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HESQ, A LOW ENERGY BEAM TRANSPORT*

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ABSTRACT

In this paper Helical Electrostatic Quadrupole (HESQ) channel is suggested for low energy beam transport of H^- beams from ion-source to the RFQ. Being an electrostatic focusing lens, the HESQ avoids neutralization time. The HESQ lenses provide stronger first-order focusing in contrast to weak second-order focusing of einzel lenses and is also stronger in focusing than the alternating gradient focusing. In this paper, we will present analytical formalism for such channel and results of PIC simulation with space charge.

INTRODUCTION

Invention of the the RFQ has solved the long existing problems at low β-end in the drift tube linac by virtue of spatially continuous external focusing forces and transfered such problem to low energy beam transport (LEBT). The LEBT is the section of linac which provides the matching between ion-source and the radio frequency quadrupole (RFQ). The LEBT consists of lenses that focus the beam into the RFQ. The beam from an ion source is relatively large in radius and divergence and must be matched to the RFQ.

Existing LEBT systems for H^- beams use magnetic focusing solenoids or permanent magnetic quadrupoles. These LEBT systems utilize charge neutralization in the background gas to minimize the required focusing strength. However, the physics of such charge neutralized beam is not fully understood. Futhermore, the neutralization time must be short compared to the pulse length; otherwise, a fraction of the beam at the front of the pulse maybe lost due to inadequate focusing. During this neutralization time the space charge force changes. Because of this the beam phase space ellipse rotates, making it difficult to match the beam to the RFQ acceptance. Additional problems arise due to beam-plasma instability and the fact that beam becomes charged again, when it enters into the electric field of accelerating structure which sweeps away the charge neutralizing ions formed in the collisions. Improper matching in such transitions and the conversion of field energy into transverse

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kinetic energy associated with changes in the beam profiles may caused significant emittance growth and particle loss.

For the Superconducting Super Colliader (SSC), one need 25 - 50 μ sec pulse length while the neutralization time is of the order of 100 μ sec in case of hydrogen as residual gas. During the first 100 μ sec we cannot use the beam. That means one would need the pulse length from ion source 125 - 150 μ sec and this reduces the lifetime of ion source by factor of two or more. The neutralization time can be reduce by introducing Xenon into the LEBT; however, full neutralization will always considerably increase the pulse length required from source. The problem of neutralization can be avoided by using focusing in the form of electric forces which will be discussed in the following section.

HELICAL ELECTROSTATIC QUADRUPOLE LENSES (HESQ)

The buildup of plasma and charge neutralization cannot occur in electrostatic lenses, as in case of magnetic lenses, since the electron-ion pairs produced in collision between beam particles and background gas are swept out of the beam region by the electric field between the electrodes. Furthermore, magnetic focusing is particularly ineffective at low beta because of the velocity term in the force equation. Electric focusing, on the other hand, has no such velocity term in the force equation and should be a prime candidate for the focusing role at low velocities. The main problems in the electrostatic focusing is breakdown and aberrations. The problem of the breakdown can be overcome by providing lower but spatially continuous focusing forces, as in the helical electrostatic quadrupole (HESQ), instead of spatially discreet but higher focusing forces as in a FODO structure. The spatially continuous focusing forces also help keep the beam size smaller all the time, thus minimizing aberrations.

An alternative scheme for the higher current is to use the HESQ in the LEBT. The HESQ is nothing but a continuously twisted electrostatic quadrupole (figure 1). The HESQ lenses provide stronger first-order focusing in contrast to weak second-order focusing of Einzel lenses, an axial symmetric beam which is necessary for the RFQ matching, and stronger focusing than the alternating gradient type. The idea of helical quadrupole is quite old[1-5]. All of theses works were about 'magnetic helical quadrupole' for different purpose.

The HESQ system must satisfy following conditions. First, voltage and spacings 'd' between neighboring electrodes must be below breakdown limit[6] given by

$$V_B[kV] = 79.9 \cdot d^{2/3}[cm]. \tag{1}$$

Second, the maximum voltage 'seen' by a particle at the edge of the beam must be less than about 20 % of the beam voltage i. e.

$$V_0/V_b \leq 20\% \tag{2}$$

This is necessary to reduce the chromatic aberration within acceptable limit. Third, the maximum ratio of beam radius and the quad radius must be less than 0.75 i.e.

$$R_{beam}/R_{quad} \leq 0.75 \tag{3}$$

To reduce higher order effects one has to satisfy following condition

$$R_{beam} \leq \lambda/10. \tag{4}$$

Where λ is pitch of the helix. If the last condition is not satisfy then particles 'see' a weak longitutinal field which increases with radius and changes its direction along the length of the HESQ and this alternating longitudinal field provides additional focusing. This can be thought that electrostatic symmetric lenses are superimposed on quadrupole field but net effect will be undesirable because of non-linearity.

