Single Electron Interference and Diffraction Experiments with a High Energy Physics Detector

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Outline

- Young's Experience
- Instrumentation:
  - Transmission Electronic Microscope
  - Nanometric Double Slit
  - Apsel 4D Sensor
  - Data Acquisition System -> HW + FW + SW
- Preliminary Tests
- Single Electron Interference
- Conclusion

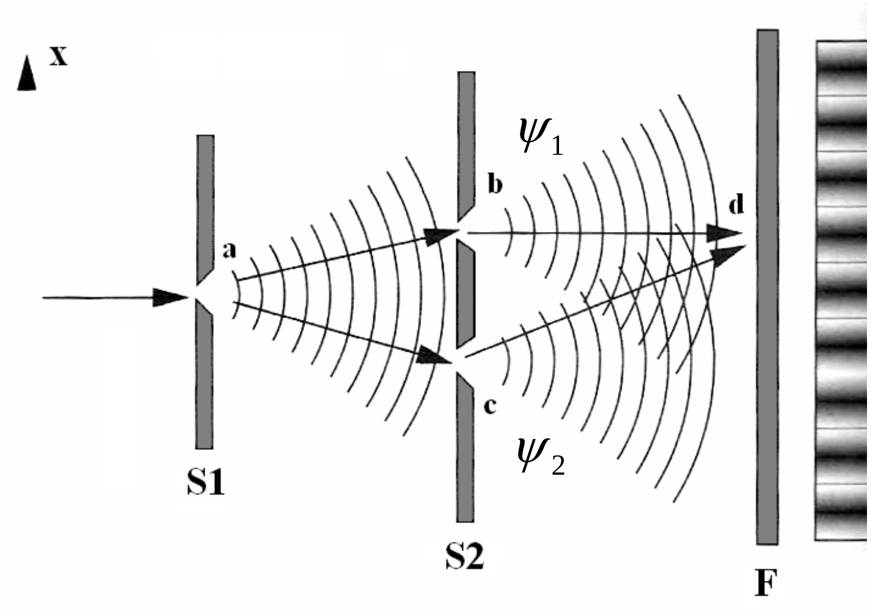
Young's Experience

Basics

- Monochromatic/Monoenergetic coherent source

  λ $\lambda_{De\ Broglie} = h/p$

- Two slits at a distance **d** create secondary coherent waves
- Screen at a distance **D >> d : Interference Pattern**



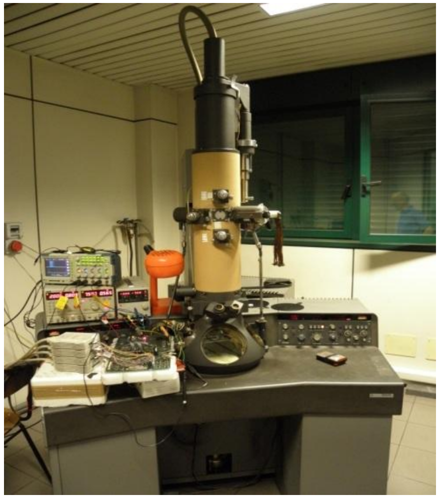
$$P(x) = |\psi_1 + \psi_2|^2 = |\psi_1|^2 + |\psi_2|^2 + \boxed{2\,\mathrm{Re}\,\psi_1^*\psi_2}$$

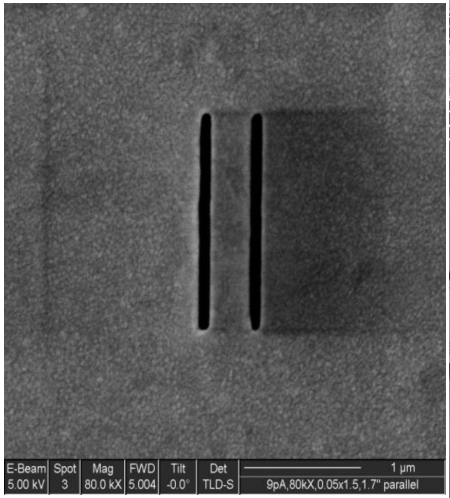
R. Feynmann: - Lecture on Physics, Vol 3

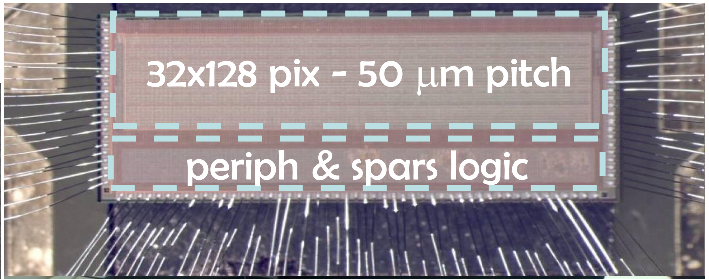
Young's experiment with the electrons can only be conceptual in nature because of the smallness of the de Broglie wavelength

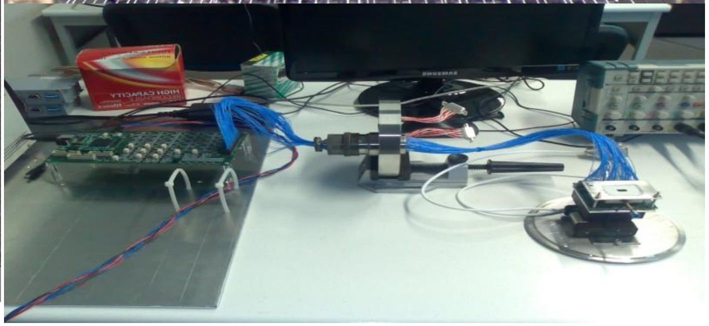
The Experimental Setup

- Instrumentation
  - Transmission Electron Microscope (TEM)
  - Nanometric Double Slit
  - APSEL 4D : High Space-Time Resolution Sensor
  - Data Acquisition System





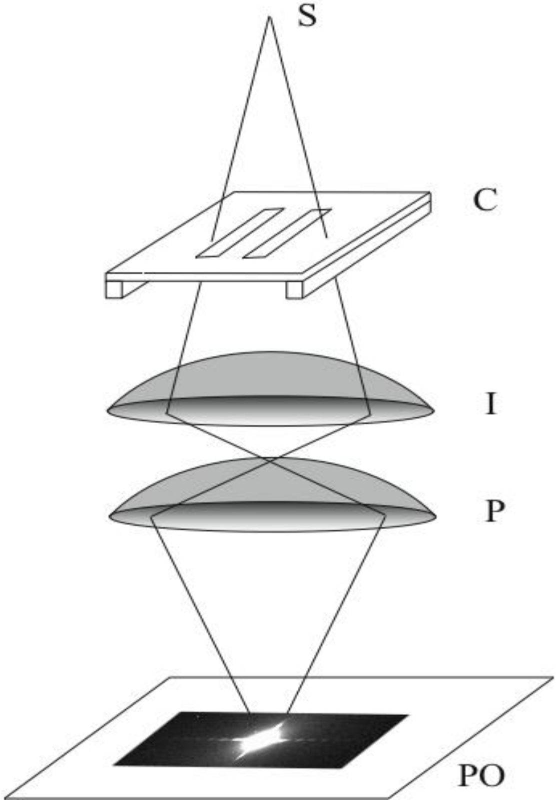




The Microscope and the Setup

TEM Philips EM400T (120 keV max)

40 keV , v=0.4 c , **λ=h/p= 5.9 pm**

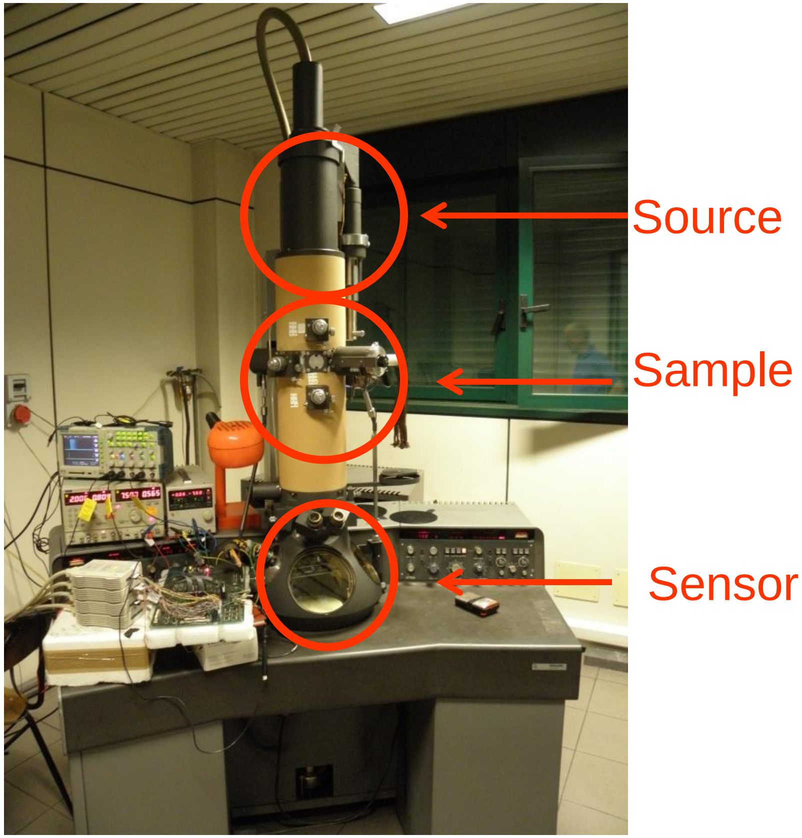


S - Small size source

C – Sample with two slits

I,P – Image and projection lenses

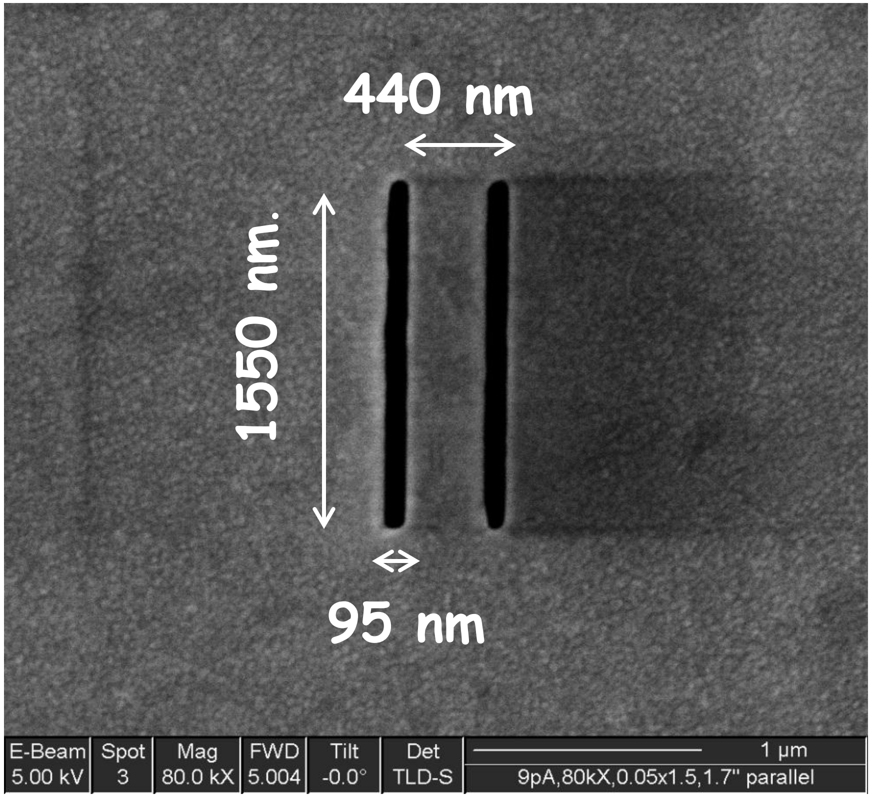
PO: projection plane

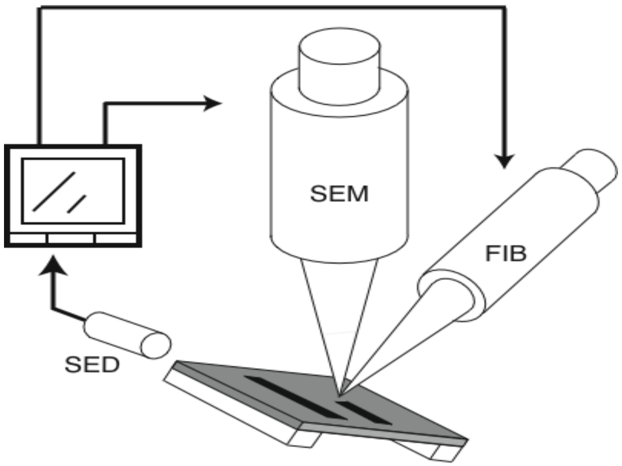


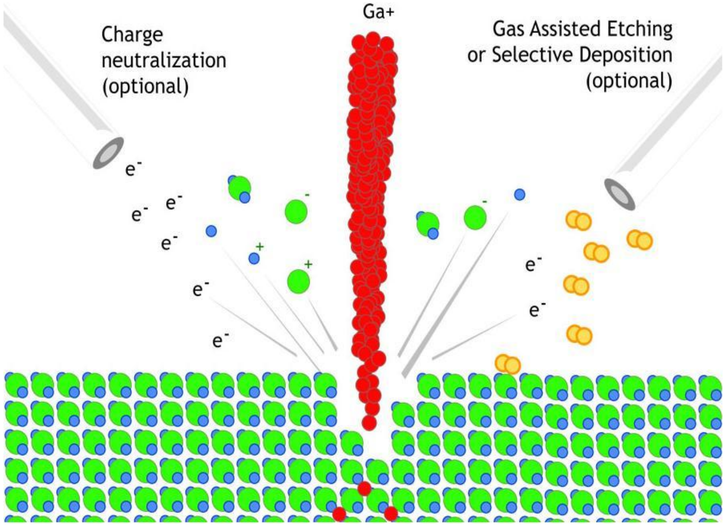
Experimental conditions: plane wave approximation (**Fraunhofer** regime)

