MAGNETIC FIELD FLUCTUATIONS IN LHC MAGNETS

PART I: INTRODUCTION AND MEASUREMENTS AT CERN

JANUARY 23-26 2006

(DRAFT)

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Abstract

Magnetic field fluctuations at the betatron frequency can lead to emittance growth in circular accelerators. Tolerances are extremely tight for the Large Hadron Colliders LHC [1]. We have started experimental studies of the fluctuations in the LHC superconducting magnets. This (first) report introduces into the problem, summarizes results of measurements at CERN in January 2006 and sets directions for future work.

1 INTRODUCTION: EMITTANCE GROWTH DUE TO MAGNETIC FIELD FLUCTUATIONS

Magnetic field fluctuations at the betatron frequency will cause miniscule turn-to-turn variation of the bending angle $\delta\theta=\theta_0\ \delta B/B$ in each dipole magnet and that will lead to the horizontal emittance growth [1, and Ref therein] :

$$d\varepsilon_N/dt= f_O\ \gamma\beta_{\mathrm{ave}}\ (\delta B_{\mathrm{eff}}/B)^2/(2N) \qquad (1)$$

where f_o is the revolution frequency, γ is the relativistic factor, β_{ave} is average beta-function, N is the total number of dipoles and $\delta B_{\mathrm{eff}}/B$ is the effective rms amplitude of the field fluctuations which for "colored" noise with power spectral density $S(f)$ can be defined as

$$(\delta B_{eff}/B)=[2\ f_o\ \Sigma S(f_o|n-Q|)]^{1/2} \qquad (2),$$

Q is the horizontal tune. Table 1 from [1] presents relevant parameters of large hadron colliders and values of $\delta B_{eff}/B$ which will lead the emittance doubling over the characteristic time intervals (store time for VLHC-Stage I, LHC and Tevatron, synchrotron radiation damping time for VLHC-Stage II). One can see that the tolerances for all machines , including the LHC are very tight ($\delta B_{eff}/B \sim 10^{-10}$). Tevatron dipole field fluctuation measurements performed at FNAL Magnet Test Facility in 2000-2001 have shown that the amplitude of field fluctuation falls with frequency and thus, lower betatron frequency in the LHC (wrt Tevatron) is to disadvantage. Another conclusion was that turbulence of the He flow may laed to the field fluctuations – in the case of the LHC it's of a big concern because the beam screen inside the magnet aperture (quite light object by itself) will be cooled by 5-20K Helium flow (presumably turbulent). Tevatron dipole results are summarized in Fig. 1.

Table 1: Parameters and $\delta B_{\mathrm{eff}}/B$ tolerances for large hadron colliders

	VLHC-I	VLHC-II	LHC	Tevatron
ε_N, µm	1.5	0.2	3.75	3.3
τ, hrs	10	2	10	10
ε_N/τ, fm/s	40	27	100	90
γ	20000	87000	7000	1000
f_o, kHz	1.3	1.3	11.3	48
N	3440	13800	1200	774
β_{ave}, m	170	170	67	50
Q	212.3	212.3	64.28	20.55
$f_{\mathrm{res}}=f_o\Delta Q$,Hz	400	400	3400	20000
$\delta B_{eff}/B$, 10^{-10}	7.8	6.0	2.8	2.1

Similar effect of turn-by-turn filed variation may be caused by vibration of quadrupoles, corresponding theory and estimates can be found in e.g. [2], some experimental results in [3]. Notably, the tolerances on vibrations for arc quadrupoles are in the range of few Angstroms (0.1nm) at the betatron frequencies.

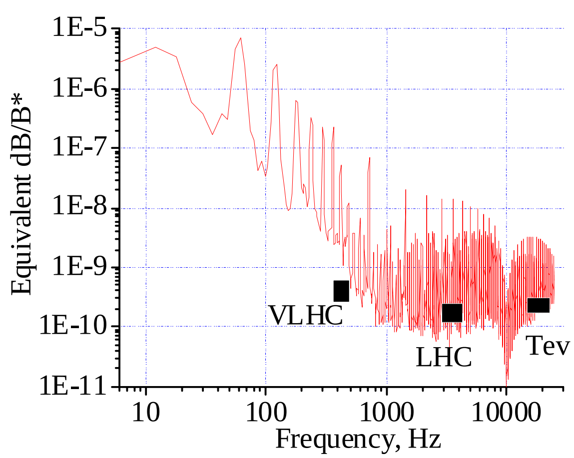

Figure 1: Equivalent rms field fluctuations in Tevatron dipole at 4T and tolerances for large hadron colliders.

