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TEVATRON AC DIPOLE SYSTEM*

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Abstract

The AC dipole is an oscillating dipole magnet which can induce large amplitude oscillations without the emittance growth and decoherence. These properties make it a good tool to measure optics of a hadron synchrotron. The vertical AC dipole for the Tevatron is powered by an inexpensive high power audio amplifier since its operating frequency is approximately 20 kHz. The magnet is incorporated into a parallel resonant system to maximize the current. The use of a vertical pinger magnet which has been installed in the Tevatron made the cost relatively inexpensive. Recently, the initial system was upgraded with a more powerful amplifier and oscillation amplitudes up to 2-3σ were achieved with the 980 GeV proton beam. This paper discusses details of the Tevatron AC dipole system and also shows its test results.

INTRODUCTION

An AC dipole is a tool to excite transverse motions of a beam in a synchrotron for machine diagnosis. It produces an oscillating dipole field and drives the beam. Unlike a conventional single turn kicker/pinger magnet, it can produce large transverse oscillations without the emittance growth and decoherence [1].

AC dipoles have been used in the AGS and RHIC at BNL [1, 2] and was also tested in the CERN SPS [3]. For the FNAL Tevatron, after preliminary tests in last year [4], the system was upgraded and a vertical AC dipole has been in operations. There is also an ongoing project to develop AC dipoles for LHC too [5].

THE MAXIMUM AMPLITUDE

The amplitude of the oscillations excited by an AC dipole is approximately given by

$$\frac{B\ell}{4\pi(B\rho)|\delta|}\sqrt{\beta_{\text{acd}}\beta}\ , \qquad (1)$$

where B and ℓ are the maximum field strength and length of the AC dipole, $(B\rho)$ is the magnetic rigidity, δ is the difference between the driving tune and natural tune[1], and β_{acd} and β are β functions at locations of the AC dipole and observation [1, 6, 7]. For the Tevatron and its vertical AC dipole, $B\ell \lesssim 90$ Gm, $(B\rho) \simeq 3.3\ 10^3$ Tm at 980 GeV, $|\delta| \gtrsim 0.01$, $\beta_{\text{acd}} \simeq 47$ m and $\beta \simeq 100$ at a typical vertical beam position monitors (BPMs) in the arc. Hence, the maximum oscillation amplitde produced by the Tevatron vertical AC dipole is about 1.5 mm at vertical BPMs in the arc. Since the vertical beam size is 0.5-0.6 mm at these locations, 1.5 mm corresponds to 2.5σ.

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[1] In the following part of the paper, for any tunes, only their fractional parts are considered.

FREQUENCY OF THE SYSTEM

To excite large amplitude oscillations, the frequency of an AC dipole is chosen to be very close to the betatron frequency. For the Tevatron AC dipole, this frequency happens to be 20 kHz and hence it can be powered by an inexpensive high power audio amplifier.

When a circulating beam is observed at one location of a ring, only the fractional part of the tune ν or $1-\nu$ can be known. Hence, if the revolution frequency of the beam is f_r, the frequency of the Tevatron AC dipole can be $f_r\nu$ or $f_r(1-\nu)$ or any of their higher harmonics. Since the revolution frequency and tune of the Tevatron are $f_r \simeq 47.7$ kHz and $\nu \simeq 0.58$, the frequency of the Tevatron AC dipole can be 27.7, 75.4, 123.0, ... kHz or 20.0, 67.7, 115.4, ... kHz, where the lowest is 20 kHz.

SYSTEM CONFIGURATION

Fig 1 shows the schematic diagram of the Tevatron vertical AC dipole system. Esentially, the Tevatron AC dipole is a combination of an iron core magnet and audio amplifier with a resonant circuit. This may be contrasted with AC dipoles in RHIC which have to operate at higher frequencies than 20 kHz [2]. On the other hand, the AC dipoles for the LHC whose frequency is also in the audio range will be similar to the Tevatron AC dipole system: the existing pingers powered by audio amplifiers.