The Double Slit

Focused Ion Beam from a
liquid Ga+ Source
milling a 250nm thick gold layer,
deposited by flash evaporation on a copper grid
coated with carbon film







The Sensor : APSEL 4D

Vertex detector for High Energy Physics

ST 130nm CMOS Technology

4096 Monolithic Active Pixel Matrix

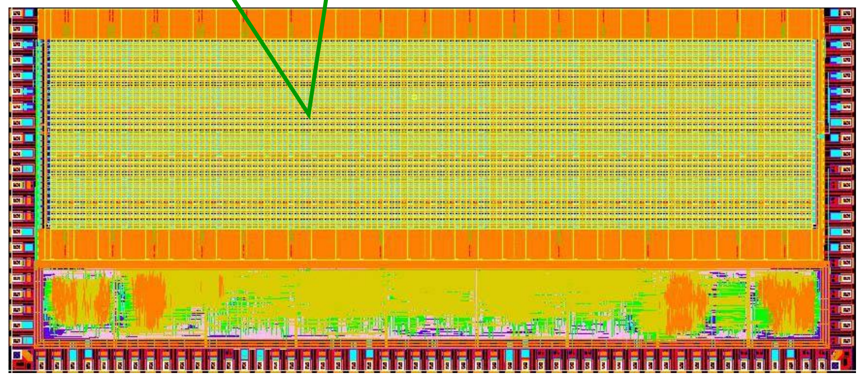
Optimized for charged particle identification

Each Pixel has Digital Output
- Hit / No Hit
- Position
- Time Stamp

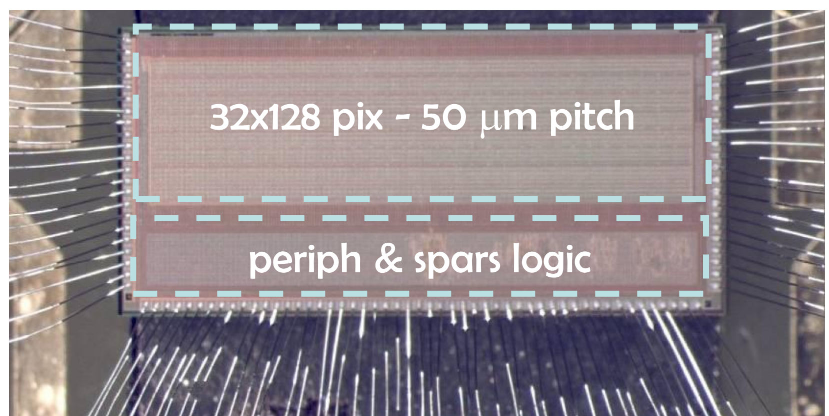
x,y: spatial resolution 15 μm
t: max time resolution 0.4 μs

Clock frequency: up to 20-50 MHz

4096-MAPS matrix



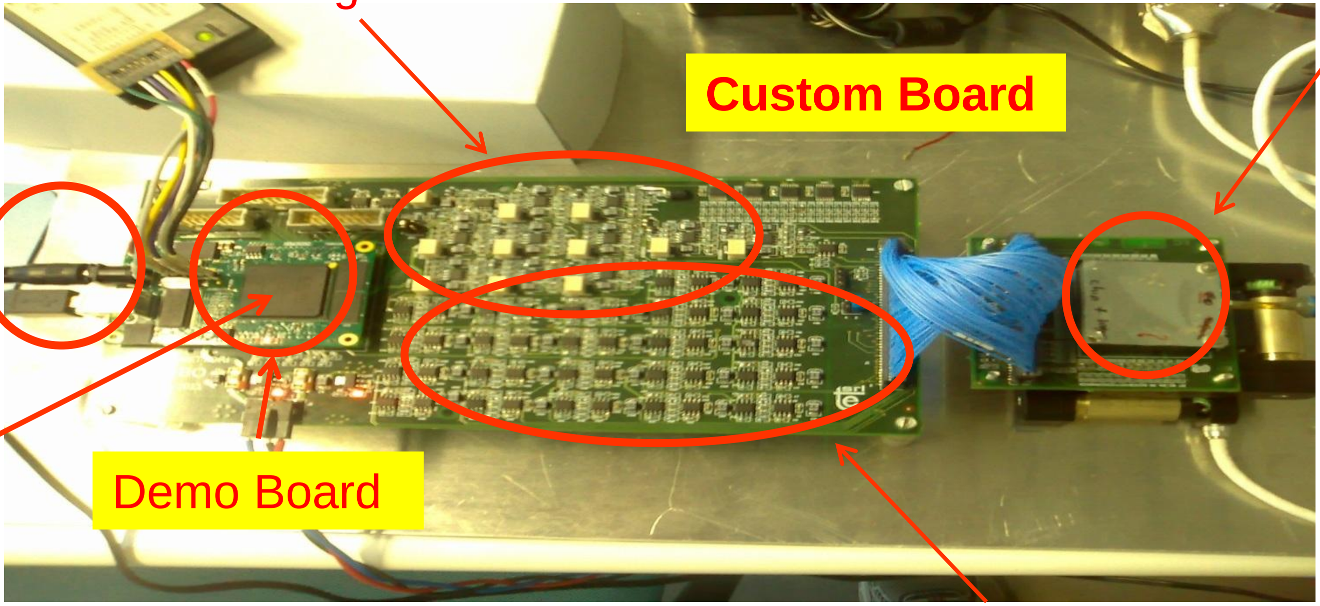
Squared Pixels 50 x 50 μm
Sensitive Area : 6.4 mm x 1.6 mm



Efficiency measured with 12 GeV proton beam at CERN: **≈ 90%**

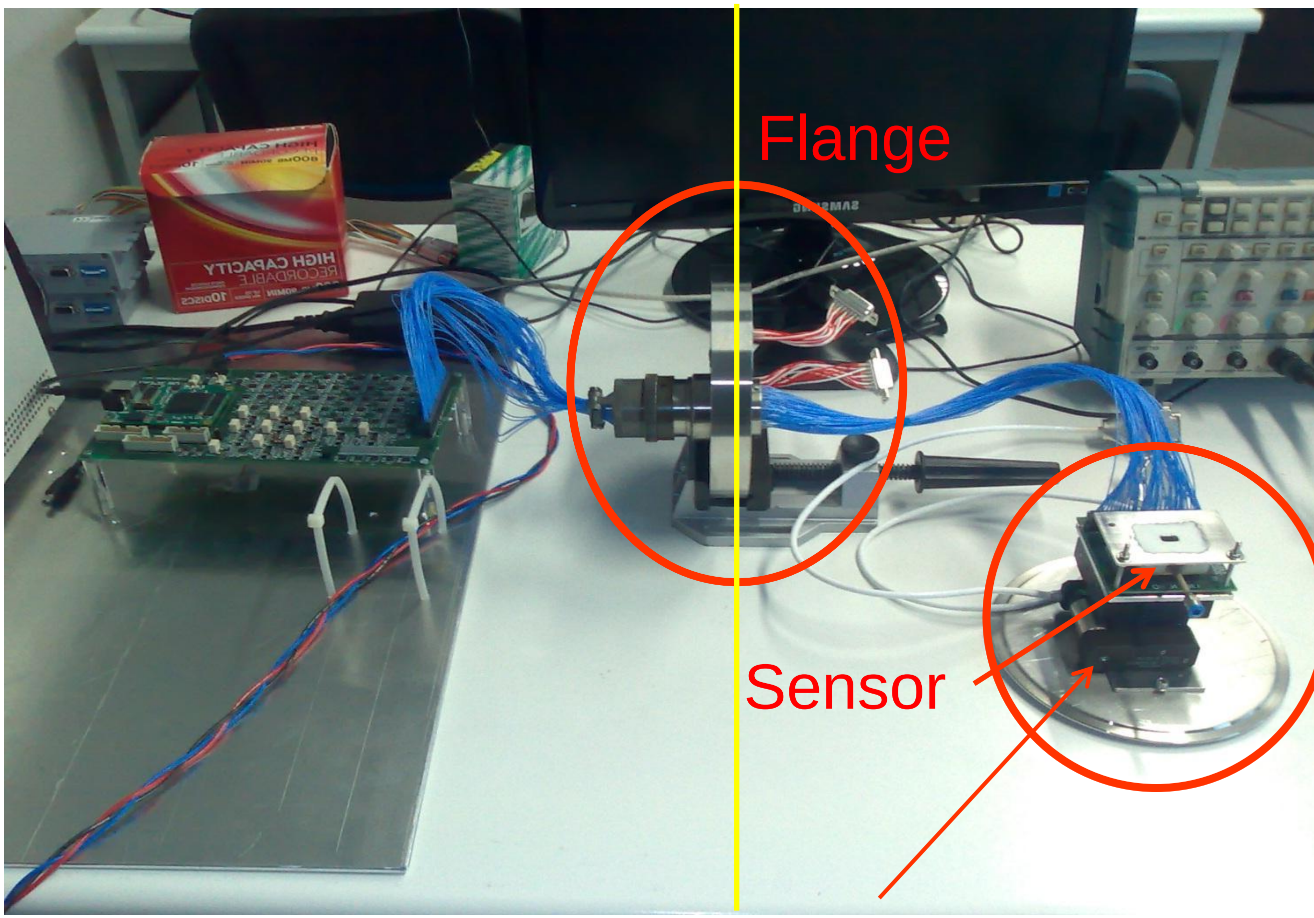
DAQ : Hardware

- Real Time Data Acquisition
- Sensor-> Board -> FPGA -> USB -> Computer
- Micrometric Bidimensional Movimentation

