BETA FUNCTION MEASUREMENT IN THE TEVATRON USING QUADRUPOLE GRADIENT MODULATION

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Abstract

Early in Run2, there was an effort to compare the different emittance measurements in the Tevatron (flying wires and synchrotron light) and understand the origin of the observed differences. To measure the beta function at a few key locations near the instruments, air-core quadrupoles were installed. By modulating the gradient of these magnets and measuring the effect on the tune, the lattice parameters can be extracted. Initially, the results seem to disagree with other methods. At the time, the lattice was strongly coupled due to a skew component in the main dipoles, caused by sagging of the cryostat. After a large fraction of the superconducting magnets were shimmed to remove a strong skew quadrupole component, the results now agree with the theoretical values to within 20%.

Gradient modulation method

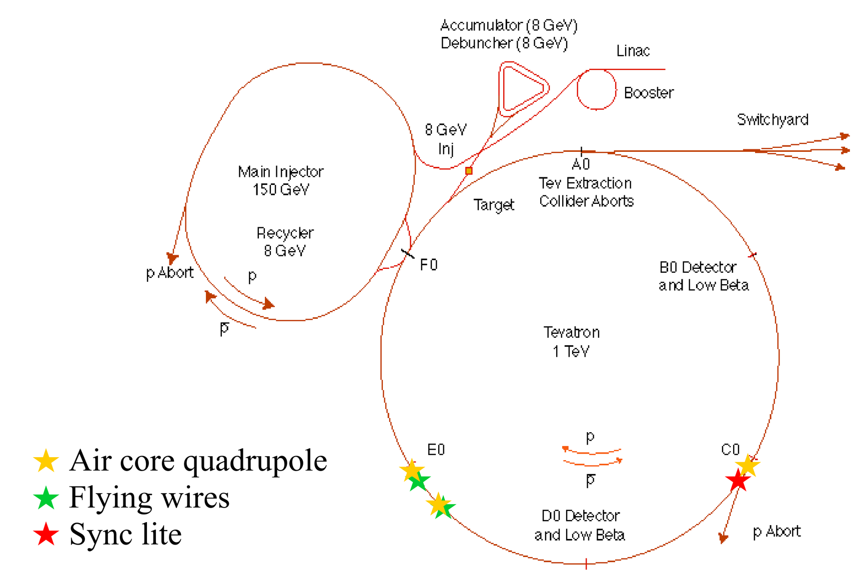
The local beta function at a quadrupole can be measured by varying its gradient, using the linearized formula

$$\beta = \pm 4\pi \frac{dQ}{dK}$$

or, if the tune is close to a half-integer resonance, the more appropriate formula to use is

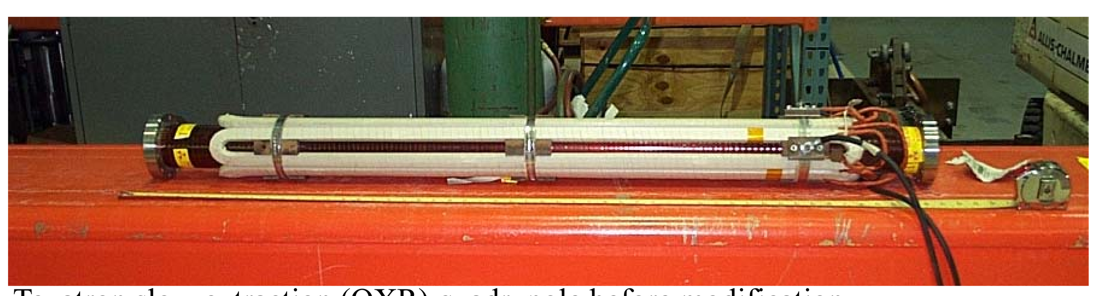
$$\beta = \pm \frac{2}{dK}\left(\cot(2\pi\, Q)\left(1-\cos(2\pi\, dQ)\right)+\sin(2\pi\, dQ)\right)$$

although, in the Tevatron, this is a small (few percent) effect. Both formulas only account for the direct change in tune, and not any indirect effects due to changing orbits. So it is important to center the beam in the quadrupole and monitor the orbit motion during the experiment.

