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THE VIVITRON CHARGE SELECTOR

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Abstract: The Vivitron tandem accelerator is equipped with a charge state selector in the high voltage terminal consisting of a displaced, quarter-quadrupole triplet lens assembly followed by a conventional, axially-centered quadrupole singlet element. Acting together, these lenses provide flexible double focusing and charge state dispersion at selection apertures located within the high energy column. Recent measurements demonstrate the effectiveness of this arrangement.

1 Introduction

Stripping of negative ions in the high voltage terminal of a tandem electrostatic accelerator produces multiple positive ion charge states (from all elements except hydrogen) which are then accelerated through the high energy (HE) stage. Ordinarily, only one charge state is of interest while the others constitute an unwanted background that adds loading to the HE stage and confuses the process of selecting one beam of unique charge and energy for delivery to experiments.

Ideally, unwanted charges should be discarded inside the high voltage terminal. This can be accomplished by applying transverse electric or magnetic dipole fields to disperse the different charge states. Folded tandem accelerators already include in the terminal a 180° dipole which provides excellent charge separation. To separate charges in the straight-line geometry of conventional tandem accelerators, two dipoles are required to avoid a change of angle within the terminal and at least three dipoles are required to confine the input and output beams to the same axis. One lens is needed to refocus the desired beam through a charge selection aperture and, in order to recover as much as possible of beam scattered to large angles, it is also desirable to place another lens downstream of the selection aperture to match a diverging beam into the HE stage. If each new element provides only one function, considerable added length is needed.

Displacing the elements of a quadrupole triplet lens assembly transverse to the beam axis introduces the desired three dipole fields while providing focusing in the same space[1,2]. Displaced quadrupole triplet charge selectors were successfully bench tested at the Weizmann Institute of Science[3] and at the Daresbury Laboratory[4]. First use in an accelerator took place at Daresbury[5]. At both facilities the terminal had been designed in advance with extra length to accomodate some form of charge selection apparatus.

2 The matching-lens charge selector

The terminal in the Vivitron[6,7,8] accelerator at Strasbourg is 3.0 m long, ample for typical foil and gas strippers followed by a lens needed to match into the long HE stage, but inadequate to accomodate the addition of a complete charge selector without severely compromising all functions. To alleviate this situation, the matching lens has been reconfigurated as a displaced quadrupole triplet lens assembly augmented by a conventional quadrupole singlet lens[9]. Together, these lenses provide charge state dispersion plus flexible focusing control at a selection aperture located within the HE stage (or at the post-stripper, when in use). An undesirable consequence of this arrangement is that unwanted charges can penetrate into the HE stage before being intercepted; however, better control of the beam permits unwanted particles to be deposited preferentially onto apertures in dead sections, instead of inside accelerator tubes, and all advantages of a much cleaner beam outside the accelerator are preserved.

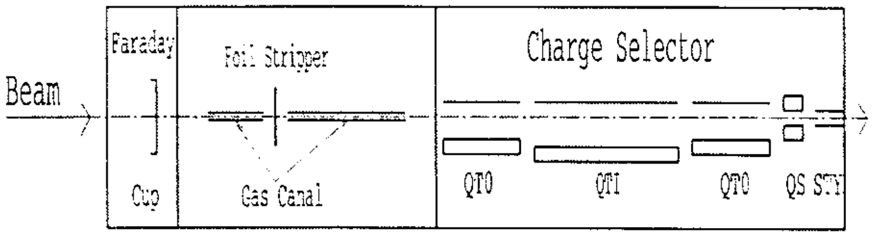

Figure 1: Overall layout of the Vivitron high voltage terminal showing stripper system and charge selector.

Figure 1 shows the Vivitron terminal layout. Figure 2 is a photograph of the triplet elements. Electrostatic components were selected for low power consumption and lightness. To distribute electrical stresses more equitably, mirror plates are insulated and driven to -3/8 of the applied voltages, poles to +5/8. The inner quadrupole (QTI) has positive polarity, the two outer ones (QTO) are negative. This hardware was installed and voltage tested in 1993, but not put into operation until this year.

