RHIC 56 MHz Cavity

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RHIC Retreat 2024

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Outline

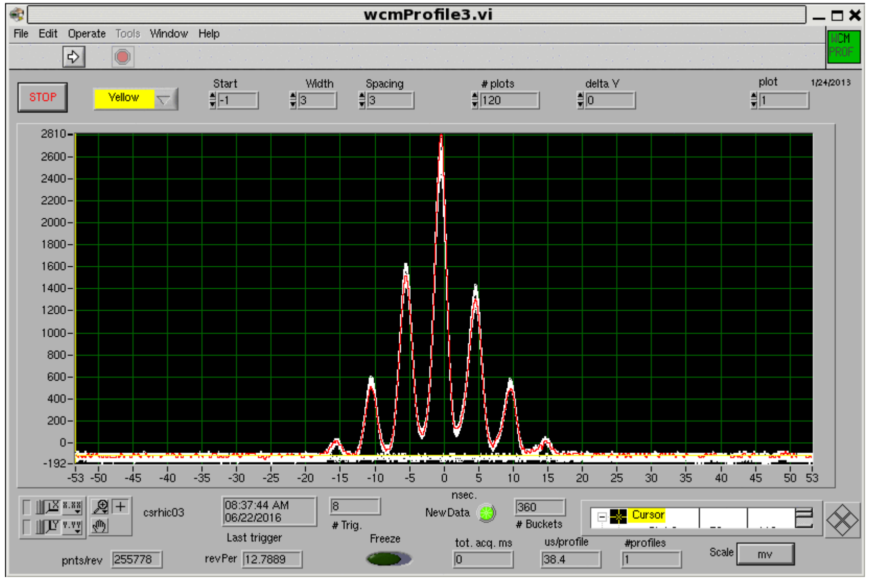
- Purpose and Intended Operation
- History
  - HOM Dampers
  - Run16
- Rework post-Run16
- Run24 Results

56 MHz Cavity Purpose

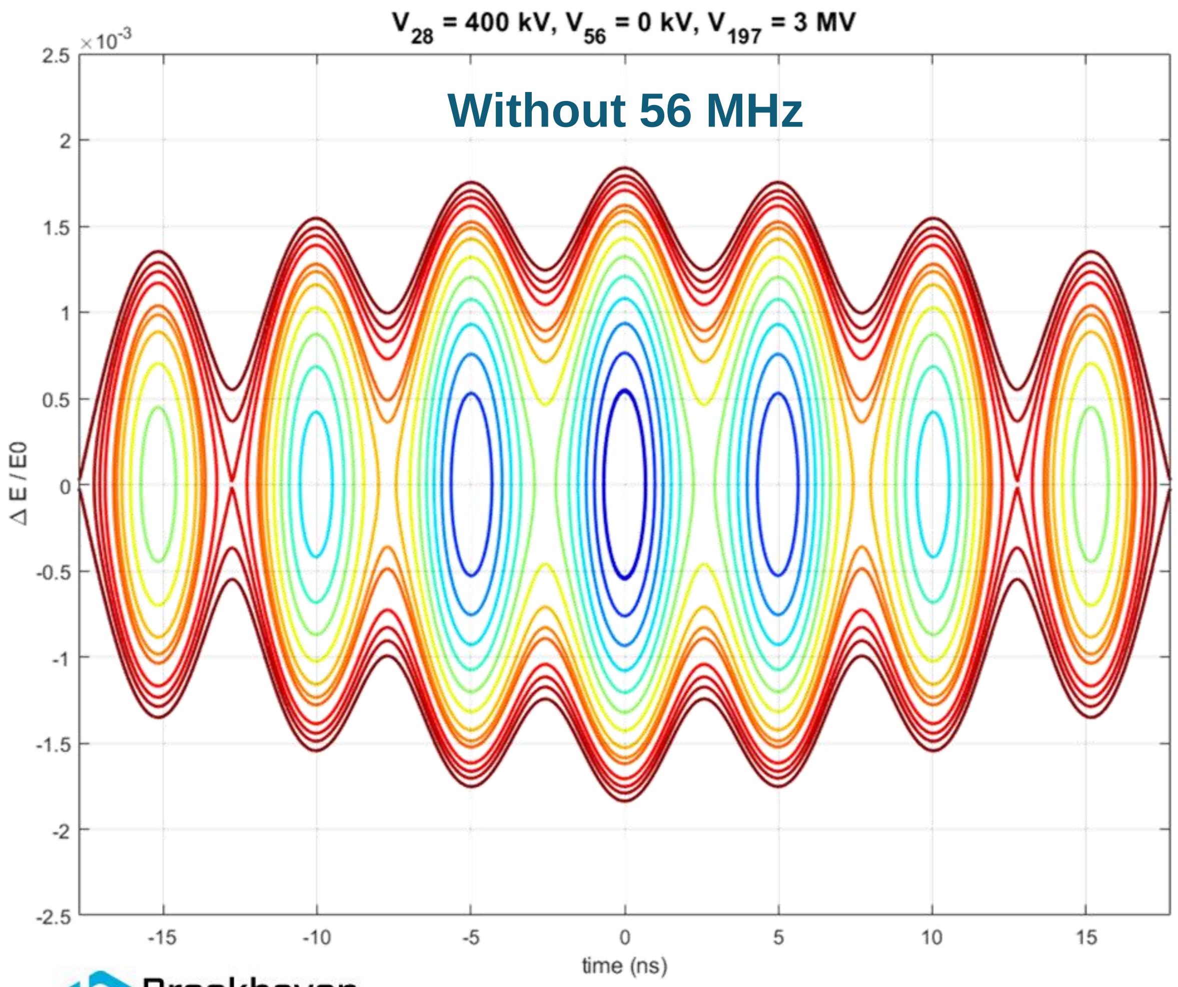
After rebucketing, beam diffuses out of the central 197 MHz bucket

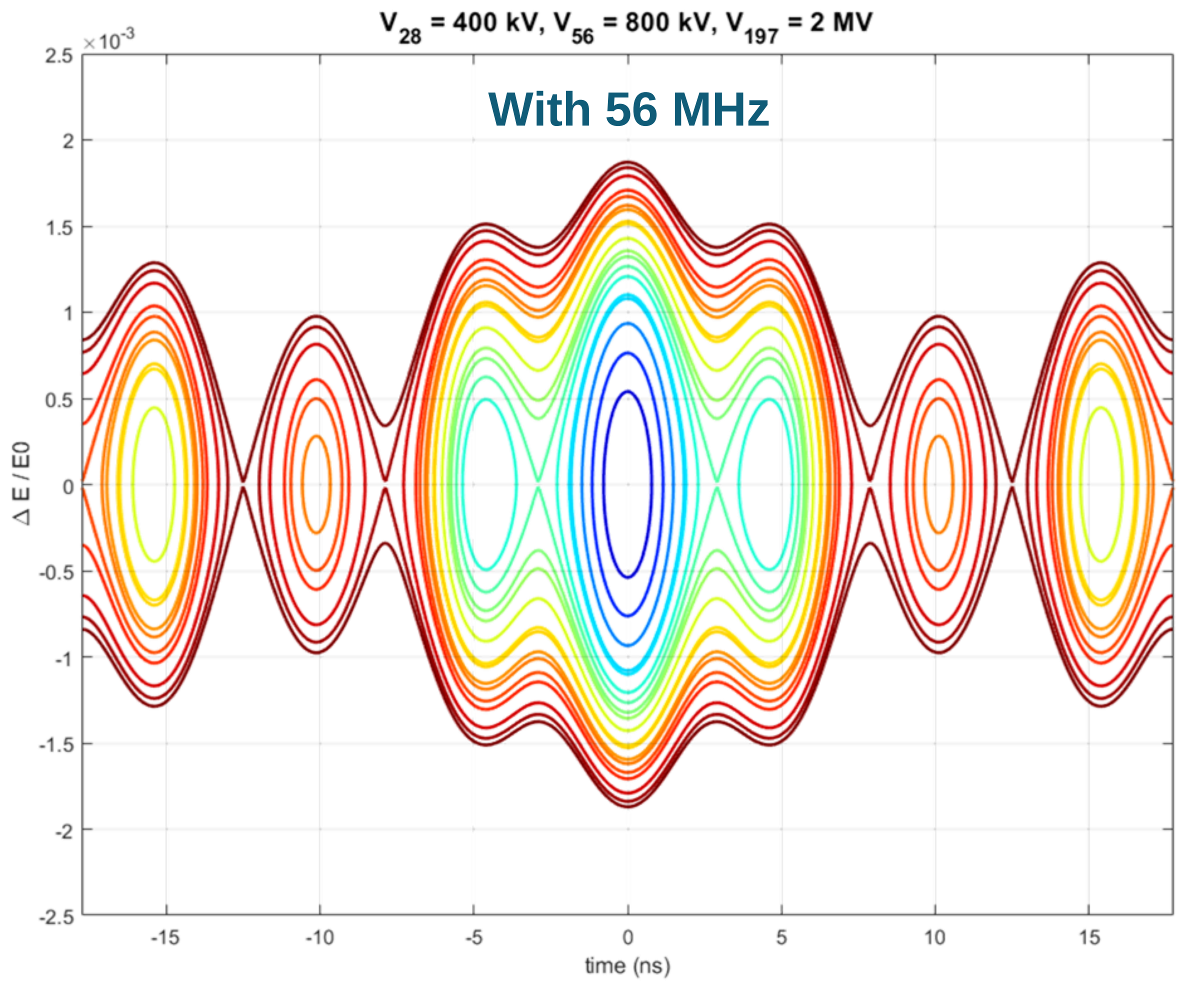
With stochastic cooling, this beam is cooled back into 197 MHz buckets, some ends up in “satellite” buckets

The 56 MHz cavity provides additional longitudinal focusing, creating a deeper potential well and minimizing diffusion to the outer satellite buckets



Longitudinal Focusing





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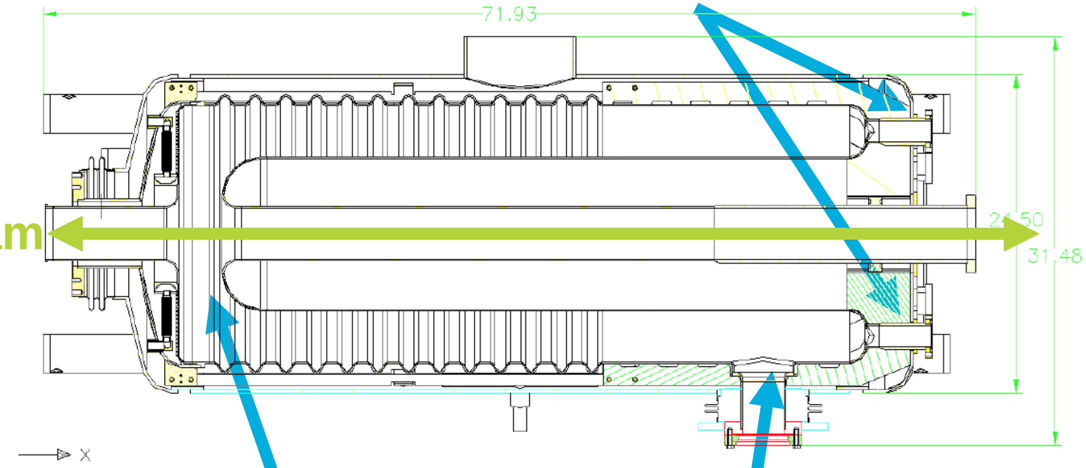
56 MHz SRF Quarter Wave Resonator

A passive* beam-driven superconducting cavity

The quarter wave ($^{\lambda}/_{4}$) structure also resonates at higher order modes (roughly $^{3\lambda}/_{4}$, $^{5\lambda}/_{4}$, $^{7\lambda}/_{4}$, etc. for longitudinal monopole modes)



* = not really passive – requires significant RF feedback to stabilize voltage

Beam Driven Cavity

Cavity fundamental voltage:

$|V_{cav}|=I_{h=720} * |Z_{cav}|_{h=720}$

On resonance, cavity impedance is large, would be too much voltage

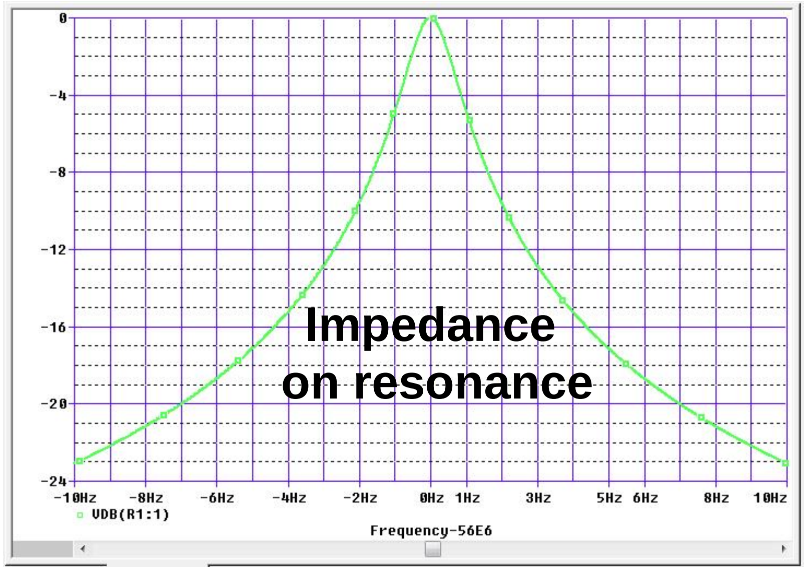
$$R_0 = {}^{R}/_{Q} \cdot Q_{ext} \approx 40 \cdot 4 \times 10^7 = 1.6 \times 10^9 \Omega$$

