SPARC-PL-21/001
24 September 2021

VACUUM SYSTEM DESIGN FOR PLASMA WAKEFIELD ACCELERATION AT SPARC_LAB TEST FACILITY

A. Biagioni, D. Alesini, M. P. Anania, S. Arjmand, S. Bini, G.Costa, G. Di Pirro, M. Ferrario, M. Galletti, A. Liedl, V. Lollo, R. Pompili, F. Villa

INFN-LNF,Via E.Fermi 54,00044 Frascati (RM)

Abstract

The development of plasma-based accelerator machines has compelled to implement plasma structures able to confine plasmas and therefore preserve the vacuum along the accelerator. In this report, we present a design of the pumping system used for vacuum chambers where the plasma source is mounted to make plasma wakefield acceleration experiments at the Sparc_lab test facility. Two different chambers have been tested by considering various operating conditions in terms of quantity of the gas injected inside them, pressure at the entrance and repetition rate of the injection. The current vacuum system allows to maintain a vacuum level around 10^{-8} mbar close to the C-band accelerating structure, when the pressure inside the plasma source reaches approximatively 20 mbar, also by using a repetition rate up to 10 Hz.

1. INTRODUCTION

Plasma chambers (COMB chambers) used for plasma acceleration experiments at Sparc_lab have to be installed at the end of the C-band accelerating structure, therefore the main constraint on the vacuum system is represented by the limit value of 10^{-8} mbar that has to be maintained outside the chamber at the C-band side. Obviously, such a request strongly affects the entire plasma structure, both chamber geometry and pumping system, since during the plasma formation at densities useful for the acceleration we need to reach pressure up to 50 mbar inside plasma sources installed in the vacuum chambers. The gas injection inside the plasma source (consisting of a thin capillary of 3 cm in length and 1 mm in diameter) is controlled by means of an electro valve placed between the hydrogen gas tank and the plasma source itself. The electro valve regulation parameters will determine different operating condition of the vacuum system to be tested.

2. FIRST VERSION OF THE VACUUM SYSTEM FOR PLASMA-BASED ACCELERATORS

The first design of the vacuum structure used to contain plasma sources is shown in Figure 1. It is essentially composed of two sections that are separated by a vacuum impedance of 6 mm in diameter, in addition to that ones placed at the end of the chamber (7.2 + 10 mm), in order to preserve the vacuum level at the C-band side, during the gas injection for the plasma formation.

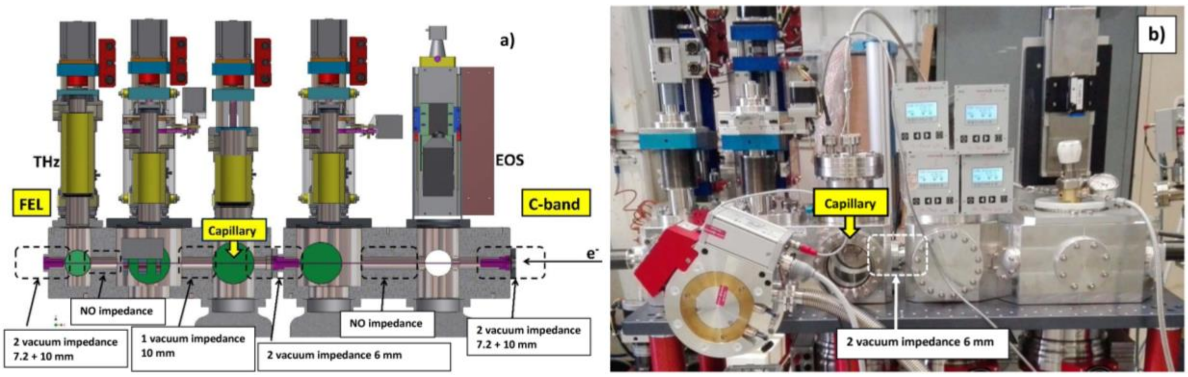

Fig. 1 First design of the vacuum system used at Sparc_lab test facility to make plasma wakefield acceleration experiments: a) longitudinal cut of the vacuum chamber (COMB chamber); b) image of the chamber and the pumping system used for testing.

