SMOOTHING OF THE TIME STRUCTURE OF SLOWLY EXTRACTED BEAM FROM SYNCHROTRON BY RF-KNOCK-OUT METHOD

A.V. Volochnyuk[1]*, A.V. Dolinskii*[2,3]*, O.A. Bezshyyko*[1]

[1]*Nuclear Physics Department, Taras Shevchenko National University, Kyiv, Ukraine*
e-mail: Volochn@univ.kiev.ua
[2]*Institute for Nuclear Research, Kyiv, Ukraine*
[3]*GSI, Darmstadt, Germany*

Results of the study are presented in work on smoothing of the time structure of the bunch, slowly extracted from synchrotron. The numerical algorithm has been designed for study of the influence of the radio-frequency field of the resonator on time structure of the bunch. The numerical algorithm is based on method Monte-Carlo, where particles in the beam have been extracted by means a slow moving to the third-order resonance conditions. Characteristics of the time structure are vastly smoothed when synchrotron oscillations have been used as first experiments showed. Theoretical motivation of the reasons, influencing upon time structure of the slowly extracted beam, is explained in given work.
PACS: 29.20.-c, 29.20.-Lq, 29.85.+c

1. INTRODUCTION

For most fixed target experiments at the *GSI* heavy ion synchrotron a slow extraction via tune variation or transverse *RF*-knock-out is used. The simulations which we will be to consider are dedicated to the slow *RF* knock out method [4]. Especially for given extraction method, aside from other standard device, the *RF* exciter is included to the devices queue of a synchrotron ring. To get an extraction time of several seconds by means *RF* method requires the even particles diffusion with constant separatrix as well as a constant tune. These non-depend time characteristics are necessary for the slow extraction during a relatively large extracting time nearest 3rd order resonance [3] and depend to the ring magnets. The tune change is disturbed in time by the variation of the magnetic field due to power supplier ripples having a main network related 50 Hz (and harmonics) frequency characteristic. Therefore, the extracted current is strongly modulated and this should be taken into account for any rate consideration for our simulations. Moreover for the cancer therapy, where an active scanning of the pencil beam is used [2], these modulations have to be measured precisely (20 μs) to control the deposited dose within the human tissue, there are. By bunching the full spill-signal of the 430 MeV/u C^{6+} beam is drawn in the insert. The *RF* cavity at a harmonics of the revolution frequency, a much smoother spill structure can be created. This is due to a time dependent momentum deviation $\Delta p(t)$ of the single particles and its coupling to the tune spread $\Delta Q(t)$ via the ξ chromaticity:

$$\Delta Q(t)/Q = \xi \cdot \Delta p(t)/p \,. \qquad (1)$$

This is an alternative approach to *RF* channeling or slow acceleration, where neither additional hardware nor dynamic software control is needed. Also the interest role of the chromaticity is observed and interpreted them with the help of a Monte-Carlo simulation.

2. THE 3RD ORDER RESONANCE SLOW EXTRACTION

The *RF*-knock-out method, which is routinely used at the *HIMAC* medical accelerator, has been also successfully tested at *GSI* [1]. The *RF*-knock out system is designed to extract a beam with a charge to masse ratio of 0.5-1 up to a maximal energy of 430MeV/u. Nearest the third order resonance on the sextupole magnets, the particles amplitudes are enhanced by means of a transverse electric *RF* field, which is generated with *AM* radio frequency and much small kick of a particles angle is about 10^{-7} per whole angle. Due to this excitation the particles are moved from the inner, stable region of the separatrix to the outer unstable part (Fig. 1) along the separatrix branches in normalized phase space [4]. This behavior can be regarded as an emittance growth in the horizontal phase plane.

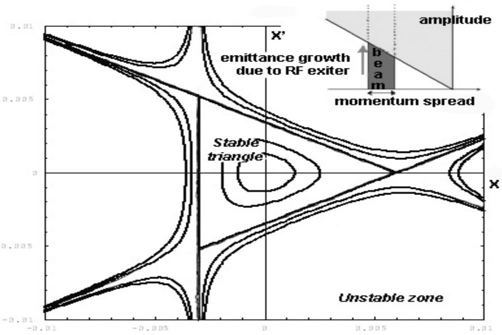

Fig. 1. *The particles trajectories are closed by the sextupole field on the horizontal normalized phase plane and Steinbach-diagram in the corner, that have schematically explain RF-knock-out method. The direct of outgoing particles to unstable region is showed. Particles have circular phase motion, where the three accelerator cycles per one whole phase circle*

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2005, № 6.
Series: Nuclear Physics Investigations (45), p. 162-165.

