Studies of the regenerative BBU at the JLab FEL Upgrade

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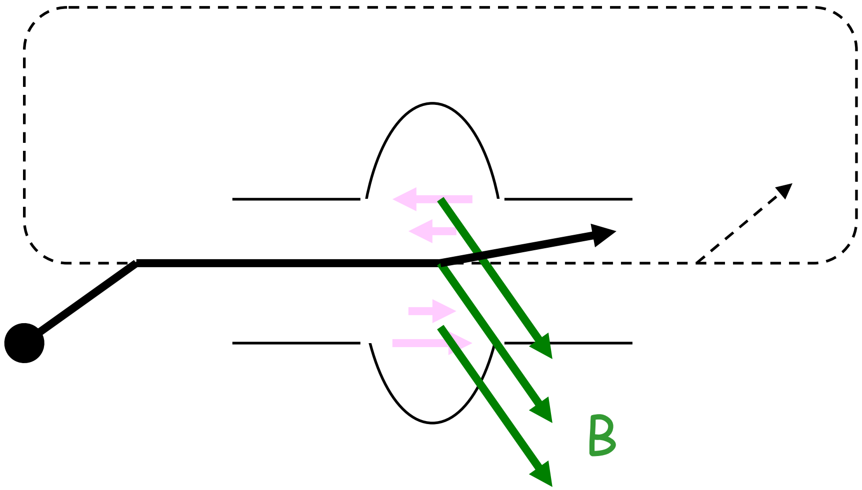
Outline

- Theoretical model of BBU (not rigorous but simple and useful)
- Measurement techniques and results
- Comparison of the experimental data to simulations and the analytical formula
- Summary and plans

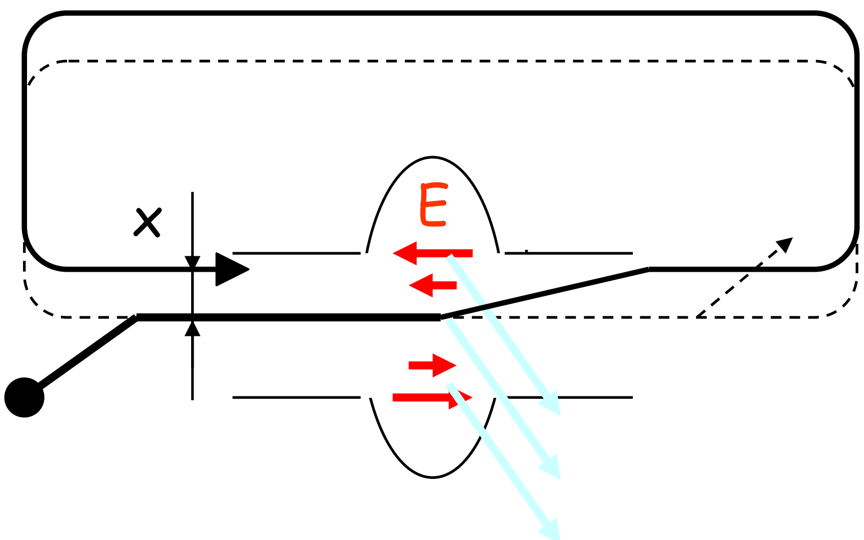
Energy transfer from the beam to HOM



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

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

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

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

BBU threshold equation

The threshold corresponds to equilibrium between deposited and dissipated power.

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

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

At the equilibrium, the stored HOM energy does not change (dU/dt=0)

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

The formula yields two regions:

$m_{12}\sin(\omega T_r)<0$ – unstable

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

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

(Thorough analysis by J. Bisognano, G. Krafft, S. Laubach,1987 Hoffstaetter, Bazarov, 2004)

Two dimensional case (single mode)

Single mode, two-pass recirculator,
arbitrary *m*(4x4), arbitrary mode polarization α

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

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

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

(Pozdeyev, 2004)

Two dimensional case (degenerate modes)

Two degenerate dipole modes polarized in x and y.

$$M(4\times 4) = \begin{bmatrix} 0 & A \\ B & 0 \end{bmatrix}$$

for $M_{14}\, M_{32} > 0$

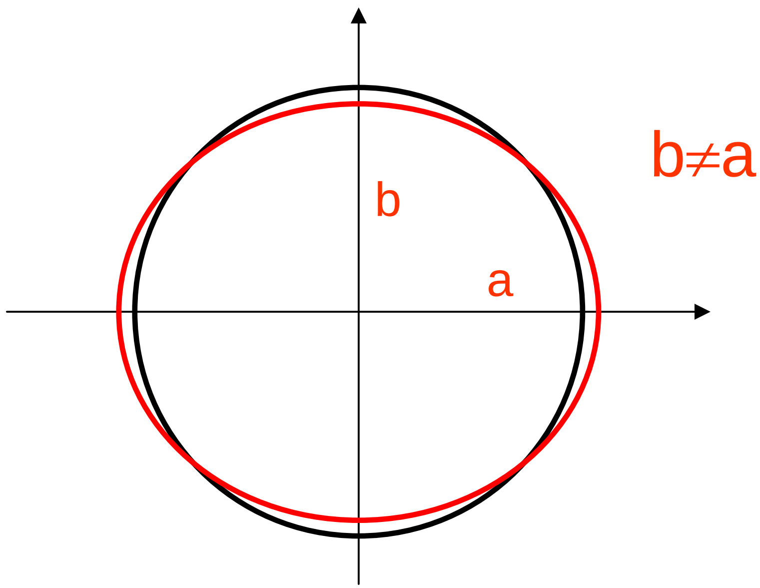
$$I_{th} = \frac{2E\,\omega \exp\left(-\frac{\omega t_\tau}{2Q}\right)}{ec\left(\frac{Z''T^2}{Q}\right)Q\sqrt{M_{14}\, M_{32}}\left|\sin \omega t_\tau\right|}$$

