Electron Beam Detection by Induced Resonance in Cylindrical Cavity

Alberto Leggieri[1,2], Davide Passi[1], Franco Di Paolo[1], Giuseppe Felici[2], Alessia Ciccotelli[2], Silvia De Stefano[2], and Filippo Marangoni[2]

[1]Dipartimento di Ingegneria Elettronica, Università degli Studi di Roma "Tor Vergata", Roma, Italy
[2]S.I.T., Sordina IORT Technologies S.p.A., Aprilia, Italy

Abstract— An investigation on the power energy injection in a resonator by electron stream is reported in this paper, by documenting the power transfer from an electron beam to a resonant cavity, coupled to an external circuitry. The proposed system has been employed to measure the radiation dose deposed by a medical electron linear accelerator. A prototype has been fabricated and tested through VNA cold measurements and dose deposition measurements. A microcontroller system has been employed to obtain a digital output, the Monitor Units. The linearity of the Monitor Units for different values of accumulated dose, have allowed to employ this system for the real time dose measurements.

1. INTRODUCTION

Real time radiation detectors are employed to control the output of artificial radiation sources. In particular, medical linear accelerators (LINAC's) design, production and operation are subjected to strict regulations mostly regarding the control of the emitted radiations. Beam current measurements of a medical mobile electron LINAC, dedicated to Intra Operative Radiation Therapy (IORT) have been performed through a particular detector and discussed in this paper. In medical accelerator field, beam monitoring system are required by the main technical standards for the real time measurement of the dose delivered to the target while the beam is crossing them [1, 2]. Beam current monitoring for the dose measurement is typically performed by employing ionization chambers connected to suitable electronic circuitry and digital data processing [3]. Traditional beam current monitoring systems are based on ionization chambers and requires high voltage biases [3, 4]. This study investigates on the electron beam current emitted by a medical electron linear accelerator using the power exchange of the beam current with a passive resonant cavity [5] placed at the output interface of the accelerator. In this paper, experimental evidence is presented showing the complete equivalency, in terms of global performance, of the current revelation performed by exploiting the cavity-beam interaction principle with the classical technology, based on ionization chambers, however without the need of high voltage.

2. DETECTION ARCHITECTURE

The proposed radiation detector is based on the power exchange of the beam current with a passive resonant cavity [5] placed at the output interface of the accelerator. The beam current, crossing the resonant cavity provides a magnetic field fluxing through a magnetic loop inserted in the cavity volume. As consequence of the beam to cavity interaction, a voltage is induced at the loop terminals. This voltage, representative of the real time beam current is then elaborated by a microcontroller based elaboration system. The information on the beam current are processed to manage the dose delivered by the accelerating machine. This device allows the measurement of a physical observable quantity directly related with the dose deposed by the beam. Furthermore, no high voltage is needed as happens for the ionization chambers, since the proposed radiation detector does not need any bias. In order to manipulate the information on the current, a frequency down conversion is performed by revealing the signal envelope. For this aim, the pickup voltage, which falls on the matched impedance, is rectified by a RF detector diode. The detector diode output is forwarded to a voltage integrator. The voltage representative of the beam current is integrated during the time duration of the macro-bunch. Since the electric charge is the time integral of the current, the voltage output of the integrator is, at this point, representative of the charge. The main block diagram representative of the operating principle is depicted in Figure 1.

The bunched current produced by the LINAC have an amplitude of $I_{beam} = 1.11\,\text{mA}$. Such current have the alternate form of charge bunches, modulated at the operating normal mode frequency $f = 2998\,\text{MHz}$ of the accelerator. Hence, quasi-Gaussian micro-bunches are separated by

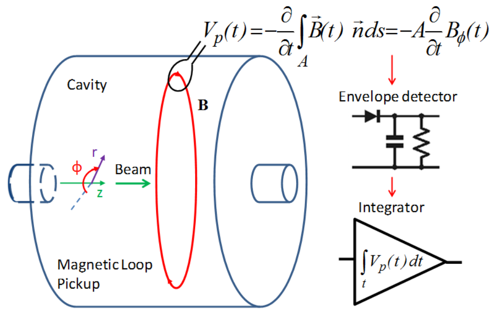

Figure 1: Operating principles — block diagram.

