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DESIGN AND HIGH POWER MEASUREMENTS OF A 3 GHZ ROTARY JOINT FOR MEDICAL APPLICATIONS

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Abstract

The TUrning LInac for Protontherapy (TULIP) project requires the transport of RF power from modulator/klystron systems at rest on the floor to the linac structures mounted on a rotating gantry, via a waveguide system that can operate over a range of angles of rotation. A waveguide rotary joint capable of transporting RF power at 3 GHz and up to 20 MW has been designed and built in collaboration between TERA Foundation, CERN Beams and CERN Engineering Departments. A high-power test of the prototype has been performed at the CLIC Test Facility (CTF3), at CERN. The design and the results of the tests are reported in this article.

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Contents

1. Introduction

The medical linac of the TULIP project [1] requires the transport of RF power at different angles of rotation between the modulator/klystron systems at rest and the linac structures mounted on the rotating gantry. 3 GHz power of 15 MW per linac structure is required to obtain 50 MV/m accelerating gradient, which is the target in novel accelerating structures envisaged for the TULIP linac [2]. The high gradient reduces the overall size of the facility. The rotary joint (RJ) should be capable to transport such high power without major losses and without phase shifts over the rotation range. Another very important requirement for such application is the compactness of the system. All the rotary joints must fit within the rotation axis of the gantry structure as shown in Fig. 1 and therefore need to be very compact in the longitudinal direction.

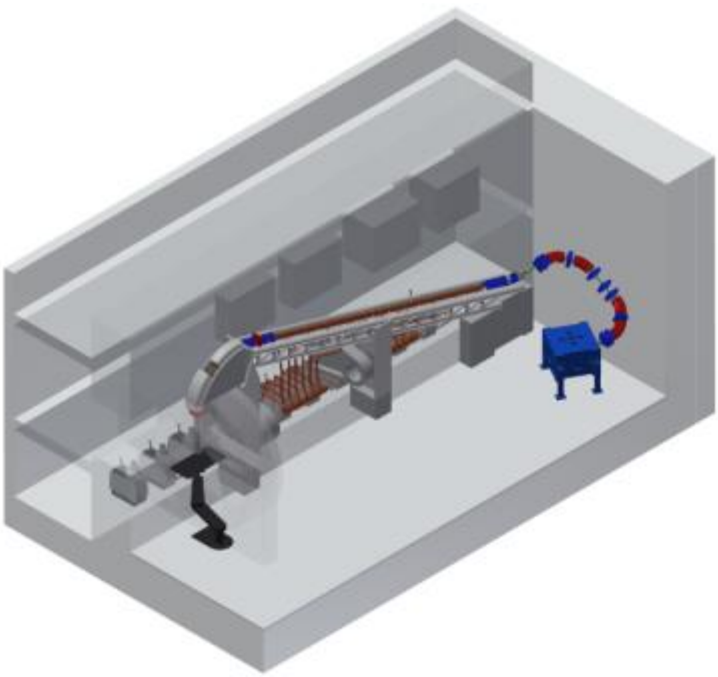

Figure 1: Artistic view of TULIP, a single-room facility for protontherapy based on linac technology.

2. Rotary joint design and manufacturing

The design of the RJ for TULIP is based on the conversion from rectangular H-type waveguide to circular waveguide and then back to rectangular. The conversion is made in double choked mode converters from rectangular TE_{10} mode to circular TM_{01} mode.

An initial design was based on a mode converter from rectangular to circular polarization added after an H-type 90° bend. This design targeted C-band operations and was 59 cm long. A new design, with a compact H_{10} to H_{11} 90° bend was developed in order to reduce the space occupied when later considering S-band. With the second design the space needed for each rotator was of 38 cm. Finally a third design based on CLIC accelerating structure type mode converter from H_{10} to E_{01} mode has been realized. The last design is the most compact and occupies only 14 cm. The three C-band designs are shown in Fig. 2.

