Experimental Reduction of Beam-Breakup Instability Growth by External Cavity Coupling in Long-Pulse Electron-Beam Transport

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Experiments have demonstrated the reduction of the beam-breakup (BBU) instability growth rate by coupling the main cavities, through which an electron beam passes, to identical dummy cavities. When seven of the ten main cavities are coupled, an average reduction of about 6 dB in BBU microwave growth, from 36 to 30 dB, is observed. This reduction is consistent with a simple mode coupling theory. The electron beam parameters are 750 kV, 210 A, 0.5 μs, with solenoidal focusing of 3.4 kG.

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Beam breakup (BBU) [1-7] is a major instability that limits the current and pulse length of linear accelerators. Several methods have been found to reduce such instability growth, including stagger tuning [2,7-9] of the cavity resonant frequencies and cavity loading in which the dominant deflecting mode is heavily damped by slots [10] or by ferrite [11]. Betatron frequency spreads have also been shown to lower BBU growth [8,12-14].

It has been recently predicted [15] that, by simply coupling the accelerating (main) cavities to identical dummy cavities, BBU growth may be reduced. This reduction occurs, according to the conjecture given in Ref. [15], because the dummy cavities share the power of the deflecting mode excited by the beam, thereby lowering the deflecting mode amplitude in the main cavities that drives the electron beam unstable. It should be emphasized that BBU control by coupled cavities is purely reactive instead of dissipative, the latter having been extensively pursued with the use of lossy materials or slots. This paper reports our experimental investigation of this concept, using a long-pulse (0.5-1 μs) electron beam of extracted current 40-400 A, guided by a solenoidal magnetic field of 1-4 kG. These parameters span the intermediate regime, where the effect of focusing field is marginally important.

The experiment is driven by the Michigan Electron Long-Beam Accelerator (MELBA) [16], which operates with diode parameters of voltage $=-0.7$ to -0.8 MV, diode current$=1$-15 kA, and flattop pulse length of 0.5-1 μs. The experimental configuration is shown in Fig. 1. The electron beam is produced by a velvet button cathode on the hemispherical end of the cathode stalk. A graphite aperture defines the 2-cm injected beam diameter and yields extracted currents of 40-400 A. The

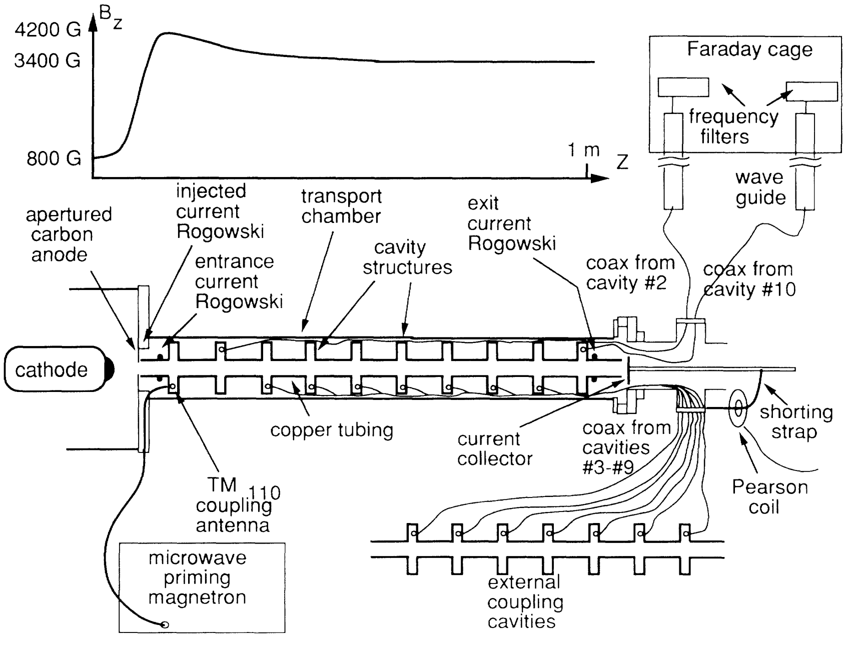

FIG. 1. Schematic of experimental configuration (lower) and magnetic field profile (upper).

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anode cathode gap is about 10.2 cm. The diode chamber is immersed in a uniform solenoidal magnetic field that can be varied from 0.5 to 1.2 kG. The beam transport chamber is a stainless-steel tube wound with pulsed solenoidal magnetic field coils. These coils produce a magnetic field that can range from 1 to 4 kG.

