OPERATION OF THE GRADED-β ELECTRON TEST ACCELERATOR

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Abstract

The Electron Test Accelerator has been built to model the behaviour of the high energy portion of a proton linear accelerator which would be suitable for breeding fissile material. The test accelerator and its control systems have been tested at 100% duty factor producing a beam of electrons at 1.5 MeV and currents up to 20 mA where the incident rf power is shared equally between the structure dissipation and the beam loading. The structure has performed satisfactorily in all respects at dissipation power densities up to 5 kW/cell where the mean energy gradient was 1.1 MeV/m. Experiments have been done on the beam loading effects in the coupling of the transmission line to the cavity, the amplitude depression in and phase tilt along the structure, and the phase lag of the structure field. The phase acceptance, the variation of transmission with buncher-accelerator phase shift and the beam energy spread are in qualitative agreement with beam dynamics calculations.

Introduction

A 100% duty factor proton linear accelerator with a mean current of 300 mA or more bombarding an actinide-element target at an intermediate energy would be suitable for breeding fissile material[1]. The operation of linear accelerator structures at room temperature, with 100% duty factor and with high mean current is new. Much experience must be acquired in the design and operation of such an accelerator before a practical demonstration and the economic assessment of a breeding scheme is possible. As a first step in acquiring this experience, two low-energy, high-current linear accelerator experiments are in progress at Chalk River[2,3]. One of these, the Electron Test Accelerator (ETA), uses a bi-periodic, side-coupled standing wave structure designed to model beam loading phenomena in the high energy section of a large accelerator. The objective of the experiments described here is to understand the behaviour of the accelerator and its control systems, first by comparing measurements using a low-current beam with results from a beam dynamics computer program, then by investigating beam loading effects on various parameters of the system. The experimental accelerator[3] comprises an electron gun and a buncher cavity as the injector, a graded-β structure and a β = 1 structure. This paper describes the operating experience with the injector and graded-β sections of the accelerator.

Injector

Beam loading of the buncher, discussed elsewhere[4], has been found to have small but important effects in high current applications. Normally, buncher beam loading is not important. In fact, if the average energy of the beam is not modified by the buncher, the beam loading is zero. But in a buncher with a longitudinal rf field, the energy gained by the incident dc beam during the accelerating half-cycle slightly exceeds the energy lost during the decelerated half. Lee-Whiting[5] has calculated the average energy gained by a particle in a buncher gap, taking into account the variation of particle velocity across the gap. To evaluate the effect, the longitudinal field strength profile (or the effective shunt impedance and transit time factor) must be known. The effective shunt impedance of the ETA buncher was measured using a filter lens apparatus as described by Simpson and Marton[6]. With 30 watts power dissipation in the buncher, the peak energy modulation was observed to be 7.3 keV giving an effective shunt impedance of 1.7 ± 0.2 MΩ. With an estimated transit time factor of 0.9 the average energy gain of an electron in the buncher was predicted to be ∼ 30 eV. The power dissipated in the buncher cavity is normally 30 watts so at 10 mA beam current, 1.0% of the power would be absorbed by the beam and the field depression would be 0.5%. A reproducible, small field depression has been observed in qualitative agreement with this prediction.

In a proton beam buncher operated at 200 MHz, beam energy 750 keV and with the same bunching factor[7] as in the present experiment, the buncher beam loading will be approximately the same as noted here.

Beam loading can also affect the phase of the field in the buncher cavity. If the phase reference signal for a multi-tank linear accelerator were derived directly from the master oscillator, the beam loading at high currents could create an intolerable phase error in the bunched beam as it arrives at the first accelerator cell. Such a method of deriving the phase reference signal is also subject to phase errors caused by mistuning of the buncher cavity and phase shifts in the buncher drive line. To avoid these errors, the buncher field probe line was chosen as the phase reference line. In this way the reference phase is more closely tied to the actual phase of the bunched beam.

Initial operating experience with the buncher showed that the increase in the effective emittance (an ellipse enclosing the distorted phase space contours) caused by radial defocussing in the buncher gap could be kept within tolerable limits by reducing the buncher power. To regain the optimum bunching, the drift distance between the buncher and the accelerator was increased from 1.0 to 1.5 metres.