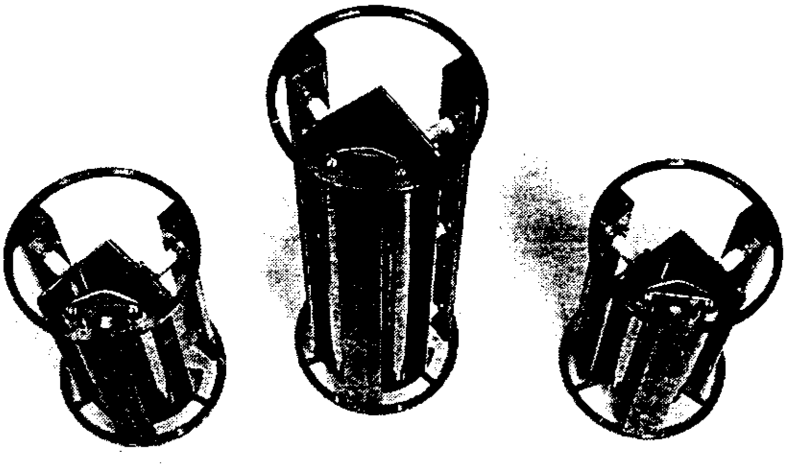

Figure 2: Photograph of the three elements of the off-axis electrostatic quadrupole triplet charge selector installed in the Vivitron terminal.

The three poles of the displaced triplet lens assembly face mirror planes in order to complete four-fold quadrupole symmetry by mirror reflection.

This quarter-quadrupole geometry is possible because the lens displacement (20 mm) is large enough to accomodate typical beams entirely within one quadrant. Beam centroids can pass nearer to an electrode than to the lens axis (intersection of the mirror planes); therefore, in order to minimize aberrations, the pole tips have hyperbolic contours, manufactured on a numerical milling machine. Rounded edges help correct for the truncation of an infinite hyperbola. The main characteristics are summarized in Table 1.

Table 1: Main characteristics of the charge selector

	Quadrupole triplet		Quadrupole singlet
	Inner element	Outer element	
Bore radius (mm)	60	50	20
Horizontal off axis (mm)	20	20	0
Mechanical length (mm)	610	328	120
Electrical length (mm)	670	378	137
Max. voltage on pole (kV)	+50	-50	±15
Max. on mirror plate (kV)	-30	+30	-

All the three elements of the triplet assembly are displaced by the same amount so that they align to a common axis and the mirrors are co-planar. Such a lens must be operated with a non-inverting, parallel-to-parallel focus in the dispersion plane to avoid deflecting the beam off axis. Therefore, some additional convergent focusing preceding and/or following the displaced triplet is required to achieve overall convergent focusing. Because the HE stage itself contributes little to focusing in the dispersion plane (which is aligned parallel to slot-shaped apertures in the inclined-field accelerator tubes), a conventional axially-centered quadrupole singlet lens was inserted downstream from the triplet assembly. This lens facilitates convergent focusing in the dispersion plane while adding divergence in the vertical plane to oppose fringing fields at the entrance to the tube THE10. Three control variables are available to the operator, two voltages on the triplet (operated symmetrically about the center) and one for the downstream singlet. These suffice to steer the selected charge state onto the accelerator axis and to fine tune the focus in both planes at the aperture.

3 Calculated charge state dispersion

3.1 Properties of the Vivitron

Because the Vivitron is long (50 m) with no lenses inside the column, beams typically arrive at the terminal nearly parallel (≤ 0.4 mrad) with corresponding large sizes that ultimately are constrained by the gas stripper canal to 9 mm diameter over 800 mm length. Gas stripping alters the beam envelope very little. Multiscattering by a foil stripper adds significantly to the angular content (e.g. 1 mrad for a Ni beam at 15 MV) but the beam has little distance in which to grow larger; therefore, the quadrupole lenses must function mostly with quasi-parallel beams and deliver these through a distant aperture in dead section DS12.