Then unstable particles are deflected due to the electrostatic septum (*ES*). For the *RF*-knock-out method the separatrix is kept constant angle of the particles at *ES* with respect to the reference orbit is almost constant. It is necessary for medical treatments, where the beam position in the synchrotron extraction channel and at the target of the treatment places can be kept constant during extraction. But in practice, under condition of existing power supplier ripples (its time and frequency characteristics are explained in [1]) the separatrix has some oscillations occur average angle there are. Thereby, once a quantity of the extracted particles is more in lot times then in another time. Therefore the time structure or spill of the extracted beam has ripple structure (Fig. 2).

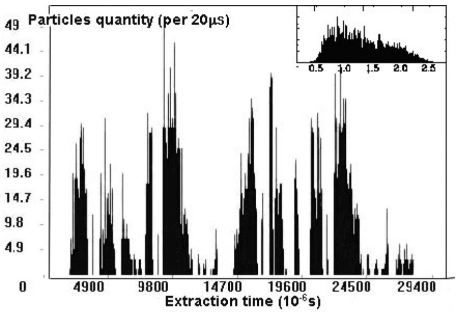

Fig. 2. *Time structure per 20µs has been simulated with 200000 ions C^{6+} 430Mev/u extracted beam for 500000 turns and over time profile for several seconds in the corner. In both cases you easily can to see over modulation of signal*

3. COMPUTER SIMULATIONS AND ITS ALGORITHM

For numerical calculations of the slow beam extraction process with a spill ripples a code using Monte-Carlo method has been written. Thin lens approximation is used for treatments of the effects of the nonlinear magnetic field and the high frequency perturbation field according to [6]. The betatron oscillation and nonlinear resonance of the beam are analyzed in the normalized horizontal phase space. The given phase space normalizations has several particularities or advantages from other similar phase spaces. It means that the beam emittance is given as a sum of new phase coordinates squares

$$\varepsilon = X^2 + X'^2 . \tag{2}$$

This transformation from standard to normalized phase space is given by equation [4]

$$\begin{pmatrix} X \\ X' \end{pmatrix} = \frac{1}{\sqrt{\beta_x}} \begin{pmatrix} 1 & 0 \\ \alpha_x & \beta_x \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}, \tag{3}$$

where α and β are the Currant-Schneider's functions; 'x' is a standard coordinate and and 'X' is a new normalized coordinates. The space normalization provides that the accelerator is not considered in detail, but phase advances $\Delta\mu_0$ between the important elements: (2 sextupoles, *RF* exciter, electrostatic septum *ES* and *RF* cavity) are taken into account. This numerical method provides the trajectories calculation for every particle every turn. Trajectories of particles are calculated by means transfer matrix [4], where $\Delta\mu_{i,j}$ has been used. The $\Delta\mu_{i,j}$ is a phase advanced, which consists of two part: first is the tune variation (Eq. 1); second is the phase between every device.

$$\Delta\mu_{i,j} = 2\pi\,(Q_{x,0} + \xi \cdot \Delta p / p) + \Delta\mu_0 , \tag{4}$$

where indexes i and j mean transformation for j-th particle at given *i-th* turn. Main part of the program algorithm is aimed to ideal extraction conditions, but for any practice rate we needs more completed algorithm, which will take to account the ripples of a magnet system power supply. The experimental data are studied in detail and two its characteristics are choose. Frequency diapason of the ripples noises are obtained where they have important role for time profile, it is 0.4 …10 kHz [1]. Another characterization of the ripple structure more suited for the specification from the experimentalists is the variation of the maximum-to-average ratio within a certain time. For a non-bunched beam, the maximum-to-average is between 10 to 20 on the 20 µs scale and decreases between 0.1 and 3 ms to about 2 in experiments [1]. For imitation of the ripple structure of an extracted beam the additional value $\Delta\varphi$ has been added to phase advanced $\Delta\mu$. The time dependence $\Delta\varphi\ (t)$ is given by equation [5]:

$$\Delta\varphi(t) = \sum_i A_i \cos(2\pi \nu_i T_{rev} (N_{rev} + N_k / N_S)) , \tag{5}$$

where A is the intensity of ripples, ν is the typical frequencies of ripples, i is a serial number of the frequency group, N_{rev} is a revolution number during extraction, $N_k(N_s)$ is the serial number of a particle (over quantity of particles into beam). The tune ripple frequency is chosen randomly in the range of 0.4-10 kHz and the corresponding amplitude for 100 % modulation.

