OPERATIONAL ASPECTS OF CRAB CAVITIES AT THE ELETTRA 2.0 STORAGE RING LIGHT SOURCE

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Abstract

We report here the Same-Order Modes (SOMs) and Higher-Order Modes (HOMs) analysis of the superconducting "crab cavity" module designed for the production of picosecond-long X-ray pulses at Elettra 2.0 storage ring light source. The module consists of three radiofrequency (RF) transverse deflecting cavities operating at 3.0 and 3.25 GHz, corresponding to the 6th and 6.5th harmonic of the fundamental frequency of Elettra 2.0. The design is based on the Quasi-waveguide Multicell Resonator (QMiR), initially developed for the Advanced Photon Source. SOMs/HOMs analysis is performed for the entire module, including tapers to connect it with the Elettra 2.0 ring. CST frequency domain solver (Eigenmode solver) is used for calculation of the impedances of SOMs and HOMs from 2.5 GHz to 7.0 GHz, which are the cut-off frequencies of the Elettra 2.0 rhomboidal vacuum chamber. The results are verified using the time domain solver, wakefield solver of CST, for the entire range, and compared with HFSS for the selected group of SOMs/HOMs.

INTRODUCTION

Elettra Sincrotrone Trieste Italy, is implementing a comprehensive storage-ring upgrade program, Elettra 2.0, aiming at a substantial reduction of the electron beam emittance, increasing thus the photon brilliance and coherence by at least two orders of magnitude [1]. Crab cavities would be installed to produce extreme ultraviolet and X-ray pulses with durations between 0.5 and 5 ps (FWHM) from the insertion devices, at repetition rates reaching up to 1 MHz. Two superconducting RF cavities operating at the 6th (3 GHz) and 6.5th (3.25 GHz) harmonics of the main ring RF generate a stationary regime in which the electron bunches acquire a vertical tilt that evolves along the storage-ring circumference. Under these conditions, the beam distribution stabilizes in the full six-dimensional phase space [2–4].

THE ELETTRA 2.0 CRAB MODULE

The Elettra 2.0 crab module is based on quasi-waveguide Multicell Resonator (QMiR) deflecting cavities which were originally developed for the ANL APS upgrade project [5,6]. The crab module shown in Fig. 1 consists of three individual crab cavities and tapers to connect to the Elettra 2.0 ring. Two side cavities (cav1) would operate at 3.0 GHz, providing a collective transverse peak voltage up to 1.5 MV, while the central cavity (cav2) would operate at 3.25 GHz and would provide a transverse peak voltage up to 1.2 MV. The impedance budget of the crab cavity module is given in Table 1. The crab module would be connected with the Elettra 2.0 ring with tapers and will be installed in one long straight section, 2.0 m in length. Individual crab cavities will be made of Niobium operating at 4 K while the tapers would be fabricated with Stainless Steel and cooled with Helium return gas from the bath to minimize the thermal input from the room-temperature chamber. In this paper, the operating modes refer to the nominal transverse deflecting modes at 3.0 GHz and 3.25 GHz. Same-order modes (SOMs) denote parasitic modes belonging to the same passband as the operating deflecting mode, whereas higher-order modes (HOMs) correspond to modes outside the operating passband.

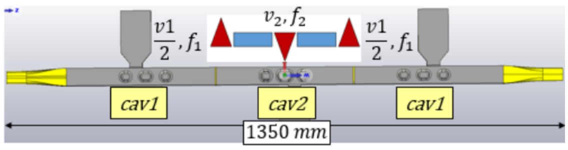

Figure 1: Proposed crabbing scheme for Elettra 2.0.

Table 1: Shunt Impedance Budget for the Crab Cavity Module

Quantity	Value	Unit
R_x	< 4.5	MΩ/m
R_y	< 1.5	MΩ/m
R_z	< 5.0	MΩ GHz

RF design

The initial RF design of individual crab cavities (cav1 and cav2) reported in [7] included circular transitions, which are eliminated in the new design due to space constraints. The new geometry shown in Fig. 2 has the same dimensions as the square waveguides for both cavities, while the distance and spacing between the stubs are used to adjust the frequency. The RF parameters of two crab cavities are listed in Table 2. The superconducting crab module would be connected to the normal-conducting Elettra 2.0 ring using Stainless Steel tapers. As shown in Fig. 3, the taper on one side would have a rhomboidal profile, while the other side would have an elliptical profile. The copper gaskets are

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introduced between the individual crab cavities for the ease of alignment and suppression of some HOMs. The distance between the individual crab cavities was selected to ensure that there is no coupling of the operating mode, as can be seen from Fig. 4, which shows the electric and magnetic field profile along the beam axis for the operating modes of each crab cavity.

