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

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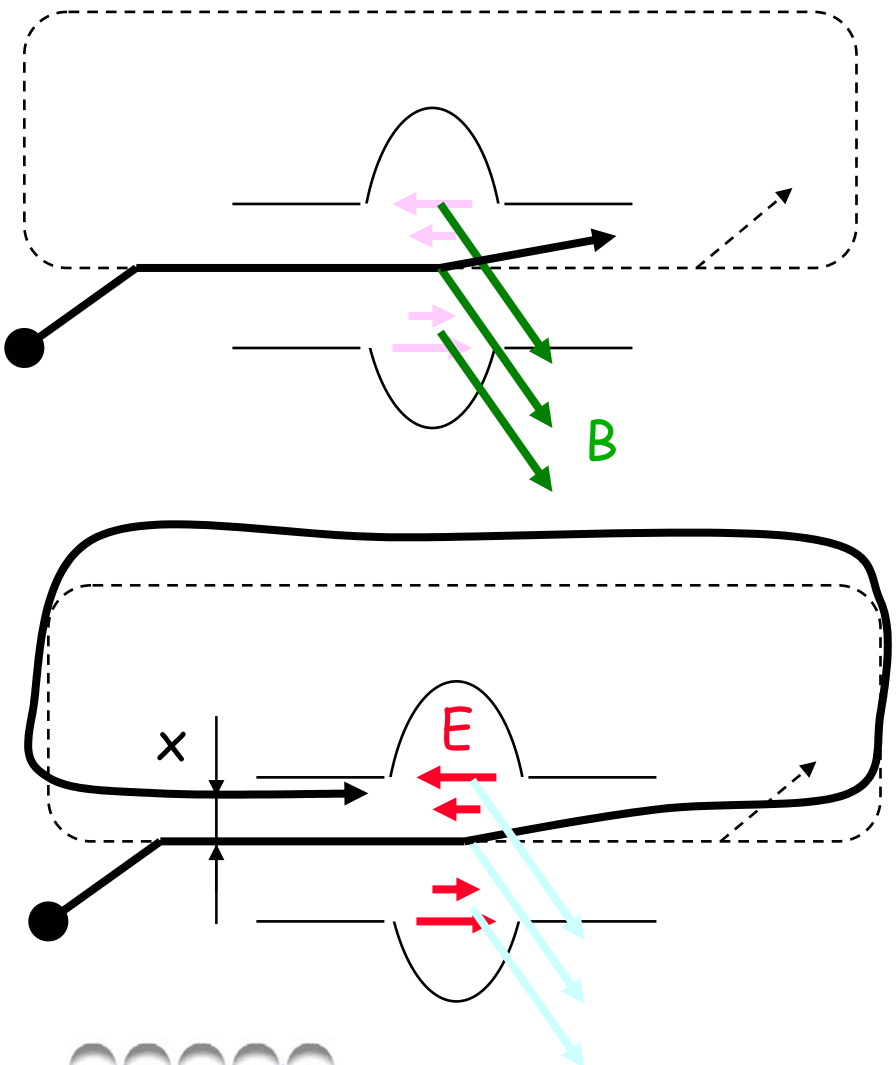
Outline

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



1st pass

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

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

2nd pass

$$x = m_{12} x'$$

$$\Delta U = -qV_a \cos(\varphi + \omega T_r)\frac{x}{a} + \frac{qV_q}{2}\frac{x}{a}$$

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

BBU threshold equation

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

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

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

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

$$x \to \vec{d} \cdot \vec{n} = x\cos(\alpha) + y\sin(\alpha)$$

$\vec{d}$=(x,y) is the 2D displacement vector, α is the HOM angle,
M(2x2) -> M(4x4)

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

$$m_{12}^{*} = m_{12}\cos^2(\alpha) + (m_{14} + m_{32})\sin(\alpha)\cos(\alpha) + m_{34}\sin^2(\alpha)$$

(E. Pozdeyev, 2004)

