A 3-D large area imaging system with very high performances

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Overview

- Background and actual status
- Main goal
- Scintillating Optical Fibers
- The tracker prototype
- Test results
- The particle residual range detector
- Towards the proton radiography real-time
- Conclusions

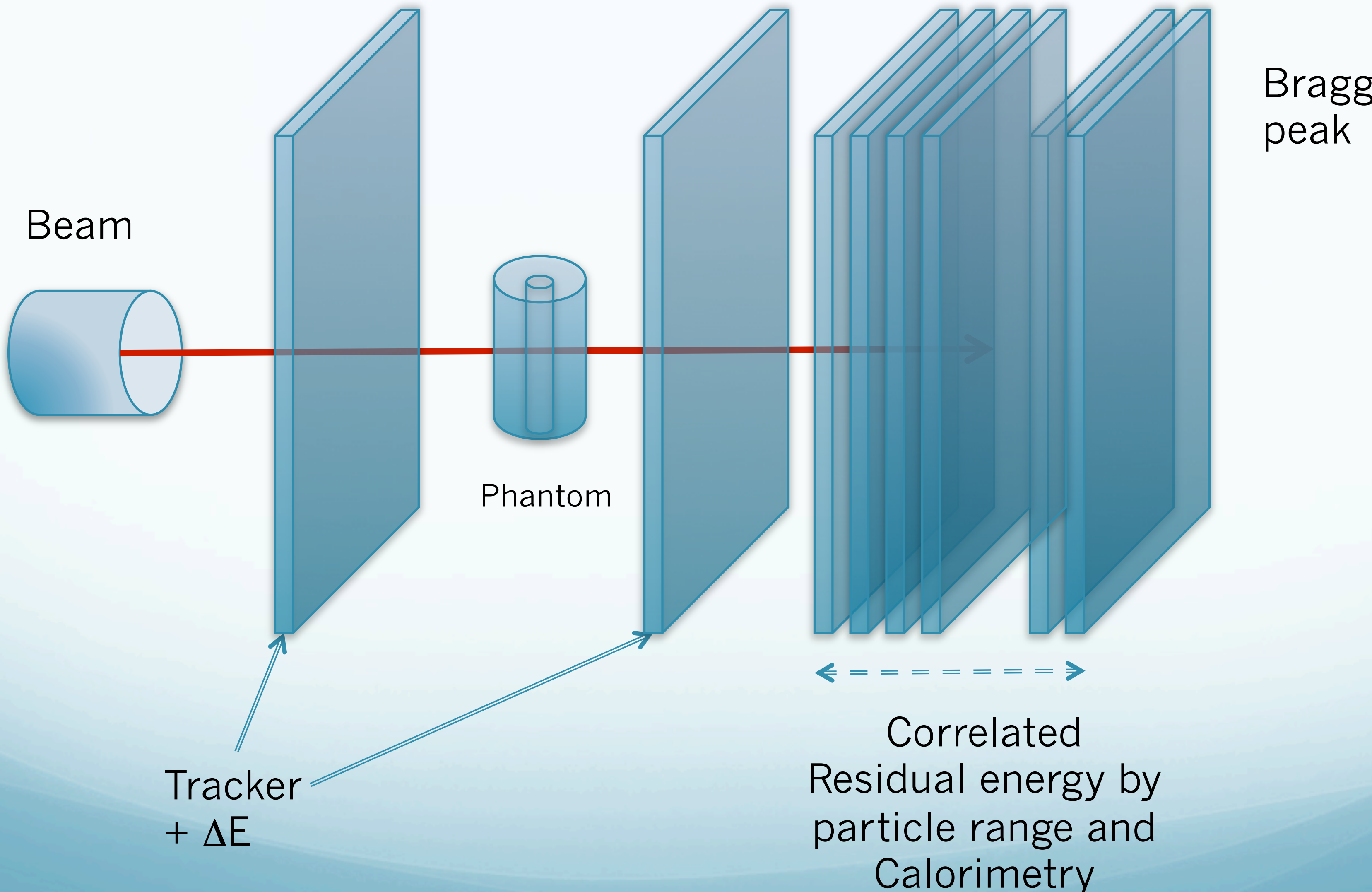
Background

- 3 years R&D project founded by CSN V INFN;

- Development of new detectors
  - Large area Imaging device
    - Trackers + Residual range detector
  - High space resolution
  - High event rate
  - Real time

- Scintillating optical fibers
- Detector read-out channel minimization
- From sensor to analysis and visualization software

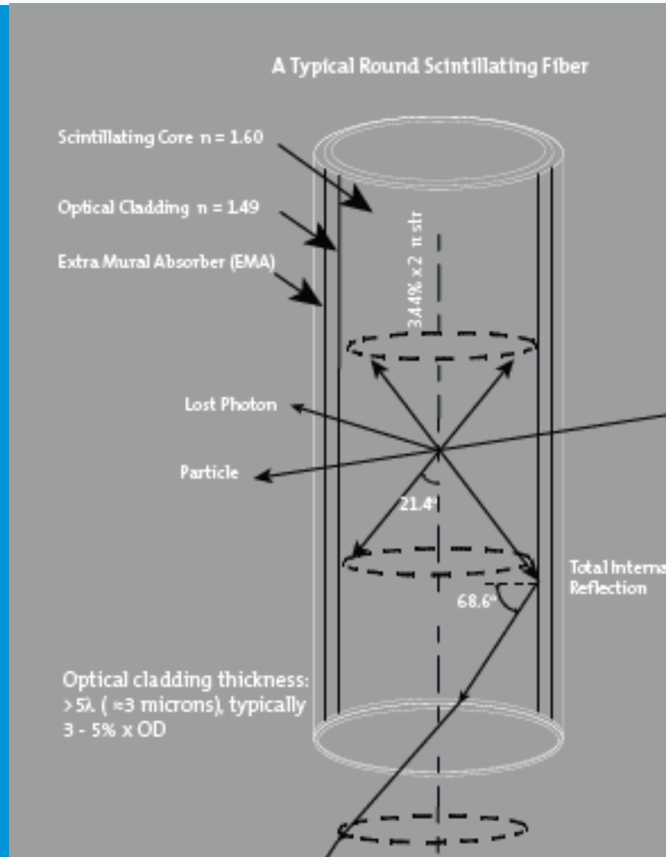
Final detector

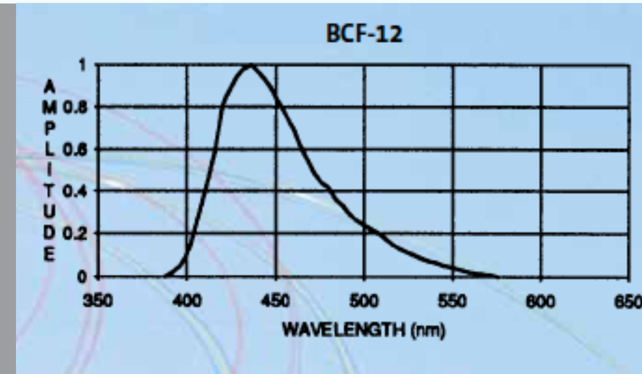


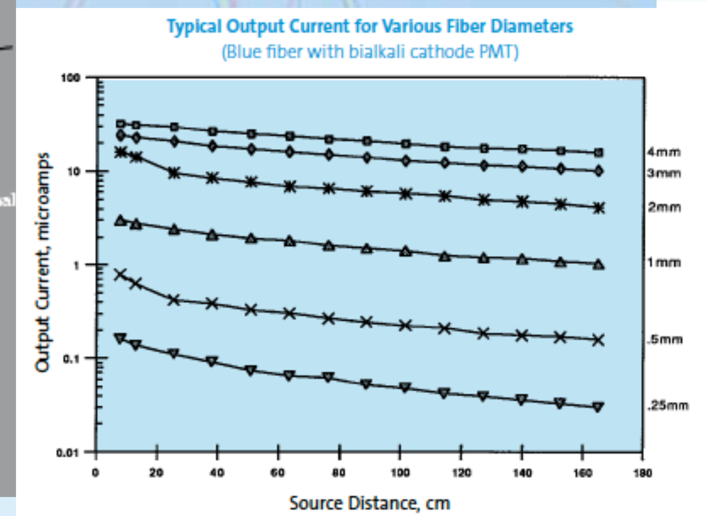
Scintillating Fibers: what manufacturer says..

Single-clad Fibers Properties	
Core material	Polystyrene
Core refractive index	1.60
Density	1.05
Cladding material	Acrylic
Cladding refractive index	1.49
Cladding thickness, round fibers	3% of fiber diameter
Cladding thickness, square fibers	4% of fiber size
Numerical aperture	0.58
Trapping efficiency, round fibers	3.44% minimum
Trapping efficiency, square fibers	4.4%
No. of H atoms per cc (core)	4.82×10^{22}
No. of C atoms per cc (core)	4.85×10^{22}
No. of electrons per cc (core)	3.4×10^{23}
Radiation length	42 cm
Operating temperature	-20°C to +50°C
Vacuum compatible	Yes

Multi-clad Fibers Properties	
Second cladding material	Fluor-acrylic
Refractive index	1.42
Thickness, round fibers	1% of fiber diameter
Thickness, square fibers	2% of fiber size
Numerical aperture	0.74
Trapping efficiency, round fibers	5.6% minimum
Trapping efficiency, square fibers	7.3%







Specific Properties of Standard Formulations

Fiber	Emission Color	Emission Peak, nm	Decay Time, ns	1/e Length m*	# of Photons per MeV**	Characteristics / Applications
BCF-10	blue	432	2.7	2.2	~8000	General purpose; optimized for diameters >250µm
BCF-12	blue	435	3.2	2.7	~8000	Improved transmission for use in long lengths
BCF-20	green	492	2.7	>3.5	~8000	Fast green scintillator
BCF-60	green	530	7	3.5	~7100	3HF formulation for increased hardness
BCF-91A	green	494	12	>3.5	n/a	Shifts blue to green
BCF-92	green	492	2.7	>3.5	n/a	Fast blue to green shifter
BCF-98	n/a	n/a	n/a	n/a	n/a	Clear waveguide

* For 1mm diameter fiber; measured with a bialkali cathode PMT
** For Minimum Ionizing Particle (MIP), corrected for PMT sensitivity

What scientific literature says...

