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Shaping the Future: Advanced EB-PVD Technology for a Diverse Range of Applications

Stefan Saager, Ludwig Decker, Lars Klose, Bert Scheffel, Matthias Tenbusch, Burkhard Zimmermann
Fraunhofer Institute for Electron Beam and Plasma Technology FEP, Dresden, Germany

Since the 1960s, pioneering work in Electron Beam Physical Vapor Deposition (EB-PVD) of metal strips has led to the installation of numerous pilot and production plants worldwide. However, the demand for ongoing development in a variety of application areas remains strong. To meet the changing challenges of modern industry, multifunctional equipment is essential. In 2000, the innovative inline vacuum coating plant for sheets and metal strips called MAXI was set into operation at Fraunhofer FEP in Dresden, Germany, to address global research and development needs. This modular system, comprising eight chambers, allows for the sequential execution of different process steps and offers the flexibility to operate in both sheet-to-sheet and roll-to-roll modes. This results in more efficient, faster, and easier progress during the early stages of development, as well as a smoother process transfer for the upscaling. In celebration of MAXI's 25th anniversary, we will provide an overview of the diverse research projects realized over the years — from metallurgy and semiconductor applications to cutting-edge solutions for today's energy technologies. Additionally, we will discuss current modernization activities.

DOI: https://doi.org/10.14332/svc25.proc.0001

Fraunhofer
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Fraunhofer Institute for Electron
Beam and Plasma Technology FEP

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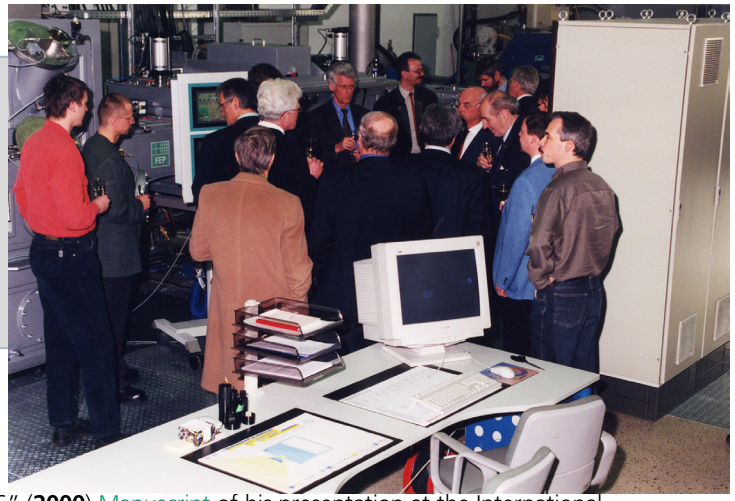
SVC TechCon 2025 Nashville

The Motivation Behind This Talk

Using hindsight for shaping the future

from the early **1960s**	■ Vacuum metallurgy at all and especially EB melting stood godfather to PVD coating of metal beginning from the early 1960s. ➢ Pioneers: **Leybold Heraeus** (West Germany), **Inst. v. Ardenne** (East Germany), **Temescal** (USA)
1970s-1990s	■ Worldwide rising installation of PVD plants for coating of metal strips, but stagnation in the 1990s ➢ Main application: corrosion protection
2000	■ Prof. Schiller (former director of FEP): »PVD-coating technology is making a comeback, with new advancements and applications in metal strips and sheets«[§] ➢ Inauguration of the In-line Vacuum Coating Equipment for Sheets and Metal Strips – MAXI[#]



[§] Siegfried Schiller, „WHY THE COME BACK OF PVD-COATING OF METAL STRIPS AND SHEETS" (**2000**) Manuscript of his presentation at the International Symposium Emergent Opportunities of PVD – Coated Metal Strips and Sheets held to mark the inauguration of the MAXI at the Fraunhofer FEP.

[#] Siegfried Schiller et al., Surf. Coat. Technol. 125 (**2000**) 240-245 10.1016/S0257-8972(99)00567-8

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2000s-2010s	■ PVD pilot lines in steel industries using thermal evaporation of Zn and Mg ■ After an initial increase of plant installation for optical and decorative applications, the further development of the technology has stagnated.
2025	■ MAXI's 25th anniversary ➢ Purpose of this talk: giving insights of the past activities @FEP & Line-up for the future

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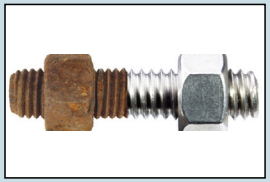
Outline

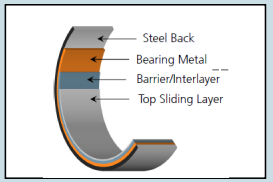
1. ✓ Motivation
2. Experimental Setup
3. Use Cases
4. Conclusions
5. Outlook

USE CASES

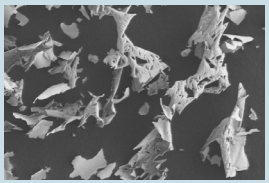


Corrosion protection

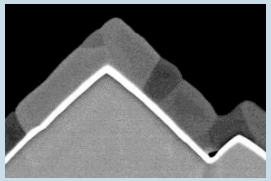
Transparent and colored coatings



Tribological coatings

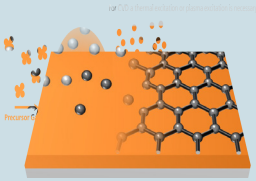


Powder synthesis

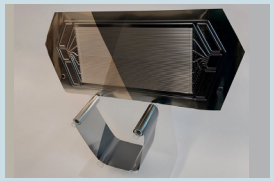


Contact layers

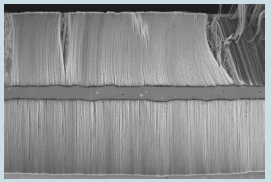
Wear-resistance



Graphene



Fuel cell coatings



Battery anodes

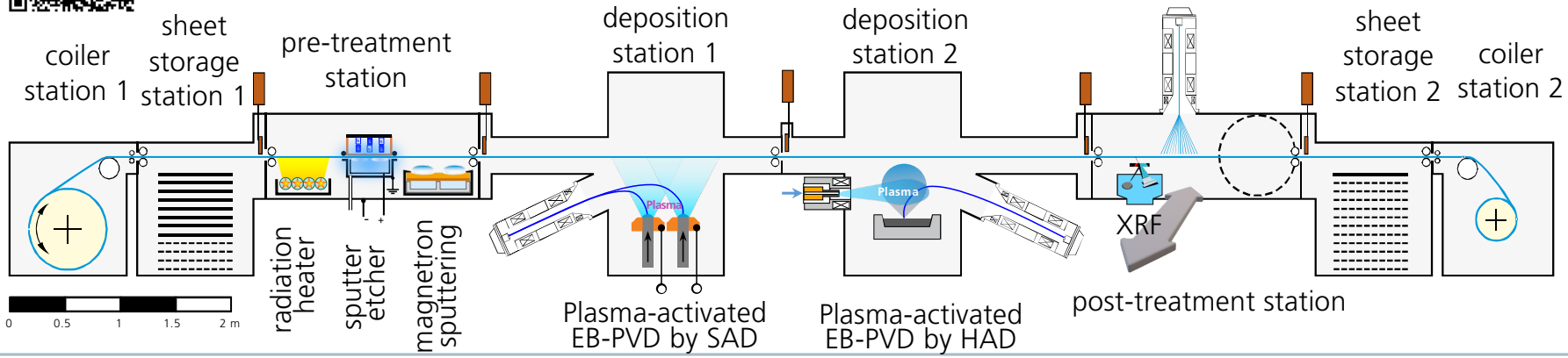
Fraunhofer FEP

PLATFORM: In-line electron beam and sputter Coater MAXI

In-line vacuum coating equipment for metal strips and sheets

Features

- Single and double side coating of metal, plastic, glass or ceramic sheets with a maximum dimension of 500 mm × 500 mm
- Coating of metal strips with a maximum width of 300 mm and a maximum thickness of 1.5 mm
- Ability to combine processes with in-situ analysis and control loop, e.g. temperature, QCM, QMS, opt. spectroscopy, XRF, strip tension
- Testing of key components under near-industrial conditions



