DIAGNOSTIC METHODS IN HADROTHERAPY

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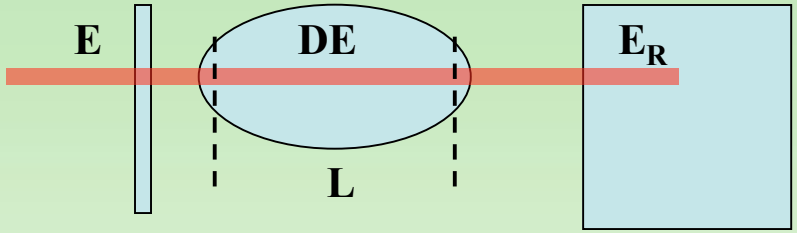
PART 2
PROTON RANGE RADIOGRAPHY

PRINCIPLES

For beam energies above total absorption in the target, a correlated measurement of track position and residual energy allows to reconstruct the integrated density image:



$$\Delta E = \int_0^L \left(\frac{dE}{dl}\right)_l dl = \int_0^L \rho(l)\, S(l,E_l)\, dl$$

RANGE RESOLUTION: $\frac{\sigma_R}{R} = \sqrt{\left(\frac{\sigma_S}{R}\right)^2 + \left(\frac{\sigma_P}{R}\right)^2 + \left(\frac{\sigma_C}{R}\right)^2}$ $\Rightarrow$ $\frac{\sigma_R}{R} \approx 1.5\%$

straggling ~1.3% beam momentum ~0.4% residual range ~0.6%

DENSITY RESOLUTION: $\frac{\sigma_\rho}{\rho} = \frac{\sigma_R}{L\sqrt{N}}$ L: target length , N: counts/pixel

Target cross section of 20x20 cm^2, 2x2 mm^2 pixels -----> 10^4 pixels

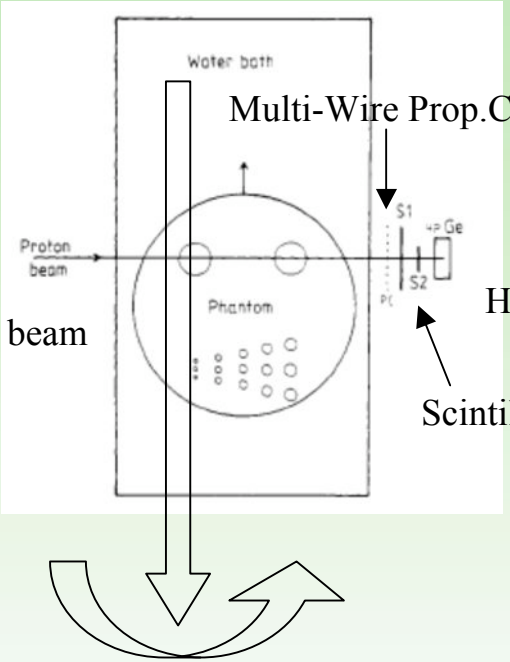
N=100 tracks/pixel (10^6 tracks)

$\Rightarrow$ $\frac{\sigma_\rho}{\rho} \approx 0.3\ \%$

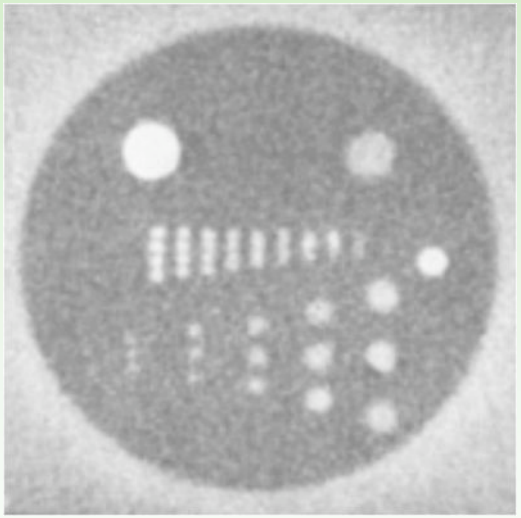
K.M. Hanson et al, Phys. Med. Biol. 26 (1981) 965

EARLY PRR MEASUREMENTS (1981 AT LAMPF)

BEAM SCAN (MOVING TARGET):



Density resolution $\frac{\sigma_\rho}{\rho} \approx 1.8\%$



K.M. Hanson et al, Phys. Med. Biol. 26 (1981) 965

PRR PROTOTYPE AT PAUL SHERRER INSTITUTE (PSI) ~ 1999

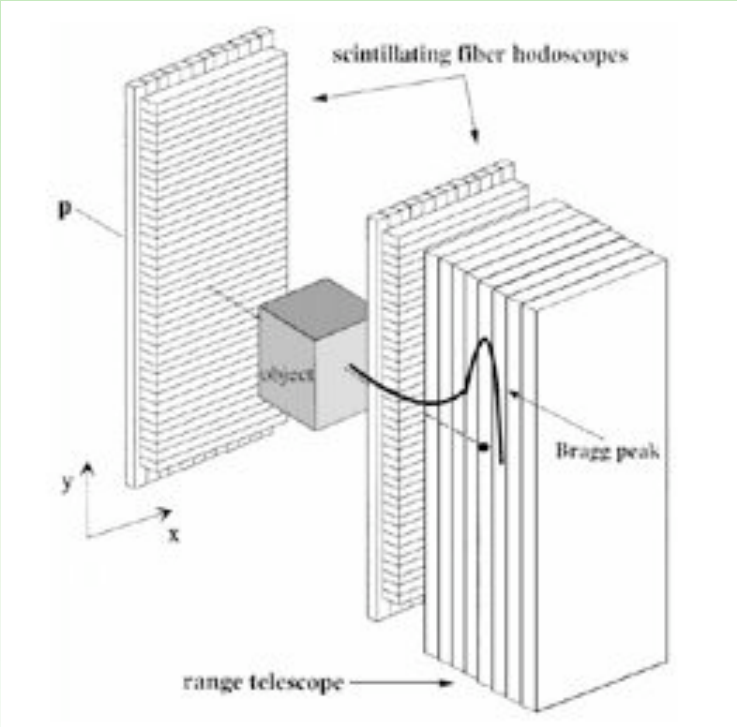
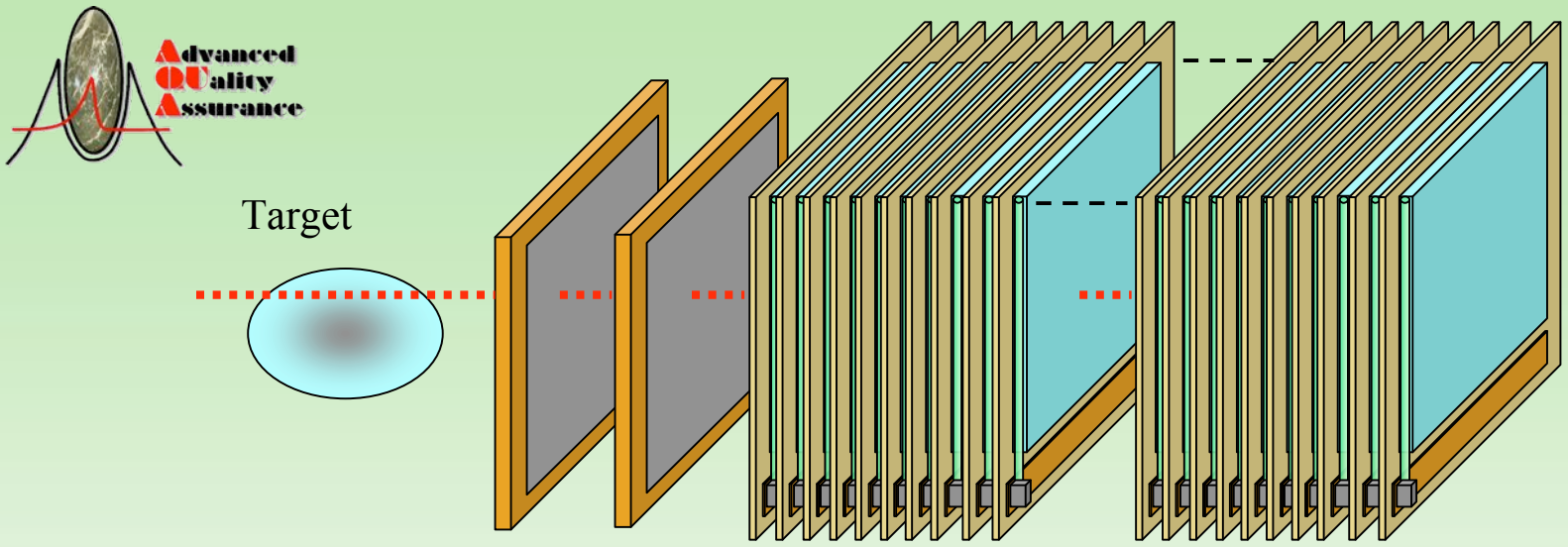


Image of 10 mm deep letters cut-out in
A 20 mm plexiglas plate:

P. Pemler et al, Nucl. Instr. and Meth. A432(1999)483

AQUA PRR SETUP (2008)



GEM1 GEM2

Scintillators stack

Tracker

Gas Electron Multiplier (GEM) detectors
2-D Strip Readout

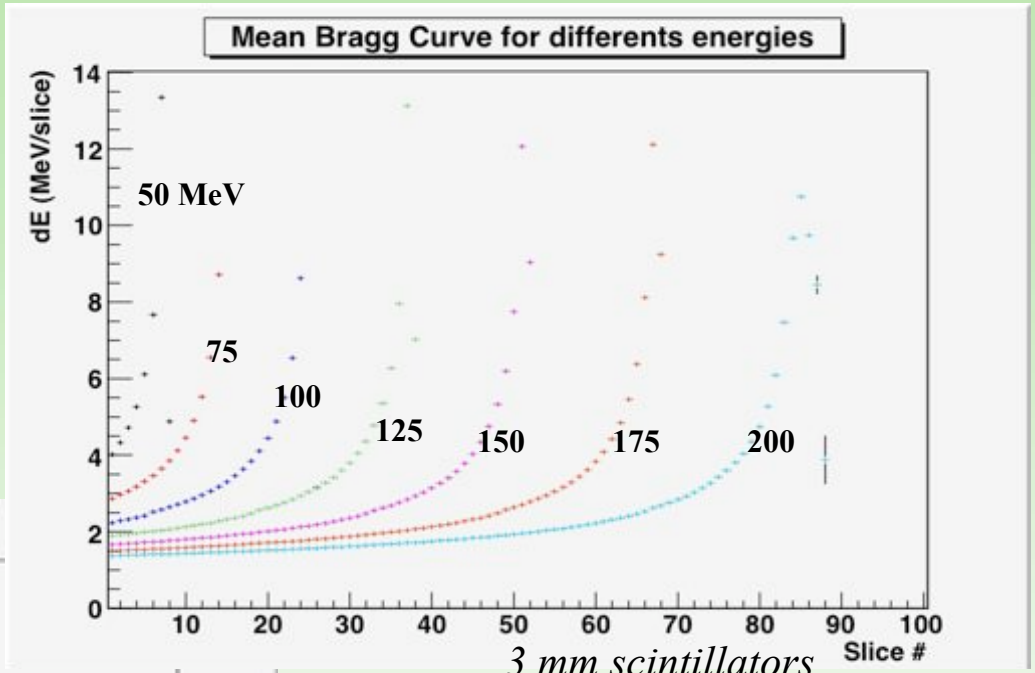
Light, 2-dimensional readout
High rate (> 1 MHz)
Radiation resistant
Large areas at low cost

Range/Energy loss

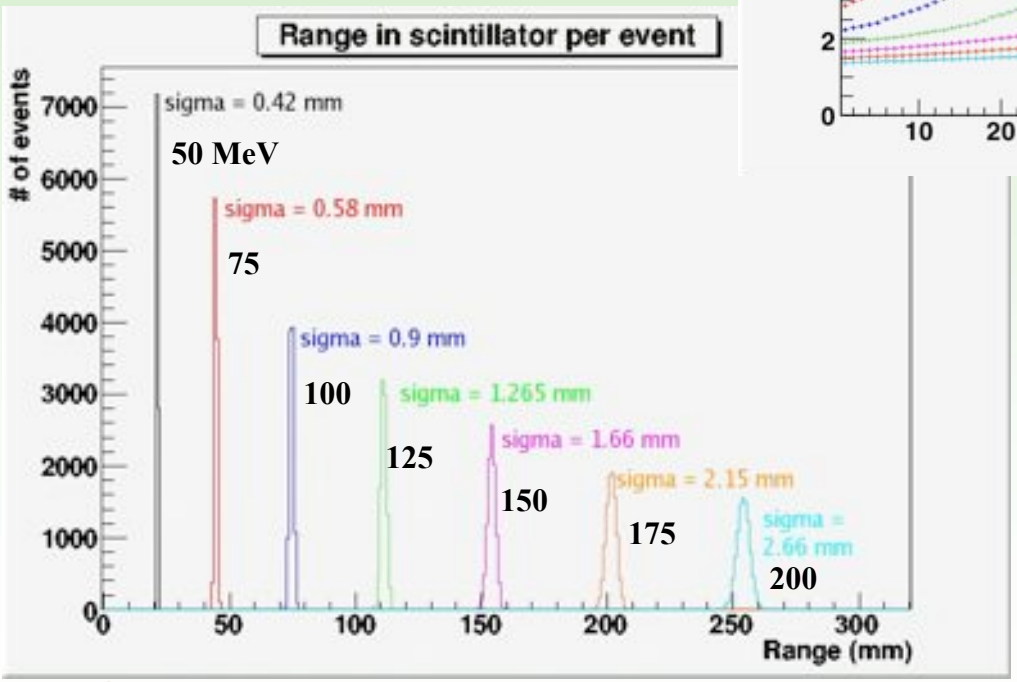
Plastic scintillator Stack
Silicon Photomultipliers Readout

Measurement of range and energy loss
High intrinsic rate capability (>1 MHz)
Density ~1 (almost tissue equivalent)
Low cost, easily scalable to larger sizes

