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MECHANICAL DESIGN OF THE BEAM GAS IONISATION (BGI) BEAM PROFILE MONITOR FOR CERN SUPER PROTON SYNCHROTON

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Abstract

The Beam Gas Ionisation (BGI) instrument of the Proton Synchrotron (PS), presently installed and operational, has been re-designed for the Super Proton Synchrotron (SPS), the following machine along the Large Hadron Collider (LHC) injector chain at CERN accelerator complex. Using the same detection technology, Timepix3, the SPS-BGI infers the beam profile from the electrons created by the ionisation of rest gas molecules and accelerated onto an imaging detector. This measurement method will allow for continuous, non-destructive beam size measurement in the SPS. In view of the upgrade, the design has been simplified and validated for integration, radio-frequency & impedance, high-voltage, and ultra-high vacuum compatibility.

INTRODUCTION

Accurate time-resolved measurements of the transverse beam profile are required to identify the causes of emittance growth. A new generation of Ionisation Profile Monitors (IPM) based on the detection of ionisation electrons with Hybrid Pixel Detectors (HPD's) installed directly inside the accelerator beam pipe, are currently being designed, produced, installed, and commissioned along the LHC injector chain [1]. Furthermore, in the scope of the High-Luminosity Large Hadron Collider (HL-LHC) upgrade, IPM's based on this technology are under development. Henceforth, the present proceeding will focus on the design phase of the new IPM's for the Super Proton Synchrotron accelerator – which at CERN are called Beam Gas Ionisation (BGI) profile monitors.

The working principle of the BGI for SPS is presented in Fig. 1. Electrons (and ions) are released by the interaction of the beam with residual gas. An electric field of 357 kV/m, formed by a cathode at -30 kV and a grounded anode, accelerates electrons onto an imaging device. The density of detected electrons is a direct measure of the transverse beam profile. The corresponding ions are transported through a hole – called the ion trap – to prevent the production of background electrons. A 0.26 T magnetic field, parallel to the electric field, ensures that the transverse position of the electrons is maintained, mitigating the effects of electron drift caused by electric field imperfections, the ionisation process, and the beam space-charge [1].

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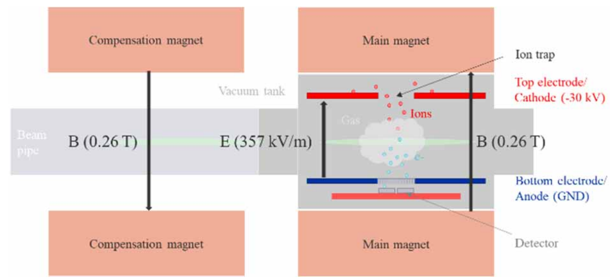

Figure 1: SPS-BGI working principle.

INSTRUMENT OVERVIEW

In the following section, a general overview of the instrument installed inside the vacuum tank will be described. The explanation will focus on the main function of the components listed in Fig. 2. The particular design features that have been implemented to address issues of radio-frequency (RF) & impedance, high-voltage (HV) and ultra-high vacuum (UHV) compatibility requirements will be described in the corresponding sections.

Structural Components

The BGI structural components are those that shape and give rigidity to the arrangement. Among them, these parts stand out: the support arms, the front reinforcement, and the Ultra-High Vacuum ConFlat (UHV CF) rectangular flange, a technology developed at CERN in 2015 for the first prototype of the BGI instrument [2].

Field Cage Design

The BGI field cage is required to provide a homogeneous electric field, protect the hybrid pixel detectors from background electrons, and shield the readout electronics from electromagnetic interference from the beam [3].

As illustrated in Fig. 2B, two parallel electrodes hold a potential difference of 30 kV. The top electrode or cathode, at -30 kV, is mechanically connected and electrically insulated from the support arm with ceramic spacers. To supress the formation of background electrons, a slit – called the ion trap – allows the corresponding ions to pass through and be directed onto the back of the cathode, where secondary (background) electrons will find no path back to the pixel detector. The bottom electrode or anode is grounded by means of fingerstock gaskets. A square pattern provides an opening in the faraday cage to allow the electrons to reach the surface of the chips, while protecting the electron detection system from electromagnetic interference.

