Ion optics in a 14 UD Pelletron terminal

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ION OPTICS IN A 14 UD PELLETRON TERMINAL (*)

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Résumé. — Le terminal de l'accélérateur Pelletron de Rehovot est prévu pour transmettre tout faisceau ayant l'état de charge désiré à travers le tube haute énergie. La sélection de charge est obtenue au moyen d'un triplet quadrupolaire électrostatique déplacé. Une lentille d'adaptation en aval dans le terminal adapte l'émittance du faisceau à l'acceptance du tube haute énergie. Une étude détaillée de l'acceptance angulaire du tube haute énergie a été effectuée en vue de vérifier une éventuelle charge du tube. La transmission à travers le tube haute énergie est fortement améliorée par la lentille d'adaptation lorsque le sélecteur de charge est en service mais également lorsqu'il n'est pas utilisé.

Abstract. — The terminal of the Pelletron accelerator in Rehovot was designed so as to transmit freely any beam of a desired charge state through the high energy acceleration tube. Charge selection is accomplished by means of a displaced electrostatic quadrupole triplet. A matching lens further downstream inside the terminal is matching the beam emittance to the high energy tube acceptance. A detailed study of the angular acceptance of the high energy tube was carried out in order to check for possible tube loading. The transmission through the high energy tube is substantially improved by the matching lens both when the charge selector is on and when it is off.

The 14 UD Pelletron has an especially enlarged terminal designed to accommodate two lenses. The first is a charge selector which selects the desired charge state and the second is a matching lens which optimizes the beam transmission through the high energy column.

A schematic lay-out of the terminal is shown in figure 1. The variety of positive charge state beams produced in either a gas or foil stripper enter the charge selector. It is an electrostatic quadrupole triplet of 76 mm diameter with off-axis displaced elements. An analyzing aperture in the image plane of

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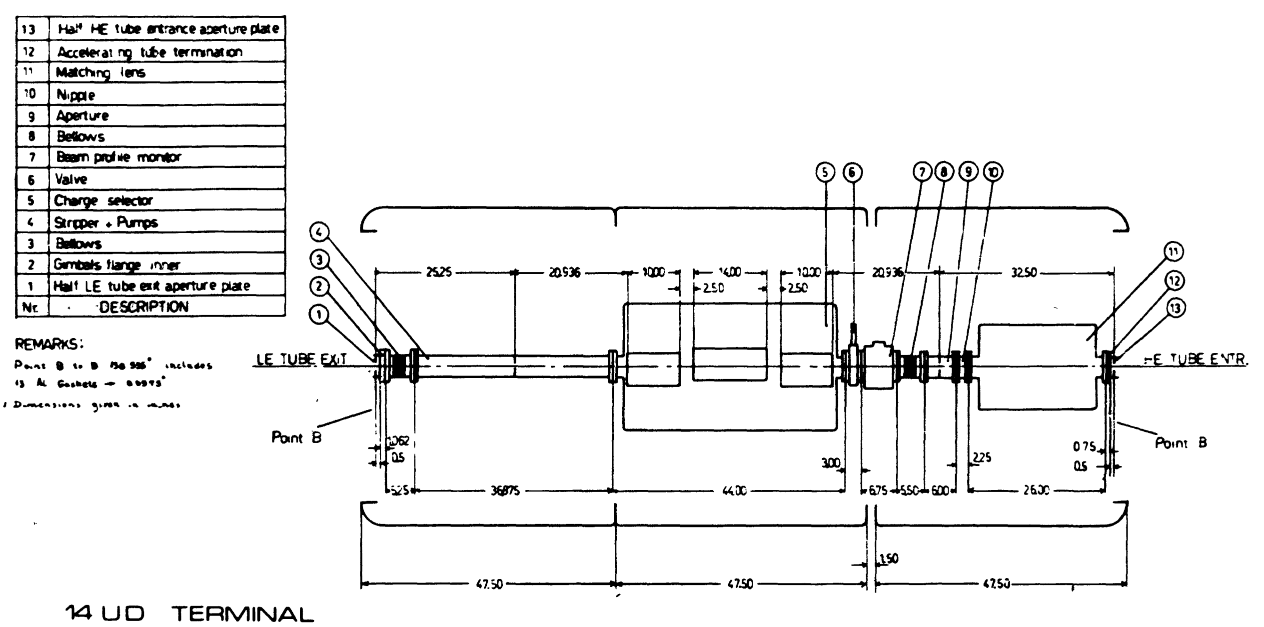

FIG. 1. — Layout in the high voltage terminal of the 14 UD Pelletron. All dimensions are in inches.

the charge selector lets the selected beam through and blocks the rest. There are three openings of different size in the analyzing aperture assembly to be chosen in order to be compatible with different ion optical modes. Since it is essential to have beam diagnostics for proper charge selection a beam profile monitor is placed ahead of the analyzing aperture. A matching lens downstream from the selection aperture serves to match the ion beam emittance with the high energy tube acceptance.

