RF DESIGN AND LOW POWER MEASUREMENTS OF A NOSE CONE SINGLE GAP BUNCHER CAVITY

O. González#, N. Garmendia, P. González, L. Muguira, J. L. Muñoz, A. Zugazaga, I. Bustinduy
ESS Bilbao, Bilbao, Spain

Abstract

A nose-cone single-gap buncher cavity for the Medium Energy Beam Transport (MEBT) has been fully designed, manufactured and measured under low-power conditions at ESS-Bilbao. In this work, the main steps of the design process are first reviewed. Second, the cavity is thoroughly measured and characterized by means of an automatic test procedure based on the bead-pull technique. Third, the simulated and measured figures of merit are compared. Specifically, the results for the resonant frequency, the coupling and quality factors, the electric field profile, the R over Q ratio, the transit time factor and the tuning range are carefully analysed.

INTRODUCTION

In the framework of the ESS-Bilbao project, a nose-cone single-gap buncher cavity for the Medium Energy Beam Transport (MEBT) has been designed with the aid of the commercial simulator COMSOL [1]-[3]. The cavity geometry has been optimized in order to maximize the effective shunt impedance (RT^2) while both fulfilling the specifications imposed by the MEBT beam dynamics design (Table 1) and avoiding the electrical discharge or multipacting. The latter is achieved by limiting the peak surface electric field (*Kilpatrick* limit). The optimization procedure followed as well as the final cavity geometry and its figures of merit can be found in [1].

Although copper was assumed as the material for the designed cavity, a first prototype has been manufactured and measured in stainless steel (figure 1) which includes: a vacuum port (A), two tuning ports (B and D), a RF coupler port (C), a pick-up port (E), a blind cover port (F) and a cradle (G). At a later stage, a copper plating technique will be applied to the cavity.

BEAD-PULL TEST BENCH

The cavity has been measured and characterized by means of an automatic test procedure based on the bead-pull technique fully developed at ESS-Bilbao.

Table 1: Cavity Specifications

Parameter	Value	Unit
Frequency	352.2	MHz
Particle Energy	3	MeV
Effective Voltage (V_0T)	140	kV
Bore diameter (aperture)	30	mm
Cavity length (L)	126	mm
Peak electric field (*Kilpatrick*)	27.5 (1.48)	MV/m

#ogonzalez@essbilbao.org

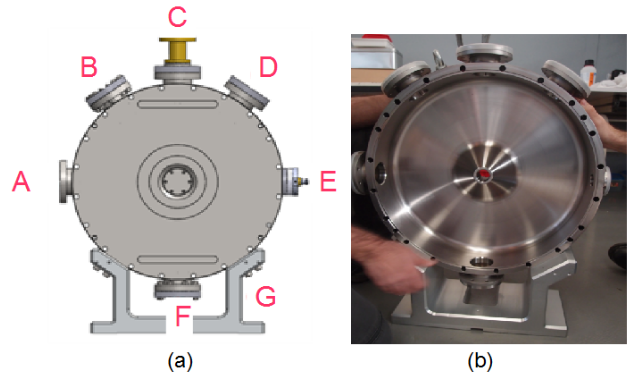

Figure 1: (a) Designed and (b) manufactured cavity.

Theory

The bead-pull technique [4,5] is based on the perturbation theory which states that when a small dielectric bead is introduced into a cavity, it causes a frequency shift given by

$$\frac{\Delta\omega}{\omega} = -F\frac{\omega E_0^2}{PQ_0}, \quad (1)$$

where F is the form factor, ω is the resonant frequency, E_0 is the absolute electric field, P is the dissipated power and Q_0 is the unloaded quality factor. The form factor F only depends on the material and geometry of the bead.

