B*ERL*inPro 7-CELL SRF CAVITY OPTIMIZATION AND HOMs EXTERNAL QUALITY FACTORS ESTIMATION*

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Abstract

The main scope of this work is the optimization of the Superconducting Radio Frequency (SRF) accelerating cavity design for the Berlin Energy Recovery Linac Project (B*ERL*inPro). B*ERL*inPro shall serve as a demonstrator for 100-mA-class Energy Recovery Liniac (ERL) with CW LINAC technology. High-current operation requires an effective damping of Higher-Order Modes (HOMs) of the 1.3 GHz main-linac cavities. Consequently it is important, at the SRF cavity design optimization stage, to calculate the external quality factors of HOMs to avoid beam break up (BBU) instabilities. The optimization of the SRF cavity design consists of two steps. In the first step, the cavities' end half-cells are tuned with respect to field flatness, effective shunt impedance and geometrical factor of the fundamental accelerating mode using robust eigenmode simulations. The second step involves frequency domain simulations and the extraction of external quality factors of HOMs from transmission S-parameter spectra using a vector fitting procedure and an automated traveling poles elimination (TPE) scheme to remove non-static poles.

INTRODUCTION

An important issue in the superconducting radio frequency cavity optimization is the estimation of external quality factors Q_{ext} of higher-order modes.

It is especially important for the next-generation energy recovery linacs, like the B*ERL*inPro which is currently under development, to design the SRF cavities with highly damped HOMs [1, 2]. The HOMs are generated by charged particle beams traveling through a superconducting cavity at the speed of light ($\beta \approx 1$). The HOMs decay very slowly, depending on localization inside the structure and cell-to-cell coupling, and may influence succeeding charged particle bunches. Thus it is important, at the SRF cavity design optimization stage, to calculate the Q_{ext} of HOMs.

The SRF cavity presented in this article is a 1.3 GHz 7-cell Cornell design modified TESLA cavity with JLab HOM waveguide couplers. Traveling poles elimination (TPE) scheme [3] was used to automatically extract Q_{ext} from the transmission S-parameter spectra and a careful eigenmode analysis of the SRF cavity was performed.

The optimization procedure also involved the optimization of end-half-cells in respect to the field flatness. Since the estimation of the Q_{ext} of HOMs and the field flatness optimization could not be performed in one procedure, a two step scheme was adopted. After the first step, where the design is optimized in respect to the field flatness using eigenmode simulations, Q_{ext} of HOMs are extracted from transmission S-parameter spectra obtained using frequency domain simulations. All the frequency domain, as well as eigenmode simulations were performed using the CST Microwave Studio 2012 (CST MWS) electro-magnetic modeling software suite [4].

END-HALF-CELL TUNING

The one of last stages of the SRF cavity design involves optimization of the endhalf-cells in order to obtain desirable field flatness, as well as appropriate damping of HOMs. The axial electric field, as well as field flatness depend on the geometry of the end-cells, thus the same dimensions as for the mid-cells cannot be used. Since the optimization in respect to the field flatness and the Q_{ext} factors of HOMs can not be performed at the same time, a two step procedure has been employed. In the first step the cavity design is optimized in respect to field flatness, using eigenmode simulations. The design candidates, with appropriate field flatness, are subsequently checked in the next optimization step for HOMs properties and damping.

Preparatory Steps Before Optimization

In the preparatory step for the B*ERL*inPro SRF cavity end-half-cell optimization, the influence of HOM waveguide couplers on the axial electric field profile, and thus on the field flatness, has been investigated. Figure 1 shows an example cavity model with the waveguide HOMs couplers and the coaxial power coupler compared to the reduced model.

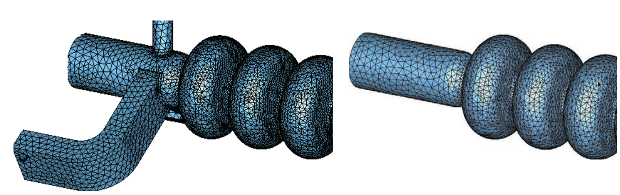

Figure 1: Comparison of the SRF cavity with (left) and without (right) the coaxial power coupler and the waveguide HOMs couplers.

