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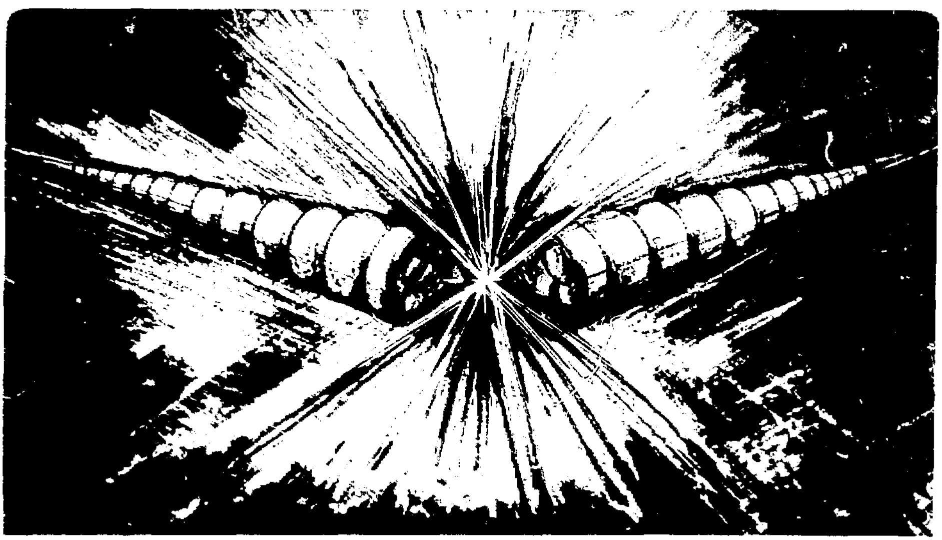

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G. Krafft

A Heavy Ion Fusion Final Focus System

Summary

A system for transporting and focusing a 10 GeV U^{+4} beam in the high current regime is outlined. First descriptions of the beam model and the beam parameters used in the design are given. The goals and requirements are then briefly discussed, and an explanation of the design approach follows. A description of the system itself is next, followed by some discussion of its tolerances, both to momentum and current deviations. A brief summary of simulation results is then included. This note concludes with a short description of possible modifications and an evaluation of the design.

Beam

The model for the space-charge behavior used in the design calculations is the envelope formalism of Kapchinskij and Vladimirskij (K-V).[1]

The equations for the beam radii r_x, r_y are

$$\frac{d^2 r_{x,y}}{ds^2} \pm K r_{x,y} - \frac{\epsilon^2_{x,y}}{r^3_{x,y}} - \frac{Q}{(r_x + r_y)} = 0, \qquad (1)$$

where $K = \frac{(dB/dx)}{B\rho}$, $\epsilon_{x,y}$ are the emittances/π, and

$$Q = \frac{4 r_p q^2 N}{A \beta^2 \gamma^3} = 1.288 \times 10^{-7} \frac{qI}{A(\beta\gamma)^3} .$$

Here N is the number of ions per unit length, I is the current in amperes, A is the atomic weight of a beam particle, $\beta\gamma$ is the momentum in units of mc, and q is the charge state.

As the beam to be focused will have been transported through a periodic transport structure, the periodic solution emerging from such a cell is used to determine the initial conditions for the envelopes entering the final focusing channel. The periodic solutions are calculated in an interative manner in the computer program SYNCH. Previous work[2] suggests that the best design for a periodic transport system has zero current betatron phase advance of 60°, with a maximum depression of the tune due to the space charge to 24°. Assuming a periodic FODO transport channel with a cell as in Fig. 1, the current transported when the phase advance is depressed from 60° to 24°, 780A, and the corresponding beam radii were calculated with SYNCH. These values were used in the rest of the design. The emittances were given by estimates on the performance of the components preceding the final focus system in a HIF device. The envelope equations (1) are integrated through the beam line between the cells and the target with SYNCH in order to determine the envelopes, and the target requirements are met by varying the gradients and positions of the magnets, using a fitting routine in that program.

The following table outlines the beam parameters used.

Table 1: Beam Parameters

Particle	U^{+4}
Atomic weight	238
Current	780 A
Energy	10 GeV
β	.2906
$\beta\gamma$	.3037
$B\rho$	56.17 T-m
Q (charge parameter)	6.39×10^{-5}
Emittances	59.8π mm-mrad

System Requirements

First, the target radius of the focused beam spot was taken to be 4mm. In addition, the drift space between the last quadrupole and the target spot was 5m. These requirements arise from reactor needs. The maximum magnet pole tip field used was 4T, which sets a limit on the field gradients possible. The magnet lengths were chosen using this limit and rounding to convenient values. It was intended to limit the maximum transverse radius of the beam to less than 35cm, the value for a previously proposed beam line[3, 4]. An important requirement is that the system should transport a beam with a realistic distribution, in addition to the K-V model which was used for design purposes. The problem of chromatic corrections is ignored in this design.

