US-LHC Accelerator Research Program

Tune, Chromaticity, and Coupling Measurement and Feedback

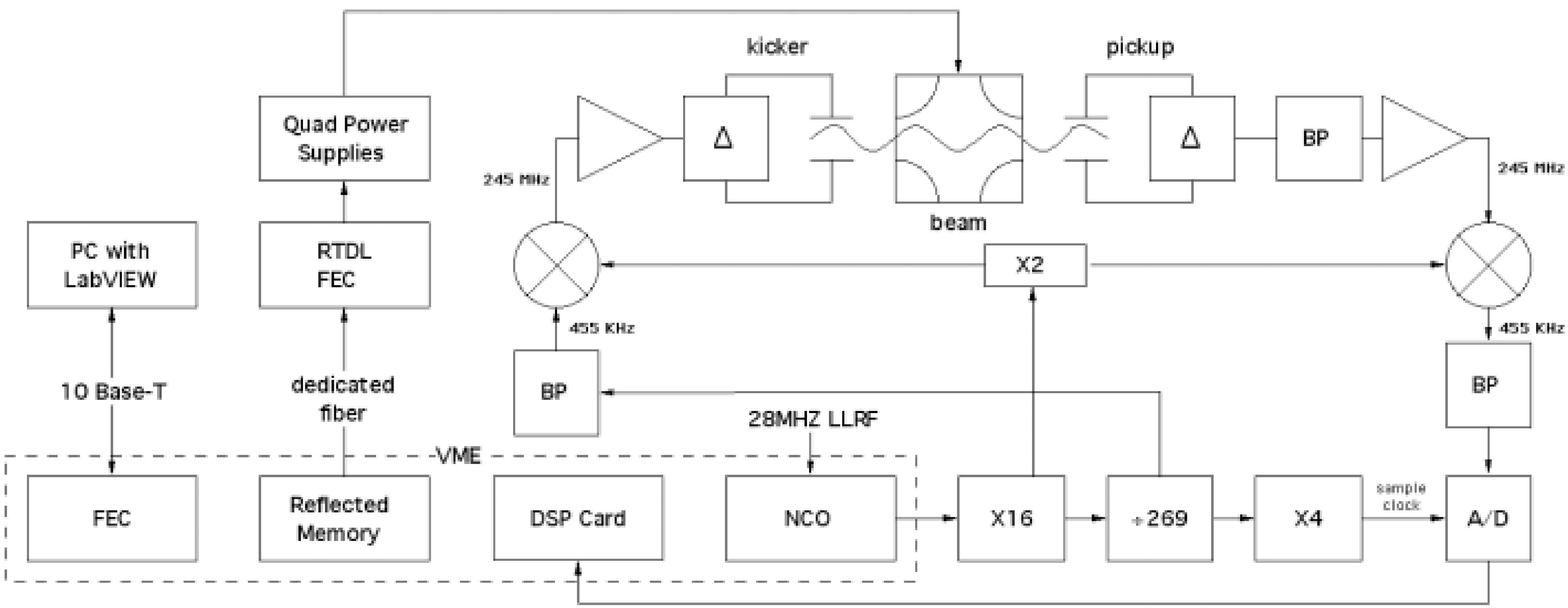
FY04 Results and Plans

Peter Cameron
BNL

Outline

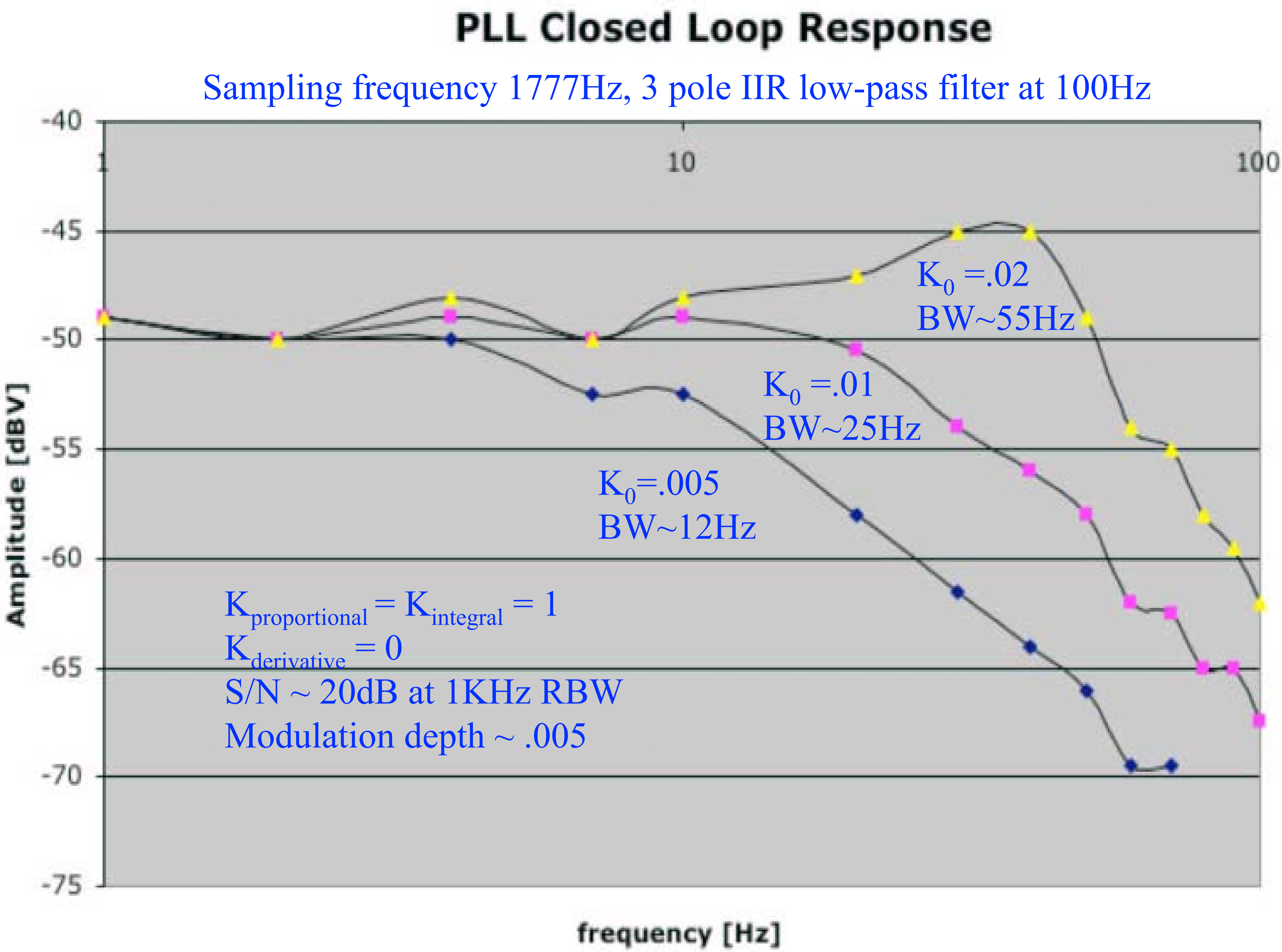
- Recent results
  - 245MHz PLL
    - Tune, chromaticity, coupling
  - Baseband PLL
    - Emittance growth
  - Plans for SPS testing
- Possible system configurations
- PLL Problems/Plans for FY05/06

PLL Block Diagram



Modeling and Beam Simulation

- PLL without beam – two models
  - Mathcad frequency domain
  - LabVIEW time domain
- Beam ‘simulator’
  - Biased ceramic filter
  - Frequency 455KHz, Q ~ 300
  - Additional mixing stage simulates Q of beam at 245MHz
- Good agreement between model and simulator results


PLL Closed Loop Response
Sampling frequency 1777Hz, 3 pole IIR low-pass filter at 100Hz
-40
-45
-50
-55
-60
-65
-70
-75
1
10
100
Amplitude [dBV]
frequency [Hz]
K0 =.02
BW~55Hz
K0 =.01
BW~25Hz
K0=.005
BW~12Hz
Kproportional = Kintegral = 1
Kderivative = 0
S/N ~ 20dB at 1KHz RBW
Modulation depth ~ .005

