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Lightning exposure of wind turbines: Field measurements and implications in the LPS design and service strategies

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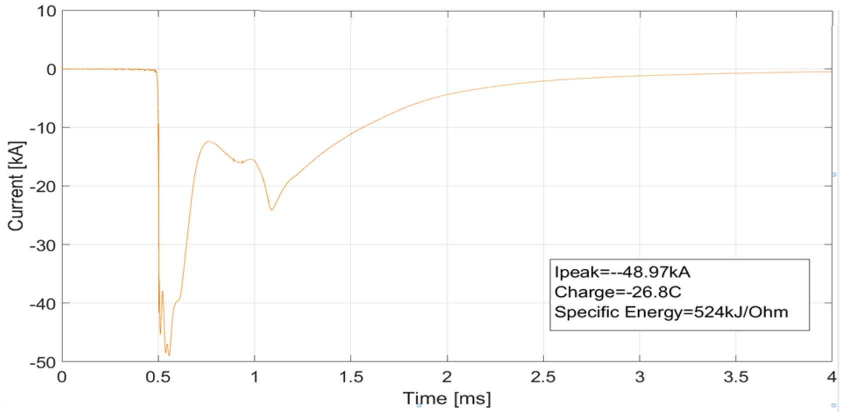
Agenda

- Lightning exposure:
  - Field measurements.
  - Accumulated exposure.
- Implications in Blade LPS design and service:
  - Understanding the risk.
  - LPS design.
  - LPS Inspection and Service
- 360° Lightning Protection

Lightning exposure

Field measurements

- Lightning dataset:
  - LKDS lightning current sensors in all blades. Rogowski coil based.
  - 1.5s recorded per strike with a resolution of 0.1µs.
  - Discrimination and analysis of all strokes within the strike.
  - Parameters defined in IEC standard measured:
    - Ipeak [kA], Q [C], AI [kJ/Ω].
    - Waveform steepness [kA/µs].
- Weather dataset: ERA5 reanalysis dataset.



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Field measurements

- Main focus on two onshore sites (1000 – 2000 m ASL, site dependent).
- Observation period: November 2021 – May 2024.
- 501 lightning strikes detected on Site 1.
- 2489 lightning strikes detected on Site 2.

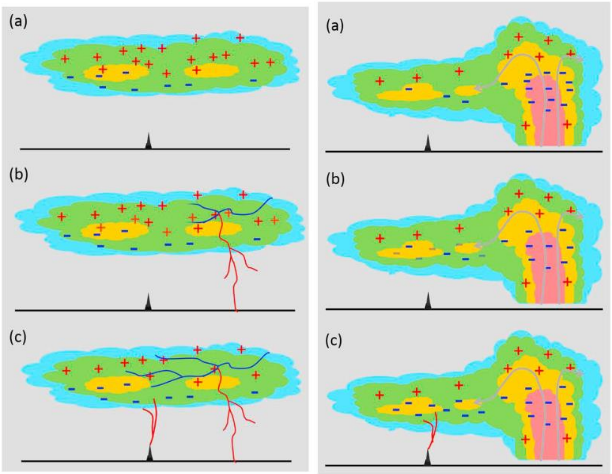
5x more strikes on Site 2

- Site 2 is ~1000m lower than Site 1.
- Lightning type distribution:

	Downward lightning	Upward lightning
Site 1	22%	78%
Site 2	18%	82%

*** For comparison of the lightning type distribution, other sites are considered, although the size of the datasets does not allow using them to obtain accurate conclusions of lightning parameters.**

