Gas Microstructures and a Micro TPC Vertex Detector

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Abstract

An R&D effort is underway to develop technologies for a Micro TPC[1] that can be used as a gas vertex detector in heavy ion collider experiments. Drifting of electrons through several inches of DME without appreciable loss has been demonstrated. A Micro Strip Gas Chamber (MSGC) has been integrated with a low noise preamplifier and shaper amplifier on a common silicon substrate. These devices were fabricated using a standard 0.8 mm Hewlett-Packard process followed by one post process step. Tests of the detector chip with an Fe^{55} X-ray source produced gas gains up to 200 and an energy resolution of 18%. The front-end equivalent noise was 80 electrons rms with a 50 ns amplifier shaping time.

Introduction

We are interested in developing an improved vertex detector for the STAR system at RHIC. One of the goals is to be able to detect Ds and do charm physics. Silicon detectors have been the traditional choice for vertex detectors in particle physic experiments because they have excellent position and two track resolution and the particles of interest have large momenta. However, for other experiments, such as heavy ion collider experiments, the majority of the particles have low momenta, and the position of the vertex determination is limited by multiple coulomb scatter, not intrinsic detector position resolution. For this reason we are pursuing a gas detector approach as an optimum solution for the lower momentum range below 1 GeV/c.

The high track density near the vertex and the high multiplicity expected in relativistic heavy ion collisions at RHIC are significant challenges to the design, but a small TPC is a good solution. By using short drift distances, < 20 cm, and low diffusion gases, the electron diffusion can be sufficiently limited to provide the required two track resolution and position resolution. The TPC under consideration will be capable of tracking within a few centimeters of the interaction point most of the particles in events with multiplicities in the thousands. The TPC has a financial cost advantage over other detectors used in high multiplicity measurements because the active pixel count scales as the square of the channel count. The main down side to the TPC approach is the limited event rate capability.

The primary R&D effort of this program has been the development of a fine-grained gas gain readout that can take advantage of the low electron diffusion inherent in a small TPC device. The requirement that a readout sensor be small, in order to achieve the required position resolution and two track resolution, forces the designer to consider new devices in place of the most dependable and stable MWPCs, but the small size also opens up new design possibilities with much lower intrinsic electronic noise and reduced pickup from external noise sources. It is with this in mind that we have developed an integrated solution with the detector structure, a MSGC, constructed with the electronics on a single silicon chip. This approach minimizes detector and connector capacitance, reducing the intrinsic amplifier noise to 80 electrons rms at the front-end. Additionally, susceptibility to external noise sources is greatly reduced because capacitive coupling between the detector and the rest of the detector structure, other than the amplifier substrate, is extremely small. Consequently, ground loops and other AC voltage variations in the detector structure do not couple into the amplifier-detector circuit. With this low noise a suitable signal to noise ratio can be achieved for minimum ionizing particles while operating the MSGC at a gas gain of only 100. This should help overcome known MSGC problems such as accelerated aging and limited ultimate gas gain.

Conceptual Design of the Micro TPC

The Micro TPC is basically a scaled down version of a traditional cylindrical TPC used in collider experiments. As shown in Fig. 1 the structure consists of a cylindrical field cage with an axial electric field. The maximum drift distance is 14 cm. For a traditional TPC, such as the STAR TPC at RHIC, the maximum drift distance is 210 cm. The readout, however, due to space constraints, is limited to 4 narrow active rings. This provides 4 concentric, sensitive cylinders for tracking much like a silicon vertex detector geometry.

Drift gas

We have chosen DME as a drift gas because it has several advantageous features for the TPC design. DME has a low diffusion constant which is, of course, essential for this application, but it also has a high electron production density, which is important because it allows us to design with a thin active shell. Keeping the shell thin improves the two track resolution for larger dip angle tracks and it permits use of shorter readout structures which means lower electronic noise. Slow electron drift velocity is another benefit of DME in this application. The low velocity means that the required two track resolution can be achieved with amplifier shaping times on the order of 300 ns which allows good noise performance with rather standard electronics. The same electronics that are suitable for large conventional TPCs can be used in this application.

