Experimental Reduction of Electron Beam Breakup Instability Using External Coupled Cavities

P.R. Menge, R.M. Gilgenbach, Y.Y. Lau, M. Walter, and C.H. Ching,
Intense Energy Beam Interaction Laboratory
Nuclear Engineering Dept., University of Michigan, Ann Arbor, MI, 48109-2104

Abstract

Experiments on electron beam transport through 10 RF cavities have shown that BBU growth can be reduced by 6 dB when seven internal beam cavities are coupled by coaxial cable to seven external dummy cavities. The experiment consists of 10 brass pillbox resonant cavities immersed in a solenoidal field. The first cavity has its TM_{110} mode primed at 2.5 GHz by a microwave pulse from an external magnetron. A 200 A e-beam is injected into the transport cavity system by the long pulse MELBA generator (t = 0.5 - 1.5 μs, V = -0.7 to - 0.8 MV, diode current = 1-15 kA). Growth (≈36 dB) of the 2.5 GHz RF is observed between the 2nd and 10th cavities. When seven internal cavities (3^{rd} - 9^{th}) are coupled to seven identical external dummy cavities via coaxial microwave cable, the 2.5 GHz RF growth is reduced to about 30 dB average. These results are shown to be in general agreement with a model using equivalent circuits to determine degree of power sharing between cavities.

Additional BBU growth experiments have been performed using 19 cavities with a propagation distance roughly twice that of the 10 cavity experiments. The experimental BBU growth has been found to scale with distance as expected using a discrete beam-mode coupled theory.

I. INTRODUCTION

The beam breakup instability (BBU) remains a major problem plaguing linear accelerators. The BBU results from an unstable coupling between a misaligned electron beam and non-axisymmetric (dipole) modes associated with the accelerating structure [1-3]. The end results of this coupling can range from brightness degradation to complete beam disruption. Recently, a novel method of BBU reduction was demonstrated at the University of Michigan [4] using coupling between the main beam cavities and separate dummy cavities. This method has been termed "external cavity coupling." The BBU reduction mechanism involves sharing of non-axisymmetric TM_{110} mode energy between the coupled cavities [4-6]. The TM_{110} is the fundamental beam breakup mode associated with the transport structure for these experiments. This power sharing results in a decrease in TM_{110} field strength in the main cavities with a corresponding decrease in the BBU growth rate. A critical parameter governing the magnitude of reduction is the coupling constant, κ [4-6]. In simplest terms κ corresponds to how well the coupled cavities are able to share energy.

This research was supported by SDIO-IST managed through an ONR contract. Support for PRM supplied by a Rackham School of Graduate Studies Fellowship.

This paper presents a review of the external coupled cavity experiments and provides a method of calculating κ that is believed to be more accurate than that presented in [4].

II. EXTERNAL CAVITY COUPLING EXPERIMENTS

The experimental configuration is shown in Figure 1. The MELBA electron beam generator is used for these experiments and is run with diode parameters of: voltage = -750 kV, diode current = 5 kA and pulselength = 0.5 μs. The beam is emitted from a hemispherical velvet field-emission type cathode. An aperture in the anode injects about 200 A into the cavity transport structure region which is immersed in a 3.4 kG solenoidal field. The cavity array generally consists of 10 brass pillbox cavities with an average TM_{110} resonant frequency of 2.5075 GHz ± 0.03 %. Each cavity contains a microwave coupling antenna oriented to be sensitive to the TM_{110} beam breakup mode which occurs at 2.5 GHz. The first cavity in the array has its TM_{110} mode primed on resonance by an external magnetron operating at 1 kW and pulselength of 3 μs. This is done to provide initial transverse modulation to the electron beam. The beam coasts through the remaining cavities where it excites the TM_{110} mode in each cavity. The power of the TM_{110} mode grows in the successive cavities as the amplifying BBU disturbance is carried along the beam. The spatial growth of the BBU is determined by measuring the difference in TM_{110} mode microwave power between the 2nd and 10th cavities.

In a typical experiment about 36 dB gain in 2.5 GHz microwave power is observed between the second and tenth cavities, when the external cavities are not connected to the coupling microwave cable. When the cables are connected, the internal and external cavities are coupled, and 30 dB growth in TM_{110} microwave power is typically observed between the second and tenth cavities. This method differs from other BBU suppression techniques in that the control is reactive and not dissipative. Figure 2 shows data from 40 experimental shots in which the uncoupled and coupled cases are alternated every three shots. This figure is reproduced from [4].