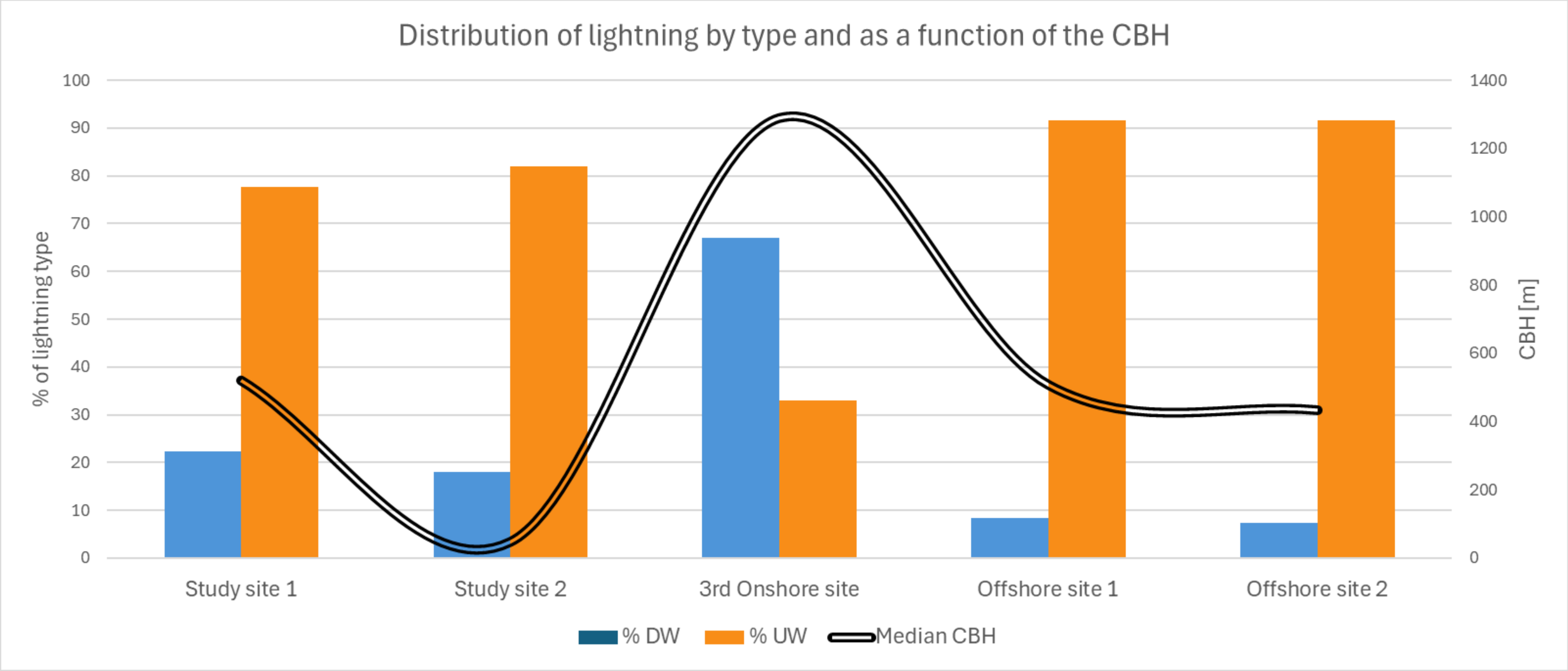
Field measurements



Yuan, Shanfeng et al. "Characteristics of Upward Lightning on the Beijing 325m Meteorology Tower and Corresponding Thunderstorm Conditions." Journal of Geophysical Research-atmospheres 122.22 (2017): 12093-12105. Web.

- Reasons for the large number of upward lightning:
  - Height of the tall structures + location at elevated terrain.
  - Weather conditions.
- Warm weather-type storms:
  - Clouds develop vertically and are located high above ground: large distance to the wind turbines leads to a more even distribution of electric field and a larger number of naturally-produced downward lightning.
  - Downward lightning can trigger upward lightning from nearby structures.
- Cold weather-type storms:
  - Shallower clouds locate close to ground: the short distance (even 0 distance) to the wind turbines leads to an uneven distribution of electric field that exposes more the turbines that are in the direction of approach of the charged clouds.
  - Downward lightning occurs spontaneously under the presence of the clouds.

