Application of a HEPE-oriented 4096-MAPS to time analysis of single electron distribution in a two-slits interference experiment

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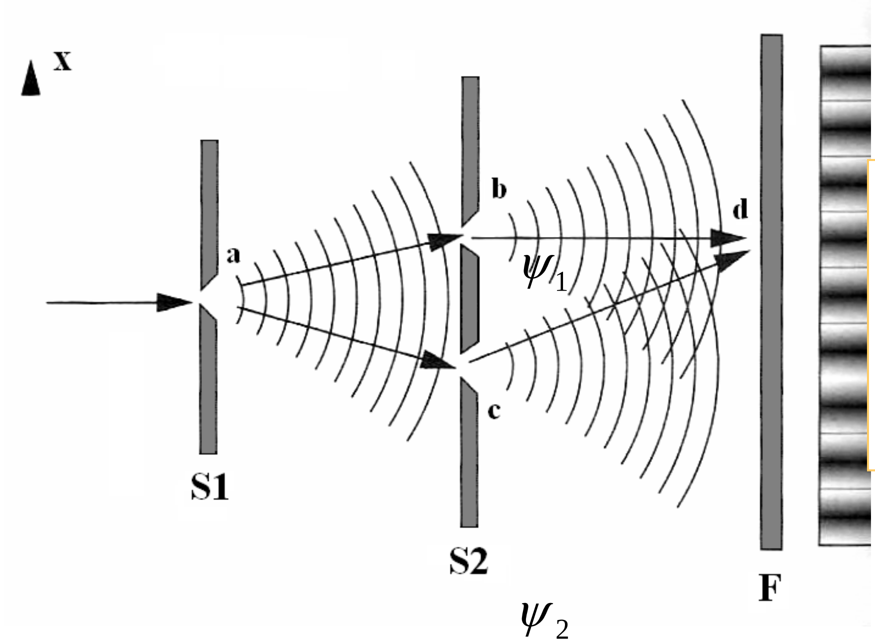
Outline

- Young's experience with single electrons
- Double slit, one electron at a time
- Instrumentation
  - Electron Microscope TEM
  - Double slit
  - **APSEL4D** MAPS sensor
- Measurements of diffraction by a grating
- Measurements of interference
- Conclusion

Young's Interference

Basics

- Monochromatic source λ, $\lambda_{De\ Broglie} = h/p$
- Two slits at a distance **d** create coherent waves
- Screen at a distance **D >> d**



ψ_1

ψ_2

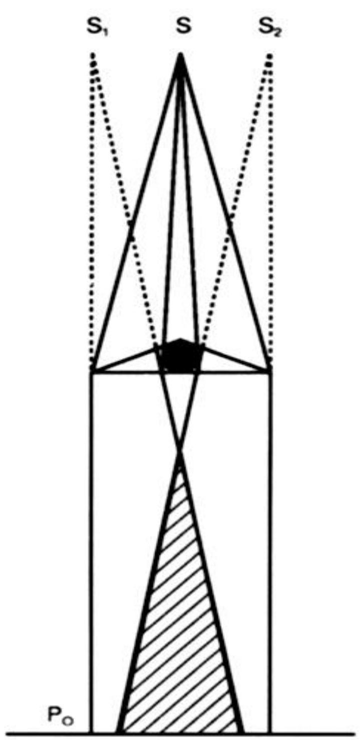
$$P(x) = |\psi_1 + \psi_2|^2 = |\psi_1|^2 + |\psi_2|^2 + 2\,\mathrm{Re}\,\psi_1^* \psi_2$$

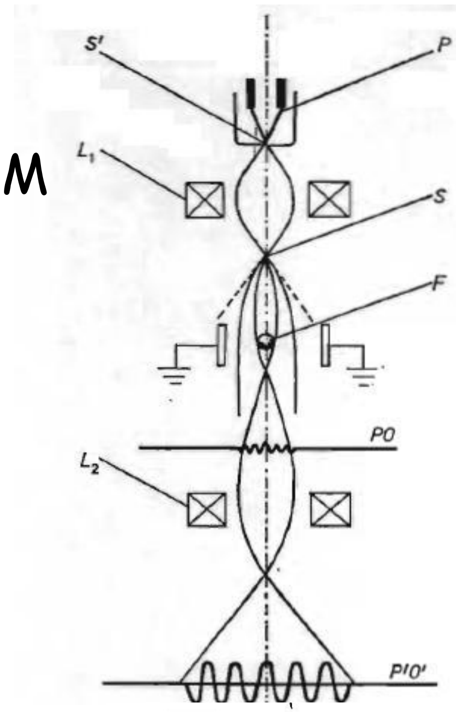
R. Feynmann: - Lecture on Physics, Vol 3

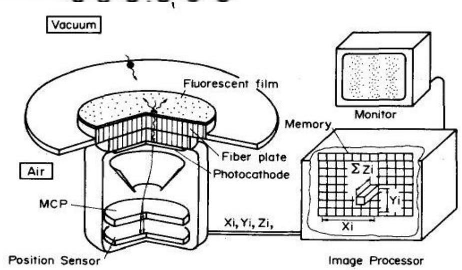
Young's experiment with the electrons can only be conceptual in nature because of the smallness of the de Broglie wavelength

