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MULTI-HARMONIC BUNCHER (MHB) STUDIES FOR PROTONS AND IONS IN ESS-BILBAO*

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Abstract

Multi-harmonic buncher cavities (MHB) are used in ion linacs to increase the bunch separation, so the beam can be injected in rings or used in applications like time-of-flight experiments. ESS-Bilbao will develop a MHB intended to be tested in the CERN-ISOLDE facility. The design and prototyping include the buncher device itself as well as the solid-state power amplifier (SSPA) to power it. The buncher design (finite elements and beam dynamics) will be carried out to optimize it for ISOLDE beams and frequencies of 1/10th of their RF frequency. The testing of the cavity at ESS-Bilbao proton beam injector has also been studied.

INTRODUCTION

The RF frequency of radioactive ion beams accelerators is usually around 100 MHz [1]. In the case of HIE-ISOLDE [2], the frequency is f_0=101.28 MHz. The bunching of the beam carried out in the RFQ results then in a bunch separation of 9.87 ns. An increased bunch spacing to approximately 100 ns is requested by several research groups targeting experimental physics at this facility. The increased bunch spacing can be obtaining by bunching the beam before the RFQ to a frequency of 1/10th of the RF frequency, f=10.128 MHz, that will result in a bunch separation of 98.7 ns. This task can be done by a MHB device, located external to the RFQ. For low intensity beams where space charge effects are not relevant, a MHB can also be used to pre-bunch the beam and to reduce the length and the longitudinal emittance of the RFQ [3]. In this paper, the preliminary design of a MHB device is presented. The design is done with the HIE-ISOLDE application as objective, but the performance of the MHB installed in the ESS-Bilbao injector [4, 5] is also studied, with the aim of the future testing of the cavity in this facility prior to tests in HIE-ISOLDE(*).

MULTIHARMONIC BUNCHING

The optimum electric field time profile to bunch a continuous beam with bunch separaion of $1/f$ is that of a saw-tooth wave profile of frequency f [3], with a linear ramp of field centered at the middle of the bunch at time $t = t_0$. The saw-tooth profile can be synthesized by summing up the first harmonics of its Fourier expansion. Usually, four harmonic terms are enough to generate an adequate approximation of the wave shape. In the MHB, the electric field is applied between two electrodes that are powered up with the combined multiharmonic RF wave. In the ideal case, the actual electric field profile will be a uniform value between the electrodes, modulated by the MHB wave. In a real device the electric field between the electrodes depends on the electrode geometry and the aperture needed for the beam, so the actual performance of the MHB will be lower than the ideal one. The shape of the electrodes is usually designed by assuming a constant voltage and computed as an electrostatics problem to obtain the electric field shape. Then this field is modulated to obtain the adequate field spatial and temporal distribution and beam dynamics simulations are run to evaluate the bunching [3, 6–8]. For low frequencies the differences in the electric field shape between an electrostatics and a RF calculations are very low.

FEM-BEAM DYNAMICS SIMULATIONS

For this work, different electrode geometries are explored. The electrode geometry and the FEM calculations are done using an integrated simulation platform that makes use of GMSH [9] and FEniCS [10] open source libraries. Beam dynamics tracking simulations are done with GPT [11]. The integrated platform is driven by Python scripts that allow for quick parametric exploration or optimization.

RESULTS

For HIE-ISOLDE a preliminary MHB electrode design has been selected after parametric exploration. The beam characteristics are shown in Table 1. The MHB electrodes have an aperture of 20 mm in diameter, and the MHB vessel has a total length of 250 mm, to keep the values already defined in [6].

Table 1: Beam Characteristics for Simulations

	ISOLDE beam	ESS-Bilbao beam
A/q	4.5	1
β	0.003 28	0.0098
ϵ_x, ϵ_y	0.62 mm mrad	0.25 π mm mrad
Intensity	1 mA	45 mA

Different geometries have been explored and the beam dynamics results compared to the basic results shown in [6]. Geometries with a tail shape (as in [7]) or conical (as in [8]) have been explored. It is worth mentioning that the main aim of this work is not to find an optimum geometry of the buncher, but to explore the possibility of testing a MHB optimized for HIE-ISOLDE radioactive beams in ESS-Bilbao

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light ion injector (Fig. 1). The tail-shape and conical geometries can be seen in Fig. 2.

