BETATRON CORE DRIVEN SLOW EXTRACTION AT CNAO AND MEDAUSTRON

M. G. Pullia#, E. Bressi, L. Falbo, C. Priano, S. Rossi, C. Viviani, CNAO Foundation, Pavia, Italy
A. Garonna, M. Kronberger, T. Kulenkampff, C. Kurfuerst, F. Osmic, L. Penescu, M. T. F. Pivi,
C. Schmitzer, P. Urschütz, A. Wastl, EBG MedAustron, Wr. Neustadt, Austria

Abstract

The Italian Centre for Hadrontherapy (CNAO) and the Austrian MedAustron Hadrontherapy Center are synchrotron-based medical accelerator therapy centers. The CNAO machine has five years of experience in patient treatments, whereas MedAustron will soon start patient treatments with protons. Their accelerator systems have common characteristics, in particular in regards to the extraction system: at acceleration flattop, particles are slowly driven through the 3rd integer resonance longitudinally by a betatron core. This setup enables smooth extracted beam intensities. The rationale behind the use of a betatron core, its impact on the extracted beam quality and the performance from operation and commissioning of the two centers will be here presented.

INTRODUCTION

CNAO is one of the five accelerators worldwide capable to perform hadron therapy with both protons and Carbon ions; to date more than 800 patients have been treated, three quarters of them with carbon ions [1].

The MedAustron accelerator which is also intended to perform hadron therapy with both protons and light ions, has been recently commissioned [2] and is expected to start clinical treatments with protons within the year.

The two facilities share the same design for the accelerator, but have implemented the PIMMS scheme in a different way, adapting the layout to local constraints and requirements.

The CNAO Layout has favoured a compact arrangement while the MedAustron geometry was chosen for a modular operation of the extraction lines, to have access to the ion sources during operation and to allow installation of the synchrotron during the commissioning of the injector. Fig. 1 illustrates the two solutions.

For clinical treatments, a beam extracted in a slow controlled process over several seconds is necessary to facilitate the measurement and control of the delivered radiation doses. Many techniques are possible to perform a slow extraction and a few of them were considered in the PIMMS [3] and can be implemented on the two accelerators.

The betatron core-driven 3rd order resonance extraction method has been chosen as the main method both at CNAO and MedAustron and it is used to extract particles from the synchrotron over a large number of turns and in a spill time period between 1 and 10 seconds. The use of a betatron core offers an intrinsic robustness in minimizing intensity ripples caused by tune ripples in the kHz region.

Furthermore, to minimize the intensity ripples, additional smoothing techniques are applied at CNAO.

An alternative extraction method often used in this field is the RF-Knock Out which consists in increasing the beam transverse emittance with an RF noise to drive the particles into the unstable region. This technique will be tested at CNAO in the near future in addition to the standard extraction.

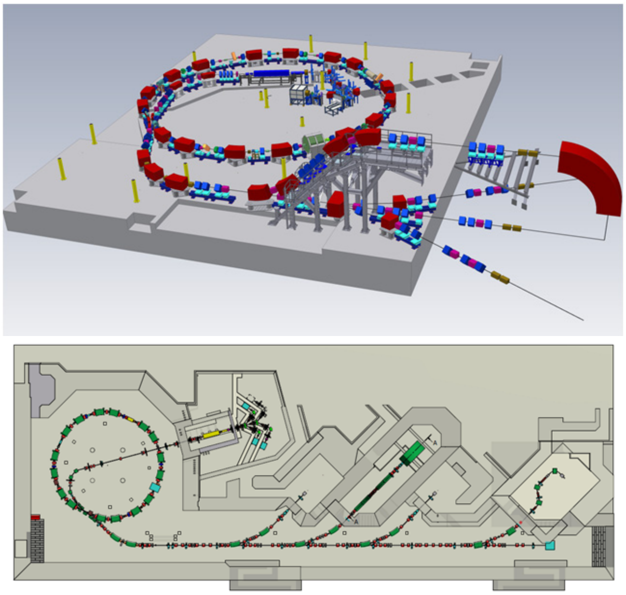

Figure 1: Layout of the CNAO and MedAustron facilities.

