Dark current spectroscopy in proton, neutron and ion irradiated CMOS Image Sensors

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Context and goal

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- The dark current distribution depends on the **type** and **distribution** of the **radiation-induced defects**
- Identifying the defects generated by **each type of interaction** could help **predicting the dark current increase** for various particles

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In this work, the dark current spectroscopy is tested on neutron, proton and ion irradiated CIS to identify the defects generated by coulomb and nuclear interactions

The dark current spectroscopy

- Hypothesis: to **each type of silicon bulk defect** corresponds a given **generation rate** (Shockley Read Hall):

$$U = \frac{\boldsymbol{\sigma} v_{th} n_i}{2\cosh\left(\frac{|\boldsymbol{E_t} - E_i|}{kT}\right)}$$

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- If each pixel contains a maximum of **one radiation-induced bulk defect**:
  - The generation rate of **individual defects** can be measured
  - Pixels which contain **similar defects** have a **similar dark current increase** after irradiation
  - The **main radiation-induced defects** are detected by the presence of **dark current peaks** in the dark current distribution

The dark current spectroscopy

- Hypothes … a given
  generatio
- If each pi… **bulk defect**:
  - The g … ed
  - Pixels … **current**
    increa
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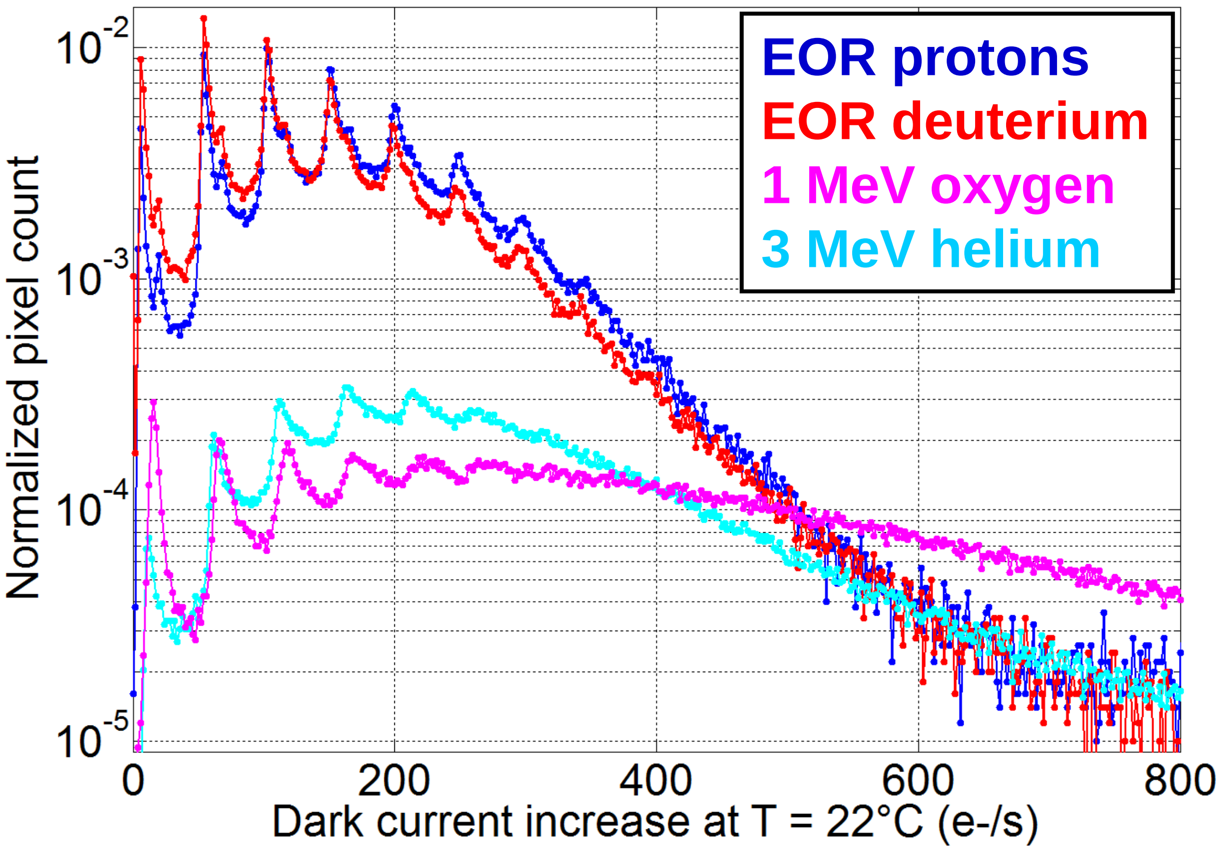
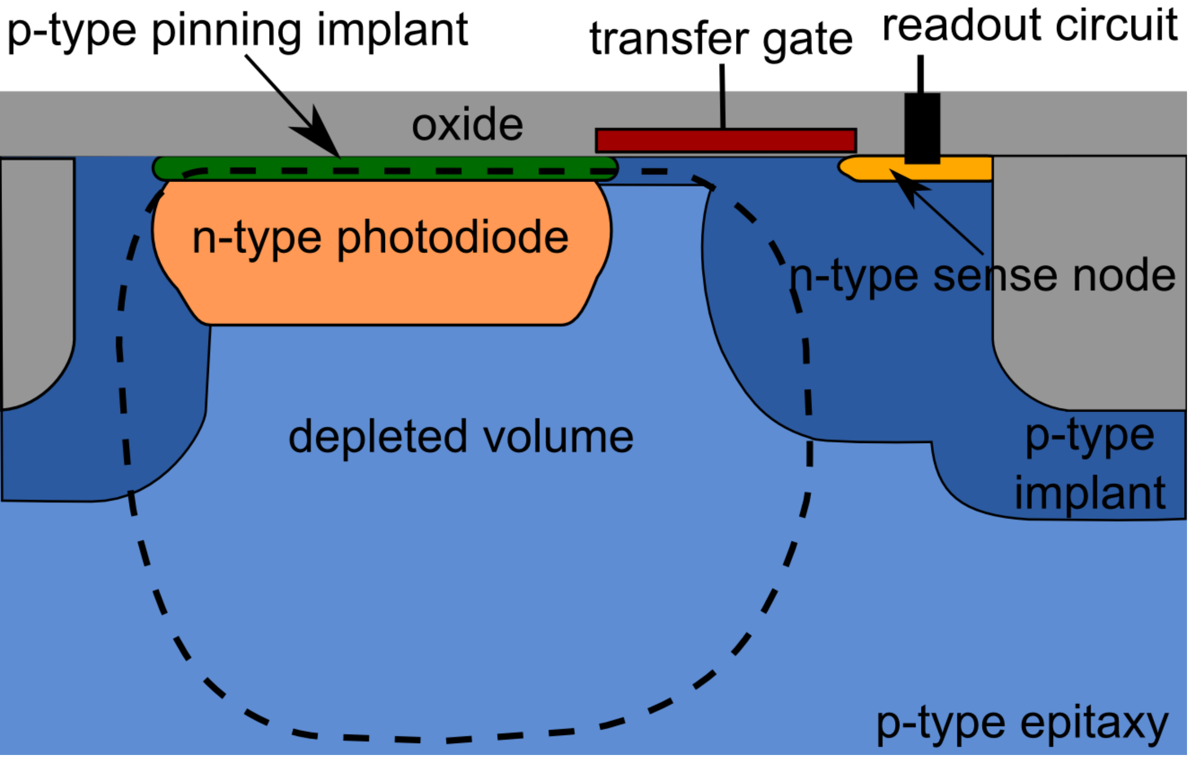
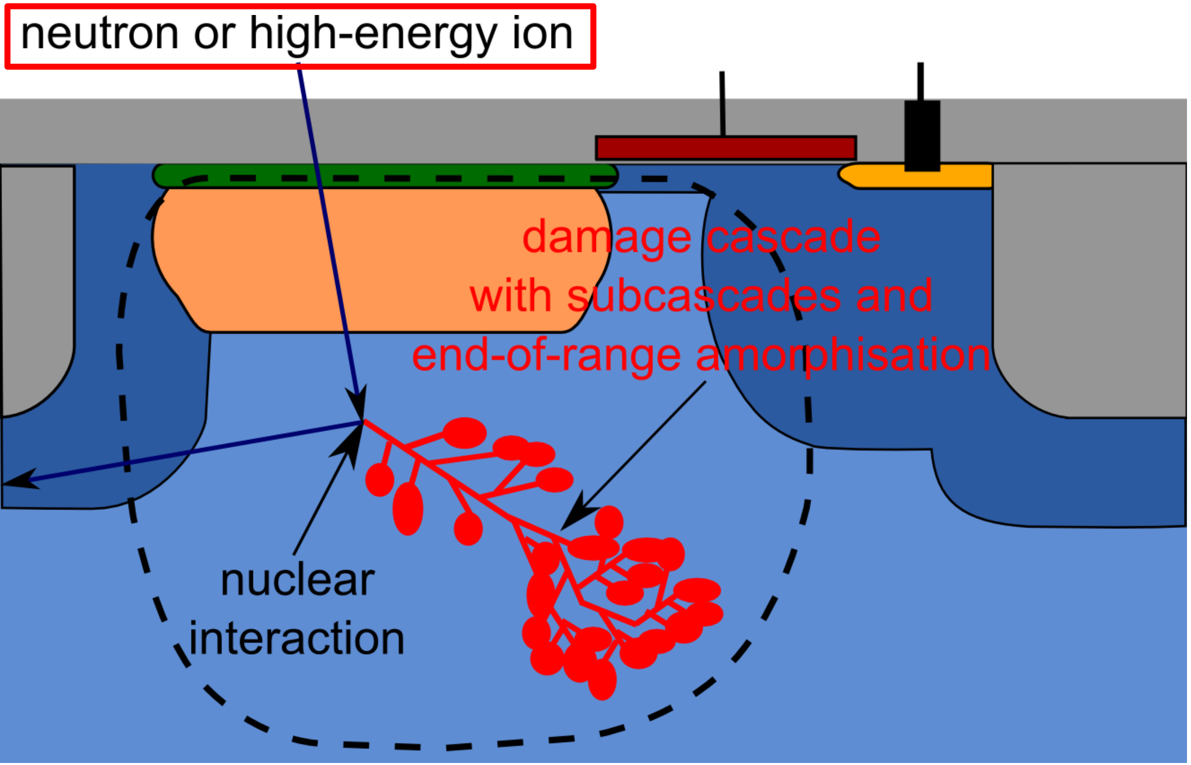


Tested device:
Pinned photodiode CMOS image sensor



- 512 x 512 pixels
- 7 µm pixel pitch
- Pinned photodiode
- Low intrinsic dark current (6 e-/s @ 22°C)

