STRAY-ELECTRON ACCUMULATION AND EFFECTS IN HIF ACCELERATORS

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Abstract

Stray electrons can be introduced in positive-charge accelerators for heavy ion fusion (or other applications) as a result of ionization of ambient gas or gas released from walls due to halo-ion impact, or as a result of secondary-electron emission. Electron accumulation is impacted by the ion beam potential, accelerating fields, multipole magnetic fields used for beam focus, and the pulse duration. We highlight the distinguishing features of heavy-ion accelerators as they relate to stray-electron issues, and present first results from a sequence of simulations to characterize the electron cloud that follows from realistic ion distributions. Also, we present ion simulations with prescribed random electron distributions, undertaken to begin to quantify the effects of electrons on ion beam quality.

INTRODUCTION

Stray electrons are becoming increasingly recognized as a serious concern for heavy-ion fusion (HIF) accelerators. Electron clouds have already been recognized as a serious issue for accelerator applications such as high-energy physics [1]. In addition to common concerns and physics issues, there are a number of aspects of HIF accelerators that distinguish stray-electron cloud accumulation, dynamics, and effects from those in accelerators for other applications. In this paper we survey the differentiating aspects, report on progress in developing a computational capability to predict electron cloud accumulation and effects, and present calculations illustrating the effect of prescribed electron cloud distributions on ion beam quality. We restrict attention here to magnetic quadrupole-based focusing systems in induction linacs. Electrostatic quadrupoles have a natural electron sweeping mechanism; solenoidal-magnetic-field-based systems have a different set of issues.

DISTINGUISHING ASPECTS OF ELECTRON ISSUES IN HIF ACCELERATORS

The relevant distinguishing features of (magnetic quadrupole-based) HIF accelerators are linear geometry with a high line-charge density, a long injected pulse (multi-μs in a driver), a relatively low energy (~ 1 MeV – a few GeV), an economic mandate to fill as large a fraction of the beamline cross section as possible, and a relatively large fraction of the accelerator length occupied by the quadrupole focusing magnets (can be > 50% at the injector end of the accelerator). Also conditioning of the beam pipe in such accelerators is difficult; hence the emission coefficients for neutral gas upon ion bombardment are large (> 10^3 per incident ion; see *e.g.* Ref. [2]). Finally, there is beam pipe only inside the quadrupole magnets.

For these reasons, the predominant source of stray electrons in the injector end of a HIF driver is expected to be ionization of neutrals released when halo ions strike the close-fitting beam pipe inside the quadrupoles. These electrons are born deeply trapped radially by the beam's electrostatic potential, and constrained to slow $\mathbf{E}\times\mathbf{B}$ and magnetic axial drift motions by the quadrupole magnetic fields until they reach a gap. In accelerating gaps they can acquire sufficient energy to escape the beam potential and will tend to do so in the fringe field of the next quadrupole; hence their lifetime is of order of the time to drift the length of a quadrupole, and their density is highest in the quadrupoles.

In the high-energy end of a driver, or in short-pulse ($\lesssim$ 1 μs) experiments, where neutrals from walls cannot penetrate far into the beam, ion-produced secondary electrons can dominate. Nonadiabatic effects (collisionless pitch-angle scattering) [3] can cause secondary electrons that pass near the beam center to be magnetically trapped and so live longer than their nominal single-transverse-transit lifetime during beam flattop.

TOWARD A MODEL OF ELECTRON CLOUD DISTRIBUTION

We are assembling a set of computational tools to enable prediction of an electron cloud distribution in the WARP particle-in-cell code. The key ingredients are: wall electron and neutral-particle source modules, which take as input the distribution of halo ions striking walls; a neutral-transport module, to follow neutral particles emitted from surfaces into the beam interior; a bulk electron source module, which provide an electron birth distribution given the volumetric neutral gas and beam densities; and modules that describe at various levels of approximation (full orbit, gyro-averaged, bounce averaged) the subsequent electron dynamics. The ultimate goal is to have a self-consistent description of the

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electron cloud, its dynamics, and its impact back on the beam-ion distribution.