EQUATION OF MOTION AND STABILITY DIAGRAM

In this section, we have used a special model[5] for continuously twisted quadrupole which also include the linear space charge effects i.e. only K-V distribution, for other distribution one has to take the approach of PIC code. The potential function for continuously twisted quadrupole channel can be written as

$$\Phi(r, \phi, z) = const \cdot I_2(\nu r) \cos 2(\phi - \nu z) \tag{5}$$

where ν is transverse rotation per unit length along the axis. In the lowest order approximation, the equation of motion is

$$\begin{aligned} x'' &= -k^2\{x \cos(2\nu z) + y \sin(2\nu z)\} + x\triangle_{sc} \\ y'' &= -k^2\{x \sin(2\nu z) - y \cos(2\nu z)\} + y\triangle_{sc} \end{aligned} \tag{6}$$

Here k is related to the quadrupole strength and $\triangle_{sc}$ represent space charge defocusing force for the K-V distribution given by

$$a\triangle_a = b\triangle_b = \frac{120eI}{mc^2\beta_r^3(a+b)} \tag{7}$$

where a and b are the simi-axis of ellipitical beam with τ charge per unit length which has electric fields inside the beam

$$E_x = \frac{4\tau}{4\pi\epsilon_0}\frac{x}{(a+b)}; \qquad E_y = \frac{4\tau}{4\pi\epsilon_0}\frac{y}{(a+b)} \tag{8}$$

and the effective k^2 and $\triangle_{sc}$ are

$$k^2 = k_{ESQ}^2 + \left(\frac{\triangle_b - \triangle_a}{2}\right); \qquad \triangle_{sc} = \frac{\triangle_a + \triangle_b}{2} \tag{9}$$

The particle co-ordinate in the rotating frame of reference is

$$u = x\cos(\nu z) + y\sin(\nu z)$$

$$v = -x\sin(\nu z) + y\cos(\nu z). \tag{10}$$

Differentiating (10) w.r.t. z one gets;

$$u' = x'\cos(\nu z) + y'\sin(\nu z) + \nu v$$

$$v' = -x'\sin(\nu z) + y'\cos(\nu z) - \nu u. \tag{11}$$

differentiating (11) w.r.t. z gives;

$$u'' = x''\cos(\nu z) + y''\sin(\nu z) + 2\nu v' + \nu^2 u$$

$$v'' = -x''\sin(\nu z) + y''\cos(\nu z) - 2\nu u' + \nu^2 v. \tag{12}$$

The equation (6) and (12) together produces

$$u'' = 2\nu v' + \nu^2 u - k^2 u + u\triangle_{sc}$$

$$v'' = -2\nu u' + \nu^2 v + k^2 v + v\triangle_{sc} \tag{13}$$

The two coupled Mathieu equation (6) have simplified to coupled linear differential equation with constant coefficients (13). The solution of (13) are

$$s_1 \equiv p^2 = \nu^2 - \triangle_{sc} + \vartheta$$

$$s_2 \equiv q^2 = \nu^2 - \triangle_{sc} - \vartheta \tag{14}$$

where

$$\vartheta = (k^4 - 4\nu^2\triangle_{sc})^{1/2} \tag{15}$$

These solution p^2 and q^2 should be real and positive for the stability requirement. That is

$$2\nu\sqrt{\triangle_{sc}} \le k^2 \le \nu^2 + \triangle_{sc} \tag{16}$$

This is represented by the shaded region in figure 2,

The general solution of (13) can be written as

$$u = A\cos P + C_1 B\sin Q \qquad v = -C_2 A\sin P + B\cos Q \tag{17}$$

where P=pz + const and Q=qz + const and

$$C_1 = \frac{2\nu^2 + k^2 - \vartheta}{2\nu q}, \qquad C_2 = \frac{2\nu^2 - k^2 + \vartheta}{2\nu p} \tag{18}$$

