Eur. Phys. J. Plus (2023) 138:1080
https://doi.org/10.1140/epjp/s13360-023-04712-9

THE EUROPEAN
PHYSICAL JOURNAL PLUS

Regular Article

Toward an environmental friendly operation of the CBM-TOF system

Ingo Deppner[1,a], **Claudia Bogdan**[2,b], **Sebastian Brad**[2,c], **Cătălin Brill**[2,d], **Daniel Dorobanţu**[3,e], **Aleksandr Grafov**[2,f], **Dong Han**[4,g], **Norbert Herrmann**[1,h], **Dongdong Hu**[5,6,i], **Alin Lazar**[2,j], **Wen Li**[5,6,k], **Mariana Petriş**[3,l], **Mihai Petrovici**[3,m], **Andrii Rozhenstev**[2,n], **Oleksandr Sirosh**[2,o], **Yannick Söhngen**[1,p], **Kai Sun**[4,q], **Yongjie Sun**[5,6,r], **Mihai Vijulie**[2,s], **Botan Wang**[4,t], **Kaiyang Wang**[5,6,u], **Xinjian Wang**[5,6,v], **Yi Wang**[4,w], **Ming Yao**[5,6,x], **Jian Zhou**[5,6,y], **Yingjie Zhou**[5,6,z]

[1] Physikalisches Institut, Heidelberg University, Im Neuenheimer Feld 226, 69120 Heidelberg, Baden Württemberg, Germany
[2] National Research and Development Institute for Cryogenic and Isotopic Technologies, ICSI Rm. Valcea, str. Uzinei, nr. 4, Rm. Valcea 240050, Romania
[3] Hadron Physics Department (HPD), National Institute for Physics and Nuclear Engineering (IFIN-HH), Str. Reactorului, 077125 Măgurele, Romania
[4] Department of Engineering Physics, Tsinghua University, Qinhuan Yuan, Beijing 100084, China
[5] Department of Modern Physics, University of Science and Technology of China (USTC), 96 Jinzhai Road, Hefei 230026, Anhui, China
[6] State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China (USTC), 96 Jinzhai Road, Hefei 230026, Anhui, China

Received: 17 July 2023 / Accepted: 20 November 2023
© The Author(s) 2023

Abstract The future fixed target high-rate compressed baryonic matter (CBM) experiment is one of the experimental pillars of the Facility for Antiproton and Ion Research (FAIR) located in Darmstadt/Germany. In order to provide an excellent particle identification (PID) of charged hadrons, the CBM-time-of-flight (TOF) group has developed a concept of a 120 m^2 large TOF wall with a system time resolution below 80 ps based on multi-gap resistive plate chambers (MRPC). Currently, timing MRPC systems are operated with a gas mixture based on tetrafluoroethane (R134a, $C_2H_2F_4$) with additions of few vol% quencher gases, e.g., sulfur hexafluoride (SF_6) or/and isobutane (i-C_4H_10). Unfortunately, these gas mixtures have a high global warming potential (GWP) in the order of 1500, and therefore, strategies to reduce the environmental impact have to be developed. The various possibilities, including studies on eco-friendly gases, and the considered strategy by the CBM-TOF group will be elaborated in this article.

---

[a] e-mail: deppner@physi.uni-heidelberg.de (corresponding author)
[b] e-mail: Claudia.bogdan@icsi.ro
[c] e-mail: Sebastian.brad@icsi.ro
[d] e-mail: Catalin.brill@icsi.ro
[e] e-mail: ddorobantu@nipne.ro
[f] e-mail: Aleksandr.grafov@icsi.ro
[g] e-mail: handong@mail.tsinghua.edu.cn
[h] e-mail: herrmann@physi.uni-heidelberg.de
[i] e-mail: hurongr@ustc.edu.cn
[j] e-mail: Alin.lazar@icsi.ro
[k] e-mail: liwen@mail.ustc.edu.cn
[l] e-mail: mpetris@nipne.ro
[m] e-mail: mpetro@nipne.ro
[n] e-mail: Andrii.rozhenstev@icsi.ro
[o] e-mail: Oleksandr.sirosh@icsi.ro
[p] e-mail: soehngen@physi.uni-heidelberg.de
[q] e-mail: sun-k21@mails.tsinghua.edu.cn
[r] e-mail: sunday@ustc.edu.cn
[s] e-mail: Mihai.vijulie@icsi.ro
[t] e-mail: wbt19@mails.tsinghua.edu.cn
[u] e-mail: czswky@mail.ustc.edu.cn
[v] e-mail: sawxj@mail.ustc.edu.cn
[w] e-mail: yiwang@mai.tsinghua.edu.cn
[x] e-mail: mmzz@mail.ustc.edu.cn
[y] e-mail: zj1994@mail.ustc.edu.cn
[z] e-mail: zhouyingjie@mail.ustc.edu.cn