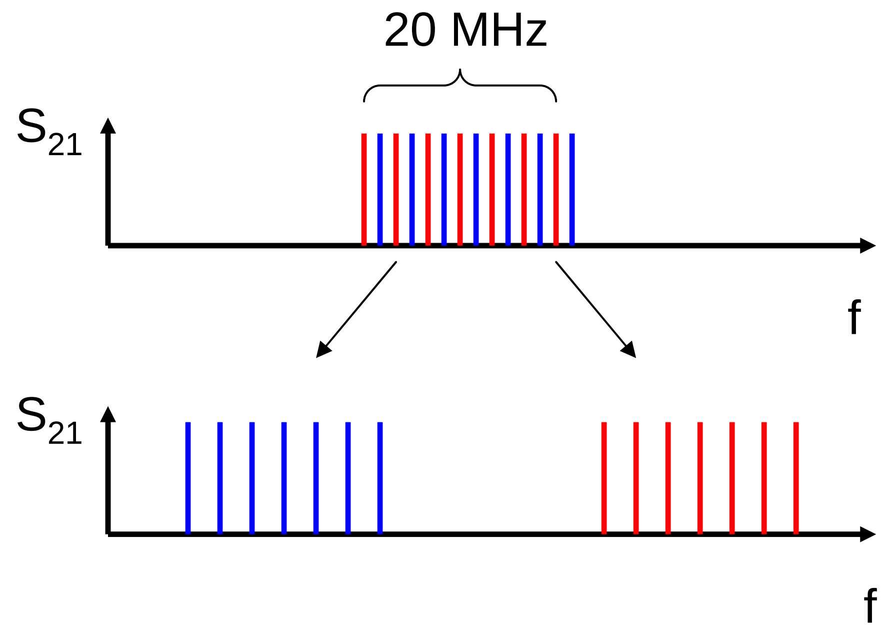
$M_{14}\, M_{32} < 0$

$$I_{th} = \frac{2E\,\omega \exp\left(-\frac{\omega t_\tau}{2Q}\right)}{ec\left(\frac{Z''T^2}{Q}\right)Q\sqrt{-M_{14}\, M_{32}}\left|\cos \omega t_\tau\right|}$$

(B. Yunn, 2005)

Splitting degenerate modes for effective BBU suppression by 90°-rotation/reflection





Frequency separation can be estimated using formula for a square cavity

$$\frac{\delta f}{f} = \frac{6}{5}\frac{\delta d}{d}$$

where $\pm\delta d$ is the variation of the cavity transverse size

Voltage evolution above and below I_{th}

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

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

$$U = U_0\exp\left(-t\,\frac{\omega}{Q_L}\frac{I_{th}-I_b}{I_{th}}\right) \qquad V = V_0\exp\left(-t\,\frac{\omega}{2Q_L}\frac{I_{th}-I_b}{I_{th}}\right)$$

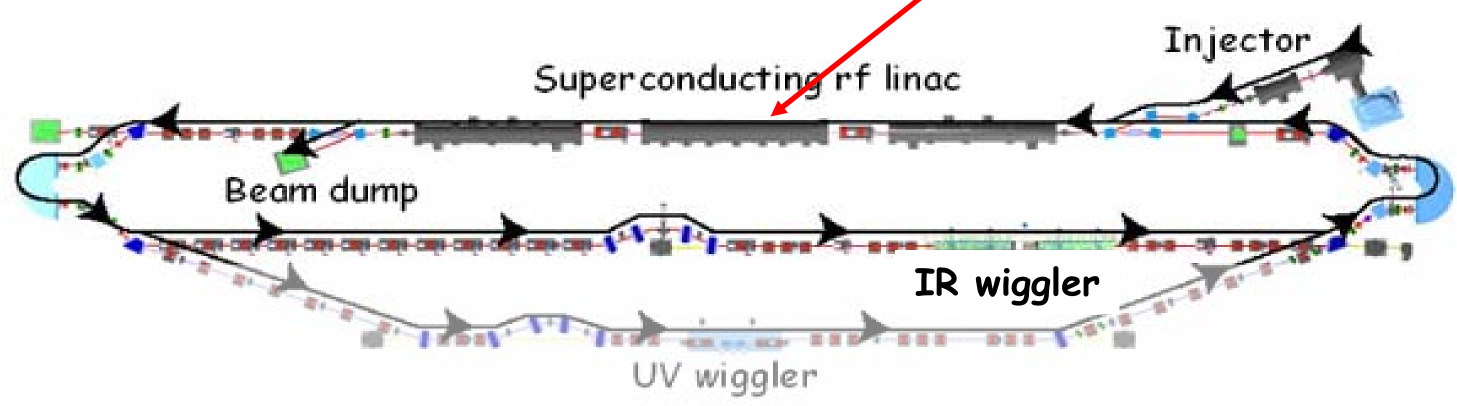
The system HOM+beam can be described by the effective quality factor:

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

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.



