New production technologies for printed electronics

Coatema

02/06/25

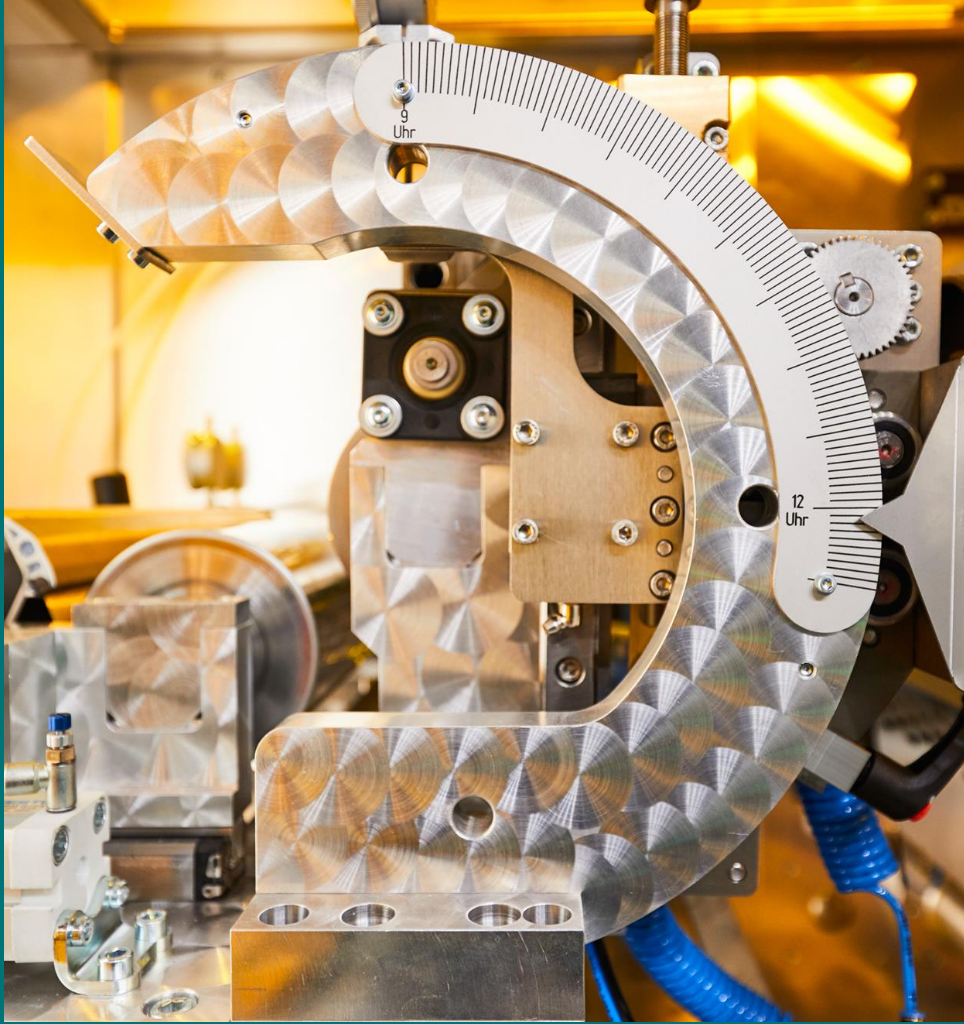
MEMBER OF ATH

Agenda

1. Introduction
2. The printed electronics market
3. Bridging the gap
4. Technologies & processes
5. Slot die for printed electronics
6. Printing processes
7. Nanoimprint
8. Drying
9. SALD
10. Summary

1.

Introduction



Overview

Quality
made in Germany

Part of the ATH Holding

S2S equipment

R2R equipment

Bespoke
equipment

Innovations

Coating

Printing

Laminating

Founded
1974

Printed electronics
Fuel cells
Membranes
Pharmaceutics
Solar
Batteries
Prepregs
Green Hydrogen

From lab 2 fab

R&D
projects & network

Worldwide
service

Group of companies

ALTONAER
TECHNOLOGIE
HOLDING

KROENERT

- ✓ Founded 1903
- ✓ Approx. 200 employees
- ✓ Located in Hamburg

DRYTEC

- ✓ Founded 1995
- ✓ Approx. 50 employees
- ✓ Located in Norderstedt

Coatema® Coating Machinery GmbH

- ✓ Founded 1974
- ✓ Approx. 50 employees
- ✓ Located in Dormagen

Represented worldwide

Coatema equipment platform strategy for lab2fab

Lab

- ✓ State-of-the-art research and development equipment
- ✓ Sheet-to-sheet to roll-to-roll systems on smale scale & footprint

Pilot

- ✓ Proven processes for printing, coating and laminating equipment
- ✓ Highest-quality pilot lines enable stable pilot production and reduce cost of operation
- ✓ Scaling laboratory equipment to enable pilot production

Production

- ✓ Full-scale production lines
- ✓ Optimize the manufacturing process, including streamlining assembly, reducing material waste, and optimizing the carbon footprint

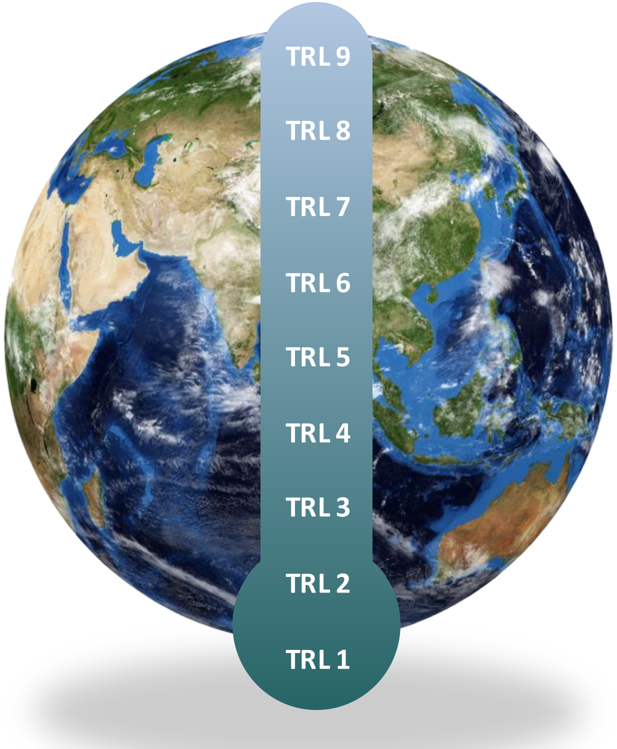
Our markets – Coatema focus areas

Green Hydrogen

Fuel cells

Batteries

Solar



Sustainability

Digital fabrication

Printed electronics

The next thing

R&D centre USP

Process development

- ✓ Feasibility study
- ✓ Ink – process study
- ✓ Process analysis
- ✓ Slot die coating simulations
- ✓ Proof of concept
- ✓ Small scale prototype

Test production

- ✓ Prototyping
- ✓ Near to market testing
- ✓ TRL evaluation
- ✓ Training of staff

Education

- ✓ Coating conference
- ✓ Partner trainings
- ✓ Education of students
- ✓ Workforce training

Development of custom-made design for equipment

- ✓ Prototyping
- ✓ Proof of concept

Public funded research projects know-how

- ✓ German funded
- ✓ Horizon 2020
- ✓ Global 2+2 projects
- ✓ B2B projects

Introduction – R&D centre





Coatema services as an overview

The Coatema R&D centre

Accelerate your innovation in our dedicated pilot facility with advanced lab & pilot lines and expert guidance – bridging the gap from #lab2fab.

The Coatema Coating Symposium

Join the global network of coating experts at our annual event, where cutting-edge developments meet industry collaboration for next-level innovation.

The Coatema Slot Die Masterclass

Master precision coating in our hands-on training program, led by industry specialists to optimize slot-die performance and product excellence.

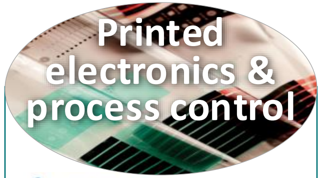
Our work in associations – global networking

Board Member:
OE-A

Advisory Board:
Fraunhofer ITA

R&D customers

R&D projects overview 2022 – 2025

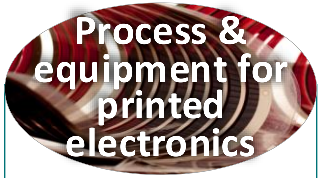


REAL NANO

In-line and real-time digital nano-characterization for flexible organic electronics

NOUVEAU

The NOUVEAU project will develop solid oxide cells (SOCs) with innovative La- and PMG-free electrode materials

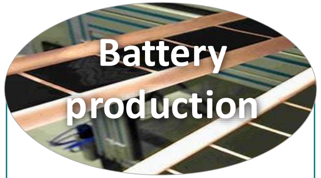


FLEX2ENERGY
AUTOMATED MANUFACTURING PRODUCTION LINE FOR IPVS

R2R production line for OPV solar with integrated backend

FLEX-G 4.0

Upscaling and development of EC based switchable films to decrease energy use in buildings



IDEEL

Implementation of laser drying processes for lithium-ion battery production

SOLiD

R2R process optimization for solid state batteries

PEP LAT

Plasmonically enhanced photocatalysis for wastewater treatment

ROLL 2 SOL

R2R nanostructuring of functional films

WATER PROOF

The WaterProof project aims at developing an electrochemical process that converts CO_2 emission

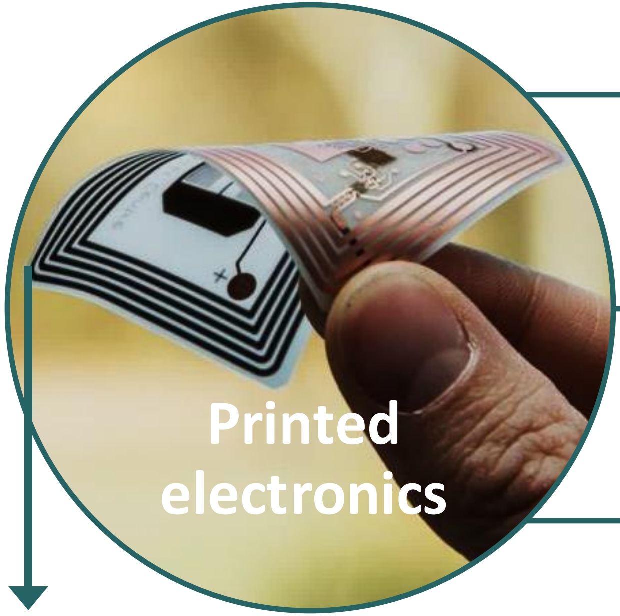
FLEX FUNCTION 2 SUSTAIN

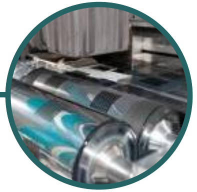
Creating an open-innovation testbed for sustainable packaging

2.

The printed electronics market

The future market





Printing

Coating

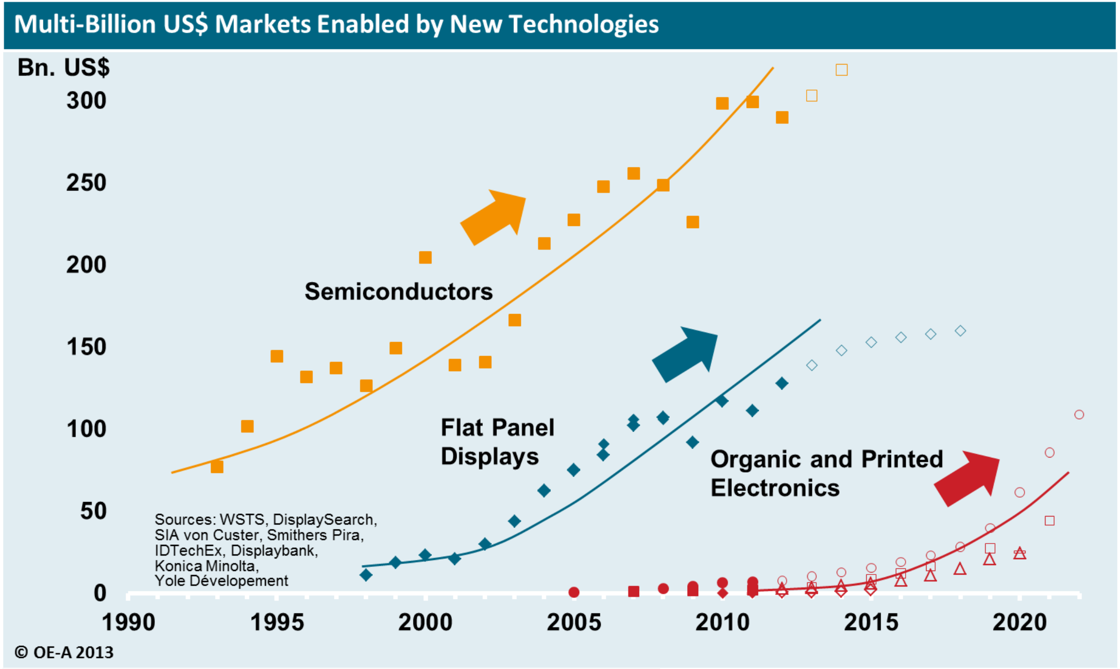
Deposition

Chemistry

Microelectronics

flexible – thin – robust – lightweight – stretchable

The future market

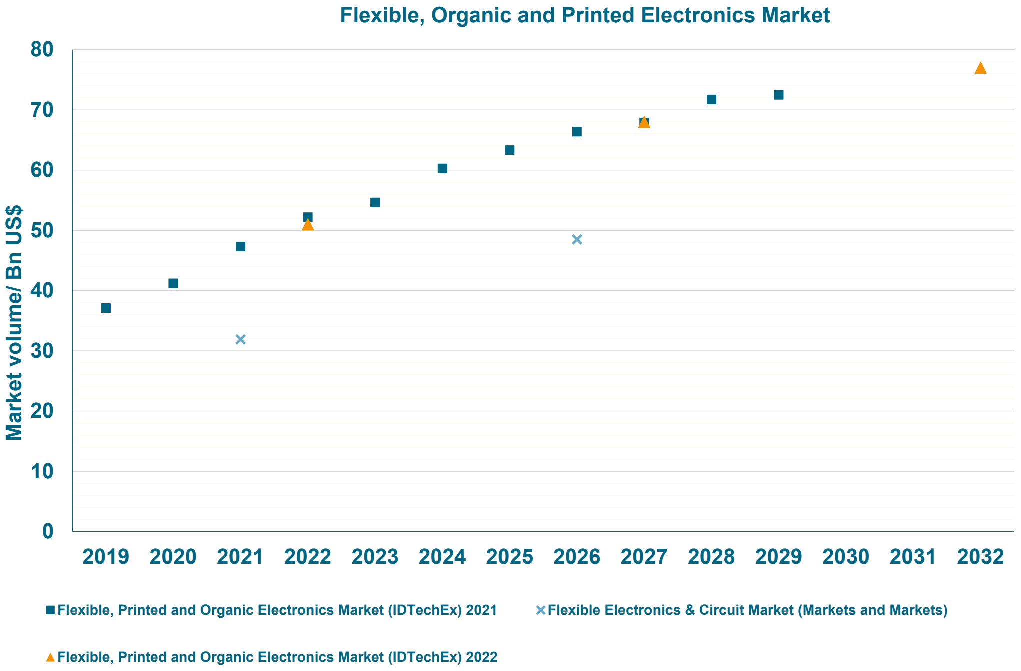


2010
2 Billion US$
predominantly by OLED displays

2012
8 Billion US$
predominantly by OLED displays

Potential
for a 50 Billion US$ market within the next 10 years driven by OPV, lighting, displays, logic, memory/RFID, sensors

The future market



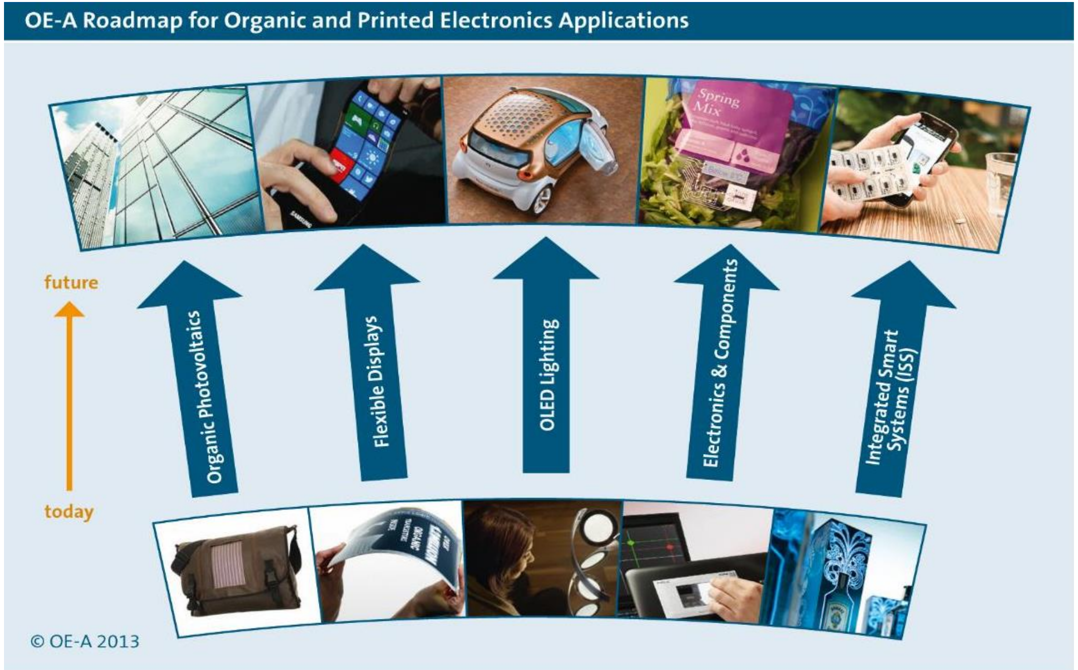
Flexible, organic and printed electronics enables
new applications and opens new markets

50+ Bn US$ Market today,
OLEDs, sensors, medtech

Large Potential
driven by displays, sensors, wearables, OPV, lighting, RFID/NFC

Source: OEA

The future market



The future market

Flexible, organic and printed electronics solutions in important industry sectors

Automotive

OLED lighting for rear lights, ambient lighting by hybrid electronics, printed (radar) antennas, seat occupancy detection, seamless integration of touch sensors, smart HMI functions, integrated heating foils

Consumer Electronics

Foldable & flexible displays for smart phones / tablets / wearables; Curved touch surfaces with sensing & signage for white goods; smart wearables and textiles; smart patches for sports tracking, OLED lighting; printed Batteries, printed QD layers in TVs, Printed OLED TVs and Monitors

Healthcare

Smart medical packages for therapy monitoring; textiles with embedded pressure sensors, temperature/ humidity sensors, continuous real-time heart monitoring, patches for therapy and vital parameter monitoring; sensors for on - and off-body biomarker diagnosis; smart wound treatment and bandages; Sensors for medical applications (Blood -Glucose-Test, intelligent incontinence solution), pressure sensor (Dental occlusion measurement films

Printing & Packaging

Automated stock replenishment system, large area capacitive sensor floor, thin film encapsulation for OLED, RFID, NFC, flexible batteries, smart packaging for food and medical with time and temperature tracking, light emitting packaging (EL, OLED), non -light-emitting technology (EPD, ECD)

Smart Buildings

Sensors for material monitoring, energy management (climate, smart windows) and wellbeing (humidity, gas); energy autonomous sensors; Heating and touch elements; BIOPV; OLED lighting, OPV on walls

Internet of Things

Connected home appliances, autonomous cars and smart wearables, precision agriculture, environmental monitoring, Supply chain management with item level tagging, data loggers for containers, voyage optimization

Image-Source: Flexenable, Holst Centre, Ynvisible, Samsung

The future market

Forecast for market entry of OPE applications

Short, medium and long term forecasts for key industry sectors:

✓ Automotive

✓ Consumer Electronics

✓ Healthcare

✓ Printing & Packaging

✓ Smart Buildings

✓ Internet of Things

Source: OEA

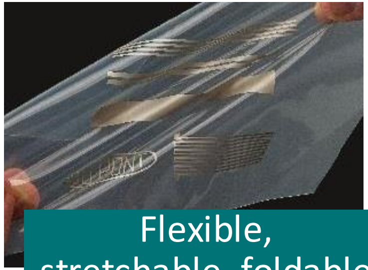
The future market – Key trends

OLED Displays

Automotive industry

Healthcare and wellbeing

Internet of Things



Flexible, stretchable, foldable

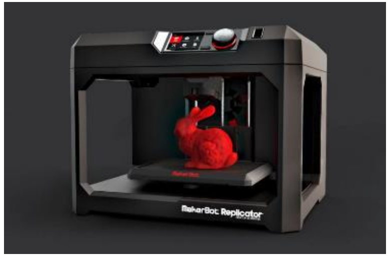
Hybrid systems

Sustainability and circularity

Strong market growth

Image source: Samsung, CES, CeNTI, VTT, DuPont, Holst Centre, shutterstock

Digital fabrication as a trend in PE



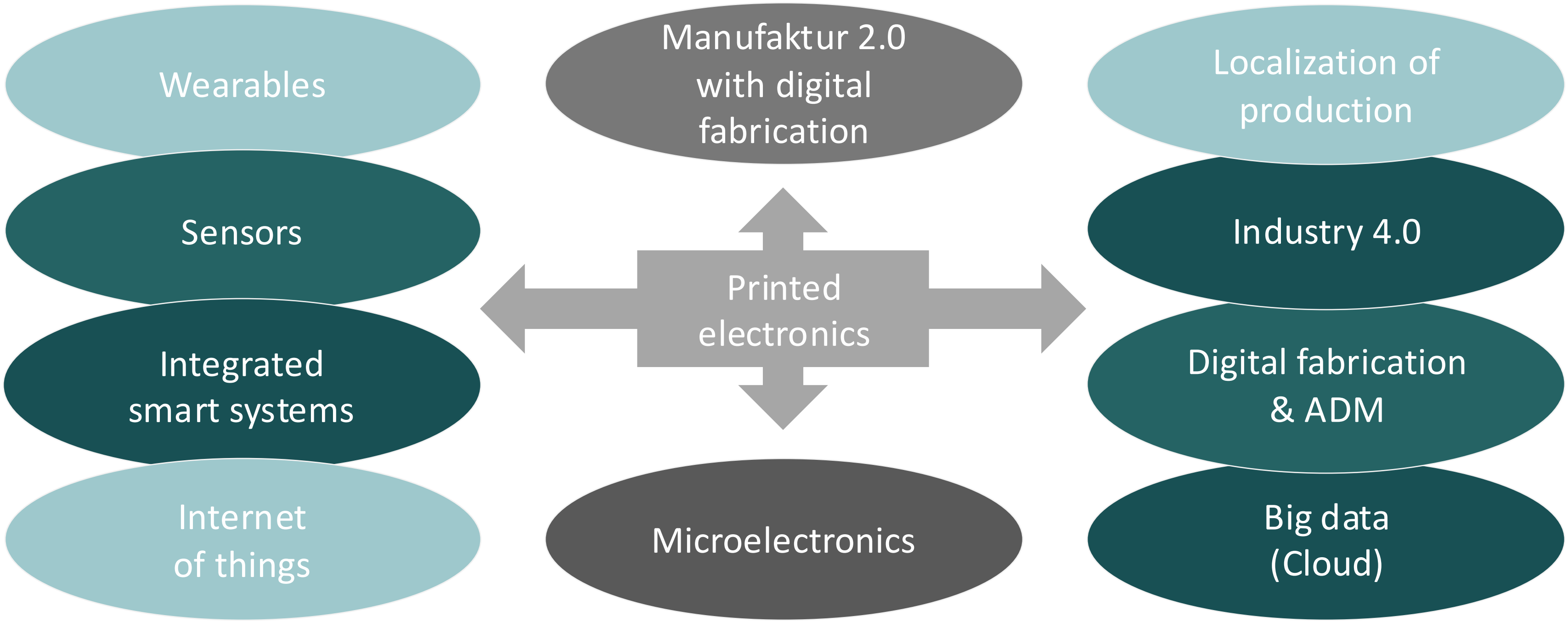
Digital fabrication is happening
– lot size 1 is real.