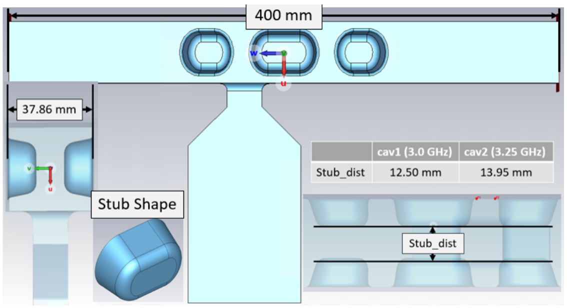

Figure 2: The new geometry of the crab cavity without circular transitions.

Table 2: RF Parameters of the Crab Cavities for Operating Modes

Parameter	Cav. 1	Cav. 2	Unit
Frequency	2998.66	3248.35	MHz
V_{def}	1.5	1.2	MV
R/Q_y	959	588	Ω
G-factor	104	112	–
E_{peak}	23	41	MV/m
B_{peak}	49	86	mT
Q_{ext}	1.3×10^5	3.25×10^5	–

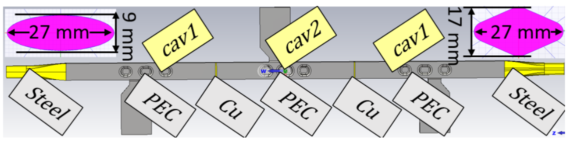

Figure 3: Simulation setup of crab module for CST and HFSS, PEC denotes Perfect Electric Conductor.

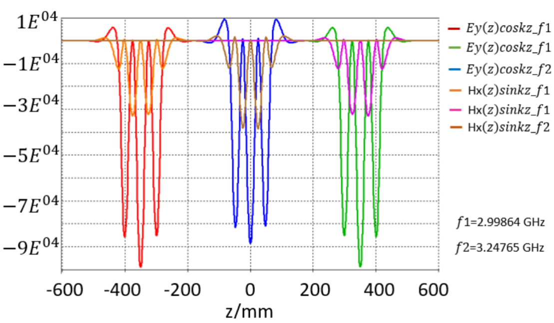

Figure 4: Field profile along the beam axis for the 3-cav crab module.

SOMS/HOMS ANALYSIS OF THE CRAB CAVITY MODULE

Simulation setup

The Eigenmode solver of "Lossy" type is mainly used for the simulation of the crab module for SOMs/HOMs analysis for the frequency range of 2.0 GHz to 7.0 GHz, lower cutoff frequency of Elettra 2.0 vacuum chambers. The simulation setup of CST is benchmarked using the HFSS eigenmode solver with the PML (Perfectly Matched Layer) boundary conditions for some HOMs. As can be seen from Table 3, the results show good agreement in terms of frequency. The discrepancy in Q calculated by the two software can be attributed mainly to the way mesh generation and Q factor calculation are performed in HFSS and CST.

Table 3: Comparison of the f/Q Parameter for Selected HOMs Obtained with CST and HFSS

CST f/Q	HFSS f/Q
$4.003\,39/6.45 \times 10^5$	$4.003\,47/5.45 \times 10^5$
$4.003\,41/6.45 \times 10^5$	$4.003\,49/5.46 \times 10^5$
$4.012\,79/2.33 \times 10^5$	$4.013\,18/2.08 \times 10^5$
$4.013\,45/5.14 \times 10^5$	$4.013\,84/3.87 \times 10^5$
$4.040\,01/3.84 \times 10^8$	$4.039\,97/6.54 \times 10^8$

The simulations are performed with three different taper lengths, 150 mm, 350 mm, and 450 mm (Fig. 5), to explore the effect of taper length on the impedance and Q of SOMs/HOMs. The longitudinal and transverse shunt impedances were extracted from the eigenmode simulations using the standard CST definitions of R/Q and loaded Q. The transverse impedances (R_x and R_y) were calculated from the dipolar wake potentials normalized to the beam offset using Panofsky-Wenzel theorem, while the longitudinal impedance (R_z) was extracted from the monopole wake potential. The impedances obtained from the simulations were directly compared with the project impedance budget.

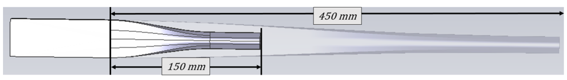

Figure 5: Layout of simulated tapers.

Analysis of the results

Figure 6 shows the impedances of SOMs/HOMs while Fig. 7 plots the Q factor for three taper lengths. It is clear from Fig. 6 and Fig. 7 that the peak impedances and Q values varied only marginally among the investigated taper lengths. Clearly, there are a number of SOMs/HOMs whose impedances are above the project limits, mostly centered around 4.5 and 5.5 GHz.