The phase space acceptance of the high energy tube was carefully examined in order to evaluate tube loading effects resulting from beam lost in the tube. In order to avoid loading, the beam emittance at the terminal should be matched well to the high energy tube acceptance.

In most electrostatic accelerators there are no lenses introduced to the terminal. In such cases the only lens effect that changes the ray trajectories is caused by the high energy tube entrance. The focal length of the tube entrance lens can be approximated by

$$f = \frac{4V}{\Delta E}$$

where V is the potential drop which would be required to accelerate the given charge state to its energy at the tube entrance. ΔE is the change in the electric field gradient between opposite sides of the lens.

The injection energy is negligible compared with the terminal voltage and therefore we get for the focal length

$$f = \frac{4l}{Q},$$

where l is the length along the high energy tube over which the accelerating voltage is applied, and Q is the charge state. Hence the strength of the entrance lens increases linearly with the charge state and is independent of the terminal voltage. The entrance lens fits naturally for the transmission of that charge state for which waist is obtained at about the middle of the high energy tube. Lower charge states than this are underfocussed while higher charge states are overfocussed. Both cases may result in hitting the tube apertures. The angular acceptance of the 14 UD Pelletron high energy tube for a point source at the stripper, 290 cm in front of the tube, is shown in figure 2. It acquires a maximum for a naturally matched charge state of about 18^+. When considering the lower charge states, which are the ones of actual interest, the maximum accepted angle is gradually decreasing towards a divergence angle as low as 1.36 mrad when going down to charge state 1^+. Any ray emerging from the stripper with an angle larger than the one which the aperture presents to a point source at the stripper will of course be intercepted by the aperture. In the terminal of our 14 UD Pelletron this aperture cut-off angle is about 4.4 mrad. Rays

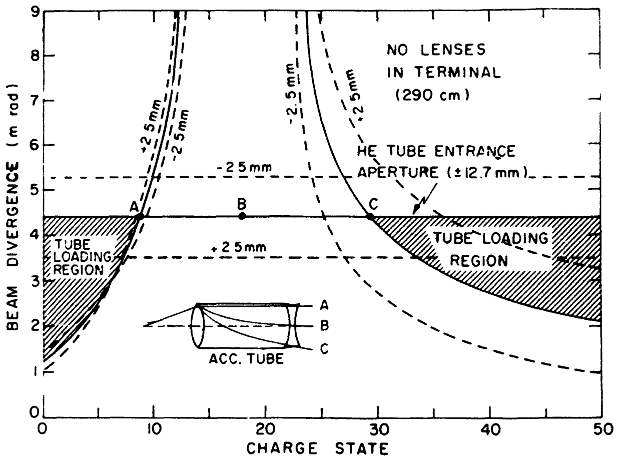

FIG. 2. — Angular acceptance of the high energy tube as function of charge state when no lenses are installed in the terminal. A point source is assumed at the stripper, 290 cm ahead of the tube entrance. The angular acceptance for the source on-axis is plotted with a full line whereas the two dashed lines correspond to shifting the point source off-axis by ±2.5 mm. The shaded area represents the region of rays emerging from the on-axis source and contributing to tube loading.

with smaller angles than the cut-off will enter the tube. Whether they will contribute to tube loading depends on their angle of entrance and charge state.

In figure 2 the region of tube loading is shown shaded. One can notice that a fairly large fraction of the low charge state beams is within the loading region. If the point source at the stripper is shifted to one side the resulting maximum accepted angles differ from the ones obtained with an on-axis point source. This is demonstrated in figure 2 with $\pm$ 2.5 mm offset of the source. In particular for the low charge states, only slight changes result as can be seen in the figure. Shifting the source also modifies the cut-off angle caused by the tube entrance aperture. However, the overall picture does not change significantly and in order to simplify the treatment only the point source will be considered in the sequel.

The matching lens in the terminal is designed to operate both with or without the charge selector. The choice of the operating mode depends on whether one wishes to transmit light or heavy ions. For light ions only the matching lens is needed while for heavy ions also charge selection is included. In either case the matching lens increases the angular acceptance. When operating the matching lens in conjunction with the charge selector some optical constraints have to be considered. The beam diverging from the stripper is focussed by the charge selector on the selection aperture which presents the object plane for the matching lens. The resulting object distance is very short compared with the image distance spanning about half the total length of the high energy tube. In order to achieve optimal beam transmission the matching lens should magnify equally in the two orthogonal planes. However, a quadrupole triplet, being the first natural choice, fails to do this for the large ratio of image to object distance involved. Therefore it was decided to look for another quadrupole lens which would better preserve the beam symmetry. The simplest of these is a quadrupole quadruplet consisting of four quadrupole elements with alternating polarities.