- Attenuation length is not so easy to be determined
- The right PMT must be chosen to fit with sci-fi
- Light yield is dependent on sci-fi dopant concentration
- Radiation hardness
- Good timing performances
- Optimal size control

A. Antonelli et al. / Nucl. Instr. and Meth. in Phys. Res. A 370 (1996) 367–371

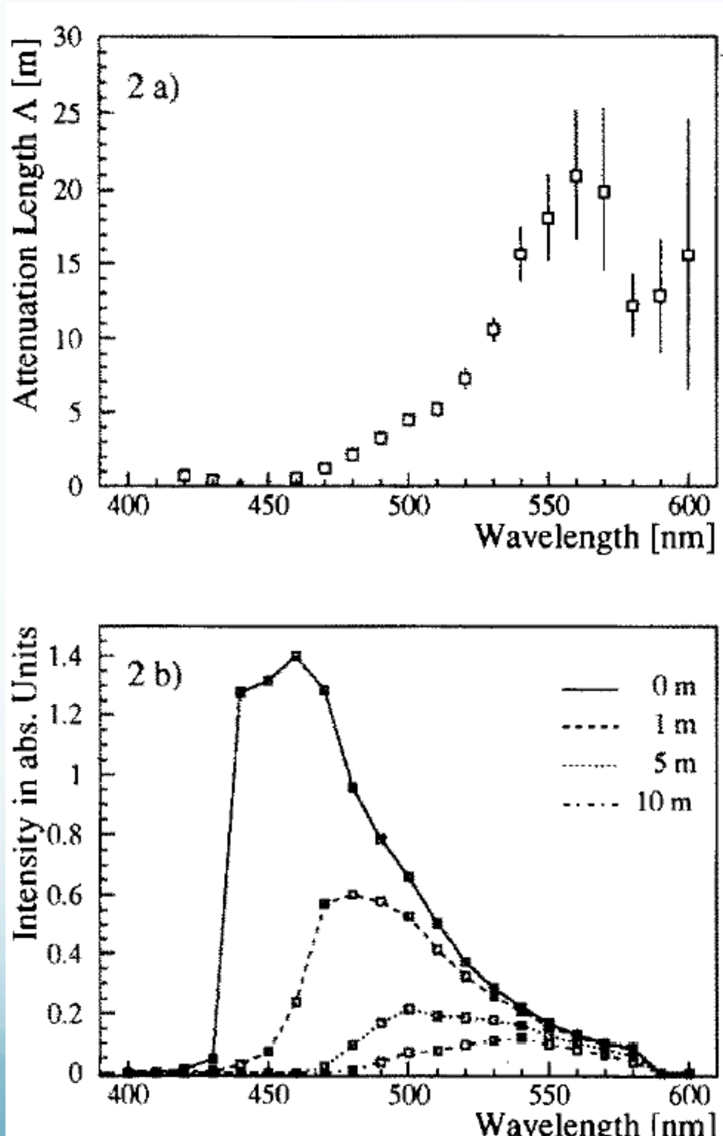
Table 2
Attenuation length and light yield

Fiber type	λ [cm]	N(0.5 m) [p.e./mm]	N(2 m) [p.e./mm]	N(3.7 m) [p.e./mm]
BCF-12 (92)	226±3	4.5±0.6	2.2±0.2	1.1±0.1
BCF-12 (93)	286±8	4.3±0.3	2.4±0.2	1.3±0.1
SCSF-81	321±5	4.2±0.3	2.4±0.2	1.5±0.1
Polifi-0046 (92)	284±5	3.5±0.5	1.8±0.2	1.0±0.1
Polifi-0046 (93)	267±6	3.9±0.5	2.2±0.2	

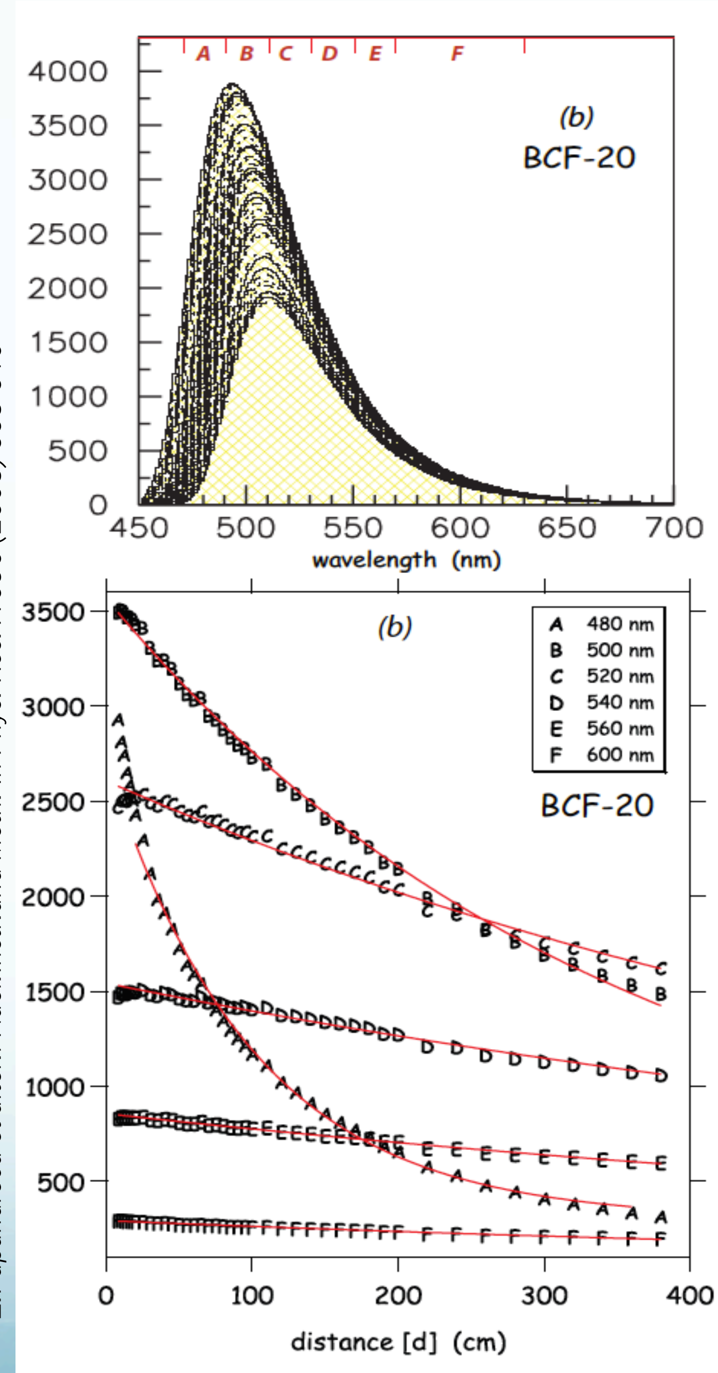
Table 3
Parameter τ and time resolutions

Fiber type	τ [ns]	σ_t (0.2 m) [ns]	σ_t (2 m) [ns]	σ_t (4 m) [ns]
BCF-12 (92)	2.42±0.08	0.23	0.34	0.52
BCF-12 (93)	2.16±0.03	0.21	0.28	0.40