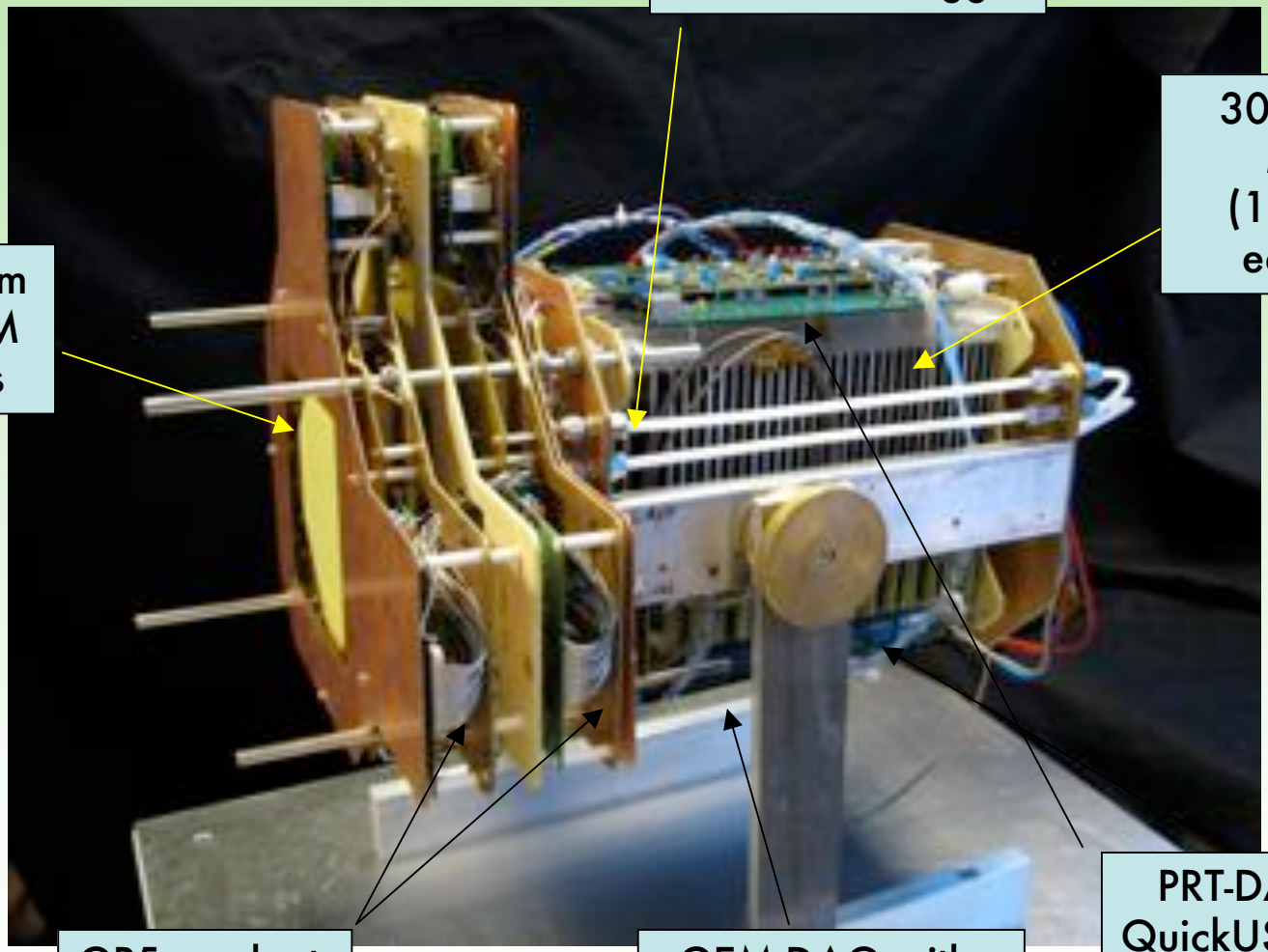
PROTON RANGE AND RANGE STRAGGLING IN SCINTILLATORS (BRAGG PEAK)



3 mm scintillators



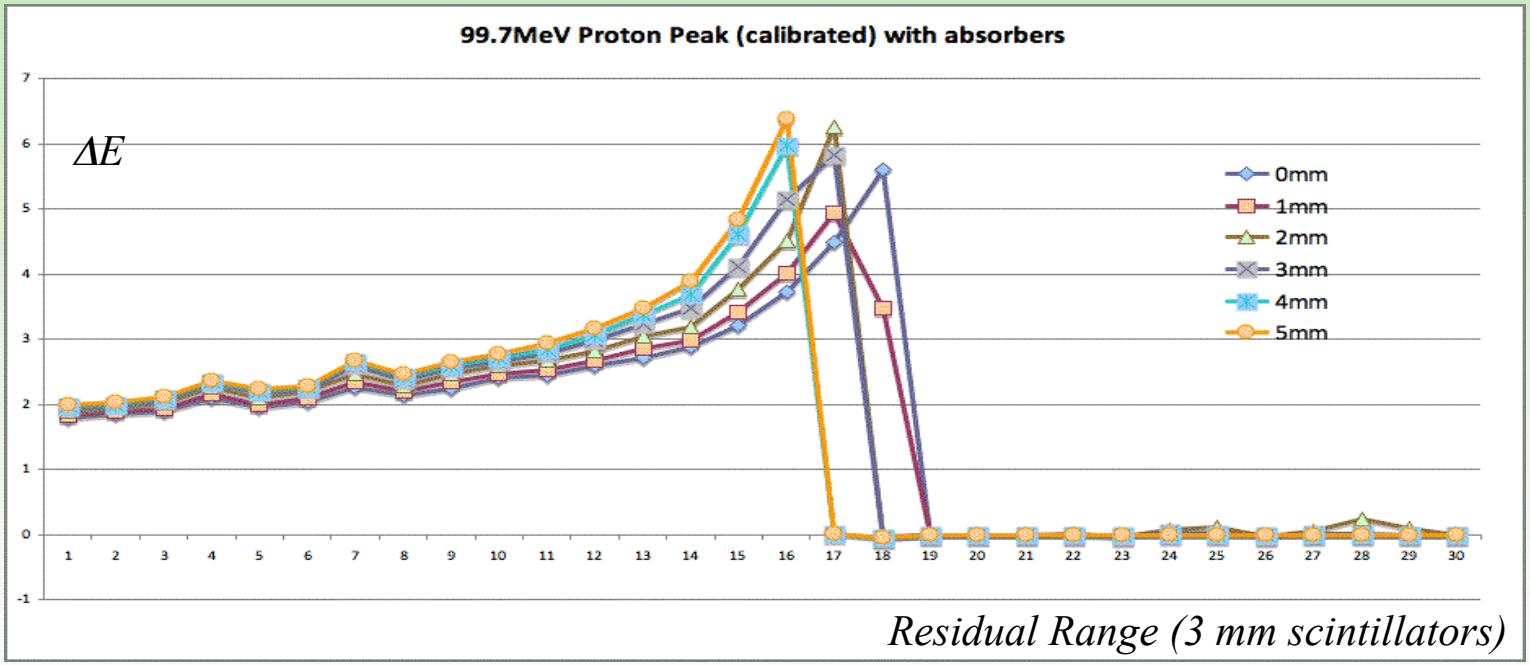
J. Samarati (GEANT4)


2 scintillator modules for trigger
30 scintillator Modules (10cm water equivalent)
2 10x10cm triple-GEM detectors
GP5 readout electronics
GEM-DAQ with QuickUSB readout
PRT-DAQ with QuickUSB readout

EXPERIMENTAL RANGE RESOLUTION

99.7 MeV PROTON BEAM AT PSI

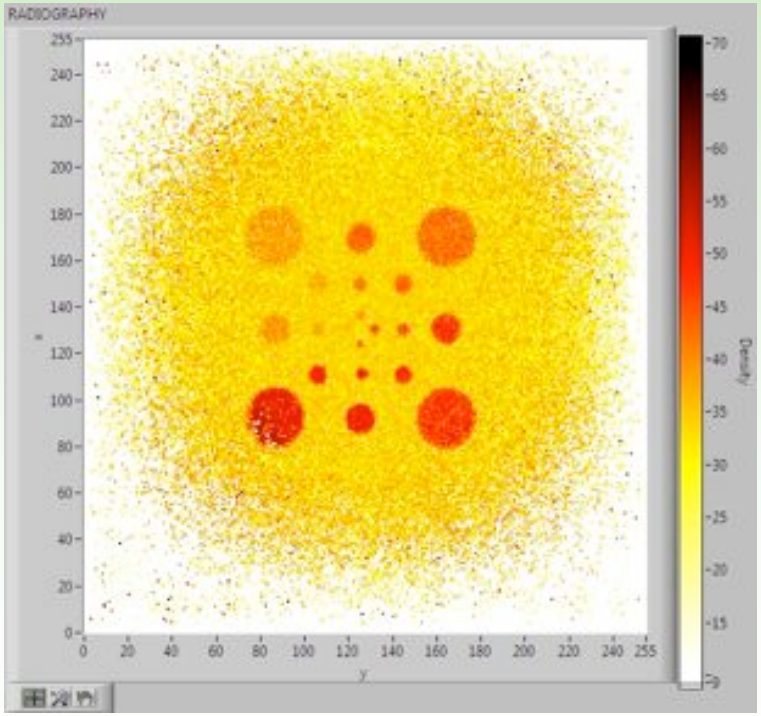
1 mm PLASTIC ABSORBERS ADDED TO MEASURE THE RANGE RESOLUTION



PRR TEST RUN AT PSI

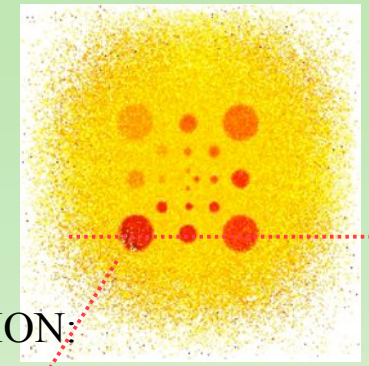
2 cm THICK PLASTIC PHANTOM
WITH HOLES FROM 1 TO 10 mm AND
4 DIFFERENT DEPTHS (0 to 20 mm)

PROTON RADIOGRAPHY AT 100 MeV:

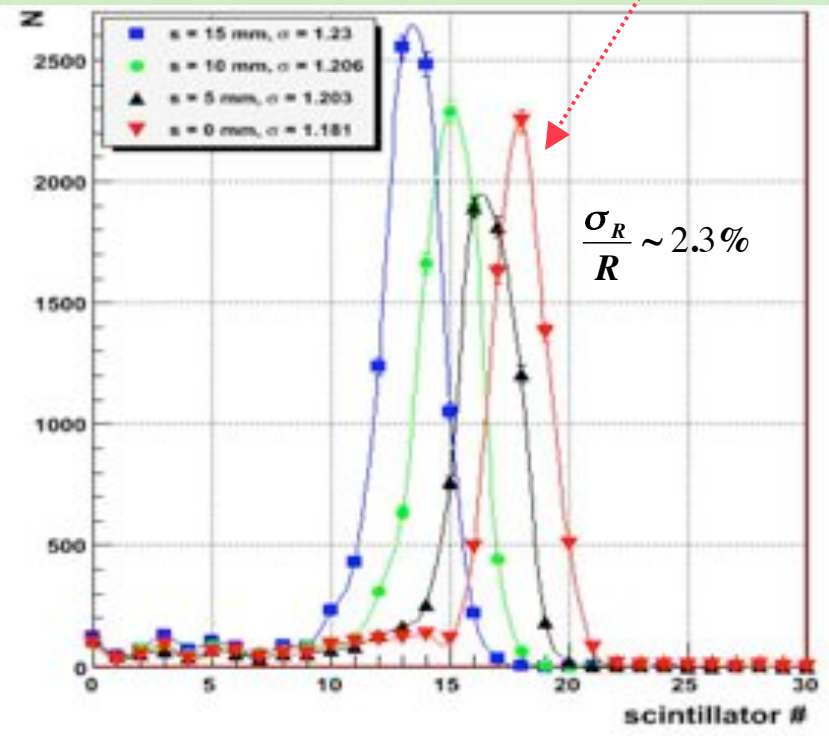


U. Amaldi et al,
Subm. Nucl. Instr. and Meth. A (Aug. 2010)

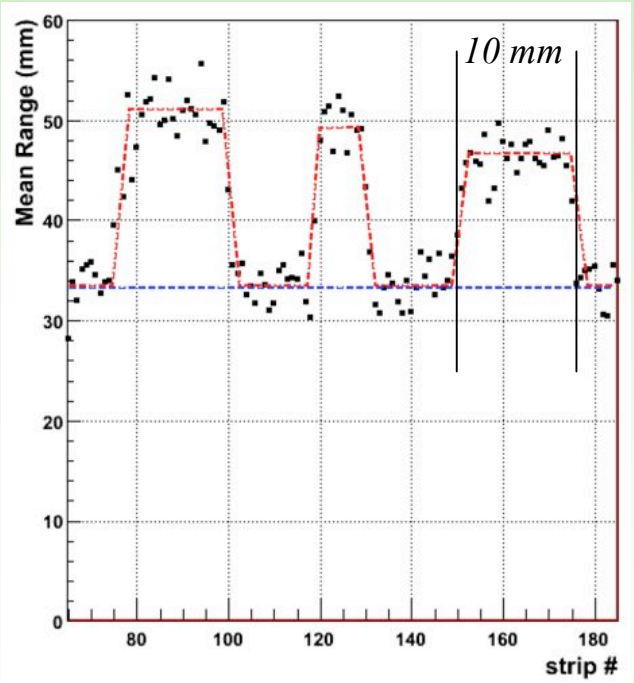
PRR RESOLUTION



RESIDUAL RANGE RESOLUTION:



SPACE (EDGE) RESOLUTION:

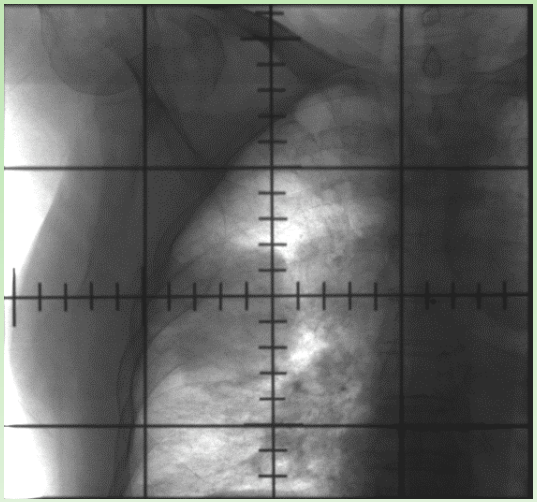


400 μm pitch

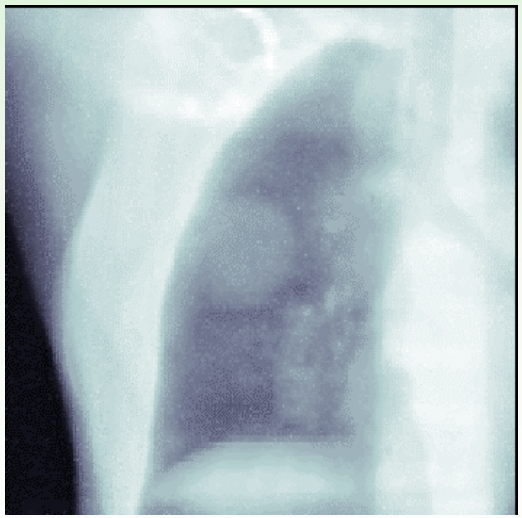
U. Amaldi et al, Subm. Nucl. Instr. and Meth. A (Aug. 2010)

PRR PERFORMANCE STUDIES

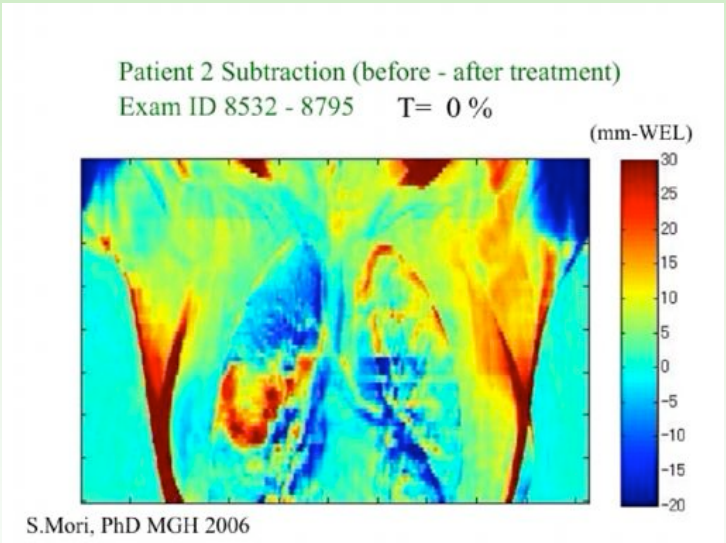
CT SCAN



SIMULATED PRR

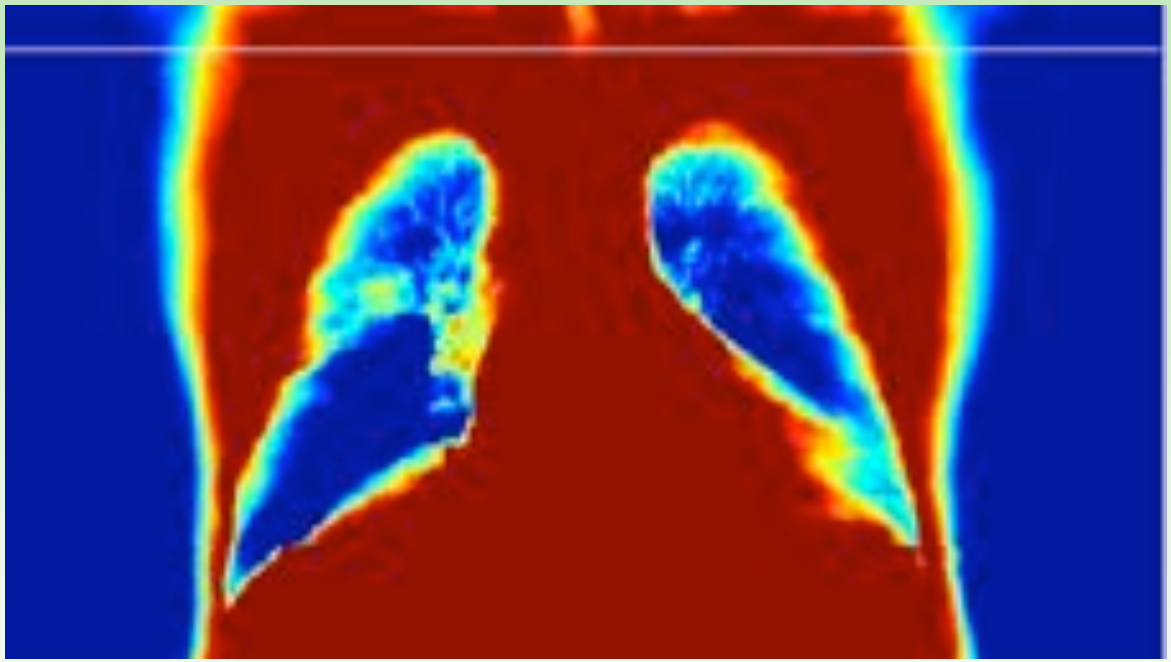


DIGITAL IMAGE SUBTRACTION
BEFORE-AFTER TREATMENT:



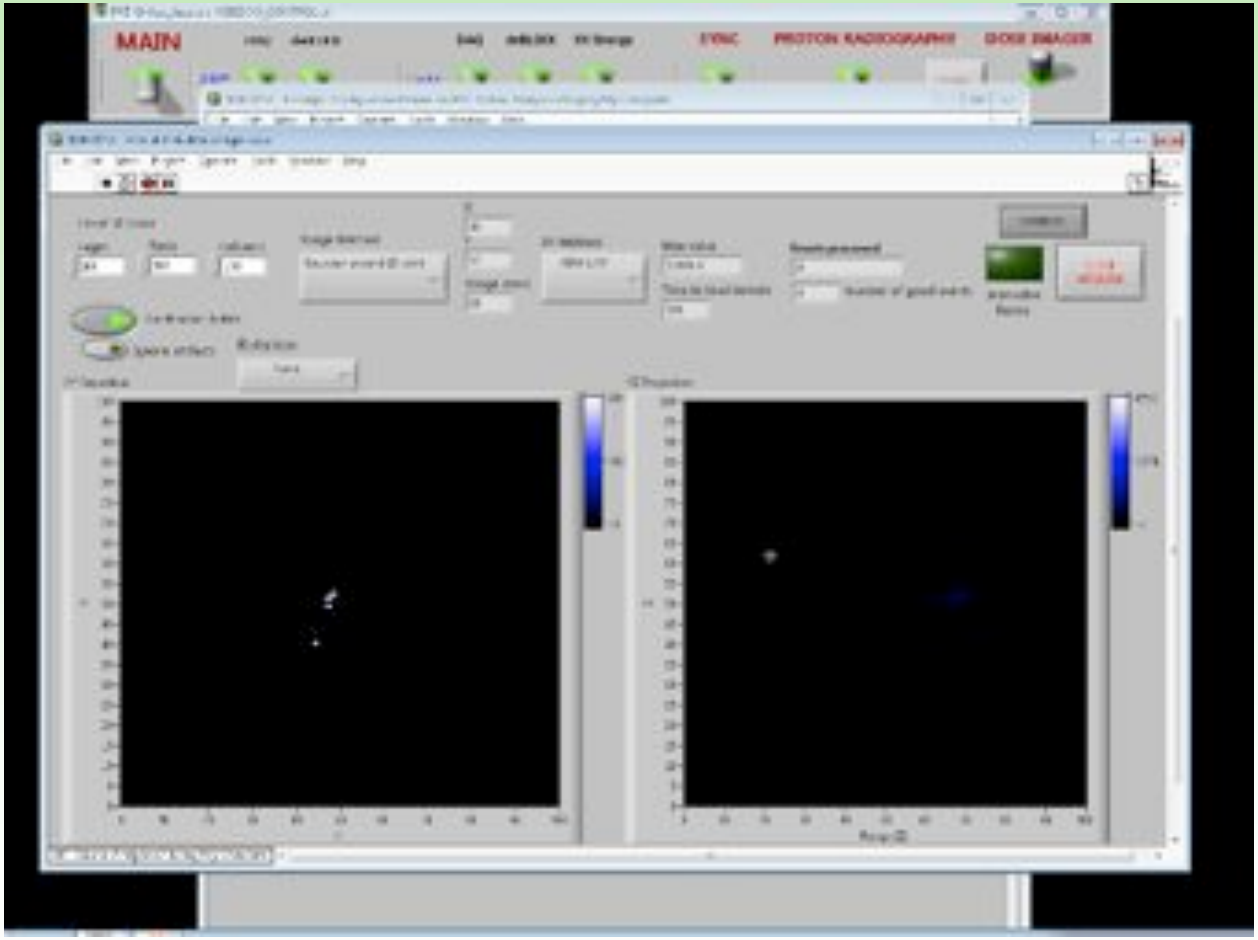
G. Chen,
Massachusetts General Hospital Boston

4-D PRR SIMULATION

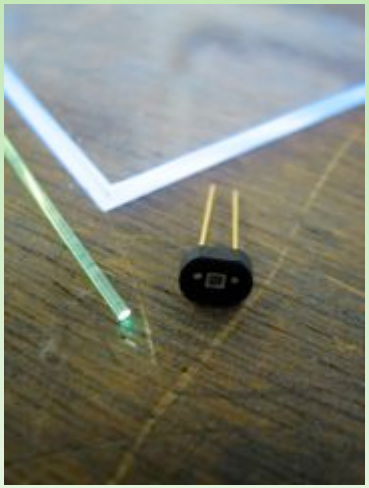


TREATMENT PLAN VERIFICATION (UNDER DEVELOPMENT)

- COMPUTE AVERAGE ENERGY LOSS PROFILE FOR SINGLE TRACKS
- ASSOCIATE PROFILE TO MEASURED TRACKS
- BUILD ON-LINE VISUALIZATION OF TREATMENT PLAN

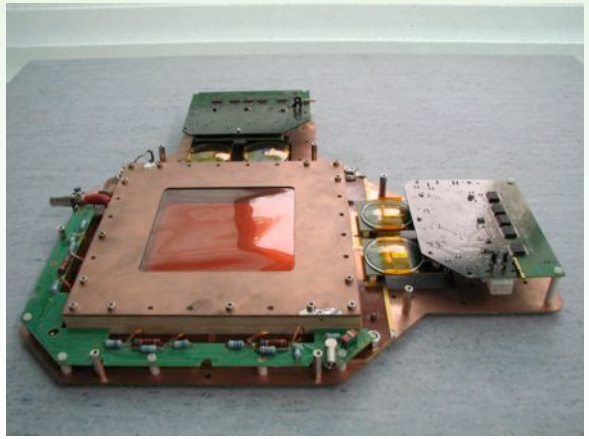


PROTON RANGE RADIOGRAPHY: THE TOOLS

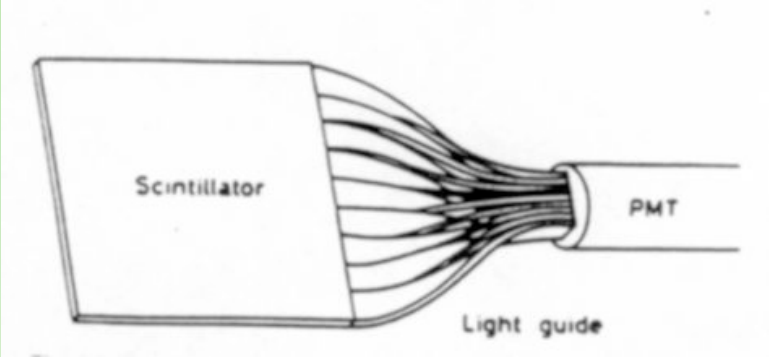


- PLASTIC SCINTILLATORS
- WAVELENGTH SHIFTER FIBRES
- LIGHT SENSORS (SOLID STATE PHOTOMULTIPLIERS)

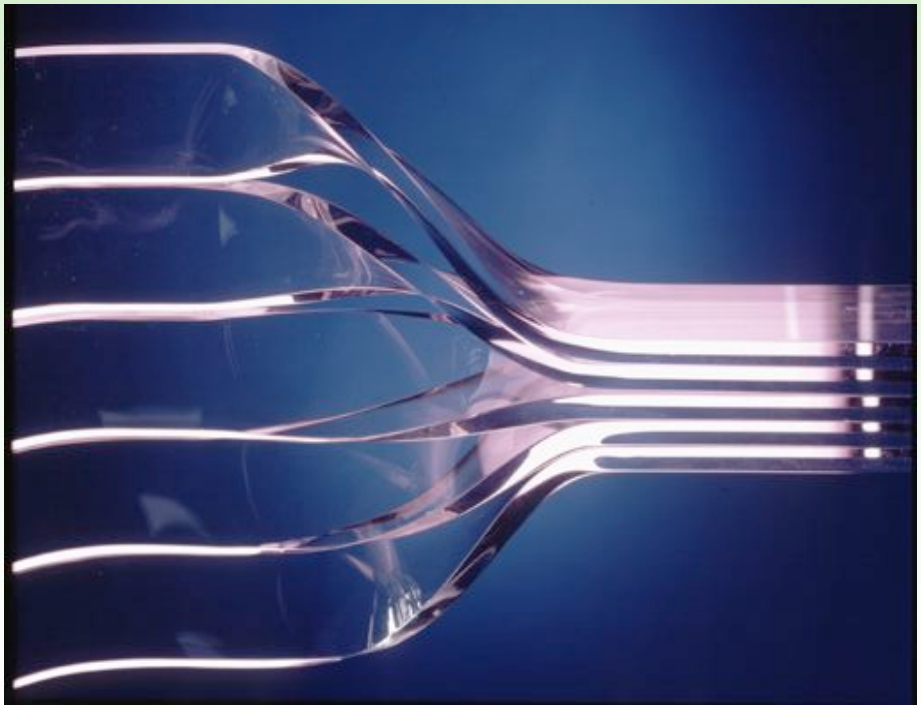
- POSITION-SENSITIVE DETECTORS
  (GEM CHAMBERS)

