EMC immunity test results of HCAL FEE.

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Abstract

The electromagnetic (EM) immunity of a device, equipment or system is its ability to perform without degradation in presence of EM disturbances. The characterization of the front-end electronics to these disturbances is an important object before the detector is integrated to guarantee the design goals and the good performance of the system.

This paper presents results of EM immunity test conducted on the front-end electronics of the CMS hadron calorimeter. These studies include the RF immunity, the voltage dip and the surge tests to characterize the FEE sensibility to external perturbations. It constitutes the last stage of the preliminary analysis for the proposal of the CMS EMC plan.

I. INTRODUCTION

During the last decades, EMC oriented design has evolved and the number of normalized EMC tests has increased due to the continuous growing of EM environment pollution. This pollution is mainly due to the proliferation of electronic equipment operating at higher frequencies and lower voltages. In high energy physics, the impact of large-scale integration of electronic devices and the large dimensions of the detectors proposed for the large hadron collider (LHC) at CERN make necessary to include during the design and integration EMC tests to preserve the original design goals of the system.

The international EMC community has been proposing and conducting tests to characterize systems and validate products to be commercialised in the market [1][2]. These tests range from the measurement of the harmonic content at the input power cables to the measurement of noise radiation and the susceptibility of systems up to 1GHz, the characterization of the equipment immunity to transient perturbations lasting from nanosecond to millisecond, *etc*. In CMS we have proposed an EMC plan [3] based on international standards and rules applied by the space community. This plan is limited to perform a few tests on the front-end electronics (FEE) and the power supplies to characterize the noise compatibility among subsystems and the FEE response to external perturbations.

EMC immunity tests allow determining the level of sensitivity of the FEE to take corrective actions in an early design stage to ensure the good compatibility among the sub-systems during the integration of the detector. Three different tests are conducted to characterize the FEE immunity: radio frequency (RF) immunity test, voltage dips and surge immunity test. The RF immunity test corresponds to the injection of perturbing currents through the input/output cables of the FEE to simulate the effect induced by conducted interference and external EM fields. These tests allow defining critical elements and inappropriate layouts responsible in the performance degradation of the FEE and taking corrective actions during the prototype stage [4].

The voltage dip immunity test is applied to determinate the susceptibly of the equipment to short voltage interruptions and voltage variations of the primary power supply. The test uses as guide the European standard EN-61000-4-11/ IEC-1000-4-11 [5]. Voltage dips of different amplitude and duration are applied independently to the voltages feeding each FEE power cable and the loss of data or loss of function is used as criteria to qualify the performance of the front-end electronics.

The surge test is conducted on the FEE to characterize the susceptibility of the equipment to malfunction or damage by over-voltage induced on the cables feeding it. Over-voltages can be generated by load changes, short circuits and faults to earth in power distribution cables, etc. The test uses as guide the standard EN-61000-4-5/ IEC-1000-4-5 [6].

This paper addresses the results of the described tests when applied to the FEE of the CMS hadron calorimeter (HCAL). These tests constitute the last stage of the preliminary analysis for the proposal of the CMS EMC plan.

II. RF IMMUNITY TEST

A. Generalities

The goal of these tests is to define the immunity level of the FEE to the conducted disturbances coupled into the input cables, identify the key elements for the noise degradation of the FEE and settle on the noise level required at the output of power supplies. Noise can be coupled to the FEE through the input power cables and slow control cables. These are the two paths for conductive coupling due to the FEE output signal is transmitted out to the counting room via optical fibre. Noise current can be induced in the cable shield by near and far external EM fields, forced to flow through the central conductors by the power supply outputs, *etc*. To emulate in a test set-up these interferences, four tests have been proposed and conducted to study FEE immunity level injecting currents through the input power cables of the FEE. These tests are:

1. Injection of shield currents.

2. Injection of common mode (CM) currents in the central conductors.

3. Injection of differential mode (DM) currents in the central conductors.

4. Injection of CM and DM currents.

B. *Experimental Set-up*

The RF immunity test is carried out using a prototype of the HCAL front-end electronics. In this prototype, the sensitive amplifier is the charge integrator encoder (QIE), which is sampled at 34 MHz (final version operates at 40 MHz). It amplifies and digitises the signal generated by a hybrid photo-multiplier located a few centimetres from the amplifier. The sampled signals are collected, serialized and send out of the detector via optical links to the acquisition system. During these tests, the RMS value of the output signal is used to evaluate the noise of the FEE. A noise level of 2.16 RMS counts is the target value for this design, corresponding to the amplifier thermal noise. It is equivalent to an Equivalent Noise Charge (ENC) at the input of the amplifier equal to 0.72 fC. or 4500 electrons. In this prototype, the output noise level for all channels is between 2.64 to 2.94 counts when no RF perturbation is injected. Further information about the FEE can be found [7].

