Basic BPM Hardware Theory

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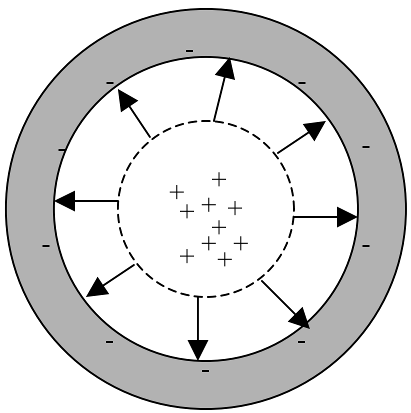
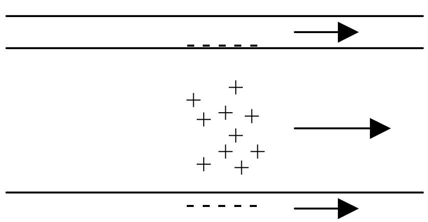
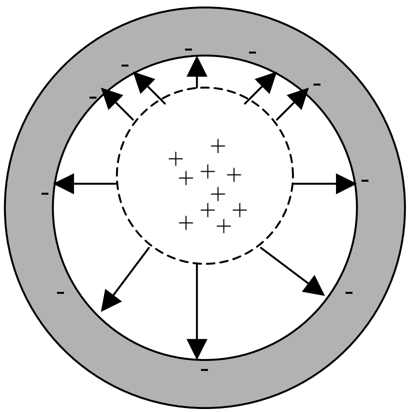
Wall Current





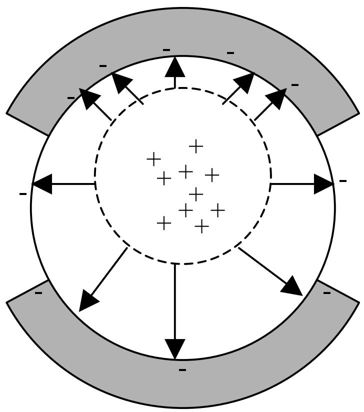
- Charge in a cylindrical perfectly conducting pipe produces an equal and opposite image charge at the edge of the conductor.
- This image charge follows a moving packet of charge through the cylinder.

Offset Wall Current



- If beam is offset in the beam pipe, field lines are more dense closer to the bunch.
- The dense field lines produce more dense image current, the image current becomes asymmetric.

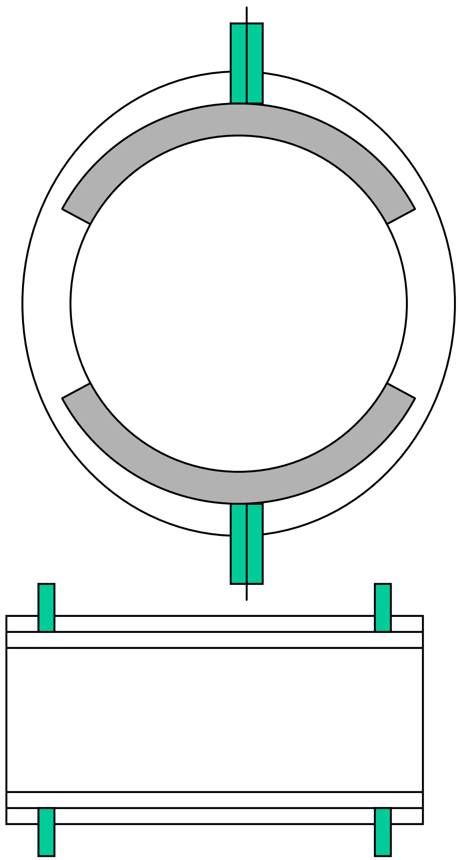
Split Plate Current



$$\Delta y \cong C \frac{I_{Top} - I_{Bottom}}{I_{Top} + I_{Bottom}}$$

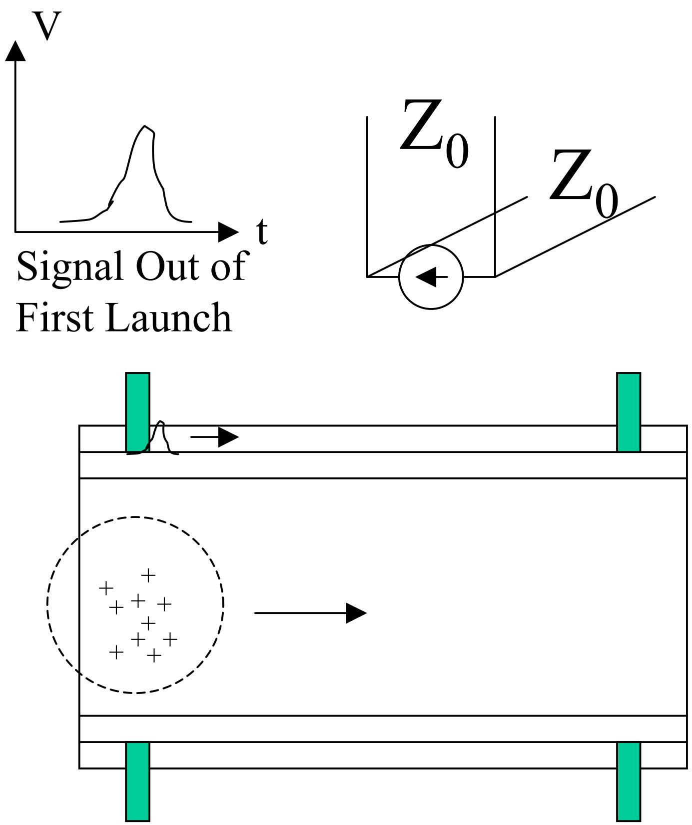
- If pipe is split and beam is offset, more current flows through plate closest to beam.
- Difference in current between different plates is proportional to beam displacement from center and beam current.
- Sum of current proportional to total beam current.
- Divide difference by sum to normalize position.