3.2 Operating modes

The displaced triplet lens exhibits two modes of operation. At low excitation, the beam passes more or less parallel through the inner element. At high excitation, the vertical component crosses over within the inner element, producing a local line focus. High excitation is preferable because it greatly enhances dispersion; however, once power-supply limits are exceeded, only the low-field option remains viable. Eventually, for any given particle energy, there is a low-charge-state cutoff below which focusing cannot be achieved. Usually, that cutoff will fall far below the equilibrium charge state and should not pose a handicap.

3.3 Beam envelopes simulation

The resolving power of the charge selector depends on how small the selected beam can be made and how large and dispersed are the out-of-focus beams of neighboring charge states[10]. To optimize transmission, the accelerator operator will seek to minimize both horizontal and vertical dimensions of the beam at the selection aperture. For calculations, it usually is more convenient to specify either point-to-point or parallel-to-point criteria for a given lens focus. Two focal criteria have proved useful for analyzing this particular lens arrangement. Large diameter beams having small angular content are well represented by a parallel-to-point focus in both planes. At somewhat larger angles (≥ 2 mrad), a mixed mode consisting of parallel-to-point in the vertical combined with a point-to-point in the horizontal (dispersion) plane serves remarkably well in simulating a double minimum at the dead section DS12 aperture.