Neutrons and high-energy ions: nuclear interactions

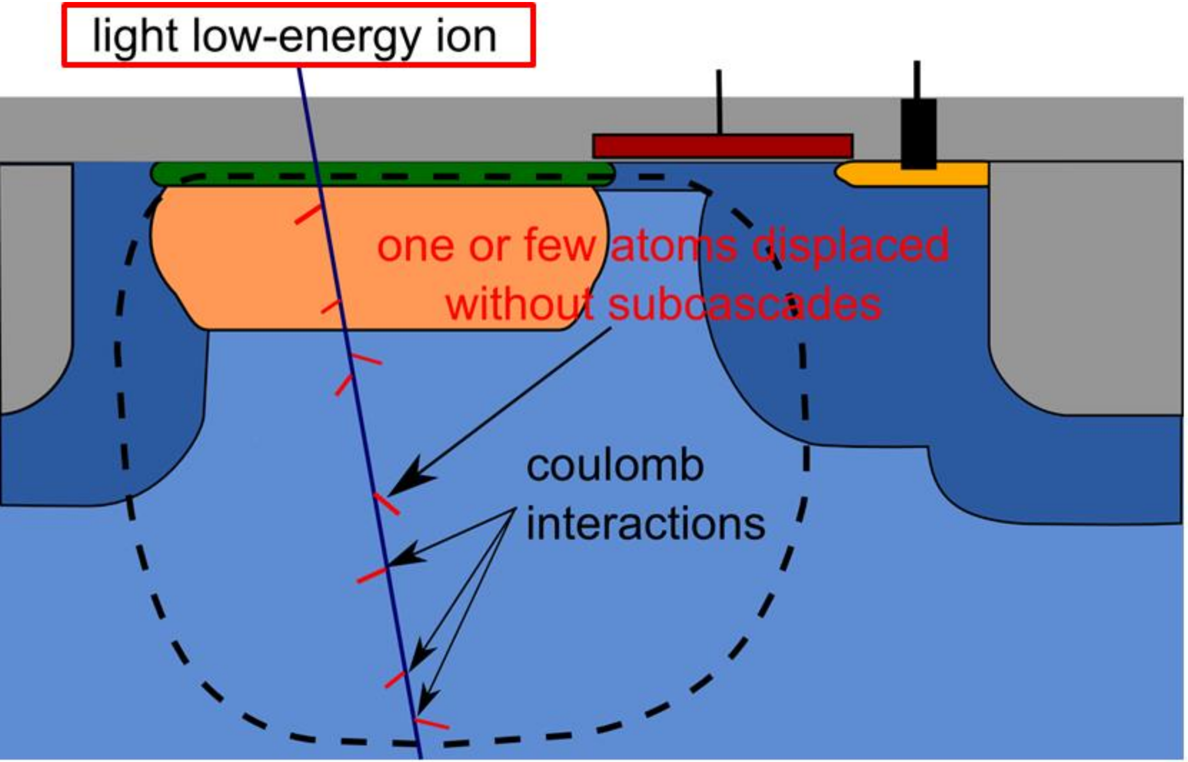


- Nuclear (elastic, inelastic): **high energy silicon PKA** (~ 100 keV)

⇒ **dense** damage

PKA = Primary Knock-on Atom (primary recoil)

Low energy light ions: low NIEL coulomb interactions



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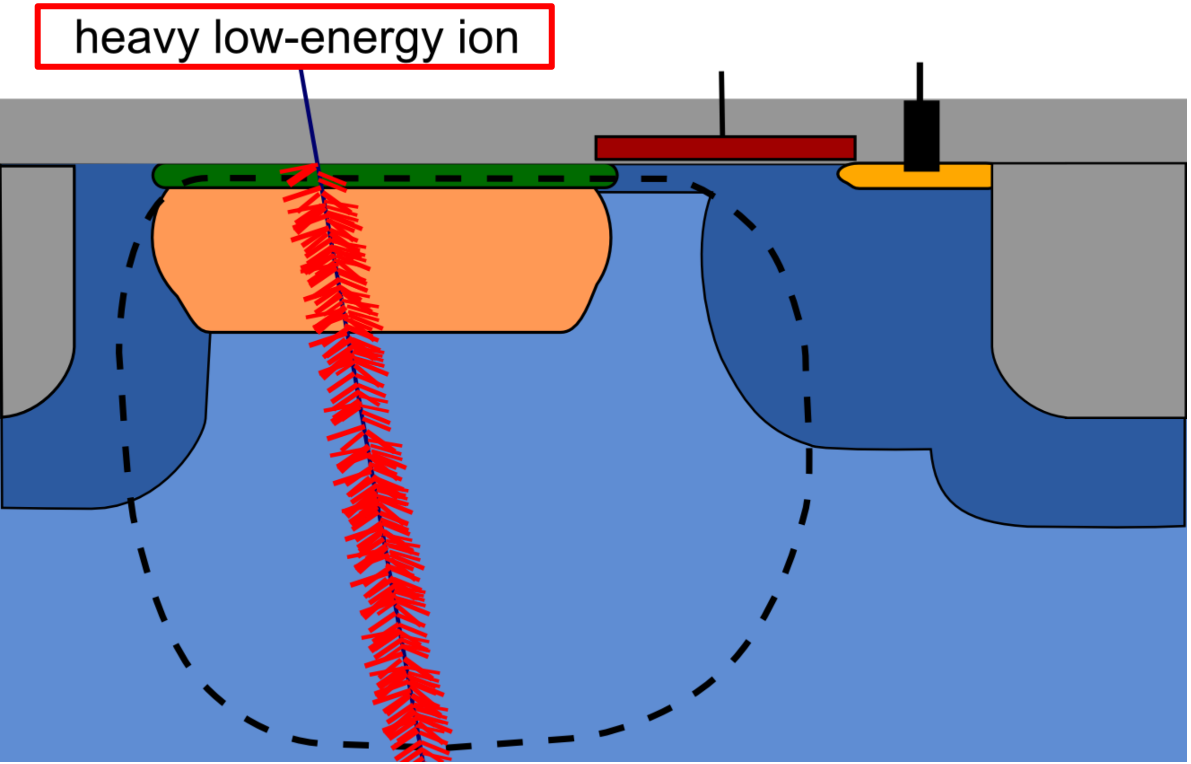

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- High NIEL coulomb: **low energy PKA** but **very close to each other**

⇒ **dense** damage

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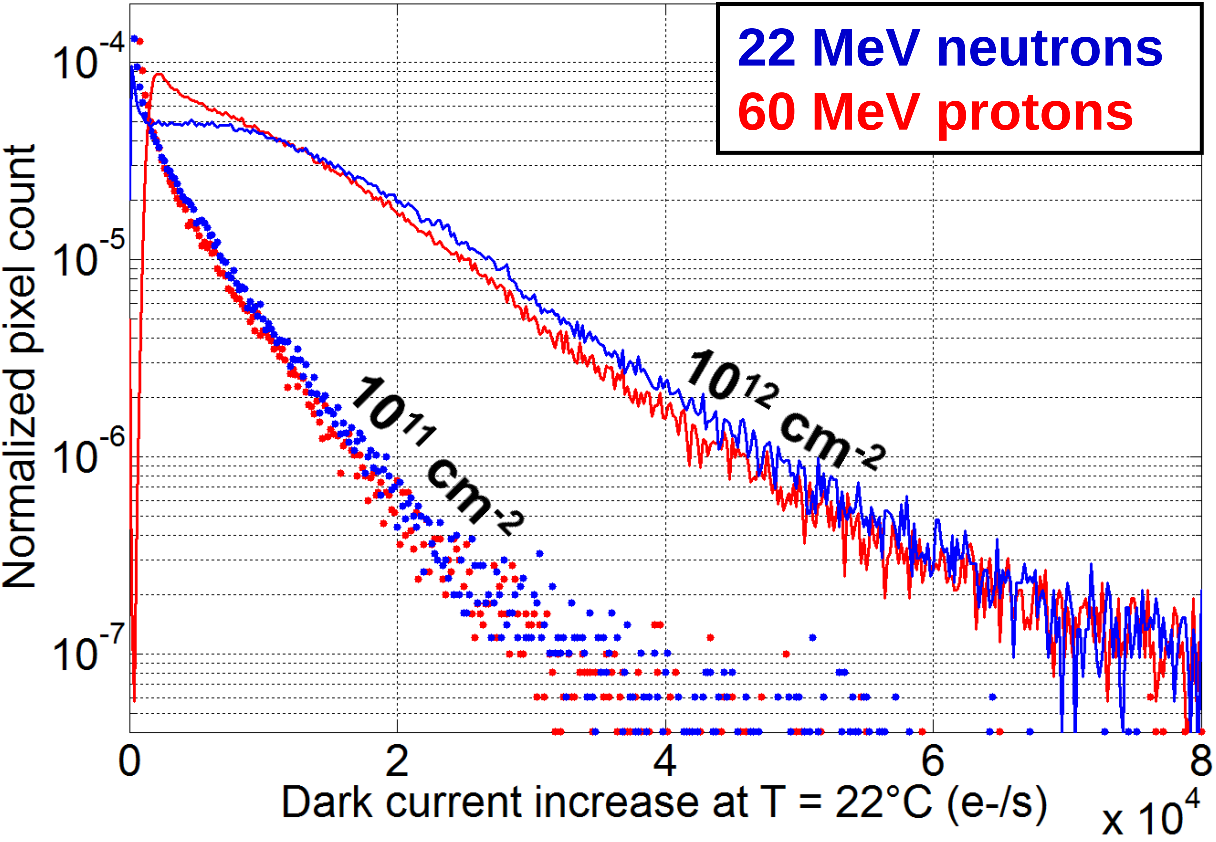
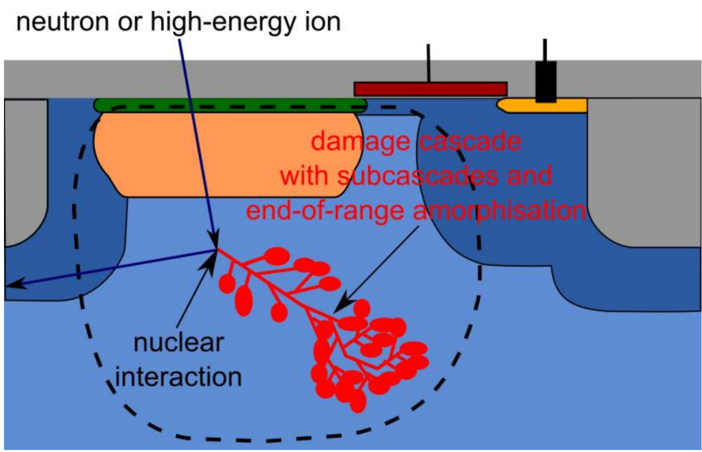
Nuclear interactions: Exponential hot pixel tail



- **Exponential hot pixel tail** (several 10,000 e^-/s) with **many hot pixels**



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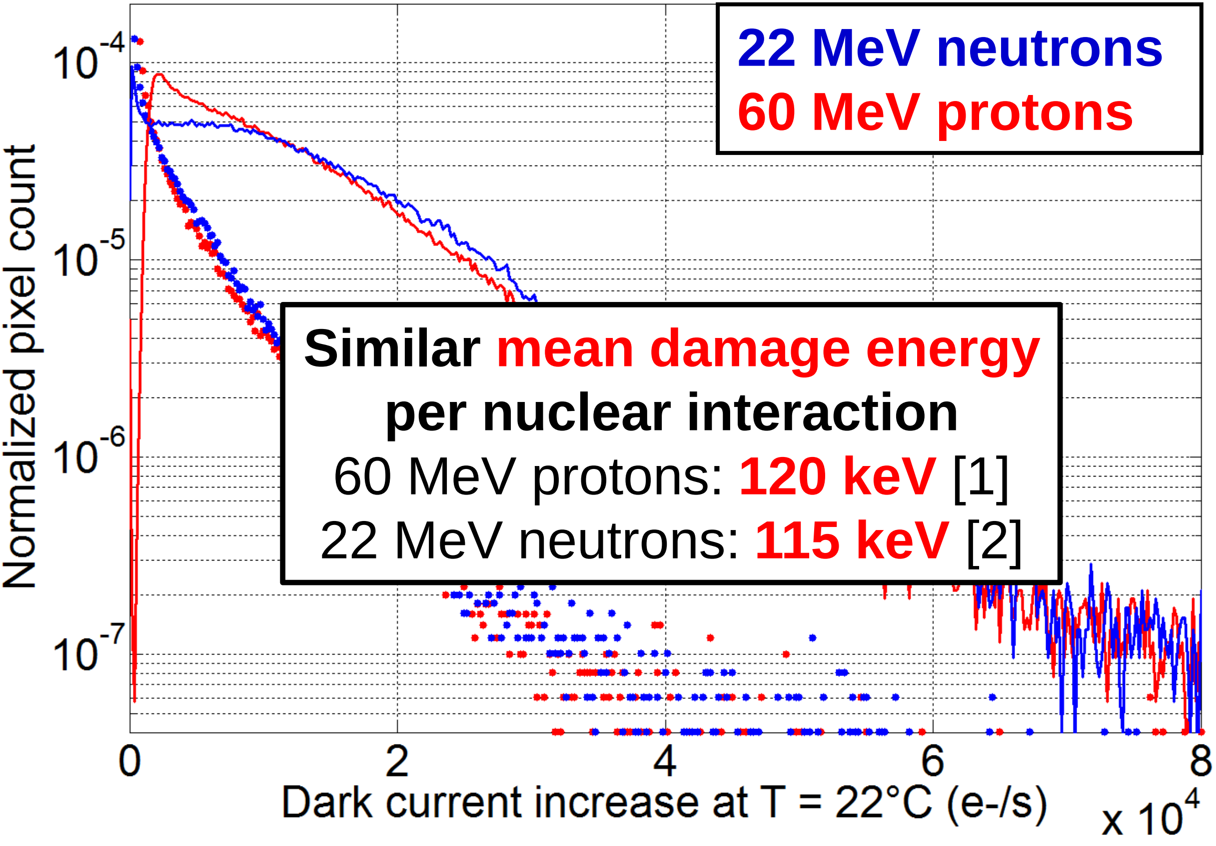

