ERL RELATED HOM MEASUREMENTS AT ELBE.

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Abstract

Higher order mode (HOM) wakefields building up in the SCRF cavities are likely to be a major factor in 4GLS. A series of measurements of the HOMs of the SCRF cavities at the ELBE light source has been performed. The power extracted by the HOM couplers over a wide bandwidth (1.7GHz -2.9GHz) has been measured using a spectrum analyser, for various bunch trajectories through the cavities. Network analysers have also been used to determine the external Q of these modes. These measurements will be used to estimate the dominant modes which will require significant damping for 4GLS.

INTRODUCTION

The ELBE accelerator [1] is a CW superconducting linac, using four 9 cell 1.3GHz TESLA cavities. The ERLP accelerator [2] in Daresbury will use the same SCRF modules, however as the ERLP is an energy recovery linac, a higher peak current will be used. In order to study the wakefields induced by the beam in these cavities a series of measurements were undertaken using one of the ELBE cavities.

The ELBE accelerator is a 40 MeV, 1mA CW linac in Rossendorf, Germany. It consists of two Stanford /Rossendorf cryomodules, each containing two 9 cell TESLA SCRF cavities. The beam can be positioned to traverse the cavities at various offsets using a pair of up-stream steerer magnets. A set of up-stream and down-stream BPMs are use to measure the beam position, and are believed to have a measurement accuracy of 0.1mm.

COUPLER MEASUREMENTS

In the first set of measurements a network analyzer was connected to the pick-ups on both Higher order mode (HOM) couplers on cavity 4. The scattering parameters were measured and were used to calculate the loaded and external Quality factors of the cavity and coupler system. First the 3 dB bandwidth of each mode is measured from either S_{11} or S_{22}, the reflections from HOM1 and HOM2 respectively. The loaded quality factor is then given by

$$Q_L = \frac{f}{\Delta f} \qquad (1)$$

where f is the resonant frequency and Δf is the 3 dB bandwidth. The external Q factor of a coupler, Q_e, can be related to the loaded Q using

$$Q_e = Q_L\left(1+\beta^{-1}\right) \qquad (2)$$

where β is the coupling parameter. The coupling parameter can be found from a polar plot of $S_{11,\,22}$ by measuring

$$\beta = \frac{1}{\frac{d_2}{d}-1} \qquad (3)$$

where d is the diameter of the Q circle, and d_2 is the diameter of the auxiliary circle, shown in Figure 1. For a perfect conductor the auxiliary circle has a diameter of 2, however the prescence of losses in the coupler reduces its diameter.

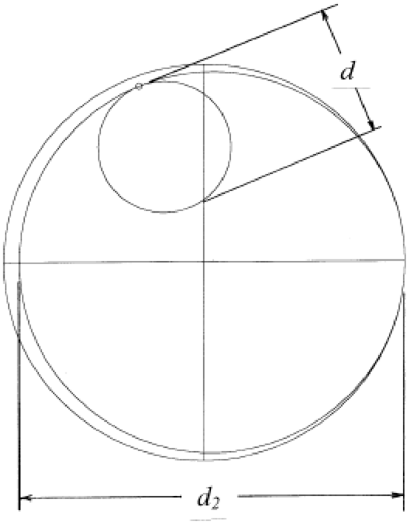
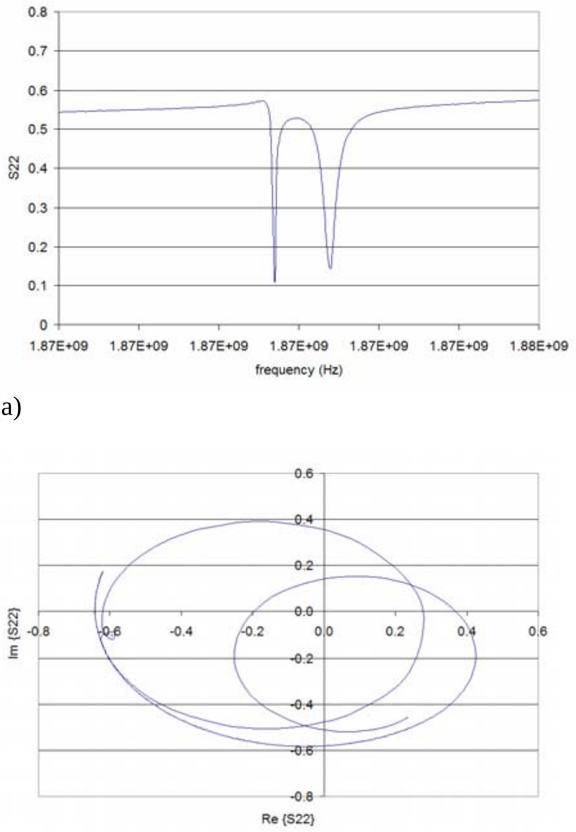