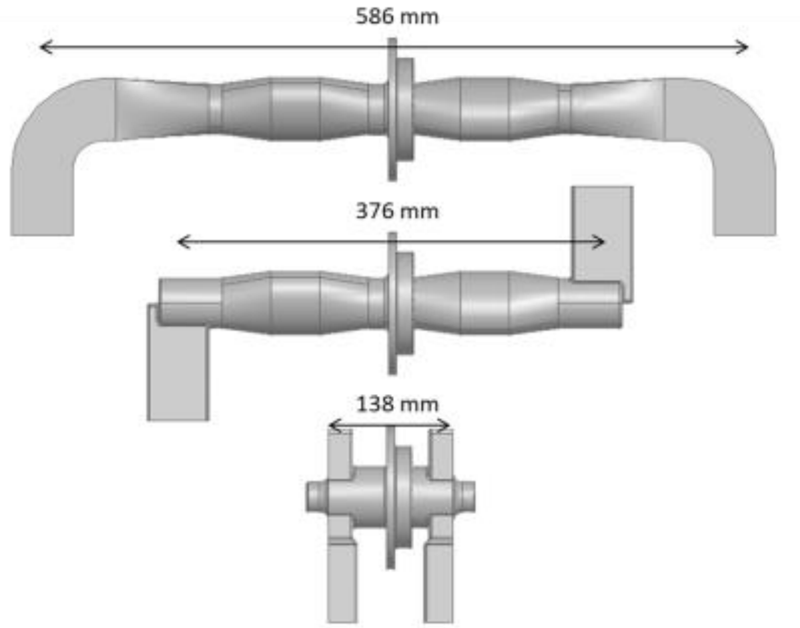

Figure 2: Three different solutions proposed for the RF rotary joint. The models are for C-band frequency. The third type has been chosen, being the most compact on the longitudinal plane.

The last design offers a compact solution for its scaling to S-band, which would almost double the size of the device since the space occupied by the RF joints is inversely proportional to the RF frequency. In addition, another advantage of this design is the fact that the output RF phase does not depend on the rotating angle.

The mode converters used in the design are similar to those used in other applications [3]. However here the waveguide system must rotate, which could influence the high-gradient performance. In order to test the high power behaviour of the device, a prototype has been designed at S-band to be connected to standard WR284 waveguides equipped with LIL flanges. The RJ body consists of four components: two sections of circular waveguides which can rotate with respect to each other and two end plates brazed to the circular waveguides (see Fig. 3). The final assembly has a diameter of about 40 cm and weighs 50 kg. The RJ parts have been manufactured at CERN central workshop. The brazing has been performed at Body-cote (Annecy - France). The vacuum tightness of the full assembly is ensured by two Fluorocarbon elastomer (FKM 75.16-04) o-ring placed between the two sections of circular waveguide. The possibility of operating the RJ under vacuum rather than with SF6 is also foreseen as long term solution. This would simplify the operation in a hospital-based environment and also reduce the issues related to the use of SF6, from a regulatory point of view. Final vacuum leak test has been performed at CERN with Helium leak detector and no leaks were detected.

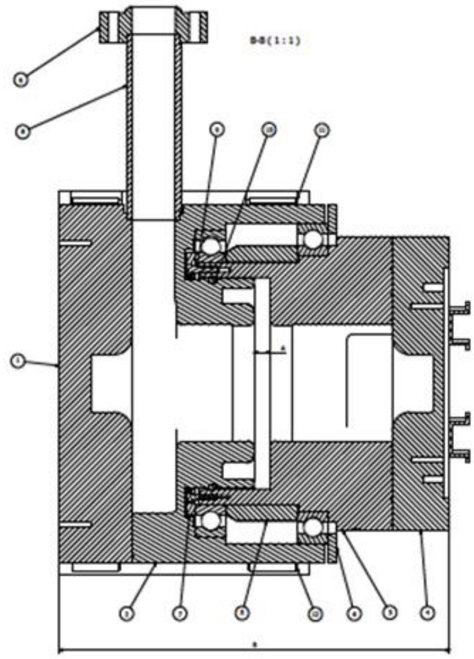

Figure 3: Section view of the rotary joint.

3. Low power measurements

The RF properties of the RJ have been characterized at low power with a vector network analyser (Rhode&Schwarz model ZVA-24). Complex scattering parameters have been measured at different rotation angles. A comparison of the expected and measured amplitude of the S11 parameter is reported in Fig. 4. The measured reflection is below -30 dB for all angles and is in good agreement with the design values.

