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Radiation-Hard Ceramic Resistive Plate Chambers for Forward TOF and T0 Systems

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Abstract

Resistive Plate Chambers with ceramic electrodes are the main candidates to be used in precise multi-channel timing systems operating in high-radiation conditions. We report the latest R&D results on these detectors aimed to meet the requirements of the forward T0 counter at the CBM experiment. RPC design, gas mixture, limits on the bulk resistivity of ceramic electrodes, efficiency, time resolution, counting rate capabilities and ageing test results are presented.

Keywords:
Multi-gap RPC, ceramic RPC, bulk resistivity, high rate, TOF, time resolution , efficiency, CBM, T0, BFTC
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1. Introduction

Precise determination of the collision time T_0 and the reaction plane in high-energy experiments at accelerators of elementary particles and heavy ions are of essential importance for time-of-flight measurements and further physics data analysis. For this purpose, T0 systems are implemented, such as the one operating in the ALICE detector [1], which also provides inputs to the trigger system and luminosity measurements. A significant advance in development of Resistive Plate Chambers (RPC) as high-resolution timing detectors was achieved during the last two decades, mostly during the R&D for the ALICE TOF project [2].

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The resulting chambers represent multiple layers of electrically floating glass electrodes with pad readout and have been successfully implemented in the ALICE [3] and STAR [4] experiments. Having proved to be a reliable solution in mid-rapidity region, the RPCs of this design, however, manifest poor rate capabilities and high cross-talk rate, unacceptable in the forward region. In this case, a low-resistivity and radiation-hard material of the RPC electrodes combined with chessboard-like single pad readout is considered as a preferable solution.

2. Beam Fragmentation T0 Counter for the CBM TOF Detector

Every time-of-flight (TOF) measurement requires the reference time T_0, or start time, referring to the moment of collision. The proposed solution for the start time determination in the Compressed Baryonic Matter (CBM) experiment [5] at the planned Facility for Antiprotons and Ion Research (FAIR) in Darmstadt, Germany, is the Beam Fragmentation T0 Counter (BFTC) [6]. It should cover the region from about 20 to 60 cm from the beam pipe (overlapping with the acceptance of the Projectile Spectator Detector) and be positioned in the centre of the TOF wall, 6 m away from the target (Fig. 1). In addition to T0 measurements, it will provide for particle identification and the reaction plane determination during heavy-ion collisions.

SHIELD simulations predict that the BFTC region will be exposed to harsh conditions with the particle flux being as high as 2×10^5 Hz/cm^2 [7]. In this environment, BFTC will have to provide the time resolution below 60 ps and the registration efficiency above 98%. A single cell size of 20×20 mm^2 is limited by the requirement that the double-hit probability should not exceed 2%. The electrical cross-talks between neighbouring cells that may produce false signals should stay within 1-2%.

As discussed elsewhere [8–11], current efforts are concentrated on RPCs with electrodes made of low-resistivity Si_3N_4/SiC ceramics that have proven to operate well in the high radiation environment and provide good rate capabilities.

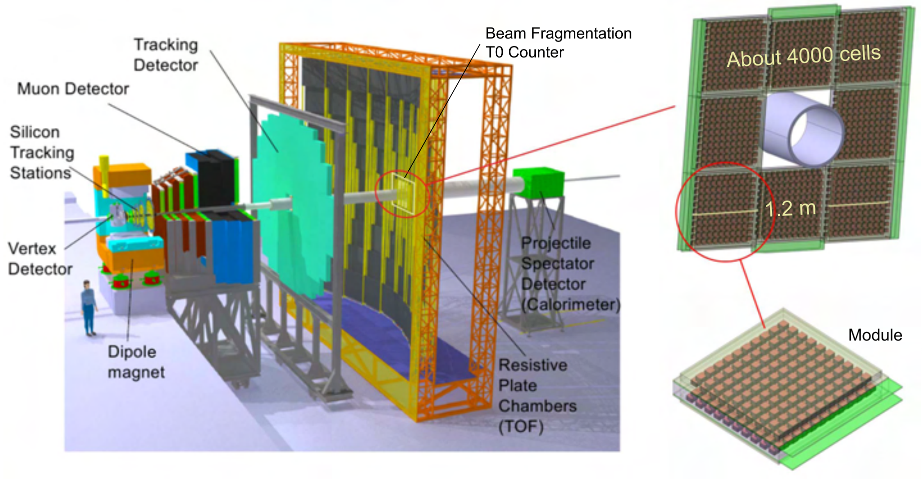

Figure 1: Positioning, size and structure of BFTC in the CBM experiment.

