Sensitivity of the Tevatron Tune to (future) C0 IR Power Supplies

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December 17, 2003

Beams-Docs-949

The sensitivity of the Tevatron tune to the setting, reproducibility, ripple, etc. of the power supplies was studied for the current design of the low-β insertion for C0 IR for the BTeV experiment (John Johnstone – 12/27/00).

http://www-ap.fnal.gov/~peterg/btev/johnstone_27dec00.pdf

It is anticipated that this I.R. design will change slightly as the requirements and optimizations evolve. This calculation can readily be applied to future I.R. configurations and tunes.

A new low-β insertion will be installed (scheduled for 2009) at C0 for the BTeV experiment. This insertion will be different from those currently at CDF and D0, especially since six LHC-style quadrupole magnets will be run in series from a single power supply. The sensitivity of the tune of the Tevatron to variations in the powering of the new elements at C0 needs to be evaluated to specify the performance of the power supplies and associated controls systems with regard to accuracy, reproducibility, ripple, and least-count setting ability over the range from injection at 150 GeV through low-β squeeze at 980 GeV.

Q1, Q2, Q3, Q4, and Q5 are LHC-type quadrupoles (nominally 170 T/m gradient at 9560 A). Q6 and Q7 are existing, but unused, Q1 magnets from CDF and D0 which use the previous low-β technology (140 T/m at 5000 A). There are additional strong corrector quadrupoles Q8 and Q9 (37 T/m at 50 A). The Q3us, Q2us, Q1us, Q1ds, Q2ds, Q3ds all run in series, with a pair of small trim quadrupoles QT, located between the Q2's and Q3's. QTus and QTds run in series (37 T/m at 50 A). Similarly, Q4us and Q4ds run in series, as for Q5us and Q5ds. All of the Q6-Q9 quadrupoles are independently powered.

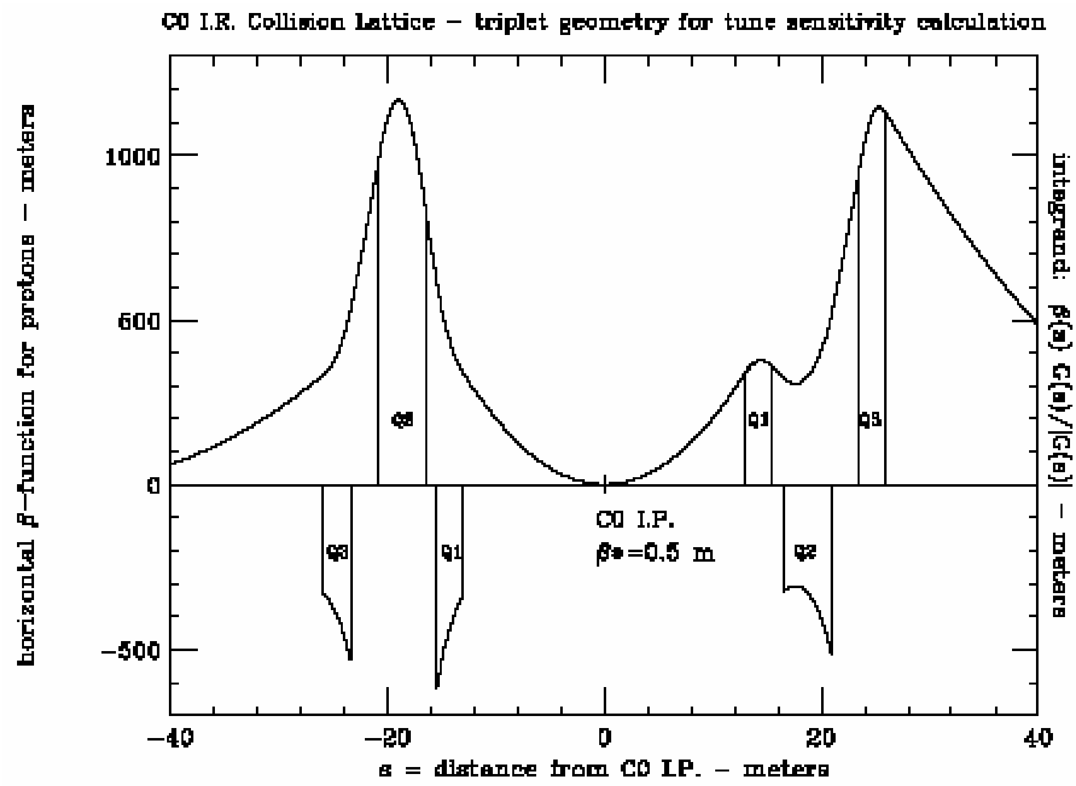
The variation in tune due to the variation in a quadrupole gradient is given by

