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LONGITUDINAL PARTICLE MOTION IN A DEDICATED PROTON SYNCHROTRON FOR HADRON THERAPY

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Introduction

An accelerator designed for hospital use must satisfy a number of requirements, which are substantially different from those of a machine to be operated in a research environment [1]. To determine energy range, beam intensity and all other beam parameters of a dedicated medical accelerator for hadron therapy, first of all, it is necessary to choose the tumour treatment method. The maximum success of hadron therapy can be expected only when the irradiation will most conform to the shape of the tumour and the dose outside the tumour is minimised. To meet this requirement, an active scanning should be fixed as a base of the designed machine [2].

Magnetic scanning requires a smooth and slow extraction of the beam from the accelerator as well as a stable position of the beam spot during the extraction. Reasonable values for the rise time of the current in the deflection magnets need a stable extraction over a period of, at least, 400 ms in which one slice will be treated. It is necessary to provide an active energy variation decreasing the particle energies successively in steps on request from the scan system and to shift the particle range from slice to slice in the target volume.

To satisfy the special requirements, the medical synchrotron should have the following features. It is necessary to provide stability of the lattice parameters during extraction. The extracted beam should have the same extraction trajectory throughout the spill time to avoid particle losses in the septa. The chromaticity of the focusing structure should be negative to ensure transverse stability of the extracting beam. It is necessary to provide injection and acceleration of particles to eliminate the structure of the beam. Special manipulations should be performed before extraction to get the unbunched particle flow with possible homogeneity. The dedicated medical machine should guarantee the step of the energy variability less than 0.4 MeV. The energy variability accuracy has to be ± 40 keV in the range of the output energy from 60 till 220 MeV. For the specific medical application of the proton beam (for the slow extraction) it is necessary to get the coasting beam structure with energy distribution as uniform as possible with required momentum spread. Moreover, a medical accelerator should be operated easily.

Investigation of the longitudinal particle motion in the medical synchrotron it is important to define behaviour of main parameters during capture, acceleration and extraction of particles. It is obviously, that the capture process should be performed to trap the injected protons into the synchrotron without beam filamentation that leads to particle losses during acceleration. Acceleration regime has to be studied to define required behaviour of the magnetic field, the accelerating RF voltage and the phase of the

RF voltage to get the required output energy and to escape particle losses during the acceleration.

Results of the numerical calculations of the capture, acceleration and special beam preparation for the slow extraction are discussed in this paper.

General parameters of the proton synchrotron

The transverse particle motion and main feature of the dedicated proton synchrotron has been studied [3]. The single-turn injection is chosen with the kinetic energy of 12 MeV to capture the proton beam with the normalised emittance of 1π mm.mrad and the intensity of $6.25 \cdot 10^{10}$ particle per pulse. The proton beam from the 12 MeV Linac could be used as an injector and for production of the short-lived radiopharmaceuticals to develop the positron emission tomography (PET).

Main parameters of the synchrotron for different values of the kinetic energy are collected in **Table 1**.

Table 1

Ring circumference	m	36.56
Injection energy	MeV	12.0
Maximum extraction energy	MeV	220.0
Minimum extaraction energy	MeV	60.0
Time of the operation cycle	sec	1.0
Minimum dipole magnetic field	Tesla	0.252
Maximum dipole magnetic field	Tesla	1.2
Minimum RF frequency	MHz	1.265
Maximum RF frequency	MHz	4.804
Transition energy		5.6
Momentum spread of captured beam		± 0.003
Phase angle	rad	± 1.8
Harmonic of revolution frequency		1

The repetition rate is equal to 1 Hz to provide the required duration of the extraction spill. The capture, acceleration and special beam preparation for the slow extraction have to be performed during 250÷300 msec. These longitudinal beam manipulations should be made to meet the following demands. First of all, it is necessary to get a maximum capture efficiency of the injected particles in the acceleration regime. During acceleration particle losses have to be escaped by a special choice of the magnetic field, the RF phase and the RF voltage, which are functions of time. Such optimisation of the synchrotron parameters should be made for the output energy from 60 till 220 MeV. For the medical application it is necessary to provide the particle capture and acceleration without beam filamentation.

