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MOCCA: A 4k-Pixel Molecule Camera for the Position- and Energy-Resolving Detection of Neutral Molecule Fragments at CSR

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Abstract We present the design of MOCCA, a large-area particle detector that is developed for the position- and energy-resolving detection of neutral molecule fragments produced in electron–ion interactions at the Cryogenic Storage Ring at the Max Planck Institute for Nuclear Physics in Heidelberg. The detector is based on metallic magnetic calorimeters and consists of 4096 particle absorbers covering a total detection area of 44.8 mm $\times$ 44.8 mm. Groups of four absorbers are thermally coupled to a common paramagnetic temperature sensor where the strength of the thermal link is different for each absorber. This allows attributing a detector event within this group to the corresponding absorber by discriminating the signal rise times. A novel readout scheme further allows reading out all 1024 temperature sensors that are arranged in a 32×32 square array using only $16 + 16$ current-sensing superconducting quantum interference devices. Numerical calculations taking into account a simplified detector model predict an energy resolution of $\Delta E_{\mathrm{FWHM}} \leq 80\,\mathrm{eV}$ for all pixels of this detector.

Keywords Metallic magnetic calorimeter · MMC · Molecule camera · Position- and energy-sensitive particle detection · Cryogenic storage ring · CSR

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1 Introduction

Due to its extreme vacuum and low-temperature environment of less than 10 K, the Cryogenic Storage Ring CSR [1] at the Max Planck Institute for Nuclear Physics in Heidelberg is able to store a wide range of atomic, molecular, and cluster ions at beam energies between 20 and 300 keV for very long storage times. It particularly allows storing heavy molecular ions in their rotational and vibrational ground state. For this reason, CSR offers the unique opportunity to investigate electron–ion interactions such as dissociative recombination or electron capture dissociation in laboratory environment under conditions that are very close to the conditions in interstellar media. To reconstruct the full kinematics of these processes and to reveal details of the interaction mechanisms, a position- and energy- sensitive detector with coincident fragment detection capability is required in order to simultaneously determine the relative momenta and masses of all produced molecule fragments. In addition, the detector needs to have a sufficiently large detection area and needs to be compatible to the cryogenic environment of CSR. But since the ions are stored at rather low energies, i.e., at energies below 300 keV, Si surface-barrier detectors that are commonly used for this kind of measurements at warm storage rings and at MeV beam energies are not suitable because the molecule fragments cannot penetrate through the surface dead layer.

Recently, metallic magnetic calorimeters (MMCs) were proposed for atomic and molecular collision experiments in the keV energy range as they fulfill the requirements mentioned above. In addition, it was found that the energy resolution for massive projectiles in the keV energy range is degraded due to backscattering of incident molecules or small molecule fragments as well as the creation of Frenkel pairs in the absorber. For this reason, the best achievable energy resolution is extrinsically limited to about 120 eV [2]. Since this value should not be increased, the intrinsic energy resolution of the detector should be certainly lower. Moreover, the detector should be highly pixelized to achieve a very high position sensitivity. Taking into account both design goals, we developed a highly pixelized MMC-based detector, MOCCA, which uses a simple readout and array scheme. MOCCA has a sensitive area of 44.8 mm $\times$ 44.8 mm which is segmented into 4096 absorbers. By coupling groups of four absorbers to a common temperature sensor and using a novel readout scheme, it is possible to read out the full detector by only 16 + 16 current-sensing superconducting quantum interference devices (SQUIDs), thus greatly reducing the overall system complexity and costs.

