Tune/Chromaticity/Coupling Measurement and Feedforward/Feedback at RHIC

Peter Cameron

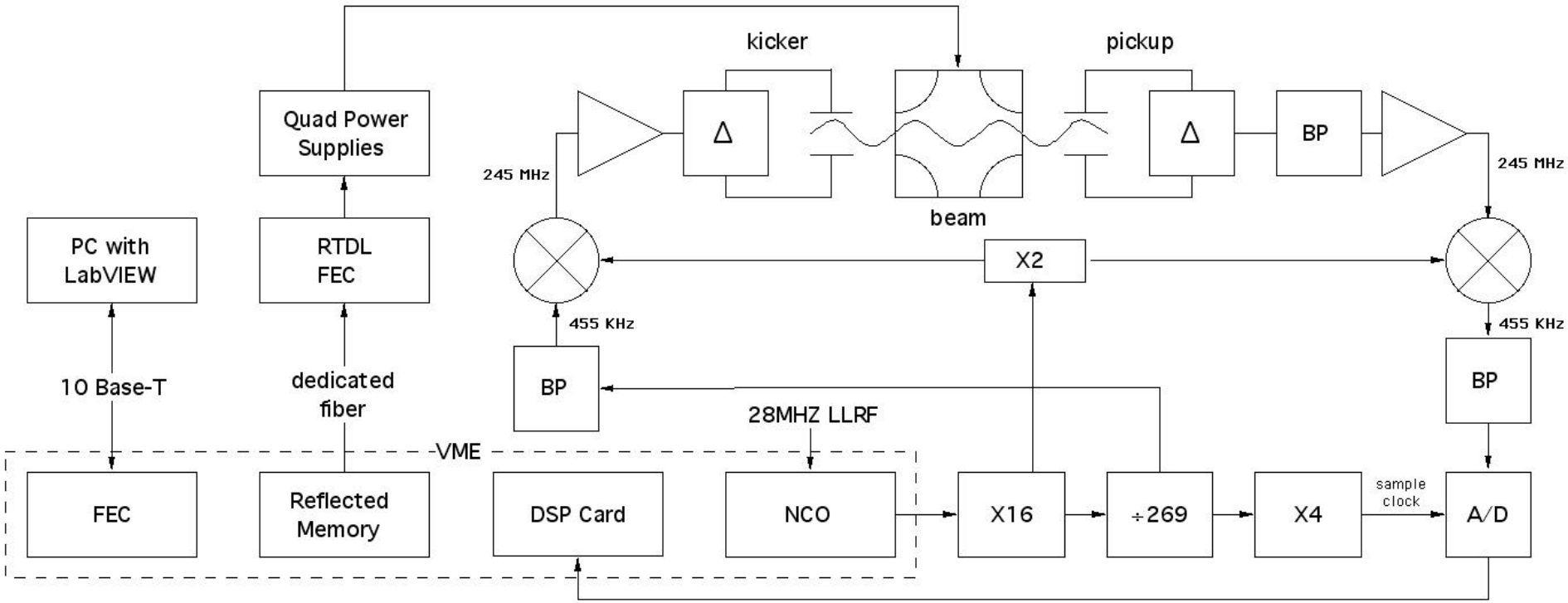
Outline

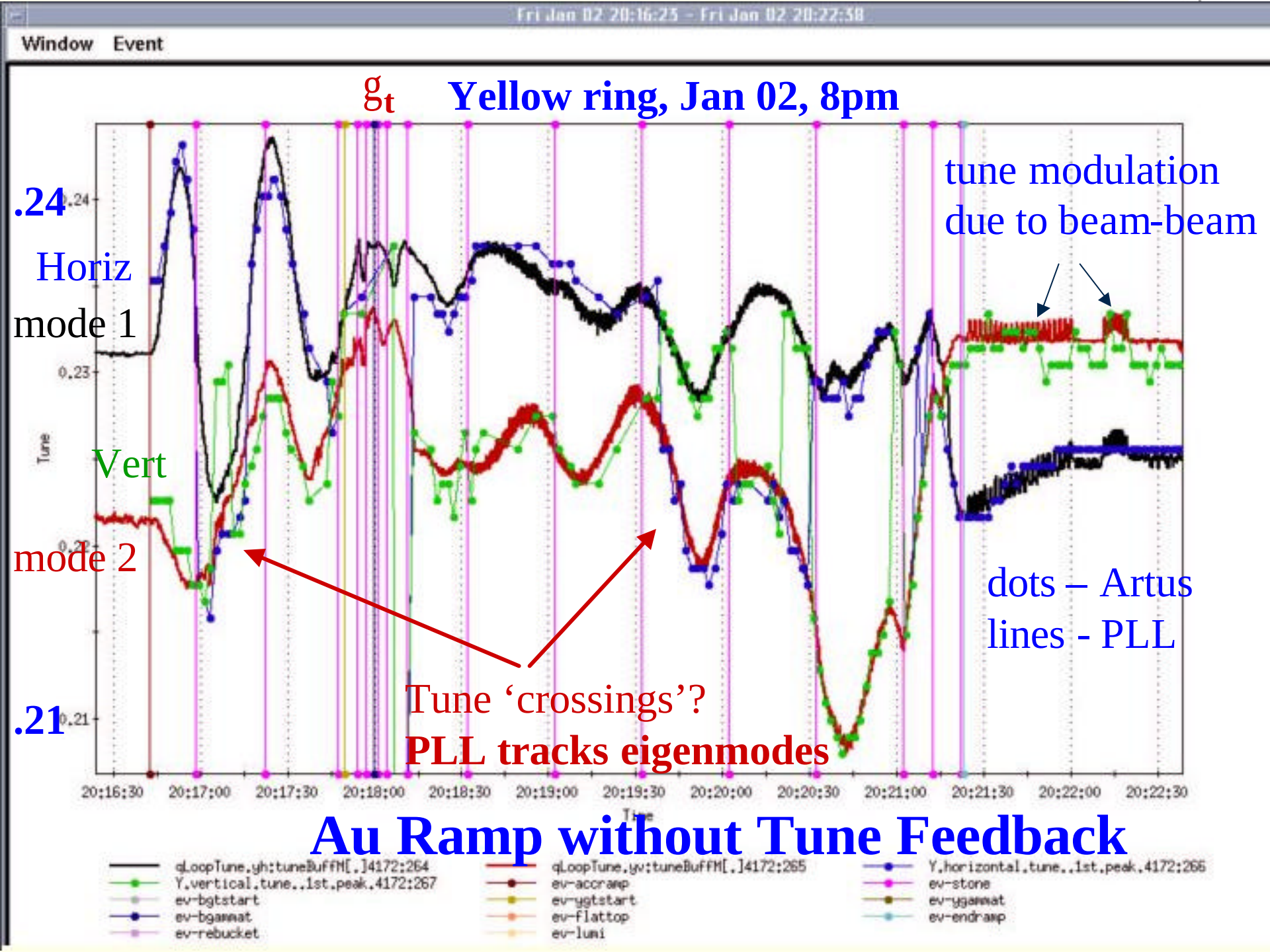
- Results from 245MHz system
  - Tune and tune feedback
  - Coupling
  - Chromaticity
  - Emittance growth
- Results from baseband systems
  - Tune tracking
  - Emittance growth
  - The 60Hz problem

245MHz System Status

- System is mature
  - main changes for RHIC Run 5 are in tuning of loop parameters
  - transition and coupling continue to be major obstacles
- Motion control is mature
  - operation of continuous feedback is reliable
  - can't cope with fast (30 msec) position changes at transition
- Further improvement requires a new approach

245MHz PLL Block Diagram




Fri Jan 02 20:16:23 - Fri Jan 02 20:22:38
Window Event
g_t
Yellow ring, Jan 02, 8pm
.24
Horiz
mode 1
Vert
mode 2
.21
Tune
tune modulation
due to beam-beam
dots – Artus
lines - PLL
Tune 'crossings'?
PLL tracks eigenmodes
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
Time
Au Ramp without Tune Feedback
qLoopTune.yh:tuneBuffM[.]4172:264
Y.vertical.tune..1st.peak.4172:267
ev-bgtstart
ev-bgammat
ev-rebucket
qLoopTune.yv:tuneBuffM[.]4172:265
ev-accramp
ev-ygtstart
ev-flattop
ev-lumi
Y.horizontal.tune..1st.peak.4172:266
ev-stone
ev-ygammat
ev-endramp

PLL locks to Eigenmodes

- 7 -

Bryant CERN ISR MA/75-28

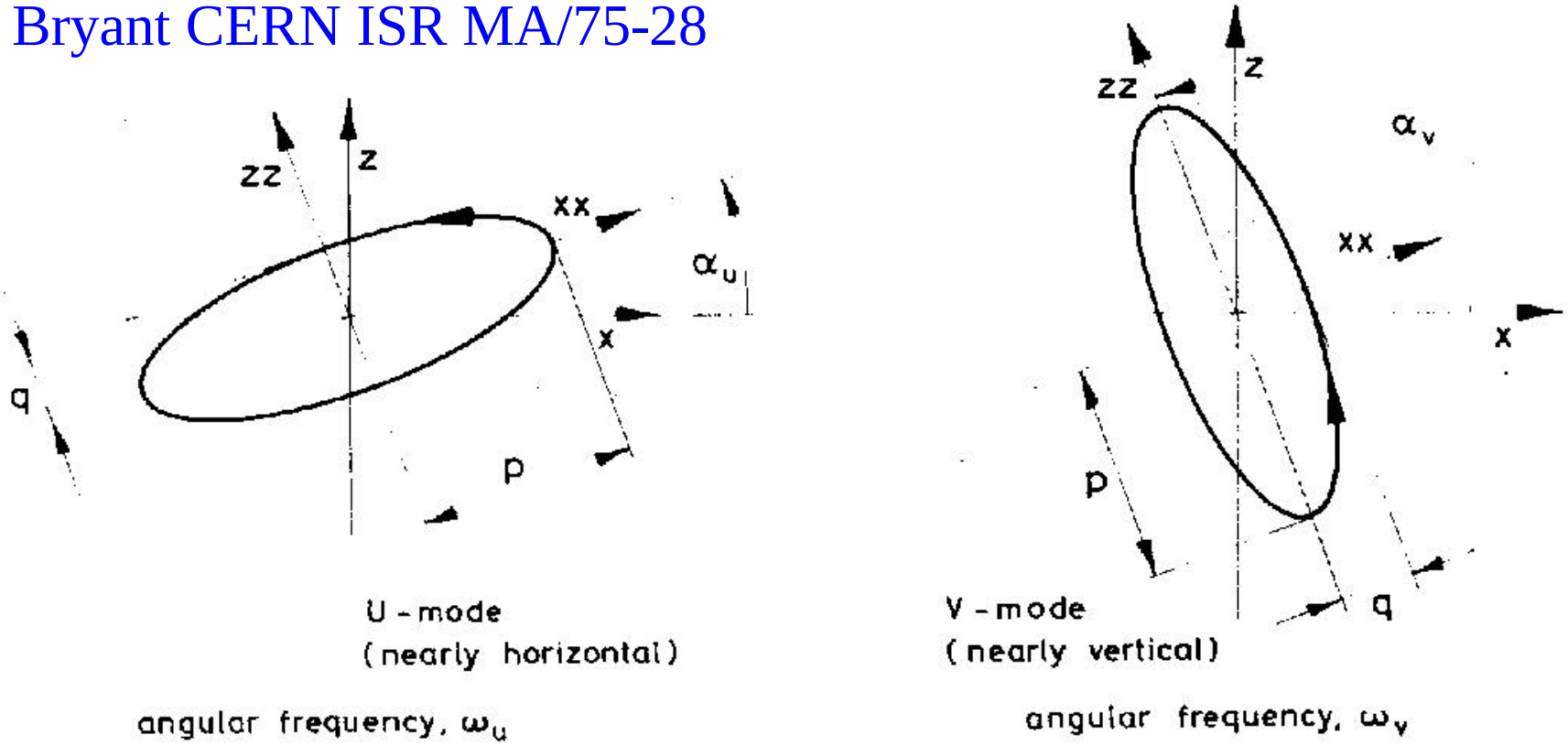
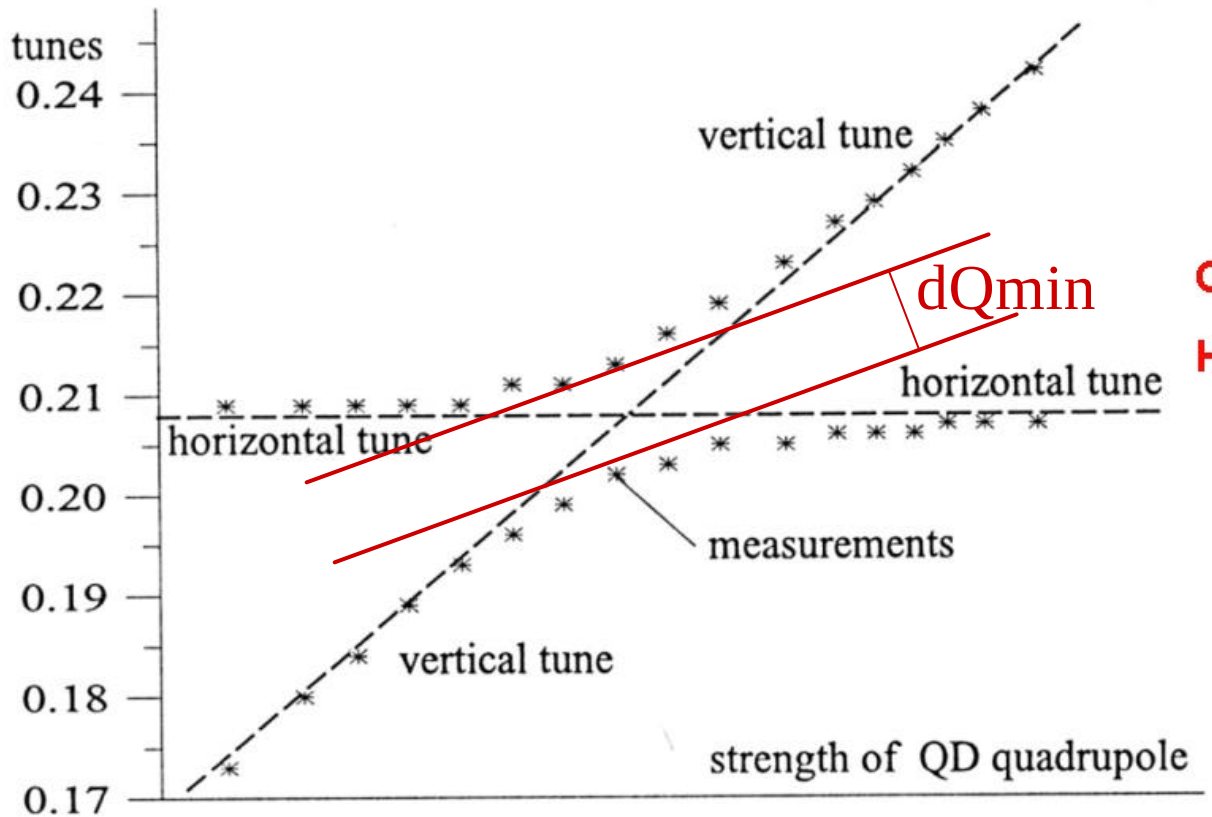


FIGURE 3 – Definition of normal modes

Tune Splitting and Crossing

- **Tune split at difference resonance:**

$$(\nu_x - \nu_y)_{\min} = 2|\kappa|$$



Two Possibilities:

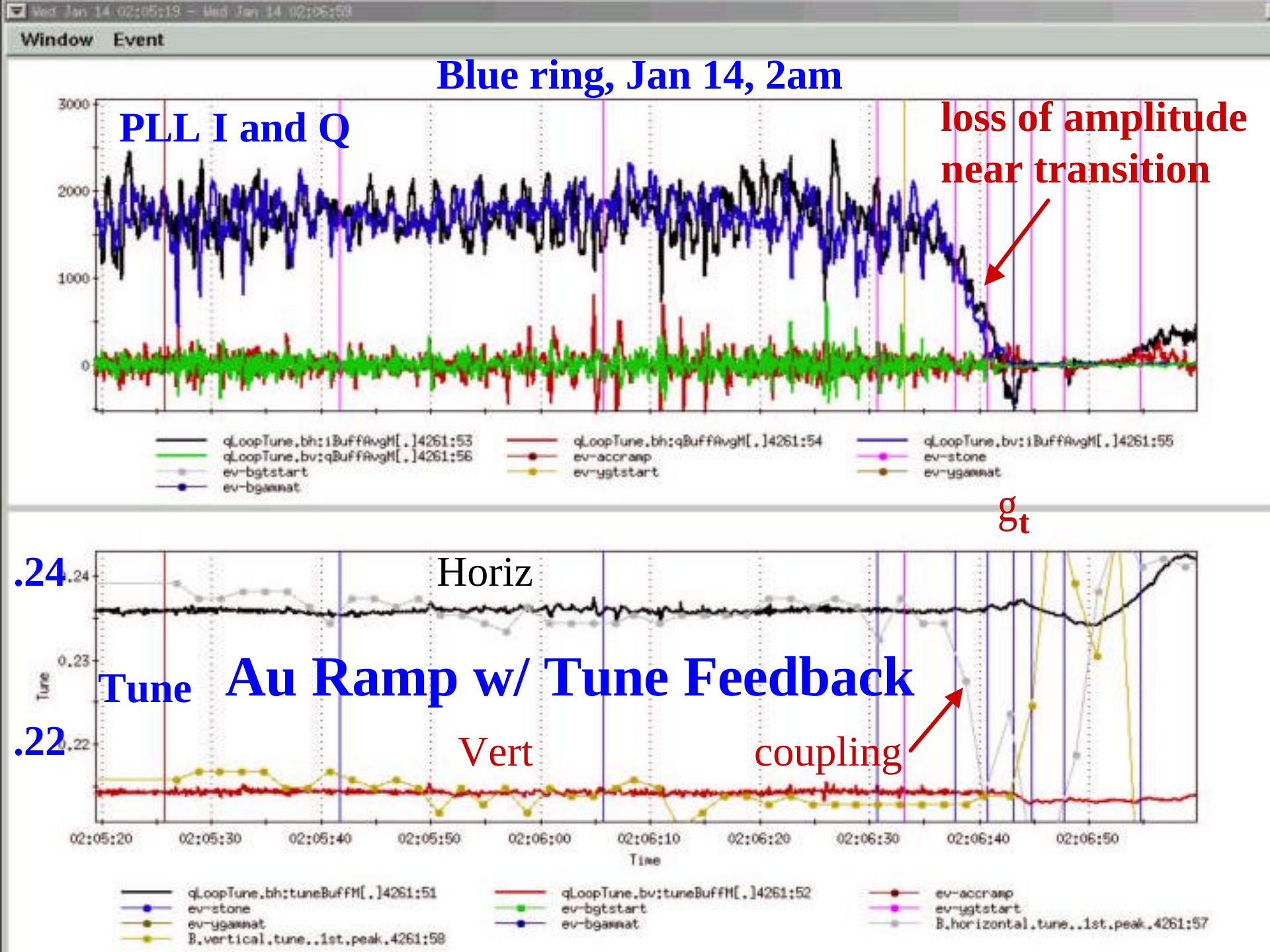
1. dQmin > filter BW
PLL does not jump
2. dQmin < filter BW
PLL may jump

Courtesy

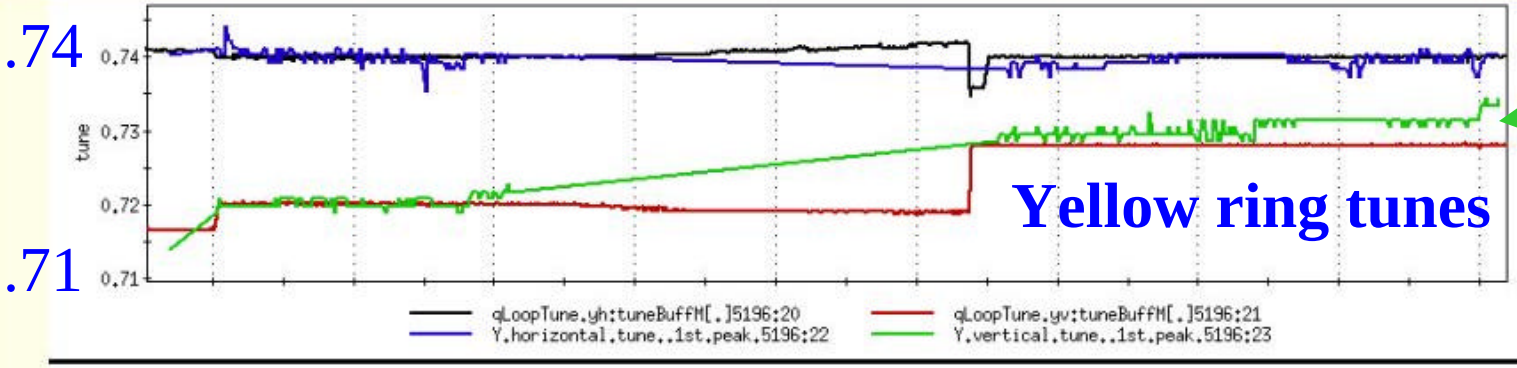
H. Wiedemann

Complications:

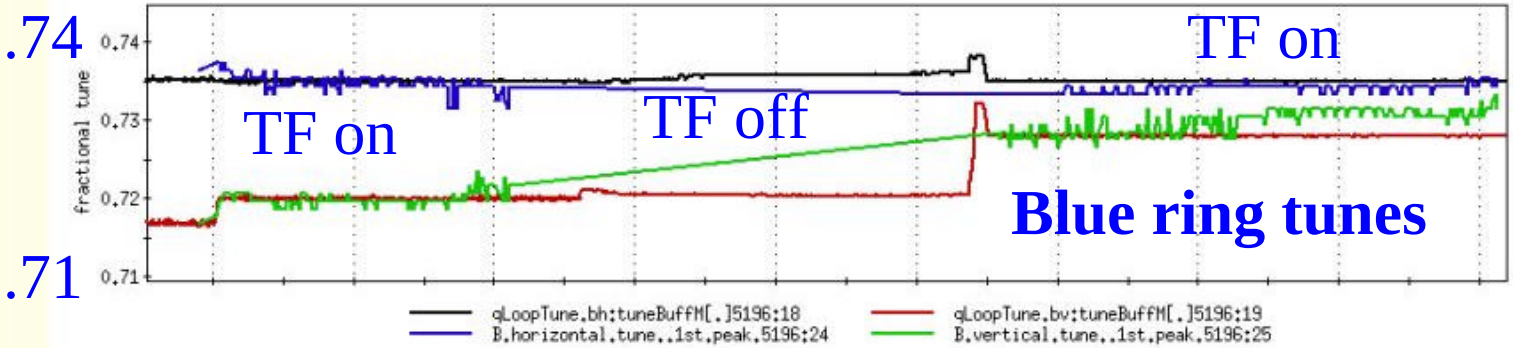
1. beta functions
2. motion control
3. feedbacks on kick and signal gain


Wed Jan 14 02:05:19 - Wed Jan 14 02:06:59
Window Event
Blue ring, Jan 14, 2am
PLL I and Q
loss of amplitude
near transition
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
g_t
.24
Horiz
0.23
Tune
Au Ramp w/ Tune Feedback
.22
Vert
coupling
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

