Secondary Emission Calorimeter Sensor Development

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Abstract: In a Secondary Emission electron(SEe) detector module, Secondary Emission electrons (SEe) are generated from an SE surface/cathode, when charged hadronic or electromagnetic particles, particularly shower particles, penetrate an SE sampling module placed between absorber materials (Fe, Cu, Pb, W etc) in calorimeters. The SE cathode is a thin (10-50 nm thick) film (simple metal-oxides, or other higher yield materials) on the surface of a metal plate, which serves as the entrance “window” to a compact vacuum vessel (metal or metal-ceramic); this SE film cathode is analogous to a photocathode, and the SEe are similar to p.e., which are then amplified by dynodes, also is in a PMT. SE sensor modules can make use of electrochemically etched/machined or laser-cut metal mesh dynode sheets, as large as ~30 cm square, to amplify the Secondary Emission Electrons (SEe), much like those that compact metal mesh or mesh dynode PMT’s use to amplify p.e.’s. The construction requirements easier than a PMT, since the entire final assembly can be done in air; there are no critical controlled thin film depositions, cesiation or other oxygen-excluded processes or other required vacuum activation, and consequently bake-out can be a refractory temperatures; the module is sealed by normal vacuum techniques (welding or brazing or other high temperature joinings), with a simple final heated vacuum pump-out and tip-off. The modules envisioned are compact, high gain, high speed, exceptionally radiation damage resistant, rugged, and cost effective, and can be fabricated in arbitrary tileable shapes. The SE sensor module anodes can be segmented transversely to sizes appropriate to reconstruct electromagnetic cores with high precision. The GEANT4 and existing calorimeter data estimated calorimeter response performance is between 35-50 Secondary Emission electrons per GeV, in a 1 cm thick Cu absorber calorimeter, with a gain per SEe >10$^5$ per SEe, and an e/π<1.2. The calorimeter pulse width is estimated to be <15 ns. With fine mesh sampling only (no thick absorbers) the resolution is ~25 MeV at 1 GeV.

1 Introduction

The initial purpose of secondary emission calorimeters is particle (e, gamma, n, p, meson, nuclei) energy measurements in extreme radiation environments and very high rates. Other benefits include fine segmentation and close packing, operation in harsh environments (space environs, high temperature/pressure environs e.g. boreholes>1 km deep), imaging detectors in medicine and industry, national security, and beyond. Calorimetry, crucial for new discoveries in Nuclear-High Energy Physics experiments often must: a) work in very high radiation environments for many years, and b)
operate very high rates and/or with sub-ns time resolution; and c) can be configurable in compact, dense and homogeneous units for “energy flow” calorimetry; d) are sufficiently inexpensive to enable large absorber volumes; e) have energy resolution capable of distinguishing signals over a large dynamic range. Additional examples of novel calorimetry include experiment operations remotely, where the detection mechanisms are both rugged and operate without need for repair, service, recalibration or resupply for many years, such as in satellites, in remote or hostile environment locations on earth, in surveillance such as homeland security, in medical or industrial imaging, and in complex physics detector systems, where the calorimeter in the assembled detector is relatively inaccessible, densely tiled, and may need to operate for many years without disassembly. One extreme example might be operation at temperatures ~200°C in deep (20,000 feet) boreholes for geophysical exploration.

2 Secondary Emission in Existing Detectors
Secondary Emission (SE) of electrons from surfaces which have ionizing radiation absorbed on them is commonly used in nuclear and medium energy physics. Examples include the dynode gain mechanism used in photomultiplier tubes, and in accelerator beam rate and position monitors.

2.1 Photomultiplier Tubes
It is estimated that the SE emission oxide surfaces of the last dynodes of PMT operate in excess of 100GigaRads from 100-300 eV electron bombardment in the 10-50 nm thick surface layer that secondary emits. Figures 1a shows sheet-like dynodes, quite appropriate for inclusion in a sampling calorimeter ionization SE electron sensor, from Hamamatsu. The etched metal sheets are used in the Hamamatsu compact PMT, and can be made in large sheets up to ~0.5m x 0.5m. A stack with a gain exceeding 500,000 per electron is 6 mm thick. These dynode sheets are similar in function but more efficient than fine metal mesh dynodes, as also shown below in 2 types in Figures 1b. Modern micromachining techniques and tooling developed for flat-panel HDTV enable complex metal structures up to ~1 m sizes.