Plane Selection

Blue Horizontal

Sum

2.88

K_0 =.01

1Hz square wave

BW~25Hz

No overshoot

Dither ~ .0004

Spectrum Unit dBVrms

Sample Rate

1777.00

Log/Linear

dB

display unit

Vrms

window

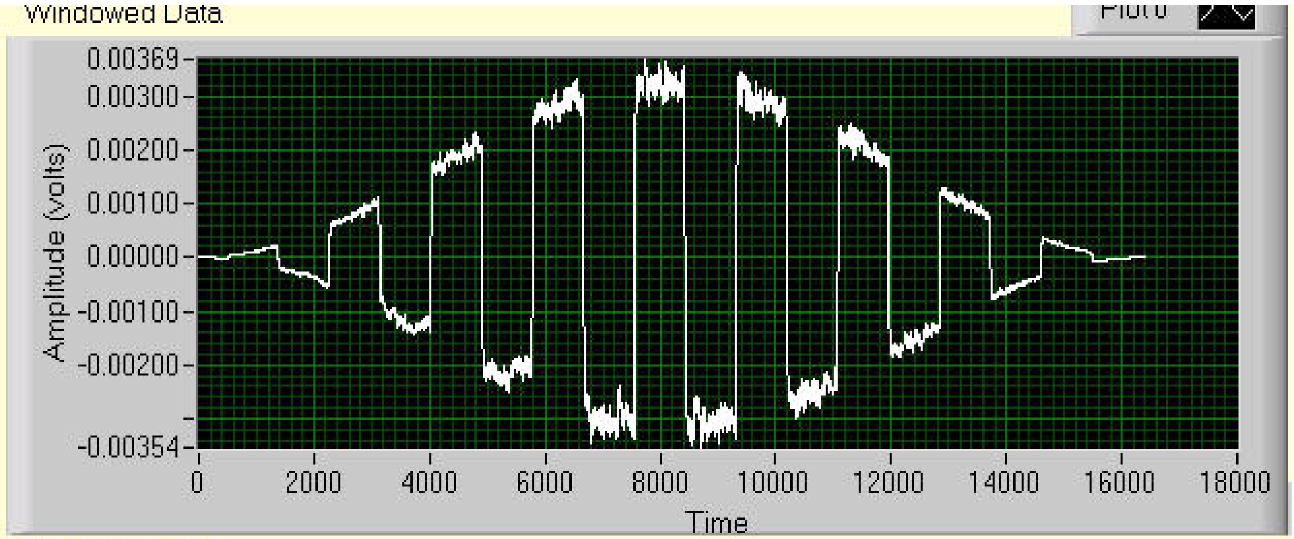
Hanning

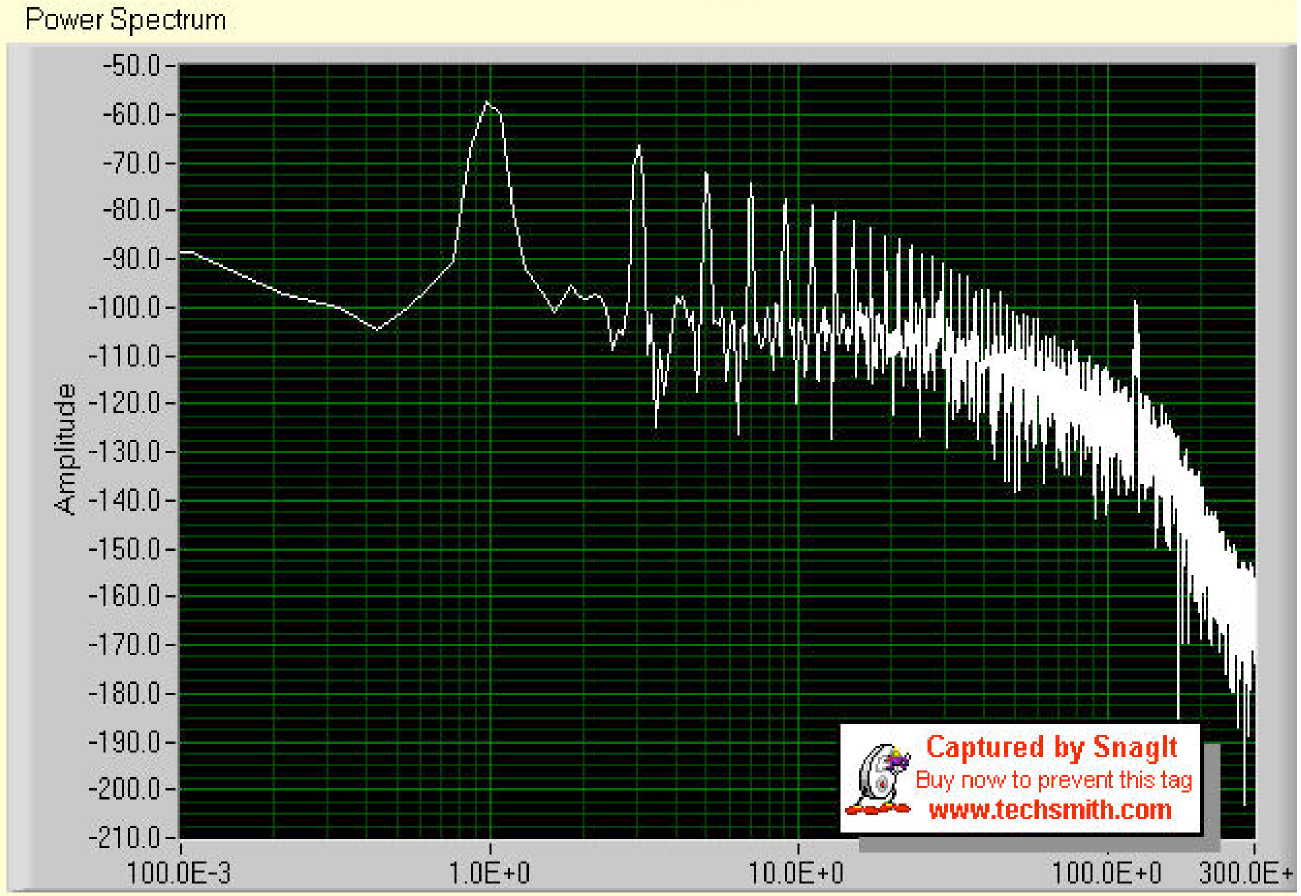
Est Freq peak

1.0063

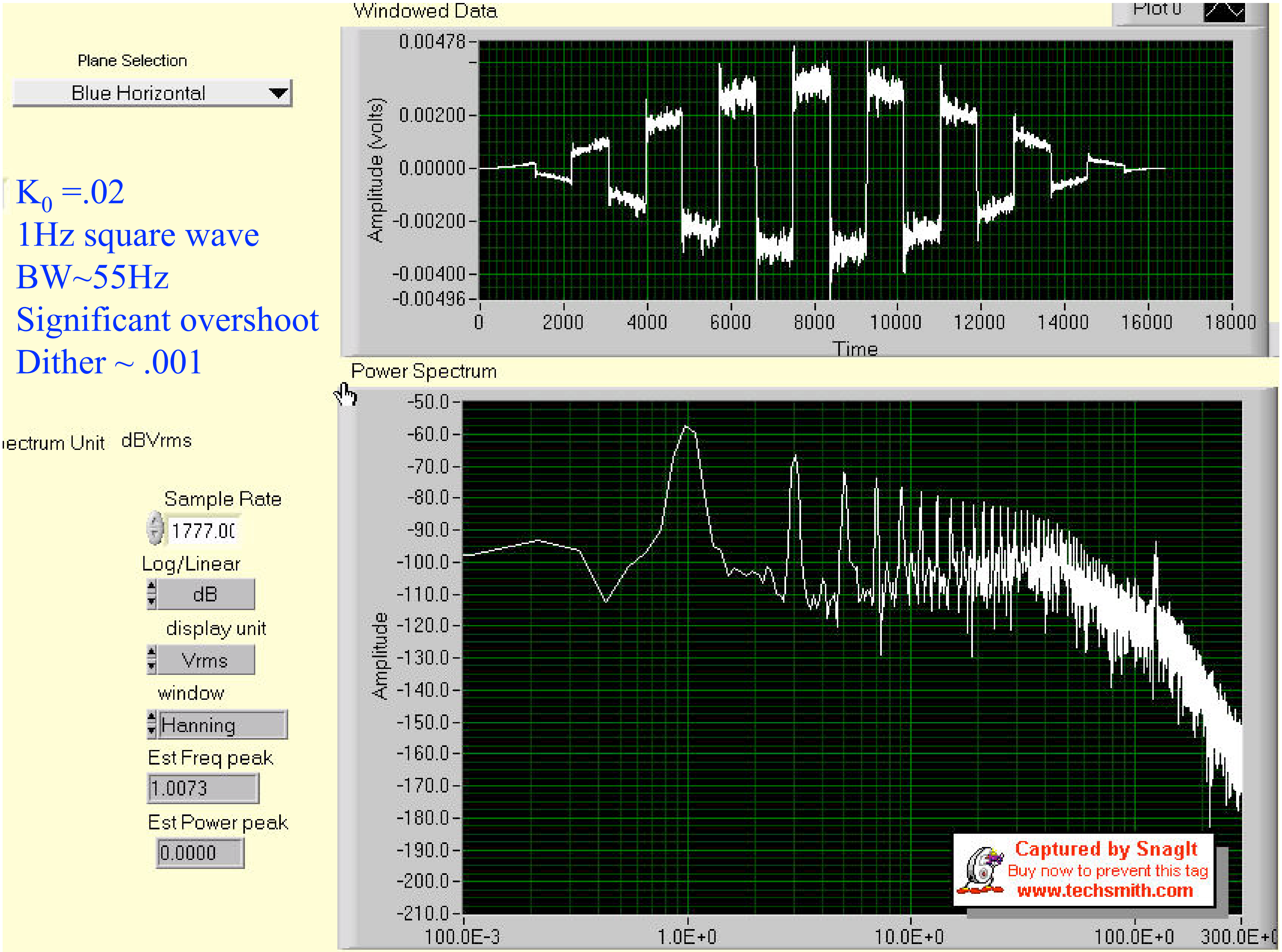
Est Power peak

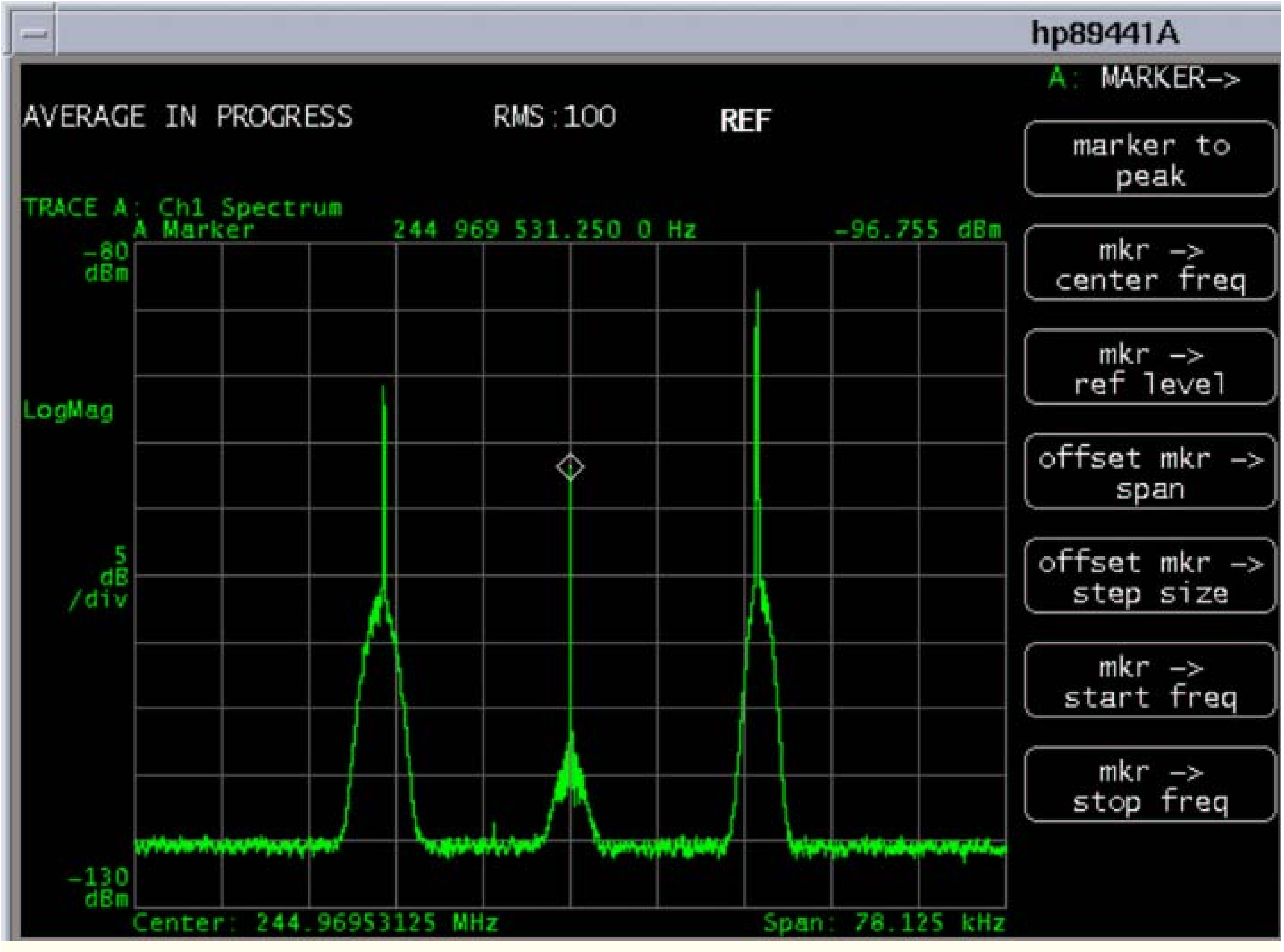
0.0000



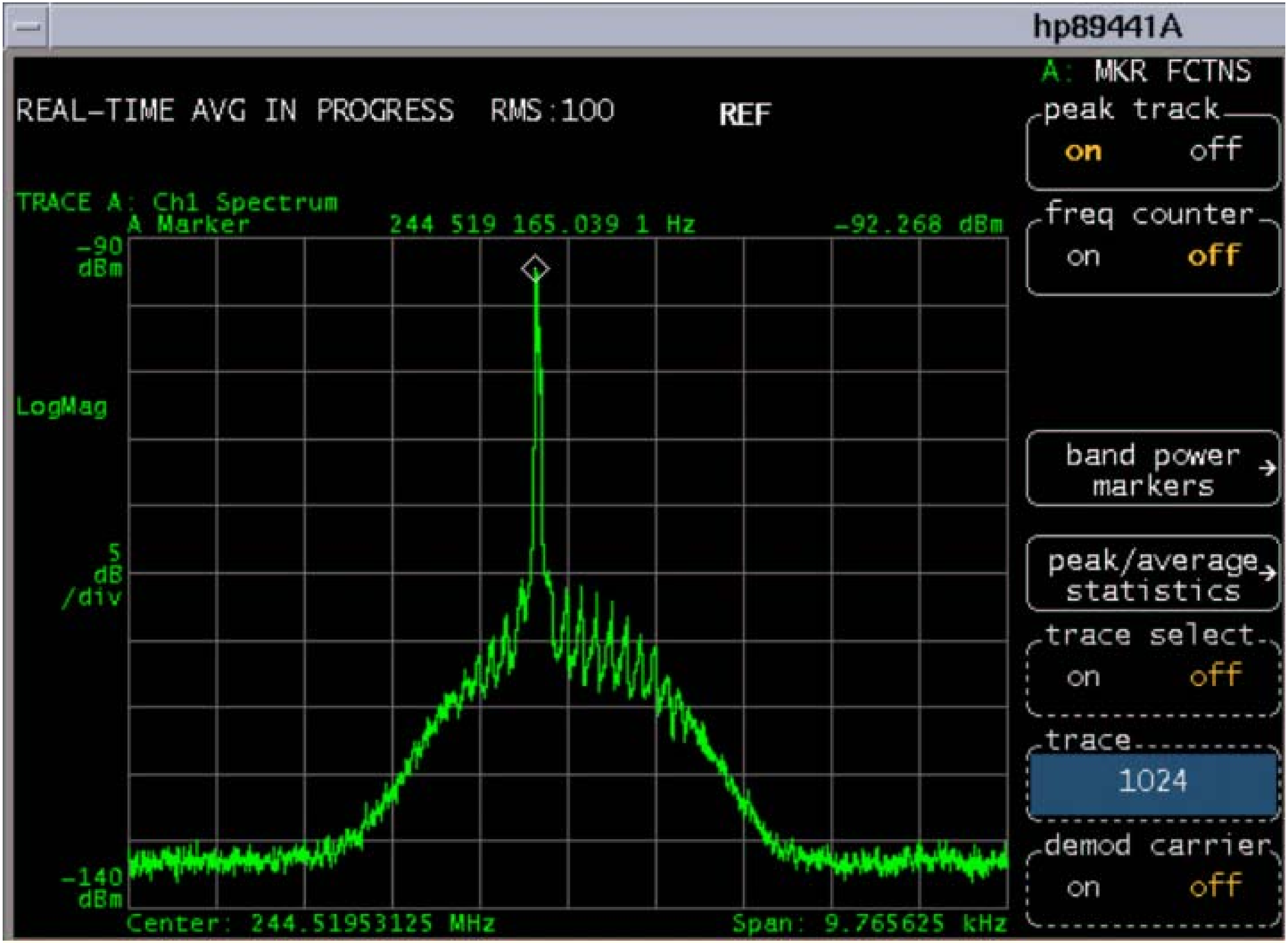


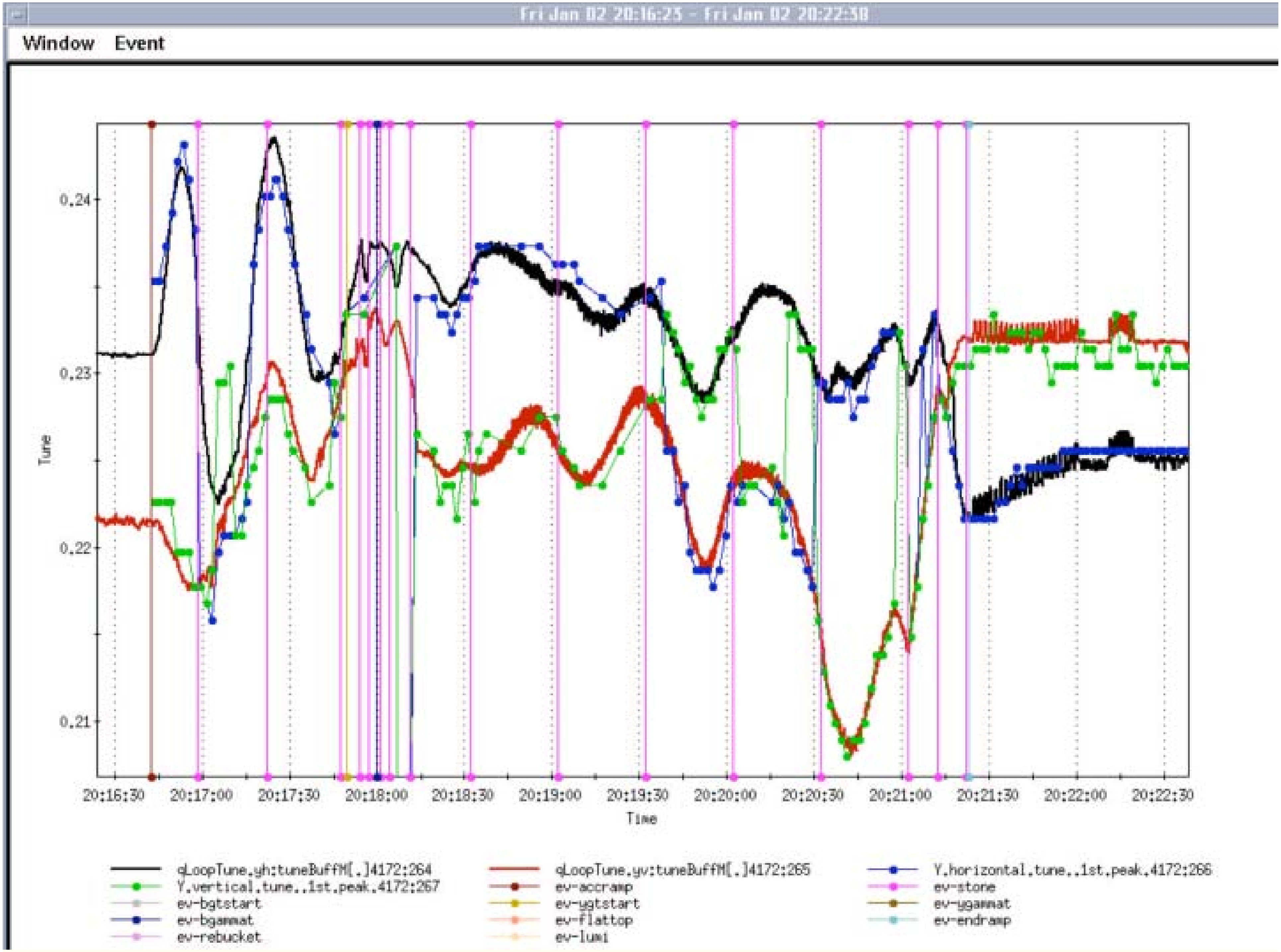
K_0 =.02
1Hz square wave
BW~55Hz
Significant overshoot
Dither ~ .001

