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Development of a Novel RF Waveguide Vacuum Valve

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Abstract

The development of a novel rf waveguide vacuum valve is presented. The rf design is based on the use of TE0n modes of circular waveguides. In the device, the TE01 mode at the input is converted into a mixture of several TE0n modes which provide low-loss rf power transmission across the vacuum valve gap, these modes are then converted back into the TE01 mode at the output. There are a number of advantages associated with the absence of surface fields in the region of the valve:

- Possibility to use commercially available vacuum valves equipped with two specially designed mode converter sections.
- No necessity for an rf contact between these two sections.
- Increased potential for high power rf transmission.

This technology can be used for all frequencies for which vacuum waveguides are used. In rectangular waveguides, mode converters from the operating mode into the TE01 mode and back again are necessary. Experimental results for the 30 GHz valves developed for the CLIC Test Facility 3 (CTF3) are presented showing in particular that the rf power transmission losses are below 1%. The rf waveguide vacuum valve installed in CTF3 has been tested with high power and is now in routine operation at power levels up to 40 MW and pulse length of 70 ns.

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DEVELOPMENT OF A NOVEL RF WAVEGUIDE VACUUM VALVE

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Abstract

The development of a novel rf waveguide vacuum valve is presented. The rf design is based on the use of TE_{0n} modes of circular waveguides. In the device, the TE_{01} mode at the input is converted into a mixture of several TE_{0n} modes which provide low-loss rf power transmission across the vacuum valve gap, these modes are then converted back into the TE_{01} mode at the output. There are a number of advantages associated with the absence of surface fields in the region of the valve:

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INTRODUCTION

The device described in this paper allows vacuum to be maintained on one side of the valve and atmospheric (or any other) pressure on the other side of the valve when it is closed, while providing low-loss transmission of rf power when the valve is open. It is based on the use of a standard commercial vacuum valve equipped with two specially designed rf mode converter sections.

The device described above has two areas of application, it can be used in transmission lines operating with the TE_{01} circular waveguide mode which by itself is an attractive solution for a high-power rf transmission line because of low ohmic losses and the absence of a surface electric field (see, for example Refs. [1,2]). It can also be used in standard rectangular waveguide transmission lines by using TE_{10} rectangular waveguide to TE_{01} circular waveguide mode converters.

PRINCIPLES OF OPERATION

The device is based on the use of TE_{0n}-modes of a circular waveguide to guide rf power through the valve. This kind of mode has zero electric field on the waveguide surface. Moreover, only the axial component of the magnetic field is non-zero on the waveguide surface which means that the surface rf current has only an azimuthal component thus avoiding the necessity of ensuring axial electric contact.

Single-mode vacuum valve

Because of these properties, propagation of the TE_{01}-mode along a circular waveguide is not perturbed by an azimuthal slot of size d at low frequency, i. e. if

$$d \ll \lambda, \quad (1)$$

where λ is the free space wavelength. Hence a single mode can be used to transmit rf power across a slot housing a vacuum gate valve which separates upstream and downstream waveguide sections when the valve is closed (see Fig. 1). When the valve is open the slot produces two types of rf losses. The first one is due to reflection from the slot. The second one is due to coupling of the rf from the waveguide to the vacuum valve housing through the slot. Both types of losses are small if condition (1) holds. The first type of loss can be further reduced by making another slot identical to the first one and separated by approximately a quarter of the waveguide wavelength in order to cancel reflections from the two slots. The second type of loss depends only on slot size d and is the main factor limiting the transmission performance and/or frequency range of the device.

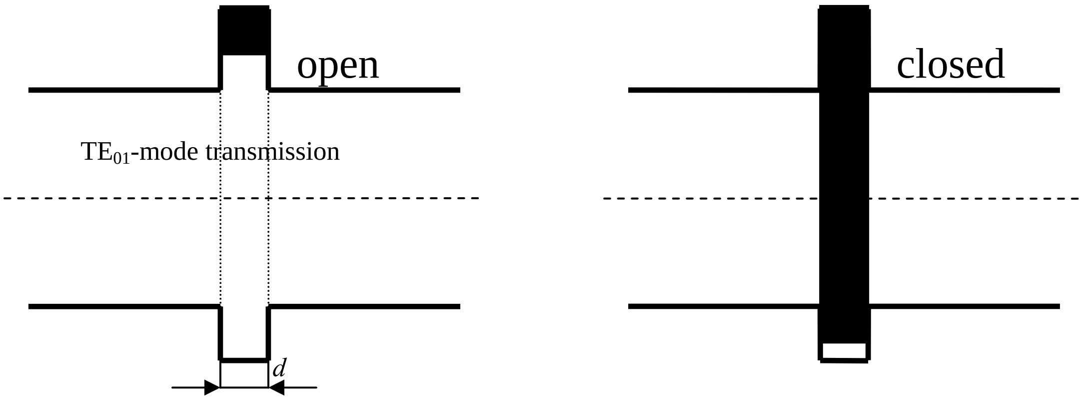

Figure 1: Schematic drawing of the single TE_{01}-mode vacuum valve for a circular waveguide showing the open (left) and closed (right) positions of the vacuum valve.

