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A FAMILY OF GAZ IONIZATION CHAMBERS AND SEM FOR BEAM LOSS MONITORING OF LHC AND OTHER ACCELERATORS

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Abstract

A serious problem for high current accelerators is the high density of the beam, which is able to destroy the equipment and to make a quench of super conductive magnets. Loss of even a small fraction of this intense beam equipment. The Beam Loss Monitor (BLM) system must be sensitive to different levels of losses in different accelerator locations. BLM system protection should limit the losses to a level, which ensures hands-on-maintenance or intervention. On the other side, the BLM system should be sensitive enough to enable the fine tuning and studies by machine with the help of BLM signals. Beam-loss monitoring is the cornerstone element in the accelerator protection and beam setup.

INTRODUCTION

The main beam loss detector type is ionization chamber (IC). The detector is originally designed for CERN Large Hadron Collider (LHC) [1-5] and 4250 nitrogen filled ionization chambers were produced in the Institute for High Energy Physics, Protvino, Russia, in 2006-2008, and currently are widely used in almost all accelerators at CERN, in IHEP (same Protvino) and other accelerators (Fig. 1).

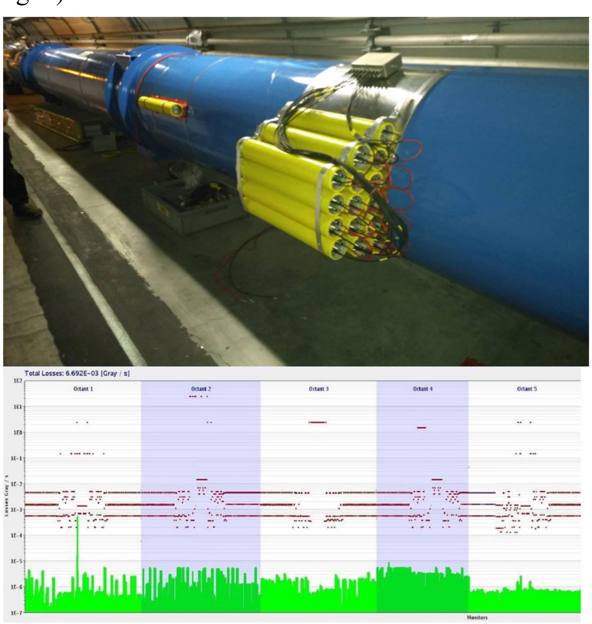

Figure 1: BLM at LHC and control room beam loss display.

In 2014-2017 a new production of 830 IC was performed to replenish spares for LHC and to make series for ESS (Sweden), GSI (Germany) (Fig. 2).

Figure 2: IC at ESS and GSI.

Apart from the IC, the 378 secondary emission monitors (SEM) for LHC, BNL (USA), 300 little ionization chambers (LIC) and 50 flat ionization chambers (FIC) have been manufactured and tested at IHEP in Protvino following their development at CERN (IC, SEM, LIC) [6-8] and IHEP (LIC, FIC).

FAMILIES OF BLM

There are different families of beam loss monitors, produced in CERN-IHEP collaboration (Fig. 3):

a) Ionization chambers (IC), which are installed at local aperture minimum and loss locations,
b) SEM - at very high dose rates locations,
c) LIC - designed to reduce the sensitivity to saturate for higher losses,
d) FIC -detectors designed to geometry considerations.

Figure 3: Family of BLM.

Signal speed and robustness against aging were the main design criteria. Each monitor is permanently sealed inside

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a stainless-steel cylinder. The quality of the welding was a critical aspect in production. The SEMs are requested to hold a vacuum of 10^{-7} bar. Impurity levels from thermal and radiation induced desorption should remain in the range of parts per million in the ICs. To avoid radiation aging (up to $2{\cdot}10^{-8}$ Gy in 20 years) production of the chambers followed strict UHV requirements. IHEP designed and built the UHV production stand [9]. Due to the required dynamic range of 10^{-8}, the leakage current of the monitors has to stay below 1 pA. Several tests during and after production were performed at IHEP, CERN, ESS, GSI, CEA. A consistently high quality during the whole production period was achieved.