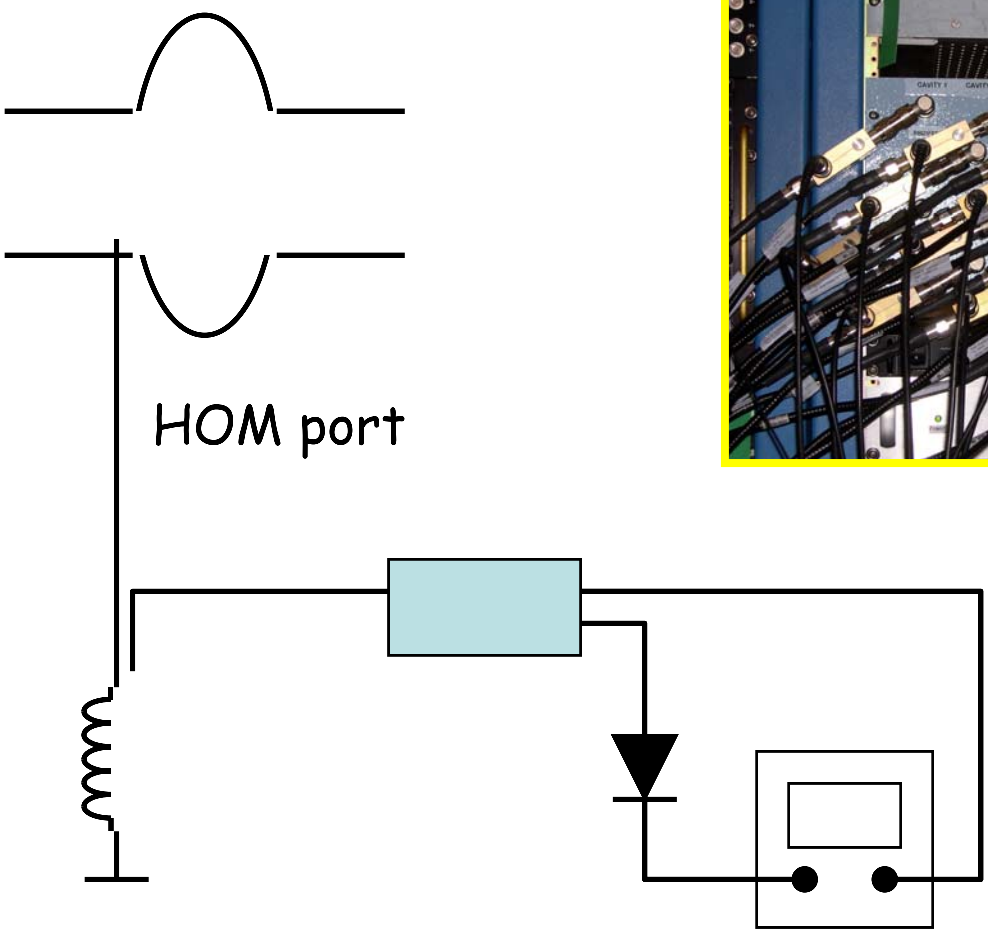
Questions we tried to answer

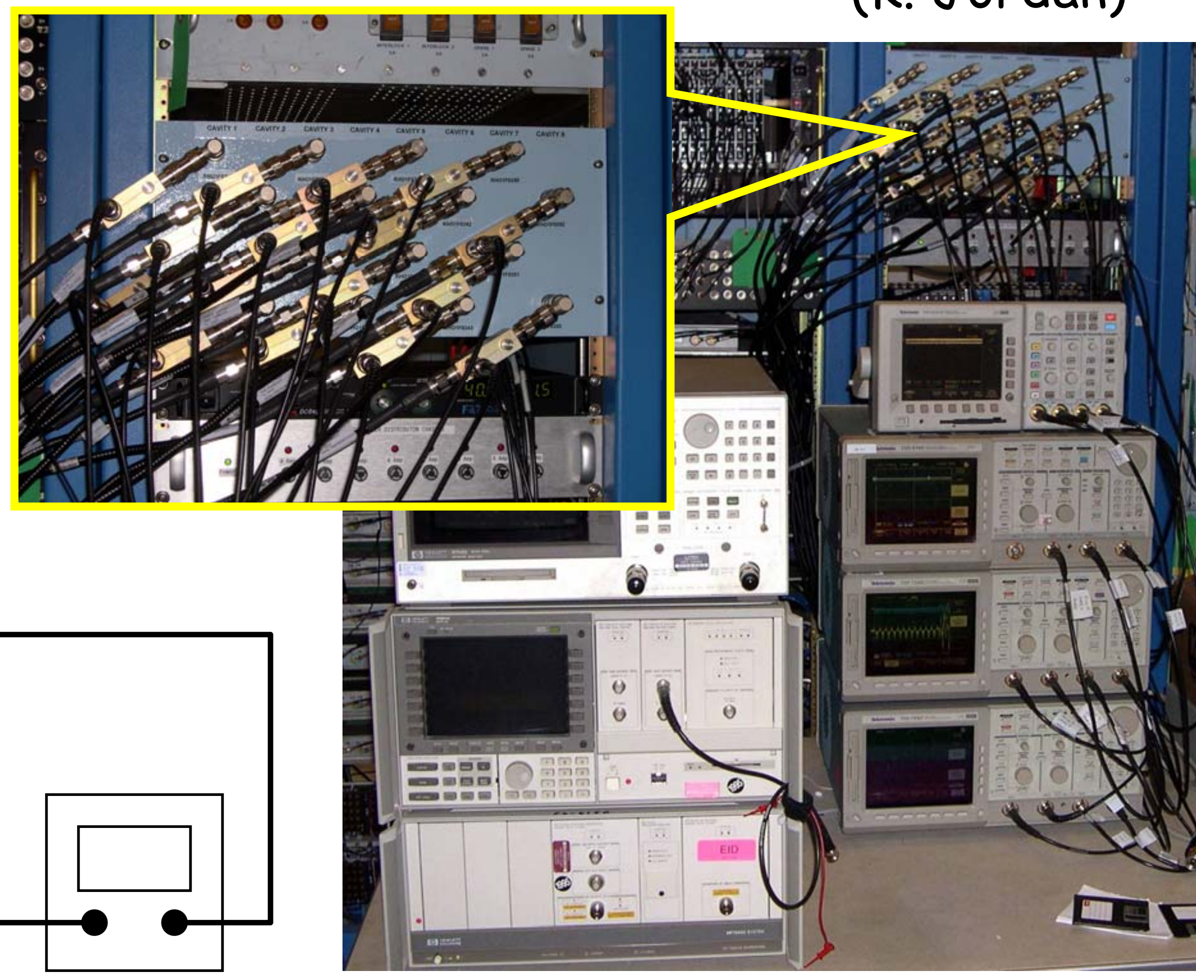
- How well do the model and simulations describe the BBU and the beam behavior
- Can we experimentally measure (predict) the BBU