https://www.fep.fraunhofer.de/en/Kernkompetenzen/Anlagentechnik/maxi.html

Fraunhofer FEP

Researcher at FEP: Dr. Bert Scheffel

USE CASE: Corrosion Protection of Steel Strip with Zn-Mg-Alloy Layers

By thermal evaporation of magnesium on galvanized steel sheets

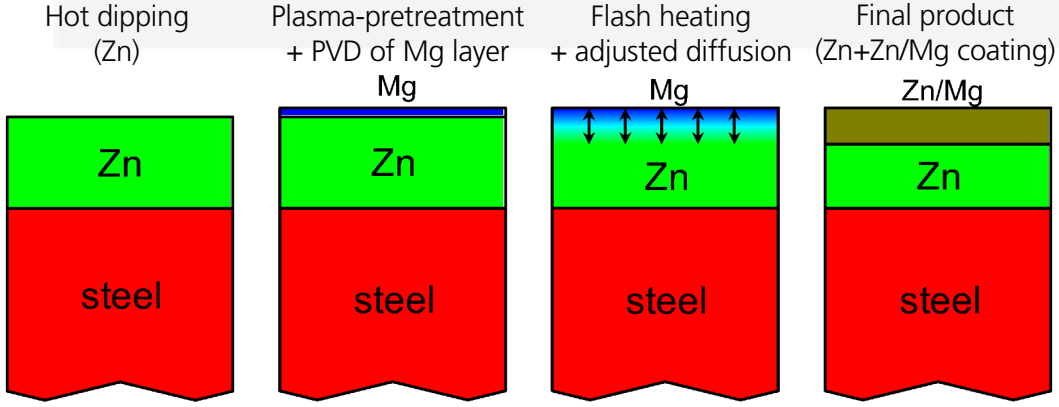
Approach

- Combination of conventional galvanizing process (hot-dip or electro-coating) + PVD of magnesium + annealing procedure

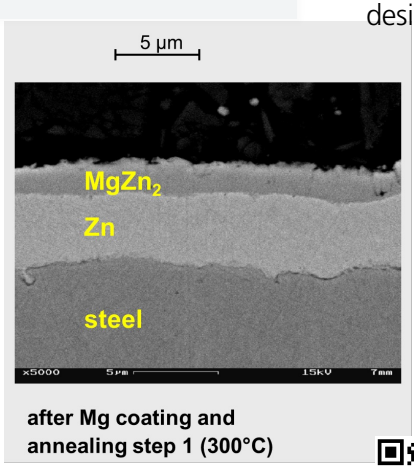
Result

- Corrosion resistance drastically improved:
  - by a factor 11 - 26 (white rust, humidity chamber test DIN 50 017)
  - by a factor 7 - 11 (red rust, salt spray test)

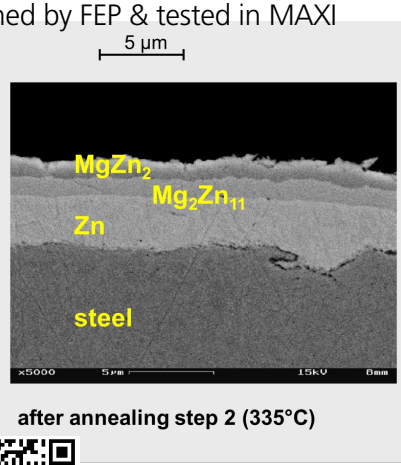
Metal sublimation equipment designed by FEP & tested in MAXI



Joint projects together with European steel industries and VDEh, financially supported by the German and Austrian governments



after Mg coating and annealing step 1 (300°C)



after annealing step 2 (335°C)

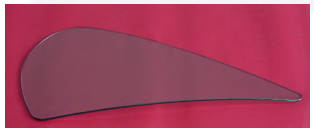
Scheffel et al., *Steel Research* 73(3) (**2002**) 114-122 doi: 10.1002/srin.200200182 & *Proceedings of 7th International Conference on Zinc and Zinc Alloy Coated Steel Sheet* (**2007**) 556-561 & Practical Metallography: 49(4) 210-220 doi: 10.3139/147.110143

Fraunhofer FEP

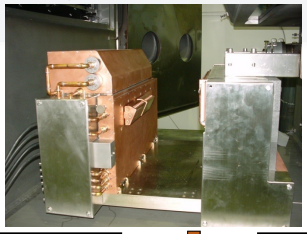
USE CASE: Deposition of Colored and Transparent Layers on Plastic and Metal

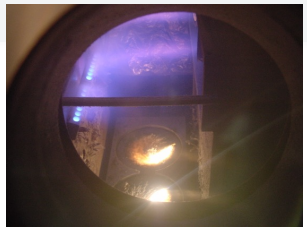
By plasma-activated EB-PVD with hollow cathode enhancement

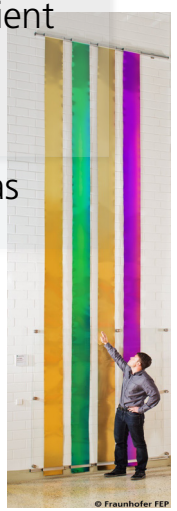
Challenge	■ High hardness of the coating, low residual stress, good adhesion also in humid ambient ■ High transparency, UV protection (plastic), excellent layer uniformity ■ Tunable refractive index: low (for transparent) or high (for decorative applications)
Approach	■ EB-PVD of ceramics (e.g. SiO_x, AlO_x) with plasma activation and admitted reactive gas

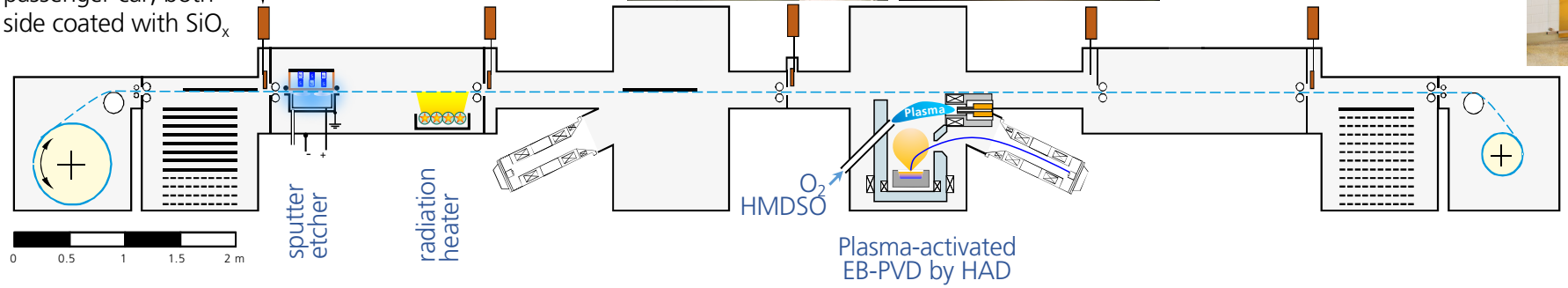


PC window of a passenger car, both side coated with SiO_x









Morgner et al., Technical Conference Proceedings of SVC (**2007**) p. 252ff. & (**2012**) p. 663ff. & Surf. Coat. Technol., 108-109 (**1998**) 513-519 doi: 10.1016/S0257-8972(98)00633-1

