Operations with Spherical Calorimetric Loads in Different Configurations at Gyrotron Test Stands at EPFL and QST

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Abstract. A research activity in the Institute for Plasma Science and Technology of National Research Council (ISTP-CNR, Italy, former IFP-CNR) and in L.T. Calcoli (LTC, Italy) is aimed at the design and construction of calorimetric loads for absorption and measurement of high power millimeter-waves in the electron cyclotron frequency range. Two CW 170 GHz loads, one for the European ITER gyrotron test facility and the other for the FALCON test-bed, both installed at the Swiss Plasma Center (SPC, Switzerland); one short pulse (2 s) load for 1 MW, designed and optimised to operate at two different frequencies (84 GHz and 126 GHz), for testing and conditioning two new dual-frequency gyrotrons for the Tokamak à Configuration Variable (TCV, Switzerland); two additional CW loads, designed for absorbing powers higher than 1 MW, delivered to the National Institutes for Quantum and Radiological Science and Technology (QST, Japan) and exploited for the acceptance tests and the conditioning of the prototype of the Japanese ITER gyrotron. The present status and the most recent experimental results achieved in the framework of this development activity are reported in the paper.

STATUS OF EXPERIMENTAL ACTIVITY WITH THE LOADS

The collaboration ISTP-CNR/LTC has been manufacturing spherical electroformed copper loads for absorption and measurement of high power electron cyclotron waves for about ten years [1]. These devices, all with 0.6 m inner diameter, are designed for different applications (in terms of power and pulse length) and are provided with a diffusing mirror [2], a suitable coating of ceramic absorber [3] and an external cooling system designed to obtain the most uniform absorption of radiation for a given set of beam parameters. All the loads are coupled with a pre-load, which is basically a metallic chamber typically provided with six accesses from outside (for load and transmission line connections, as well as for additional components such as arc detectors, visible camera and pumping systems) and with rooftop-shaped retro-reflecting mirrors put inside, helpful to block and back-reflect part of the power reflected by the load into the transmission line.

Latest Experiments with the 84 GHz/126 GHz Short Pulse Load

Among the most recent uses of the ISTP-CNR/LTC loads [4] there is a set of experiments performed at the Swiss Plasma Center (SPC, Switzerland), aimed at testing a dual-frequency new-generation gyrotron source recently installed, capable to operate 1 MW/ 2 s at the two frequencies of 84 GHz and 126 GHz. This gyrotron, the first one of two 84-126 GHz identical sources to be integrated [5] in the ECRH system of the Tokamak à Configuration Variable (TCV), is being commissioned at SPC [6] using a dual-frequency dummy load designed and built by ISTP-CNR/LTC. The inner absorbing layout and distribution of coating of this prototype load has been designed, for the first time, to operate at both frequencies emitted by the new sources. As shown in Fig. 1-a, the connection of the load with the gyrotron under test is performed with 4 m HE_{11} oversized corrugated waveguide (63.5 mm inner diameter) and two miter-bends. For greater time efficiency, power is temporarily delivered to the load using a single outlet from the MOU (the nominal one for 84 GHz) and the same transmission line for both 84 GHz and 126 GHz frequencies. Despite the sub-optimal arrangement for 126 GHz radiation, resulting in a narrower beam at the diffusing mirror of the load as well as in a higher power load at the surface near the beam entrance, the load can absorb the injected power with no drawbacks and a reasonable match with the transmission line while allowing gyrotron operation with no significant perturbation. The power reflection found in such sub-optimal condition at 126 GHz, which is expected to lead to a partial degradation of the load match, is between 3 % and 4 % measured with two cross-calibrated detectors installed on a directional coupler at a miter-bend. The same measurements will be repeated in the next future under optimal beam conditions, in order to properly assess the nominal reflectivity of the load. Up to now, a maximum power of 930 kW was measured at 84 GHz for 1.1 s, corresponding to an energy $E \approx 1.023$ MJ in the load, while 992 kW were measured at 126 GHz during a 1.2 s pulse ($E \approx 1.190$ MJ). A full 2 s pulse length was also performed at 126 GHz, 685 kW ($E \approx 1.370$ MJ) and the maximum power of 1.04 MW was measured for 500 ms. Such power levels, measured with the calorimetric system of the load at the end of the transmission line, suggest a very high efficiency of the gyrotron and, at the same time, good power sensitivity of the load. As explained in [6], the only limitations on pulse length found so far have to be ascribed to external systems, that will be improved shortly, and not to the match of the gyrotron and the load. The status of the development activity of the dual-frequency gyrotron is described in details in [6].