the period of $T = 1/f \approx 0.33\,\text{ns}$. As the bunches follow each other periodically in time, the spectral content of the current beam is a line at the accelerating pulsation $\omega_0 = 2\pi f$ and whole-number harmonics [4]:

$$I_{beam}(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega_0 t) \tag{1}$$

A simplified approach can be adopted by treating the bunched current as a square wave, whose first harmonic is given by:

$$I_1(t) = I_1 \sin(\omega_0 t) \tag{2}$$

where

$$I_1 = I_{beam} \frac{2}{\pi} \sin\left(\pi \frac{t_{on}}{T}\right) \tag{3}$$

where I_{beam} is the amplitude of the bunched beam current.

In the approximation of a square wave beam current, the duration of the high level of the current, t_{on}, corresponds to the time duration of the bunch t_{bunch}. By considering the (3), neglecting the superior harmonics, the amplitude of the injected first harmonic beam current of the analyzed LINAC is $I_1 = 0.66\,\text{mA}$. This harmonic content has been employed to induce oscillations in an opportune resonant cylindrical cavity operating in the TM_{010} mode at the accelerator normal mode frequency f. Since the minimum energy of the beam is greater than 4 MeV, no holes are required on the cavity base surface, but an opportune aluminum window (transparent to these energetic charges) is employed for allowing the beam crossing and entering the cavity. The window thickness is chosen to limit the surface scattering. The beam current cross the window and enter the cavity where exchange power with it inducing a current I_0 on the cavity walls and energy is stored. In order to extract information on the amplitude of the beam current, a magnetic loop is inserted into the cavity. Inserting a pickup in the cavity, the output power derived from such device must come from the work done by the beam against the fields which it itself generates [6].

The voltage induced between the loop terminals V_p can be derived starting from the second Maxwell's equation applied to B_ϕ [7]. The positioning of the loop in the cavity is chosen making the loop encloses a surface A perfectly normal to the azimuthal direction. In such conditions the $V_p(t)$ can be given by:

$$V_p(t) = -\frac{\partial}{\partial t} \int_A \vec{B}(t)\vec{n}\,ds = -A\frac{\partial}{\partial t} B_\phi(t) \tag{4}$$

The cavity behaves as though its shunt impedance were similarly located in the beam tube wall; hence when either type of device is connected to an external electric circuit, it behaves as though its electrical impedance were identical with its shunt impedance. A consequence of the latter result is that for such a device to behave as a matched load, it must be connected to the external circuit via an impedance matching device such as a transformer [6]. For this reason it's of vital importance for the consistence of this dissertation that the cavity shows a critical coupling, identifiable by a coupling factor $k = 1$, observable with the frequency behavior of the impedance shown to the loop terminals. This means that all the power per cycle is extracted by the loop without reflections [8]. Another vital constraint of the model regards the operating frequency of the LINAC and the cavity used as detector. The cavity needs to operate in the TM_{010} mode at the normal mode pulsation ω_0. If the frequency of the LINAC changes without the frequency of the cavity detector changing in the same manner, the output signal will be attenuated, as regulated by the filtering effects of the cavity over the harmonics induced by the beam current crossing. The attenuation can be identified by deriving the modulus of the 3 dB transfer function of the standard parallel RLC resonator described in [9]. In absence of frequency shift, the maximum voltage is obtained and its value coincides with V_p. The voltage attenuation is regulated by the unloaded quality factor of the cavity Q_0 [8].

By considering the definition of the current as the variation of charges in the time unit [7], the charge emitted by the LINAC per bunch is given by:

$$Q_{bunch} = -\int_{t_{bunch}} I_{beam}(t)dt = -\int_{0}^{t_{bunch}} I_{beam}\sin(\omega_0 t)dt = I_{beam}\frac{\cos(\omega_0 t_{bunch}) - 1}{\omega_0} \tag{5}$$

While knowing the energy $W_{beam}(\omega_0 t)$ of the charges e crossing the detector, the value of the deposed dose per micro bunch pulse can be obtained by the energy ratio per unit of effective mass $m(E)*$ of the matter where the dose D_{bunch} is deposed from each bunch, as expressed by (6):

$$D_{bunch} = \frac{\partial W_{beam}(\omega_0 t)}{\partial m\left(E\right)^*} \cong \frac{\int_0^{t_{bunch}} W_{beam}(\omega_0, t)\cdot I_{beam}(\omega_0, t)dt}{em\left(E\right)^*} \tag{6}$$

