The Tevatron in Jan 2005
-- or my stint as Tevatron Coordinator

C.Y. Tan

24 Feb 2005

Tev Coordinator

- As Tevatron coordinator in Dec 2004 and Jan 2005, like every coordinator hoped for:
  - Shoot and store.
  - Don't lose it!
- Unfortunately, the Universe does not grant such wishes and so ...
  - RF trips (3)
  - Beam blowups (1)
  - Separator sparks (many)
  - Plus quenches from wet engine failures (2)

Jan 2005 Events

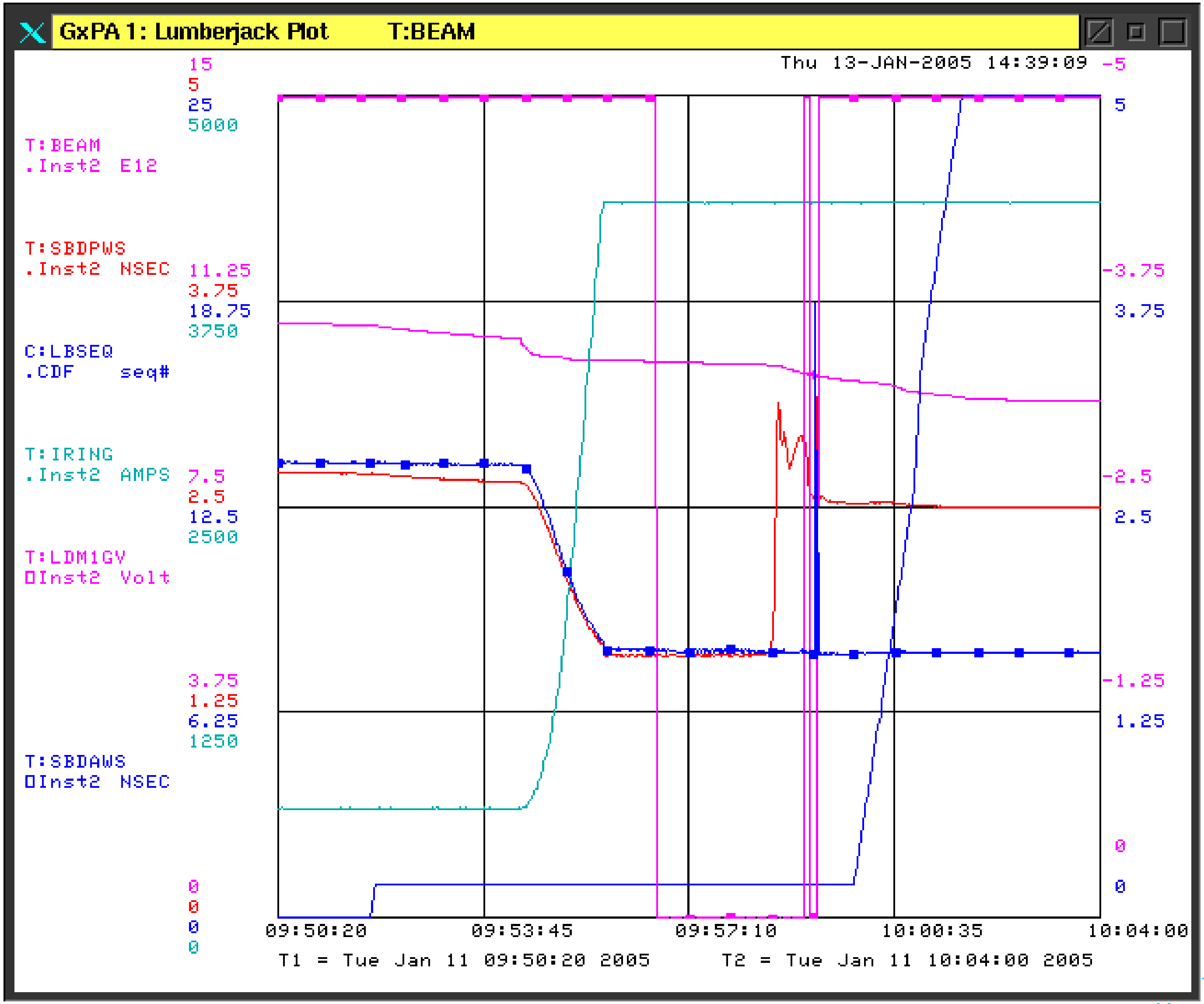
- When you get lemons, it's time to make lemonade that is **if** the beam stays in the machine!
  - Dampers not turned on at flattop
    - Can infer parasitic mode which causes instability
  - RF trip
    - Can calculate β^* and crossing angle.
- Install new instrumentation
  - Base Band Tune Direct Diode Detector (BBQ-3D)

Longitudinal Bunch blowup

Longitudinal Bunch Blowup

- This happened in store 3918
- The reason was that the longitudinal dampers were not turned on at flattop.
- This helps us understand why we need dampers.

The Blowup



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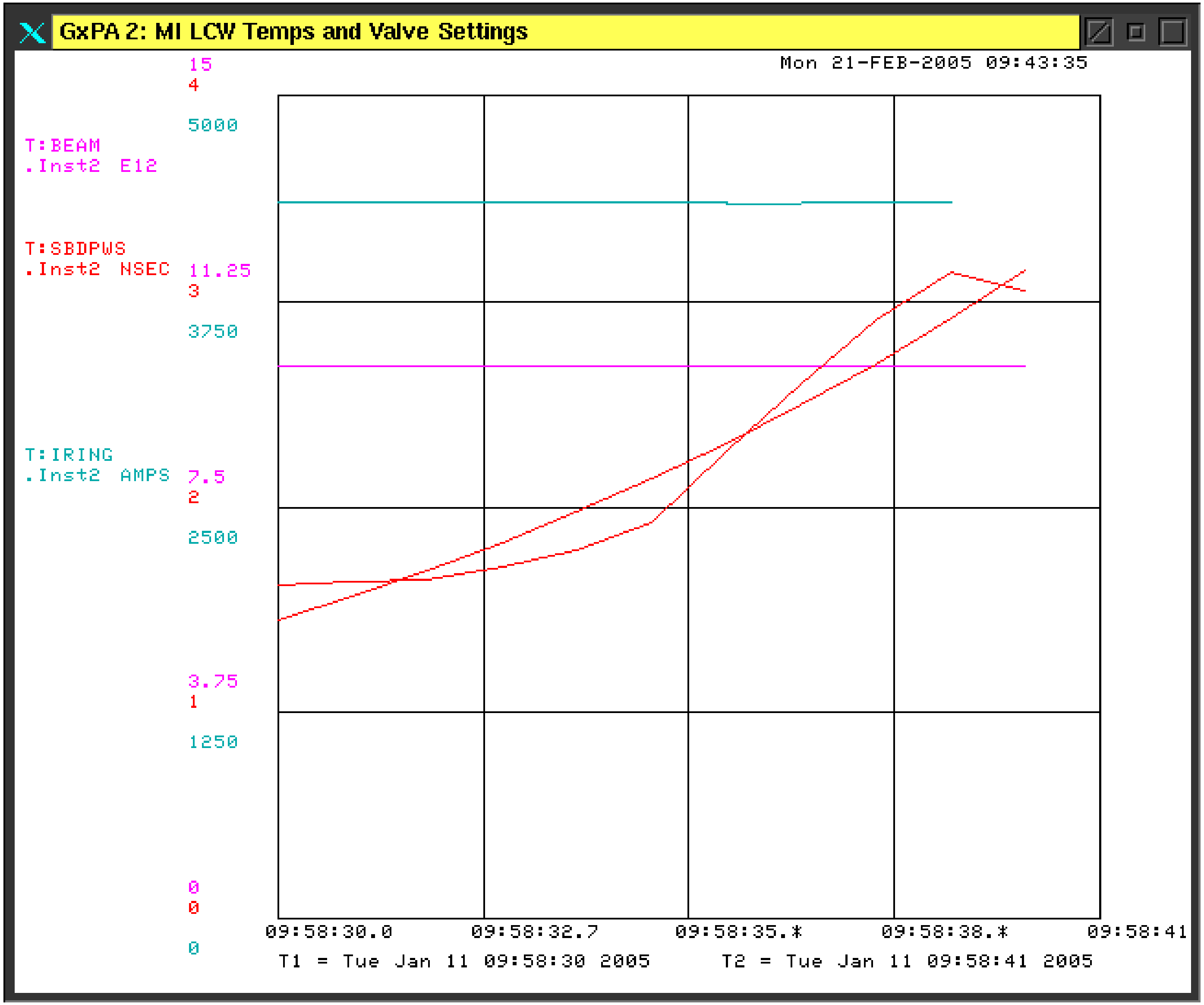
Zoom in



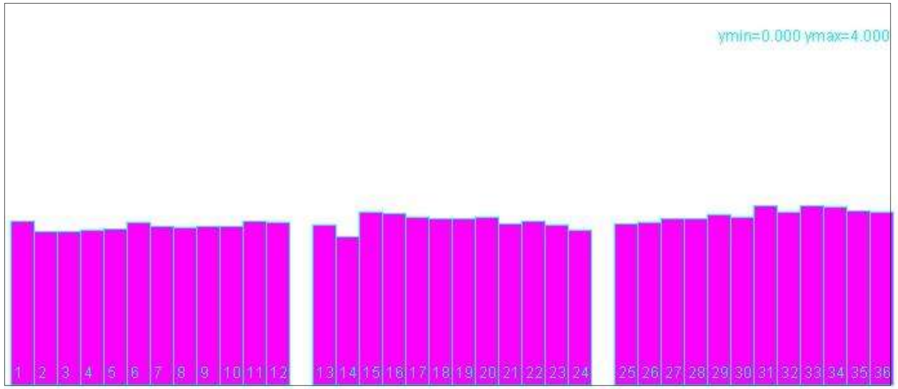
Growth not exponential. But use it anyway to get some idea.

E time is 13 seconds

Individual Bunch blowup

Vertical : T:SBDPWS
Horz: bunch #

Vert: 0 to 4 ns



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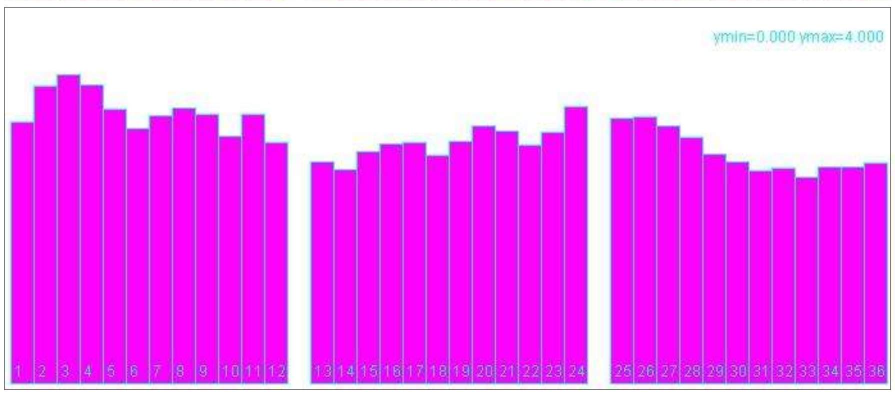

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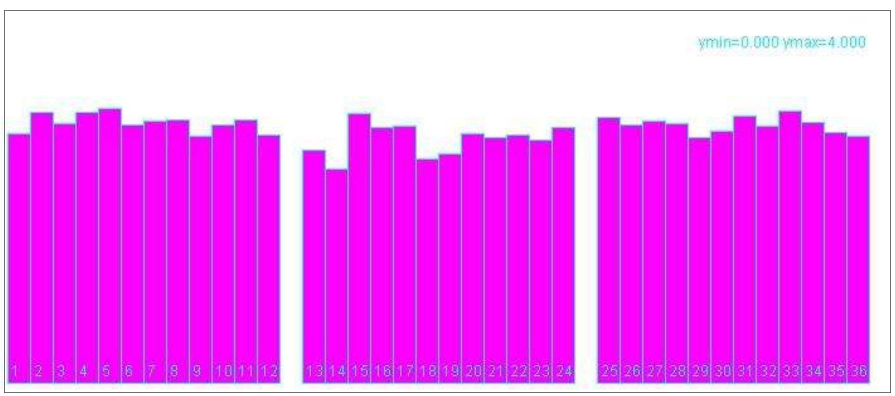

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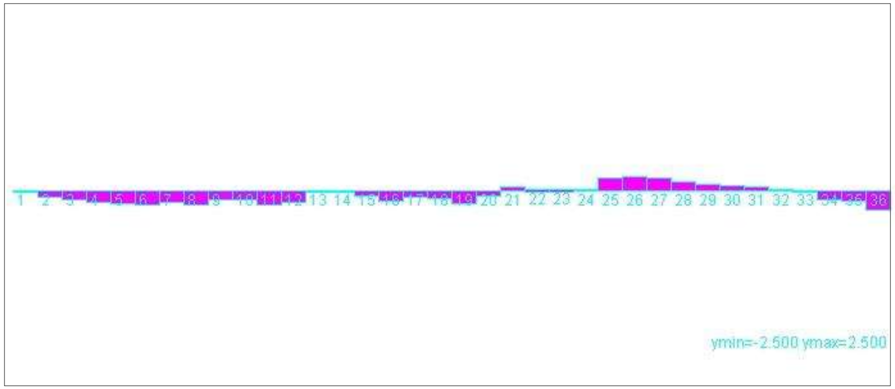
Coupled Bunch Mode 1



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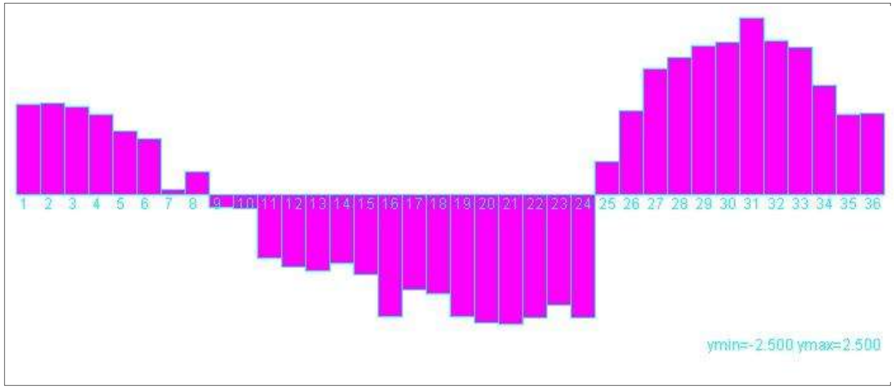