What scientific literature says…

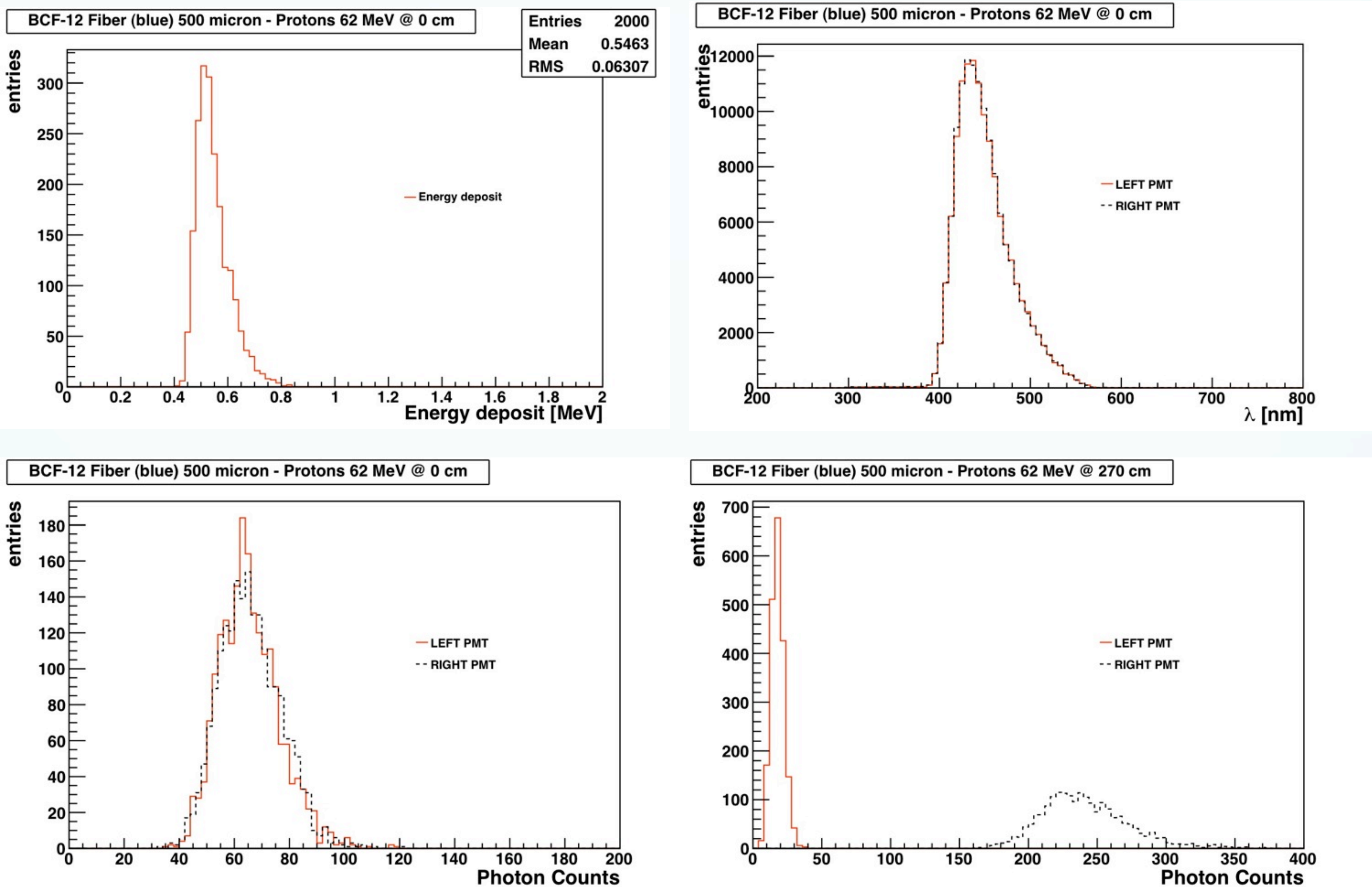


G. Drexlin et al. / Nucl. Instr. and Meth. in Phys. Res. A 360 (1995) 245–247



Z.Papandreou et alter./Nucl.Instr.and Meth. In Phys. Res. A 596 (2008) 338-346

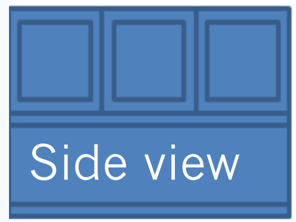
Geant4 simulations

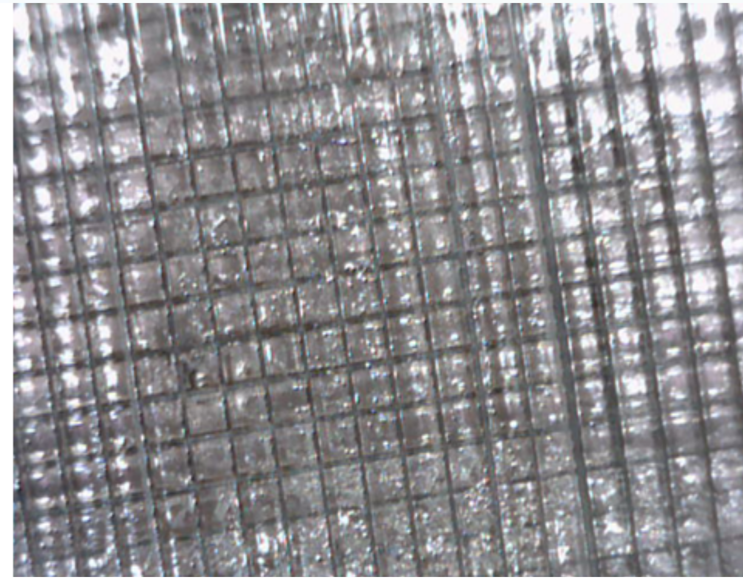


The Tracker

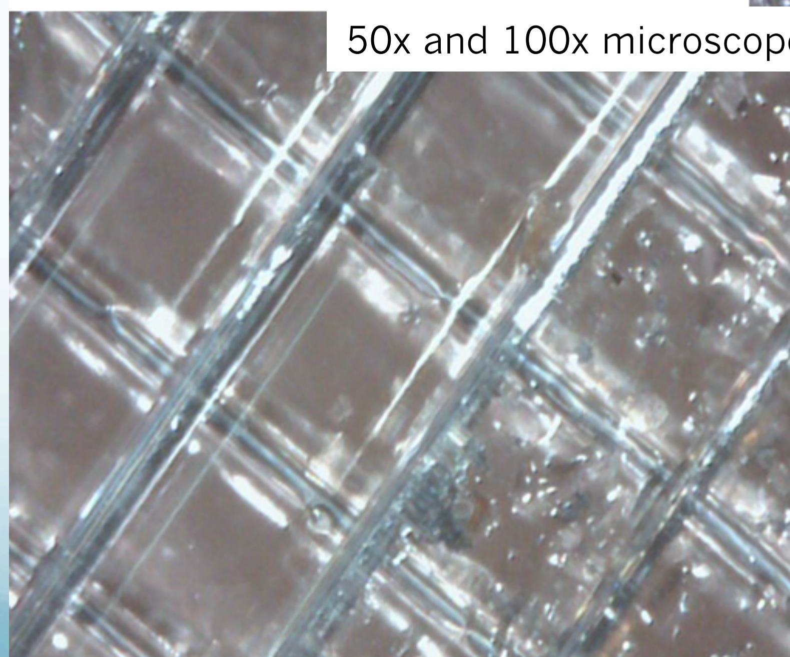
- Scintillating optical fiber Bi-dimensional strip detector
- Optical channel reduction:
  - Each sci-fi is read at both end for coincidence
  - 4√N channel reduction factor

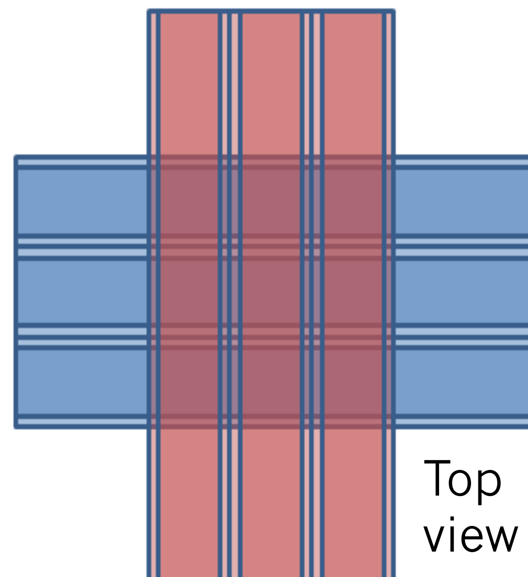
- Fast comparator array front-end
- Digital coded output for position
- Analog output for ΔE – PSPM
- dynode signal





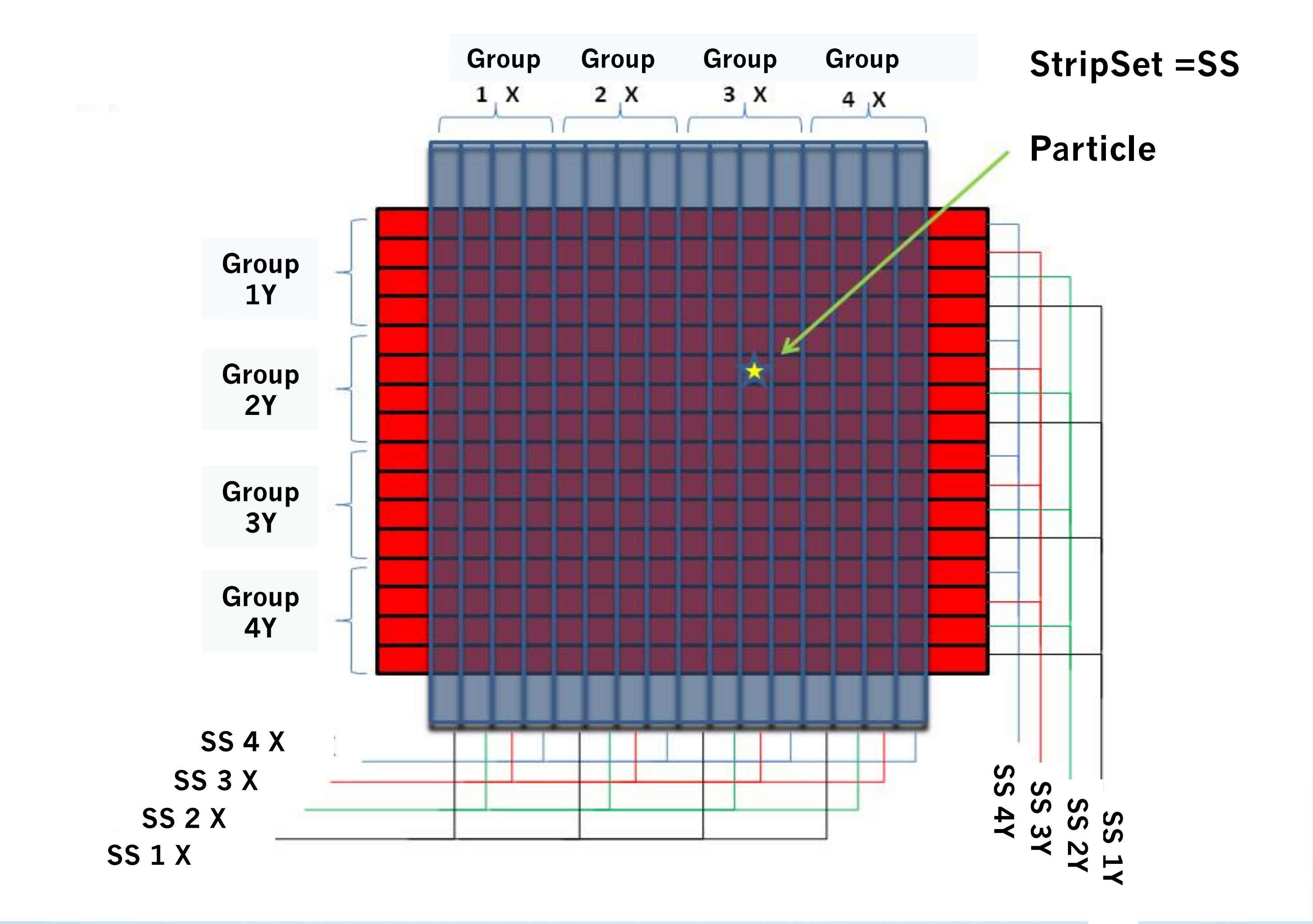
50x and 100x microscope image of the tracker sensitive area