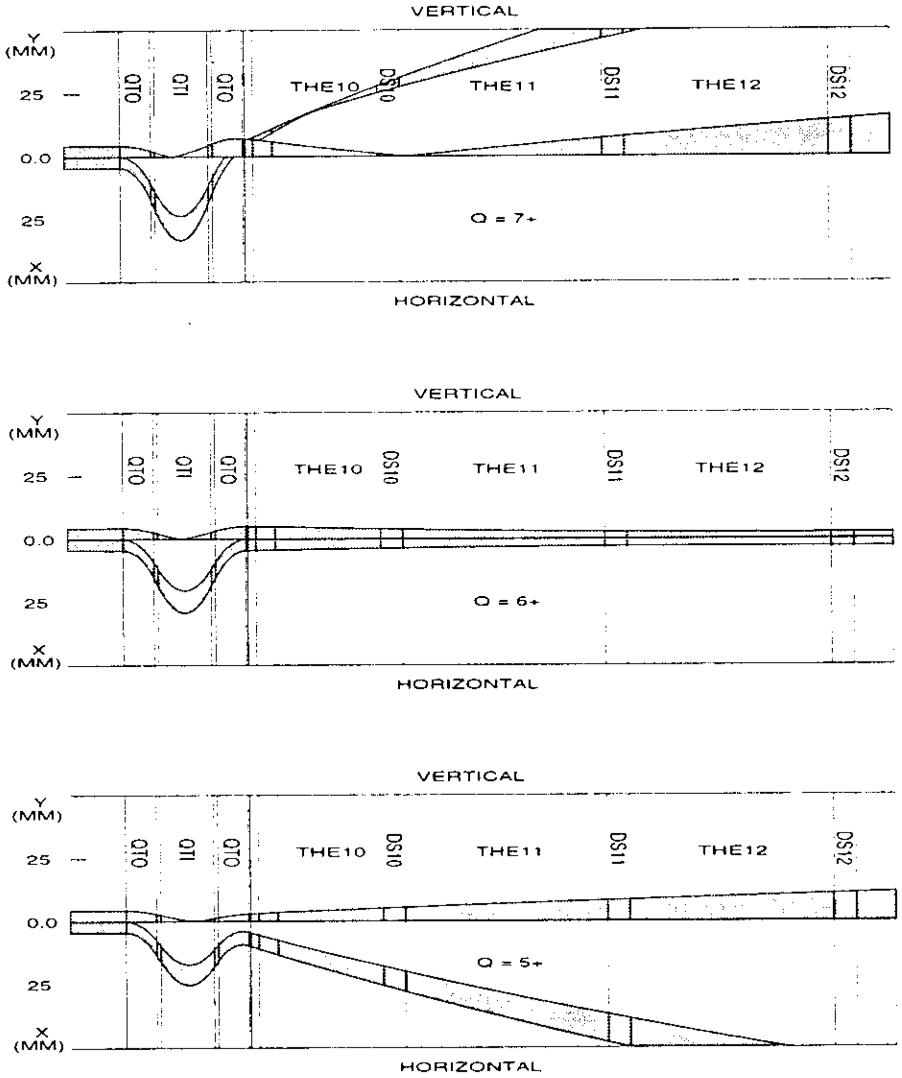

Figure 3: Calculated horizontal and vertical beam half envelopes between terminal-stripper and the post-stripper located in dead section DS12. Starting from the left, the initial beam is circular with ± 0.5 mrad divergence. Focusing is parallel-to-point in both planes. The selector is tuned to charge state 6^+ (center panel). Adjacent charges $7^+$and 5^+(upper and lower panels) are deflected off axis in the horizontal plane where they will strike limiting apertures in the dead sections.

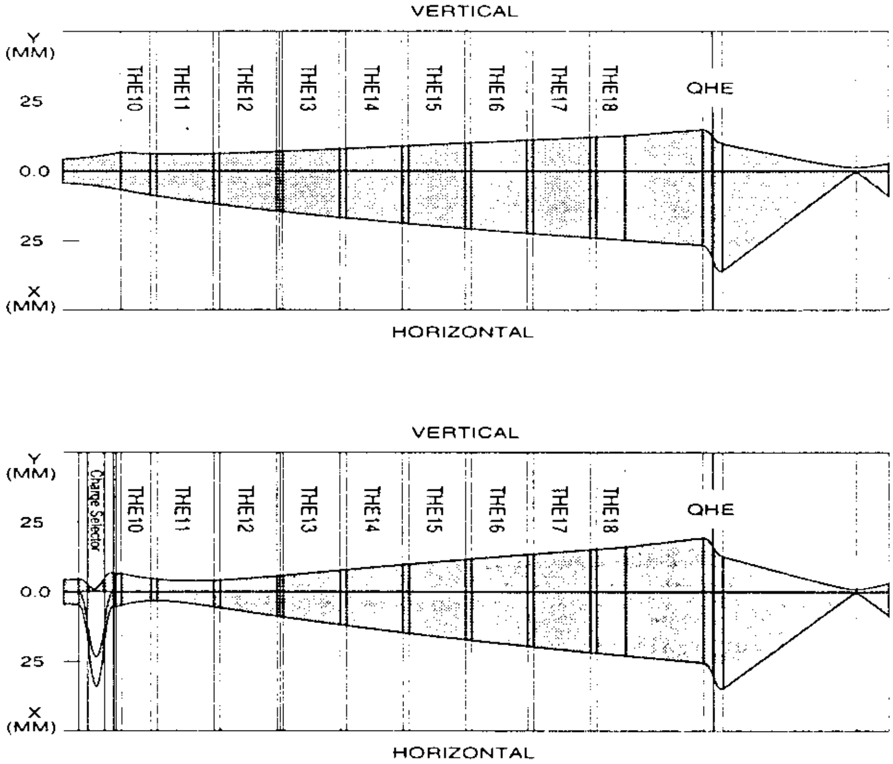

Figure 4: Calculated horizontal and vertical beam half envelopes between terminal-stripper and the image point of the HE quadrupole doublet (QHE). Initial divergence of the beam is ± 2.0 mrad. In the upper panel, the charge selector is switched off. In the lower panel, charge state 13^+ is selected with mixed mode focusing.

