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RESONANT CAVITY FOR BEAM CURRENT DIAGNOSTICS IN MEDICAL ACCELERATORS

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Abstract

Beam currents of particle accelerators used for cancer treatment are often on the nanoampere level. These currents are too low for standard beam current diagnostics used in other fields of particle accelerator science, e.g. current transformers. This led to the general adoption of ionization chambers for beam current and dose rate determination in medical accelerators. However, the development of the so-called FLASH radiation therapy requires beam currents too high for normal ionization chambers yet still too low for standard current transformers.

Resonant cavities have shown their capability to precisely detect nanoampere to microampere beam currents which renders them interesting for FLASH radiation therapy accelerators. After the design of a resonant cavity at Paul Scherrer Institut (PSI), a collaboration between PSI, Instrumentation Technologies, and Bergoz Instrumentation was established with the goal to develop a complete turnkey beam current diagnostics system readily available for medical accelerators. Two prototype systems were manufactured, installed, and tested at PROSCAN/PSI. We discuss the layout of the measurement systems and compare expected performance to beam current measurements.

INTRODUCTION

For particle therapy accelerators, monitoring the delivered dose is of highest importance. Dose is the ratio of total kinetic energy of the particle beam pulse and mass of the irradiated sample volume. Hence, particle beam and sample characteristics need to be well known for a successful radiotherapy.

Before treatment the correlation is established between a calibrated dose measurement device at the irradiation location and some other particle beam diagnostics system installed at the end of the accelerator beam pipe. For this purpose, ionization chambers have become the standard particle beam diagnostics system in particle therapy accelerators [1].

Ionization chambers have proven to be well adapted for the nanoampere beam currents used for conventional radiotherapy. But they are less well adapted when beam currents surpass some hundred nanoamperes [2-4], as required for the FLASH radiotherapy currently under study. Additionally, ionization chambers are not fully non-interceptive devices as they slightly alter beam properties [5, 6]. Other types of particle beam diagnostics may be better suited.

A cavity resonator is capable of measuring particle beam currents in a non-interceptive way. Its potential to detect extremely low currents has been demonstrated before [7].

Based on a study performed at PSI [8], an industrialized Cavity Resonator Current Diagnostics System (CRCDS) consisting of a cavity resonator beam current monitor (CR-BCM) and the accompanying analog and digital read-out electronics has been developed, manufactured, installed, and tested in the PROSCAN accelerator at PSI [9].

CAVITY RESONATOR

A resonating cavity is a passive device coupling to a small spectral range of the electromagnetic fields induced by the particle beam. This renders it a truly non-interceptive beam diagnostics device. Cavity response is beam size and position independent. No cavity maintenance is required throughout its lifetime.

Particle therapy accelerators create macropulses, which are successions of very short pulses at a certain repetition frequency. Cavity resonance frequency must equal this repetition frequency or an integer multiple of it. Since cavity resonance rise time depends on the cavity resonance bandwidth, bandwidth needs to be wide enough to follow beam current changes and to resolve the total length of the macropulse.

Dielectric-filled re-entrant cavities can be adapted to a wide range of beam repetition frequencies and harmonics, while keeping a compact design. Two such cavities were developed and installed for testing in the Gantry 2 beamline at PROSCAN (Fig. 1); one cavity resonating at the second harmonic of the beam pulse repetition frequency and one cavity resonating at the third harmonic:

$$f_{\mathrm{res,2nd}} = 2 \times 72.85\ \mathrm{MHz} = 145.70\ \mathrm{MHz}$$
$$f_{\mathrm{res,3rd}} = 3 \times 72.85\ \mathrm{MHz} = 218.55\ \mathrm{MHz}$$

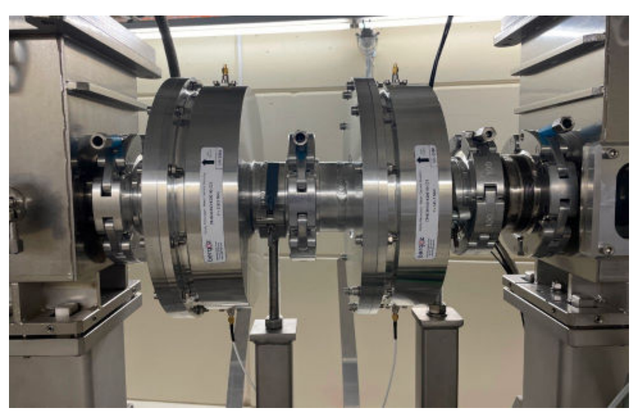

Figure 1: Resonating cavities installed at PROSCAN.

