

DESIGN AND SIMULATION STUDIES OF A ONE-TENTH SCALE FINAL FOCUS SYSTEM FOR HEAVY ION FUSION

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Abstract

A scaled test of a final focus lattice for Heavy Ion Fusion (HIF) is planned at LBNL. The test parameters have been set by scaling the length dimensions of the envelope equation by one tenth while maintaining the generalized perveance. The values to be scaled were taken, in large part, to be those of the HIBALL-II final focus system [1]. The tenth-scale test will focus a 120 keV Cs⁺ beam to a radial spot size of 0.25 mm. Tracking studies of the tenth-scale system have been performed using a version of COSY INFINITY [2] modified to include a linear space charge force. A description of the planned experimental system, the beam parameters, and simulation results are presented.

1. INTRODUCTION

The HIBALL-II parameters were chosen for scaling since it represents one of the more comprehensive designs of a final focus system for heavy ion fusion. The HIBALL-II final focus system specifies a 10 GeV, 1.25 kA, Bi⁺ beam. The beam emittance at the entrance to the final focus system was assumed to be 30 π mm-mrad with a momentum spread Δp/p of ±1%. Under these conditions, simulations predict a radial beam spot size of 3.5 mm at the final target position. The HIBALL-II lattice consists of two magnetic quadrupole triplets between which are two dipoles. (Note that the dipole elements are not significant relative to the transverse optics [~3° each], and were not included in this analysis.) Shown in Figure 1 are the HIBALL-II lattice and the beam envelopes predicted with a modified version of COSY INFINITY.

The beam envelope equation for a uniform, isolated beam of elliptical cross-section with semi-major and semi-minor axes of a and b respectively, and a beam emittance of ε is given by:

$$\frac{d^2X}{dz^2} = -\frac{B'X}{B\rho} + \frac{\varepsilon^2}{X^3} + \frac{2K}{a(a+b)}$$

Where X is the physical size of the beam envelope and K is the generalized perveance given by:

$$K = \frac{I}{I_0} \frac{2}{(\beta\gamma)^3} \text{ with } I_0 = 31 \frac{A}{Z} \times 10^6 \text{ (A)}$$

Following the philosophy of scaling the length dimensions of the beam envelope equation by a factor of 0.1 while maintaining the generalized perveance K, the

HIBALL-II parameters result in those given in Table 1 for the tenth-scale final focus experiment [3]. (Note that the momentum spread does not result from scaling, but rather from specific experimental test issues.)

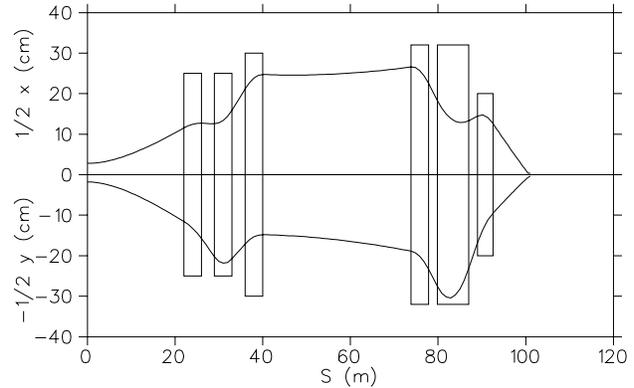


Figure 1. Lattice and beam envelopes of HIBALL-II.

Ion	Cs ⁺
Energy	120 keV
Beam Current	63 μA
K	1.13 x 10 ⁻⁵
Emittance	3.0 π mm-mrad
Momentum Spread	±0.2%
Final Radial Beam Size	0.25 mm

Table 1. Tenth-Scale Final Focus Experiment beam parameters.

