# A BETATRON CORE FOR OPTIMISED SLOW EXTRACTION IN A PROTON/ION MEDICAL SYNCHROTRON

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*Abstract*

The beam quality required from medical synchrotrons for hadron-therapy implies stringent requirements on the spill homogeneity over the full extraction period of about one second. The use of a betatron core to optimise third-order resonant extraction appears particularly promising to satisfy these needs [1]. This core accelerates the beam into the resonance keeping all lattice functions, and hence the resonant conditions, constant which results in a very stable extraction over a broad bandwidth. Compared to small quadrupoles that are normally used to drive the resonance, the large stored energy in a betatron core represents an inherent safety feature because it is less sensitive to transients that could send large beam spikes to the patient. To complete the study, a possible implementation of a feed-forward system to correct for low-frequency ripples in the extracted beam is analysed. A mechanical and electrical betatron core design with a feed-forward system is presented. Experiments performed at the Saturne National Laboratory LNS, CEA Saclay, using the extraction betatron core "Gephyrotron" [2] are outlined. They confirm the utility of such a device to extract a high-quality beam for medical applications.

## 1 MEDICAL REQUIREMENTS

A feasibility study of a dedicated medical synchrotron for accelerating protons and light ions (e.g. carbon) for cancer treatment is being pursued at CERN by the Proton Ion Medical Machine Study (PIMMS) group. PIMMS is a five-way collaboration between the TERA Foundation, AUSTRON, CERN, GSI and Onkologie 2000.

Synchrotrons for applications in radiotherapy should provide sufficiently long spills of variable duration and intensity for both particle species. Short spills of 0.25 s are needed in the case of passive beam spreading systems, while active scanning techniques require up to a few seconds of beam to paint a single tumour slice. Furthermore irradiation of subsequent tumour slices requires cycle to cycle variability of the beam energy and intensity. Highest intensity is needed when irradiating the distal part of a tumour volume, and rapidly decreases when proceeding with the treatment of proximal layers. These have already received part of their dose during irradiation of deeper layers. Using a betatron core to drive the resonant extraction enables control of both length and intensity of the spill, whatever the actual value of the extraction energy.

Adjustment of the spill intensity also implies control over its uniformity. Statistical fluctuations in the extracted current, mainly due to power supply (PS) ripples, cause time structures at many frequencies in the particle pulses that would lead to hot and cold spots in the target volume. A dose uniformity of $\pm 2.5\%$ is still tolerable and the maximum acceptable spill modulation is about 20% for the 2 kHz component [3]. The use of a betatron core to move the waiting beam into the resonance is particularly well suited to produce a uniform spill. Moreover the large stored energy in a betatron, as compared to a small quadrupole, is a safety feature since it responds less quickly to transients that could send intolerable beam spikes to the patient.

In order to guarantee the security of the treatment, a fast beam abort within a few hundreds of micro-seconds is required to prevent exceeding the dose limit.

## 2 THE PIMMS BETATRON CORE

### 2.1 *Betatron Core Working Principle*

The proposed extraction method from the synchrotron is a third-integer resonant scheme driven by sextupoles. The particles moved in momentum by the betatron into the unstable region gradually increase their amplitude of betatronic oscillation until they are extracted. Extraction with a betatron core makes it possible to front-end the beam with an empty bucket into the resonance [4] to accelerate it and reduce the ripple effect.

A simplified view of a betatron core is depicted in Fig. 1. During extraction this smooth high-inductance device is

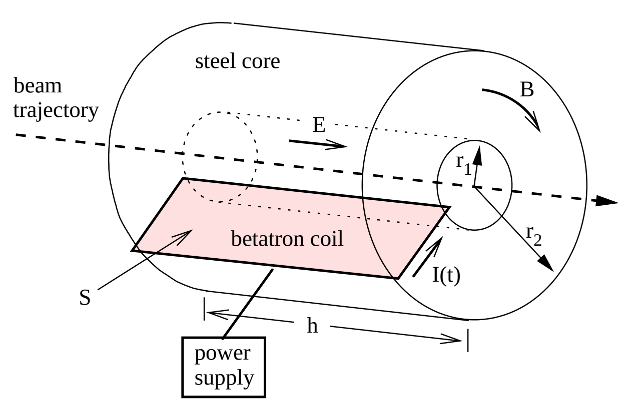


Figure 1: Schematic view of the betatron core.

the only active element. All the other elements, and thus also the lattice functions, are kept static, the RF voltage is switched off. Therefore, the energy of the extracted beam is kept constant, no RF structure can appear in the spill and sources of ripples are minimised. This enables production of very homogenous spills.