Why now?

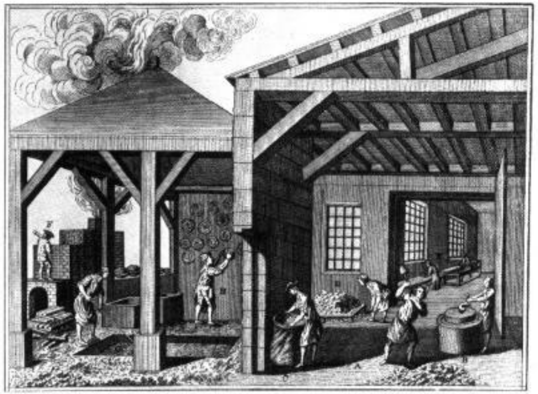
Digital fabrication and additive manufacturing will disruptively change the world of manufacturing we know today!

Coatema®
Coating Machinery GmbH

Disruptive!



The „4th“ industrial revolution



- ✓ Digital fabrication means to have the abillity to produce lot size one for the same cost as for lot size million.
- ✓ Manufacturing at the site with personalized design for each customer.
- ✓ It will change global manufacturing to local manufacturing.
- ✓ Productivity boost for the old economies and Europe, the real 4th revolution.
- ✓ The „Manufaktur“ will come back – as the „digitale Manufaktur 2.0“.

Coatema®
Coating Machinery GmbH

Disruptive

Sustainibility

Produced at place of use

Low carbon footprint

„Die digitale Manufaktur 2.0“

Digital

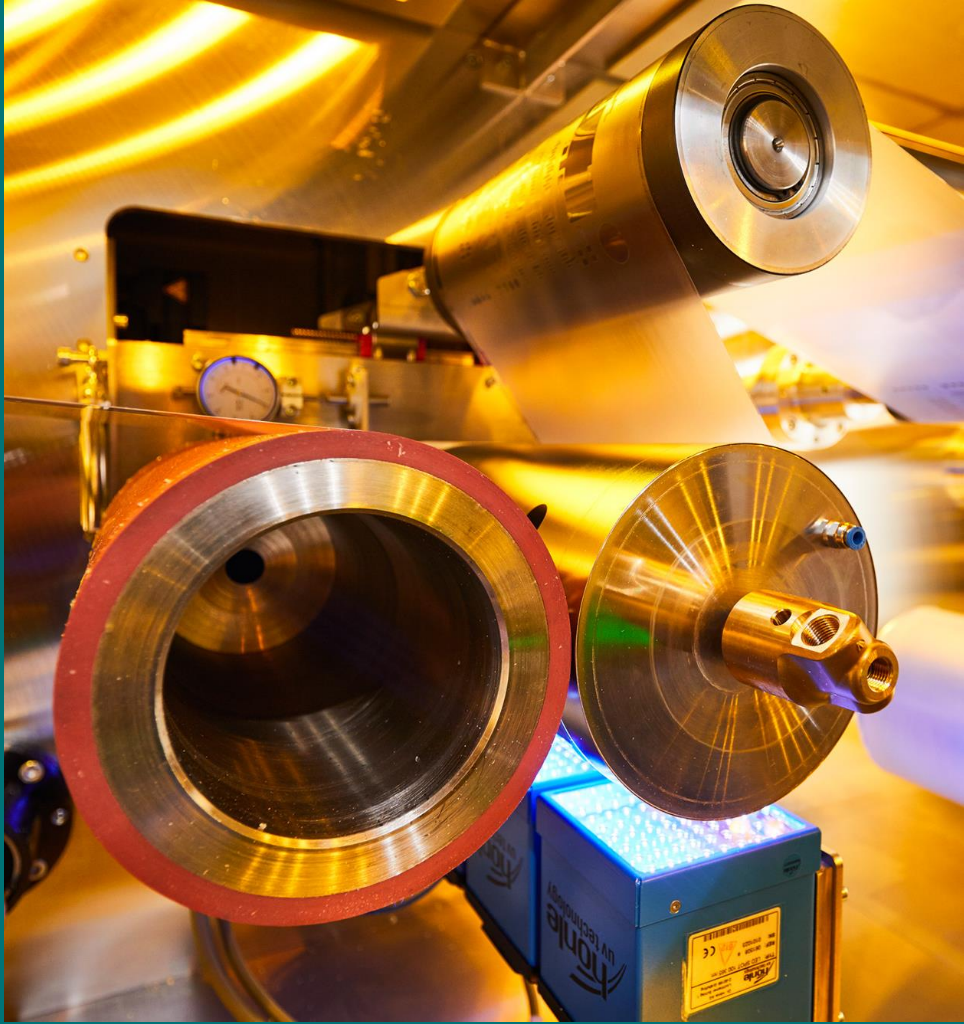
From globalization
To localization
of production

Personalized products

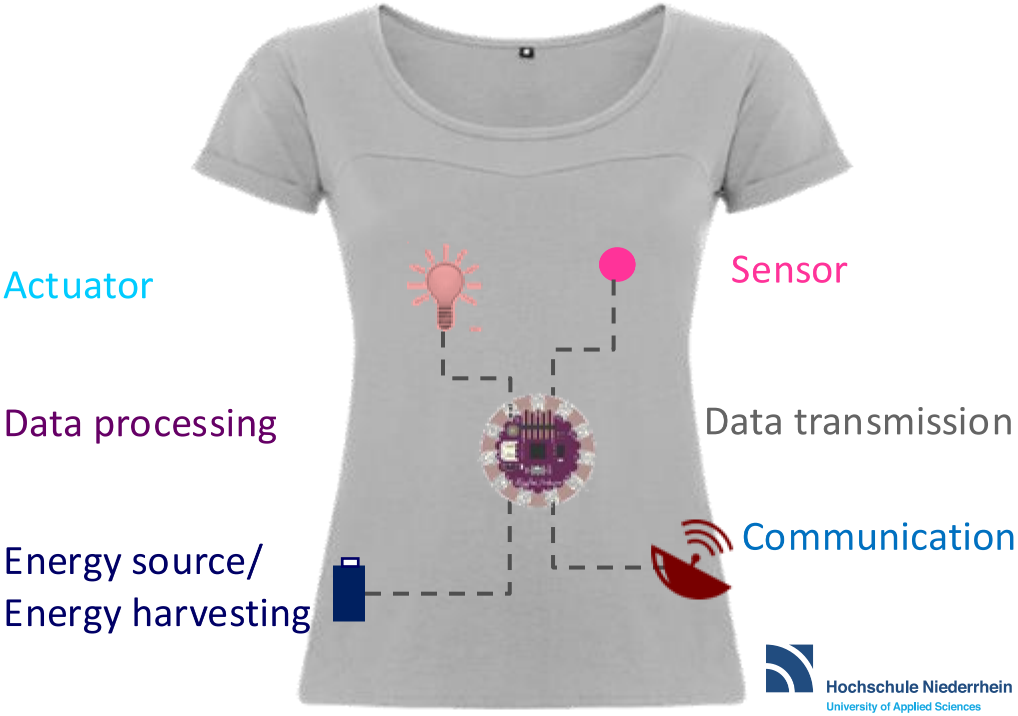
Produced on demand

3.

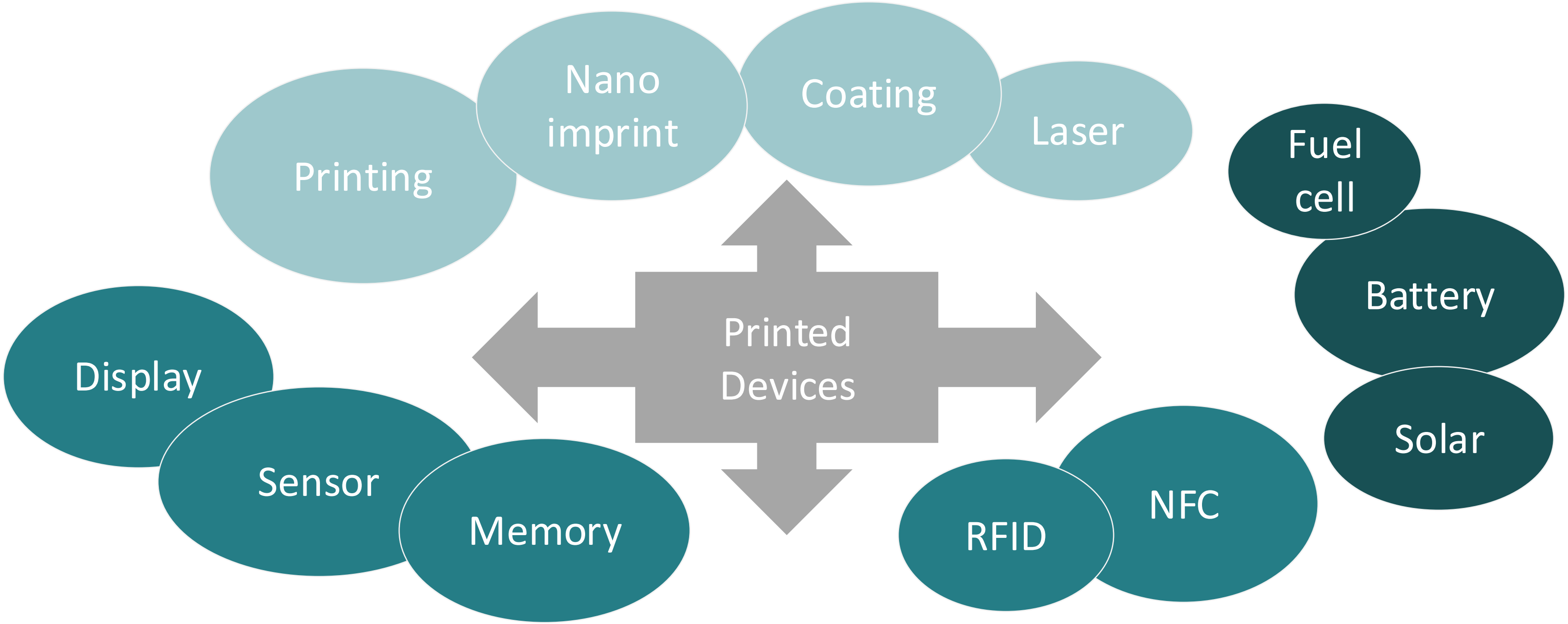
Bridging the gap



From 2008 till today – PE as the flexible bridge

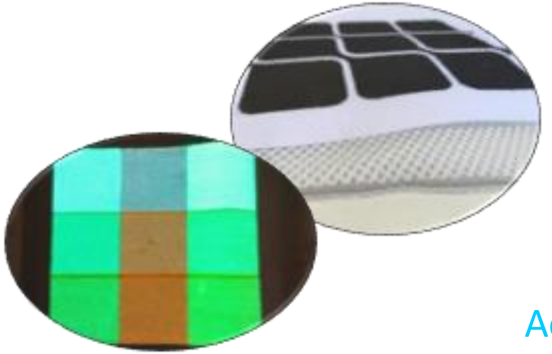


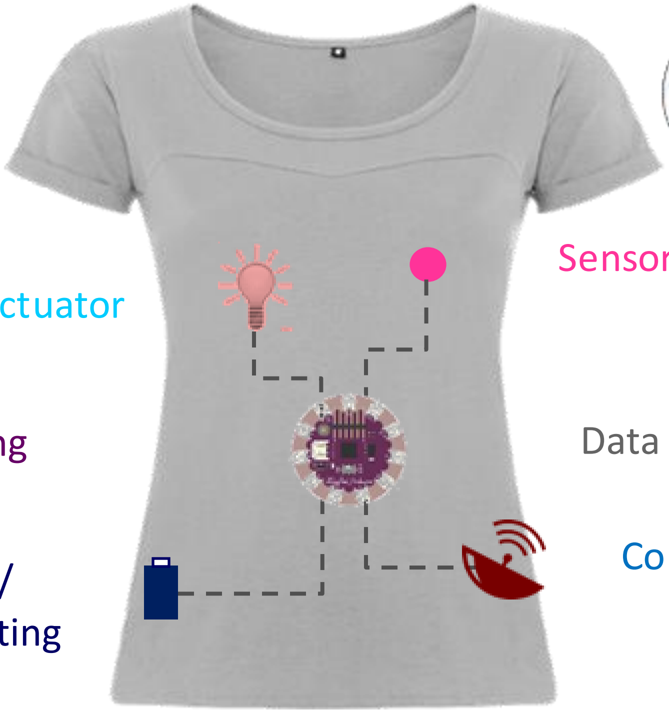
Printed electronics – bridging the gap

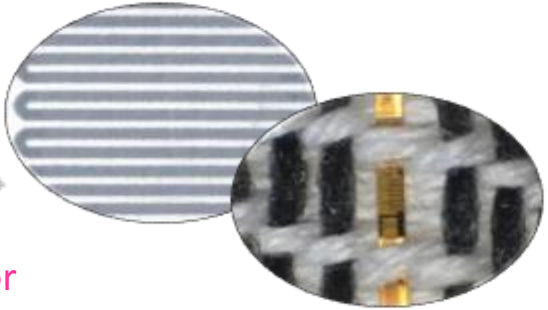


What could be the pathway on to textiles or also integrated into textiles?

From 2008 till today – PE as the flexible bridge







Actuator

Sensor

Data processing

Data transmission

Communication

Energy source/
Energy harvesting

Case study – design principles

Authors: Juha-Veikko Voutilainen, Tuomas Happonen, University of Oulu

Figure 1. Printed temperature sensor and layout

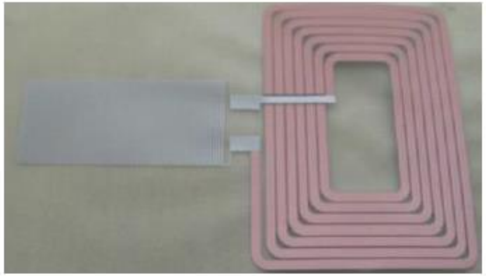
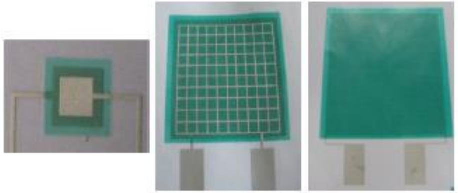


Figure 2. A remote readable RH sensor.

Authors: Tuomas Happonen, Juha-Veikko Voutilainen, University of Oulu



(a) (b) (c)

Figure 1. Printed capacitive humidity sensor structures

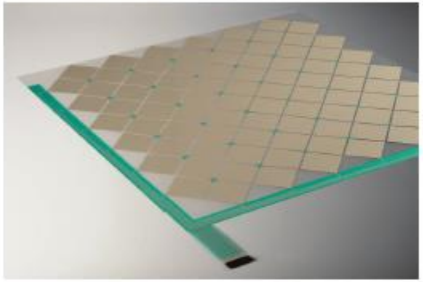


Figure 1. Capacitive touch sensor

Figure 1. Electrochemical biosensor

Authors: Elina Jansson, Jukka Hast, VTT

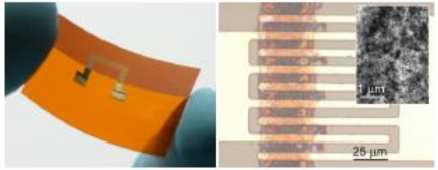


Figure 1. Printed gas sensors

PrintoCent

Designer's Handbook 2014

4.

Technologies & processes

Coating parameters

Coating chemistry
- ✓ Rheology
- ✓ Viscosity
- ✓ Viscoelasticity
- ✓ Type of solvents
- ✓ Solid content
- ✓ Van der Waals force
- ✓ Sheer ratio
- ✓ Adhesion/Cohesion

Coating processes
- ✓ Coating systems
- ✓ Single or multilayer coatings
- ✓ Direct coatings
- ✓ Transfer (indirect) coatings
- ✓ Substrate speed
- ✓ Layer thickness
- ✓ Coating accuracy

Process control
- ✓ Process layout
- ✓ Tension control system
- ✓ Material guiding system
- ✓ Inline parameter control
- ✓ Quality control

Drying
- ✓ Convection drying
- ✓ Contact drying
- ✓ Infrared drying
- ✓ Sintering
- ✓ NIR
- ✓ High frequency
- ✓ UV crosslinking systems

Substrate
- ✓ Surface tension
- ✓ Dimension stability
- ✓ Surface structure
- ✓ Contact angle

Pretreatment
- ✓ Corona
- ✓ Plasma
- ✓ Cleaning

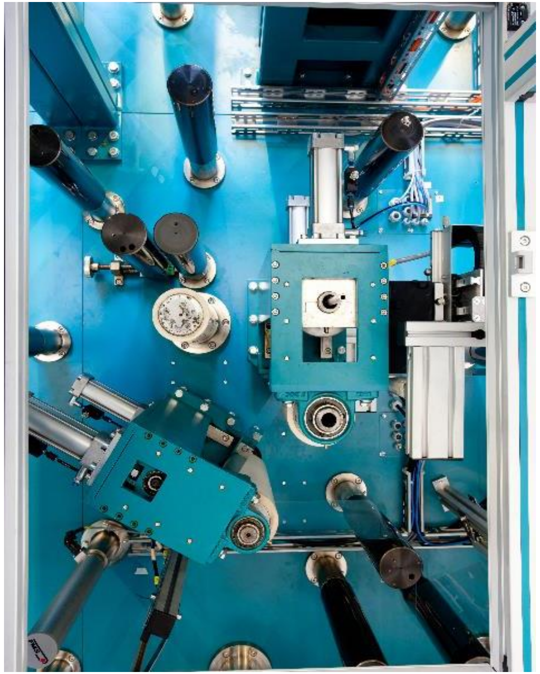
Environment
- ✓ Humidity
- ✓ Temperature
- ✓ Inert conditions

Finishing
- ✓ Calendaring
- ✓ Embossing
- ✓ Slitting

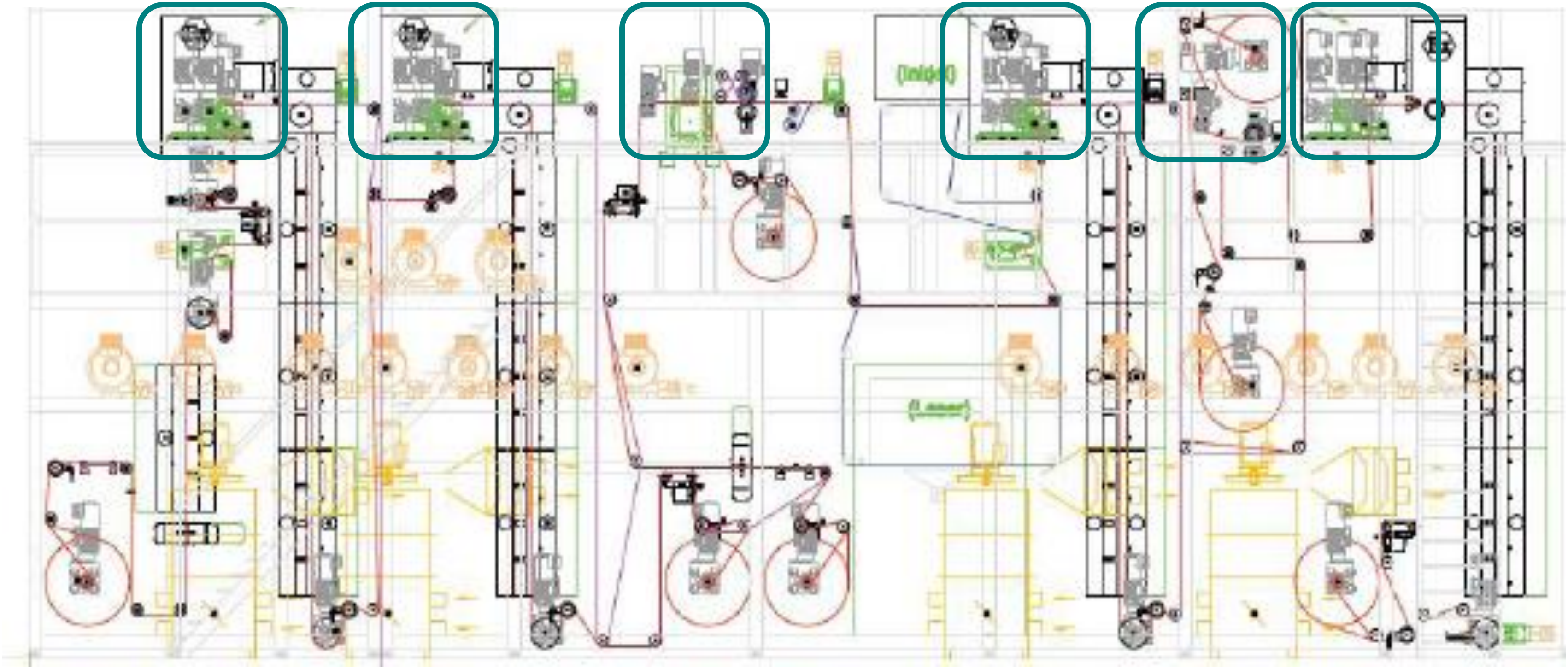
Processes

Surface treatment	Printing	Coating	Digital fabrication Inkjet Printing Laser Patterning
Nano-imprint	Lamination	Encapsulation	Pick & place