Activity with the two European CW Loads

The activity with the loads is continuing also on the two European facilities at SPC, where two similar 170 GHz/CW loads (Fig. 2-b and 2-c) have been provided by ISTP-CNR/LTC for test, conditioning and operation of two 1 MW/1000 s prototype gyrotrons, both belonging to Fusion for Energy (F4E). The first load (nominally designed for 1.4 MW) is committed to the European ITER prototype source [7] while the second one (for 2 MW) is installed on the FALCON test facility [8], where a Russian source is used to test high power transmission line components for ITER. A half shell of the second load had already been tested previously at the National Institutes for Quantum and Radiological Science and Technology (QST) in Naka (Japan) at an equivalent power higher than ~1.8 MW/15 s and ~1.0 MW/300 s with the Japanese prototype gyrotron for ITER, as described in detail in [9].

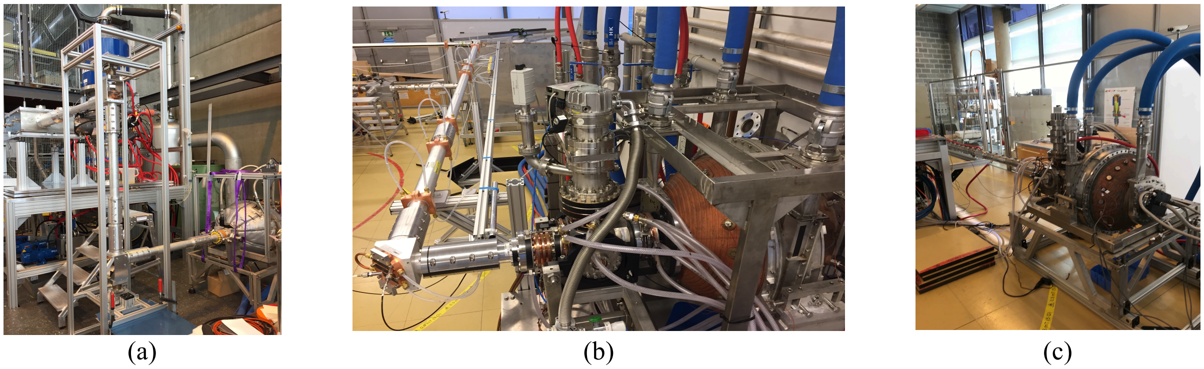
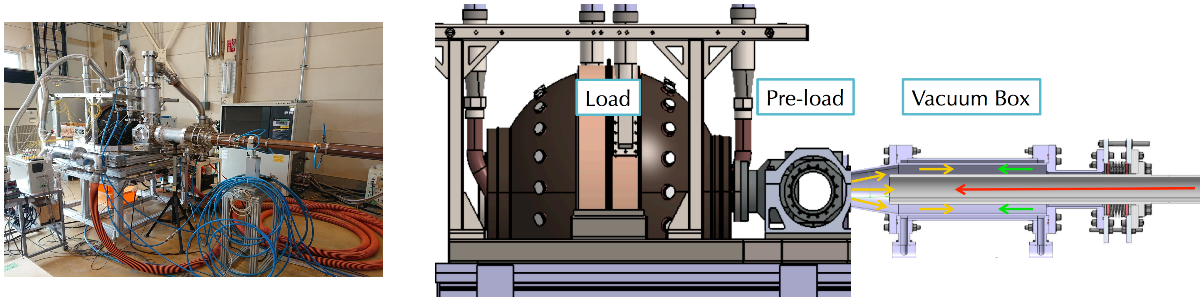

(a) (b) (c)

FIGURE 1. (a): Dual-frequency load installed on the 84 GHz/126 GHz gyrotron at SPC. (b): EU 1 MW/CW load coupled at the end of the EU ITER gyrotron transmission line. (c): 2 MW/CW load, provided for the FALCON test facility.

Up to now, the two loads could properly absorb and routinely measure up to ~740 kW for several tens of seconds on both test facilities, and a mean power of ~400 kW during a full pulse length of 1000 s on FALCON. So far, pulse energies were not limited by the gyrotrons or the loads, but mostly by overheating of components, such as the Matching Optics Units and the pre-load, by outgassing from some parts that would still need to be further conditioned and by security trip limits. During experiments, cross-calibration between the signal detected by a Schottky diode detector installed at a power monitor miter-bend and the measurement of the RF load allowed implementing an instantaneous power monitor. The maximum pressure reached in the load during the longest shots was near ~10^{-4} mbar and the estimated power losses along the transmission line was close to 10 kW.

Installation for the Japanese ITER Gyrotron Factory Acceptance Tests

Between 2017 and 2018 two 170 GHz/CW loads, the first one for a nominal power of 1.2 MW and the other for 1.5 MW, were built and delivered to the QST institute in Naka (Japan), to be installed on the test facility of the Japanese ITER gyrotron [10]. In 2018 the factory acceptance test of the first gyrotron were carried out at QST [11], absorbing and measuring the power with the first load. As described in [11], the gyrotron could be successfully tested with a power level higher than 1 MW (delivered by the $TE_{31,11}$ cavity mode for 300 s) leading to $HE_{1,1}$ mode power of 950 kW, as measured with the calorimetric system of the 1.2 MW/CW load installed at the end of a transmission line (see Fig. 2-a). The estimated overall power loss in the <MOU + transmission line>, including the power fraction reflected by the load, is reported in [11] to be 50 kW. With the objective of increasing the amount of power finally absorbed (and thus measured) in the load during acceptance tests, the usual <load + pre-load> setup was supplemented with a further component [12], designed at QST (Fig. 2-b), consisting of a metallic vacuum box installed in front of the pre-load and capable of housing the final part of the 63.5 mm inner-diameter waveguide under vacuum, while letting part of the radiation reflected by the load diffuse back again into the pre-load and the load.

