Tuned Window for Standing Wave Linear Accelerators

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Abstract— This paper proposes a dielectric window for Standing Wave Linear Accelerators (LINAC's) which can be tuned after brazing and welding, in order to compensate the electromagnetic alteration due to these production processes. This study investigates the in-frequency return loss behavior of the LINAC, in order to improve matching and transmitting conditions while maintaining the optimum coupling between LINAC and High Power Microwave (HPMW) source. Device design is single-frequency based and considers the dielectric window interface as an Input Matching Network (IMN) at the LINAC normal mode working frequency. Thus, design formulas are provided and Computer Aided Design techniques are proposed. A prototype has been made and tested by performing cold S-parameter measurements of a LINAC with the proposed dielectric window and with a traditional dielectric window. The proposed device offers more energy transport attitude over the traditional dielectric window, as shown by a return loss increase of 167% of the complete system.

1. INTRODUCTION

Dielectric windows are microwave devices which separates Ultra High Vacuum (UHV) inside vacuum devices (as vacuum tubes or LINAC) to the normal atmosphere in the transport waveguide (which connects the HPMW source), ensuring the microwave power transmission. These windows are made by a waveguide section, in which a dielectric plate is inserted. Typically, energy transport systems are based on rectangular waveguide (RWg) and, due to technological reason; dielectric windows are based on circular waveguide (CWg) sections. For these reasons, the most common kind of window is the pill-box type which consists of a CWg section, at which centre a dielectric (typically ceramic) cylindrical plate is enclosed. CWg section terminates on both sides to two CWg to RWg transitions. Vacuum windows also enable the RWg to be filled with SF6 for high-power transmission [1].

Several technological solutions can be adopted, as for example long pill-box type windows, with a very long longitudinal size [2], or with oversized diameter [3]. Usually, design of Radiofrequency (RF) structure can be achieved by using a circuit model and in all cases RF analysis, using high-frequency simulation codes, allows to optimize properties of the RF structure [2, 3]. For high power transfer, oversized circular plates are sometimes employed in order to reduce the RF field strength on the ceramic surface by increasing the diameter of its ceramic part compared to an ordinary pill-box type window [3]. Clearly this solution may result in an unwanted encumbrance.

This paper shows the design of a dielectric window for a Standing Wave LINAC to be employed in a medical mobile electron LINAC, dedicated to intra operative radiation therapy (IORT). The whole medical device is required to be as small and light as possible: Therefore, oversized and long structures are preferably avoided. After the manufacturing process, every LINAC may present a degradation of its electromagnetic characteristics, which inter alia may results in an increase of its reflection coefficient. By connecting to the LINAC input port a dielectric window made with a high insertion loss, these reflections reduce, but transmission efficiency decrease. Choosing a low insertion loss one, the transmission increases but multipath reflections through the LINAC may increase with respect to using a high insertion loss medium. In this paper, we propose a design technique to reduce these reflections. The Tuned Window consists of a low insertion loss pill-box type vacuum window with alumina ceramics connected to an input matching network (IMN).

In this paper a new formula for the calculation of the Pill-box radius is proposed and other formulas, taken from literature, are reported. In the LINAC technological production process, dielectric window is brazed or welded to the LINAC power coupler (LPC). During this factory step, the input characteristics of the system can be modified. In this paper, we propose to compensate such alteration by inserting a reactive IMN at the low pressure interface of the dielectric window.

Since the IMN is placed in the low pressure section and it can be inserted by screws without vacuum loss, it can be sized basing on the effective measured input parameters of the LINAC at the resonance. A design technique for the Tuned Window and a numerical method for optimization are proposed. Finally, a prototype is described.

2. THE TUNED WINDOW PRINCIPLE

Due to manufacturing production process, every LINAC has a proper normal mode working frequency, typically different to the others (up to 0.03% in band, respect to the design frequency). This phenomenon is due principally to the LINAC first brazing process, during which a very little, but not fully controllable, quantity of brazing alloy can penetrate into the resonant cavities. After the first brazing process, the LINAC is tuned. Such issue results in a LINAC own normal mode resonant frequency. However, global characteristics can be further degraded by following brazing or welding processes, as for example the dielectric window welding.