The application of a time-dependent current to the betatron coil gives rise to a magnetic flux variation $\Delta\phi$ inside the steel core. The temporal change of the flux itself produces an electric field parallel to the main axis of the betatron, accelerating the particles into the resonance. The magnetic flux variation, the relative momentum change $\Delta p/p$ of the particles and the magnetic rigidity $B\rho$ are related by

$$\Delta\phi = CB\rho\frac{\Delta p}{p}\ , \tag{1}$$

where $C$ is the machine circumference.

### 2.2 Parameter List

The betatron coil lamination $x$ is an important parameter for ripple minimisation [1]. The voltage applied to the coil of Cockerill steel presents ripples generating current and magnetic field with frequency dependent components. For a PS voltage $V$ with ripple frequency $\omega$=$2\pi f$, the frequency dependent component of the current generated in a coil of inductance $L$ and steel conductivity $\sigma$ is

$$I(\omega) = \frac{V}{L\omega\sqrt{1+\tau_{ec}^2\omega^2}}\ , \quad \tau_{ec} = k\frac{\sigma\mu_0\mu_r}{8}x^2\ , \tag{2}$$

where $k$ is a correction factor equal to 4 in the case of the PIMMS betatron. The interesting feature of Eq. (2) is that already for relatively low frequency ($f\geq$100 Hz) the estimation $\omega\tau\gg1$ holds and the smoothing dependence becomes inversely proportional to $\omega^2$. The current ripple $I(\omega)$ is also reduced by increasing the eddy current time constant, i.e. by increasing the lamination thickness $x$. The present lamination (cf. Table 1) is a common choice in transformator design, leading to a 6 ms time constant. If necessary it is possible to further increase the lamination thickness, at the cost of higher power dissipation.

For the betatron specifications, a total momentum variation of $\Delta p/p$=0.5% is used. Extraction is assumed to start with a stack positioned at a $\Delta p/p$=0.1% from the resonance and that the stack has up to $\Delta p/p$=0.4%. The maximum total magnetic flux variation (carbon ions at 400 MeV/u) needed in the betatron to sweep the whole stack through the resonance is $\Delta\phi$=2.38 Wb.

## 3 EXPERIMENTS AT SATURNE

The spill intensity measurement system consists of 3 successive scintillators in coincidence placed in the extraction line. The bandwidth of the system is variable by changing the time constant $\tau_{\rm RC}$ of an RC-circuit in the readout electronics. The experiments were performed on a $^4$He beam at 400 MeV/u and $10^{10}$ particles in the machine.

Table 1: Main betatron core parameter

| | PIMMS | SATURNE |
|---|---|---|
| Length $h$ [m] | 1.5 | 2.09 |
| Internal radius $r_1$ [m] | 0.08 | 0.125 |
| External radius $r_2$ [m] | 0.75 | 0.428 |
| Lamination thickness $x$ [mm] | 0.5 | 0.3 |
| Number of coil turns | 10 | 12 |
| Max. flux variation $\Delta\phi$ [Wb] | 2.38 | 1.85 |
| Max. inductance $L$ [H] | 0.43 | 0.3 |
| Total coil resistance $R_{\rm tot}$ [$\Omega$] | 0.11 | 0.037 |

### 3.1 Spill Time Uniformity

The time uniformity of the extracted spill was measured with a $1/\tau_{RC}$=20 kHz bandwidth. The signal obtained is shown in Fig. 2 curve 1. The smoother curve 2 is obtained from the first one by averaging over 9 acquisitions. Finally curve 3 is an enlargement of the central part of curve 1. It shows that the spill indeed satisfies the medical requirements of a maximum amplitude modulation of $\pm$20% at 2 kHz.

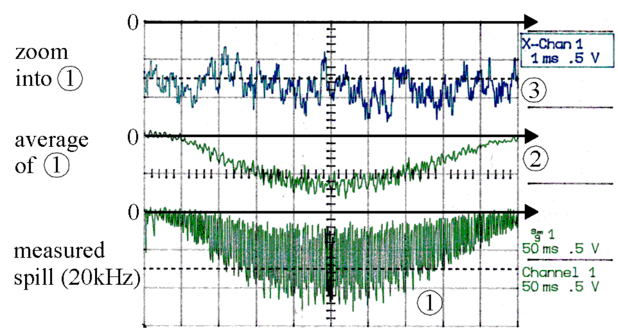


Figure 2: Spill measurement. The time scale for curve one and two is 50 ms/division, for curve three 1 ms/division.

### 3.2 Fast Beam Abort

The aim of the beam abort measurements was the evaluation of the time required to interrupt the extraction process, acting on the betatron core only. The lower curve in Fig. 3 displays the betatron power supply voltage, while the upper curve shows the intensity of the extracted spill measured with a 20 kHz bandwidth and averaged over 9 measurements. As can be seen from the plot a beam abort within 300 $\mu$s is possible.

