Innovative IGBT & SiC busbar technology for Improved Temperature, Partial Discharge Inception Voltage and Power Density

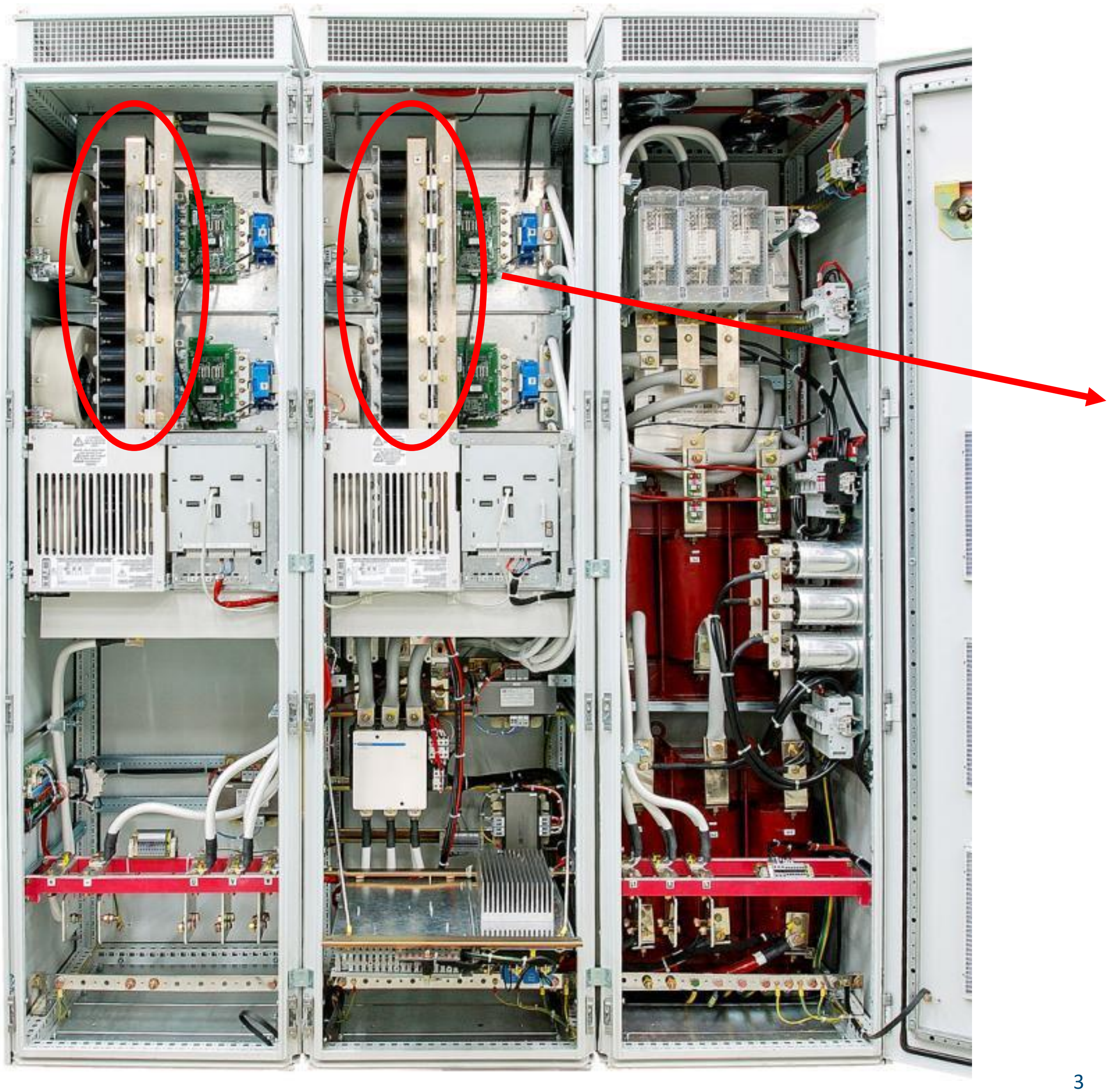
Presented by:
John E. Mills
Business Development Manager, Power Products
Amphenol Global Interconnect Systems
john.mills@amphenol-gis.com
860-560-6612

Fabien DIJOLS
Business Development Manager,
Amphenol-Auxel
Amphenol Global Interconnect Systems
fabien.dijols@auxel.com
+33 (0)6 23 16 53 05