At the normal mode frequency of resonance, without the window, the LPC shows the external reflection coefficient $\rho_{\rm Ext}$ to the outside; $\rho_{\rm Ext}$ consists of the LINAC reflections coefficient ρ, transformed by the LPC. A pill-box dielectric window is connected to the LPC and $\rho_{\rm Ext}$ is transformed to $\rho'_{\rm in}$ by the window. This connection is performed by a brazing process.

After brazing, $\rho'_{\rm in}$ can be measured and an opportune IMN can be designed, to provide the right matching condition between the LPC and the HPMW source and ensuring the optimum reflection coefficient $\rho_{\rm Opt}$ shown by the LPC to the LINAC (Fig. 1).

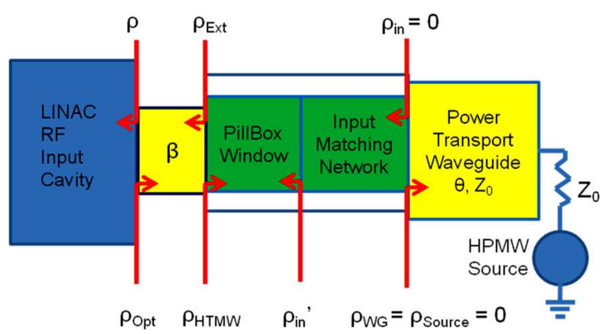

Figure 1: Devices disposition and reflections coefficients at the interfaces.

Due to technological production process, circular pill-box window has been chosen: A circular ceramic-disk was chosen for easy machining and brazing [3]. This dielectric plate, which has a metallization across its border, has been brazed to the waveguide section. The brazing process of the dielectric window is carried inside a vacuum oven with a maximum temperature of 780°C in which the component materials are welded by a CUSIL alloy of 28% Cu and 72% Ag. This temperature may deform the interface between the guide and the dielectric plate. Therefore, during this process, equally distributed forces have to be applied to the interface. The described operation is easier to perform, by using circular symmetry, then using a rectangular one. From an analysis on commercial available dielectric materials, the Alumina Al_2O_3 97.6% has been chosen, which provides the high transparency to the microwave in order to obtain very low insertion loss and great stress resistance.

After building and brazing or welding the pill-box window section to the LPC, reflection coefficient $\rho'_{\rm in}$ can be measured and the opportune values of the matching elements can be obtained. For this reason, the IMN has been made by an iris loaded waveguide, which is easily realizable, perfectly according to the exact normal mode working frequency of the brazed LINAC, on which the Tuned Window will be mounted. We show the design of the waveguide section and capacitive iris, a field simulation and a system optimization. After all, scattering parameters, cross sectional electric fields, transmitted and reflected waves are shown.

3. TUNED WINDOW DESIGN

Pill-box dielectric window was widely analyzed as a typical problem of waveguide junctions in microwave circuit in [1] and compact design formulas are described in [4] which can be employed to quickly design an initial dielectric window that can be optimized by adopting numerical codes. In this work we propose a design technique for a Pill-box dielectric window with good electromagnetic performance and the IMN for matching the LINAC. Such whole system is the Tuned Window.

