A New Design of Helical Electrostatic Quadrupole and Its Quasi-Octupole Mode of Operation*

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Abstract

A new design of a continuous-type helical electrostatic quadrupole (HESQ) is presented. It is expected that the performance in its quasi-octupole mode of operation (with all four rods at some positive voltage) will be superior compared with the performance of the normal mode of operation as a quadrupole. The main advantage is the elimination of chromatic effects which distort the beam shape in phase space. Construction of this HESQ is in progress at Texas Accelerator Center.

1. INTRODUCTION

Helical electrostatic quadrupole (HESQ) for transporting a low energy H^- beam from the source to the RFQ was originally proposed by Raparia[1] in 1990. The main advantages of HESQ emphasized by him were: 1) spatially continous strong focusing, and 2) elimination of the buildup of neutralization during the beam pulse which causes a time-varying rotation of the beam shape in phase space.

Following the design of Raparia, we built a HESQ which had a discrete structure, and tested its performance with a 30 keV H^- beam in order to establish the proof of existence.[2,3] Although the transmission was clearly hampered by the maximum voltage achievable in the first segment, some 40 to 55% acceptance figures were obtained when the transmitted current was between 2.5 mA and 5 mA. The discrete structure, shown schematically in Figure 1, was chosen because of the ease of construction in spite of many operational shortcomings.[3] By numerically tracking particles through exact electric field which was obtained with the computer code RELAX-3D, we could see various types of beam shape distortions in phase space and these were visible in some of the measurements as well.

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We now believe that, at least for the cases we have studied, the major cause of distortion is chromatic aberration rather than nonlinearity of the field near quadrupole electrodes. (Figure 2) This is not surprising since the HESQ potential is not much less than the kinetic energy of the incoming beam.

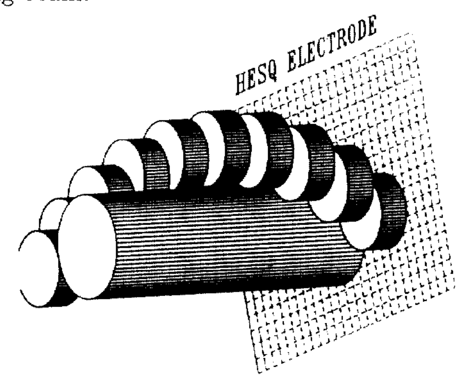

Figure 1. Model of discrete HESQ structure.

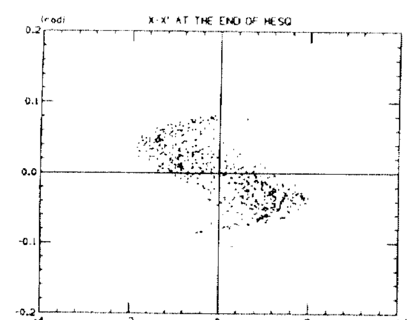

Figure 2. Calculated emittance showing the effects of chromatic aberration on particles transported through the old HESQ.

A continuous type HESQ which retained the ideal helical structure of the quadrupole rods was built at KEK, Japan, in 1991 by Y. Mori and his collaborators.[4] They successfully focused and transported a Cu^- ion beam of more than 1 mA. In particular, the emittance growth through the HESQ was observed to be much less than when an einzel lens was used for a similar beam. This test is significant in establishing the potential use of HESQ for transporting intense (a few mA) negative heavy ion beams.

2. DESIGN OF A NEW CONTINUOUS HESQ

Encouraged by the success at KEK, we decided to build a new continuous-type HESQ for the second phase of our project, abandoning further studies of the discrete structure. The design was completed in January 1992 and the construction is in progress at the Texas Accelerator Center (TAC). We expect to finish the construction and start testing it in June 1992 with a high intensity 30 keV proton beam. Some features of the new design are shown in Figure 3. The entire system of chamber and HESQ will be built in such a way that the azimuthal orientation of the HESQ field relative to the incoming beam can be changed easily. Furthermore, we will be incorporating more instrumentation into the chamber to perform more detailled measurements of the transmission efficiency and the conditions of the injected proton beam.

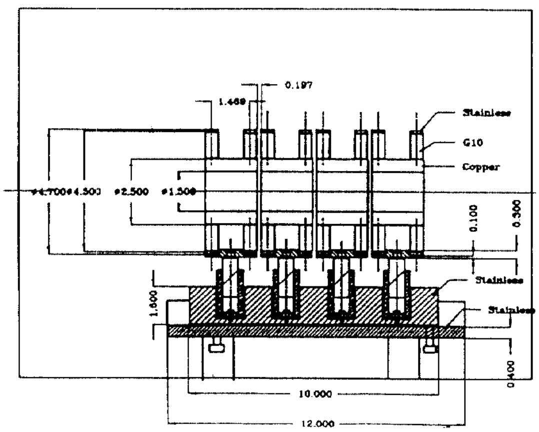

Figure 3. Side view of new HESQ. Each segment is individually mounted in its holder. All dimensions are in inches.

In order to arrive at the optimum design parameters, we have studied many combinations with an extensive use of RELAX-3D and beam tracking. For an accurate calculation of the field near the entrance and exit of HESQ as well as between segments, all four segments must be taken together in RELAX-3D. The main parameters of our new HESQ are given in Table 1. We will use eight power supplies each capable of up to 20 kV so that there will be no limitation in performance imposed by the maximum achievable rod voltage. We have also constructed a new, automated Allison-type emittance scanner [5] for fast and easy emittance measurements.