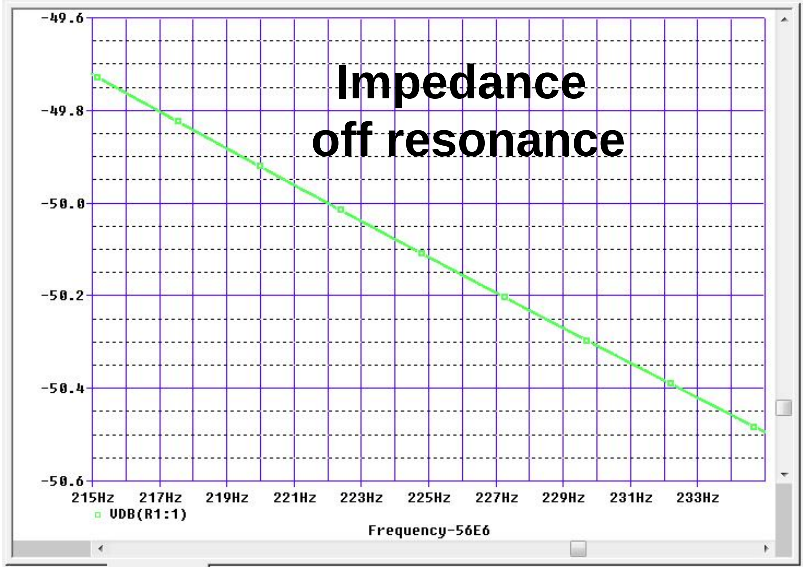
$$\Rightarrow V_{cav} \approx 800\ MV$$

Detuned cavity:

$$Z_{cav} = \frac{R_0}{1+j\frac{\Delta f}{BW_{1/2}}} \Rightarrow |Z_{cav}| \approx \frac{\left(\frac{R}{Q}\right)\cdot f_0}{2\cdot\Delta f} \text{ for } \Delta f \gg BW_{1/2}$$

Cavity detuning regulates voltage (and also gives required 90° phase shift to focus beam)





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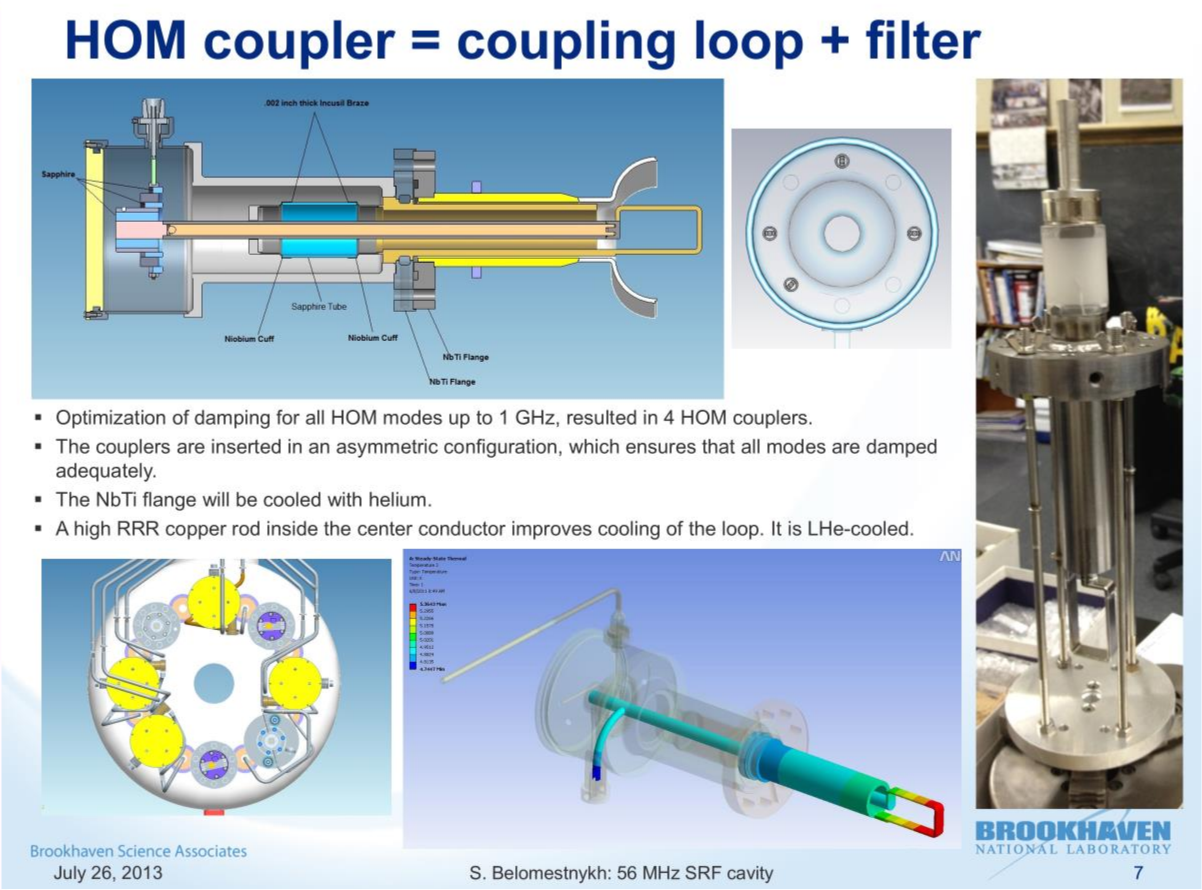
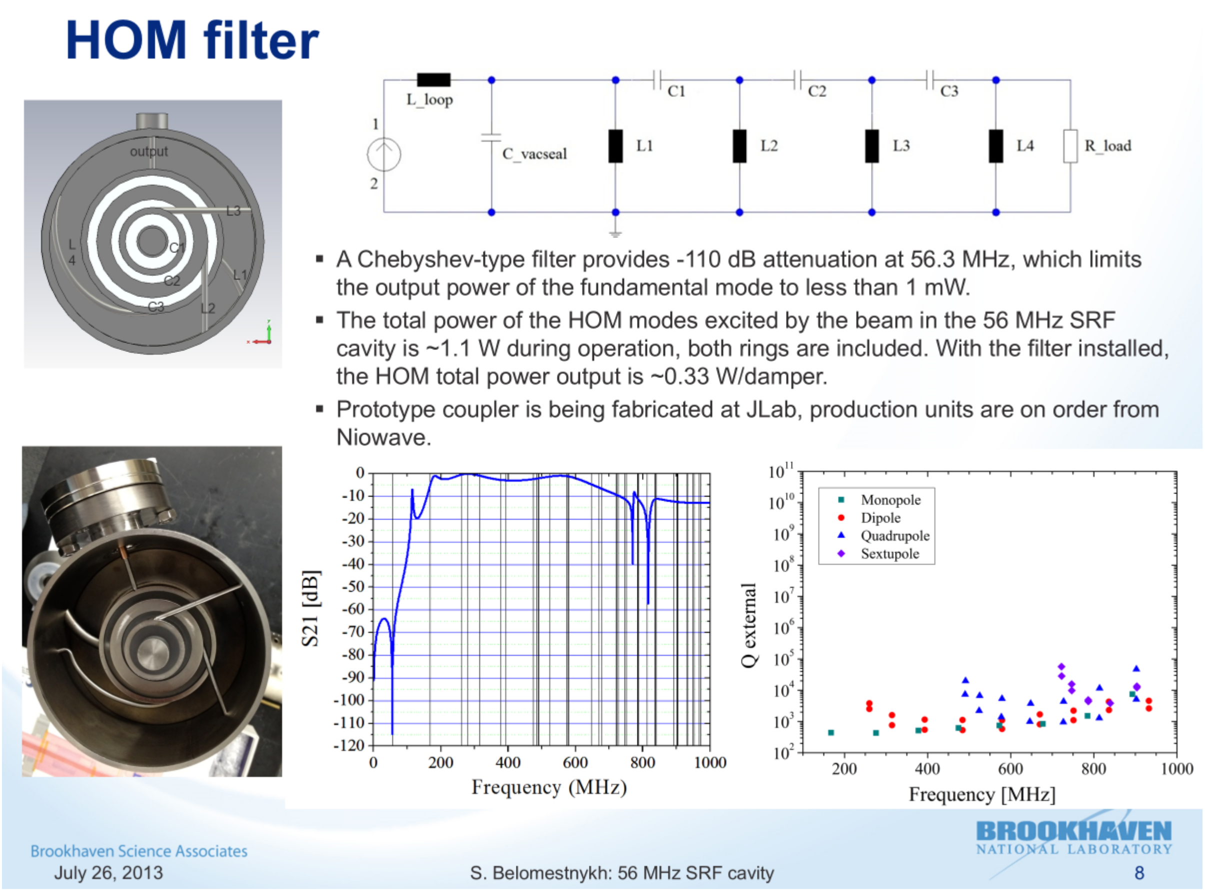
History of 56 MHz Cavity

A journey through past retreats

HOM Damper





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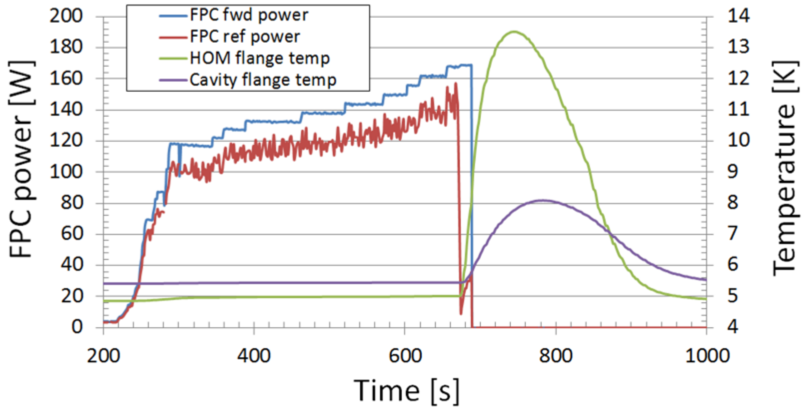
From S. Belomestnykh, 2013 RHIC Retreat

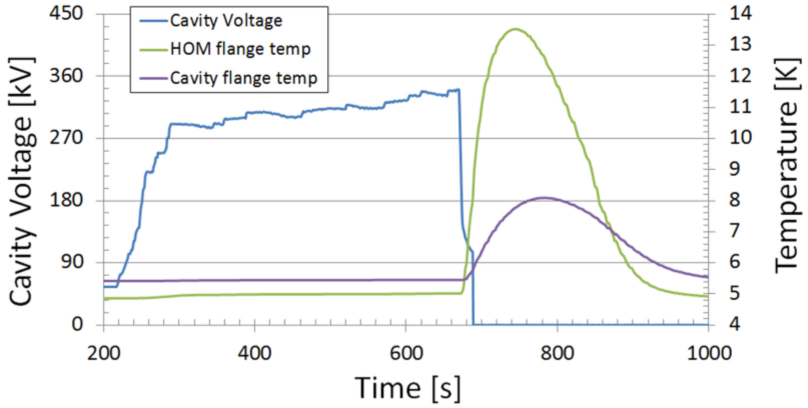
HOM Damper (v1) Quench

Commissioning Problems (1): HOM Coupler Quench



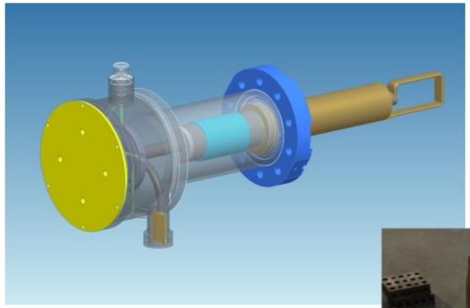
The cavity voltage was limited by a quench in the HOM coupler assembly. The maximum reached cavity voltage was:

- 350 kV DC
- 550 kV pulsed with amplifier

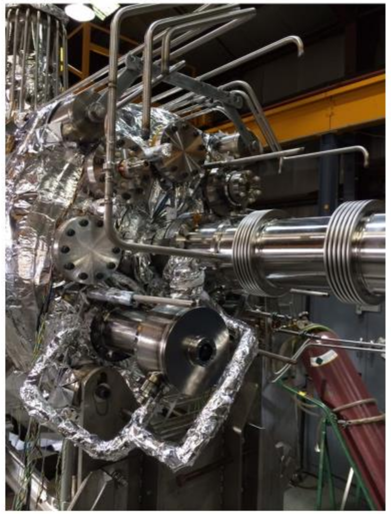


The LLRF measured voltage is 10% lower than the Schottky calibration.

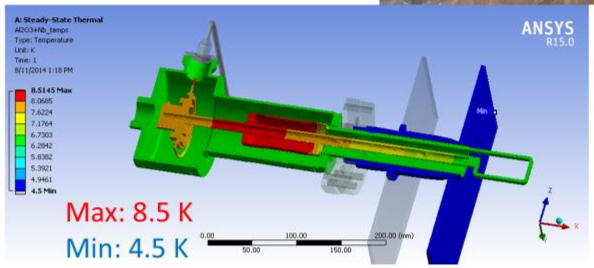
Thermal analysis of the HOM coupler quench



3D model of the HOM coupler assembly (left) and view after installed on the cavity (right).



The HOM coupler has a sapphire RF window that is designed for separating the high-pass filter section from the cavity vacuum.



The braze material at the sapphire – Nb cuff joint is InCuSil, which is normal conducting at 4.5 K.

Thermal analysis (Steve Bellavia) shows that at 1/6th of the design field, the InCuSil material would bring the adjacent Nb (T_c = 9.2 K) to 8.5 K. It is currently our best candidate for the quench.

