MULTIPASS BEAM BREAKUP IN THE CEBAF SUPERCONDUCTING LINAC*

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Abstract

Multipass beam breakup can severely limit current in superconducting linear accelerators due to the inherently high Q's of transverse deflecting modes of the RF cavities. The success of higher-order-mode damping in increasing threshold currents for the 4-pass CEBAF SRF linac design is investigated with computer modeling. This simulation is shown to be in agreement with theoretical analyses which have successfully described beam breakup in the Stanford superconducting, recirculating linac. Numerical evaluation of an analytic treatment by Gluckstern[1] of multipass beam breakup with distributed cavities is also found to be consistent with the computer model. Application of the simulation to the design array of 400 five-cell CEBAF/Cornell cavities with measured higher-order-mode damping indicates that the beam breakup threshold current is at least an order of magnitude above the CEBAF design current of 200 μA.

Introduction

The beam current of RF linacs has been limited by a variety of beam breakup phenomena. In normal conducting linacs single-pass cumulative and regenerative beam breakup have threshold currents of tens to hundreds of milliamperes. Since higher-order-mode Q's of the superconducting RF cavities of the CEBAF linac will be reduced by couplers to levels (10^4) characteristic of room temperature cavities, these single-pass effects should not be of significance at the few-hundred-microampere-per-beamlet values of the present design. Multipass regenerative beam breakup, on the other hand, has limited the beam current of superconducting CW linacs such as the Stanford recyclotron to tens of microamperes and requires careful evaluation for the CEBAF design. The damping achieved in the 55-cell cavities used at Stanford, however, reduced HOM Q's to values still in excess of 10^7.

The following discussion presents a detailed investigation of multipass regenerative beam breakup in the CEBAF CW linac. Computer modeling of beam breakup has been developed, and includes accurate accounting for time delays, mode frequency spread, and lattice function variation. Application of this simulation to the long array of five-cell cavities of the CEBAF design indicates that beam breakup occurs only when currents exceed ten milliamps per beamlet—at least an order of magnitude above CEBAF's design current of 200 μA.

Phenomenology of Beam Breakup

Consider the excitation of a single parasitic mode of a cavity by a charge q passing at transverse position r off axis. A charge e passing τ behind will experience a transverse momentum kick of

$$\frac{c}{e}\Delta p \equiv W(\tau) = \frac{Z''lc}{2Q} qr \sin(\omega\tau) e^{-\omega\tau/2Q} \qquad (1)$$

where Z'' is the transverse coupling impedance (ohms/m^3) and l is the active length of cavity structure. Consider now a series of bunches spaced by f_b with average current I_0 and charge per bunch of $q = I_0/f_b$. Let $W_0 \cos(\omega t + \phi)$ be some initial wakefield excitation of the cavity. A bunch will experience a momentum kick

$$\Delta p = \frac{e}{c} W_0 \cos(\omega t + \phi) \qquad (2)$$

After recirculation, this bunch returns to the cavity with a transverse displacement

$$r_{12} = B_{12}\Delta p \qquad (3)$$

where B_{ij} is the transfer coefficient (momentum to transverse position) between the ith and jth passes. On traversing the cavity the second time, an additional wakefield

$$\Delta W = \frac{Z''lc}{2Q} q (B_{12}\Delta p) \sin(\omega\tau) e^{-\omega\tau/2Q} \qquad (4)$$

is excited.

Steady state is maintained if the bunch excitation compensates for losses in the cavity walls and HOM couplers. At higher current levels there will be instability.

With the assumption of a most-pessimistic conspiracy of time delay, the steady-state condition yields the threshold condition

$$I_{th} = \frac{2\omega}{eZ''l|B_{12}|} \qquad (5)$$

In an n-pass recirculation configuration, there are n beamlets passing through the cavity. One beamlet has been kicked $(n-1)$ times and has a perturbed transverse position described by the transfer coefficients B_{1n} through $B_{(n-1)n}$. Another beamlet has been kicked $(n-2)$ times with corresponding coefficients $B_{1(n-1)}$ through $B_{(n-2)(n-1)}$, and so forth. Thus, for an n-pass recirculating linac, the threshold current is (again, assuming a worst-case phase conspiracy)

$$I_{th} = \frac{2\omega}{eZ''l \sum_s \sum_{r<s} |B_{rs}|} \qquad (6)$$

where the maximum values of the B_{ij} are taken to obtain a most-pessimistic result.

