# Microwave growth from the beam breakup instability in long-pulse electron beam experiments

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The beam breakup (BBU) instability has been investigated in high-current, long-pulse electron beams propagating through microwave cavities. Experiments are performed using a relativistic electron-beam generator with diode parameters: 0.7–0.8 MV, 1–15 kA, and 0.5–1.5 $\mu$s. The magnitude of the solenoidal magnetic field places these experiments in an intermediate regime between strong focusing and weak focusing. The electron-beam transport system consists of ten identical pillbox cavities each containing a small microwave loop antenna designed to detect the $TM_{110}$ beam breakup mode. The $TM_{110}$ microwave mode is primed in the first cavity by a magnetron tuned to the resonance frequency of 2.5 GHz. The BBU instability growth is measured through the amplification of the 2.5 GHz microwaves between the second and tenth cavities. Strong growth (25–38 dB) of the $TM_{110}$ microwave signal is observed when the initial cavity is primed exactly on resonance, with a rapid decrease of the growth rate off-resonance. The magnitude of microwave growth is consistent with the predictions of BBU theory.

The beam breakup (BBU) instability is one of the most serious instabilities in high-current and long-pulse electron-beam accelerators. The BBU instability results from the coupling between the transverse motions of the electron beam and the nonaxisymmetric $TM_{110}$ mode of the cavity structure.[1] This important instability can cause numerous effects on electron beams, such as emittance degradation, loss of current, and pulse shortening.[2,3] Recently, there has been interest in using transverse *e*-beam modulation to produce high-power microwaves.[4–7] While the theory of the BBU instability has been advanced considerably in recent years,[8–13] there have been few journal publications where BBU is systematically studied in experiments and compared with theories.[14]

In this letter, we study the evolution of BBU instability in a few (ten) cavity system. This problem is of interest to multicavity klystrons and magnicons,[15] and may serve as a stringent test of the continuum description of BBU in a few-cavity system. The present experimental approach utilizes a long-pulse electron beam coasting through a series of identical microwave cavities. The first cavity is primed at the $TM_{110}$ resonance frequency by a kilowatt microwave magnetron. The parameters for these experiments place the BBU growth rate scaling close to the boundary between the weak[1] and strong focusing[9,16] regimes (defined in Ref. 3).

The electron-beam accelerator used for the experiments is the Michigan Electron Long Beam Accelerator (MELBA) with diode parameters: voltage $= -0.7$–$0.8$ MV, current $= 1$–$15$ kA, and pulse length $= 0.5$–$5$ $\mu$s, with voltage flattop provided by an Abramayan-type compensation stage over 1.5 $\mu$s.[17]

The experimental configuration is shown in Fig. 1. The electron beam is produced by a field/explosive emission button cathode. The cathode is covered with cotton velvet and is mounted on a hemispherical-end cathode stalk. The anode consists of a graphite plate located 10.8 cm from the end of the cathode. Centered in the anode is a circular aperture (2-cm diam) which extracts 40–300 A into the transport chamber. The diode chamber is immersed in a uniform solenoidal magnetic field that can be varied from 0.5–1.2 kG.

The transport chamber consists of a stainless-steel vacuum drift tube wound with solenoidal coils pulsed independently from the diode. These coils produce a quasi-dc magnetic field of up to 3.5 kG (duration $=$ 20 ms). Figure 1 (upper) illustrates the magnetic-field profile of the experiment. Within the drift tube are ten brass pillbox resonant cavities with a radius of 6.9 cm and a length of 2.0 cm. Inside each cavity is a small loop antenna (0.7-cm diam) oriented to be sensitive to the $TM_{110}$ cavity mode. The average $TM_{110}$ resonant frequency is $2.5075 \pm 0.0026$ GHz, and the average $Q$ is $215 \pm 45$. These low-$Q$ values were obtained by loading each cavity with a ring of microwave absorber. The cavities are separated by smaller diameter copper tubes (radius $=$ 1.9 cm, length $=$ 6.5 cm). The purpose of these tubes is to cutoff the electromagnetic propagation of the microwaves between the cavities. Thus, there is negligible cavity-to-cavity crosstalk and the system is immune to the regenerative BBU instability. The measured attenuation of the 2.5 GHz, $TM_{110}$ microwaves is 26 dB from cavity-to-adjacent cavity.