A New Way for Busbars in Power Conversion.
What we'll discuss…

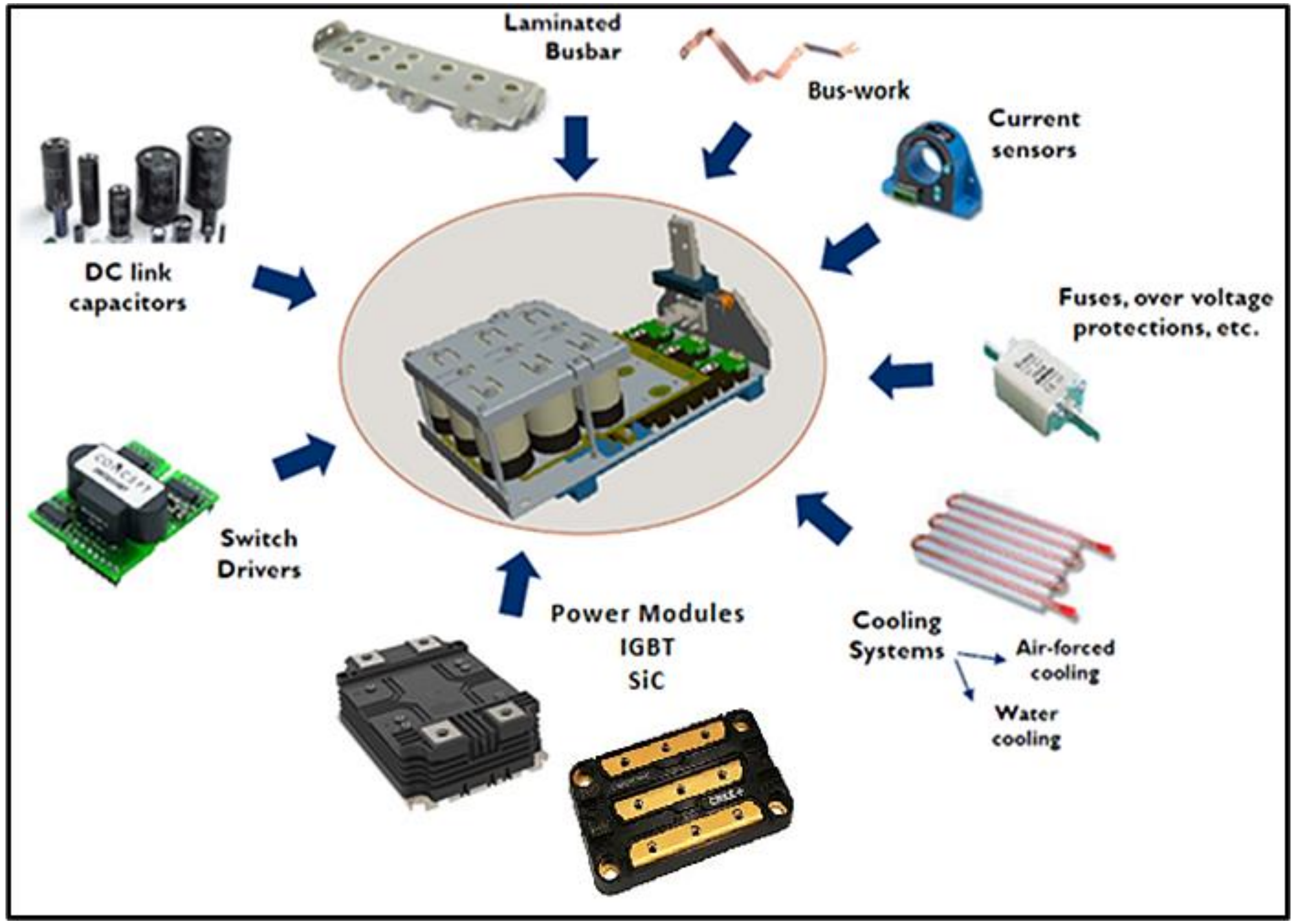
- The Power Converter and Stack
- Overview of today's low inductance busbars;
- Legacy challenges for busbar insulation systems
- New challenges for busbar insulation systems
- A new insulating solution
    - Advantages to address current and new challenges
    - Materials…
    - Tests…
    - Manufacturability…
    - Applications
- Wrap Up

A Power Converter…



The Power Stack

Power electronic stacks are assemblies that include the power semiconductor **modules**, **busbars**, gate drivers, snubber capacitors, protection, **DC-link capacitors** and cooling.



Source: Yole Development

Conventional Busbars

A laminated busbar is an electrical power interconnection circuit consisting of several flat conductors insulated from each other.

