FIELD FLUCTUATION AND BEAM SCREEN VIBRATION MEASUREMENTS IN THE LHC MAGNETS*

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Abstract

We present experimental methods and results for the measurement of the magnetic field fluctuation and beam screen vibration in the LHC magnets. These noises can lead to an emittance growth in proton beams if they have spectral components at the betatron lines. Preliminary estimates of the effects are given.

EMITTANCE GROWTH DUE TO MAGNETIC FIELD FLUCTUATIONS

Magnetic field fluctuations at the betatron frequency will cause miniscule turn-to-turn variations 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]:

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

where f_o is the revolution frequency, γ is the relativistic factor, $\beta_{\rm ave}$ is average beta-function, N is the total number of dipoles and $\delta B_{\rm eff}/B$ 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. The tolerance for the LHC is very tight [1], $\delta B_{eff}/B \sim 3\times10^{-10}$ will double the emittance over 10 hrs of store time. Tevatron dipole field fluctuation measurements [1] have shown that the amplitude of field fluctuations falls with frequency and, thus, a lower betatron frequency of 3.4 kHz in the LHC (vs 20 kHz in Tevatron) is a disadvantage. The turbulence of the He flow may lead to the field fluctuations, too – in the case of the LHC this is of big concern because the beam screen inside the magnet aperture will be cooled by a 5-20 K Helium flow. The broad band Helium turbulence leads to a jitter of the light beam screen walls; the screen changes its shape due to quadrupole oscillations that result 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, the beam screen radius is R=25 mm, and one needs only $\delta R=10^{-5}$ µm to get the value of $\delta B/B=3\times10^{-10}$. A similar effect – the induction of a dipole magnetic field can be caused by fast beam screen motion in the quadrupole magnets – see Fig.1.

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

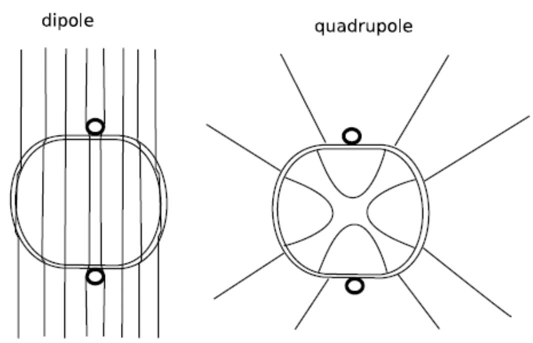

Figure 1: "Frozen" magnetic field lines in the LHC beam screen with shape oscillations (dip), and vibrations (quad).

FIRST MEASUREMENTS OF FIELD FLUCTUATIONS

Calibration of coils, beam screen resonances

Five coils used for the B-field fluctuation measurements were calibrated at the Bld.181 test stand. The stand consisted of a pair of Helmholtz-like dipole coils received from FNAL, size 20cmx120cm, 100 turns each placed 20 cm above one another, excited by an Agilent 10 V AC function generator. The current in the excitation coil was measured as voltage across a 1 Ohm resistor. The resistance of the excitation coils was 5.5 Ohms. They create a vertical magnetic field of 2.95+/-0.1 Gauss/A at the frequency of the generator. The calibration results are listed in the Table below.

	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

An ~2 m long piece of the LHC dipole beam screen was inserted inside a 10 cm long B=700 G permanent dipole magnet. Coil #4 was installed inside the screen at the location of the magnet. Then, the beam screen was pinged (by a screwdriver) and the coil detected a B-field ripple induced by the vibrations of the screen. The spectrogram (short time FFT versus time) of such signals is presented in Fig.2. Notable peaks due to the free standing beam screen resonances are at frequencies 1 kHz, 2.2 kHz, 3 kHz, and 5 kHz.

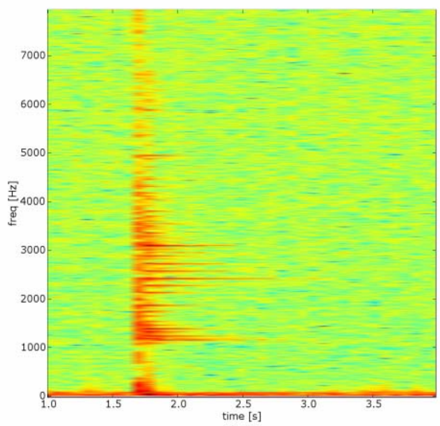

Figure 2: Spectrogram of the signals induced by hitting a beam screen immersed in a 700 Gauss B-field, illustrating the resonance frequencies of the beam screen sample.

