RF PHASE FOCUSING IN PORTABLE X-BAND, LINEAR ACCELERATORS

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SUMMARY

In order to minimize the size and weight of the x-ray or neutron source for a series of portable radiographic linear accelerators, the x-ray head was packaged separately from the rest of the system and consists of only the linac accelerating structure, electron gun, built-in target, collimator, ion pump and an RF window. All the driving electronics and cooling are connected to the x-ray head through flexible waveguide, cables, and waterlines. The x-ray head has been kept small and light weight by using the RF fields for radial focusing, as well as for longitudinal bunching and accelerating the beam. Thus, no external, bulky magnetic focusing devices are required. The RF focusing is accomplished by alternating the sign of the phase difference between the RF and the beam and by tapering from cavity to cavity the magnitude of the buncher field levels. The former requires choosing the right phase velocity taper (mix of less than vp=c cavities) and the latter requires the right sizing of the cavity to cavity coupling smiles (irises).

INTRODUCTION

This paper discusses the theory of radial RF focusing and presents some examples of its application to two, portable, radiographic, linear accelerators that have been built for non-destructive testing. A companion paper[1] describes the system details and performance capabilities.

The design of light, portable radiographic, linear accelerators differs from the design of accelerators for research. Of primary importance is minimizing the size, weight, and complexity of the accelerator. Good capture efficiency, good launching, good spectrum, and emittance are of secondary importance. However, wasted power is wasted weight in power supplies, cooling system, and most importantly, in the RF source. Even more important is the fact that at X-band, which is the natural choice for these small accelerators, the maximum power available is rather low. Hence, any beam which absorbs RF power without reaching full energy (to within about 5%) reduces the full energy (and full penetration) of the x-rays which can be produced. So while high capture is not important, it is important to have a sharp demarcation line between those electrons which are captured and accelerated to > 95% of full energy, and those which are lost early. Similarly, it wastes RF power to accelerator electrons part away through the accelerator and then lose them radially.

ELECTROMAGNETIC FOCUSING

Clearly wrapping one of these small accelerators in a solenoid is far from the optimum. Since the weight of a solenoidal lens is proportional to the integral of B·dl and the focal strength is proportional to the integral of $B^2 \cdot dl$, it pays to concentrate the field with iron in a thin lens. Consideration of the radial orbits in most one-section accelerators reveals that a single lens appropriately placed near the downstream end of the buncher would prevent radial loss of electrons. However, such a lens, if it is a conventional copper and iron solenoid, would significantly increase the weight of one of these accelerators.

RF FOCUSING

There are a number of alternatives for light focusing systems such as periodic permanent magnet systems, perhaps using one of the new rare earth materials. We decided to pursue a different approach; that is, RF focusing which has been suggested by a number of authors[2,3,4]. The approach which can be called alternating phase focusing seemed the most straight forward. In alternating phase focusing, the electrons alternate between forward of the accelerating crest where they are longitudinally bunched and behind the crest where they are radially focused. By this means, both radial and phase stability can be achieved. The process is easily understood by referring to Figs. 1 and 2 which show the longitudinal and radial motion, respectively, in the 1.5 MeV travelling-wave accelerator, which is powered by a 200 kW X-band magnetron. In Fig. 1, we plot the phase o of the electrons relative to the quasi-synchronous space harmonic. At the phase stable field null $\phi = 0$, at the accelerating crest, $\phi = -90^{\circ}$, and at the phase unstable field null, $\phi = -180^{\circ}$. In Fig. 2 the radial motion of three macro particles are plotted as a function of z expressed as the cell numbers.