The basic idea of the test set-up is to keep its topology as close as possible to the final one. The FEE and the auxiliary equipment are placed on a cooper plane 1 meter above the floor. This cooper sheet (2x2 meters) is the reference ground plane. The perturbing signal is injected to the FEE input power cables using a bulk injection current probe, a RF amplifier and a RF signal generator. The level of the injected signal is monitored using an inductive current clamp and a spectrum analyser. To represent the effect of very long cables, normalized common impedances (CI) (Common Mode and Differential Mode impedance) based on lumped components are used to standardize the measurements. The output signal of the FEE is measured by its own acquisition system. The experimental set up to study the immunity of the FEE is shown in Fig. 1.

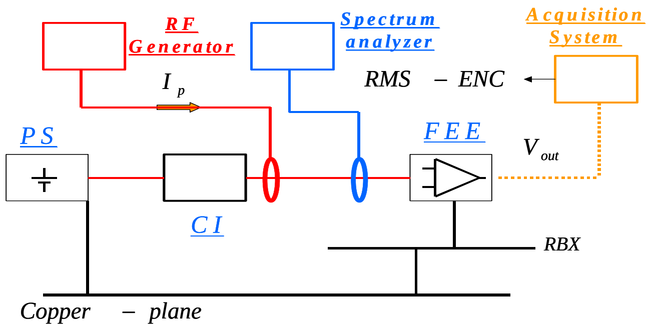

Figure 1: Test set-up

The test procedure consists on injecting a sine-wave perturbing current at different frequencies and amplitudes to the FEE through the input cables (mainly the input power) and evaluating the performance of the FEE measuring the output noise. 12 channels distributed in two identical boards, each of them connected to the back-plane are used in this test. The frequency range of the sine-wave signal is between 150 kHz and 50 MHz.

C. *Susceptibility to shield currents*

High frequency currents flowing through the power cable shield can be generated by far and near electromagnetic fields coupled to the shield or by high frequency ground currents flowing in the system. To emulate its effect on the FEE, a sine-wave current is injected to the power cable shield. This shield current, in addition, couples CM currents to the internal conductors through to the surface transfer impedance of the cable. All these currents affect the performance of the FEE and its effect depends on the amount of noise current I_{pert} coupled into the sensitive areas of the FEE as depicted in fig. 2.

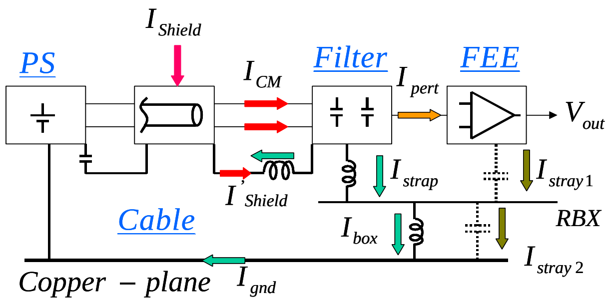

Figure 2: Current distribution into the FEE for an injected shield current

Due to slight differences in the connection between the amplifier and the photo-detector the perturbing current does not affect equally all the channels. Fig. 3 depicts the RMS value of the amplifier output voltages for all channels when perturbing currents of 6 mA RMS at 5 MHz and 10 MHz are injected. These values are compared with the output of each channel when no perturbation is injected (reference).