III. EXTERNAL CAVITY COUPLING THEORY

Previous analysis [4] has shown that the BBU spatial growth rate, Γ (where total BBU growth is given by $e^{\Gamma z}$), is modified by a factor of $1/(1+\kappa^2 Q^2)$ to account for cavity coupling though a mutual inductance model [5-7]. Thus, the

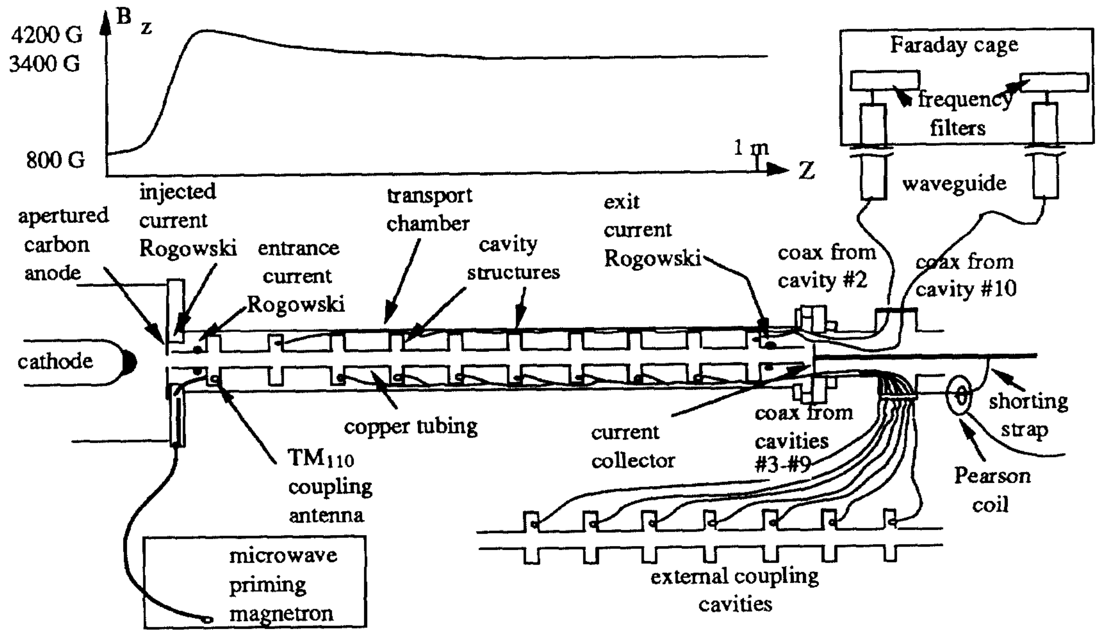

Figure 1. Schematic of experimental configuration (lower) and magnetic field profile (upper).

external coupled cavity growth rate is $\Gamma/(1+\kappa^2Q^2)$. Here, κ is the coupling constant and Q is the cavity quality . This factor of κ^2Q^2 represents the ratio of power leaked to the dummy (external) cavity to the power remaining in the main (internal) cavity [4]. A cold test was performed on a network analyzer (HP-8510) using two model cavities each with two coupling antennas. One antenna in each cavity was used to inject the microwaves and the second was used to transmit the RF power out of the cavity. This cold test experiment indicated that the power sharing ratio for this arrangement is $\kappa^2Q^2 = 0.13$. Using this value in the reduction factor yields an expected experimental reduction to 36 dB(1/1.13) ≈ 32 dB.