Comparing Figs. 1 and 2, we see that in cells #1 through 4 most of the electrons, which are captured, are forward of the crest and are longitudinally bunched and radially defocussed. From cell 4 through 12 or 14 (depending on which particle one is following), the bunch is behind the crest so that it is radially focused. In Fig. 2, the effect is striking, particularly for the particle which had an initial phase of $\phi = -30^{\circ}$. This particle would have been lost radially were it not for the RF focusing behind the crest. Then the bunch is moved forward of the crest again for a little more bunching. In the radially bunching region from cell 4 to 14, the particle developed a positive correlation between position and momentum in the longitudinal plane. These would have caused significant debunching by the end of the accelerator. In cells 14 through 26, this correlation is reversed so the bunch contracts by a factor 4 by the end of the accelerator.

Electrons which entered the buncher over a phase interval of 60° are bunched into 8° by the end of the accelerator. The gun for both of these accelerators produces a 0.5 mm radius waist at the entrance to the accelerator. By the end of the 46 cm long structure the beam radius has increased to about 1 mm. Figure 3 gives the calculated energy spectrum for the 1.5 MeV accelerator and Figure 4 gives the calculated load line.

Figures 5 through 8 present the longitudinal orbits, radial orbits, energy spectrum, and load line for the 6 MeV accelerator. This accelerator is a 52 cm long, side-coupled, standing-wave accelerator driven by a 1.2 MW X-band magnetron. From the point of view of buncher design with RF focusing, there are some important differences between a standing wave and a travelling wave accelerator. The first effect is that the space harmonic focusing is about a factor of four stronger[5] for the standing wave accelerator (assuming equal average acceleration). From reference 5, we find the radial force on an electron is:

$$F_r = -1/2\ er\left[\frac{d}{dz} + \frac{k}{\beta\gamma^2}\left(\frac{\partial}{\partial\phi}\right)\right] E\ (z,\phi). \qquad (1)$$

The second term is the force due to the synchronous space harmonic which is in phase quadrature with the acceleration. It is this term which is used in the alternating phase focusing. Because it arises from a difference between magnetic field force and an electric field force in an approximately synchronous wave, it decreases as $1/\gamma^2$. The first term in Equation (1) is the total derivative of the axial electric field along the particle path. The ripple in the axial electric field is accompanied by alternating radial electric fields. This produces a net inward force which is represented in the smooth force approximation by:

$$F_r = \frac{-e^2 r}{4\beta\gamma mc^2}\ (\langle E^2\rangle - \langle E\rangle^2) \qquad (2)$$

The leading term is the a_{-1} space harmonic:

$$F_r \simeq \frac{-e^2 r}{8\beta\gamma mc^2}\ (a^2_{-1}E^2) \qquad (3)$$

In the typical travelling-wave, disk-loaded guide a_{-1} is between 0.4 and 0.5. In a standing-wave accelerator $a_{-1} = 1$. Hence, the radial focusing force differs by a factor of typically greater than 4. Since the n = 0 space harmonics are far from synchronous, the approximate cancellation between electric and magnetic field forces does not occur, so the force decreases as $1/\gamma$ rather than $1/\gamma^2$.

For the 1.5 MeV accelerator discussed here, the space harmonic focusing is equivalent to a solenoid of about 50g. This is certainly weak, but by no means negligible in the radial dynamics. For the 6 MeV standing wave accelerator, the equivalent axial magnetic field is 230 g. In both cases the space harmonics produce a radially focusing force in the second half of the accelerator where the bunch is approximately on the crests. This is apparent in Figs. 2 and 6.

CONCLUSIONS

Both radial and phase stability have been achieved in the design of two small portable x-band linear accelerators through a combination of alternating RF phase focusing and the inevitable space harmonic focusing. In the travelling wave accelerator electrons entering during 1/6 of an RF cycle are both radially and longitudinally stable. In the standing wave accelerator, electrons entering during 1/4 of an RF cycle are similarly stable. We hasten to point out that these are not the first electron linear accelerators which rely solely on RF focusing. However, we believe this is the first case in which specific designs of alternating phase focused electron accelerators have been published. At least one other design is known to have been implemented.[6,7]

REFERENCES

1. R.G. Schonberg, et al, "Portable, X-band Linear Accelerator Systems", IEEE Trans, NS-32, Oct., 1985.

2. C.A. Makhnenko et al, "High Frequency Focusing in Linear Accelerators", Zh. Techn. Fiz., 35, #4, pp. 618-22, 1965.

3. L.B. Mullet, AERE-GP/M-147, Harwell, Bershire, England, 1953.

4. P.M. LaPostelle and A.L. Septier, Eds., "Radiofrequency Focusing in Heavy Ion Linear Accelerators, Linear Accelerators, pp. 1073-87. North Holland Pub. Co., Amsterdam, 1970.

