A THEORETICAL AND EXPERIMENTAL STUDY ON THE LONGITUDINAL SPACE-CHARGE EFFECTS IN PROTON LINACS

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The space-charge effect in proton linacs is experimentally studied by an electron model. Electrons are accelerated in the first 24 cells of the model cavity which has half-size dimensions of the designed proton linac. The output energy is 1.6-keV which corresponds to 2.8-MeV for protons. The output currents as a function of input currents are measured without changing the other accelerating conditions. A maximum current of 160 μA which is equivalent to a proton current of 300 mA in the space-charge effect is obtained. The output currents show a saturation around this value. These results are explained in terms of the longitudinal space-charge effect. The theoretical study of this effect shows that the space-charge limited currents will be determined at the low energy end but the effect of acceleration will considerably increase the currents. The experimental results are compared with the computations taking into account the acceleration effect.

I. Introduction

So far several authors have attempted to solve the longitudinal space-charge effect in proton linacs by analytical methods, which are divided into two different types. One is the application of the method introduced by Nielsen and Sessler for a cyclic machine to linacs.[1,2,3] In this method the charge density in a longitudinal phase space is assumed to be uniform within the phase stable boundary. In the other method a beam bunch is assumed to be a uniformly charged ellipsoid (or cylinder)[4,5]. The space-charge limited currents given by these methods are determined at the low energy end of a linac tank where the smallest longitudinal spread corresponds to a given constant phase spread. These analytical methods give too small space-charge limited currents on account of neglecting the accelerating effect.

From computational approaches,[5,6] it has pointed out that the accelerating effect considerably increases the limited current. It was found that the agreement between the analytical and computational results is obtained if the limited current is analytically calculated for the position at which the velocity of protons is 2 ~2.5 times larger than at the low-energy end.

This can be explained by a prediction that the primary effect of a parameter change takes place during the first phase oscillations, and that one can make an estimate of the increased acceptance by using the static results for a velocity corresponding to approximately one phase oscillation after injection.[5,7]

In the computational or analytical methods, a few assumptions are introduced to simplify the calculations. Therefore, it is necessary to investigate this problem experimentally.

II. Experimental Method

Electrons are accelerated in the half -size model cavity which has the first 24 unit-cells of the linac designed for Japanese proton synchrotron project.[8] It corresponds the proton energy region from 0.75-MeV to 2.8-MeV. Problems of proton dynamics in actual linac may be simulated by electrons in this model cavity, if the electron energies are decreased by a factor of mass ratio (m_e/m_p=1/1836) compared with the design values for protons. The space-charge effect in proton linacs may be realized at a current of electrons lowered by the same factor.

To get necessary quadrupole fields for beam focusing, wires are wound around the drift tubes which are made of aluminum. The field arrangement is taken as an FDFD system. The 400 MHz RF power is fed into the cavity to accelerate electrons. Electrons from an electron gun are injected directly into the cavity without a buncher. The injected currents are easily varied by changing the currents heating the gun cathode. The accelerated electrons are collected by a Faraday cup which has an auxiliary magnet to suppress secondary electrons.

III. Results and Discussion

The experimental output current as a function of input current is shown in Fig. 1. The computational results for the relation between input current and output current are also shown in Fig. 1 by dashed lines. In the computational calculation the phase spread of the initial cylindrical beam was taken to be from -79° to 31° and the energies of injected particles were taken to be constant over this phase spread. For a beam current of a few hundred mA, the space-charge forces deteriorate so strongly the phase motion that the output current does not change for the beam having an energy spread of a few tens keV at the injection. When we compare between the computational and experimental results, we assume that the particles injected outside the initial phase spread used in the computations have no influence on the output beam currents.

The observed output beam diameter in this experiment was about 4mm (8mm corresponding to the calculation for an actual linacs). The agreement between experiment and computation is satisfactory for the relation between input current and output current.

