ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB272

VALIDATION OF TWO RE-BUNCHER CAVITIES UNDER HIGH BEAM LOADING FOR LIPAc*

D. Gavela†, I. Podadera, F. Toral, Ciemat, Madrid, Spain
I. Moya, Fusion For Energy, Garching, Germany
F. Scantamburlo, IFMIF/EVEDA, Rokkasho, Japan

Abstract

Two re-buncher cavities were installed at the Medium Energy Beam Transport line of the LIPAc accelerator, presently being commissioned at Rokkasho (Japan). They are IH-type cavities with five gaps providing an effective voltage of 350 kV at 175 MHz for a nominal operation of 125 mA CW deuterons at 5 MeV. After full conditioning and beamline integration in Europe, the cavities were installed in the accelerator with special care given to the alignment with respect to the rest of the components. The RF line, cooling circuits and instrumentation were also mounted. The cavities were operated with a FPGA based LLRF system. A re-conditioning of the cavities was performed in first place, followed by tests with a pulsed beam with increasing currents. A maximum pulsed beam current of 100 mA was reached while operating the buncher cavities, under which they reached voltages up to 340 kV and 260 kV respectively. As expected, the beam loading was significative, leading to a series of difficulties and required strategies for a good operation that are discussed in this paper. The effect on the beam dynamics, measured by beam position monitors downstream of the bunchers is also discussed.

INTRODUCTION

The LIPAc accelerator is a LINAC for deuterons in CW with an average current of 125 mA [1]. Its purpose is to serve as prototype for a future IFMIF facility dedicated to the production of high neutron fluxes with which to irradiate and evaluate future candidate materials for fusion reactors. The final energy of the accelerator will be 9 MeV, although the work presented here was done during a previous commissioning phase at which the energy was 5 MeV in pulsed mode.

Both bunchers are located at the MEBT line [2], which also includes several BPMs, quadrupole magnets and scrapers. It was completely designed, mounted, aligned at Ciemat in Madrid. The bunchers are normal conducting, IH-type cavities with 5 gaps each [3]. They operate under the 175 MHz working frequency of LIPAc. Each of them can provide up to an effective voltage of 350 kV with a power consumption of 9.5 kW [4, 5].

*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, the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan and the Euratom research and training programme under the DONES preparatory phase, project No. 870186. The views and opinions expressed herein do not necessarily reflect those of any of these parties.
† daniel.gavela@ciemat.es

The cavity vessel is made of stainless steel with an internal copper coating, with external surface cooling. The stems are made of solid copper in one piece, with internal cooling (Fig. 1). Each cavity has two plungers for tuning automatically operated with stepper motors. The coupler is loop-type, custom designed, with a brazed alumina window. A pickup signal made from a commercial coaxial feedthrough with a soldered copper loop is used to measure the cavity voltage and phase.

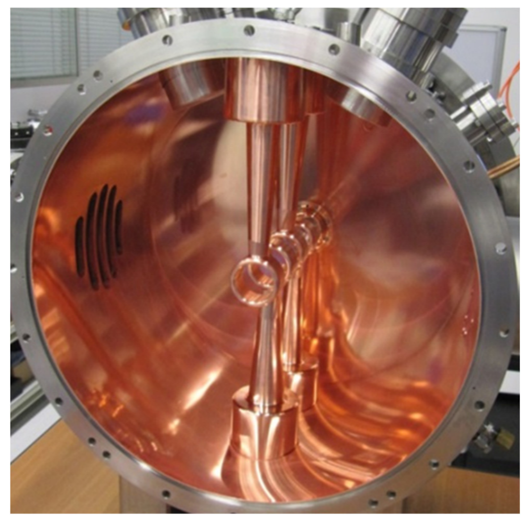

Figure 1: Detail of the interior of a buncher cavity.

The RF power is provided by solid state amplifiers and transferred to the cavities with 3 ¼ inches coaxial rigid lines. The LLRF system is FPGA-based [6]. It includes very fast loops for inter and intra-pulse control of the cavity voltage and phase, manages the movement of the tuning plungers and includes a very fast RF cut in case of an arc detection, which can be triggered both from optical arc detectors or from a sudden increase of the reflected power signal. The LLRF system is integrated into the EPICS control system of the whole accelerator.

