

# Secondary Emission Calorimetry

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# Secondary Electron Emission Principle

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

**The SE electrons in a calorimeter module will be amplified exactly like photoelectrons in the PMTs.**

# An Electromagnetic Calorimeter Based on Secondary Electron Emission Principle

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  $\sim 10^5 - 10^6 e^-$  per SE  $e^-$

## A) Muon MIP:

Expect  $\sim 0.1$  SE  $e^-$  per sample module x number of modules\*  $\rightarrow$  MIP Signal:

$\sim 2.5$  SE  $e^-$  / muon in a 25  $X_0$  EM module calorimeter

but we measure  $\sim 8x$  this in Test Beam!

\* E. J. Sternglass, "Theory of Secondary Electron Emission by High-Speed Ions", Phys. Rev. 108, 1, 1957

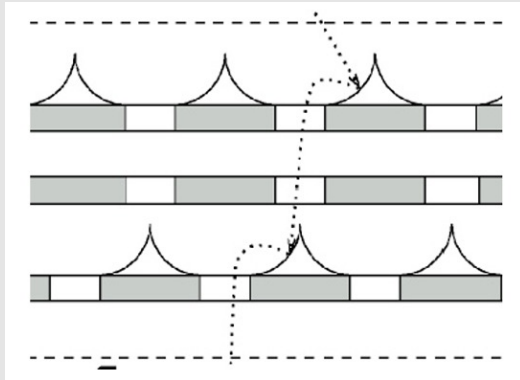
## B) EM Showers:

$\sim 900$  shower electrons/GeV yields 45 - 90 SE  $e^-$  / GeV

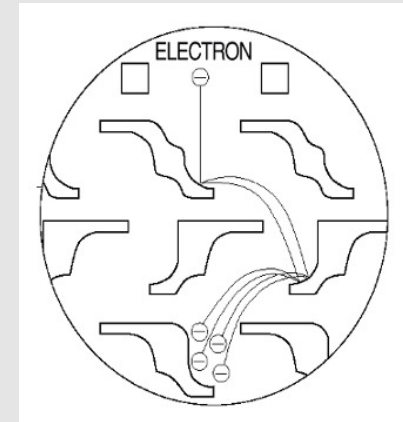
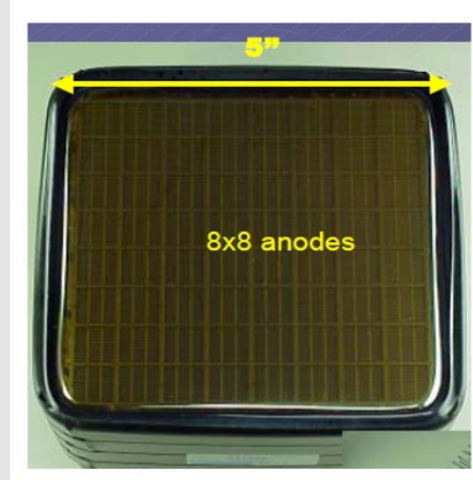
Note that this estimate is based on the MIP response estimate which is a lower limit.

# SE Sensor Options

**Metal Screen Dynodes** which are basically mesh dynode variants. Usually the dynode separation is 0.9 mm and the wire diameter is  $5\ \mu\text{m}$ . The gains of these devices are at the order of  $10^5$ . The figure shows a picture of a similar device and the mesh dynode structure.