Young's Interference
Past Experiments

Base Tecnique:
Fresnel Biprism
applied into a TEM

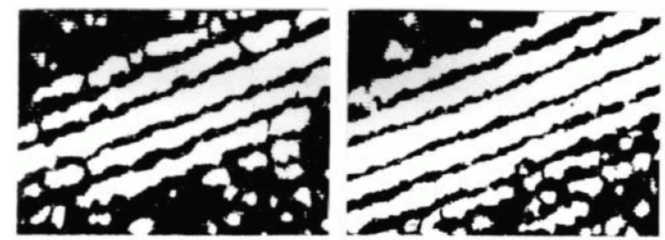






Esperiments in literature
Merli, Missiroli, Pozzi (1976)
A. Tonomura et al. (1989)

single electron conditions



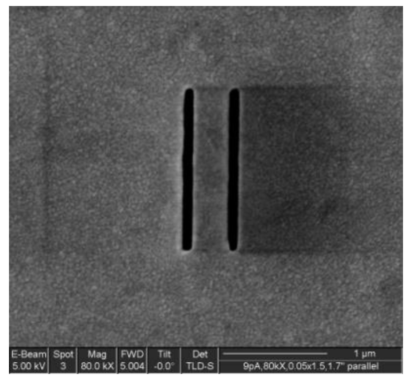
Demonstration:
Wave character of the electron

The base interference is that of an **electron with itself**

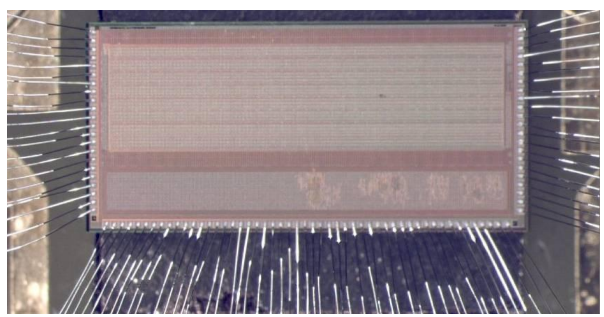
Physics World (2002):
The most beautiful experiment in physics, according to a poll of *Physics World* readers, is the interference of single electrons in a Young's double slit. Robert P Crease reports

Instrumentation

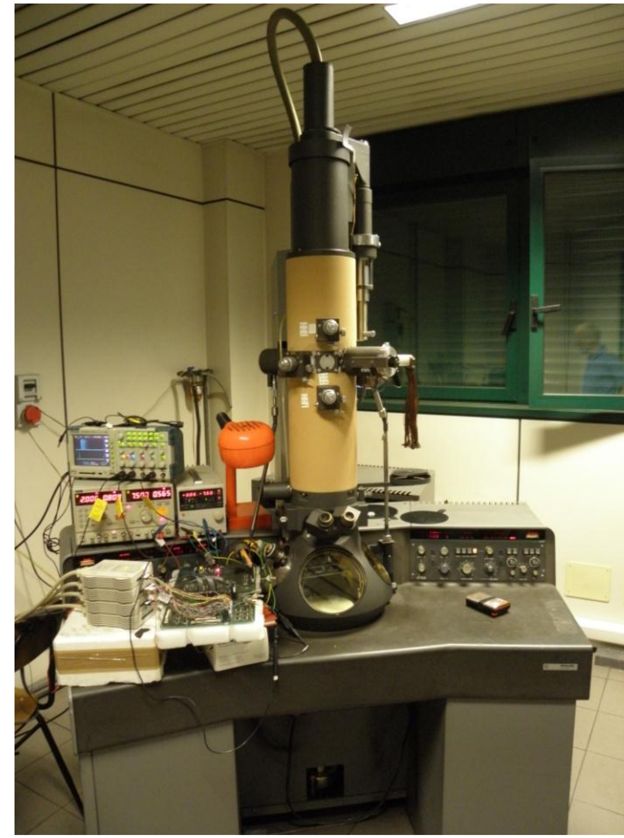
- TEM **Philips M400T** (120 keV max)
- Two nanometric slits



