MEDAUSTRON SYNCHROTRON RF COMMISSIONING FOR MEDICAL PROTON BEAMS

C. Schmitzer, F. Farinon, A.Garonna, M. Kronberger, T. Kulenkampff, C. Kurfürst, S. Myalski, S. Nowak, L. Penescu, M. Pivi, A. Wastl, F. Osmic, P. Urschütz,
EBG MedAustron Gmbh, Wiener Neustadt, Austria

Abstract

MedAustron is a medical accelerator facility for hadron therapy cancer treatment using protons and carbon ions. The facility features 4 irradiation rooms, 3 of which are dedicated to medical treatment, with one currently being medically commissioned, and 1 irradiation room for non-clinical research (NCR) which will be put into operation this year. A 7MeV/n Injector feeds a 77m circumference synchrotron which provides flexible beams for treatment and research. The Synchrotron is driven by a 0.47-3.26 MHz Finemet® loaded wideband cavity powered by 12x 1kW solid state amplifiers connected to a digital Low Level RF system. It was developed in collaboration with CERN and put to operation at MedAustron in early 2014. The main Synchrotron RF (sRF)commissioning steps for proton beams involved the setup of the adiabatic capture process, the setup of the frequency and voltage ramps and feedback loops for fast acceleration and the RF jump for extraction. The adiabatic capture process was optimized in terms of energy and voltage mismatch by analyzing longitudinal empty bucket scans after beam injection into the synchrotron. The acceleration ramp optimization was based on calculations using a software tool developed in-house and adapted experimentally to minimize losses at injection and during acceleration. This paper provides an overview of the acceleration system and describes the commissioning process of the sRF system and the related beam commissioning efforts at MedAustron. Typical corrective measures are described as well as typical acceleration cycles and optimization tools.

INTRODUCTION

The PIMMS[1] based MedAustron Particle Therapy Accelerator (MAPTA) involves three ECR ion sources feeding a 400keV/n RFQ and a 7MeV/n IH Drift tube linac (DTL) injecting [2] into a 77 metre circumference synchrotron. The Synchrotron provides medical proton and carbon beams in the respective energy ranges of 60-250MeV/n and 120-400MeV/n via slow resonant extraction spills of typically 5 seconds duration. For NCR purposes, proton beams with energies of up to 800 MeV can be provided. The 32µs-long pulse from the Injector is injected to the synchrotron during an 80µs-long injection horizontal orbit bump. The coasting proton beam is then adiabatically bunched and accelerated with ramp rates of up to 2.2T/s. During acceleration, the horizontal on-momentum tune is slowly changed to the 3rd order resonance. Due to the slow extraction process used, the beam aperture is asymmetric and off-momentum operation maximizes intensity. For protons energies 60-250MeV, the flat top beam positions are set to 20-30mm, respectively, which are applied during the acceleration ramp to stay clear of the resonance stop-band. To provide long and smooth intensity spills, the sRF system blows up the momentum spread and shapes it via a linear voltage increase and a phase jump to the unstable RF phase [3].

SYNCHROTRON RF SYSTEM

The sRF consists of a digital VME-based LLRF[4] system, a pre-amplification system, 12x 1kW solid state amplifiers[5], a PLC-based cavity slow control and a Finemet®-loaded coaxial resonator cavity consisting of 12 independent cells. Each cell is loaded with 2 Finemet® FT-3L rings mounted on a water cooled copper disc around an independent acceleration gap. Every cell is driven by a 1kW 58dB solid state amplifier powered by 35V-100A power converters. A PLC-based slow control monitors temperatures, water and air cooling of all components as well as power converter voltage/current levels, collects internal error messages and serves as an interface to the beam interlock system. The digital LLRF system consists of 3 VME carrier boards (card A,B,C), each holding an ADSP-21368 SHARC DSP and two Xilinx Virtex5 FPGA's. They are mounted with different daughter cards depending on their use: a direct digital synthesiser, three analogue-to-digital converter modules and two digital-to-analogue converters. Three rear-transition-modules, an optical transceiver card and a cavity control interface module collect main timing system triggers, B-train signals, and emit tune kicker triggers and HLRF-enable signals.

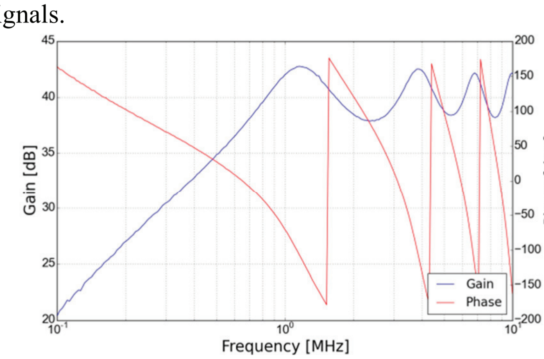

Figure 1: Transfer function of the amplifier-cavity ensemble used for the LLRF compensation table.