A comparison of the beam size and angle in the two orthogonal planes at image after passage through either a triplet or a quadruplet is shown in figure 3. The improved performance of the quadruplet over the triplet leads to the choice of the first as a matching lens. In order to facilitate the control of the quadruplet lens all its elements are designed so as to require equal voltages.

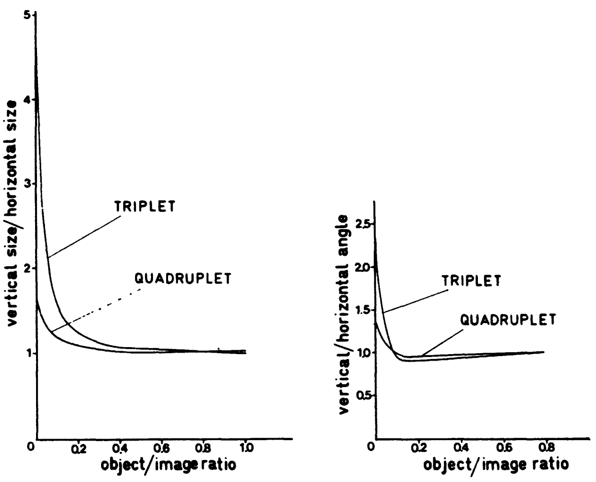

FIG. 3. — Comparison of the symmetry properties of a quadrupole triplet and quadruplet. The ratio in the two orthogonal planes of the image size and angle is plotted for beams passing through either one of the two lenses.

The matching lens can be roughly looked upon as superimposed on the entrance lens thus increasing its strength at will. This modification improves the matching for charge states lower than the one which was naturally matched in the presence of the fringing field only. The gain is largest for protons for which the matching lens increases the maximum accepted angle from 1.36 mrad to about 5 mrad. When going to higher charge states this improvement diminishes. An example is worked out for charge state 10^+ matched for transmission through the tube. The angular acceptance of the tube calculated for this case is shown in figure 4. It resembles the angular acceptance figure which was obtained for the terminal without lenses (Fig. 2), but displays some variation in shape. The angular acceptance is now shifted so as to be centered around the matched charge state 10^+ and has a much narrower peak. An additional feature of the change in the shape is the enhanced acceptance for low charge states. Despite this increase a large loading region still exists as demonstrated by the shaded area in figure 4. As can also be seen in the same figure, the cut-off angle of the tube entrance aperture increases with the charge state when a matching lens is introduced.

When heavy ion beams are accelerated, the loading problems, which severely limit the Pelletron performance, lead to the need of charge selection in the high voltage terminal.

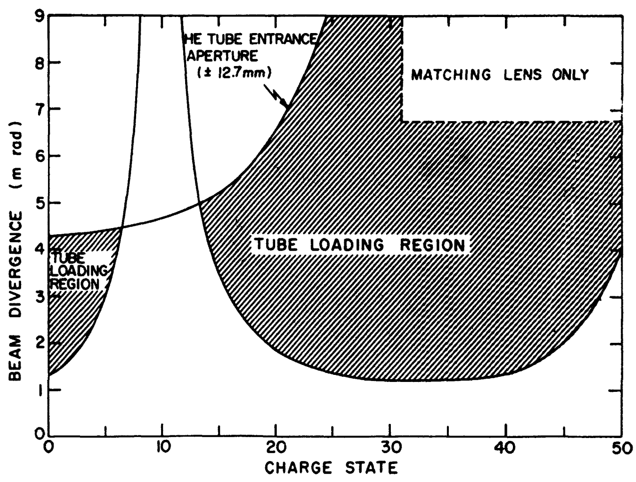

FIG. 4. — Angular acceptance of the high energy tube as a function of charge state when a matching lens is installed in the terminal. 10^+ beam which diverges from a point source on axis is matched to optimum transmission through the tube. The shaded area represents the region of rays contributing to tube loading.

A prototype of the charge selector was experimentally checked [1] by simulating heavy ion beams of high charge states by proton beams of appropriate energy. A thorough study of aberrations in the selected beam was carried out both experimentally and theoretically [2]. It showed that beam aberrations caused by the charge selector have only a negligible effect on the beam quality. Further analysis also convinced that the leakage of non-selected charge states is rendered very small.