Laminated busbars

- Backbone of the power stack
- DC-link
- Low inductance design
- Several production processes:
  - Stacked Busbar: preferred for large volumes but not suitable for HV applications
  - Laminated busbars with thermo-glued insulating films : suitable for low inductance and HV (partial discharges)

Conventional Busbars

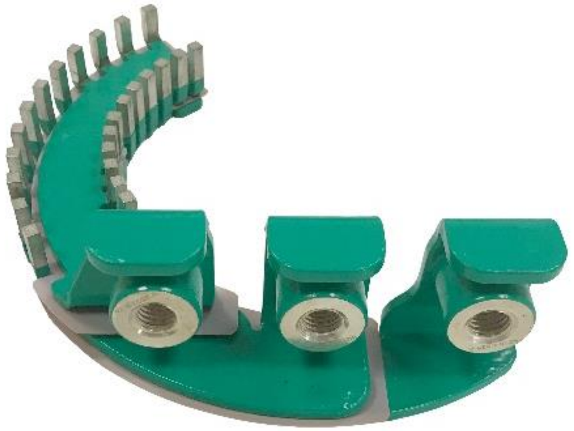
A laminated busbar is an electrical power interconnection circuit consisting of several flat conductors insulated from each other.

Laminated busbars

- Backbone of the power stack
- DC-link
- Low inductance design
- Several production processes:
  - Stacked Busbar: preferred for large volumes but not suitable for HV applications
  - Laminated busbars with thermo-glued insulating films : suitable for low inductance and HV (partial discharges)

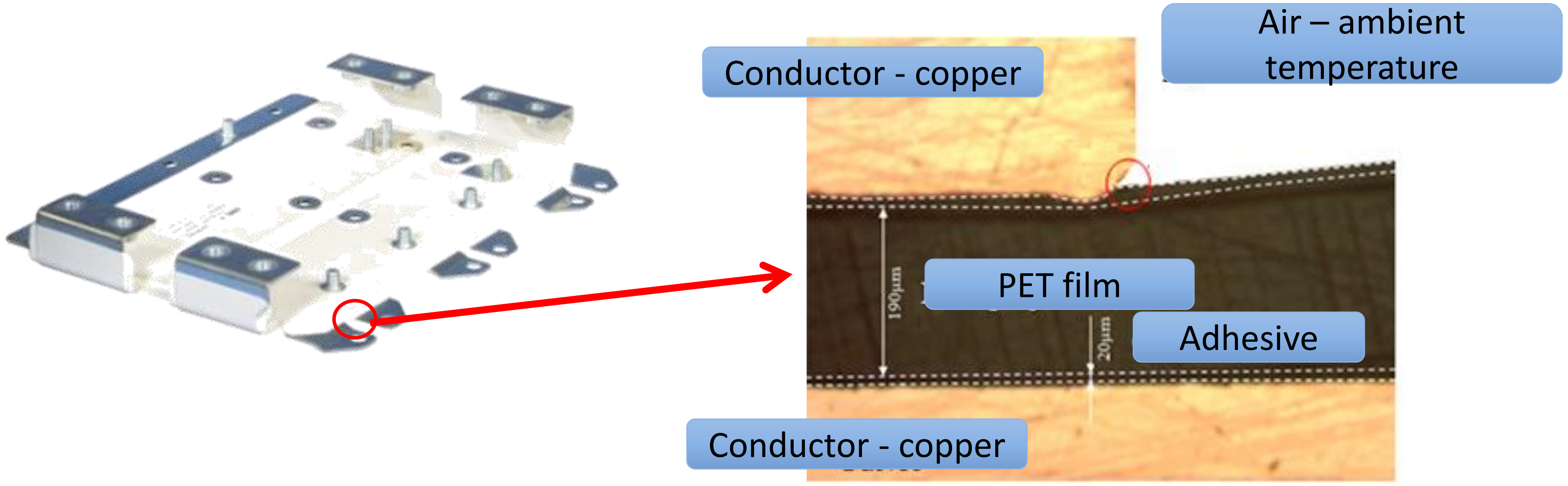
Several insulating materials

- Thin films: PET, PEN, etc. (main limitation: cost, manufacturability)
- Powder coating (main limitations: inductance and partial discharge via micro-pores)
- Plastic (large volumes, LV applications)
- Silicone resins - dipped



Applications: renewable energy, motor speed control, EV, railway, commercial air, marine, military systems…

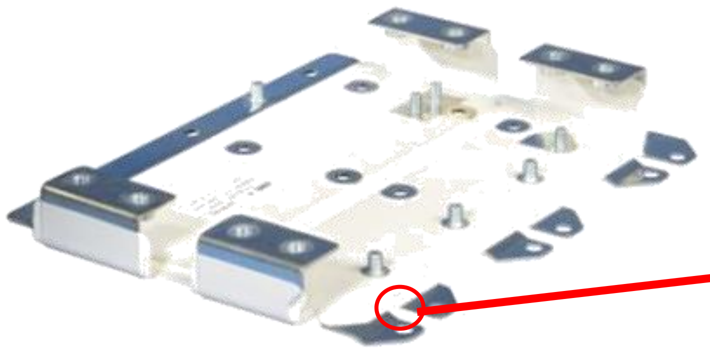
Partial Discharge Phenomenon in Multilayer Busbars