Two beam position monitor (BPM) signals in high dispersion regions of the 2-fold symmetric synchrotron feed the radial position regulation loop (card A) while two BPM's up- and downstream of the cavity serve as input for the phase loop (card B). The frequency program (card A) can be based on the 300kHz B-train counter (0.1G resolution), a manually programmed B-field waveform or an internal B-train simulator. The voltage regulation loop (card C) acts on a combined feedback of all 12 cell voltage monitors. The corresponding DSP can predict the system behaviour via a frequency dependant gain/phase compensation table (Figure 1) which is scaled up in case of a cell failure. The system will still operate nominally even with only 6 cavity cells in operation.

All regulation loops act within a 10µs fast loop cycle and can be configured via a second order biquadratic filter to adapt the frequency response. Figure 2 shows a step response measurement of the three regulation loops and a frequency response to a Dirac impulse of the phase loop.

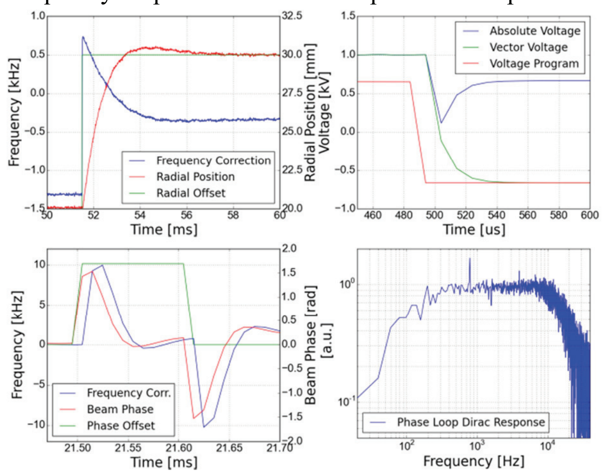

Figure 2: Step response of the radial loop (top left), voltage loop (top right), double step (lower left) and Dirac impulse response (lower right) of phase loop.

CAPTURE SETUP

The injector comprises a debunching cavity operating at 216MHz downstream of the IH-tank, enabling adjustment of the momentum spread before injection into the synchrotron.

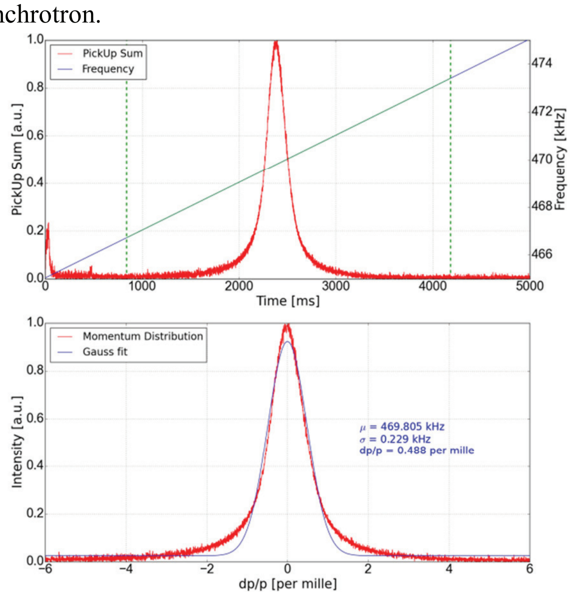

Figure 3: Empty Bucket scan on a coasting beam after synchrotron injection. Frequency sweep with envelope of BPM sum signal (top) and momentum distribution (bottom).

The minimised momentum spread was measured via an empty bucket scan of the coasting beam, i.e. a 10V bucket is slowly moved through the frequency range of interest using a 2kHz/s ramp recording BPM sum signals (Figure 3). From the empty bucket measurement we obtain an injection momentum spread of 0.5‰, resulting in an adiabatic capture bucket voltage of 106V for a filling factor of 70%. The calculated capture voltage highly depends on the definition of bunch area limits in longitudinal phase space. An adiabaticity of 0.05 was chosen for the voltage ramp to obtain a prudent capture process which lasts 130ms130 ms.

The scan also reveals the centre frequency of the momentum distribution and the corresponding radial position. However, this centre frequency does not necessarily correspond to the optimal capture frequency in terms of post capture intensity. Therefore, several captures were attempted using different injection frequencies while monitoring the beam intensity (Figure 4).

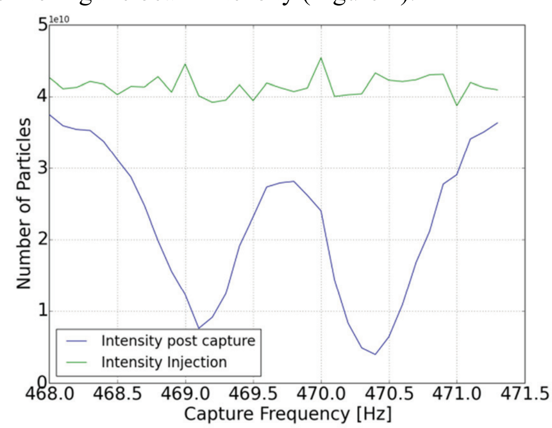

Figure 4: Typical injection frequency scan for adiabatic capture with a 106V bucket and a 0.05 adiabaticity. The plot shows the initial intensity after injection and the remaining intensity after capture.

