Results from the BNL 245MHz System

Peter Cameron

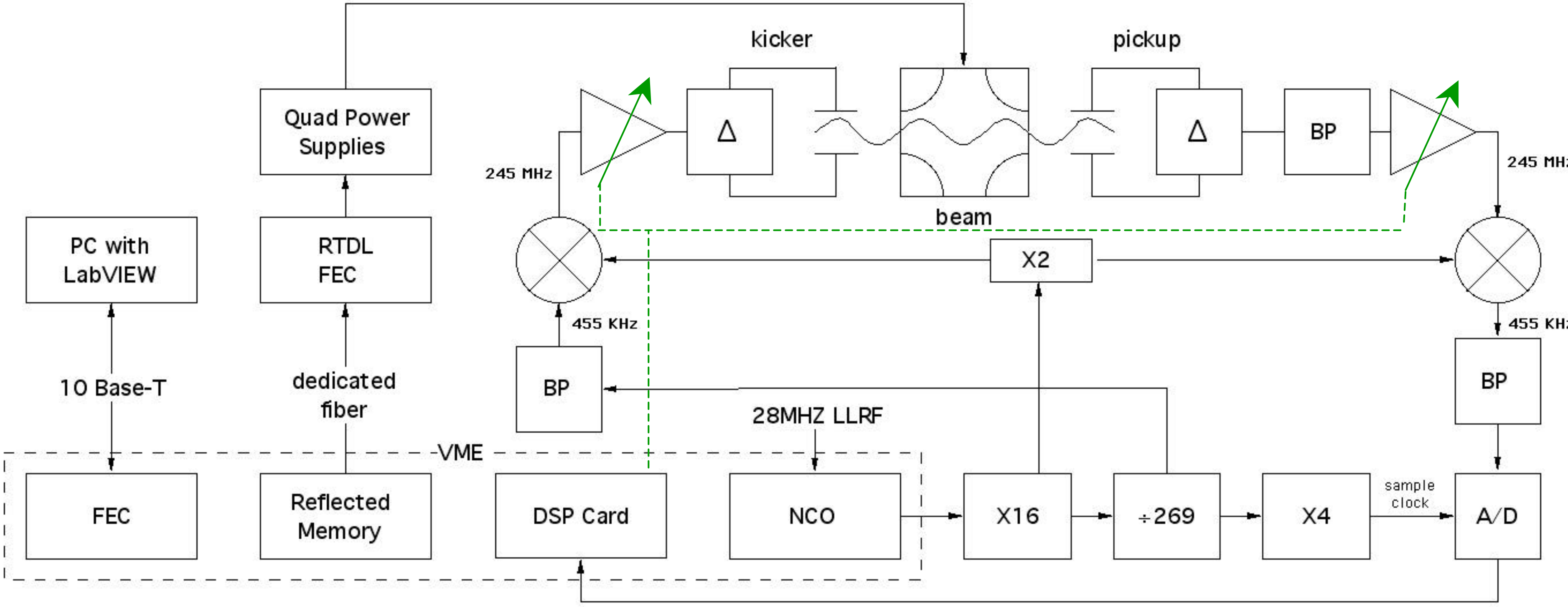
Outline

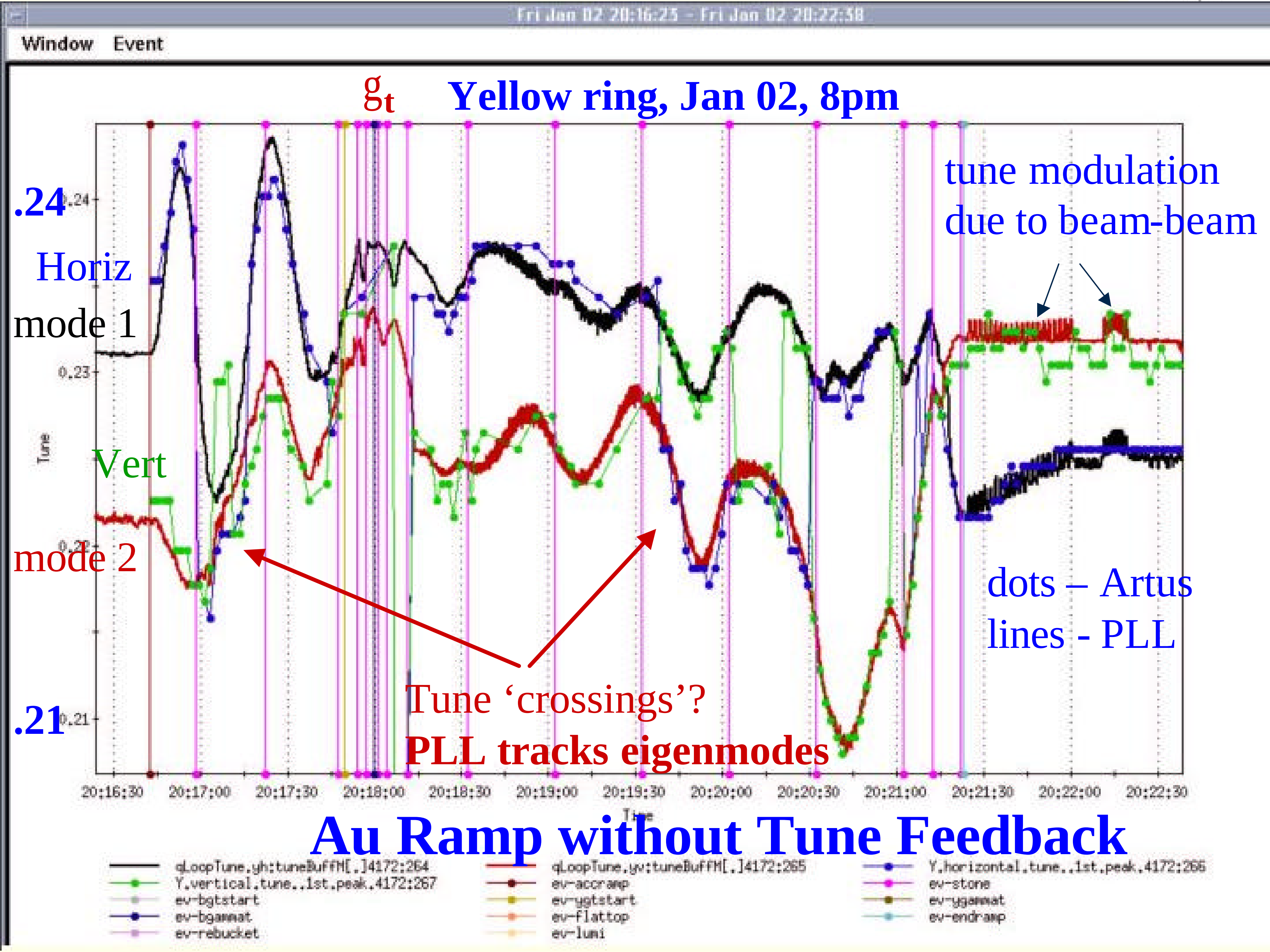
- Tune
- Tune feedback
- Coupling
- Chromaticity
- Emittance growth

245MHz System Status

- System is mature - first successful TF ramp 4 years ago!
  - main changes for RHIC Run 5 were in tuning of loop parameters
  - **transition** is a major obstacle **- dynamic range**
    - short bunches, coherence at 245MHz - also LHC, with 400MHz RF
    - fast position and tune changes
    - coupling,...
  - **coupling** is a major obstacle
    - without TF it confuses PLL, causes it to be not robust
    - with TF the system becomes unstable
- Motion control is mature
  - operation of continuous feedback for pickup centering is reliable
  - can't cope with fast (30 msec) position changes at transition
- **Further improvement requires a new approach**
  - solve the dynamic range problem - work at baseband
  - solve the coupling problem - better measurement, perhaps feedback

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
tune modulation
due to beam-beam
.24
Horiz
mode 1
Vert
mode 2
.21
0.24
0.23
0.22
0.21
Tune
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:tuneBuffFM[.]4172:264
Y.vertical.tune..1st.peak.4172:267
ev-bgtstart
ev-bgammat
ev-rebucket
qLoopTune.yv:tuneBuffFM[.]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