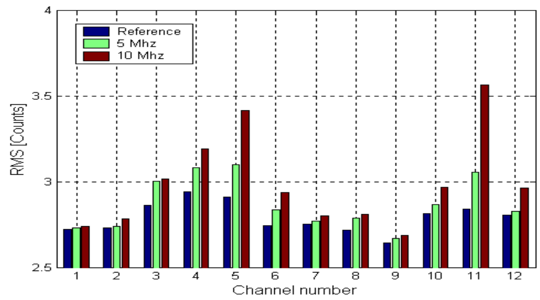

Figure 3: Noise perturbation distribution per channel

Fig. 4.a shows the variation of the RMS value of the amplifier output voltage respect to the change in magnitude of the current injected at 10 MHz for channels 1, 4, 5 and 11. At low current values, the output signal is dominated by the thermal noise contribution of the amplifier, while at high currents, it is dominated by the injected signal. The frequency response for all these channels to a perturbing current of 6 mA RMS is shown in the fig, 4.b. At low frequencies, the current amplitude is not large enough to disturb the channels and the output signal is dominated by the thermal noise. At high frequencies, the perturbing signal is the dominant one, defining the frequency response of the charge amplifier to the coupled current noise.

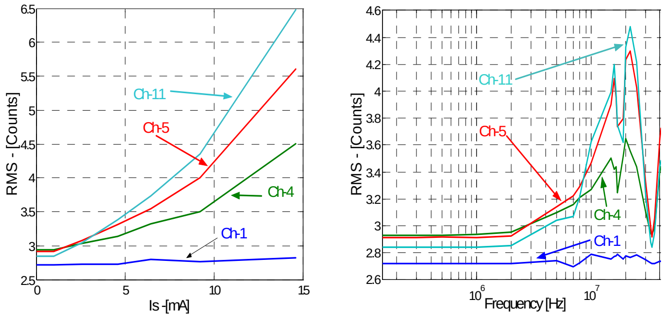

Figure 4: Output noise variation of 4 channels. a) Respect to the magnitude for an injected current of 10 MHz, b) Respect to the frequency for an injected current of 6 mA RMS.

The transfer function defined as the ratio between the AC output voltage and the injected current is used to quantify the sensitivity of the FEE and analyse the noise contribution in the system for any perturbing signal. The transfer function is defined as:

$$TF\ (\omega) = \frac{V_{1out}\ (\omega)}{I_{1shield}\ \ (\omega)} \tag{1}$$

where $I_{1shield}(\omega)$ is the magnitude of the perturbing sine wave and $V_{1out}(\omega)$ is the magnitude of the AC output. The measured transfer function between 500 kHz and 50 MHz of channel 5 is shown in fig. 5. Low frequency values are not shown because the FEE output voltage is dominated by the thermal noise and the transfer function is poorly measured.

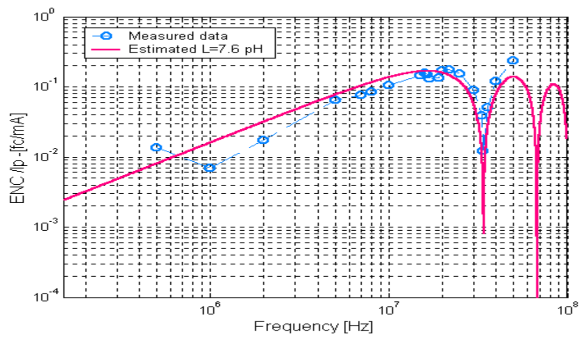

Figure 5: Measure and fitted transfer function of channel 5 for shield currents

The transfer function in the range of frequencies between 150 kHz and 100 MHz can be estimated using a mathematical model for the FEE frequency response. This model is proposed by combining the transfer function of the QIE with an external component, which represents the inductive coupling mechanism at the input. The transfer function can be mathematically represented as

$$TF\ \ (\omega) = \left| \frac{\sin\left(\omega \cdot \dfrac{\tau}{2}\right)}{\omega \cdot \dfrac{\tau}{2}} \right| \cdot \left| \frac{1}{1 + \left(\dfrac{j \cdot \omega}{\omega_b}\right)} \right| \cdot \left| j \cdot \omega \cdot L_m \right| \tag{2}$$

where τ represents the sampling period of the sampled integrator (1/34 MHz), ω_b the cut-off frequency of the input stage (~70 MHz) and *Lm* the equivalent coupling inductance. The transfer function is parameterized by *Lm* and can be fitted to the measured values estimating the magnitude of *Lm* by the least square method.

