56MHz for Run (14, 15) 16, 17, 18 …

Kevin Smith

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Syllabus

- *Refreshments Are Being Served*
  - How it’s supposed to work.
  - How it’s not supposed to work.
  - Maybe it works without an HOM Damper!

- *When You Come to a Fork in the Road – Take It.*
  - Once more unto the breach, dear friends, once more.
  - Solving For Unknowns.
  - Navigating The Minefield.

- *Final Exam Results*

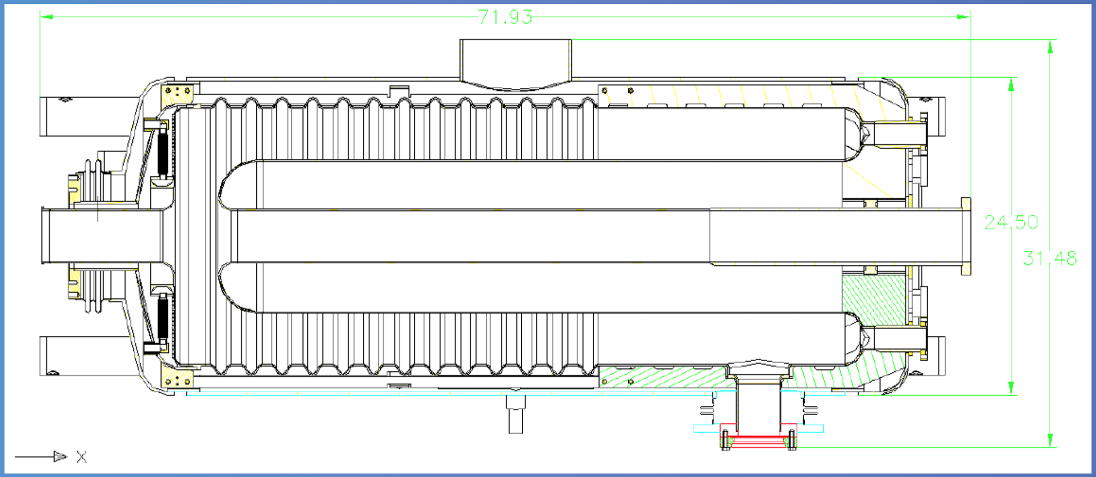
- *Forward – Ever Forward …*

- *Acknowledgements*

Refreshments Are Being Served

Refresher on How This Thing Works

(mode d'opération)



A “Passive” Beam Driven Cavity

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

$I_{h=720} = 0.5A$

$|Z_{cav}|_{f0} = R_0 = 1.6E9$ ohm !!!
(Qext = 4E7, Q0 = 3E9)

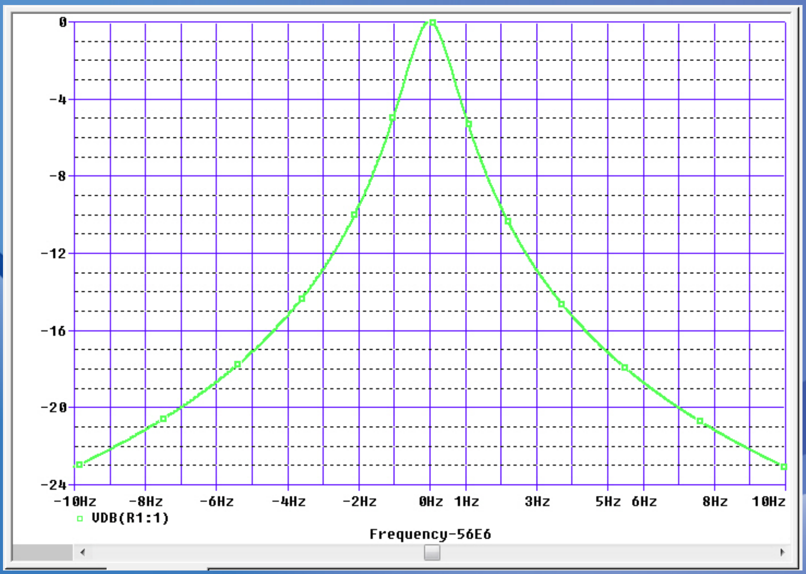
800 MV on resonance ???!!!

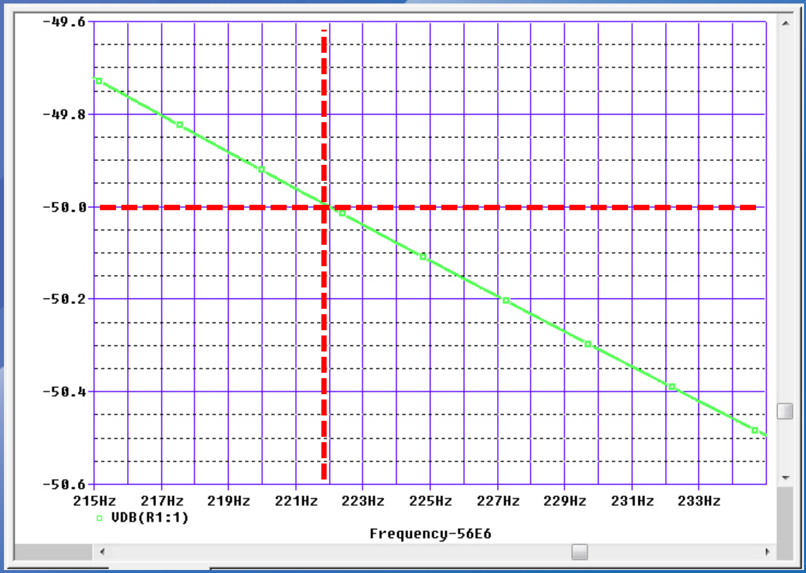
Detune …

800 MV – 50dB => 2.5 MV

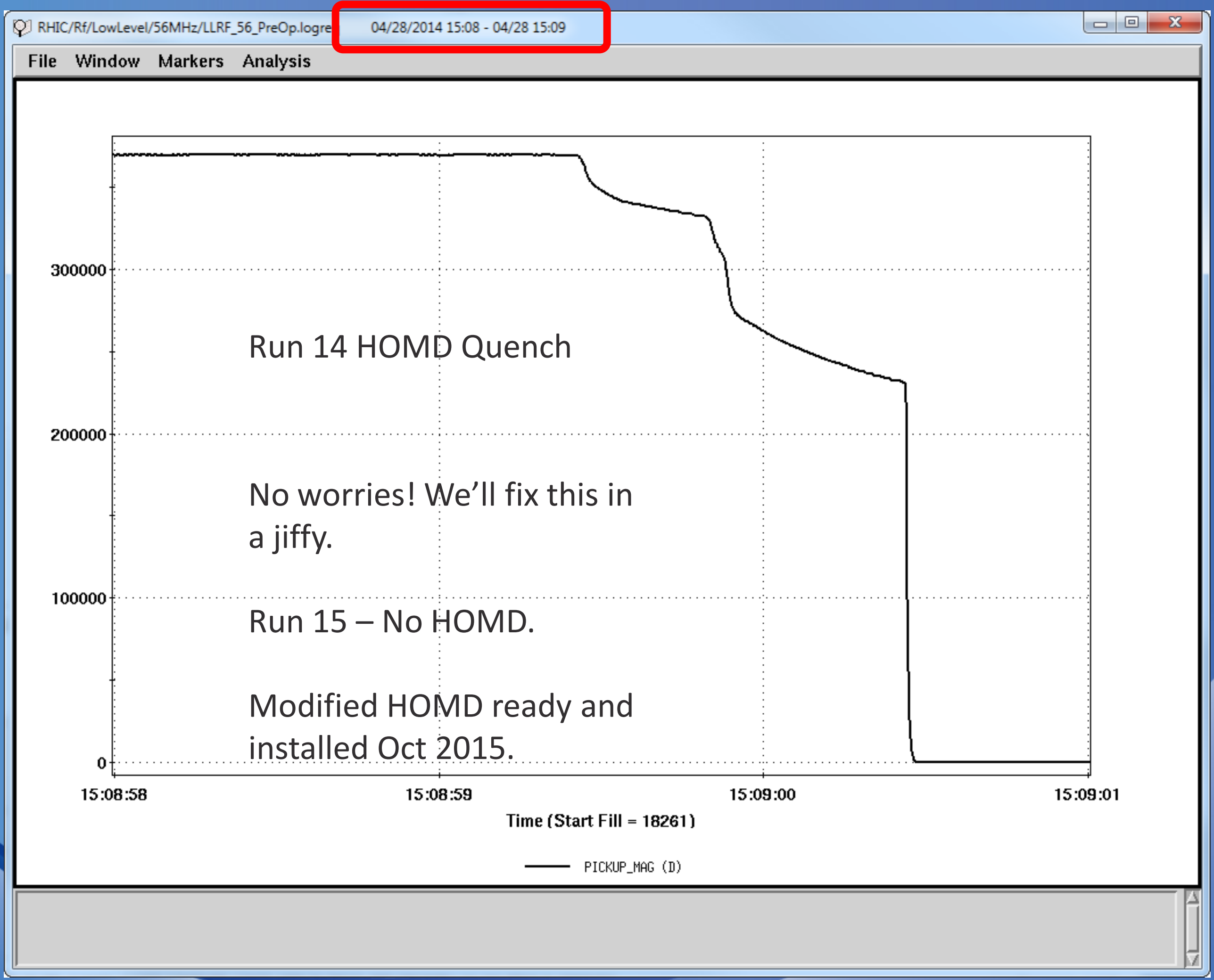
$$Z_{cav} = \frac{R_0}{1+j\frac{\Delta f}{BW_{½}}} \qquad \Delta f \gg BW_{½} \implies |Z_{cav}| = \frac{(R/Q)*f_0}{2*\Delta f_0}$$

