New development in high resolving power W-Si calorimeters

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Abstract.

The Relativistic Heavy Ion Collider (BNL) collides heavy nuclei and creates a strongly coupled medium at unprecedented density and temperature. Characteristic event structures may be efficiently selected with calorimeters, which can provide triggers on high-pT particles, "jets" of particles, or large transverse energy, along with precision measurements of the structures. The importance of calorimeters in studies of ultrarelativistic heavy-ion collisions was first recognized by W. Willis [1]. The key requirements are photon identification and measurements, and high resolving power to handle extreme occupancies common to this kind of interactions. We present a fully developed and beam tested concept of the W-Si sampling calorimeter built to this specifications. Novel features of this design are concepts of silicon micromodules, use of microconnectors for the silicon alignment purposes and passive signal summation to form readout towers. A prototype calorimeter was built in collaboration between BNL and a number of University groups from USA, Russia, Korea, Finland and Czech Republic and exposed to particle beams at CERN PS and SPS.

1. Introduction

Calorimetry is one area of the instrumentation in physics which is well developed and reasonably well understood. Library of performant simulation and analysis tools describing particle propagation in matter is enormous and constantly growing providing the experimentalist with nearly unlimited possibilities to verify his basic ideas in detector construction well before the detector is even considered for implementation.

New developments in tracking and particle identification resulted in RHIC and LHC experiments being is scale comparable to that of D0/CDF but much more performant. To continue, this trend must be supported by a similar progress in calorimetry which takes over energy and momentum measurements for particles in the momentum range of 50 GeV/c and up. Probably the biggest challenge for such a takeover are measurements of $\pi^0$'s and photons which tend to produce nearly identical showers in traditionally structured hodoscopic calorimeters.

The FOCAL[2] (W-Si tracking electromagnetic calorimeter) detector concept was developed for the PHENIX [3] experiment at RHIC to study electromagnetic probes emanating from quark gluon plasma created in heavy ion collisions. A system prototype which has all main features of proposed detector was built in spring of 2009. The detector was bench tested and preassembled at BNL and delivered to CERN for beam testing in June 2009. The prototype was exposed in the electron and $\pi$-meson beams at the CERN PS (1-6 GeV/c momentum range) and SPS.
Figure 1. Longitudinal structure of a single calorimeter supertower (one sensor wide) showing the locations of the three calorimetric segments, S0, S1, and S2, and the high-resolution position sensitive layers.

(10-100 GeV/c momentum range). Results of the test beam experiments are summarized in Dr. Y. Kwon contribution to these Proceedings.

2. The FOCAL Design: A Tracking Calorimeter
The FOCAL is a highly segmented tracking calorimeter designed to reconstruct and identify electromagnetic signals at intermediate rapidities in close proximity to the production vertex. FOCAL is composed of an active preshower segment (S0) and two identically structured energy sampling segments (S1 and ES). Each of the three segments is \( 8 L_{rad} \) deep and have seven energy sampling cells: a layer of tungsten followed by pad-structured (15.5 \( \times \) 15.5 mm\(^2\)) silicon sensors. Sampling cells 2-5 of the preshower segment also include two strip structured (pitch 500 \( \mu m \)) position sensing sensors each (at a depths of \( \sim 2X_0 \) (L0), \( \sim 3X_0 \) (L1), \( \sim 4X_0 \) (L2) and \( \sim 5X_0 \) (L3)). Strip layers serve to count hits, measure hit-to-hit separation, and estimate the energy sharing between possible contributors to the high energy tracks constructed from clusters seen in the pad-structured calorimeter segments. The longitudinal structure of the calorimeter tower is sketched in Fig. 1.

The FOCAL is proposed for positioning around the beam pipe at 44 cm from the nominal collision point, on the pole of the PHENIX central magnet, and has a geometrical depth of 16 cm. The Molière radius of FOCAL is \( \sim 14 \, mm \).

An extensive set of performance measures based upon a standalone simulation chain implementing a free standing FOCAL in GEANT3 was developed to select its design parameters. The FOCAL design was then integrated into the complete PHENIX GEANT simulation, which includes all material in PHENIX, allowing for the study of all aspects of operating the FOCAL as part of the PHENIX experiment. The pattern recognition algorithms were further refined to optimize energy and position resolution, along with efficiency and sensitivity to shower shape measurements.