Top view

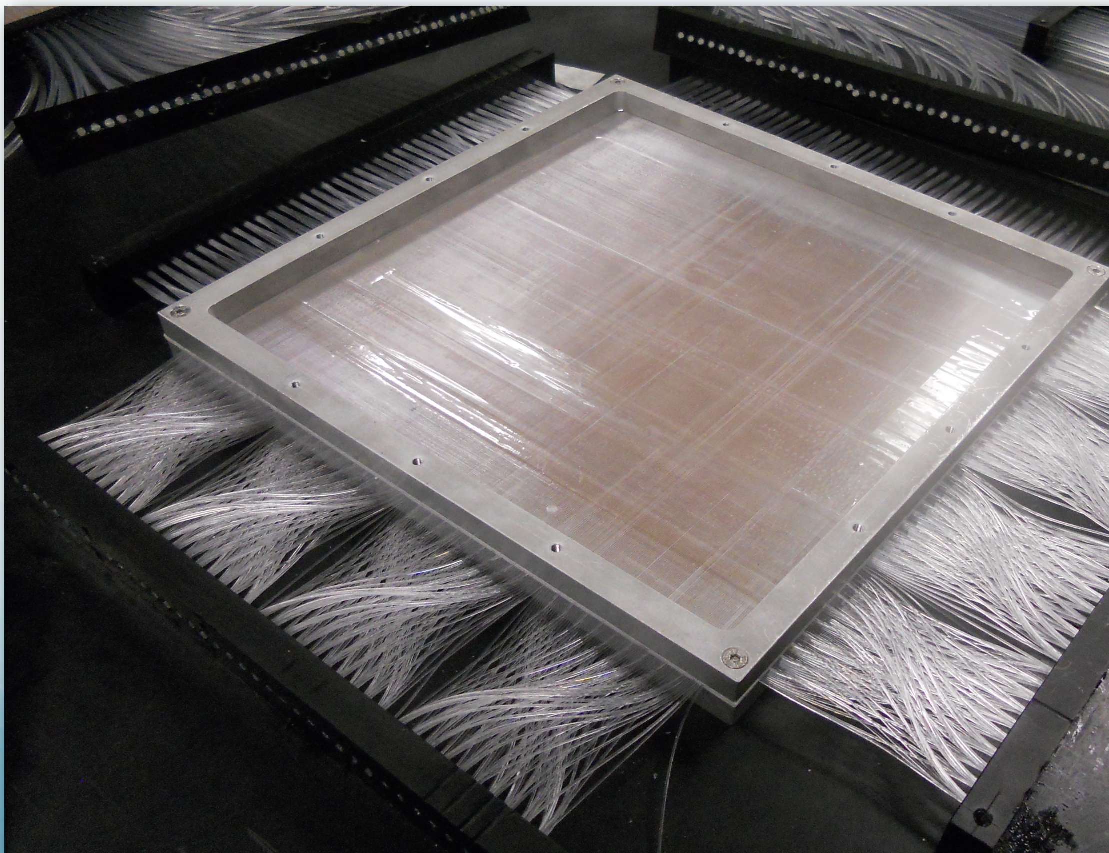
Read-out channel reduction system

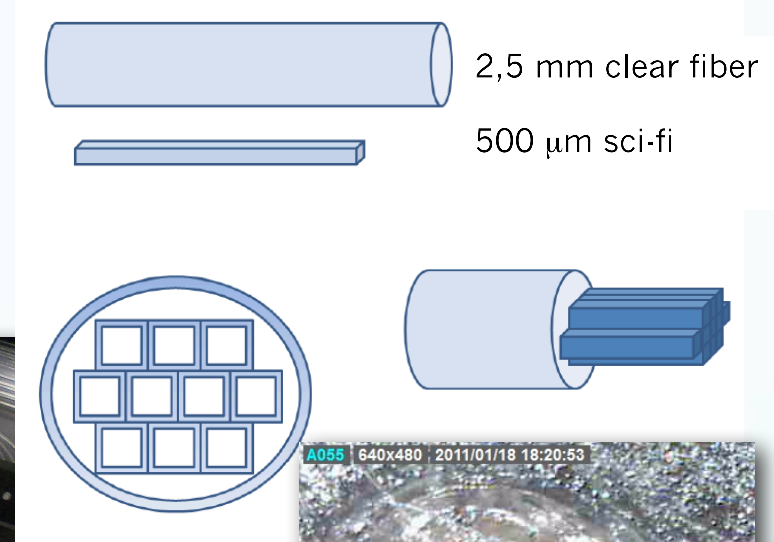


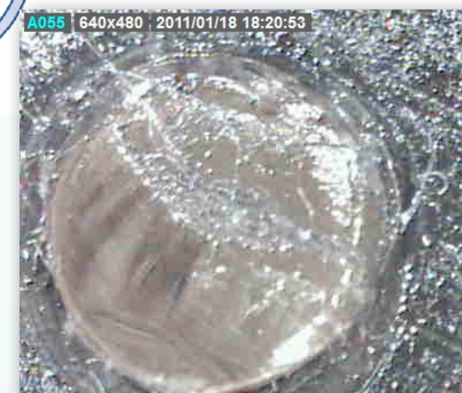
$Strip_{hit}$=Group* n + StripSet

Read-out channel reduction system

- Optical and mechanical coupling
- Optical gel
- Cut and lapping of each fiber
- Smallest bending radius with minimum attenuation



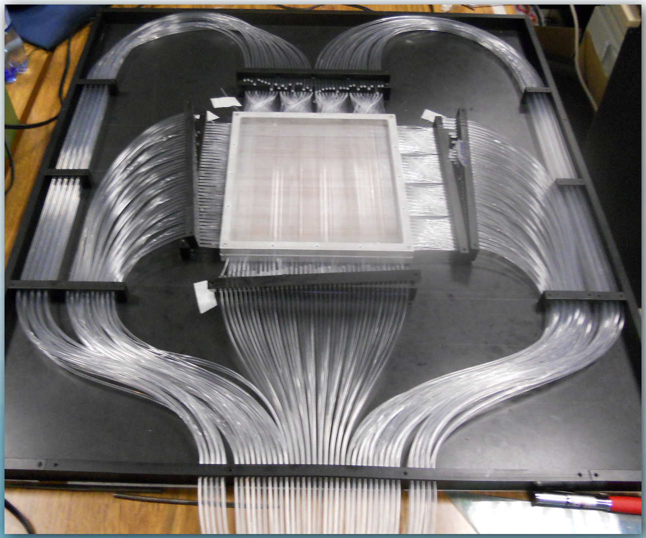


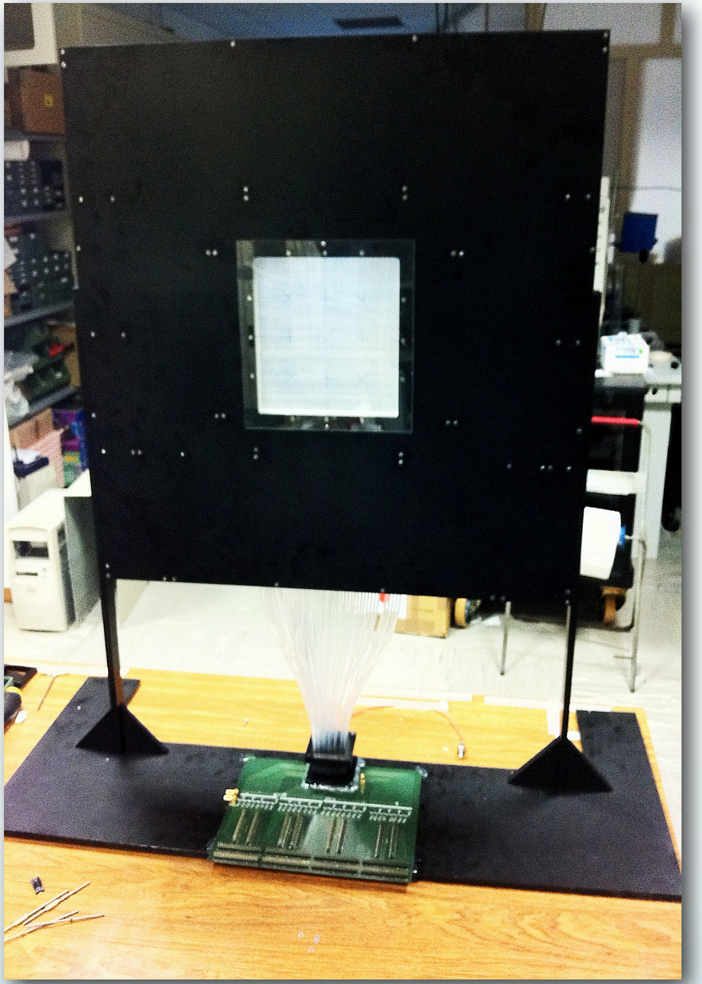


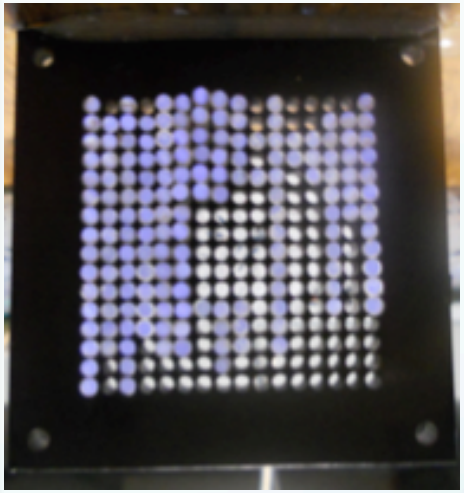
The Tracker

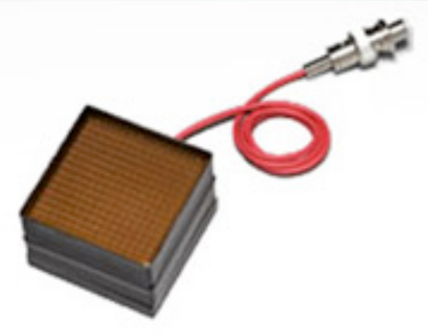
Prototype complete

- $20x20\ cm^2$
- 160 channels
- >10 MHz
- 500 μm sci-fi BCF-12
- Hamamatsu PSPM 16x16
    - ΔE Dynode signal
- Full custom FE
- NI PCI-RIO 7811 DAQ
- $70x100\ cm^2$