(i.e. ind. Of Qext)



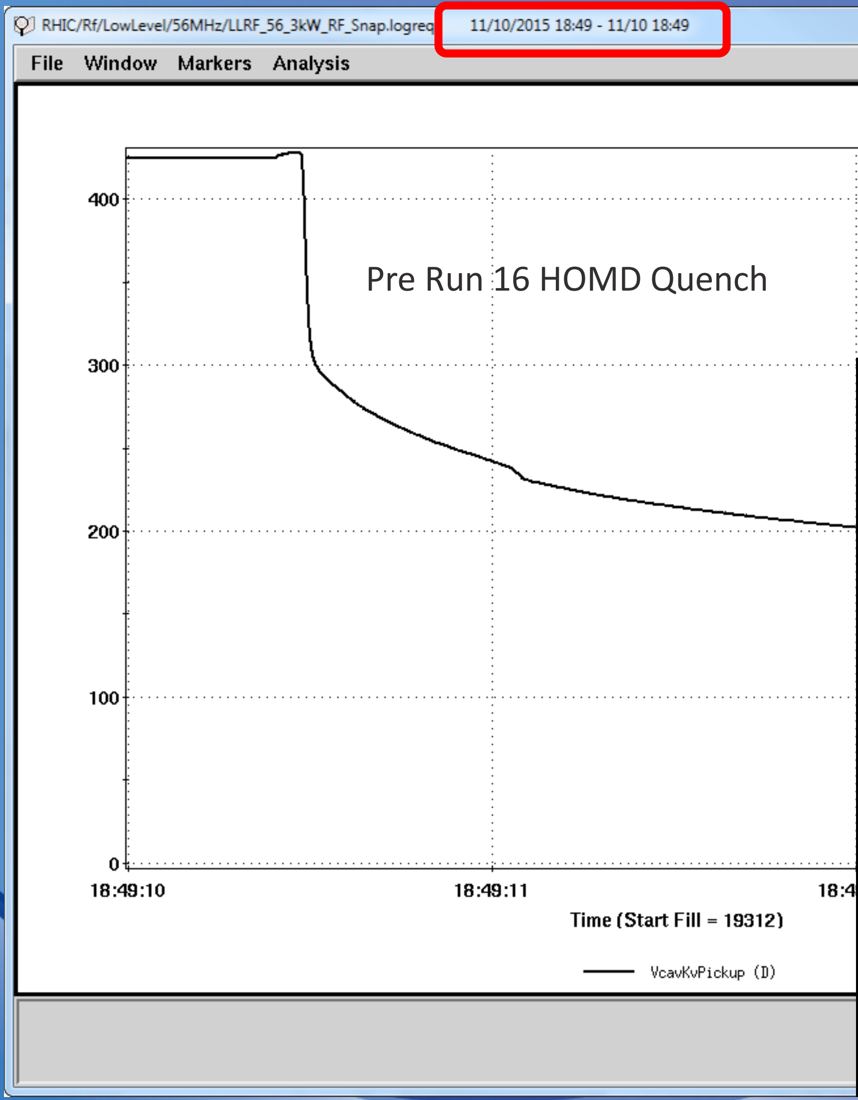


Refresher on How It's Not Supposed to Work
(Run 14 raison d'nêtre: le éteindre de amortisseur mode haut original)



Refresher on How It's Not Supposed to Work
(Run 16 raison d'nêtre: le éteindre de amortisseur mode haut nouveau)

Pre Run 16 Dewar Testing: The Agony of Defeat



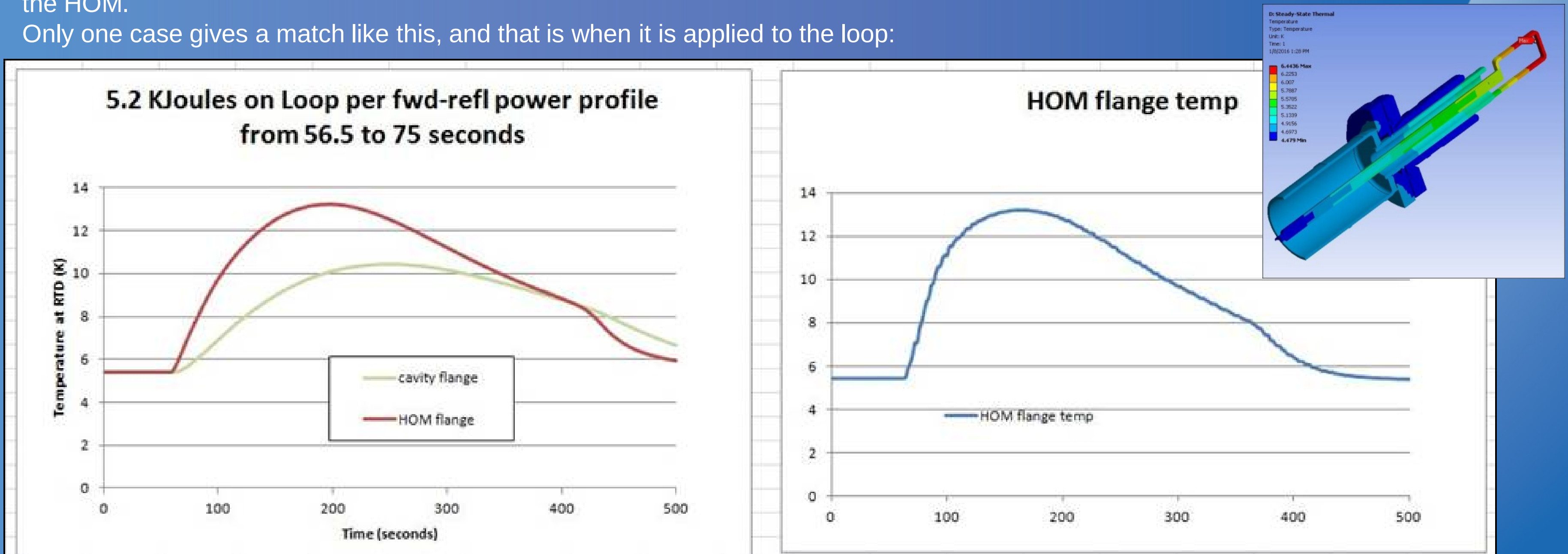
Refresher on How It's Not Supposed to Work
(Run 16 raison d'nêtre: le éteindre de amortisseur mode haut nouveau)

Refresher on How It's Not Supposed to Work
(Run 16 raison d'nêtre: le éteindre de amortisseur mode haut nouveau)

e-mail, S. Bellavia, 12/20/2015

Maybe we've found the real problem?