From the technical point of view the maximum magnetic field ramp have to be less than 10 T/sec and the maximum RF frequency ramp - less than 40 MHz/sec.

The theory of the longitudinal particle motion in synchrotrons is presented in many reports [4,5,6]. To meet the requirements, first of all, the adiabatic capture and acceleration should be performed. In this case main parameters of the synchrotron should be chosen so that the change of the synchrotron frequency is small during the synchrotron period. Under the adiabatic condition the motion of any arbitrary particle in terms of deviations from the synchronous particle can be expressed by the following set of the first order differential equations:

$$\frac{d\delta}{dt} \approx \frac{\omega_0}{2\pi\beta^2 E} q\tilde{V}(\sin\Phi - \sin\Phi_0) \qquad (1)$$
$$\frac{d\Phi}{dt} = h\omega\eta(\delta)\delta$$

where δ is the momentum deviation, Φ is the RF phase of the particle, q is the charge of the particle, h is the number of harmonic of the revolution frequency, β is the relative velocity of the particle, E is the full particle energy, ω_0 is the angular revolution frequency of the synchronous particle. $\tilde{V}$, ω_0, Φ_0 are varying functions of the time. $\eta(\delta)$ is the phase slip factor which in the adiabatic region can be expressed as $\eta(\delta) \approx \eta_0$, $\eta_0 = (\alpha_0 - \frac{1}{\gamma_0^2})$, $\alpha_0 = \frac{1}{\gamma_t^2}\Big|_{\delta=0}$. Here γ_0 is the relativistic factor of the reference particle.

Calculation results

Capture process

At low energy synchrotrons, the space charge force and the microwave growth for the intense beam usually limit parameters of the injected beam. The peak voltage is limited by the power supply. The RF voltage requirement in the low energy synchrotrons has to have enough bucket height for the injected beam during the injection. Theoretically very little loss in the synchrotron phase space can be achieved with $\phi_0 = 0$.

Injection over half the circumference of the synchrotron into a matched bucket and RF capture and acceleration on the fundamental harmonic of the revolution frequency (h=1) are considered. The bunch is injected into the synchrotron in the quasi-adiabatic regime while the RF voltage is on and set to a value $\tilde{V}_0$ such that the bucket aspect ratio matches

that of the bunch in the longitudinal phase plane. To achieve this value of the momentum spread, a debuncher it is necessary to use at the exit of a RFQ/DTL Linac .

The amplitude of the accelerating voltage ($\tilde{V}$) have to be increased till the maximum value V_f on the following law

$$\tilde{V} = \frac{V_f}{\left(\left(\frac{V_f}{V_0}\right)^{0.5} - \alpha\left(\frac{t}{T_s}\right)\right)^2} \qquad (3)$$

where V_0 the initial RF voltage, α is so-called adiabatic factor, T_s is the synchrotron period. The bending magnet field is constant during the capture. Choosing the adiabatic factor one can capture the beam without any losses and beam filamentation.

To model of the longitudinal particle motion the beam is presented by the group of non-interectional particles. The number of the particles in the numerical experiments is equal to 300.

The initial distribution on the longitudinal phase-plane has the form of rectangle with the momentum spread equal to ± 0.00125 and the phase angle equal to ± 1.8 radians (**Fig.1**). The initial momentum spread is chosen to get the momentum spread of the trapped beam less than ± 0.003.

As is mentioned above the RF voltage should be changed accordingly (3). This value of the adiabatic factor is chosen to get a 'good' particle distribution in the captured beam. The time dependence $\tilde{V}(t)$ is shown in **Fig.2**. The first curve is according to adiabatic factor α = 0.2, the second one - α =0.02.

In the first case there were no losses of the particles from the separtrix, but one can see filamentation of the beam (**Fig.3**), that leads to losses of one third of the particles in the acceleration regime. In the second case (**Fig.5**) the particle losses are 4 particles from the initial three hundreds, i. e. smaller than 1.4%. The histograms of momentum spread in these cases are shown in **Fig.4** and **Fig.6**, respectively.