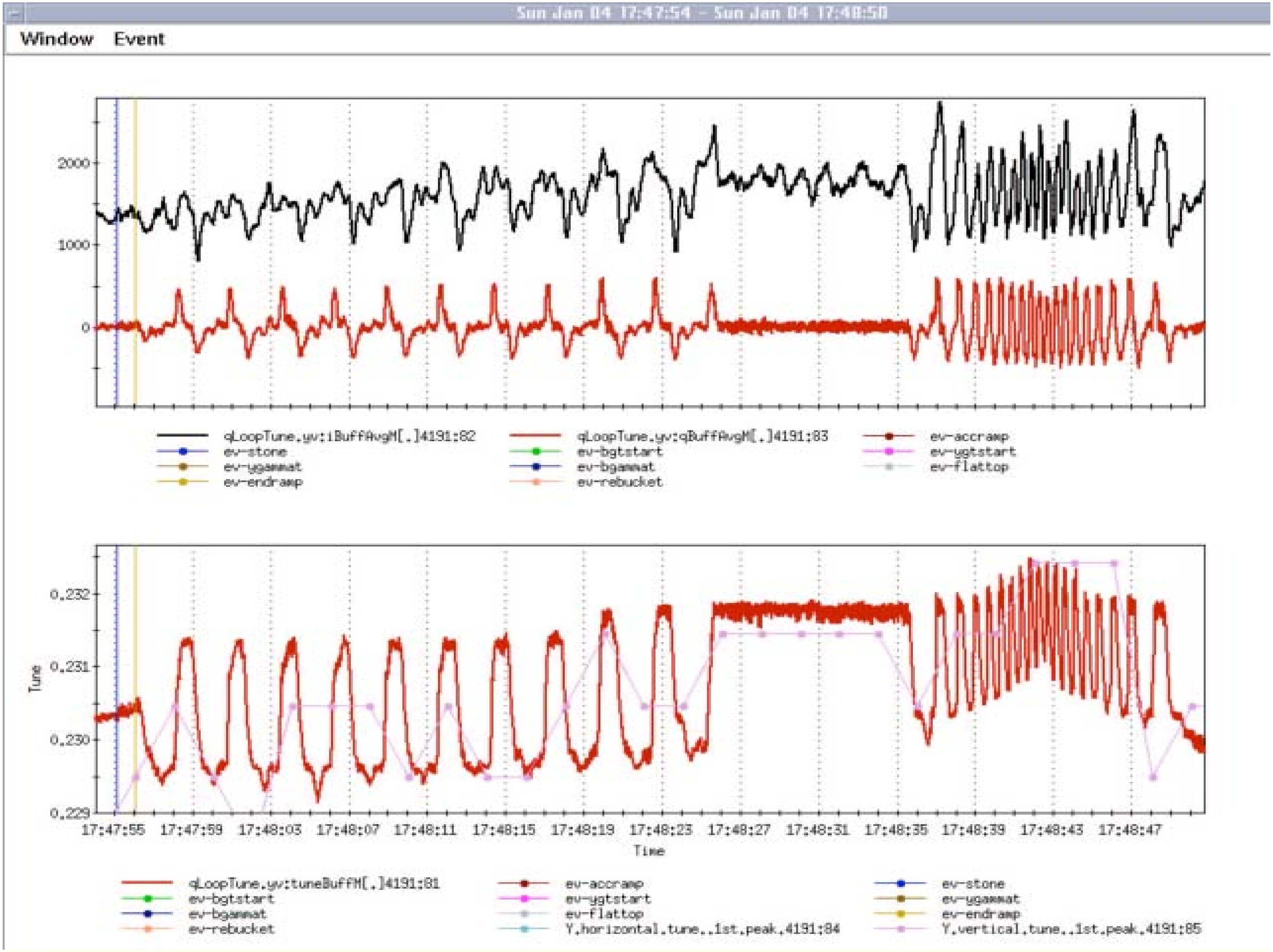


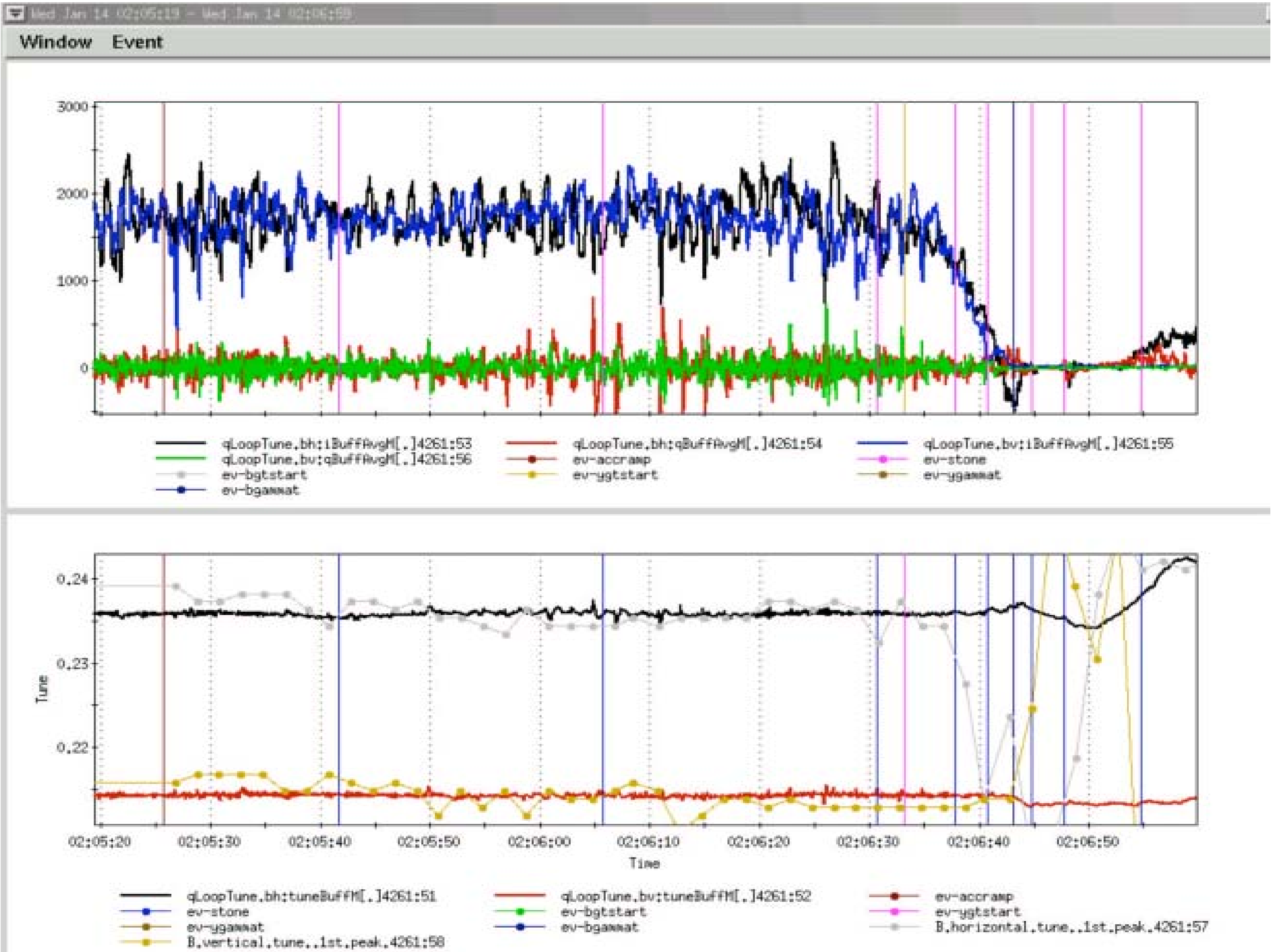


hp89441A
AVERAGE IN PROGRESS
RMS:100
REF
TRACE A: Ch1 Spectrum
A Marker 244 969 531.250 0 Hz -96.755 dBm
-80 dBm
LogMag
5 dB /div
-130 dBm
Center: 244.96953125 MHz
Span: 78.125 kHz
A: MARKER->
marker to peak
mkr -> center freq
mkr -> ref level
offset mkr -> span
offset mkr -> step size
mkr -> start freq
mkr -> stop freq


hp89441A
REAL-TIME AVG IN PROGRESS RMS:100
REF
A: MKR FCTNS
peak track
on off
freq counter
on off
band power markers
peak/average statistics
trace select
on off
trace
1024
demod carrier
on off
TRACE A: Ch1 Spectrum
A Marker 244 519 165.039 1 Hz -92.268 dBm
-90 dBm
LogMag
5 dB /div
-140 dBm
Center: 244.51953125 MHz
Span: 9.765625 kHz


Fri Jan 02 20:16:25 - Fri Jan 02 20:22:38
Window
Event
Tune
0.24
0.23
0.22
0.21
Time
20:16:30
20:17:00
20:17:30
20:18:00
20:18:30
20:19:00
20:19:30
20:20:00
20:20:30
20:21:00
20:21:30
20:22:00
20:22:30
qLoopTune.yh:tuneBuffM[.]4172:264
qLoopTune.yv:tuneBuffM[.]4172:265
Y.horizontal.tune..1st.peak.4172:266
Y.vertical.tune..1st.peak.4172:267
ev-accramp
ev-stone
ev-bgtstart
ev-ygtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp
ev-rebucket
ev-lumi


Sun Jan 04 17:47:54 - Sun Jan 04 17:48:50
Window Event
2000
1000
0
qLoopTune.yv:iBuffAvgM[.]4191:82
qLoopTune.yv:qBuffAvgM[.]4191:83
ev-accramp
ev-stone
ev-bgtstart
ev-ygtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp
ev-rebucket
Tune
0.232
0.231
0.230
0.229
17:47:55 17:47:59 17:48:03 17:48:07 17:48:11 17:48:15 17:48:19 17:48:23 17:48:27 17:48:31 17:48:35 17:48:39 17:48:43 17:48:47
Time
qLoopTune.yv:tuneBuffM[.]4191:81
ev-accramp
ev-stone
ev-bgtstart
ev-ygtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp
ev-rebucket
Y.horizontal.tune..1st.peak.4191:84
Y.vertical.tune..1st.peak.4191:85



Wed Jan 14 02:05:19 - Wed Jan 14 02:06:59
Window
Event
3000
2000
1000
0
qLoopTune.bh:iBuffAvgM[.]4261:53
qLoopTune.bh:qBuffAvgM[.]4261:54
qLoopTune.bv:iBuffAvgM[.]4261:55
qLoopTune.bv:qBuffAvgM[.]4261:56
ev-accramp
ev-stone
ev-bgtstart
ev-ygtstart
ev-ygammat
ev-bgammat
0.24
0.23
0.22
Tune
02:05:20
02:05:30
02:05:40
02:05:50
02:06:00
02:06:10
02:06:20
02:06:30
02:06:40
02:06:50
Time
qLoopTune.bh:tuneBuffM[.]4261:51
qLoopTune.bv:tuneBuffM[.]4261:52
ev-accramp
ev-stone
ev-bgtstart
ev-ygtstart
ev-ygammat
ev-bgammat
B.horizontal.tune..1st.peak.4261:57
B.vertical.tune..1st.peak.4261:58