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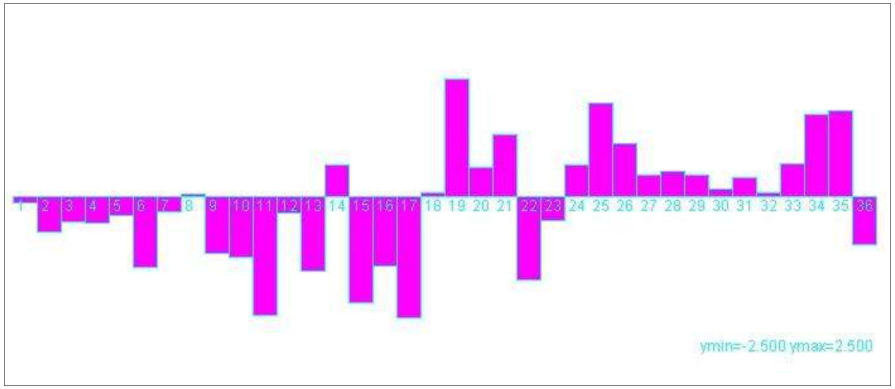

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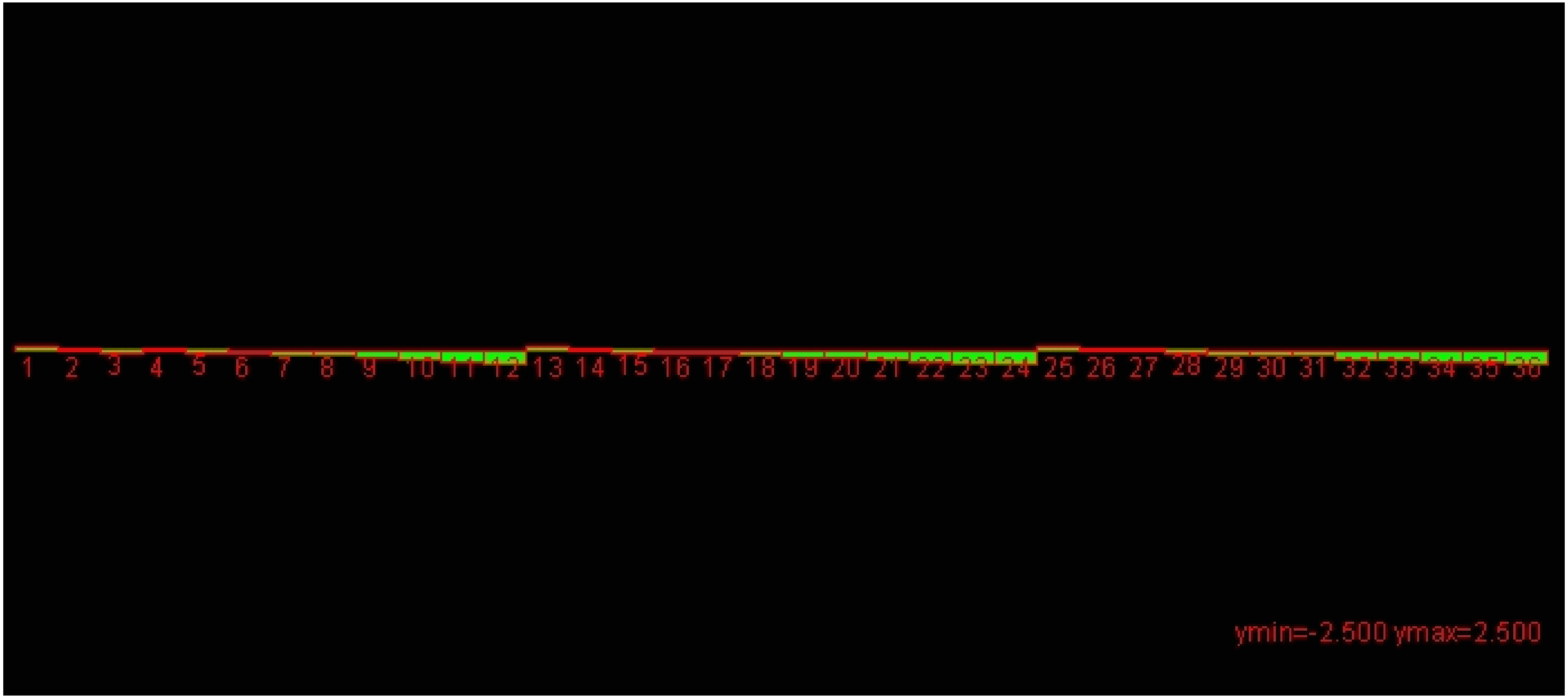
Vert: T:SBDPCS
Horz bunch #

Vert Scale: -2.5 to 2.5 ns

Motion of the Longitudinal Centroid in Blowup



What can we learn from this?

- It's probably a parasitic mode in the RF cavities.
- Which one? 311MHz is possibly a candidate. (Note we have 8 of them)
  - Since it is mode 1, it is not the fundamental because the Q=6500, df = 6kHz.
- Can I simulate this blowup? Yes I can

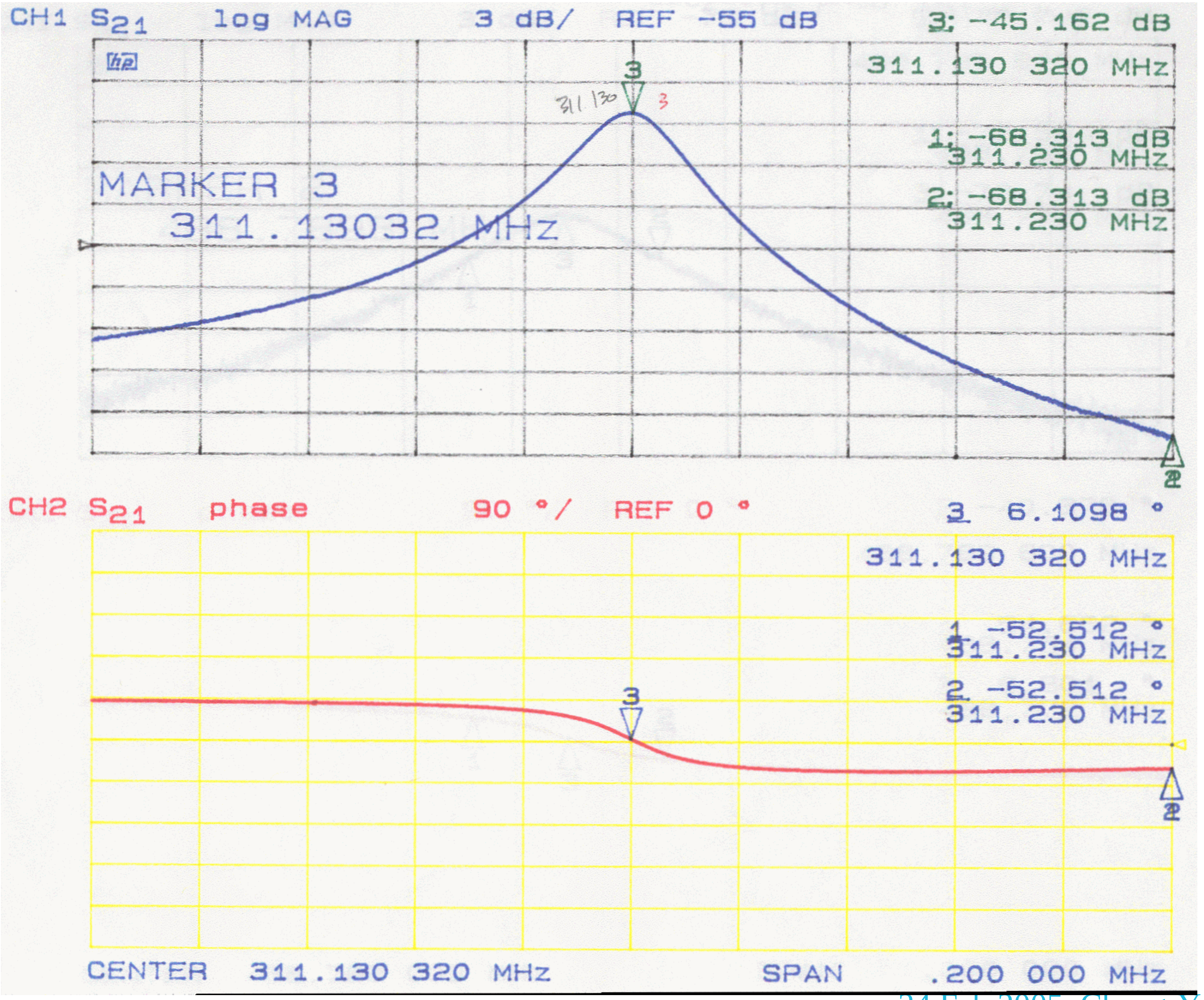
311 Mhz Parasitic Modes (07 Sep 2000)

311 Mhz cavity pickup

Station #	Mode centre Freq Mhz	Q	Rs
1	311.104	1.63E+004	124k
2	311.152	1.56E+004	124k
3	310.913	1.44E+004	124k
4	310.787	1.31E+004	124k
5	310.644	1.60E+004	124k
6	310.996	1.52E+004	124k
7	310.956	1.48E+004	124k
8	311.289	1.46E+005	124k

Note Q of 311MHz is LARGER than Q of 53MHz! Df of 311MHz is about 21kHz.
D. Sun measured the same Q in 25-27 Jan 1995. Rs measured by D. Sun.
In order to get the same time scale in the blowup, I had to lower Rs by factor of 10.

Example of 311MHz Parasitic Mode



Analytic & Simulation Parameters

- Make things simple to illustrate physics rather than detailed simulation.
- 1 mode selected: 310.996 Mhz.
  - Depends on cavity temperature.
- 36 point bunches at 980GeV.
- Change Rs so that blow up takes approximately the same time as observation. Need to reduce Rs by factor of 10.
  - Measured Q did not change between 1995 to 2000, so take that as constant. (Use loaded or unloaded Q? Factors of 2).

Analytic Solution

Growth rate for coupled bunch mode 1 is given by Ng's analytic formula (9.49) "Physics of Intensity Dependent Beam Instabilities".

$$\frac{1}{\tau_{1\mu}} = \frac{\eta e^2 N M \omega_r}{2\beta^2 E_0 T_0^2 \omega_s} Z_0\left(qM\omega_0 + \mu\omega_0 + \omega_s\right)$$

$\eta = 0.0029$ $N = 250\text{e}9$ $M = 36$

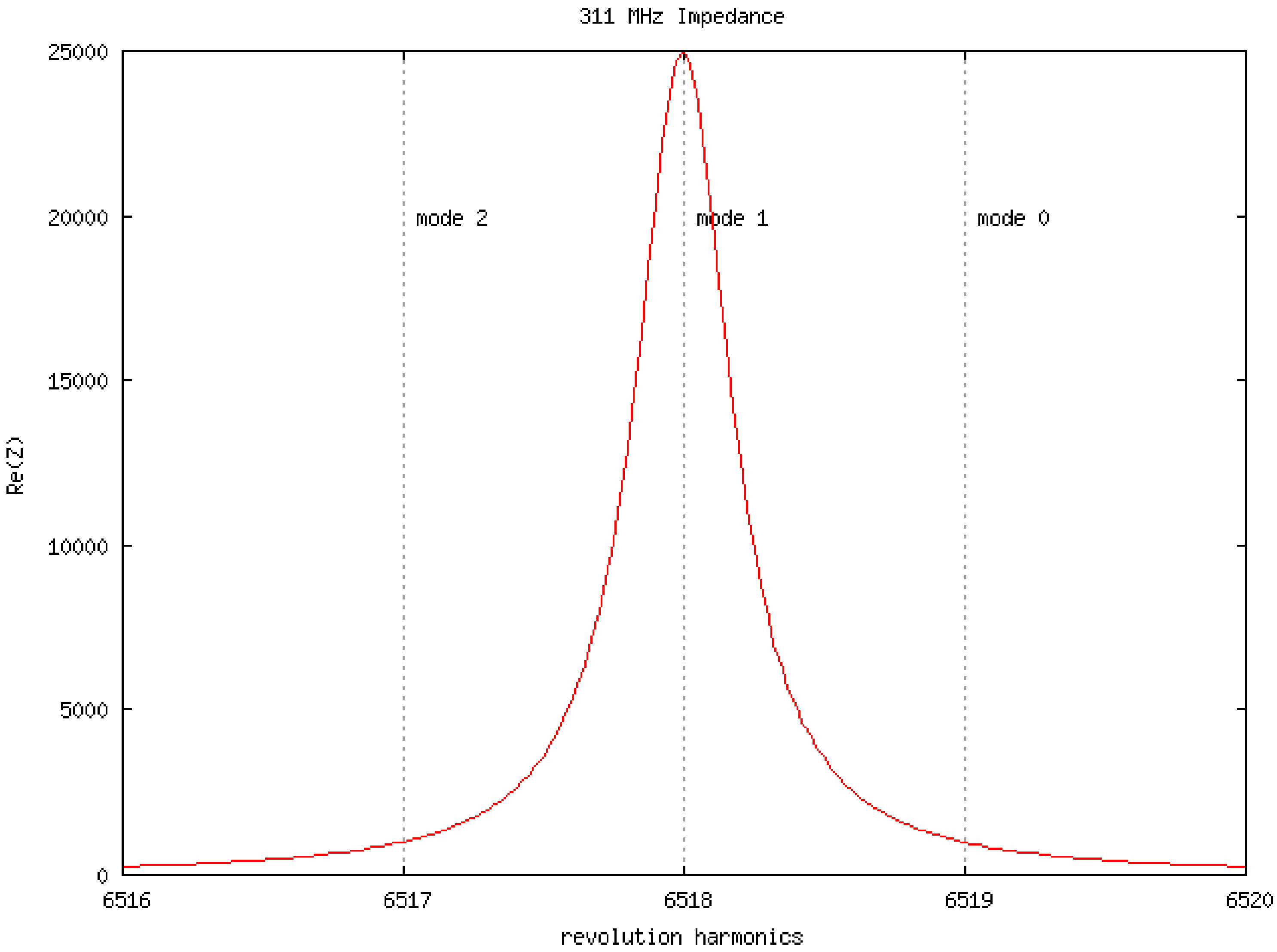
$\omega_r = \text{parasitic mode freq} = 2\pi\, 311\text{e}6\,\text{s}^{-1}$ $\beta = 1$ $E_0 = 980\,\text{GeV}$

$T_0 \approx 21\,\mu\text{s}$ $\omega_s = \text{synchrotron frequency} = 2\pi\, 34\,\text{s}^{-1}$

