Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

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]Università degli Studi di Roma "Tor Vergata", Dipartimento di Ingegneria Elettronica, 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 between the electron current to a resonant system. The beam current emitted by an electron linear accelerator (LINAC) has been monitored through a particular radiation detector. This device was developed for the dose measurements of a Medical Linear LINAC where monitoring system are required for the real time control of the dose delivered to the patient [1-4].

The power transfer has been observed employing the relation of interaction of the LINAC beam current with a passive resonant cavity [5] placed at the output interface of the accelerator. The LINAC beam current have a bunched form. The spectral content is a line at the accelerating pulsation $\omega_0=2\pi f$ and whole-number harmonics [4]. The beam has been used to induce TM_{010} mode oscillations in a cylindrical cavity at the frequency f [6]. The current drives the cavity in resonance and the energy exchange is heavily regulated by the transit time factor T [7] and the coupling factor k [8]. A magnetic loop antenna is inserted in the cavity in order to perceive the magnetic flux at the TM_{010} resonance. A voltage induced on the terminals of the magnetic loop is forwarded to an envelope detector through a coaxial transmission line loaded (Fig. 1).

The envelope detector shows a matched impedance to the loop-cavity system where a certain amount of power is dissipated. The cavity modeling has been performed on POISSON SUPERFISH and the whole system consisting of the cavity and the magnetic loop has been optimized and finally simulated on HFSS version 15 of ANSYS (Fig. 2).

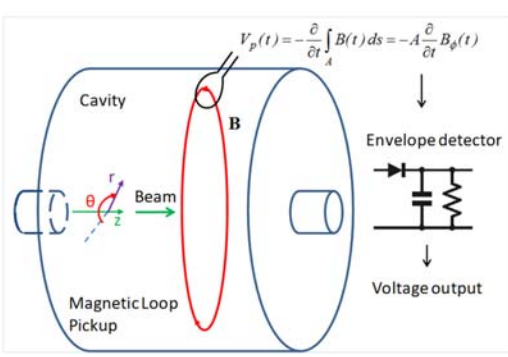


Fig. 1: Block diagram of the operative principle.

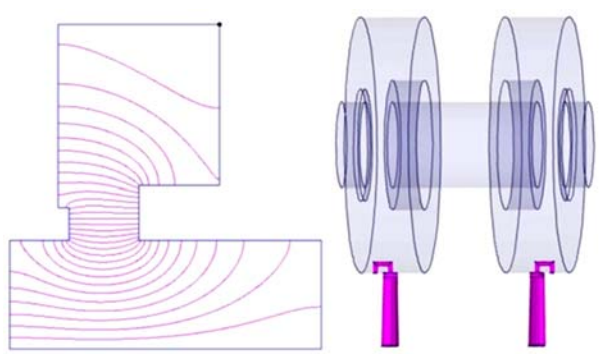


Fig. 2: Field profile of a quarter of the re-entrant cavity modeled in POISSON SUPERFISH (left) and the whole cavity-loop system in ANSYS-ANSOFT HFSS 3D model (right).

A prototype has been fabricated (Fig. 3) and tested through VNA cold measurements and by shooting a beam current in the while cavity observing the output voltage. The input characteristic of the cavity system has been measured showing a quality factor $Q_0=2.24\cdot10^3$, a Return Loss of 23 dB a cross talk of -34 dB and a Coupling Factor k=1.019, (Figs. 4, 5 and 6).

The output voltage has been digitalized by a microcontroller, obtaining numerical values. The system has been calibrated by relating the radiation dose, measured by a certified electrometer, to this digital output, yielding the monitor units [1] (Fig. 7). The linearity of the monitor units for different values of accumulated dose (Fig. 8), have allowed to employ this system for the real time measurements of ionizing radiation emitted by a medical LINAC [1-3].

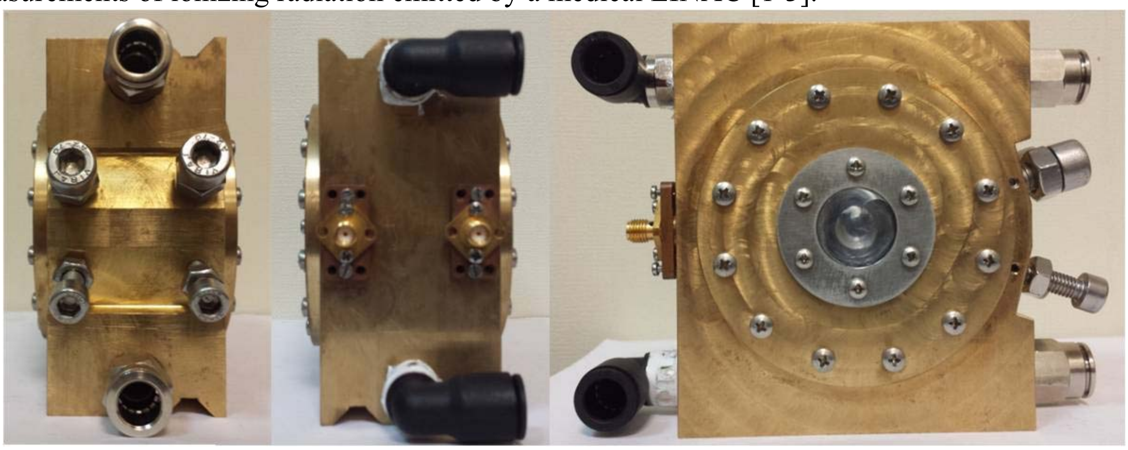


Fig. 3: Prototype of the proposed detector in main profile views.

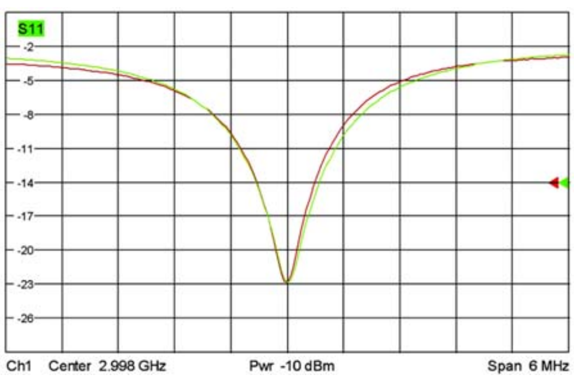


Fig. 4: Measured scattering reflection parameters.

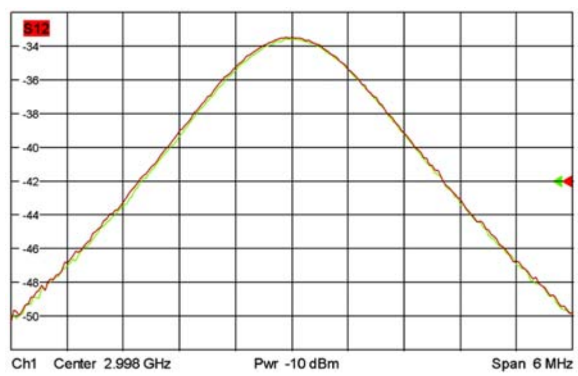


Fig. 5: Measured scattering transmission parameters.

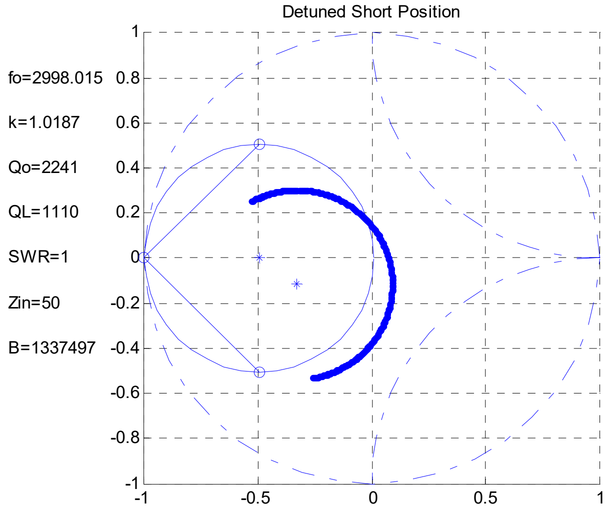


Fig. 6: Detuned short position elaboration for coupling analysis.

