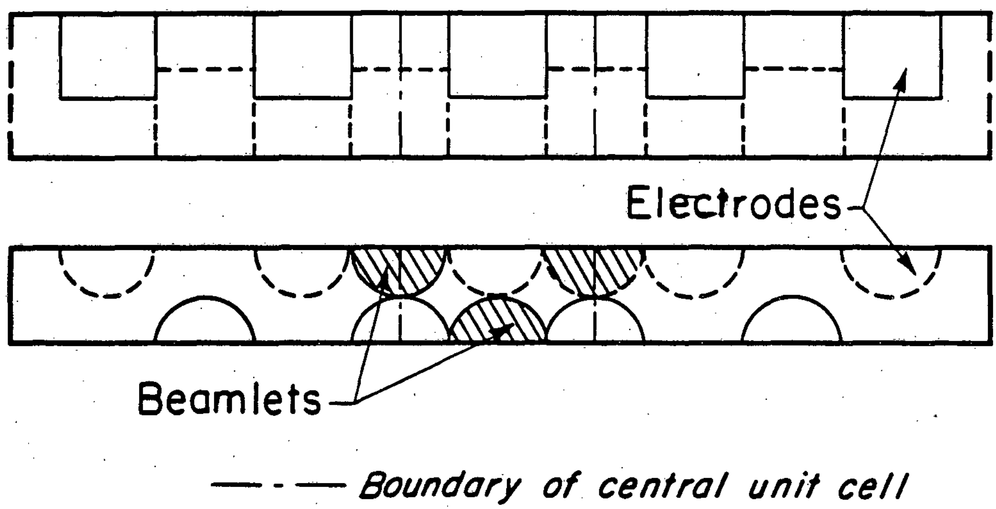

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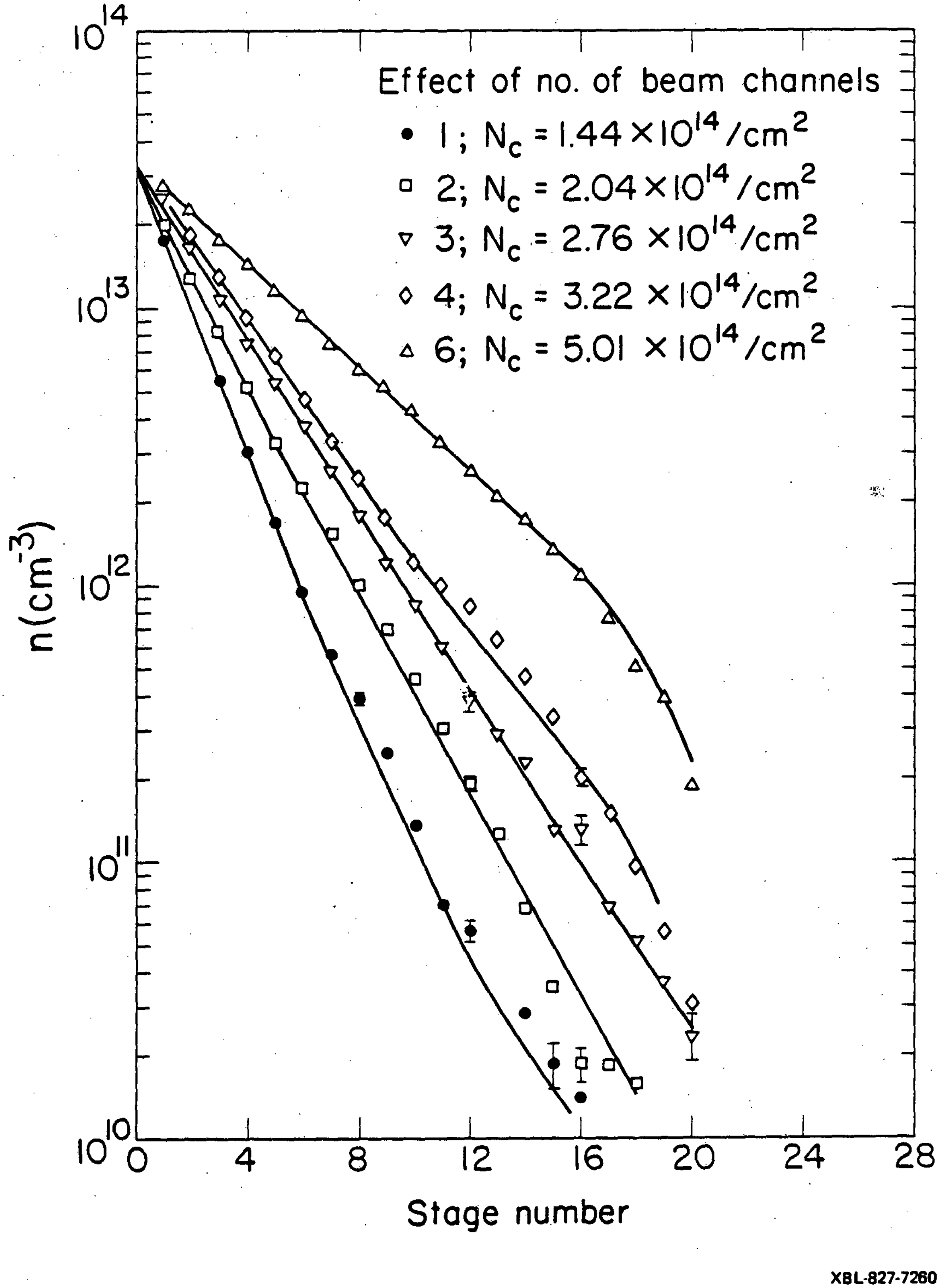
Fig. 2



