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# Investigations on Inter-System Ground Noise in LLRF System at FLASH Accelerator

***Abstract:*** *Measurements of disturbances in power supply lines showed that the ground system in FLASH accelerator is a source of inter-system ground noise. Inter-system ground noise means unwanted disturbances in the data and RF lines between electronic devices due to unbalanced reference voltages in the ground loop. The problem is different than common-mode noise, normal-mode noise, electromagnetic and RF interference. Result of measurements and simulations and possible solutions to minimize the problem are described in the paper.*

***Streszczenie:*** *Pomiary zakłóceń obserwowane w liniach zasilających akcelerator FLASH wykazały, że system uziemienia jest źródłem zakłóceń międzysystemowych przekazywanych przez uziemienie. Z powodu sygnałów zakłócających w różnych fragmentach sieci uziemiającej istnieją różne poziomy odniesienia, które wpływają na linie przesyłu danych oraz sygnałów wielkich częstotliwości. Problem ten różni się od zakłóceń szumowych, elektromagnetycznych i interferencyjnych. Przedstawiono również możliwe sposoby redukcji problemów w praktyce (**Badania zakłóceń międzysystemowych przenoszonym przez uziemienie w systemie LLRF akceleratora FLASH**).*

**Keywords:** inter-system ground noise, ground loop, disturbances, noise
**Słowa kluczowe:** zakłócenia międzysytemowe przenoszone przez uziemienie, pętle masy, zakłócenia, szumy

## Introduction

FLASH (**F**ree-electron–**LAS**er) in DESY, **H**amburg is a superconducting linear accelerator with a free electron laser for radiation in the vacuum-ultraviolet and soft X-ray range of the spectrum. FLASH free-electron laser is a worldwide unique facility delivering intense ultra-short femtosecond coherent radiation in the wavelength range between 44 nm and 4.1 nm [1]. FLASH is 315 m long and consists of many subsystems and elements like 6 sets of 8 superconducting cavities, klystrons supplying RF power to them etc. All systems starting from electron injector through accelerating structures supplied with 1.3 GHz RF power from klystrons up to undulators have to be synchronized. Due to pulse method of operation and distributed nature of the system its synchronization is a very demanding issue. The system responsible for synchronization, automatic control and diagnosis is called Low Level RF (LLRF) system. It provides stable and synchronous RF signal with main 1.3 GHz reference produced in Master Oscillator and several other signals at lower frequencies. The requirements for field gradient in accelerating cavities can be fulfilled when the phase stability of the signals providing synchronization is of the order of and 0.1°. The LLRF system is also responsible for automatic control of the laser. For example it measures the fields inside superconductor cavities and provides feedback for the RF power level delivered by klystrons. Moreover, measured signals can be collected and observed in so called DOOCS (Distributed Object Oriented Control System). The better is quality of LLRF signals the more stable is laser beam produced. In such a big system even designed and realized with unusual care there are observed noise and disturbing signals. The spectrum of such unwanted signals is quite wide spanning from several Hz up to hundreds of MHz.

The noisy and unstable characteristics of the probe signal from the accelerating cavities observed in DOOCS were the reason to start investigation for the sources of distortions. In the paper one of the possible ways of spurious signals propagation is investigated. After careful measurements of the signal in power supply lines it was found that the ground system in FLASH facility could be a source of inter-system ground noise. Inter-system ground noise means unwanted disturbances in the data lines between electronic devices communicating with each other due to unbalanced reference voltages in the ground loop. The result of measurements and possible solutions to a problem are described in the paper.

## Observations of noisy and spurious signals

Signals observed at different points of the system reveal noise and distortions. An example of such observations is shown in Fig. 1.

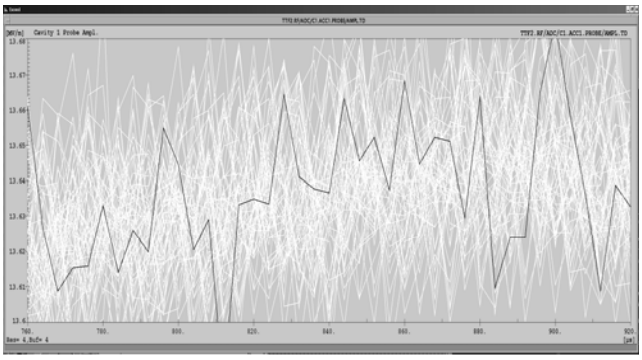

Fig. 1. Signals in time domain observed in cavity at pulse flat top (TTF2.RF/ADC/C1.ACC1.PROBE/AMPL. TD, ¼ resolution).