Experience and Design Approach

Previous calculations had produced examples of systems within design specifications when the K-V distribution was used. As realistic beams are expected to be different, a system which also focuses non-K-V beams adequately is needed.[5] Previous schemes failed to focus non-K-V beams to the extent desired. However, these designs contained narrow beam waists occurring before the final focus, and sensitivity to any disturbance seemed to be associated with them. Consequently, one goal is to eliminate these waists.

Past designs used fewer quadrupoles than the present one. As a consequence the envelopes calculated fluctuated considerably in size, since the quadrupoles must be made strong in order to focus the beam to the given spot size. In order to eliminate the narrow waists that occurred from the envelopes, quadrupoles were added and distributed to produce more smoothly varying envelopes.

Another consideration in the design is to produce as round a beam as possible. It was felt that having a round beam would improve the performance of the system when non-K-V beams were introduced and would reduce the asymmetry between the x and y envelopes in their sensitivity to current and momentum deviations. This difference initially suggested that increased sensitivity was related to the presence of a waist in one of the two dimensions. Thus the first set of lenses was used to form a round waist roughly the size of the beam emerging from the transport channel. From that point on an ideal envelope would be something like the one shown in Fig. 2, symmetric in the x and y directions. Of course the alternating gradient nature of the lenses precludes this from being a real envelope.

In order to obtain an approximately round beam, two triplets were placed around the plane AA' in a roughly symmetrical manner (Fig. 2). The idea was to use the first triplet to form an envelope with slopes vanishing on the plane AA'. Then the final triplet compensates for the small deviations from roundness introduced by the middle triplet while at the same time strongly focusing the beam to the target. This approach allowed one to modularize the problem, by designing each triplet separately. Use of symmetric doublets was also attempted but found to be inadequate.

Note that due to the small spot size and 5m distance to the spot from the last quadrupole, the envelope must have a radius of about 11cm and a considerable slope on emerging from the last quadrupole. The maximum size of the envelope is thus not arbitrarily small. The beam expands more slowly from the first waist after the cells since the beam is larger at this point than at the final focus. This explains the relatively long drift length (~20m) between the first and second triplets compared to the 5m between the last triplet and the target.

Design System

The zero current design based on these considerations is shown in Fig. 2. Current was then added in 20% increments of the maximum (24^{o}) current in conjunction with the optimizing routine within SYNCH to give the system of Figure 3 and Table II for the 780 A beam. To obtain the 780 A system it was expedient to change quadrupole positions somewhat, especially for the first triplet.

Table II: Information On 780 A Final Focus System

ELEMENT	POSITION* (m)	LENGTH (m)	GRADIENT (T/cm)	MAX (r_x, r_y) (cm)
Periodic Cell				
QF/2	-3.75	.5	.344	3.1
QD	-2.00	1.0	-.344	3.1
QF/2	-.25	.5	.344	3.1
Final Focus System				
Q1	4.31	.5	.504	4.2
Q2	5.67	.7	-.662	6.0
Q3	6.72	.5	.543	4.4
Q4	25.85	1.0	.0599	13.9
Q5	28.14	1.5	-.0956	17.5
Q6	31.21	1.0	.0750	21.2
Q7	33.41	1.0	.141	22.1
Q8	35.79	1.5	-.160	18.3
Q9	37.84	1.0	.118	12.8
Target Waist	43.34			0.4

*Longitudinal distance of quadrupole centers from end of cells

Tolerances

Having produced a system within design goals, checks of the momentum and current sensitivity of the system were made. Figures 4, 5, and 6 are traces of the envelopes for beams with momentum deviation +1%, 0, -1% respectively. On each plot are simultaneous calculations for current deviations roughly -10%, -5%, 0, 5%, 10%. The charge density N is varied in 5% increments and the $(\beta\gamma)^{-2}$ dependence in Q and the $(\beta\gamma)^{-1}$ dependence in K are included in these calculations. Also note that the beams were matched separately to the periodic envelopes in the transport cells for each beam momentum and current.

