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SCALING EXPERIMENT FOR HEAVY-ION FUSION FINAL FOCUSING*

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A scaling experiment will be performed to test the feasibility of proposed solutions to several problems associated with the final-focus system of heavy-ion driver for Inertial Confinement Fusion. The experiment will be conducted at the Lawrence Berkeley Laboratory using a 120-keV Cs^+ beam. The experiment will test the proposed techniques for correcting geometric aberrations and for focusing variable-current beams using fixed strength quadrupoles.

1 INTRODUCTION

In a Heavy Ion Fusion (HIF) driver system, a high-current (several kiloamperes) beam of high-energy (several GeV) heavy ions must be focused to hit a small target pellet (several mm in radius) in a short time interval (a few nanoseconds). To produce the proper compression of the pellet, the beam current deposited on the target must vary in a prescribed manner over the pulse. Approximately 60% of the beam energy should be delivered to the target during the final 20% of the pulse. Consequently, the final-focus system must be designed to focus a variable-current beam onto a fixed-radius target. A possible solution to this problem has been proposed.[1]

After the heavy-ion beam has been accelerated to its final energy, it is longitudinally compressed to the desired pulse length as it is transported to the final-focus system through a periodic array of quadrupole magnets. The final-focus system consists of: 1) a drift space of several meters which allows the beam to expand transversely; 2) several large-aperture quadrupole magnets to focus the beam onto the target; and 3) a drift space of several meters through the reaction chamber to the target. The fringe fields of the large-aperture quadrupoles can produce third-order geometric aberrations that distort the beam in transverse phase space. An energy spread in the beam can cause chromatic aberrations. Unless they are eliminated or corrected, these aberrations, together with nonlinear space-charge forces, can cause a significant

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fraction of the beam to miss the target pellet. Several proposals[2,3,4,5] have been made for using octupoles to correct the third-order geometric aberrations.

Although it is not practical to study the abovementioned problems and their possible solutions in a full-scale experiment, a scaled-down experiment can demonstrate some of the same problems and test the feasibility of some of the proposed solutions. In the early 1980s, a Single Beam Transport Experiment (SBTE) was conducted at Lawrence Berkeley Laboratory (LBL) to study emittance growth in space-charge-dominated beams being transported through a periodic focusing channel.[6] In the SBTE, a 120-keV Cs^+ beam was transported through a periodic array of 82 electrostatic quadrupoles. The scaling experiment discussed here calls for the SBTE apparatus to be recommissioned and for the downstream portion of the quadrupole array to be replaced by four large-aperture quadrupoles. The main purposes of the scaling experiment are: 1) to demonstrate that the beam size at the target can be kept relatively constant as the current is varied by a factor of three or four; 2) to show that the geometric aberrations can be corrected by using octupoles; and 3) to study the effects of chromatic aberrations on the beam size at the target.

2 FOCUSING A VARIABLE-CURRENT, CONSTANT-EMITTANCE BEAM

Theoretical studies and numerical simulations[7] both indicate that the transverse emittance of the beam remains relatively constant as the beam is being compressed longitudinally. At the entrance of the final-focus system, the transverse emittance should therefore be constant along the beam pulse, even though the current varies. Also, if the beam is matched to the transport system at the beginning of the longitudinal compression, it should remain matched throughout the transport system and at the input of the final focus. Because of the high currents required for HIF, the beam will undoubtedly be space-charge-dominated in the final-focus region, which means that the beam size will be proportional to the square root of the current. If this condition also applies near the target, then the final focusing quadrupoles should be adjusted to produce the desired spot size for the highest current in the pulse. The lower-current portions of the pulse will produce a smaller spot size at the target.

However, because of the small size of the target, the beam may not be space-charge-dominated near the target. The envelope equation for a circular beam in a drift space is:

$$r'' - \frac{q^2 J}{2\pi\varepsilon_0 mc^3(\beta\gamma)^3 r} - \frac{E^2}{r^3} = 0,$$

where r is the outer radius of the beam, q is the charge state, J is the particle current, ε_0 is the permittivity of free space, m is the mass of the heavy ions, c is the velocity of light, β and γ are the standard relativistic parameters, and E is the total unnormalized emittance (4 times the rms emittance). The prime denotes differentiations with respect to the longitudinal coordinate. The second and third terms in the above equation are the space-charge and emittance terms, respectively. As the beam size decreases, the emittance term increases much faster than the space-charge term.

