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Conference Paper · April 2017

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A Novel Design of Deep Space 25KW Water-cooled Feeder at X-band and High Power Test Campaign Aspects

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INTRODUCTION

Future deep-space missions will generate increasing quantities of data from hundreds of millions of kilometres, requiring much higher RF power level as well as higher frequency bands to increase data transmission capacity. The European Space Agency (ESA) operates a network S/X/Ka-band antennas for Telemetry, Tracking and Command (TT&C) operations of different categories of spacecraft. Present ESA Deep Space Stations are (DSS) equipped with a 20 KW X Band High Power Amplifier (HPA). Future missions will demand larger uplink power levels, for distant spacecraft or for critical phases like entry descending and landing or for emergency situations of missions.

This paper presents a part of the work done in the frame of an ESA TRP activity "X-band Cryogenic Feed Prototyping". The emphasis is given on development of the transmitting part that has to deal with minimum 25KW of RF power as well as on the preparation of the testing campaign. In order to prove target properties of the feeder, as a main task appears definition of the corona discharge and power handling test. A novel feeder concept is applied and developed with objective to provide a compact solution that offers superior properties as well as a simple interface with cryogenic receiver. The RF design of the feeder components is refined using SPARK3D software to assure absence of the corona discharge under operational conditions. The transmitting part of the feeder shall be equipped with fully integrated and efficient water-cooling system maintaining the complete system on the optimal temperature. The envisaged tests shall be performed in pressurized chamber with 1KW RF power.

1. TECHNICAL APPROACH

New generation of the Deep Space (DS) feed systems at X-band shall provide as a main innovation cryo-cooling of all passive elements in the downlink channel, jointly with high RF power transmitting function. This fact represents a challenge in design and real implementation of such system in order to offer superior noise properties as well as to increase DS station EIRP usually operating with 20-25KW of RF continuous power. Besides all aforementioned basic requirements a proper redundancy concept shall be implemented to redirect the received signal to the redundant channel in case of failure. The redundant receive channel shall not introduce any performance degradation. Proper water cooling of the feed system shall be designed in order to deal with high power uplink. The DS feed main functionalities can be resumed as follows:

- Dual circular polarization operation is needed at receiver and transmitter side
- Simultaneous Tx (7.145-7.235GHz) and Rx (8.400-8.500GHz) operation should be enabled

A standard feed configuration for performing these operations usually consists of common components for receiving and transmitting signal paths: crrugated horn feed, broadband dual mode polarizer and broadband OMT for polarization discrimination at receiver and transmitter side. Additionally these components are followed by filter waveguide sections that should provide sufficient isolation and selectivity level between the high power RF transmitting signal and weak received one. More over a water-cooling should be applied on RF components and horn throat where high power RF is signal pass.

From the figure 1 it can be concluded that spatial distribution of the components significantly elevate difficulties in applying cryo-cooling of RF receiver chain components requiring two dewar interfaces (vacuum windows and thermal gaps). Since it is needed a very accurate assembly of these interfaces, the whole assembly of the feed is affected by applying of this approach. The vicinity of the high power RF source to the receiver chain makes additional problem in thermal aspect solving and implementing of a water circuit devices as well as to make an efficient thermal isolation between Tx and Rx signal path. From the point of view or RF design diplexer RxTx isolation is principally addressed to a careful filter design in obtaining its high selectivity. In order to cover both receiving and transmitting bands the RF components belonging to the common RxTx signals path should be broadband (corrugated horn, OMT an polariser). It means that additional effort in design of these components should be put in order to obtain high performances (excellent matching, low inserted losses and high purity of the both sense of circular polarization).

1.1. Modified OMTJ Feed Configuration

OMTJ block is fully transparent for the receiving signal and coupling with Tx Rf chain has been done by four port coupling network, each containing a filter for transmitting band. Dual CP operation at Tx side is accomplished by switching on one of the ports of 90 degrees hybrid circuit. On the side of receiver, dual polarization operation is performed by introducing additional polariser block with a receiving band filter placed in front of it. It is clear that with this configuration it is possible to obtain a physical separation of the transmitted and receiving chain and minimize a common TxRx signal path. Employment of the OMTJ block simplifies implementation of the cryo-cooled RF chain together with water-cooling of the high power signal path.

2. FEED CONFIGURATION AND IMPLEMENTATION CONCEPT

The figure 2 presents a block diagram of the full feed configuration based on employing OMTJ comprising all aforementioned advantages as well as simplicity. High RF power area is clearly separated from the dewar enclosure, which should facilitate implementation of cryocooling of RF receiver chain components.
A full feed configuration is presented on the figure 3. The figure 4 depicts a mechanical compact implementation of the transmitter part and full mechanical arrangement of the Tx and Rx part., as well as a view on the fully assembled feeder configuration. Since the future system should be applicable for different sight installation additional flexibility in feeder real implementation could be applied by adding bended waveguide sections.