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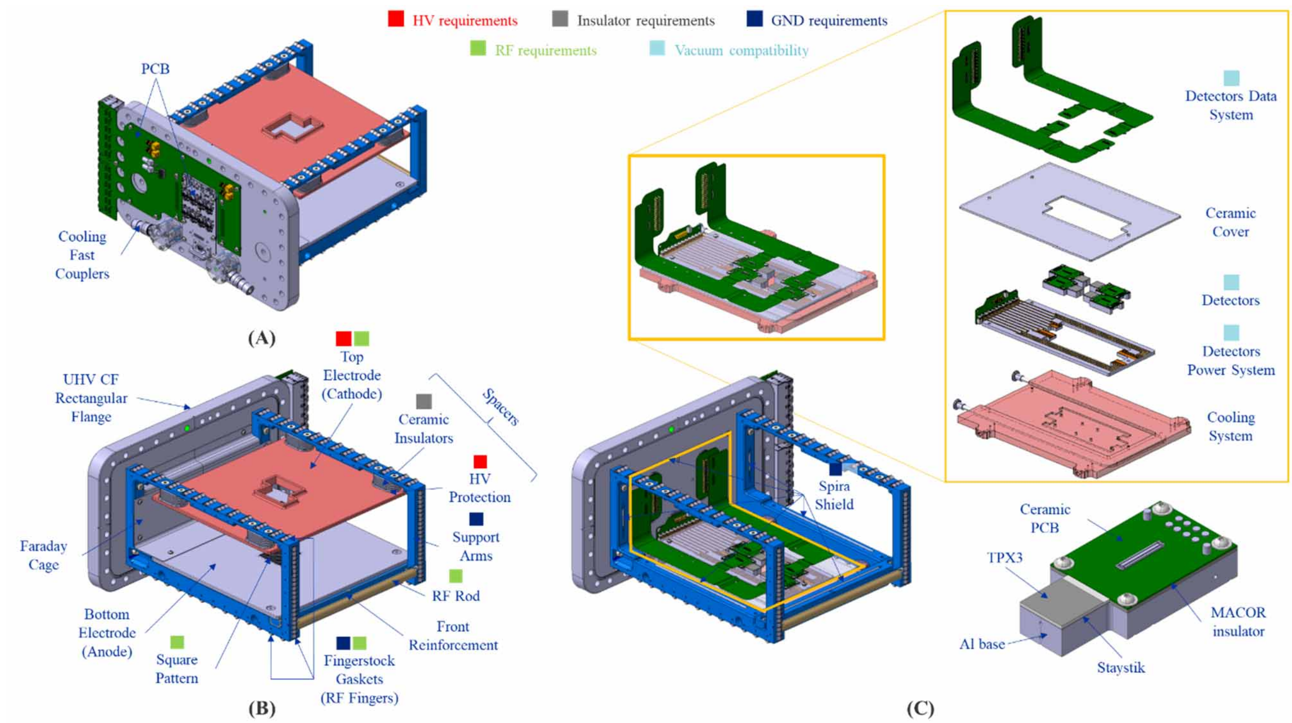

Figure 2: Instrument overview. Component classification based on HV, RF and UHV compatibility requirements.

Detection System

The detection system consists of a set of in-vacuum (Fig. 2C) and air side (Fig. 2A) components.

Detector Modules The ionisation electron detector module consists of a Timepix3 hybrid pixel detector (TPX3) attached to a metal base using a "Staystik 672" thermoplastic adhesive. The aluminium base is the thermal interface between the TPX3 chip and the cooling system. The TPX3 chip is also wire-bonded to a ceramic PCB, which provides the interface for the electrical and power connections. The ceramic PCB itself is directly secured onto the metal base through an electrical insulator. A total of four modules are used to cover a detection width of 54 mm and oriented to optimise the data readout [4].