IONIZATION CHAMBER

Parallel plate gas ionization chambers developed by CERN for LHC and manufactured and tested at IHEP in Protvino, are chosen as main beam loss detectors for all CERN accelerators, including the new production for SPS, for the ESS linear accelerator and for GSI (Fig. 4). Due to their fast response, no gain variation, the robustness against aging, as well as the large dynamic range 10^8 (pA-mA), the little maintenance of chambers is required.

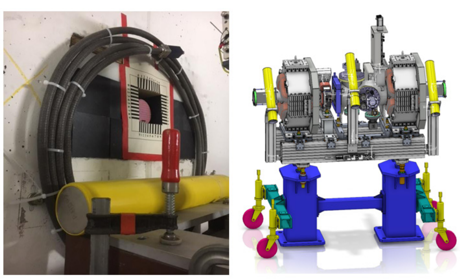

Figure 4: Installed IC at GSI and the ESS IC layout.

The detectors active zone consists of 61 parallel electrodes with a 5.75 mm distance between them in ionization chambers which were produced in 2008 (Fig. 5). The distance between electrodes in the ionization chambers produced in 2017 is reduced to 5.71 for every 2 electrodes, keeping the same spacer length. The new gap between electrodes is built to reduce the drift path and the recombination probability of the ions and electrons, and hence to get the requested linearity.

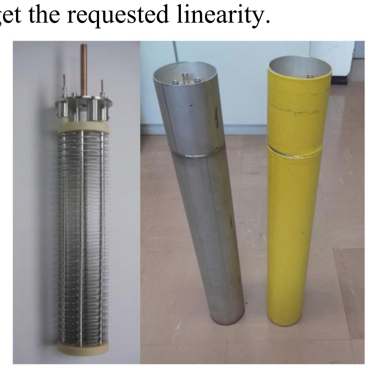

Figure 5: Ionization chamber.

The collection time of the electrons and ions is of order of 300 nsec and 80 μsec respectively.

The IC have a fast reaction time, which implies a high ion mobility of the detector gas. The 99.9999 % nitrogen filled at 1.1 bar detector is permanently sealed inside a stainless-steel cylinder. Should a leak occur in a detector and air enter the chamber, the detection properties would not change severely as air consist 79% of nitrogen, and therefore would not lead to system immediate failure. In systematic testing with a radioactive source, a lower signal due to lower gas pressure will be detected. The composition of the chambers gas is very important so as this is the only component in the IC which is not remotely monitored.

Each signal electrode is surrounded by two bias electrodes maintained at 1500 V in normal operation. The assembly is attached to the stainless-steel cylinder via two very high resistivity ceramics (Al_2O_3) plates, the electrodes are connected by two ceramics feedthroughs. Feedthroughs testing is done at CERN after reception and in IHEP just before chambers assembly. The acceptance criteria for leakage current is set below 1 pA at 2000 V.

The dynamic range of an ionization chamber is defined by its lowest and highest current signals. It is limited by leakage current through ceramic insulator, which should be less than 1 pA for lowest signals and by saturation due to space charge for highest signals which is the in mA range.

The ceramics insulator is the key component of IC, limiting the lower limit of its dynamic range. In 2008 monitors, ceramics insulators were produced by SCT, France. No degradation has been observed over 10 years of operation at LHC. In 2017 IC, ceramics insulators are produced by Friatec, Germany. Various investigations on 2017 ceramics insulators include vacuum, chemical, electrical, cleaning, and heating tests (Fig. 6) which all lead to improvement of the quality of the ceramics.

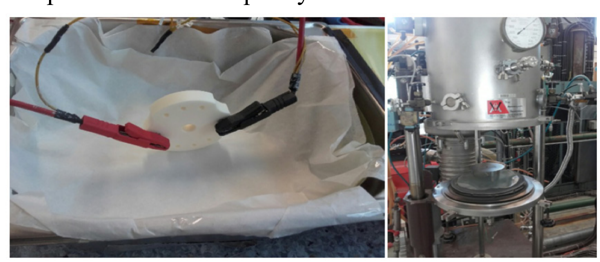

Figure 6: Ceramics test in vacuum.