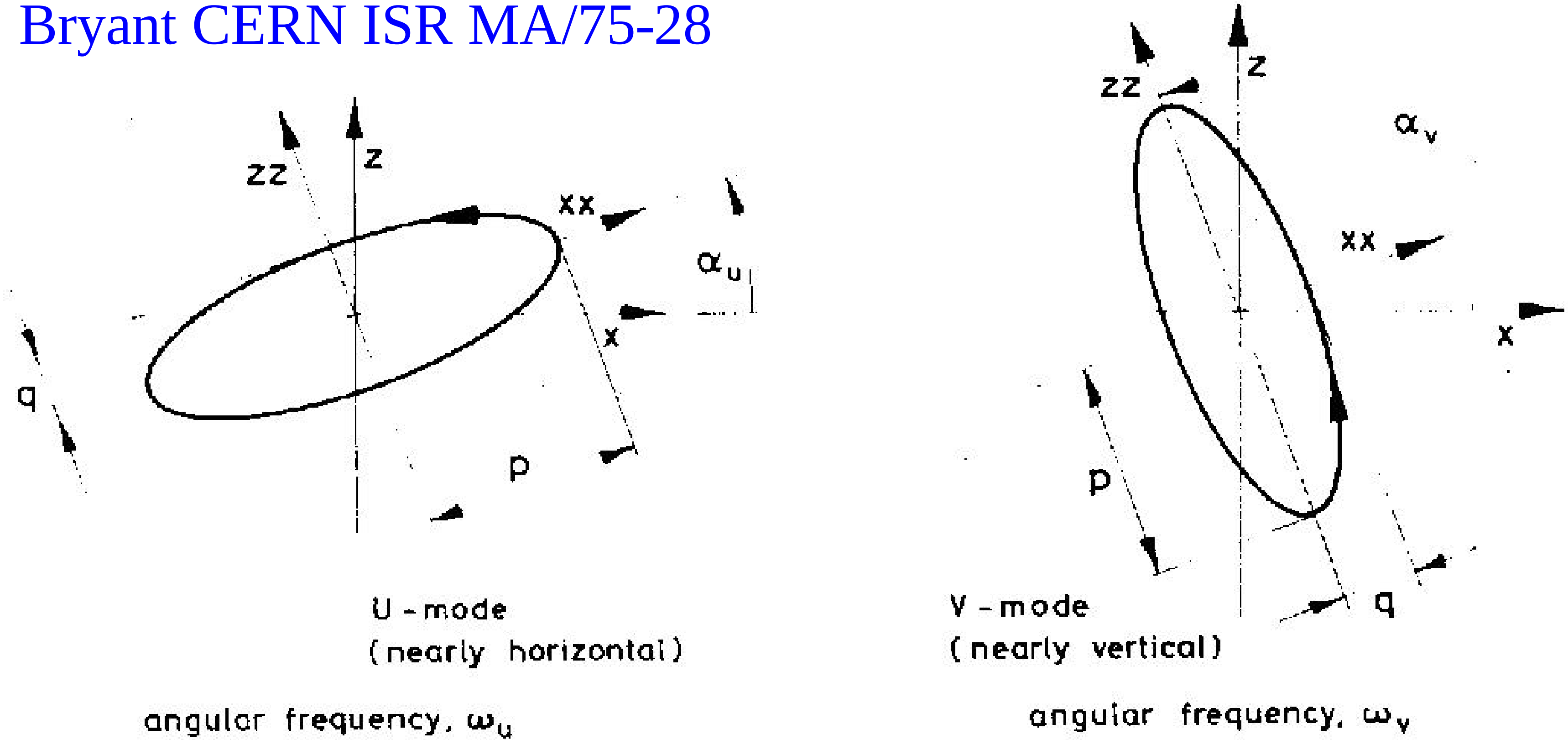
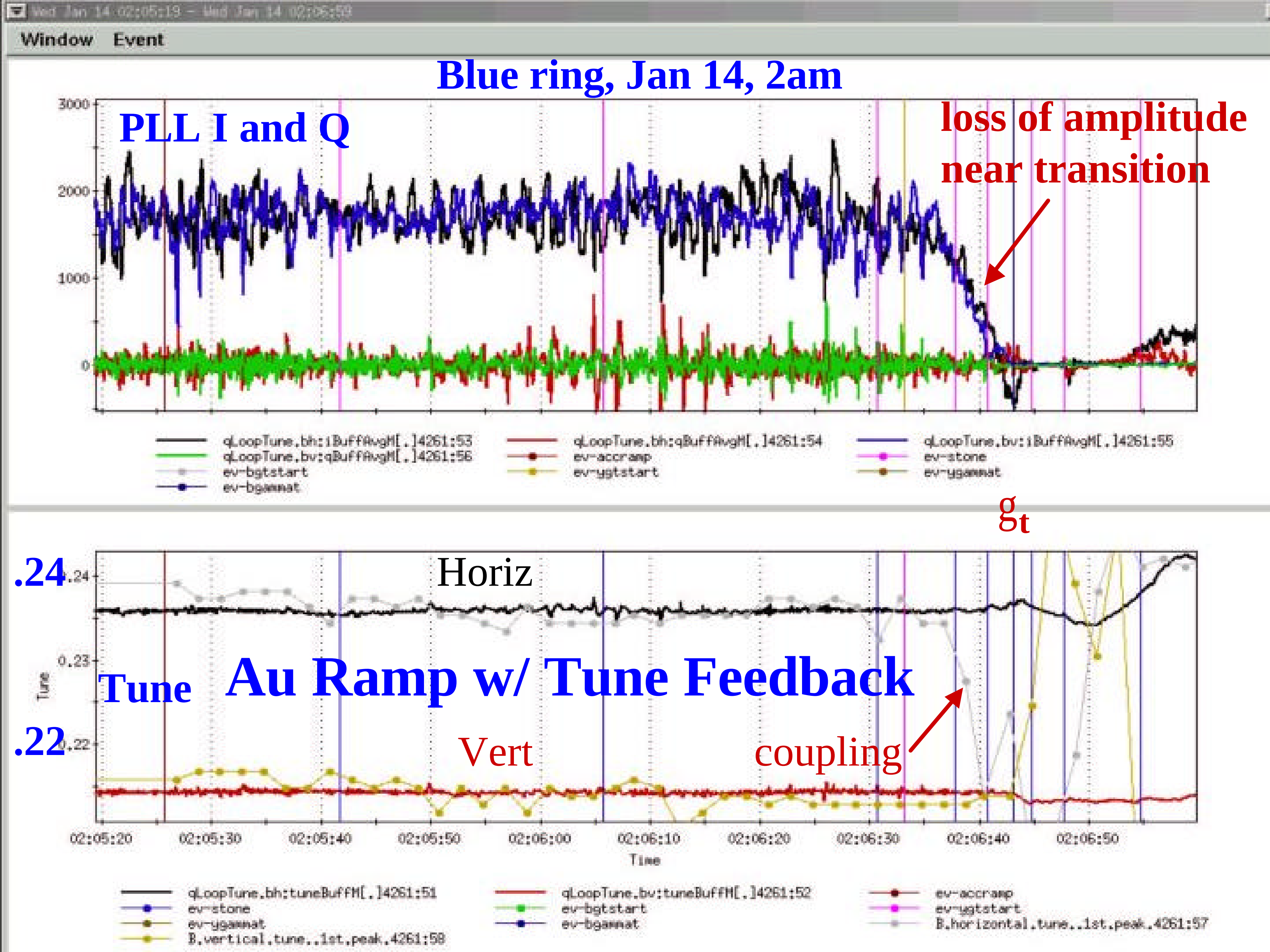
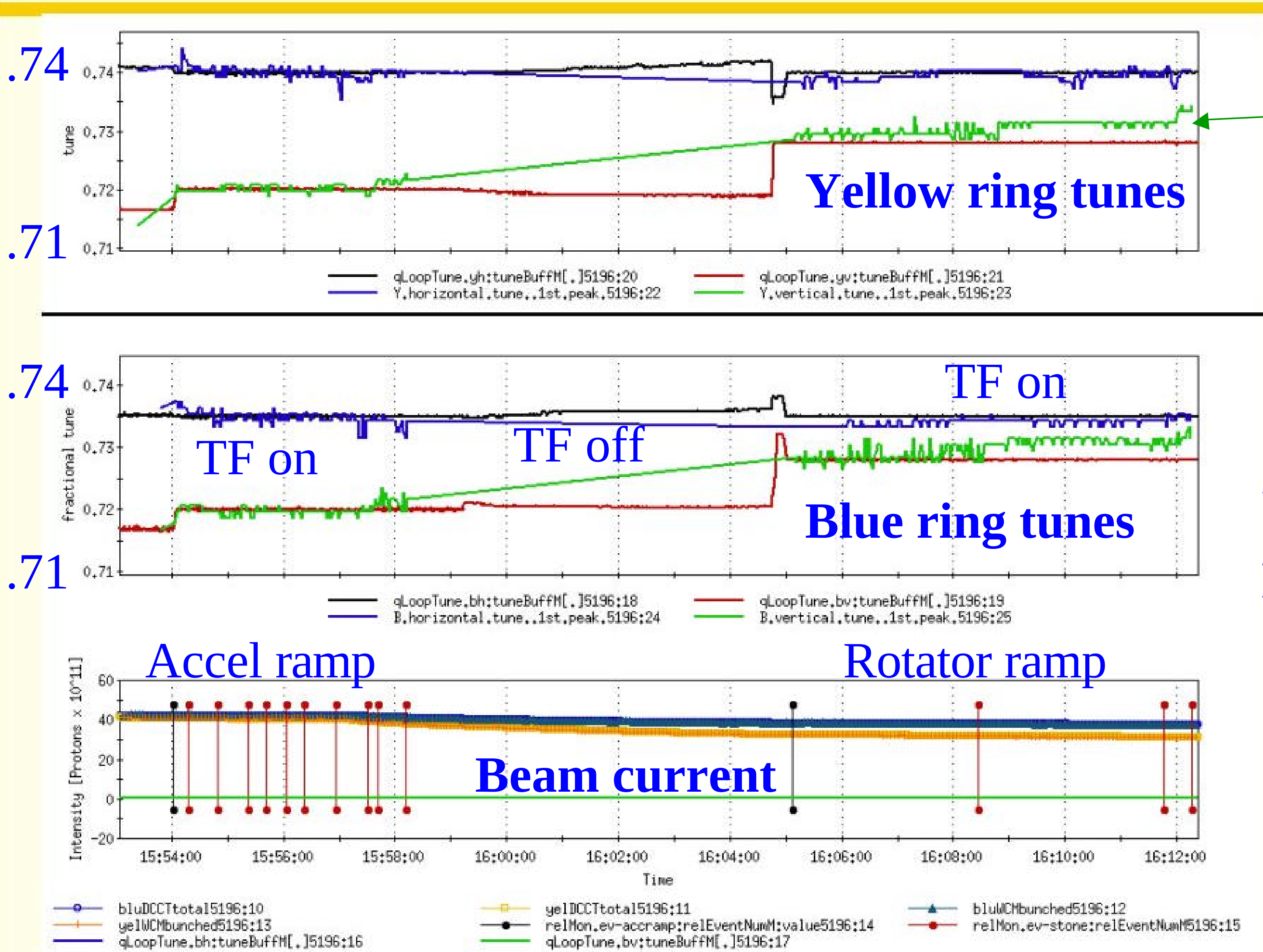


FIGURE 3 - Definition of normal modes



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.bv:qBuffAvgM[.]4261:56
ev-bgtstart
ev-bgammat
qLoopTune.bh:qBuffAvgM[.]4261:54
ev-accramp
ev-ygtstart
qLoopTune.bv:iBuffAvgM[.]4261:55
ev-stone
ev-ygammat
g_t
.24
Horiz
Tune
Au Ramp w/ Tune Feedback
.22
Vert
coupling
0.24
0.23
0.22
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
ev-stone
ev-ygammat
B.vertical.tune..1st.peak.4261:58
qLoopTune.bv:tuneBuffM[.]4261:52
ev-bgtstart
ev-bgammat
ev-accramp
ev-ygtstart
B.horizontal.tune..1st.peak.4261:57

Tune feedback – from Mei's talk



coupling effect?

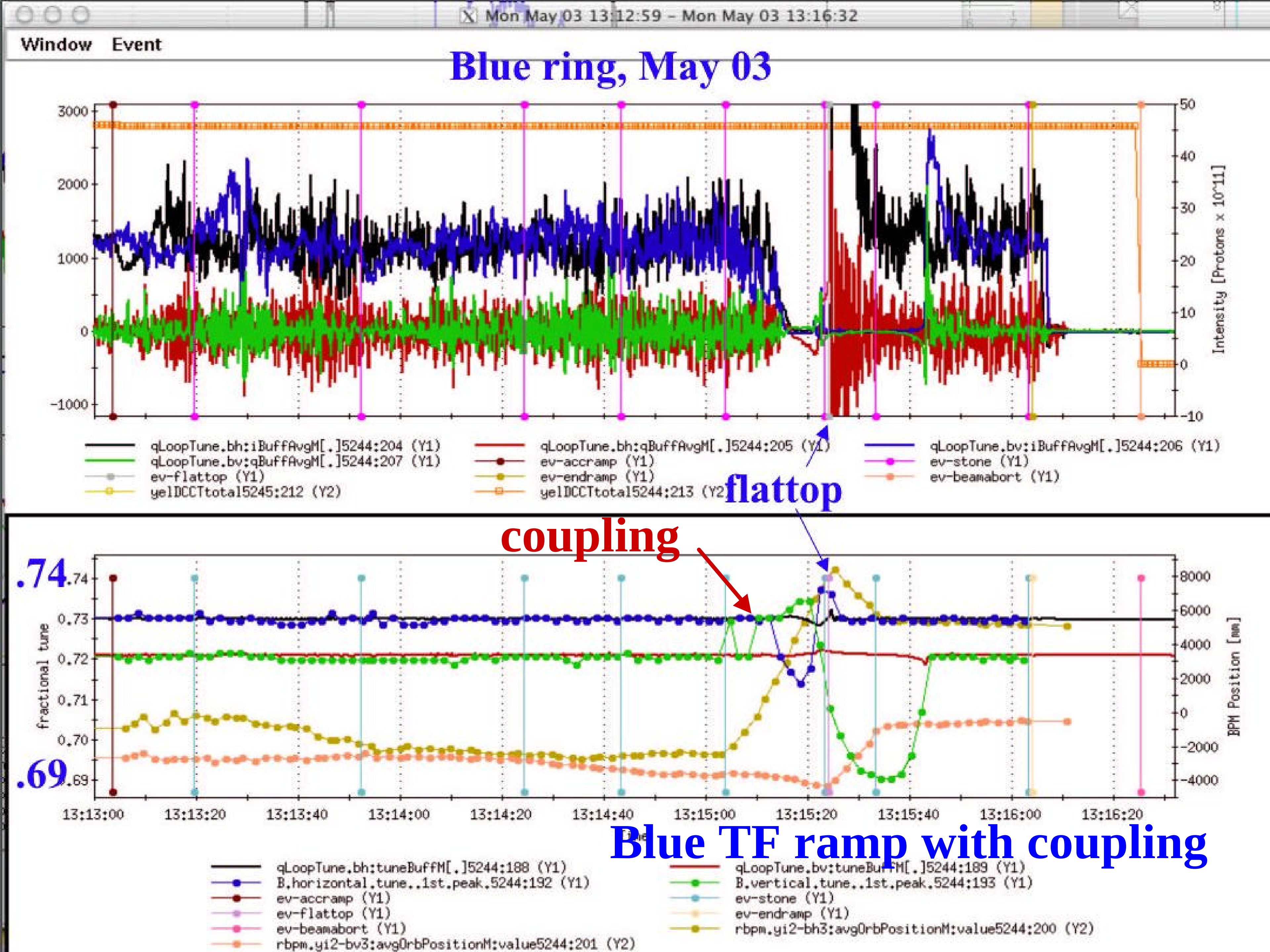
Ramp 5196

Polarized protons

Effect of Coupling on TF

- Previous slide showed successful ramp w/ TF
  - Coupling was well corrected prior to ramp
- Next slide shows slightly less successful ramp
  - 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