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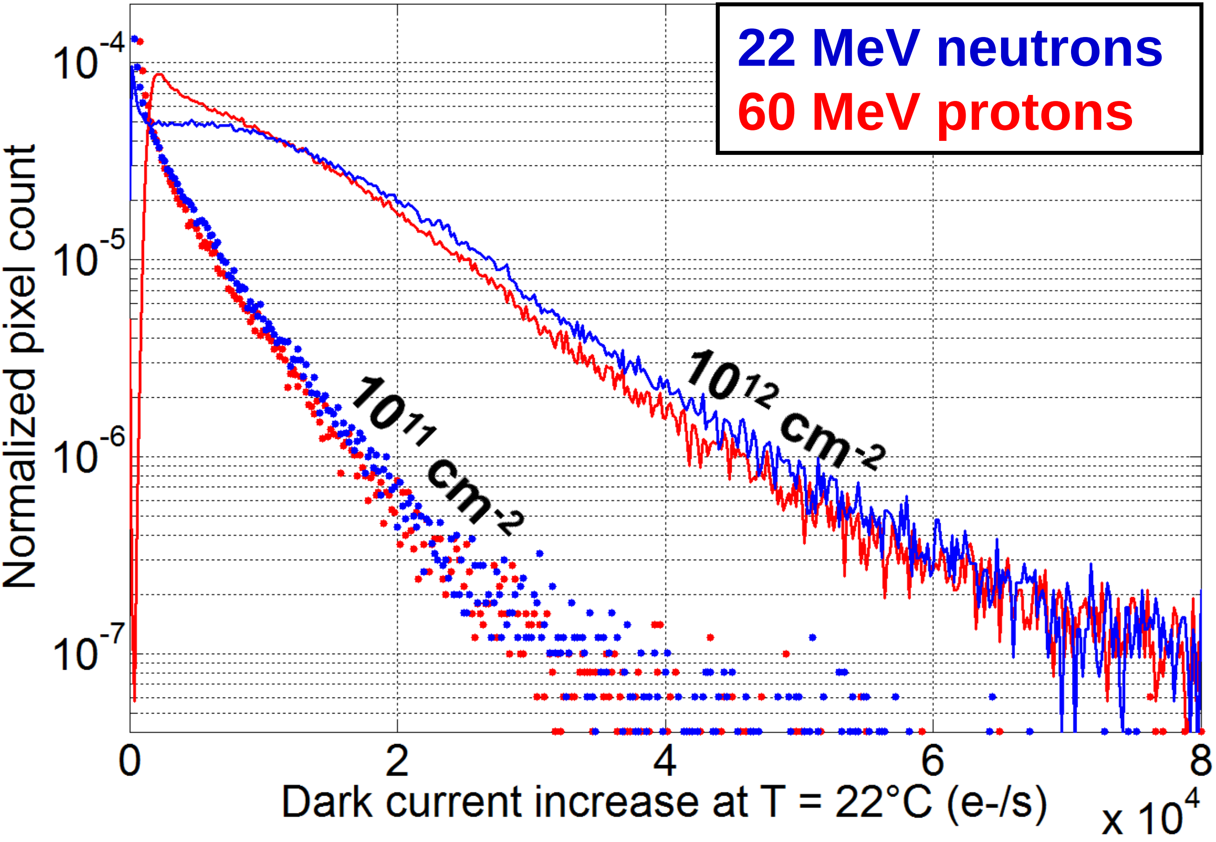
- Similar **exponential mean** for neutrons and protons ($4.3.10^3$ e^-/s)

[1] Dale et al., IEEE TNS, 1994.
[2] Srour et al., IEEE TNS, 1986.

Nuclear interactions: Exponential hot pixel tail



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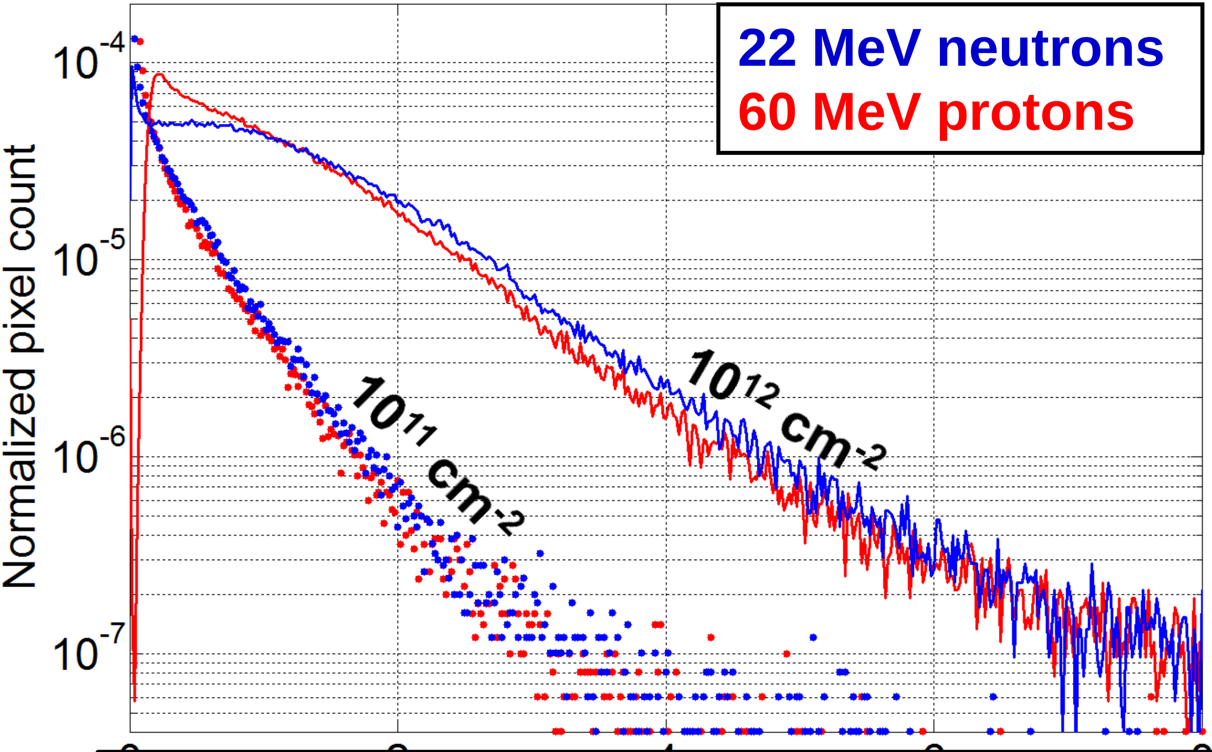
- Similar number of hot pixels at similar fluence due to **similar nuclear NIEL**
  - Neutrons: 4.0 keVcm²/g
  - Protons: 2.7 keVcm²/g

Nuclear interactions: Exponential hot pixel tail



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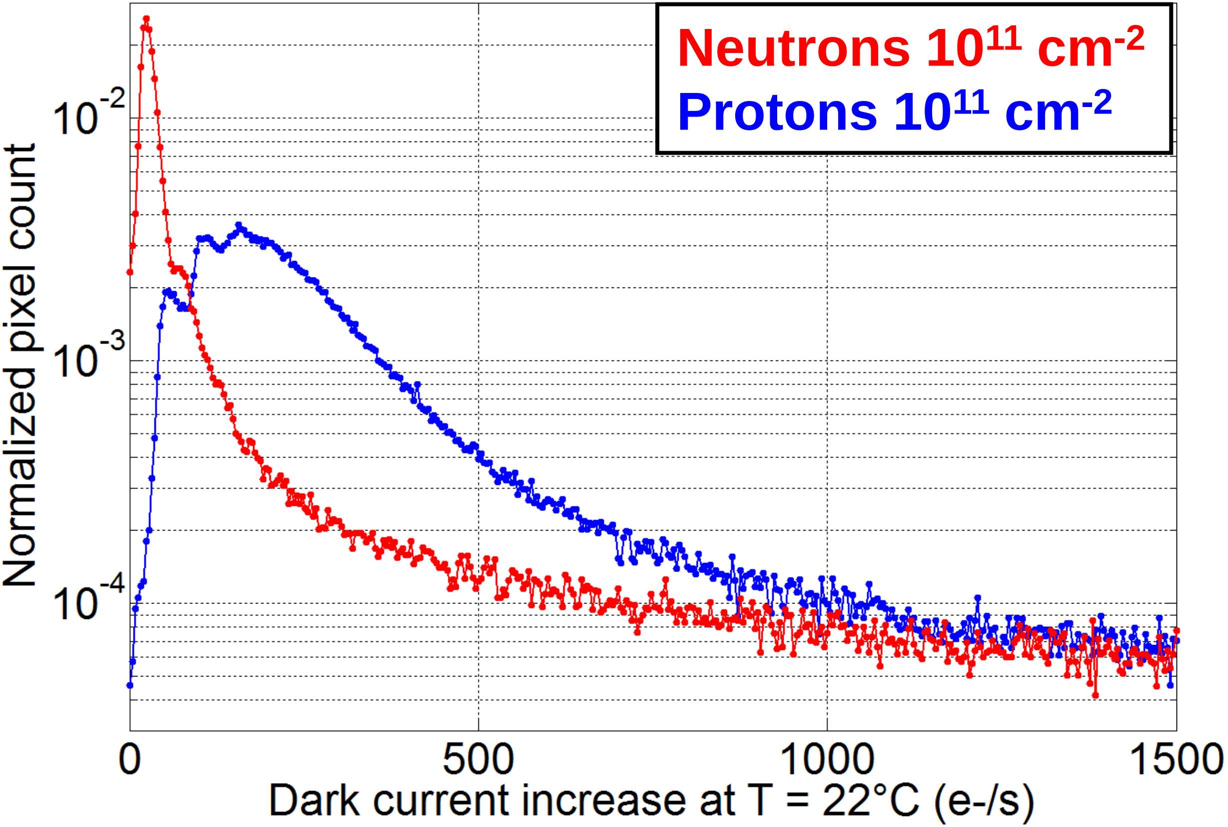
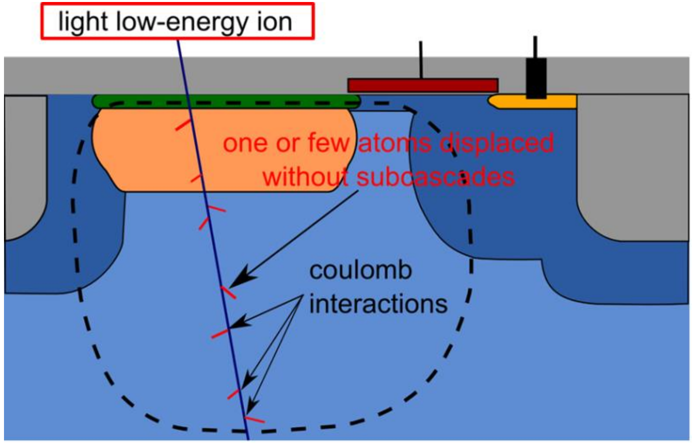
Nuclear interactions ⇒ high dark current exponential hot pixel tail