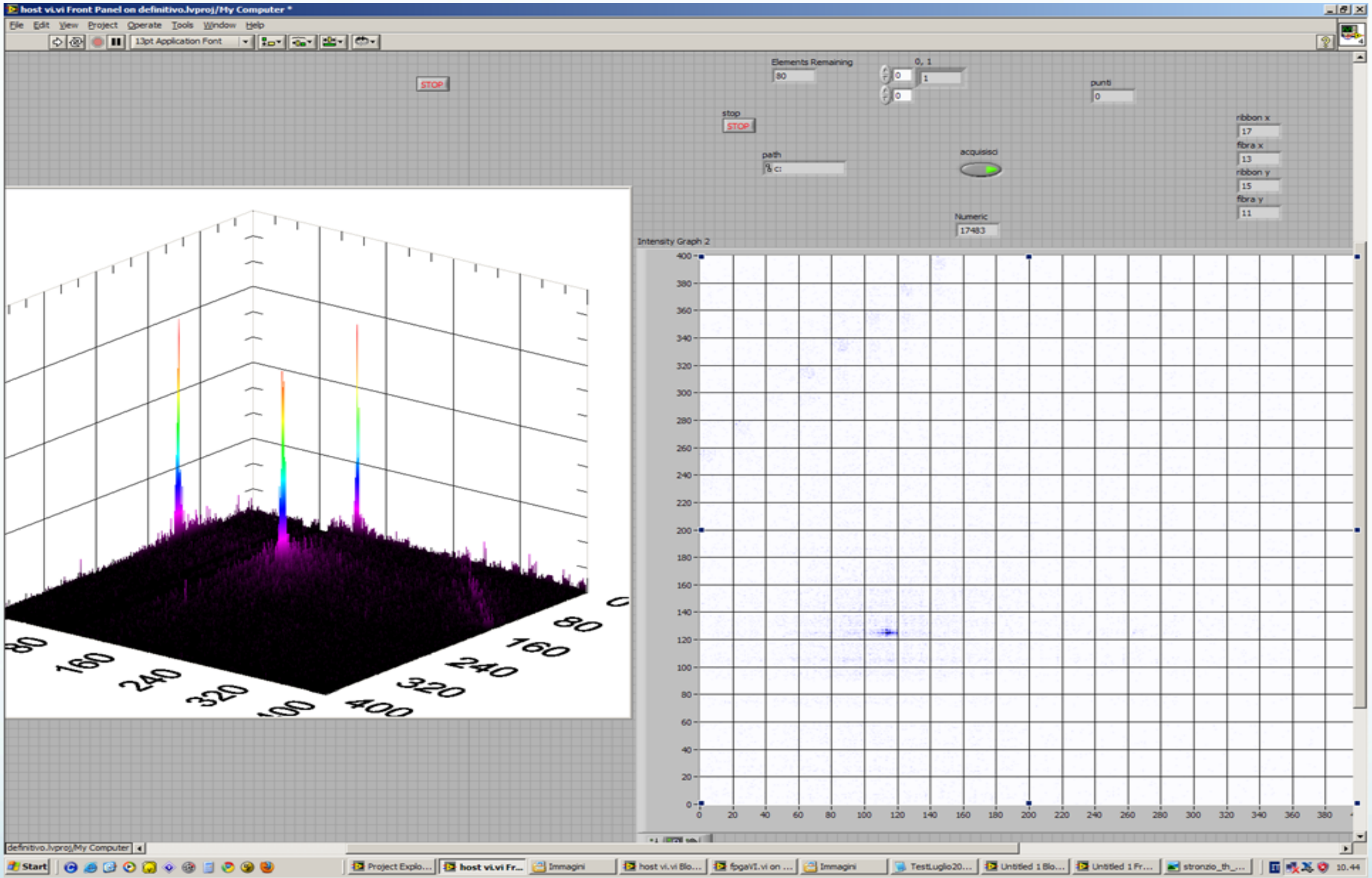








Software and Hardware



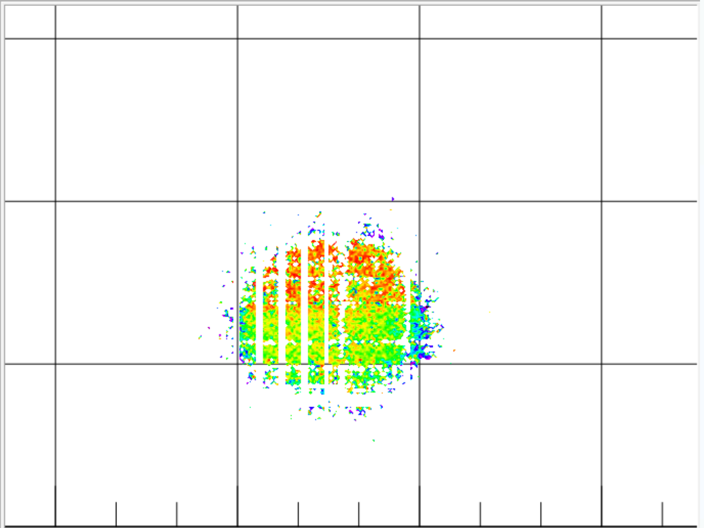
- FPGA based DAQ board by National Instruments;
- Platform LabView

Actual status

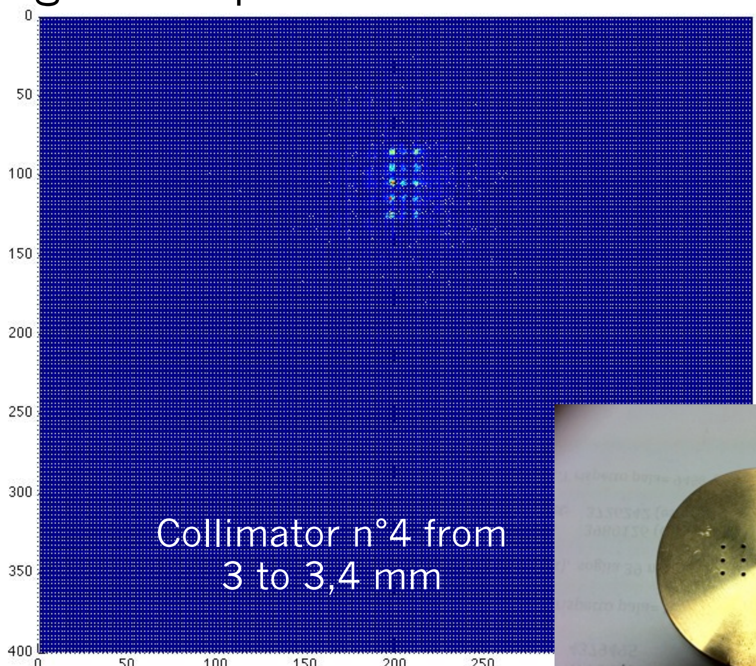
- Real time imaging device for charged particles based on scintillating optical fibers;
- High space resolution (150 μm) and large area tracker, (20x20 cm^2);
  - 500 μm multi-clad square scintillating optical fibers;
  - Particle track and ΔE;
  - Real Time;
  - Max event Rate 10 MHz;
- High space resolution (80 μm) and large area tracker, (12x16 cm^2);
  - 250 μm multi-clad square scintillating optical fibers;
  - Particle track and ΔE;
  - Real Time;
  - Max event Rate 10 MHz;
- Residual energy detector by particle range:
  - Area 4,5x4,0 cm^2
  - Estimated energy resolution 3%;
  - Proton up to 62 MeV/A;
  - Real Time;
  - Max event Rate 10 MHz;

OFFSET Tracker Measurements

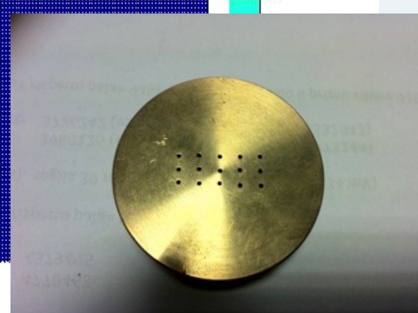
- UV Laser
- Cosmic rays
- Beta Source ^{90}Sr
- 62 to 30 MeV proton beam