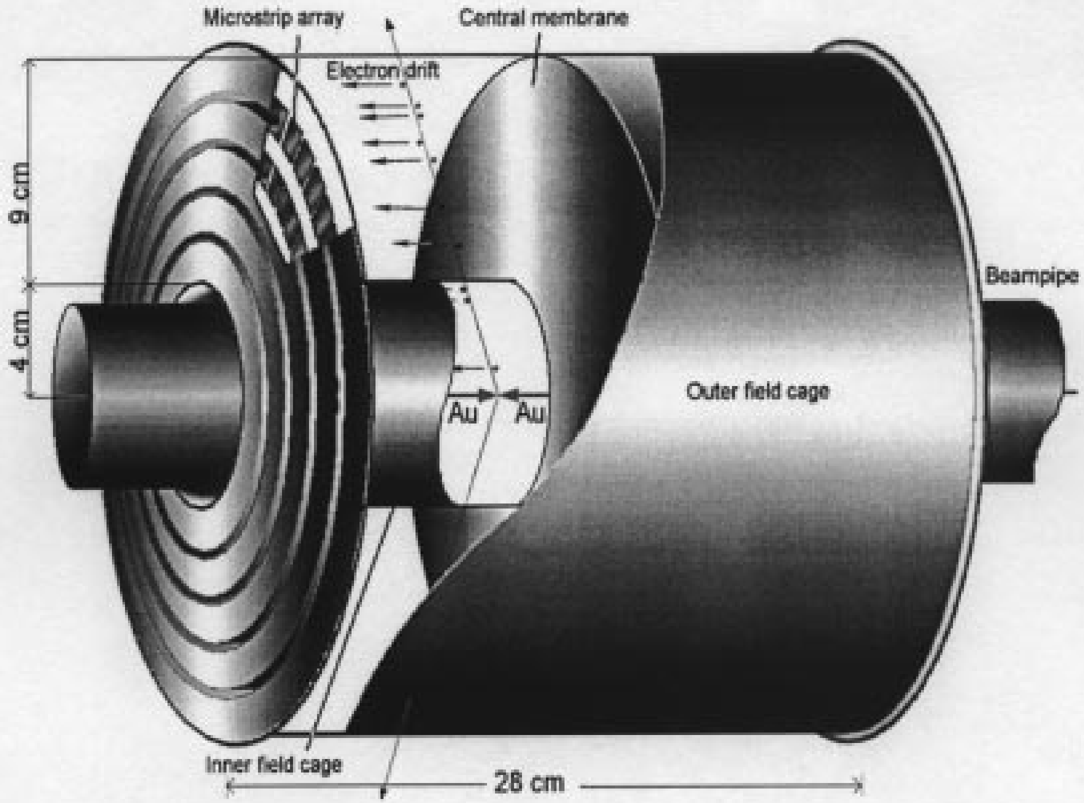

Figure 1 Conceptual Design of the Micro TPC

Field cage structure

The small field cage structure can be kept quite thin by constructing it with self-supporting, thin film metal-plastic or glass laminates. The total expected thickness for components that are important for multiple scattering are shown in Table 1. The main limit to vertex resolution in this design is the beam pipe (1 mm Be = 0.28% radiation length).

Carbon-epoxy shell	16 mil	0.14%
Al gas envelope	3 mil	0.09%
Outer FC (glass)	2 mil	0.05%
DME	8 cm	0.04%
Inner FC (glass)	2 mil	0.05%
Insulator (plastic)	20 mil	0.11%
Al gas envelope	3 mil	0.09%
Total		0.57%

Table 1 Thicknesses and radiation lengths of Micro TPC elements

Readout structure

The readout system is composed of 4 rings of MSGCs arranged with 3 mm long readout anodes aligned along the radius on a 300 μm pitch around the rings. The pitch of 300μm matches the electron diffusion cloud such that roughly 3 anodes will have signals above threshold for each track crossing. The readout modules will be supported on alumina surface mount boards which will mount on water cooled heat-sink end caps. The two endcap structures split in half and can be removed as a unit for service and installation of the electronics.

Expected Performance of the Micro TPC Design

The Micro TPC design was analyzed to determine the accuracy of track impact parameters and to determine the two track resolution.

Isolating secondary tracks from primary tracks is the main function of the vertex detector. This is what reduces the combinatorial background and makes possible the measurement of secondary particle decays. A vertex detector is judged by its ability to accurately project a track back past the primary interaction point. This is referred to as impact parameter resolution. We have analyzed the Micro TPC's impact parameter resolution as a function of particle momentum and compared this with a similar analysis for a 3 layer silicon tracker. The calculation of projection resolution includes intrinsic position resolution and multiple coulomb scattering. The result is shown in Figure 2.