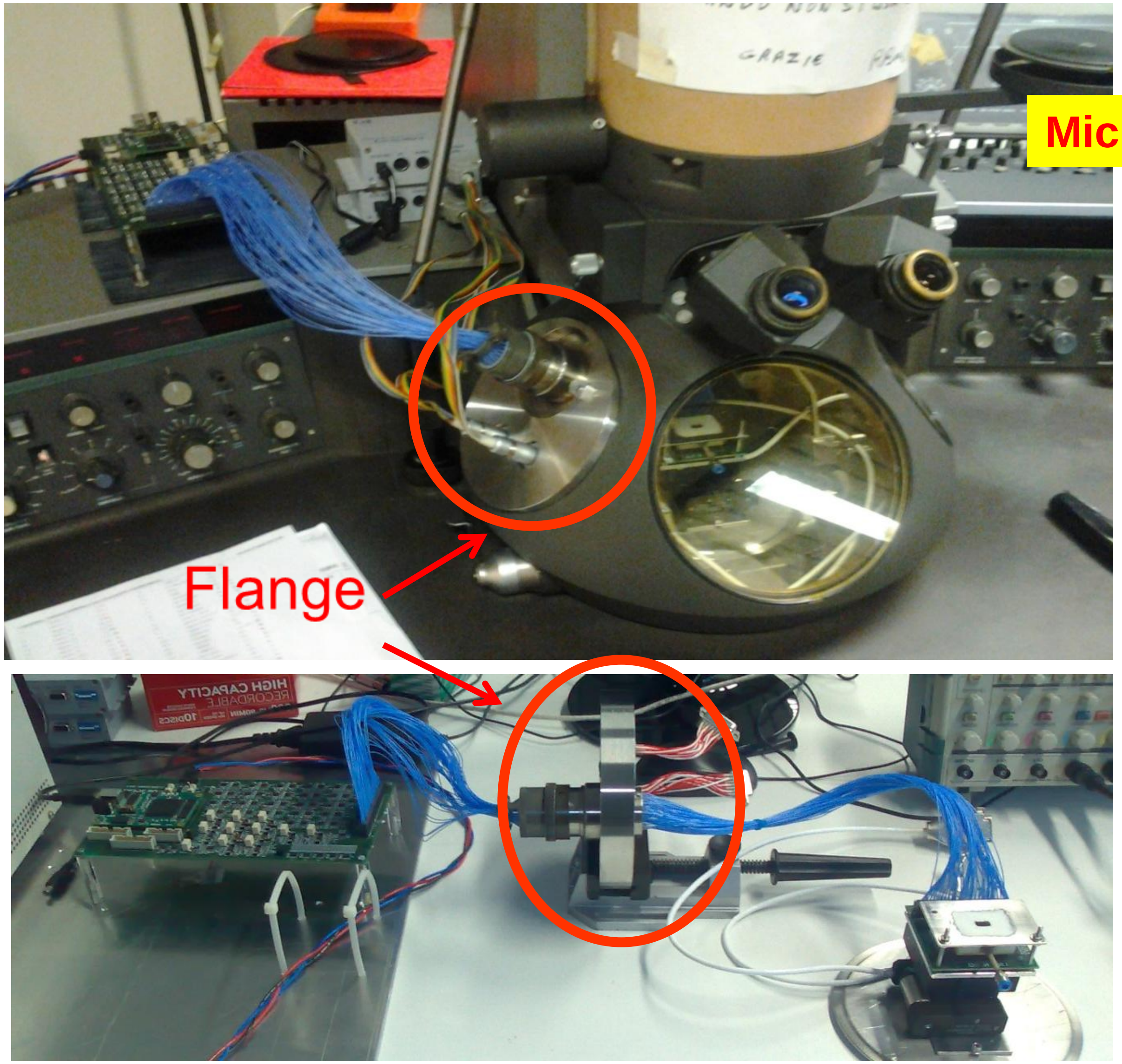


Hardware

- Connections and Movimentation



Chip placement inside TEM



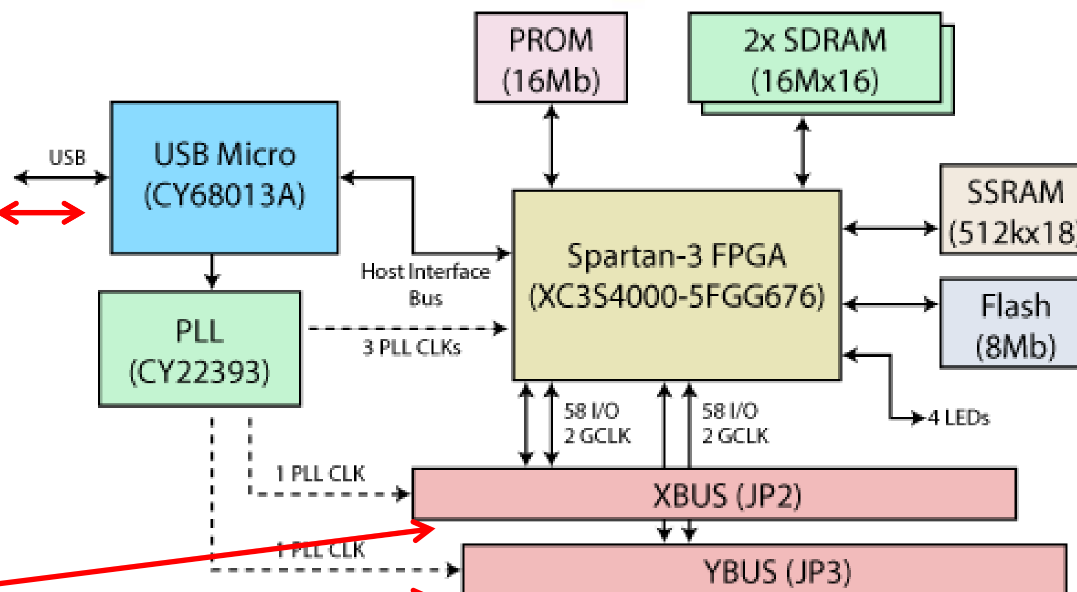
The Programmable Board

FPGA

Opal Kelly XEM 3050

- Low Cost
- Small Dimensions (75mm x 50mm x 15.9mm)
- Firmware/Software Libraries for
  FPGA-PC interface

USB 2.0 Connector :   **PC**



Xilinx Spartan-3 FPGA

7000 CLB ~600 User I/O
1.8 kbit di Block RAM
4 Digital Clock Manager

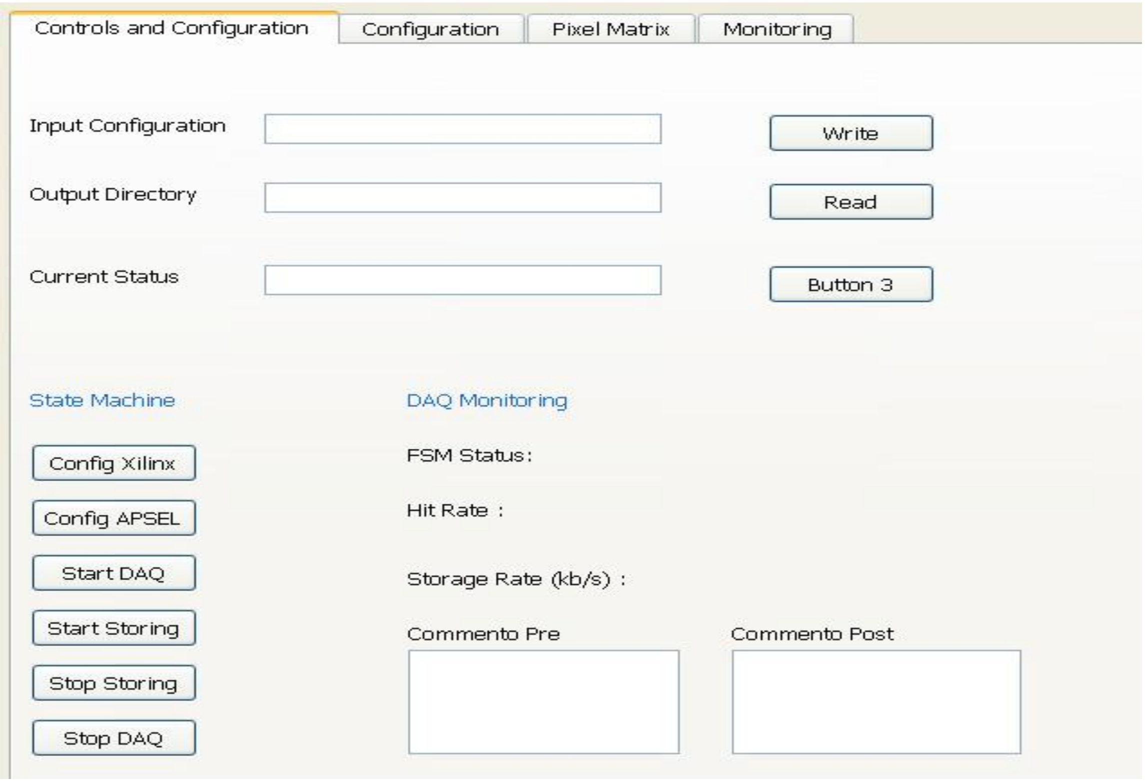
2 High Density 80-pin
Expansion Connectors

The Firmware

- VHDL Code
  - Chip Configuration and Control
  - Data Reception, Elaboration, Formatting and Transmission to PC
  - Clock Management
    - Fast clock for Electronics
    - Slow control clock for Chip Configuration
    - Time Counter clock for the Sensor

Software

Graphic Interface for Chip control and Data Acquisiton



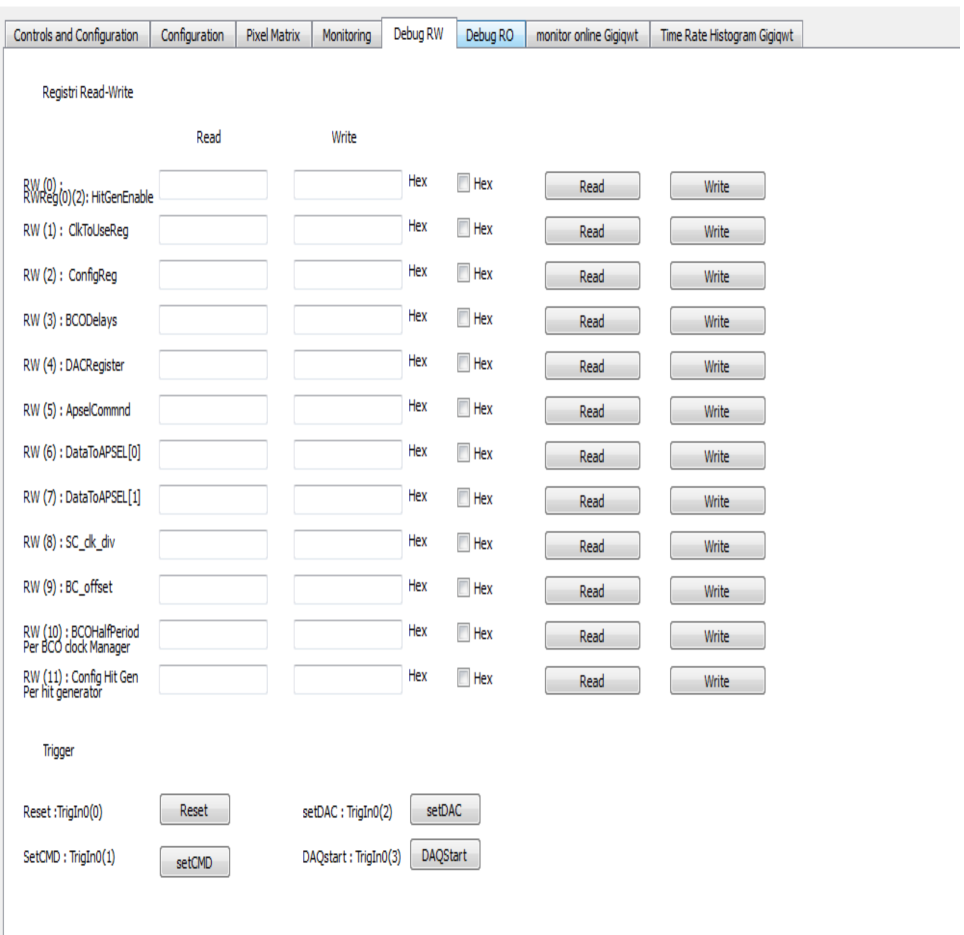
- C++ code
- Qt widget-based graphical libraries
- Qwt libraries for graphical visualization of events and histograms

