Calorimetry/Detectors $\eta>2.5$, 100 TeV pp Colliders

David R Winn*
Fairfield University

+ contributions from collaborators from CMS*

Exploring the Physics Frontier With Circular Colliders"

**Disclaimer: Not a CMS talk, but approved by CMS HCal.*

Surprises at 100 TeV?

Fairfield
UNIVERSITY

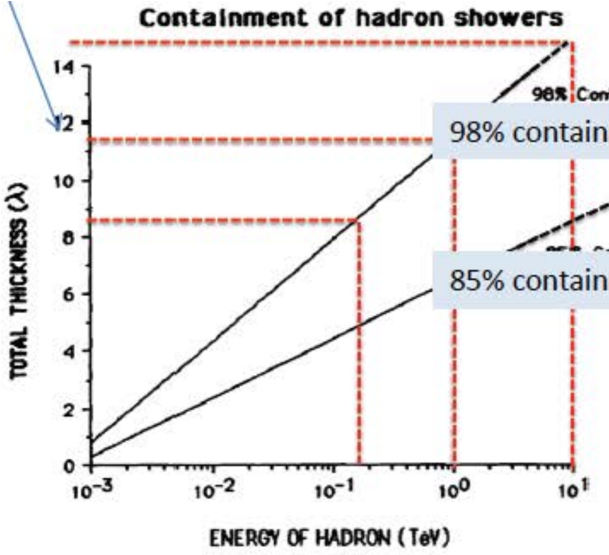
- What was **your** last *surprise* in HEP?
- c, b, t, W, Z, H all “predicted”. Only the masses not known with any precision.
- ν–oscillations? “Predicted” 1957, 1968 homestake 1/3 solar rate….
- τ was a surprise.
- Dark Energy:”surprise, surprise” (ok, not HEP per se, as of yet).
- We expected SuSY…Is its absence our surprise???
- *The only Orthodoxy is Facts” –JJ Sakurai*

But "Be Prepared"= *Cautious Optimism!*

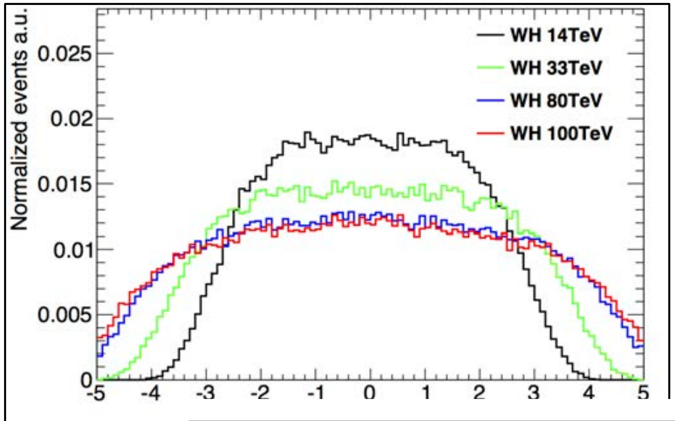
- Cast your mind ~15-20 years *before* detector designs for LHC – ie mid1970's the possibilities for detectors then would ***not*** be what happened in 1990's
- ***Examples now*** of what we did not have c.1995. yet ~20 years *before* FCC designs:
  - 10 nm lithography (and scaling down)
  - Submicron through-wafer via's (full 3D electronics) + low K dielectrics (Si on Air)
  - Graphene
  - Carbon fiber, other high strength/weight ratio adaptable technologies
  - ALD + stochiometric engineered materials (20 psec large area MCP)
  - III-V [100] wafers in large sizes + Practical synthetic diamond wafers
  - Thin film flexible wafer substrates and
  - Water-clear Silica aerogels (n~1.1)/Cerenkov compensation
  - Nanofabrication/replication/indenting techniques; nanomaterials
  - 3D printing
  - Robotics
  - Photonic band-gap engineering
  - Quantum Computing!?? But add our new simulation tools (EE,ME, Detectors etc)
  - SiPM + ALD-based MCP
  - Low cost, low noise, 20 GHz waveform chips
  - Particle Flow/High Granularity/Cerenkov-β compensated Calorimetry
  - Nb_3Sn, HTS for detector magnets
  - ***SO….. in 2030-2035???***

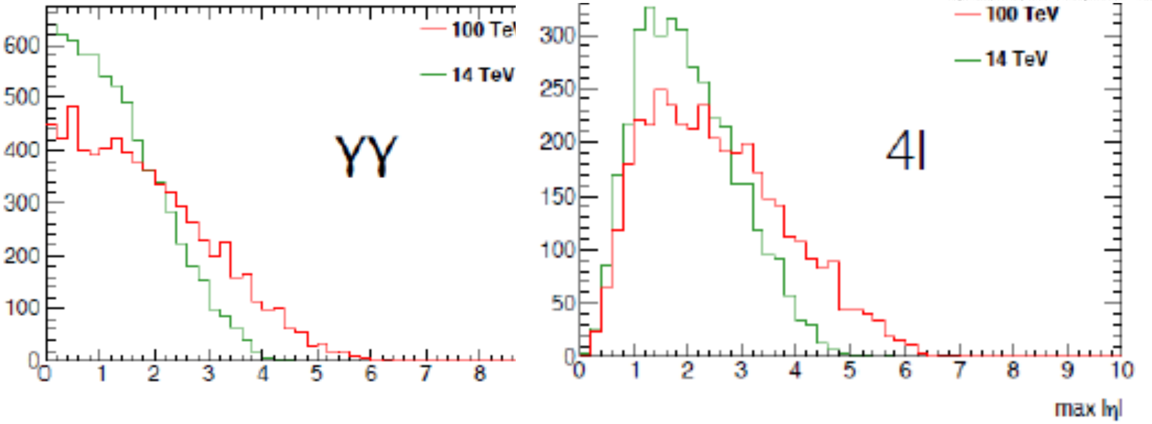
Yet 5×10^{35},100 TeV; $\eta \geq 2.5$ => *STILL Very Bad Bongoes!*

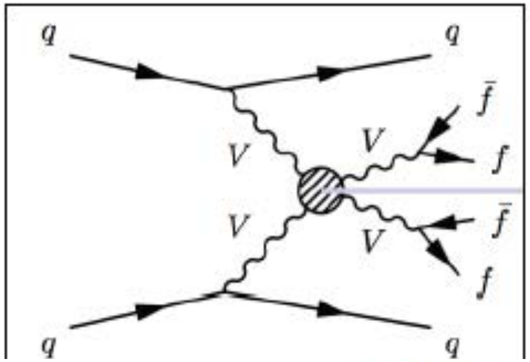
- Radiation Damage >20 GRad (3k fB^{-1})
- Pileup > 300–500
- 1 TeV p_T parton jet size at ~10 m ~1+ cm
  - Separation between key partons/jets is often of the same or smaller size as the jets themselves – w/o pileup…
  - Compare properties of Cu, W, PbWO3: X_o, L_{int}, $R_{Moliere}$
- Calorimeter: 10 TeV jet 98% containment~15 λ!
- Not enough solenoid bending
  - Forward μ:Need dipole or toroid
- Detector Mass: >x10 CMS/ATLAS
  - Mechanical engineering
  - Beam pipe

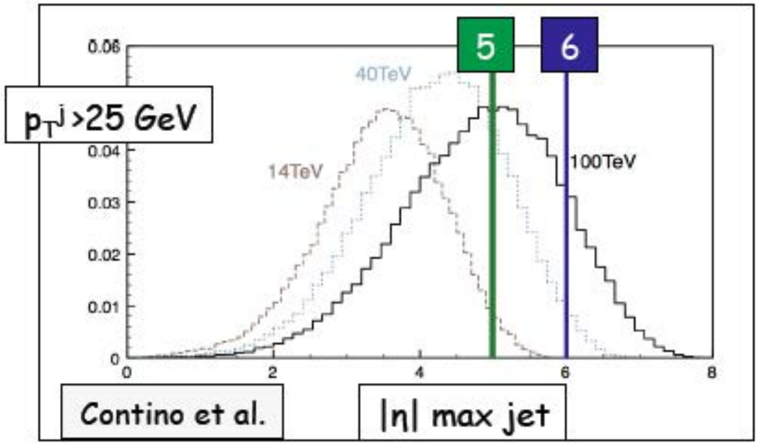


Examples of desired η Coverage









- η=6 <-> θ=0.28°

At 20 m, ~10cm from beam!