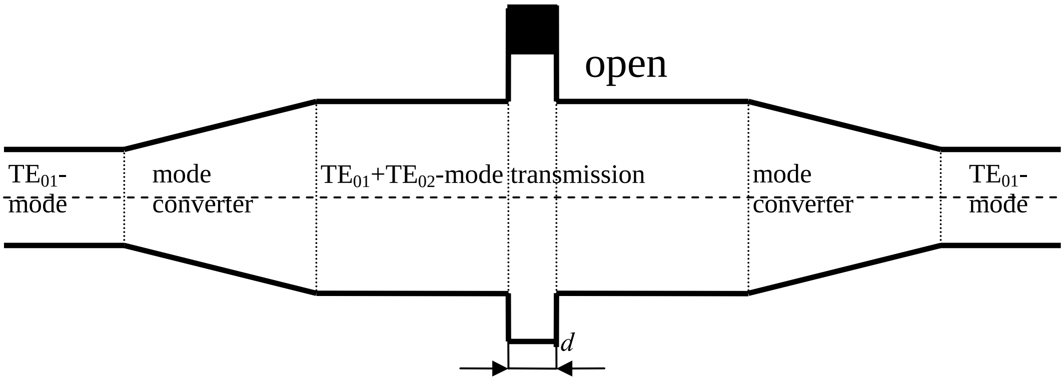

Figure 2: Schematic drawing of dual-mode vacuum valve for a circular waveguide is shown in the open position.

Dual-mode vacuum valve

At higher frequencies, condition (1) cannot be satisfied and corresponds to the regime when

$$d \sim \lambda. \quad (2)$$

In this case, the TE_{01}-mode is strongly coupled to the slot and the transmission losses of the single mode are high. Mixing two (TE_{01} and TE_{02}) modes reduces the transmission losses to an acceptable level. To do this, two mode converter sections are introduced on both sides of the slot as shown in Fig. 2. These sections convert the incoming TE_{01}-mode into a mixture of TE_{01} and TE_{02} modes with a certain amplitude and phase relation, which minimizes the surface magnetic field in the region of the slot. In this case, the electromagnetic field of the $TE_{01}$and TE_{02} mode mixture is concentrated on the axis and the coupling to the slot is small.

Quasi-optical vacuum valve

At even higher frequencies condition (2) cannot be satisfied. Hence we are in the quasi-optical regime when

$$d >> \lambda. \quad (3)$$

and several TE_{0n}-modes, where n=1,2,3,…, must be used to minimize transmission losses as explained in the previous subsection. Using geometrical optic language which is probably more appropriate in this case, the transmitted power must be focused on the axis to pass through the valve without diffraction on the slot.

COMPACT DUAL-MODE VALVE

RF design of a 30 GHz dual-mode vacuum valve is presented in Fig. 3. Given the diameter of the input waveguide and the diameter of the vacuum valve aperture the rf design is fixed if the following requirements are met simultaneously: there are no reflections from mode converter sections and the TE_{01} and TE_{02} modes have right amplitude and phase to set the surface magnetic field to zero at the position of the vacuum valve. This results in a rather compact design: the overall length is about 100 mm, the diameter of the central waveguide section which contains the TE_{01}+TE_{02} mode mixture is 30 mm.

Two symmetric mode converter sections have been made of stainless steel in order to eliminate brazing and simplify the fabrication procedure of the first prototype. The final assembly is shown in Fig. 4, where one can see the standard commercial DN40 vacuum valve with pneumatic actuator and two mode converter section on both sides. The transmission measurements of the fully assembled valve show losses of about -0.1dB. This is in a very good agreement with the simulations predicting losses of -0.082dB for the stainless steel mode converter. These losses consist of two contributions: diffraction losses of -0.033dB and ohmic losses of -0.049dB. The second contribution can be significantly reduced by using copper instead of stainless steel. In this case, the power losses will be below 1%.