At high momentum the resolution is limited only by the intrinsic position resolution of the detector and is constant independent of momentum. At lower momentum the multiple scattering increases as $1/\beta$ and this dominates the resolution. From Figure 2 it is clear that below a

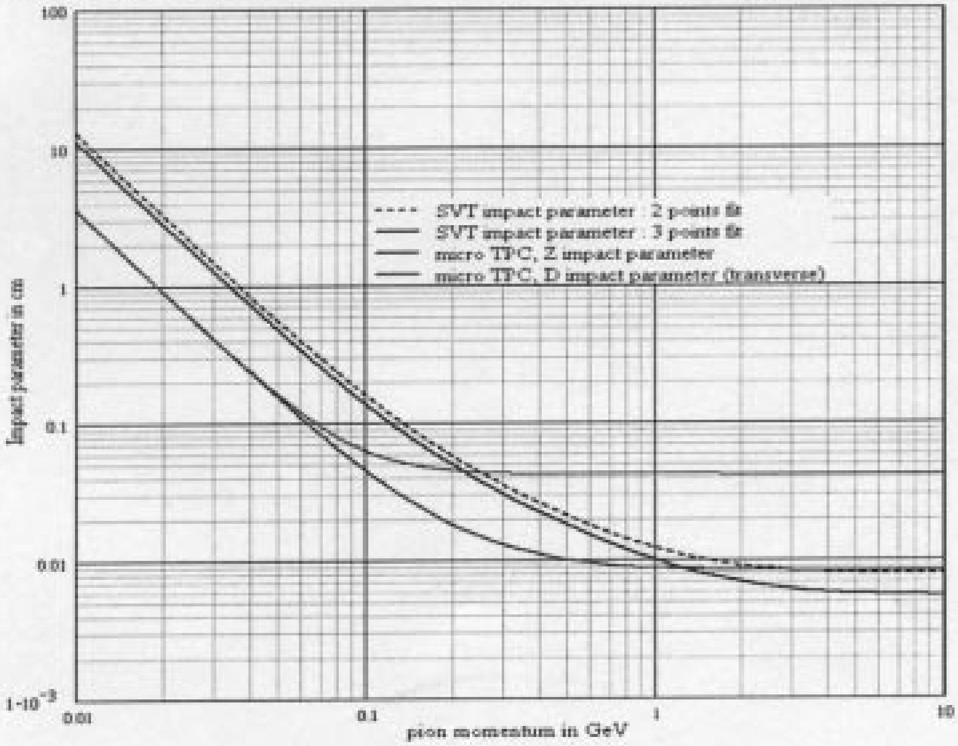

Figure 2 Comparison of impact parameter resolution for Micro TPC and a silicon tracker.

momentum of 1 GeV/c the gas detector performance is superior, but above this momentum silicon does better because of its better intrinsic position resolution. Note also that using 3 layers of silicon instead of 2 gives only marginal improvement in the projection resolution. This is because multiple scatter in the inner most layer is what basically sets the projection performance. Any reduction in the radius or thickness of this first layer directly improves the performance. The low momentum performance for the gas detector, on the other hand, is set by the beam pipe which, in this example, is 1 mm of Be at 4 cm radius

In the proposed application the Micro TPC must work in a high track density environment. The two track resolution in this device is set by the electron diffusion spreading in the azimuthal direction and by the projected length of the anode readout structure in the z direction along the cylindrical axis of the TPC. These two directions establish a hit resolving area. Using Poisson statistics the fraction of tracks resolved is given by:

$$FHR = e^{-A \cdot \rho}$$

where FHR is the fraction of hits resolved, A is the hit resolving area and ρ is the local hit density on the active cylinder. The hit density was estimated using a FRITIOF simulation of Au on Au at 100 GeV per nucleon. The results of this analysis are shown in Figure 3 as a function of z for two active cylinders with different radii. Since the interaction is centered ($z = 0$) on the cylinder, the z location depends directly on dip angle. At this radii and B field we correctly approximate the track paths as straight lines. As shown in the figure, the fraction of hits resolved is at least 89%. This is with a hit resolving area that is 4 mm by 0.9 mm at large z.