The vacuum test has been performed to the first version of the COMB chamber by using the experimental apparatus shown also in Figure 2. It shows the pumping system we have used both inside and outside the chamber to reproduce the real operating conditions that were needed when the first chamber was mounted in the accelerator machine. For this purpose, in addition to four *turbo pumps* and four *Scroll pumps* mounted on the chamber, outside it we have inserted two pumping systems (*ionic pumps*) and two vacuometers to simulate the real operating conditions when the chamber is placed on the accelerator machine: between a Free electron laser (FEL) and a C-band accelerating structure. As already said, our main constraint concerns the vacuum value at the C-band side, that must be lower than 10^{-8} mbar. In order to evaluate the vacuum of the COMB chamber, we have considered three different parameters (table 1): the aperture time of the electro valve (EVT), the repetition rate of the electro valve (EVRR) and the overall operating time (OOT) whose vacuum level inside the chamber must conform to our constraint. It should be noted that the larger are the parameters values, the higher is the vacuum level in the chamber (bad condition).

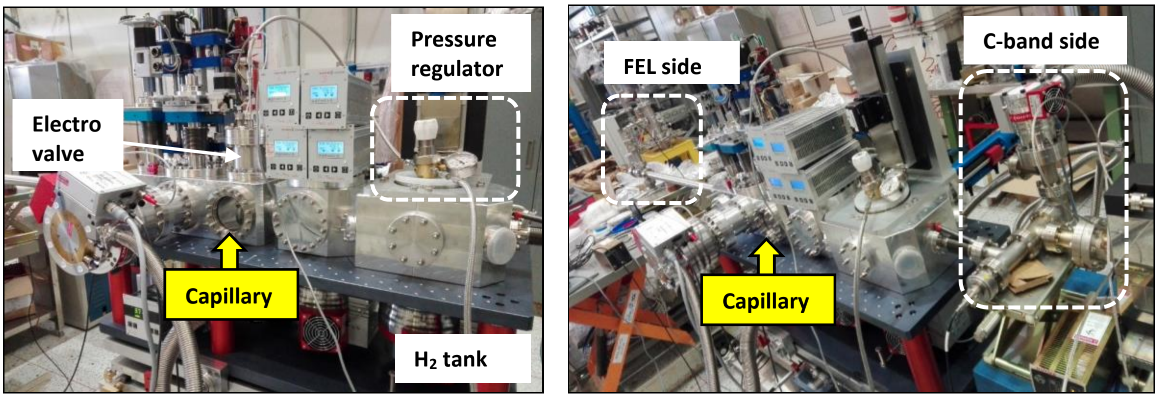

Fig. 2 Images of the experimental setup used to make the vacuum tests of the first version of the COMB chamber.

A further mechanical pressure regulator optimizes the gas flow coming from the hydrogen gas source, therefore it is mounted between the electro valve and the hydrogen generator (Fig. 2). The electro valve input pressure imposed by such pressure regulator represents another parameter to take into account, which is set to 300 mbar for the vacuum tests presented in this report.

Table 1

Parameter lists	
EVRR (Hz)	**1/5/10**
EVT (ms)	**2/3**
OOT (minutes)	**Until 120 min**

The pumping system we have used to test the COMB chamber off-line (out of the accelerator) is summarized in the table 2; It should be noted that this apparatus represents a very similar pumping system we have employed on-line (we have replaced one Scroll pump of 30 m^3/h with another one of 60 m^3/h).

Table 2

Pumping system		**Off-line**	**On-line**
4 Turbo pumps	**445 l/s**	**1780 l/s**	**1780 l/s**
4 Scroll pumps	**30 m³/h**	**120 m³/h**	**150 m³/h**
1 or 2 Turbo pumps at the exit of Scrolls	**80 l/s**	**160 l/s**	**160 l/s**

Results of the main test are reported in the table 3. In this case, the parameter setting describes the operating conditions that are usually used during plasma acceleration experiments: repetition rate and aperture time of the electro valve set to 1 Hz and 3 ms respectively, as well as the input pressure of the electro valve set to 300 mbar.