- η=6 particle through a beam pipe: ~200x pipe thickness.
- Sci-Fi 2mm Al pipe:1Lint;4.5Xo

A tower at η=6, jet cone = Δη x Δϕ =0.08 x0.08 at 10m is ~3-4mm high and ~1.8 cm wide.

Where to scallop the pipe?

Desired Properties $\eta > 2.5$

Needed:

- η coverage to ≥ 6!

- Transverse/longitudinal segmentation for isolated γ, e, μ ($H \to \mu\mu$) ID
  - Particle flow? Enough granularity to detect and remove overlap

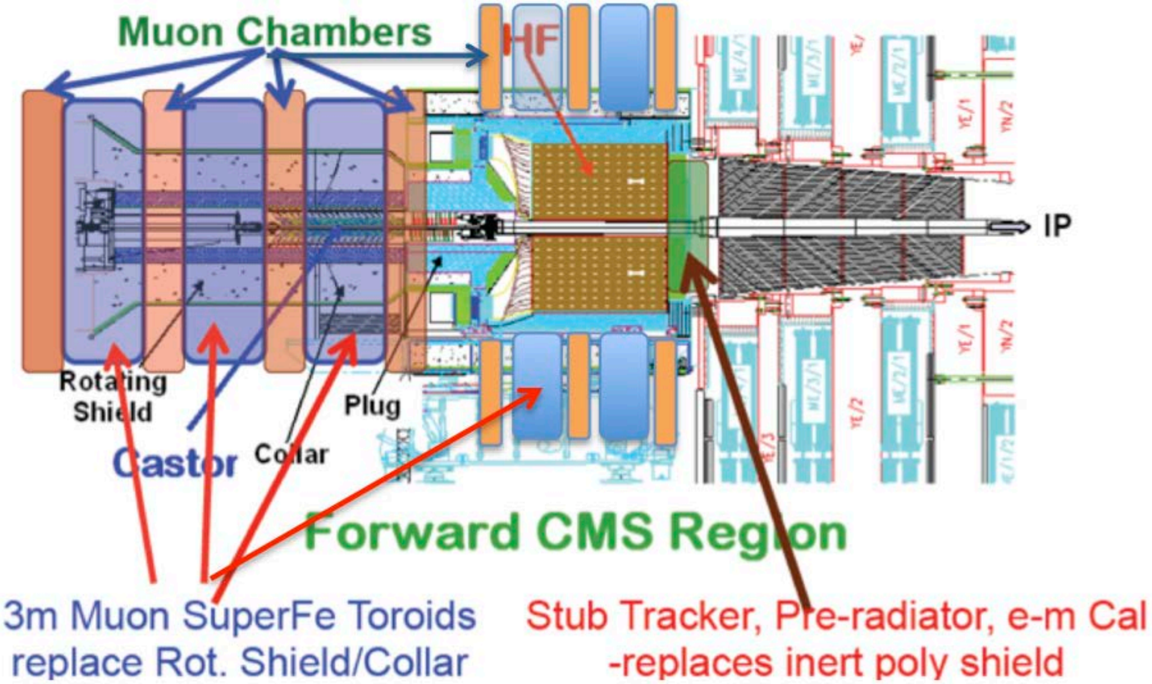
- Jet ID from W, Z, t, b, τ, H decays – in the presence of pileup –
  - -> Larger radii from IP
  - -> Transverse segmentation >3-4 times smaller than jet cone (PF)

- e-m Energy Resolution for $H \to \gamma\gamma$ (ex:triple Higgs coupling) – matching or exceeding present LHC detectors->Cerenkov Compensation

- Jet $\sigma_E/E \sim 15\%/\sqrt{E} + 1\%$ -> to reliably reconstruct/separate W,Z's by jetjet

- $\eta \geq 2.5$ Muons: Integrated muon/calo system – toroids or dipoles– with the calorimetry; use dE/dx multiple sampling to confirm muon ID and TRD for $|\mathbf{p}|$

Muon/Calorimeter



3m Muon SuperFe Toroids replace Rot. Shield/Collar

Stub Tracker, Pre-radiator, e-m Cal -replaces inert poly shield

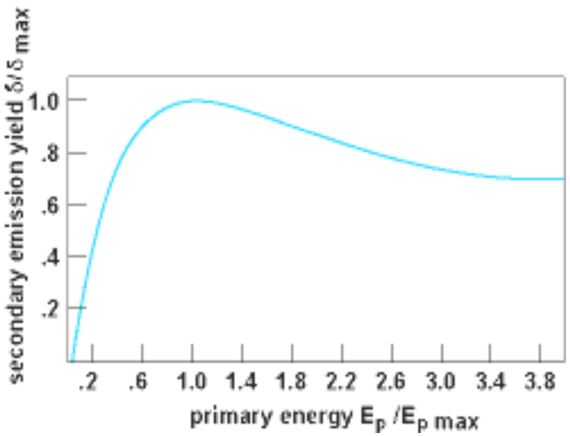
Forward muon toroid and calorimeter – muon system consisting of 0.5-1 Lint superferric HTC tape muon toroids interspersed with:
pixel detectors, dE/dx calorimeter pads and TRD (straw tubes).
Z: $6 \leq \eta \leq 4.5$ compartment ~ 20m. Thickness (½ iron ½ detectors/coils) ~16m
Extreme: toroid 20m in depth, Al absorbers inside

High Raddam Calorimetry

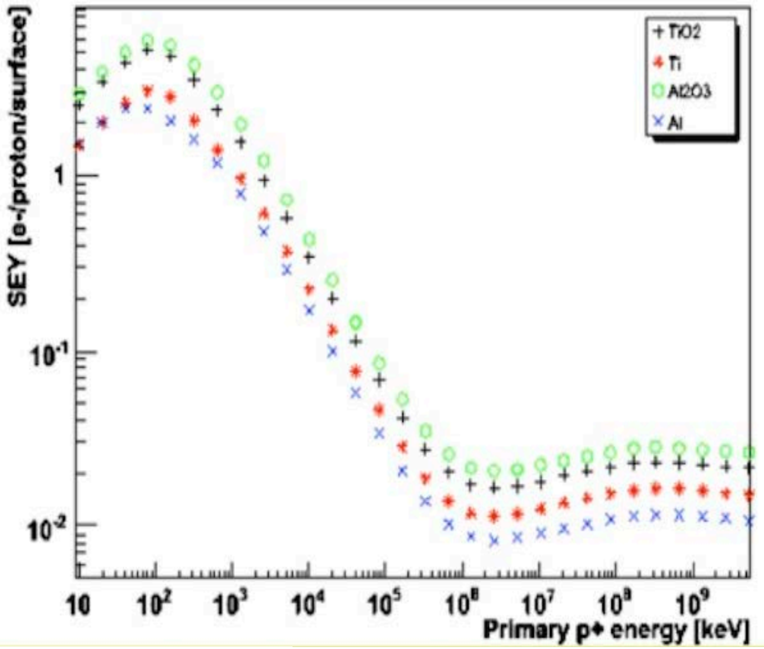
- Secondary Emission
- Exceptionally radiation resistant solid scintillators and Cerenkov Glasses
- Noble Liquid Scintillation
- Replaceable organic Liquid Scintillators
- High Bandgap Semiconductors:
  - Ga_xAs_{1-x}, InGaP, Diamond, Graphene, …..
- Integration with muon system at highest η
- Enable: *Tile "Cerenkov" Compensation/Particle Flow*

