End-to-End Simulation: The Front End*

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Abstract

For the intense beams in heavy ion fusion accelerators, details of the beam distribution as it emerges from the source region can determine the beam behavior well downstream. This occurs because collective space-charge modes excited as the beam is born remain undamped for many focusing periods. Traditional studies of the source region in particle beam systems have emphasized the behavior of averaged beam characteristics, such as total current, rms beam size, or emittance, rather than the details of the full beam distribution function that are necessary to predict the excitation of these modes. Simulations of the beam in the source region and comparisons to experimental measurements at LBNL and the University of Maryland are presented to illustrate some of the complexity in beam characteristics that has been uncovered as increased attention has been devoted to developing a detailed understanding of the source region. Also discussed are methods of using the simulations to infer characteristics of the beam distribution that can be difficult to measure directly.

Introduction

In order to focus sufficient power onto an inertially confined target, it is necessary to accelerate and transport a beam that is highly space-charge dominated. Such a beam supports collective warm-plasma collective modes[1, 2] that can persist for times comparable to the beam lifetimes in a typical fusion driver design. Details of the initial beam distribution, which affect the excitation of these collective modes, can therefore affect the evolution of the beam for the entirety of the accelerator. Successful use of end-to-end simulation as a design tool, or to explain experimental measurement, therefore depends on the ability to adequately specify the initial mode excitation. The excitation of such modes depends, in turn, on internal correlations in the beam distribution function. Two parallel methods are currently being explored for adequately specifying the initial beam distribution. The first, to be discussed here, is to conduct "first-principles" simulation from the emitter surface to predict the distribution as it enters the accelerator. The second method, as discussed by Friedman et al.[3], explores the reconstruction of the distribution from the measured characteristics downstream from the emitter region.

A significant difficulty, shared by both methods, in adequately specifying an initial distribution is lack of knowledge as just how precise a specification is needed. It is similarly difficult to determine adequate precision required of measurements of the beam distribution at any stage of the accelerator system. And it is usually challenging to obtain sufficiently detailed and accurate measurements at the number of diagnostic locations that would be ideal for a complete understanding of the detailed relationship between simulations and actual measurement.

The work discussed here is therefore of an ongoing nature that is being constantly refined as more measurements become available. Two experimental systems are discussed along with recent examples of progress on understanding the source characteristics of each. These are the High

Current Experiment (HCX)[4] sited at the Lawrence Berkeley National Laboratory and the University of Maryland Electron Ring (UMER).[5]

High Current Experiment

In order to avoid the development of a current spike at the beam head, it is necessary for the current rise to be sufficiently fast.[6] Since it is difficult to achieve a sufficiently short rise time from the main pulse, the HCX diode employs a control electrode that is relatively close to the emitter surface. Therefore, only a modest voltage needs to be switched rapidly in order to achieve a rapid current rise at the beam head. In the first generation HCX diode design discussed here, the control electrode causes transverse anhormonic forces that are sufficient to cause distortion in the transverse density profile. The most notable manifestation of this is a very sharp rim of increased density at the beam edge. Simulations were therefore performed to predict the beam profile in addition to expected current from the emitter.

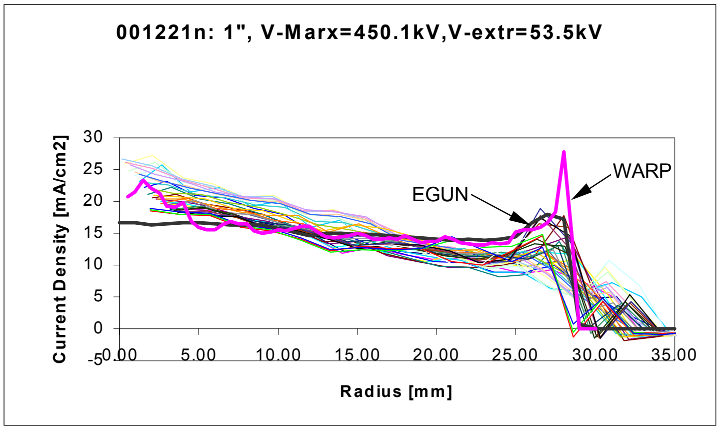


Fig.1. Measured beam profiles of the beam exiting the source region. Profiles at several angles are compared to EGUN and WARP simulations.

Figure 1 is an example of the successful use of simulation to reproduce experimental measurement. The experimental curves were obtained by an array of current probes to measure the current across the beam, which was rotated to obtain a set of curves as a function of angle. The curves were then corrected for the error introduced by the offset of center of the beam from the center of the measurement array. Also plotted on the same axes are the curves generated by the EGUN and WARP codes. It should be noted that the measured current was constrained to agree within a few percent to the simulated value by adjusting the nominal applied voltage. This same adjustment was shared by both the EGUN and WARP simulations. Note that WARP curve predicts a sharper peak at the beam rim than both the measured data and the EGUN curve. This is likely a result of reduced resolution in the measurements, which have an approximately 1mm aperture, and the relatively small number of rays used in the EGUN calculations. It should be noted that Kapton witness plate data somewhat further downstream from the diode exit plane, even though it is integrated over the entire pulse and many shots, does exhibit a rim whose sharpness is similar to what is observed in the WARP curve.

