CAVITY DESIGN FOR CORNELL'S ENERGY RECOVERY LINAC *

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Abstract

This paper discusses the optimization of superconducting RF cavities to be used in Cornell's Energy Recovery Linac, a next generation light source. We discuss the determination of a parameter corresponding to beam break-up current and the results of introducing a realistic higher-order-mode absorber constructed of carbon nanotubes rather than a ferrite based absorber. We conclude by comparing the threshold current of the new design and show differences are due to the new absorber material.

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

The 7-cell cavity is a 1.3 GHz design. This work is an extension of an initial cavity design which minimized the cryogenic losses ($R/Q \cdot G$) for the fundamental mode[2], and a preliminary optimization to maximize the threshold current in the cavity and make the design stable under unavoidable perturbations due to machining [3].

The initial cavity design was optimized to obtain a large value of $R/Q \cdot G$ for the fundamental mode (1.3 GHz), and minimizes the dynamic cryogenic load, while limiting the ratio of peak electric to accelerating field E_{pk}/E_{acc} to 2.1, minimizing the risk of electron field emission. These constraints must still be satisfied for any subsequent design.

Preliminary optimization sought to make the figures of merit of the cavity stable under small shape perturbations that are unavoidable during the machining process. This was achieved by increasing the cell-to-cell coupling of the center cells of the cavity. Increased coupling increases the bandwidth of higher-order-mode (HOM) passbands that limit the threshold current through the accelerator, and results in a stable design.[3] The end cells were then modified to maximize the damping of HOMs by the HOM absorbers.

New features of the current cavity design include a new HOM design, introduction of a Carbon Nanotube (CNT) absorber instead of a ferrite based absorber, TT2. The change in absorber material is motivated by the fact that TT2 absorber tiles are subject to DC charging, and while it is a good absorber a low frequencies, its properties depend strongly on frequency. Previous optimizations used an idealized frequency independent absorber (IFIA) based on TT2 properties at ∼2 GHz. Real CNT absorbers have almost frequency independent properties, and can be manufactured to have DC conductivity, mitigating problems with the IFIAs.

These changes were made to the design, and further end cell optimization was carried out. Also previous calculations only calculated HOMs from 1.6-5 GHz. The current optimization includes HOMs up to 10 GHz.

We begin by discussing the determination of a new beam-break up (BBU) parameter for use in the optimization routine and optimization methods. Next, the threshold current is compared between the new and old design. Finally, we show the difference in threshold current is directly attributable to the CNT material properties.

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 modeling the accelerating structure, inputing HOM properties, defining a cavity-to-cavity frequency spread and running hundreds of instances of BMAD, a particle tracking program,[4] to gather sufficient statistics on the maximal beam current. In total, determining the threshold current for this process with 90% certainty can take hundreds of computer-hours. To speed design, it is essential to find a deterministic (rather than statistical) figure of merit corresponding to BBU current.

The threshold current, I_{th}, through an isolated cavity has been modeled as

$$I_{th} = -\frac{2}{(2\pi)^2 e \left(\frac{R}{Q}\right)_\lambda (Q_L)_\lambda/\omega_\lambda} \frac{1}{T^*_{12}\sin(\omega_\lambda t_r)}^{1} \quad (1)$$

where ω_λ is the HOM frequency with quality factor Q_λ, R/Q is measured in Ω/cm^2, t_r is the bunch return time, and T_{12} is the 1-2 element of the transfer matrix [5]. This suggests that minimizing the beam break-up parameter, $R/Q \cdot Q_L/f$, increases I_{th} through the accelerator.

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[1] We have changed R/Q's dimensions from Ω to Ω/cm^2, causing ω to appear in the numerator, instead of the denominator.