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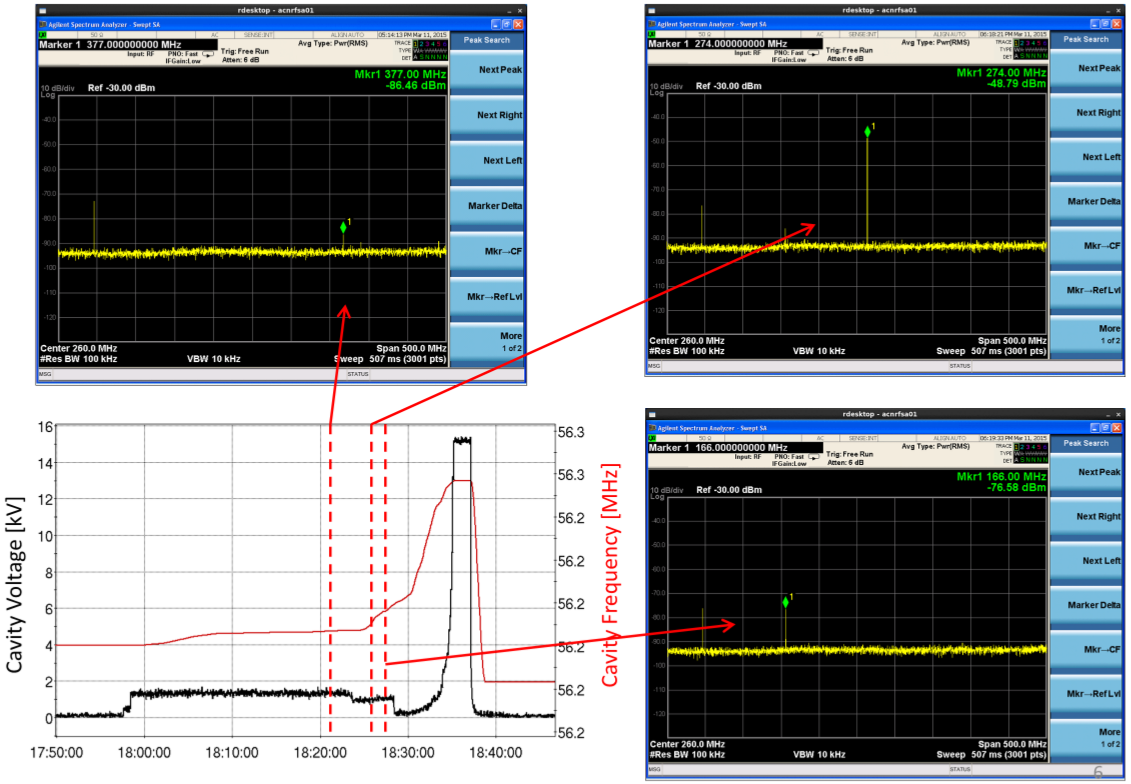
From Q. Wu, 2014 RHIC Retreat

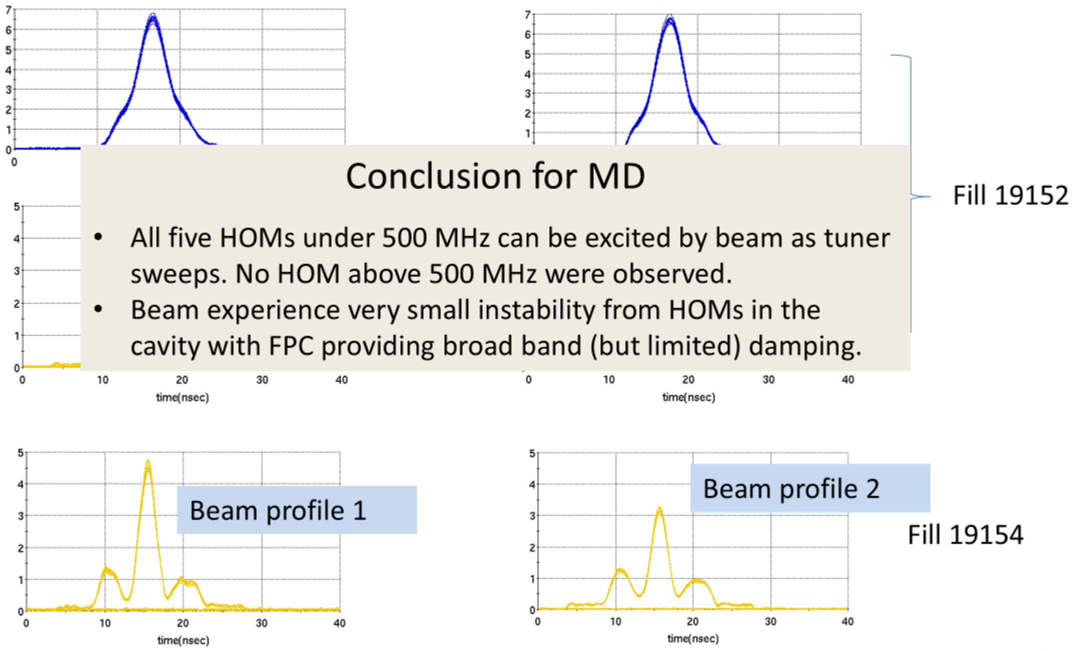
Test Run without HOM Damper

11 bunches of proton in a 12 bunch pattern. Total intensity: 2.39e12



Beam profile before we swept through multiple (5) HOM resonance lines

Beam profile after we swept through multiple HOM resonance lines

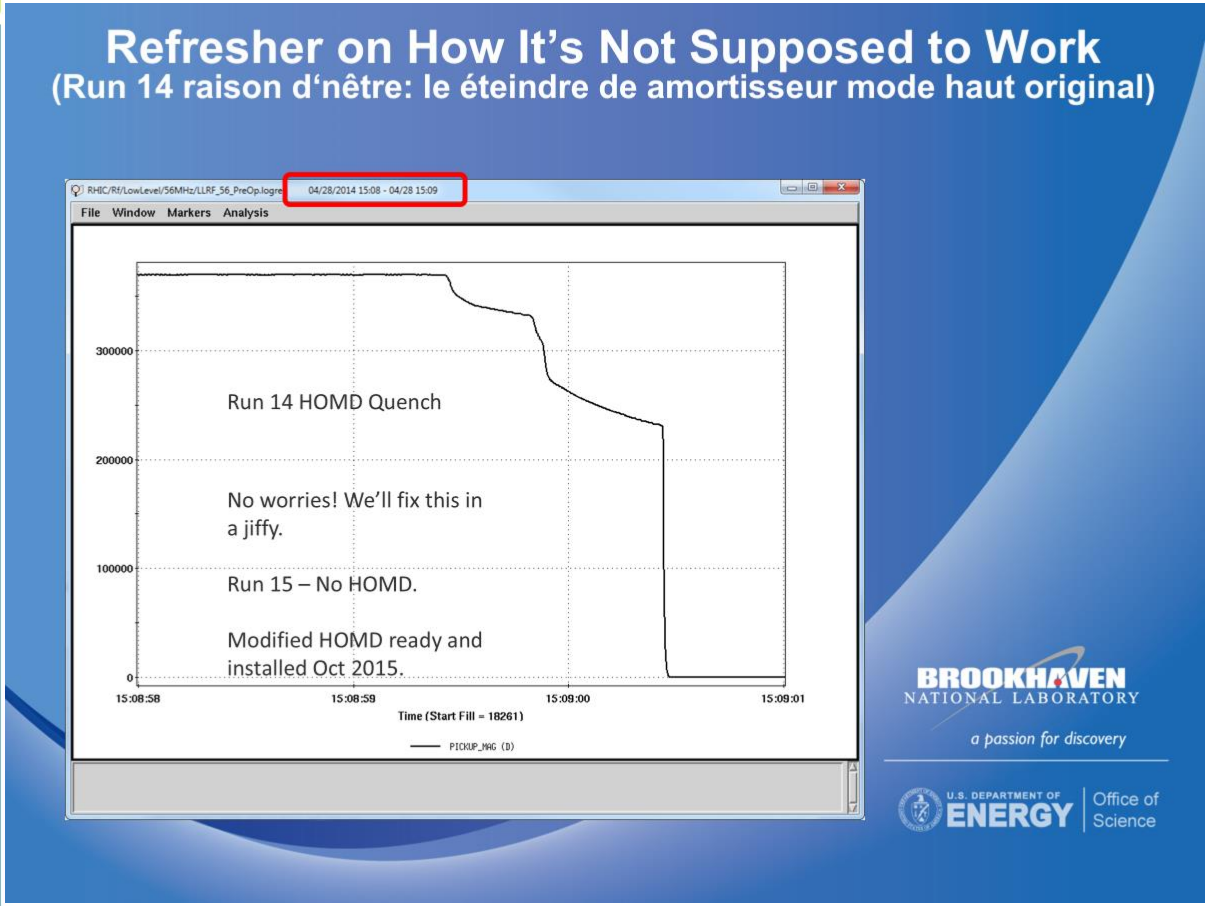


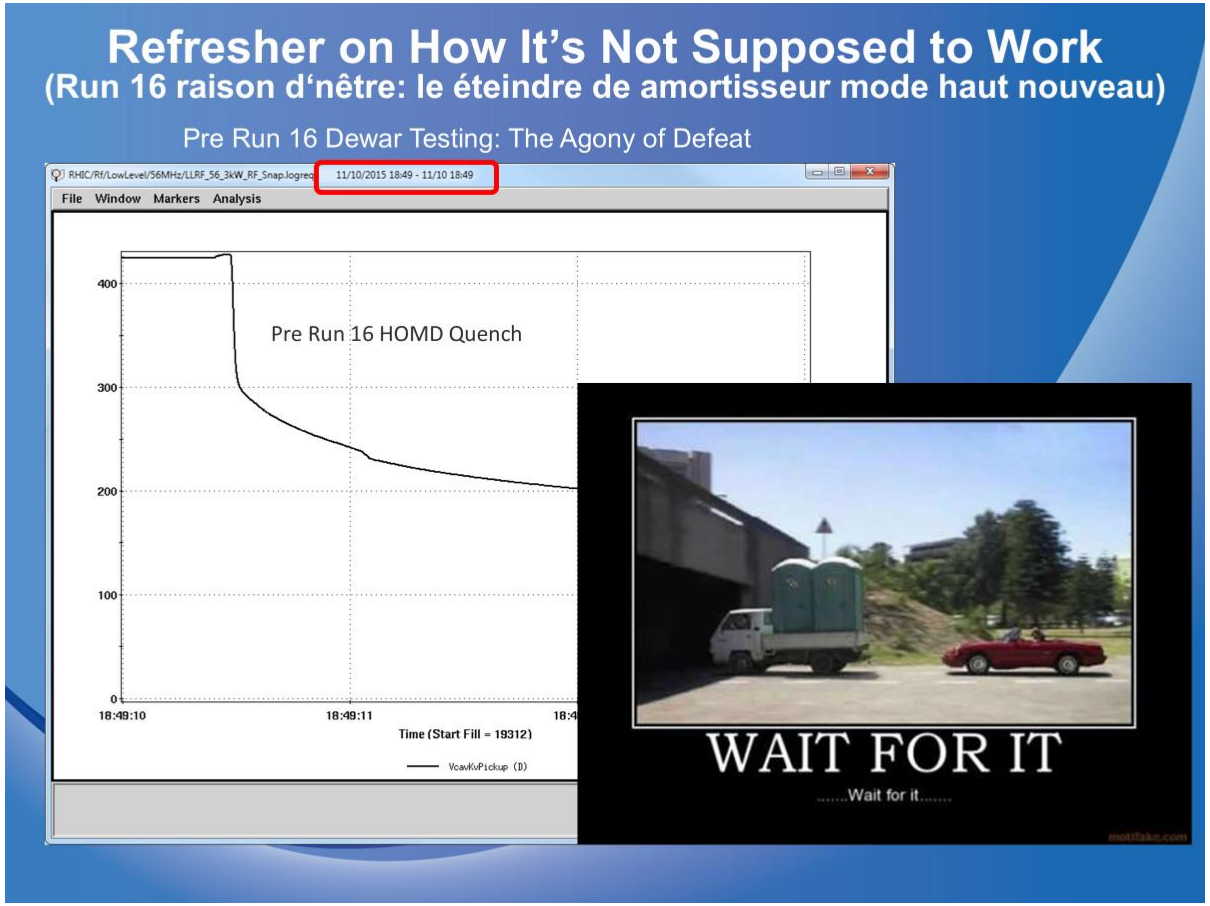
Conclusion for MD

- All five HOMs under 500 MHz can be excited by beam as tuner sweeps. No HOM above 500 MHz were observed.
- Beam experience very small instability from HOMs in the cavity with FPC providing broad band (but limited) damping.

From Q. Wu, 2015 RHIC Retreat

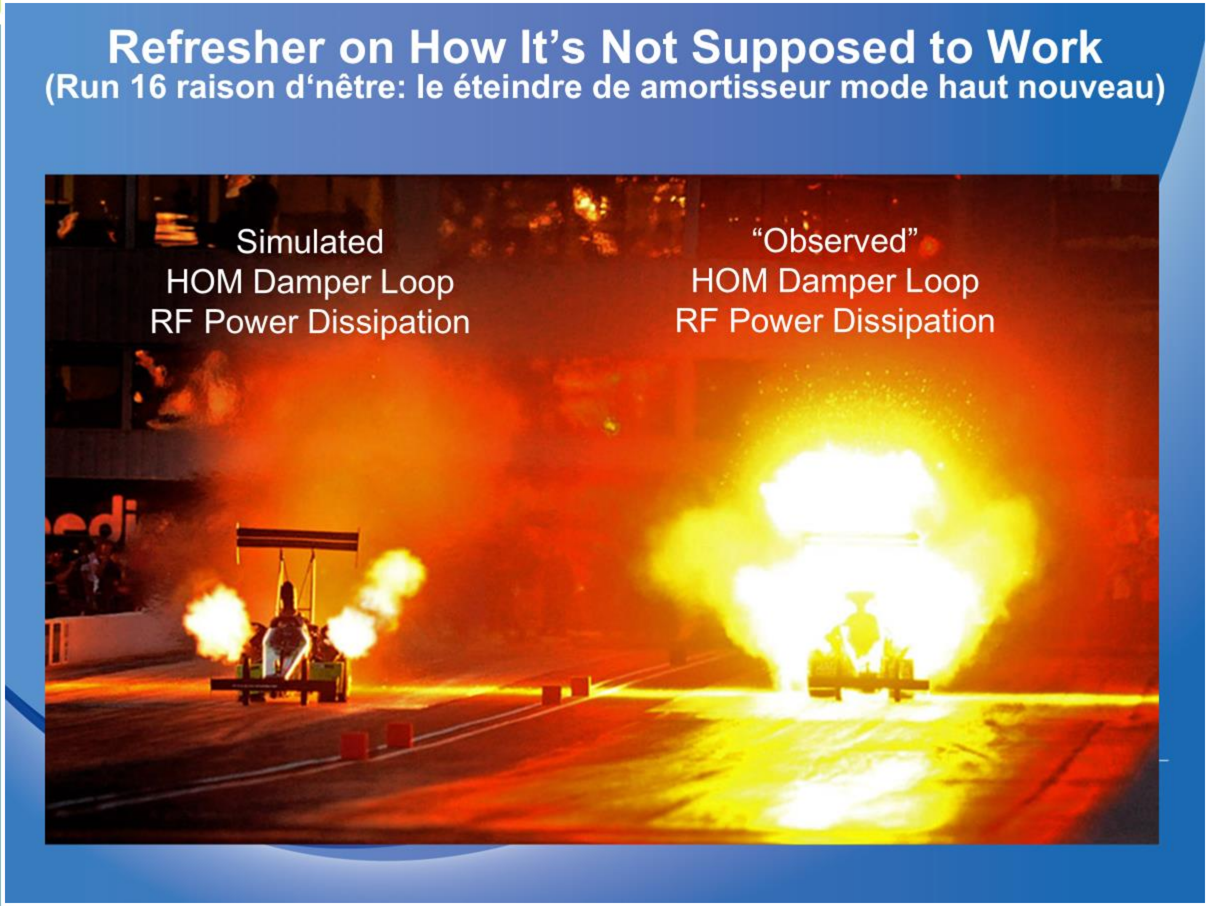
HOM Damper (v2) Quench





From K. Smith, 2016 RHIC Retreat

HOM Damper Removed for Run16



Once more unto the breach, dear friends, once more.