The transmission properties of the charge selector were calculated assuming a point source at the stripper. Figure 5 presents the angular emittance at the analyzing plane of the displaced quadrupole triplet.

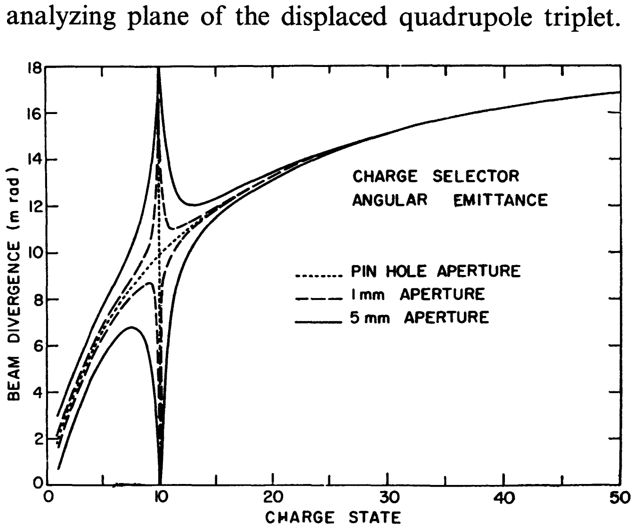

FIG. 5. — Angular emittance in the analyzing plane of the charge selector as a function of charge state when 10^+ is selected. A point source at the stripper is assumed to be the object for the charge selector. Plots of the angular emittance transferred through three different apertures are given.

This figure displays the angular region of rays transmitted through the selection aperture as a function of charge state when charge 10^+ is assumed to be selected. The size of the aperture, of course, determines the limits of this angular region. The angular emittance for a pin-hole selection aperture is represented in figure 5 by the dashed line. As expected, it has a sharp peak at exactly the selected charge state. When the selection aperture is made wider the angular emittance that can be transferred through it grows bigger. The area limited by the full lines applies to the angular emittance of a beam passing through a 5 mm aperture.

The angular emittance at the analyzing plane should be compared with the angular acceptance of the high energy tube. Operation of the charge selector brings the object plane of the matching lens close to the high energy tube entrance. The angular acceptance of the tube for this case can be seen in figure 6. The general features are similar to those in figure 4, where a point source was located at the stripper. In spite of the fact that the operation of the matching lens differs in these two cases the resulting matching effect is almost the same.

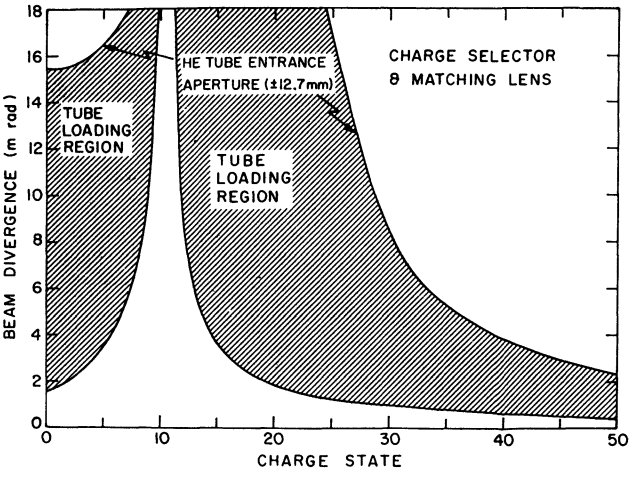

FIG. 6. — Angular acceptance of the high energy tube as a function of charge state when both the charge selector and the matching lens are operated. The lenses are adjusted so as to optimize the transmission of the 10^+ beam through the tube. The shaded area represents the region of rays which contribute to tube loading. However, the loading is further limited to those rays which pass the charge selector analyzing aperture (cf. Fig. 5).

In order to estimate the extent of tube loading that can be expected the angular emittance of the beam (Fig. 5) should be compared with the tube acceptance (Fig. 6). The amount of overlap between the transmitted emittance through the aperture and the loading region of the tube will determine the actual loading. Examination of this overlap reveals that neighbours adjacent to the selected charge are transmitted freely through the tube, while all other charge states cause loading. Should this loading become troublesome, the selection aperture could be reduced. The attenuation of the low charge states however was calculated to be so high that probably quite large selection apertures (of the order of 5 mm) can be used.

References

[1] GOLDRING G., SEGALOV Z. and SKURNIK E., *Nucl. Instrum. Methods* **126** (1975) 355.

[2] GOLDRING G., SEGALOV Z. and SKURNIK E., *Nucl. Instrum. Methods* **141** (1977) 307.