Tune feedback – from Mei's talk

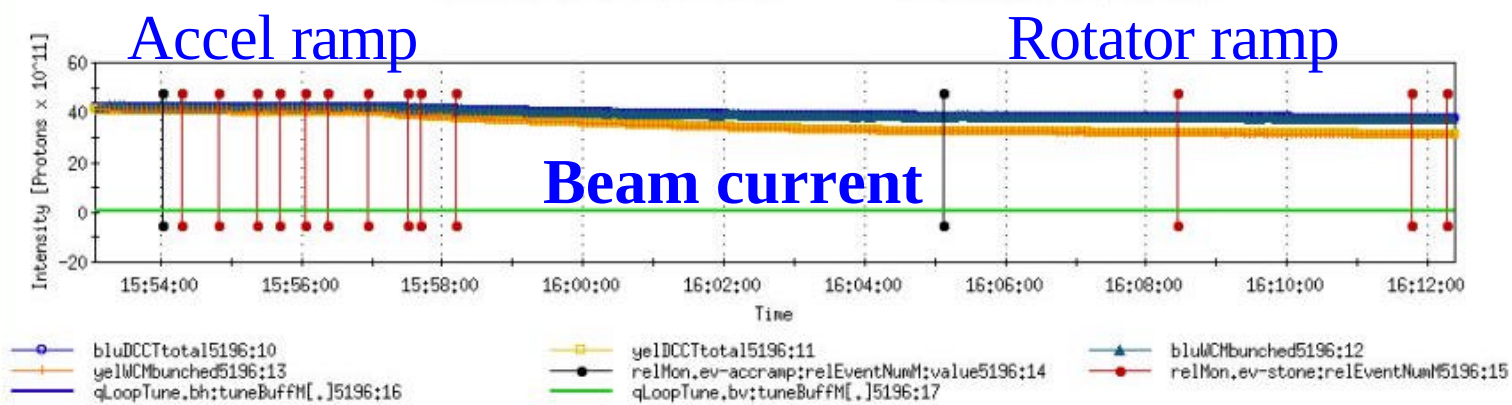


amplitude-dependent tune shift



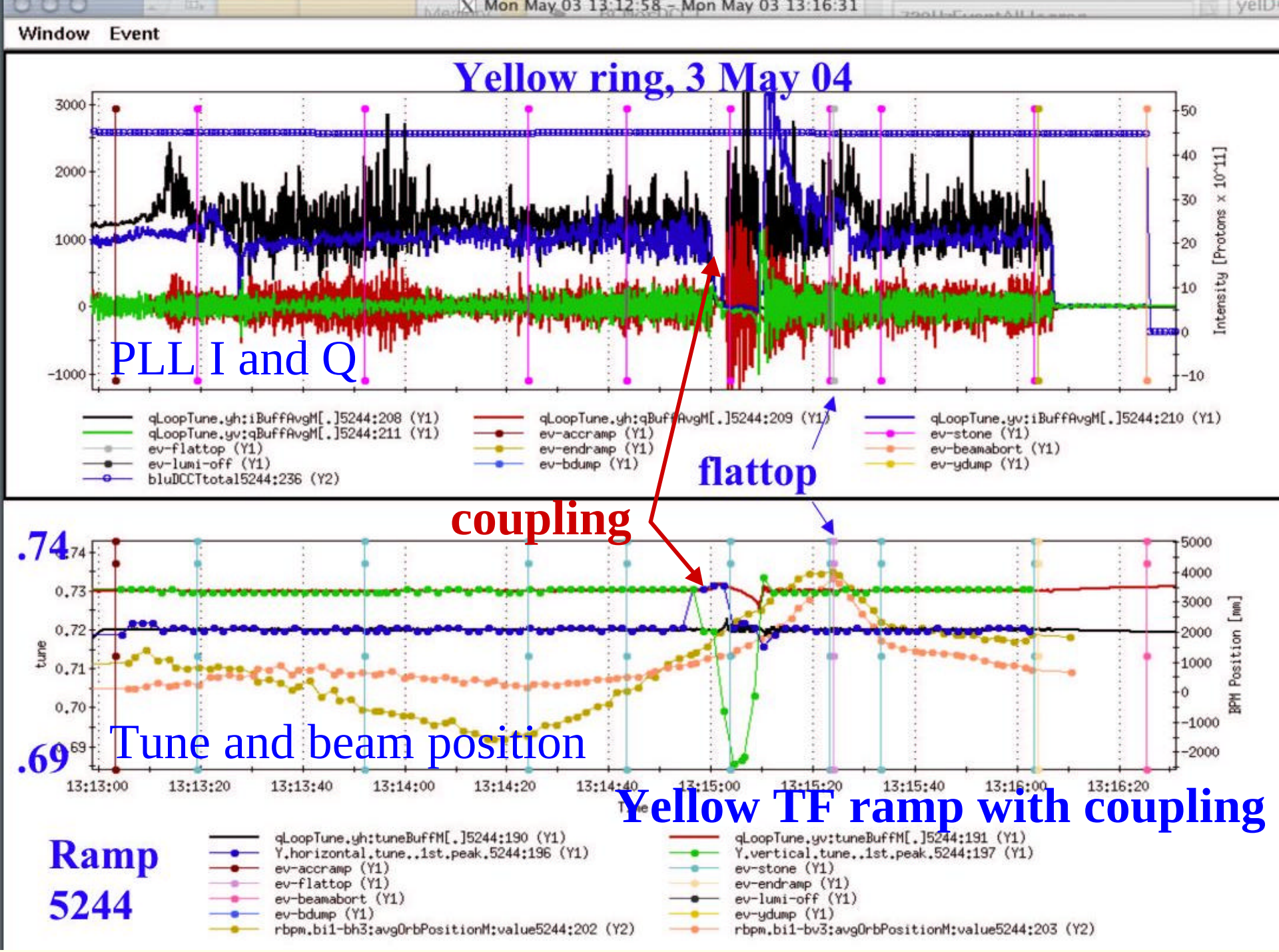
Ramp 5196

Polarized protons

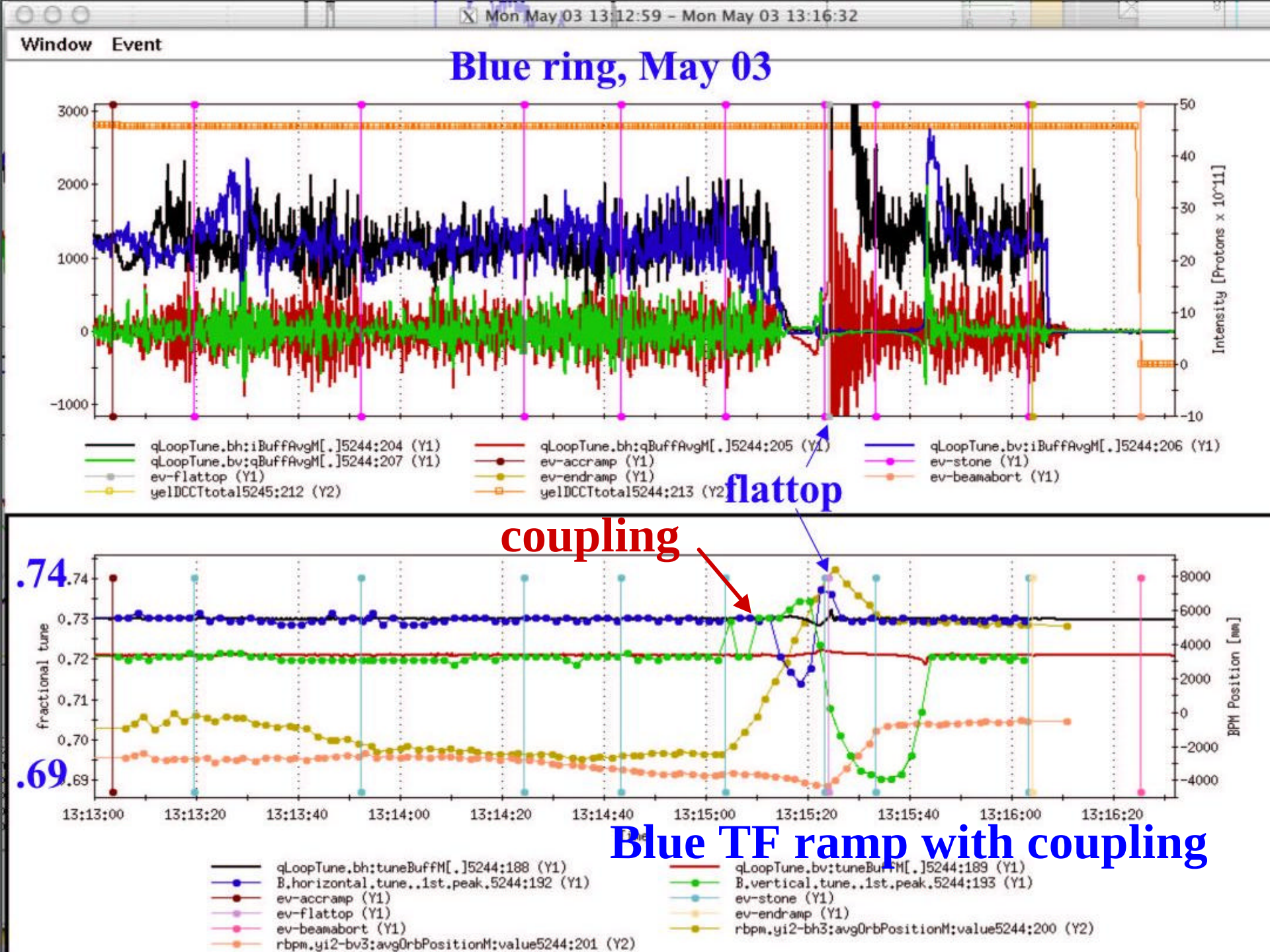


Effect of Coupling on TF

- Previous slide showed successful ramp w/ TF
  - Coupling was well corrected prior to ramp
- Next two slides show slightly less successful ramps w/ TF
  - Coupling not so well corrected (due to change of Bdot as ramp approaches flattop)
  - Tune excursions during times of large coupling
  - No beam loss, but probable polarization loss


Mon May 03 13:12:58 – Mon May 03 13:16:31
Window Event
Yellow ring, 3 May 04
PLL I and Q
Intensity [Protons x 10^11]
qLoopTune.yh:iBuffAvgM[.]5244:208 (Y1)
qLoopTune.yh:qBuffAvgM[.]5244:209 (Y1)
qLoopTune.yv:iBuffAvgM[.]5244:210 (Y1)
qLoopTune.yv:qBuffAvgM[.]5244:211 (Y1)
ev-accramp (Y1)
ev-stone (Y1)
ev-flattop (Y1)
ev-endramp (Y1)
ev-beamabort (Y1)
ev-lumi-off (Y1)
ev-bdump (Y1)
ev-ydump (Y1)
bluDCCTtotal5244:236 (Y2)
flattop
coupling
.74
.69
tune
BPM Position [mm]
Tune and beam position
13:13:00
13:13:20
13:13:40
13:14:00
13:14:20
13:14:40
13:15:00
13:15:20
13:15:40
13:16:00
13:16:20
Yellow TF ramp with coupling
Ramp
5244
qLoopTune.yh:tuneBuffM[.]5244:190 (Y1)
qLoopTune.yv:tuneBuffM[.]5244:191 (Y1)
Y.horizontal.tune..1st.peak.5244:196 (Y1)
Y.vertical.tune..1st.peak.5244:197 (Y1)
ev-accramp (Y1)
ev-stone (Y1)
ev-flattop (Y1)
ev-endramp (Y1)
ev-beamabort (Y1)
ev-lumi-off (Y1)
ev-bdump (Y1)
ev-ydump (Y1)
rbpm.bi1-bh3:avgOrbPositionM:value5244:202 (Y2)
rbpm.bi1-bv3:avgOrbPositionM:value5244:203 (Y2)

Blue ring, May 03



Blue TF ramp with coupling

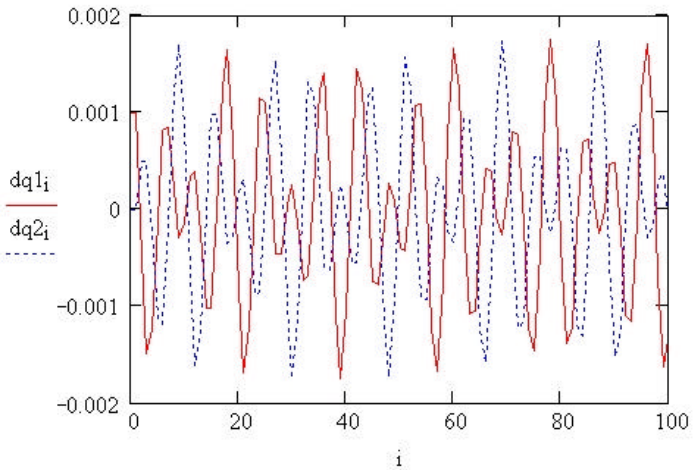
$$\begin{pmatrix} dq1_0 \\ dq2_0 \\ kx_0 \\ ky_0 \end{pmatrix} := \begin{pmatrix} .001 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad c := 0.25$$

initial perturbation .001

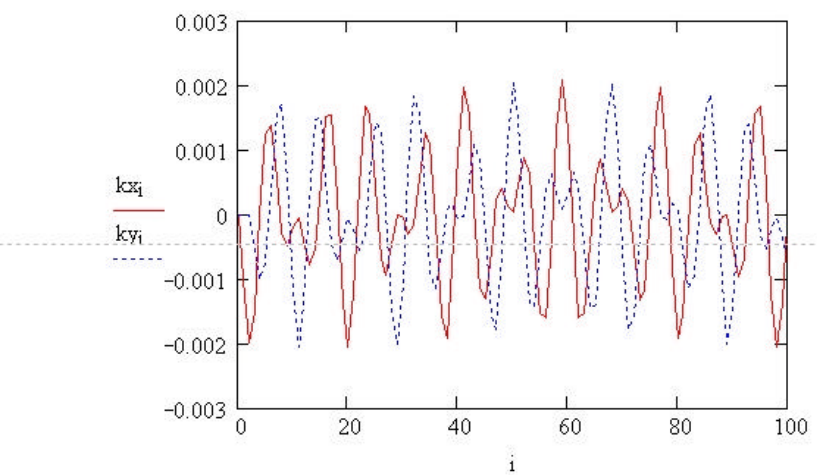
coupling coefficient .25

$$\begin{pmatrix} dq1_{i+1} \\ dq2_{i+1} \\ kx_{i+1} \\ ky_{i+1} \end{pmatrix} := \begin{bmatrix} dq1_i + \left[(1-c)kx_{i+1}\right] + -c\cdot ky_{i+1} \\ dq2_i + \left[\left[(1-c)\cdot ky_{i+1}\right] + -c\cdot kx_{i+1}\right] \\ kx_i - dq1_i \\ ky_i - dq2_i \end{bmatrix}$$

coupling terms



tune



correction strength

x axis span ~ 0.5 sec
PLL BW ~ tens of Hz
Quad BW ~ a few Hz

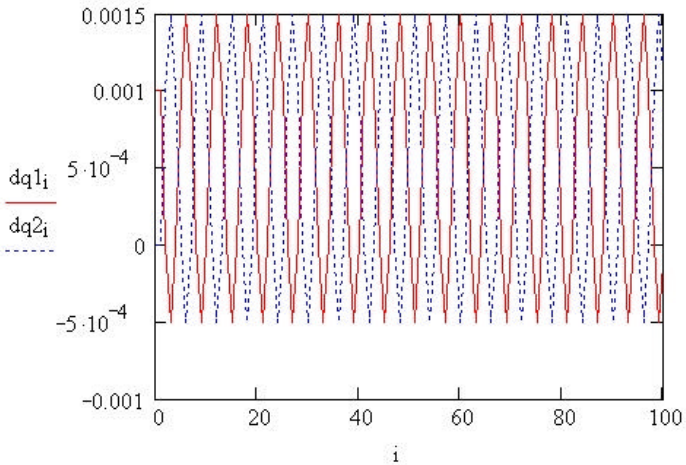
Here coupling coefficient is 0.25, system of tune feedback is stable

$$\begin{pmatrix} dq1_0 \\ dq2_0 \\ kx_0 \\ ky_0 \end{pmatrix} := \begin{pmatrix} .001 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad c := 0.50$$

initial perturbation .001

coupling coefficient .5 (45 deg)

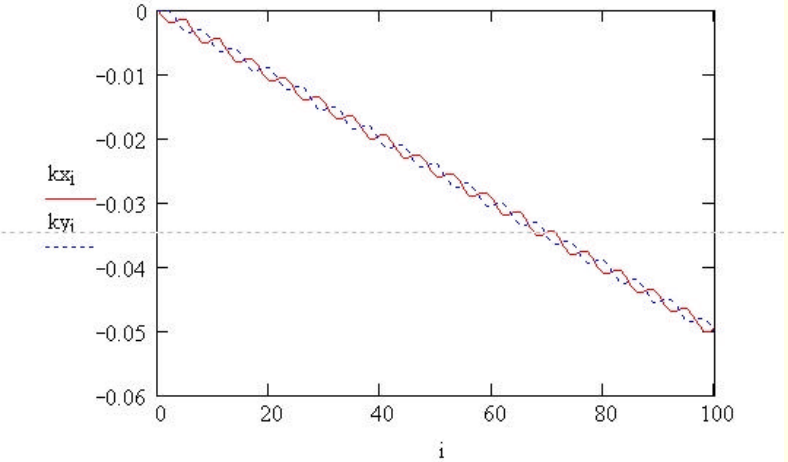
$$\begin{pmatrix} dq1_{i+1} \\ dq2_{i+1} \\ kx_{i+1} \\ ky_{i+1} \end{pmatrix} := \begin{bmatrix} dq1_i + \left[(1-c)kx_{i+1}\right] + -c\cdot ky_{i+1} \\ dq2_i + \left[\left[(1-c)\cdot ky_{i+1}\right] + -c\cdot kx_{i+1}\right] \\ kx_i - dq1_i \\ ky_i - dq2_i \end{bmatrix}$$



tune

Here coupling coefficient is 0.5

- tune remains stable
- correction strength diverges



correction strength

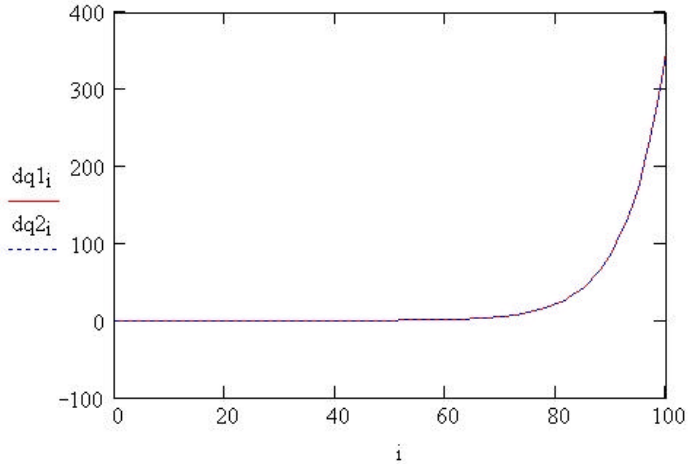
$$\begin{pmatrix} dq1_0 \\ dq2_0 \\ kx_0 \\ ky_0 \end{pmatrix} := \begin{pmatrix} .001 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$c := 0.51$$

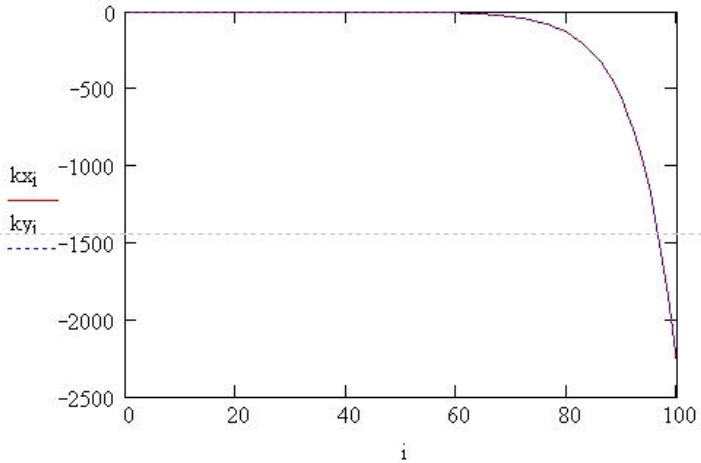
initial perturbation .001

coupling coefficient .51

$$\begin{pmatrix} dq1_{i+1} \\ dq2_{i+1} \\ kx_{i+1} \\ ky_{i+1} \end{pmatrix} := \begin{bmatrix} dq1_i + \left[(1-c)kx_{i+1}\right] + -c\cdot ky_{i+1} \\ dq2_i + \left[\left[(1-c)\cdot ky_{i+1}\right] + -c\cdot kx_{i+1}\right] \\ kx_i - dq1_i \\ ky_i - dq2_i \end{bmatrix}$$



tune



correction strength

Here coupling coefficient is 0.51

- tune diverges
- correction strength diverges

PLL measures normal modes

- stable in the presence of coupling

TF corrects x and y

- not stable in the presence of strong coupling

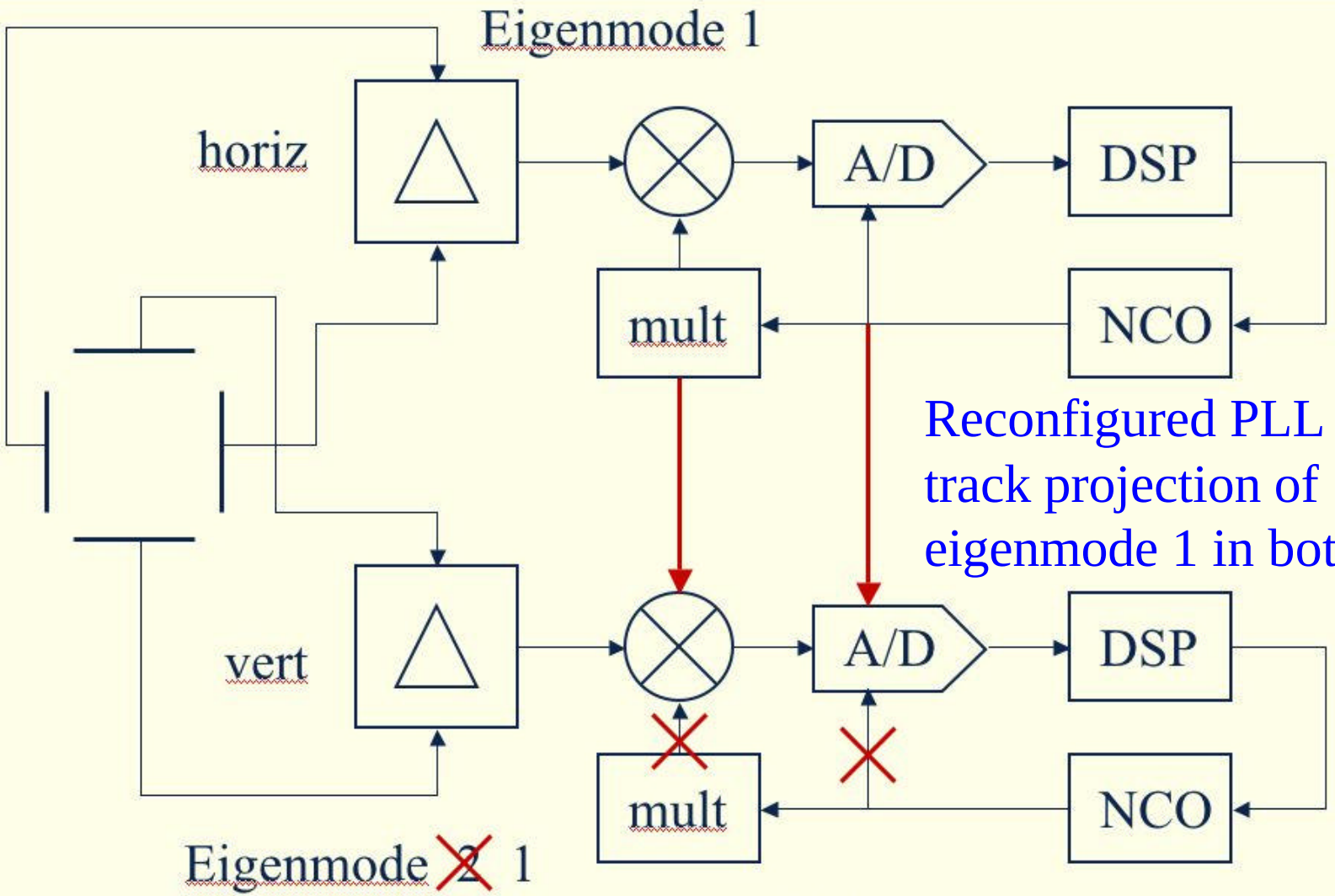
What We Learned and Did

- What we Learned
  - PLL is stable in the presence of coupling (as long as tune separation > 100Hz digital filter BW)
  - The system of

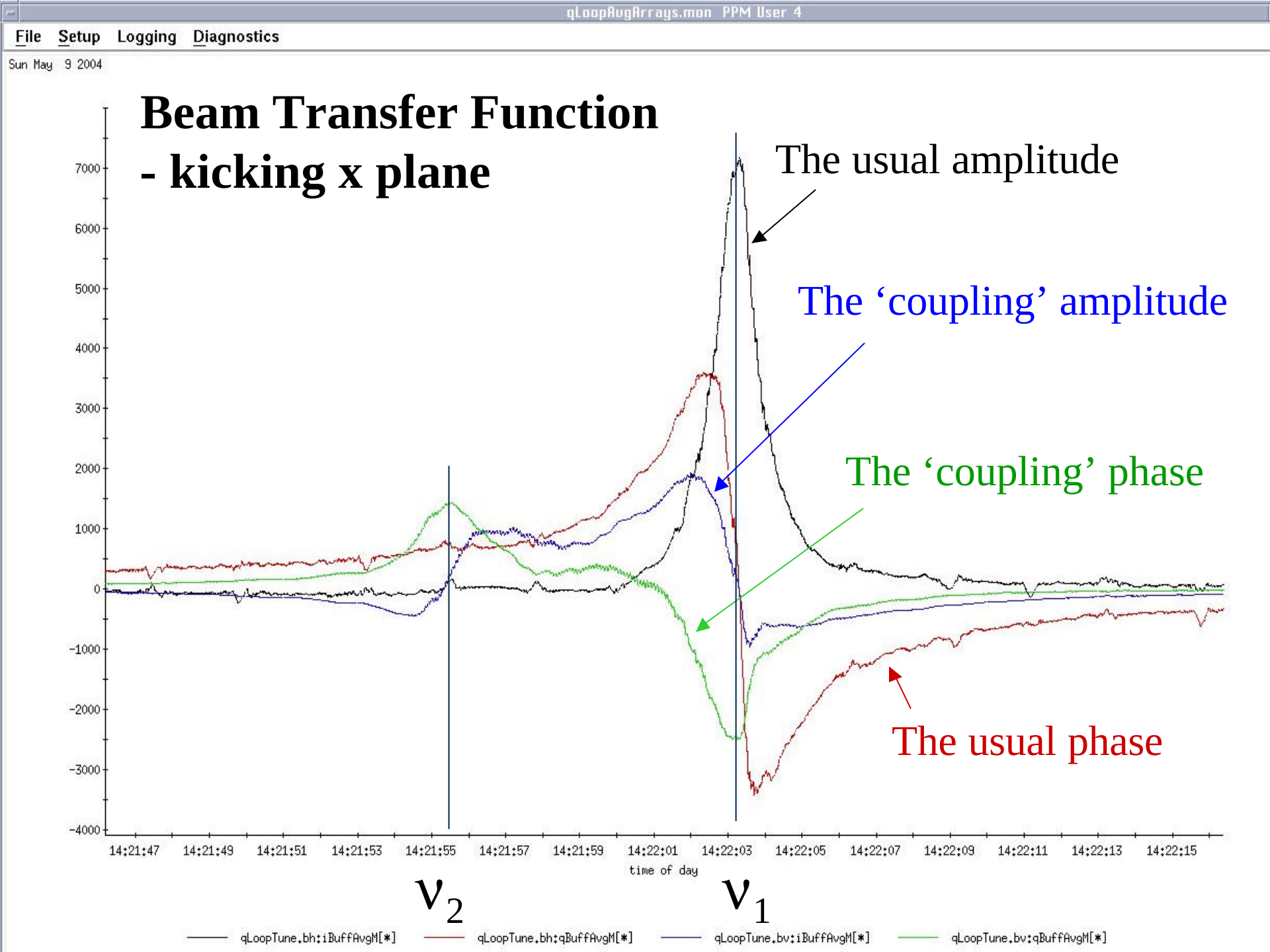
    Tune Feedback = PLL + magnet control

    is not stable in the presence of coupling
- What we Did
  - Improved coupling measurement
  - Investigated two correction possibilities