3.1. Circular Waveguide Cross Section

Pill-box dielectric window consists principally of a RWg to CWg mirrored transitions [1]. Each discontinuity may insert mathematically infinite modes, but only the modes over cut off can propagate in the adjacent spaces. Other modes (evanescent modes) may store and release reactive energy. This phenomenon considerably reduces transmitting and reflecting performances. Such behavior can be avoided if, at the desired frequency, the wave does not view the discontinuity, so that the fundamental mode of the RWg leads only the fundamental mode of the CWg. The discontinuity will result locally in-frequency invisible to the wave, if the fundamental mode wavelength propagating into the RWg will remain the same in the CWg. The fundamental propagating mode in a RWg is the TE_{10} and into a CWg is the TE_{11}. Fundamental mode wavelengths into the RWg and the CWg are respectively expressed in (1) and (2) [5].

$$\lambda_{gR} = \frac{\lambda_0}{\sqrt{\epsilon_r - \frac{\lambda_0^2}{\lambda_{cR}^2}}}, \tag{1}$$

$$\lambda_{gC} = \frac{\lambda_0}{\sqrt{\epsilon_r - \frac{\lambda_0^2}{\lambda_{cC}^2}}} \tag{2}$$

where

$$\lambda_{cR} = 2a\sqrt{\varepsilon_r \mu_r}, \tag{3}$$

$$\lambda_{cC} = \frac{2\pi r}{p'_{11}\sqrt{\varepsilon_r \mu_r}} \tag{4}$$

and

$$\lambda_0 = \frac{c_0}{f} \tag{5}$$

is the wavelength on free space, ε_r is the dielectric constant and μ_r the magnetic permittivity of the medium which fills the waveguides, a is the long side of the RWg and r is the radius of the CWg. p'_{11} is the first zero of the one order Bessel function derivative ($p'_{11} = 1.841$), f the normal mode resonant frequency of the LINAC and c_0 is the speed of the light in the vacuum.

The pill-box window consists of a CWg section of length L, at which centre a dielectric disk is inserted and at which ends CWg to RWg transitions are placed. One RWg face is connected to the LINAC and the other is connected to the HPMW source. The CWg subsection on the LINAC side is in an UHV atmosphere and the subsection on the HPMW side is filled by dry air or SF6 at the typical pressure of about 2 Bar. Due to the similarity of the dielectric constants of vacuum, air and SF6, for simplicity we can approximate the two CWg sectors as filled by the same dielectric. Since the CWg is partially filled with alumina ceramic, this may be treated as equivalent to the CWg filled uniformly with a dielectric having effective relative permittivity ε'_r. For most of the high power pill-box windows, the value of ε'_r will vary between 1.0 and 2.0. A value of 1.5 is reasonable for ε'_r [4]. Magnetic permeability of these mediums has been considered as 1. Since the power transport system is based on RWg, we can consider λ_{gR} as a known value. By substituting (4) in (2), setting $\lambda_{gR} = \lambda_{gC}$ and replacing ε_r with ε'_r, we obtain the value of the CWg radius which ensures the local transparency of the discontinuity. The proposed formula is expressed in (6):

$$r = \frac{\lambda_0 p'_{11}}{2\pi\sqrt{1 - \frac{\lambda_0^2}{\varepsilon'_r \lambda_{gR}^2}}} \tag{6}$$

3.2. Dielectric Disk

In order to have high electromagnetic transmission by minimize the wave scattering due to the crystal atoms, high purity alumina can be employed as the dielectric medium for the disk interposed between the two CWg subsections.

Such disk should be designed at least with the minimum thickness which ensures the structural capacity to endure the direct stress σ applied from the atmosphere normal force F_n, avoiding breakdowns or significant deformations. According to [6], this direct stress corresponds to the pressure P which the dielectric cylindrical disk experiences on its area in contact to the UHV.

$$\sigma = \frac{F_n}{\pi r^2} = P \tag{7}$$

Dielectric medium mechanical characteristics are to be provided by the vendor and optimized according to the brazing facility expertise. Thickness t of the dielectric plate is to be optimized by using computer-aided design tool in order to maximize the microwave transmission efficiency of the dielectric window. Due to the waveguide pressurization adopted, the maximum pressure on the plate can be assumed to be less than 2 Bar. As high transparency medium for the dielectric plate, we have chosen alumina WESGO Ceramics type AL300, which is an Al_2O_3 97.6%. In order to employ a plate radius of about 30–40 mm, a good thickness in the above condition, should be around 2.5 mm.

