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 TM110 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.

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 TM110 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 TM110 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 TM110 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.
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).

\[
\begin{align*}
\kappa (\omega) &= \pm \frac{2 \omega \pm \sqrt{2 \omega_c^2 + \frac{NQ^2}{D} (\omega^2 - \omega_c^2)}}{2v} \left[ \frac{\frac{-4Q\epsilon \omega_o^4}{D}}{D} + \frac{\frac{-\omega_c^2}{D} - \frac{NQ}{D} (\omega^2 - \omega_c^2) + i \frac{N \omega \omega_o}{D}}{2} \right]^{\frac{1}{2}}
\end{align*}
\]

where,\n\[
D = Q^2 (\omega^2 - \omega_o^2)^2 - \omega^2 \omega_o^2 + 2iQ (\omega \omega_o)^2 - \omega^3 \omega_o
\]

N = 4Q\epsilon \omega_o^4

Here \( \kappa \) is the wavenumber, \( \omega \) is the frequency of the beam
breakup wave, \( \omega_o \) is the TM$_{110}$ cavity frequency, \( \omega_c \) is the
relativistic cyclotron frequency, Q is the cavity quality factor,
and \( \epsilon \) is a dimensionless factor dependent on the beam current
and energy.[3]

A plot of \( \text{Im}[\kappa(\omega)] \) versus \( \omega/2\pi \) for the experimental
parameters is shown in Figure 2. \( \text{Im}(\kappa) \) is the spatial growth
rate at the frequency \( \omega/2\pi \); \( \text{Im}(\kappa)^{-1} \) is the e-folding length.
Here \( \kappa \) has been multiplied by 1 m to make it dimensionless.
Peak growth occurs for \( f = f_0 \). The parameters used are: beam
energy=650 keV, beam current=300 A, magnetic field=800 G,
Q=200, and \( f_0 = 2.5 \text{ GHz} \).

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 \( \omega_c^2 << 2\epsilon Q\omega_o^2 \). Strong focusing refers to the
growth rate scaling approximation described in [2] and [4] and
occurs when \( \omega_c^2 > 2\epsilon Q\omega_o^2 \).

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-beam voltage</td>
<td>0.6-1 MV</td>
</tr>
<tr>
<td>diode current</td>
<td>1-10 kA</td>
</tr>
<tr>
<td>extracted current</td>
<td>100-400 A</td>
</tr>
<tr>
<td>pulselength</td>
<td>0.5-1.5 ( \mu )s</td>
</tr>
<tr>
<td>beam radius</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>cavity radius</td>
<td>6.9 cm</td>
</tr>
<tr>
<td>TM$_{110}$ frequency</td>
<td>2.5 GHz</td>
</tr>
<tr>
<td>average cavity Q</td>
<td>200</td>
</tr>
<tr>
<td># of cavities</td>
<td>10</td>
</tr>
<tr>
<td>cavity length (( \xi ))</td>
<td>2 cm</td>
</tr>
<tr>
<td>cavity spacing (L)</td>
<td>3 cm</td>
</tr>
<tr>
<td>magnetic field</td>
<td>800 G</td>
</tr>
</tbody>
</table>

Figure 2. Spatial growth rates versus microwave priming
frequency for MELBA parameters.
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 TM110 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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