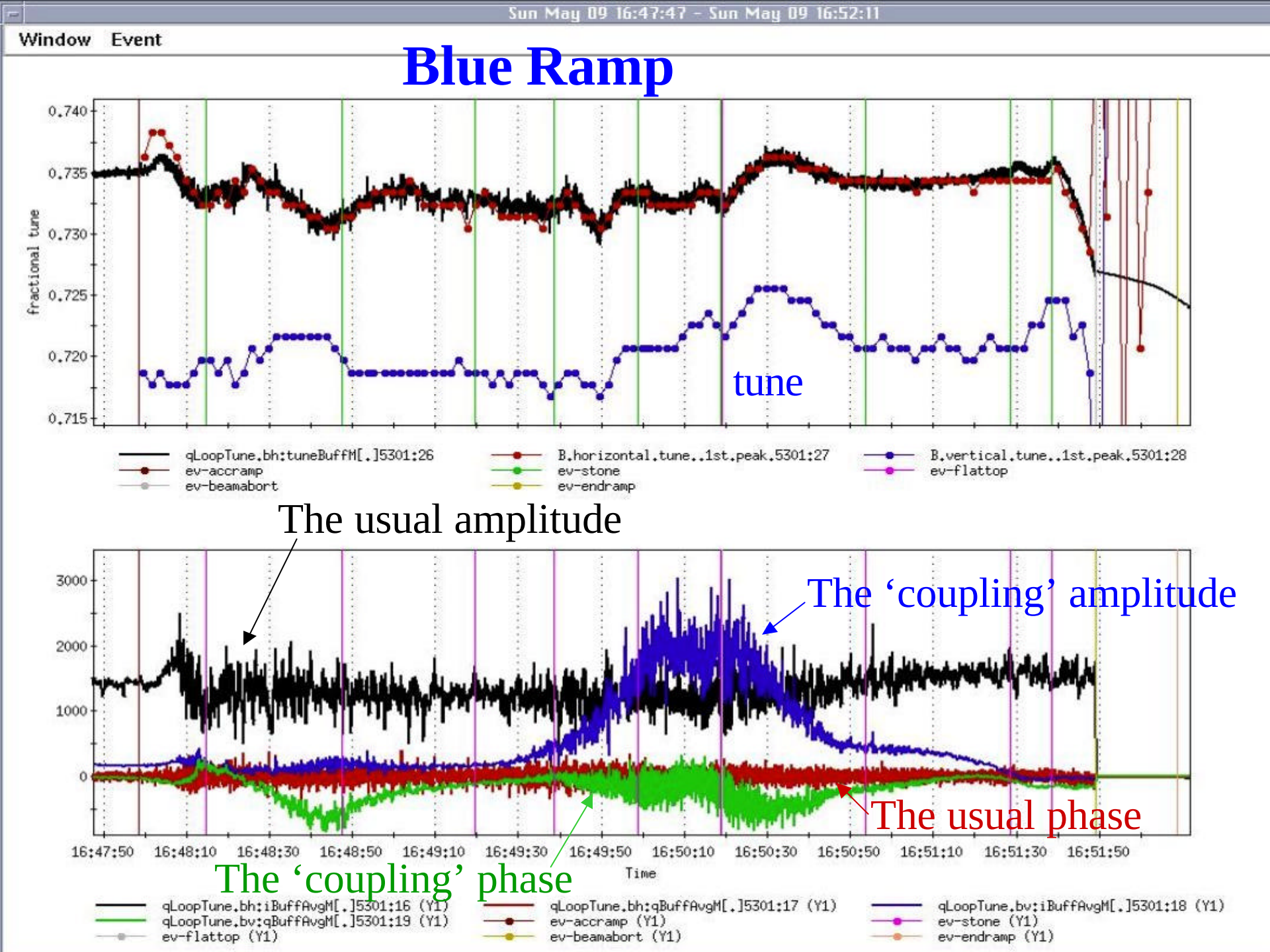
Coupling Measurement



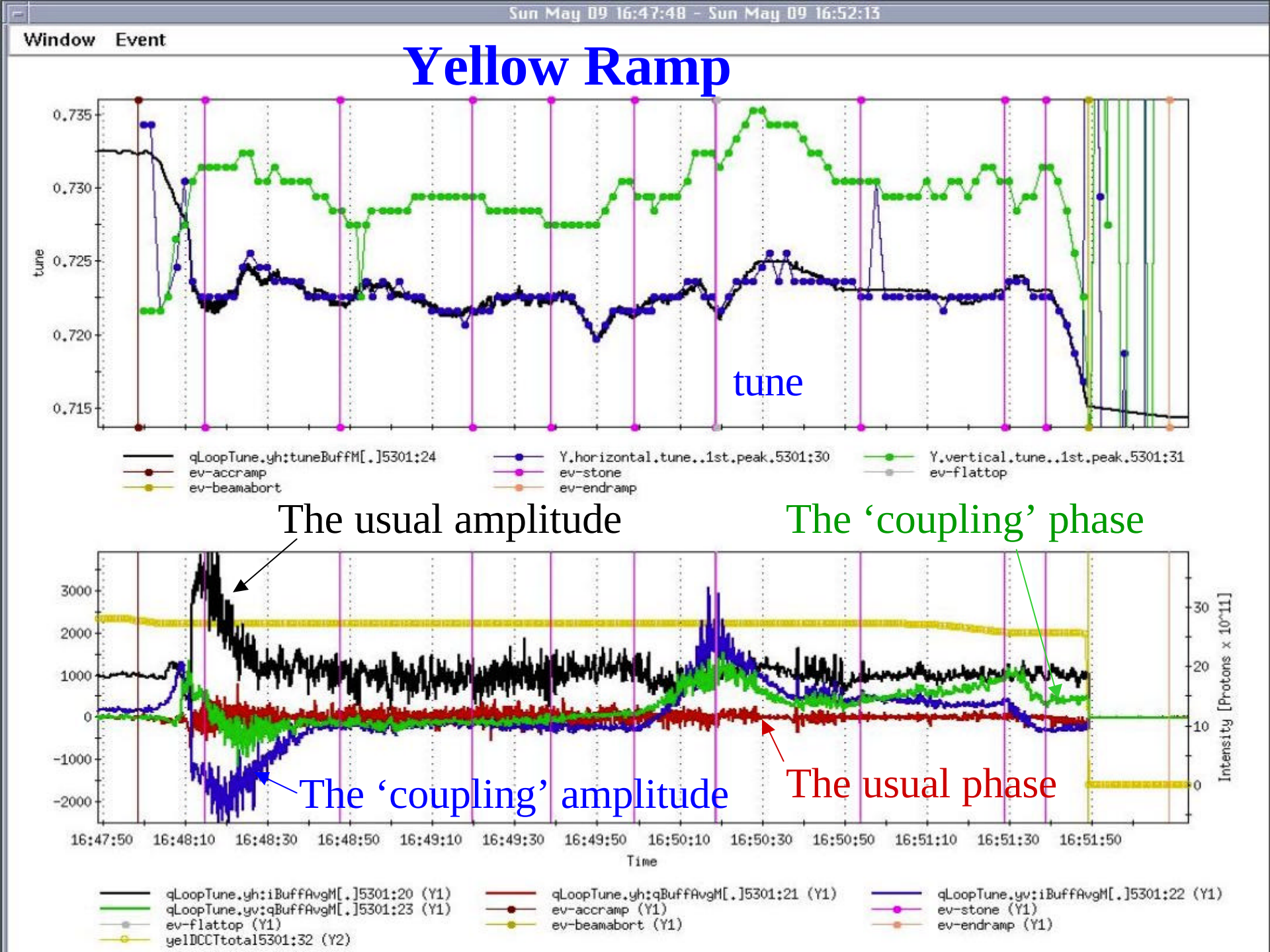
Reconfigured PLL to track projection of eigenmode 1 in both planes


qLoopAvgArrays.mon PPM User 4
File Setup Logging Diagnostics
Sun May 9 2004
Beam Transfer Function
- kicking x plane
The usual amplitude
The 'coupling' amplitude
The 'coupling' phase
The usual phase
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
14:21:47
14:21:49
14:21:51
14:21:53
14:21:55
14:21:57
14:21:59
14:22:01
14:22:03
14:22:05
14:22:07
14:22:09
14:22:11
14:22:13
14:22:15
time of day
ν_2
ν_1
qLoopTune.bh:iBuffAvgM[*]
qLoopTune.bh:qBuffAvgM[*]
qLoopTune.bv:iBuffAvgM[*]
qLoopTune.bv:qBuffAvgM[*]

Blue Ramp

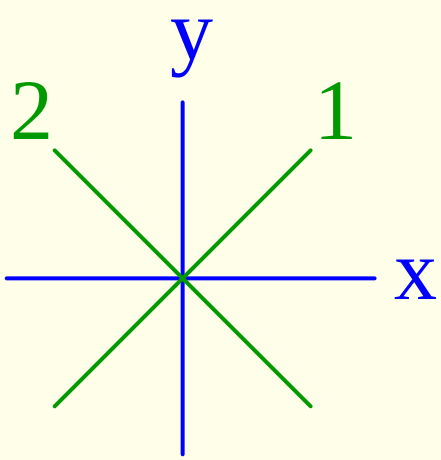

Sun May 09 16:47:47 - Sun May 09 16:52:11
Window Event
fractional tune
0.740
0.735
0.730
0.725
0.720
0.715
tune
qLoopTune.bh:tuneBuffM[.]5301:26
ev-accramp
ev-beamabort
B.horizontal.tune..1st.peak.5301:27
ev-stone
ev-endramp
B.vertical.tune..1st.peak.5301:28
ev-flattop
The usual amplitude
The 'coupling' amplitude
The usual phase
The 'coupling' phase
3000
2000
1000
0
16:47:50
16:48:10
16:48:30
16:48:50
16:49:10
16:49:30
16:49:50
16:50:10
16:50:30
16:50:50
16:51:10
16:51:30
16:51:50
Time
qLoopTune.bh:iBuffAvgM[.]5301:16 (Y1)
qLoopTune.bv:qBuffAvgM[.]5301:19 (Y1)
ev-flattop (Y1)
qLoopTune.bh:qBuffAvgM[.]5301:17 (Y1)
ev-accramp (Y1)
ev-beamabort (Y1)
qLoopTune.bv:iBuffAvgM[.]5301:18 (Y1)
ev-stone (Y1)
ev-endramp (Y1)

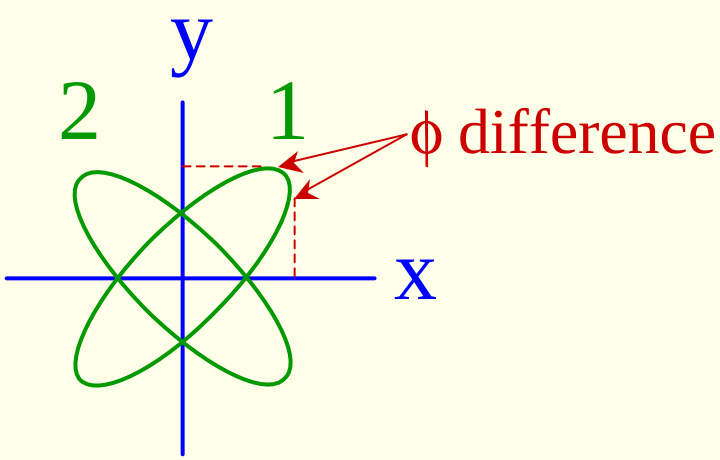
Yellow Ramp


Sun May 09 16:47:48 - Sun May 09 16:52:13
Window Event
tune
0.735
0.730
0.725
0.720
0.715
qLoopTune.yh:tuneBuffM[.]5301:24
ev-accramp
ev-beamabort
Y.horizontal.tune..1st.peak.5301:30
ev-stone
ev-endramp
Y.vertical.tune..1st.peak.5301:31
ev-flattop
The usual amplitude
The 'coupling' phase
The 'coupling' amplitude
The usual phase
3000
2000
1000
0
-1000
-2000
30
20
10
0
Intensity [Protons x 10^11]
16:47:50
16:48:10
16:48:30
16:48:50
16:49:10
16:49:30
16:49:50
16:50:10
16:50:30
16:50:50
16:51:10
16:51:30
16:51:50
Time
qLoopTune.yh:iBuffAvgM[.]5301:20 (Y1)
qLoopTune.yv:qBuffAvgM[.]5301:23 (Y1)
ev-flattop (Y1)
yelDCCTtotal5301:32 (Y2)
qLoopTune.yh:qBuffAvgM[.]5301:21 (Y1)
ev-accramp (Y1)
ev-beamabort (Y1)
qLoopTune.yv:iBuffAvgM[.]5301:22 (Y1)
ev-stone (Y1)
ev-endramp (Y1)

Eigenmodes

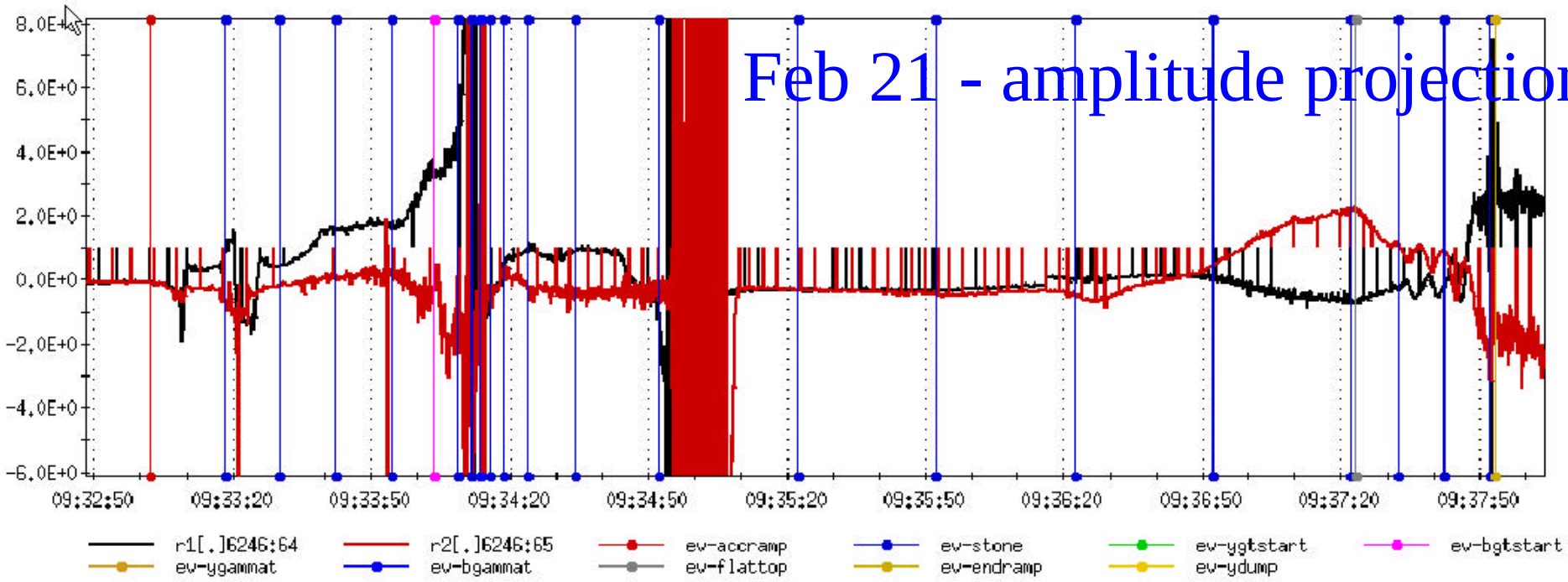
- PLL locks to eigenmodes
- Driven oscillator – whence ϕ shift between projections?
- What determines ellipse width? Phase of coupling source relative to pickup?

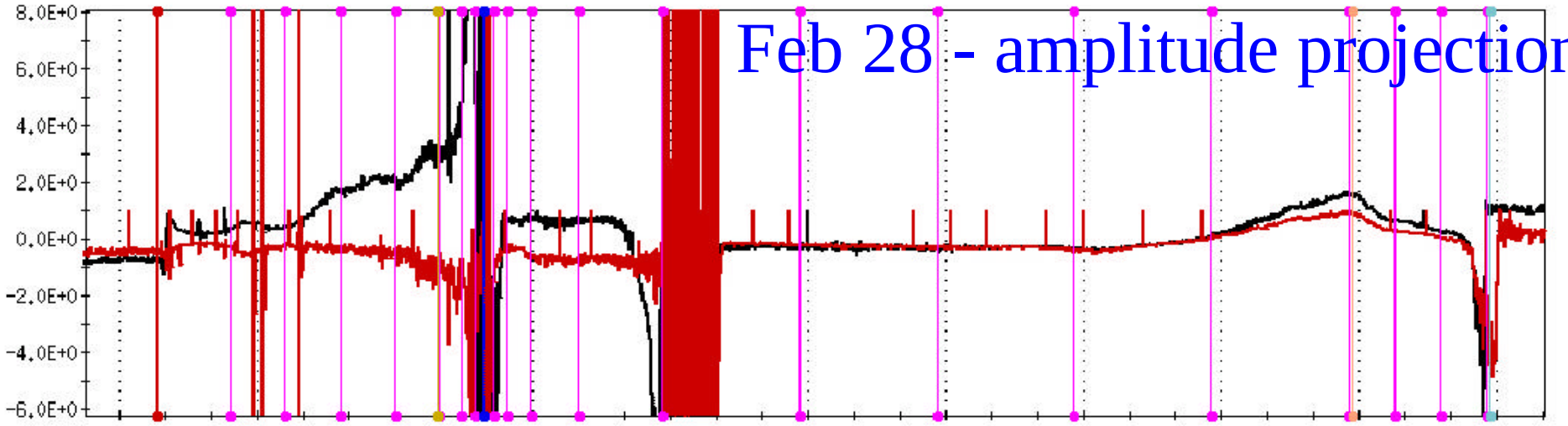


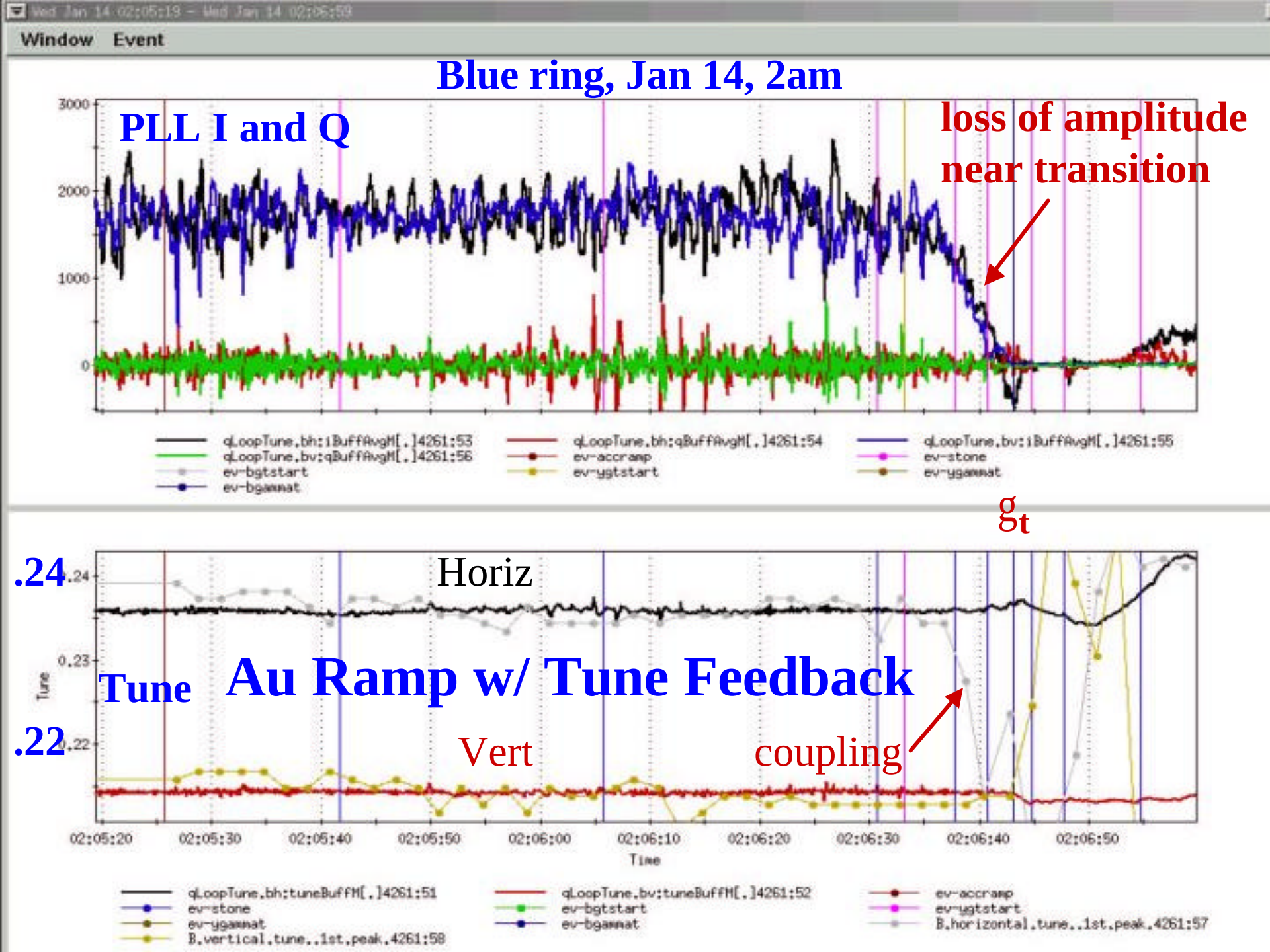


Wed Feb 23 09:18:16 - Mon Feb 28 09:29:37

Window Event



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loss of amplitude
near transition
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1000
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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
g_t
.24
Horiz
0.23
Tune
Au Ramp w/ Tune Feedback
.22
Vert
coupling
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

Alternative method – skew mod

- New technique - phase modulation
- Perturbs the beam ~.002 tune modulation
  - Stresses the PLL
  - In the presence of chromaticity modulation, things could get difficult and confusing
- Measurement and correction is becoming reliable
- Yun's talk for more