Transition Crossing

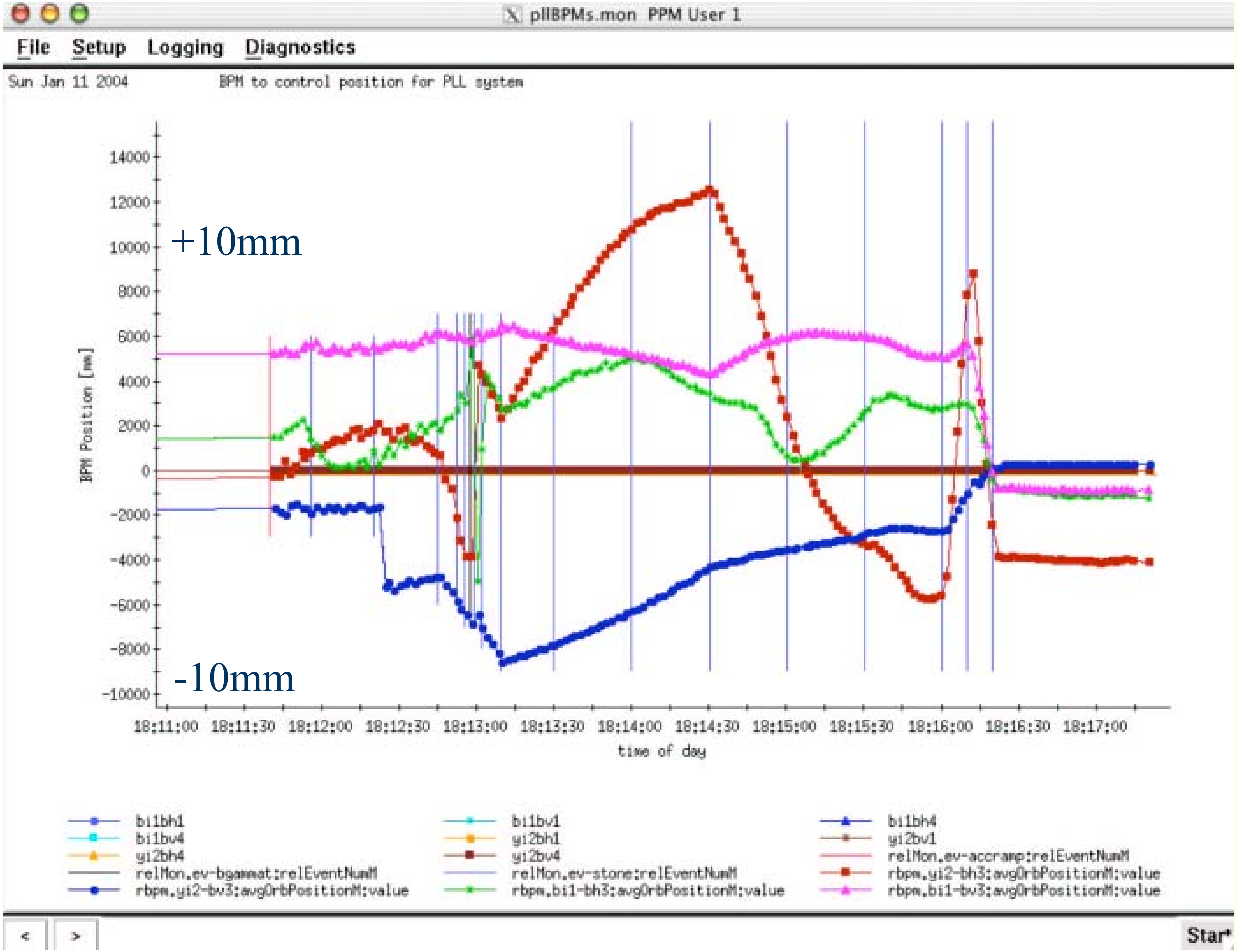
Dynamic Range Problem

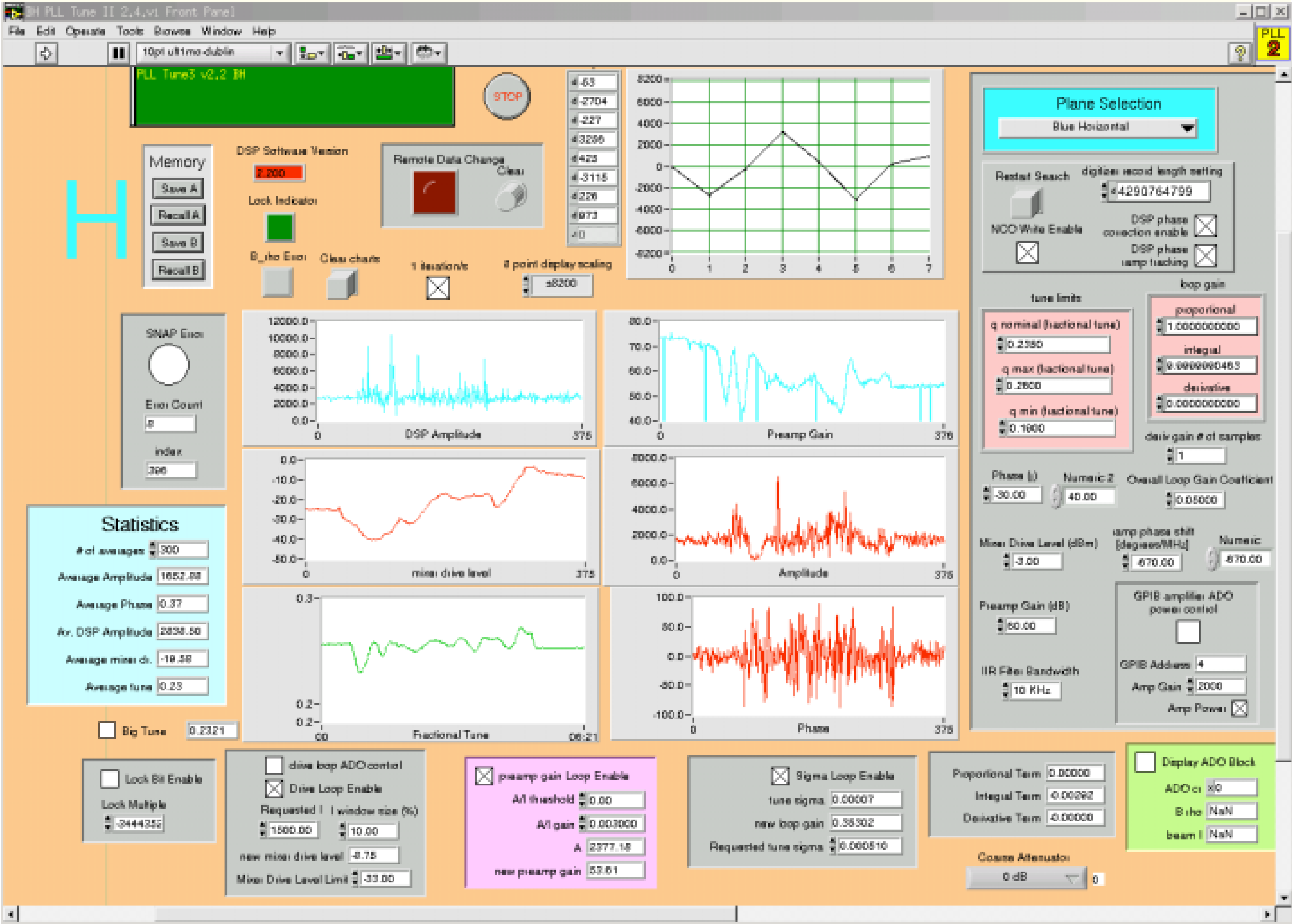
- Bunches get short - lots of energy up at 245MHz
- Bunches get short – reduced effectiveness of resonant pickup (ξ~400nsec vs 2.25μsec for 6 bunches)
- Fast changes in orbit
- Fast changes in tune

Available dynamic range

- 14 bit digitizer - 84dB
- Feedback on kicker power - 30dB
- Feedback on signal path gain - 60dB

requires feedback on loop gain

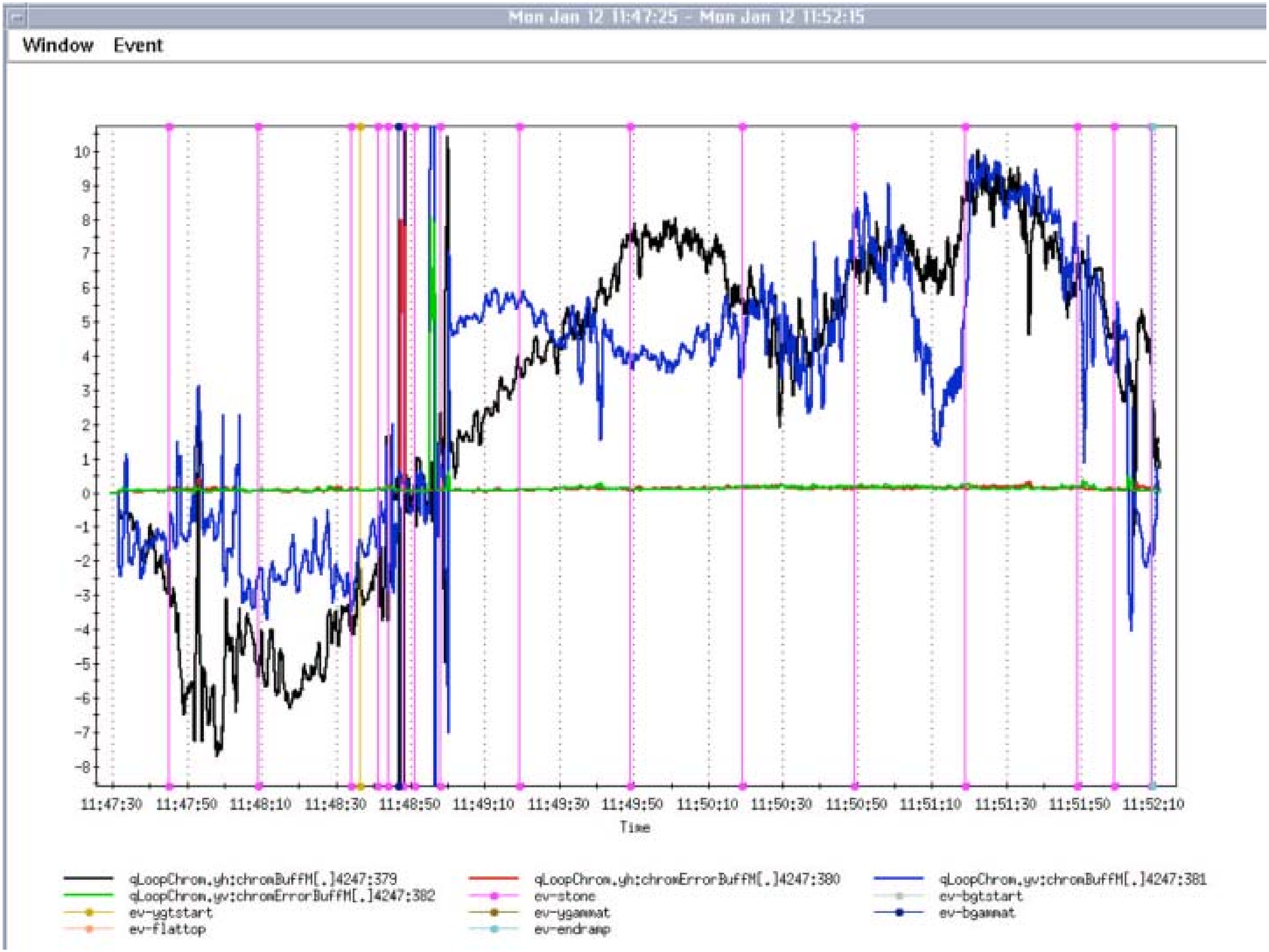

pllBPMs.mon PPM User 1
File Setup Logging Diagnostics
Sun Jan 11 2004
BPM to control position for PLL system
BPM Position [mm]
+10mm
-10mm
14000
12000
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
18:11:00 18:11:30 18:12:00 18:12:30 18:13:00 18:13:30 18:14:00 18:14:30 18:15:00 18:15:30 18:16:00 18:16:30 18:17:00
time of day
bi1bh1
bi1bv1
bi1bh4
bi1bv4
yi2bh1
yi2bv1
yi2bh4
yi2bv4
relMon.ev-accramp:relEventNumM
relMon.ev-bgammat:relEventNumM
relMon.ev-stone:relEventNumM
rbpm.yi2-bh3:avgOrbPositionM:value
rbpm.yi2-bv3:avgOrbPositionM:value
rbpm.bi1-bh3:avgOrbPositionM:value
rbpm.bi1-bv3:avgOrbPositionM:value
Start



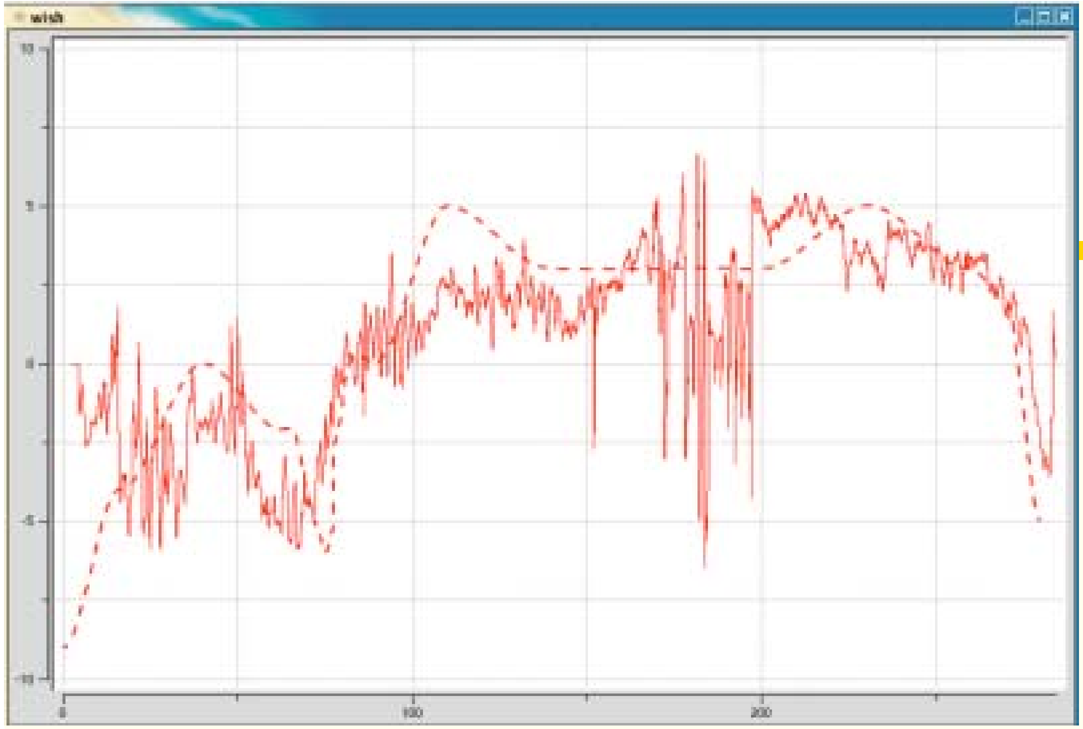
PLL Tune3 v2.2 BH
STOP
Memory
Save A
Recall A
Save B
Recall B
DSP Software Version
Lock Indicator
Remote Data Change
Plane Selection
Blue Horizontal
Restart Search
NCO Write Enable
DSP phase correction enable
DSP phase ramp tracking
tune limits
loop gain
proportional
integral
derivative
SNAP Error
Error Count
index
Statistics
# of averages
Average Amplitude
Average Phase
Av. DSP Amplitude
Average tune
DSP Amplitude
Preamp Gain
mixer drive level
Amplitude
Fractional Tune
Phase
Big Tune
Lock Bit Enable
Lock Multiple
Drive Loop Enable
new mixer drive level
Mixer Drive Level Limit
preamp gain Loop Enable
new preamp gain
Sigma Loop Enable
tune sigma
new loop gain
Requested tune sigma
Proportional Term
Integral Term
Derivative Term
Coarse Attenuator
Display ADO Block
Overall Loop Gain Coefficient
Mixer Drive Level (dBm)
Preamp Gain (dB)
IIR Filter Bandwidth
GPIB Address
Amp Gain
Amp Power

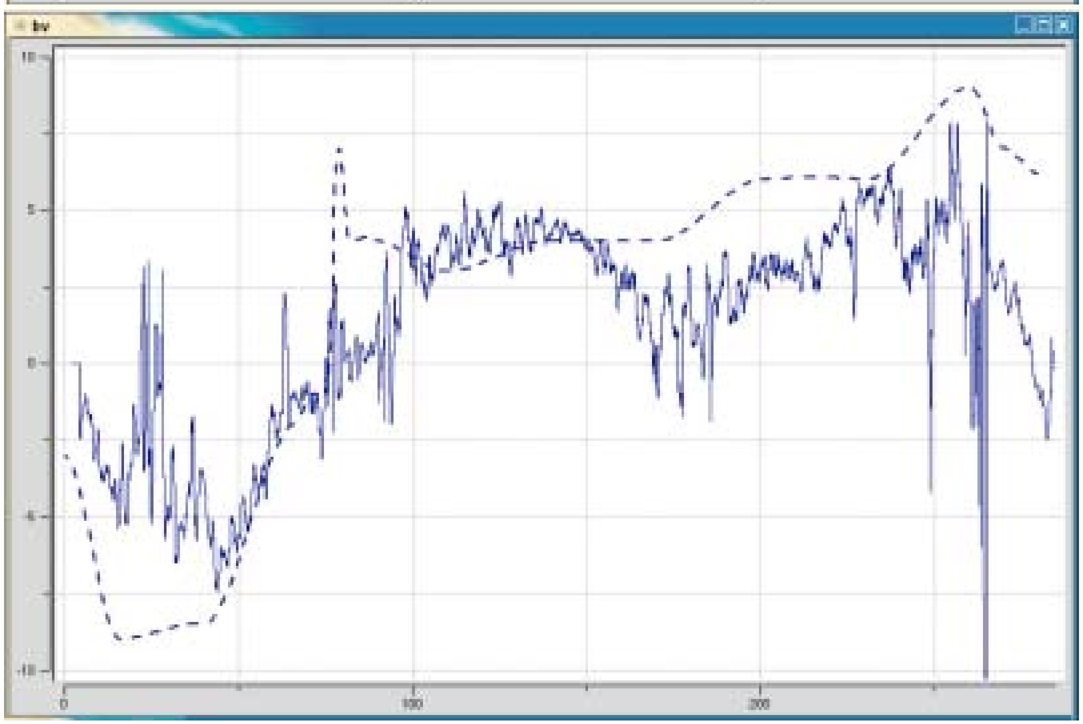
Chromaticity Measurement with PLL

- Good complement to kicked tune (Artus), useful for static measurements using standard frequency shift method
- For ramps, 200μ radial modulation at 1Hz
- Affected by Artus kicks, AGS cycle
- Measurement quality approaching the level needed for LHC?
- Possible to do chrom feedback without tune feedback?