We presently have operational a subset of these tools, specifically a wall electron source module [4] and a full-orbit electron dynamics calculation. A sample result is shown in Fig. 1, applicable to a (hypothetical) transport experiment that would consist of 100 quadrupoles of the type now in the High-Current Experiment (HCX) [5]. In this simulation, a wall ion beam distribution from a WARP simulation is input to the electron source module, which then provides information about the local emission of secondary electrons [4]. The full orbits of the emitted electrons are then followed (until lost or to a maximum of 4000 time steps). Fig. 1 is a contour plot of the resulting electron distribution, projected into a plane transverse to the beam propagation. Almost all of the incident ions impinged on the wall in a location where magnetic field lines are confined close to the pipe wall, as one would expect based on simple beam envelope considerations. Hence almost all of the electrons are concentrated there as well. The contours that extend into the interior are produced by electrons that drift into the magnetic-field-free gap before being lost. This calculation underscores the importance of folding into the secondary-electron production calculation the effects of ion scattering at the surface; such scattering can lead to an enhanced ion flux on the walls closer to the quadrupole principal axes (*i.e.,* the straight field lines that pass through the middle), and was not included in the results shown.

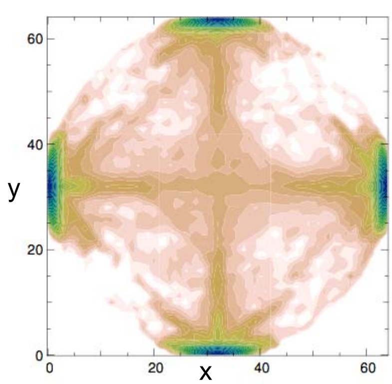

Fig. 1. Contour plot of accumulated electron density (logarithmically spaced contours span a factor of 10^4).

EFFECT OF SPECIFIED ELECTRON DISTRIBUTIONS ON BEAM QUALITY

To begin to assess the effect of electrons on the beam-ion distribution, we have run a series of WARP ion simulations (in a mode which follows a slice of a beam through a set of magnets) with specified negative charge distributions to mock up the electron cloud. Such simulations of course cannot address ion phenomena associated with mutually consistent electron and ion dynamics, such as electron-driven ion instabilities. But it provides an indication of the level of electron contamination required to produce significant levels of halo, emittance growth, etc., via uncompensated reduction of the beam space charge.

We consider three types of electron distributions: spatially uniform, random variations in density, and random displacements of the electron cloud centroid. For all cases we consider the electron density distribution to be uniform within the nominal ion beam envelope inside a quadrupole (but possibly displaced transversely). This is in recognition that the electrons live for of the order of the time to drift through a quadrupole in an accelerator, and that they random-walk with a step size of a quadrupole half-lattice period in a (focused) drift section. For the cases with displacements of beam centroid, the displacements are taken to be along one or the other of the lines 45° from the quadrupole principal axes, a restriction consistent with electron bounce motion. In all cases the ions are followed through 100 lattice periods (200 quadrupoles).

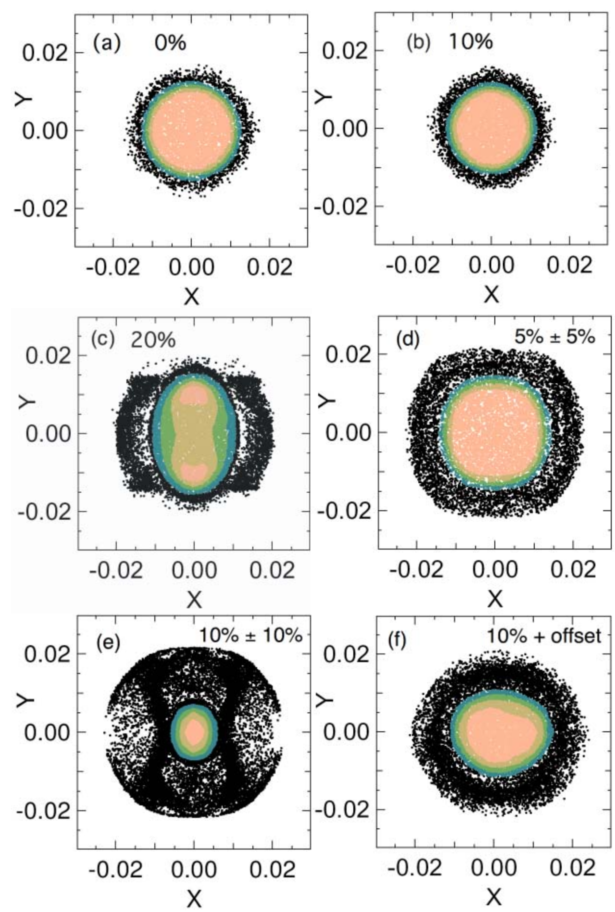

Fig. 2. x-y ion scatter plots for (a) no electrons; (b-c) constant density; (d-e) randomly modulated density; (e-f) random displacements. Percentages are mean electron density relative to peak beam density.