Blue ring, May 03



Blue TF ramp with coupling

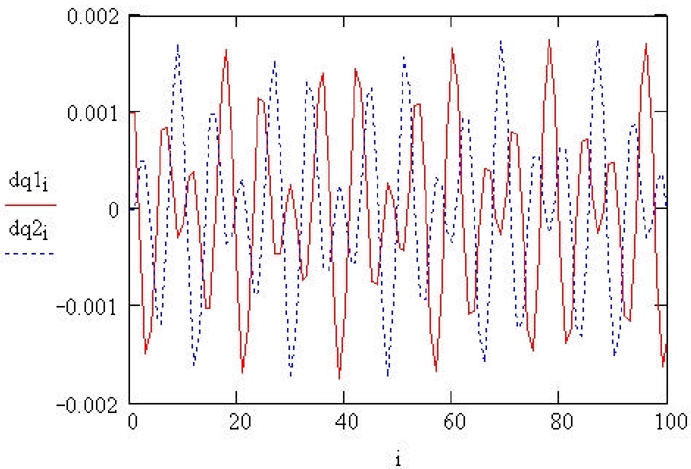
$$\begin{pmatrix} dq1_0 \\ dq2_0 \\ kx_0 \\ ky_0 \end{pmatrix} := \begin{pmatrix} .001 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad c := 0.25$$

initial perturbation .001

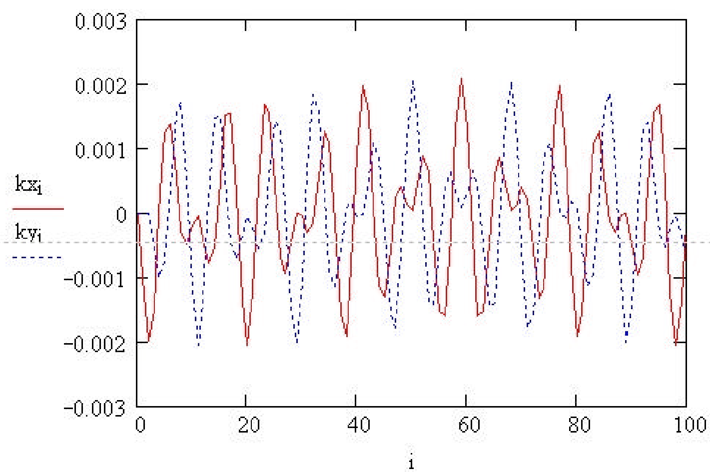
coupling coefficient .25

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

coupling terms



tune



correction strength

x axis span ~ 0.5 sec
unrealistic assumption
PLL does not correct the perturbation

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

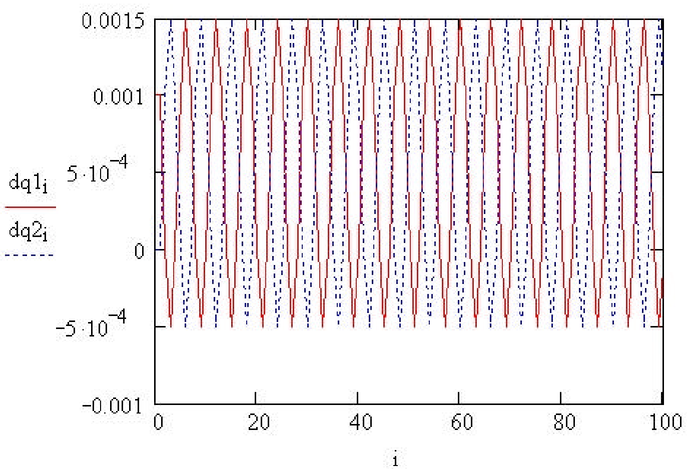
$$\begin{pmatrix} dq1_0 \\ dq2_0 \\ kx_0 \\ ky_0 \end{pmatrix} := \begin{pmatrix} .001 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

initial perturbation .001

$$c := 0.50$$

coupling coefficient .5 (45 deg)

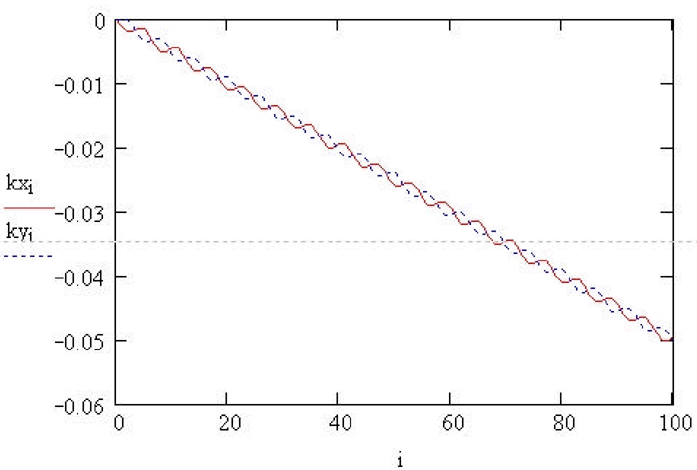
$$\begin{pmatrix} dq1_{i+1} \\ dq2_{i+1} \\ kx_{i+1} \\ ky_{i+1} \end{pmatrix} := \begin{bmatrix} dq1_i + \left[(1-c)kx_{i+1}\right] + -c \cdot ky_{i+1} \\ dq2_i + \left[\left[(1-c) \cdot ky_{i+1}\right] + -c \cdot kx_{i+1}\right] \\ kx_i - dq1_i \\ ky_i - dq2_i \end{bmatrix}$$