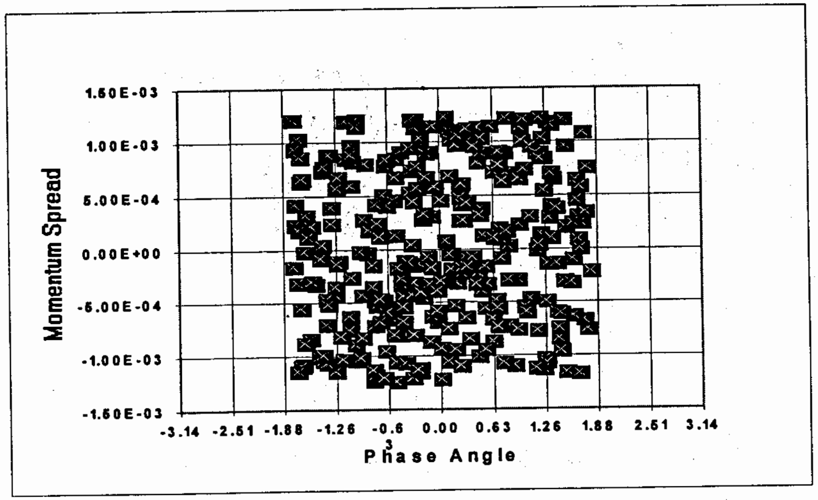

Figure 1: Initial particle distribution

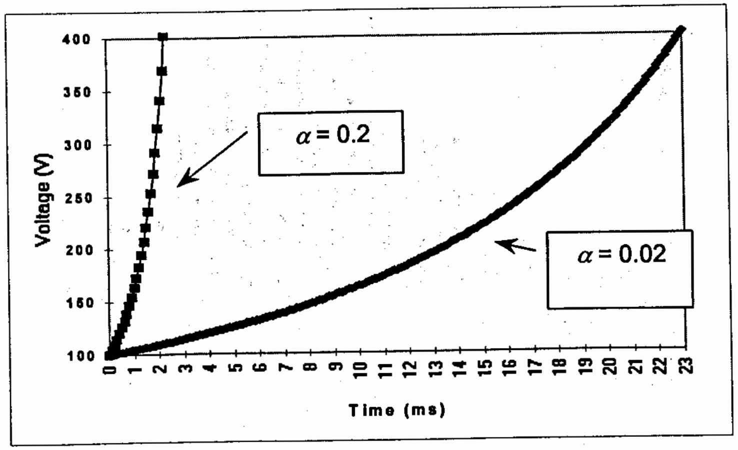

Figure 2: Time dependence of trapped voltage

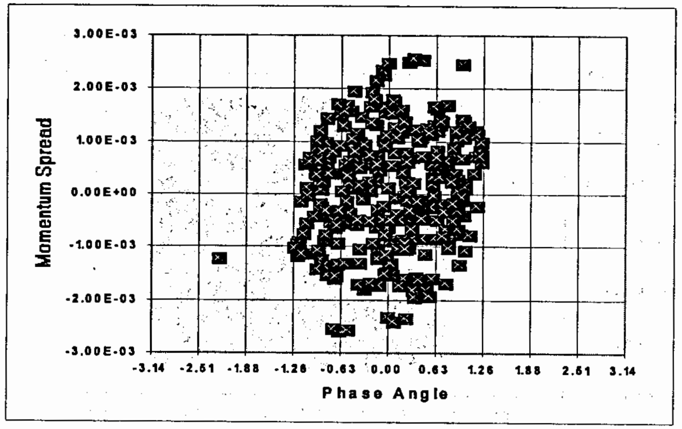

Figure 3: Distribution of trapped beam (adiabatic factor = 0.2).