The bulk resistivity of Si_3N_4/SiC is variable within a wide range from 10^7 Ω cm to 10^{12} Ω cm and can thus be optimized for BFTC operating conditions. A single RPC cell represents a 3-layer sandwich of double-gap RPCs (see Fig. 2). The outer electrodes are made of aluminium oxide Al_2O_3 covered by metal evaporation with thin conductive layers of Cu/Cr that are used for high voltage distribution and signal readout. Si_3N_4/SiC electrodes are used as internal electrodes and are kept electrically floating. All electrodes have Rogowski-shaped edges (internal Si_3N_4/SiC electrodes—on both sides) to minimize the electric breakdown probability. Gas-filled gaps are kept 250 μm wide by means of rectangular spacers made of Al_2O_3. Such multilayer design implements the Dielectric Resistive Plate Chamber technology that has long since proved to be a promising timing technique for high radiation conditions [12]. The working gas is mixed of $C_2H_2F_4$ and SF_6 in 90%/10% or 95%/5% proportions. As reported in [9], the use of iso-butane has been abandoned due to its observed harmful effect on the surface of metallized electrodes resulting in the formation of localized polymer whiskers.

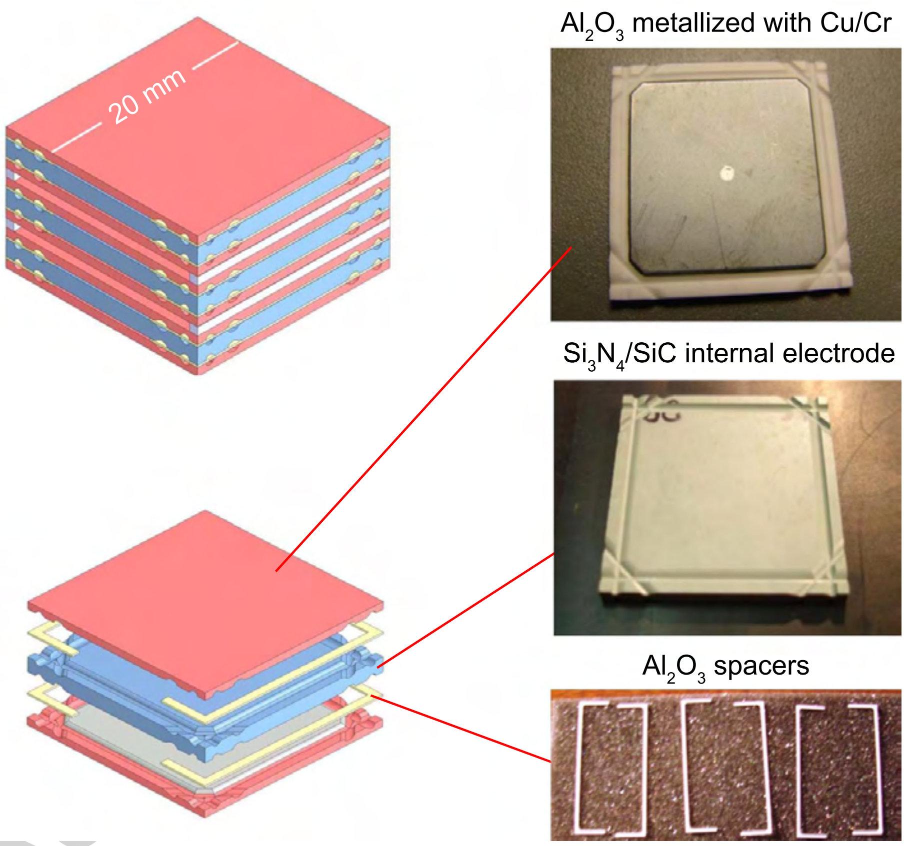

Figure 2: Structure of a single cell of BFTC.

3. Latest Progress on RPCs for BFTC

In 2015, the finalized design of outer RPC electrodes was implemented. Cu/Cr layer is now coated with an improved mask on grooved Al_2O_3 ceramic electrodes sized 2×2 cm^2. For best timing performance, the signal is read-out from the centres of electrodes: the soldering spot may be seen as a white dot on the electrode surface in top right photo in Fig. 2.

The optimal bulk resistivity of the floating electrodes was studied with beams of 30 MeV electrons in November 2015 at the radiation source ELBE at HZDR [13]. Four final size chambers (2×2 cm^2, 6×250 μm gaps) with different values of resistivity of the floating electrodes, were produced. Namely, mCRPC0 had floating electrodes with the bulk resistivity of 2×10^{10} Ω cm, mCRPC1—3×10^9 Ω cm, mCRPC2—5×10^8 Ω cm, mCRPC3—7×10^9 Ω cm. Test results for all four chambers are compared in Figs. 3 and 4. The chamber mCRPC2 became unstable already at 87-88 kV/cm producing multiple streamers and manifesting poor time resolution of over 140 ps. The rest of the chambers showed stable and efficient operation. The chamber mCRPC3 could not be tested within the whole electric field range due to the lack of the beam time. RPCs manifested the efficiency of 95-97% under particle fluxes of a few kHz/cm2. It has been observed that for higher fluxes, the bulk resistivity of 10^{10} Ω cm is too high, resulting in the drop of efficiency to 74% under 160 kHz/cm^2. Due to technical problems, the chambers mCRPC1 and mCRPC3 were measured only up to 70 kHz/cm^2. The drop of efficiency was related to the resistivity of the chambers as was expected. The bulk resistivity of the floating electrodes of the order of 10^9 Ω cm has proved to be the most appropriate for BFTC purposes.