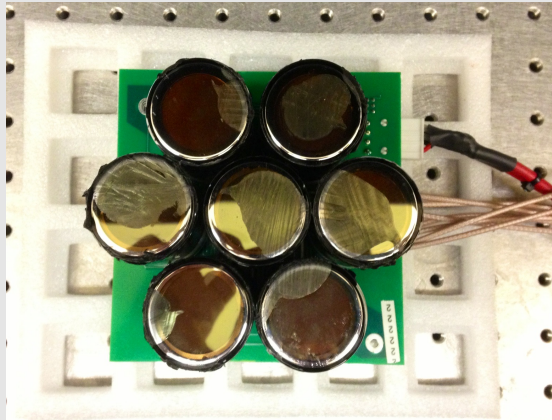
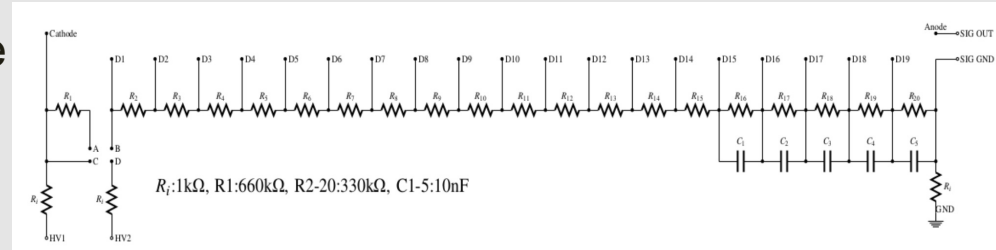
**Etched Metal Sheets** option is identical to the Hamamatsu dynodes that are  $\sim 50$  cm long in some existing designs. The dynodes are diced from large sheets. The figure shows the picture of a multi-anode PMT of 5" edge size and a sketch of the electron multiplication.



# Construction of SE Calorimeter Modules

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

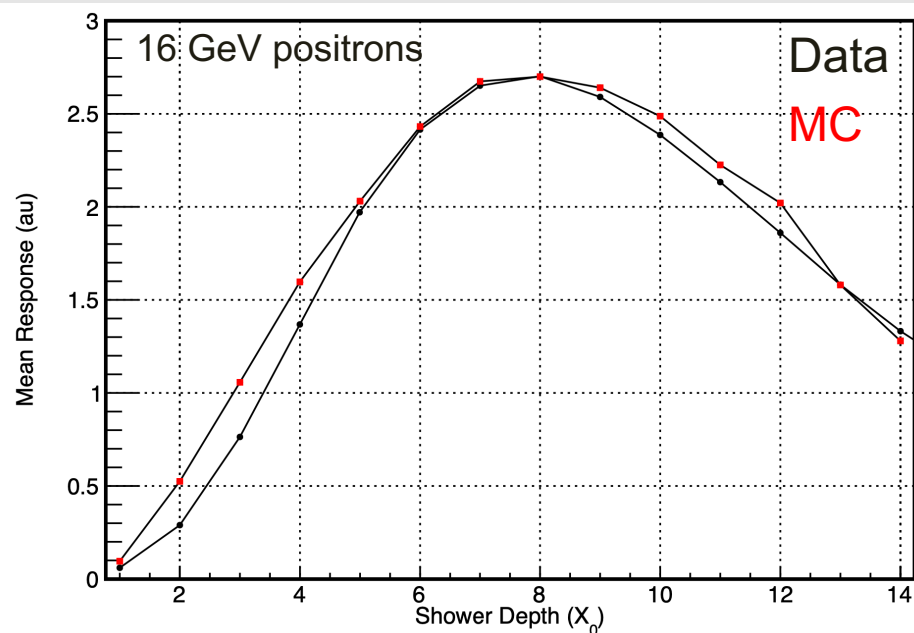
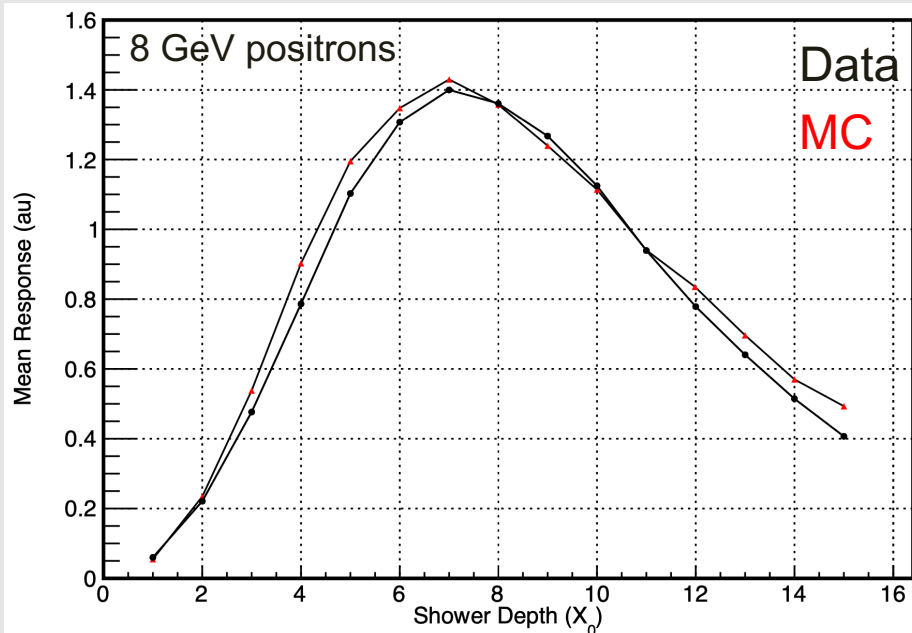
- Normal divider (photomultiplier) mode
- Cathode – first dynode shorted mode
- Floating cathode mode



