DEVELOPMENT OF A PASSIVE CAVITY BEAM INTENSITY MONITOR FOR PULSED PROTON BEAMS FOR MEDICAL APPLICATIONS

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Abstract

In this work the design of a passive cavity beam intensity monitor to be used in the TOP-IMPLART medical proton linac for the on-line measurement of beam current is presented. It will be used to monitor the beam between modules and at the linac exit. TOP-IMPLART produces a pulsed proton beam with 3 us duration at 200 Hz repetition rate with a current between 0.1 uA and 50 uA. The current required for medical applications is less than 1 uA and has to be known with an accuracy better than 5%. Large dynamic range and space constraints make the use of usual non-interceptive beam diagnostics unfeasible. The proposed system consists of a resonant cavity working in the TM010 mode, generating an electromagnetic field when the beam enters the cavity; a magnetic pickup senses an RF pulse whose amplitude is proportional to the current. The RF pulse is amplified and subsequently detected with zero-biased Schottky diodes. The cavity operates in vacuum when used in the inter-module space. The work reports also the results of preliminary measurements done on a copper prototype in air at the exit of the TOP-IMPLART linac to test the sensitivity of the system on the actual 35 MeV proton beam.

INTRODUCTION

The use of proton beams for cancer treatment presents advantages over conventional (photon based) particle therapy. Protons lose their energy in a narrow range of depth near their stopping range. This characteristic yields to a more conformal mapping of the treatment volume with the possibility of sparing nearby organs. Most of the commercial medical accelerators for proton therapy consist of circular accelerators (cyclotrons and synchrotrons).

However, it is identified the need of developing more compact and more efficient accelerators that can reduce the duration of the treatment, improve the precision of dose delivery, and lower the overall cost of the facilities. It is with this aim that TOP-IMPLART (Terapia Oncologica con Protoni, Intensity Modulated Proton Linear Accelerator for Radiotherapy) program is developing a fully linear solution for proton therapy. The accelerator, bearing the same name, is under construction at the ENEA Frascati Research Center. It is a compact pulsed RF linac, consisting of a 7 MeV Hitachi-AccSys PL7 injector (425 MHz) followed by an S-band booster (2997.92 MHz) accelerating the beam up to 150 MeV. TOP-IMPLART, recently, achieved an energy of 35 MeV with the successful commissioning of its first booster section, consisting of four SCDTL (Side Coupled Drift tube Linac) modules powered by a single 10 MW peak power klystron [1]. The accelerator delivers its proton beam in 1 µs to 4 µs long pulses (FWHM) with a Pulse Repetition Frequency in the 10 to 100 Hz range.

The peak pulse current can be set between 0.1 µA and 50 µA changing the injected current. The output current range is broader than the one needed for therapeutic applications, that lies between 0.1 µA and 1.0 µA, because TOP-IMPLART beam is used also for non-biological experiments, requiring higher proton fluence [2]. Pulse current is an important parameter for machine control; therefore, non-interceptive current monitor shall be installed along and at the output of the linac. Measurements of currents lower than 10 µA, which is the typical limit of commercial AC current transformers, has been performed during linac commissioning, on the extracted beam, with the ionization chambers used for dose delivery control. However, this type of diagnostic cannot be inserted in the inter-module space in vacuum. For this reason a high sensitivity, short, non-interceptive detector based on a passive resonant cavity has been developed.

RESONANT CAVITY BEAM INTENSITY MONITOR

A radiofrequency cavity working in the TM010 mode whose resonance frequency is tuned to the micro-bunch frequency of the beam ($1/T_b$ in Fig. 1) can be used as a beam intensity monitor [3].

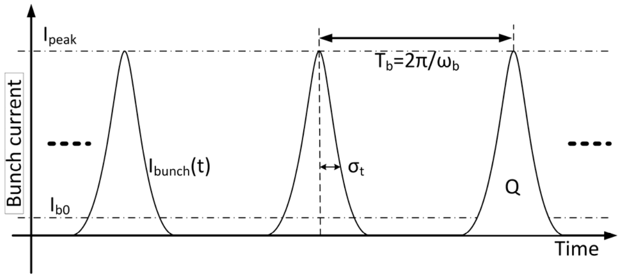

Figure 1: Proton beam structure (micropulse).