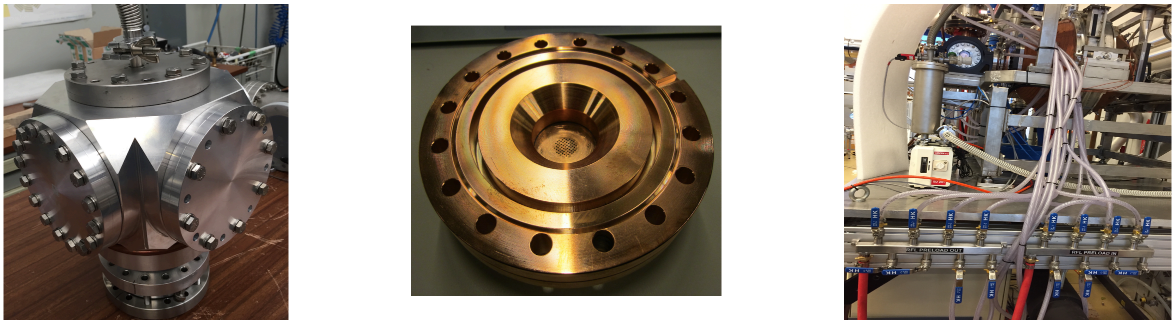


(a) (b)

FIGURE 2. (a): The 1.2 MW/CW load provided by ISTP-CNR/LTC for test [11] and conditioning of the Japanese ITER gyrotron installed on the test facility at QST. (b): Sketch of the QST vacuum box [12] installed during the factory acceptance tests of the Japanese gyrotron to partially reflect again into the load (green arrows) the component of the injected radiation (red arrow) back-reflected by the load towards the gyrotron direction (yellow arrows).

DESIGN OF A NEW PRE-LOAD

According to the experience gained during the last years with long pulse operation, the pre-load is the component experiencing the largest power load from radiation reflected from the spherical body. In general, a minimum level of back-reflection is unavoidable in a load, since the presence of an entrance for the beam implies the cavity inside the load cannot be an ideal black body. In practice, the amount of reflected power found during an experiment strongly depends on the experimental conditions. In particular, any deviation of parameters (such as beam alignment, beam dimension and mode content) from the design conditions can significantly affect back-reflection, leading to a hardly predictable degradation of both match and performance. The overheating often found during past experiments on specific regions of the pre-load has to be (at least partially) ascribed to insufficient cooling provided by the water circuits in the main body of the component. The main body of the ISTP-CNR pre-load is made at present of stainless steel and it is provided with inner cooling circuits. Nevertheless, parts of the pre-load body that are far from the circulating cooling water can likely heat up during long pulses. The inner surface of the CW pre-loads is copper- or gold-coated, in order to minimize the absorption of stray power, but stainless steel is hardly compatible with efficient cooling, even with dedicated circuits. More than temperature rise in the stainless steel wall, which in principle poses no risks, the most critical drawback consists of strong heating of vacuum flanges, where standard copper O-rings can become weaker at high temperatures. To counteract this problem a prototype pre-load, completely made of aluminum, is being developed at ISTP-CNR (Fig. 3-a). Based on the same geometrical design and inner layout with rooftop-shaped retro-reflecting mirrors, the aluminum pre-load does not require coatings to enhance reflectivity, since the complete structure itself ensures a good reflectivity and a high thermal exchange with the cooling channels, in this case provided on the external side of the body. The thermal conductivity of aluminum is high enough to significantly reduce the risks in spite of the lower fusion temperature limit with respect to stainless steel. To maximize heat extraction from the vacuum sealing regions and counteract the risk of vacuum leaks due to temperature increase, also the CF100 flanges placed at the sides are made of aluminum or in stainless steel coated with copper (Fig. 3-b) or, in another version, coated with absorber and cooled at the back side. A proper cooling of the pre-load and flanges was provided at SPC with a dedicated cooling water distribution installed on the stand of the CW loads, as shown in Fig. 3-c.



(a) (b) (c)

FIGURE 3. (a): First prototype of pre-load completely made with aluminum. (b): To lower the chance of pre-load overheating, any surface reached by the stray radiation, such as the flanges, is either absorbing (inside) and actively cooled (outside) or reflective, enhancing the reflectivity with copper or gold. The picture shows a copper-coated side flange for arc detector and camera access. (c): Improved distribution of water at the load stand, to ensure proper cooling to the different components installed at the pre-load level.

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