To identify the optimal radial position for injection, in terms of surviving particles, the main ring dipole field was scanned while performing an injection frequency scan for each dipole setting (Figure 5).

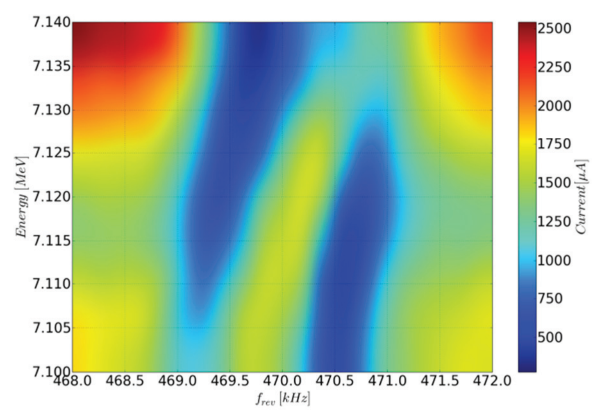

Figure 5: Varying the main ring dipole field at injection in terms of energy equivalent and the capture frequency reveals the local particle current optimum at 470kHz and 7.125MeV.

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A calculated injection energy of 7.125MeV and a capture frequency of 470.05kHz was found to maintain >2e10 particles in the main ring.

ACCELERATION SETUP

The acceleration cycle optimisation in terms of the longitudinal dynamics is handled in a dedicated python module, the MedAustron Longitudinal Cycle Optimiser (MALCOlm)[6], requiring input on the initial momentum spread or capture voltage, the transverse emittance, and the horizontal dispersion and position of aperture-limiting elements (horizontal beam dump and electrostatic extraction septum). MALCOlm calculates the distortion of the bucket due to the synchronous phase and the expected particle losses. Simultaneously, the radial beam position and beam size is evaluated at the expected loss points. If longitudinal losses begin to dominate due to a high B-field ramp rate, the bucket voltage is increased which reduces longitudinal losses yet increases the momentum spread and thus the transverse beam size at main ring loss points. Thus, an iterative process is executed until both loss mechanisms are within user defined relations and the risk of particle losses is minimized. Figure 6 shows a typical voltage curve as well as the bucket reduction factor and the evolution of transverse beam size throughout the cycle.

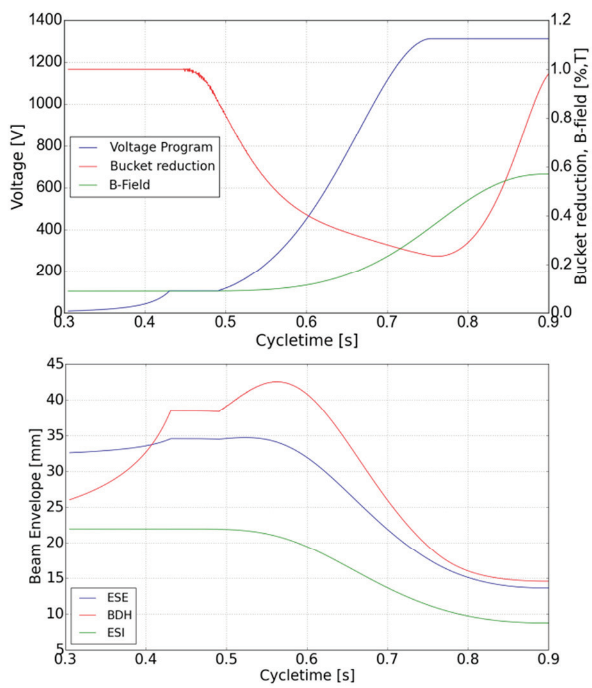

Figure 6: Optimised voltage program and bucket reduction factor for a 252.7MeV cycle and a ramp rate of 2.2T/s (top). Evolution of beam envelope (bottom) at electrostatic extraction and injection septum (ESE/ESI) and horizontal beam dump (BDH).

The presented cycle data was calculated for a ramp rate of 2.2T/s and energies of up to 252.7MeV. After the initial adiabatic capture process the acceleration starts as fast as possible to minimise the risk of losses at flat bottom. Particle losses below 12% have been observed during the acceleration ramp, usually, occurring during the initial round off of the main ring dipole ramp.

The subsequent preparation of longitudinal phase space for extraction via a dedicated voltage program and RF phase jump is described by Kulenkampff et al. [3].

CONCLUSION AND OUTLOOK

The synchrotron RF system of MAPTA was developed together with CERN, successfully installed and commissioned at MedAustron. Necessary adaptions and tuning were successfully executed with the support of the CERN RF group and CNAO experts. Regulation loops have been optimised for performance and stability. The capture process was adapted to injector momentum spread and the main ring dipole field. The acceleration cycle was improved using a dedicated optimisation algorithm to minimise losses caused by longitudinal and transverse limitations. Ramp rates of 0.9-2.2T/s for medical energies of 60-250MeV have been tested without observing particle losses during acceleration.

Future developments and tests might include an improved and more flexible trigger system, regulated higher order mode suppression and RF noise generation to enable different extraction mechanisms.

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