Detailed High-Current Beam Optics Design for Ions and Electrons†

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Abstract

Many modern industrial accelerator applications require high current and impose demanding specifications on the final beam properties. The Grumman TOPKARK code [1] has been developed for the detailed design of high-order, high-current beam optics lines for both ion and electron applications. We consider two examples here: a D^+ final focus applicable to Fusion Materials Irradiation Facility (FMIF) configurations, and an e^- beamline for the BNL Center for Radiation Chemistry Research (CRCR)*. The ion example consists of 125 mA of 35 MeV deuterium delivered to a flowing lithium target. As for neutron spallation sources, the beam on target must be both square and uniformly-distributed, which requires careful use of octupole and duodecapole magnets. The CRCR beamline has been designed to deliver 10 nC pulses of 9 MeV electrons, each with a final FWHM duration of < 5 ps. This beamline uses an achromatic 90 degree bend to longitudinally compress the electron bunches by a factor of three. Both of these optics designs yield significantly different simulation results when differing space charge models are used. TOPKARK employs three distinct space charge models and can model the initial particle bunch as either a Gaussian or a uniformly-filled 3-D ellipsoid, or input particles from a PIC code. This sort of flexibility allows one to test the robustness of an optics design. Comparisons are also made between TOPKARK and other optics/dynamics codes.

Introduction

The utility of TOPKARK lies in its combination of high-order magnet models with reasonably fast and accurate space charge models. The code currently implements a number of uniform-field magnet elements, including a dipole (with arbitrary entrance and exit angles) and quadrupole through duodecapole multipoles. "Thin fringe" elements are also used.

TOPKARK uses three space charge models, each imposing ellipsoidal symmetry on the bunch. The uniformly-filled 3-D ellipsoid model yields linear fields, generally underestimating space-charge-induced emittance growth, but is very fast and agrees well with TRACE 3-D. The Gaussian ellipsoid model, which is significantly slower, often shows strong third-order aberrations. The third and more detailed model is due to Garnett and Wangler [2] (henceforth referred to as G&W), which Fourier expands in a radius-like variable, obtaining the expansion coefficients from the particle ensemble.

35 MeV D^+ Optics Channel

We show in Fig. 1 the evolution of a 0.714 nC (125 mA at 175 MHz) D^+ bunch through a nonlinear optics channel designed to yield a transverse profile that uniformly fills a 10 cm square. The figure shows both the maximum excursion (dashed lines) and the full-width at half maximum (FHWM, solid lines) for both x (above center line) and y (below center line).

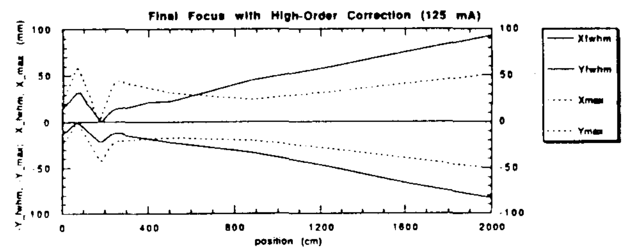

Fig. 1 Beam envelope in nonlinear optics channel.

The beam is waisted, first in y, then in x. A combined-function octupole/duodecapole is placed at each waist. This allows an almost 1-D modification of the beam, avoiding the x-y coupling that would otherwise arise from these high-order elements. As the tails of the distribution fold over and the beam becomes square, the FWHM exceeds the maximum beam excursion.

We show in Fig. 2 an x-y projection of the beam on target. The upper figure was obtained without the high-order magnets, and the lower figure was generated using these magnets. Fig. 2 shows dramatically that the desired effect has been achieved. Nonlinear optics channels of this type have been discussed in detail in the literature [3], [4].

The plots in Fig. 2 are from zero-current simulations. We now consider the effects of space charge. This example is far from being space charge dominated, as the quadrupoles need only be changed by a few percent to maintain the final beam size and to keep the beam waists in the same location. However, space charge has a strong dynamical effect at higher order.