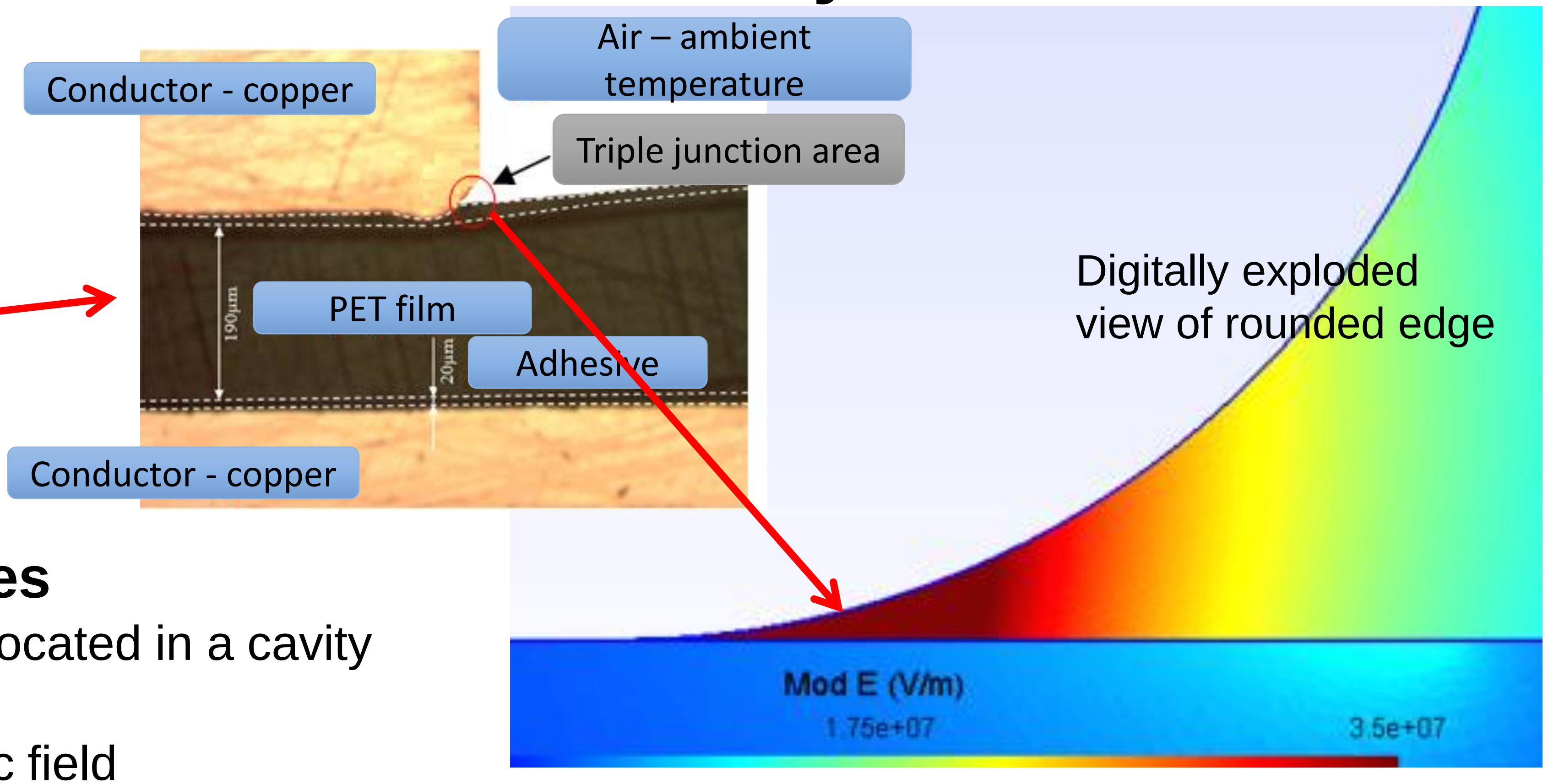


- **Internal partial discharges**
  - Micro electrical discharges are located in a cavity of an electrical insulation
  - Will appear under an electric field
  - A random phenomenon which will cause progressive erosion of the insulation system

(Amphenol & LSEE thesis - Mahdi SELLAH)