Table III summarizes the results. Current deviations seem less significant than momentum deviations. In cases with momentum deviation one can see from the figures that the waist size does not increase, but its location is shifted from the design target position. Finally observe that when momentum deviations are present the current deviations cause much more spot size growth at the target position.

Table III: Growth In Spot Sizes r_x, r_y And Area $A = r_x r_y$ At Target Position Due To Density And Momentum Errors

$\Delta N/N$	$\Delta P/P$	r_x(mm)	r_y(mm)	A/A_0
-.1	-.01	7.37	5.86	2.73
0	-.01	6.75	5.50	2.32
.1	-.01	6.38	5.21	2.08
-.1	0	4.12	4.16	1.07
0	0	4.00	4.00	1.00
.1	0	4.00	3.90	.98
-.1	.01	5.98	5.33	1.99
0	.01	6.63	5.57	2.31
-.1	.01	7.20	5.80	2.61

An estimate of the momentum acceptance of the system is found by requiring the spot cross-sectional area to stay within twice the design area. Given this condition, the maximum $\Delta P/P$ transportable is

$$\Delta P/P \sim 0.9\%,$$

compared to about 0.3% in the previously reported design[3].

Distribution Dependence

A major requirement for the system is that it should transport a non-K-V distribution without overly large spot enlargement. To test the system Irving Haber's simulation code was used. This code requires a thin lens system and thus the design whose envelope appears in Fig. 7 was developed. Roughly, it arose from rounding the center points of the quadrupoles to half meter positions along the beam line and reducing the widths of the quadrupoles while increasing the strengths proportionately. Presumably, due to the rather close match to the thick lens system the conclusions drawn from the thin-lens test would be applicable to the system given.

The results obtained by Haber[6] on this thin lens system are summarized in Table IV. The first line gives the simulation results when a K-V beam with the design current is transported. The values check adequately with those determined from the envelope integration (bottom line). The remaining results are obtained using the result of tracing a non-K-V beam through many transport cells. Current is added in increments slowly enough so that an equilibrium distribution is established as the beam is traced. The emittances and rms radii for the equilibrium beam are then calculated. To provide better comparison with the non-K-V beam, a K-V beam with emittance equal to these results was also tracked, and is shown on the second line. The third line gives the beam size enlargement when the equilibrium non-K-V beam is traced. The area roughly doubles and the radius increases by about a third. Figures 8 and 9 give beam profiles for the second and third runs.

Table IV Simulation Results At Target (rms distances in mm)

Distribution	x rms	y rms	$\Delta A/A$
Design K-V	2.12	2.05	1.09
Normalized K-V	1.94	1.83	.89
Non-K-V	2.45	2.83	1.73
K-V Envelope Integration	2.00	2.00	1.00

These quantities should be compared to those from a similar simulation of the previous system.[6] Here the non-K-V distribution was focused to a spot with x rms = 7.1 mm and y rms = 4.9 mm. The target area resulting from simulation is roughly twice the design area in the present scheme, whereas previously it was a factor of nine greater. Thus the present design is much less prone to error arising from using the K-V model for a real particle beam.

Modifications and Conclusion

Modifications of the system are conceivable to further improve its performance. First, reduction of the total length of the system and the maximum size of the beam will be discussed. The best way to reduce the total length would be to try to form the first waist sooner after the beam enters the focusing system. Also if the first waist were allowed to be smaller, the length could be reduced since the envelope could expand faster. However, it appears that such schemes would not reduce the length by much more than a few meters, and may increase sensitivity to errors. Within the 4T pole tip limit, reduction in the maximum size of the beam is possible only with the addition of more quadrupoles, and it is doubtful whether the reduction would be significant. It should be noted that on these two points considerable improvement was produced with this system over previous ones.

The most troublesome aspect of this system seems to be its momentum sensitivity, although this is relatively good compared to that of previous systems. By use of correcting elements, the momentum acceptance could probably be increased.

It also seems clear that smaller spot sizes are possible, but at the expense of greater maximum beam size. The quadrupole fields are presently below the pole tip limit by about 25% so that some leeway is possible.

A trivial estimate allows one to conclude that approximately 200 lines similar to the one proposed are required to deliver 400 TW instantaneous power. As this is likely to be too many, using a lower charge state should be considered. A design similar to the above one still appears possible, and would be likely to retain the relative independence of its focusing properties on the incoming particle beam distribution.

In conclusion, it seems that the given system satisfies the rather rough requirements placed on it. The system is relatively flexible due to the large number of quadrupoles involved. This allows further optimizations of the design to be performed as more exact requirements arise. The growth in spot size due to errors appears manageable, and a non-K-V distribution is adequately focused with the system. It is believed that this study indicates the feasibility of designing a satisfactory final focus system.