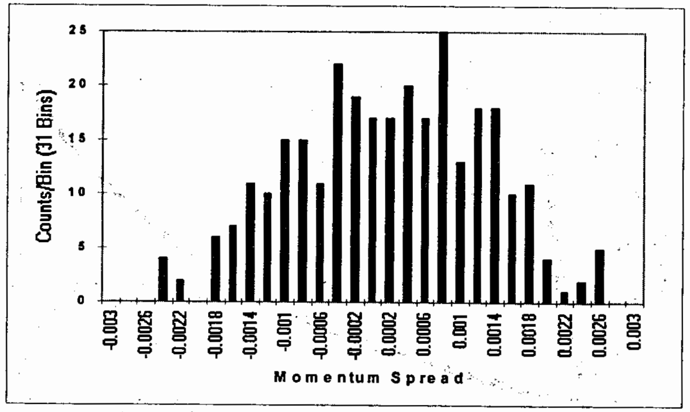

Figure 4: Histogram of momentum spread of the trapped beam (adiabatic factor = 0.2).

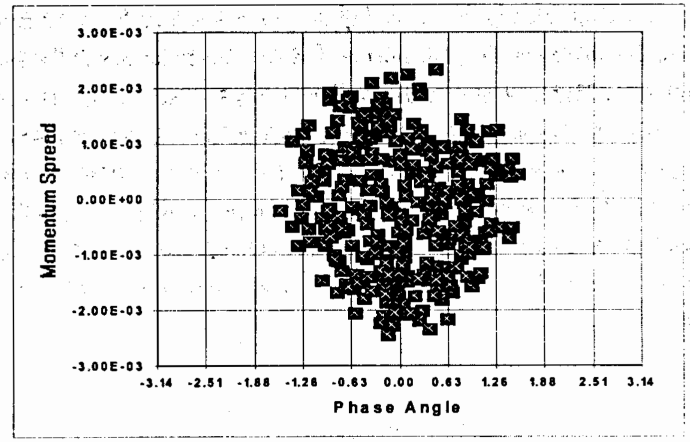

Figure 5: Distribution of trapped beam (adiabatic factor = 0.02).

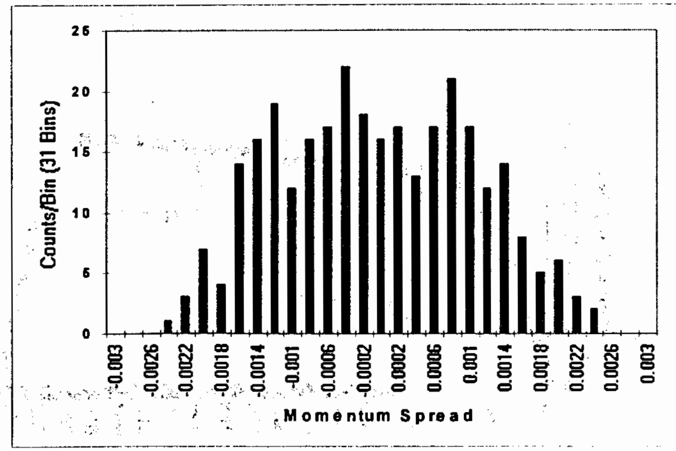

Figure 6: Histogram of momentum spread of the trapped beam (adiabatic factor = 0.02).

Acceleration process

The next stage of the working cycle of proton synchrotron is the acceleration of the beam. There are two independent parameters of accelerating electric field: the amplitude of voltage and the RF phase of this field. The investigation of the time dependencies of these values is fulfilled for the synchronous particle. The running of the group of particles is made in the finding fields for the control of particle losses from the separatrix to study the behaviour of particles on the phase-plane. The time dependencies of the amplitude of voltage and RF phase are shown in **Fig.7** and **Fig.8**, respectively. The RF phase dependence has the following character. At the initial and final stages of acceleration the RF phase is quadratic function of the time. In the middle region the phase has a tendency to linear growth. The first derivatives in the points of sewing together are equal each other from the left hand and right hand sides. In the first stage of acceleration the voltage has linear growth from 400 V up to 547 V and then slowly decreases to 320 V with the time dependence of:

$$V = \frac{\xi \tilde{V}_0}{(1 - 0.001 \sin \Phi_0)^3} \qquad (4)$$

$$\xi = \left(\frac{\gamma_0}{\gamma}\right)^3 \frac{1 - \alpha_0 \gamma^2}{1 - \alpha_0 \gamma_0^2}$$

