A high resolution scanning set-up for defect detection on electrodes

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JG|U PRISMA DETECTOR LAB

XeSAT2023, 8th June 2023

Electrode stability's imprint on physics results

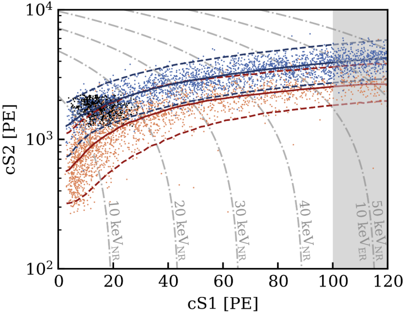


FIG. 1. NR and ER calibration data from ^{241}AmBe (orange), ^{220}Rn (blue) and ^{37}Ar (black). The median and the $\pm 2\sigma$ contours of the NR and ER model are shown in blue and red respectively. The gray dash-dotted contour lines show the reconstructed NR energy ($\mathrm{keV_{NR}}$). Only not shaded events up to a cS1 of 100 PE are considered in the response model fits.

$$E_\mathrm{d} = 23\,\mathrm{V\,cm^{-1}}$$

(arXiv: 2303.14729)

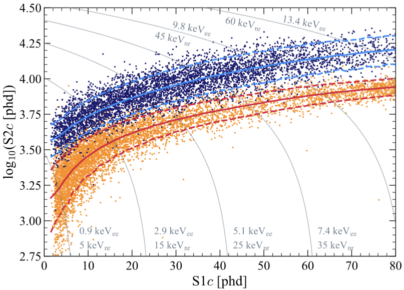


FIG. 1. Calibration events in $\log_{10}$S2c-S1c for the tritium source (dark blue points, 5343 events) and the DD neutron source (orange points, 6324 events). Solid blue (red) lines indicate the median of the ER (NR) simulated distributions, and the dotted lines indicate the 10 % and 90 % quantiles. Thin grey lines show contours of constant electron-equivalent energy ($\mathrm{keV_{ee}}$) and nuclear recoil energy ($\mathrm{keV_{nr}}$).

$$E_\mathrm{d} = 193\,\mathrm{V\,cm^{-1}}$$

(arXiv: 2207.03764)

Field emission

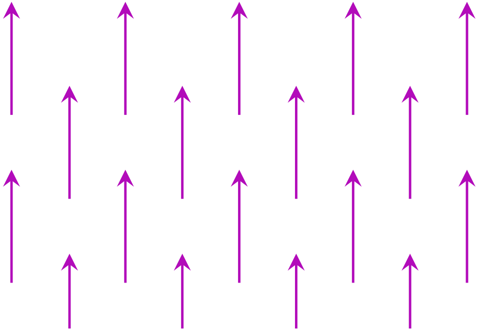
Fowler-Nordheim field emission current density:

$$J = \frac{c_1}{\phi} \cdot 10^{\frac{c_2}{\sqrt{\phi}}} (\beta E)^2 \cdot \exp\left(\frac{-c_3 \sqrt[3]{\phi}}{\beta E}\right)$$

β: **Field enhancement** factor

ϕ: Work-function of steel in liquid xenon

E: Electric field in the bulk



- Field enhancement created through (*e.g.*) asperities on the electrodes' surface
- Impurities may reduce the work-function ϕ
- Electrons emitted from cathodic surfaces, may not only lead to backgrounds but in the worst case to breakdown

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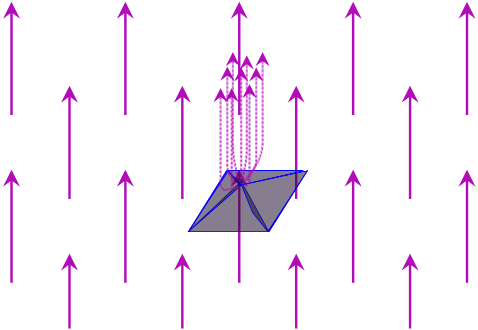

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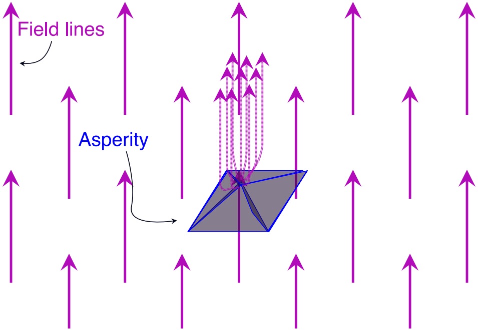

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Dark Matter searches with xenon: XENONnT dual phase TPC

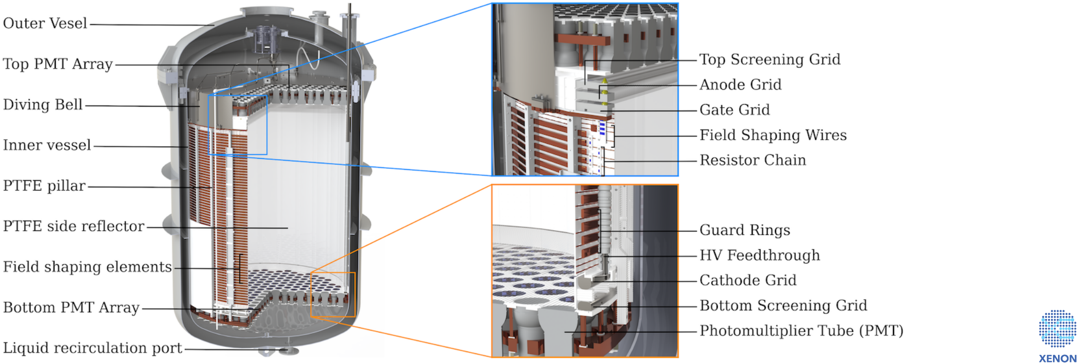
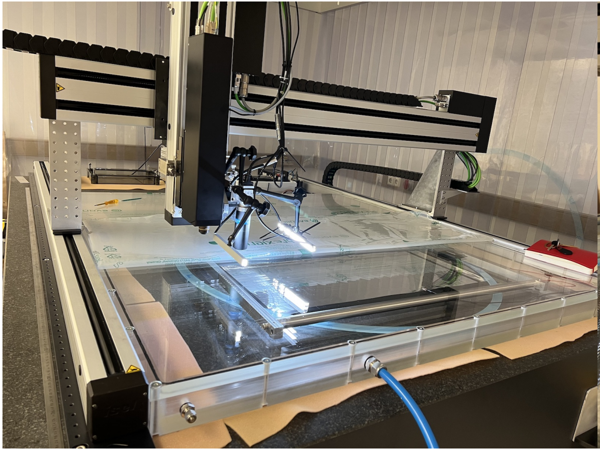