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

# Tests of SE Modules – Metal Screen Dynodes

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.

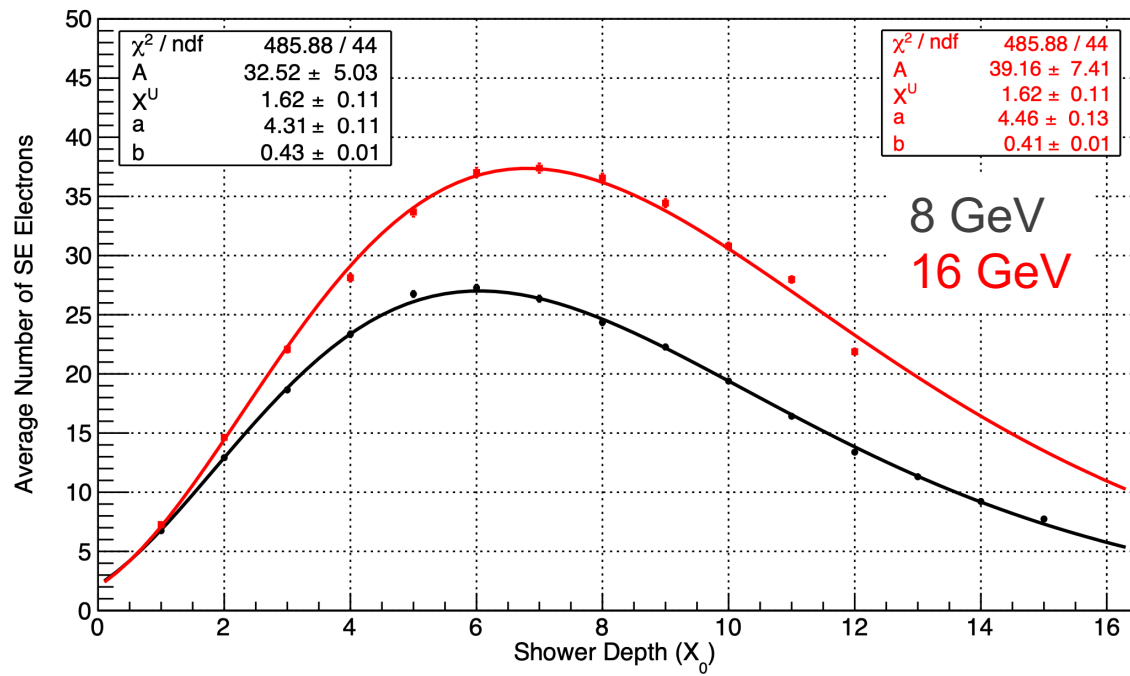


The results validate the principle of SE calorimetry.