Once again, we attract attention to the fact that field fluctuations in the LHC dipoles and quadrupole center vibrations can be enhanced in the presence of the beam screen. The broad band Helium turbulence leads to jitter of the beam screen walls, the screen changes its shape (quadrupole oscillation) that results in the magnetic field fluctuations because of the "frozen magnetic flux" effect at high frequencies. Indeed, the beam pipe radius variation of δR will result in the field variation of $\delta B/B=-\delta R/R$. For the LHC dipole beam screen radius R=25 mm, and one needs only $\delta R=10^{-5}$ μm to get the value of $\delta B/B=3\times10^{-10}$.

Objectives of our work are: a) measure the spectrum of magnetic field fluctuations in the LHC dipole at nominal field in the frequency range from 100Hz to 20kHz with and without beam screen; b) measure the spectrum of the quadrupole magnet center in the LHC quadrupole at nominal field in the frequency range from 100Hz to 20kHz with and without beam screen; c) study the dependence of the filed fluctuations on the rate of cooling He in the beam screen and its temperature; d) study correlations of the fluctuations along the length of the magnet. Experimental data are needed for estimates and modeling the LHC beam emittance growth and – if the latter will be found unacceptable - for design of a corresponding damper (a low-noise feedback system which damps coherent beam oscillations caused by turn-by-turn noises can effectively reduce the emittance growth rate).

2 MEASUREMENTS AT CERN IN JANUARY 23-26, 2006

The first measurements have been performed in January 2006 and they were mostly preparatory. Main results will be presented below and include: a) calibration of 5 different types of coils which can be used for field fluctuation measurements; b) determination of natural frequencies of the beam screen; c) field fluctuation measurements in the MQY quadrupole at "block 4" test facility; d) measurements of the warm LHC dipole transfer function at frequencies upto dozens of kHz; e) additional transfer function reduction by beam screen.

2 a): Calibration of coils

Five coils were calibrated at the Bld.181 test stand. The stand consisted of pair of Helmgoltz-like dipole coils received FNAL 20cx120cm 100 turns each placed 20 cm above one another, excited by Agilent 10 V AC function enerator. The current in the excitation coil was measured as voltage across 1 Ohm resistor. Resitatnce of the excitation coils was 5.5 Ohm. They create vertical magnetic field in between them of 2.95+-0.1 G/A at the frequency of the generator.

	Coil#1&2	Coil#3	Coil#4	Coil#5
C, V/G/Hz	6e-3	2e-3	1.3e-4	1.3e-4
Max.freq,*kHz*	6	2	20	40
R, Ohm	332	4500	600	300
#of turns	930	256	150	36
Length, cm	50	200	24	120
Area, m^2	10	7.66	0.32	0.31

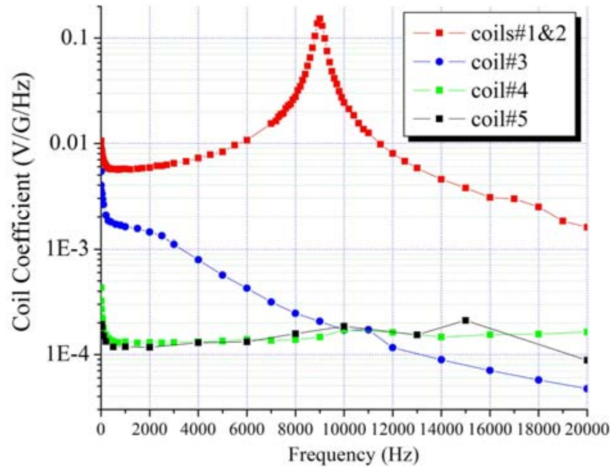

Figure 2: Calibration coefficients of the measurement coils vs frequency.

2 b): Natural frequencies of the beam screen

About 2 m long piece of the LHC dipole beam screen was inserted inside 10-cm long B=700 G permanent dipole magnet. Coil #4 was set inside the screen at the location of the magnet. Then, the beam screen was pinged (by a screwdriver) and the coil detected B-field ripple induced by the waves in the screen. Fig.3 shows and example of the coil signal.