The amount of dose deposed by a macro-bunch pulse of duration t_{pulse} can be found by multiplying D_{bunch} for the number of micro-bunches per macro-bunch pulse. This value can be obtained my multiplying the LINAC normal mode frequency for the duration of the macro-bunch pulse, linearly approximated by:

$$D_{pulse} = D_{bunch} t_{pulse} f \tag{7}$$

The direct relation between the dose deposed by the beam and the beam current can be noted.

3. SYSTEM DESIGN

One of the principal requirements for the proposed detector is the small thickness, needed to insert the system at the end of the LINAC radiant head. Moreover, the cavity needs to be integrated with another cavity to compose a redundant system composed by two cavities disposed along the same axis. This requirement will further reduce the available space. Hence, in order to reduce the size as much as possible, a length of $\lambda/16$, corresponding to $L_{gap} = 6.25$ mm has been chosen for the initial pillbox cavity length. A tradeoff between the power losses and the operative bandwidth of the cavity was performed, yielding to the selection of the brass as the material for the realization of the device. This choice was leaded by the fact that the device is subjected to thermal effects due to the variability of the external environment conditions. A lower quality factor can make the system more robust to such variation. The trade off originates by the fact that lowering Q increases the losses reducing the voltage output. After the analytical design a computational electromagnetic modeling using the finite elements method has been implemented. In order to realize the system of two integrated cavity avoiding normal mode coupling between them, a cylindrical section has been added to the cavity to allow the beam current exiting from the first cavity to enter in another identical cavity without inserting a metallic shield. The radial aperture of such cylindrical section is enough large to allow the beam crossing without increasing the electrical coupling between the two cavities. Basing on the specification of the drift tube, a reasonably larger aperture has been chosen. A reentrant cavity shape has been individuated by employing POISSON SUPERFISH to find the desired profile ensuring good values of quality factor and shunt resistance, while maintaining the presence of the drift tube. The cavity radius has been increased in order to make the cavity tunable by inserting opportune tuning screws. For this reason the design frequency has been decreased to $f = 2997.5$ MHz. This cavity presents a shunt impedance of $Z_s = 12.8\,\mathrm{M\Omega m^{-1}}$ and a quality factor of $Q_0 = 3.4 \cdot 10^3$ while the transit time factor is $T = 0.766$. A complete electromagnetic modeling has been performed on HFSS version 15 of ANSYS. A rectangular magnetic loop have been employed for the power extraction. The profile of the loop, as well as the distance from the cavity lateral walls, have been chosen to obtain the critical coupling between the cavity and the load, with the minimum reflections [8]. In order to allow for the connection of an SMA, a tapered coaxial line has been added as impedance transformer from the section the magnetic loop to the SMA. The 3D simulated structure of the whole system is shown in Figure 2, where the magnetic loops and the coaxial lines are highlighted for a better view.

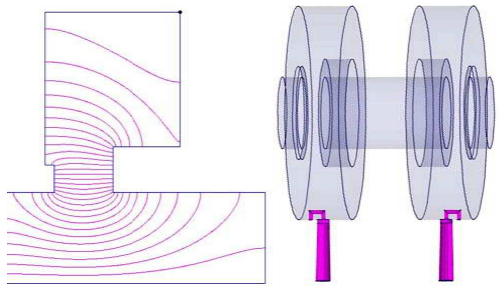

Figure 2: Field profile of a quarter of the re-entrant cavity modelled in POISSON SUPERFISH (a) and the whole cavity-loop system in ANSYS-ANSOFT HFSS (b) model.

This condition has allowed for the maximum available power transfer and ensured the applicability of the theory formulated in this paper. The simulated S-parameters are given in Figure 3, S_{11}, and 4, S_{21}. The proposed cavity to magnetic loop system ensures a maximum cross talk between the two channels of -32 dB and a return loss of 20.7 dB at the designed resonance.