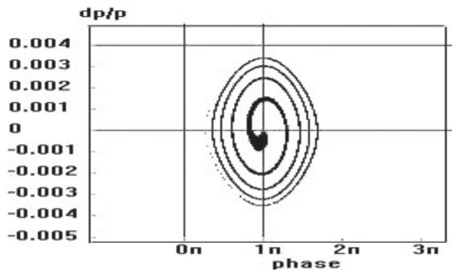

Fig. 3. *Distribution of the particles inside of the separatrix after 10000 turns. The RF voltage is about 2 kV*

Due to the bunching, the time dependent momentum deviation is calculated solving the differential equation for the longitudinal motion [6]

$$\begin{cases} \dfrac{d(\Delta p/p)}{dt} = \dfrac{Z_{ion} h \omega_{rev} V_{rf}}{2\pi\beta^2 E_s} [\sin(\varphi) - \sin(\varphi_s)] \\ \dfrac{d(\Delta\varphi)}{dt} = -\omega_{rev}\eta \dfrac{\Delta p}{p} \end{cases} , \tag{6}$$

$\Delta\varphi = \varphi - \varphi_s$, s corresponds to the reference orbit of particles motion, h is the harmonic number of synchrotron's oscillating frequency $\omega = h\omega_{rev}$, V_{rf} is a voltage amplitude of RF cavity, E_s is the energy of the particle on the reference orbit with ψ_s phase [5]. Under influence of RF field the synchrotrons oscillations appear and longitudinal motion is divided to bunches with certain separatrix (Fig. 3). The parameters used in the simulation are corresponded to the 430 MeV/u of C^{6+} beam. The speed of the resonance line moving to the beam is $\Delta Q/turn = 2 \cdot 10^{-8}$. The calculated time profile for an unbunched beam is shown in Fig. 2. Computer simulation has been carried by means of the computer programmer's language *C* and developed by *C*++, as a modern software package for simulations. The chromaticity effect smoothing is studied by variation parameter of the simulations.

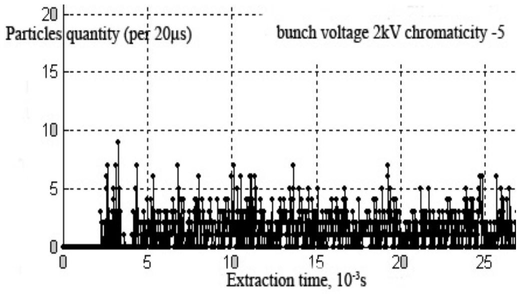

Fig. 4. The spill structure for bunched beam (see Fig. 2) under RF voltage 2 kV and chromaticity -5

4. INTERPRETATION AND EXPLANATION

The intensity modulation can be described in a Steinbach diagram, as shown in (Fig. 5a). A 'stripped resonance bands' with increasing amplitude over the time need to be proceed from the unstable region outside of the separatrix to the position of the *ES*. The slopes of these resonance bands are given by the chromaticity. The time profile of the extracted beam current can be obtained by summing up the projection of these stripes, leading to a strong modulation in case of small chromaticity and momentum spread. For a bunched beam this situation is changed (Fig. 5b). In this case at definite time all particles with amplitudes on the resonance line do not become unstable simultaneously as in the case of an unbunched beam. Now the time to reach the unstable region depends on the momentum of the particle because of the synchrotron oscillation that causes a time dependence of the momentum. In the Steinbach diagram it is seen that a particle with a certain momentum deviation can move back to the stable region. Such a particle performs excursions into the stable region during several synchrotron periods, while the particle betatron amplitude will be increased enough to reach finally the *ES*. This additional velocity component results in an increased slope of the stripped band equivalent to an enhancement of the chromaticity. Our calculation shows that time delay of the extracted bunched beam nearest to U_{rf} = 2 kV is about 8/5 times more compared then unbunched beam. Such time delay of some fraction of the particles results in an improvement of the spill quality (Figs. 4,6). The correspondence between measurement and calculation

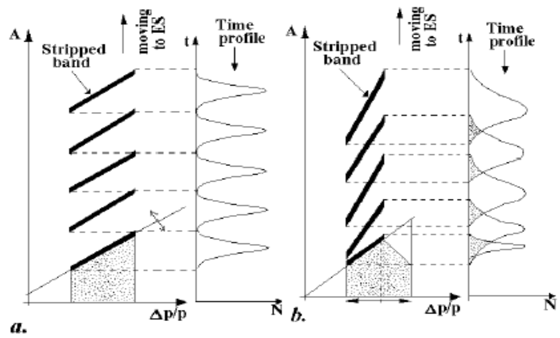

Fig. 5. Steinbach-diagram to visualize that the flux of particles is obtained by summing over the 'strip profiles' without bunching (left) and with bunching (right)