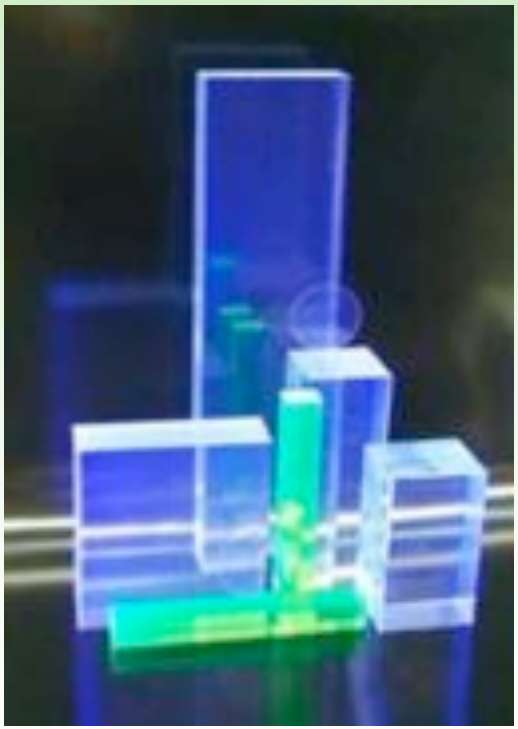


ORGANIC (PLASTIC) SCINTILLATORS

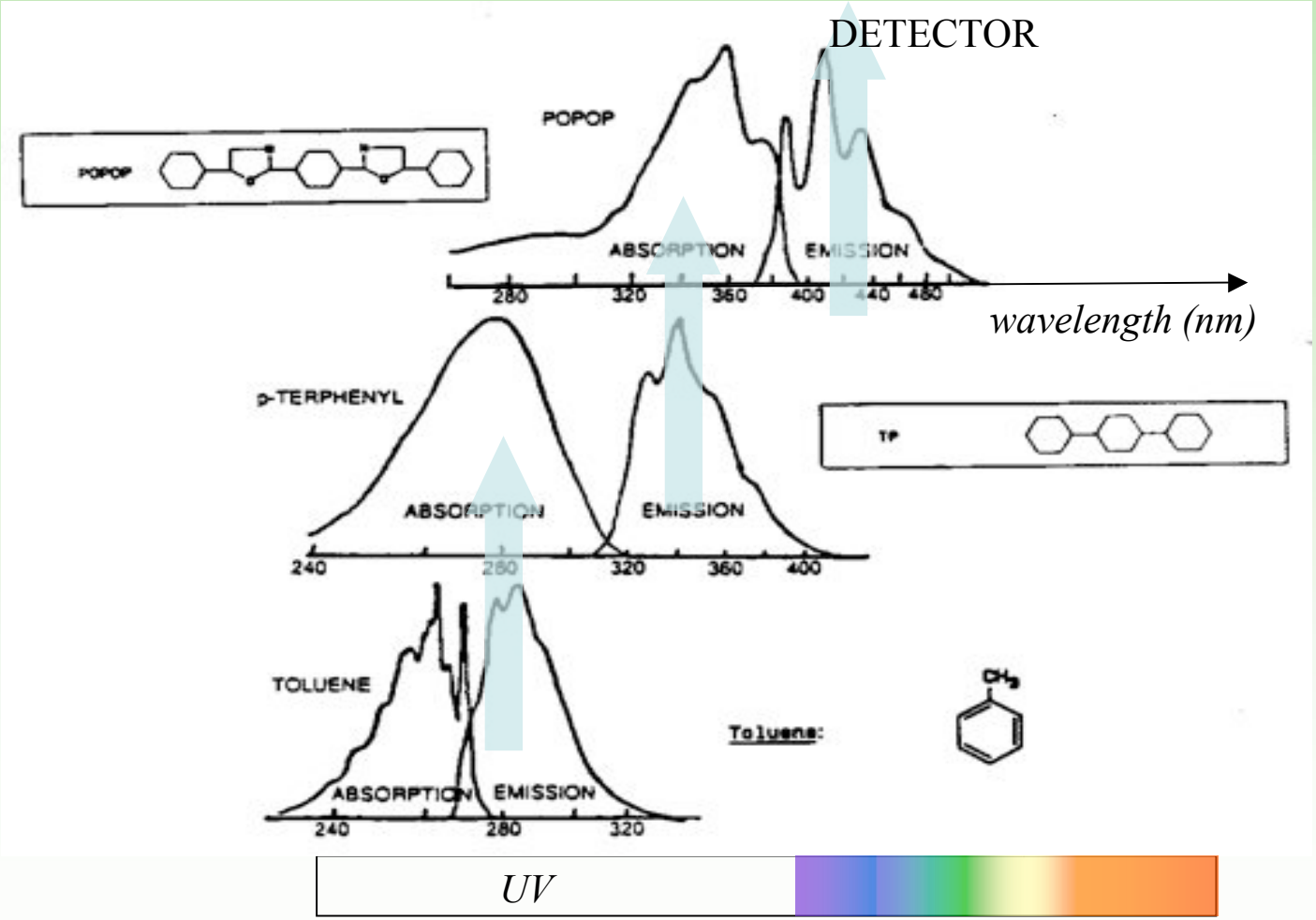


THE ENERGY RELEASED IN THE SCINTILLATOR BY IONIZING RADIATION IS CONVERTED TO FLUORESCENCE PHOTONS.

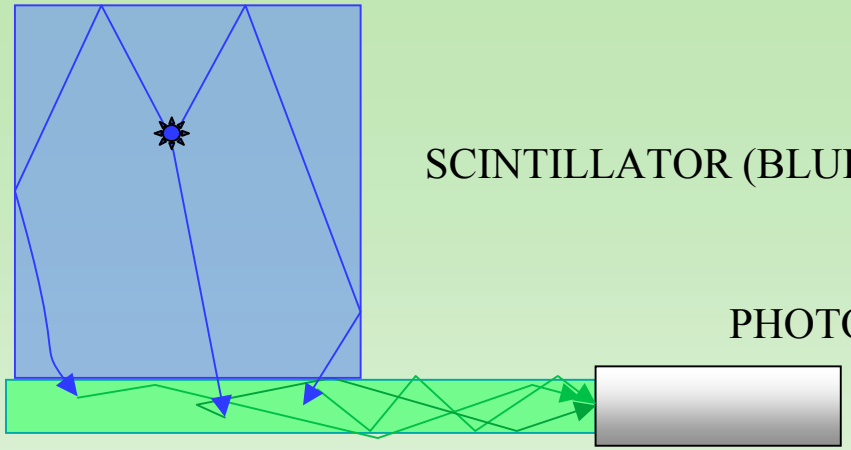




INTERNAL ADDITIVES (WAVELENGTH SHIFTERS)SHIFT THE SCINTILLATION TO LONGER WAVELENGTHS, EASIER TO DETECT:



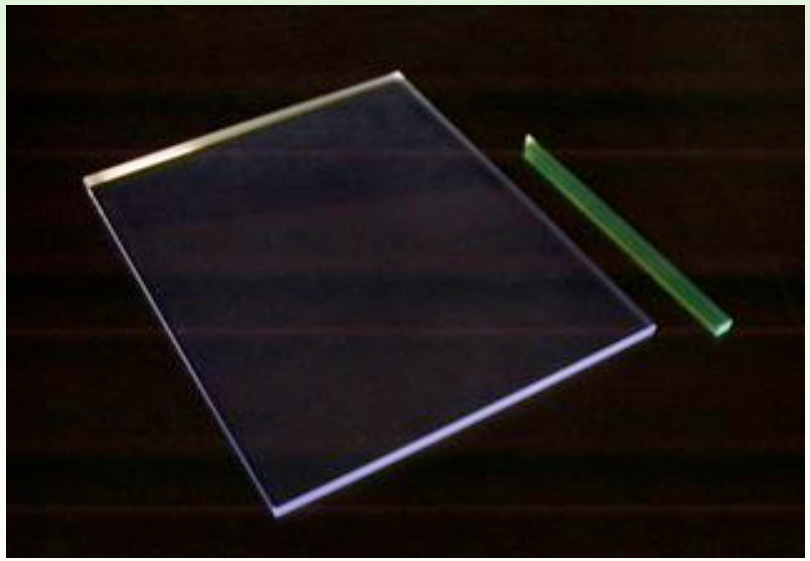
PLASTIC SCINTILLATORS+WAVELENGTH SHIFTERS

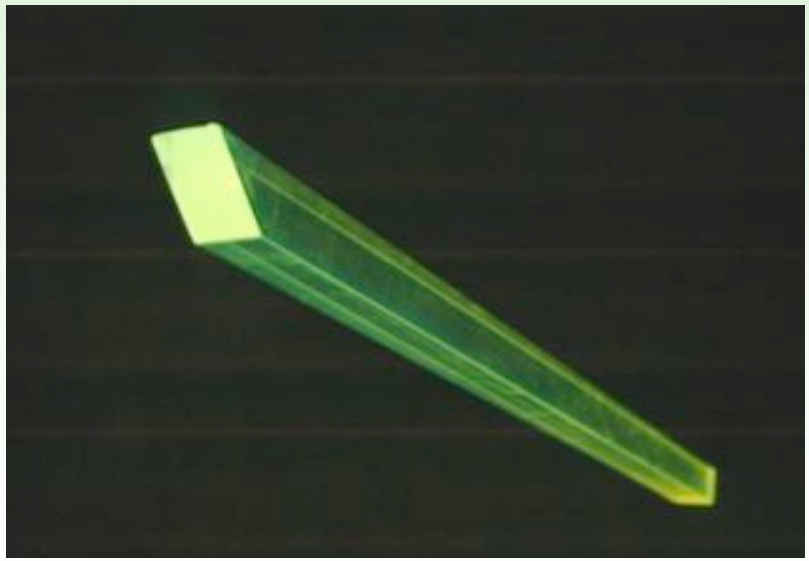


SCINTILLATOR (BLUE)

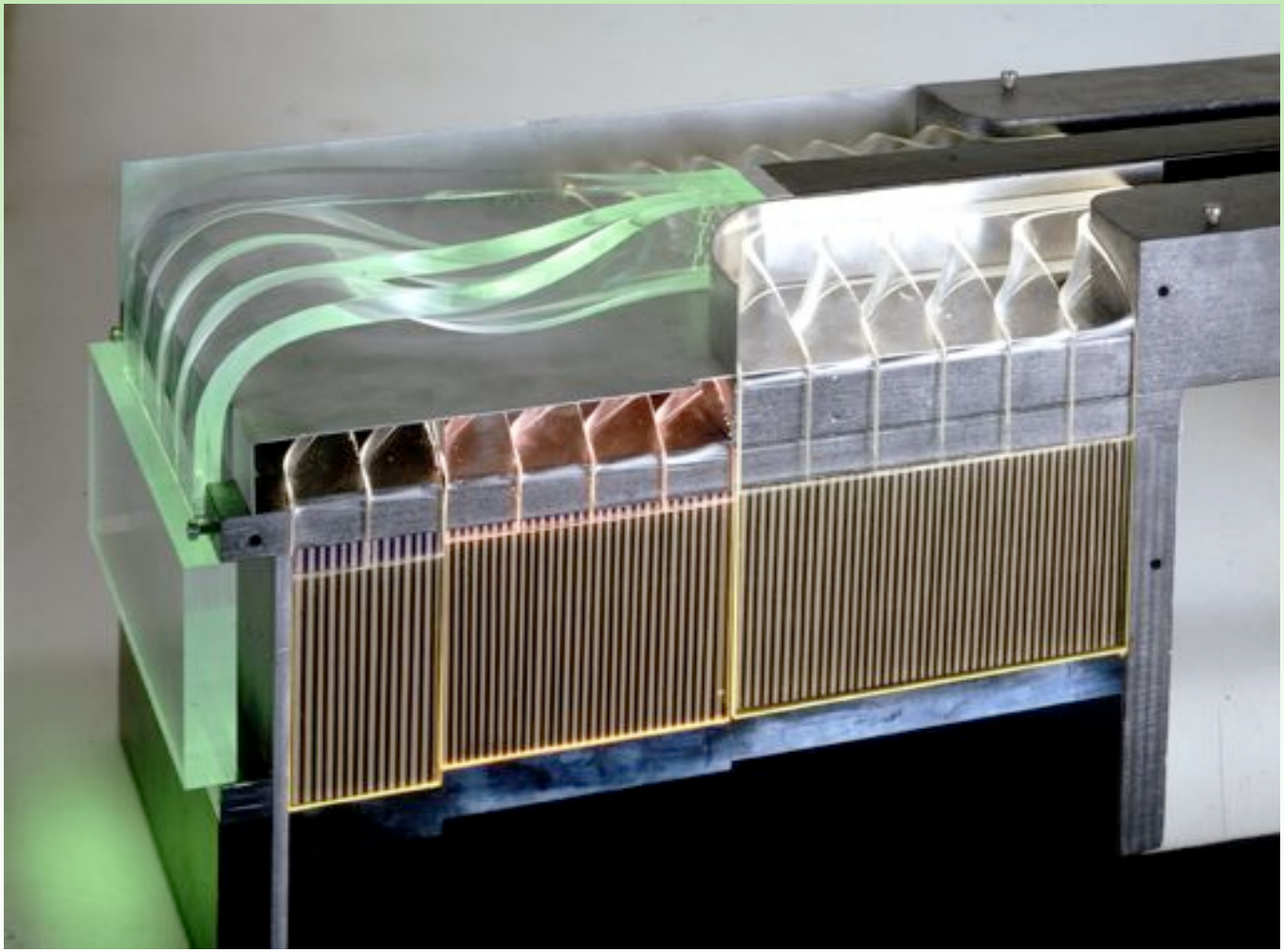
PHOTOMULTIPLIER

WAVELENGTH SHIFTER (BLUE TO GREEN)