threshold doing measurements below the threshold
- Can we suppress BBU (C. Tennant, next talk)

Direct observation of the BBU threshold

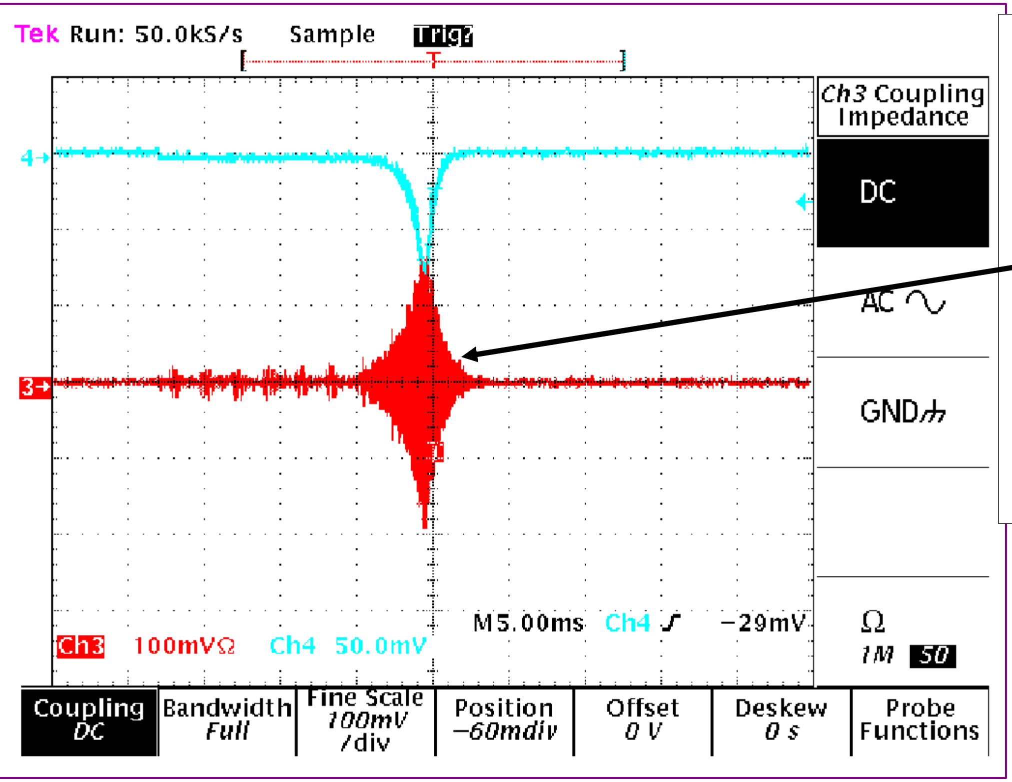
Schottky diodes where used to measure HOM power from the HOM ports.