3.3. Circular Waveguide Length

In order to transfer maximum of microwave power from rectangular to circular and then vice-versa for downward transmission, it is required that at the junction, impedance of the rectangular waveguide should match with the impedance of circular waveguide both in the input & output side. The junction is placed at the half of the CWg. From the junction, we can consider two CWg subsections of length L' given by (8). By considering the effective permittivity $\varepsilon'_r = 1.5$, according to [4], for impedance matching of rectangular and circular waveguide, we need to set wavelength of a single CWg section, loaded with this effective dielectric constant, to an opportune value, given by (9) in which a and b are respectively the long and the short side of the RWg cross section. Using standard transmission line theory on quarter wave length transformer for matching the length of the CWg subsections, L' can be written as in the (10) [4]:

$$L' = L/2 \tag{8}$$

$$\lambda'_{gC} = \frac{b}{0.816a}\lambda_{gR} \tag{9}$$

$$L' = \lambda'_{gC}/4 \tag{10}$$

3.4. Dimensioning and Numerical Optimization

For an S-Band LINAC operating at $f = 2998$ MHz and driven through a RWg WR284, which have $a = 72.14$ mm and $b = 34.04$ mm, by applying the (1) with $\varepsilon'_r = 1$ we obtain $\lambda_{gR} = 138.72$ mm and from the (5) we have $\lambda_0 = 100$ mm. From the (9) results that $\lambda'_{gC} = 80.17$ mm and by the (10) $L' = 20.04$ mm, so from the (8) the total length of the CWg is $L = 40.08$ mm. By applying (6) with $\varepsilon'_r = 1.5$ results in $r = 36$ mm.

The analytical design procedure, is a simplification of the real dimensioning problem, in which we have more difficulties given mostly from spatial distribution and complex value of dielectric constant. In fact, effective dielectric constant depends by the length of the CWg, resulting in a recursive problem, thus we need to set a value of ε'_r, and a numeric optimization is mandatory. Length L of circular waveguide sections as well as thickness t of dielectric plate can be optimized by an electromagnetic (EM) simulation. For this operation we have chosen Comsol Multiphysics® (Version 4.0), which is based on the Finite Element Method (FEM). By using this software, the simulation can be extended to a Thermo-structural analysis, in order to compute the electromagnetic behavior modifications due to the thermo mechanical induced conditions, as described in [7].

The aim of the simulation is to search the optimum values of L and t which provide the minimum reflection parameter and the maximum transmission parameter at the two ports of the Pill-box Window. The EM simulation has been performed setting two vacuum circular sections of radius r and variable length L, which enclose the dielectric plate, as previously defined. Two standard RWg WR284 sections are connected at the open faces of the CWg section. All the waveguide boundaries are made of copper with an Impedance Boundary Condition which considers the field penetration inside the conductor, according to its skin depth. At the RWg's external faces, TE ports are placed. The solution is computed by a Stationary solver at the normal mode LINAC operative frequency f, by sweeping the length L and the thickness t and calculating the scattering parameters at two ports. The simulation has been initially set with the dielectric window values analytically calculated above, and an Al_2O_3 97.6% plate of thickness $t = 2.5$ mm. This Alumina presents a dielectric constant of $\varepsilon_r = 9.0$ in S band, which in the simplified analytical dimensioning has not been considered properly. By introducing this value in a numeric computation, we obtained an accurate dimensioning of the structure.

The optimization has shown an optimum length of the circular sections $L = 27$ mm and optimal dielectric plate thickness $t = 2.4$ mm. With such values, an EM simulation has been performed in the operative range of the HPMW source, according to the normal mode operative frequency variation due to the LINAC cavities variable thermal conditions, which are in the range of 2993–3003 MHz. In this range, scattering parameters have been evaluated: The maximum reflection parameter is $|S_{11}|_{\text{dB}} = -34.5$ dB and the minimum transmission parameter is $|S_{21}|_{\text{dB}} = -0.0044$ dB. As we expects, by exciting the TE_{10} mode of the RWg, in the cylindrical section the propagating mode is the TE_{11} of the CWg, as shown in Fig. 2.