Table 3

Parameters: 1 Hz/3 ms/300mbar		
Overall operating time (OOT)	**CMBVGA01(inside)**	**AC3VGA01(outside)**
Starting vacuum	**$2.1x10^{-9}$**	**$7.4x10^{-10}$**
t_0	**$3x10^{-8}$**	**$1.1x10^{-8}$**
2 min	**$9.5x10^{-8}$**	**$1.2x10^{-8}$**
10 min	**$1.4x10^{-7}$**	**$1.2x10^{-8}$**
20 min	**$1.5x10^{-7}$**	**$1.2x10^{-8}$**
40 min	**$1.6x10^{-7}$**	**$1.3x10^{-8}$**
70 min	**$1.5x10^{-7}$**	**$1.1x10^{-8}$**
100 min	**$1.5x10^{-7}$**	**$1.3x10^{-8}$**
120 min	**$1.4x10^{-7}$**	**$1.2x10^{-8}$**

Pressure levels have been measured by means of two vacuometers mounted at the C-band side of the chamber, where the vacuum system have to satisfy a stricter constraint: the first one, inside the chamber (CMBVGA01) and the second one outside the chamber (AC3VGA01). This test has been useful to know if the vacuum impedance between chamber and C-band is able to prevent any contamination of the latter device, at least within 10^{-8} mbar. It should be also noted that after 120 minutes have passed, the test has been closed. Indeed, we did not observe any overload of the pumping system, in terms of temperature and absorbed current, thus we consider this operating condition as a safety setting of the parameters for the vacuum system.

Other operating conditions have been tested on this vacuum chamber, which are more restrictive than the previous ones in order to know the usage limits of the chamber. Results and parameter settings are reported below, in tables 4 and 5.

Table 4

Parameters: 5 Hz/2 ms/300mbar		
Measurement duration	**C-band (outside)**	**FEL (outside)**
Starting vacuum	**$1.3x10^{-7}$**	**$6.4x10^{-8}$**
t_0	**$1.6x10^{-7}$**	**$3x10^{-7}$**
15 min	**$1.5x10^{-7}$**	**$4.9x10^{-7}$**
30 min	**$1.4x10^{-7}$**	**$5.2x10^{-7}$**
45 min	**$1.4x10^{-7}$**	**$5.3x10^{-7}$**
60 min	**$1.4x10^{-7}$**	**$5x10^{-7}$**
90 min	**$1.3x10^{-7}$**	**$5x10^{-7}$**
120 min	**$1.3x10^{-7}$**	**$5x10^{-7}$**

Table 5

Parameters: 10 Hz/2 ms/300mbar		
Measurement duration	**C-band (outside)**	**FEL (outside)**
Starting vacuum	**1.2x10^{-7}**	**1.2x10^{-7}**
t_0	**1.4x10^{-7}**	**3.3x10^{-7}**
15 min	**1.9x10^{-7}**	**9.8x10^{-7}**
35 min	**1.9x10^{-7}**	**1.8x10^{-6}**
50 min	**1.9x10^{-7}**	**4.9x10^{-6}**

Firstly, about two last tests, it should be noted that we have changed the positioning of vacuometers (see Fig. 1): the first one is now placed outside the chamber at the C-band side (the same position of the AC3VGA01) and the second one is mounted at the FEL side. Also, we have used an electro valve time of 2 ms (a little less restrictive of 3 ms) because if we used 3 ms we would overload the pumping system and the vacuum level would be immediately bad, in both cases. As we expected, when the EVRR is 10 Hz the vacuum level reaches bad values only after 50 minutes and we have to switch off the turbo pumps because was overloaded (absorption current becomes too high, around 4-5 A).

Finally, we should note that such tests show a different behaviour of the vacuum levels between C-band side and FEL side. In order to get a better understanding of this phenomenon we have to see figure 2. During the test we have injected the hydrogen gas in the chamber through the capillary from which the gas expands. Before it reaches the vacuometer at the C-band side, there are one more turbo pump and a very strong impedance (2x6 mm) with respect to the path towards the FEL side. Such a design of the chamber allows to prevent any contamination of the C-band, that represents the section we want to defend, but for operating condition shown in the table 3 (*EVT* = 3 ms and *EVRR* = 1 Hz).

