Secondary Emission Calorimetry

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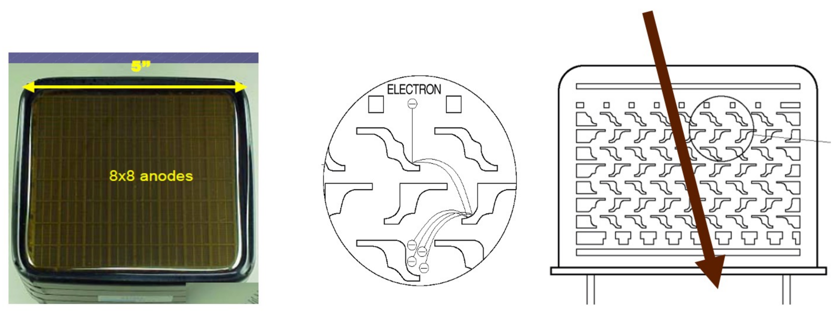
Why Secondary Emission Ionization Calorimeters?

- **Secondary Emission (SE) signal:** Generated with SE surfaces inside electromagnetic/hadronic showers:
  - – SE yield δ: Scales with particle momentum
  - – SE e^-: $3 < \delta < 100$, per 0.05 <e^-<100 keV (material dependent)
  - – $\delta \sim 0.05 - 0.1$ SE e^- per MIP
- **SE Calorimetry:** Radiation-Hard + Fast
  - – a) Metal-Oxide SE PMT Dynodes survive > 100 GRad
  - – b) SE Beam Monitors survive 10^{20} MIPs/cm^2

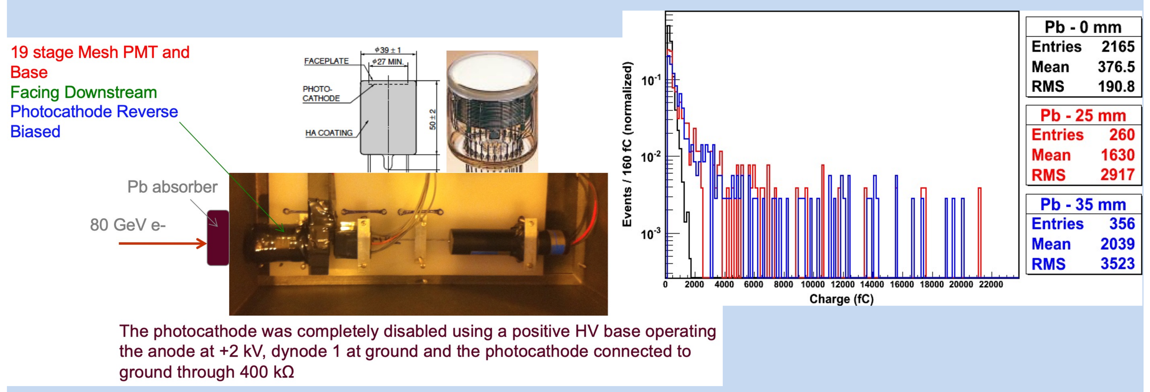
Expect ~ 60-240 SE e^- per 100 GeV pion shower w/ MIPs alone
BUT in an SE calorimeter module, SE e^- will be amplified exactly like photoelectrons in the PMTs.

SE Sensor Options - 1

- **Etched Metal Sheets:** This option is identical to the Hamamatsu dynodes that are ~ 50 cm long in some existing designs. They are already diced from large sheets. The figure shows the picture of a multi-anode PMT of 5" edge size (left), and sketches of the electron multiplication (middle) and utilization as an SE module with the traversing particle shown with an arrow.



First Tests of Principles of Operation of SE Sensors



Charge > 160 fC cut applied. **(1 SE e^- ~ 160 fC)**
Scales with X_0 (shower not laterally contained)

SE Calorimeter Envisaged for Future Implementations

16 - 25 X_0 Forward EM Calorimeter
1 X_0 W + SE Sensor Module ; less than 1 cm thick

The SE sensor modules will work like a PMT as an SE e^- is statistically similar to a photoelectron

Target gain ~ $10^5 - 10^6$ e^- per SE e^-

A) Muon MIP:

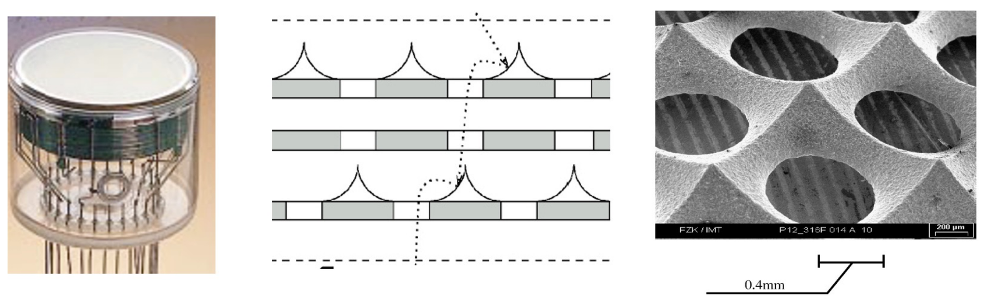
Expect ~ 0.1 SE e^- per sample module x number of modules → MIP Signal:
~ 2.5 SE e^- / muon in a 25 X_0 EM module calorimeter
but we measure ~ 8x this in Test Beam!

B) EM Showers:

~ 900 shower electrons/GeV yields 45 - 90 SE e^- / GeV
Note that this estimate is based on the MIP response estimate which is a lower limit.

SE Sensor Options - 2

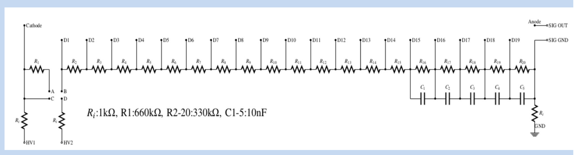
- **Metal Screen Dynodes:** These are basically mesh dynode variants. Usually the dynode separation is 0.9 mm and the wire diameter is 5 μm. The gains of these devices are at the order of 10^5. The figure shows a picture of a similar device and the fine mesh dynode structure.

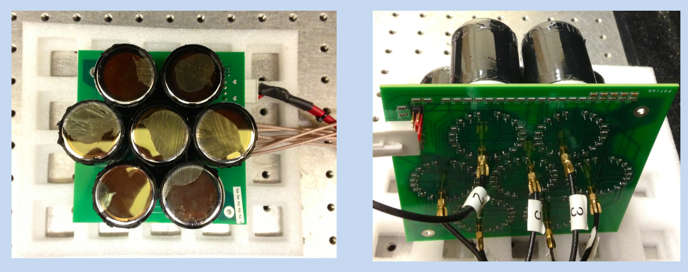


Construction of SE Modules

SE modules with 7 Hamamatsu R7761 19 stage mesh dynode PMTs were constructed. The baseboards were designed to provide three operation modes:

- Normal divider (photomultiplier) mode
- Cathode – first dynode shorted mode
- Floating cathode mode



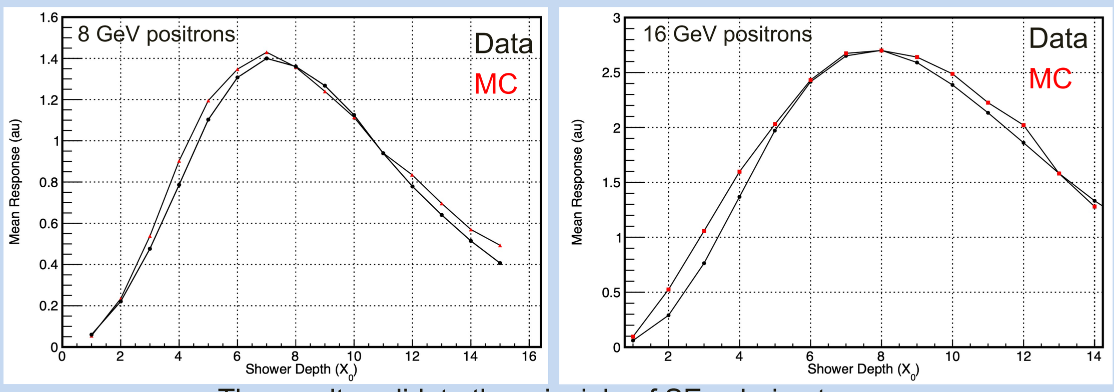


The default operation mode for the SE module was the cathode - first dynode shorted mode (B-C bridge) with an average gain of 6-9×10^5.

E. Tiras, et.al., JINST 11 P10004, 2016

Tests of SE Modules

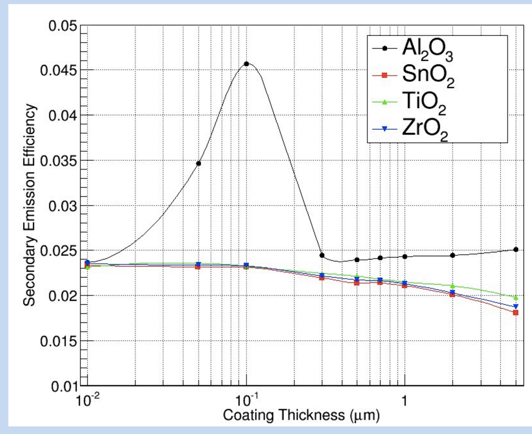
The SE modules were tested at FTBF with 8 GeV and 16 GeV positrons. The lateral coverage of the modules does not allow an effective measurement of the shower development with steel absorbers. The measurements were taken with the central sensor and up to 16 3 cm × 3 cm × 0.35 cm tungsten absorbers. MC matching is still under development.