Fig. 3 shows the x-p_x phase space at the target. The upper plot was obtained without high-order magnets, and the middle plot was generated using these magnets; both are from zero-current simulations. The middle plot shows how the tails of the distribution have been folded over by the octupoles. The bottom plot was obtained from a simulation which included the high-order magnets and used the G&W space charge model. Strong third-order aberrations due to space charge are visible in

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this bottom plot; they are so strong, that it was necessary to change the signs of the octupoles and fold the phase space in the opposite direction as shown by the middle plot.

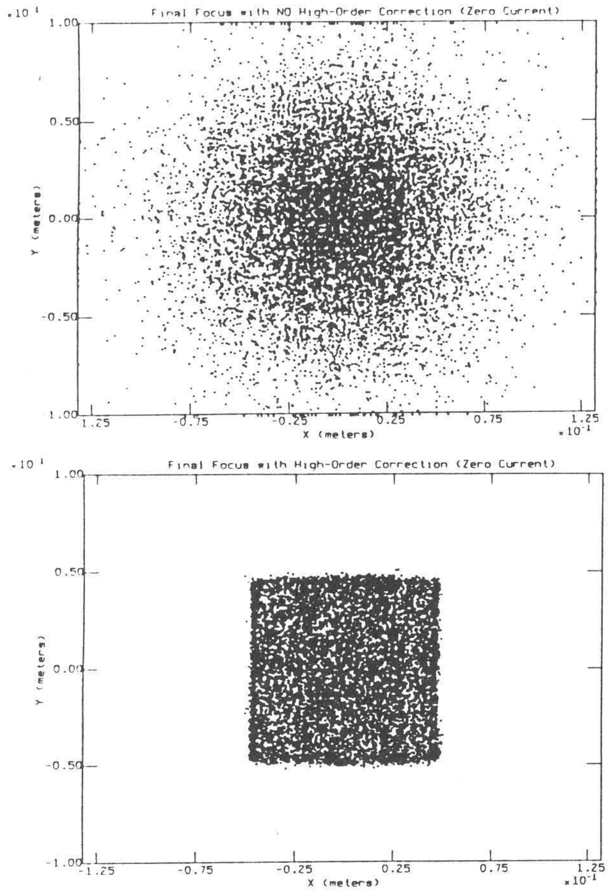

Fig. 2 Beam on target with (below) and without (above) use of octupole and duodecapole magnets.

9 MeV e⁻ Bunch Compression Beamline

Fig. 4 shows the evolution of a 10 nC, 9 MeV electron bunch through a bunch compression beamline. The upper plot is a TRACE 3-D output, showing the solenoid which focusses the bunch out of an electron gun, followed by four quadrupoles that match the beam into a 90° achromatic bend, and finally four more quadrupoles that focus the beam on target. The achromat compresses the bunch longitudinally to a FWHM pulse length of <5 ps. The middle plot in Fig. 4 shows TOPKARK results for the FWHM beam excursion of x (solid) and y (dashed), as well as the FWHM pulse length in ps (dotted). This plot shows that the beam is focussed to a 2 mm spot, with a pulse length of 3 ps. The bottom plot shows the maximum excursions in x (solid) and y (dashed). The straight solid lines indicate the location of the beam pipe, and the dotted line indicates the number of simulated particles (in arbitrary units). This plot shows that there is some beam scraping in y.