The black line denotes last pulse while white lines represent previous measurements. As can be seen the signal measured by the probe inside first cavity changes with time. Moreover it changes suddenly and unpredictably. The changes are relatively small, below 0.5 % of the signal level. Even such small changes would cause unstable laser beam what was actually not observed. Thus observed noise or distortions are related to the parts of the system such as receivers and digital signal processing units rather than to reference signals. To find out the possible sources of noise and distortions the analysis of the observed distortions has been carried out. The signals collected from probe in cavity 1 have been prepared in such a way that the flat top of the pulse has been extracted. Then the level of the signal has been substracted from the recorded values and obtained signal has been transformed to the frequency domain. The DFT has been applied. Several of such signals have been analyzed. The obtained spectra have been each time different thus it was impossible to draw any reasonable conclusion. The common spectral lines were 250 kHz (but with different levels) and lines in the range 46 – 48 kHz (again at different levels). Surprisingly low frequency spectral lines (2–10 kHz) dominated in strength over higher frequencies. Levels of the harmonics are low – usually below 40 dB the maximum level of the signal. The presence of 250 kHz says that there is crosstalk between parts of the receiver and DSP board. Other signals that have been obtained included following frequencies: 16.25 kHz, 27.5 kHz, 36.25 kHz, 71.25 kHz, 150 kHz. The presence of many spectral lines suggested that there are spurious signals unintentionally distributed in LLRF system. Subsequently the more extensive measurements have been done using a spectrum analyzer and oscilloscope. In the measurements Le Croy WR 6100 digital oscilloscope and R&S FSP3 spectrum analyzer have been used. Due to pulse operation of the system, oscilloscope measurements have been more important and the spectrum analyzer has been used as a reference device. The measurements of subsytems in working FLESH have been limited to some output signals only. Thus the measurements initially concentrated on output signals provided intentionally for test purpose in Master Oscillator (MO) and amplifiers of IQ modulator. The MO is a stable, low phase noise device providing clean 1.3 GHz signal. The measured spectrum of MO revealed spurious signals at small distance from the main signal. They had relatively low level (-90 dB) and frequencies shifted of 1.72 kHz, 2.16 kHz and 2.56 kHz from 1.3 GHz. The outputs of IQ modulator are part of the Local Oscillator (LO). LO produces also 1.3 GHz modulated signals used in automatic control system. Vector Modulator uses IQ modulation to control RF power inside cavities. The measured spectra showed a lot of spurious signals. The output signals of IQ modulator should have symmetric spectrum of modulated 1.3 GHz carrier frequency. Measurements showed the full list of the spurious signals located symmetrically and asymmetrically round 1.3 GHz. Some of them have been easily identified e.g. 48 kHz is the frequency of a typical switched voltage regulator. Such voltage regulators have been used in the system but not in the actually measured subsystems. A signal with frequency 250 kHz corresponds to the frequency of ADC clock signal. The other question is how the spurious signals propagate in the system. They can be transferred by electromagnetic couplings (crosstalk) or by conductive connection through power lines and data cables. The former case has been easily rejected after measurements with a 1.5 m long wire acting as the antenna connected to spectrum analyzer. The crosstalks are related to the internal structure of devices and subsystems and can be minimized through careful design and shielding.

**Observations of signals on power supply lines**

The interference signals on power lines have been measured by means of oscilloscope [2]. The measurement setup is shown in Fig. 2. The 1 m long wire with only one end connected to the oscilloscope produced spectrum with signals below –90 dBm level. The result for oscilloscope itself (without wire) was 10 dB better. When 1 m long wire have been connected to the ground line in the 220 V AC socket a variety of different signals was observed in frequency domain and changing with time level of noise in time domain. In Fig. 3 a typical picture of the observed "noise" is presented. As can be noticed there are quiet and noisy periods. Moreover the ground average level during quiet period is lower (close to 0 V) that during noisy period (close to 5 mV). The same observation in frequency domain shown in Fig. 4 has revealed plenty of different signals present on the ground line. Frequencies and levels of observed signals have been compared with frequencies and their levels observed at the outputs of IQ modulator.