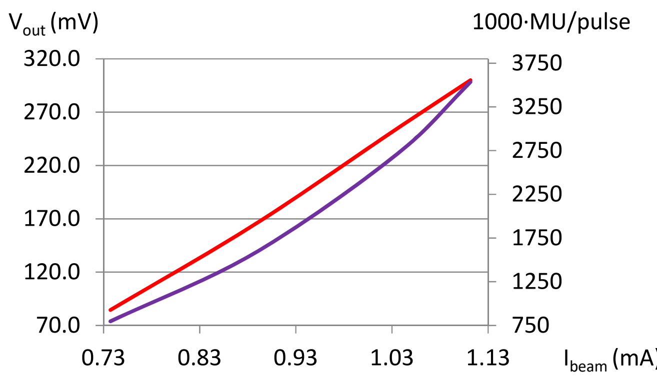


Fig. 7: Measured output. Vout and 10^3MU/pulse vs. Ibeam.

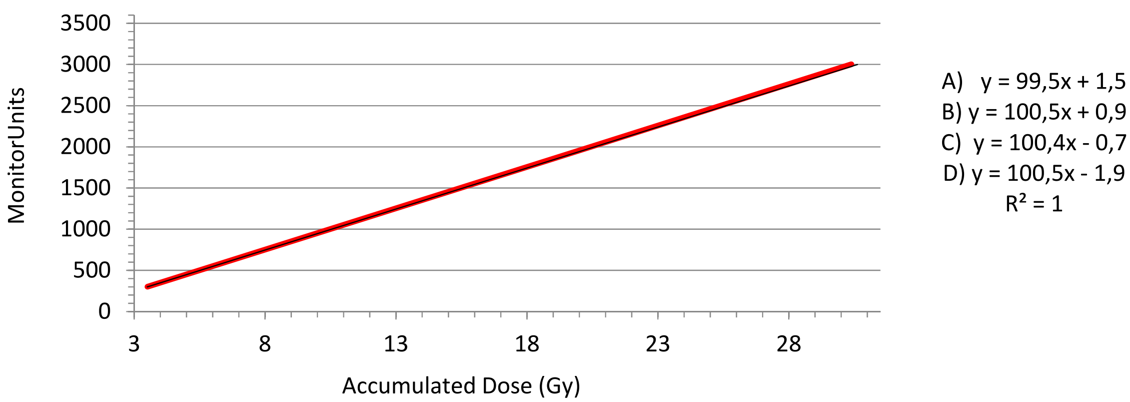


Fig. 8: Linearity. Accumulated dose MU vs Gy

Keywords: Accelerator instrumentation, electron beams, microwave devices, radiation detectors, resonant cavities.

References:

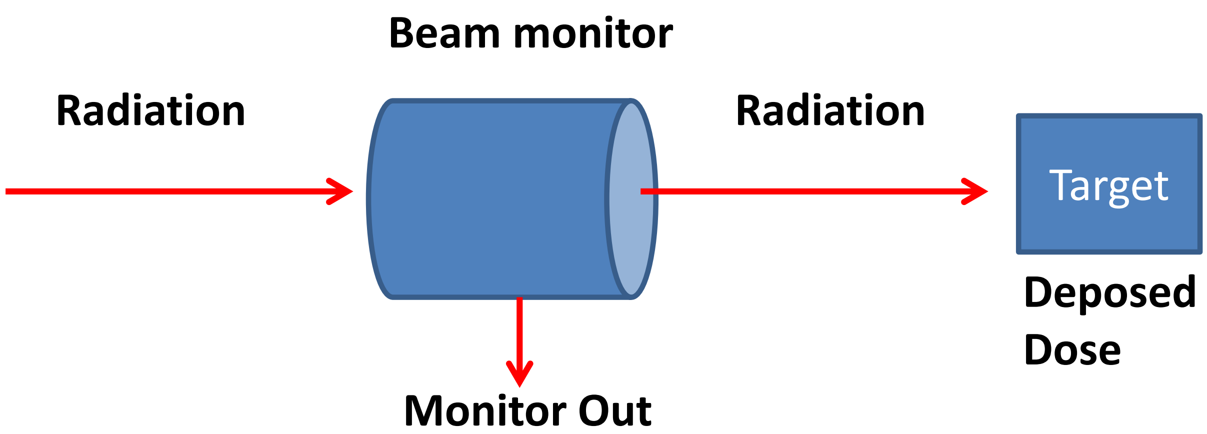
1. International Standard EN 60601-2-1 "Medical electrical equipment - Part 2-1: Particular requirements for the basic safety and essential performance of electron accelerators in the range 1 MeV to 50 MeV ", 3rd edition, International Electrotechnical Commission, 2009.
2. A. P. Turner, "Regulations, Standards and Guidelines for the Use of Medical Electron Linear Accelerators", IEEE Transactions on Nuclear Science, Vol. NS-26, No. 1, 1979.
3. Uvarov, V.L. et Al., "A beam monitoring and calibration system for high-power electron LINACs", Proceedings of the Particle Accelerator Conference, Vancouver, BC, 1997.
4. M. Ruf, S. Muller, S. Setzer and L. P. Schmidt; "Beam Position and Energy Monitoring in Compact
Linear Accelerators for Radiotherapy", IEEE Transactions on Biomedical Engineering, Vol. 61, No. 2, 2014.
5. J.B. Rosenzweig, "Accelerator technology II: waveguides and cavities" in Fundamentals of Beam Physics, Oxford University Press, Oxford, 2003, pp. 183-193.
6. D.A. Goldberg and G.R. Lambertson, "Dynamic Devices a Primer on Pickups and Kickers", pp.540-561.
7. S. Ramo, J. R. Whinnery, T. Van Duzer, "Resonant Cavities" in "Fields and Waves in Communication Electronics", 3rd ed., New York, John Wiley & Sons, 1994, p. 303-310, 699-701,719-723.
8. A. Leggieri, D. Passi, G. Felici, S. De Stefano and F. Di Paolo, "Magnetron High Power System Design", International Journal of Simulation System Science and technology, Vol. 16, 2015.
9. F.Di Paolo, "Resonant Elements" in "Networks and Devices Using Planar Transmission Lines", CRC Press LLC, 2000, pp. 505-512.
10. S.I.T. S.p.A., LIAC-S® product description, Italy, 2013. Available: http://soiort.com
11. IAEA TRS 398 "Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water", Vienna, December 2000.
12. PTW Freiburg GmbH, Mephysto Software Suite product description, Germany, 2012. Available: http://www.ptw.de/2082.html

Outline

- Motivations
- Operating Principles
- System Design
- Measurements
- Conclusions

Motivations

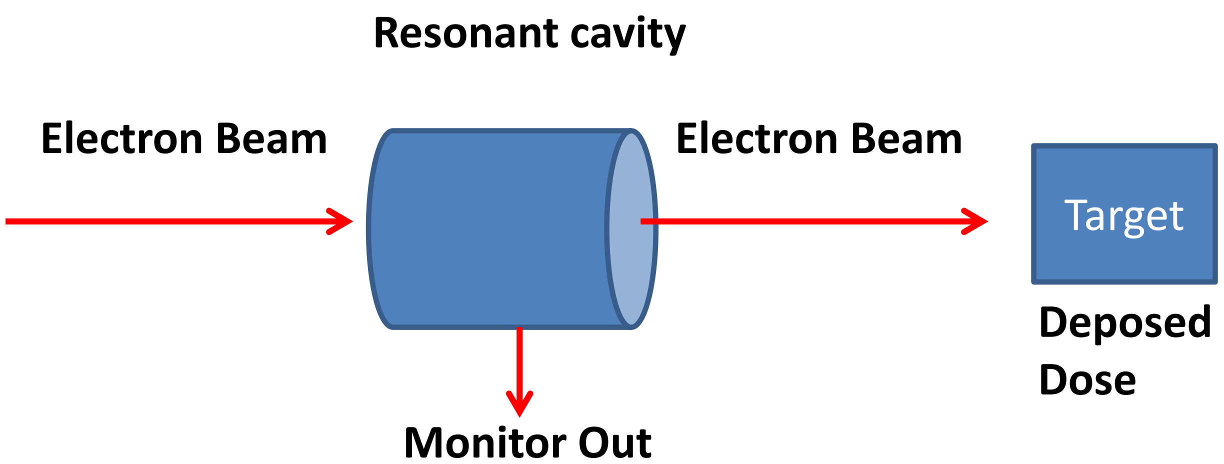
Real Time Radiation Monitoring



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 [1-3]. 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. Beam monitoring for the dose measurement is typically performed by employing ionization chambers connected to suitable electronic circuitry and digital data processing [3].

