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Simulation of Transient Effects in the Heavy Ion Fusion Injectors *

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Abstract

We have used the 2-D PIC code, GYMNOS[1], to study the transient behaviors in the Heavy Ion Fusion (HIF) injectors. GYMNOS simulations accurately provide the steady state Child-Langmuir current and the beam transient behavior within a planar diode. The simulations of the LBL HIF ESAC injector experiments[2] agree well with the experimental data and EGUN[3] steady state results. Simulations of the nominal HIF injectors have revealed the need to design the accelerating electrodes carefully to control the ion beam current, particularly the ion loss at the end of the bunch as the extraction voltage is reduced.

I. INTRODUCTION

The transient effects in an injector can be caused by the time-varying emission of the ion source due to the time varying gap voltage pulses, the time-varying space charge redistribution within the beam pulse (or space charge debunching), secondary electron current arising from beam spilling and the beam loading effects[4,5]. These transient behaviors of a ion beam may lead to undesirable head-to-tail variations in beam energy and current, and even current loss. The transient problem is one of main concerns in an injector for the proposed Induction Linac Systems Experiments (ILSE)[6] where the ion pulse length is comparable to the injector length. Two options are considered for the ILSE injector[7]: one uses a set of axisymmetric electrodes arranged in an electrostatic accelerating Pierce column (ESAC), and the other uses an axisymmetric front end, such as a small ESAC pre-injector, followed by a sequence of electrostatic accelerating quads (ESQ). We have used the 2-D code, GYMNOS, to study beam emittance and the ion transient effects in several of the ILSE injector variants that have been proposed and tested during the design phase and have found excellent agreement in most cases in which comparison was possible.

We have found that the beam transients can be controlled easily by adding a low time-varying voltage "current valve" wire mesh[8,9] located closely to the the anode while fixing all other downstream electrodes at their steady-state values. However, to use the current valve transient control with a spherical anode would require fragile, curved current valve meshes in a very hostile environment. We have also found that careful design of the accelerating electrodes is needed to control the ion beam current, particularly the ion loss at the end of the bunches as the extraction voltage is reduced.

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II. TESTS OF EMISSION ALGORITHM

In this section, we show the simulation results of an 1-D potassium (A=39) diode with a gap distance of 1.6 cm and a voltage of -6.56 kV that verify that GYMNOS simulations can provide the accurate beam transients and current. The GYMNOS calculated steady state current is 0.057 mA, within PIC noise, as predicted by the Child-Langmuir law for the cases of varied number of mesh points (8-240) in the A-K gap and a relatively small time step (0.5 ns) in the simulations[10].

Since one of the purposes of doing the time-dependent simulations is to study the effect of transients, we show in Figs. 1a and 1b the simulation results of the same 1-D potassium diode using the A-K voltage waveform given by

$$\phi(t) = \left[\frac{4}{3}\frac{t}{t_{\rm rise}} - \frac{1}{3}\left(\frac{t}{t_{\rm rise}}\right)^4\right]\phi_0, \qquad t \le t_{\rm rise} \quad ,$$
$$\phi(t) = \phi_0, \qquad t > t_{\rm rise} \quad , \qquad (1)$$

where $t_{\rm rise}$ is the rise time of the voltage pulse. Only 8 mesh points in the A-K gap were used in the simulations. For the case in Fig. 1a, we used the Lampel-Tiefenback voltage waveform[11] with the rise time equal to the ion transit time for crossing the A-K gap, $t_{\rm trans}$, We obtained the predicted constant current profile for the front end and the flat-top of the beam pulse. When $t_{\rm rise} < t_{\rm trans}$, we expect the same asymptotic Child-Langmuir current at the flat-top portion of the beam pulse led by a higher current during the rise time (shown in Fig. 1b). In the case $t_{\rm rise} =$ 150 ns, the current during the rise time is estimated to be roughly 0.08 mA.

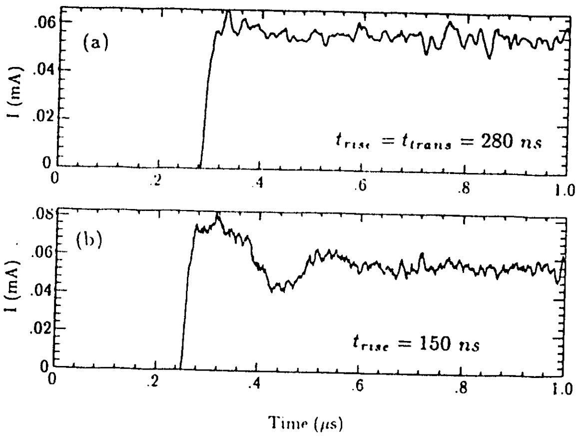

Fig. 1 The current profile calculated by GYMNOS when the A-K gap voltage waveform's rise time is (a) equal to and (b) less than the ion transit time, respectively.