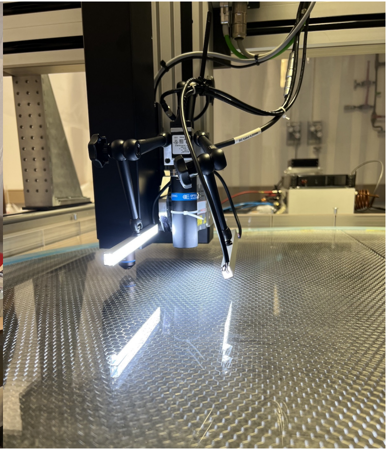
Image credit: XENON Collaboration

- Wire grids with 200 m to 300 m of wire per grid → DARWIN (*e.g.*): Factor 10 larger

→ Automatisation of wire screening desirable

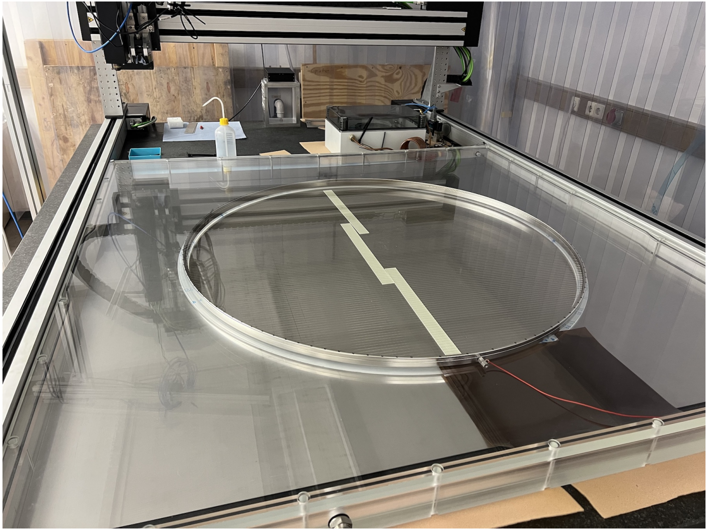
→ A better understanding of what defects may be harmful needed





⇒ Objects with a size up to $2.0 \times 1.4\,\mathrm{m}^2$ can be scanned fully automatically

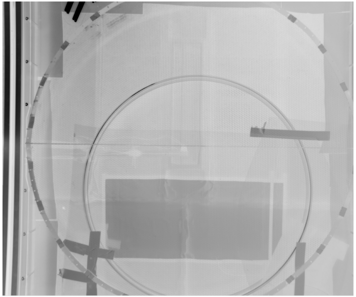
Electrode test-box



- Inner volume of $\sim 140 \times 140 \times 4\,\mathrm{cm}^3$
- Can be flushed with gases, *e.g.* argon
- Ground plane
- High voltage (HV) feed-throughs

$\Rightarrow$ Possible to conduct HV tests of electrodes under gas

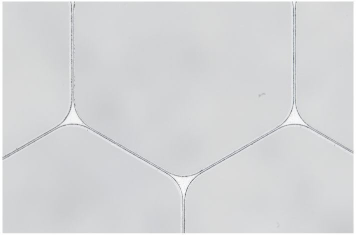
Overview camera for $\sim 1.5 \times 1.5\,\mathrm{m}^2$ imaging



$\sim$1.4 m

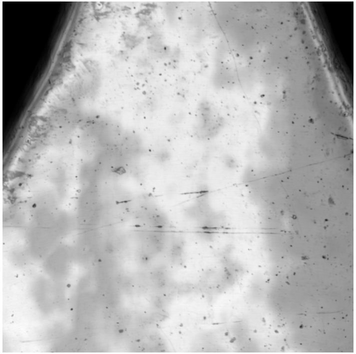
- 5 Mpixels, working distance $\sim 1\,\mathrm{m}$
- Resolution: $\sim 0.6 \times 0.6\,\mathrm{mm}^2$ imaged in one pixel

High resolution camera for close-up inspection



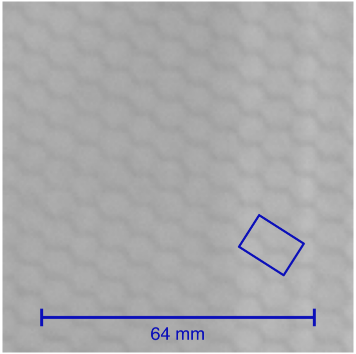
- $\sim$15 Mpixels, working distance 43.1 mm
- Resolution: $\sim 1.4 \times 1.4\,\mu\mathrm{m}^2$