Within the transport chamber are ten brass pillbox resonant cavities with a radius of 6.9 cm and a length of 2.0 cm. Separating each cavity is a smaller-radius (1.9 cm) copper tube of length 6.5 cm used to prevent electromagnetic cross talk (−26 dB measured) and thus eliminate the regenerative BBU instability. Inside each cavity is a small loop antenna (0.7 cm diameter) oriented to be sensitive to the TM_{110} mode for cold-testing and *e*-beam experiments. The average cold-test TM_{110} resonant frequency is 2.5075 ± 0.0026 GHz. A small annulus of microwave absorber is loaded into the cavities to lower the deflecting mode quality factor Q to an average of 215 ± 45.

The coupling loop in the first cavity is utilized for priming the TM_{110} mode with the signal from a kW-level microwave pulse generator. The priming microwave pulse is generally 3 μs long, and begins before the *e* beam is present. The coupling loops in the second and tenth cavities are used to measure the growth of the microwaves corresponding to the frequency of the TM_{110} beam-breakup mode [17]. The microwave signals are propagated out of the transport chamber by coaxial cables and transmitted to a Faraday cage by *S*-band waveguides. At the waveguide termination the microwaves are sent into a filter which passes 2.5075 ± 0.0115 GHz, thus ensuring that any measured growth is due to only the BBU signal of the TM_{110} mode resonant frequency. The microwave signals are then attenuated to a level appropriate for measurement on crystal detectors. For the coupled-cavity experiments, the coupling loops on the internal, intervening seven cavities (3 through 9) are connected to seven identical external dummy cavities by a set of equal-length (16λ) coaxial cables. For baseline experiments the cables are disconnected between the internal (main) and the seven external (dummy) cavities.

The beam current is measured in five places along the beam path. A *B*-dot loop in the MELBA oil tank measures the cathode stalk current. Calibrated Rogowski coils are used to determine the current injected into the transport chamber immediately after the apertured anode, just before entering the first cavity, and just after exiting the last cavity. After exiting the cavity structure, the beam propagation is terminated by a carbon collector plate grounded by a cable which passes through a Pearson current transformer.

Typical experimental data are presented in Figs. 2 and 3. In order to compare the BBU growth for the uncoupled-cavity baseline case to the coupled-cavity case, a typical experimental run alternated between three shots for each case. Figure 2 shows data signals from an uncoupled-cavity shot, while Fig. 3 presents corresponding signals from the consecutive shot in which seven pairs of cavities were coupled. The uppermost trace (a) is the MELBA diode voltage in which the flattop occurs at 750 kV and lasts for 500 ns. The second trace (b) shows the microwave power in the second cavity after passing through a frequency filter. The third trace (c) shows the microwave power in the tenth cavity after passing

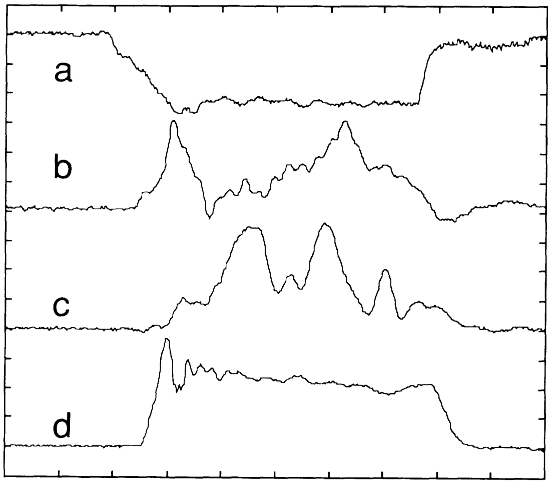

FIG. 2. Experimental data for uncoupled cavities: (a) Electron beam voltage (310 kV/div); (b) microwave diode detector signal in the second cavity, filtered at 2.5075 ± 0.0115 GHz (50 mV/div); (c) microwave diode detector signal in the tenth cavity filtered at 2.5075 ± 0.0115 GHz with 36-dB attenuation (50 mV/div); (d) transported current leaving tenth cavity (92 A/div) from a different shot. Applied solenoid field is 3.4 kG.