III. LBL HIFAR ESAC INJECTORS

The GYMNOS results for the first prototype ILSE E-SAC injector are presented in Ref. [2]. The simulation results of the ILSE ESAC injector scaled experiment[2] with and without a current valve located closely to the anode are shown in Figs. 2a and 2b in this section. Tables I and II show that GYMNOS calculations of current, normalized emittance, beam envelope radius, and beam divergence agree very well with the experimental measurements, and EGUN's results[2] for both cases. The range of EGUN calculated emittance given in the Tables were obtained by using different initial transverse beam velocity distribution functions at the current valve location to characterize the initial transverse temperature and the emittance in the EGUN calculations. When a current valve mesh was used to control the beam pulse, the beam radius is comparable to the electrodes' aperture size as shown in Fig. 2a. Hence, the beam experiences a large nonlinear external field and its normalized beam emittance grows from its intrinsic value of 0.05 mm-mr at the source to 0.25 mm-mr at the emittance diagnostics location.

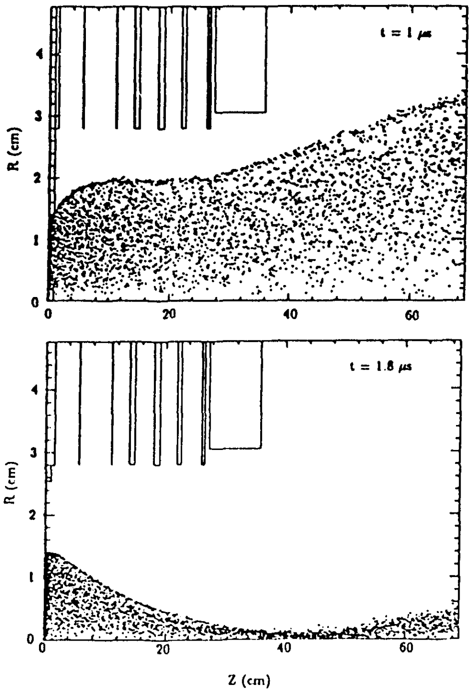

Fig. 2 The ESAC injector (a) with and (b) without a current valve

When the current valve was removed, the voltage on the emitting anode and the first electrode (at z=1.2 cm in Fig. 2b) were the same. This voltage arrangement results in curved equipotential surfaces near the anode so that the beam is pinched by a very strong radial focusing force near the ion emitting surface and the first electrode, and focused roughly to a 1mm radius spot size at the injector exit. The space-charge limited current is then reduced. Since the beam radius is much smaller than the electrodes' aperture size, the external field seen by the beam is linear. There is no normalized emittance growth in this case. We did not use enough resolution to simulate the small beam size (1mm) and beam divergence properly. Nevertheless, we have obtained very good agreement in the values of current and normalized emittance with experiments and EGUN calculations as given in Table II.

Table I The ESAC injector with a current valve

	GYMNOS	EXP	EGUN
Current (mA)	82	80	80
Normalized emittance (mm-mr)	.26	.25	0.07-0.2
Beam radius (mm)	32.5	31.2	31.0
Beam divergence (mr)	34.5	38.4	36.0

Table II The ESAC injector without a current valve

	GYMNOS	EXP	EGUN
Current (mA)	20	>24	19
Normalized emittance (mm-mr)	.06	.04	0.05
Beam radius (mm)	5.0	1.2	0.9
Beam divergence (mr)	19	6	8

IV. ILSE INJECTORS

GYMNOS simulation results of the ILSE ESAC injector with a wire mesh located closely to the anode show that the transient effects in this injector configuration is small (as given in Fig. 3 and Fig. 4). The injector voltage pulse used in all the ILSE injector simulations has a 300 ns rise time and a 300 ns fall time with a 1 μs long flat-top. An early version of the ILSE ESQ pre-injector has a simple diode configuration without any current extraction control