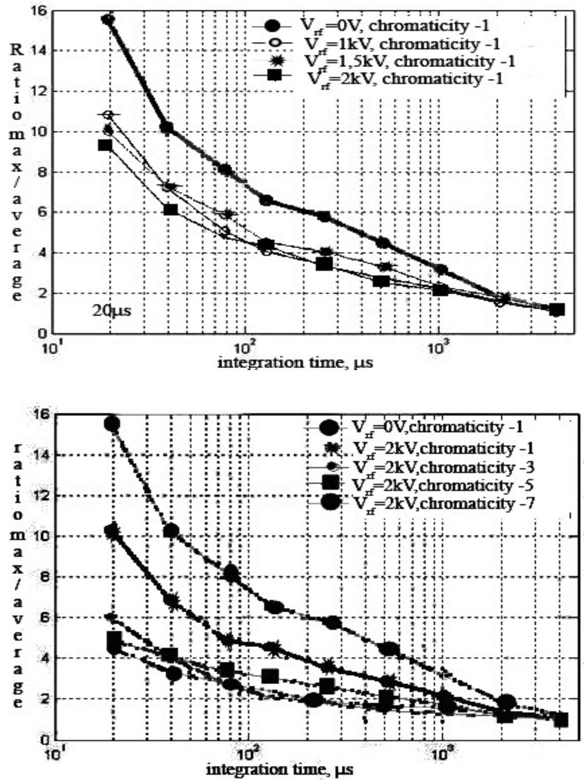

Fig. 6. The ratio max/average time depended characteristics for the same beams with different: RF voltage amplitude (top) and chromaticity parameter (bottom)

is quite good taking experimental uncertainties and numerical simplifications into account. It is clear that overlapping of the stripped bands will be higher if the angles of these bands are increased resulting in an improvement of the spill quality. Simultaneous using of *RF*-field modulation with chromaticity variation brings about significant result (Fig. 6). Whole improvement of the spill quality has been reached under condition of amplitude U_{rf} = 2 kV and ξ = -5 (Fig. 5), when simulations well describe the experimental data [1,7].

REFERENCES

1. P. Forck, H. Eickhoff, A. Peters, A. Dolinskii. *Measurements and improvements of the time structure of a slowly extracted beam from a synchrotron*. Proc. of EPAC2000. 2000, Vienna, Austria, p. 2236-2238.
2. L. Badano et al. Synchrotrons for hadron therapy // *Nucl. Instr. and Meth. in Phys. Res. Section: A.* 1999, v. 430, p. 512-522.
3. P. Forck, T. Hoffmann. Cancer therapy // *LNF-97/048(IR)*. 1997, p. 165-171.
4. A. Volochnyuk. *Slow beam extraction by RF knock out method.* Summer school student reports in GSI, 2003, p. 35-39
5. K. Hiramoto, M. Nishi. Slow beam extraction with constant separatrix // *Nucl. Instr. and Meth. in Phys. Res. Section: A.* 1992, v. 322, p. 154-160.
6. W. Pirkl. *Longitudinal beam dynamics.* Proc. of CAS Rhodes. 1995, CERN 95-06, p. 233-257.
7. T. Furukawa et al. Recent improvement of slow-extraction at HIMAC synchrotron // *Nucl. Instr. and Meth. in Phys. Res. Section: A*. 2004, v. 522, p. 196-204.

СГЛАЖИВАНИЕ ВРЕМЕННОЙ СТРУКТУРЫ ПУЧКА, МЕДЛЕННО ВЫВЕДЕННОГО ИЗ СИНХРОТРОНА RF-KNOCK-OUT МЕТОДОМ

А.В. Волочнюк, А.В. Долинский, О.А. Бесшейко

Представлены результаты исследования по сглаживанию временной структуры пучка, медленно выводимого из синхротрона. Разработан численный алгоритм для изучения влияния высокочастотного поля резонатора на временную структуру пучка. Численный алгоритм основан на методе Монте-Карло, где бетатронные колебания частиц в ускорителе рассматриваются с учетом того, что пучок медленно выводится резонансным методом третьего порядка. Как показывают первые эксперименты по медленному выводу пучка, подверженному синхротронным колебаниям, временная структура значительно сглаживается. Теоретическое обоснование причин, влияющих на временную структуру медленно выводимого пучка, приведено в данной работе.

ЗГЛАДЖУВАННЯ ЧАСОВОЇ СТРУКТУРИ ПУЧКА, ЩО ПОВІЛЬНО ВИВОДИТЬСЯ З СИНХРОТРОНУ RF-KNOCK-OUT МЕТОДОМ

А.В. Волочнюк, О.В. Долінський, О.А. Безшийко

Подано результати дослідження по згладжуванню часової структури пучка, повільно виведеного з синхротрону. Розроблено числовий алгоритм для вивчення впливу високочастотного поля резонатора на характеристики часової структури пучка. Числовий алгоритм базується на методі Монте-Карло, де бетатронні коливання частинок в прискорювачі розглядаються з урахуванням того, що повільний вивід пучка відбувається за резонансним методом третього порядку. Як показують перші експерименти з повільним виводом пучка, часова структура значно згладжується завдяки виникненню повздовжніх синхротронних коливань. Теоретичне обґрунтування причин, що впливають на часову структуру повільно виведеного пучка, наведено в даній роботі.