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THE RF CYCLE OF THE PIMMS MEDICAL SYNCHROTRON

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Abstract

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This paper presents the design of the RF cycle of the medical synchrotron of the PIMMS (Proton-Ion Medical Machine Study) hosted at CERN. The cycle comprises adiabatic trapping, acceleration and RF gymnastics, for either protons or fully stripped carbon ions. The injection energy is 20 MeV for protons and 7 MeV/u for carbon. Maximum extraction energies are 250 MeV for protons and 400 MeV/u for carbon ions. The cycle duration is less than 1 s, with a maximum magnetic field ramp below 3 T/s. The simulations show that the beam stays inside the aperture of the machine, and that, theoretically, there are no longitudinal losses. At the end of the cycle the beam is ready for extraction with a $\Delta p/p = 0.4\,\%$. The peak RF voltage is 3 kV and the frequency ranges from 0.4 to 3 MHz.

1 INTRODUCTION

In early 1996, a four-way collaboration between CERN, GSI, Med-AUSTRON, Onkologie-2000 and TERA, denominated PIMMS was launched to design a synchrotron optimised for hadrontherapy [1]. This paper describes the RF cycle for proton and carbon ion acceleration, as studied in that framework. Three tools are used for the computations. RFAC (Radio Frequency Analytical Code), a code developed for this purpose, calculates the evolution of the beam parameters for a perfect adiabatic cycle. ESME [2], a multi-particle tracking code for protons, taking also into account the non-perfect adiabaticity of the cycle. TSC1D [3] (Tracking with Space Charge 1D), a multi-particle tracking code recently developed for ions, that takes into account the contribution of the longitudinal space charge. The results of the three codes have been compared throughout the study, see for example Figure 1.

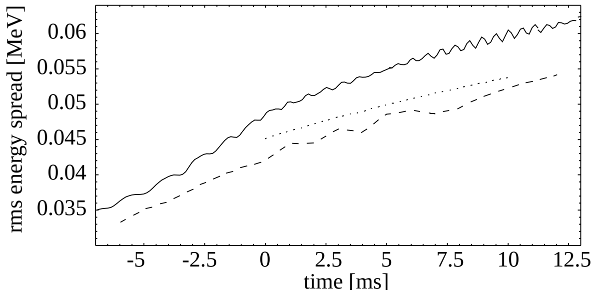

Figure 1: Rms bunch energy spread around the onset of acceleration (at t=0) for the 20-250 MeV proton cycle. Continuous line: TSC1D, dotted: RFAC, dashed: ESME. TSC1D values are 15-20 % higher due to space charge.

2 SPACE CHARGE

The modest intensities required for radiation therapy, especially when light ion beams are applied, suggest that direct space charge effects are negligible. For proton intensities, however, in combination with the very low injection energy of 20 MeV, this is no longer true: the RF cycle ignoring longitudinal space charge resulted in a ≈10 % beam loss shortly after the onset of acceleration. This was evidenced by multi-particle tracking simulations using TSC1D. The used code is based on Track1D [4], but makes use of a wavelet optimised finite difference Poisson solver.

The standard equations to treat synchrotron motion

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_s}\right) = \frac{q}{2\pi}\left[V(\phi) - V(\phi_s) + V_{sc}(\phi)\right]\,, \quad (1)$$

$$\frac{d}{dt}\Delta\phi = -\frac{h\omega_s\eta}{\beta^2 E}\Delta E\,, \quad (2)$$

are integrated numerically by a leap-frog scheme. Here $\Delta E = E - E_s$, $\Delta\phi = \phi - \phi_s$, $\eta = 1/\gamma^2 - 1/\gamma_t^2$ with γ_t the Lorentz factor at transition. E and ϕ are the total energy and the phase of the particle, $V(\phi)$ is the instantaneous applied RF voltage, ω the frequency and h the harmonic number. The suffix “s” refers to the synchronous particle. The space charge voltage $V_{sc}(\phi)$ is given by the derivative of the line density $\lambda(\phi)$

$$V_{sc}(\phi) = \frac{g_0 h^2}{2\varepsilon_0\gamma^2 R}\cdot\frac{d\lambda(\phi)}{d\phi}\,, \quad (3)$$

where ε_0 is the permittivity of free space and g_0 is the geometry factor. $V_{sc}(\phi)$ decreases the effective RF voltage and, since the line density changes along the bunch, distorts the bunch shape.