- 4096 MAPs Sensor ST 130nm CMOS



- DAQ system

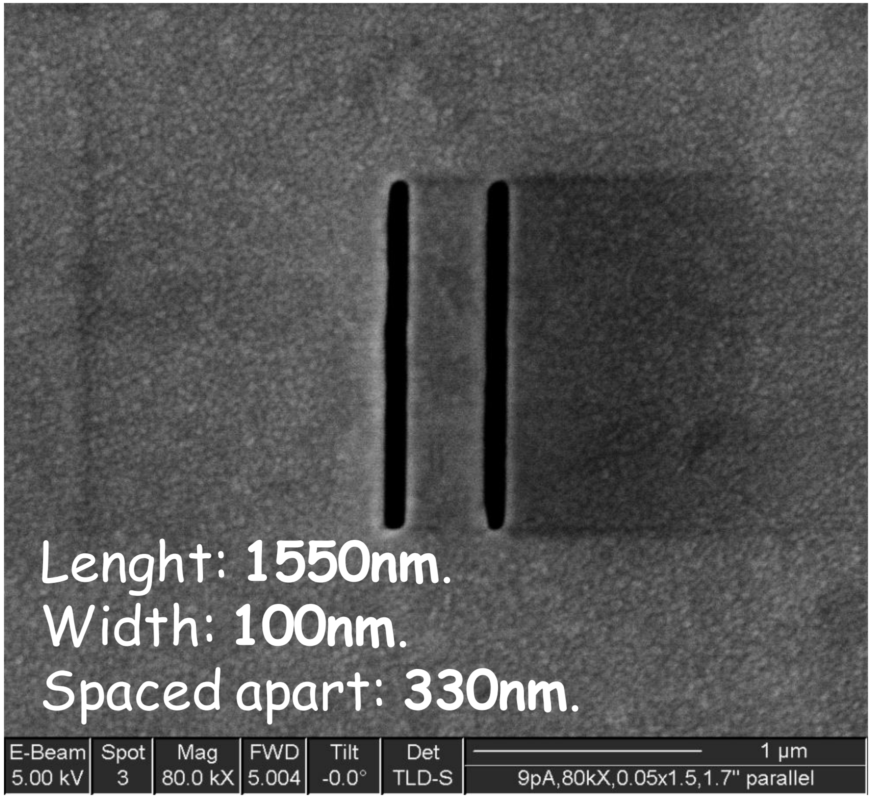


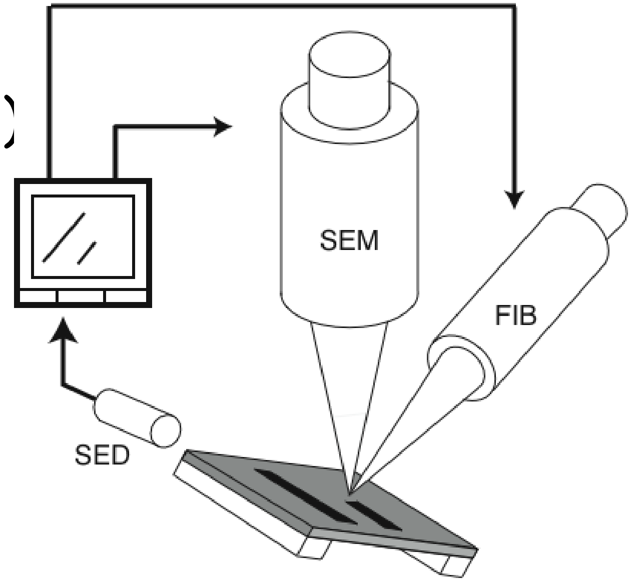
The two slits

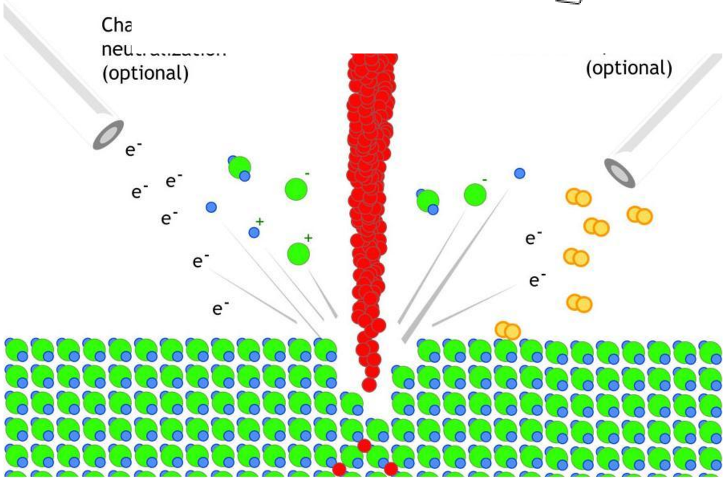
Constructed via a FIB process

(Focused Ion Beam from a liquid Ga+ source)

Carbon plus gold (thichkness 50-100nm).







The APSEL4D MAPS sensor

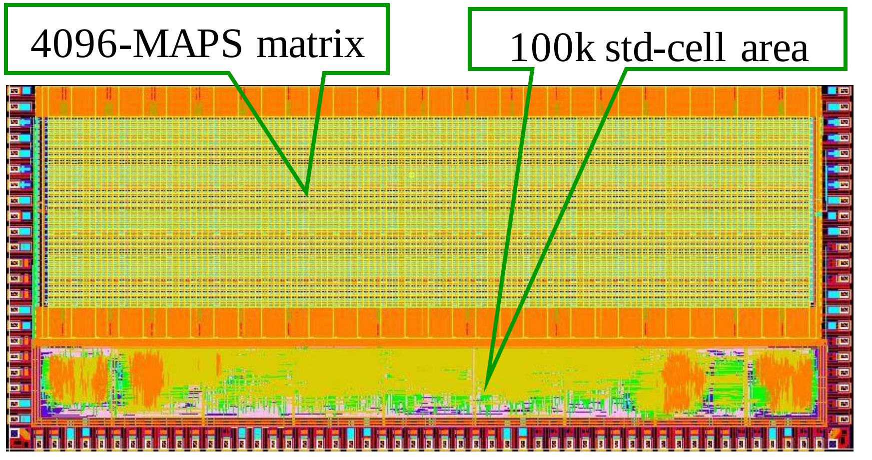
R&D project for HEPE →
- Vertex detector oriented to the SuperB project
- Technology ST 130 nm

Readout:
- Data Driven
- Sparsification logic
- Optimized for charged particle identification