Upscaling from lab 2 fab – going to fab-technologies



From lab 2 fab



Process parameters

Process parameters are:

- ✓ Operation speed
- ✓ Rheology of coating and printing inks
- ✓ Substrate condition
- ✓ Tension control MD / CD
- ✓ Edge control
- ✓ Resolution and registration accuracy of printing / laminating systems
- ✓ Precision of coating operations
- ✓ Curing / drying / crosslinking

Inline process integration

Tension control

- ✓ Load cell
- ✓ Dancer
- ✓ Pulling devices
- ✓ Design of drives

Edge guide control

- ✓ Different sensors
- ✓ Mechanical stress

Quality control

- ✓ Particle contamination analysis
- ✓ Defect detection
- ✓ Thickness control
- ✓ Function control of the device or layer
- ✓ Big data (Cloud)
- ✓ Artificial inteligence

Registration control

- ✓ Camera
- ✓ Fiber optic
- ✓ Design of drives
- ✓ Algorithm control

Process analysis

- ✓ Statistic parameters
- ✓ Product flow analysis
- ✓ Yield
- ✓ Cost of ownership
- ✓ Artificial inteligence

Inline process integration and measuring points

Winder speed / Diameter / Cross position / tension / particle contermination / substrate defects / registration marks

Unwinder | OET 4 Axis system | 3m dryers | ps laser | OET 4 Axis system | Ink jet | 3m dryers | IPL | In-line optical metrology (SE, Raman) | LBIC | Rewinder

- Number of measuring points
- Amount of measurements per time

Winding / cleaning

Unwinding cabinet

- ✓ Can receive rolls with core of 3 inch
- ✓ Max diameter of 500 mm
- ✓ Max weight 50 kg
- ✓ Web width of 300 mm
- ✓ Automated forward and reverse movement of the web
- ✓ Speed of 1 – 20 m/min.
- ✓ Tension control of the web within the range of 5 – 250 N

Web cleaning system

- ✓ Contact cleaning rollers for particles of >1µm diameter

Inline process integration

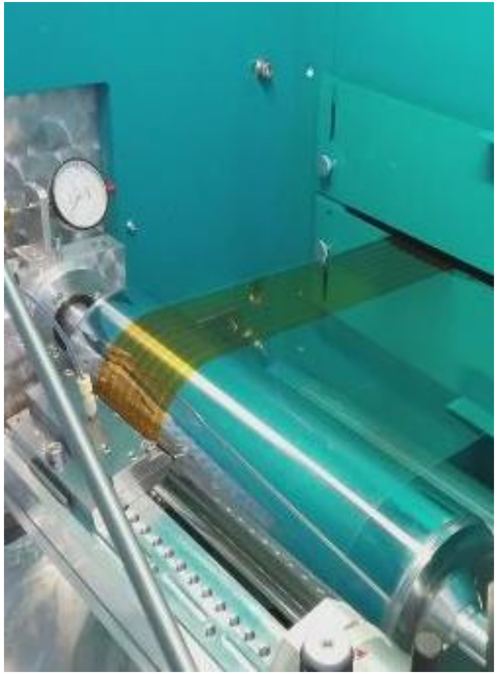
1st Printing

- ✓ Web surface activation with Plasma Treatment

Dryer 1

- ✓ 3 meter dryers
- ✓ Hot air and heated nitrogen
- ✓ Temperatures up to 230 °C

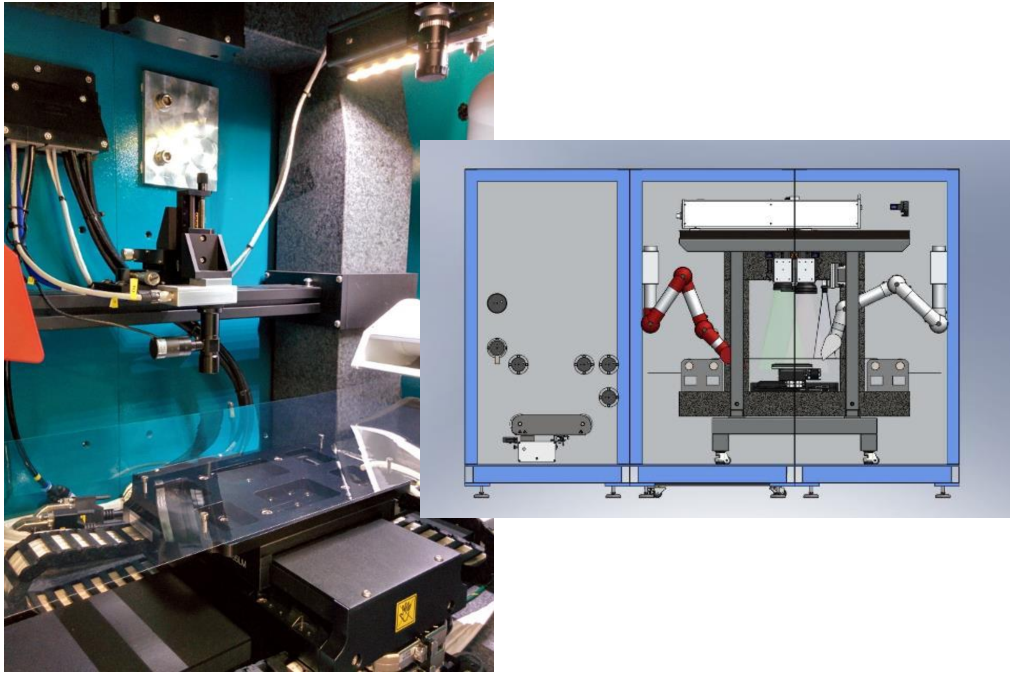
Slot die coating



Slot die coating station compatible for materials used in OEs

- ✓ Print solutions with viscosity range of 10 – 1000 mPas
- ✓ The above range can lead to layer thickness range of 10 – 1000 nm
- ✓ Lateral accuracy of ±1%

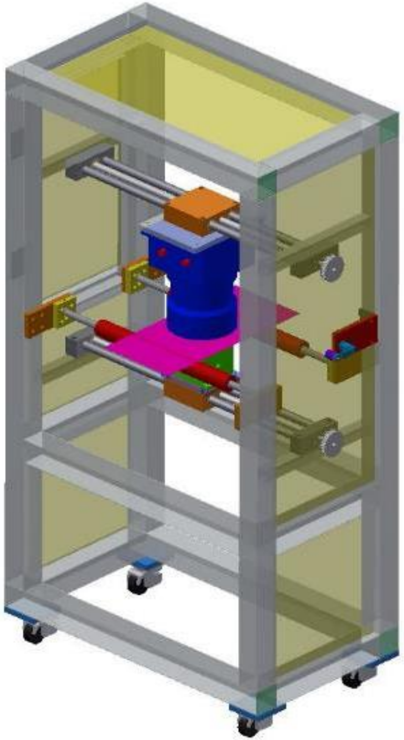
Laser patterning



Laser scribing/patterning

- ✓ Picosecond laser for patterning OE materials
- ✓ 3 meters cabinets
- ✓ Tension and driving web control
- ✓ System ±100 µm of accuracy

Module for the registration camera



Technical specifications:

- ✓ Measurement accuracy = +/-20 µm
- ✓ ATEX proof
- ✓ 300 mm roller width
- ✓ Web speed: 1 – 20 m/min; Optimum speed is 3 – 20 m/min.
- ✓ PLC-driven correction adjustment system
- ✓ Module to be operated under N_2

Rotary screen printing

2nd printing station

✓ Rotary screen printing

✓ Coating width of 300mm

✓ Lateral accuracy ±5%

Dryer 2

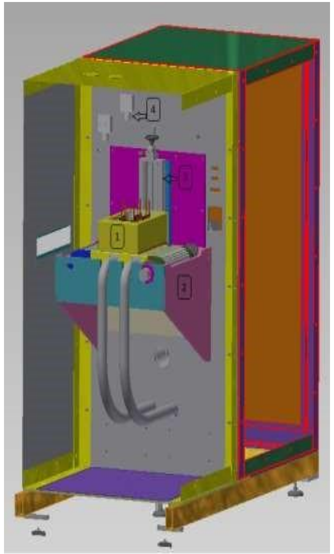
✓ 3 meters dryers

✓ Hot air and heated nitrogen

✓ Temperatures up to 230°C

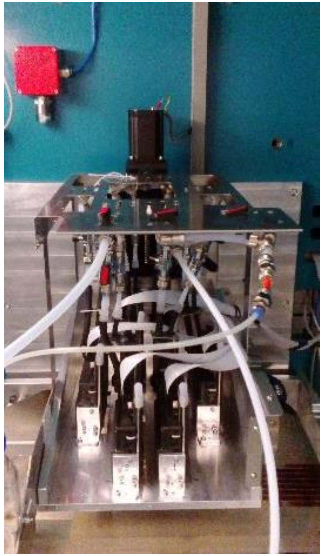
Inline process integration

Inkjet station

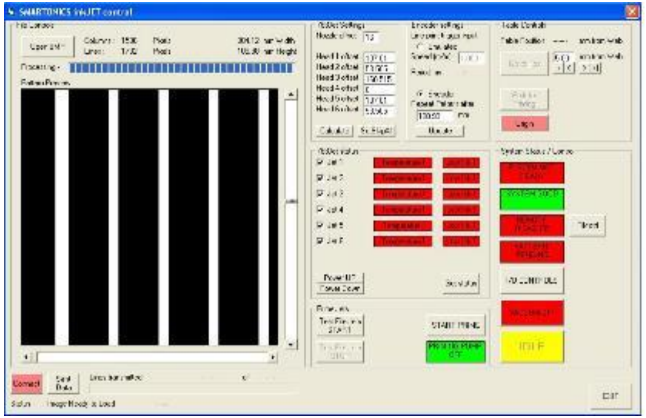


Inkjet station

System



Coatema software



Already integrated:
Fujifilm Dimatix

Encapsulation

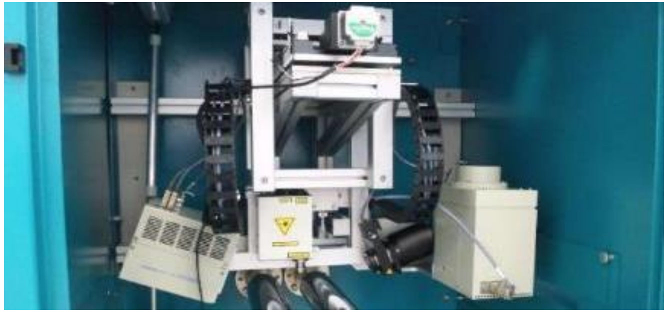
Rewinding station

- ✓ The rewinding station has a retaining roller
- ✓ Identical specs to the unwinding station
  - ✓ 3 inch core rolls
  - ✓ Automated forward and reverse movement of the web
  - ✓ Speed of 1 – 20 m/min.
  - ✓ Tension control and edge guide system

Lamination / delamination station

- ✓ Compatible with 300 mm web width
- ✓ Web control with edge guide system
- ✓ Lateral accuracy of ±100 µm / 20 µm

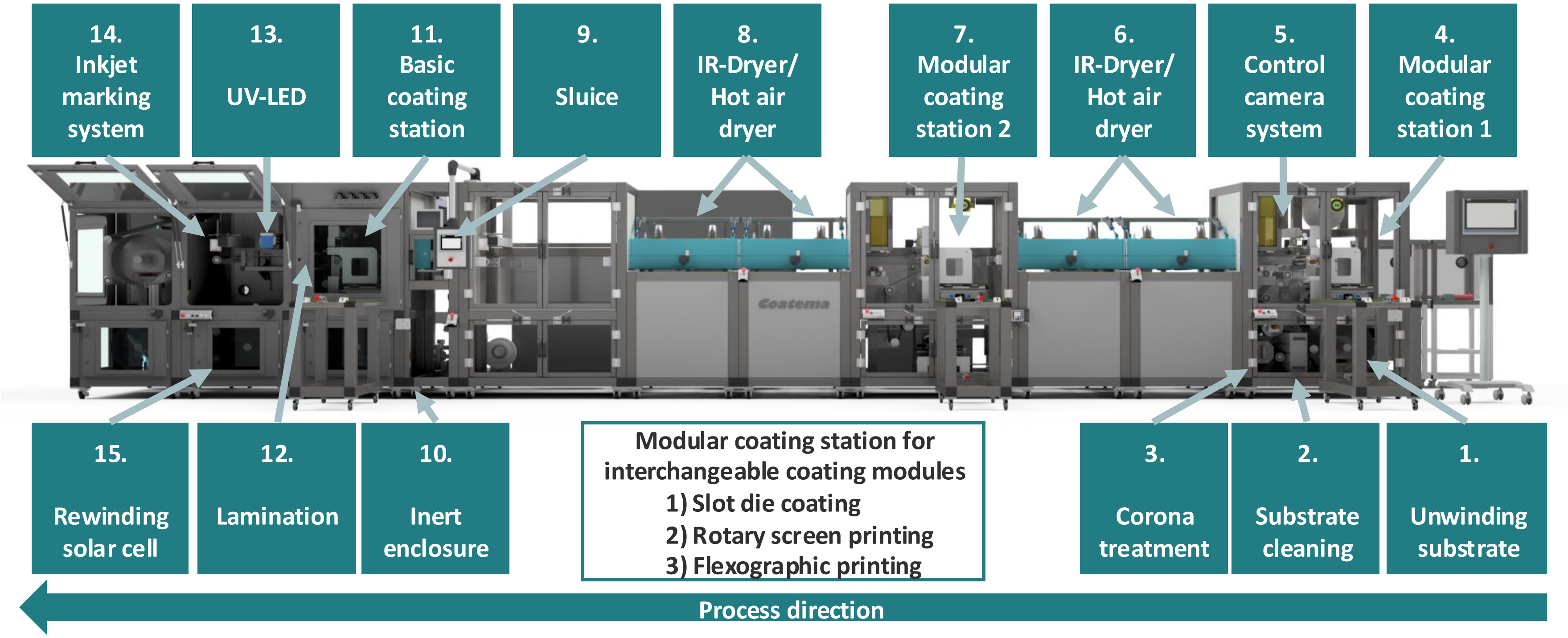
Inline quality control – Ellipsiometry and inline Raman by Horiba



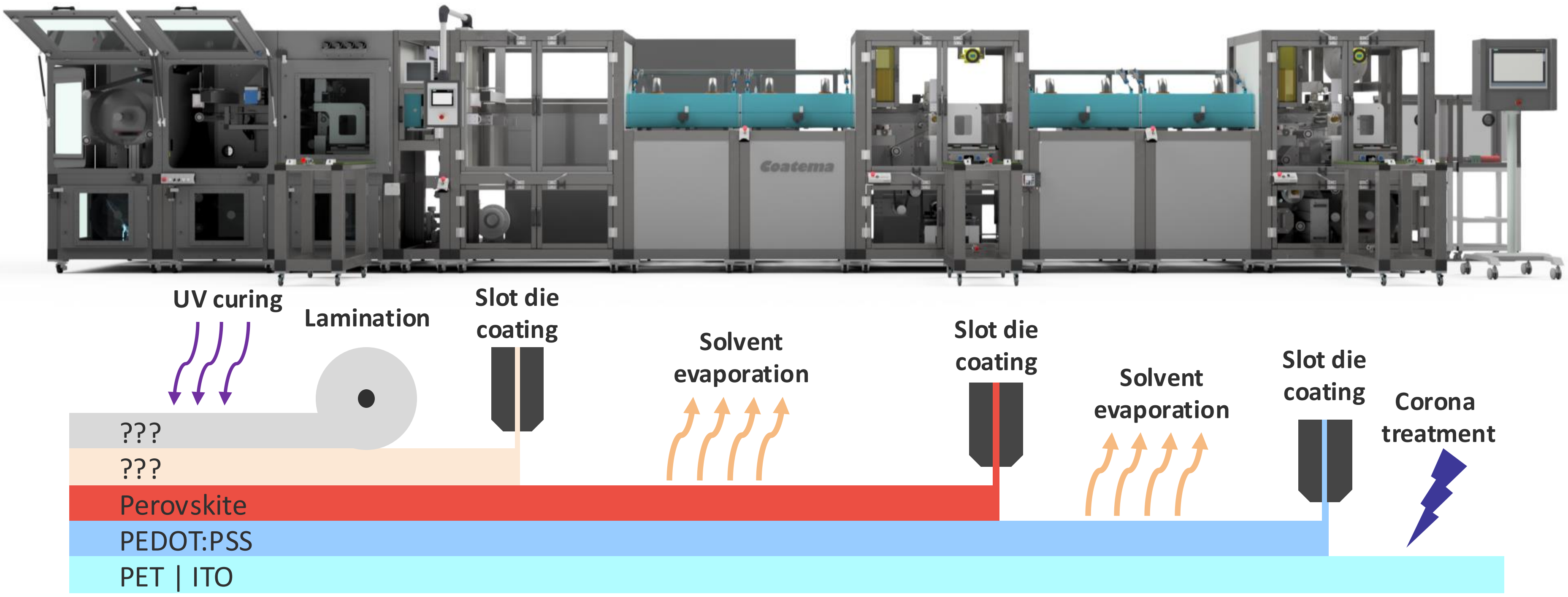
Summary

- ✓ 19 m in length
- ✓ 300 mm working width
- ✓ 30 m/min production speed
- ✓ 3 print stations
- ✓ Plasma treatment
- ✓ 6.000 mm dryers
- ✓ Registration control
- ✓ Laminating station
- ✓ 36 measuring points
- ✓ 3 quality control systems
- ✓ How many data points in one 7h shift?

Coatema Perovskite PV Manufacturing plant – Click&Coat™



Coatema Perovskite PV Manufacturing plant – Click&Coat™

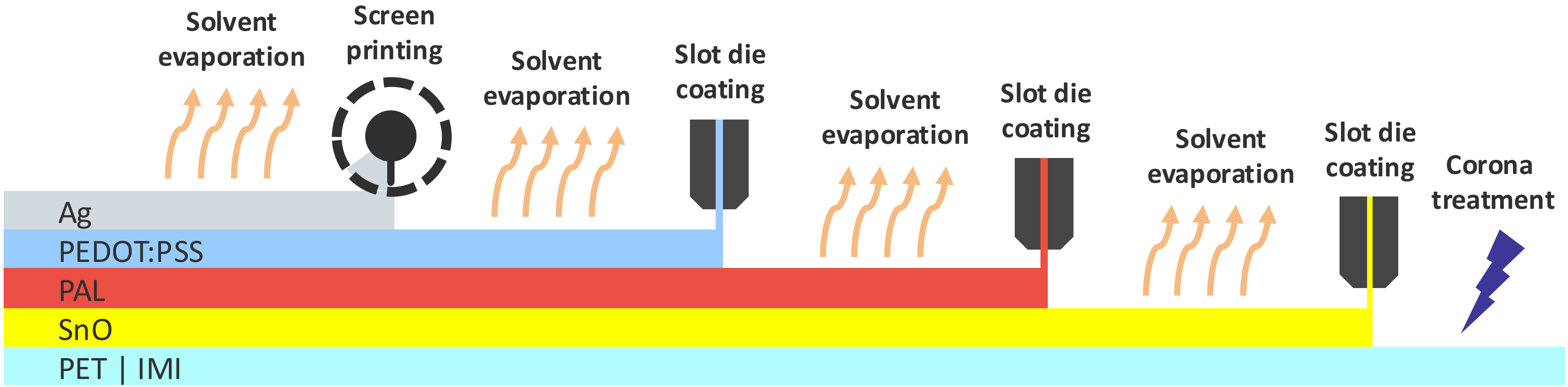


Coatema OPV PV Manufacturing plant – Click&Coat

Coatema® Coating Machinery GmbH

FLEX2ENERGY

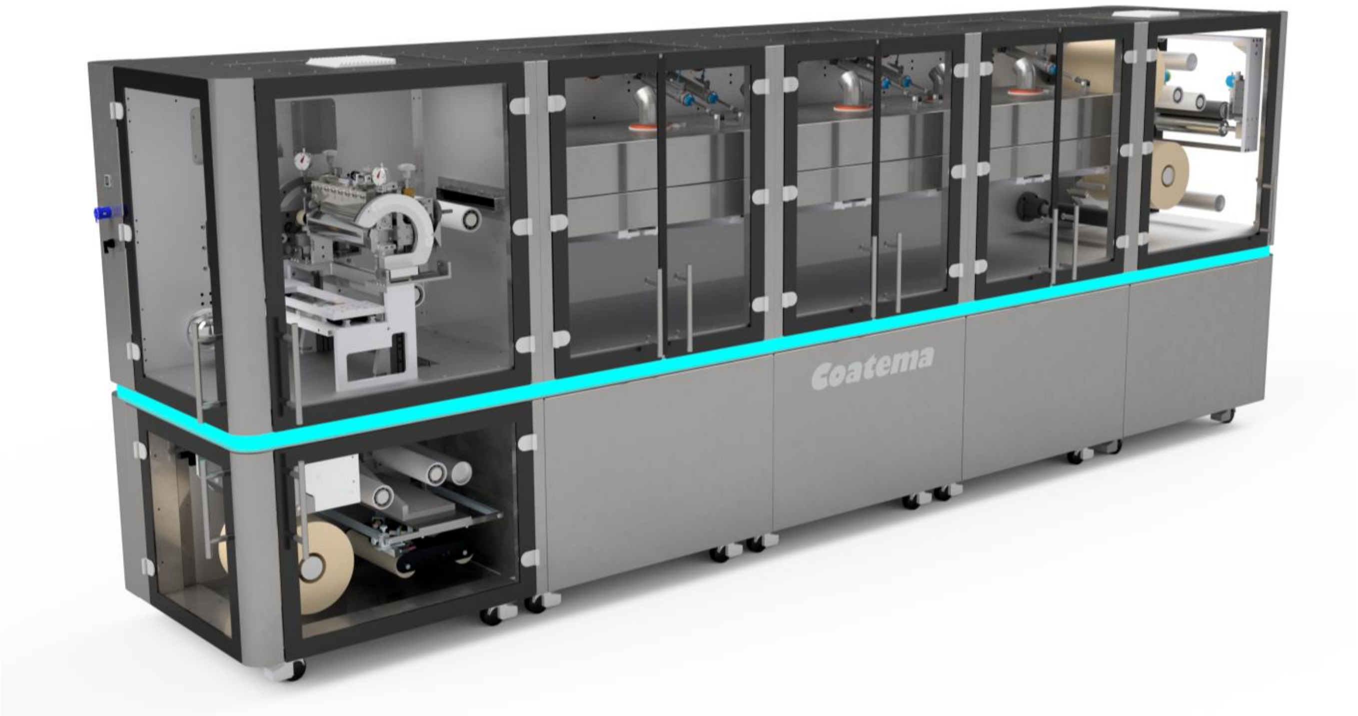
AUTOMATED MANUFACTURING
PRODUCTION LINE FOR IPVS



5.