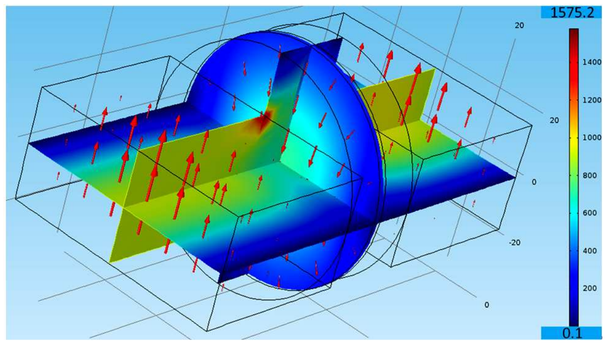

Figure 2: Geometry and electric field (V/m) distribution in the RWg and dielectric window on bisecting planes @ 2998 MHz (RWg TE_{10} and CWg TE_{11}) for $L = 27$ mm with $t = 2.4$ mm.

3.5. Input Matching Network

The aim of inserting this network is to compensate the various alterations of the electromagnetic device characteristics due to the brazing and welding fabrication processes. Various matching strategies for microwave devices are available in literature and can be applied to such design [8]. This network will be realized through a RWg section loaded by an iris element earned in a flanged parker gasket. Such IMN can be inserted in the normal atmosphere interface of the window, between the RWg flanges of the dielectric window and the flanges of the power WG.

In order to physically realize the dielectric window, the CWg sections are welded at both the two interfaces: one (at the UHV side) welded to the LINAC and the other (at the normal atmosphere side) to a RWg flange. At this flange the transport RWg will be connected by screws and the reflection coefficient ρ'_{in} can be measured at the normal mode resonant frequency of the LINAC. In order to match the entire structure, a capacitive/inductive window can be placed at the input section of the structure.

Unfortunately, the complexity of the structure produces a coupling between the evanescent and propagating modes that makes very difficult to obtain a simple formula for the choice of the geometry of the window, like those discussed in [9]. Hence, more complex models based on equivalent circuits that take into account the presence of evanescent accessible modes [10, 11] must be used. The matching window has been implemented by a capacitive iris (see Fig. 3) realized in a Parker gasket with $d = 21.7$ mm and $t = 3.3$ mm (see Fig. 4).

4. PROTOTYPE MEASUREMENTS AND COMPARISONS

The Tuned Window has been simulated in the Department of Electronic Engineering of the University of Rome "Tor Vergata", realized in T.S.C. S.r.l. factory and gently tested in the RF department of S.I.T. S.p.A.

The circular section of the window is inserted between two steel slabs. Each slab has, at the center, a rectangular hole of 72.14 mm × 34.04 mm which represents the CWg to RWg transition. Due to technological production reasons, the steel slab in the UHV side has 6 mm of thickness and the other one, on the normal pressure side, is 16 mm deep, at which end the iris has been inserted. The iris has been realized in the internal profile of a RWg WR284 Parker gasket with 3 mm of thickness. Iris is connected to the remaining structure by the typical ten WR284's screws. This solution allows to insert the iris after brazing or welding the UHV side of the window without any other welding process.

The LINAC reflection coefficient, moved by the window, ρ'_{in} has been measured by considering the modification due to the welding process. The Tuned Window prototype is made using the following materials: Oxygen Free High Conductivity (OFHC) 99.99% copper for the circular waveguide section and iris, AISI316L steel for the CWg to RWg transitions and WESGO Ceramics AL300® 97.6% Alumina for the dielectric disk. The prototype of the Pill-box Window without IMN has been tested using an Agilent E5071B VNA in the operative range of 2993–3003 MHz. Setup is depicted in Fig. 5. Measured and simulated scattering parameters are reported in Fig. 6. In this range, the maximum measured reflection parameter have $|S_{11}|_{\mathrm{dB}} = -35.2\,\mathrm{dB}$ and the average transmission parameter is $|S_{21}|_{\mathrm{dB}} = -0.003\,\mathrm{dB}$. Such window will operate in transmitting a pulsed power of 2.5 MW with pulse duration of 4 µs and repetition frequency of 5 Hz.