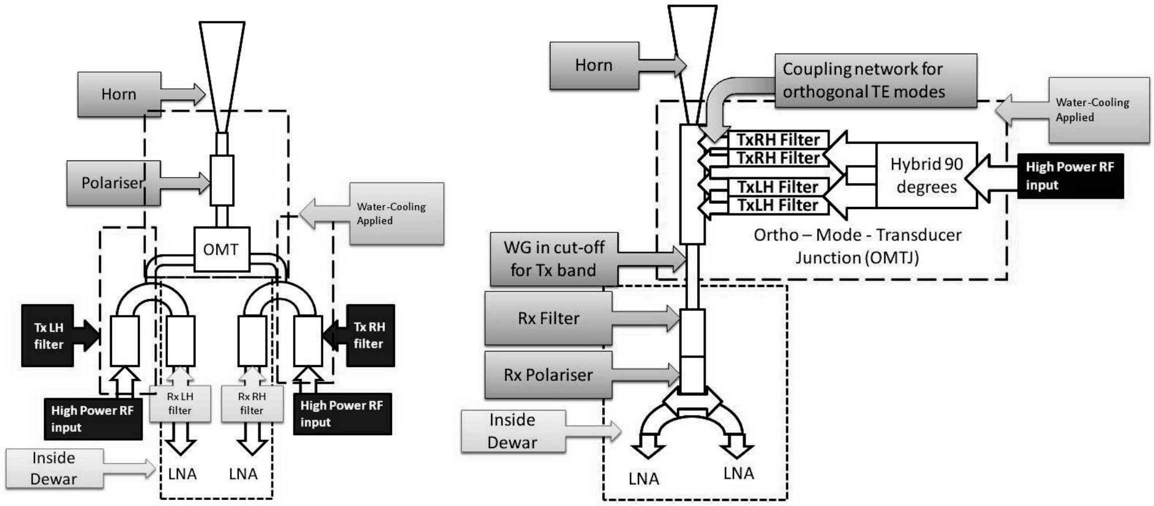

Fig. 1. Block diagrams of configuration with turn style OM and alternative feed configuration using OMTJ block