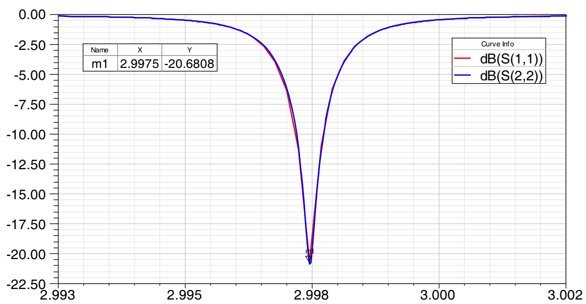

Figure 3: Simulated S_{11} amplitude in dB.

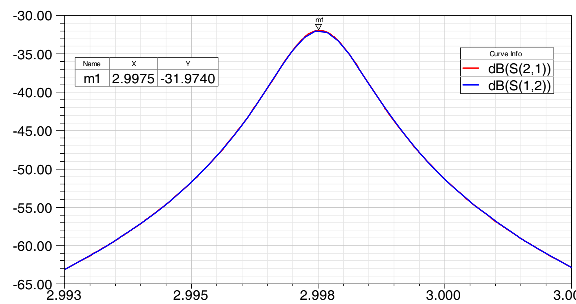

Figure 4: Simulated S_{21} amplitude in dB.

4. FABRICATION AND MEASUREMENTS

Cold measurements of scattering parameters and hot measurements of the dose deposition have been performed on the detector prototype. Since the detector output can be influenced by the temperature exposition, the cavity shares the thermostatation circuit of the LINAC where flowing controlled temperature water. The detector prototype is depicted in Figure 5 where tuning screws, SMA connectors and thermostatation pipes can be noted.

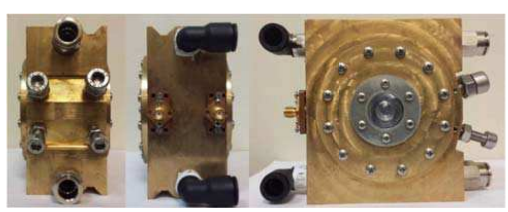

Figure 5: Radiation detector prototype.

Table 1.

Energy Setting	Mean Energy [MeV]	Beam Current [mA]	Voltage Output [mV]	MU/pulse
A	*5.5*	*0,74*	*84.5*	*0.797*
B	*7.1*	*0,90*	*164.0*	*1.570*
C	*9.0*	*1.03*	*253.5*	*2.695*
D	*10.5*	*1.11*	*300.0*	*3.534*

Measured reflection parameters in the frequency bandwidth have been exported from a Rohde and Schwarz ZVL 12 VNA and elaborated through a custom MATLAB code, computing the quality factor and the coupling factor by the detuned short position technique [8]. The device have shown a quality factor $Q_0 = 2.25 \cdot 10^3$, a return loss $RL = 23\,\text{dB}$ a cross talk between the two integrated cavities of $IL = -34\,\text{dB}$ and a Coupling Factor $k = 1.02$, as described in Figures 6, 7 and 8. In order to asses quantitatively the results achieved, a direct measurement of the accelerated beam has been performed. The output current of the LINAC has been forwarded into the cavity observing the output voltage of the envelope detector. Radiation measurements have been performed on the LIAC-S® accelerating structure, by varying the LINAC energy settings [10]. The machine has been set with the parameters described in Table 1. The pulse duration of the macro-bunch is $\tau = 3.5\,\mu\text{s}$ and the pulse repetition frequency is $f_{PRF} = 10\,\text{Hz}$. Mean electron beam energy has been measured according to IAEA TRS 398 protocol [11] at the application point of the ionizing radiation. Percentage Depth Dose (PDD) curves have been measured using PTW MP3 XS water-phantom with suitable detectors and PTW Mephysto mc^2 processing software [12] and reported in Figure 9. The output measurements have shown a $R_{50} = 4.5\,\text{cm}$, corresponding to an average energy of about 10.5 MeV, as shown by the curve reported in Figure 9.