The Pill-box window shown in this paper is a traditional dielectric window with high trans-

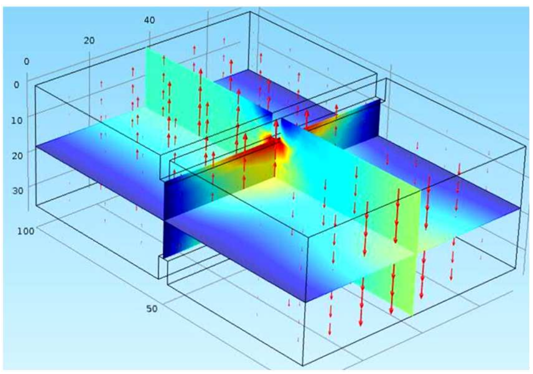

Figure 3: Capacitive iris structure on the RWg sector and fundamental mode (TE_{10}) electric field distribution on bisecting planes at 2998 MHz.

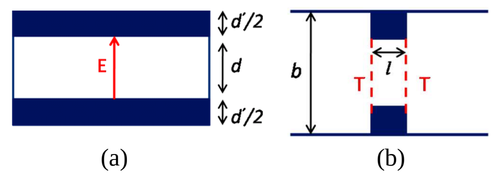

Figure 4: Capacitive iris: (a) longitudinal section, and (b) front views.

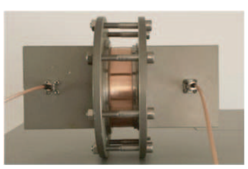

Figure 5: The pill-box window under test between two RWg launchers.

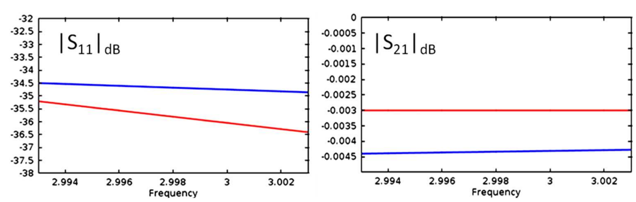

Figure 6: Simulated (blue) and measured (red) scattering parameters of the designed pill-box window without IMN. S_{11} and S_{21} in dB (vertical axis), versus frequency in GHz (horizontal axis).

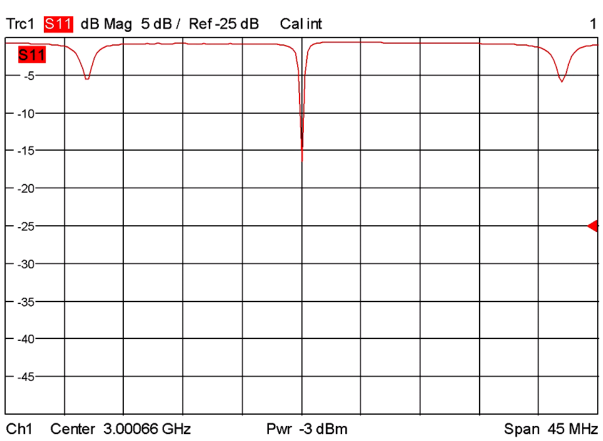

Figure 7: Measured reflection scattering parameter of the LINAC with only the traditional pill-box window. $|S_{11}|$ dB (vertical axis) versus frequency (horizontal axis) from 2.978 GHz to 3.023 GHz: The return loss is 16.5 dB.

