I руб. 40 коп.

Индекс 3649

ПРЕПРИНТ 92-83, ИФВЭ, 1992

IFVE-92-83

Fermilab Library
0 1160 0015490 6

INSTITUTE FOR HIGH ENERGY PHYSICS

12

IHEP 92-83
OKY

E.A.Myae, E.S.Nelipovich, P.T.Pashkov, A.V.Smirnov

REGROUPING OF THE BEAM IN THE IHEP PS FOR THE UNK p-p PROGRAMS

FERMILAB
DEC 9 1992
LIBRARY

Protvino 1992

UDK 539.1.076 M–24

Abstract

Myae E.A. et al. Regrouping of the Beam in the IHEP PS for the UNK p-p Programs: IHEP Preprint 92-83. – Protvino, 1992. – p. 12, figs. 5, tables 1, refs.: 5.

Possibilities to form particle bunches in the IHEP machine whose longitudinal parameters would satisfy the requirements imposed by the UNK p-p programs are analyzed. In the case of the 3×3 TeV $p-p$ program the accelerated proton beam in the IHEP PS after preliminary quasiadiabatic debunching process will be recaptured into a stable oscillating mode at 33.3 MHz. The peculiarities of the RF system designed for these purposes with an account of strong beam loading are discussed. For the 0.4×3 TeV UNK colliding beam regime it is necessary to compress the accelerated proton bunches in the IHEP PS so that their length will be 4 times less. The main difficulties arising during "RF gymnastics" which is used for beam compressing, are caused by nonlinearities of the external accelerating field and also the fields induced in the RF cavities by the beam. The compensation of such effects with the help of the special RF system is discussed.

Аннотация

Мяэ Э.А. и др. Перегруппировка ускоренного пучка в протонном синхротроне ИФВЭ для $p-p$ программ УНК: Препринт ИФВЭ 92-83. – Протвино, 1992. – 12 с., 5 рис., 1 табл., библиогр.: 5.

Анализируются возможности формирования в ускорителе ИФВЭ сгустков частиц с продольными параметрами, удовлетворяющими требованиям $p-p$ программ УНК. Для (3×3) ТэВ $p-p$ программы УНК разработан переход на более высокую кратность ускорения, для чего после квазиадиабатической разгруппировки пучка в ускорителе ИФВЭ будет происходить перезахват частиц на частоте 33,3 МГц. Обсуждаются особенности конструкции соответствующей ВЧ-системы, работающей в условиях очень сильной нагрузки ее резонаторов током пучка. Для режима $(0,4 \times 3)$ ТэВ пучков в УНК, в ускорителе ИФВЭ необходимо сжать ускоренные сгустки частиц в продольном направлении в 4 раза. При использовании для этой цели "ВЧ-гимнастики" пучка основную опасность представляют нелинейности как внешнего, так и наведенного пучком на резонаторах напряжений. Рассмотрена компенсация подобных нелинейностей с помощью специальной ВЧ-системы.

© Institute for High Energy Physics, 1992.

Мяэ Э.А.

Перегруппировка ускоренного пучка в протонном синхротроне ИФВЭ для p-p программ УНК.

Редактор А.А.Антипова. Технический редактор Л.П.Тимкина. Корректор Е.Н.Горина.

Подписано к печати 18.06.92 г. Формат 60x90/16. Офсетная печать. Печ.л.0,75. Уч-изд.л.0,94. Тираж 260. Заказ 327. Индекс 3649. Цена 1р.40к.

Институт физики высоких энергий, 142284, Протвино Московской обл.

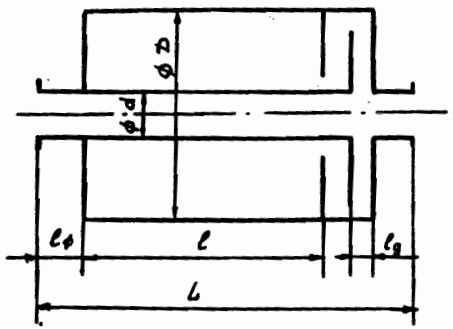

Figure 5. The design of the coaxial resonator for the bunch compressing in the IHEP PS.

