INVESTIGATION OF THE IHEP PROTON SYNCHROTRON BEAM DEBUNCHING DURING ITS INTERACTION WITH A THIN INTERNAL TARGET

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A simultaneous operation of 6-7 experimental facilities in each acceleration cycle is carried out at the IHEP proton synchrotron. In addition to the fast extraction (FE) and resonant slow extraction (RSE) use is made of internal targets (IT), producing secondary particle beams for 4-5 different beam lines, and of nonresonant slow extraction (NRSE) of a proton beam [1,2]. At present an important peculiarity of the U-70 operation is that the proton beam remaining in the accelerator chamber after fast extraction of a considerable fraction of the intensity, has a very distinct time structure of 200 kHz, thus complicating its use when the beam is guided onto the internal target. "Thin" internal targets [3] allow one not only to suppress the RF 200 kHz ripples (without using the RF methods of the beam debunching, e.g., as in ref. [4]) but to suppress the low frequency ripples as well. As a result the time structure of the extracted beams was improved by an order of magnitude for all the facilities working simultaneously, and it is now 7-10% [2,4].

Further investigations have shown that the suppression of the RF ripples in the extracted beams when working with the thin target is a consequence of the inner structure changes (both in the transverse and longitudinal directions), which occur only in the part of the circulating beam that interacts with the target. The remaining part (more dense) of the circulating beam conserves its azimuthal inhomogeneity, which is caused by FE. And remains during all the time of interaction with IT (up to 2 s) at the flat top of the magnetic cycle.

Experimental Results

Fig. 1 shows the oscillograms, which demonstrate the presence of the accelerator circulating beam in two states, which was reported above. The oscillograms of fig.1a and b from the filter, which singles out the harmonic of 200 kHz from the signal induced by the beam onto the pick up electrode of U-70, point to the presence of the RF structures with the 200 kHz frequency in the accelerator circulating beam. Fig.1a corresponds to the case when only 5 bunches (out of 29) remain in the machine after switching off the accelerating voltage when the circulating beam was not used for extraction (IT out of operation), but it was debunched according to the dependence [5] (the case with one bunch)

$$t_{db} \approx \gamma_{tr}^2 (2 f_o \cdot \frac{\Delta p}{p})^{-1}, \qquad (1)$$

where t_{db} is debunching time, γ_{tr} is the γ value for the critical energy, f_o is the repetition rate of the beam in the machine, and $\Delta p/p$ is the value for the beam momentum spread. Fig.1b corresponds to the case of the accelerated beam interaction (the same 5 bunches) with two ITs of the machine, one of them being thin [3]. As is seen there is also one - turn structure with the frequency of 200 kHz during the beam interaction with the targets. The reduction in the signal amplitude is explained by the decrease of the common intensity of the circulating beam caused by the nuclear interactions with the target.

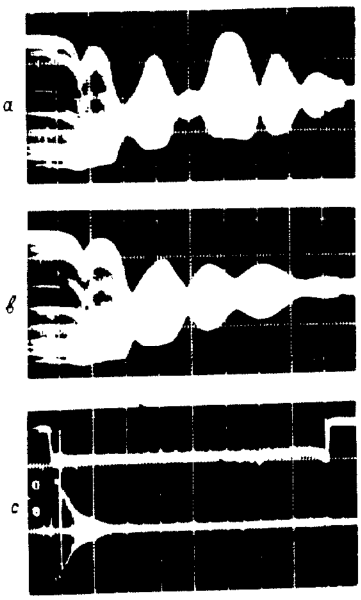

Fig. 1.
HF 200 kHz structure on the flat top of magnetic cycle after FE (200 ms/div):
a - internal targets not work;
b - at the simultaneous work of the "thick" (ch. No 4) and "thin" (ch. No 2) targets;
c - upper trace - channel No 4 secondary beam spill structure, lower trace - attenuation of HF 200 kHz structure in the channel No 4.

The oscillograms in fig.1c show the signals from the scintillation monitor, which provides the feedback for the systems guidening the beam onto the internal target (upper trace) and from a similar monitor at the head of the beam line. Its signal was used for the selection of the 200 kHz harmonics (lower trace). The time scale is 200 ms/div.

As is clearly seen from fig.1c a fast attenuation of 200 kHz ripples in the extracted beams is a characteristic feature of the operation of the thin target. This makes their influence on the time structure impossible during the whole flat top of the magnetic cycle. Such attenuation is provided by smoothing the azimuthal density of the particles interacting with the target. As is shown in [3], two factors favour the smoothing of the particle azimuthal density. One of them is an additional increase of $\Delta p/p$ of the particles per each target crossing and secondly, a considerable growth (more than by two orders of magnitude) of their time-of-life as compared with that for the case with a "thick" target [6].