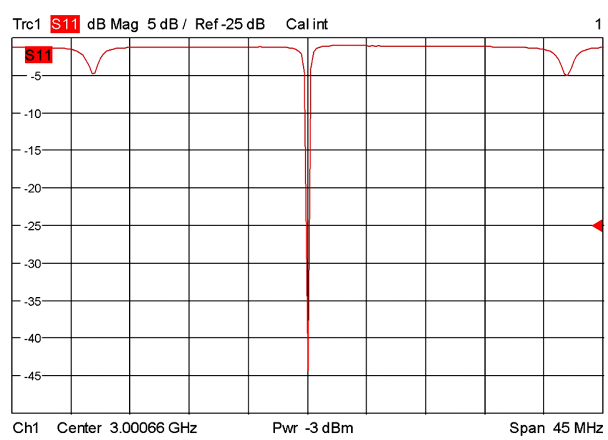

Figure 8: Measured reflection scattering parameter of the LINAC with the whole tuned window. $|S_{11}|$ dB (vertical axis) versus frequency (horizontal axis) from 2.978 GHz to 3.023 GHz: The return loss is 44 dB.

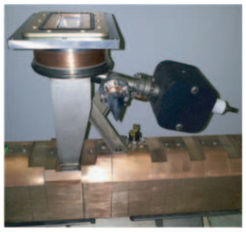

Figure 9: Side view of the tuned window on the LINAC.

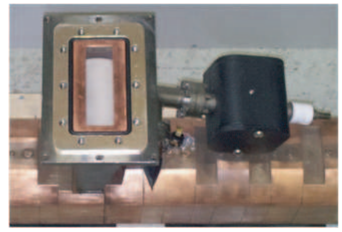

Figure 10: Top view of the tuned window on the LINAC.

parency performances, comparable to the windows described in the already present literature [2, 4].

The Tuned Window prototype has been designed for an R.F. standing wave side coupled LINAC of the IORT dedicated mobile accelerator NOVAC 111®, described in [12], working a 2.998 MHz in $\pi/2$ mode. Cold Measurements of the prototype have been performed by using a Rhode & Swartz ZVL VNA. The input characteristic of this LINAC has been measured without dielectric window in normal atmosphere and with the only traditional pill-box dielectric window in UHV. In both cases, with negligible differences, it has shown quality factor $Q_0 = 12200$, a Coupling Factor $k = 1.35$ and a return loss of 16.5 dB, as described in Fig. 7. By using the complete Tuned Window we have obtained a return loss of 44.0 dB, as shown in Fig. 8, while maintaining a good value of $Q_0 = 12140$ and improving $k = 0.99$. The Tuned Window, inserted on the NOVAC 11® LINAC, is shown in Figs. 9 and 10.

5. CONCLUSIONS

LINAC input characteristic has been investigated, in particular with the need to separate UHV inside the accelerating structure to the normal atmosphere in the transport waveguide, while maintaining the better transparency to electromagnetic waves. In order to ensure vacuum shielding and transparency to the microwave, an useful solution has been found. A particular dielectric window which includes a waveguide iris-based matching network has been designed and built. Design formulas have been provided and computer aided design techniques have been proposed.

An after brazing global improvement of the accelerator figures of merit is possible by employing the proposed device.

With the Tuned Window inserted on a standing wave electron LINAC we have obtained several advantages over the traditional dielectric window, as it has been documented by several measurements on the NOVAC 11® LINAC.

Measurements of the reflection parameter at the LINAC input port, with the Tuned Window, have shown a return loss increase of 167%, from a return loss of 16.5 dB to a return loss of 44.0 dB over the LINAC with a traditional dielectric window. Such resulting structure is much better matched and coupled to the generator, with respect to the LINAC with a traditional window. This improvement is possible since the iris was designed for the specific LINAC, by considering its reflection coefficient at the working frequency measured after the brazing processes. However, we noted that the same iris can be employed to match several other similar LINACs with good results. This improvement allows to use lighter and cheaper insulators or circulators in the Radiofrequency power transmission chain, and a bit lower power sources. This solution can offer a decrease of power line size, weight and cost.

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