

## FOCUSING OF HEAVY ION BEAMS ON A FUSION TARGET\*

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### Summary

A beam line has been designed for transport between a periodic channel and a fusion target in a way intended to minimize effects of non-uniform transverse and longitudinal densities and of momentum spread. Principles used for the design are explained. The beam line is described and its performance as shown by envelope integration and particle simulation is presented.

### Introduction

At a recent HIF workshop studies of beam lines for transport between the periodic cells and the target were made. One design included sextupole chromatic correction but ignored space charge<sup>1</sup>. A second line including space charge<sup>2</sup> was derived from the first one, but it had too much chromatic sensitivity and tests using particle simulation showed that the beam behaved badly with a non-uniform distribution.<sup>3</sup> The object of the present study is to produce a beam line without dipoles and sextupoles that represents a closer approach to a workable system, by application of certain design criteria.

The envelopes of ref. 2 have several features which seemed to be related to the high sensitivities: they are very different with and without current, there is a small intermediate beam waist and no transverse symmetry. In the next section the strategy and procedure to produce an improved line are described. The resulting system is given in scaled variables together with a table giving several possible realizations. The system is explained and its sensitivity to current and energy variations is presented. Lastly, self-consistent particle simulations with various initial distributions are described.

### Design Strategy and Procedure

In order to reduce sensitivity to current variations, and to non-linear density distributions, the effect of space-charge forces should be reduced by minimizing beam radii. Small intermediate beam waists which produce large radii and gradients in adjacent quadrupoles should be avoided. The envelopes should be as smooth and symmetrical between the two transverse planes as possible.

### Strategy

Three sets of quadrupole triplets are deployed, see Fig 1: Q1, Q2, Q3 produces a symmetrical waist W1, of radius comparable to those in the periodic lattice. Q7, Q8, Q9 matches the beam between the small radius waist W3 at the target and a large waist W2; also the radii are minimized and the transverse maxima are made roughly equal in this triplet. Q4, Q5, Q6 matches the beam between the waists W1 and W2.

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### Procedure

The computations were made with the SYNCH computer program. The beam-line was designed using matrix methods and the gradients recalculated for the high current beam using envelope integration.

The gradient of the periodic cells is calculated to produce a given phase advance per cell  $\mu_0$  for zero current. The corresponding beta-functions are used as initial conditions for the beam line design. The current is chosen for the desired space charge depressed phase  $\mu$ . The phases were chosen to avoid instabilities due to perturbations of the space charge potential<sup>4</sup>, namely  $\mu_0 = 60^\circ$ ,  $\mu = 24.4^\circ$ . The cell packing fraction is 1/2.

For design purposes, the beam was assumed to have the Kapchinskij-Vladimirskij (K-V) distribution<sup>5</sup>. In this case the envelope radii  $a_x$ ,  $a_y$ , obey

$$\frac{d^2 a_{x,y}}{ds^2} \pm K a_{x,y} - \frac{\epsilon^2}{(a_{x,y})^3} - \frac{Q}{a_x + a_y} = 0, \quad (1)$$

$$Q = \frac{4r_0 q^2 N}{A\beta^2 \gamma^3} = 1.288 \times 10^{-7} \frac{q^2 I_p}{A(\beta\gamma)^3}. \quad (2)$$

Here  $s$  is the path length,  $K = (dB/dx)/(B\rho)$ ,  $\pi\epsilon$  is the emittance,  $q$  the charge state,  $N$  the number of particles per unit length,  $A$  the atomic weight,  $\beta$  and  $\gamma$  the relative velocity and energy, and  $I_p$  is the particle current in amperes.

### Scaling

The results are given in terms of scaled variables that make Eq. (1) dimensionless<sup>6</sup>. The gradient, path length, radius, and space charge parameters  $\kappa$ ,  $\theta$ ,  $u$ , and  $Q'$  are given by

$$\begin{aligned} K &= K_C \kappa, & s &= K_C^{-1/2} \theta, \\ a &= K_C^{-1/4} \epsilon^{1/2} u, & Q &= \epsilon K_C^{1/2} Q', \end{aligned} \quad (3)$$

where  $K_C$  is the cell gradient. The value  $Q' = 1.364$  corresponding to  $\mu = 60^\circ$ ,  $\mu = 24.4^\circ$  was used. Table I shows four parameter sets consistent with the designed system. Cases A - C represent scalings to the parameters of ref. 7. Case D gives the values actually used in this study and in ref. 2. All cases have the same pole-tip fields, and the maximum value is 4 Tesla.