Motivations

Cavity-Beam Interaction

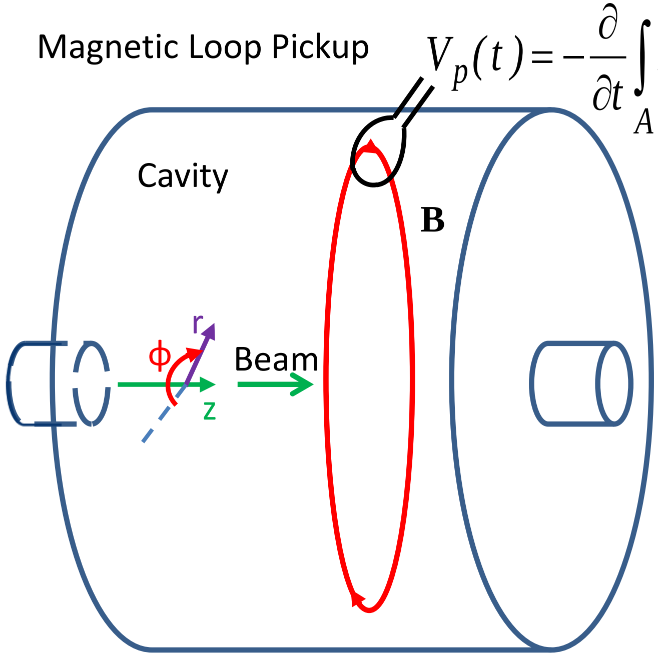


This study investigates on the electron beam current emitted by a medical electron linear accelerator using the power exchange of the beam current with a passive resonant cavity [5] placed at the output interface of the accelerator. In this paper, experimental evidence is presented showing the complete 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. 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.

Operating principles

Detection Architecture

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

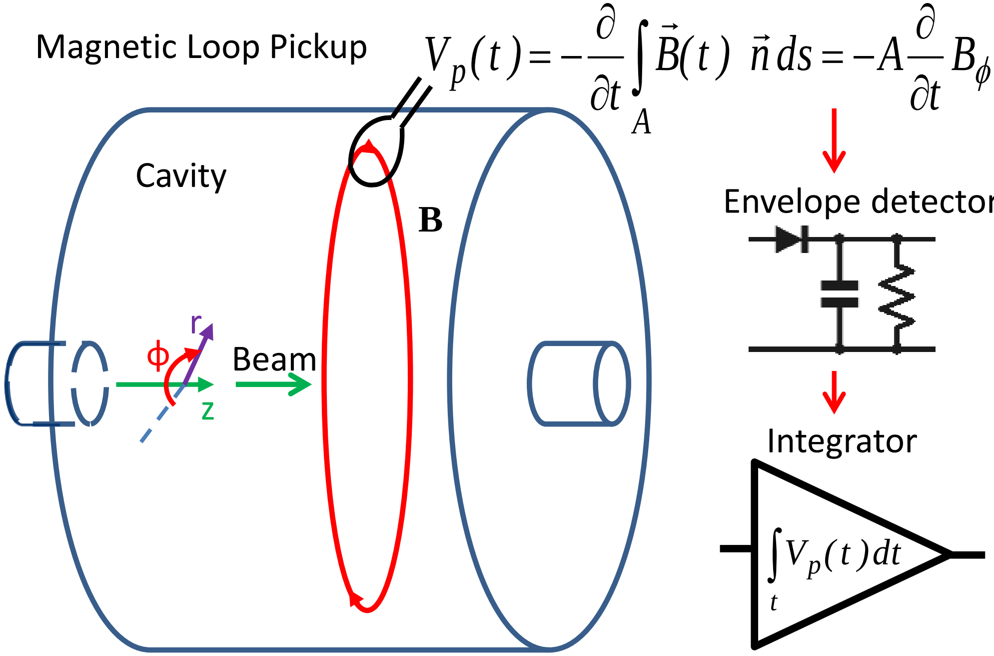


The proposed radiation detector is based on the power exchange of the beam current with a passive resonant cavity[5] placed at the output interface of the accelerator. The beam current, crossing the resonant cavity provides a magnetic field fluxing through a magnetic loop inserted in the cavity volume. 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.

Operating principles

Detection Architecture

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



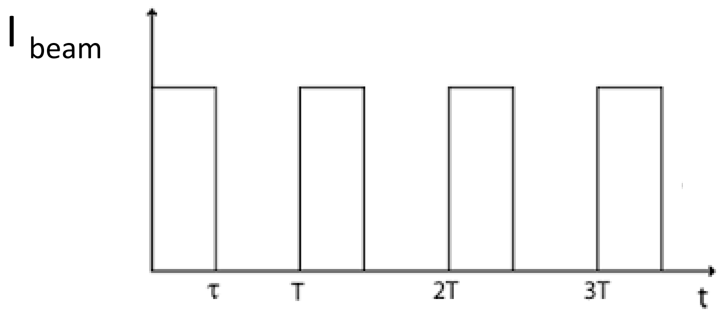
In order to manipulate the information on the current, a frequency down conversion is performed by revealing the signal envelope. For this aim, the pickup voltage, which falls on the matched impedance, is rectified by a RF detector diode. The detector output is forwarded to a voltage integrator. The 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.

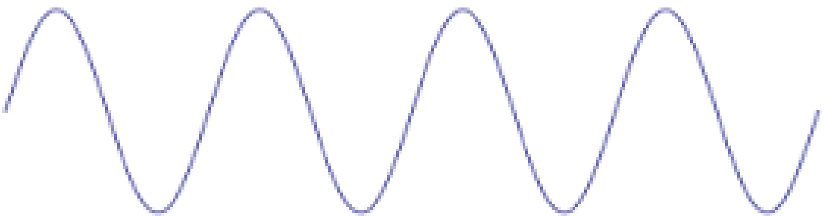
Operating principles

Bunched Beam Current (Approximation)

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

$$I_1(t) = I_{beam} \frac{2}{\pi} \sin\left(\pi \frac{t_{on}}{T}\right) \sin(\omega_0 t)$$

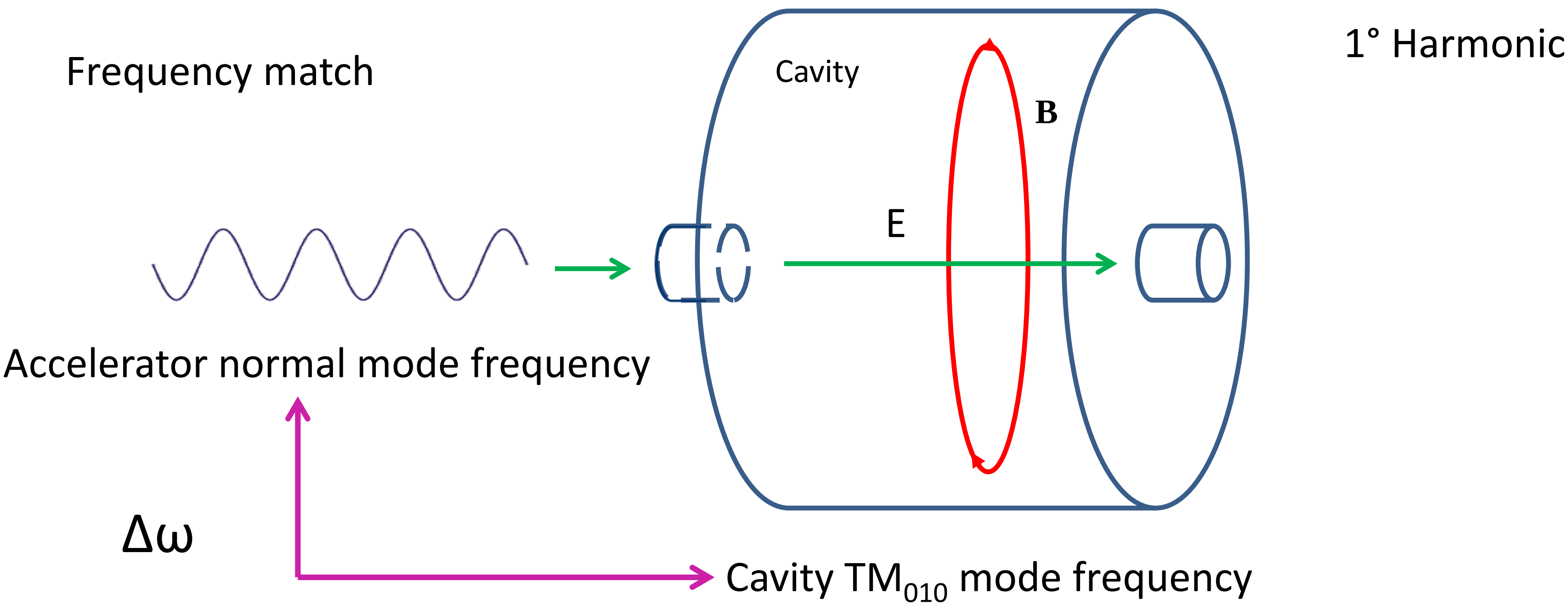




The bunched current produced by the LINAC have an amplitude of I_{beam}=1.11 mA. Such current have the alternate form of charge bunches, modulated at the operating normal mode frequency f =2998 MHz of the accelerator. Hence, quasi-Gaussian micro-bunches are separated by the period of $T=1/f \approx$ 0.33ns. 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} 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 mA.