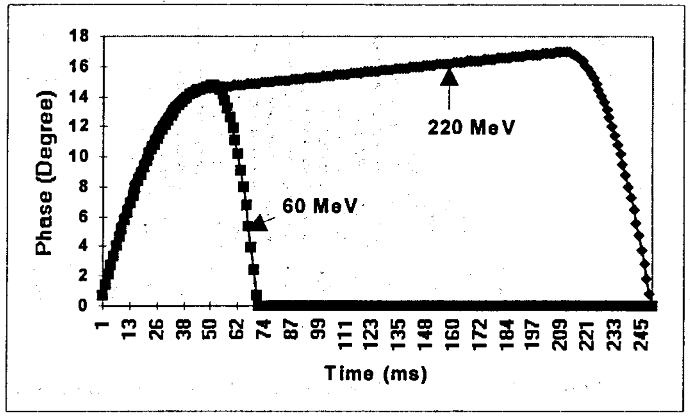

Figure 7: The phase of accelerating field

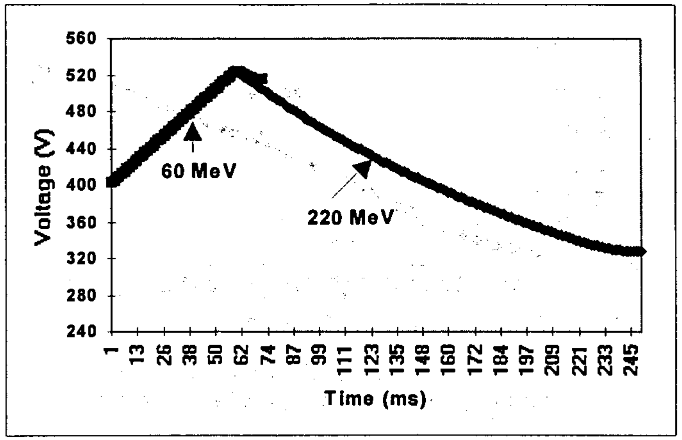

Figure 8: The amplitude of accelerating field

During acceleration of the particles in the region from 60 to 220 MeV the time dependencies are of identical forms, but the time of acceleration varies from 74 msec for energy 60 MeV up to 250 msec for energy 220 MeV (**Fig.9**). There were no losses of particles in this stage.

Time dependencies of RF frequency and synchronous magnetic field are shown in **Fig.10** and **Fig.11**, respectively. The maximum change of the amplitude of magnetic field is no more than 6.8 T/sec. The maximum change of the RF frequency is approximately equal to 30 MHz/sec that essentially smaller than the restrictions on these parameters. The particle distributions of the accelerated beam are shown in **Fig.12** (60 MeV) and **Fig.14** (220MeV). As one can see from the obtained results, the momentum spread is of the same order with the momentum spread of the injected beam (< ±0.001). The histograms of the momentum spread of the beam for the kinetic energy of 60 MeV and 220 MeV are shown in **Fig.13** and **Fig.14**, respectively.

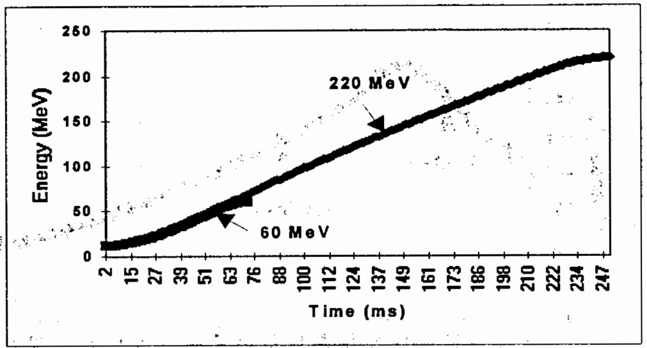

Figure 9: Kinetic energy as a function of time for two values of final energy (60 and 220 MeV)