Depending of the loss location the BLM detectors, are exposed to different radiation fields. The energy of the particles is large ranging from keV to TeV.

The IC is very sturdy, offering a good radiation hardness. The consistent, long-term (20 years of operation) high quality of IC requires materials testing and various tests during and after production in IHEP, after reception at CERN, ESS, GSI, CEA (France).

SECONDARY EMISSION MONITOR

In accelerator areas with very high dose rates SEM chambers are employed to increase the dynamic range. The SEM is characterized by a high linearity and accuracy, low sensitivity, fast response and a high radiation

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tolerance. The signal and bias electrodes are made of Ti to make use of Secondary Emission Yield stability (Fig. 7).

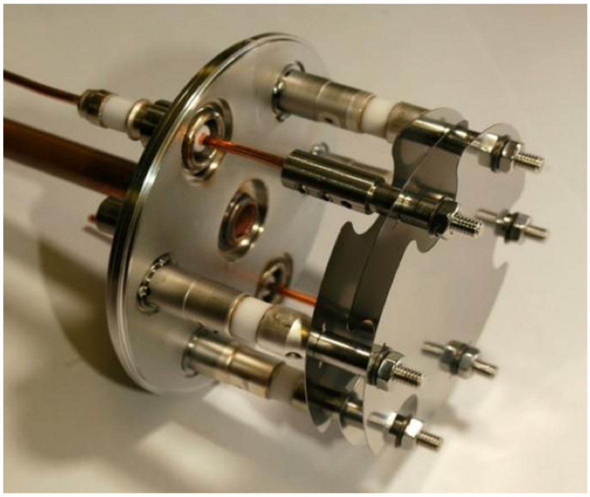

Figure 7: Internal components of SEM. The middle Ti electrode is connected to signal output while the other two plates are connected to high voltage input.

The emission of the electrons from surface layer of metals by the passage of charged particles is only measurable in a high vacuum, which leads to an ultrahigh vacuum preparation of the components and to an additional active pumping performed by a getter pump (NEG). The sensitivity is about a factor of $3 \cdot 10^{-4}$ smaller than in the ionization chamber (Fig. 8).

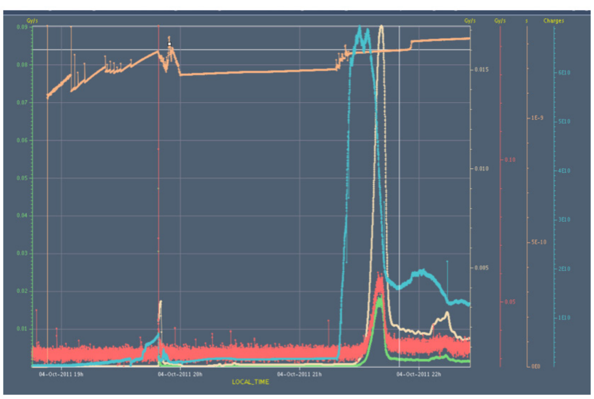

Figure 8: The signal of a SEM and Interaction region 3 of the LHC in 2011.

LITTLE IONIZATION CHAMBER

The LIC detectors have been designed by IHEP to reduce the sensitivity to saturate for higher losses with respect to LHC IC and to be a good extension to the IC. While IC performance works well for protection, the limited dynamic range of read-out electronics are saturated for high losses and LIC is the most feasible detector. The LIC active zone consists of 3 parallel aluminium electrodes, nitrogen filled with ceramics insulator SEM type (Fig. 9).

Figure 9: Little ionization chamber.

108 LICs are installed in LHC injection regions. Figure 10 shows a comparison of measured absorbed dose rates in IC and LIC in location with similar impact angle [2]. In this case the IC/LIC ratio appears to be close to 1.