Published online: 05 December 2023

1 Introduction

The compressed baryonic matter experiment (CBM) [1, 2] will be one of the main research pillars of the Facility of Antiproton and Ion Research (FAIR) which is currently under construction in Darmstadt/Germany. CBM aims to investigate strongly interacting matter at large baryon densities by colliding heavy ion beams provided by the SchwerIonenSynchotron SIS100 accelerator on a gold target, enabling center-of-mass energies $\sqrt{s_{NN}}$ up to 4.9 AGeV. The main research interests are the exploration of the QCD phase diagram in the baryon-rich region and the determination of the equation of state of QCD matter. These goals can be reached by measuring not only all produced bulk particles (protons, kaons, pions) but also a variate of rare probes like multi-strange (anti-)hyperons and (multi-)strange hypernuclei. A further statistic hungry observable intended to be measured extensively by CBM is the invariant mass spectra of di-lepton pairs (both, in the electron and muon channel) which provides information at essentially each moment of time during the collision. For this purpose, an extremely high interaction rate of up to 10^7 Hz is anticipated (conf. right panel of Fig. 1). Figure 1 shows on the left panel the setup of the CBM experiment. On the right panel, the interaction rate of several present and future heavy ion experiments is compared. The location of the CBM experiment is highlighted in the plot by the red ellipse. Inside a 1 Tm dipole magnet, tracking stations for vertex reconstruction and momentum determination will be available. For charged hadron identification, a time-of-flight (TOF) wall of about 120 m^2 will be installed at about 8 m from the interaction point. For clear electron separation, a ring imaging detector (RICH) and a transition radiation detector (TRD) are foreseen. The TRD delivers additionally further tracking information which increases the pointing accuracy of tracks on the TOF wall. The RICH can be exchanged by the Muon Chamber (MuCH) when the di-muon program is going to be measured. For event plane determination, a fragment spectator detector (FSD) is installed in the back of the experiment. It is evident that all subsystems require radiation hard detectors with large rate capability.

Timing multi-gap resistive plate chambers (from now on called MRPC) are gaseous detectors [4] providing nowadays an excellent time resolution in the order of 50 ps [5] with an efficiency of more than 95%. The major advantage of MRPCs compared to scintillator bars, read out by PMTs, is their extremely low cost per readout channel, making systems with more than 100,000 channels affordable. The CBM-TOF system [6–8] will be composed of about 1500 MRPCs with different granularity starting from 5 cm^2 strip area up to 53 cm^2, respectively. Counters with higher granularity are placed in the center of the wall where the track multiplicity and the charged particle flux are highest (up to 50 kHz/cm^2) while counters with the largest granularity are located in the outermost regions of the TOF wall where the flux gradually decreases to about 100 Hz/cm^2. Several MRPCs are grouped in gas tight aluminum boxes called modules (230 modules in total), with a total gas volume of about 25 m^3.

In order to reach such a high performance as stated above, MRPCs operate nowadays typically with gas mixtures composed of 90– 95% tetrafluoroethane (TFE) $C_2H_2F_4$ (also known under the name R134a), 0–5% isobutane i-C_4H_{10} and/or 0–5% sulfur hexafluoride SF_6. SF_6 is introduced as an electron quencher, and consequently, it inhibits the streamer production. Isobutane is known to act as a photon quencher, stabilizing the avalanche dynamics. Since isobutane is a flammable gas, in some cases experiments like ALICE abandoned it lately. Measurements have shown that gas mixtures without isobutane reach similar detector performances [9].