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References

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2. L. J. Laslett and L. Smith, IEEE Trans., Nuc. Sci., NS-26 No. 3, Pg. 3080, June 1979 and references therein

3. Al Garren, Proc. of Heavy Ion Fusion Workshop, Oakland, CA, Nov. 1979, Pg. 397

4. Irving Haber, Proc. of Heavy Ion Fusion Workshop, Oakland, CA, Nov. 1979, Pg. 341

5. Irving Haber, Technical Digest, San Diego ICF meeting, 68(1980) discusses the problem involved.

6. I. Haber, private communication

Figure Captions

On all figures quadrupole height is proportional to strength

Fig. 1: Transport Line Cell

Fig. 2: Ideal and Actual Zero Current Design

Fig. 3: 780A Final Focus System. Note that the final cell of the transport structure contains a half meter quadrupole. Normally the structure is constructed of one meter quadrupoles.

Figs. 4, 5, 6: K-V Envelopes for +1%, 0, -1% Momentum Deviation. In Figs. 4, 5, and 6 curves for $\Delta N/N$ = -10%, -5%, 0, 5%, 10% are included.

Fig. 7: Thin Lens Simulation System. Note that the quadrupole heights are in a different scale than in the previous figures.

Fig. 8: Beam Intensity Profile at Target for Normalized K-V Beam

Fig. 9: Beam Intensity Profile at Target for Non-K-V Beam
In Figs. 8 and 9 the profile P(r) gives the fraction of particles outside radius r. Thus

$$P(r') \equiv \int_{r'}^{\infty} f(r)\, r\, dr \Big/ \int_{0}^{\infty} f(r)\, r\, dr,$$

where f(r) is the radial particle distribution function. So for Fig. 8 about 88% of the particles are within 4mm radius, and for Fig. 9 about 86% are within that radius.

