Studies of the Regenerative BBU Instability at the JLab FEL Upgrade

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CASA Seminar

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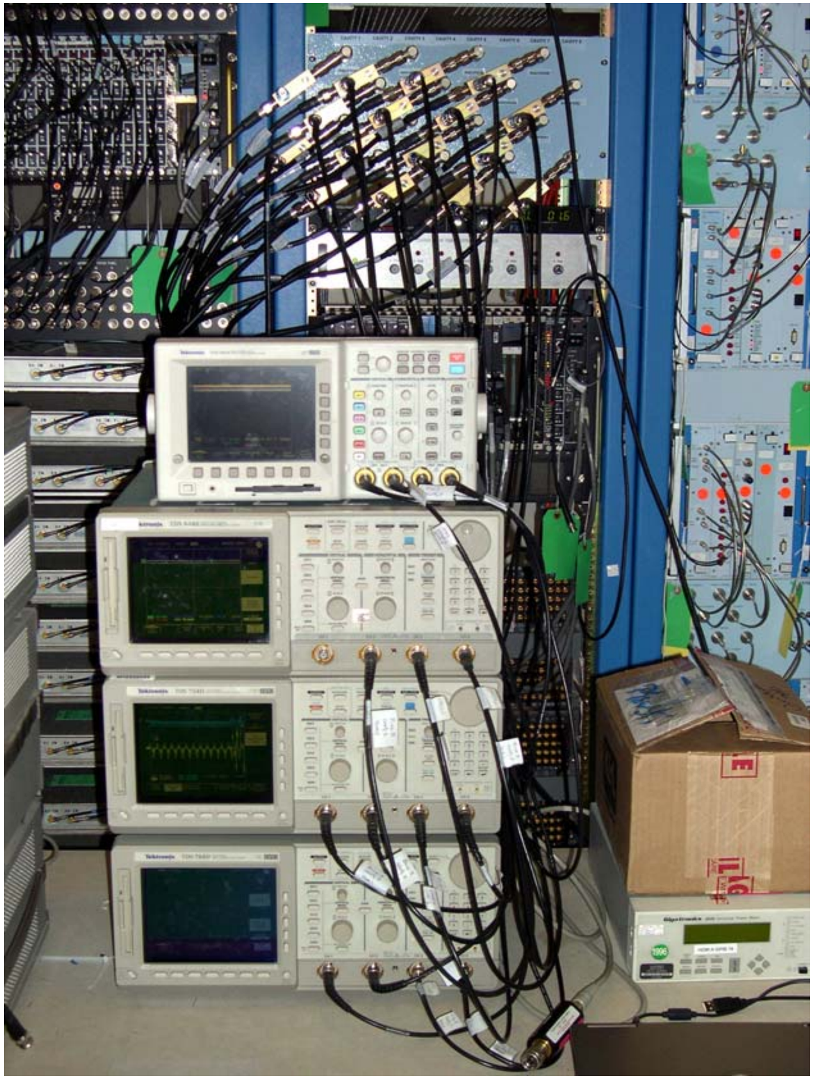
Outline

- **Methods of BBU Suppression**
- **Beam Optical Schemes**
  - Theory
  - Experimental
    - ✓ *Phase trombone*
    - ✓ *Pseudo-Reflector*
- ***Q*-Damping Schemes**
  - Active damping circuit
  - 3-Stub tuner
- **Summary and Future Plans**



Analytic Model for Multipass BBU

- For the case of a two-pass ERL with a single cavity, containing a single HOM the equation for the BBU threshold current is given by

$$I_{threshold} = -\frac{2V_{beam}}{M^{*}k(R/Q)Q\sin(\omega T_{recirc})}$$

$$M^{*} \equiv M_{12}\cos^{2}\alpha + (M_{14}+M_{32})\sin\alpha\cos\alpha + M_{34}\sin^{2}\alpha$$

- ✓ Inject at higher energy
- ✓ Change HOM frequency
- ✓ Change recirculation time
- ✓ Damp HOM quality factor
- ✓ Alter beam optics
  - Change phase advance
  - Reflect betatron planes
  - Rotate betatron planes

where V_{beam} is the beam voltage at the cavity, k is the wavenumber (ω/c) of the HOM, $(R/Q)Q$ is the shunt impedance, T_{recirc} is the recirculation time and the M_{ij} are the elements of the recirculation transport matrix

Effect of Reflecting Optics

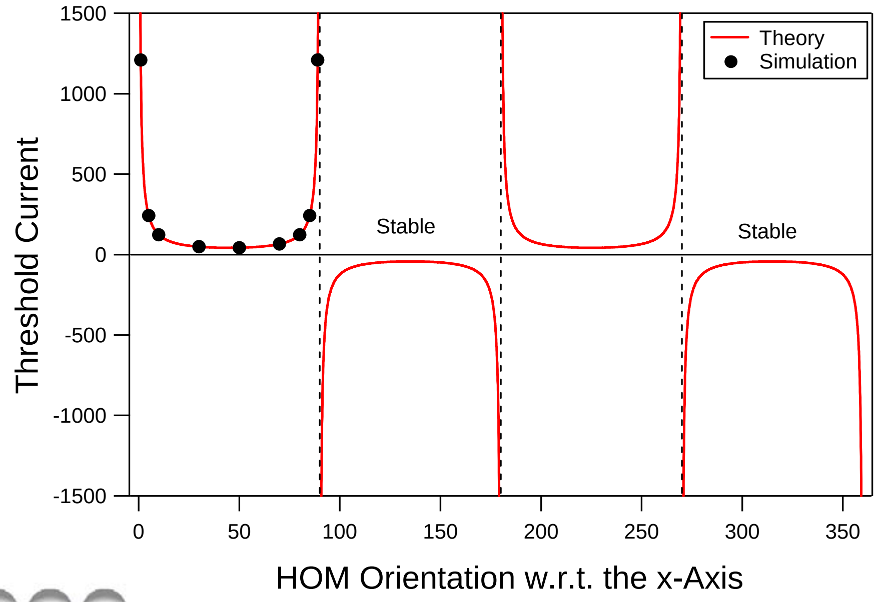
Recall… $$I_{threshold} \propto -\frac{1}{M_{12}\cos^2\alpha + (M_{14}+M_{32})\sin\alpha\cos\alpha + M_{34}\sin^2\alpha}$$

I. Reflecting Optics will Suppress BBU if…

I. The transfer matrix from an unstable cavity back to itself takes the form

$$\begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix} \rightarrow \begin{matrix} M_{12} = M_{34} = 0 \\ M_{14} = M_{32} \end{matrix}$$

II. The HOMs are oriented at either 0 or 90 degrees $\rightarrow$ $\sin\alpha\cos\alpha = 0$



If α is different from 0 or 90 degrees, the effectiveness of reflecting optics in BBU suppression rapidly diminishes.