Differentiating (17) one gets,

$$u' = -pA\sin P + C_1 qB\cos Q, \qquad v = -C_2 pA\cos P - qB\sin Q \tag{19}$$

Elimination of the terms in P,Q leads to the two invariants

$$\frac{(u'-C_1qv)^2}{D_1^2} + \frac{(C_1v'+qu)^2}{D_2^2} = A^2, \qquad \frac{(C_2u'-pv)^2}{D_1^2} + \frac{(v'+C_2pu)^2}{D_2^2} = B^2 \tag{20}$$

where $D_1 = p - C_1C_2q, D_2 = C_1C_2p - q$. The maximum radial excursion is R is the larger of

$$C_1A + B \qquad or \qquad A + C_2B \tag{21}$$

There are two normal modes each with two distinct frequencies in the rotating frame (u,v). The procedure of transforming back to lab frame introduces another frequency that of coordinate rotation. This is the reverse of the more usual situation in which a system has pure frequency in a fixed coordinates system.

PHASE SPACE PROJECTION, TRANSVERSE EMITTANCES

Unlike the FODO channel, the HESQ transport system is coupled in x and y plane. In this transport system the four dimensional mean square emittance[7]

$$\epsilon_{4d}^2 = <x^2><p_x^2> - <xp_x>^2 + <y^2><p_y^2> - <yp_y>^2$$
$$+2<xy><p_xp_y> -2<xp_y><yp_x> \tag{22}$$

is constant while its projections in x and y plane vary depending upon the coupling terms (last two terms in the above equation). Brown and Servranckx[8] shown that (1) if a beam is uncoupled at the beginning of a system, and the initial x and y emittances are equal, then at all the point downstream, the projected emittances in x and y plans will be equal to each other, independent of the magnitude of the x-y coupling at that point. Their magnitude may, however, be equal to or greater than the values of the intial, uncoupled emittances. (2) At any position downstream, where x-y coupling is present the sum of the square of projected x and y emittances will be equal to or grater than square of four dimensional emittance (eq 22).

EXAMPLE: HESQ at TAC

At Texas Accelerator Center, we are building a HESQ for matching circular symmetric Megnetron ion - source to a 470 MHz four rod RFQ[10]. The main parameters are given in Table I. In the design quadrupole rotation is done in steps of 18 deg [figure 3]. The field calculation, which is done using RELAX3D[9], shows that the longitudinal electric field components are not more than 3-5 % anywhere in the HESQ. A PIC simulation of the beam through the HESQ is shown in the figure 4, notice that beam size is always less than equal to 1 cm, i.e., less that 70% of the aperture. Figure 5 shows the input and output phase space plot of this HESQ. Figure 6 shows the projected emittance in horizantal and verticle planes and four dimensional emittance as beam traverses through the HESQ which agrees with the theoritical results given by Brown and Servranckx[8].

Table I HESQ specifications

length	19. [cm]
voltage	07. [kV]
break down voltage	80. [kV]
pitch of helix	10. [cm]
electrode spacing	01. [cm]
bore radius	1.3 [cm]
input beam parameters :	
beam current	10. [mA]
transverse emittance (n,rms)	0.18 [pi.mm.mrad]
output beam parameters:	
beam Current	10. [mA]
transverse emittance (n,rms)	0.2 [pi.mm.mrad]

CONCLUSION

Use of the HESQ in H^- LEBTs avoids neutralization time. It is stroger focusing system than einzel lens and alternating gradient quadrupoles. It also provide an axial symmetric beam which is necessary for the RFQ matching. Being spatially continuous focusing system, the HESQ keeps the beam size smaller all the time, thus minimizing aberrations. The HESQ is presently being developed and may have superior performance and reliability than other LEBTs.

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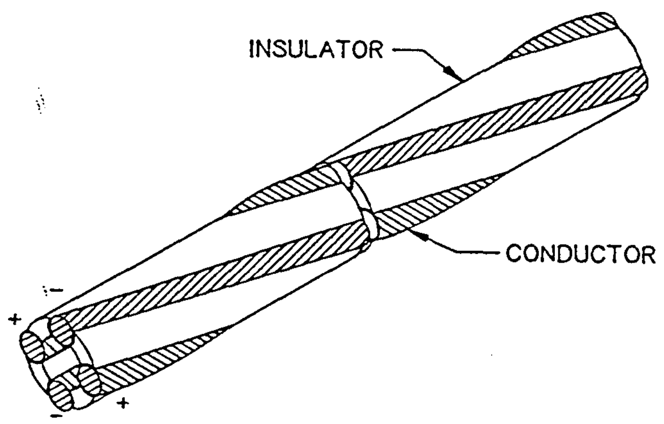

Figure 1: Conceptual design of the HESQ.