The particle beam passing through the cavity excites an electromagnetic field whose azimuthal magnetic component is picked up and converted into an electric signal proportional to the pulse current. According to [4], the power extracted from the cavity can be expressed as:

$$P = (a_1)^2 (R_s/Q_0) T^2 Q_{load} \frac{\beta}{(1+\beta)} \cos^2 \varphi \,, \qquad (1)$$

where a_1 is the first term of the Fourier series expansion of the beam current signal, R_S is the shunt impedance of the cavity, T is the transit time factor, Q_0 and Q_{load} are the unloaded and loaded quality factors, respectively, and β is the coupling coefficient between the loop and the cavity.

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The $\cos^2\varphi$ term accounts for the difference between the cavity resonance frequency and the actual micro-bunches repetition rate frequency.

A simple, yet powerful, analytical model can be developed considering a Gaussian bunch train (with reference to Fig. 1) with each bunch having a Gaussian shape:

$$I_{bunch}(t) = I_{peak}\exp\frac{t^2}{2\sigma_t^2} = \frac{Q}{\sqrt{2\pi}\sigma_t}\exp\frac{t^2}{2\sigma_t^2},$$

where Q is the charge in the bunch. The Fourier series expansion over one period T_b gives the following first order coefficient (corresponding to the signal component at the resonance frequency of the cavity):

$$a_1 = 2I_{b0}\exp\left(-\frac{\omega_b^2\sigma_t^2}{2}\right),$$

where $I_{b0} = I_{peak}\sqrt{2\pi}\,\sigma_t/T_b$ and the cavity shunt impedance is defined as [4]:

$$R_S = \frac{V^2}{2P_{loss}}; V = \left|\int_0^L E_z(r,\varphi,z)e^{i\left(\frac{\omega_0 z}{c}\right)}dz\right|.$$

The detuning factor can be expressed as follows [4]:

$$\cos^2\varphi = 1/\left[1+4Q_{load}^2\left(\frac{\Delta f}{f_0}\right)^2\right].$$

Equation (1) shows that the power extracted from the resonant cavity is proportional to its loaded quality factor, the R_S/Q_0 ratio and to the beam intensity. The upper limit of the quality factor is given by the cavity field filling time: $t_{fill} = 2Q_{load}/\omega$ (the cavity must be "empty" when the next current pulse comes).

TOP IMPLART BEAM STRUCTURE

The typical TOP-IMPLART output current macro-pulse, measured with a Faraday cup, is shown in Fig. 2. The accelerator operates at 2997.92 MHz corresponding to a 333 ps distant micro-bunches, with a $\sigma_t = 8.5$ degrees of RF.

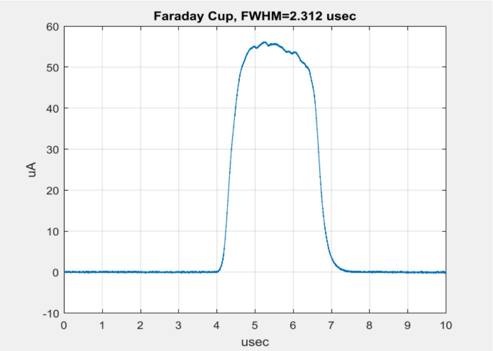

Figure 2: TOP IMPLART output pulse.

However not all the micro-bunches contain the same proton charge due to the non-integer ratio between the operating frequencies of the injector (425 MHz) and of the booster (2997.92 MHz). Thus, the micro-bunch structure of TOP-IMPLART shows a complex structure reflecting the non-harmonic relation, that produces a continuous sliding in the relative phase. Figure 3(a) shows a simulation of the sliding, limited to 8 ns time window for clarity.

Injector bunches have a periodicity of 2.35 ns, each one spanning three RF periods of the booster due to the lengthening of the injected bunch in the transport line connecting it to the booster. The sliding phase causes a micro-bunch intensity modulation of the output beam (see Fig. 3(b)), i.e. the intensity of each booster micro-bunch is different from pulse to pulse.

