PROBLEMS OF THE BEAM LOSS IN INTENCE ION LINEAR ACCELERATORS

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Linacs of meson factory type have opened up a new era in medium-energy physics. A jump in the intensity of a primary proton beam by two or three orders of magnitude (the average beam current ~1 mA) leads to an increase in the intensity of secondary beams (of mesons, neutrons and neutrinos) by two or three orders of magnitude and, which is no less important, to a significant improvement of their monochromaticity. However, the increase in the linac intensity has posed quite a new problem - limitation of the particle loss at a level of $\sim 10^{-4}$, which is 100 times less than the loss in accelerators of the preceding generation. Precisely this fact - the difficulty of bringing tothe design intensity due to the danger of the linac activation - determines a long running-in period of linacs of meson factories.

To illustrate possible ways of solving the problem at hand, we consider a linac of the Institute for Nuclear Research - Moscow Meson Factory (MMF). Meson factories make it possible to accelerate four types of particles (H^+, H- and H^+, H^- polarized). For this purpose it is more convenient to use sources with a low energy of about 100 keV wiht subsequent acceleration in a RFQ up to 0.75-2.0 MeV. Then the beam is accelerated in the Alvarz structure (the first part of the linac) at RF of ~ 200 MHz. At an energy of 100 MeV a transition is made from the Alvarez structure to a disc and washer structure, which is accompanied by a 4-5-fold increase in the RF, involving extra difficulties in the provision of radioactive purity.

The linear accelerator is considered radioactively pure [1] if the dose power of induced activity gamma radiation does not exceed the professional norm of 2.8 mrad/hr at a distance of 1 m from the long-operating linac one hour after its shutdown. In terms of this definition Fig.1 gives the energy dependence of the absolute permissible loss of protons or H^- per unit length of the linac. It thus appears that for intensity beams (with a current of ~ 1 mA) rigid limitations are imposed on the value of the relative loss of particles, especially high-energy ones.

There are three main groups of causes of the particle loss: the loss of longitudinal and transverse stability and the charge exchange of H^- ions on residual gas.

The radial loss can be eliminated if the channel acceptance is always greater than the effective beam emittance. For this purpose use is made of collimating filters with the aperture smaller than that of the channel. Another efficient means of reducing the transvers loss of particles is the use of systems of damping coherent transverse beam oscillations, wich compensates for the increase in the effective emittance (displacement from the linac axis). It is desirable to have several such systems equally spaced apart since the increase in the effective beam radius is $\sim\sqrt{n}$ (n - is the number of focusing periods).

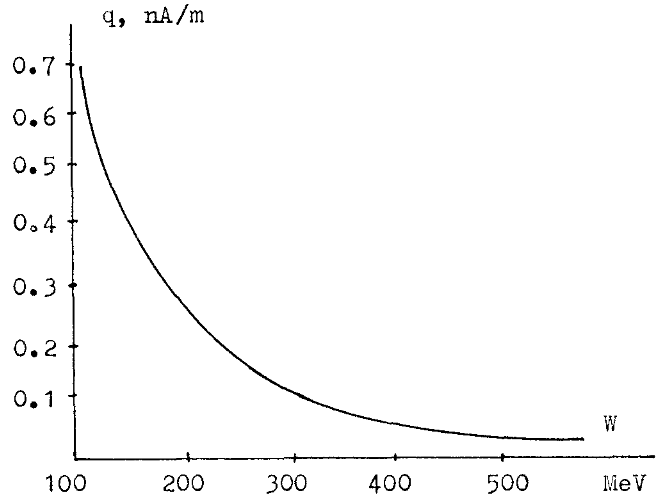

Fig.1. Energy dependence of the permissible particle loss for radioactively pure linac.

For the eliminating the particle loss due to the charge exchange of H^- on regidual gas the vacuum must be better than 10^{-8} torr.