By design, the FOCAL segments are structured into mechanically non-projective towers. The sub-towers in the FOCAL (readout towers in individual segments) have an aspect ratio of \( \sim 2 \) (ratio of the sub-tower depth to its lateral size measured in the diagonal direction) which helps to keep occupancy in the individual segments low – even on the periphery of the detector. Figure 2 shows, for each of the three calorimeter segments, how the number of towers that contribute to a cluster depends on the impact angle. The tower cluster multiplicity per track rises by less than 50\% between minimum and maximum impact angles.

Digital projectivity due to longitudinal segmentation have a dramatic effect on the FOCAL
performance as a particle identification detector, allowing it to effectively reject hadronic showers by comparing the measured longitudinal shower development to the parametrized electromagnetic shower shape.

2.1. Mechanical design

A modular design was developed for the FOCAL to allow for a relatively easy industrialization of the construction project. The calorimeter is built of “bricks”, three bricks (preshower brick and two energy sampler bricks) stacked together form a “superbrick” (see Fig. 3). All bricks are a double 6.2×6.2 cm$^2$ silicon sensor wide. Each brick has a tungsten plate facing upstream and a copper skin enclosing it on all other sides, save one for connections to external electronics.

2.2. Silicon sensors and concept of micromodules

The basic element of the FOCAL readout chain is micromodule which consists of a silicon sensor (pad or strip structured), an interconnect board hosting passive and/or active readout components, connections to a grounding plane, and ceramic backing tile(s) which protect sensors and insure micromodule rigidity. Components of the micromodule are glued together using silicon-based adhesive.

Two kinds of silicon sensors (and two different micromodules) are used: pad structured and strips. All silicon detectors in the FOCAL are 6.2×6.2 cm$^2$ diced either from 4” or from 6” wafers 300 μm (strips) or 525 μm (pads) thick. Critical to the success of the experiment will be the reliable operation of these sensors in a high radiation environment. The estimates based upon ionization losses of collision related particles produced in pp interactions at √s=500 GeV at a luminosity of 10$^{32}$ cm$^{-2}$ s$^{-1}$ result in radiation dose of ∼10 Krad/year close to the beam pipe. Albedo neutrons from the calorimeter absorber will constitute 3 to 10% of the value of the MIP fluence but will induce ×10 higher damage effectively doubling the radiation dose to ∼20 Krad/year of operation [4, 5]. In 10 years of running at RHIC luminosity the sensors in the central region of FOCAL will begin showing signs of radiation damage. To alleviate the possible consequences of exposure, all sensors in FOCAL are used in AC coupled mode (external RC decoupling network) thus allowing us to handle at least a ×10 increase in the leakage current. In addition, the mechanical design of the readout units allows for replacement of problematic sensors without collateral losses (although this cannot be done without moving calorimeter bricks.
to a “gray” repair area).

The silicon sensors for FOCAL are built using single-sided single-metal p+ on n– bulk silicon devices. A short summary of sensor parameters is given in Table 1.

Both pad and strip sensors have first been prototyped at ELMA (Russia), ON Semiconductor’s (Czech Republic) then at ETRI (South Korea) and BARC (India).

2.3. Pad-Structured Readout Layers
An assembled and exploded (for clarity) micromodule is shown in Fig. 4.

![Figure 4. Pad-sensor micromodule sandwich components. From bottom to top: backing ceramic tile, silicon sensor, interconnect board, and ceramic spacer.](image)

The bonding pads on the interconnect board are wire bonded to the aluminized pad centers.

| Specification               | Pad-structured sensors | Strip sensors |
|-----------------------------|------------------------|---------------|
| Wafer thickness             | 525 μm                 | 300 μm        |
| Depletion voltage           | 100-120 V              | 80-100 V      |
| Diode capacitance           | 25 pF                  | 5 pF          |
| Bias voltage                | Full dep. V + 20 V     | Full dep. V + 20 V |
| Leakage current             | <300 nA total, <20nA/pad | <1 nA per strip |
| Junction breakdown          | >300 V                 | >300 V        |
| Implant area                | 15×15 mm²              |               |
| Al area                     | 15.02×15.02 mm²        | 0.45×61 mm².  |
| Interpad (strip) capacitance| <2 pF (pad-pad) or <8 pF (pad-all neighbors) | <1 pF (strip-strip) |
| Maximum heat dissipation    | <~50 mW / sensor       | <~50 mW / sensor |
| Heat dissipation from on-the-sensor electronics | no major heat sources | 0.5 W / sensor |
through 3 mm diameter vias. Low-profile RC-network components are placed on the interconnect board close to the bonding point locations – hidden inside large diameter vias in the ceramic spacer separating the interconnect and carrier boards. Gold plated copper foil is bonded and glued to the aluminum plating on the sensor common side and soldered to the ground pad on the interconnect for the ground connection. Two 20 pin low profile (0.9 mm total height) connectors are installed close to the edges of the interconnect board to connect the sensor stack to traces on the carrier board which is conductively glued (grounded) to the tungsten plate.