Partial Discharge Phenomenon in Multilayer Busbars





- **Internal partial discharges**
  - Micro electrical discharges located in a cavity of an electrical insulation
  - Will appear under an electric field
  - A random phenomenon which will cause progressive erosion of the insulation system

- **Triple junction area**
  - Critical zone where the electric field is at its maximum
  - Air is both in contact with conductor (copper) and insulation (ex: polymer)
  - 5µm - 15µm (in air environment, ambient temperature)
    - Below 5µm: PD will not appear
    - Above 15µm: PD can possibly appear (Cf. Paschen curve)

(Amphenol & LSEE thesis - Mahdi SELLAH)

Avoiding Partial Discharges (PD)

PD Def: micro electrical discharges located in a cavity of an electrical insulation under an electric field. These micro-discharges will cause progressive erosion of the insulation.

1. **Avoid air gaps** in the insulation system (dielectric strength of air is very low)
   - **Insulation bonded** to the conductor
   - Limit the **size of the air gaps** to < 10 microns (use better material)
   - Fill the **"singular" areas** with insulating material
2. Limit the **intensity of the electric field**, where there would be air gaps
   - **Increase space** between conductors (will increase inductance - not acceptable)
   - **Avoid peak effect, use round edges**,
   - Reduce relative **permittivity** level of the insulation system,
   - Reduce electric **field intensity**.
3. Use **PD resistant insulation** (use of inorganic material)

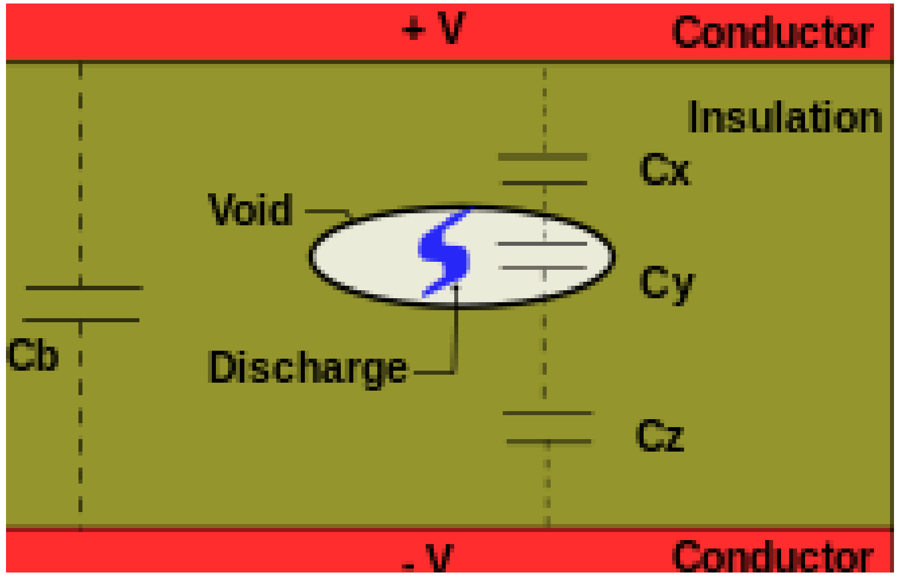
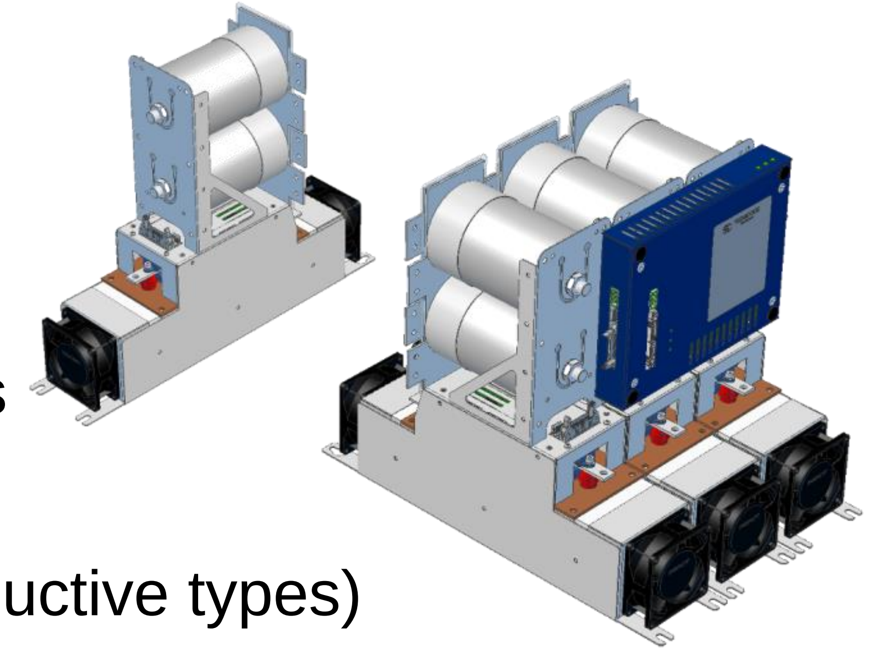