In-Vacuum Electronics Flexible cables, made with a Liquid Crystal Polymer (LCP) substrate, connect the ceramic PCB to electrical feedthroughs on the vacuum flange. Power is distributed to the detector modules by means of micro-copper bus bars embedded in ceramic insulators.

Air Side Electronics Front-end readout electronics located beneath the instrument are used to transmit the data outputs from the TPX3 chips via radiation hard optical transceivers to back-end readout electronics based on COTS components [3]. The front-end is connected by ethernet cables to a PCB mounted on the air side of the vacuum flange, which connects to the electrical vacuum feedthroughs and hosts the DC/DC voltage regulators for the TPX3 chips.

Cooling System Each TPX3 chip produces ~2 W of heat that must be removed by conduction. The cooling system is based on the circulation of ambient temperature demineralised water in a continuous stainless-steel pipe that is brazed into a copper plate. Each detector module is fixed to the copper plate, which provides the thermal path for the heat, but also defines the positions of the detector modules.

INTEGRATION REQUIREMENTS

In Fig. 3, a section of the instrument in the vacuum tank inside the magnet reveals the narrow margin between the assemblies. The main constraint comes from the aperture of the dipole magnets, which are being reused from an old design.

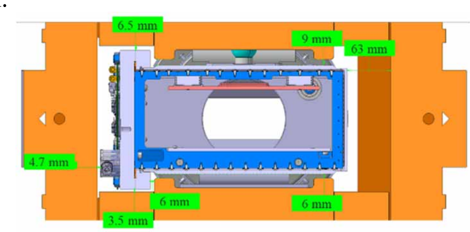

Figure 3: Section view of the final assembly.

The installation procedure has been designed to allow a straightforward maintenance of the equipment, whereby the instrument needs to be accessible and easily disassembled. Only three steps will be required during the installation process. First, the instrument will be integrated inside the vacuum tank with yoke handles. Second, the electrical feedthrough, air side vacuum electronics and cooling system will be connected. Finally, the magnet will be slid into the nominal position and aligned (Fig. 4).

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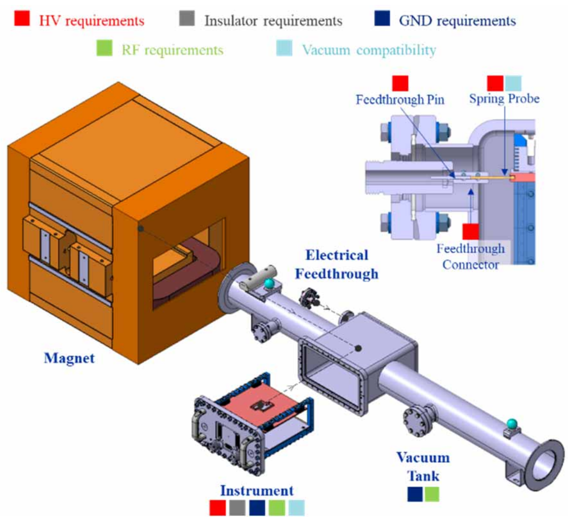

Figure 4: Integration overview. Component classification based on RF, HV and UHV compatibility requirements.

RADIO-FREQUENCY & IMPEDANCE REQUIREMENTS

An impedance study has investigated possible resonances which may occur inside the instrument causing beam induced heating and instabilities during the operation. The longitudinal impedance optimisation of the SPS-BGI has been done by Wakefield and Eigen solvers of CST Particle and Microwave Studios, respectively [5]. Among the implemented design changes:

- The support arms are fully covered by fingerstock gaskets (RF fingers) to provide good RF contact.
- A highly resistively metal coated ceramic cathode has been selected instead of a stainless-steel electrode. In consequence, the cathode is "transparent" to the beam and possible resonances are mitigated.
- A low resistivity coated ceramic rod is placed between the support arms and hidden from the beam to help minimise resonances below 1.5 GHz.