Coupling summary

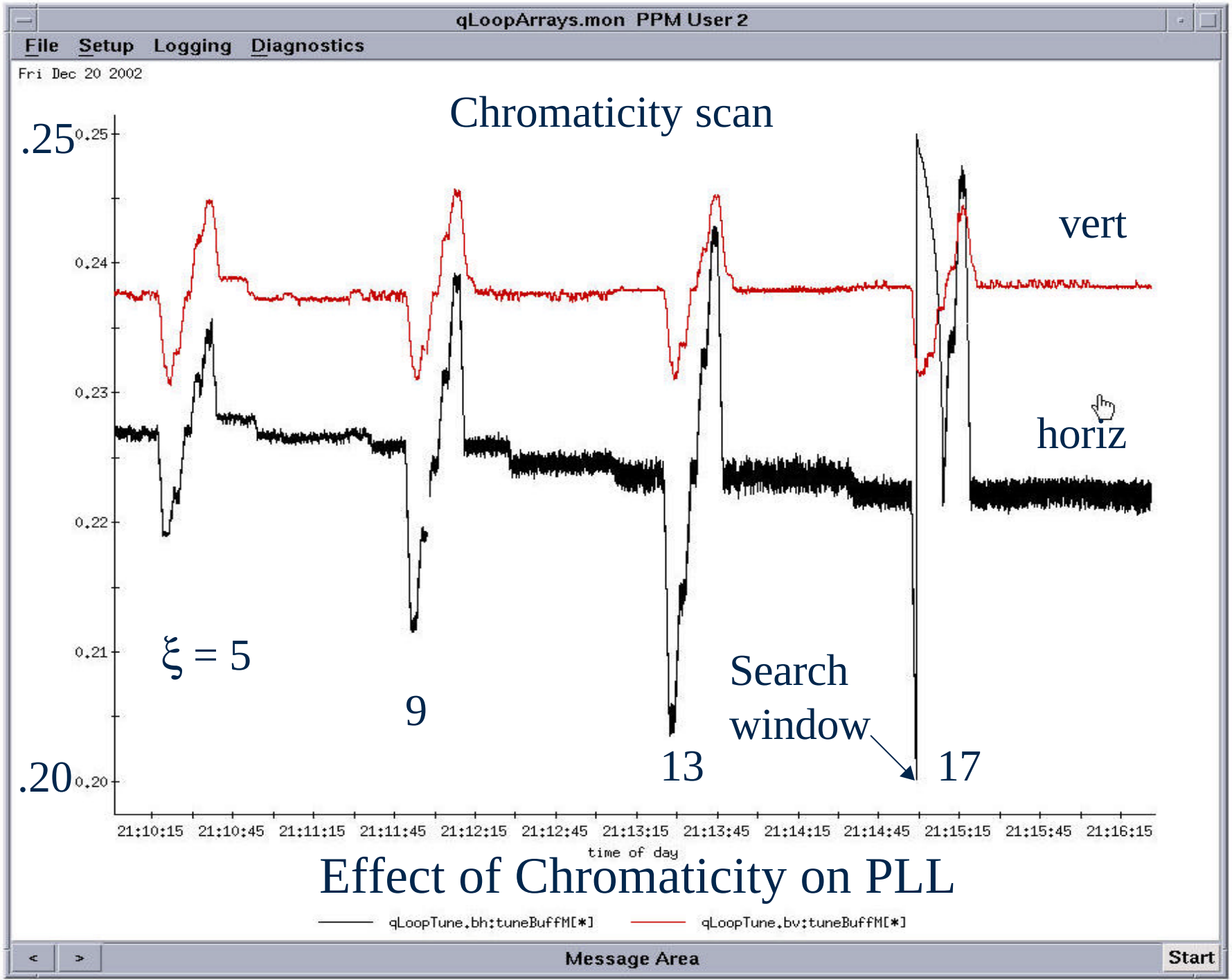
- New understanding
  - Coupling a moderately serious issue for PLL
  - Coupling a very serious issue for tune feedback
- New measurement technique
  - Non-perturbative
  - Excellent S/N
  - Delivers both amplitude and phase of coupling
  - Possibility of coupling correction using this data is being actively investigated – Yun Luo, Steve Peggs, Richard Talman

Thoughts on 'Robust' Measurement

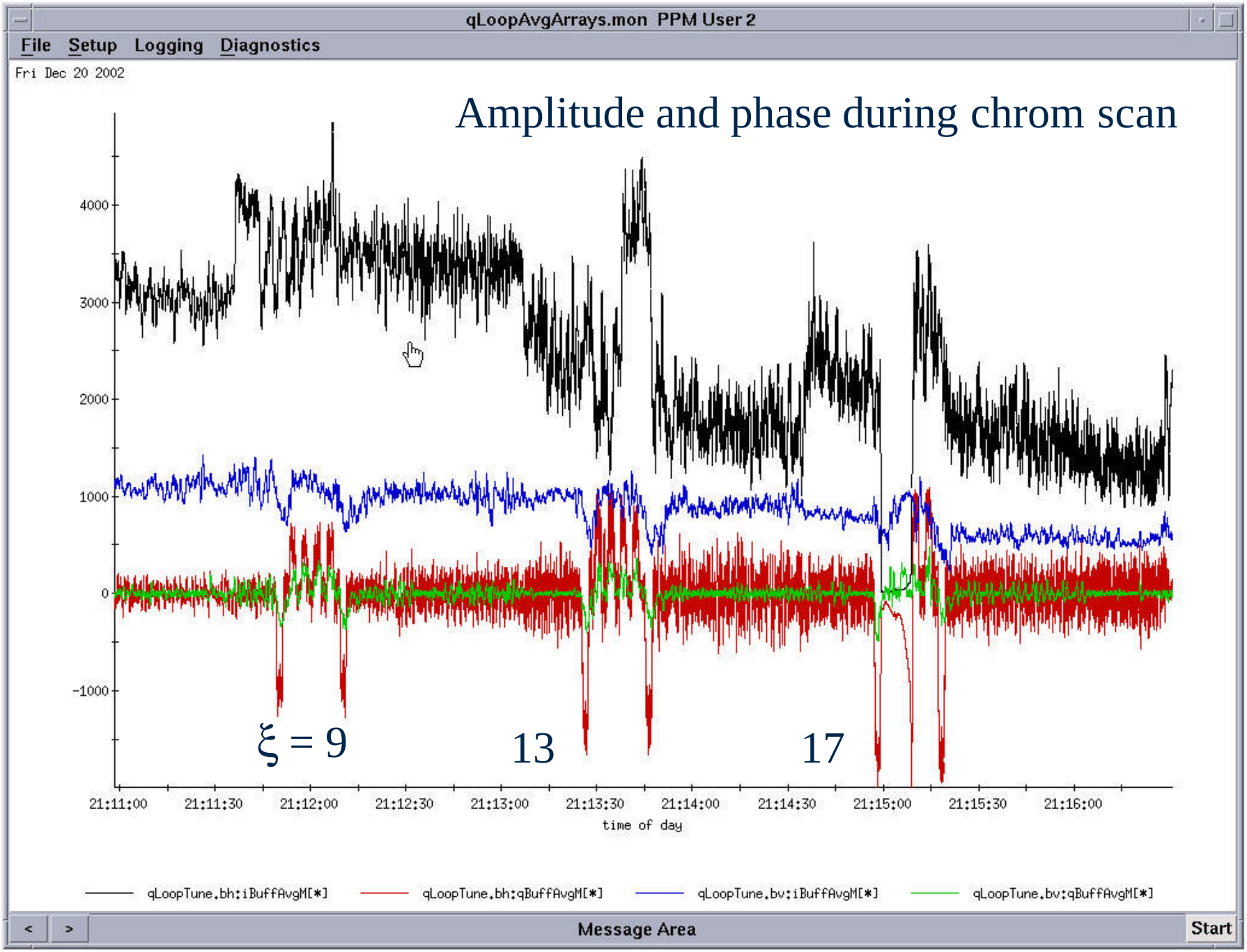
- AP types keep setting upon BI types about making PLL 'robust' in the presence of coupling
- Is this in principle even possible?
- If possible in principle, is it possible in practice?
  - beta functions, ramp squeeze (RHIC)
  - PLL internal feedbacks on kickere power and signal path gain are essential to reliable operation
  - motion control
- Solution may be to keep coupling small (feedback), rather than ask PLL to identify and maintain lock to rotating eigenmodes

Outline

- Results from 245MHz system
  - Tune and tune feedback
  - Coupling
  - **Chromaticity**
  - Emittance growth
- Results from baseband systems
  - Tune tracking
  - Emittance growth
  - The 60Hz problem


qLoopArrays.mon PPM User 2
File Setup Logging Diagnostics
Fri Dec 20 2002
Chromaticity scan
.25
0.25
0.24
0.23
0.22
0.21
.20
0.20
vert
horiz
ξ = 5
9
13
Search window
17
21:10:15 21:10:45 21:11:15 21:11:45 21:12:15 21:12:45 21:13:15 21:13:45 21:14:15 21:14:45 21:15:15 21:15:45 21:16:15
time of day
Effect of Chromaticity on PLL
qLoopTune.bh:tuneBuffM[*]
qLoopTune.bv:tuneBuffM[*]
Message Area
Start

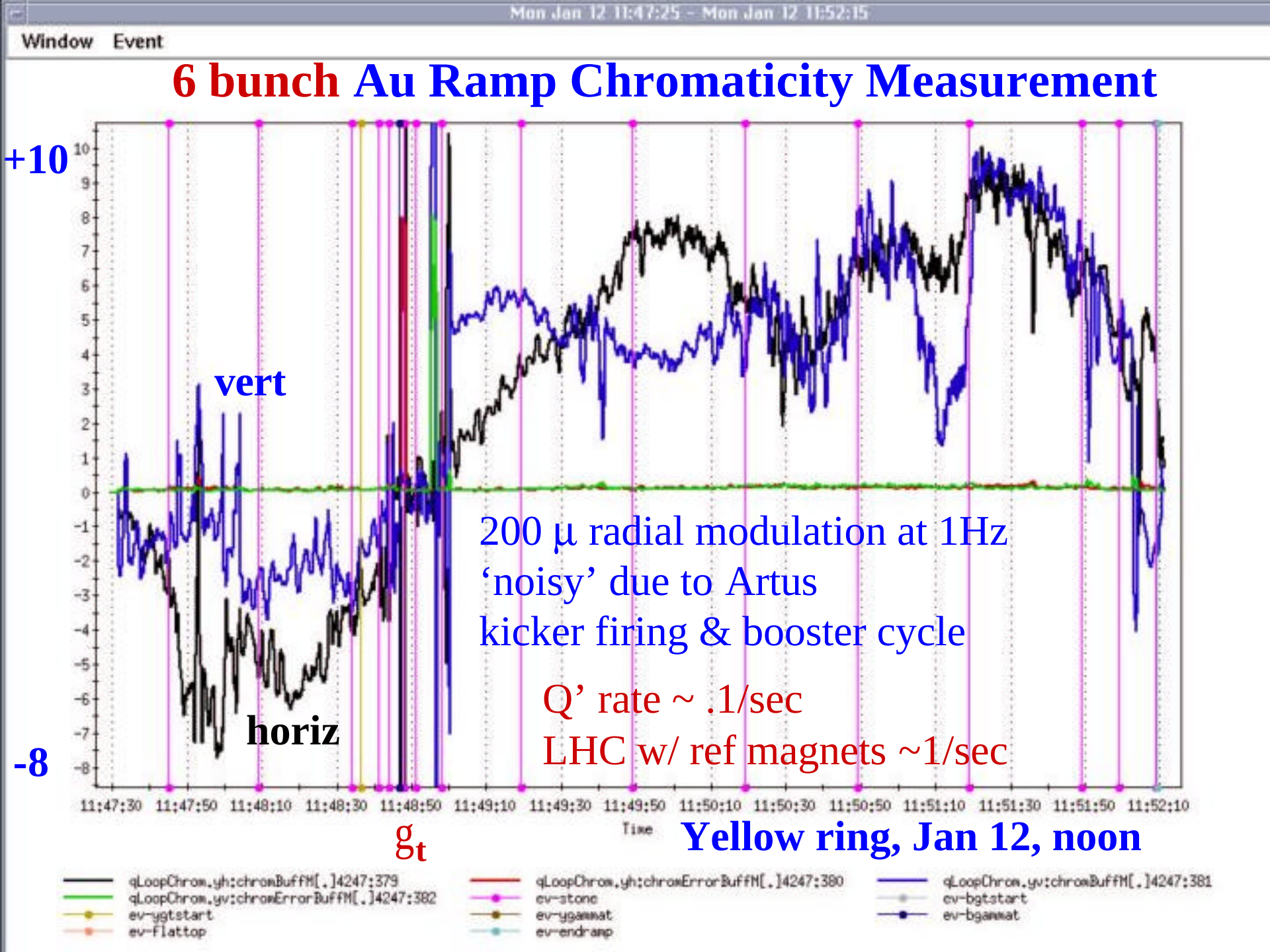
Amplitude and phase during chrom scan

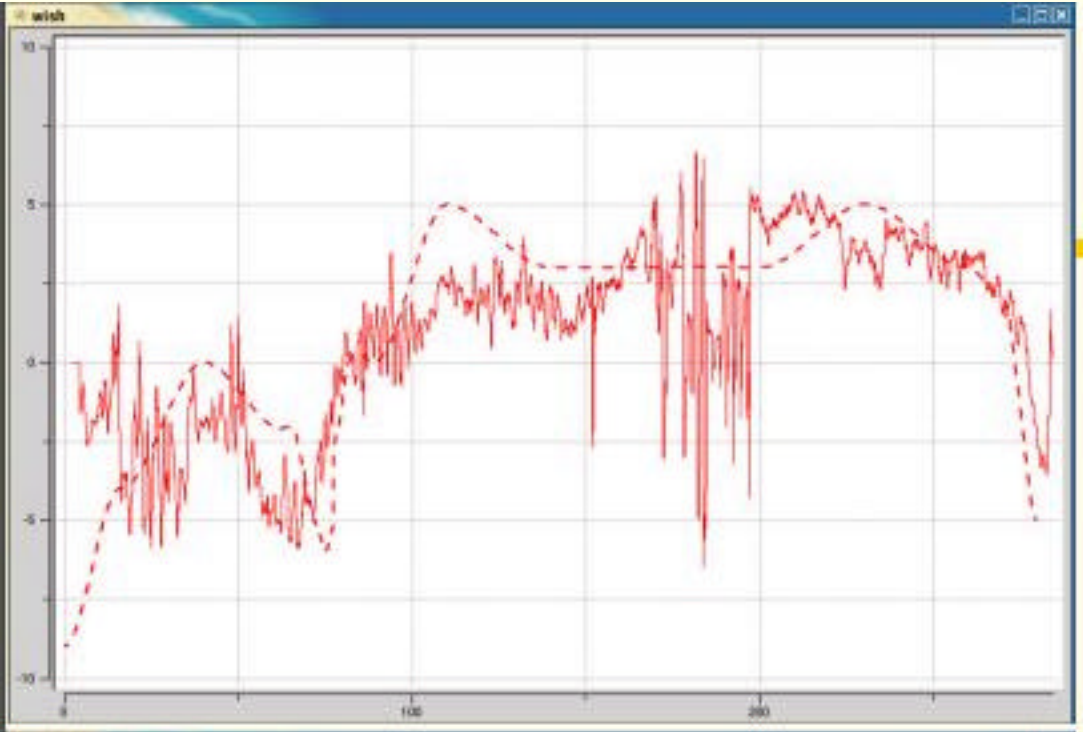


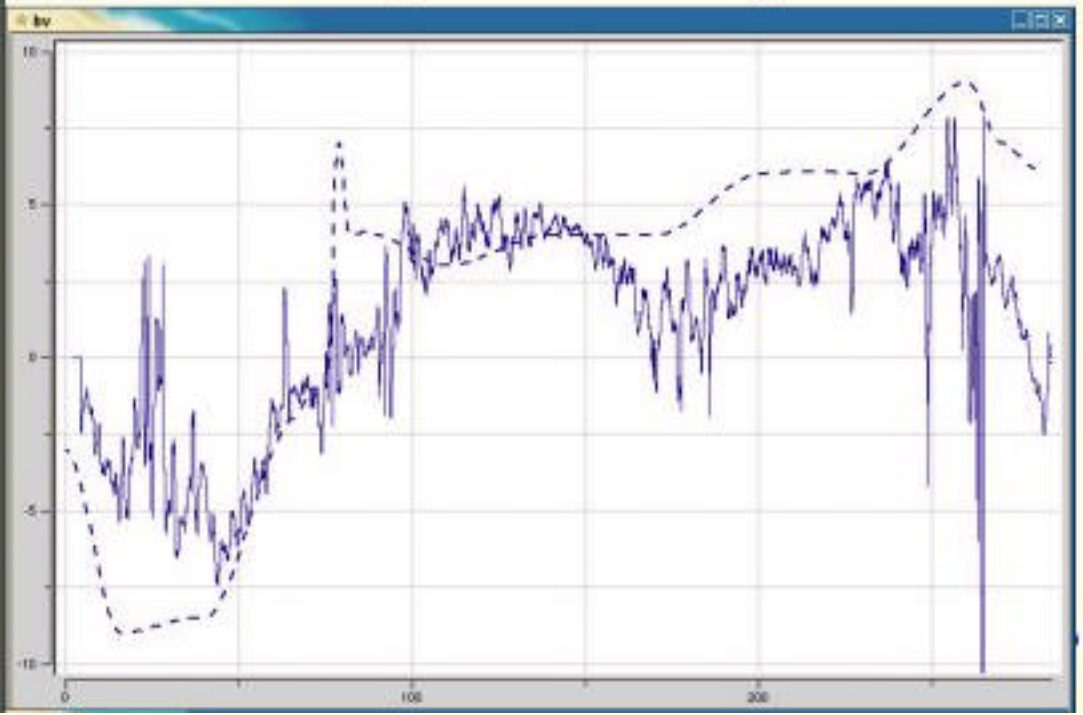
Chromaticity Effect on PLL

- Conclusion from chromaticity study (and years of experience with beam) is that 245MHz PLL tune measurement comfortably copes with a large range of chromaticity (resonantly excites low δp subset of momentum distribution)
- Chromaticity control is not an issue for 245MHz PLL tune measurement and tune/chrom feedback – further study required for baseband system, but we expect similar behavior
- Chromaticity control is an issue primarily in the usual operational sense – line broadening and resonance overlap

6 bunch Au Ramp Chromaticity Measurement





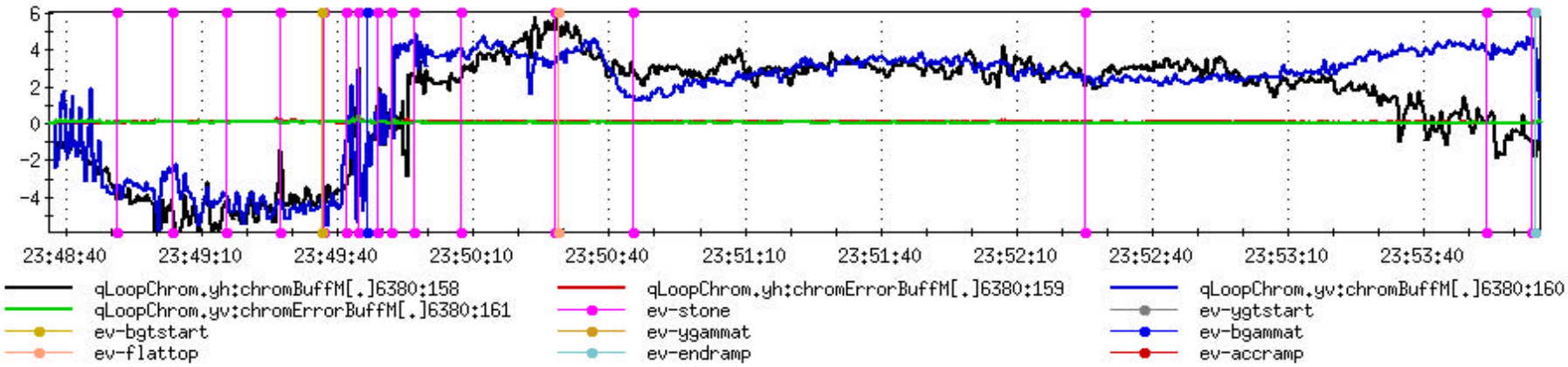


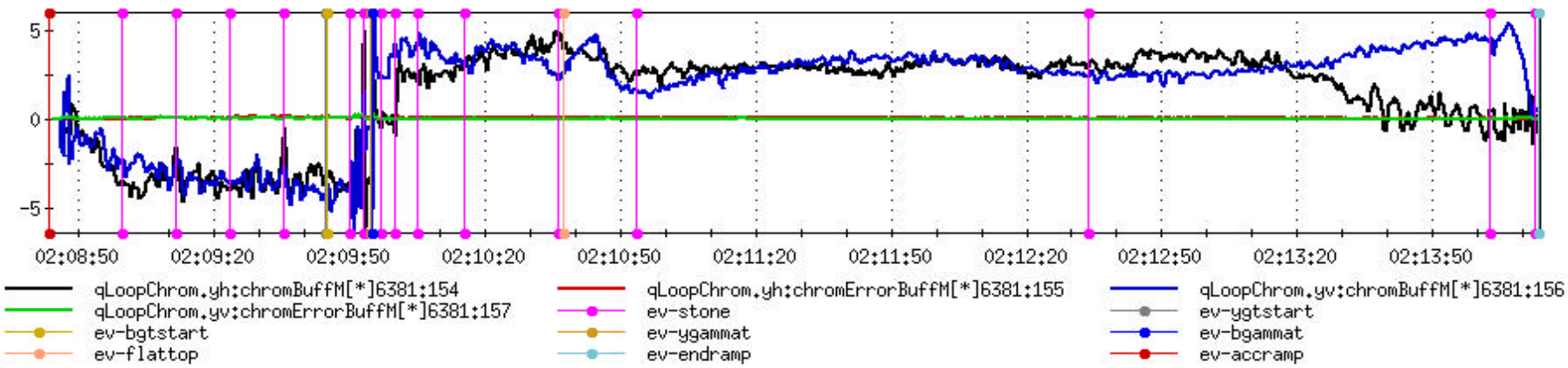
Example of feedforward and improvement of magnet model:

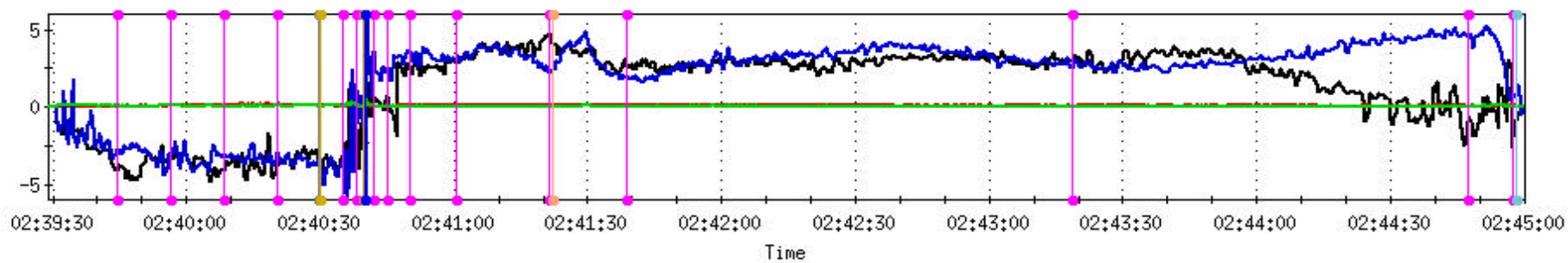
Measured horiz and vert chromaticity data and fit, assuming 10 units of b2 in the DX magnets

Mon Mar 07 23:48:36 - Tue Mar 08 02:45:00

Window Event







Summary of Chromaticity

- Radial modulation method gives good data
- Useful data gathered for feedforward and magnet model
- Bandwidth in present form adequate for LHC snapback feedback correction? perhaps
- No testing of phase modulation methods
  - Need ~1KHz PLL BW – not practical?
- Chromaticity not an issue for reliable operation of PLL

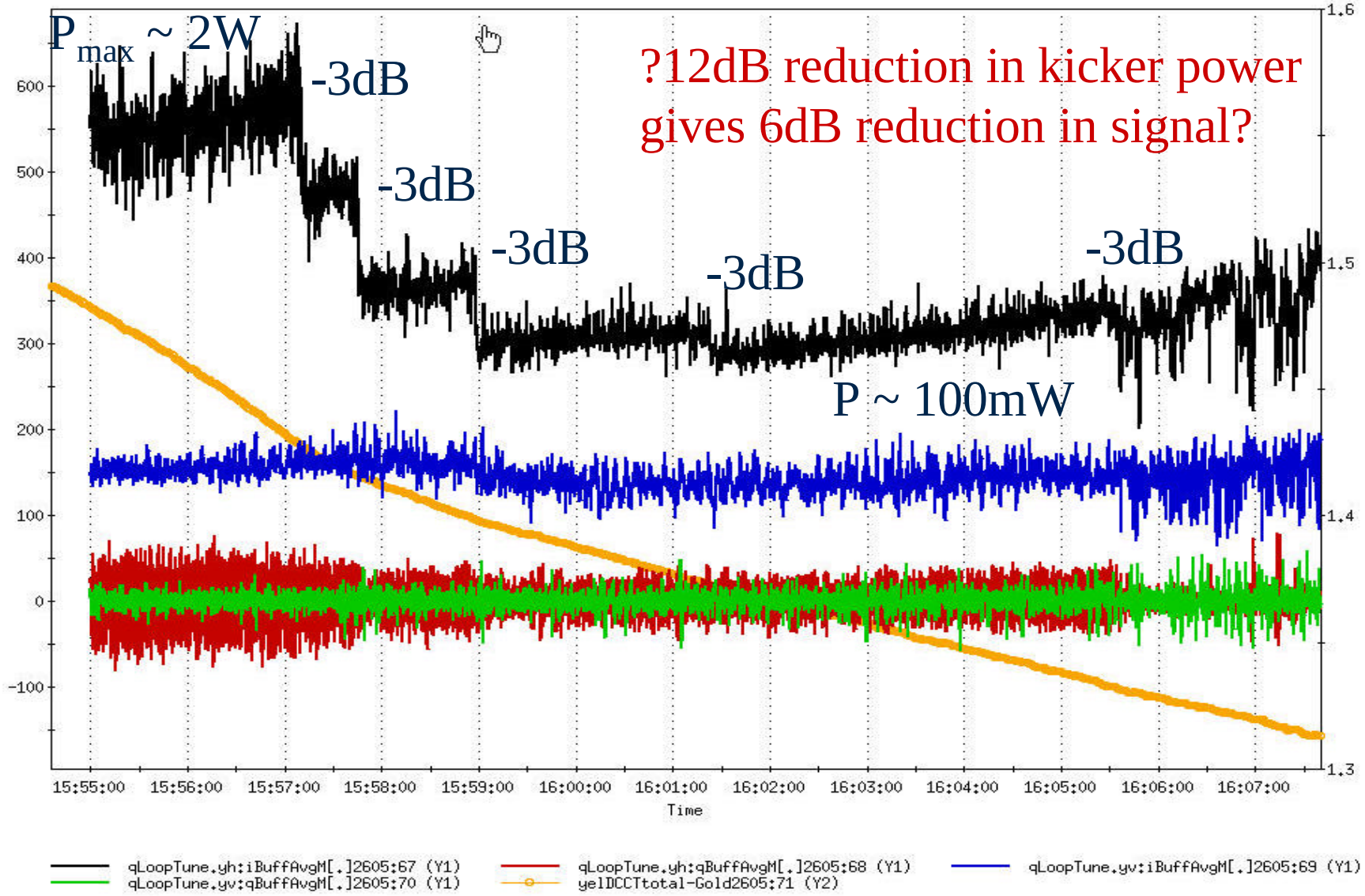
Outline

- Results from 245MHz system
  - Tune and tune feedback
  - Coupling
  - Chromaticity
  - **Emittance growth**
- Results from baseband systems
  - Tune tracking
  - Emittance growth
  - The 60Hz problem

