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Parameter Study for the Autoresonant
Acceleration Proof-of-Principle Experiment**

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BEAM PULSE LENGTH AND GUIDE FIELD STRENGTH PARAMETER STUDY FOR THE AUTORESONANT ACCELERATION PROOF-OF-PRINCIPLE EXPERIMENT

by

Brendan B. Godfrey and Rickey J. Faehl

ABSTRACT

Generator and diode problems have reduced electron beam parameters for the proof-of-principle autoresonant collective ion acceleration experiment from 3 MeV, 30 kA, and 200 ns to 2.25 MeV, 15 kA, and 100 ns. This reduction limits acceleration of hydrogen ions to about 4 MeV, if present experimental plans are followed. The output ion energy can be increased to a more acceptable level by reducing the electron beam radius at the diode and by accelerating ions in a weaker guide magnetic field. Analysis further suggests that preacceleration of ions is necessary for efficient trapping in the slow cyclotron waves. The maximum ion current is of order 15 A.

I. INTRODUCTION

Hardware problems continue to plague the Austin Research Associates, Inc. (ARA) autoresonant collective ion acceleration proof-of-principle experiment. It now appears that the useful electron beam pulse for the experiment will be 100 ns long (flat top portion) at a current of 15 kA and an energy of 2.25 MeV.¹ This represents a substantial reduction from originally projected values of 200 ns, 30 kA, and 3 MeV.² In a recent report we analyzed the effects of the reduction in beam current and energy, finding that acceleration lengths were increased by a factor of approximately 2.5.³ However, no account was taken of the change in pulse length. We were unaware of the change at that time.

Pulse length is, however, very important. We find here that the new electron beam parameters limit hydrogen ion energy to 4 MeV, if the original experimental plans are otherwise followed. Operating at weaker guide-field strengths increases ion energy to 7 MeV. As noted in Ref. 3, decreasing the beam radius further increases maximum ion energy. Since 4 MeV obviously is unacceptable even for a proof-of-principle experiment, redesign of the experiment is called for.

This report also addresses ion loading in the slow cyclotron waves. For any reasonable combination of initial wave phase velocity and well depth, trapping of stationary ions does not appear possible. Some sort of ion injector or preacceleration mechanism is required to bring the initial ion velocity up to that of the cyclotron waves. The corresponding ion energy is of order 1.25 MeV according to current plans.

Initial loading of the cyclotron waves with ions places limits on the ion currents. For the present electron beam parameters, maximum ion current is of order 15 A. This estimate is very crude.

Section II discusses the effects on ion acceleration of electron beam pulse length, providing numerical data for a number of specific cases. Both aspects of the ion-loading process, the need for preacceleration and the ion current limit, are treated in Sec. III. Section IV summarizes our findings.

II. ION ACCELERATION

We consider first ion acceleration by an electron beam with original experimental design parameters, 30 kA, 3 MeV, and 200 ns. An ion energy of 30 MeV is desired. As before, the variation of wave properties and the corresponding increase in ion energy are determined from conservation of wave energy flux and from the ion equations of motion. The principle point of our computations here is to establish the time required for ion acceleration. The elapsed time is related to quantities already known simply by

$$t = \int dz/v \quad . \quad (1)$$

Figure 1 shows the variation with time of the wave phase and group velocities, the axial electric field as felt by a moving ion, the relative modulation locally of the beam radius, the ion energy, the wave potential well depth, and the ion position. Potential well depth and ion energy are in MeV, the electric

field in MV/cm, the axial distance in cm, and the time in ns. In this calculation the axial magnetic field decreases from 25.5 to 1.7 kg. The wave frequency is chosen to be 286 MHz, corresponding to a phase velocity of 0.022 c at maximum magnetic field strength, where ion loading occurs. The amplitude of the cyclotron wave at the entrance to the acceleration region is set to $\delta a = a/2$. Larger values of the beam envelope modulation are impractical.

From Fig. 1 we see that 165 ns is needed to achieve the desired ion energy of 30.0 MeV. The experimental design, in principle, can quite comfortably attain its goal. Incidentally, cutting the pulse length to 100 ns but leaving beam current and voltage unchanged gives an ion energy of 17.4 MeV, below design goals but probably still acceptable. Ion energy scales as

$$U_i \propto (\bar{E}_z \tau)^2, \quad (2)$$

with $\bar{E}_z$ the average axial electric field experienced by an ion. Since the axial electric field decreases slowly with decrease in the magnetic guide fields, $\bar{E}_z$ is about 25% larger for 100 ns of acceleration than for 165 ns of acceleration, partially offsetting the loss in ion energy due to the shorter acceleration time alone.

