ACDIV-2015-17
May, 2015

High power testing of the fisrt re-buncher cavity for LIPAc

F. Toral, C. de la Morena, D. Gavela, I. Podadera, D. Regidor, M. Weber, CIEMAT, Madrid
B. Bravo, R. Fos, J.R. Ocampo, F. Pérez, A. Salom, P. Solans, CELLS, Cerdanyola del Vallès

Abstract

Two re-buncher cavities will be installed at the Medium Energy Beam Transport (MEBT) of the LIPAc accelerator, presently being built at Rokkasho (Japan). They are IH-type cavities with 5 gaps and will provide an effective voltage of 350 kV at 175 MHz for deuterons at 5 MeV. The first prototype has been designed at CIEMAT and built by the Spanish industry. The high power tests and RF conditioning have been successfully performed at the ALBA/CELLS RF laboratory. A solid state power amplifier, which has been developed by CIEMAT and its partner companies at Spain for the LIPAc RF System, has been used for the tests. The cavity has shown a performance according to calculations, regarding the dissipated power, peak temperatures and coupling factor. RF conditioning was started with a duty cycle of 3%, which was increased gradually till continuous wave (CW), which is the nominal working mode in LIPAc.

Accelerator Division
Alba Synchrotron Light Source
c/ de la Llum, 2-26
08290 Cerdanyola del Valles, Spain

HIGH POWER TESTING OF THE FIRST RE-BUNCHER CAVITY FOR LIPAC*

F. Toral#, C. de la Morena, D. Gavela, I. Podadera, D. Regidor, M. Weber, CIEMAT, Madrid
B. Bravo, R. Fos, J.R. Ocampo, F. Pérez, A. Salom, P. Solans, CELLS, Cerdanyola del Vallès

Abstract

Two re-buncher cavities will be installed at the Medium Energy Beam Transport (MEBT) of the LIPAc accelerator, presently being built at Rokkasho (Japan). They are IH-type cavities with 5 gaps and will provide an effective voltage of 350 kV at 175 MHz for deuterons at 5 MeV. The first prototype has been designed at CIEMAT and built by the Spanish industry. The high power tests and RF conditioning have been successfully performed at the ALBA/CELLS RF laboratory. A solid state power amplifier, which has been developed by CIEMAT and its partner companies at Spain for the LIPAc RF System, has been used for the tests. The cavity has shown a performance according to calculations, regarding the dissipated power, peak temperatures and coupling factor. RF conditioning was started with a duty cycle of 3%, which was increased gradually till continuous wave (CW), which is the nominal working mode in LIPAc.

INTRODUCTION

Two re-buncher cavities will be installed in the MEBT line [1], as part of the Spanish contribution to LIPAc. Electromagnetic and mechanical simulations led to a design based on a 5-gap IH-type cavity providing a 350 kV effective voltage at 175 MHz [2]. The first of the two cavities has been manufactured and tested with low power [3]. Last step to validate this cavity is the high power test.

EXPERIMENTAL SETUP

The high power test of the re-buncher prototype was performed at CELLS RF laboratory. It is equipped with a bunker with a useful surface about 15 m^2. Ancillary equipment (cooling, power, instrumentation) is available to ease the test of different cavity configurations.

Two vacuum pumps (one ionic and one turbomolecular) were installed at the CF160 ports on both sides of the cavity. A cold cathode gauge was installed at the beam pipe port, to measure the vacuum level as close as possible to the region with higher electric field, that is, the drift tubes. It was connected through a 100 mm long pipe to avoid the influence of the RF fields. A RGA analyser was installed at the other beam pipe port. An arc detector was also present (Fig. 1).

Six PT100 sensors were located at the expected hottest spots at the cavity, according to FEM simulations: one on each endplate, in front of the nearest stem; on the input coupler; two at the top part of the main body and the last one at the bottom, close to the central stems base.

The mechanical performance of the tuners was checked: position of limit switches and movement accuracy were within specifications. One tuner is manual and its initial position was set to get the nominal resonant frequency when the motorized one is at midpoint. The automatic tuner was powered using the ALBA standard driver for step motors, which also manages the limit switches.