Stripline Pickup Model



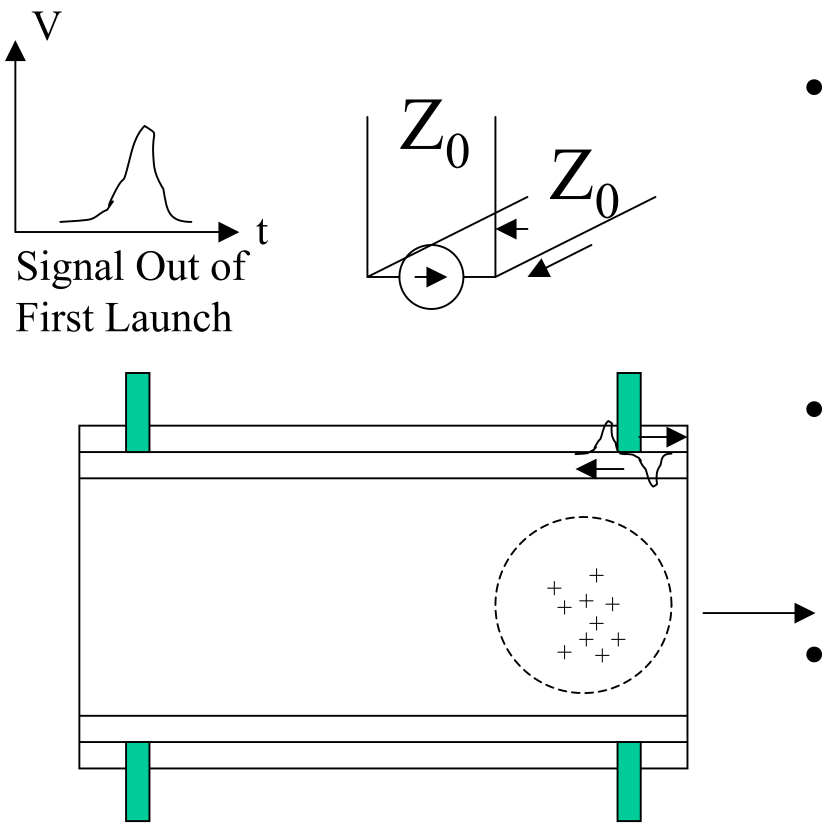
- Model of current Tevatron BPM pickup.
- Called a stripline pickup because the conducting plate forms a transmission line with beam pipe.

Stripline Pickup Model



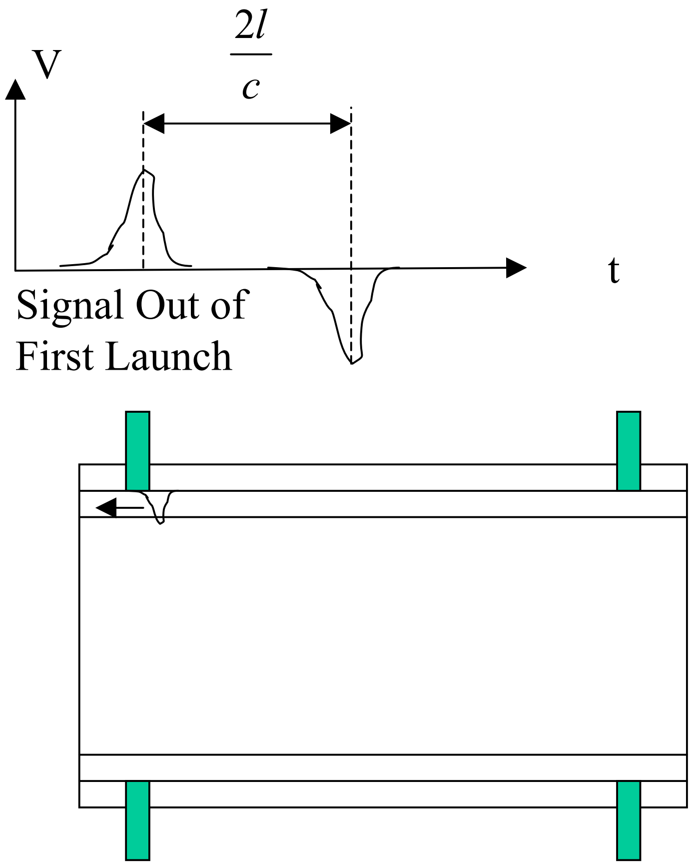
- Beam current enters the pickup, and the image current excites the stripline.
- Half the current goes through the launch and the other half enters the transmission line (assuming matched impedance).
- Current pulse in the stripline transmission line travels with the beam.