The main issue with the currently used RPC [10] and MRPC gas mixtures is their high global warming potential (GWP over 100 years period) of 1430 for TFE, 3.3 for isobutane (negligible) and 23900 for SF_6 [11]. Other literature quotes slightly lower values [12]. In order to reduce the environmental impact during the operation of the detectors to an acceptable level, the following possibilities are conceivable [12]:

- As a first step, experiments introduced a closed loop gas system in their setup in order to lower the emission. This is nowadays standard.

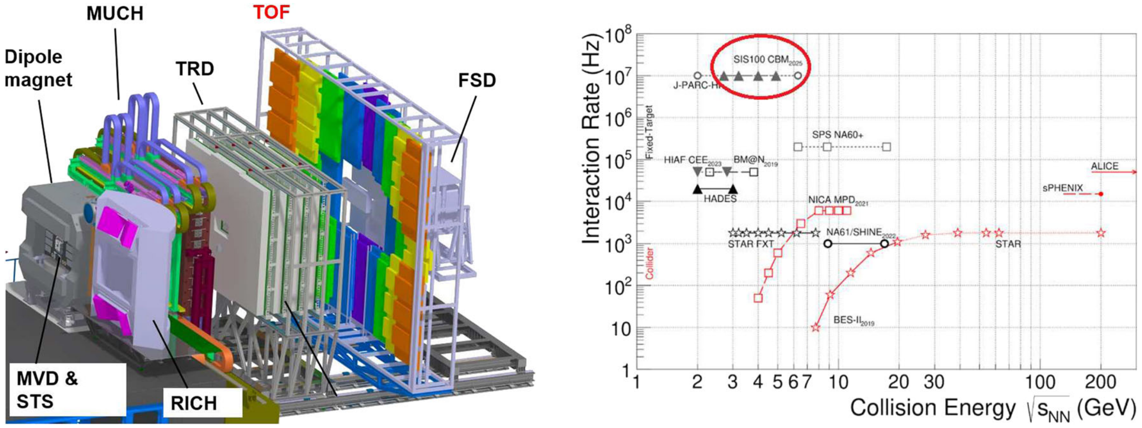

Fig. 1 Left panel: setup of the CBM experiment. Right panel: comparison of the interaction rate for present and future heavy ion experiments [3]. The red ellipse guides the eye to the anticipated interaction rate of CBM

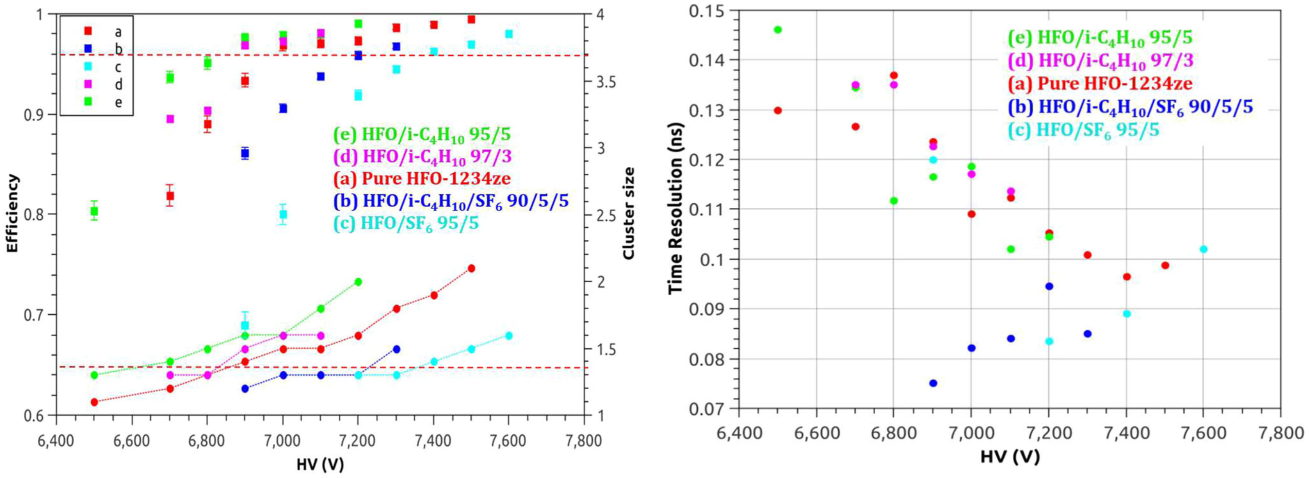

Fig. 2 Left panel: efficiency and cluster size as function of applied high voltage for various gas mixtures based on HFO. Right panel: time resolution as function of applied high voltage for various gas mixtures based on HFO

- Usage of alternative gases with lower GWP as a replacement for TFE and SF_6 also known as eco-friendly gas mixtures. Finding proper replacements is currently a very active research topic.
- The 100% recuperating/recycling of all gasses and their re-injection in the gas circuit. This possibility is discussed in the community, and first recuperation prototypes are in use at CERN.
- Disposal of the gas at the exhaust. This possibility is not seriously considered in the community.