- So we have an HOMD which limits the cavity to ~350kV – 400 kV and we need to make this cavity work in RHIC.
- Took the decision to remove the "new" HOMD and try hard to find a way to make the cavity operational without it, with a goal of achieving 1MV at Store.
- Needed some alternative for damping the dangerous HOMs.
- Best option: trying to dual purpose the Fundamental Mode Damper (FMD) as an FMD & HOMD.
- A daunting challenge with many unknowns, requiring a lot of effort in a short period of time.

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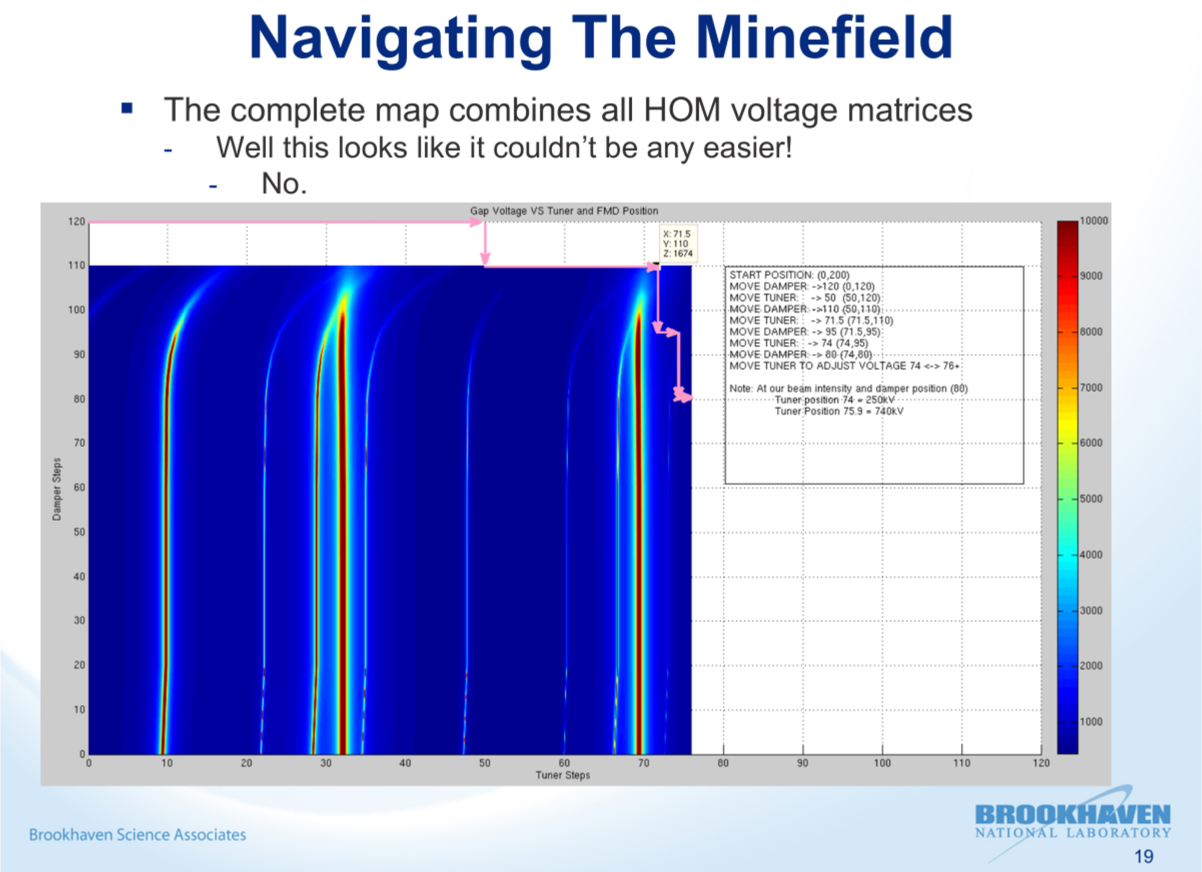
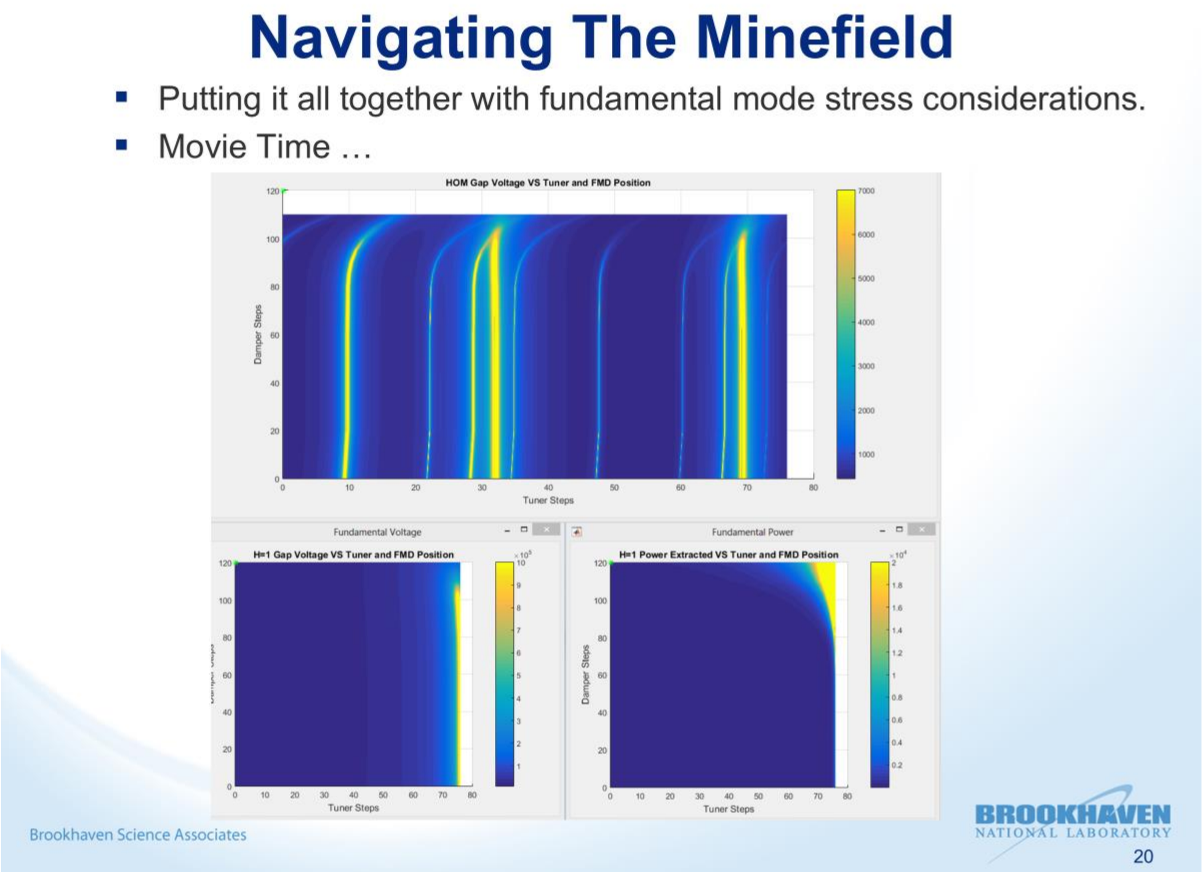
From K. Smith, 2016 RHIC Retreat

Run16 Operation





Coordinated movement of FMD and tuner was able to avoid exciting any beam-destroying HOMs during the process of bringing up the cavity voltage while avoiding excessive voltage and thermal stress on the FMD and cavity

Post-Run17 Modifications

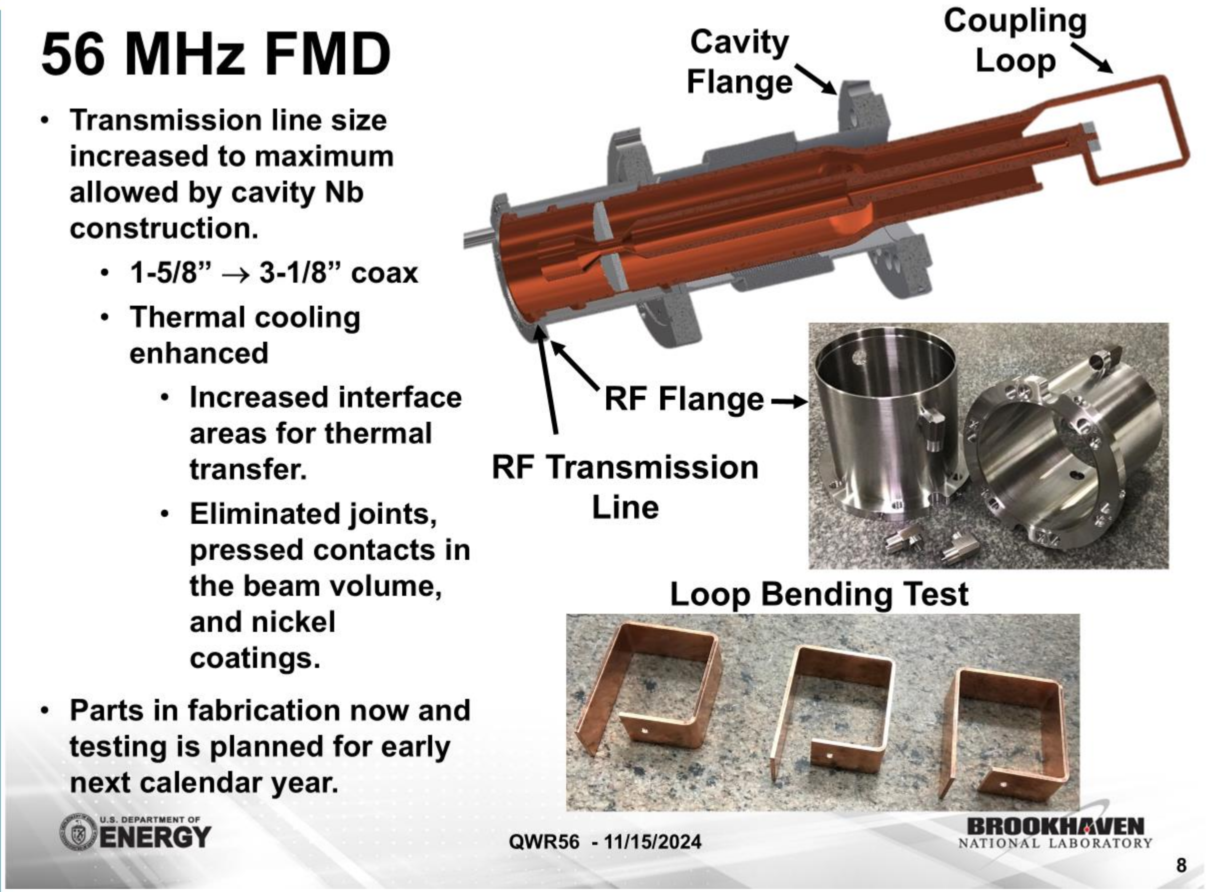
Removal and complete rebuild of cryomodule addressing numerous issues

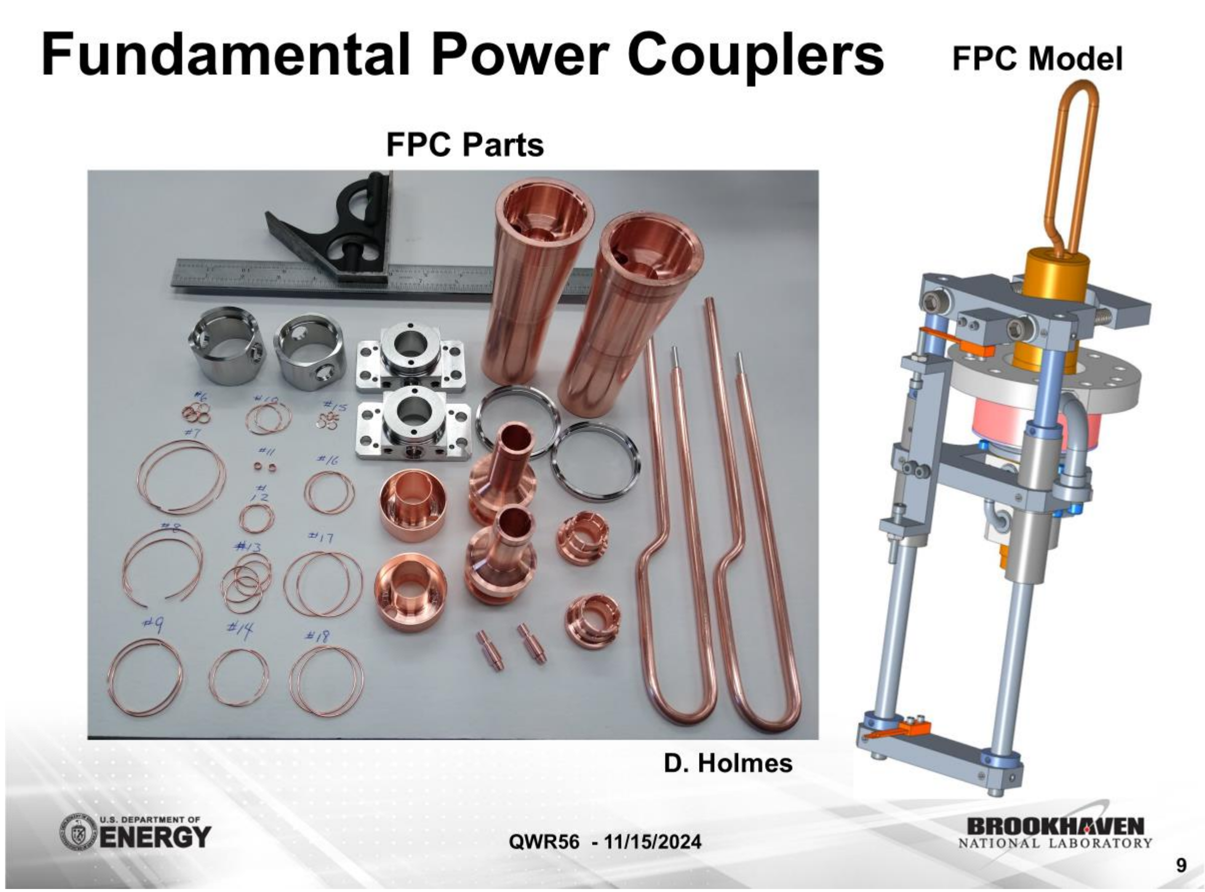
- 2 new Fundamental Power Couplers (arcing in insulating vacuum on previous design, greater range of coupling)
- New Fundamental Mode Damper (higher power, improved motion control)
- Cryo piping, vacuum pumps, add second pickup probe
- Cavity cleaned (HPR) and low-particulate assembly

