ROBUSTNESS OF THE SUPERCONDUCTING MULTICELL CAVITY DESIGN FOR THE CORNELL ENERGY RECOVERY LINAC*

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Abstract

Cornell University is developing an Energy-Recovery-Linac driven x-ray light source. One of the major components of this accelerator will be its 5 GeV superconducting main linac. The design of the superconducting RF cavities in an ERL linac is often optimized primarily for two objectives: (1) low RF losses from the accelerating mode to minimize refrigeration cost and (2) strong Higher-Order-Mode damping to preserve low emittance and prevent beam break-up instability at high beam current. In this paper we study the robustness of an example cavity design with respect to small cell shape fluctuations from fabrication errors.

MOTIVATION

The maximum current that can be accelerated in an Energy Recovery Linear Accelerator (ERL) can be limited by the transverse recirculating beam-breakup instability (BBU) [1]. It is therefor critical to understand this potential limitation well. Numerical beam tracking is usually used to determine the BBU threshold current for a given accelerator optics and RF cavity design. Parameters of the Higher-Order-Modes of a given ERL main linac cavity design are calculated - including their frequencies f, quality factors Q and r/Q values, and then used in the BBU simulations. A useful parameter for quantifying the potential harmfulness of a given Higher-Order-Mode is the factor $(r/Q)Q/f$. The higher this factor, the stronger the resulting limitation on beam current might be. In addition to this parameter, the BBU threshold current will also depend on the accelerator optics, the total number of cavities, as well as the frequency spread of a given HOM between cavities. BBU Simulations are usually done with ideal cavities, i.e. with HOM parameters calculated for a main linac cavity as designed. In this case, the same r/Q and Q values are used for all the cavities in an ERL main linac under study. HOM frequency spread from cavity to cavity of several MHz is then introduced artificially to avoid that contributions to BBU from different cavities add up coherently, which would result in a low BBU current [2]. It is obvious that this is a significant simplification, which, as we will discuss below, might not be always valid.

In reality, all cavities will have small shape imperfections from fabrication errors, so non of the cavities in an ERL main linac will be identical. The shape perturbations will introduce a frequency spread of the order of a few to several MHz between cavities, which is desirable, but at the same time they will result in significant changes in the relative cell-to-cell field distribution of a given HOM in a given multi-cell main linac cavity. This change in HOM field distribution within a multi-cell cavity will impact the damping of the mode by RF absorbers in the beam pipe (or by other means like waveguides at the beam tube sections of the cavity) as well as the (r/Q) factor of the Higher-Order-Mode. In this paper we show that this effect can have severe impact on the BBU current limit.

METHOD

To quantify the impact of small shape imperfections in multicell ERL cavities and the BBU threshold current, we have developed and set up the following approach:

- A set of tens to hundreds of numerical cavity models is generated with shapes having small, random deviations from an given ideal cavity design. We have written a Matlab code for this part.
- For each cavity model, the individual cells are tuned for field homogeneity and correct frequency of the fundamental mode. The 2-D cavity eigenmode solver CLANS is used for this step [3].
- After tuning, all Higher-Order-Modes up to a given maximum frequency and their damping by RF loads in the beam pipes are calculated in each imperfect cavity with the codes CLANS and CLANS2. Since this is a time consuming step, and a large number of HOMs in a large number of cavities need to be calculated, we use parallel computing in this step. A High-Power-Computing system at Cornell is used, which allows to run up to 120 instances of CLANS/CLANS2 in parallel on a computer cluster with 120 cores [4].
- The results of these HOM calculations are then used in BBU tracking with individual, imperfect cavities in the ERL main linac to determine the threshold current. The sequence of the individual cavities in the main linac is determined randomly, and several, different sequences are modeled.

Using this method, we can study the robustness of a given cavity design with respect to small shape imperfections within a few hours, and can use the outcome to further guide the cavity design.

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Table 1: BBU threshold current from tracking simulations for an ERL with 384 SRF cavities as function of rms frequency spread artificially introduced between HOMs in different cavities. In all cases, the five dipole HOMs with highest $(r/Q)Q/f$ values in the ideal cavity of given type "A" or "B" where included. (r/Q) and Q values used are identical in all cavities, as calculated for the ideal cavity.