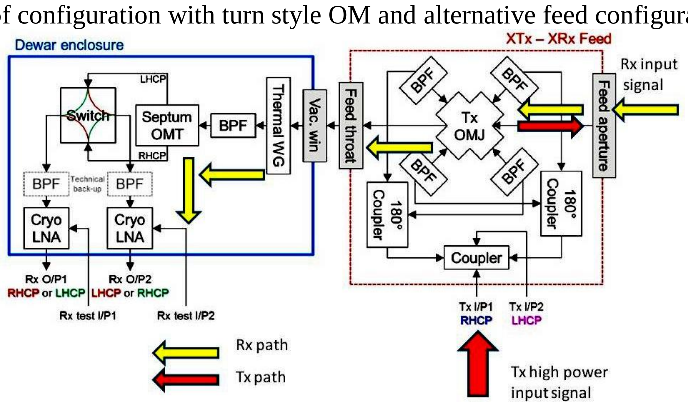

Fig. 2. Baseline design configuration of the Antenna Deep Space feeding system

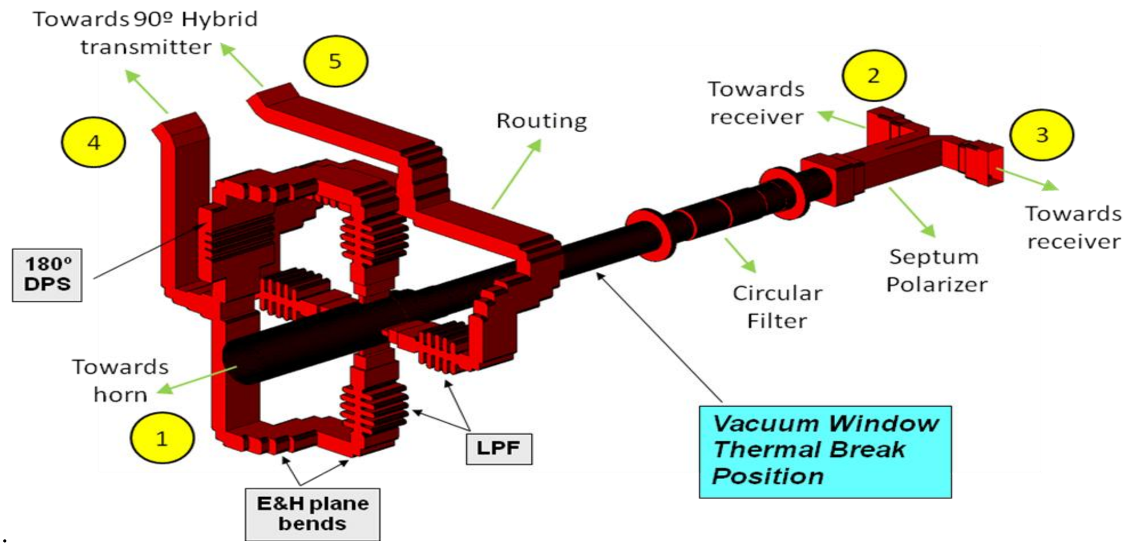

Fig. 3. Baseline design configuration of the Antenna DS feeding system

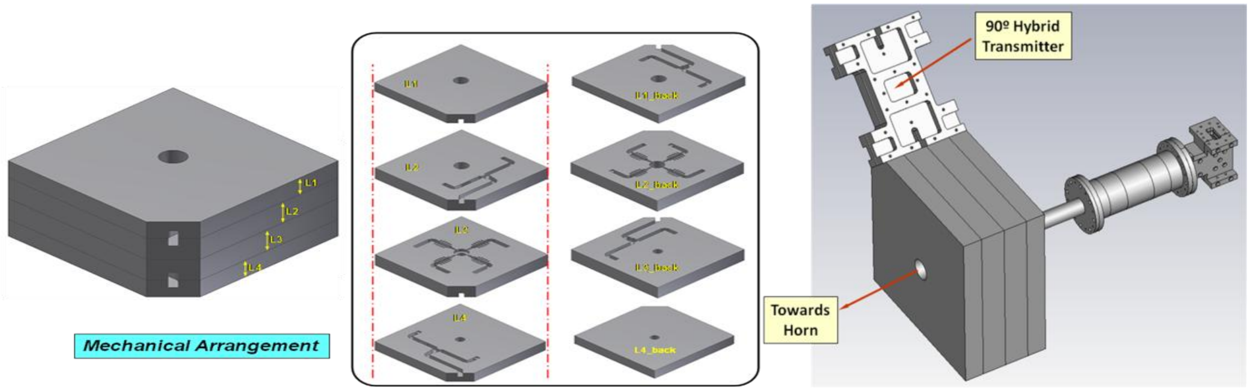

Fig. 4. Mechanical implementation of the OMTJ block (On the left and middle) and compact mechanical implementation of the Full Feeder (figure on the right)

2.1. Measured Results

The figure 6 shows a fabricated model of the Tx part of the feeder. Since it is envisaged to conserve the existing corrugated horn feed on DS stations, the assembly contains a smaller radiating load for the purposes of envisaged tests in anechoic chamber. On the same figure is a photograph of OMTJ block with marked relevant ports for better understanding of the following measured results of the most critical feeder system part. On the figure 6 is presented a block diagram of the tests setup and relevant measured scattering parameters, showing excellent high power input matching and good isolation between inputs ports. On the same figure it is depicted a very good matching at the horn port. The figure 8 shows relevant measured results towards receiver, with emphasis of excellent TxRx isolation better than 109dB.

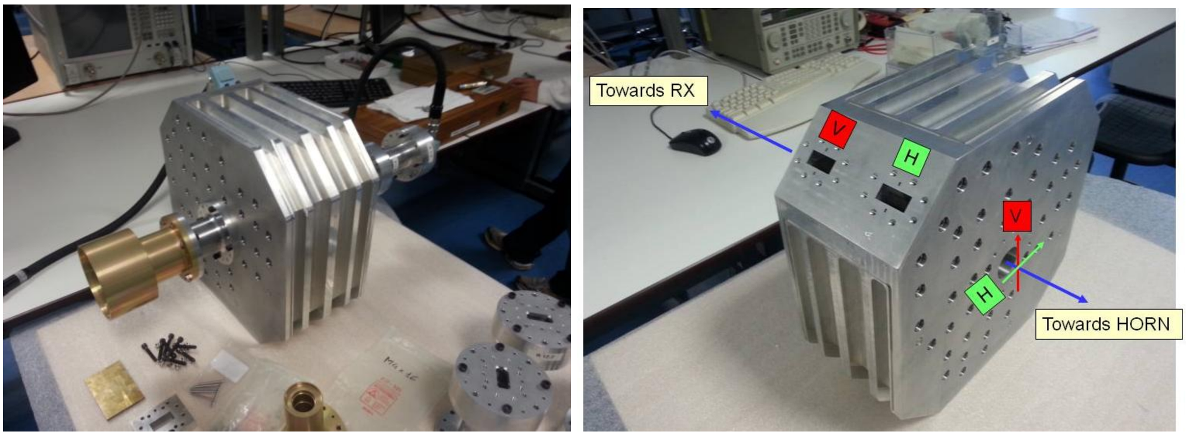

Fig. 5. Tx part of the feeder (on the left) and OMTJ block with marked ports (on the right)