Field measurements



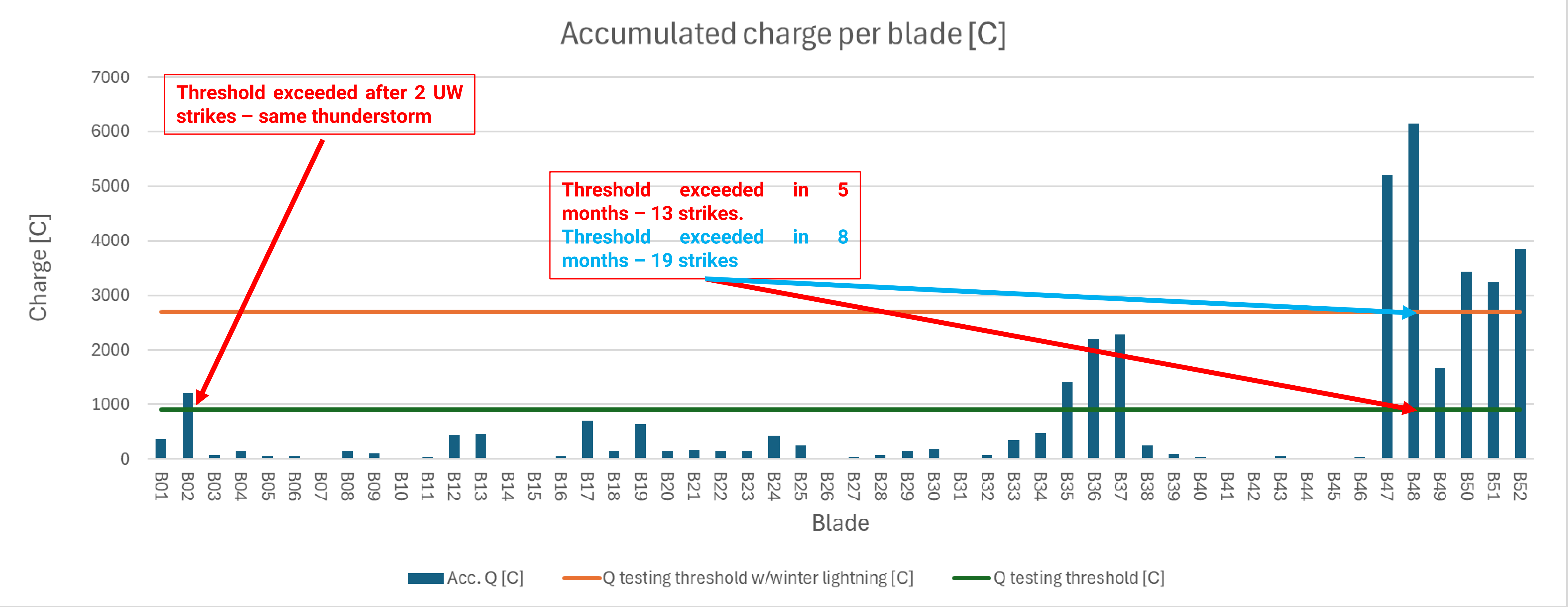
Field measurements – Accumulated exposure

- Lightning parameters measured and how they compare to IEC parameters.
- Maximum and accumulated parameters according to the IEC testing requirements:
    - Maximum peak current in a single strike = 200 kA.
    - Long stroke charge threshold = 300 C.
    - Maximum accumulated charge =
        - 900C in an accumulated exposure test.
        - 2700C in a winter lightning accumulated exposure test.
    - Maximum specific energy in a single strike = 10 MJ/Ω.
- In terms of exposure, for charge related damages, accumulated values can be more relevant than the number of strikes exceeding parameters.
- Inspection and maintenance must be **driven by the exposure**, and not by a calendar

~1000C

~2500C

Site 1 – Charge accumulation



19% of the blades exceed the 900C charge threshold.

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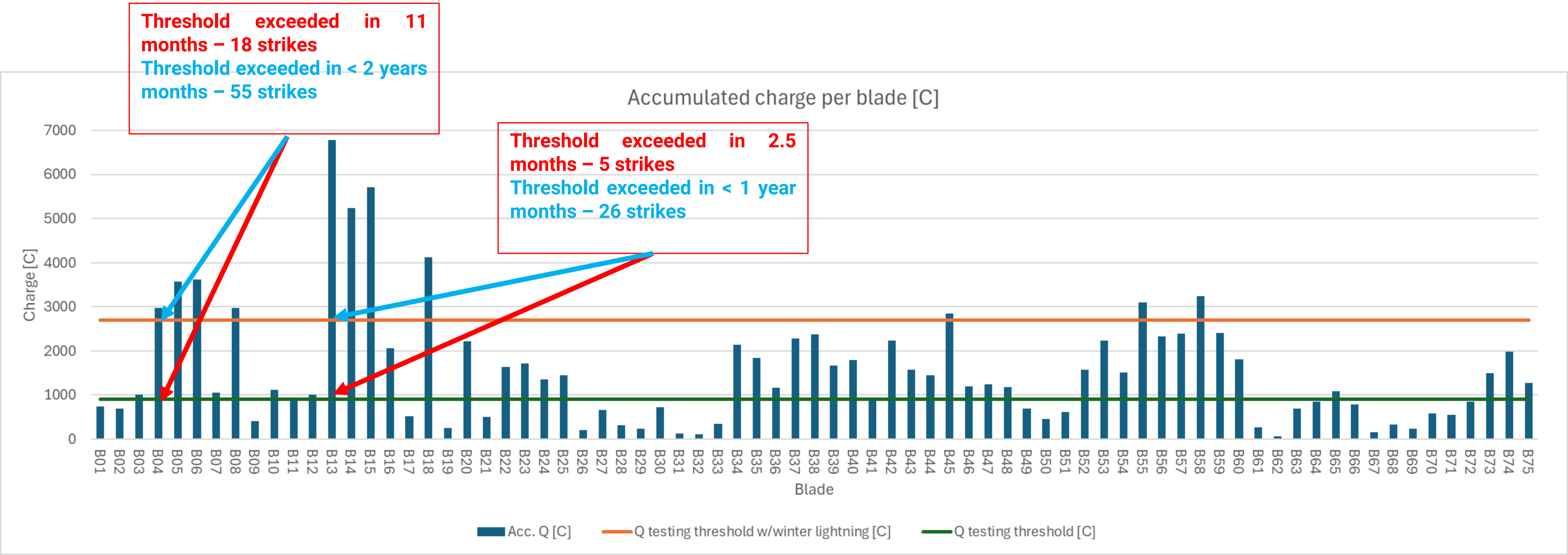
Site 2 – Charge accumulation