References

[1] B.V.Plodukhin. The coaxial range resonators. - Moscow, Sovietskoe radio, 1956.

[2] E.P.Goryunov, B.M.Guther et al. The Soviet Jour. of Tech. Phys., 1977, v. 47, p. 2338.

[3] R.Garoby, J.Jamsek et al. - Preprint CERN, PS 89-28 (RF), 1989.

[4] F.Ferger, W.Shnell. Proc. of the II Soviet Conf. on Accel., Moscow, 1972, p. 128.

[5] V.I.Balbekov, A.Yu.Malovitsky. - Preprint IHEP 91-141, Protvino, 1991.

Received June 18, 1992

According to the requirements following from the physical detection apparatus which will be used on the UNK 3×3 TeV colliding beams the time interval between two sequent bunch interactions must not be less than 25 ns. Having filled the particles in each sixth separatrix it is possible to provide the particle bunches colliding with 30 ns periodicity. In this case it will be necessary to change harmonic number q in the IHEP PS from 30 to 165 prior to the injection process into the UNK.

For the 0.4×3 TeV colliding proton beams program the length of particle bunches at high energy in the IHEP PS should be reduced approximately 4 times. Corresponding rebunching of the beam including preliminary stretching of the proton bunches placed into the separatrix unstable points and following rotation of them in the buckets are considered. The UNK synchrotron capture dependence on the second and the fourth RF harmonics added to the main RF field in the IHEP PS to improve the longitudinal matching of the injected bunches has been investigated. The calculation results of the RF system main parameters to realize these harmonics in the IHEP PS are presented.

1. THE ACCELERATED BEAM RECAPTURE AT 33.3 MHz

The 3×3 TeV UNK colliding beams program restricts the longitudinal emittance ϵ of the particle bunches injected from the PS to the value ~0.075 eV·s. Since the harmonic number changes from q=30 to q=165 will turn each initial bunch into new 5.5 particle bunches so before the beam debunching the longitudinal emittance must be less than 0.4 eV·s. We will use ϵ=0.3 eV·s as an initial value which at present usually corresponds to the longitudinal emittance in the PS at the injection energy. To preserve this emittance it is clearly necessary to undertake appropriate measures to suppress longitudinal beam instabilities which are most probable near the transition and the top energies.

A "macroparticle" method was used to investigate the debunching process. The time dependence of the RF amplitude was presented in the form of three linear intervals. On the first linear interval the RF amplitude was changed from the initial value of 350 kV up to 20 kV during the time t_1. Phase oscillation period at $t = t_1$ is 39 ms so one should have t_1 >40 ms (for calculations t_1 was put equal to 80 ms).

At the end of the second linear interval ($t = t_2$) the RF amplitude is 180 V. At this moment the phase volume limited by separatrix is equal to that of the bunch. The optimum duration of the second interval is 0.35 s. The duration of the third interval where the RF amplitude falls down to zero, was chosen from the condition of minimum linear charge density variations in the debunched beam.

The relative value of the beam current I/I_o (I_o – the average value of the current) in one of the RF periods is given on fig.1 for t_2=0.43 s and at the debunching end for $t = t_3$=0.98 s (curves 1 and 2 respectively). For that case the final momentum dispersion value is $6.7 \cdot 10^{-3}$ $m_o c$ (m_o – proton rest mass, c – light velocity). It corresponds to 1.7 times growth of the effective phase volume. However the particle momentum distribution analysis makes it clear that 90% of the particles are concentrated in the central part of the distribution with momenta limited by the values $\pm 3.6 \cdot 10^{-3}$ $m_o c$. The particles in the distribution "tails" can be, in principle, extracted from the accelerator during the further passage to the harmonic number q=165.