Sun Dec 29 15:54:35 - Sun Dec 29 16:07:40

Window Event

(single bunch?) PLL amplitude for kick reduced in 3dB steps



qLoopTune.yh:iBuffAvgM[.] successfully displayed
qLoopTune.yh:qBuffAvgM[.] successfully displayed

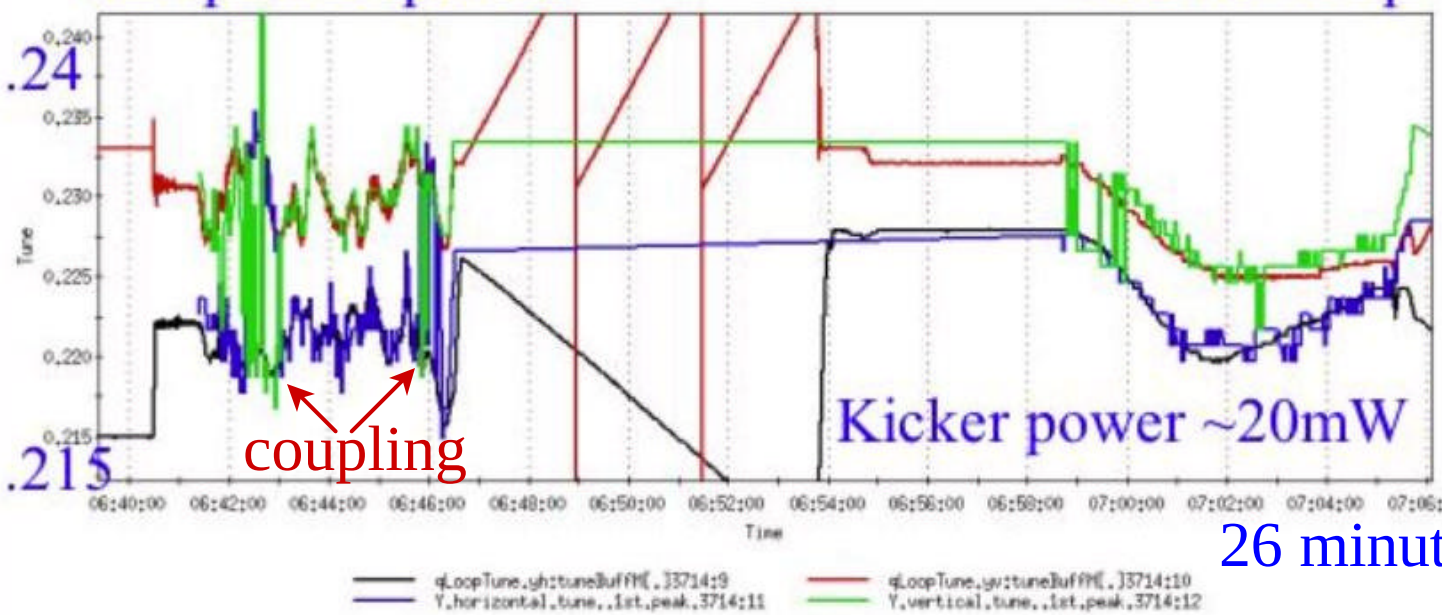
With reasonable care, emittance growth not an issue

Amplitude and phase

Beam decay

Ramp and squeeze

Rotator ramp



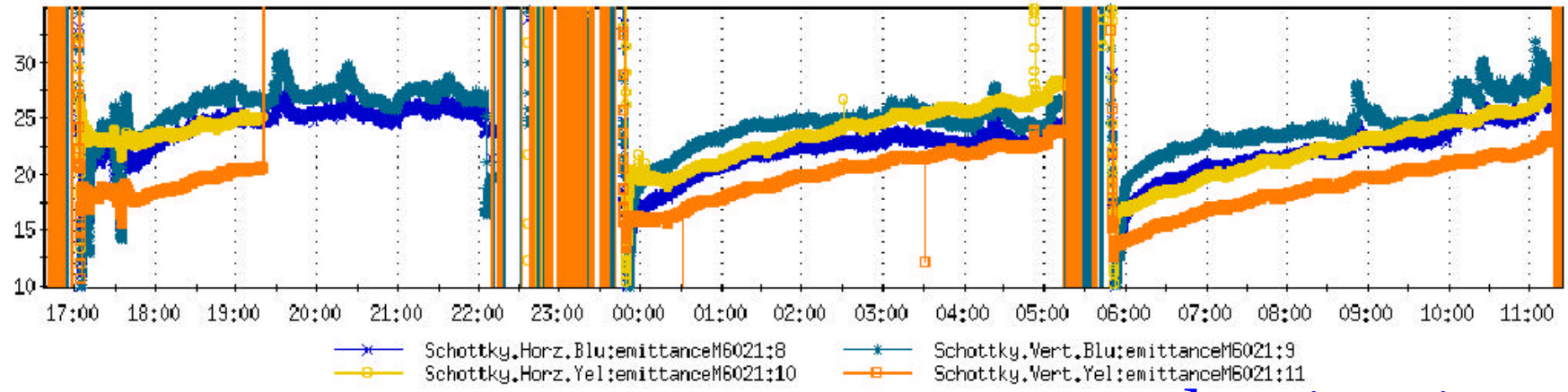
PLL and kicked tunes

26 minutes total

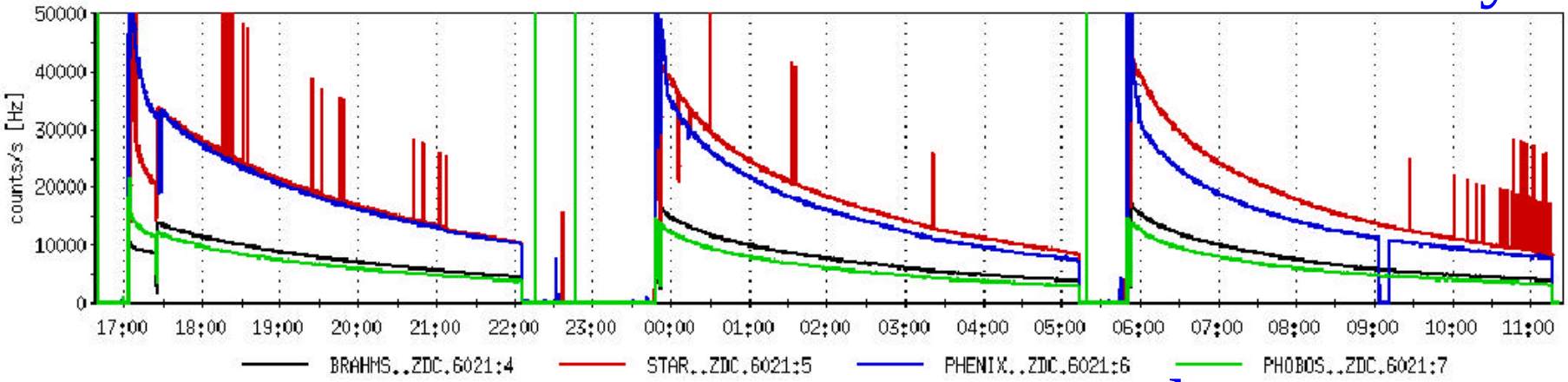
Fri Jan 28 16:40:10 - Sat Jan 29 11:23:06

Window Event

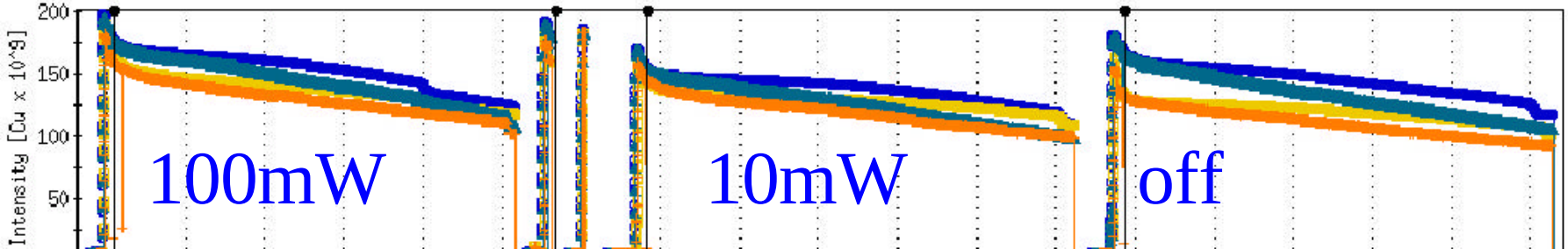
emittance



luminosity



beam current



Summary of emittance growth

Difficult to draw accurate conclusions (many parameters), but consensus is

- At 100mW kicker power PLL makes measureable contribution to emittance growth
- At 10-20mW it's hard to see any difference
- Preliminary data from FNAL leads to similar conclusion
- 245MHz system is on the edge in this regard, but primarily because of dynamic range (rev line drives signal path gain, results in tens of mW kick rather than sub-mW)

Outline

- Results from 245MHz system
  - Tune and tune feedback
  - Coupling
  - Chromaticity
  - Emittance growth
- **Results from baseband systems**
  - Tune tracking
  - Emittance growth
  - The 60Hz problem

Baseband PLL

- **Dynamic Range -** γ_t and 400MHz RF solution is to live always in the coherent spectrum
- Filters much easier (dynamic range/rev line problem)
- 24 bit digitizers - 144dB (better than available preamps!)
- Improved CMRR possible at audio frequencies
- Synchrotron satellites/linewidth - less of an issue
- Eliminates need for phase compensation - of more interest at RHIC (~700 degrees during ramp)
- Simplicity – get rid of tracking mixers?
- Possibility of many cheap receivers scattered throughout ring **(coupling!)**

Approaches to Baseband PLL

- Need to live under the damper - a few microns
- Resonant pickup (primarily BNL)
  - Filters revolution line, Improves S/N by Q~100 (20dB)
  - Not yet approved by LHC impedance police
  - Tuning as operating point changes, hi-Z preamp noise,…
  - De-Qing - sensitive to power levels
- Diode detection (primarily CERN)
  - Not envelope detection - use betatron oscillation to gate diode
  - Improves S/N by root h, h=number of lines mixed down h~10000 (20dB)
  - With many bunches, spectrum becomes sparse - “AGC” - good and bad
- Homodyne detection (primarily BNL)
  - Use revolution comb to mix down betatron comb
  - Same principle as diode detection (S/N, “AGC”,…)
  - Uses COTS components

Comparison - Homodyne and Resonant

Assume 100MHz BW for homodyne, Q=100 for resonant

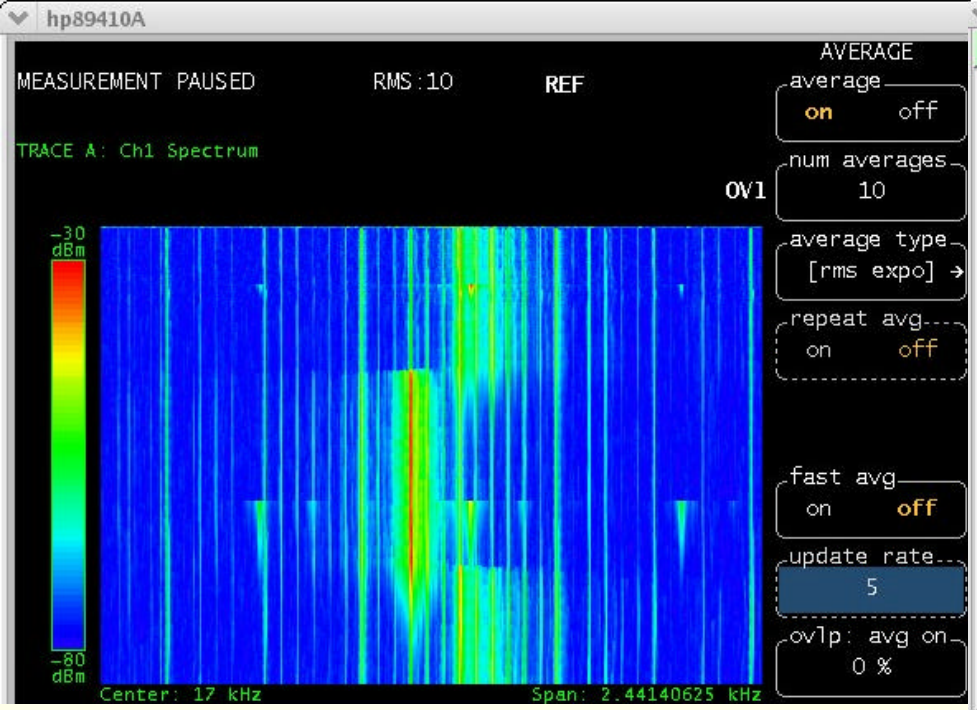
S/N relative to single bunch single line, S/N ~ N * sqrt(n)

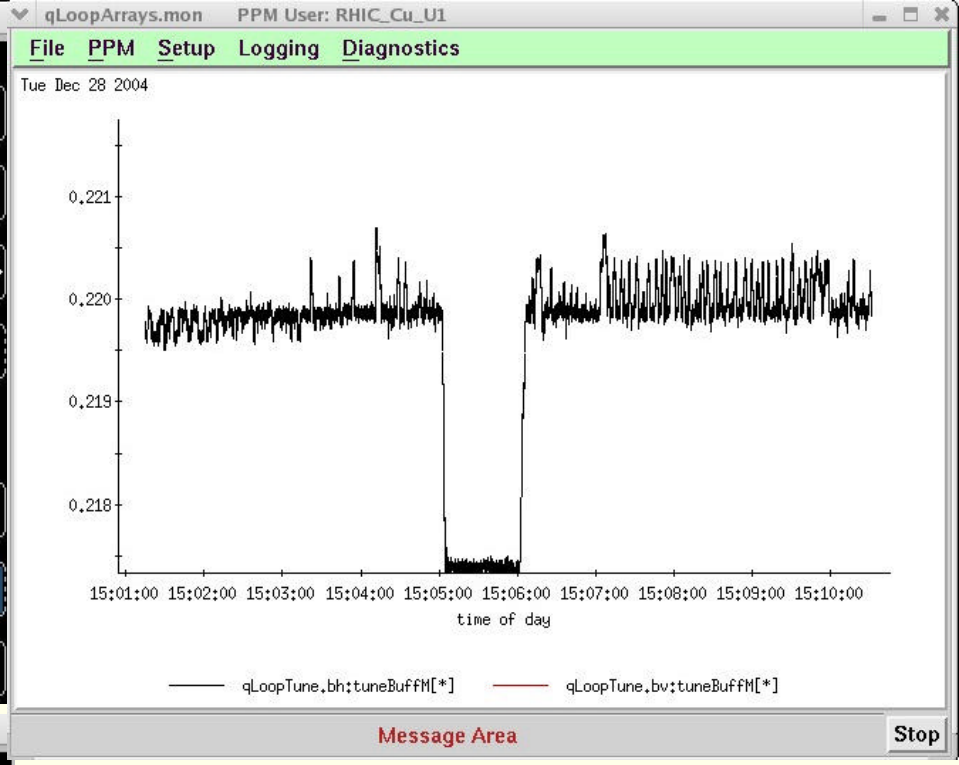
N = # of bunches	RHIC 1	RHIC 6	RHIC 60	LHC 1	LHC 2808
n = # of lines	1280	213	22	9090	5
sqrt n	36	15	4.7	95	2.2
H'dyne S/N, [dB]	16	20	24	20	38
BB Res S/N, [dB]	20	28	38	20	54
245 Res S/N [dB]	0 to 3	7 to 10	38	N/A	N/A

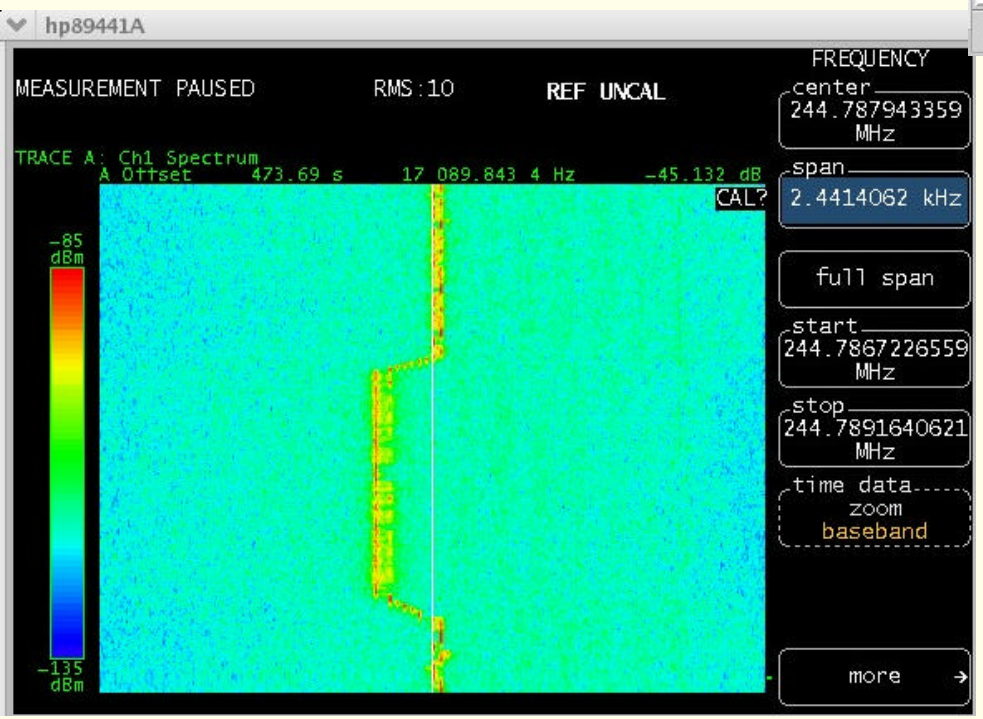
Conclusion - for now we focus on homodyne detectors

Status

- 1m long pickups installed w/ motion control, both planes, both rings
- 1m long kickers installed
- In blue, 3D on both planes
- In yellow, homodyne on vertical
- Tune evident without excitation - monitor at store?
- Transition captures are easy - dynamic range no problem
- PLL tracking without emittance blowup - superior to 245MHz system, both in tracking and emittance growth
- **60Hz at the betatron line - observed with 3D at SPS, Tevatron at RHIC, and with hdyne, 245MHZ, and million turn BPM**