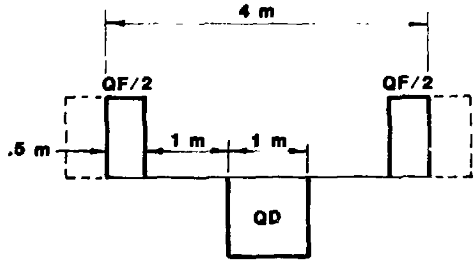

FIG. 1: TRANSPORT LINE CELL

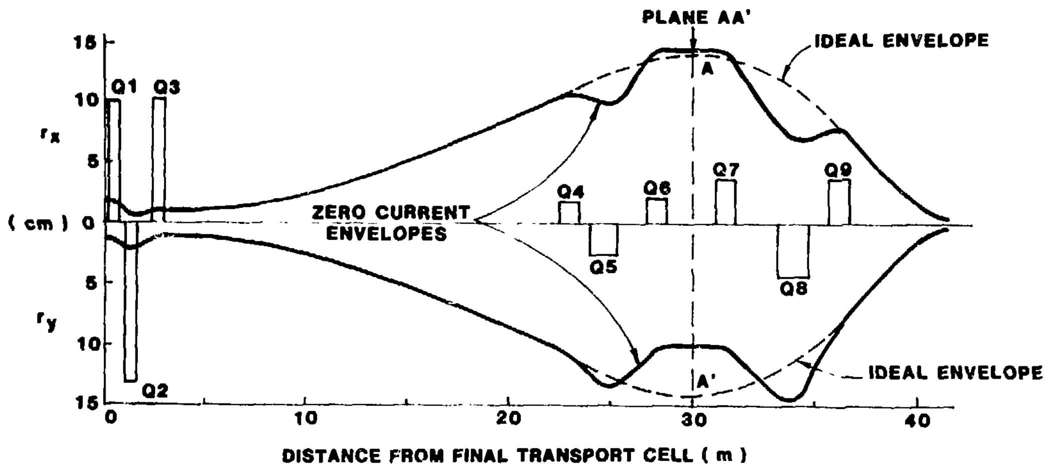

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FIG. 2: IDEAL AND ACTUAL ZERO CURRENT ENVELOPES

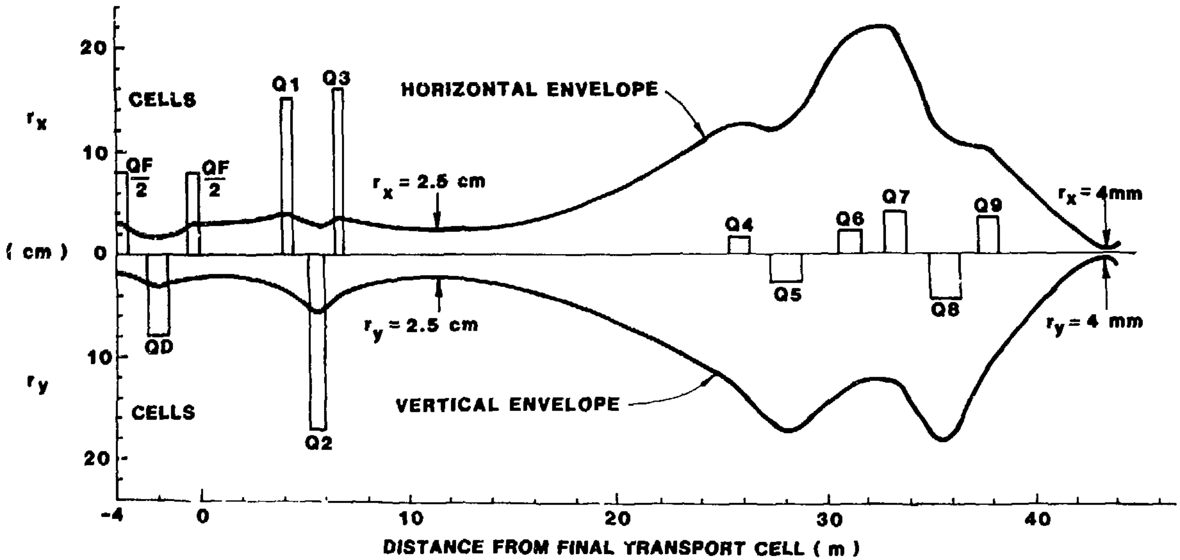

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FIG. 3: 780 A FINAL FOCUS SYSTEM

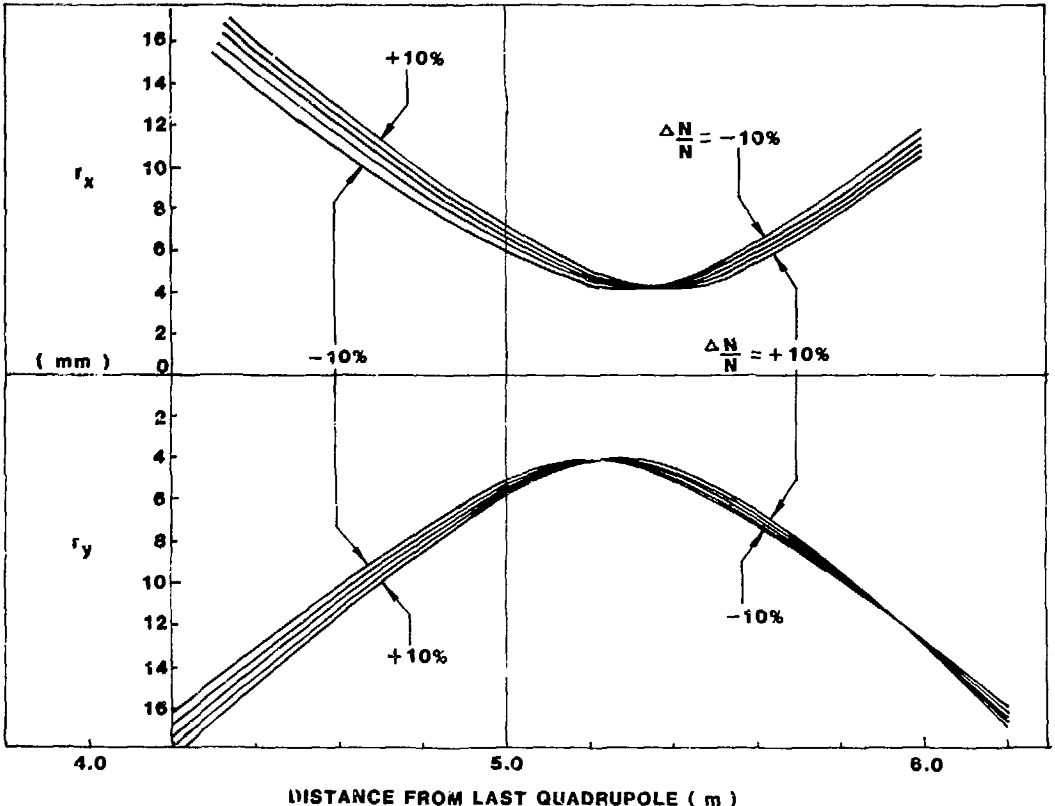

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FIG. 4: ENVELOPES FOR +1% MOMENTUM ERROR