Stripline Pickup Model



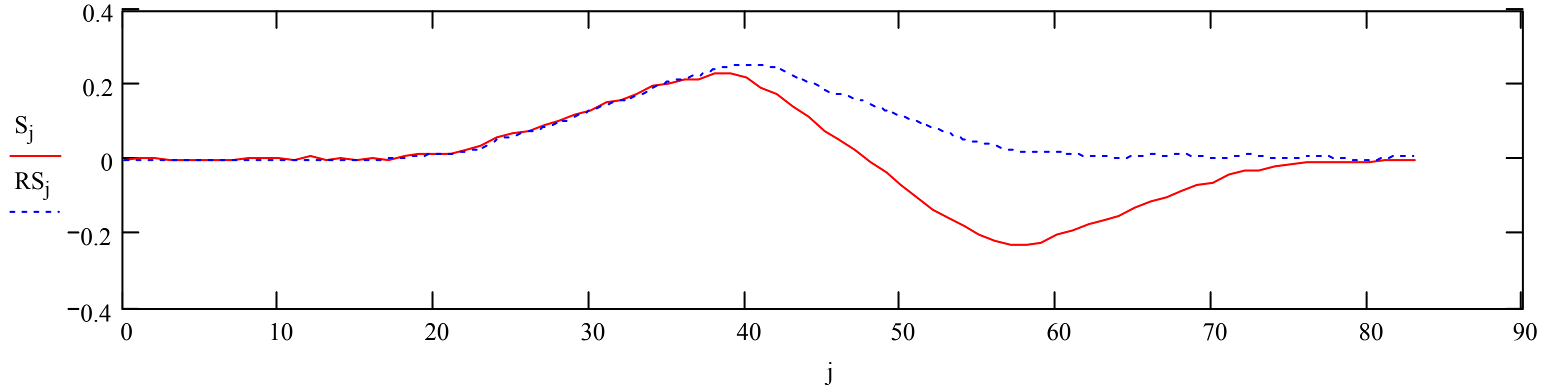
- As beam exits the detector, it produces an equal amplitude but inverted pulse in the transmission line.
- The counter-directional pulses cancel each other at the downstream launch.
- Inverted pulse continues down the transmission line in opposite direction.

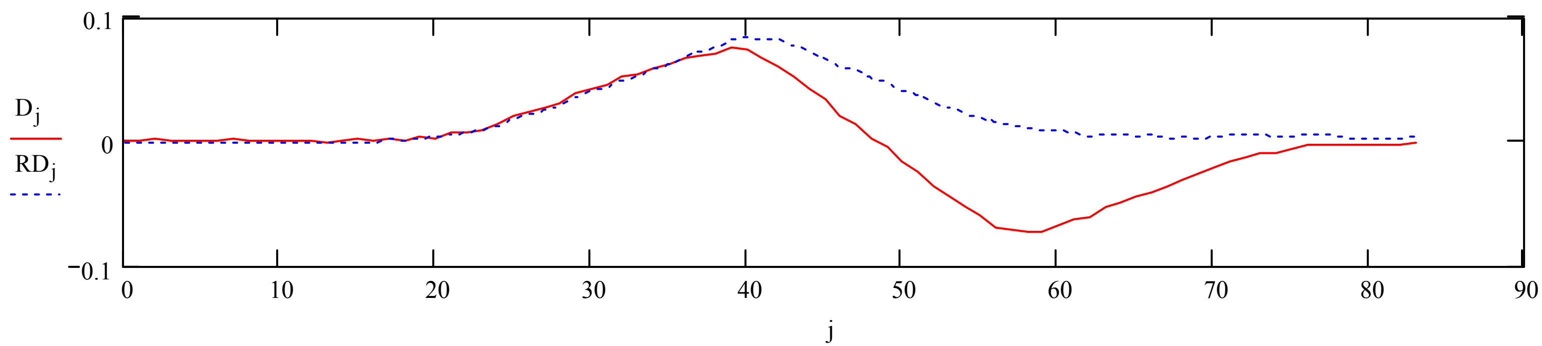
Stripline Pickup Model



- Inverted pulse reaches other end of transmission line.
- The two pulses combine at the upstream launch to produce the doublet effect.

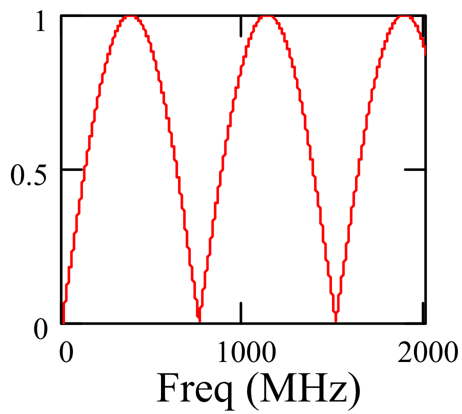
Beam Signal from Stripline





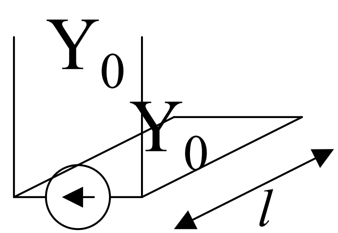
Sum (top-red) and difference (bottom-red) signals from 1m long stripline pickup in the Tevatron.

Response of Stripline Pickup



Fraction of total current transmitted to launch for 20cm stripline.

$$\frac{I_{launch}}{I_{total}} = \frac{jY_0}{Y_0 \cot(\frac{\omega l}{c})}$$



- Downstream end of stripline looks like a short circuit.
- Response of pickup to beam spectrum looks like response of shorted single stub tuner.
- No DC response.