The detector voltage output has been integrated by an operational amplifier during the macro bunch pulse time. The integral output has been elaborated through a microcontroller system,

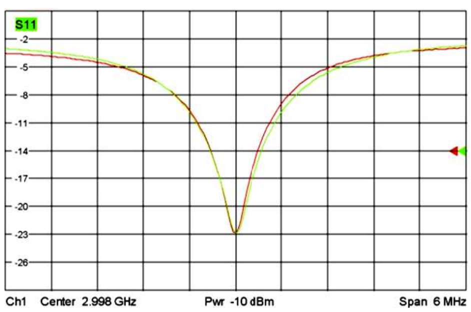

Figure 6: Measured S_{11} amplitude in dB.

Figure 7: Measured S_{21} amplitude in dB.

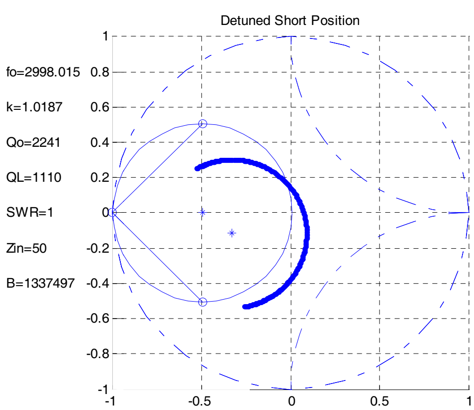

Figure 8: Coupling analysis computation.

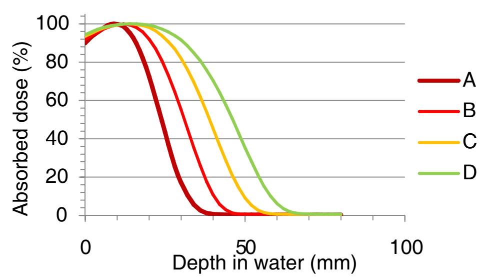

Figure 9: Percentage Depth Dose measurements.

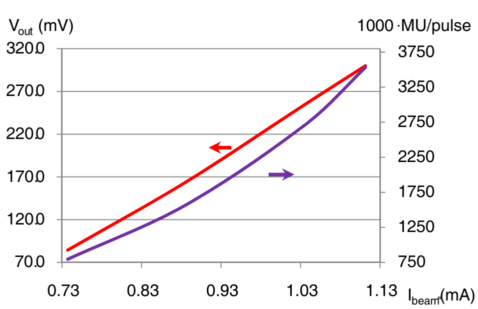

Figure 10. Voltage output and 10^3 MU/pulse vs I_{beam}.

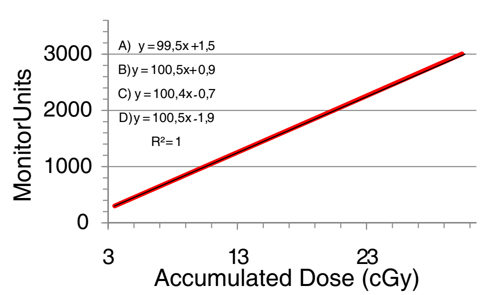

Figure 11. Linearity: Accumulated Dose, MU vs Gy.

obtaining a digitalized value representative of the dose emission, the monitor units per pulse (MU/pulse) [1]. The system has been calibrated to yield the precise measurement of the deposed dose also yielding the secondary interactions. Each monitor unit has been calibrated to 1 cGy. The relation between the injected beam current and the output of the detector diode is reported in Figure 10. The linearizable behavior of the peak voltage output (V_{out}) and dose digital representation (MU/pulse) against the beam current can be noted.

The measurements shown in Figure 11 report the linearity of the accumulated monitor units for different values of total emitted dose. This results allows for the employment of the proposed system in a medical electron LINAC for controlling dose delivered to the patient.

5. CONCLUSIONS

This paper proposes an investigation on the power energy injection in a resonator by electron stream. A novel approach for beam monitoring of a medical electron accelerator is proposed. This kind of device requires strong reliability monitoring system for the real time measurement of the dose delivered to the patient. In this paper, the complete applicability of the proposed principle to such requirements has been shown. The proposed technology is based on the power exchange of the LINAC beam current with a passive resonant cavity placed at the output interface of the accelerator. This detector can operate without high voltage biases, required by the traditional beam monitors based on ionization chambers. Several prototype measurements have shown the complete equivalency of the proposed device with the traditional ionization-based systems but presenting several advantages, as the absence of high voltages and the fact that the proposed system measures the physical observable quantity directly related with the dose, the beam current.

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