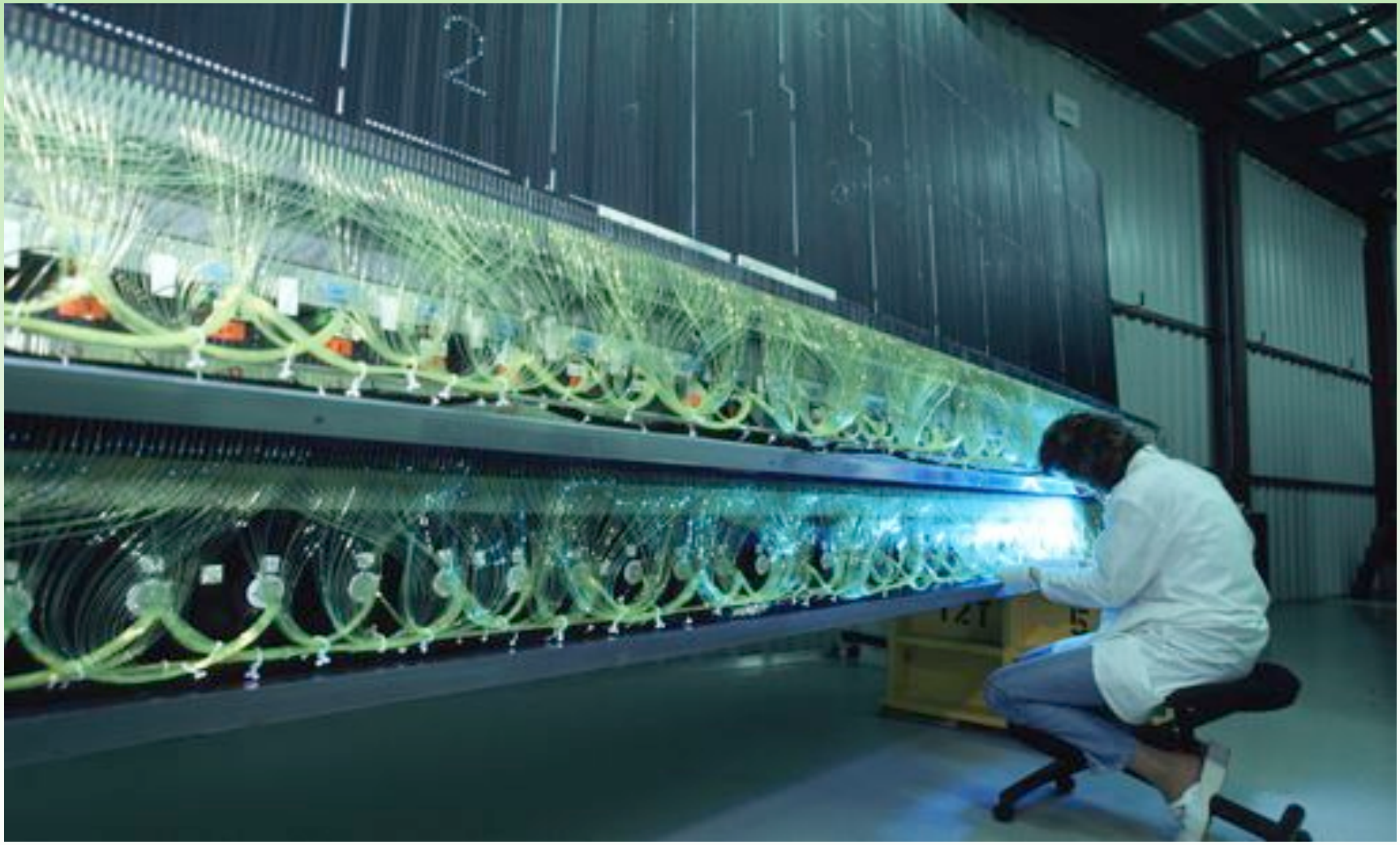




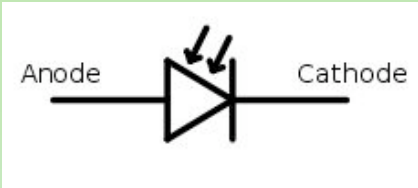
EXAMPLE OF CALORIMETER:
STACK OF SCINTILLATORS WITH WLS LIGHT COLLECTION

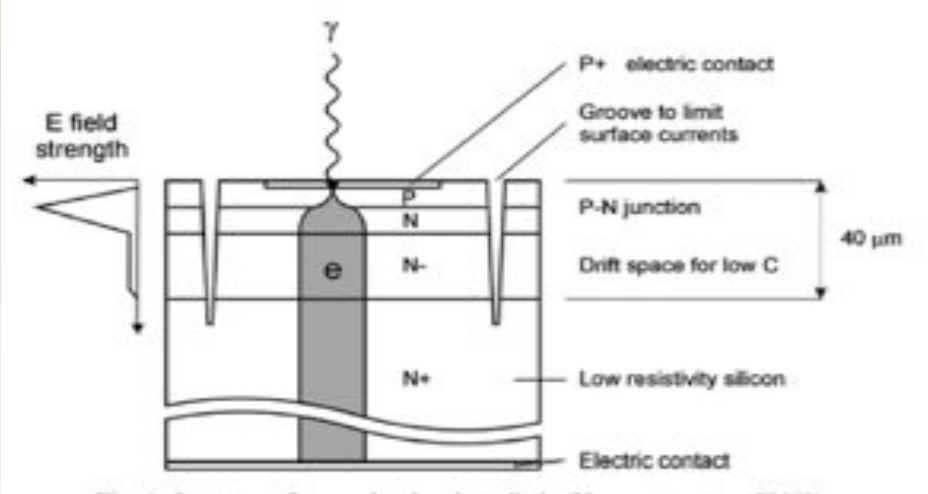


ATLAS HADRONIC CALORIMETER; SCINTILLATORS WITH WLS FIBERS

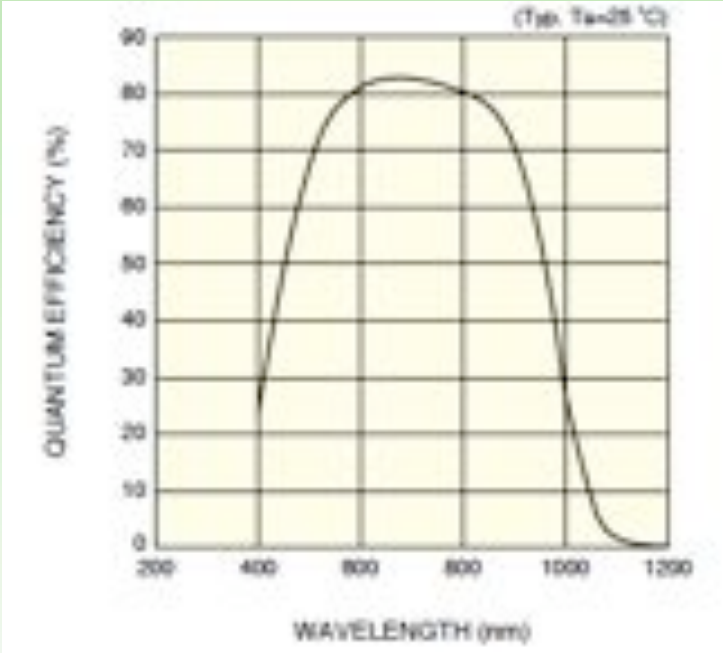


PHOTODIODE:





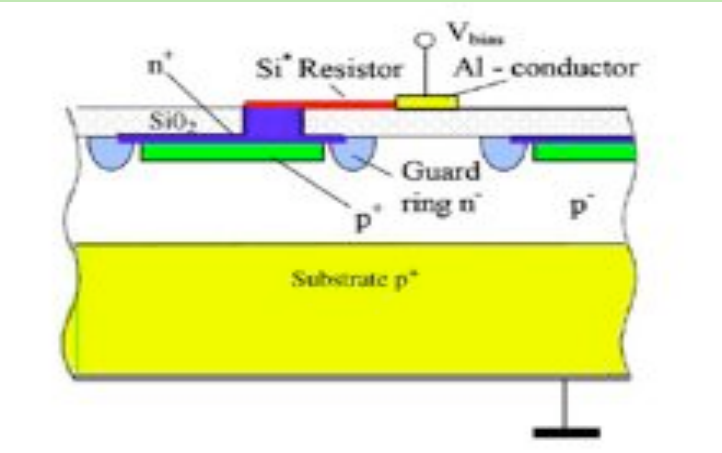
TYPICAL SPECTRAL RESPONSE:

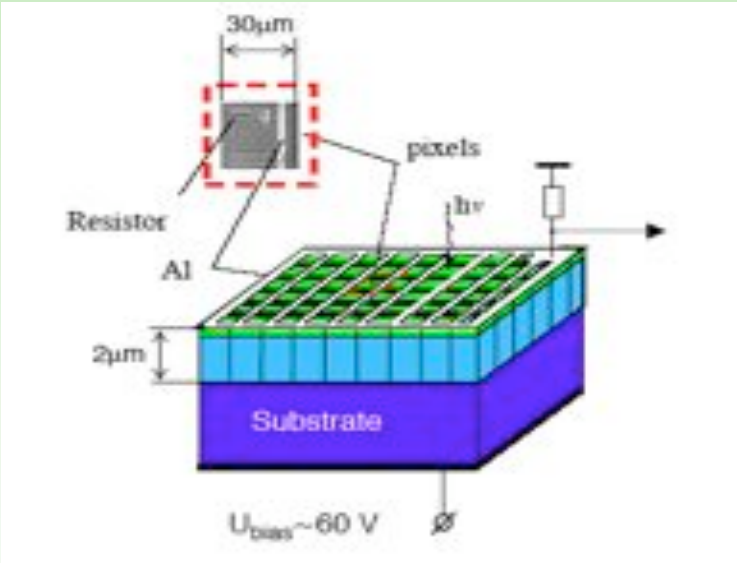


AVALANCHE PHOTODIODE: GAIN ~ 100
SUITABLE FOR CALORIMETRY
(LARGE LIGHT YIELD)

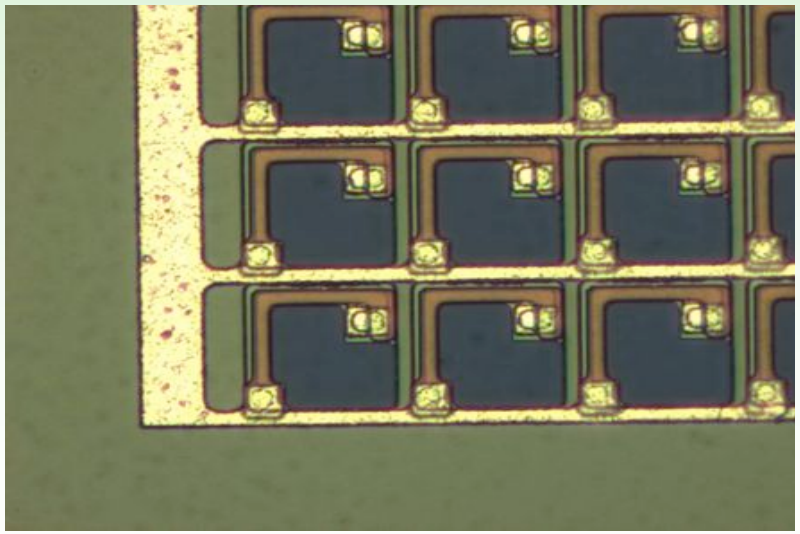
SILICON PHOTOMULTIPLIERS (SIPM)
MULTI PIXEL PHOTON COUNTERS (MPPC)

ARRAY OF INDEPENDENT AVALANCHE
PHOTODIODES OPERATED IN THE GEIGER MODE





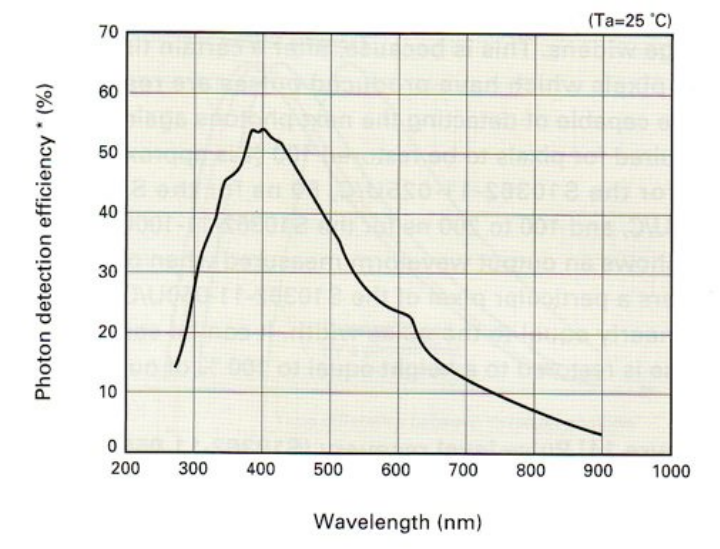
- Very high gain (~10^5)
- Single photon sensitivity
- Fast response (sub-ns)



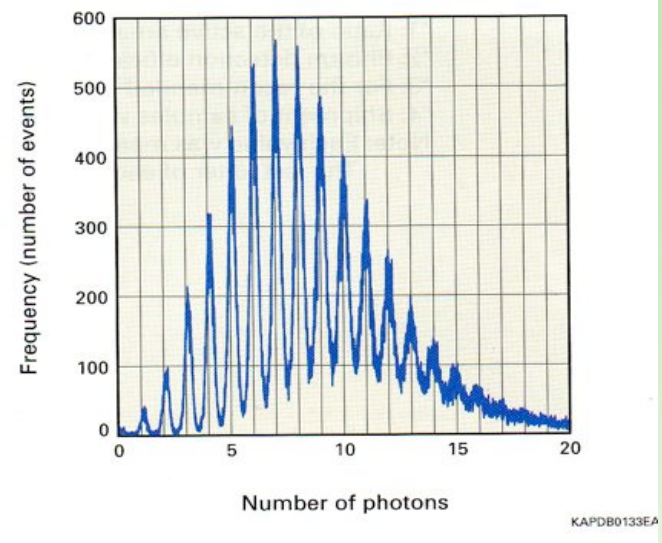
P. Buzhan et al, Nucl. Instr. and Meth. A 504(2003)48

