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IMPACT OF ION SOURCE STABILITY FOR A MEDICAL ACCELERATOR

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Abstract

MedAustron is a synchrotron-based hadron therapy center located in Lower Austria. Accelerated proton beams with energies of 62-252 MeV/u are used to treat patients since 2016. The carbon ion beam is currently under commissioning and will provide treatment in 2019 with energies of 120-400MeV/u. Two of the four irradiation rooms are used for clinical treatment while the preparation of the Gantry beam line is ongoing. Proton beams of up to 800 MeV will be provided for non-clinical research. The Injector features three identical ECRIS from Pantechnik, two of which are used to generate the proton and the carbon beam respectively. The medical environment of the accelerator puts strict requirements on the ion source long-term stability operation. The extracted beam current from the source allow for maximum current fluctuations on the order of ±2.5% on continuous run. In this work we discuss the impact of the ion source performances on the characteristics and stability of the entire accelerator. Further, we discuss the latest progress on carbon commissioning and the future perspectives with particular emphasis on the source requirements.

INTRODUCTION

The MedAustron is a synchrotron-based therapy center for cancer treatment. The design of the accelerator is based on PIMMS and CNAO [1,2]. Currently 26 patients (fractions) per day are treated with proton ion beams since 2016. Medical treatment with carbon ions is planned to start in 2019 [3]. A proton beam up to 800 MeV/u will be provided for non-clinical research.

The Injector shown in Fig. 1 features three identical Supernanogan ECRIS from Pantechnik. One is reserved for proton beams production and one for carbon beams production. The third is foreseen as future use for clinical and non-clinical research. The extracted beam from the source at 8 keV/u is transported through the LEBT line to the linear accelerator. The LINAC contains a Radio Frequency Quadrupole (RFQ) module which accelerates the beam to 400 keV/u followed by a Buncher and an IH-Tank cavity where the energy reaches 7 MeV/u and finally by a Debuncher cavity. Through the Mid Energy Beam. Transport (MEBT) line the beam is then injected in the synchrotron where it reaches the clinical e non-clinical energies mentioned before. A slow extraction 3rd order resonance method via Betratron Core is used to extract the particles from the synchrotron. Through the High Energy Beam Line (HEBT) the beam is sent to four available irradiation rooms: IR1 with horizontal beamline for non-clinical research, IR2 with a horizontal and a vertical beamline, IR3 with a horizontal beamline and IR4 with a proton Gantry. The weekly machine uptime during clinical operation between 90% and 97% [4].

THE IONS SOURCE

The identical design and the availability of three independent source lines allows for parallel running of the sources and for source switching in case of emergency. The ion beam in the source is produced through the Electron Cyclotron Resonance (ECR) heating mechanism [5]. The neutral gas is brought into a state of plasma magnetically confined in the vacuum vessel and the ions are extracted from the chamber with a dedicated extraction system. The Supernanogan of Pantechnik has been described in detail in [6]. It operates at 14.5 GHz heating frequency and is it entirely equipped with permanent magnets both for the radial magnetic field than for the longitudinal magnetic field with a B_{ECR} of 0.5 T. An axial mirror ratio B_{max}/B_{min} about two times higher than the ECR resonance magnetic field is obtained [5].

The plasma has limited contact to the chamber walls and the high charge state ions concentrate in the center of the extracted beam with a triangular intensity distribution. The longitudinal beam profile depends mainly on extraction parameters with respect to the plasma potential. The source body is placed at 24 kV, while a puller electrode is placed at negative potentials of about 2 kV to accelerate the beam towards the focus. The focus electrode on the order of 1.5 kV is fine tuned to adapt the beam size to the focal point of the dipole magnet for a good transmission into the beam line and further matching into the RFQ. The DC Bias tip, introduced from the backside of the vacuum chamber into the plasma, reduces the ion losses towards the injection. The RF tuner position is used to reduce the reflected power. The typical source parameters used for the proton and the carbon source are indicated in table 1:

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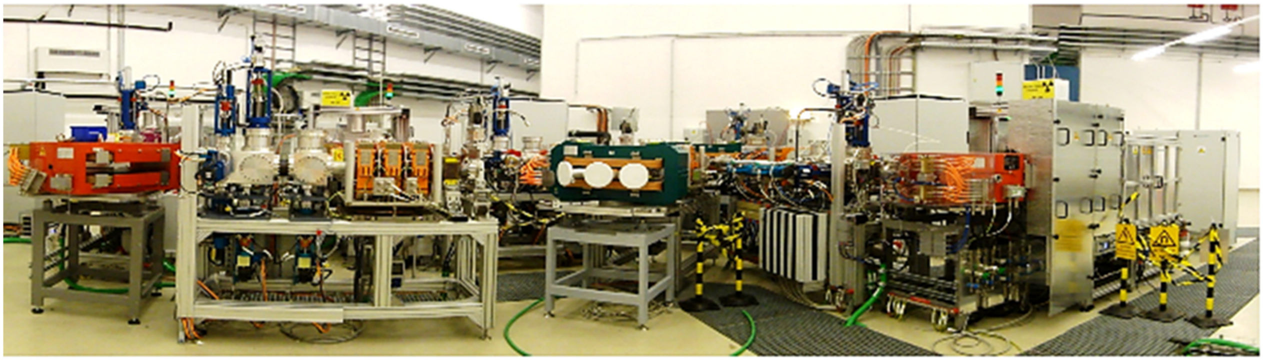

Figure 1: Injector Hall at MedAustron. The source is located within the lead protected cabinet visible on the right side of the figure. The complete layout of the source is shown in [6].

Table 1: Typical Source Parameters for Medical Treatment

Parameter	Proton Source	Carbon Source
RF Frequency (GHz)	14.451	14.464
RF Power (W)	8-10	90-160
Gas Type	H_2	CO_2+He
Extracted Current (μA)	660	95-150

SOURCE PERFOMANCES VERSUS ACCELATOR STABILITY

The stability of the extracted source current is fundamental for medical treatment. The commissioning of the source occurs according to the main requirements of the entire accelerator (i.e. acceptance window of the RFQ, required intensity into the treatment room etc.). For the acceptance tests, once the stable source settings are found, the extracted current needs to be monitored for more than 24 hours [6]. The extracted current stability needs to be on the order of ± 2.5%. The source performances are constantly monitored via a current transformer (CTA) located into the LEBT (non-destructive BD device) during the daily beam quality assurance before clinical treatment starts (i.e. the daily QA) (mainly for the proton source) or via destructive devices (Faraday Cups) during beam commissioning (currently mainly for the carbon source). Figure 2 shows the daily recorded current from the proton source with the LEBT-CTA and the current recorded with the current transformer in the MEBT line. One can observe how the current is slowly drifting over months towards higher values for fixed source parameters (within 6 months from 675 uA to 700 uA, i.e. of 4%). Also, it was measured that the source emittance slowly drifted towards bigger values with respect to the reference. In turn, this drift influences the intensity into the room, which slowly decreases over time and leads to longer treatments times. Longer treatment time, i.e. the in-room time is not beneficial for the patient neither for an efficient treatment and this is why to eventually recover the intensity by recommissioning the source.

After the source recommissioning, the MEBT-CTA recovers of about 20% and also the shot to-shot reproducibility improves. It is also interesting to note that while the MEBT-CTA increases, the LE-CTA decreases before and after the recommissioning. During recommissioning it was needed to find a complete new set-point for the source due to a drift of emittance which was increasing towards higher values with respect to the reference. The source recommissioning occurs within a strict release process, which has to be planned in advance. It is not possible to change or adapt the source parameter during clinical treatment without having first a detailed impact of analysis of the change and the by having the approval from the QA department. Once a stable set-point is found it is not possible to adapt any parameter in case of need, but a new release has to be planned.