Fraunhofer FEP

Researcher at FEP: Dr. Jens-Peter Heinß

USE CASE: EB-PVD of thick Al-Alloys on Flat Blanks for Producing Bearing Shells

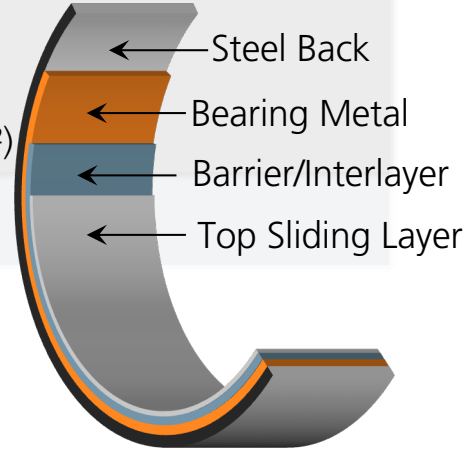
By EB-PVD with continuous feeding

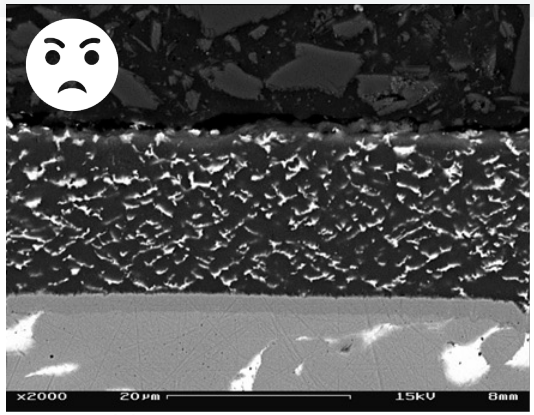
Challenge

- Thickness: ~500 µm, narrow Temperature range of 120-170 °C, good adhesion
- High-throughput, reliable constant layer composition
- Fine distribution of tin clusters by applying high coating rates
- Uniform properties on large substrate dimensions (500 x 340 mm²)

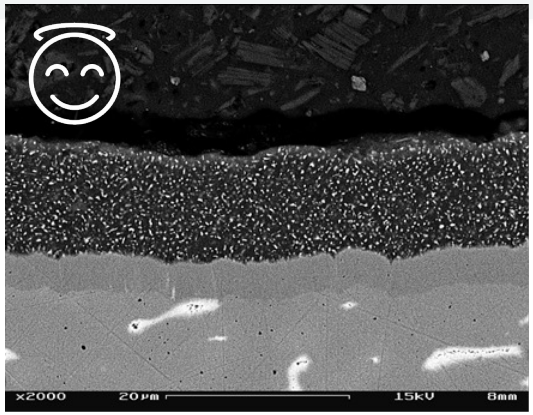
Approach

- EB-PVD of Al-alloy with continuous feeding





coated by magnetron sputtering



coated by EB-PVD

Main technological steps inside vacuum:

a) Pretreatment = Fine cleaning
b) Intermediate layer (NiCr)
c) Sliding layer (AlSnCu)

J.-P. Heinß, "Vacuum Deposition of Aluminum Alloys with 1 µm/s on Different Types of Semi-Finished Products", (**2023**) Technical Conference Proceedings of SVC 10.14332/svc23.proc.0054
& J.-P. Heinß, Surf. Coat. Technol., 478 (**2024**) 130313 doi: 10.1016/j.surfcoat.2023.130313

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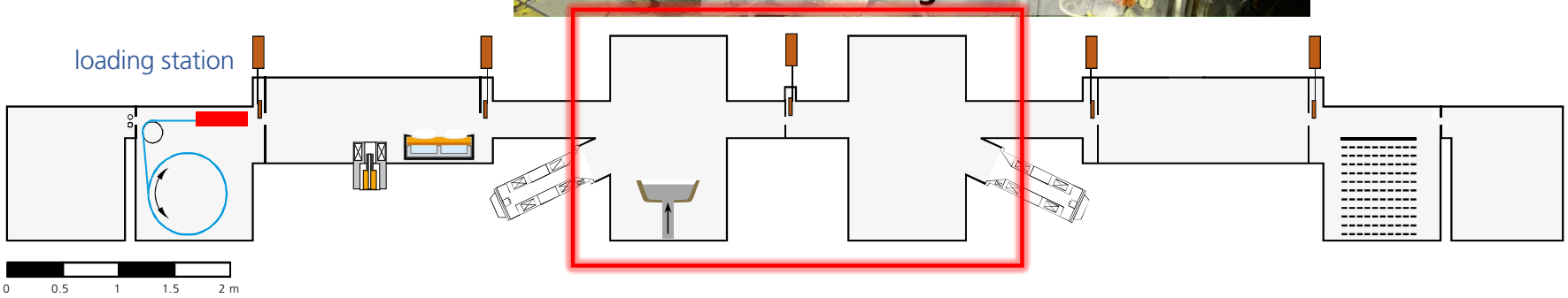

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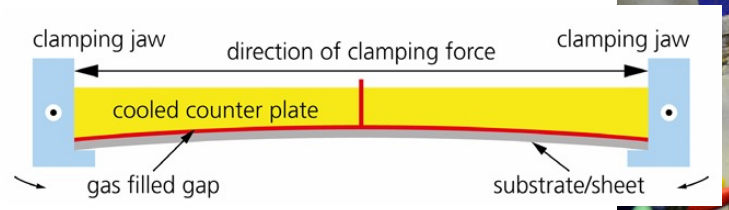
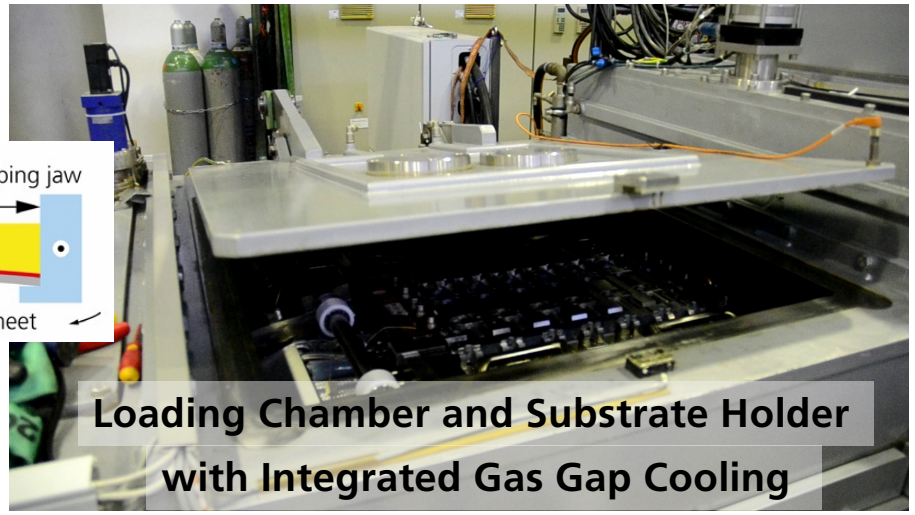
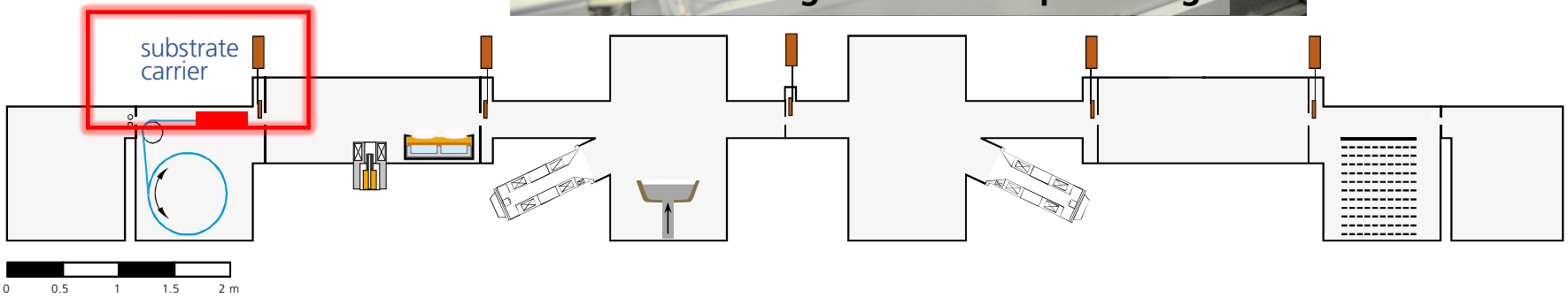




