# BUNCH SHAPE MEASURING TECHNIQUE AND ITS APPLICATION FOR AN ION LINAC TUNING

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## Abstract

A bunch shape measuring technique for an accelerated ion beam has been developed. The principle of operation is based upon the transverse rf modulation of low energy secondary emission electrons produced by ion beam passing through thin foil. A method for correct setting of phase and amplitude of the rf fields in bunchers and Alvarez tank is developed by using bunch shape measurements. Another application of developed technique is described for a longitudinal beam emittance measurements with the help of accelerating structure for a bunch rotation.

## 1. Introduction

Longitudinal bunch density distribution in ion linac is one of the main characteristics of accelerated beam. Taking advantage of this parameter one may conclude about longitudinal tuning quality. For example, the information about a bunch shape after buncher makes possible to find rf voltage upon a buncher gap. Results of bunch shape measurement after accelerating tank may be used to set rf phase and amplitude. Longitudinal bunch density may be used to calculate energy spectrum and longitudinal beam emittance. Bunch shape information is extremely importante for medium energy accelerators consisting as a rule of two main parts with multiple wavelength of accelerating rf field. If bunch shape is known, the problem of longitudinal matching is simplified considerably.

Qualitive measurement of a bunch shape is rather complicated technical problem and requies development of special apparatus. This paper is devoted to the description of bunch shape measuring technique and methods of its application for an ion linac tuning.

## 2. Bunch shape measuring technique

The main requiement to a bunch shape measuring technique is a good phase resolution. As far as we know, the best result is obtained, when effect of low energy secondary emission from thin target is used. The ion beam under study crosses the target and knocks out secondary electrons. Time delay of secondary emission is extremely small, so bunch shape of electrons is the same as that of ion beam. Measurement of bunch shape of electrons is based on a synchronous conversion of longitudinal position to a transverse position through rf modulation. The monitors described in papers[1,2] use longitudinal modulation and have resolution of order of few degrees with power consumption 3.5 kW[1] and 60 W[2]. The monitor we have developed uses rf modulation of secondary electrons too, but direction of modulation is transverse rather than longitudinal. The schematic diagram of the monitor is given in fig.1.

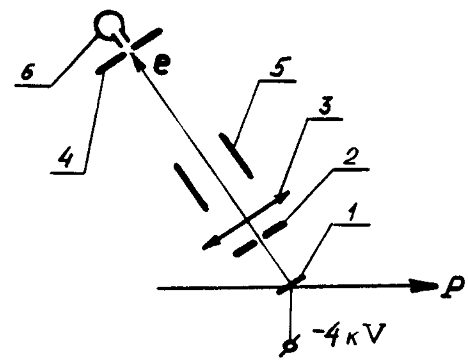


Fig.1 The schematic diagram of the monitor

The potential of target 1 is negative. Being accelerated up to energy 4 keV electrons pass through the input collimator 2. The electrostatic lens 3 is used to obtain the image of the beam at the output collimator 4. The transverse modulation of electrons is made by the rf deflector 5. The value of deflection depends on a phase of deflecting field, which is synchronous with the field in linac. As the time of flight from the target to the deflector is constant, collector 6 registraits electrons knocked out by ions having a definite phase. That is, the current through the collector is proportional to a definite point of longitudinal bunch density distribution. Another points are obtained by changing of phase of rf deflecting field.

When analysing phase resolution we considered the following factors: time delay and initial energy and angular dispersion of secondary emission electrons, distortion of electron bunch density because of finite target dimensions and while passing from the target to the deflector, finite image dimensions of a focused beam because of the target and input collimator finite dimensions. Fig.2 shows the dependance of phase resolution (f=198.2 MHz) on the amplitude of rf voltage on the plates of the deflector for the slit of input collimator 3 mm, two kinds of targets (wire 0.1 mm diameter and strip 2 mm width) and different frequencies of deflecting field. It is seen, that there is the optimum value of voltage corresponding to the minimum value of resolution. Further increasing of voltage leads to aggravation of resolution because of appreciable displacement of electrons from the axis of the deflector to the region of a nonuniform deflecting field.