The loop antenna in the first cavity is connected to a 1-kW level external microwave pulse generator (magnetron) to prime the cavity's $TM_{110}$ mode. The priming microwave pulse is 3-$\mu$s long and begins before the *e* beam is present. In the second cavity, the *e* beam-induced microwave signal is received by the loop antenna and propagated out of the vacuum chamber through coaxial cable to an *S*-band waveguide. At the end of the waveguide, the microwave signal is attenuated and filtered for frequency information. Part of the microwave signal is diverted into a filter which passes $2.5075 \pm 0.0115$ GHz. The filter rejects all frequencies except that which corresponds to the $TM_{110}$ beam breakup mode. The microwave power is measured with diode detectors. The rf in the tenth and last cavity is

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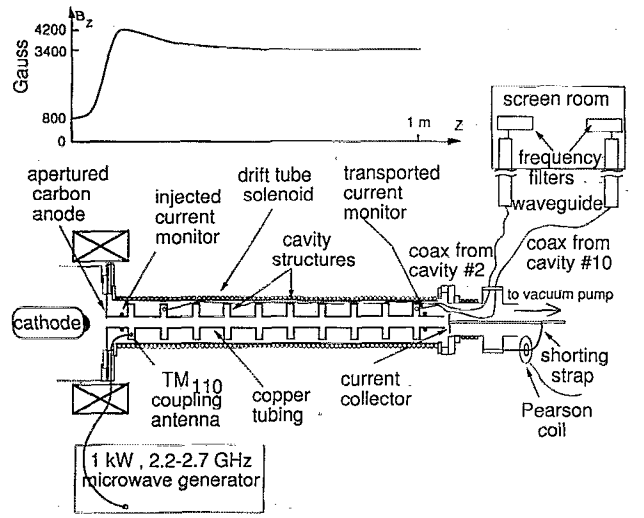

FIG. 1. Experimental configuration (lower), with typical magnetic-field profile (upper).

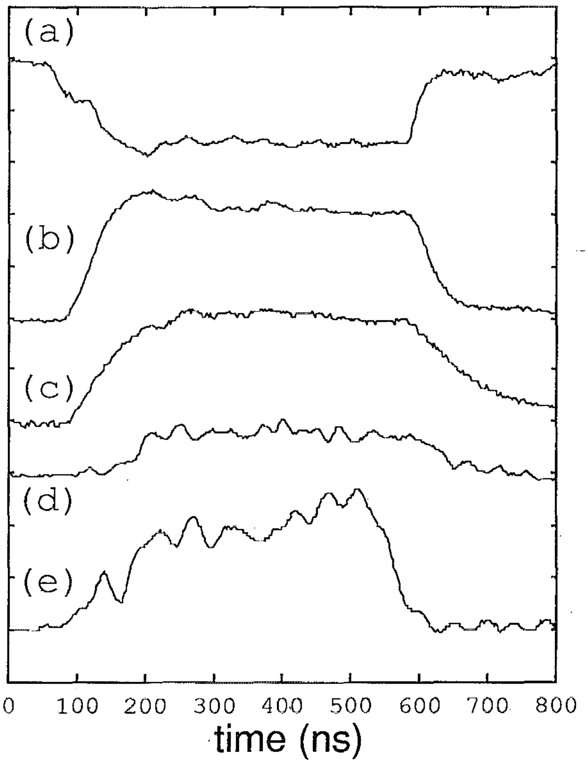

FIG. 2. Experimental data: (a) electron beam voltage (465 kV/div); (b) injected current into first cavity (92 A/div); (c) transported current leaving tenth cavity (92 A/div); (d) microwave diode detector signal in the second cavity, filtered at 2.5075±0.0115 GHz, 6-dB attenuation; (e) microwave diode detector signal in the tenth cavity filtered at 2.5075 ±0.0115 GHz, 35-dB attenuation.

measured in the same way with its own cable, waveguide, and filter. The BBU growth is determined by the decibels of growth in 2.5-GHz microwave power between the second and tenth cavities.