The strategy to reduce the global warming impact during operation in CBM-TOF will be elaborated in the following chapters.

2 Investigation on eco-friendly gas mixtures

During the last several years, an enormous research effort has been made to find eco-friendly gas mixtures as a replacement for the usually used "standard" gas mixtures in the RPC [13–24] and MRPC [25–27] community. As a replacement for TFE, the hydrofluoroolefin (HFO-1234ze) with a GWP of 7 turned out to be the most suitable candidate. It shows similar behavior as TFE, however, shifts the working point of RPCs and MRPCs by typically a few thousand volts to higher values. This might be a non-overcoming problem for some existing experiments, since present installations are not designed to operate at higher voltages and a replacement is not feasible. Therefore, a huge effort is ongoing to find complementary gases which lower the working point to acceptable values [26]. As a replacement of SF_6, many new alternative gasses with all their advantages and disadvantages were presented and discussed here [28].

The TOF group of CBM investigated via cosmic tests five different eco-friendly gas mixtures based on other results reported in the literature:

1. Pure HFO-1234ze
2. HFO/isobutane 95%/5%
3. HFO/isobutane 97%/3%
4. HFO/isobutane/SF_6 90%/5%/5%
5. HFO/SF_6 95%/5%

The aim was to replace the TFE while keeping the usual quencher gases and verify the counter performance in terms of efficiency, cluster size and time resolution. With our standard mixture (TFE/isobutane/SF_6 90%/5%/5%), an efficiency of 97% was reached. The cluster size, which is a proxy for the produced charge, was in the order of 1.35. A counter time resolution in the order of 60 ps could be obtained at a working point of 5400 V. Figure 2 shows the results obtained with cosmic muons with the 5 different eco-friendly gas mixtures. The efficiency (left panel) requirements of 96% indicated by the upper red dotted line were reached for all mixtures but with a shifted working voltage of up to 2 kV. The cluster size shows slightly higher values for the mixtures without SF_6 which is identical with TFE mixtures without SF_6. However, for the time resolution (right panel) only the mixtures containing SF_6 could show somewhat convincing results.

In conclusion: based on the presented results, a change to a more eco-friendly gas mixture could be considered, even though a better time resolution would be desirable.

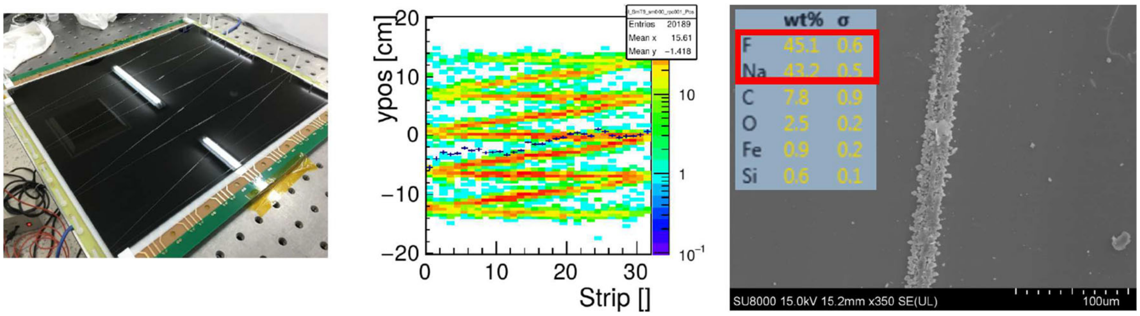

Fig. 3 Left panel: open MRPC counter-spacers are visible arranged in a triangular manner. Middle panel: position reconstruction of the dark rate hits. A clear pattern of the fishing lines is visible. Right panel: traces of a white substance below spacers were found. Chemical analysis revealed the composition of the substance