2. CODE DEVELOPMENT

COSY INFINITY is a beam physics code, which uses differential algebraic (DA) methods to provide systematic calculations of particle trajectories resulting from passage through arbitrary optical elements. Since COSY INFINITY allows the computation of dependencies on system parameters and has the ability to compute and use high-order maps, it was considered an appropriate tool for the analysis of the final focus system. However, the generally available version of COSY INFINITY does not have a provision for the inclusion of the space charge force. The initial effort was to include a simple (linear) space charge force in COSY INFINITY.

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The implemented space charge model assumes a uniform, isolated beam of elliptical cross-section with semi-major and semi-minor axes of a and b respectively, beam current I , and beam Lorentz factors β and γ .

The combined electric and magnetic fields generated by the beam space charge distribution acting on a particle at transverse position (x,y) are given by:

$$E_x = 2F \frac{I}{\beta\gamma^2} \frac{x}{a(a+b)}, \quad E_y = 2F \frac{I}{\beta\gamma^2} \frac{y}{b(b+a)}$$

Where:

$$F = \frac{1}{2\pi\epsilon_0 c}$$

The potential is then given by:

$$\Phi(x,y) = -F \frac{I}{\beta\gamma^2} \left(\frac{x}{a(a+b)} + \frac{y}{b(a+b)} \right)$$

This space charge induced potential Φ is used in the modified version of COSY INFINITY to calculate the transfer matrices and maps.

3. TENTH-SCALE FINAL FOCUS EXPERIMENT SYSTEM DESIGN

The tenth-scale final focus experiment system will consist of a gun module, a matching section, and the tenth-scale final focus magnetic quadrupole lattice. Figure 2 shows the system configuration of the tenth-scale final focus experiment and the beam envelopes predicted with the modified COSY INFINITY.

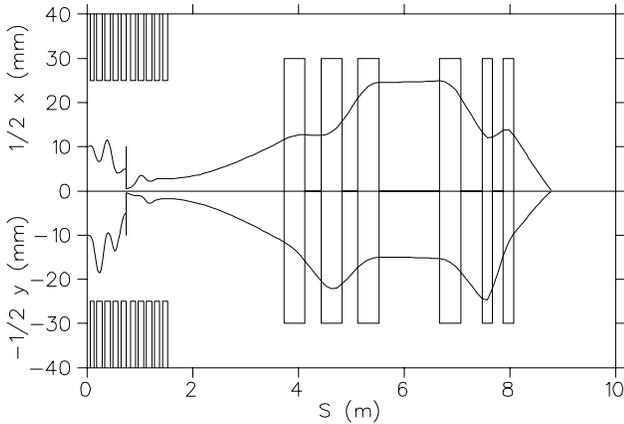


Figure 2. Lattice and beam envelopes of the Tenth-scale Final Focus experiment system.

The gun module consists of the LBNL 120 keV Cs⁺ gun and a lattice of five electrostatic quadrupoles followed by a circular aperture. The gun parameters provide for a 6.3 mA beam with an emittance 30π mm-mrad. To create the beam required for the final focus experiment ($63 \mu\text{A}$ in 30π mm-mrad), five electrostatic quadrupoles will be used to focus the source image (10 mm radius) to a spot 5 mm in radius at the position of an emittance truncation aperture plate. The emittance truncation aperture will be a circular hole of 0.5 mm in radius. Therefore, the beam current and emittance will be truncated by a factor of 0.01

and 0.1 respectively, providing a beam of $63 \mu\text{A}$ in 3.0π mm-mrad.

Following the aperture plate, an additional five electrostatic quadrupoles will be used to match the phase space of the truncated beam to that required for the tenth-scale final focus lattice. Note that the electrostatic quadrupoles were modeled as hard-edged with the pole voltages symmetric about ground. (Adjacent poles were assumed to have equal and opposite voltages.)

The tenth-scale final focus magnetic quadrupole lattice will use two magnetic quadrupole triplets to focus the 120 keV Cs⁺ beam to a radial spot size of 0.25 mm at the target position. The length dimensions and quadrupole settings of the module have been modified slightly from the scaled values of HIBALL-II lattice to reduce the number of quadrupole types required. In addition, the drift space between triplets has been reduced to bring the overall length to 8 m.