Designs for new HOM dampers were investigated, but RF dissipation for any damper using available ports would be too high

Cavity vertical test in 2019 and cryomodule horizontal test in 2022

Cavity Hardware Modifications





From Z. Conway, 2020 RHIC Retreat

56 MHz Cavity in Run24

A journey back to the present day

Cavity Limitations

There is a hard quench limit just above 1 MV (at 1.02 MV) – based on this, operating voltage should be limited to ~800 kV

FMD and FPC power limits – FMD can handle high power (~100 kW) for short intervals (seconds to minutes), but longer-term response was unknown, FPCs have ~5 kW power limit

Cavity frequency response of fundamental and HOMs to tuner/damper position was remapped this run – it appears to be worse than run16 (there is a smaller, perhaps non-existent, gap between destroying the beam and melting the FMD)

FMD/Tuner Path for Run24

- Tuner and FMD motion is different, need to remap the turn-on path
- Initial plan was to duplicate "corners" in path based on fundamental mode frequency and Q_{ext} – this would cross $^{3\lambda}/_{4}$ HOM with insufficient damping
- Modified path adding more steps – more aggressive damping to avoid exciting $^{3\lambda}/_{4}$ HOM while skirting high FMD power region

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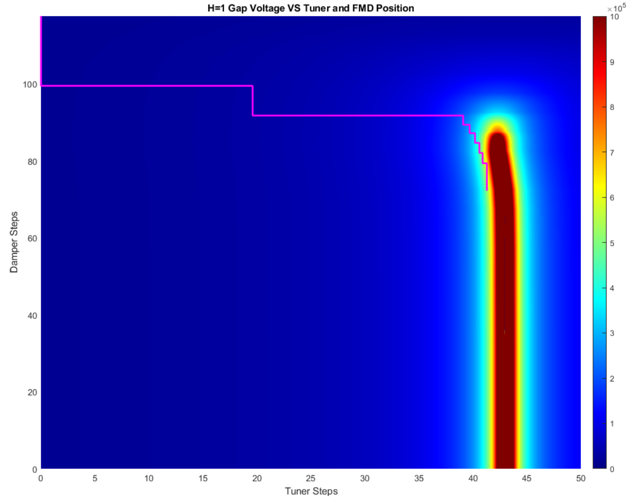
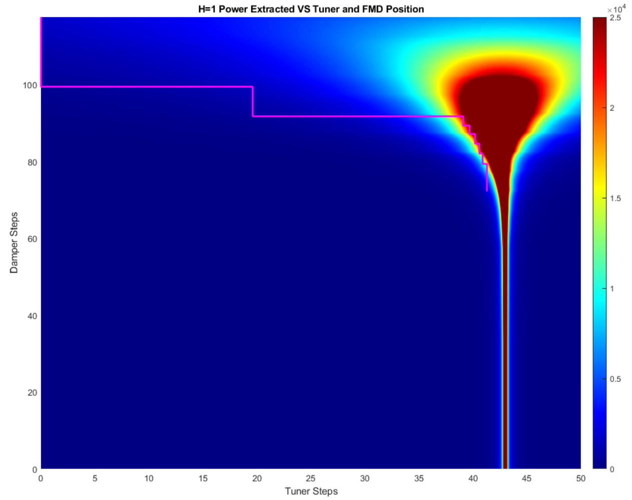
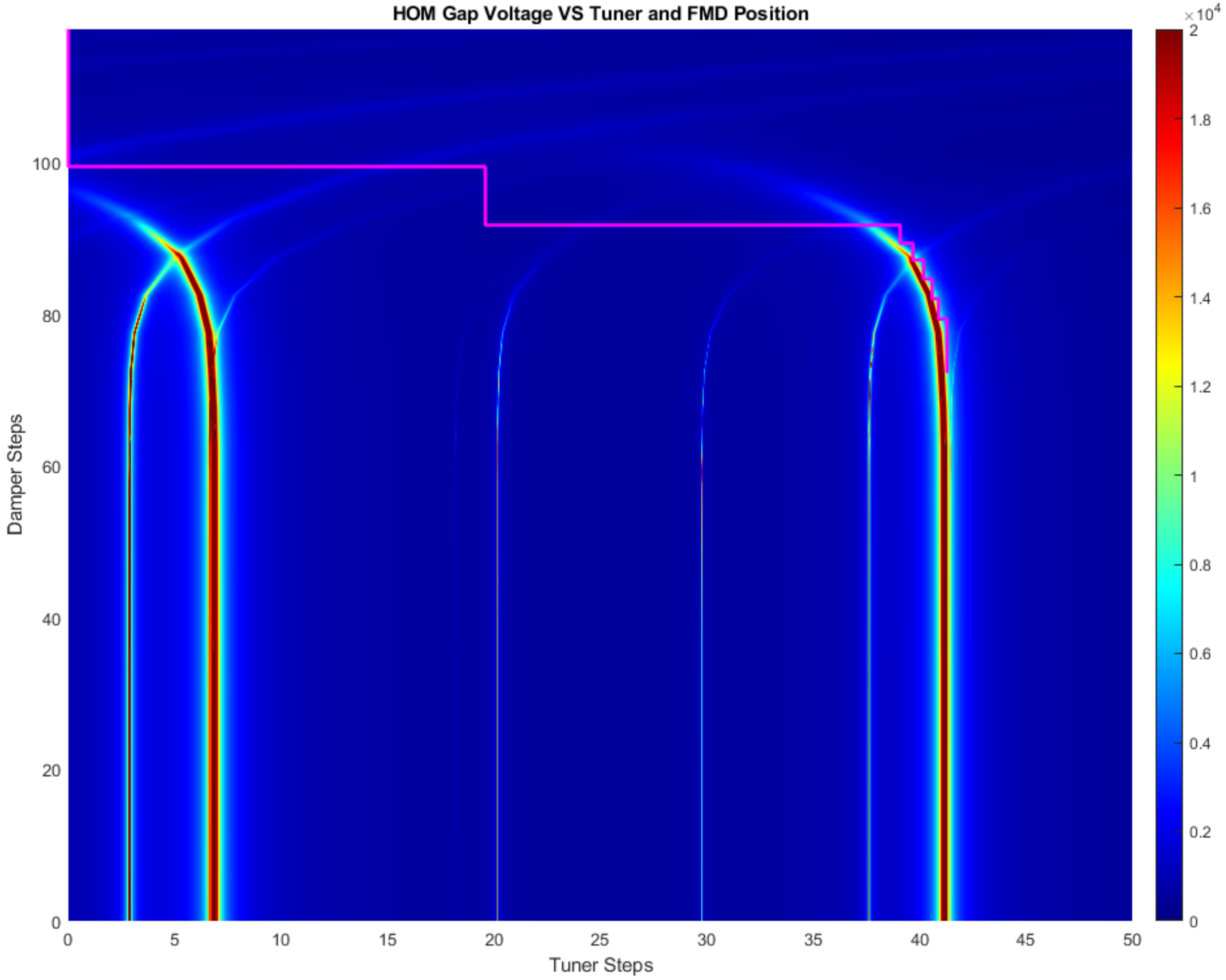
FMD/Tuner Path for Run24





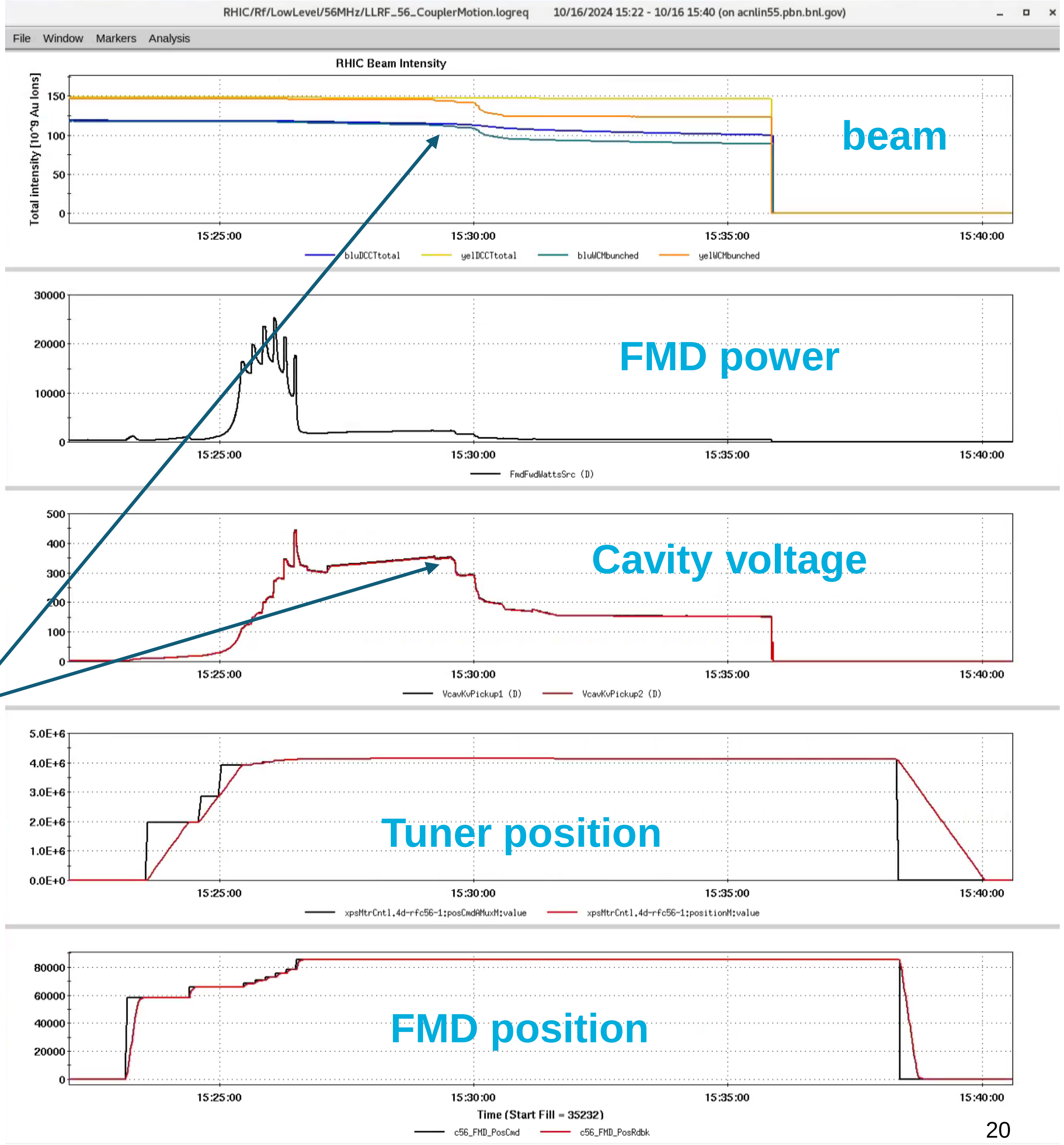


First Beam Test

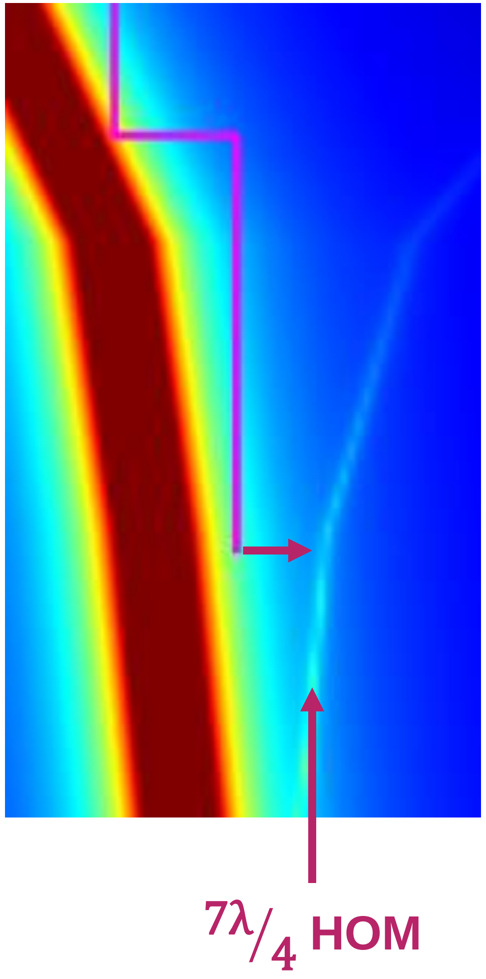
10/16 – after a couple 12x12 tests, ran 111x111