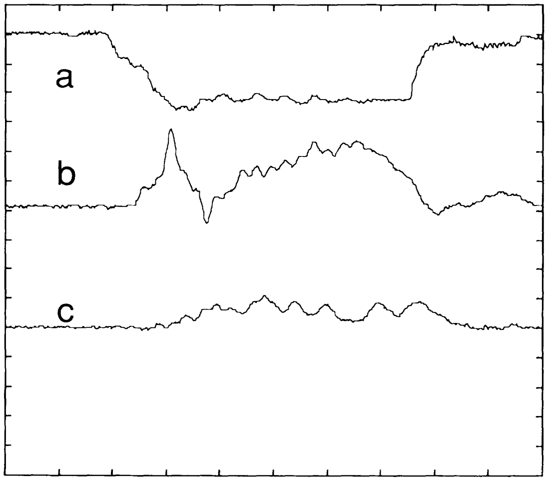

FIG. 3. Experimental data for externally coupled cavities: (a) Electron beam voltage (310 kV/div); (b) microwave diode detector signal in the second cavity, filtered at 2.5075 ± 0.0115 GHz (50 mV/div); (c) microwave diode detector signal in the tenth cavity filtered at 2.5075 ± 0.0115 GHz with 36-dB attenuation (50 mV/div). Applied solenoid field is 3.4 kG.

through a frequency filter; the microwaves have been attenuated by 36 dB. Note the approximately 4 times reduction in rf power in the tenth cavity between Figs. 2(c) and 3(c). The last trace, Fig. 2(d) is a typical transported current signal with a flattop corresponding to 210 A.

A summary of beam-breakup-instability microwave growth data from some forty shots is presented in Fig. 4(a). The data show a consistent reduction of BBU growth from an average of 36 dB ($\sigma = \pm 1.5$ dB) for the uncoupled case to an average of 30 dB ($\sigma = \pm 2.4$ dB) for the coupled-cavity case. Therefore, we measure an average BBU growth reduction of about 6 dB for the present system in which seven main cavities are coupled to dummy cavities. The variations in experimental BBU signal growth amplitudes could be related to pulse-to-pulse variations in *e*-beam current amplitudes, shown in Fig. 4(b). All shots were taken with a solenoidal magnetic field of 3.4 kG. The *B*-field profile is shown in Fig. 1.

Theoretical research on coupled cavities [15] has predicted a growth rate reduction by up to a factor of 2, depending upon the coupling strength κ between the main cavity and the dummy cavity. A simple theory of the BBU instability including coupled cavities may be developed by starting with the force law in the continuum description [1,4–7]:

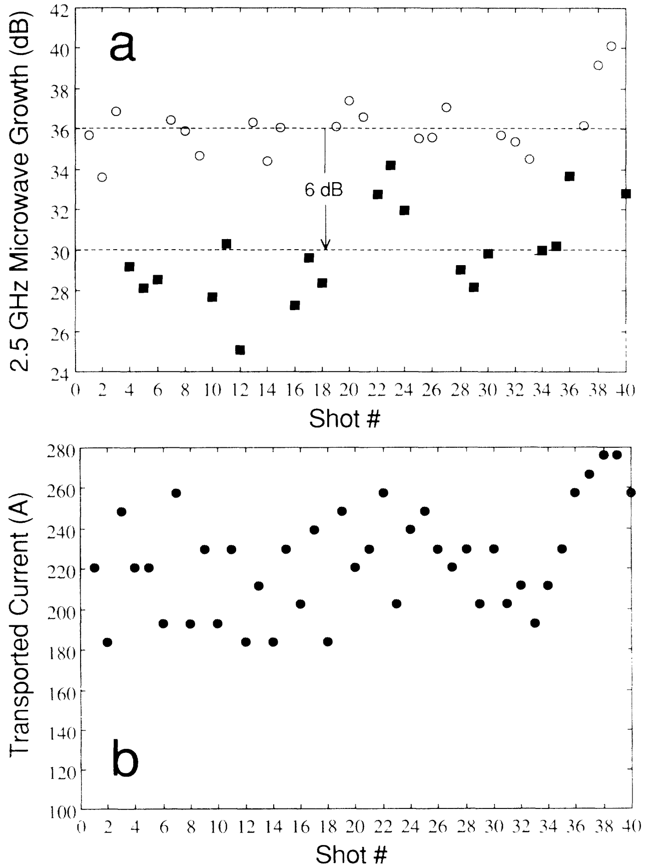

FIG. 4. (a) Growth (dB) of the 2.5-GHz microwave power for forty different electron beam pulses showing uncoupled shots (open circles) and externally coupled shots (solid squares). (b) Transported electron beam current (A) for the corresponding shot numbers of (a).