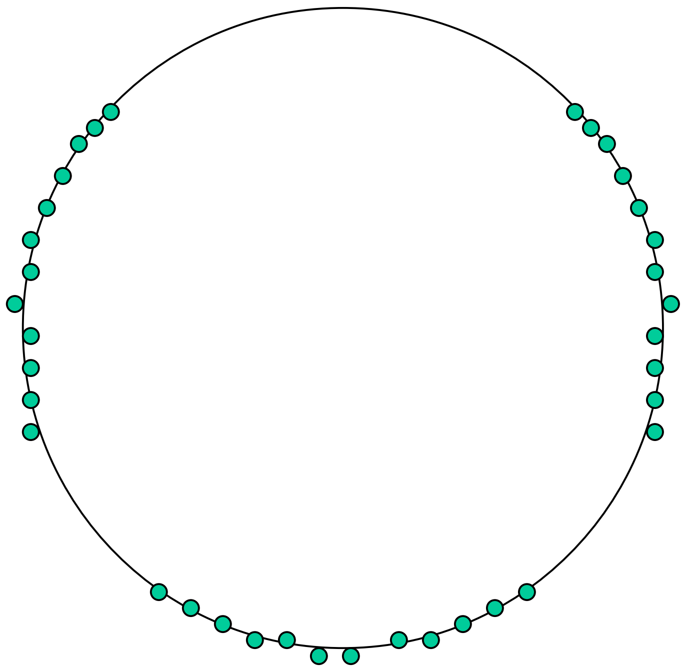
Beam Properties Measured by BPM

- Beam Intensity
- Phase
- Dispersion
- Betatron Oscillations
- Mean Position

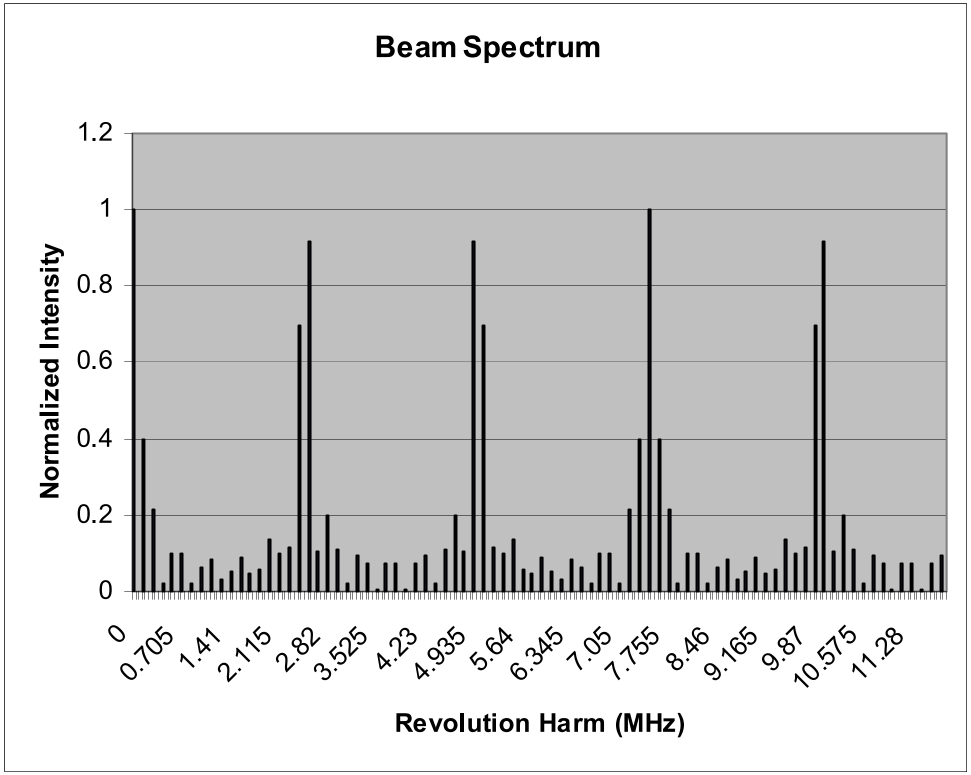
Beam Intensity

- Signal from launch proportional to beam position and beam intensity.
- Combining signal from both planes, in phase, produces pure intensity signal.
- Intensity spectrum without any modulation is confined to revolution harmonics (47kHz in Tev). Relative intensity of revolution harmonics determined by bunch spacing.

Standard Store Configuration

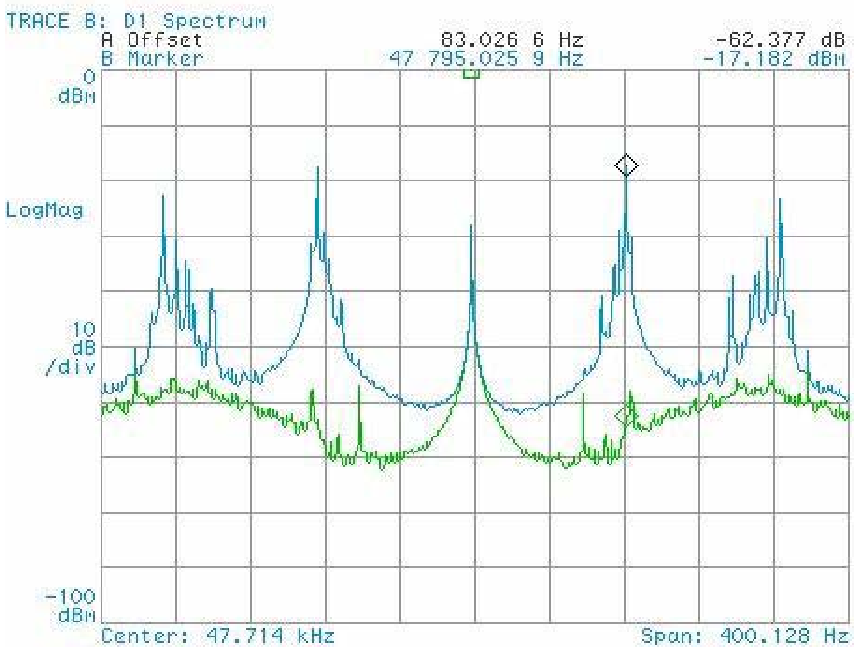


Distribution of protons in a standard store. Pbars not included



Fourier spectrum of beam starting at DC. Note that for equal bunch population, only every third harmonic is visible due to 3-fold symmetry.