Operating principles

Resonance Injection



The first harmonic content of the beam current 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*. the cavity where exchange power with it inducing a current I_0 on the cavity walls and energy is stored.

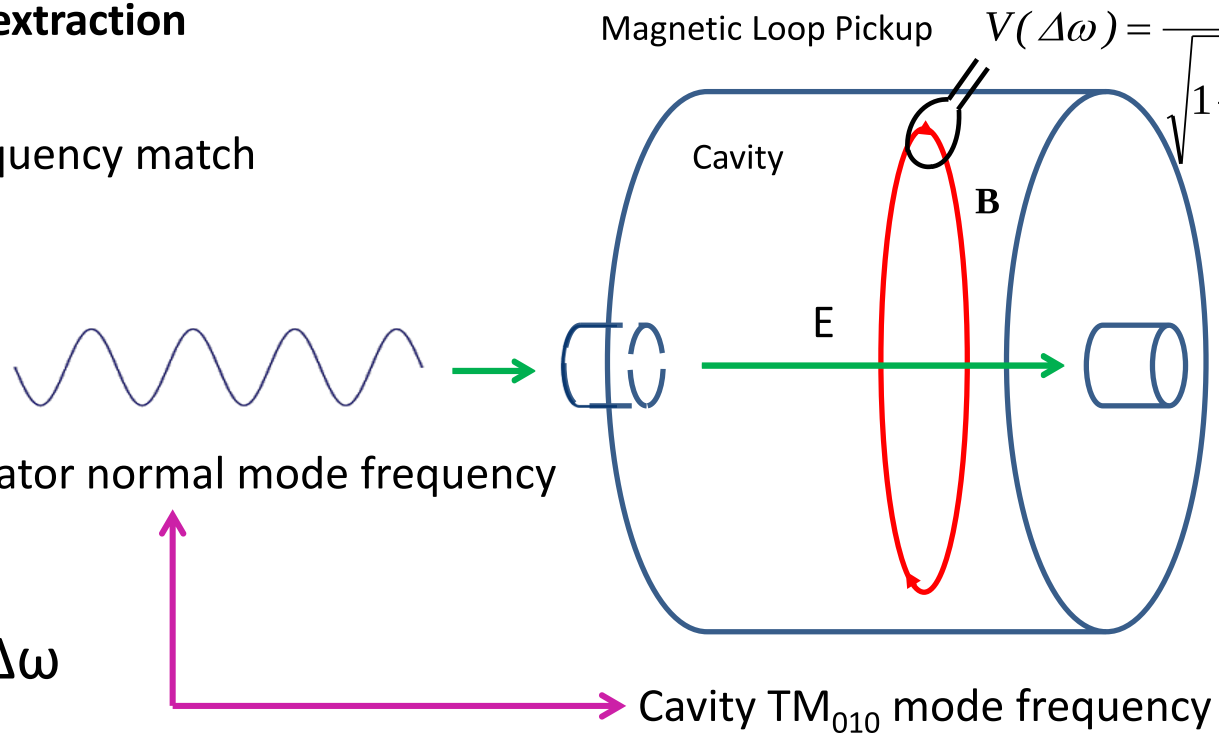
UNIVERSITA' DEGLI STUDI DI ROMA Tor Vergata

Operating principles

Power extraction

Frequency match

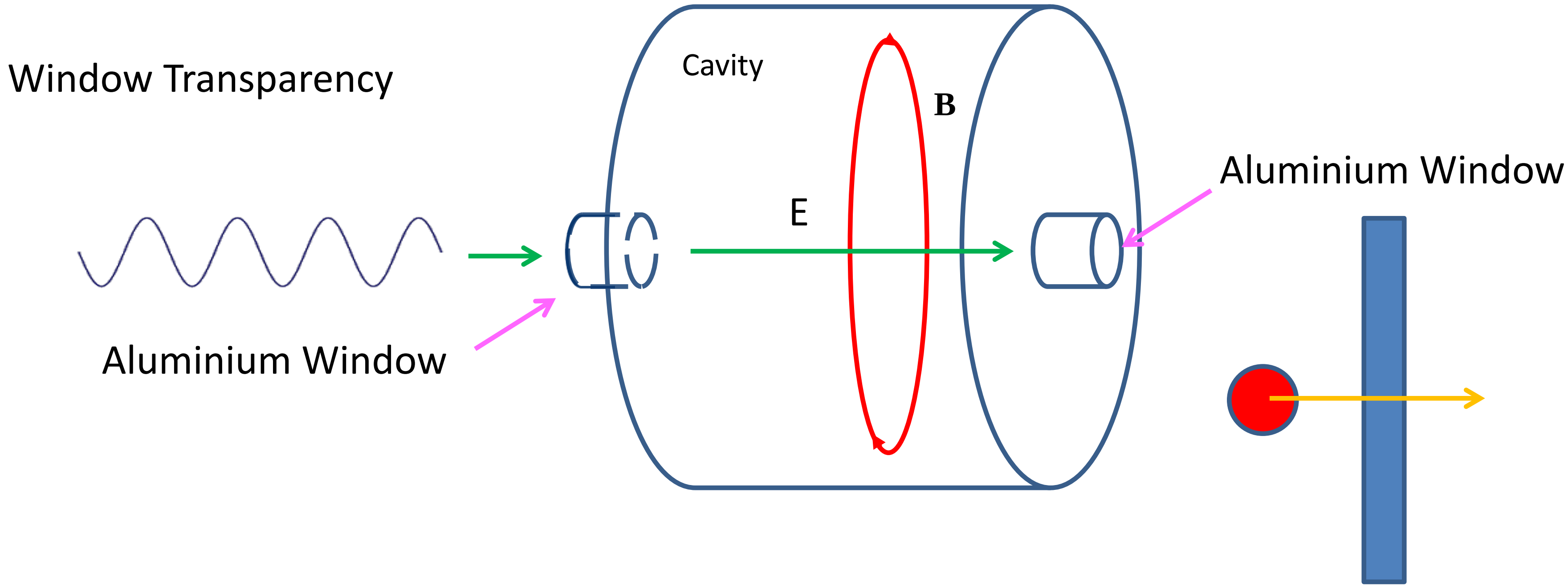
$$V(\Delta\omega) = \frac{V_p}{\sqrt{1 + Q_0^{\,2}\left(\frac{\omega_0}{\omega_0 + \Delta\omega} - \frac{\omega_0 + \Delta\omega}{\omega_0}\right)}}$$



The output power derives from the work done by the beam against the fields which it itself generates[6]. The loop terminals voltage $V_p(t)$ derives from the second Maxwell's equation applied to B_ϕ [7]. 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 following the modulus of the 3 dB transfer function of the standard resonator [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].