3 TIMING OF THE CYCLE

The RF cycle is composed of four parts: adiabatic trapping at fixed frequency (flat bottom), acceleration with RF frequency increase, RF gymnastics at fixed frequency (flat top), RF frequency decrease back to the starting point (no beam). The present paper describes the first three points. The RF cycle is synchronised with the main dipoles’ magnetic field cycle [1]. The maximum field ramp is 3 T/s. The timing for both protons and carbon ions for minimum and maximum extraction energies is presented in Table 1.

4 TRAPPING PROCESS

The debunched linac beam ($\Delta\phi = 360°$) is trapped using the adiabatic trapping process [5]. The process is called

Table 1: Timing of the proton and ^{12}C^{6+} carbon cycles for the respective minimum and maximum extraction energies.

Energy MeV/u	Trapping [ms]	Accel. [ms]	Extr. [ms]	Total [ms]
p^{+} 20-60	26.8	110.8	30	167.6
p^{+} 20-250	26.8	259.0	30	315.8
^{12}C^{+6} 7-400	40.4	340.0	22	402.4
^{12}C^{+6} 7-400	40.4	694.0	22	756.4

adiabatic when its duration is long with respect to the synchrotron period T_s. In the present case $T_s \approx 1\,\text{ms}$. The parameters that define the process are chosen in order to satisfy three criteria: the capture efficiency – the ratio between injected and captured particles – has to be close to unity. The dilution – the longitudinal emittance increase – has to be minimum. The bunching factor – the ratio between the phase length of the bunch and the RF wavelength – has to be maximum to reduce space charge forces. To satisfy these criteria, the adiabatic factor α, the bucket-to-bunch area ratio A_B/A_b, (A_B is the bucket area, and A_b is the bunch area) and the ratio between the final and initial cavity voltage V_f/V_i have been fixed to

$$\alpha = \left|\frac{\frac{dA_b}{dt}T_s}{A_b}\right| = 0.1\,, \quad \frac{A_B}{A_b} = 1.5\,, \quad \frac{V_f}{V_i} = 10\,. \tag{4}$$

This choice completely defines the trapping process. The simulations give a theoretical 100 % efficiency. Table 2 presents the relevant parameters of the process.

Table 2: Adiabatic trapping, relevant parameters.

	p^{+}	^{12}C^{6+}
Nb. of injected particles	$6.8\,10^{10}$	$7.9\,10^{8}$
Injection energy [MeV/u]	20	7
$(\frac{\Delta p}{p})_{\sqrt{5}\,\mathrm{rms}}$ at injection [%]	±0.12	±0.12
Revolution frequency [MHz]	0.81	0.486
Revolution period [μs]	1.23	2.06
Bunch emittance [eV s]	0.117	0.827
Harmonic number h	1	1
Stable phase [deg]	0	0
V_f [kV]	0.35	0.291
Trapping time [ms]	26.8	40.4
Synchrotron period T_s [ms]	1.2	1.9
Filling factor (A_b/A_B) [%]	66.6	62.5
$(\frac{\Delta p}{p})_{\sqrt{5}\,\mathrm{rms}}$ after capture [%]	±0.244	±0.248

The RF voltage increase with time is given by [5]

$$V(t) = \frac{V_f}{\left[\sqrt{\frac{V_f}{V_i}} - \frac{\alpha}{T_s}t\right]^2} \tag{5}$$

5 ACCELERATION

The RF system used for particle acceleration is composed of a single gap resonator [6]. The hardware imposes the maximum RF voltage, the maximum frequency swing and the maximum tuning rate attained during acceleration. The losses are minimised choosing low values for the momentum spread $\Delta p/p$, for the tune shifts $\Delta Q_{H,V}$ and for the filling factor defined as A_b/A_B. The horizontal machine acceptance is $-60 < x < +35\,\text{mm}$, where $x = 0$ corresponds to the central orbit. The inner limit of the dipoles good field region is at -60 mm, and the edge of the electrostatic septum is at +35 mm [1]. The cycle is fully determined by the temporal evolution of two variables: the magnetic field $B = B(t)$ and the applied RF voltage $V = V(t)$. For $B(t)$ a cosine-like time dependence was assumed. The energy gain of a particle with charge q and mass A_n is linked to the B-field variation by [7]