This expression (with differing notation) is consistent with the work of Gluckstern,[1] Vetter,[2] and Herminghaus[3] for multipass BBU induced by a localized structure. In addition, experiments on beam breakup at the Stanford recylotron[4] appear to confirm this result. Because of the high Q's ($\approx 10^7$) associated with the modes of the Stanford structure there was little mode frequency overlap among the major sections of the linac. The instability had a local character appropriate to the above analysis.

Within the limits of this model, determining the threshold current in CEBAF requires estimates of both the transfer functions B_{ij} of the linac/recirculator and the expected transverse impedance of the RF cavities. The HOM impedance of the Cornell five-cell structure is well documented in the literature.[5] The Z'' and Q for the four worst modes are listed in Table 1.

Table 1
Strongest Transverse Modes of 5-Cell Cavity

Frequency	(MHz)	1888	1969	2086	2110
Q	(10^4)	3.2	0.4	1.0	1.3
Z''/Q	$(10^4$ ohm/m$^3)$	6.95	16.4	5.0	10.0
$Z''l$	$(10^9$ ohm/m$^2)$	445.	131.	100.	260.
$(Z''l)_{\text{eff}}$	$(10^9$ ohm/m$^2)$	89.0	94.3	47.0	104.

$l = 200$ m for the CEBAF CW Linac

The linac will consist of some 400 of these five-cell (0.5-meter active length) cavities and have a total active length of 200 meters. Manufacturing tolerances will yield mode frequency variations of about 1 MHz full width. Thus, there will not be perfect coherence of 400 modes of a given type since mode widths are typically less than 1 MHz. On the other hand, some frequency overlap along the full length of the linac can be expected and the instability will not be well localized.

At threshold there exists a steady-state modulation of the linac beam at some frequency, and it will be the value of the impedance at this frequency (modulus the bunching frequency) that will drive the beam above threshold. In light of the partial mode overlap, the effective impedance offered by the RF cavities is

$$(Z''l)_{\text{eff}} = \frac{Z''}{Q} \cdot Q \cdot 200\text{m} \cdot F(Q) \qquad (7)$$

where $F(Q)$ estimates the fraction of modes of a particular type acting coherently. Computation of the impedance sum of randomly distributed resonators gives $F(32000) = 0.2$ and $F(4000) = 0.72$ for a uniform distribution of modes centered at 2 GHz with full width of 1 MHz. The last two entries in Table 1 give the total $Z''l$ (assuming no manufacturing variations) and the effective $Z''l$ (assuming 1 MHz variations) for the four modes listed.

The linac lattice is modeled by a 9.4 meter half-cell-length lattice with a phase advance per cell of 120° for the first-pass energy. The recirculator is assumed to offer an identity transformation. Without any lattice optimization, a maximum value of $\sum |B| = 56.0\text{cm}/(\text{MeV/c})$ was found in the four pass configuration. Insertion of this value and the $(Z''l)_{\text{eff}}$ of Table 1 into Equation (6) yields lower bounds on threshold currents, between 1.5 and 3.3 mA/beamlet for the four Cornell modes.

These values represent a worst-case analysis, with effectively all passes assumed to have time delays yielding maximal coherence and with the cavities localized on the largest value of B_{ij}. However, these worst-case thresholds exceed the design current of 200 μA by nearly an order of magnitude.

The analysis summaried in Equation (6) is strictly appropriate to a localized structure. Some uncertainty, therefore, remains concerning the effects of cavity-to-cavity mode frequency variations and the distribution of interacting cavities along the length of the linac in improving the threshold currents. These issues among others have been addressed with a computer simulation which is discussed in the next section.

