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The GEMPix detector

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ABSTRACT

The GEMPix is a novel detector developed at CERN, designed and built by coupling a small triple Gas Electron Multiplier with a quad Timepix ASIC for the readout. This structure has the advantage to have higher sensitivity to soft X-ray and high radiation tolerance for good spatial resolution of 2D images of intense particle beams. Several applications of this detector have been studied in the last years and some of them will be described in detail.

1. Introduction

The GEMPix (Murtas, 2014) is a novel detector developed in CERN Radiation Protection Group in the course of the EU-funded Marie Curie project ARDENT (2012–2016) (Silari, 2012) coordinated by CERN. The detector was designed by coupling two CERN technologies, a small triple Gas Electron Multiplier (Sauli, 1997) (GEM) ($3 \times 3 \times 0.3$ cm^3 active volume) to a quad Timepix (Llopart et al., 2007) ASIC with 262,144 pixels of 55×55 μm^2 area each for readout (Fig. 1). The GEMPix can be built in head-on or side-on configurations and with different size of detection volume.

Essentially the usual silicon sensor, bump bonded on a Timpix ASIC, is replaced by a small triple GEM structure with the advantage to have a detector with higher sensitivity to low energy X-ray ($1 \div 5$ keV) (Curioni et al., 2017) and with a higher radiation tolerance (Alfonsi et al., 2006). The particles are detected by ionization in a gas volume behind a thin Mylar entrance window approximately 20 μm thick. A continuous flow of an $Ar : CO_2 : CF_4$ (45:15:40 ratio) gas mixture is supplied externally at a rate of $5l/h$. The electrons produced by the ionization are driven by an applied high voltage towards three layers of GEM foils where multiplication takes place due to approximately $320V$ per GEM crated by a suitable HV power supply (Corradi et al., 2007). The GEM foils are typically spaced by one or two mm with the aim to reduce and optimize the electron cloud diffusion. Changing the GEMs voltages the multiplication gain of the detector can be easily tune up to 10^4. The resulting electrons are then detected by the quad Timepix ASICs and read out by the FITPix device (Kraus et al., 2011) with the Pixelman software package (Turecek et al., 2011). The chosen readout mode, time over threshold (ToT), provides a value proportional to the deposited charge by the primary particle. In time over Arrival mode (ToA) the detector is able to reconstruct in 3D a track of an impinging particle inside the sensitive volume (George et al., 2015) acting as a small TPC. Other gas mixtures such as $Ar : CO_2$ could be used, but it increase the lateral electron diffusion and therefore reduce the cluster analysis performance. The GEMPix detector has been included in the CERN Knowledge Transfer Program starting from 2016 (Murtas and Araujo, 2016). A more detailed description of the GEMPix can be found in refs (Murtas, 2014) and (Curioni et al., 2017). Different applications have been already found in various domains: as a mini Time Projection Chamber (TPC) for particle tracking in high energy physics (George et al., 2015); as a soft X-rays diagnostic tool for laser produced plasmas (Pacella et al., 2016) (Claps et al., 2016); for studies on a dark matter detector with a negative ion TPC read by a GEMPix (Baracchini et al., 2018); for determining the specific activity of the $6keV$ photon emitter ^{55}Fe (which cannot be measured by γ-spectrometry) in metallic waste (Curioni et al., 2017); for use in proton tomography studies (Radaelli, 2015); to test the capability of GEMPix as real time dosimeter in external photon beam radiotherapy (Claps, 2015); for 3D measurements of the energy deposition by clinical carbon ion and proton beams in a water phantom (Leidner et al., 2018). It also has potentially very interesting application as microdosimeter, with the possibility to measure the track structure of ionizing radiation down to the equivalent scale of tens of nanometres.