Figs. 1a: Machined/Etched Metal Mesh
Hamamatsu etched metal mesh dynode examples. The “tube” at left is 12.5 cm (5”) across –right shows a closeup of the metal mesh. 2” (52mm) square H10966-type PMT. Such metal mesh dynodes can be made in large sheets and could be used to amplify secondary electrons generated in a thin film cathode from the particles in calorimeter showers.

Figs. 1b: Fine Wire Mesh: Two configurations of mesh dynodes as used in PMT, especially for operation in magnetic fields; ~15 dynodes yield a gain of 5 x 105. The mesh-mesh spacings are between 0.5-1 mm, as designed c1985. The compact tube at right has 19 mesh dynodes in <1cm. It operates in 107 gain in 1.25 T magnetic fields. Modern micromachined meshes can be spaced at 0.3 mm. A commercial metal mesh similar to that used in the mesh tubes: CuBe Mesh 37% transparent 75 μm apertures, cost <$20/m2.

The risetime of such mesh dynode tubes is typically less than 1.5 ns, transit times < 8ns, with bandwidths exceeding 300 MHz, reflecting the speed and rate capability (when properly powered) of SE dynodes as a gain mechanism, which we propose to apply in large areas to amplify SEe which are produced by showers crossing SE surfaces in calorimeters.
2.2 Secondary Emission Accelerator Beam Monitors

As an example, the secondary emission BLMS (Beam Loss Monitor System) used at CERN has a quoted life of 80 MGy per year, for 20 years. The SE Yield was found to be constant up to 10^20 p/cm^2 of integrated dose (!), which far exceeds many calorimeter requirements. Additionally, the risetime of these detectors are sub-nsec. This BLM is shown in Fig.2. Based on these proven technologies, SE electrons that could be produced by charged particles in sampling calorimeter showers are a candidate for use in high radiation, high rate experiments.

![Cartoon of operation and realization of the SEe beam loss monitor element used at CERN. A similar device with mesh-dynode-like gain stages would be used for the SEe calorimeter sensors.](image)

Fig. 2: Cartoon of operation and realization of the SEe beam loss monitor element used at CERN. A similar device with mesh-dynode-like gain stages would be used for the SEe calorimeter sensors.

Fig 3 (R): Cartoon of Secondary emission as used in an accelerator beam monitor, and as would be used in a calorimeter. Electrons freed by ionization random walk into the surface oxide, a thickness typically 10-50 nm thick, over typically 1-2 μm in the underlying metal. A few escape into the vacuum, enhanced by an applied electric field, becoming “secondary electrons”.

3 Secondary Emission Precis for Calorimeter Sensors

The calorimeter sensor herein proposed is based on the Secondary Electron (SE) emission from solids. When a charged particle passes through the signal cathode, it can excite conduction band or inner shell electrons. These so called “True Secondary Electrons” can diffuse only several nm, as they usually have energies lower than 50 eV independent of the primary particle’s energy and type in contrast to the “knock-on” delta electrons. The material from which SE electrons escape is only from a thin surface layer of the traversed material, and are subsequently drifted into vacuum, usually helped by a bias electric field. The Secondary Electron Emission Yield (SEY) is proportional to the electronic energy loss of the particle in the surface layer of the signal electrode. A cartoon of this process is shown in Figure 3. It is not straightforward to simulate the SE in GEANT4 as it has no corresponding process defined. A modified semi-empirical formula of Sternglass (the contribution of δ electrons to the true SEY could also be included) can be used to calculate the SEY for metal oxide (TiO₂, Al₂O₃, MgO, BeO etc) surfaces.