Voltage evolution above and below I_{th}

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

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

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

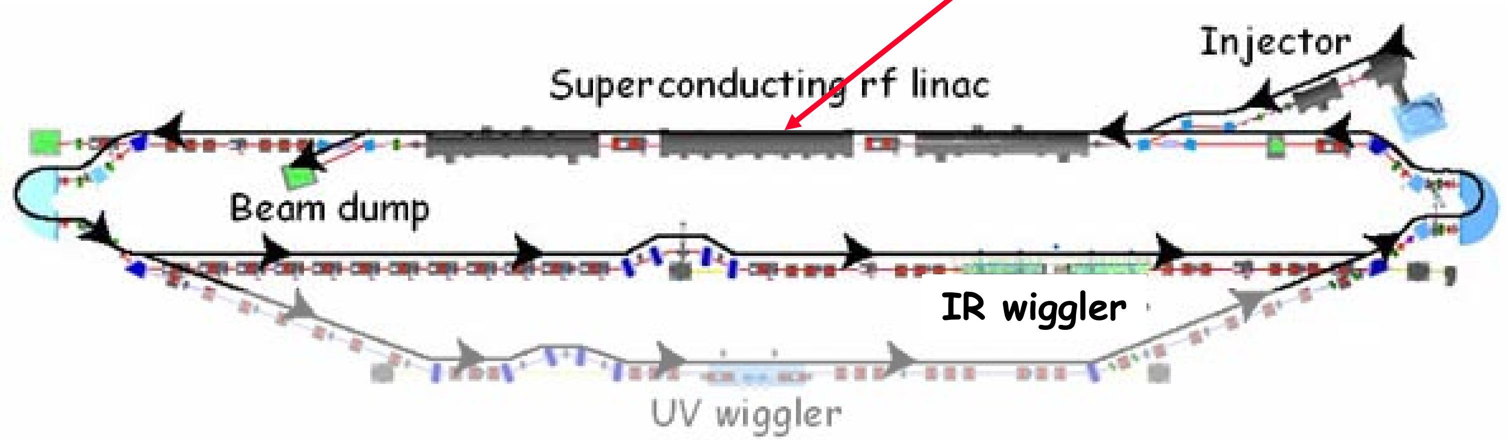
$$V = V_0 \exp\left(-t \frac{\omega}{2Q_L} \frac{I_{th} - I_b}{I_{th}}\right)$$

$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I} \quad \Leftrightarrow \quad \tau_{eff} = \tau_0 \frac{I_{th}}{I_{th} - I}$$

JLab FEL Upgrade

Energy(MeV)	80-200
Charge per bunch (pC)	135
Bunch rep.rate (MHz)	4-75
Average current (mA)	10
Laser power (kW)	10

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.



