

OCTOPOLE CORRECTION OF GEOMETRIC ABERRATIONS FOR HIGH-CURRENT HEAVY-ION FUSION BEAMS*

D. D.-M. Ho,† I. Haber,†† K. R. Crandall,††† and S. T. Brandon†

Abstract

The success of heavy-ion fusion depends critically on the ability to focus heavy-ion beams to millimeter-size spots. Third-order geometric aberrations caused by fringe fields of the final focusing quadrupoles can significantly distort the focal spot size calculated by first-order theory. We present a method to calculate the locations and strengths of the octopoles that are needed to correct these aberrations. Calculation indicates that the strengths of the octopoles are substantially less than that of the final focusing quadrupoles.

Introduction

The ability to focus high-current, e.g. kA, heavy-ion beams to millimeter-size spots is critical to the success of heavy-ion fusion (HIF). However, the focal spot size predicted by first-order theory is substantially distorted by third-order geometric aberrations caused by fringe fields of the final focusing quadrupoles. Various authors attempted to correct these aberrations, for beams with and without significant space charge, by octopole magnets.¹⁻⁷ However, to our knowledge, no rigorous presentation on how to calculate the appropriate locations and strengths of the octopoles for high-current beams has appeared so far. In this paper, we show, to a very good approximation, that in calculating the locations and strengths of the octopoles for high-current beams, the third-order contributions from space-charge force can be neglected. Thus, the procedure becomes almost identical to the treatment for low-current beams except that the data from the first-order beam line calculation including the space charge are used to calculate the third-order correction. Calculations indicate that the required octopole pole-tip field strength is very small, e.g. a few percent of the strength of the final quadrupoles.

Calculation of Third-Order Geometric Aberrations

To calculate the effect of space charge forces, it is important to note that if the initial beam profile in the FODO transport is essentially uniform, it remains essentially uniform both during its radial expansion phase and after it enters the final focusing lens system. This is because the ratio of the space charge force to the thermal force is large in the transport system, and this ratio becomes even more pronounced during the radial expansion. Note that for intensely-charged beams, even if the initial profile is nonuniform, it has a tendency to become uniform after radial expansion.⁸ Thus, to a good approximation, the radial electric field is linear. The single particle equation of motion that includes expansion of quadrupole fields to third order, in the x direction, then has the form^{7,9}

$$X'' + (k - k_{sx})x = [(-\frac{1}{2}k + k_{sx})xy'^2 + kx'yy' + k'xyy' + \frac{1}{4}k''xy^2] + [-(\frac{3}{2}k + k_{sx})xx'^2 + \frac{1}{12}k'''x^3] \quad (1)$$

where $k = qB/amv$, a is the bore radius, q is the charge of the particle, k_{sx} is the linear space charge force per unit mass in the x direction, and the primed quantities are the derivatives of these quantities w.r.t. the longitudinal coordinate s . To obtain the equation in the y direction, simply exchange x for y, k for -k, and k_{sx} for k_{sy} .

Assume the solution to the first-order particle equation of motion has the form

$$\begin{aligned} x &= C_x(s)x_0 + s_x(s)x'_0 \\ y &= C_y(s)y_0 + s_y(s)y'_0 \end{aligned} \quad (2)$$

where the quantities with subscript zero are the particle initial conditions at the exit of the FODO transport system. The particles that stay close to the beam edge are those which start near the beam edge and with $x'_0 = y'_0 = 0$.

Solution to Eq. (1) with the above initial conditions and first order solution in the form of Eq. (2) is

$$\begin{aligned} x(s_F) &= S_x(s_F) \int_{s_0}^{s_F} \{ [(-\frac{1}{2}k + k_{sx}) C_x^2 C_y'^2 \\ &+ k C_x C_x' C_y C_y' + \frac{1}{2} k' C_x^2 C_y C_y' \\ &- \frac{1}{2} k' C_x C_x' C_y^2] x_0 y_0^2 + (-\frac{3}{2} k C_x^2 C_x'^2 \\ &- \frac{1}{3} k' C_x^3 C_x' + k_{sx} C_x^2 C_x'^2) x_0^3 \} ds \quad (3) \end{aligned}$$

where s_0 and s_F represent the locations at the exit of the FODO system and at the focal spot, respectively.

As a numerical example, we choose a beam consisting of ions with atomic number 210 and charge state +2. The electrical current is 3 kA and the emittance is 2×10^{-5} m rad. The focal spot radius is 3mm and the beam line configuration is shown in Fig. 1. The first order beam line is designed using the envelope code TRACE. Note that in designing the beam line, we tried to keep the total length as short as possible. This is because, otherwise, the beam can expand in the longitudinal directions and chromatic aberrations will be induced. We assume that the magnetic potential at the ends of each quadrupole fall linearly to zero over a distance of 50 cm. If the size of the beam cross section at the exit of the FODO system is 2.37 cm and 1.33 cm in the x and y directions respectively, it can be shown from Eq. (1) that the maximum aberration experienced by a particle starting at the beam edge with no initial transverse motion is about 11.4mm at the focal spot. Thus, the third-order aberration is a serious effect.