Photo credit : Wtshymanski at English Wikipedia

Evolving Insulation system challenges

- Higher **switching frequency** (from Si IGBT to SiC MOSFET)
  - 10/20kHz…. 50kHz…. 200kHz
- Higher **temperatures**
  - SiC chips can operate at a much higher temperature
  - Some specific applications already require 200°C busbars
- Higher **voltages**
  - Additional stress on insulation systems (especially low inductive types)
  - Partial discharge
- Long product **life cycle** expectations
  - New systems = 30y lifetime
- System **compactness**



Source: E-guasch.com

Our new technology will provide solutions to these constraints…

A Solution to the challenges:
<u>Varnish Insulated Busbar</u>

- **Very thin layers of varnish coating**
- A new technique for busbars, but varnish is **widely used** in the electrical field (as enameled wire) for electric motor and transformer windings:
  - **existing standards** (eg: temp class IEC60085; insulation class, etc.)
  - **proven** robust electric & thermal performance

Thin layer deposition by Microspraying & UV Curing

- Charge transport and molecular displacement explains the higher dielectric strength of a thin insulating layer (compared to a thick layer)*

  Example :
    - 160 µm (2 layers of 80 µm) => 5.0 kVAC
    - 160 µm (4 layers of 40 µm) => 5.8 kVAC

- *Thin layers increase thickness homogeneity & control specific (triple junction) areas*.
- Avoid bubbles & micro-cavities (fewer partial discharges)
- *Ability to coat the edge*
    - Varnish application in multiple thin layers (5-10µ)
    - Final thickness of this test is 150-200µm also on the edges
    - Use of thixotropic agent

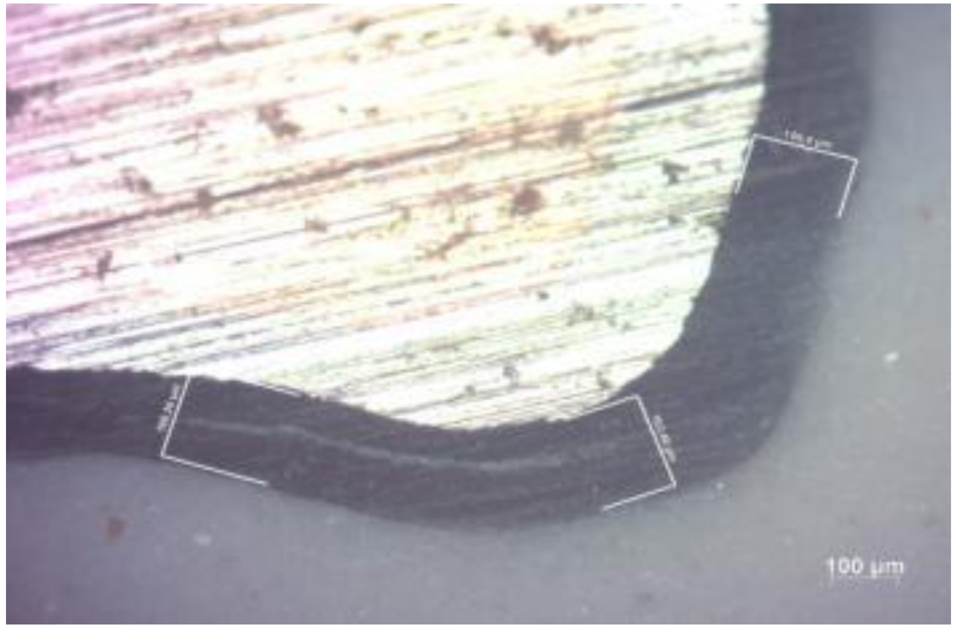


Image of busbar edge. White is CU busbar, black is varnish along the edge.