3D confocal microscope



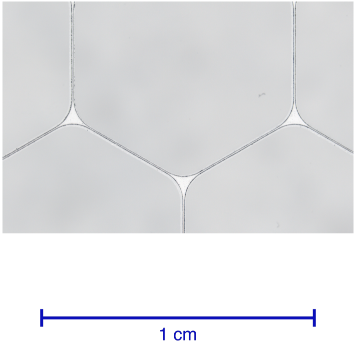
- $\times 10$, $\times 20$, $\times 50$ (photo)
- 1.4 Mpixels, working distance $\sim 11 - 1\,\mathrm{mm}$
- Res.: $\sim 0.96 \times 0.96\,\mu\mathrm{m}^2$ to $\sim 0.3 \times 0.3\,\mu\mathrm{m}^2$

Overview camera for $\sim$1.5 × 1.5 m^2 imaging



- 5 Mpixels, working distance $\sim$1 m
- Resolution: $\sim$0.6 × 0.6 mm^2 imaged in one pixel

High resolution camera for close-up inspection



- $\sim$15 Mpixels, working distance 43.1 mm
- Resolution: $\sim$1.4 × 1.4 µm^2

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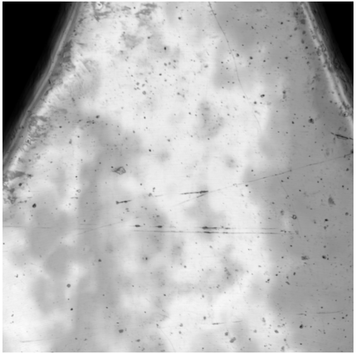
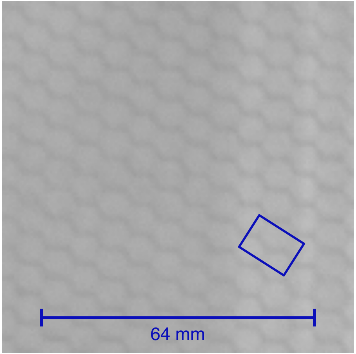
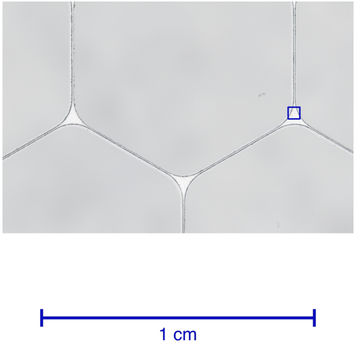
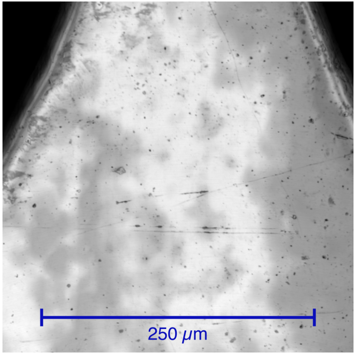
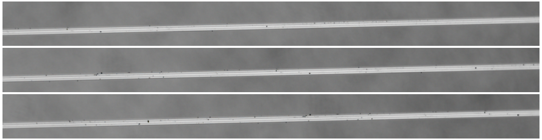
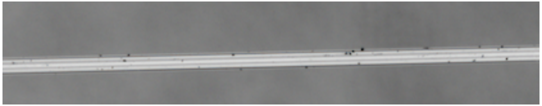


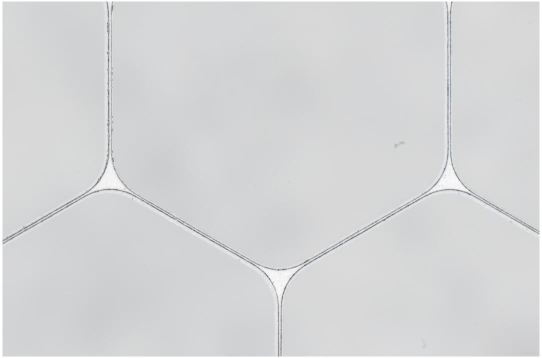
- ×10, ×20, ×50 (photo)
- 1.4 Mpixels, working distance $\sim$11 – 1 mm
- Res.: $\sim$0.96 × 0.96 µm^2 to $\sim$0.3 × 0.3 µm^2

Overview camera for $\sim 1.5 \times 1.5\,m^2$ imaging	High resolution camera for close-up inspection	3D confocal microscope
		
▶ 5 Mpixels, working distance $\sim$1 m ▶ Resolution: $\sim 0.6 \times 0.6\,mm^2$ imaged in one pixel	▶ $\sim$15 Mpixels, working distance 43.1 mm ▶ Resolution: $\sim 1.4 \times 1.4\,\mu m^2$	▶ $\times 10$, $\times 20$, $\times 50$ (photo) ▶ 1.4 Mpixels, working distance $\sim 11 - 1$ mm ▶ Res.: $\sim 0.96 \times 0.96\,\mu m^2$ to $\sim 0.3 \times 0.3\,\mu m^2$



Zoomed wire:





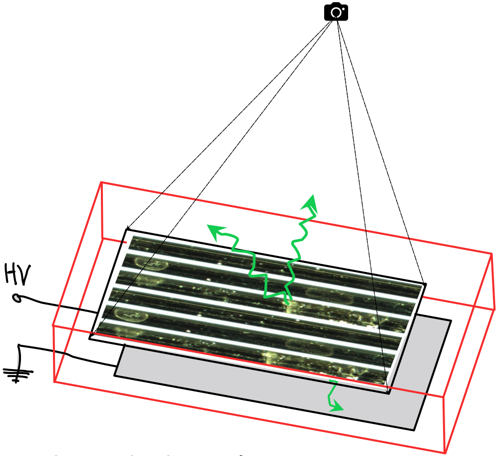
Zoomed leg:

- Various spots seen on wires and ledges
- Which would lead to local field enhancement and electron emission?