The results of beam envelope calculations[11] which include the effects of charge state dispersion are shown in figures 3 and 4. Figure 3 spans the region from the terminal stripper through the outer (QTO) and inner (QTI) elements of the displaced quadrupole triplet lens, the on-axis singlet lens (QS, not labeled), three HE tube modules (THE10, THE11 and THE12) and a post-stripper located in dead section DS12. The distance from stripper to stripper is about 10 m. Half of the vertical beam envelope appears in each upper half plot. Horizontal half envelopes start out entirely within each lower half plot but as dipole forces move the beam off axis, the beam center is tracked wherever it goes either below or above the axis. In figure 3 the terminal voltage was set to 15 MV. The beam entered with 4.5 mm radius. After gas scattering the divergence was assumed to be ±0.5 mrad. The lenses were adjusted to transmit charge state 6^+ and to provide parallel-to-point focusing in both planes. The center panel shows the selected charge state taking a looping excursion away from the horizontal axis inside the displaced triplet lens before returning back to the axis. A vertical minimum inside element QTI forced the lenses to operate in high dispersion mode. The upper and lower panels show adjacent charge states 7^+ and 5^+ being deflected off axis where they can be intercepted by apertures placed in dead sections.

Figure 4 shows calculated beam half envelopes from the terminal stripper through the entire HE stage to the image point of the external HE quadrupole lens QHE. In this example the terminal voltage was 20 MV. A divergence of ±2.0 mrad, appropriate for foil stripping, was assumed. In the upper panel all lenses were turned off. In the lower panel the lenses were adjusted to transmit charge state 13^+ and to produce a mixed mode of focusing: parallel-to-point in the vertical combined with point-to-point in the horizontal. With or without charge selection, a matching lens confers the advantage of reduced beam size at the post-stripper in DS12.

4 Measured charge state dispersion

The properties of the charge selector were studied at 16 MV on the terminal with a ^{32}S beam using foil stripping and at 15 MV with ^{58}Ni beam using both gas and foil stripping. Beam current measurements were made using the HE Faraday cup located at the exit of the accelerator. The most abundant charge state was selected first and then voltages on the quadrupole lens elements fine tuned to maximize transmission. In every instance this happened when:

1. Voltages of the inner and outer elements of the triplet were equal in magnitude (opposite in polarity).

2. The singlet lens was turned off completely (suggesting that polarization of this lens might be incorrect).

Voltages that balance agree well with calculations which predict imbalances of only 1% for the symmetric parallel-to-point focus. These results are not consistent with the mixed focal mode where imbalances of about 9% were predicted; nevertheless, in the case of foil stripped ^{58}Ni, where mixed mode was expected to be of some benefit, the predicted average focusing power did come out closer to the mixed mode (within about 2%) compared to the double parallel-to-point focus (which predicted about 10% low).

Once the best conditions for transmission of the most abundant charge state were established, selectivity was measured by stepping the charge selector in 200 V steps from 15 to 40 kV. In every scan (see figure 5) the available charge states were clearly identified. At low charge states, where the fractional jump from charge to charge is large, the peaks do not even overlap. At least part of the extra peak broadening observed in the lower panel of figure 5 for foil-stripped ^{58}Ni can be attributed to difficulties encountered because the Vivitron was being operated without feedback regulation from slits or GVM.

An attempted run with a ^{16}O beam, for which excellent selectivity can be expected, proved unsatisfactory for this reason.

Even where peaks do overlap, leakage from neighboring charges will remain small because in actual operation the selector will be centered on one peak and only tails from neighbors that reach to the center of that peak can pass through.