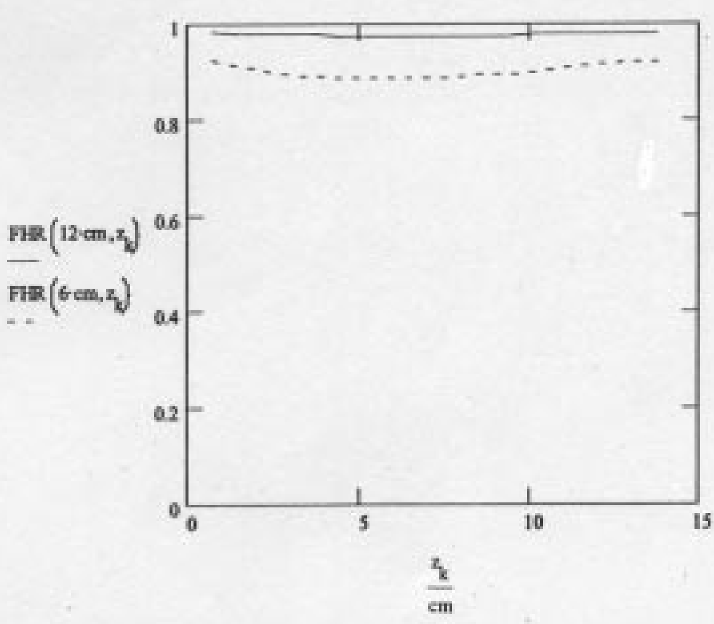

Figure 3 Fraction of track crossing hits resolved without overlap as a function z for two defferent radii.

Electron Drift tests in DME

The use of DME as a drift gas was initially a concern because of reports of excessive electron attenuation[2] in DME and there were no reported detectors using multi-cm drift distances. Therefore we performed attenuation tests in DME with a 9 cm drift distance and found that the attenuation can be reduced to negligible levels by using new supplies of Dupont-manufactured DME or older supplies filtered with a Nanochem filter[3].

Design of the MSGC/Amplifier Chip

We have built and tested a MSGC integrated with a pre-amp shaper on a silicon chip. The chip was submitted to MOSIS and manufactured by Hewlett-Packard using one of their standard 3 metal, 0.8 µm processes. The MSGC portion of the chip was constructed using the upper metal. The other two metal layers were removed to obtain the maximum SiO^2 thickness between the cathode (which runs at an elevated voltage) and the grounded substrate. The MSGC design, shown in Figure 4, consists of 3 mm x 3 µm anodes on a 200 µm pitch. The intervening cathodes are 97 µm in width. The anodes are read out with amplifiers on the chip and are operated at ground potential, the same potential as the underlying substrate. Since this geometry will not produce a field at the anode with a naked dielectric, we use a resistive, post-process layer of silicon carbide doped $\sim 10^{14}\Omega/\square$ to define a uniform potential gradient on the surface from the cathode strip to the anode strip. The resistive layer defines the potential boundary condition and produces the high field at the anode required for gas gain. Resistive layers are commonly added to MSGCs for another purpose, namely to stabilize the gain by preventing charge build up on the dielectric surface. One should note that using a resistive layer produces a less than ideal field configuration. That is, the field is not significantly stronger at the anode than the cathode. It is preferable to have the strong field asymmetry that makes a standard MWPC so

