A MAPS detector application in a Young-Feynman interference experiment with single electrons

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Outline

• Young’s double slit interference experiment
• Historical notes on electron interference
• Setup of a quantum experiment with single electrons
• The digital sensor
• Measures and results
• Conclusions
Young’s double slit experiment

LIGHT
- Monochromatic and coherent source
- Two slits at distance \( d \) (primary wave split into 2 sources of coherent waves)
- Detection on screen at distance \( D \gg d \)
- Fringes at multiples of \( \theta = \frac{\lambda}{d} \)

PARTICLES (i.e. electrons)
- Mono-energetic and coherent (small) source

\[ \lambda_{\text{De Broglie}} @ 60 \text{ KeV} \sim 5 \cdot 10^{-12} \text{ m} \quad (0.05 \text{ A}) \]
\(~ 1/20 \text{ Hydrogen’s Bohr diameter}~\)

R. Feynmann: “We should say right away that you should not try to set up this experiment”
*Lecture on Physics, vol 3. (1963)*
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Electron Diffraction at Multiple Slits on the American Journal of Physics (1974) 42, 4-11
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From *gedanken* to real, a step further

TEM Philips M400T

Thermo-ionic electron emitter

**actual double slit mechanical stopper**

HEP MAPS sensor

APSEL4D chip by SLIM5 (INFN)

Custom DAQ board

“Digital movie” shot @ 6000 fps → single counts AND Time-tagging
DAQ Boards

Back-end board

Vacuum connector

MAPS sensor
Nanometric Double Slit

**FIB** (Focuses Ion Beam) 30 keV Ga+ source. 10 pA beam. Carbon membrane with Au deposition (50-100nm thick).

**SEM Image**

Length: 1550nm.
Width: 100nm.
Distance: 450nm.

The MAPS sensor APSEL4D

Developed by the **INFN SLIM5** collaboration: R&D for HEP collider experiments.

- **MAPS**: Monolithic Active Pixel Sensor CMOS ST.13 μm technology
- Thickness 300 μm, pitch 50x50 μm
- 4096 channels (32x128)
- ENC 75 e⁻
- S/N ~ 20 (MIP)
- Signal **discriminator** with extern. threshold
- **Binary hit** information.
- **Digital readout**:
  - Data Driven
  - **Sparsified** hit extraction
  - Time tagging down to 1 μs.
- Clock frequency 20-50 MHz
- **Efficiency** ~ 90% measured at CERN with 12-GeV proton beam.

**Sparsified Digital Readout**

**Macro Pixels (MP) have dedicated lines**
- 1 Fast OR
- 1 Latch enable
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Pixel hit extraction
• 1 column at a time
• Only fired MP are inspected column by column
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  - Fired pixel in the active column are coded by sparsifier components
  - Hits converge on a common formatted output.
The Measures
System test: Carbon-grating diffraction

Grid sample pitch: 400 nm

40 keV electrons: $\lambda = \frac{h}{p} = 5.9 \text{ pm}$; $\theta \sim 10^{-5} \text{ rad}$

3 ms time resolution: 333 fps

High average number of electrons per frame

Peak distance: 13 pixels $\Rightarrow 0.65 \text{ mm}$
The single electron interference experiment results

• 40 keV electrons
• 165 μs time resolution: ~6000 fps
Vast majority of frames are empty (empty/hit ~ 70)
The edited movie

1st part: Both empty and single-electron frames are being played
2nd part: Empty frames are being skipped.
3rd part: Single electron frames are overlapped together

96k e\(^{-}\) recorded
~20 min. run

~80 e\(^{-}\)/s \(\Rightarrow\) 1500 km av. Distance (\(\beta\sim.5\))
Frame data analysis

Electron multiplicity in frames

- Zero-multiplicity (empty frames) \( \sim 7 \times 10^6 \)

Time distance between electrons

- Almost every electron was already “on tape” before the next one was emitted
Conclusions

• A Young-Feynmann experiment with a sub-micron double slit, a HEP pixel sensor and a Transmission Electron Microscope was setup.

• 40KeV Single electrons could be detected, time-tagged with a 165 µs time resolution and taped out one by one → For the 1\textsuperscript{st} time the arrival time distribution (mean ~10 ms) has been reconstructed.

• The double slit interference pattern was build up off-line with a statistic of about 100k electrons that travelled at an average distance of ~1500 km between each other.
Thank you
Still image of the overlapped single electron frames