2. GEMPix in particle detection studies and microdosimetry

The GEMPix has been deeply studied in a proton and pion test beams

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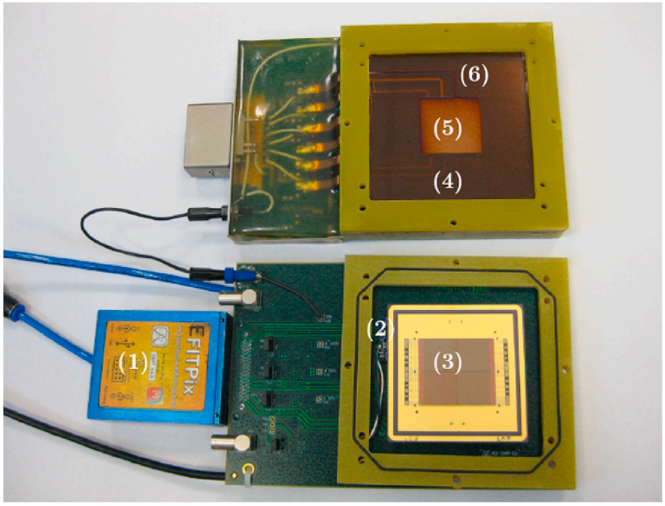

Fig. 1. The opened GEMPix detector with the FITPix (1). The temperature, pressure and humidity sensor (2) is glued behind the board of the four Timepix ASICs (3). Only the centre of the Kapton foil (4) is prepared as a GEM and therefore covered with copper (5).

with momenta of 120 GeV/c at the CERF facility at CERN measuring the 3D track reconstruction performance. The active area was $3\times\ 3\ cm^2$ with 12 mm thick drift volume. The first version of Timepix ASIC cannot simultaneously measure deposited charge (via the ToT measurement scheme) and time of arrival. However, as the clusters are typically extended over many pixels, we can operate the GEMPix in a so called mixed mode where 1 in every 16 pixels measure ToA while the rest measure ToT. Fig. 2 shows a sample track at 30° measured using this dual mode scheme.

In order to construct tracks the pixels are first grouped into clusters within 40 ns and then grouped into tracks. The 3D path of the tracks were reconstructed and the angular resolution measured varied from $6.2 \div 1.3$ degrees at a $10 \div 30°$ angle of altitude respectively. The track spatial resolution of the detector was estimated to be 170 μm, which is limited by the resolution of the time measurement (20 ns clock). The energy deposited in the detector was found to match well to the Geant4 simulation when it was convolved with an additional energy dependent smearing term. Other small TPCs has been built up to now with a drift distance up to 5 cm with good results. One of them has been used in preliminary studies for negative ions TPC in the framework of *R&D* on Dark Matter detectors (Baracchini et al., 2018).

The use of the Timepix3 ASIC (Poikela et al., 2014) could considerably improve the performance of the GEMPix. This chip measures time and charge simultaneously removing the need for a mixed mode and features a time resolution of 1.5 ns which corresponds to a distance on the order of the pixel pitch (with an equivalent triple GEM setup). Finally the Timepix 3 offers a data driven readout (which sends out the measured information as soon as pixels are no more over threshold) with maximum data throughput rate of $85 Mhits/s$ which should improve the dead time, or remove it entirely in low count rate situations. The use of Timepix4 with his Through-silicon-via (TSV) technology will provide the possibility of reading the chips through copper-filled holes that bring the signals from the front side of the chip to its rear. Because of this structure, large detector areas will be covered without dead spaces, overcome the actual limitation of $3 \times 3\ cm^2$. One of our target applications is to use the GEMPix as a particle tracker that can measure energy deposition/track structure in tissue equivalent gases over biologically relevant site sizes, i.e. as a Microdosimeter. The central principle of such a detector is that the atomic composition and number of atoms in a given path length is the same as that found in a biological site, such as a cell nucleus. This seems eminently achievable with the GEMPix; in fact the length of a HeLa cell nucleus is some 10 μm, corresponding to a path of 90 pixels in a propane based tissue equivalent gas at atmospheric pressure. New studies are in progress and they are focusing on producing appropriate algorithms to extract micro-dosimetric spectra and validation of the GEMPix against existing devices (typically Tissue Equivalent Proportional Counters, TEPC). Fig. 3 shows a typical particle track measured by GEMPix compared with the equivalent human cell dimension.

3. GEMPix as dosimeter in hadron therapy and radio therapy

Measurements were performed at CNAO, the Italian Centre for Oncological Hadrontherapy in Pavia, which is equipped with a synchrotron delivering scanning proton and carbon ion beams to three treatment rooms.