Hi,
After a concentrated effort by Scott and I, during this short work week, we have attained a positive ID on the thermal transient fingerprint, for the 56 MHz HOM damper.
We built a simple, but very representative FEA model, and ran several cases, applying the 5 KJoules of energy to various portions of the HOM.
Only one case gives a match like this, and that is when it is applied to the loop:



The curve on the left is from the simulation, the curve on the right is the temperature readout from the RTD on the flange.
I have attached a detailed report, but we should have a meeting to discuss this further.
Happy New Year!

Steve
P.S. This successful simulation is in large part due to Scott Seberg's relentless perseverance to not only find a solution to the problem, but to find its root cause as well.

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Refresher on How It's Not Supposed to Work
(Run 16 raison d'nêtre: le éteindre de amortisseur mode haut nouveau)

Editorial Digression: See Title Slide – Share Victory. Share Defeat.

No fewer than 10 people spent a significant amount of time analyzing the Run 14 HOMD quench problem – a lot of smart people, and me as well. In the end, we all agreed on the apparently obvious problem – don't put normal conducting braze in an SRF HOMD. A lot more work went into removing the sapphire window (and braze) and then overcoming new issues resulting from that. In the end, it turned out that the HOMD had still more problems and continued to quench at "low" field.

We lick our wounds, learn from our mistakes and move on.

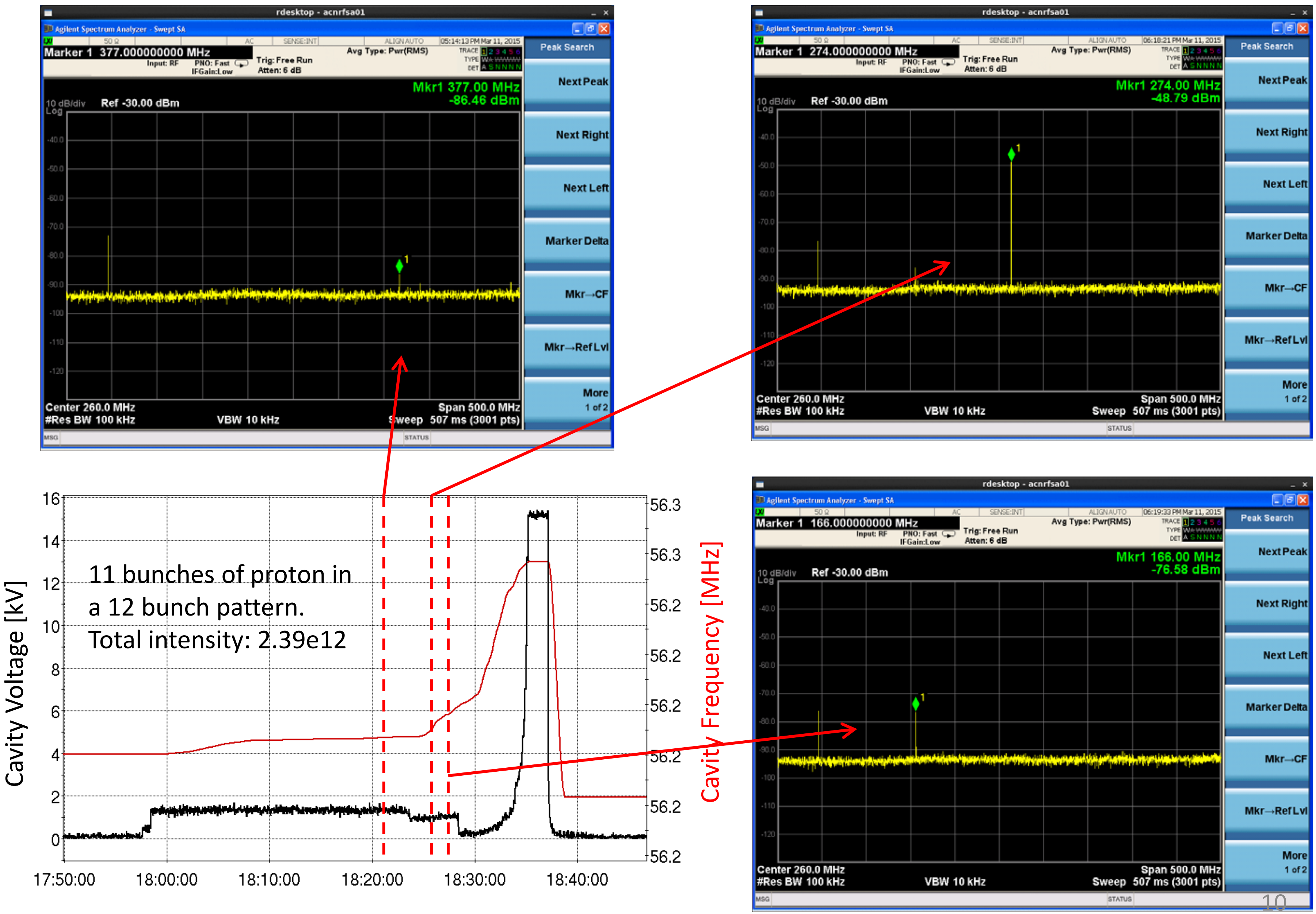
My own personal thoughts:

1) SRF is hard living – don't underestimate just how hard.
2) New ("innovative") SRF designs will always take A LOT of time to validate. Many things can go awry.
3) It is imperative to perform thorough testing of fully dressed SRF systems prior to operational installation – aka horizontal test.

In the case of the 56MHz, RHIC was our horizontal test.
Same for the CeC PoP Gun and 5-Cell.
We need to avoid this going forward. But right now, we play the hand we're dealt.

Refresher on How This Thing Works without an HOMD

(It Doesn't - Retreat 2015, Q.Wu)



Refresher on How This Thing Works without an HOMD

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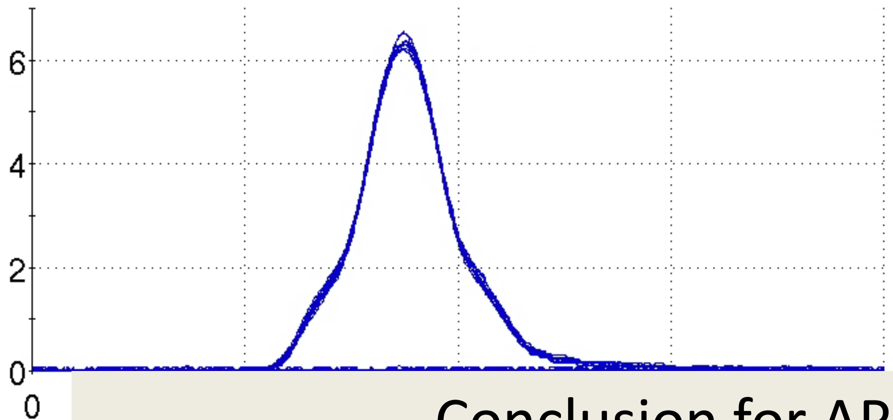
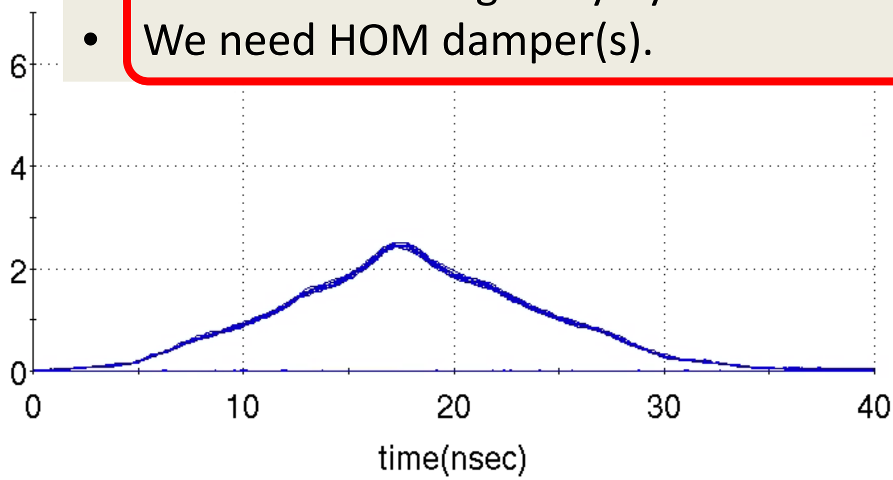


Beam profile 1

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

Conclusion for APEX

- The cavity frequency sweeps through first four monopole HOM resonance lines within the full tuning range.
- No observation of excited dipole/quadrupole HOMs.
- Beam is affected greatly by the excited HOMs in the cavity.
- We need HOM damper(s).



