

HOM STUDY OF THE PERLE'S BOOSTER CAVITY

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Abstract

The injector for the PERLE ERL in construction at IJCLab is based on a booster containing 4 superconducting cavities to reach 7 MeV for 20 mA of cw current. The cavities are single cell at 801.58 MHz. Due to the high average current, issues of beam break-up and power dissipation induced by the higher order modes of the cavities are a matter of concern. In this paper, we will report on the systematic survey of the HOM thanks to CST simulations up to 8 GHz. An analysis of their harmfulness as a function of the current spectrum will be shown.

INTRODUCTION

This work takes place in the framework of the design and construction of the PERLE accelerator [1] near Paris in France. PERLE is an Energy Recovery Linac (ERL) aiming to reach 5 MW of electron beam power thanks to a high current, 20 mA and an energy of 250 MeV. For this accelerator, an injector [2] providing such current but with an energy of 7 MeV is required where the main acceleration is given by a booster composed of four single cell superconducting cavities.

A critical issue for superconducting cavities is the potential excitation of high-order modes (HOMs). HOMs correspond to cavity electromagnetic modes at frequencies higher than the fundamental accelerating mode and can be excited when their frequencies coincide with harmonics of the beam repetition rate, which is 40 MHz. The beam consists of a train of electron bunches with a temporal length of 10 ps. Given this short bunch length, the corresponding frequency spectrum is broad, with a rms width of approximately 16 GHz, as determined by the Fourier transform of the bunch temporal profile. The spectrum therefore consists of 40 MHz harmonics modulated by this Gaussian envelope. HOMs can interact with the beam either transversely or longitudinally. Transverse electric (TEM_{np}) modes can impart transverse kicks to the beam, potentially leading to beam break-up (BBU) instabilities and degradation of the transverse emittance. Longitudinal (TM_{mnp}) modes, on the other hand, can perturb the accelerating field, causing a reduction in beam energy and/or deterioration of the energy spread and bunch length. Because the field decay times of the cavity are long compared to the bunch spacing, these effects can accumulate over successive bunches, making the control of HOM excitation essential for stable beam operation.

In this paper we will give the exhaustive list of all HOM found with CST microwave studio below 8 GHz and we will show their impact on the beam stability does not worth

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to use complex and expensive countermeasures as HOM extracting couplers or absorbers.

RF SIMULATIONS UP TO 8 GHz

First, using CST Microwave studio, we scanned resonant modes up to 8 GHz for our model of the RF cavity and identified a total of 2290 modes. The relevant parameters for HOM analysis are the mode frequency and its detuning relative to the nearest beam harmonic, the external quality factor Q_{ext} , the longitudinal shunt impedance over quality factor R/Q (R/Q)_{||} and the transversal shunt impedance over quality factor R/Q (R/Q)_⊥. While the Microwave studio does not directly provide the transversal shunt R/Q (R/Q)_⊥, it can be computed using the Panofsky-Wenzel theorem [3] as expressed in equation 1.

$$(R/Q)_{\perp} \approx \frac{|V_{||,n}(x_0,0) - V_{||,n}(0,0)|^2}{k_n^2 x_0^2 \omega_n U_n} \frac{|V_{||,n}(0,y_0) - V_{||,n}(0,0)|^2}{k_n^2 y_0^2 \omega_n U_n} \quad (1)$$

where $V(x,y)$ is the voltage, k , the wave number, ω , the pulsation and U the stored energy equal to one in the simulation. The transverse R/Q _⊥ was evaluated at an offset position of $x_0 = y_0 = 3$ mm from the cavity axis. Plots of these quantities are shown in Fig. 1 and Fig. 2.

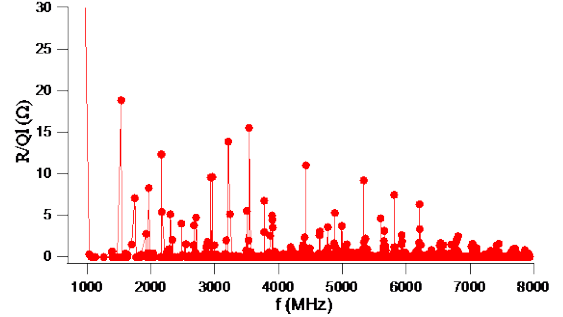


Figure 1: longitudinal R/Q _{||} as a function of frequency.

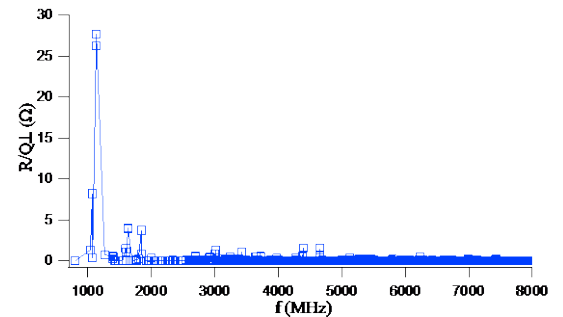


Figure 2: the transversal R/Q _⊥ as a function of frequency.