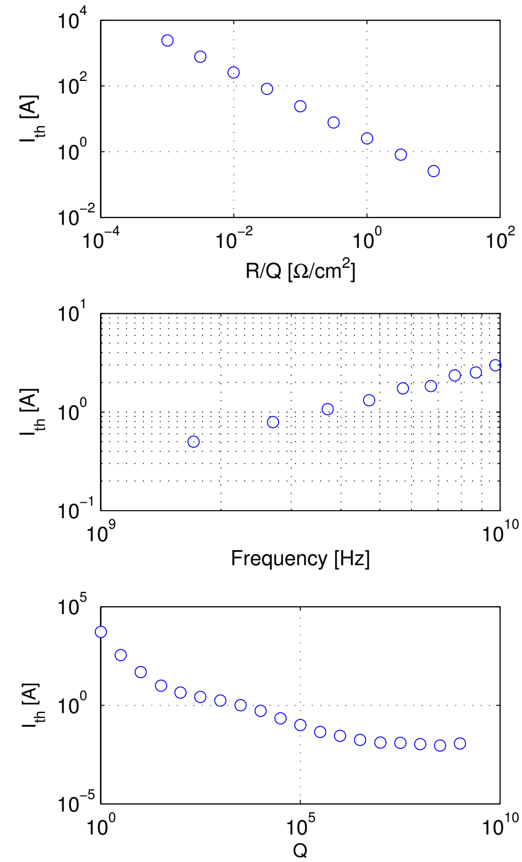

Figure 1: Scaling of the threshold current vs R/Q, frequency and Q, assuming a frequency spread $\sigma_f/f = 5 \times 10^{-3}$. For all plots, $R/Q = 5\Omega/\text{cm}^2$, $Q = 10^4$, $f = 1.7$ GHz, except when a given parameter is the independent variable. The circles mark the threshold current obtained by at least 90% of the random runs.

In the linac, modeling the cavities as isolated is inaccurate. Coherent effects, for example, could influence I_{th} through the linac. Thus, a new BBU parameter should be determined, though it is expected to depend on the same parameters as the isolated cavity model.

Previous work[3] found that a the 1.7 GHz passband contained modes that were limiting the threshold current. The worst mode had a Q of $\sim 10^4$ range, and $R/Q \sim 5\Omega/\text{cm}^2$. To determine scaling laws of the threshold current, 500 particle tracking runs were performed on the 384 cavities comprising the linac, varying one parameter at a time, assuming a relative frequency spread of 5×10^{-3}.

The conclusion of the BMAD runs from Fig. 1 is that I_{th} increases linearly with the frequency of the mode, decreases linearly with the R/Q of the mode, and decreases with $Q^{-1/2}$ for $10^2 < Q < 10^4$. Thus, the current is maximized by minimizing the BBU parameter

$$\zeta = \frac{R}{Q} \cdot \sqrt{Q} \cdot f^{-1}. \quad (2)$$

Note that ζ does not directly correspond to beam current, but is a useful heuristic in the optimization. After ζ is minimized, it is still necessary to run particle tracking on the resultant cavity, to calculate the threshold current.

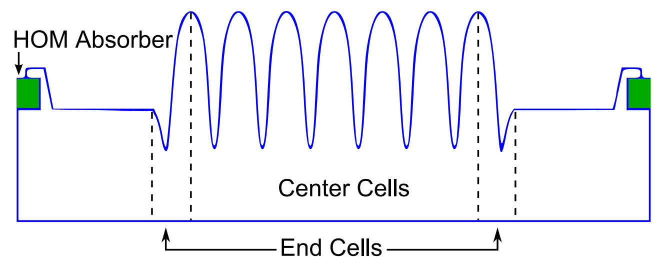

Figure 2: Schematic of 7-cell. The end cell designs are optimized to maximize I_{th}. HOM absorbers appear in green.

The end cells were optimized by varying 5 ellipse half-axes of 3 ellipses. A schematic of the design is presented in Fig. 2.

The optimization used an unconstrained downhill simplex search method. Though the solver implemented does not handle constraints (solvers with constraints were frustrated by the problem's non-analyticity), physical requirements necessitate constraining the system. This was accomplished by severely penalizing search points that violate (1) Non-physical/non-smooth geometries, (2) $E_{pk}/E_{acc} > 2.1$, (3) wall angles $> 87.5°$ measured from the horizontal (no re-entrant designs permitted) and (4) small curvatures because reliably producing very small curvatures is technologically challenging.

Each HOM passband was calculated using the four combinations of electric and magnetic boundary conditions to simulate a chain of identical cavities. This is more realistic than open boundary conditions because open boundary conditions are only applicable in the case of an isolated cavity, not one in a long chain of cavities. Thus, the HOMs computed here much more accurately reflect what one could expect in the main linac.

The optimization routine minimized the worst BBU parameter for HOMs from 1.6–10.0 GHz. This is not as simple as simply simultaneously minimizing each HOM's BBU parameter, because geometry changes that reduce the strength of one HOM can drastically increase the strength of another HOM. Thus, the problem is to find a cavity shape that simultaneously minimizes the BBU parameters of all the HOMs, is intrinsically non-analytic.