Phase Oscillations



Plot showing synchrotron oscillations in the Tevatron at 150 GeV around the first revolution harmonic. Blue trace is after injection, and green trace is after dampers are on.

- Bunches of beam perform time oscillations about a synchronous orbit.
- These oscillations phase modulate the intensity spectrum, producing sidebands around the revolution harmonics.

Phase Oscillations

- In Tevatron, modulation frequency varies from ~80 Hz at 150 GeV to ~30 Hz at 980 GeV.
- Relative distribution of synchrotron line amplitudes around revolution lines determined by phase distribution of bunch oscillations.
- Synchrotron lines are modulations of fundamental frequency not revolution harmonics. There can be large synchrotron lines around revolution lines that are nulled by the bunch pattern.

Dispersion

- Dispersion quantifies the dependence of beam displacement on beam energy.
- Dispersion can be measured by giving beam a known energy change and measuring relative displacement in average position.
- Synchrotron oscillations are modulations in energy as well as time. Effects of dispersion are seen as amplitude modulation of the position at the synchrotron sidebands.

Betatron Oscillations

- Resonant oscillation of beam position caused by number, strength, and spacing of quadrupole magnets.
- Much higher frequency modulation than synchrotron oscillation (many oscillations per turn).
- Oscillation frequency can (and should) be different for each plane.
- As with synchrotron oscillations, betatron lines are distributed around revolution lines according to the phase distribution of each bunches amplitude modulation. There can be large betatron lines around small or nulled revolution lines.

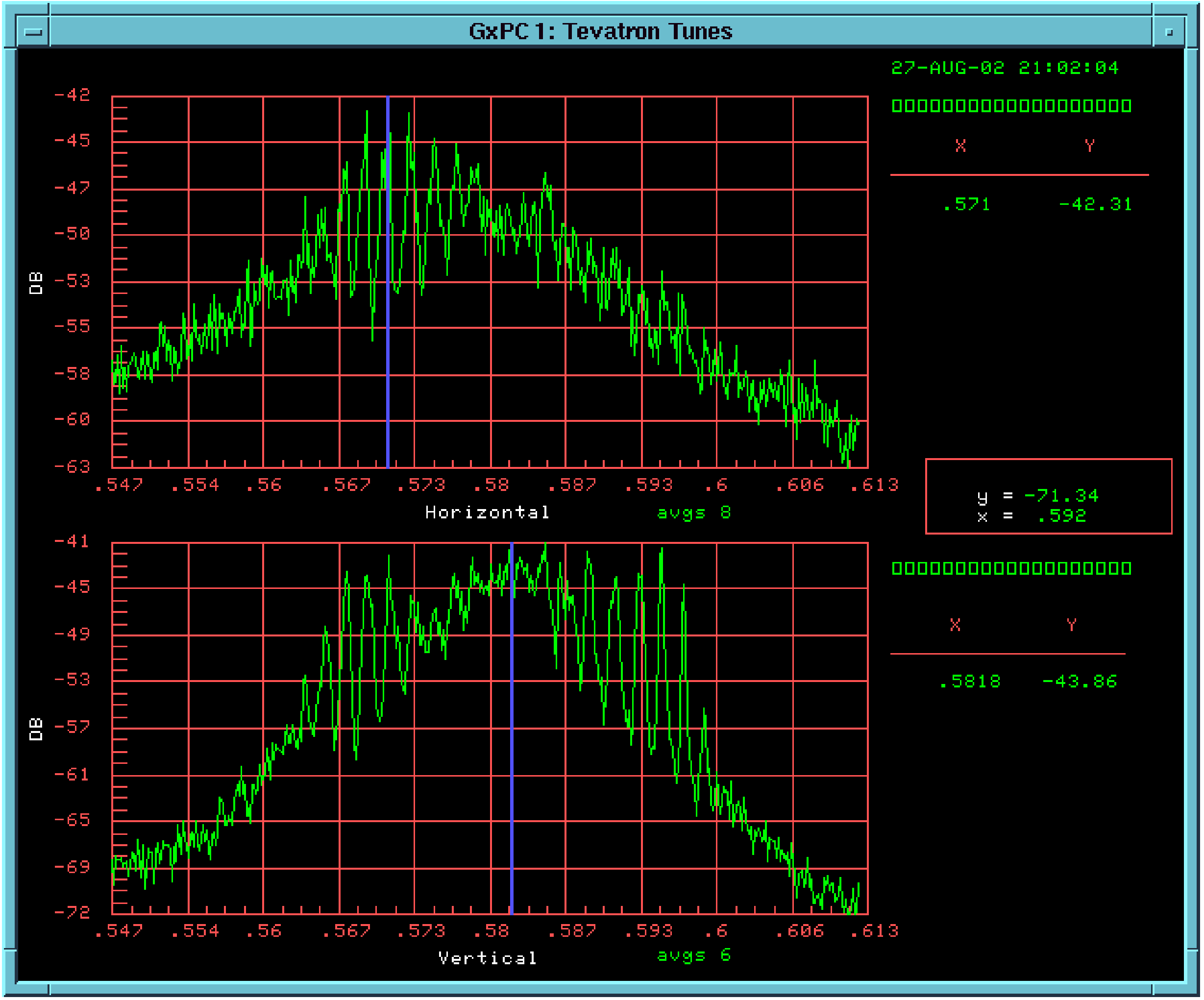
Chromaticity

- Chromaticity describes the change in betatron resonant frequency (tune) as a function of beam momentum.
- Synchrotron oscillations modulate the beam energy which modulates the tune through the chromaticity.
- Tune lines show FM modulation in the presence of synchrotron oscillations.