$$qV\sin\phi_s = 2\pi R A_n \frac{d(B\rho)}{dt}\,, \tag{6}$$

with synchronous phase ϕ_s, orbit mean radius R and magnetic rigidity $B\rho$. In equation (6) $qV\sin\phi_s$ is the energy gain per turn. The voltage at the onset of acceleration is determined by V_f, the voltage at the end of the adiabatic trapping process (see Table 2). After a few ms the voltage reaches 3 kV, a compromise between the need for a sufficiently large bucket area (i.e. small filling factor) and a small $\Delta p/p$. The way the voltage is increased and the optimum duration of this process are found by an optimisation procedure: both the RF voltage $V(t)$ and its derivative must be continuous. Moreover the adiabatic factor has to be as low as possible. Relevant parameters of the acceleration are presented in Table 3.

Table 3: Characteristic parameters for proton 20-250 MeV and ^{12}C^{6+} 7-400 MeV/u acceleration. The superscript max refers to maximum values occuring during the cycle.

	p^{+}	^{12}C^{6+}
	After Trapping / Before Extraction[a]	
Nb. particles	$6.8\,10^{10}/6.8\,10^{10}$	$7.9\,10^{8}/7.9\,10^{8}$
E [MeV/u]	20 / 250	7 / 400
p [GeV/c]	0.195 / 0.729	0.114 / 0.951
$B\rho$ [Tm]	0.65 / 2.432	0.763 / 6.346
f_{RF} [MHz]	0.81 / 2.445	0.486 / 2.85
$(\frac{\Delta p}{p})_{\sqrt{5}\,\mathrm{rms}}$[%]	±0.12 / ±0.2	±0.12 / ±0.2
H,V $\varepsilon^{*}_{\mathrm{rms}}$ [μm]	2.5π	6.1π
$V^{\max}$ [kV]	2.9	2.7
$\phi^{\max}$ [deg]	16.9	20.6
RF harm. nb. h	1	1
Freq. swing	3	5.9
$\dot{f}^{\max}_{RF}$ [Hz/s]	$10.4\,10^{6}$	$6.0\,10^{6}$
$\dot{B}^{\max}$ [T/s]	2.6	2.98
$(\frac{\Delta p}{p})^{\max}_{\sqrt{5}\mathrm{rms}}$ [%]	±0.33	±0.29
$\Delta Q^{\max}_{H}$	0.08 (at 20.9 MeV)	0.001 (at 7.9 MeV/u)
$\Delta Q^{\max}_{V}$	0.12 (at 22.6 MeV)	0.001 (at 8.3 MeV/u)

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[a] After RF gymnastics, that is prepared for slow extraction.

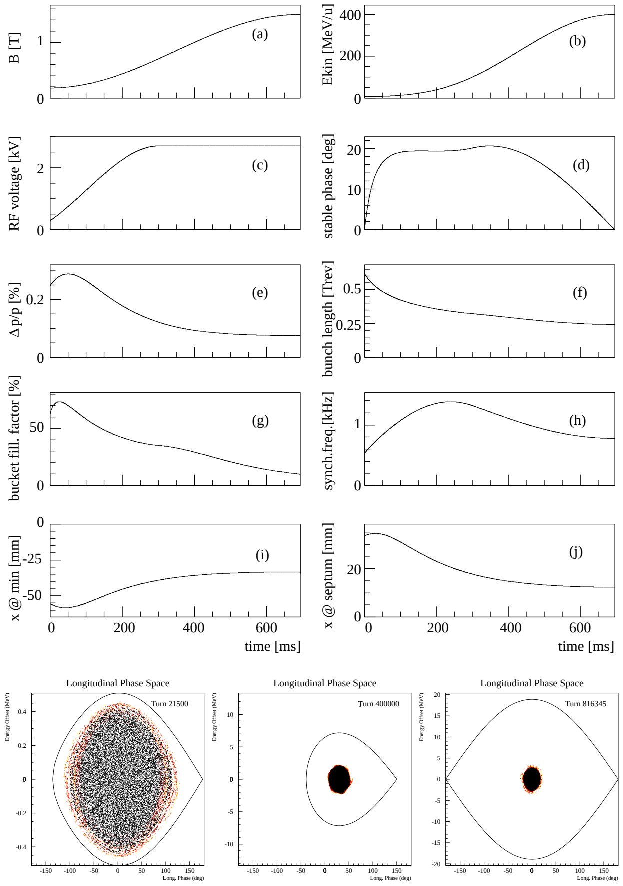

Figure 2: The ^{12}C^{6+} cycle for 7-400 MeV/u. Temporal evolution of selected parameters as computed by RFAC (top) and TSC1D phase space plots (bottom) at the end of trapping, in the middle of acceleration and at top energy.