Mon Jan 12 11:47:25 - Mon Jan 12 11:52:15
Window
Event
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
11:47:30
11:47:50
11:48:10
11:48:30
11:48:50
11:49:10
11:49:30
11:49:50
11:50:10
11:50:30
11:50:50
11:51:10
11:51:30
11:51:50
11:52:10
Time
qLoopChrom.yh:chromBuffM[.]4247:379
qLoopChrom.yh:chromErrorBuffM[.]4247:380
qLoopChrom.yv:chromBuffM[.]4247:381
qLoopChrom.yv:chromErrorBuffM[.]4247:382
ev-stone
ev-bgtstart
ev-ygtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp





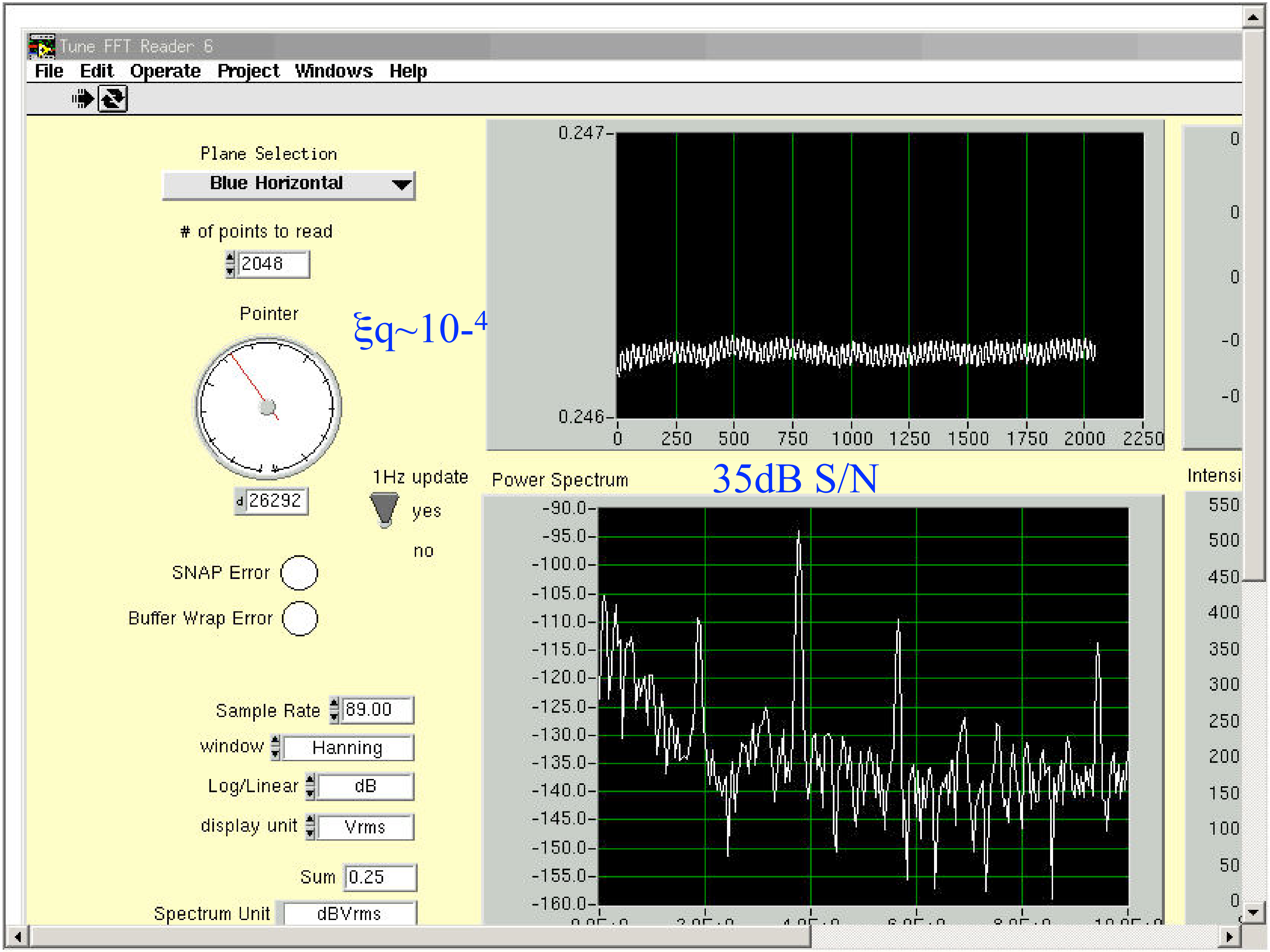
Measured horiz and vert chromaticity data and fit, assuming 10 units of b2 in the DX magnets

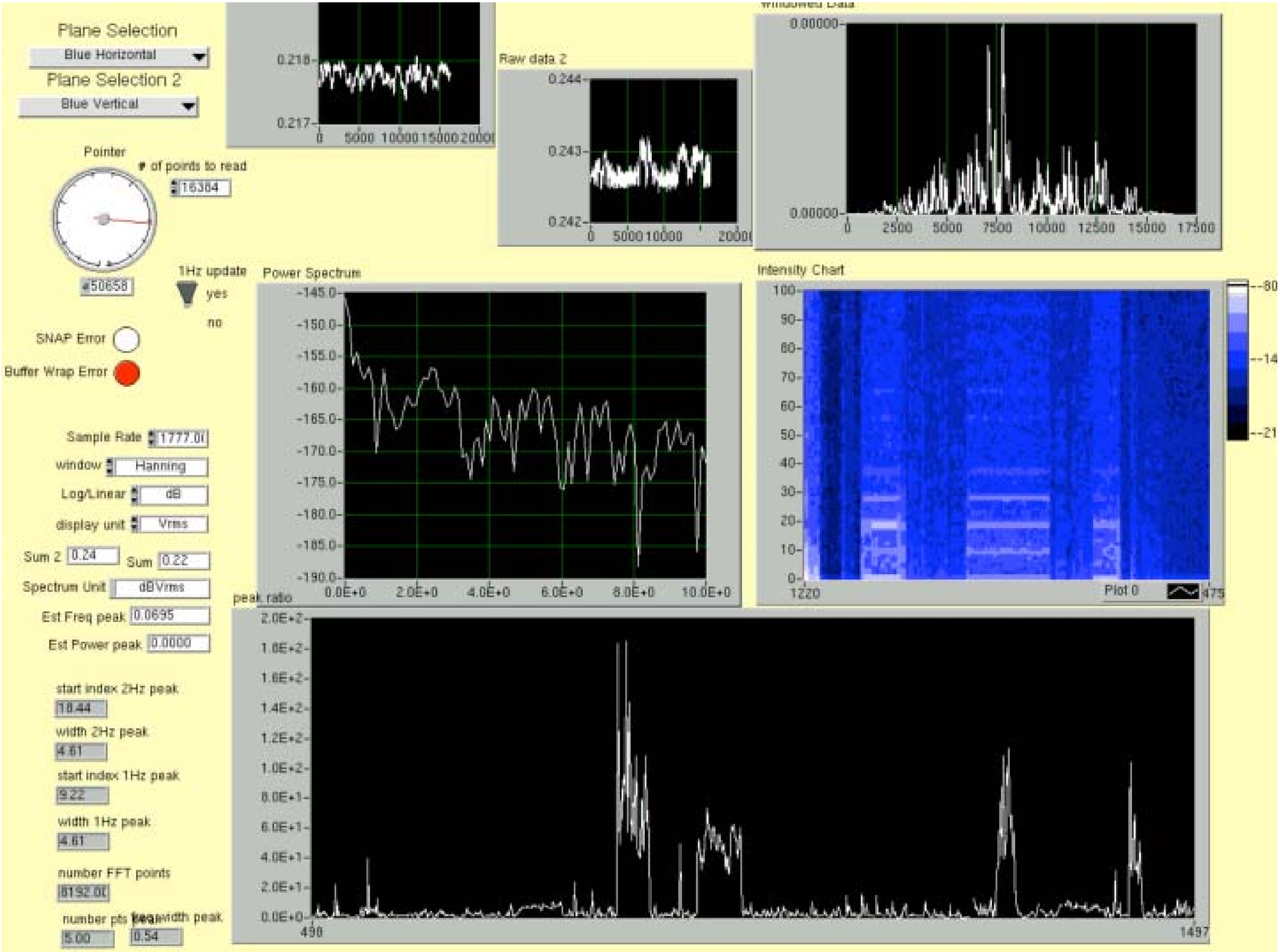
Chromaticity Effect on PLL

- Conclusion from chromaticity studies is that PLL tune measurement can cope with a large range of chromaticity
- Chromaticity control is not a primary issue for PLL tune measurement and tune feedback
- Chromaticity control is an issue primarily in the usual operational sense

Coupling on the ramp

- Separate excitation in either time or frequency domain
  - Drive first half of bunch train H, last half V - LEP
  - Drive H and V at different harmonic numbers – RHIC
  - This may help a bit, but coupling is in the beam
- Potential exists to measure and correct coupling with skew quad modulation and PLL FFT
- This has been given extensive study time in an effort to measure and correct ramp coupling, more required to firmly establish the method
- Three families of skew quads requires 3 mod freqs, adding chrom mod makes four, this becomes a driver of PLL BW. Chrom mod should be highest freq, due to BW limit of skew quads


Tune FFT Reader 6
File Edit Operate Project Windows Help
Plane Selection
Blue Horizontal
# of points to read
2048
Pointer
26292
ξq~10-4
1Hz update
yes
no
SNAP Error
Buffer Wrap Error
Sample Rate 89.00
window Hanning
Log/Linear dB
display unit Vrms
Sum 0.25
Spectrum Unit dBVrms
0.247
0.246
0 250 500 750 1000 1250 1500 1750 2000 2250
Power Spectrum
35dB S/N
-90.0 -95.0 -100.0 -105.0 -110.0 -115.0 -120.0 -125.0 -130.0 -135.0 -140.0 -145.0 -150.0 -155.0 -160.0
Intensi
550 500 450 400 350 300 250 200 150 100 50 0


Plane Selection
Blue Horizontal
Plane Selection 2
Blue Vertical
Pointer
# of points to read
16384
450658
1Hz update
yes
no
SNAP Error
Buffer Wrap Error
Sample Rate
window
Hanning
Log/Linear
dB
display unit
Vrms
Sum 2
0.24
Sum
0.22
Spectrum Unit
dBVrms
Est Freq peak
0.0695
Est Power peak
0.0000
start index 2Hz peak
18.44
width 2Hz peak
4.61
start index 1Hz peak
9.22
width 1Hz peak
4.61
number FFT points
number pts peak
5.00
freq width peak
0.54
Raw data 2
Power Spectrum
Intensity Chart
Plot 0
peak ratio

Status of 245MHz PLL at RHIC

- "Day One" tune feedback would have been an incredible blessing
- "Year Four" we have the ramp under control
  - Operational burden of TF is considerable
  - Chromaticity on the ramp is very helpful
  - Coupling on the ramp is under active investigation
  - Very useful tool for beam experiments
  - Polarized protons – feedforward certain, feedback remains to be seen

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- Recent results
  - 245MHz PLL
    - Tune, chromaticity, coupling
  - Baseband PLL
    - Emittance growth
  - Plans for SPS testing
- Possible system configurations
- PLL Problems/Plans

Baseband PLL

- Advantages – Marek Gasior, Rhodri, Hermann,…
  - Filters are much easier – dynamic range and revolution line
  - 24 bit digitizers - 144dB dynamic range
  - CMRR >100dB, vs ~40dB at 250MHz
  - Synchrotron satellites are less of an issue?
  - Eliminates need for phase compensation - of more interest at RHIC (~700 degrees during ramp)
  - Simplicity – get rid of mixers
  - If resonant (hybrid resonator?), characteristic time is much longer – figure of merit is Q/freq
- Disadvantages
  - Emittance blowup?
  - Else?