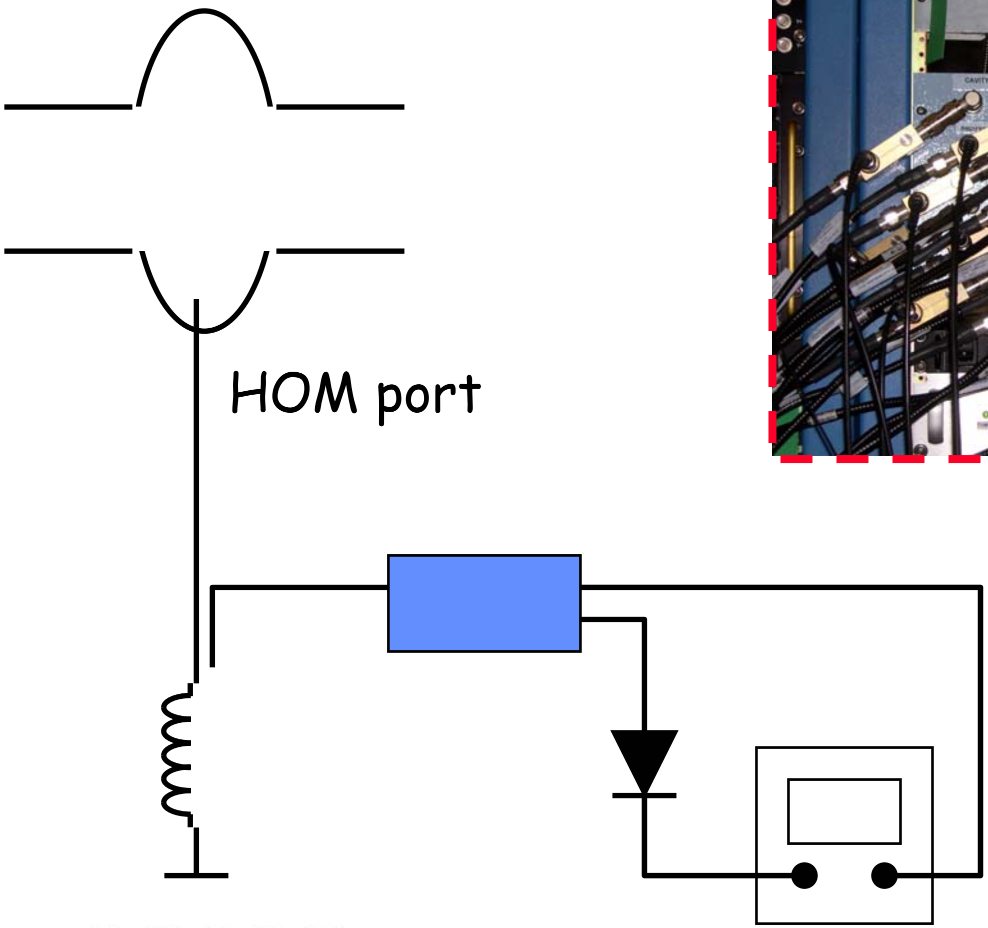
Questions

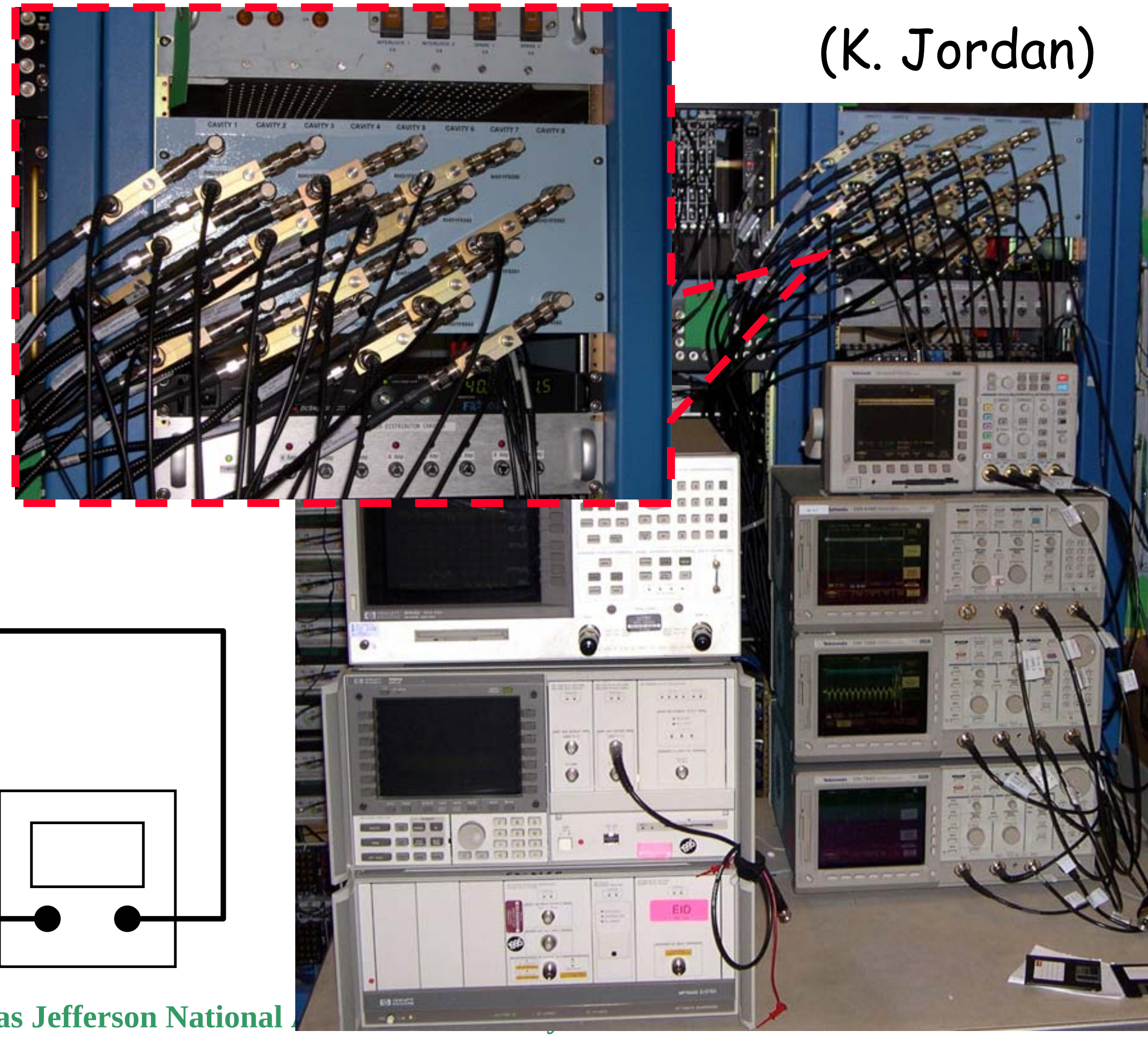
- How well do the model and simulations describe the BBU and the beam behavior
- Can we reliably predict the BBU threshold below the threshold
- Can we suppress the BBU (C. Tennant, this seminar Part II)