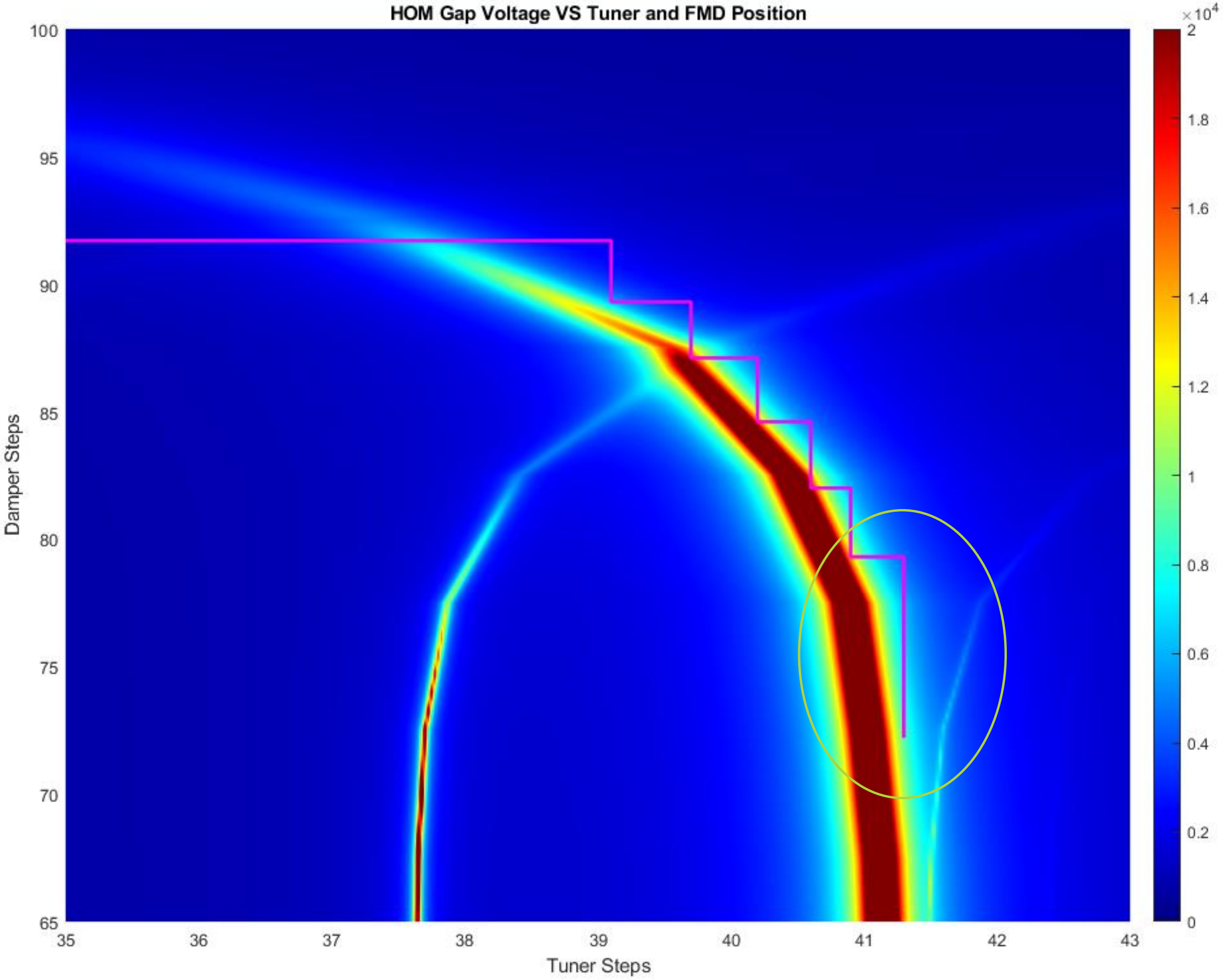
1.35e9 Y, 1.06e9 B

Ran through turn on path without issue, but when tuning cavity to increase voltage, had an instability



First Beam Test





Second Beam Test

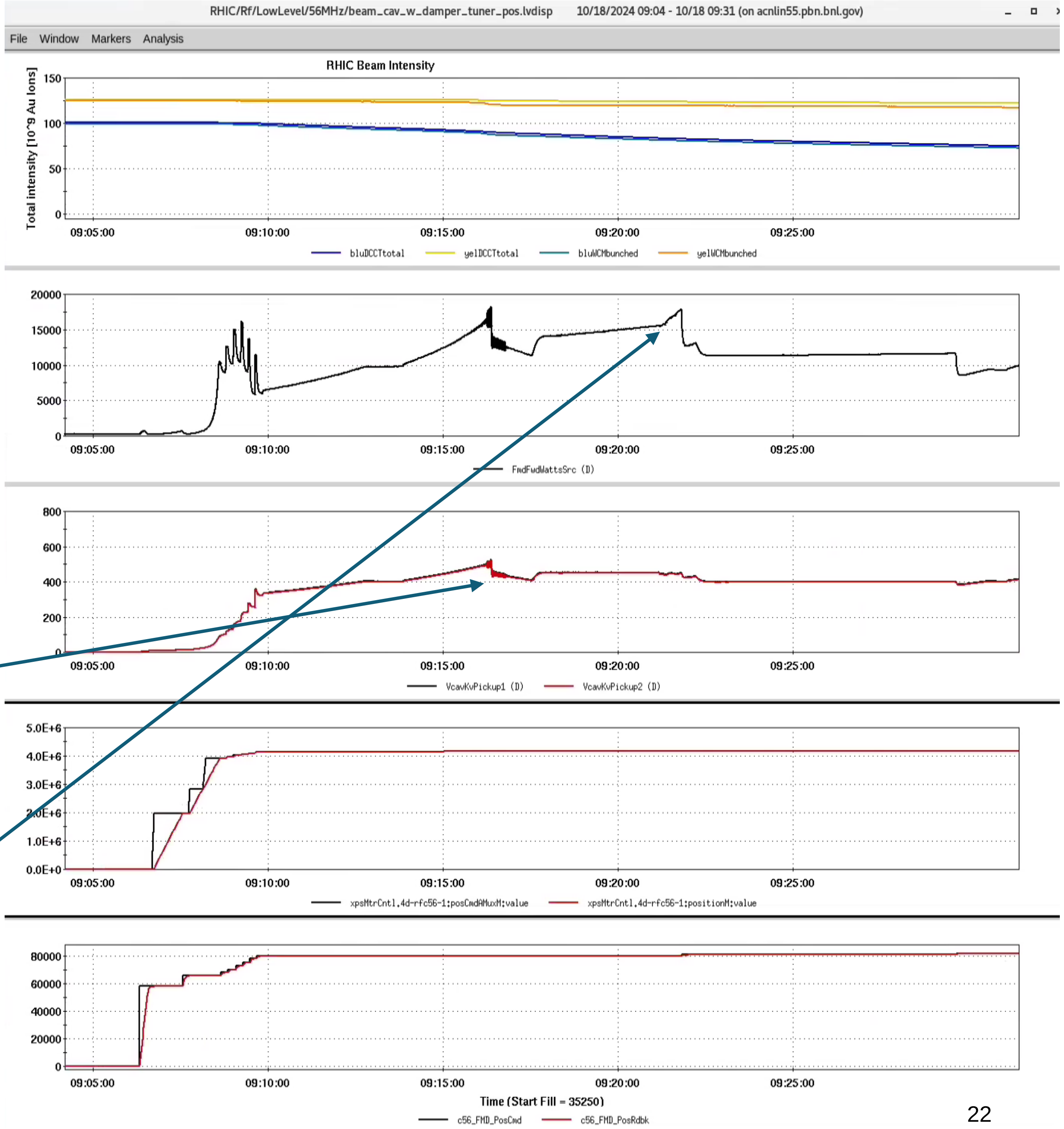
10/18 – 111x111

1.14e9 Y, 0.90e9 B

Left FMD further in at last step, higher extracted power

Had issue with voltage stability, LLRF configuration related

More concerning, power runaway on FMD (thermal runaway?)



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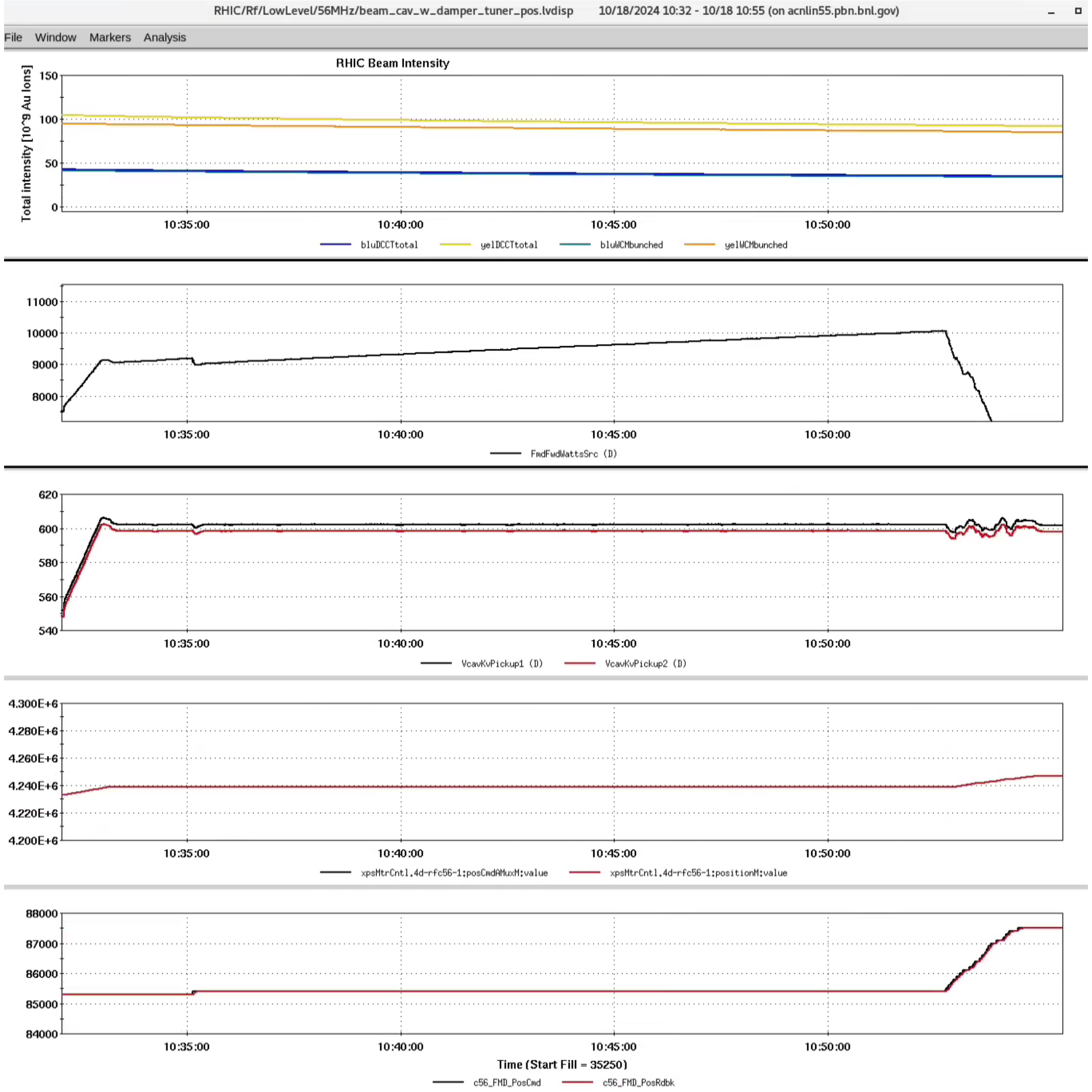
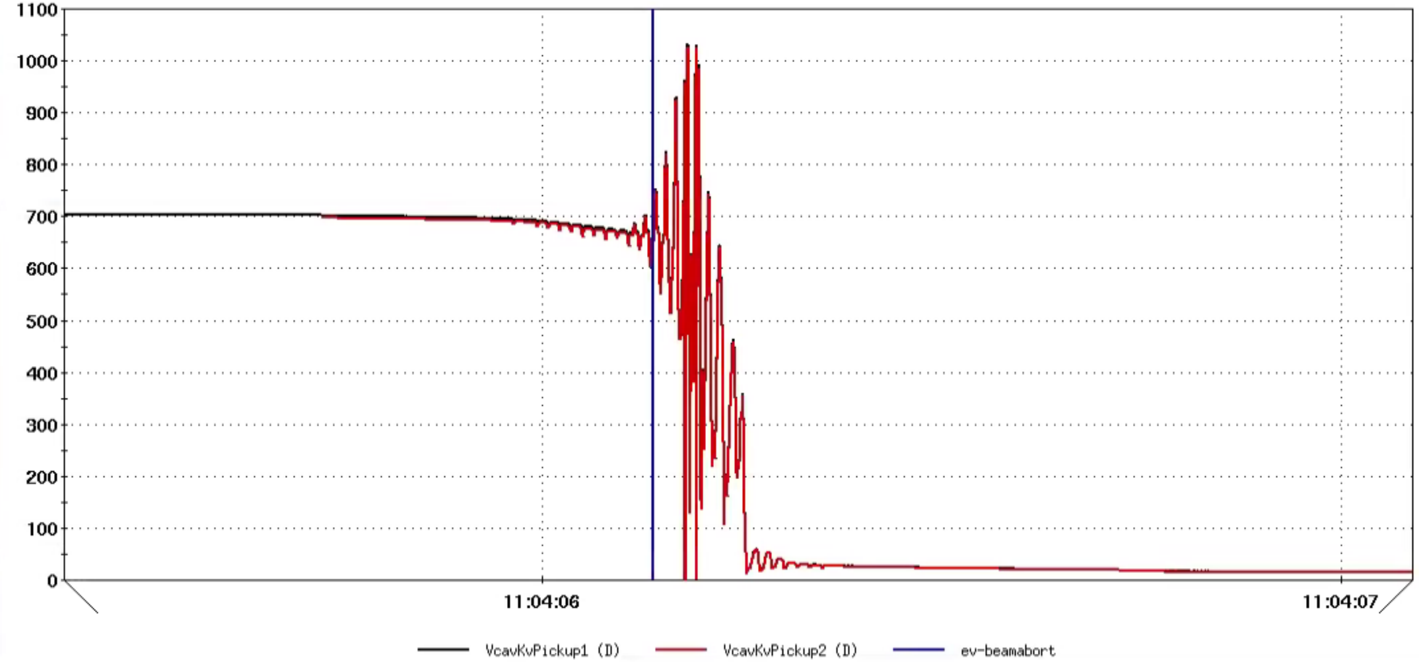
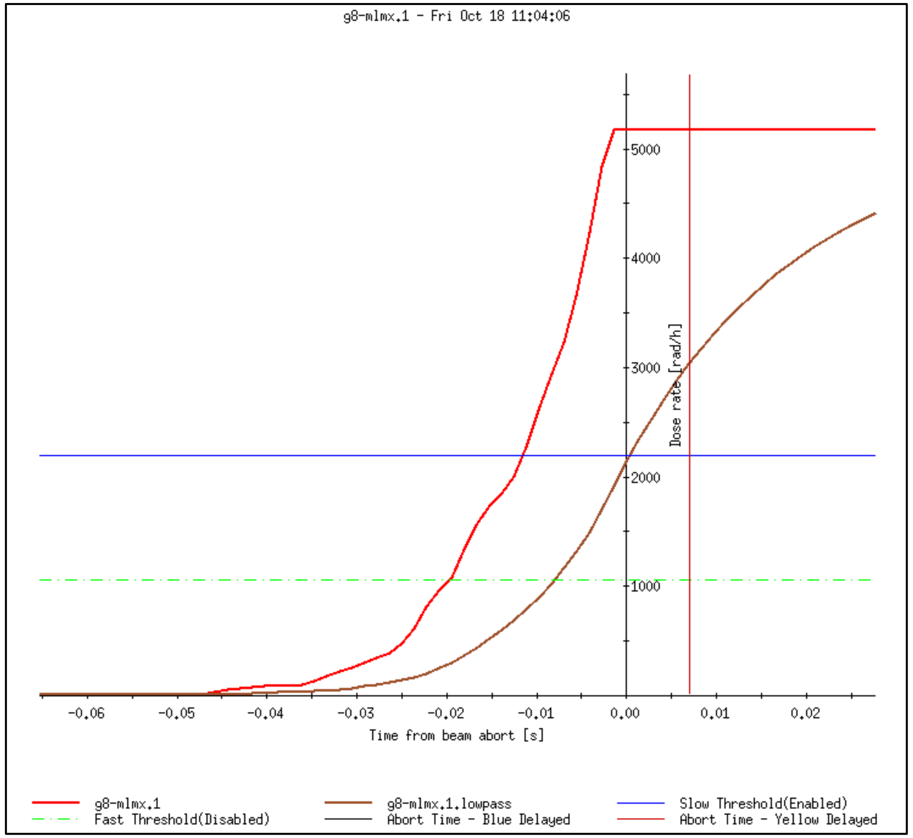
Second Beam Test