	σ_f=0 MHz	σ_f=5 MHz	σ_f=10MHz
"Type A"	0.033A	0.54±0.06A	0.89±0.10A
"Type B"	0.083A	1.5±0.1A	2.4±0.2A

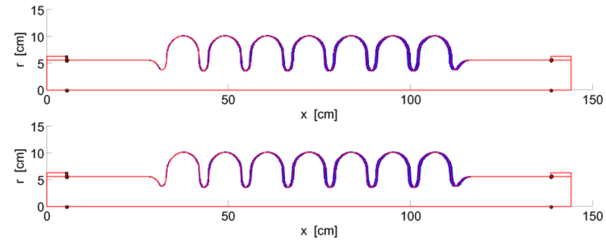

Figure 1: Example cavities used for this study. Red: Cavity without shape deformations. Blue: 50 cavities with $\pm 1/8$ mm shape deformations and subsequently tuning for fundamental mode field homogeneity. Top: "Type A". Bottom: "Type B".

FIRST RESULTS

As an initial test case, we have performed the steps outlined above for two, slightly different 1.3 GHz 7-cell example cavity designs. The only difference in the two designs are small changes in the outer half end cells. Design "A" is purely optimized for low losses of the fundamental mode. Design "B" has been adjusted for somewhat improved HOM damping. It is important to point out that both designs have not been optimized for strongest possible HOM suppression nor robustness of the HOM damping against small shape imperfections. A summary of the current status of cavity optimization for the Cornell ERL can be found in [5].

For comparison, BBU threshold currents have been calculated for both cavity designs first using ideal, identical cavities and artificially introduced HOM frequency spread, see Table 1. The same example ERL with 384 cavities is considered throughout this paper for all BBU simulations. For both cavity designs, the BBU limit current is of the order of 1 A for rms HOM frequency spreads of $\sigma_f = 10$ MHz. Note that the threshold current strongly increases with frequency spread.

We have then generated sets of unique, imperfect cavities for the "type A" and "type B" cavity designs by randomly adding small shape perturbations to all cavity parameters, see Figure 1. All cavities have been re-tuned for the fundamental mode, and then all HOM dipole modes with frequencies below 3.5 GHz have been calculated. For the random deformations, a uniform distribution between $-1/8$ mm and $1/8$ mm has been assumed in this first study. Such deformations result in rms HOM frequency spreads of 2 to 10 MHz between cavities, which is about twice of the spread measured in real SRF linacs [6]. All Q and (r/Q) values of the dipole modes of the individual,imperfect cavities are show in Figure 2 and 3 in addition to the resulting BBU parameter $(r/Q)Q/f$. For comparison, these values are also shown for the two cavity types as designed, i.e. without shape perturbations. The dramatic increase in the Q and (r/Q) values of some HOMs in some of the imperfect cavities is obvious. Not surprisingly, most susceptible are passbands with narrow frequency width, i.e. small cell-to-cell coupling. Using these sets of imperfect cavities, the BBU thresholds have been recalculated, this time without any artificial HOM frequency spread added. The results are quite low BBU threshold currents of 2 ± 1 mA and 0.1 ± 0.1 mA for cavities based on the "type A" and "type B" design respectively. The very low BBU current for design "B" is determined solely in this example by one cavity with one very high quality factor mode.

This first example demonstrates that tight control of fabrication tolerances of ERL cavities is essential, together with a robust cavity design. In addition, it might be beneficial to measure the properties of some of the strongest Higher-Order-Modes in the SRF cavities prior to installing them in an ERL to eliminate the worst outliers.

SUMMARY AND OUTLOOK

We have developed a method to get realistic BBU threshold current estimates for a given ERL layout and SRF cavity design, which takes into account small shape imperfections present in real cavities from cavity manufacturing and preparation. The first example discussed in this paper shows that care needs to be taken to void severe reduction of the BBU limit current as a result of such shape imperfections. This work is at its early stages, and as a next step we will apply such studies to the ongoing cavity design work for the Cornell ERL main linac to guide the shape optimization of these cavities.