It is necessary to note that the debunching regime described here imposes strict demands on the RF system of the IHEP PS. For the realization of the first interval – the RF amplitude reduction from 350 to 20 kV – the resonator automatic systems should greatly be altered. Further RF amplitude reduction can be realized by successive switching of the accelerating stations with time intervals of ~ 9 ms. For this purpose it is necessary to create new electronics control in the RF system. As far as the beam dynamics is concerned the corresponding numerical calculations have shown that the same results were obtained both for smooth and for step RF amplitude reduction laws in the interval considered.

Right away after switching off the resonator it is necessary to shorten its accelerating gap to reduce the longitudinal impedance and to prevent selfbunching of the beam at the self-frequency of the switched off resonator that is also a series technical problem. And finally the RF amplitude reduction to zero during 0.55 s can be carried out with the help of a special resonator which should be constructed in the future. The permissible value of the longitudinal impedance $|Z_n/n|$ is minimum at the end of the debunching process and according to the

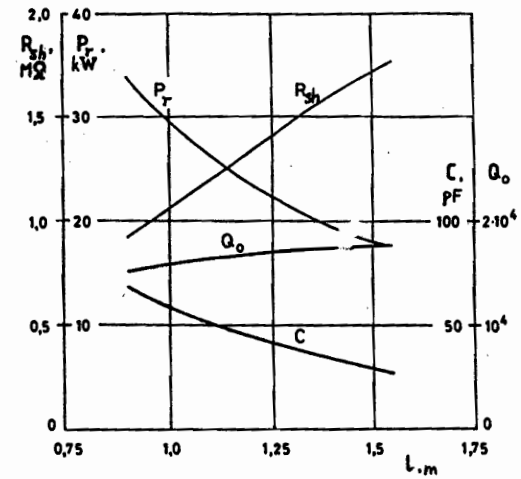

Figure 3. The main resonator parameters via its coaxial length l (V_r=250 kV).

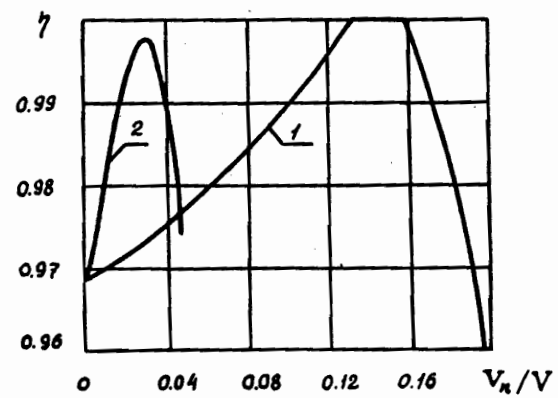

Figure 4. The UNK synchrotron capture efficiency via the second (1) and the fourth (2) RF harmonics amplitudes in the IHEP PS.

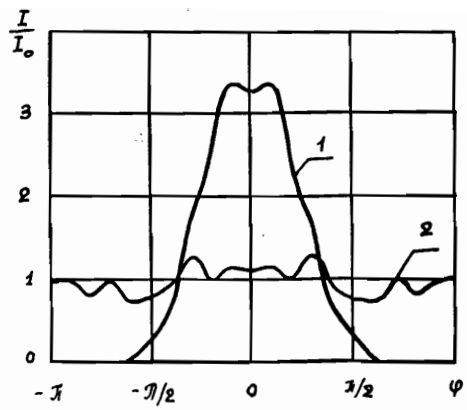

Figure 1. The beam current for $t_2 = 0.43$ s (1) and $t_3 = 0.98$ s (2).

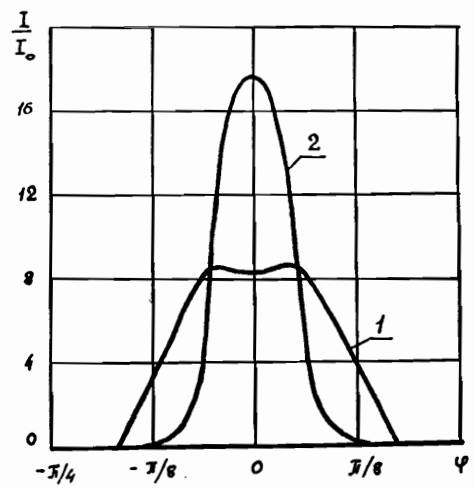

Figure 2. The bunch pulse at the rebunching end (1) and at the RF gymnastics finishing (2).

calculations carried out it is equal to $\sim 20\Omega$ that is two times as much than that of the IHEP reconstruction project.