Effect of Rotating Optics

Recall… $$I_{threshold} \propto -\frac{1}{M_{12}\cos^2\alpha + (M_{14}+M_{32})\sin\alpha\cos\alpha + M_{34}\sin^2\alpha}$$

II. Rotating Optics will Suppress BBU if…

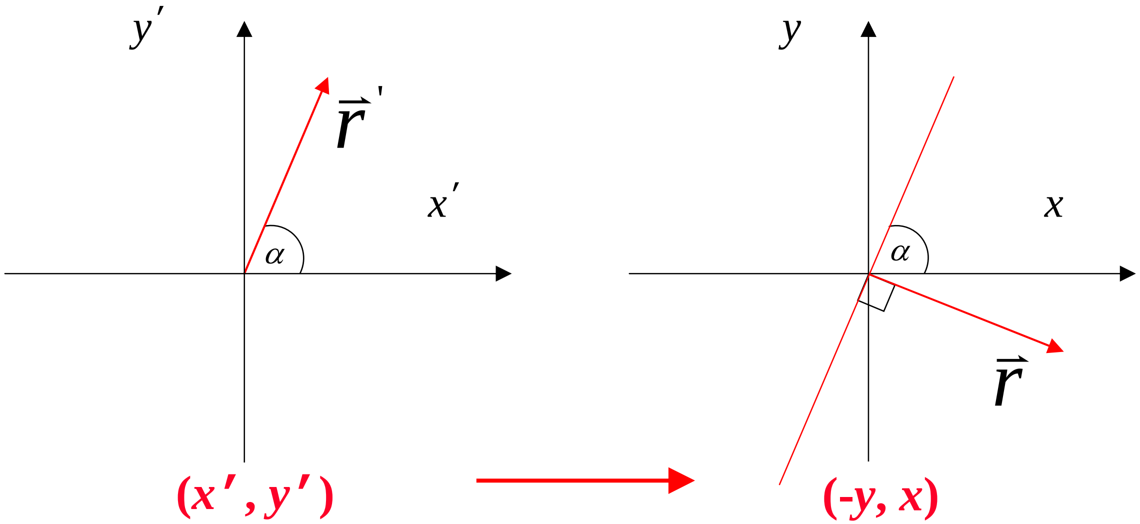
I. The transfer matrix from an unstable cavity back to itself takes the form

$$\begin{pmatrix} 0 & M \\ -M & 0 \end{pmatrix} \rightarrow \begin{aligned} M_{12} &= M_{34} = 0 \\ M_{14} &= -M_{32} \end{aligned}$$

A rotation is effective regardless of the orientations of the HOMs

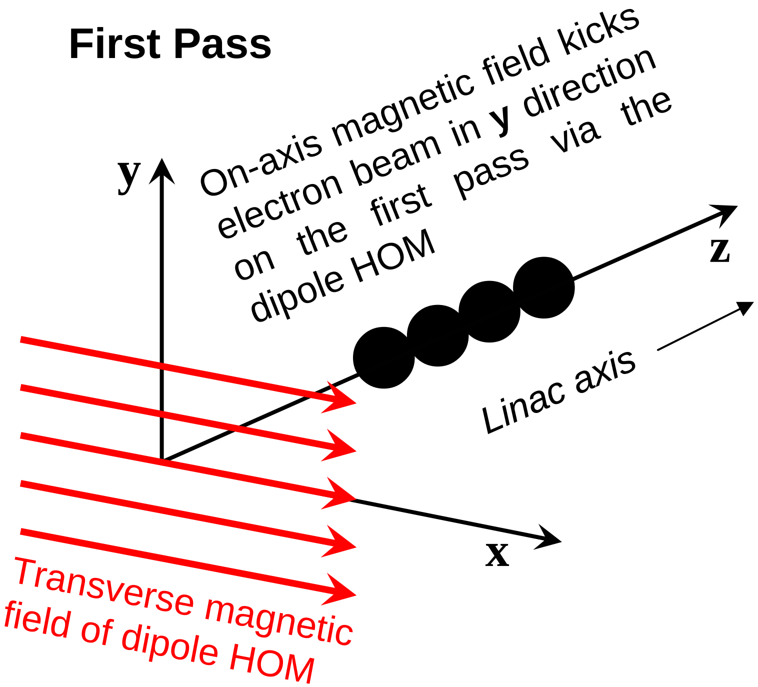
First pass
The offending mode imparts an angular deflection, α, to a bunch

Second pass *(after rotation)*
The resultant displacement will be **orthogonal** to the offending HOM. The bunch will be unable to couple energy to the mode that caused the deflection.