Operating principles

Resonance Injection



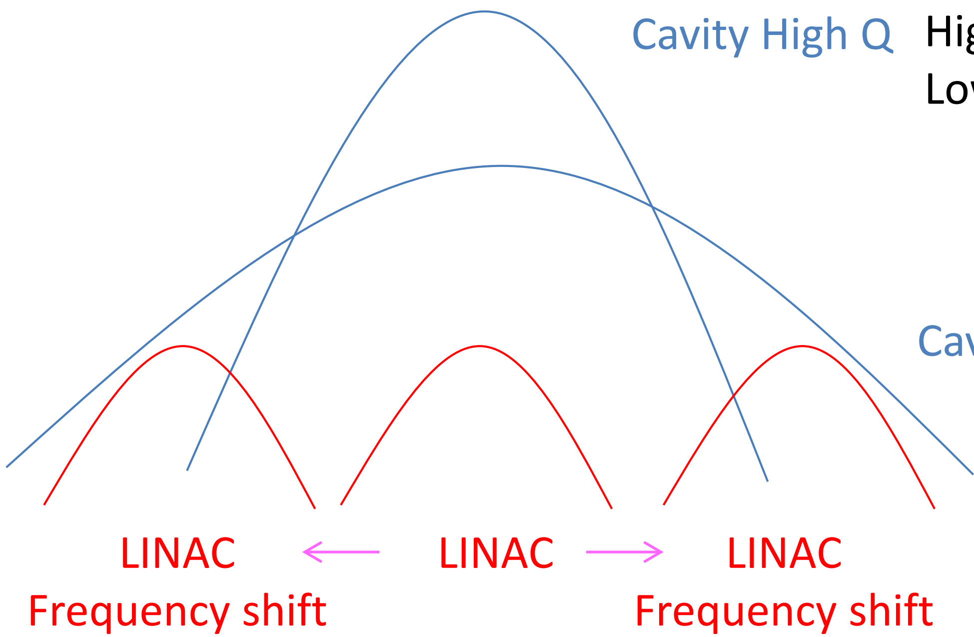
Since the minimum energy of the beam is greater than 4 MeV, no holes are required on the cavity base surface, but an opportune aluminum window (transparent to these energetic charges) is employed for allowing the beam crossing and entering the cavity. The window thickness is chosen to limit the surface 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.

PIERS

System Design

UNIVERSITA' DEGLI STUDI DI ROMA Tor Vergata

Design Requirements



Copper:
High Vout
Low bandwidth

Brass:
Trade-off

Cavity Low Q

Steel:
Low Vout
High bandwidth

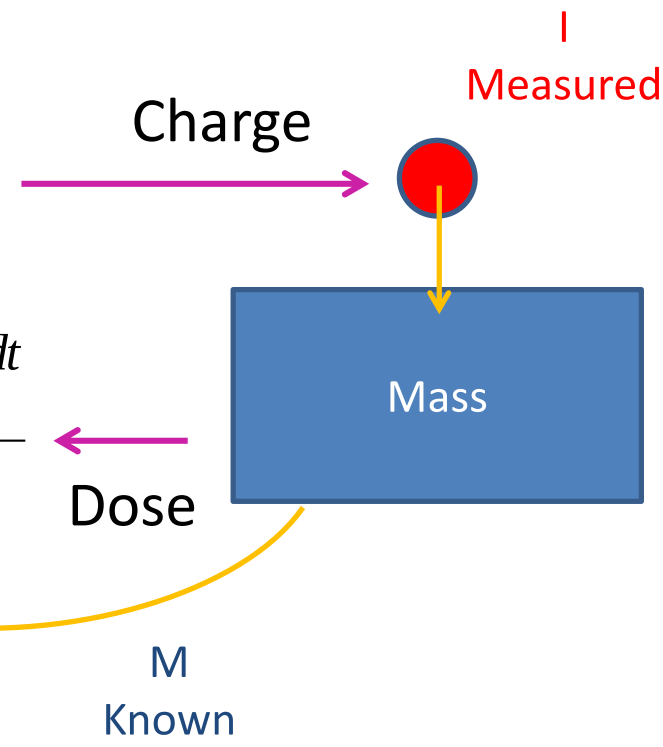
A tradeoff between the power losses and the operative bandwidth of the cavity was performed, yielding to the selection of the brass as the material for the realization of the device. This choice was leaded by the fact that the device is subjected to thermal effects due to the variability of the external 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.

Operating principles

From Beam Current to Radiation Dose

$$Q_{bunch} = -\int_0^{t_{bunch}} I_{beam}\sin(\omega_0 t)\,dt = I_{beam}\frac{\cos(\omega_0 t_{bunch})-1}{\omega_0}$$

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



W
Known

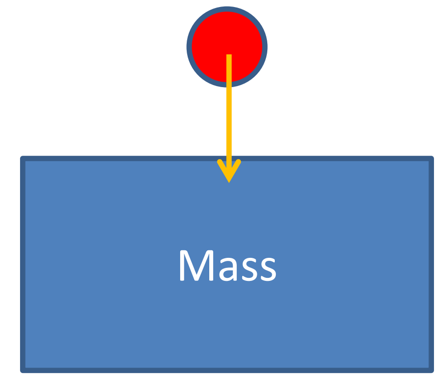
The charge emitted by the LINAC per bunch is given by considering the definition of the current as the variation of charges in the time unit [7]. While knowing the energy $W_{beam}(\omega_0 t)$ of the charges e crossing the detector, the value of the deposed dose per micro bunch pulse can be obtained by the energy ratio per unit of effective mass $m(E)^*$ of the matter where the dose D_{bunch} is deposed from each bunch.

Operating principles

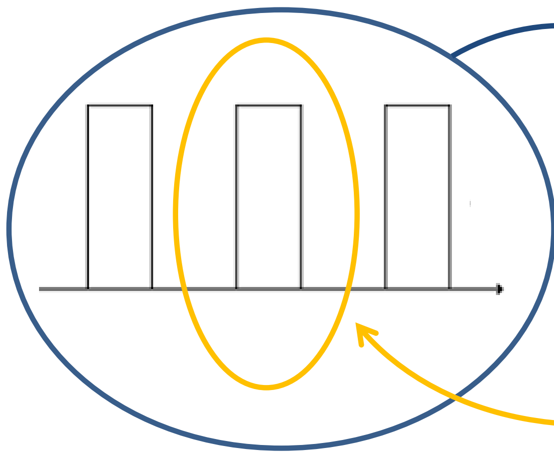
From Beam Current to Radiation Dose

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

Dose



Macro-bunch pulse



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

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

System Design

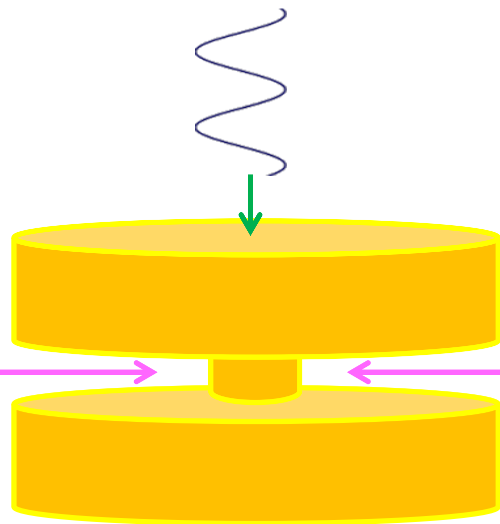
Design Requirements

Industrial requirements

small thickness

two cavities redundant system

Standard requirements



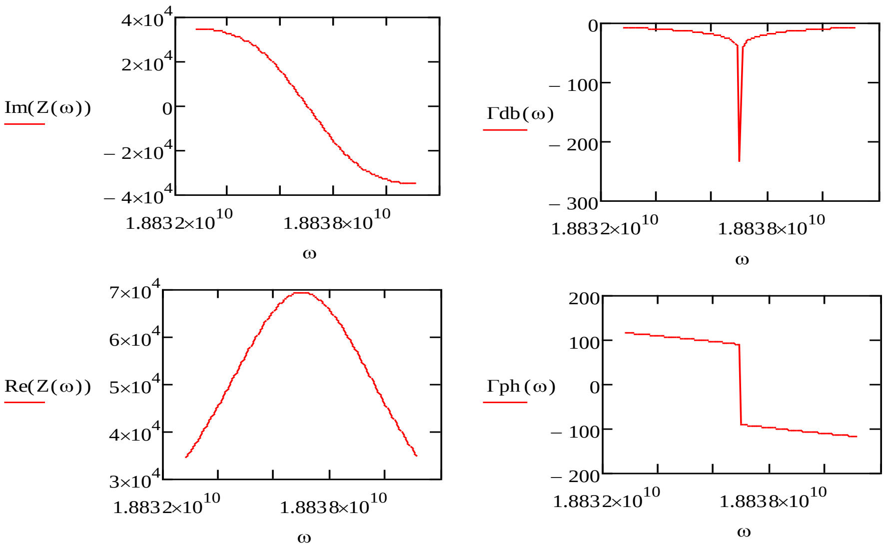
$\lambda/16$ L_{gap}=6.25 mm

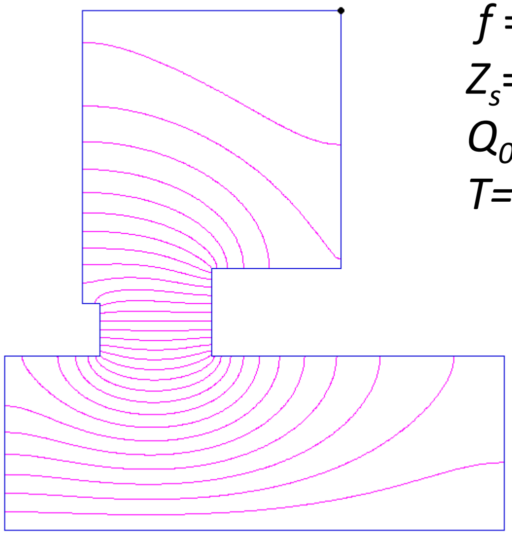
cylindrical section

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.
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.