3. QUASI-OCTUPOLE MODE OF OPERATION

Because of a reduction in the space charge defocusing action, octupole focusing sytems are expected to be superior to quadrupole systems in transporting or accelerating low energy, high intensity beams. This results from a much reduced charge density at the beam center as the potential becomes flatter, r^4 dependence, for octupoles compared with quadrupoles for which the dependence is r^2 . A radio-frequency octupole (RFO) system has been studied analytically as well as numerically at the Los Alamos National Laboratory.[6] At high currents, results of their simulation have shown that the beam can develop a hollow radial distribution which reduces the space charge defocusing as expected.

Table 1.
Parameters for New HESQ

Number of segments	4	
Length of segment	5	cm
Helical pitch	27	deg./cm
Gap between segments	5	mm
Rod radius	1.3	cm
Aperture (radius)	1.8	cm
Total length	21.5	cm

It should be possible to take advantage of this desirable feature of octupole symmetry without building a true helical octupole with eight electrodes. The introduction of eight electrodes within a rather confined area will make the construction more complicated, and the maintenance of high voltage more difficult. For an infinitely long (two-dimensional) HESQ with circular rods, it is possible to approximate the resulting electrostatic potential by considering four helical line charges q/unit length at $r = a$. For an octupole symmetry, $V(r, \theta + \pi/4; z) = -V(r, \theta; z)$, the potential takes the form

$$V(r, \theta; z) \propto (r/a)^4 \cos[4(\theta - \alpha z)] + (1/3)(r/a)^{12} \cos[12(\theta - \alpha z)] + \cdots \quad (1)$$

where the helical pitch is α per unit length along z-direction. If the four rods of HESQ are kept at the same voltage instead of alternating in polarity, the resulting symmetry is neither quadrupole nor octupole but $V(r, \theta + \pi/2; z) = V(r, \theta; z)$ and the potential is

$$V(r, \theta; z) \propto (r/a)^4 \cos[4(\theta - \alpha z)] + (1/2)(r/a)^8 \cos[8(\theta - \alpha z)] + \cdots \quad (2)$$

with the same radial dependence for the leading term. Since this dependence is responsible for reducing the space charge effects, the quasi-octupole mode of HESQ operation should be tried to see if higher currents can be transported. Switching from the normal quadrupole mode to quasi-octupole mode is easily accomplished by connecting all of the electrodes to the same power supply.

With all four rods at the same potential, the quasi-octupole mode resembles einzel lens system. Figure 4 shows the longitudinal electric field E_z at $x = y = 0$ calculated with RELAX-3D for a typical combination of rod voltages in four independent segments. By comparing this with E_z

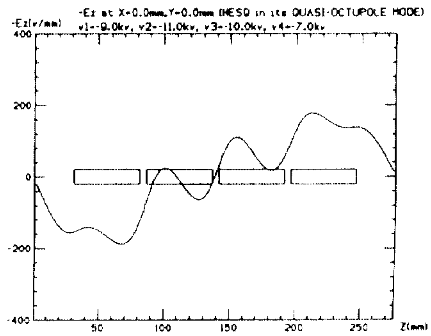

Figure 4. Longitudinal electric field of the HESQ operated in quasi-octupole mode.

at various transverse locations, one can see that E_z is almost independent of the transverse coordinates within a beam. Whatever accelerating or decelerating actions take place for particles through the HESQ, the chromatic aberration should be much less in the quasi-octupole mode compared with the aberration in the normal quadrupole mode. We have confirmed this by tracking particle motions for several combinations of rod voltages. Figures 5a and 5b show the calculated horizontal and vertical emittances at the end of the octupole-mode HESQ. Notice that these emittnces exhibit much less distortion than the normal HESQ emittance shown in Figure 2.

4. SUMMARY

Based on our experience with the first HESQ, which is a discrete structure, we have designed a new, continuous HESQ. We anticipate a much better performance from the new HESQ which will be completed in June 1992. Furthermore, we expect a significant reduction in the chromatic aberration when it is operated in the quasi-octupole mode.

5. REFERENCES

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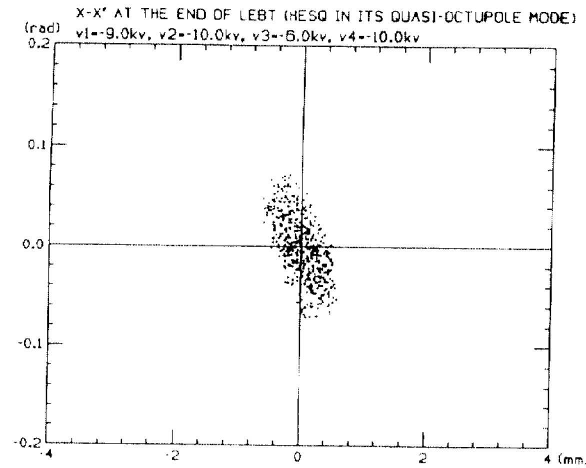
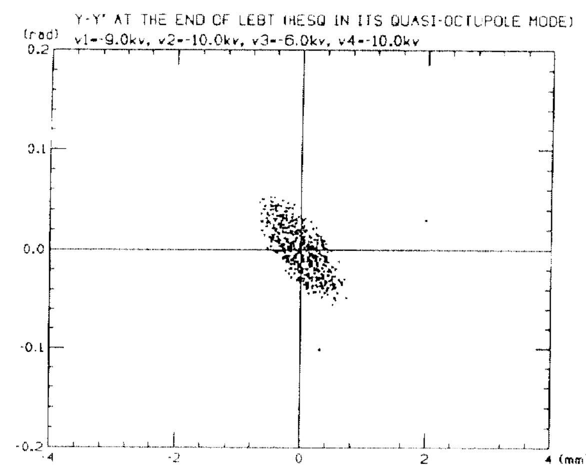


a)



b)

Figure 5. Calculated phase space of particles passing through the continuous HESQ operated in the quasi-octupole mode.
a) Horizontal b) Vertical

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