2 Detector Design

MOCCA is schematically depicted in Fig. 1. It has a square detection area of 44.8 mm $\times$ 44.8 mm which is segmented into 64 $\times$ 64 massive particle absorbers that are made of electroplated gold. The absorbers are free standing, i.e., they are connected via four posts made of Au to their associated temperature sensor and do not have any direct contact to the underlying Si substrate. This arrangement reduces not only the loss of energy, e.g., in the form of athermal phonons, but also a potential position dependence within the absorbers, both potentially degrading the energy resolution of

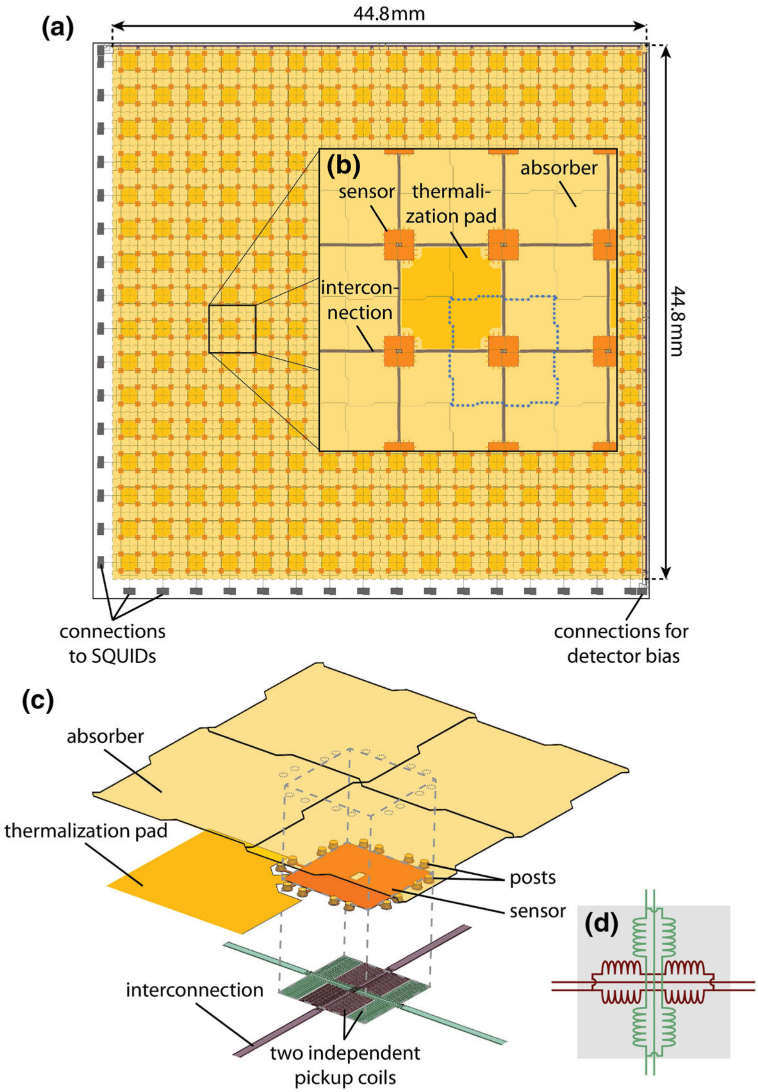

Fig. 1 **a** Schematic of the MOCCA detector showing the overall chip layout, the connections to the SQUIDs as well as the connections for the detector bias. **b** Magnification of the area that is marked in **a**) by the continuous *black square*. It indicates the arrangement of the temperature sensors, the interconnections as well as the particle absorbers. For clarity, the absorbers are shown in transparent *color*. **c** Exploded view of the region marked in **b**) by a *dotted frame*. It shows the two independent pickup coils (marked by *different colors*), their interconnections, the temperature sensor, the posts connecting the sensor and the absorbers as well as a part of the thermalization pad. **d** Schematic of the wiring of the two independent pickup coils, each consisting of two parallel-connected individual coils (Color figure online)

the detector. Each particle absorber is $700\,\mu\mathrm{m} \times 700\,\mu\mathrm{m}$ large and $3\,\mu\mathrm{m}$ thick, and has non-straight but slightly s-shaped edges to minimize the number of particle impacts in superconducting wiring structures running underneath the gap between two particle absorbers (see Fig. 1c). Such impacts might weaken superconductivity in the wiring structures and can therefore lead to a loss of the persistent current in these structures that is required for biasing the detectors. The spacing between two adjacent absorbers is 2 μm resulting in an absorber filling factor of 99.4 % of the full detection area. Groups of four absorbers are each coupled to a common paramagnetic temperature sensor using thermal links with different lengths resulting in predicted signal rise times of 4, 20, 40, and 80 μs for the different absorbers. According to [3], this allows attributing a detector event to the corresponding absorber by discriminating the signal rise times.