3 Aging of MRPCs operated at standard gas mixtures at high charged particle flux

As stated in the introduction, CBM aims to operate at 10 MHz interaction rate. This demands stable operating detectors at charged particle fluxes up to 50 kHz/cm^2. During high-rate beam tests (with fluxes above 30 kHz/cm^2) at the SIS18 machine at GSI/Germany, two kinds of phenomena leading to an increase in dark rate and dark detector current were observed. First a temporal aging effect emerged as a rapid increase (within several hours) in dark current and rate of up to five times the original value, which decreases exponentially and returns back to its almost nominal value within a few weeks. Second, a steadily increasing dark rate and current was observed, which we refer to as permanent aging. After each high-rate beam time, we noticed that the chambers do not recover fully and show more and more detector noise. Since we read out the detector on both ends of the readout strips, the noise source could be localized. From the middle panel of Fig. 3, it became evident that the noise is generated homogeneously very close to the spacers (fishing lines) as is visible when compared to the left panel of Fig. 3. In order to investigate the noise source in more details, a few MRPCs were opened, and a white substance was found on the touching surface of the spacers (conf. right panel of Fig. 3). The chemical analysis of the substance revealed a high concentration of fluorine and sodium. The fluorine clearly has to come from reaction products (F-radicals and F$^-$) of the gas, while the sodium is a compound of the glass material. That these impurities, which are responsible for the dark current, are preferentially developed close to the spacers is not surprising or unexpected. Close to the touching point of the round spacer (on the flat glass surface) where the gas gap becomes very small the electric field is substantially higher (simulations show up to a factor of 4), and therefore, the chemistry in this location is enhanced. In addition, a rapid exchange of the gas close to the spacers is suppressed, which generates a large retention time for radicals close to this area. In order to investigate the permanent aging in more details, a gamma irradiation test was performed at IRASM Bucharest/Romania [29] where similar chemical composition of the deposits was found [30].

The speed of permanent aging seems to correlate linearly with the received dose during operation, which is a severe problem when operating MRPCs at high particle fluxes. A mitigation strategy could be to guide the gas flow primarily inside the gaps in order to enhance the gas exchange more rapidly. On the other hand, it is well known that bonds of eco-friendly gases break up more easily (which is actually the reason why these gases have a lower GWP) which leads to an enhanced F$^-$ and radical production [31].

In conclusion: it is very likely that eco-friendly gas mixtures will lead to a strongly increased permanent aging of the detector at high particle fluxes and a shortening of its lifetime.

4 Gas recuperation system for CBM-TOF

A very promising method to reduce the environmental impact during operation of MRPC systems could be the recycling of each gas of the mixture. The idea here is to separate the gases first, eventually clean them from other impurities and re-inject them into the gas circuit. This implies high investment costs for the recuperation system in the beginning but saves running costs later on by reusing the recycled gas and only the losses due to gas leaks in the system have to be procured. First thoughts in this direction were done at CERN [32] and even a first prototype unit recuperating the TFE is in operation at CMS [33]. However, the separation of gasses from the standard mixture is not straight forward. A combination of TFE and isobutane forms an azeotropic mixture, which means that these gasses cannot be separated by distillation to a purity level of 100% [34]. Furthermore, SF_6 has its triple point at a temperature of −49.60 °C and a pressure of 2.314 bar [35], i.e., it cannot be separated from TFE by fractional distillation at normal pressure. Therefore, a pressurized distillation unit or a solid phase cold trap has to be considered if a recycling of SF_6 is desired. For these reasons, the CBM-TOF group decided to abandon the isobutane and operate the MRPCs with a gas mixture of 97.5% TFE and only 2.5% SF_6. Figure 4 shows the first layout of a closed loop gas system with a recuperation system attached designed for CBM-TOF.

