PHASE-DEPENDENT QUADRUPOLE EFFECTS IN ON-AXIS COUPLED LINACS

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Abstract

Distorted beam profiles produced by slot-coupled electron linacs have been associated with the quadrupole forces resulting from the perturbation of cavity fields by the coupling slots. Calculations indicate that these forces are phase-dependent, resulting in an increase in the effective emittance of an accelerated beam having significant phase width. An on-axis slot-coupled accelerating structure was equipped with a chopper system to investigate this effect. The results of detailed measurements of the beam profile as a function of injection phase are discussed.

Introduction

The coupling slots of on-axis slot-coupled $\pi/2$-mode electron linear accelerator structures have been found to introduce weak quadrupole fields [1-5], which perturb the accelerated beam. These fields have been measured using bead-pull techniques [4] and have been calculated [3,5] using the MAFIA computer code [6]. The effect on an accelerated beam has been found to depend on the orientation of the coupling slots in an accelerator structure.

As we have shown in reference [4], the quadrupole forces may be expressed in terms of a phase-dependent quadrupole focusing force

$$\Gamma(\phi) = \Gamma' + \Gamma'' \times \tan(\phi) \qquad (1)$$

where ϕ is the rf phase as the electron crosses the centre of the accelerating cavity. Unless $\Gamma'' = 0$, a beam that is not well-bunched at the peak accelerating phase will be distorted by the rf phase-dependence of the quadrupole forces, and the beam profile will be a superposition of ellipses of varying eccentricity. Γ' and Γ'' are calculated to be on the order of 10^{-4} mm^{-1} for a structure having coupling slots rotated by 90° across the accelerating cells. Γ' and Γ'' can both be reduced to zero for a $\beta \approx 1$ accelerating structure by aligning the coupling slots on opposite cavity walls.

A simple experiment comparing an aligned-slot structure against a rotated-slot structure confirmed that alignment of the coupling slots reduces the emittance of the accelerated beam [4]. An electron linac assembled with the coupling slots rotated 90° across the accelerating cells produced a beam that was large, cruciform and had an increased divergence. The beam produced by the aligned-slot structure had a much smaller divergence and a much smaller profile, although it was not perfectly round.

Experiment

The current investigation of phase-dependent quadrupole effects was concentrated on the further improvement of the emittance of the beam produced by the aligned-slot structure. A deflecting cavity and aperture were placed on the input end of the BEDROCS accelerator structure to chop the input electron beam [4]. The rf drive for the deflecting cavity was obtained from a -20 dB directional coupler inserted in the waveguide supplying the accelerator structure. An attenuator and a phase shifter were placed in the rf drive line for the deflecting cavity, and the chopped input beam was injected into the accelerating structure at different phases relative to the structure rf (see Fig. 1).

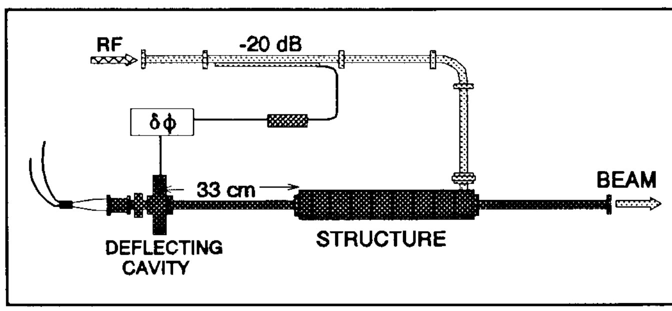

Fig. 1 The beam-chopping system used for the study of the phase-dependence of the beam profile.

The chopper system used produces two beam bunches per rf cycle, with the bunches separated by 180° of rf phase. With the deflecting cavity driven at the structure frequency, the accelerated current has a maximum every 180° of rf phase, rather than the expected 360°.

The electron gun was a triode type using a Wehnelt electrode for current control. The gun produced up to 500 mA of electrons at a cathode voltage of 33 kV. Space-charge effects in the low-energy electron beam from the gun decreased the effectiveness of the chopper system. This effect was eliminated by redesigning the Wehnelt electrode profile to reduce the gun current to 50 mA at 33 kV. When the accelerator was operated with the deflecting cavity not driven, the accelerator output current was roughly 5.0 mA.

The output beam energy was kept at approximately 5.4 MeV. The beam profile was studied at the end of a two-metre-long evacuated drift pipe attached to the output end of the accelerator. A 0.08-mm-thick titanium window was mounted on the end of the beam line, and the films were placed against the air side of the window. Images of the beam profile were captured on Far West radiation dosimetry film.