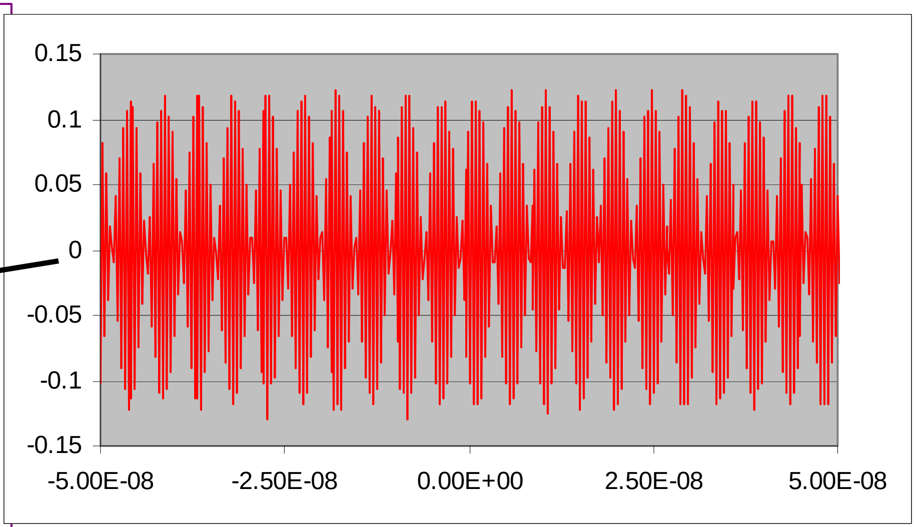
(K. Jordan)





