Title: RnD for low-mass silicon sensors in vacuum
Acronym: VERVE (Vertexing in Extreme Radiation & Vacuum Environment)
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1. Research objectives

Low mass silicon detectors are key components of modern particle detectors in different fields, including but not limited to hadron, nuclear and particle physics detectors. They are crucial to provide the required position resolution for tracking and vertexing detectors. Concretely, the vertexing detector envisaged for ALICE 3 will enable novel measurements of dielectrons and (multi-)charm baryons, which are not accessible at other existing or planned facilities. The quest for ultimate precision of vertex reconstruction in collider experiments necessitates proximity to the interaction point (extrapolation uncertainty) and minimal material (multiple scattering). The beam pipe typically constitutes a substantial contribution to the latter. To circumvent the limitations of material and distance, the placement of the detector within the beam pipe will allow a significant boost in performance. This implies the installation and operation in vacuum and a significant increase in particle flux hence leading to more stringent radiation tolerance requirements.

With this project, we propose R&D activities to explore new territory for the operation of radiation-tolerant, light-weight detectors in vacuum. The technology of choice is monolithic CMOS pixel sensors, which allow minimal material but pose challenges on the radiation tolerance. Specifically, we target a combination of approximately 0.1% of a radiation length, resilience to irradiation with 10^{16} 1 MeV n_{eq} / cm^2 Non-Ionizing Energy Loss (NIEL) and 5 MGy Total Ionizing Dose (TID), and operation in ultra-high vacuum (~10^{-10} Torr). This line of R&D is critical for the ALICE 3 Vertex Detector, highly relevant for potential future upgrades of fixed target experiments, e.g. CBM and NA60+, as well as for envisaged FCC-ee vertex detectors.

Existing CMOS pixel sensors have been demonstrated to remain operational after an irradiation with approximately 10^{15} 1 MeV n_{eq} / cm^2 (cf. Digital Pixel Test Structure 'DPTS' in a 65 nm CMOS process). This is an order of magnitude below the target value (s. above). An additional challenge arises from the integration in a large-acceptance experiment. While retractable detectors in close proximity of the interaction point in a collider exist (LHCb VELO), they benefit from the large available volume outside of the fiducial volume of the experiment. In the case of ALICE 3, the vertex detector is fully contained within the main tracker, such that services and mechanical support contribute to the material budget.

A viable implementation requires an increased integration density employing light, and ultra-high-vacuum-compatible materials.

The proposed project comprises the following two main areas of research and development:

A) Evaluation and qualification of materials for in-vacuum integration of pixel sensors

The operation of detectors in an environment with critical requirements on the vacuum conditions, including the compatibility with machine protection protocols, poses significant limitations on the materials to be used for the detector and its integration. While expertise exists on lightweight and radiation tolerant materials for tracking detectors from previous detector projects (e.g. ALICE ITS2 and ITS3), additional challenges arise from the different mechanical and operating conditions (e.g. cooling down to approximately -25ºC instead of room temperature and the resulting mechanical stress). This requires the systematic evaluation of materials for detector assemblies suitable for operation in ultra-high vacuum (UHV) conditions (10^{-10} Torr). We envisage the following studies:

- Evaluate the compatibility of selected key materials and components with UHV environments, including electrical substrates (such as polyimide-based flexible printed circuits (FPCs) and redistribution layers (RDLs)), mechanical substrates (e.g. carbon-based materials) and adhesives with particular attention to thermal-cycle-induced stress.
- Establish handling procedures for the detector assembly, with particular attention to hydrophilic materials such as polyimide-based FPCs and support structures made in carbon foam or ceramics.

Particular emphasis shall be given to outgassing properties. This shall be performed by methods for which expertise and infrastructure exists in the participating institutes, specifically:

- Residual Gas Analysis (RGA), identifying desorbed species from materials (e.g. H_2O, CO, CO_2, hydrocarbons) and monitoring vacuum cleanliness.
- Thermal Desorption Spectroscopy (TDS), monitoring the species desorbing during heat treatment under vacuum.

B) Enhancing radiation tolerance of CMOS pixel sensors

With the combination of proximity and high interaction rates, the radiation tolerance of existing CMOS pixel sensors is insufficient for systems, such as the ALICE 3 vertex detector. To alleviate this limitation, an improvement of radiation tolerance by about an order of magnitude is required. Efforts towards this goal use modifications of the implants in the pixel to optimize the field configuration to improve charge collection and to reduce the pixel capacitance. As this marks new terrain, experimental data on the performance and its dependence on various parameters, e.g. irradiation and operating temperature as well as reverse substrate bias, is crucial. This requires the systematic characterisation of irradiated CMOS pixel chip prototypes, including access to analogue information. To this end, we foresee the following activities:

- Study of the charge collection properties through in-pixel position dependent studies with a resolution of a few micrometers of the detection efficiency at test beam and, possibly, measure time response employing radioactive sources in the laboratory.
- Systematically compare characterisation results to simulations of the charge collection properties across the pixels to refine the modelling of pixel implant structures.

For these sensor characterisation activities, dedicated setups are required for operating the sensors at different temperatures. We envisage the construction of test setups providing the following features:

- Allowing to cool prototype chips down to -25ºC in a dry, non-condensing atmosphere.
- An entrance and exit window of the cooling enclosure featuring a combined thickness of approximately 100 µm aluminium limiting multiple scattering for use with the test beam.
- Moreover, the cooling enclosure has to be compact in the beam direction to be able to bring the telescope close by and to limit the extrapolation uncertainties so that position dependent studies with a resolution of a few micrometers become feasible.

2. Connection to Transnational Access infrastructures (TAs)
The VERVE project addresses novel approaches by combining aspects, for which relevant expertise exists across the participating institutes. For example, the project will make use of test beam facilities at CERN (SPS/PS) and Frascati (BTF) as well as the existing infrastructure and expertise on sensor characterisation at these institutes. For the detailed study of in-vacuum behaviour, the INFN institutes will contribute infrastructure and know-how. Such access to transnational infrastructures and close collaboration will amplify the potential of the individual groups and open up new possibilities.
The technology developed by the VERVE project will serve for vertex detectors at future experiments or upgrades of current experiments and the test beam setup has the potential to serve for other cryogenic sensor test activities.
For an efficient programme, start-up and wrap-up meetings will be held at CERN.

3. Estimated budget request
The estimated budget includes the following components:

- **€120,000** to cover **2.4 years** of a **3-year doctoral position** based at CERN;
- **€80,000** to fully support a **3-year doctoral position** at an Italian university;
- **€50,000** corresponding to **25% indirect costs**.

This brings the total requested funding for the four-year period to **€250,000**.

4. Participating and partner institutions
CERN, INFN (Bari, Cagliari, Catania, Frascati, Padova, Torino, Trieste)