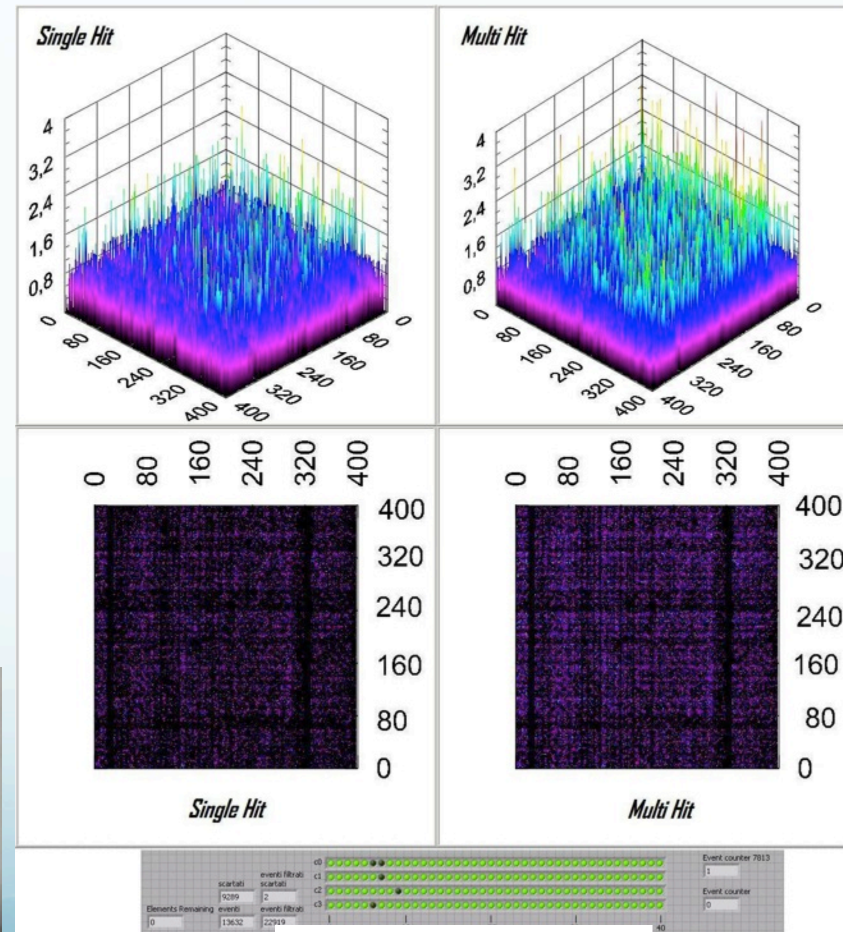


Proton Radiography
OFFSET+PRIMA Calorimeter
Plexiglass step 1 cm



Collimator n°4 from
3 to 3,4 mm

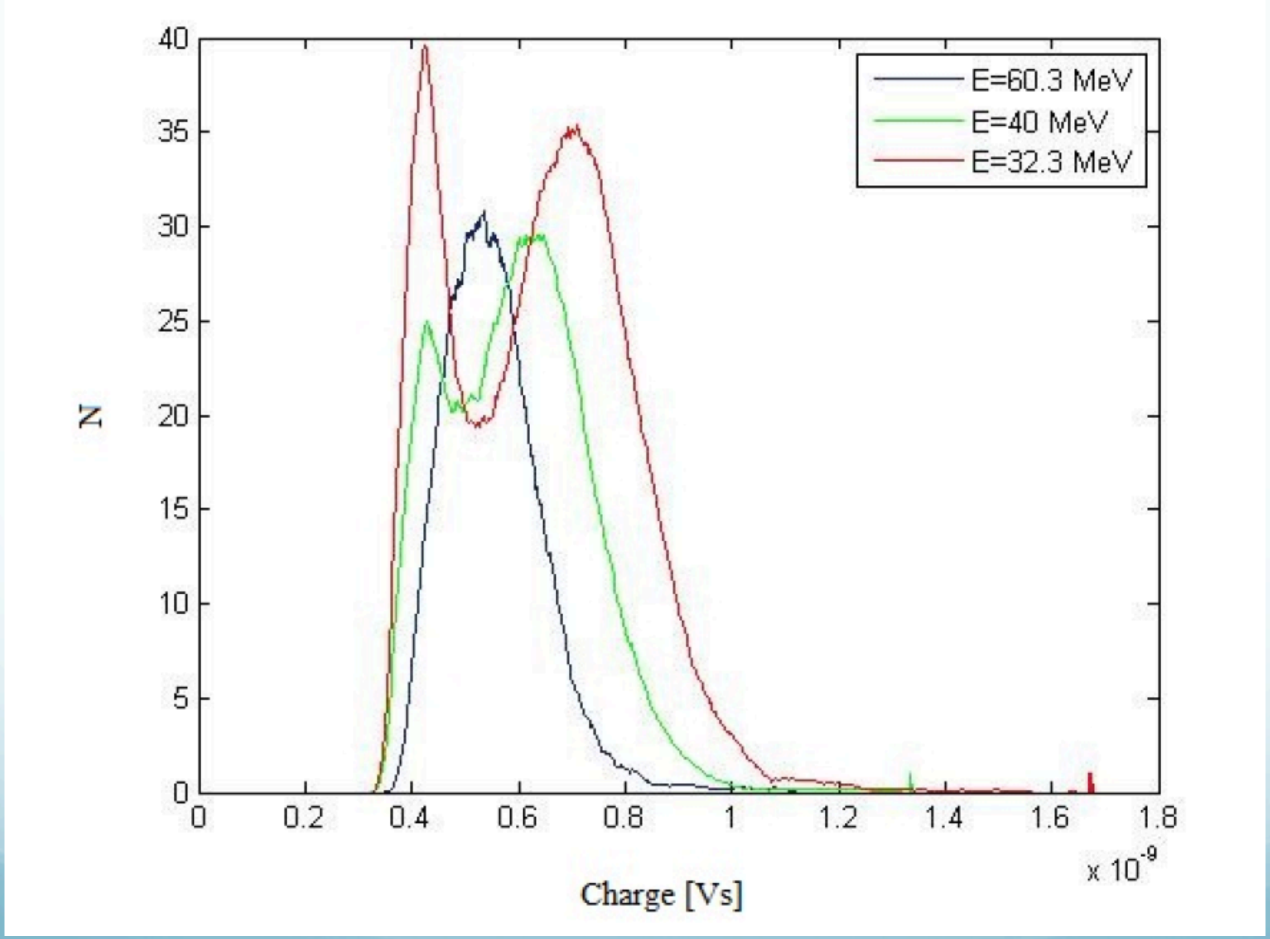




Cosmic Rays

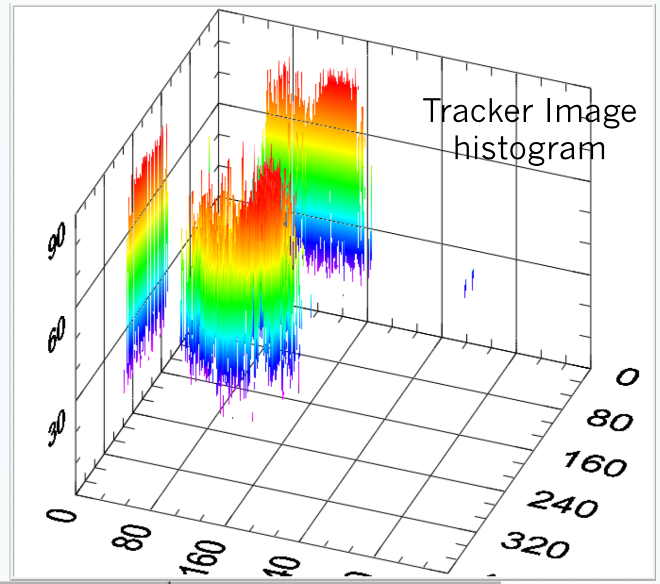
OFFSET Tracker
ΔE measurement

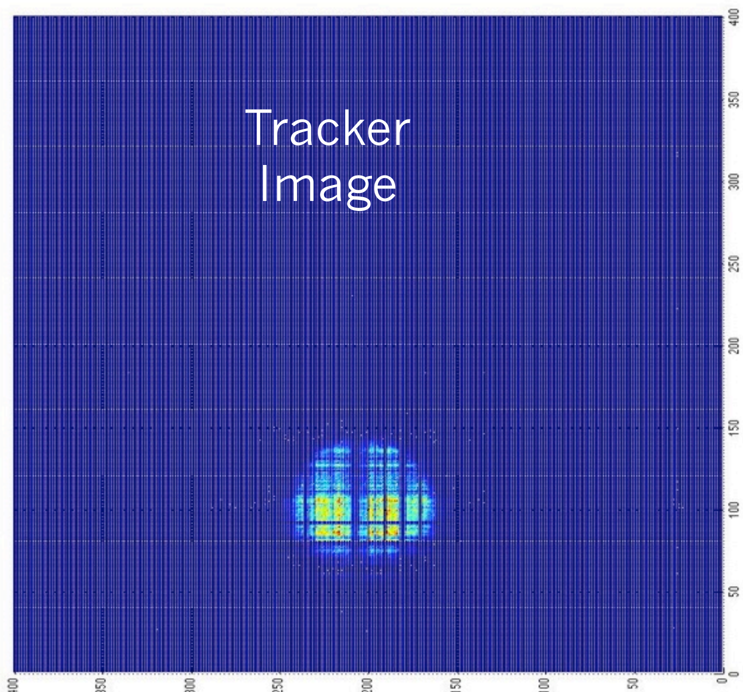
- PSPM dynode signal acquisition by digital oscilloscope;
- No correction by the crossing position of the particle;
- 4 pixel PSPM involved.

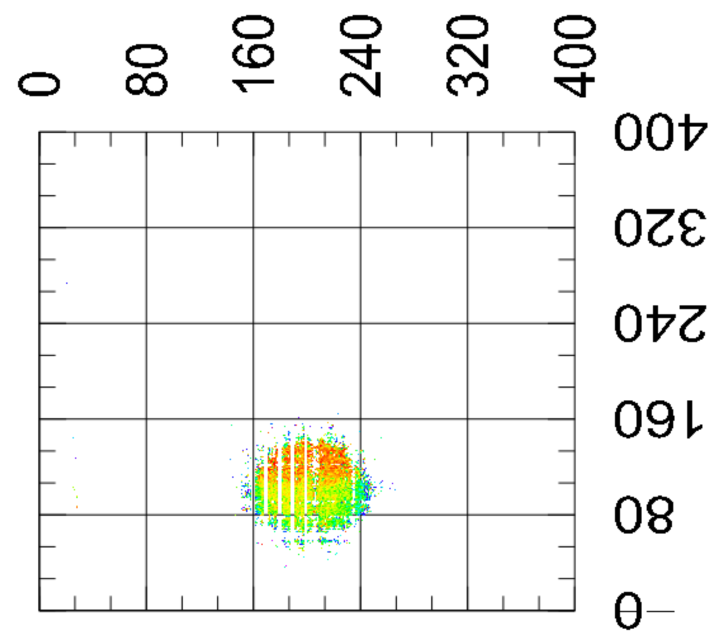


Proton radiography of a 1 cm plexiglass sheet

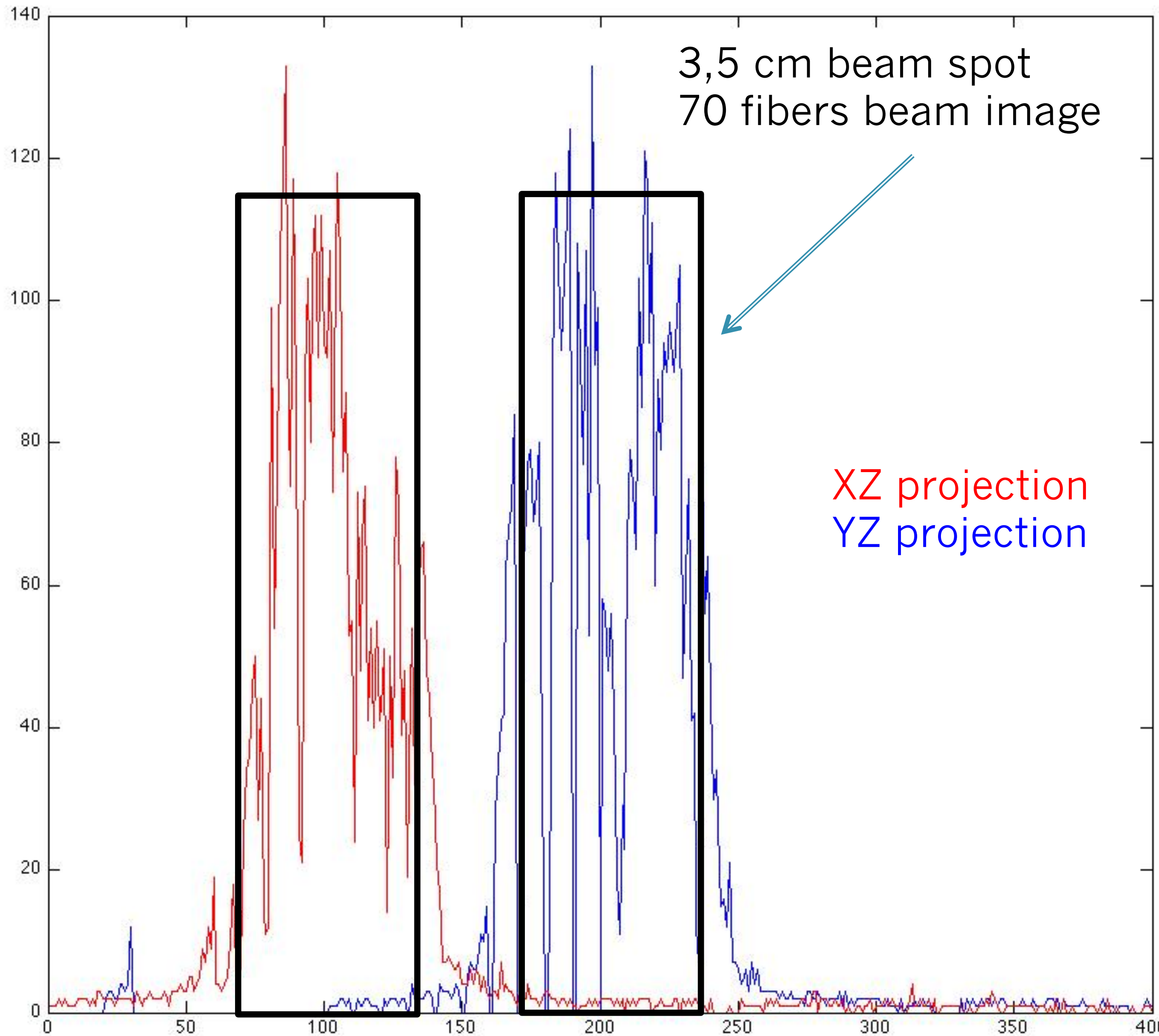
- Tracker in front of a YAG calorimeter (PRIMA)
- 62 MeV Proton beam
- Trigger given by the tracker
- Event counter
- Time stamping
- Offline reconstruction