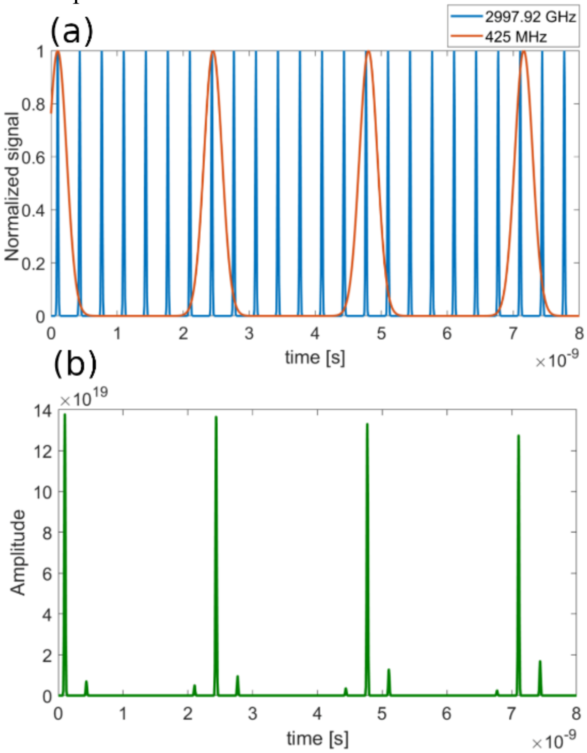

Figure 3: (a) Simulation of temporal superposition of the injector and booster current pulses (8 ns window); (b) Simulation of booster (2997.92 MHz) micro-bunch intensity (amplitude in arbitrary units).

This micro-bunch level modulation does not produce appreciable effects on the charge in the output pulse (to which the dose is related) because all the 360 degrees of phase shifts occurs during the 3 µs pulse duration. Consecutive pulses will carry the same charge, differently distributed among micro-bunches. Hence, this substructure does not affect the result of the measurement with the passive cavity that is sensitive only to the macro-pulse current according with Eq. (1).

BEAM INTENSITY MONITOR

Following the analytical model and the analysis of the micro-bunch structure, the design of a cavity-based, beam intensity monitor has been done, assisted by numerical simulations based on CST software. A reentrant cavity with an overall length L = 12 mm has been chosen as basic design (see Fig. 4).

The cavity length "L" is set by the available space in the machine layout, all others parameters have been numerically optimized, obtaining the final values shown in Table 1. The model for the simulations has been completed adding the loop to extract the RF signal and a tuning screw to adjust the resonance frequency as shown in Fig. 5.

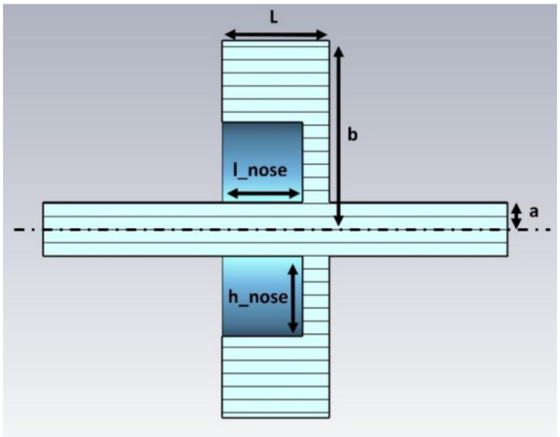

Figure 4: Simplified model of the cavity with the principal geometric parameters.

The resulting copper cavity, tuned to 2998 MHz has quality factor $Q_0 = 4257$, shunt impedance $R_S = 212k\Omega$ and transit time factor $T = 0.87$.

Table 1: Cavity Geometrical Parameters

Parameter	Value	Definition
a	3 mm	Radius of the beam pipe
b	21 mm	Radius of the cavity
l_nose	9 mm	Reentrant depth
h_nose	9 mm	Reentrant height
L	12mm	Length of the cavity

The magnetic pick-up loop position has been optimized in order to obtain critical coupling (l_probe=5.7 mm in Fig. 5). Cavity fine tuning to 2997.92 MHz is obtained positioning the tuning screw 1 mm inside the cavity (tuner_pos = 1 mm in Fig. 5). The final motorized tuner can shift the resonance frequency more than 10 MHz, enough to compensate temperature variation of the cavity during machine operation.

