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LARGE-APERTURE D⁺ ACCELERATORS

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Abstract

Accelerator designs are described for D⁺ produced by double charge exchange, by the ion magnetron, and by the LBL bucket source; in all three cases the accelerators employ a single slot per module. High and low energy designs are discussed; in the latter cases the perveances are much larger than in typical D⁺ accelerators.

1. Introduction

Magnetic fusion applications may require large currents of D⁺ in the next few years. Since D⁺ is not as easy to produce as D⁺⁺, a different approach to accelerator designs is indicated for the two cases. In multi-grid D⁺ accelerators, 60-60% of the ion current flowing toward the grids is transmitted on through the accelerator; the grids intercept the rest. In the case of D⁺⁺, with less copious production, it is desirable to avoid this interception. Therefore, in the D⁺ accelerators described here, multiple grids are not used; each module has one large entrance aperture which transmits essentially 100% of the D⁺ ions produced by the source. Accelerators for three types of sources are discussed: double charge exchange, ion magnetron, and the LBL D⁻ source.

A convenient module in each case has an entrance aperture 5 cm by 50 cm (or perhaps 10 cm by 100 cm).

These large slot dimensions give additional benefits: electrodes are rugged, voltage gradients are low, and stripping cells are conveniently accommodated.

Certain problems or unusual situations may occur in these designs. For example, in early stages of testing one may wish to accelerate large currents to relatively low energies (40 - 100 keV). This leads to accel gaps which may be shorter than the size of the entrance aperture. The associated problems are discussed in Sections 3 and 5. In these lower energy designs the incoming D⁺ beam may already have a significant fraction of its final energy, with the effect discussed in Section 3.

Sections 4 and 5 illustrate cases in which the incoming D⁺ beam has a large systematic divergence which must be eliminated by the accelerator. A more difficult problem arises from non-uniform current density over the entrance aperture; this is discussed in Section 5.

2. Computational model

The results presented here were obtained with the WOLF code. This code can adjust electrode shapes, positions and voltages to minimize the beam divergence. It also finds the correct emitter shape, where the “emitter” in WOLF terminology stands for an equipotential sheath edge. In positive ion applications the E-field on the plasma side of the emitter (the left side in Fig. 1a) is first found by solving the Tonks-Langmuir equation. Then, on the right side of the emitter, an iteration is done: WOLF computes ion trajectories and solves Poisson’s equation (including electrons) with the equipotential boundary condition. The shape of the emitter is adjusted until the computed field equals the Tonks-Langmuir field.

With negative ion sources, the neutralizing plasma on the left of the emitter contains both positive ions and at least a few) electrons. In some cases the presence of three species could make the computational work more difficult. But in the present applications the WOLF computational model is actually simplified: there is a pure D⁺ beam being accelerated to the right of the emitter (Fig. 1a); positive ion and electron space charges are neglected. And the electric field Eem at the plasma edge (the emitter) is so small that it may be set equal to zero. The analysis which leads to this model is given in Ref. 10.

In physical terms, the electrode system accelerates the D⁺ beam (and any electron current) but turns back the neutralizing positive ions from the plasma on the left. These neutralizing ions are too cold (characteristic energy certainly less than 1 eV) to penetrate appreciably into the acceleration region, this is a basic simplification. Ref. 10 shows that one can choose an equipotential emitter surface on which n⁺ << nbeam and also Eem < 50 V/cm; the initial energy is assumed (consistent with the following examples) to be in the range 200 to 15000 eV. Furthermore, plasma electrons may also be ignored in these examples. In a practical
accelerator, an electron current as large as 10% of the D\textsuperscript{+} current would probably be unacceptable, and would need to be suppressed (eg. by magnetic fields\textsuperscript{1,2} or by a flow pattern\textsuperscript{1}) before the D\textsuperscript{+} beam reaches the accelerator aperture. The calculation for the worst case gives \( n_e/\text{beam} \approx 0.1 \) at the emitter surface.\textsuperscript{10} But this ratio falls very rapidly to the right because of the small electron mass, and the effect of electron space charge can be represented by a very slight shift in the emitter position, without noticeable effect on the beam optics.

3. Double charge exchange D\textsuperscript{+} accelerator

The first case studied was a low energy (100 keV) test accelerator for a 10 keV D\textsuperscript{+} beam obtained from a sodium cell.\textsuperscript{3,5} The entrance aperture width \( w \) was 5 cm, with \( J = 20 \) mA/cm\textsuperscript{2}. The perveance per square \( P_s \) was therefore \( 1.6 \times 10^{-8} \) pervs, which is rather large for deuterium. (Compare 2.2 \( \times 10^{-9} \) pervs for TFTR). The accel electrode is therefore quite close to the entrance aperture, as seen in Fig. 1a; in fact the ratio of accel length to aperture size is only 1.40. To reduce aberrations the electrodes were given the special shapes shown in the figure. A trim electrode curves the equipotential lines near the emitter as shown. It has nearly the same potential as the entrance electrode, and could be formed as an extension of it. But as a separate piece, with adjustable potential, it provides convenient experimental control over the optics.

