Experiments on the Beam Breakup Instability in Long-Pulse Electron Beam Transport Through RF Cavity Systems

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ABSTRACT

Experiments have been performed to investigate the beam-breakup-up (BBU) instability in high current electron beams transported through RF cavity systems. Experiments utilize long-pulse electron beam accelerators operating with parameters: energy = 0.3-0.8 MeV, current = 0.1-1 kA, and pulselength = 0.3-1.5 μs. The transport system consists of 10 RF cavities separated by tubes which are cut-off to the RF. Each cavity has a microwave probe to detect growth of e-beam emission in the TM_{110} mode at 2.5 GHz, corresponding to the BBU. Solenoidal magnetic fields of 0.8-5 kG are applied. Experiments show that 40% of the injected current was transported through the cavity system. The growth of the 2.5 GHz RF was found to be 4.4 dB per cavity; this compares well with the theoretical growth of 3.9 dB per cavity.

I. INTRODUCTION

The beam breakup instability is one of the most important instabilities in electron beam accelerators. This instability results in transverse beam deflection by the non-axisymmetric TM_{110} mode of the accelerating cavities. While the theory of the BBU instability has advanced considerably in recent years,[1-5] a great deal of experimental research is required to understand the scaling of the BBU over a wide range of electron beam parameters. Experiments at the University of Michigan utilize long pulse, high current electron beam accelerators to investigate the beam breakup instability in RF cavity structures.

II. EXPERIMENTAL CONFIGURATION

The accelerator for these experiments is the Michigan Electron Long Beam Accelerator (MELBA) [6], which operates with parameters: voltage = -0.8 to -1 MV, diode current = 1 - 10 kA, and pulselength = 0.3 - 5 μs, with flattop voltage provided by compensation over 1.5 μs. The experimental configuration is depicted in Figure 1. A planar velvet field emission cathode is utilized to generate an electron beam, part of which is extracted by a 2 cm diameter aperture in the graphite anode. A solenoidal magnetic field of 0.8-5 kG is applied to the 1 m transport region. A set of 10 microwave cavities are connected by cutoff sections of small diameter copper tubes. The cavities are designed so that the resonant frequency of the TM_{110} mode is 2.5 GHz; this frequency cannot propagate through the cutoff sections (dia.=3.9 cm, length=1 cm). This frequency is convenient for microwave priming of the first cavity by a magnetron. Each cavity has one or two small coupling probes oriented to detect the TM_{110} mode. The specifications of the cavities are given in Table 1. The growth of the BBU instability is detected by measuring the attenuation required to match the magnitudes of the TM_{110} mode RF signals at 2.5 GHz from the second and tenth cavity.

Extracted current from the diode is measured by a Rogowski coil in the diode flange. Current transported through the cavities is collected by a copper plate connected to a rod which is grounded through a Pearson current transformer.

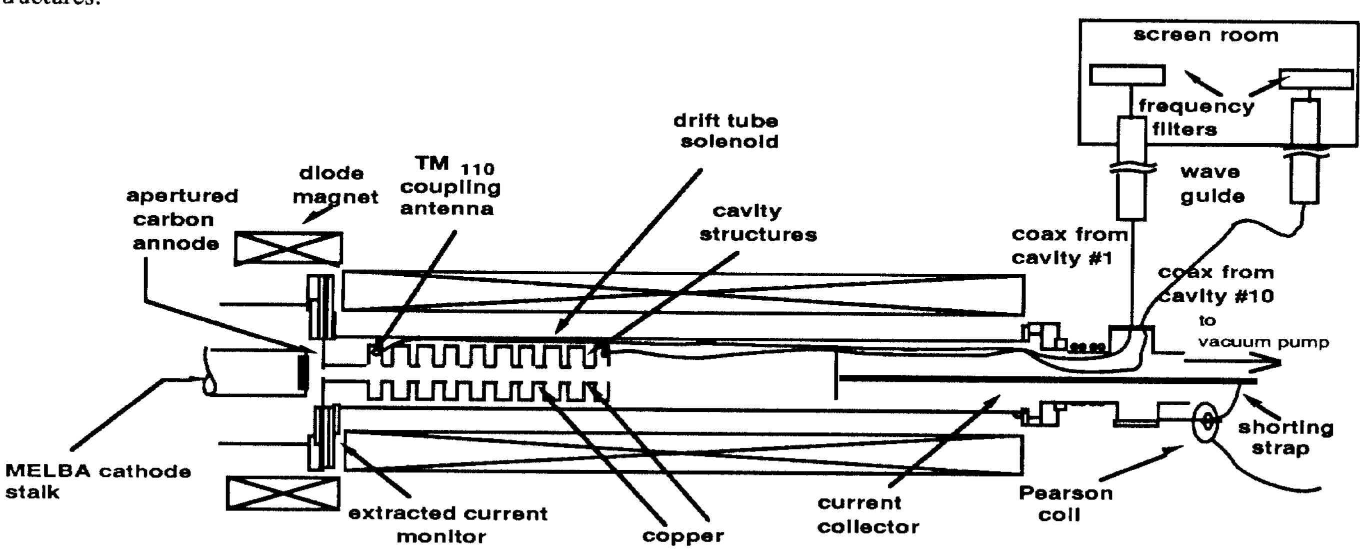

Figure 1. Experimental configuration

III. Theoretical Growth Rates for BBU Instability

The frequency dependence of the BBU growth rate is important in designing an experiment for which the TM_{110} mode is primed in the first cavity, because a mismatch between the priming frequency and the TM_{110} mode frequency could result in a substantial decrease in the initial growth rate. To examine this, the two-dimensional BBU dispersion relation is examined [5]. The 2-D model applies to the case of cylindrical symmetry where deflection in both transverse directions can couple and grow. The dispersion relation is given by eqn. (1).