Result for 1 e-time is $\tau_{1\mu} = 0.25\,\text{s}$

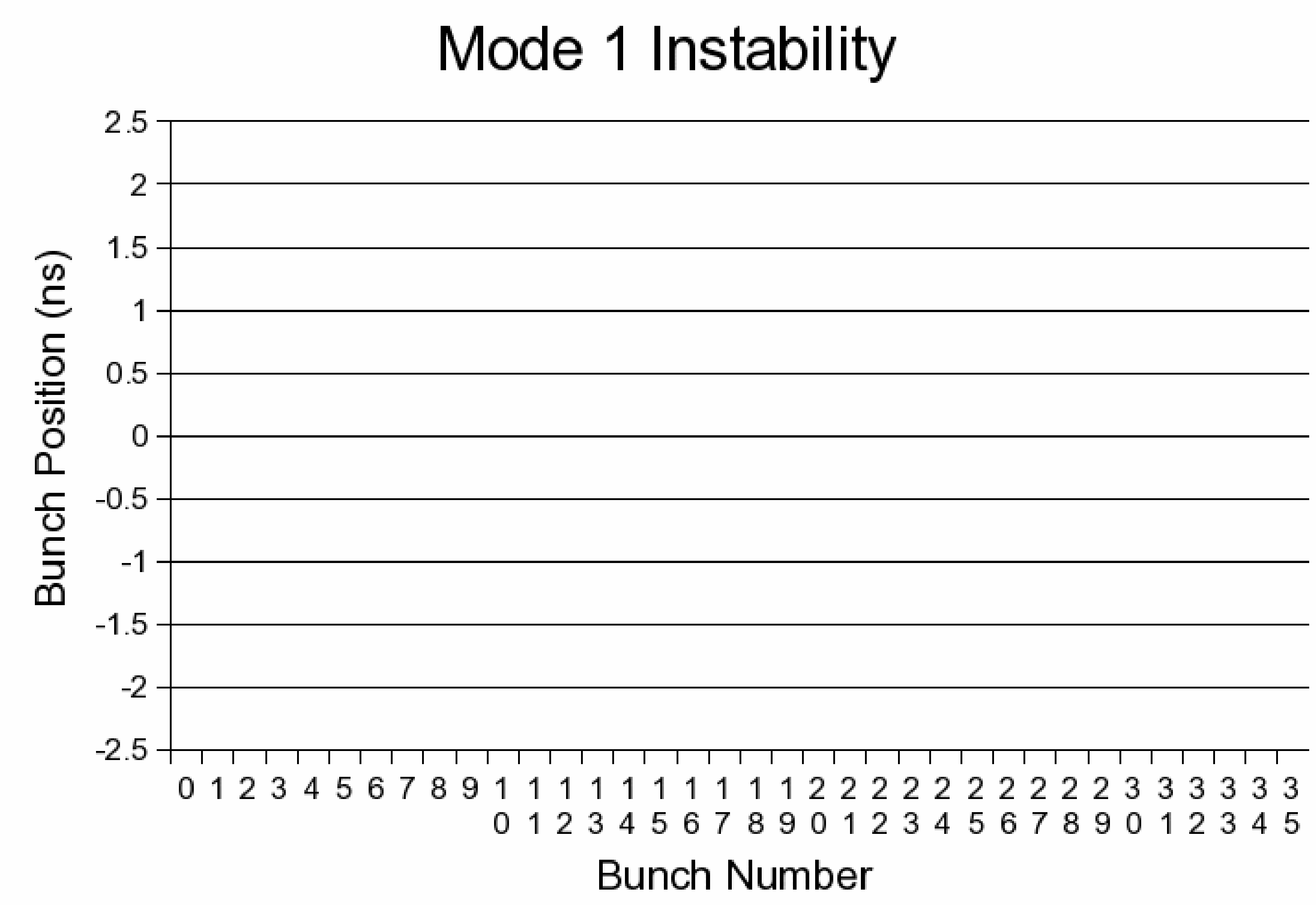
Solution with Rs=124k is too fast. Same as simulation. So reduce Rs by 10 and get idea of what's going on.

Why 310.996MHz?

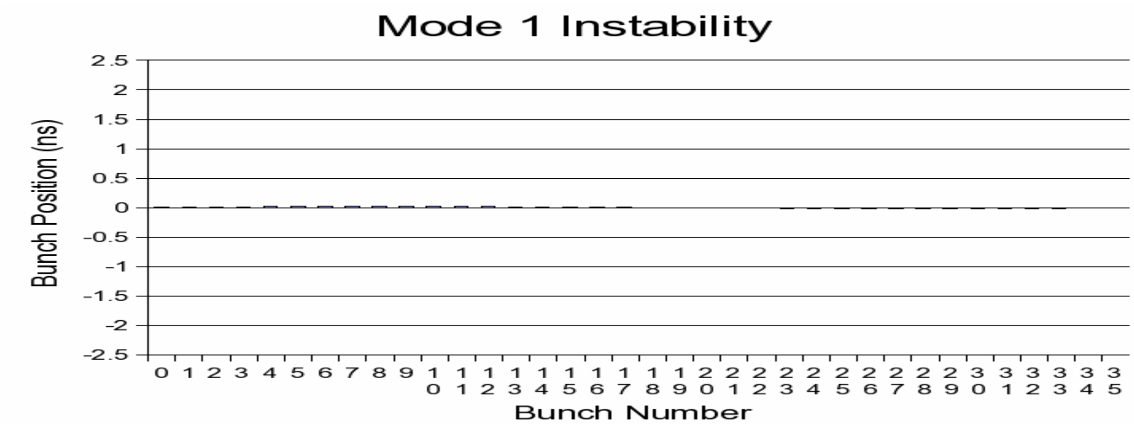


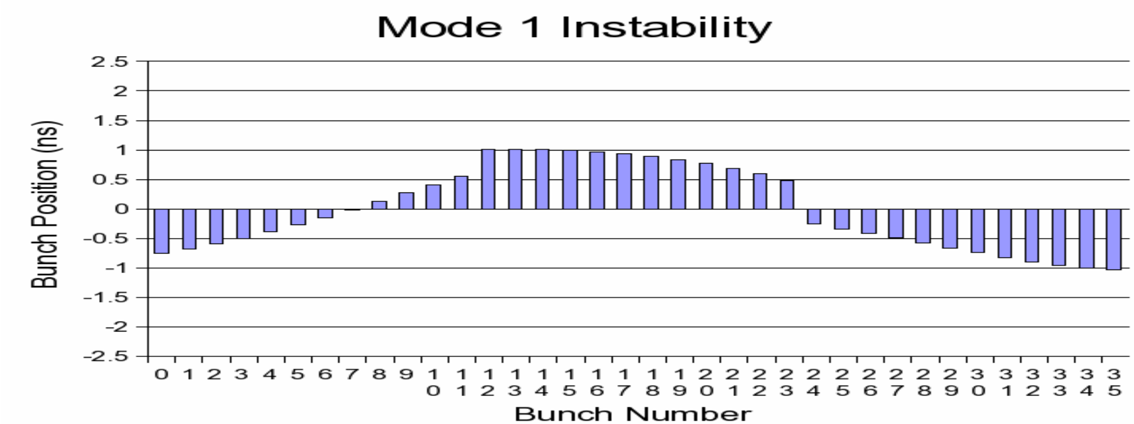
Difference between peak and rev harmonic: 2.7kHz. Peak is higher than rev harmonic which means unstable.

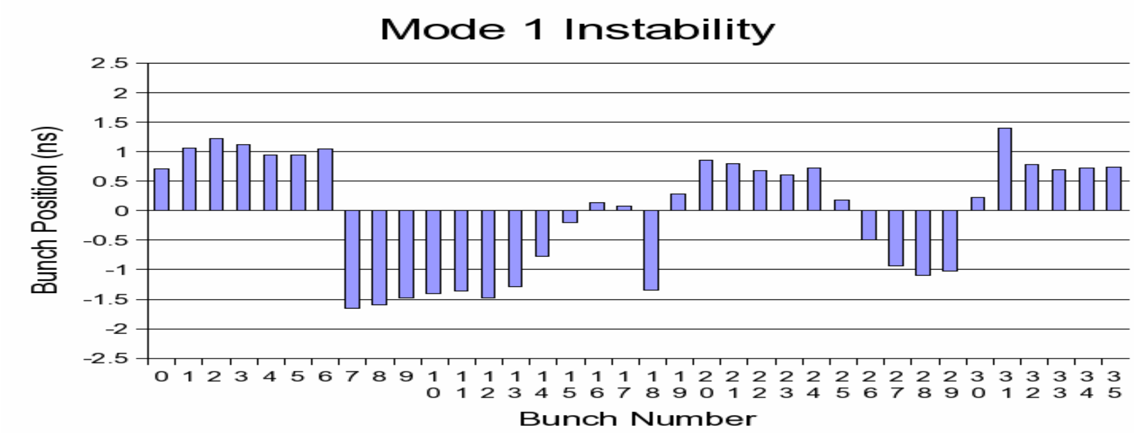
Blowup with Simulation



Simulation Results







Vert scale = +/- 2.5 ns

Horz = bunch #

Start of instability

t=0

t=8 seconds

T=15 seconds

Longitudinal Blowup Conclusion

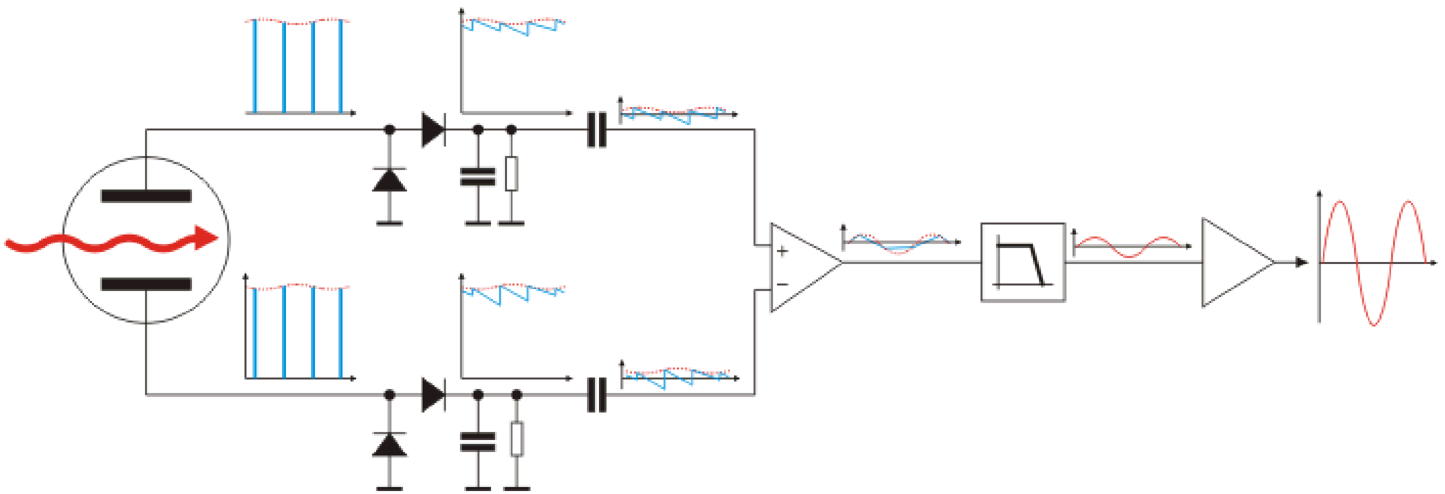
- The 311MHz mode is a good candidate for source of longitudinal instability.
- Simulations shows understanding to some level to a factor of 10.

Tevatron BBQ

What is the BBQ?

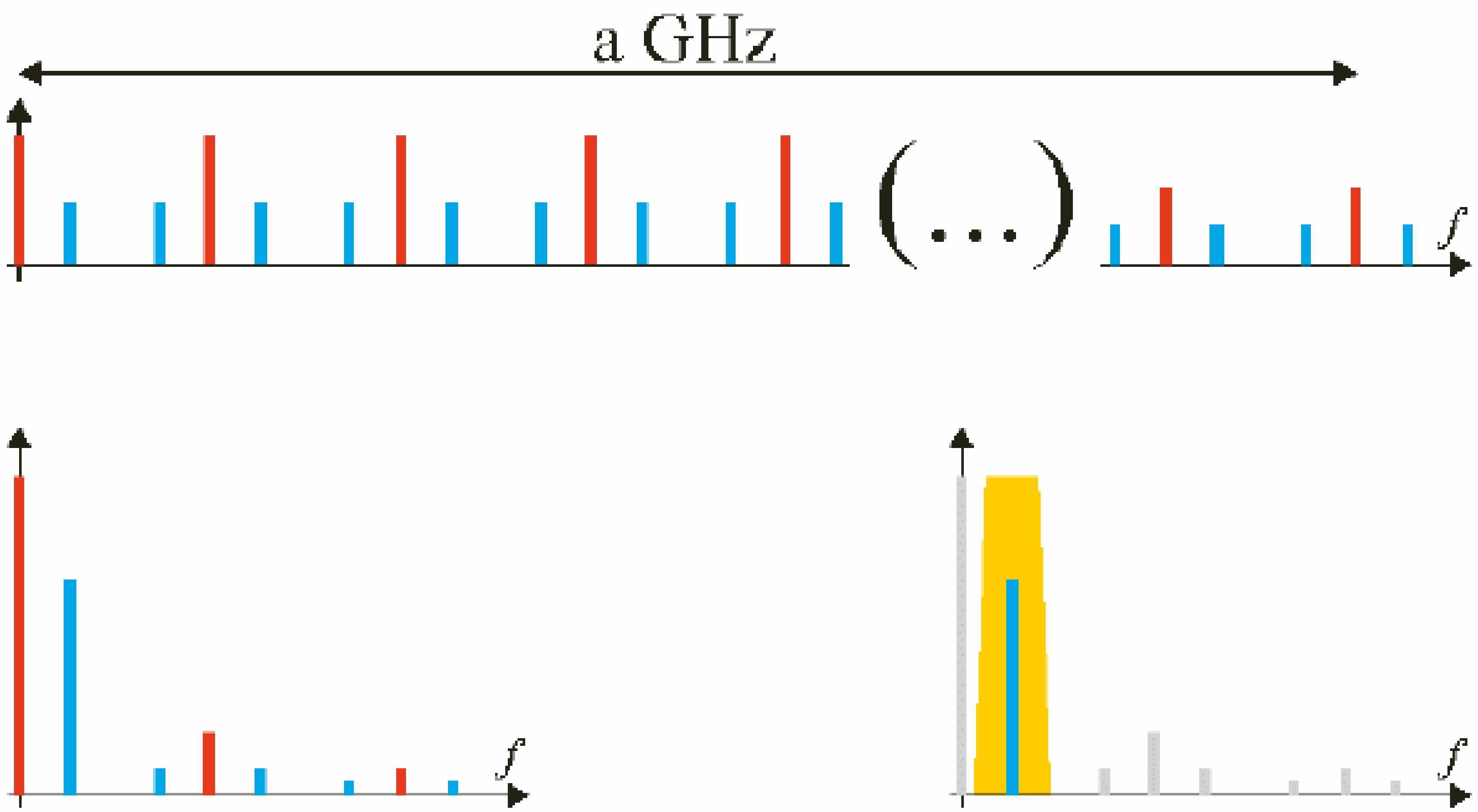
- BBQ stands for Baseband Tune.
  - A slight misnomer because “Baseband” doesn't mean baseband in the usual sense that we measure the tune below the 1st revolution harmonic. Rather it folds down tunes from 0 to 200MHz to baseband.
- Built/Invented by M. Gasior of CERN.
- Tested in the Tevatron as part of the US-LARP collaboration.
  - Installed in E0 using horz and vert stripline pickups

The BBQ Block Diagram (M. Gasior)



Basically an AM radio circuit with a lot of gain.
Note: because of the way the filter is made, measurement of tune is the one BELOW the ½ integer.