\[
\text{SEY} = 0.01C_F L_S \frac{dE}{dx} ; \quad L_S = (0.23N^1/3)^1/16 \text{ cm}^2.
\]

Where \(dE/dx\) stands for ionization energy loss, \(L_S\) for effective penetration distance of secondary electrons to the surface, \(N\) for number of atoms per unit volume and \(C_F = 0.8\) is used in order to match the experimental data for Al₂O₃ [7] and TiO₂ [8]. The SE yield curves for Alumina, Titania, Al and Ti are shown in Figure 4 for protons at normal incidence between 10 KeV and 5 TeV. The emission yields for other charged particles (pions, electrons, etc) scale as the momentum, according to the Bethe-Bloch formulae for \(dE/dx\).

The universal curve for the secondary emission yields normalized to the peak yield vs the energy ratioed by the peak yield energy is shown in Figure 5a. Briefly, the yield rises from zero incident energy to a maximum yield at a particular material dependent energy, and then falls, since the specific ionization per track length falls, and ionized electrons formed deeper in the SE surface cannot escape to the surface. Fig. 5b shows the yield for MgO vs energy in KeV. At the present state of this proposal, the angular distributions of the incident calorimeter shower particles on the SE surface and that of the secondary electrons are not considered. Suffice it to say, this serves as a lower limit, since the secondary yield is a strong function of incident particle angle, typically increasing by x1.5 at 45 degrees and doubling at 60 degrees incident. Diamond thin film yield is shown below in Fig. 5c. Nucleating diamond crystalites on a W thin film surface could create many SE electrons, as shown below – a prelude for subsequent research.
Fig. 4a: The Sternglass formula $SE$ vs proton energy in KeV - for the secondary electron yield from 4 different surfaces A for protons of normal incidence, as used for the design of the CERN BLM. SEY for other particles scale as gamma-beta. The DESY Beam Monitors, similar, yield about 0.05-0.07 SEe per mip.

Fig. 5a, b, c (L) The universal curve of SE emission from metal oxides as ratioed by the maximum emission vs the ratioed particle energy to that of the maximum emission. (M) The emission from MgO as an example. For example, Cu-BeO peaks at a yield of 8 SEe per electron at 800 V. (R) Synthetic Diamond terminated with Cs SE emission, exceeding 120 per strike at 3 KeV electrons – remarkably, the Cs dipole bound to the C SE surface is stable in air. Since tungsten is a pseudo lattice match, W foils or plates overcoated with 10-100 nm crystallites would make a unity detection efficiency e-m module SE cathode, and possibly an e-m preradiator/isolated charged particle detector (future work beyond this proposal).

4 Generation of Secondary Emission Electrons by E-M and Hadronic Shower Particles

We now turn to predicting or estimating the number of secondary emission electrons that could be generated from showers in calorimeters – i.e. the number of ionizing charged particles that are produced and could traverse SE cathode surfaces in a reasonably configured/sampled sampling hadron or electron calorimeter. As can be seen in Figure 6, a basic first approximation of the average SE yield is between 0.05-0.1 electrons per particle for essentially all particles (e, pi being the most important for calorimeters) above 40-50 MeV.

4.1 Estimates from Existing Data

Typically the response of a near-compensated hadron calorimeter with 5cm iron/scintillator sampling is the equivalent to the response of about 16 MIP equivalents/GeV$^2$ (Holder et al., 1978) ($dE/dx$ Fe $\sim$ 2 GeV/meter). Scaling to an increase in sampling from 5 cm to 1 cm absorbers would produce $\sim$100 MIP equivs per GeV x 0.05 SEe/MIP = 5 SEe/GeV. We note that a MIP is the SE lowest yield (above $\sim$100 of eV incident particle energy), and thus 5 SEe/GeV represents a minimum likely signal. A rough equivalent might be a response of 5 p.e./GeV for a scintillator calorimeter, assuming the SE can be amplified like a p.e. to a detectable level (see next section). In a more direct measurement of particles, the CALICE collaboration$^6$ measures (corrected data for containment) $\sim$12 hits per GeV in a purely digital (i.e. each RPC readout pad is either hit or not, with no proportional energy or count of particles within a pad) energy flow/tracking hadron calorimeter consisting of 1 cm square RPC readout pad arrays between 2 cm thick steel plates (but only about 4 Lint thick). This
again sets a \textit{lower} limit on a SE signal in 1 cm thick sampling of about 24 hits/GeV x 0.05 SEe/hit = 1.2 SEe per GeV. A more realistic signal estimate for SEe is considerably higher, since a yes/no hit pad may have several particles through it, and many of the particles have a higher SE yield than 0.05 SEe per hit as at minimum ionizing (as shown in the SE yield curves vs energy shown above).