61% of the blades exceed the 900C charge threshold.
15 % exceed the 2700C threshold.

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Implications in Blade LPS Design and Service

Understanding the risk

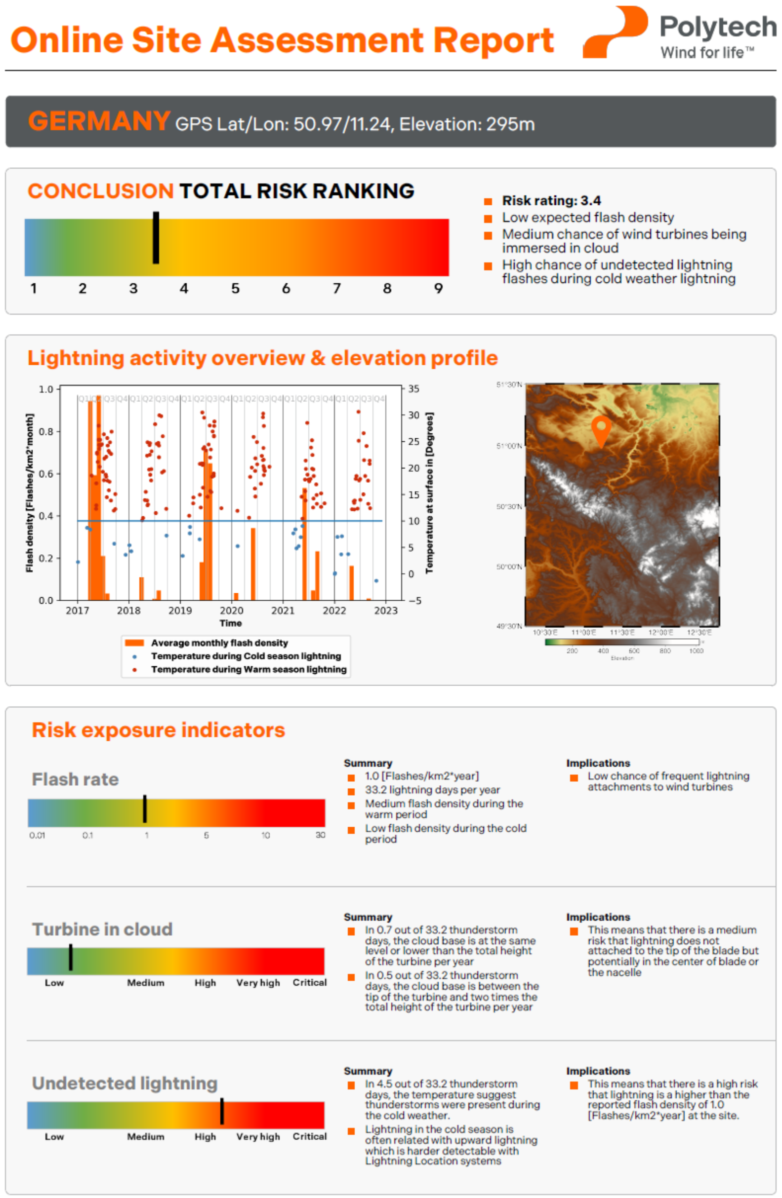
- Risk assessment is already part of IEC 61400-24.
- Understanding the expected exposure of existing or future sites is a first steps towards:
    - Lightning protection considerations.
    - Lightning monitoring needs.
    - Scheduling onsite operations and maintenance.