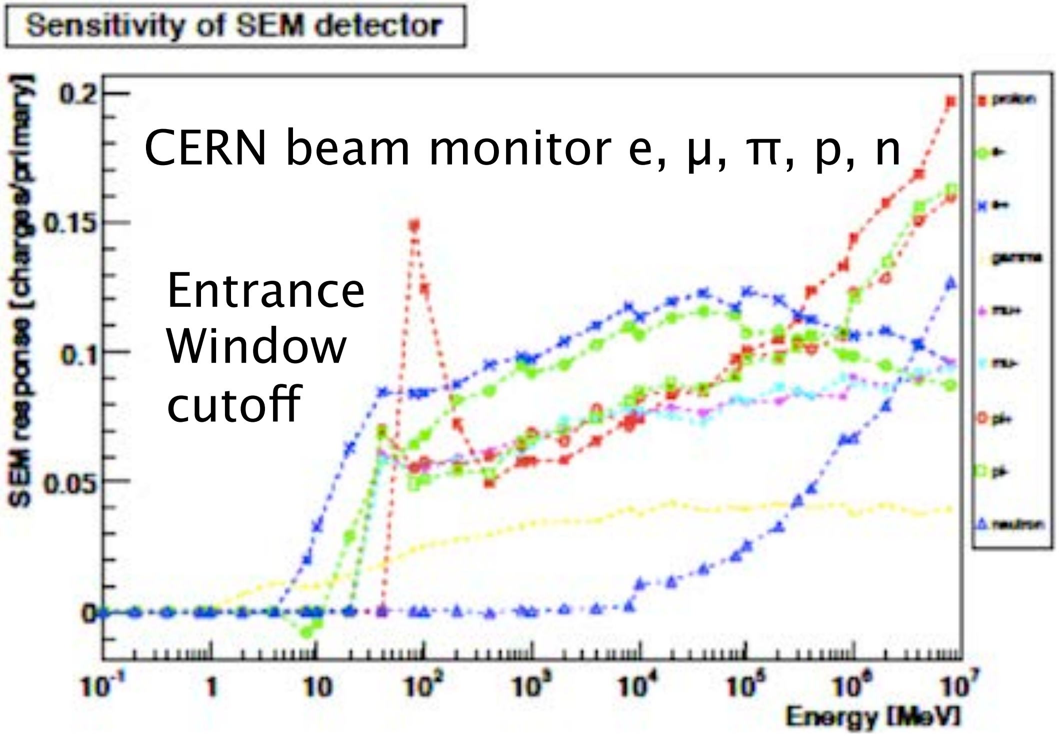
Secondary Emission

- 0.1–10 ps timescales
- Metal oxides: Al_2O_3, TiO_2, MgO, BeO…
- Exceptional radiation resistance
  - 10^{21} mip/cm^2 CERN beam monitors
  - Many GRad electron bombardment in high current PMT
- SE yield vs incident particle energy follows dE/dx. Max yields C[100] or GaP~ 100 @2kV (3 stages ~ 10^6)



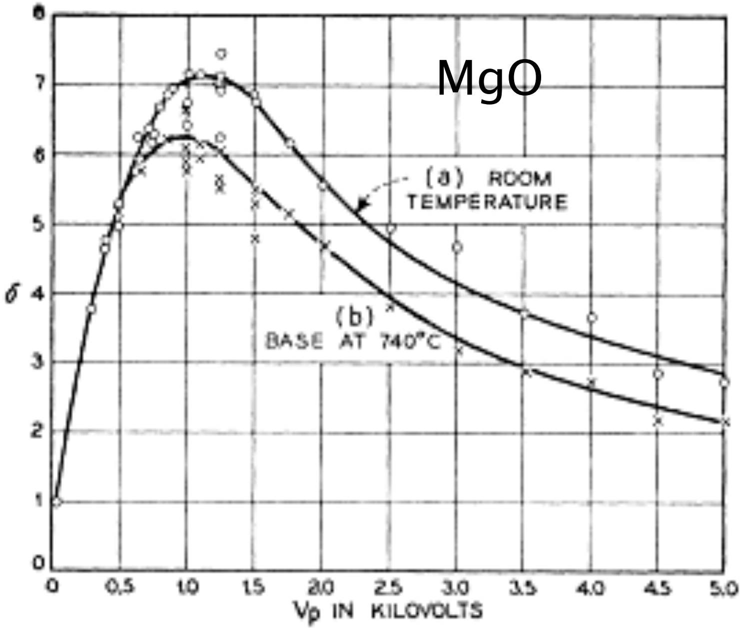
SE Yield/Semi-empirical Sternglass formula: the universal curve of SE emission: SE yield normalized to maximum yield vs particle energy normalized to the energy of max yield.