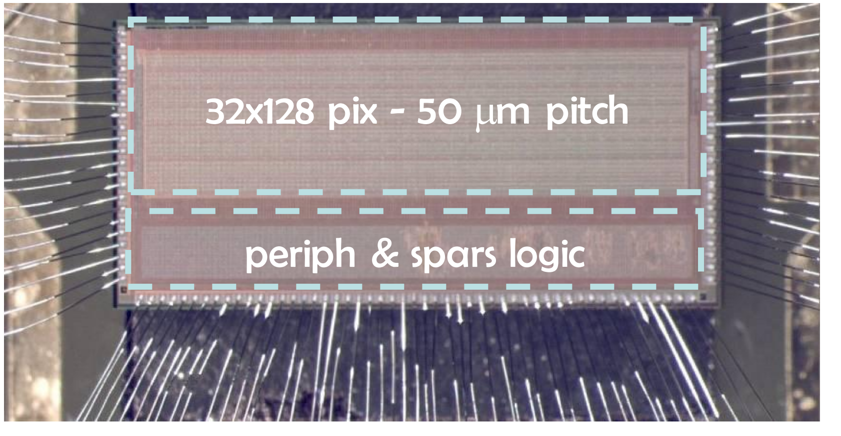
Output infos:
- z: thickness 300 μm
- x,y: spatial resolution 15 μm
- t: time resolution (BCO) > 0.4 μs

Clock frequency: 20-50 MHz

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



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

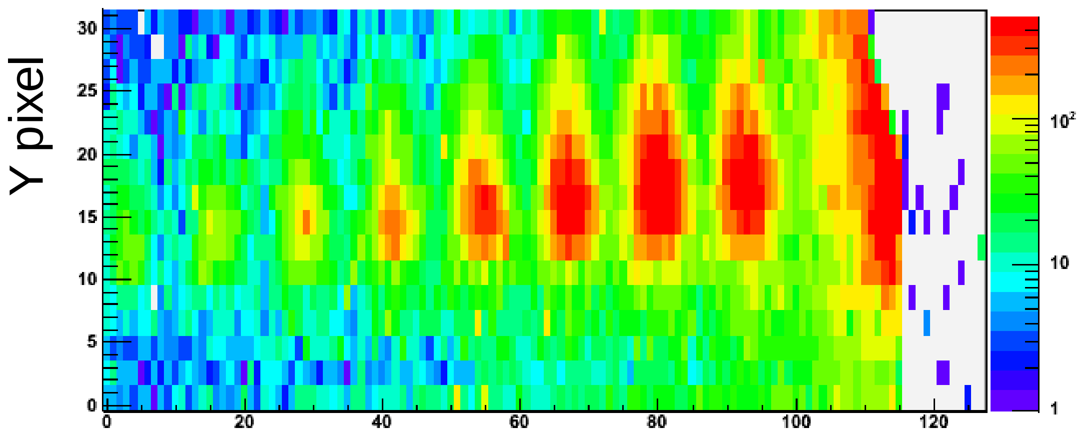


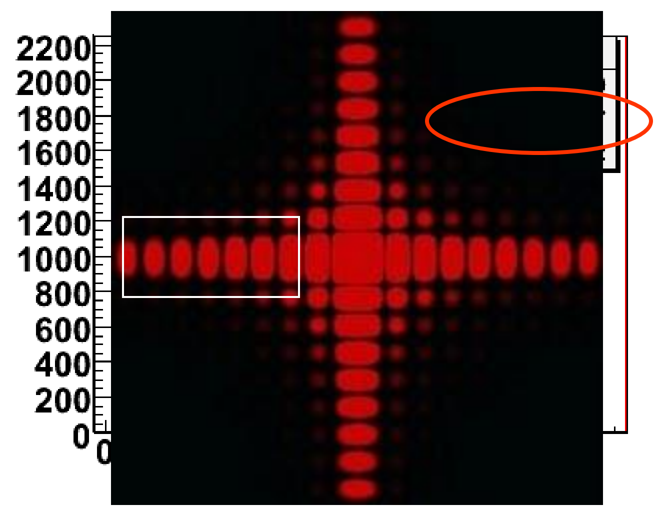
Carbon Grating Diffraction

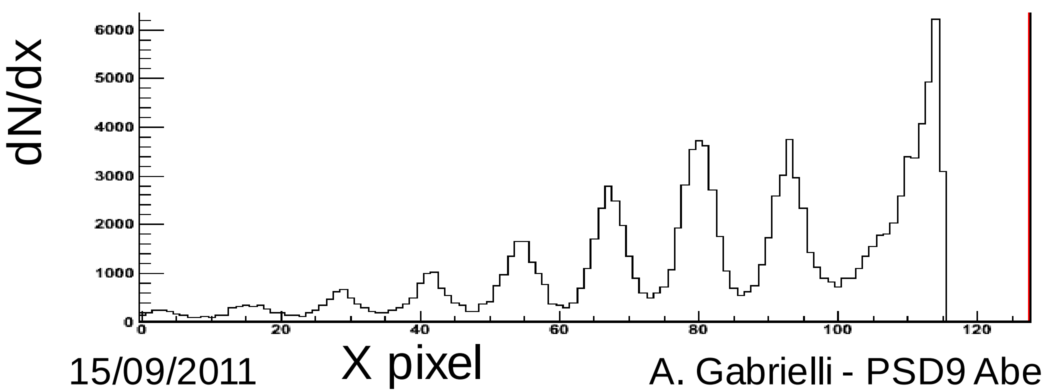
Carbon diffraction grating: pitch 400 nm typical