Slot die for printed electronics

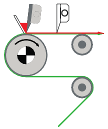
Basic principle



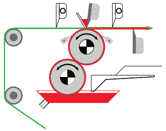
Coating parameters

Ink properties	Coating processes	Process control	Drying
✓ Rheology ✓ Viscosity ✓ Viscoelasticity ✓ Type of solvents ✓ Solid content ✓ Van der Waals force ✓ Sheer ratio ✓ Adhesion/Cohesion	✓ Coating systems ✓ Single or multilayer coatings ✓ Direct coatings ✓ Transfer (indirect) coatings ✓ Substrate speed ✓ Layer thickness ✓ Coating accuracy	✓ Process layout ✓ Tension control system ✓ Material guiding system ✓ Inline parameter control ✓ Quality control	✓ Convection drying ✓ Contact drying ✓ Infrared drying ✓ Sintering ✓ NIR ✓ High frequency ✓ UV crosslinking systems
Substrate	**Pretreatment**	**Environment**	**Finishing**
✓ Surface tension ✓ Dimension stability ✓ Surface structure ✓ Contact angle	✓ Corona ✓ Plasma ✓ Cleaning	✓ Humidity ✓ Temperature ✓ Inert conditions	✓ Calendaring ✓ Embossing ✓ Slitting

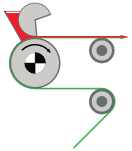
Coating systems



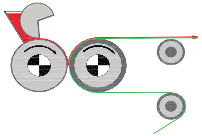
Knife system



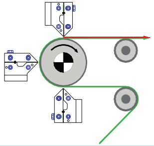
Double side coating system



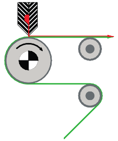
Commabar system



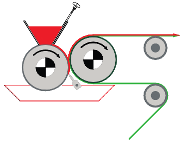
Reverse commabar system



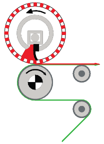
Slot die system



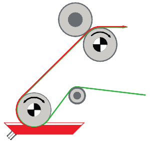
Curtain coating system



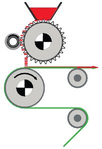
Case knife system



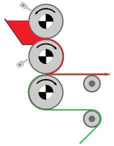
Rotary screen system



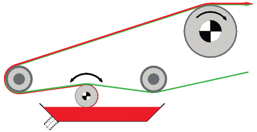
Dipping system (Foulard)



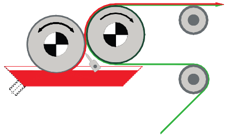
Powder scattering system



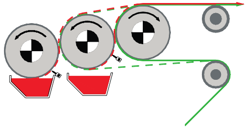
Reverse roll coating system



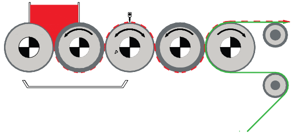
Micro roller coating system



2-roller coating system

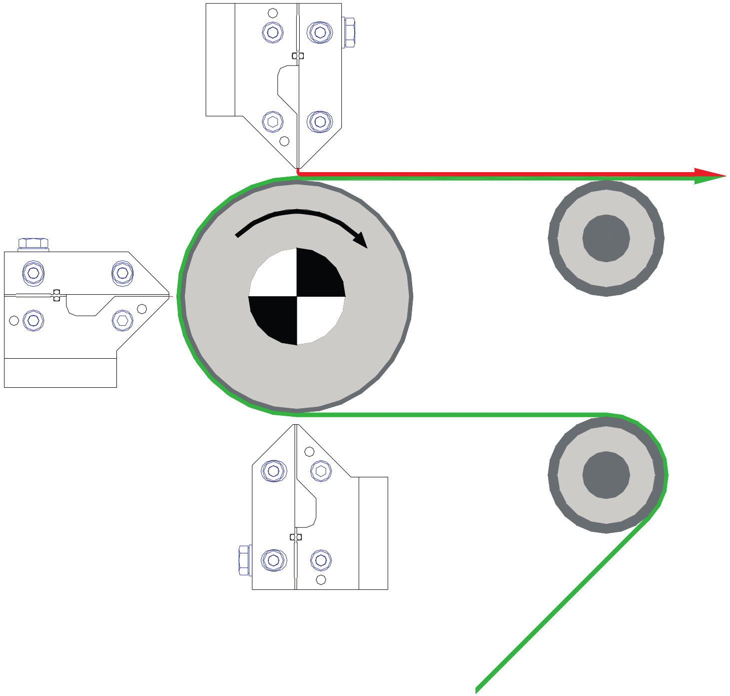


3-roller combi coating system



5-roller coating system

Basics of slot die coating – range of parameters



Coating speed

✓ 0.1 – >1000 m/min

Ink viscosity

✓ 1 – 300 000 mPas

Layer thickness (dry)

✓ 0.1 – >200 µm

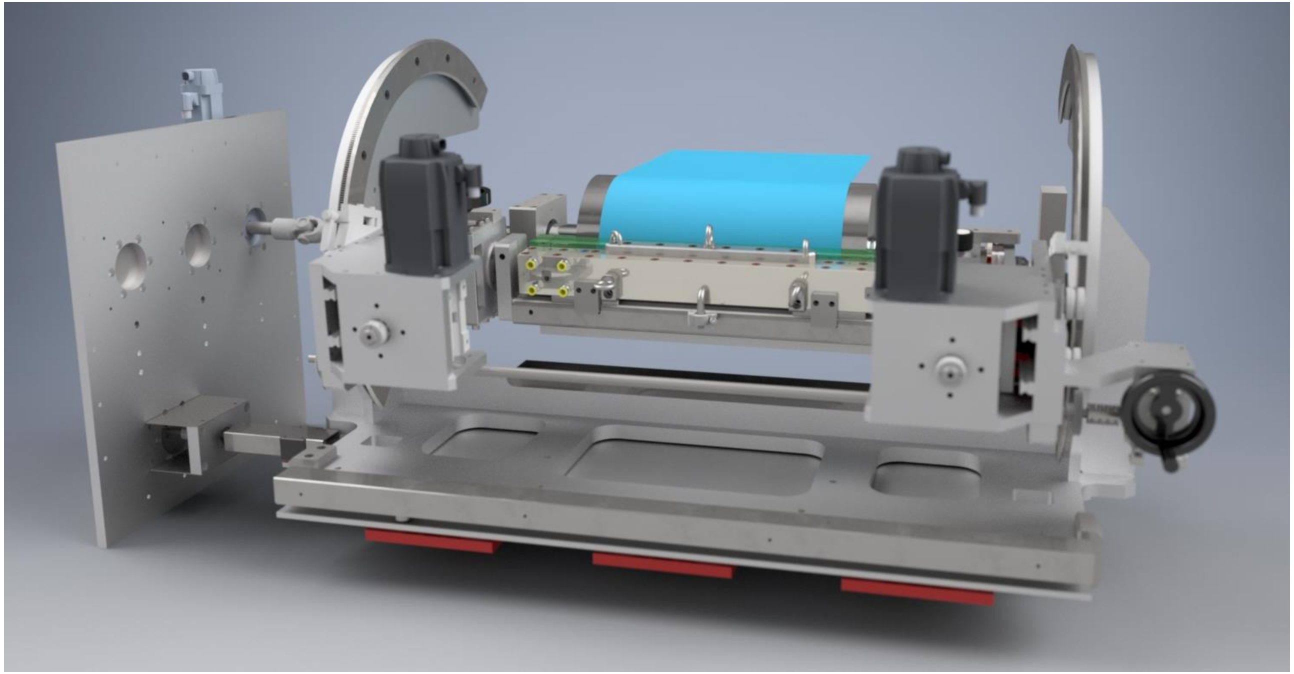
Coating accuracy

✓ <1% (2 – 5%)

Coating width

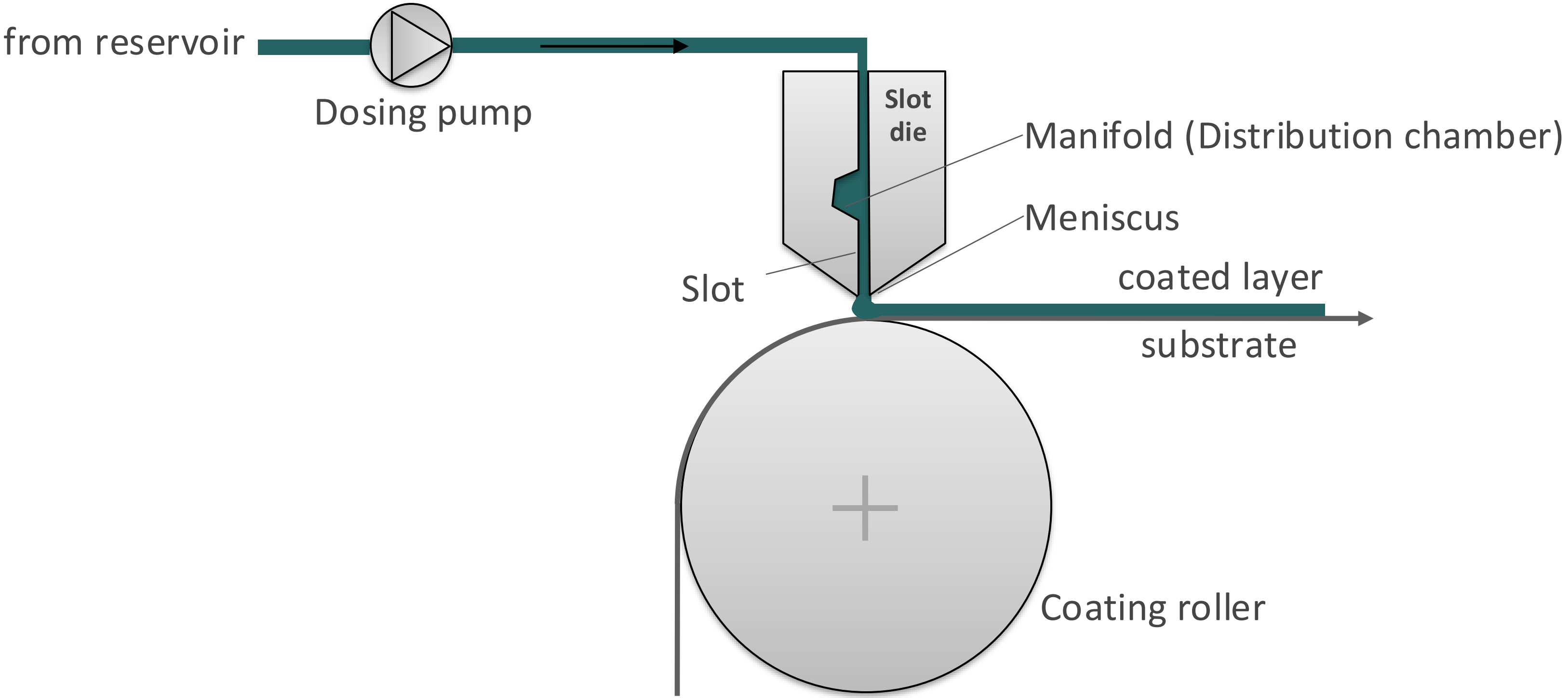
✓ up to approx. 3 m

Basic principle

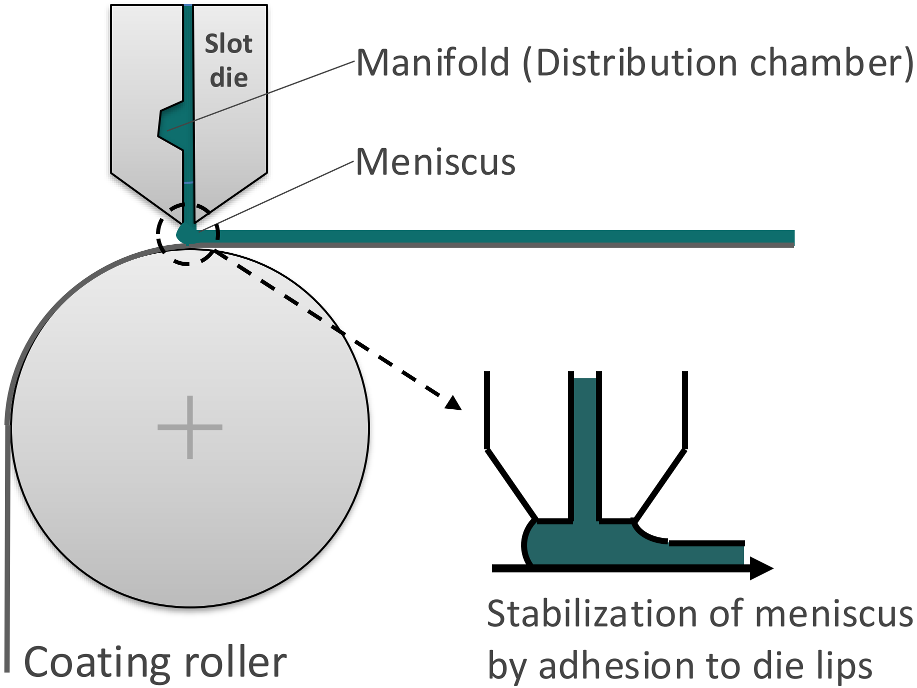


Basic principle

Basic principle

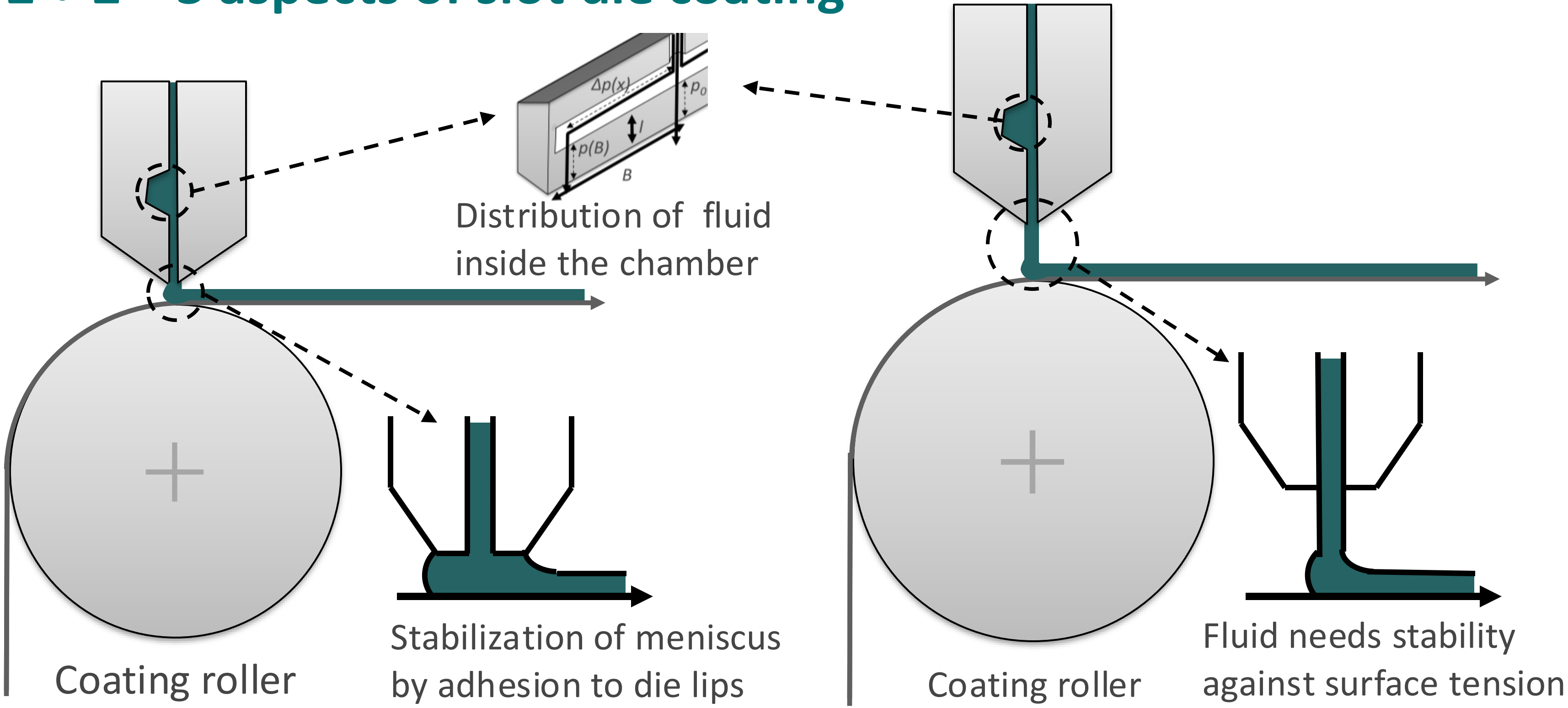


Bead mode



- ✓ Meniscus is formed between die lips and substrate
- ✓ Adhesive stabilization of meniscus by die lips
- ✓ Very low minimum flow rate possible
- ✓ For a stable process the range of rheological parameters is limited
- ✓ Preferrably for low coating speed

2 + 2 = 3 aspects of slot die coating



Theoretical background – „Basic“ fluid dynamics for advances geometries

$$\oint \rho v dA = 0$$

Continuity equation (conservation of mass)

Any flow of liquids is described by a set of differential equations:

To describe the meniscus flow of a slot die means, to solve these differential equations for given boundary conditions.

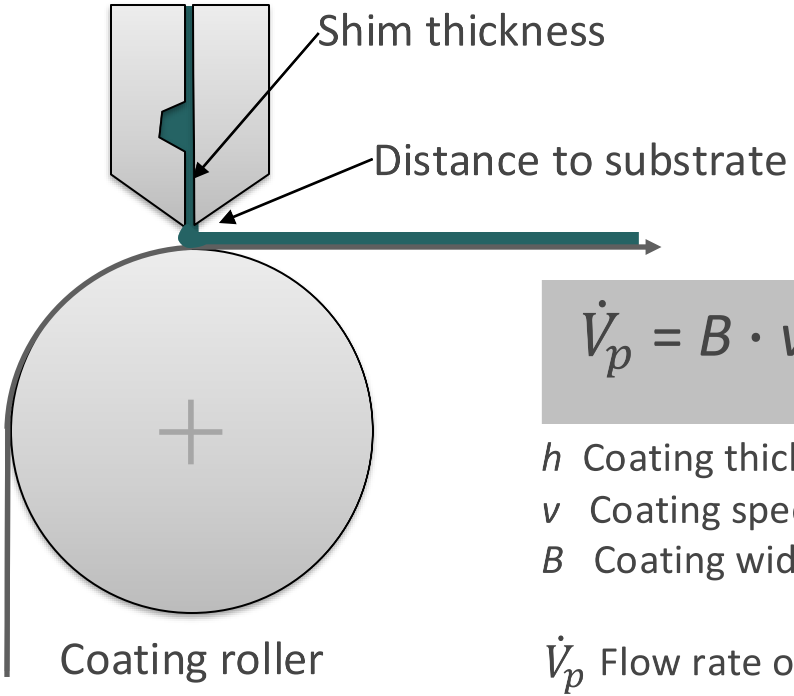
Can be done by appropriate computer programs.

$$\frac{\partial v}{\partial t} + (v\nabla)\, v = \frac{(-\nabla p + \eta \Delta v + f)}{\rho}$$

Navier-Stokes-equations (equations of motion for incompressible fluids, ρ = const)

Δ,∇= differential operators

Theoretical background



$$\dot{V}_p = B \cdot v \cdot h$$

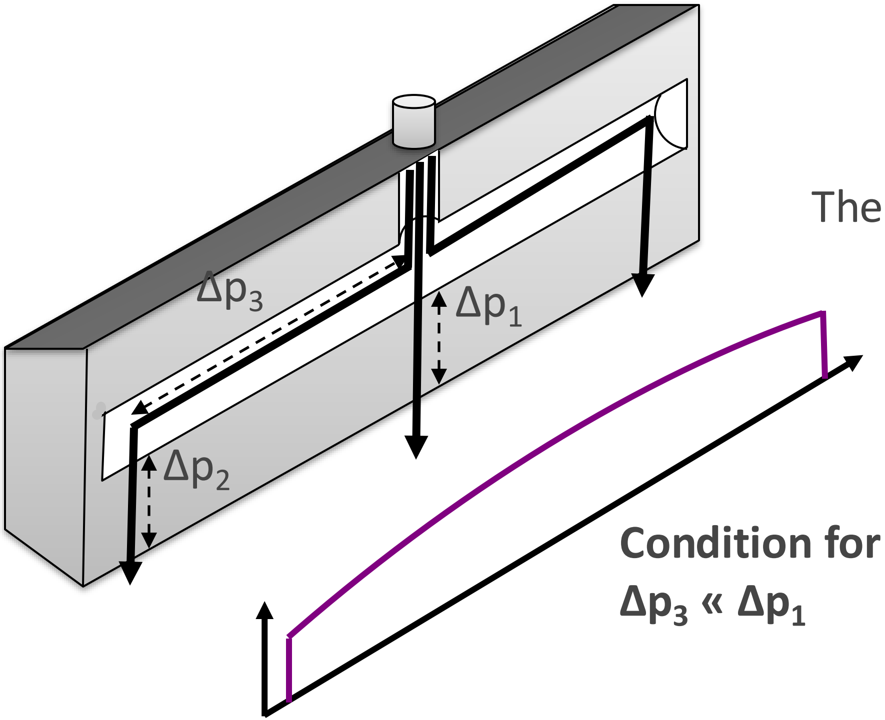
h Coating thickness wet
v Coating speed
B Coating width

$\dot{V}_p$ Flow rate of the pump

Contrary to a widespread misunderstanding the wet coating thickness does not depend on the shim thickness.

Shim thickness and distance to substrate only help to stabilize the meniscus.

Why should a slot die coat homogeneously?