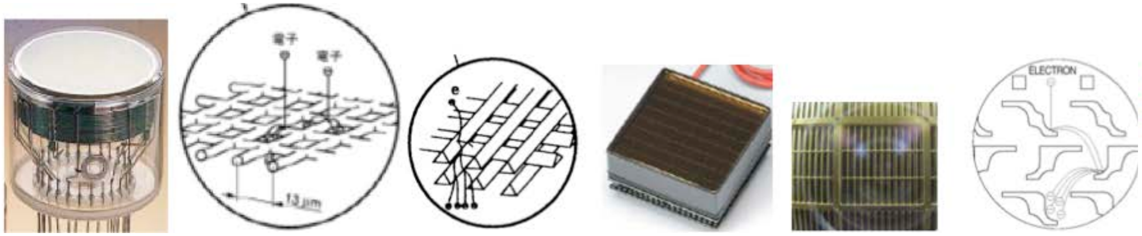
CERN beam monitor e, μ, π, p, n

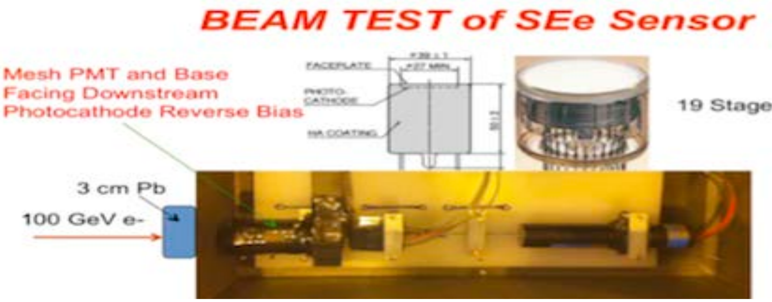
Entrance
Window
cutoff



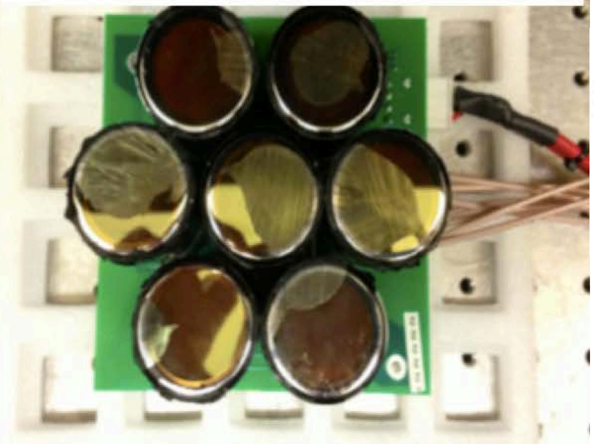
MgO

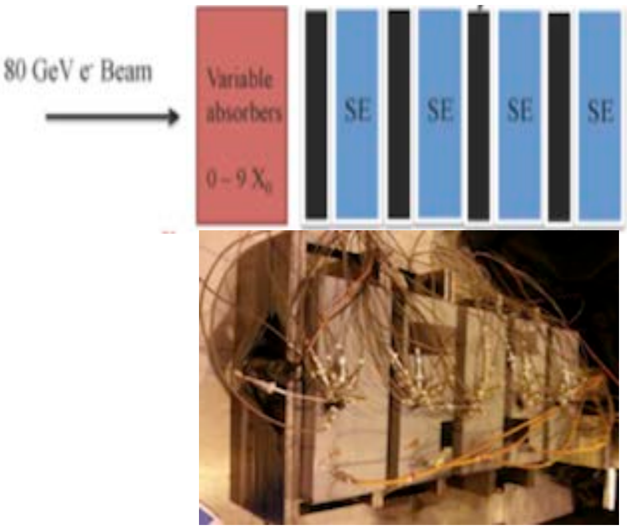
Mesh Dynode PMT's for Test

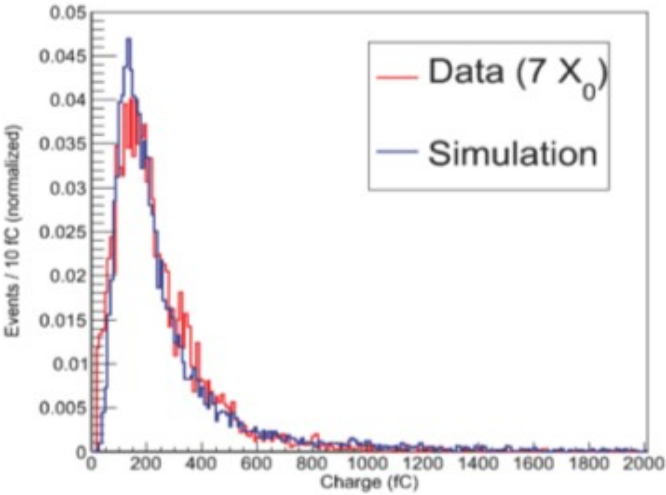




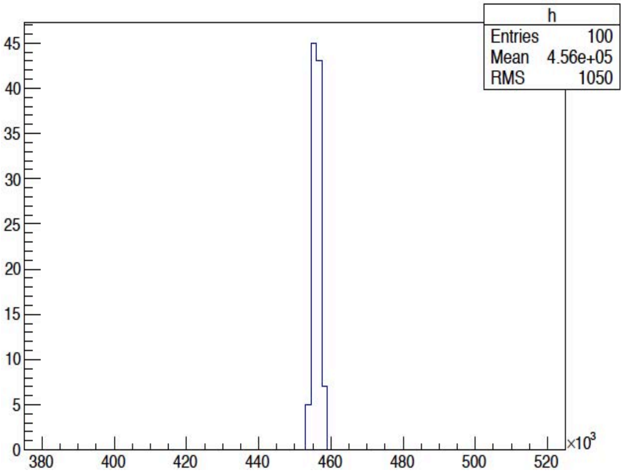
Secondary Emission Module

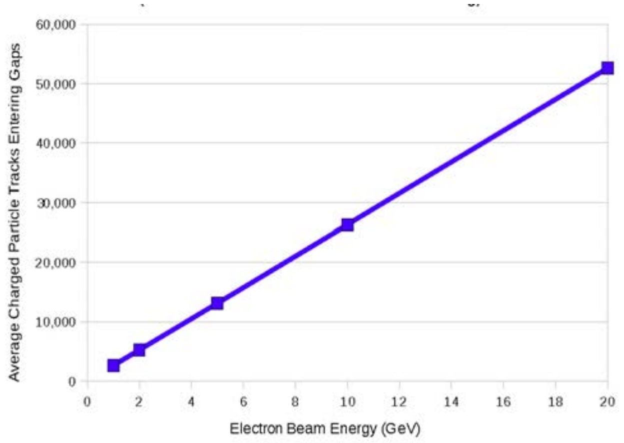






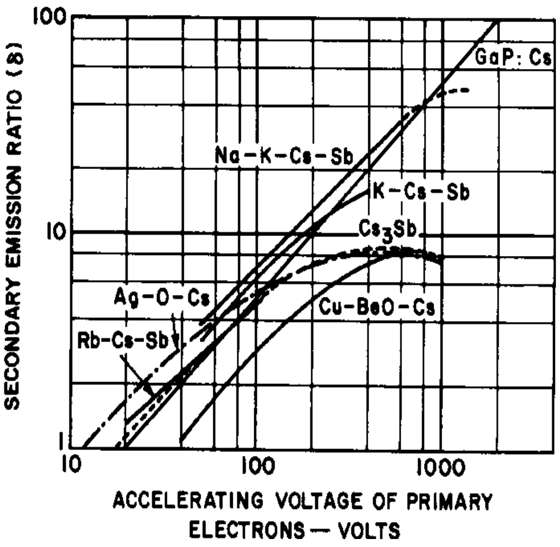
SE Calorimetry Projections



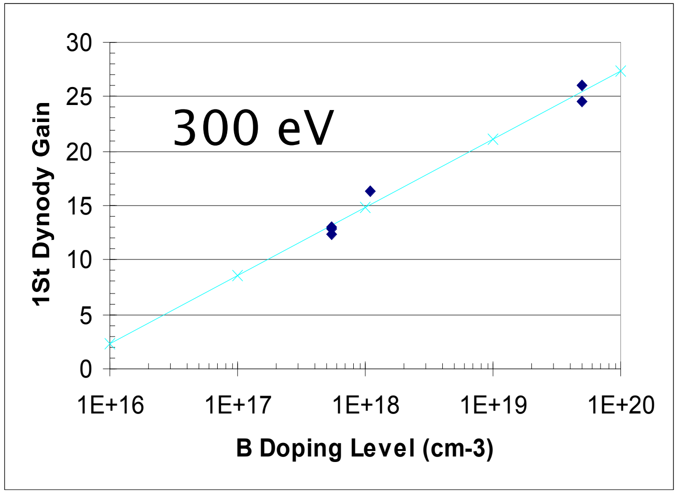


MC: monotonous(quasi-homogeneous/*no absorber*) 10 μm W mesh, 30% open; 10μm spacing. (Xo~1mm); SE yield max 3 @ 100V. 100 events, 100 GeV electrons; Histogram of collected charge in SEe (10^5 electrons); Excellent Linearity 1-20 GeV. ***RMS/E at 100 GeV = 0.0022***