Magnet and Cables

The magnet of the Tevatron vertical AC dipole is a single turn iron core magnet with a ceramic beam pipe. It has been already installed in the Tevatron as a vertical pinger and was tested to work as a 20 kHz AC dipole [4]. Fig 2 is the design drawing of its cross section. Since its length is $\ell = 1.89$ m and gap width is $g = 3.125$ inch, the integrated field strength $B\ell$ and current in the magnet I satisfy

$$B\ell = \frac{\mu_0 I\ell}{g} \simeq 0.3I \quad \text{Gm}\ . \qquad (2)$$

The magnet is connected to other components of the system through two 22 m coaxial cables RG-220. The combination of the magnet and two cables has $L = 8.2\ \mu$H and $R = 100$ mΩ at 20 kHz and it is estimated that 2.8 μH and 25 mΩ come from cables. Here, the capacitance of the

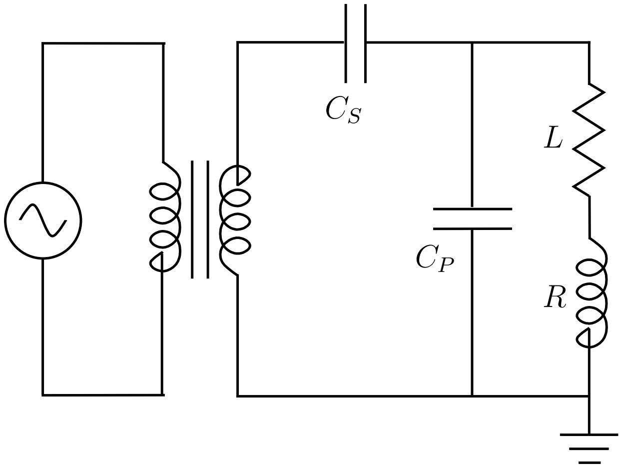

Figure 1: Schematic diagram of the Tevatron vertical AC dipole system. The frequency of the system is about 20 kHz. The power supply is an 8 kW audio amplifier. At 20 kHz, the magnet and cables have $L = 8.2\ \mu$H, $R = 100$ mΩ and its impedance is $|Z_{\text{mag}}| = |R + i\omega L| \simeq 1.0\ \Omega$. A capacitor $C_P = 8.0\ \mu$F is added to form a parallel resonant system. The series capacitor $C_S = 6.2\ \mu$F is filtering the low frequency noise from the amplifier. The (1:1) transformer is used for the conversion from balanced side to the unbalanced side. At 20 kHz, the total impedance seen from the amplifer is $|Z_{\text{tot}}| \simeq 10\ \Omega$.

cable is ignored because its contribution to the reactance is less than 0.1% at 20 kHz.

Power Supply

An 8 kW Crown I-T8000 audio amplifer is used to power the Tevatron vertical AC dipole system. The maximum output power of the amplifier is achieved when the total impedance is 8 Ω [8]. In general, a transformer can convert

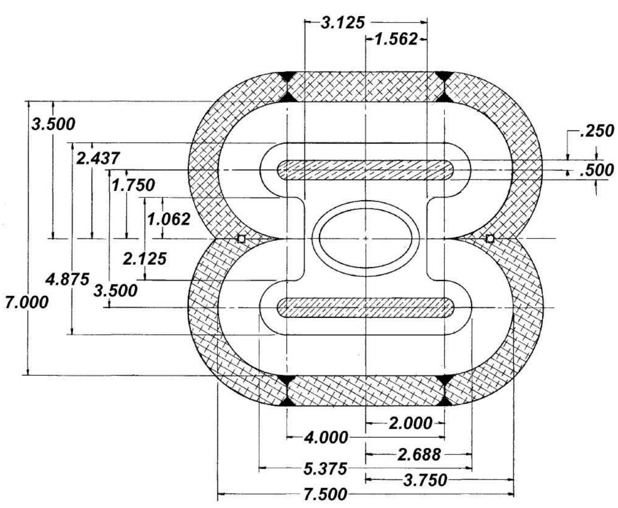

Figure 2: Design drawing of the Tevatron vertical AC dipole magnet. Dimensions are given in inches.