Figure 5 shows the longitudinal impedance reduction after the study, together with SPS 26 GeV and 450 GeV beam spectrums. Pending the final resistivity values after coating, some simulations will have to be repeated to verify these results. To check the simulations outcome, RF tests (wire and probe measurements) will be performed before the installation of the vacuum tank and instrument assemblies [6].

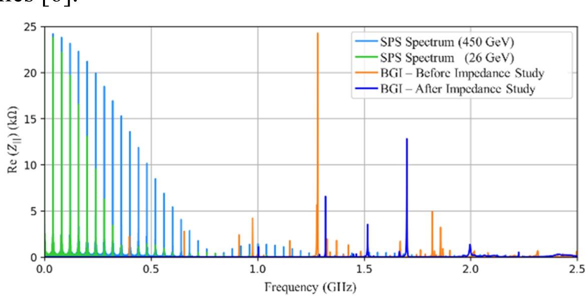

Figure 5: Longitudinal impedance after the optimisation study compared to SPS 26 GeV and 450 GeV beam spectrums.

HIGH-VOLTAGE REQUIREMENTS

All the components of the instrument and vacuum tank assembly can be classified into three groups detailed in Fig. 6. A section view illustrating these categories for the different parts of the assembly is shown in Fig. 7. Components operating at HV (-30 kV) have required particularly careful design to avoid breakdown, for example, by mitigating triple junction effects (HV protection), and ensuring a minimum vacuum gap between HV and GND [7].

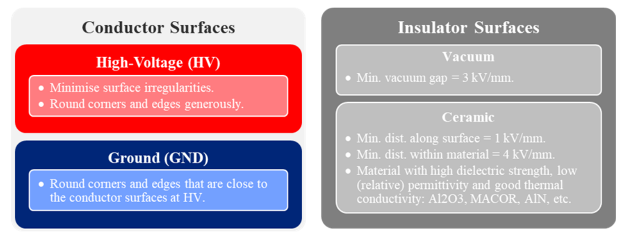

Figure 6: Schematic of HV, Insulator and GND design requirements [7].

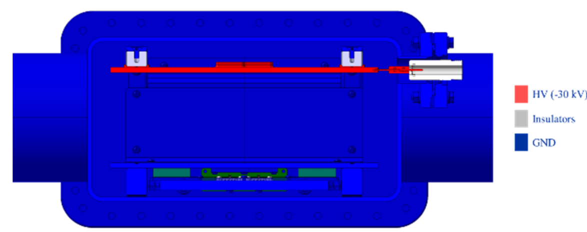

Figure 7: Section view of all the components of the instrument plus vacuum tank assembly classified into HV, Insulator and GND parts.

VACUUM COMPATIBILITY

To provide CERN accelerators and experiments with the required residual gas pressure, vacuum acceptance tests are essential. They include the measurement of leak tightness, level of contamination, and outgassing and inleakage (or virtual leak) rates [8].

The quality of a vacuum system is firstly based on the choice of materials and its mechanical design. For example, metals and ceramics are preferred over polymers, and vented screws are used to avoid virtual leaks. Secondly, the fabrication processes of assemblies or subassemblies exposed to beam vacuum are subjected to different criteria to prevent the above-mentioned problems [9].

CONCLUSION

The design of the BGI profile monitor for the SPS has been successfully adapted from the PS design and integrated within the constraints of an existing dipole magnet. It has also been optimised to simplify assembly & long-term maintenance, and particular focus has been put on minimising longitudinal impedance.

Two instruments (horizontal and vertical) are planned to be installed during 2023/24 winter shutdown. The successful installation and commissioning of these instruments will allow operators and beam physicists to obtain continuous non-destructive measurements of the transverse beam profile in the SPS.

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