Challenge: Which of the many "spots" may enhance the local field and possibly lead to electron emission or even breakdown ?

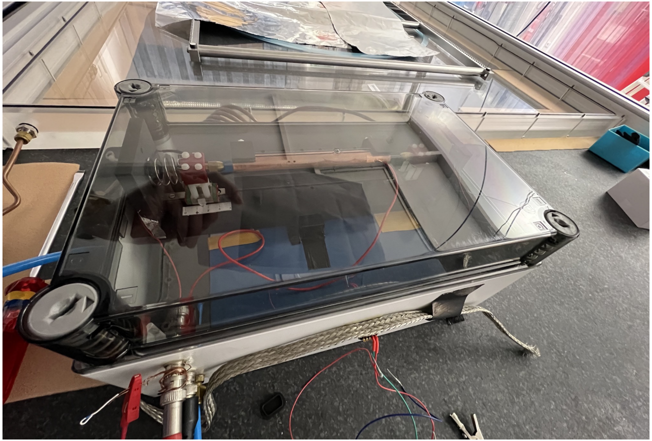
Ansatz:

- Place an electrode on a ground plane and in an atmosphere of choice (air, argon...)
- Apply HV. If "spots" are defects which enhance the electrical field locally, they may seed corona discharges
- Image the light (electroluminescence) of the discharge



⇒ Such a measurement would also be much faster than a high resolution image scan

Small scale, exploratory set-up



- In parallel to the commissioning of the large set-up, a small one was build to test single wires.
- Box with high voltage and low voltage feed-throughs as well gas connections
- Contraption to stretch wires
- Possibility to test various grounding schemes

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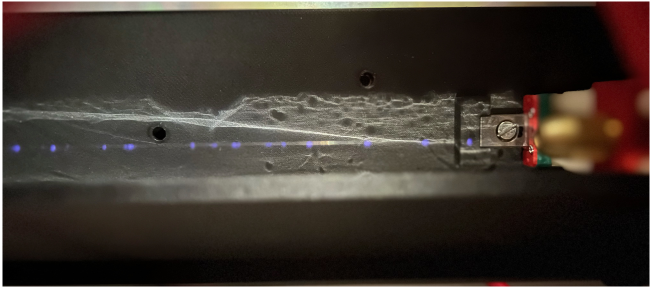

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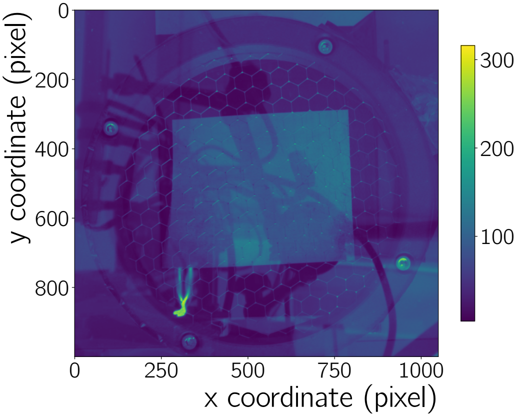

Example discharge,
overlay with the bright image

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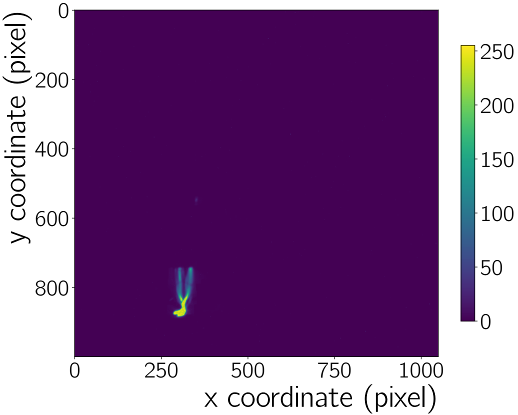

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Corona discharges

$$E_{\text{c}} = 31 \cdot \delta \cdot \left(1 + \frac{0.308}{\sqrt{\delta r\,[\text{cm}]}}\right) \left[\text{kV}\,\text{cm}^{-1}\right]$$

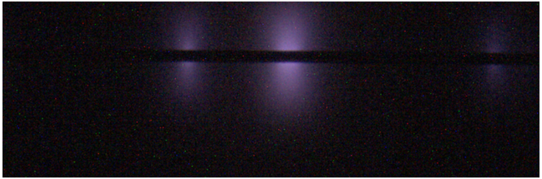
$$V_{\text{c}} \sim \frac{E_{\text{c}}}{2} r \cdot \ln\left(\frac{2d}{r}\right)$$

Using corona discharges for electrode tests:

- Ideally: Keep the HV on the electrodes below the limit of corona discharges caused by the wire geometry itself
- Field enhancing defects on wires: $V_{\text{c}}^{\text{defect}} < V_{\text{c}}$
- Corona emission below the wire in geometry: Ground plate – wire – camera

Preliminary correlation of defects and corona – 1/2

Example: Air, high resolution camera:



dark

- Scan wires (XENONnT quality) with the high resolution camera and measure argon corona
- Use corona and scanning images to train a binary class convolutional image classifier with dense processing layers (tensorflow sequential)
- The following is only based on ~60 cm of wire in the small scale, exploratory set-up

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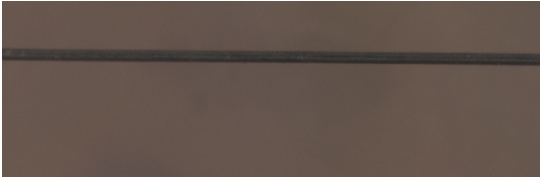