Direct measurements of the BBU threshold

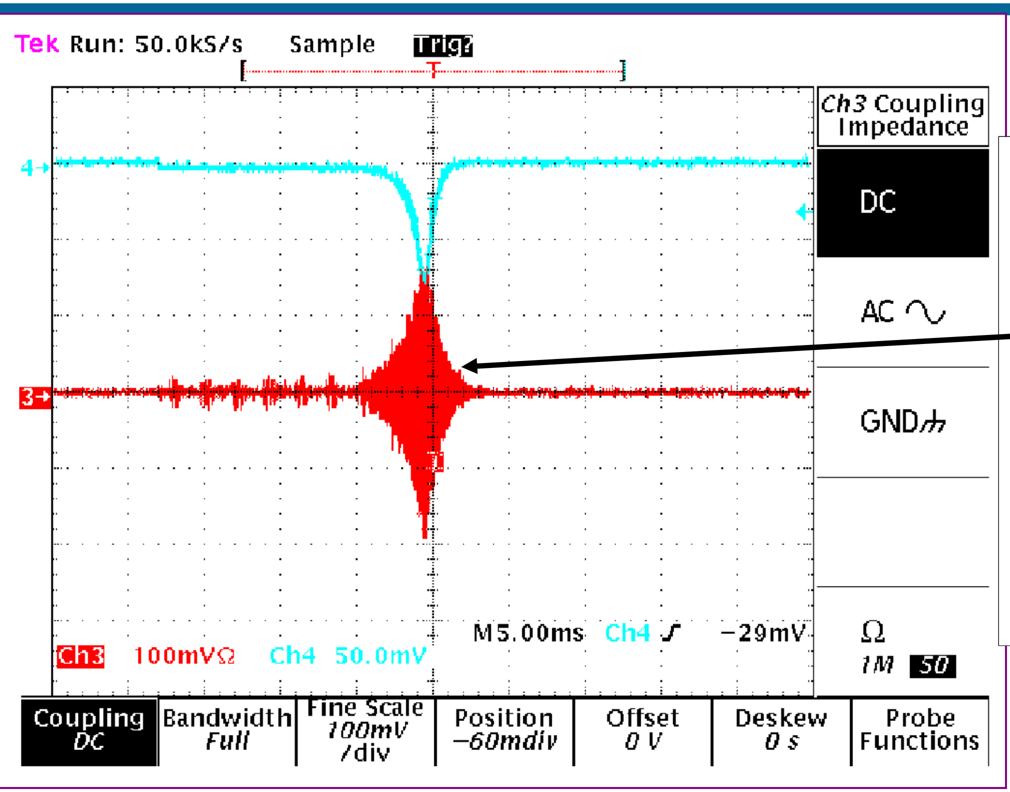
Schottky diodes where attached to all the HOM ports. The voltage from the diodes was monitored on oscilloscopes.

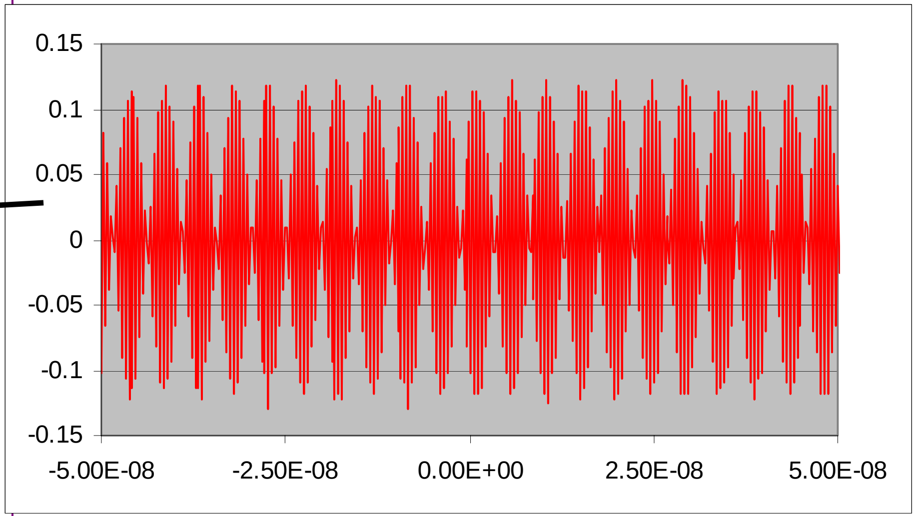
(K. Jordan)





Direct measurements of the BBU threshold

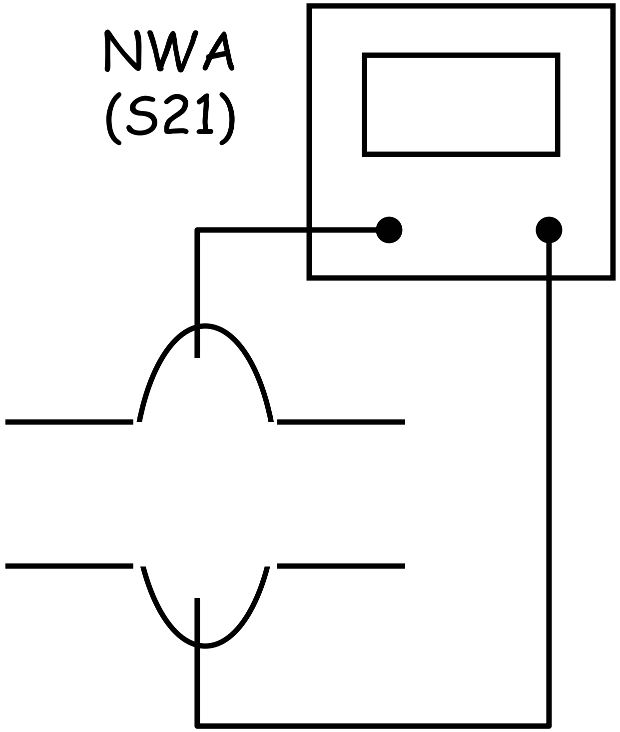




Schottky diode signal (blue) yields a cavity where BBU happens,
FFT of the voltage (red) signal yields the HOM frequency:

Cav 7, F_{hom}=2106 MHz, Ith=2.7 mA

Beam Transfer Function (BTF) measurements



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

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

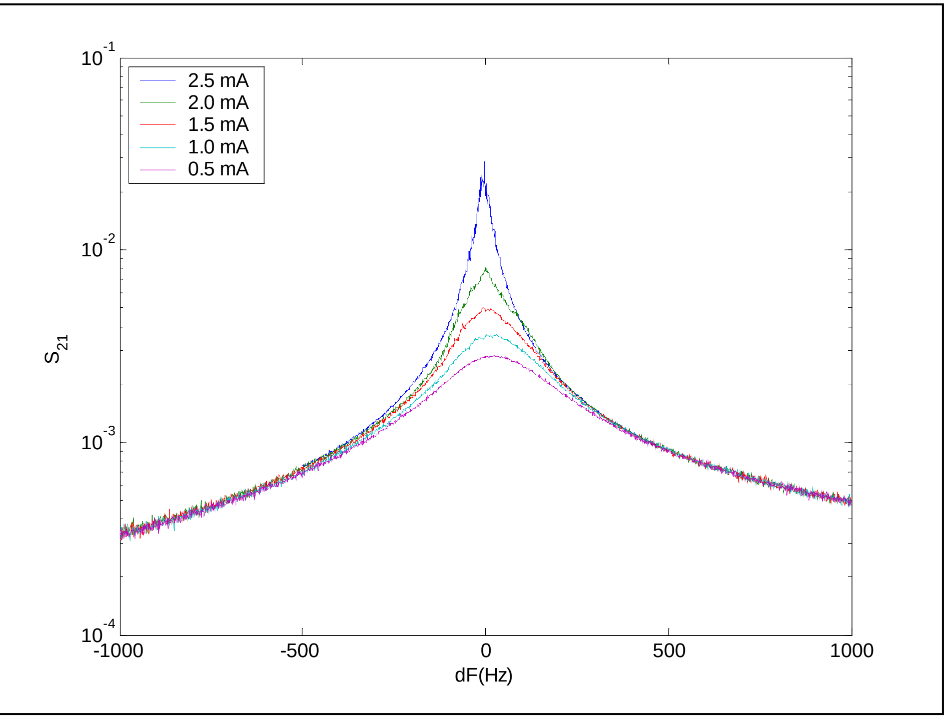
one can predict the BBU threshold below the threshold.

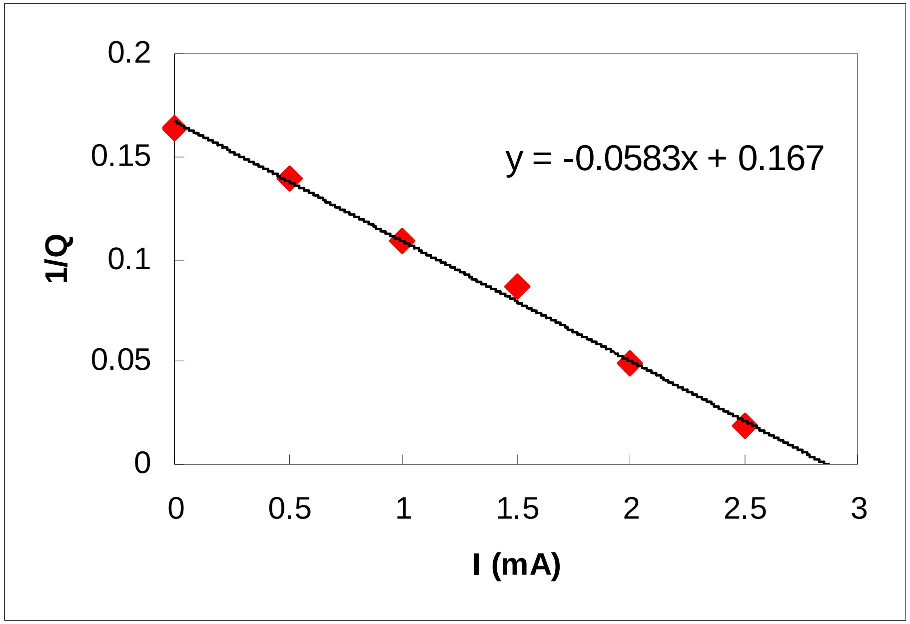
+'s: 1) stronger signal
2) no need for RF amplifier
3) no need for kicker