6 BEAM PREPARATION FOR EXTRACTION

A third integer slow extraction scheme respecting the Hardt condition was chosen for the PIMMS synchrotron [8]. For the maximum smoothness of the extracted spill, a large momentum spread in combination with a small transverse emittance is needed [1]. Therefore, before extraction the bunch is manipulated by the RF system to obtain an unbunched beam of a $\Delta p/p = \pm 0.2\,\%$, with a particle distribution as uniform as possible. The RF manipulation has to be as simple as possible and can last at most a few ms. The RF voltage should not exceed 3 kV. The procedure is divided in two steps: a 100 μs, 180° RF phase jump is performed to allow bunch elongation along the separatrices until the desired $\Delta p/p$ is reached. Then the RF is switched off and a few tens of ms are left for the bunch to fully populate the longitudinal phase space. This procedure was simulated with the ESME code. The example for the 250 MeV proton extraction energy is given in Figure 3.

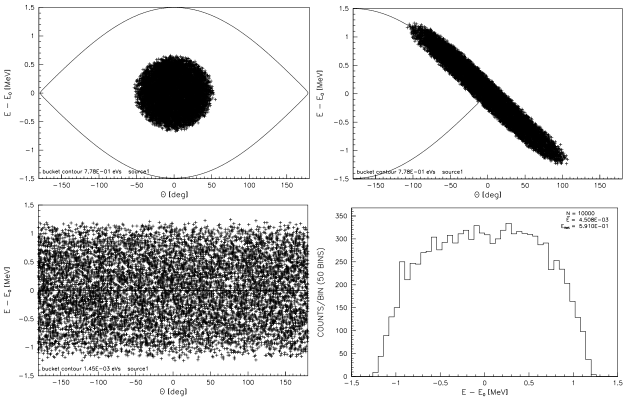

Figure 3: ESME simulation of the RF phase jump with 250 MeV protons and debunching before extraction.

7 CONCLUSION

The design of the RF cycle for protons and carbon ions as required by the PIMMS synchrotron is given. The results take space charge effects into account, which are relevant for protons at injection and especially in the first 10 ms of acceleration. The parameters of the cycle are set according to the available hardware and respect the limits imposed by the PIMMS synchrotron magnet cycle.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

[1] Accelerator Study Group supported by Med–AUSTRON, Onkologie 2000 and TERA Foundation, hosted by CERN, *The Proton–Ion Medical Machine Study (PIMMS) – Part I*, CERN/PS 99-010-DI, 1999.

[2] J. MacLachlan, J.-F. Ostiguy, “User’s Guide to ESME V8.2”, Fermilab, Chicago, 1996.

[3] P. Knaus, “Injection and Ejection Studies in High Intensity Accelerators”, Ph.D. thesis, Inst. f. Exp. Kernphysik, Univ. Karlsruhe TH, 2000.

[4] Ch. Prior, “Computer Simulation of Charged Particle Beams under Space–Charge”, RAL-TR-1998-48, 1998.

[5] U. Bigliani, “Système HF du Booster. Capture dans l’Espace de Phase Longitudinal”, CERN/SI/Int. EL/68-2, 1968.

[6] M. Crescenti, A. Susini, G. Primadei, A. Schnase, F. J. Etzkorn, C. Fougeron, “The VITROVAC RF Cavity in the TERA/PIMMS Medical Synchrotron”, These proceedings.

[7] C. Bovet, R. Gouiran, I. Goumowski, K. H. Reich, “A Selection of Formulae and Data Useful for the Design of A.G. Synchrotrons”, CERN/MPS-SI/Int. DL/70/4, 1970.

[8] W. Hardt, “Ultraslow Extraction out of LEAR (Transverse Aspects)”, CERN Int. Note PS/DI/LEAR M Note 81-6, 1981.