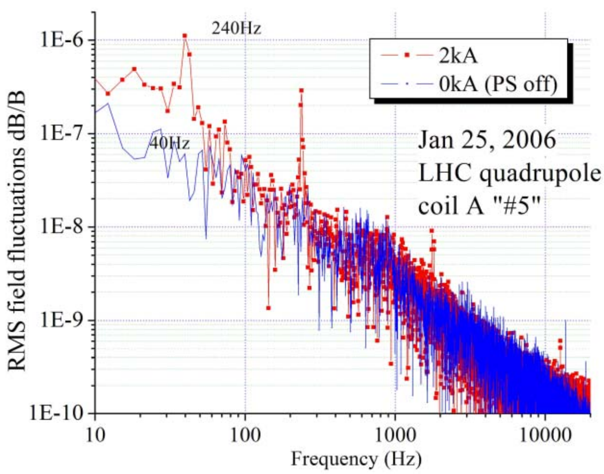

Figure 3: Signal from coil #5 placed in a SC MPY quadrupole at 2 kA.

Magnetic field fluctuations in a MQY quad

On Jan 25, 2006, we had 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 "coil #5". The quadrupole was immersed in a 4.5K Helium bath. There was no beam screen installed in the quad. The maximum current in the quadrupole was limited to 2kA (out of max 3.6kA which corresponds to a gradient of 160 T/m). The voltage from "coil A" (most radially outward coil) was recorded by a Tektronix 3062 digital scope (20 kHz LPF was used). The B-field at the location of the coil was about B=2 T. The relative field fluctuation amplitude can be estimated using the known coil coefficient as $\delta B/B=\delta V/C/f[Hz]/B$ – see results in Fig. 3. One can see peaks in the spectrum at 40 Hz, 240 Hz and 1750 Hz and 1820 Hz. Note, that at frequencies above a few kHz, the noise signal (recorded with the quad power supply turned off) is comparable to the 2 kA signal. A higher resolution ADC and more averaging helped to improve signal to noise ratio in subsequent measurements.

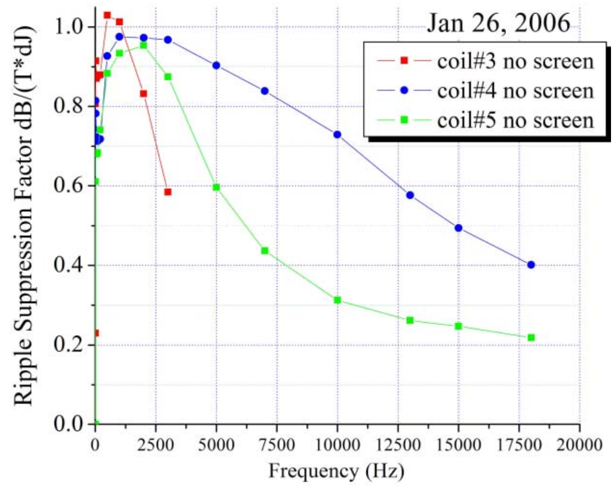

Figure 4: B-field ripple suppression vs frequency.

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 a dU=10V AC voltage from a function generator and recorded the voltage induced in the measurement coils #3, 4, and 5. The dipole current amplitude is $dJ=dU/(6Ohm+2*3.14*f[Hz]*0.1Hm)$. The signal induced in the measurement coil is approximated as $dV= K*dB[G]$ (that is not exactly true - see section 2). The function $R=0.7[G/A]*dJ*K/dV$ is plotted in Fig.4. Coefficients K for each coil were adjusted "by hand" in order for R to be 1 at low frequencies. The 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, the suppression factor is about 0.9 at 3 kHz and about 0.3-0.7 at 10 kHz. For reference, the skin depth in SS is about 7 mm at 5 kHz.

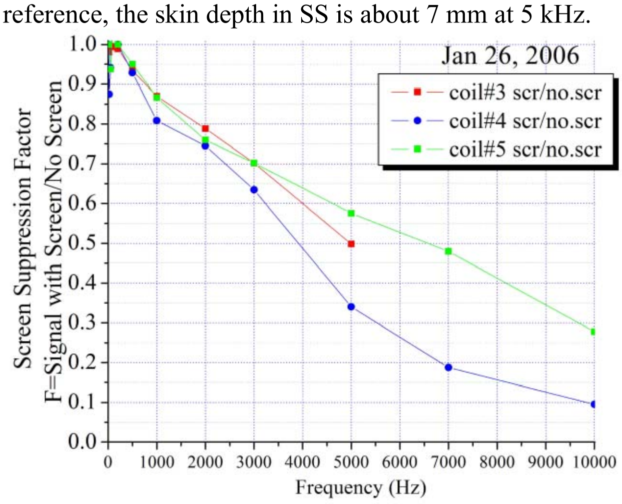

Figure 5: Additional field suppression by beam screen versus frequency.

