BEAD-PULL MEASUREMENT METHOD AND TUNING OF A PROTOTYPE CLIC CRAB CAVITY

R. Wegner, W. Wuensch, CERN, Geneva Switzerland
G. Burt, B. Woolley, Lancaster University, UK

Abstract

A bead-pull method has been developed which measures in a single bead passage the amplitude and phase advance of deflecting mode travelling wave structures. This bead-pull method has been applied to measure and tune a Lancaster University-designed prototype crab cavity for CLIC. The technique and tuning results are described.

INTRODUCTION

The prototype CLIC crab cavity, designed by Lancaster University [1], is a multi-cell travelling wave cavity with ten regular and two single-feed coupling cells. In order to provide synchronism with the beam, the phase advance of each cell needs to be adjusted to its nominal value to correct for machining deviations, etching and assembly artefacts. This adjustment process is called tuning.

Figure 1 shows the electric field of the deflecting mode inside the crab cavity and the coordinate system used. The Brillouin diagram of the first modes in the regular cell is plotted in Fig. 2. The desired quasi-TM$_{11}$-mode has a phase advance of -120° per cell (backward wave) at the operating frequency of 11.994 GHz and a group velocity of ~3.3% of the speed of light c_0.

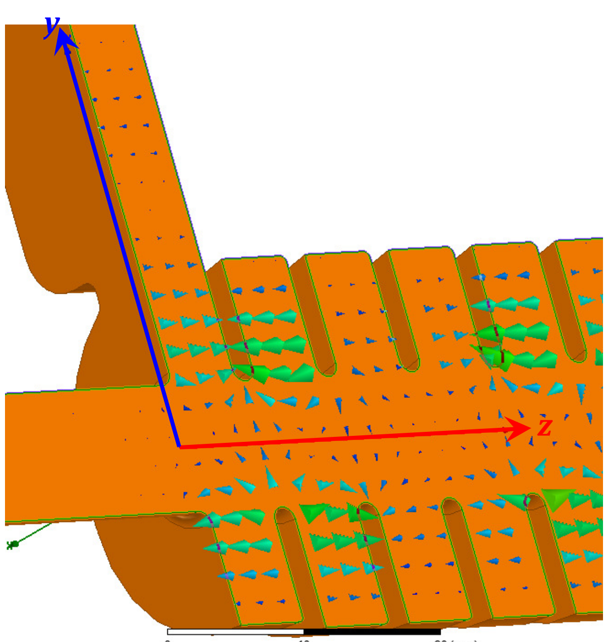

Figure 1: Electric field distribution of the deflecting quasi-TM$_{11}$-mode in a cross section of the crab cavity. The power is fed into the structure via the input coupler (top left). The following coordinate system is used: z is the beam axis and y is the direction of desired deflection.

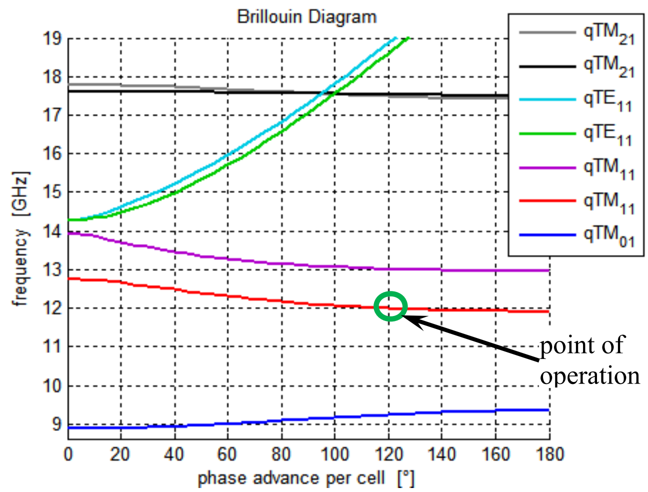

Figure 2: Mode spectrum of the first seven modes. The operating quasi-TM$_{11}$-mode (red) is well separated in frequency from the fundamental mode and the higher order modes, including the x-polarised quasi-TM$_{11}$-mode (purple).

ELECTOMAGNETIC FIELDS AND BEAD-PULL MEASUREMENTS

A charged particle is subject to the Lorentz force and inside the crab cavity it is deflected by the electric (E) and the magnetic (H) field of the operating mode. The relevant components for a deflection in y-direction are:

$$F_y = q\left(E_y + c_0\mu_0 H_x\right) = q\left(E_y + Z_{F0} H_x\right), \quad (1)$$

assuming that the charge q travels at the speed of light in z-direction. The vacuum permeability is denoted by μ_0 and the impedance of free space by Z_{F0}.