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Similar number of tetrahedral mesh cells was used in both cases, with basic setup of 4 steps per wavelength, and the upper frequency limit of 3.3 GHz in CST MWS. The results of the field flatness comparison of the full structure and the cavity with beam pipes only showed that the maximum of the difference between both profiles do not exceed 0.75%, as shown in figure 2. This indicates none or very small influence of the HOMs waveguide couplers on the axial electric field profile and on the field flatness. Using the reduced model for the optimization of the cavity, in respect to the field flatness, allows performing much less complicated simulations. Since only the π-mode has to be simulated to obtain the axial electric field profile (and the field flatness), all three symmetries can be used, thus speeding up the optimization process.

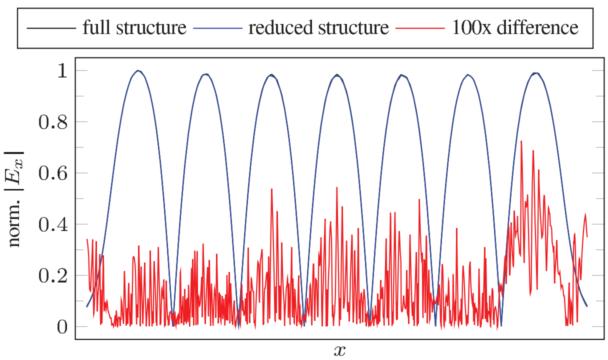

Figure 2: Comparison of the axial electric field strength for the full structure and the reduced structure without the coaxial and the waveguide couplers. The maximum of difference of these two profiles does not exceed 0.75%, indicating none or very small influence of the HOMs waveguide couplers on the field flatness.

Furthermore a convergence study was done to see how the mesh quality influences the axial electric field profile. The convergence study simulations of the cavity without the waveguide HOM couplers were performed using the eigenmode solver in CST MWS, only for the fundamental π-mode, utilizing all possible symmetries. Tetrahedral mesh with increasing steps per wavelength has been used with three adaptive mesh refinement steps for every case. Table 1 shows results for the reduced cavity model with the mesh cells setting from 4 to 10 steps per wavelength (λ). study. The results show that there is only 0.8% difference between the case with $533k$ and the case with $71k$ tetrahedral mesh cells. The small difference between the dense and the sparse mesh means that there is little consequence of using a lower quality mesh, allowing further acceleration of the optimization procedure.

Eigenmode Analysis

The eigenmode analysis was performed to obtain general properties and behavior of the SRF B*ERL*inPro cavity. Two separate eigenmode simulations for just a single cell, with periodic boundary conditions, were computed, with the phase shift from one cell to the other of 0° and 180° [5]. The eigenmode simulations were performed using a tetrahedral mesh with curved elements (2nd order) and with the frequency range of 1.2 - 3.3 GHz. Total number of 52 simulated eigenmodes were used to estimate the pass bands of the cavity, as well as cell-to-cell coupling factors [3]. The cell-to-cell coupling factors give a preliminary knowledge of which modes can be dangerous or trapped, as shown in figure 3. Furthermore the eigenmode analysis provides the information about shunt impedance and R/Q values for different monopole modes. It also provides the information about dipole, quadrupole and sextupole modes, which have influence on the off-axis beams.

Table 1: Convergence study of the mesh quality influence on the longitudinal electric field component on the beam axis. The solver times are given for a machine equipped with Intel XEON 3.2 GHz processor

Case Nr.	Mesh Cells/λ	Mesh Cells	Solver Time	Max. Diff. vs. Case 7
1	4	71k	3min 32s	0.800 %
2	5	110k	4min 23s	0.541 %
3	6	163k	6min 41s	0.469 %
4	7	259k	12min 01s	0.335 %
5	8	350k	17min 03s	0.230 %
6	9	454k	27min 16s	0.218 %
7	10	533k	38min 15s	-

External Quality Factors Estimation

In the project framework the automation of the extraction procedure of the external quality factors of higher order modes has been developed. The traveling poles elimination (TPE) scheme, based on the fast implementation of the vector fitting with rational functions procedure [6, 7], was used to automatically extract Q_{ext} from the transmission spectra and careful eigenmode analysis of the SRF cavity was performed to confirm TPE results [3], as presented in figure 3. In this method, unlike the common way of the calculation of Q_{ext} using eigenmode solver, the HOMs' Q_{ext} factors are extracted from the transmission S-parameter spectra. The TPE scheme is a simple iterative procedure which main purpose is to detect static poles and calculate external quality factors. The additional benefit of the TPE procedure is the supplementary self-correlated statistical data on every calculated Q_{ext} factor.