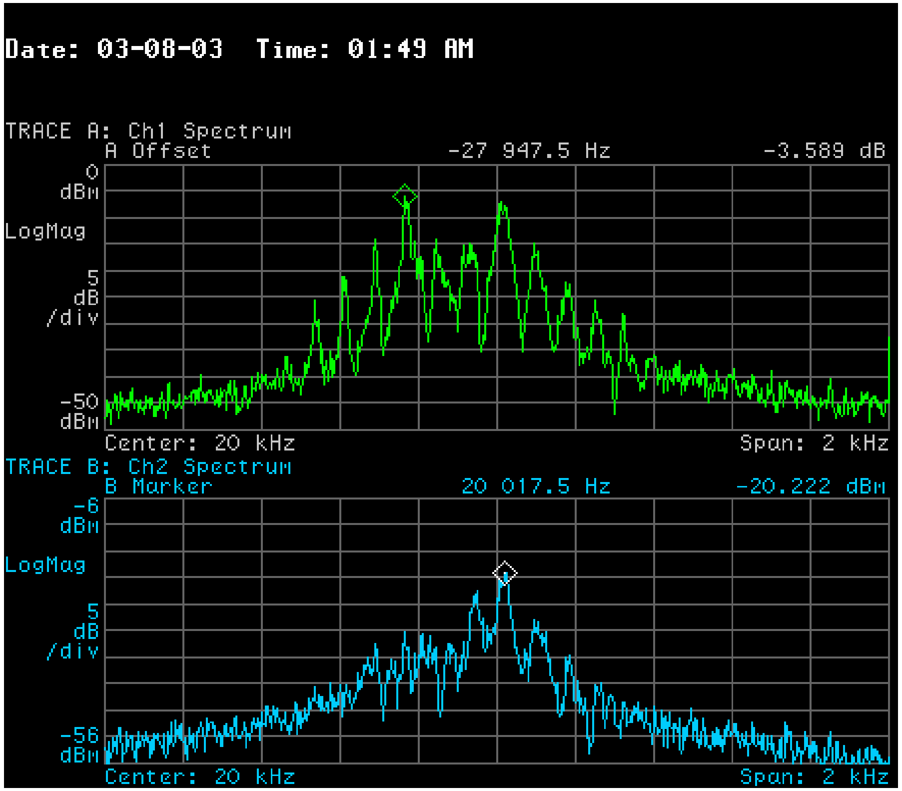
How it works (M. Gasior)

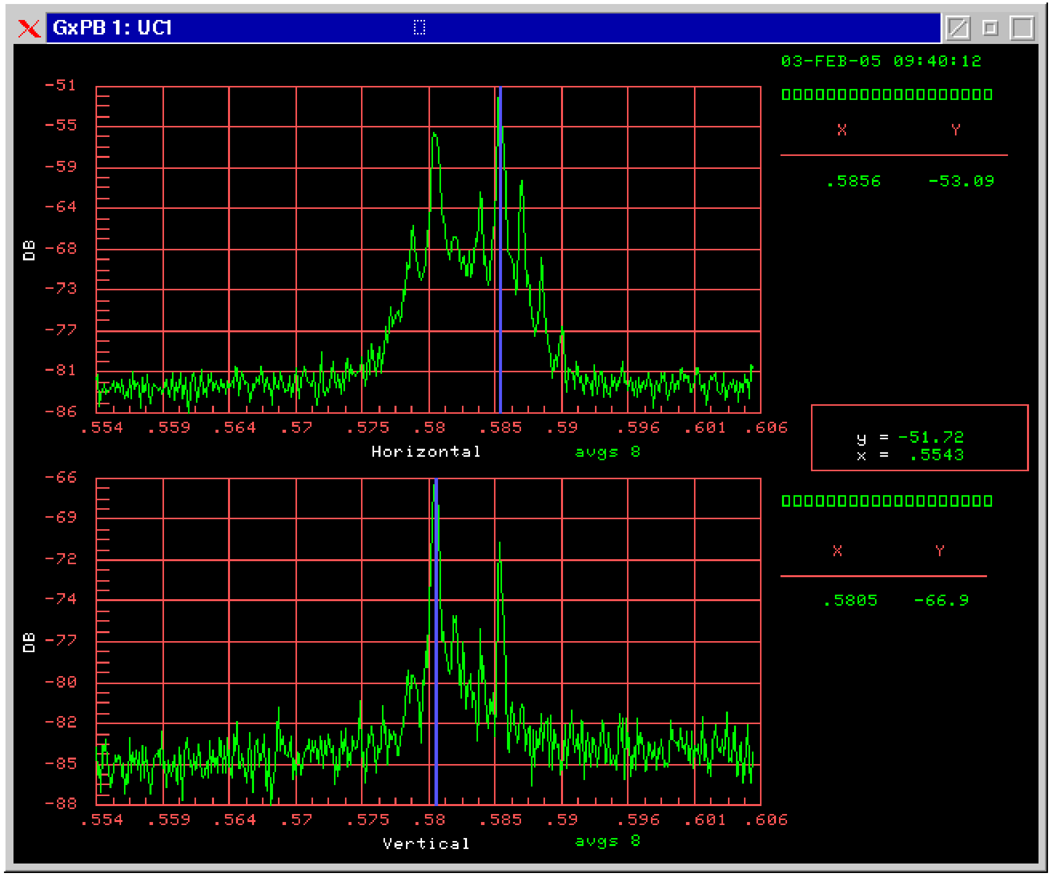


Some Notes on comparing BBQ with 21.4MHz Schottky

- The BBQ measures tune below the ½ integer
- The 21.4MHz Schottky measures tunes above the ½ integer
- This means the tunes should be mirror images around the revolution harmonic, i.e.
  - Q(Schottky) = 1- Q(BBQ)

Uncoalesced Beam (VTICK on) 150GeV

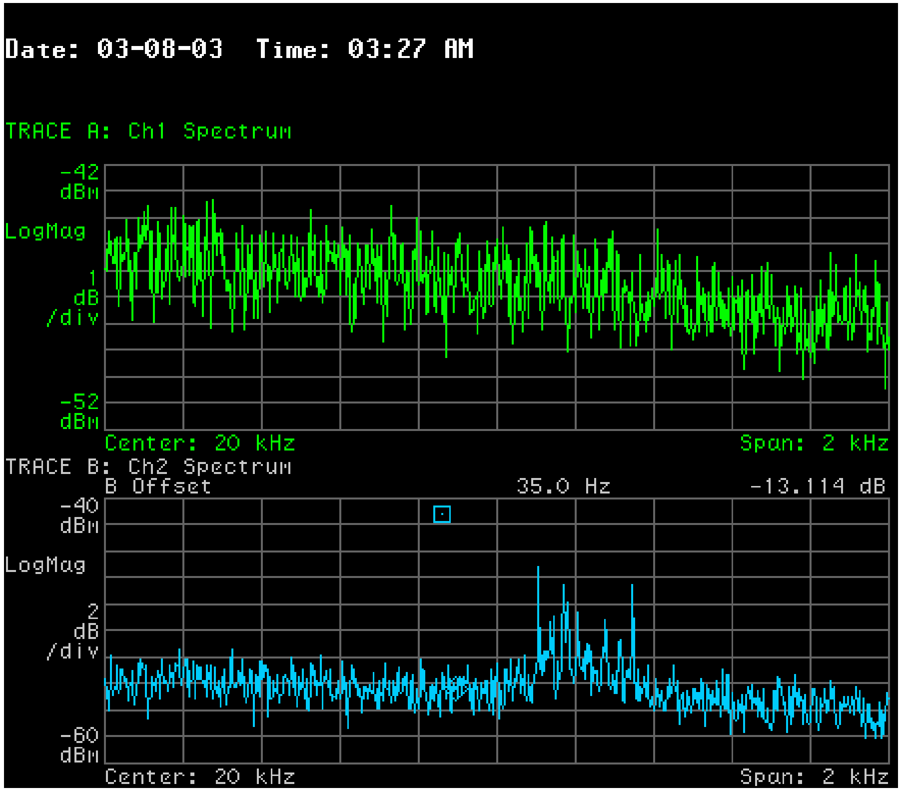


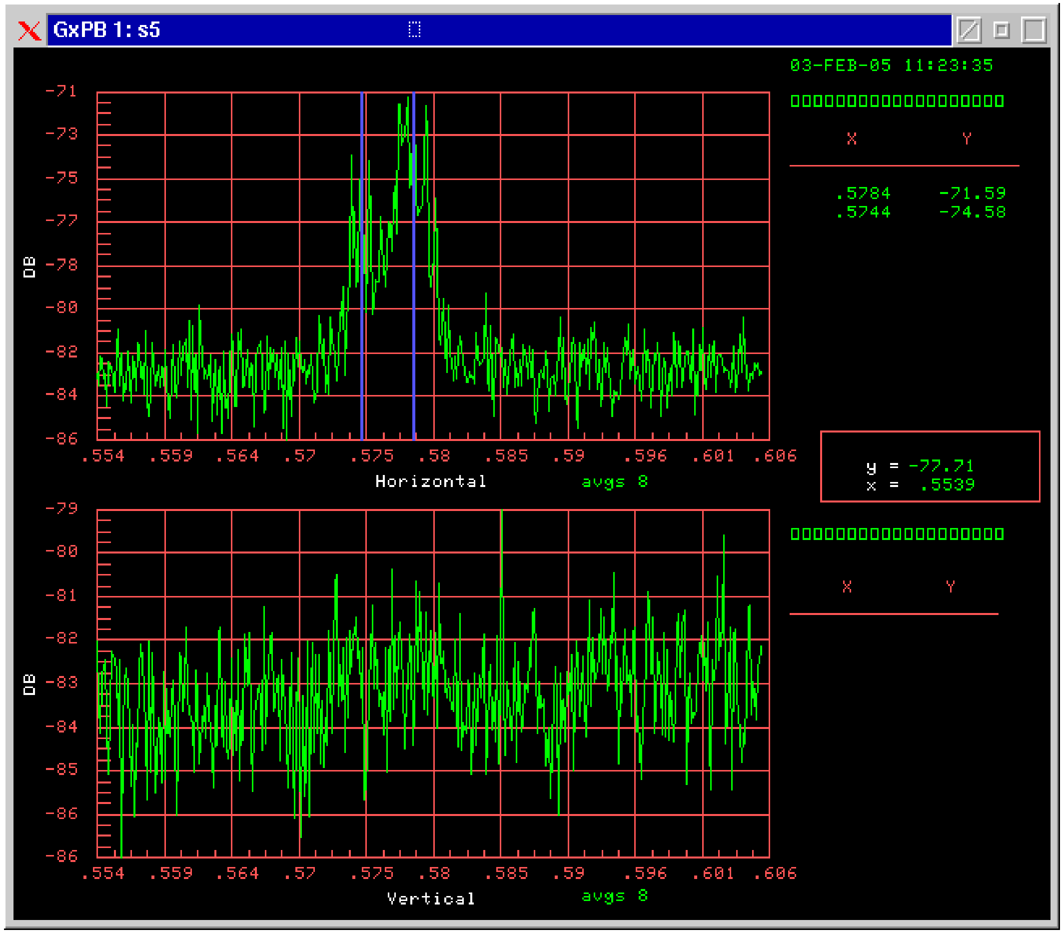


BBQ Qh = 0.5855
BBQ Qv = 0.5804

Schottky Qh = 0.5856
Schottky Qv = 0.5805

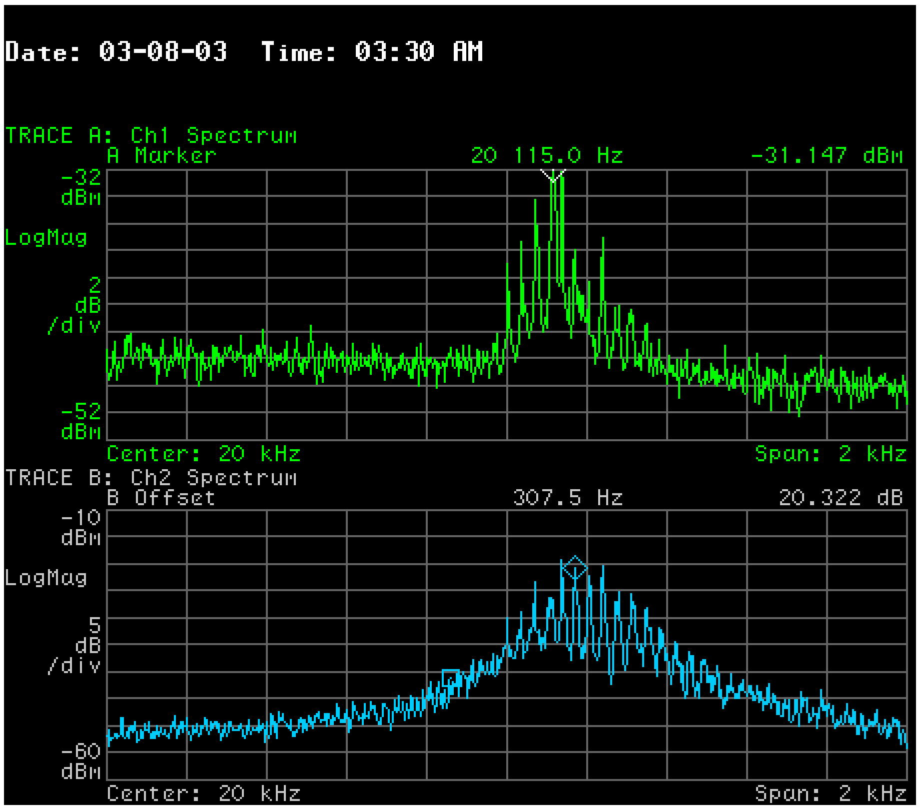
At low beta 4x0 (VTICK off)

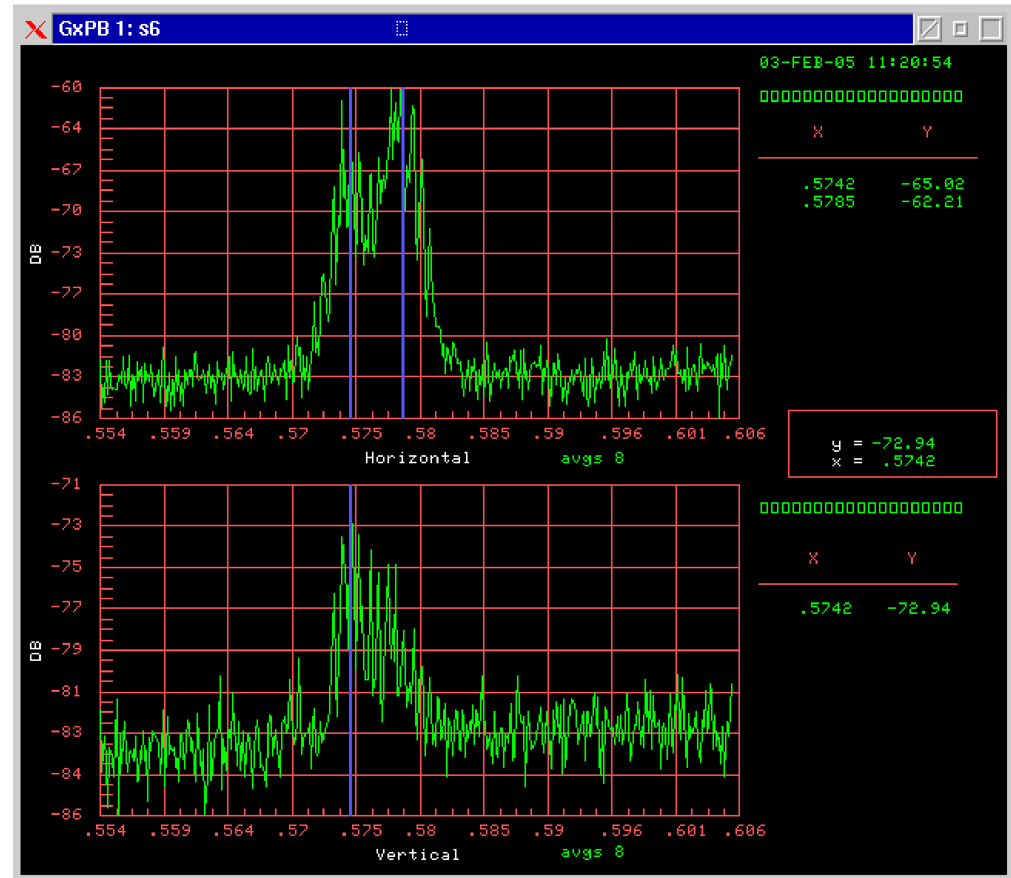




No signal from BBQ horz and Schottky vert. Beam hitting plates?