By monitoring the temperature of four particle absorbers using only one temperature sensor, the total detector can be read out by 1024 $Au{:}Er_{300\,ppm}$ temperature sensors that are arranged in a 32×32 square array. Each sensor has the form of a square with a side length of 400 μm and is 1.3 μm thick. For thermalization, groups of four sensors are connected to a thermalization pad made of sputtered Au using well-defined thermal links that are designed to give a signal decay time of about 3 ms. To connect the pads to the actual heat bath, i.e., the sample holder, through-wafer vias are used. For this, parts of the substrate underneath the pads are etched away and the resulting holes are filled up with electroplated Au forming low-ohmic posts through the substrate which will be pressed onto the sample holder in the final setup.

As can be seen in Fig. 1d, each temperature sensor is read out using two independent superconducting pickup coils which are arranged in a way such that the electromagnetic crosstalk between these coils is as low as possible. They are each formed by two 1.1 nH meander-shaped coils with a 5 μm linewidth and a 9 μm pitch which are connected in parallel to make the detector fault tolerant for fabrication failures and therefore to greatly simplify the fabrication process. This is essential since the readout circuit consists of several tens of meters of continuous 5 μm-wide superconducting lines and any interruption of one of these lines would otherwise lead to a failure of a significant part of the detector. One of both independent coils is connected in series with all other coils of the same row and the other coil is connected in series with all other coils of the same column (see Fig. 2). Each row and column therefore behaves like a single, large pickup coil consisting of several smaller coils and providing a summed temperature signal from all the temperature sensors in the respective row and column. Two neighboring lines, i.e., two neighboring rows or columns, are connected in parallel with the input coil of a current-sensing SQUID to form a superconducting flux transformer. A consequence of this wiring is that neighboring lines that are read out by the same SQUID show signals with different polarity. Since each sensor is read out by two SQUIDs, one connected to the pickup coil of the corresponding row and one connected to the pickup coil of the respective column, the temperature sensor creating a signal can be determined by looking which SQUIDs show a signal. This novel readout scheme therefore allows reading out the full detector by only 16 + 16 SQUIDs, thus greatly reducing the number of electronic channels.

It is worth to mention that all electrical connections of the detector, i.e., the electrical lines for biasing the detector and for connecting the SQUIDs, are positioned along only two sides of the detector. This fact allows combining four such detector tiles to an even larger detector with more than 12k pixels covering a detection area of about 90 mm × 90 mm. Moreover, the number of absorbers that are connected to a common