# Tests of SE Modules – Etched Metal Sheet Dynodes

16 mm x 16 mm active area, cathode – first dynode shorted mode, calibration was obtained using the laboratory gain measurements in the same mode.

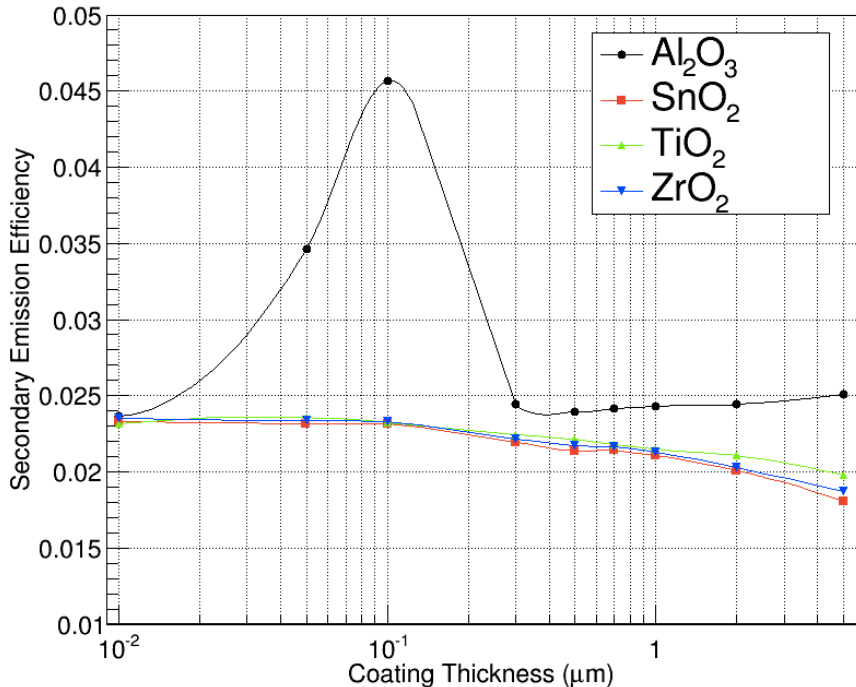
~280 SE e<sup>-</sup> for 8 GeV and ~400 SE e<sup>-</sup> for 16 GeV; 25-35 SE e<sup>-</sup> / GeV → limited lateral coverage



$$\text{Fit to } A \frac{(X+X_0^U)^{a-1} e^{-c(X+X_0^U)}}{\Gamma(a)}$$

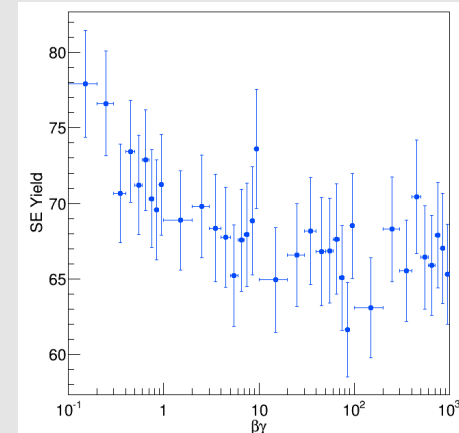
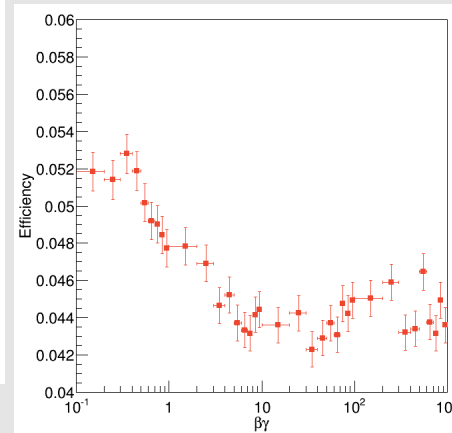
# Enhancement of Secondary Electron Emission

The cathode and the dynodes of the SE sensors can be made by coating the mesh copper foils with secondary emitters like  $\text{Al}_2\text{O}_3$ ,  $\text{SnO}_2$ ,  $\text{TiO}_2$  or  $\text{ZrO}_2$ . The coating can be done with magnetron sputtering with the simplest options being  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$ .