To 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 $\equiv M$ [6]. Minimization improves the BBU parameter by controlling the worst mode; all other modes are required to fall below M for the point to be in the search space. This process effectively 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. Thus the non-analytic problem is decomposed into an analytic problem with a non-analytic constraint.

The optimization was carried out in parallel on 256 processors leased from Cornell's Center for Advanced computing, and the electro-magnetic fields were solved with 2D finite element codes CLANS for the monopole mode and CLANS2 for dipole modes [7].

RESULTS

New HOM absorber geometry and CNT properties were introduced to the model, and the end cells were re-optimized. Optimization reduced the maximum BBU parameter to $\sim$ 270Ω/(cm^2·GHz) for HOMs from 1.6–10.0 GHz, and is shown in Fig. 3. BMAD was used to compute the final threshold current through an ERL composed of ideal 7-cell cavities.

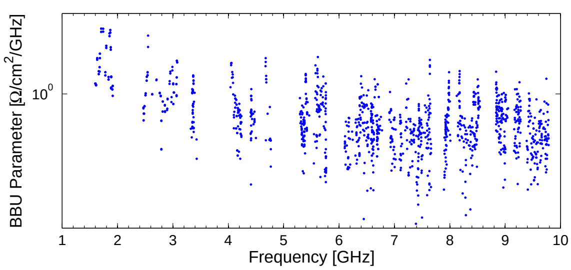

Figure 3: Beam break-up parameter vs Frequency for 1692 dipole HOMs for the optimized 7-cell cavity.

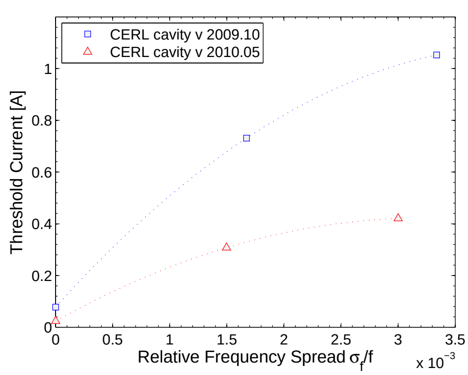

Figure 4: Beam break-up current versus relative frequency spread for simulated ERLs. Blue points are the old cavity design with an IFIA, and red marks the new cavity design with a realistic CNT absorber. The new design only supports half the current of the old design, but its absorber properties are more realistic than those of the old design. To achieve 100 mA threshold current with the new design, a relative frequency spread of 3.3×10^{-4} is required.

Figure 4 shows that as the relative frequency spread increases, so does the threshold beam current. In practice, the frequency spread will be introduced by slight variation in cavity shapes. Previous work has shown that ERLs constructed from cavities with realistic shape perturbations are capable of similar BBU currents[3].

The new design has lower threshold current not due to a worse cavity design but because CNTs are less effective at absorbing HOM power than the IFIA used in the previous optimization. To show this, a plane wave striking a 3 cm thick absorber with given electromagnetic properties was modeled. The are shown in Fig. 5. The plot shows the realistic CNT absorber only absorbs about half the power compared to the IFIA. Note, however, that CNT absorbers are realistic, whereas the IFIA properties are unobtainable.

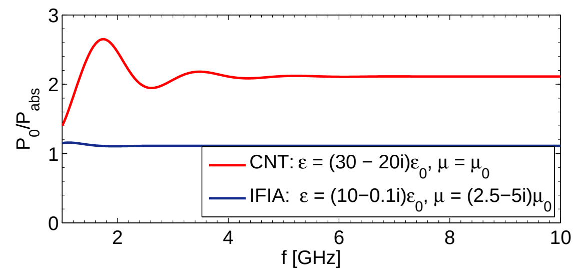

Figure 5: Total HOM power, P_0, over power dissipated in absorber, P_{abs}, vs HOM frequency assuming a plane wave incident normally on an ideal 3 cm thick absorber.

CONCLUSIONS

We successfully optimized the end cells of the 7-cell cavity for Cornell ERL with a realistic HOM absorber geometry and material. The new design allows roughly half the threshold current compared to the design with the idealized absorber, but this is due to the properties of the CNTs to be used in the absorber. This is reasonable, however, since the CNT properties closely models the real absorber over a broad frequency range.

Further study will include power coupler design, 3D modeling of the cavity, and design of several classes of cavities to introduce frequency spread to the main linac.

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