The FEE immunity to currents flowing through the power cable shield basically depends on the connections between the filter box and reference plane. This connection is made with a cooper strap of about 15 cm and it is represented in fig. 2 by the inductance between the filter box and the RBX. To evaluate its impact on the FEE noise sensitivity different values of inductance are tested. This inductance is changed by modifying the length and the routing of the strap connection to the RBX. Fig. 6 shows the transfer function for channel 5 for different strap configurations. The best configuration is labelled as Ground 3 and corresponds to the lowest inductance connection between the filter box and the RBX. It is achieved by a short strap and located close to the reference plane (RBX).

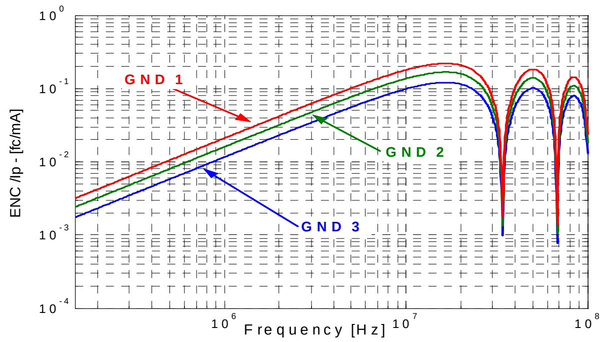

Figure 6: Channel 5 fitted transfer functions for different ground configurations

D. Susceptibility to CM currents

To study the effect of the common mode noise currents flowing through the internal power conductors, the perturbation current is injected to both the active and return power cables. In practice, this CM noise is generated by the power supplies. Fig. 7 shows the block diagram of the selected circuit to study the immunity of the HCAL FEE to CM currents as well as the distribution of the CM currents in the HCAL RBX

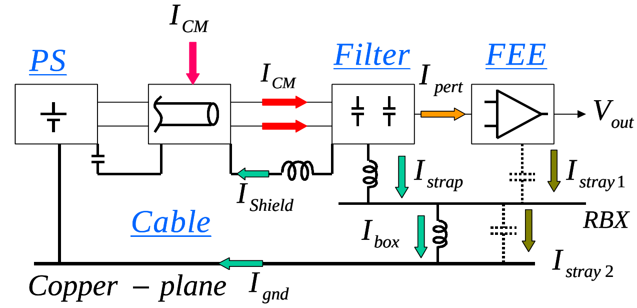

Figure 7: Current distribution into the FEE for injected CM current in the central conductors.

For the CM currents, the system has two paths to bypass these currents and avoid that the perturbation flows though sensitive areas in the FEE. These paths are the cable shield and the straps. Most of the CM currents return through the shield, but the input filter has to provide a low CM impedance to set the CM circuit around the filter.

The test procedure followed is similar to the previous one. A sine-wave current is injected as CM perturbation and the FEE output signal is measured. Similarly to the previous test, the noise does not distribute equally in all channels. The FEE immunity to CM currents is quantified by the transfer function, defined as the relation between the AC output voltage and the perturbing CM current. Mathematically it can be expressed as

$$TF(\omega) = \frac{V_{1out}(\omega)}{2 \cdot I_{1CM}(\omega)} \quad (3)$$

where $2.I_{1CM}(\omega)$ is the injected current and $I_{1CM}(\omega)$ is the common mode current .

The TF(ω) magnitude is mainly defined by attenuation of the input filter to CM components. Fig. 8 shows the transfer function of channel 5 fitted to measured values for the cases of the FEE with and without CM input filter. The FEE without CM filter is about 5 times more sensitive than the FEE with filter. It is evident that it is necessary to protect the FEE from the common mode noise currents by avoiding that these currents flow inside the RBX through FEE sensitive paths. The level of the attenuation of the CM filter showed in this analysis is relatively low because the filter does not include any magnetic component to improve the CM attenuation. Inside the CMS detector, the FEE can not use components with magnetic material because the FEE operates under a strong continuous magnetic field, residing the CM rejection of the filter in the selection of power cables with shield and CM mode filters based only on capacitors.