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

Observation windows: 3-7 ms



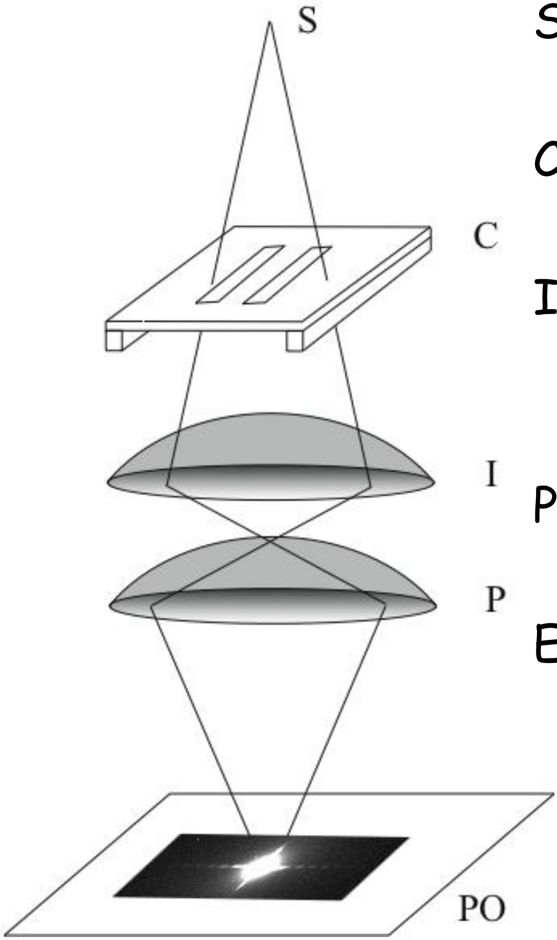




Great average number of electrons
Good signal;