Details about location

Summary paragraph

Lightning activity overview

Individual risk indicators



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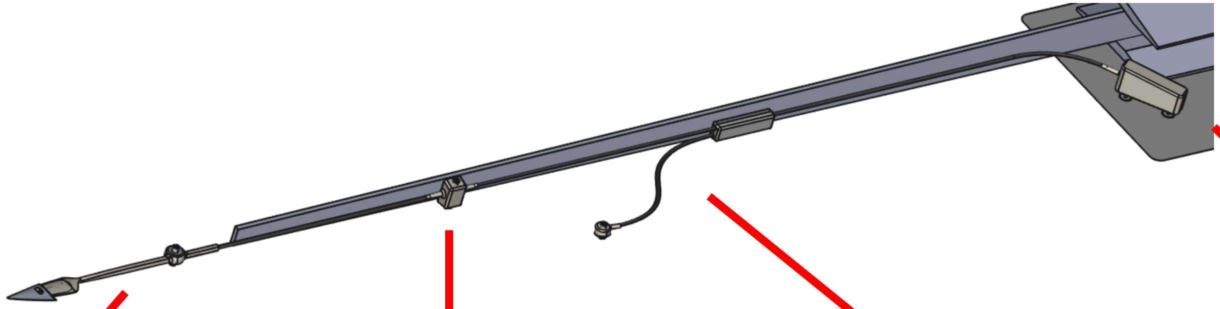
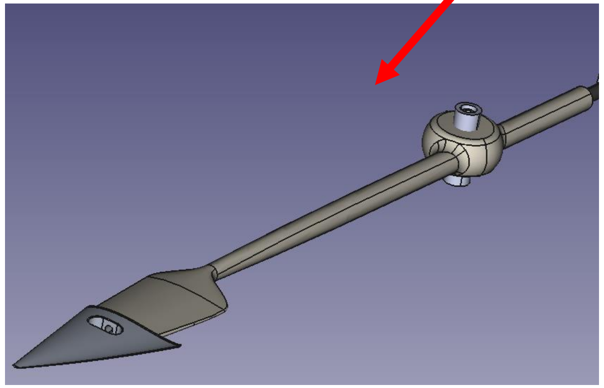
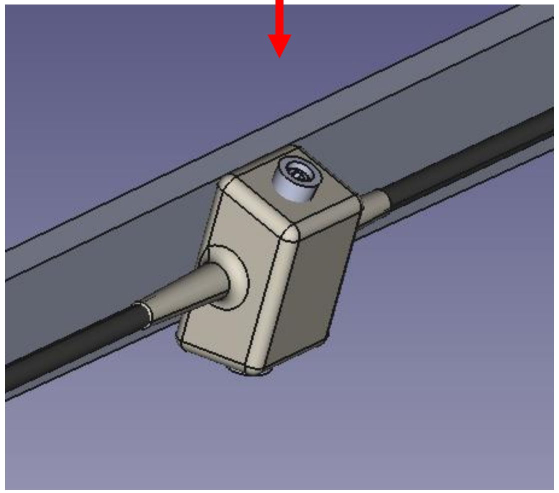
Taking control over lightning attachment