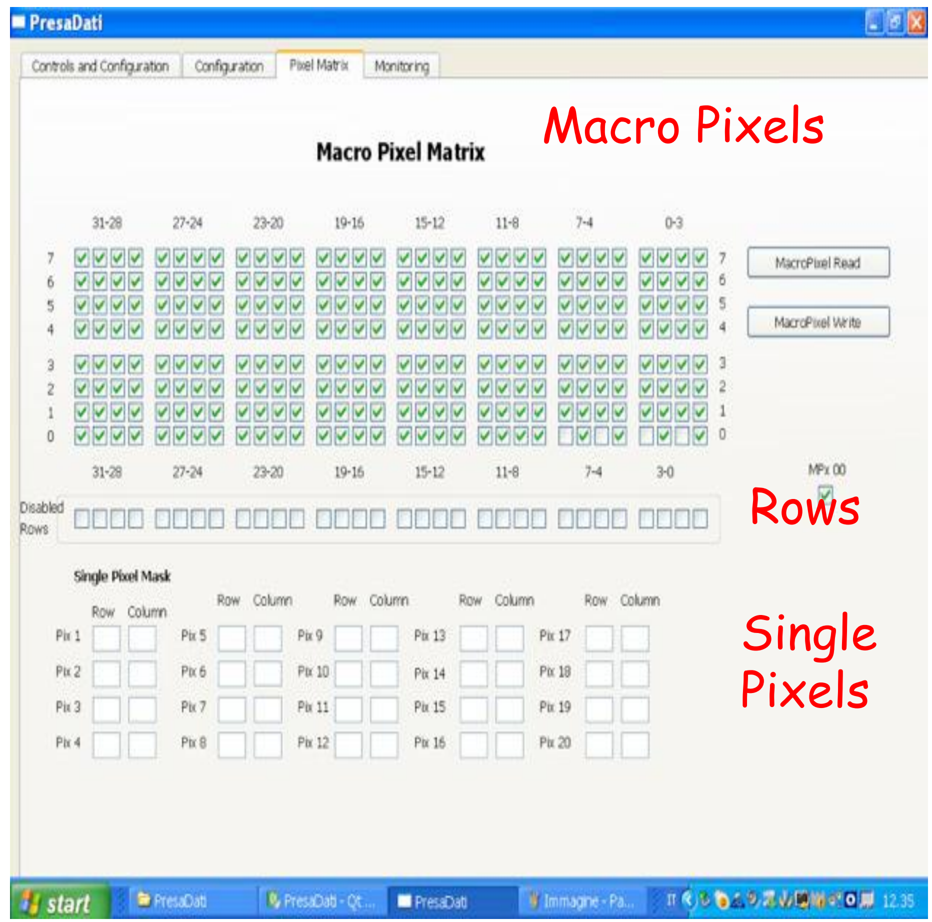
← **Standard user interface**

Software

Single Registers

Pixel Configuration Interface

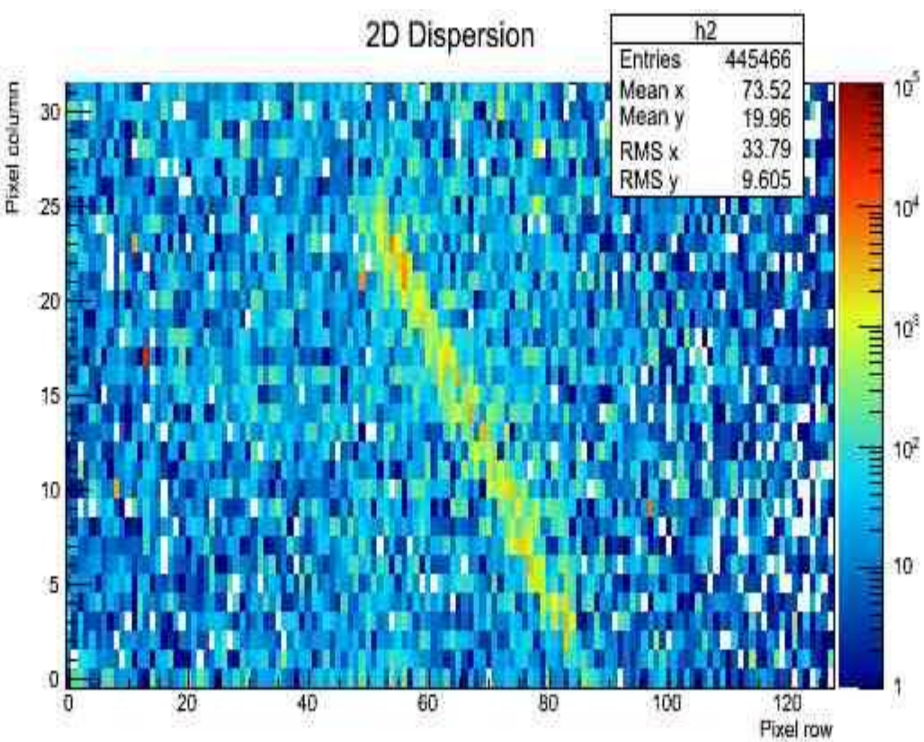




Setup Test : Imaging

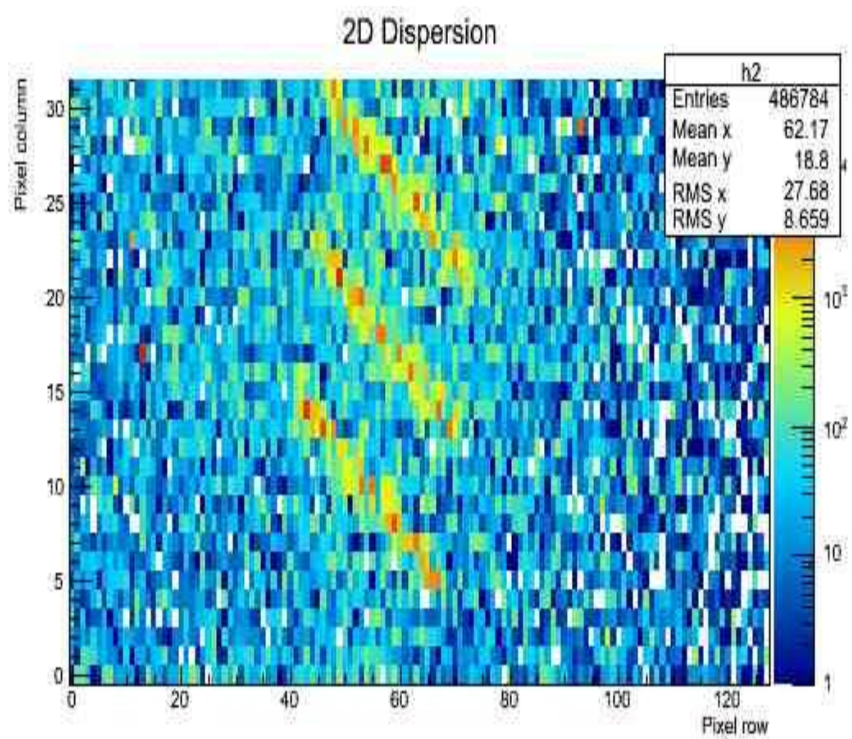
Images of Single and Triple Slit on the sensor

Single Slit



32 x 128 Pixel Matrix

Triple Slit



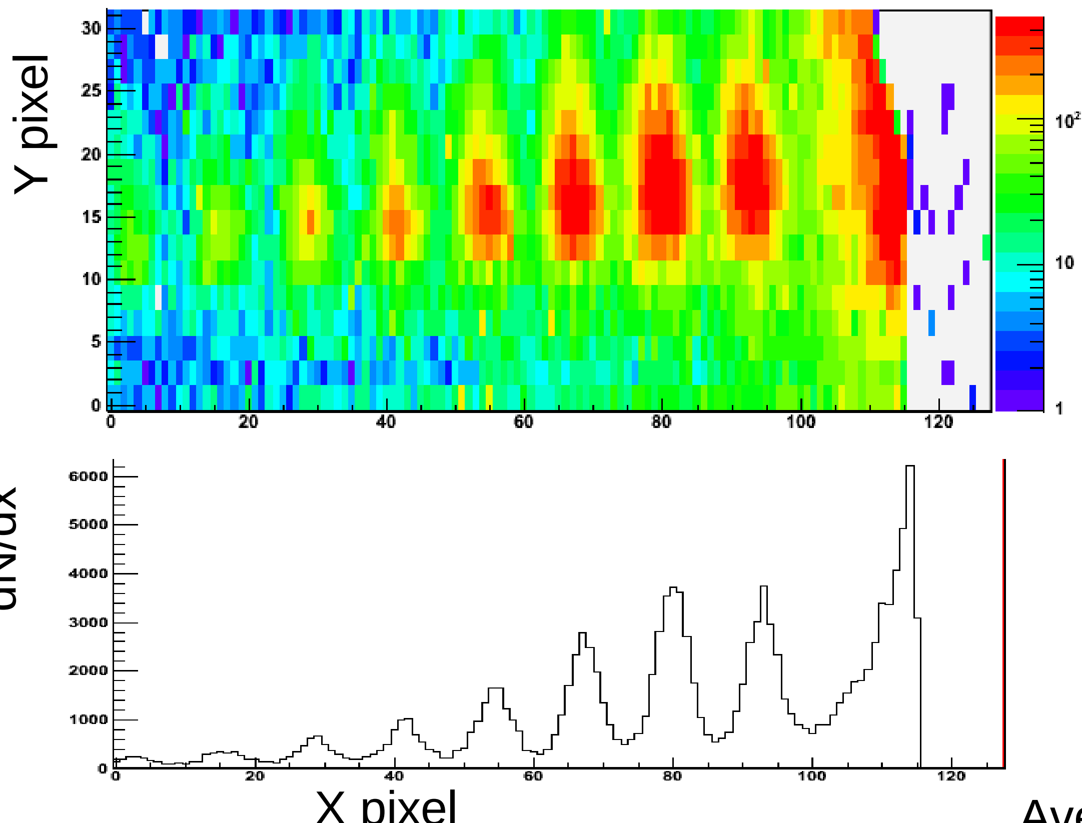
32 x 128 Pixel Matrix

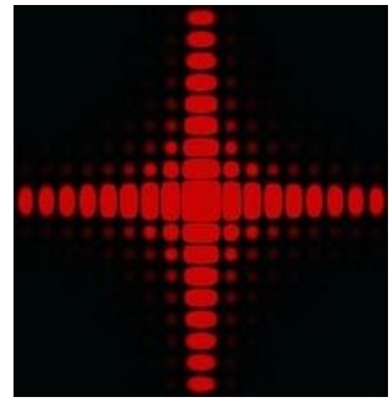
Carbon Grating Diffraction

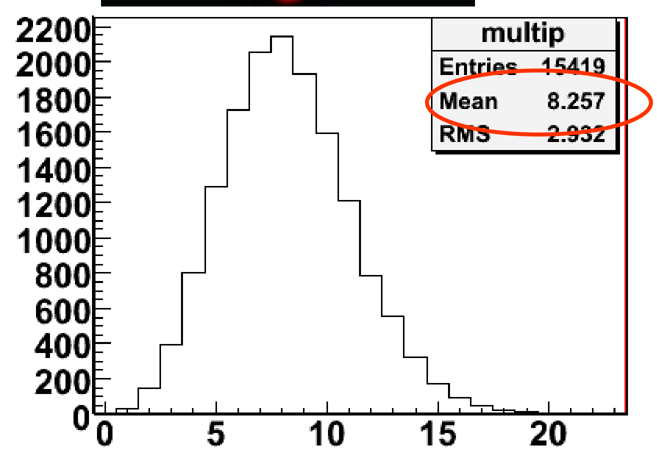
Carbon diffraction grating: typical pitch 400 nm

40-60 keV electrons: $\lambda = h/p =$ 5-6 pm, typical angle 10^{-5} rad

Observation windows: 165 μs (6k fps)