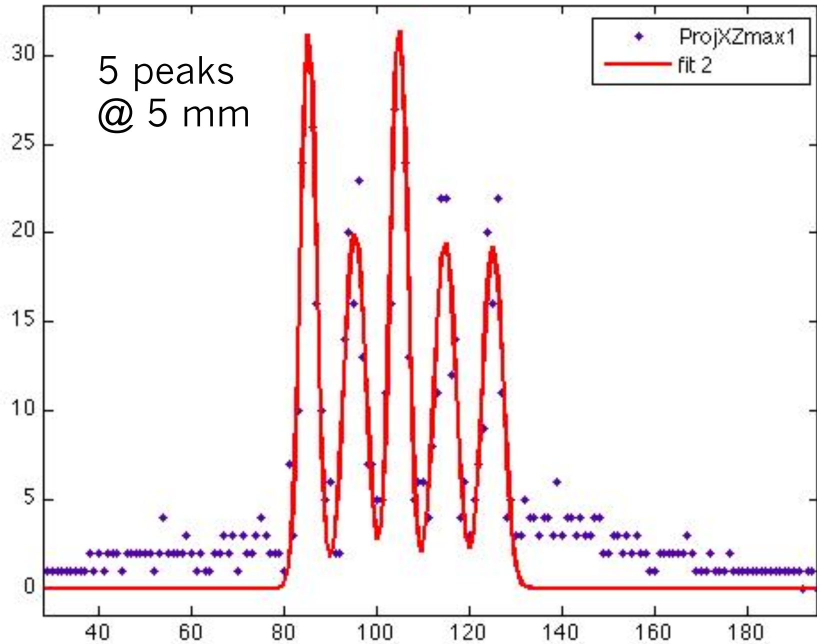


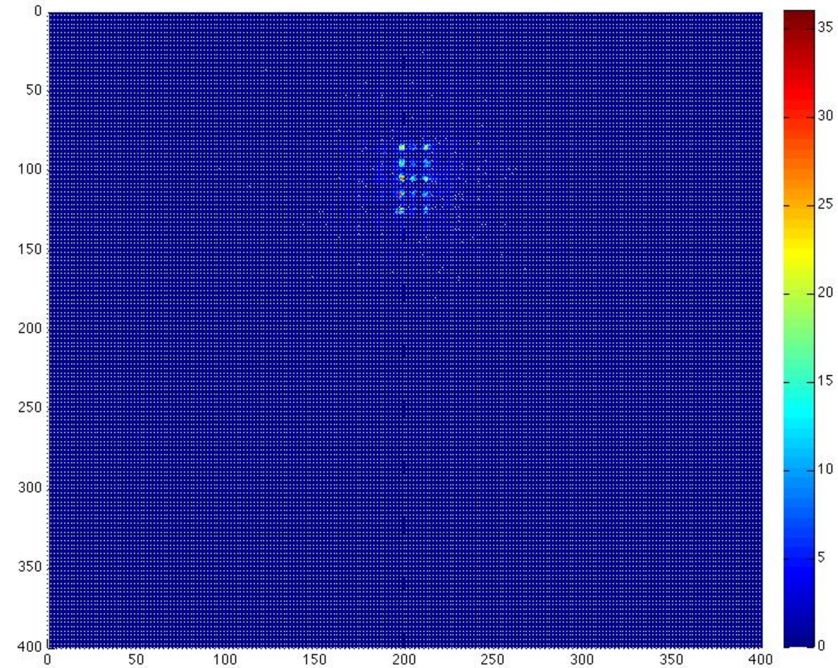


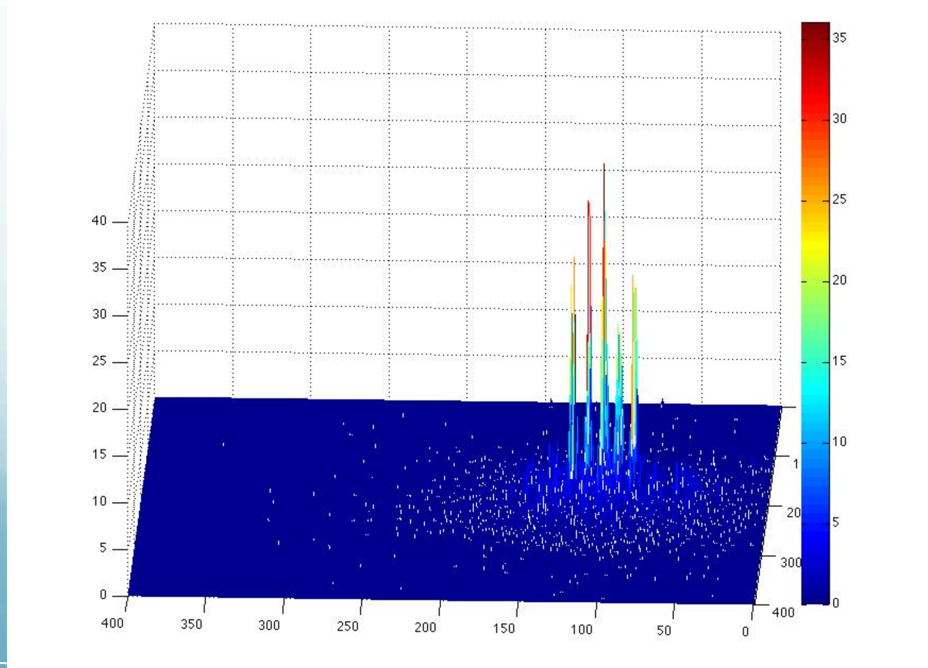


Proton Radiography

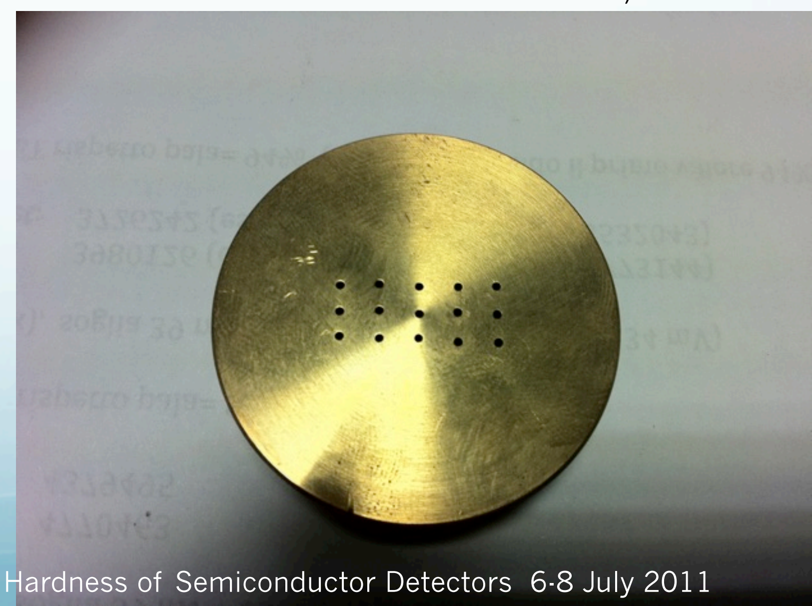

3,5 cm beam spot
70 fibers beam image
XZ projection
YZ projection
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
350
400

