LARGE LINAC-BASED ELECTRON COOLING DEVICE

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The electron beam for electron cooling is traditionally obtained by direct electrostatic acceleration. But for the higher electron energies (above 5 MV), the difficulties in implementing sharply increase and set natural limits for such method in use.

That is why it is interesting to consider alternative ways for obtaining a high energy electron beam applicable for the electron cooling. Thus, to obtain the electron cooling at the collider ENC for GSI storage ring, it is necessary to have an electron beam with an energy of 15 MV, a current of up to 1A, an energy spread of $\frac{\Delta\gamma}{\gamma} \sim 10^{-4}$, and $\frac{\Delta P_\perp}{P_\parallel} \sim 10^{-4}$ spread in a transverse momentum.

As the ion beams cooled at GSI are bunched with a σ_z of 10 cm, and the bunches follow each other at a 60 MHz frequency, the cooling electron beam can be bunched as well.

The usual source of bunched electron beam of such energy and intensity is a linear accelerator. The main problem for using the linear accelerator for our purposes is a way to meet high precision requirements to the energy and momentum spreads of beam.

For the sake of definiteness, let us consider a device, one of possible rough drawing of which is given in Fig.1. The version of linear accelerator under consideration consists of six identical units, each unit consists of four 60 MHz frequency resonant cavities with a 700 KV voltage, one 180 MHz frequency resonant cavity, and one 300 MHz frequency resonant cavity (2 of these 6 units are shown in the figure). A rough drawing of the main 60 MHz resonant cavity is given in Fig.2. The supposed characteristics of the resonant cavities are given in Table 1.

Table 1.

N	1	2	3
Frequency of a cavity (MHz)	60.0	180.0	300.0
Voltage at a gap (kV)	700.0	466.0	56.0
Amount of cavities	24	6	6
Shunt resistance (ohm)	$2.4 \cdot 10^6$	$3.5 \cdot 10^6$	$15 \cdot 10^3$
Q-factor	$15.5 \cdot 10^3$	$33 \cdot 10^3$	$14 \cdot 10^3$
Power dissipated by (kW) one cavity	104.0	31.0	1.5
Total power dissipated by all the cavities (kW)	2500	181	9
Power consumed by electron beam in one cavity (kW)	70.0	-47.0	5.6
Total power consumed by electron beam in all the cavities (kW)	1680	-287	34

The bunched electron beam of 0.5 - 1 MV energy is injected to the linear accelerator from an electrostatic preinjector. The whole cavity system as well as the preinjector is immersed in a longitudinal 0.5 T magnetic field, created by a superconducting solenoid.

The main factors, affecting the energy and momentum spreads of the electron beam in this linear accelerator, are the following:

1. The time dependence of the accelerating RF voltage in the accelerating gap during the passage of a short electron bunch.

2. The influence of a space charge field on the energy spread of particles.

3. The influence of inhomogeneity of the longitudinal magnetic field and of the electric field transverse components of the cavity on an increment in transverse momentum of particles.

4. The influence of the wake field upper harmonic of the cavity on the motion of particles.

We shall briefly consider each of these factors.

1. The way to obtain the rather constant RF voltage in a cavity during the passage of a short bunch through the accelerating gap is well known. For this one needs only to add the required quantity of upper harmonics of a necessary amplitude to the main RF harmonic. In order to meet a requirement of $(\frac{\Delta\gamma}{\gamma})_{gap} \sim 10^{-4}$ for every section of the accelerator, one need only to add both the third harmonic with a relative amplitude of 0.167 and the 5th one with a relative amplitude of 0.02 to the leading harmonic. The additional correcting cavities of 180 and 300 MHz frequencies, shown in Fig.1, are used for this purpose.

2. When the short bunch passes through, the particles which are at a distance s from its center are affected by the longitudinal component of the space charge force. Let us suppose that the density distribution of bunch particles is parabolic in form.

$$n(s) = \frac{3}{4} \cdot \frac{N}{\sigma_x} \cdot (1 - \frac{s^2}{{\sigma_x}^2})$$

Then once the bunch passed the distance l, the particle being at a distance s from the bunch center has an additional longitudinal momentum.

$$\frac{\Delta P_\parallel}{P} = \frac{3}{2} \cdot \frac{N r_e g}{{\sigma_x}^3 \gamma^3 \beta^2} \cdot ls$$

Here: $g = 1 + 2ln(\frac{a}{b})$,
N is the number of the electrons in the bunch
a is the radius of the beam
b is the radius if a vacuum chamber
r_e is the classical electron radius of 2.810^{-13} cm.

At high energies ($\gamma \sim 10$) this value is negligibly small ($\sim 10^{-5}$) when the bunch passes the distance of 100 m. But at low energies ($\gamma \geq 1$) the value $\frac{\Delta P_{\parallel}}{P}$ will be equal to 10^{-3} just after the bunch passes 1 m. But, as the phase dependence of the longitudinal momentum increment is a linear one at a chosen special form of the density distribution of bunch space charge, this effect can be easily corrected.