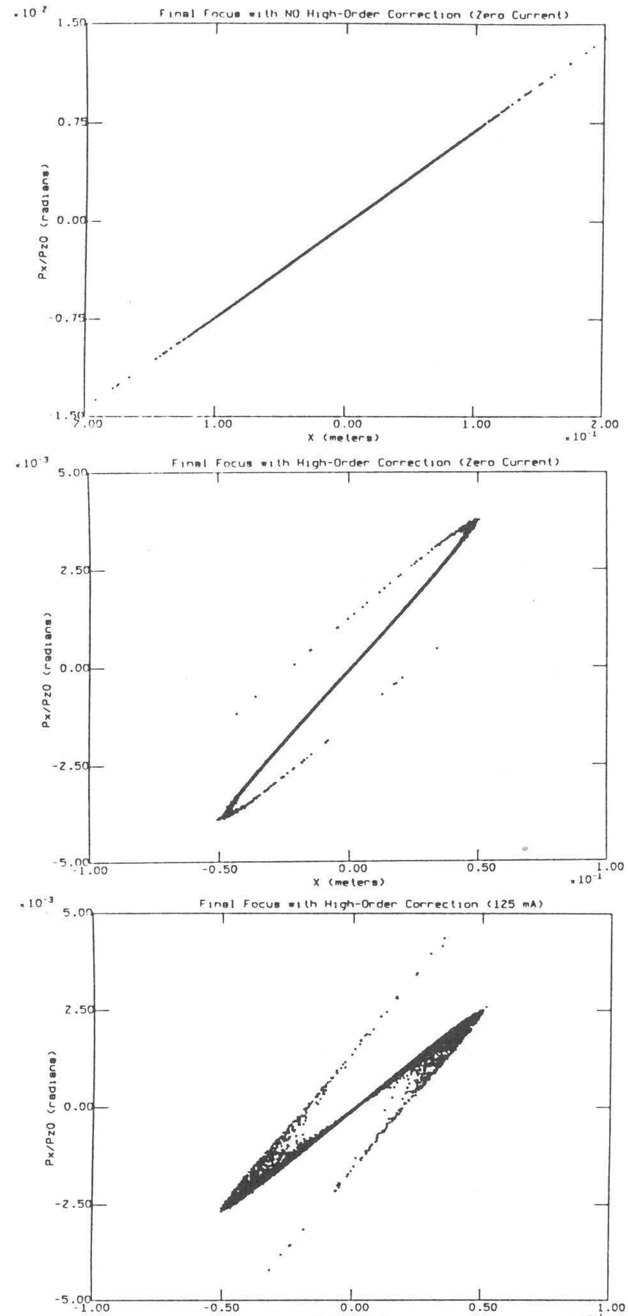

Fig. 3 X-P_X phase space for beam on target without octupoles or space charge (top), with octupoles but not space charge (middle) and with both octupoles and space charge (bottom).

In Fig. 5, we show an x-δz projection of the beam on target as obtained from simulations using the linear (top), G&W (middle) and Gaussian (bottom) space charge models. In each case, the FWHM in x is 2 mm and the FWHM in δt (i.e. δz/c) is ~3 ps. The linear space charge acts most strongly on the tails of the distribution, so the upper plot shows a relatively dense core, while the Gaussian space charge acts most strongly on the core, yielding the much more diffuse distribution seen in the bottom plot. The x-δz coupling arises in the bend.

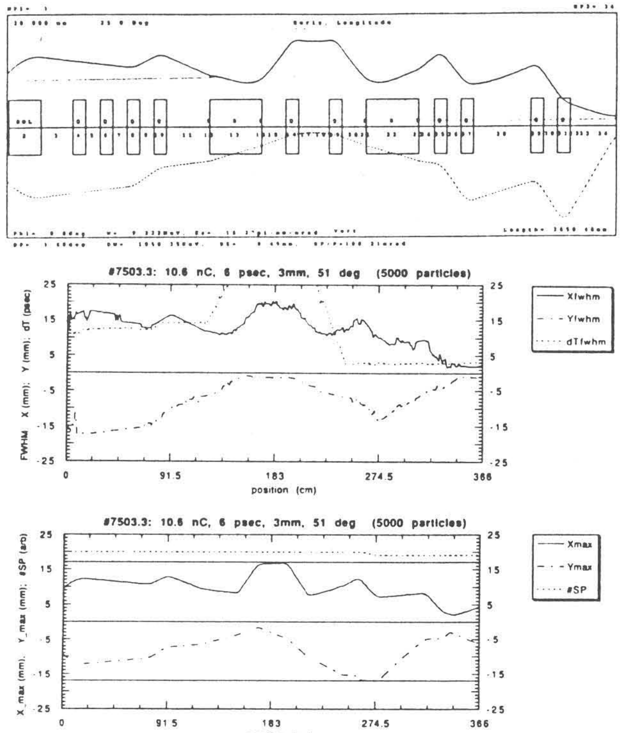

Fig. 4 Beam envelope for 9 MeV e⁻ bunch compression beamline: from TRACE 3-D (top) and TOPKARK (middle and bottom).