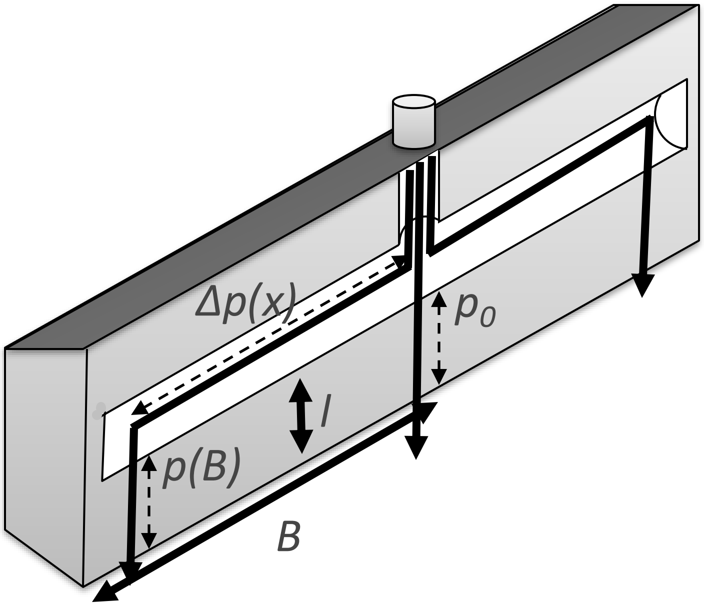


Theoretical thickness profile

Condition for good profile

$\Delta p_3 \ll \Delta p_1$

Fluids in the manifold: 1.5D approximation



Pressure drop Δp(x) via pumping through finitely sized distribution chamber leads to:

Theoretical pressure profile:

$$p(x) = p_0 \cdot \frac{\cosh \frac{W-x}{\lambda}}{\cosh \frac{W}{\lambda}}$$

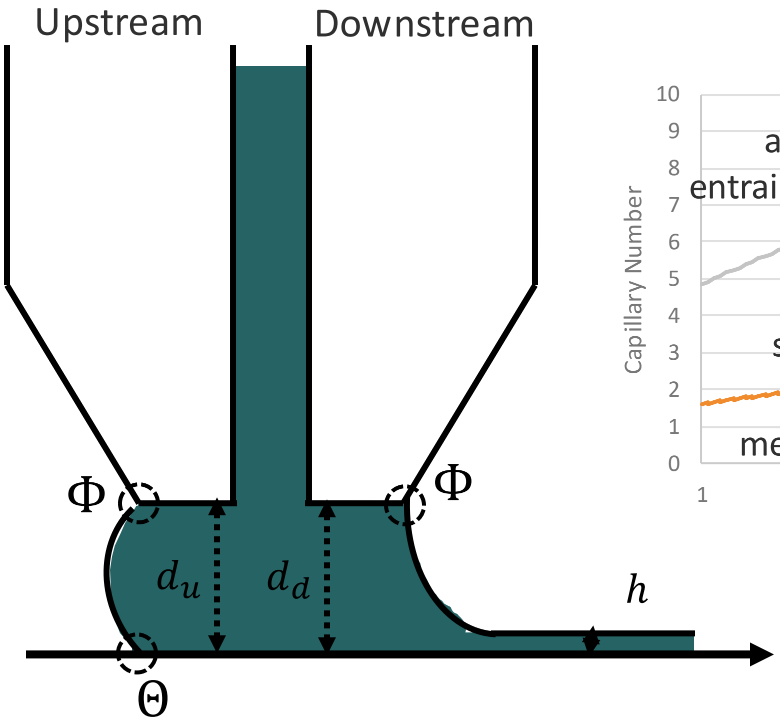
Theoretical thickness profile:

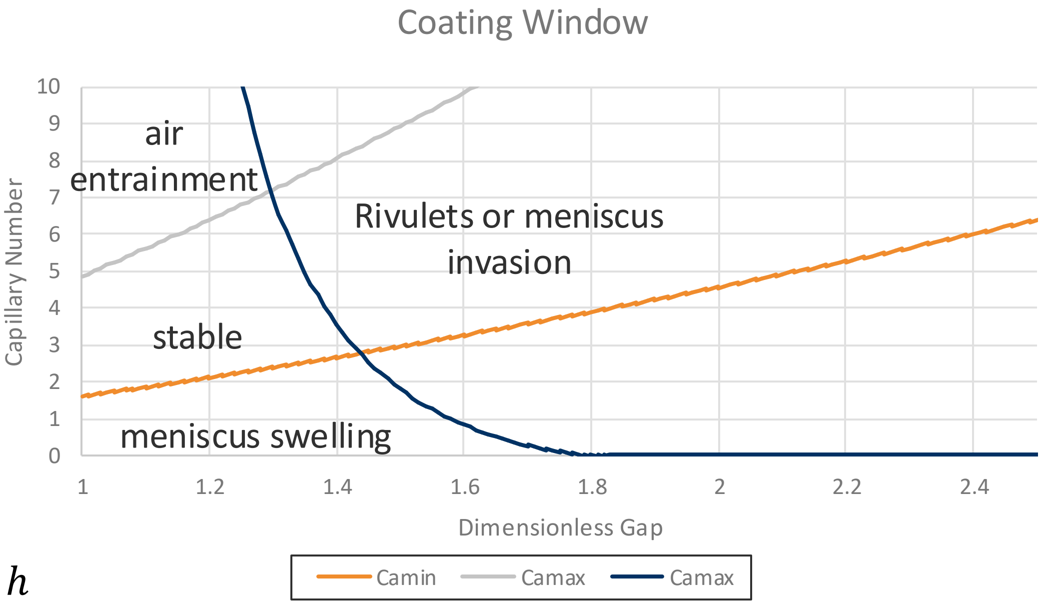
$$h(x) = \frac{B \cdot h_0}{\lambda} \cdot \frac{\cosh \frac{W-x}{\lambda}}{\sinh \frac{W}{\lambda}}$$

$$\lambda = \sqrt{\frac{3\pi \cdot l \cdot r^4}{2\delta^3}}$$

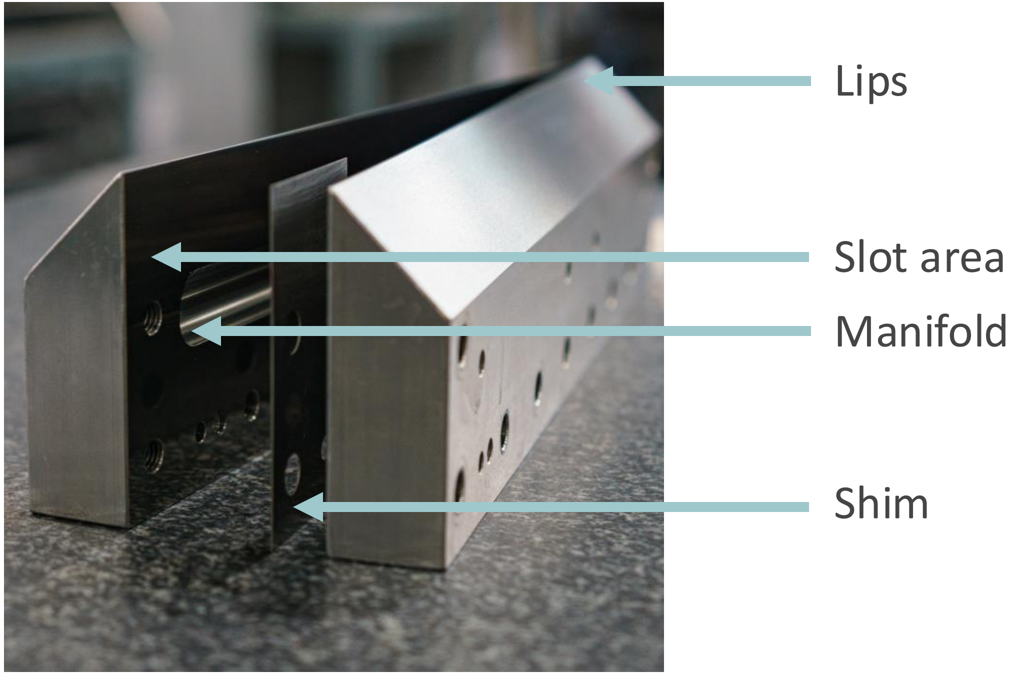
„slot die geometry parameter“

Calculation of the meniscus stability





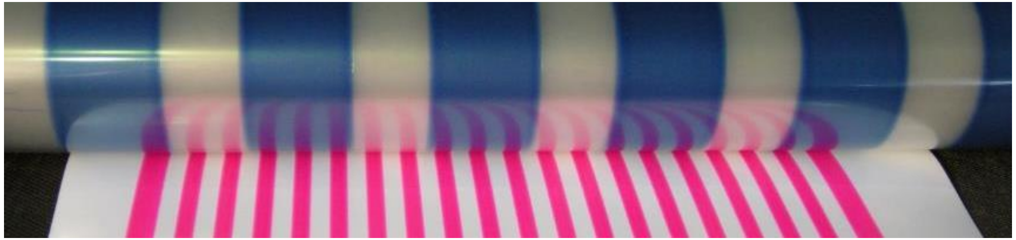
Coatema standard layout – one design among many available

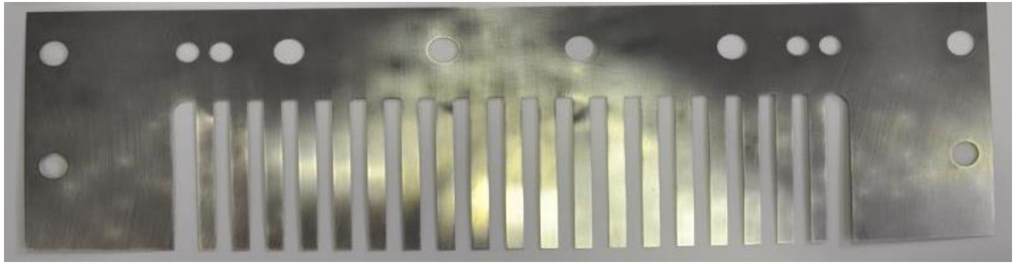


Structured coating – levels of complexity

		Current status
1	Full area, homogeneous	Requirements are met, thickness profile variation of 0.5 %
2	Stripes downweb	Requirements are met, good edge definition
3	Stripes crossweb (intermittent coating)	Requirements are partially met, edge definition of 0.5 – 1 mm depending on liquid
4	Arbitrary patterns	Requirements are not met, concepts for realization exist, research project is going on

Level 2 – downweb stripes

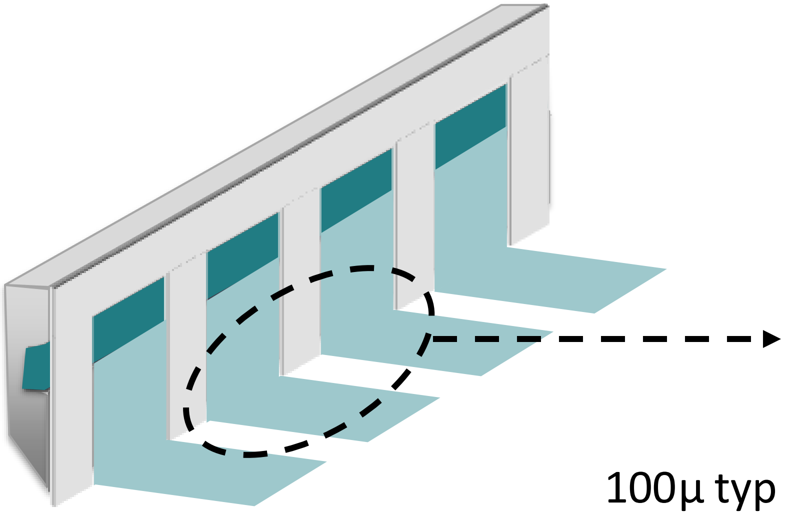




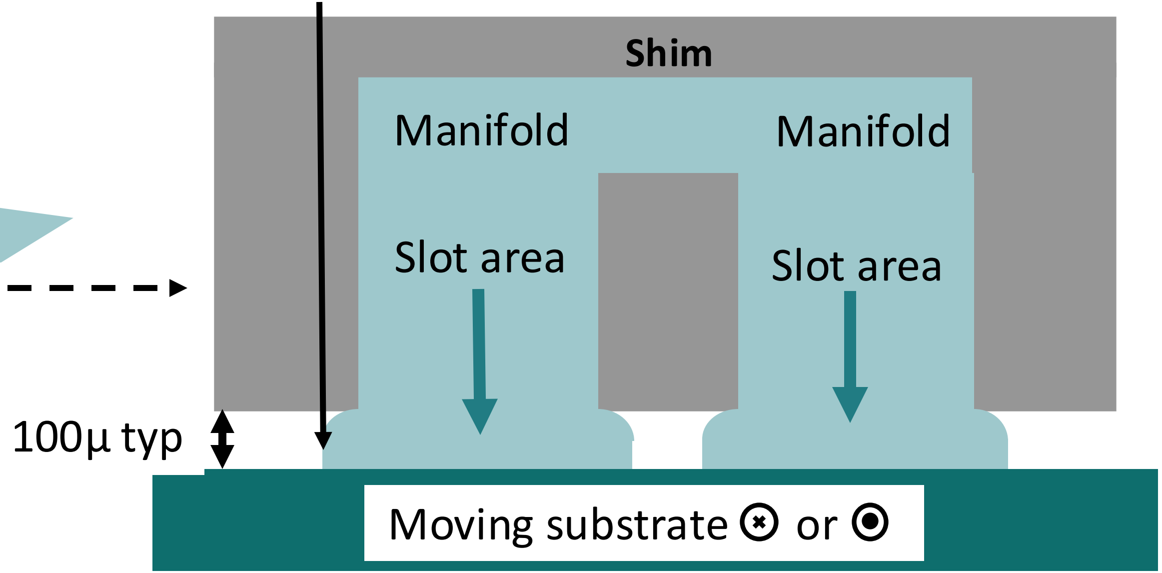
Downweb stripes of different width …

… are made by appropriate shims, lasercut from steel or kapton

Level 2 – downweb stripes

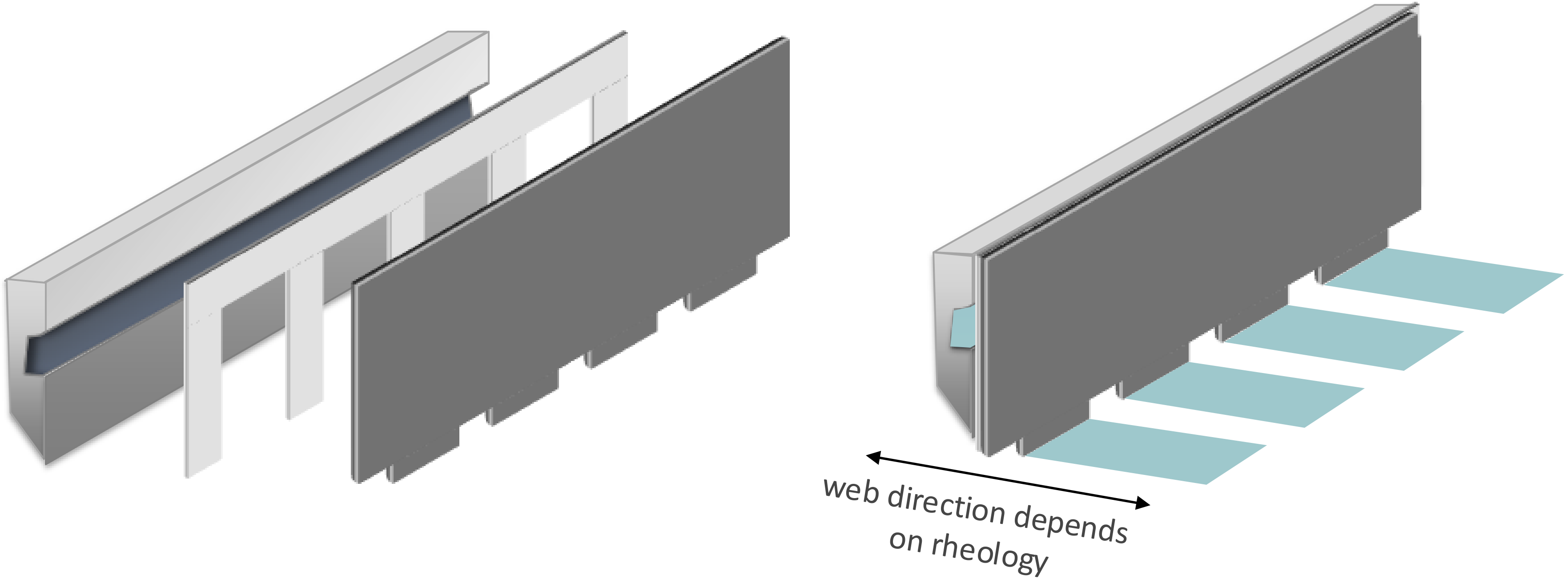


Problem:
Stripe widening by capillary forces at the edges of the shim teeth

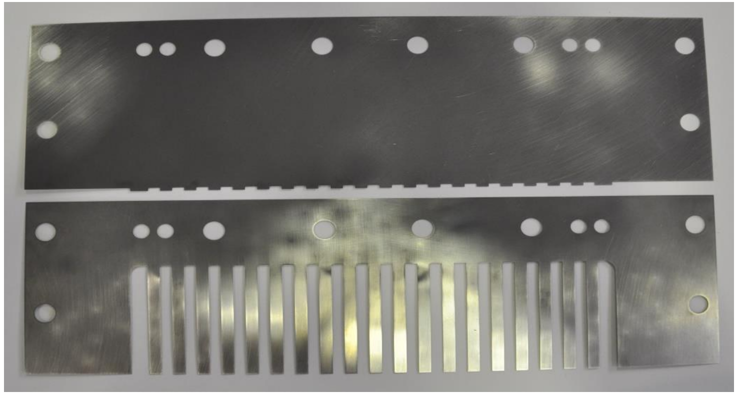


Level 2 – downweb stripes

Manifold + Shim + Meniscus guide = well defined stripes



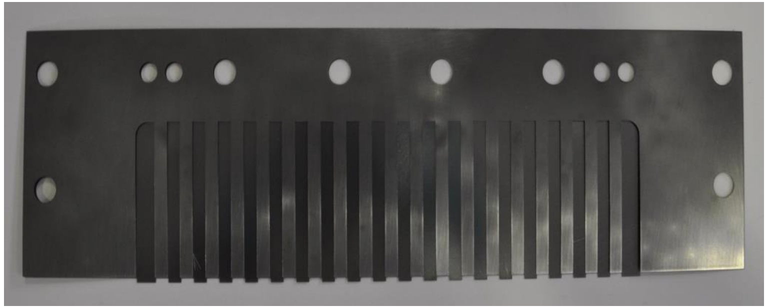
Level 2 – downweb stripes

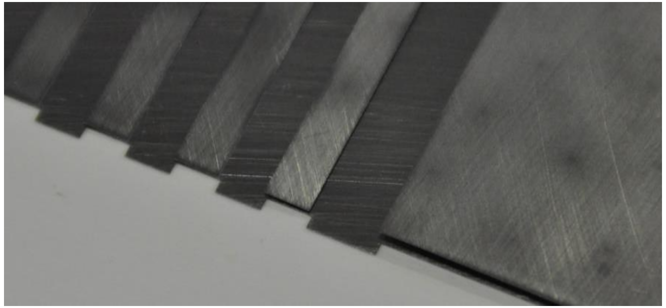


Meniscus guide

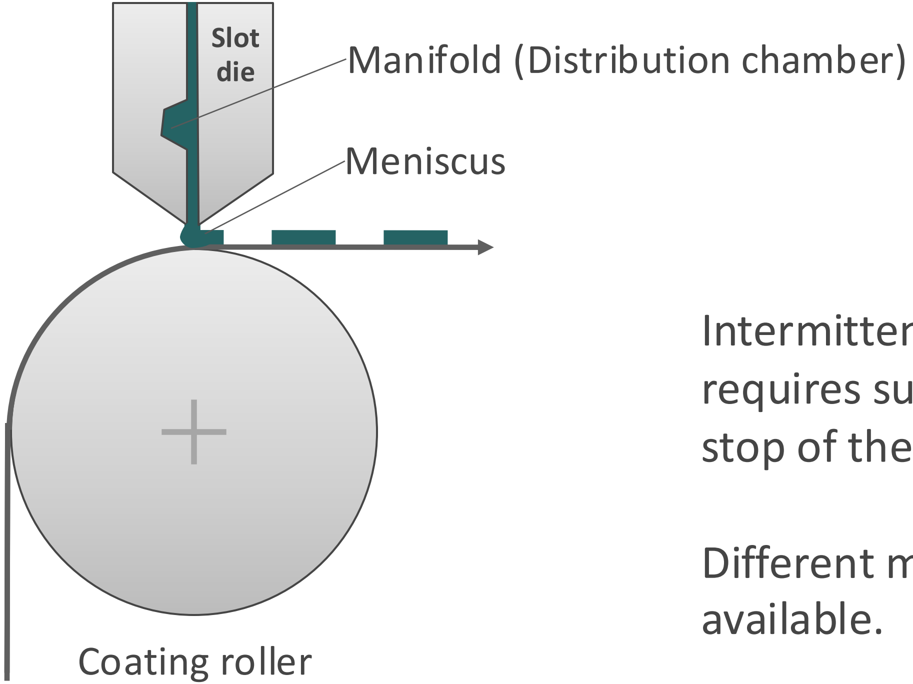
Shim

Meniscus guide + shim





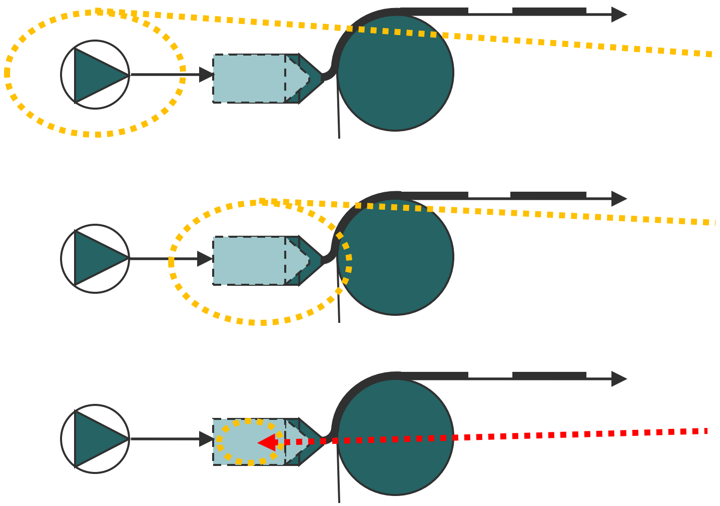
Structured coating – crossweb stripes (intermittent)



Intermittent coating requires sudden start / stop of the fluid flow.

Different methods are available.