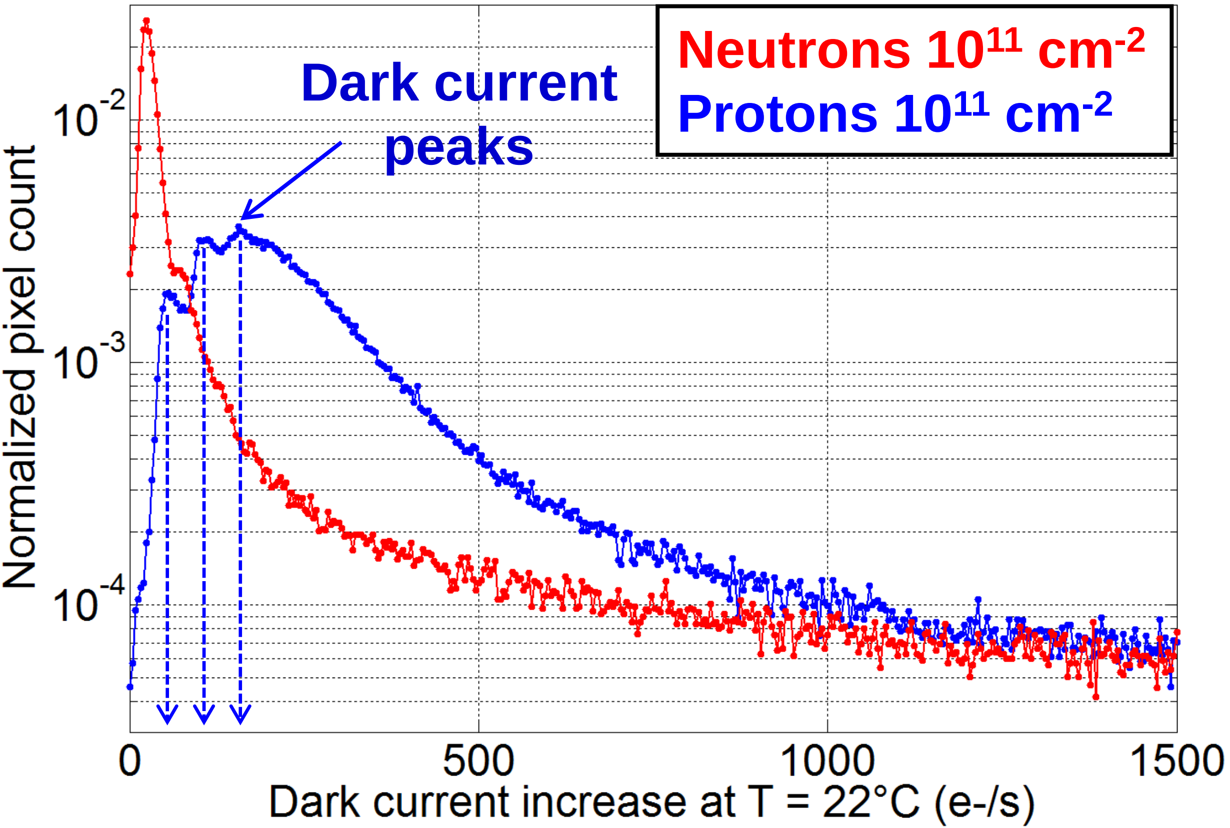
Low NIEL coulomb interactions: dark current peaks



- More pixels with **small dark current increases** (few 100 e^-/s) for protons



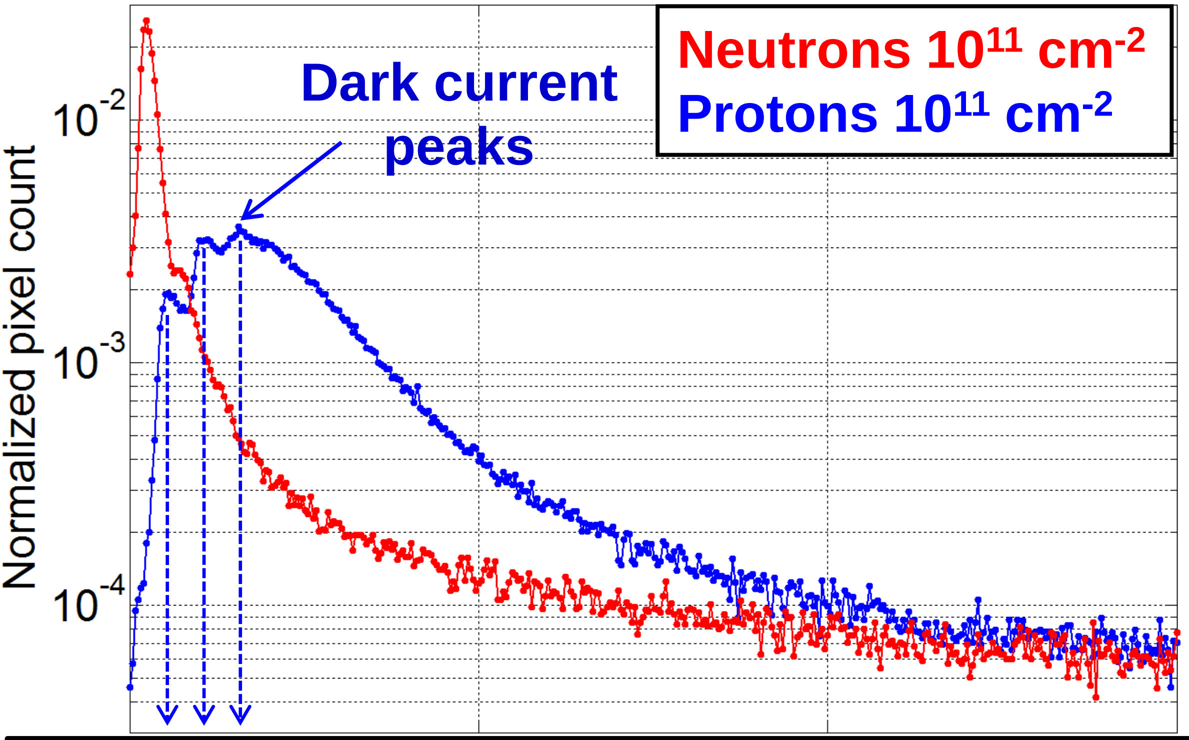
Low NIEL coulomb interactions: dark current peaks



- More pixels with **small dark current increases** (few 100 e^-/s) for protons
- Dark current peaks separated by 50 e^-/s

⇒ specific point defects with generation rate of **50 e-/s**

Low NIEL coulomb interactions: dark current peaks



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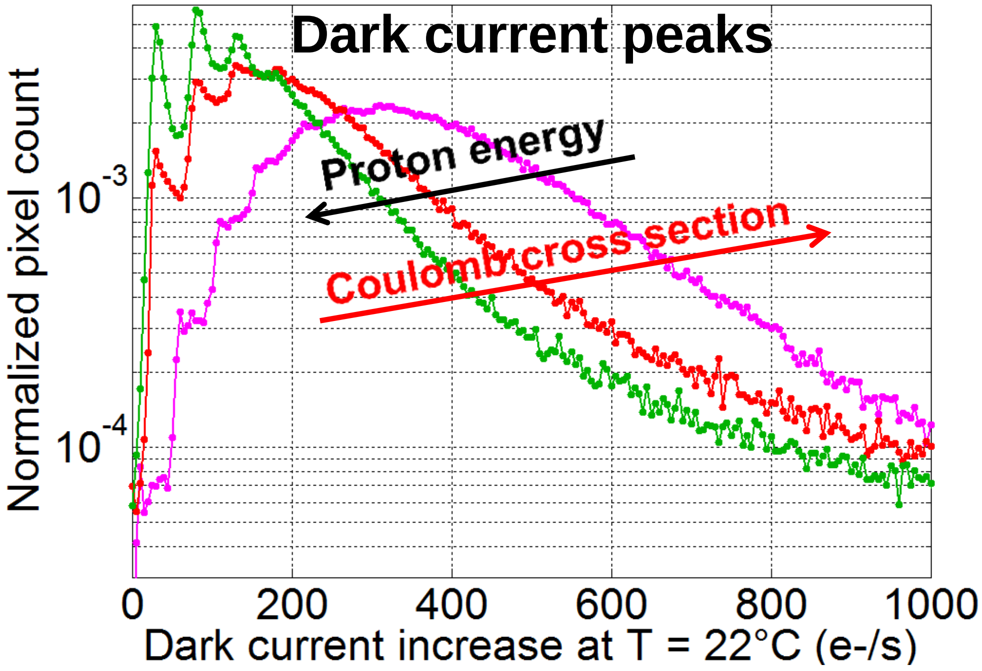
- Dark current peaks separated by 50 e$^-$/s

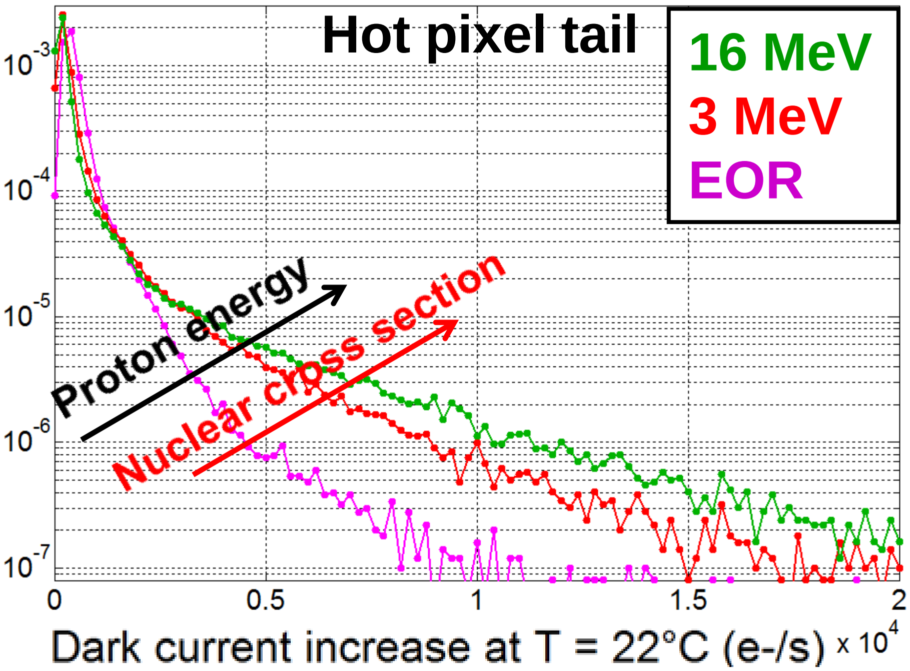
⇒ **specific point defects** with generation rate of **50 e-/s**

⇒ generated by **coulomb interactions** (only for protons)

Low NIEL coulomb interactions ⇒ dark current peaks (point defects)