The cooling was designed with a pressure drop of 2.3 bar for a flow of 31 l/min: four parallel channels, two with 12 l/min and other two with 3.5 l/min. However, a pressure drop of 3.8 bar was measured for a flow of 27.8 l/min, likely due to underestimated pressure drops at the cross section steps and elbows. The valves present in each parallel channel were used to balance the pressure drops accordingly. This regime was kept during the conditioning and shown to be enough.

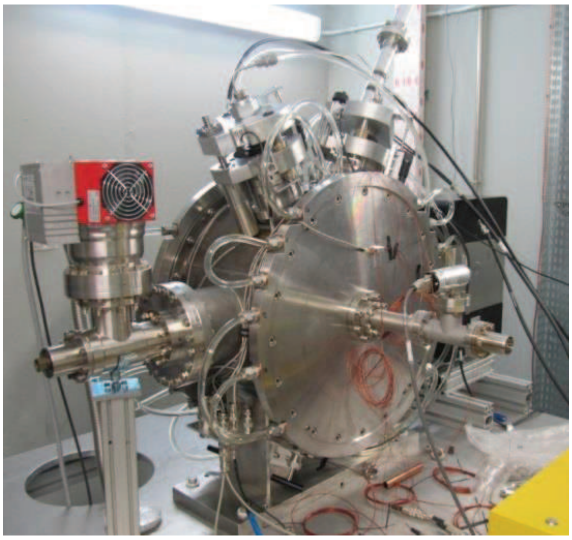

Figure 1: Test bench.

A solid state power amplifier (SSPA) [4] manufactured by BTESA (Spain) under CIEMAT specifications was used for the conditioning. It consists of ten parallel modules, each able to provide up to 2 kW. The low level RF system developed by CELLS/CIEMAT was used for the conditioning test bench, because all the local interlocks were already integrated: vacuum gauge, arc detector, reflected power, SSPA, temperatures, cooling flow, tuner limit switches and others. The enhanced low level RF system to be used in LIPAC has been developed by CIEMAT in collaboration with SevenSolutions (Spain).

*Work partially supported by Spanish Ministry of Economy and Competitiveness under projects AIC-A-2011-0654 and agreement published in BOE, 16/01/2013, page 1988
#fernando.toral@ciemat.es

ISBN 978-3-95450-168-7

BAKING

Flexible heating wires were wrapped around the cavity, and then the assembly was covered with aluminized foil for thermal insulation. The cavity body cooling is performed by water flowing through copper tubes soldered to its external surface with SnAg, which has a melting point of 221ºC. All the rest of cavity parts can withstand higher temperatures, except the polyurethane cooling hoses, which were disassembled. To avoid excessive local temperatures that could affect those joints, the direct contact between the heating wires and the tubes was avoided by using thermal insulation. In the same sense, the temperature sensors used by the controller were in contact with the heating wires, to limit their temperature to 170ºC, to avoid the softening of the solder. With that setpoint, the temperature at the cavity was 105ºC, enough to speed up the water pumping. The heating ramping rate was very slow, 20ºC per hour, to limit the thermal stresses induced by the poor thermal conductivity of the stainless steel. The baking lasted for 100 hours. Finally, a RGA analysis showed that no contaminants or leaks were present.

HIGH POWER TEST

The data acquisition system was able to register the following signals: vacuum level, tuner position, low level set point, drive signal from the low level system to the amplifier, forward and reflected power at the input coupler and cavity voltage from the pickup probe.

RF conditioning strategy consisted of starting with a low duty factor, 3%, raise the input power till reaching the nominal effective voltage, and then increasing the duty factor progressively. The low level RF system was able to keep a constant ramping rate of the input power. The tuner could be driven in closed-loop or manually. Interlock levels were set at 10^{-6} mbar for vacuum, 10 kW for forward power and 1 kW for reversed power.

First interlock triggers were due to reflected power at low effective voltages, from 3 to 30 kV. Next Section includes a careful analysis concluding that these triggers match the predicted multipacting between the drift tubes.

The readings of the cold cathode were very unstable when the cavity was powered, which could be caused by electrons arriving through the drift tube aperture. The problem was solved using a small dipole made of permanent magnets, which deflected those electrons. Figure 2 shows an infrared photograph of that region, with a peak temperature of 62ºC due to electron impacts. Besides, some triggers were due to a steady increase of the vacuum level. Since only the ionic pump was used, it was decided to install again the turbomolecular pump. That kind of triggers was eliminated with the enhanced pumping capacity. The tuner was driven manually by the operator at these first steps, to minimize the movements, which also avoided interlock triggers, although the reflected power was a bit higher.