Loading Chamber and Substrate Holder with Integrated Gas Gap Cooling



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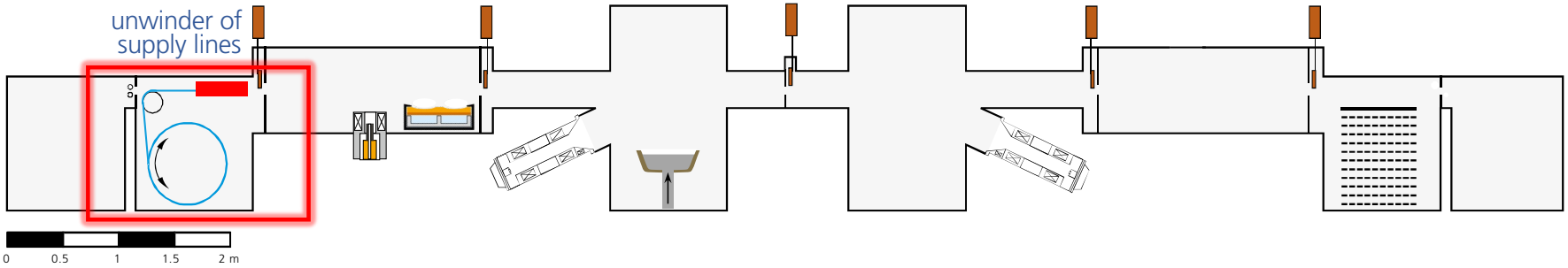

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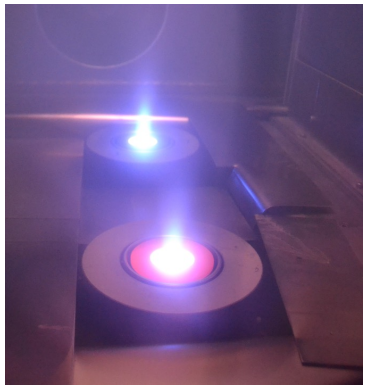
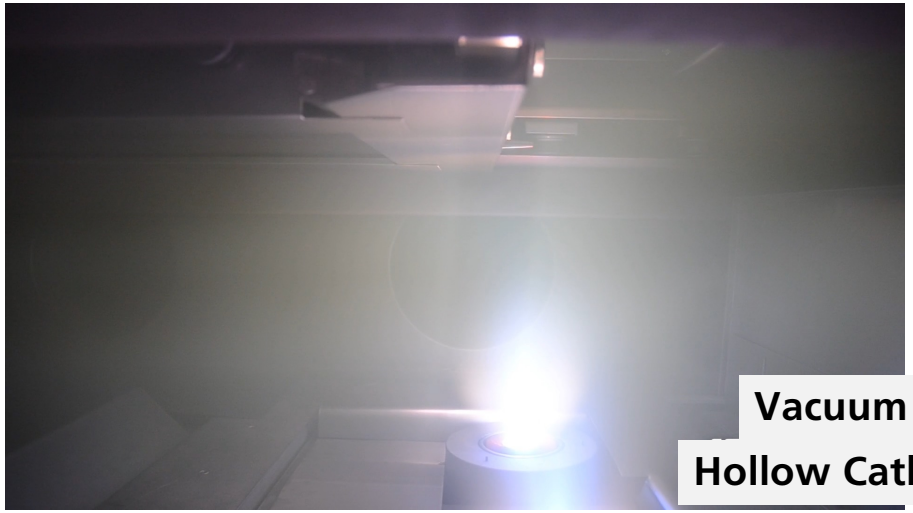
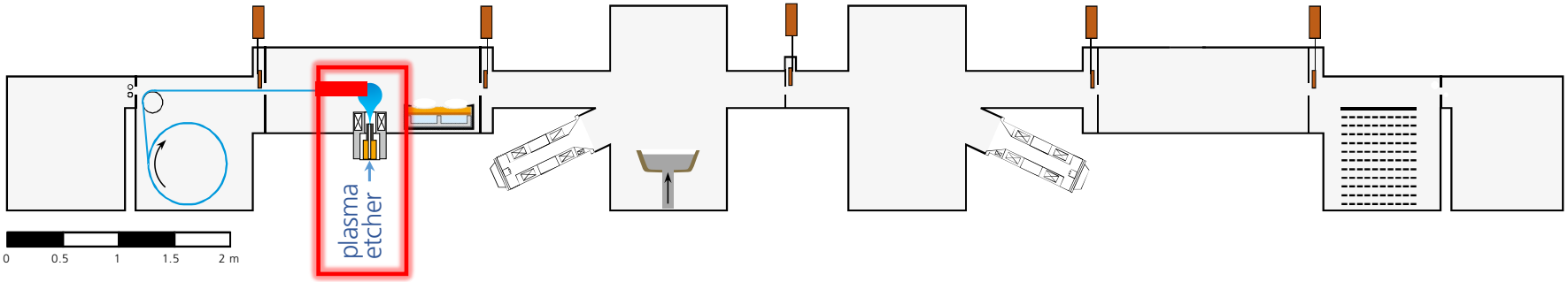


side by side arranged hollow cathodes



Vacuum Pretreatment by Hollow Cathode Sputter Etching



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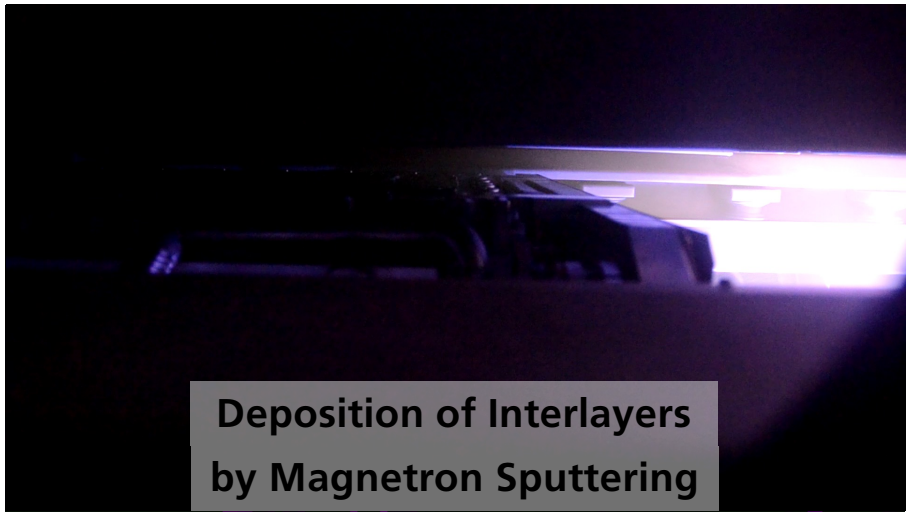

