OG 1179

BNL-45021

BNL--45021

DE92 007448

# The Uranium Liquid Argon Calorimeter of the DØ Experiment: Experience in Realizing a Large System

**Włodek Guryn**

*Brookhaven National Laboratory*
*Upton, New York 11973*
*USA*
for the DØ Collaboration*

## ABSTRACT

The major aspects in realizing the calorimeter system of the DØ experiment are discussed. They include: technologies developed for calorimeter production, schedule, and experience with module production.

Submitted to the Proceedings of the Second International Conference on Calorimetry in High Energy Physics, 14-18 October, 1991 Capri, Italy.

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* The DØ collaboration includes: University of Arizona, Brookhaven National Laboratory, Brown University, University of California - Riverside, Columbia University, Fermi National Accelerator Laboratory, Florida State University, University of Florida, University of Hawaii, Indiana University, Lawrence Berkeley Laboratory, University of Maryland, University of Michigan, Michigan State University, New York University, Northern Illinois University, Northwestern University, University of Rochester, CEN Saclay France, Institute for High Energy Physics Protvino USSR, State University of New York at Stony Brook, Tata Institute of Fundamental Research Bombay India, Texas A&M University and Yale University.

## Introduction

The DØ experiment is one of the two major detectors at Fermilab's Tevatron collider, and DØ is scheduled to take its first data in spring 1992. Proposed and approved in 1983, the DØ detector was designed to emphasize good lepton identification and jet energy measurement. As a result, calorimetry has been the focus of this experiment.

The DØ calorimeter covers the rapidity range $-4 < \eta < 4$ and the full azimuthal angle. Depending on rapidity, the thickness of the calorimeter ranges from 8-10 interaction lengths.

The calorimeter is divided into three: the central calorimeter (CC) and the two end calorimeters (EC). Each of these calorimeters consists of three types of modules: the electromagnetic modules (EM), the fine hadronic modules (FH), and the coarse hadronic modules (CH). The major differences among the module types are in absorber-plate materials and thicknesses: 3 mm and 4 mm uranium plates were used for the EM modules in the CC and EC, respectively; 6 mm plates of uranium-niobium alloy, with 1.5% Nb, were used in the FH. The CH sections have 46.4 mm copper plates in the CC, and stainless steel plates of the same thickness in the EC.

With the gap structure common to all modules, the unit sampling cell is composed of: an absorber plate, 2.3 mm liquid argon (LAr) gap, signal board, and another LAr gap.

From design through construction, the DØ calorimeter cost $22.8 million. Installation added another $2.4 million and electronics another $2.8 million to the cost, making the total $28.0 million. More details on the calorimeter may be found elsewhere [1-7].

## Technologies

While LAr calorimeters have been built before, the DØ calorimeter is one of the largest built in terms of size and the number of channels. The total weight of the three calorimeters is 900 tons, and the number of electronics channels is about 50,000.

The calorimeter's requirements of $4\pi$ geometry and good missing transverse energy resolution challenged the design to minimize dead areas. As a result, physics and engineering considerations placed many new constraints on well known LAr technology.

For example, because of the lack of access to the calorimeters essentially for the duration of the DØ experiment, no major repairs can be made during data taking. Therefore, the system had to be designed and built robustly. In addition, though the modules operate at LAr temperatures, they were built and tested at room temperature; hence room-temperature testing had to be developed that would assure that the modules would work at LAr temperatures without repair for long periods.

To simplify construction of various types of calorimeter modules, common technologies were employed where possible. Besides the calorimeter components made by industry such as calorimeter plates, connectors, cables, and cryostats, the following technologies and methods were developed within DØ:

1. **Resistive coating.** To provide a high-voltage electrode, the surface of the signal boards was screen-printed with a resistive coating composed of carbon-loaded epoxy. This arrangement allowed the blocking capacitance to be built into the board structure, therefore eliminating the need for space-consuming high-voltage blocking capacitors. The resistivity (40 megohms/square at room temperature) was chosen to minimize the cross talk between adjacent channels and the voltage drop due to the uranium-leakage currents or due to the presence of the ionization from the signal.
2. **Connections.** To minimize the space needed for connections, insulation-displacement connections (IDC) were used in most of the calorimeter. To reduce electron noise due to the capacitance and inductance of the connections, what is called local ganging was employed. Local ganging is accomplished by placing the signal return path as close as possible to the signal path. For signal return, percussion welding of niobium wire to the uranium absorber plates was developed. A signal return was provided for every 2-4 signals.
3. **Signal and readout board fabrication.** Most signal collection boards were fabricated by DØ; the exceptions were the small angle modules for which commercially built multilayer boards with internal signal trace layers were used. Signal electrodes were made from two laminated 1-mm G10 sheets The board fabrication procedure included five major steps: screen printing of the resistive coating; routing the pad patterns; routing the high voltage patterns; laminating the two G10 sheets; and cutting the boards. Following their fabrication, the boards were tested under high voltage, and the continuity of the signal connections was checked with a capacitance meter.
4. **Cooldown procedures.** So as to assure that the calorimeter modules would survive the cooldown mechanically and electrically to LAr temperatures (87K), the modules were first tested in liquid nitrogen. Then, to minimize mechanical stress due to the temperature differences in the module array, the cooldown to LAr temperatures was carefully monitored and controlled. This was achieved by instrumenting the modules and support structures with more than 250 temperature sensors in each of the three cryostats. These sensors provided information about the temperature differences within the modules, the module interconnections, and the module-support structure. As a result, it was easy to maintain a maximum cooling rate consistent with structural limitations, which corresponded to maximum temperature difference of 50K between any two temperature sensors in each cryostat. For example, the cooldown of the CC took only 14 days.
5. **LAr purity monitoring.** The purity of LAr is one important factor that determines its response uniformity and stability. To prevent LAr poisoning, all materials used in the calorimeter were tested to see their effect on charge collection in LAr. Poisoning tests were done in a special test cell, in which the signals from alpha and beta sources were measured for one week or more. Materials were accepted if signal-loss rates corresponded to less than 2%/year in the actual calorimeters. For most materials, this was the limit of the test sensitivity. In addition, production modules were tested in LAr, and the signal-loss rate was less than few parts per thousand over 100 days. More information about the LAr purity monitoring can be found elsewhere [8–9].

## Experience With Module Production

The DØ calorimeter modules were produced at four different labs: the CC modules were built at Brookhaven; the EM modules for the EC were constructed at LBL; the stainless steel frames for the coarse EC modules were provided by IHEP, Protvino, USSR; and the remaining EC modules were produced at Fermilab. This production arrangement was beneficial, because the different production teams collaborated on solutions to common production problems, but developed unique solutions for problems particular to their specific calorimeter.

Module-production factory startup was rather slow because initial procedures were based on experience with prototypes. As experience was gained with the production modules themselves, procedures were refined and, so, production increased. The production of calorimeter modules took about two years.

Quality control was an important aspect of module production from the beginning: all modules to be installed in the calorimeters, including those first built, had to satisfy the same criteria. Quality inspections were performed upon receiving materials for module production, as well as at the end of each production step. A quality-assurance document traveled with each module, and steps had to be checked off on that form as the module was built.

Testing, as a part of quality assurance, included the measurement of cell capacitances to verify that all connections were intact and a high-voltage (HV) test (at 3 kV) during which leakage cuurents were measured. High leakage currents indicated shorts, which had to be removed before progressing with the module. Capacitance and HV tests were also done in liquid nitrogen to make sure that the modules could operate in LAr. Before installation, modules were retested in orientations corresponding to their possible locations within the cryostat.

To keep track of physics parameters and module-testing results, data bases were established to follow the history of the modules from production through installation. The most important data-base items were tower capacitances, leakage currents, and mechanical measurements relating to sampling fraction determination. The latter included plate thicknesses, module height, signal and and readout board thickness, and weights.