Standard techniques for intermittent coating



Pump:
stop – reverse – restart

Slot die body:
move back – move forth to minimum gap – move back to working gap (wedge procedure)

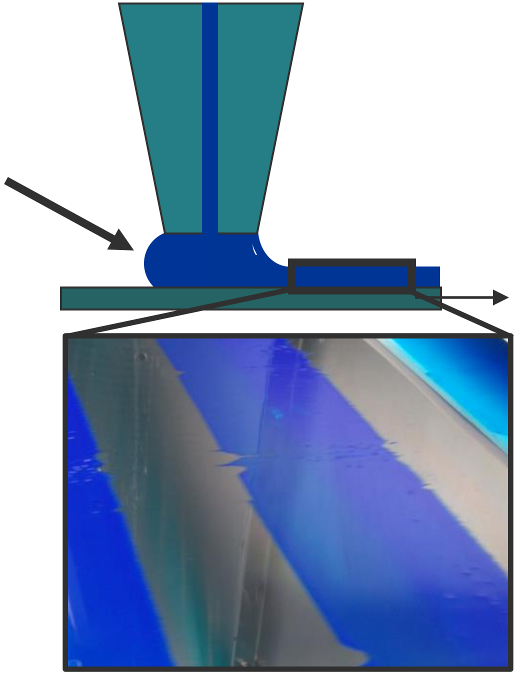
Slot die internal:
stop and redirect the flow by shutters and valves. Pump flow continues, die flow stops.

All 3 techniques (single or in combination) work quite well, if the viscosity is rather high and the required edge defintion is not more precise than around 1 mm. All techniques may be combined with a vacuum pump upstream to stabilize the meniscus and suck away residual liquid.

Structured coating – reason for bad edges at low viscosity

- ✓ Mensicus has to be interrupted
- ✓ Low viscous liquids do not break along a straight line
- ✓ Meniscus has to be sucked back and restored
- ✓ Speed is of essence

→ For low viscosity, all of the three methods are too slow and too indirect



PI-SCALE
SHAPING THE FUTURE IN OLED LIGHTING

PHOTONICS[21]
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Structured coating – new concepts for low viscosity liquids

Two new concepts allow to interrupt and restore the meniscus much faster:

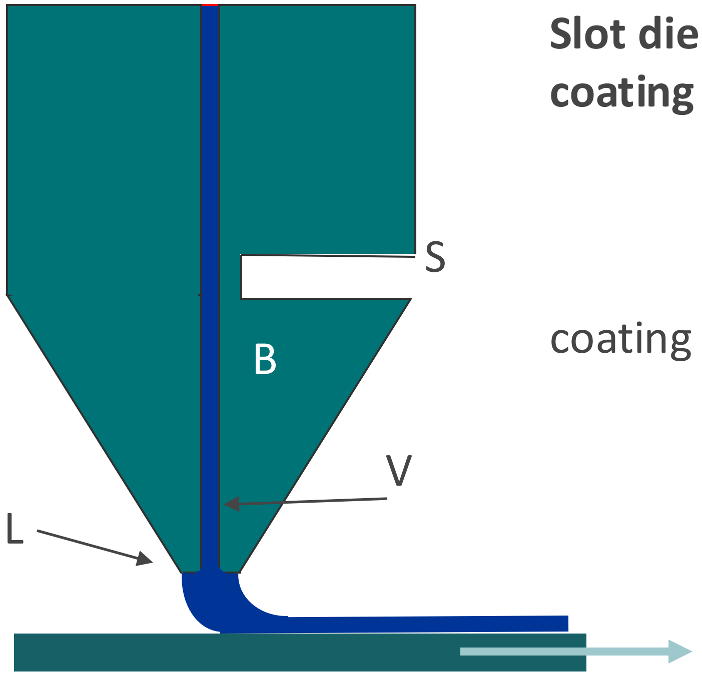
✓ **Double chamber slot die**
with modified chamber geometry and Piezo driven suck back pump

✓ **Switching lip slot die**
with a Piezo driven lip opening mechanism that sucks back the meniscus right where it is

PI-SCALE
SHAPING THE FUTURE IN OLED LIGHTING

PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Structured coating – the switching slot die lip



Slot die with movable lips:
coating mode

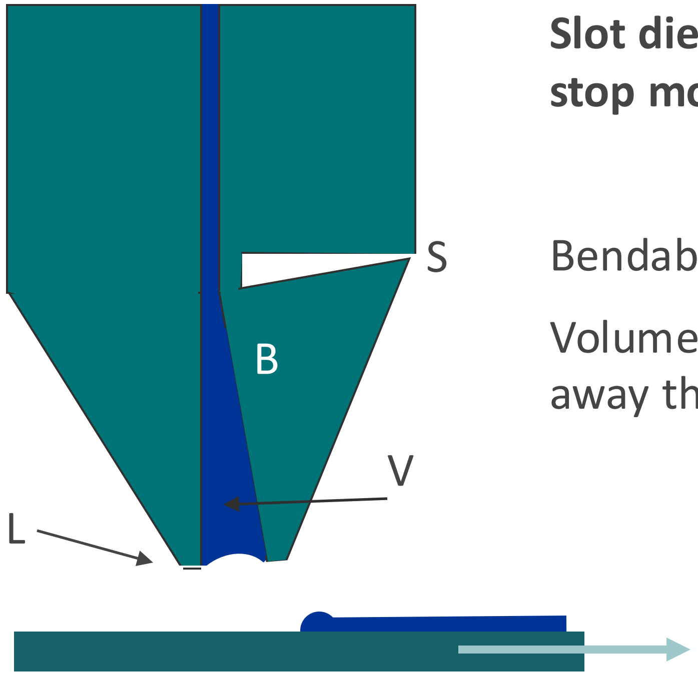
L lip
V slot volume
B bendable lip
S bending slot

coating works as usual

PI-SCALE
SHAPING THE FUTURE IN OLED LIGHTING

PHOTONICS^{21}
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Structured coating – the switching slot die lip



Slot die with movable lips:
stop mode

Bendable lip B flips open

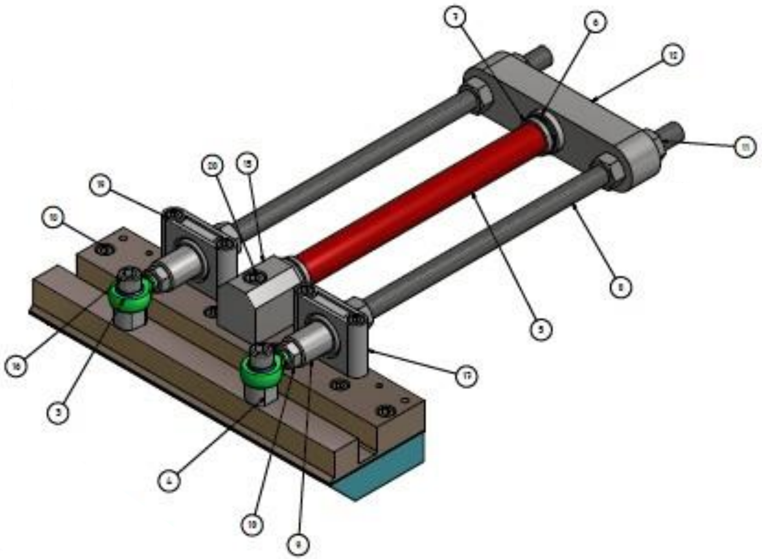
Volume V increases and sucks away the meniscus

L lip
V slot volume
B bendable lip
S bending slot

PI-SCALE
SHAPING THE FUTURE IN OLED LIGHTING

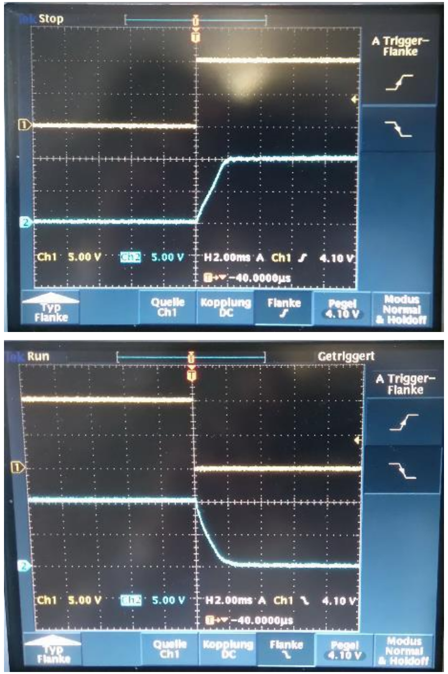
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Structured coating – technical implementation with Piezo-Drive



Control Voltage

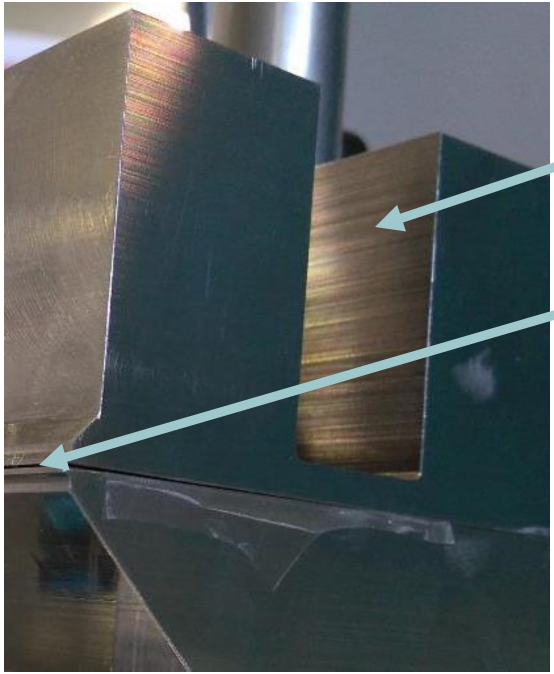
Piezo Response



Extremely fast action:
within few ms from coating to stop mode and vice versa

PI-SCALE
SHAPING THE FUTURE IN OLED LIGHTING

Structured coating – technical implementation with bendable lips

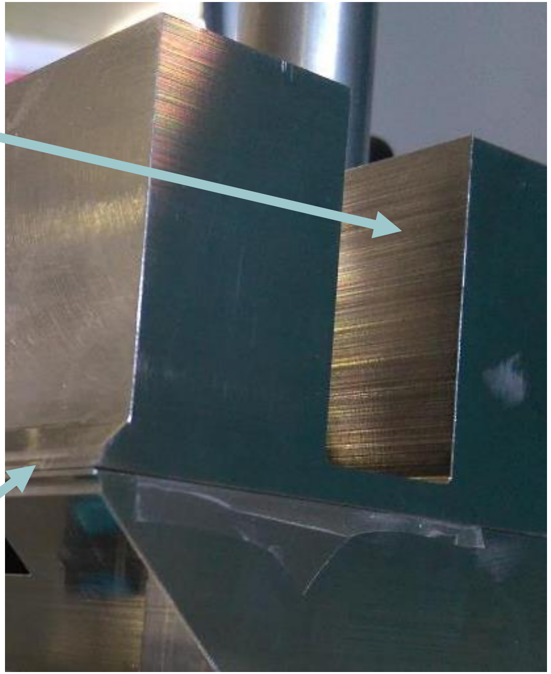


Bending slot

Lips open

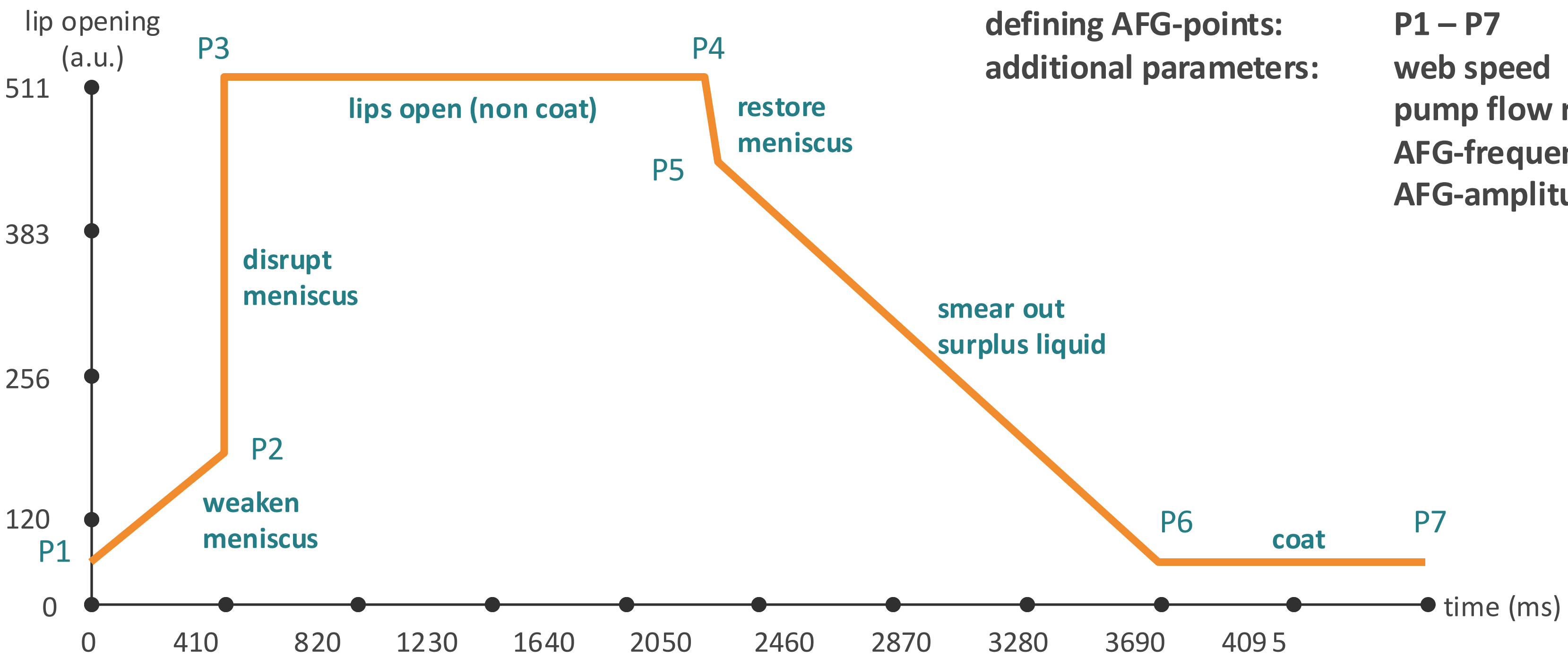
Difference is 300 µm only

Lips closed



Technical implementation with bendable lips in action

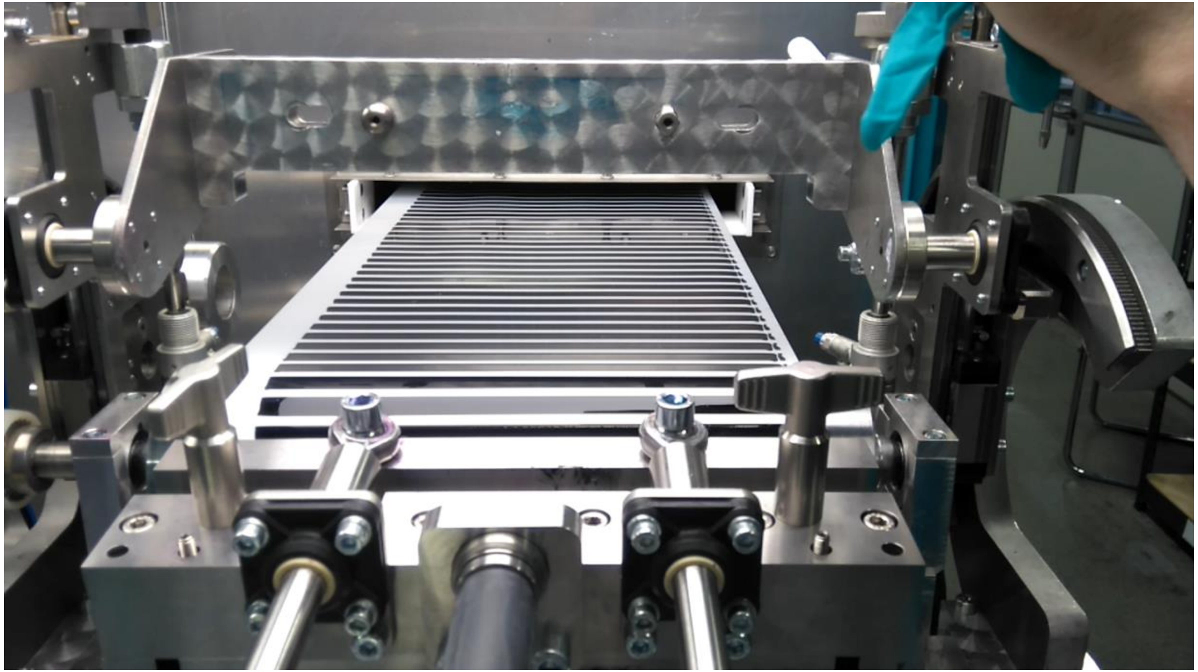
Structured coating – stages of lip motion

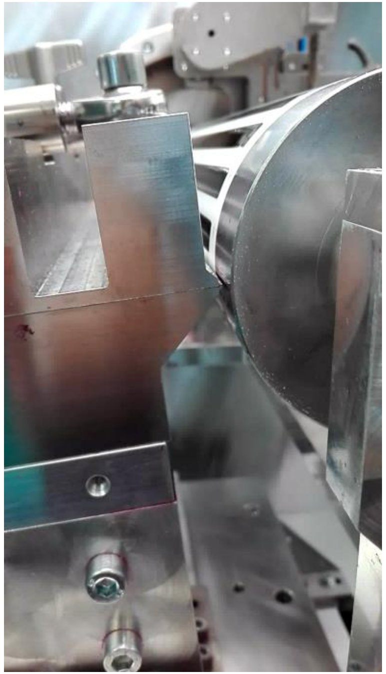


defining AFG-points: P1 – P7

additional parameters:
- web speed
- pump flow rate
- AFG-frequency
- AFG-amplitude

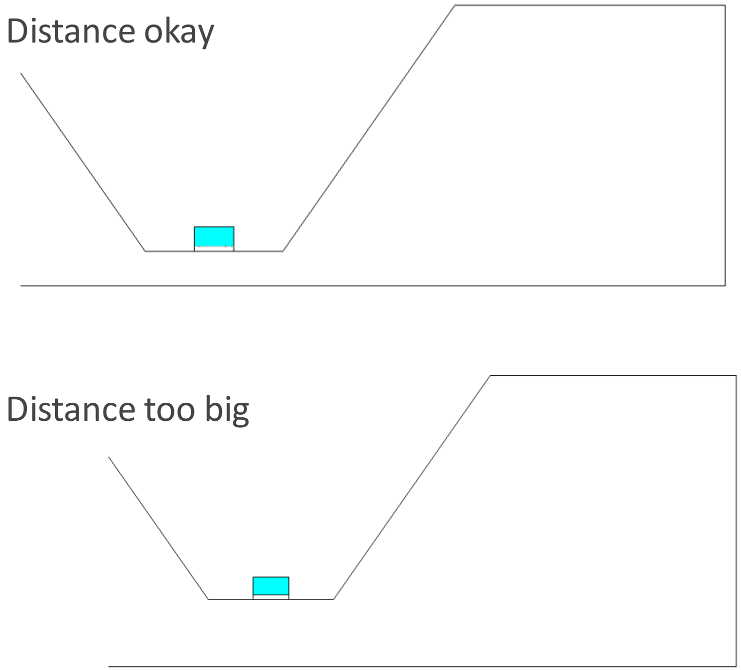
Structured coating – ongoing trials: stripe coating of fuel cell paste





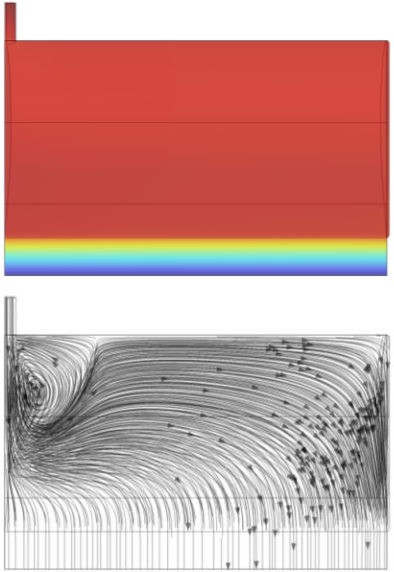
Simulation of anode Coating with slot die

- ✓ Example for anode electrode coating
- ✓ Fluid data taken from real world (shear-thinning power law fluid)
- ✓ Process parameters for 90 m/min 400 µm coating and 300 mm width
- ✓ No „fancy” slot-die „just” Coatema standard

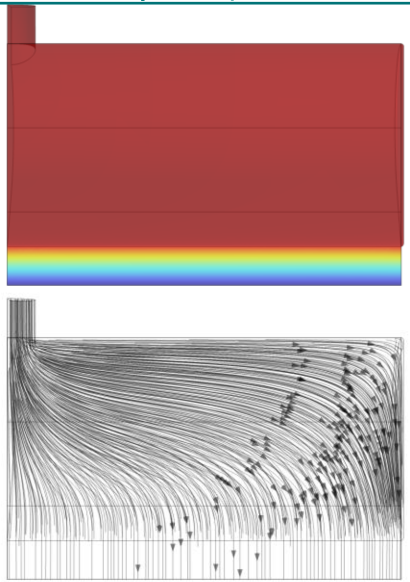


Streamlines and pressure distribution in the slot die

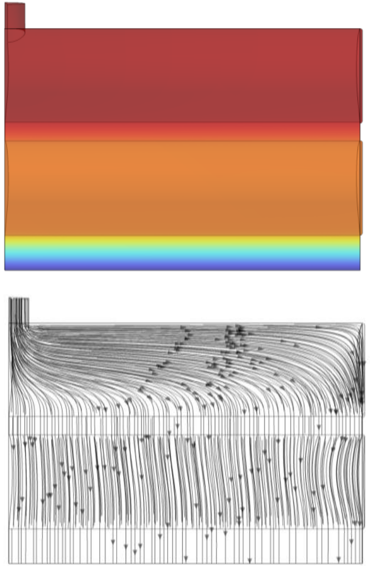
Single Chamber with too small inlet (4 mm)



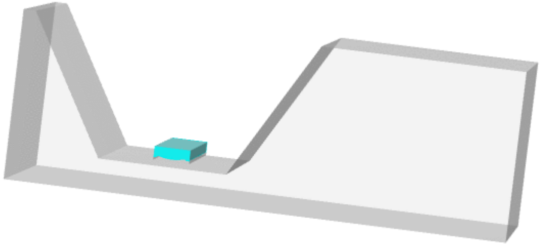
Single Chamber with correct chamber layout (10 mm inlet)