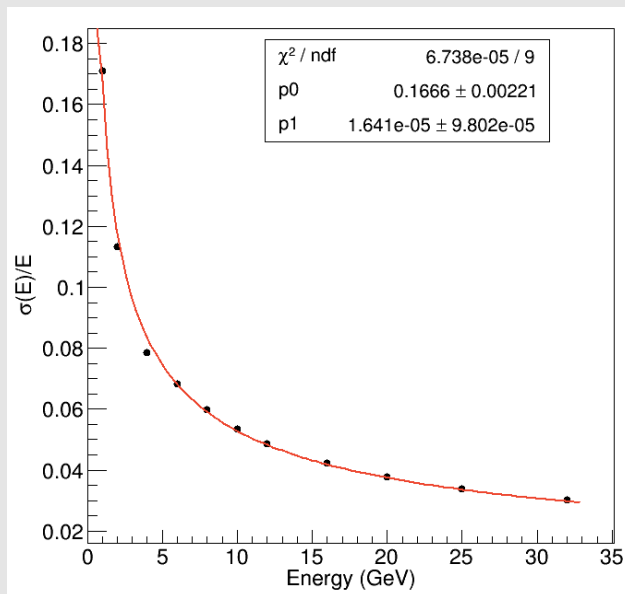
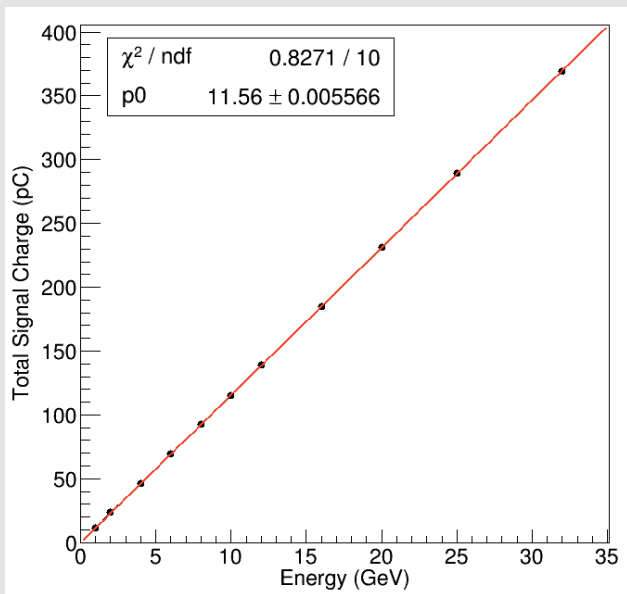
Average secondary electron emission efficiency was calculated for various thicknesses of  $\text{Al}_2\text{O}_3$ ,  $\text{SnO}_2$ ,  $\text{TiO}_2$  and  $\text{ZrO}_2$  with 4 GeV muons (MIP).

The best performance was predicted to be with 100 nm thick  $\text{Al}_2\text{O}_3$ .



# Projection to a Full-Scale SE Sensor

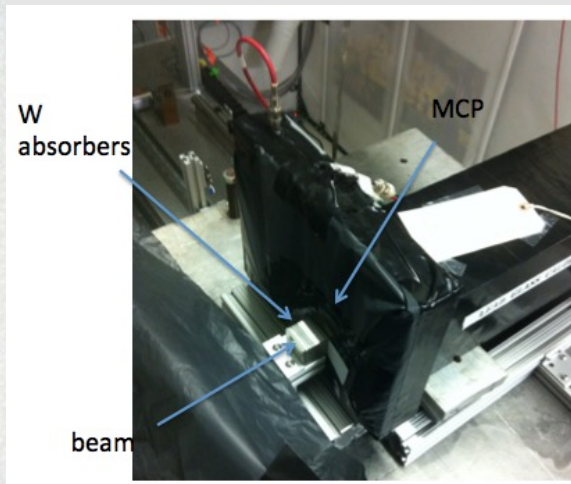
- The mesh structure made by holes of size between 10 and 100 microns and hole spacing of 50 – 100 microns.
- 150 microns distance between the dynode layers.
- Vacuum housing (no dramatic vacuum requirements).
- Start with a 9-stage multiplication and 16 active layers interleaved with 1  $X_0$  tungsten absorbers