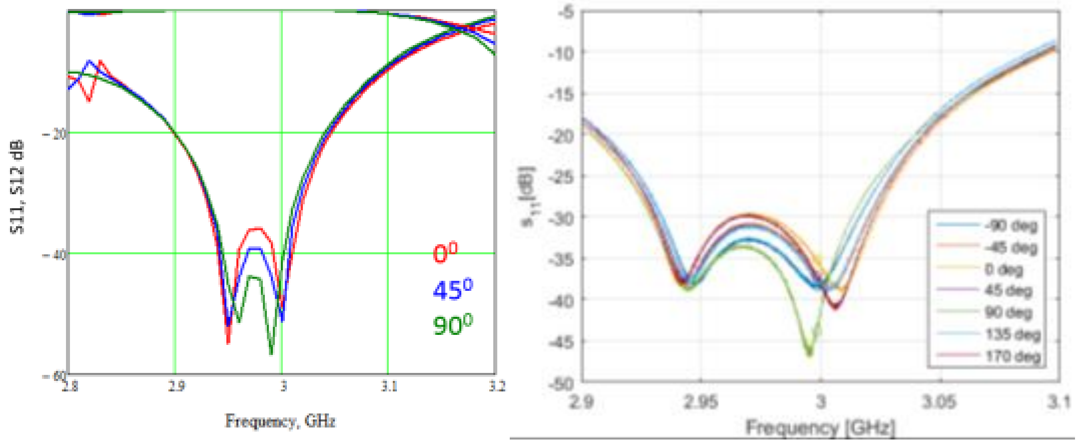

Figure 4: Expected S11 parameters from simulations for three rotation angles (left) and measured S11 parameters (right).

The phase of the S21 parameter for different angular position of the RJ is shown in Fig. 5. The measured data at the central frequency of 2.9985 GHz are constant within ± 0.5 deg.

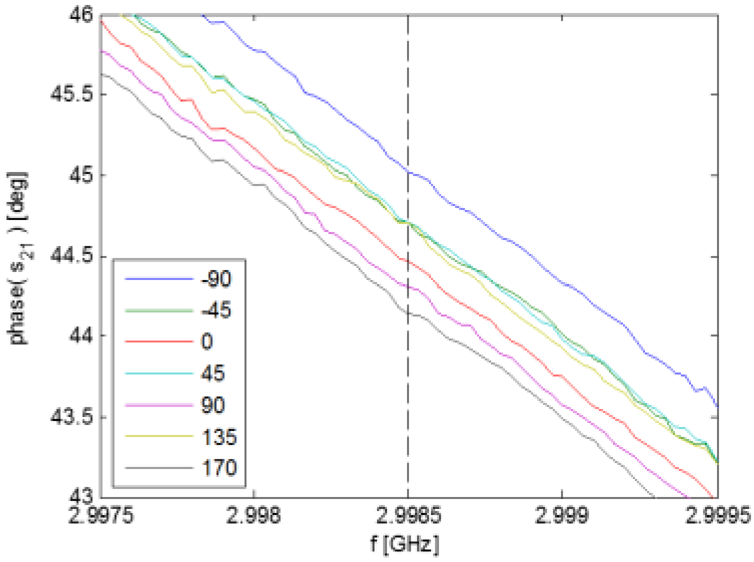

Figure 5: Measured phase of the transmitted signal (S21 parameter) for different angular position of the RJ.

4. High power test

The RJ was installed in CTF2 for high power testing at beginning of 2015 using klystron MKS14 of the CTF3 linac as the power source. Two weeks of time were allocated for the test of the device. The setup used during the high power test is shown in Fig. 6 and consists of (from top left to right): a ceramic window to isolate the section under vacuum from the waveguide network kept under SF6, a bi-directional coupler used to measure forward and reflected power, an H-bend WR284 waveguide section, a pumping connected to the ionic pump and a pressure gauge used to measure vacuum level, the Rotary Joint (fixed to a supporting table), a directional coupler used to measure transmitted power and a water cooled load.