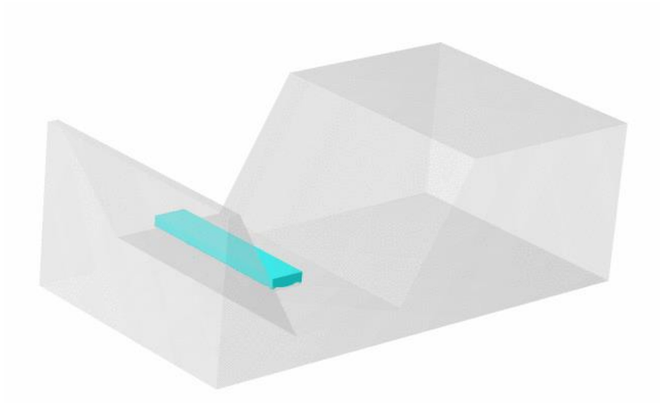


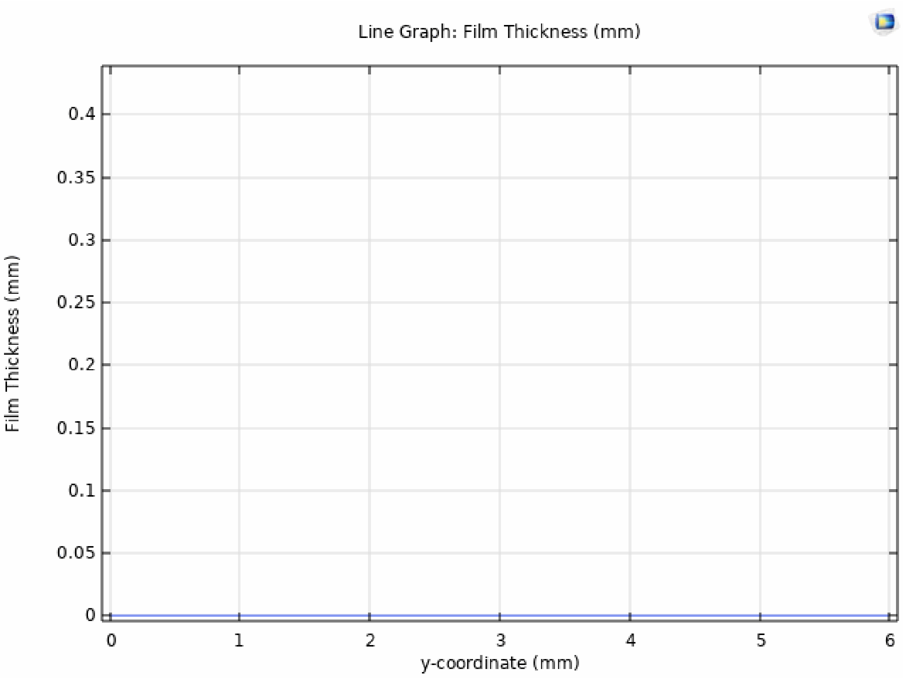
Dual chamber slot die (8 mm inlet same dead volume)



Meniscus makes or breaks Homogeneity



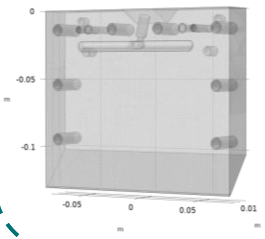




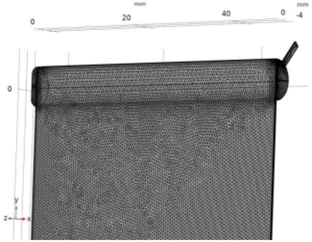
Design of an inner manifold, slot die

Customized slot die is built

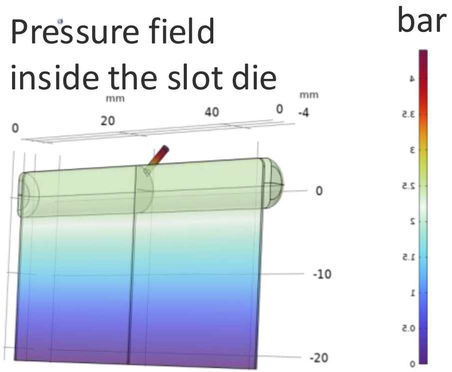
CAD design of a slot die

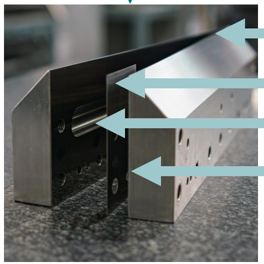


Flow domain is extracted+ mesh



Pressure field inside the slot die





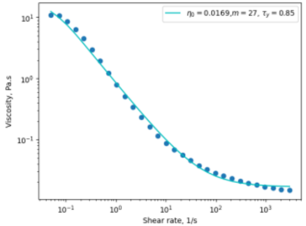
Undergoes parameter sweep and iterative design changes to achieve optimal performance for the specific fluid

Goal: ✓ Uniform Coating Thickness for the specific fluid

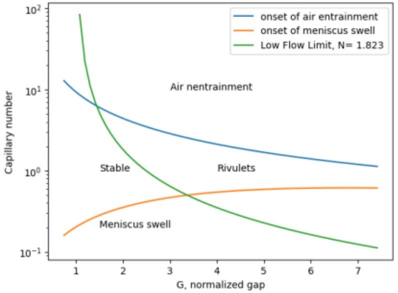
✓ Design the die to handle variations in pressure, especially in cases where the complex fluid exhibits non-Newtonian behavior.

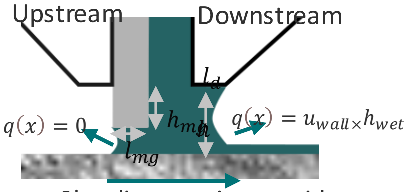
Coating process optimization

- ✓ Shear thinning
- ✓ Yield stress



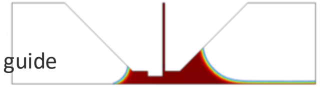
Customized coating window



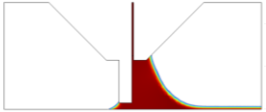


Slot die+ meniscus guide

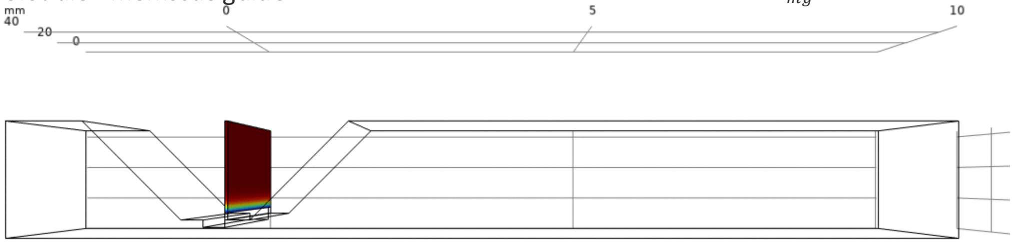
Selecting the suitable meniscus guide



$h_{mg} = 0.1\ mm$



$h_{mg} = 1.0\ mm$



6.

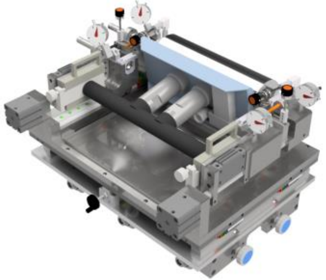
Printing processes

Printing parameters

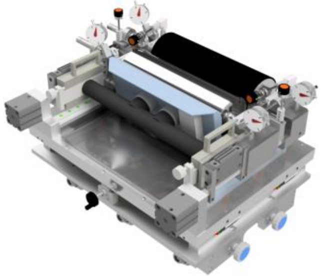
Printing method	Printing speed (m/s)	Nip pressure (MPa)	Ink viscosity (Pas)	Layer thickness (µm)	Feature size (µm)	Registration (µm)
Flexography	3 – 10	0.1 – 0,5	0.01 – 0.5	0.04 – 8	40 – 80	20 – 200
Gravure	10 – 16	1.5 – 5	0.01 – 0.2	0.1 – 12	20 – 75	>10
Offset	8 – 15	0.8 – 2	1 – 100	0.5 – 3	25 – 50	>10
Screen printing	2	–	0.1 – 50	3 – 100	75 – 100	>25
Inkjet	1 – 5	–	0.001 – 0.03	0.01 – 0.5 20 (UV)	10 – 50	<10

Printing parameters

Gravure printing

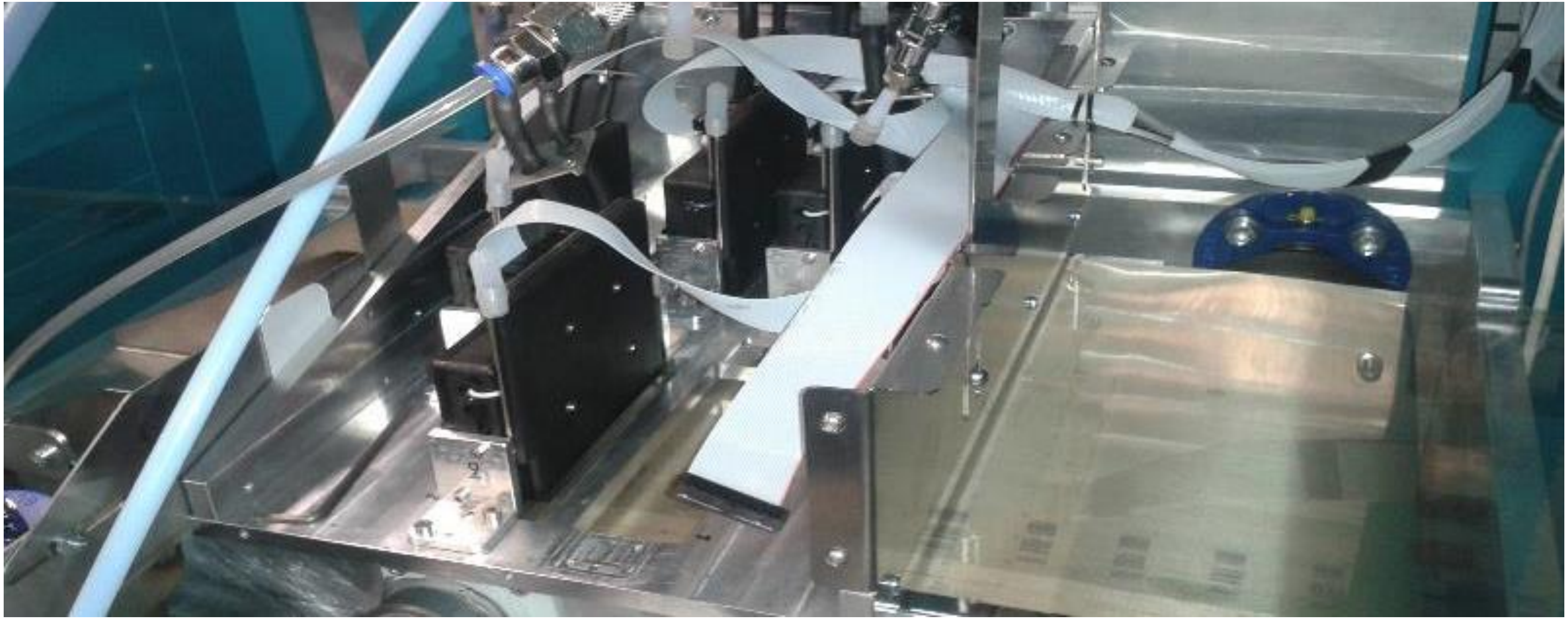


Flexo printing



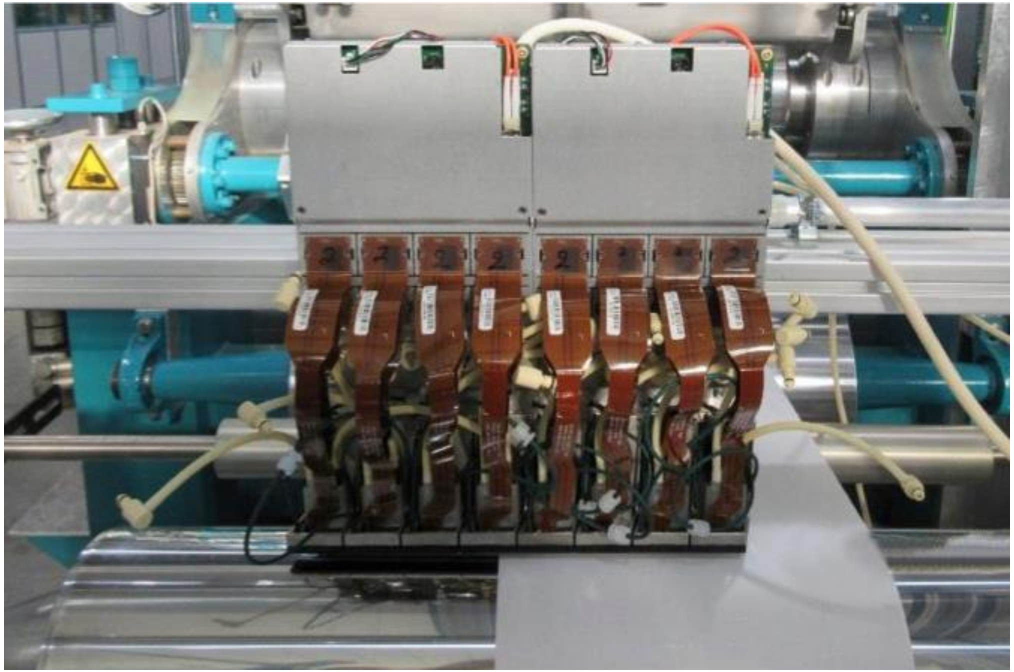
Screen printing

Inkjet printing



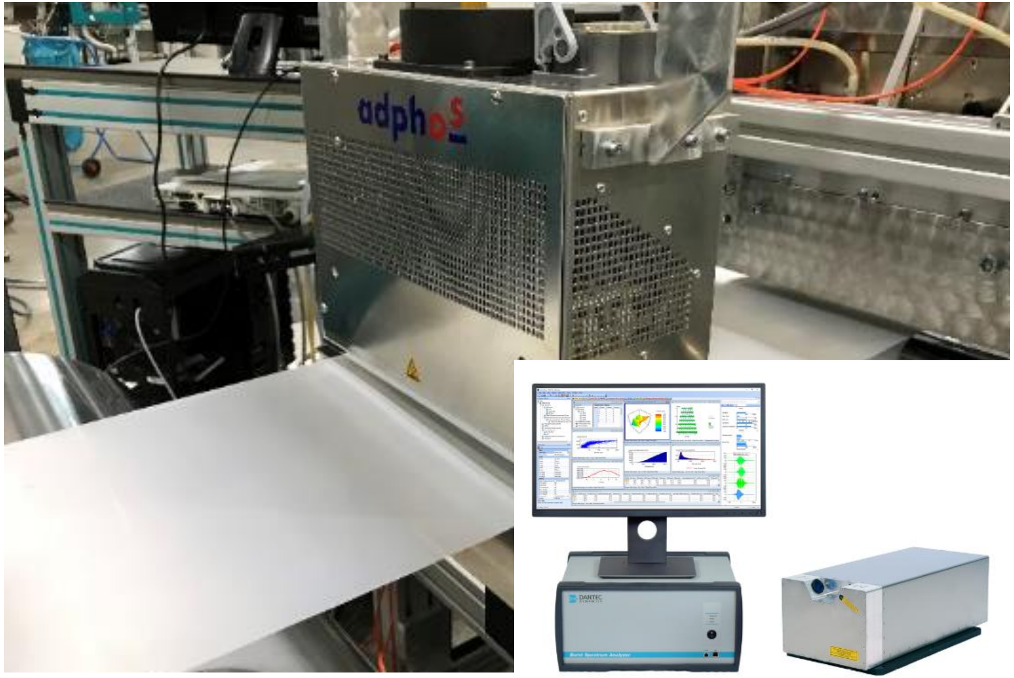
Inkjet printing

Integration of the „inking“ system – current status



- ✓ Printing head and mounting (Fujifilm Dimatix Samba)
- ✓ Fluid recirculation system
- ✓ Power supply
- ✓ Computer

Integration of analysis and sintering units – current status

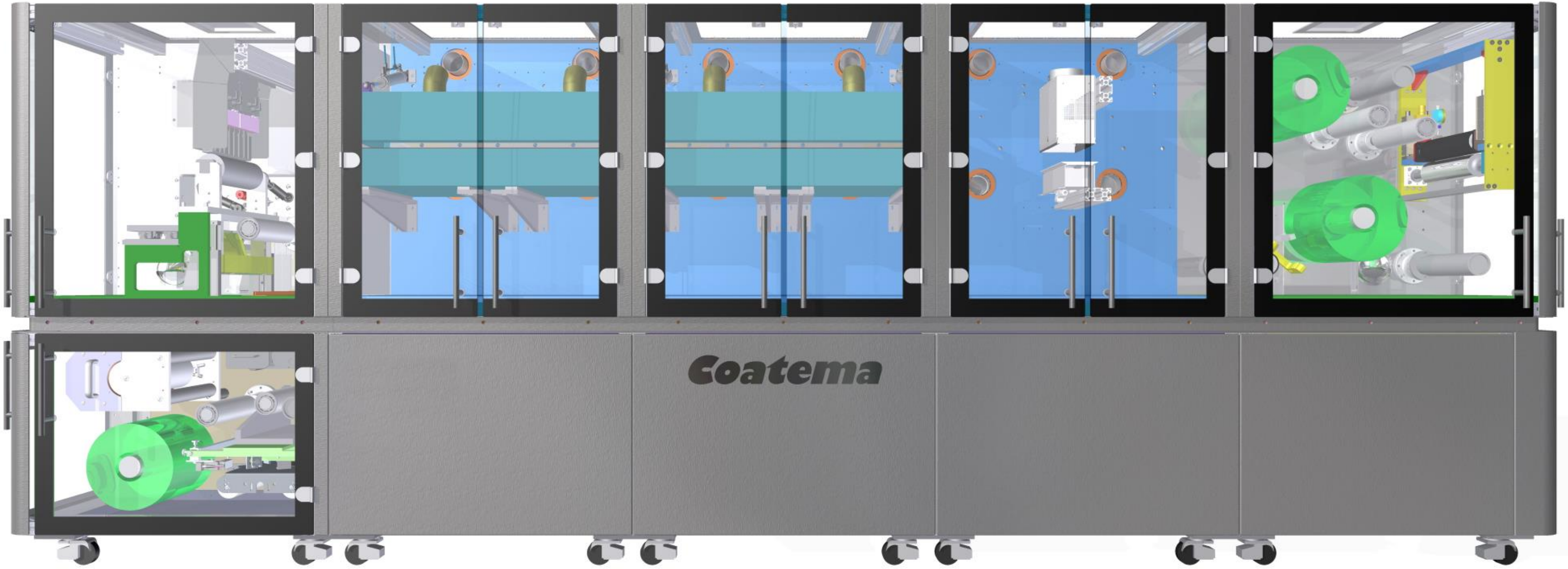


- ✓ Dantex dynamics „dropwatching“
- ✓ Velocity
- ✓ Size
- ✓ Sphericity
- ✓ Drying / Sintering
- ✓ Adphos NIR
- ✓ IR lamp
- ✓ Photonic sintering
- ✓ Hot air dryer

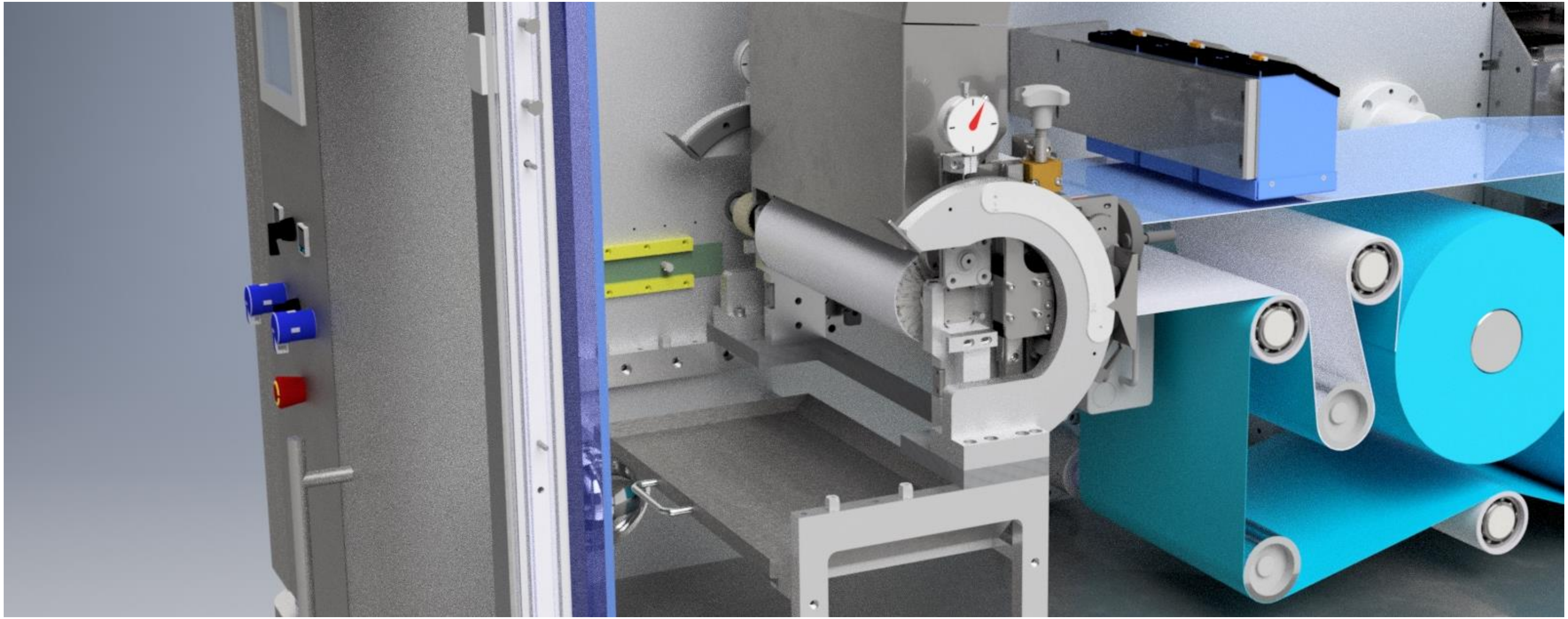
Integration into new and existing platforms

- ✓ Combination of print heads with high precision granit stone
- ✓ Several sintering methods possible
  - ✓ Hot air dryer to remove solvents (LEL)
  - ✓ NIR / IR / Photonic sintering for conductivity
- ✓ Droplet analysis
- ✓ Possibility to combine inkjet with NIL