3. SECOND VERSION OF THE VACUUM SYSTEM FOR PLASMA-BASED ACCELERATORS

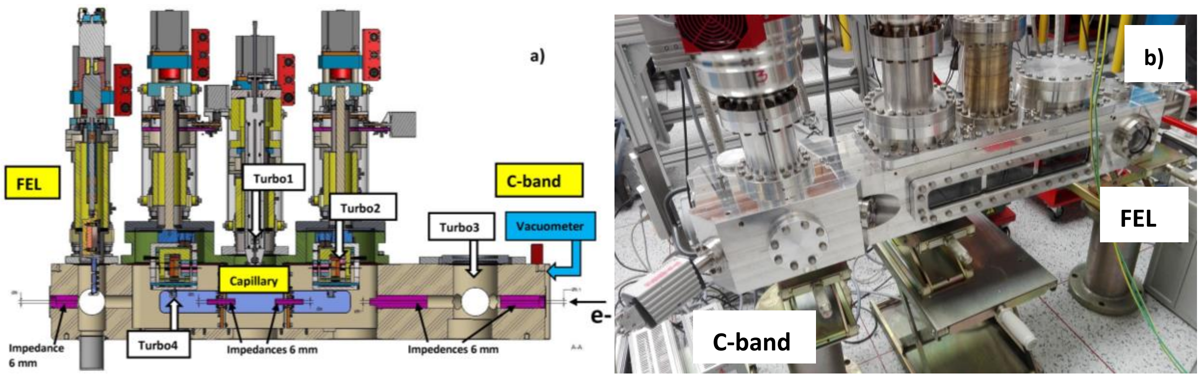

Fig. 3 Second design of the vacuum system used at Sparc_lab test facility to make plasma wakefield acceleration experiments: a) longitudinal section of the new COMB chamber that shows the impedances to the hydrogen gas expansion (6 mm diameter) and the internal divisions where will be positioned the capillary; b) image of the chamber and the pumping system used for testing.

It should be pointed out that data concerning the vacuum tests about the second version of the COMB chamber (that is the current chamber installed at the Sparc_lab accelerator), shown in Figure 3, are relating to a pumping system that is a little bit different from that one we use when the chamber is mounted in the accelerator machine (on-line); as described in the following, the latter pumping system is the stronger one. Also for this chamber, our main constraint concerns the vacuum value at the C-band side, that must be lower than 10^{-8} mbar. Figure 4 shows internal sections created to reduce the gas expansion towards the c-Band accelerating structure.

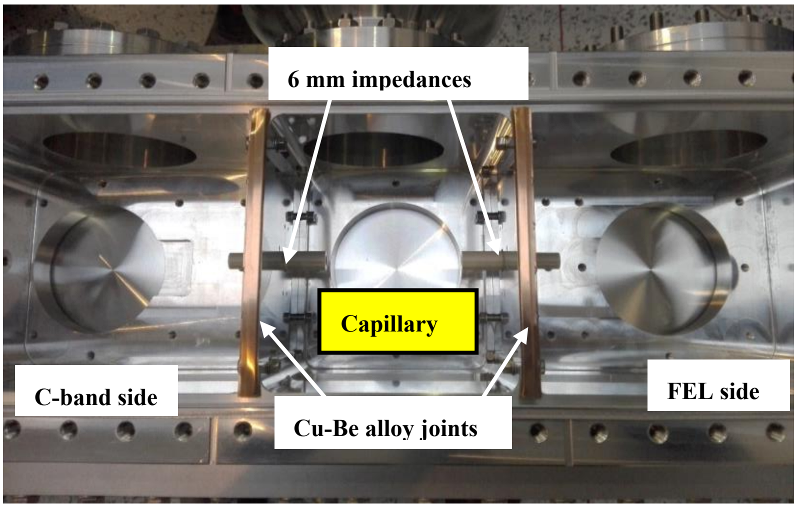

Fig. 4 View of internal sections of the COMB chamber created to reduce any gas expansion towards the accelerating structures.

The pumping system used to make the vacuum test (off-line) is partially shown in Figure 3. It is composed of 4 turbo pumps and 5 Scroll pumps mounted on the chamber, with a total ability to pump the gas of 1490 l/s concerning the turbo pumps and 85 m^3/h concerning the Scroll pumps, with respect to 1780 l/s and 150 m^3/h respectively, concerning the real pumping system mounted on the accelerator machine. All data are summarized in the table 6. It has to be remarked that two Scroll pumps of 15 m^3/h are connected to the turbo pump 2 (it is close to the capillary and smaller than others) because its absorbed current is higher than the currents absorbed by other turbo pumps.