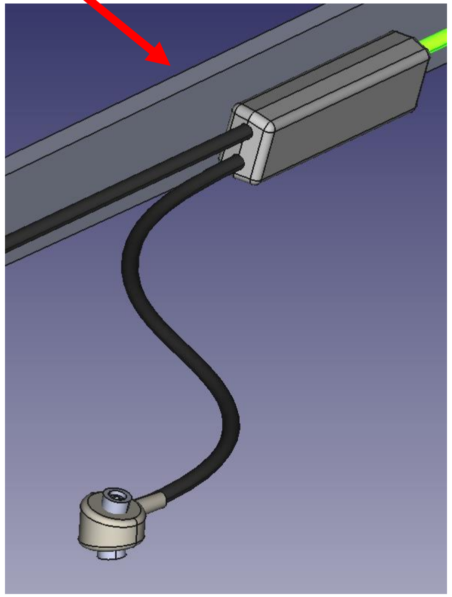




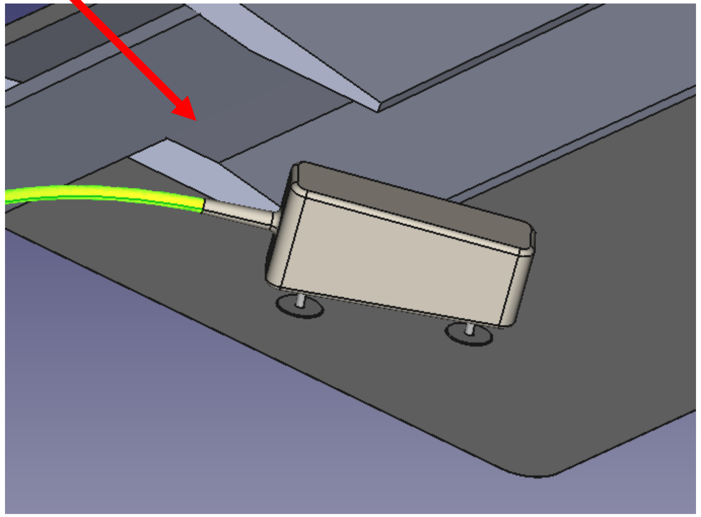
Tip implant with first
side receptor



Second side receptor
Inline type



Third side receptor
Branch type



Connector block to interface to
Expanded Metal Foil

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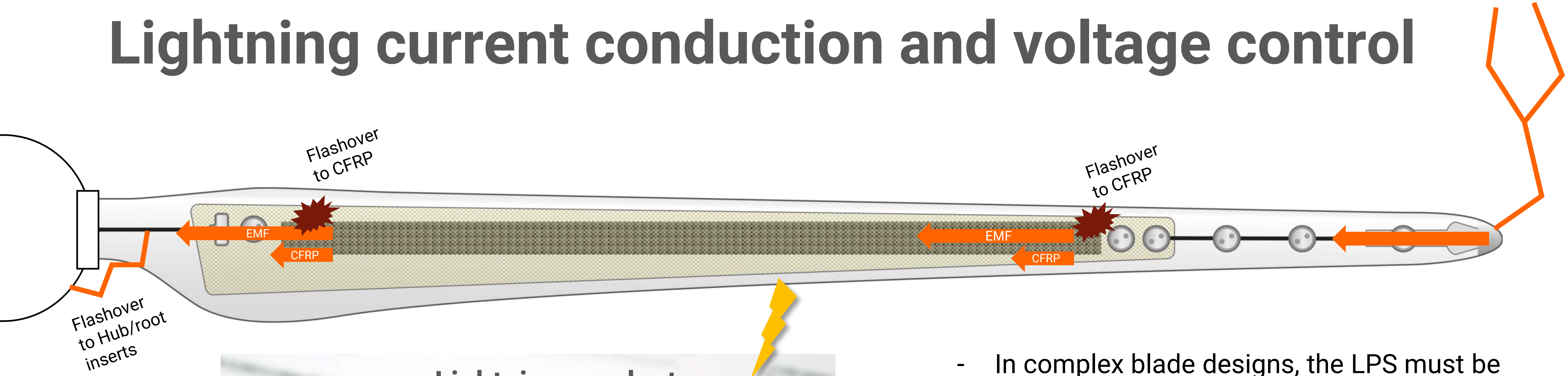
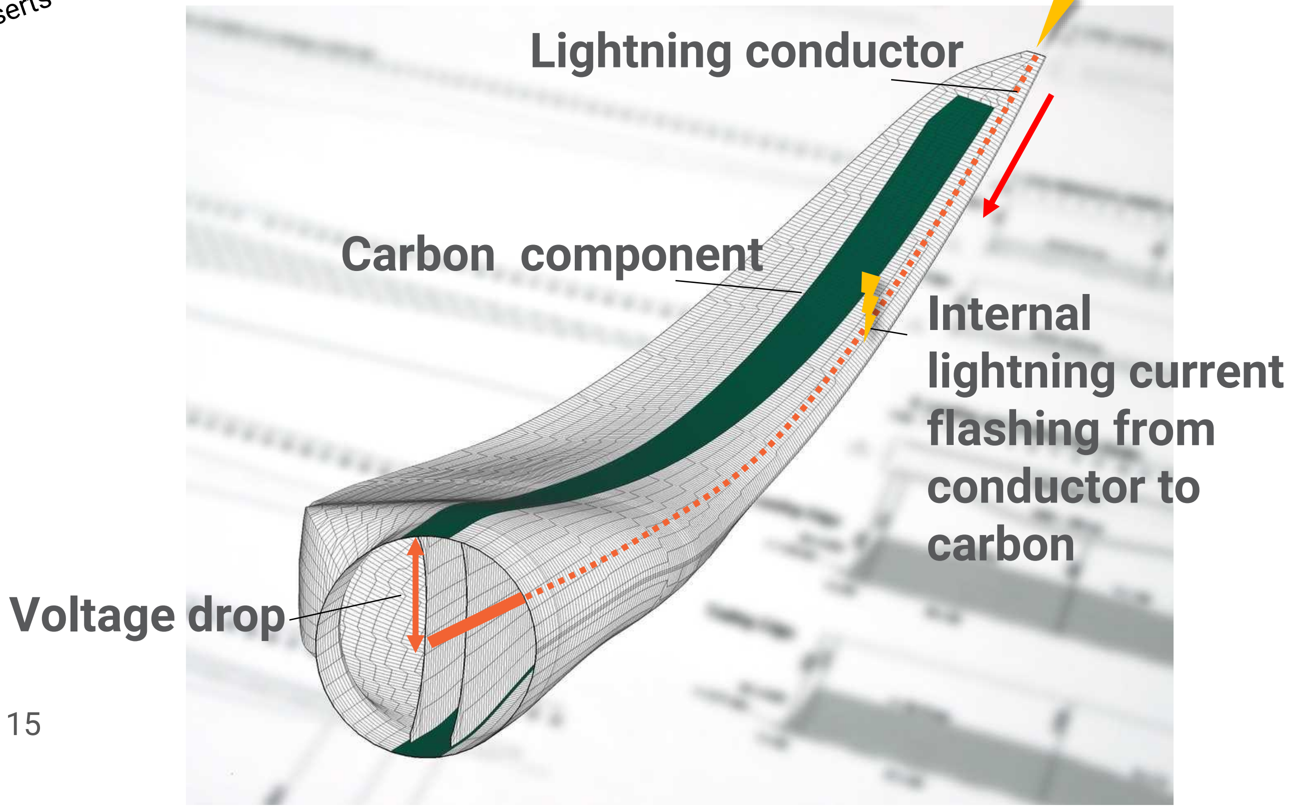
Lightning current conduction and voltage control





