THE COUPLERS FOR THE IFMIF-EVEDA RFQ HIGH POWER TEST STAND AT LNL: DESIGN, CONSTRUCTION AND OPERATION

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Abstract

In order to assess the critical aspects of the IFMIF-EVEDA RFQ construction procedure and operation, it was decided to perform a High Power Test of a subset of the RFQ consisting in its last 550 mm three modules (out of 18) plus a Prototype Module, 390 mm long, used as RF plug. These modules are going to be tested at full power in CW of INFN LNL Labs, in the so-called RFQ High Power Test Stand. For such a purpose, a RF tube-based amplifier capable of 220 kW CW output power at the operational frequency of 175 MHz was purchased from an Italian company. A critical component of this test is the RF power coupler. Therefore INFN-LNL developed a design of two identical water-cooled loop antenna couplers, built with OFE copper and vacuum sealed with a commercially available 6”1/8 Alumina planar window. These couplers were tested separately on an aluminium coupling cavity. In particular one of them acts as a power feeder, while the other one, connected with a 200 kW water-cooled load, acts as a receiver. In this paper, the main aspects of the design, construction and tests performed on the couplers and coupling cavity will be described.

HIGH POWER COUPLER DESIGN AND CONSTRUCTION

The High Power Coupler is designed to be critically coupled with the 2 meter long RFQ, in conditions of minimum acceptable Q_0 value of Q_{0min}=9000 (ideal Q_0=15000)[1]. Moreover, it must be properly cooled in order to manage its RF losses induced by the high power feeding the RFQ (up to 220 kW) and travelling on the RF coaxial line. The design of the loop therefore has a coaxial inner radius R=20 mm, an insertion depth of 29 mm and a thickness of 8 mm. The coupling was verified both with analytical calculations and with HFSS simulations. Should the Quality Factor be higher, a rotating flange can accomplish a proper change of the coupling. The power dissipated in the loop is about 100 W for an input power of 200 kW. The coupler and RF window are two separate devices coupled with a standard 6-1/8 IEC coaxial interface. In particular, the Coupler material is copper OFHC, and the water heat exchange coefficient is maintained near 10000 W/m^{2}K on the whole heat exchange surface: water velocity is above 2.5 m/s both in the external and internal spiral and in the loop. The coupler inner connection is used to remove power from the RF window.

In Fig.1 the power density of the coupler is shown, for an input power of 200 kW. With this power density, thermo-structural simulations have shown that the temperature in the copper bulk does not exceed 45ºC, for a water flux of 15 l/min, and that all the thermal-induced stresses are far below from the safe engineering limits (70 MPa).

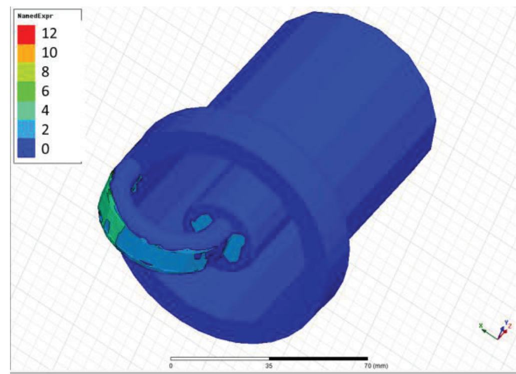

Figure 1: RF power density in the loop.

As far as the construction procedure is concerned, the coupler is made of OFE copper. Demineralized water cooling path is a double-spiral in the outer and inner conductors connected through double-channel in the loop (Fig.2).

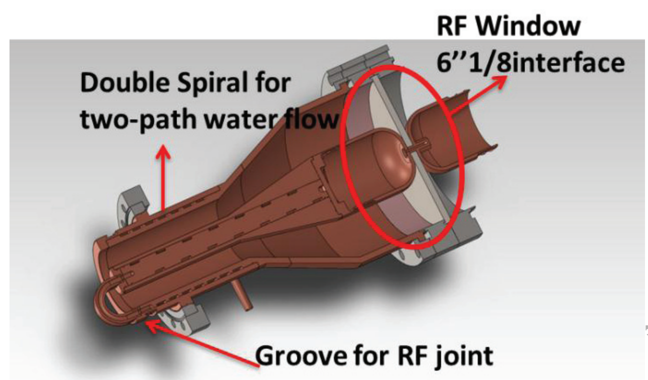

Figure 2: Coupler assembly in its final configuration.

The construction procedure foresees three brazing steps. In the first step, the cooling spirals are brazed separately on inner and outer conductors and also the SS flange seats and the water tubes are brazed on the copper bulk. In the second step, the plugs are brazed at both ends of the inner conductor and the outer conductor with cooling spiral is brazed with the tapered coaxial. Finally, in the third step the inner and outer conductors are brazed to the loop, and the assembly is completed. After both the first and the second brazing step, machining is required and brazing defects can be eventually recovered.