All geometries share some characteristics that are taken from [6] and kept for compatibility: the gap between electrodes is 5 mm, they have a minimum aperture with radius 10 mm, and the length of the buncher cavity is 0.25 m, with the electrodes centered.

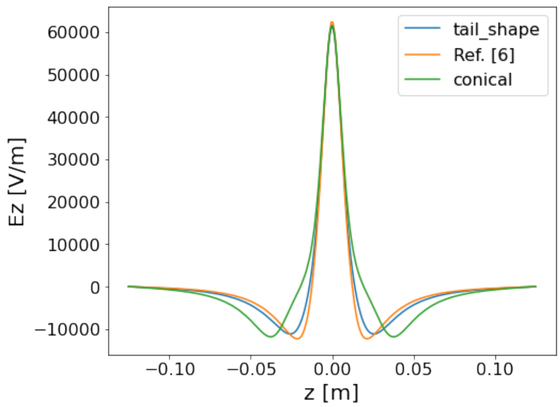

Figure 1: Comparison of on-axis field profile, $E_z(z)$, for three basic MHB geometries.

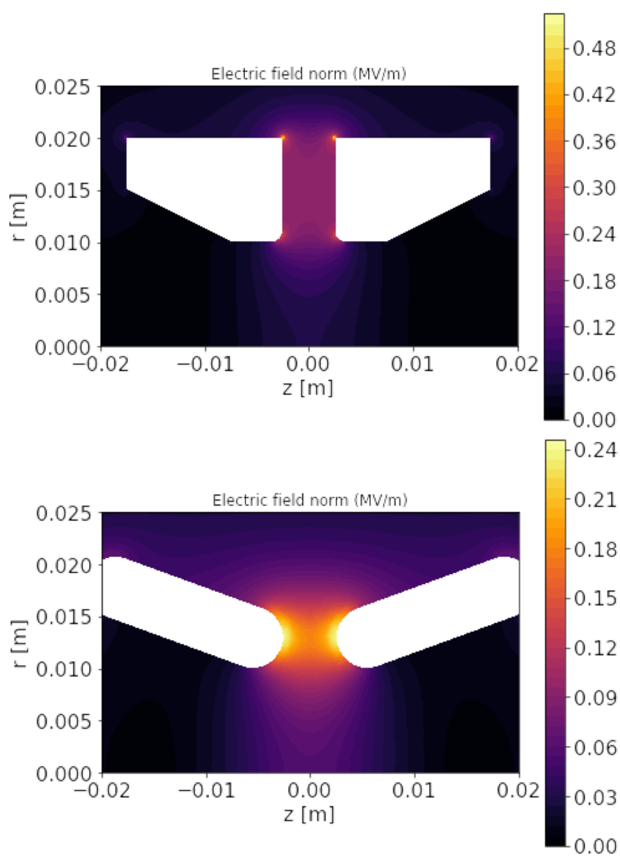

Figure 2: Electric field maps for the axisymmetric models with tail shape (top) and conical (bottom) buncher electrodes. Voltage between electrodes is 1 kV in both cases

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In all results shown in this paper, the multiharmonic sawtooth profile is built using harmonic weights of (1.0, -0.428, 0.215, -0.101). The bunching efficiency $b(z)$ is defined as the ratio of particles that arrive at coordinate z within a time window of 10 ns.

Results with HIE-ISOLDE Beam

Beam dynamics results of the MHB with ISOLDE parameters can be summarized in Fig. 3. Performance is similar for different geometries, with focusing distance around 2.7 m from the electrode center for an electrode voltage of 500 V. The increase of the electrode voltage (RF power) results in shorter focusing length, but not in better bunching efficiency. In figure 4 a heat map plot of the bunching efficiency of the MHB as a function of electrode voltage and focal length can be seen. This figure can be compared to the results obtained for ESS-Bilbao beam.