Table 1
Experimental Parameters

e-beam voltage	0.6-1 MV
diode current	1-10 kA
extracted current	100-400 A
pulselength	0.5-1.5 μs
beam radius	1.0 cm
cavity radius	6.9 cm
TM_{110} frequency	2.5 GHz
average cavity Q	200
# of cavities	10
cavity length (ℓ)	2 cm
cavity spacing (L)	3 cm
magnetic field	800 G

Equation (1)

$$k(\omega) = \frac{2\omega \pm \sqrt{2}\left\{\omega_c^2 + \frac{NQ}{D}\left(\omega^2 - \omega_c^2\right) - i\frac{N\omega\omega_o}{D} \pm \left[\frac{-4NQ\varepsilon\omega_c^4}{D} + \left(-\omega_c^2 - \frac{NQ}{D}\left(\omega^2 - \omega_c^2\right) + i\frac{N\omega\omega_o}{D}\right)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}}{2v}$$

where,

$$D = Q^2\left(\omega^2 - \omega_o^2\right)^2 - \omega^2\omega_o^2 + 2iQ\left(\omega\omega_o^3 - \omega^3\omega_o\right)$$

$$N = 4Q\varepsilon\omega_o^4$$

Here k is the wavenumber, ω is the frequency of the beam breakup wave, ω_o is the TM_{110} cavity frequency, ω_c is the relativistic cyclotron frequency, Q is the cavity quality factor, and ε is a dimensionless factor dependent on the beam current and energy.[3]

A plot of Im[k(ω)] versus ω/2π for the experimental parameters is shown in Figure 2. Im(k) is the spatial growth rate at the frequency ω/2π; $[\mathrm{Im}(k)]^{-1}$ is the e-folding length. Here k has been multiplied by 1 m to make it dimensionless. Peak growth occurs for $f \approx f_o$. The parameters used are: beam energy=650 keV, beam current=300 A, magnetic field=800 G, Q=200, and f_o=2.5 GHz.

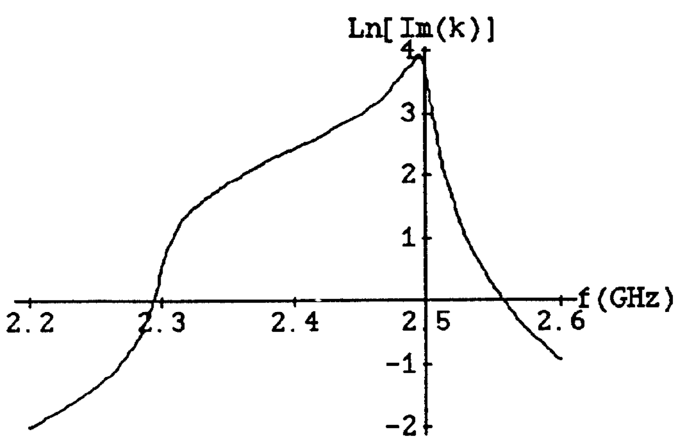

Figure 2. Spatial growth rates versus microwave priming frequency for MELBA parameters.

Figure 2. shows that if the priming source is mismatched above $\omega_o/2\pi$ by more than 25 MHz (1 %) then the initial growth rate is reduced by an order of magnitude. On the other hand, there is less critical fall off if the priming source is mismatched on the lower frequency side of the cavity TM_{110} frequency. Overall, however, it is important to accurately match the priming and cavity frequencies.

Further investigation of equation (1) using the above parameters reveals that our MELBA experiments fall under the "weak focusing" approximation. A plot showing this is given in Figure 3. The wavenumber has been multiplied by 1 m and the beam current has been divided by 1 A to make them dimensionless. *Weak focusing* refers to the growth rate scaling described in [1] and [4]. In effect, weak focusing can be described as the situation where the betatron wavelength is much greater than the BBU e-folding length. This leads to the condition $\omega_c^2 \ll 2\varepsilon Q\omega_o^2$. *Strong focusing* refers to the growth rate scaling approximation described in [2] and [4] and occurs when $\omega_c^2 \gg 2\varepsilon Q\omega_o^2$.