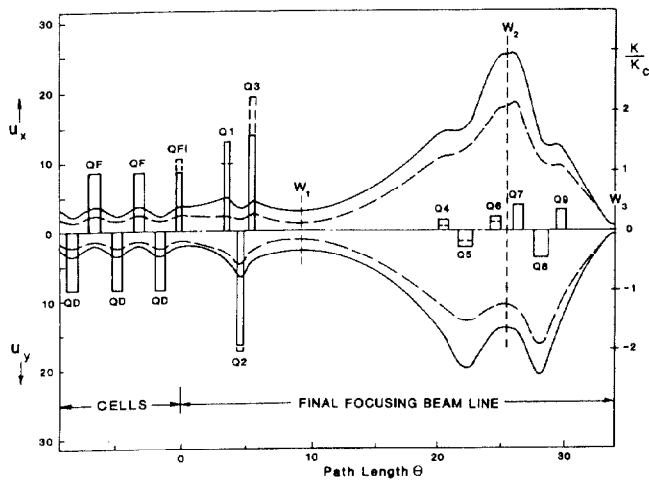


Fig. 1. Beam line design. Dashed/solid curves show zero/full current envelopes

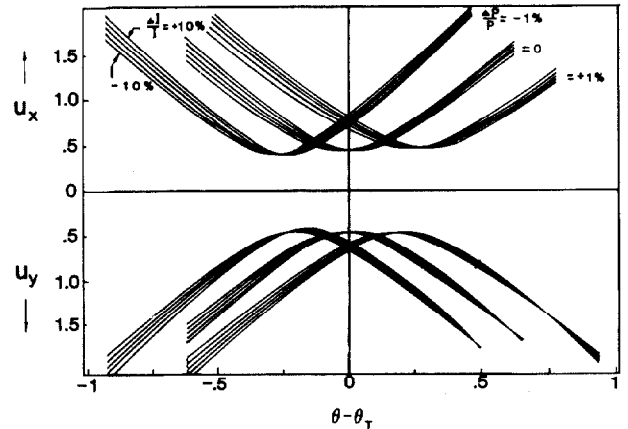


Fig. 2. Beam envelopes near the target for variations of  $\pm 1\%$  in momentum and up to  $\pm 10\%$  in current.

Table I: Beam line parameters derivable from the system shown in Table II, and Figure 1, for  $U_{238}$ , cell pole-tip field  $B'a = 1.061$  T,  $Q' = 1.364$

		A	B	C	D	
Charge state	q	1	1	1	4	
Kinetic energy	T	5	10	10	10	GeV
Rigidity	$B\rho$	158	225	225	56	T-m
Particle current	$I_p$	205	519	830	208	A
Emittance	$B\gamma\epsilon$	2.7	4.5	9.1	12.2	mm-mr
Cell gradient	$K_C$	.436	.245	.153	.613	$m^{-2}$
Beam radius maxima:						
cells	$a_c$	1.5	1.9	3.1	3.1	cm
beam-line	$a_B$	11.0	13.8	22.1	22.1	cm
target	$a_T$	0.2	0.25	0.4	0.4	cm
Lengths:						
cell	$L_C$	4.7	6.3	8	4	m
beam-line	$L_B$	51.4	68.5	86.6	43.3	m
Q9-target	$L_T$	5.9	7.9	10	5	m

### Beam-Line

The beam-line is presented in Table II and Fig. 1. Table II specifies the magnet gradients for the zero/full current cases. In Fig. 1, note that the envelopes show the desired smoothness, symmetry, and similarity between zero and full current. The waists  $W1$  and  $W3$  are symmetrical,  $W2$  is not but the radii of the largest peaks near  $W2$  are about equal.

Table II: Beam Line

Magnet	Exit position $\theta$	Length $\Delta\theta$	Gradient $K/K_C$
QF	-2.74	0.78	1.00/1.00
QD	-1.17	0.78	1.00/1.00
QFH	0.00	0.39	1.21/1.00
Q1	3.57	0.39	1.13/1.46
Q2	4.71	0.59	2.03/1.92
Q3	5.46	0.39	2.23/1.58
Q4	20.63	0.78	0.08/0.17
Q5	22.63	1.17	0.18/0.28
Q6	24.83	0.78	0.14/0.22
Q7	26.55	0.78	0.42/0.41
Q8	28.61	1.17	0.47/0.47
Q9	30.02	0.78	0.35/0.34

The sensitivity of the system to current and momentum variations is shown in Table III and Fig. 2. In each case the initial conditions are those of a periodic envelope in the cells. The momentum acceptance corresponding to a doubling of the target spot area is  $\Delta p/p \approx \pm 0.9\%$ . For current variations of  $\pm 10\%$  the spot size increases by about 10%.

Table III: Sensitivity of beam dimensions  $a_x/a_0$ ,  $a_y/a_0$  at the target due to intensity and momentum variations.