- In complex blade designs, the LPS must be coordinated with all conductive components in the blade:
  - CFRP structural elements.
  - Sensors, cables, actuators.
  - Anti/De-icing systems.
- Accurate modelling and simulation is a powerful tool to understand the need and placement of bonds and the design parameters.

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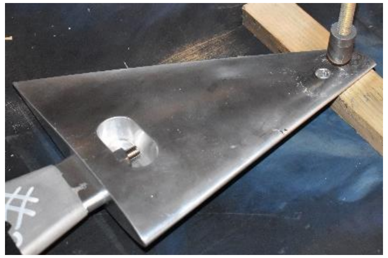
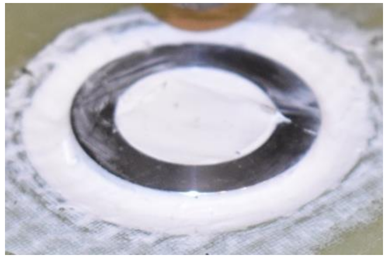
LPS Inspection and Service

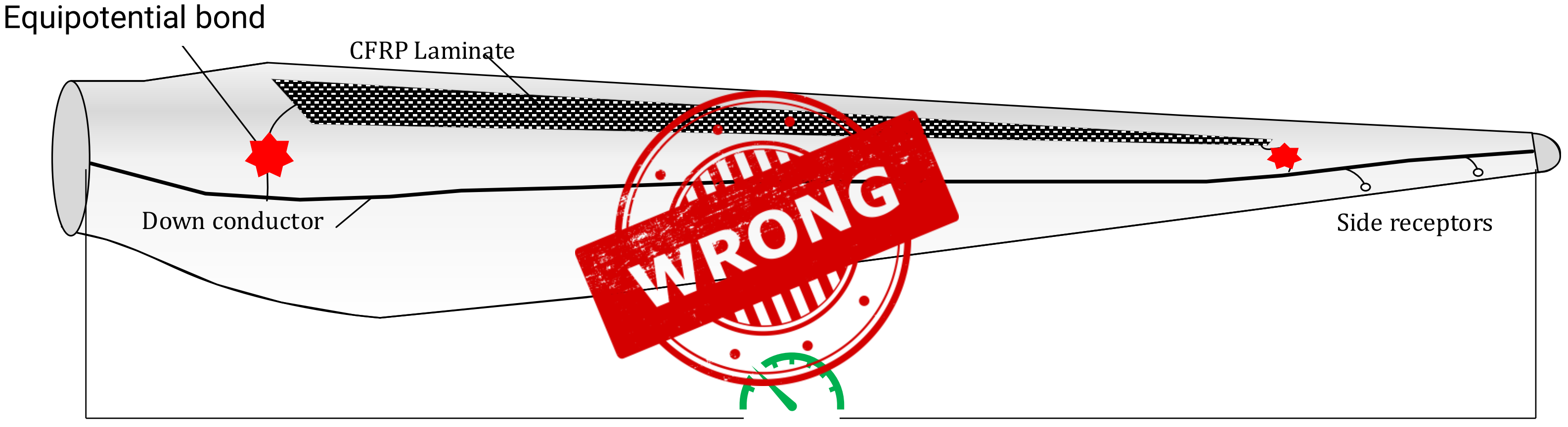
- Link to IEC 61400-24 and IEC 61400-32
- The maintenance of the LPS is fully connected to the exposure and the wear of the different components.


