HOM ANALYSIS AND MITIGATION STUDIES FOR THE ELETTRA 2.0 RF CAVITY

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Abstract

The 500 MHz Elettra type cavities have been implemented in the 3rd-generation light source Elettra Sincrotrone Light Source since the beginning of its operation. These are normal conducting, single cell cavities with no High-Order-Modes (HOMs) dedicated dampers. The very same cavities will be used for the new low-emittance Elettra 2.0 (E2.0) project. E2.0 will host four independent RF accelerating cavities, each fed with its own amplifier. A complete investigation of the possible coupled bunch longitudinal instabilities has been carried out due to the most demanding beam quality requirement, together with the installation constraints given by the new vacuum chamber of the E2.0 layout with respect to the Elettra storage ring. Results in the time domain and frequency domain up to 7.0 GHz have been double-checked. Some high impedance high frequency longitudinal HOMs have been identified thanks to this analysis. The feasibility of implementing a dedicated HOM damper for the most dangerous modes that could also fit the available space is also investigated.

INTRODUCTION

The Elettra 2.0 project significantly enhances beam brilliance and reduces emittance through a high-density magnetic lattice featuring combined-function elements (3 dipoles and 4 quadrupoles) [1]. For the radio-frequency system, the new low-emittance machine will retain the Elettra-type 500 MHz single-cell normal conducting (NC) copper cavities (see Fig. 1) [2]. These cavities lack dedicated Higher Order Mode (HOM) dampers; instead, longitudinal and transverse coupled-bunch instabilities (CBIs) are mitigated by precisely shifting the HOM frequencies through an active cavity body temperature control system. The available space for cavity installation in E2.0 is limited to 1260 mm, including tapers, and is shorter than in the present Elettra ring. This reduces the attenuation volume for evanescent modes. In addition, the E2.0 vacuum chamber cross-section is 8.8 times smaller, increasing the beam pipe cut-off frequency from 2.2 GHz to 7.0 GHz. The combined effect of reduced length and smaller aperture requires steeper tapers. A comparison of the two vacuum chamber geometries is shown in Fig. 2.

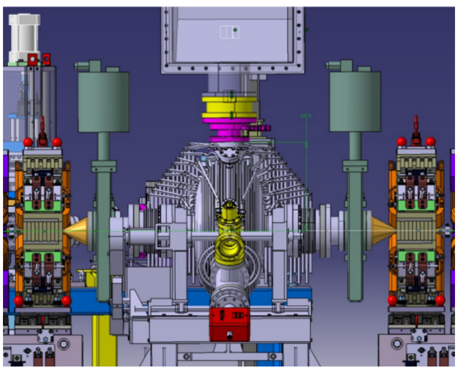

Figure 1: Elettra-type RF cavity. Rendering of Elettra 2.0 installation.

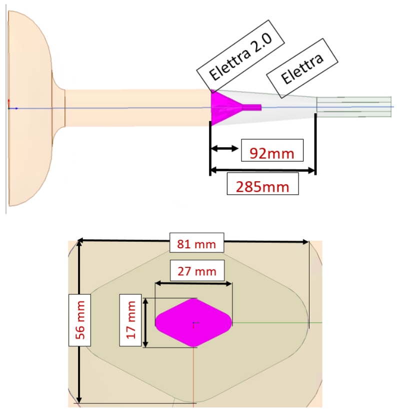

Figure 2: Comparison of the vacuum chamber of E2.0 (pink shapes) with Elettra. Top: Side view. Bottom: Cross-section.

SIMULATION SETUP

A detailed study of Elettra cavity HOMs up to 6.5 GHz was performed to assess potential multibunch instabilities. Numerical simulations were carried out in both time (CST W wakefield Solver) and frequency domains (CST eigenmode Solver and HFSS), using a simplified model in which the three equatorial ports for the Input Power Coupler (IPC), the ultra-high vacuum (UHV) pump, and the Higher Order Mode Frequency Shift (HOMFS) plunger were omitted, since their impact on the on-axis impedance is negligible. The model nevertheless includes the full beam path up to the Elettra 2.0 vacuum chamber (cavity, bellows, valves, and tapers), as shown in Fig. 3. The wakefield solver of CST is used for the time domain simulations, which are benchmarked using the frequency domain solver (eigenmode solver) of both CST and HFSS.