Computer Simulations of Beam Breakup

From the Stanford experience it appears that the dominant mechanism for multipass regenerative beam breakup can be modeled by an impulse approximation. This is also the regime appropriate to single-pass cumulative beam breakup as observed in SLAC where extensive computer modeling has been successful. The SLAC program (authored by R. Helm) has been modified at CEBAF to include multipass recirculation with both random and systematic bunch displacement as initial conditions. A second generation code which includes x-y coupling and takes full advantage of the CRAY computer has been recently developed. For the single-pass cumulative breakup the chief diagnostic is the final bunch position at the output of the linac. A threshold is determined by a scraping condition at the beam pipe wall. For multipass regenerative breakup, there will be exponential growth of cavity fields. For a particular amplitude of initial condition, beam displacement may remain small for the duration of a run even though cavity fields are growing exponentially. However, for CW operation these fields will eventually grow to the point of producing beam loss. Therefore, the chief diagnostic in determining threshold currents is the observation of exponential growth of the cavity wakefields.

The analytic work as presented above represents a worst-case analysis in that time delays were assumed to conspire for maximum effect and the largest values of the machine transverse transfer function were taken even though the cavities are uniformly distributed along the linac. The simulation offers the possibility to study more realistic distributions of time delays and lattice functions, and, in addition, allows for investigation of the effects of modal frequency spread.

The analysis summarized in Equation (6) is appropriate to a localized, single mode with no frequency spread and as was discussed earlier described the experience with BBU at the Stanford recyclotron. Since the threshold current for this case can be simply calculated including exact pass-to-pass time delays, it offers a clear test of the simulation. Both 2-pass and 4-pass threshold current values were calculated for a FODO linac lattice structure with a mode frequency of 1890.0 MHz. These configurations were also modeled with the simulation code. Simulation and analytic threshold current values were found to agree well within a factor of two. Figure 1 shows results for a 4-pass configuration with a localized transverse impedance equivalent to 1 m of CEBAF structure with no frequency variation.

As discussed by Gluckstern[1] in this conference, evaluation of n-pass beam breakup threshold currents for a spatially distributed set of cavities can be reduced to finding zeros of the determinant of a $2(n-1)$ dimensional matrix. Although this matrix is in general the product of matrices describing beam transport and bunch interaction at all the cavity sites and is therefore quite messy, the matrix dimension remains modest. The problem of searching for determinant zeros as a function of current has sufficiently good behavior to be amenable to numerical methods. A computer program has been developed based on this analysis which scans in real frequency and generates a plot of complex threshold current. Figure 2 illustrates such a plot for a single cavity, two-pass configuration. Each crossing of the positive real axis represents a possible physical threshold current at a corresponding real frequency. The multiple roots result from the succession of favorable time delays as the frequency is scanned. As the number of distributed cavities is increased, the number of families of roots is found to increase. Figure 3 shows the lowest root curve for a four-pass, two cavity configuration. A second, but not third, root family was also found. Threshold currents obtained with the simulation and the zero-finder codes have been found in agreement for two separated cavities with two, three, and four pass configurations.

Another study compared the single 1890.0 MHz (Q = 32000) threshold with that of 100 modes uniformily distributed between 1890.0 and 1891.0 MHz. Each mode was given 1% of the single-mode transverse impedance and all were localized at the same point on the lattice. The threshold current has been found to be a factor of 6 higher for the distributed modes and is in reasonable agreement with the factor-of-5 estimate included in the worst-case analysis presented earlier. This result firmly establishes the benefits of mode frequency spread in easing beam breakup.

Runs were performed to model the full CEBAF cavity array distributed along the linac with a FODO lattice at 4 GeV final energy. Threshold currents for the four strongest Cornell cavity modes are summarized in Table 2. All threshold currents are greater than 18 mA/beamlet for four passes. At 2 GeV, the lowest final energy that requires 4 passes through the linac, the simulations indicate stability if the beam·current does not exceed 10 mA.

Table 2
Computer Simulation Estimates of Beam Breakup Thresholds

	1888 MHz	1969 MHz	2086 MHz	2110 MHz
I_{th}	21 mA	18 mA	56 mA	26 mA

A final set of runs was performed to observe any interaction of modes of significantly different frequency. Each of fifty "supercavities" was allowed to have four modes at frequencies of 1890, 1969, 2108, and 2120 MHz with no cavity-to-cavity frequency spread. Each mode was given an impedance equal to the 1890 mode. The observed threshold current and growth rate were within 25% of single-mode values and do not indicate any significant mode interaction.