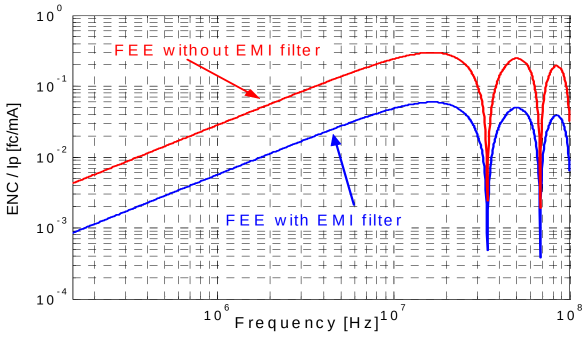

Figure 8: Transfer function of channel 5 for CM currents

The overall effect of CM currents on the FEE can be addressed combining the use of common mode filters at the FEE input with power supplies having low level output noise emission. The election of only one of this solution can give poor results. In the particular case of CMS, CM input filters can not use magnetic materials due to the high magnetic field around the FEE area, being the CM filter attenuation relatively poor. The use of power supplies with very low CM noise level can lead to linear or custom powers supplies, which are quite expensive. Optimal solutions could be found combining both EMI filter at the FEE power inputs and power supplies based on switching power converters with CM and DM output filters.

E. Susceptibility to DM currents

To study the effect of differential mode noise currents flowing through the power cables, the perturbation current is injected to the active power cable. In addition, to increase the CM impedance of the system layout, the ground connection of the power supply and normalized common impedance box is disconnected (Fig. 9). In this case, the injected current in the active power cable is forced to return through the return power cable and the CM noise injected to the FEE is negligible.

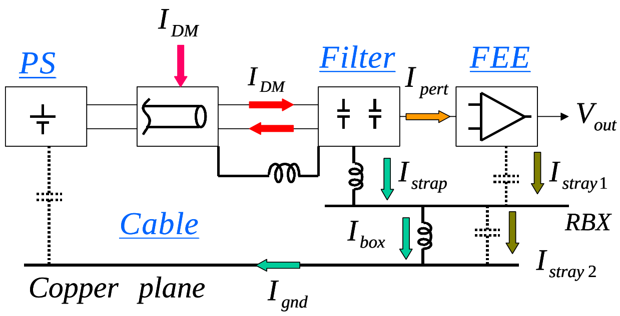

Figure 9: DM current distribution in the FEE

A sine-wave current is injected as DM perturbation and the FEE output signal is measured. The FEE immunity to DM currents is quantified by the transfer function, defined as the relation between the AC output voltage and the perturbing DM current. Fig. 10 depicts the transfer function to DM perturbing currents. There is a resonance at 20MHz due to the interaction between the strap inductance and the parasitic capacitance between the ground plane and the RBX. The resonance in this test set-up appears because the normalized common impedance box is disconnected from ground and it does not damp the resonance as in the previous set-ups. This resonance can be moved to higher frequencies using multi-strap connections between the RBX and the ground plane to reduce the parasitic inductance.

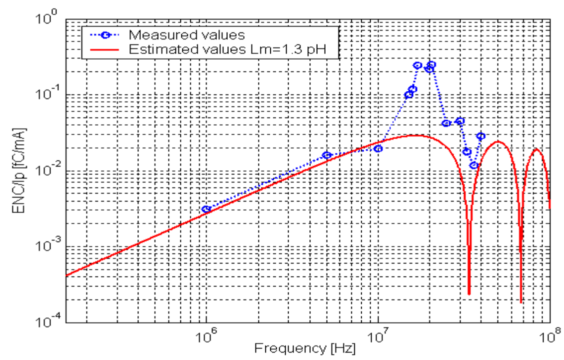

Figure 10: Transfer function of channel 5 for DM currents

F. Susceptibility to CM+DM

This test is performed to analyse what component, the common mode or the differential mode current has more influence in the FEE sensitivity and also to define the normalized specifications for the output noise of the power supplies. Assuming the total current flowing in each power cable can be expressed as: $I_a + I_b \cong I_{shield} + I_{gnd} = I_T$, where I_a, and I_b are the currents flowing through the central conductors, I_{shield} and I_{gnd} are the return currents through the shield and the ground plane. The currents flowing through the central conductors can be decomposed in two orthogonal components as:

$$I_{CM} = 0.5\,(I_a + I_b); \qquad I_{DM} = 0.5\,(I_a - I_b)$$

If the injected current I_a can be decomposed in two components I_{CM} e I_{DM}, multiplying each current by the respective TF, and adding the resulting output voltages, the calculated TF following this method should be equal to the TF obtained by the present measurement.