Beam Optical Control of BBU

First Pass

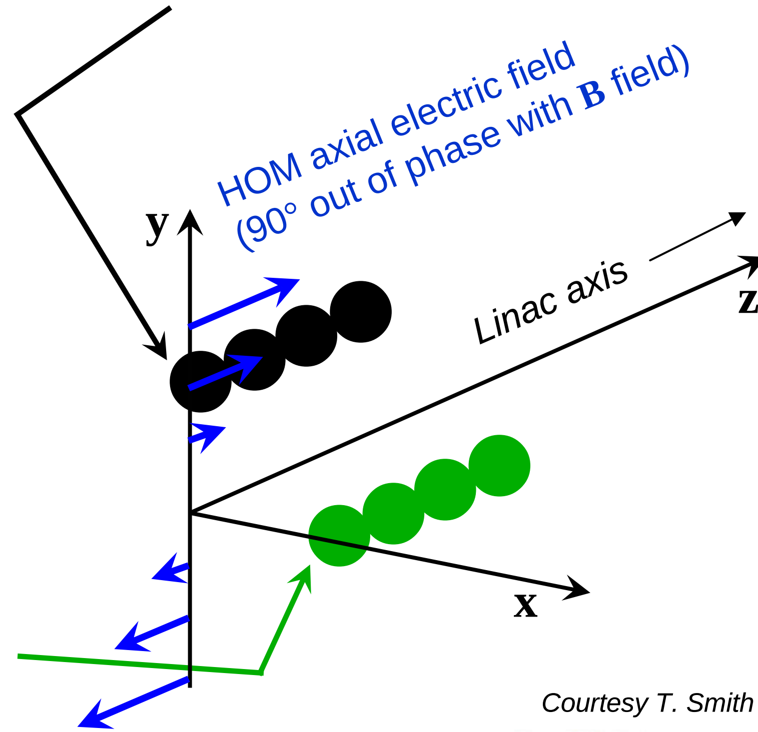


Second Pass: Nominal Optics

The **y** kick results in a **y** displacement on the second pass through the cavity. This puts the electrons in a region of longitudinal field and they can deposit energy into the HOM field

Second Pass: 90° Rotated Optics

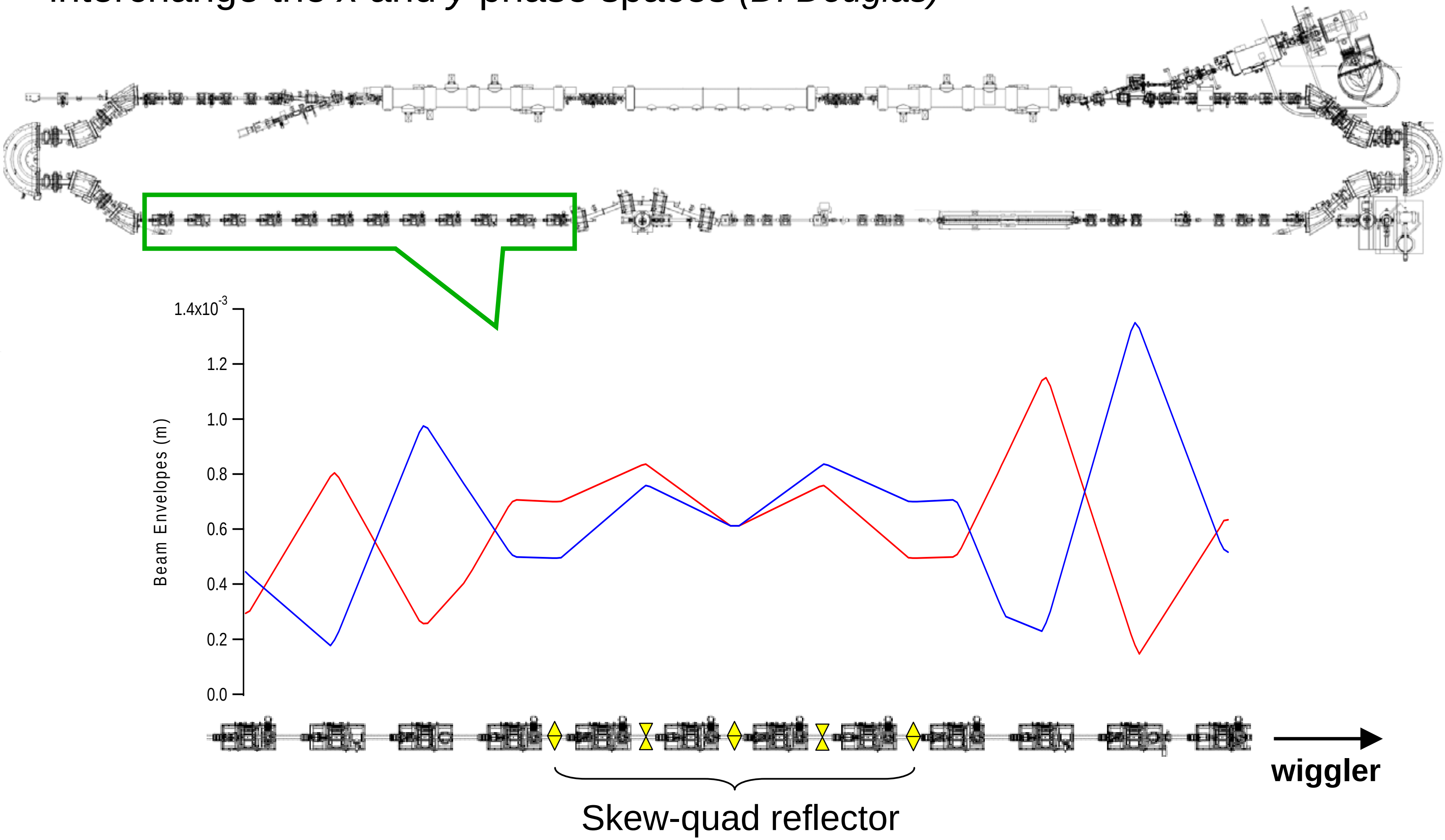
The **y** kick results in an **x** displacement on the second pass through the cavity. The bunches are in a region of zero longitudinal field and they **cannot** give energy to the HOM field. *The feedback between the beam and HOM has been broken!*



Courtesy T. Smith (HEPL)

Skew-Quadrupole Reflector in the FEL

- 5 skew-quadrupoles were installed in the backleg of the FEL to (*locally*) interchange the *x* and *y* phase spaces *(D. Douglas)*



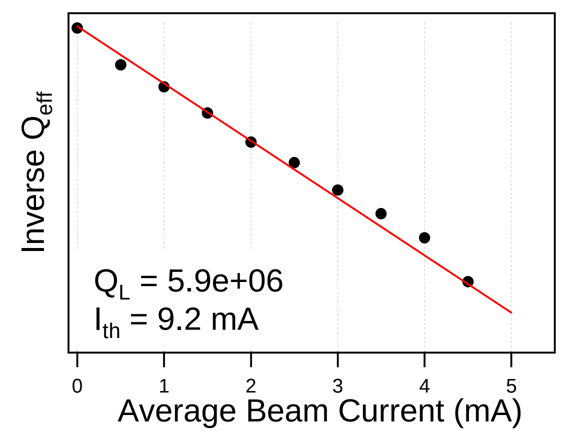
Local Reflector

- With the reflector activated, we also investigated the stability of several other potentially dangerous HOMs