The approximate voltage levels at which interlock triggers occurred were 40, 120 and 230 kV. Above 300 kV, the trigger levels were quite unpredictable, not located around a given level. When the nominal effective voltage of 350 kV was reached, the forward power was 9.2 kW, with a reflected power of 530 W. These values matched the calculations. With low power RF, the measured coupling factor was 1.217 (nominal value was 1, but it is very sensitive to the angular position of the coupler loop) and the unloaded quality factor Q_0 was 8761, 25% worse than calculated Q_0 with HFSS. The measured power loss is consistent with this difference.

Once the nominal voltage level of 350 kV was reached, the duty factor was increased to 5%, and then to 10, 20, 40, 80 and, finally, 100% (CW). For duty factor of 20%, it was necessary a long time (25 hours) to overcome the aforementioned multipacting levels, because once a interlock triggered the system, the power ramp should be very slow to avoid new triggers at the multipacting voltage levels. Therefore, the conditioning strategy was changed: for 40% duty factor, when several triggers took place at the same voltage level, the conditioning was started at 80% duty factor. It was observed that the first trigger happened at a higher voltage. Afterwards, coming back to 40% duty factor, one could reach without triggers the voltage level with the same average power than the last trigger at 80% duty factor, that is, 1.41 times the voltage. With that approach, the conditioning duration was shortened.

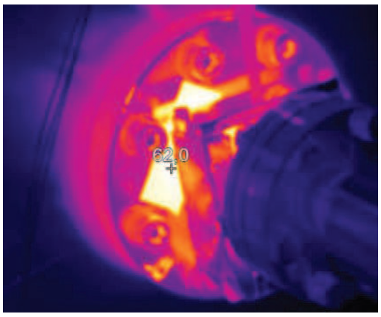

Figure 2: Infrared image of the beam pipe flange.

Obviously, the cavity warms up with increasing duty factor, which enhances the power losses due to the reduced copper conductivity. At nominal effective voltage of 350 kV and CW, the input power is 9.5 kW. The maximum temperature at the cavity sensors is 45ºC. The peak temperature measured with the infrared camera is 61ºC at the manual plunger bellow. Therefore, the cooling regime was validated.

The radiation spectrum was measured with a gauge in front of the beam pipe at nominal effective voltage of 350 kV. Most of the radiation takes place about 90 keV, being 300 keV the highest detected energy (see Fig. 3). The voltage at the central gap is 166 kV.

A maximum of 358 kV was reached with 9.96 kW, the maximum input power allowed by the interlock setpoint. Finally, 420 kV was the highest effective voltage reached at 5% duty factor with 12.2 kW of input power, which proved the proper conditioning of the cavity and input coupler. This regime is very interesting to deal with the high beam loading effect expected in LIPAc.

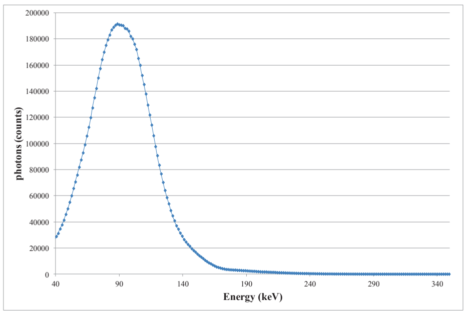

Figure 3: Radiation spectrum at nominal voltage.

MULTIPACTING

A detailed analysis was done to understand the voltage levels where triggers commonly happen. The likely cause is multipacting at the drift tube ends or the coupler coaxial conductors. Both can be simply modelled as parallel plate capacitors. Some analytical formulas predict the voltage V and the impact energy U for that geometry [5], when the initial phase of the particle is 0º (i.e. the particle leaves the surface exactly when the electric field is null). A generalization of those formulas has been done for the general case of a particle starting with a delay phase δ between 0 and 90º:

$$V = \frac{4\pi m_0 c^2 L^2}{e\lambda^2(2n+1)\left[\cos\delta + \frac{2\sin\delta}{\pi(2n+1)}\right]}$$
$$U = \frac{8 m_0 c^2 L^2}{\lambda^2(2n+1)^2\left[1+\frac{2\tan\delta}{\pi(2n+1)}\right]^2} \quad (1)$$

where m_0 is the electron rest mass, c is the speed of light, L is the gap length, e is the electron charge, λ is the wave length at vacuum, n = 1, 2 … is the multipacting order, V is the gap voltage and U is the impact energy on the opposite side of the gap.