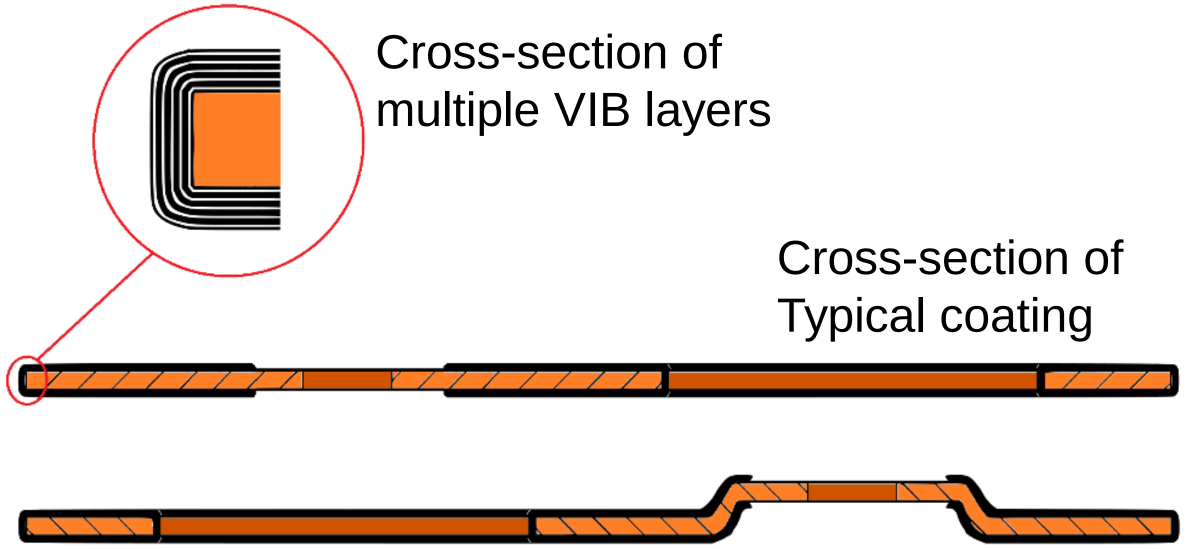
Bibliography
*Thickness-Dependent DC Electrical Breakdown of Polyimide Modulated by Charge Transport and Molecular Displacement
Daomin Min , Yuwei Li, Chenyu Yan, Dongri Xie , Shengtao Li , Qingzhou Wu and Zhaoliang Xing - 2018

Continued…

Thin layer deposition (cont'd.)

- Possible to **coat layers of different kinds** (adhesion primer, special coating,...)
- **Clean process** - low material loss - slight masking of connection areas is sufficient
- UV LED curing - **low power** consumption;
- **Fast UV process** - 1 conductor: 10-15 minutes

Making a Varnish Insulated Busbar (VIB)



Conductors

- **Copper or aluminum** conductors
- **Surface treatment**: tin, nickel silver, unplated…

Varnish base

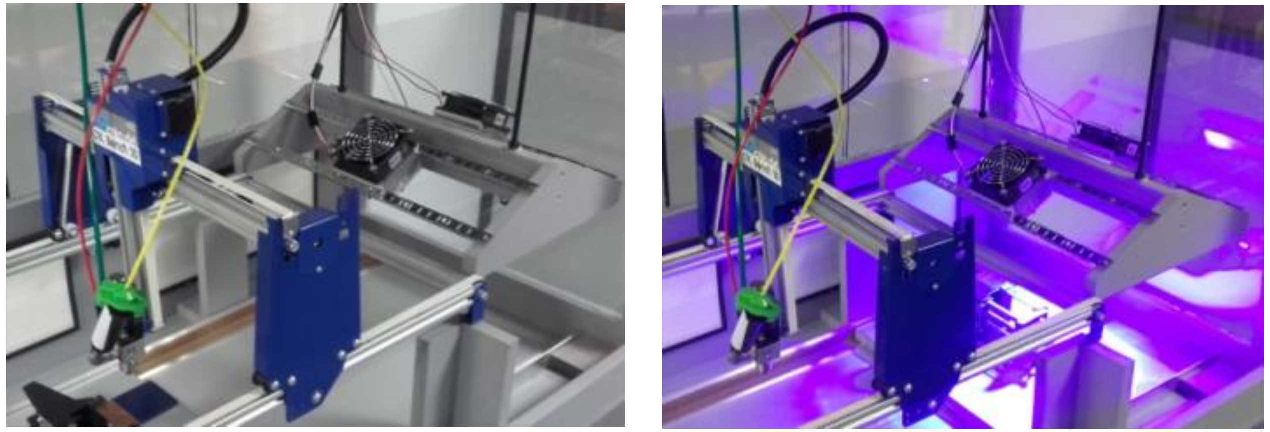
- **Non-aqueous acrylic base**
- **Solvent-free**
- **With thinner** (viscosity & flexibility to final coating)
- **With photo-initiator** for UV cross-linking LEDs
- **With thixotropic additive** for viscosity and an adhesion promoter
- Possibility to **add inorganic charges** to improve electrical performance

Insulation

- **Each conductor** is individually insulated by multiple thin coats of varnish
- A **precise deposit** is insured using by micro-spraying with robotics
- **UV cross-linking** for each layer/coat
- **5-20 microns** per layer (to obtain 80-200µm insulation voltage comparable to standard PET film, but improved inductance and homogeneity.