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Geometries of the two cavities are the same. Frequency adaptation is achieved by inserting different ceramic rings into the cavities. Details of the cavity design are discussed in [8].

Cavity response to an excitation by beam pulses is like the response of a band-pass filter. Resonance envelope will follow beam current variations with a response time of:

$$\tau \approx \frac{0.35}{\Delta f/2}$$

Δf is the resonance bandwidth measured at -3 dB with respect to the resonance apex. Resonance bandwidths and response times of the two prototype cavities are:

$$\Delta f_{\mathrm{2nd}} = 4.8\ \mathrm{MHz} \Rightarrow \tau_{\mathrm{2nd}} = 146\ \mathrm{ns}$$
$$\Delta f_{\mathrm{3rd}} = 6.2\ \mathrm{MHz} \Rightarrow \tau_{\mathrm{3rd}} = 113\ \mathrm{ns}$$

Cavity sensitivities were deduced from beam measurements and CST simulations:

$$S_{\mathrm{cav,2nd}} = -125.4\ \mathrm{dBm/nA}$$
$$S_{\mathrm{cav,3rd}} = -122.5\ \mathrm{dBm/nA}$$

Each cavity has two output ports which both need to be 50 Ω terminated. During normal operation, one is connected to the read-out system and the other is terminated by a 50 Ω load. For on-line calibration verification a signal can be injected into this port.

PRE-AMPLIFIER

For the expected beam currents, the cavity output signal levels are below the detection threshold of the digitizer used (see next section). Consequently, pre-amplifiers are required to boost the signal.

The pre-amplification chain consists of a high-pass filter, low noise amplifiers and a band-pass filter. High-pass filter and band-pass filter are required to avoid that noise saturates either amplifiers or digitizer (Fig. 2).

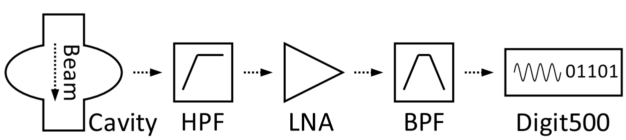

Figure 2: Schematic of the CRCDS measurement chain.

Without accounting for losses in the coaxial cable, total gain factors of the pre-amplification chains are:

$$g_{\mathrm{pa,2nd}} = 66\ \mathrm{dB}$$
$$g_{\mathrm{pa,3rd}} = 78\ \mathrm{dB}$$

Amplifier compression points are specified at:

$$P_{\mathrm{1dB,2nd}} = 22\ \mathrm{dBm}$$
$$P_{\mathrm{1dB,3rd}} = 12\ \mathrm{dBm}$$

Consequently, to avoid amplifier saturation maximum allowed beam currents are:

$$I_{\mathrm{max,2nd}} < 12000\ \mathrm{nA}$$
$$I_{\mathrm{max,3rd}} < 670\ \mathrm{nA}$$

The first value is very high compared to the possible beam currents at PROSCAN. The second value is somewhat low. That means, both pre-amplifiers are not perfectly adapted to their respective measurement systems and the expected beam currents. Though this is just an oversight during prototyping and not a fundamental shortcoming.

DIGITAL READ-OUT AND SIGNAL PROCESSING

The pre-amplifier analog output signal is digitized and processed by a customized Libera Digit500 [10], which is a combination of a fast ADC and an FPGA for real-time data processing. Input sampling rate is 500 MS/s at 14bit nominal resolution. The digitizer integrates into accelerator control systems via the EPICS protocol or a MATLAB interface. Additionally, it can be controlled by a web GUI. An integrated DAC and an analog voltage output port allow to create fast interlock signals.

