BASELINE CAVITY DESIGN FOR CORNELL'S ENERGY RECOVERY LINAC *

N. Valles† and M. Liepe, Cornell University, CLASSE, Ithaca, NY 14853, USA

Abstract

This paper discusses the baseline superconducting RF cavity design to be used in Cornell's Energy Recovery Linac, a next generation light source. We discuss the methods used to obtain the design and present the cavity's figures of merit. The baseline cavity design is ready for prototyping, which will begin in the fall of 2010. Finally, we introduce small variations in the center cell design to increase the threshold current through the cavity by increasing the higher order mode relative frequency spread in the main linac, that have the effect of more than doubling the threshold current to 450 mA

INTRODUCTION

Central to the intended operation of an Energy Recovery Linac (ERL) is the proper design and functioning of the superconducting RF cavities comprising its main accelerating structure. Cornell has chosen to implement superconducting niobium seven-cell accelerating structures into the main linac design enabling a high current (100 mA), very low emittance (30 pm-rad at 77 pC bunch charge) 5 GeV beam capable of producing short pulses ($\sigma_z/c = 2$ ps) of hard x-rays with a high repetition rate (1.3 GHz)[1].

Because of the large number of free parameters available in a 7-cell cavity, the design was broken down into several steps. This reduced the number of degrees of freedom at each level, allowing for a robust cavity design within a reasonable time frame.

The 7-cell cavity is a 1.3 GHz design. The design process began by minimizing the cryogenic losses ($R/Q \cdot G$) for the fundamental mode[2]. To make the RF properties of the cavity stable under unavoidable machining perturbations in fabrication, the center cell design was modified to maximize the width of certain higher-order mode (HOM) dipole passbands[3], without causing a significant drop in $R/Q \cdot G$ for the fundamental mode. The baseline design includes a new higher-order mode absorbing material, constructed of carbon nanotubes, which has approximately frequency independent RF properties. Finally, the baseline design includes a re-optimized end cell design that damps the HOMs that most strongly limit beam-break up current[4].

To further reduce the coherent effects of HOMs on the beam break-up (BBU) current, we have also made small-variations to the center-cell design to be used in conjunction with the baseline design. The additional designs have higher-order mode passbands shifted relative to the baseline design. Including differently shaped cavities within the same linac increases the relative HOM frequency spread between cavities, which increases the threshold current that can pass through the machine.

This paper discusses the physical considerations that must be implemented into the baseline cavity design and the methods used to optimize cavities under the physical constraints mentioned above.

METHODS

The Cornell ERL is specified to run currents of 100 mA through the main linac. This current is limited by higher-order-modes in the cavity that are excited and cause beam loss. In general, determining the threshold current through an accelerator is a very computationally intensive process. The basic process consists of modelling the accelerating structure, which is a function of a large number of free parameters, inputting HOM properties, defining a cavity-to-cavity frequency spread and running hundreds of instances of a particle tracking program to gather sufficient statistics on the maximal beam current. In total, determining the threshold current with 90% certainty can take hundreds of computer-hours per HOM. To speed design, it is essential to find a deterministic (rather than statistical) figure of merit corresponding to BBU current.

Previous work showed that the beam break-up current is inversely related to a parameter, ζ, that is a function of each HOMs' R/Q, Q and frequency, f, by

$$I_{th}^{-1} \propto \zeta_\lambda \equiv \left(\frac{R}{Q}\right)_\lambda \cdot \sqrt{Q_\lambda} \cdot f_\lambda^{-1}, \tag{1}$$

where the subscript λ is the index of a given HOM[4]. Thus, minimizing $\max(\zeta_\lambda)$ in the optimization routine, instead of performing statistical beam tracing operations at each iteration, significantly reduced the computational load for the optimization. This allowed us to check modes up to 10 GHz for their effect on threshold current, while still arriving at an optimized cavity in a reasonable amount of time.

It is important to mention that ζ does not directly correspond to beam current, but is a useful heuristic in the optimization. After $\max(\zeta_\lambda)$ is minimized, it is still necessary to run particle tracking on the resultant cavity, to calculate the threshold current.

To further simplify the optimization, the simultaneous minimization of n-HOMs was treated as the analytic problem of minimizing the worst HOM, under the non-analytic constraint that each BBU parameter of all other dipole modes in the spectrum be less than the maximal BBU parameter of all the modes $\equiv M$. This process effectively

* Work supported by NSF Grant No. PHY-0131508, and NSF/NIH-NIGMS Grant No. DMR-0937466

† nrv5@cornell.edu

minimizes all the HOMs simultaneously. Furthermore, should the control HOM be below another mode that had a smaller value earlier in the optimization, the optimization switches to control the new mode. This decomposes the non-analytic into an analytic problem with a non-analytic constraint.