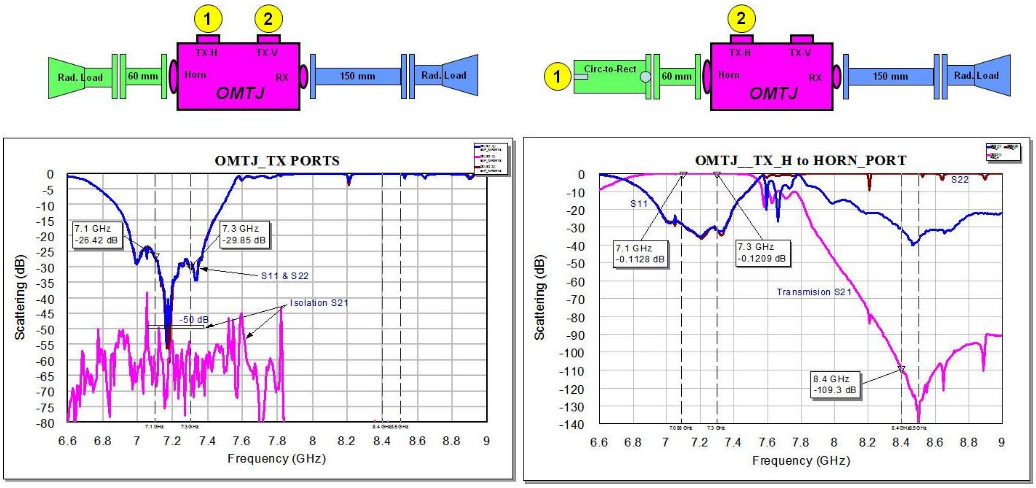

Fig. 6. Measured results of Tx part of the feeder: Input ports matching and isolation (on the left), horn port matching and inserted losses (on the right)

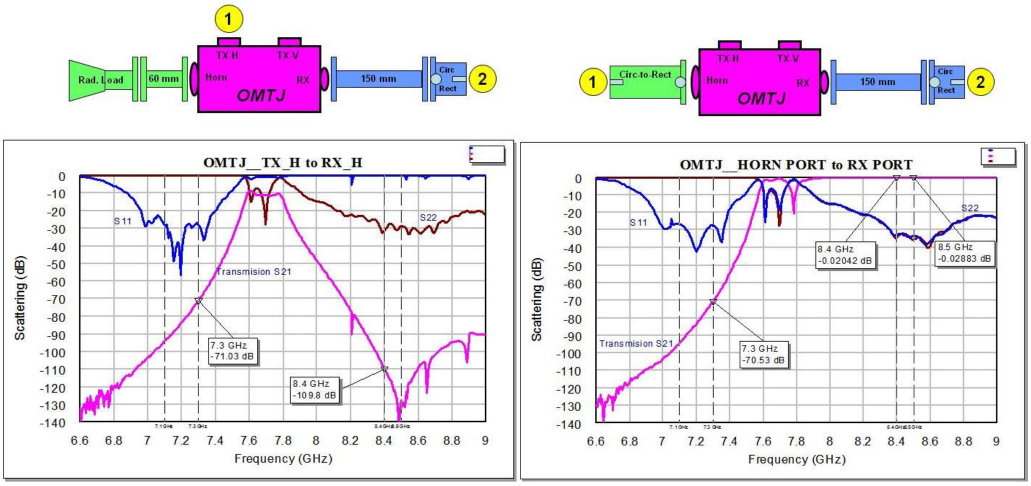

Fig. 7. Measured results of Tx part of the feeder: Isolation between input power port and Rx (on the left), Isolation between horn port and Rx port (on the right)

2.2. Water-cooling sub-system implementation

Due to the large amount of power passing through this system and even though the ohmic losses should not be much large, the temperatures reached by the system could deform the waveguide affecting its electromagnetic behavior. That's why water cooling refrigeration system is needed to be designed and simulated, so the working temperatures of the system will allow it to keep a correct functioning during the useful life of the feeder. The water cooling is designed to be fully compatible with the Non- deionized (NDI) water supply system present in the station.As an example, the NDI described below correspond with the one present in ESA Cebreros Station. The strategy in implementation of water-cooling system is based on idea that it should form an integral part of the TX feeder system part (Fig. 9). On the figure 6 it can be oserved uncovered water conducts as an integral part of the OMTJ block. Thermal analysis shows that system disipates a relativelly small portion of energy resulting in residual heat below 700W. The stress analyis perfomed on base on thermal computaion showed that RF componnets perfomances are not affected due to deformations caused by disipated heat, under operational conditions and applying 25KW RF CW power.

3. TX COMPONENTS DESIGN WORK LOGIC AND CORONA FEEDBACK

Using Spark3D software package it is possible to perform a quite accurate prediction of the RF components behaviour with respect to the corona discharge effect and to obtain a valuable feedback in case that some changes are necessary in order to avoid undesirable damage during real operability of the feed. From the other hand this analysis is a base for the high power test execution that shall be explain further in this document. As an example a continuation are presented the results of the analysis using Spark3D simulator in case of OMTJ critical part. Also is given a diagram showing dependence of break down RF power level with pressure. The results of this analysis can be resumed as follows:

- This component should be able to handle 25 KW.
- The breakdown power level at ambient pressure is around 185 KW.
- This component is free of discharge with a margin of around 8.5 dB.
- This device could work in an updated system up to 100 KW with around 2.5 dB margin.

