CONTROL OF THE SLOW EXTRACTION PROCESS IN A DEDICATED PROTON SYNCHROTRON FOR HADRON THERAPY

A.Yu.Molodozhentsev[#], G.I.Sidorov, JINR, Russia

Abstract

The ring design of the synchrotron [1] for cancer treatment, based on the third-order resonant extraction, was been performed to meet the special medical requirements. The uniformity of the slow extracted beam from the proton synchrotron is the main requirement on the beam quality determined by the medical application. The smooth extraction during at least 400 msec should be realized for the 'raster' scanning of tumours. Control of the slow extraction over the whole spill time is discussed in this report. To keep all lattice functions of the ring constant during the extraction a slow moving of the accelerated particles into the resonance can be used. To reduce a degradation of the uniformity of the extracted beam by ripples from the power converters of the magnetic elements, the RF empty-bucket channeling method [2] should be utilized. This method allows reduce the ripple influence during slow extraction. Both methods are analyzed to control the slow extraction for the dedicated proton synchrotron. Main parameters of the betatron core for this machine are determined. To realize the 'empty-bucket' technique, the RF system of the synchrotron can be used with the maximum voltage at least 1.5 kV. Influence of the high-frequency ripple on the multiplying factor and the duty factor of the spill is studied.

1 INTRODUCTION

A conventional synchrotron seems to be the most acceptable accelerator for the 'active scanning' of tumours. The dedicated proton synchrotron should be designed to meet specific medical requirements on the beam quality, in particular, the spill homogeneity over full extraction period. The 'active scanning' technique needs in the slow extraction of the accelerated particles to perform on-line dosimetry at the patient and to switch the beam on and off according to the dose required. This directly determines the performance of the machine [1]. The customised lattice of the synchrotron has been developed to apply the Hardt condition. To perform the ultra-slow extraction, the moving the coasting beam into the resonance region is chosen. This method has the great advantage of leaving the optical parameters of the machine constant during the extraction. In particular, the beam is accelerated towards the stationary resonance by a betatron core [3], installed in the dispersion-free drift space of the ring. The uniformity of the slow-extracted beam is degraded by ripples from the power supply of the magnetic elements of the synchrotron. Making the beam particle cross more quickly from the stable to the unstable region can reduce this effect. The RF-bucket channeling seems to be a good candidate for compensating low frequency ripples (<1MHz) in spills of the order of one second. The combination of these two accelerations ('smooth' and 'fast' accelerations) should guarantee the required beam quality for the medical application. Fig.1 illustrates this method of control of the slow extraction process.

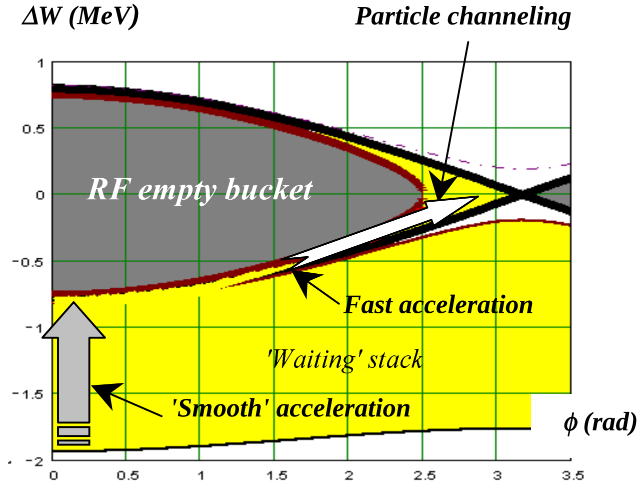

Figure 1: Illustration of the technique of moving the accelerated particles into the unstable region.

During the extraction (400 msec) the betatron core 'drives' the 'waiting stack' slowly into the resonance (changing $\Delta p/p_0$) to provide smooth acceleration of the particles with the momentum spread from the value of (-0.005) till (-0.001) [1]. The maximum deviation of the particle momentum from the resonance value ($\Delta p/p_0=-0.005$) is chosen to avoid crossing of dangerous high-order resonance lines during the extraction. Changing the momentum, the particles will be pushed into the RF channel and will be accelerated rapidly. The particle velocity in this channel is increased, but the density is reduced. Then the particle flux is constant that determines the required quality of the extracted proton beam. To realize this scenario, it is necessary to determine the main parameters of the betatron core with the power supply and adapt the RF-system [4] for the 'empty' bucket

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[#] Email: molod@se.jinr.ru

technique. Main parameters of the accelerated proton beam are collected in Table 1.

Table 1: Parameters of the dedicated proton machine.