The optimization was carried out with MatLab, utilizing 256 processors in parallel to solve electro-magnetic fields of the cavities. We implemented a 2D finite element code field solver CLANS for the monopole modes and CLANS2 for dipole modes [5].

The threshold current through the baseline cavity was computed as a function of HOM frequency spread, and is presented in Fig. 1. Simulations show that due to expected machining tolerances, with only the baseline cavity, there will be a cavity-to-cavity relative frequency spread of 0.5×10^{-3}. This corresponds to a threshold current of approximately 200 mA. Note that Fig. 1 shows that increasing the relative HOM frequency spread between the cavities increases the threshold current through the linac.

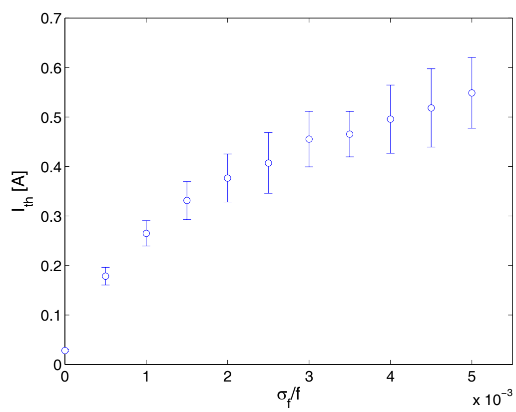

Figure 1: Threshold current through Cornell's ERL vs relative frequency spread. Taking into account expected machining errors to the baseline design, we expect a realistic ERL to have a relative frequency spread of approximately 0.5×10^{-3}, which corresponds to a threshold current of just under 200 mA.

So as to not rely on fabrication variation as the sole source of relative frequency spread, we are interested in designing different classes of cavities, with slightly shifted HOM passbands to be incorporated in the main linac. This necessitates making small variations in the center cell design. Also, previous work showed that simply relaxing fabrication tolerance was not sufficient to obtaining a robust design[3], as this can produce cavities with HOMs with very different properties than design values. Instead, it is important to reliably produce cavities with small machining tolerances with designs that introduce cavity-to-cavity relative frequency spread.

To find an additional center cell shapes with frequency shifted HOM bands, a parameter sweep was performed on the center cell parameters. The center cell shapes were chosen that maximize the frequency differences between the HOM passbands. This effectively reduces coherent effects, which would increase the threshold current through an ERL composed of both of these cavities.

The parameter sweep only included cavity shapes that met four conditions: E_{peak}/E_{acc} had to remain below 2.1 MV/m, the R/Q·G of the fundamental mode had to stay within $\pm 5\%$ of the base line design, the wall angle of the cavity had to be less than $85°$,[1] and the radius of curvature everywhere on the cell could not be smaller than 6 mm.[2] The parameter sweep was carried out in parallel on 256 processors, allowing a resolution of 1.0 mm to be explored for the 4 ellipse axes that generate a center cell shape. A schematic is shown in Fig. 2.

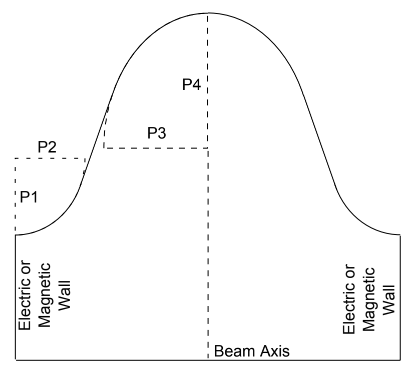

Figure 2: Schematic of center cell geometry. The parameters P1-P4, were swept in 1 mm increments in a region of 5 mm around their design values. After choosing a parameter set, the geometry was tuned to 1.3 GHz. The cell is symmetric about the dotted line down the center. The boundary conditions were varied to obtain the 0 and π mode of each passband.

RESULTS

The cavity optimization successfully completed, and we obtained a baseline design. The figures of merit for the baseline cavity design are presented in Tables 1–3.

All monopole modes up to 10 GHz have been calculated for the linac cavity shape to ensure that modes that could have been driven resonantly are sufficiently damped. Wakefield losses were computed using ABCI[6], and were shown to result in approximately 200 W of power being dissipated in the HOM absorbers when running at 100 mA design current, which is within design specifications.

Calculations performed with Omega3P[7], a 3D frequency domain finite-element code, on the baseline geometry agreed with the fundamental mode properties calculated in 2D with CLANS. Wakefields calculated with a time-domain code, S3P, also agreed with the results of the 2D simulations obtained through ABCI.

[1] The wall angle constraint is a necessity for proper chemical treatment and cleaning by high-pressure rinsing.

[2] This consideration is necessary for making reproducible bends in the fabrication process.