Electrically-isolated aluminum plates were positioned behind the beam window and used for measurement of the accelerated beam current. The plates were connected to an oscilloscope by coaxial cables. Low noise levels allowed measurements to an accuracy of ± 1 mV, with a sensitivity of 50 mV/mA collected on the plates.

Low-energy and high-energy components of the beam current were separated by using stacked plates to stop the beam. The low-energy component of the beam current was collected on the first plate, while the high-energy component passed through the first plate and was collected on the second plate. Separation of the beam current into more than two energy components was achieved by varying the thickness of the first plate.

Results

The current collected at the accelerator output was 5.0 mA when the deflecting cavity was not driven. To produce a clear image, the film required exposure to roughly 200 beam pulses. The beam profile image shown in Fig. 2 was produced by 200 beam pulses with the deflecting cavity not operating. The image has been digitally processed to enhance contrast, and has been enlarged by a factor of 4 relative to the spot on the film.

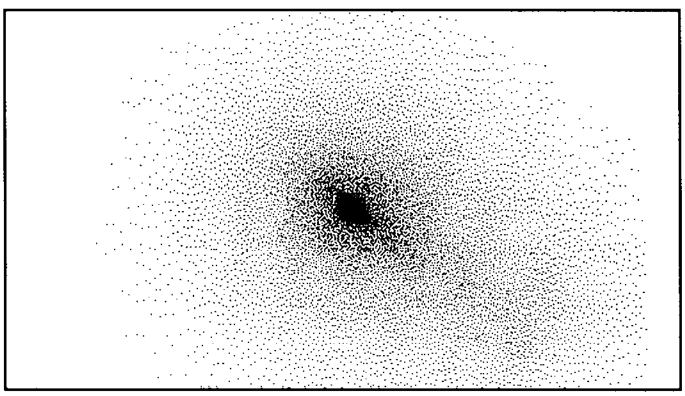

Fig. 2 An image of the profile of the accelerated beam produced with the deflecting cavity not driven.

The current was roughly 0.8 mA when the deflecting cavity was driven at the rf phase that produced maximum accelerated energy and current. An exposure of 2000 pulses was used when the deflecting cavity was driven. The beam profile image shown in Fig. 3 was produced by 2000 beam pulses with the deflecting cavity driven at the rf phase that produced maximum accelerated energy and current. This corresponded to a chopper phase shifter reading of 180°. The image in Fig. 3 has also been enlarged by a factor of 4. The image has been digitally processed to enhance contrast.

Measurements of the accelerated current were made with the deflecting cavity not driven and as a function of rf drive phase with the deflecting cavity driven. The total beam current was separated into low-energy and high-energy components for the measurements made with the cavity driven (see Fig. 4). Note that the accelerated beam current is greatest at the same phase for all energy components. This would generally be considered the optimum phase for operation of the chopper system.

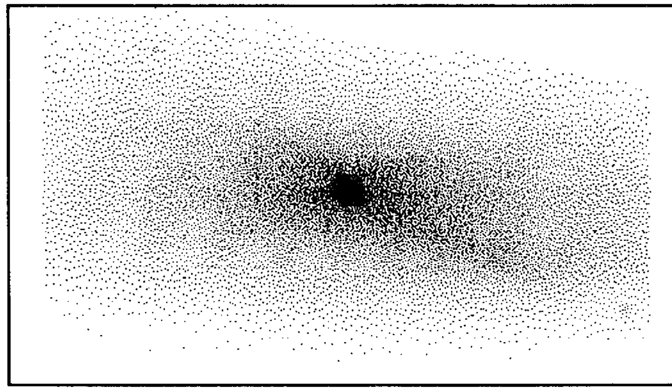

Fig. 3 An image of the profile of the accelerated beam produced with the deflecting cavity driven at the rf phase yielding maximum beam current and energy.

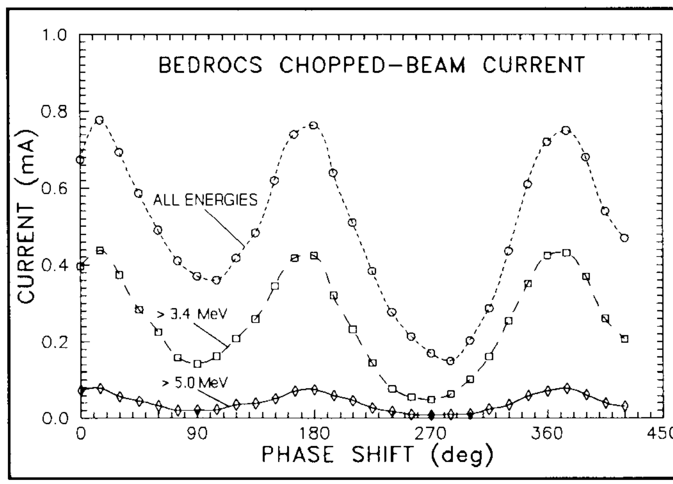

Fig. 4 Accelerated current produced with the deflecting cavity driven at various rf phase shifts. The indicated phase shift is the phase shifter reading.