Baseband PLL preliminary results

- Visit of Rhodri Jones and Marek Gasior from CERN, 12-20 February, baseband PLL discussions began on 17 February
- During this time (4 days)
  - System architecture was conceived
  - Necessary circuitry was designed, built, and installed
  - BTFs were taken
  - The loop was locked
  - Tune changes were tracked
  - Important observation – emittance growth

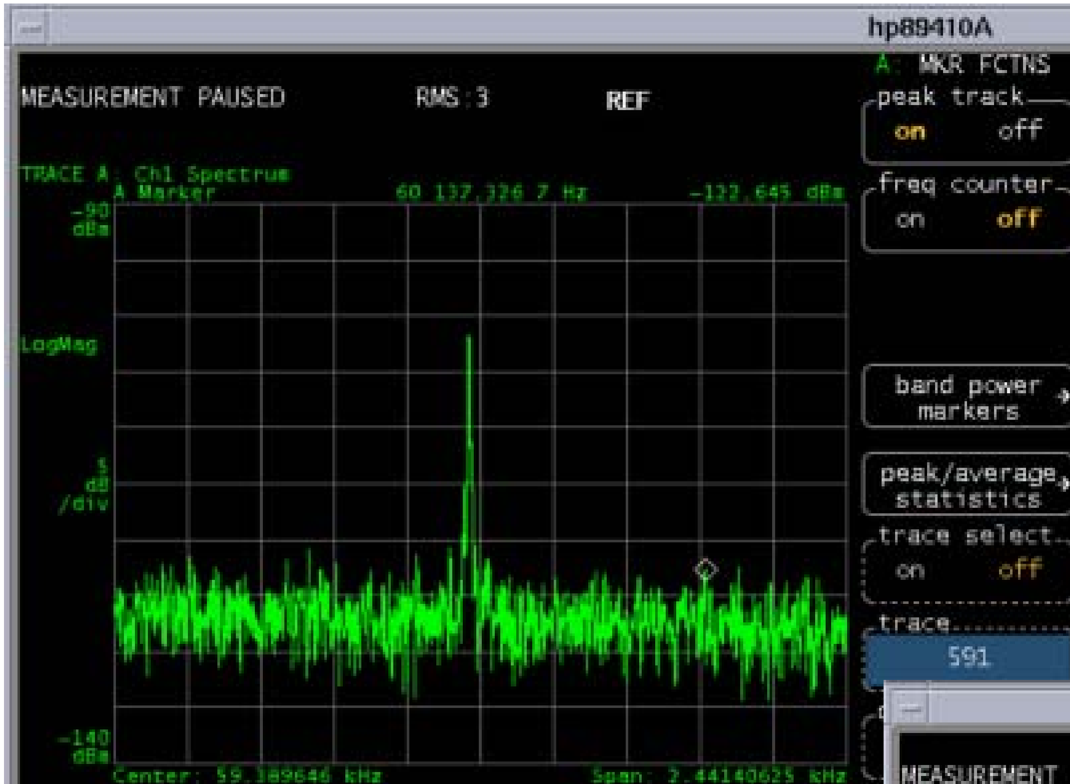
Baseband PLL system setup

Equipment :
krohn hite 3945
sri 844
hp 8648D
krohn hite 3343
lecroy lt584
hp dsa's
minicircuits zsc2-
1

kicker chain:
0dBm from 8648 split to lockin
reference and krohn hite 3343 (used
as
power amp) with 20dB of gain and
10dB of output atten, driving a
single 2m stripline blue horiz sector
1.

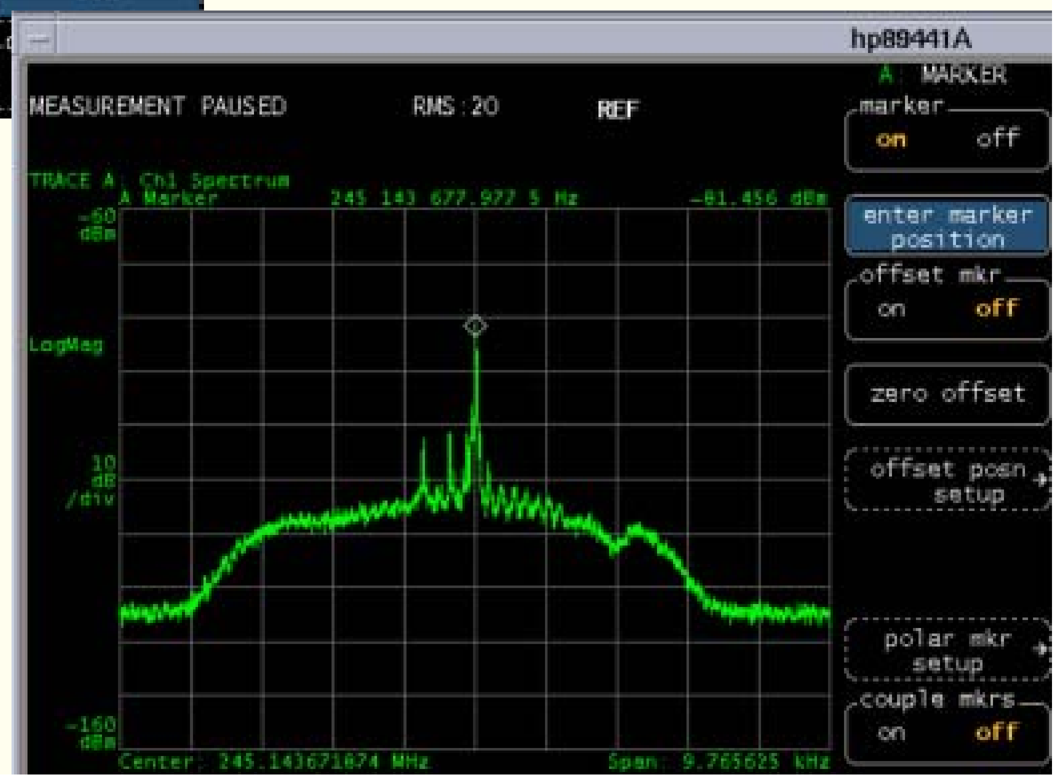
Pickup chain:
signal from 1 m stripline (open circuit) to Marek's box (40dB gain), then to two series Krohn Hites 3945 LP butterworth cutoff at 60KHz, no gain. From there split to lockin and DSA. Lockin settings 300msec time const, 6dB/oct filter, wide reserve high, sensitivity lo noise (close reserve), sensitivity 30 microvolts full scale. Phase output from lockin to DC FM input of 8648, 20db attenuated. Generator 60.29KHz center freq, 1KHz FM deviation max

Baseband noise floor?

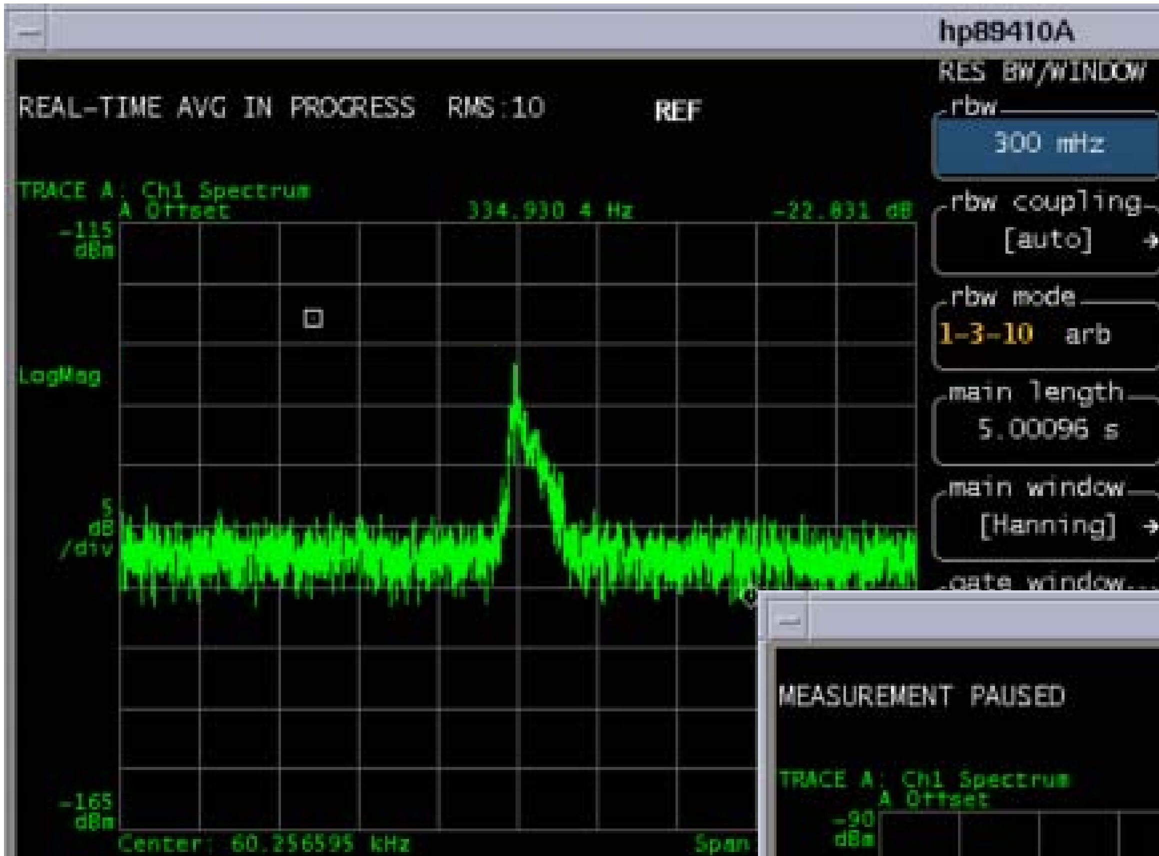


245MHz signal
~30dB above
Schottky

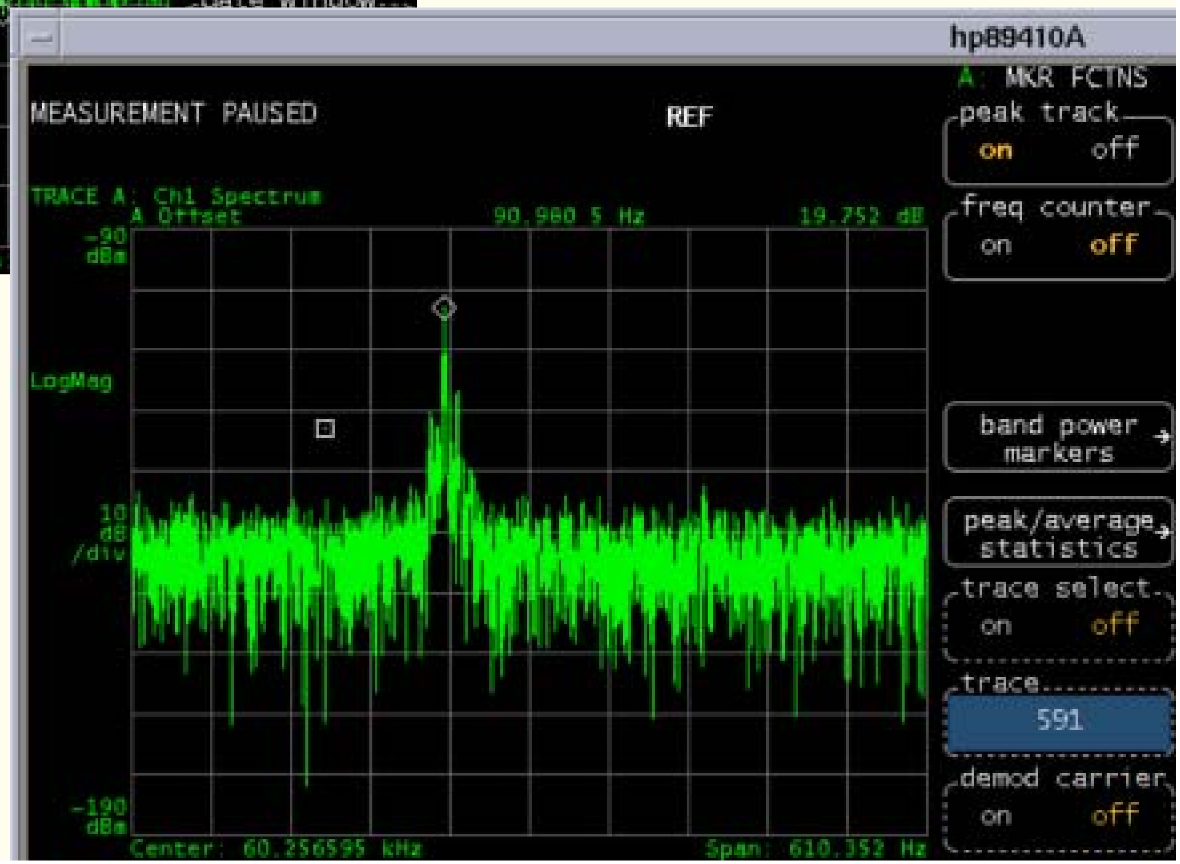
Baseband S/N ~25dB



Baseband PLL locked
6 bunches at injection
Beam driven at ~60KHz
With ~200mW kicker pwr