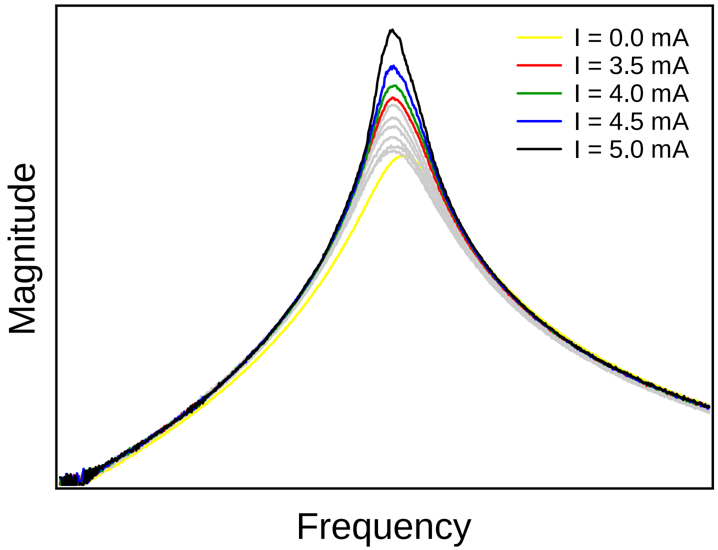
Frequency (MHz)	Loaded Q	(R/Q) (Ω)	Threshold Current (mA)	Orientation	Location
2102.607	2.61×10^6	29.90	7.07	x-axis	Cavity 8
2104.683	1.94×10^6	29.90	7.86	x-axis	Cavity 5
2106.007	6.11×10^6	29.90	2.85	y-axis	Cavity 7
2114.156	5.21×10^6	28.80	3.68	x-axis	Cavity 4
2115.201	2.17×10^6	28.80	8.28	y-axis	Cavity 6
2116.055	3.06×10^6	28.80	4.99	x-axis	Cavity 1
2116.585	6.66×10^6	28.80	4.18	x-axis	Cavity 7

Table 3: Summary of the MATBBU simulation showing mode properties of those HOMs which are predicted to produce threshold currents below 10 mA.

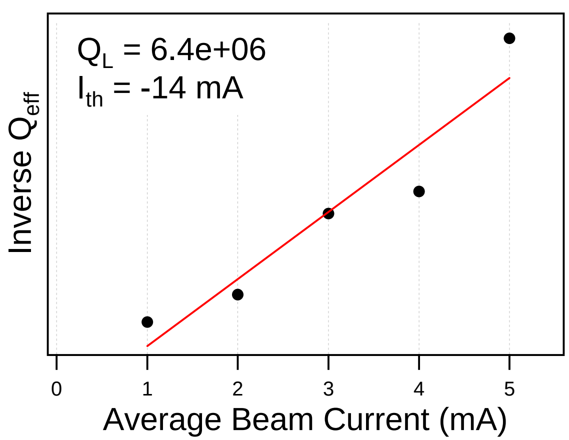
2106 MHz in Cavity 7



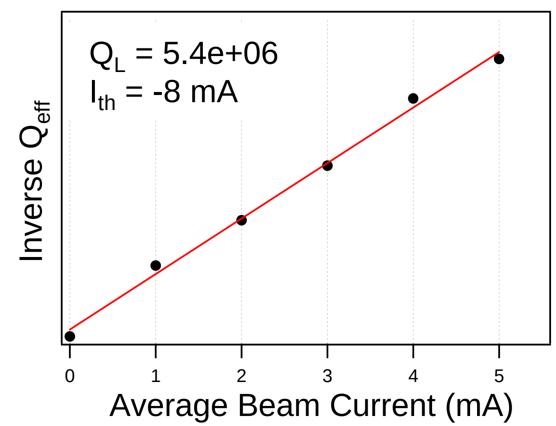
BTF of 2106 MHz with Reflector ON



2116 MHz in Cavity 7



2114 MHz in Cavity 4



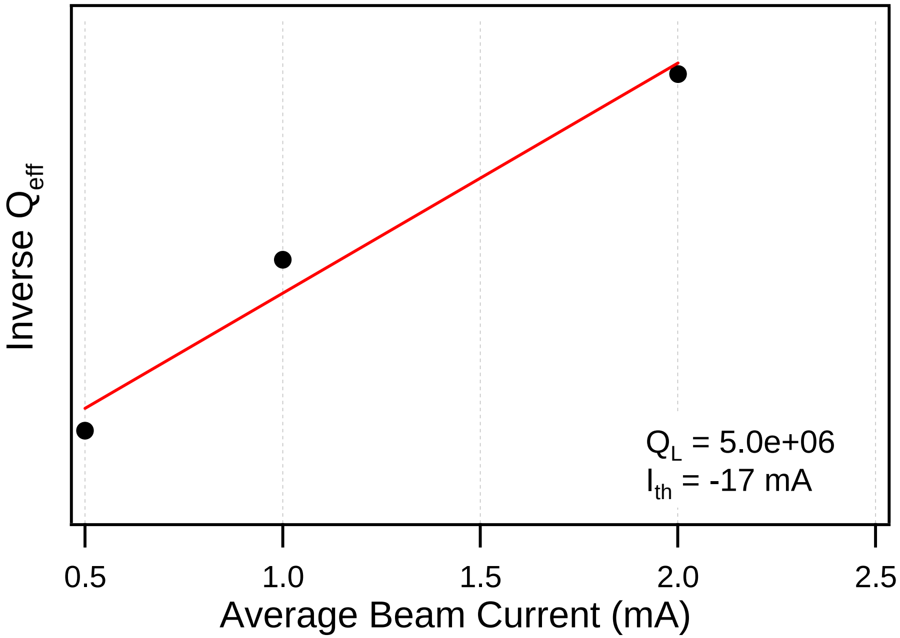
Local Reflector with a Change in Phase Advance

- Ideally we would like to create a pure 90 degree rotation from the unstable cavity back to itself

- Can you create a "*global*" rotation with a "*local*" reflector?
- **Yes**. By decreasing the vertical phase advance and then activating the local reflector, you can create a 90 degree rotation from the middle of Zone 3 back to itself *(D. Douglas)*.