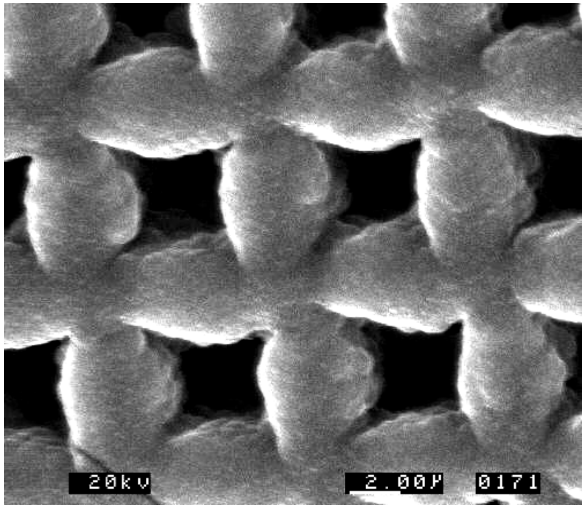
-> Stochastic $\sigma_E/E \lesssim 2.2\%/\sqrt{E}$



High Yield SE materials



B-doped diamond film on Si



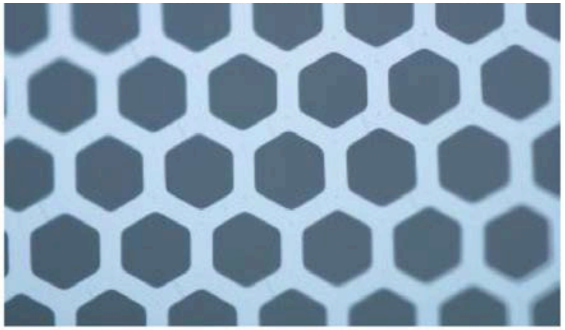
SE Calorimetry Issues

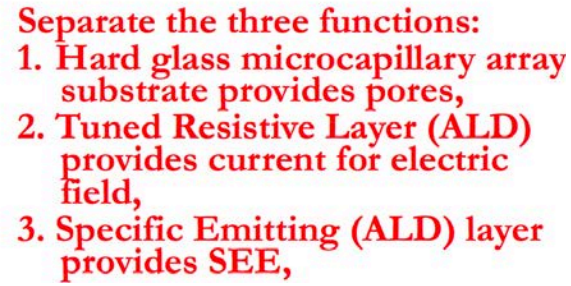
Fast Timing: A Rule of Thumb: ≥10% of risetime
RT compact mesh ~ 0.1ns -> 10-20 ps
RT MCP with 60:1 L/d ~50 ps -> 5-10 ps

MCP Breakthrus: Rad-hard and long life: ALD binary thin metal controlled resistance film followed by metal oxide ALD – on rad-hard substrate like quartz. Very low change of gain vs total charge drawn/area. Caution about thermal effects – the wall is like a resistor chain – and rate effects.

B-field Operation:
Best Measured Gain Mesh: 10% of Max at 45° at 2T.
MCP: – 2.5-3 T

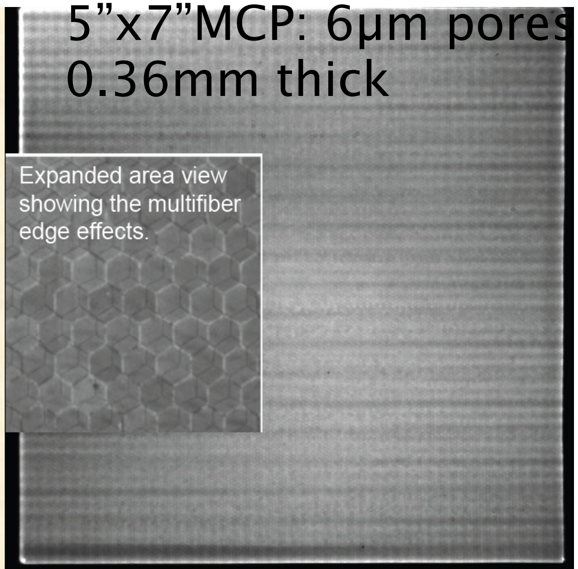
Construction Issues (Compare to PMT):
- operable vacuum: 1000x worse than PMT ok
- Assy T: ~1000°C vs PMT<300°C (photocathode)
  i.e. brazing, metal ceramic forming, etc ok.
- Assembly: Assembly in air – PMT req. full vac.
- no glass-metal seals for window required.
- Transverse granularity: ~mm ok (η~6!)
- Using ~1/3 mm thick MCP and diamond web
  compact high gain SE calorimeter sensors….





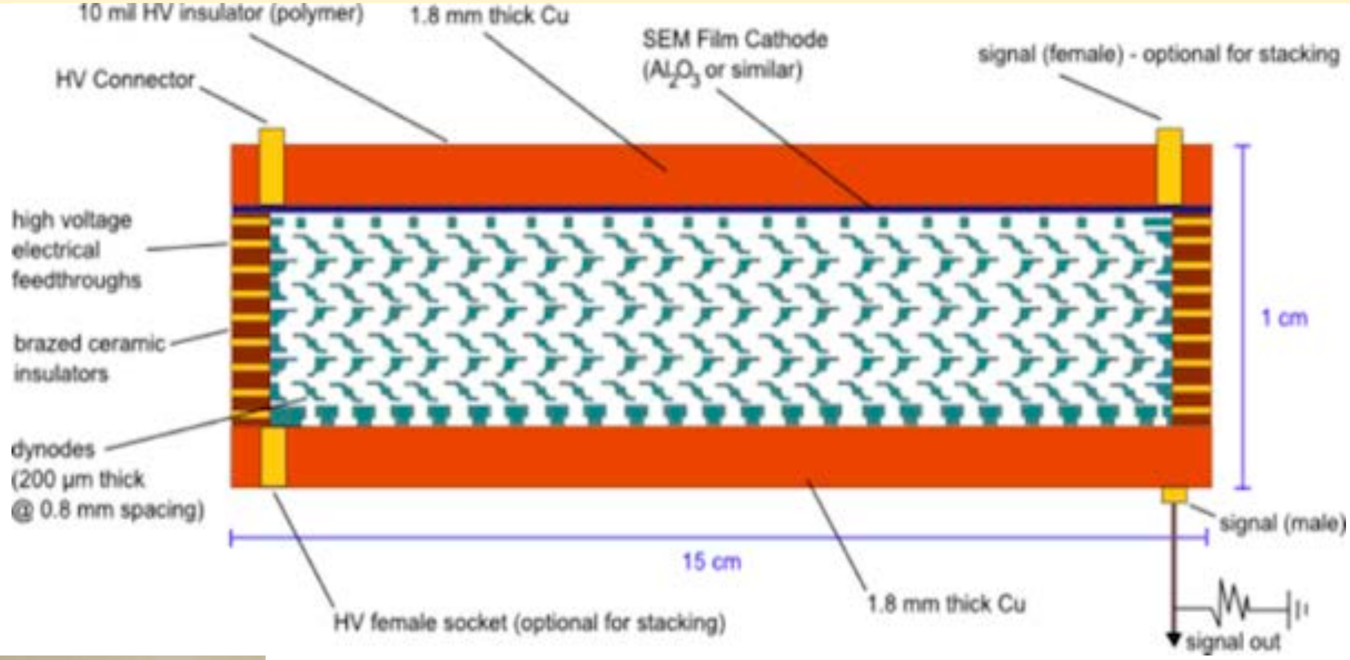
Separate the three functions:
1. Hard glass microcapillary array substrate provides pores,
2. Tuned Resistive Layer (ALD) provides current for electric field,
3. Specific Emitting (ALD) layer provides SEE,