Coupling

- Coupling describes the dependence of the motion in one plane on position in the other plane.
- Magnets are not perfectly orthogonal. Some non-linear components produce bending/focusing in one plane that is dependent on some product of the positions in both planes.

Betatron Oscillations



Plot showing the spectrums from the Schottky pickups in the Tevatron. The center frequency is set to be close to the tune line. The bandwidth is about 27 kHz.

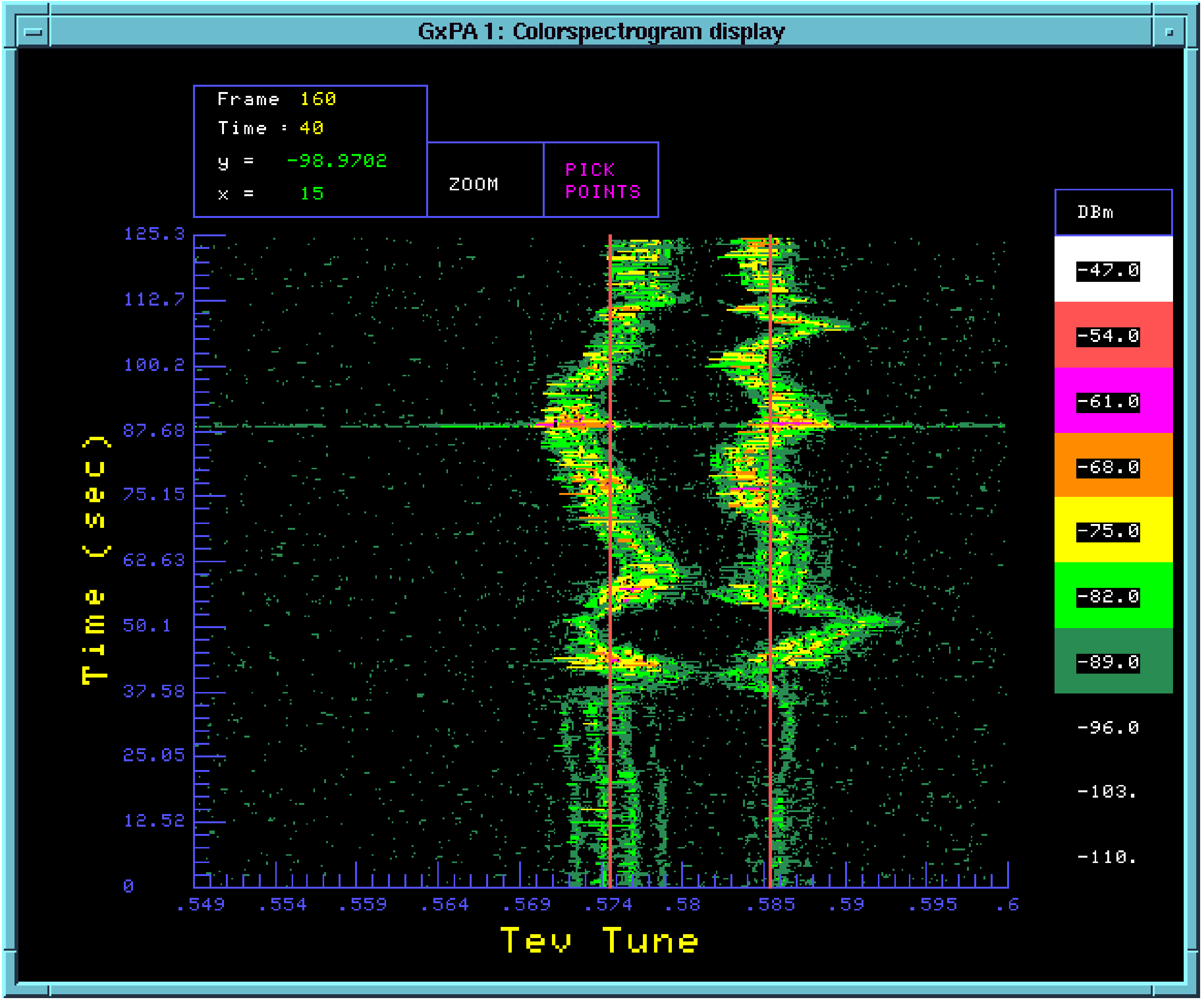
Mean Position

- I define mean position of the beam as the beam position with the betatron and synchrotron motion averaged out.
- The mean position information is located in the revolution harmonics.
- Resolution bandwidth of system must be good enough to discern revolution harmonics without corruption from synchrotron and betatron sidebands.

Lattice Definition

- The lattice is defined as the type, strength, and spacing of the magnets in the accelerator.
- The lattice changes as the Tevatron transitions between different operations and energy.
- The lattice dictates tunes, chromaticity, dispersion, coupling, etc. It is very important that the lattice is monitored and controlled.