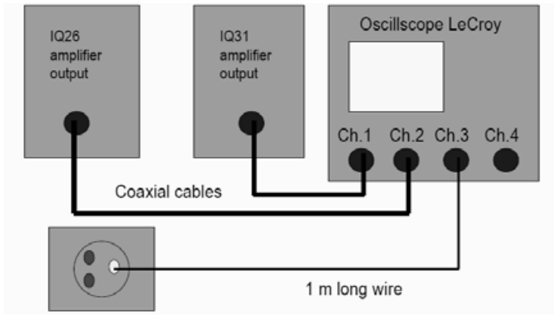


Fig. 2. Measurement set up. (1 m long wire connected to the safety ground line in 220 VAC socket).

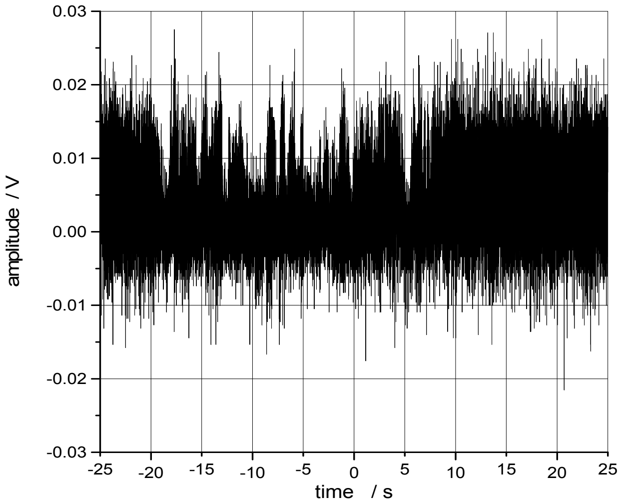


Fig.3. Measurements of ground line in time domain.

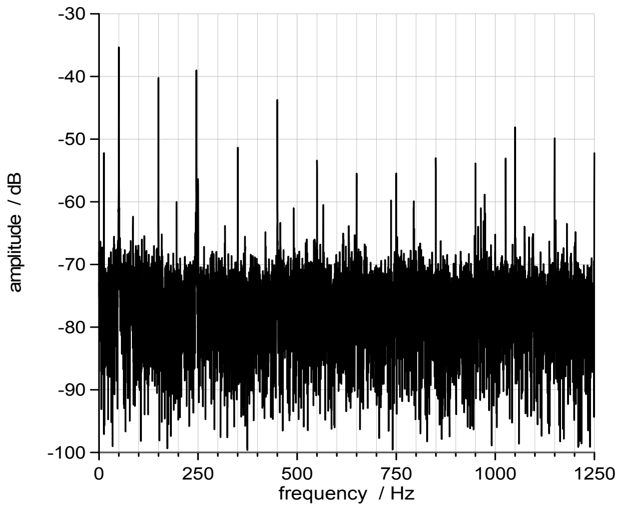


Fig.4. Measurements of ground line in frequency domain.

Obtained PSRR (Power Supply Rejection Ratio) [3] of the supply converters in IQ modulators is not very high as far as the ground line is concerned. The PSRR is 20 to 35 dB in the up to 200 MHz. The ground line is carrying a lot of spurious signals and noise. These signals interfere with useful signals produced in LLRF system and are transferred to output signals thus also to microwave signals in the cavities. Due to very high Q of the cavities the influence of distortions on laser beam is limited. Switching laser on and off requires also switching on and off high power klystrons, cooling fans and air-conditioners, strong magnets etc. All of these subsystems produce pulses of current in supply lines and simultaneously produce distortions influencing the system. During operation laser is switched on every 0.2 s. Observations of ground line noise and outputs of IQ modulator are perfectly matched as can be seen in Fig.5. A bunch of electrons travelling through the system is reflected as changed level of the signal on ground line.