4x0 low beta (VTICK on)



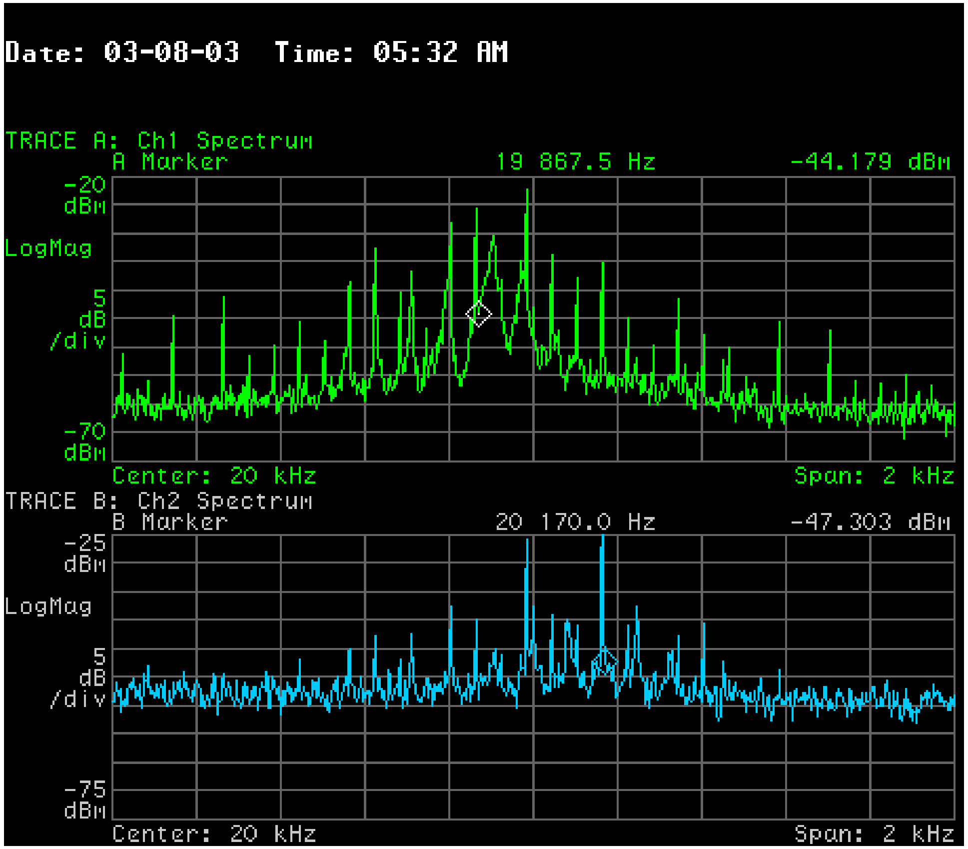


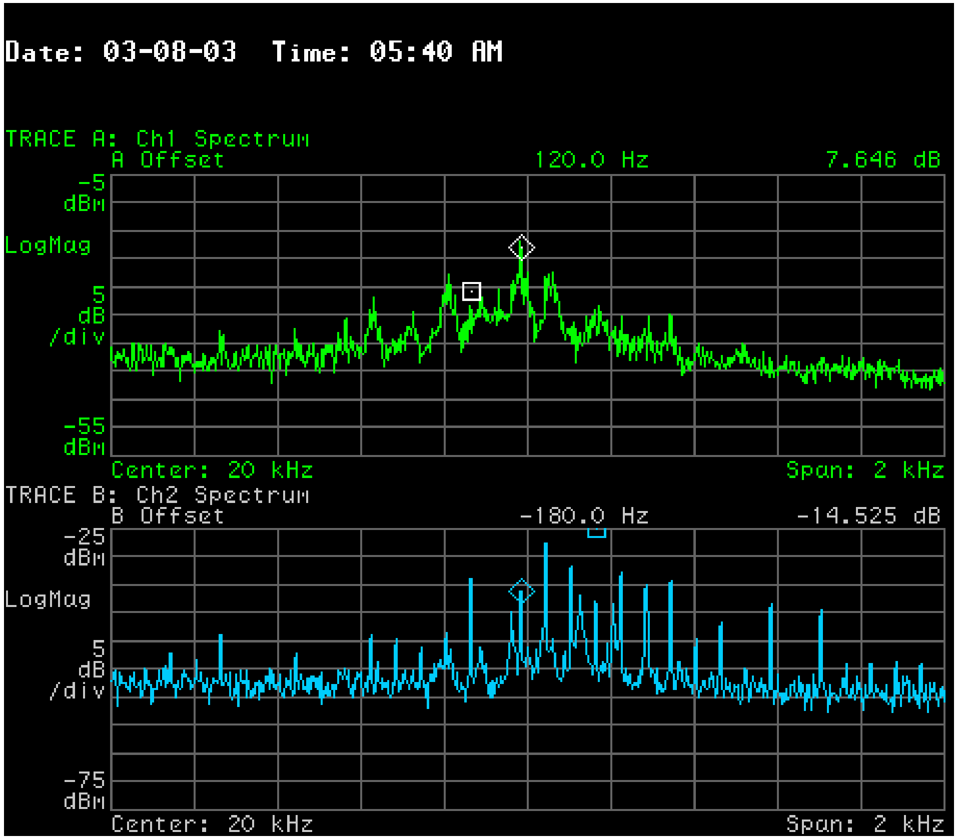
BBQ Qv=0.5784

Schottky Qv=0.5785

Note differences in shape.

36x0 at 150GeV (VTICK off)



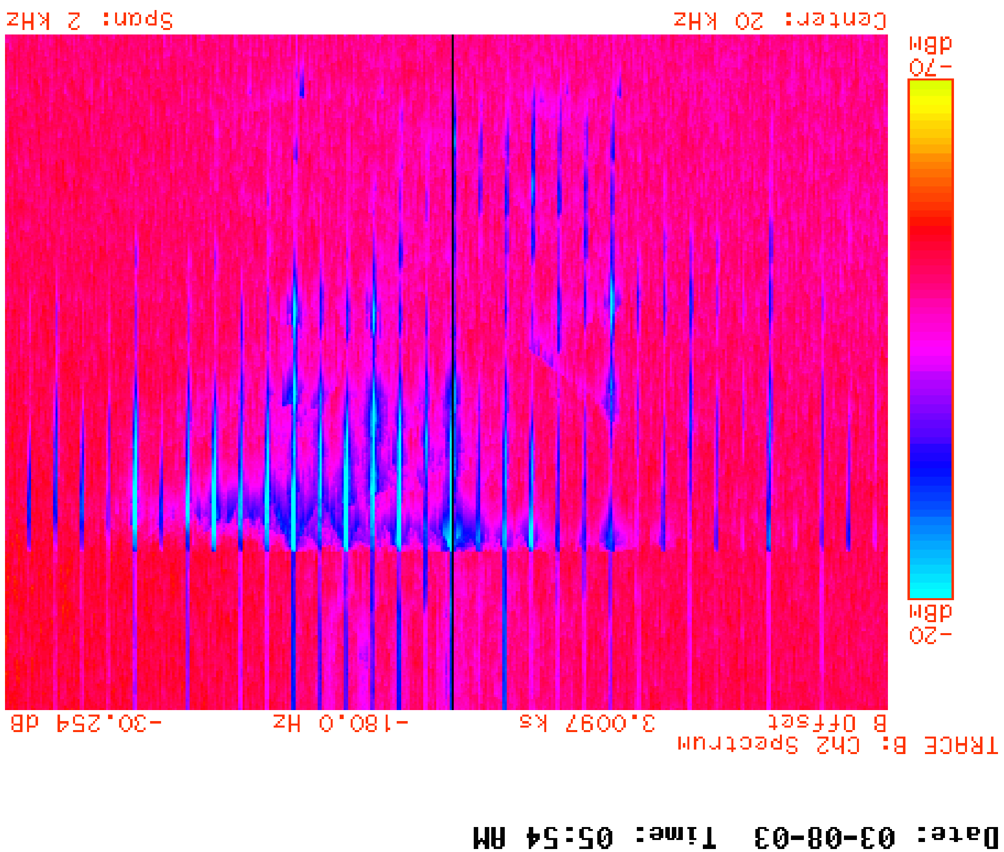


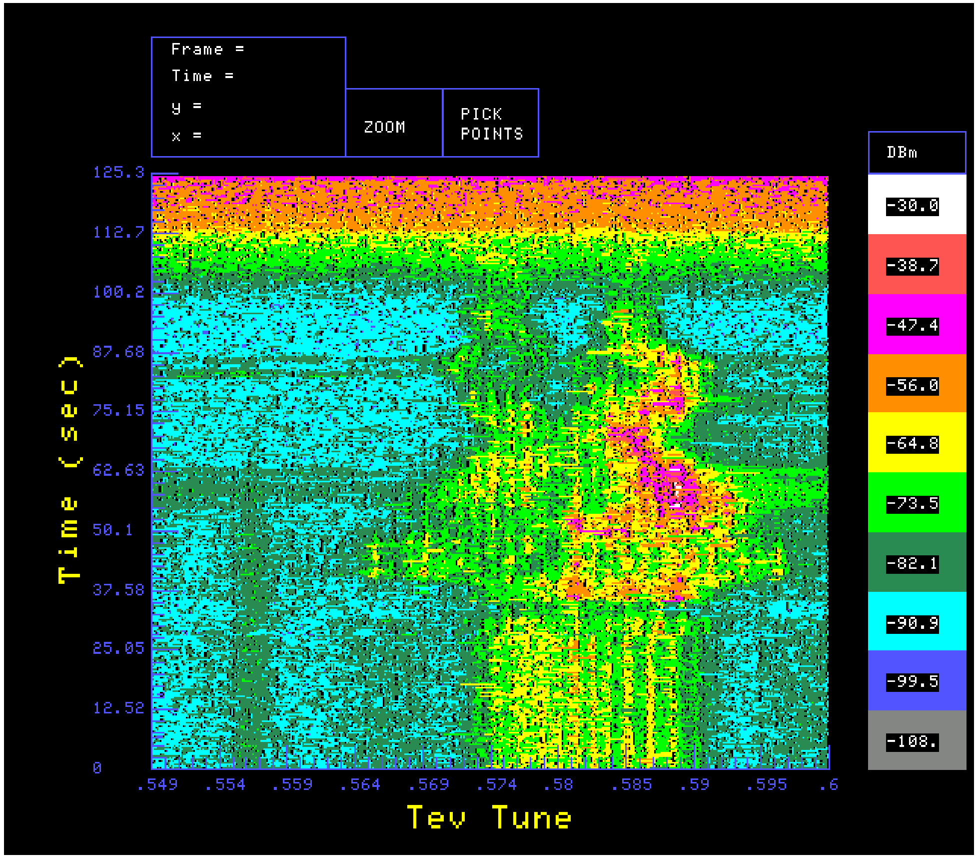
Helix off

Helix on

Note: 60Hz lines disappears on helix for horz but not vert. Vert pos changes by approx -4mm and horz by +3mm.Electronics?