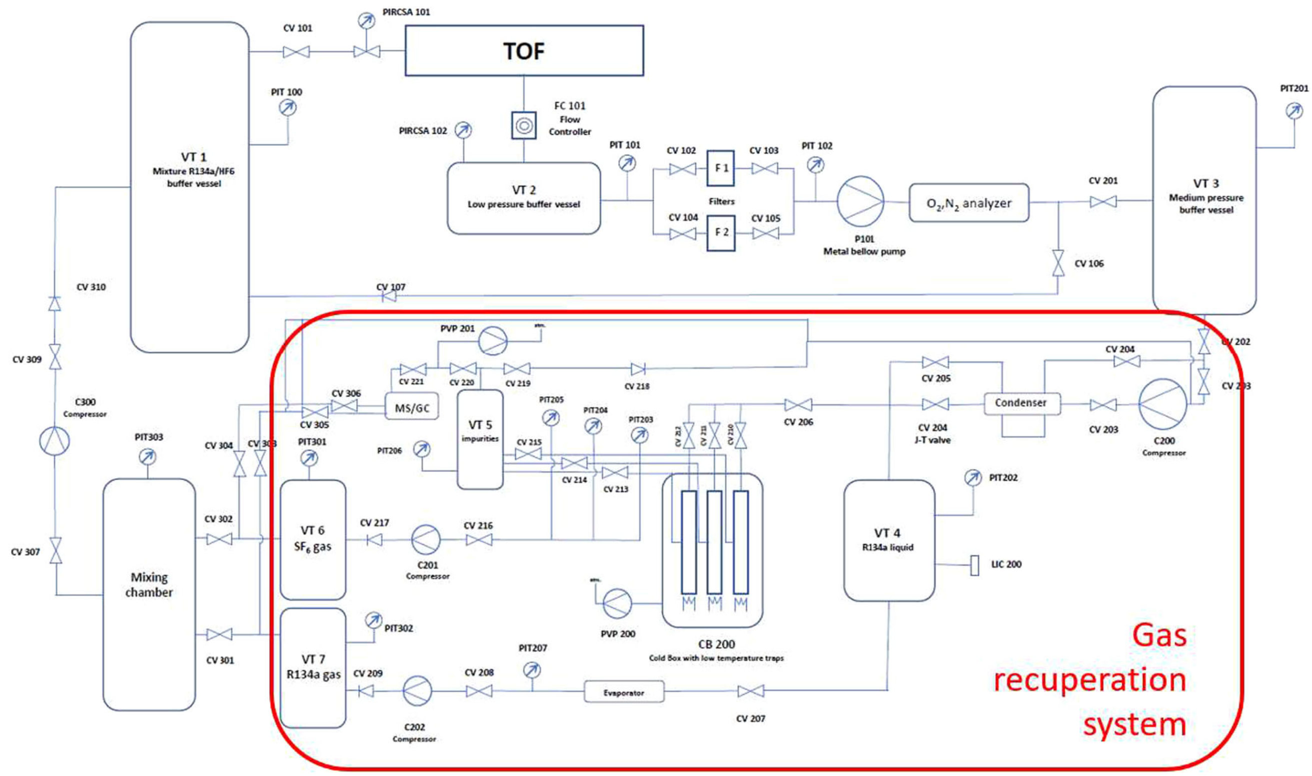

Fig. 4 First layout of the CBM-TOF gas system including a gas recuperation system

The aim is to separate first the TFE from the SF_6 and potentially other impurities via a pressurized condenser and in a second stage freeze out the SF_6 in the solid phase via cold traps. The system is designed to operate three traps in a consecutive manner to allow for loading and emptying the traps simultaneously. The recycled gasses are stored in vessels (VT6 and VT7) and re-injected in the system.

In conclusion: a recuperation system could be an alternative to eco-friendly gasses in order to minimize the environmental impact. However, it should be considered that the industrial production of TFE and SF_6 is going to be reduced or possibly even stopped in the future, which will lead to an increase in price. Nevertheless, since eco-friendly gasses will generate similar operating costs, a recuperation system could be considered for these gasses as well.

5 Summary

The CBM experiment is one of the main research pillars at FAIR. It aims to operate at an interaction rate of up to 10 MHz, which demands radiation hard and rate capable detectors. For charged hadron identification, a 120 m^2 TOF wall composed of MRPCs with rate capabilities of up to 50 kHz/cm^2 is planned to be installed at 8 m from the target. Even though detector performance results obtained with eco-friendly gasses mixtures were promising in terms of efficiency and time resolution, it is a measured fact that gas molecules with low GWP get destroyed much more effectively under RPC operation conditions and the fluorine-ion (F^-) production is increased in comparison with the standard gasses. Similar chemical processes are expected to be present during the MRPC operation, i.e., at higher electric fields as well. Keeping in mind the observed permanent detector aging at high particle fluxes (which turned out to be caused by fluorine compound deposits close to the spacers) which would be clearly strongly enhanced using eco-friendly gasses, the TOF group decided to continue to use a mixture of 97.5% TFE and 2.5% SF_6. The TOF group aims to recuperate both gasses and re-inject them in the circuit. This should reduce the operating costs and lead toward an environmental friendly operation of the CBM-TOF system.