BETATRON CORE EXTRACTION

Third Order Resonance Extraction

During the acceleration process in the synchrotron, the beam horizontal tune is moved close to a third order resonance value. Before extraction, a sextupole in a non-dispersive synchrotron region is switched on to excite the 3rd order resonance. Then, the betatron core slowly accelerates the beam into the resonance activating the extraction process, by effectively moving the horizontal tune towards the third order integer resonance $Q_x = N \pm 1/3$. A fraction of the particles become unstable and their amplitude grows until they reach an electrostatic septum that deflects them into the extraction channel. In Figure 2, the betatron driven extraction mechanism is described in the usual Steinbach diagram [4].

Particles of different amplitudes enter the unstable region at the same time (red line in Fig. 2). The time needed for these particles to reach the septum is consequently spread over a "wide" interval originating the so called "band profile" shown in Fig. 3 [5].

#marco.pullia@cnao.it

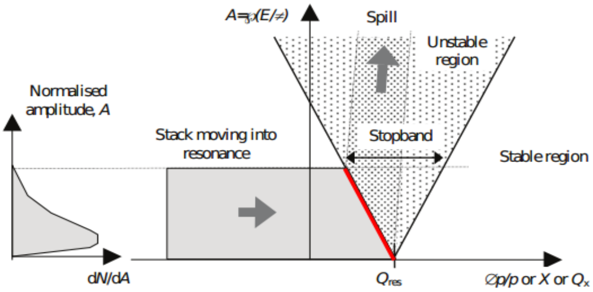

Figure 2: Betatron driven extraction mechanism.

The band profile describes the number of particles reaching the septum as a function of time, and thus being extracted, after a unit step of the betatron driving all of them into the unstable region at the same time.

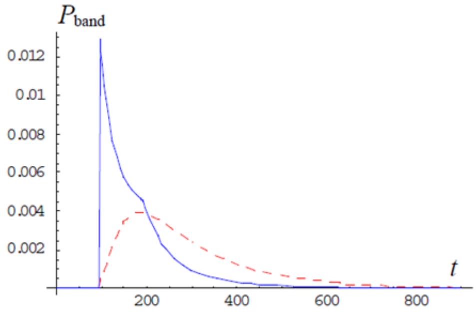

Figure 3: The "Band Profile" originates from the superposition of the transit time spread of particles entering the unstable region at different amplitudes. The red and blue lines correspond to different distributions in the circulating beam. Time is measured in "3 turns" units.

When describing slow extraction, time is expressed in "3 turns" units which, when expressed in seconds, depend on the extraction energy.

The stable region and the extraction separatrices for two different amplitudes (and therefore different momenta) are shown together in Fig. 4.

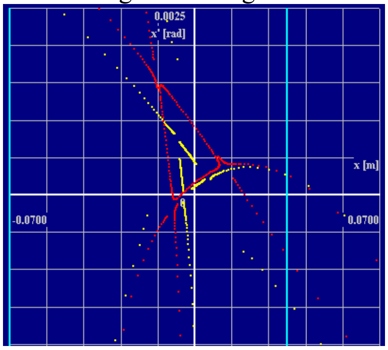

Figure 4: Stable regions and separatrices for Δp/p = -0.001 and Δp/p = -0.0005.

At CNAO and MedAustron, chromaticity is adjusted to fulfil the "Hardt condition" [3] which overlaps the separatrices in phase space at the electrostatic septum entrance to minimize losses.

Particles moving on different separatrices, jump into the septum by different amounts (spiral step) and have different momenta. This implies that during the initial and the final phases of extraction, when only a fraction of the particle amplitudes are involved, the beam width and the beam average momentum vary while during the central part of the spill all the amplitudes participate at the same time and the beam parameters are constant.

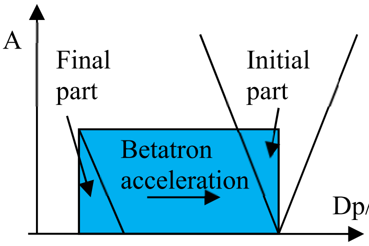

Figure 5: During the initial and final phase of extraction the beam distribution varies.

BEAM MEASUREMENTS

Based on the above, in a dispersive region, one expects to observe a beam movement during the head and the tail of the spill, and a stable beam position during the central part.