System Design

Electromagnetic Model





f = 2997.5 MHz

Z_s=12.8 MΩm^{-1}

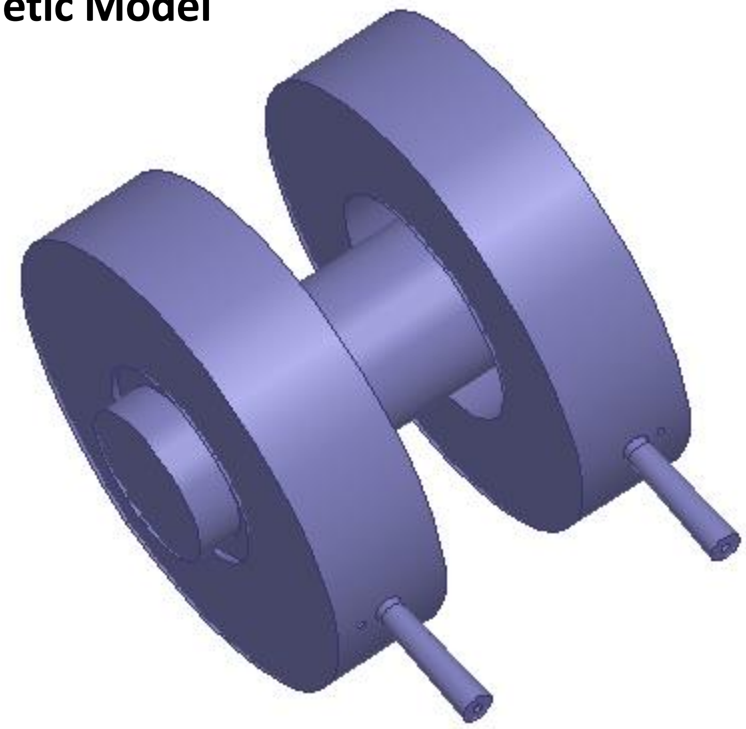
Q_0=3.4·10^3

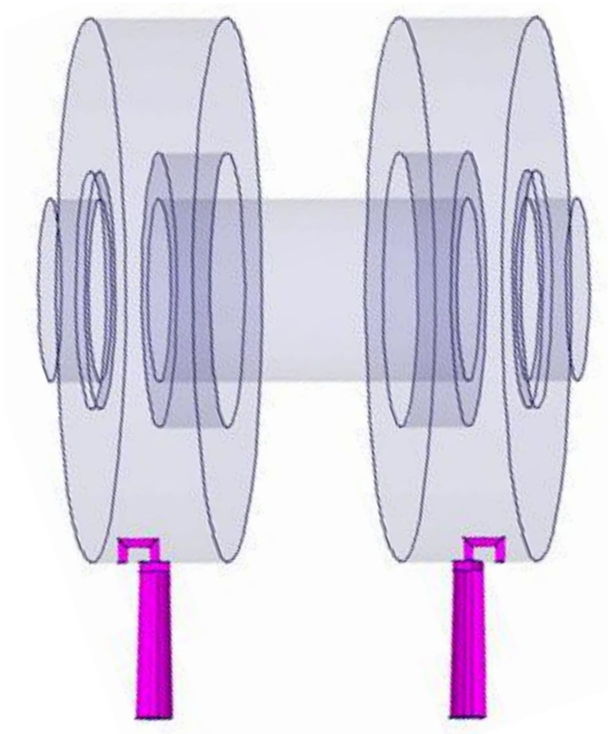
T=0.766.

After the analytical design a computational electromagnetic modeling using the finite elements method has been implemented. 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 MΩm^{-1} and a quality factor of Q_0=3.4·10^3 while the transit time factor is T=0.766. A complete electromagnetic modeling has been performed on HFSS version 15 of ANSYS.

System Design

Electromagnetic Model

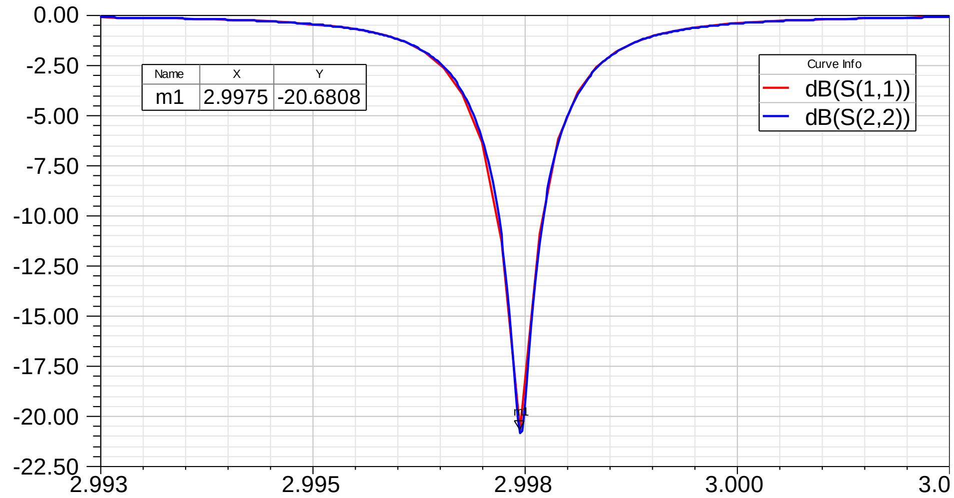


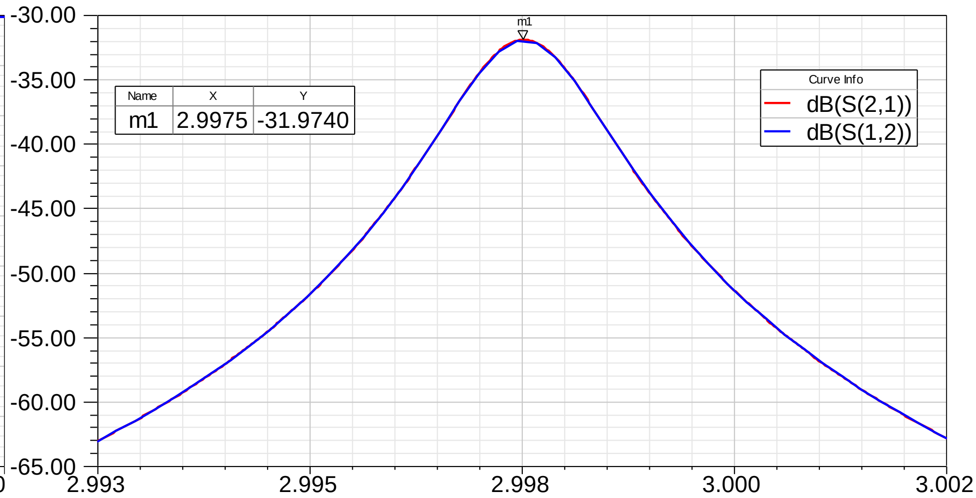


A complete electromagnetic modeling has been performed on HFSS version 15 of ANSYS. A rectangular magnetic loop have been employed for the power extraction. The profile of the loop, as well as the distance from the cavity lateral walls, have been chosen to obtain the critical coupling between the cavity 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.