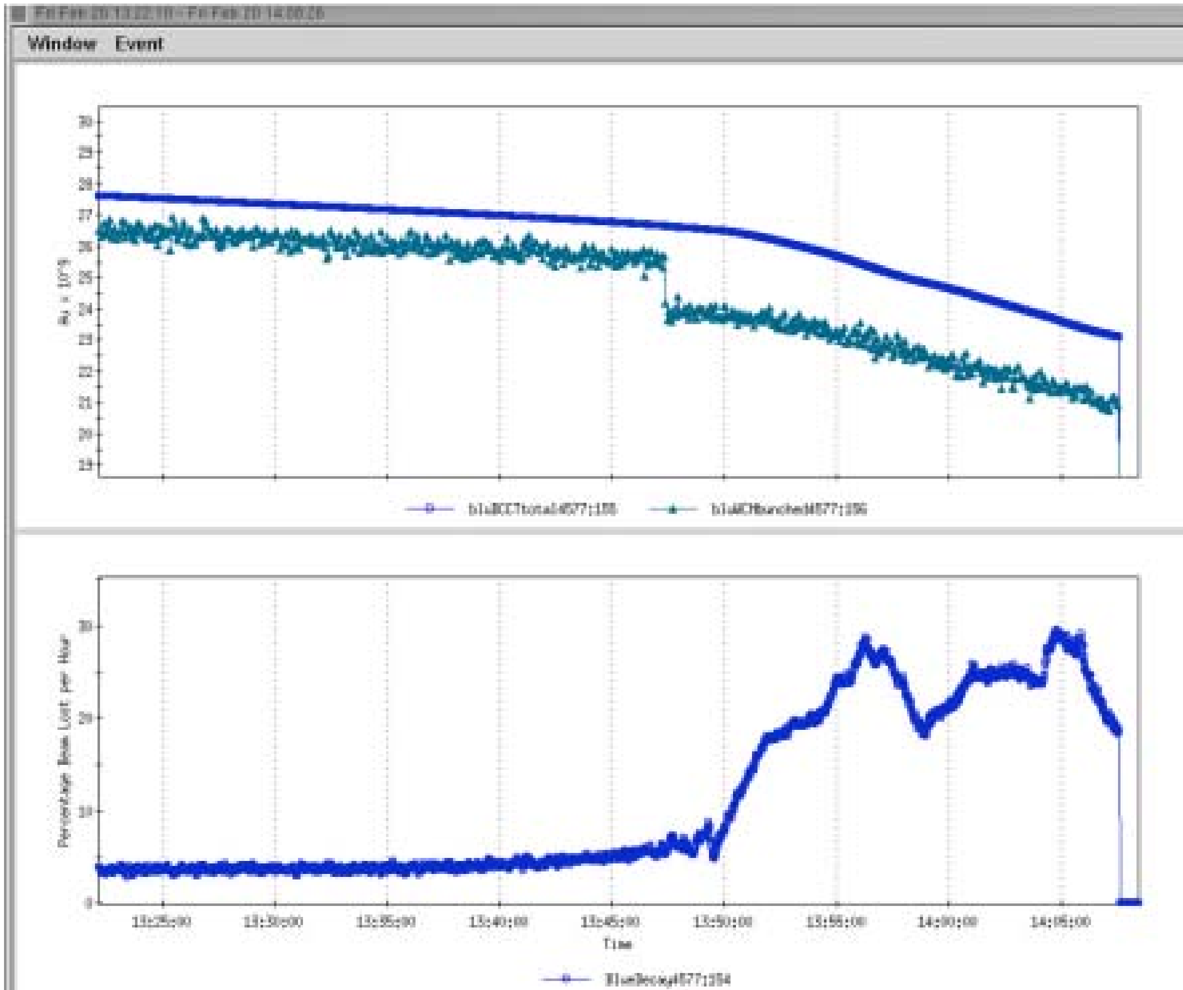


Beams anti-cogged
S/N ~ 40dB



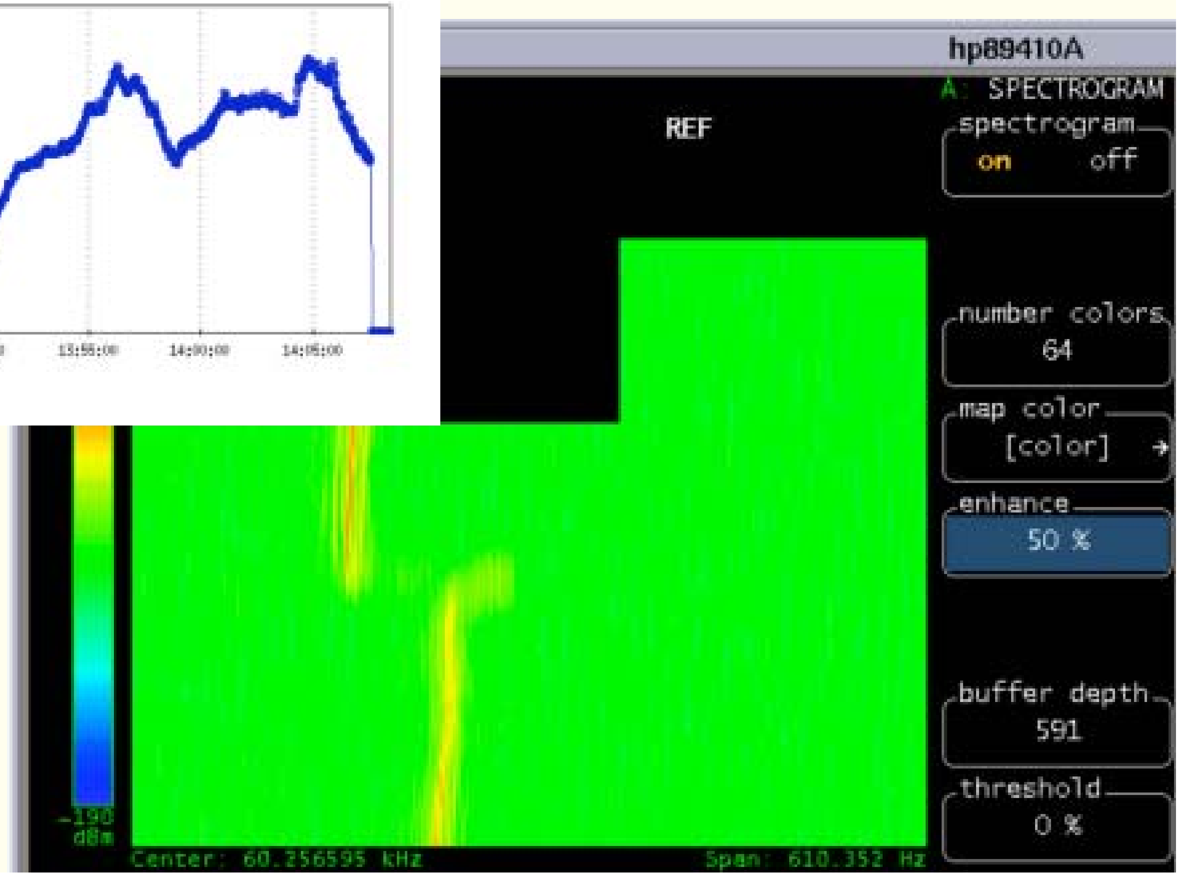
Beams cogged
S/N ~15dB

Baseband PLL locked
46 bunches at store



Tracking .001

Tune change



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Plans for FY04 SPS Testing

- Two periods of ~1 week each, early June and late September
- Two systems? Baseband and 245MHz?
- 245MHz status
  - Resonant pickup installed and tested
  - Complete system assembled and tested at CERN
  - Latest rev of analog and digital boards to be delivered to CERN late April/early May
  - Latest rev of software will accompany hardware
  - Stand-alone VXworks crate concept is being explored

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Possible System Configurations

- Baseband Q~10? All available for single bunch
- 245MHz Q~300?
- 2.5GHz – comparison of $n\xi\, dp/p$ Q~5000?
  - RHIC 245MHz - 3000x.01x.001 = .03 ~2.5KHz
  - LHC 2.5GHz - 250000x.0002x.0001 = .005 ~50Hz
  - Additional advantage – resonate on single bunch
- Superconducting pickup – 250MHz? 2.5GHz?

Superconducting Pickup?

- Relatively modest $Q \sim 10^6$
  - Q limited by frequency swing on ramp
  - Less exotic technologies possible – lead plating?
  - Single bunch enhancement ~ x30
- Also get filtering on revolution line
- Preliminary modeling of both capacitive and transmission line resonated pickups complete
  - Conclusion is that circuit values are impractical
  - Superconducting cavity – freq >1GHz

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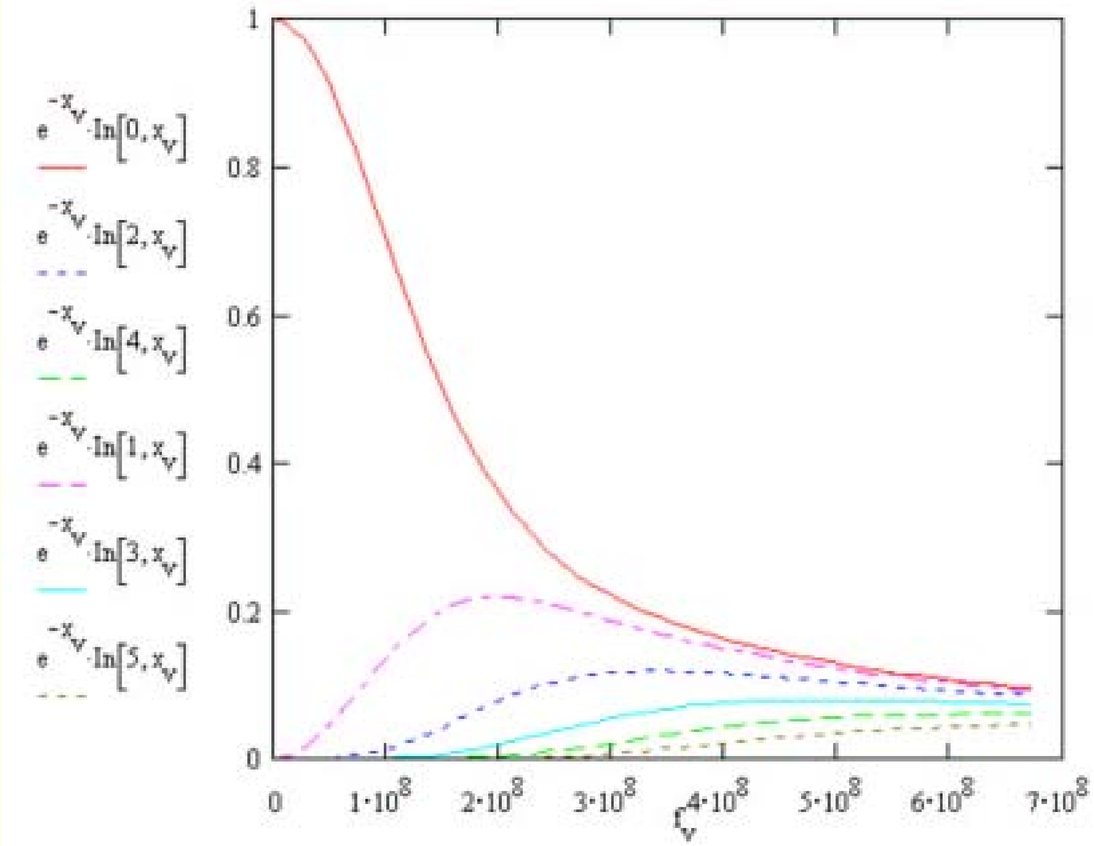
PLL Problems/Plans

chirp, multi-carrier, synch satellites
multiple systems
damper noise floor
signal-to-noise
stability and loop tuning
dynamic range
phase stability
emittance growth
tune crossing
autoexcitation
modeling
beam simulator
chromaticity measurement
coupling measurement
beam experiments considerations

Chirp, Multi-carrier, Synch Satellites

- Chirp – tried with RHIC PLL early on, result was diminished performance
- Multi-Carrier
  - Driven by synch satellite problem?
  - Complexity, emittance growth
- Synchrotron satellites
  - No problem at RHIC
  - Baseband favored



LHC, for Q`=1, f_ξ=50MHz

PLL Problems/Plans

chirp, multi-carrier, synch satellites
multiple systems
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signal-to-noise
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dynamic range
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autoexcitation
modeling
beam simulator
chromaticity measurement
coupling measurement
beam experiments considerations

Two Systems?

- Single bunch commissioning - a useful resonant pickup is difficult, S/N is a serious issue
  - System similar to LEP PLL?
  - Accept emittance blowup during single bunch commissioning
  - Ramp development tool
- Multi bunch commissioning/operations
  - RHIC style system is applicable
- Added cost and complexity, handoff required at potentially awkward time

PLL Problems/Plans

chirp, multi-carrier, synch satellites
multiple systems
→ damper noise floor
→ signal-to-noise
stability and loop tuning
dynamic range
phase stability
emittance growth
tune crossing
autoexcitation
modeling
beam simulator
chromaticity measurement
coupling measurement
beam experiments considerations

Damper Noise Floor and S/N

- Plan is to have damper operating continuously in LHC
- Damper guys seek ~ 1 micron threshold?
- PLL needs 20dB S/N minimum
- Potential solutions
  - Minimize PLL BW???
  - Resonant pickup - S/N ~ log Q
  - Cryogenic pickup (not necessarily superconducting) and amplifiers ~ 20dB
  - High frequency (2.5GHz) pickup
  - Damper notch filter (doesn't work for baseband?)
  - Else?

PLL Problems/Plans

Modeling, beam sim, beam-beam →

chirp, multi-carrier, synch satellites
multiple systems
damper noise floor
signal-to-noise
stability and loop tuning
dynamic range
phase stability
emittance growth
tune crossing
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beam simulator
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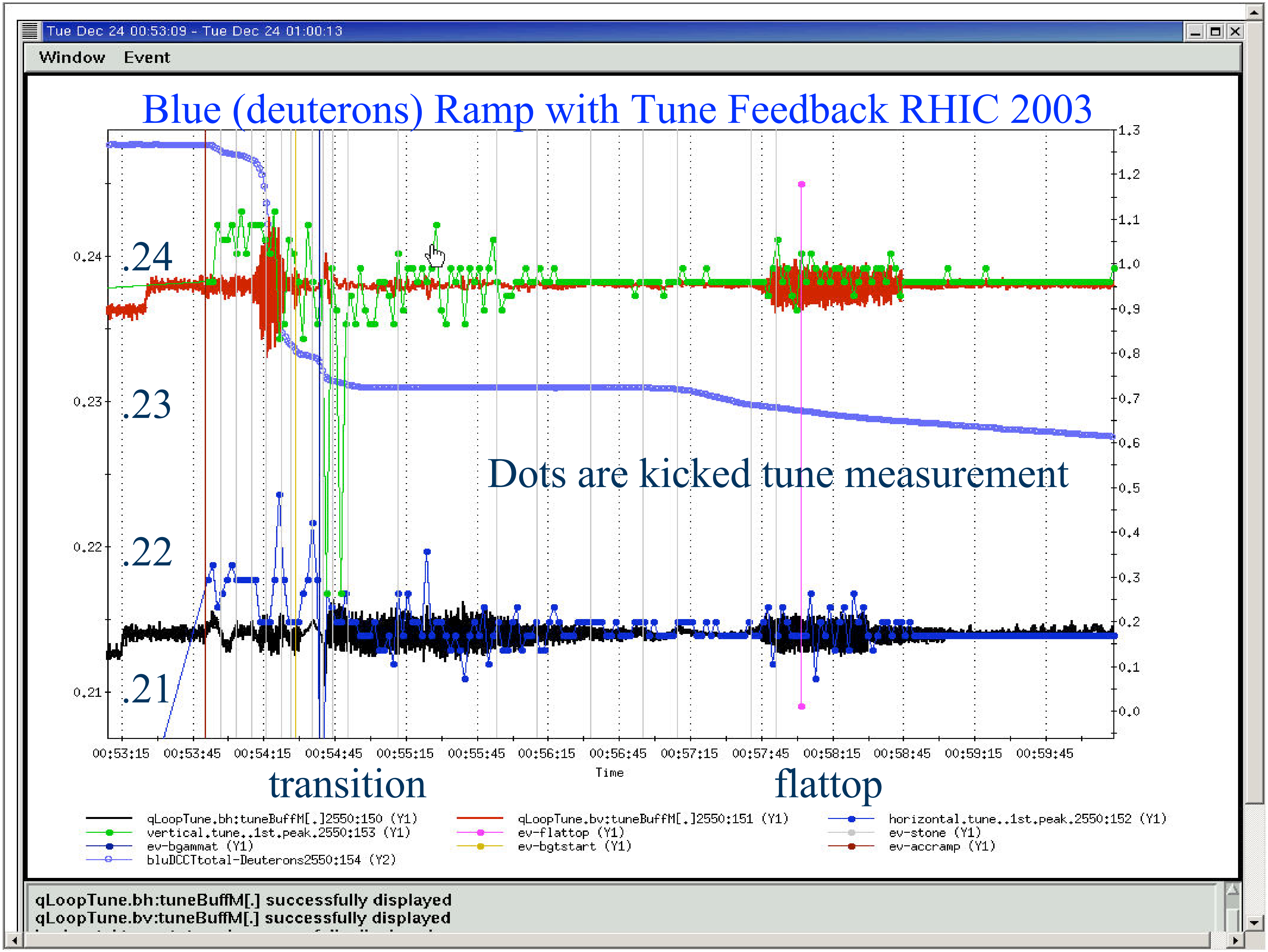
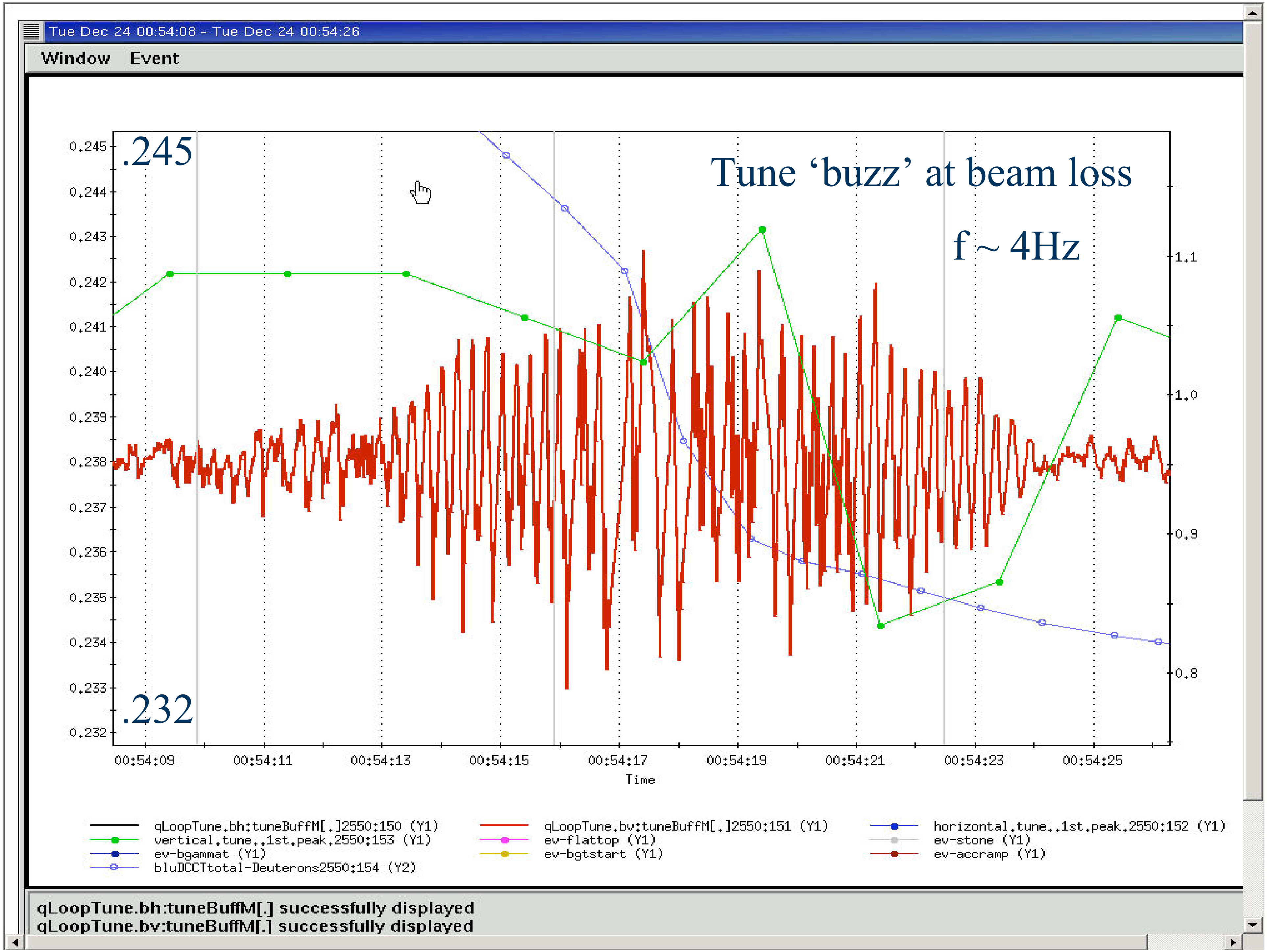
Stability at RHIC