5. R.H. Helm and R.H. Miller, "Particle Dynamics", ibid., p. 132.

6. Private communication with J. Haimson of Haimson Research Corp., Palo Alto, CA.

7. Tronc, Proc. of Europhysics Conf., Berlin, Germany, Sept. 1983.

fig.1 Minac 1.5, longitudinal orbits

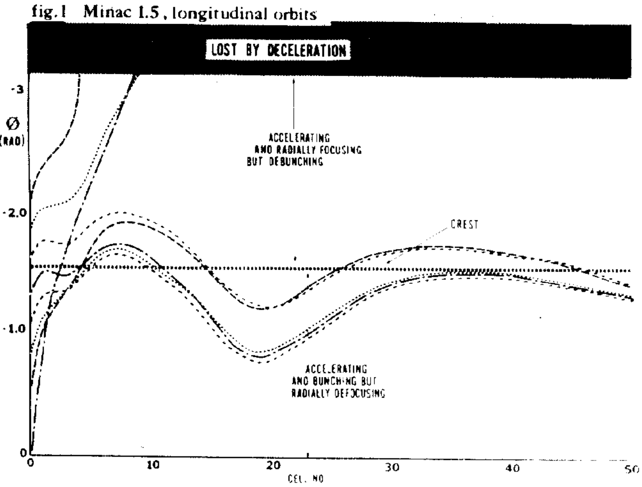

fig.2 Minac 1.5 radial orbits

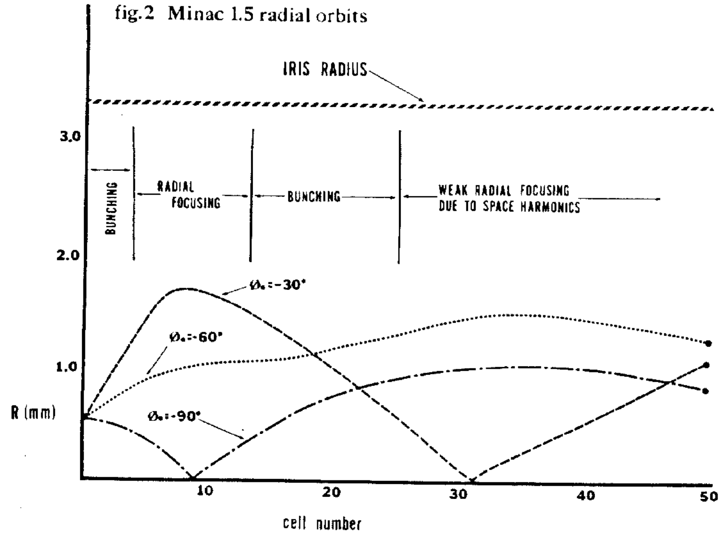

fig.3 Minac 1.5 calculated energy spectrum at 40 mA