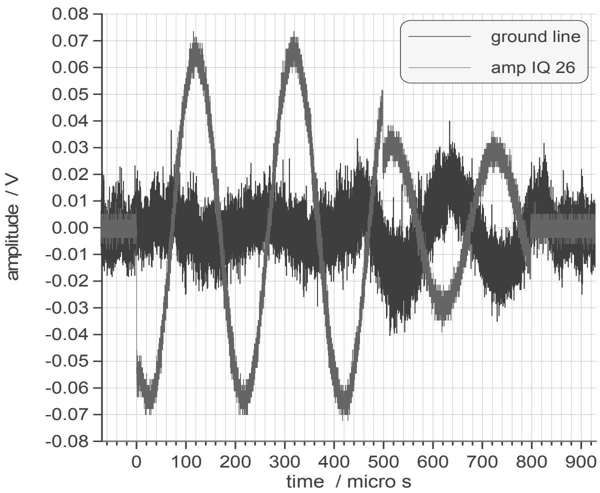


Fig. 5. Signal on ground line and at the output of IQ 26 amplifier.

**Inter-system ground noise**

Results of measurements lead to the conclusion that power lines and especially ground line carry noise and disturbances. The accelerator has a problem that is called inter-system ground noise (ISGN) [4-6]. ISGN means unwanted disturbances in the data lines between two or more electronic devices communicating with each other due to unbalanced reference voltages in the ground loop. Causes are poor building grounding at one or more of the electric panels, power supplies that transfer unwanted noise into the ground line (ground noise injection) and voltage surges due to ground faults and lightning strikes. In a system that includes equipment interconnected via ground referenced data or RF lines, this safety grounding arrangement leads to a conflict. Every interconnected device has two connections that are attempting to establish the common reference voltage for the communications circuit. The common wire in the transmission line, which connects the device to other equipment, is in conflict with the device`s safety grounding wire. This situation is sometimes known as a ground loop. The existence of ground loops can lead to differences in the common reference voltage existing between interconnected devices, which in turn, corrupt data and at most can damage equipment. Ground loops do not cause problems when all of the following things are true: none of the wires in the loop carries any current, the loop is not exposed to external magnetic fields, there is no radio frequency interference nearby. Unfortunately ground lines and wires are not perfect. Calculated inductance of the ground line at FLASH facility is 2.32 $\mu$H/m what gives reactance of 15 $\Omega$/m at 1 MHz [7]. Moreover the quality of ground provided by the mechanical contact of panels with the racks (rails, mounting strips etc.) is in question.

RS-232 lines, long printer cables and USB cables, RF cables, network AUI wiring are subject to ISGN. Such connections should be kept short and the interconnected equipment should be powered from the same branch circuit. Optical fibers and Ethernet connections are free of ISGN.

**Possible solutions**

The solution to the problem of inter-system ground noise, common-mode noise and differential-mode noise is filtering of the power supply and careful designing of the subcircuits, avoiding of pulse voltage regulators and using Ethernet or optical signal and data connections. If computers as well as analog equipment are used in an industrial or medical environment, the best method to limit EMI problems is when the all interconnected equipment is using a dedicated supply circuit. Such solution is impossible in our accelerator. But proper filtering method can be applied. Ground loops can be broken if earth line (ground line) chokes are used. Common and differential mode noise can be limited using EMC/EMI filters e.g. inlet filters. These two solutions can be combined in filters with earth line chokes, which are already available [8]. Some of the connections to ground like grounding of racks are realized in a way that application of earth line chokes is difficult or impossible. Thus elimination of ground loops cannot be accomplished completely. Anyway it can limit the problem to some extends. Some of the ground loops can be eliminated other can be decreased. The influence of ground line choke on inter-system ground noise has been measured. The choke inductance at 100 Hz was 3.95 mH thus effectively the choke influenced the circuit above 100Hz. A special power cable has been prepared in which the earth line has been cut and the choke has been substituted in. Measurements have been done connecting the power cable into the 220 VAC socket inside the rack filled with equipment. The inputs of the oscilloscope (set to 50 Ω input impedance) have been connected on both sides of the “choke” and signals have been measured both in time and frequency domain. The choke limited the noise level by 3 to 5 dB.

**Conclusions**

The results of measurements, analysis and solutions for noise and distortions problems in LLRF system at FLASH facility have been described. It can be stated that the FLASH accelerator is prone to inter-system ground noise. Some of the spurious signals are generated inside the LLRF system and are transferred between different subsystems through supply lines and crosstalk. Moreover the supply lines bring distortions and noise generated in other system of FLASH. To avoid the problem the cheapest and reliable solution can be application of ground line chokes. Commercial inlet filters with earth line chokes can be effective in the range 1 kHz to 10 MHz

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