However, the cold test of the power sharing ratio differs from the actual experimental configuration. In the experiment, each cavity has only one coupling loop, thus the cold test may underestimate the magnitude of power sharing since the extra antennas provide additional inductance to the overall circuit. An alternative method to determine κ has been developed using an equivalent circuit model similar to those used in coupled cavity klystron analyses [8]. The equivalent circuit representing the experimental configuration is shown in Figure 3. The critical parameter that governs the magnitude of power sharing is the mutual inductance, M, connecting the loop antenna circuits to the cavity circuits. The mutual inductance can be found from the formula [9,10]:

$$\frac{\omega_o^2 M^2}{R} = \frac{2s^2 J_1^2\left(\frac{3.83\,r}{b}\right)Q}{J_0^2(3.83)\varepsilon_o r^2 \pi b^2 \ell Z_o \omega_o},$$

where ω_o is the angular TM_{110} resonant frequency, R is the resistance assigned to the cavity circuit, s is the area of the coupling loop, r is the radial position of the antenna in the cavity, b is the radius of the cavity, ℓ is the cavity length, and Z_o is the characteristic impedance of the coupling cable. Solving for power in the main and dummy cavities with the circuit program SPICE [11] yields a power sharing ratio of $\kappa^2Q^2 = 0.18$. Use of this value in the reduction factor gives a predicted value of 30 dB growth for the coupled cavity experiments. This results in better agreement between theory and experiment than that reported in [4].

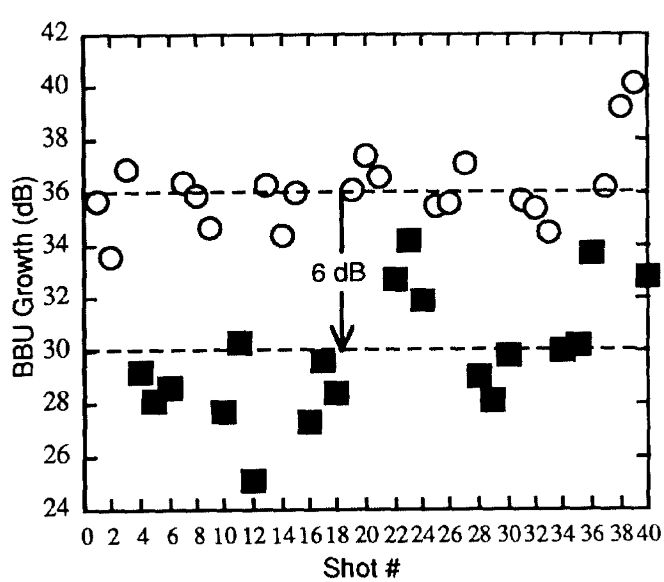

Figure 2. BBU instability growth for uncoupled cavity (open circles) and coupled cavity (black squares) configurations showing an average decrease of 6 dB in growth when cavities are externally coupled. (Reproduced from Ref. [4]).

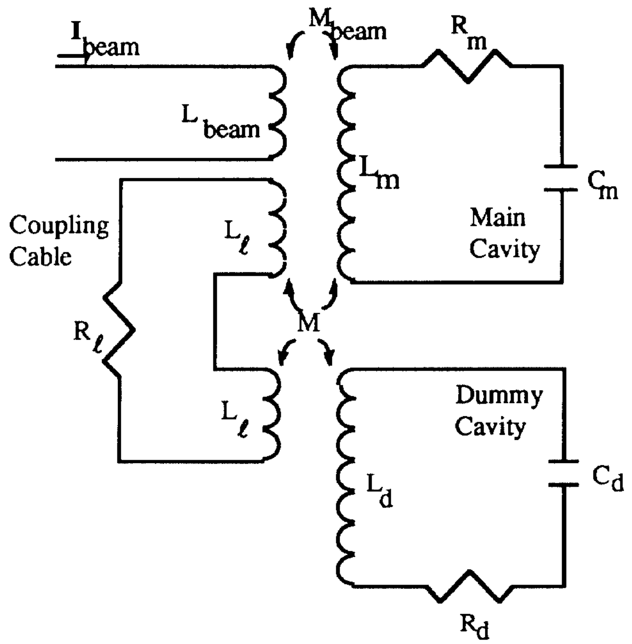

Figure 3. Equivalent circuit representing external cavity coupling configuration.

IV. NINETEEN CAVITY BBU GROWTH EXPERIMENTS

Previously, these University of Michigan experiments examining the BBU growth scaling have been limited to relatively short (≈ 1 m) propagation distances using 10 resonant cavities [12]. Recently, experiments designed to study the behavior of BBU growth rates over longer propagation distances have been performed. These experiments use a 2 m solenoidal vacuum chamber using cavities nearly identical to those used above and in [4,12]. The configuration can be represented by Figure 1 without the external cavities and coupling cables, but with a longer transport chamber and nine additional cavities filling the extra length. Most diagnostics and measuring techniques are identical to those used in [12]. The major difference is that in the earlier, 10 cavity experiments the BBU growth was measured between the second and tenth cavities spanning a propagation distance of 68 cm. These 19 cavity experiments measure the BBU growth over the 144.5 cm between the second and nineteenth cavities.