- How to schedule inspections/service?
- Lightning exposure is site specific.
- Basing the inspections on a calendar can be risky: a receptor that looks good today can be completely worn out in a couple of weeks and still may need to survive a couple of years until the next inspection.
- The examples presented from the sites monitored clearly show that a threshold of accumulated charge can be exceeded in just a couple of strikes.

The challenge with inspections

- Inspections focus many times on the outside of the blade.
- It is difficult to assess the condition of internal components and connections of the LPS.
- Even internal inspections may not be accurate in the sense that it is difficult to judge whether a connection is about to become loose or is even broken.
- Continuity measurements only work if there is a full disconnection of a simple LPS system, i.e. the down conductor is disconnected from the tip receptor or a receptor block.



Low resistance – measurement shows everything is OK.

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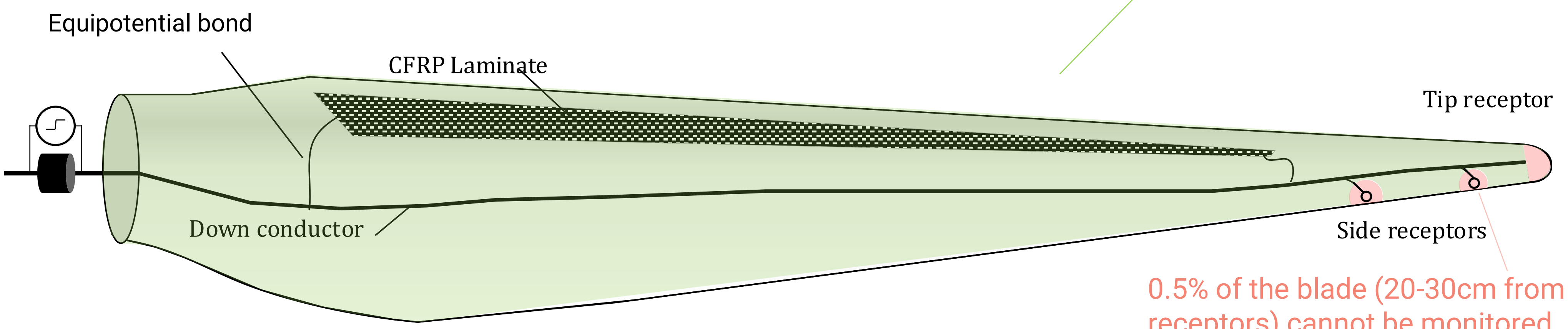
Condition monitoring of the LPS

Based on results of measurement campaign 1 - 4

99.5% of the blade can be monitored



0.5% of the blade (20-30cm from the tip and side receptors) cannot be monitored

Fundamental idea:

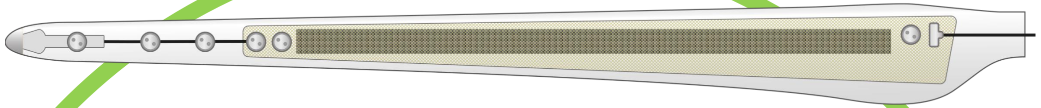
- ✓ Injection of a signal into a blade and determine the status of the LPS by analyzing the response of the signal.
- ✓ Status of the LPS can be evaluated during idle times or at specific load points.
- ✓ Cross-comparison of many samples to evaluate if changes to LPS happened.

Expected LPS signature performance

- ✓ Continuous monitoring of the LPS integrity of GFRP and CFRP blades
- ✓ Single or multiple down conductors
- ✓ Detection of:
  - ✓ Disconnected conductors
  - ✓ Disconnected bonds to Mesh or CFRP
  - ✓ Missing Solid metal tips >= 50cm
- ✓ Provide a warning signal if something has happened
- ✓ Provide a damage location
- ✓ Resistive changes LPS > 5Ω

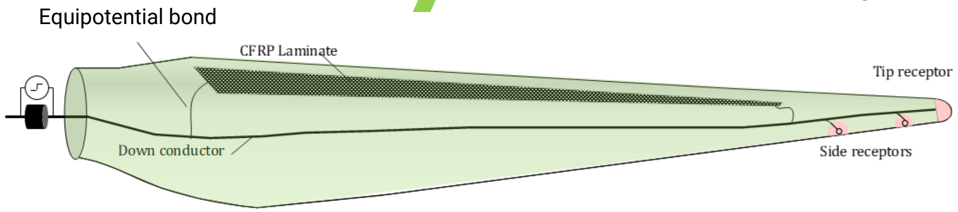
360° Lightning Protection

Robust & Verified LPS design



Accurate and continuous lightning activity monitoring

Real-time LPS condition monitoring



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Thank you

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