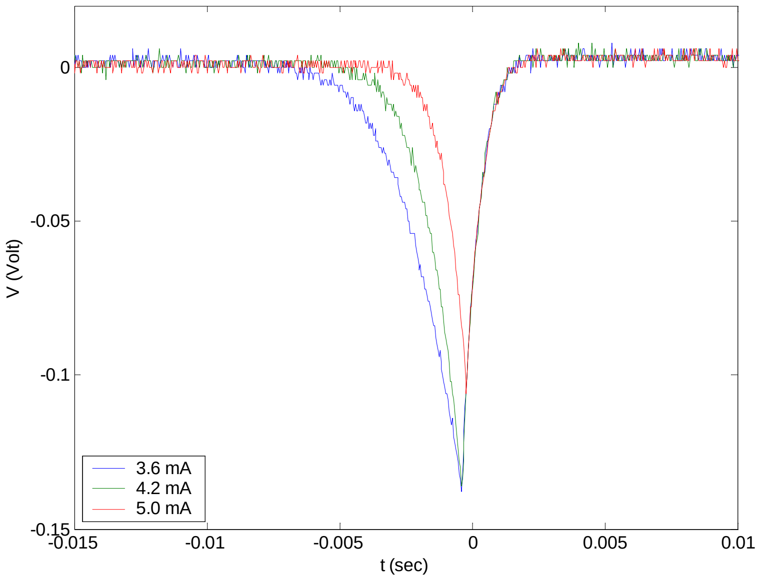
Direct observation of the BBU threshold



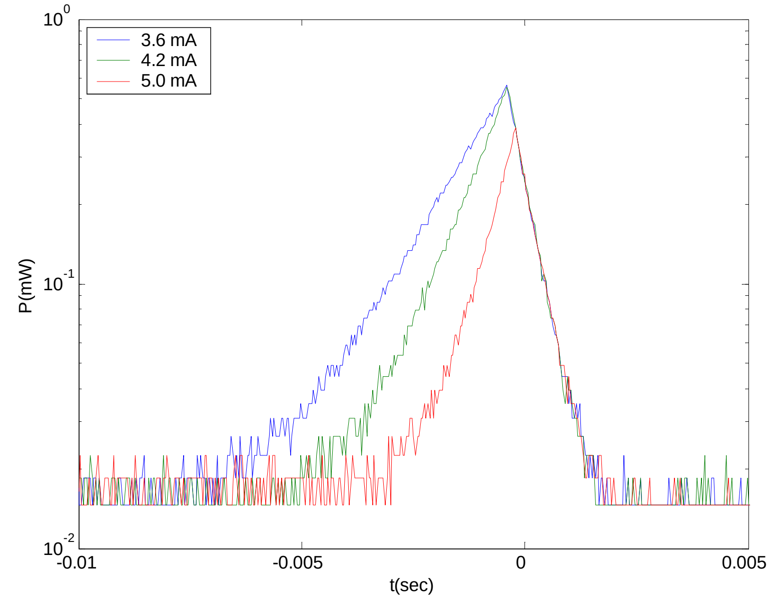


Cav 7, F_{hom}=2106 MHz, Ith=2.7 mA

HOM voltage growth rate measurements

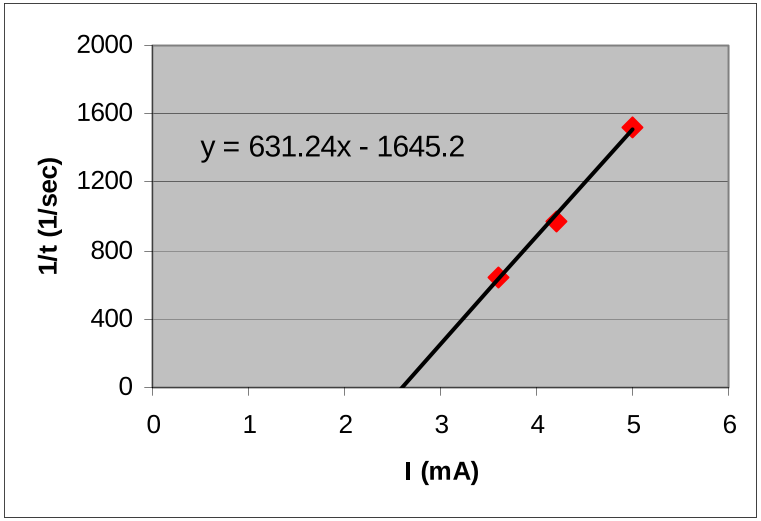


invert
+
adjust
+
log

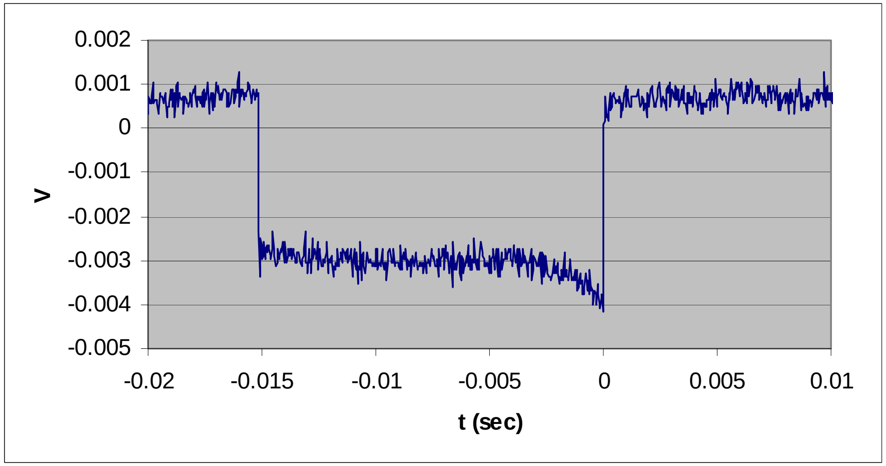


$$\tau_{eff} = \tau_0 \frac{I_{th}}{I_{th} - I}$$

Cav 7, F_{hom}=2106 MHz,
Ith=2.61 mA



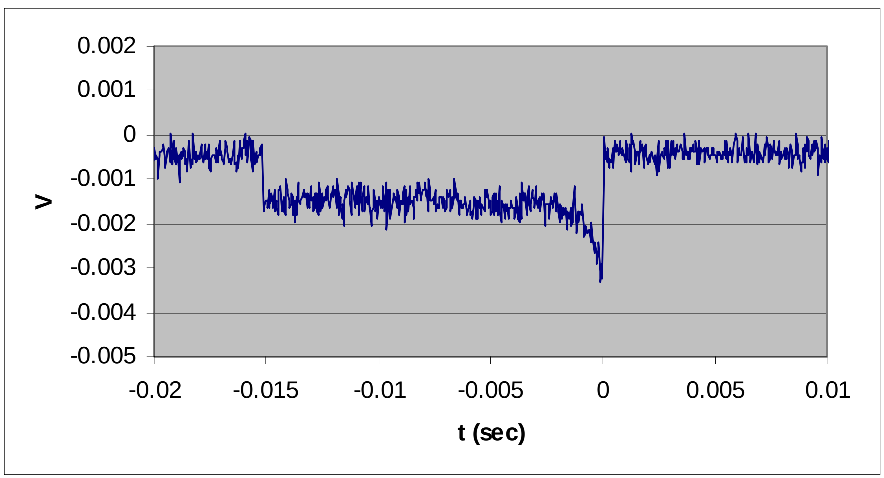
What about other HOMs?