Acknowledgements We would like to express our thanks to all members of the CBM-TOF group. This work is partially funded by BMBF contract 05P21VHFC1. This work was carried out with the support of the internal research and development program of the National Research and Development Institute for Cryogenic and Isotope Technologies—ICSI Rm. Vâlcea. The work is supported by National Natural Science Foundation of China under Grant No. 11420101004, 11461141011, 11275108, 11735009, U1832118 and 11975228. This work is also supported by the Ministry of Science and Technology of China under Grant No. 2015CB856905, 2016 YFA0400100 and by the National Key Program for S &T Research and Development under Grant NO. 2018YFE0205202.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability Statement This manuscript has associated data in a data repository. [Authors' comment: Data analyzed and presented in Fig. 2 are obtained in cosmic tests with MRPC detectors at Tsinghua University and are not public available. They will be made available on reasonable request].

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. N. Herrmann, Status and Perspectives of the CBM experiment at FAIR. EPJ Web Conf. **259**, 09001 (2022). https://doi.org/10.1051/epjconf/202225909001
2. T. Ablyazimov et al., Challenges in QCD matter physics-the scientific programme of the compressed baryonic matter experiment at FAIR. Eur. Phys. J. A **53**(3), 60 (2017). https://doi.org/10.1140/epja/i2017-12248-y
3. T. Galatyuk, Future facilities for high μ_B physics. Nucl. Phys. A **982**, 163–169 (2019). https://doi.org/10.1016/j.nuclphysa.2018.11.025
4. P. Fonte, C. Williams, A. Smirnitsky, A New high resolution time-of-flight technology (1999)
5. M. Petriş et al., High time resolution, two-dimensional position sensitive MSMGRPC for high energy physics experiments. Nucl. Instrum. Meth. A **1045**, 167621 (2023). https://doi.org/10.1016/j.nima.2022.167621
6. I. Deppner et al., The CBM time-of-flight wall. Nucl. Instrum. Meth. A **661**, 121–124 (2012). https://doi.org/10.1016/j.nima.2010.09.165
7. I. Deppner et al., The CBM Time-of-Flight wall-a conceptual design. JINST **9**(10), 10014 (2014). https://doi.org/10.1088/1748-0221/9/10/C10014
8. I. Deppner, N. Herrmann, The CBM time-of-flight system. JINST **14**(09), 09020 (2019). https://doi.org/10.1088/1748-0221/14/09/C09020
9. A.V. Akindinov et al., Study of gas mixtures and ageing of the multigap resistive plate chamber used for the Alice TOF. Nucl. Instrum. Meth. A **533**(1), 93–97 (2004). https://doi.org/10.1016/j.nima.2004.07.007
10. R. Santonico, R. Cardarelli, Development of resistive plate counters. Nucl. Instrum. Meth. **187**, 377–380 (1981). https://doi.org/10.1016/0029-554X(81)90363-3
11. Y.W. Baek, D.-W. Kim, W.S. Park, M.C.S. Williams, R. Zuyeuski, MRPC with eco-friendly gas. JINST **14**(11), 11022 (2019). https://doi.org/10.1088/1748-0221/14/11/C11022
12. M. Capeans, R. Guida, B. Mandelli, Strategies for reducing the environmental impact of gaseous detector operation at the CERN LHC experiments. Nucl. Instrum. Meth. A **845**, 253–256 (2017). https://doi.org/10.1016/j.nima.2016.04.067
13. L. Quaglia et al., Eco-friendly Resistive Plate Chambers for detectors in future HEP applications (2022). arXiv:2212.09572[physics.ins-det]
14. G. Rigoletti, R. Guida, B. Mandelli, Studies on RPC detectors operated with environmentally friendly gas mixtures in LHC-like conditions. Nucl. Instrum. Meth. A **1048**, 167961 (2023). https://doi.org/10.1016/j.nima.2022.167961
15. G. Proto et al., Eco-friendly gas mixtures for future RPC detectors. PoS ICHEP2022, (2022). https://doi.org/10.22323/1.414.1195