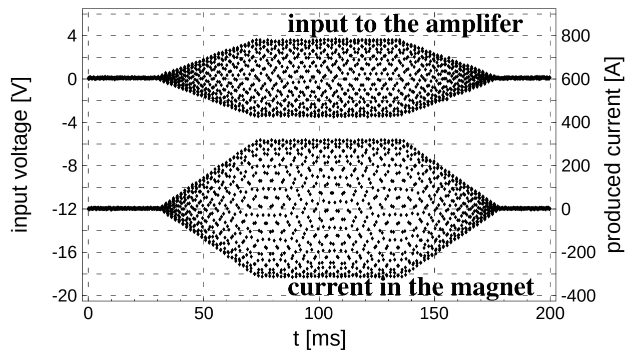

Figure 3: Input signal to the amplifier and current in the magnet. The input is created by two waveform generators. One creates 20 kHz sine waves and the other modulate its amplitude. The signal noise ratio of the current in the magnet was more than 20 dB in this case.

the total impedance to the optimum value for the amplifier. As explained in the next section, when the resonant system is formed, the low impedance of the magnet with cables $|Z_{\text{mag}}| \simeq 1.0\ \Omega$ is converted to the $|Z_{\text{tot}}| \simeq 10\ \Omega$ which happens to be not far from the ideal value (8 Ω) for the Crown amplifier. Hence, nothing has been done to fix this 2 Ω difference so far[2].

When the field strength of an AC dipole is adiabatic ramp up and ramp down before and after the beam excitation, the beam emittance is preserved. Fig 3 shows an example of the input signal to the amplifier and current in the magnet. To produce such input signals, two waveform generators are used. One produces a sine wave with the proper frequency (∼20 kHz) and its amplitude is modulated by the trapezoidal envelope function created by the other.

Parallel Resonant Circuit

A capacitor C_P is added to the magnet and cabels to form a parallel resonant system and maximize the current in the magnet. The capacitance $C_P = 8.0\ \mu$F is determined from the resonant condition: $1/\omega C_P \simeq \omega L$. When the resonant condition is satisfied, the total impedance becomes maximum[3]: $|Z_{\text{tot}}| \simeq (\omega L)^2/R \simeq 10\ \Omega$.

Fig 4 shows the measured total impedances (magnitude and phase) of the system for various frequencies. As expected, the peak of the magnitude is about 10 Ω and around 20 kHz.

CURRENT IN THE MAGNET

With the system described in the previous section, more than 300 A of current is produced in the magnet (Fig 3). Notice, thanks to the parallel resonant circuit, the current going through the amplifier is suppressed to about 30 A at

[2]If this 2 Ω difference is fixed by changing the winding ratio of the transformer, the gain in the current is $(10/8)^{1/2} - 1 \simeq 12\%$.

[3]The contribution to the total impedance from the series capacitor C_S is estimated about 1% and simply ignored here.

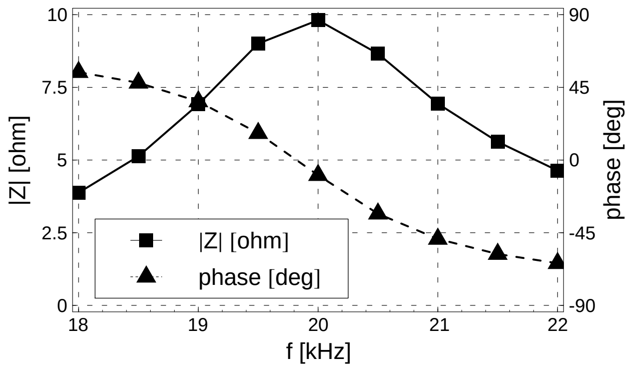

Figure 4: The total impedance vs frequency for the Tevatron vertical AC dipole system. The peak of the magnitude is 10 Ω at 20 kHz as expected. Q value is about 10.