TYPICAL SILICON PHOTOMULTIPLIER PERFORMANCES

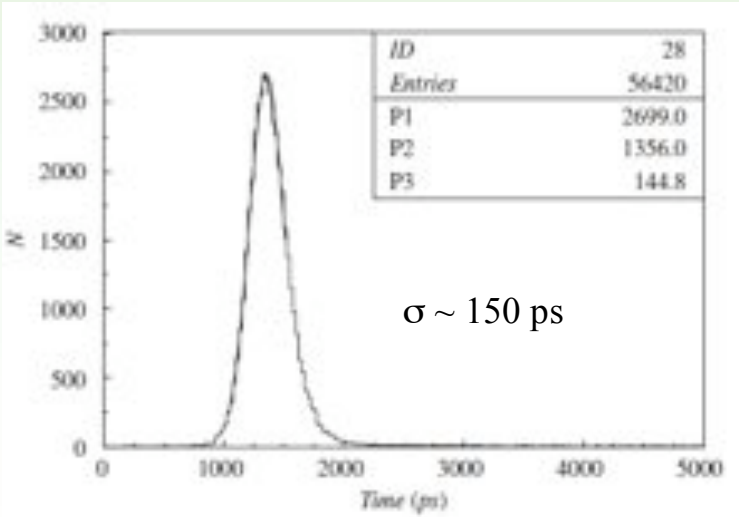
QUANTUM EFFICIENCY:



SINGLE-MULTI PHOTON RESPONSE:



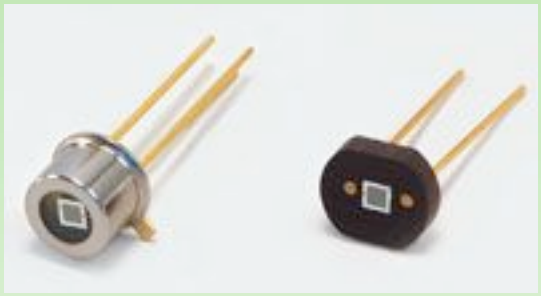
TIME RESOLUTION:



OUTPUT PROPORTIONAL TO NUMBER OF PHOTONS FOR

$N_{photons} < N_{cells}$

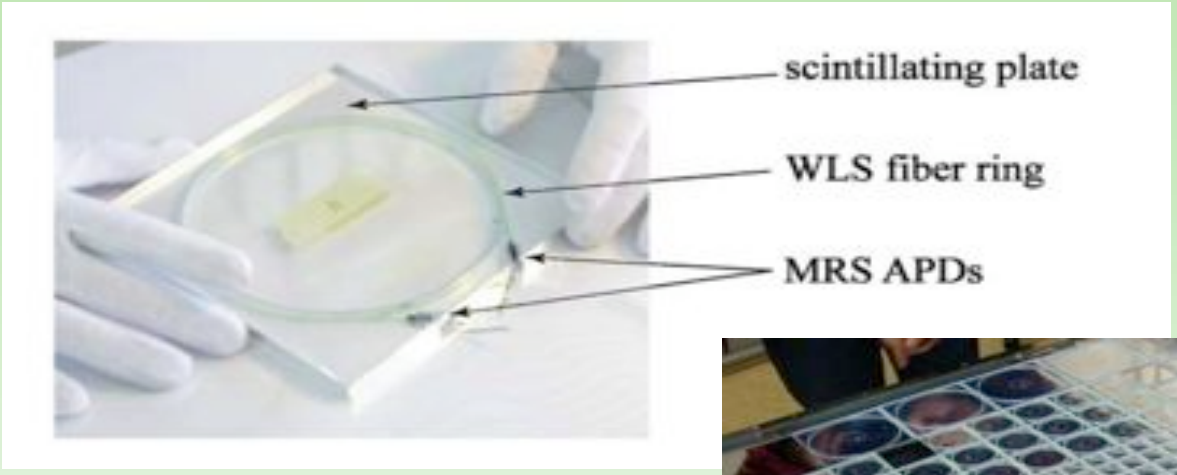
SILICON PHOTOMULTIPLIERS

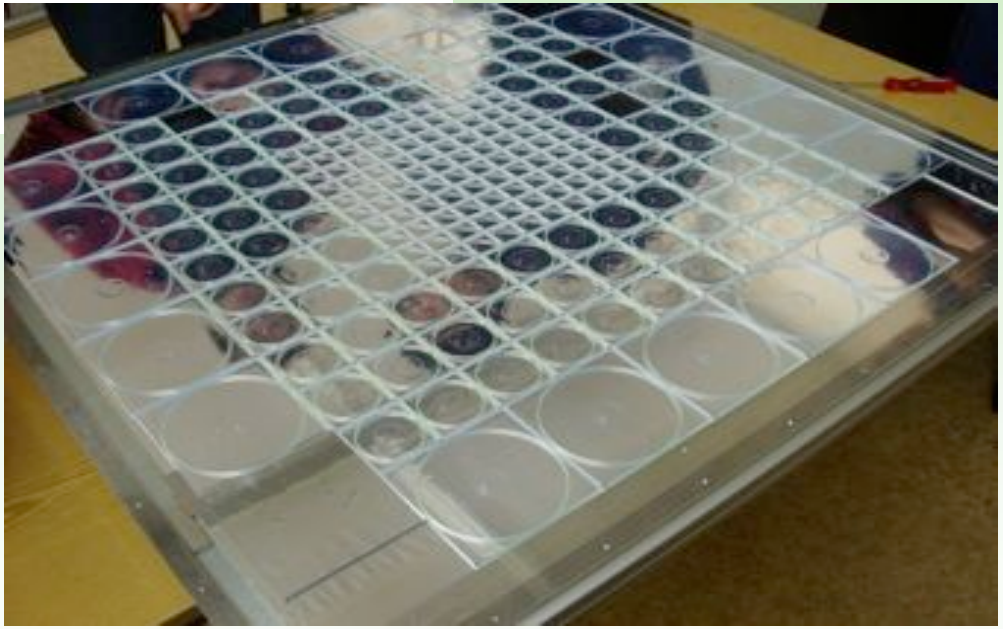


HAMAMATSU

sensL

SILICON PHOTOMULTIPLIERS FOR CALORIMETRY

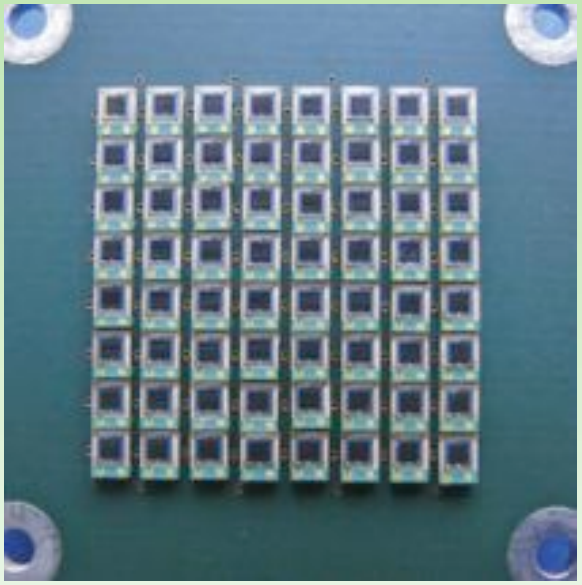




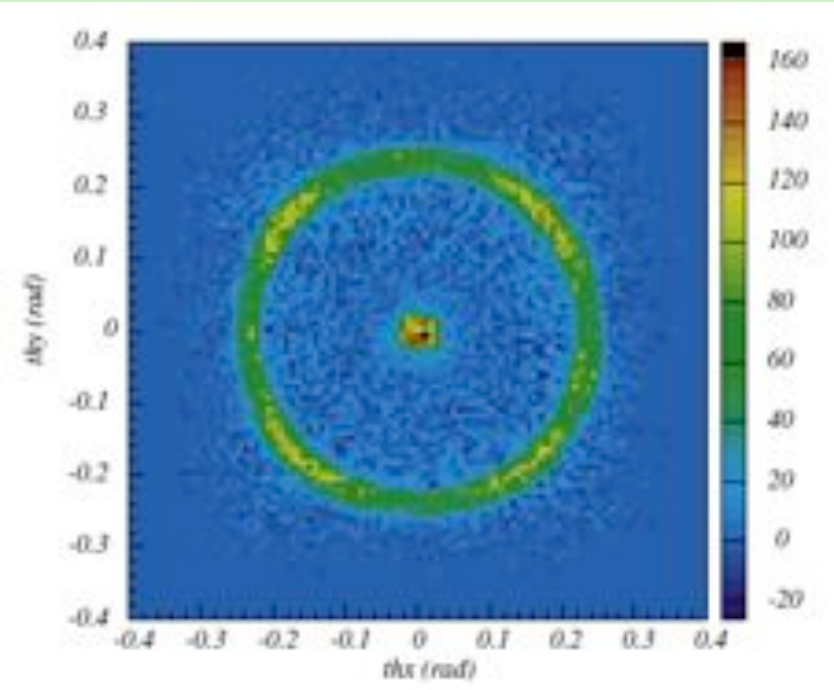
A. Akindinov et al, Nucl. Instr. and Meth. A539(2005)172

V. Andreev et al, Nucl. Instr. and Meth. A540(2005)368

SiPM ARRAYS FOR CHERENKOV RING IMAGING



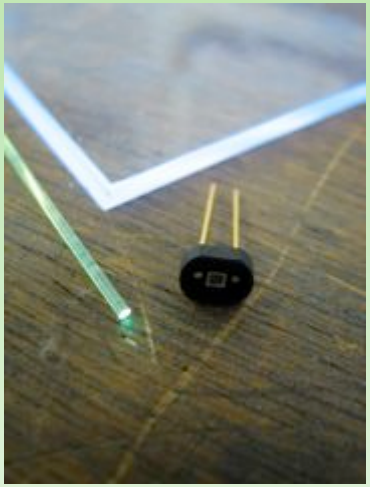
BEAM TEST



S. Korpar et al,
Nucl. Instr. and Meth. A613(2010)195

AQUA PRR: PLASTIC SCINTILLATORS WITH WLS FIBRE READOUT

Fast scintillator: BC-408
- Rise/decay time 0.9/2.1 ns
- Peak emission 425 nm

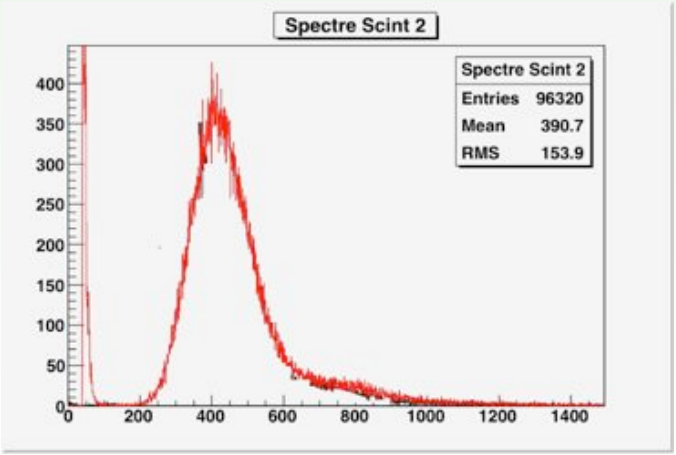


WLS: BC-482A 1mm
- Decay time 12 ns
- Absorption peak 420 nm
- Emission peak 494 nm

SiPM: Hamamatsu S-10362-11-050C
- 1 mm^2 active, 400 pixels
- Quantum efficiency 40% at 500 nm
- Time resolution 200-300 ps

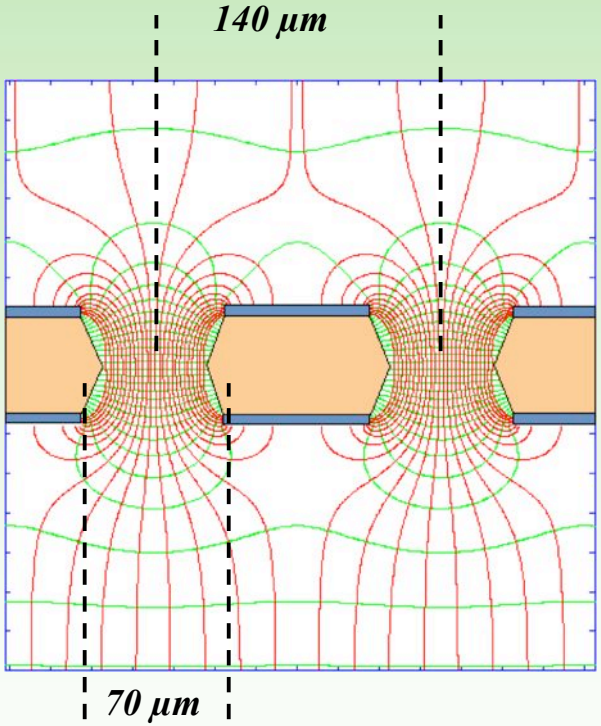
Each module has:
- 12-bit ADC
- 5V DAC for SiPM bias adjustment

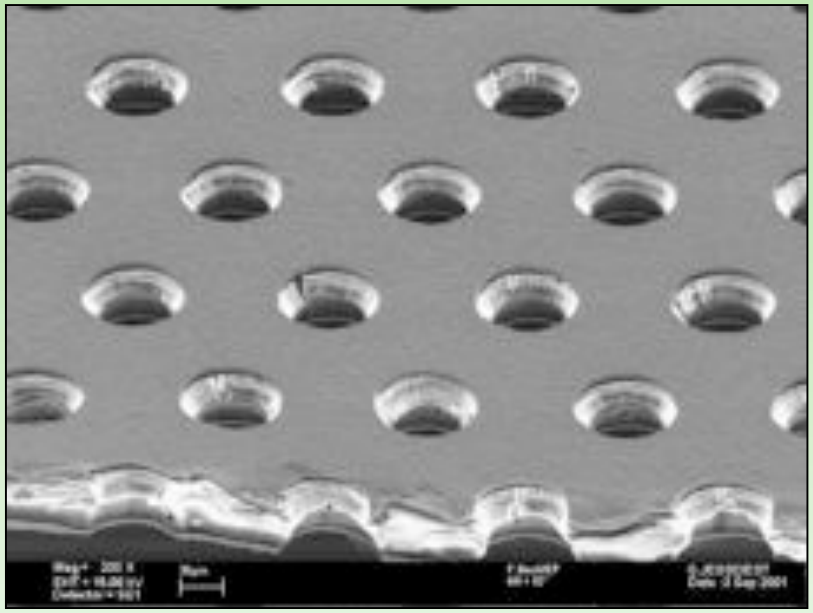
PH response for
100 MeV protons:



GAS ELECTRON MULTIPLIER

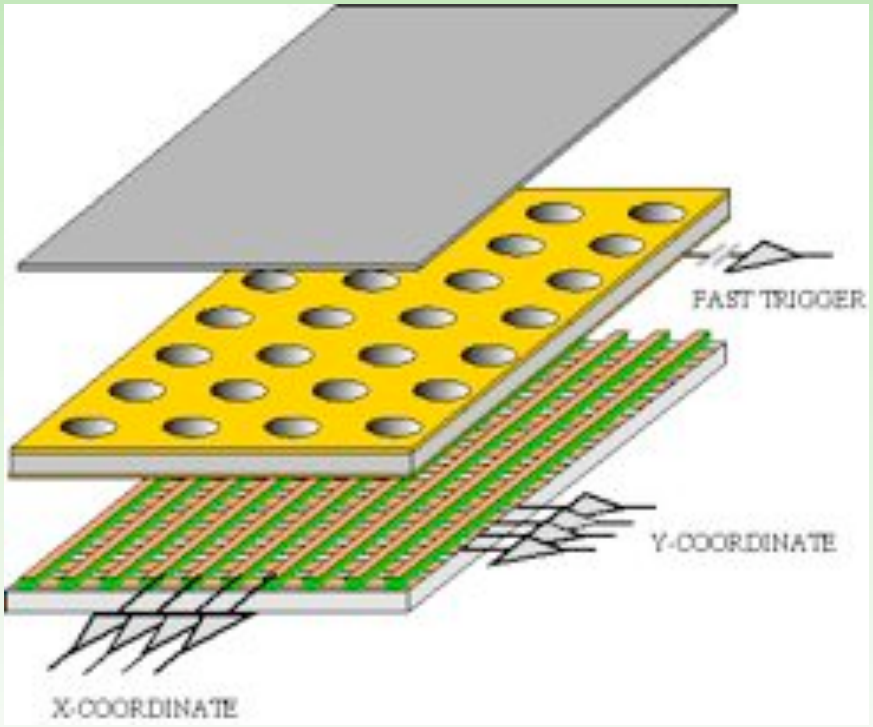
Dense hole pattern on metal-clad polymer foil



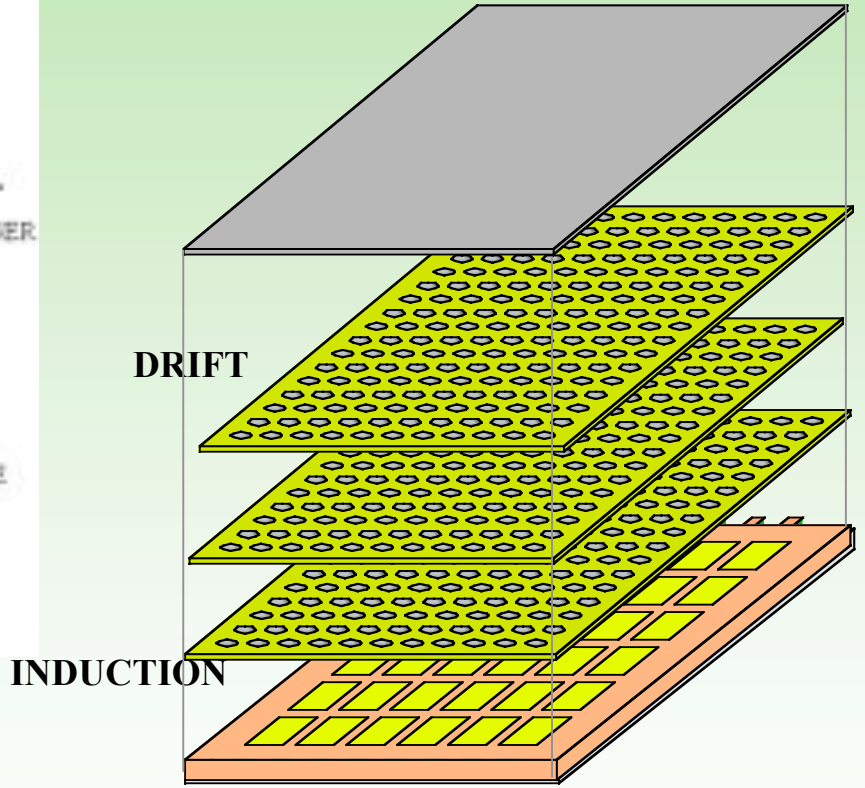


F. Sauli, Nucl. Instrum. and Meth. A386(1997)531

SINGLE GEM DETECTOR WITH 2-D READOUT:



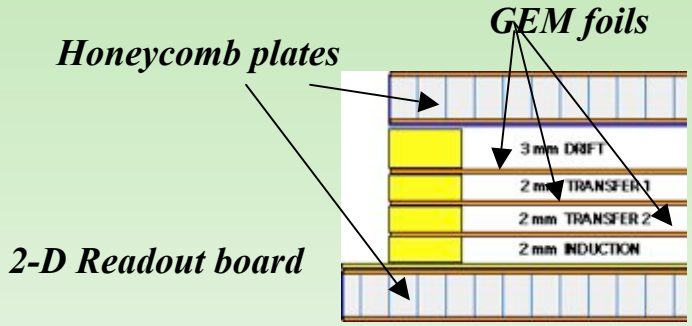
MULTI-GEM WITH PAD READOUT:



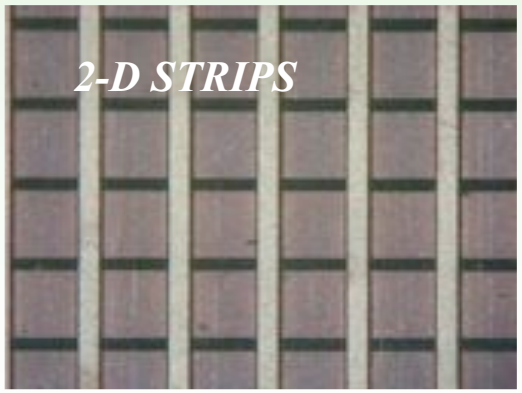
C. Büttner et al, Nucl. Instr. and Meth. A409(1998)79
S. Bachmann et al, Nucl. Instr. and Meth. A438(1999)376

TRIPLE GEM DETECTORS FOR COMPASS (CERN): 22 CHAMBERS OPERATIONAL

- LIGHT CONSTRUCTION
- 31X31 CM^2 ACTIVE
- 2-D STRIP READOUT
- THICKNESS IN ACTIVE AREA ~ 0.7% X_0



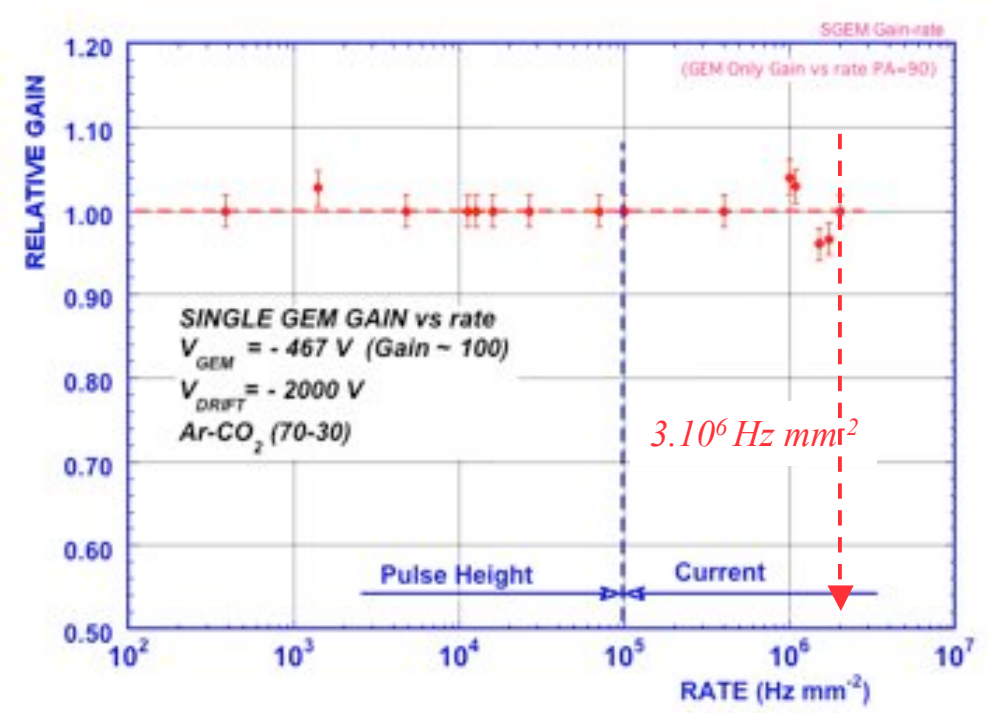
Pitch: 400 µm
Top strips: 80 µm
Bottom strips: 350 µm



C. Altumbas et al, Nucl. Instrum. Methods A490(2002)177
B. Ketzer et al, Nucl. Instr. and Meth. A535(2004)314

GAS ELECTRON MULTIPLIER PERFORMANCES

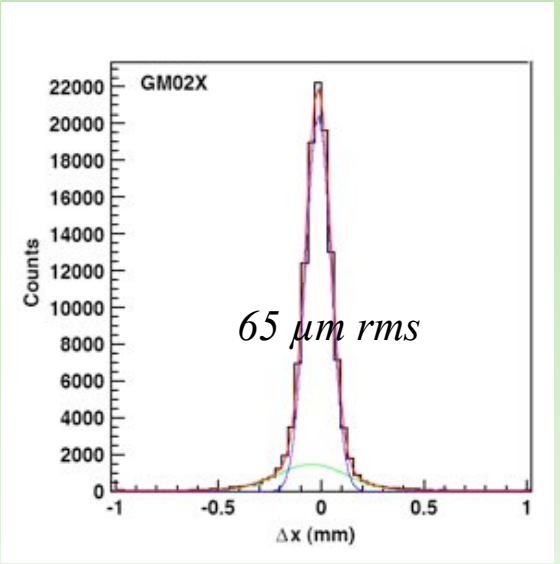
VERY HIGH RATE CAPABILITY:



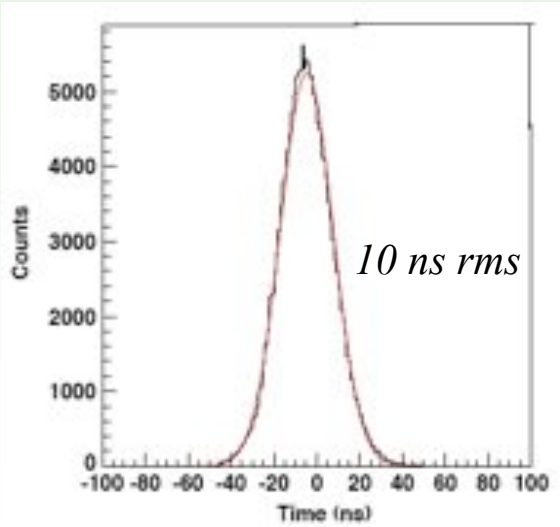
J. Benlloch et al, IEEE NS-45(1998)234

B. Ketzer et al, Nucl. Instr. and Meth. A535(2004)314

POSITION ACCURACY:

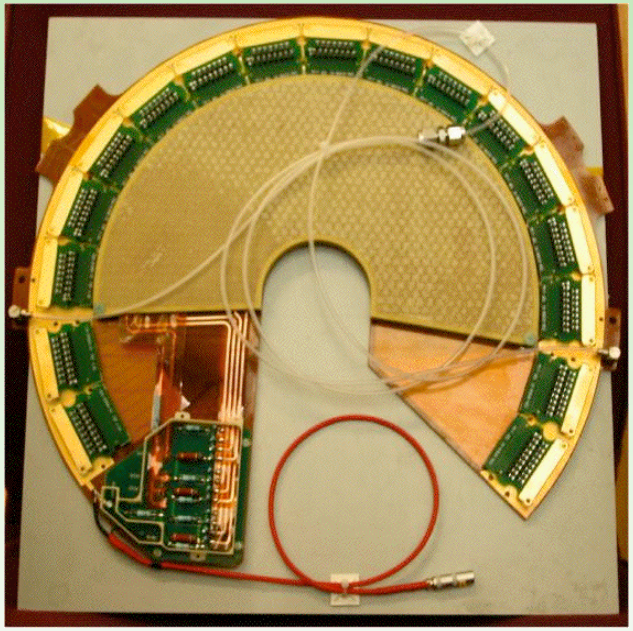


TIME RESOLUTION:

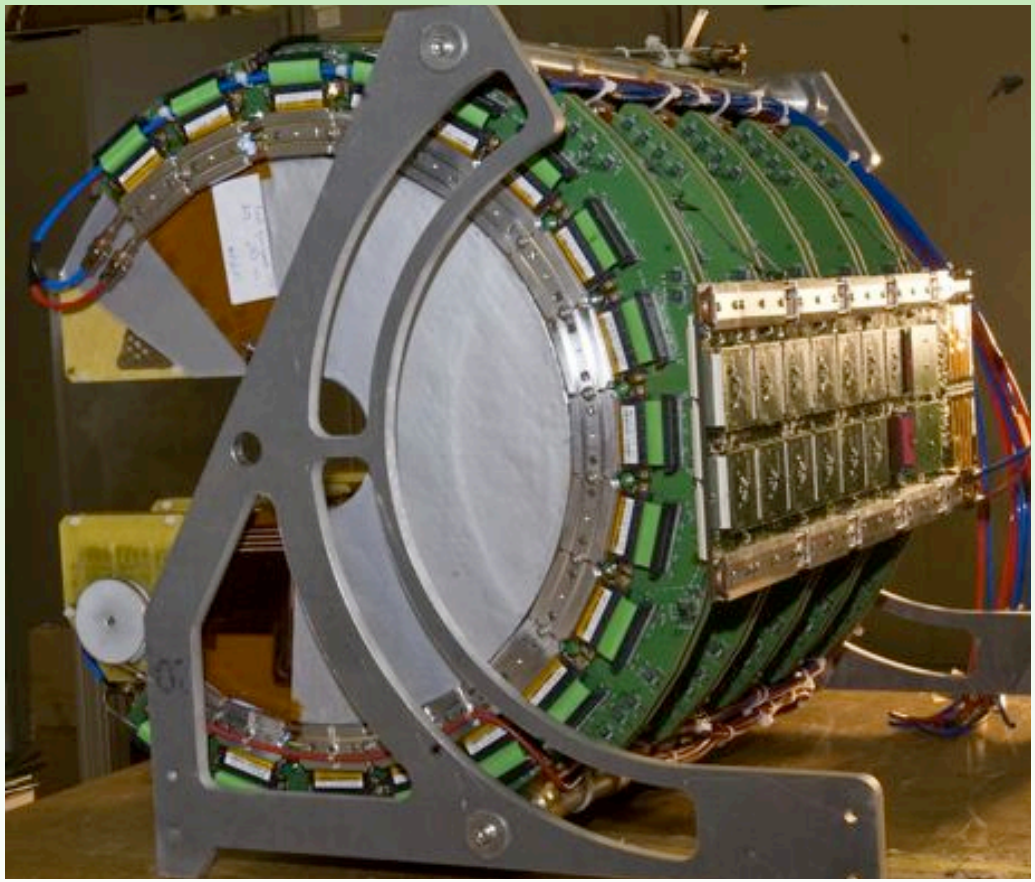


TOTEM GEM TRACKER AT LHC

4 x 10 MODULES WITH STRIPS AND PADS READOUT:

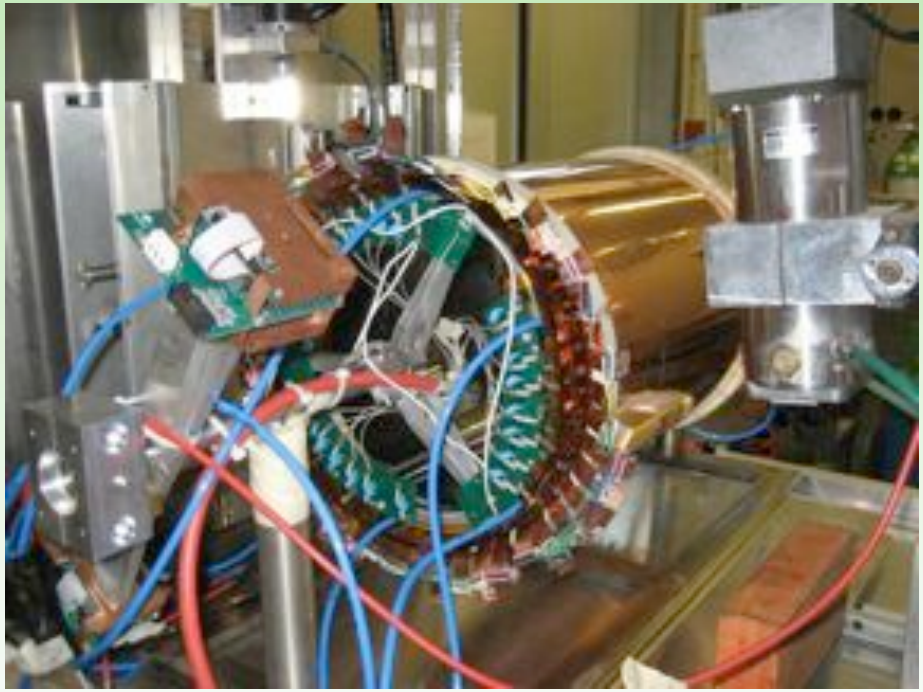


M.G. Bagliesi et al,
Nucl. Instr. And Meth. 617(2010)313



CYLINDRICAL GEM DETECTORS

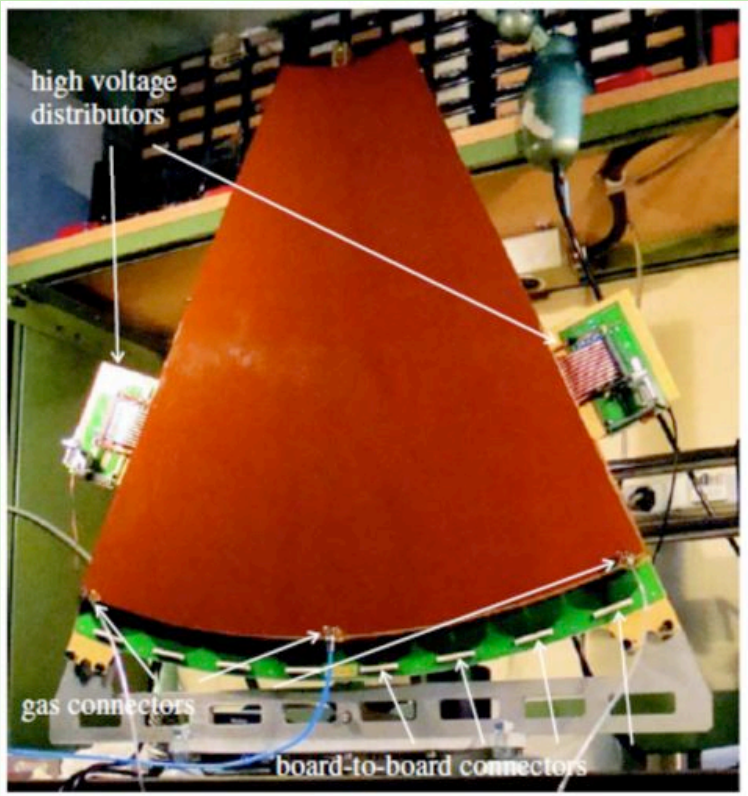
L. Ropelewski, Vienna Instr. Conf. 2007



G. Bencivenni, Nucl. Instr. and Meth. A581(2007)221

LARGE SIZE GEM

TWO LARGE (33 x 66 cm^2) GEM FOILS THERMALLY BONDED TOGETHER
2000 cm^2 ACTIVE AREA

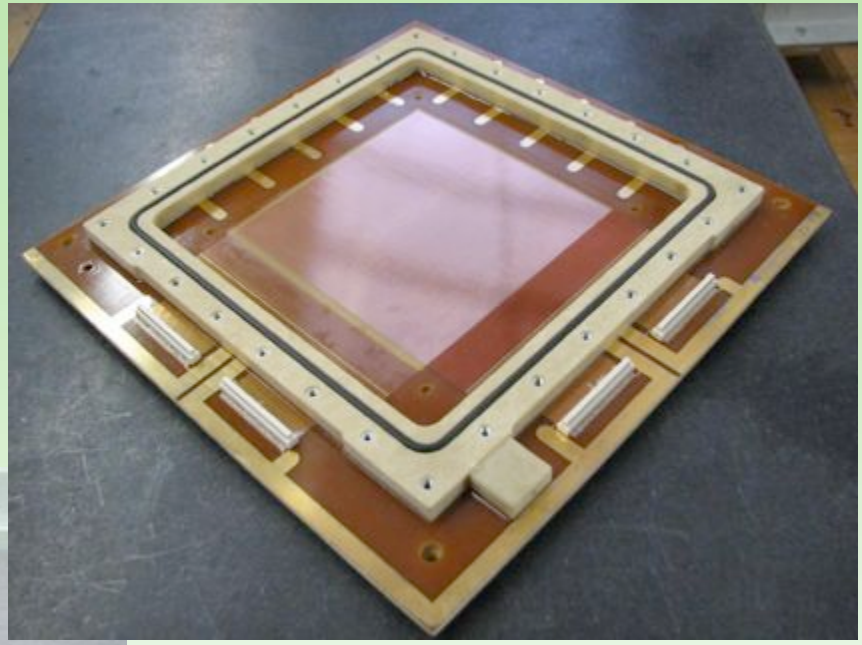


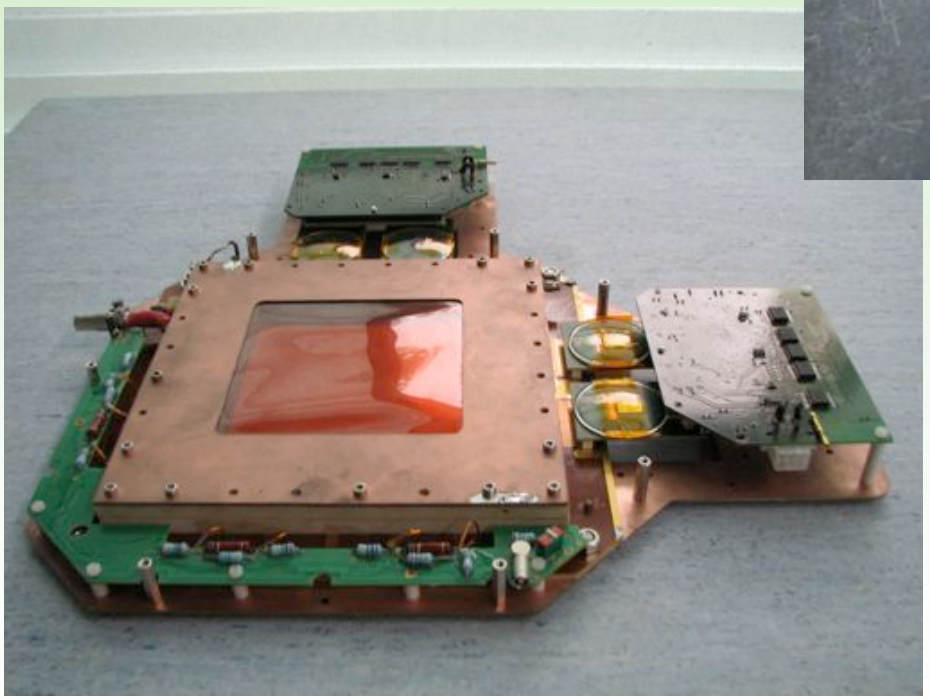
M. Alfosi et al, Nucl. Instr. And Meth. A617(2010)151

RD51 COLLABORATION
UNDER CONSIDERATION FOR CMS HIGH-ETA TRIGGER AND TRACKING UPGRADE

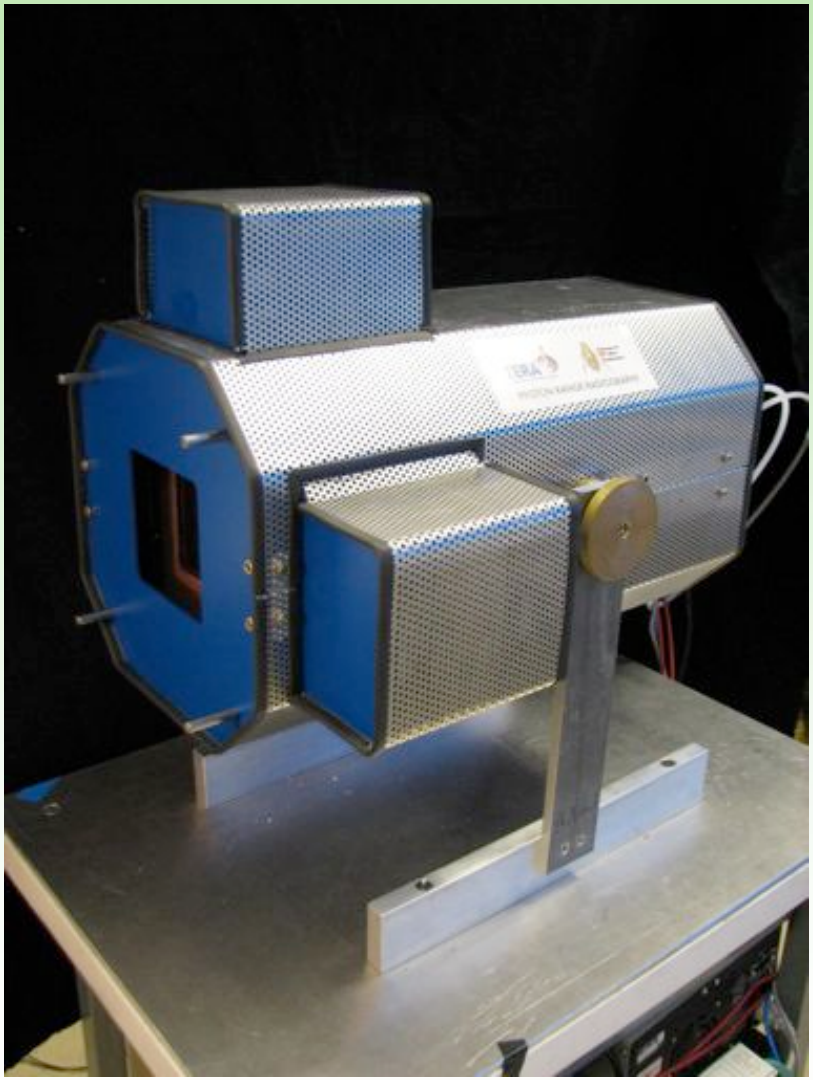
GEM DETECTOR FOR PRR

10 x 10 cm^2 TRIPLE-GEM MODULES
X-Y PROJECTIVE ANALOGUE READOUT





AQUA PRR: THE FINAL PROTOTYPE



10 x 10 cm^2 ACTIVE AREA
32 x 3 mm SCINTILLATORS

30 MeV < RESIDUAL RANGE< 130 MeV

30 x 30 cm^2 PRR IN CONSTRUCTION