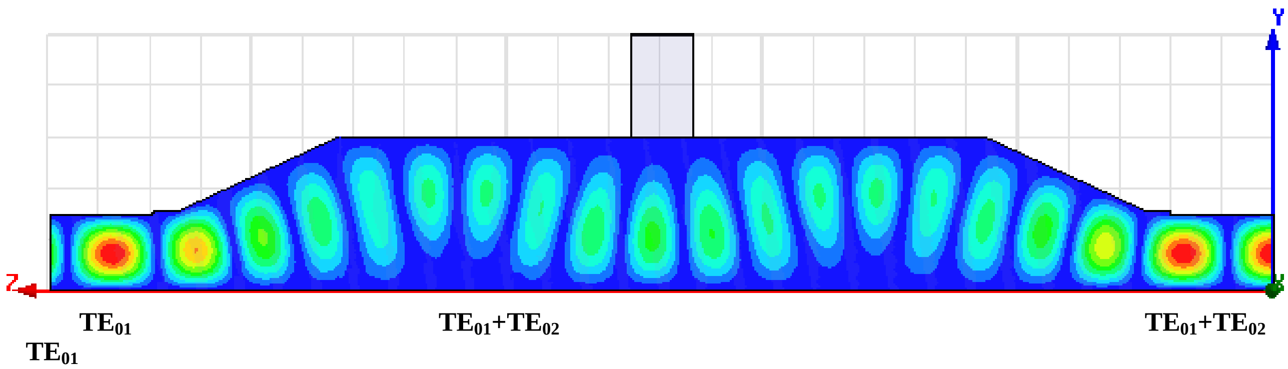

Figure 3: Instantaneous distribution of electric field in the 30 GHz dual-mode vacuum valve. Focusing of the electro-magnetic fields at the position of the valve is demonstrated.

Figure 4: Fully assembled 30 GHz compact dual-mode rf waveguide vacuum valve.

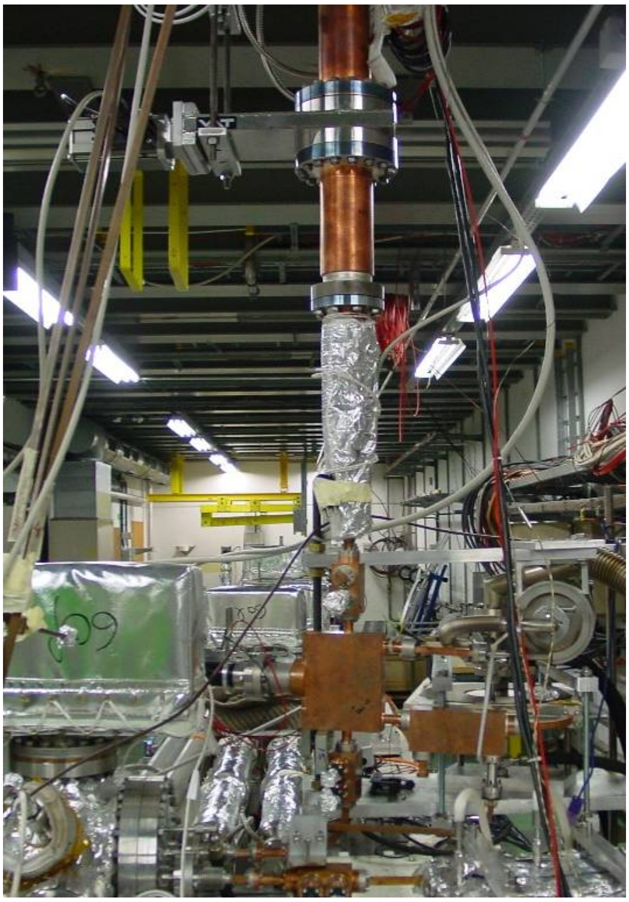

Figure 5: Quasi-optical rf waveguide vacuum valve, installed at the down-stream end of the CTF3 high-power transmission line before the 30 GHz test stand, is shown at the top. The test stand waveguide network and accelerating structure vacuum tank are also visible at the bottom.

QUASI-OPTICAL VALVE FOR CTF3

One of the aims of CTF3 is to generate 30 GHz rf power for CLIC accelerating structure tests [3]. CTF3 has a specially designed Power Extraction and Transfer Structure (PETS) which generates rf power, and a 17 m long high-power transmission line [1] which guides the power to the 30 GHz test stand. To separate the vacuum of CTF3 PETS and the test stand a quasi-optical vacuum valve has been designed. Since the input and output aperture and the length of the fully assembled valve are the same as the standard half meter long waveguide section which is a building block of the high-power transmission line, it can be installed at any position by replacing one section by the valve. Rf design of the mode converters for the quasi-optical valve is similar to the rf design of the mode converter sections of miter bends used in a high-power transmission line [1].

The quasi-optical rf waveguide vacuum valve has been assembled, measured and installed in CTF3 at the down-stream end of the high-power transmission line. Fig. 5 shows the 30 GHz test stand with the valve installed right above the test stand. The measurements show that only about 1% of power is lost in the valve mainly due to diffraction. This is very good result compared to the other high-power high-frequency rf components. The valve has been tested with high power. It is now in routine operation at power levels up to 40 MW and pulse length of 70 ns. The power and pulse length are limited by the structure under test and not by the valve or any other rf component.

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