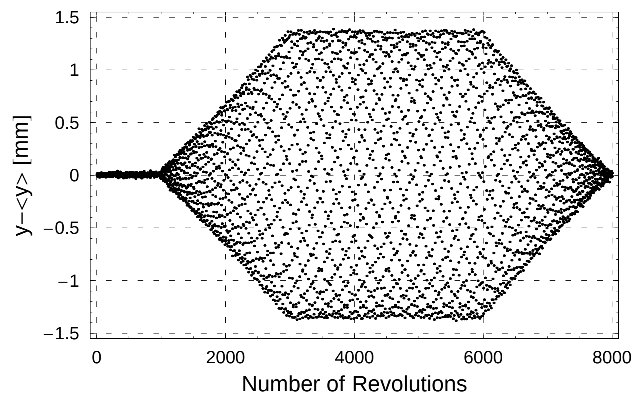

Figure 6: Turn-by-turn positions of the oscillations excited by the Tevatron vertical AC dipole.

the same time. Since the most of current is comfined between the capacitor and inductor, a parallel resonant circuit helps to produce large current from an amplifier with a low current limit. The current limit of the Crown I-T8000 is about 45 A [8].

The maximum current produce by the system was also measured for various frequencies. Fig 5 shows the maximum current between 18 to 22 kHz which corresponds to ± 0.04 of tune. Notice the current is still as high as 270 A at 18 kHz and 200 A at 22 kHz. This wide peak and, hence, wide tunability come from low Q value of the magnet ($Q \simeq 10$). Asymmetry of the curve is caused by the typical roll-off of audio amplifiers when frequency is over 20 kHz.

TEST WITH BEAM

The system was tested with 980 GeV proton beam in the Tevatron. Fig 6 shows turn-by-turn vertical positions of the beam excited by the AC dipole. The data was recorded by a BPM in the arc of the Tevatron. The produced amplitude was 1.3-1.4 mm whereas the expection is about 1.5 mm from Eq 1. Fling wire measurements showed no sign of beam size growth in either of transverse directions before and after the excitation.

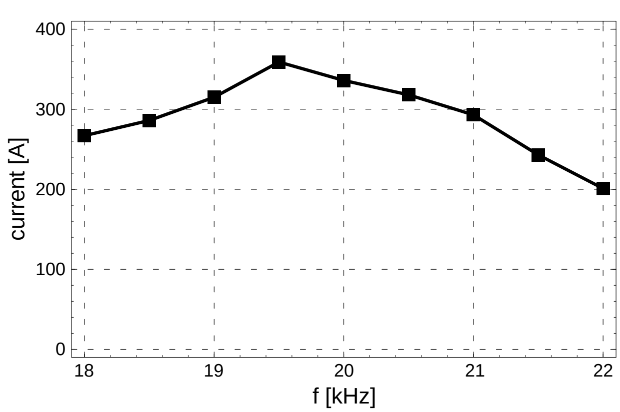

Figure 5: The maximum produced current vs frequency.

PLANS FOR UPGRADES

There are two upgrade plans for the power supply. The first is to use the other 13 kW amplifier, Lab Gruppen FP13000. The second is to stack two Crown I-T8000 amplifiers by using transformers.

CONCLUSION

For a large synchrotron whose betatron frequency is in the audio range, an iron core kicker/pinger magnet may be used as an AC dipole and powered by an inexpensive audio amplifier. The current in the magnet of the Tevatron AC dipole system is maximixed by forming a parallel resonant system. With a Crown audio amplifier I-8000, 300 A of the current is produced in the magnet and the oscillation amplitude of 2.5σ is achieved for a 980 GeV proton beam without any significant beam size growth or beam losses.

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