- For our measurements, the vertical phase advance was changed. Only after the difference orbit measurements have been analyzed, will we know what kind of transfer matrix was generated with this change in phase advance…

2106 MHz with Reflector ON and Phase Advance Changed



Because of the limited time setting up this configuration, the transmission was not good.

What BBU "Looks Like"

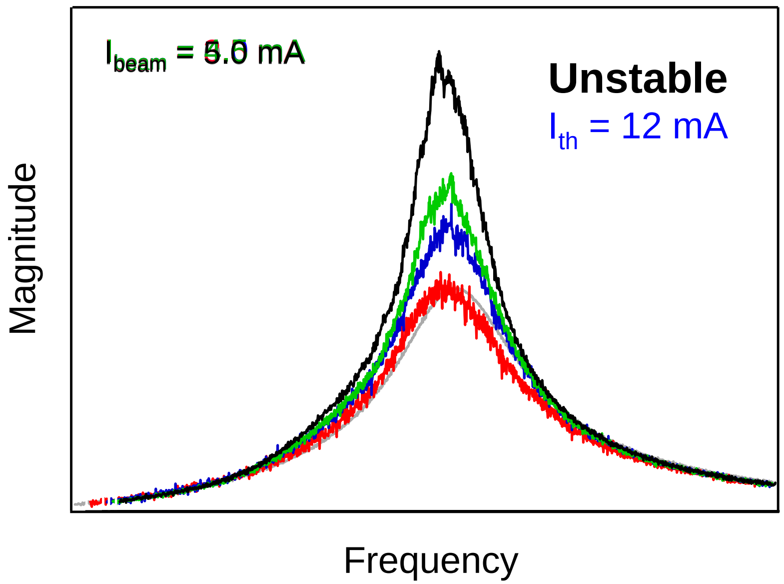
PLAY

Phase Trombone

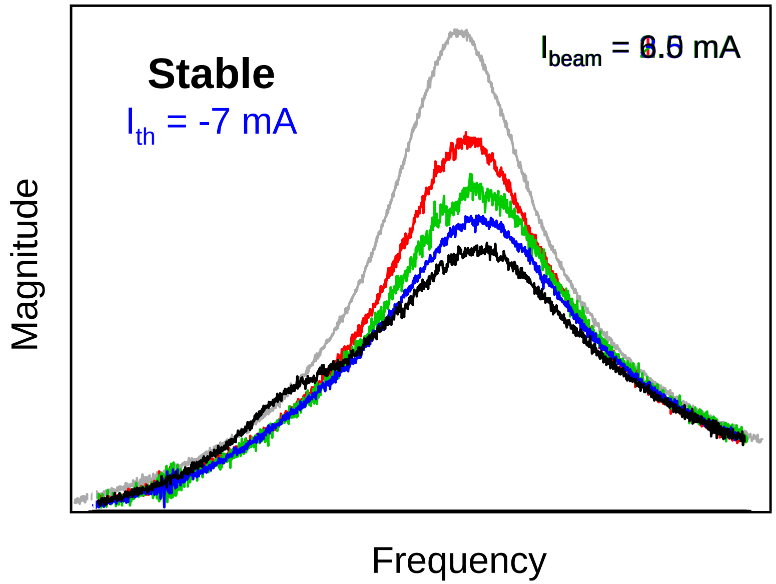
Recall… $I_{threshold} \propto \dfrac{1}{M_{12,(34)}}$

- By all indications the 2106 MHz HOM is a *vertically* polarized mode
- We change 4 vertically focusing quadrupoles in the recirculator to vary the vertical phase advance