Peak separation:13 pixels→ 0,65 mm

Set-up inside the TEM



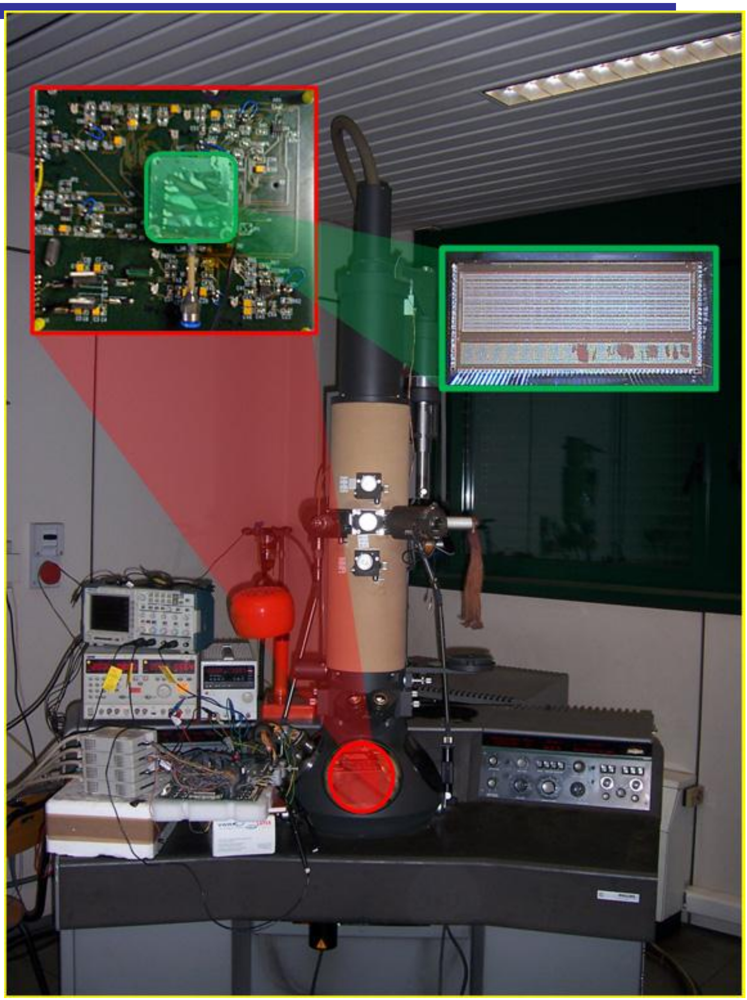
S- Small size source

C – Sample with two slits

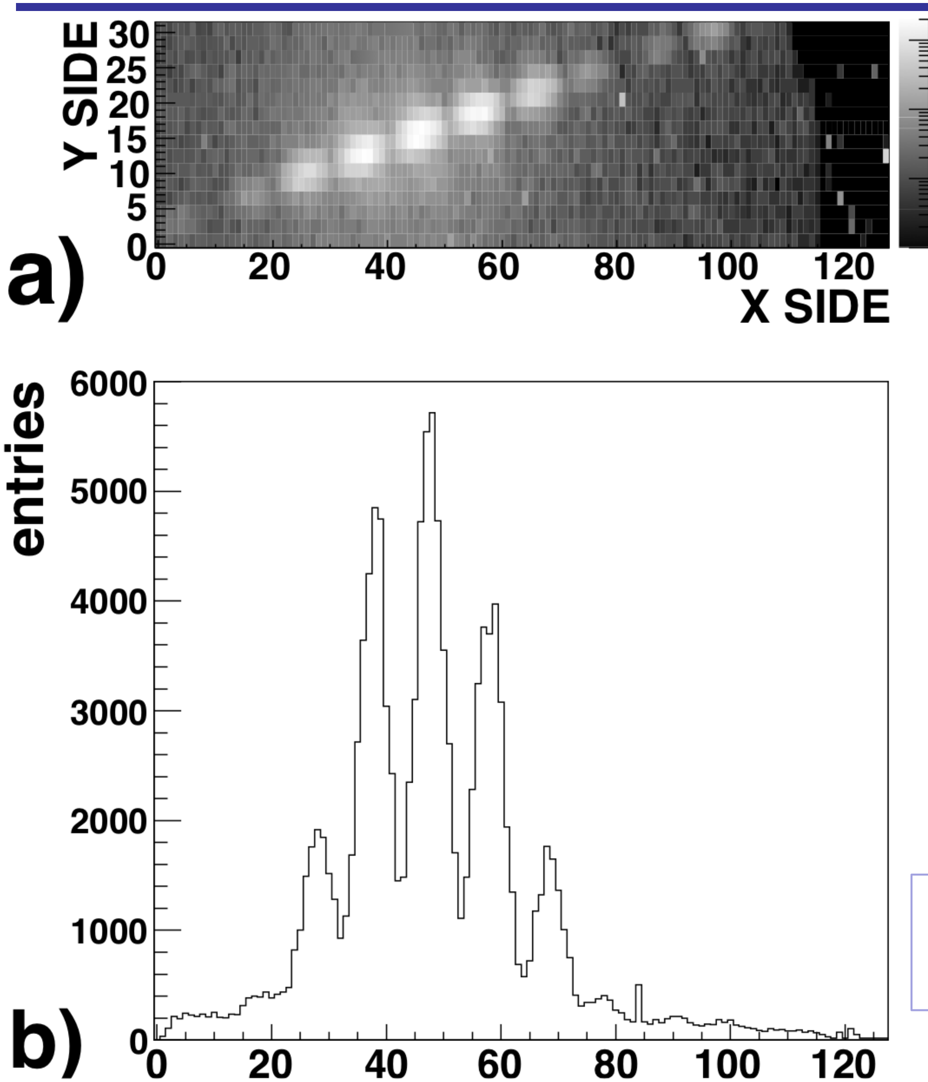
I,P – Image and projection lenses

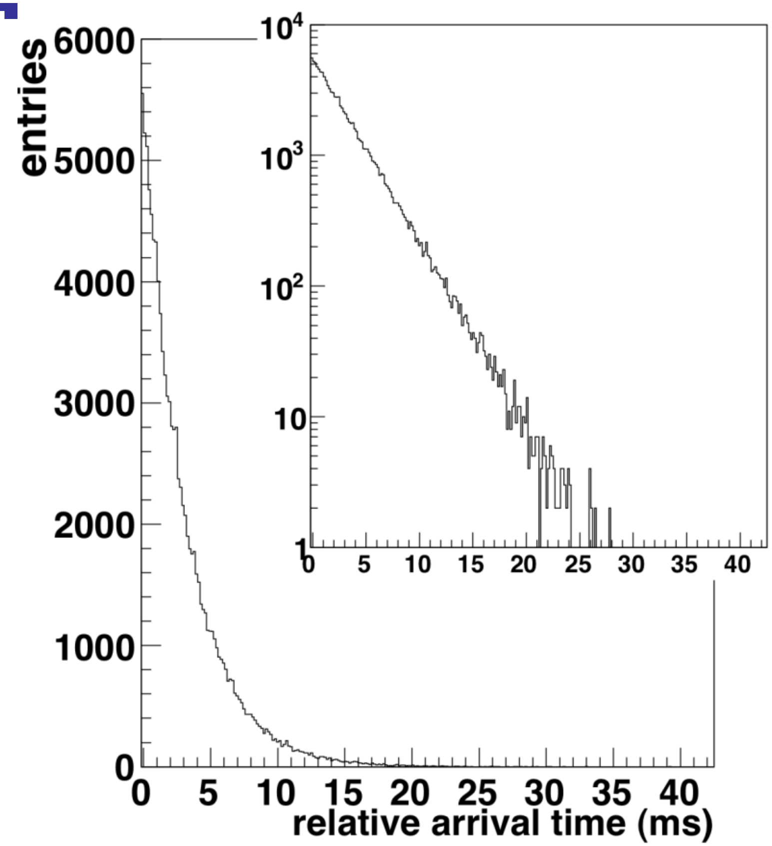
PO: projection plane

Experimental conditions:
Fraunhofer regime (plane wave approximation)