Moreover, the characteristic impedance or ratio "R over Q", which exclusively depends on the cavity geometry and not on the material properties, can be computed as [5]

$$\frac{RT^2}{Q_0} = \frac{1}{F\omega}\left[\int_{-L/2}^{L/2}\sqrt{\frac{\Delta\omega}{\omega}}\, e^{\frac{j\omega z}{\beta c}}\, dz\right]^2, \quad (2)$$

where z is the longitudinal axis of the cavity, β is the normalized velocity and c is the speed of light.

Design and Measurement Procedure

Figure 2 shows the test-bench implemented to carry out the measurements. It includes: 1) a cradle to support the

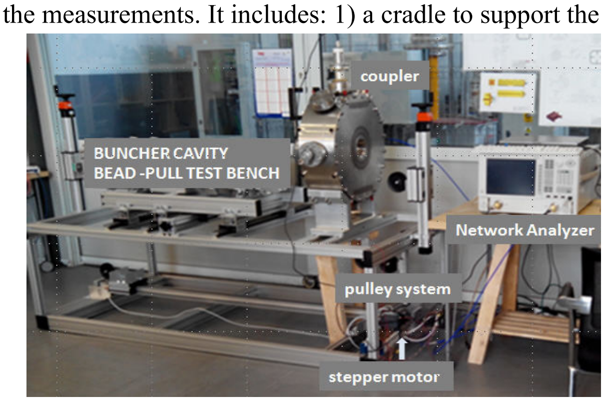

Figure 2: ESS-Bilbao bead-pull test bench design.

Table 2: Simulated and Measured Figures of Merit of the Buncher Cavity shown in Figure 1

Figures of Merit	Simulated (No ports)	Simulated (1 pick-up, 1 coupler, rest blind covers)	Measured (Teflon)	Measured (Glass)	Measured (Macor)
Frequency TM_{010}, [MHz]	352.1517	351.16	350.814	350.814	350.814
Quality factor $(Q_0)_{TM010}$	3233	3158	3012	3011	3000
Effective Voltage (V_0T), [kV]	140	140	140	140	140
Transit Time Factor (T)	0.593	0.591	0.58	0.58	0.58
R over Q (RT^2/Q_0), [Ω]	59.57	59.47	61.3	61.2	60.6

cavity and to align the wire, 2) a pulley system to fix the position of the wire in the transversal plane, 3) a Dyneema-type wire to lead the bead, 4) an integrated stepper motor to pull the bead through the cavity and 5) a network analyzer to measure the field profile from the *Scattering* parameters.

Moreover, when the bead perturbation is very small in the cavity, the shift in the resonant frequency $\Delta\omega$ is hard to measure. A more efficient method in terms of accuracy and time is to measure the phase shift of the transmission parameter (S_{21}) at the original resonant frequency of the cavity (also called *"unperturbed"* resonant frequency) as the bead is pulled throughout the cavity. Then, the normalized frequency shift is computed as [6]

$$\frac{\Delta\omega}{\omega}=\frac{1}{2Q_l}\tan(\Delta\phi), \qquad (3)$$

where Q_l is the measured loaded quality factor and $\Delta\varphi$ is the measured phase shift at the *"unperturbed"* frequency.

Therefore, the measurement procedure to characterize the cavity comprises the following steps:

- Measure the unperturbed resonant frequency ω, and the loaded Q_l and unloaded Q_0 quality factors.
- Pull the bead through the cavity by using the motor and measure $\Delta\varphi$ as a function of the bead position to finally compute $\Delta\omega/\omega$ by using equation (3).
- Compute RT^2/Q_0 and the absolute field E_0 by using equations (2) and (1), respectively.

Bead Calibration

In order to compute the form factor F empirical formulas can be used [4]. However, to more accurately characterize a cavity, it is strongly recommended to derive its actual value from a known field [5], i.e. from a resonant cavity with analytical solution. Moreover, the fields in the cavity used for calibration should have the same field distribution that the one in the analysed cavity.