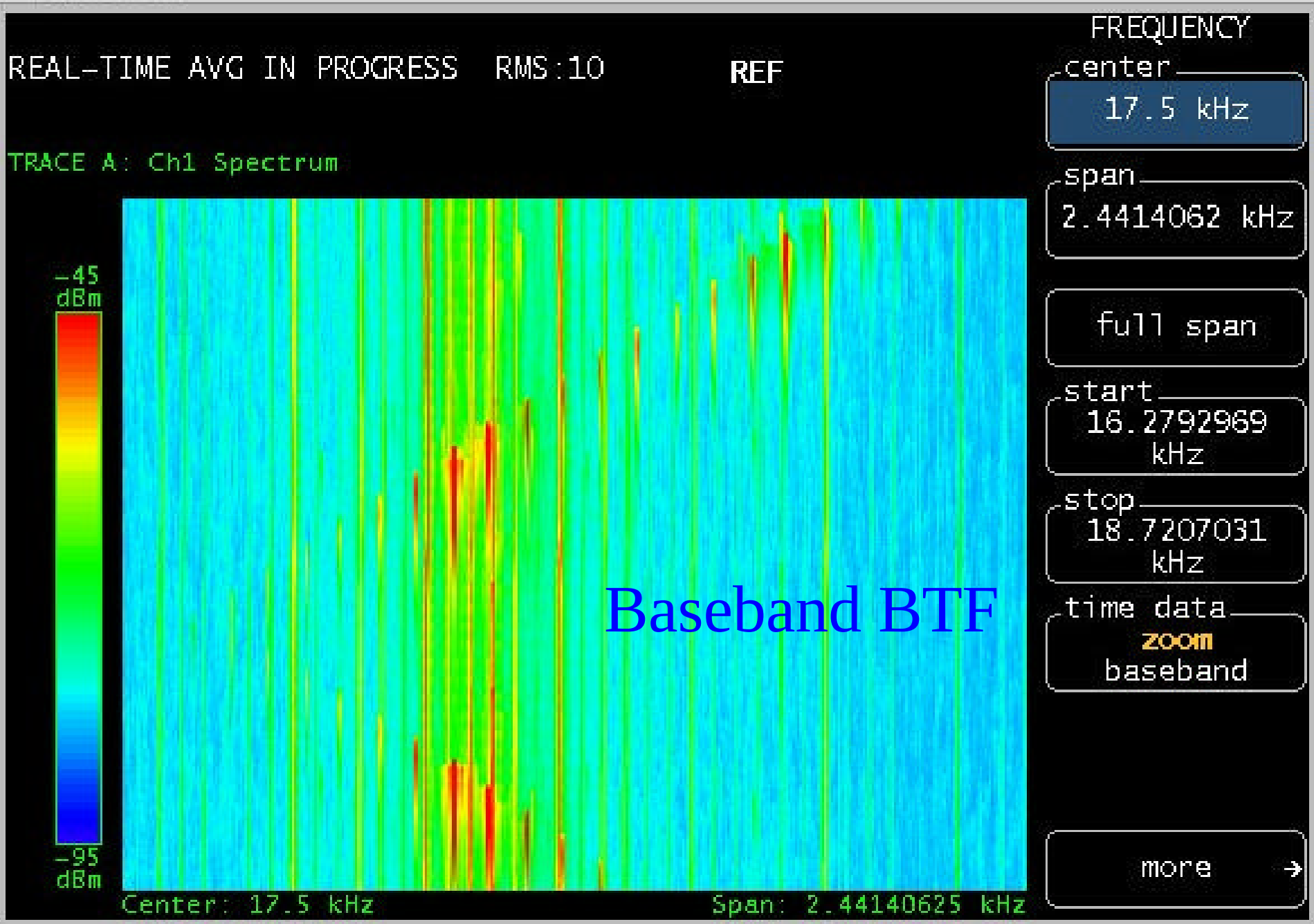


PLL

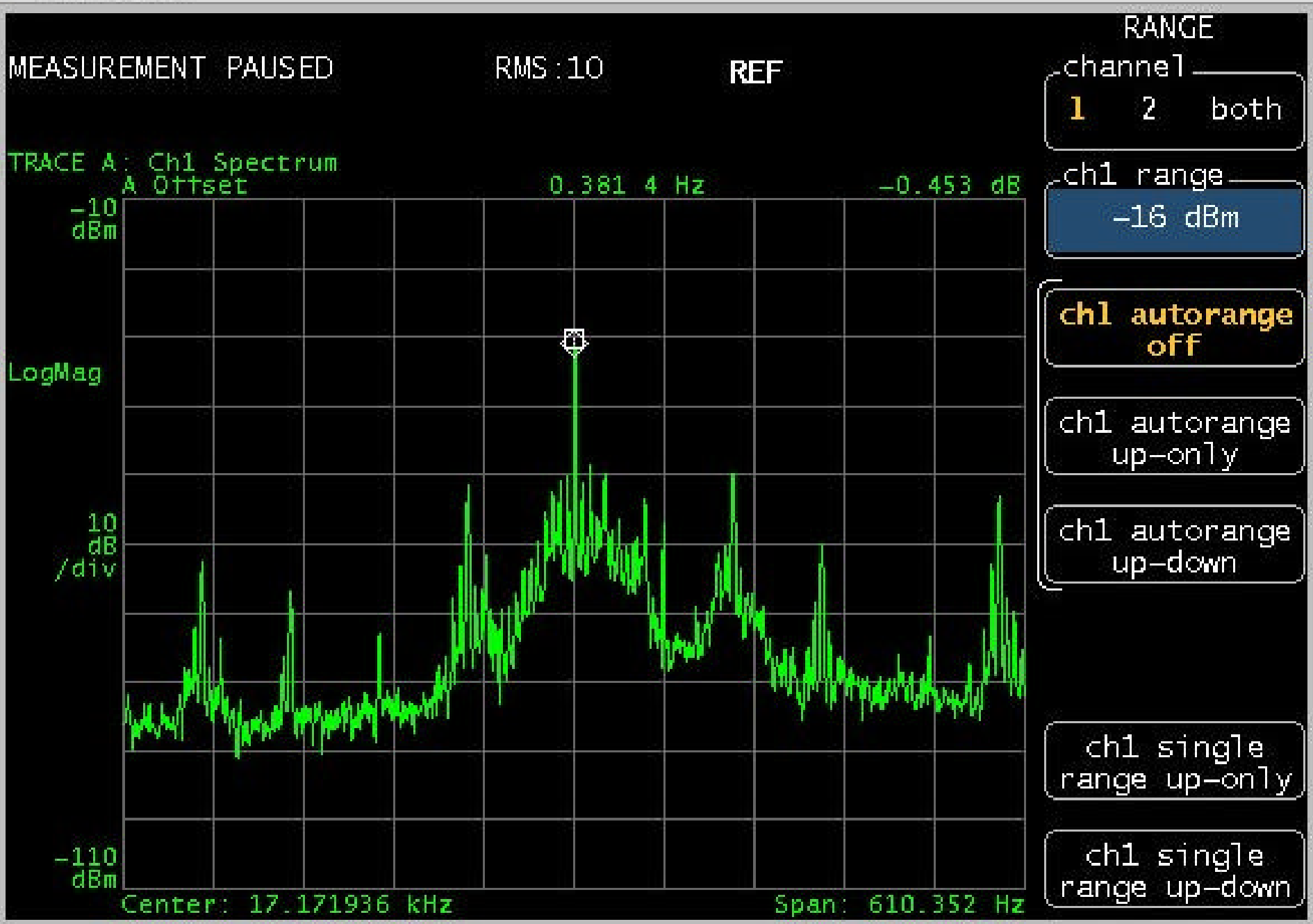
Baseband

LF Schottky

hp89410A

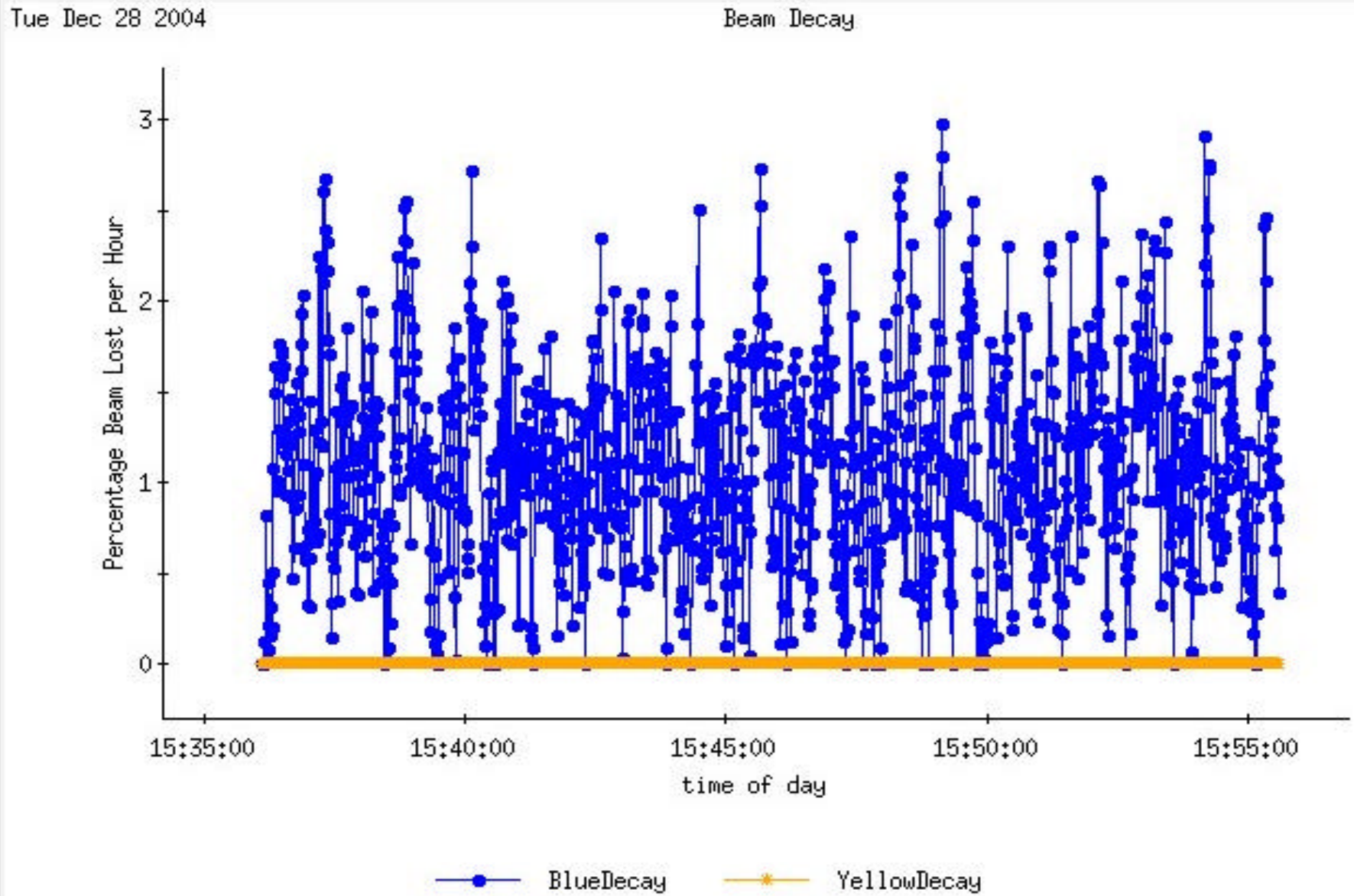

REAL-TIME AVG IN PROGRESS RMS:10
REF
TRACE A: Ch1 Spectrum
-45 dBm
-95 dBm
Baseband BTF
Center: 17.5 kHz
Span: 2.44140625 kHz
FREQUENCY
center
17.5 kHz
span
2.4414062 kHz
full span
start
16.2792969 kHz
stop
18.7207031 kHz
time data
zoom
baseband
more

hp89410A


MEASUREMENT PAUSED
RMS:10
REF
RANGE
channel
1
2
both
TRACE A: Ch1 Spectrum
A Offset
0.381 4 Hz
-0.453 dB
-10 dBm
LogMag
10 dB /div
-110 dBm
Center: 17.171936 kHz
Span: 610.352 Hz
ch1 range
-16 dBm
ch1 autorange off
ch1 autorange up-only
ch1 autorange up-down
ch1 single range up-only
ch1 single range up-down

BeamDecay.mon PPM User: RHIC_Cu_U1

File PPM Setup Logging Diagnostics

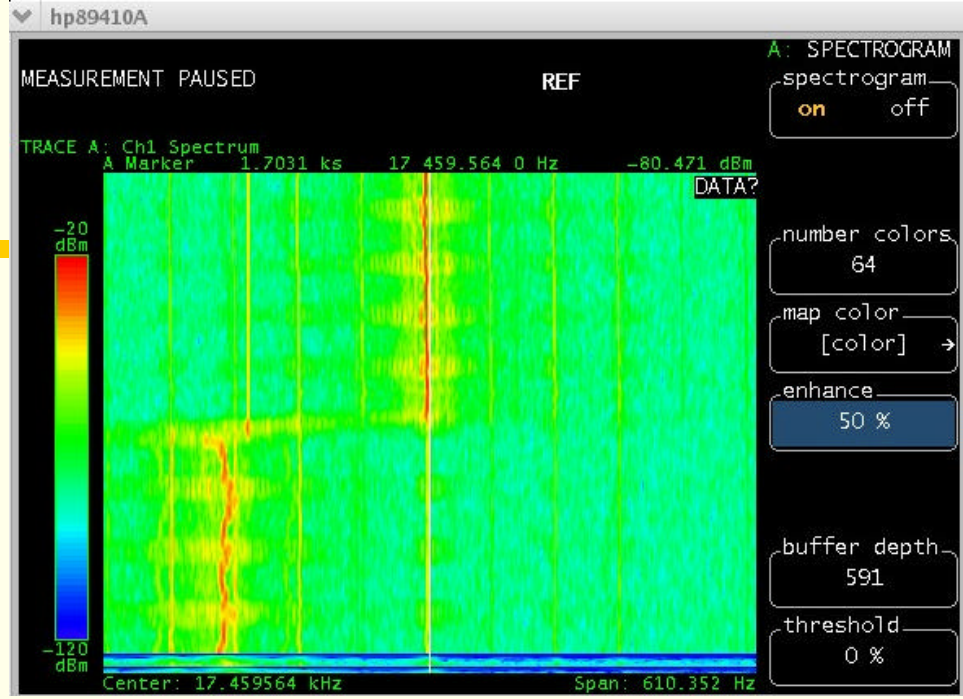


Message Area

Stop

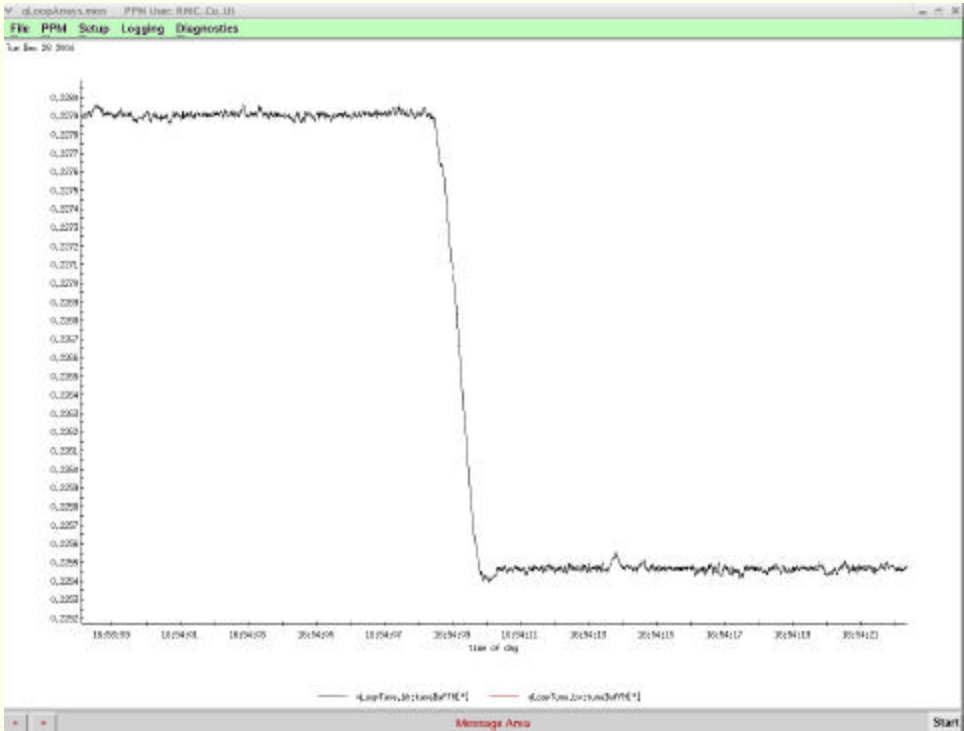
Tracking

Baseband →

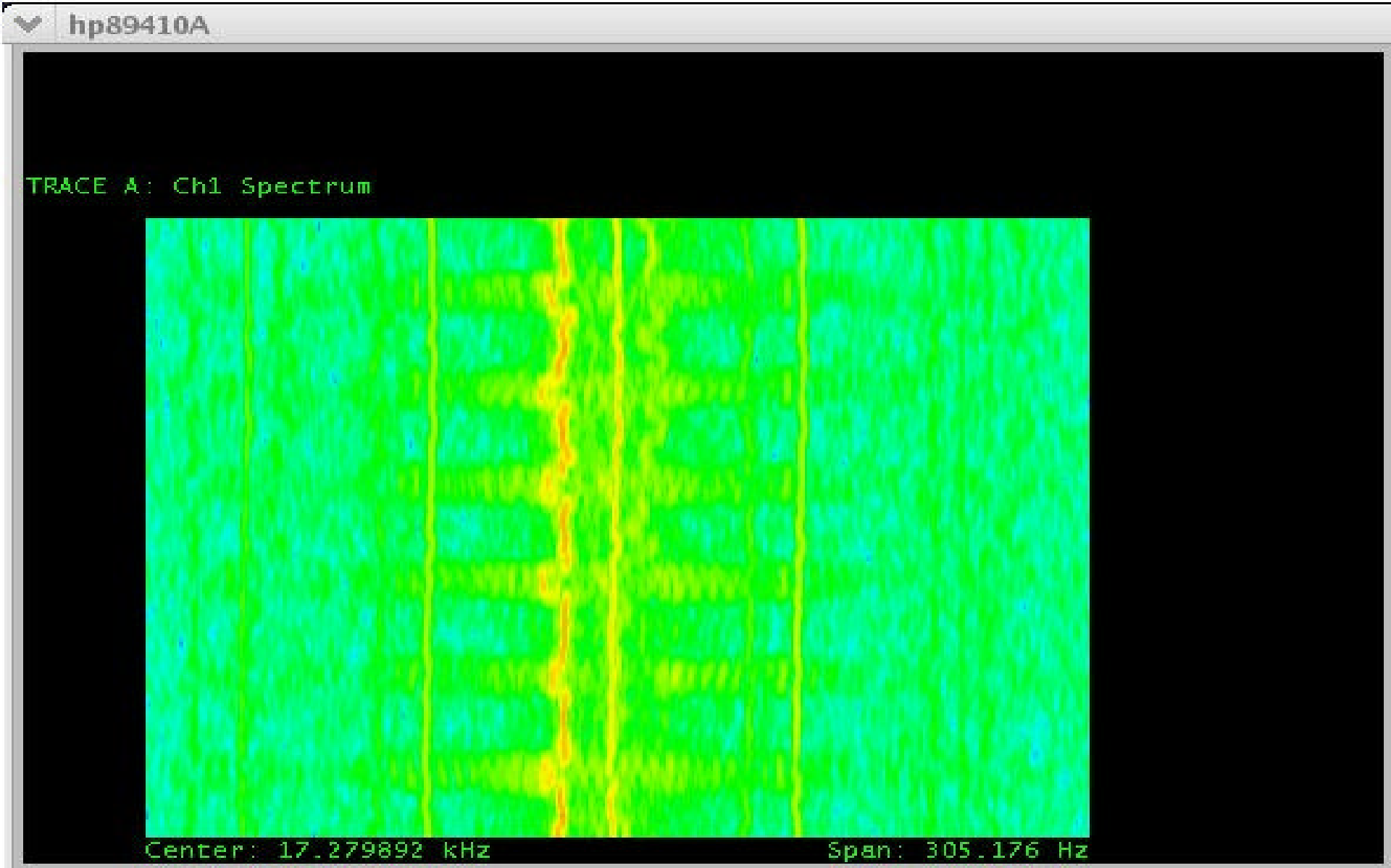


~.003 jump

PLL →



AGS Cycles ~5 e-4



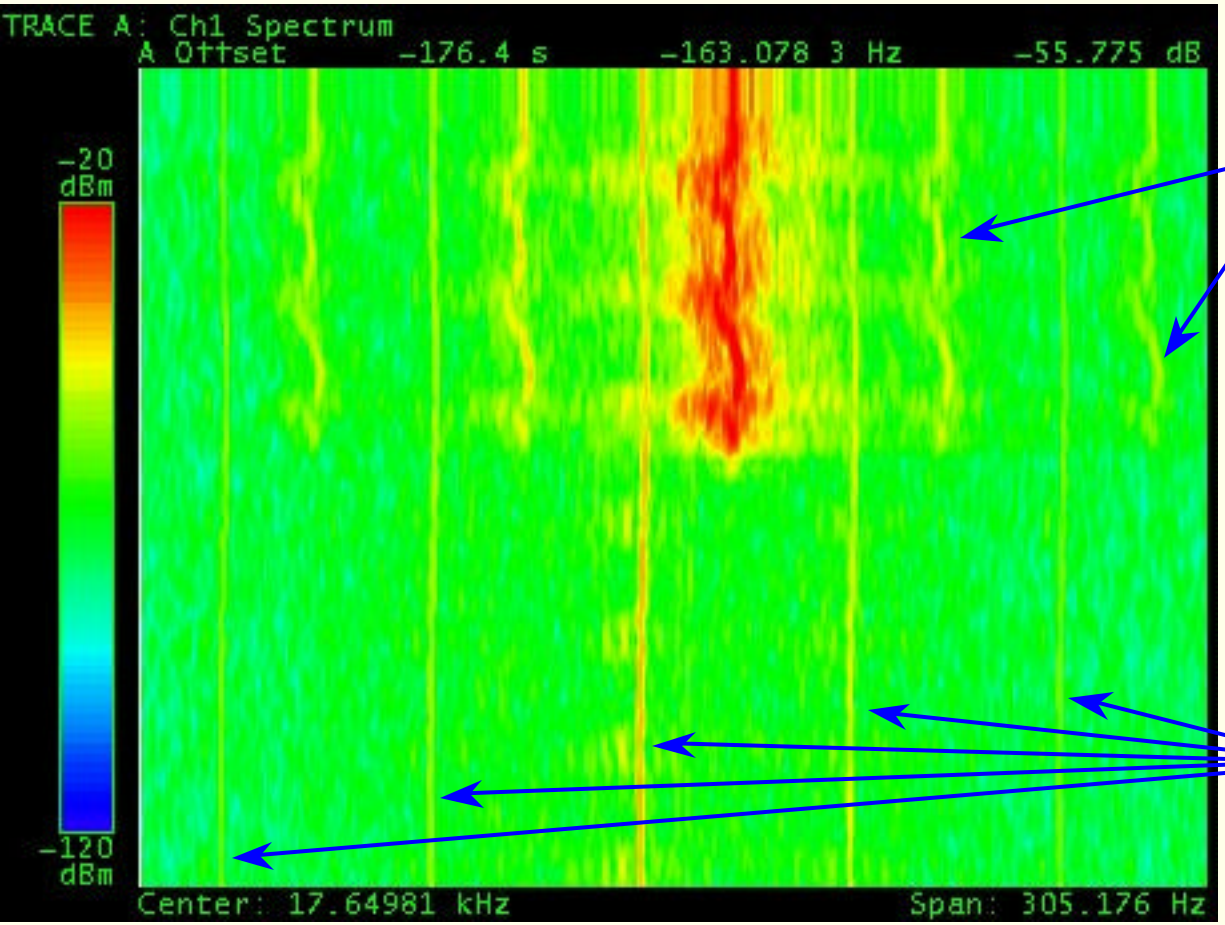
Tracking/Emittance Growth Conclusions

- Performance appears superior to 245MHz system in both regards, even in this early stage of development
- Systematic quantative measurements have not yet been done - focus has been 60Hz problem

Outline

- Results from 245MHz system
  - Tune and tune feedback
  - Coupling
  - Chromaticity
  - Emittance growth
- Results from baseband systems
  - Tune tracking
  - Emittance growth
  - **The 60Hz problem**