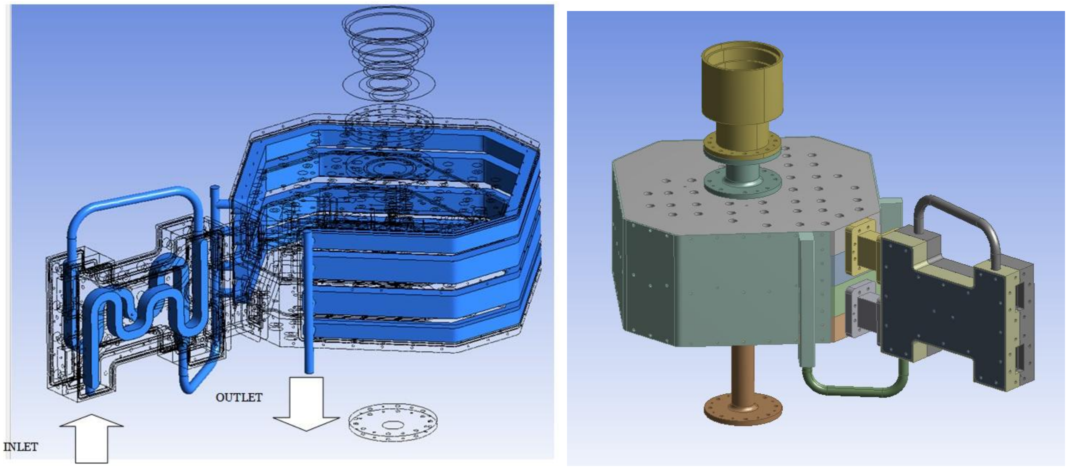

Fig. 8. Water circuit for refrigeration (figure on the left) and complete system geometry

This analysis showed that finding a critical physical point of corona discharge; a RF component design could be improved. In this particular case of OMTJ, rectangular waveguide entrance into circular waveguide was reshaped as it depicted on the following figure by adding a small radio instead of making a sharp edge (Figure 10).

4. HIGH POWER FEED PROPERTIES VERIFICATION APPROACH

The frame all testing activities have to be executed within poses hard requirements regarding RF power. It is out of discussion that no testing range or facility will dispose of an 25 or 100 KW power source. It is clear that some sort of scalability concept will have to be applied.

4.1. Pulsed Power Approach vs. CW Power Approach

In this approach, the component is treated as if it were excited by a pulse-modulated carrier. There are several motivations for adopting a pulsed test approach, which give rise to differences in detail as illustrated below:

- The pulsed approach is selected for testing in order to achieve the testing peak power levels whilst controlling the mean power level for thermal or other reasons to avoid overstressing the device under test.
- The pulsed approach is selected for testing depending on availability of existing high power sources at X-band.

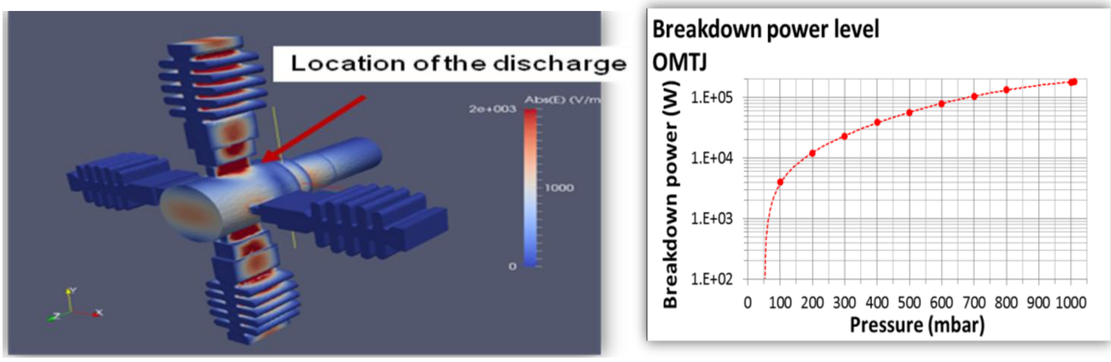

Fig. 9. OMTJ Spark 3D analysis indicates a point where the corona discharge occurs