As in the previous example, this beamline is not space charge dominated in the usual sense; the quadrupoles need only be changed by ~10% in going from full current to zero current. However, Fig. 5 shows that different space charge models yield very different final distributions. Here, the use of various space charge models provided evidence that our design was robust and could meet system specifications without sensitive dependence on the details of the particle distribution. The PARMELA code, which utilizes a gridded space charge model, was used to verify that the final distribution had a FWHM pulse length of <5 ps. For both TOPKARK and PARMELA, the initial particle distribution was generated directly from the results of a MAGIC simulation of the electron gun.

Conclusions

Modern accelerators for industrial applications frequently require detailed control of the final particle distribution at high current and moderate energy. We have considered two examples which are not "space charge dominated" but for which space charge plays a significant dynamical role. Design of such beamlines requires a code like TOPKARK that combines high-order optics with adequate space charge models.

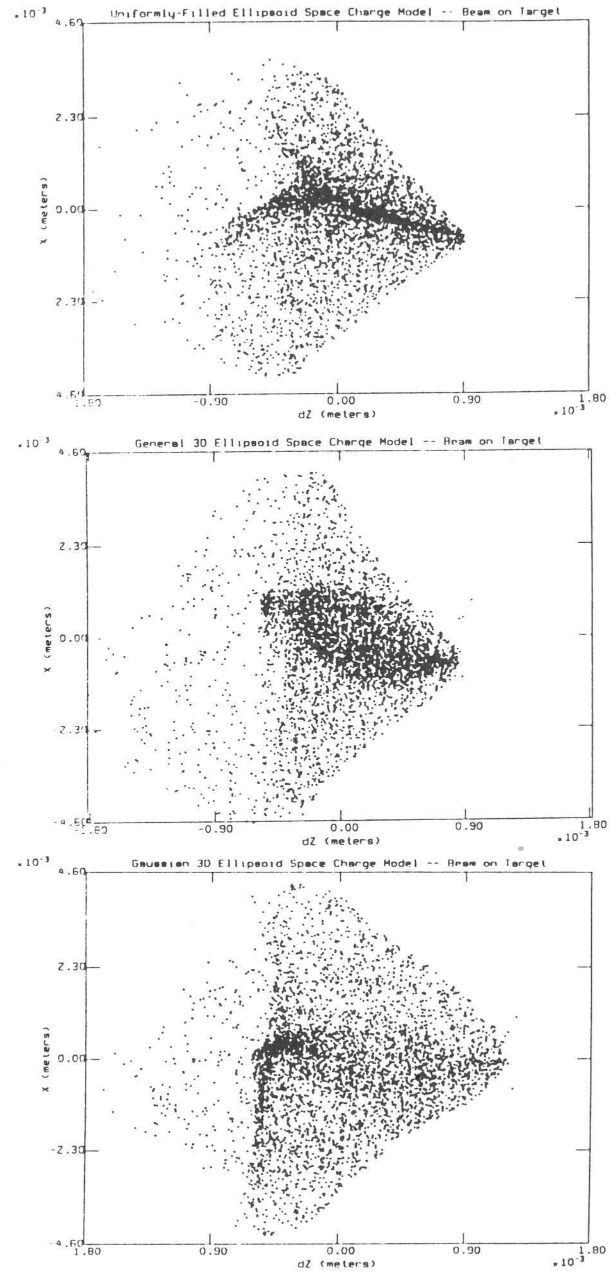

Fig. 5 9 MeV e⁻ beam on target using linear (top), G&W (middle) and Gaussian (bottom) space charge models

References

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