Quads changed +200 G



Quads changed +300 G

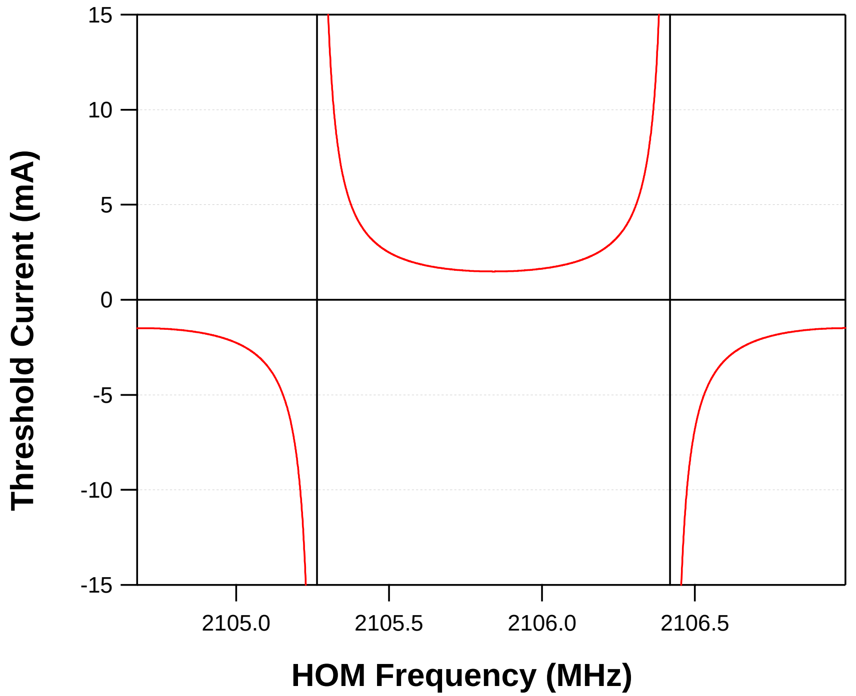


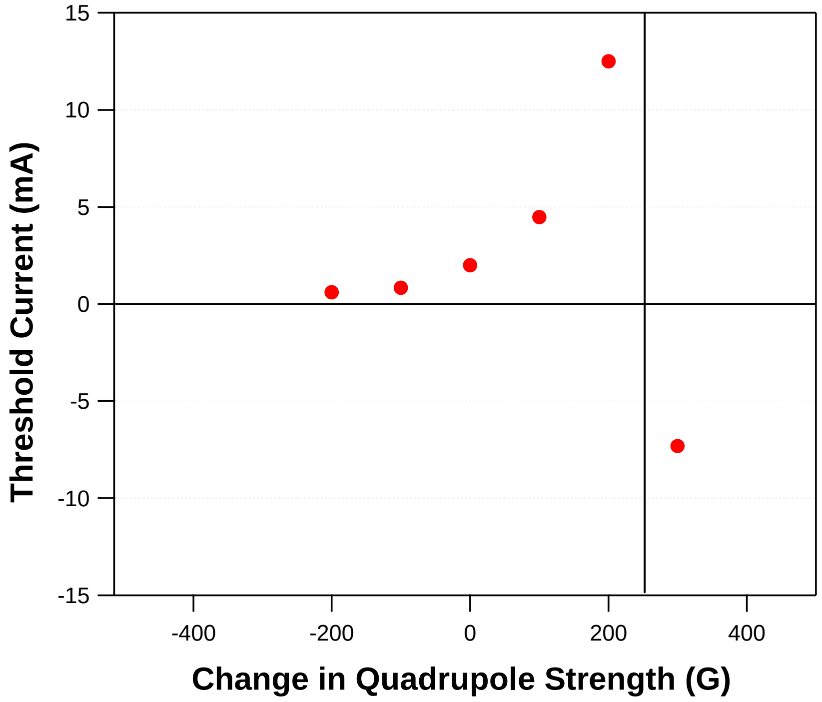
Phase Trombone (cont'd…)

- We were able to easily change the quadrupole strengths from their nominal settings from -200 G to +300 G
- We observe a (1/*sin*) trend in the threshold current from measurements

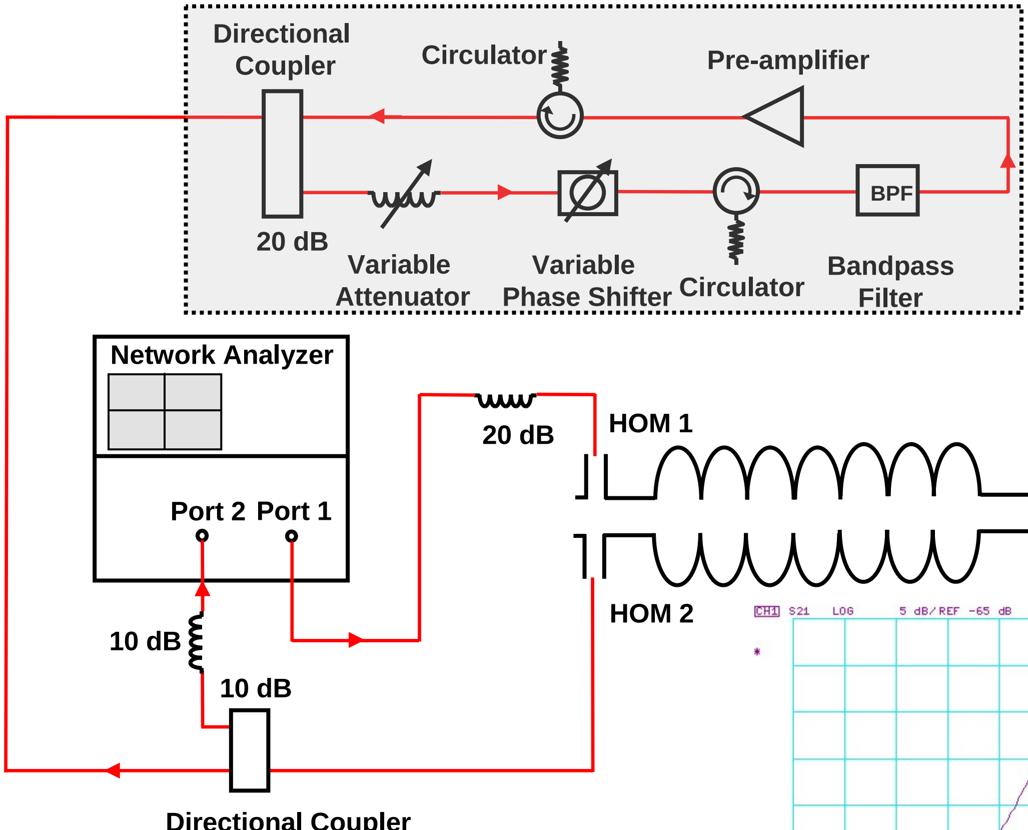
$$I_{threshold} \propto \frac{1}{M_{34}\sin(\omega_{HOM}T_r)}$$

$$I_{threshold} \propto \left[\frac{1}{\sin(\omega_{HOM}T_r)}\right]\frac{1}{\sqrt{\beta_1\beta_2}\,\sin(\Delta\psi)}$$





Q-Damping Circuit



Concept: couple power from one of the HOM ports, shift it 180 degrees in phase, amplify the signal and feed it back through the same HOM port.

"Tuning Knobs": the circuit is optimized by carefully tuning the phase and gain of the feedback loop

Active damping of an HOM located at 2106 MHz. The effect of the damping (right picture) is to **decrease the loaded *Q* by a factor of ~ 10**.

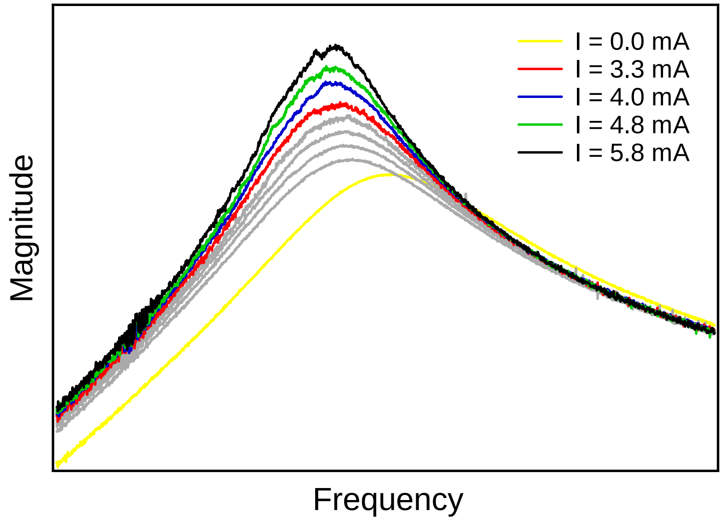
Q-Damping Circuit (cont'd…)

