SIMULATION OF TRANSIENT EFFECTS IN THE HEAVY ION FUSION INJECTORS

Yu-Jiuan Chen and Dennis W. Hewett
Lawrence Livermore National Laboratory, Livermore, CA USA

This paper was prepared for submittal to the
1993 Particle Accelerator Conference
Accelerator Science and Technology Proceedings
Washington, DC USA
May 17-20, 1993

May 12, 1993

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Simulation of Transient Effects in the Heavy Ion Fusion Injectors *
Yu-Jiuan Chen and Dennis W. Hewett
Lawrence Livermore National Laboratory
University of California
Livermore, California 94550

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 tran-
sient 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 dep-
bunching), 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 cur-
rent 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 com-
parable 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 se-
quence 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
case in which comparison was possible.

We have found that the beam transients can be con-
trolled easily by adding a low time-varying voltage “current
valve” wire mesh[8,9] located closely to the anode while
fixing all other downstream electrodes at their steady-state
values. However, to use current valve transient control
with a spherical anode would require fragile, curved cur-
rent 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.

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

\[
\phi(t) = \begin{cases}
\frac{4}{3} \left( \frac{t}{t_{\text{rise}}} - \frac{1}{3} \left( \frac{t}{t_{\text{rise}}} \right)^4 \right) \phi_0, & t \leq t_{\text{rise}} \\
\phi_0, & t > t_{\text{rise}}
\end{cases}
\]

where \( t_{\text{rise}} \) 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, \( t_{\text{trans}} \). We obtained
the predicted constant current profile for the front end and
the flat-top of the beam pulse. When \( t_{\text{rise}} < t_{\text{trans}} \), 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 \( t_{\text{rise}} =
150 \text{ ns} \), 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.](image-url)

* Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48.
III. LBL HIFAR ESAC INJECTORS

The GYMNOS results for the first prototype ILSE ESAC 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](image)

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>
<thead>
<tr>
<th>Current (mA)</th>
<th>GYMNOs EXP EGUN</th>
</tr>
</thead>
<tbody>
<tr>
<td>82</td>
<td>80 80 80</td>
</tr>
<tr>
<td>Normalized emittance (mm-mr)</td>
<td>0.25 0.07-0.2</td>
</tr>
<tr>
<td>Beam radius (mm)</td>
<td>31.2 31.0</td>
</tr>
<tr>
<td>Beam divergence (mr)</td>
<td>38.4 36.0</td>
</tr>
</tbody>
</table>

Table II The ESAC injector without a current valve

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>GYMNOs EXP EGUN</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>&gt;24 19</td>
</tr>
<tr>
<td>Normalized emittance (mm-mr)</td>
<td>0.04 0.05</td>
</tr>
<tr>
<td>Beam radius (mm)</td>
<td>1.2 0.9</td>
</tr>
<tr>
<td>Beam divergence (mr)</td>
<td>6 8</td>
</tr>
</tbody>
</table>

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](image)
tor configurations, we found that transients in an ILSE [12] E. Ilensestroza, S. Eylon, H. Rutkowski, and S.S. Yu for their useful discussions during the course of this study.

V. ACKNOWLEDGMENT

The authors would like to thank J.J. Barnard, E. Henestroza, S. Eylon, H. Rutkowski, and S.S. Yu for their useful discussions during the course of this study.

VI. REFERENCES

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