The beam current is measured before entering the first cavity and after exiting the last cavity using calibrated Rogowski coils. After exiting the cavity structure, the beam propagation is terminated by a copper collector plate grounded by a cable which passes through a Pearson current transformer.

Figure 2 depicts typical experimental data. The uppermost trace (a) is the MELBA diode voltage in which the flattop occurs at 750 kV and lasts for 600 ns. The second signal (b) is the current entering the first cavity with a peak which corresponds to 200 A. Signal (c) is the current exiting the tenth cavity, and the peak corresponds to 190 A. The fourth signal (d) is the microwave power signal in the second cavity after being filtered at 2.5 GHz; the signal has been attenuated by 6 dB. The lowermost signal (e) is the microwave power in the tenth cavity after being filtered at 2.5 GHz; this signal has been attenuated by 35 dB. Allowing for the difference in signal amplitudes and detector sensitivities, the growth of the 2.5-GHz microwaves is measured to be about 36 or 4.5 dB per cavity. These data were taken at a solenoidal magnetic field of 3.4 kG.

The theoretical magnitude of beam breakup instability growth can be obtained by calculating the imaginary wavenumber in the BBU dispersion relation. If the continuum theory[3,18] is used the appropriate dispersion relation is

$$(\Omega^2-\omega_c\Omega+\Gamma)(\Omega^2+\omega_c\Omega+\Gamma)=0, \qquad (1)$$

where, $\Omega=\omega-vk$

$$\Gamma=\frac{2\omega_0^4\epsilon}{-\omega^2+\omega_0^2+i\omega\omega_0/Q},$$

$\omega_c$ is the relativistic betatron frequency, $\omega$ is the frequency of the beam breakup wave, $v$ is the velocity of the electron beam, $k$ is the wavenumber, $\omega_0$ is the angular frequency of the $\mathrm{TM}_{110}$ mode, $Q$ is the quality factor of the cavity, and $\epsilon$ is the dimensionless coupling factor.[19] Using the data from Fig. 2, the calculated BBU growth is 34 dB.

If the betatron wavelength or the BBU $e$-folding length does not greatly exceed the spacing of the accelerator cavities, then the transverse impulsive forces from the cavities can no longer be treated as a continuous force per unit length. If this condition exists, then a continuum model may be inappropriate, and a model treating the cavities as discrete entities would be more applicable. This is the case here, for the betatron wavelength of the MELBA beam at 3.4 kG is 7.8 cm, and the cavity spacing is 8.5 cm. Thus, a more accurate dispersion relation is[20]

$$k(\omega)=\frac{\omega}{v}\pm\frac{\omega_c}{2v}-\frac{1}{L}\arccos\left(\cos\frac{L\omega_c}{2v}+\frac{\Gamma L}{\omega_c v}\sin\frac{L\omega_c}{2v}\right), \qquad (2)$$

where $L$ is the distance between adjacent cavity centers. Using the data from Fig. 2, the calculated growth rate is 35 dB for the discrete-cavity asssumption.

Figure 3 shows the 2.5-GHz microwave signal growth plotted for various values of $I/B$ ($I/B$ is the ratio of transported current to the magnetic field). The theoretical BBU growth rate is approximately linearly proportional to $I/B$. The solid circles are experimental data which were obtained by varying the magnetic field. The open circles are the discrete-cavity [Eq. (2)] theoretical growth points as calculated from the parameters of the corresponding ex-