Effect of the coulomb and nuclear cross section





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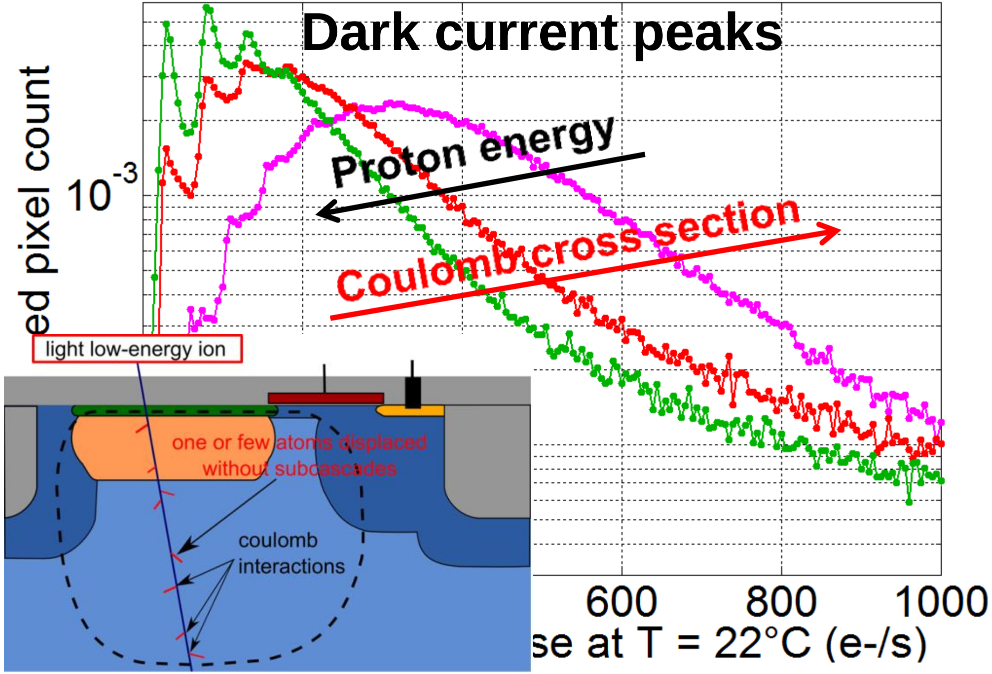
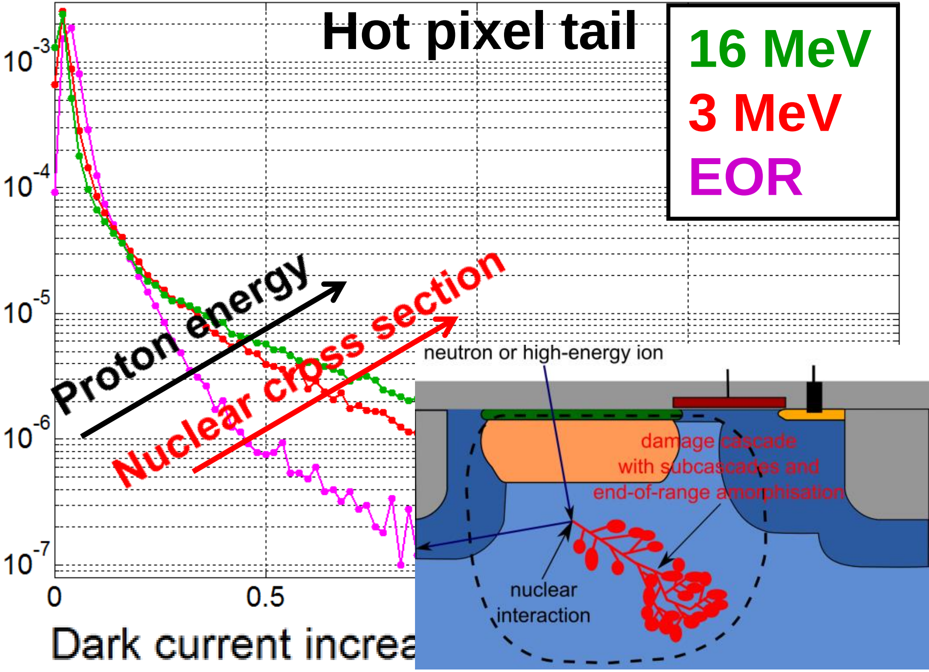




Low NIEL coulomb interactions

⇓

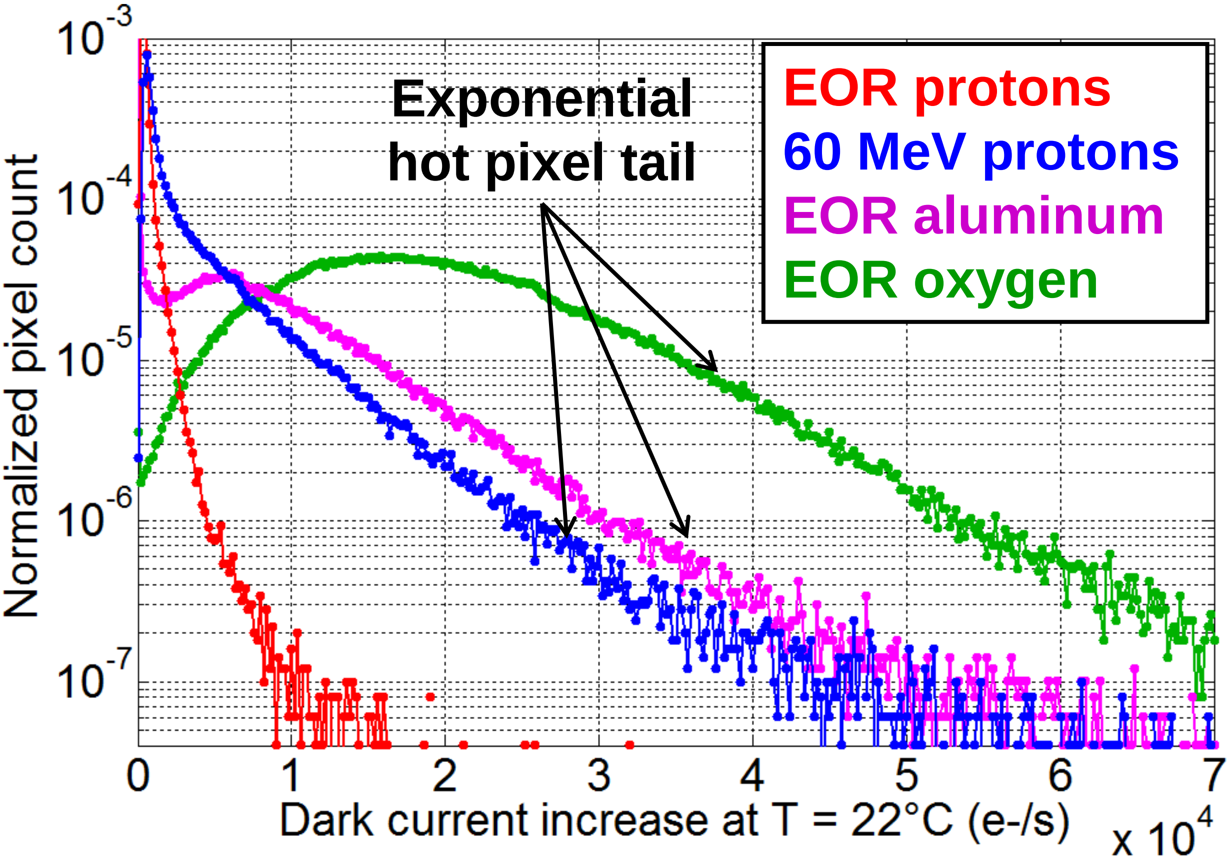
Dark current peaks

Nuclear interactions

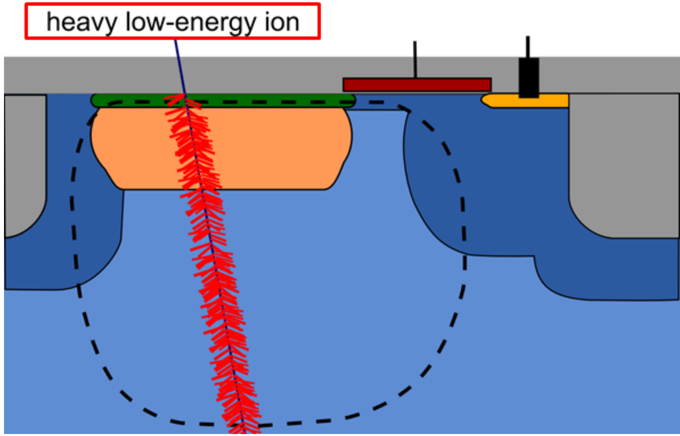
⇓

Exponential hot pixel tail

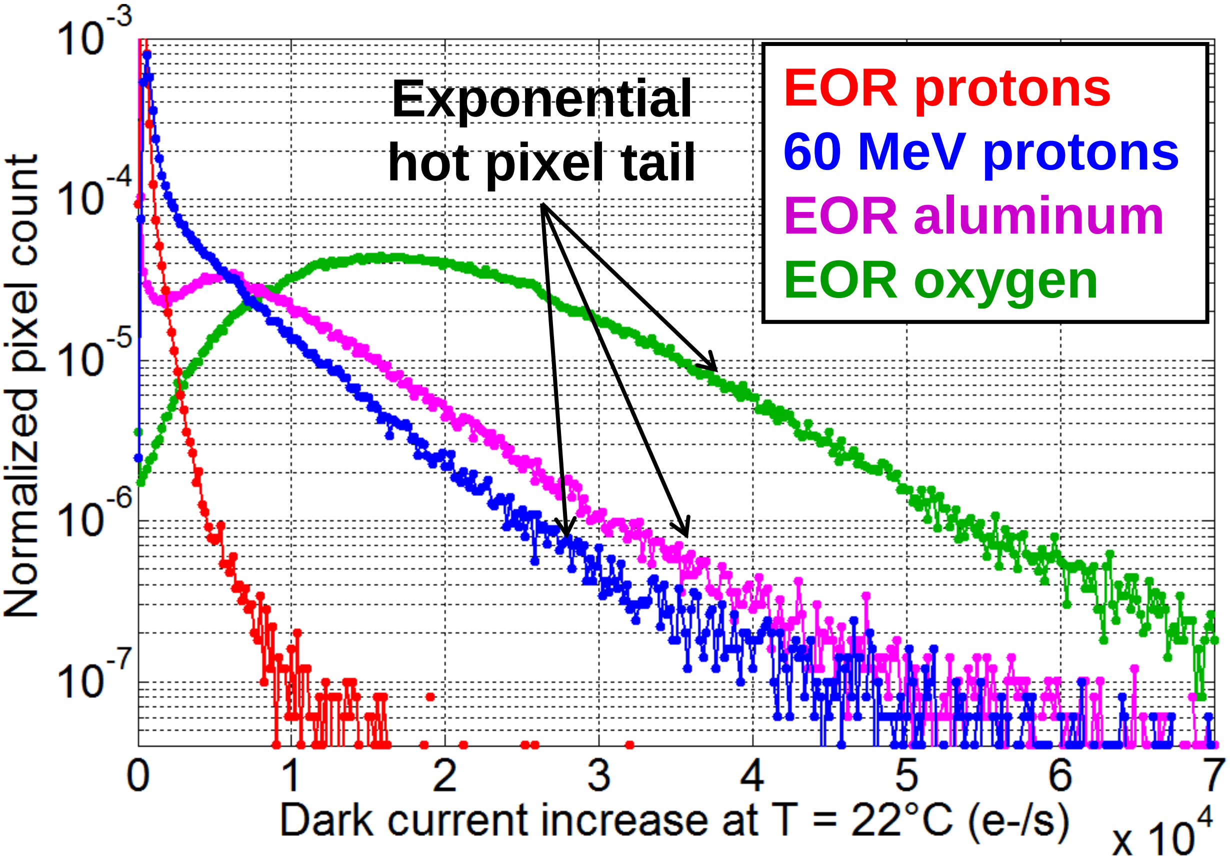
High NIEL coulomb interactions: exponential hot pixel tail