Following the operation experience reported earlier[3], an unexpected difficulty was encountered when water-cooled copper (oxygen-free high

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conductivity) apertures were installed as beam scrapers in the injection line. The dispenser cathode used in the electron gun was repeatedly poisoned whenever a few tens of microamperes of beam was normally incident on copper within one metre of the gun. Subsidiary experiments demonstrated that copper atoms were being sputtered preferentially along the perpendicular to the surface. The sputtering is probably caused by the negative oxygen ions emitted by the dispenser cathode[8,9] rather than by the electron beam itself which at the 80 keV energy used, is incapable of transferring sufficient energy to copper atoms in single collisions to exceed the sputtering threshold (∿ 5 eV for many metals[10]). Tapered apertures, with the intercepted beam halo incident at a grazing angle of 10°, solved this problem. As a precaution, such apertures are now used throughout the accelerator beam line. With water cooling, they are capable of intercepting several milliamperes of beam indefinitely without poisoning the cathode.

The Graded-β Structure

The shape of the end walls of the eleven accelerating cavities in the graded-β structure is similar to that used in the LAMPF accelerator for $\beta = 0.65$ but the cell length is varied to match the increase in β from 0.54 at injection to 0.95 at the output. The structure is driven through a coupling port in a bridge-coupler cell (see Fig. 1 of ref. 3). The design gradient of 0.8 MeV/m is achieved with a structure dissipation power of 32 kW at 805 MHz. The performance of the accelerator is modelled by a beam dynamics computer code, LINGUN, similar to PARMILLA[11] and adapted for use with the π/2-mode, side-coupled structure with focussing provided by solenoidal magnetic gap lenses at the ends of the tank sections. The structure was operated with beam currents of less than 1 mA while measuring the transmission, phase acceptance and beam energy spread. The results were then compared with the calculations.

Figure 1 shows the variation of beam transmission with gun voltage. The transmission is defined as the current I measured in an output Faraday cup expressed as a fraction of the dc current I_0 from the gun. The experimental data shown as solid circles were taken with the buncher off and the solid square point with the buncher on and with the gun at its normal operating voltage. The lack of detailed agreement may be attributed in part to the sensitivity of the low energy electrons in the injection line to the beam transport settings.

The transmission was then measured with a variable phase shift between the buncher and accelerator. The results of runs at structure dissipation powers of 20, 26 and 32 kW[b] are shown in Fig. 2 together with a predicted curve for 32 kW. The broad features of the transmission-phase curves are insensitive to the structure power; the measurements are in fair agreement with the prediction.

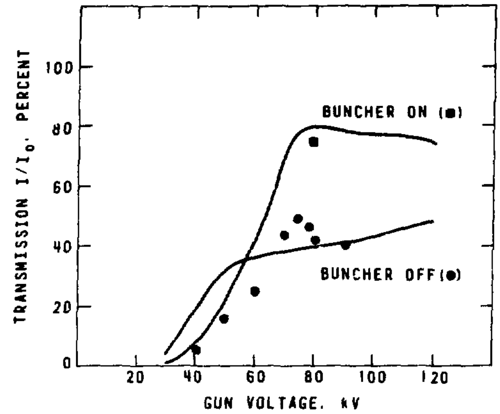

Fig. 1 Beam transmission vs. gun voltage with and without the buncher operating. I is the current in a Faraday cup at the output of the accelerator and I_0 is the dc current from the gun. The curves were calculated, the solid circles measured with buncher off and the single square point measured with buncher on and with the normal gun voltage.

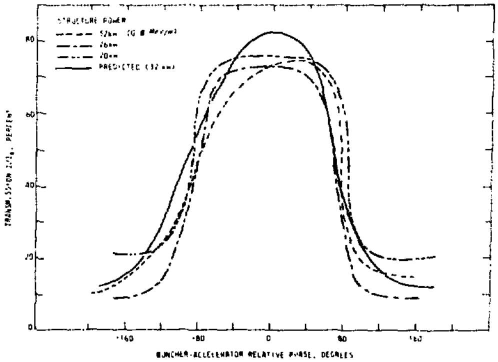

Fig. 2 Beam transmission vs. phase between buncher and accelerator for various tank dissipation powers.

The energy spectrum of the output beam was measured with a magnetic spectrometer consisting of a 30° bending magnet, water-cooled object and image slits and a Faraday cup. The magnet was calibrated using 626 keV conversion electrons from a ^{137}Cs source. Two different object apertures were used, a 3 mm diameter aperture transmitting typically 30% of the beam and a 1 cm x 1 cm square aperture with 95% transmission. With the smaller object aperture, the momentum resolution with the 1 mm image slit was 1%.

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[b] The mean accelerating gradient is frequently quoted to characterize the operating conditions but in a graded-β structure the gradient is not simply related to the structure power.

The energy distributions measured with both object apertures for a tank power of 32 kW are shown in Fig. 3. The spectrum measured with the larger aperture has a full width at half maximum of 110 keV. The LINGUN prediction for this aperture is 95 keV and for the smaller aperture less narrowing of the peak is predicted than observed. The mean value of the beam energy obtained with the spectrometer was 1.55 ± 0.1 MeV; using the LINGUN code a mean value of 1.44 MeV is calculated. The beam energy obtained from a calorimetric measurement of beam power and the measured beam current was 1.50 ± 0.06 MeV.