We now focus on the modes with a transverse or longitudinal magnitude larger than one in order to assess their potential impact on the beam. The results are summarized in Table 1 and Table 2 for the transverse modes and longitudinal modes, respectively including Δf which denotes the

frequency difference with respect to the nearest beam harmonic of the beam.

Table 1: Transverse Modes Parameters

F (MHz)	R/Q $^{\perp}$ (Ω)	Q $_{\text{ext}}$	Δf (MHz)
1035.9	1.34	6.8×10^5	5.3
1068.57	8.2	2987	12.7
1128.32	26.4	3985	7
1130.97	27.1	15.7	9.5
1594.3	1.5	3.8×10^8	8
1631.6	4.0	6.5	11
1844.3	3.7	33	1.44
3011.6	1.34	323	6.4
3421.6	1.1	7086	15.7
4394.7	1.6	800	13.2
4649.7	1.5	4.4×10^7	1.3

We defined a threshold of 3 MHz on Δf beyond that there is no chance to excite a HOM because frequencies are too far from the nearest beam harmonic. To assess potential frequency shifts due to mechanical tolerances, we performed a simulation with a change of 0.2 mm of the cavity elliptical shapes resulting in a maximal frequency shift of 2 MHz for the first 20 HOMs. It is worth noting that 0.2 mm represents a large mechanical error, typically an order of magnitude larger than standard fabrication tolerances. Hence, after mechanical adjustments to reach the correct frequency for the fundamental mode the risk of significant HOM frequency shifts is minimal. In Table 1, two modes are potentially critical at 1844.3 MHz and 4649.7 as they lie approximately at 1 MHz from the closest beam harmonic. The first mode is not problematic due to its a very low Q_{ext} , which allows the energy to be quickly extracted from the cavity. The second mode has a very high Q_{ext} , but paradoxically the probability of overlap with a beam harmonic remains very weak. Indeed, bandwidth of this mode is $f/2Q_{\text{ext}} \approx 50$ Hz while the bandwidth of the current's harmonic derived from the laser stability (source of the current) is only 6×10^{-6} , namely 25 kHz for 4.6 GHz. Hence, in order to reach an efficient energy transfer from the beam harmonic to this mode, it requires practically the frequency gap to be zero instead of 1.3 MHz which is very unlikely.

The results are similar for the longitudinal modes (see Table 2). Modes with largest R/Q, as the one at 1535,2 MHz with R/Q of 18.8 are far from a beam harmonic, 13 MHz in that case. Only one mode, at 6.21 GHz is located at 1.44 MHz from the beam harmonic and exhibit a noticeable R/QI. However, given its high Q_{ext} , the mode bandwidth is 0.16 MHz while the beam harmonics bandwidth is 0.036 MHz making significant overlap quite unlikely.

Apart the few modes with large (R/Q), many modes have (R/Q) around one and mostly TM modes. As one can see in Fig. 2, TE modes above 2 GHz have an amplitude close to zero. So, we focused on longitudinal modes. Although

individually weak, their large number could still have an effect.

Table 2: Longitudinal Modes Parameters

F (MHz)	R/QI (Ω)	Q $_{\text{ext}}$	Δf (MHz)
1535,2	18,8	2297	13
1966,2	8,3	3565	3,2
2166,5	12,3	447	3,02
2938,9	9,5	3834	14
3211,8	13,8	276	6,2
3539,9	15,5	3464	12,8
4430,8	11	4990	17
5333,6	9,2	39261	3,8
5812,8	7,5	1.6×10^6	2,2
6212,9	6,3	18597	1,44
6815,3	2.5	22248	2,7

Applying the additional criterion that the mode frequency is within 1 MHz of the nearest beam harmonic, we identified 117 modes among the 2290 ones initially found. Their R/QI and Q_{ext} are shown in Fig. 3 and in Fig. 4, respectively.

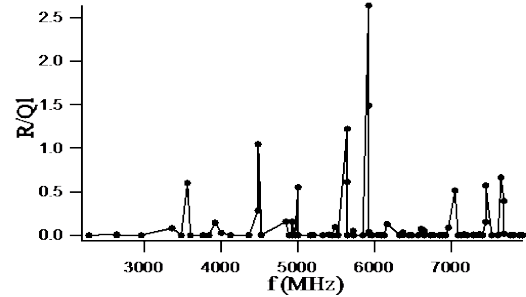


Figure 3: longitudinal R/Q for modes within 1 MHz from the nearest beam harmonic frequency as a function of frequency.