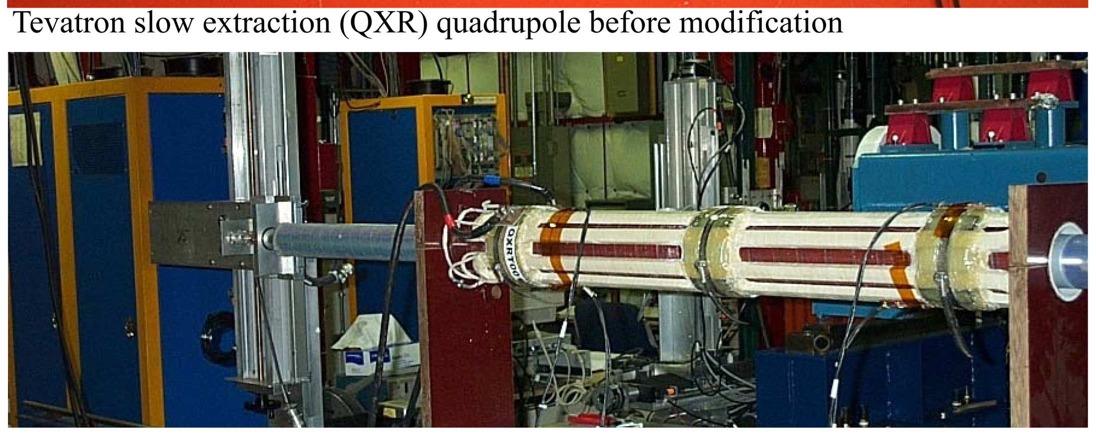


Magnet	E0QT	E1QT	C0QT
Distance from B0	3153.65m	3357.68m	1168m
Close to	E11 flying wires	E17 flying wire	Sync lite
Hor beta	89 m	77 m	100m
Ver beta	65m	32m	60m