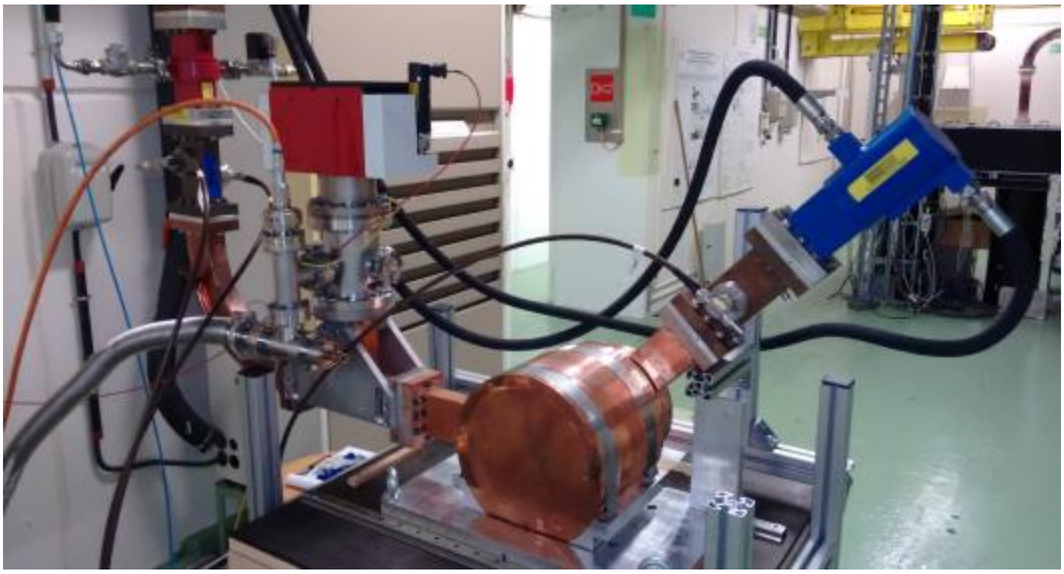

Figure 6: Setup of the high power test of the RJ in CTF2 at CERN.

A scheme of the control and acquisition system used is shown in Fig. 7, which was a simplified version of the setup in use for the X-band klystron-based test-stand (X-boxes) operated at CERN [4]. The incident, reflected and transmitted power (measured with directional couplers) were converted into voltage signals with diodes. A fast ADC (NI 5761, 14-bit 250 Ms/s, with FPGA module NI PXIe-7975R) was used to digitize the signals that were then processed with the same software used for X-box2. The vacuum signal generated by the gauge placed at the pumping port, was also recorded and used as interlock.

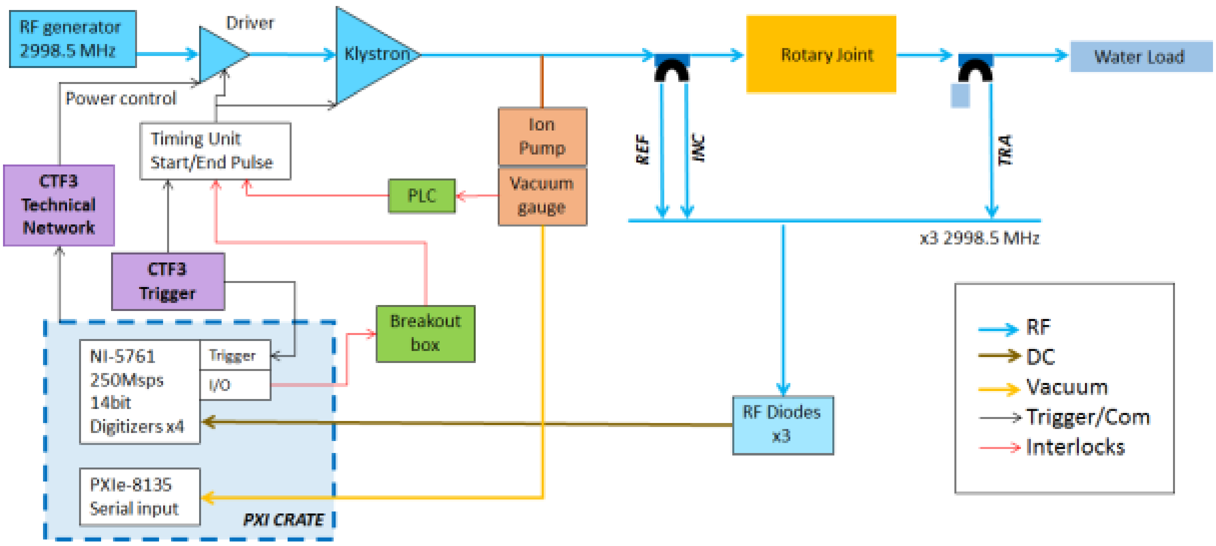

Figure 7: Scheme of the control and acquisition system of the RJ high-power test

Operation started with a pulse width of 100 ns. The power was ramped automatically, by adapting the conditioning algorithm written for the test of the CLIC structures. A constant power ramping rate was applied for the first 4 days. After that a conditioning algorithm based on the measured pressure has been used. In this configuration the control variable for the power feedback loop is the difference between the measured pressure and a pressure setpoint, which was fixed at 10^{-7} mbar. During the conditioning, the pulse length was gradually increased from 100 ns up to 5 µs. At each step in pulse width the power was backed off, following the typical process used for the conditioning of CLIC structures [5]. After ten days of operation, the RJ was operated at 20 MW, 5 µs pulses at 50 Hz repetition rate. The conditioning and testing history is summarized in Fig. 8.