The analysis of fig.1 gives us a possibility to make a conclusion that at the flat top of the magnetic cycle in the circulating beam which has from the very beginning a distinct one-turn structure, there exists a part of the beam which has an azimuthal density close to the homogeneous one. It consists of particles scattered from the dense part of the primary beam during its interaction with the thin IT. The azimuthal homogeneity keeps during the whole interaction time due to uniform slow displacement of the beam to the target by the c.o. bump. The procedure is controlled by the feedback monitor signal.

Results of Mathematical Simulation

When the accelerated proton beam interacts with the internal target during the magnetic cycle flat top the following processes take place

- the growth of the amplitude of particle betatron oscillations caused by multiple Coulomb scattering in the target matter;
- a decrease of the particle momentum and displacement of the equilibrium orbit toward the accelerator center because of the ionization losses of energy;
- reduction of the proton beam intensity because of the particle nuclear interaction in the target.

These processes were taken into consideration in the program modeling the changes of the beam azimuthal distribution density in U-70. In the program each particle is characterized by the amplitude of betatron oscillations A_r and momentum spread $\Delta p/p$. The quantity

$$r = A_r + \psi \cdot \frac{\Delta p}{p}, \qquad (2)$$

where ψ is the dispersion function, is the maximum coordinate of the particle w.r.t. the equilibrium orbit in the horizontal plane. Since the beam was guided onto the internal targets installed at the coordinates $r > 0$ and $r < 0$ w.r.t. the central orbit [7], we dealt with two variants of the thin target operation. The dynamics of the particles interacting with the internal target differs greatly in the two cases.

When the target is installed with the coordinates $r < 0$ the particle after its interaction with the target, increases its betatron oscillation amplitude and shifts at the same time toward the target owing to the processes mentioned above. The vertical sizes of the thin target are larger than those of the beam, therefore the probability for the particle to hit the target in the vertical plane is taken to be equal to unity. The probability for the particle to hit the target in the horizontal plane is determined by the amplitude of betatron oscillations A_r and the distance from the target edge to the equilibrium orbit of the given particle. This probability will increase each time after interaction with the target. Consequently the time interval between two subsequent interactions will decrease. The dependence of each particle momentum on time, which is determined by the initial $\Delta p/p$ and by its changes during interactions with the target, affects greatly beam debunching process.

In the second case when the coordinate are r 0 the processes of the betatron oscillation amplitude rise and particle orbit competiting shift will be. For each particle there exist the boundary values for the amplitude, when the increments to the betatron oscillation amplitudes and the values for the particle closed orbit shifts become equal. Using 8 one may obtain the values for the amplitude

$$A_{bou} = (\Delta A_r)^2 \cdot P_o / 2\psi \frac{dE}{dx} \cdot h, \qquad (3)$$

$\Delta A_r = \frac{|\varphi|_T^2}{W_o} \langle\theta\rangle$, $\langle\theta\rangle$ is the R.M.S. scattering angle of a particle in the target material, $|\varphi|_T$ is the module of the Flocket function at the point of the target location, W_o=1 m, and dE/dx are ionization losses of energy, h is the target thickness. It is assumed that $\Delta A_r << A_r$. For the variant we consider $A_r \approx 7$ mm. The particle will interact with the target so to say in several stages.

At $A_r < A_{bou}$ the increment of the betatron oscillation amplitudes exceeds the shifts of the closed orbit, the probability to cross the target P_r will increase (however with smaller velocity, than with the target coordinates $r<0$), the time interval between individual interactions will become less. When achieving A_{bou} the probability P_r will go on decreasing up to the moment when the particle crossing the target one more time gets to its edges. After that the time interval between interactions will depend on the shape of the function of the particle distribution along the radius in the beam at a given instant of time and it will be higher than in the previous cases. In this case the fraction of the particles interacting with the target will essentially be larger than with the coordinates $r < 0$.

When modeling the described processes [3] we used the Relay laws for the initial distribution of the accelerated beam particles over betatron oscillation amplitudes, and the distribution $\Delta p/p$ was governed by a standard law. The maximum momentum spread $(\Delta p/p)$ was taken to be equal to $\pm 1 \cdot 10^{-3}$ at 99% level. We consider the case of five subsequent bunches of identical intensity on the orbit. The spill time during which it was necessary to provide a uniform intensity spill was taken equal to 1 s. The circumference was divided into 90 equal segments.

Proceeding from the first phase equation [8] one may obtain the following formula for calculating the functions of the azimuthal density of particles interacting with the target

$$\varphi_n = \varphi_o + 2\pi f_o \alpha \left(\frac{\Delta p}{p}\right)_o \sum_{i=1}^{n} \Delta t_i + 2\pi f_o \alpha \frac{dE}{dx} \cdot \frac{h}{p_o} \sum_{i=1}^{n} \Delta t_i \cdot i, \qquad (4)$$

where f_o is the particle circulation frequency in the machine, φ_n is the particle azimuthal coordinate after n-th passing through the target, φ_o is the initial azimuthal coordinate, α is momentum compaction factor, $(\Delta p/p)_o$ is the initial particle momentum spread, Δt_i is the time interval between two subsequent interactions of the particle with the target.