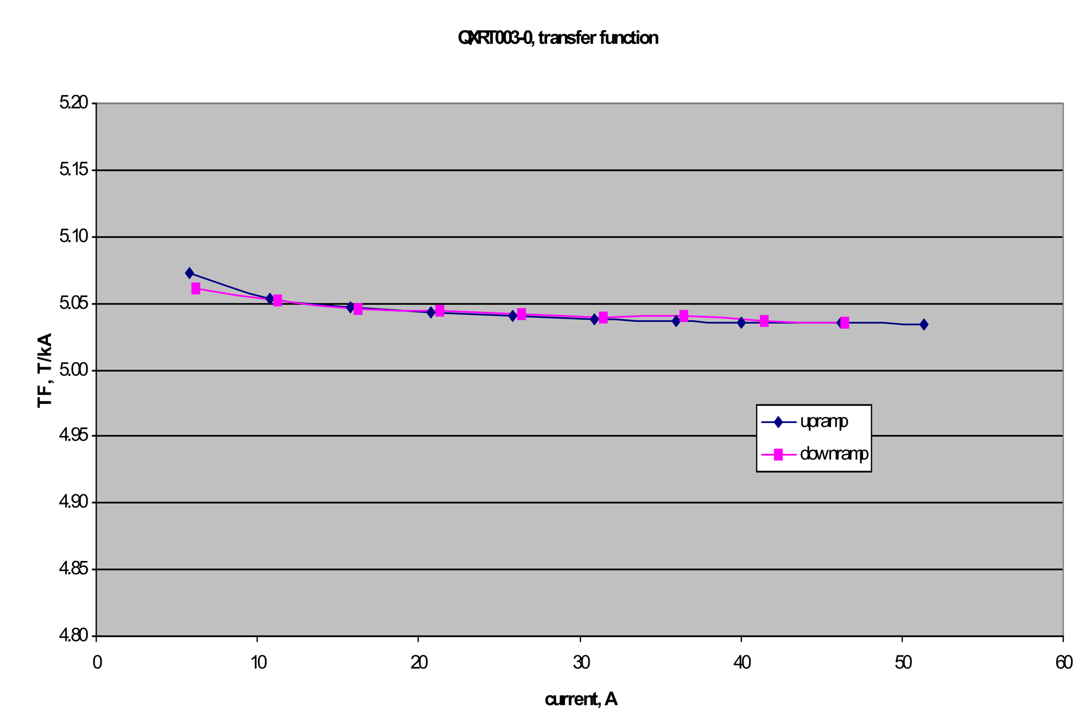
Air-core quadrupole magnets



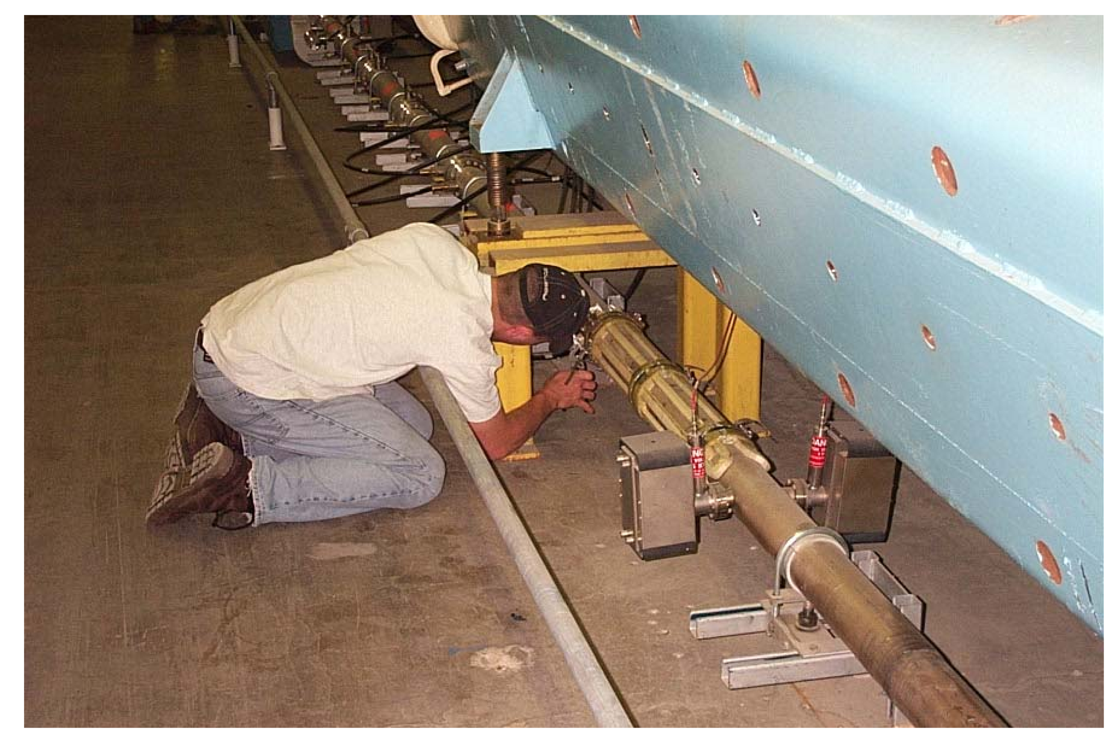
Tevatron slow extraction (QXR) quadrupole before modification



The air-core quadrupole was modified to fit on a 4" beam pipe. Above it is being measured in the Magnet Test Facility (MTF) using a rotating coil.