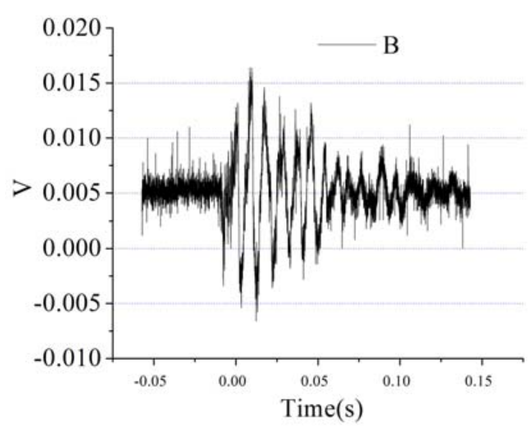

Figure 3: Signal from the coil#4 induced after beam screen ping.

The FFT of such signals and spectrum of the noise (no ping) are presented in Fig.4. Notable peaks are at frequencies 112Hz, 200Hz, 260Hz, 1070Hz, 1500Hz, 3500Hz. Rms noise amplitudes at frequencies >1000hz are about 50 uV.

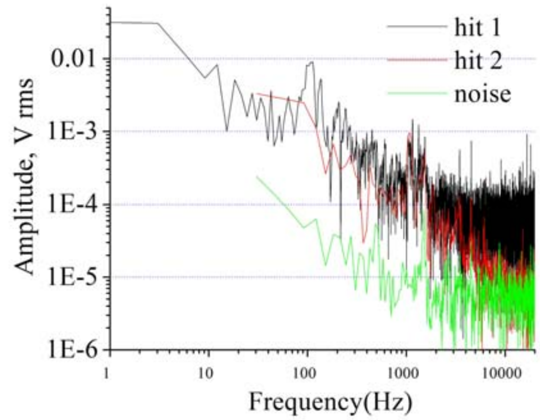

Figure 4: Spectra of the signals induced by hitting beam screen immersed in B-field and of background noise.

2 c): *Magnetic field fluctuations in MQY quad*

On Jan 25, 2006, we got several hours to measure field fluctuations in the "block 4" vertical cryostat facility where a MQY quadrupole was installed and equipped with rotating coils of type as "coil #5". The quadrupole was immersed in 4.5K Helium bath. There was no beam screen installed in the quad. Maximum current in the quadrupole was limited to 2kA (out of max 3.6kA which corresponds to 160 T/m gradient). Voltage from "coil A" (most radially outward coil) was recorded by Tektronix 3062 digital scope (20khz LPF was used) - an example of coil signal at 2kA is presented in Fig.5.

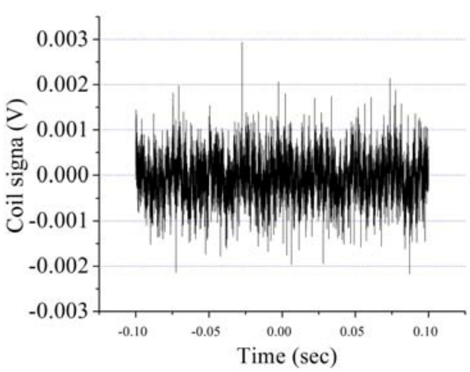

Figure 5: Signal from a coil #5 placed in SC MPY quadrrupole at 2kA.

Spectrum of the signal is presented in Fig.6. One can see prominent peak sat 40 Hz (?) 240 Hz(?) and 1750 Hz and 1820 Hz. If one assumes that the field at the location of the coil is about B=2T, then, the relative field fluctuation amplitude can be estimated as using known coil coefficient as $\delta B/B=\delta V/C/f[Hz]/B$ – see results in Fig. 7. Note, that at the frequencies above few kHz , the noise signal (recorded with quad PS turned off) takes over the 2kA signal. A higher resolution ADC and more averaging would help to improve signal to noise ratio. Similar spectra were calculated for the DCCT signal (proportional to the PS current as 0,65 V/A) but they were completely dominated by noise ~1e-6 level.

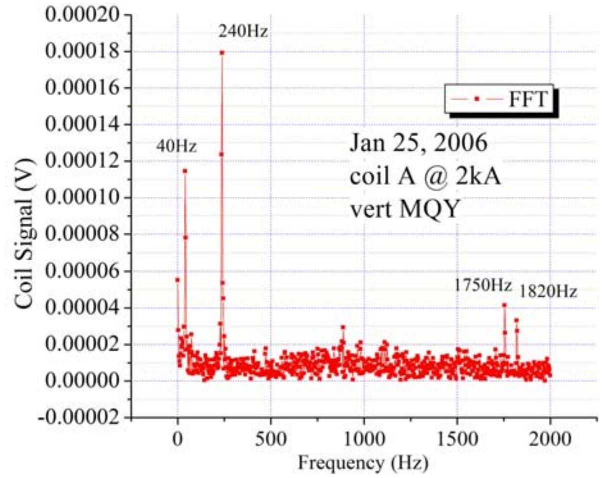

Figure 7: Signal from a coil #5 placed in SC MPY quadrrupole at 2kA.