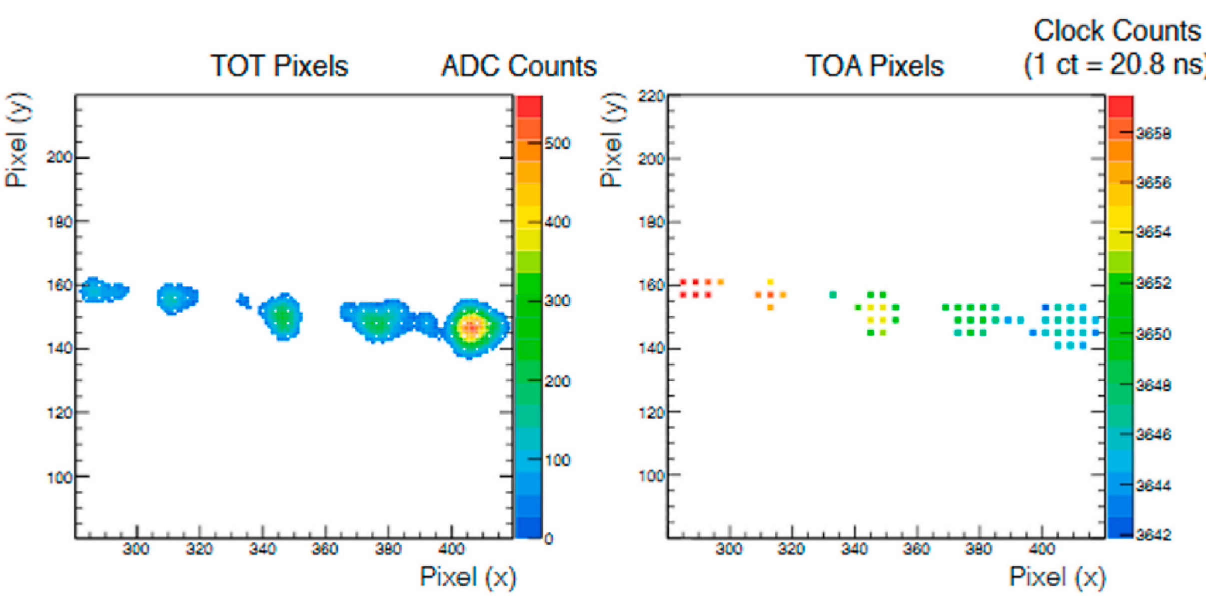

Fig. 2. Example of a track incident at 30° degrees measured in mixed mode operation. 15 out of 16 pixels measure ToT (left) and 1 out of 16 measure ToA (right). The ToA pixels are drawn at twice lateral size for illustrative effect. Knowing the drift velocity of electrons in the gas, the relative Z coordinate between clusters can be measured, that allows the track angle reconstruction (George et al., 2015).