Figure 2 gives results for currently available electron beam parameters, 15 kA and 2.25 MeV. The wave frequency is increased to 350 MHz in order to keep the wave phase velocity for ion loading unchanged. Otherwise, conditions are the same as for Fig. 1. With a full 200-ns pulse ion energy is 10.1 MeV. This value is nearly a factor of three below plans but is perhaps still tolerable. However, for a 100-ns pulse ion energy drops to 3.9 MeV, which is unacceptable.

Apart from the obvious solution of increasing electron beam current and pulse length, two approaches to improving ion energy suggest themselves. As mentioned in the earlier report, reducing the electron beam radius by a factor of two fully compensates the loss of beam current.³ The improvement results from decreasing the ratio of beam radius to cyclotron wavelength, leading to a much increased potential well depth for a given wave modulation amplitude.^{4,5} Reducing the beam radius with the magnetic field profile held fixed necessitates redesign of the generator diode and of the beam drift tube. Although unappealing, this course of action is feasible experimentally.

A third option is to reduce the maximum axial magnetic field and, thereby, to operate at longer cyclotron wavelengths. This method also decreases the ratio of beam radius to cyclotron wavelength, but is less successful than the preceding approach in that the increase in cyclotron wavelength tends to decrease the electric field for a given well depth, partially offsetting the gain in well depth. Figure 3, computed for a magnetic field ranging between 17.0 and 1.7 kg, is a typical case. For a 200-ns pulse ions reach 14.0 MeV, while for a 100-ns pulse they reach 6.0 MeV. We have also examined the case of a 11.9- to 1.7-kg field profile. Further improvement is insignificant, with ion energy after 100 ns rising to 7.0 MeV. Therefore, adjustment of the guide field profile is by itself inadequate for bringing ion energy back to a reasonable value. Used in conjunction with the first two approaches, however, it seems quite fruitful. Experimental modifications needed are minor, and such related tasks as adiabatic compression actually are simplified.

The various cases analyzed are summarized in Table I. Listed are the electron energy in MeV, the electron current in kA, the wave frequency in MHz, the pulse length in ns, the axial magnetic field traversed in kg, the corresponding acceleration length in cm, the ion energy reached in MeV, and the initial potential well depth in kV. The potential well depth at maximum magnetic field strength is pertinent to ion trapping. It is discussed in Sec. III.

TABLE I

MAXIMUM ION ENERGY, ACCELERATION DISTANCE, AND INITIAL POTENTIAL WELL DEPTH FOR VARIOUS COMBINATIONS OF ELECTRON ENERGY AND CURRENT, PULSE LENGTH, AND MAGNETIC FIELD PROFILE. THE WAVE FREQUENCY IS CHOSEN SO THAT THE INITIAL PHASE VELOCITY IS ROUGHLY 0.023 c.

U (MeV)	I_e (kA)	ω_0 (MHz)	B_0 (kg)	τ (ns)	Z (cm)	U_i (MeV)	ϕ_t (kV)
3.00	30	286	25.5 - 1.9	165	814	30.0	25
3.00	30	286	25.5 - 2.5	100	361	17.4	25
2.25	15	358	25.5 - 3.8	200	509	10.1	4
2.25	15	358	25.5 - 6.7	100	175	3.9	4
2.25	15	239	17.0 - 2.1	200	669	14.0	14
2.25	15	239	17.0 - 3.3	100	215	6.0	14
2.25	15	167	11.9 - 1.7	146	419	10.5	30
2.25	15	167	11.9 - 2.2	100	246	7.0	30

Before closing this section, it is important to note that the times cited are for acceleration only and do not include times for wave growth, ion loading, etc. Wave growth should consume no more than about 5 ns of the flat-top pulse. Ion loading may require 10 to 20 ns, depending on details of the methods used.

III. ION LOADING

The last column of Table I lists for each case considered the cyclotron wave potential well depth available for phase-stable trapping of ions. Option two mentioned in the preceding section for improving ion energy, reducing the electron beam radius by a factor of two, results in an initial potential well depth computed in Ref. 3 to be 72 kV. For a fixed ratio of cyclotron frequency to plasma frequency, the potential well depth scales linearly with beam current. However, at short wavelengths the well depth varies inversely and very rapidly with the cyclotron frequency to plasma frequency ratio. These dependencies are quite evident in Table I.