Note that the phase shift in Fig. 4 is the reading of the phase shifter on the deflecting cavity drive, and is not a phase measurement relative to the accelerating structure fields.

The current at the middle of the beam bunch produced by the chopper system is assumed to be equal to the current with the deflecting cavity not operating. The transmission data can be used to determine the phase width of the beam bunch produced by the chopper system. Since the chopper system produces two beam bunches per rf cycle, the current accelerated with the deflecting cavity driven, integrated over 360° of rf phase shift and divided by the full width at half maximum of the beam bunch, should be twice the accelerated current produced with the deflecting cavity not driven. Thus, the chopper system produced a beam bunch with a full width at half maximum of roughly 19° phase.

Consider the image in Fig. 3, which shows an image of a beam bunch 19° in width accelerated near peak accelerating phase. A visual comparison with Fig. 2 reveals a horizontal blurring of the fainter areas of the image. Note that the deflecting cavity sweeps the electron beam in the horizontal plane. Thus, the blurring presumably results from the increased horizontal divergence of the chopped beam pulses at the input end of the accelerator structure. The two images in Fig. 2 and Fig. 3 otherwise appear very similar. In both Fig. 2 and Fig. 3, the central beam spot appears somewhat square. This shape was found to be quite reproducible and independent of the gun optics.

As described above and in references [3] and [4], the square shape of the central beam spot in Fig. 2 was initially hypothesized to be due to the superposition of perpendicular ellipses oriented at 45° from the horizontal, generated by the effects of phase-dependent quadrupole forces on electrons accelerated at different rf phase. Due to the short beam bunch phase width produced by the chopper system, the ellipses were not expected to appear in the beam profile shown in Fig. 3. The similarity of the shape of the central beam spot in Fig. 3 implies that the shape is generated by an effect other than phase-dependent quadrupole forces. The nature of that effect could not be determined from this investigation.

Figure 5 shows an image of the beam profile produced with the deflecting cavity drive delayed in phase by 45° relative to Fig. 3. This corresponds to a chopper phase shifter

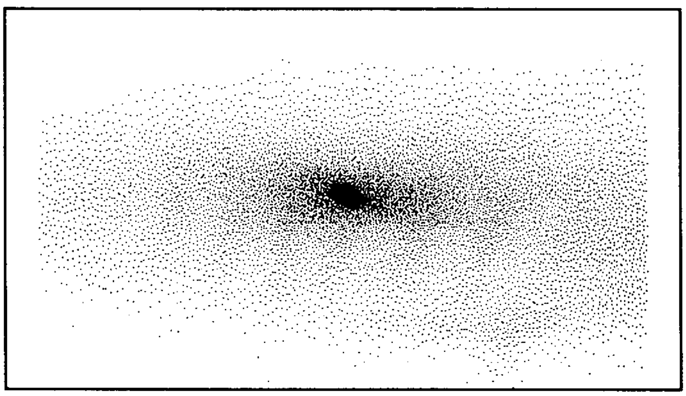

Fig. 5 An image of the beam profile with the deflecting cavity driven at an rf phase delayed 45° relative to that of Fig. 3. Beam current is reduced by 50%.

reading of 225°. The central beam spot in Fig. 5 appears to be more symmetric than in Fig. 3, but Fig. 4 shows that the accelerated current is greatly reduced at this phase. The reduction in the high-energy component of the beam also shows that the accelerated beam energy is reduced at this phase. Thus, the shape of the beam profile is improved, but at the expense of reduced output beam energy and reduced accelerator input acceptance.

Given that the beam images were made at the end of a 2-metre drift pipe and that the image in Fig. 5 has been enlarged by a factor of 4, the small size of the central beam spot implies a divergence of less than ± 0.5 mrad. The lack of the expected phase dependence for the accelerated beam profile implies that the quadrupole forces produced by the coupling slots in the aligned-slot geometry are too small to be observable in this experiment.

Conclusions

The symmetry and divergence of a bunched electron beam accelerated by an on-axis slot-coupled linac with coupling slots aligned across the accelerating cells depend on the phase of injection of the rf bunch. The profile of the chopped, accelerated beam cannot be fully explained by a simple model of time-dependent quadrupole fields. The optimum injection phase for input acceptance and beam energy, though, is not necessarily the optimum injection phase for output beam symmetry and divergence.

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