After the debunching process the resonator which creates in the accelerator an RF electric field with the frequency f=33.33 MHz, will be switched on, and the amplitude will grow during the beam recapture from zero to the final value $V = V_{max}$. To study the beam recapture with the help of a computer a rectangle on the phase plane uniformly filled by "macroparticles" was taken. The length of the rectangle was equal to 2π and the momentum dispersion value was within $\pm 3.6 \cdot 10^{-3}\ m_o c$. Each "macroparticle" was given weight in accordance with the parabolic distribution over the momentum axis.

The beam recapture was investigated in four stages. First the quasidiabatic beam capture into stable phase oscillations was studied. In this interval the RF amplitude was linearly increased from zero up to 2 kV. The minimum interval with $\sim$ 100% capture efficiency was computed to be 80 ms. Then in the second 0.6 s long interval where the RF amplitude was changed according to the parabolic law from 2 up to 500 kV the bunches were longitudinally compressed. The beam pulse for this case is given on fig.2 (curve 1).

Further the bunch was compressed through the beam's gymnastics method – the RF phase was sharply reversed and the bunch length approximately doubled during $\sim 0.5\ ms$. Then again the RF phase was reversed to the initial value and the unmatched bunches began to rotate in the phase plane. The bunch length minimum is reached 1.85 ms later the second phase switch, so at this moment the particles must be extracted from the IHEP PS and injected to the UNK.

The resulting form of the bunch pulse before extraction of the particles from the PS is shown on fig.2 (curve 2). It is clear from the curve that 97% of the particles are concentrated in the phase interval $\sim 0.16\pi$ long. In that case the momentum dispersion equals 0.075 $m_o c$ so that the longitudinal emittance containing 97% of the particles in the bunches is $\sim$ 0.088 eV·s.

We shall calculate the main characteristics of the RF system proceeding from the demands formulated above. Since the frequency needed has relatively low value it is worth while to examine a quarter wave coaxial resonator as only in that case it is possible to obtain acceptable dimensions.

To calculate the resonator shunt impedance R_{sh}, quality factor Q_o and capacity C one may use the formulae (see, for example, [1])

$$R_{sh} = \frac{2\pi\rho^2 sin^2\alpha l}{R_s\{[1+(1+\frac{15}{\rho})cos^2\alpha l]ln\frac{D}{d} + l(\frac{1}{D}+\frac{1}{d})(1+\frac{sin2\alpha l}{2\alpha l})\}}; \qquad (1)$$

$$Q_o = \frac{R_{sh}(2\alpha l + sin2\alpha l)}{4\rho sin^2\alpha l}; \quad (2)$$

$$C = (2\pi f \rho tg\alpha l)^{-1}, \quad (3)$$

where $\rho = 60ln\frac{D}{d}$ – the wave resistance of the coaxial line in Ohm (D and d – the coaxial line outer and inner diameters, respectively), $\alpha = \frac{2\pi}{\lambda}$ (λ – the wave length in free space); l – the length of the resonator coaxial part; R_s – surface resistivity.

The results which have been calculated with the help of formulae (1)-(3) are given on fig.3, where parameters R_{sh}, Q_o and C are presented versus the coaxial length l for a copper cavity ($R_s = 1.7{\cdot}10^{-3}$ Ohm) with d=0.2 m and D=1 m. The figure also presents the total dissipated power $P_r = V_r^2/2R_{sh}$ for V_r=250 kV on the unlocked end of the resonator. It is clear from the figure that changing the coaxial length of the resonator within the limits $0.9 \div 1.5$ m results in the increase of the shunt impedance R_{sh} from 0.9 MΩ up to 1.7 MΩ, the quality factor Q_o equals $\sim 1.6 \cdot 10^4$ and the dissipating energy P_r loweres from 34 to 18 kW.