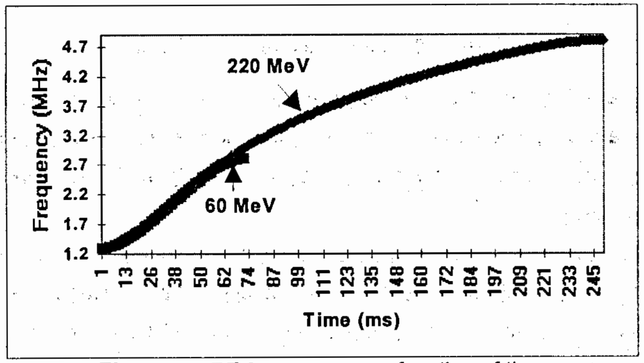

Figure 10: RF frequency as a function of time for two values of final energy (60 and 220 MeV)

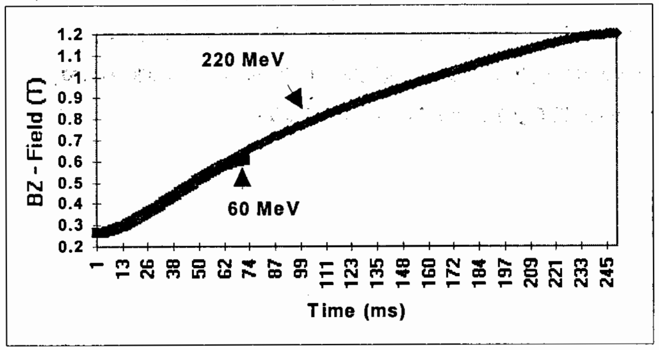

Figure 11: Magnetic field as a function of time for two values of final energy (60 and 220 MeV)

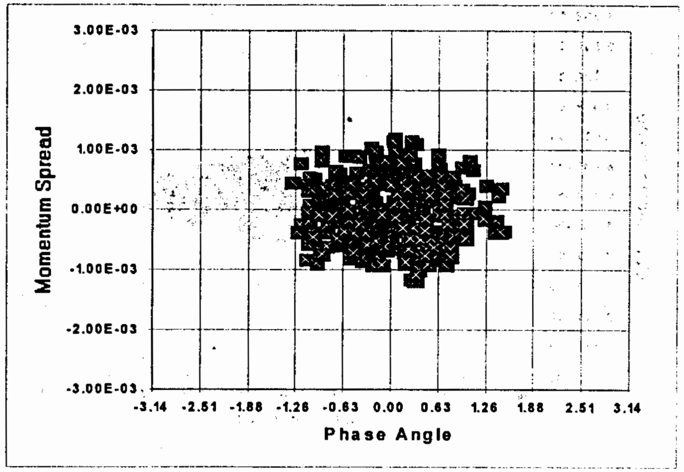

Figure 12: Particle distribution of accelerated beam (60MeV)

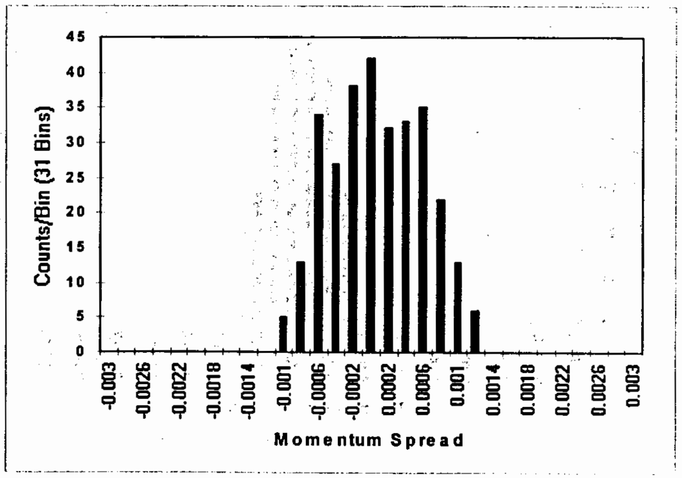

Figure 13: Histogram of momentum spread of the accelerated beam (60MeV)