Table 6

Pumping system		Off-line	On-line
4 Turbo pumps	**2x445, 2x300 l/s**	**1490 l/s**	**1780 l/s**
5 Scroll pumps	**30, 3x15, 10 m^3/h**	**85 m^3/h**	**150 m^3/h**
Turbo pumps at the exit of Scrolls	**No pumps**	**-**	**160 l/s**

In order to take into account the real operating conditions that are used during our experiments (chamber on-line), the vacuum measurement has been performed by using the parameters shown in the table 7. These parameters setting allow to compare two versions of the COMB chamber, because we have chosen the same values, although two pumping systems are slightly different.

Table 7

Parameter lists	
EVRR (Hz)	**1/5/10**
EVT (ms)	**3**
OOT (minutes)	**Until 120 min**

With regard to the positioning of the vacuometers to measure the pressure levels, we have mounted only one device at the C-band side, which acquires the vacuum level inside the chamber (see Fig. 3). Such decision is based on previous tests about the first version of the COMB chamber, from which we should consider that it is possible to obtain a vacuum improvement around a factor 10^{-1} when the pressure level is measured outside the chamber, at C-band side (that means in the C-band structure). Such a behavior is produced by the impedance mounted between the chamber and the C-band pipe (Fig. 3a), which is better (of 6 mm diameter) than the impedance used for the first COMB chamber (7.2 mm + 10 mm) on the same side (Fig. 1a). As we made with the first version of the chamber, the main test of the new one concerns the same operating conditions: *EVRR* and *EVT* of the electro valve 1Hz and 3 ms respectively, but the input pressure set to 1400 mbar (300 mbar in the previous case) because the pressure regulator (between electro valve and hydrogen generator) was not available. This last condition is more restrictive and has to be taken into account. The results of the main test are reported in the table 8.

Table 8

Parameters: 1 Hz/3 ms/1400mbar				
Measurement duration	**C-band (inside) (mbar)**	**Current Turbo1 (A)**	**Current Turbo2 (A)**	**Current Turbo3 (A)**
Starting values	**$1.2x10^{-9}$**	**0.62**	**1.34**	**0.97**
t_0	**$1x10^{-7}$**	**1.1**	**1.34**	**0.98**
10 min	**$1.2x10^{-7}$**	**1.1**	**1.34**	**0.94**
20 min	**$1.2x10^{-7}$**	**1.15**	**1.34**	**0.97**
30 min	**$1.2x10^{-7}$**	**1.18**	**1.37**	**0.97**
40 min	**$1.2x10^{-7}$**	**1.18**	**1.43**	**0.97**
50 min	**$1.2x10^{-7}$**	**1.18**	**1.46**	**0.98**
60 min	**$1.2x10^{-7}$**	**1.18**	**1.46**	**0.98**
80 min	**$1.1x10^{-7}$**	**1.17**	**1.45**	**0.97**
100 min	**$1.1x10^{-7}$**	**1.18**	**1.45**	**0.96**
120 min	**$1.2x10^{-7}$**	**1.18**	**1.46**	**0.96**

Some considerations can be made about these measurements. Despite the pumping system is weaker than that one we use when the chamber is mounted on the accelerator, the vacuum levels reached inside the chamber (C-band side) at the nominal operating conditions (1 Hz/3 ms) are within our constrain of 10^{-8} mbar in the C-band structure. We have measured, after 120 minutes of gas pumping, $1.2x10^{-7}$ mbar, that corresponds to 10^{-8} mbar if we consider the vacuum improvement around a factor 10^{-1} produced by the impedance mounted between the chamber and the C-band pipe. Also, the absorbed currents by turbo pumps are within safety values, that are around 8 A.

A direct comparison between tables 3 and 8, that is between two different COMB chambers, underlines the improvements due to the new design of this device. Indeed, it should be noted that the comparison has to consider a different pumping system (see tables 2 and 7) and the use of the pressure regulator for the first chamber with respect to the second one. More restrictive tests for other operating conditions confirm such a behavior. Results and parameter settings are reported in the tables 9 and 10.