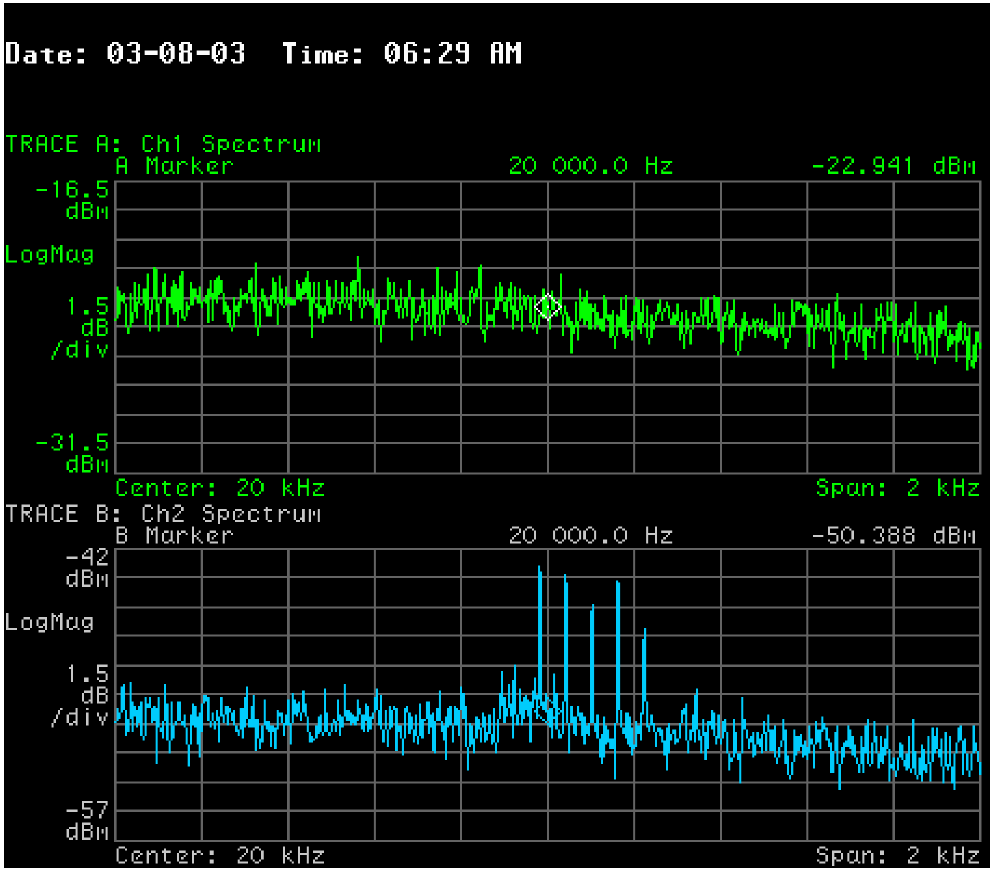
36x36 going up the ramp

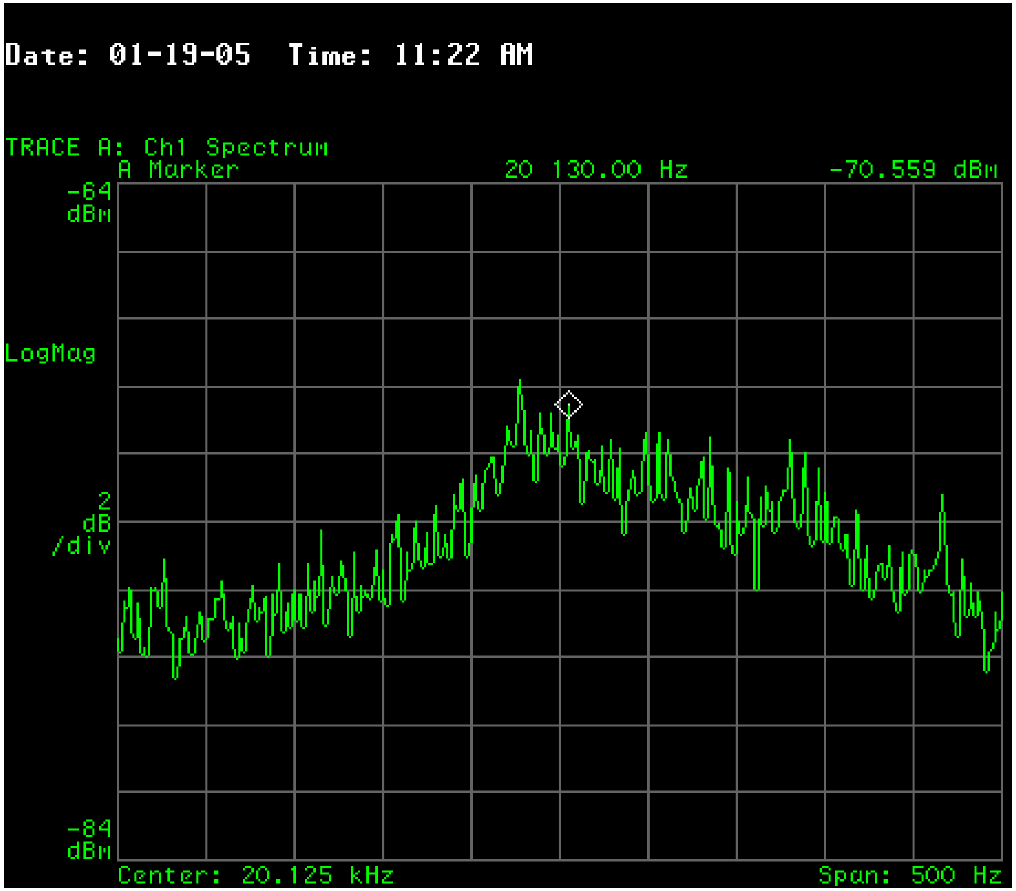




Going up the ramp, BBQ dominated by 60Hz lines

36x36 low beta

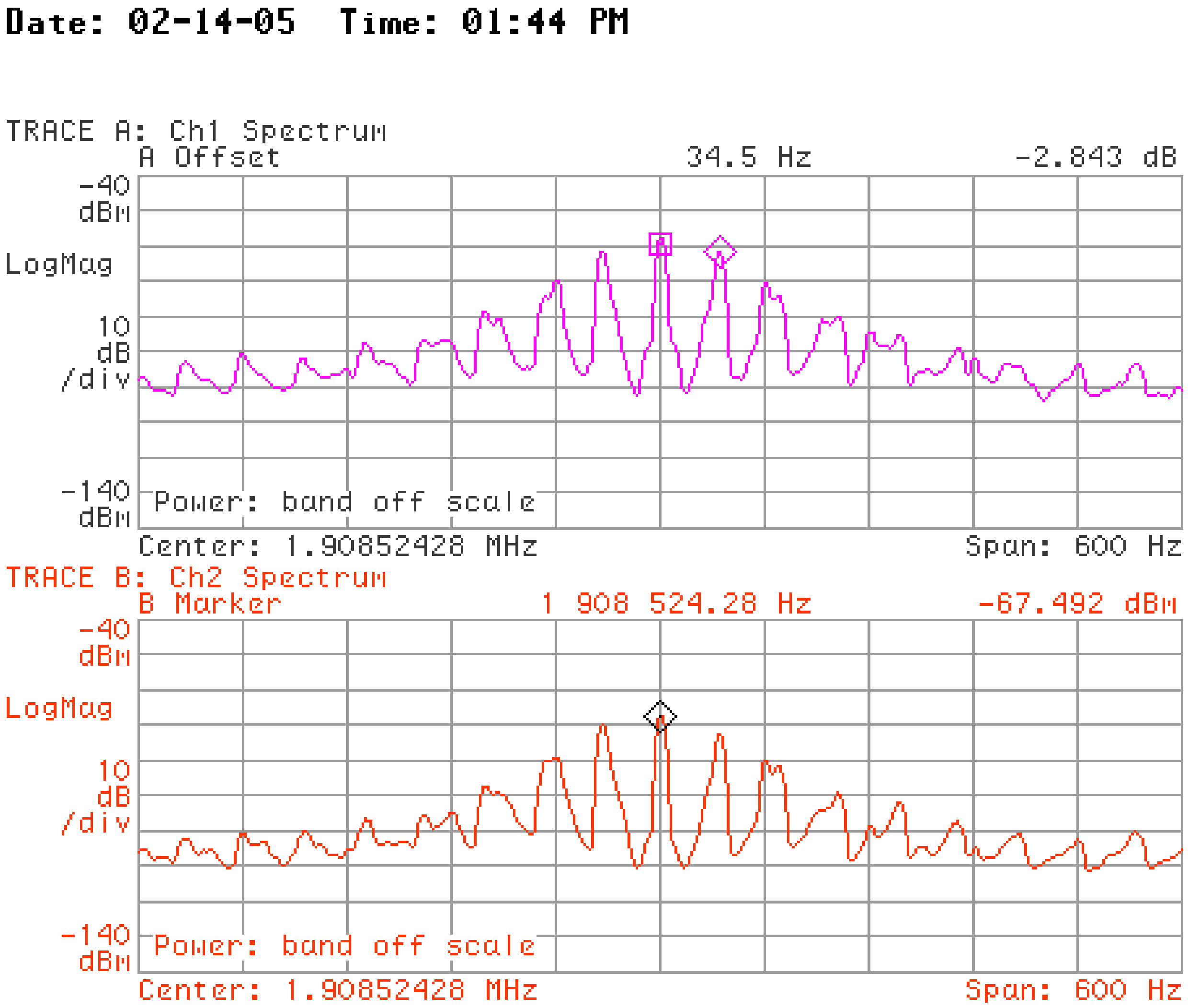




Strong 60Hz lines at the start of store.

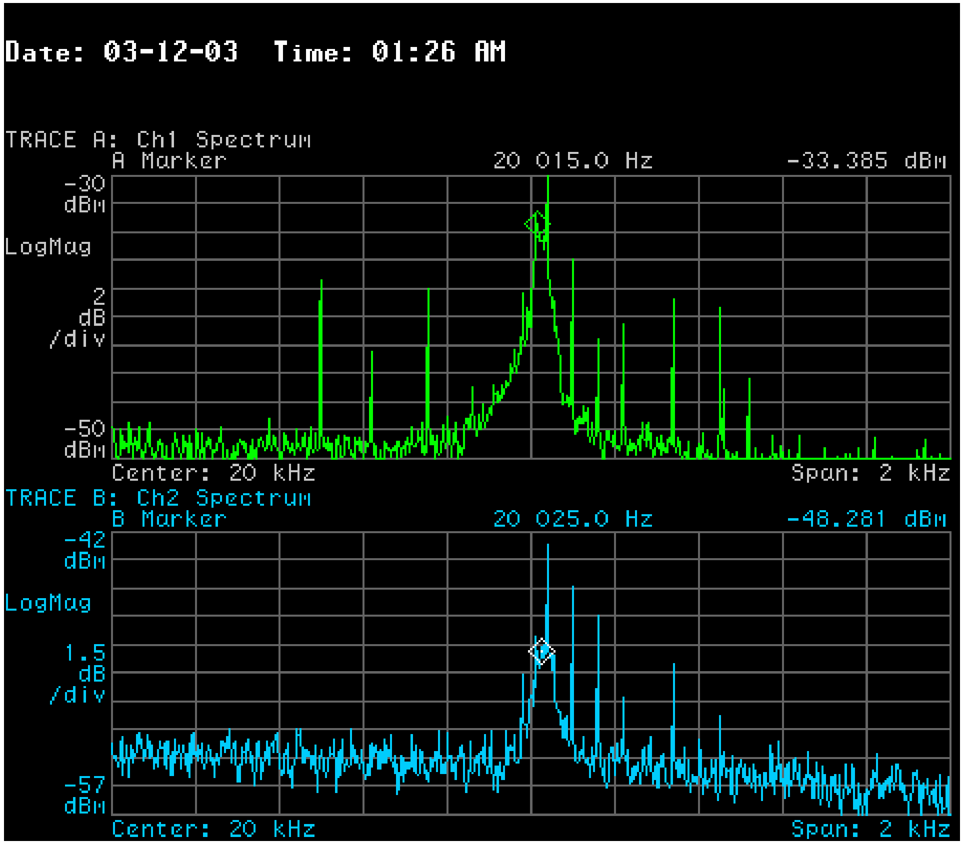
Not seen on 21.4MHz Schottky. Note: 8000e9 protons

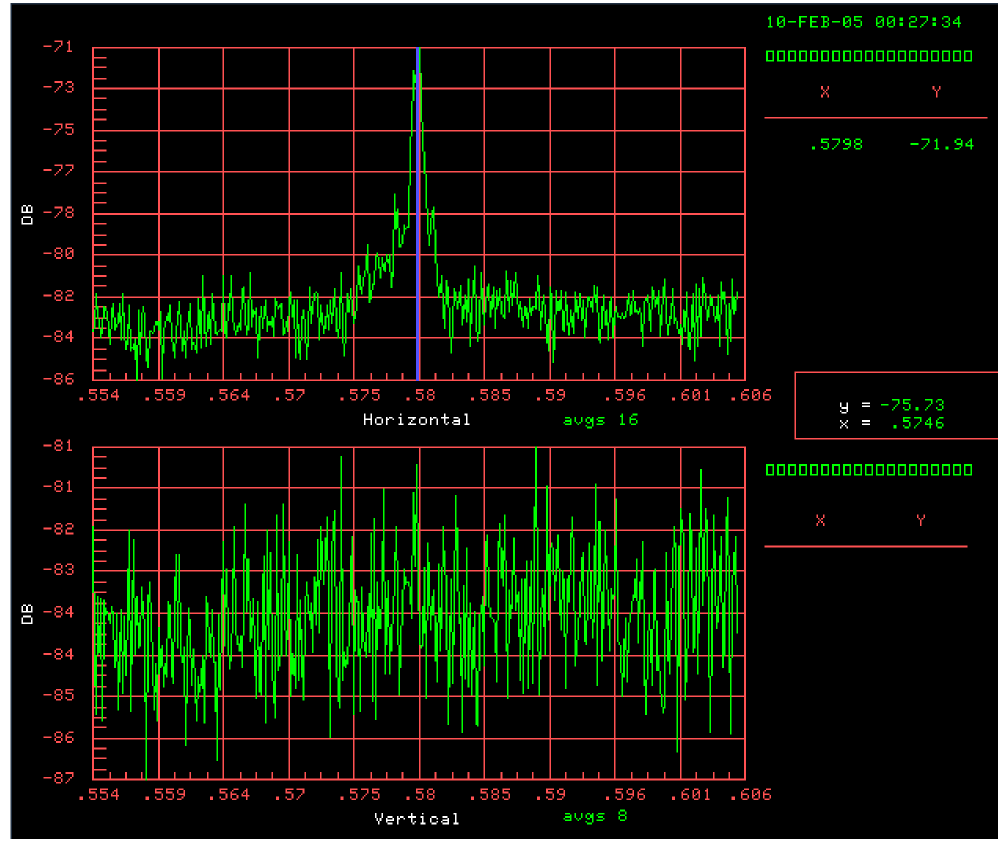
Looking at 1.7GHz (BW 100MHz)



60Hz comparable in size to synchrotron tune (each box is 60Hz)