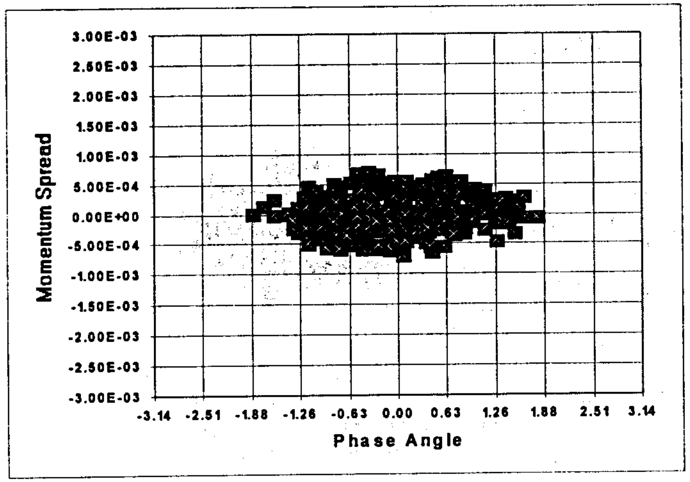

Figure 14: Particle distribution of accelerated beam (220MeV)

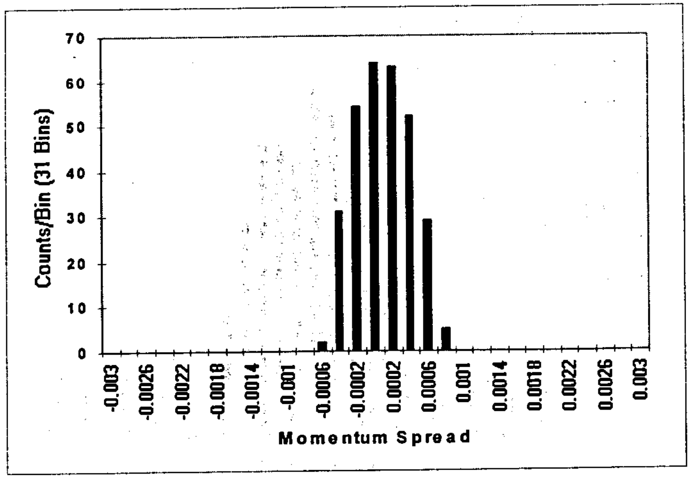

Figure 15: Histogram of momentum spread of the accelerated beam (220MeV)

Special beam manipulation before the slow extraction

The last phase of the working cycle of the dedicated proton synchrotron for hadron therapy is the preparation of the beam for the resonance extraction. This process consists of two stages. As a first step, it is necessary to increase maximum momentum spread of the accelerated particles (in particular, till ± 0.003). And as a second step, the accelerated beam has to be debunched to get coasting proton beam with the momentum distribution as uniform as possible with required momentum spread.

The process is studied for the 220 MeV beam. Increasing the voltage from the final value (~320 V) up to 1.4 kV during the time of 0.1 msec (after the acceleration phase) one can solve the first task. The resulting particle distribution is shown in **Fig.16.**

The second task may be solved under the following conditions. It is necessary to overturn the RF-phase from zero value to the phase, which is equal to π (so-called, RF gymnastic). The amplitude of the RF-voltage has to be reduced to zero value. The result of this procedure is shown in **Fig.17**, where one can see that the angle size of the beam is equal to 2π.