tune

Here 'coupling coefficient' is 0.5

- tune remains stable
- correction strength diverges



correction strength

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

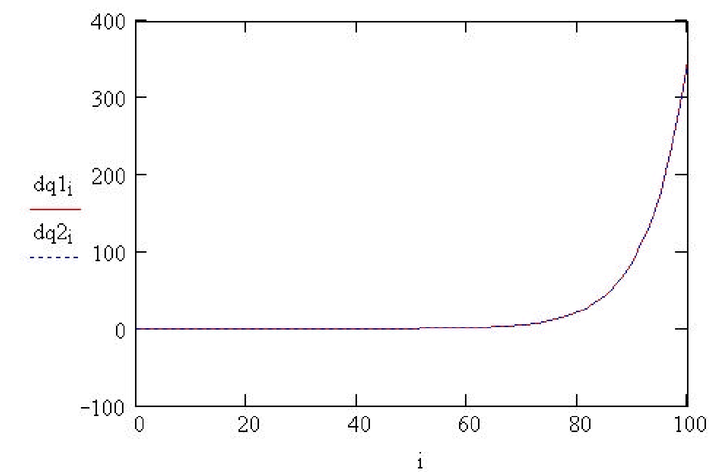
initial perturbation .001

$$c := 0.51$$

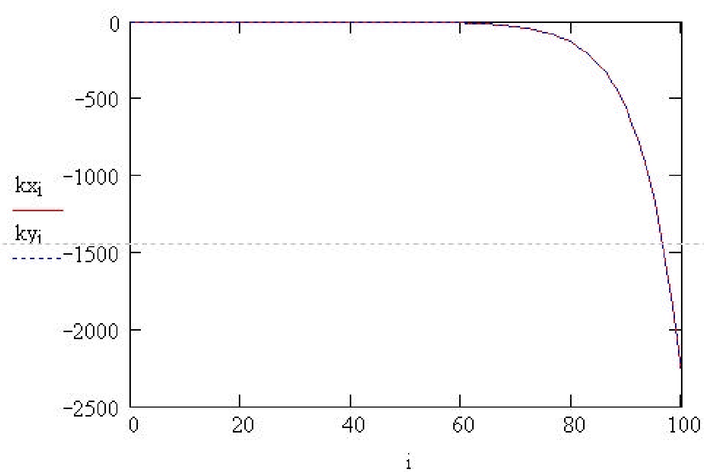
coupling coefficient .51

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

tune



correction strength



Here coupling coefficient is 0.51

- tune diverges
- correction strength diverges

PLL measures normal modes

- 'stable' in the presence of coupling

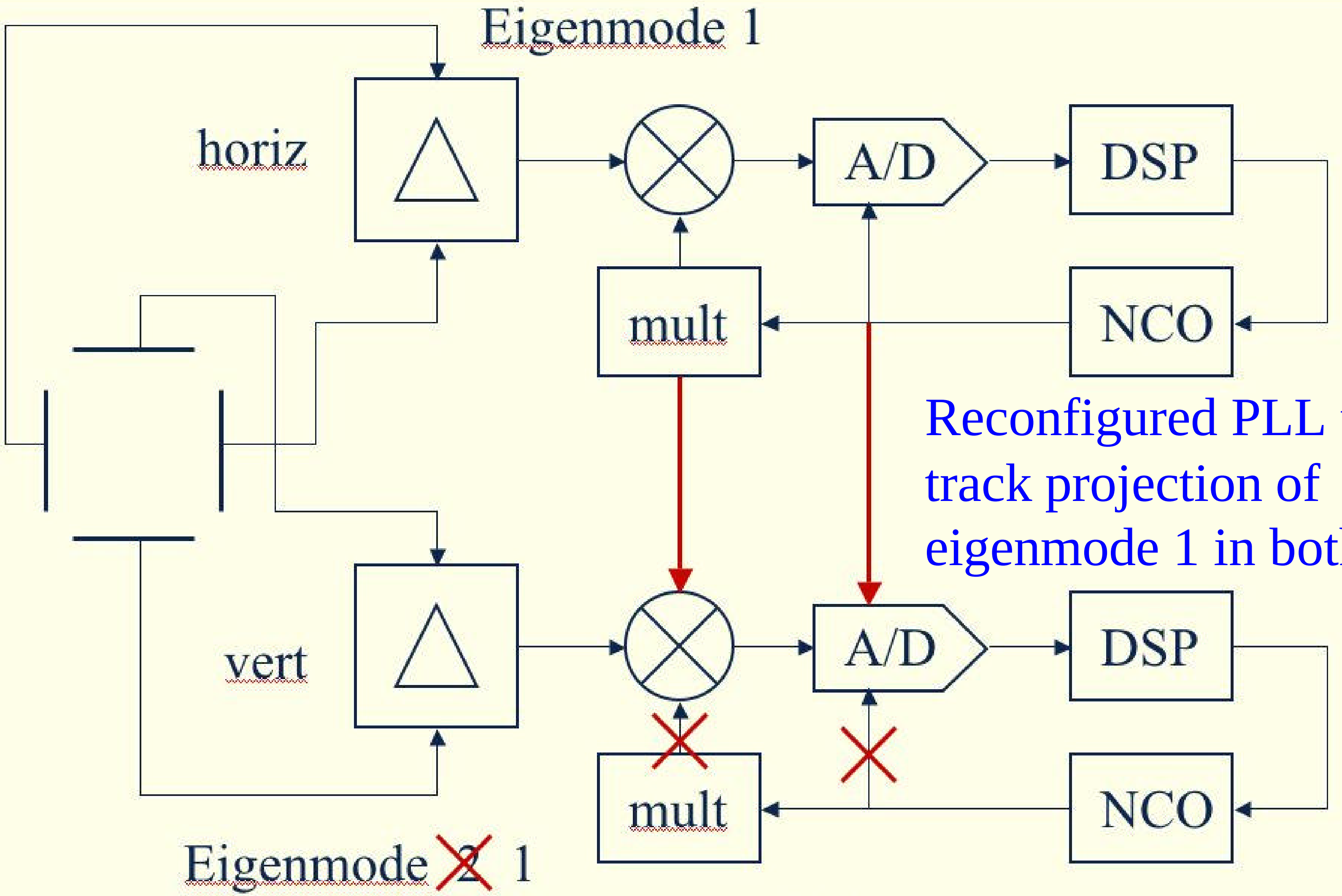
TF corrects x and y

- not stable in the presence of strong coupling

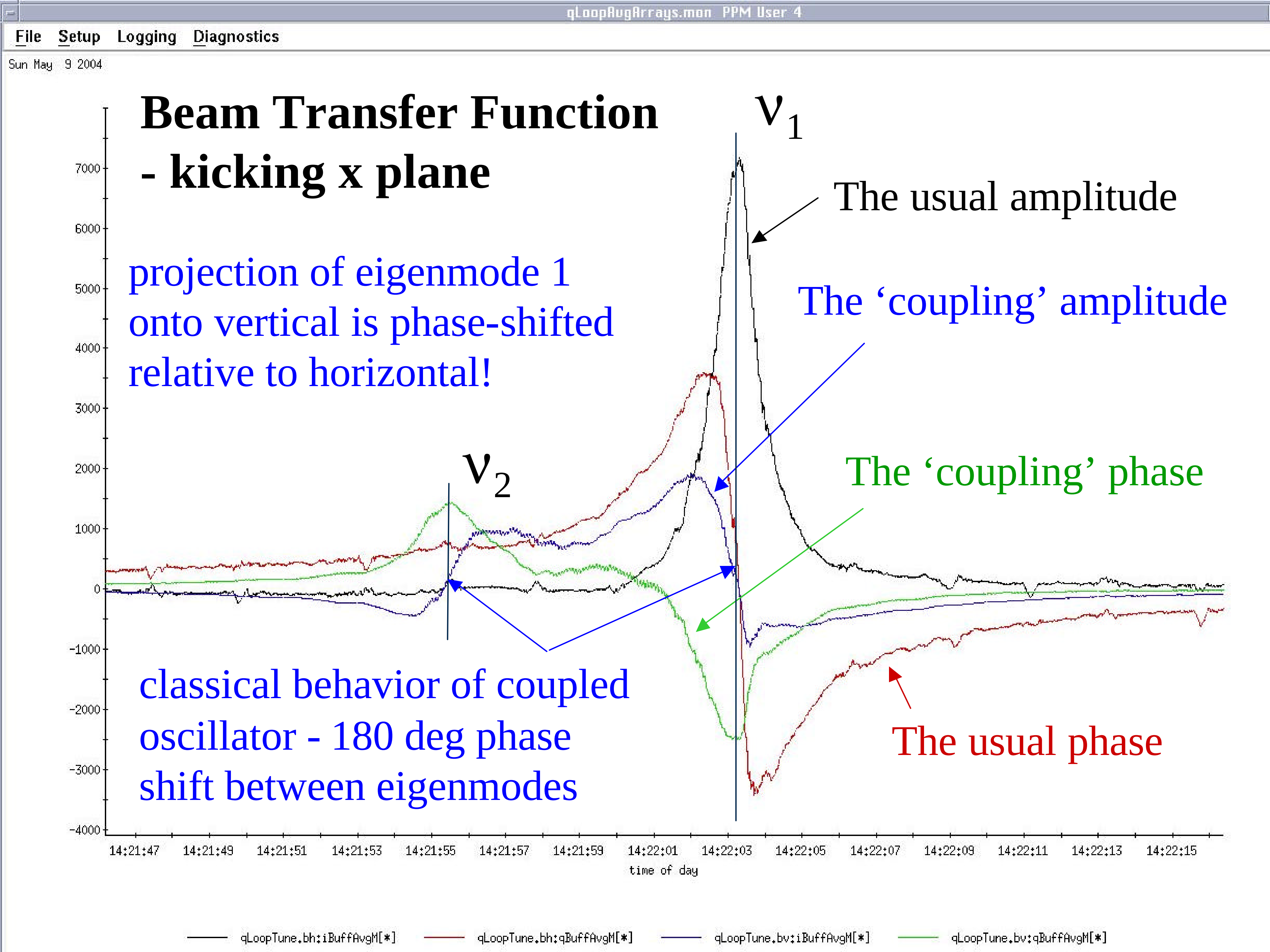
What We Learned and Did

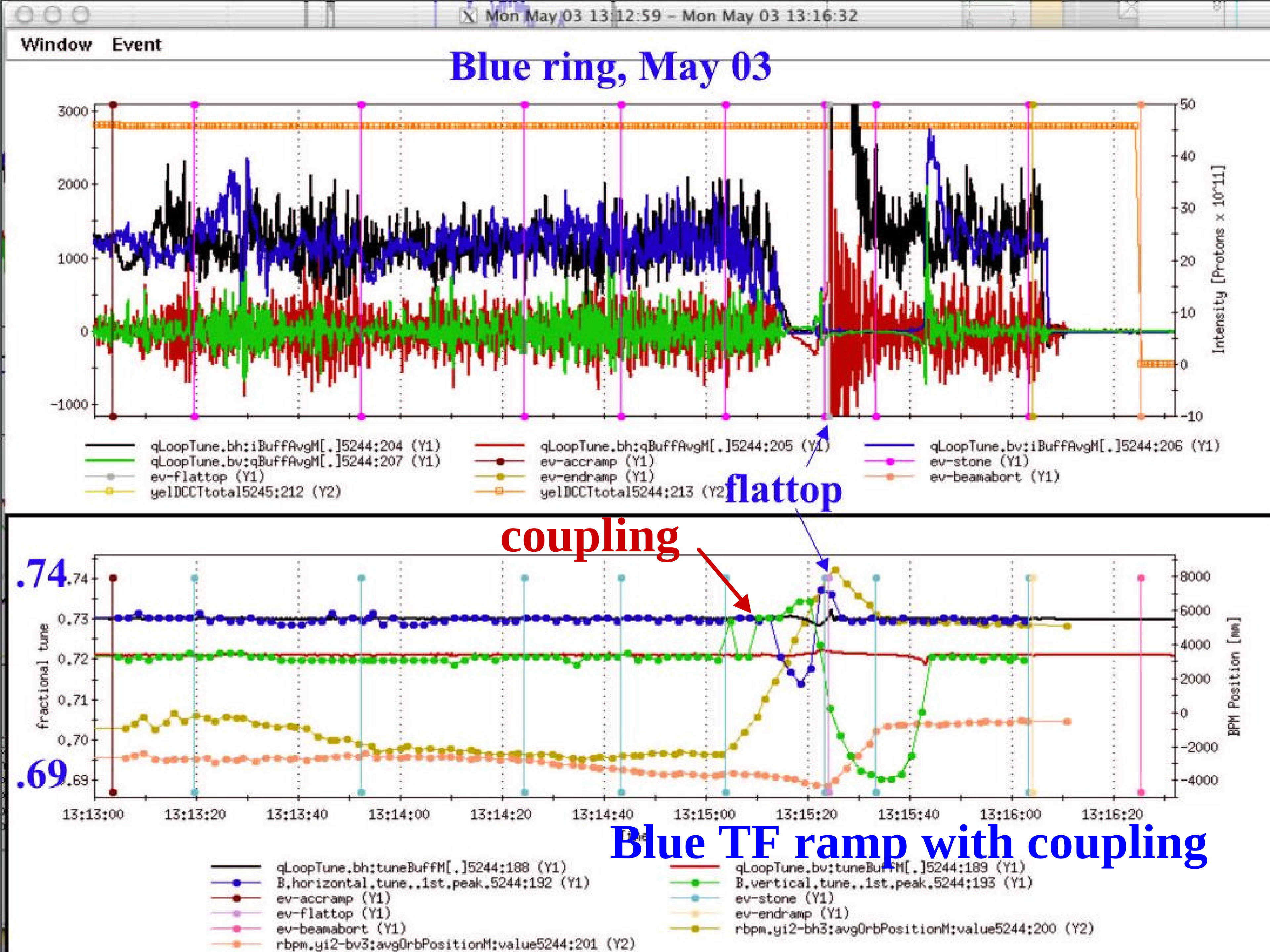
- What we Learned
  - PLL is 'stable' in the presence of coupling w/ caveats
    - tune separation > 100Hz digital filter BW
    - beta functions
    - motion control
    - feedback loops on kicker excitation and signal path gain
  - The system of Tune Feedback = PLL + magnet control is not stable in the presence of coupling
    - first thought - dQ_{min} pushes tunes apart, can still live in the tails
    - later realization - system unstable with >45 deg eigenmode rotation, onset of the problem is not gradual, but abrupt
- What we did
  - Improved coupling measurement
  - Investigated new correction and feedback possibilities