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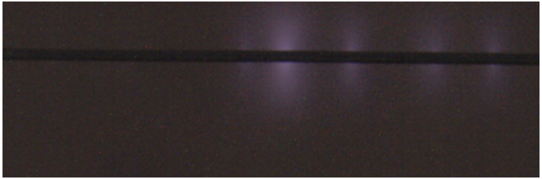

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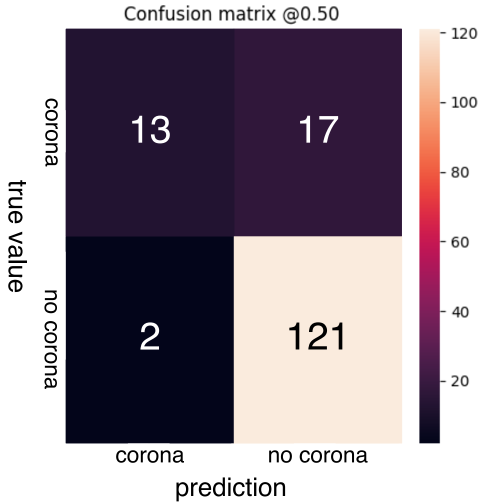
Preliminary correlation of defects and corona – 2/2

- Match coordinate system in high resolution images and corona images
- Label "spot" locations – *i.e.* potential defects – in images ($N_{\mathrm{d}}^{\mathrm{train}} = 675$), label corona locations ($N_{\mathrm{c}}^{\mathrm{train}} = 175$).
- Train the image classifier to predict *corona* or *no corona* based on a *spot*

⇒ The prediction power for *corona* is not great yet, but there is a correlation between *spots* and *corona*

⇒ Need higher statistics for the actual result



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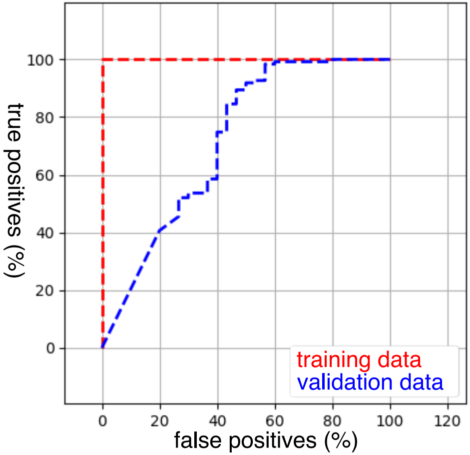

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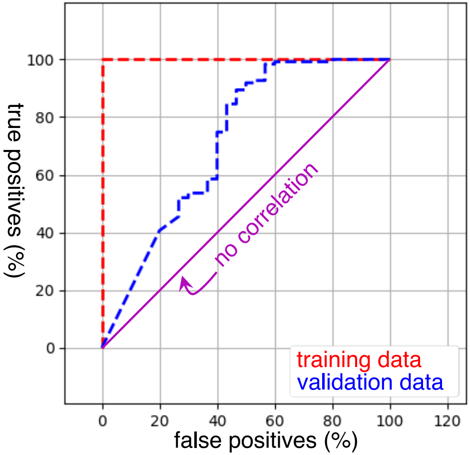


Summary & Outlook

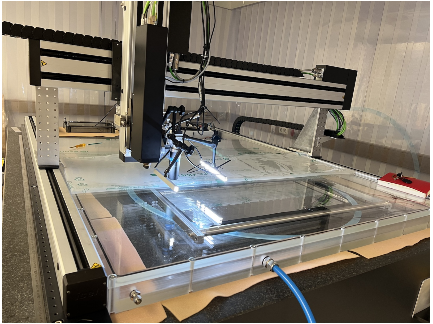
- Field emission can lead to backgrounds and breakdown
- Goal: Identify electrode defects automatically
- Mainz PRISMA Detector Laboratory test stand:
  - Electrode sizes up to $1.4 \times 1.4\,\mathrm{m}^2$
  - High resolution imaging (camera) & z-profile scanning (3D confocal microscope)
  - Corona discharge recording (overview camera) & HV tests in different gases
  - Sagging measurements with a laser distance measurement system
- Correlation studies of "defects" and "corona" underway
- Still on our ToDo list: Use high resolution imaging and luminescence measurements to explore how different cleaning procedures affect the wire quality

$\Rightarrow$ Develop improved screening and cleaning procedures for future noble liquid experiments

Backup

XYZ Camera set-up to image electrodes

- isel 3-axis positioning system on a granite table
- High resolution camera for close-up inspection
  - About 15 Mpixels, lens working distance 43.1 mm, depth of field $\sim$2 mm
  - $\sim 1.4 \times 1.4\,\mu m^2$ of an object imaged in one pixel
- Overview camera for $\sim 1.5 \times 1.5\,m^2$ imaging
  - 5 Mpixels, lens working distance $\sim$1 m
  - $\sim 0.6 \times 0.6\,mm^2$ imaged in one pixel
- Confocal microscope
  - $\times$10, $\times$20, and $\times$50 lens
  - 1.4 Mpixels, working distance $\sim$11 mm ($\times$10) to $\sim$1 mm ($\times$50)
  - $\sim 0.96 \times 0.96\,\mu m^2$ ($\times$10) to $\sim 0.3 \times 0.3\,\mu m^2$ ($\times$50) imaged in one pixel



Corona discharges

Occur only in highly uniform electric fields and when the field near one (both) electrode(s) is much stronger than everywhere else.