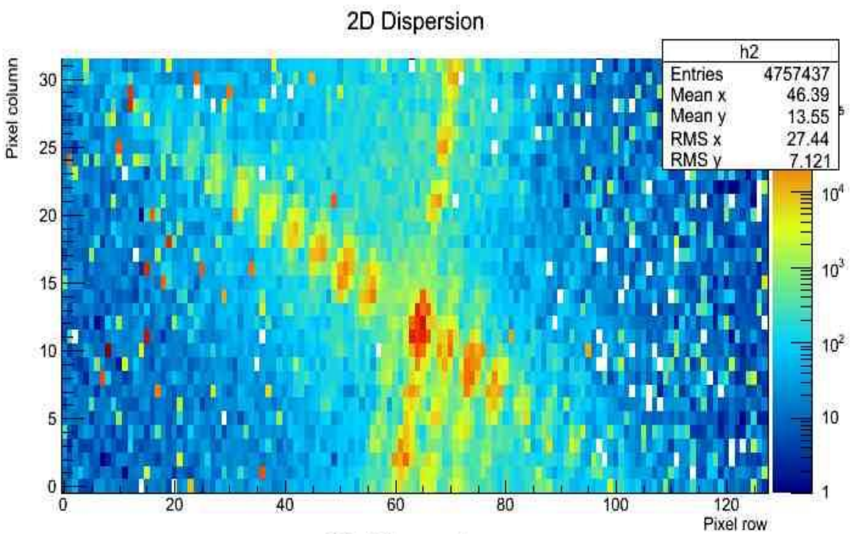


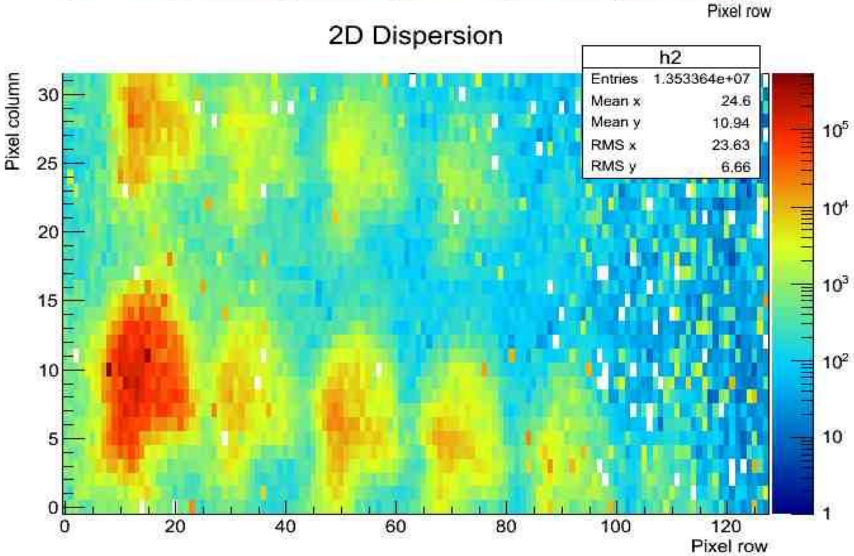


Average number of electrons : 8

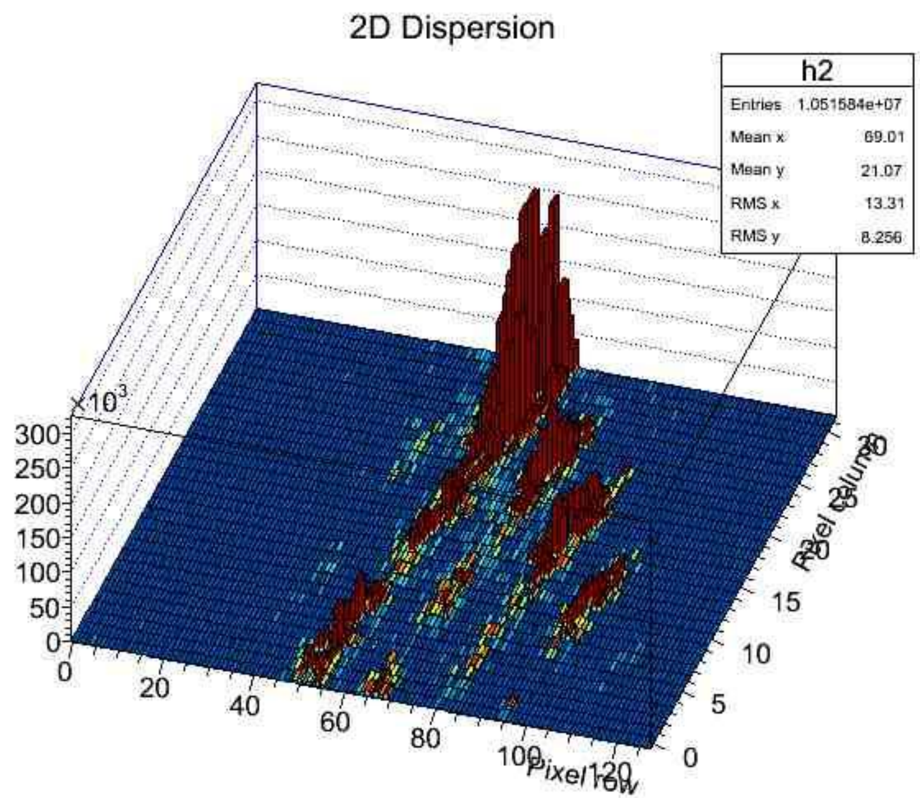
Peak separation:13 pixels→ 0,65 mm

Carbon Grating Diffraction





Very High Statistic ~ 10 Million Hits

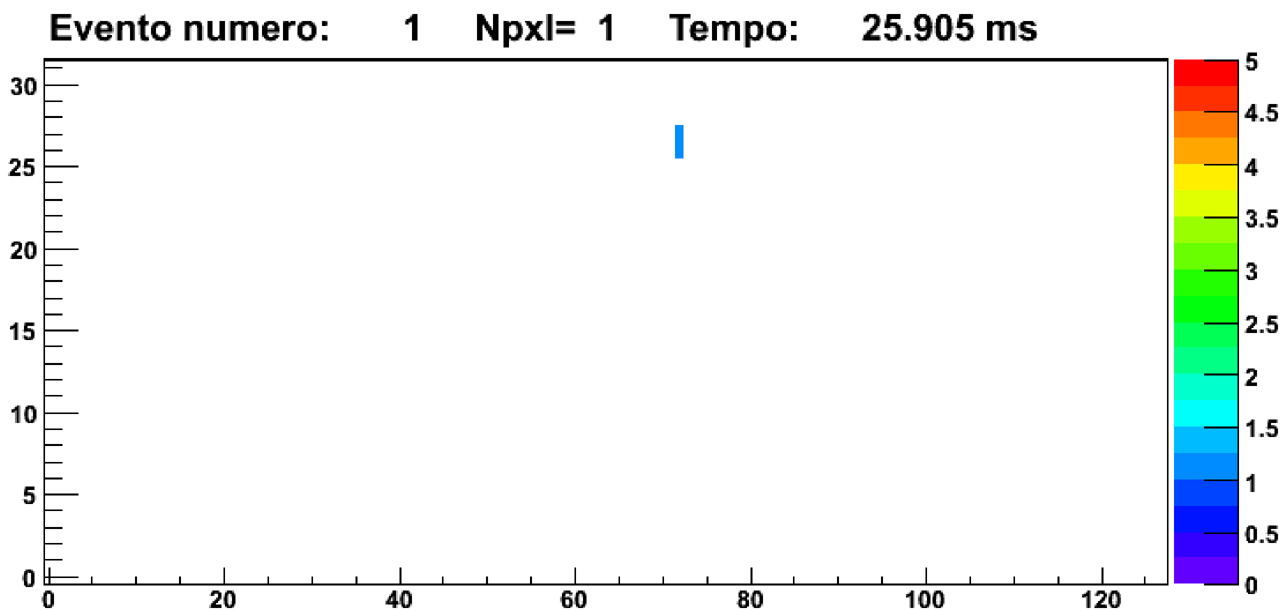


Single-electron interference I

Double slit: distance d = 440 nm

40 keV electrons: $\lambda = h/p = 5.9$ pm

Observation windows : **165 μs (6k fps)**



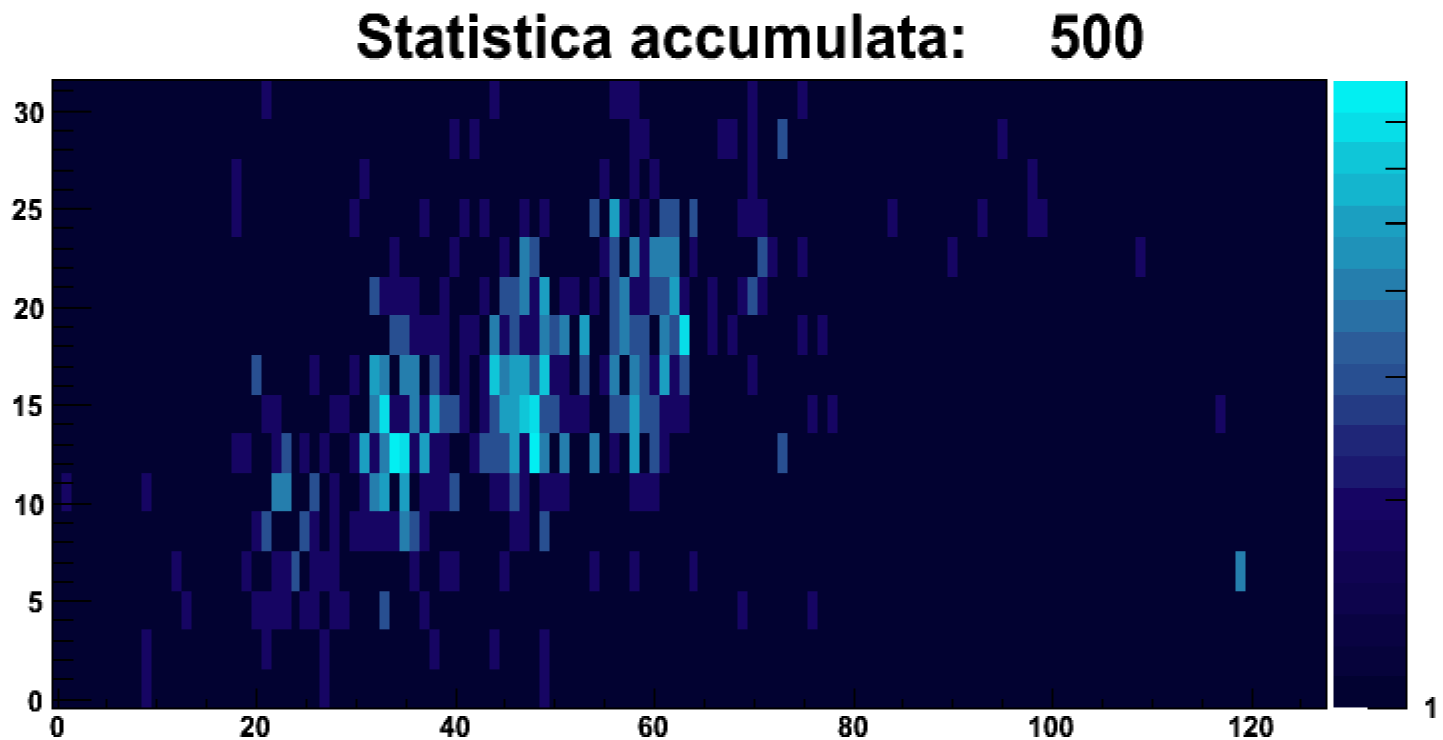
Single-electron interference II

Double slit: distance d=440 nm

40 keV electrons: $\lambda = h/p = 5.9$ pm

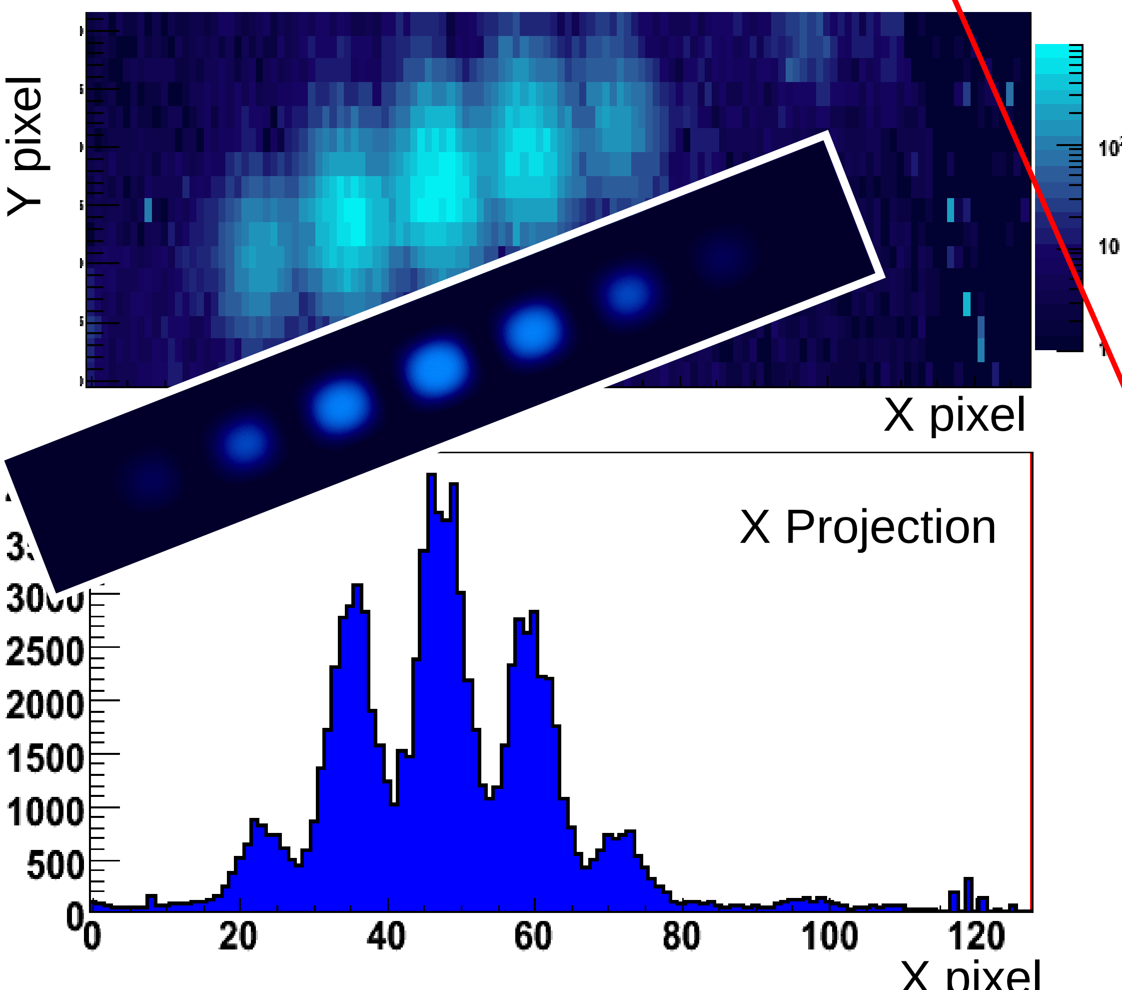
Observation windows **165 μs (6k fps)**

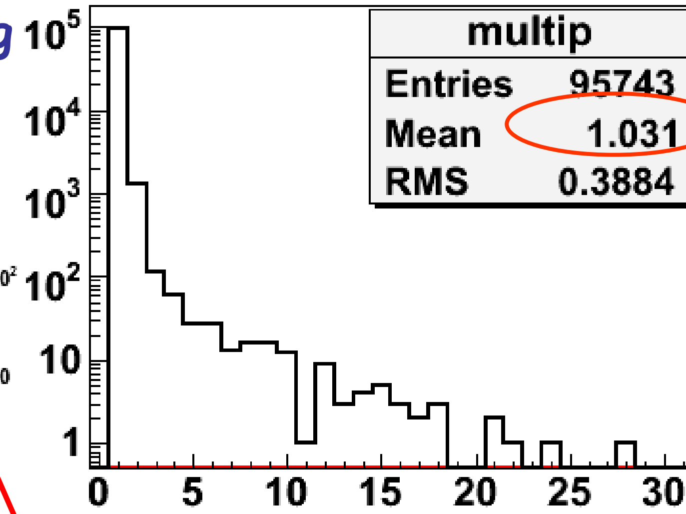
Add Frames



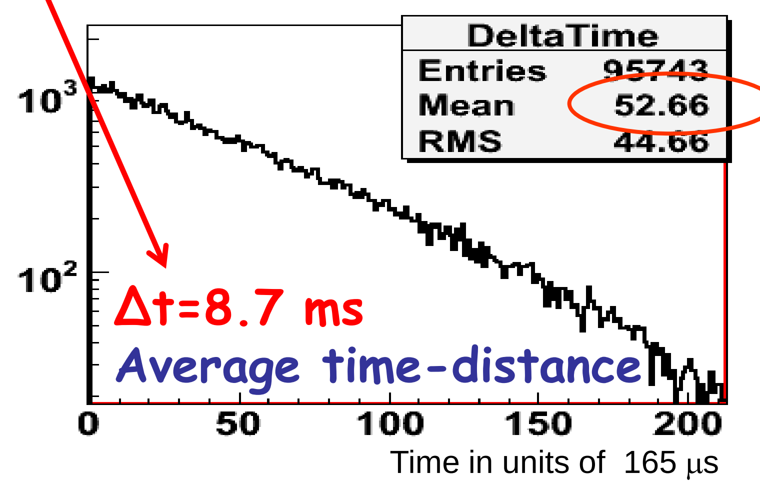
Single-electron interference III

100k e^- observed in about 20min data taking
At 0.4 c -> source-sensor ~ 20 ns





99.1% hits with single e^-



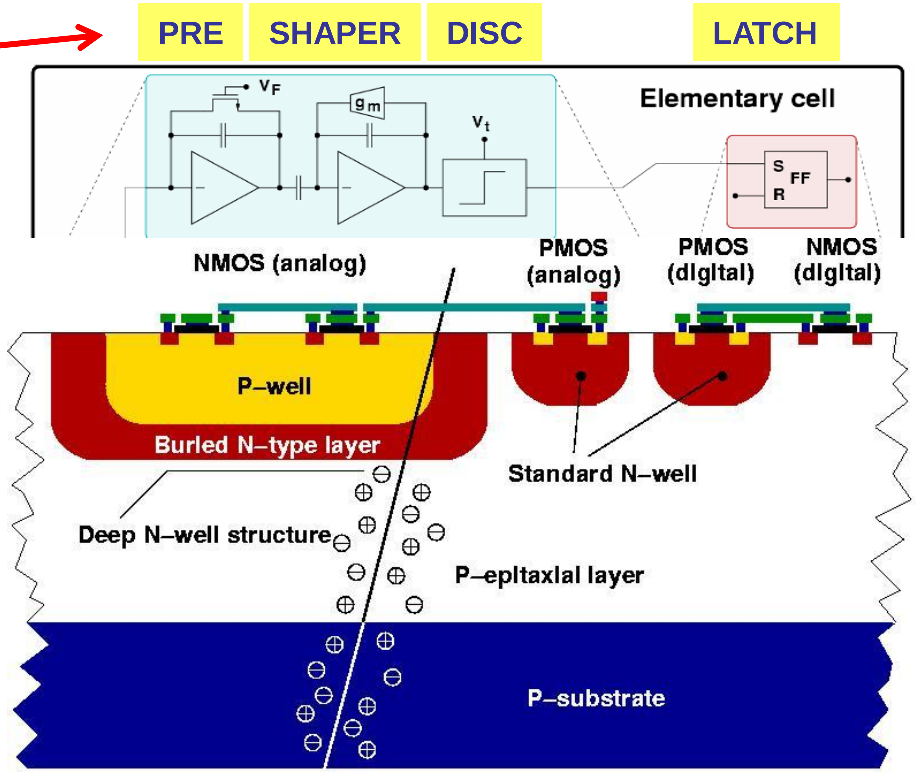
Conclusion

- We used for the first time a system of **nanometric-slits** with a high **space-time** performance sensor
- **APSEL 4D** (4096 pixels, 6k fps→2M fps) developed by INFN via a R&D project oriented to the next generation of silicon trackers (SLIM5).
- Developed a **custom** Hardware-Firmware-Software full DAQ chain
- **Reconstructed the Young interference with single electrons**
- **The DAQ chain can be used for Chip and Electronics Characterization**
- **The time resolution characteristics can be used in a new field of electron microscopy: the study of dynamic phenomena.**