- EOR heavy ions (oxygen and aluminum):
  - **exponential hot pixel tail**



High NIEL coulomb interactions: exponential hot pixel tail



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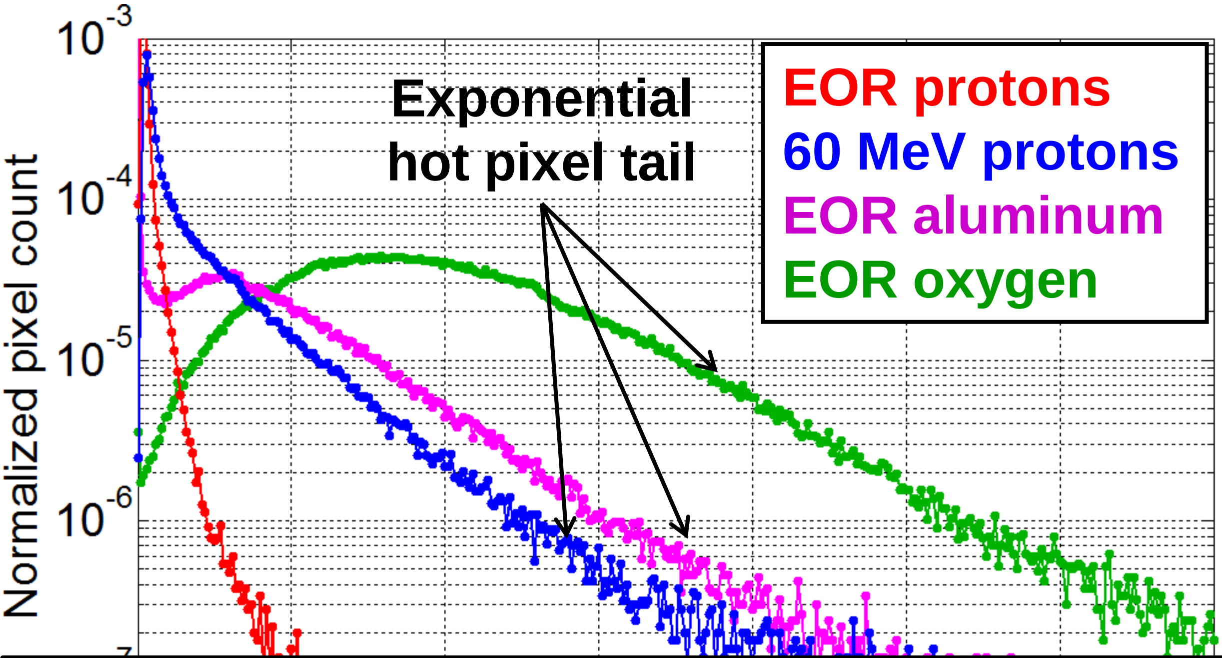

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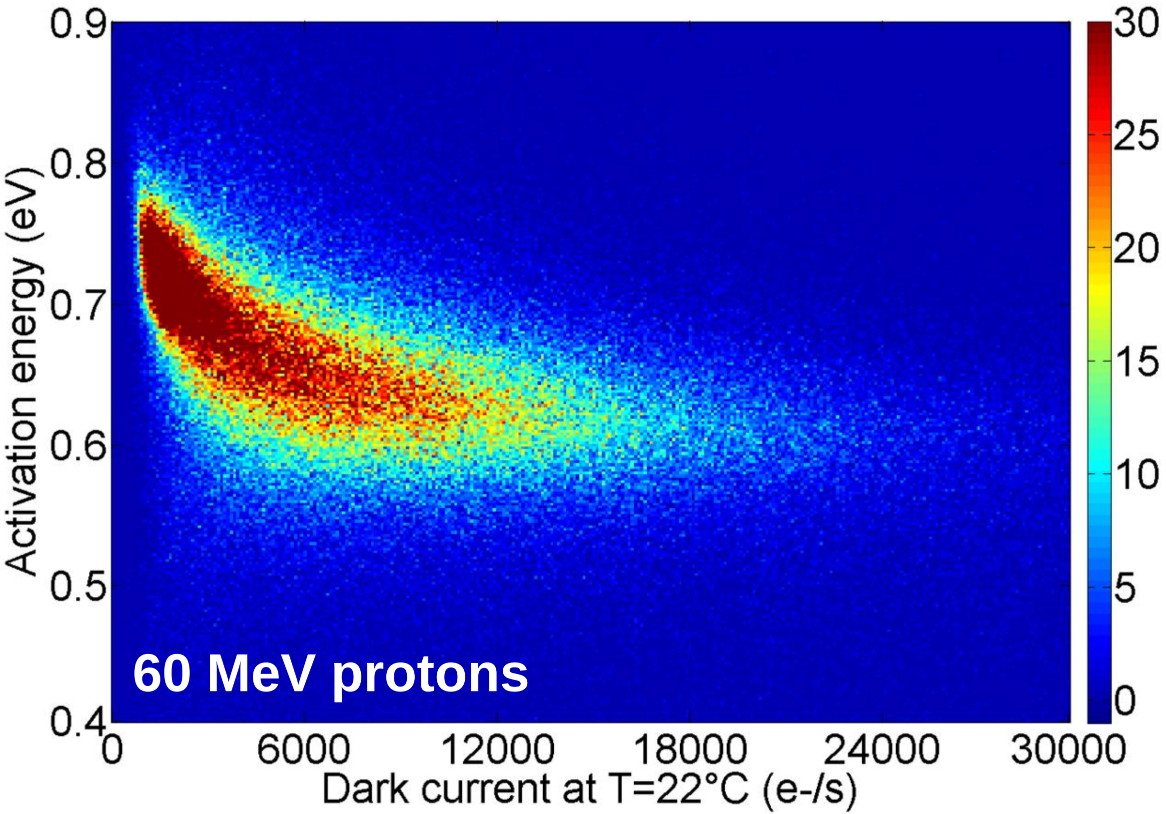
Dense damage (**nuclear interactions** or **high NIEL coulomb interactions**)

⇓

Exponential hot pixel tail

Dark current activation energy of the exponential hot pixel tail



$$I_{dark} \approx A\exp\left(-\frac{qE_a}{kT}\right)$$

$$E_a \simeq |E_t - E_i| + 0.63\ \mathrm{eV}$$

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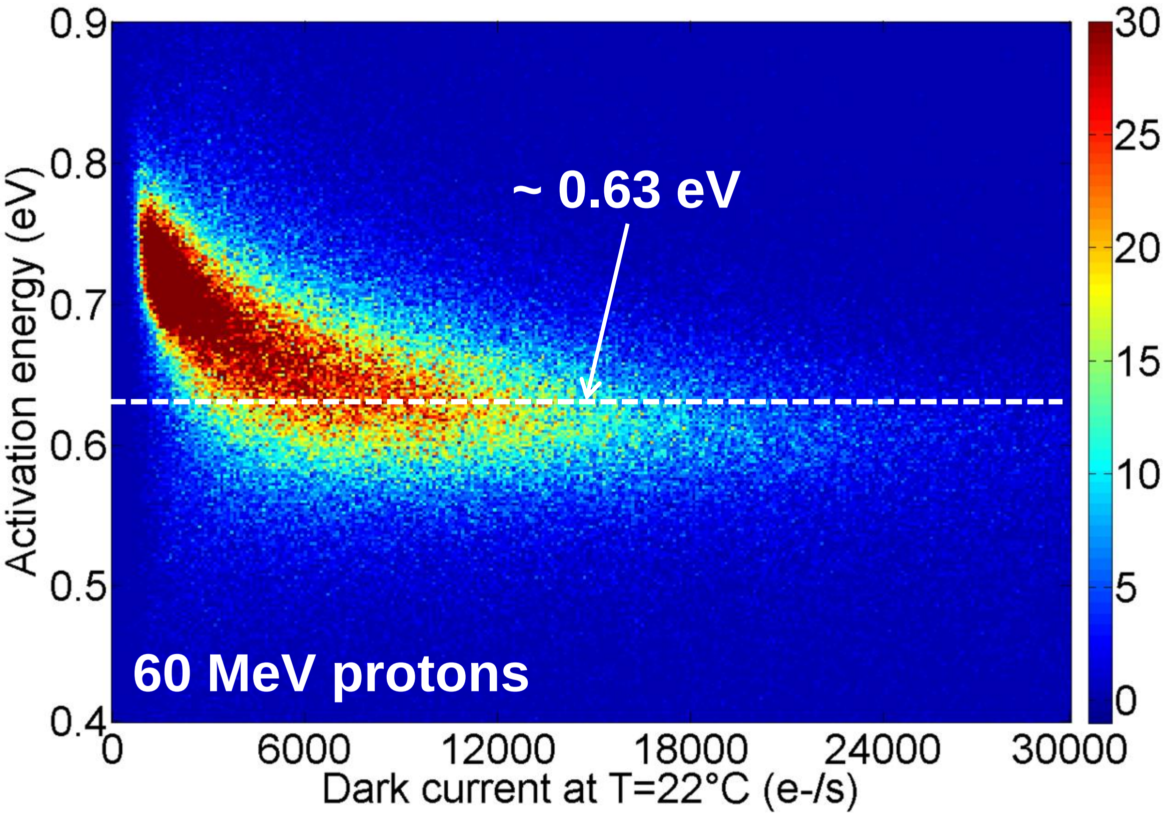

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- High dark current: **0.63 eV**

⇒ **midgap energy levels**

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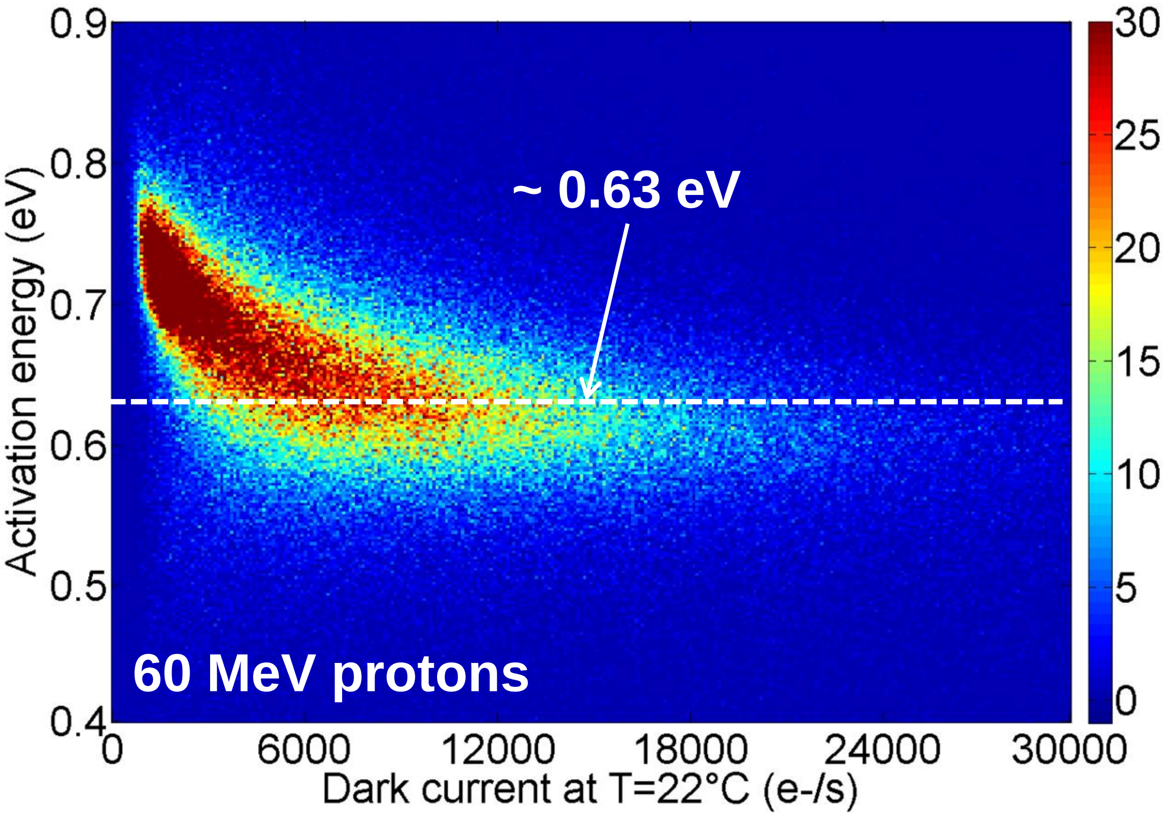