- Condition $d/r > 5.85$ for parallel wires (radius r, distance d) or a wire and a flat surface (→ Common along power transmission lines!)
- Phenomenological description for the ignition field:

$$E_c = 31 \cdot \delta \cdot \left(1 + \frac{0.308}{\sqrt{\delta r\,[\mathrm{cm}]}}\right) \left[\mathrm{kV\,cm^{-1}}\right] \qquad V_c \sim \frac{E_c}{2} r \cdot \ln\left(\frac{2d}{r}\right)$$

- At 760 Torr, $25\,^\circ\mathrm{C}$, $r = 300\,\mu\mathrm{m}$, $d = 1\,\mathrm{cm} \rightarrow V_c \sim 86\,\mathrm{kV\,cm^{-1}}$, $E_c \sim 5425\,\mathrm{V}$

Corona discharges: Measurement

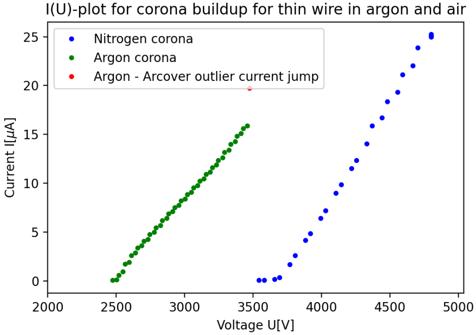
$$E_c = 31 \cdot \delta \cdot \left(1 + \frac{0.308}{\sqrt{\delta r\,[\mathrm{cm}]}}\right) \left[\mathrm{kV\,cm^{-1}}\right]$$

$$V_c \approx \frac{E_c}{2} r \cdot \ln\left(\frac{2d}{r}\right)$$

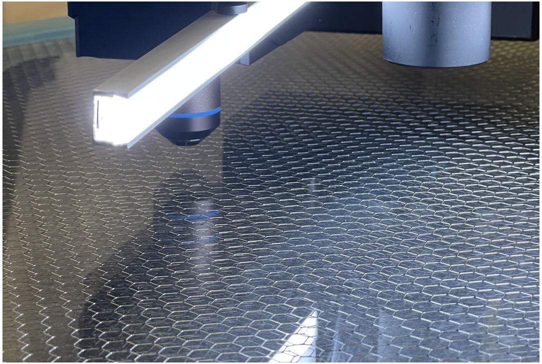
- Set-up with $r = 100\,\mu\mathrm{m}$, $d = 9\,\mathrm{mm}$, $\delta \sim 1$ (room temperature, atmospheric pressure)
- **Challenge: When does Corona start ?** Here: When $I \geq 1\,\mu\mathrm{A}$ for 1 cm of wire
- Expectation, air: $E_c = 125 - 130\,\mathrm{kV\,cm^{-1}}$, $V_c = 3.1 - 3.5\,\mathrm{kV}$
- Measurement, air: $V_c = (3.6 \pm 0.2)\,\mathrm{kV}$; Measurement, argon: $V_c = (2.6 \pm 0.2)\,\mathrm{kV}$
- Interpret the $31\,\mathrm{kV\,cm^{-1}}$ as the breakdown field in air: $E_c^{\mathrm{Ar}} \approx (0.72 \pm 0.07) \cdot E_c^{\mathrm{air}}$ (Literature: $E_c^{\mathrm{Ar}} \sim E_c^{\mathrm{air}} \cdot 0.55$)

Current monitoring

- Preliminary measurement of the power supply current for the same low quality wire in the single wire test-setup
- Corona discharges visible by eye at about 10 μA
- Wire thickness: $\sim$100 μm, ground distance about 9 mm
- The measurement is stopped at by the operator after reaching a few 10 μA

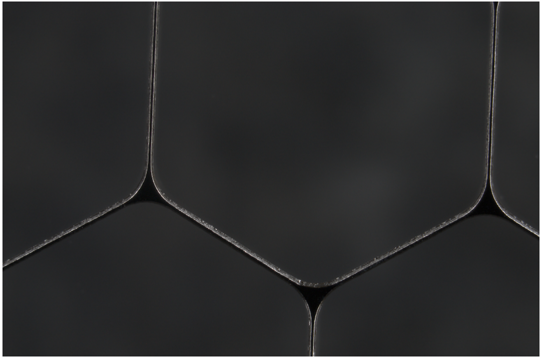


Scanning of a hex-mesh



- Test scan of a not stretched prototype cathode mesh to test optical scanning
- Scanning a hex-mesh requires a special optimisation of light conditions as it is not just parallel wires
- As the mesh is not stretched, large fluctuations in z distance can be measured with the auto-focus
- The data from the hex-mesh scan will be used to train an auto-decoder for defect detection

Scanning of a hex-mesh



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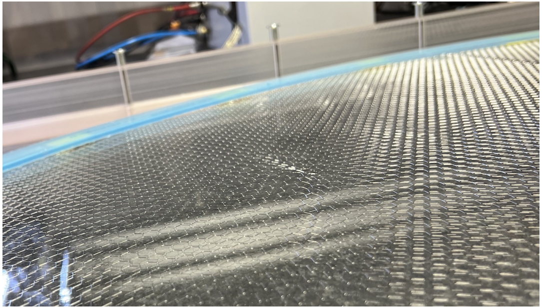

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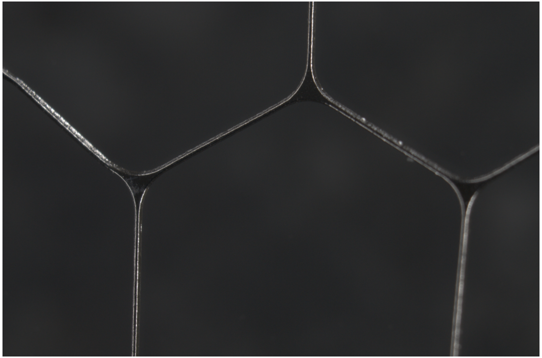
- Scanning a hex-mesh requires a special optimisation of light conditions as it is not just parallel wires
- As the mesh is not stretched, large fluctuations in z distance can be measured with the auto-focus
- The data from the hex-mesh scan will be used to train an auto-decoder for defect detection