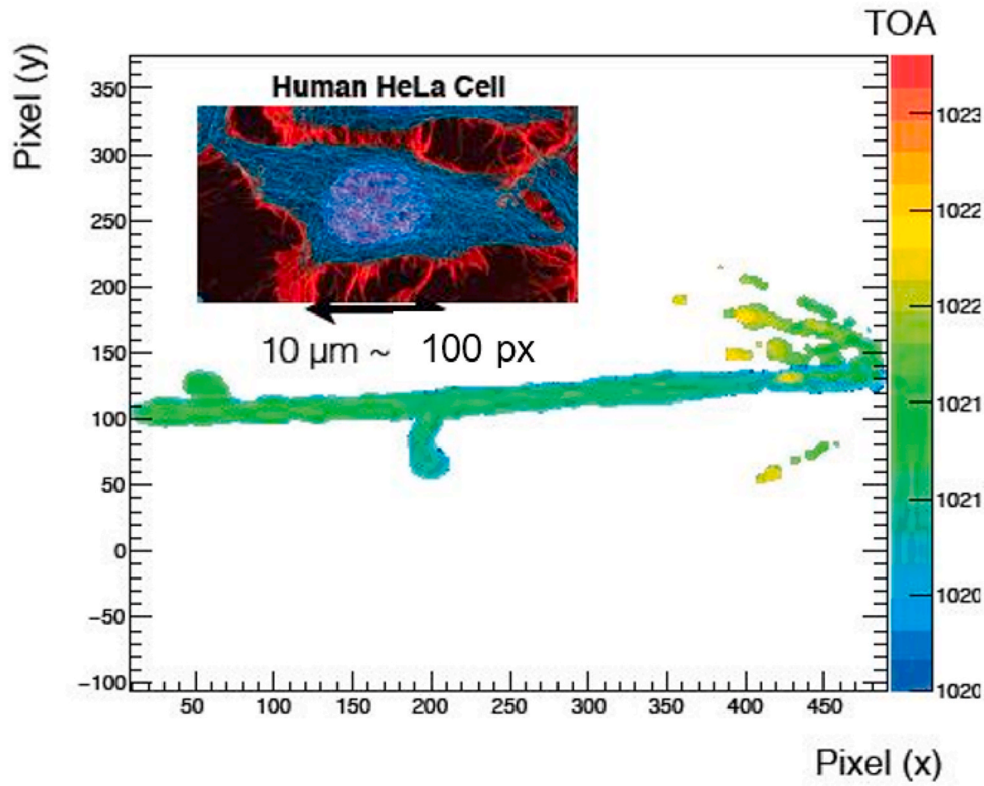

Fig. 3. A track in the GEMPix detector schematically compared to the size of a human cell, using the magnification by the gas ($Ar/CO_2/CF_4$) density (George et al., 2015).

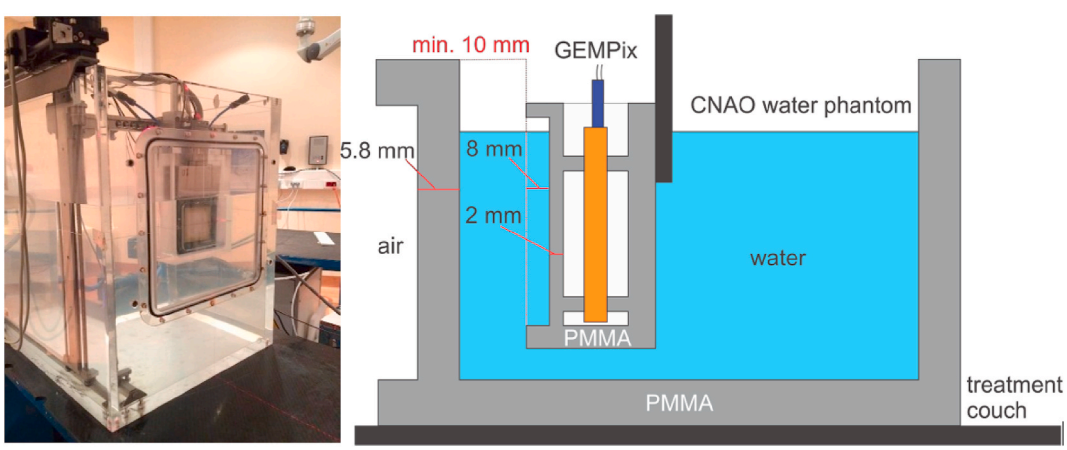

Fig. 4. The GEMPix mounted on the water phantom in one of the treatment rooms. On the right the cross section of the system (Leidner et al., 2018).

The GEMPix was placed inside a water tight PMMA box mounted on the 3D positioning system of the motorized water phantom (see Fig. 4). The CNAO synchrotron provided carbon ions with kinetic energies of 280 MeV/u or 332 MeV/u with either a pencil beam (single beam spot) or scanned field. It has been shown that the GEMPix is capable of measuring the 3D energy deposition of the ion beam in a water phantom as depicted in Fig. 5. The 2D images of the beam, the Bragg curve with the ion fragments produced and the 3D reconstructed energy deposition can be obtained in a single depth scan that lasts about 15 min. The differences on the Bragg curve measured with the GEMPix and a PTW Peakfinder (P Karger et al., 2010) remain within 15% as described in (Leidner et al., 2018) and (Leidner, 2019).

The GEMPIX detector has been used also to test dosimetry measurements in radiotherapy (Claps, 2015). Due to the high flux of gammas, the electric field of the drift zone has been reduced to obtain the effective ionization only near the holes of the first GEM foil. A very little fraction of the Compton electron are back scattered in the active volume. The ones that comes near the GEM holes are multiplied and produce current pulse signals. The detector is able therefore to work at very low efficiency but enough to count proportional to the photon beam fluence. The measurements shown good linearity with the Pulse Repetition Frequency of the source and the dose rate. In Fig. 6 the comparison of the two image of field of treatment realized with the GEMpix and with radiochromic film with different time of exposure.