I=5mA

Cav. 3, F=1786.206

BTF measurements: the HOM is very far from the threshold (BTF-predicted I_{th}=34 mA)

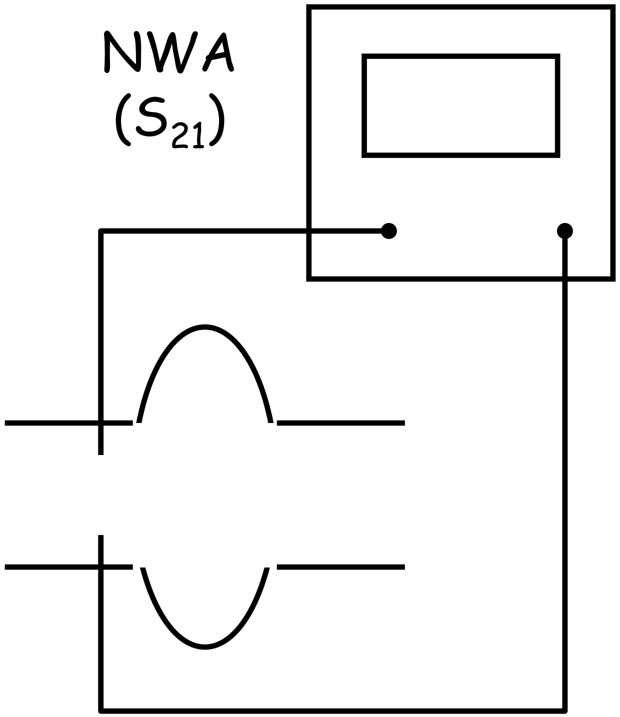


Cav. 8, F=1881.481

BTF measurements inconclusive. Cross-talk prevented us from taking accurate BTF data.

We are not sure what causes this voltage rise

Beam Transfer Function (BTF) measurements



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

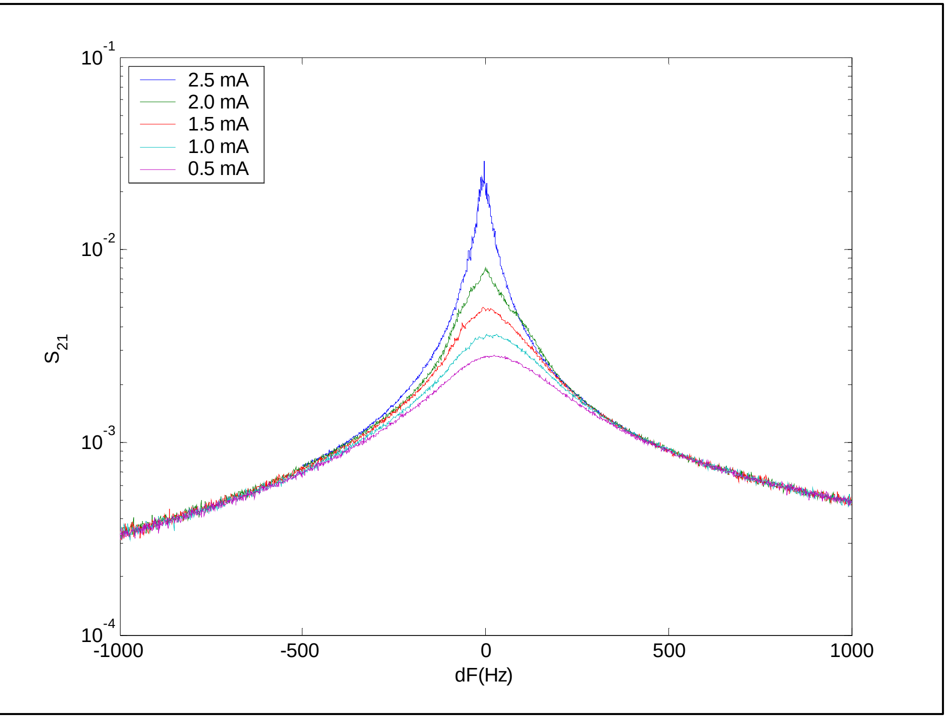
$$Q_{eff} = Q_L \frac{I_{th}}{I_{th} - I}$$

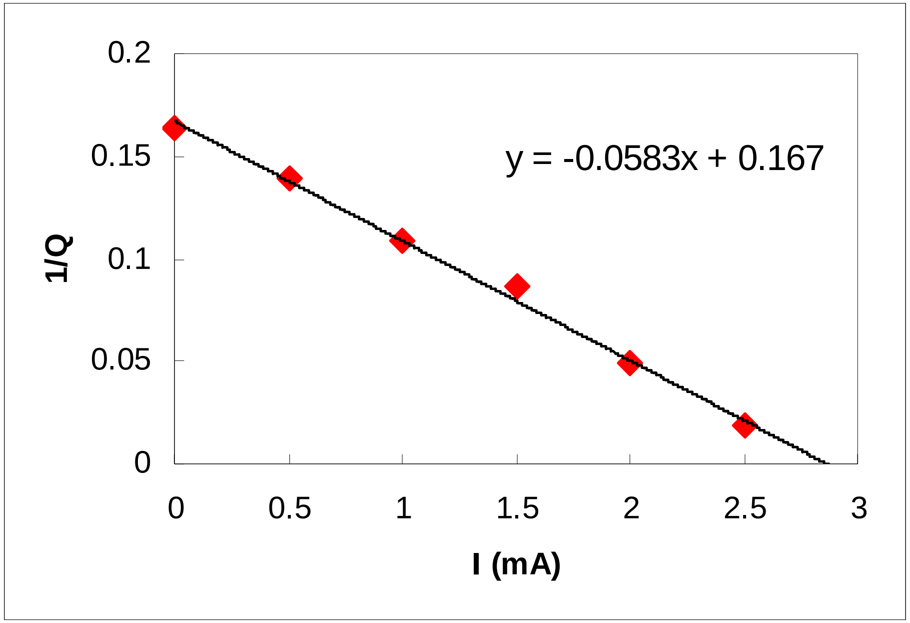
one can predict the BBU threshold below the threshold.