The single-electron interference I





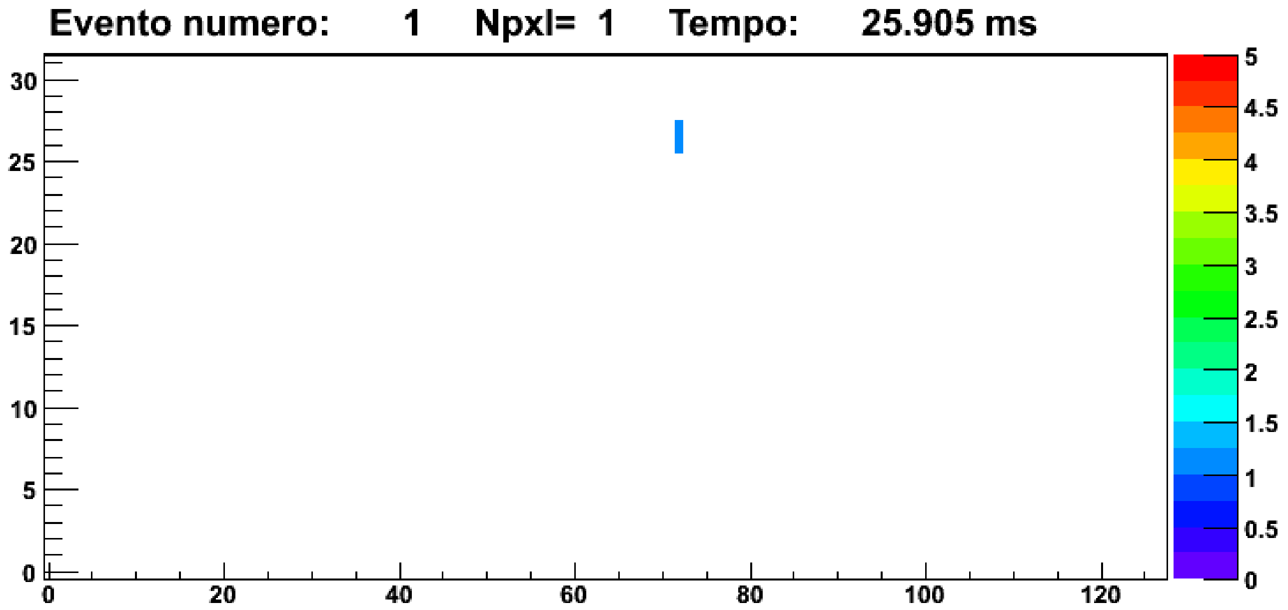
Average time = **3.1 ms**
Time of flight within TEM = **10 ns**

The single-electron interference II

Double slit: distance d=300 nm

40-60 keV electrons: λ=h/p= 5-6 pm, typical angles 10^{-5} rad; v=0,4 c

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



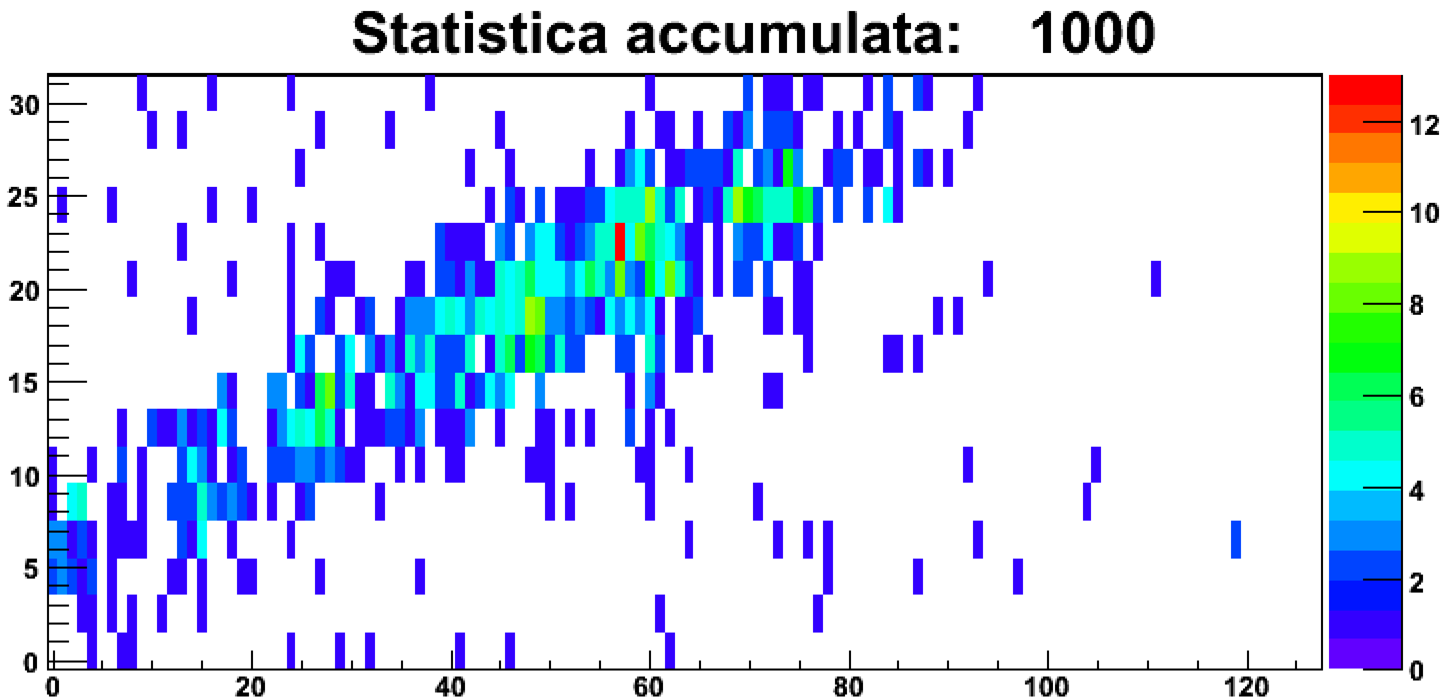
15 full frames per second → 1 / 7 Actual speed

The single-electron interference III

Double slit: distance d=300 nm

40-60 keV electrons: $\lambda = h/p =$ 5-6 pm, typical angles 10^{-5} rad; v=0,4 c