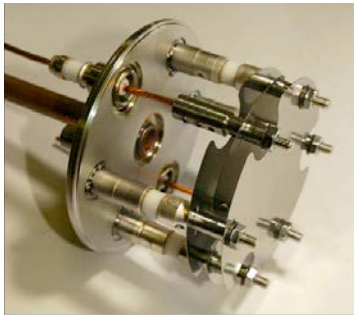
5"x7"MCP: 6μm pores, 0.36mm thick



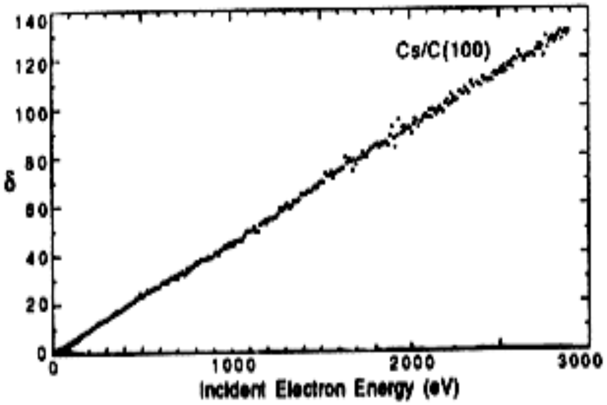
Expanded area view showing the multifiber edge effects.

Simple SE Calorimeter Module Point Design

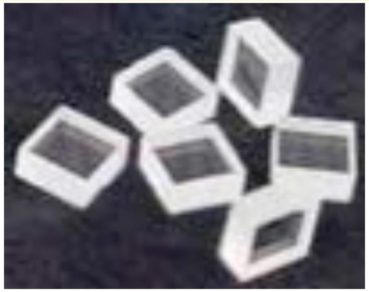


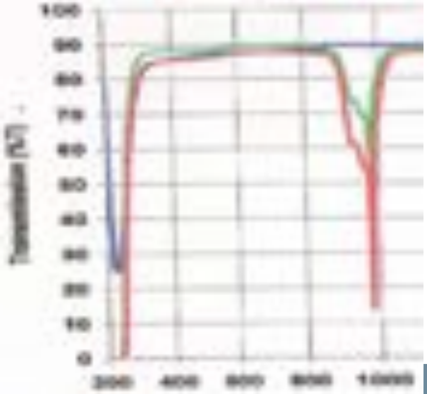


CERN
Beam
Monitor
Native Oxide
Goes to air



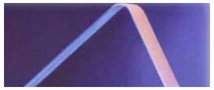
Optical Materials – radhard/fast





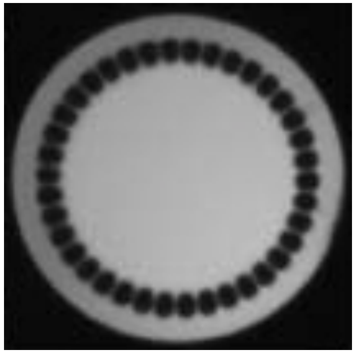
- **Fluorophosphate glasses**: Samples & fiber (buffer scraped off for clarity) post 1.2 GRad γ + $8x10^{20}$ n/cm^2 Irradiation. **Trans** per cm, 200–1000 nm, before/after irrad. Glass compositions: Ba-,Bi-, Ge-fluorophosphates: alkali-free, w/ transition metals, rare earths up to 20 wt% (wide glass-former domain). ρ~4.2–4.5 g/cc. Radiation resistance: large r molecule; fluorine electronegativity. **Ce-doped Scintillator:** Fast fluorescent glass.

- **Silica Aerogels: $n \geq 1.1$; TeflonAF $n=1.3$ –Cerenkov compensation!**

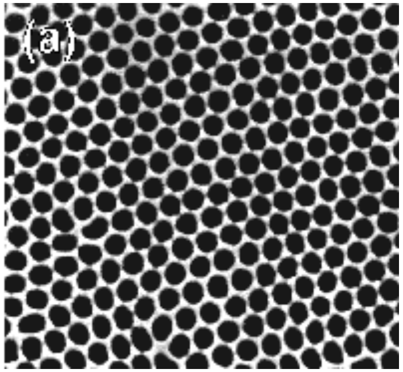


- ***Sodium-Lithium- polyTungstates***, (metaTungstates): 3(Na/Li)2WO$_4$9WO$_3$•H$_2$O [Na$_6$/Li$_6$[H$_2$W$_{12}$O$_{40}$] form clear, stable, non-toxic aqueous or *alcohol* solns, $\rho \leq 3.1$ (mineral sep. –50lb bags). Li forms slightly denser, clearer fluid. Calculated $\rho=3$: Xo~0.9 cm; R_M~2cm. A quartz cell ~2.2x2.2x25cm: fast Cerenkov E-M tower. Meta-Tungstates in~40% ETOH/60% benzyl Alc/5g/l PPO/0.2g/l POPOP->yield~20% toluene LS->replaceable "xtal"scintillator

Rad-Hard High NA Fibers



MEMS “air clad”
40 μm core, glass

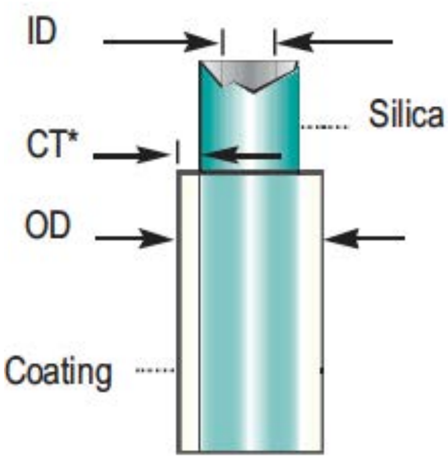


Nanoporous Alumina film
~40nm pores ~6μm deep
65%-70% air. N~1.1
NA ~ 0.9 -> 3x-4x light
Alumina -> accelerator
magnet insulators.

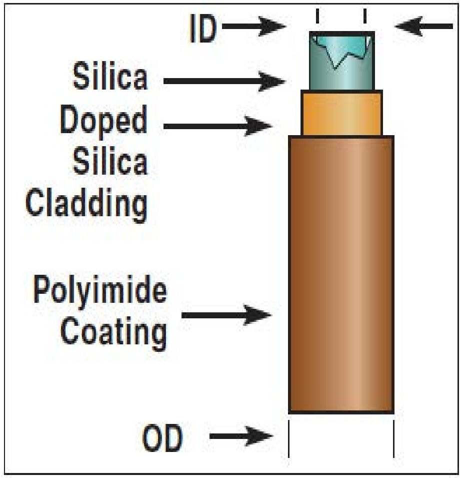
Cladding on analog transmission fibers; rad-hard scintillator/WLS fibers:

Rad-Hard Scintillating and WLS Fibers:

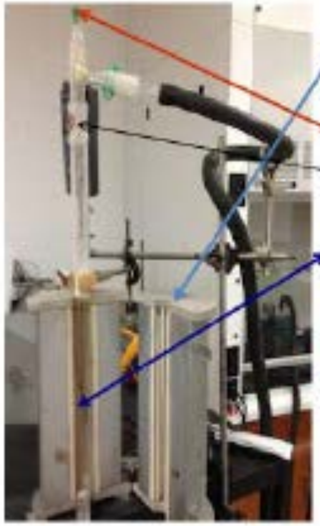
- Basic Idea: Use existing-technology flexible quartz capillaries, cladded with fluorided quartz and clear buffer
- Fill capillary with pure rad-resistant WLS/Scintillator materials, as molten, flow thru CVD, sol-gels, or ALD. Harden to inner film on wall, or full core.
  - Molten at temperature with capillary imbibition
  - Solvent-Conveyed + vacuum/thermal dried