Figure 1. Polar plot of a mode resonance

Dipole modes are known to have two polarizations which will each couple differently to the HOM couplers. The presence of any asymmetry in the cavity caused by couplers or mechanical errors in the cavity will also cause these modes to have slightly different frequencies. This means that the measurements will often be perturbed by the two polarizations being superimposed.



(a)

(b)

Figure 2 (a) A linear magnitude plot of S_{22} of a dipole resonance measured from HOM2, showing both polarisations 2 (b) a polar plot of the same modes

The measured loaded Q factors were then compared to those measured at DESY, reported in [3]. The measured quality factors agree well with those reported in the TESLA report for the 2nd dipole pass-band between 1.8 – 1.9 GHz. The measured quality factors for the 1st dipole pass-band, from 1.7-1.8 GHz were slightly higher than the DESY values.

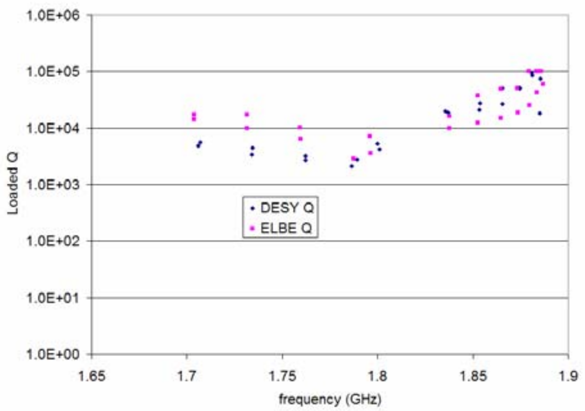


Figure 3. The External Q factors calculated from the S-parameter measurements compared to the values quoted in [3]

TOTAL MONOPOLE POWER

The beam energy was set to 25.9 MeV at a CW current of 480 µA and was centred on what was believed to be the axis using a series of kickers, with BPMs before and after the cavity used to measure the beam position. The bunch repetition rate was set to 101.56 kHz CW, which is the accelerator's minimum repetition frequency, in order to resonantly excite most of the cavity HOMs as the modal bandwidths are mostly of the same order of magnitude. The power spectrum between 1.7-2.9 GHz was then measured using a Rhode & Schwarz spectrum analyser. The measurements were taken with 8001 points with a low sample rate and hence as the beam was operating CW did not need to be triggered.

It was found that the 2nd monopole pass-band between 2.4 -2.5 GHz made the largest contribution to the power in the coupler, hence the power spectrum measured using a spectrum analyzer was integrated from 2.2 – 2.5 GHz, shown in Fig 4. The total power measured for this pass-band was 0.84 Watts.

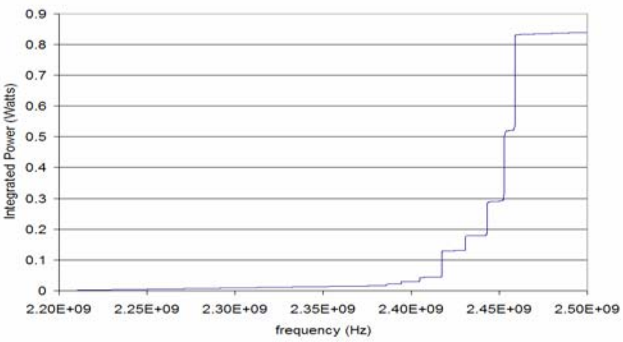


Figure 4. The Power measured at HOM2 integrated from 2.2GHz to the frequency given in the x-axis

POWER EXCITED IN DIPOLE MODES

In order to study the power dissipated by the beam into the dipole modes of the cavity as the beam traverses the cavity, the power spectrum was measured using a spectrum analyzer. 480 µA bunches repeating at 101.56 kHz Continuous Wave (CW) were used to excite the modes in the cavity. The position of these bunches were measured using up-stream and down-stream BPMs and the position of the bunches were systematically varied in steps of 1mm in both the horizontal and vertical planes, between -5 mm and 5 mm.