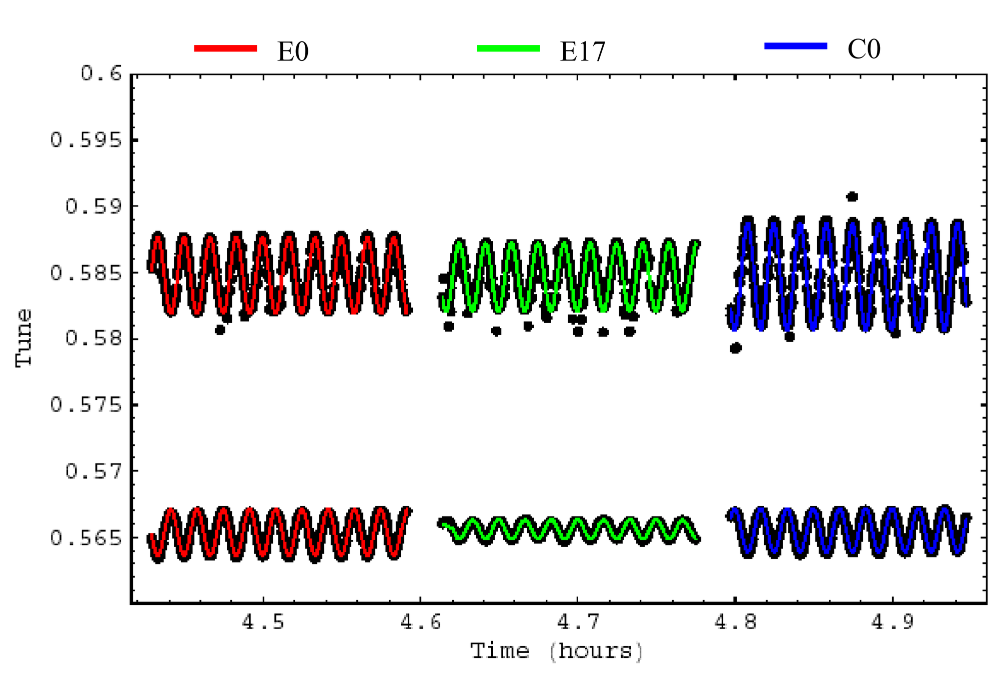


Measured transfer function (integrated gradient per unit current).



Air-core quadrupole being installed at E0. The magnets clamp onto the existing beam pipe without any need for breaking vacuum.

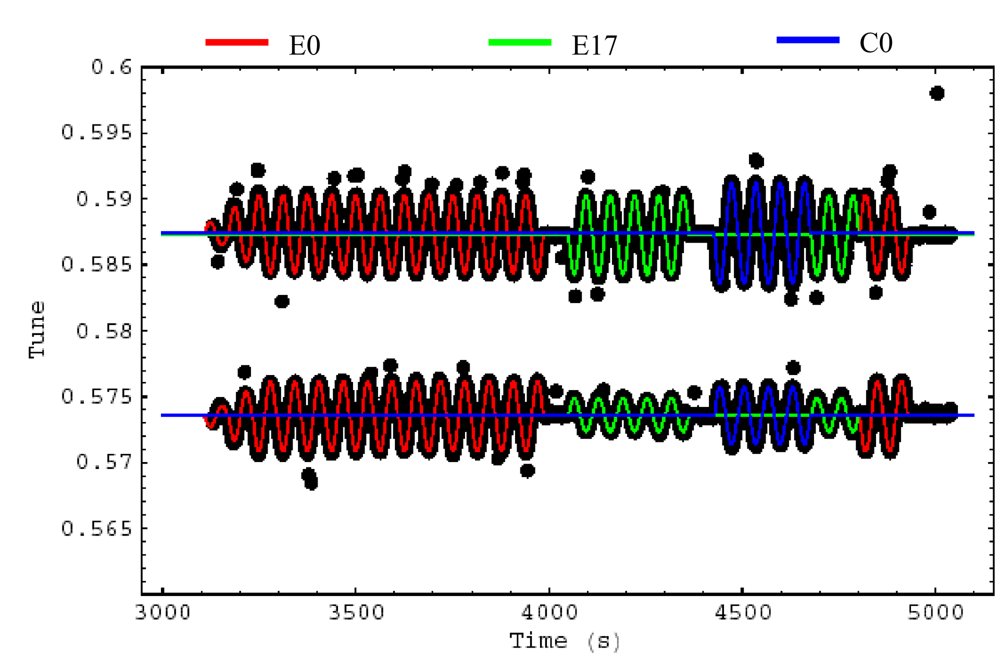
Measurements in 2003



	E0QT	E1QT	C0QT
Horizontal tune modulation	0.00284	0.00252	0.00395
Measured horizontal beta	71.1 m	62.4 m	98.6 m
Horizontal discrepancy	**-22%**	**-21%**	**-5%**
Vertical tune modulation	0.00172	0.00072	0.00163
Measured vertical beta	43.0 m	17.9 m	40.6 m
Vertical discrepancy	**-37%**	**-47%**	**-35%**

In 2003, a rather large disagreement was observed between measured and design beta functions. The results also disagreed with lattice measurements using differential orbits. All values were significantly smaller than expected