Tune sidebands at 60Hz

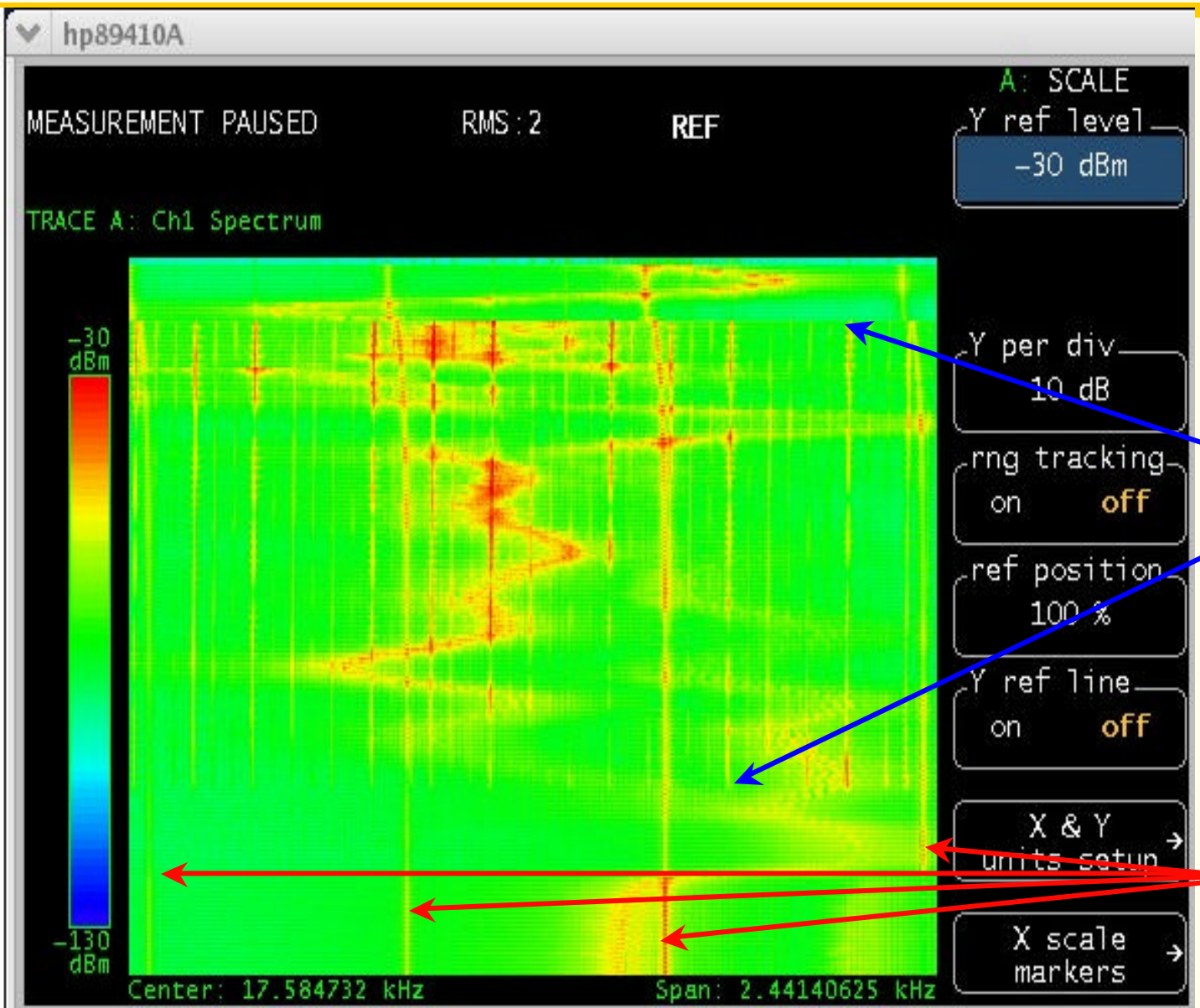


sidebands

← Kicker off

continuous 60Hz lines

3D Ramp - 1 Jan 05

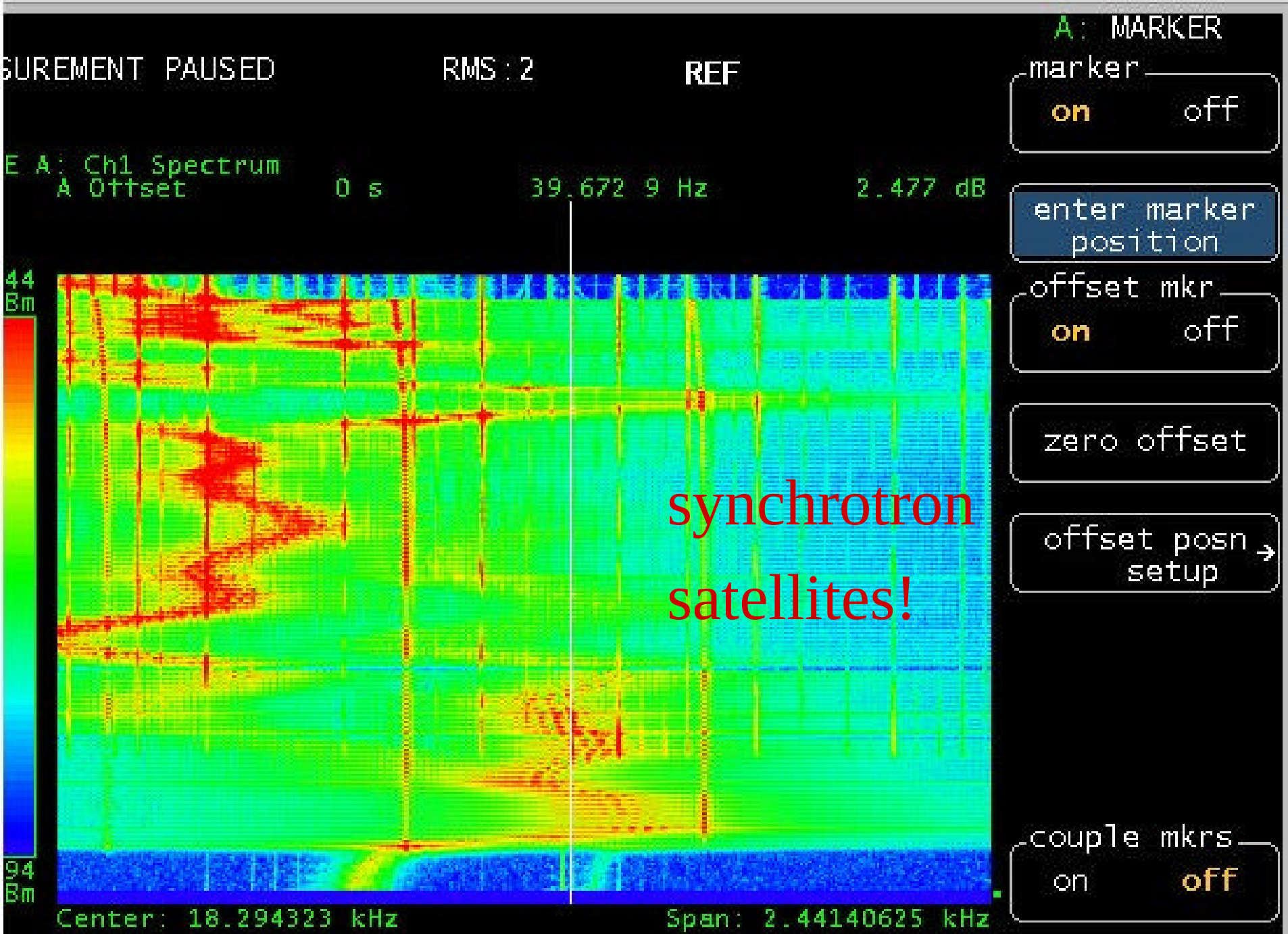


dominant spacing is 360Hz

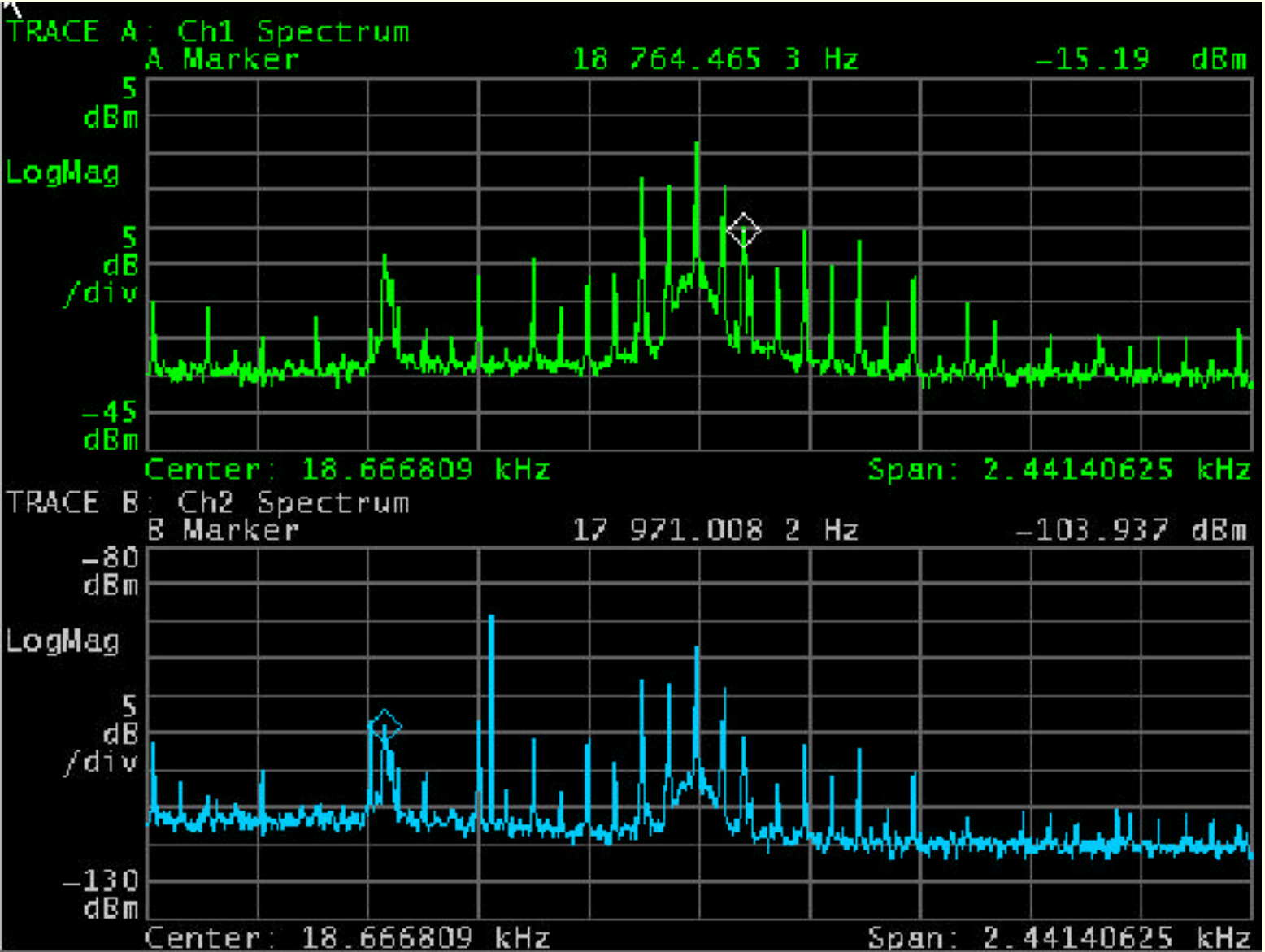
60Hz onset

60Hz end

IPM every 100 turns? (780 Hz)


p89410A
SUREMENT PAUSED
RMS : 2
REF
A: MARKER
marker
on
off
E A: Ch1 Spectrum
A Offset
0 s
39.672 9 Hz
2.477 dB
enter marker position
offset mkr
on
off
zero offset
offset posn setup
44 Bm
94 Bm
synchrotron satellites!
couple mkrs
on
off
Center: 18.294323 kHz
Span: 2.44140625 kHz

3D and Homodyne - 'identical'

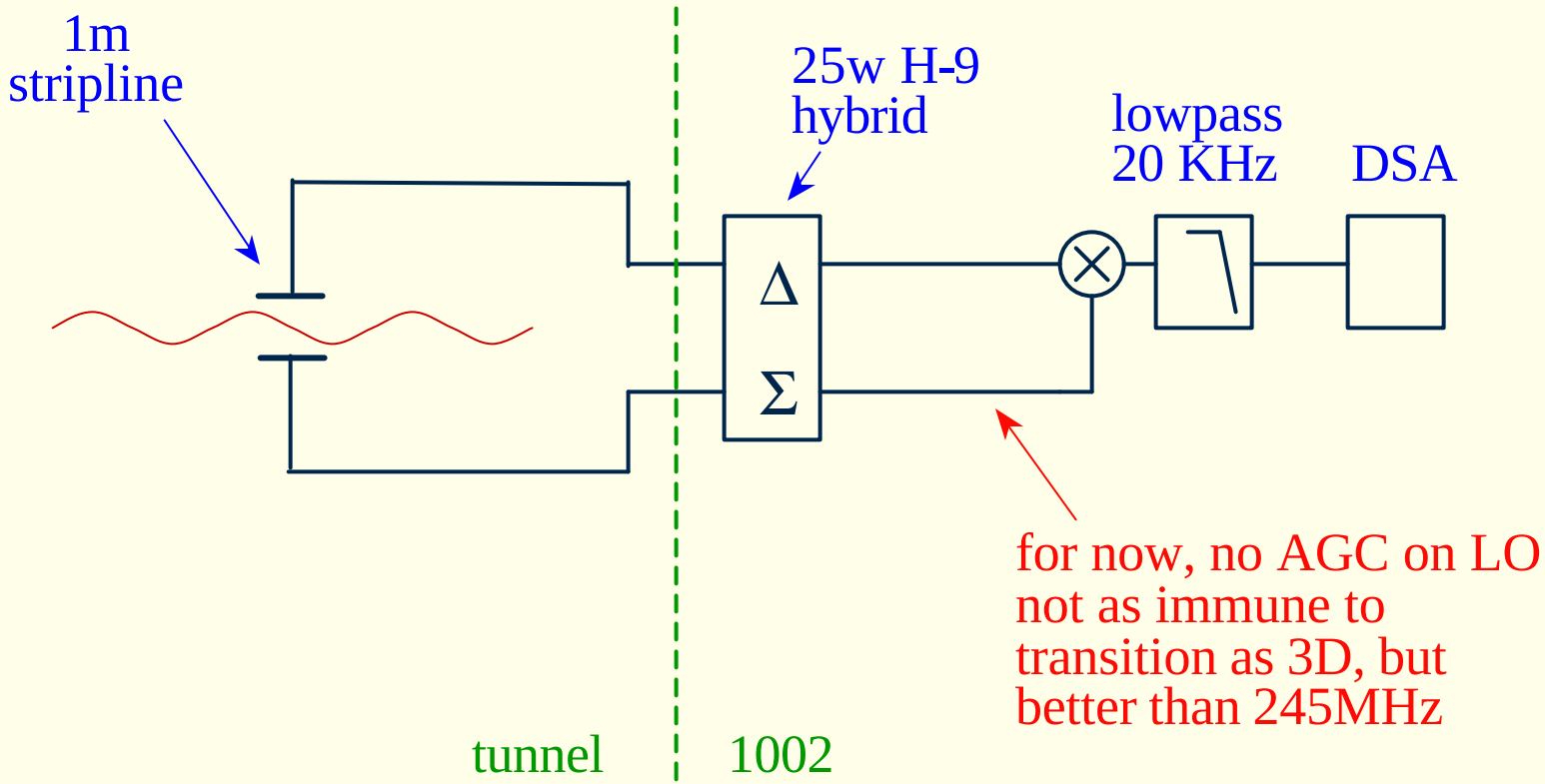


3D

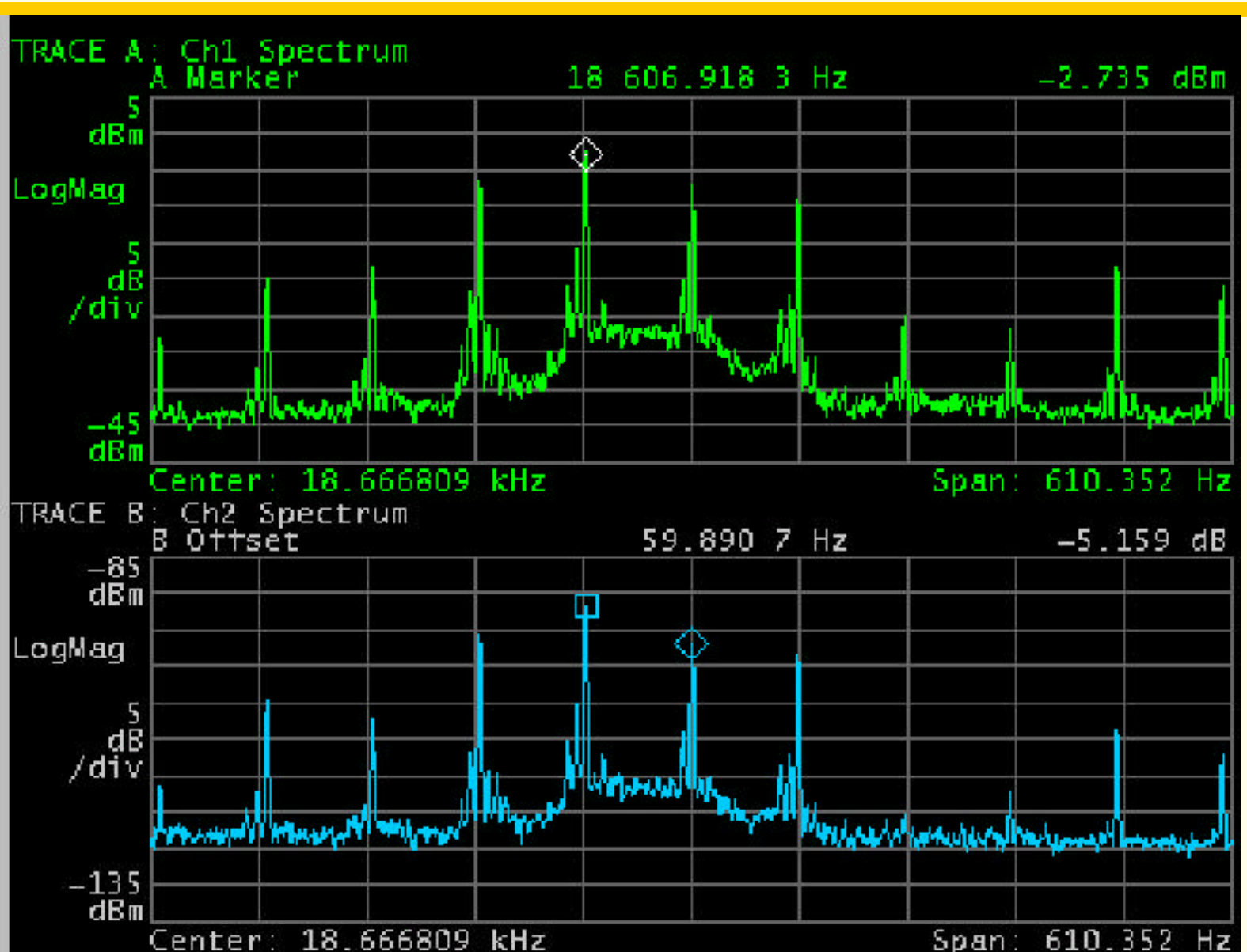
at store
37 bunches
200MHz on

hdyne

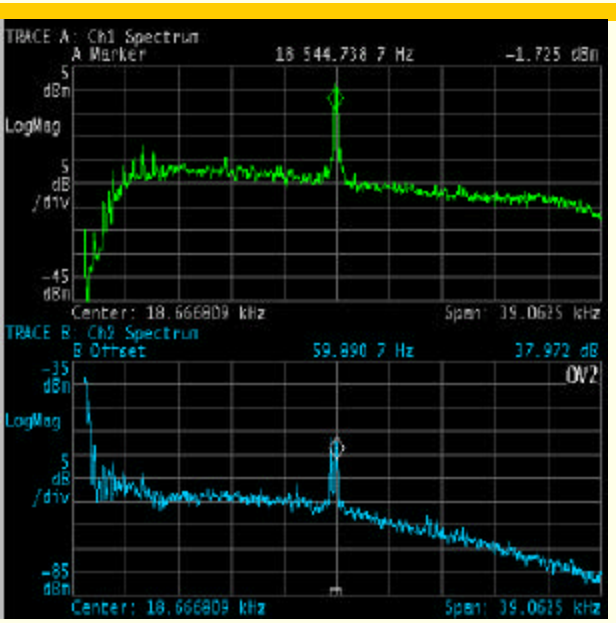
Homodyne detection method

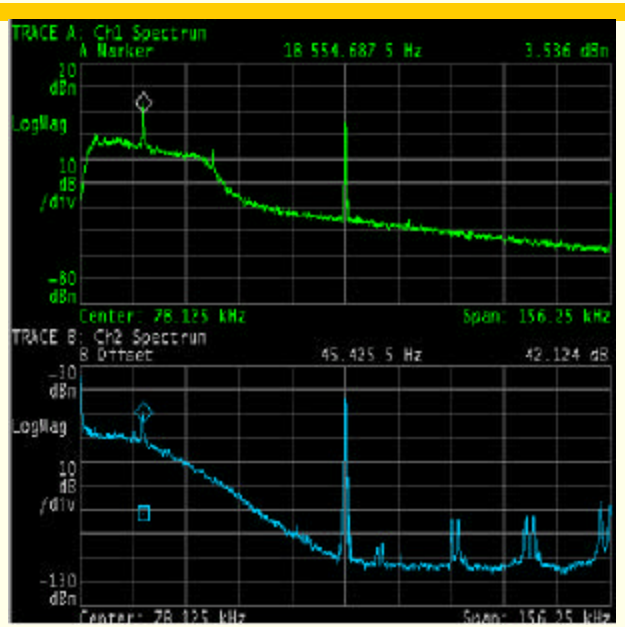


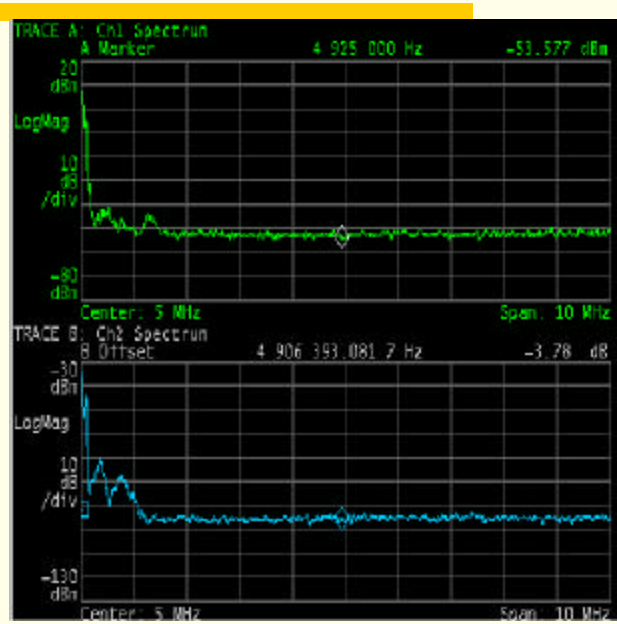
3D and Homodyne - 'identical' 2



3D and Homodyne - 'identical' 3







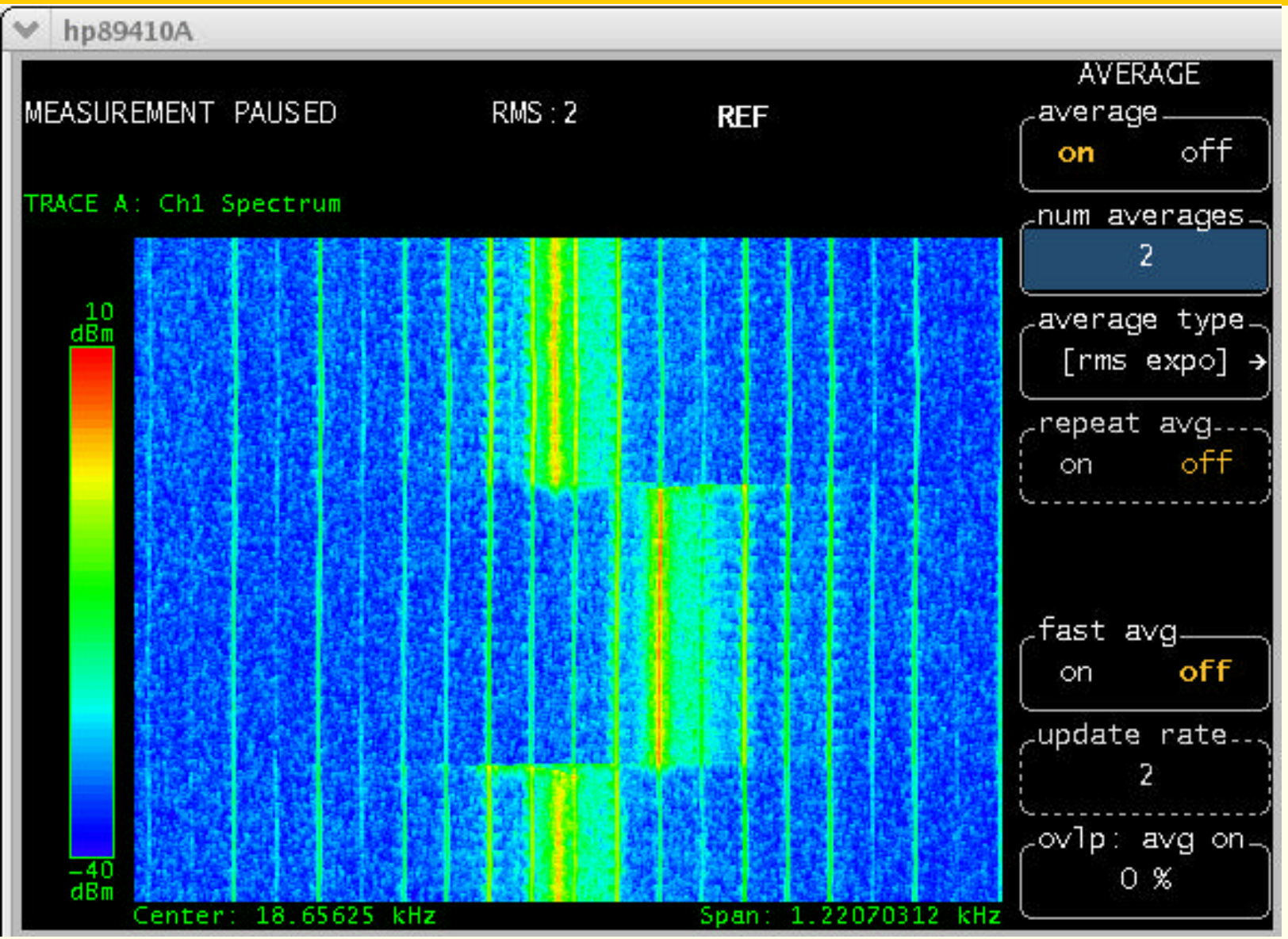
span 39KHz

span 156KHz

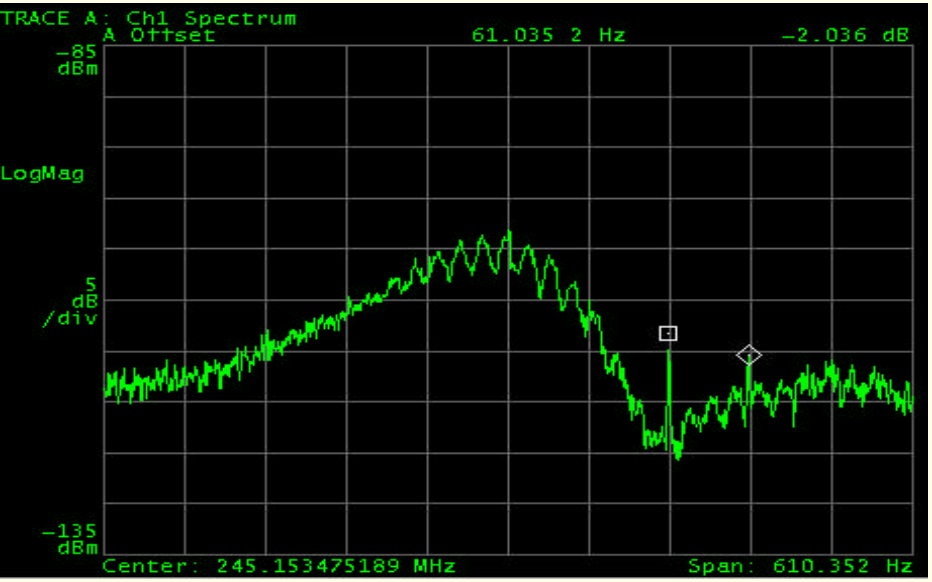
span 10MHz

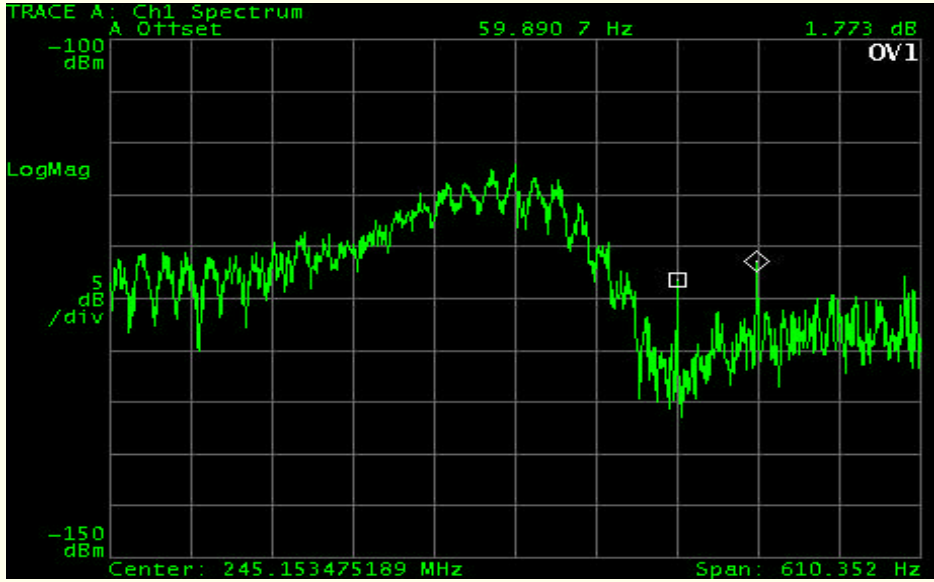
no obvious evidence (noise floor rising, additional lines,...) of non-linearity

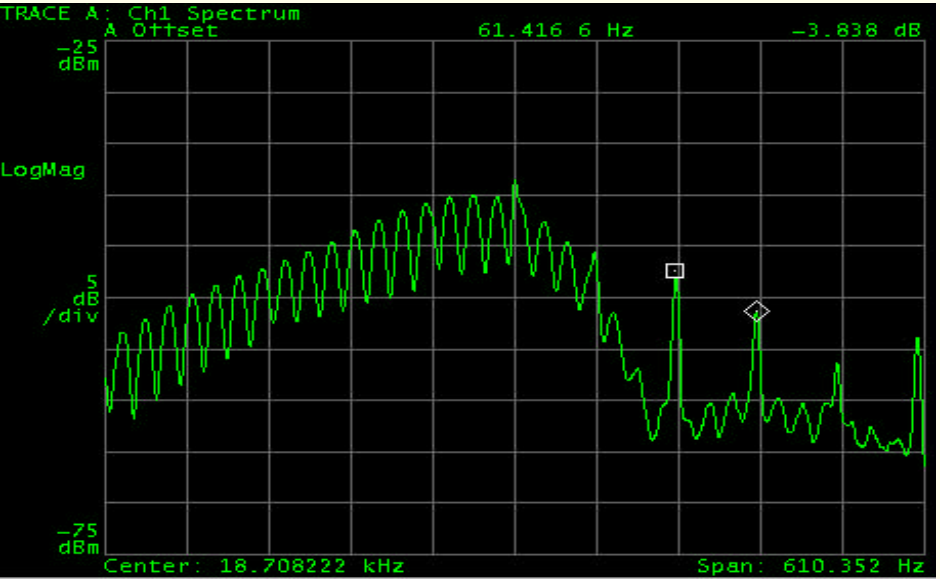
Tune Shift - 60Hz lines don't move

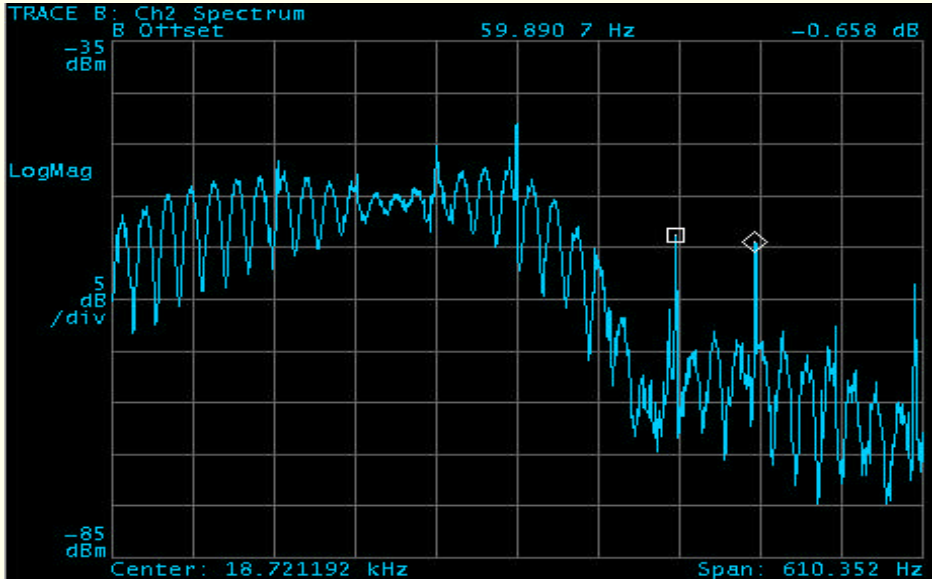


3D and 245MHz - need 200MHz RF!