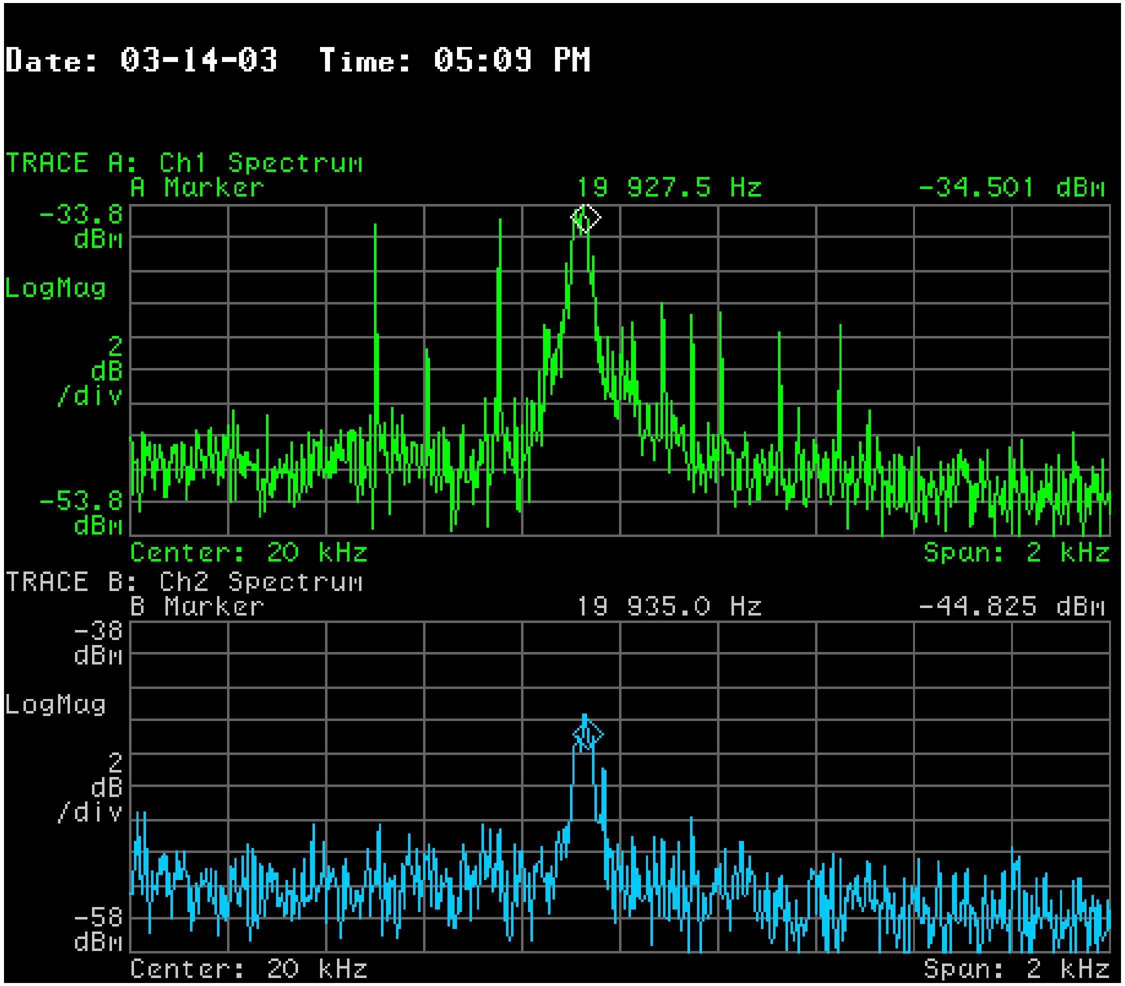
36x36 low currents (EOS)





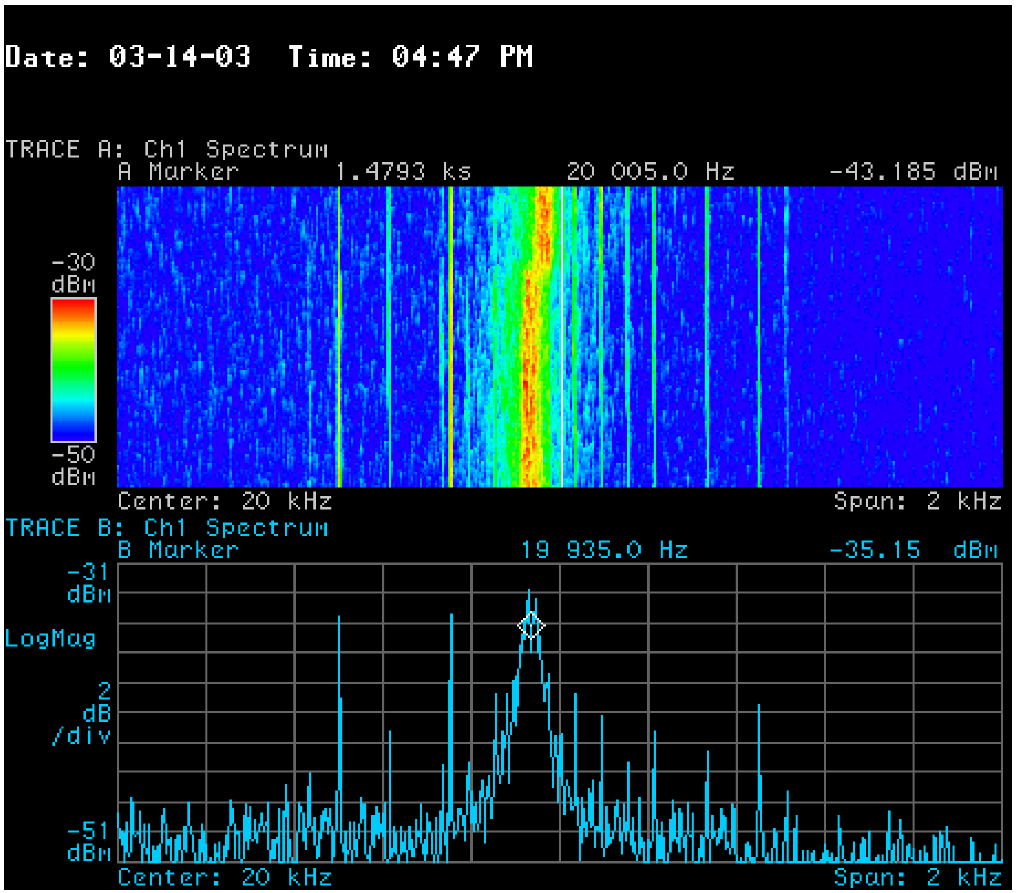
But with low currents 6300e9 protons, Qh and Qv seens clearly. BBQ electronics saturation for higher beam currents?
Note shape of tune and 60Hz lines (some lines got 1.5dB smaller). Noise Floor became better by about 3 to 4.5dB

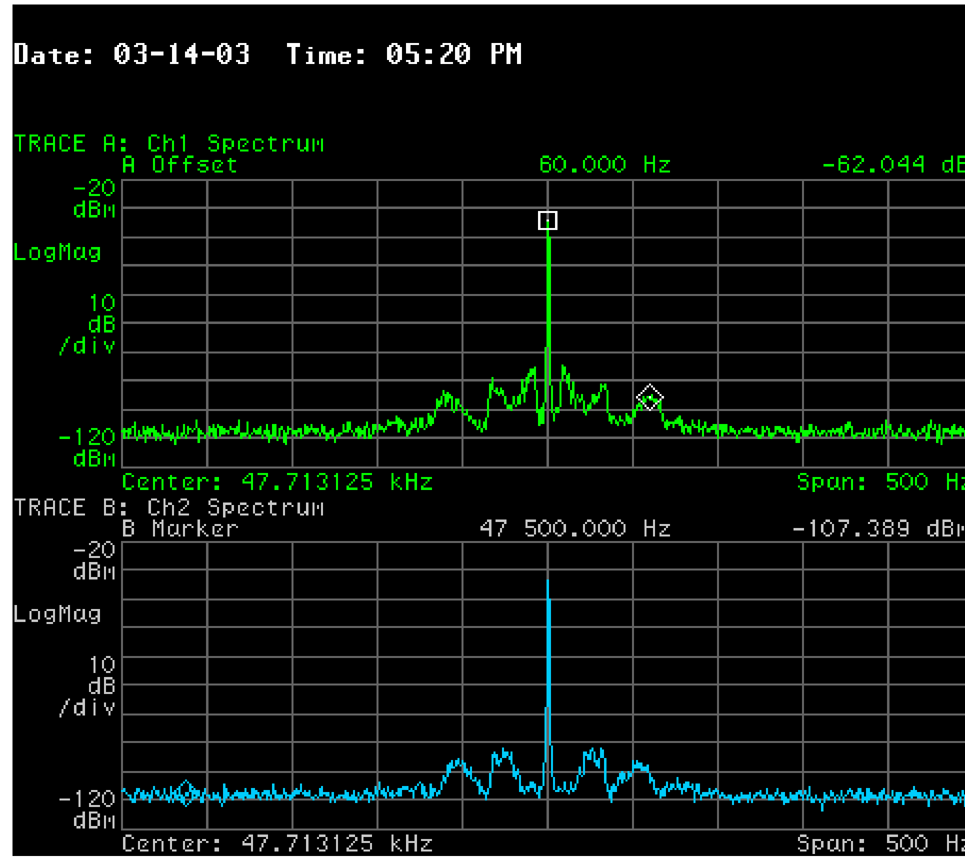
60Hz and tune position



Note disappearance of 60Hz in vert!

60Hz Characteristics

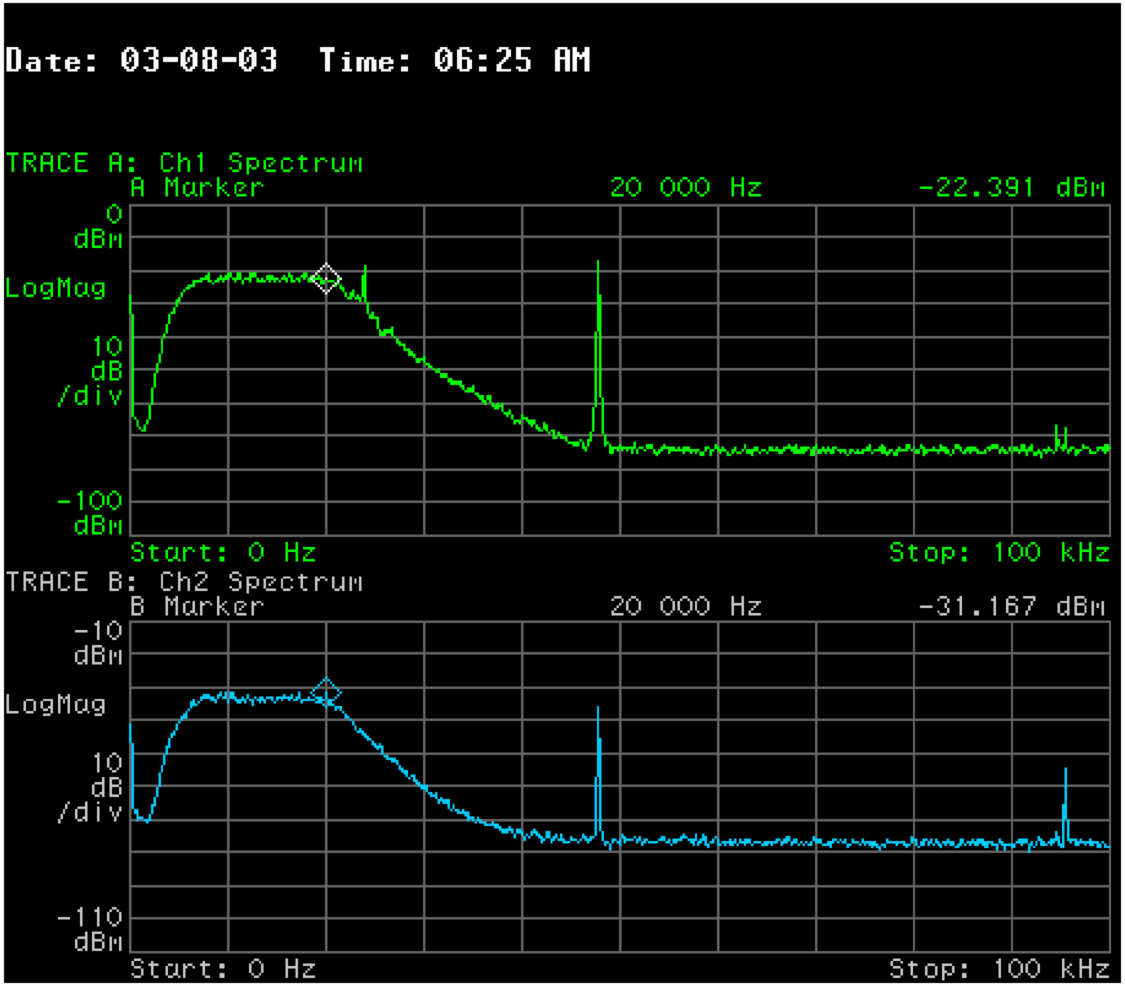




60Hz does not move when the tune moves.

No 60Hz around revoltution harmonics

½ frev (how?)



Indications of nonlinearity or saturation

BBQ Conclusion

- BBQ does measure tune
- It has 60Hz problems
  - Source beam or electronics? Probably electronics but not cables. Note that RHIC sees 60Hz in all their instruments
    - Depends on beam position.
    - Depends on tune position.
    - Bunch length?
    - Not seen in 21.4MHz or 1.7GHz Schottkys
  - ½ frev indicates nonlinearity and saturation.
- Needs more work on the bench.

Calculating β* and crossing angles

Calculating β* and crossing angle

- Motivation is that the luminosity measured by CDF and D0 are different by as much as 15%
  - Can this be explained by different β* or crossing angles at the experiments?

Use Stores with RF trips

- Use stores 3873 and 3876 which had TRF1 trips which caused bunch lengthening and loss in luminosity which allows us to calculate the following:
  - Expected luminosity loss from theory.
  - β^* from data.
  - Relative crossing angles between CDF and D0
- Store 3873 had TRF1 trip near middle of store.
- Store 3876 had TRF1 trip near the start of store.

Theory

Start with usual luminosity formula with the usual definitions of variables:

$$L = \frac{10^{-5} f\, B\, N_p N_{\bar{p}} (6\beta_r \gamma_r)}{2\pi\beta^* \sqrt{(\epsilon_p + \epsilon_{\bar{p}})_x (\epsilon_p + \epsilon_{\bar{p}})_y}} H(\beta^*, \sigma_p, \sigma_{\bar{p}})$$

$L = \text{luminosity}$ $\quad N_p = \text{num protons}$ $\quad N_{\bar{p}} = \text{num pbars}$

$B = 36$ $\quad f = 47.7\,\text{kHz}$ $\quad \beta_r \gamma_r = 1045 @ 980\,\text{GeV}$

$\beta^* \approx 35\,\text{cm}$ $\quad \epsilon_p = \text{proton emit.}$ $\quad \epsilon_{\bar{p}} = \text{pbar emit.}$

$H = \text{hourglass factor}$ $\quad \sigma_p = \text{proton bunch length}$ $\quad \sigma_{\bar{p}} = \text{pbar bunch length}$

Theory (cont'd)

Use phenomenological model from V. Shiltsev and V. Lebedev for *H*:

$$\begin{aligned} H(\beta^*, \sigma_p, \sigma_{\bar{p}}) &= \frac{1}{(1+a z^2)^{1/3}} \\ z^2 &= \frac{\sigma_p^2 + \sigma_{\bar{p}}^2}{2\beta^{*2}} \\ a &= 1.32 \end{aligned}$$

Can show that:

$$\frac{\Delta L}{L} = \frac{\Delta H}{H} = -\frac{1}{3} \frac{a(\sigma_p \Delta\sigma_p + \sigma_{\bar{p}} \Delta\sigma_{\bar{p}})}{\beta^{*2}(1+a z^2)}$$

Theory (cont'd) crossing angle

- If we assume round beams i.e. $(\epsilon_p+\epsilon_{\bar{p}})_x=(\epsilon_p+\epsilon_{\bar{p}})_y=\epsilon$
- It can be shown that

$$\delta L=(\Delta L_m-\Delta L_c)=-\Delta\sigma_z\frac{k}{\beta^{*4}\epsilon^2}\times\frac{3\beta^{*2}+a\sigma_z^2}{6\left(1+\frac{a\sigma_z^2}{2\beta^{*2}}\right)^{4/3}}\delta\theta^2$$

$$\begin{aligned}\Delta\sigma_z &= \Delta(\sigma_p+\sigma_{\bar{p}})\\ k &= 10^{-5} f\,B\,N_p N_{\bar{p}}(6\beta_r\gamma_r)/2\pi\\ \delta\theta &= \text{crossing angle}\end{aligned}$$

$$\begin{aligned}\Delta L_m &= \text{measured luminosity}\\ \Delta L_c &= \text{calculated luminosity}\end{aligned}$$