5 Conclusions

The Vivitron charge selector appears to be working much as planned with a few discrepancies between calculations and observation still to be reconciled. Transmission efficiency through the accelerator is not diminished (this was tested with the ^{58}Ni beam) and although column currents are perturbed by beam currents intercepted in the HE dead sections, this has not yet created serious problems. The greatest advantage conferred by a terminal charge selector is in resolving ambiguities between the multipliciy of charges introduced by double stripping. Without the charge selector, the ^{58}Ni beam creates some 20 combinations of charge pairings whose intensities exceed 2% of the total. Several of these have magnetic rigidities which differ by less than 1% and two beams (9^+ going to 16^+ and 13^+ going to 17^+) are separated magnetically by only 0.1%. The charge selector completely resolves

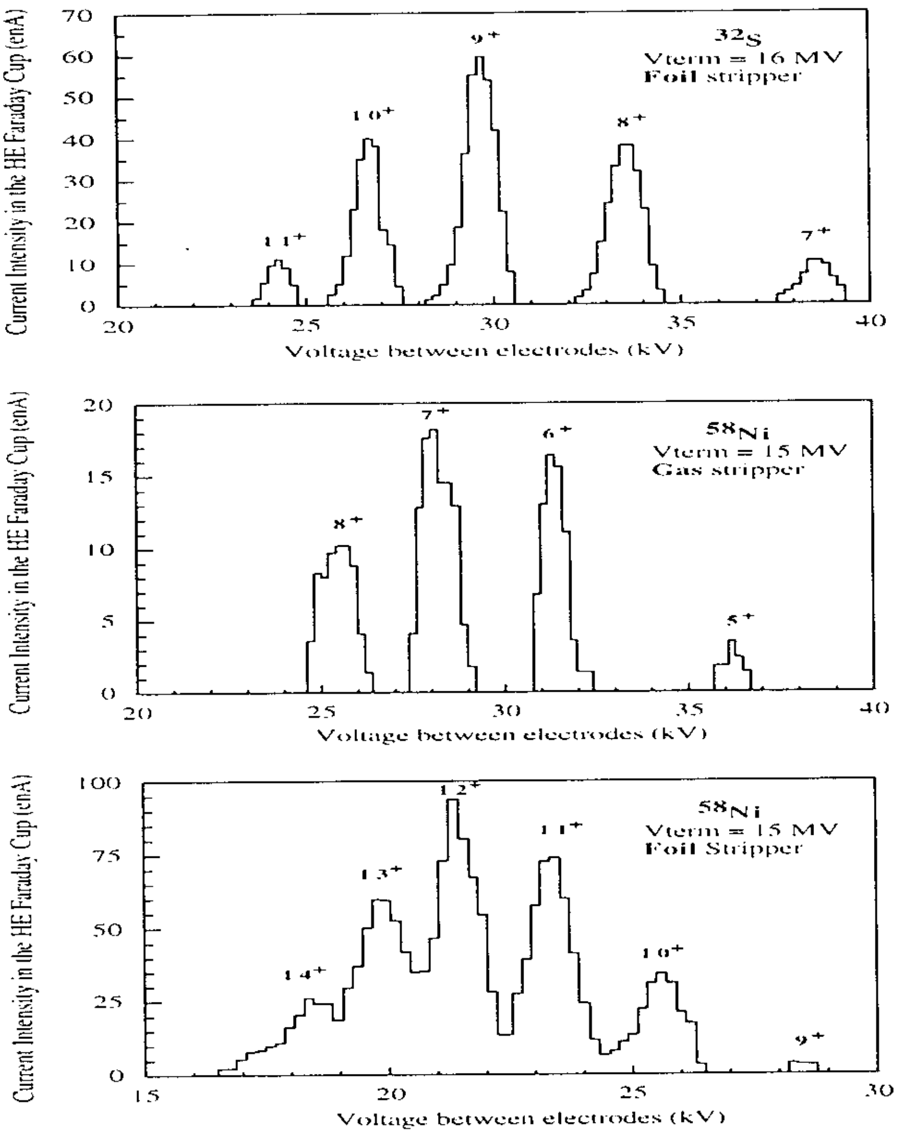

Figure 5: Measured selectivity of the matching-lens charge selector. Voltage is scanned in steps of 200 V.

such ambiguities by delivering a single charge to the post-stripper so that a final charge state with precisely known properties is selected easily and without interference by the analyzing magnet.

Acknowledgment

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