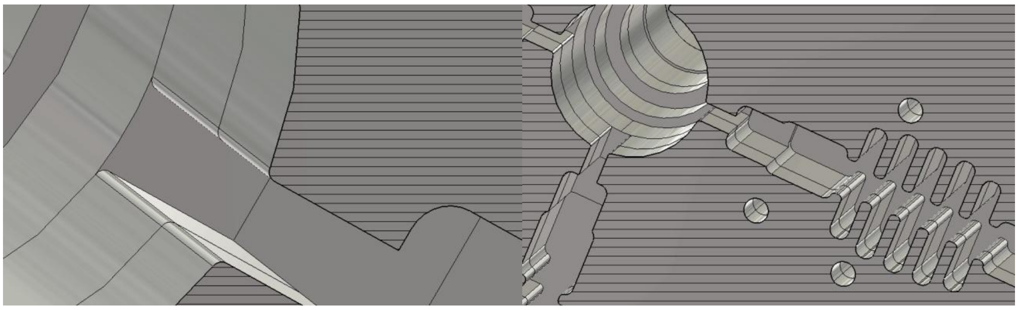

Fig. 10. A detail showing modified point of OMTJ in order to reach corona free design under operational conditions up to 100KW of RF power applied using Spark 3D analysis

The pulsed approach is appropriate for components operated where the CW approach is rejected either because it can lead to over design or because the implied power levels can make the testing uneconomic or impracticable. For units that experience CW excitation in service, pulsed testing can be used to achieve the maximum test power whilst keeping the mean power within the specification of the unit and permitting the use of test equipment which is available for the project. In general, CW excitation is a must regarding Power Handling tests meanwhile pulsed power excitation is a valid approach for the peak power depending Multipactor and Corona effects.

4.2 Corona Discharge Test Scalability Aspect

In absence of the required RF power source the all electrical discharged test could be scaled using the fact that exists correlation between the voltage and the corona charge and that current nearly linearly increases with pressure. Therefore the corona discharge pulse is function of applied pressure, which means that on the basis of experimental curves of applied voltage versus pressure for the particular waveguide line, is it possible to estimate a breakdown voltage at ambient normal pressure applying certain under-pressure within the measurement chamber.

4.3. Corona Test Rationale and tests setup

Based on the scalability concept previously mentioned and the use of pulsed power, already justified, the aim of the test is to demonstrate a margin of 3 to 6 dB with respect to corona threshold predicted by analysis at a several pressure values. So, the main objective is to detect no discharge when testing the prototype. The measuring system ability to detect the corona discharge shall be tested on a test probe (Figure 11.), specially designed to trigger corona discharge at power levels similar to the ones being applied during the prototype testing, will be carried out.
Feeder Test Configuration is presented on the figure 12 and consists of OMTJ block, which is identified as the most critical component with corresponding waveguide extensions. On the same figure on are denoted interfaces with measurement equipment. The Rx waveguide that is in cut-off for the Tx band shall be left open and to be used for electron seeding. ECSS standard recommends employment at least of two methods for the detection simultaneously. In case of the corona discharge tests four methods shall be applied in parallel as follows:

- Envelope detection
- Charge probe (detection of the rapid charge density increase)
- Third harmonic detection
- Nulling method

The figure 13 shows in more details test setup with DTU and employed measuring equipment:

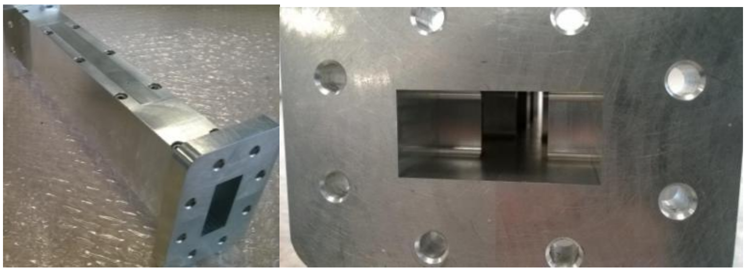

Fig. 11. Test probe based on five cavity band pass filter at centre frequency 7.2GHz in Tx band