Summary

A computer model of multipass regenerative beam break up that includes mode frequency spread and lattice variation has been developed. For a single, localized mode, this simulation is found to be in agreement with analytic estimates which have been successful in describing beam breakup in existing recirculating linacs. For the CEBAF design, a threshold current for beam breakup in excess of 10 mA/beamlet is found. This estimate exceeds the design goal of 200 μA by more than an order of magnitude. Further studies are underway using both the zero-finder and simulation codes.

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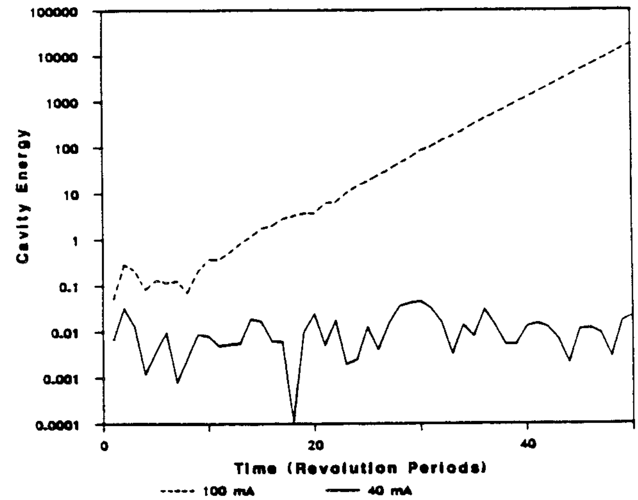

Figure 1. Simulation of beam breakup driven by localized structure. Analytic threshold current is 70mA.

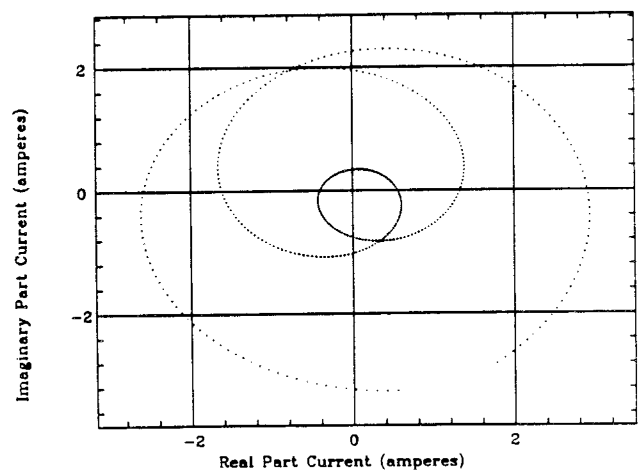

Figure 2. Complex current plot for 1 cavity, 2 pass configuration.

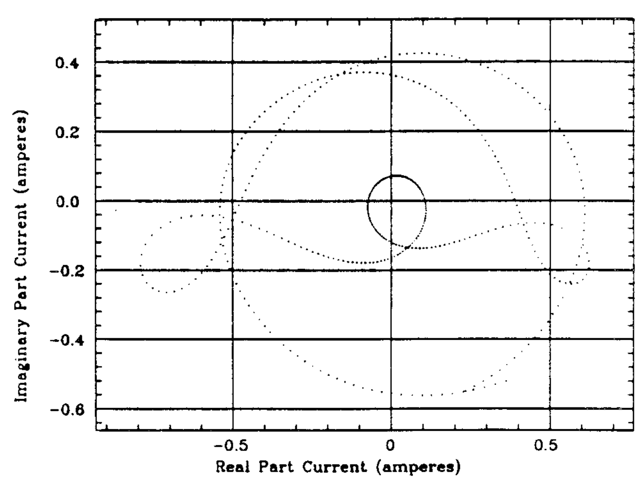

Figure 3. Complex current plot for 2 cavity, 4 pass configuration.