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.

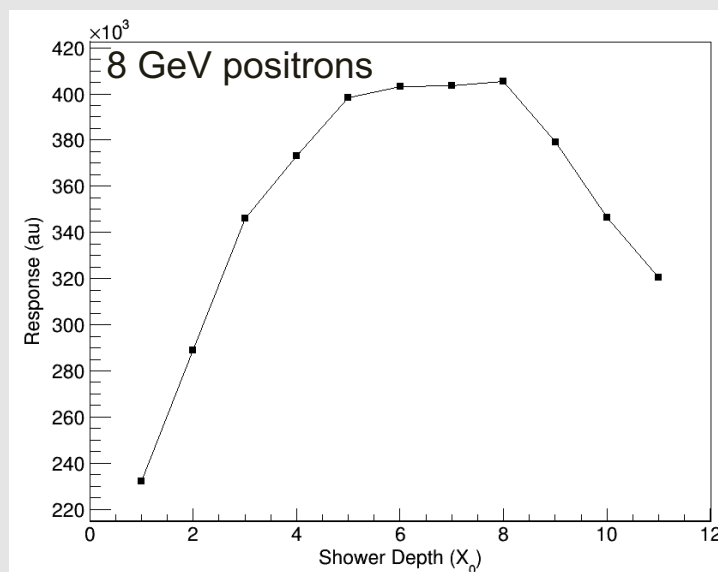
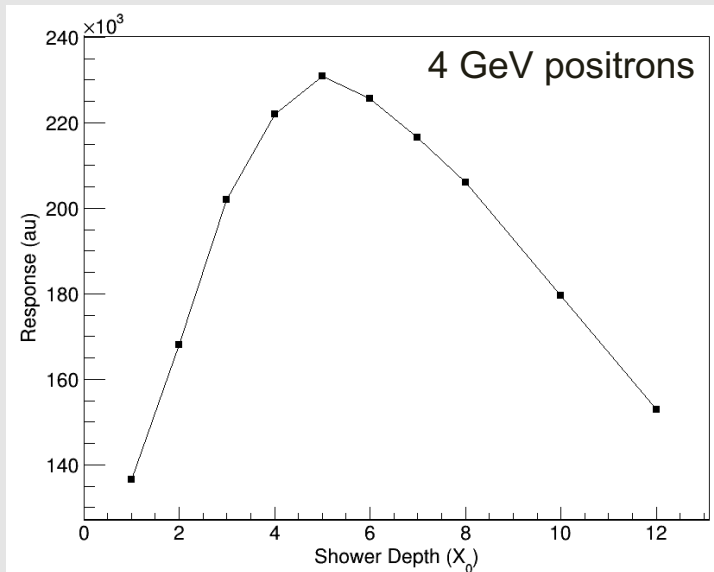
# Alternative SE Sensors

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.

# 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.

# 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.

# Conclusions

- Secondary electron emission principle provides opportunities to develop new generation particle detectors as well as to enable the evolution of the existing detectors.
- High secondary electron emission materials can be easily applied on various surfaces in the laboratory and facilities that can apply them in much larger areas exist.
- 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 dedicated secondary emission sensor modules is simple. The envisaged modules are compact, robust and cost effective.
- The preliminary tests validate the idea of using secondary electron emission materials for various detector types.
- Highly segmented readout for imaging calorimetry is possible.