4. HARDWARE REQUIREMENTS

A total of 10 electrostatic quadrupoles are required to match the beam phase space from the gun to that required for the tenth-scale final focus module. The maximum voltage required is 10 kV with a radial aperture of 2.5 cm. The first quadrupole following the gun has an effective length of 0.0762 m with the remainder having an effective length of 0.1016 m. The electrostatic quadrupoles as well as the 120 keV Cs⁺ gun have been constructed and successfully operated at LBNL.

For the tenth-scale final focus module, a total of six of magnetic quadrupoles with a radial aperture of 3 cm and an integrated strength of 2.3 m^{-1} are required for the two triplets. Four of the quadrupoles will have an effective length of 0.4 m and a maximum pole tip field of 1.0 kG. The other two will have an effective length of 0.2 m and maximum pole tip field of 2.0 kG. The quadrupoles are located within existing vacuum tanks and powered with nominal 1.0 ms half-sine, pulsed waveforms. As such, they are easy to modify or reposition, and other configurations could be tried.

5. SIMULATION STUDIES

The system was evaluated by particle tracking using a 5th order map generated by the modified COSY INFINITY. Due to the large intensity reduction (0.01) at the emittance truncation aperture, the tracking was done in two steps; from the gun to the emittance truncation aperture and from the plate to the final target.

For the gun to aperture plate tracking, ten random seeds were used to populate 4,000 particles within an initial transverse phase space of 30π mm-mrad for each of three momentum values ($\Delta p/p = 0$ and $\pm 0.2\%$) giving 12,000 particles. Of these 12,000 particles, 165 particles shown in Figure 3 fall within the phase space defined by the 0.5 mm radial aperture. The number of surviving particles

(165) is statistically consistent with that predicted by the 0.01 reduction in beam current (120 particles).

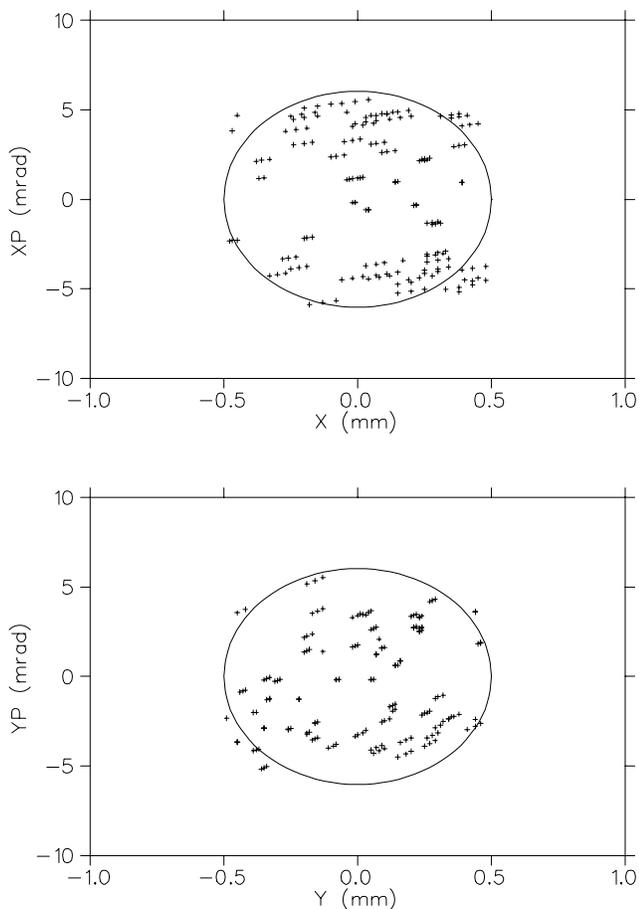


Figure 3. Transverse phase space of surviving particles for the gun to aperture plate tracking.