The laminate of the 4 mm tungsten plate and carrier board with installed sensor micromodules form a readout unit (sampling cell) which is used throughout the whole calorimeter depth (see Fig. 5).

![Figure 5. FOCAL pad-structured readout unit.](image)

The interplate gap reserved for the carrier board with installed micromodules is 2.5 mm wide. 0.5 mm of this space is silicon, ~0.2 mm is FR4 (carrier board), and 0.2 mm is the FR4 interconnect board. 0.9 mm, partially filled with ceramic spacer, is used to accommodate connectors and RC-network distributing bias voltage to individual diodes. 0.4 mm is used by ceramic backing which protects the ground side of the silicon sensor. The remaining ~0.3 mm gap is to ensure that no pressure is applied to the surface of the sensors.

2.4. Strip Readout Layers
The readout system for the strip-structured silicon detectors is based on the SVX4 [6] chip developed at FNAL for the D0-detector upgrade. Data from SVX4 chips is collected by custom developed FEM’s which are optically connected to Data Collection Modules (DCM’s) which are part of the PHENIX DAQ system. Similarly to the pad sensors, strip sensors are used in AC-mode. They are connected to SVX4 inputs through a discreet component based RC network, which is located on the Strip Readout Control (SRC) boards glued to sensors (see Fig. 6).

3. Resolving close showers in PreShower segment
In order to understand the performance of the proposed design, we conducted extensive simulation studies, intended to closely mimic what we would expect to observe with the FOCAL in real collisions. To that end, a simulation chain was put in place, which included the detector response, reconstruction, and several stages of analysis. The reconstruction identifies
Figure 6. Strip-sensor micromodule sandwich components. From bottom to top: backing ceramic tile, silicon sensor, and interconnect board.

the measured energy clusters in the FOCAL subtowers and strip layers, associates clusters into tracks and assigns to each track a $\chi^2$ value describing the quality of its fit to an electromagnetic hypothesis. It is this input data that is then turned over to the strip pattern recognition routines.

The strip tracking uses a Hough-type [7] methodology to determine the angular direction of photons within the FOCAL. Hough tracking transforms all the hit positions into Hough parameters — in the case of straight line tracking, these are simply the slope and the intercept. As the number of hit positions is small, the vertex position is used to form the intercept so the slope is the only free parameter available for tracking.

Strips are analyzed independently for $x$-type and $y$-type strips. The methodology used in the tracking was developed with emphasis on the difference between direct-$\gamma$ and $\pi^0$'s in the FOCAL.

All strips inside the regions-of-interest defined by track energies are scanned for distinct maxima in the hit distributions weighted directly by energies in the strips. The two tracks may merge in the $x$ and/or $y$ directions, one of the photons may be lost due to conversion probabilities or, in the case of very asymmetric decays, land outside region of interest, which leads to some $\pi^0$ contamination of the $\gamma$ signal. In PHENIX geometry, $\pi^0$'s below $E < \sim 5$ GeV are reconstructed as two single $\gamma$. In the energy range $(5 < E < 10$ GeV — Fig. 7), a prominent $\pi^0$ peak is clearly visible when two distinct maxima are found in strip distributions.

In the range $10 < E < 25$ GeV (two photons from $\pi^0$ decay are separated by $> 5$mm in the first strip layer), the reconstruction is at its best. The two photon decay tracks are generally close enough together to be considered (by the strips, but not the pads) as two tracks, but far enough apart that finite resolution effects are not yet prevalent. In this region, a clear, dominant, $\pi^0$ peak is seen.

The finite strip resolution effects begin to come into play above $E \sim> 25$GeV As the decay tracks from the $\pi^0$ become closer together, and the energy increases, the strip width determines a minimum separation at which the $\pi^0$ can be reconstructed correctly. The effects of this do not actually limit the reconstruction until $E \sim> 60$ GeV (< 3mm two shower separation).
4. Summary
A conceptual design for the novel W-Si electromagnetic tracking calorimeter with fine lateral
and longitudinal segmentation is presented. Simulated data are used to demonstrate its ability
to resolve electromagnetic showers from $\pi^0$ decays down to 3 mm separation (from 60 GeV $\pi^0$'s
at 40 cm from production vertex). The prototype calorimeter implementing major ideas of new
design was built and tested in the particle beams at CERN (see the talk of Dr. Y.Kwon from
Yonsei University, Korea) in 2009.

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