Effect of no. of beam channels
1 ; $N_c = 1.44 \times 10^{14}/cm^2$
2; $N_c = 2.04 \times 10^{14}/cm^2$
3; $N_c = 2.76 \times 10^{14}/cm^2$
4; $N_c = 3.22 \times 10^{14}/cm^2$
6; $N_c = 5.01 \times 10^{14}/cm^2$
$n(cm^{-3})$
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
0
4
8
12
16
20
24
28
Stage number
XBL-827-7260

Fig. 3

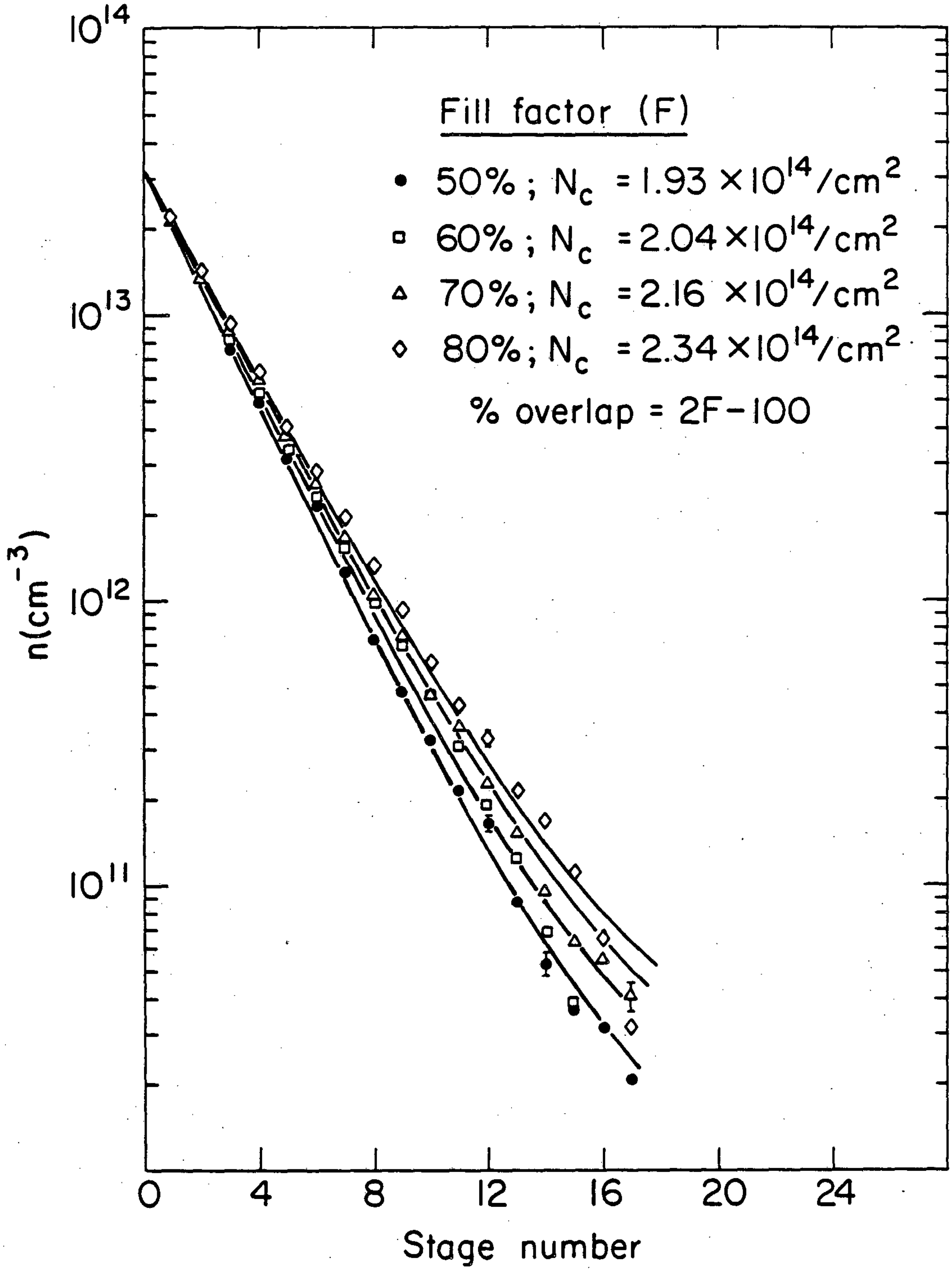