Here it is pertinent to note the following. At a first glance it would seem that the accelerator operating in a range of rather short wave lengths of about $1 \div 10$ cm is more attractive, as its overall dimensions are relatively small as well as its cost. But as $\frac{\Delta P_{\parallel}}{P} \sim {\sigma_z}^3 \sim {\omega_0}^3$, where ω_0 is a main frequency, it is obvious that the difficulties, related to the effect of space charge on the accelerator particle dynamics, sharply increase with an increase in the accelerator working frequency and become insuperable. Besides, there are much more problems connected with the necessity to obtain super short electron bunches at a stage of their injection to accelerator and to significantly elongate the accelerated bunch. In this connection it is seen that we should use the minimum RF frequency. So the accelerator working frequency is chosen considering the reasons just listed.

3. The particle can acquire an additional transverse momentum, when it moves in the inhomogeneous electrical field of the cavity, and effected by small inhomogeneities of the longitudinal magnetic field.

It can be shown that in the case of small disturbances the transverse momentum increment of a particle can be compensated by a special correcting magnetic lens. This lens creates an additional disturbance of longitudinal magnetic field of the required amplitude. It should be located at a point determined by a phase of a Larmour motion. Fig. 3 shows the possibilities to compensate the transverse momentum increment of a particle moving in the inhomogeneous electrical field of the cavity. There are shown trajectories of particle motion in the transverse momentum space for the case of absence of such compensation (b) and for the case of presence of a correcting lens (c). Fig.3(a) presents strength component distributions of the cavity electrical RF field and of the leading magnetic field along the direction of particles movement.

The precise adjustment of all the correcting lenses positioned after every resonant cavity is a delicate and labour-consuming work. Besides, errors in production and alignment of the cavities lead to an increase in the transverse momentum of particles. This casts some doubt upon the real ability to obtain the accelerated electron beam of required characteristics and hence upon the serviceability of the proposed device. But there is one rather elegant way to avoid these difficulties. Let us assume the bunch moves along the system of cavities, acquiring the transverse momentum component increment at the accelerating gaps for some reasons. Assume there is a special correcting lens at the accelerator outlet (for some cases, when the total value of transverse momentum is sufficiently small, its role is played by the electrical field inhomogeneity of the last cavity).

Let us consider an ideal case, when the particle motion disturbances caused by cavity fields are in one plane, for example X-Z (Z is the direction of the particle motion). Here we can always eliminate the increment of particle transverse momentum, acquired during the acceleration. For this we need to properly choose the value and phase of the disturbance created by the correcting lens.

Obviously for the case of one-dimensional disturbances, we can always eliminate the residual increments of particle transverse momentum, acquired during the acceleration, by a proper choice of these two parameters. To show the efficiency of the described method we have simulated the simplest model. We supposed that the disturbance in the transverse motion of particles was due to a random error in the cavity angle alignment in a plane (X–Z) (Z is the direction of particles motion; the value of a standard deviation in our calculations was adopted as 0.01). We calculated the particle transverse momentum (at the accelerator outlet) depending on the value of the leading longitudinal magnetic field. The results are presented in Fig.4(a) and Fig. 4(b). It is seen that this value is close to zero at a specific b. The extension of the described method to the case of non-one-dimensional disturbances of the particle transverse motion is obviously out of principal difficulties. This correction method was successfully used for electron cooling at INP.

4. The wake fields of upper harmonics for the current with a peak amplitude of 1A, and a bunch length of 10 cm following each other at a frequency of 60 MHz were calculated for the main 60 MHz resonant cavity. Relatively small dimensions of the cavity provide a low beam–imposed voltage at an accelerating interval. Fig.4(a) shows the spectrum of upper axial symmetrical modes in the cavity, which are excited by the beam. The values of both active and reactive components of the imposed RF voltage are given in Fig. 4(b) and 4(c), respectively. As is evident, the imposed voltage values are small. Moreover, the reactive component of the imposed voltage, contributing significantly to the amplitude, linearly depends on phase, and this value can be easily corrected when needed.

So, the results of the above estimations show, that there are reasons to hope to obtain the electron beam parameters required for electron cooling. This will enable to extend the use of electron cooling of heavy particles in a several GeV range energies per nucleon.

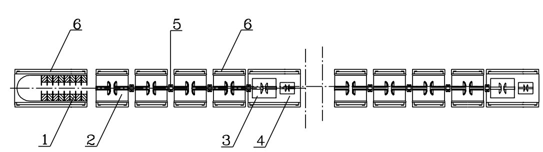

Fig.1 General view of LINAC

1–preinjector,
2–main cavity (F=60MHz),
3–correcting cavity (F=180MHz),
4–correcting cavity (F=300MHz),
5–correcting magnet lens,
6–superconducting solenoid