Fig. 6: The number of SE electrons per primary collected in the CERN BLMS system cell (alumina) vs primary energy- \(p\) (red square), \(e^-\), \(e^+\) (green-solid, blue-x), \(\mu^+\), \(\mu^-\) (purple, magenta), \(p^+\), \(p^-\) (red-circle, green-open box), \(n\) (blue triangle), \(\gamma\) (yellow) primaries. The high yields above \(\sim 10\) GeV are speculated to be from delta-rays. From Ref.\textsuperscript{7}: B. Dehning et al. The energy bins < \(\sim 10\) MeV have a threshold from the thick metal entrance window. (NB: negative signal at 8 MeV is absorption of \(e^-\) inside the signal electrode).

4.2 \textit{Estimates from Monte Carlo}

To obtain a more direct estimate of the response we use the GEANT4 Monte Carlo to estimate calorimeter configuration yields.

4.2.1 Sampling Calorimeter Simulation

To obtain a more direct estimate of an SE calorimeter signal, we have made a simple GEANT4 simulation, simply tabulating the numbers of charged particles crossing each 1 cm thick absorber sampling gap in Cu, 30 x 30 cm wide x 1.6m (160 gaps) long in several energy bins. Note that GEANT4 is not accurate at calculating shower particle energies below \(\sim 1\) KeV, where the secondary yield is maximal for e, p, p secondary shower particles. Figures 7 show 100 GeV pions and 10 GeV electrons in the 1 cm sampling Cu block, with the number of shower particles crossing from a 1 cm absorber per KeV incident per longitudinal distance vs energy of incident shower particles and vs longitudinal distance. We averaged 100 particles of 10, 100 GeV x electrons, pions. GEANT4 tabulates ~740 particles per GeV for pions crossing those gaps in 1 cm layers of Cu, and ~900 for electrons (and is the same within errors at both 10 & 100 GeV). Assuming a very conservative minimal signal of 0.05 SEe per particle as entering an SEe module in the calorimeter gaps, we predict ~37 SEe per GeV for pion showers, and ~45 for electron showers, with an \(e/\pi \sim 1.2\), a reasonable first guess. A caveat is that the spectra of incident particle energies generating SEe is similar in electron and pion initiated showers, as seen above, but not identical, and with different particle types – so \(e/\pi\) will be different when properly weighted by the energy & particle dependence This forms the basis for a very good signal, provided that the SEe can be amplified by subsequent dynodes to a level consistent with fast electronic measurement – a gain typically of \(\sim 10,000\) would be a minimal requirement to stand out from electronic noise. We remark in passing that the number of SE electrons in terms of calorimeter performance are comparable to the photoelectrons in a scintillator or Cerenkov calorimeter. In the optical/scintillator case, \(\sim 10-100\) thousands of photons are generated in a sampling calorimeter per GeV. but typically only 0.001-0.0001 are collected and converted to p.e., whereas in the SEe case, the produced SEe are far fewer, but essentially all are collected and amplified, giving a similar performance to a possible SE calorimeters.
4.2.2 Fine Quasi-Homogeneous Electromagnetic Calorimeter Simulation

We have run a detailed simulation using 20 micron Cu meshes spaced at 20 microns, as the entire calorimeter (Note: 100 Volts mesh-mesh voltage/20 microns = 5 volts/micron < 10 V/µm, the acceptable electric field in vacuum). Gammas of 1 GeV generated ~8,000 shower electrons of energy >100 eV, crossing the mesh gaps. This generated an average of 1,600 SE electrons(SEe)/GeV, which when amplified by the meshes, would be a resolution as good as +/-25 MeV at 1 GeV. Even finer meshes are available (10 micron meshes) of W, and the 50/50 metal/vacuum ratio means that a calorimeter with ~half the density of tungsten is possible.