Time Domain Simulations

The cavity with the beam pipes and tapers is simulated using the wakefield solver of CST with the copper boundary

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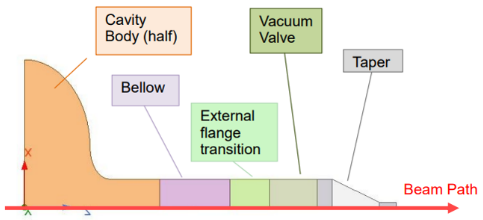

Figure 3: All beam path inclusive cavity model profile as implemented for the EM simulations (CST and HFSS).

conditions. The wakefield simulations were performed using an on-axis Gaussian bunch with a charge of 1.753 nC, corresponding to the nominal Elettra bunch charge. A bunch length of 10 cm and a wake length of 100 m were selected as a compromise between spectral resolution, computational resources, and simulation time, while still ensuring reliable identification of the dominant trapped HOMs in the investigated frequency range. The wakefield integration line is shown in Fig. 4. The simulation results for the longitudinal

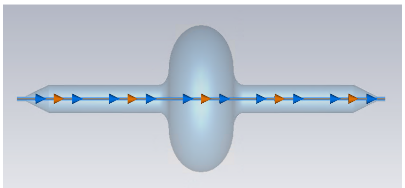

Figure 4: CST wakefield simulation setup.

impedances of HOMs for E2.0 are plotted together with the simulation results of Elettra for the sake of comparison in Fig. 5. Time-domain result Fig. 5 shows ten significant peaks

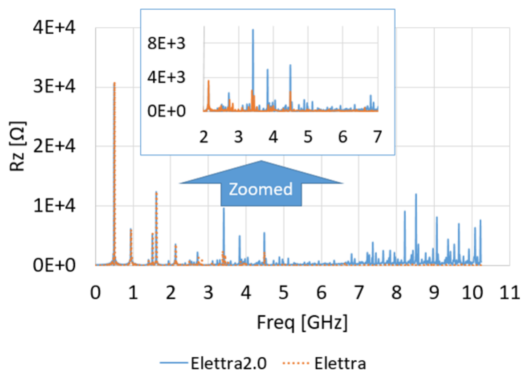

Figure 5: Comparison of wakefield simulation results of E2.0 with Elettra.

due to trapped HOM up to 7.0 GHz for E2.0. Those below 2.2 GHz are already well known and mitigated during the operation in Elettra. New longitudinal trapped modes occur up to 7.0 GHz due to the reduced length and chamber cross section which are still unknown. Because the wakefields do not fully decay to zero within the simulated distance, truncation errors affect the results. Therefore, the absolute values of the impedance peaks are not fully reliable and require further assessment using frequency-domain simulations.

Frequency Domain Simulations

To better assess the impedance contribution of trapped modes, frequency-domain analysis was performed using the eigenmode solver of CST, which was benchmarked using HFSS and the measured data, up to 2.2 GHz. Symmetry is exploited and one quarter of the model with appropriate boundary conditions (Fig. 6) is used to reduce the computational load. To avoid missing resonances due to symmetry constraints, simulations were repeated using both electric and magnetic symmetry boundary conditions on all symmetry planes, grouping the HOMs into odd and even EM field features along the cavity symmetry axis. The obtained spectrum was cross-checked against wakefield simulations.

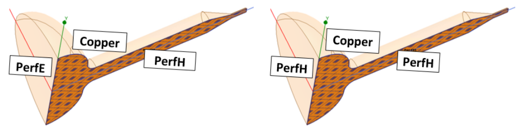

Figure 6: Frequency domain (Eigenmode solver) simulation setup for both CST and HFSS.

As reported in Table 1, the CST and HFSS results match the measured data obtained from RF measurements performed on the existing Elettra cavity, thus confirming the relevant trapped HOMs parameters due to the new E2.0 geometry.

Table 1: Benchmarking of Frequency Domain Solver Setup

	CST	**HFSS**	**Measured**
Mode 1 (f)	0.5 GHz	0.5 GHz	0.5 GHz
Mode 1 (R/Qz)	79.87 Ω	79.91 Ω	79.91 Ω
Mode 2 (f)	0.95 GHz	0.95 GHz	0.95 GHz
Mode 2 (R/Qz)	28.93 Ω	28.92 Ω	28.91 Ω
Mode 3 (f)	1.06 GHz	1.06 GHz	1.06 GHz
Mode 3 (R/Qz)	0.68 Ω	0.68 Ω	0.67 Ω
Mode 4 (f)	1.42 GHz	1.42 GHz	1.42 GHz
Mode 4 (R/Qz)	4.82 Ω	4.81 Ω	4.81 Ω
Mode 5 (f)	1.51 GHz	1.51 GHz	1.51 GHz
Mode 5 (R/Qz)	4.97 Ω	4.96 Ω	4.97 Ω

After the benchmarking, a complete analysis is performed for E2.0 up to 7.0 GHz (Fig. 7). More than 1200 even and an equal number of odd resonances can occur in the Elettra 2.0 model. Although a few resonances show very high quality factors ($Q > 2.5 \times 10^5$), their longitudinal shunt impedance is very low and therefore they are not expected to drive instabilities. Despite the large number of modes, only those with a longitudinal shunt impedance exceeding the natural Elettra 2.0 impedance threshold need to be considered potentially harmful.