-'s: cross-talk can complicate Q-measurements

Beam Transfer Function (BTF) measurements

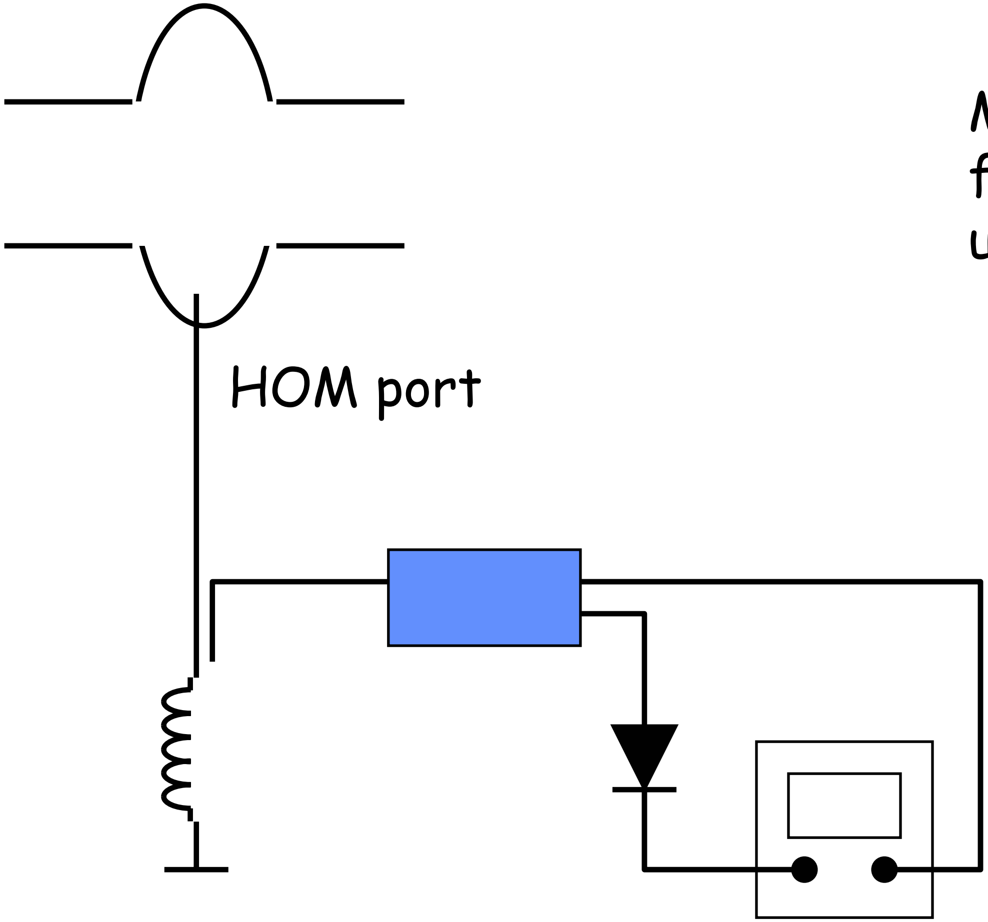
Cav 7, F_{hom}=2106 MHz





Projected threshold current is 2.86 mA

HOM voltage growth rate measurements



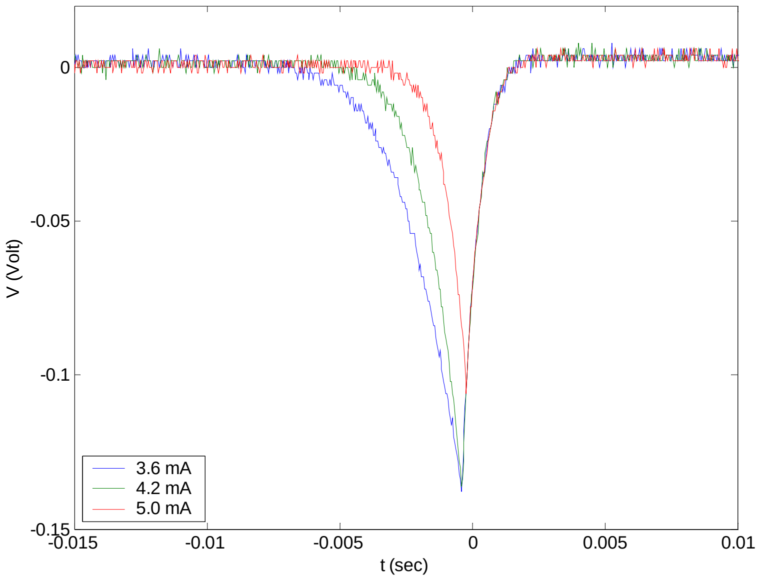
Measuring HOM voltage growth rate for several beam current values and using the formula:

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

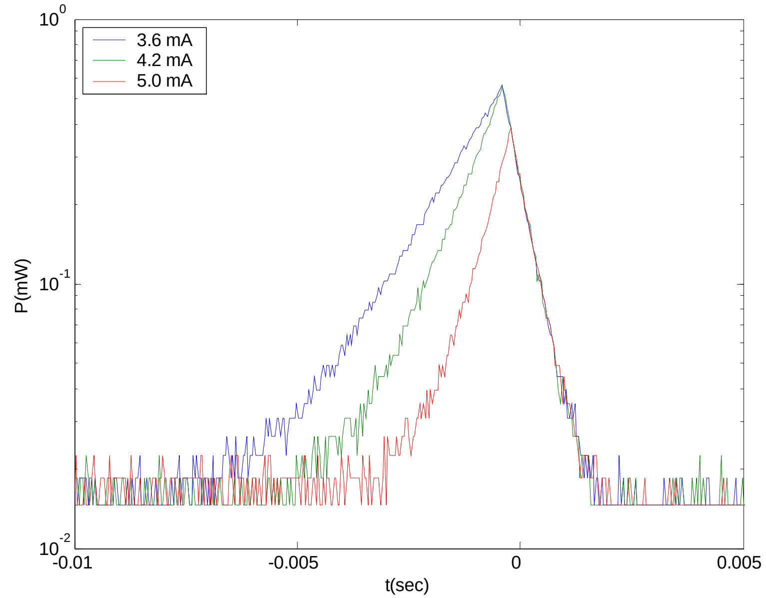
one can calculate the BBU threshold above the threshold.

Note, knowing τ_0 is not necessary

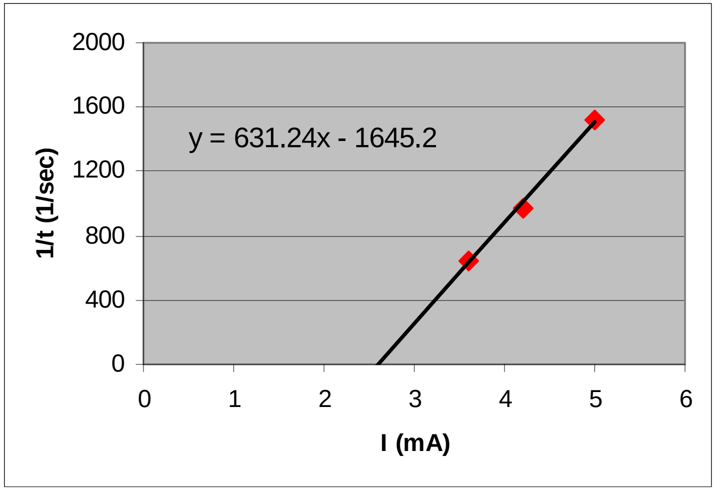
HOM voltage growth rate measurements



invert
+
adjust
+
log

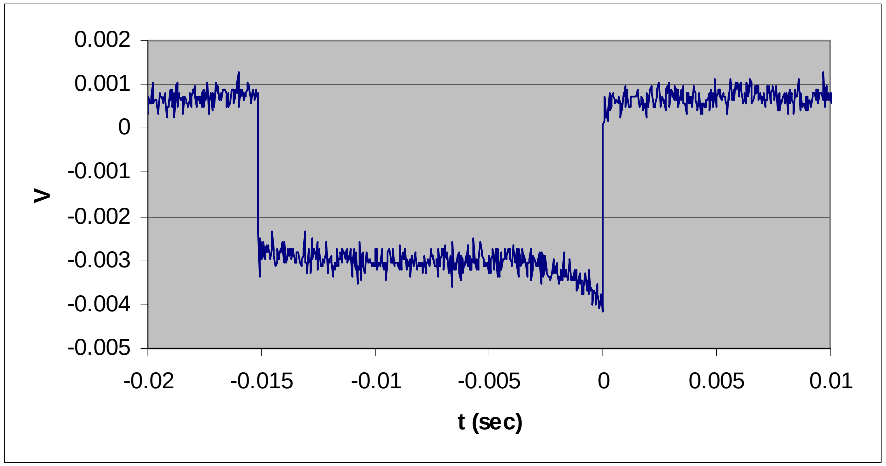


Cav 7, F_{hom}=2106 MHz



I_{th}=2.61 mA

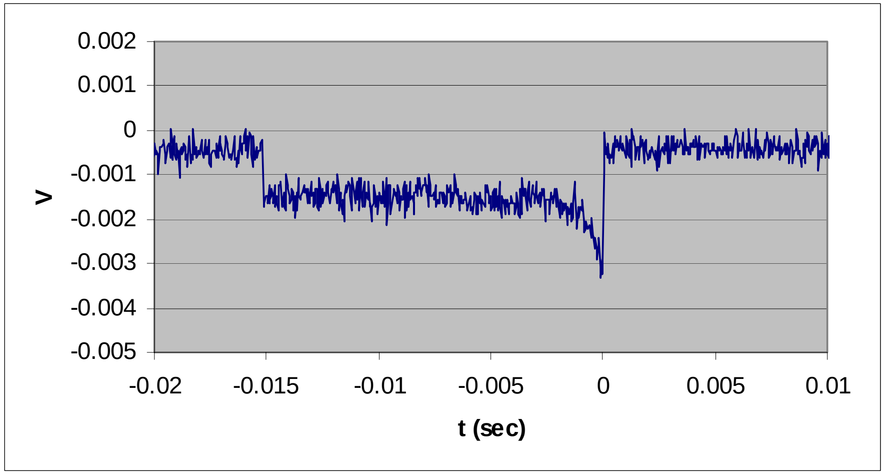
What about other HOMs?