The averaged curve also shows a good reproducibility of the signal and suggests a feed-forward compensation for the recurring frequencies.

### 3.3 Harmonic Compensation

Higher order harmonics of the power supply frequency appear in the spectrum of the extracted beam. This experiment aimed at compensating these harmonics using a sim-

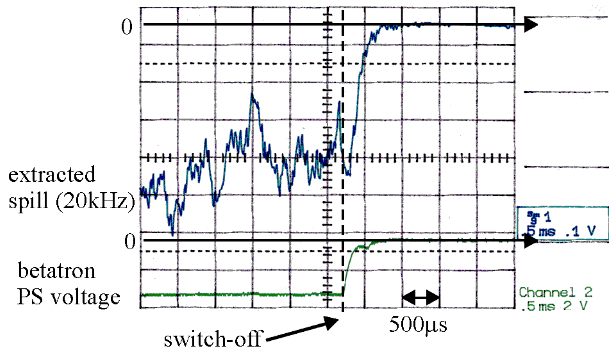


Figure 3: Betatron core abort time.

ple feed-forward system to modulate the power supply intensity at these frequencies.

The extracted spill was measured with a 30 kHz bandwidth and its spectrum evaluated via FFT. The spectra obtained were averaged over 20 acquisitions. Changing amplitude and phase of the correction signal, the 74 Hz line and its first harmonic were compensated for (cf. Fig. 4). This peculiar frequency stems from the dipole magnets

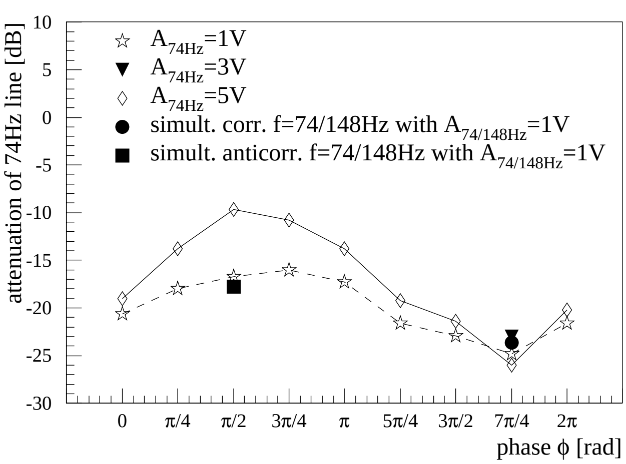


Figure 4: Harmonic compensation of the 74 Hz PS frequency and its first harmonic as function of the correction signal phase $\phi$ and amplitude $A$.

driven by a 74 Hz “rotative” power supply. As concluded from Fig. 4 attenuation of these components with the feed-forward system is possible. The attenuation increases with increasing amplitude of a phase-correct compensation signal. A simultaneous correction of both the 74 and 148 Hz components did not result in the expected even stronger effect. Instead a slightly weaker attenuation was observed than with the 74 Hz correction alone. This is thought to be a problem of inaccurate phase information.

### *3.4 Saturne Servosystem Measurements*

The aim of this experiment was to produce a spill of intensity as constant as possible. A rectangular waiting stack is only obtained by shaping the circulating beam. Unshaped beams have approximately Gaussian momentum distributions. Independent of shaping it is possible to influence the slope of the extracted spill by using a fast correction coil. The spill shown in Fig. 5 was obtained using the Gephyrotron power supply. This is an open loop system consisting of a multiple turn correction coil that uses the feedback of the spill to calibrate the input voltage. For PIMMS a single turn coil is foreseen, having an inductance $n^2$ times smaller, where $n$ is the number of turns, and a just as short reaction time. It is aimed to correct even beyond the 400 Hz.

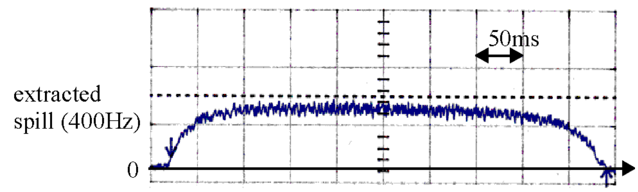


Figure 5: Extraction with servo system, BW 400 Hz.

## 4 CONCLUSIONS

Use of a betatron core to fulfil the medical requirements on the extracted beam is proposed for the PIMMS machine. Tests on a core with similar characteristics fulfilled the expectations. Beam abort within 300 $\mu$s has been demonstrated possible and the idea of a betatron core to improve spill quality should be attractive for other future medical machines.

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