As the shunt impedance value turned out to be high enough so for the RF system correct construction it is necessary to take into account the heavy beam loading. If, for example, one has a resonator with R_{sh}=1.5 MΩ then the ratio of the voltage V_b induced on the cavity by the beam RF harmonic to the total voltage V will change from 200 to 2 and reaches its highest value at the recapture beginning. The cavity tune measured in frequency bandwidths changes within the same limits. It is expedient to narrow the RF system operating range dividing it into 2 regions. Then the recapture beginning will be provided with the RF system containing a resonator with low shunt impedance. After switching it off till the end of the recapture the second, more powerful, RF system will operate.

We first consider the characteristics of the second stage. In this case one can use two identical resonators situated in one of the accelerator long straight sections fulfilling their RF feeding through a matched T-brigde or a circulator if it uses only one resonator. The bridge is built of coaxial line pieces. The resonator impedance changes caused by beam loading do not disturb the RF generator matching with reference to the bridge (circulator), which permits to install the generator valves out of the PS hall.

Beam loading is considerably greater in the first RF system operating from the recapture beginning till the voltage is V=100 kV. At the same time low energy losses in the resonator enable one to apply active autotuning with the help of the magnetic ferrite core. As it has been found out the maximum losses

AFC system then the maximum RF power losses in the ferrite tuner will be small enough: they are less than 200 W for the second harmonics and 1.5 kW for the fourth one. In a more dangerous case of the fourth harmonic the permissible value of the resonator shunt impedance is 50 kΩ according to formula (4). The coupling resistance reduction can be achieved if one shunts the resonator by the RF generator.

During the acceleration cycle when the resonators are switched off the coupling impedance must be sufficiently reduced: its maximum value must not be greater then 10 Ω, i.e. it has to be diminished at least 200÷250 times. This is a sufficiently simple problem as compared with that considered in the previous section.

The obtained data analysis indicates the following advantages of the system for creating the fourth RF harmonic in the PS as compared with the second one:

a) the external resonator diameter is twice less and the cavity can operate at atmospheric pressure and will therefore have a rather simple structure;

b) the necessary power of the RF generator is 10 times less;

c) for the unvacuum cavity preliminary surface training is not required and high frequency electron discharge is absent;

The final selection of the construction type can be made after more detailed study of the project.

One cannot also except in the future the possibility of combine using both variants considered above especially if we are not quite a success in decreasing the longitudinal phase volume of the particle bunches in the PS down the value 0.2 eV·s adopted before in the calculations. It has been found out through numerical solving of equation (8) that if the second and the fourth RF harmonics are operating simultaneously then the 100% synchrotron capture into the UNK separatrixes can be obtained for 20% greater longitudinal emittance.

The value of the permissible longitudinal impedance $|Z_n/n|$ is minimum at the end of the bunch stretching processes and equals 7Ω according to the calculations done, which is rather close to the value given in the IHEP PS reconstruction project.

Now we shall analyze possible ways to realize the second and the fourth harmonics in the IHEP PS. We also note right now that it is inexpedient to alter the part of the existing accelerating stations to the second RF harmonic. Though it is the most simple way but it is impossible to decrease the main RF amplitude by $60 \div 80$ kV as it has been found out when studying this problem. So in both cases one can only speak about separate RF systems.

Like in the previous section the acceptable radial sizes are obtained in the case of the coaxial resonators. The geometrical dimensions of such resonators (see fig.5) and also the shorting capacity C, the shunt impedance R_{sh} and the quality factor Q_o can be calculated with the help of formulae (1), (2), (3). The results of the calculations are given in the table for the resonator which will be placed in the short straight sections of the PS (L=1.5 m, d=0.2 m). The resonator voltages needed and the corresponding power losses P_r are also given there.