Coupling Measurement

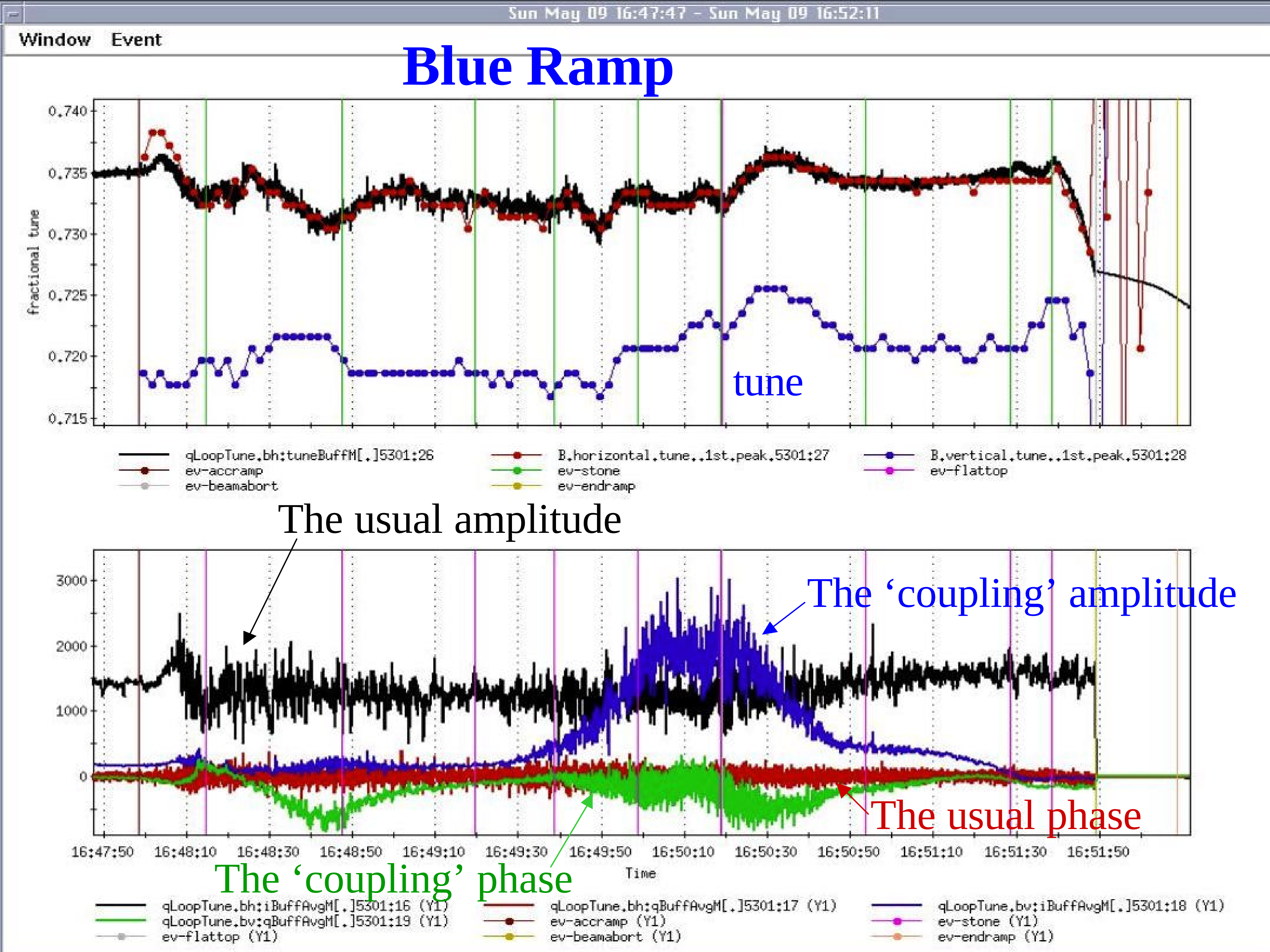


Reconfigured PLL to track projection of eigenmode 1 in both planes


qLoopAvgArrays.mon PPM User 4
File Setup Logging Diagnostics
Sun May 9 2004
Beam Transfer Function
- kicking x plane
ν1
ν2
The usual amplitude
projection of eigenmode 1
onto vertical is phase-shifted
relative to horizontal!
The 'coupling' amplitude
The 'coupling' phase
classical behavior of coupled
oscillator - 180 deg phase
shift between eigenmodes
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
qLoopTune.bh:iBuffAvgM[*]
qLoopTune.bh:qBuffAvgM[*]
qLoopTune.bv:iBuffAvgM[*]
qLoopTune.bv:qBuffAvgM[*]

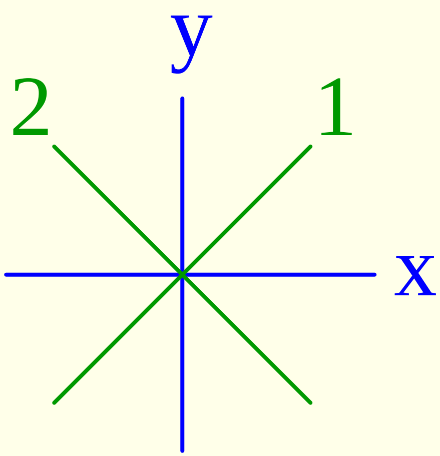

Mon May 03 13:12:59 - Mon May 03 13:16:32
Window
Event
Blue ring, May 03
3000
2000
1000
0
-1000
50
40
30
20
10
0
-10
Intensity [Protons x 10^11]
qLoopTune.bh:iBuffAvgM[.]5244:204 (Y1)
qLoopTune.bv:qBuffAvgM[.]5244:207 (Y1)
ev-flattop (Y1)
yelDCCTtotal5245:212 (Y2)
qLoopTune.bh:qBuffAvgM[.]5244:205 (Y1)
ev-accramp (Y1)
ev-endramp (Y1)
yelDCCTtotal5244:213 (Y2)
qLoopTune.bv:iBuffAvgM[.]5244:206 (Y1)
ev-stone (Y1)
ev-beamabort (Y1)
flattop
coupling
.74
.69
0.74
0.73
0.72
0.71
0.70
0.69
fractional tune
8000
6000
4000
2000
0
-2000
-4000
BPM Position [mm]
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
Blue TF ramp with coupling
qLoopTune.bh:tuneBuffM[.]5244:188 (Y1)
B.horizontal.tune..1st.peak.5244:192 (Y1)
ev-accramp (Y1)
ev-flattop (Y1)
ev-beamabort (Y1)
rbpm.yi2-bv3:avgOrbPositionM:value5244:201 (Y2)
qLoopTune.bv:tuneBuffM[.]5244:189 (Y1)
B.vertical.tune..1st.peak.5244:193 (Y1)
ev-stone (Y1)
ev-endramp (Y1)
rbpm.yi2-bh3:avgOrbPositionM:value5244:200 (Y2)

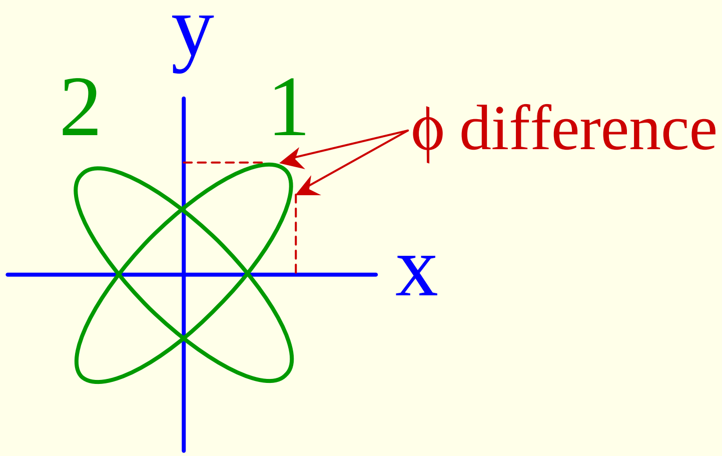
Blue Ramp


Sun May 09 16:47:47 - Sun May 09 16:52:11
Window Event
tune
fractional tune
0.740
0.735
0.730
0.725
0.720
0.715
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)

Eigenmodes

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





"Yun's Parameters"

C-A/AP/174 - Possible phase loop for the global betatron decoupling, Y. Luo et al

http://www.rhichome.bnl.gov/AP/ap_notes/cad_ap_index.html

Define:

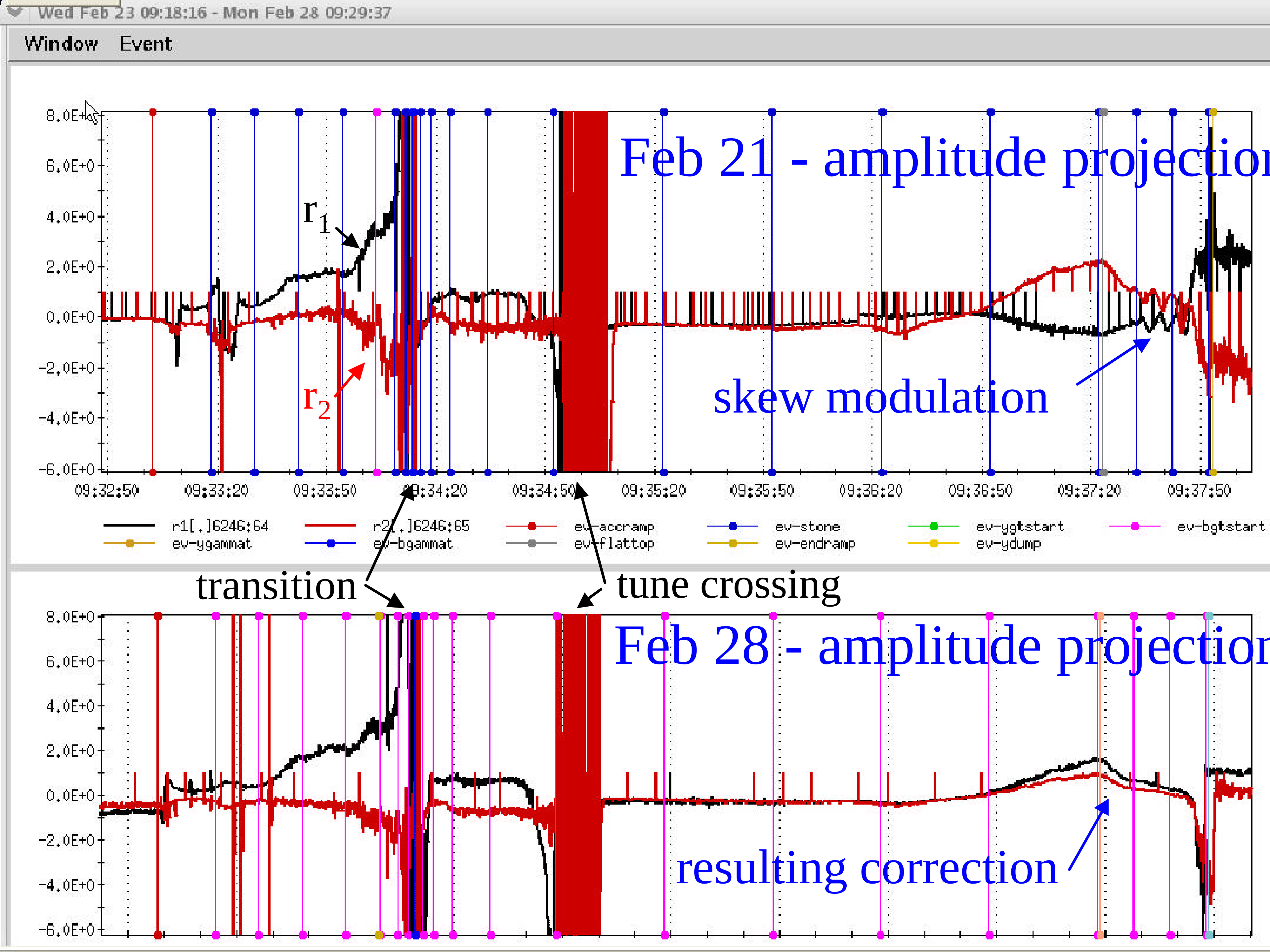
Q_1 = eigentune 1 Q_2 = eigentune 2

$A_{1,x}$ = amplitude of eigenmode 1 in x-plane,...

$\phi_{1,x}$ = phase of eigenmode 1 in x-plane,...