$$\Delta \upsilon = (1/4\pi) \int \Delta \kappa(s)\, \beta(s)\, ds \qquad \text{where} \quad \kappa\ (m^{-2}) = 0.2998\ G(T/m)/p(GeV/c).$$

Since the nominal gradient setting is G_o at current I_o, $\Delta G = G_o\, \Delta I/I_o$, and we can write for the slope at I_o

$$\Delta \upsilon/(\Delta I/I_o) = 0.2998/(4\pi\ p) \int G_o(s)\, \beta(s)\, ds \quad .$$

Thus the variation in tune, at a given momentum, is a constant times the integral over the quadrupole(s) of the product of the nominal gradient times the local β-function.



The following tune sensitivity calculations were done for the collision and injection lattices. These were calculated as per John Johnstone's design at 1 TeV, rather than 980 GeV. Since the β-functions do not change much over the shorter Q4-Q9 and QT quadrupoles magnets, the average β-function was assumed over the length of these quadrupoles. The β-function was integrated over the constant gradient for Q3us–Q2us-Q1us–Q1ds–Q2ds–Q3ds.

The parameters for each quadrupole and the calculational details are outlined in the following spreadsheets and summarized below:

http://www-ap.fnal.gov/~peterg/btev/low_beta_current_sensitivity.xls

C0 I.R. Collision Lattice – β* = 0.5 meter

Quadrupoles	$\Delta\upsilon/(\Delta I/I_o)$us	$\Delta\upsilon/(\Delta I/I_o)$ds	$\Delta\upsilon/(\Delta I/I_o)$us+ds
Q8-Q9 (50 A)	0.0606		independent (maximum sensitivity)
Q7 (5 KA)	-0.0565	0.2620	independent
Q6 (5 KA)	0.3085	-0.1701	independent
Q5 (10 KA)	-0.3618	0.6510	0.2883
Q4 (10 KA)	0.8852	-0.0233	0.8620
Q1-Q2-Q3 (10 KA)			**18.38**
QT (50 A)			0.0003

C0 I.R. Injection Lattice - β* = 2.6 meters

Quadrupoles	$\Delta\upsilon/(\Delta I/I_o)$us	$\Delta\upsilon/(\Delta I/I_o)$ds	$\Delta\upsilon/(\Delta I/I_o)$us+ds
Q8-Q9 (50 A)	0.0606		independent (maximum sensitivity)
Q7 (5 KA)	-0.0793	0.3414	independent
Q6 (5 KA)	0.4305	-0.1052	independent
Q5 (10 KA)	-0.0578	0.6058	0.5480
Q4 (10 KA)	0.4566	-0.0508	0.4059
Q1-Q2-Q3 (10 KA)			**3.57**
QT (50 A)			0.0077

For comparison, the similar tune sensitivity was calculated for CDF/D0 where the Q3 magnets are powered separately from the Q2-Q4 quadrupoles.

