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A METHOD FOR ENERGY VARIATION OF HEAVY PARTICLE BEAMS IN LINACS

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A method is described for achieving continuous variation of the energy of the beam accelerated in a linear accelerator. This is accomplished by accelerating with a higher order mode than the one ordinarily used. The mode used has at least one node in its axial field pattern. Beyond the node the field is reduced to zero by introduction of a stub through the end wall of the cavity. The paper describes procedures for varying the position of the node which terminates the accelerating field.

The peculiar feature of heavy particle linear accelerators of a drift tube cavity type is the necessity of a strict equality of the electric field strength along the accelerating structure to its design value. Any deviation towards a higher or smaller value would disturb the synchronism and infringe the acceleration process. This is the reason why in heavy particle accelerators with the operating mode E_{010}, as a rule, it is not possible to vary the energy of accelerated particles.

Attempts to obtain intermediate ion energies in linacs have been undertaken before[1]; however, they were not a success because they were accompanied by considerable deterioration of the beam characteristics and by the complication of the operating conditions for the accelerator. That is why in modern developments of the linacs which should produce intermediate energies one realizes the design of the accelerator which is divided into a large number of separate sections[2] or even separate cells.[3] However, this method involves considerable difficulties in synchronous rf power excitation of individual sections to a required level and in providing frequency and phase correspondence. In this case, a serious drawback also lies in considerable rf energy losses in separating walls which leads to a general decrease in efficiency in accelerating structures.

The present report discusses a new method of particle energy variation in the linear accelerator which was suggested at the Kharkov Physico-Technical Institute and is realized in practice with the operating accelerators; a 9-MeV proton linear accelerator (PLA-9) and a multicharged ion linac with the design energy 10-MeV/μ (LUMZI-10). This method is already described in scientific[4,5] and patent[6,7] publications. Therefore, we shall discuss here only the results of studying the processes of mode transformation which is in the base of the new method of accelerating field formation, as well as some features of compensation resonant devices and also the results obtained for the characteristics of the accelerator under the operating conditions of a smooth accelerated particle energy variation.

As mentioned earlier[4] the principle of the smooth accelerated particle energy variation lies in the establishing of a region with a uniform distribution of an accelerating field the extent of which can be shorter than a cavity length, and this extent is adjusted along the accelerator axis. This continuous adjustment of the mentioned extent of a region is realized by deforming the field distribution corresponding to the E_{011} mode. The problem is to shift the node peculiar to this mode field distribution along the accelerating structure and to form the region with a uniform field distribution and with a rather steep slope from the left-hand branch of the field (Figure 1).

The right-hand branch should be suppressed, otherwise it would have an important effect on the parameters of the accelerated beam with an intermediate energy and would also involve additional rf power losses.

The problem of the formation of such field distribution is solved by using a combination of tuning devices of two types: the resonant type device designed as a conducting post of the con-

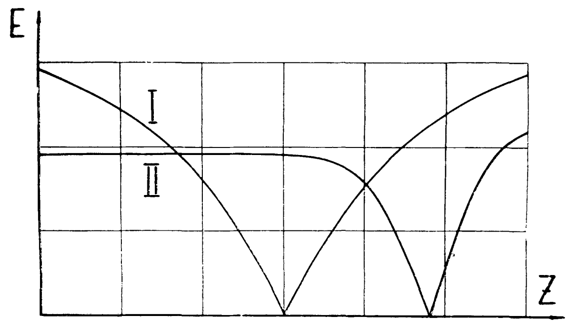

FIGURE 1 The field distribution along of the drift tube cavity excited at the mode E_{011} (a) all cavity cells are tuned in the some resonant frequency, (b) the cells frequencies are perturbed to obtain the shorter uniform field range.

trolled length placed at the output end wall of the cavity, which will be called hereafter a 'resonance longitudinal compensator' (RLC) (Figure 2), and volume tuning devices of the usual type placed at the side wall of the cavity. The RLC shifts the node of the field and compensates the right-hand branch, whereas the volume tuners ensure a uniform distribution of the left-hand branch and the slope steepness.