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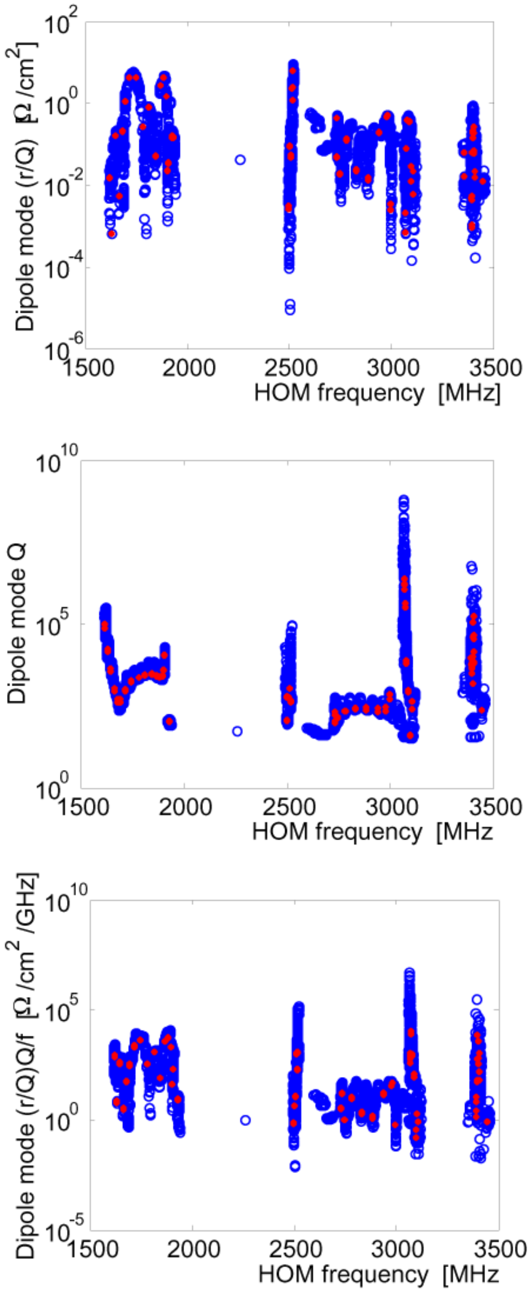

Figure 2: Higher-Order Dipole Modes in 50 "type A" cavities with $\pm 1/8$ mm shape deformations. Blue circles: cavities deformed and subsequently tuned. Red stars: "Type A" cavity without shape perturbations. Top: (r/Q) in circuit definition. Middle: Quality factor Q. Bottom: BBU parameter $(r/Q)Q/f$.

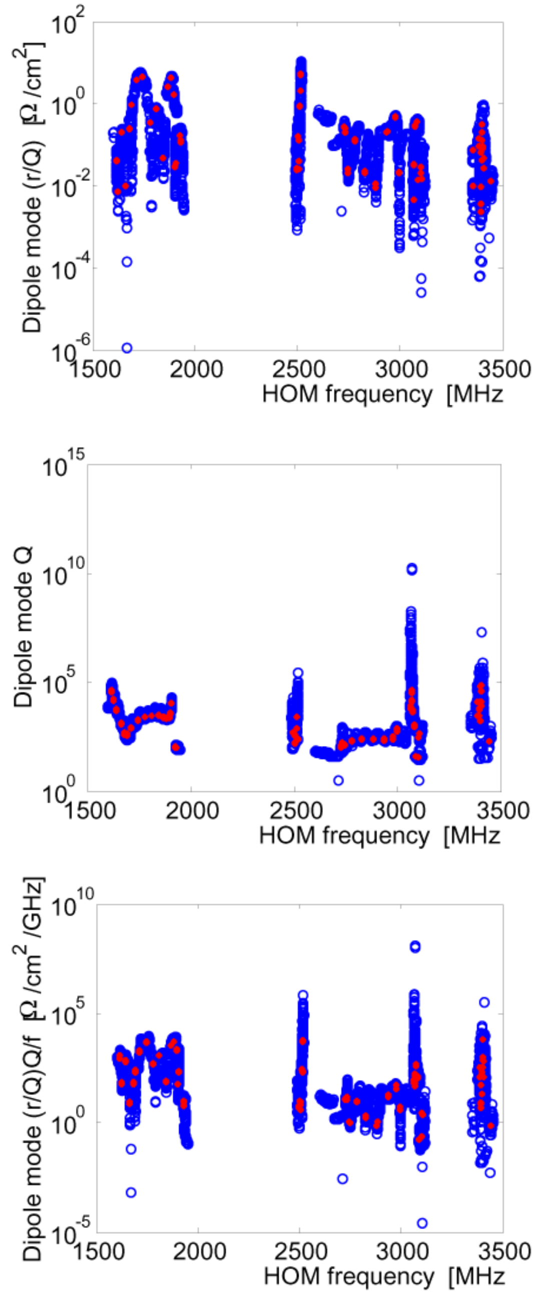

Figure 3: Higher-Order Dipole Modes in 50 "type B" cavities with $\pm 1/8$ mm shape deformations. Blue circles: cavities deformed and subsequently tuned. Red stars: "Type B" cavity without shape perturbations. Top: (r/Q) in circuit definition. Middle: Quality factor Q. Bottom: BBU parameter $(r/Q)Q/f$.

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