A HEAVY-ION POST ACCELERATOR AND A NEW BEAM BUNCHING SYSTEM FOR THE UNIVERSITY OF TSUKUBA TANDEM

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ABSTRACT

The construction and operation of the heavy-ion post accelerator at the University of Tsukuba are described. Ions of ^{35}Cl were accelerated from 110 to 140 MeV with an rf power of 7.4 kW at 100.5 MHz. In order to improve the phase acceptance of the post accelerator, and to obtain a better energy resolution of the post accelerated beams a new beam bunching system has been designed.

INTRODUCTION

The upgrading of electrostatic accelerators can be done to some extent by improving ion sources, accelerating tubes, vacuum and charging systems. The use of a post accelerator provides the most significant upgrading as far as the energy performance is concerned. Linear rf accelerators are well suited for this purpose. In fact, tandem-linac combinations have recently been developed at several laboratories[1-5]. For large scale linacs, superconducting cavities would be the best choice from the view point of power consumption. It has been pointed out, however, that for small linacs or linacs which are not operated during a large fraction of beam time in the year, room temperature cavities are still preferable[6].

The post accelerator described in this report has been developed as a small energy booster for our 12 UD Pelletron tandem accelerator. The interdigital-H structure, which has successfully been operated at Munich[2], is the most attractive type of cavities, since the effective shunt impedance is extremely high for velocities of heavy ions delivered by our tandem accelerator. Our post accelerator has been designed to accelerate ^{35}Cl (15^+) ions from 110 to 140 MeV with an rf power of about 10 KW. The frequency was chosen to be around 100 MHz, so that an rf system for TV broadcasting service could easily be used. In order to preserve the quality of beams from the tandem accelerator, the injection of properly bunched beams is very important. A new beam bunching system has been designed to meet these requirements. The system consists of a pre-tandem harmonic buncher, a post-tandem chopper and a post-tandem buncher.

ACCELERATING CAVITY

Fig. 1 shows a schematic view of the accelerating cavity. The diameter and the length are 0.75 and 3.03 m, respectively. The cavity consists of a top hat, a middle frame and a bottom vase. The middle frame is sandwiched in between the top hat and the bottom vase with two O-rings for vacuum sealing. Aluminum wires 0.8 mm in diameter are placed close to the O-rings to obtain good rf contact. The cylindrical surfaces of the top hat and the bottom vase are are cooled by water. The middle frame is shaped with two ridges on both sides of the cavity axis. The ridges are 2.3 m long and 60 mm thick, and are cooled by water. All the inner surfaces are covered with copper plating. The thickness of the copper layer was measured to be 50±5 μm on the average. Drift tubes are made of solid copper. A total of 18 tubes are mounted alternately on both ridges. The outer diameter of a drift tube is 50 mm, whereas the bore is 25 mm. The vacuum in the cavity is generated by a cryogenic pump with a pumping speed of 3000 l/s for nitrogen.

To prepare a drift tube table, the axial electric fields between adjacent tubes must be exactly known. Since the structure of the present cavity is rather complicated, the electromagnetic field can not be obtained from analytical calculations. We have developed,

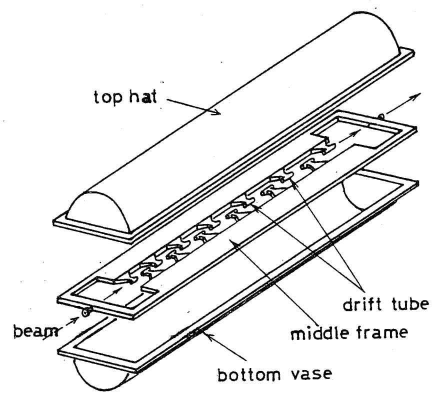

Fig. 1 Schematic view of the accelerating cavity

therefore, an empirical method for the determination of lengths of drift tubes. Our criterion was to achieve an uniform distribution of electric fields. A flat distribution of fields is preferable because the effective shunt impedance is high and unwanted local heating in the cavity can be avoided. The fields are distributed in a sinusoidal form if drift tubes are arranges so that the value β (the ratio of the ion velocity to the light velocity) and the ratio g/l are constant. The symbols g and l are the length of a gap and an unit cell. We have adjusted the ratio g/l with a weight of a sinusoidal function. After several attempts, a reasonably flat distribution of fields could be obtained. The ratio g/l for the n-th gap is given by the following expression:

$$(g/l)_n = 0.5(l_n/l_c)[(l_c/l_n)\sin(\pi z_n/L)]^{1/2}, \qquad (1)$$

where l_c is the unit-cell length at the center of the cavity, L denotes the total length of the accelerator and z_n is the coordinate of the center in the n-th gap. The origin of the coordinate is taken to be the entrance of the cavity. Fig. 2 shows a typical result of measurements of electric fields with drift tubes for the acceleration of $^{35}Cl(15^+)$ ions from 110 to 140 MeV. The resonance frequency was 100.5 MHz. The quality factor Q was as high as 2.4×10^4. From this distribution of fields, energy gains and transit time factors were calculated for each gap. Fig. 3 shows the gap voltages V_n, transit time factors T_n and the ratios $(g/l)_n$. The effective shunt impedance was estimated to be 137 MΩ/m.

BEAM DYNAMICS

Simple calculations of longitudinal beam dynamics have been made. The energy gain of a particle in the n-th unit cell is given by

$$\Delta W_n = qV_nT_n\cos\phi_n \qquad (2)$$

where q is the charge of the particle, V_n is the gap voltage, T_n represents the transit time factor and ϕ_n is the phase of the rf field when the particle is at the center of the unit cell. For synchronous particles, the phase ϕ_n is replaced by a constant value ϕ_s. In the general case, the phase at the (n+1)-th unit cell is given by

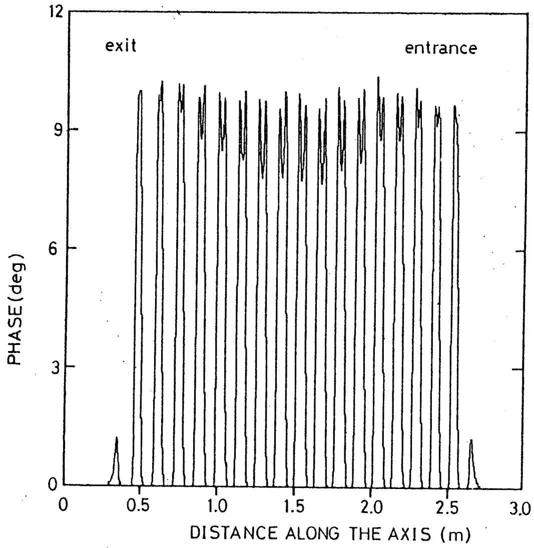

Fig. 2 The distribution of electric fields measured by perturbation method

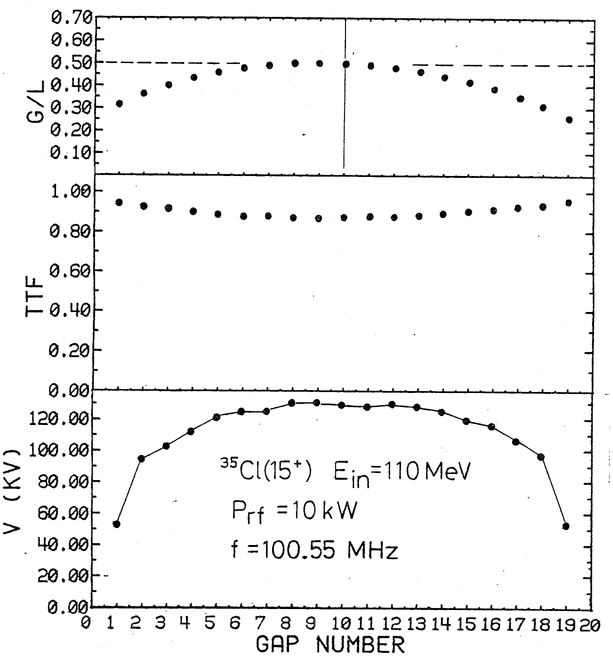

Fig. 3 The ratio of g/l, transit time factors, and gap voltages obtained from the field distribution in Fig. 2.