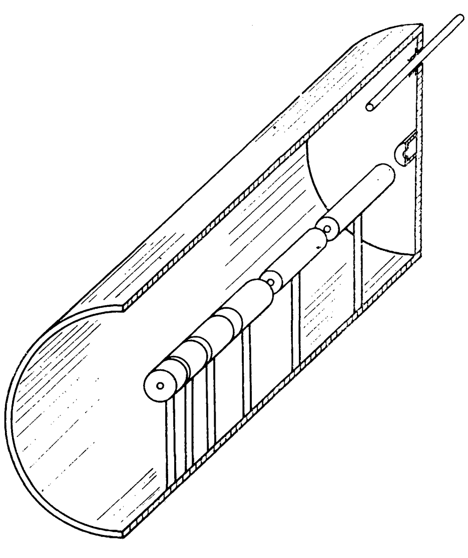

FIGURE 2 The accelerating structure with a resonant longitudinal compensator.

The papers[4,5,8] present the pictures of the fields formed in the way mentioned as well as the parameters of the accelerated beams. A continuous variation of particle energies was realized with PLA-9 and LUMZI-10 in the range of $(0.3–1)W_{max}$ with the beam intensity and monochromacy remaining unchanged. Simultaneously an important increase in the stability of the accelerator's operating parameters was attained which was due to the decrease of the field distribution sensitivity to frequency perturbation caused by mechanical and temperature deviations. As was shown, these new advantages followed from the field formation method itself, as well as from the peculiarities of the compensation device used.

As an example Figure 3 shows the excitation functions for the cross sections of the proton elastic scattering on carbon nuclei at an angle of 60° measured with a 20–40 keV step. The experimental results obtained using the accelerators with a variable energy are described in Refs. 9 and 10.

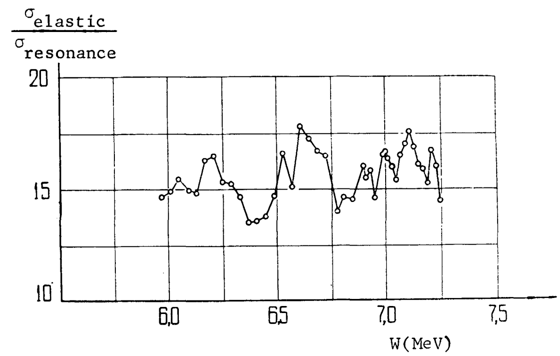

FIGURE 3 The cross section of the excitation function for the elastic scattering on the carbon nucleus.

The experiment made with PLA-9 has shown that the introduction of the resonant compensator in the form of a conducting post placed at the output end wall of the cavity parallel to its axis gives a maximum possibility for affecting the field distribution in the whole mode spectrum

$$E_{01l}\ (l = 0, 1, 2, \dots).$$

Its position parallel to the electric field lines provides a maximum coupling between the fields of the modes mentioned and the field of the RLC itself. Figure 4 shows the effect of such a resonant longitudinal compensator placed near the side wall of the cavity. It shows some stages of successive changes in the electric field distribution for the hybrid mode resulting from the interaction of the E_{011} mode field and the field of a single longitudinal compen-

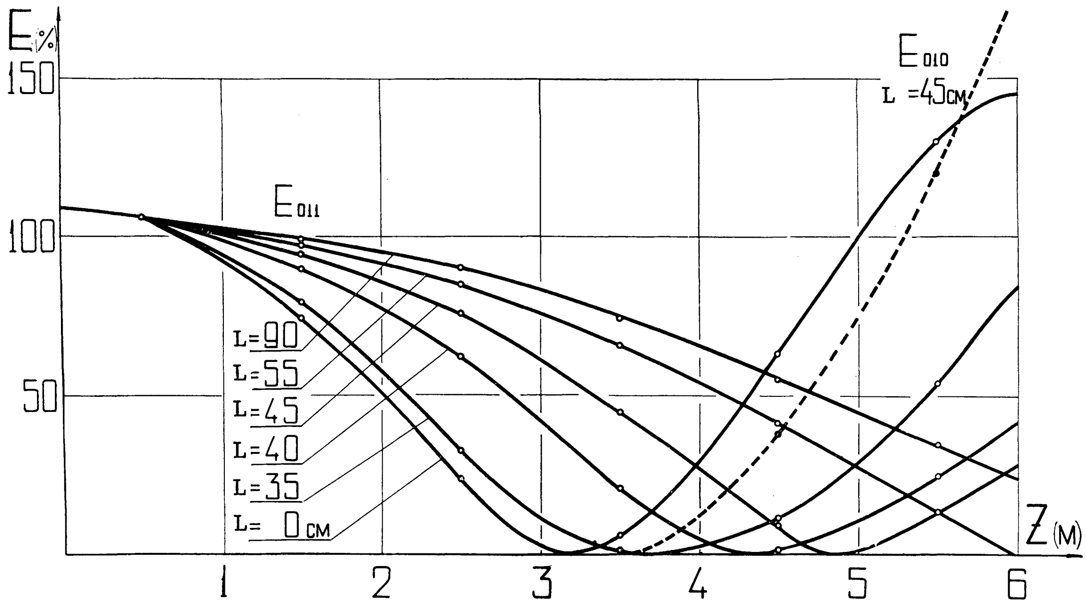

FIGURE 4 The field distribution along of the cavity excited at the mode E_{011} for different RLC length.