For avoiding the longitudinal particle loss it is necessary that the beam phase volume should be within the capture area. For this purpose it is necessary to have a well bunched beam with the phase density maximum at the centre of the separatrix and minimum at the edges. To this end use is made of bunchers or, which is more efficient, RFQ accelerators. In the former case a filter is also required since any buncher does not get rid of peripheral particles in the longitudinal motion. However, in contrast to the radial filtration, the use of the longitudinal filtration may lead to a significant decrease in the intensity. This is explained by the fact that the character of particle dynamics in the filter and in the linac is different: together with "future peripheral" particles quite "good" particles are also removed. Therefore the implovement of RFQ accelerators has an undeniable advantage.

During the motion of a beam in the linac occure two opposite processes. On the one hand, the phase dimensions of the bunch are damped in accordance with adiabatic laws. On the other hand, the effective dimensions also increase due to errors in the channel by These errors can be both static (the error in setting the amplitude and phase of the accelerating field and the nonideality of the field distribution along the cavity) and dynamic (temporal).

In the first part of the linac the particle velocity varies in a considerable range (from 0.04 to 0.4). As a result the damping of the bunch phase dimensions far exceeds the increase in the effective parameters and no longitudinal particle loss practically occurs. At the same time the final beam parameters in the first part become initial at the entrance to the main part of the linac. Therefore even in the first part of the linac provision is made for a system of damping coherent beam oscillations and for fairly stringent requirements for stabilization systems.

The maximum damping coefficient of such system is determinated by the minimum bandwidth covering the cut-off frequency of the stabilization system. This diminishes the efficiency of compensation for static errors but helps to solve the problem of diminishing the influence of instabilities of the RF field.

The maximum stabilization coefficient is determined by both the system itself and the cavity properties. What is meant here ? For suppressing the distortions of the average field level in the cavity (fundamental mode) the stabilization system initiates the input/output of an additional RF power which excites all adjacent modes. Obviously, the maximum stabilization coefficient can be determined from the equality of the influence of these two processes on the beam

$$K = \sqrt{(\Delta\omega/\omega)\, Q_n \,/ f_n}$$

where $(\Delta\omega/\omega)_n$ is the distance to the adjacent excited n-th mode with the quality factor Q and f is the coefficient of the influence of the n-th mode on the beam parameters, normalized to the coefficient of the fundamental mode. Since the $f(n)$ decreases with increasing n as $1/n^2$ it is necessary to strive for increasing the n. This is achieved by branching the RF power supply. For example, in the case of RF power supply from the two ends of the cavity n =3. The minimum attainable instability for the cavities of the first part in this case will be ~ 0.5% with allowance for the perturbation of the accelerating field by the beam at a level of ~20% and at K =40. In the case of RF power supply at one point (in the middle of the cavity) the maximum coefficient K is 35 and from the edge of the cavity K =17. The minimum instability of the field also changes correspondingly.

All this should also be taken into account in choosing the ratio of the RF beam power to ensure the required rate of acceleration. And this, in the final analysis, determines the required duration of an RF pulse for obtaining the required average beam current.

Fig.2 shows the dependence of the phase length of the capture area (curve 1) and of the effective bunch with 99.99% of the particles to the left of the synchronous phase on the number of the cavity in the second part of the MMF at the instability of the amplitude and phase of the RF field of 0.5% and 0.5° in the first part and of 0.5% and 0.5° (curve 3) and 1%, 1° (curve 2) in the second part. It is evident from this figure that the instability of 1%, 1° does not meet the requirements for the limitation of loss.