The energy spread of the output beam at the maximum current was about 6 per cent (in FWHM). This large value may have been caused by experimental errors in RF field strength at each accelerating gap. The energy spreads, however, will be determined by a complicate phase oscillations before a stationary charge distribution is attained.

For obtaining the maximum beam current, the field gradient corresponding for actual proton linacs was set to be 12 kG/cm at entrance. Approximate transverse acceptances as a function of quadrupole field gradient are calculated for various beam currents. In this calculation, the linearlized space-charge force is assumed, so that the emittance growth is neglected. The results are shown in Fig. 2. We see from Fig. 2 that for a higher focusing field condition only a slight reduction of acceptance will occur due to the transverse space-charge effect even for a beam current as large as 300 mA. From these considerations, we conclude that the observed saturation of the output current around 300 mA was caused by the longitudinal space-charge effect.

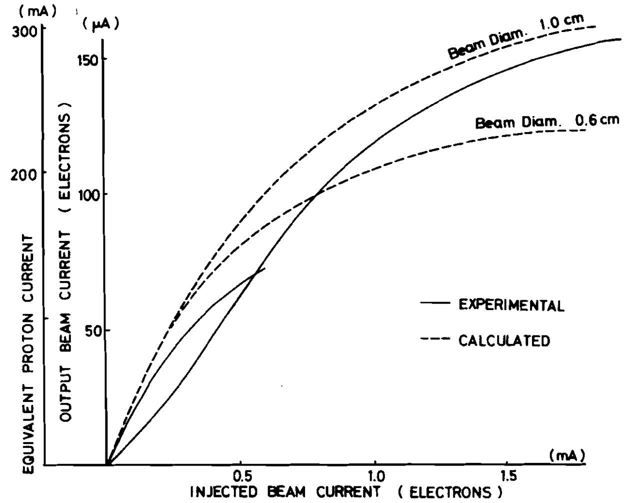

Fig. 1. Output beam currents as a function of injected current. The solid lines show the experimental results. The dashed lines are computational results obtained for fixed transverse beam diameters of 0.6 cm and 1.0 cm in the designed proton linac.

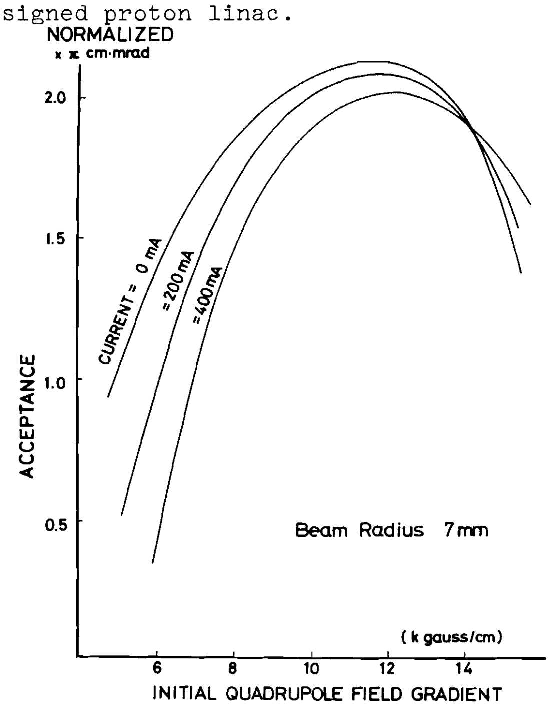

Fig. 2. Calculated transverse acceptances in the designed proton linac as a function of the initial quadrupole field gradients for different beam currents. The calculations were made only for the synchronous particles. The other quadrupole field gradients are decreased inversely proportional to the momenta of the synchronous protons. Lengths of quadrupole magnet are taken as half the cell-lengths. An ellipsoid beam bunch is assumed and transverse semi-axis is taken to be 7 mm.

References

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8. More detailed description of this experiments will be given in the paper to be published in the "Particle Accelerators"