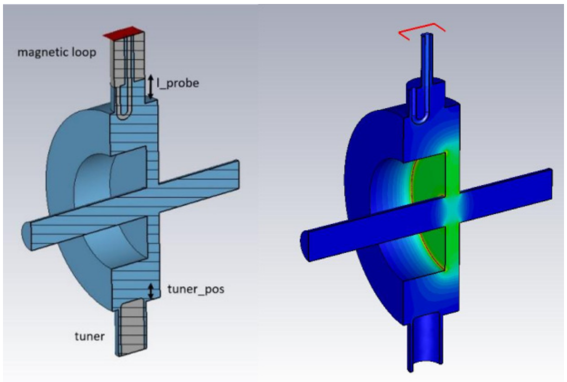

Figure 5: Simulated cavity model (left) and electric field for the TM010 mode (right).

The filling time of the cavity, $t_{fill} = 230$ ns, is compatible with the pulse length and the pulse repetition frequency.

Comparison of the RF power at the cavity probe, obtained from numerical simulations, matches the analytical model described by Eq. 1 in the 0.1 µA to 50 µA range (see Fig. 6).

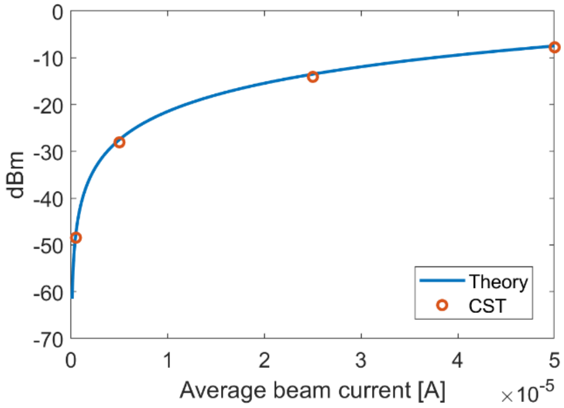

Figure 6: RF power extracted from the cavity as computed by the numerical simulations with particle beam (CST) and the analytical model (Theory).

Prototype Cavity

A prototype cavity has been realized following the results of the numerical simulations. Figure 7 depicts the cavity with CF16 beam pipe flange and the access ports for tuner screw and RF output. The measured parameters of the prototype are: $Q_0 = 4471$, coupling coefficient $\beta = 0.997$, filling time is $t_{fill} = 238$ ns.

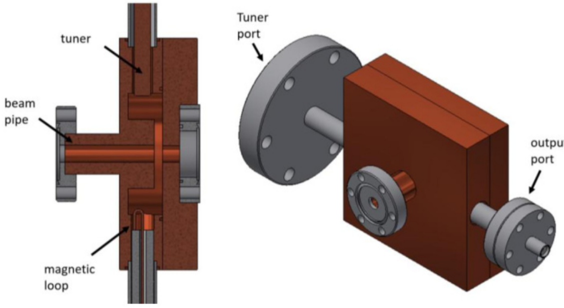

Figure 7: Cavity prototype drawing.

The cavity has been installed in air at the output of the last SCDTL module, following a calibrated current transformer and ionization chamber, to measure the pulse current and has been tested on a current range between 2 µA and 45 µA (see Fig. 8).

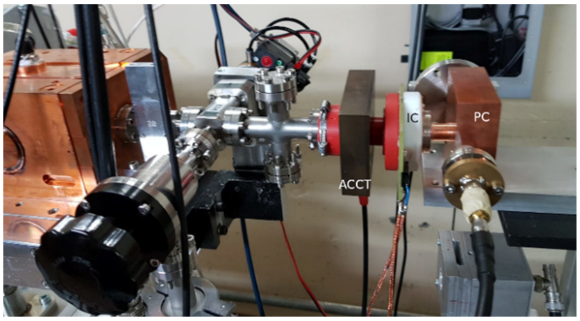

Figure 8: Passive cavity prototype at linac exit (PC), installed after other diagnostic instrumentation: a current transformer (ACCT) and a ionization chamber (IC).

Preliminary measurements are shown in Fig. 9. The measurements reported have been carried out with a spectrum analyser in span zero mode. The output signal level spans the -40 dBm to -12 dBm range, compatible with the analytical model in (1), predicting a -48 dBm to -7.7 dBm range for currents between 0.1 µA and 50 µA.