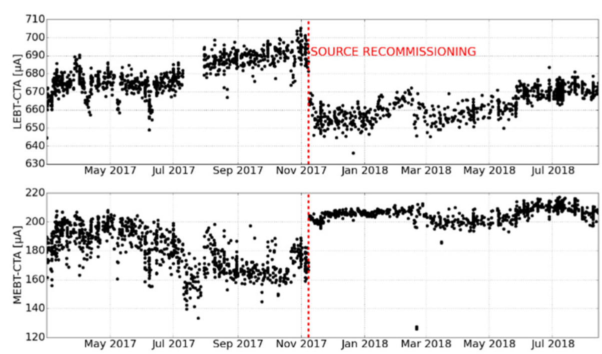

Figure 2: LEBT (top) and MEBT (down) current versus time measured during the daily quality assurance of the beam before medical treatment, i.e. during beam QA. The main source parameters that are tuned are: the RF Frequency and the forward RF power, the extraction voltages such DC Bias and Focus Voltage, the gas amount injected into the plasma chamber, the RF Tuner position and the solenoid current placed at the entrance of the RFQ.

The overview on how the source recommissioning impacts over the whole machine performances is visible in Fig. 3. In this figure, the transmission over the different sections of the accelerator is shown. The LEBT to LINAC transmission is improved of almost 10%, and, overall the transmission is improved in the entire accelerator. The number of

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extracted particles increases from about $1.1\cdot10^9$ to $2.1\cdot10^9$ particles at extraction.

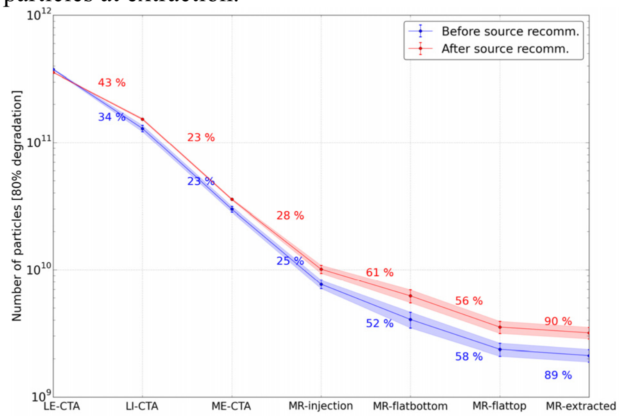

Figure 3: Transmission efficiency in the different sections of the accelerator before and after source recommissioning from LEBT to LINAC, from LINAC to MEBT, from MEBT to synchrotron injection (MR-injection), from injection to capture (MR-Flatbottom), from start to end acceleration (MR-Flattop), from end acceleration to extraction (MR-extracted).

CARBON SOURCE COMMISSIONING PHASE II

First carbon source commissioning occurred at the end of 2017 together with the rest of the injector (LEBT and LINAC) [6]. Source was recommissioned at the end of May 2018 after the plasma chamber was exchanged due to carbon deposition on the chamber wall. Since end of May, the carbon source runs continuously over 24 hrs end will be used for clinical treatment in 2019. Current studies focus on source degradation and long-term maintenance strategies. As it can be seen in Fig.4, after the plasma chamber was exchanged, the source current could not be stabilized immediately and exponentially dropped from 163 uA to 145 uA within about 45 days under the circumstances of not changing or adapting any source parameter. This strategy aims to have a realistic view of the source behavior during the future clinical treatment. Since end of July the source reached a stable point at around 143 uA. This drift of course cannot be accepted once the source will be used for clinical treatment due to the stability requirements. Therefore, the latest studies focused on finding a stable setpoint where the extracted current can be decreased or increased according to the intensity requirements into the treating room and to make the RF power as a clinically modifiable parameter. Ideally, this will be done by only adapting the RF forward power without necessarily tuning the other source parameters out of an official release process.