The results validate the principle of SE calorimetry.

Enhancement of Secondary Electron Emission

The cathode and the dynodes of the SE sensors can be made by coating the mesh copper foils with secondary emitters like Al_2O_3, SnO_2, TiO_2 or ZrO_2. The coating can be done with magnetron sputtering with the simplest options being Al_2O_3 and TiO_2.

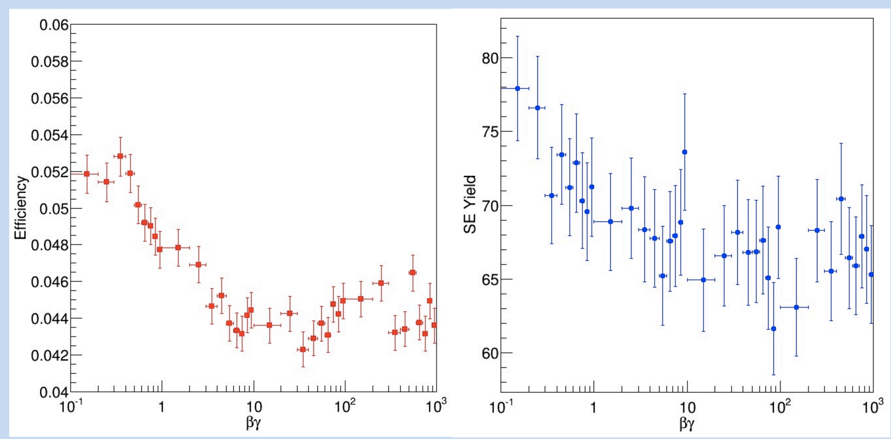


Average secondary electron emission efficiency was calculated for various thicknesses of Al_2O_3, SnO_2, TiO_2 and ZrO_2 with 4 GeV muons (MIP).

The best performance was predicted to be with 100 nm thick Al_2O_3.

Enhancement of Secondary Electron Emission

The secondary electron emission efficiency and the e^- yield of the 100-nm Al_2O_3 coated copper cathode/dynode was simulated as a function of the βγ of the traversing particle (muon). The minimum ionization occurs around βγ of 40 which corresponds to roughly 4 GeV of muon energy. The average secondary electron yield is around 68.



Projection to a Full-Scale SE Sensor

- The mesh structure made by holes of size between 10 and 100 microns and hole spacing of 50 – 100 microns.
- 150 microns distance between the dynode layers.
- Vacuum housing (no dramatic vacuum requirements).
- Start with a 9-stage multiplication.

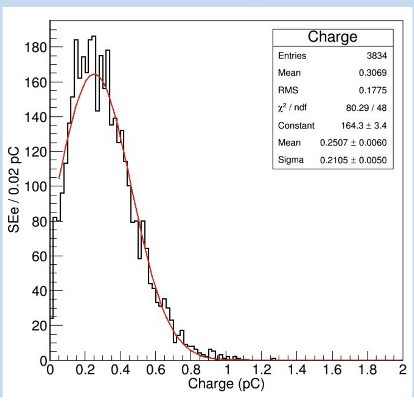
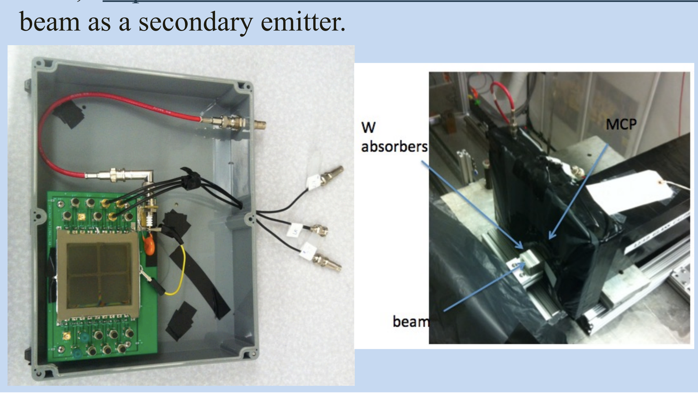


Figure shows the charge spectrum for a 9-stage secondary emission device for a minimum ionizing particle that is efficient at the cathode. With an average of 300 fC, the signal can be recorded with commercial oscilloscopes.