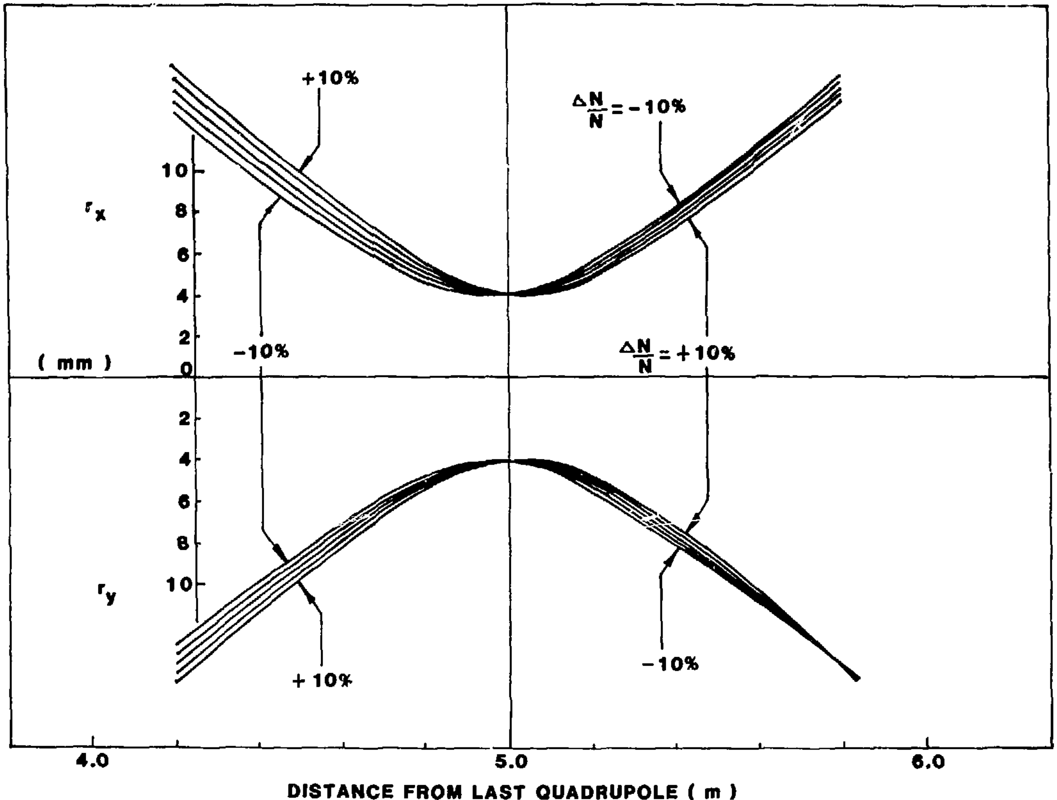

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FIG. 5: ENVELOPES FOR ZERO MOMENTUM MIRROR