Beam profile 2

Beam profile after we swept through multiple HOM resonance lines

When You Come to a Fork in the Road – Take It.

"IF NO ONE COMES FROM THE FUTURE TO STOP YOU FROM DOING IT, THEN HOW BAD OF A DECISION CAN IT REALLY BE?"

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.

Solving For Unknowns

- Goal:
  - Use the fundamental damper to damp the high order modes too.

- Unknowns:
  - Important modes to avoid.
    - Need to know the mode spectrum, and which one's are a problem.
    - Need to know to beam spectrum.
  - Mode Frequency and Qext variation as a function of tuner and damper positions for all pertinent modes.
    - Not a static problem.
  - Power limitations of FMD and FPC.
    - FPC never designed for high CW power.
    - FMD designed for high transient power.
      - Not designed for high power CW operation.

- Figure out the solution in two months.

Solving For Unknowns (Modes)

- Reduced the complexity of the problem by only analyzing monopole modes below 500MHz.
  - Run 15 experience showed that these are the primary troublemakers.

Monopole Modes Considered for Analysis (Roughly h=1,3,5,7,9)

1) fo ≈ 56MHz (the fundamental mode)
2) fo ≈ 166MHz
3) fo ≈ 274MHz
4) fo ≈ 377MHz
5) fo ≈ 474MHz

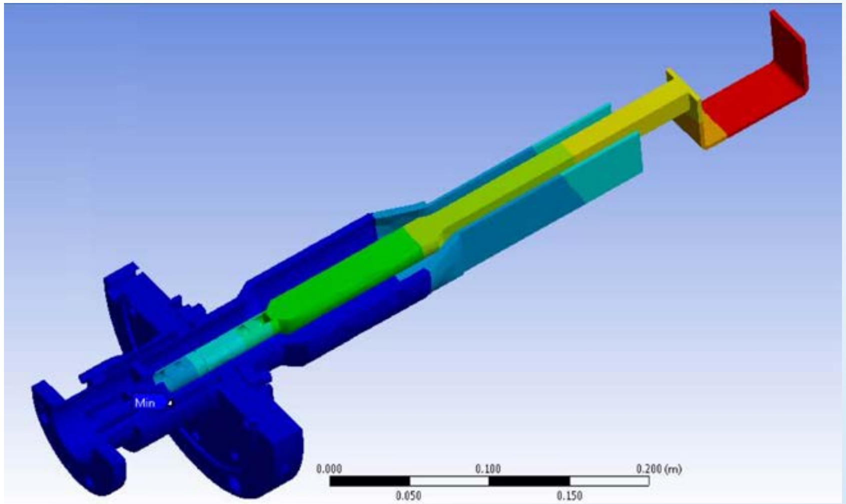
- Qiong Wu performed RF simulations.
- Kevin Mernick performed careful and tedious measurements of frequency and external Q for various tuner and damper positions.
- S. Polizzo translated the data into a usable map.
- Used the map to walk through the minefield.

Solving For Unknowns (Power)

- Performed steady state and transient thermal simulations of the fundamental damper
  - Power extracted = 20kW

Damper Loop Temperature and Radiated Power

Time (s)	Temp (K)	Rad Power (W)
0	298.15	0.044520175
5	325.0978	0.062932298
10	340.2814	0.075538822
30	377.0896	0.113918969
60	412.1609	0.162586603
120	453.4506	0.238197767
3600	655.378	1.039405542

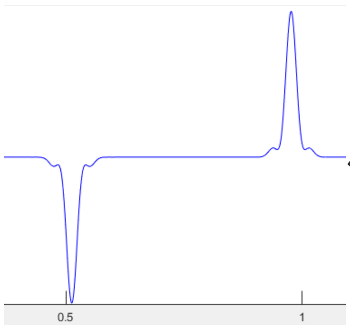


- Empirically optimized FPC extracted power and required amplifier power.
- Closely monitored pertinent cyro heat loads.
- This operating mode was never envisioned in original design.

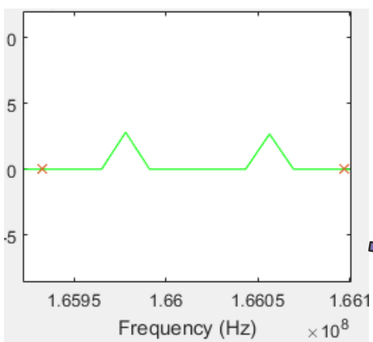
Navigating The Minefield

- Matlab code written to map the HOM landscape.
  - Code compiles the mode frequencies and associated external Q data into matrices that are then interpolated to improve data resolution.
  - These matrices are then used to resolve the HOM impedances for all applicable damper and tuner positions.
  - A time domain bunch train is created to have the same characteristics as post re-bucketed beam at the 56MHz gap.
  - Each beam revolution line within a given HOM tuning range is evaluated independently and the cumulative sum of the resulting voltages are displayed.