$$\phi_{n+1} = \phi_n + (2\pi L_n/\lambda\bar{\beta}_n) - \pi \quad , \qquad (3)$$

where L_n stands for the unit cell length, λ is the resonance wave length and $\bar{\beta}_n$ is the mean velocity. The energy gains and the phase advances were successively calculated for each gap. The total energy gain is shown in Fig. 4 as a function of the entrance phase. In this figure, the energies are not uniform around the synchronous phase. This fact suggests that the phase focussing is rather weak in our accelerator. This is attributed to the fact that our post accelerator has a small number of gaps (19 gaps), and that the total energy gain is quite small as compared to the incident energy. Particles pass through the accelerator before they oscillate around the synchronous phase. Therefore, we have decided to accelerate sharply bunched beams at the phase ϕ_s=0°. This choice of the phase is not necessarily unreasonable, because 1) the radial deforcussing is extremely weak and 2) the maximum value of the gap voltage can be used. Since the phase focussing is weak, our post accelerator is somewhat flexible for the acceleration of slightly asynchronous particles. For the later comparison with test experiments, a calculated energy spectrum for the acceleration of a dc beam is diplayed in Fig. 5.

OPERATION OF THE POST ACCELERATOR

The first operation of our post accelerator was in September 1983. The tandem accelerator was operated at a terminal voltage of 11 MV. ^{35}Cl ions were extracted from the 90° analyzing magnet with an energy of 110 MeV (15^+). A carbon foil was inserted in front of the 90° magnet as a second stripper. The ion beam was then transported to the post accelerator through quadrupole

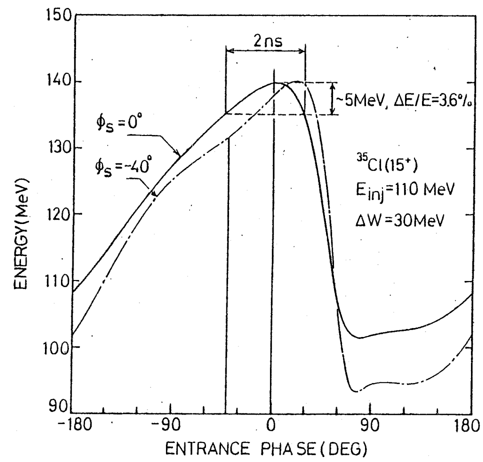

Fig. 4 Output energy of the post accelerator as a function of the entrance phase at the first gap.

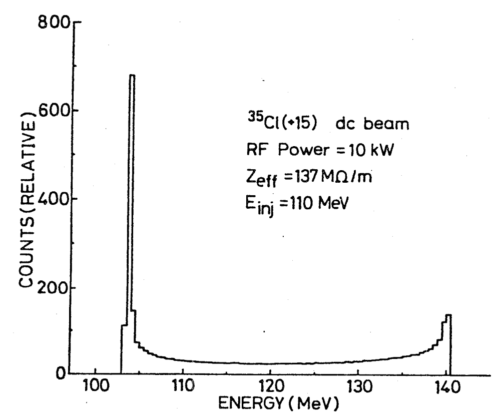

Fig. 5 Calculated spectrum for the acceleration of a dc beam.

magnets. The energies of post accelerated beams were measured by observing the elastic scattering on gold with a silicon surface-barrier detector placed at 20 or 30° lab.

At first, a dc beam was injected to compare the spectrum with that obtained from beam dynamical calculations. The experimental spectrum shown in Fig. 6 is in qualitative agreement with the calculation represented in Fig. 5. The high energy edge of the spectrum corresponds to the narrow phase region around 0° (Fig. 4). The energy at the edge in Fig. 6 was estimated to be 136.5 MeV. The total accelerating voltage is then 1.8 MV. This value agrees well with the value calculated from the rf power of 7.4 kW and the effective shunt impedance of 137 MΩ/m. Total accelerating voltages measured at several levels of rf power are shown in Fig. 7.

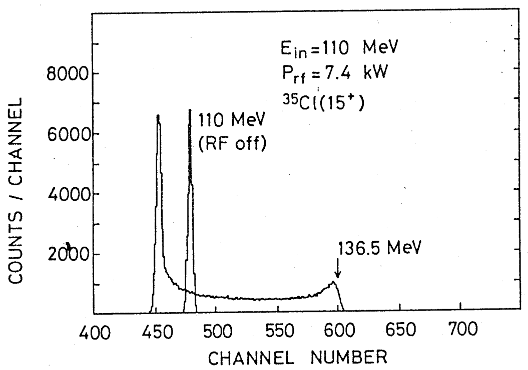

Fig. 6 Energy spectrum of a post accelerated beam for the injection of a dc beam. A line spectrum corresponds to the beam delivered by the tandem accelerator.