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- High dark current: **0.63 eV**

⇒ **midgap energy levels**

- Smooth hot pixel tail

⇒ **various generation rates**

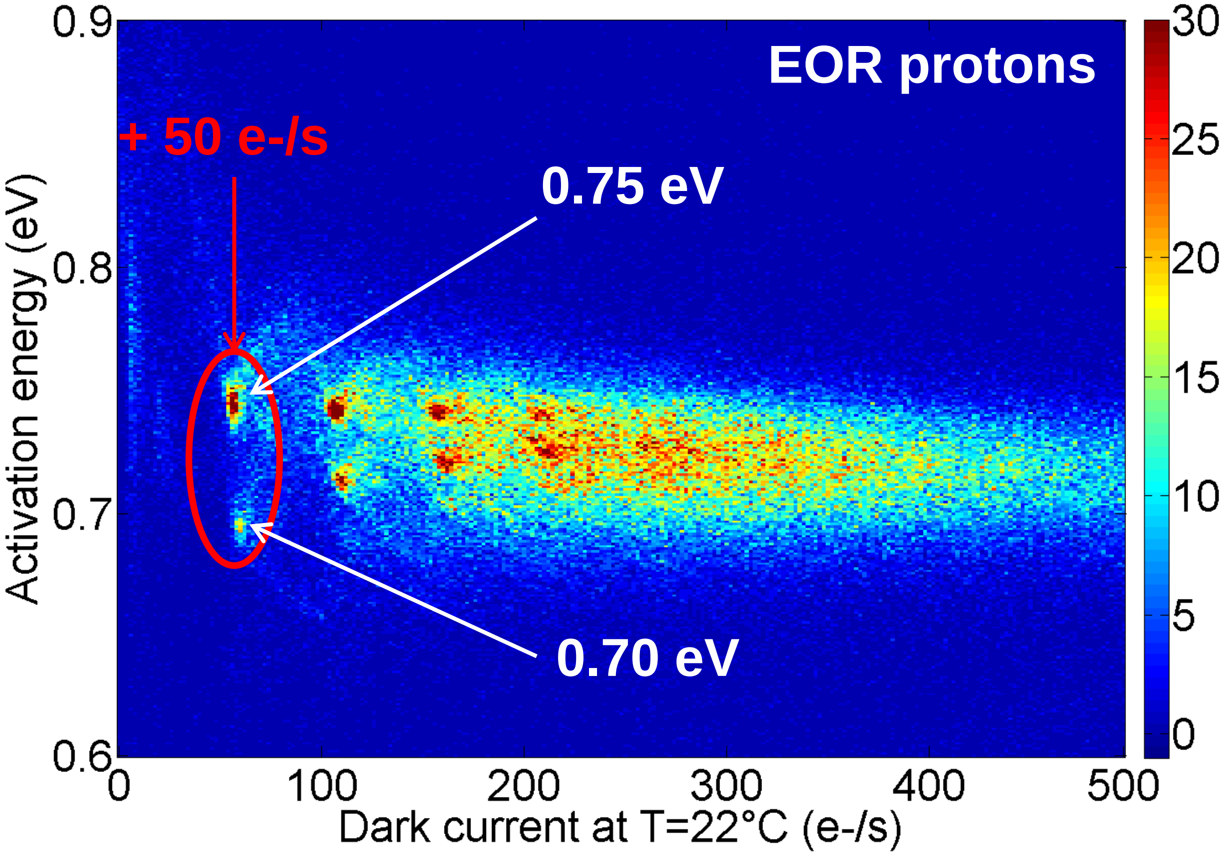
⇒ **many possible structures**

⇓

Clusters?

Amorphous inclusions?

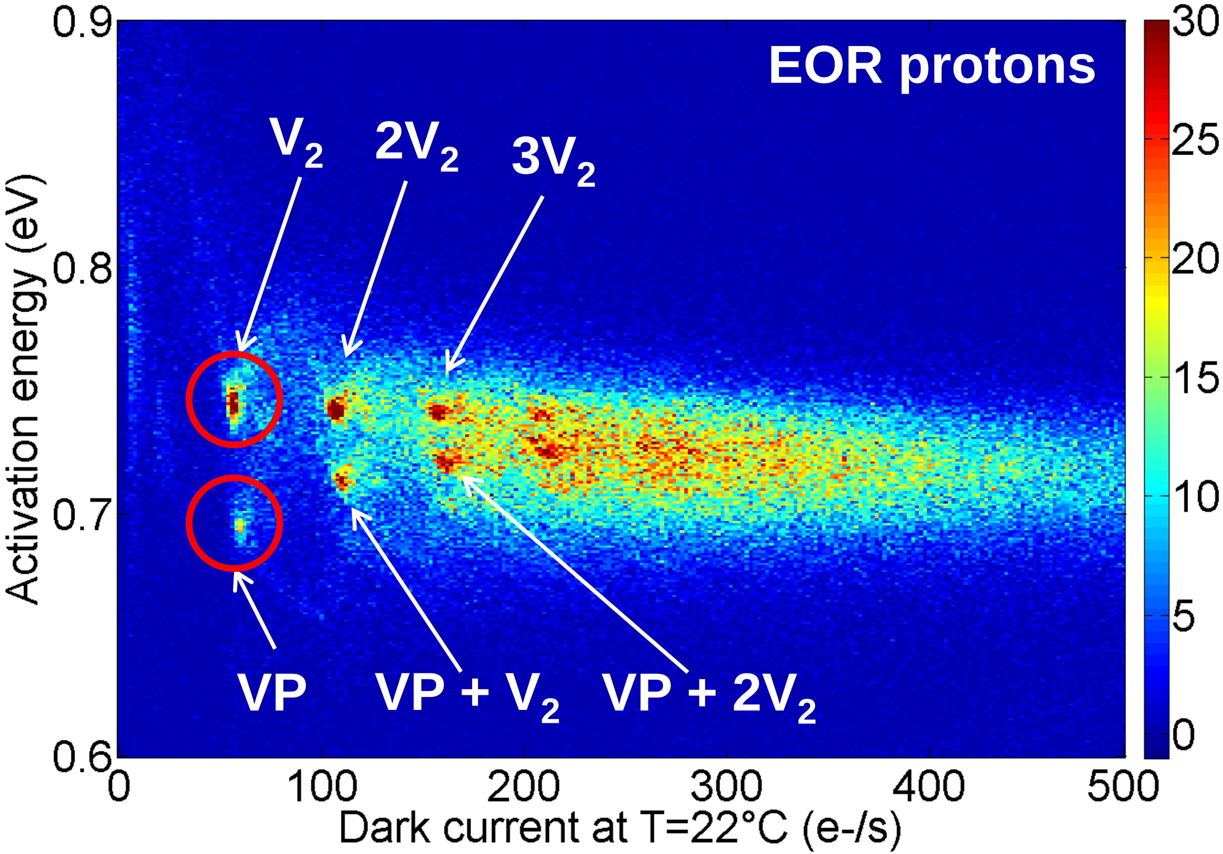
Dark current activation energy of the dark current peaks



- First dark current peak (**+50 e-/s**):

⇒ Two possible activation energies: **0.70** and **0.75 eV**

Dark current activation energy of the dark current peaks



- First dark current peak (**+50 e-/s**):

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⇒ **Two different defects**

- **$E_A \simeq$ 0,75 eV**

⇒ $|E_t - E_i| \simeq$ 0,12 eV ⇒ **V_2**

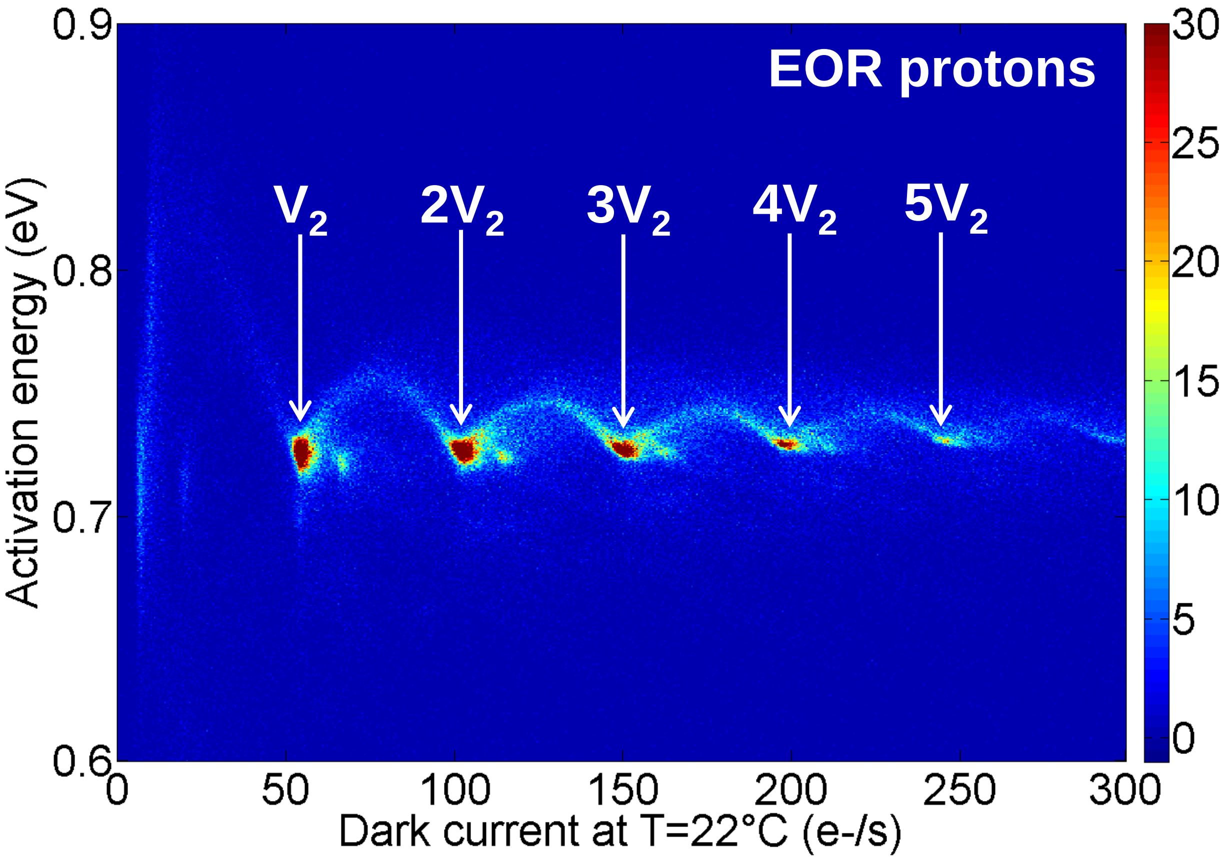
- **$E_A \simeq$ 0,70 eV:**

⇒ $|E_t - E_i| \simeq$ 0,07 eV ⇒ **VP**

[1] Tivarus et al., IEEE TNS, 2008.