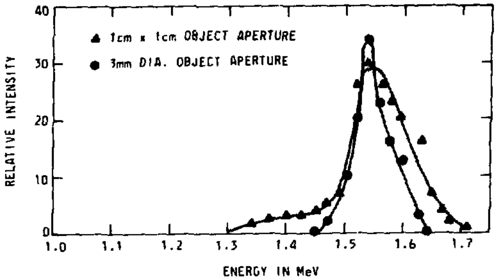

Fig. 3 Energy spectra measured with a magnetic spectrometer using 3 mm diameter and 1 cm x 1 cm rectangular object apertures.

The percentages of the beam intercepted by and transmitted through the 1 cm x 1 cm aperture as the buncher phase is varied are shown in Fig. 4. The solid curves are drawn through the measured points and the calculated transmitted and stopped beam fractions are shown as dashed lines.

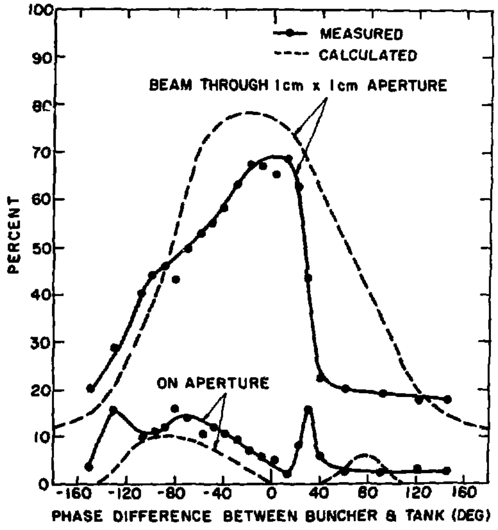

Fig. 4 Beam transmission and aperture current vs. phase between buncher and accelerator tank.

We concluded that the LINGUN model calculations account fairly well for such average beam properties as mean energy, transmission and radial acceptance. More detailed agreement with the observed beam parameters would probably be obtained if a more accurate representation of the magnetic gap lenses were available. Imperfect modelling of the lenses and perhaps of the accelerating cells undoubtedly affects the low energy portion most seriously.

Beam Loading Experiments

An accelerator operated at 100% duty factor factor is well suited to experiments on steady-state beam loading. All difficulties associated with transients during the build-up of the structure field and of the beam current are eliminated. The steady-state measurements of fields and, more importantly, phases, are straightforward. Experiments have been done on the beam loading effects in the coupling of the transmission line to the cavity, the amplitude depression in and phase tilt along the structure and the phase lag of the structure field.

The first stage of the experiments with the accelerator is designed to accommodate beam currents of up to 20 mA. During fabrication and tuning of the graded-β section, the coupling iris between the waveguide and the bridge coupler was machined to give an overcoupled termination without a beam. The expected effect of the beam loading was to change the mismatch from over- to undercoupled. The size of the iris was initially chosen for the experimental tests so that the voltage standing wave ratio (VSWR) in the waveguide would be the same value at incremental beam powers of zero and 26 kW, and be unity (structure critically coupled) at 11 kW. For optimum efficiency the reverse power should be zero (VSWR = 1.0) at the design level of beam power.

The VSWR's observed when varying beam load and with the structure power held constant are shown in Fig. 5. The smooth curve is the theoretically predicted VSWR, with the value of beam power corresponding to critical coupling as an adjustable parameter. As the incremental beam power increased from zero to 22 kW, the VSWR initially fell until it reached a minimum value of 1.04 at 12 kW (9 mA). The smooth curve is the best fit to the data which implies that critical coupling is reached at a beam power of 11.7 kW. The measured beam current at this point was 8.6 mA, giving a beam energy gain in the tank of 1.36 MeV. Adding the injector energy gives a total of 1.44 ± 0.07 MeV, in good agreement with the LINGUN prediction but lower than the spectrometer and calorimeter measurements given above.

The field depression induced by the beam loading was measured in the two end cells of the structure. For a beam current of 15 mA, the fields decreased by less than 0.3% from their values at zero beam current.

The phase tilt along the structure was obtained by comparing the phase of signals from the first and seventh accelerating cells. The results are shown in Fig. 6. At the design accelerating gradient of 0.8 MeV/m, the magnitude of the phase shift was 0.0082 ± 0.0006 deg/mA or a phase tilt of 0.0014 deg/(mA·cell). In a high-current proton linear accelerator, the existence of a small but finite beam-induced phase tilt will have to be taken into account.