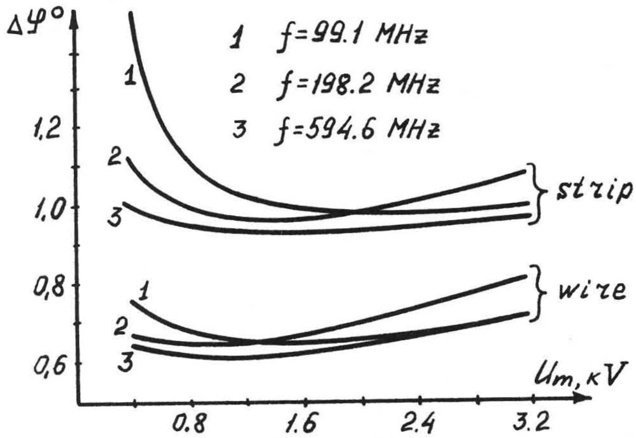


Fig.2 The dependance of phase resolution upon the amplitude of rf voltage on the deflecting plates

As the authors of the papers above mentioned have done, we used a thermionic emission to simulate electron beam for testing and adjusting of electron optics. The target was replaced by a tantalum filament and the image was visually observed on the phosphor coated plates of the output collimator. The dimension of the image was about 0.3-1.0 mm and depended on the filament and input collimator dimensions. Thermionic emission was used to measure equivalent resistance of the rf deflector $R_e=U_m^2/2P$, where $U_m$-amplitude of rf voltage on the plates, P-rf power dissipated in deflector. The value of $R_e$ is equal to $9.10^4$ Ohm. As one can see from fig.2, the optimum value of resolution for f=198.2 MHz is obtained for P=3 W.

Preliminary test of the bunch shape measuring technique was made at the $H^+$ injection channel of the USSR meson factory. We visually observed the image produced by secondary electrons on the phosphor. The dimension of the image was a little larger, than that produced by thermal electrons. This effect well agrees with computer results previously obtained. The proton beam current was varied up to 30 mA and we did not observe any changing of image dimensions. This fact indicates, that space charge effects do not influence the electron optical characteristics of the device. The common view of the apparatus installed in injection channel after buncher is given in fig.3. Fig.4 shows equivalent cirquit and common view of rf deflector.

## 3. Application of bunch shape measuring technique for a linac tuning

### Setting of rf phase and amplitude in klystron bunchers

To find rf voltage on a buncher gap, one can use a well known dependance of instantaneous current $I_1$ at a distance L from the buncher gap on the phase of particle $\varphi_0$

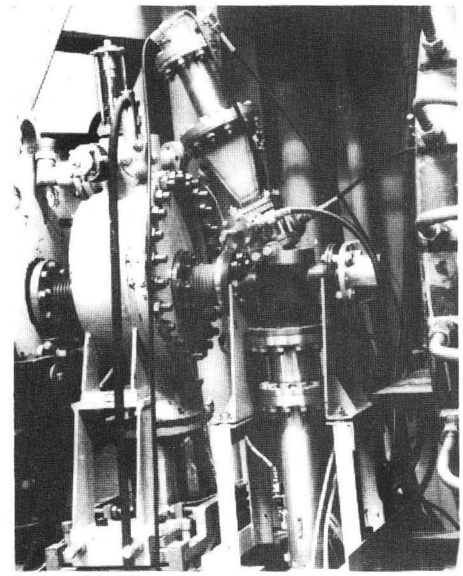

Fig.3 The bunch density distribution technique

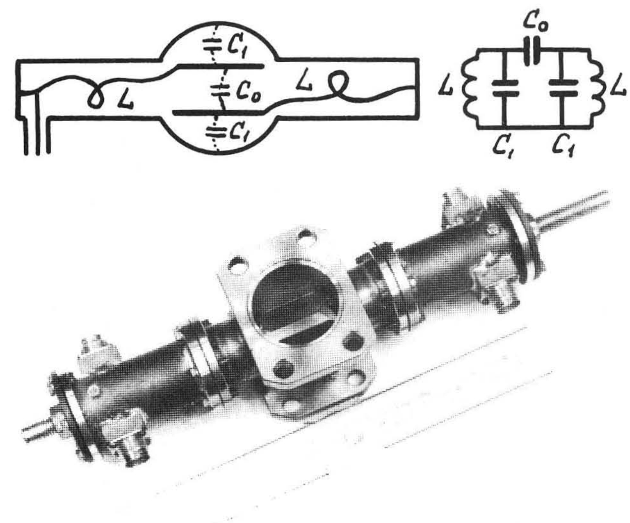


Fig.4 The rf deflector

with respest to zero of a bunching voltage:

$$I_1 = \frac{I_0}{1-a\cos\varphi_0} ,$$

where $I_0$-continuous beam current, $a= eVL/\beta\lambda W$, $\beta$ and $W$ -velosity and energy of particles, $\lambda$-wavelength, V-amplitude of effective voltage on a buncher gap. If a>1, one can measure $I_0$, $I_m=I_0/(1+a)$, $I_M=I_0/(1-a)$ and voltage V may be calculated by using for example the following expression:

$$V= \frac{\beta\lambda W}{\pi eL} \cdot \frac{I_M+I_m-2I_0}{I_M-I_m}$$

If a<1 the bunch has sharp buundaries and the dependance of its phase length $\Phi$ on a factor a is given by the formulas:

$$\Phi =2 \left|\arccos 1/a-\sqrt{a^2-1}\right| .$$

This expression may be used to find V.

Bunch density analyser may be used to set a proper phaseshift between two bunching cavities. To do it, one should shift a phase in one of the cavities by $180^0$ and measure a changing of phase position of a bunch center. If a phaseshift is adjusted properly, the changing of a bunch phase position does not occur. The uncertainty of phase setting $180^0$ may be easily removed by measuring a form of a bunch density distribution.

The accuracy of amplitude and phase setting is affected by the errors of energy W and distance L measurements, instability of W, instability of phase and amplitude in buncher under study, phase resolution of bunch length measuring technique, errors of $I_0$, $I_M$, $I_m$ and $\Phi$ measurements. The analysis showed, that one may practically obtain the accuracy of amplitude and phase setting 1% and 1° accordingly by using statistical treatment of experimental results.

## Setting of rf phase and amplitude in a first tank of ion linac

The formation of a bunch in an ion linac occurs mainly in a first accelerating tank. So there are special requiements to the accuracy of setting of rf phase and amplitude in a first tank. The traditional method based upon a compare of experimental dependances of accelerated current on phase and amplitude with theoretical ones enables to solve the problem, but there are some difficulties[3]. They are due to inevitable inagreement of mathematical model of accelerating tank with real one. Setting of rf phase and amplitude with a help of a bunch shape monitor depends on a mathematical model of a tank less rigorously. To set rf phase and amplitude in a first tank of ion linac, we use its specific property-comparatively large number of longitudinal linear oscillations N. In case of the first tank of the INR linac N=3.83 (energy of protons at the exit of the tank 20 MeV). Changing of rf amplitude leads to a changing of N:

$$\frac{\Delta N}{N} = \frac{1}{2\sin\varphi_s}\,\frac{\Delta E}{E}\,,$$

where $\varphi_s$-the synchronous phase. For example, if $\Delta E/E$=4%, then N=0.25. The longitudinal phase portraits and the bunch density distributions at the exit of the tank numerically obtained in case of injection of monochromatic beam for different E are shown in fig.5.

The bunch length and bunch density distribution depend on the amplitude of rf field and are strongly affected by the particles making linear oscillations. The dependances of a phase length of a bunch at 0.5 level and maximum of longitudinal bunch density distribution $I_M$ on the amplitude of rf field at the exit of the first tank are shown in fig.6. One can observe periodic changing of $\Phi$ and $I_M$ for the amplitudes exceeding "cut off" amplitude. The second minimum of $\Phi$ and maximum of $I_M$ is obtained, when the amplitude $E_1$ is 0.5 % less than the nominal value $E_0$.