Then these 6 parameters are a complete description of coupling:

Q_1	Q_2
$r_1 = abs(A_{1,y} / A_{1,x})$	$r_2 = abs(A_{2,x} / A_{2,y})$
$\Delta\phi_1 = \phi_{1,y} - \phi_{1,x}$ → ~ 0	$\Delta\phi_2 = \phi_{2,x} - \phi_{2,y}$ → ~ 0 (this is the PLL function)



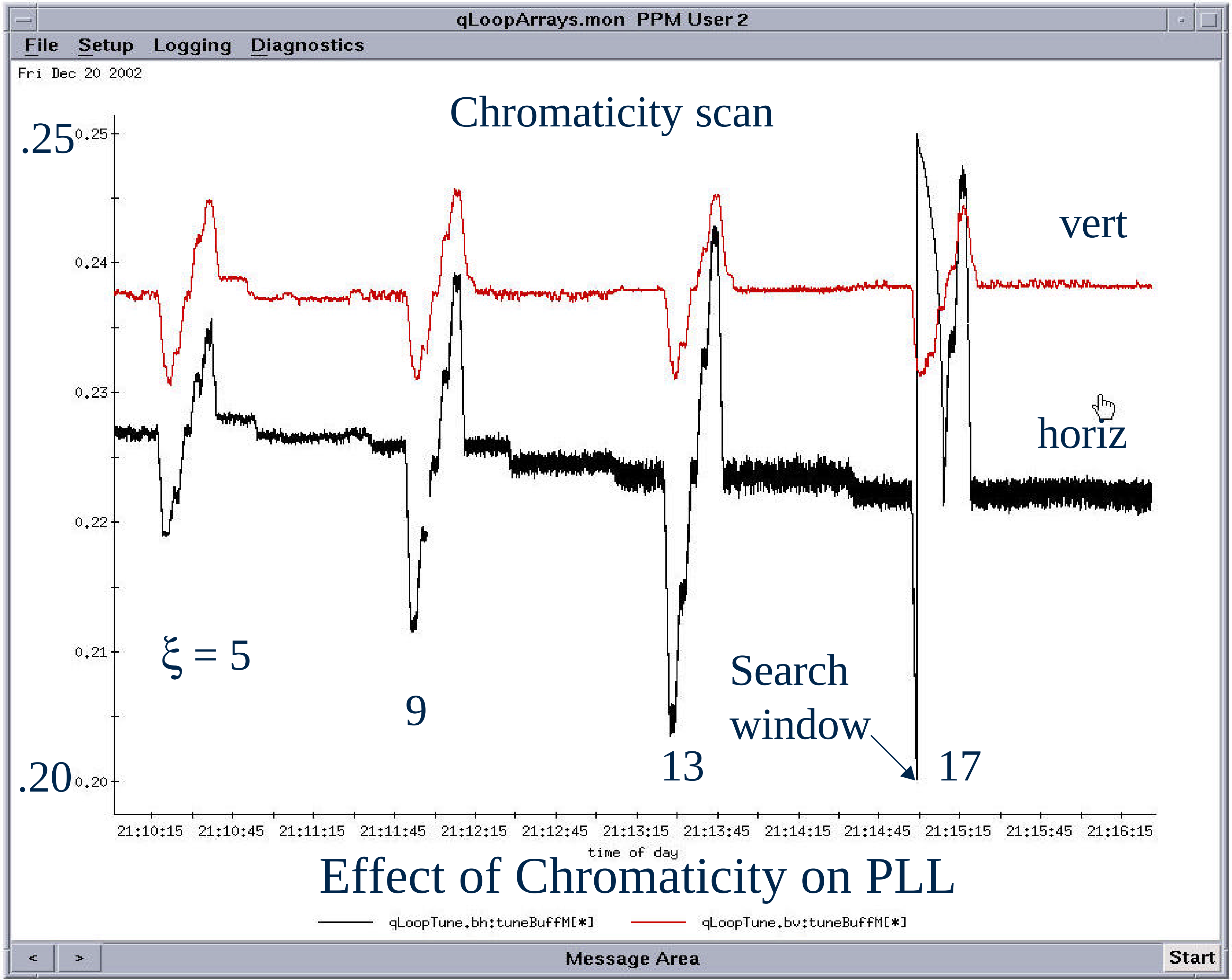
Wed Feb 23 09:18:16 - Mon Feb 28 09:29:37
Window
Event
Feb 21 - amplitude projection
r1
r2
skew modulation
r1[.]6246:64
r2[.]6246:65
ev-accramp
ev-stone
ev-ygtstart
ev-bgtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp
ev-ydump
transition
tune crossing
Feb 28 - amplitude projection
resulting correction

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
  - Coupling correction/feedback is being actively investigated – Yun Luo, Steve Peggs, Richard Talman
  - method/formalism similar to LHC - Stephane Fartouk

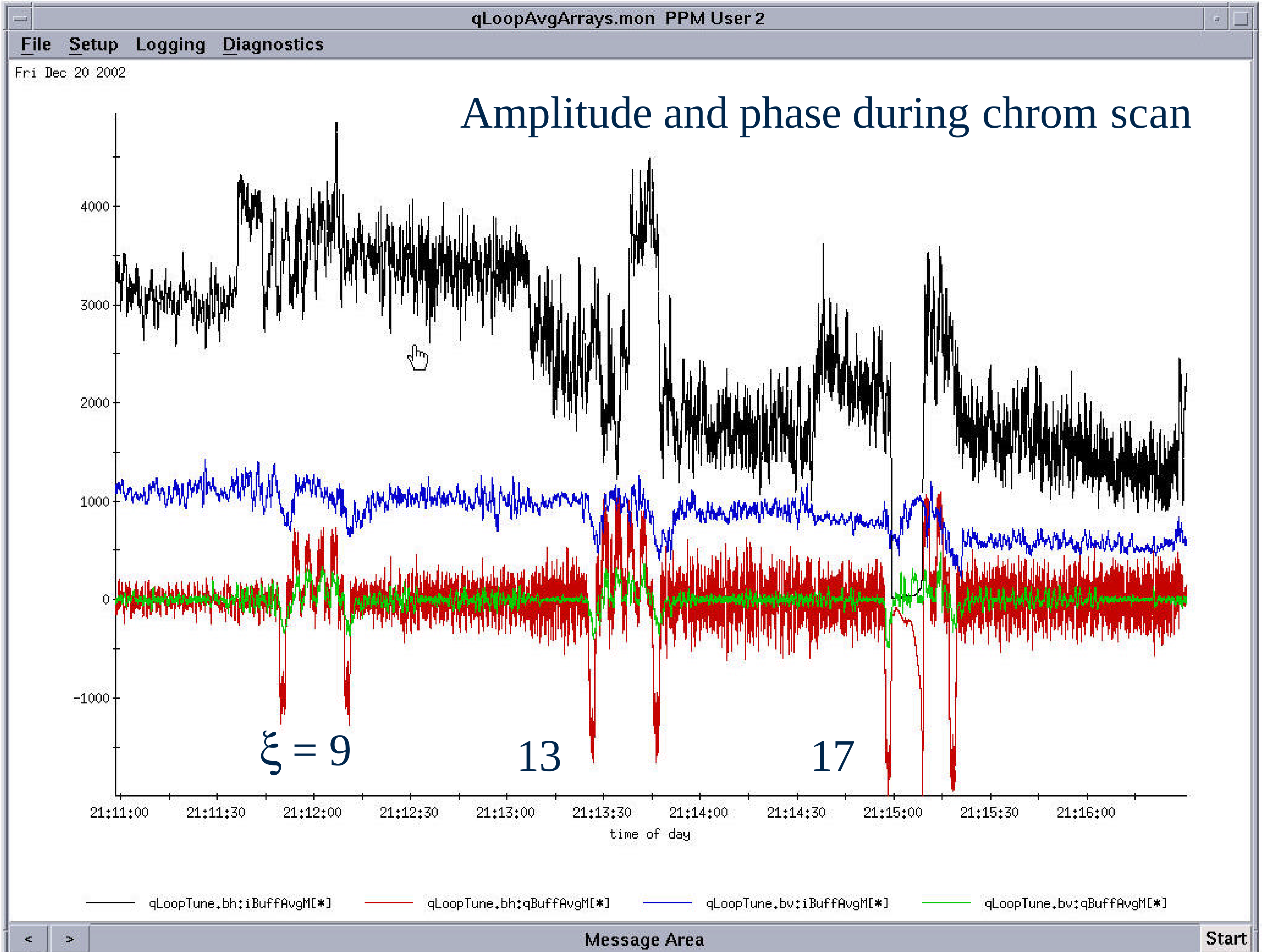
Outline

- 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
17
Search window
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



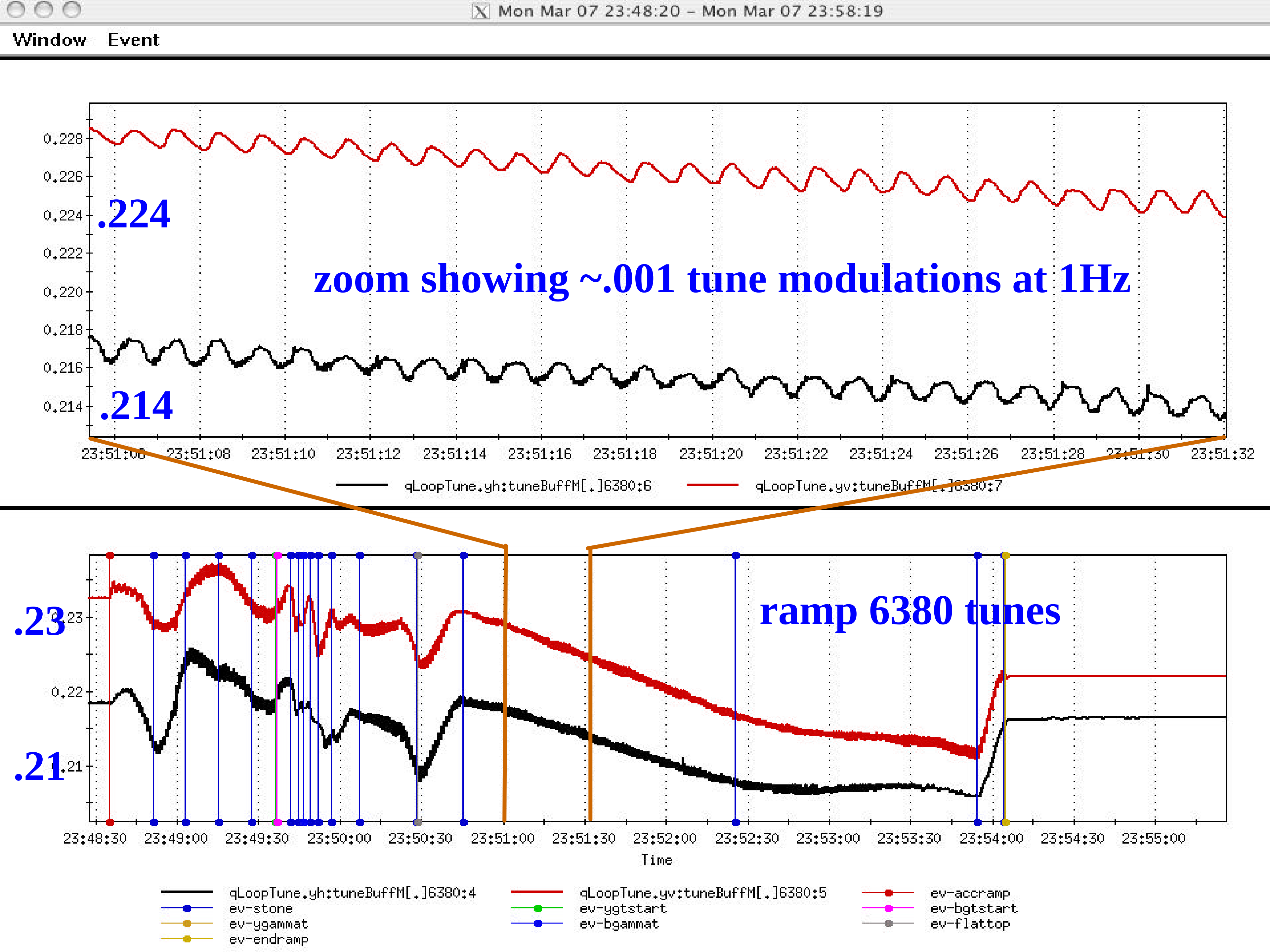
Chromaticity Effect on PLL

- 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
- Chromaticity control is an issue primarily in the usual operational sense – line broadening and resonance overlap