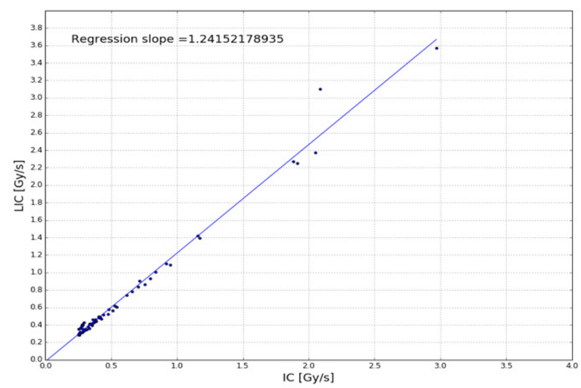

Figure 10: Measured absorbed dose rates in IC - LIC pair installed behind a collimator in Interaction Region 7 of the LHC.

FLAT IONIZATION CHAMBER

The FIC detectors also designed by IHEP with geometry considerations and foreseen to be located and currently installed in LHC booster (Fig. 11).

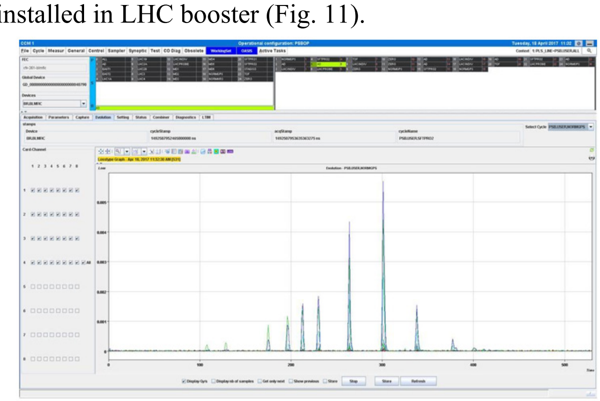

Figure 11: The first signal of FIC at booster of LHC.

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The prism FIC active zone consists of 3 parallel aluminium electrodes, nitrogen filled with special designed ceramics insulator SEM type (Fig. 12).

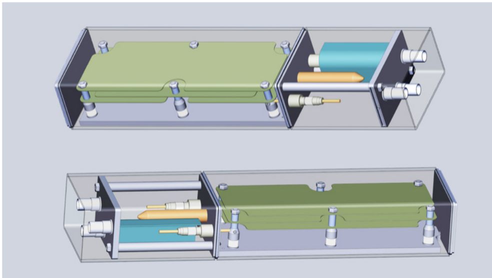

Figure 12: Flat Ionization chamber.

IHEP VACUUM STAND

IHEP designed and built the Ultra High Vacuum production stand (Fig. 13), which is equipped by quadrupole mass spectrometer, detecting the composition of the gases inside the system. The pumping system consists of two arms – manifolds with 18 connection ports with individual valves for each ionization chambers of different types and dimensions, SEM or proportional chambers.

Figure 13: IHEP production stand.

QUALITY TEST AT DETECTORS PRODUCTION

Aging of chambers depends on the quality of materials to high radiation (ceramics, feedthroughs). To avoid radiation aging (electronegative gases, organic compounds), a strict cleaning procedure for the chambers is followed. Impurity levels due to thermal and radiation induced desorption are estimated to stay in the ppm range. No organic material is present, neither in the production process (pumping, baking, filling) of the detectors, nor in the detectors themselves. Standardized test samples analysed at CERN periodically helped to check the cleaning performance. For example, the conclusion of X-ray photoelectron spectroscopy (XPS) from 2016-12-13 is the following: “From the point of view of carbon contamination, the stainless steel and aluminium samples are considered UHV compatible” (Fig. 14).

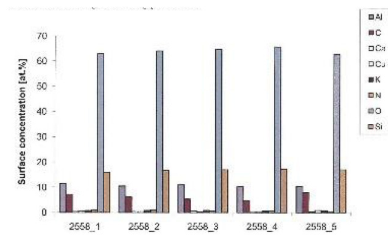

Figure 14: Results of sample analyses.

The various tests were performed at IHEP before, during and after the production to verify the quality of chambers. All welds are He leak tested, including the head (Fig. 15).