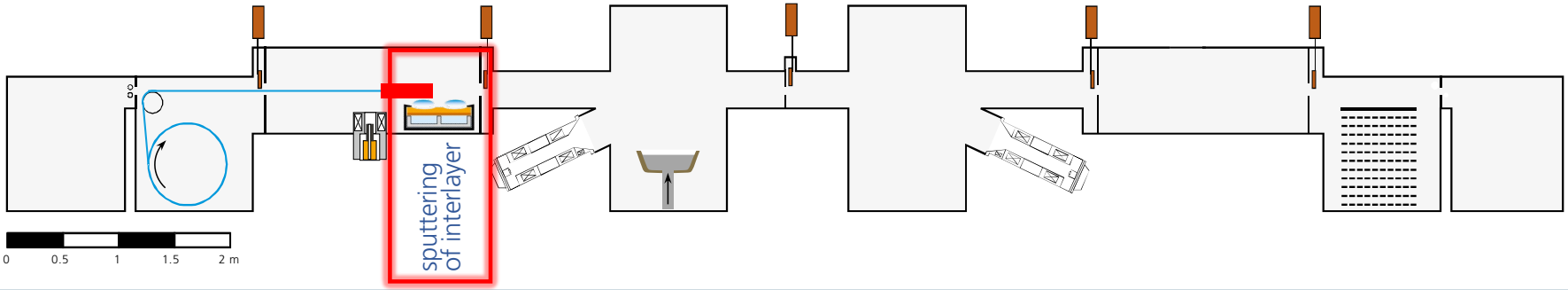

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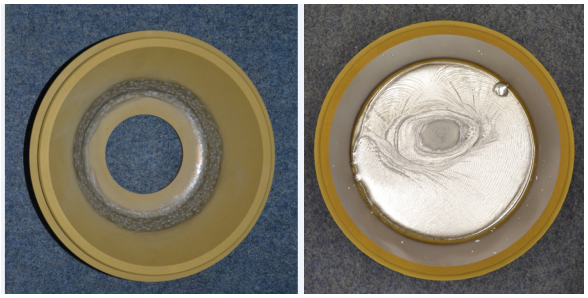
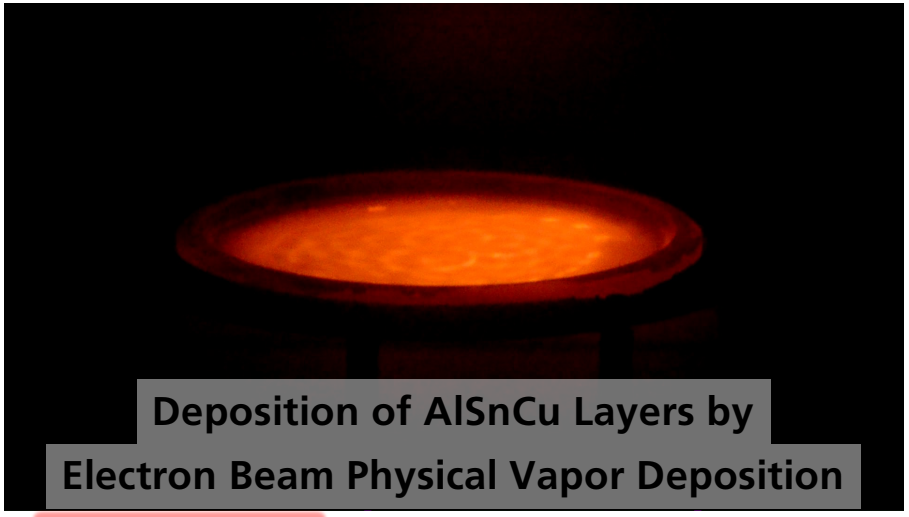
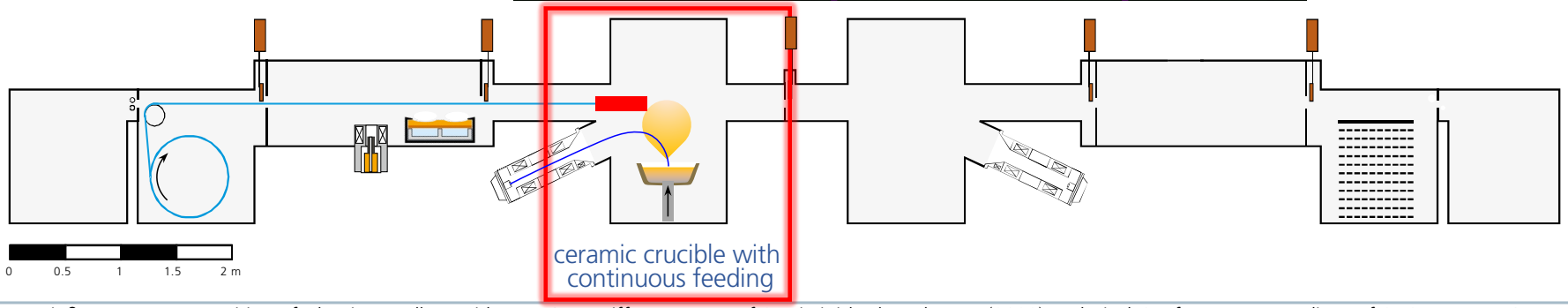


ceramic crucible
before after
EB-PVD





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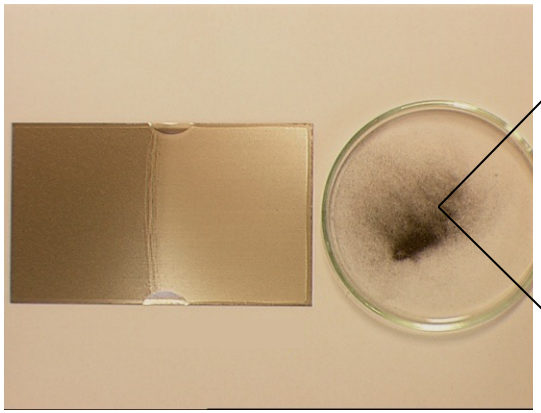
Fraunhofer FEP

Researcher at FEP: Dr. Bert Scheffel

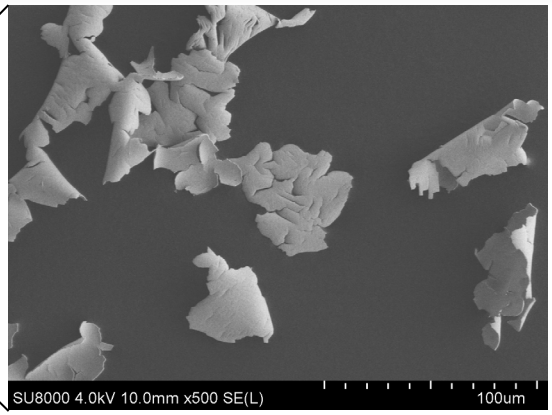
USE CASE: Synthesis of Powder Particles with High Surface

Challenge	■ Formation of flakes with high aspect ratio to realize a high particle surface ■ High purity ■ High-throughput
Approach	■ Continuous EB-PVD of refractory metals on metal substrates with release inter layer

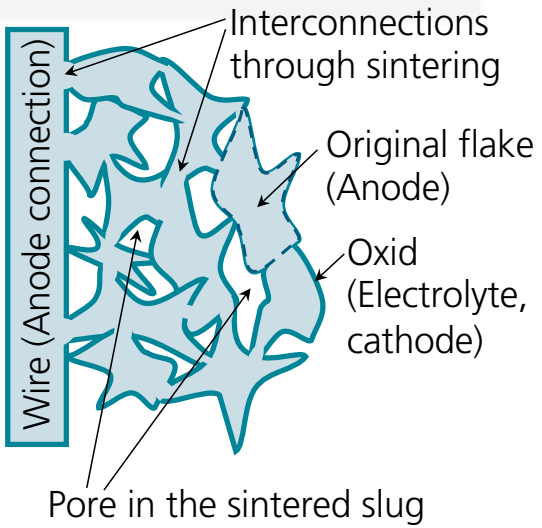
$$C = \varepsilon \cdot \frac{A}{d}$$



Coated steel substrate with mechanically detached particle on the right side



Flakes with a thickness of 0.1-1 µm



H.C. Starck GmbH, Tantalum and niobium carbide from H.C. Starck, https://www.hcstarck.com/en/products/tantalum-and-niobium-carbide/