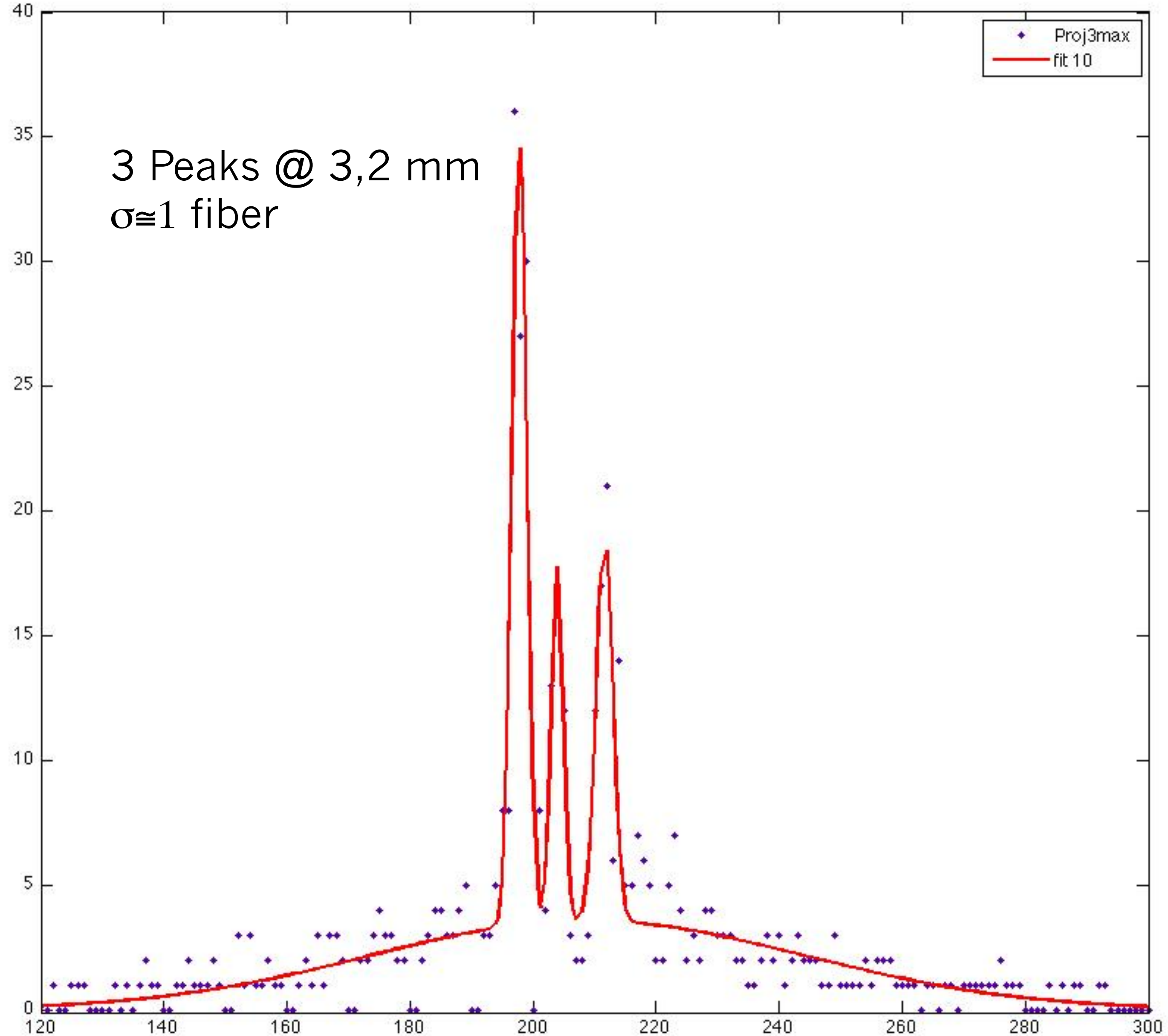






Collimator n°4 from 3 to 3,4 mm




3 Peaks @ 3,2 mm
σ≅1 fiber
Proj3max
fit 10
0
5
10
15
20
25
30
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40
120
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220
240
260
280
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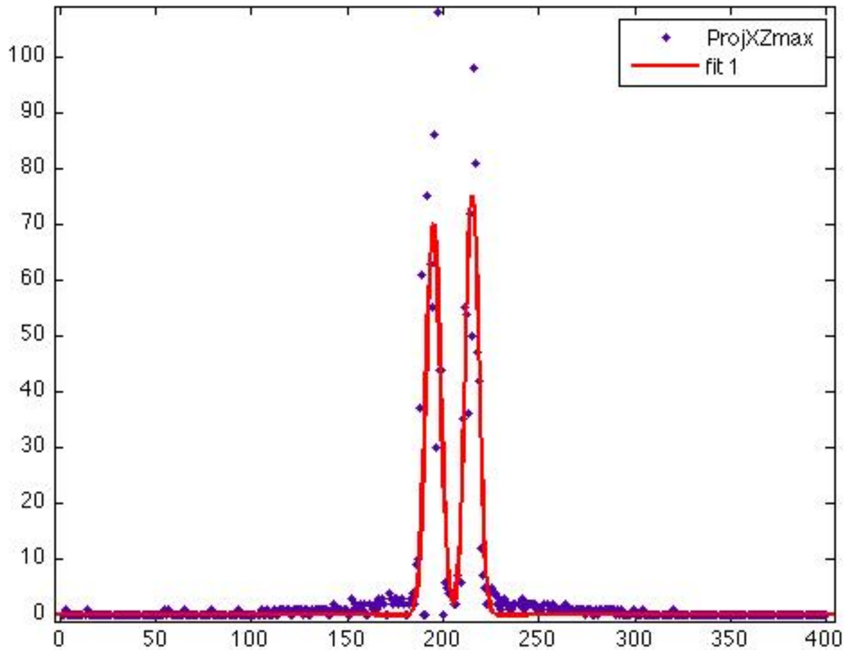
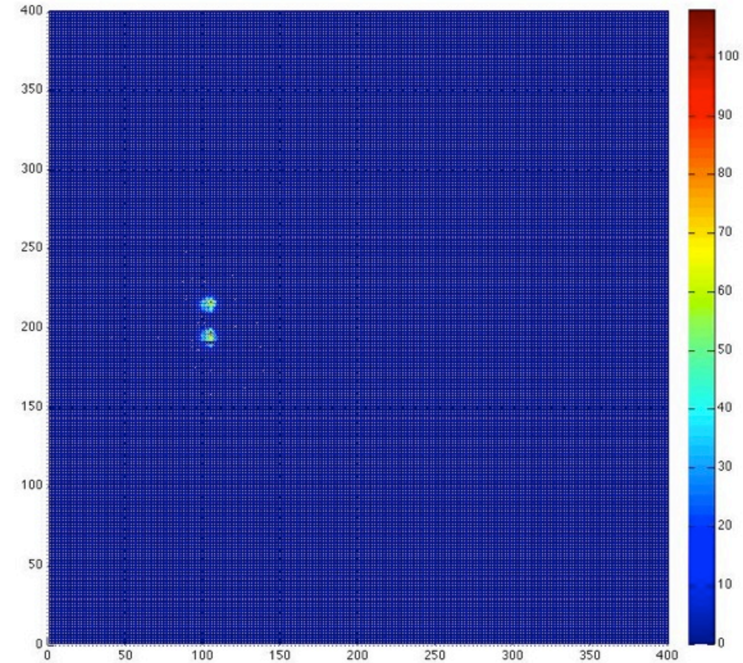
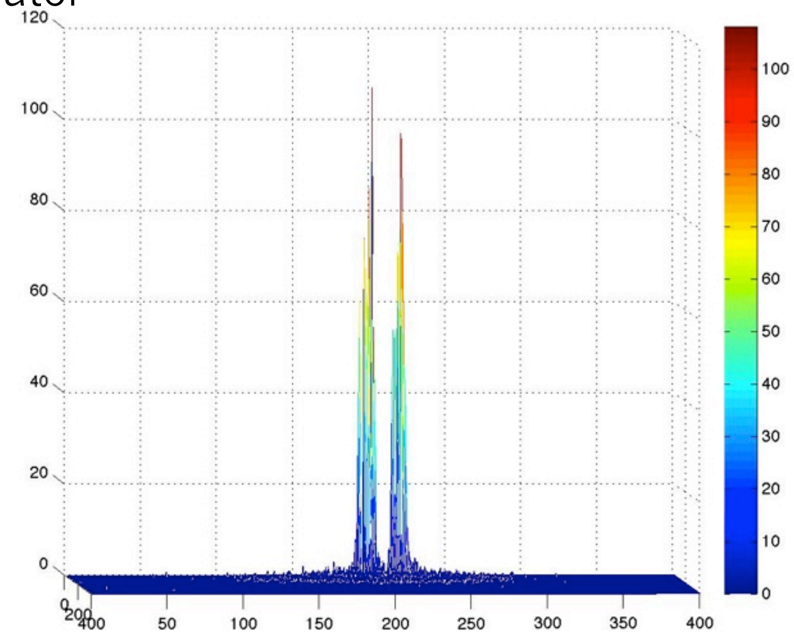
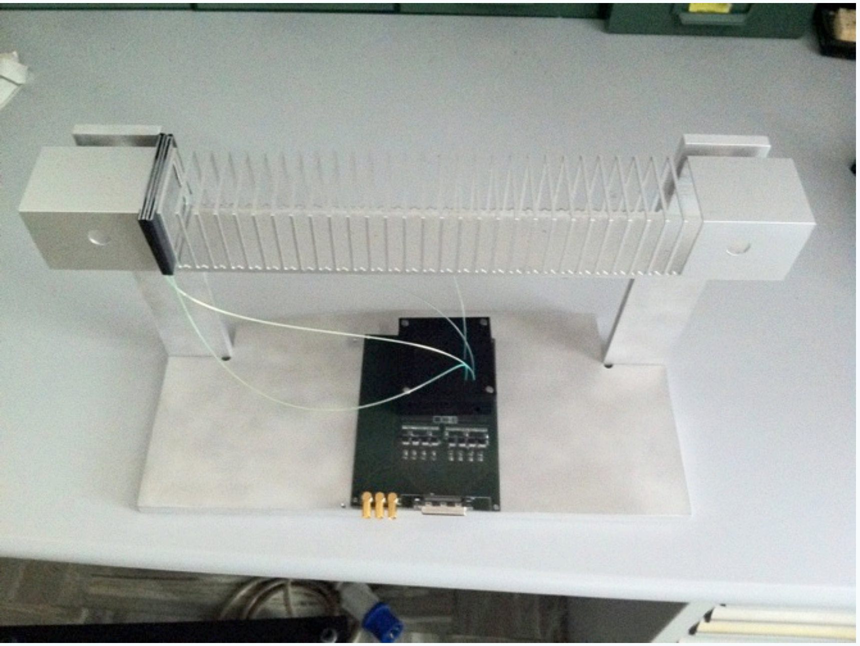


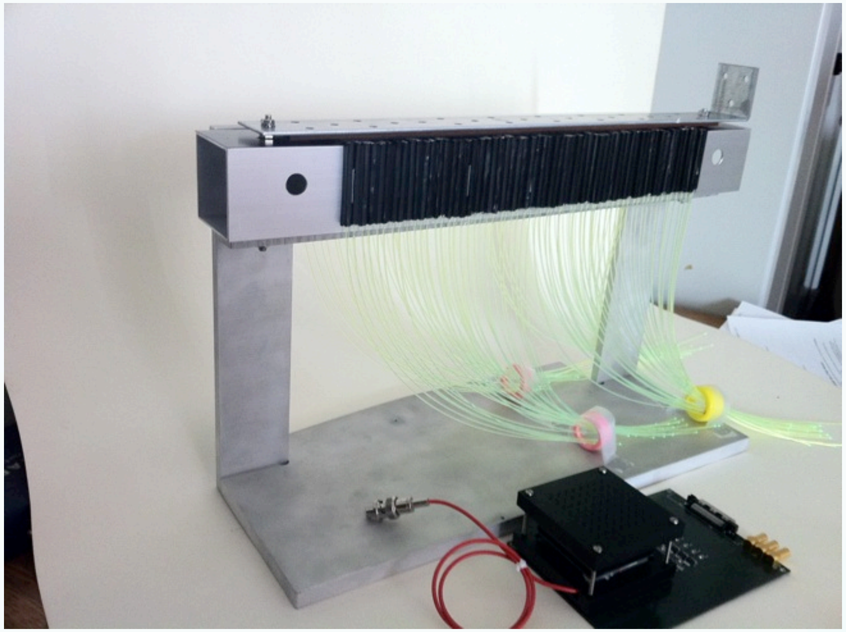


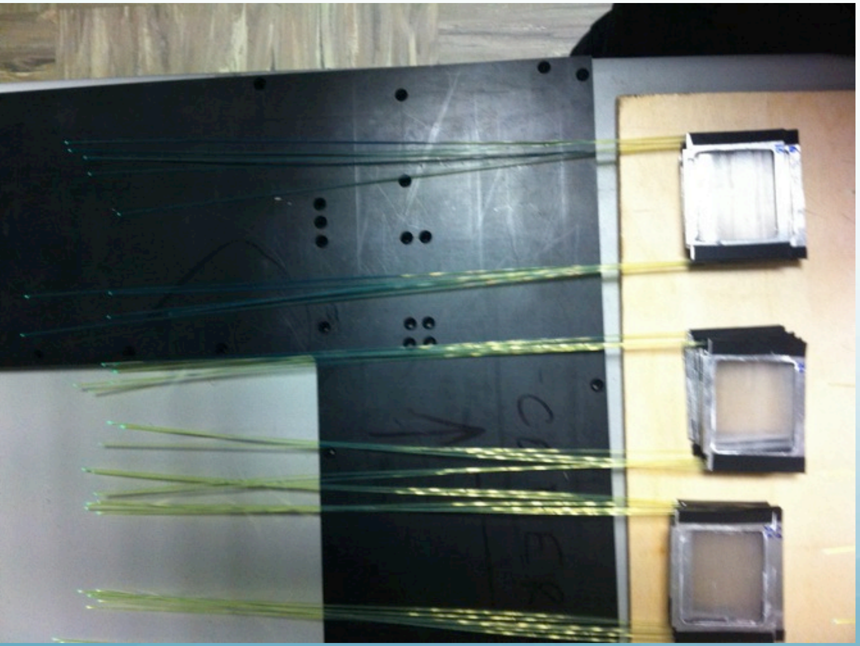
Two 2,5mm holes collimator



Residual range detector







- 60 scintillating fiber layers BCF-12;
- 45x40 mm^2 area;
- 500 μm multi-clad square scintillating optical fibers;
- 1mm wavelength shifter x2;
- 64 channels Hamamatsu PSPM
- Read-out channel reduction
- Time over threshold
- Real time

Next steps

- First prototype of the tracker
  - Demonstration of the technique
  - Planned DAQ electronics upgrade
  - Planned overall size reduction
- New prototypes of tracker and residual range detector under construction
- Development of a particle radiography device real time, large area and high space resolution
- ....PCT real time

Conclusions

- The read-out channel reduction allows for a faster front-end and DAQ electronics
- Scintillating optical fibers are suitable for medical imaging at high rate and high space resolution
- The detectors under study and development can be combined to form modular and complex detector
- The main issue is the mechanical frame for larger detectors