sator C_1. Further on, this hybrid mode will be denoted as E_1C_1. From Figure 4 it is seen that the field distribution characterized by a symmetry of the two branches relative to the node for the RLC length equal to zero, begins to distort with the increase of L and the node shifts towards the end wall. It is also seen that the field still continues to change after the node approached the wall.

The frequency change for the mode interaction mentioned is shown in Figure 5. The dashed lines show the frequency dependence on the length of an RLC which is near the resonator axis. It is seen that the frequencies of all hybrid modes E_lC_1 change within the range $f_l - f_{l-1}/2$. This is due to the fact that for a certain length L, the last node of each mode in the lower edge of the band $E_{01l}(l>0)$ approaches the wall where the RLC is mounted, which means that here there is no longer a longitudinal component of the electric fields, therefore a further increase of L would not practically affect the field distribution.

Removal of the RLC from the cavity axis region results in a different frequency dependence. In Figure 5 the solid lines show the frequency change of the hybrids E_0C_1, E_1C_1, E_2C_1, E_3C_1 when the RLC is positioned in the vicinity of the side wall of the cavity. It is seen that in this case the frequencies

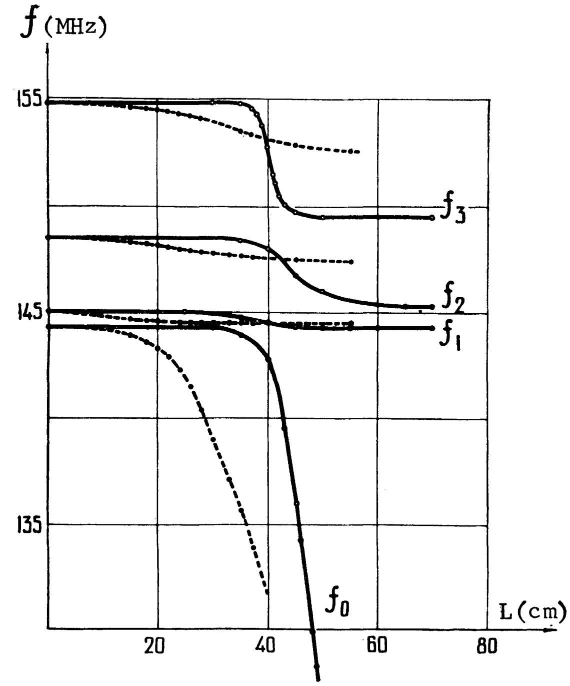

FIGURE 5 The frequency dependences for the PLA-9 cavity vs. RLC length.

change by a value close to $f_l - f_{l-1}$. Investigation of the hybrid mode field transformation has shown that in this case compensation of the whole half-wave of the initial E_{01l-} field distribution occurs. For small values of L there is first a compensation of longitudinal components of the last right-hand branch and then, with the increase of L transverse components of electric fields begin to be compensated.

The process of the frequency mode transformations in the lower edge of the band E_{01l} as a function of the distance from the cavity axis is presented in Figure 6 where the frequency behavior is shown for the compensators of different lengths.

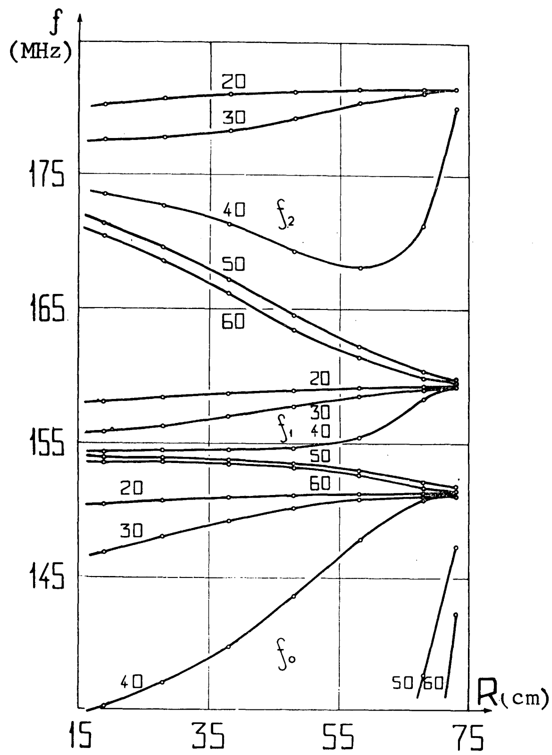

FIGURE 6 The frequency behavior of the PLA-9 cavity for different RLC length vs. its radial location.