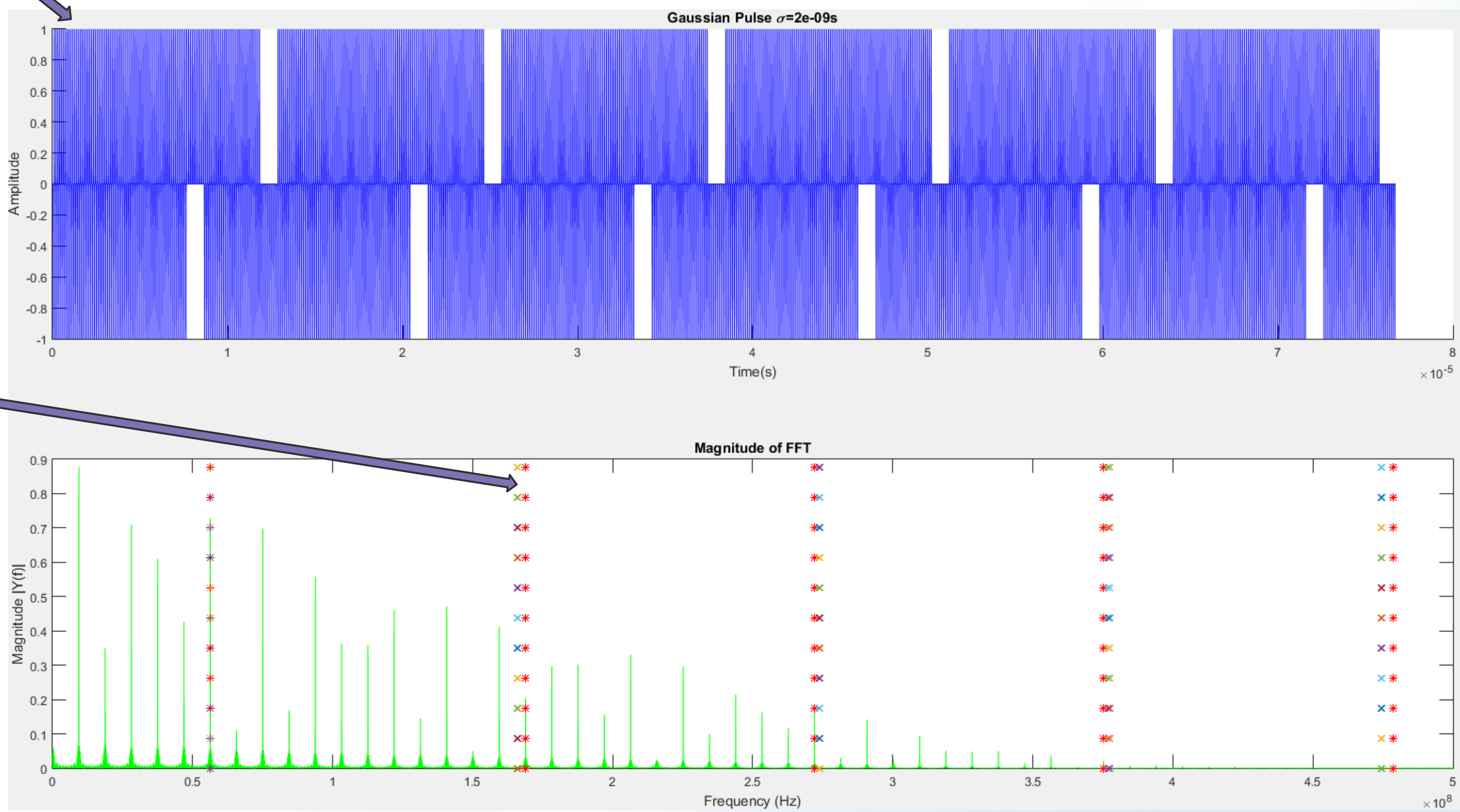
Navigating The Minefield



Bunch Train at 56MHz Gap

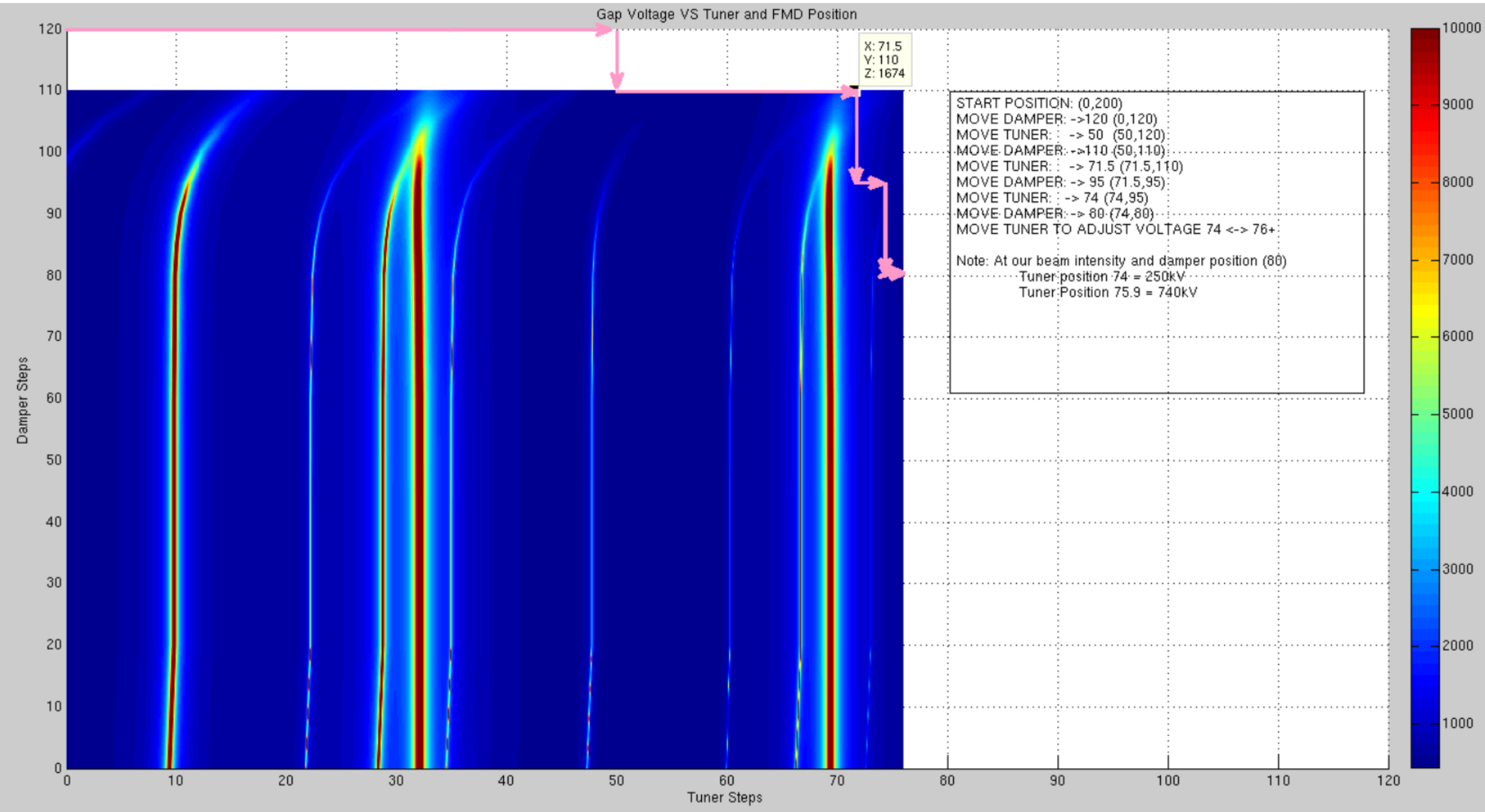


H=3 Example



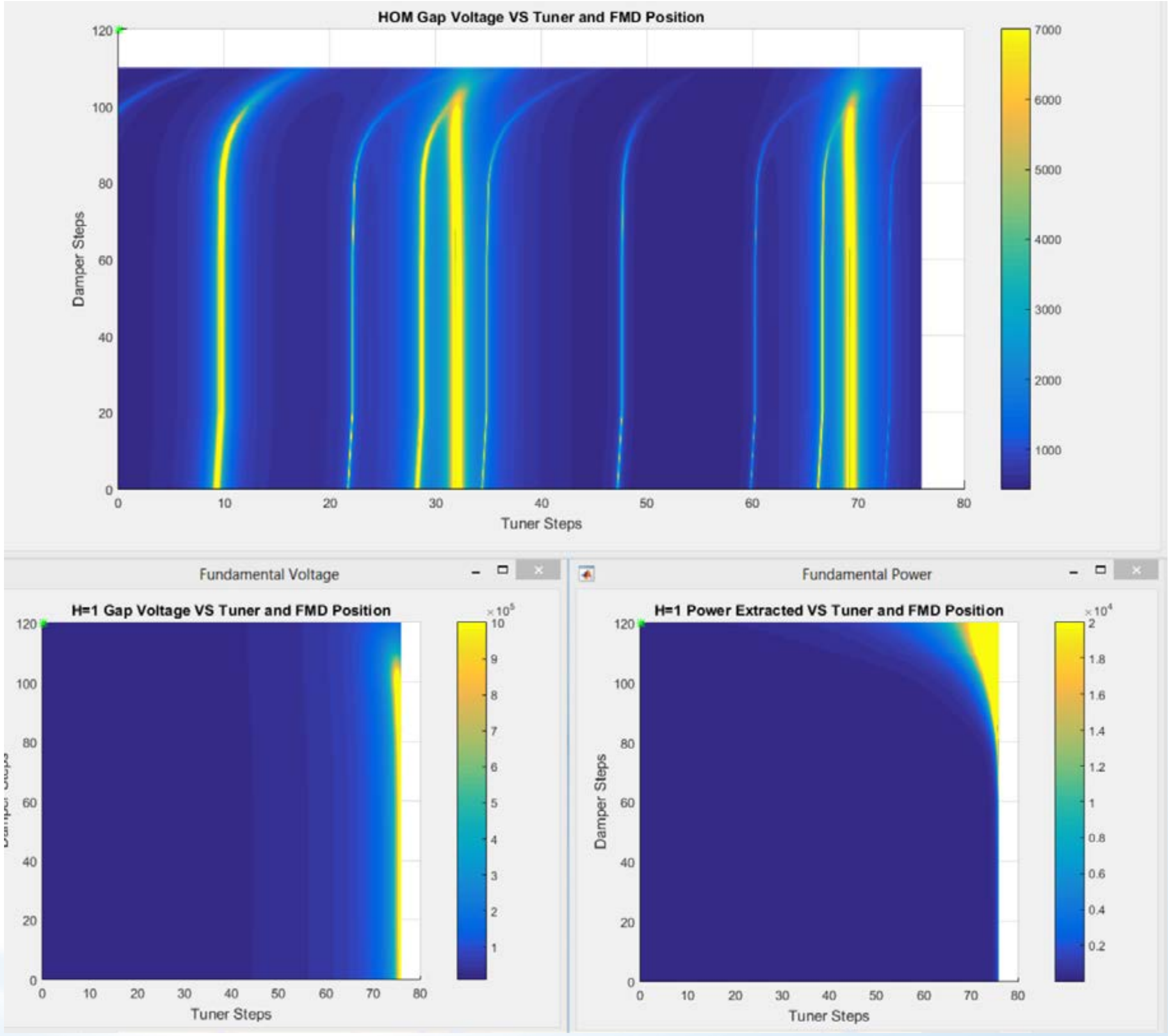
Navigating The Minefield

- The complete map combines all HOM voltage matrices
  - Well this looks like it couldn't be any easier!
    - No.



Navigating The Minefield

- Putting it all together with fundamental mode stress considerations.
- Movie Time …

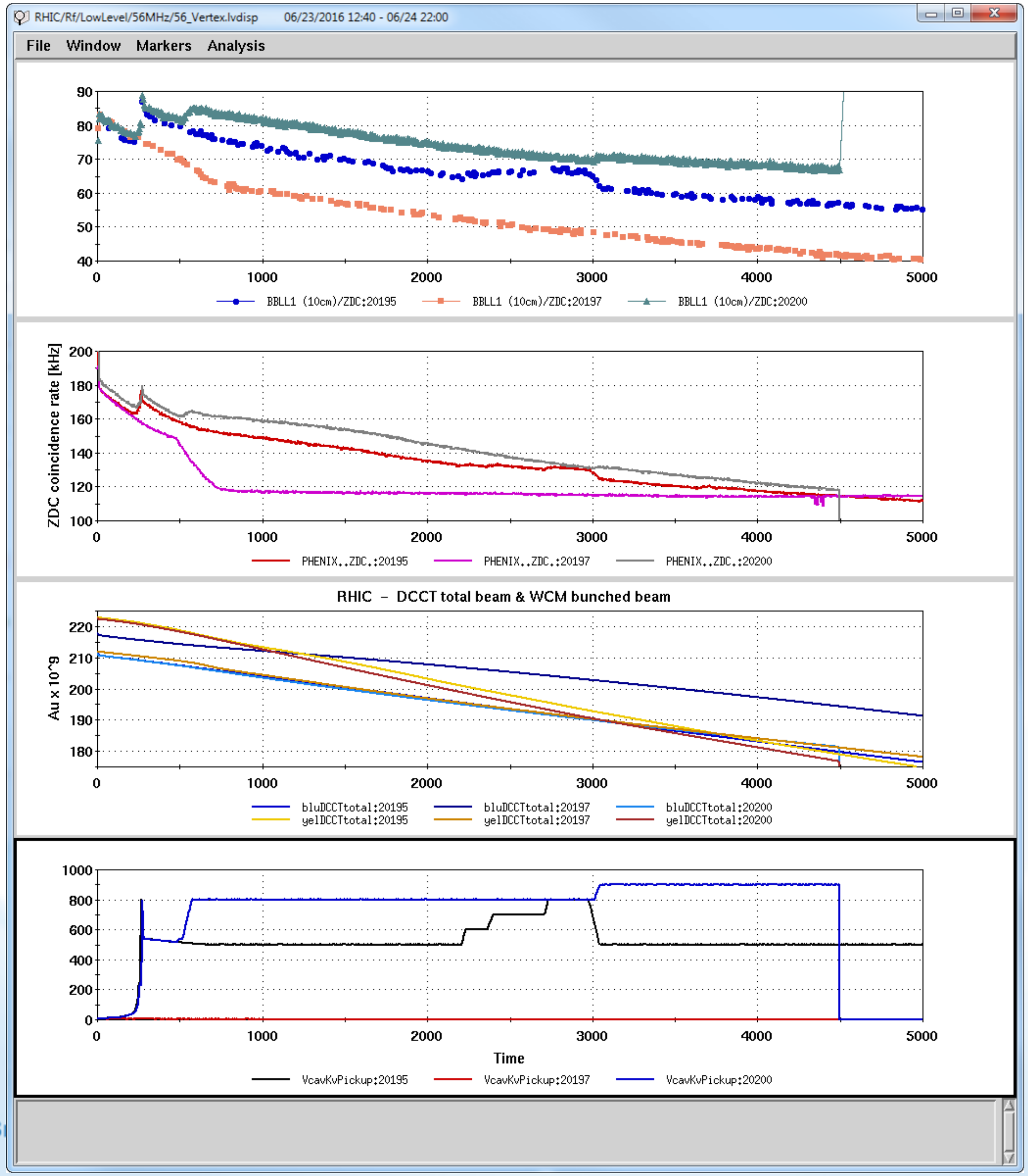


Final Exam Results

56 MHz SRF Cavity Run 16 Timeline

- Nov 3-4 2015 : Test of modified HOMD reveals continued quench problem.
- Nov 2015 – Jan 2016:
  - Open cryomodule, remove HOMD, close cryomodule.
  - Evaluate options and settle on FMD as best path forward.
  - Detailed RF simulations, HOM mapping, power / thermal simulations.
  - Develop recipe for turn on path.
- Jan 26 : Cavity cold and RF (no beam) testing began.
- Feb 25 : First testing with beam.
- March 3 : Reached 1MV with beam (1/2 intensity).
- April 13 : Reached 750kV with full intensity beam, lost control due to RF power saturating, quench.
- April 22 : Reached 725kV with full intensity, stable. Thwarted by machine issues.
- April 25 : Reached 750 kV with full intensity, stable. Thwarted by FMD motion.
- April 27 : Reached 750 kV with full intensity, stable. Thwarted by a “discharge event”.
- …
- May 13 : First full store operation, at 500kV (d-Au).
- May 14 : Full store at 600kV (d-Au).
- May 16 : Full store at 700kV (d-Au).
- May 17-18 : Full store at 800kV & 900kV (d-Au).
- May 19 : Half store at 900kV, half at 1MV.
- May 19 : 10 minutes at 1MV, then “discharge event”.
- May 19 : Full store at 1MV.
- May 19-20 : 1.5 hour store, then another “discharge event” at 1MV. Burst disc rupture.
- June 24 : Final attempt. FMD partially inserted for operation to damp parasitic FPC resonance. At 900kV, tripped MPS and pulled permit on a cryo interlock. FMD RF dissipation is the likely cause, but this hasn’t been analyzed yet.

What Effect Does the 56MHz Have?