Table 1: Main Linac Cavity Parameters for Cornell's ERL

Parameter	Value
Type of accelerating structure	Standing wave
Accelerating Mode	TM010 π mode
Design Gradient	16.2 MV/m
Intrinsic quality factor, Q_0	$> 2 \times 10^{10}$
Loaded quality factor, Q_L	6.5×10^7
Cavity half bandwidth	10 Hz
Cell Iris diameter	36 mm
Beam tube diameter	110 mm
Number of cells	7
Active length	0.81 m

Table 2: Fundamental Mode Properties for Baseline Design

Parameter	Value
Fundamental Frequency	1300 MHz
Cell-to-cell coupling	2.2%
Geometry factor	270.7 Ω
R/Q	387 Ω
E_{peak}/E_{acc}	2.06
H_{peak}/E_{acc}	42.0 Oe/(MV/m)

Dispersion curves for the perturbed center cell shapes is presented in Fig. 3. The results of the parameter sweep show that by choosing different center cell shapes, the HOM passbands can be frequency split in regards to one another.

Center cell designs with a minimal relative frequency shift of 11.5 MHz were obtained. These designs still maintain sufficiently wide passbands to mitigate machining variation. The minimal frequency splitting is for the 3.0 GHz passband, and the splitting are much larger for the other passbands. The baseline design has the strongest HOM in the 1.7 GHz, band, where the frequency splitting is 23 MHz, which gives a relative frequency spread of approximately 3.9×10^{-3}, corresponding to a threshold current of 450 mA. This result is more than double the threshold current obtained previously.

Since machining variations introduce a frequency spread of 0.5×10^{-3}, to obtain the relative spread of 3.9×10^{-3}, 8 cavity classes are necessary.

Table 3: Baseline Design Loss Factors for σ=0.6 mm Bunch

Parameter	Value
Total longitudinal loss factor	14.7 V/pc
Longitudinal loss factor, from non-fundamental	13.1 V/pc
Transverse loss factor	13.7 V/pc/m

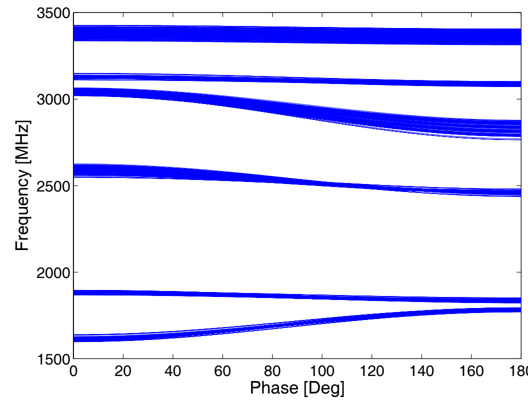

Figure 3: Dispersion curves of the first 6 dipole bands. Only bands having a minimum bandwidth of 20 MHz have been plotted, which is necessary for a robust design.

CONCLUSIONS

We successfully optimized a cavity for the main linac of Cornell's ERL with a realistic HOM absorber geometry and material, and have obtained a baseline design that is ready for prototyping. This was accomplished by reducing the complex problem with many degrees of freedom into several subsections and optimizing them individually, with the extensive usage of parallel computing.

The current design introduces relative frequency spread as a result of unavoidable fabrication errors. This frequency spread can be further increased by included different cell shapes in the main linac of the ERL.

Preliminary studies show that the HOM passbands can be shifted by at least 11.5 MHz, while still maintaining broad enough HOM passbands to be stable under manufacturing variations. However, for the worst mode, the relative frequency spread of 3.9×10^{-3} is achievable, more than doubling the threshold current limit to 450 mA.

REFERENCES

[1] J. A. Crittenden et. al. "Developments for Cornell's X-Ray ERL," PAC 2009.

[2] V. D. Shemelin "Suppression of HOMs in a Multicell Superconducting Cavity for Cornell ERL," SRF 2009.

[3] N. Valles and M. Liepe, "Seven-cell Cavity Optimization for Cornell's Energy Recovery Linac," SRF 2009.

[4] N. Valles and M. Liepe, "Cavity Design for Cornell's Energy Recovery Linac," IPAC 2010.

[5] D.G. Myakishev, "CLANS2-A Code for Calculation of Multipole Modes in Axisymmetric Cavities...," PAC 1999, pp 2775-2777.

[6] Chin Yong Ho, "User's Guide for ABCI Version 9.4 (Azimuthal Beam Cavity Interaction) And Introducing the ABCI Windows Application Package." 2005. Kek Rep.

[7] Lie-Quan Lee, Zenghai Li, Cho Ng, and Kwok Ko "Omega3P: A Parallel Finite-Element Eigenmode Analysis Code for Accelerator Cavities."