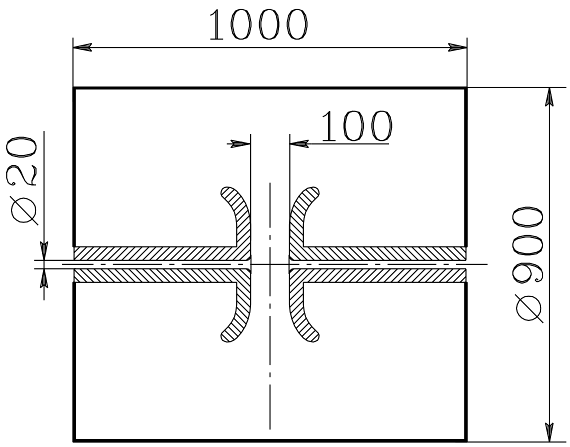

Fig.2 General view of main cavity,
(F=60MHz, U=700kV)

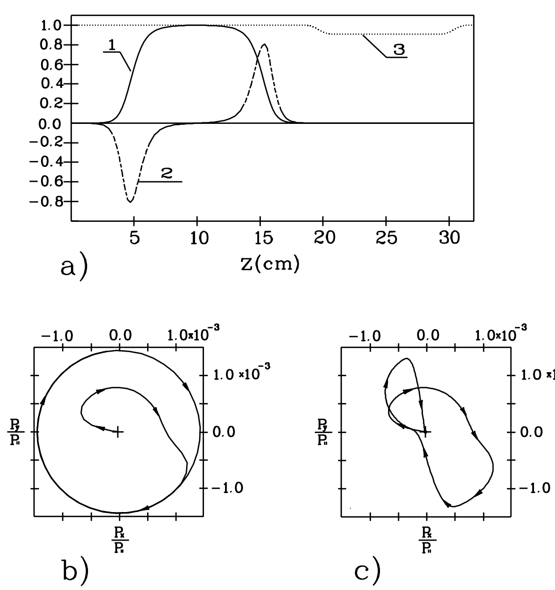

Fig.3 Correction ot the influence of inhomogenity in cavity electric field on the transverce motion of electron.

a) distribution of fields
  1–longitudinal electric field of cavity
  2–radial electric field of cavity
  3–longitudinal magnetic field
b) trajectory of the particle motion in a transverse momentum spase (correcting lens is absetnt)
c) trajectory of the particle motion in a transverse momentum space (correcting lens is present)

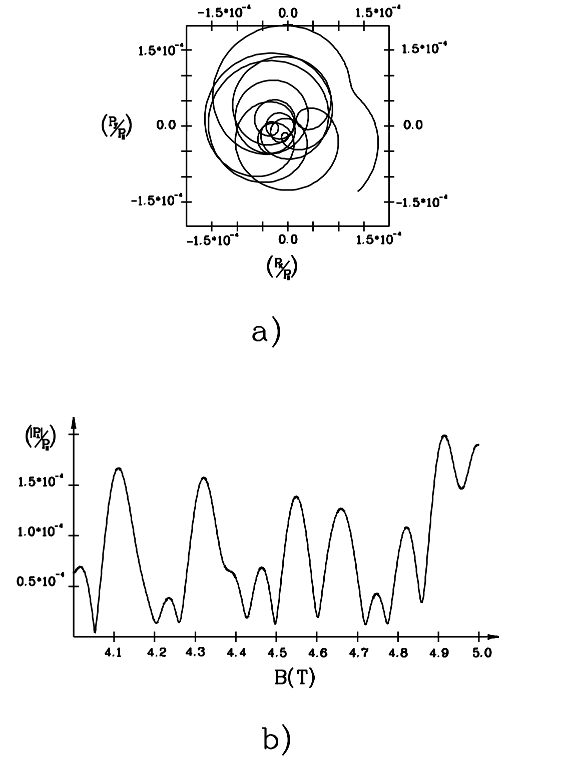

Fig.4

a) position of a particle in its transverse momentum space at accelerator outlet, depending on the longitudinal magnetic field.
b) dependence of transverce momentum, aquired by particle after its passage througtout the accelerator on the longitudinal magnetic field

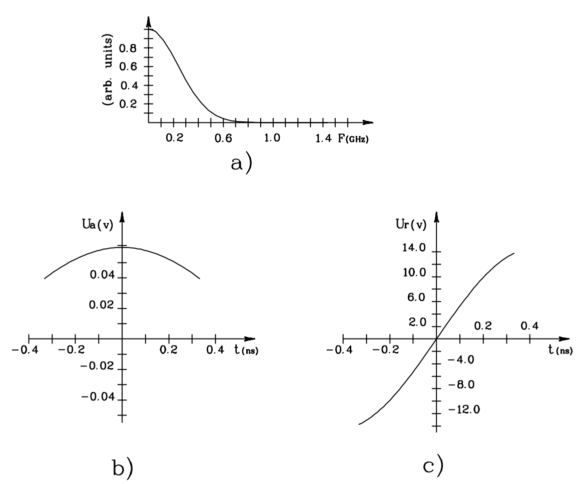

Fig.5 Cavity fields awaked by accelerated electron beam.(peak electron current is 1 A electron banch duration is 60 MHz, length of bunch 20cm).

a) wake field spectrum
b) active component of wake field volage
c) reactive component of wake field voltage