System Design

Electromagnetic Model

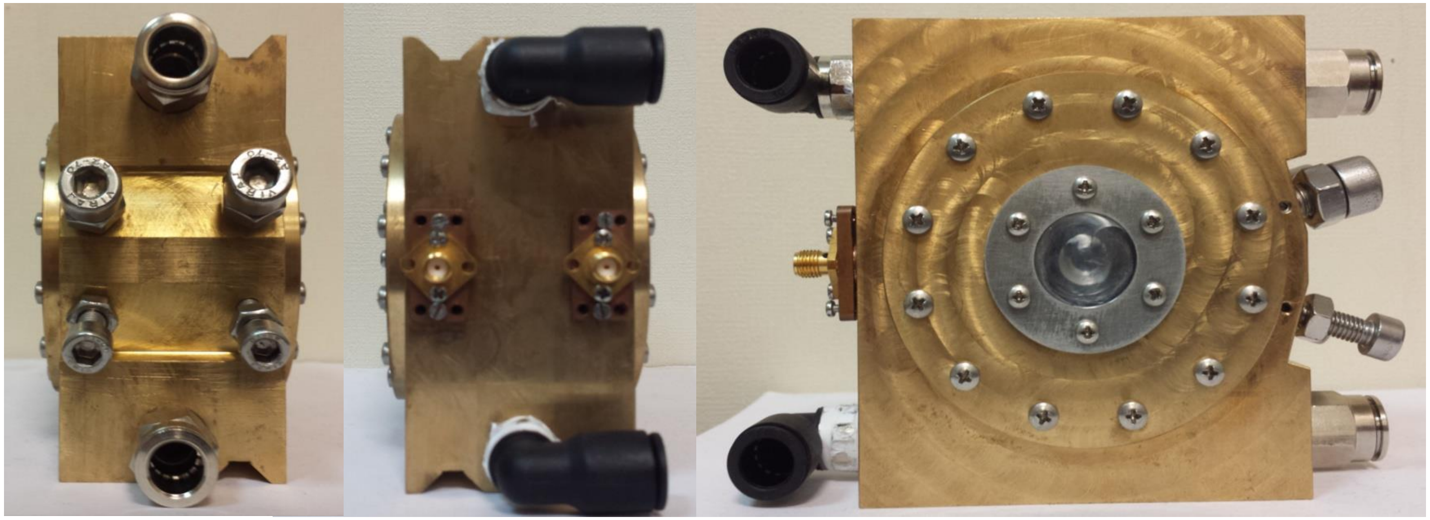




The proposed cavity to magnetic loop system ensures a maximum cross talk between the two channels of -32 dB and a return loss of 20.7 dB at the designed resonance.

Measurements

Prototype



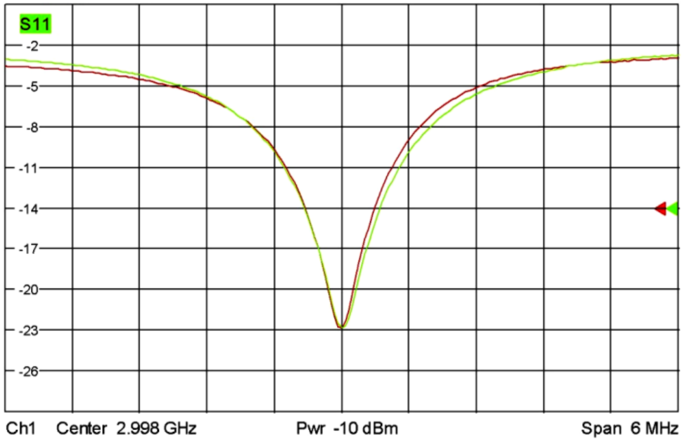
Cold measurements of scattering parameters and hot measurements of the dose deposition have been performed on the detector prototype. Since the detector output can be influenced by the temperature exposition, the cavity shares the thermostatation circuit of the LINAC where flowing controlled temperature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

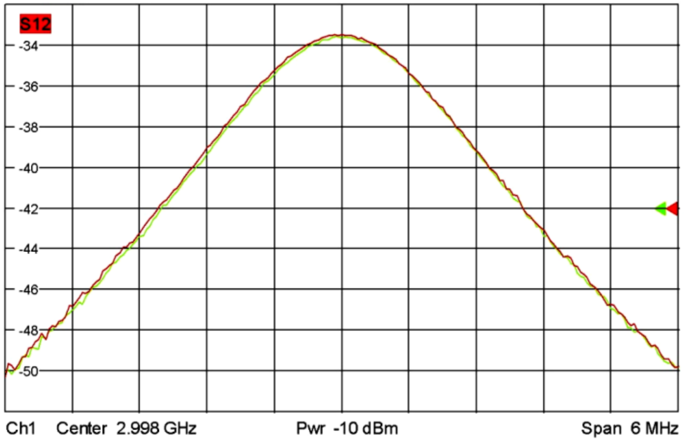
PIERS

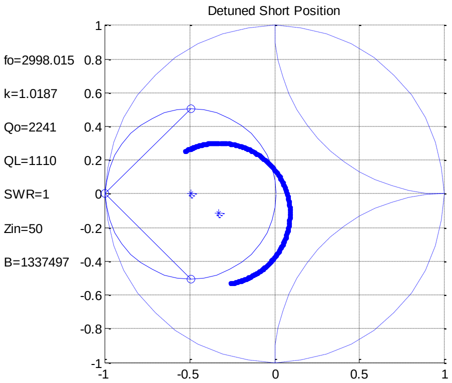
Measurements

UNIVERSITA' DEGLI STUDI DI ROMA Tor Vergata

Cold Measurements:



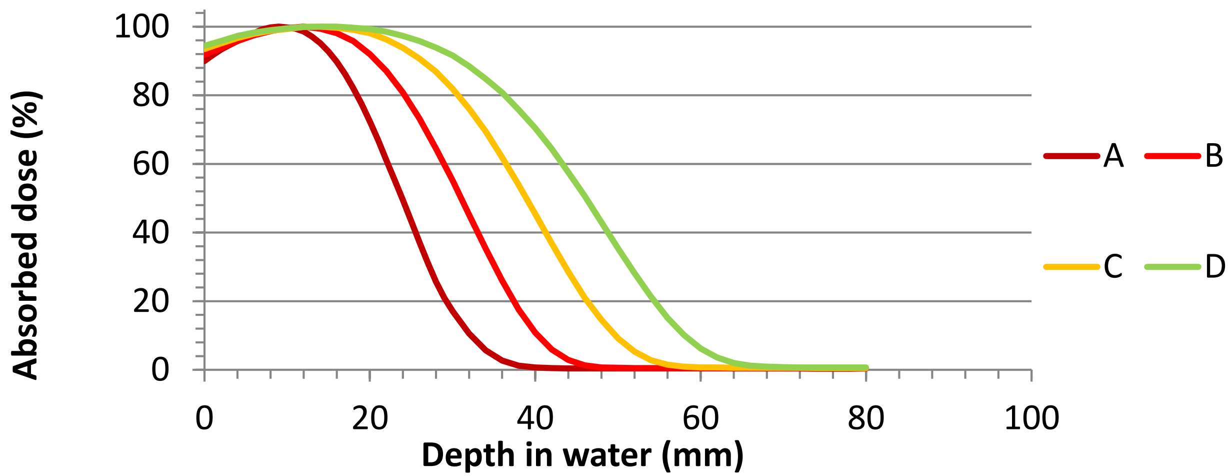




Measured reflection parameters in the frequency bandwidth have been exported from a Rohde and Schwarz ZVL 12 VNA and elaborated through a custom MATLAB code, computing the quality factor and the coupling factor by the detuned short position technique [8]. The device have shown a quality factor Q_0=2.25·10^3, a return loss *RL*=23 dB a cross talk between the two integrated cavities of *IL*= -34 dB and a Coupling Factor *k*=1.02, as described in Fig. 6, 7 and 8.