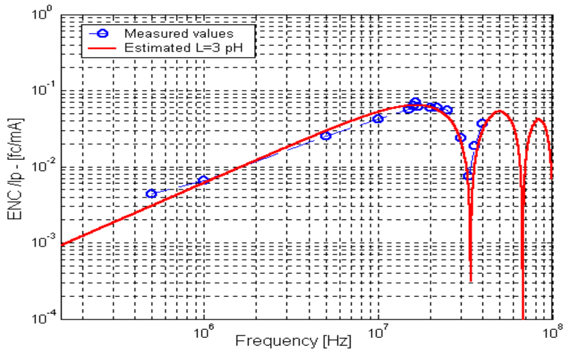

Figure 11: Transfer function of channel 5 for a current injected in the active power conductor

Using a set-up similar to the one used for shield currents and CM current tests, a sine wave current was injected into the active power cable. The transfer function obtained is depicted in fig. 11. Taking as example the magnitude obtained at 10MHz and comparing with the TF obtained by decomposing the injected current into I_{CM} and I_{DM}. At 10MHz, a perturbing signal of 19.5 mA is injected active power conductor and the output noise measured at channel 5 was equal to 3.81 counts. The current injected is decomposed in the two orthogonal modes, mainly, by the impedance of the normalized common impedance box. Based on preliminary measurements, $I_{DM} = 0.63\ Ia$ and $I_{CM} = 0.37\ Ia$. Multiplying these components by the transfer functions of figs. 8 and 10, the estimated output noise is 4.1 counts (*error* $\cong$ *7.5%*), which is quite close to the measured value. From these calculations, it can be seen that 71% of the noise contribution is due to CM currents and only 29 % is induced by DM currents, although $I_{DM} = 1.7\ I_{CM}$. This example shows the main responsible for the degradation of the FEE noise immunity is the CM current. Based on the transfer function estimated for injected CM and DM currents, the effect on the FEE output noise of switching mode power supplies (SMPS) has been analysed. Preliminary results show that SMPS with CM-DM filters at the output can be used to bias this FEE without degrading its noise performance. Although the EU standard does not define the level for conductive noise at the output of power supplies, the noise output level required to SMPS for optimal performance of the FEE should be equivalent to the specified by EU-55022 class B.

III. VOLTAGE DIP IMMUNITY TESTS.

The goal of this test is to define the susceptibility of the equipment to short voltage interruptions and voltage variations of the primary power supply. This test uses as guide the standard EN-61000-4-11/ IEC-1000-4-11 [5]. The experimental set-up used to conduct this test is similar to the one used to characterize the RF immunity. Voltage dips were applied independently to both the analogue and digital power supplies feeding the FEE and the loss of data or loss of function was used as criteria to qualify the performance of the system. As example some results of this test are shown in tables 1 and 2. The two upper rows resume the operation when the input voltage is applied continuously without any perturbation superimposed but with a magnitude lower than the nominal voltage. The rest of the table describes the operation when the voltage is kept at the nominal value (6.5V for analogue, 5.5V for digital) and repetitive voltage dips with different amplitude and duration are applied. The system performance was evaluated by the loss of data transmitted, loss of clock, etc. and also if the system recovers after removing the perturbation or if it necessary to reset the system.

Minimum Voltage	**Voltage Dip**	**Dip Duration**	**Status**	**System recovery**
5.15 V		Constant	OK	-
5 V		Constant	Loss of Gain	Yes
5.12 V	1.38 V	3ms	OK	-
4.8 V	1.7 V	3ms	Loss of Gain	Yes

Table 1: Results for voltage dips applied to the analogue power supply. (*Vdip = Vnom-Vmin*)