On the FPGA narrowband digital filters and I/Q demodulation are implemented to detect extremely low signal levels. The resulting output data stream has a data rate of 1000 S/s and an effective signal bandwidth of about 500 Hz. Optimized processing routines shall increase these values by a factor of 10 in the future.

ADC input signals must stay below 28 mVpeak (-21 dBm), which corresponds to a beam current limit of:

$$I_{\mathrm{max,2nd}} < 83\ \mathrm{nA}$$
$$I_{\mathrm{max,3rd}} < 15\ \mathrm{nA}$$

for the full CRCDS measurement system, i.e. cavity, pre-amplifier and Digit500, but neglecting cable losses. Since the Digit500 includes switchable input attenuators, maximum input current can be scaled by up to 31 dB:

$$I_{\mathrm{max,2nd}} < 2950\ \mathrm{nA}$$
$$I_{\mathrm{max,3rd}} < 530\ \mathrm{nA}$$

Note that the Digit500 always saturates at lower beam currents than the pre-amplifiers.

BEAM MEASUREMENTS

A major motivation for the development of the resonant cavity is the non-linearity of ionization chambers towards higher beam currents. At PROSCAN a comparison of the two cavities (CRCDS2 and CRCDS3), a reference ionization chamber (MMAC3) and a Faraday cup (BMB1) was performed. For the measurements, beam currents were varied between 1 nA and 750 nA.

The reference ionization chamber MMAC3 is well calibrated for the low beam currents typically used at PROSCAN, i.e., up to several 10 nA. But it may show small saturation effects towards high beam currents, which is typical for ionization chambers. The Faraday cup BMB1 is known to have a linear response with beam current. But it is probably not that well calibrated.

Since MMAC3 is located in front of beam kicker, degrader and energy selection system, which are used to adapt beam energy and macropulse length to the desired values, and BMB1 is located behind, beam losses will lower BMB1 signal compared to MMAC3.

For these reasons, a comparison in absolute terms would be complex. Beam losses may depend on average beam current and consequently could also hinder a comparison of linearity.

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Figure 3 shows the measured currents, using BMB1 as a reference. Linear least-squares fits were used to scale signals of the other systems. Fit parameters were calculated from data with currents <150 nA. Figure 4 shows differences between BMB1 and the other systems.

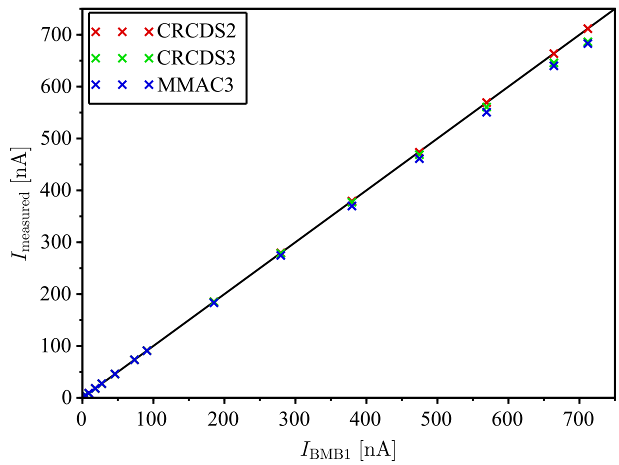

Figure 3: Currents measured by CRCDS2 (red), CRCDS3 (green) and MMAC3 (blue) versus BMB1.

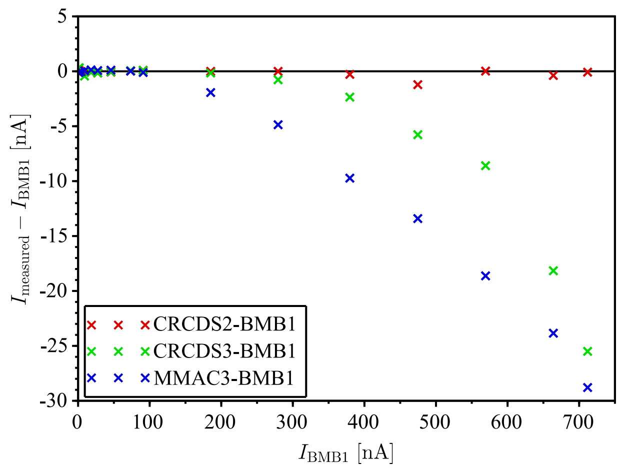

Figure 4: Differences of currents measured by BMB1 and CRCDS2 (red), CRCDS3 (green) and MMAC3 (blue).