Circumference	m	41
Accelerated particles		proton
Number of circulating particles		6.25×10^{10}
Slow extraction scheme		Third-integer resonance
Maximum kinetic extraction energy, E_c	MeV	220
β at E_c		0.586361
γ at E_c		1.23449
Momentum at E_c	MeV/c	679.123
Revolution period at E_c	μsec	0.2334
Beam intensity at E_c	mA	41.13
Magnetic rigidity at E_c	T·m	2.265
$(\Delta p/p)_{full}$ of the beam at E_c	%	0.4
Repetition rate	Hz	1
Typical cycle: Injection Acceleration Extraction flat top Fall	Ms	 50 200 500 (400) 250

2 BETATRON CORE

To determine the main parameters of the betatron core and of the power supply, the required calculations have been made for the *Cockerill steel.* The required total magnetic flux variation needed to provide the momentum variation of 0.004 is equal to *0.371 Weber* for the developed synchrotron. To get this flux, the magnetic field should be changed from B_{max} till $B_{min}= -B_{max}$. The maximum average magnetic field $<B>_{max}$ inside the betatron core should be equal to *1.2 Tesla* to avoid the steel saturation. The core length should be *0.6 meter* to be installed in the ring. The transverse dimensions of the betatron core are as follows: $r_{in}=0.120$ m, $r_{ext}=0.378$ m. Some special function of the current variation during the half of the whole cycle *IN(t)* has been defined (Fig.2) to meet the requirement ($d\Phi/dt = Constant$).

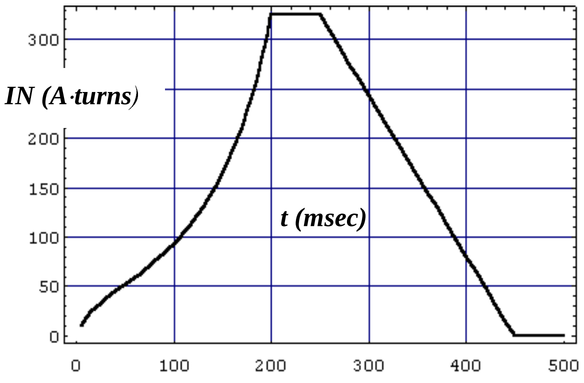

Figure 2: Current variation during a half of the time cycle.

The main characteristics of the betatron core and the power supply system are collected in Tables 2-3. It is necessary to underline that the extraction energy should be changed step by step from a maximum value till a minimum one to treat tumours.

Table 2: Main parameters of the betatron core

Required flux variation during extraction	Wb	0.371
Length	m	0.60
Maximum average magnetic field in yoke	T	1.2
Internal radius	m	0.12
External radius	m	0.378
Area of the section perpendicular to the magnetic field lines	m^2	0.155
Lamination thickness	mm	0.5
Steel density	kg/m^3	7870
Steel mass	kg	1'890

Table 3: Main parameters of the power supply

Number of turns of the coil		10
Section of the wire	mm^2	10
Length of the wire	m	17.2
Copper resistivity at 60 °C	Ω·m	2.035×10^{-8}
Maximum value of inductance	mH	100.93
Minimum value of inductance	mH	4.15
Maximum current density	A/mm^2	3.25
Total coil resistance (copper + eddy current)	mΩ	48.38 (35+13.38)
Total resistive power	W	14.4
Maximum absolute value of voltage	V	32

To evaluate the influence of the high-frequency ripple of the power supply, it is necessary to consider the voltage applied to the coil in the following form $V_{coil}=V_0+V\cdot\cos(\omega t)$. . The eddy currents in the betatron core prove a smoothing effect in the case of the high-frequency ripple. Increasing of the lamination thickness can reduce the current ripple. The present choice of laminations of *0.5 mm* gives a time constant of about *8.3msec*. Then for the ripple voltage of the order of 3.5×10^{-5} (or *0.001 mV*) at a frequency of *600 Hz* the resulting current ripple is of the order of 3.3×10^{-6} *A*. This high-frequency current ripple is by 100 times smaller than the low-frequency component. Increasing the lamination thickness one can increase the eddy current time constant and the smoothing of the magnetic field ripples. But in this case the power dissipation will be bigger. The optimization of the power supply and the lamination thickness should be performed before the betatron core is developed for the dedicated proton synchrotron.

3 RF-CHANELLING

As was mentioned above, ripples from the power converters of the magnetic elements and the power supply of the betatron core degrade the uniformity of the slow-extracted beam from the synchrotron. The empty buckets cause obstacles for particle motion in the longitudinal phase-plane and create the channel for these particles. Using the betatron core the beam is pushed into this channel 'smoothly'. In this channel *dN/dQ* is reduced, and *dQ/dt* increased.