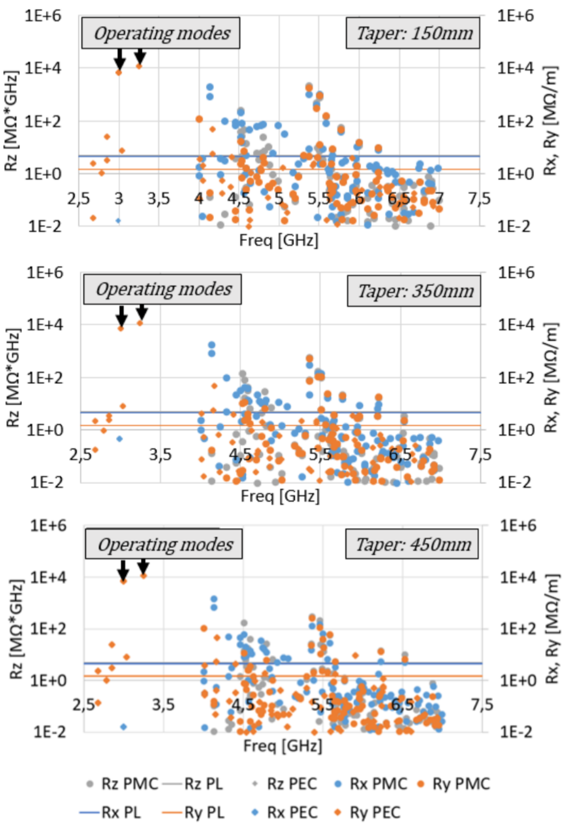

Figure 6: Effect of length of tapers on the impedance of HOMs of 3-cav crab module.

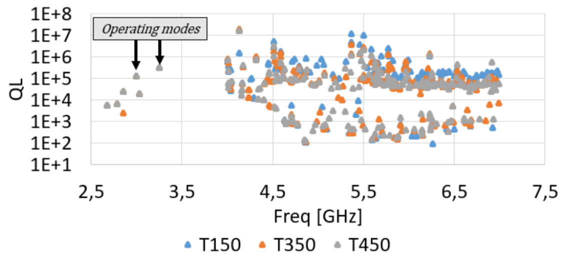

Figure 7: Effect of length of tapers on the Q factor of HOMs of 3-cav crab module.

TIME DOMAIN ANALYSIS OF THE CRAB CAVITY MODULE

CST wakefield solver is used for the time domain simulations of the crab module. The beam is defined 1.0 mm off-axis while the integration line is defined on the beam axis to explore the longitudinal and transverse wakefields at the same time. A Gaussian bunch with $\sigma = 4.5\ mm$ (nominal bunch length of Elettra 2.0) and a wake length of 200 m is used to allow enough time for wakefields to decay to zero.

Figure 8 shows the wake impedance spectrum of the crab module with tapers, which is plotted together with the data from the eigenmode solver of CST in Fig. 9. From Fig. 9, it is clear that the time domain solver result shows very good agreement with the frequency domain solver in terms of modal frequencies for all SOMs/HOMs. However, in the case of magnitude, the discrepancy appears in the case of SOMs/HOMs, which have a very high Q factor $\geq 10^5$. This is due to the fact that for a high Q mode, the wake potential does not decay to zero, resulting in the truncation error, which results in the underestimation of the amplitude of wake impedance of high Q mode.

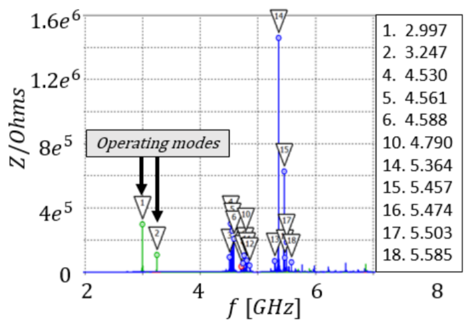

Figure 8: Impedances of HOMs for 3-cav crab module, including 450 mm tapers calculated using CST wakefield solver.

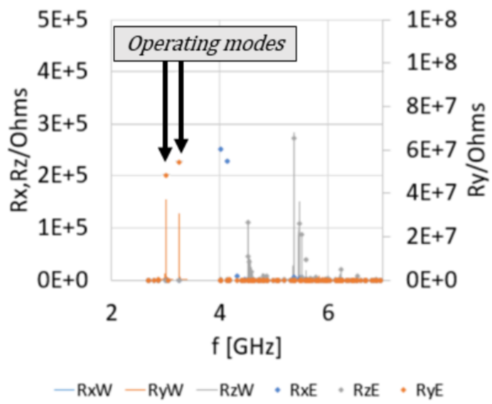

Figure 9: Comparison of the Higher-Order Mode (HOM) impedances in the 3-cavity crab module calculated using the CST eigenmode solver and the CST Wakefield solver.

CONCLUSIONS

SOMs/HOMs analysis of the compact three-cavity crab module for Elettra 2.0 was performed using the CST eigenmode and wakefield solvers for different taper lengths. The results indicate that the taper length has a negligible impact on the modal spectrum, impedance, and Q values within the investigated range. Several SOMs/HOMs around 4.5 GHz and 5.5 GHz were identified above the impedance budget of Elettra 2.0 and therefore require further optimization and damping studies. Possible mitigation measures under investigation include optimization of the cavity geometry and additional HOMs damping features. Comparison between CST eigenmode and wakefield solvers also demonstrated very good agreement in the modal frequencies, while discrepancies in impedance magnitude for high-Q modes were mainly attributed to truncation error in the wakefields.

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