5 Amplification of the SE electron signal

For practical device with 20:1 S/N at ~100 MHz requires a gain of >10,000, or 10k electrons as a least count for 1 SEe (similar to 1 p.e. in optical calorimeters). This is possible with dynode-like amplification: since the SEe are generated in vacuum, this is possible by making a vacuum box with a metal “window” with an SE surface on the inside, and using planar proximity collected SEe from the entrance metal oxide cathode – using the mesh-type dynodes as shown above. A detector somewhat similar to this has already been fabricated by EMI as a beam monitor. It used a standard Thorn PMT, simply replacing the photocathode with an Aluminum film SE cathode! Figure 8 shows the data sheet from Thorn-EMI of a beam monitor used by DESY.

6 Initial Tests of SE Calorimetry

We have tested this concept at a CERN test beam using metal mesh PMT as shown in Fig 10 below. The photocathode was disabled by using a +HV base, operating the anode at ~ +2KV, D1 at ground,
and the photocathode at small positive voltages or connected to ground through 400kOhms. Blue LED showed that the photocathode was insensitized. The tube was operated mainly with particles entering from the base side, with the photocathode window blackened. The tube was exposed to beams of 225 GeV muons and 100 GeV electrons entering a 3cm radiator, to simulate shower max.

The muon signal was 74% efficient, consistent with 3 pe, consistent with MIP delta rays/SE electrons >50 eV from the photocathode surface, and SE from the 19 dynodes. The electron shower max was fully efficient, with a mean number of SEs of ~30-40, roughly what would be expected for a sample of a 100 GeV shower at 5.5 Lrad and the dynode stack diameter. This implies with homogeneous mesh stack calorimeter (no other absorber) that >600 SEe per GeV are possible with this mesh, fairly consistent with the MC in section 4, and a resolution of ~4%/\sqrt{E}.

Fig. 10(L): Hamamatsu 19 stage mesh PMT in the CERN test beamline, in the phototube test box. 225 GeV $\mu^+$ or 100 GeV e$^-$ hitting 3 cm of Pb radiator incident from left. The photocathode was disabled using a +HV base, anode at +2.1KV, Gain=8x10$^4$, and D1 grounded. Photocathode: +10V or ground through 400k Ohms.

Fig 11(R): Beam test results of Mesh SEe “sensor”: 100 GeV electrons into 3 cm Pb (as shown in 10), with one SE sampling “cell”. Peak in mesh PMT signal corresponds to 41 SEelectrons (mesh gain ~10$^5$) at about shower max. The large width is essentially entirely consistent with shower fluctuations on a single shower sampling after 3 cm Pb. This implies > 600 SEe/GeV possible - the same as ~600 pe in a scintillator calorimeter.

7. Conclusions

The properties of Secondary Emission generated electrons as a calorimeter sensing signal has been outlined, and shown to be promising in initial test, consistent with MC and calorimetric data estimates. Very high radi-hardness, and speeds nearly cotemporal with shower development times are evident, and thereby applications to LHC or NLC forward calorimetry at $\eta$>3 are of high interest. With a homogeneous mesh-dynode stack SE sensor - effectively a very high sampling fraction - precision calorimeters at the ~2%/\sqrt{E} are indicated by MC, depending on the fine-ness of the mesh (or other) dynodes. While an SE is similar to a p.e. in terms of signal, SE amplifiers can be constructed in air and taken to high temperatures, as contrasted with PMT. Construction techniques and practical examples are explored in subsequent publications.

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