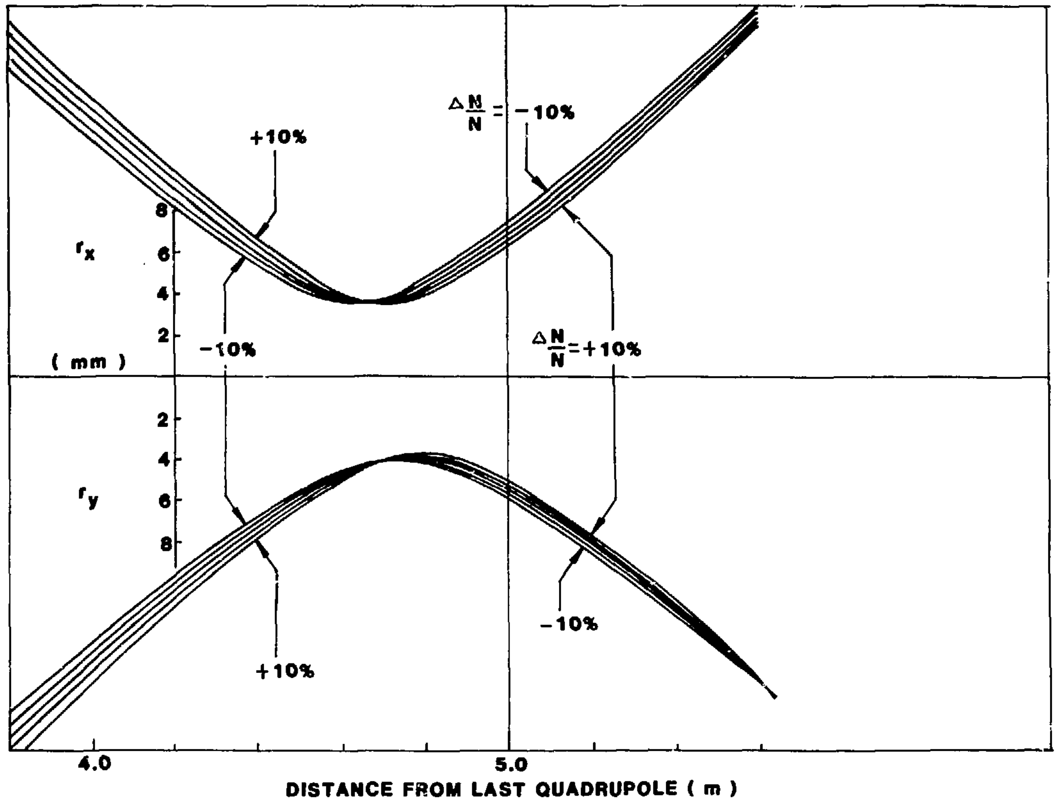

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FIG. 6: ENVELOPES FOR −1% MOMENTUM ERROR

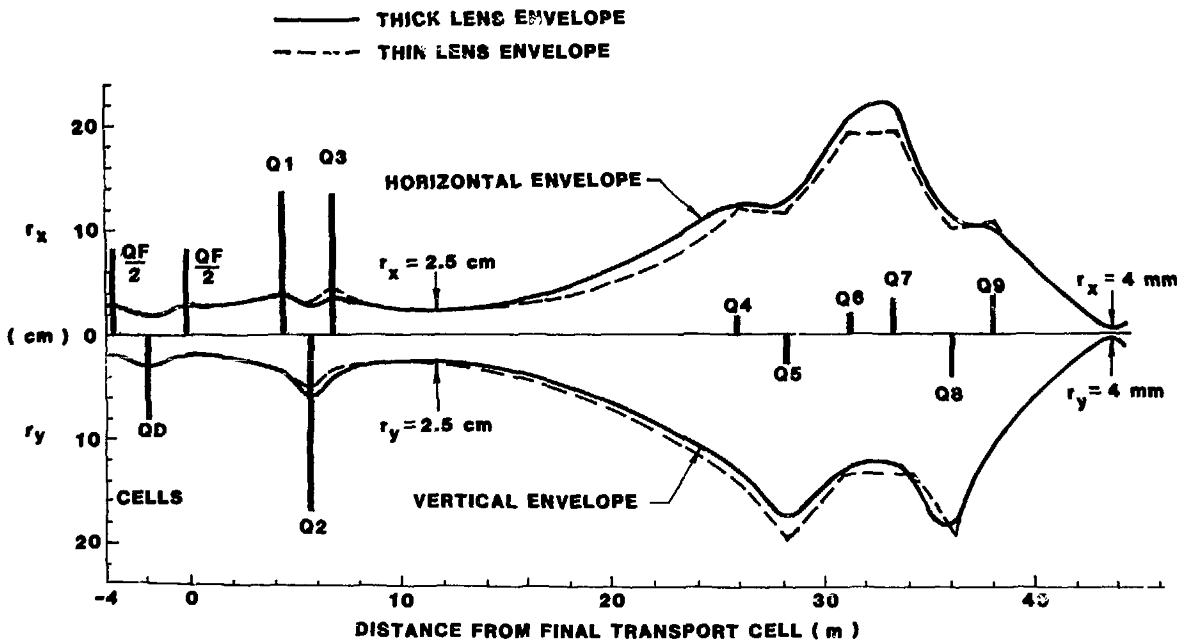

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FIG. 7: THIN LENS SIMULATION SYSTEM