Port-to-port BTF:
+'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

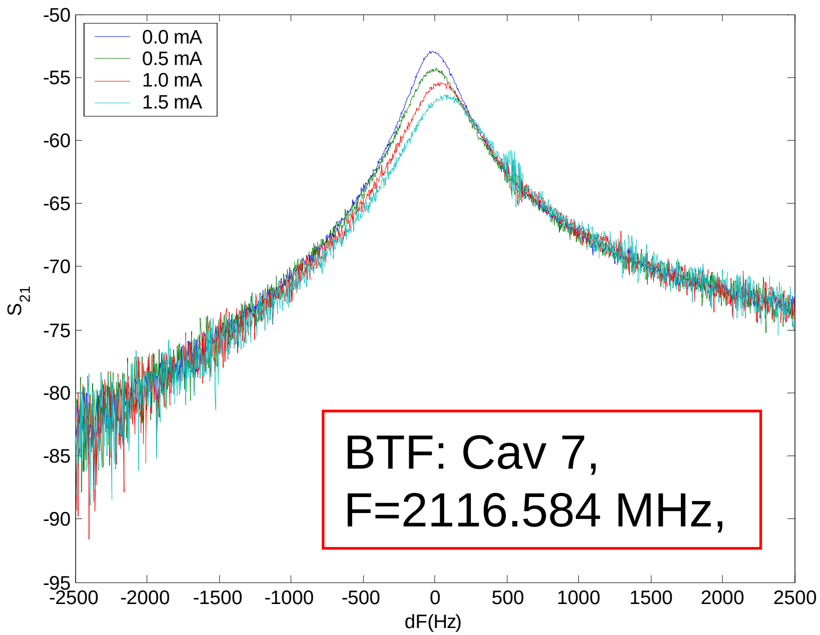


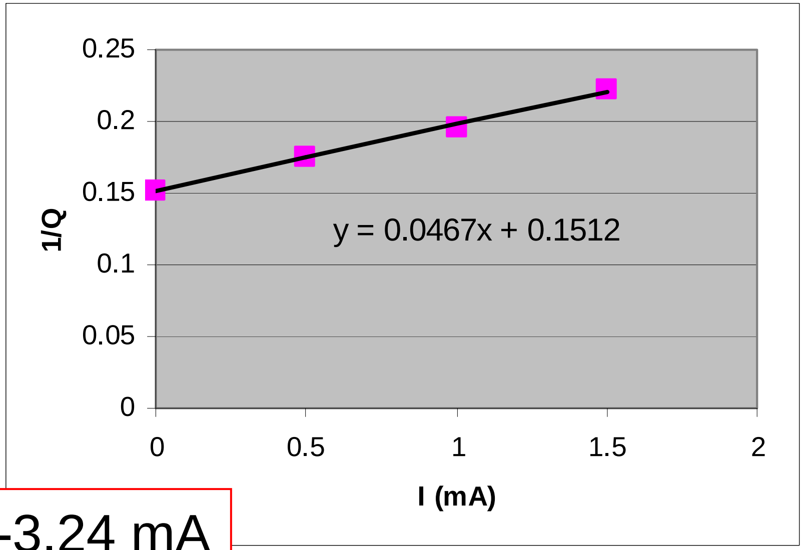


Projected threshold current is 2.86 mA

The "pseudo"-stable region ($m_{12}\sin(\omega T_r)>0$)

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





I_{th}=-3.24 mA

For $m_{12}\sin(\omega T_r)>0$, BBU still can happen at very high currents (~10A).
(J. Bisognano, G. Krafft, S. Laubach (1987), Hoffstaetter, Bazarov (2004))

Comparison to simulations and the threshold formula

May 2004: TDBBU, MATBBU, ERLBBU simulations:
Simulated threshold 2.7 mA, Measured threshold 2.5 mA

Dave Douglas' optics file (Nov.2004) with "All Save" quadrupole values

			Formula	Measured
Cavity	f_{hom}(mA)	Orientation	I_{th} (mA)	I_{th} (mA)
7	2106	Y	2.5	2.7
7	2116.58	Y	-3.1	-3.1
4	2114.15	X	-27	-9.5
3	1786.2	X	156	34

(C. Tennant)

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).

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

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

(This formula can fail for extremely high currents or/and larger accelerators)

- Measuring the Q 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.

Conclusions and Plans

- Programs TDBBU, MATBBU, and ERLBBU accurately predicted the threshold in the JLab FEL Upgrade. More work is needed for accurate comparison of the experimental data to simulations.
- Measurement of HOM polarization and betatron coupling 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

Acknowledgements

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Single-pass ERL