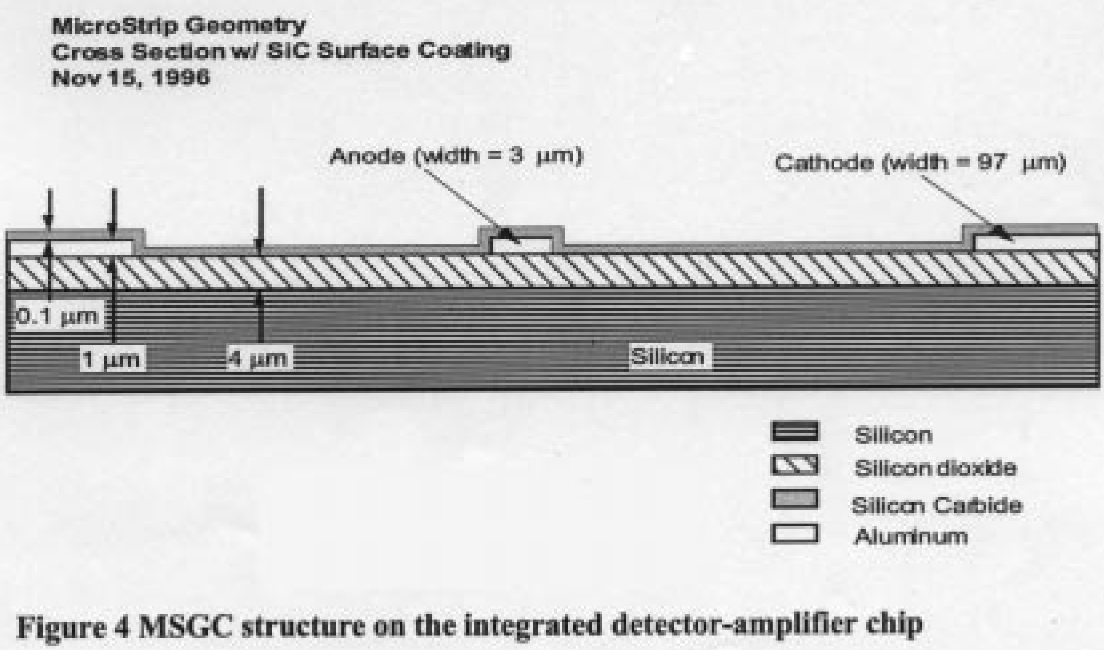

Figure 4 MSGC structure on the integrated detector-amplifier chip

stable and invulnerable to sparking. The resistive silicon carbide layer was 0.1 µm thick and was deposited on the surface using plasma enhanced chemical vapor deposition.

The amplifier design used on this chip was borrowed from an earlier LBNL chip[4]. The preamplifier is optimized for a detector capacitance of 0.26 pF. The shaping time of the amplifier is adjustable from 50 ns to 150 ns. For this work the amplifier was operated with a 50 ns FWHM shaping time. The gain of the system is 25 mV/1000e and the power consumption per channel is 50 µW. The electronics gain was measured using an onboard 8.9fF capacitor to inject a known charge into the front-end. A photograph of the integrated MSGC amplifier chip is shown in Figure 5.

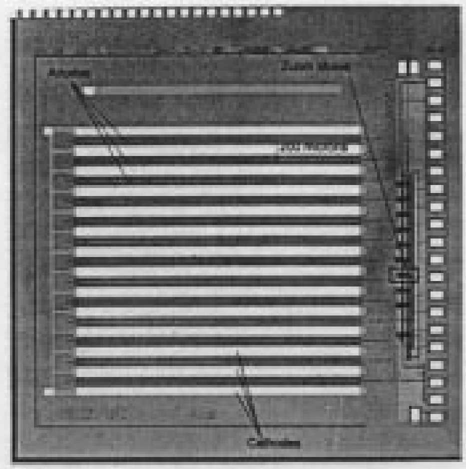

Figure 5 Photograph of the integrated MSGC/Amplifier chip. The MSGC structures are 3 mm long.

Test Setup

The detector was tested in a small chamber with a 1 cm drift region above the chip. A grid and field plate separated the drift field from the gain region. A collimated Fe^{55} X-ray source was arranged such that the electrons from X-rays converting in the gas drift a few mm into the detector region. The device was tested with two different gas mixtures, Ar-CO_2 (75-25) and Ar-ethane (50-50). The signals from seven anodes were read out in coincidence on separate CAMAC ADC channels using LabView on a PC. The cluster of electrons created by the X-ray extends over three anodes so the full signal from the X-ray is recorded by summing anode

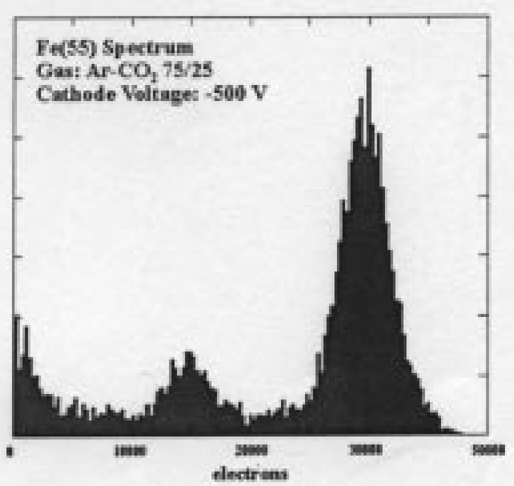

Figure 6 Pulse height histogram taken with the MSGC/Amplifier chip.