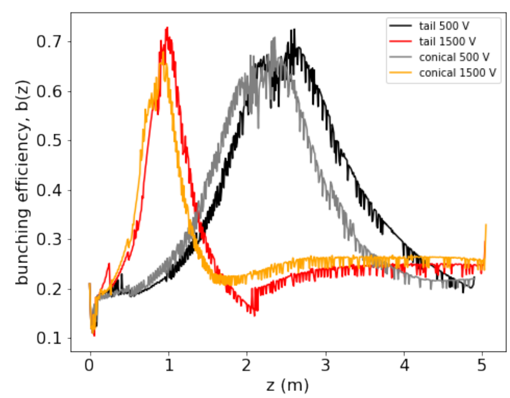

Figure 3: Bunching efficiency as a function of z for different geometries and electrode voltage, for HIE-ISOLDE beam.

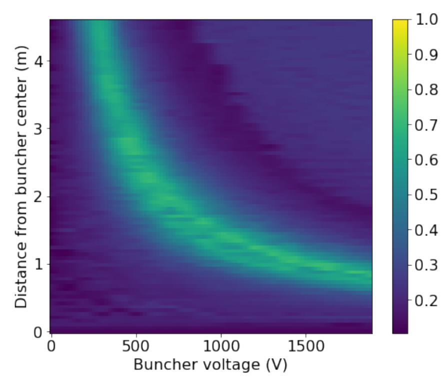

Figure 4: Heat map of bunching efficiency as function of electrode voltage and focal length, for ISOLDE beam.

Results with ESS-Bilbao Beam

In order to test the possibility of installing the MHB in ESS-Bilbao, several calculations have been done. ESS-Bilbao injector is a proton injector that consist on a ECR ion

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source, a LEBT and an RFQ (that is under fabrication). The protons are extracted with an energy of 45 keV. Other ions (like He) have also been successfully extracted. The ESS-Bilbao proton beam has very different characteristic than the beam at ISOLDE (see Table 1), so it is expected that the MHB will not operate directly. By reducing extraction energy or increasing the bunching frequency to 35.2 MHz (that would allow the beam to be transported through ESS-Bilbao RFQ), the bunching of the proton beam can be realized with an adequate focal length (see Figs. 5 and 6).

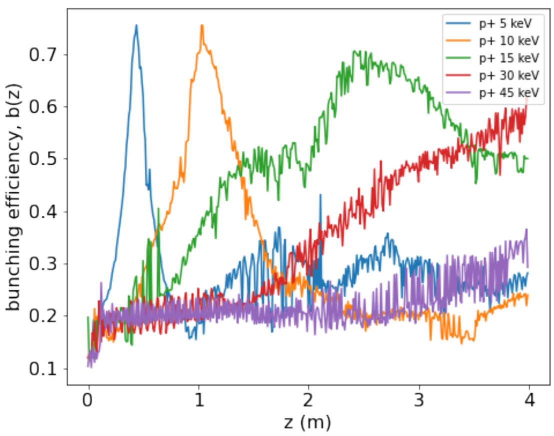

Figure 5: Bunching efficiency as a function of distance from the buncher center, for ESS-Bilbao proton beam with different extraction voltages.

CONCLUSION

A MHB device designed for HIE-ISOLDE can be tested at ESS-Bilbao using the beam from the light ion injector, after modifications in extraction voltage or RF frequency are performed.

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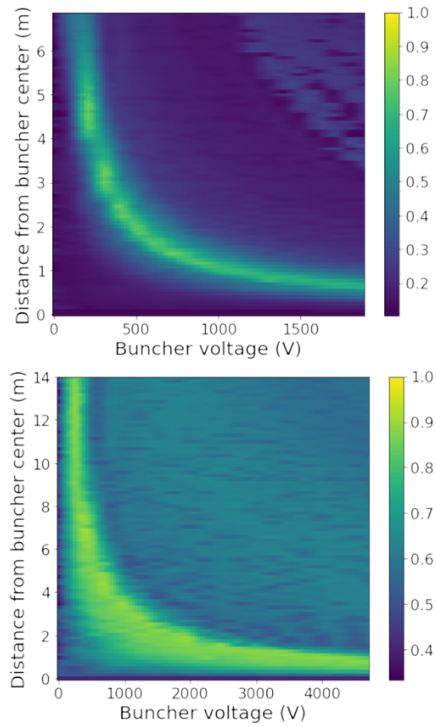

Figure 6: Heat map of bunching efficiency as a function of distance from the buncher center and electrode voltage, for ESS-Bilbao proton beam at 10 keV (top) and at an RF frequency of 35.2 MHz and 45 keV (bottom).

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