The electromagnetic field has been measured via a bead-pull measurement – a perturbation measurement where a bead is pulled through the cavity [2]. The change of input reflection is recorded and is proportional to the weighted sum of all electromagnetic field components squared [3] at the position of the bead, assuming a small perturbation:

$$\Delta S_{11} = S_{11,\,perturbed} - S_{11,\,unperturbed}$$

$$\Delta S_{11} = \sum_{*=x,y,z} \{(e_* E_*)^2 - (Z_{F0} h_* H_*)^2\} \quad (2)$$

The complex components e_x, e_y, e_z, h_x, h_y and h_z describe the polarisation and magnetisation effects of the bead in the local electromagnetic field. For the tuning of structures, it is usually sufficient to measure and evaluate only one out of the six electromagnetic field components. E_z is typically chosen for accelerating structures.

It is more difficult however to separate out only the desired components in case of a deflecting mode cavity. In some techniques, the electric and the magnetic fields are determined by a measurement with two different beads (e.g. a dielectric and a conductive bead) in combination with calculations to separate the field components [4].

For the tuning of the prototype CLIC crab cavity, the electromagnetic fields were studied and a method was found to select and measure a single field component – as for accelerating structures. The functional dependence of the deflecting mode's fields (y-polarised) in the vicinity of the cavity axis (x=0, y=0) are in first order approximation:

$$\begin{aligned} E_y(x,y,z) &\approx E_{y0}\cdot x^0\cdot y^0\cdot f_1(z)\\ E_z(x,y,z) &\approx E_{z0}\cdot x^0\cdot y^1\cdot f_2(z)\\ E_x(x,y,z) &\approx 0\\ H_x(x,y,z) &\approx H_{x0}\cdot x^0\cdot y^0\cdot f_3(z)\\ H_z(x,y,z) &\approx H_{z0}\cdot x^1\cdot y^0\cdot f_4(z)\\ H_y(x,y,z) &\approx 0\,. \end{aligned} \tag{3}$$

It is hard to find a material for a bead which perturbs magnetic fields and is transparent to electric fields. On the other hand, a dielectric bead which couples to electric fields and leaves magnetic fields unperturbed can be made (e.g. from appropriate paint or nail polish). Therefore, the focus is on the E_y component. In Fig. 3 the electric field components E_y and E_z are compared in the proximity of the cavity axis. $Z_{F0}H_x$ is added for academic reasons to visualise the relation between the deflecting forces from the electric and the magnetic field. With a small dielectric bead E_y can be measured with a small error contribution caused by E_z. The size of the bead is chosen as a compromise between good signal strength (from E_y) and small error contribution (from E_z). Even if the bead runs exactly on the cavity axis, the E_z field component will be perturbed due to the bead's transverse dimensions. For the presented measurements, a spherical bead of 1.3 mm diameter was used.

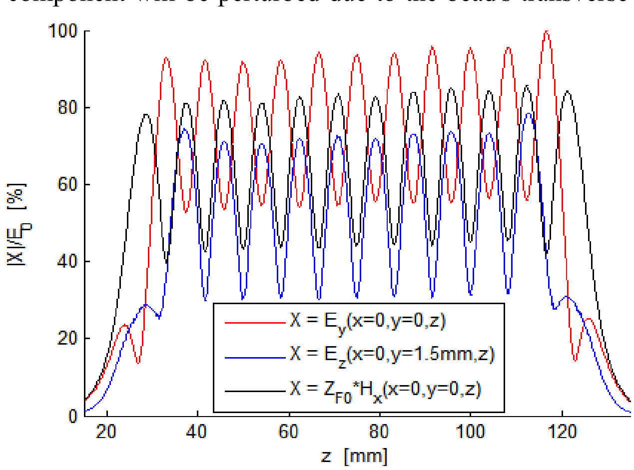

Figure 3: Comparison of different field components E_y, E_z and $Z_{F0}H_x$ along the cavity in the vicinity of the axis. E_z rises linearly with an offset in y-direction.