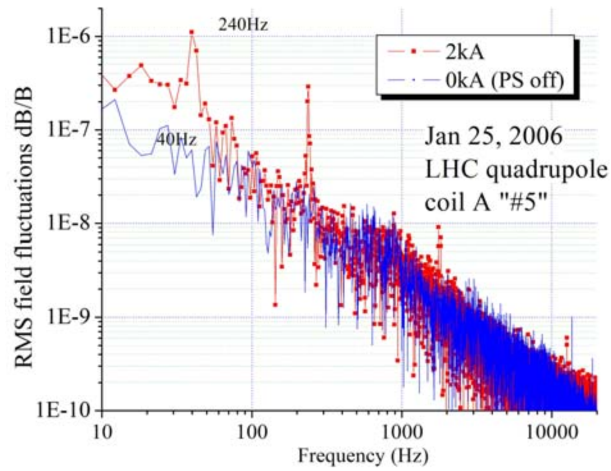

Figure 8: Signal from a coil #5 placed in SC MPY quadrrupole at 2kA.

2 d): *Magnetic field ripple from current*

If the magnet current is not stable, the magnetic field inside the bore will fluctuate as well. We excited a warm LHC dipole in Bld.181 by dU=10V AC voltage from a function generator and recorded voltage induced in the measurement coils #3,4, and 5. The dipole current amplitude is $dJ=dU/(6Ohm+2*3.14*f[Hz]*0.1Hn)$. Signal induced in the measurement coil is approximated as $dV= K*dB[G]$ (that is not exactly true - see paragraph 2a). The function $R=0.7[G/A]*dJ*K/dV$ is plotted in Fig..yyy. Coefficients K for each coil were adjusted "by hand" in order R to be 1 at low frequencies. Difference in suppression factors measured by different coils could be explained by significant interference due to stray-capacitance induced signals (though, not everything is understood yet). In any case, suppression factor is about

0.9 at 3kHz and about 0.3-0.7 at 10 kHz. For reference, skin depth in SS is about 7 mm at 5kHz.

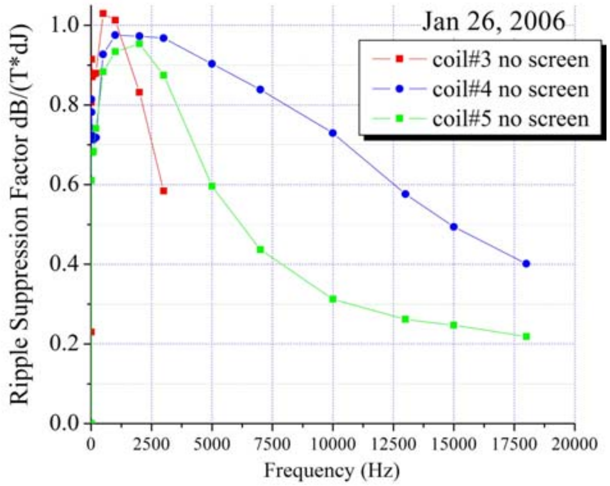

Figure yyy: Magnetic field ripple suppression vs frequency.

2 e): *Field suppression by beam screen*

The same measurements as in 2 d) were performed with beam screen. Ratios of signals from all three coils with and without the beam screen are presented in Fig.xxx. One can see that the screen provides additional reduction of about 0.7 at 4kHz and about 0.1-0.3 at 10kHz. Skin depth in copper at 5kHz at room temperature is about 1mm, so at 2K it will be ~5-7 times thinner or ~150-200 um, which is still several times bigger than 50 um thickness of the Cu layer on inner surface of the screen – thus, one should not expect significant difference in the screen effect at room and nominal temperatures.