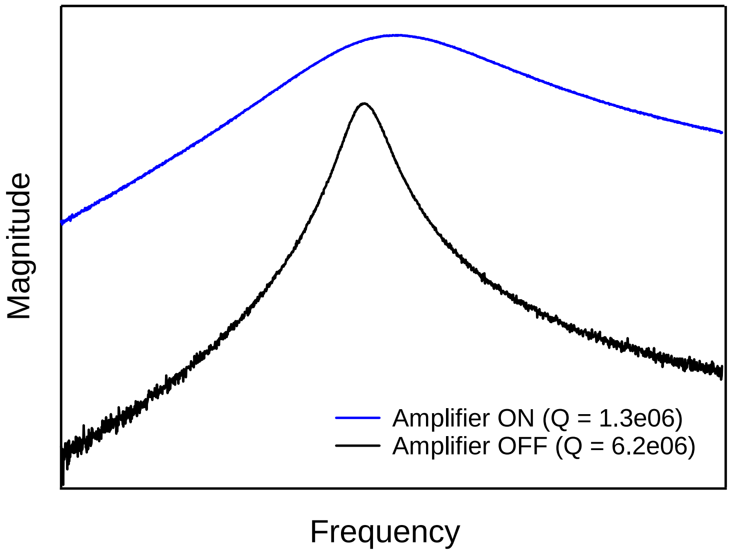
Recall… $I_{threshold} \propto \dfrac{1}{Q_{HOM}}$

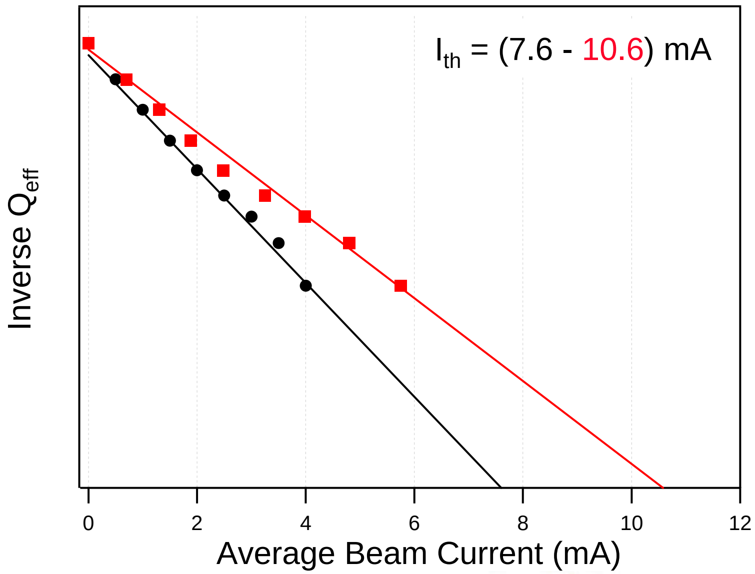
- Damping circuit easily reduced the *Q* of the 2106 MHz mode by a factor of 5

  (Above a factor of about 10, the system becomes sensitive to external disturbances)