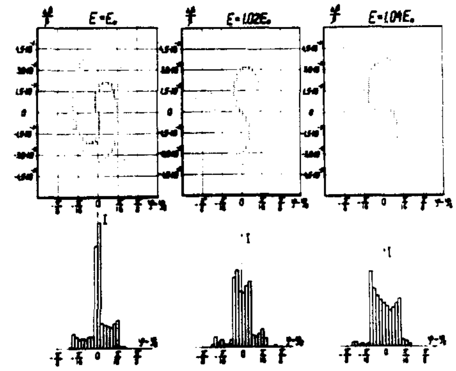

Fig.5 The longitudinal phase portraits and bunch density distributions at the exit of the first tank

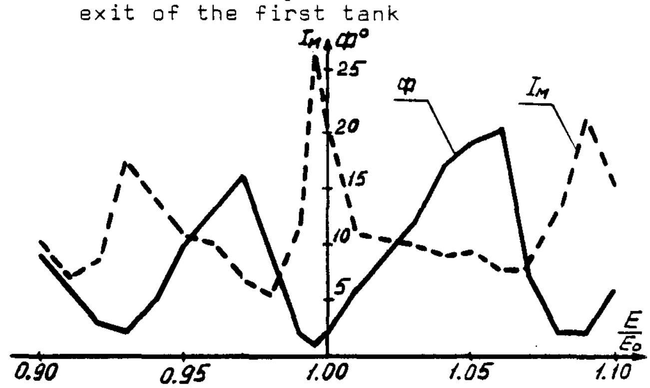


Fig.6 The dependances of a phase length of a bunch $\Phi$ at 0.5 level and maximum of bunch density distribution $I_M$ on the amplitude of rf field.

The method of setting of rf phase is qualitively explained in fig.7 (adiabatic damping of longitudinal oscillations is neglected).

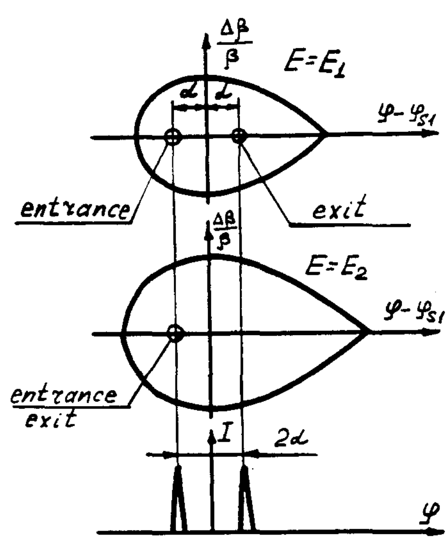


Fig.7 Qualitive explanation of the rf phase setting method.

The value of rf amplitude $E_1$ is setted $E_1=0.955E_0$. In this case N=3.5. Let the difference of the phase position of the bunch center at the tank entrance and the synchronous phase $\varphi_{s1}$ be equal to $\alpha$. The value of difference at the exit of the tank will be the same, but its sign will reverce. Next, the rf amplitude $E_2$ is setted $E_2=1.035E_0$ (N=4.0) and the phase is changed by the value $|\varphi_{s1}-\varphi_{s2}|$. In this case the phase position of the bunch center at the exit of the tank with respect to the synchronous phase will be the same as that at the entrance. As a result, the changing of rf amplitude and the appropriate changing of rf phase lead to a phase shift of a bunch center by the value of $2\alpha$. If the injection phase $\varphi_{en}$ in case of $E=E_1$ is equal to $\varphi_{s1}$, the phase shift of the bunch center at the exit of the tank does not occur. To improve the accuracy of phase setting, the bunch must have a distinct center. It is obtained if bunching voltage is defined by the formulae $V=\beta\lambda W/\pi e d$, where d is the distance from the center of the bunching gap to the entrance of the tank. Fig.8 shows the results of computer simulation of six dimensional beam dynamics without space charge for $E_1=0.955E_0$ and $E_2=1.035E_0$.

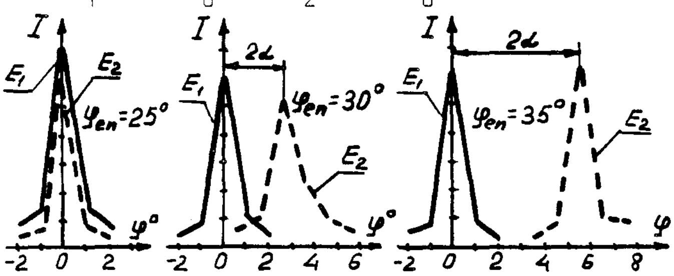


Fig.8 Bunch density distributions and relative phase positions of bunchs for $E_1=0.955E_0$, $E_2=1.035E_0$ and different $\varphi_{en}$.