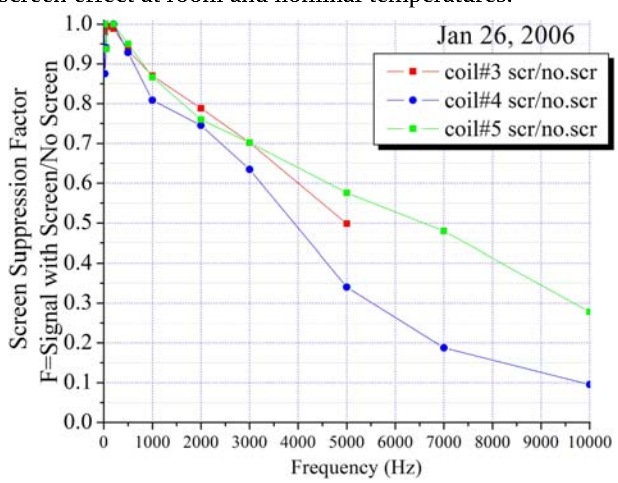

Figure xxx: Additional field suppression by beam screen vs frequency.

3 PLANS FOR FUTURE STUDIES

Preliminary studies show viability of field fluctuation measurements with coils. To achive objectives of this work (see Section 1) a series of preparatory actions have to be undertaken:

1. a suitable (piezo?-)accelerometer should be found which can be put inside the screen (attached to it) at 2K to measure screen vibrations at frequencies 100-10000 Hz
2. a set of G10 fixtures has to be designed and built to hold coils and piezo accelerometers inside dipoles/quadripoles inside beam screen/without beam screen (some engineering help might be needed)
3. as noises and grounds are important for he measurements, cables/twisted pairs, flanges and feedthrus which are needed to deliver signal from coils/acceleromters to out of cryostat should be carefully considered and selected
4. a better ADC – preferreably >16 bit with bandwith of >20kHz and sampling rate ~50kHz - should be found and tested prior to the measurements

Some prelimary dates for the dB/B and vibration measurements in horizontal test facility (SM18) should be set and we have to be prepared for it. It is important to keep R.deMaria – besides all others - involved: a) it's along the lines of his PhD work; b) he will talk to SC RF guys to figure out what kind of accelerometers they have to measure microphonics); c) later, he can use the measurement data in the LHC beam dynamics simulations/tracking.

A bit extended action item list (RdM):

- understand the mechanical properties of the beam screen(calculation of the natural oscillation modes with numerical codes)
- understand the connections of the beam screen with the beam pipe and other equipment which may dump/enhance the oscillation modes (talk to Luca)
- understand the working condition of the Helium flow and estimate the power spectrum, typical length (talk with Luca, cryogenics people, fluid dynamics experts)
- understand the coherence length of the oscillation in the bean screen
- design a coil with flat response up to 20kHz (the longitudinal length of the coil should be less than 1/20kHz * 5km/s = 25cm the wave length of a 20kHz oscillation in SS; talk with RF people; calibrate at low temperature).

4 REFERENCES

[1] V.Shiltsev et. al, Proc PAC'01 (see attached)

[2] V.A. Lebedev, V.V. Parkhomchuk, V.D. Shiltsev, G.V. Stupakov, ``Emittance Growth due to Noise and its Suppression with the Feedback System in Large Hadron Colliders", Particle Accelerators , vol.44, No. 3-4, pp. 147-164 (1994).

[3] B.Baklakov et. al, PhysRevSTAB, 031001 (1998)

ADDENDUM 1: *PAPER FROM PROCEEDINGS OF IEEE 2001*

MAGNETIC FIELD FLUCTUATIONS IN SC DIPOLE MAGNET

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Abstract

Magnetic field fluctuations at the betatron frequency can lead to emittance growth in circular accelerators. Tolerances are extremely tight for large hadron colliders like LHC and VLHC[1]. We performed experimental studies of the fluctuations in a stand-alone superconducting Tevatron magnet. Here we give a general description of the experimental set-up, present main results and discuss consequences for the colliders.

1 INTRODUCTION

Fig.1 shows general layout of the experimental set-up. Two 930 turn coils (dimensions 50cm×2cm×1cm) are set one after another on a G10 bar which is inserted inside the Tevatron dipole magnet. The magnet has been operated in a stand-alone mode in the magnet test facility (MTF) of the Fermilab Technical Division. It has a separate power supply to provide some 4T (vertical) dipole magnetic field at 4,000 A of current in superconducting coils. The plane of the measurement coils (see Fig.1) is perpendicular to the magnetic field, so any variation of the magnetic field flux through the coil results in induced voltage

$$dU=-d(Flux)/dt=-2\pi f\, dB*A \qquad (1)$$

where f is frequency and A=100cm^2 is the coil area. The induced voltage was measured by HP3458A digital voltmeter (DMM) with 19 bit resolution at 50 kHz sampling rate.