Optimization Details

The optimization was performed in CST MWS using the eigenmode solver and the particle swarm optimization algorithm. The tetrahedral mesh was used to discretize the reduced model of the cavity according to the conditions described above. The goal function was set to obtain results for designs with the fundamental π-mode frequency as close to the 1.3 GHz frequency as possible, and with the value of R/Q higher than 770 Ω. The cavity design geom-

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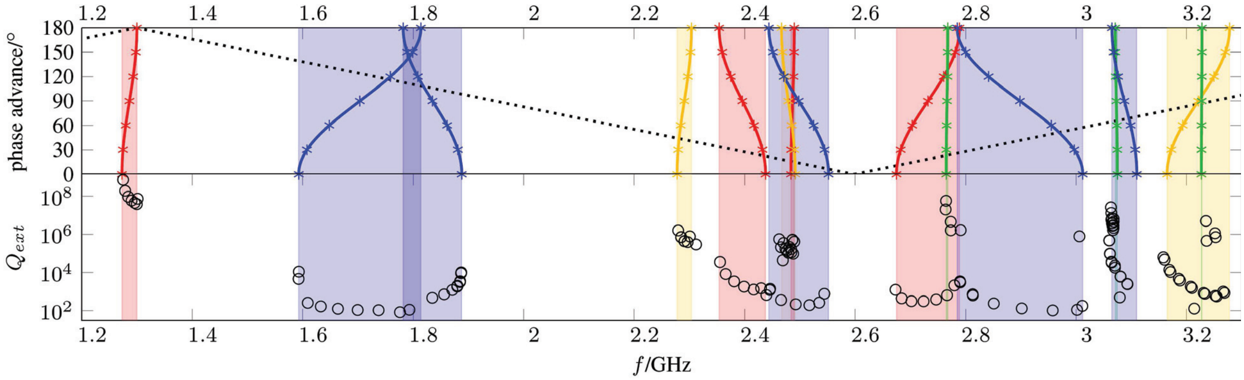

Figure 3: Band diagram for the 7-cell cavity (top) and a set of Q_{ext} factors for the design candidate nr. 5. The indicated bands are colored according to the type of the mode, that is, monopoles (red), dipoles (blue), quadrupoles (orange) and sextupoles (green). The external quality factors (black circles) were automatically obtained using the vector fitting and TPE procedure.

etry was optimized over two eliptical parameters and the length of both end-half-cells. Since the B*ERL*inPro SRF cavity will have unsymmetrical end-half-cells, in total 6 parameters were varied during the optimization.

RESULTS

The optimization results were analyzed with special emphasis on the field flatness and the Q_{ext} factors of the fundamental mode, as well as the HOMs. The field flatness was calculated according to [8],

$$\eta_{ff} = \frac{E_{peak,max} - E_{peak,min}}{\frac{1}{N}\sum_{i=1}^{N} E_{peak,i}} \times 100\%, \quad (1)$$

where $E_{peak,max}$ and $E_{peak,min}$ are the maximum and the minimum of the peak electric field on the beam axis respectively, $E_{peak,i}$ is the peak electric field of the i-th cell, and N the number of cells in the cavity. In table 2 are presented selected design candidates, for which the best results were obtained. The design candidate 5 and 2 have the best field flatness, however the R/Q values are lower than for the other selected design candidates. The analysis of the Q_{ext} factors revealed that these two design candidates have both, higher Q_{ext} of the π-mode, and lower Q_{ext} values for the first two dipole bands and the first quadrupole band, than the other selected design candidates.

CONCLUSIONS

In this work we have presented an optimization scheme, where the optimized cavity design is checked for the best properties using a two step procedure. In the first step the emphasis is put on the field flatness, as well as resonance frequency and the interaction with the beam. In the second step the design candidates are checked for the most appropriate HOMs properties. The overall speed up in the optimization time was found to be significant.

Table 2: Comparison of the selected cavity design candidates

Design Nr.	f / GHz	R/Q / Ω	η_{ff} / %
1	1.30024	770.248	2.593
2	1.30022	770.169	1.716
3	1.30026	770.056	2.673
4	1.30028	770.168	2.692
5	1.30023	770.112	1.052
6	1.30026	770.080	2.234
7	1.30028	770.511	2.878
8	1.30026	770.389	1.856

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