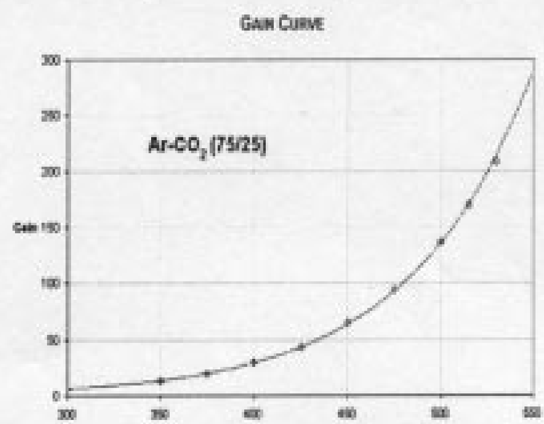

Figure 7 Apparent gas gain as a function of cathode voltage.

signals. The effective gas gain was determined using a value of 220 electrons for the X-ray signal and comparing the measured X-ray amplitude with a known charge injected into the amplifier front-end.

Test Results of the MSGC/Amplifier Chip

Using the Fe^{55} X-ray signal we have measured the effective gas gain of the detector chip as a function of cathode bias voltage. The electron cluster from the converted X-ray extends over roughly 3 anodes, so the full amplitude was obtained by summing anode signals for those events where the signal was centered on the 7 readout anodes. An example histogram of the summed signal amplitude for Ar-CO_2 (75-25) is shown in Figure 6. The main peak corresponds to the 5.9 KeV X-ray and the second peak is the escape peak. The energy resolution, FWHM, of the main peak is 18%. The effective gain is shown in Figure 7 as a function of cathode voltage. A maximum gas gain of 200 was achieved. This is ~2 times what is required for minimum ionizing signals in DME since the measured amplifier noise is only 80 e rms.

Conclusion and Other Development Possibilities Using GEMS

Tests of the integrated MSGC/amplifier show that it meets the noise and gain requirements for operation in a Micro TPC when used with Ar-CO_2. It remains, however, to be tested with DME. We have found that, even operating at the very low gains that we require, the chip is not as robust as we had hoped and as a result is not ready for a working detector system. The main source of failure is the opening of a via. We attribute this failure to micro discharges on the surface that have been reported in other MSGC detectors.[5,6] The weakest link in the current design is a small via connecting the detector anode to the amplifier. A redesign of the via is potentially a simple fix, but the preamplifier could be vulnerable, although amplifier failure has not been a problem.

In light of this observed failure mode the recently developed Gas Electron Multiplier[7] (GEM) detector presents an interesting modification to our approach. The GEM is a kapton film with copper clad on both sides that has been drilled with holes. The copper films are biased to create a large field in the holes so that gas amplification occurs as electrons pass through the holes. Gains of several thousand have been reported. This device is particularly interesting in the Micro TPC application because a grid is required anyway to isolate the large drift region in the TPC from the readout devices. Replacing the grid with a GEM would allow us to isolate the gain region from the readout device, automatically reducing electronic vulnerability to small discharges. In this approach the cathodes would be removed and the anodes would be made larger to reduce the anode field, permitting charge collection without avalanche multiplication at the readout electrode. We are currently exploring this option with tests on GEMs and working on developing a means for production. The details and optimization of the readout structure need to be reconsidered as we learn more about the capabilities of the GEM. Our strategy motivating the integration of the detector with the electronics was to maximize signal to noise by reducing detector capacitance and by reducing coupling to outside noise sources. The introduction of the GEM allows us to accomplish the same end while decoupling the gas amplification region with its potential for discharges from the sensitive electronics.

Acknowledgements

We thank Wan-Shick Hong for coating the chips with silicon carbide. We also thank John Kadyk, Fabio Sauli and Herb Steiner for useful discussions.
This work was supported by the Director, Office of Energy Research, of the U.S. Department of Energy, under contract No. DE-AC03-76SF00098.

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