SET UP AND RE-CONDITIONING

The cavities arrived at Rokkasho site installed within the MEBT line. The RF rigid line, water cooling and instrumentations were installed and tested (Fig. 2).

Each cavity includes 8 PT100 sensors (water inlet and outlet temperature, plus six metal temperatures on the locations where higher temperatures are expected). Each tuner carries a potentiometer for the position of the plunger, plus two limit switches. All those signals were integrated

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into the MEBT OPI in the EPICS system, together with the cavity voltage, forward and reverse powers taken from the LLRF. A logic of alarms and interlocks was developed in case of excessive temperature or tuners at the end of the stroke. The OPI can also be used to operate the tuners manually.

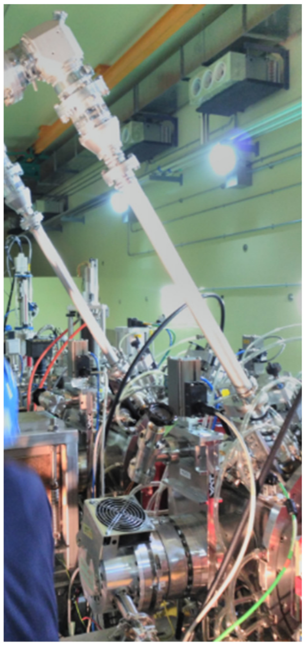

Figure 2: RF rigid coaxial line connected to the buncher cavities installed at the accelerator hall.

A re-conditioning (the cavities had previously been conditioned at an RF laboratory in Spain) was performed. It was done quite fast directly in CW mode. Both cavities reached the nominal voltage in less than 10 hours of operation each.

BEAM OPERATION

The results presented here correspond to a phase in which the beam was in pulsed mode. At the time of operation the beam chopper in the injector was not working. This produced a highly variable beam along the pulse, with a very progressive growth of the beam current from zero to a current close to the nominal value during the first 200-300 µs of the pulse during which the phase of the bunches varied also in a range of about 80º. After that initial phase, which probably should be cut when the chopper is working, the beam quality improved, the bunch phase was constant, although the beam current still increased in the order of 25% in that time (Fig. 3).

This poses a very difficult challenge for the LLRF. First of all, the beam loading with the cavity perfectly tuned is extreme (in the order of 800 kV, more than twice the cavity nominal voltage) and of reactive type. A large detuning is therefore compulsory to reduce it. The typical required detuning would be between 80 and 300 kHz, corresponding to detuning angles of 75 – 86 º.

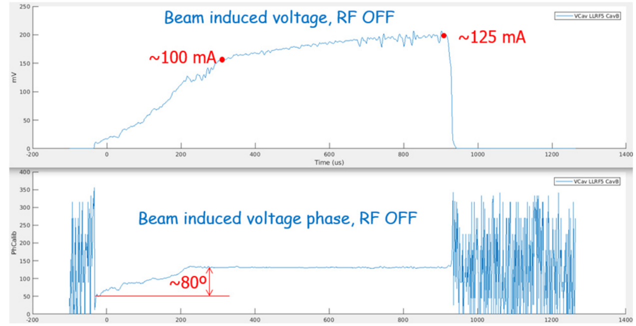

Figure 3: Beam induced voltage, magnitude and phase during a working pulse.

Hence the cavity response is reduced by a factor between 4 and 14 with respect to a perfectly tuned cavity condition not only for the beam loading, but also regarding the response to the RF power from the amplifier. As it can be seen in Fig. 4, the cavity voltage is mostly produced by the beam itself, with just a small correction created by the amplifier. The cavity works consequently almost as a passive component, with 88% of the cavity voltage produced by the beam itself.

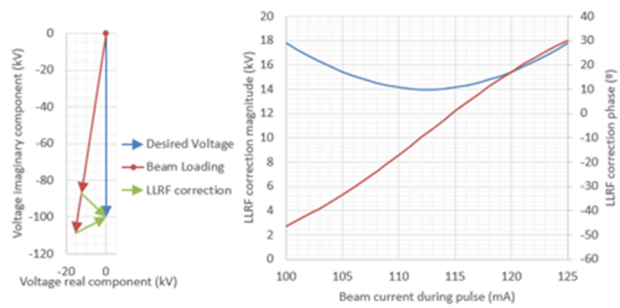

Figure 4: Beam loading and LLRF correction for a desired cavity bunching voltage of 100 kV and beam current between 100 and 125 mA. Complex representation (left). Amplitude and phase of the correction as a function of the beam current(right).