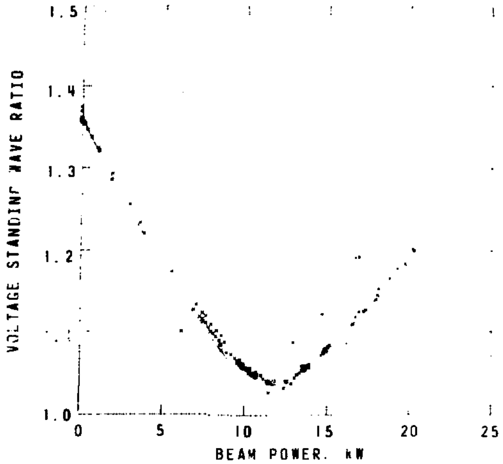

Fig. 5 Variation of voltage standing wave ratio in the transmission line to the structure with incremental beam power. The points are measured values and the smooth curve is the theoretical best fit for critical coupling at 11.7 kW.

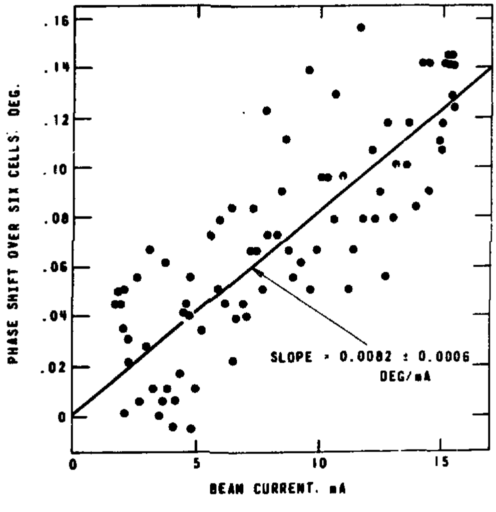

Fig. 6 Beam-induced phase shift in the accelerating field over six cells of the structure.

The reactive effects of beam loading have been studied by measuring the phase change between the accelerating cavity field and the drive field as a function of beam loading. The graded-β structure was designed for a synchronous leading phase angle of 26°. A tightly bunched beam injected at a phase angle ϕ_s ahead of the accelerating field induces a decelerating field giving a resultant structure field that lags the rf driving field by a phase angle ϕ. According to the beam loading theory developed by Nishikawa[12], Knapp et al.[13], and others[14] the relation between the cavity phase lag ϕ and the beam bunch mean phase angle ϕ_s is

$$\tan \phi = \alpha \tan \phi_s$$

where the beam loading parameter α is the ratio of incremental beam power to total rf power.

Measurements were made while the beam loading parameter α was varied from zero to 0.4, corresponding to beam currents of zero and 16 mA respectively. The buncher-accelerator phase and beam transport were adjusted for maximum transmission at the higher current, then the beam current reduced to zero. Throughout this experiment the reverse power in the transmission line was held at a minimum and the accelerating field held constant. The resonant frequency, as determined by the condition of minimum reverse power[15], was observed to vary less than 1 kHz. The phase angle between a signal from the forward power port in a directional coupler in the waveguide feed and a magnetic coupling probe in one of the accelerating cells was observed to change by 4°. This suggests that the mean beam phase angle for the conditions of the experiment was 10° although the interpretation of the results is not clear.

The operation of the β = 1 structure will make possible additional experiments not now feasible on the graded-β structure. With the former, it will be possible to inject a tightly bunched beam at an arbitrary phase angle. This will permit a more direct test of reactive beam loading theory.

Conclusions

Experiments on the graded-β structure of the Electron Test Accelerator have shown that it is a satisfactory experimental facility for detailed studies of beam loading phenomena. It has been found that as a consequence of beam loading effects the phase reference signal should be derived from a probe in the buncher.

Critical coupling of the waveguide feed to the bridge coupler was achieved close to the predicted incremental beam power of 11 kW. The acceptance, energy gain and energy spread are in fair agreement with the calculated values. The amplitude depression and phase changes along the structure induced by the beam are small, but finite, and must be taken into account in the design of longer structures.

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DISCUSSION

E.A. Knapp, LASL: Do you have any trouble with multipactoring or other rf conditioning problems at these low fields in cw operation?

Fraser: Not serious troubles. I think when the tank was first conditioned we had to do some pulsing of the power but in the usual turn-on procedure the multipactoring level (about 2 kW structure power) is easily avoided.

Knapp: In your computer representation of these tanks, is the phase shift per cell as a function of beam loading given?

Fraser: No.