The emittance diagram (Fig. 1b) shows exit angle vs position for each accelerated beamlet. The random transverse D\textsuperscript{+} energy at the entrance aperture (emitter) was taken to be 9 eV, based on 1 eV at the D\textsuperscript{+} source, and a compression factor of 3 in the D\textsuperscript{+} accelerator. The resulting emittance diagram at the exit is seen to be dominated by random energy rather than aberrations; \( \sigma_{\text{rms}} \) is 18.7 mrad giving \( \varphi_{\text{rms}} = 1.52\textsuperscript{o}.\textsuperscript{*} \)

Acceleration from 5 keV entrance energy was studied, using the same configuration and potentials as for 10 keV.\textsuperscript{2} As might be expected, the plasma surface is shifted for this case. The shift is in the downstream direction as predicted by a simple analysis.\textsuperscript{12} A consequence of this shift is that in mixed beams resulting from the presence of molecular ions in the original source (eg. mixed 5 and 10 keV D\textsuperscript{+} beams) the emitter position lies between the two extremes. At the minimum rms divergence, one component is underfocussed and the other overfocussed.\textsuperscript{2}

* \( \varphi_{\text{rms}} \) would be the 1/e halfwidth for the case of a Gaussian transverse energy distribution.

Figure 1a can be scaled to represent a 200 keV D\textsuperscript{+} accelerator with 14 mA/cm\textsuperscript{2} entering at 20 keV over a 10 cm aperture width. If the slot were 140 cm long, then 20 A of D\textsuperscript{+} would be accelerated. The effective beam divergence would be reduced to about 1\textsuperscript{o}.

Although in Fig. 1 the current density is assumed uniform over the aperture, a variation is expected in practice, with the results shown in Ref. 2. A similar problem is discussed for a different type of source in section 5 of the present report.
4. Ion magnetron sources

The steady-state sources being developed at BNL are expected to produce 0.5 to 1.0 A of beam per unit. The current density at the cathode is quite large, but the extracted beam (around 15 keV) has a half angle of 200 mrad and quickly expands to sizes and current densities of the sort discussed in Sections 3 and 5. In fact, it is easy to arrange an array of BNL sources which would fill one of these entrance slots fairly uniformly. The problem is the large transverse energy (600 eV using the above numbers). However, Fig. 2 shows that these diverging beams can be successfully straightened. This example has electrodes and parameters similar to those in Fig. 4a, Section 5. A higher current example would look like Fig. 1a.

![Fig. 2a: Acceleration of 15 keV diverging beam from ion magnetron source.](image)

![Fig. 2b: Emittance diagram.](image)

5. LBL source

The D- source being developed at LBL uses a converter plate similar in shape to the BNL cathode but scaled to much larger size with appropriately lower current density, so that it is naturally compatible with large-aperture acceleration. The separate extractor (≈5 keV) used at BNL is not needed. The accelerators shown in Figs. 3 to 6 work directly with the D- or H+ beam which is produced at the converter plate and accelerated through the sheath. The entrance energy is therefore around 200 eV; there may be an additional cold component from volume production, which tends to be small at low gas pressures and is neglected in the present computations. Two cases have been studied: a 40 keV test accelerator with a single module, and a 200 keV multiple module version. The first configuration, shown in Fig. 3a, is similar to the one in Section 3 except that the aspect ratio is even more unfavorable (the accelerator spacing is actually smaller than the entrance size). The perveance per square is 2.5 x 10^-9. The emittance diagram (Fig. 3b) shows strong aberrations. Although these could be reduced with further design effort, the design may be adequate for initial tests. Fig. 3 does at least demonstrate once again that a diverging entrance beam is readily straightened and focussed.

![Fig. 3a: Low energy accelerator for LBL bucket source: 1.4 A of H+ entering 5 cm x 25 cm slot.](image)

The 200 keV design (Fig. 4a) allows nearly complete control of aberrations as shown in the emittance diagram (Fig. 4b). The favorable aspect ratio here allows slender electrodes with high transparency for gas pumping. The exit beam divergence (0.48°) is near the theoretical limit for the input conditions. This design is intended for modular stacking as shown in Fig. 5. The open electrode arrangement gives fast enough pumping to eliminate nearly all D- stripping up to and through the accelerator.
finite width of the collimating slit. In such an arrangement, though, a good part of the \( D^+ \) current passing through the collimating slit fails to enter the entrance aperture and is wasted.

Thus in the practical system shown in Fig. 5 a compromise is effected: the converter plates would just map onto the entrance apertures if the collimating slits were infinitely thin. Then, when the slits are opened to practical sizes (eg. 2 cm), most of the \( D^+ \) is accelerated, but vignetting occurs as seen in the current profile in Fig. 7a. This leads to a difficulty, because the beam can not be accelerated by the Pierce gun principle, which is used in Figs. 1-4 (and in the LBL positive ion accelerators). In the Pierce gun a suitably angled entrance electrode is in contact with the edge of a uniform beam. Pierce's solution does not apply to a vignette beam.

In the computations for Figs. 3 and 4, the current density was taken to be uniform over the entrance aperture (except for a small cosine effect). This corresponds to a system without vignetting, as illustrated in Fig. 6: the converter plate is large enough (relative to the entrance aperture) to allow for the

Fig. 7b shows the actual results of running the vignette beam (Fig. 7a) through the electrode system of Fig. 4. The emittance diagram (Fig. 7b) shows extreme overfocussing of the edge beamlets, which cross over before reaching the exit. For comparison, the unvignetted emittance outline (Fig. 4b) is roughly represented by the dashed line seen superimposed on Fig. 7b.
Fig. 6: Configuration assumed for Fig. 3; note converter plate extensions.

Fig. 7a: Vignetted current profile at accelerator entrance aperture (unextended converter plate; 2 cm collimating slit).

There are obvious ways to circumvent this problem without wasting D⁻ ions: one could perforate (or otherwise modify) the central region of the converter plates to reduce D⁻ production relative to the edges, or one could seek for a different entrance electrode arrangement not based on the Pierce gun principle. The latter approach is under investigation, with encouraging results.

Fig. 7b. Emittance diagram for vignetted beam (Fig. 7a). See text.

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References

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