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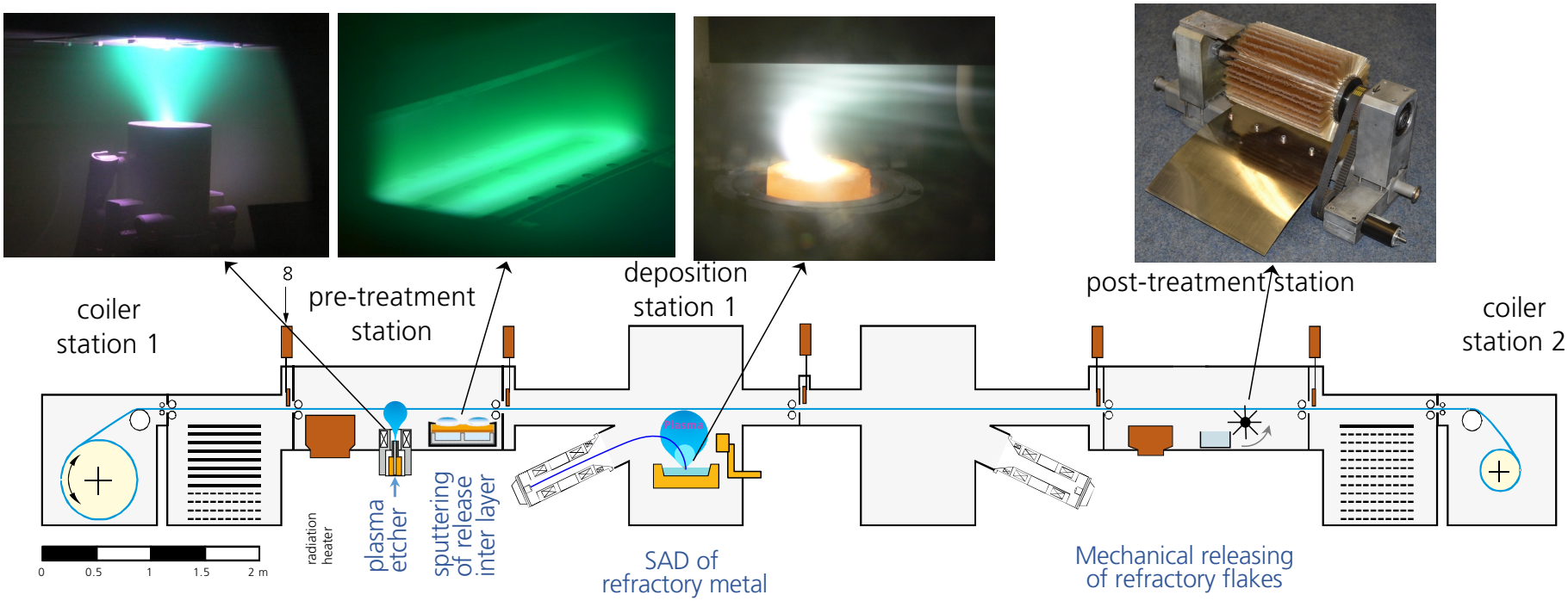
Researcher at FEP: Dr. Bert Scheffel

USE CASE: Synthesis of Powder Particles with High Surface



H.C. Starck GmbH, Tantalum and niobium carbide from H.C. Starck, https://www.hcstarck.com/en/products/tantalum-and-niobium-carbide/

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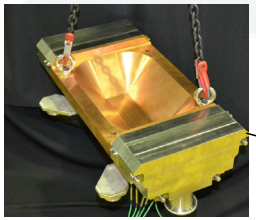
Researcher at FEP: Dr. Jens-Peter Heinß

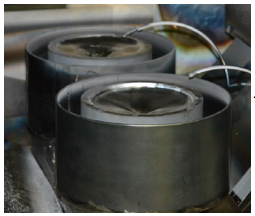
USE CASE: Al Back Contacts for Si-Hetero-Junction Solar Cells

By EB-PVD out of hot crucibles

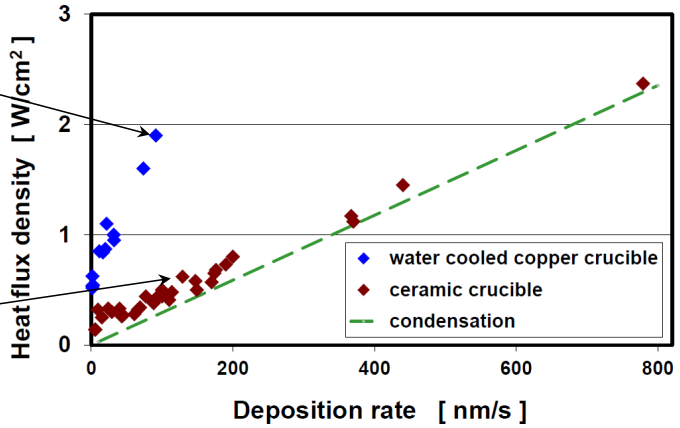
Challenge	■ Maintaining a temperature limit of 200°C during the deposition of several µm of Al ■ Maximizing the throughput while ensuring layer properties and heat load
Approach	■ Used ceramic and water-cooled copper crucibles for testing. ■ Conducted inline coating in pilot-scale equipment to optimize processes.

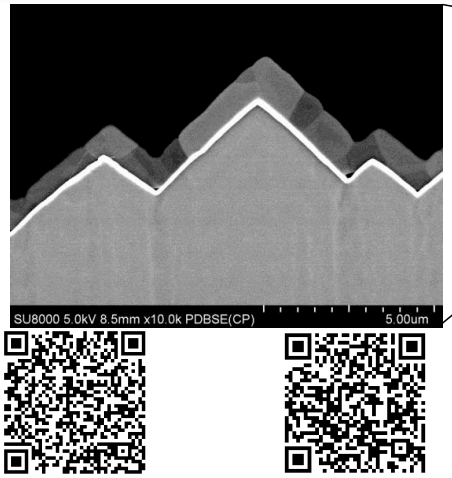


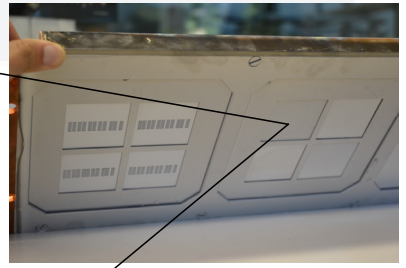
Water cooled Cu crucible

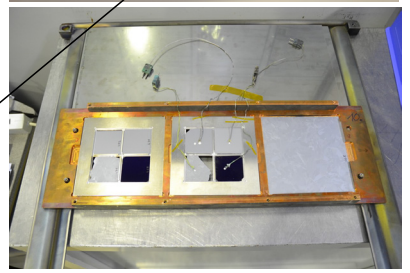


Ceramic crucibles with wire feeding









J.-P. Heinß et al. 10.4229/26thEUPVSEC2011-2CV.2.47 (**2011**) & 10.4229/EUPVSEC20162016-2BV.7.49 (**2016**)