Largest Q-Capillary *w/ UV-clear buffer:*
100μm core, 360μm OD
HE plastic WLS fiber
Core~500μm



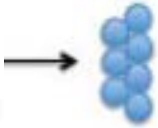
Adapt Anthracene Core Quartz Capillary Scintillating Fiber Molten Imbibition Techniques to WLS Materials In Q-Capillaries with Clear Buffer

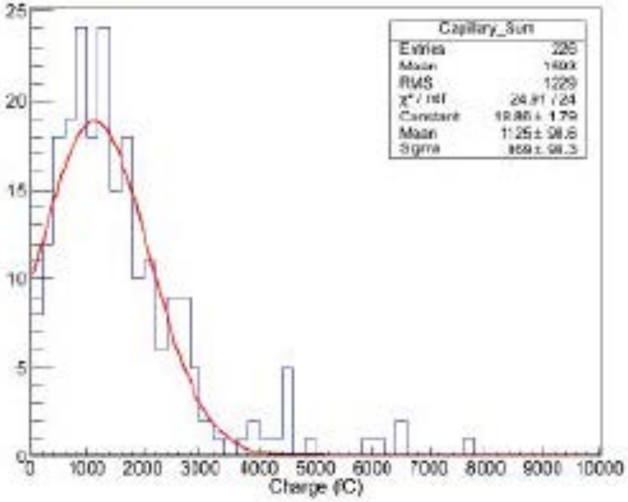


- 30cm tube furnace for 25cm Capillary fibers
- Vacuum thermometer
- Pyrex vacuum burette
- Fibers placed vertically In 5 mm dia pyrex melt tube

- At ~240° C, μ<0; *Liquid Anthracene fountains from tops of fibers!*

Nested pyrex tube double boiler – Molten anthracene shown



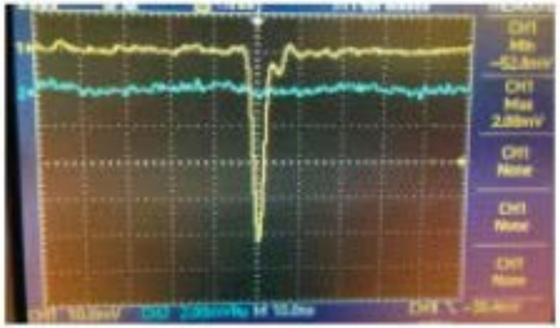


25 cm Anthracene Core Quartz Capillary Fibers

NA = 0.43
Core Diameters: 250-750 μm

Expected Anthracene Fiber Pulse:
~200 KeV/mm x 0.25mm x 40 photons/KeV x 2% transmission x 20% QE ~ 8 p.e.

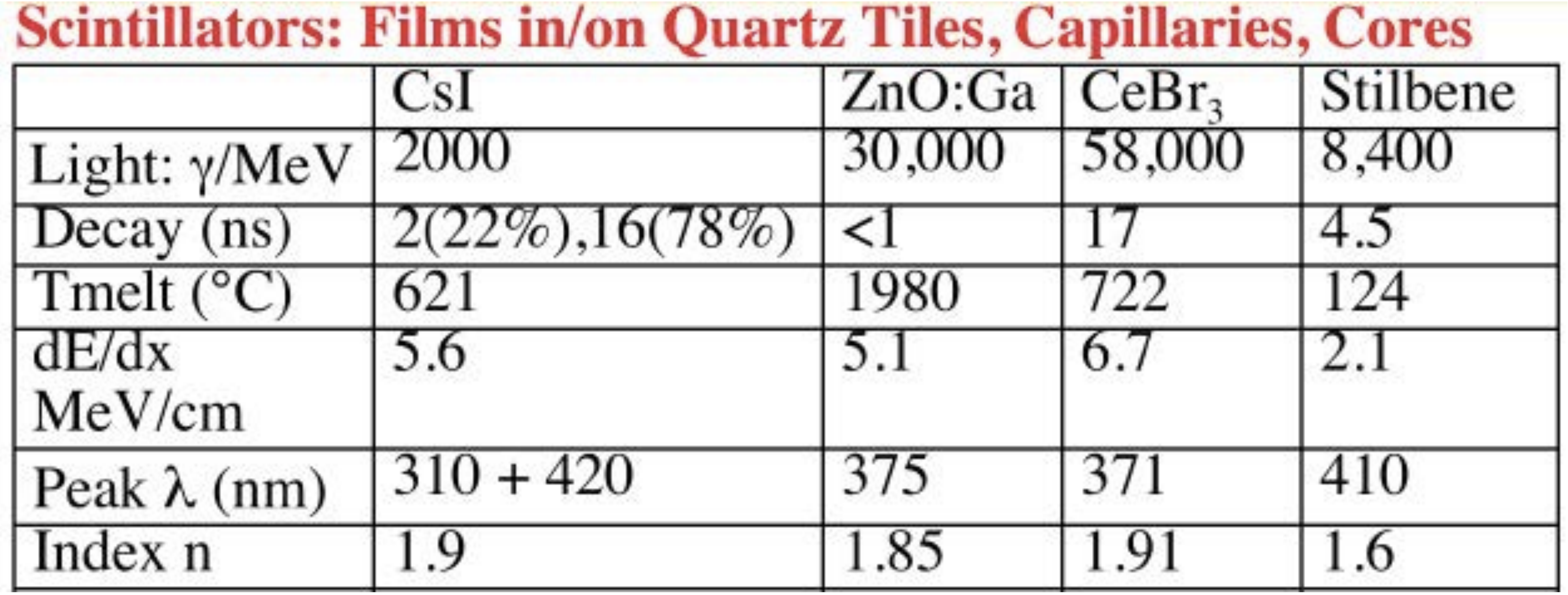
Typical Observed Pulse:
~ 8-9 p.e.



Typical pulse in 80GeV e⁻ beam

Add: • Solvent-Conveyed WLS (Toluene et al. + vacuum dry)

Fast Rad-Hard Scintillators

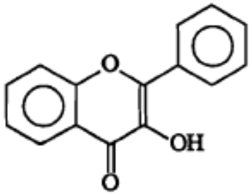


Scintillators: Films in/on Quartz Tiles, Capillaries, Cores

	CsI	ZnO:Ga	$CeBr_3$	Stilbene
Light: γ/MeV	2000	30,000	58,000	8,400
Decay (ns)	2(22%),16(78%)	<1	17	4.5
Tmelt (°C)	621	1980	722	124
dE/dx MeV/cm	5.6	5.1	6.7	2.1
Peak λ (nm)	310 + 420	375	371	410
Index n	1.9	1.85	1.91	1.6