Measurements

Beam Energy and Dose Measurements



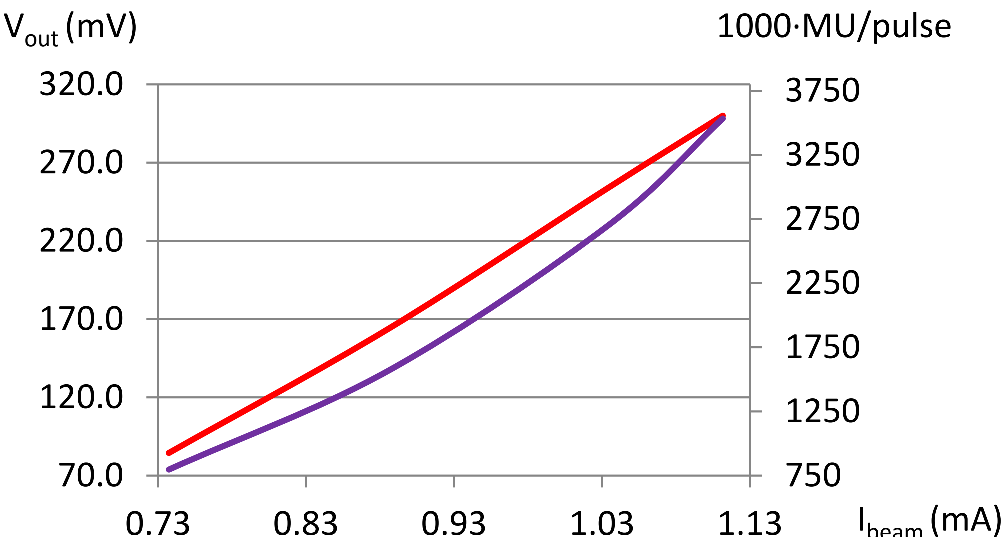
In order to asses quantitatively the improvement achieved, a direct measurement of the accelerated beam has been performed. The output current of the LINAC has been forwarded into the cavity observing the output voltage of the envelope detector. Radiation measurements have been performed on the LIAC-S® 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 τ=3.5μs and the pulse repetition frequency is f_{PRF}=10Hz. 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 mc² processing software [12] and reported in Fig. 9. The output measurements have shown a R_{50}=4.5 cm, corresponding to an average energy of about 10.5 MeV, as shown by the curve reported in Fig. 9.

PIERS

Measurements

UNIVERSITA' DEGLI STUDI DI ROMA TorVergata

Detector output Measurements



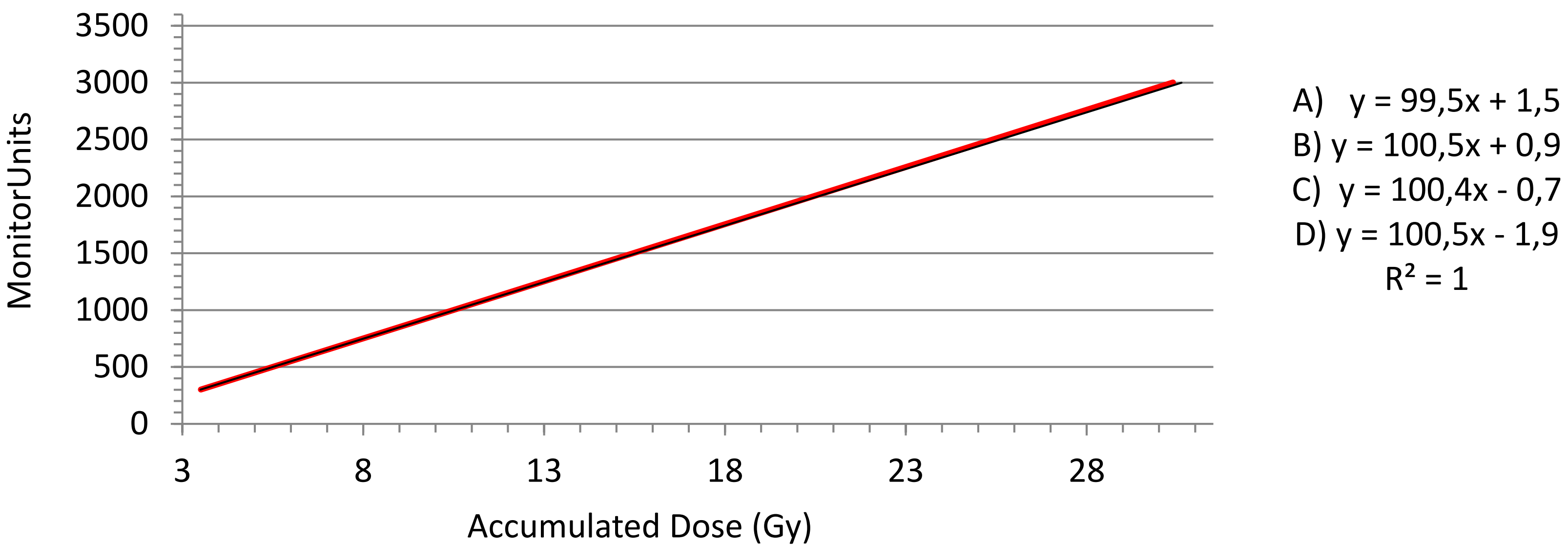
Energy Setting	Mean Energy [MeV]	Beam Current [mA]	Voltage Output [mV]	MU/ pulse
A	*5.5*	*0,74*	*84.5*	*0.797*
B	*7.1*	*0,90*	*164.0*	*1.570*
C	*9.0*	*1.03*	*253.5*	*2.695*
D	*10.5*	*1.11*	*300.0*	*3.534*

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, 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 is reported in Fig. 10. The linear behavior of the peak voltage output (V_{out}) and the linearizable behavior of the dose digital representation (MU/pulse) against the beam current can be noted.

Measurements

UNIVERSITA' DEGLI STUDI DI ROMA Tor Vergata

Detector output Measurements



The measurements 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.

PIERS

Conclusions

UNIVERSITA' DEGLI STUDI DI ROMA Tor Vergata

An investigation on the power energy injection in a resonator by electron stream has been proposed in this study. 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.

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] Università degli Studi di Roma "Tor Vergata", Department of Electronic Engineering,
[2] S.I.T. – Sordina IORT Technologies S.p.A.

Thank you for your kind attention

UNIVERSITA' DEGLI STUDI DI ROMA
TorVergata

TSC

EH Frontier
Expanding High-frequency Frontier

alberto.leggieri@uniroma2.it
www.ehfrontier.uniroma2.it
http://soiort.com

SIT

References

1. International Standard EN 60601-2-1 “Medical electrical equipment - Part 2-1: Particular requirements for the basic safety and essential performance of electron accelerators in the range 1 MeV to 50 MeV “, 3rd edition, International Electrotechnical Commission, 2009.
2. A. P. Turner, “Regulations, Standards and Guidelines for the Use of Medical Electron Linear Accelerators”, IEEE Transactions on Nuclear Science, Vol. NS-26, No. 1, 1979.
3. Uvarov, V.L. et Al., “A beam monitoring and calibration system for high-power electron LINACs”, Proceedings of the Particle Accelerator Conference, Vancouver, BC, 1997.
4. M. Ruf, S. Muller, S. Setzer and L. P. Schmidt; “Beam Position and Energy Monitoring in Compact
5. Linear Accelerators for Radiotherapy”, IEEE Transactions on Biomedical Engineering, Vol. 61, No. 2, 2014.
6. J.B. Rosenzweig, “Accelerator technology II: waveguides and cavities” in Fundamentals of Beam Physics, Oxford University Press, Oxford, 2003, pp. 183-193.
7. D.A. Goldberg and G.R. Lambertson, “Dynamic Devices a Primer on Pickups and Kickers”, pp.540-561.
8. S. Ramo, J. R. Whinnery, T. Van Duzer, “Resonant Cavities” in “Fields and Waves in Communication Electronics”, 3rd ed., New York, John Wiley & Sons, 1994, p. 303-310, 699-701,719-723.
9. A. Leggieri, D. Passi, G. Felici, S. De Stefano and F. Di Paolo, “Magnetron High Power System Design”, International Journal of Simulation System Science and technology, Vol. 16, 2015.
10. F.Di Paolo, “Resonant Elements” in “Networks and Devices Using Planar Transmission Lines”, CRC Press LLC, 2000, pp. 505-512.
11. S.I.T. S.p.A., LIAC-S® product description, Italy, 2013. Available: http://soiort.com
12. IAEA TRS 398 “Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water”, Vienna, December 2000.
13. PTW Freiburg GmbH, Mephysto Software Suite product description, Germany, 2012. Available: http://www.ptw.de/2082.html

UNIVERSITA' DEGLI STUDI DI ROMA
TorVergata

TSC

EH Frontier
Expanding High-frequency Frontier

XSIT