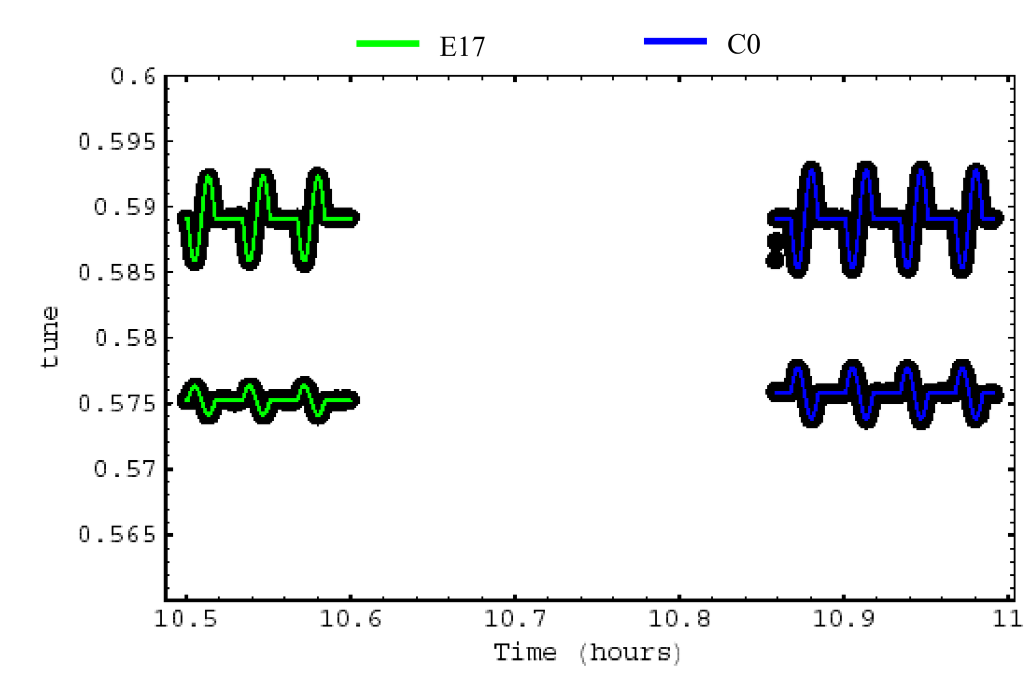
Measurements in 2004



	E0QT	E1QT	C0QT
Horizontal tune modulation	0.00294	0.00298	0.00383
Measured horizontal beta	73.3 m	74.4 m	95.4 m
Horizontal discrepancy	**-18%**	**-4%**	**-10%**
Vertical tune modulation	0.00265	0.00126	0.00216
Measured vertical beta	66.1 m	31.5 m	53.8 m
Vertical discrepancy	**+1%**	**0%**	**-5%**

In 2004, the measured values were found to agree with design to within 20%. Moreover, the systematic shift toward lower values seemed to be gone, or at least less pronounced. Between 2003 and 2004, 14% of the Tevatron main dipoles were re-shimmed, reducing the coupling in the machine significantly.

Measurements in 2005



	E1QT	C0QT
Horizontal tune modulation	0.00324	0.00374
Measured horizontal beta	80.7 m	93.3 m
Horizontal discrepancy	**+5**	**-7%**
Vertical tune modulation	0.00111	0.00193
Measured vertical beta	27.6 m	48.1 m
Vertical discrepancy	**-14%**	**-20%**

In 2005, the measured values still agree with design to within 20%. Between 2004 and 2005, another 53% of the Tevatron main dipoles were re-shimmed. In 2005, the measurements were taken using the new tune tracker.