Figures 6 and 7 show respectively MedAustron measurements of the beam in the first beam profile monitor, which is in a dispersive region, and in the last monitor, which is in a non dispersive region.

Inside the blue frames the horizontal axis corresponds to the horizontal position, the vertical axis corresponds to time and the color code indicates the intensity.

The red frames enclose the plots of beam position (c.o.g., center of gravity) vs time.

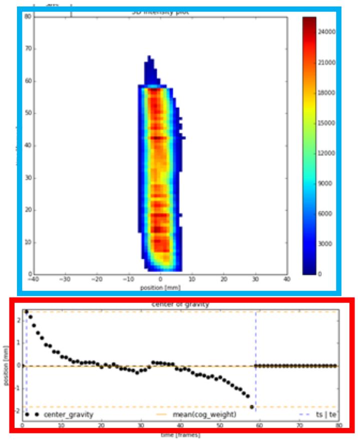

Figure 6: During the initial and final phase of extraction the beam distribution and position varies in a dispersive region. Inside the red frame, the beam position moves between +2 mm and -2 mm.

In Fig. 7 the first 700 ms are "missing". This is not an error in the measurement but rather the action of the "HEBT chopper", a fast device that allows to switch the beam on and off in less than 200 us. The chopper is closed when the extraction starts and opens when the "head" is finished.

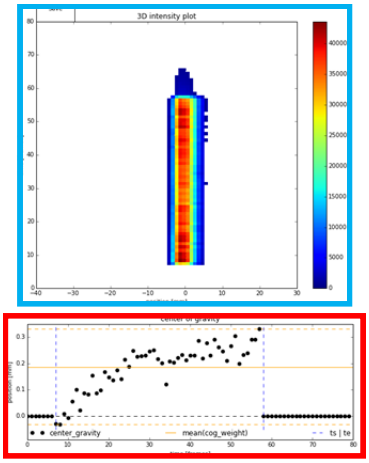

Figure 7: Beam profile measurements along the spill in a non dispersive region. Inside the red frame, the beam position moves between 0 mm and 0.3 mm.

When the intensity fluctuations are taken into account, the different power supply characteristics at CNAO and MedAustron allow an interesting insight in the extraction phenomenology.

An important quality factor is the ratio between the maximum intensity along the spill and the average value.

With a grid spacing for the beam position of 3 mm, to deliver 2 Gy to the distal slice approximately 50×10^{6} protons per spot are required. Assuming to deliver 10^{10} particles per spill with a 1s spill this means that each spot lasts 5 ms and if one aims to obtain a ±2% precision a measurement frequency of 10 kHz is needed and within the corresponding 100 us period a maximum peak to average of 2 can be accepted.

If the same 10^{10} particles per spill are distributed along a 5s spill, then the same tolerable amount of particles within the 100 us time interval corresponds to a peak to average of 10.

In absence of the ripple mitigation measures routinely applied, the intensity fluctuations at CNAO are large and dominated by low frequency ripple. This allows to observe the structure of the spill, which matches very well the band profile, as illustrated in Fig. 8.

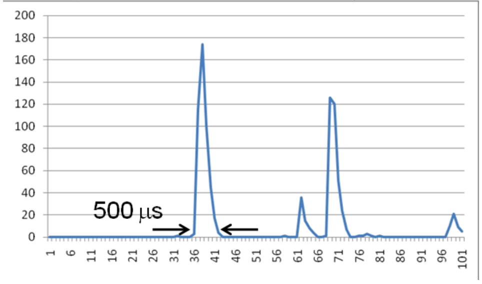

Figure 8: Zooming into the uncompensated CNAO spill allows identify the band profile foreseen (140 MeV, 3Trev = 1.5 us).

At MedAustron the spill is dominated by the 4kHz ripple of the synchrotron dipole power supply. Figure 9 shows the spill measured at minimum and maximum energy.