Full circles are experimental values. The solid line indicates the voltages calculated as a function of rf power by assuming the effective shunt impedance to be 137 MΩ/m.

The second test was the acceleration of bunched beams to obtain a line spectrum. A pulsed beam 2 ns wide (FWHM) was injected into the post accelerator. The phase of the pulsing system was adjusted so as to fit the peak of the line spectrum on the high-energy edge of the continuous spectrum in the case of dc beam injection. The result is shown in Fig. 8. The rf power was 3.5 kW in this case. The energy spread of the post accelerated beam was estimated to be 1.7 MeV (ΔE/E=1.4 %). This spread is 3 times as large as that of tandem beams. Thus, more sharply bunched beams are required for the improvement of the energy resolution of post accelerated beams.

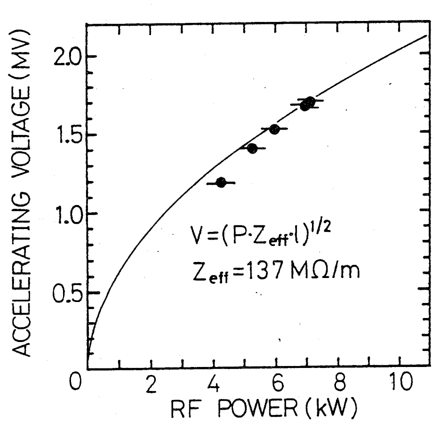

Fig. 7 Total accelerating voltage vs rf power. Full circles are obtained from the high-energy edge of continuous spectra.

NEW BEAM BUNCHING SYSTEM

As mentioned above, it is very important to inject bunched beams with a sufficiently narrow width to improve the energy resolution of post accelerated beams. Another requirement for the bunching system is higher bunching efficiency, since the beam intensity is limited by the lifetime of terminal stripper foils and by the use of second stripper. Our old pre-tandem buncher is a conventional 2 gap buncher driven with a single

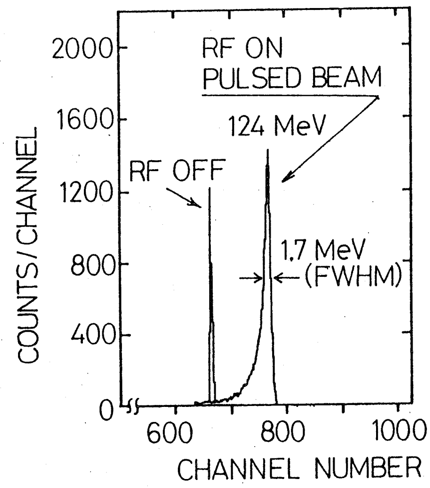

Fig. 8 Energy spectrum obtained by injecting a pulsed beam.

frequency. The fraction of a dc beam compressed into a time window is only 10-15 %. The energy modulation to give complete bunching of a dc beam is expressed by

$$e_m(t) = E_0/(1-t/\tau)^2 - E_0 \fallingdotseq 2E_0 t/\tau \qquad (4)$$

where E_0 is the ion energy and τ is the transit time when ions without energy modulation travel from the bunching gap to the time focus. The voltage given by Eq. (4) can be produced by synthesizing the first 4 Fourier components. The bunching factor is about 4 times as large as that for a conventional 2 gap buncher[7].

In our design, the fundamental frequency is 25 MHz (1/4 of the frequency of the post accelerator). To minimize the transit time effect in the bunching gap, grids with 90 % transmission are used. The gap is 3 mm wide.

The post-tandem chopper sweeps away the unwanted beam tail and suppresses the dark current between beam bursts. The frequencies are 12.5, 6.25, 3.125 and 1.5625 MHz. Anyone of these frequencies can be chosen according to the experimental requirements.

The post-tandem buncher is the most essential part of the new bunching system. Since the velocity of heavy ions is generally slow, serious debunching occurs in the acceleration through the tandem accelerator and in the beam transport system. Then the beam should be rebunched at the high-energy end of the tandem accelerator.

A spherical resonator is used for this purpose. A gap is made between two cones loaded in the sphere. The mode of resonance is the TEM mode excited in a shorted conical transmission line. The diameter is 1.3 m and the frequency is the same as that of the post accelerator (100 MHz). The phase acceptance of the post accelerator can be increased from a few degree to 90°. The construction of this new system is in progress.

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