Typical impact energies which produce multipacting are in the range from 100 to 1500 eV [5], for which the secondary emission coefficient of copper is greater than 1.

For the re-buncher gaps (32 mm long), one can find that first order multipacting at 175 MHz is possible for $0 \leq \delta \leq 77$º, and second order multipacting for $0 \leq \delta \leq 50$º. No higher order multipacting would be possible in the gaps. These delay ranges correspond to a gap voltage range of 1.89 kV $\leq V \leq$ 2.65 kV and 0.73 kV $\leq V \leq$ 0.93 kV, respectively. The subsequent effective cavity voltage ranges are detailed in Table 1. These values fit the interlock triggers.

Multipacting in the coupler has been also analysed. In this case, the gap is 21.9 mm, and the multipacting (only first order) is expected between 0.89 and 1.09 kV, corresponding (in case of no reflected wave), to a forward signal between 7.9 and 11.9 kW, and cavity voltages between 319 kV and well over the nominal value.

A fast data logger allowed recording the signals at the moment of the interlock trigger. Figure 4 shows the difference of the cavity energy dissipation after an arc in the input coupler, when the cavity energy dissipates in 20 µs according the cavity time constant decay; and after an arc in the cavity, when the cavity energy suddenly dissipates in 0.3 µs. Stored energy was very similar in both cases, corresponding to 320 kV effective voltage.

Table 1: Expected Cavity Voltage Ranges for Multipacting in the Gaps

From (kV)	To (kV)	Gap	Order
1.56	1.99	Central	2
1.82	2.32	Intermediate	2
4.05	5.68	Central	1
4.72	6.62	Intermediate	1
7.30	9.30	End	2
18.9	26.5	End	1

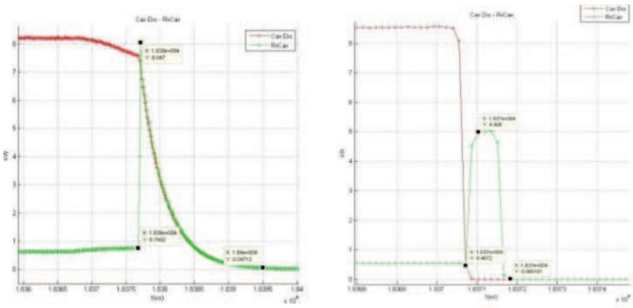

Figure 4: Cavity energy decay (red) and reflected power (green) after an arc in coupler (left) and cavity (right).

CONCLUSION

High power tests on the re-buncher cavity prototype for LIPAC have been successfully performed at CELLS RF laboratory. Measurements nicely fit the calculations. After this validation, the fabrication of the second re-buncher cavity is ongoing, based on the same design.

ACKNOWLEDGMENT

The authors warmly thank the companies involved in the fabrication of the buncher (HTS, ZEHATZ, DMP and Ecor Research) and also CELLS colleagues supporting the assembly of the test system.

REFERENCES

[1] I. Podadera et al., WEPS058, Proc. of IPAC'11, San Sebastián, Spain (2011), http://www.JACoW.org
[2] D. Gavela et al., THPRI050, Proc. of IPAC'14, Dresden, Germany (2014), http://www.JACoW.org
[3] D. Gavela et al., THPRI051, Proc. of IPAC'14, Dresden, Germany (2014), http://www.JACoW.org
[4] M. Weber et al., "RAMI Optimization-Oriented Design for the LIPAc RF Power System", these proceedings, WEPMN055, Proc. of IPAC'15, Richmond, Virginia, USA (2015).

[5] R. Parodi, “Multipacting”, CERN Accelerator School 2010: RF for Accelerators, Ebeltoft, Denmark, CERN-20101-007, pp. 447-458 (2010).