Table 9

Parameters: 5 Hz/3 ms/1400mbar				
Measurement duration	**C-band (inside) (mbar)**	**Current Turbo1 (A)**	**Current Turbo2 (A)**	**Current Turbo3 (A)**
Starting values	**$2.2x10^{-9}$**	**0.59**	**1.4**	**1**
t_0	**$8x10^{-8}$**	**2.12**	**1.53**	**0.99**
10 min	**$9x10^{-8}$**	**2.12**	**1.75**	**0.97**
20 min	**$1x10^{-7}$**	**2.15**	**1.9**	**0.65**
30 min	**$1x10^{-7}$**	**2.15**	**2**	**0.99**
40 min	**$1.1x10^{-7}$**	**2.12**	**2**	**1**
50 min	**$1x10^{-7}$**	**2.12**	**2**	**0.9**
60 min	**$1x10^{-7}$**	**2.15**	**2**	**0.65**
80 min	**$1x10^{-7}$**	**2.12**	**2.06**	**0.96**
100 min	**$1.2x10^{-7}$**	**2.12**	**2.06**	**0.98**
120 min	**$1.2x10^{-7}$**	**2.12**	**2.06**	**0.98**

Table 10

Parameters: 10 Hz/3 ms/1400mbar				
Measurement duration	**C-band (inside) (mbar)**	**Current Turbo1 (A)**	**Current Turbo2 (A)**	**Current Turbo3 (A)**
Starting values	**$1.3x10^{-9}$**	**0.65**	**1.37**	**0.98**
t_0	**$5.3x10^{-8}$**	**2.53**	**1.96**	**1**
10 min	**$6.1x10^{-8}$**	**2.56**	**2.34**	**0.97**
20 min	**$7.6x10^{-8}$**	**2.62**	**2.59**	**0.64**
30 min	**$7.9x10^{-8}$**	**2.62**	**2.81**	**1.01**
50 min	**$8.1x10^{-8}$**	**2.62**	**2.81**	**0.94**
60 min	**$8.4x10^{-8}$**	**2.62**	**2.84**	**0.99**
70 min	**$8.7x10^{-8}$**	**2.62**	**2.87**	**0.99**
80 min	**$8.9x10^{-8}$**	**2.62**	**2.84**	**0.65**
90 min	**$8.9x10^{-8}$**	**2.62**	**2.87**	**0.98**

Two last sets of data (5 Hz and 10 Hz) show that the new COMB chamber could be used also when the operating conditions are more restrictive than the nominal case (1 Hz), although for a limited time only. Also in these cases a factor 10^{-1} has to be considered. The absorbed currents of turbo pumps reach stationary values around 2.87 A (Turbo2, which is the weaker turbo pump we have used) with respect to 1.46 A relating to the nominal operating conditions (1 Hz), but such behavior does not represent an obstacle because the limit value is 8 A. Also the operating temperature is within the safe limits: we have measured 43 °C as maximum value, with respect to 65 °C which is the limit value. However, based on the positioning of turbo pumps on the chamber, the Turbo1 (it has placed in the section where the gas is injected) should undergo the higher workload (2.62 A), even if in our measurements the Turbo2 absorbs 2.87 A, this happens because the Turbo2 is weaker than the Turbo1. The impedances protect the other pumps and the vacuum level in the other sections.

Anyway, if we want to use the chamber at the operating conditions 10 Hz/3 ms, we will have to monitor the absorbed currents and the operating temperatures during the experiments. It should be noted that the previous version of the COMB chamber does not allow us to work at these operating conditions: 10 Hz/3 ms.

Finally, a comment can be made about the comparison among data relating to the pressure values measured at different operating conditions. At 10 Hz, the pressure levels seem better than the pressure values measured at 1 and 5 Hz. Actually, in the latter conditions we report the maximum value we read by vacuometer, but the real data oscillate between 3-4x10^{-8} and 1.2x10^{-7} mbar, while at 10 Hz the pressure levels remain constant at 7-8x10^{-8} mbar. We can observe such a behavior when we work at low repetition rates (1 and 5 Hz), because in this case between two pulses the hydrogen gas can accumulate inside the tube before the electro valve, generating a pulse pressure when the valve will open. This problem should be fixed by using the pressure regulator between hydrogen generator and electrovalve to work at 300 mbar instead of 1400 mbar.

4. CONCLUSIONS

The vacuum tests we have made about the new COMB chamber have pointed out that it can work at nominal operating conditions, that is 1 Hz/3 ms, even though the pumping system we have used is lower than that one is used when the chamber is mounted on the accelerator machine. Also, we have observed an interesting improvement with respect to the previous version of the chamber: it is possible to impose operating conditions that are more restrictive (10 Hz/3 ms) than the nominal case, although for a limited time only. The latter workload produces an increase of the absorbed currents and the operating temperatures, which remain always within the safety limits.