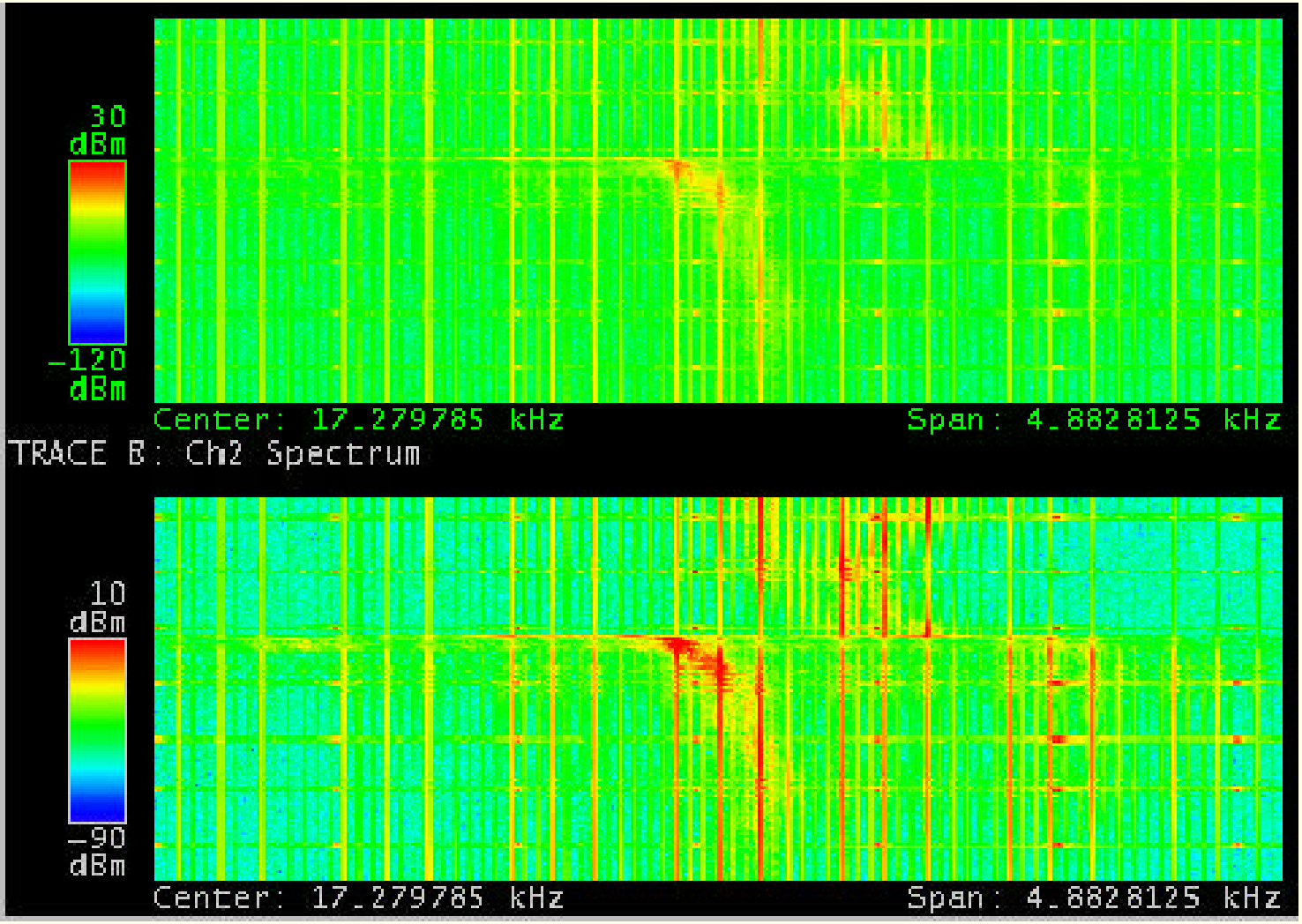








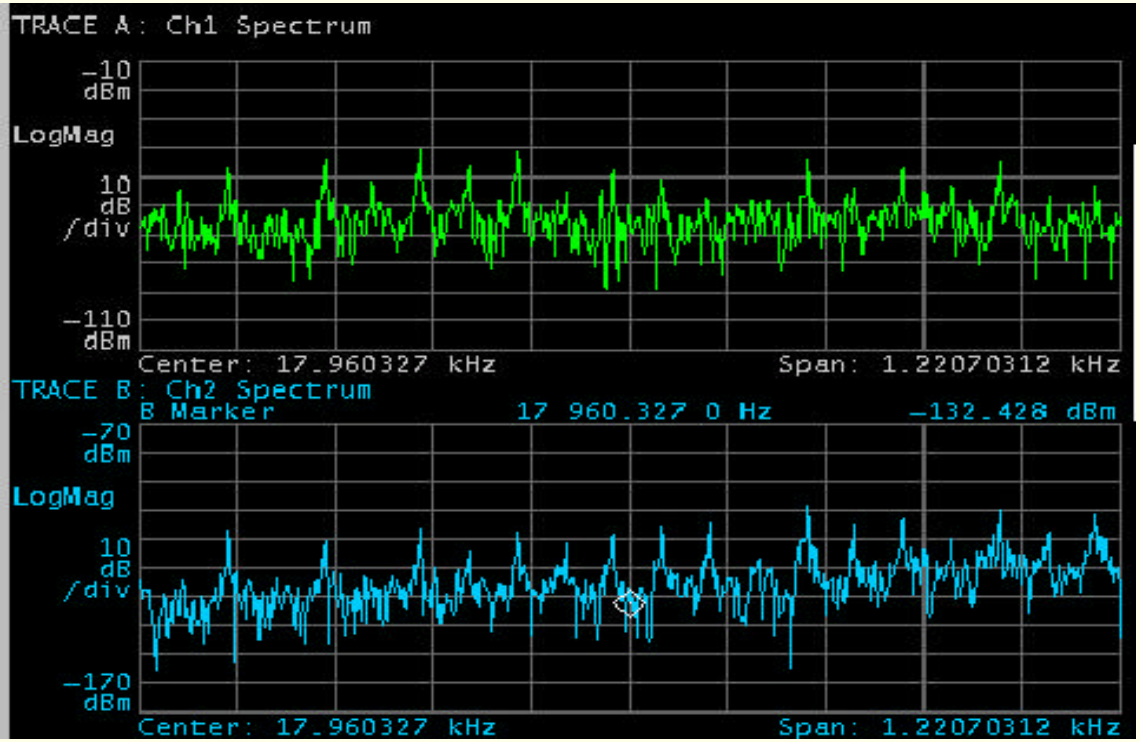
3D with 50MHz high pass



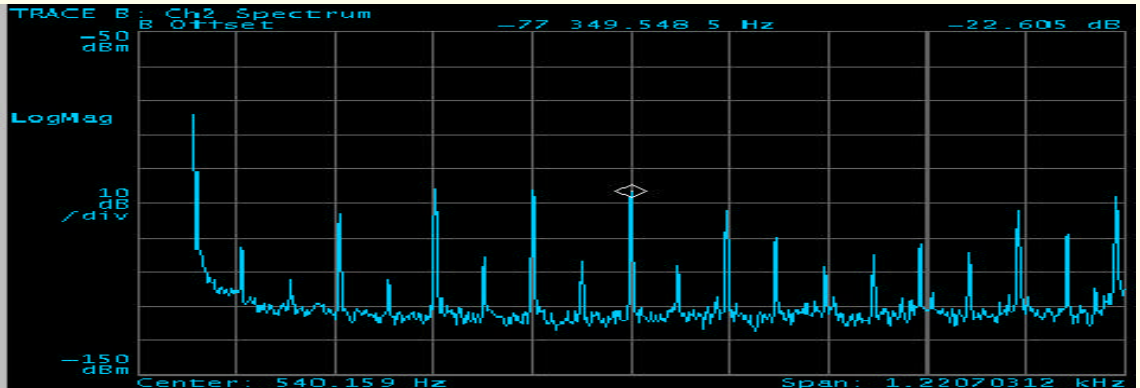
3D horiz

3D vert, with 50MHz hipass

Comparison with DC

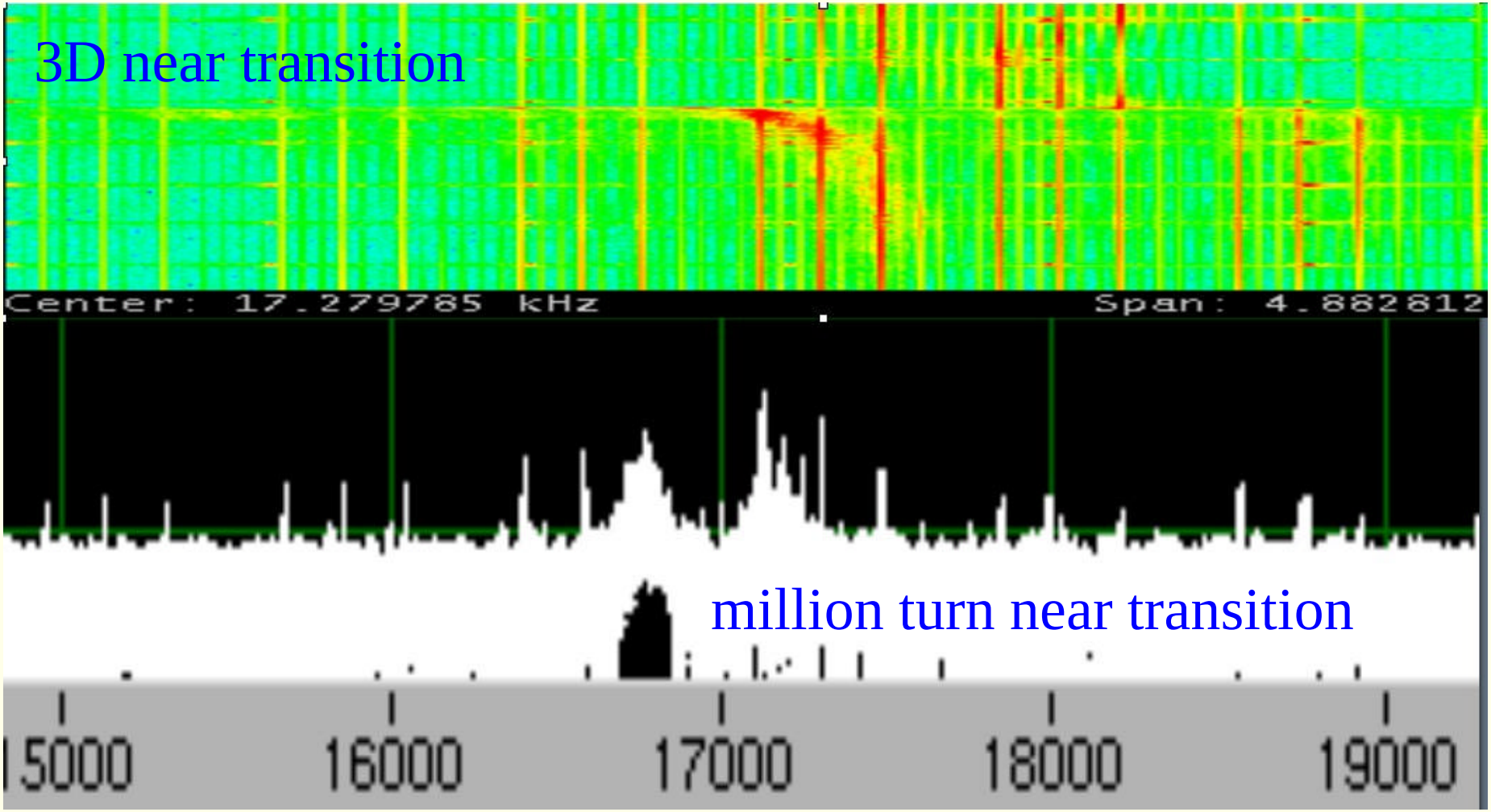


3D blue H and
V (w/ 50MHz hipass),
at betatron line



homodyne
yellow horiz,
at DC

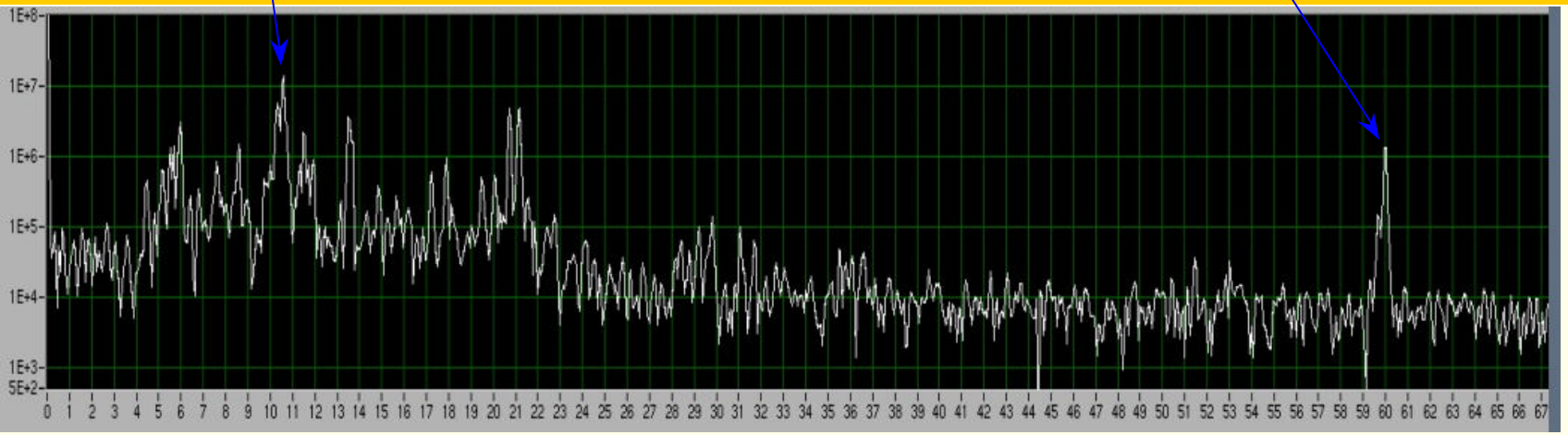
Million Turn BPM 1



estimate ~5m at betatron line

300 micron 10Hz cryostat vibration (0dB)

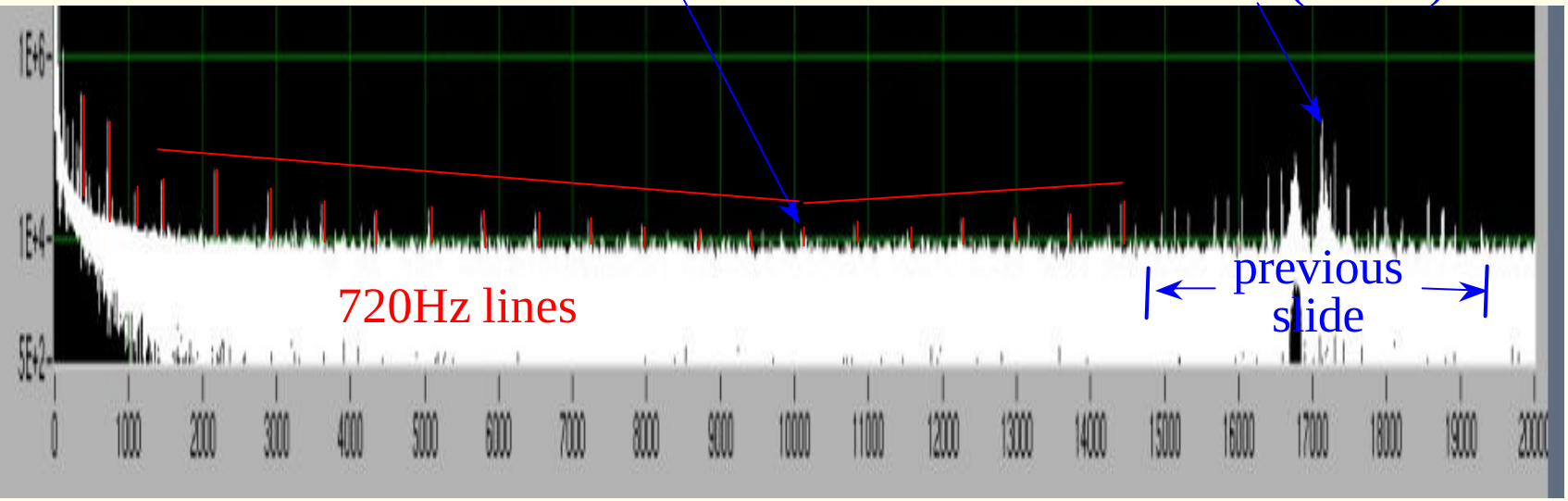
60Hz (-20dB)



40dB

720Hz x 14 (-60dB)

betatron line (-35dB)



the same 40dB

From Todd (Million Turn BPM)

Injection:

beta*gamma=12, emittance=10 pi um, betax(bpm)=49m

=> sigma(beam at bpm) = 2.6 mm

Peak-peak oscillations observed at bo2-bh10: about 350 um

=> Injection vibrations are about 10-15% of beam size

Store:

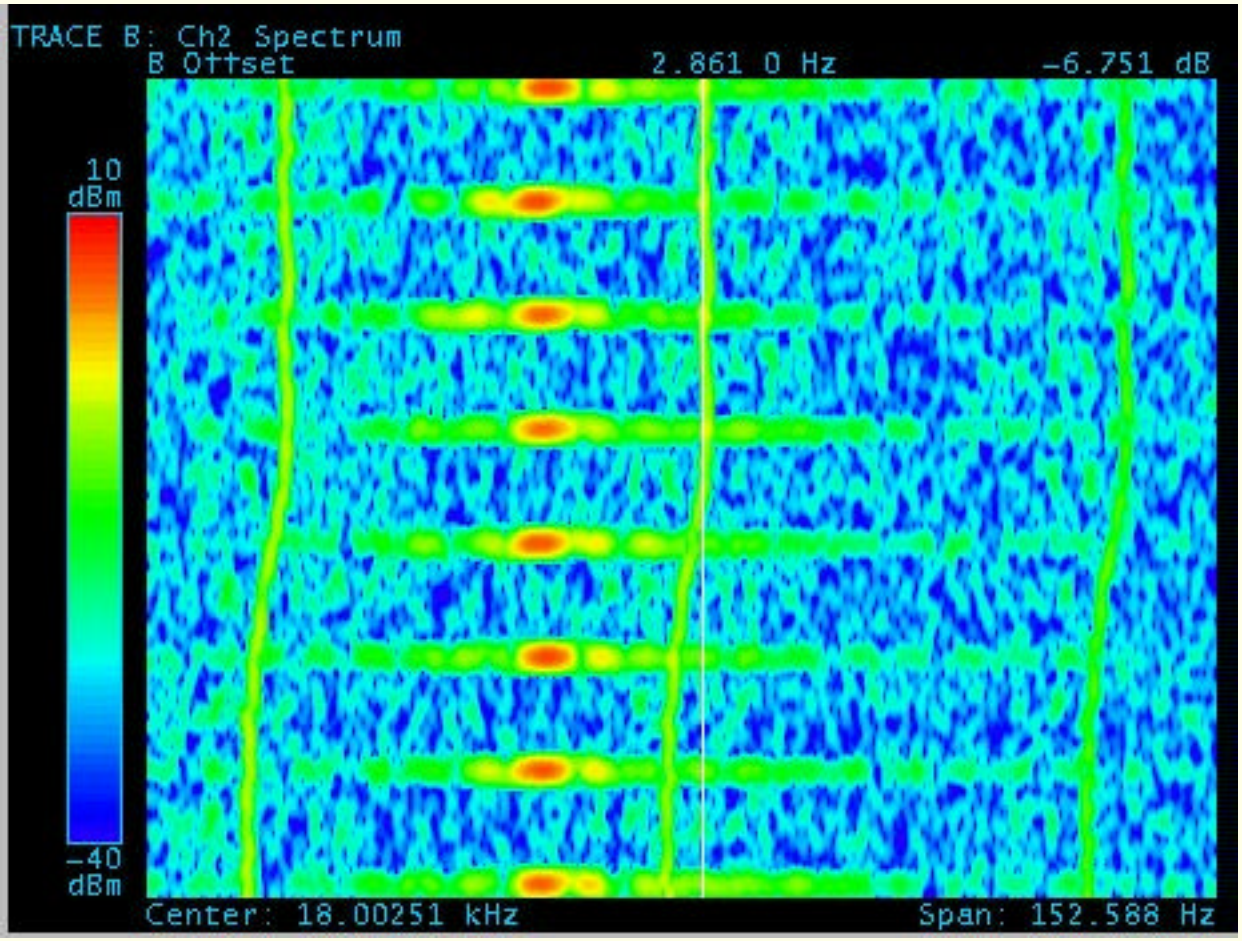
beta*gamma=108, emittance=20 pi um, betax(bpm)=45m

=> sigma(beam at bpm) = 1.2 mm

Peak-peak oscillations observed at bo2-bh8: about 350 um

=> Storage oscillations are about 30% of beam size

60Hz lines move!



span = 152Hz

over 30 seconds, variation is ~3Hz at h~300, or 0.01Hz at 60Hz

Things we've tried

- Tune shift - 60Hz lines don't move
- Look for 60Hz **at betatron line** on other pickups
  - seen on homodyne
  - seen on RHIC 245MHz LF Schottky
  - seen on CERN SPS 400MHz and FNAL 21.4MHz Schottky
  - seen on million turn BPM
- Isolation transformers in the signal path
- Running the 3D on batteries (Tevatron)
- 50MHz high pass in front of the diodes
- UAL simulation (Nikolay Malitsky) - in progress

60Hz Conclusions

- 60Hz is on the beam (as Rhodri and Marek said all along)
- Pattern and intensity are different at injection/store and on the ramp
- It gives some insight into the robustness and sensitivity of the 3D/BBQ AFE - kudos to Marek
- Approximate equality of H and V suggests quad bus is responsible
- How to cope? Tomorrow morning's discussion
- One thought for now - run digitizer clock from multiple of line frequency?

Conclusions

- 245MHz system is mature, a workhorse, runs day in and day out with minimal attention, very useful both for operations and beam experiments, but transition (or coherent spectrum for LHC) and coupling remain serious weaknesses
- Baseband system appears promising, superior to 245MHz in tune tracking and emittance growth, but 60Hz problem must be solved
- Robust performance is difficult/impossible in the presence of coupling
  - difficult even to measure coupling for feedforward
  - coupling feedback needs consideration
- We need BMX on chrom and coupling feedback