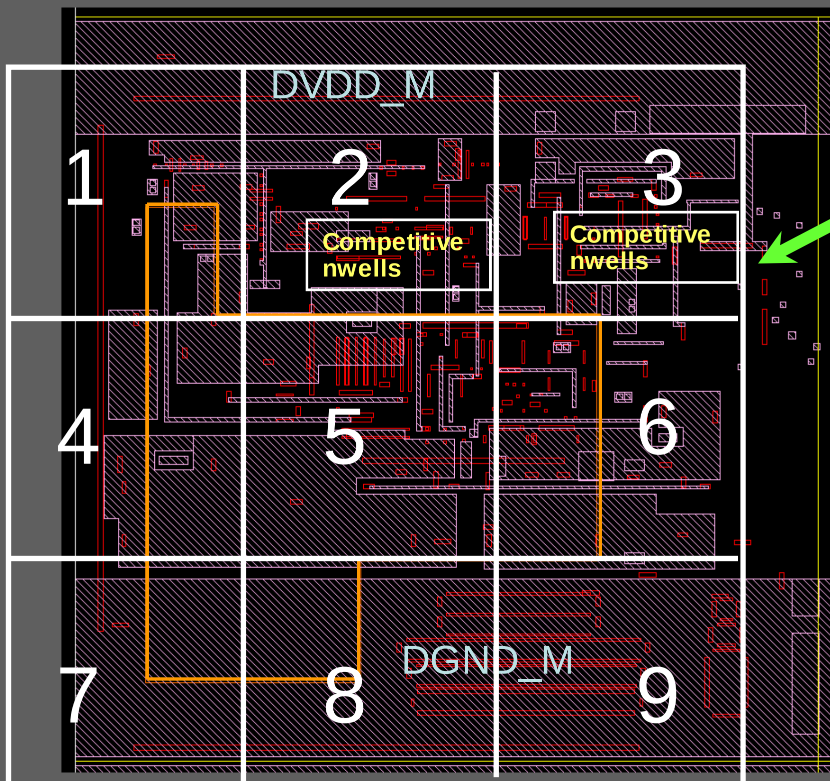

QUANTUM JUNCTION
GET IN BOTH LANES
Max
30^2

Deep NWell MAPS design

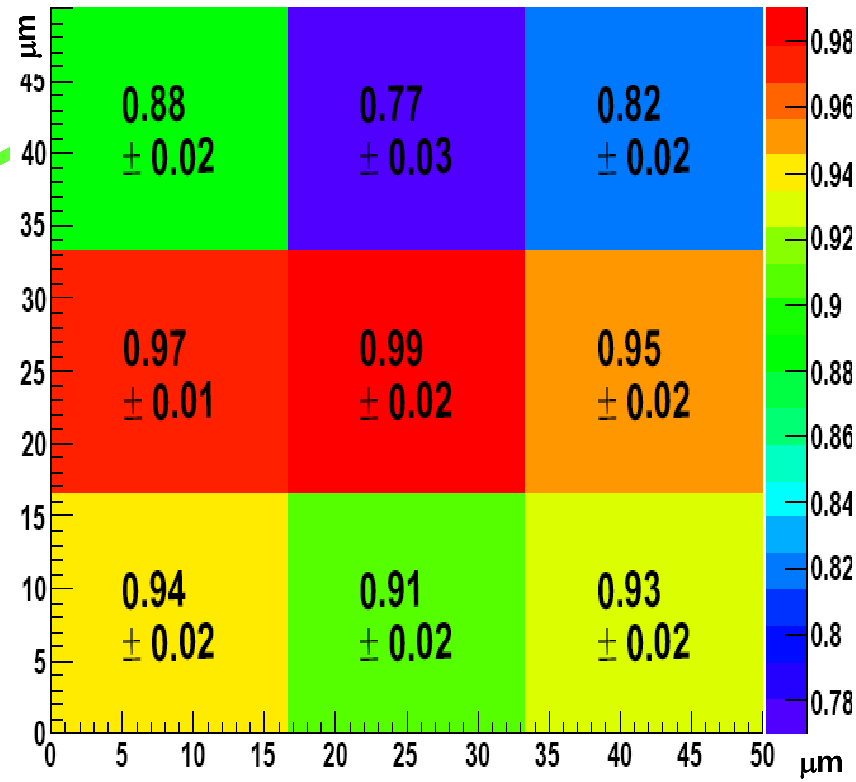
- CMOS MAPS for future vertex detectors: thin (OK!) but also need to be fast (i.e. bkgd rate @ SuperB: several MHz/cm2)
- New approach: hybrid-pixel-like structure to improve the readout speed
- Full in-pixel signal processing chain exploiting triple well CMOS process
  - Deep NWell as collecting electrode with most of the front-end overalapped in the pwell
  - Can extend collecting electrode (charge preamp --> gain independent of sensor cap.)
  - Allow design with small "competitive" nwells for PMOS inside the pixel. Area kept to a minimum:, they steel signal to the main DNW electrode.
  - Fill factor = DNW/total n-well area ~90% in present design



MAPS efficiency vs position within pixel



Correspondence between the pixel layout and the efficiency map.

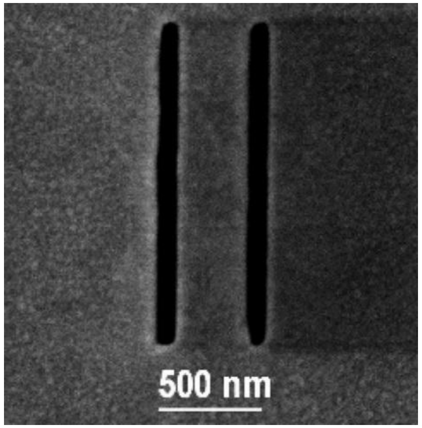


Efficiency map inside pixel cell. Cross feed unfolded results.

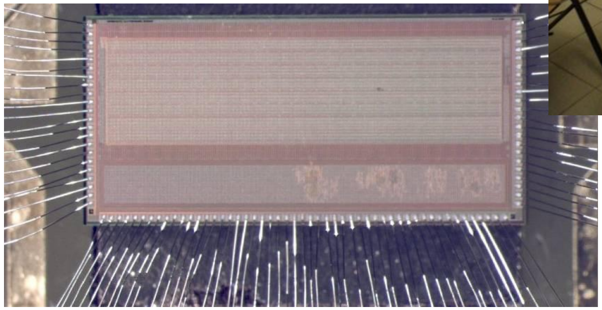
Instrumentation

- TEM **Philips M400T** (120 keV max)

- **Two nanometric slits**
- slit width 95 nm
- Slit length 1550 nm
- Slit distance 440 nm

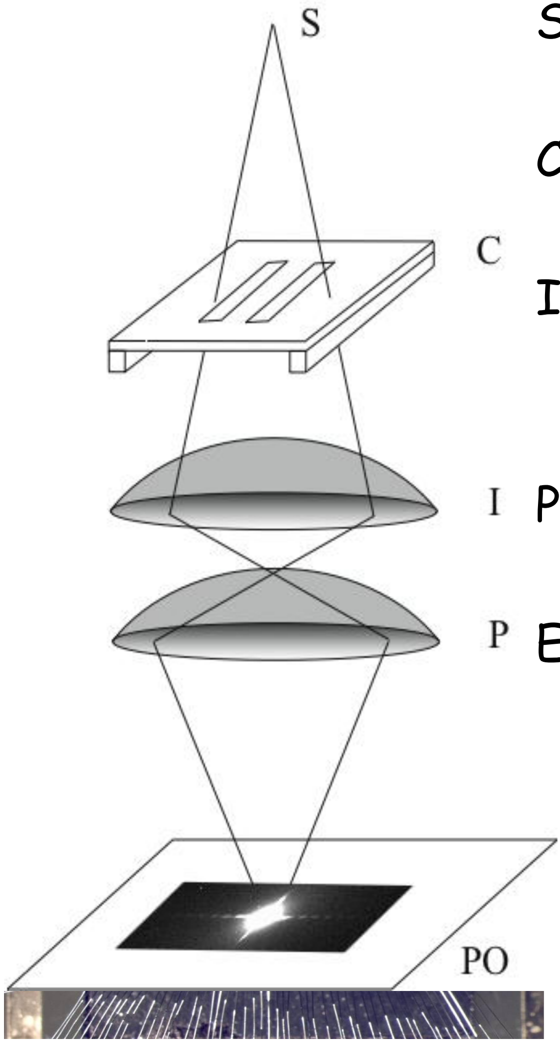


- **4096 MAPs Sensor**
  ST 130nm CMOS



- DAQ system

Set-up inside the TEM



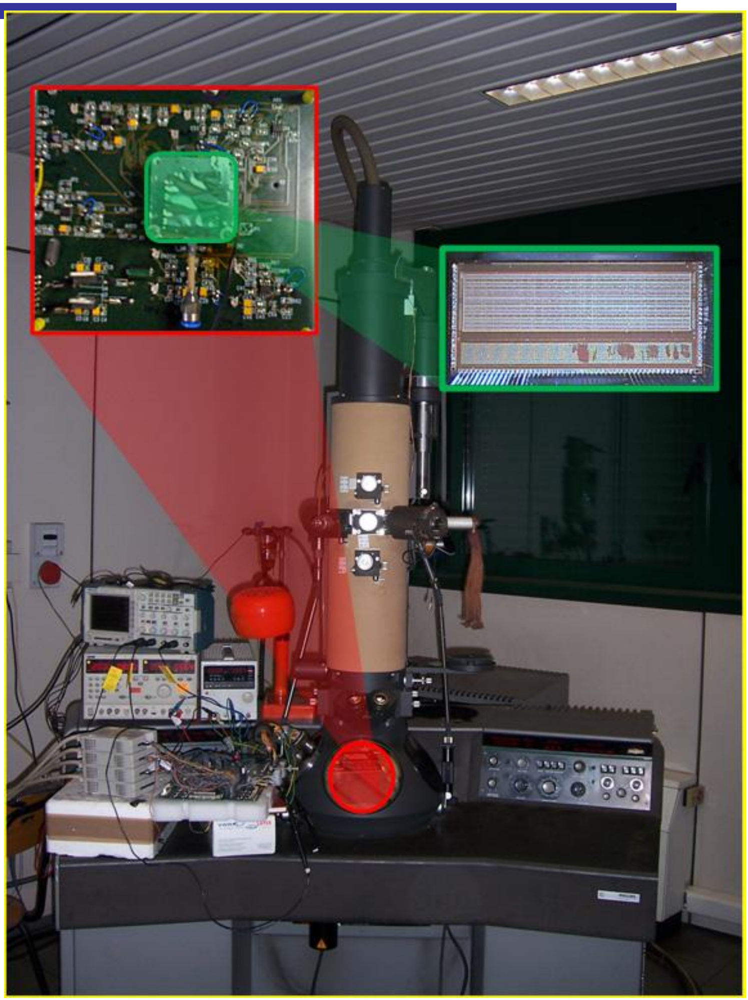
S- Small size source

C – Sample with two slits

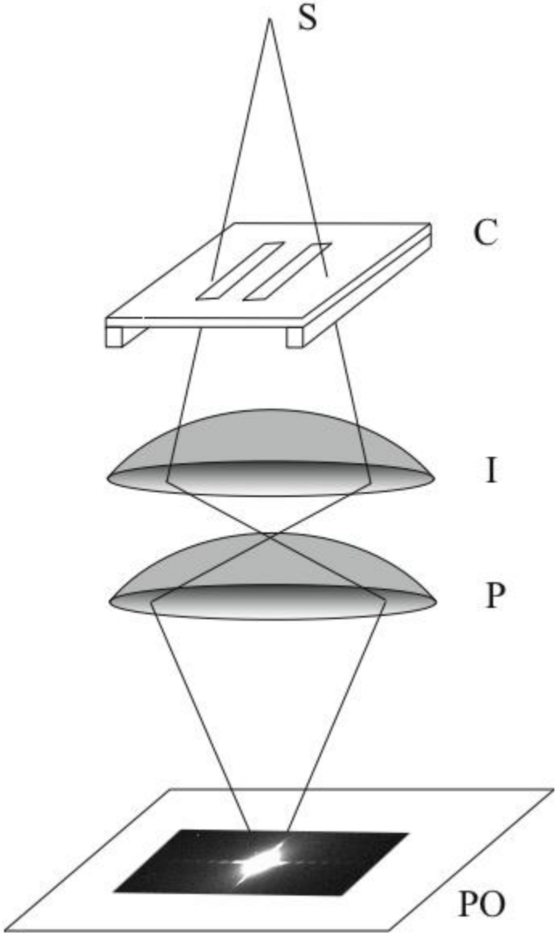
I,P – Image and projection lenses

PO: projection plane

Experimental conditions:
Fraunhofer regime
(plane wave approximation)