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The construction was carried out by CINEL Strumenti Scientifici, Vigonza (PD), while the brazing and thermal treatments were performed at the LNL brazing facility.

The RF window is a planar type window, purchased from MEGA Industries (USA). The material used is Alumina 99% with 1.5 to 3 nm TiN coating, with nominal RL of 40 dB and Insertion Loss of less than 0.01 dB. Fig. 3 shows the final result of the coupler construction.

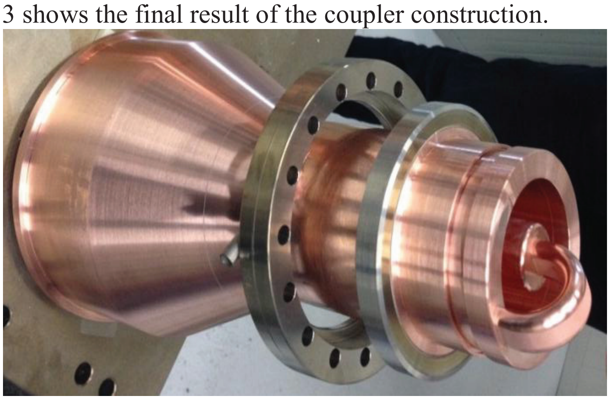

Figure 3: One of the two RF High Power Couplers.

THE ALUMINUM COUPLING CAVITY

The coupling cavity is an Al6068 coaxial-re-entrant aluminium resonator, with external radius=26 cm, internal radius=9.5 cm, height =19 cm and gap = 2 cm. The aim of this device is to allow safe conditioning of the couplers with a relatively low power loss inside the cavity. The cavity is designed to have a resonance at the nominal frequency of f_0= 175 MHz, when all thermal and pressure gradient induced effects in operation are taken into account. The main cavity parameters (RF designed with HFSS) are the following

-Maximum pd= 5 W/cm^2 @Pinput = 200 kW

-IL (Insertion Loss) = 0.31 dB @ $f=f_0$

-RL (Return Loss) = 29 dB @ $f=f_0$

The cavity, constructed by CINEL Strumenti Scientifici, Vigonza (PD) as well, is assembled with aluminum sheets and SS is used for flanges and reinforcement bars. Due to the high frequency sensitivity with gap ($\partial f/\partial gap$=-3MHz/mm), the rough tuning of the cavity with the gap variation prior to final machining is foreseen, and a further tuning range of [0 MHz, 1 MHz] is foreseen with a plunger tuner insertion depth variation of [0 mm, 30 mm]. Moreover, the thermo-structural simulations show that, under the RF power loads given by simulations, with a 50% margin, the maximum temperature, localized in the inner conductor, is equal to 36 ºC. The overall cooling water flux needed to cool the cavity is equal to 125 l/min. The target f_{01} frequency is 175.7 MHz at the end of the gap and tuner optimization procedure, which corresponds to the nominal frequency in vacuum and under full power operation. Finally, the measured value of RL and IL correspond to 22 dB and 0.44 dB respectively. It is worth noticing that the measured loaded quality factor of this structure (with the couplers set at maximum coupling) is equal to about 510, corresponding to an unloaded quality factor of about 10000, since each of the couplers, taken individually, has a coupling coefficient of about 10.7. This implies that the loaded 3dB bandwidth of the system is equal to about 350 kHz, and therefore it is not strictly necessary to use a circulator for this test.

THE HIGH POWER TEST STAND

The High Power Test Stand consists of the High Power Amplifier, (with its associated Power Supplies and cooling system), the 6"1/8 to 9"3/16 adapter placed immediately after the amplifier output, the 9"3/16 coaxial waveguide, the 9"3/16 to 6"1/8 adapter, a straight 6"1/8 line, the couplers along with the coupling cavity (with their associated cooling systems) and a High Power water cooled load, capable of withstanding up to 200 kW absorbed power (courtesy of Japanese team). In particular one of the couplers acts as a power feeder, while the other coupler, connected to the load, acts as a receiver. The Test Stand (Fig. 4) is completed by the Vacuum System (based on TCP256 turbomolecular pump) and by the Diagnostic/Control System.

Figure 4: Detail of the High Power Coupler test Stand. Coaxial waveguides, the coupling cavity and the water load are recognizable.