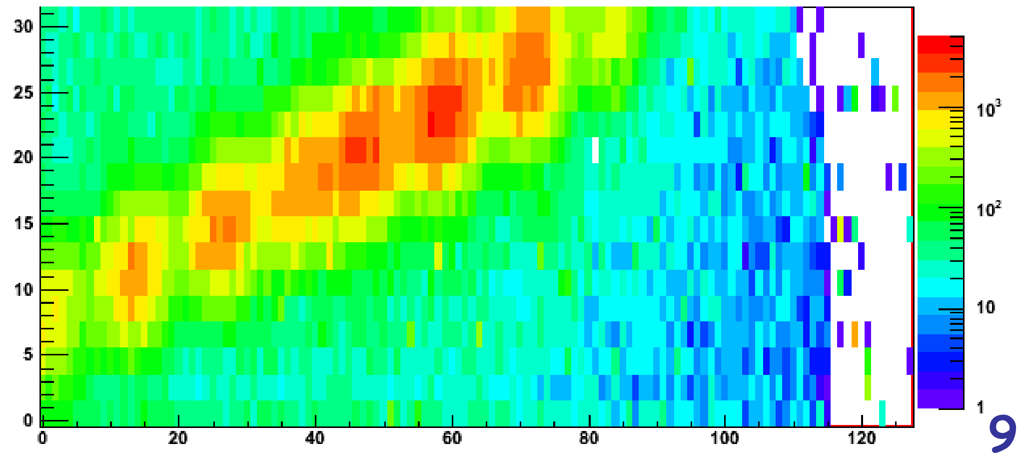
Observation windows **165 μs (6k fps)**

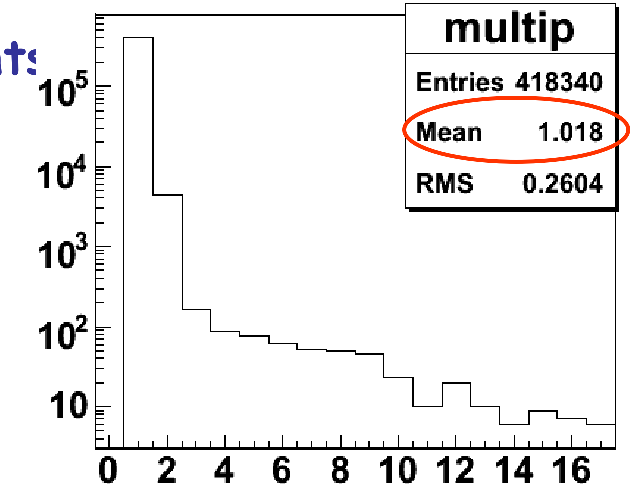


15 fps; 1 frame=9 s of data taking → 135 times actual velocity

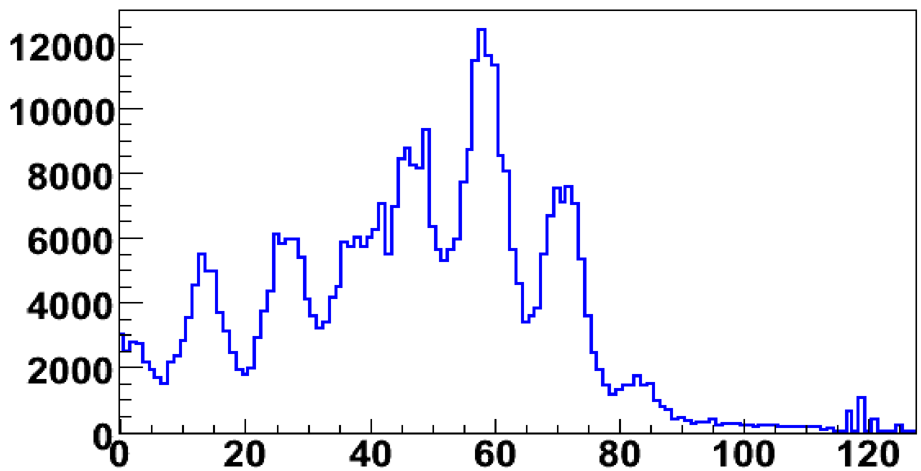
The single-electron interference IV

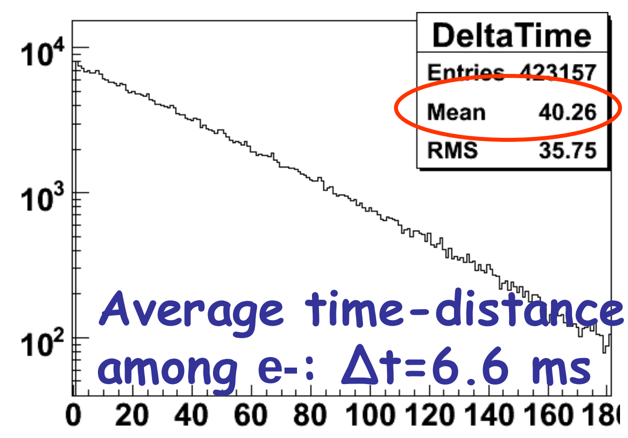
430k observed electrons in about 1h of measurements





98.8% images of single e^-





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

Conclusion

- Used for the first time a system of nano-slits with a high time-performance sensor
- (4096 pixels, 6k fps→2M fps) developed by INFN via a R&D project oriented to the next generation of silicon trackers (SLIM5).

- **Reconstructed the Young interference with single electrons**
  - Significant conceptual clarity to show the wave behavior of single electrons
- 98.8% of frames with single electrons. Average time among electrons has been measured to: 3 – 7 ms.

- **The sensor APSEL4D worked very well in a way not initially expected. The temporal characteristics can be used in a new field of electron microscopy: the study of static phenomena.**

Thanks to the SLIM5 collaboration