Changes in Lattice Up the Ramp

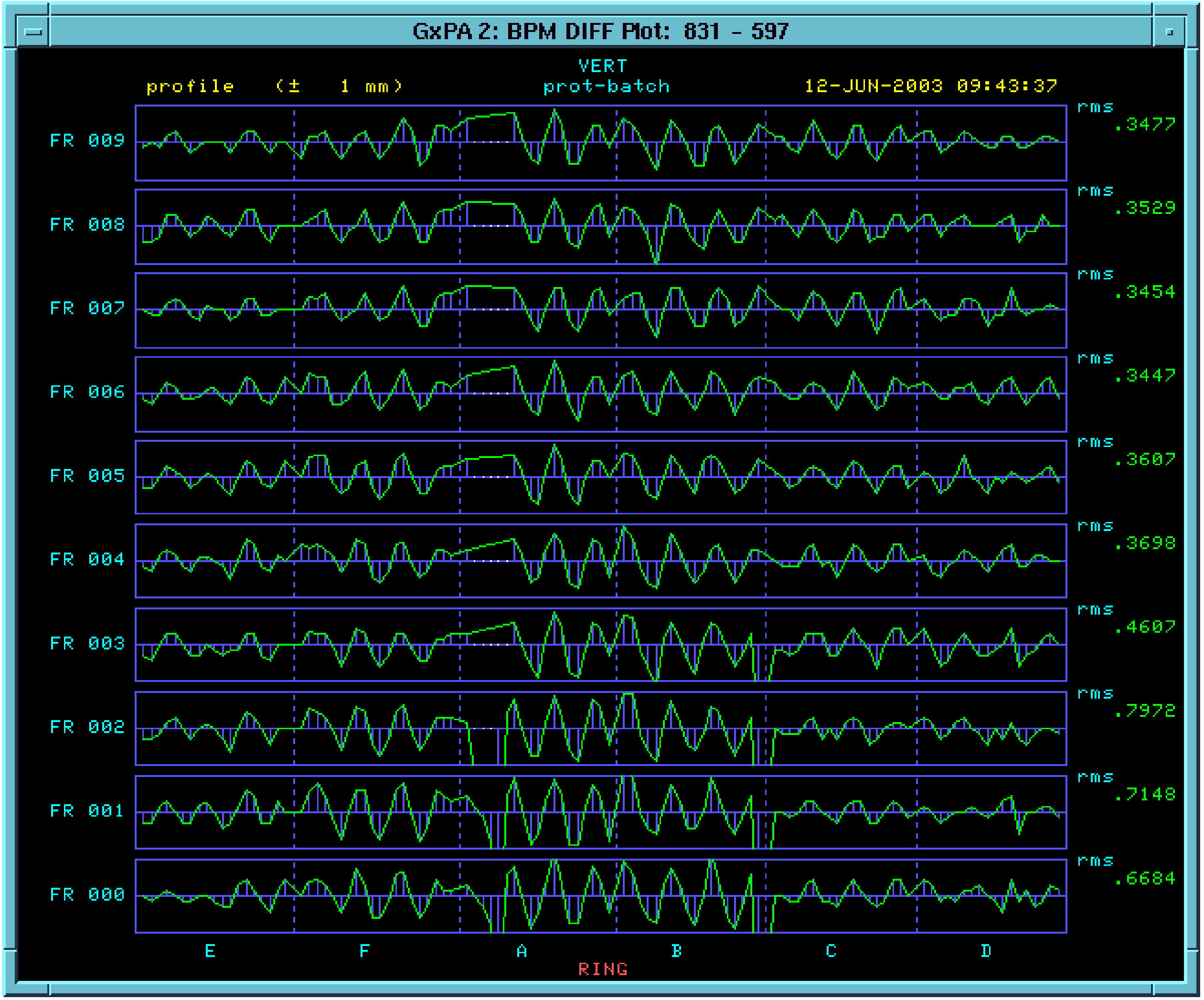


Plot showing the time evolution of tune up the ramp on the pbar helix.

Lattice Measurement

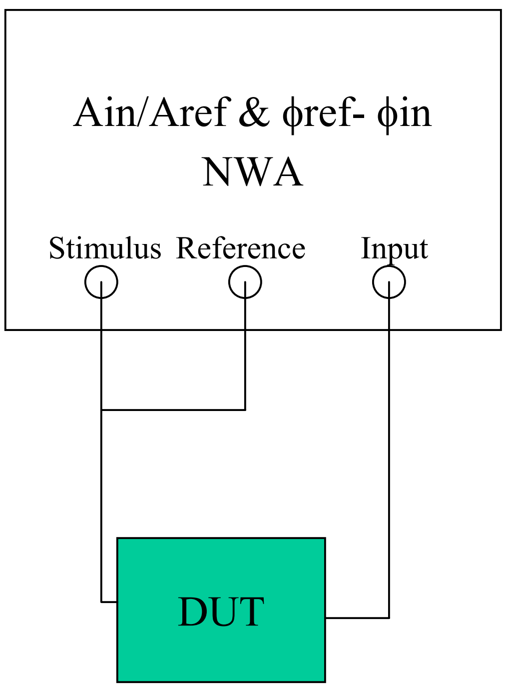
- The lattice is measured by displacing the beam in one location and measuring the effect of the displacement around the ring.
- Displacement may be static by applying a well calibrated offset current to a dipole magnet. Measure the average position at all BPMs (both planes). Only reveals relative amplitudes of beta functions.
- Displacement may be dynamic by applying a ping, chirp, or sine wave stimulation to a magnet or stripline. Data from multiple BPMs can be correlated to get more info about beta functions.