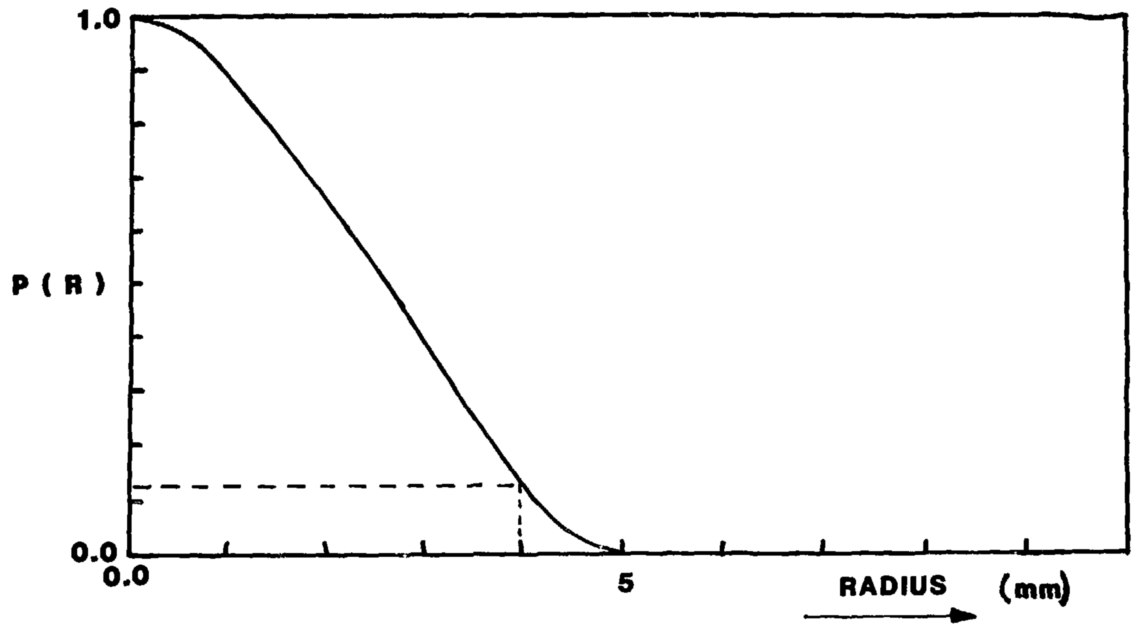

FIG. 8: BEAM INTENSITY PROFILE AT TARGET FOR NORMALIZED K-V DISTRIBUTION

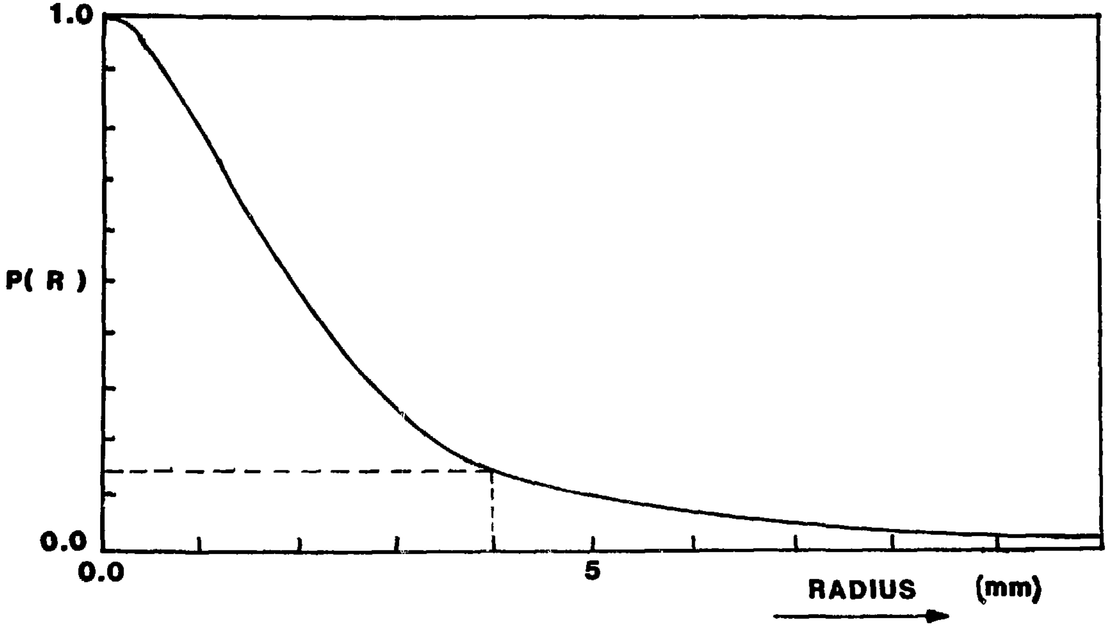

FIG. 9: TRANSPORTED BEAM INTENSITY PROFILE AT TARGET FOR NON-KV DISTRIBUTION