Scanning of a hex-mesh



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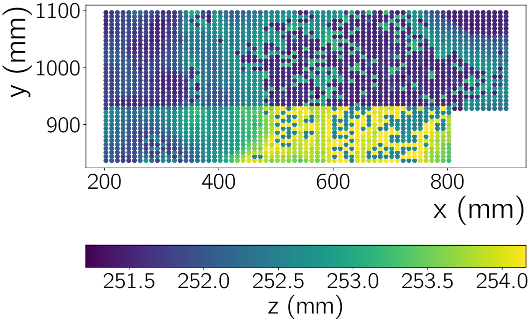

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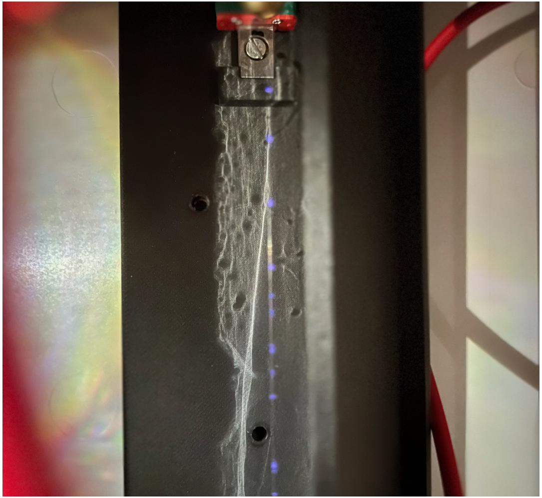
Corona discharges on single wires – first experiments

- The photos on the right were taken with a low quality wire (from a cable), with a phone camera in air
- The low quality wire was chosen deliberately to test if the different components of the set-up work and to commission the camera set-up with a source of a lot of scintillation light



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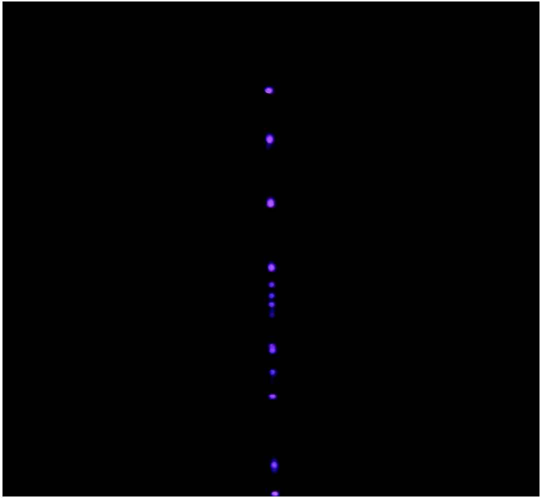


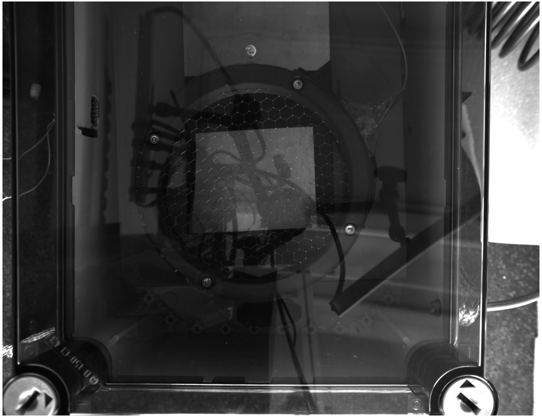
Tests with a small hex-mesh

Cut mesh with passivated edge

- A rectangular part of the mesh is cut, stretched and fixed between two 3D printed Onyx[a] frames. The frames are 1 cm thick and set the ground-to-mesh distance.
- First tests with the full rectangular mesh show sparking on the inner side of the mesh frame
- Cutting the mesh round (passivating the outer edge) still shows sparking on the inner side of the mesh frame. (See next slide)

a: Details for Onyx here. It is a mix of nylon with 15 % carbon short fibres. Its resistance is more than 500 MΩ over a as small distance as we could measure.

Tests with a small hex-mesh



The mesh as seen by the overview camera

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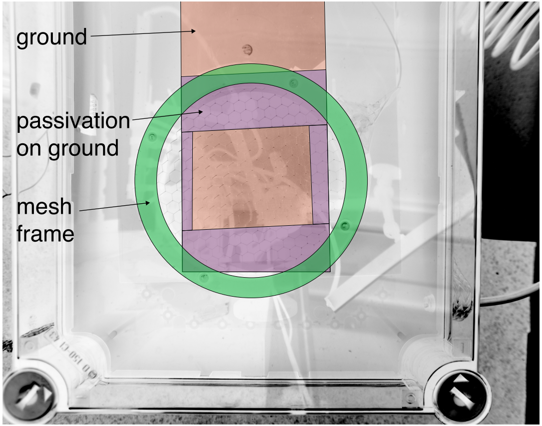

Details on the set-up

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Comments on discharges

- Tests are conducted in an argon atmosphere. We passivate the ground (GND) to achieve no overlap between exposed GND and mesh frame)
- Images are recorded with the overview camera an subsequent 10 s exposures
- Discharges start to develop around 2500 V for the passivated GND. They occur at lower voltages with a fully exposed GND
- Breakdown always occurs from the mesh edge/frame to GND. We do not see corona discharges at lower voltage.