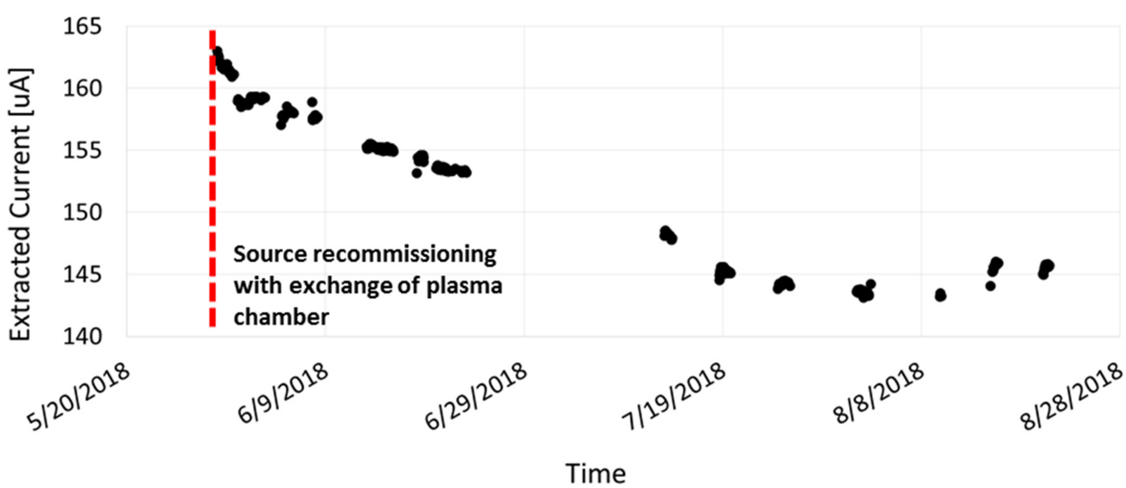

Figure 4: Extracted current vs. time recorded with a Faraday Cup since last plasma chamber exchange. It is not possible to record the current with the Faraday Cup continuously due to ongoing beam commissioning with carbon.

To be able to investigate such scenario we first of all performed a frequency tuning and measured the extracted current versus the resonance frequency below 14.5 GHz. The results are shown in Fig. 5 together with the reflected power measured at 30 W of forward RF Power. Even if different resonance peaks can be found within 14 GHz and 14.50 GHz we defined as “unstable range” the one between 14 to 14.4 GHz. The unstable range is hardly tunable due to high reflected powers when ramping up the RF power even by tuning the other source parameters at the detected resonance points. In the stable range instead, it is possible to ramp up the RF power while keeping a low reflected power.

In the stable range it is also possible to keep a low signal to-noise ratio for a large range of powers as shown in Fig.6 where the extracted current versus the RF power is plotted for three different frequencies. As it can be seen from this figure, the best results in terms of low signal to-noise ratio in a large range of RF powers are obtained around 14.46 GHz. Also, the emittance does not change while ramping up the power in the stable range [7].

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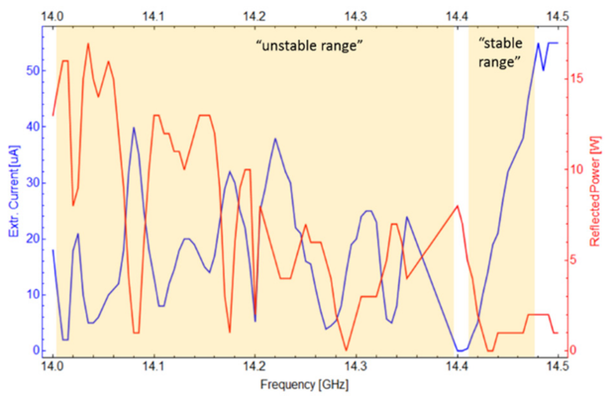

Figure 5: Extracted current and reflected power vs. frequency performed at low RF power (30 W).

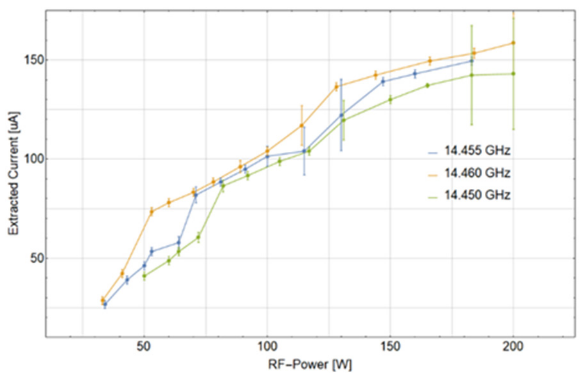

Figure 6: Extracted Current vs. RF Power for three different frequencies.