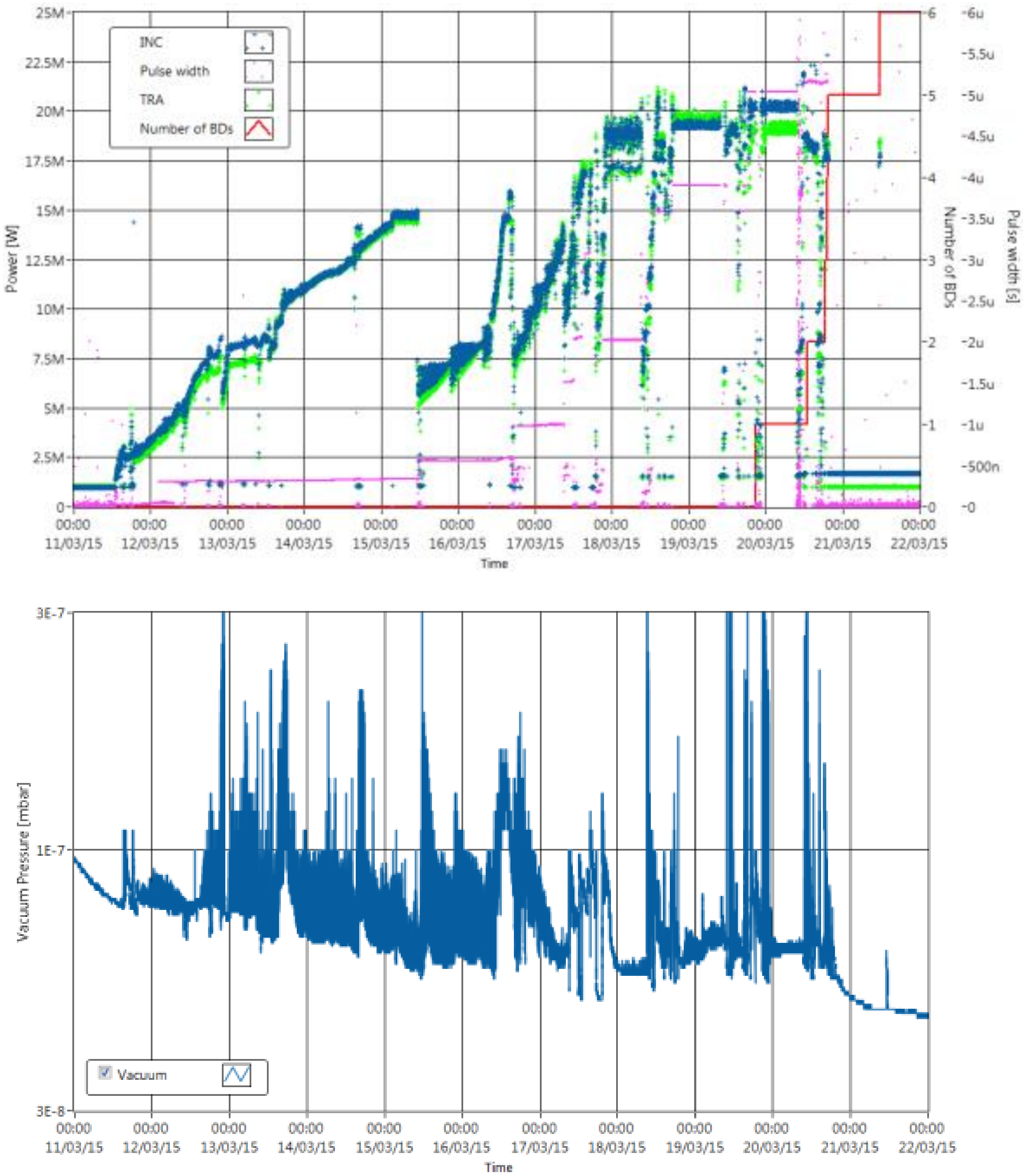

Figure 8: History plot of the RJ test, which shows the measured incident power, transmitted power, pulse width and accumulated number of breakdowns (top), and the vacuum levels (bottom).

Finally, measurements of Incident and Transmitted power at four different angles of the RJ were taken. The pulse shapes measured with a peak power meter are reported in Fig. 9. The measured values confirm that the RJ can transmit the RF power at different angles without significant changes in the pulse shapes. The reflected signal measured at different angles was always 20 dB lower than the incident signal.