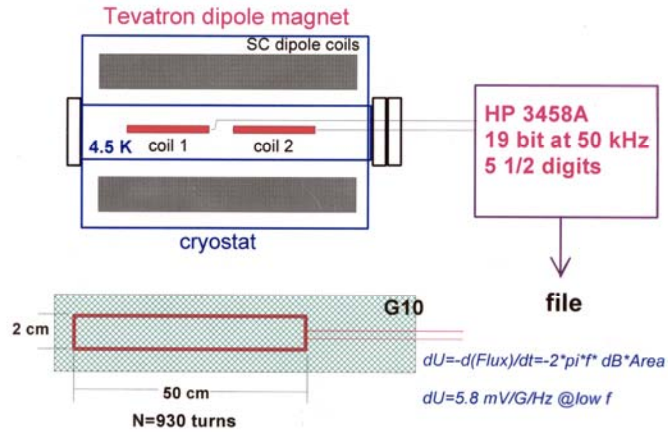

Figure 1: General layout of the set-up to measure *dB/B* fluctuations.

Because of the coil capacitance and resistance, its frequency characteristics differs from pure inductance. Result of the coil sensitivity calibration is presented in Fig.2. One can clearly see a resonant peak with $Q\approx20$ at f=10kHz. The calibration was performed at room temperature, while the coil stays at about 4.5 ^{o}K when inside the SC Tevatron dipole. Because of the material shrinking, the resonant peak may be shifted at low temperatures as well as change its quality factor. We had no possibility to calibrate the coils at the liquid Helium temperatures.

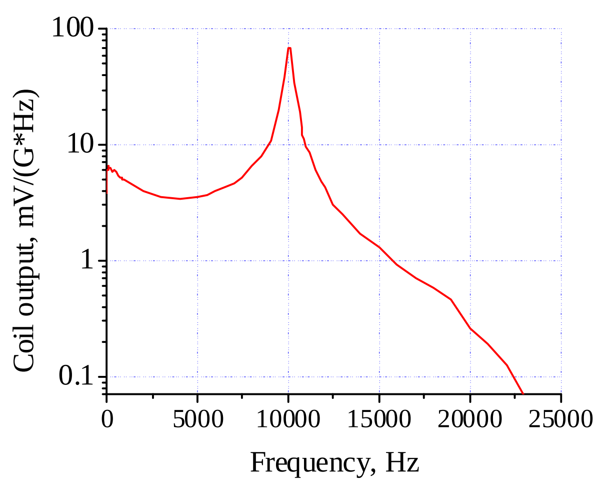

Figure 2: Sensitivity of the measurement coil.

2 RESULTS

The field fluctuation measurements were carried out in October 1999 at the Fermilab TD/MTF.

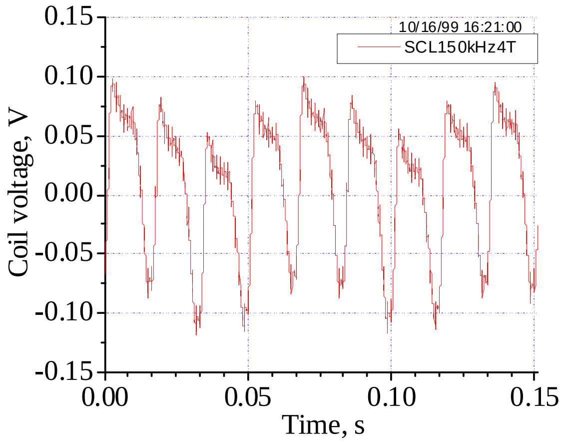

Figure 3: Coil voltage induced at 4T magnetic field.

Fig.3 shows a typical time record of the coil voltage induced in 4T field. The most visible is 60 Hz component, while high-frequency components are seen, too. The time records were processed by the FFT with Hanning window and resulting spectra are presented in Fig.4. Here the lowest curve shows the spectra of the DMM noise measured when the DMM input was connected to the ground. Two intermediate curves reflect noises in the coil with the magnet power supply off and with the power supply on but set at zero current. Finally, two upper curves are for the voltages induced in the coil at 2T and 4T magnetic field

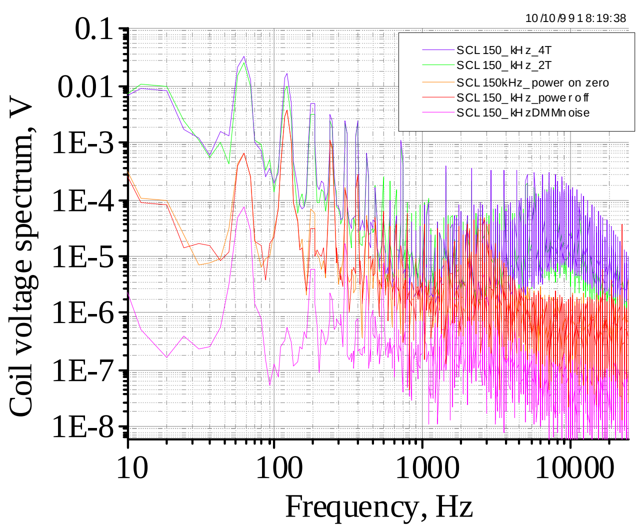

Figure 4: Coil voltage spectra.