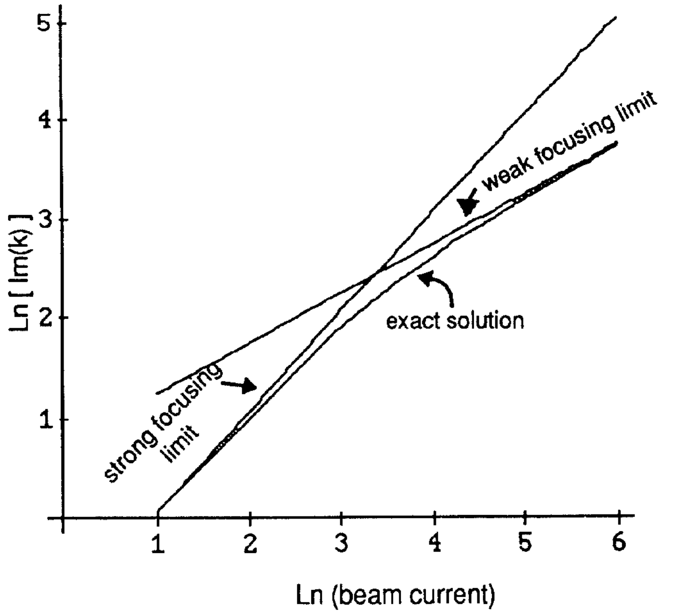

Figure 3. Spatial growth rate versus beam current for MELBA parameters

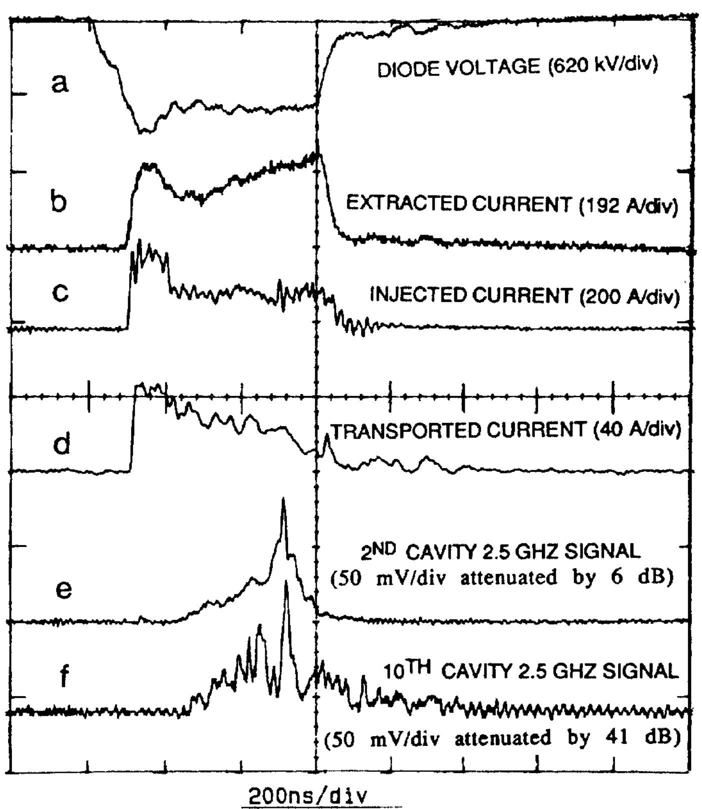

Figure 4. MELBA data: a) Diode voltage (Shot #M2578), b) Extracted current (current exiting 2.0 cm anode aperture) (Shot #M2578), c) 1st cavity exit current (Shot #M2592), d) 10th cavity exit current (Shot #M2578) e) 2nd cavity 2.5 GHz RF signal with 6 dB attenuation (Shot #M2581) f) 10th cavity 2.5 GHz RF signal with 41 dB attenuation (Shot #M2581). The time scale is 200 ns/div. Solenoidal magnetic field is 800 G.

IV. Experimental Results

Experimental data from electron beam transport of the MELBA beam through a 10 cavity system are presented in Figure 4. The data shown are oscilloscope traces from three similar shots.

Extracted current varies from about 115 A to 230 A after the initial voltage overshoot. Injected current measured after the first cavity is about 100 A during the voltage flattop. The current transported through the 10 cavity system decreases from about 40 A to 10 A during the voltage flattop period. Radio frequency emission at 2.5 GHz was measured on the second and tenth cavities by similar detectors with adjustable attenuators. The second cavity RF signal increases over about 300 ns to a peak and then decays. The tenth cavity RF signal is 35 dB higher than the second cavity signal and exhibits a similar shape with more spiky structure.

This data shows that the beam current decreases substantially during its transit through the cavity system while the RF signal corresponding to the TM_{110} breakup mode increases with time and distance. This is indicative of BBU growth.

From equation (1) and Figure 3 which give amplitude growth, the calculated e-folding length is about 6.7 cm. The beam travels 24 cm between the second and tenth cavity giving a predicted growth of 3.9 dB per cavity which yields a total growth of 31 dB. This compares well with the observed 4.4 dB/cavity and 35 dB total growth.

V. Acknowledgements

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VI. References

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$$\varepsilon = 0.422 \frac{\ell}{L} \frac{I\,(kA)}{17} \frac{\beta}{\gamma}$$

where ℓ is the cavity length, L is the cavity spacing, I is the beam current, and β and γ are the usual relativistic velocity and mass factors.
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