Studies of the regenerative BBU at the JLab FEL Upgrade (Part I)

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Outline

1. Theoretical model of the BBU: fresh look at the problem
2. Measurements techniques and results
3. Comparison of the experimental data to the model
4. Summary and Plans
Energy transfer from the beam to HOM

$V(r = a) = V_a \cos(\varphi) = \int E_z^{\text{max}} (r = a) dz \cos(\varphi)$

$x' = \frac{V_{\perp}}{V_b} = \frac{-cV_a}{\omega a} \sin(\varphi)$

$V_q = qa^2 \frac{\omega}{2} \left( \frac{\omega}{c} \right)^2 \left( \frac{R}{Q} \right) \frac{x}{a}$
BBU threshold equation

\[ \dot{U}_{\text{cav}} = \dot{U}_{\text{beam}} - P_c = \langle \Delta U_{\text{in}} + \Delta U_{\text{out}} \rangle \cdot f_b - P_c \]

\[ P_c = \frac{V_a^2}{(\omega/c)^2 a^2 \left( \frac{R}{Q} \right) Q_L} \]

\[ \frac{dU}{dt} = -\frac{V_a^2}{a^2} \left( I_b \frac{m_{12}}{V_b} \frac{c}{\omega} \sin(\omega T_r) \right) + \frac{1}{(\omega/c)^2 \left( \frac{R}{Q} \right) Q_L} \]

The condition \( dU/dt = 0 \) yields the threshold

\[ I_{th} = -\frac{2V_b}{(\omega/c) \left( \frac{R}{Q} \right) Q_L m_{12} \sin(\omega T_r)} \]

\( m_{12} \sin(\omega T_r) < 0 \) – unstable

\( m_{12} \sin(\omega T_r) > 0 \) – “pseudo”-stable

(J. Bisognano, G. Krafft, S. Laubach, 1987, N. Sereno, 1989)
Two-dimensional case

\[ x \rightarrow \vec{d} \cdot \vec{n} = x \cos(\alpha) + y \sin(\alpha) \]

\( \vec{d}=(x,y) \) is the 2D displacement vector, \( \alpha \) is the HOM angle, 
\( M(2\times2) \rightarrow M(4\times4) \)

\[
I_{th} = -\frac{2V_b}{(\omega / c)\left(\frac{R}{Q}\right)Q_L m^*_1 \sin(\omega T_r)}
\]

\[
m^*_1 = m_{12} \cos^2(\alpha) + (m_{14} + m_{32}) \sin(\alpha) \cos(\alpha) + m_{34} \sin^2(\alpha)
\]

(E. Pozdeyev, 2004)
Voltage evolution above and below $I_{th}$

\[ \frac{V_a^2}{a^2} = \omega \left( \frac{\omega}{c} \right)^2 \left( \frac{R}{Q} \right) U \]

\[ \frac{dU}{U} = -dt \frac{\omega}{Q_L} \frac{I_{th} - I}{I_{th}} \]

\[ U = U_0 \exp \left( -t \frac{\omega}{Q_L} \frac{I_{th} - I_b}{I_{th}} \right) \]

\[ V = V_0 \exp \left( -t \frac{\omega}{2Q_L} \frac{I_{th} - I_b}{I_{th}} \right) \]

\[ Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I} \quad \Leftrightarrow \quad \tau_{eff} = \tau_0 \frac{I_{th}}{I_{th} - I} \]
**JLab FEL Upgrade**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>80-200</td>
</tr>
<tr>
<td>Charge per bunch (pC)</td>
<td>135</td>
</tr>
<tr>
<td>Bunch rep. rate (MHz)</td>
<td>4-75</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>10</td>
</tr>
<tr>
<td>Laser power (kW)</td>
<td>10</td>
</tr>
</tbody>
</table>

Cavities of Zone 3 have higher accel. gradient than Zone 2,4. The Q of dipole HOMs is also higher. HOMs of Zone 3 impose BBU limit.
Questions

• How well do the model and simulations describe the BBU and the beam behavior

• Can we reliably predict the BBU threshold below the threshold

• Can we suppress the BBU (C. Tennant, this seminar Part II)
Direct measurements of the BBU threshold

Schottky diodes were attached to all the HOM ports. The voltage from the diodes was monitored on oscilloscopes.

(K. Jordan)
Direct measurements of the BBU threshold

Schottky diode signal (blue) yields a cavity where BBU happens, FFT of the voltage (red) signal yields the HOM frequency:

Cav 7, $F_{\text{hom}} = 2106$ MHz, $I_{\text{th}} = 2.7$ mA
Beam Transfer Function (BTF) measurements

Measuring $Q(I)$ for several beam current values and using the formula

$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I}$$

one can predict the BBU threshold below the threshold.