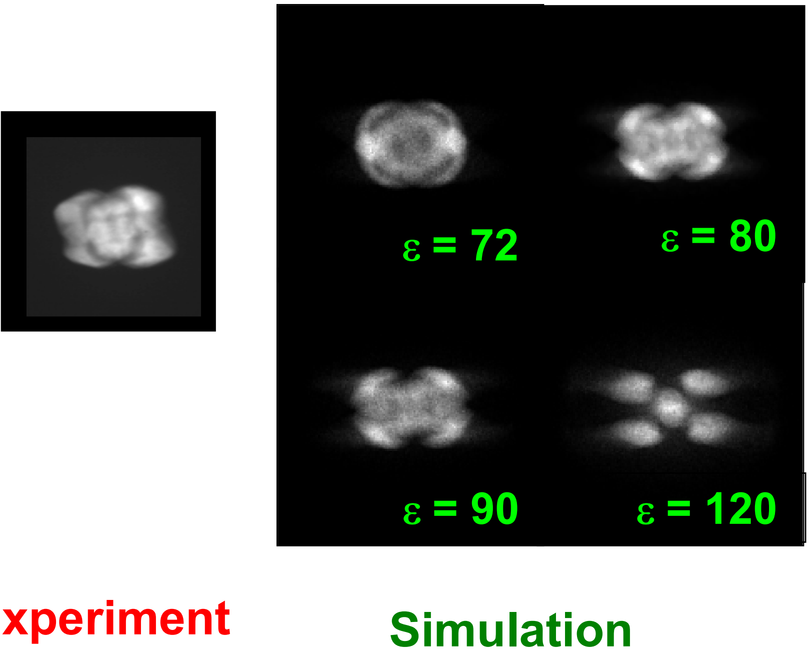
An additional feature of the WARP simulation, which is fully time dependent, is that there are observed oscillations in the peak in density toward the beam center. The curve shown was integrated over a period of approximately 1 μs, to match the time resolution of the measured data. Which is a much longer period than the period of these oscillations.

The degree of agreement seen here was not universally obtained. For example, when the measurement plane was moved 10 cm downstream, the measured beam radius assuming the same adjustment to the nominal voltage, does not increase as would be predicted by the expected space charge spreading. This is thought result from electrons generated in the field-free region that which stream into the beam. Also noteworthy is that a second-generation diode geometry designed to have better control of the beam current, as well as reduced beam nonuniformity, has not exhibited the same agreement reported above. This is currently under active investigation.

The UMER Experiment

The gun in the UMER experiment is in many ways different from the HCX structure. Nevertheless many of the issues associated with predicting its behavior are shared with the HCX gun. In the UMER case, an electrode to control the time evolution of the beam pulse was also required. But since UMER is a scaled electron experiment, control of the beam current is effected by the use of a grid close to the cathode. This gridded-gun configuration avoids the gun aberrations associated with a complex control electrode geometry such as is employed in the HCX gun structure, but it comes at the cost of possible emittance growth from the beam interacting with the grid. Also, since a Pierce gun geometry is generally optimum only for a specific current, variation of the current away from the nominal as the grid voltage is varied also changes the current density variation across the beam cross section. This is further complicated because the gun perveance can be varied by mechanically varying the anode-cathode distance.

Simulations of the full gun structure, which include the grid, are quite difficult because of the disparate scales involved. For example, the grid spacing is approximately 0.15 mm, while the grid to anode spacing is approximately 25 mm. Simulations were therefore performed to investigate the sensitivity of the output beam characteristics to variations in the current injected at the plane of the grid, but neglecting the detailed microstructure which results from the interaction of the beam with the cathode grid.[7] Separate simulations of the beam behavior in the cathode to cathode-grid region are currently underway in order to provide a model for the beam distribution function emitted from that region. Measurements of the gun characteristics are also underway to determine an appropriate operating point for UMER operation.



Experiment

Simulation

Fig.2. Comparison of downstream phosphor screen measurement to simulations that assume a range of initial emittances.

A particular experiment in this connection was the insertion of a five-beamlet mask in a quincunx pattern was used as a measure of the beam emittance. From previous phosphor screen measurements of the evolution of such a configuration[8] it was observed that details of the pattern evolution were a relatively sensitive function of the initial beam emittance. This was used as a method for measuring the beam emittance, as shown for a particular plane, in Fig. 2. It should be noted that the implied 4×rms beam emittance of 80 μm implied by this measurement is more than 4 times the emittance calculated from the product of the cathode temperature and the beam radius.

This is taken as indication that the combination of the disturbance to the beam distribution by the cathode grid and the aberrations in the gun structure can significantly increase the beam emittance.

Conclusions

Some preliminary simulations and comparison to experiment have been presented to illustrate progress in understanding the level of detail necessary to adequately characterize the beam distribution injected into the transport system of experiments currently underway. Because the aim of this work is to develop the capability to predict the evolution of a space-charge-dominated beam over long transport distances, this work is ongoing. Refinements will require measurement of beam characteristics over longer propagation distances than have been performed to date. Refinements will also be possible from the incorporation of techniques currently under development[3] to use experimental measurement for the construction of a full distribution function consistent with those measurements.

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