I=5mA

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 ($m_{12}\sin(\omega T_r)>0$)

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

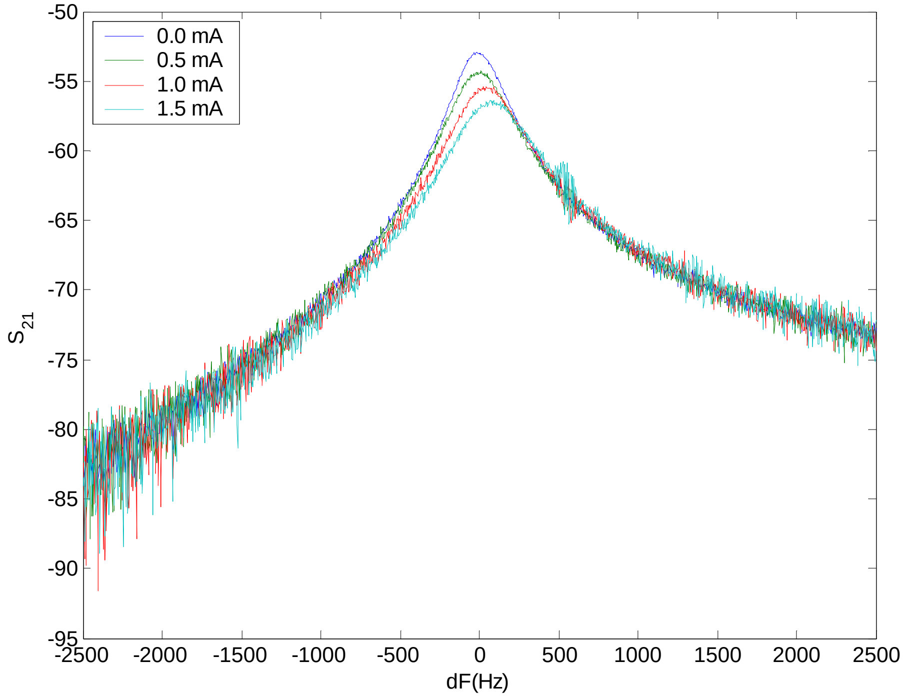
For $m_{12}\sin(\omega T_r)>0$, this formula yields a negative threshold. Although it sounds bizarre, the negative threshold current can be "measured" and, thus, has a physical meaning… Sort of… According to the Q-formula,

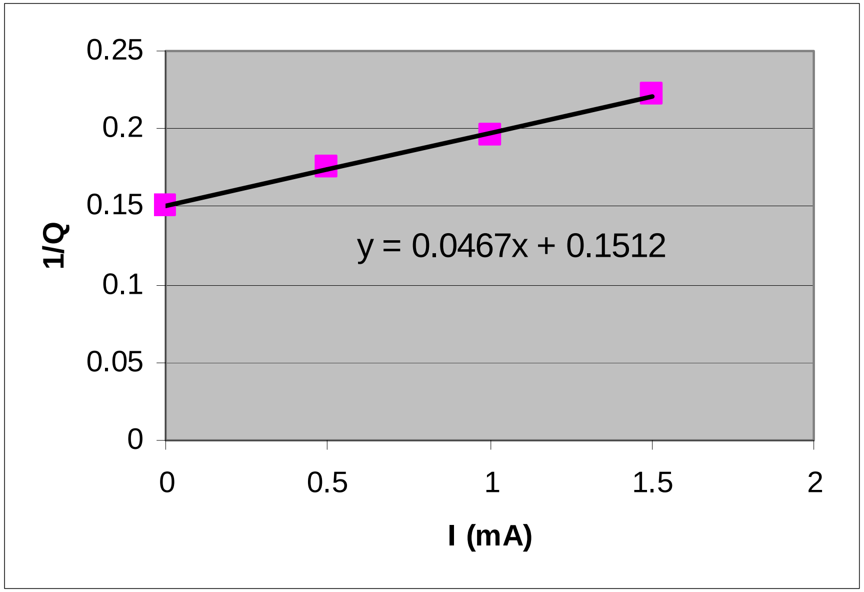
$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I} = Q_L \frac{-\left|I_{th}\right|}{-\left|I_{th}\right| - I} = Q_L \frac{\left|I_{th}\right|}{\left|I_{th}\right| + I}$$

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





Ith=-3.24 mA

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

Comparison to the analytical formula

Dave Douglas' original Excel spreadsheet:
November 2004

	Measured	Calculated
Cav.7 f=2106 (if y-polarized):	2.7 mA	3.3 mA
Cav.7 f=2116 (if x-polarized):	-3.24 mA	-14 mA
Cav.4 f=2114 (if x-polarized):	-9.5 mA	-5.4 mA
Cav.3 f=1786 (if x-polarized):	34 mA	100 mA
Cav.8 f=1881 (if x-polarized):	?	63 mA

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:

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

where I_{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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