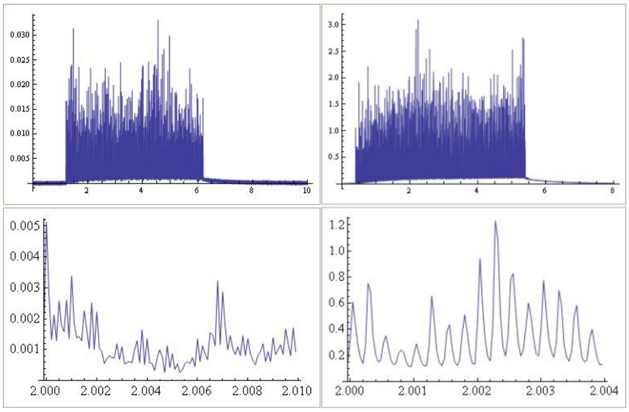

Figure 9: On the left the spill at 62 MeV and on the right the spill at 252 MeV. On the bottom plots a zoom of the spill at the ms level is shown.

At 252 MeV 3Trev =1.2 us and the band profile width is in the order of 350 us, just slightly larger than the 4 kHz period, while at 62 MeV 3Trev = 2.2 us and the band profile width is 650 us. Direct inspection of Fig. 9 shows that the 4 kHz modulation is clearly present, the intensity never goes to zero, in the 62 MeV spill, the intensity modulation is less strong as expected for a wider band profile. Plots of the intensity normalized to the average value for the two spills above, are shown in Fig. 10.

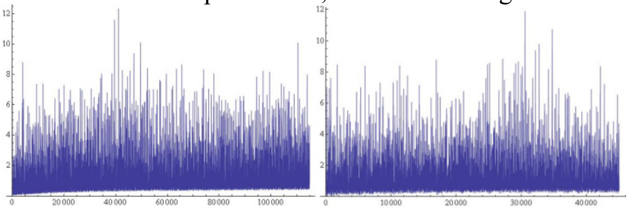

Figure 10: On the left the beam intensity normalised to average at 252 MeV and on the right the same at 62 MeV.

As anticipated, at CNAO ripple mitigation is performed by means of the "empty bucket channelling" [6] and "High Frequency Ripple Injection" [7], performed either by an air core quadrupole or by sweeping an empty bucket back and forth. The results are summarized in Fig. 11 showing that peak to average values in the order of 2 are obtained and that the spill quality can be further improved with feedback [8].

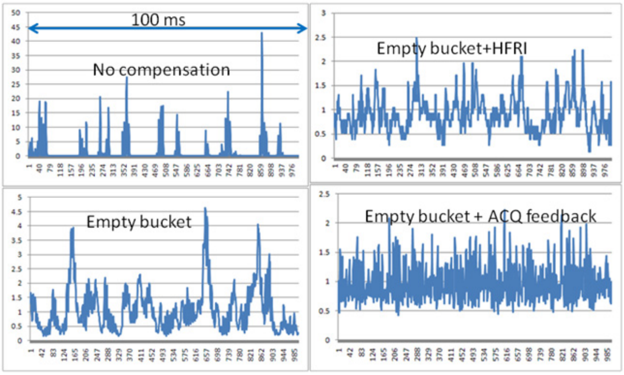

Figure 11: Spill quality improvements by empty bucket channelling and use of an air core quadrupole at CNAO.

REFERENCES

[1] S. Rossi, Eur. Phys. J. Plus, 126 8 (2011) 78.

[2] A. Garonna *et al.,* "Status of Proton Beam Commissioning of the MedAustron Particle Therapy Accelerator", presented at IPAC'16, Busan, Korea, May 2016, paper THOAB01, this conference.

[3] P. Bryant *et al.*, "PIMMS", CERN/PS 99-010 (DI), CERN/PS 2000-007 (DR).

[4] G. Feldbauer, M. Benedikt, U. Dorda, "Simulations of Various Driving Mechanisms for the 3rd Order Resonant Extraction from the MedAustron Medical Synchrotron", *in Proc. IPAC'11*, pp. 3481-3483, paper THPS029.

[5] M. Pullia, "Detailed Dynamics of Slow Extraction and Its Influence on Transfer Line Design", PhD thesis, 1999.

[6] M. Crescenti, Cern note, ps-97-068.

[7] M. Pullia, report in preparation.

[8] M. Caldara *et al.*, "Online Spill Intensity Monitoring for Improving Extraction Quality at CNAO", *in Proc. IPAC'15*, pp. 907-909, paper MOPHA050.