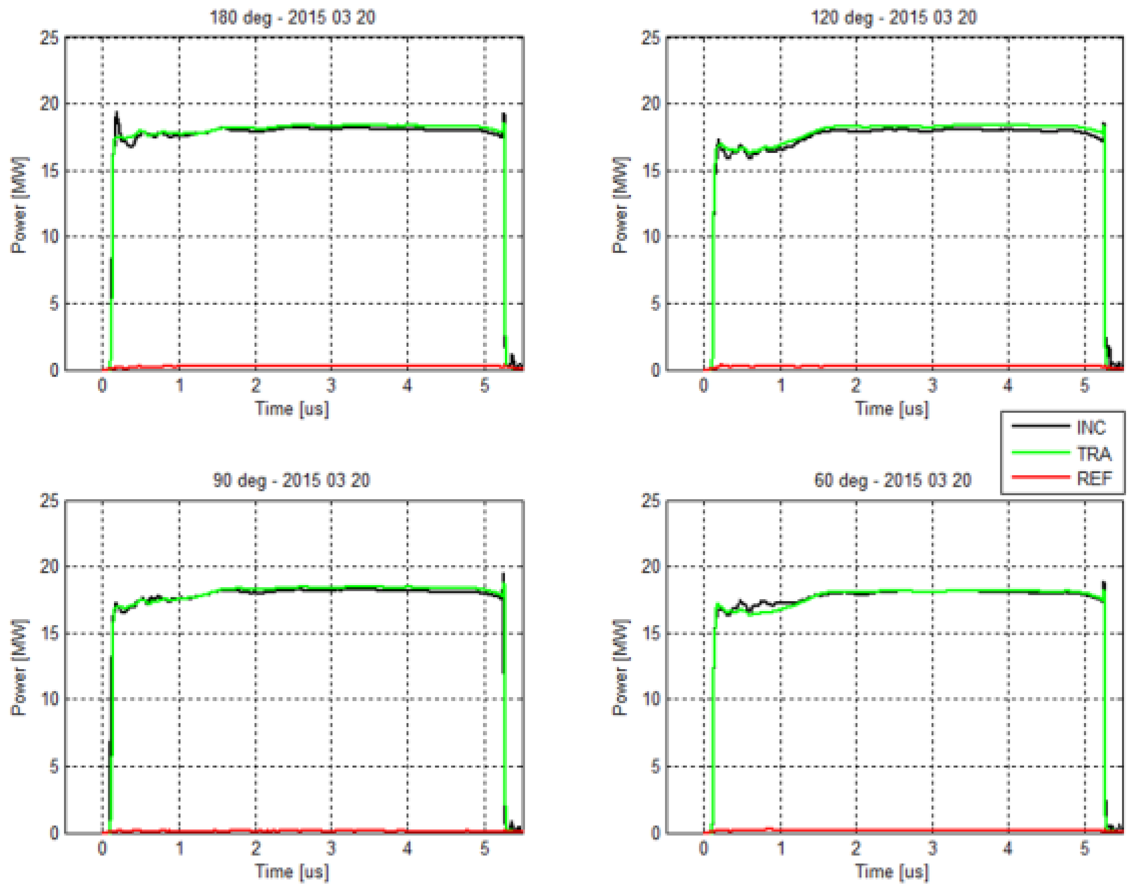

Figure 9: RF pulse profiles taken at different angles of the RJ.

5. Conclusions

An S-band waveguide rotary joint for high power applications has been successfully designed, manufactured and tested at CERN. After few days of conditioning the RJ was able to transmit a power of 20 MW (in 5 µs pulses at 50 Hz) at different angles. Almost no breakdown in reflected power were detected over more than 40 million pulses. Activity in the vacuum was recorded during the conditioning process, but the overall pressure level continued decreasing during the 10 days of test. Another important consideration is that the test could be performed under vacuum, avoiding the use of SF6 in the RJ. This is very important from the regulatory and operational point of view, also taking into account the fact that the machine is supposed to be operated in a medical environment.

The rotary joint is one of the critical components for the TULIP concept and successful operation means that the RF network can be designed to bring the power to the linac structures mounted on the rotating gantry support. Stabilization of waveguide length during operation and phase delay feedback at each single accelerating structure need now to be investigated for the integration of the system, which foresees waveguides (connecting the RJ on axis to the linac structures) of 6-7 meters in length. Another possibility which was proposed more recently is instead to simplify the overall design by making use of the new compact and more efficient Multi Beam Klystrons (that can operate at 52 kV without need of oil tank) mounted directly close to the accelerating structure.

Acknowledgements

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