$$-\gamma[(\omega - kv)^2 - \omega_\beta^2]\xi = A\,, \tag{1}$$

where A denotes the complex amplitude of the deflecting mode in the main cavity, ξ is the transverse deflection of the beam, k is the wave number, v is the *e*-beam velocity, γ is the usual relativistic mass factor, ω is the angular frequency of the injected signal which undergoes BBU growth, and ω_β is the relativistic betatron frequency. The main cavity is excited by the beam's transverse displacement ξ and by the dummy cavity when coupling is present. Using a simple mutual inductance model for cavity coupling, A is governed by [15]

$$LA = 2\gamma\omega_0^4\varepsilon\xi + \kappa\omega_0^2 D\,, \tag{2}$$

where D denotes the complex amplitude of the dummy cavity field, ε is the dimensionless parameter that measures BBU strength [18], ω_0 is the TM_{110} mode angular resonant frequency, and $L \equiv d^2/dt^2 + (\omega_0/Q)d/dt + \omega_0^2$ is the familiar operator. In this model, the equation for D reads

$$LD = \kappa\omega_0^2 A\,. \tag{3}$$

Equations (1)–(3) constitute three equations in three unknowns, A, D, and ξ. The BBU dispersion relation may be obtained which yields the spatial exponentiation rate k_i as a function of ω. At resonance, $\omega = \omega_0$, and for sufficiently large ω_β, it reads

$$k_i = \left(\frac{\omega_0}{v}\right) Q\varepsilon \frac{\omega_0}{\omega_\beta} \frac{1}{(1+\kappa^2 Q^2)}\,, \tag{4}$$

which shows that the BBU growth rate is reduced by a factor $1 + \kappa^2 Q^2$ when cavity coupling is present ($\kappa \neq 0$).

This reduction has a simple interpretation. First note that at resonance ($\omega = \omega_0$), $L = j\omega_0^2/Q$, and Eq. (3) gives

$$\kappa^2 Q^2 = \left|\frac{D}{A}\right|^2 = \frac{\text{power leaked to dummy cavity}}{\text{power in main cavity}}\,. \tag{5}$$

Thus, the factor $1/(1+\kappa^2 Q^2)$ in Eq. (4) becomes the fraction of rf power that resides in the main cavity in a coupled-cavity system. In other words, the BBU growth reduction, according to Eq. (4), is a result of the sharing of rf power by the dummy cavity [19].

Experimental measurements were made of the power sharing by a pair of model cavities each having two coupling loops. The signal from an HP-8510 network analyzer was fed into one cavity which was coupled by type .405/U cable to the second cavity. The received power in the second cavity was found to correspond to 13% of the first cavity's power, or $\kappa^2 Q^2 = 0.13$ according to Eq. (5). Thus, for an uncoupled BBU growth of 36 dB, the theory predicts a coupled-cavity BBU growth of 31.9 dB, consistent with the data given in Fig. 4(a). The inferred value of κ is 0.17%.

In conclusion, the coupling of seven pairs of cavities gave an experimental reduction of the beam-breakup-instability in general agreement with a very simple theoretical model. While we have made no attempt to optimize the degree of cavity coupling, it is interesting to note that a value of κ as low as 0.17% already leads to appreciable BBU reduction in a seven-cavity system, as observed in the present experiment. One may wonder if this technique of coupled-cavity beam-breakup-instability reduction would also have the tendency to control higher-order BBU modes.

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[18] The epsilon factor for the TM_{110} mode is $\varepsilon = 0.422 \times (l/L)[I(\mathrm{kA})/17]\beta/\gamma$, where l is the cavity length, L is the distance between cavity centers, I is the beam current, and β and γ are the usual relativistic velocity and mass factors. See Refs. [4] and [8] for further explanation.

[19] We should mention that these coupled-cavity effects may occur naturally in certain recirculating accelerators, as addressed in Ref. [15]. If additional loss is introduced to the main or dummy cavity, the analysis may simply be modified by assigning a lower value of Q in the operator L in Eqs. (2) and (3), and the growth rate may be assessed in a similar manner.