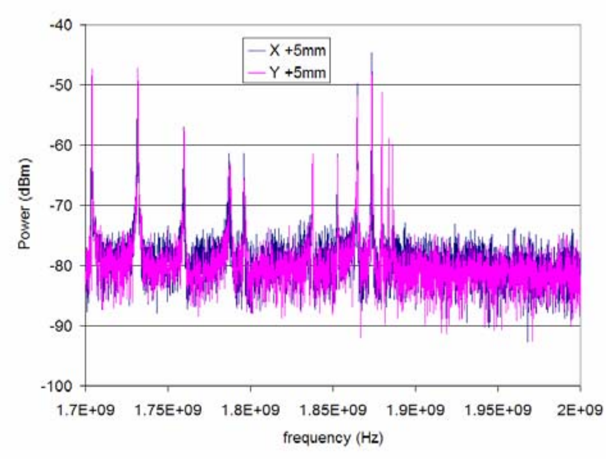


Figure 5. The spectrum analyser measurement from HOM2 at 480 μA.

The power flowing out of the HOM coupler from each mode can be found by integrating the power spectrum along the mode in frequency, and accounting for the cable losses. By doing this for each position we can find the radial dependence of the power flowing down the coupler. The cable losses were measured to be 10.0 dB at 1.9 GHz and 11.4 dB at 2.5 GHz.

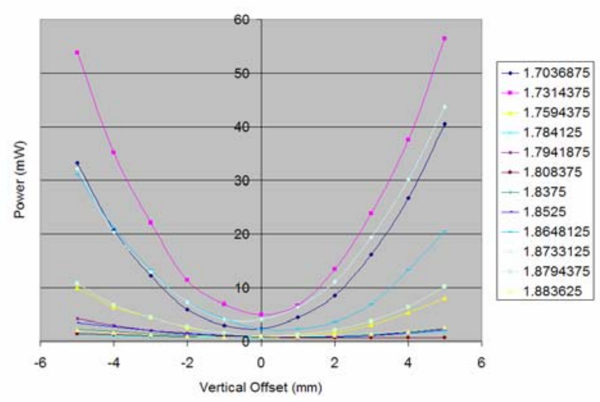


Figure 6. The total power measured at HOM2 vs. the vertical offset of the beam for various dipole modes.

If we look at the radial dependence of the power flow in the vertical plane, shown in Figure 6, we find that it varies roughly with

$$P = P_0 + A\left(r_{beam} + r_{centre}\right)^2 \quad (4)$$

where P_0 is power from noise and from other modes, A is a constant, r_{beam} is the offset of the beam from the ideal path, and r_{centre} is the offset of the electrical centre of the mode from the ideal electron path. The maximum power flowing out the coupler, at a vertical beam offset of 5 mm, due to a dipole mode was 56.5 mW from the mode at 1.731 GHz in the 1st dipole pass-band and 5 mW was found to be flowing out the coupler from this mode with no offset.

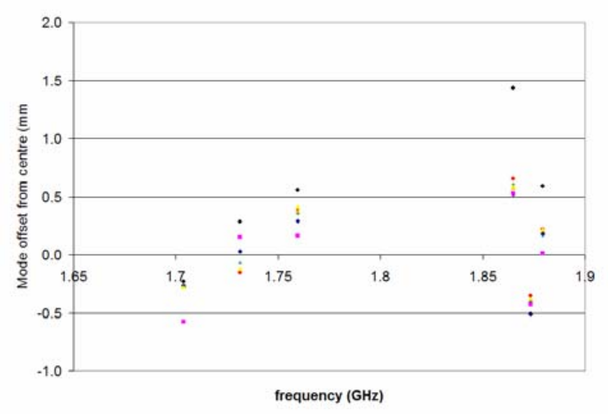


Figure 7. The electrical centre of the 6 dipole modes with the largest loss factors in the first two passbands.