- Minimize phase shifts – two sources
  - Sampling delay – RHIC 2003 was 4 degrees/Hz with 90Hz update rate
  - BW limiting filter – RHIC 2003 was 40Hz IIR
  - Result was loop was twitchy, always close to instability, efforts went into derivative, auto loop gain,…
- For RHIC 2004
  - Increased sampling rate to ~ 14KHz
  - Moved filter to ~100Hz, switchable digital filters
  - Result was ~x10 improvement in loop bandwith, gain margin,…


Tue Dec 24 00:53:09 - Tue Dec 24 01:00:13
Window Event
Blue (deuterons) Ramp with Tune Feedback RHIC 2003
.24
.23
.22
.21
Dots are kicked tune measurement
transition
flattop
Time
qLoopTune.bh:tuneBuffM[.]2550:150 (Y1)
vertical.tune..1st.peak.2550:153 (Y1)
ev-bgammat (Y1)
bluDCCTtotal-Deuterons2550:154 (Y2)
qLoopTune.bv:tuneBuffM[.]2550:151 (Y1)
ev-flattop (Y1)
ev-bgtstart (Y1)
horizontal.tune..1st.peak.2550:152 (Y1)
ev-stone (Y1)
ev-accramp (Y1)
qLoopTune.bh:tuneBuffM[.] successfully displayed
qLoopTune.bv:tuneBuffM[.] successfully displayed



Tue Dec 24 00:54:08 - Tue Dec 24 00:54:26
Window
Event
.245
.232
Tune 'buzz' at beam loss
f ~ 4Hz
Time
qLoopTune.bh:tuneBuffM[.]2550:150 (Y1)
vertical.tune..1st.peak.2550:153 (Y1)
ev-bgammat (Y1)
bluDCCTtotal-Deuterons2550:154 (Y2)
qLoopTune.bv:tuneBuffM[.]2550:151 (Y1)
ev-flattop (Y1)
ev-bgtstart (Y1)
horizontal.tune..1st.peak.2550:152 (Y1)
ev-stone (Y1)
ev-accramp (Y1)
qLoopTune.bh:tuneBuffM[.] successfully displayed
qLoopTune.bv:tuneBuffM[.] successfully displayed

Loop tuning

- PID loop tuning
  - loop is artificially constrained (by maximum dither ~ .001 in RHIC), usual tuning algorithms do not apply
  - the beam transfer function portion of the loop gain varies considerably
- Magnet transfer function uncertainties?

- **extensive studies with modulated test resonator, comparison between results and model**
- **need a model that includes the beam**
- **need dedicated time for loop tuning with beam**

- **Ultimately, we have been relying on feedback on loop gain**

PLL Problems/Plans

Already covered? →

Thermal effects,… →

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PLL Problems/Plans

Baseband beam dynamics →

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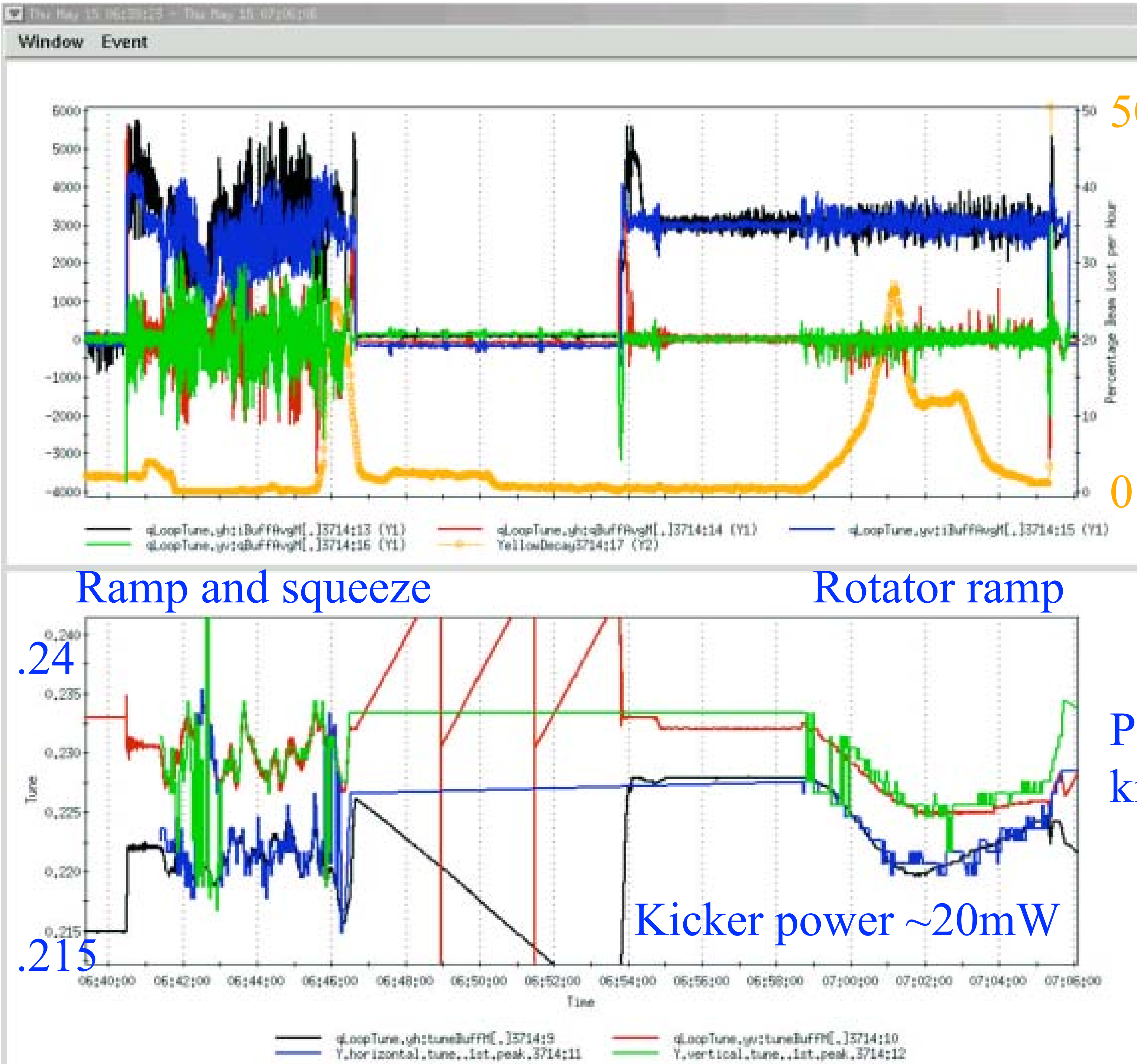
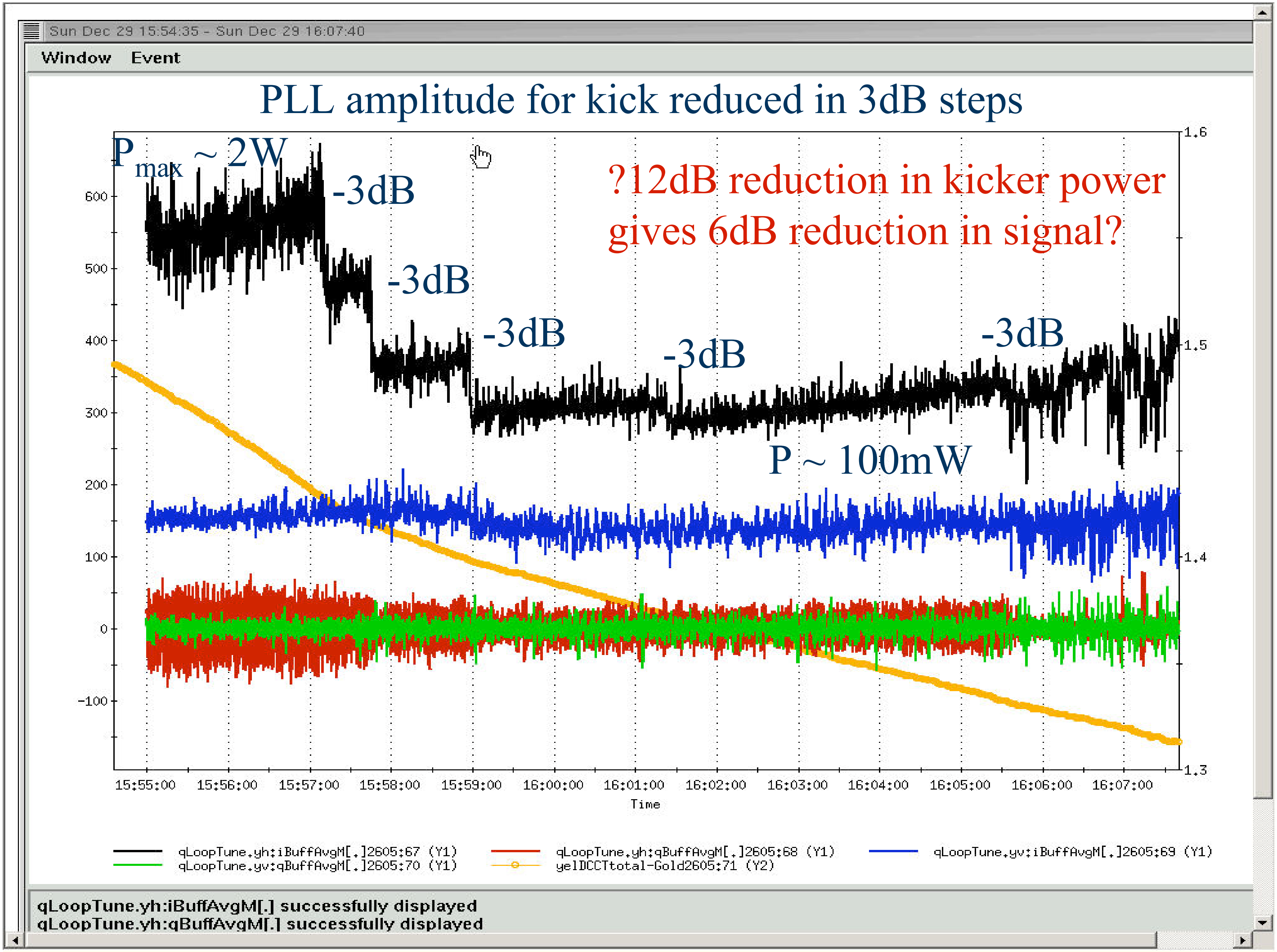


Amplitude and phase

Beam decay

PLL and kicked tunes

PLL amplitude for kick reduced in 3dB steps



PLL Problems/Plans

No crossing with
TF, always a problem
otherwise? →
Coupling is a problem,
Even without crossing

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PLL Problems/Plans

Becomes an issue as we seek to improve S/N →

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Useful, but must be driven by experience with beam → modeling, beam simulator

PLL Problems/Plans

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Already covered → chromaticity measurement, coupling measurement

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PLL is very useful tool, design must include this aspect →

Conclusions

- Present 245MHz RHIC PLL might well meet the needs of LHC with refinement and multi-bunches
- Other options all have a lot to recommend them
- It is crucial to properly evaluate all options as quickly as possible
- Proper evaluation must include extensive testing with beam at the earliest possible stage
- It is crucial to keep things as simple as possible