The parameters of the RF bucket are determined by the process of extraction. The RF frequency should be equal to the revolution frequency to keep the particle energy constant at the synchronous phase. The 'resonance' energy of the particles depends on their betatron amplitude: the higher betatron amplitude - the lower the 'resonance' energy. To get a high multiplying factor for all the extracted particles, the RF empty bucket should be located properly with the required bucket height.

To create the channel between the RF empty buckets, the reference phase should be a non-zero value, which can be obtained from the following condition. The energy change in the bucket should be compensated by the changes in the machine that are caused by the betatron smooth acceleration. From this relation of the main machine parameters it is possible to get a definition of the required phase of the RF system:

$$|\Gamma| = |\sin\phi_0| = \frac{\Pi_{ring}}{V_m}(B\rho)\frac{(\Delta p/p_0)}{T_{spill}} \quad . \qquad (1)$$

The RF empty bucket should be positioned so to get an improvement for all the betatron amplitude. The determined beam parameters require the 'waiting stack' to be located below the resonance energy.To study the ripple influence, the multiplying factor (*K*) and the duty factor ($\Im$) can be written in the following form:

$$K(\Delta E,\omega) = 1 + \frac{\cos[\phi_2(\Delta E)] - \cos[\phi_1(\Delta E)]}{[\phi_2(\Delta E) - \phi_1(\Delta E)] \cdot \left(\frac{\Pi_{ring}}{qV_m}\right) \cdot p_0 \cdot |v_0 + \omega\alpha_R\cos(\omega t)|} , \qquad (2)$$

$$\Im(\Delta E,\omega) = \frac{1}{1 + \frac{1}{2K^2(\Delta E,\omega)} \cdot \left(\frac{\dot{p}_R}{\dot{p}_0}\right)^2} , \qquad (3)$$

where $v_0 = (\Delta p/p_0)/T_{spill}$, and $\alpha_R \approx {}^{pR\omega}/_{p_0}$

The function *K(ΔE)* for some values of the RF voltage (*1000 V*, *1600 V*, *1800 V*) is shown in Fig.3. The reference phase of the RF system for $V_m=1600$ V is equal to $\Gamma=5.813\times10^{-4}$ ($\phi_0=-0.033$ *gedree*).

The RF-empty bucket technique becomes less effective in the case of the high-frequency ($\omega>1000$ Hz) ripple (Figure 3). Another specific feature of this method is that particles are extracted in a small interval of the RF phase ($\Delta\phi$). This results in modulation of the spill at the high harmonics of the RF system (few *MHz*). Nevertheless, for the medical machine the slow extraction process, the physical spot size and the integration time average this spill modulation in the on-line dosimetry system.

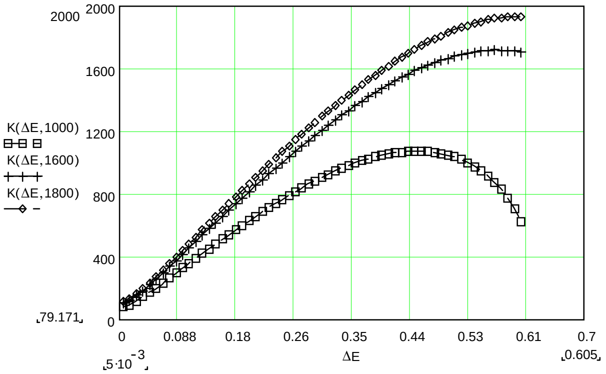

Figure 3: *K*-factor as a fuction of *ΔE* for different values of V_m *(1000kV, 1600 kV, 1800 kV).*

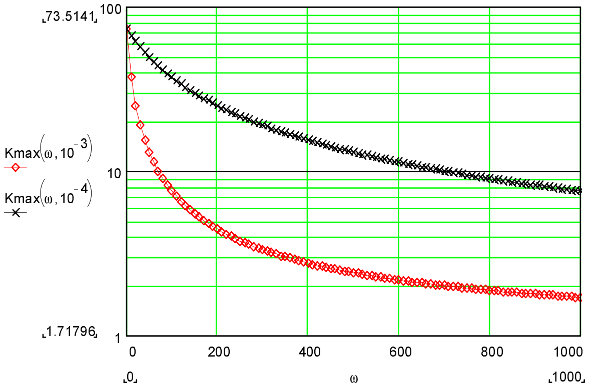

Figure 4: K-factor as a function of the ripple frequency for different values of α_R (10^{-3}, 10^{-4}).

4 CONCLUSION

Combination of the 'smooth' and 'fast' acceleration during the long extraction spill for the medical proton synchrotron has been studied. For the RF-channeling of the 'fast' acceleration of the extracted particles the RF system of the machine can be used.

We wish to thank Ph.Bryant, Ch.Steinbach and S.Rossi (PIMMS, CERN) for helpful discussions.

5 REFERENCES

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