If we fit the data obtained to equation (4) we are able to find the electrical centre of each mode: this is shown in Figure 7.

SIMULATIONS

A series of simulations of a nine cell TESLA cavity without couplers were performed in MAFIA using the 2D eigensolver. Beampipes of length 300 mm were used and 400,000 mesh lines were used in the MAFIA automesh. The simulations concentrated on dipole modes between 1.7 and 1.9 GHz. The frequencies and loss factors of these modes were recorded. The simulations were then used to theoretically calculate the power flowing out of the cavity via HOM2 using the Q measurements from HOM2 in Cavity 4.

Table 1 The dipole modes between 1.7 and 1.9 GHz simulated in MAFIA.

frequency (GHz)	k/a^2 ($V/pC/m^2$)
1.709	262.88
1.736	414.97
1.764	62.78
1.792	37.44
1.803	18.07
1.840	15.00
1.856	6.93
1.869	180.86
1.878	269.27
1.884	68.08
1.889	0.91
1.891	5.00
1.893	0.06

The energy dissipated in the cavity by a single bunch can be found from,

$$U_{single} = \frac{k}{q^2} \tag{5}$$

It can be shown that the energy in the cavity just before the arrival of a bunch after several bunches have passed, U_{sum}, is related to the energy dissipated by a single bunch by

$$U_{sum} = U_{single} \left|F\right|^2 \tag{6}$$

where F [4] is given as

$$F = \frac{\sinh d}{2\left(\cosh d - \cos \omega t\right)} - \frac{1}{2} + i\frac{\sin \omega t}{2\left(\cosh d - \cos \omega t\right)},$$

d is $\omega T/2Q_L$, and T is the bunch separation. As the bunch repetition frequency was of similar magnitude to the modes loaded bandwidth for all modes, it is assumed that each mode is in resonance with the bunches i.e. $\omega T=2n\pi$. Hence F reduces to

$$F = \frac{\sinh d}{2\left(\cosh d - 1\right)} - \frac{1}{2} \tag{8}$$

and the peak power flowing out the coupler can be given as

$$P_e = \frac{\omega U_{sum}}{Q_e}. \tag{9}$$

The power flow in the HOM couplers was then predicted from the simulation frequencies and loss factors, where the values of Q_L and Q_e are the values measured using the network analyser. The power in both polarisations for each mode was summed. Figure 8 shows the calculations for a 3 mm beam offset compared to the measurements in HOM2 of Cavity4 for a vertical beam offset of 3 mm, for the 1st two dipole pass-bands.

The predictions give good agreement with the measurements for the dominant modes.

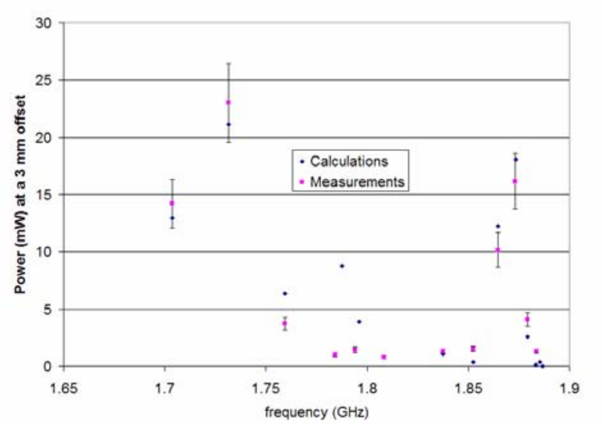


Figure 8. The measured power at HOM2 vs. the calculated power from MAFIA measurements and measured external Q factors.

CONCLUSIONS

The measurements taken at the ELBE accelerator have been used to calculate the loaded and external Quality factors of the TESLA cavities in the Stanford/Rossendorf Modules.

The measurements of the dipole modes power as a function of position have shown that each dipole mode has a different electrical centre. This means that the cavities do not have a universal on-axis position, which could lead to a decrease in the cumulative BBU threshold current, as the beam is likely to have larger offsets from the electrical centre.

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