Making a Varnish Insulated Busbar

UV Cross-Linking



Crédit photo :AUXEL

Multiple Conductors - Mechanical Assembly

- **Bonding by UV** thermo-adhesive
- **Assembly by VPI** (vacuum pressure impregnation)
- **Mechanical assembly**, …

Benefits of the Varnish Insulated Busbar

Crédit photo :AUXEL

- **High temperature** (180°C continuous - target: 220°C)
- **Excellent PD** performance including at the edge
- Suitable for **high voltage applications**
- **Improved inductance**
- **Higher frequency operation**
- **Possible cost decrease** (compared to existing technologies)
- **Environmentally friendly** production:
  - **low material waste** (localized micro-spraying)
  - **low energy** – no intensive heating-press
  - **no (VOC)** Volatile Organic Compounds

Continued…

Benefits (cont'd.)

- Favorable **manufacturing conditions**
  - **robotics** + micro spraying + UV Led lamp + clean room ISO class 7-8)
  - easy to produce **complex and/or large geometries**,
  - well-suited to **small to medium production runs**
  - **no additional tooling costs**
- Easily **adaptable layer thickness**
- **Power Density**
  - **Compact, thinner** + **eliminates sealed edges**
  - Much **thinner for multi-kV structures.**
- Solvent free resin to eliminate **outgassing**
- **Proven technique** is widely used in the motor-winding industry
- The VIB technique is also **applicable to single conductor busbars**, such as AC Output
- Possible to use **inside power modules**

Crédit photo :AUXEL

Comparison of Insulation for busbars
VIB vs Several Insulation Types

	Powder coating	Silicone coating	Plastic injection	PET film (stacked LBB)	PET film glued (heating press)	PEN | PI film glued (heating press)	Varnish Insulation, UV Cured
Dielectric Strength	Yes	Yes	Yes	Yes	Yes	Yes	**Excellent**
High Temperature	155 to 180°C	200°C	80 to 200°C	105 to 200°C	105°C	130 to 180°C	**200°C+**
High Voltage	Yes	Yes	Yes	No (<1000V)	Yes	Yes	**Excellent**
High PDIV	No	No	No	No	Yes	Yes	**Excellent**
Low Inductance	Medium	Medium	Medium	Yes	Yes	Yes	**Excellent**
Environmental Considerations	Large power consumption, Smoke	Energy consumption, vapors	Ok	Ok	Large power consumption	Large power consumption	**Solvent free, Low-energy**

VIB – Research Partnerships

- R&D **Consortium**
  - Received funding from the Clean Sky 2 Joint undertaking via the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 821065.
  - Topic Leader : ZODIAC AERO ELECTRIC (Subsidiary of SAFRAN Group)
  - Consortium: Amphenol AUXEL (as consortium leader), LSEE (Artois University - France)

Clean Sky 2
JOINT UNDERTAKING

- R&D **Status**
  - Technology Readiness level (TRL) : 6
  - Technology available for collaborative research & **commercial prototypes**

Horizon 2020
European Union Funding
for Research & Innovation

SAFRAN

- International **Patents** (EUR, USA, CN, IN)
  - WO2019068969 – Multilayer connector with conductors insulated by enameling
    - https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019068969
  - WO2019068968 – Multilayer connector insulated by impregnation with resin
    - https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019068968
  - Co-inventors : LSEE (Artois University) & Amphenol

Wrap-up…

- Need for improved technologies
  - SiC, Electric Aircraft (MEA), Electric Vehicles (EV), Military systems, etc. These have placed new demands on the interconnection system!
- New insulation concept for busbars
  - high temperature,
  - high PDIV,
  - high power Density
  - compact design,
  - complex geometries
  - cost advantages
- Limited technological risks
  - Based on existing technologies (motors and transformers)
- Technology is ready for collaborative research & commercial prototypes
- Underway - several interesting projects for further technology research.

Thank You!!

Amphenol
GLOBAL INTERCONNECT SYSTEMS

Your Global Value Added Service Provider

Presented by:
John E. Mills
Business Development Manager, Power Products
Amphenol Global Interconnect Systems
john.mills@amphenol-gis.com
860-560-6612

Fabien DIJOLS
Business Development Manager, Amphenol-Auxel
Amphenol Global Interconnect Systems
fabien.dijols@auxel.com
+33 (0)6 23 16 53 05