Table 1. The main parameters of the resonators

Freguency MHz	V_n kV	l_g cm	l cm	D cm	C pF	Material	R_{sh}, kΩ	Q_o	P_r kW
12.1	60	1.5-2	94	90-100	560-600	Copper	210-240	9560 10300	7.5-18.5
						Alloy AMG-2	105-120	4780 5150	17-15
24.2	15	1.4	120	170	170	Copper	260	7800	0.43
						Alloy AMG-2	130	3900	0.86

The second RF harmonic of the beam current increases during the bunch compression from 0.5 to 0.6 A and, accordingly, the fourth one – from 0.2 till 0.6 A. The maximum displacement of the resonator self-frequency caused by the reactive impedance of the beam corresponds to one frequency bandwidths for the second RF harmonic and five bandwidth for the fourth one. To decrease the beam loading down to the acceptable level it is necessary automatically to control the resonators' frequencies during the rebunching process in the PS. In that case the maximum tuning speed is less than 15 MHz/s. The evaluations have shown that if the heat frequency deviations are suppressed by the same

in the core are commensurable with those of the resonator but taking into consideration their small values ($P_{r\ max} \leq 5$ kW) and also short duration of the first RF stage operation one can expect a small level of the core heat yield release.

The core losses are insufficient to reduce the resonator impedance down to the level set by the stability criterion of the RF phase and amplitude autoregulation systems [2]

$$R_{sh} \leq \frac{2V sin\phi_s}{I_q sin2\phi_r}, \tag{4}$$

where I_q – the RF harmonic amplitude of the beam current; ϕ_s – synchronous phase; ϕ_r – detuning angle of the unloaded resonator. The value of R_{sh} is minimum for $\phi_r = \pi/4$ and the maximum value of the ratio I_q/V, i.e. at the recapture beginning ($R_{sh\ min} \simeq 10$ kΩ).

The impedance of the resonator can be lowered by shunting with the RF generator. It is found out that the resistance brought to the RF generator clamps must be ~ 100 Ω therefore it is necessary to use a deep negative feedback correction. As an additional measure one can also use a program correction of the voltage induced by the beam [3,4]. At the end of the first RF stage operation the requirements to the resonator shunting become considerably weaker. The resonators being switched off, it is necessary to shorten their accelerator gaps. At this moment the shunt resistance must be lowered at least 1000 times as compared with the case of the unloaded resonators, which, in principle, can be achieved by using $p-i-n$ microwave commutator diodes as electronic switches out of the radioaction zone in combination with coaxial line peices. One more damping system must suppress dangerous highorder resonances.

2. FORMING OF THE BUNCHES FOR THE UNK 0.4×3 TeV COLLIDING BEAM PROGRAM

In [5] a possibility of the accelerated PS proton beam rebunching has been investigated for the 0.4×3 TeV UNK beams. There it was suggested to add the second harmonic to the main RF field in the PS to improve the longitudinal bunch matching at the injection into the UNK. For that purpose we shall also use the fourth RF harmonic which together with the second one makes it possible to further decrease the external RF field nonlinearity in the PS. We shall discuss the demands to the RF system needed for the RF harmonics creation in the IHEP PS too.

At injection the longitudinal emittance of the UNK buckets equals 0.4 eV·s. That imposes a strict requirement onto the longitudinal emittance of the accel-

erated bunches in the PS: it must not exceed 0.2 eV·s if one takes into account imperfections in the longitudinal matching process in the UNK at injection. We must note here that the longitudinal emittance in the IHEP PS exceeds the present value even at the beginning of the acceleration cycle – at injection energy. That is why it is necessary to foresee a direct forming of the longitudinal emittance in the PS at about top energy.

In our further calculations we shall assume the longitudinal emittance in the PS to be equal to 0.2 eV·s. In that case the equilibrium bunches are 4.3 m long so they must be shortened ~4 times before extracting them from the PS. This can be realized in the two stages: first, for example, one can stretch them by placing them into unstable separatrix points; then at the end of the second stage the bunch length can be shortened down to the necessary value after rotating unmatched bunches in the phase plane.