Fig. 2 presents the particle distribution functions over azimuth in 300 ms after the beginning of the interaction with the thin target with the coordinates $r < 0$, curve 1 - for the whole beam, curve 2 - for the part of the beam interacting with the target. As is seen for the part of the beam, interacting with the thin target, the depth of the modulations for the azimuthal distribution density is less evident than for the beam as a whole. This means that the modulations of the time structure of the particle beam extracted from the accelerator, will manifest itself at a less extent, though as is seen from curve 2, the density modulations make up 50%.

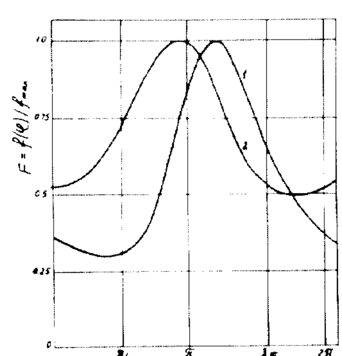

Fig. 2.
Functions of azimuthal distribution of particles at the thin target on $r<0$:
1 - for the whole beam,
2 - for the part of the beam interacted with target.

Fig.3 (curves 1 and 2) show similar dependence but for the case when the target has the coordinates $r>0$ (this is right the coordinate range where the thin target operates in beam line No 2). It is clear that the situation is much better than in the previous case (see fig.2). Moreover for the part of the beam interacting with the thin target, the depth of the density modulations is only 25%, and the ratio $(f_{max}-f)/f_{max}$ is approximately three times better.

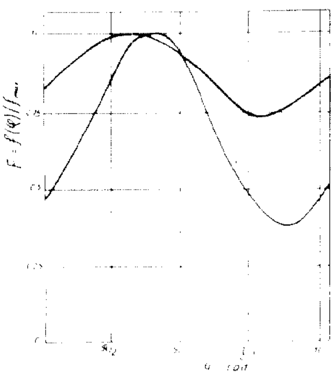

Fig. 3.
The same as fig. 2 for the thin target on $r > 0$.

It follows from the experimental data (see fig.1), that the frequency and character of the 200 kHz RF structure modulations change when the accelerator beam is debunched. It was suggested that the shape of the bunch influences the beam debunching process. To check this idea we made calculations of the debunching process for remaining bunches for different distribution functions of the particles over $\Delta p/p$ (IT are switched off). The initial conditions correspond to those described above. Fig.4 shows the dependence of the modulation parameter $\Phi=(A_{max}-A_{min})/A_{max}$ on time, where A_{max}, A_{min} are maximum and minimum values for the density of the beam distribution function over the accelerator azimuth. Curves 1 and 2 (fig.4a) correspond to the Gaussian and parabolic laws of particle distribution in bunches. Curves 3 and 4 (fig.4b) correspond to the triangular and uniform distributions. As is seen the bunch shape greatly affects the character of the density modulation over azimuth, and, consequently, the 200 kHz RF structure. The distance between the characteristic points is determined by the debunching time for one bunch (see formula (1)) and for our case it is equal to 225 ms, which agrees with the results obtained. The plots in fig.4 are of a qualitative character, since the debunching process is affected not only by the target, but by some other factors (e.g., nonidentity of the bunches). However we may assume that using the beam density modulation signal we shall be able to estimate the maximum value for $\Delta p/p$ and give a qualitative picture of the bunch shape and its evolution from cycle to cycle.

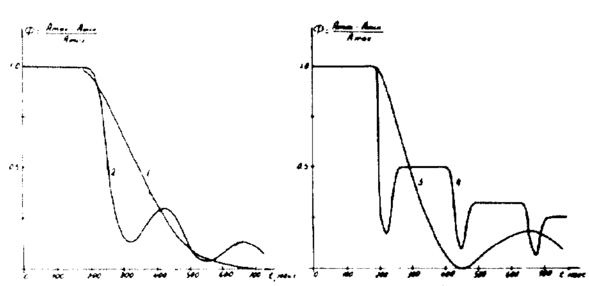

Fig.4. Parameter of HF 200 kHz structure modulation time-dependence for the different laws of the particle distribution in a bunch. 1 - normal, 2 - parabolic, 3 - triangle, 4 - uniform.

Hence when the thin target is in operation the circulating beam in U-70 consists of two parts after fast extraction. These two parts have different transverse and azimuthal densities, one of them is slowly (classically) debunched, Time depends on the number of extracted bunches. The second part consists of protons sufficiently uniformly distributed in the accelerator azimuth, and their betatron oscillation amplitudes are quite large. This uniformity is achieved by varying the momentum spread during the interaction with the target and a sharp increase of the particle time-of-life due to a considerable reduction of the target thickness (as compared with the one used before). This effect is the most vividly observed when the thin target works at positive (w.r.t. the central orbit) coordinates.

The dependence of the character of the RF structure modulations on the bunch shape and momentum spread of the beam particles remaining in the accelerator after fast extraction should also be mentioned here. This phenomenon awaits its study.

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