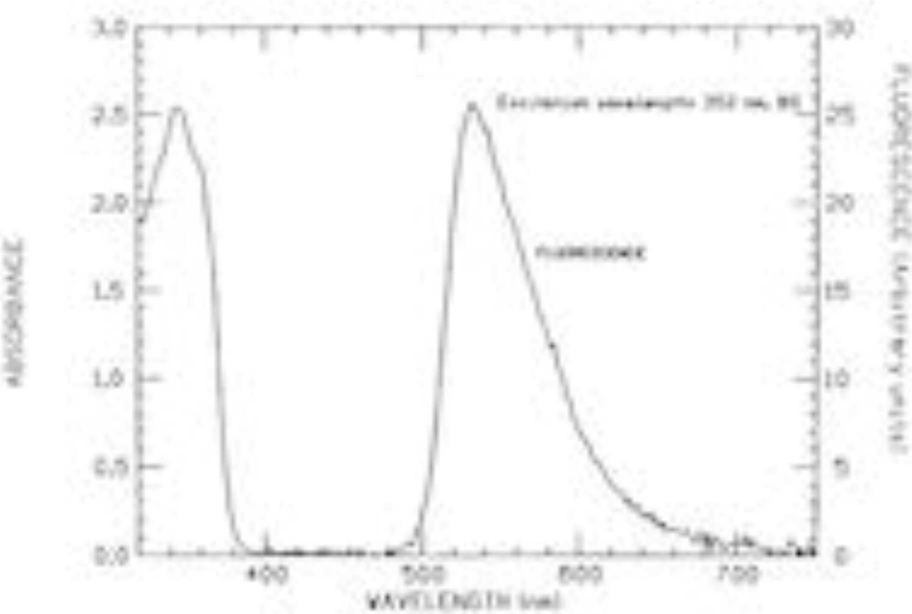
Near UV/Blue->Green WLS Materials

Fairfield
UNIVERSITY

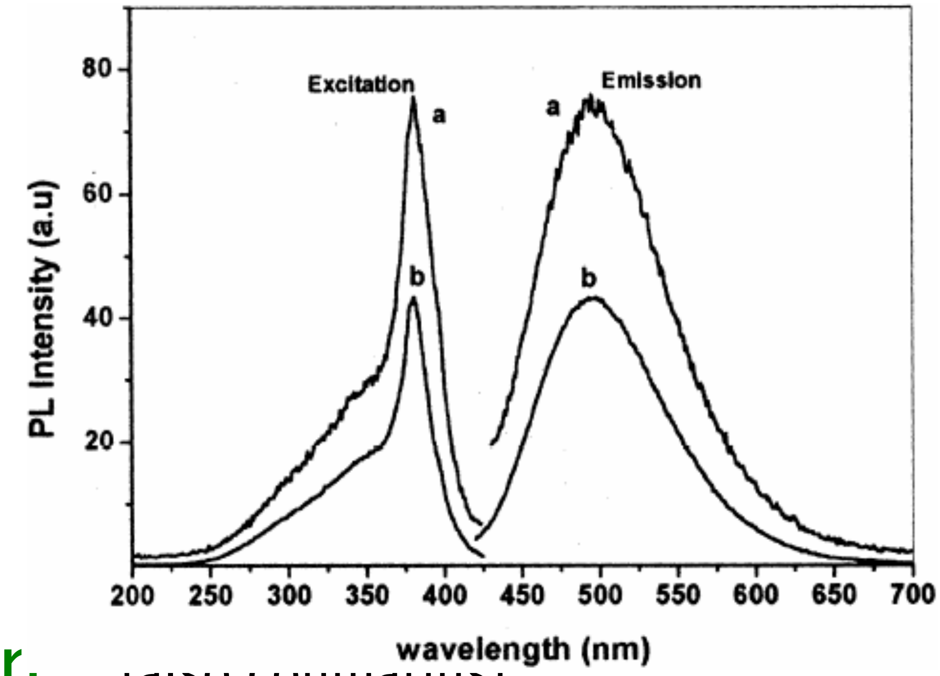


- **3HF** – T_{melt}~170°C, n=1.68, <10ns
- ***Large Stokes Shift(~180nm) – low self absorption***
- ***Rad Resistant (100 MRad)*** [A.Bross & A.Pla-Dalmau, Radiation effects in intrinsic 3HF scintillator NIM A, v.327, 337 (1993)]
- ***Matches pTP:Anth, PET, ZnO:Ga, or plastic scint 1 UV->near UV fluor***

3HF



ZnO:Zn

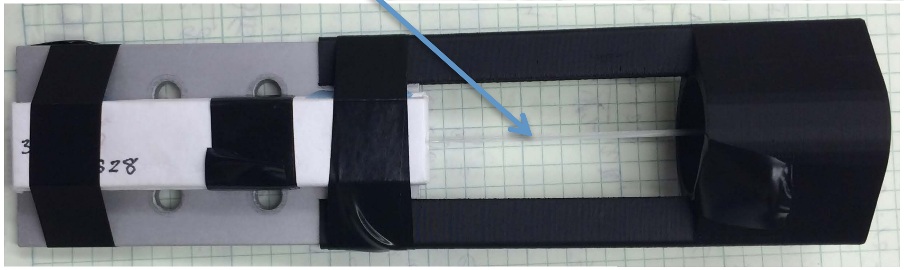


- ***ZnO:Zn*** blue -> green…. (also coumarins)

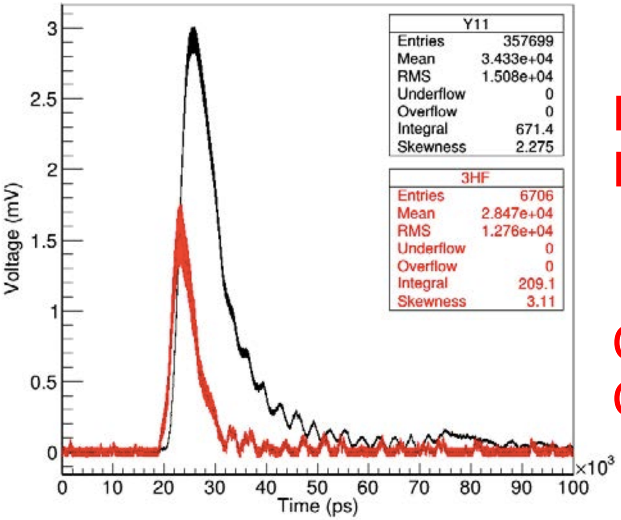
Fairfield
UNIVERSITY

HE Scintillator Grooved Finger ~1"x5"

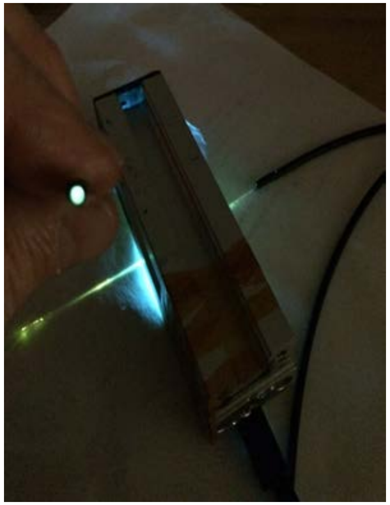
WLS "fibers"



PMT insert



MIPs after 2m clear coupling:
Ratios: Integral3HF ~ 31% Y11
Means: 3HF ~ 50% Y11
MPVs: 3HF ~ 50% Y11
Core Area of 2 3HF fibers/Y11 = 25%
Core Volume 3HF/Y11 = 4%



An Amusing Physics Process at pp 100 TeV
Can we do it?

Fairfield UNIVERSITY

- $\tau \to \mu\gamma$, $e\gamma$, $\mu\mu\mu$ present limits < few x 10^{-8} .
- At FCC, scaling from CMS, expect ~10^{11-12} identified τ from $Z \to \tau\tau$ or $W \to \tau\mu$.
- Some expect the lepton flavor BR to scale as m^2 or more, compared to $\mu \to e\gamma$
- Can we set a better limit? Would it be competitive in informing as observing $\mu \to e\gamma$ or μ-e conversion?