The amplitude V before the RF generator phase jump is given by the formula

$$V = V_g cos\phi_r - I_q R_{sh} cos\phi_r sin\phi_r, \tag{5}$$

where V_g is the voltage amplitude created on the resonators by the RF generators and the phase ϕ_r is equal to

$$\phi_r = -arctg\frac{I_q R_{sh}}{V}. \tag{6}$$

The amplitude of the total RF voltage remains unchanged after the phase switching but its phase is changed by the value $\Delta\phi = 2\phi_r$ which can be made equal to zero if at the same time one reverses $sign\phi_r$. For that purpose it is necessary simultaneously with the phase switch to increase the resonators' self frequency by the value $\Delta\omega_r$,

$$\Delta\omega_r = \frac{I_q R_{sh}\omega_{ro}}{QV}, \tag{7}$$

where ω_{ro} – the self-frequency value before the phase switching, Q – a quality factor.

We must note that the pointed out RF frequency change will indeed result automatically from the automatic frequency control (AFC) operation. This is determined by the coupling coefficient $K\beta$ of the system. The most inertial section of the RF system in the PS is the magnetic coil with the ferrite core whose time constant is $\tau_c \simeq 3.6$ ms. Assuming the time Δt needed for the resonator tuning process essentially less than the time when the particles have been staying in the separatrix unstable points ($\Delta t = 100$ μs) one can easily

evaluate the coupling coefficient $K\beta \simeq 3\tau_c/\Delta t$=110 which is much less than $K\beta$ value in the existing AFC system.

We shall also evaluate the average speed of the resonators' self-frequency changing $\dot{f}_r$ during the phase switch, by substituting into formula (4) the following PS parameters: I_o=0.64 A, V=400 kV, $R_{sh}/Q \simeq$6 kΩ, $\omega_r/2\pi = 6{\cdot}10^6\ s^{-1}$. Considering further that the frequency change will take place within the time interval $\Delta t = 100$ μs we have $\dot{f}_r = 500\ MHz/s$ which approximately corresponds to the top speed of the frequency change in the PS resonators. Thus the voltage induced on the resonators by the RF harmonics of the beam current is practically completely compensated because of the AFC operation.

The phase motion of the particles was investigated by numerical solving of the phase equation which one can write in the form

$$\begin{cases} \phi'' = sin\phi, & 0 \le t \le \Delta t; \\ \phi'' = -sin\phi + \Sigma_n \frac{V_n}{V} sinn\phi, & 0 < t - \Delta t_1 \le \Delta t_2. \end{cases} \tag{8}$$

The differentiation in formula (8) is carried out over the variable $\tau = \Omega t$ (Ω - synchrotron frequency), Δt_1 is the time period during which the bunches of particles are put in the separatrix unstable points, V_n the amplitudes of the RF harmonics used for better longitudinal matching of the bunches injected from the PS into the UNK. During the integration process the ellipse limiting the longitudinal emittance value ϵ=0.2 eV·s on the phase plane and uniformly filled by the particles, was taken as the initial bunch boundary. The initial distribution of the particles $F_o(\Delta p, \phi)$ in the most of calculated variants was taken as the paraboloid: $F_o \sim 1-(\Delta p/\Delta p_m)^2-(\phi/\phi_m)^2$ (Δp_m and ϕ_m – respectively the vertical and the horizontal dimensions of the phase-plane ellipse). The case of the uniform distribution $F_o = const$ has been also investigated which is probably more close to the real distribution especially for the longitudinal emittance forming of the bunches when a significant fraction of the periphery particles is removed from the accelerator. The stretching time Δt_1 and the time of the bunch rotating Δt_2 were selected to minimize the longitudinal emittance value in the UNK; their optimal values turned out to be equal to ~2 ms and 3.5 ms, respectively.

We shall consider here two cases when the second and the fourth RF harmonics are separately added to the main RF harmonic. The synchrotron capture efficiency η via their amplitudes V_n is given on fig.4. The data are obtained through numerical solving of equation (8) with a computer. One can see that in the case of the second harmonic (curve 1) 100% capture efficiency in the UNK can be realized if its amplitude is equal to $V_2 \simeq$60 kV. In the case of n=4 approximately four times less amplitude is needed as curve 2 shows.