We have found that, as long as the space-charge term is not much lower than half of the emittance term at the target, the final-focus quadrupoles can be set to produce an almost constant beam size as the current is varied by a factor of 3 or 4.[1] Additional requirements are that the beam must be space-charge-dominated at the entrance to the final-focus system and the beam must be axisymmetric at the beginning of the expansion drift space.

3 CORRECTING THIRD-ORDER ABERRATIONS WITH OCTUPOLES

Third-order aberrations, produced mainly in the fringe fields of the large-aperture quadrupoles, can distort the beam in phase space and cause a significant fraction of the beam to be outside of the target radius. Octupole magnets, which also exert third-order forces on a charged-particle beam, can theoretically be used to cancel the third-order quadrupole aberrations. For this technique to be successful, both the quadrupole aberrations and the octupole corrections must not be large enough to significantly perturb the first-order dynamics in the vicinity of the quadrupoles.

There are three major third-order aberration terms produced by the quadrupole fringe field and therefore a minimum of three octupoles are required for their correction. More than three octupoles should be used so that the correction terms can be relatively small. The octupoles give the best results when they are placed where the beam is the largest, which implies that some octupoles should be superimposed on quadrupoles. Others could be placed between quadrupoles.

4 SCALING EXPERIMENT

The results of the SBTE reported in reference 6 indicate that the beam current and emittance are in acceptable ranges to be useful for testing the validity of the proposed solutions to some HIF final-focus problems. Up to 15 mA of 120-keV Cs^+ ions were transported through the electrostatic quadrupole array and the measured normalized emittance was about 0.1π mm-mrad (70π mm-mrad, unnormalized) when the zero-current phase advance was set at 59° per period. The space-charge and emittance terms in the envelope equation are equal when

$$I = 0.0057\ E^2/r^2,$$

where I is the current in mA, r is the beam radius in mm, and E is the emittance in π mm-mrad. Choosing an emittance of 60π mm-mrad and a target radius of 2.5 mm gives a value of 3.3 mA for the current at which the space-charge and emittance terms are equal. A suitable current range for the experiment would then be from 2 to 8 mA, for example. The current would be adjusted without changing the emittance by using various filters. The emittance and the current could both be reduced by a series of apertures.

The first step in the experiment is to recommission the SBTE apparatus, which consists of vacuum enclosures with pumps; a Cs^+ ion source and high-voltage power supply; 5 electrostatic quadrupoles for matching the beam from the ion source to the periodic quadrupole array; several periods of an electrostatic quadrupole lattice; several types of diagnostic hardware; and an automated data acquisition system. After recommissioning this apparatus, the beam will be characterized as to its emittance and current range. A special electrostatic quadrupole may need to be added to the end of the periodic array so that the beam can be made axisymmetric at this point.

The preliminary design of the final-focus system calls for a 45-cm expansion drift to be followed by four magnetic quadrupoles. (Electrostatic quadrupoles were intended to be used, but these cause much larger aberrations because of the energy variation produced in the beam as it passes through these elements.) The two inner quads would have effective lengths of about 25 cm and the two outer quads would have effective lengths of 15 cm. There would be 20 cm between quadrupoles and 10 cm from the end of the last quad to the target. An 8-mA beam with an emittance of 60π mm-mrad would have a maximum radius of about 65 mm in the inner quads, so these quads would need a relatively large aperture. Furthermore, these two quads would have octupole elements superimposed. The outer two quads could have smaller apertures, perhaps half as large as the inner two. Short octupoles could be placed between the quads. The magnetic fields at the pole tip of these quadrupoles would be on the order of 10 kilogauss. The pole tip field required for the octupoles could be 1 or 2 kilogauss.

After characterizing the beam, the next step would be to find a focusing solution for the highest current to be used. This will probably not be trivial because the third-order aberrations will complicate matters. It is difficult enough to find a theoretical solution in a computer simulation in which the third-order effects can be turned on or off. It will be much more challenging to find a solution experimentally.

Most of the experimental measurements will be made using the central part of the few microsecond pulse, in which the beam is essentially monoenergetic. Space-charge forces will cause an energy deviation in the beam at each end of the pulse. The effects of chromatic aberrations in the final-focus system can be studied by observing the spot sizes at the ends of the pulse.

At this writing, the scaling experiment is still in the design phase. A search is being made for suitable large-aperture quadrupoles. If these cannot be found for a reasonable cost, the experiment will have to be modified. The emittance and the current could both be reduced to allow the final-focus quadrupoles to have small apertures. The variable-current focusing could still be tested, but the third-order aberrations might be relatively insignificant, which would negate one of the purposes of the experiment.

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