Two samples of low-resistivity ceramic plates were exposed to non-ionizing radiation doses of the order of 10^{13} $n_{\mathrm{eq}}/\mathrm{cm}^2$ at the neutron beam of MEDAPP at FRM II in Munich [14]. The bulk resistivity of both probes was measured before and after the irradiation, and decreased by a factor of 2. This decrease has no impact on the efficiency and time resolution. Irradiation of the Al_2O_3 electrodes with fluxes of up to 10^{15} $n_{\mathrm{eq}}/\mathrm{cm}^2$ does not lead to any degradation

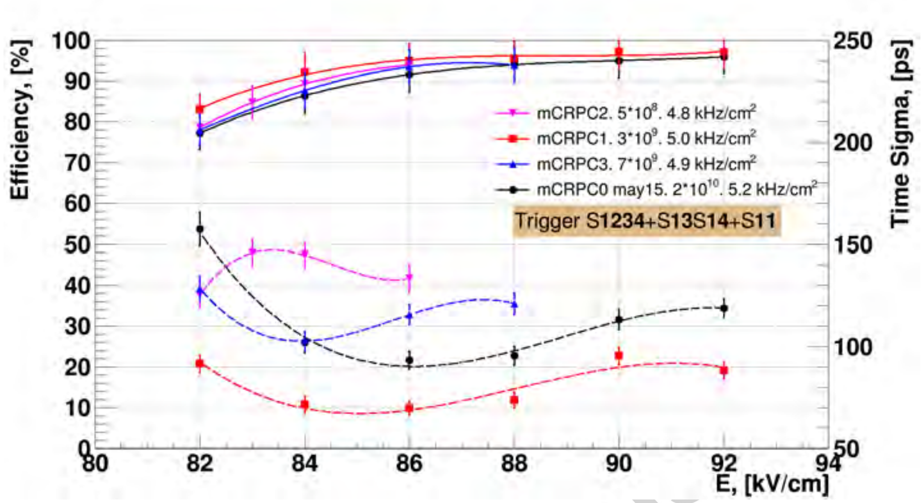

Figure 3: Efficiency and time resolution (after time-walk correction) measured with different types of 2×2 cm^2 chambers as a function of applied electric field.

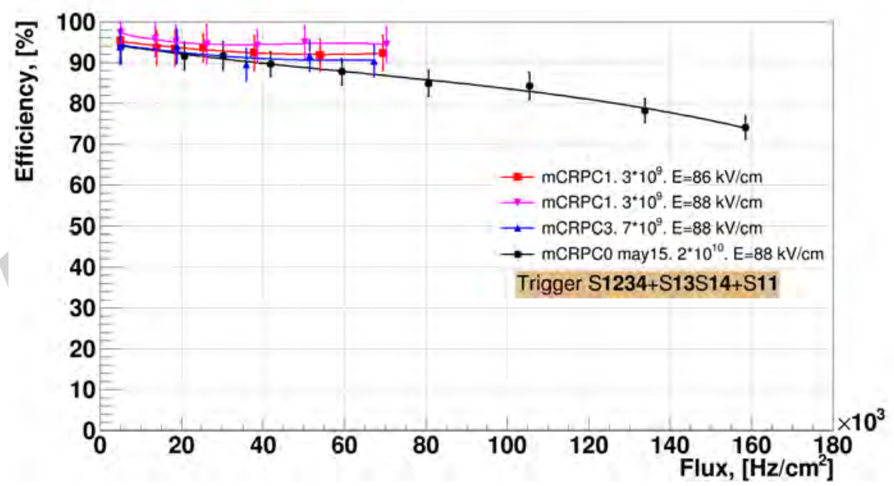

Figure 4: Efficiency of 2×2 cm^2 chambers as a function of hit rate.

of detector performance.

4. Conclusions and outlook

The presented R&D results look very promising. The radiation hardness of ceramics has been confirmed. Use of the 90% $C_2H_2F_4$ / 10% SF_6 gas mixture showed no aging effects on the RPC material after a few months of continuous operation. Rough limits for the optimal bulk resistivity of internal electrodes have been found. A more precise scan of 8 new chambers with the bulk resistivity of internal electrodes between 1.5×10^9 Ω cm and 8×10^9 Ω cm is scheduled to be performed in 2016 at the ELBE accelerator. The goal is to find the best resistivity value that could provide a stable RPC operation with the efficiency above 95% within the whole range of hit rates up to 200 kHz/cm^2.

Also, a significant improvement of the time resolution is expected with the implementation of advanced CBM PADI front-end electronics.

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