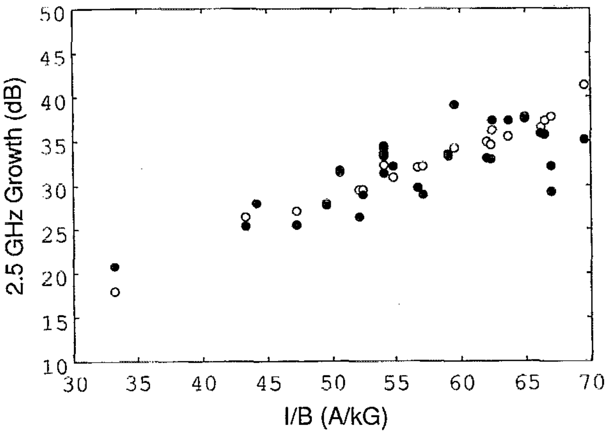

FIG. 3. Microwave growth (2.5 GHz) dependence on the current to magnetic-field ratio, *I/B*. The filled circles are experimental data and the open circles are theoretical predictions calculated by the discrete-cavity theory [Eq. (2)] from the corresponding experimental points with the same *I/B*.

perimental points. The values of $\epsilon$ for the plotted points range from $5.6\times10^{-5}$ to $5.2\times10^{-4}$. The agreement between theory and experiment is excellent at low currents. The larger difference between theory and experiment at higher currents could be due to *e*-beam-induced detuning of the cavity resonance from its cold-test value.[14]

Figure 4 shows the effect of priming the first cavity at frequencies other than its exact $TM_{110}$ mode resonant frequency. The plotted points are experimental data taken at the same magnetic field (3.4 kG) and nearly the same *e*-beam current (190–215 A). The solid curve is the BBU growth as predicted by the discrete-cavity equation (2) using $I=210$ A and letting $\omega$ vary as the priming angular frequency. The dashed curve is the continuum BBU growth equation (1) for the same parameters. This experimental data is strongly peaked near the central $TM_{110}$ resonant frequency of 2.5075 GHz, showing that this mode, and thus, the beam breakup instability, is responsible for the observed microwave growth. It should be noted that the experimental beam breakup instability growth more closely follows the discrete-cavity theory than the continuum theory. This is expected because the continuum theory assumes that the distance between cavities is negligible compared to the betatron wavelength and the BBU *e*-folding length. For this experiment, both the betatron wavelength and the *e*-folding length are comparable to the distance between cavity centers.

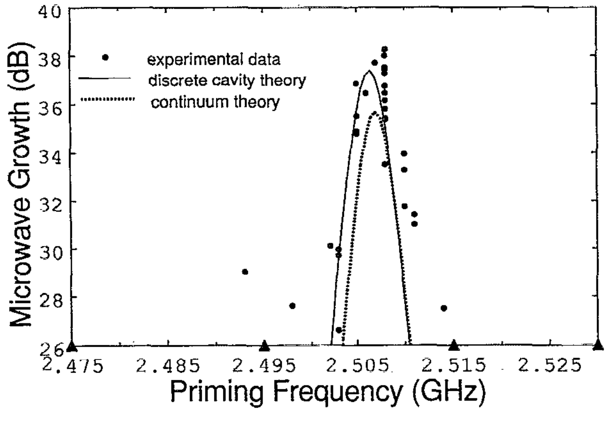

FIG. 4. Microwave growth dependence on the frequency of microwaves injected into the first cavity. The filled circles are experimental data. The solid curve is the theoretical growth predicted by the discrete-cavity mode coupled theory, Eq. (2) (see Ref. 20). The dashed curve is the theoretical growth predicted by the continuum cavity mode coupled theory, Eq. (1) (see Refs. 3 and 18). The triangles along the abscissa indicate experimental growth below the level of detectability (i.e., below 26 dB).

In conclusion, the beam breakup instability has been experimentally studied for the difficult regime of intermediate focal strength. The adequacy of the continuum BBU description for few-cavity systems is tested, even under conditions where the betatron wavelength is comparable to the cavity spacing. Strong instability growth is only found by microwave priming at the resonance frequency of the $TM_{110}$ microwave mode, a characteristic of the beam breakup instability.

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[19] The epsilon factor for the $TM_{110}$ mode is $\epsilon=0.422(l/L)[I(kA)/17](\beta/\gamma)$, where $l$ is the cavity length, $L$ is the cavity spacing, $I$ is the beam current, and $\beta$ and $\gamma$ are the usual relativistic velocity and mass factors. See Refs. 3 and 12 for further explanation.

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