CDF and D0 Collision Lattice - β* = 2.6 meters

Quadrupoles	$\Delta\upsilon/(\Delta I/I_o)$us+ds
Q2-Q4 (5 KA)	**5.44**
Q3 (5 KA)	**12.13**

It is apparent that the largest sensitivities for the C0 IR quadrupoles are for the triplets (single power supply) for both the collision lattice and for the injection lattice. This should not be surprising since they are the longest quadrupole magnets, the calculation integrates over 6 quadrupoles, and the β-function is largest within these magnets. Note that summing the sensitivities over Q2-Q4 + Q3 for the CDF/D0 low-β insertion gives a comparable $\Delta\upsilon/(\Delta I/I_o) = 5.44 + 12.13 = 17.57$.

What is an acceptable variation in tune $\Delta\upsilon$? V. Shiltsev, "Requirements on new Tevatron equipment", Beams-Doc-877, v.1 10/17/2003 lists a requirement of tune and coupling change < 0.0005 (which is 5×10^{-4}, including differential). On December 8, 2003, Vladimir Shiltsev verbally stated more restrictive requirements that ripple should have $\Delta\upsilon <$ a few x 10^{-5} at < 10 Hz, $\Delta\upsilon < 2 \times 10^{-6}$ at 35-90 Hz (range of synchrotron frequencies up the ramp), and $\Delta\upsilon \sim 10^{-9}$ for ~ 10 KHz (betatron frequencies – which is too high a frequency to be driven by magnet ripple).

Dan Wolff (December 11, 2003) stated that the low-β power supplies currently in use at CDF/D0 have $\Delta I/I_o \sim$ 10 parts per million (10^{-5}) in terms of accuracy, stability (ripple), and repeatability, and are driven with a 16-bit D/A converter (# settings = 2^{16}-1 = 65,535 or 1.6×10^{-5} of maximum setting for least count). Is this performance adequate to meet the Tevatron requirements for the most sensitive C0 IR triplet Q1-Q2-Q3 for collision lattice?

$\Delta\upsilon = \Delta\upsilon/(\Delta I/I_o) * \Delta I/I_o = 18.38 * 10^{-5} = 1.8 \times 10^{-4} \sim 0.0002$ for collision lattice,

which satisfies the criterion of Beams-Doc-877, but not Vladimir's verbal requirements.

In terms of setting accuracy due to least-count of the D/A converter, if we assume that 170 T/m maximum performance corresponds to 9,560 A or full-scale of 65,535 setting units, then the least significant bit corresponds to 0.146 A.

$\Delta\upsilon = \Delta\upsilon/(\Delta I/I_o) * \Delta I/I_o = 18.38 * 1/65,535 = 0.00028$ for collision lattice,

also within the Beams-Doc-877 requirement.

From injection through ramp to 980 GeV, the injection lattice is used, giving

$\Delta\upsilon = \Delta\upsilon/(\Delta I/I_o) * \Delta I/I_o = 3.57 * 10^{-5} = 3.6 \times 10^{-5} << 0.0005$ for injection lattice

in terms of accuracy, stability (ripple), and repeatability. For least count setting accuracy, the current at injection must be considered = 9,560 A * 150 GeV/1000 GeV = 1, 434 A. Using 0.146 A least count setting from above, this corresponds to

$\Delta I/I_o = 0.146\ A/1,434\ A = 0.00010 = 10^{-4}$ and

$\Delta\upsilon = \Delta\upsilon/(\Delta I/I_o) * \Delta I/I_o = 3.57 * 10^{-4} = 3.6 \times 10^{-4}$ for least count at injection,

again, just within the $\Delta\upsilon < 0.0005$ requirements of Beams-Doc-877.

Since the sensitivity of tune to other quadrupole power supplies in the C0 low-β insertion is much less that for the quad riplet at collision or for the least significant bit at injection. Similar 10 ppm power supplies with 16 bit D/A converters will be more than sufficient for these other quadrupoles. In fact, the requirements for QT, Q8, and Q9 could even be relaxed to 10% power supplies.