Field suppression by the beam screen

The same measurements as above were performed with beam screen. The ratios of signals from all three coils with and without the beam screen are presented in Fig.5. One can see that the screen provides an additional reduction of about 0.7 at 4 kHz and about 0.1-0.3 at 10 kHz. The 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 to be compared with the 75 um thickness of the Cu layer on the inner surface of the screen. At cryogenic temperatures we should thus see a larger shielding of the magnetic field ripple due to the beam screen.

SCREEN VIBRATIONS

Direct measurements of screen vibrations were performed using a very light (30g) and small (20 mm height) EndevCo 2272 piezo-accelerometer (suitable for operation at He temperatures) and a 2775B Signal Conditioner.

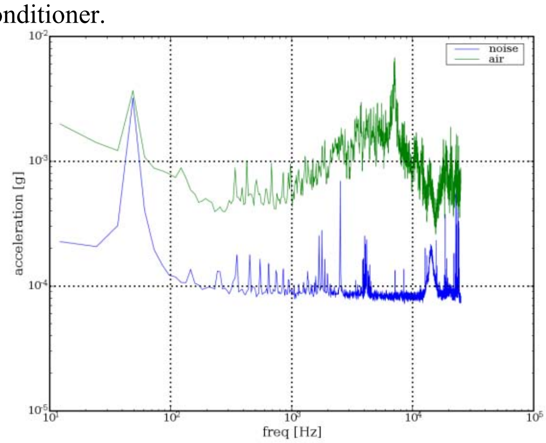

Figure 6: Spectrum of the piezo-accelerometer signal induced by an airflow in the beam screen cooling channel.

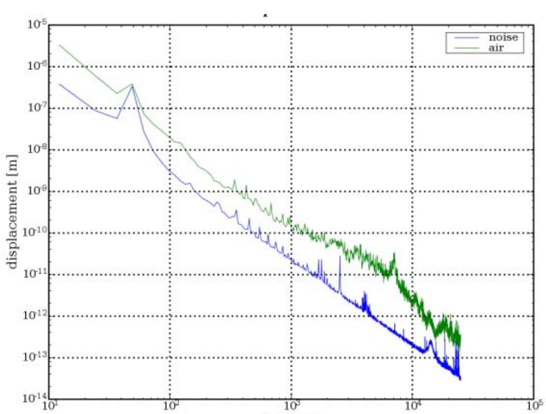

Figure 7: Spectrum of the piezo-accelerometer displacement signal induced by an airflow in the beam screen cooling channel.

The accelerometer sensitivity is 11.568 pC/g, the accelerometer capacitance 2700 pF. The output voltage of the signal conditioner was digitized by an HP3458A digital voltmeter (DMM) with 19 bit resolution at 50 kHz sampling rate. The accelerometer was placed inside the beam screen and tightly connected to it using a specially made fixture.

We did not have the possibility of measuring screen vibrations at cryogenic temperatures. Instead, we installed the beam screen inside a warm LHC dipole and blew air through the cooling channels of the beam screen using an 8 bar air compressor. One can see in Fig. 6 that the air flow excited screen vibrations in the frequency range from 1 kHz to 10 kHz.

The spectra of displacement x – calculated as $x=a/(2\pi f)^2$ where a is the measured beam screen acceleration, and f is the frequency – are shown in Fig.7. The blue curve represents the spectrum of the noise in the system of “accelerometer, signal conditioner, and DMM” measured when the air compressor was off. The green curve represents the measured vibration amplitude with full scale air flow. One can see that at the lowest LHC betatron frequency of f=3.4 kHz, the screen vibration amplitude is about $\delta R=5\times10^{-5}$ μm, which is equivalent to field fluctuations $\delta B/B=20\times10^{-10}$ or about factor of 5 above the tolerance.

CONCLUSION

In summary, we have measured the suppression of the transfer ratio of “current fluctuations/field fluctuations” for the LHC dipole in the frequency range from 10 Hz to 25 kHz. The reduction of the current induced field fluctuations by the conducting materials of the LHC beam screen was found to be roughly 0.5-0.6 at the lowest LHC betatron frequency of f=3.4 kHz. The only measurements of the field fluctuations with pick up coils inside an energized LHC SC magnet (quadrupole) were dominated by noise and revealed peaks in the spectrum at 40 Hz, 240 Hz and 1750 Hz and 1820 Hz. The effect of the 8 bar airflow through the cooling channels of a warm LHC beam screen inside a dipole magnet showed vibration amplitudes in the frequency range from 1kHz to 10kHz up to a factor of 5 above the collider tolerance. Our main goals for the next studies are to measure $\delta B/B$ and the vibration spectra inside 8.3T LHC SC dipole with beam screen installed and cooled by He.

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