- Even at lower power, the FMD extracted power continues to run away (or maybe more like walk away)
- In 15+ minute test, no sign of reaching equilibrium



Second Beam Test





Cavity voltage went unstable at the end of the test when we were getting ready to dump beam (we know why and can avoid this particular failure mode in the future)

Abort caused by g8-mlmx.1 loss monitor at sPHENIX (our 56 MHz MPS input didn’t catch it, even though I wrote a feature explicitly to try to detect this type of failure)

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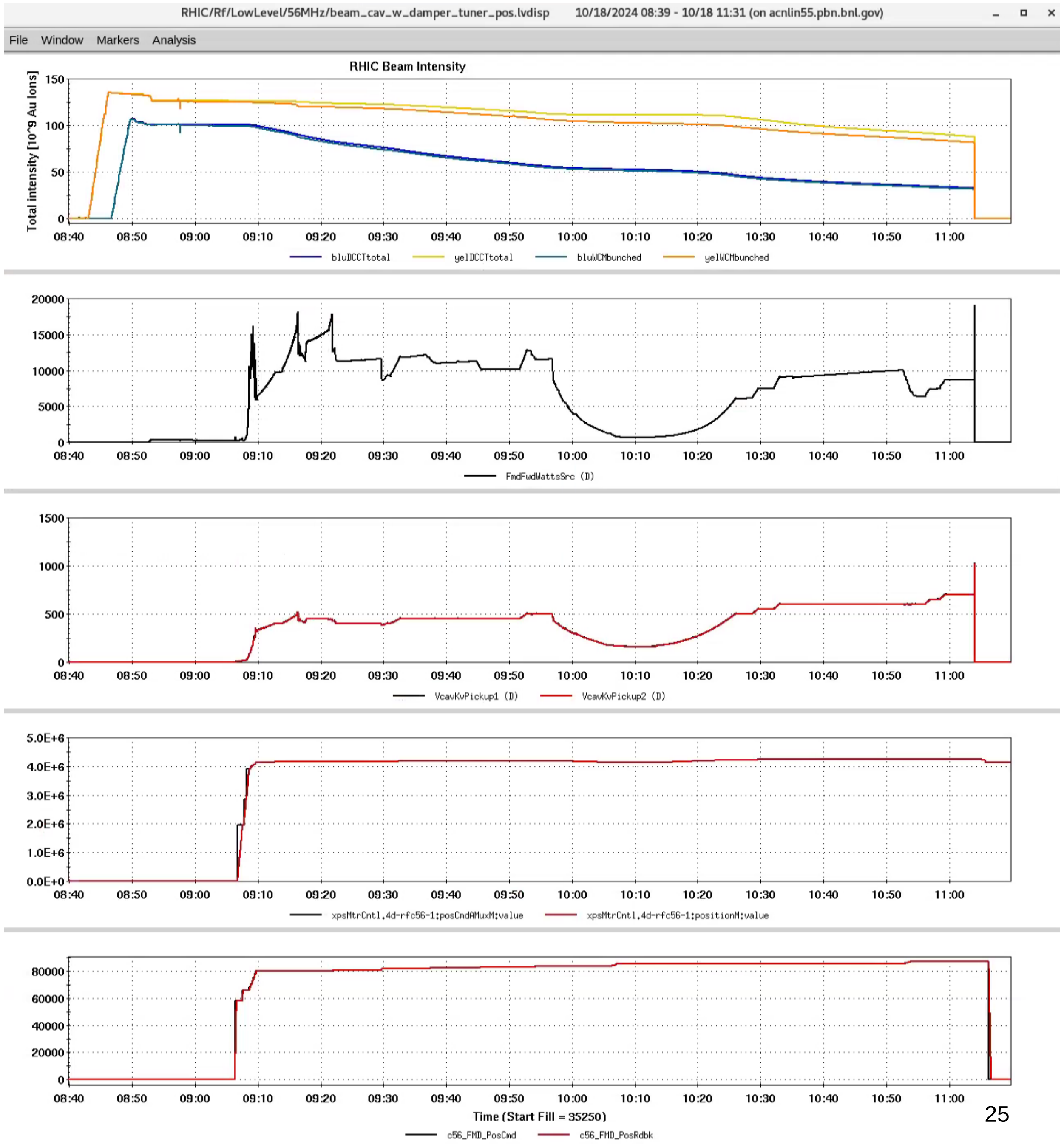
Second Beam Test

Full test store on 10/18



Conclusion

Things went better than I feared, but far from "success"

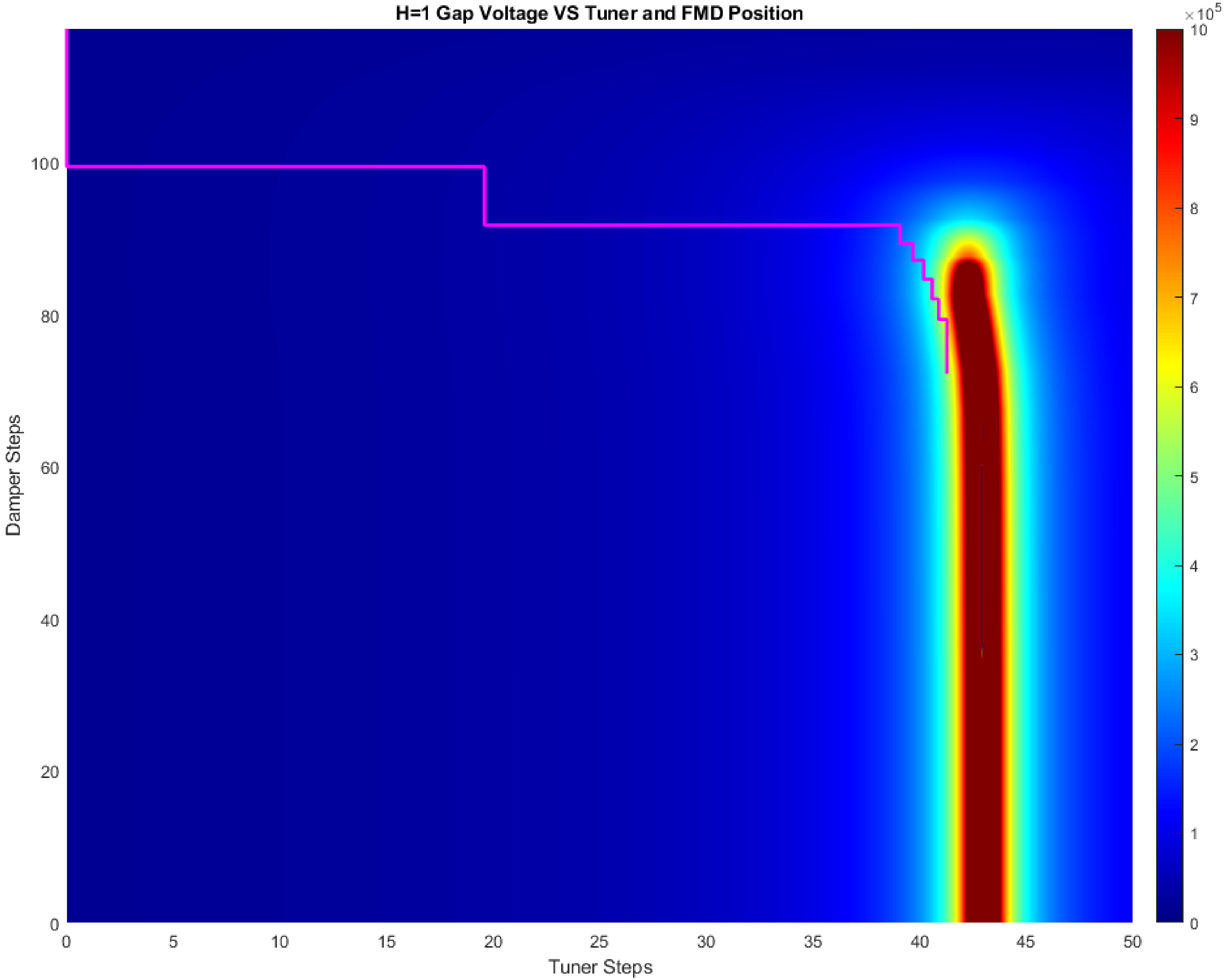
I don't know if there is a path to operation of the cavity at nominal Au beam intensity

- FMD power dissipation during initial turn-on sequence is function of beam current squared – also might need increased HOM damping at higher beam current which would further increase FMD power
- Tuner/damper working point for voltage-controlled operation will be close to exciting ${}^{7\lambda}/_{4}$ HOM – working point is a function of beam current

If we can make it work, I don't know if we can make it work reliably – this is a system of band-aids on top of band-aids on top of workarounds

Backup Slides

Bigger versions of plots



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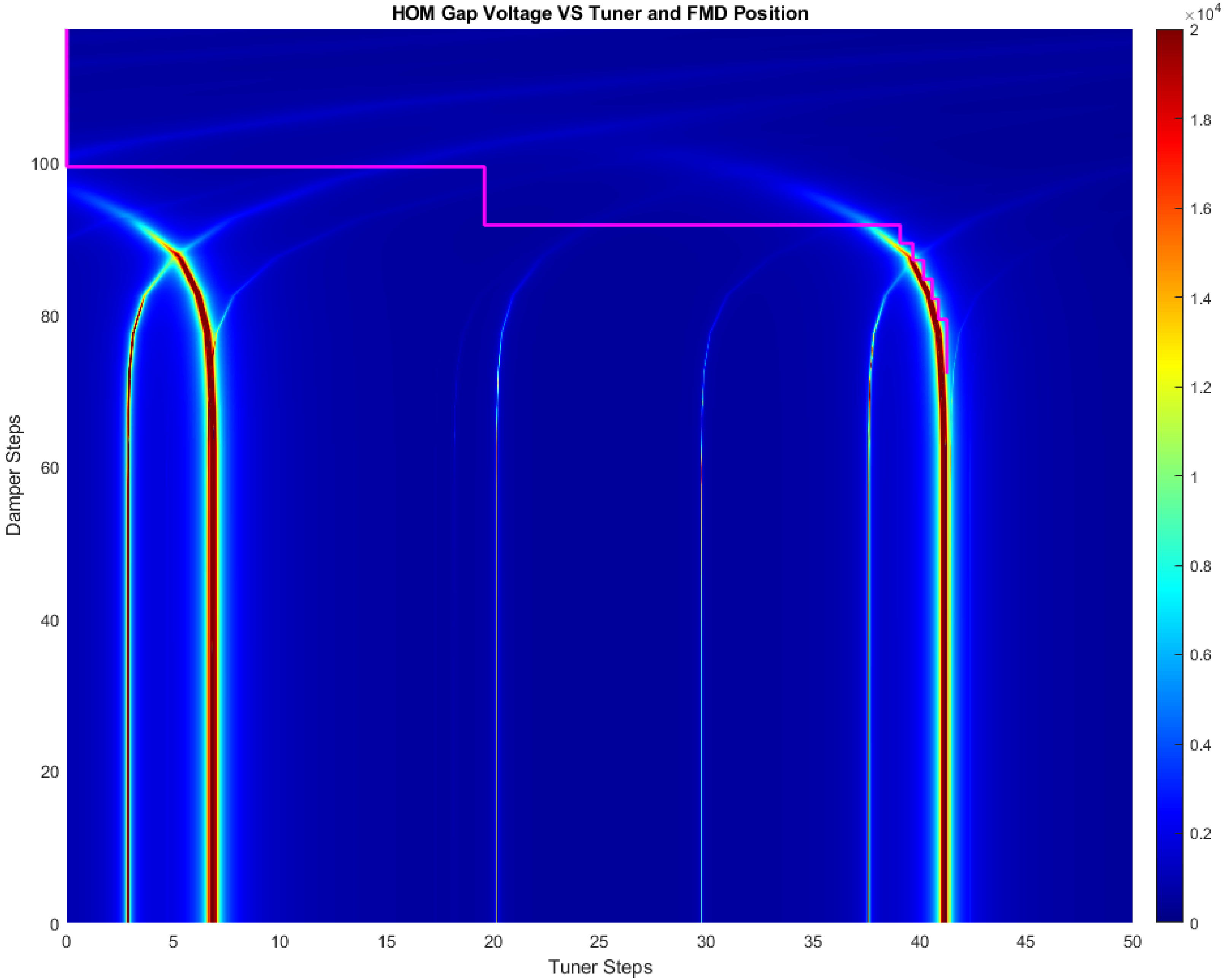