Min. Voltage	**Voltage Dip**	**Dip Duration**	**Status**	**System recovery**
3.2 V		Constant	OK	-
3 V		Constant	Loss of Data Clock Fails	**No.** Reset System
3.3 V	2.2 V	5ms	OK	-
2.3 V	3.2 V	5ms	Loss of Data	Yes
3.3 V	2.2 V	10ms	OK	-
2 V	3.5 V	10ms	Loss of Data	Yes
1.88 V	3.62 V	10ms	Loss of Data . Clock Fails	**No.** Reset System

Table 2: Results for voltage dips applied to the digital power supply. (*Vdip = Vnom-Vmin*)

IV. SURGE IMMUNITY TEST

Due to the CMS detector is located under ground, surges or slow transients will be in general produced by switching transients. Switching transients can be generated by load changes (sudden change of the FEE power consumption), short circuits and faults to earth in power cables, *etc.*

The surge immunity test is based on the European standard [6]. The goal of this test is to study the effect on the internal voltage distribution of surge perturbations. A surge signal of 200V in DM and CM configuration of both positive and negative polarities is applied to the system where the FEE is now replaced by dummy boards. Each dummy board consists of filter capacitors, the LV regulator and resistors to simulate the FEE board. The input power filter has a transient voltage suppressor (TVS) of 1500 W and nominal voltage of 7.5 V. The current injected through the input power lines reaches a peak value of 85A for both positive and negative polarities.

The voltages at the input of the dummy board (back-plane voltage) and the output of the LV regulator when the transient is applied are shown in figure 12. For the positive voltage surge (Fig. 12.a), the system is protected without any problem. The TVS and the HF capacitor placed on the back-plane limit the peak voltage in the back-plane to 8 volts. The transient voltage is completely attenuated by the LV linear regulator giving clean 3.5V to bias the digital electronics. However for a surge with negative polarity (Fig. 12.b), the TVS and the voltage regulator do not work generating on the 3.5V line a voltage dip of short duration, which could produce malfunctions in the digital section. Similar effects have been observed for the CM configuration, however the order of magnitude of the over voltages and dips are lower.

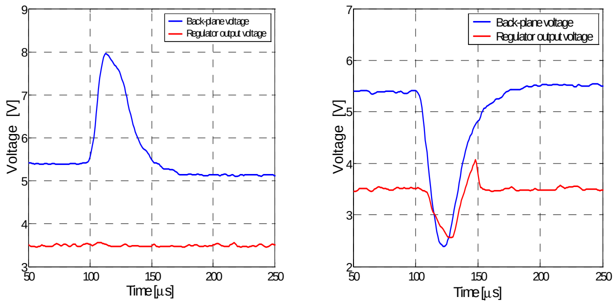

Figure 12: Back plane and LV regulator output voltages during a surge transient

This test allows us to validate a Pspice model to identify the energy distribution among protection components and study the limitations of the input filter. Based on this model, it was analysed that the FEE back-plane capacitors absorb part of the transient, and also there is a large over-voltage in the back plane if a TVS is not used. As example, for a surge voltage of 500 V, the over-voltage in the back-plane reaches a peak of 9 V if a TVS is included in the input filter, while a peak over-voltage of 18 V appears when a TVS is not used.

These simulations give us a tool to define the energy distribution absorbed by different components during the transient and optimise its distribution among the devices in the protection chain.

V. CONCLUSIONS

Results of EMC test conducted on the HCAL FEE have been presented. RF immunity tests have quantified the susceptibility of the FEE to perturbing current injected through the shield and the central conductors of the power cables. A transfer function between the output signal and the perturbing current was estimated to calculate the output noise contribution for any external perturbing current. It allows defining the noise level at the output of power supplies to achieve a good performance of the FEE.

The FEE immunity to transient perturbation was characterized conducting the voltage dip and the surge tests. The digital part of the FEE is sensitive to voltage dips forcing to reset the system for limiting values of the perturbation. The surge test has been focused on the characterization of the protection devices included into the FEE.

VI. ACKNOWLEDGEMENTS

The authors would like to thank to A. Ciccollela and P. Langet from the EMC & Antenna Measurement Section of the European Space Agency for their help during the development of these studies and T. Shaw, S. Los, J. Elias and the US-HCAL from Fermilab for their help during the measurements. One of us (C.R.) thanks to US CMS-Fermilab and the Department of Energy (U.S.A.) for the support of this work under contract No. DE-AC02-76CH03000.

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