12 and 15 stage SE sensors are also practical.

Alternative SE Sensors

A highly feasible alternative to the dynode chain as the secondary emitter and multiplier is the microchannel plates (MCPs). In order to assess basic performance estimations, we tested the Argonne Large Area Picosecond Photodetector (LAPPD) (see e.g. Junqi Xie, Recent Progress on Development of MCP-PMT at Argonne National Laboratory, TIPP 2021, https://indico.cern.ch/event/981823/contributions/4304793/) in the Fermilab test beam as a secondary emitter.



The LAPPD is a photodetector that utilizes MCPs as the photoelectron multiplier. The anode is segmented into strips. The LAPPD was tested with 4 GeV and 8 GeV positron beams with increasing number of 1 X_0 tungsten absorber layers immediately upstream in order to measure the shower development.

Construction of Dedicated SE Sensors

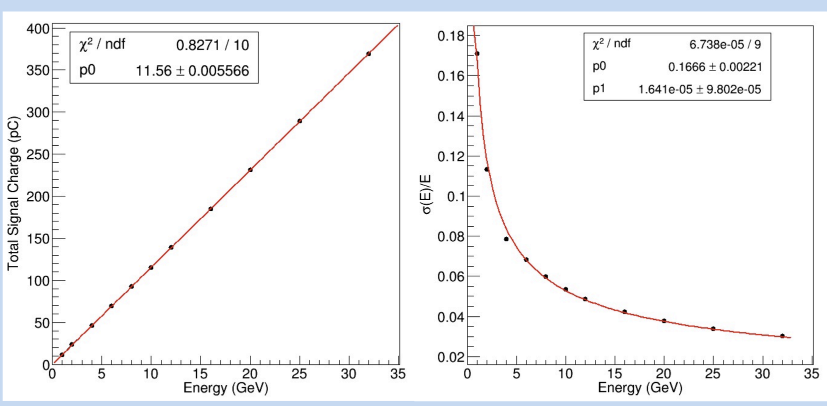
The construction requirements for an SE Sensor Module are much easier than a PMT, since:

1. The entire final assembly can be done in air. Dynodes used as particle detectors in Mass Spectrometers or in beam monitors cycle to air repeatedly.
2. The thin film deposition procedure and the handling of the coated SE layer are not as delicate procedures as for the photocathodes.
3. The SE module is sealed by normal vacuum techniques.
4. The vacuum necessary is 100 times higher than that needed for a PMT photocathode.

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.

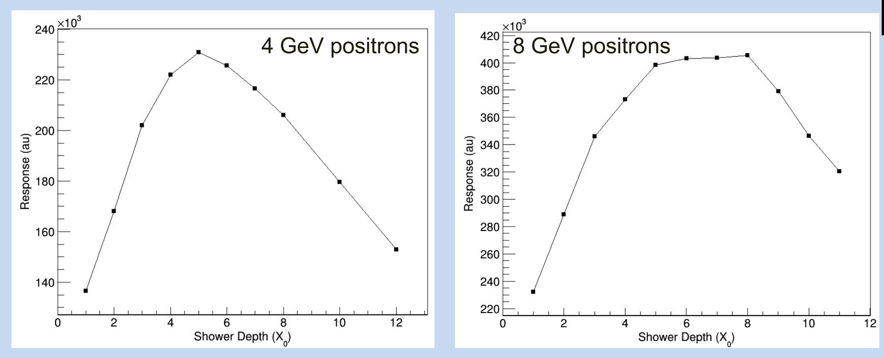
Projection to a Full-Scale SE Calorimeter

The electromagnetic response of an SE calorimeter prototype with 16 active layers interleaved with 1 X_0 tungsten absorbers is also simulated. The SE sensor is the previously described 9-stage SE device.



The detector response is linear in the energy range of 1-32 GeV and the electromagnetic energy resolution is obtained as $16.7\%/\sqrt{E}$ with a negligible constant term.

Alternative SE Sensors



Two major limitations exist in these measurements:

- The relatively thick glass window of the LAPPD created background by introducing Čerenkov light (irreducible background).
- Limited lateral coverage of the readout (only three strips were read out resulting in degraded shower maximum at 8 GeV).

Nevertheless, the idea of using MCPs as SE sensors is validated.

Conclusions

- Secondary emission calorimetry is a feasible option particularly for electromagnetic calorimetry in high radiation environments, as well as other implementations such as beam loss monitors and Compton polarimeters.
- The construction of the sensor modules is simple. The envisaged modules are compact, robust and cost effective.
- The preliminary tests validate the idea and suggest a full-scale SE calorimeter prototype.
- Highly segmented readout for imaging calorimetry is possible.