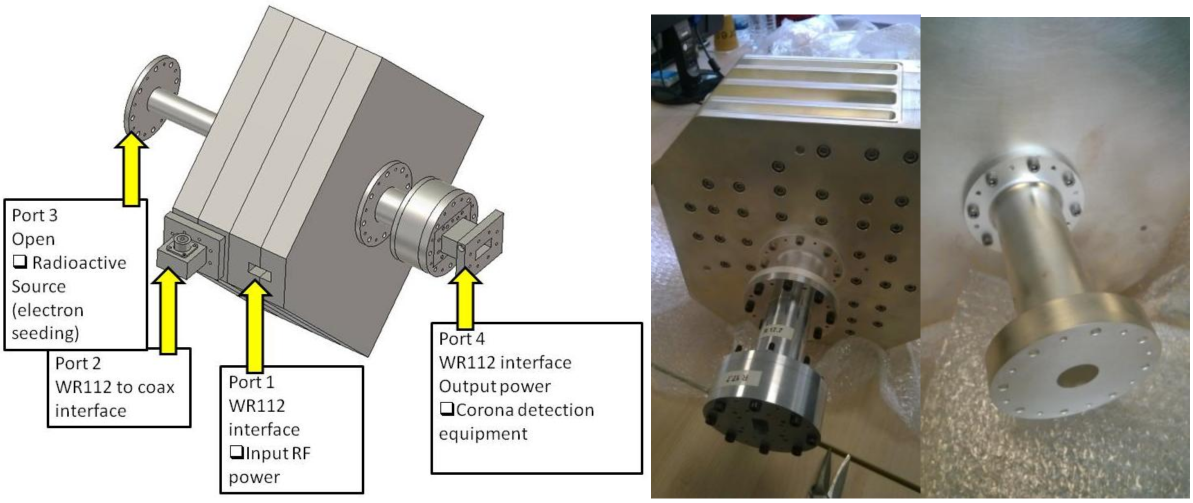

Fig. 12. Corona discharge test relevant interfaces for the test setup

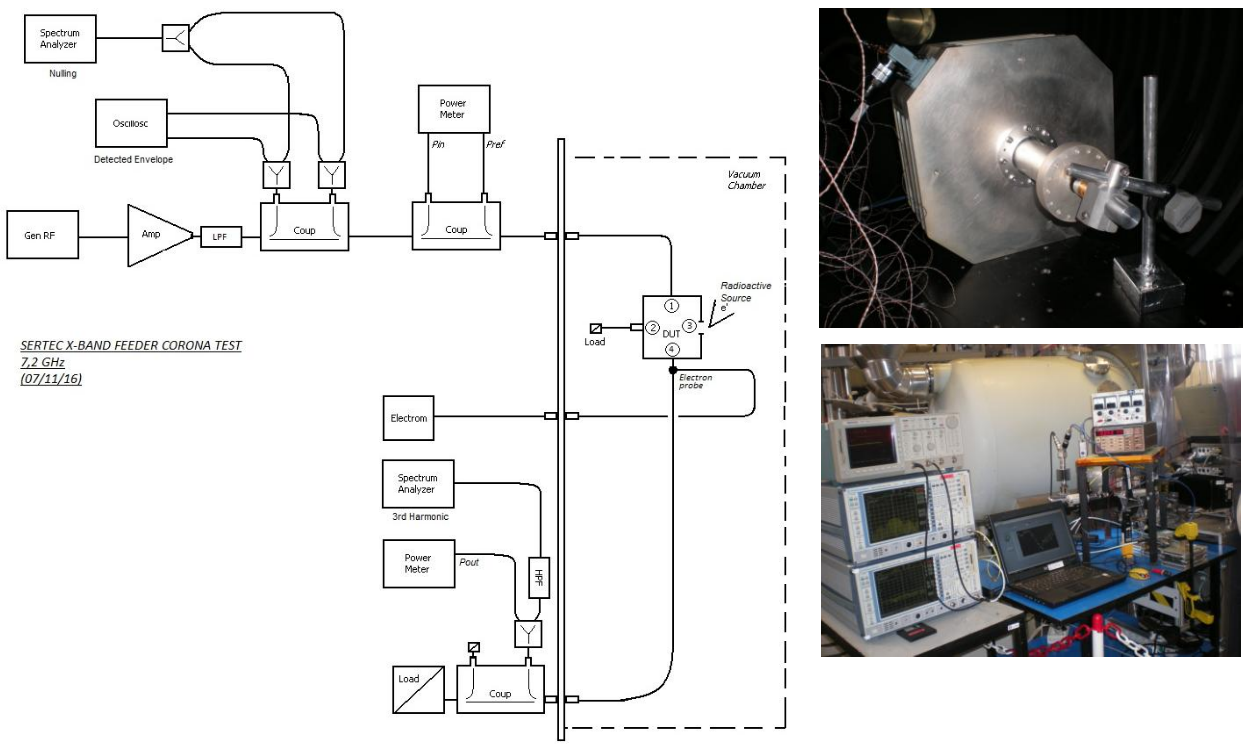

Fig. 13. Multiple methods test setup for corona discharge test and connections with measuring equipment (on the left), DUT inside pressurized chamber (top on the right); view on test setup (bottom on the right) at INTA

5. CORONA DISCHARGE TEST CRITERION ESTABLISHING AND TEST EXECUTION

In definition of the test goals the following logic is applied:

- On the normal ambient pressure, by simulation in SPARK3D, it is denoted existence of the margin between corona prediction (183kW) and nominal operational power at the critical signal path (12.5kW) of 11.66dB.
- If the envisaged threshold at for example, 400mBar pressure is 36kW it can be concluded applying aforementioned rationale that nominal power would be 11.66dB below, which means to apply 2.46kW. A test power level of 5KW would be in vicinity of 3dB over the threshold envisaged for the corona discharge.
- Applying the same criterion in case of 200mBar pressure we have for the 11kW threshold a nominal power level of 751W.
- Following the same rationale at 200mBar pressure it is possible to take a conclusion that in case of nominal power of 751W, achieving a power level of 3kW (751W +6dB) in absence of discharge, it shall be demonstrated that DUT at least has a margin of 3dB.