This happens at an optimally detuned cavity, which was adjusted for the middle of the pulse. The deviations of beam current (below and above the average) require from the amplifier a larger correction and a signal the phase of which changes a lot between the beginning and the end of the pulse.

An example of the cavity regulation in such conditions in the real world is shown in Fig. 5. An acceptable regulation was achieved, except for the first 300 µs of the pulse, which should be eliminated when the chopper is working. The LLRF is close enough to achieve an almost constant cavity voltage and phase. No dangerous jumps in the forward or reverse signals were observed.

The reverse power does not reach any dangerous level for the amplifiers or the circulators, even at the initial moments of the pulse during which the low beam current makes the cavity detuning suboptimal. Indeed, they are capable of working with full reflected power for several sec-

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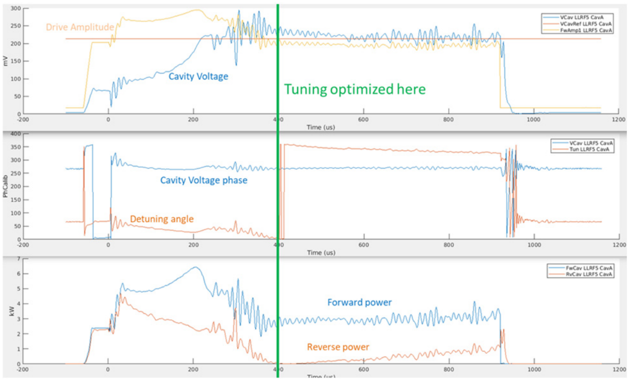

Figure 5: Cavity signals during a typical high beam current pulse.

onds. A feature was implemented in the LLRF system for a change in the working frequency when there was no beam (while waiting for it), but it created an undesirable jump in the cavity conditions at the moment of the frequency change that led us to discard that feature for the moment.

REQUIREMENTS FOR LLRF

With the accumulated experience, some general requirements for the LLRF system, specific for buncher cavities under high beam loading have been determined, especially in pulsed mode. All of them have been implemented on LIPAc LLRF or have been defined for its implementation for next commissioning phase.

- Deal with the angular response to the drive signal. The large detuning of these cavities produces a response to the drive signal almost perpendicular between the perfectly tuned and the optimally detuned situations. The PID loop has to take this effect into account when calculating the drive signal from the error one.
- Deal with the big variations in the required drive signal (both in amplitude and phase), which are necessary to apply with small variations of beam current.
- Deal with drive signals working in different quadrants at the beginning and end of the pulse. If the current is slightly growing during the pulse, the phase difference between the required drive signals at the beginning and end of the pulse can in the order of 90º.

BUNCHERS EFFECT ON THE BEAM

The beam was measured by three BPMs located downstream of the bunchers. The bunch length (inversely related to the BPM current) decreases when the buncher voltage is increased up to a minimum corresponding to the focal point located at the centre of the BPM (Fig. 6).

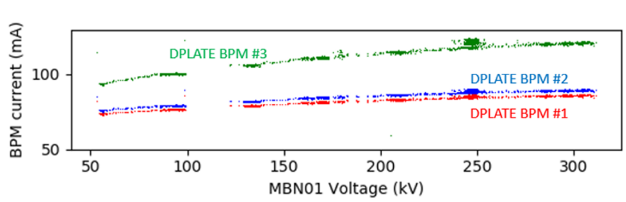

Figure 6: BPM current measured downstream of the bunchers as a function of the voltage of buncher #1.

A complete map including the voltages of both bunchers was performed for the characterization and optimization of the beam at the MEBT line.

CONCLUSION

The re-buncher cavities were operated at high beam current in pulsed mode. The beam loading poses big challenges, specific to the buncher cavities, that involve a very high detuning and special difficulties with the phase regulation. An acceptable optimization of the cavities voltage and phase was achieved. Some modifications that will be introduced in the LLRF system for the next beam phase have been described. The bunching effect of the cavities was measured and presented. A complete characterization of the beam at the MEBT line was performed.

ACKNOWLEDGEMENTS

The authors would like to thank the persons involved in the LLRF system development, including Ciemat RF team and Seven Solutions, and everybody working in the LIPAc operation at Rokkasho site.

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