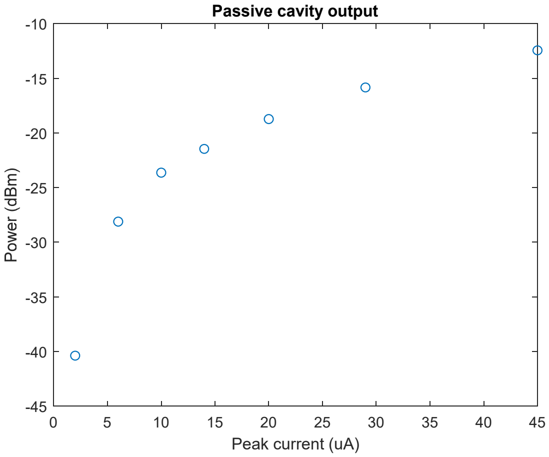

Figure 9: Cavity output power vs pulse current.

The pulse current value in Fig. 9 has been obtained from the pulse charge measured by the ionization chamber (IC in Fig. 8), and confirmed, for values higher than 10 µA, by the ACCT readings. The pulse current value has been computed dividing the pulse charge by the FWHM pulse width.

RF SIGNAL DETECTION

The use of the passive cavity as on-line beam current monitor integrated in the machine control system requires the detection of the envelope of the RF output from the cavity. The system employed in the preliminary tests is based on zero-bias Schottky diodes that produce an output voltage proportional to the RF input power. The Crystek CPDELTS-4000 detector diode presents a good compromise between cost and performance. It can detect RF signals whose power lies between -7 dBm (1.7 mV diode output) and 15 dBm (400 mV diode output).

The analytical model and the measurement on the cavity prototype both show that the expected dynamic range for the RF signal is about 40 dB. The CPDETLS-4000 diode has a dynamic range of 20 dB. Detection of the cavity output requires an amplification system employing two diodes to cover the 40dB dynamic range.

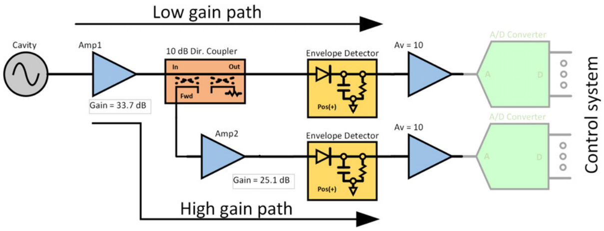

Figure 10: Cavity amplification chain.

The amplification system consists of two amplification paths as show in Fig. 10, driving the envelope detectors. The low gain path has a measured gain of 33 dB and the high gain one 48 dB. The output of the detectors is further amplified by a factor ten to match the dynamic of available analog to digital converter. Figure 11 shows the output of the detector diodes measured before the baseband amplifiers (not yet available). The LO gain path can be used from 10 µA up to 45 µA whereas the HI gain tends to saturate at 20 µA. Within each range the response is approximately linear.

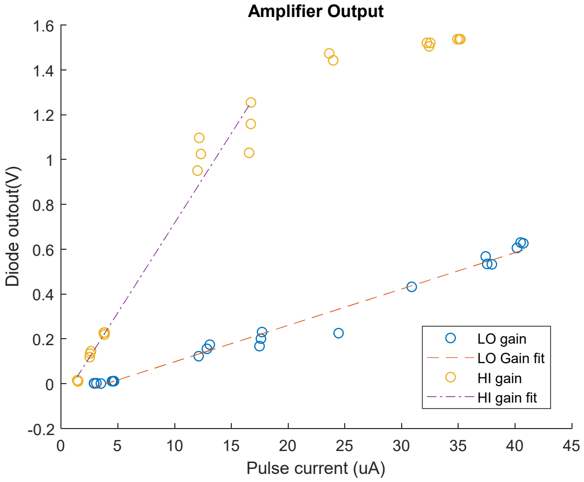

Figure 11: Diodes output for the LO and HI gain paths from actual measurements with the beam.

The pulse current value has been computed as in Fig. 9 from the pulse charge read by the ionization chamber.

CONCLUSION

A resonant cavity beam intensity monitor for pulsed proton medical linacs has been presented. A prototype of the cavity has been realized and tested on the TOP-IMPLART particle accelerator, with a custom designed amplification electronics. In the next months, the cavity will be permanently installed in vacuum on the machine and a newer optimized electronics will be built.

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