- The threshold is increased accordingly: from 2 mA to ~10 mA

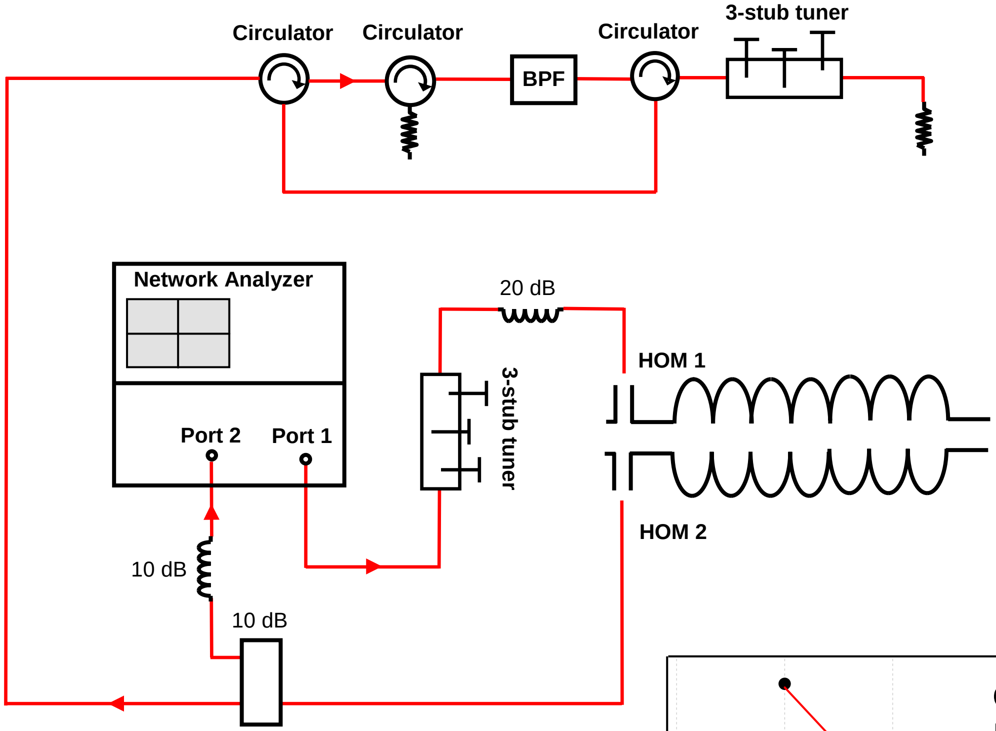


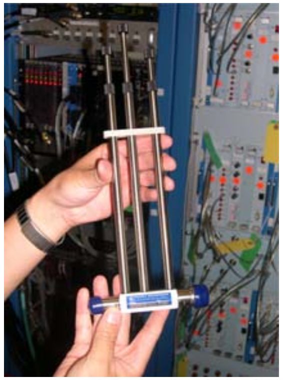


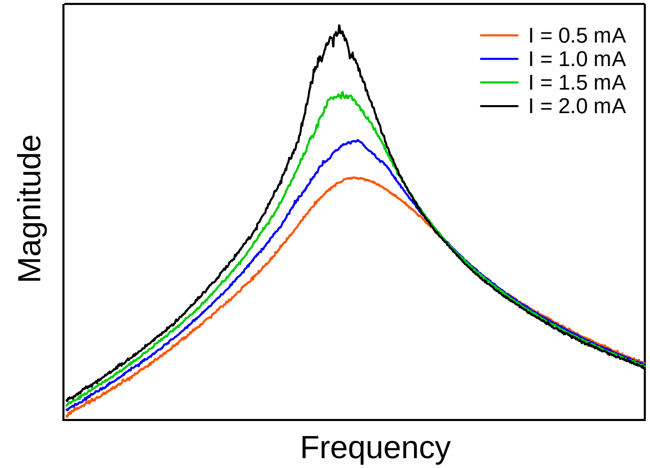


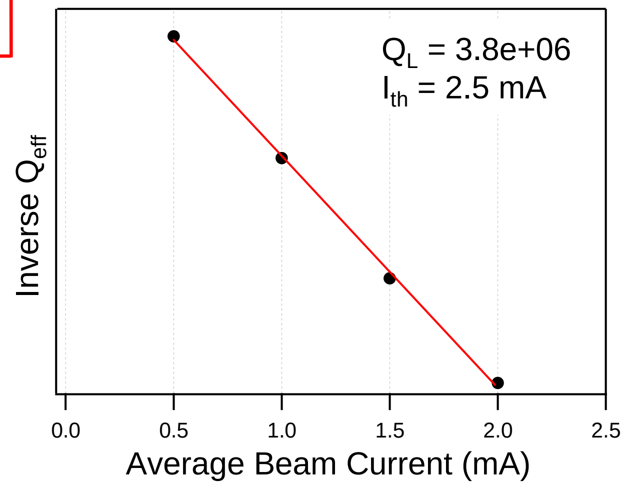
3-Stub Tuner

- The optimal setup requires a 3-stub tuner for each HOM port on the cavity
- Had a difficult time and not such great data - perhaps because of broken HOM cable from Cavity 7









Summary of Suppression Techniques

		Effect on 2106 MHz HOM	Considerations for Implementation
Q-Damping	Damping Circuit	5 x I_{th}	• Works for only *1 mode per cavity* • Not as effective at raising the threshold as beam optical methods • Long term stability of system • Does **not** effect beam optics
Q-Damping	3-Stub Tuner	1.5 x I_{th}	
Beam Optics	Phase Trombone	*Stabilized*	• Can *stabilize* the mode against BBU • What are the effects on other HOMs? • Do they prevent reaching the requirements needed for a suitable lasing configuration?
Beam Optics	Pseudo-Reflector	*Stabilized*	

Summary and Future Plans

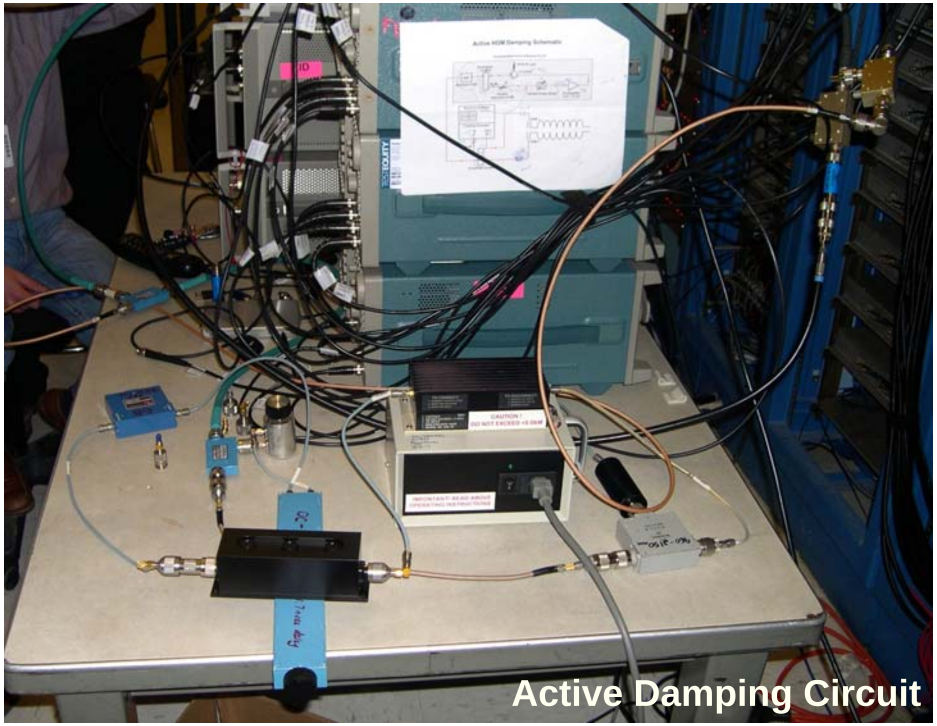
- **Summary**
  - Several methods proved to be effective at raising threshold current
  - It was demonstrated that using beam optical schemes, the dangerous HOM could *stabilized* (i.e. it can no longer cause BBU)

- **Future Plans**

Benchmark BBU Simulation Codes

- Measure HOM polarizations
- Perform BBU simulations using measured machine optics and compare with measurements

*Attempt to suppress via beam-based feedback (i.e. do not effect optics **and** stabilize the mode)*



Active Damping Circuit

Acknowledgements

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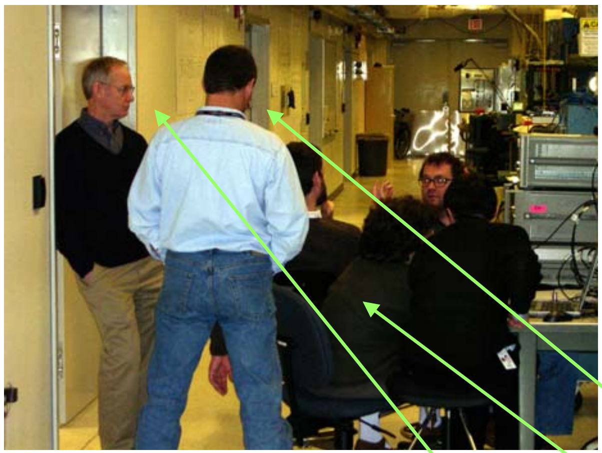

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