4. GEMPix in ^{55}Fe dosimetry in radioactive waste

A new method to measure the ^{55}Fe content in radioactive waste

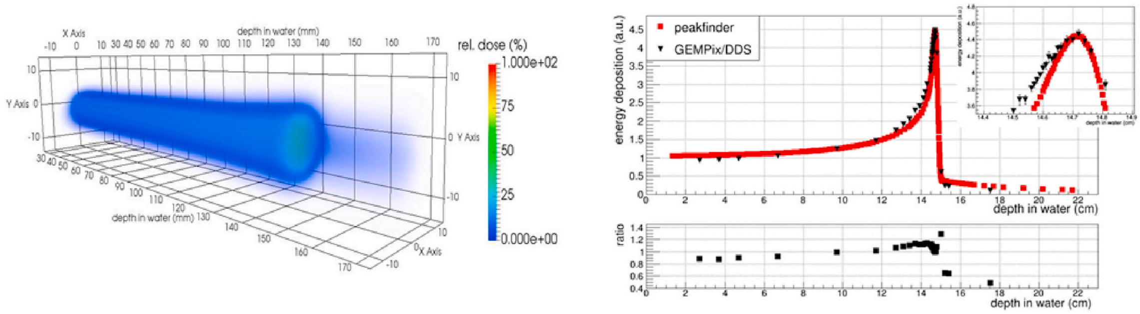

Fig. 5. On the right the 3D reconstruction of the energy deposition; the Bragg peak at a depth of around 147 mm in water, the spread out of the beam from the entrance point towards the Bragg peak and the tail produced by the fragments are well visible (Leidner et al., 2018). On the left the standard projection in z and the comparison with the commercial Peakfinder.

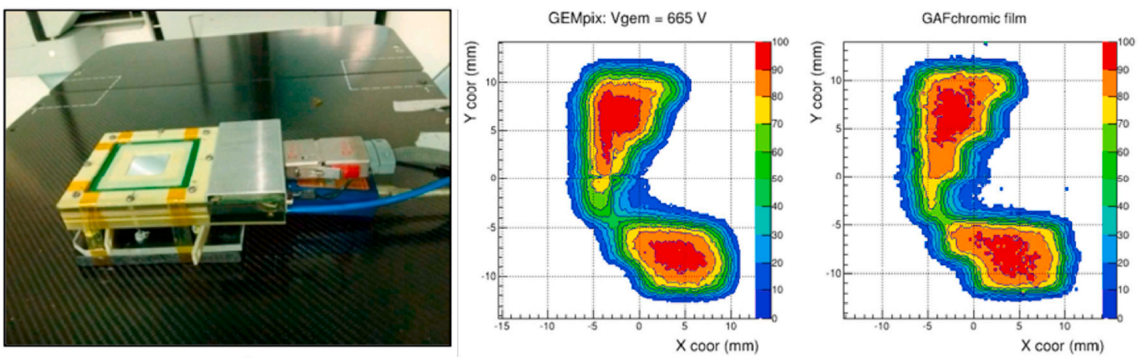

Fig. 6. On the left, the detector used in front of the gamma source in a radiotherapy center. On the right, the difference can be seen between the image obtained with the GEMPIX in 1 min of acquisition as compared to an image taken in 10 min with gafchromic film. The GEMPIX is sensitive to a single Linac pulse (Claps, 2015).

samples using GEMPix, has been developed at CERN. The detector is able to measure the energy released by 6 *keV* X-ray with a good energy resolution avoiding the background produced by Cobalt gamma source inside the metal waste. A correction of the high voltage (and therefore of the gain) as function of temperature, pressure and humidity in the detection volume was developed in order to obtain a more stable system and reduce systematic uncertainties. Typically, measurement of one radioactive waste sample takes approximately 4.5 h compared with few days needed with the radiochemical method. Measured counts are converted into specific radio activity using a calibration curve based on reference data from radiochemical analyses of the same samples. From the analysis of forty-five samples, good agreement has been found between the two methods, reaching a sensitivity of 30 Bq/g, much better respect to the actual Swiss exemption limit of 1 kBq/g for ^{55}Fe. An operational test phase for this method is planned at CERN. With this new exemption limit the time of the measurement could be reduced.