BMB1 and CRCDS2 show almost perfectly linear correlation over the full measurement range. This is a strong indication that, as expected, both systems have a linear dependence on beam current.

CRCDS3 slowly starts to saturate around 300 nA, which is compatible with the expected amplifier and digitizer saturation levels.

MMAC3 starts to deviate already around 200 nA. However, deviation between BMB1 and MMAC3 remains within 4% even at the highest current levels. Such a behaviour could be explained by MMAC3 saturation. A first analysis of beam losses showed that these probably cannot explain the observed behaviour. However, given that the observed deviation is small, and analysis of beam losses is difficult, further studies would be required to reach to a more compelling conclusion.

Apart from high current performance, also low current performance of the resonating cavities was explored by lowering the beam current to the lowest measurable levels. MMAC3 was used as a reference for these measurements because it is known to show very good performance at low current levels (Fig. 5).

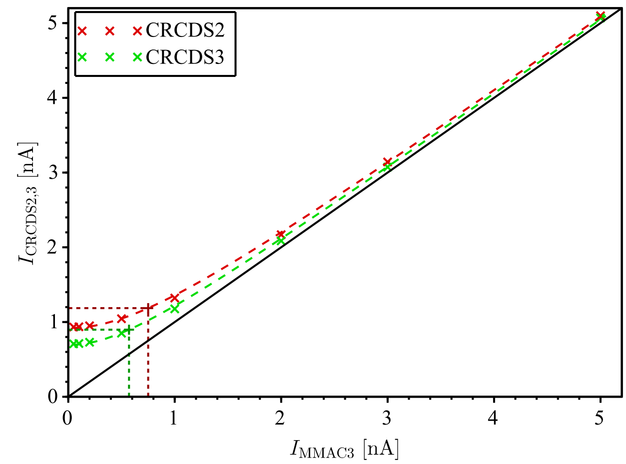

Figure 5: Low current response of CRCDS2 (red) and CRCDS3 (green).

The CRCDS output value is given by the uncorrelated RMS amplitudes of the beam-induced cavity resonance U_{res} and the noise U_{noise} at the digitizer input:

$$U_{\mathrm{out}} = \sqrt{U_{\mathrm{res}}^2 + U_{\mathrm{noise}}^2}$$

which explains the non-linearity of the CRCDS response towards zero current. Based on the measured data, detection thresholds of:

$$I_{\mathrm{DT,CRCDS2}} = 0.74 \text{ nA}$$
$$I_{\mathrm{DT,CRCDS3}} = 0.57 \text{ nA}$$

could be determined. Measured output signal noise was at:

$$\sigma_{\mathrm{CRCDS2}} = 0.073 \text{ nA}$$
$$\sigma_{\mathrm{CRCDS3}} = 0.056 \text{ nA}$$

Principal noise sources are the 50 Ω terminations on the unused cavity ports and the noise figures of the pre-amplifiers, despite being very low noise amplifiers.

CONCLUSION

A resonating cavity is a simple and reliable non-interceptive beam current monitor well adapted for particle therapy accelerators.

The Cavity Resonator Current Diagnostics System (CRCDS) consists of a cavity, pre-amplifiers with filters and a digitizer with FPGA real-time data processing capabilities. They form a complete turnkey solution for beam current measurements which is straightforward to install, easy to use and simple to maintain.

Two industrialized solutions (cavity resonances at second and third harmonic) have been tested in the Gantry 2 beam line of PROSCAN at PSI with beams as used for FLASH therapy (high current macro-pulses) and conventional therapy (low current CW). They showed highly linear response, low detection threshold and very good resolution.

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