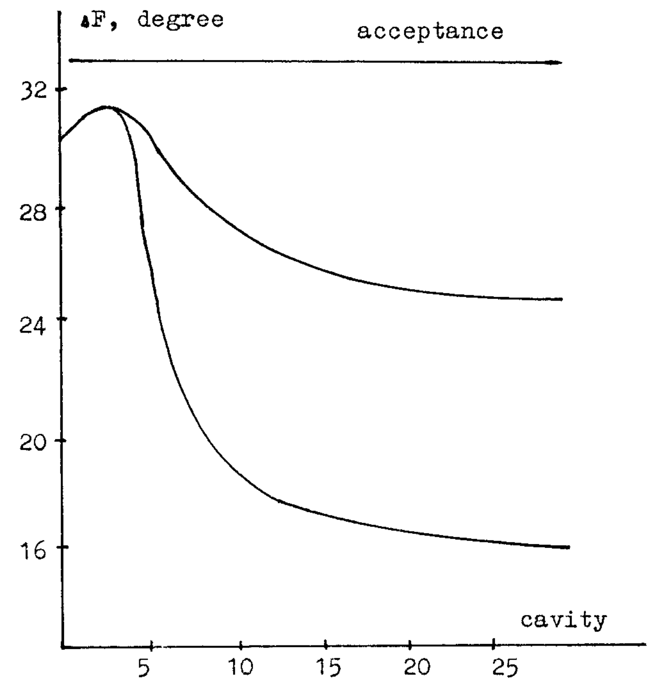

Fig.2. Dependence of the phase length of the capture area and of the effective bunch to the left of the on the number of the cavity in the main part of MMF.

Apart from instabilities, the static errors also lead to an increase in coherent bunch oscillations. For diminishing these oscillations, special tune procedures, e.g. a ΔT-procedure, have been developed. However, in that procedure [2] no account was taken of possible errors in making cavities, that may lead to an incorrect interpretation of the result obtained.

In refs. [3] and [4] new aspects of the ΔT-procedure are outlined which will help to avoid this. Since errors in the making and RF tuning of cavities are unavoidable, special attention was given to their influence on the generalized characteristics - the synchronous phase and synchronous level of the cavity energy.

In Ref.[4], relations were obtained for $\delta\beta/\beta_s$, $\delta\varphi_s$ which make it possible to dterminate the contribution of the perturbations with a certain wavelength to the increase in the amplitude of coherent phase oscillations. Specifically, if the field amplitude modulation in a cavity of length L appears as

$$\frac{\Delta E_z}{E_z} = \varepsilon \cos\frac{\pi k z}{L}$$

where k =1, 2, ... and ε is the perturbation amplitude, then we obtain

$$\frac{\delta\beta_s}{\beta_s} = \frac{\Omega}{\omega}\,\frac{\varepsilon\, ctg\,\varphi_s}{(\pi k/\mu)^2-1}\cdot\frac{1-(-1)^k}{2}\,\frac{\sin\mu}{1-\cos\mu}$$

where μ and (Ω/ω) - are the phase advance and the frequency of linear longitudinal oscillations in the cavity. At the same time the change in the length L of macroperiod "section + drift space" by ΔL also leads to a corresponding change in the quasi-equilibrium (or equivalent) phase velocity

$$\frac{\delta\beta_s}{\beta} = \frac{\Delta L}{L}\left(1 - tg\frac{\alpha}{2}\right)$$

where α is the time-of-flight factor of the section.

The authors of Ref. [3-4] proposed that an additional stage be introduced into the T-procedure which includes a correction of the macroperiod length in order to compensate for electric and geometric perturbations and to minimize the $\delta\varphi_s$ and $\delta\beta/\beta_s$. As a result the capture area in the longitudinal motion is completely restored.

And to conclude, turn to Fig.2. It follows from it that the most important problems of the particle loss will arise in the first four cavities of the main part of the MMF. On the other hand, the results of numerical simulation indicate that the particle lost in the longitudinal motion at energies of above 160 MeV will be transferred by the focussing channel to the end of the linac. For this purpose one can increase the field level in the first four cavities and accelerate the future lost particles to an energy that will allow the radial stability to be retained up to the end of the linac, thereby localizing the particle loss.

References

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