funding reference: 100095132

Europa fördert Sachsen. EFRE Europäischer Fonds für regionale Entwicklung

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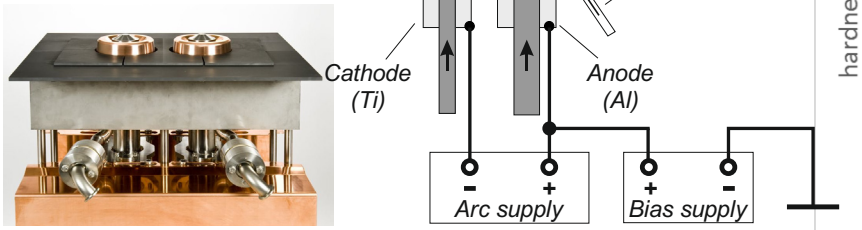
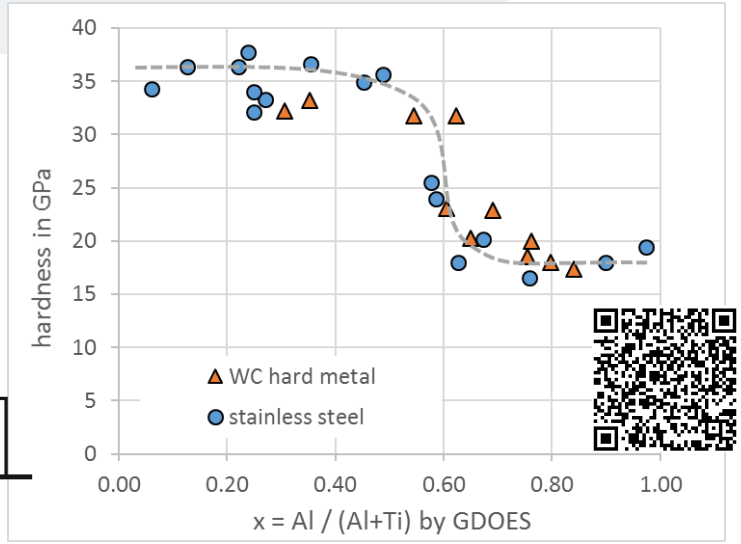
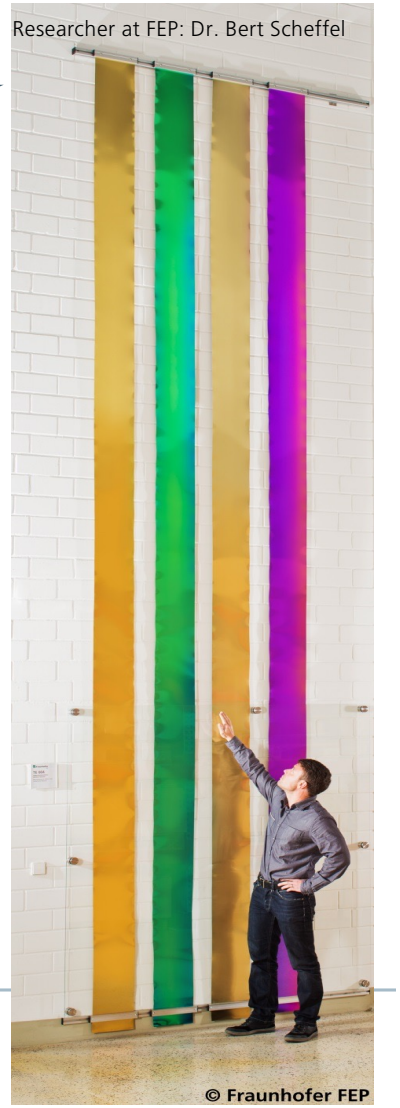
USE CASE: TiN and $Ti_{(1-x)}Al_xN$ Coatings by SAD Process

- Hard $Ti_{(1-x)}Al_xN$ – coatings on stainless steel and WC hard metal substrates
- not available without plasma activation
- x = 0 (TiN) up to x = 0.98 (AlN)



Water-cooled dual crucible





Scheffel et al., Surf. Coat. Technol., 287 (**2016**) 138-144 doi: 10.1016/j.surfcoat.2015.12.061

USE CASE: TiN and $Ti_{(1-x)}Al_xN$ Coatings by SAD Process

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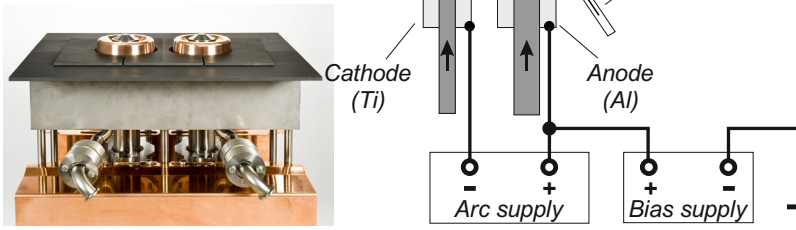

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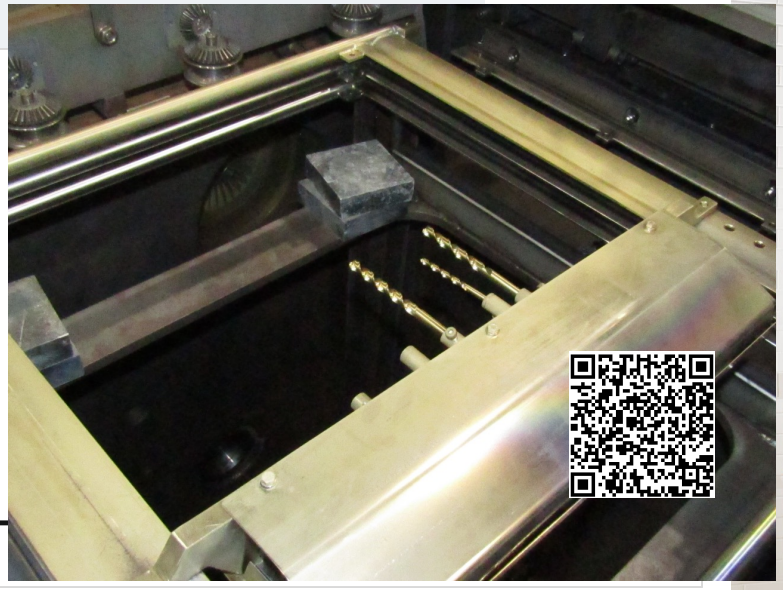


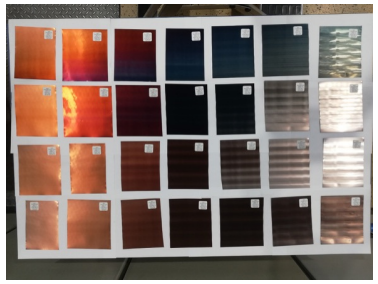
Scheffel et al., Surf. Coat. Technol., 287 (**2016**) 138-144 doi: 10.1016/j.surfcoat.2015.12.061

Researcher at FEP: Dr. Stefan Saager

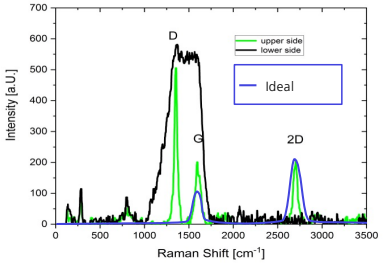
USE CASE: Deposition of Graphene Layers

by plasma-enhanced chemical vapor deposition in a roll-to-roll process

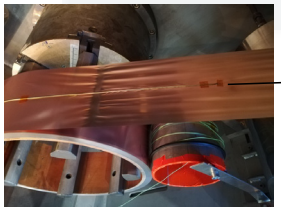
Process	■ Double side coating of a steel strip with copper catalyst ■ Rapid heating up to 1000°C by inverse magnetron device ■ Addition of precursor gas ➔ deposition of graphene by PE-CVD
Reached results	■ Formation of graphene has been proven by Raman ■ Quality of the layers needs to be optimised



processed pieces of steel strip



Raman spectrum



Saager et al., Technical Conference Proceedings of SVC (**2022**) doi: 10.14332/svc22.proc.0026

funding reference: 862100

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USE CASE: Deformable Protective Coatings for PEM BPP

Using high-rate plasma-activated EB evaporation

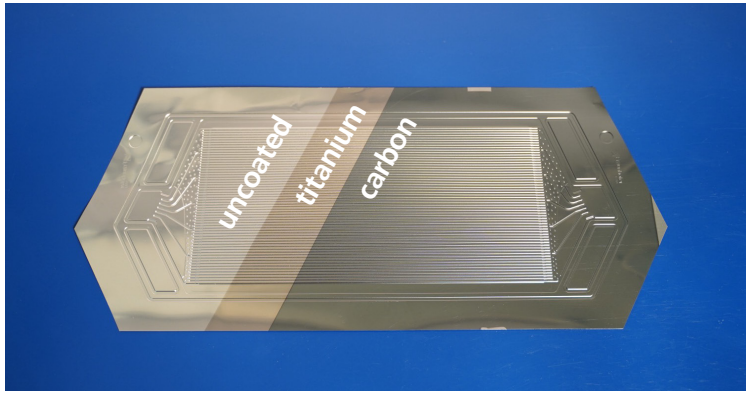
Demands	■ Low contact resistance ■ High resistance to corrosion in a wide oxidizing potential range ■ **Good formability** without layer cracking ■ Low cost processing
Technology	■ High-power plasma processing + High-rate EB evaporation ■ Roll-to-Roll vacuum processing with thin metal strips (pre-coating)