During the course of module production, a number of surprises occurred, including high-voltage discharges, and uranium oxidization of the absorber plates:

**High-voltage discharges**. In 1985, in the test beam of the DØ prototype[6], it was shown that the uranium noise could be reduced by 25% by drifting electrons towards the absorber plates held at ground potential. In this test, the signal boards had no resistive coat. In the next beam test[7] in 1987, the CC EM production modules were studied using resistive coat boards. With negative polarity HV applied to the boards to minimize the uranium noise, discharges were found to be present. These pulses occurred at rates $\sim$ 10-100 Hz for signals corresponding to >5 GeV; the rise times were $\sim$5-50$\mu$s. In Fig. 1, the rate of discharges as a function of time is shown. Around day 1 and 28, the HV was turned off. The rate of discharges increased initially, reaching maximum after two to three days, and then decreased with a very long time constant of about 20 days. The spectrum of pulses fell off slowing with increasing amplitude. The rate of discharges varied significantly between the modules and sections of a module.

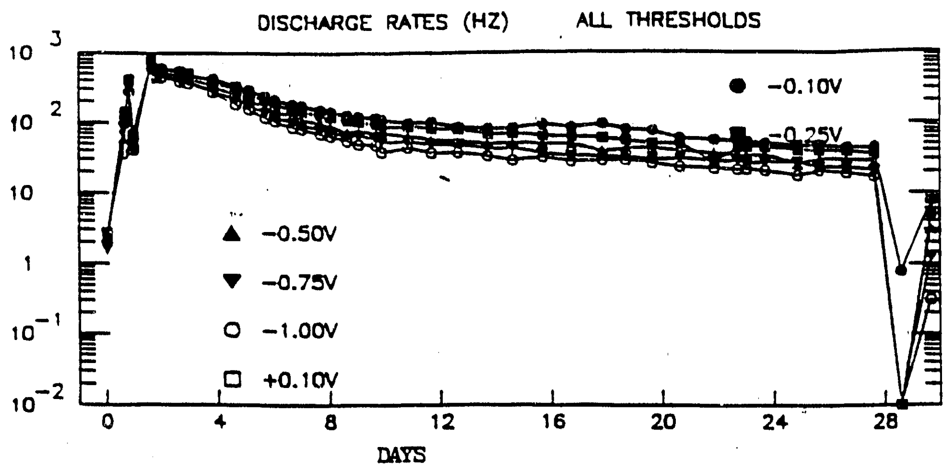


**Figure 1:** The rate of discharges (Hz) as a function of time for different threshold settings.

It was found experimentally that, if the positive HV was applied to the resistive coat so that ionization electrons drift away from the absorber plates, the discharges were eliminated. This HV polarity, however, resulted in anomalous time-dependent HV leakage currents larger than those expected from the uranium radioactivity by a factor of three to eight. This was a concern because of the resistance built into the HV planes. Subsequent measurements of the HV plateau and the better than 2% uniformity of response in the EM modules proved that those anomalous leakage currents were not a problem for the operation of the calorimeter.

Though the sources of the discharges or the leakage currents have not been conclusively determined, interesting explanations have been suggested [10] within DØ: Discharge and anomalous current phenomena are both believed to be related to the Malter effect [11] through which charge buildup on insulating layers on the negative polarity electrodes result in large local fields and consequent injection of electrons into the argon gap.

**Uranium oxide**. The oxidization of uranium is a well known phenomenon: it proceeds through the absorption of water $U + 2H_2O \rightarrow UO_2 + 2H_2$ and is accelerated in an oxygenless atmosphere [12]. This was rediscovered while testing modules in liquid nitrogen: during the warm-up phase of the test, the modules were kept in the gaseous nitrogen, which resulted in the formation of $UO_2$ powder on the uranium plates' surface. To minimize the oxidization during the warm-up stage as well as during module storage and shipping, a small amount of $O_2$, about 2%, was mixed with the gaseous nitrogen.

## Summary

The realization of a large liquid argon calorimeter system poses a many challenges. The excellent experience and tests to date with the DØ calorimeters demonstrate that it can be done. The major lesson learned, according to this author, is that the robustness of large systems is most important, and therefore that prototyping and testing are crucial and should be an integral part of any schedule.

## Ackowledgements

The author would like to thank his DØ colleagues for their help in preparing this paper and for the very exciting seven years of working together.

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