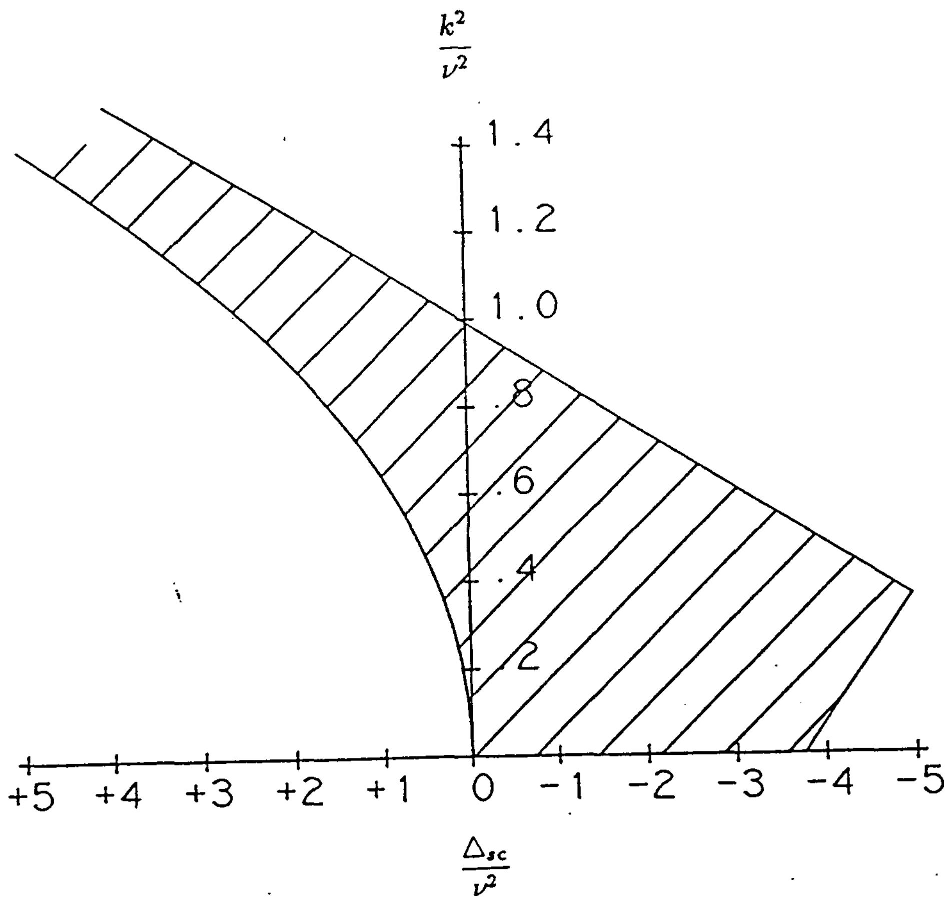

Figure 2: Region of stability, Quadrupole gradient vs Space Charge Defocusing strength.

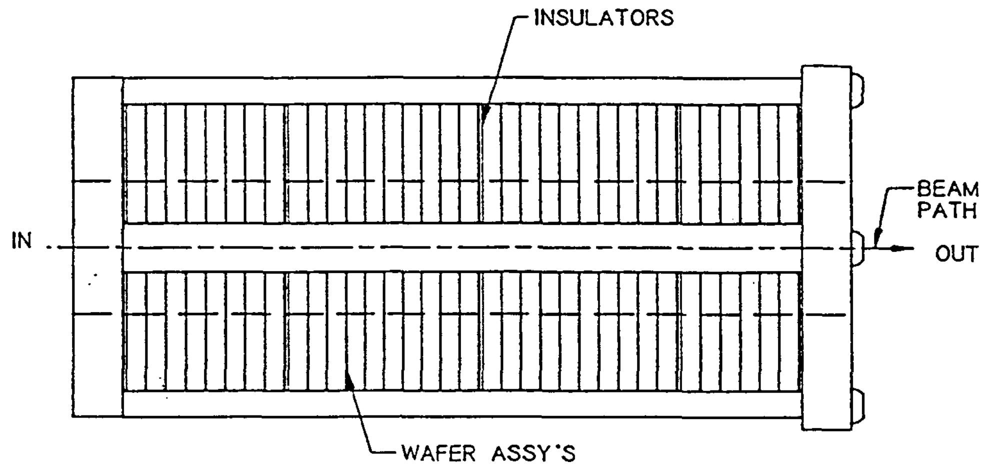

Figure 3: HESQ at TAC. Quadrupole rotation is done in steps of 18 deg.