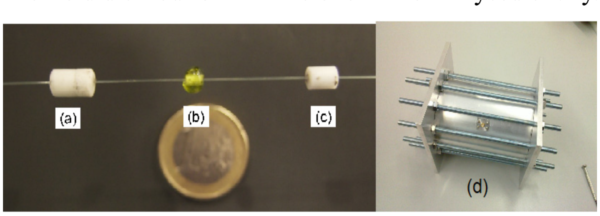

Figure 3: (a) macor (ε_r=6), (b) glass (ε_r=4.5) and (c) teflon (ε_r=2.1) dielectric beads and (d) manufactured pillbox cavity in aluminium (radius = 65 mm, length = 200 mm).

In ESS-Bilbao, the pillbox cavity shown in figure 3-(d) has been used for this purpose since it fulfills the two aforementioned conditions: it has an analytical solution and the field distribution of the TM_{010} mode is the same that for the buncher cavity. The form factors for each of three beads shown in figure 3 have been obtained.

RESULTS

Figures of Merit

Table 2 shows the figures of merit for the buncher cavity. The following aspects can be pointed out:

- A frequency shift of around 1.3 MHz between the designed and the manufactured cavity is observed. This is so because the different ports of the cavity were not taking into account during the design process. To prove that, the model is again simulated including a pick-up, a RF coupler, while letting the rest of the ports as blind covers. The frequency shift between simulations and measurements is now reduced to 0.3 MHz, which is mainly due to manufacturing issues related to the final dimensions.
- The measured Q_0 shows a good agreement with the simulated one (only a 7% lower) for stainless steel.
- The measured Transit Time Factor (T) shows a good agreement with the simulated one, thus indicating that the electric field has been well sampled by the phase difference $\Delta\varphi$ induced by the bead. A suitable digital filtering of the measurement noise is a key issue to obtain accurate results.
- The simulated value of RT^2/Q_0 is well reproduced by the measurements. Since this figure of merit depends only on the geometry, this result indicates that the cavity is quite well manufactured.
- Moreover, figure 4-(a) shows a comparison of the measured and simulated frequency shifts caused by the beads as a function of the axial position z when pulling the Teflon bead inside the cavity. A good agreement is observed.
- Finally, with the aid of equation (1), a comparison of the absolute electric field on the axis E_0 is presented in figure 4-(b). As it can be seen, a good agreement is once more observed.

ISBN 978-3-95450-142-7

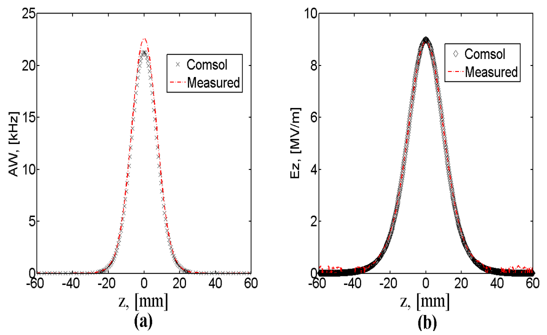

Figure 4: Comparison of the measured and simulated (a) frequency shift $\Delta\omega$ and (b) the absolute electric field E_0, as a function of the axial position z for the teflon bead.

Table 3: Tuning Range for the Buncher Cavity

Tuner Penetration (2 tuners) , [mm]	f_{TM010},[MHz] (Simulated)	f_{TM010},[MHz] (Measured)
No tuners (blind covers)	351.16	350.814
0 (flush position)	351.24	350.95
5	351.33	351.07
10	351.45	351.19
15	351.48	351.31
20	351.71	351.43
25	351.87	351.55
Tuner Range, [MHz] (Sensitivity)	0.63 (25kHz/mm)	0.6 (24 kHz/mm)

Tuning Range

The tuning system designed for the buncher cavity [2] consists of two slug tuners (diameter = 47 mm) which must be able to tune the operating frequency of the cavity due to manufacturing and alignment errors. Table 3 shows the results obtained. A measured tuning range of 0.6 MHz is obtained when both tuners are inserted at the same time up to 25 mm. It shows a good agreement with the simulated one, thus validating the tuning system.