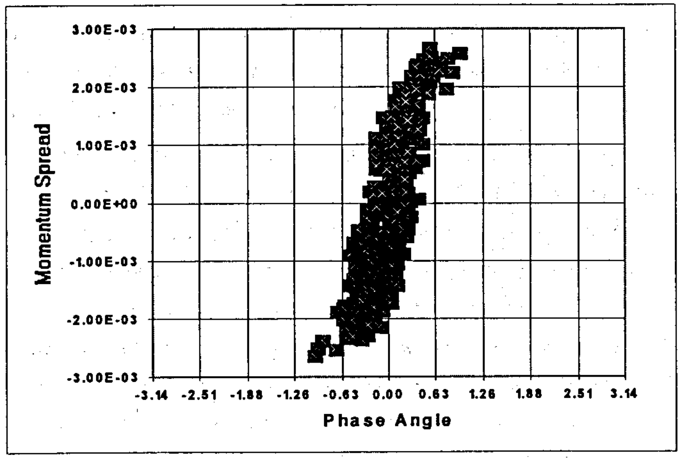

Figure 16: Particle distribution of the accelerated beam with increased momentum spread

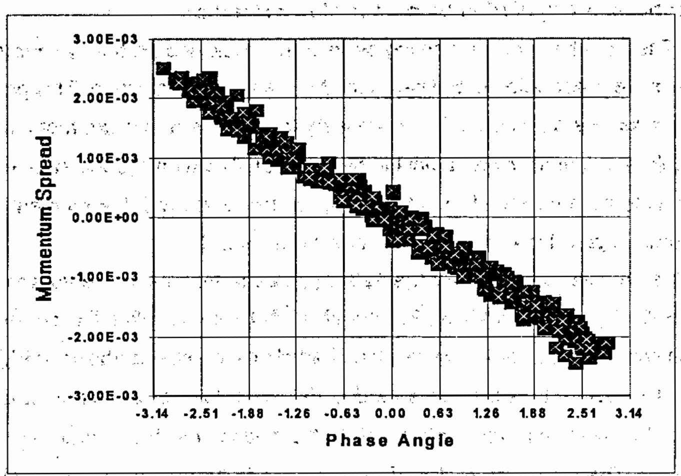

Figure 17: Particle distribution of the coasting beam

Conclusion

The optimisation of the RF parameters and of the magnetic field is performed. The capture of the injected beam in the acceleration regime requires the following RF-parameters: V_0 = 100 V, V_f = 400 V, the time of the capture is of the order of 23 msec. The losses of particles are smaller than 1.4%. The momentum spread of the injected beam has to be less than ± 0.00125 and the phase length is equal to ± 1.8 rad. The time dependencies of the RF-parameters and the synchronous magnetic field have been determined. The maximum RF voltage in the acceleration phase of the working cycle is equal to 547 V. The parameters meet the requirements on the values of their ramps and provide the acceleration of the beam in the region of energies from 60 MeV up to 220 MeV. The maximum change of the amplitude of magnetic field is no more than 6.8 T/sec. The maximum change of the RF frequency is approximately equal to 30 MHz/sec. The possibility of the special beam manipulation to get the coasting beam with the required momentum spread and phase angles has been shown.

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Исследование продольного движения частиц в специализированном протонном синхротроне для радиотерапии

Исследуется продольное движение частиц в специализированном протонном синхротроне для радиотерапии. Проведена оптимизация основных параметров ускоряющей системы и поворотного магнитного поля ускорителя. Выполнено численное моделирование процессов адиабатического захвата частиц, ускорения и специального манипулирования ускоренным пучком перед медленным выводом частиц из синхротрона.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ при поддержке Фонда «Онкология 2000» (Прага, Чешская Республика).

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Longitudinal Particle Motion in a Dedicated Proton Synchrotron for Hadron Therapy

The longitudinal motion of the charged particles in the dedicated synchrotron for proton therapy is investigated. Optimization of the RF parameters and of the magnetic field of the accelerator has been obtained. The quasi-adiabatic capture, acceleration and the special beam manipulation before the slow extraction have been calculated using the designed multi-particle-tracking program.

The investigation has been performed at the Laboratory of Particle Physics, JINR and the «Oncology 2000» Foundation, Prague, Czech Republic.

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