Thin film materials:

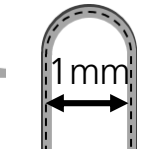
- Dense corrosion resistant layers of e.g. Ta, Ti, Nb
- Contact layers of doped amorphous carbon
- Increased ductility and formability by plasma-activated evaporation
- EBPVD: high throughput technology

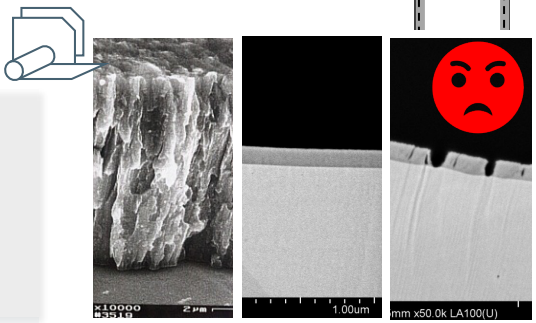
in cooperation with

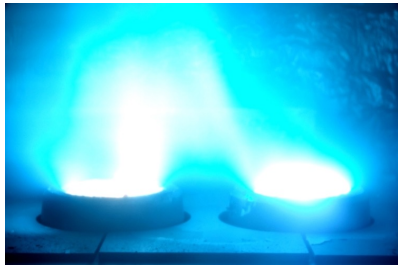
VON ARDENNE Fraunhofer IWU



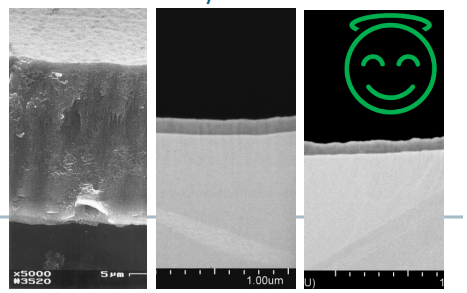
Researcher at FEP: Ludwig Decker







Plasma effect on the microstructure of thin titanium layers



Saager et al., Proc. of FC³ Fuel Cell Conference (**2024**) , pp156-165 doi: 10.60687/2024-0125
Technical Conference Proceedings of SVC (**2024**) doi: 10.14332/svc24.proc.0013

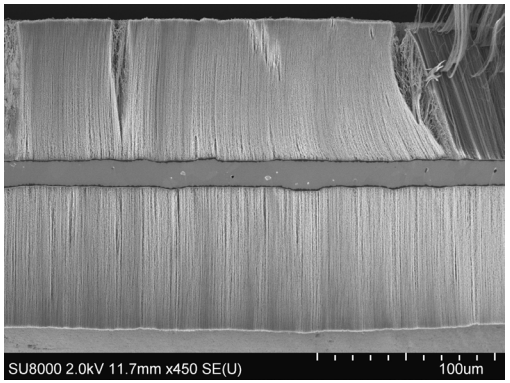
PEM – Proton Exchange Membrane
BPP – Bipolar Plate
R2R – Roll-to-Roll
SAD – Spotless-arc Activated Deposition

Researcher at FEP: Dr. Bert Scheffel

USE CASE: Deposition of Carbon Nano Tubes (CNTs)

By chemical vapor deposition (CVD)

Process	■ Double side coating of a metal strip with catalyst ■ Heating by thermal radiation ■ Addition of precursor gas ➔ CVD of CNTs
Reached results	■ Double side deposition of CNTs in an inline mode ■ Various substrate materials usable



Cross section of CNTSs deposited (partially damaged by preparation)

Top side CNTs ~80 µm

Metal foil 13 µm

Bottom side CNTs ~80 µm

It's the blackest material ever seen!

Fraunhofer FEP Annual Report 2022/23 (Page 17) & Abdul-Rahman Raji, "Vertically Aligned Carbon Nanotube Coatings for Dendrite-free and Stable Lithium-Metal Battery Anodes" Talk ENinv1, 67th SVC TechCon (**2024**), Chicago

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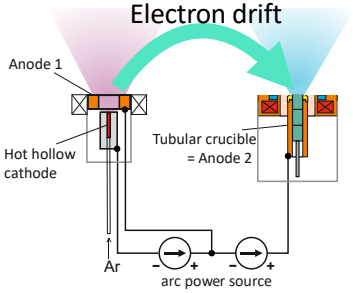
Conclusions

- To meet the changing challenges of modern industry and to address complex demands of R&D, multifunctional equipment is essential
- At the millennium, the MAXI was set into operation to address global research and development needs
- A collection of the diverse research projects realized over the years was presented, showcasing the versatility of the MAXI tool
- After 25 years in operation, the MAXI continues performing faithfully

Outlook

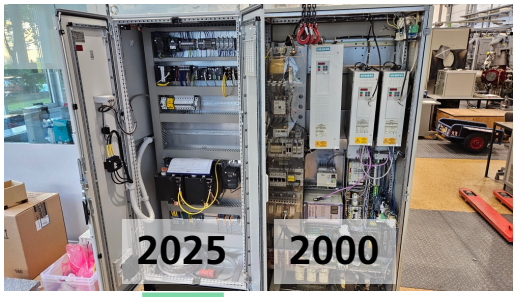
Line-up for the future

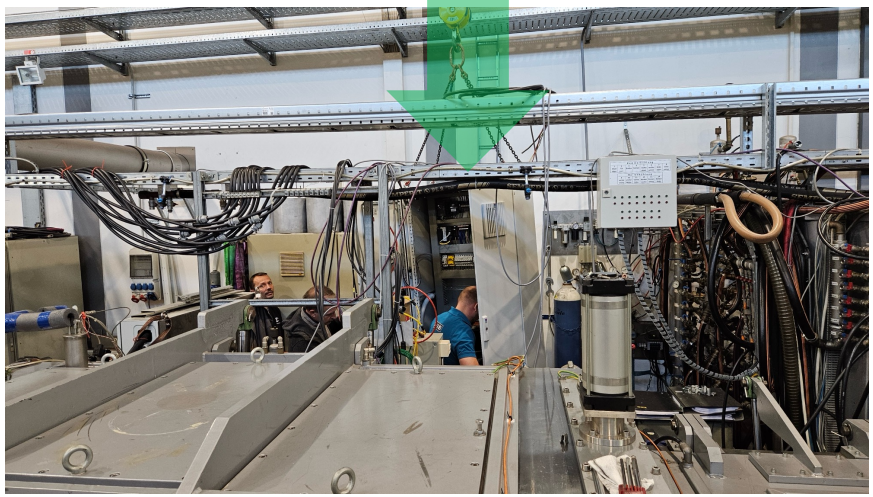
- Retrofitting electronics to be ready for the next decades of challenging R&D topics
- Upgrading the XRF inspection tool
- Combining well-established processes with innovative technologies such as new plasma-assisted coating methods for cutting-edge applications, e.g.:



Anodic arc evaporation of graphite for deposition of ta-C diamond-like films

control cabinets with PLC





Installation of new control cabinet at MAXI in May 2025

Scheffel et al., Thin Solid Films, Vol. 731 (**2021**),138731, DOI 10.1016/j.tsf.2021.138731.
Scheffel et al., Surf. Coat. Technol. Vol. 477 (**2024**), 130305, DOI 10.1016/j.surfcoat.2023.130305.

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Thank you for your kind attention!

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Fraunhofer Institute for Electron Beam and Plasma Technology FEP

Contact

Dr. Stefan Saager
Coating Metal & Energy Applications
Tel. +49 351 2586-316
stefan.saager@fep.fraunhofer.de

Fraunhofer Institute for Electron Beam
and Plasma Technology FEP
Winterbergstr. 28
01277 Dresden, Germany
www.fep.fraunhofer.de

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