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

†Lawrence Livermore National Laboratory, Livermore, CA 94550

††Naval Research Laboratory, Washington D.C. 20375

†††AccSys Technology, Inc., Pleasanton, CA 94566

Octopole Correction

In calculating the aberration using Eq. (3), we notice that the answer is changed by no more than a few percent if we leave out the contributions due to space-charge effect, e.g. terms with k_{SX} . Thus, the effect of the space charge contribution to the aberration can be ignored in calculating the locations and strengths of the octopoles that are needed to correct this aberration. Consequently, we can follow the method of Fenster² to calculate the locations and strengths of the octopoles. The constraints on the calculation are: 1) we want to minimize the strengths of the octopoles; 2) the strengths of the octopoles should not be too different from each other in order to minimize the sensitivity of the final spot size to envelope fluctuations.

We find that the dominate aberrations can be corrected by placing six octopoles at locations shown in Fig. 1. The pole-tip strengths of these octopoles are: $S_1 = -S_2 = -0.10T$, $S_3 = -S_4 = 0.11T$, and $S_5 = -S_6 = 0.14T$.¹ These strengths are between two and three percent of the final quadrupoles. It is also interesting to note that using two octopoles with strengths about twice that of the octopoles just quoted, up to about 90% of the aberration of the extreme particles can be suppressed. We are now performing fully self-consistent particle simulations to investigate the degree that the octopoles with strengths obtained from single particle equations of motion can correct beams with realistic distributions, e.g. semi-Gaussian.

References

- [1] D. Neuffer, "Geometric Aberrations in Final Focusing for Heavy Ion Fusion," Proc. of the Heavy Ion Fusion Workshop, Argonne, ANL-79-41, 1978, pp. 333-339.
- [2] S. Fenster, "Octopole Correction of Third Order Aberration," ipid 355-364.
- [3] E. P. Colton, "Correction of Chromatic and Geometric Aberrations Using Sextupoles and Octopoles," ipid 365-378.
- [4] J. R. M. Maidment and C. R. Prior, "Final Focusing of 10 GeV Bismuth Ions," Proc. of the Symposium on Accelerator Aspects of Heavy Ion Fusion, Darmstadt, W. Germany, 1982, pp. 376-386.
- [5] I. Hofmann and I. Bozsik, "Final Transport and Focusing for the HIBALL Heavy Ion Fusion Conceptual Reactor Study," Max-Planck-Institut fur Plasma physik, IPP 0/47, Garching, W. Germany, 1981.
- [6] E. A. Heighway, private communication.
- [7] E. P. Colton, "Space-Charge and Third-Order Aberrations in Quadrupole Focusing Systems," Los Alamos National Laboratory, LA-10795, 1986.
- [8] HIBALL-II: An Improved Conceptual Heavy Ion Beam Driven Fusion Reactor Study, Kernforschungszentrum Karlsruhe, W. Germany, 1985, p. 65.
- [9] K. G. Steffen, High-Energy Beam Optics, John Wiley & Sons, Inc., New York, 1965.

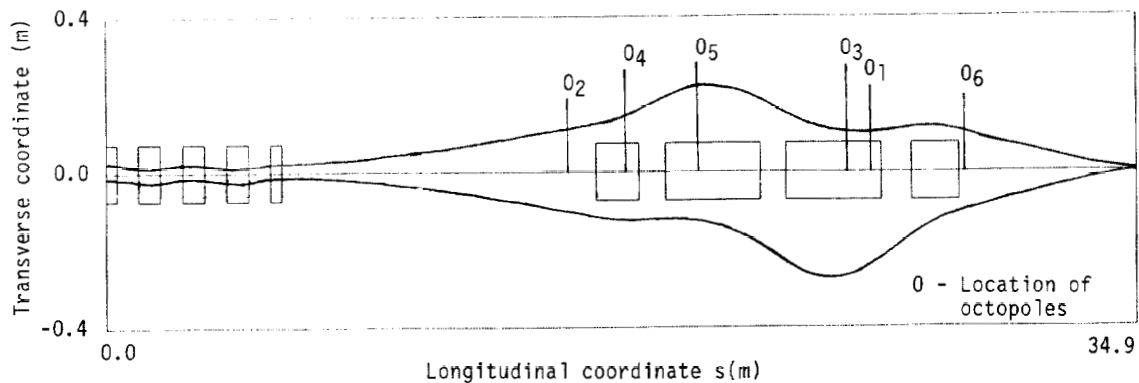


Fig. 1. Configuration of the final focusing section for charge state +2 beam with 3 kA and atomic number 210.