PHENIX 10cm / ZDC

PHENIX ZDC

Au-Au 100 GeV

B&Y DCCT

56 MHz Voltage (kV)

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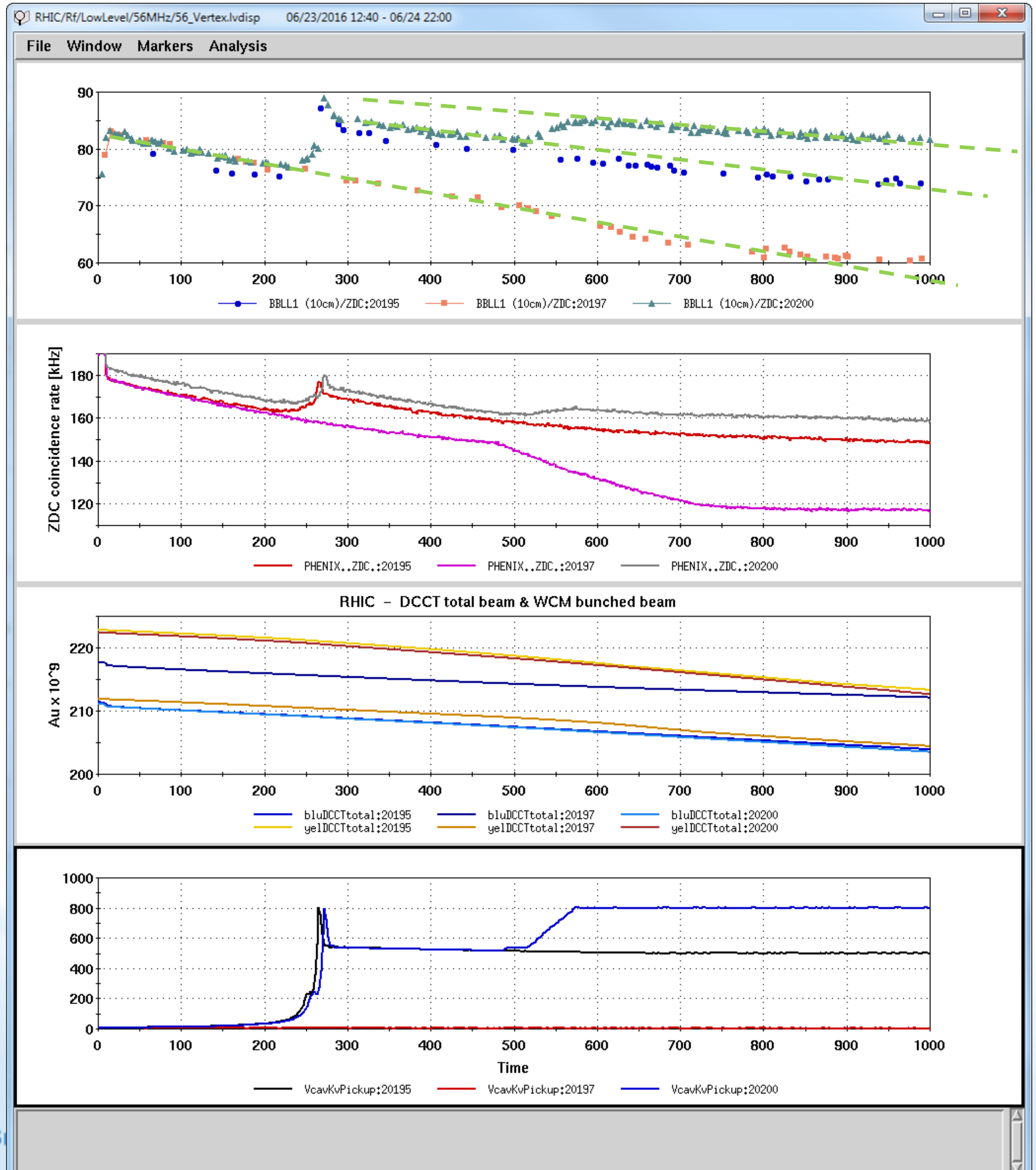
What Effect Does the 56MHz Have?