+’s: 1) stronger signal
   2) no need for RF amplifier
   3) no need for kicker

-’s: cross-talk can complicate

Q-measurements
Beam Transfer Function (BTF) measurements

Cav 7, $F_{\text{hom}}=2106$ MHz

Projected threshold current is 2.86 mA
HOM voltage growth rate measurements

Measuring HOM voltage growth rate for several beam current values and using the formula:

\[ \tau_{eff} = \tau_0 \frac{I_{th}}{I_{th} - I} \]

one can calculate the BBU threshold above the threshold.

Note, knowing \( \tau_0 \) is not necessary.
HOM voltage growth rate measurements

Cav 7, $F_{\text{hom}}=2106\ MHz$

$I_{\text{th}}=2.61\ mA$

$y = 631.24x - 1645.2$

Thomas Jefferson National Accelerator Facility
Operated by the Southeastern Universities Research Association for the U.S. Depart. Of Energy
What about other HOMs?

Cav. 3, F=1786.206
BTF measurements: the HOM is very far from the threshold (BTF-predicted $I_{th}=34$ mA)

Cav. 8, F=1881.481
BTF measurements inconclusive. Cross-talk prevented us from taking accurate BTF data.

We are not sure what causes this voltage rise
The “pseudo”-stable region \((m_{12}\sin(\omega T_r) > 0)\)

\[
I_{th} = -\frac{2V_b}{\left(\frac{\omega}{c}\right)\left(\frac{R}{Q}\right) Q_L m_{12} \sin(\omega T_r)}
\]

For \(m_{12}\sin(\omega T_r) > 0\), this formula yields a negative threshold. Although it sounds bizarre, the negative threshold current can be “measured” and, thus, has a physical meaning... Sort of...

According to the Q-formula,

\[
Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I} = Q_L \frac{-|I_{th}|}{-|I_{th}| - I} = Q_L \frac{|I_{th}|}{|I_{th}| + I}
\]

the effective Q has to become smaller as the beam current increases.
The “pseudo”-stable region \( (m_{12}\sin(\omega T_r) > 0) \)

**Cav 7, mode F=2116.584 MHz**

The mode that was causing the BBU in Spring 2004, F=2114.156 in Cav. 4 was also “stable” \( (I_{th}=-9.5 \text{ mA}) \)

\[ y = 0.0467x + 0.1512 \]

\[ I_{th}=-3.24 \text{ mA} \]
Comparison to the analytical formula

Dave Douglas’ original Excel spreadsheet:  
November 2004

<table>
<thead>
<tr>
<th>Cav.</th>
<th>Frequency (GHz)</th>
<th>Polarization</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cav.7</td>
<td>2106</td>
<td>y-polarized</td>
<td>2.7 mA</td>
<td>3.3 mA</td>
</tr>
<tr>
<td>Cav.7</td>
<td>2116</td>
<td>x-polarized</td>
<td>-3.24 mA</td>
<td>-14 mA</td>
</tr>
<tr>
<td>Cav.4</td>
<td>2114</td>
<td>x-polarized</td>
<td>-9.5 mA</td>
<td>-5.4 mA</td>
</tr>
<tr>
<td>Cav.3</td>
<td>1786</td>
<td>x-polarized</td>
<td>34 mA</td>
<td>100 mA</td>
</tr>
<tr>
<td>Cav.8</td>
<td>1881</td>
<td>x-polarized</td>
<td>?</td>
<td>63 mA</td>
</tr>
</tbody>
</table>
Conclusions and Plans

- The dipole HOM in Zone 3 Cav. 7 with F=2106 had the lowest BBU threshold in the machine (2.7 mA). The mode in Zone 3 Cav. 4 with F=2114.156, which set the BBU limit in June 2004 was “stable”.

- Behavior of the HOM+beam system can be described by the effective quality factor, given by:

\[ Q_{\text{eff}} = Q_L \frac{I_{\text{th}}}{I_{\text{th}} - I} \]

where \( I_{\text{th}} \) is the threshold current. The formula works above, below the threshold, and even for \( m_{12}\sin(\omega T_r) > 0 \), if the beam current is not too high. (This formula works for the JLab FEL but can fail for larger machines)
Conclusions and Plans

- Measuring the Q of an HOM as a function of current (BTF) below the threshold and measuring the rise time above the threshold, we were able to accurately predict the threshold. The threshold predicted by both methods agrees well with the threshold measured directly by tripping the beam.

- Preliminary results show qualitative agreement with the threshold formula. More work is needed for accurate comparison of the experimental data to simulations.

- Measurement of HOM polarization is required for accurate comparison of the experimental data with simulations and theory. Interesting modes are Cav.7 f=2106, Cav.7 f=2116.584
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