HARMFUL HOMS

As shown in Fig. 8, in the frequency range of 0.5 GHz to 7.0 GHz, about 130 HOMs exhibit longitudinal impedance

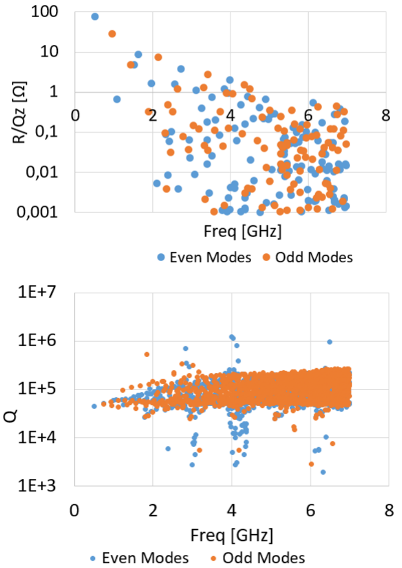

Figure 7: HOMs for E2.0. Top: Longitudinal R/Q. Bottom: Unloaded Q factor.

above the natural threshold of E2.0 in the worst case scenario, i.e., when their resonant frequency overlaps the positive synchrotron sideband:

$$f_{HOM} = p_M + n f_{riv} + f_{syn}$$

This number is significantly reduced if the effective impedance threshold of E2.0 is increased through the combined action of the third-harmonic cavity (3HC) and the longitudinal multi-bunch feedback system.

HOMS DAMPERS

Of the 130 HOMs above threshold, only 11 have a longitudinal impedance greater than 100 kΩ and can potentially drive multibunch instabilities. These coincide with the modes identified in time-domain simulations. Below 2.2 GHz, they are already known from Elettra operation and are effectively controlled by cavity temperature tuning and Landau damping from the third-harmonic cavity (3HC); their field profiles in E2.0 remain unchanged (Fig. 9). In the 2.2–4.5 GHz range, at least six additional modes may affect beam quality. Their fields are either mainly trapped in the cavity or shared between the cavity and beam pipe, with peaks in the taper region—hence the need for water cooling of the tapers. Based on the HOM field analysis, a possible and minimally invasive mitigation strategy is to use one of the equatorial ports as an HOM damper (Fig. 10 left). This solution does not affect the fundamental mode (Fig. 10 right), since the cutoff frequency of the equatorial port is sufficiently high. A dedicated circular waveguide damper for HOMs trapped in the cavity body is currently under study.

Figure 11 shows the effect of damping at one HOM at 2.71 GHz, resulting in the reduction of impedance.

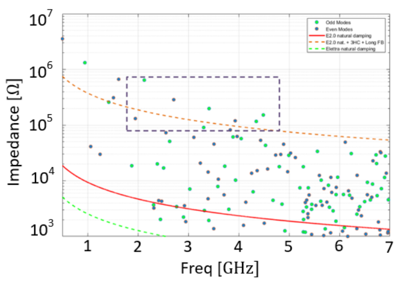

Figure 8: The longitudinal impedance of harmful even and odd HOMs plotted with the impedance threshold of Elettra and E2.0.

CONCLUSIONS

A complete analysis of the longitudinal HOMs with respect to the multibunch instabilities for the E2.0 vacuum chamber is performed using time and frequency domain solvers. Both simulation approaches show very good agreement and have highlighted several previously unidentified potentially dangerous HOMs up to 4.5 GHz. A preliminary design of the least invasive damping scheme that can help to reduce the impedance of some HOMs without affecting the fundamental mode is under investigation. It's a very simple solution even if it will be effective for a limited number of HOMs.

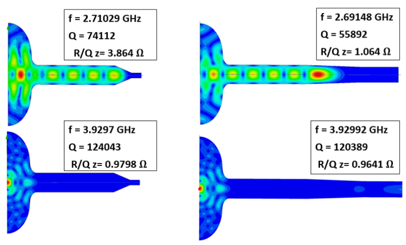

Figure 9: The comparison of the field profiles of some HOMs of E2.0 with Elettra.

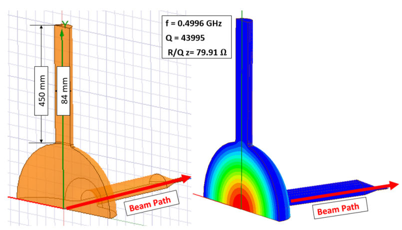

Figure 10: Right: The proposed HOMs damper. Left: Isolation of the fundamental mode.

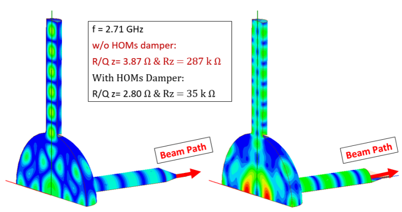

Figure 11: The effect of damper on one harmful HOM.

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