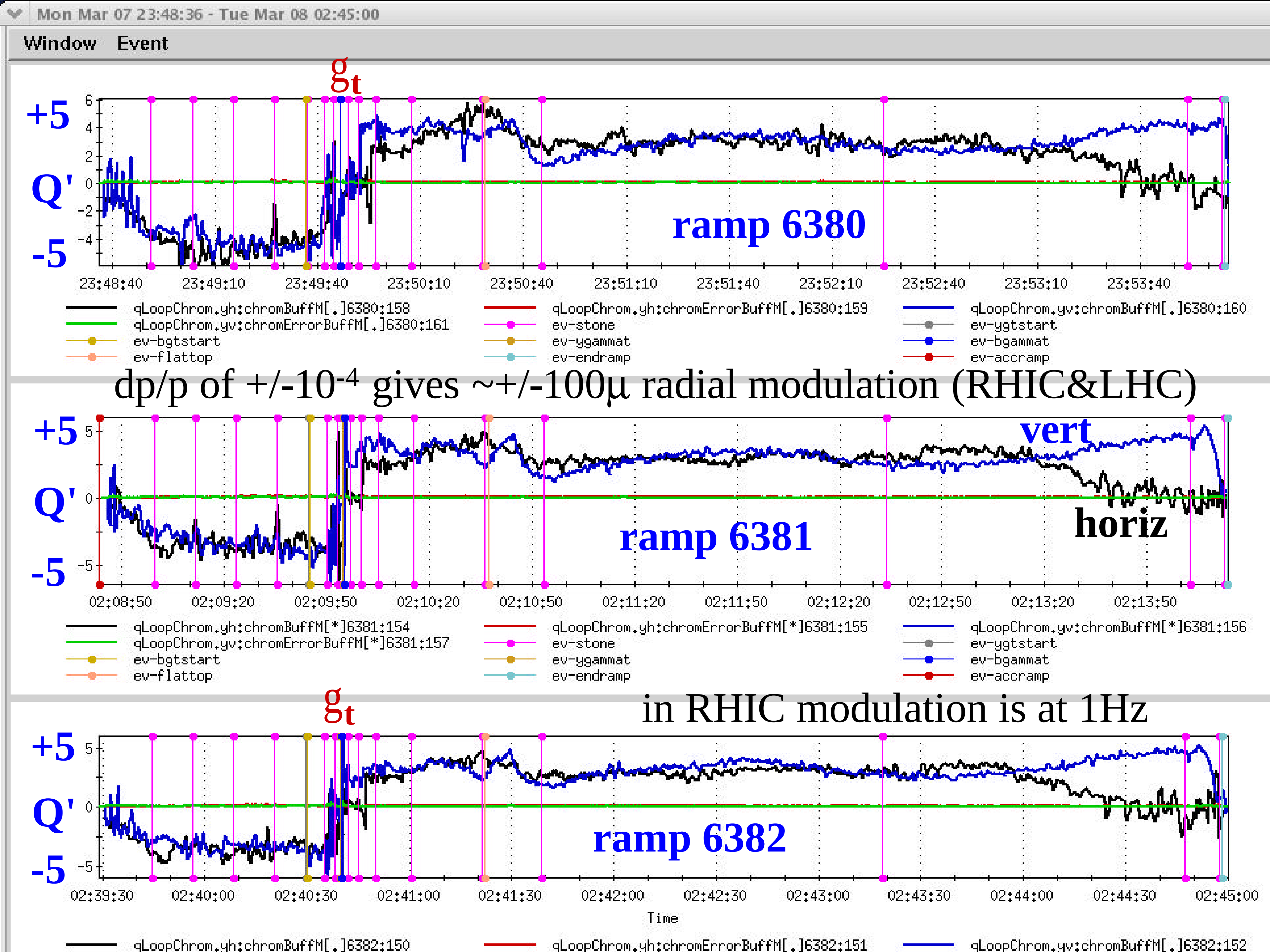
Chromaticity Measurement

The method:

- $\xi = (dq/Q)/(dp/p)$ or $Q\xi = dq/(dp/p)$
- measure tune variation resulting from momentum variation
- $dp/p \sim \gamma_{tr}^2 \, dR/R$
  - $+/-10^{-4}$ dp/p gives ~+/-100μ radial modulation
  - ~true at both RHIC and LHC
- modulation frequency 1Hz
- fit the tune modulation with a sliding window
- calculate chromaticity



Mon Mar 07 23:48:20 - Mon Mar 07 23:58:19
Window
Event
zoom showing ~.001 tune modulations at 1Hz
.224
.214
0.228
0.226
0.224
0.222
0.220
0.218
0.216
0.214
23:51:08
23:51:10
23:51:12
23:51:14
23:51:16
23:51:18
23:51:20
23:51:22
23:51:24
23:51:26
23:51:28
23:51:32
qLoopTune.yh:tuneBuffM[.]6380:6
ramp 6380 tunes
.23
.21
0.22
23:48:30
23:49:00
23:49:30
23:50:00
23:50:30
23:51:00
23:51:30
23:52:00
23:52:30
23:53:00
23:53:30
23:54:00
23:54:30
23:55:00
Time
qLoopTune.yh:tuneBuffM[.]6380:4
qLoopTune.yv:tuneBuffM[.]6380:5
ev-accramp
ev-stone
ev-ygtstart
ev-bgtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp



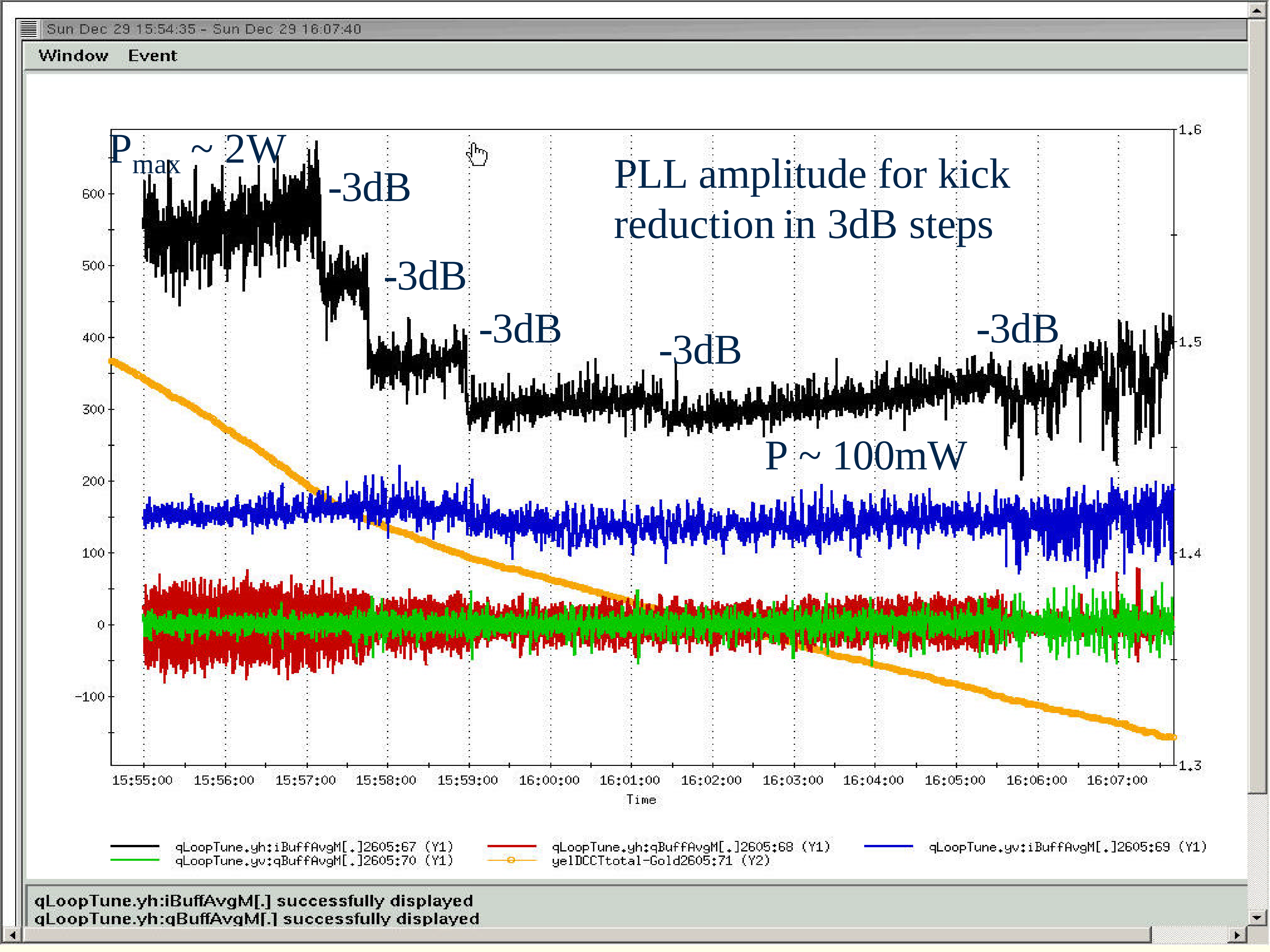
Mon Mar 07 23:48:36 - Tue Mar 08 02:45:00
Window Event
g_t
+5
Q'
-5
ramp 6380
23:48:40 23:49:10 23:49:40 23:50:10 23:50:40 23:51:10 23:51:40 23:52:10 23:52:40 23:53:10 23:53:40
qLoopChrom.yh:chromBuffM[.]6380:158
qLoopChrom.yh:chromErrorBuffM[.]6380:159
qLoopChrom.yv:chromBuffM[.]6380:160
qLoopChrom.yv:chromErrorBuffM[.]6380:161
ev-stone
ev-ygtstart
ev-bgtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp
ev-accramp
dp/p of +/-10^{-4} gives ~+/-100µ radial modulation (RHIC&LHC)
+5
Q'
-5
vert
horiz
ramp 6381
02:08:50 02:09:20 02:09:50 02:10:20 02:10:50 02:11:20 02:11:50 02:12:20 02:12:50 02:13:20 02:13:50
qLoopChrom.yh:chromBuffM[*]6381:154
qLoopChrom.yh:chromErrorBuffM[*]6381:155
qLoopChrom.yv:chromBuffM[*]6381:156
qLoopChrom.yv:chromErrorBuffM[*]6381:157
ev-stone
ev-ygtstart
ev-bgtstart
ev-ygammat
ev-bgammat
ev-flattop
ev-endramp
ev-accramp
g_t
in RHIC modulation is at 1Hz
+5
Q'
-5
ramp 6382
02:39:30 02:40:00 02:40:30 02:41:00 02:41:30 02:42:00 02:42:30 02:43:00 02:43:30 02:44:00 02:44:30 02:45:00
Time
qLoopChrom.yh:chromBuffM[.]6382:150
qLoopChrom.yh:chromErrorBuffM[.]6382:151
qLoopChrom.yv:chromBuffM[.]6382:152