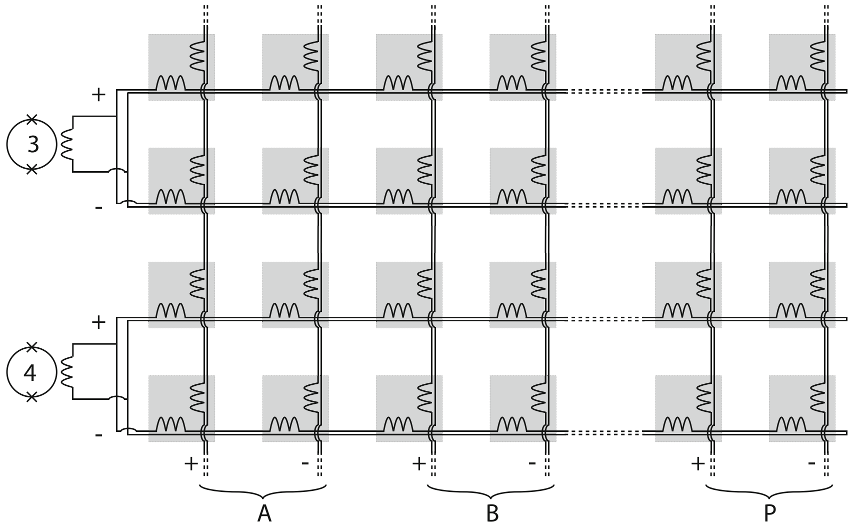

Fig. 2 Schematic of four *lines* out of the readout scheme that is used for reading out 32×32 temperature sensors using $16+16$ dc-SQUIDs. The SQUIDs reading out two *rows* are labeled with numbers 1–16 while the SQUIDs reading out two *columns* are labeled with characters A to P. For *each line* the polarity of the detector signal is marked by $+$ and $-$

temperature sensor can be easily increased allowing to enhance either the sensitive area or the segmentation and therefore the position sensitivity of the detector.

3 Expected Detector Performance

To predict the detector performance, i.e., the energy resolution of the detector, we numerically calculated the expected signal-to-noise ratio including the thermodynamic properties of the sensor and absorber materials, the detector geometry, all dominant noise sources of MMCs as well as SQUID noise. However, since groups of four absorbers are read out by only one temperature sensor, the shape of the detector signals is much more complex compared to a detector with only one absorber that is connected to a temperature sensor. More precisely, the heat in one of the absorbers which is created by an incident particle can not only flow through the sensor to the heat bath but also back into the other absorbers. For this reason, the signal shape depends on the absorber in which the particle is stopped. In addition, there is a fast signal decay immediately after the pulse formation due to the heat flow back to the other absorbers. Although this complex behavior can be modeled, we used a simplified detector model assuming a worst-case scenario. It is assumed that only one absorber with a heat capacity of 12.8 pJ/K at 30 mK is present whose heat capacity is given by the sum of the heat capacities of all four absorbers, i.e., the heat created in one of the absorbers can flow infinitely fast into the other absorbers, and that the thermal conductance between this hypothetical absorber and the temperature sensor is given by the thermal link of the absorber in which the event is happening. Using this model and assuming a bath temperature of 30 mK, we calculated an intrinsic energy resolution between 50 and 80 eV depending on the actual rise time of the detector signal where the fastest signal rise time gives the best energy resolution. Our detector is therefore very well suited for the measurements at CSR, in particular since the intrinsic energy resolution of the detector is smaller than the line broadening of more than about 120 eV caused by backscattering and the creation of Frenkel pairs [2].

4 Present Status

MOCCA is currently being fabricated in the cleanroom facilities of the Kirchhoff-Institute for Physics and will be finished within the next months. To be able to reliably produce several meters of 5 μm-wide Nb wires on the entire 3 inch wafer, we replaced our contact mask aligner by a new direct laser lithograph [4]. In parallel, we are testing a small version of MOCCA employing 256 particle absorbers that cover a 11.2 mm × 11.2 mm detection area. The sensor and pickup coil elements of this small detector are identical to MOCCA, but the fabrication complexity is very much reduced due to the smaller size. Preliminary tests indicate that the crosstalk between the two independent pickup coils reading out one temperature sensor is smaller than 0.05 %. Here, we therefore fully match our design goal.

5 Conclusions

We have developed MOCCA, a large-area MMC-based detector that is suited for the position- and energy-resolving detection of neutral molecule fragments produced in electron–ion interactions at the Cryogenic Storage Ring at the Max Planck Institute for Nuclear Physics in Heidelberg. MOCCA consists of 4096 particle absorbers covering a detection area of 44.8 mm × 44.8 mm. Groups of four absorbers are thermally coupled to a common paramagnetic temperature sensor where the strength of the thermal link is different for each absorber. This allows attributing a detector event within this group to the corresponding absorber by discriminating the signal rise times. A novel readout scheme allows reading out all temperature sensors using only 16 + 16 current-sensing SQUIDs. Numerical calculations predict an energy resolution between 50 and 80 eV depending on the rise time of the detector pixel.

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