Figure 15: “Head” after welding.

Additional tests have been performed on 2017 IC, including the test of each ceramic insulator before its assembly. The quality of the production has been continuously controlled and recorded from the vacuum stand, from the leakage current measurements of the components, and by tests of the assembled monitors. All data was logged into CERN’s Manufacturing and Test Folders database.

The BLM have 5 kV HV, series SHV and coaxial, series BNC connectors. The connectors insulating material is chosen to resist to an ionizing dose of up to 10 mGy. The insulator in 2008 chambers is PEEK, the one in 2017 is Polystyrene. Both insulators have similar properties in radioactive dose, the only difference is temperature limit.

DETECTORS` VERIFICATION

After monitors transportation, reception and calibration tests were performed at CERN, ESS, CEA, and GSI. At CERN each detector is calibrated by using a strong gamma source in the CERN Gamma Irradiation Facility (GIF) (Fig. 16).

Figure 16: Test set-up at GIF++.

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For each detector the tests consists of leakage current and radioactive source induced signal measurements (Fig. 17).

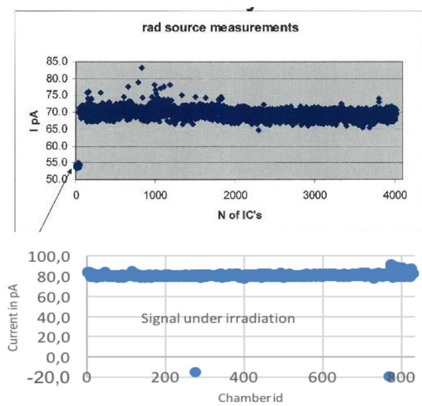

Figure 17: 4250 IC in 2008 and 830 IC in 2017 BLM test results.

Calibration tests are performed in mixed fields at HiRadMat in order to obtain irradiation conditions as close as possible to operational accelerator dose. These tests allow a comparison between 2008 and 2017 chambers, for which tests are ongoing (Fig. 18).

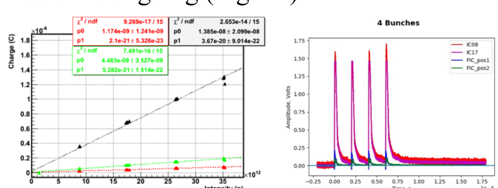

Figure 18: HiRadMat calibration results, 2015 and 2017 -2018.

Currently the monitors are continued to be tested in different environments: Xrays measurement in Spiral2 by J. Marroncle (CEA) and ESS team in Uppsala (Sweden), in magnetic field at 1.5 Tesla in H2 channel at CERN (Fig. 19).

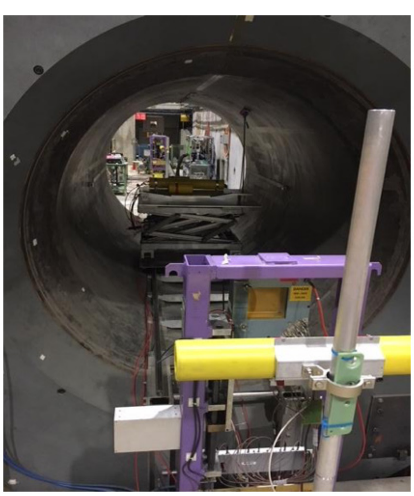

Figure 19: Set up for BLM test in magnetic field.

CONCLUSIONS

About 6000 different types of ionization chambers and SEMs have been produced in 2005-2018 at IHEP for the CERN, ESS, GSI, LIPAC, BNL beam loss monitoring system, following a first production with modifications. These chambers become the main beam loss detector for accelerators without any evidence of degradation or aging in more than 10 years of LHC. The detectors are working perfectly (no damages, no quenches). The future plans are to produce around 1000 ICs for SPS, the LIC with IC ceramics. In 2018, IHEP has designed and produced 4 first prototypes of the proportional chambers for problems location at LHC, 16 and 31 of L2.

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This paper is dedicated to the memory of the project leader, Dr. Bernd Dehning, who passed away in January 2017.

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