Looking at the situation from another point of view, the undesired coupling to the E_z component can be used to control the quality of the bead-pull measurements: Firstly, the contribution of E_z to the observable ΔS_{11} is smaller than the one of E_y in the proximity of the cavity axis, which is even boosted by measuring the square of the fields. Secondly, in longitudinal (z) direction, $|E_z|$ reaches its maxima in the middle of cells where $|E_y|$ has a minimum and vice versa at the irises between cells. Consequently, the peaks of ΔS_{11} (more precisely $\Delta S_{11}(z_{x,n})$ with $z_{x,n}=\max_{\{z \text{ cell } n\}}\Delta S_{11}(z)$) are the points least perturbed by E_z while contributions of E_z strongly influence the shape of the bead-pull pattern in the region of minimum $|\Delta S_{11}|$. The extraction from three example measurements is shown in Fig. 4 to illustrate the effect of the E_z component.

After each bead-pull measurement the bead-pull pattern was examined carefully to validate to bead's trajectory. During our tuning a few measurements were repeated to guarantee a good reproducibility, corresponding to an amplitude variation below ±1.0% and a phase variation below ±0.25° in E_y. The error due to the coupling to the E_z component was with less than 0.3% negligible.

A tuning program developed by J. Shi [2] was employed to extract the peaks of ΔS_{11}, to calculate the forward and reflected wave amplitudes and to determine the electric field profile in amplitude and phase.

Two comments for the presented method: Firstly, E_y is mainly located in the irises and not in the cells while the tuning pins act on the cells and hence affect E_y on either side. Secondly, a disadvantage of basing the measurement on the E_y component exclusively is that the magnetic field component H_x – which equally contributes to the deflection – cannot be measured directly.

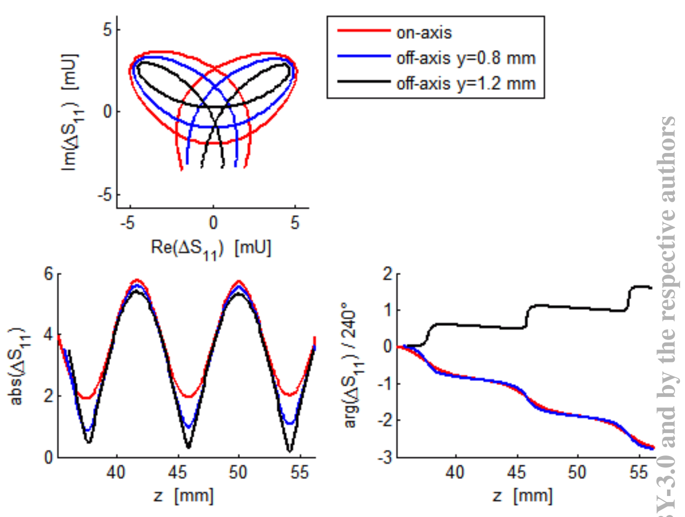

Figure 4: Change of input reflection ΔS_{11} for a bead running on axis (x=0, y=0) and off-axis (x=0, y=0.8 / 1.2 mm) through two regular cells. Top: ΔS_{11} in the complex plane, bottom left: magnitude of ΔS_{11} and bottom right: normalised phase of ΔS_{11} along the longitudinal direction.

ISBN 978-3-95450-142-7

TUNING

The tuning of the 12-cell prototype crab cavity (Fig. 5) was done in a pragmatic way. Going from the output to the input, firstly a bead-pull measurement was performed, then the electric field pattern (of E_y) was calculated and finally the cell under consideration was tuned via a brazed tuning pin (allowing both, a frequency increase and decrease) while observing ΔS_{11}. Thereafter the bead-pull measurement was repeated and the effect of the performed tuning evaluated. The tuning of each cell was repeated until the electric field pattern was satisfactory. Subsequently the next cell towards the input was tuned. Occasionally, a cell already tuned had to be revised. After 26 steps the phase advance per cell of all ten regular cells was in average within 120°±0.1° and did not vary more than ±1.0° over all cells so that the tuning could be finished. The final bead-pull measurement is shown in Fig. 6. Table 1 summarises the tuning for each cell. All cells apart from cell 9 had to be increased in frequency by 0.8 MHz in average for regular cells. The spread of 0.7 MHz (standard deviation) corresponds to a spread of 1 µm in the cell's diameter (racetrack shape, nominal diameters 24 and 29 mm) and underlines the excellent machining and assembly quality.