Theory (cont'd)

- If we assume β* are equal at both IPs we can show that

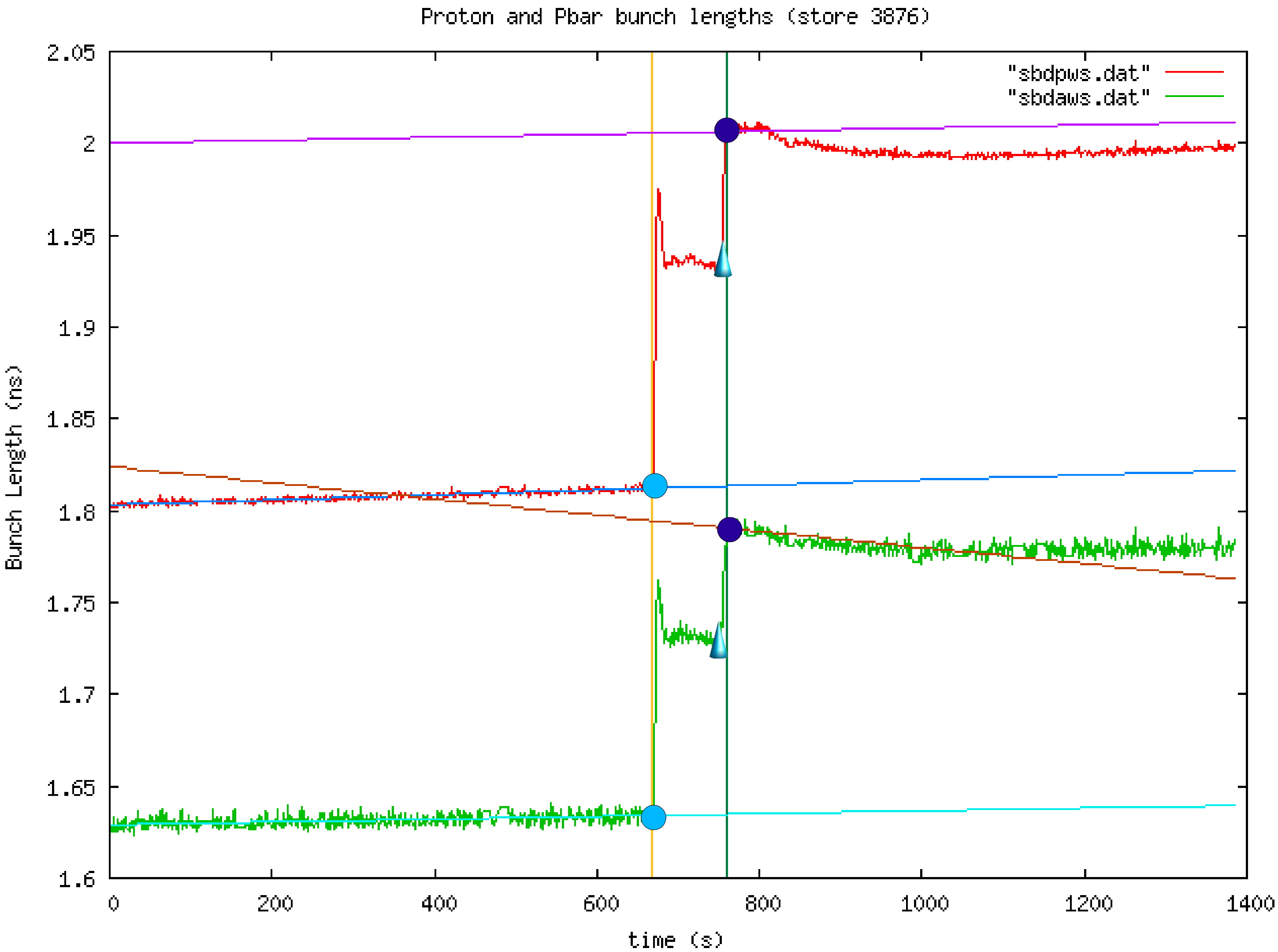
$$\frac{\delta L_{CDF}}{\delta L_{D0}} = \left(\frac{\delta \theta_{CDF}}{\delta \theta_{D0}} \right)^2$$

This will enable us to find the relative size of the crossing angle between CDF and D0 from the difference in measured and calculated ΔL.

What can be calculated from ΔL

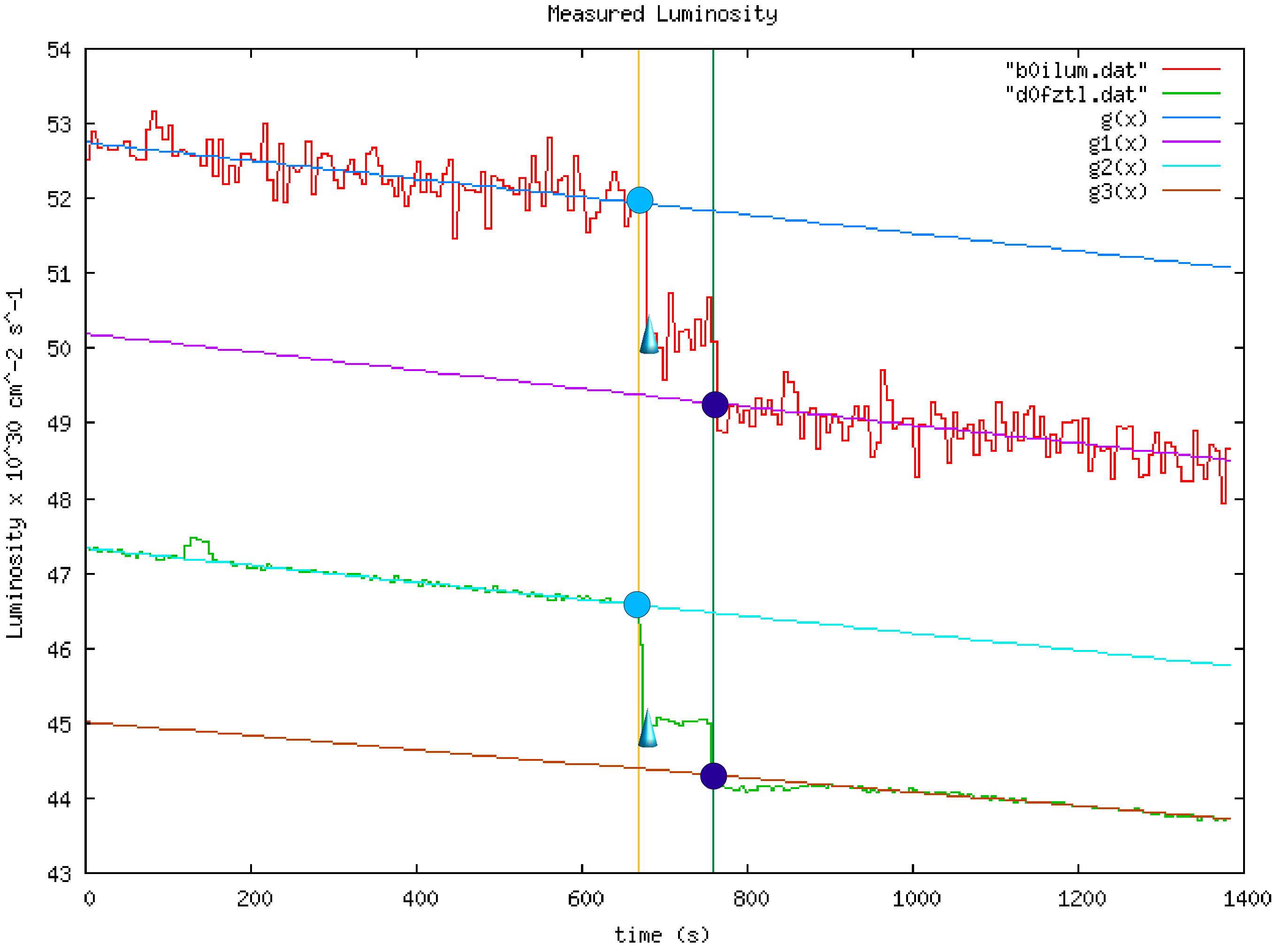
- If we assume β* = 35 cm then we can calculate the expected loss in luminosity at both experiments from knowledge of $\sigma_p, \Delta\sigma_p, \sigma_{\bar{p}}, \Delta\sigma_{\bar{p}}$
  - From difference between ΔL measured and calculated, we can have handle on relative crossing angles at CDF and D0.
- If we assume that CDF and D0 measures ΔL correctly, then we can calculate β* from knowledge of $\Delta L, \sigma_p, \Delta\sigma_p, \sigma_{\bar{p}}, \Delta\sigma_{\bar{p}}$

Data from Store 3876



Tan

Data from Store 3876



Results from store 3876 • → •

Measured Before TRF1 trip

$$\sigma_p = 1.8122 \pm 0.0001\,\text{ns}$$
$$\sigma_{\bar{p}} = 1.634 \pm 0.0002\,\text{ns}$$
$$L_{CDF} = (51.94 \pm 0.02) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$$
$$L_{D0} = (46.577 \pm 0.002) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$$

Measured after TRF1 trip

$$\Delta\sigma_p = 0.1958 \pm 0.0004\,\text{ns}$$
$$\Delta\sigma_{\bar{p}} = 0.1558 \pm 0.0008\,\text{ns}$$
$$\Delta L_{CDF} = (-2.67 \pm 0.03) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$$
$$\Delta L_{D0} = (-2.316 \pm 0.003) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$$

Calculated drops in luminosity assuming β* = 35 cm

$$\Delta L_{CDF} = (-2.63 \pm 0.01) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$$
$$\Delta L_{D0} = (-2.361 \pm 0.006) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}$$

Calculated relative luminosity drop

$$\frac{\Delta L_{CDF}}{L_{CDF}} = \frac{\Delta L_{D0}}{L_{D0}} = 5.1\,\%$$

Measured relative luminosity drop

$$\frac{\Delta L_{CDF}}{L_{CDF}} = 5.2\,\%$$
$$\frac{\Delta L_{D0}}{L_{D0}} = 5.2\%$$

Results from store 3876 • →

Measured Before TRF1 trip

$$\begin{aligned}
\sigma_p &= 1.8122 \pm 0.0001\,\text{ns} \\
\sigma_{\bar{p}} &= 1.634 \pm 0.0002\,\text{ns} \\
L_{CDF} &= (51.94 \pm 0.02) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1} \\
L_{D0} &= (46.577 \pm 0.002) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}
\end{aligned}$$

Measured after TRF1 trip

$$\begin{aligned}
\Delta\sigma_p &= 0.1244 \pm 0.0005\,\text{ns} \\
\Delta\sigma_{\bar{p}} &= 0.0980 \pm 0.0008\,\text{ns} \\
\Delta L_{CDF} &= (-1.74 \pm 0.08) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1} \\
\Delta L_{D0} &= (-1.551 \pm 0.008) \times 10^{30}\,\text{cm}^{-2} s^{-1}
\end{aligned}$$

Calculated drops in luminosity assuming β* = 35 cm

$$\begin{aligned}
\Delta L_{CDF} &= (-1.666 \pm 0.007) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1} \\
\Delta L_{D0} &= (-1.494 \pm 0.007) \times 10^{30}\,\text{cm}^{-2}\text{s}^{-1}
\end{aligned}$$

Calculated relative luminosity drop

$$\frac{\Delta L_{CDF}}{L_{CDF}} = \frac{\Delta L_{D0}}{L_{D0}} = 3.2\%$$

Measured relative luminosity drop

$$\begin{aligned}
\frac{\Delta L_{CDF}}{L_{CDF}} &= 3.4\% \\
\frac{\Delta L_{D0}}{L_{D0}} &= 3.3\%
\end{aligned}$$

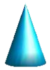
Results from store 3876

Crossing angles:

Calculated relative crossing angles, results are consistent with **zero** relative crossing angles because measured ΔL is really close to calculated ΔL, so for amusement

• → •

$$\frac{\delta\theta_{CDF}}{\delta\theta_{D0}} = \sqrt{\frac{-0.04 \pm 0.3}{0.045 \pm 0.04}} = \text{imaginary}$$

• → 

$$\frac{\delta\theta_{CDF}}{\delta\theta_{D0}} = \sqrt{\frac{-0.074 \pm 0.08}{-0.057 \pm 0.01}} = 1.1$$

Results from store 3876 cont'd

Since the difference between measured and calculated ΔL is second order in crossing angle, assume crossing angle is zero and calculate β*

$$\beta^*_{CDF} = (34 \pm 1)\,\mathrm{cm}$$
$$\beta^*_{D0} = (36.3 \pm 0.2)\,\mathrm{cm}$$

$$\beta^*_{CDF} = (32 \pm 3)\,\mathrm{cm}$$
$$\beta^*_{D0} = (32.4 \pm 0.3)\,\mathrm{cm}$$

Averaging

$$\beta^*_{CDF} = (33.5 \pm 1)\,\mathrm{cm}$$
$$\beta^*_{D0} = (34.7 \pm 0.1)\,\mathrm{cm}$$

This is consistent with β*=35 cm

Results from store 3876 cont'd

Since the difference between measured and calculated ΔL is second order in crossing angle, assume crossing angle is zero and calculate β*

• → •

$$\begin{aligned}\beta^*_{CDF} &= (34 \pm 1)\,\text{cm}\\ \beta^*_{D0} &= (36.3 \pm 0.2)\,\text{cm}\end{aligned}$$

• →

$$\begin{aligned}\beta^*_{CDF} &= (32 \pm 3)\,\text{cm}\\ \beta^*_{D0} &= (32.4 \pm 0.3)\,\text{cm}\end{aligned}$$

Averaging

$$\begin{aligned}\beta^*_{CDF} &= (33.5 \pm 1)\,\text{cm}\\ \beta^*_{D0} &= (34.7 \pm 0.1)\,\text{cm}\end{aligned}$$

This is consistent with β*=35 cm

Results from store 3873 cont'd

Calculated relative crossing angles

$$\frac{\delta\theta_{CDF}}{\delta\theta_{D0}} = \sqrt{\frac{-0.28 \pm 0.01}{-0.243 \pm 0.002}} = 1.1 \pm 0.1$$

This means that the crossing angle are the same at both experiments.

β* Conclusion

- β* are the same at both experiments
- Crossing angles are the same at both experiments
- Discrepancies in *L* cannot be explained by β* or crossing angles.

Final Conclusion

- It was an interesting 6 weeks as coordinator
  - Lots of other things happened that we could not salvage any physics out of.
- See ya as coordinator in 1½ to 2 years.