Shown in Fig. 2 are transverse-position ion scatter plots at the end of the run for following distributions of electron density n_e: no electrons; uniform 10% and 20% relative (to ions) density, random quad-to-quad n_e variations with mean densities 5% and 10% of the ion density (with 100% maximum modulation in both cases), and 10%

mean with random radial displacements (uniformly distributed out to a displacement equal to a beam radius).

Not shown are cases with random amplitude variations about a 2% mean and radial displacements of a 20% electron cloud; the former shows only small departures from the case with no electrons; the latter is similar to fig. 2e.. Also not shown is a 100% amplitude-modulated 10% density case, but with the mean subtracted out (that is, "electron" densities vary from –10% to +10%); the results are qualitatively indistinguishable from the case with the mean present. From these figures we conclude that, over the length considered, a uniform electron cloud has little effect through at least 10% relative density, while at 20% relative density significant beam degradation occurs. But the effects are stronger for random offsets, and stronger yet for random amplitude variations; in particular, with the random variations, significant spreading is observed with lower fractional electron densities.

We can also analyze the evolution of various statistical quantities as the beam propagates. For all cases with finite n_e, the beam emittance grows approximately linearly (or a bit faster) until the envelope becomes large enough that significant scrape-off on the pipe (r = 2.3 cm) occurs, and, for the highest-n_e cases, subsequently grows dramatically. During the same time interval, the beam envelope grows roughly linearly for the random amplitude and offset cases, and faster than linear for constant n_e. The beam current is nearly constant during this period (but decreases significantly after). As examples, we show the principal-direction emittances and and envelopes (twice the r.m.s. transverse coordinates) as functions of axial position for the 5% and 10% density-with-amplitude-modulation cases. These results illustrate that the change in statistical quantities varies more rapidly than the electron density; we will characterize this trend more quantitatively in the future.

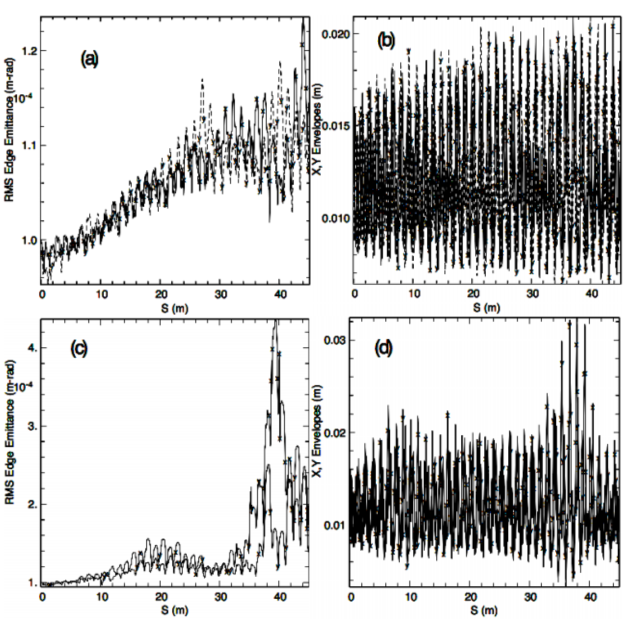

Fig. 3. x-y emittances (a,c) and envelopes (b,d) for randomly modulated density about 5% (a,b) and 10% (c,d) relative electron density

DISCUSSION

We have reported on first steps in a program to develop a self-consistent picture of electron clouds and their effects on ions in HIF accelerators. Our suite of simulation tools will be applicable to a broad range of accelerators, though our focus in this paper is on the unique aspects of the HIF application. The HIF application is distinguished by its geometry (linear), its long pulse length, high current, and high fraction of the radial cross section filled by beam.

The results on the electron clouds produced from secondary electrons associated with ion scrape-off show expected behavior: ions are scraped off predominantly in the interior of the quadrupole where the elliptical distortion of the beam envelope is greatest; most ion loss is then at azimuthal positions where field lines are short and nearly tangent to the walls. The results lack, and underscore the need to include, surface ion scattering, which will result in more electrons being released on field lines that penetrate significantly into the beam.

The simulations of frozen negative charge perturbations on ion beam quality provide a useful preview of effects that may be expected in fully self-consistent electron-ion simulations. In particular they indicate that random fluctuations, particularly of the electron density, are considerably more effective than a constant electron density in destroying the ion beam quality. They also indicate that the emittance and envelope grow gradually over the length of the beam until the beam envelope reaches the vicinity of the beam pipe, and that their growth scales faster than linear with the electron density.

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