PHENIX 10cm / ZDC

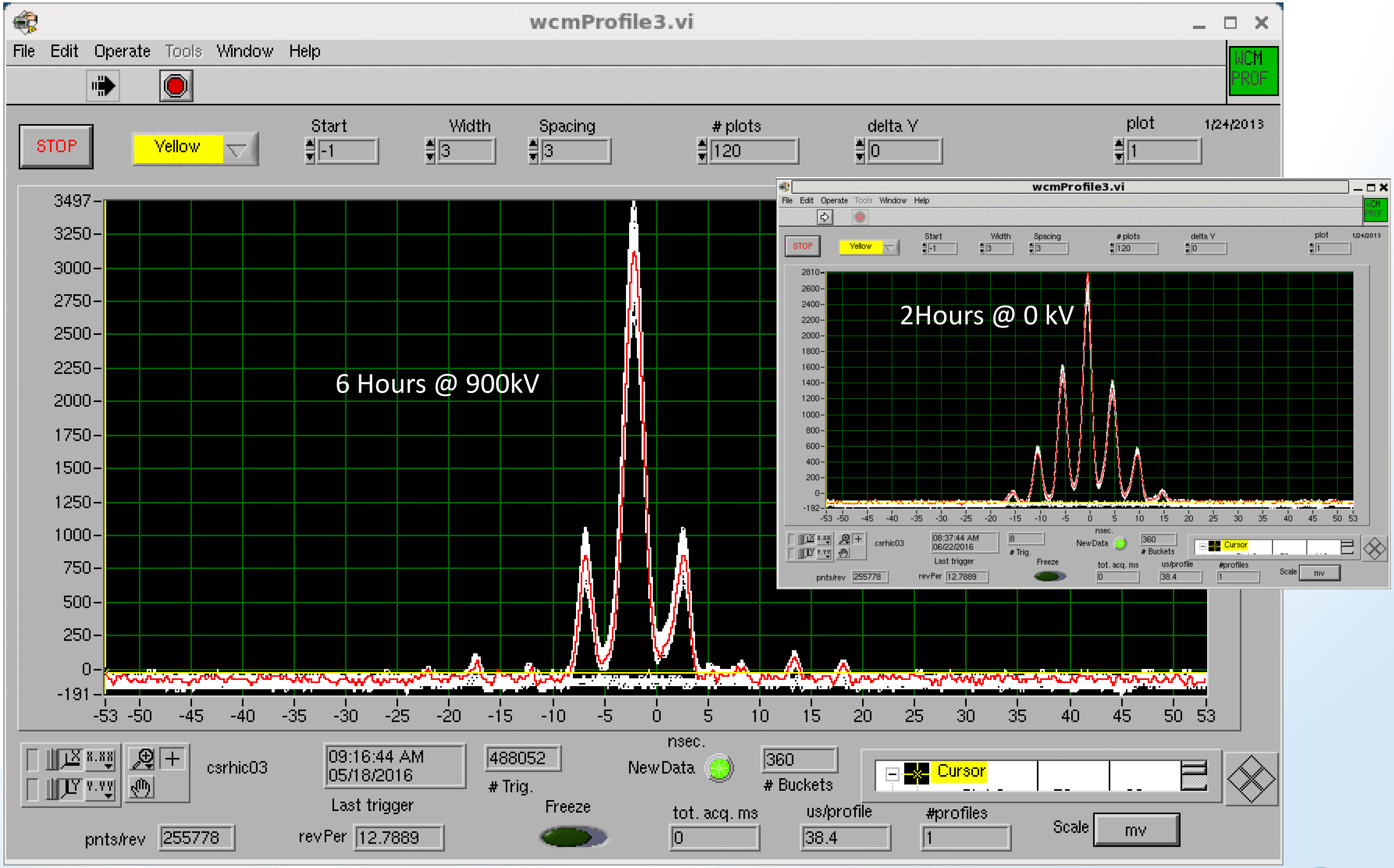
PHENIX ZDC

Au-Au 100 GeV

B&Y DCCT

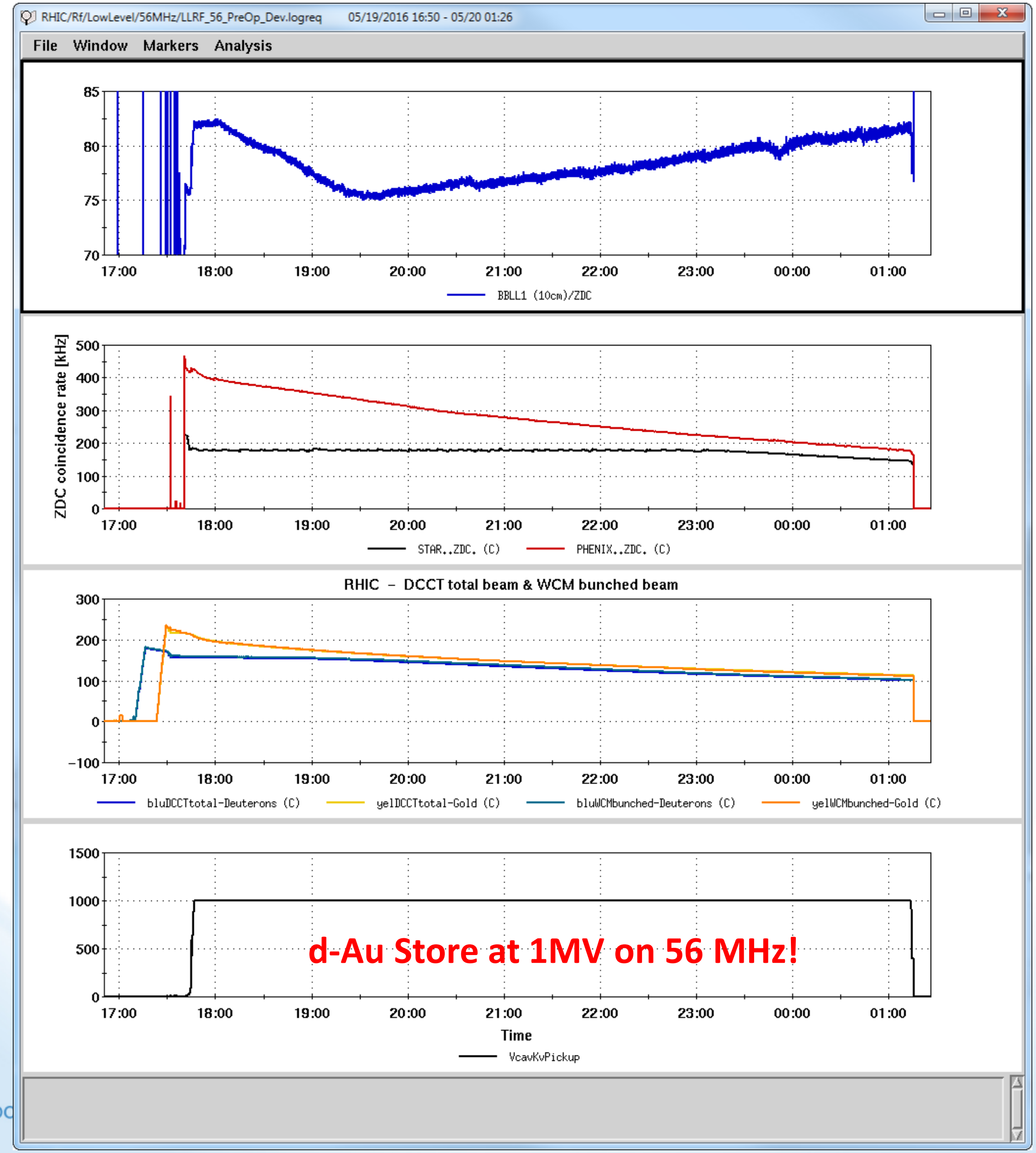
56 MHz Voltage (kV)

What Effect Does the 56MHz Have?



d-Au: Yellow Au WCM

Full d-AU Store with 1MV on the 56MHz



PHENIX 10cm / ZDC

PHENIX & STAR ZDC

B&Y DCCT

56 MHz Voltage (kV)

Full d-AU Store with 1MV on the 56MHz

Achieving 1MV operation is a great step forward for C-AD.

Proved that we can successfully operate an SRF cavity in an operational machine.

A very good first step in establishing SRF credibility.

Forward – Ever Forward

Looking Forward

- Achieving 1MV operation is a great step forward for C-AD.
  - Proved that we can successfully operate an SRF cavity in an operational machine.
  - A very good first step in establishing SRF credibility.
  - Provided us with a tremendous amount of experience and information as to overall cavity operation and behavior.
  - Validated the HOM map and the dominance of the monopole modes.
  - Proved that we can provide adequate HOM damping up to 1MV using only the FMD.
  - Provided valuable data on optimization of the FPC Qext.
    - Trade offs between FPC emitted power and PA forward power required for stabilization.
  - Exposed weaknesses in the cavity and RF.
    - Drift in the high power circulator.
    - Parasitic resonance in the FPC.
    - Limited CW power handling in the FPC and FMD.
    - Exposed weakness in the LLRF protection scheme.
      - Provided validation of new protection methods.
    - Problematic spurs in the RF PA output.
  - Provided validation of the LLRF feedback loops used to stabilize the cavity.

Looking Forward

- Run 17 (250 GeV PP)
  - The cavity is not needed for operational running.
  - But need to continue to operate and gain experience.
    - And, we may get some ion running.

  - Shutdown 16/17
    - Opening the cryomodule to assess and remediate observed problems with the FPC.
    - Will likely be replacing the internal FPC heliax RF cable with a more robust transmission line.
      - We suffered what appear to be multiple breakdown events internal to the FPC cable.
    - See what else we find that needs fixing or modification.

  - Run 17
    - Expect to initially run the cavity during MD.
    - Desirable to run operationally at store as well, if benign.
    - Primary goal is to improve our understanding of the cavity, its limitations, etc.
    - Because …

Looking Forward

- Run 18 (Fancy Ions)
  - The cavity is needed for operational running.
  - Our goal is to operate stably at store at greater than 1MV.

  - But …
    - 1MV was essentially our observed operational limit in Run 16, due to:
      - PA power limitations and non-linearity.
      - FPC power limitations.
      - FMD power limitations.
      - FPC parasitic resonance.

    - In order to achieve stable operation above 1MV, we need to address these issues.
      - Run 17 provides our last chance to learn what we need to learn.

    - Run 17/18 Shutdown
      - Have a well conceived and detailed plan to make all remaining required modifications to provide stable running above 1MV in Run 18.
      - Another very resource heavy effort which has to begin before Run 17 ends.

Looking Forward

- sPHENIX (2022?)
  - The 56 MHz cavity will need to run at its design voltage of 2MV.
  - Following Run 18:
    - Remove the cavity from RHIC and relocate to the 912 test cave (former ERL experiment).
    - Develop and test all modifications needed for 2MV.
      - Final HOM Damper scheme.
        - Not yet clear what this is.
        - I do not expect it to involve SRF HOM Dampers.
      - Final FPC scheme.
        - Not yet clear what this is.
      - Disassemble cryomodule, reprocess cavity, vertical testing, reassemble cryomodule.
      - Modifications to internal cryo plumbing.
      - Cavity conditioning to operational 2MV CW.
      - Reinstall in the 4IR.

Acknowledgments

- There were many challenges and many parallel efforts that needed to be addressed along the way. The 56 team had to put forth a tremendous amount of effort to pave this path to 1MV.
- Efforts and Difficulties
  - HOMD Install & Removal (S. Seberg, Cryo, Vacuum, Instrumentation …)
  - Linearizing the 3kW QEI amplifier with a pre-distortion scheme
  - AC coupled IQ loop margin – circulator temperature drift
  - Optimization of FPC forward vs reflected power
  - If it could go wrong, it did (blown cable, S/A glitches, …)
  - FPC parasitic resonance
  - Very limited time available for testing and debug
  - Development of added cavity protection mechanisms in LLRF
- Some other projects that required the team's attention
  - Development, installation and commissioning of five new Linac LLRF systems.
  - Development and commissioning of CeC RF systems, including 704 MHz 5-Cell SRF cavity, new this year.
  - Roll-out and commissioning of new LLRF FPGA firmware across all machines to support 2Gb/s Update Link.
  - Commissioning of new 9MHz cavity.
  - Support of operations across all machines.

More Acknowledgments

- There are many, many people and groups who contributed to this effort – too many to list, but don't doubt your efforts are recognized.
- I'd like to specifically thank:
  - Sal Polizzo
    - Sal's extensive RF expertise, creativity and tenaciousness were the key to our success.
  - W. Fischer and A. Zaltsman
    - Provided unwavering support under very challenging circumstances.
  - B. Christie
    - Supported the effort and gave us every opportunity we requested.
      - This was a critical run for STAR.
      - Made very difficult choices and did a great job wearing both his hats.
      - Even gave us a shot in the final week when the stakes were highest!

Thank You