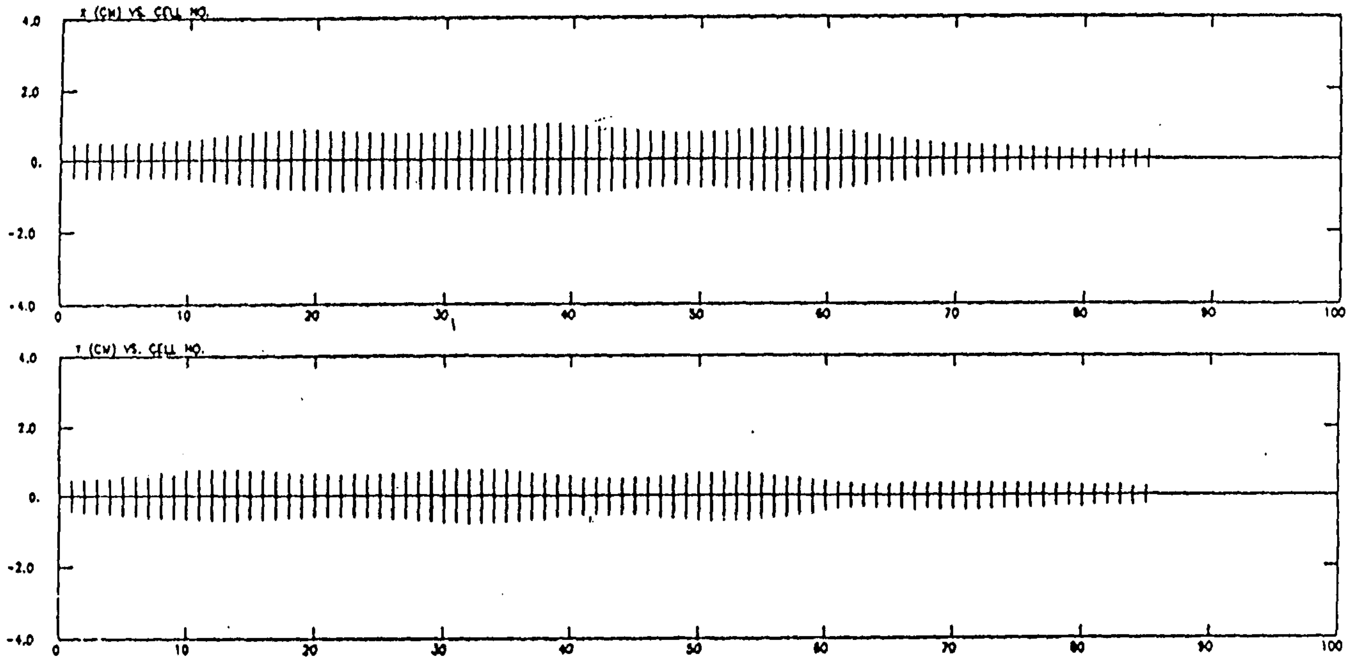

Figure 4: x and y profiles through the HESQ.