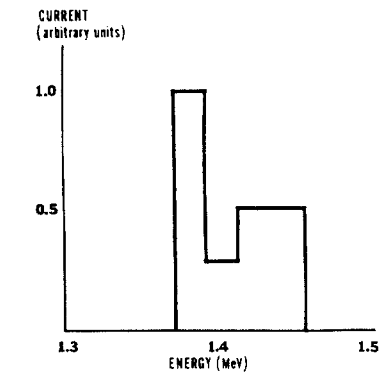

fig. 4 Minac 1.5 Loadline

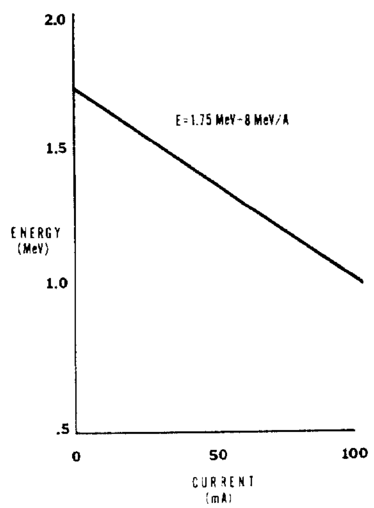

fig. 5 Minac 6 , longitudinal orbits

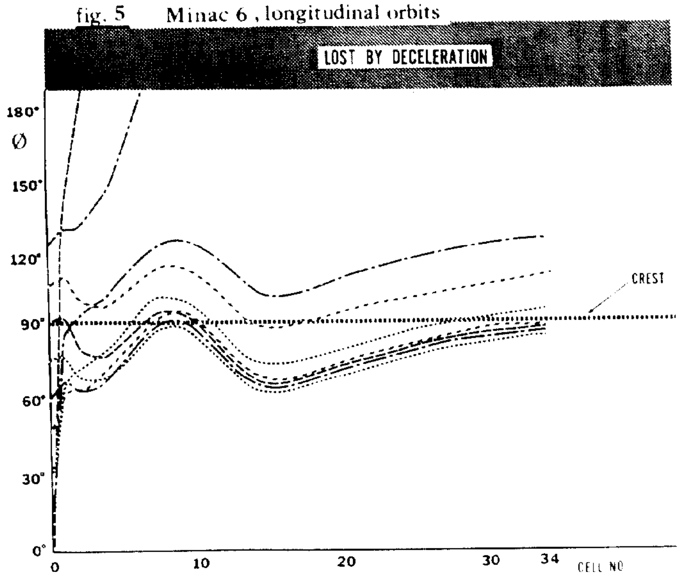

FIG 6 Minac 6 radial orbits

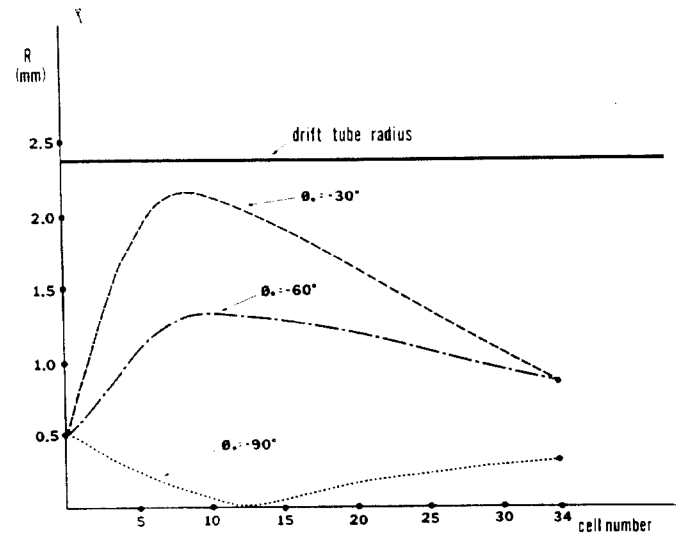

FIG. 7 Minac 6 Calculated energy spectrum at 70 mA

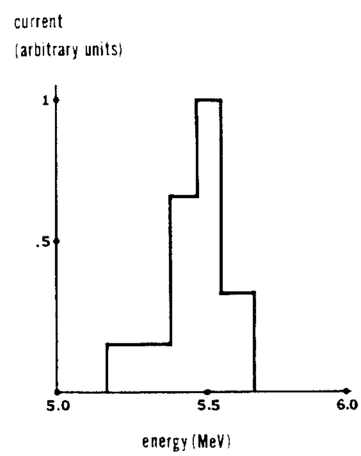

FIG. 8 Minac 6 Loadline