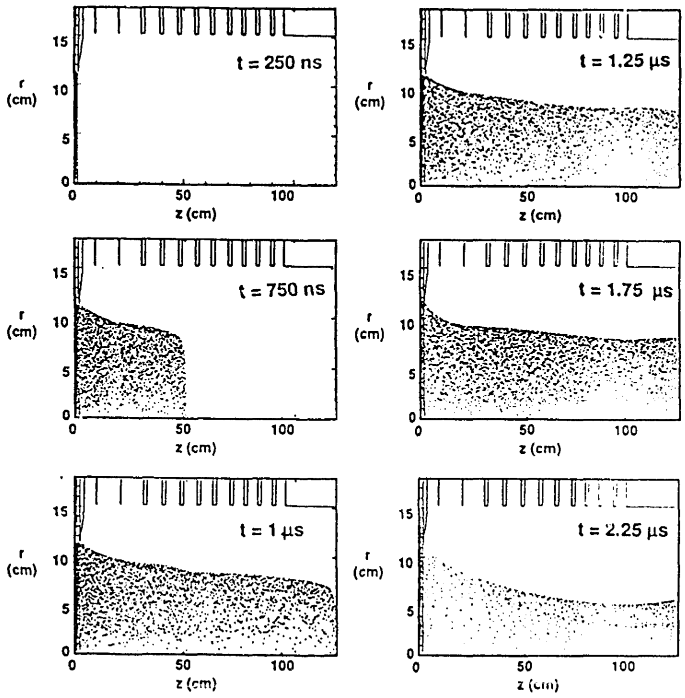

Fig 3 GYMNOS simulation of the ILSE ESAC injector

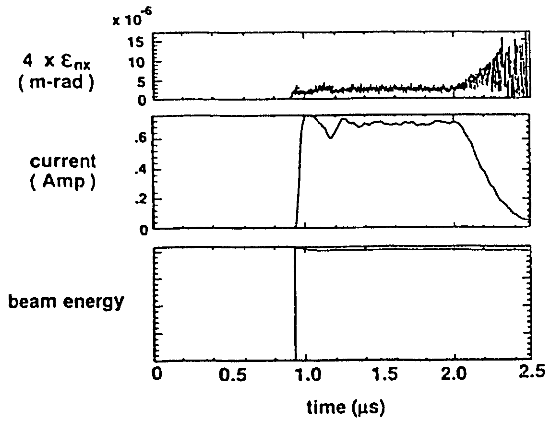

Fig.4 GYMNOS calculated normalized emittance, current and beam energy at the ILSE ESAC injector exit

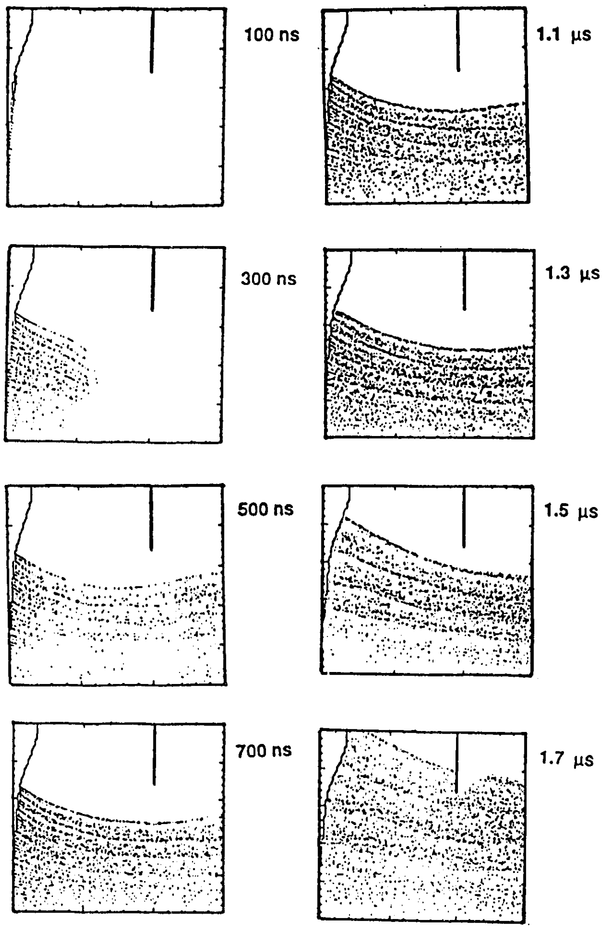

Fig. 5 GYMNOS simulation of an ILSE ESQ pre-injector

electrode. The simulation of this ILSE pre-injector indicates a large ion loss at the end of the current pulse as the time-varying injector voltage is turned off (see Fig. 5). Comparing the simulation results of these two injector configurations, we found that transients in an ILSE injector can be controlled easily by using a time-varying low voltage wire mesh, "current valve", located closely to the anode while fixing all other downstream electrodes at their steady-state values. The current valve divides the injector into two parts. In the region between the anode and the current valve, the transient behaviors are controlled by the current valve's voltage waveform. From the current valve to the injector exit, the transient behaviors caused by the time varying current valve voltage are negligible if the current valve voltage is much smaller than the full injector voltage. While this vavle is a good current controller in a planar configuration, a spherical anode would require fragile, curved current valve meshes in a very hostile environment. We are now investigating the new injector configuration[12] needed to control transients without using the current valve.

V. ACKNOWLEDGMENT

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