16. L. Quaglia et al., Searching for an eco-friendly gas mixture for the ALICE Resistive Plate Chambers. In: 10th Large Hadron Collider Physics Conference (2022)
17. L. Terlizzi et al., Studies on environment-friendly gas mixtures for the Resistive Plate Chambers of the ALICE Muon Identifier. In: 10th International Conference on New Frontiers in Physics (2022)
18. G. Proto et al., On a new environment-friendly gas mixture for Resistive Plate Chambers. JINST **17**(05), 05005 (2022). https://doi.org/10.1088/1748-0221/17/05/P05005
19. M. Kang et al., Study of eco-friendly gas mixtures for SHiP RPCs. J. Korean Phys. Soc. **80**(1), 1–12 (2022). https://doi.org/10.1007/s40042-021-00325-6
20. G. Proto, Study of the performance of the RPC detector with new eco-friendly gas mixtures. Nuovo Cim. C **44**(2–3), 70 (2021). https://doi.org/10.1393/ncc/i2021-21070-1
21. G. Rigoletti, et al., Studies of RPC detector operation with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility. PoS EPS-HEP2019, (2020) https://doi.org/10.22323/1.364.0164
22. M. Abbrescia et al., Eco-friendly gas mixtures for resistive plate chambers based on tetrafluoropropene and helium. JINST **11**(08), 08019 (2016). https://doi.org/10.1088/1748-0221/11/08/P08019
23. M. Abbrescia et al., Preliminary results of resistive plate chambers operated with eco-friendly gas mixtures for application in the CMS experiment. JINST **11**(09), 09018 (2016). https://doi.org/10.1088/1748-0221/11/09/C09018
24. L. Benussi, S. Bianco, M. Ferrini, L. Passamonti, D. Pierluigi, D. Piccolo, A. Russo, G. Saviano, A study of HFO-1234ze (1,3,3,3-Tetrafluoropropene) as an eco-friendly replacement in RPC detectors (2015) arXiv:1505.01648 [physics.ins-det]
25. Y. Baek, D. Kim, M.C.S. Williams, Study of the ecological gas for MRPCs. Nucl. Instrum. Meth. A **927**, 366–370 (2019). https://doi.org/10.1016/j.nima.2019.02.051
26. S. Pisano et al., New Eco-gas mixtures for the Extreme Energy Events MRPCs: results and plans. JINST **14**(08), 08008 (2019). https://doi.org/10.1088/1748-0221/14/08/C08008
27. E. Bossini et al., Studies on new eco-gas mixtures for extreme energy events project. Nucl. Instrum. Meth. A **1046**, 167754 (2023). https://doi.org/10.1016/j.nima.2022.167754
28. B. Mandelli, Possible alternatives to SF_6 for Resistive Plate Chambers. Presentation on the RPC2022 conference (2022). https://indico.cern.ch/event/1123140/
29. C.C. Ponta, I.V. Moise, E. Bratu, IRASM - A multipurpose irradiation facility in Romania. IAEA-TECDOC-1023 **29**, 531–540 (1998)
30. D. Bartos et al., Ageing studies of multi-strip multi-gap resistive plate counters based on low resistivity glass electrodes in high irradiation dose. Nucl. Instrum. Meth. A **1024**, 166122 (2022). https://doi.org/10.1016/j.nima.2021.166122
31. R. Guida, B. Mandelli, G. Rigoletti, Measurements of fluoride production in resistive plate chambers. Nucl. Instrum. Meth. A **1054**, 168393 (2023). https://doi.org/10.1016/j.nima.2023.168393
32. R. Guida, B. Mandelli, G. Rigoletti, Studies on alternative eco-friendly gas mixtures and development of gas recuperation plant for RPC detectors. Nucl. Instrum. Meth. A **1039**, 167045 (2022). https://doi.org/10.1016/j.nima.2022.167045

33. R. Guida, G. Pugliese, Private communication (2022)
34. R. Guida, RD strategies for optimizing the greenhouse gas consumption at the CERN LHC experiments. Presentation on the RPC2022 conference (2022). https://indico.cern.ch/event/1123140/
35. https://encyclopedia.airliquide.com/sulfur-hexafluoride#properties