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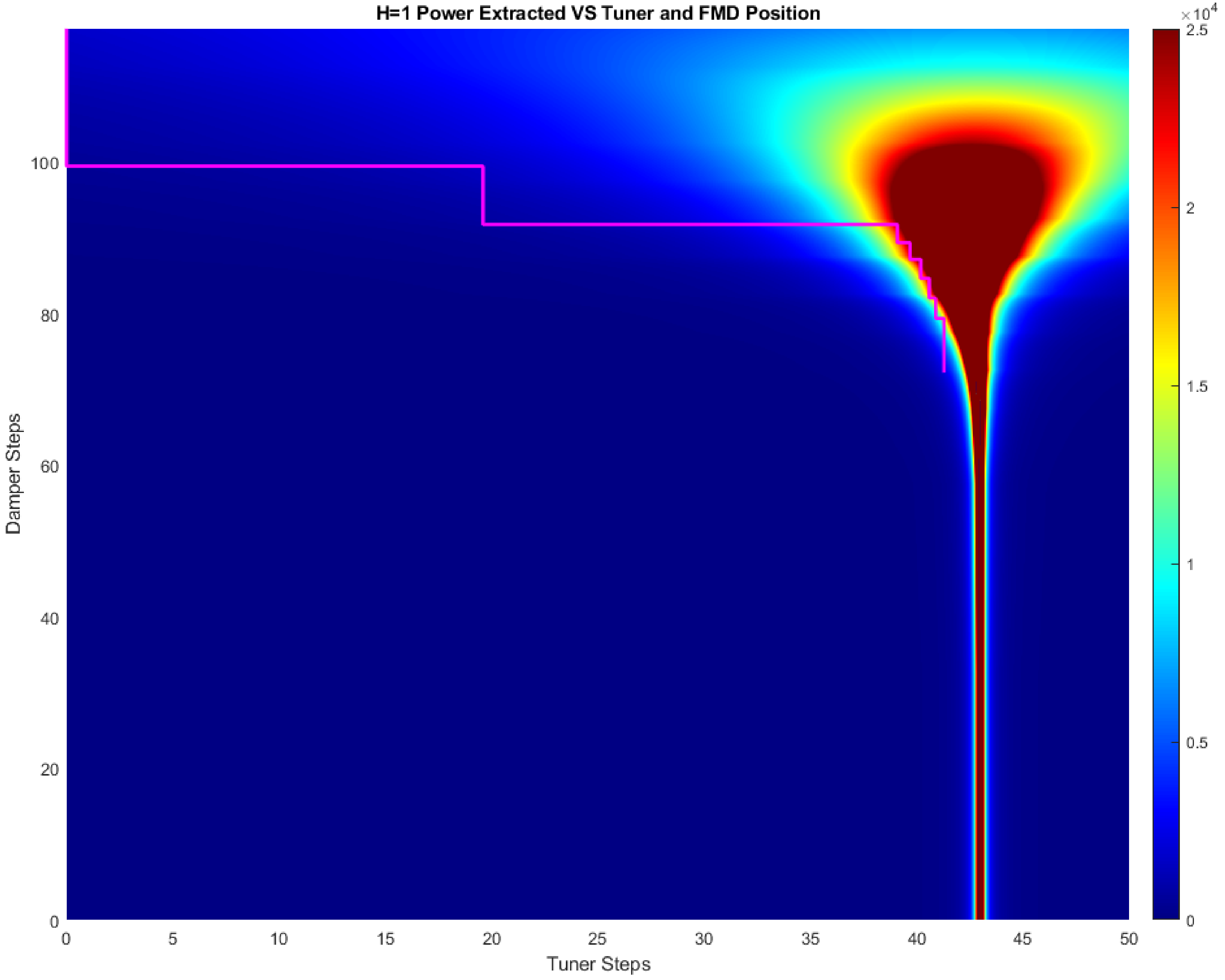

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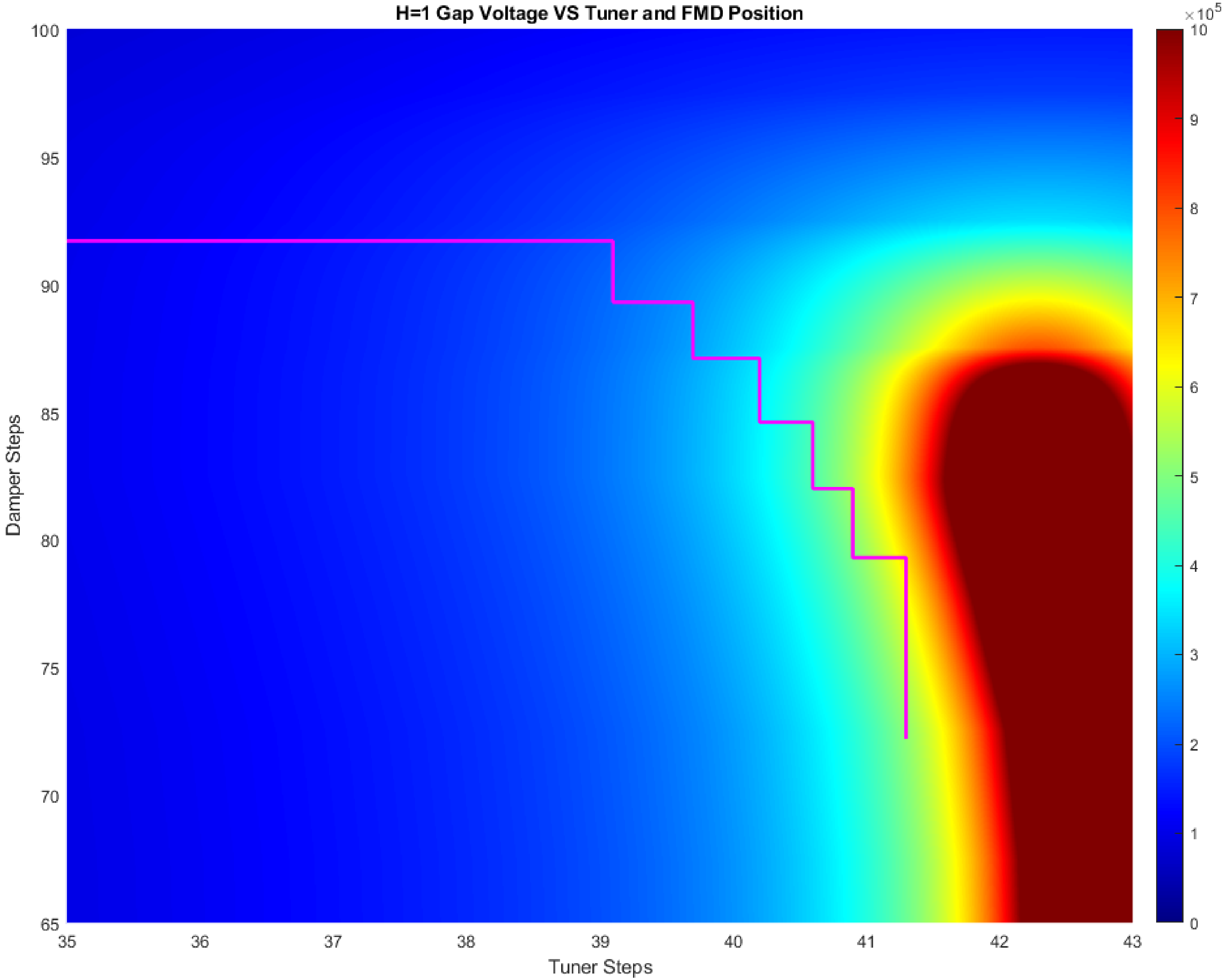

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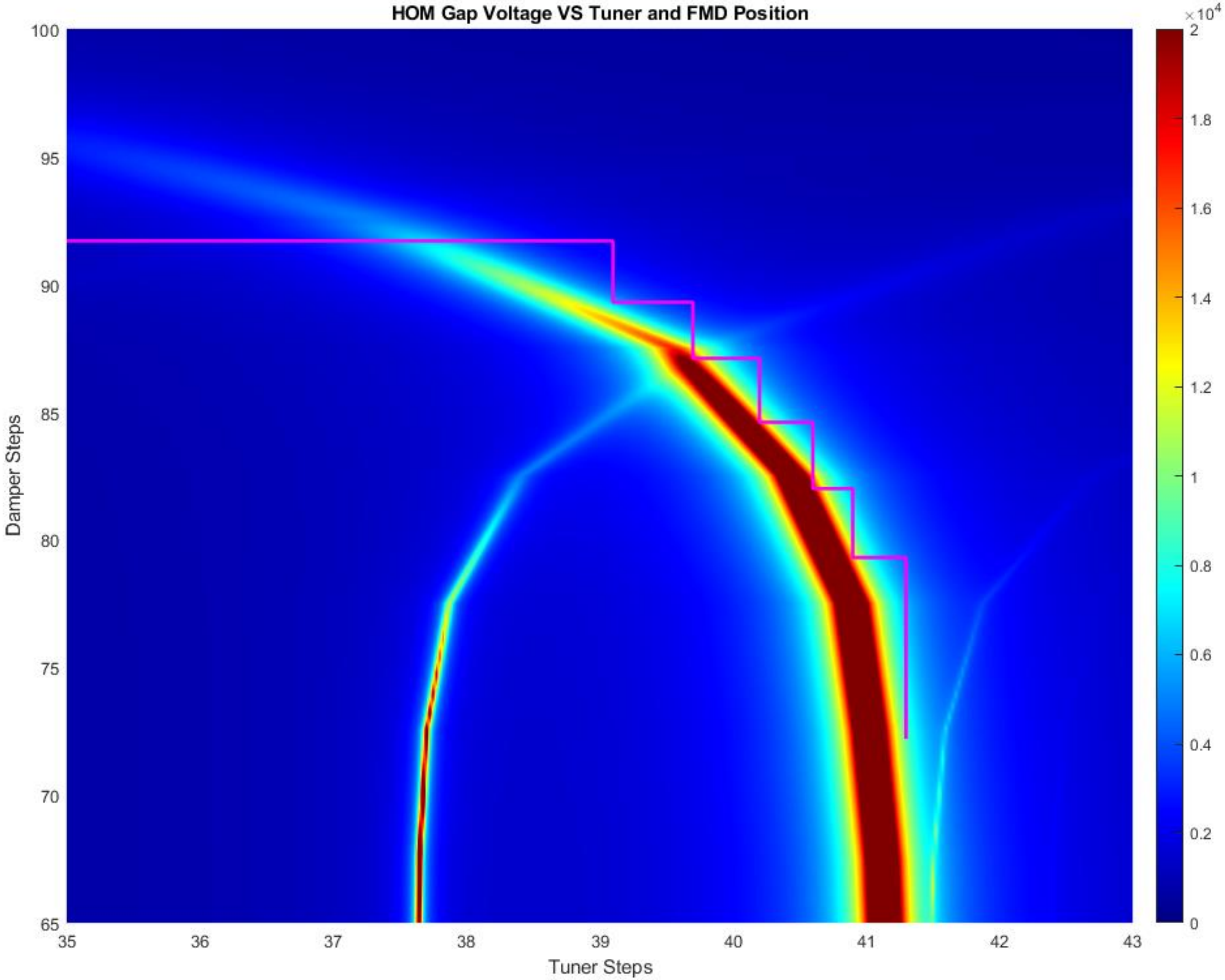

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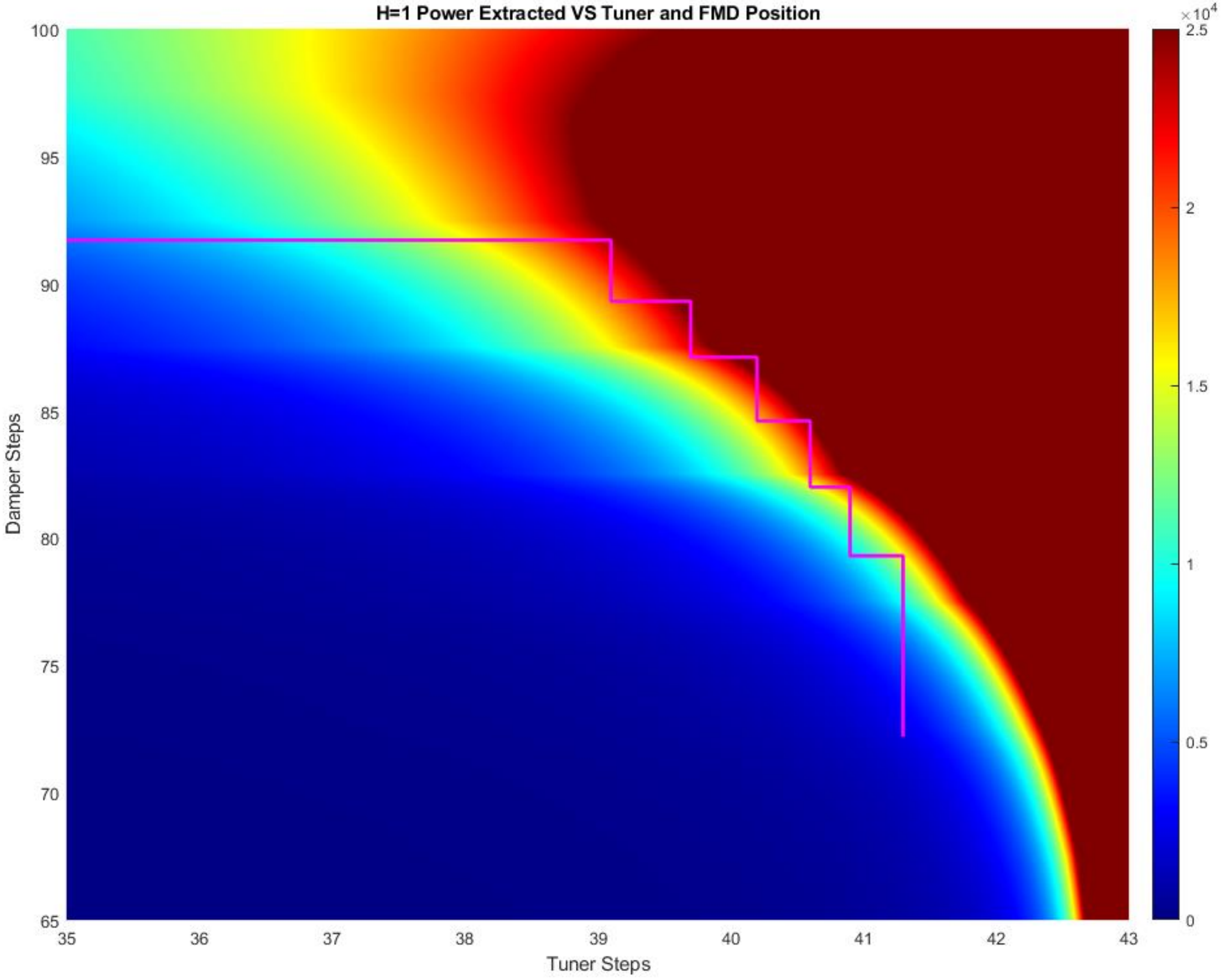
H=1 Power Extracted VS Tuner and FMD Position
Damper Steps
Tuner Steps
100
95
90
85
80
75
70
65
35
36
37
38
39
40
41
42
43
×10^4
2.5
2
1.5
1
0.5
0