Lattice Measurement



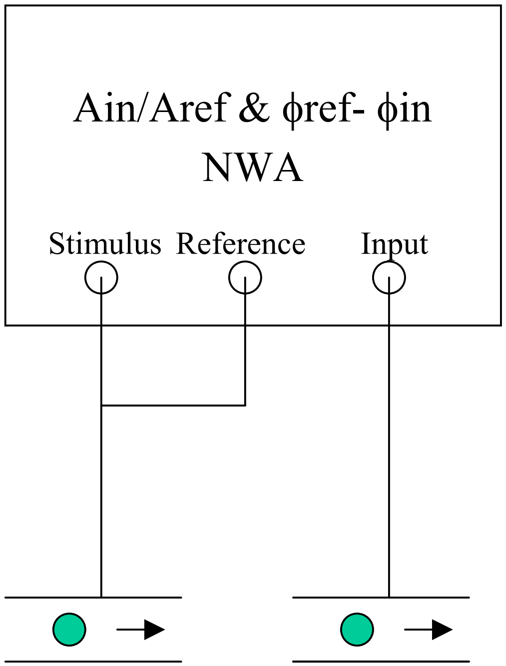
Plot showing effect of errors in the lattice with the BPMs. Notice the pattern of the amplitude functions.

Response Measurements



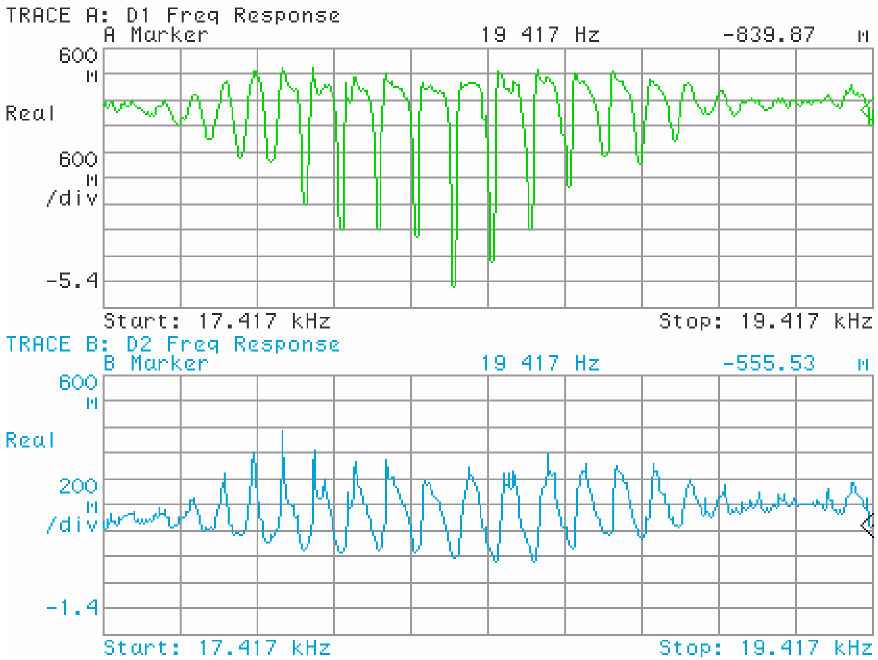
- A known input signal is applied to some device and the output of the device is compared to the input.
- Processing of the two signals reveals their relative amplitude and phase differences.
- Network analyzers and vector signal analyzers are examples of response instrumentation.

Beam Response Measurements



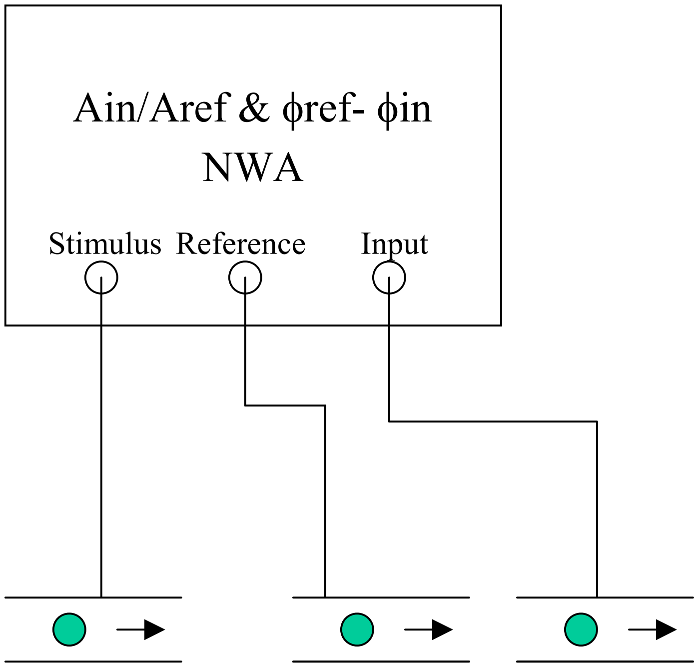
- Same as regular response measurement, but beam is tickled and the response is measured at a different point in the ring.
- The frequency of interest moves from the revolution line to the betatron line.
- Can get both relative amplitude and relative phase info.
- Need enough resolution bandwidth to discern tune line from synchro-betatron lines.

Beam Response Measurement



These plots show the response of the beam around the tune line. Stimulus is a chirp.
Top (green) plot shows the relative Real component of the beam response in the horizontal plane. Bottom plot (blue) shows vertical.

Beam Response Measurements



- The stimulus is not required to be the reference for beam response measurements.
- The relative phase and amplitude between two separate pickups can be measured.
- Only one kicker required for whole ring, no synchronization with BPMs required.
- Can get both relative amplitude and relative phase info.