Coupler and Pick-up

Figure 5-(a) shows the RF coupler designed at ESS-Bilbao [3]. The input interface is a standard 1-5/8 in flanged rigid coaxial and a window has been designed to protect the vacuum of the cavities. During operation, the coupler must inject a maximum peak power of 15 kW.

In order to minimize the reflected power, a loop has been designed to obtain a suitable coupling factor. A coupling factor of β=1.5 was obtained for a quality factor of Q_0 = 23477 (copper cavity). Once the cavity is re-simulated with stainless steel, the measured coupling factors agree well with the simulated value for different positions and configurations of the couplers, thus validating the design process.

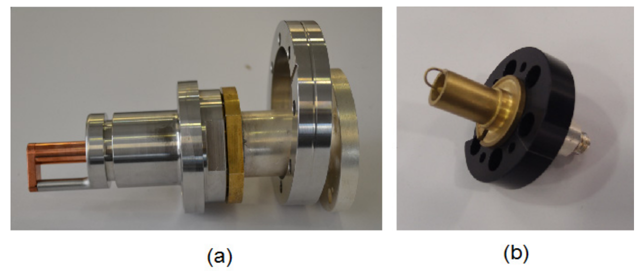

Figure 5: (a) RF coupler for the buncher cavity designed at ESS-Bilbao; (b) LEP pick-up designed by CERN.

Finally, the LEP pick-up designed by CERN has been used to perform measurements in transmission mode. As shown in figure 5-(b) it consists of a loop-type probe whose coupling factor is always lower than $\beta<0.03$, to cause a negligible perturbation in the cavity, while sampling with enough accuracy.

CONCLUSIONS

Generally speaking, the measured figures of merit of the buncher cavity agrees well with those obtained by COMSOL, thus validating the design process.

Specifically, it has been shown that the effects of the different ports of the cavity must be taken into account at the design stage. Once this is achieved, the discrepancy in the resonant frequency between simulations and measurements is reduced to barely 0.3 MHz which can be easily compensated with the tuning system.

Moreover, it has been shown that the bead-pull system developed at ESS-Bilbao shows a promising performance provided that a calibration step is performed with the aid of a cavity with analytical solution and with the same operating mode that the cavity under analysis.

Finally, since the measured quality factor is only a 7% lower than the simulated one, both the coupling factor and the tuning range computed during the tests agrees well with the designed value.

As future work, a copper plating technique will be applied to the cavity and it will again be characterized by means of the bead-pull test stand presented in this work.

ACKNOWLEDGMENT

The authors would strongly like to thank R. Suitbert and M. Vretenar for their valuable comments.

REFERENCES

[1] O. González, et al., "Preliminary Electromagnetic Design of the Re-bunching RF Cavities for the ESS-MEBT", ESS-AB Technical Note 35, 2012, http://ess-scandinavia.eu/ess-ad-technical-notes

[2] O. González, et al., "Electromagnetic Design of the Tuning System for the Re-bunching RF Cavities of the ESS-MEBT", ESS-AB Technical Note 36, 2012, http://ess-scandinavia.eu/ess-ad-technical-notes

[3] O. González, et al., "Electromagnetic Design of a Power Coupler for the ESS-MEBT", Chapter 4 ESS-AB Technical Design Report, 2013.

[4] McGinnis et al., "Microwave Measurements and Beam Instrumentation Laboratory", USPAS, http://uspas.fnal.gov, January 2012.

[5] "Bead-pull notes", USPAS, http://uspas.fnal.gov, January 2010.

[6] J. Byrd et al.,"Microwave Measurement Laboratory", USPAS, http://uspas.fnal.gov, June 2010.

ISBN 978-3-95450-142-7