Set-up nel Microscopio



S- Sorgente di piccole dimensioni
Elettroni da **40 keV** , $v=0.4\ c$
$\lambda=h/p=$ 5.9 pm (1/18 diametro H),

C – Campione a due fenditure
distanza **d=440 nm**

I, P – Lenti immagine e di proiezione

PO: piano di proiezione delle fenditure

Condizioni sperimentali:
Regime di Fraunhofer
(approssimazione di onde piane)

APSEL 4D Sensor

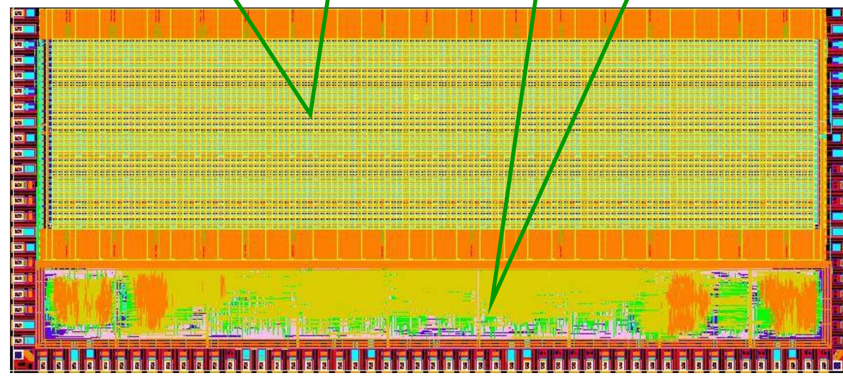
Sviluppato dalla **Collaborazione SLIM5** per un progetto per esperimenti di fisica delle particelle→
Rivelatore di vertice di SuperB
(INFN: BG, BO, PI, PV, TS)

Sensore Monolitico a Pixel Attivi
Tecnologia CMOS ST 130 nm

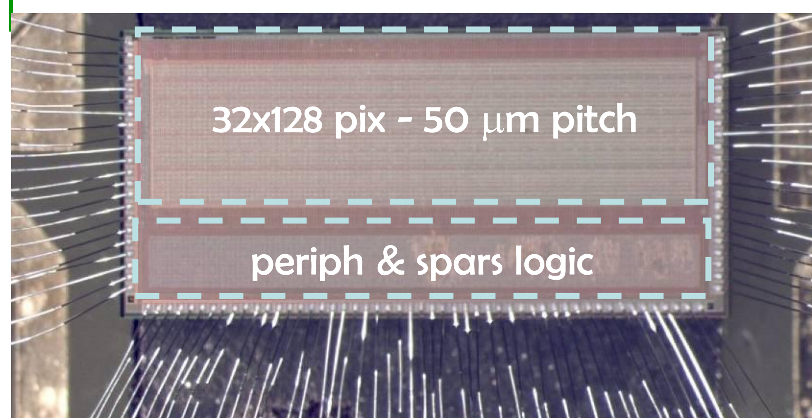
Architettura di readout integrata, ottimizzata per il tracciamento di particelle cariche

Informazione di uscita 3D:
- x,y: risoluzione spaziale 15 μm
- t: risoluzione temporale > 0.4 μs

Frequenza di clock: 20-50 MHz



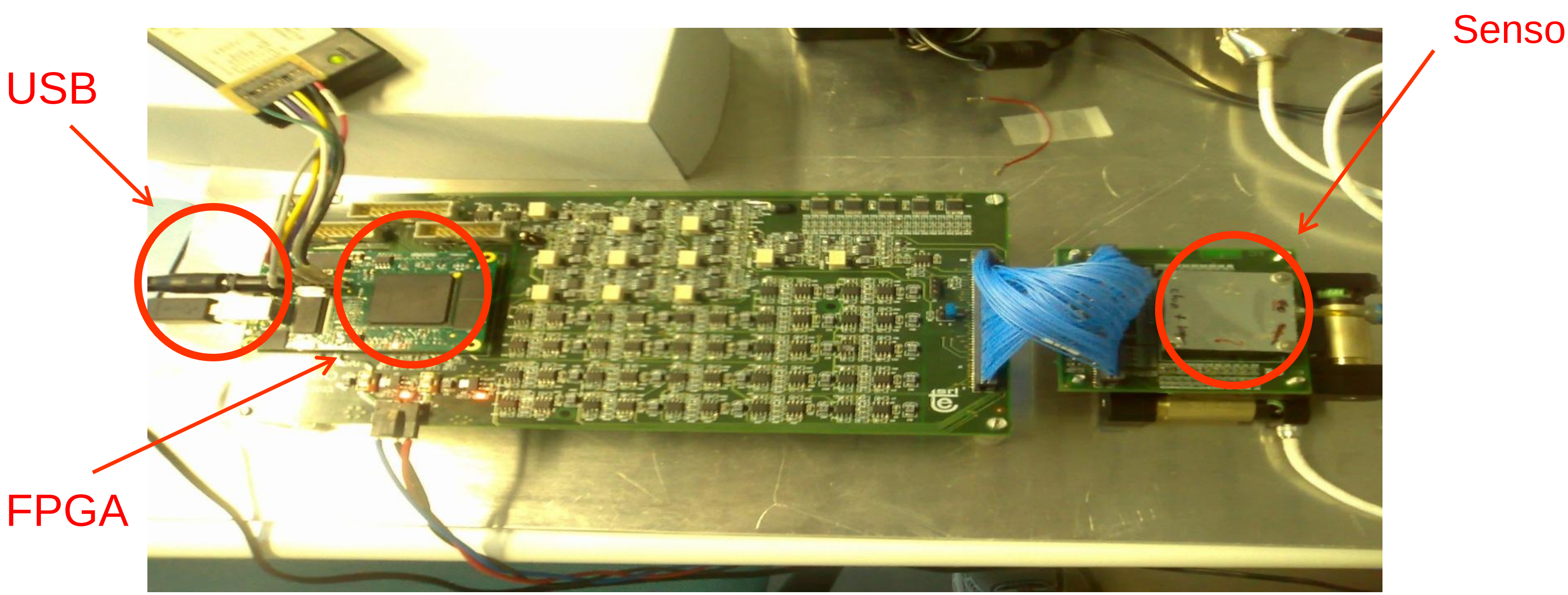
Pixels quadrati di lato 50 μm
Area sensibile: 6.4 mm x 1.6 mm = 10 mm^2



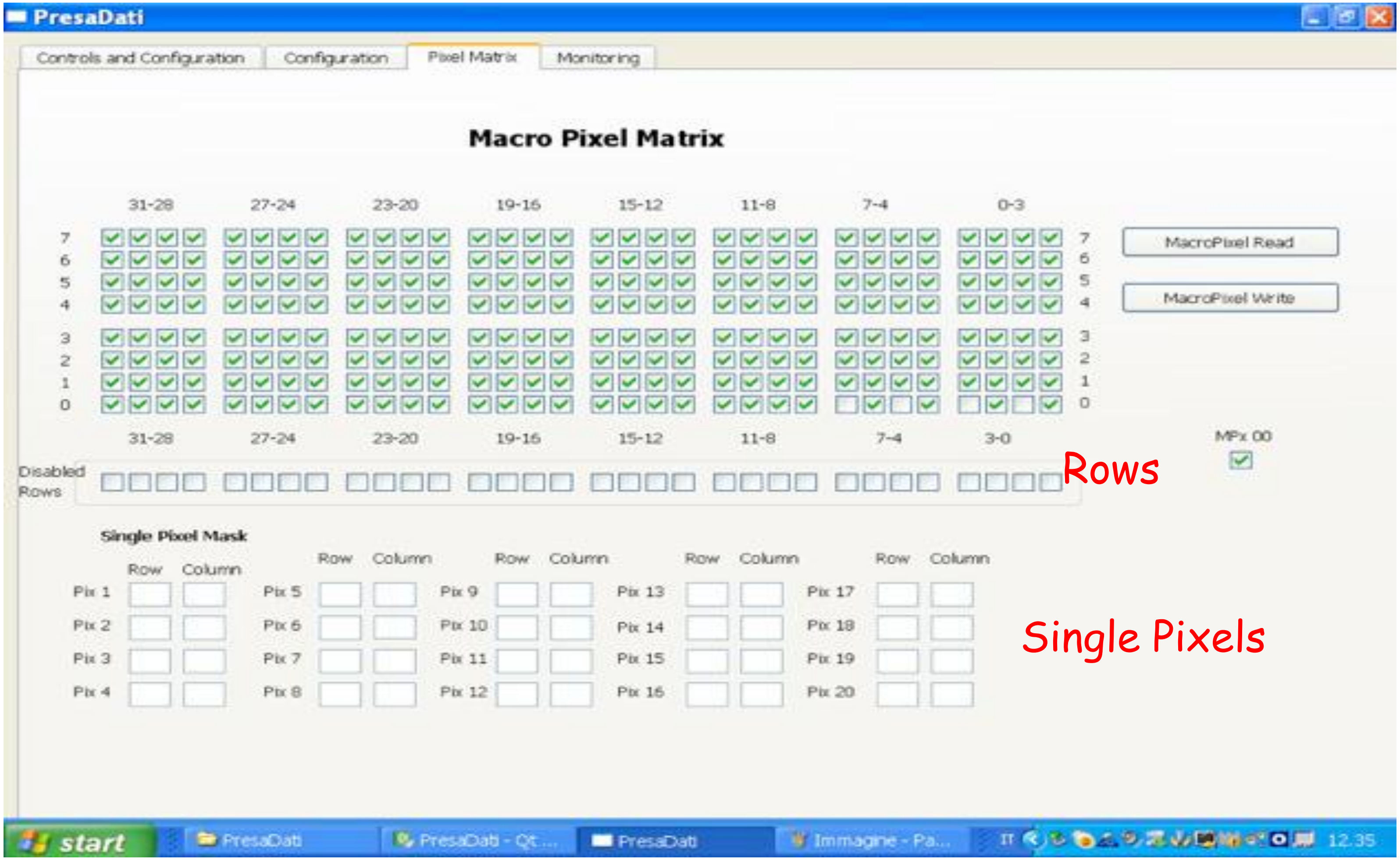
Efficienza misurata con fasci di protoni da 12 GeV: **≈ 90%**

Data Acquisition

- Real Time Data Acquisition
- Sensor-> FPGA -> USB -> Computer
- Micrometric Bidimensional Movimentation