[2] M. Moll, PhD thesis, 1999.

Dark current activation energy after 200°C annealing



- **VP** anneals below 200°C
- V_2 is stable at 200°C

[1] Tivarus et al., IEEE TNS, 2008.
[2] M. Moll, PhD thesis, 1999.

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  - **Nuclear interactions** or **high NIEL coulomb interactions**:
    - **Dense** displacement damage
    - **Exponential hot pixel tail** with many hot pixels **(few 10,000 e^-/s)**

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  - **Nuclear interactions** or **high NIEL coulomb interactions**:
    - **Dense** displacement damage
    - **Exponential hot pixel tail** with many hot pixels **(few 10,000 e^-/s)**
- The **main radiation-induced defects** depend on the **damage density:**
  - **Sparse** displacement damage: **point defects** such as V_2 and **VP**
  - **Clustered** displacement damage: **midgap defects** such as **clusters**

Thank you for your attention!

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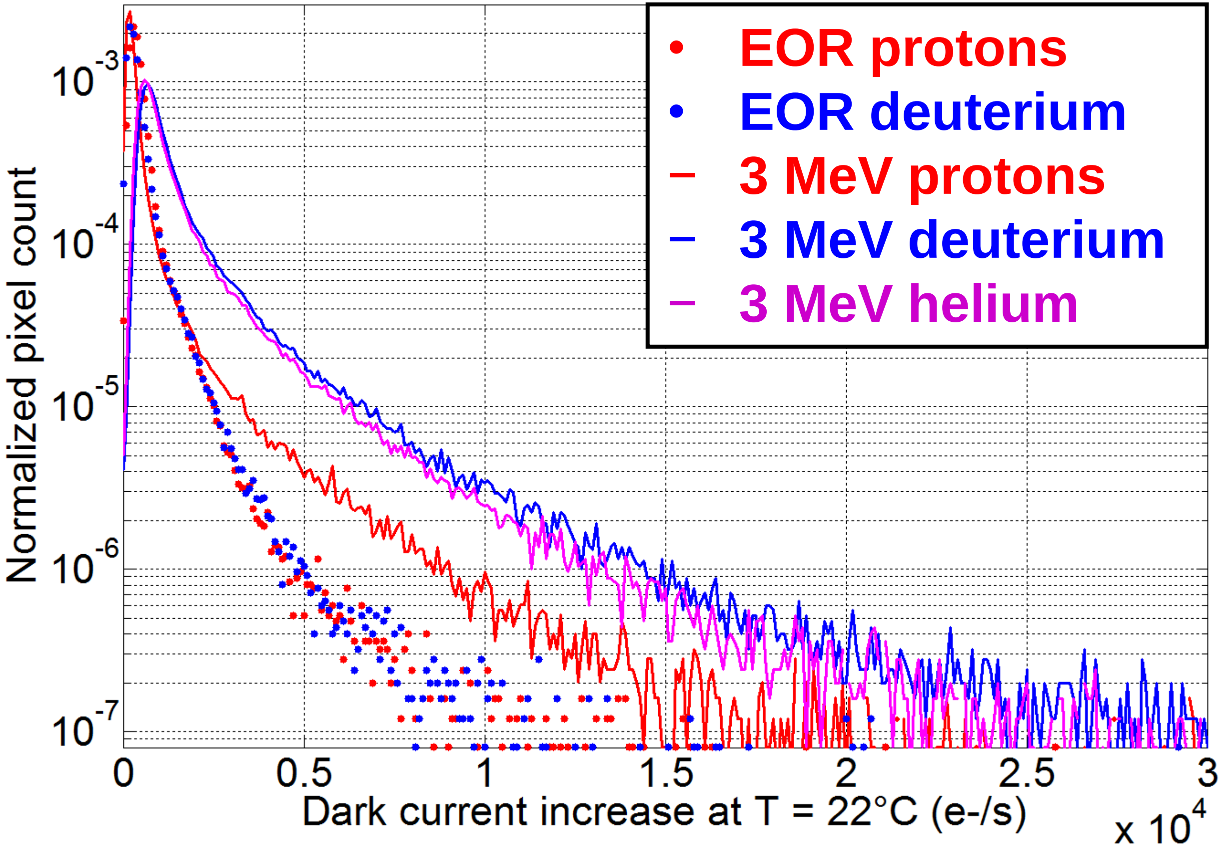
End-of-range light ions (low NIEL coulomb)
3 MeV light ions (some nuclear interactions)



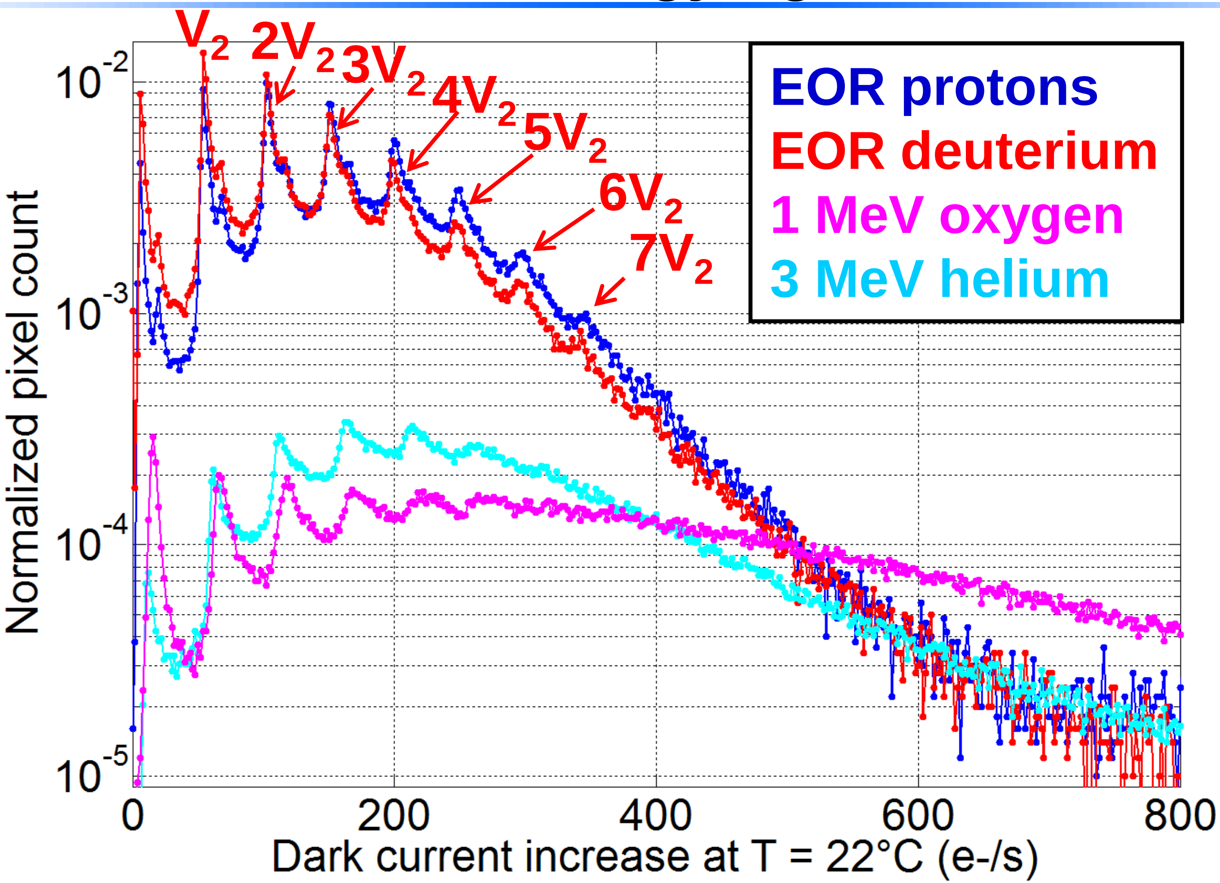
- **End-of-range:**
  - non-exponential hot pixel tail
  - very few hot pixels

⇒ **mainly point defects**

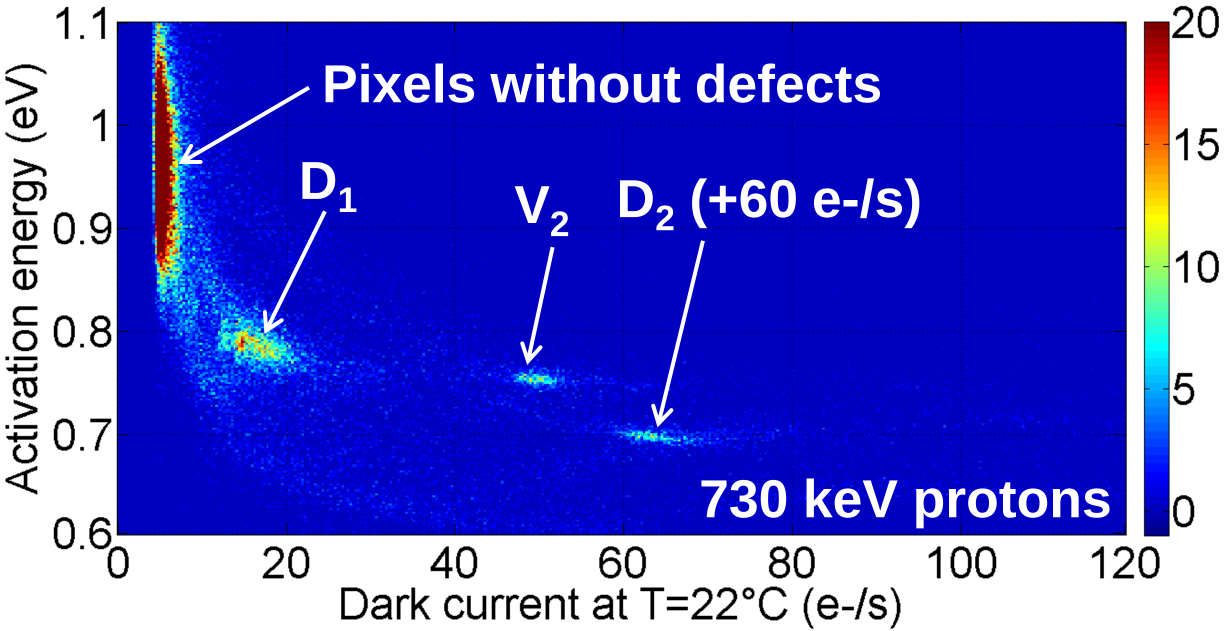
- **3 MeV:**
  - exponential hot pixel tail
  - less hot pixels than high-energy ions

⇒ **only few clusters**

Dark current peaks after 200°C annealing for low energy light ions



Dark current activation energy after 300°C annealing



- **VP** anneals between 150°C and 200°C
- V_2 is stable up to 260°C
- New defect noted D_1 (13 e^-/s) visible after 200°C annealing
- Other defects appear after 260°C annealing and above:
  - D_2: +60 e-/s, $E_A \simeq 0{,}70$ eV
  - D_3: +700 e-/s, $E_A \simeq 0{,}60$ eV

Displacement damage density effect

Particle	Maximum coulomb nuclear stopping power (eV/Å)
End-of-range protons	0.1
End-of-range deuterium	0.2
End-of-range carbon	11
End-of-range oxygen	17
End-of-range aluminum	36
End-of-range silicon **(nuclear interaction)**	40

Non-exponential hot pixel tail with low probability (0.1, 0.2)

Exponential hot pixel tail (11 to 40)

- 9 eV/Å ~ 1 displaced atom per lattice plan (E_D ~ 21 eV)

⇒ Exponential hot pixel tail (clusters) for **clustered displacement damage**