Table 1: Summary of tuning applied to the prototype CLIC crab cavity. The amount of tuning is quantified by the change of resonant frequency Δf as well as the change of input reflection $|\Delta S_{11}|$.

cell	$\lvert\Delta S_{11}\rvert$ [mU]	Δf [MHz]	cell	$\lvert\Delta S_{11}\rvert$ [mU]	Δf [MHz]
input	9.8	0.60	7	8.4	0.54
2	20.4	1.31	8	23.6	1.52
3	27.9	1.79	9	-12.3	-0.79
4	9.1	0.58	10	11.0	0.71
5	9.5	0.61	11	19.4	1.25
6	10.7	0.69	output	28.6	1.79

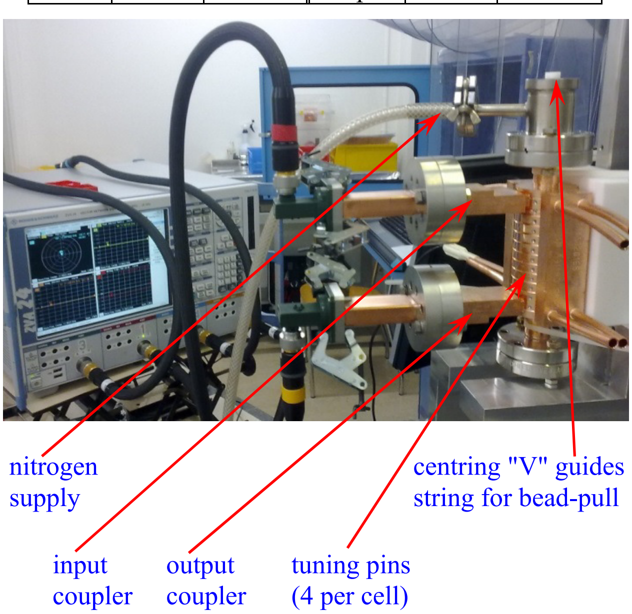

Figure 5: Setup during tuning of the CLIC crab cavity.

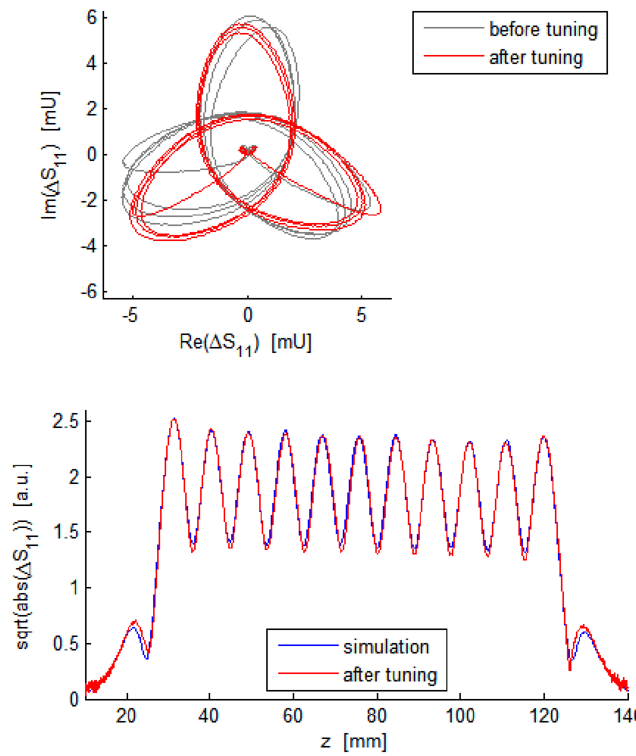

Figure 6: Bead-pull measurement results before (grey) and after (red) tuning compared to simulations (blue).

CONCLUSIONS

Through a good choice of a) the bead's material, b) the bead's size and c) the precise control of the bead's trajectory, the deflecting electric field of the prototype CLIC crab cavity was determined in amplitude and phase by a single passage bead-pull measurement. This technique was applied to tune the crab cavity iteratively from the output to the input.

ACKNOWLEDGMENT

We wish to thank P. K. Ambattu for providing the simulation model and the extraction of the electro-magnetic fields for the prototype CLIC crab cavity.

REFERENCES

[1] G. Burt et al., "Prototype development of the CLIC crab cavities", these proceedings, Linac'14, Geneva, Switzerland 2014

[2] J. Shi et al., "Tuning of X-band traveling-wave accelerating structures", Nucl. Instrum. Methods A 704, 2013, p. 14-18

[3] C. W. Steele, "A Nonresonant Perturbation Theory", IEEE Trans. Microwave Theory Tech., vol. MTT-14, no. 2, 1966, p. 70-74

[4] B. Hall, "Designing the Four Rod Crab Cavity for the High-Luminosity LHC upgrade", PhD thesis, 2012