In particular, the RF amplifier is based on a 16 kW Solid State Driver and a TH781 tube and was built by the DB Elettronica company. Its main parameters are the following (Table 1)

Table 1: RF Amplifier Main Parameters

Frequency	175	MHz	
Max. Output Power	220	kW	
1dB bandwidth	≥ ±1	MHz	
Linearity	±1	dB	In the range [20 kW-220 kW]
Total Efficiency	65	%	P_{RF}/P_{Mains} @ full power
Harmonics	-30	dBc	
Spurious	-60	dBc	

The diagnostics equipment of the test stand includes: forward and reflected power detection for both couplers, vacuum level of the system (based on a vacuum gauge placed in the coupling cavity), temperatures on the critical parts of the cavity, of the couplers and of the water load and two arc detectors placed on the coupling cavity positioned in order to detect possible spark-induced light emissions coming from each coupler. It should be noted that, due to the absence of the circulator, there is a double mismatch at both ends of the coaxial line connecting the amplifier with the input coupler, and in particular at the amplifier, the impedance of which is equal to 60 Ω. This provokes a standing wave on the line and causes the reading of the forward power to be affected by the position of the directional coupler. Actually, during the tests, the value of the forward power was measured by reading the value of the RF power entering the load, subtracting the reflected power and assuming 10 % of power lost in the cavity, as for (IL=0.44 dB previously measured).

Data acquisition and storage is performed by Siemens® S7-300 PLC connected via ethernet to a PC equipped with the HMI. The HMI, which includes archive functions, was developed with the software WinCC. Data are then passed to the EPICS platform for storage. As for interlocks are concerned, the LCS (Local Control System) permits to set thresholds for vacuum, forward and reflected powers and temperatures, which, once exceeded, cause to fire the slow interlock (100 ms) and RF power to be cut. As for arc detection, the fast interlock (few μs) directly connected with the amplifier input cuts the RF drive signal once an arc is detected, and permits the recovery of the RF power in 100 μs. Indeed, the Signal generator (Rohde & Schwarz SMA100A) is remotely controlled via EPICS and all parameters (in particular frequency, amplitude, pulse durations τ and rep. rate T) are set via GUI (Fig.5)

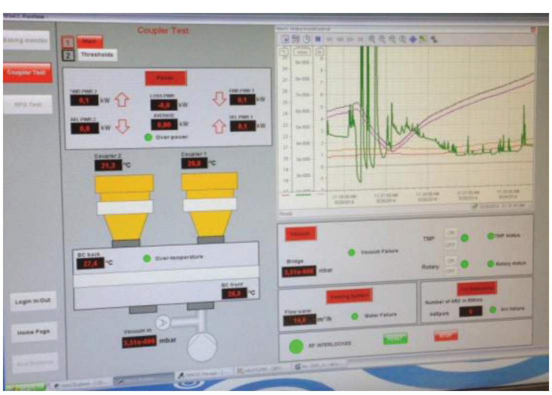

Figure 5: Screenshot of the Coupler High Power Test Data Acquisition System.

HIGH POWER TESTS

Prior to High Power Conditioning, the couplers and the cavity were baked out under vacuum up to the temperature of 95°C, for 2 days. Then, on 2014 May 26th, the RF conditioning started. As a general rule, the conditioning rate was paced by the vacuum level or multipacting. As the duty cycle was increased, the presence of vacuum instabilities (typically above 10^{-6} mbar) drove the maintenance of the pulse length and rep rate up to re-establishment of the baseline vacuum level (up to $7*10^{-7}$ mbar depending on the average RF power). When the vacuum instability was persistent, typically the pulse length was decreased in order to limit the outgassing activity before proceeding with higher power levels. In any case, during the absence of the operator (overnight), the system was always left in a stable condition (no vacuum instabilities). In the beginning, conditioning started with τ=20 μs and T=200 ms with a few kW peak power level, and the peak power level was then progressively increased up to the nominal value. At this point the duty cycle was increased by acting first on the pulse duration, then to the repetition rate. When performing an increase of Duty Cycle, the drive signal ouput power was typically first reduced then little by little increased. During this process, some multipacting levels were encountered in the regions between 40 and 80 kW and 120 and 160 kW. Moreover, due to some overheating, the tuner on the coupling cavity was removed, and the operational frequency increased of about 300 kHz, still within the amplifier bandwidth. On June 4th the duty cycle reached 100 % with about 150 kW input power, and later on the nominal 200 kW power value at CW was reached and maintained for about 2 hrs. Then in the following days the conditioning continued, although not around the clock, and up to the 13th of June, an integrated time of about 72 hrs at 200 kW power in CW was collected (f=175.22 MHz). During the conditioning, the maximum value of the temperature read on each coupler did not exceed 39°C and the temperature read on the aluminium cavity was equal to 33ºC, exactly the same value predicted by thermo-structural calculations. This confirms *a posteriori* the correctness of the forward power calculations shown in the previous paragraph.

CONCLUSION

The High Power Couplers have successfully undergone the Conditioning process on the Coupling Cavity and no noticeable issue was encountered during the conditioning process. The next steps foresee therefore the dismounting of those couplers and the usage of one of them for the High Power Tests of the 2m long RFQ subset.

REFERENCES

[1] A. Pisent et al "IFMIF-EVEDA RFQ design" Proceedings of EPAC08, Genoa, Italy.