Figure 4 plots the BBU growth versus the ratio of beam current to applied solenoidal magnetic field, I/B (A/kG). The data from the 19 cavity experiments is seen on the left side of the graph. For each experimental growth datum (black squares), the corresponding predicted BBU growth from theory (open squares) is also plotted. A two-dimensional discrete cavity theory is used [13]. For reference, the data from the 10 cavity experiments are seen on the right side of the graph (from Ref. [12]). The lower I/B values for the 19 cavity data are a result of lower transported beam currents. Note that the slope in Fig. 4 for the 10 cavity case is approximately half that for the 19 cavity case, as expected. The 10 cavity data is reproduced from [12].

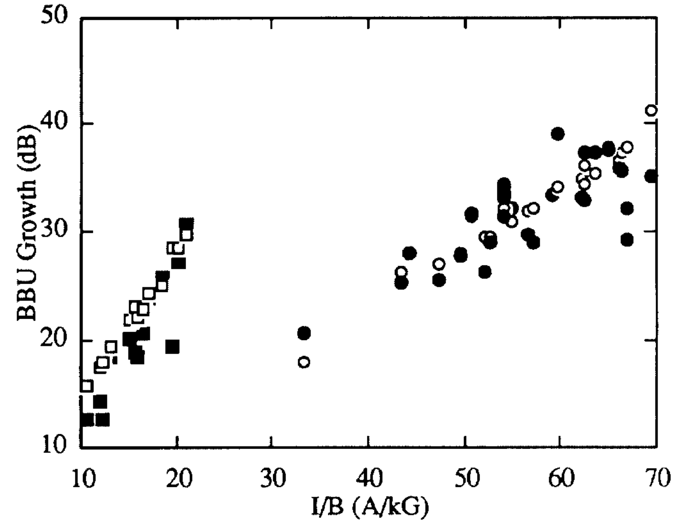

Figure 4. BBU growth (dB) versus ratio of beam current to magnetic field, I/B (A/kG). Experimental data (filled symbols) are plotted with corresponding theoretical growth (open symbols). Two experimental cases are shown: 19 cavities (squares) and 10 cavities (circles).

V. REFERENCES

[1] W. K. H. Panofsky and M. Bander, Rev. Sci. Instrum. **39** (2), 206, 1968.

[2] V.K. Neil and R.K. Cooper, Part. Accel. **1**, 111, 1970.

[3] Y.Y. Lau, Phys. Rev. Lett. **63** (11), 1141, 1989.

[4] P.R. Menge, R.M. Gilgenbach, and Y.Y. Lau, Phys. Rev. Lett. **69** (16), 2372, 1992.

[5] D. Colombant, Y. Y. Lau, and D. Chernin, Part. Accel. **35**, 193, 1991.

[6] D.G. Colombant and Y.Y. Lau, J. Appl. Phys. **72** (9), 3874, 1992.

[7] D. Colombant and Y. Y. Lau, Nuclear Instruments and Methods **A311**, 1, 1992.

[8] c.g. R.E. Collin, *Foundations for Microwave Engineering* (McGraw-Hill, Singapore 1966), Chapter 9.

[9] R.A. Bosch, P.R. Menge, and R.M. Gilgenbach, "Reduction of Beam Breakup Growth by Coupling to External Bleeding Cavities", unpublished (1991).

[10] P.R. Menge, Ph. D. Dissertation, The University of Michigan, 1993.

[11] P.W. Tuinenga, *SPICE, A Guide to Circuit Simulation and Analysis Using PSpice* (Prentice Hall, Englewood Cliffs, NJ, 1988).

[12] P.R. Menge, R.M. Gilgenbach, and R.A. Bosch, Appl. Phys. Lett. **61** (6), 642, 1992.

[13] R.A. Bosch, P.R. Menge, and R.M. Gilgenbach, J. Appl. Phys. **71** (7), 3091, 1992.