Summary of Chromaticity

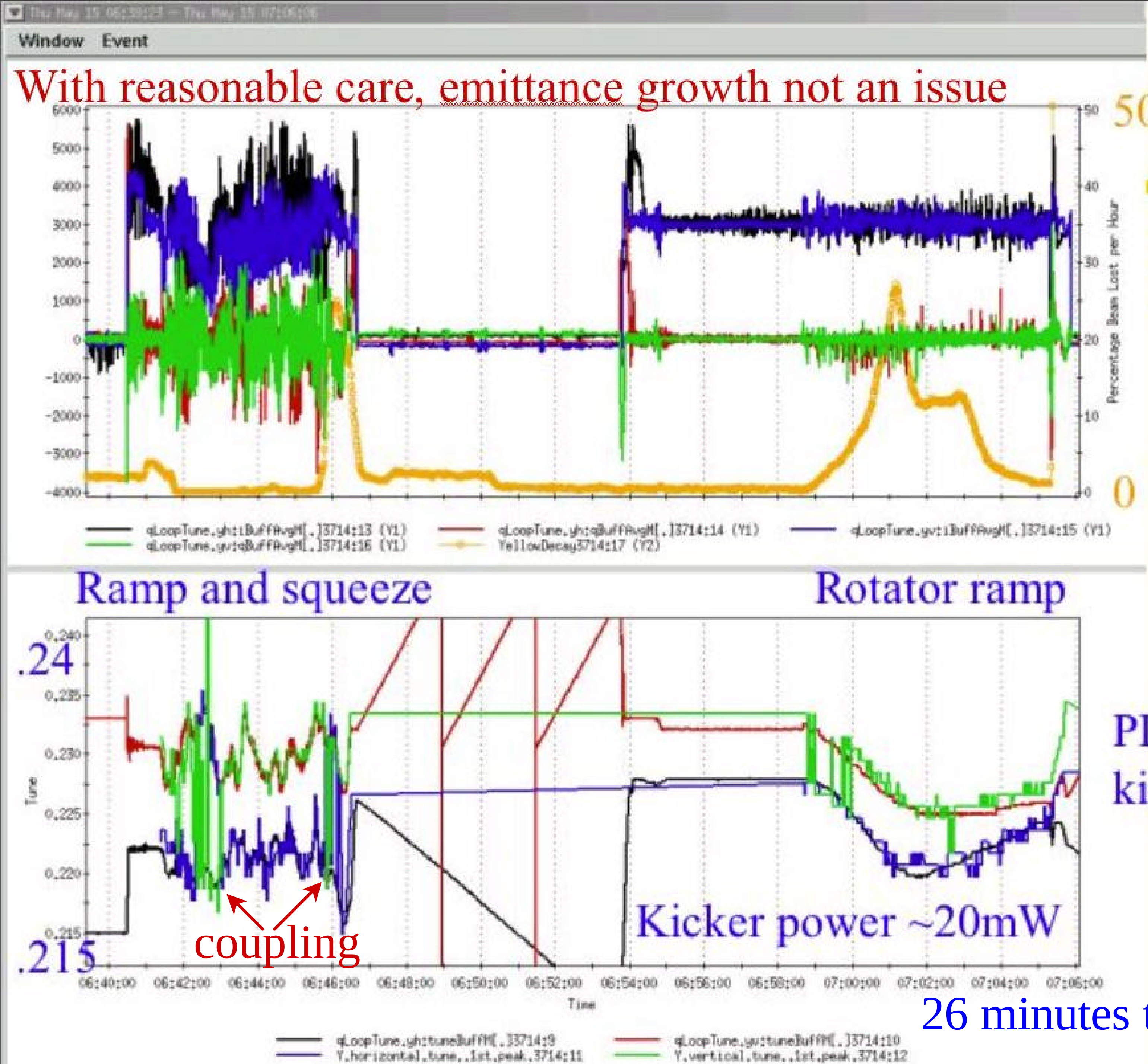
- We need BMX time for chrom feedback this run
- Radial modulation method gives good data
- Useful data gathered for feedforward and magnet model - b2 in dipoles
- Bandwidth in present form adequate for LHC snapback feedback correction? perhaps
- No testing of phase modulation methods
- Chromaticity not an issue for reliable operation of 245MHz PLL - this may be less true for baseband

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
P_{max} ~ 2W
-3dB
-3dB
-3dB
-3dB
-3dB
PLL amplitude for kick reduction in 3dB steps
P ~ 100mW
600
500
400
300
200
100
0
-100
1.6
1.5
1.4
1.3
15:55:00
15:56:00
15:57:00
15:58:00
15:59:00
16:00:00
16:01:00
16:02:00
16:03:00
16:04:00
16:05:00
16:06:00
16:07:00
Time
qLoopTune.yh:iBuffAvgM[.]2605:67 (Y1)
qLoopTune.yv:qBuffAvgM[.]2605:70 (Y1)
qLoopTune.yh:qBuffAvgM[.]2605:68 (Y1)
yelDCCTtotal-Gold2605:71 (Y2)
qLoopTune.yv:iBuffAvgM[.]2605:69 (Y1)
qLoopTune.yh:iBuffAvgM[.] successfully displayed
qLoopTune.yh:qBuffAvgM[.] successfully displayed



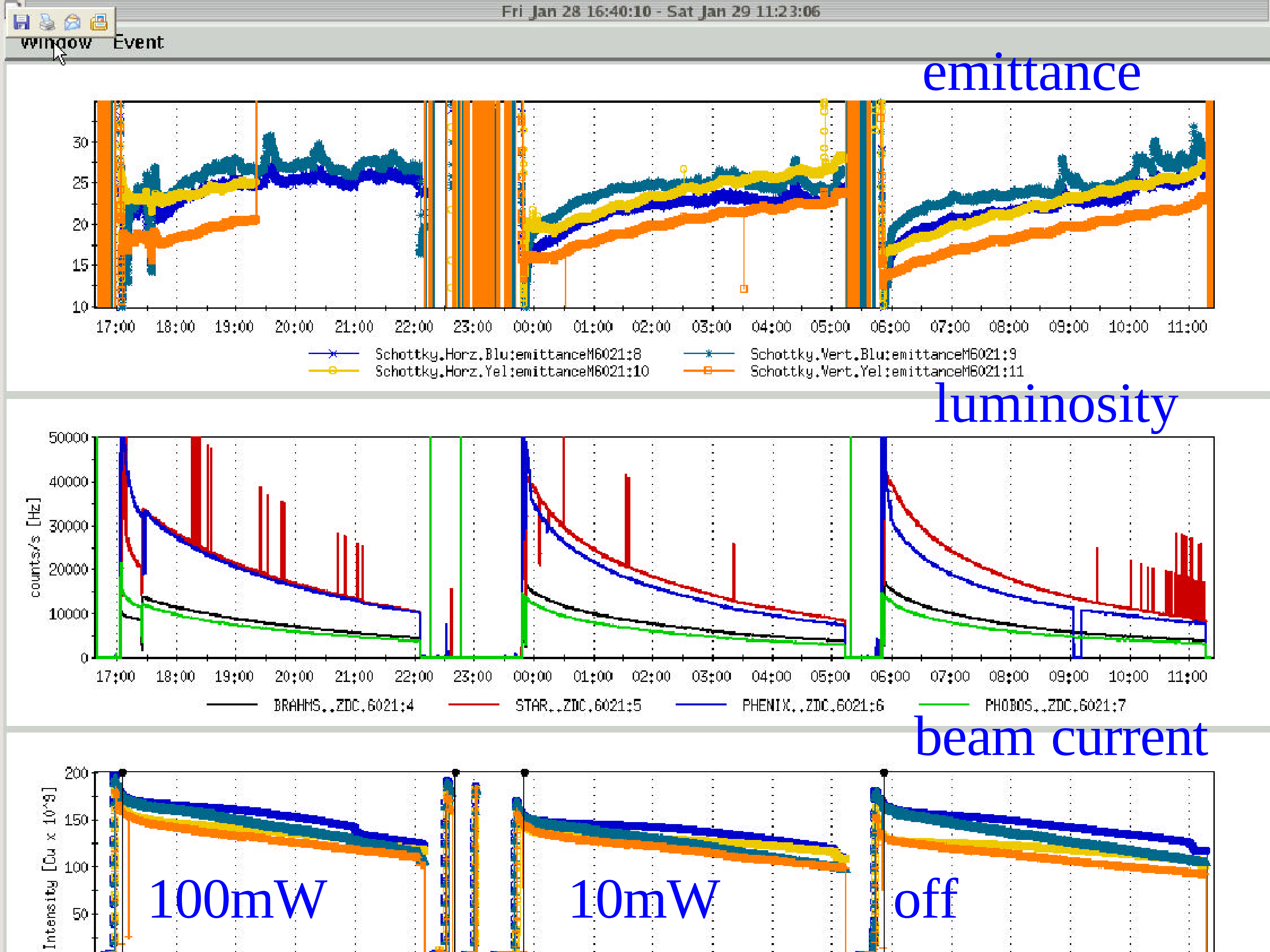
US LARP

Amplitude and phase

Beam decay

PLL and kicked tunes

26 minutes total



Fri Jan 28 16:40:10 - Sat Jan 29 11:23:06
Window Event
emittance
Schottky.Horz.Blu:emittanceM6021:8
Schottky.Vert.Blu:emittanceM6021:9
Schottky.Horz.Yel:emittanceM6021:10
Schottky.Vert.Yel:emittanceM6021:11
luminosity
counts/s [Hz]
BRAHMS..ZDC.6021:4
STAR..ZDC.6021:5
PHENIX..ZDC.6021:6
PHOBOS..ZDC.6021:7
beam current
Intensity [Cu x 10^9]
100mW
10mW
off

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)

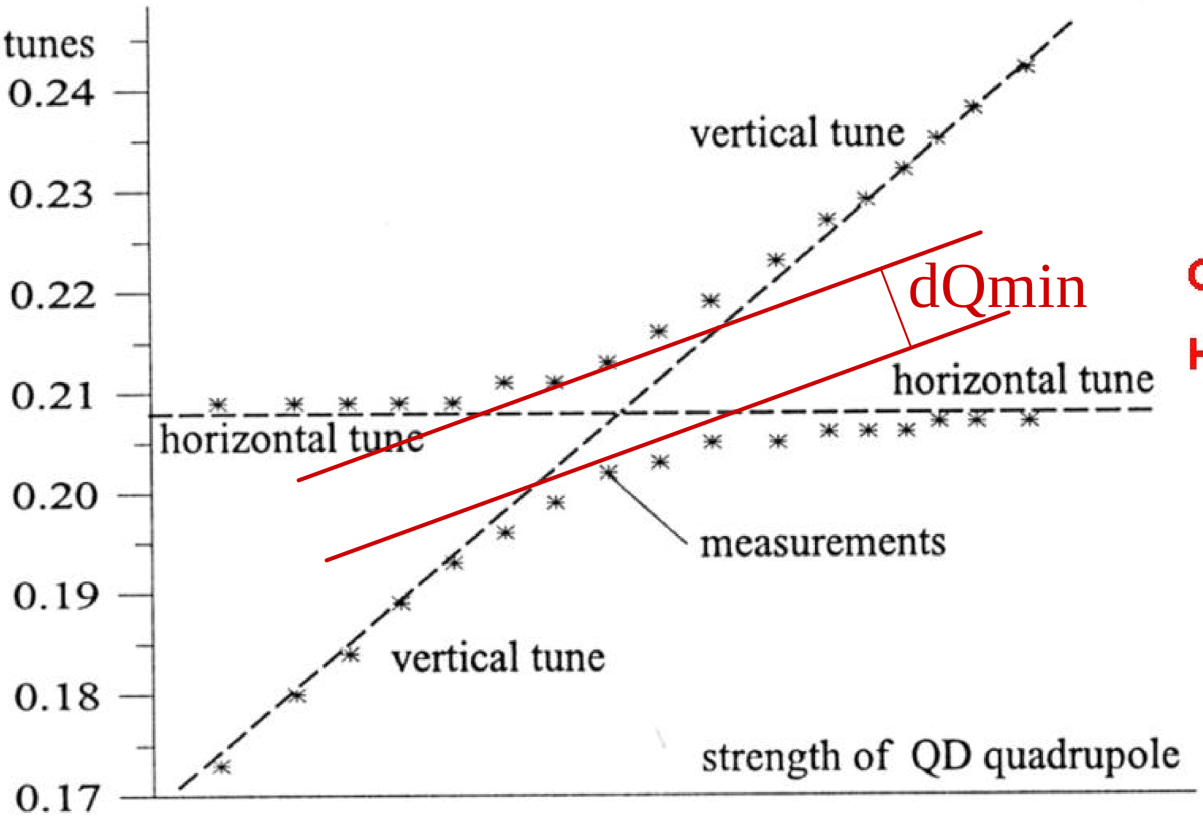
Conclusions

- 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
- Robust performance is difficult in the presence of coupling
  - difficult even to measure coupling for feedforward
  - coupling feedback needs consideration
- We need BMX on chrom and coupling feedback

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