One can conclude that the signal to noise ratio exceeds 10 over the entire frequency range of 10 to 25,000 Hz.

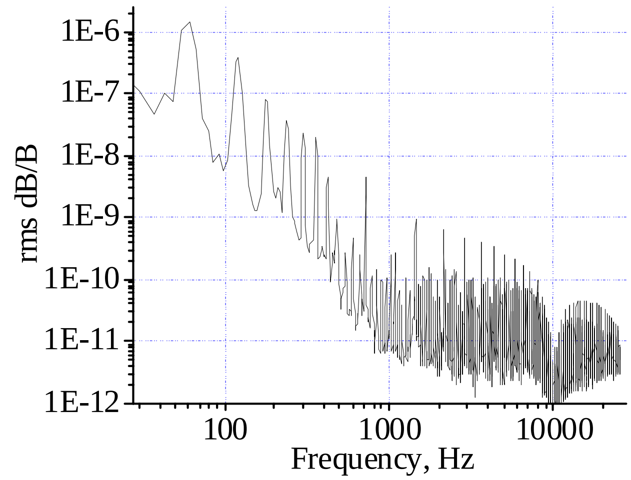

Figure 5: Rms field fluctuations in Tevatron dipole at 4T.

Applying calibration data to the raw signal spectrum and dividing by the maximum DC magnetic field we get rms *dB/B* fluctuation spectrum as depicted in Fig.5. One can see following remarkable features: a) the maximum noise amplitude takes place at 60 Hz and does not exceed the value of 2×10^{-6}; b) 60 Hz harmonics dominate the spectrum until about 1000 Hz, the harmonic amplitude goes down approximately as $1/f^3$; c) there is a dip at 10,000 Hz that reflects known coil calibration which may be incorrect at LHe temperatures because we do not see any narrow peak at 10kHz in the raw data spectra – see Fig.4; d) above 700-1000 Hz, the spectrum flattens. The latter is of certain interest as that frequency range includes betatron frequencies of the VLHC, the LHC and the Tevatron.

We studied these excessive fluctuations in the second coil and found that while signals *U1* and *U2* look the same, the difference voltage between them grows at frequencies above 600 Hz – see Fig.6. The value of *rms (U1-U2)(f) /rms U1(f)* is about 0.007-0.009 at frequencies below 400 Hz, but it grows up to 0.3-0.5 above 600 Hz.

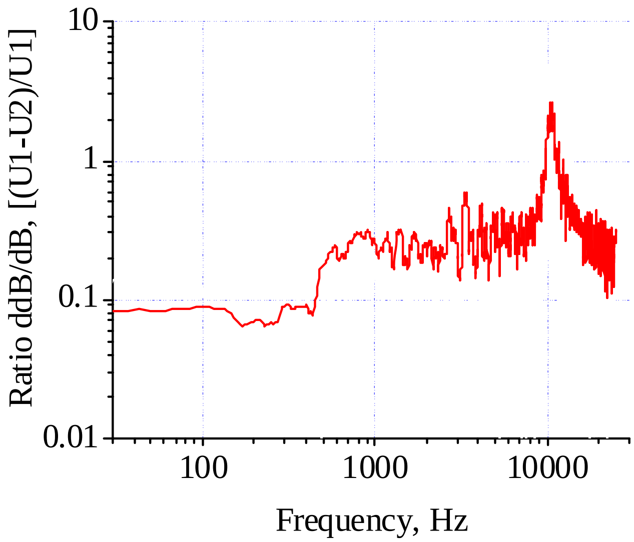

Figure 6: Spectral ratio of (signal difference)/(signal) .