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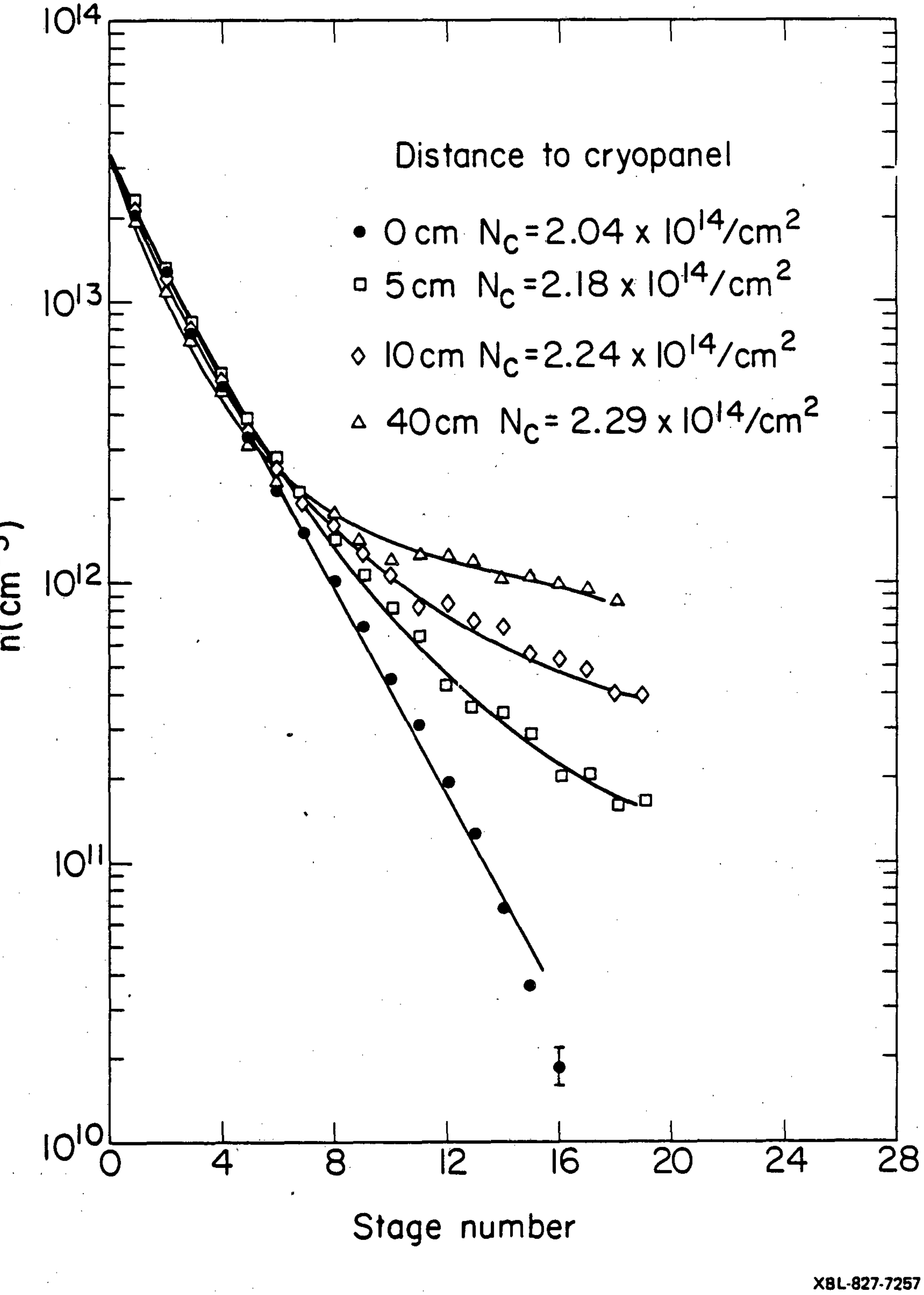
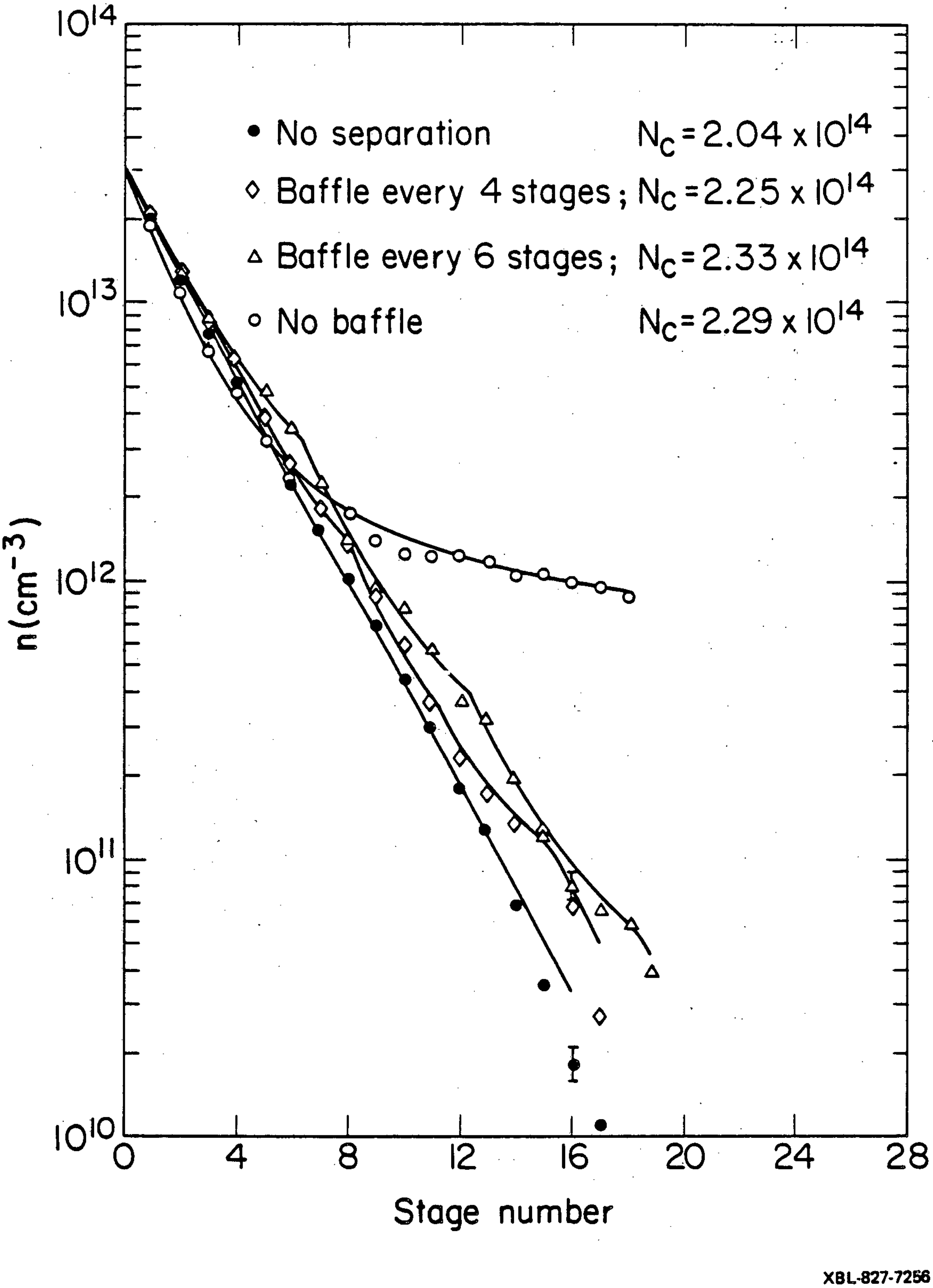
Fig. 4



Distance to cryopanel
0 cm $N_c = 2.04 \times 10^{14}/cm^2$
5 cm $N_c = 2.18 \times 10^{14}/cm^2$
10 cm $N_c = 2.24 \times 10^{14}/cm^2$
40 cm $N_c = 2.29 \times 10^{14}/cm^2$
$n(cm^{-3})$
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
0
4
8
12
16
20
24
28
Stage number
XBL-827-7257

Fig. 5



● No separation N_C = 2.04 x 10^14
◊ Baffle every 4 stages; N_C = 2.25 x 10^14
△ Baffle every 6 stages; N_C = 2.33 x 10^14
○ No baffle N_C = 2.29 x 10^14
n(cm^-3)
10^14
10^13
10^12
10^11
10^10
0
4
8
12
16
20
24
28
Stage number
XBL-827-7256

Fig. 6

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