For the emittance aperture to final target tracking, 400 particles within an initial beam emittance of $3.0 \pi \text{ mm}^2$ were tracked for each of three momenta values ($\Delta p/p = 0$ and $\pm 0.2 \%$) giving 1,200 particles. Figure 4 shows the phase space of these particles at the target position. The real space area at the target position is $0.056 \pi \text{ mm}^2$ for the case of $\Delta p/p=0$ and $0.069 \pi \text{ mm}^2$ including particles with momenta of $\Delta p/p = \pm 0.2 \%$. The final beam spot area at the target position as function of momenta ($\Delta p/p$) is given in Figure 5. For the tenth-scale final focus experiment lattice, the tracking results indicate that the chromatic effects do not generate any significant increase in the final beam spot size, and therefore, higher-order correction will not be necessary.

6. SUMMARY

The Tenth-scale Final Focus design evaluations predict that this test will provide a cost-effective, experimental basis for future full-scale design evaluations.

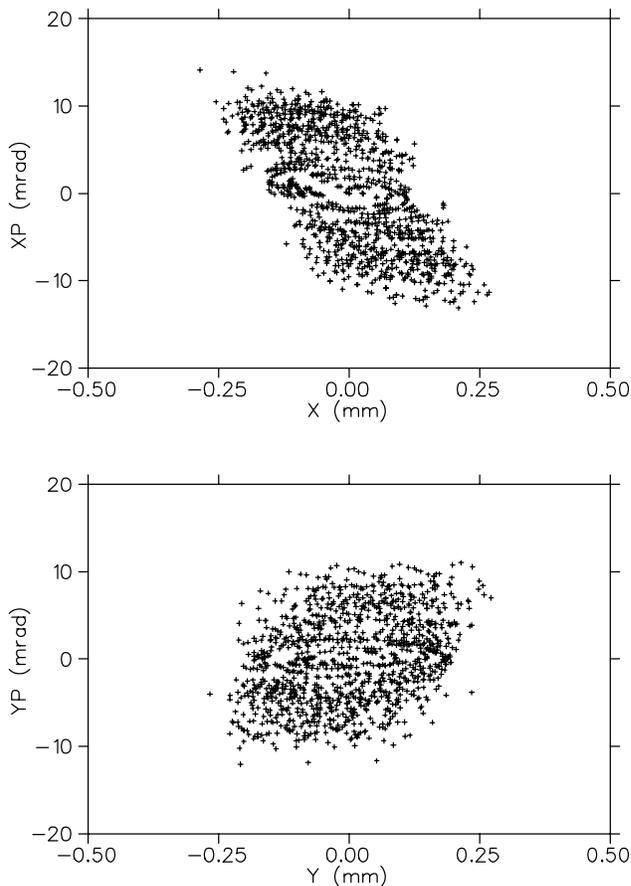


Figure 4. Transverse phase space for particles tracked from the aperture plate to the final target position.

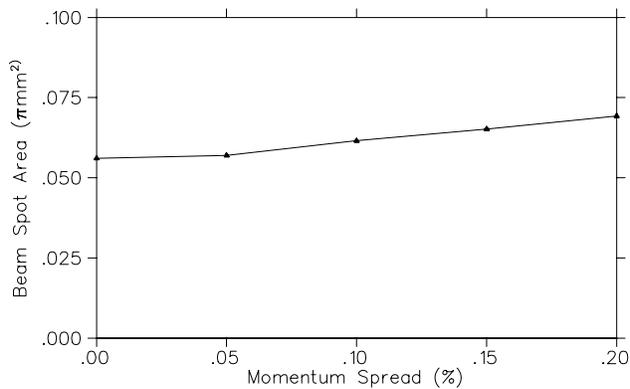


Figure 5. The final beam spot area at the target position as a function of momentum spread.

7. REFERENCES

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