Once the stable set-point is found, the intensity into the room is measured as a function of the RF power. The highest intensity into the room that was measured so far is of $1.6{\cdot}10^9$ particles with an RF power of 163 W and an extracted current from the carbon source of around 150 μA as shown in Fig. 7a. We then reduced the source power due to our target intensity target at flattop (CTS-target) and into the room (DDS-target), i.e. measured through the Dose Delivery System developed from CNAO [8]. With a RF frequency of 14.455 GHz the target is reached with about 98 W. With a RF frequency of 14.464 GHz the target is reached with 89 W as shown in in Fig.7b. In this case we also decreased the DC Bias Voltage of 100 V to reduce its degradation over time and adapted the focus voltage. The limitation of intensity is due to safety reasons related to the maximum intensity allowed into the synchrotron for medical treatment.

It is very important to emphasize that for this stable set-point it is possible to increase or decrease the RF power without affecting the transmission from LEBT to LINAC which is kept at a constant value of around 60% as shown in Fig.8. Thus, the goal of just tuning the RF power according to the needed intensity into the room is reached without necessarily tuning the other source parameters. This is beneficial to compensate for the current decrease shown in Fig.4.

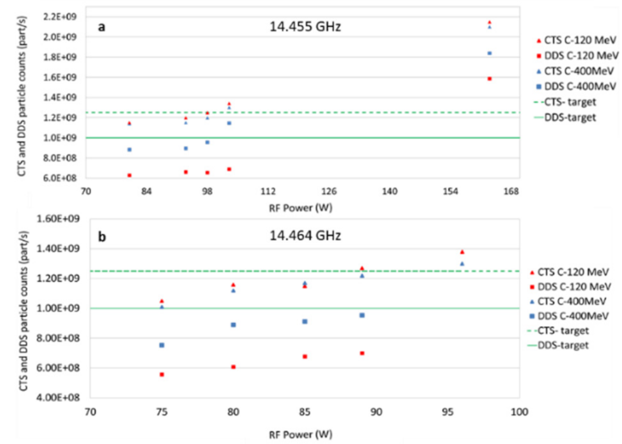

Figure 7: Particle intensity measured into the room with the Dose Delivery System (DDS) and at flattop (CTS) for carbon at 400 MeV and for carbon at 120 MeV with no degradation as a function of source RF Power for 14.455 GHz (a) and 14.464 GHz (b). The current target for the CTS and DDS are also indicated in the figures which corresponds respectively to 1.25·109 and 1·109 particles maximum.

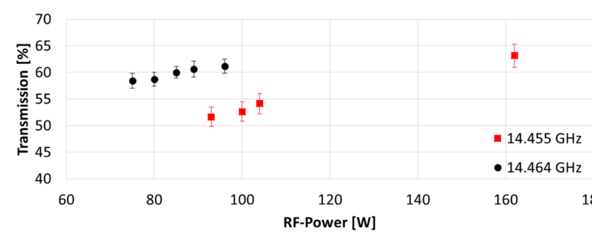

Figure 8: Transmission from LEBT to LINAC versus RF Power for 14.455 GHz and 14.464 GHz.

CONCLUSIONS AND FUTURE PERSPECTIVES

In this work it was shown how the source operation and stability over long term impacts on the performances of a medical accelerator. By retuning the proton source, it is possible to compensate for intensity drifts into the treating room, but to get a full picture of the source behavior, the extracted current trend has to be correlated to the measurements in the different sections of the accelerator. Due to the strict requirements of needed source stability and intensity, which need to be fulfilled on continuous run, a proper maintenance is another key factor for the proper operation of the source. This includes planned slots for re-commissioning which are only possible within official release processes. On the other hand, for the carbon source, it would be beneficial to make the RF power as a clinically modifiable parameter as it is not possible to wait for long stabilization time of several days. Towards this strategy, a stable source set-point was found for which it is possible to have the RF power as unique parameter to tune the intensity into the treating room without affecting the performances of the rest of the machine. Future studies will focus on long term carbon coating effects and needed cleaning scenarios. In

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the next future it is also planned to start with the commissioning of the spare third source that could be used as a test stand for plasma physics studies using Langmuir Probes, Optical Spectroscopy or for the production of different ion species such as oxygen and helium.

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