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), firstly 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 (Eigen mode 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, wake solver of CST, for the entire range, and even 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. To achieve that, the 12-fold symmetric double bend achromat of the old lattice is replaced by a 12-fold symmetric enhanced six bend achromat (S6BA-E), whereby combined dipoles are used with transverse and longitudinal focusing as well as reverse bend quadrupoles [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, 3].

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 [4]. 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 would be installed in one long straight section, 2.0 m in length. Individual crab cavities would 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.

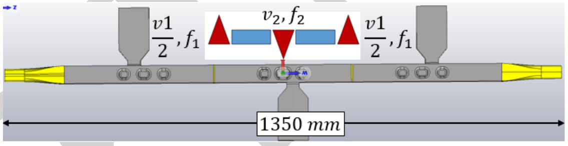

Figure 1: Proposed crabbing scheme for Elettra 2.0.

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 [5] 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 of 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 taper on one side would have a rhomboidal profile, while the other side would have an elliptical profile. The copper rings are introduced between the individual crab cavities. 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

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Fig. 4, which shows the electric and magnetic field profile along the beam axis for the operating modes of each crab cavity.

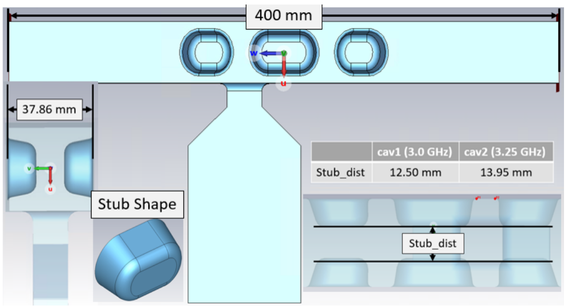

Figure 2: The new geometry of the crab cavity w/o circular transitions.

Table 2: RF Parameters of the Crab Cavities

Parameter	Cav. 1	Cav. 2	Unit
Frequency	2998.66	324.835	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	–

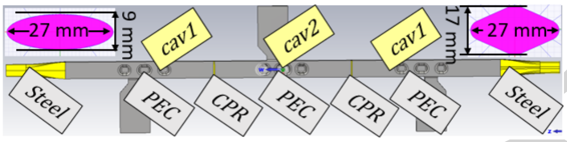

Figure 3: Simulation setup of 3-cav crab module for CST and HFSS including tapers.

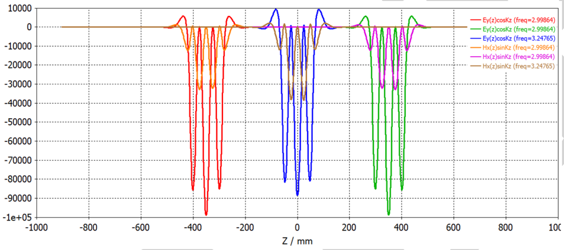

Figure 4: Field profile along the beam axis for the 3-cav crab module.

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 eigensolver with the PML boundary conditions for some HOMs. As can be seen from Table 3, the results match perfectly.

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.

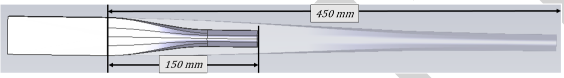

Figure 5: Layout of simulated tapers.

Analysis of the results

Fig. 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 there is very little effect of length on the impedance spectrum. Clearly, there are a number of SOMs/HOMs whose impedances are above the project limits, mostly centered around 4.5 and 5.5 GHz.

TIME DOMAIN ANALYSIS OF THE CRAB CAVITY MODULE

CST wakefield solver is used for the time domain simulations of the crab module. As can be seen in Fig. 8, 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 wakes at the same time. A Gaussian bunch with $\sigma = 4.5\ mm$ and a wake length of $2E^5$ mm is used to allow enough time for wakefields to decay to zero. Fig. 9 shows the wake impedance spectrum of the crab module without tapers, which are plotted together with the data from the Eigensolver of CST in Fig. 10. From Fig. 10, it is clear that the time domain solver result matches perfectly the frequency domain solver result for the frequency 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 $\geq 10^5$. Finally, in Fig. 11, the wake impedance spectrum for the crab module with tapers is shown.

CONCLUSIONS

SOMs/HOMs analysis of the crab module with the new compact crab cavities is performed using the eigenmode solver of CST for different taper lengths. The results indicate that the taper length has a negligible impact on the impedance of SOMs/HOMs, and there are a number of

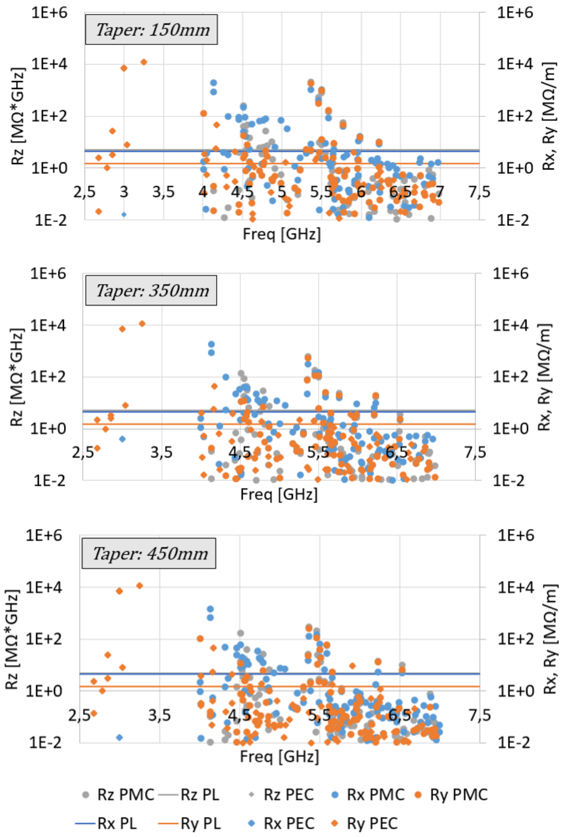

Figure 6: Effect of length of tapers on the impedance of HOMs of 3-cav crab module.