Effects of coupling

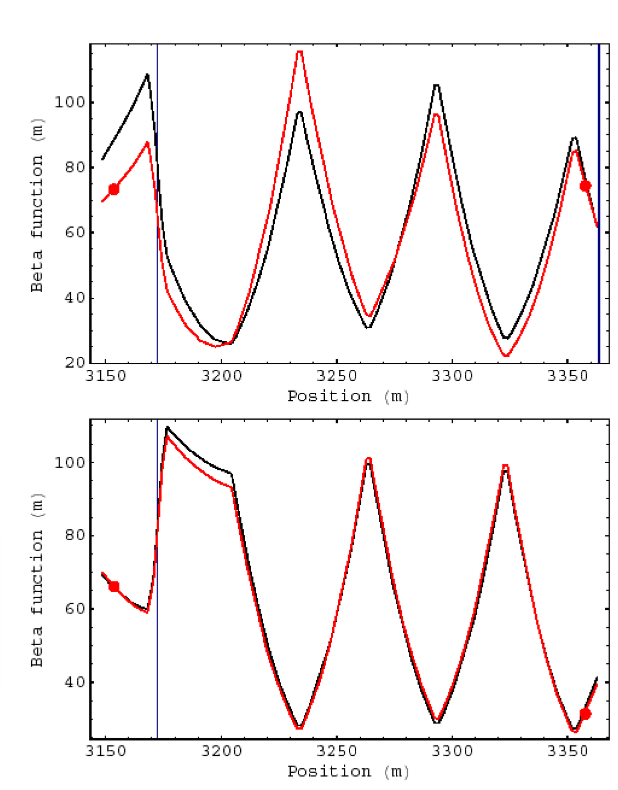
If there are sources of coupling in the machine, the measured tune separation is

$$\Delta Q_{\mathrm{observed}} = \sqrt{\Delta Q_{\mathrm{lattice}}^2 + C^2}$$

so that close to the diagonal, the observed tune change for a given change in set (lattice) tune is **less** than expected, as was observed in 2004. However, the effect is small is the tune separation is much larger than the global coupling parameter *C* (minimum tune split). Therefore, the effect should only have been a few percent in the 2003 data.
A more likely suspect is local coupling. If the normal modes are significantly inclined at the location of the trim quadrupole, the beam will see it as a skew quadrupole instead on a normal one, yielding less effect on the tune.

Betas at Flying Wires

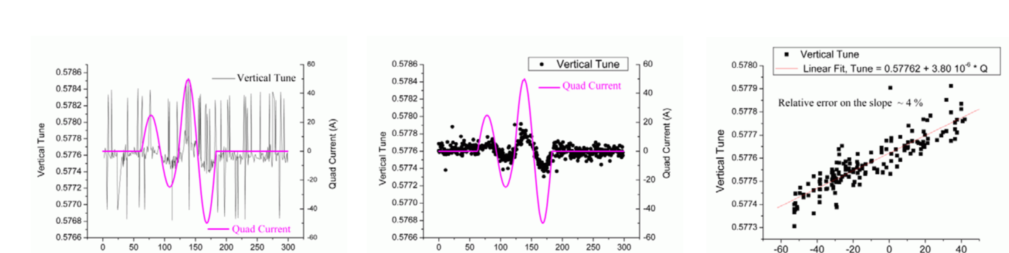
The quadrupoles were installed to get a handle on the local beta function error at the instruments measuring beam size, in order to understand (and correct) the error in the emittance calculation. However, due to space restriction, the magnets had to be installed some distance away from the instruments
Since there are two data points in the E-sector, the phase an amplitude of the beta beat wave can be calculated, assuming that there are no error sources between the two locations. From this, the beta functions at the exact flying wire locations can be calculated from the 2004 data.



	E11 Horizontal	E11 Vertical	E17 Horizontal
This measurement	**66.0 m**	**81.4 m**	**60.2 m**
MAD design lattice	82.1 m	83.1 m	59.8 m
Values used in Flying Wires	83.5 m	80.9 m	62.5 m
Differential orbits*	86.9 m	101.3 m	67.6 m

* measured in 2004 by V.Lebedev, results in BeamDoc #1465

Measurements at 980GeV



At 980 GeV, the tune modulation is only barely above the noise level of the tune fitter, and smaller than the synchrotron frequency. Occasionally, the tune fitter picks the wrong synchrotron line, but this component of the noise can be removed with post-processing of the data.

The new tune tracker may provide more accurate data, making the air-core quadrupoles useful at 980 GeV as well.

So far, little time and effort have been spent on measurements at flattop.

Particle Accelerator Conference
Knoxville, Tennessee, USA • May 16-20, 2005