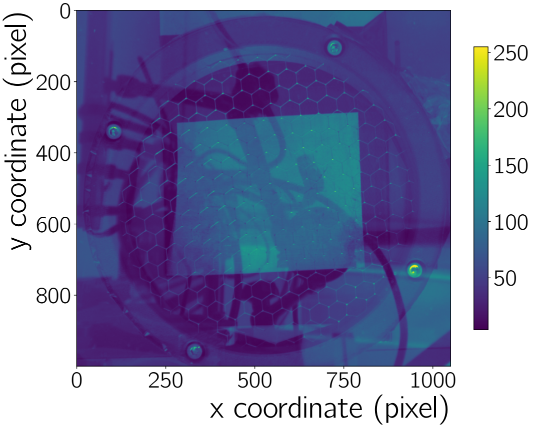

Image with the lights on

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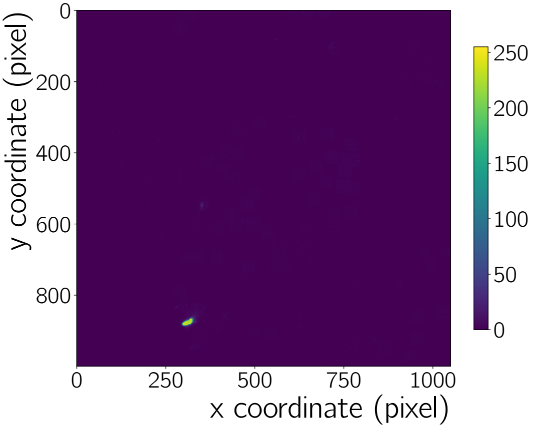

Example discharge #1

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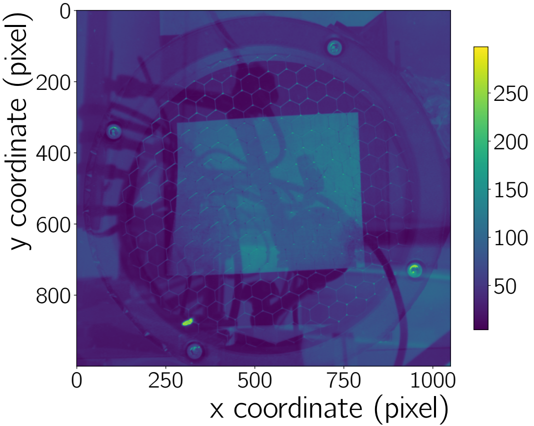

Example discharge #1
overlay with the bright image

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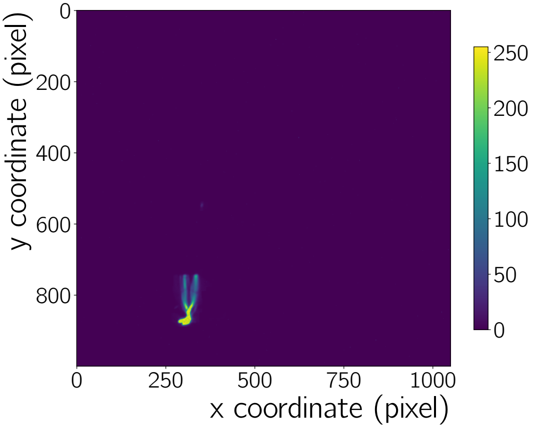

Example discharge #2

Comments on discharges

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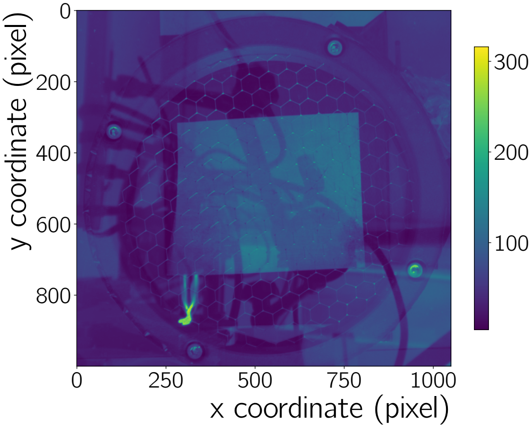

Example discharge #2
overlay with the bright image

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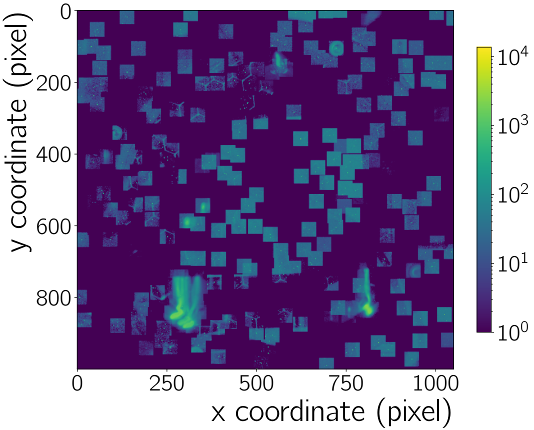

Integrated image of all bright regions

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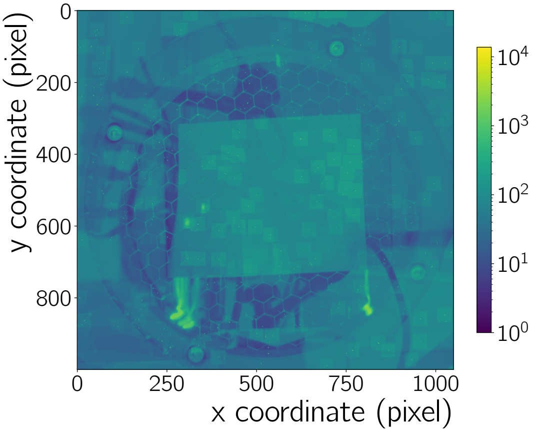

Integrated image of all bright regions overlay with the bright image