Experimental plans call for a cyclotron wave phase velocity in the range 0.020 to 0.025 c at the point of ion loading. A hydrogen ion moving at these speeds has an energy of order 250 keV. It is clear, therefore, that stationary ions cannot be picked up by the cyclotron waves under the conditions considered so far. Two remedies are apparent. Either the wave velocity can be reduced or the ions can be preaccelerated before trapping.

Reducing the initial wave phase velocity while keeping the final velocity unchanged requires an increase in the axial variation of the guide magnetic field, because

$$v_i^{\text{final}}/v_i^{\text{init}} \cong B_0^{\text{max}}/B_0^{\text{min}} \quad . \quad (3)$$

Consider now the parameters of the last line in Table I. In order to trap stationary ions in a 30-kV potential well, the initial wave velocity must be reduced by a factor of three, giving for the right side of Eq. (3) the value 16.2. Let us choose $B_0^{\text{min}} = 1.2$ kg, because for smaller fields no equilibrium exists. (In practice, operating so near the Brillouin limit probably is dangerous.) Then, $B_0^{\text{max}} = 19.4$ kg, and ϕ_t is reduced to roughly 11 kV. So, trapping still isn't possible. Similar results are obtained for the other sets of

parameters from Table I. It appears that reduction of initial wave phase velocity is not, in itself, sufficient for effective ion loading.

Preacceleration of ions, on the other hand is effective and should not prove difficult. A 250-kV ion gun is an obvious source of preacceleration. It may even be possible to use the DC fields of the electron beam itself, say by tapering the drift tube in the ion-loading region.⁶

Let us now estimate the maximum ion current which can be accelerated. Suppose that 1/3 of the injected ions are trapped by cyclotron waves and carried off, and 2/3 remain in the ion loading section. If the density of accumulating ions is not to exceed the electron beam density, then

$$I_i < \frac{1}{2} \frac{v_i}{c} \frac{\tau_\ell}{\tau} I_e, \quad (4)$$

where τ_ℓ is the time required for any given cyclotron wave to pass through the ion-loading region and τ is the electron beam pulse length. Assuming $\tau_\ell/\tau \sim 0.1$, we find for present experimental parameters that I_i is limited to about 15 A. If electron-ion or ion-ion two-stream instabilities in the loading section prove serious, then I_i may have to be reduced further. On the other hand, if the residual ions can be swept out of the loading region, Eq. (4) becomes irrelevant.

A second estimate can be obtained by demanding that the average ion density near the beginning of the acceleration region not seriously exceed the density needed for force-neutral equilibrium. This yields

$$I_i < 2 \gamma^{-2} \frac{v_i}{c} I_e, \quad (5)$$

or, again, about 15 A. It is important to remember that these two estimates are quite crude and should be viewed as giving order-of-magnitude values only. Incidentally, if available energy were the only constraint, ion currents as large as several hundred amps could be expected.

IV. CONCLUSIONS

This report first analyzes the effect of reduced pulse length on the auto-resonant acceleration proof-of-principle experiment. We find that present

experimental parameters, line 4 of Table I, yield very little ion acceleration. However, even if electron beam parameters cannot be improved significantly, much greater ion acceleration can be achieved by decreasing the electron beam radius throughout the system and by operating at lower magnetic field strengths. More specifically, one should, in order of decreasing effect, (1) raise I_e to 30 kA, (2) reduce the beam radius by a factor of two, (3) increase τ to 200 ns, and (4) reduce $B_0^{\max}$ to about 15 kg.

The report next addresses ion-loading problems. In view of the small potential wells available for ion trapping, some sort of ion preacceleration scheme seems necessary. Ion current is limited to of order 15 A by the constraint that the electron beam equilibrium be not too strongly distorted by the ions.

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Fig. 1

Variation of cyclotron wave parameters, ion energy, and ion position with elapsed time in the acceleration section of the proof-of-principle autoresonant acceleration experiment for a 3-MeV, 30-kA electron beam. Wave frequency is 286 MHz. The magnetic guide field ranges from 25.5 to 1.7 kg.

Fig. 2.

Variation of cyclotron wave parameters, ion energy, and ion position with elapsed time in the acceleration section of the proof-of-principle autoresonant acceleration experiment for a 2.25-MeV, 15-kA electron beam. Wave frequency is 358-MHz. The magnetic guide field ranges from 25.5 to 1.7 kg.

Fig. 3.

Variation of cyclotron wave parameters, ion energy, and ion position with elapsed time in the acceleration section of the proof-of-principle autoresonant acceleration experiment for a 2.25-MeV, 15-kA electron beam. Wave frequency is 239 MHz. The magnetic guide field ranges from 17.0 to 1.7 kg.