Full Current $\Delta I/I$	$\Delta p/p$		
	-0.1	0.0	+0.1
-0.1	1.8/1.5	1.0/1.0	1.5/1.3
0	1.7/1.4	1.0/1.0	1.7/1.4
+0.1	1.6/1.3	1.0/1.0	1.8/1.5
Zero current	1.3/1.3	1.0/1.0	1.3/1.4

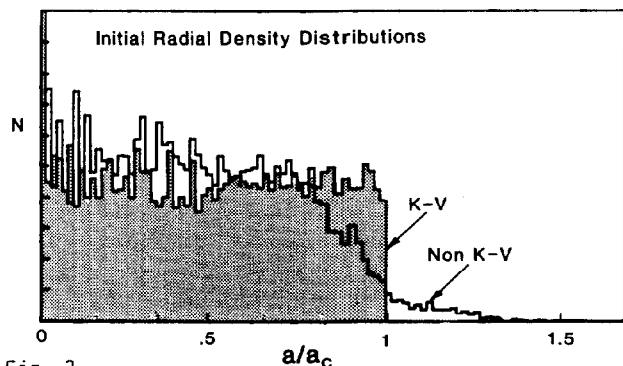


Fig. 3.

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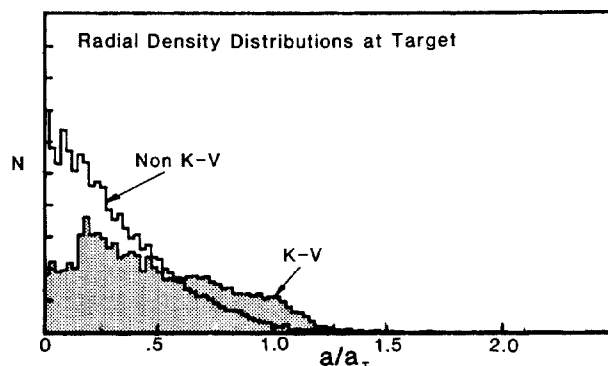
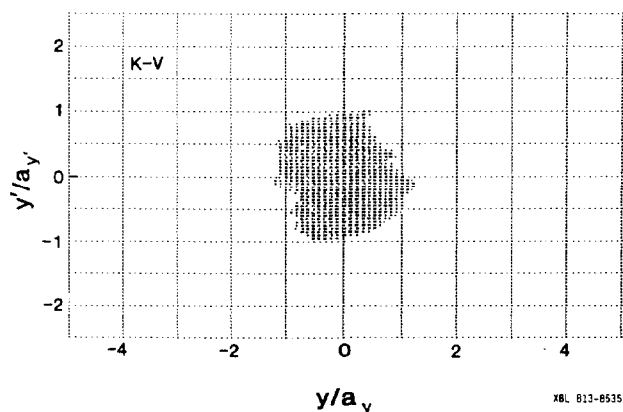
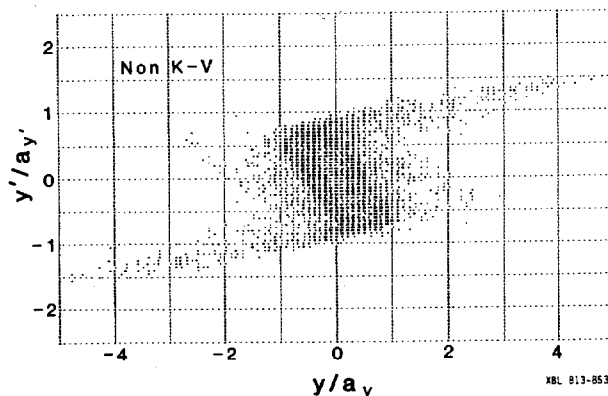


Fig. 4.

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Fig. 5. Phase-space distributions at target spot

### Particle Simulation

Simulations were performed to examine the sensitivity of the lens system to space charge aberrations caused by the non-uniform cross section. Spot degradations ranging from 30% to factors of two have been previously observed (3, 8-11). The simulations follow several thousand particles in their self-consistent electric fields. Figure 3 is a plot of the beam density as a function of radius for the initial K-V and non K-V distributions. Fig. 4 shows plots of the beam densities at the target spot resulting from these initial distributions. A small tail has formed and some hollowing of the beam at the center has occurred for the K-V case. Figs. 5 a, b show the phase-space distributions of the particles at the spot. Fig. 4 shows that for the beam that started out as a K-V distribution the statistical deviations have grown, and distorted the phase space ellipse. The target rms dimensions are listed in the first two lines of Table IV.

The non K-V distribution entering the lens system was established by slowly increasing the current in a matched low current beam which has a quadratic (water bag) main body and a linearly decreasing tail (11). The low current distribution was chosen so that the 90% emittance was the same as the design K-V distribution. The central density at the spot is actually greater than the reference K-V case. It is found that 90% of the particles are contained in a circle which has a radius of about 1.1 times the reference spot radius. Additionally, a K-V distribution with the same rms value as the non K-V system was also run. (Case 3 of Table IV.)

### Conclusions

A line for focusing heavy ion beams on a target has been designed and shown by envelope integration and particle simulation to better accept non-uniform densities and variations in momentum and current.

Table IV: rms dimensions at target from particle simulations, divided by design rms values.

Distribution	$X_{rms}$	$Y_{rms}$	$A/A_0$
1 Ref. K-V	1.06	1.03	1.09
2 Non K-V	1.23	1.42	1.73
3 K-V	0.97	0.92	0.89

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