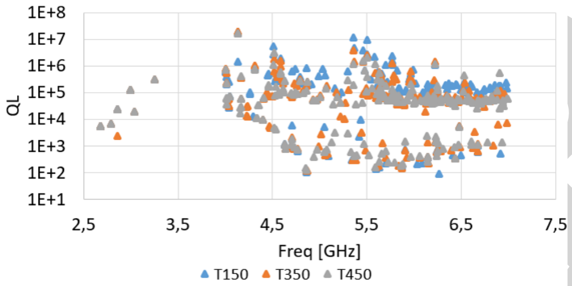

Figure 7: Effect of length of tapers on the Q factor of HOMs of 3-cav crab module.

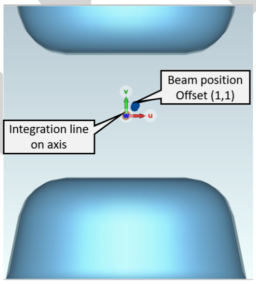

Figure 8: CST wakefield simulation setup.

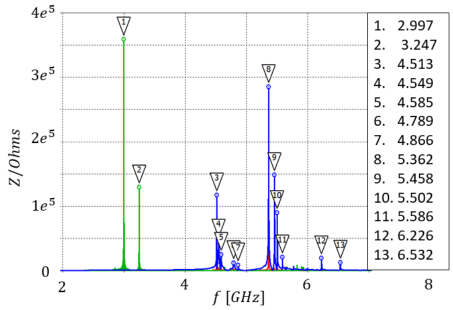

Figure 9: Wake impedances of HOMs for 3-cav crab module without tapers calculated with the CST wakefield solver.

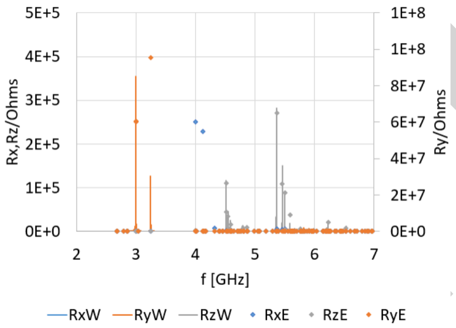

Figure 10: Comparison of the Higher-Order Mode (HOM) impedances in the 3-cavity crab module calculated using the CST Eigenmode solver and the CST Wakefield solver.

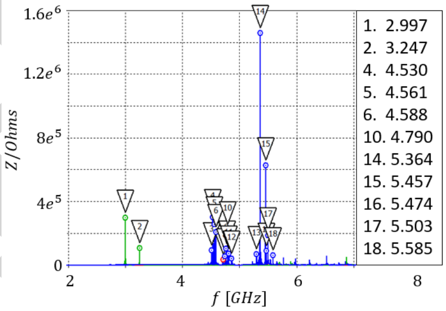

Figure 11: Impedances of HOMs for 3-cav crab module including tapers calculated using CST wakefield solver.

SOMs/HOMs around 4.5 and 5.5 GHz frequencies above the impedance budget of the crab cavity module (Table 1). Further geometry optimization is ongoing to reduce the strength of these modes, as well as the evaluation of their potential impact on the beam dynamics. At the end, time domain analysis using CST wakesolver is presented, and the results are benchmarked with the frequency domain solver, showing very good agreement.

REFERENCES

[1] E. Karantzoulis, S. Di Mitri *et al.*, "Design strategies and technology of Elettra 2.0 for a versatile offer to the user community", *Nucl. Instrum. Methods Phys. Res. A*, vol. 1060, 2023. `doi:10.1016/j.nima.2023.169007`

[2] A. Zholents, "A new possibility for production of sub-picosecond x-ray pulses using a time dependent radio frequency orbit deflection", *Nucl. Instrum. Methods Phys. Res. A*, vol. 798, 2015. `doi:10.1016/j.nima.2015.07.016`

[3] X. Huang *et al.*, "Beam dynamics issues for the two-frequency crab cavity short pulse scheme", *Phys. Rev. Accel. Beams*, vol. 22, p. 090703, 2019. `doi:10.1103/PhysRevAccelBeams.22.090703`

[4] A. Lunin *et al.*, "Design of a quasi-waveguide multicell deflecting cavity for the Advanced Photon Source", *Physics Procedia*, vol. 79, 2015. `doi:10.1016/j.phpro.2015.11.062`

[5] N. Shafqat *et al.*, "Radio frequency design and analysis of quasi-waveguide multicell deflecting cavities for the production of picosecond x-ray pulses for Elettra 2.0", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1266–1269. `doi:10.18429/JACoW-IPAC2024-TUPG23`