The formation of uniform field ranges with a regulated length which is necessary for the continuous particle energy variation was realized in practice by changing L within the length range up to 45 cm. In this case, as seen from Figure 5, the difference between the operating mode frequency which is the hybrid E_1C_1, and those corresponding to the hybrid E_lC_1 $(l = 1, 2, 3, \ldots)$ exceeds essentially the difference between unperturbated wave frequencies $(L = 0)$. And it is known[11] that the stability of the accelerating field distribution is characterized by this particular difference.

The experimental studies of the accelerating field distribution with PLA-9 ($h = 6$ m, $\lambda = 2$ m) have shown that in operation with the transformed mode E_{1T0} the stability increased by a factor of 6 as compared with the operation at the usual mode E_{010}. The field stability increase has improved the beam characteristics accompanying the continuous particle energy variation.

The ratios of the rf power consumed to obtain the accelerated beam under different operating conditions are of practical interest. For the method described above of forming uniform field ranges which are shorter than the cavity length it was shown that for the excitation of the design accelerating field strength in the cavity volume corresponding to the length of the ranges mentioned the losses in the accelerating structure surfaces were proportional to the length of these ranges. In the remaining part of the volume where energy was not stored essential losses were observed. Thus, the particle energy decrease was accompanied by a corresponding decrease of the rf power consumption. For the particle acceleration up to the maximum energy in the operating conditions of the transformed mode E_{1T0}, the rf power consumption corresponded practically to that in the operating conditions of the unperturbated mode E_{010}, the measured value of Q was about 43,000 in both cases.

Figure 7 shows the rf power losses in the compensator walls as a function of the compensator's length, which determines the introduced perturbation of the E_{011} mode field. As is seen, in the length range $L \leqq 35$ cm the power losses in the compensator are insignificant and are about 10 W or 5 kW peak. In the region $35 < L < 40$ cm the losses reach their maximum value 47 W or 24 kW peak, which is about 5 per cent of total losses in the cavity of the PLA-9. With the further compensator length increase the losses decrease again. The dependence shown of the loss changes in the compensator is in agreement with the transformation of the mode field distribution.

Thus, the rf energy lost in the compensator, even in the extreme case, is insignificant and may be readily taken away by water cooling.

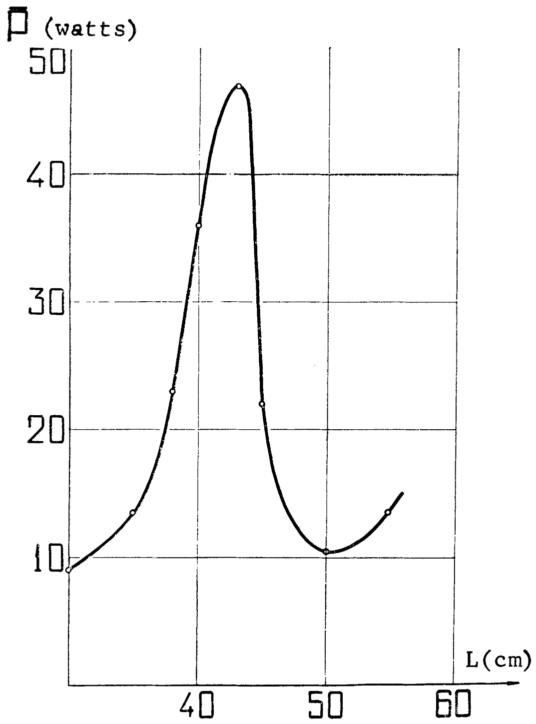

FIGURE 7 RF power loss in RLC vs. the depth of the on post immersion in PLA-9 cavity.

The method considered of variation of accelerated particle energy differs also by a proportional decrease of the consumed rf energy. Due to its simplicity this method may be realized in accelerators already operating as well as in still to be designed linear accelerators of protons and multicharged ions.

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