One of the possible explanations of such behavior is that the field fluctuations are excited by sound waves due to turbulent flow of liquid Helium. The broad band turbulence leads to jitter of the beam pipe walls, the beam pipe changes its shape (quadrupole oscillation) that results in the magnetic field fluctuations because of the “frozen magnetic flux” effect at high frequencies [2]. Indeed, the beam pipe radius variation of δR will result in the field variation of $\delta B/B=-\delta R/R$. For the Tevatron dipole pipe radius R=35 mm, and one needs only $\delta R=10^{-6}$ μm to get the observed value of $\delta B/B=3\times10^{-11}$. Noteworthy to mention that $\delta R=10^{-4}$ μm vibrations in the frequency range of 600-1400 Hz were observed on the cold mass of the SSC dipole magnet [3].

3 EMITTANCE GROWTH DUE TO MAGNETIC FIELD FLUCTUATIONS

Magnetic field fluctuations at the betatron frequency will cause miniscule turn-to-turn variation of the bending angle $\delta\theta=\theta_0\ \delta B/B$ in each dipole magnet and that will lead to the horizontal emittance growth [1] as:

$$d\varepsilon_N/dt= f_O\ \gamma\beta_{\mathrm{ave}}\ (\delta B_{\mathrm{eff}}/B)^2/(2N) \tag{2}$$

where f_o is the revolution frequency, γ is the relativistic factor, β_{ave} is average beta-function, N is the total number of dipoles and $\delta B_{\mathrm{eff}}/B$ is the effective rms amplitude of the field fluctuations which for “colored” noise with power spectral density $S(f)$ can be defined as

$$(\delta B_{eff}/B)=[2\ f_o\ \Sigma S(f_o|n-Q|)]^{1/2} \tag{3},$$

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$\delta B_{eff}/B$, 10^{-10}	7.8	6.0	2.8	2.1

In Fig.7 we compare the tolerances with the equivalent field fluctuation amplitude calculated from experimental data for the 4T Tevatron magnet as $(\delta B/B)^*=[2\ f\ \Sigma S(f)]^{1/2}$ -compare with Eq.(3). One can see that the tolerances are about equal or less than the experimental data. That situation requires following comments: first, contrary to Fig.6, there was no indication in the Tevatron that the beam emittance grows due to the external noises – most of the growth is due to intra-beam scattering (emittance doubles in some 10 hours). The contradiction can be explained as that each magnet of the machine is a part of a long magnet line which has in total very large inductance which allows to filter 60 Hz (power line) harmonic very effectively, especially at high frequencies. The second possible reason of the absence of the emitance growth is that the rms field fluctuations are measured over 0.5 long section of 6 m long magnet, and it seems quite possible that the magnetic field fluctuations in different parts of the magnet may cancel each other, thus, producing less effect. Fig. 6 is quite in line with such a supposition. We also believe that the turbulent Helium effect should have coherence length much smaller than the magnet length (probably, comparable with the magnet transverse dimensions).

As for the other colliders, we have to note that the field fluctuations depend not only on the power supply stabilization but also on the magnet design. Therefore, no one expects to have the same fluctuations in the LHC and VLHC dipoles as in the Tevatron, because the magnets are very different from each other. Each of the magnet types needs to be measured separately for making specific predictions.

And finally, it is known that a low-noise feedback system which damps coherent beam oscillations caused by turn-by-turn noises can effectively reduce the emittance growth rate [4].

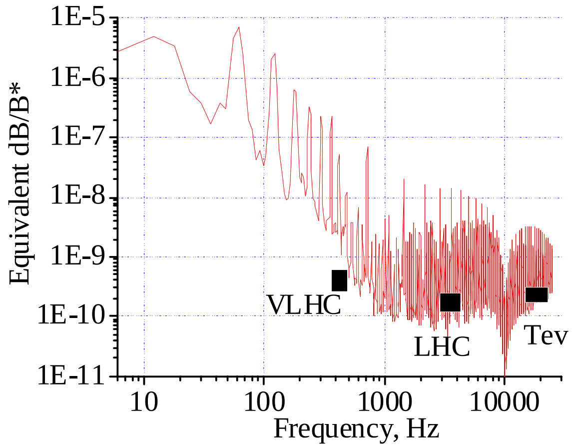

Figure 7: Equivalent rms field fluctuations in Tevatron dipole at 4T and tolerances for large hadron colliders.

Our future plans include magnetic field fluctuation measurements in the low-field VLHC SC dipole magnet and in the LHC SC final focus quadrupole magnets, which are under construction at Fermilab. In the case of quadrupoles, a system of four orthogonal coils will be used.

We are thankful to P.Schlabach, M.Tartaglia, D.Orris and P.Aarseth for valuable assistance in our studies.

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