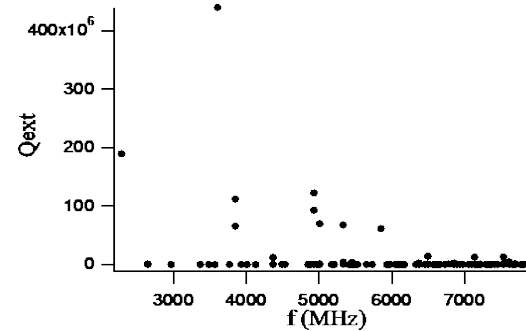


Figure 4: Q_{ext} of longitudinal modes within 1 MHz from the nearest beam harmonic frequency as a function of frequency.

It is possible to assess the voltage induced by the beam using equation 2.

$$V_{\text{ind}} = \frac{R}{Q} Q_L T^2 I_{\text{harm}} \quad (2)$$

With loaded Q , $Q_L \approx Q_{\text{ext}}$ and $I_{\text{harm}} \approx 2I_b \sqrt{2\pi} \frac{f_{\text{rep}}}{\sigma_f}$ with σ_f (equal to 16 GHz) is the standard deviation of the frequency spectrum of the beam and T is the transit time factor.

In principle, the parameter T should be calculated for every mode; however, this is very time-consuming. Moreover, most of the modes exhibit highly fluctuating field patterns, as illustrated by the example in Fig. 5.

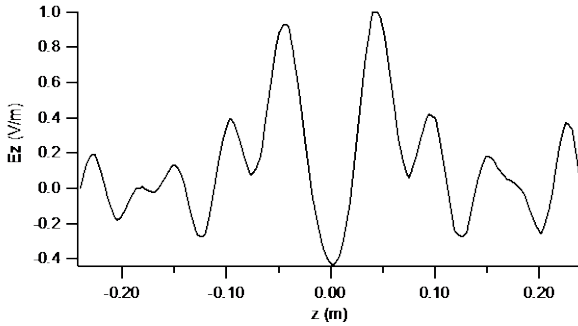


Figure 5: curve of the electrical field one HOM at 7,91 GHz along the longitudinal axis of the cavity.

The transit time factor for this mode is 0.1. We used this value for all the modes. Summing all modes gives a total voltage of 0.24 V and a power of 5 mW, which is very small.

BEYOND 8 GHz

So far, we showed all the modes found in the RF simulations and discarded them either because their frequencies are too far from a beam harmonic or their amplitude being negligible. However, the beam spectrum extends up to 32 GHz, but simulating such high frequencies in CST is impractical. By analysing the number of modes versus frequency, we found a quadratic trend as shown in Fig. 6.

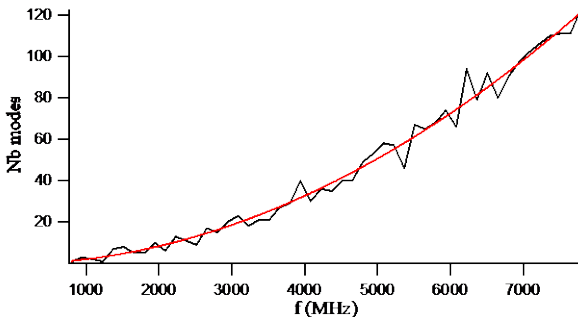


Figure 6: black curve, histogram of total number of modes as a function of frequency; red curve, quadratic fit.

It allows us to extrapolate about 4,046 modes between 8 and 32 GHz within 1 MHz of a beam harmonic. By applying a simple proportionality factor based on the 117 modes below 8 GHz, we estimate a total voltage of 8.5 V and a

power of 0.17 W. This represents an overestimation, as it assumes the same harmonic current up to 32 GHz, whereas the current actually decreases according to the Gaussian shape of the beam spectrum. The induced voltage is negligible compared to the accelerating voltage of 1.53 MV, and most of the HOM power is extracted from the cavity, since the mode frequencies are well above the cut-off frequency of the beam pipe.

CONCLUSION

We reported on the systematic scan of the HOM using CST simulations up to 8 GHz. Most of the dangerous modes can be discarded because they are far away from the beam harmonics. Study of the number of modes as a function of the frequency showed it follows a quadratic law. Then we deduced the number of modes within 1 MHz from the beam harmonics and evaluated the induced voltage and the power up to 32 GHz. The total voltage seems to be negligible compared to the accelerating voltage of 9 MV/m. Regarding the HOM power, it is evacuated from the cavity because it is well above the cut-off frequency and therefore it does not increase the thermal load of the cavity. Therefore, the implementation of HOM couplers or beamline absorbers appears unnecessary. This nice result is mainly due to the booster having single cell cavities while in linac there are usually multi-cells cavities as for instance the 9 cells of the TESLA type cavity. In the latter, the number of HOM increases tremendously as well as the closeness to the beam harmonics. In that case, the implementation of HOM extracting couplers and absorbers is unavoidable and is designed for the PERLE ERL linac which is based on 5 cells cavities.

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