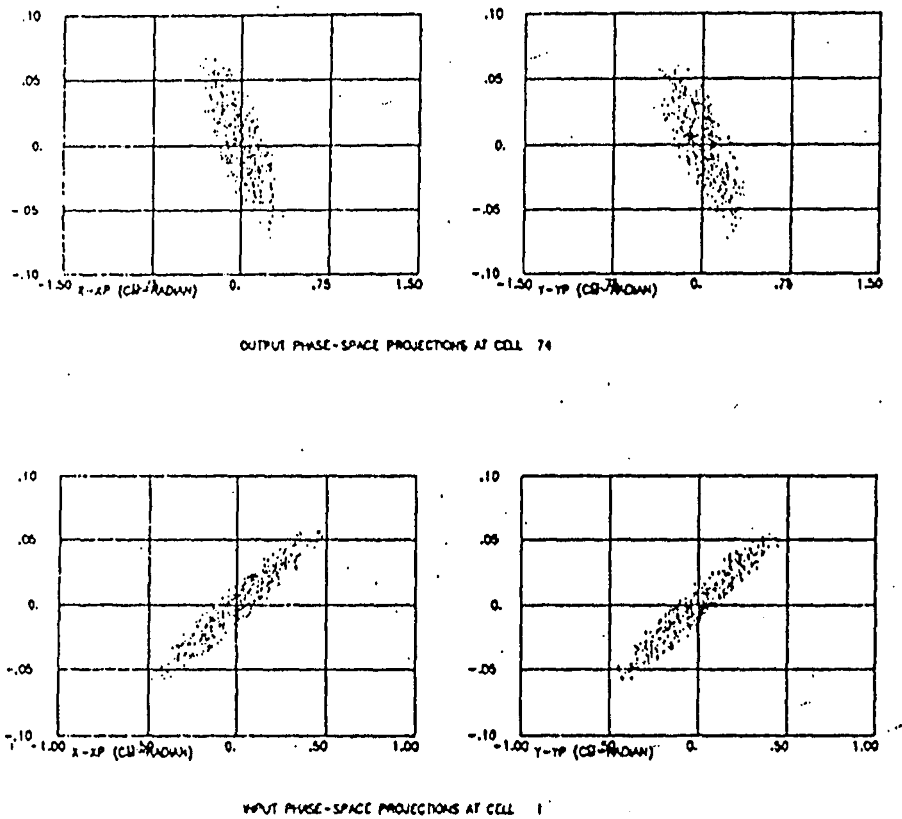

Figure 5: Input and output phase-space projection in x and y planes.

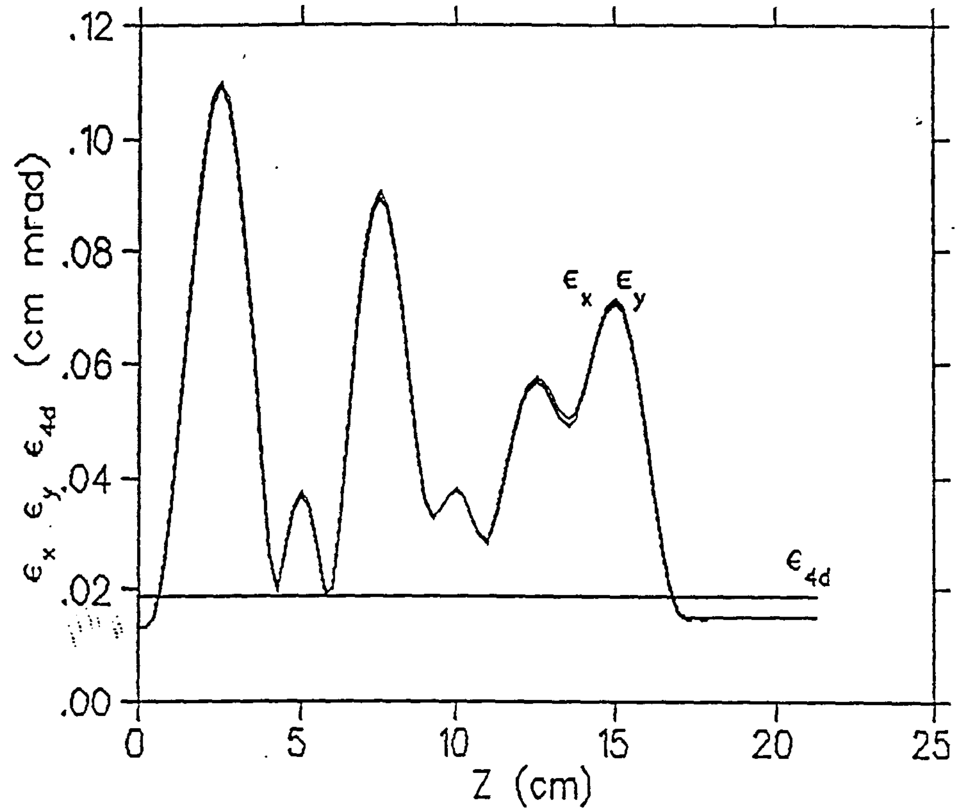

Figure 6: The projected emittences (normalized, rms) in x and y planes and four dimensional emittance as beam traverses through the HESQ.