5.1. Corona test execution resume

Following steps were performed:

- Radioactive source (electron gun) pointing through port 3 (Fig. 12)
- Pulsed power RF signal shall be employed
- Test objectives :
    - Obtaining of a margin of approximately 3dB with respect to the corona threshold predicted by analysis at 200mbar
    - Obtaining of a margin of approximately 6dB with respect to the corona threshold predicted by analysis at 400mbar

It has been demonstrated the following facts:

- Test setup has been checked to be corona free at 200mbar and 400mbar pressures applying 3000W and 5000W of pulsed RF power, jointly with electron seeding produced by radioactive source
- Discharge has produced and detected on sample probe at 200mbar
- It has not been detected discharge on DUT at 400mbar and 200mbar applying 5kW and 3kW of pulsed power respectively.

On the figure 14 are shown different parts of the tests setup at INTA test facilities.

6. POWER HANDLING TEST RESUME AND EXECUTION.

Regarding the power handling test it is reasonable to use the same configuration due to following reasons:

- The highest temperatures, according the thermal analysis, are spotted in area around the band pass filters. Since it is available only 1kW of RF power and dissipated heat in that case shall be relatively small, the expected temperature variation shall be also minor and therefore it is recommendable to put as much as possible higher portion of power through the path containing the filters. By excluding the hybrid circuit it is possible to maximise the power passing a pair of filter sections.
- The small changes of temperatures in that case shall be measurable by distributed thermo sensors and compared with the theoretically obtained results in case of 1kW RF power applied.

During this test activity it has been performed following steps:

- Execution of the full cycle of power levels until it achieved steady thermal situation, at +23°C temperature and atmospheric pressure.
- Application of 900W CW RF power (maximum available) until is reached steady thermal situation, while the observed temperatures values are recorded.

CONCLUSIONS

A novel proposed feeder configuration regarding the high power aspects shows full compliance with SOW requirements.

ACKNOWLEDGMENTS

Authors would like to thank to ESA responsible officer Stéphane Halte on efficient project guiding, to Callisto team Mr. Steven Rawson, Cédric Chambon and Benoit Faroux on exceptional collaboration regarding receiving part of the feeder and relevant cryogenic aspects. A special gratitude authors would like to express to Mr. José Revuelta manager of the ESA DSS Cebreros on providing valuable information in relation with real feed implementation and installation.

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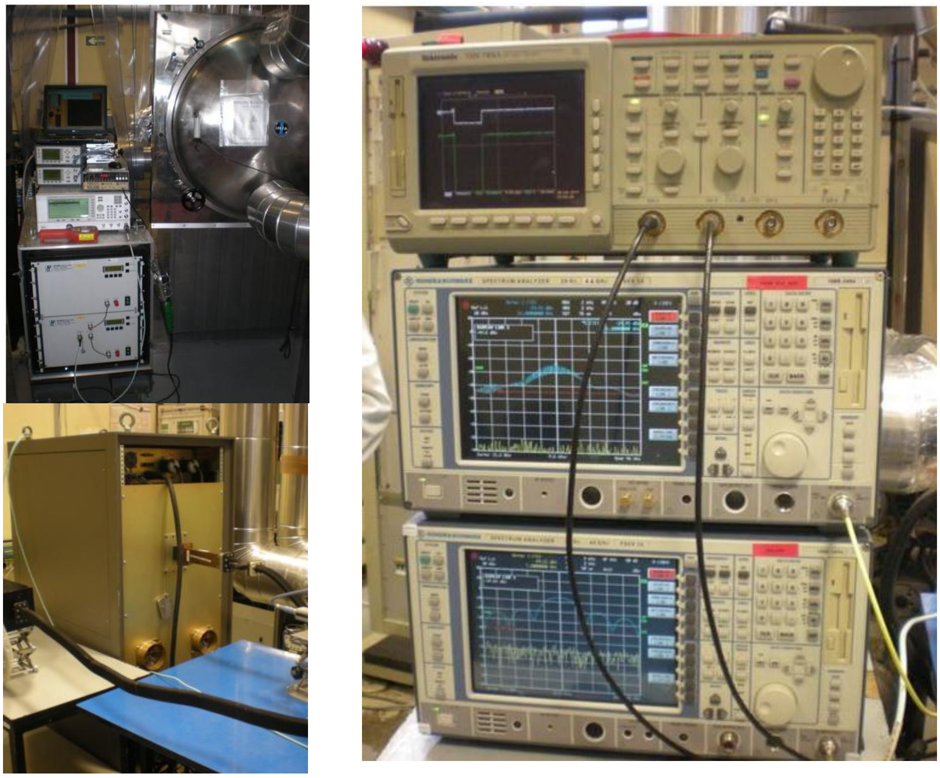

Fig. 14. Pressurized thermal chamber (top on the left), 1KW CW RF power amplifier (bottom on the left) and measuring system at the moment of capturing corona discharge using test probe and recording it using three methods (from top to bottom): envelope detection, third harmonics and nulling at INTA facilities