5. GEMPix as X-ray monitoring burning plasma physics

The GEMPix has been recently used also for the studies on soft X-ray emitted by Laser Produced Plasmas (LPPs). First experiments have been performed at the ABC Laser Facility in Frascati (Pacella et al., 2016) and

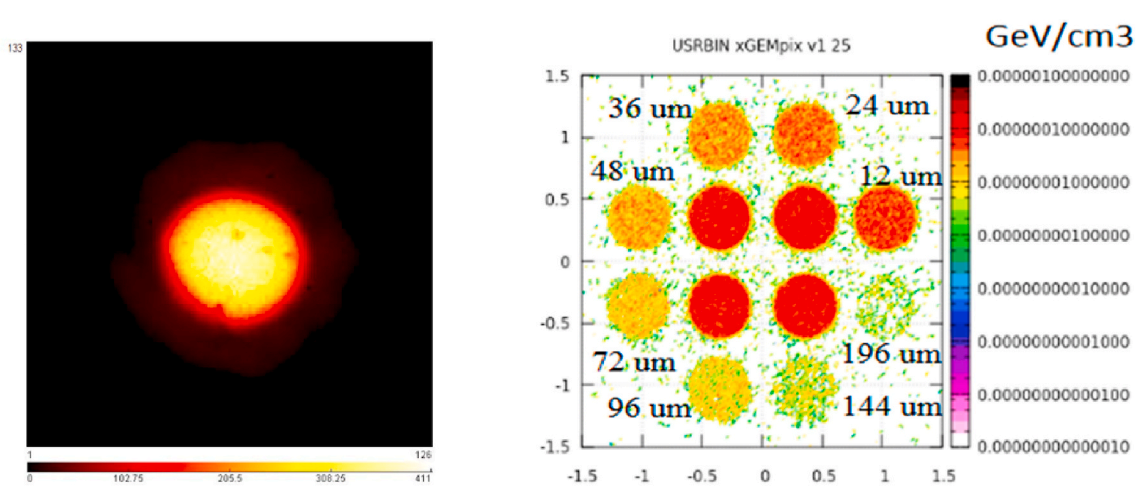

Fig. 7. The image of the plasma at ABC (left). On the right the simulated X-ray flux seen by the GEMPix with different thickness of alluminum filters placed in front of the detector. The central spots (with no filters) are used for normalization.

subsequently at Eclipse in Bordeaux (Claps et al., 2016), (France) and on the VEGA2 in Salamanca, (Spain). The study of X-ray emission from this kind of plasma is important not only to characterize them (as electron temperature and stability) but also to study the possible applications of these intense X-rays, gamma and neutron sources. In 2017, further measurements of soft-X rays using the GEMPix detector have been realized. For LPPs, $ArCO_2$ gas mixture has been used as active medium, with Timepix electronics worked in ToT mode, which allows a digital measure of the integrated charge reaching the chips after amplification on the GEM foils. At the ABC facility a soft X-ray imaging on the plasma through a pin-hole system has been realized (see Fig. 7); in the other facilities some energy measurements of soft X-rays produced by a laser pulse of 40 *fs* and an energy of 170 *mJ* hitting different targets have been made. Recently alluminum filters with different thickness have been placed in front of the GEMPix detector to measure the X-ray fluxes as a function of the energy. This is the only way to do it in a femto second pulse laser produced plasma due to pileup of the charge in front of each Timepix's pixel; the simulation of the flux seen by the detector is shown in Fig. 7.

5. Conclusions

The GEMPix is by now a reliable detector used in different application fields. It has been used to study in detail the detection efficiency of thermal neutron and ions with the aim to optimize the design of new gas detectors. It has shown good performance measuring the characteristics of high intensity beam used in cancer treatment and at the same time is able to measure the effect produced by the fragments. It has been used also for the monitoring of plasmas using the soft X-ray not visible by room temperature silicon detector. The microdosimetry with tissue equivalent gas could be the next promising application field.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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