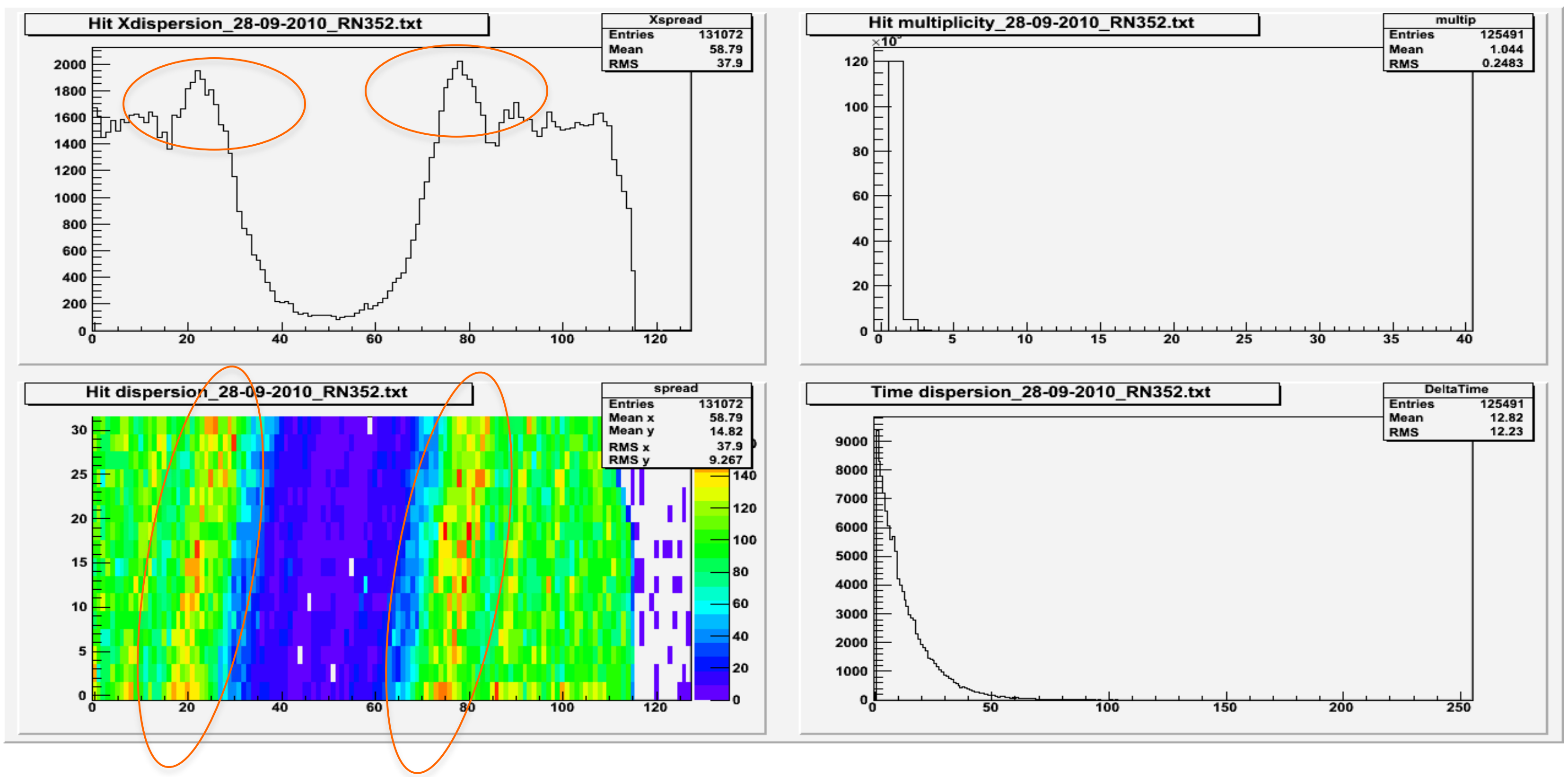
Pixel Configuration Interface



Thin wire Diffraction

40-60 keV electrons: $\lambda = h/p =$ 5,9 pm, typical angle 10^{-5} rad

Average Hits per frame ~ 1 -> Single Electron



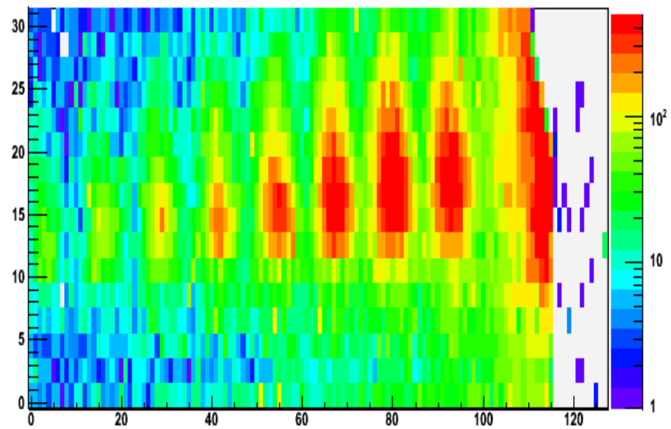
X pixel

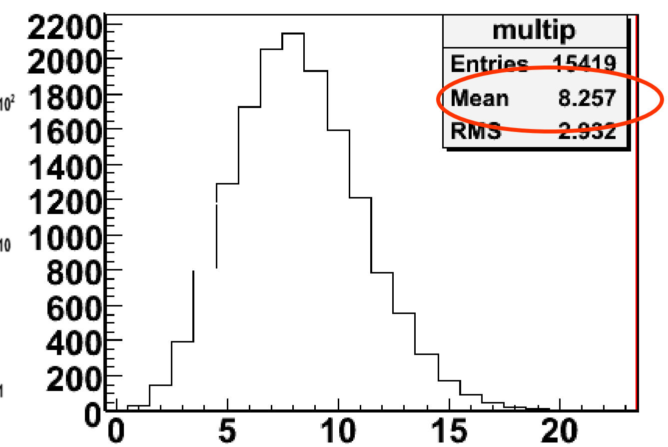
Calibration : Carbon Grating Diffraction

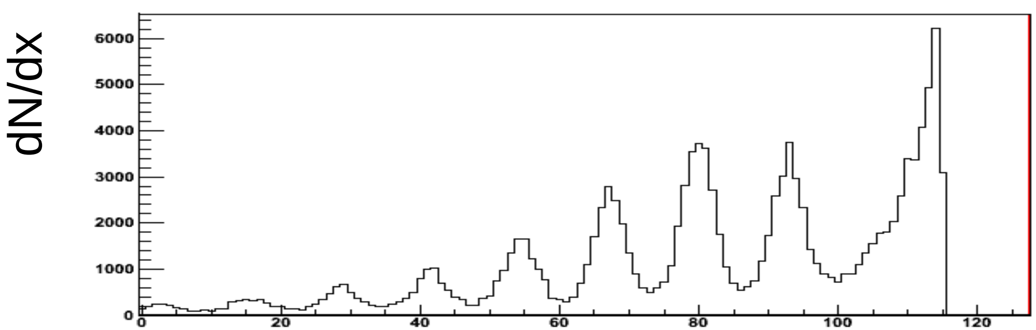
Carbon Grating Diffraction: typical step 400 nm

40 keV Electrons : $\lambda = h/p =$ 5,9 pm, angles $\approx 10^{-5}$ rad

3 millisecond observation windows







High Average Electron Number

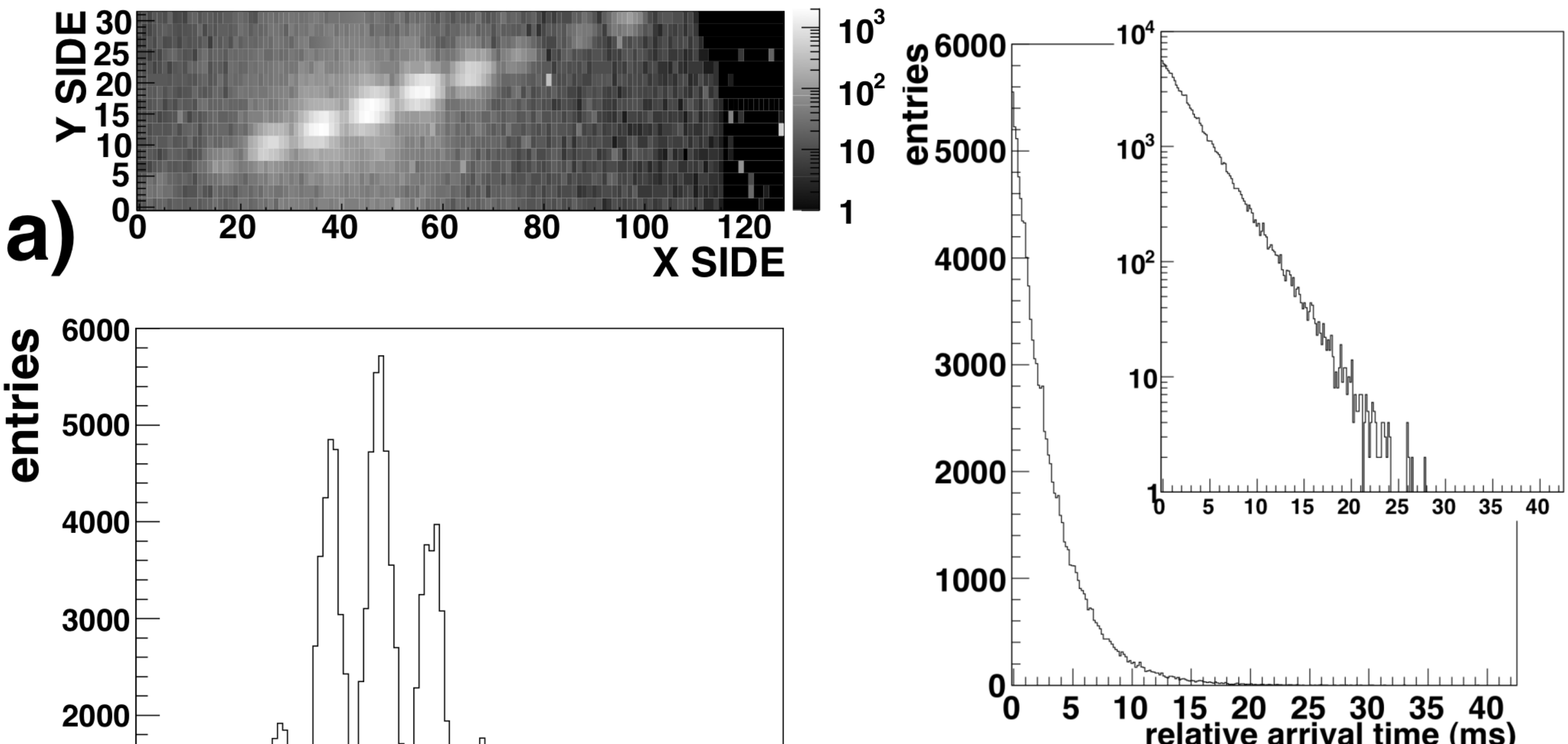
Good Signal;

No significant background

Distance between peaks:

13 pixels → 0,65 mm

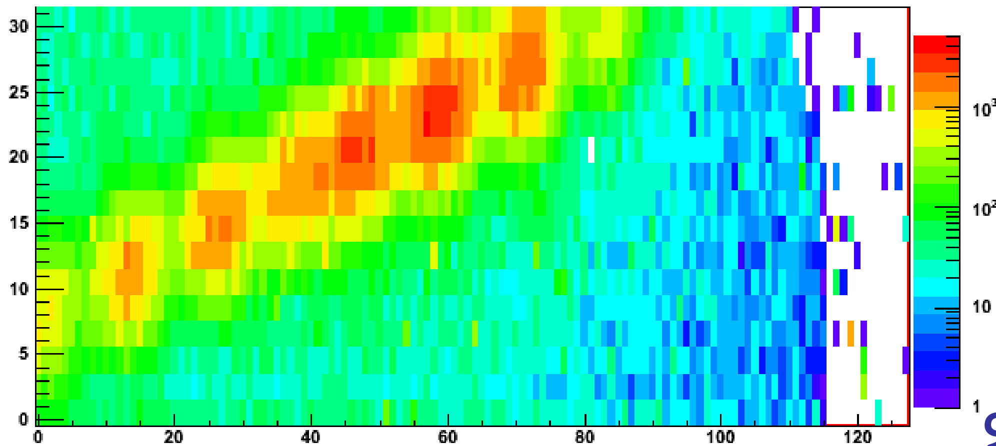
The single-electron interference III

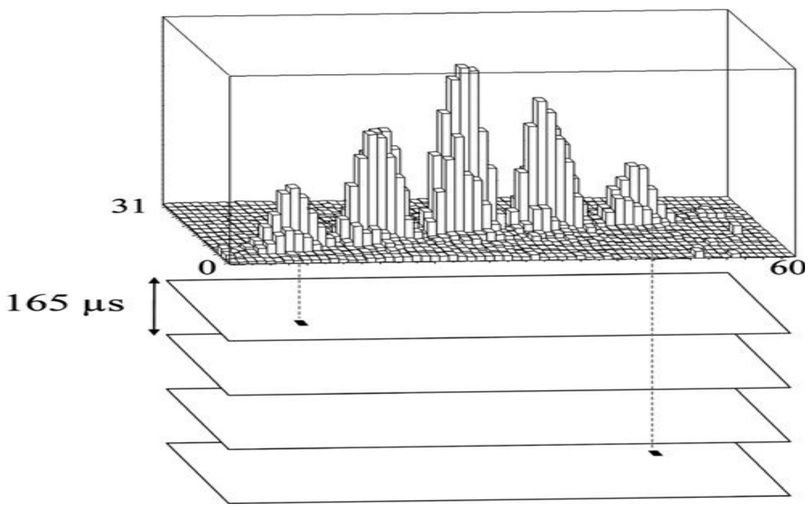


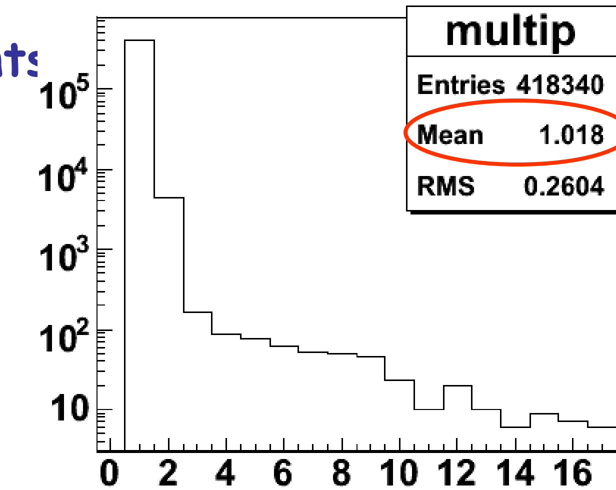
Average arrival time distance **3.1 ms**
Time of flight within TEM **10 ns**

The single-electron interference IV

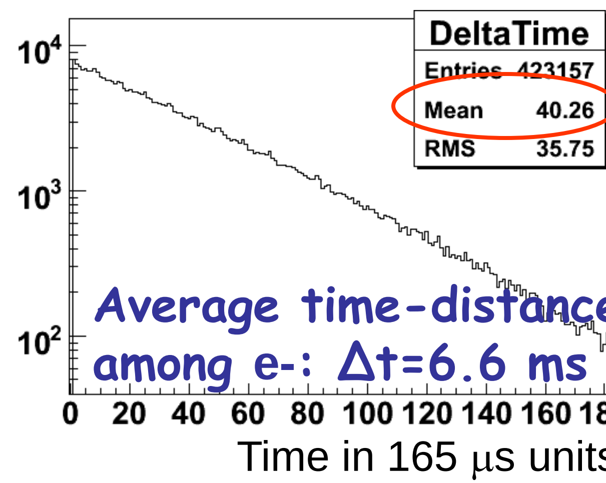
430k observed electrons in about 1h of measurements







98.8% images of single e-



Average time-distance among e-: Δt=6.6 ms