The synchronous phase is not constant along the first tank of INR linac. So the value of $2\alpha$ is not equal to zero, but 1.33°, when in case of $E_1=0.955E_0$ $\varphi_{en}$ is equal to $\varphi_{s1}$. The computer results show the value of $2\alpha$ to be equal to 1.33° when $\varphi_{en}=27.6°$. This result well agrees with that obtained from $E\cos\varphi_s$=const ($\varphi_{s1}=27.35°$).

When considering the accuracy of phase and amplitude setting we took into account the following factors: phase resolution of a bunch density monitor, instability of injection energy, instability of phase and amplitude in accelerating tank and buncher, tilt and perturbation of rf field distribution in the accelerating tank. The analysis showed, that the accuracy of phase and amplitude setting in the first tank of the INR linac will be 1° and 1% accordingly.

Method of longitudinal beam emittance measurement at the exit of the initial part of the INR linac

Longitudinal bunch density measuring technique will be used to measure a longitudinal beam emittance at the exit of the initial part of the INR linac. It is known, that if a phase portrait of a beam is ellipse, its coeffitients may be found by three times measuring of a bunch length after passing the beam through a device with known longitudinal linear motion matrix $M_i$ (i=1,2,3). The fifth accelerating tank (the last tank of the initial part of the linac) will be used for this purpose. The regulation of rf amplitude and appropriate changing of phase will be done to obtain different $M_i$. The specific property of the fifth tank is its relatively small length. So the phase shift of particles even those uncaptured into the stability region is small. The computer simulation showed, that a motion of particles with respect to each other is linear even for the amplitudes less than critical value $E_{cr}=E_0\cos\varphi_{so}$, where $E_0$ and $\varphi_{so}$ are the nominal amplitude and synchronous phase. This fact enables to increase a band of amplitude regulation thus improvig the accuracy of emittance measurements. The accuracy $\gamma$ is defined in the following way: real ellipse must be situated inside a ring obtained by increasing and decreasing of geometrical dimensions of measured ellipse $1+\gamma$ times while keeping its orientation. The value of $\gamma$ depends on the accuracy of measurement of absolute value of accelerating field and its stability, phase resolution of a bunch length measuring device, dimensions and orientation of real ellipse. It is shown[4], that practical value of error will be of order 3-5%. Another constituent of the error is due to a space charge of a beam. We used elliptical model of a bunch to analyse the influence of space charge effects. Fig.9 shows the dependance of $\gamma$ on beam current for ellipses of different dimesions and normalized emittance $0.15\pi$ cm.mrad. Increasing of normalized emittance 2 times leads to decreasing of $\gamma$ 1.2-1.3 times. To improve the accuracy one should either collimate a beam at the entrance of the tank thus decreasing the influence of a space charge or to take space charge effects into account when unfolding beam emittance.

## 4. Conclusion

The bunch shape measuring technique will be used for INR linac tuning. We plan to study the bunching system and the first tank this year.

## Acknolegememt

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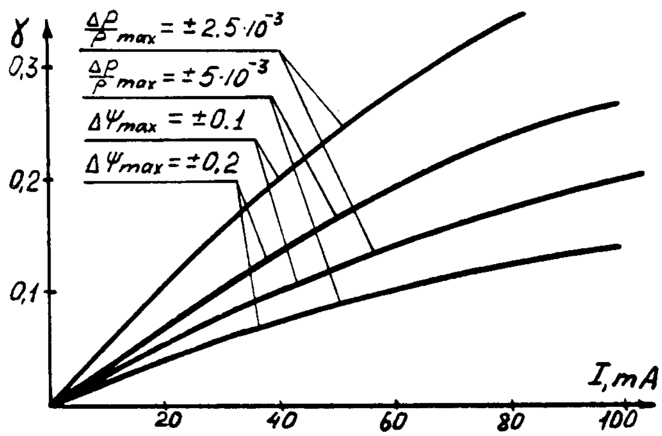


Fig.9 The influence of space charge effects on the accuracy of emittance measurements