Integration – machine layout



Integration – machine layout



Integration – machine layout

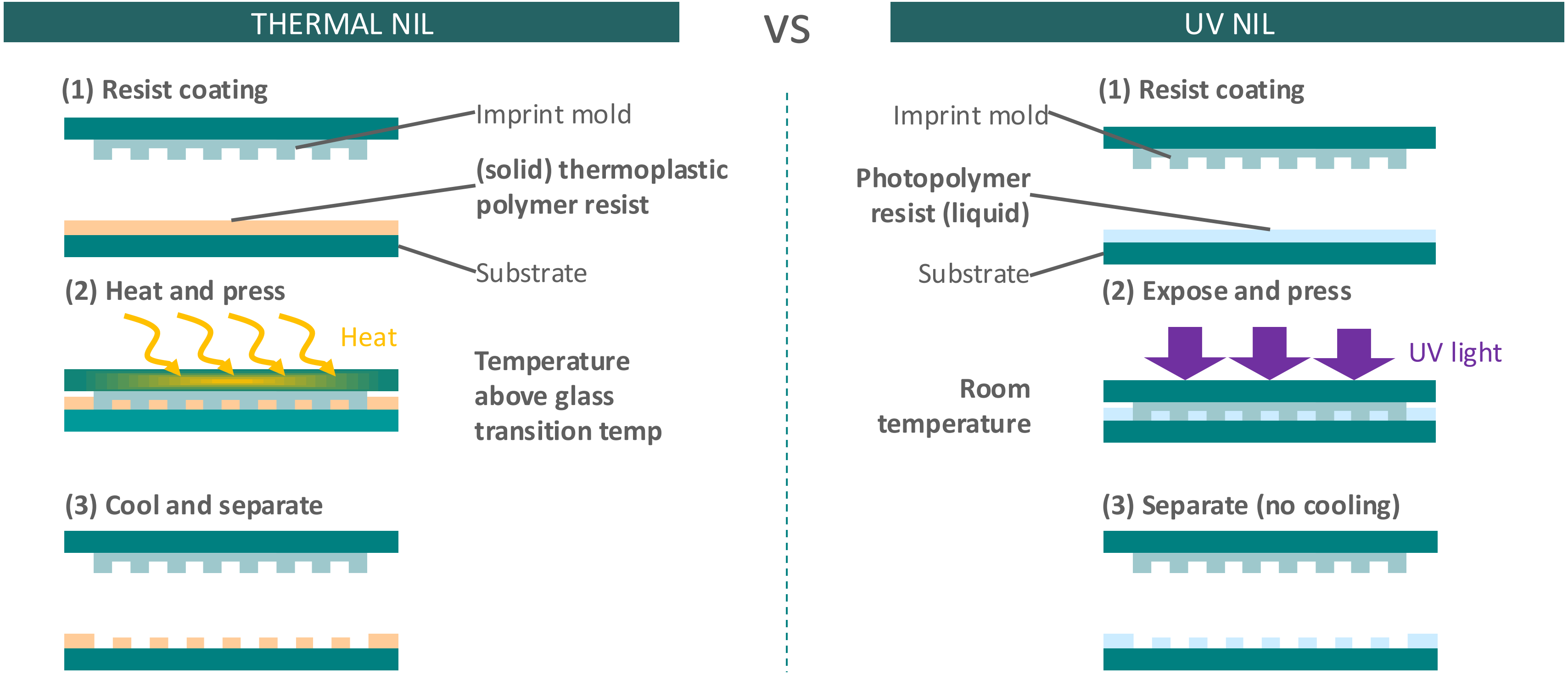
Summary

- ✓ Inkjet provides a step towards a more flexible and customizable production
- ✓ Inkjet is successfully integrated in a R2R process on 300 mm width
- ✓ Width is scalable
- ✓ Speeds up to 10 m/min were tested
- ✓ Different curing / drying systems were tested
- ✓ A layout for a inkjet dedicated machine is available

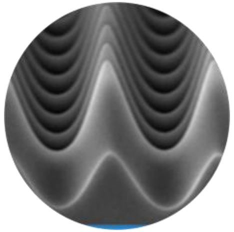
7.

Nanoimprint

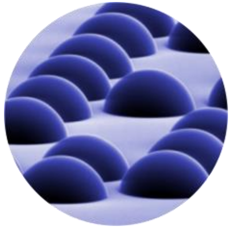
Basic principle of nanoimprint lithography



Applications

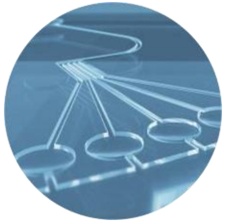


Display

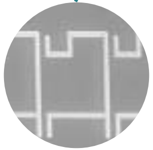


Photonics

Bionics



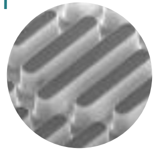
Life science



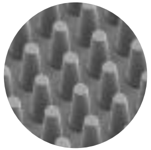
Printed electronics

Retroreflectors

Diffractive optical elements

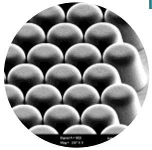


Antibacterial surfaces



Super hydrophobic surfaces

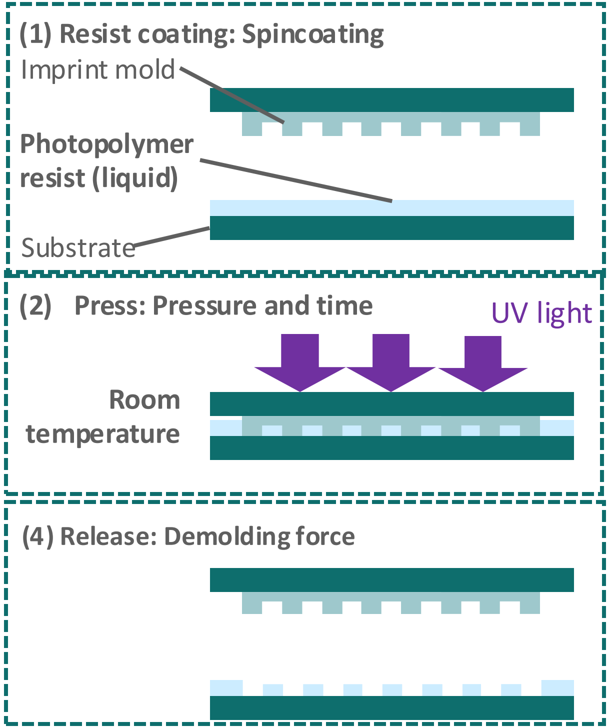
Shark skin

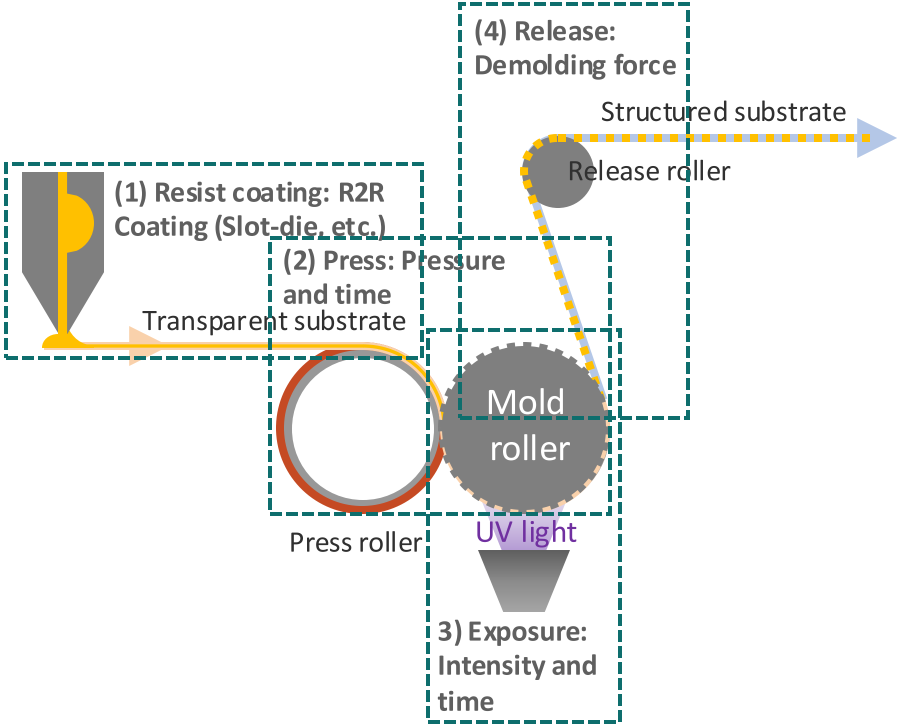


Haptic surfaces

Microfluidic structure

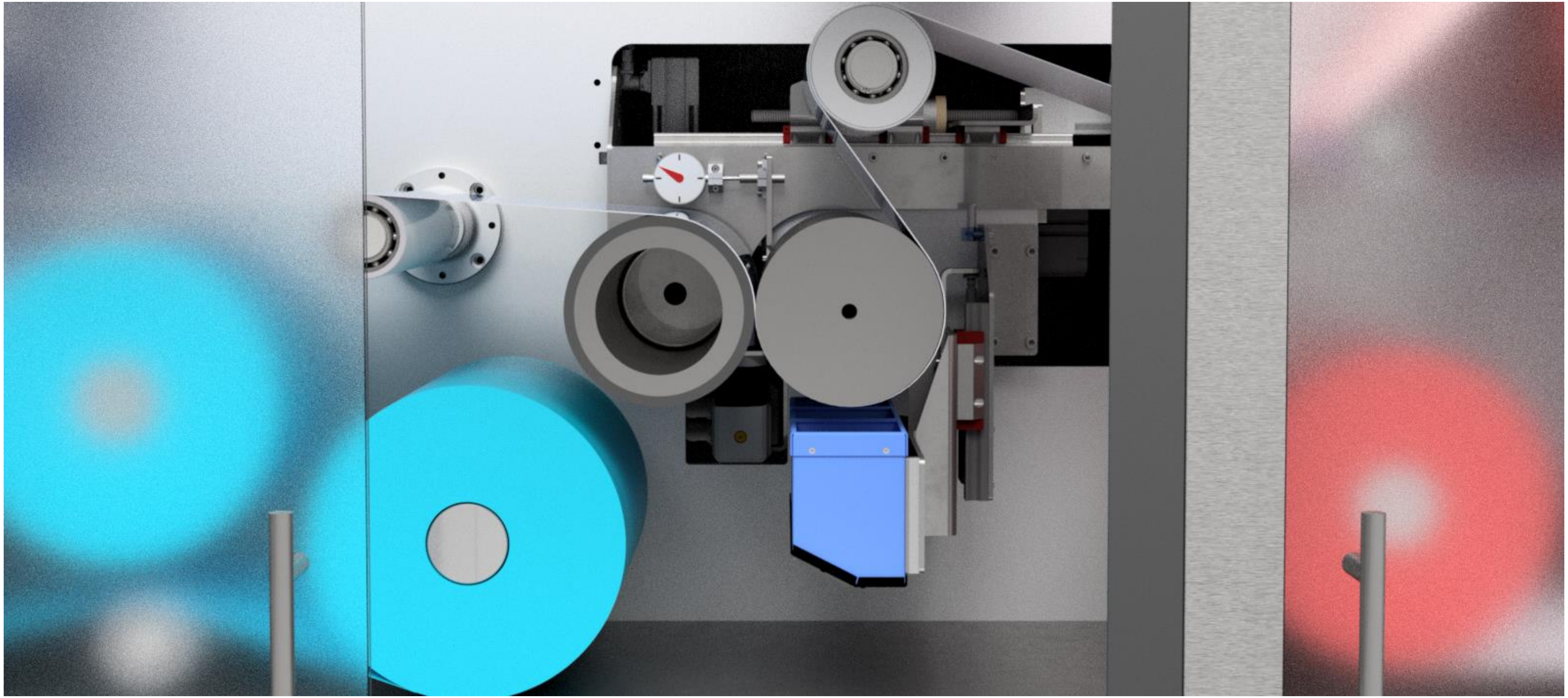
Translating from P2P to R2R





Nanoimprint lithography – technologies and processes

Nanoimprint lithography – technologies and processes

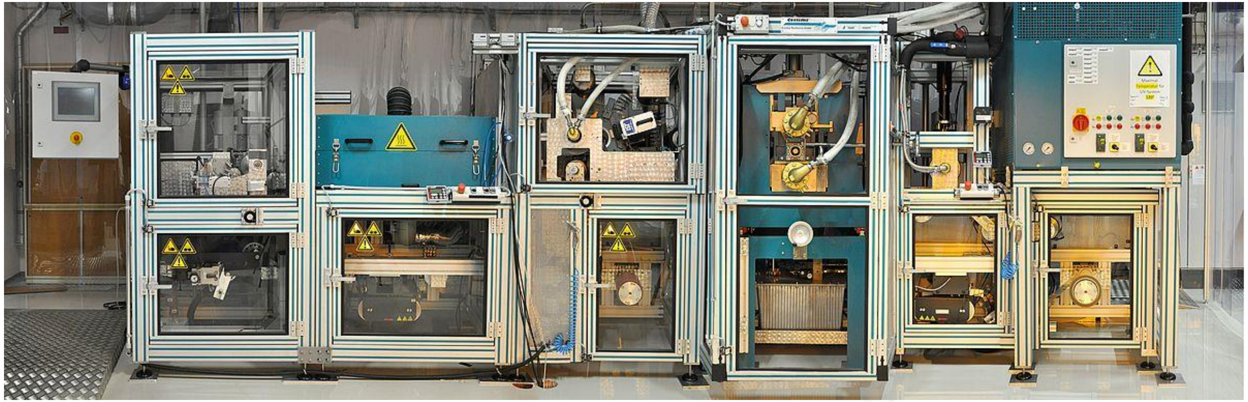


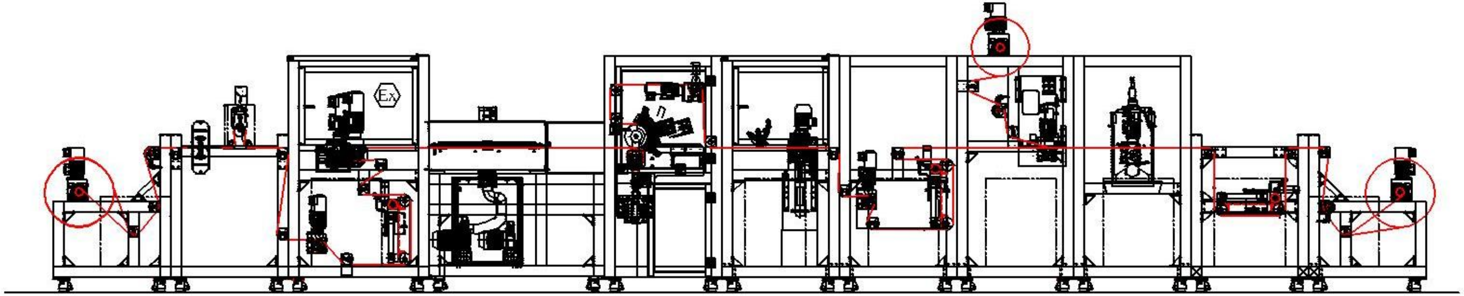
R2R UV-NIL equipment

Coatema2go

Test Solution R2R

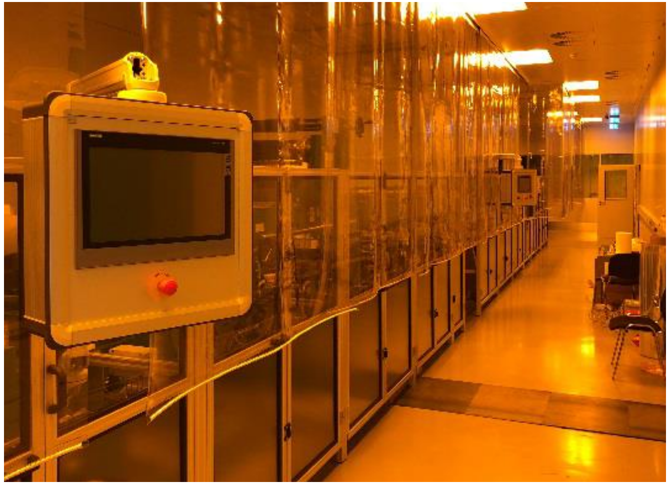
Equipment

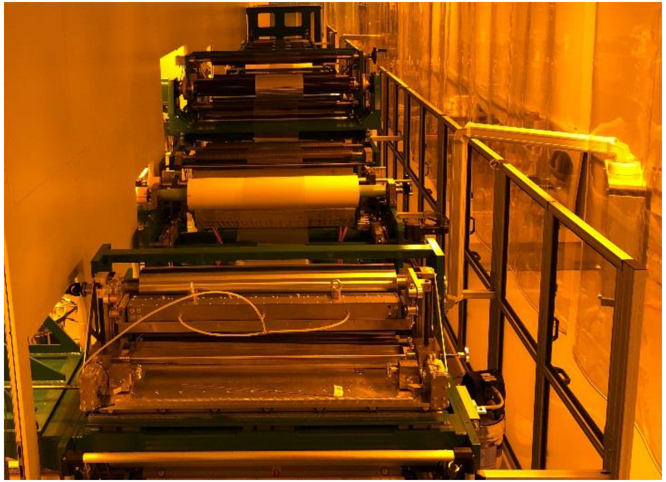


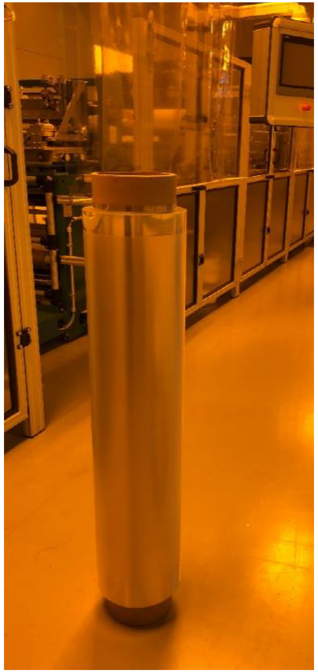


Equipment

- ✓ Rollimprint Production Line (Roll-to-Roll, Roll-to-Plate)
- ✓ Films up to 1.0m width, panels up to 1.0m x 1.6m
- ✓ Cleanroom class ISO 5







Equipment

R2R + R2P-Machine

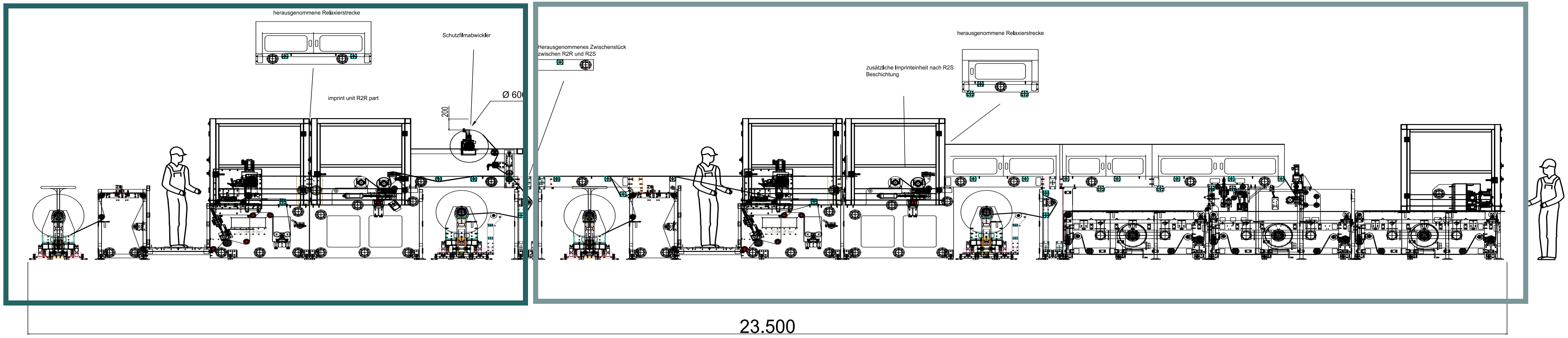
Specs:

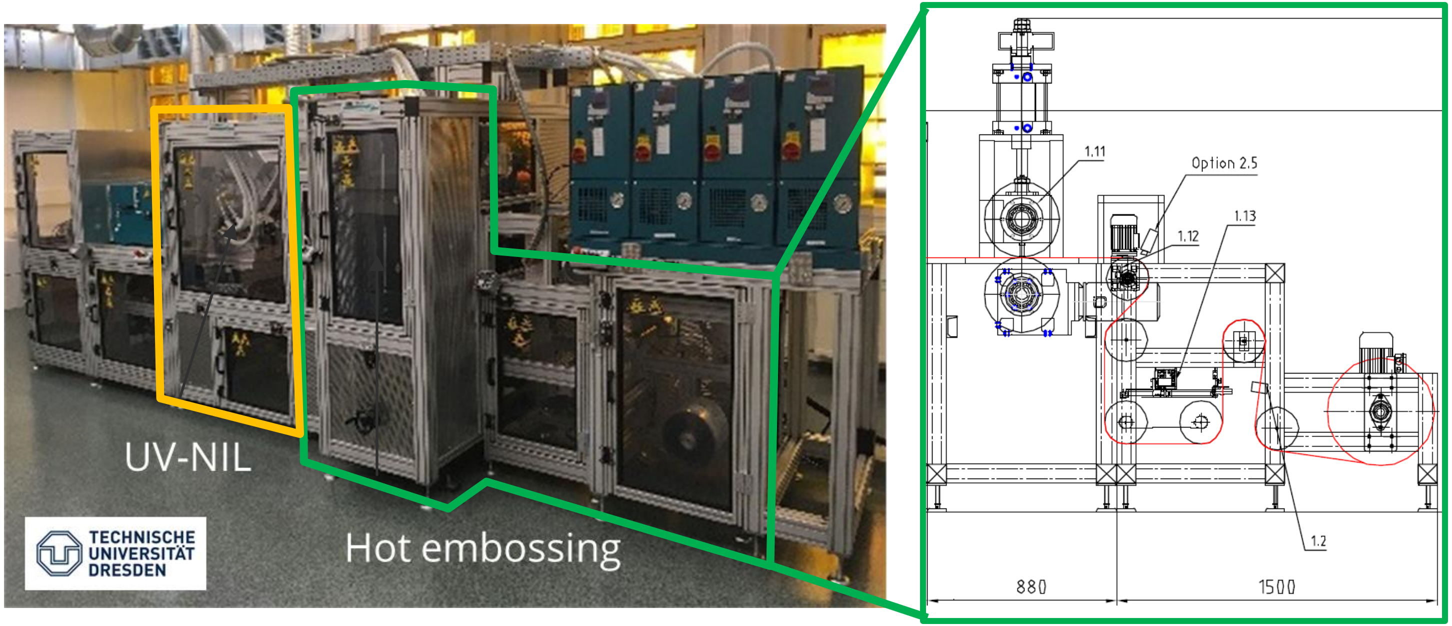
Working width R2R: 1100 mm

Dimensions R2P: 1000 mm x 1600 mm

Speeds: 6 – 60 m/min

Coating Unit: Slot die coating



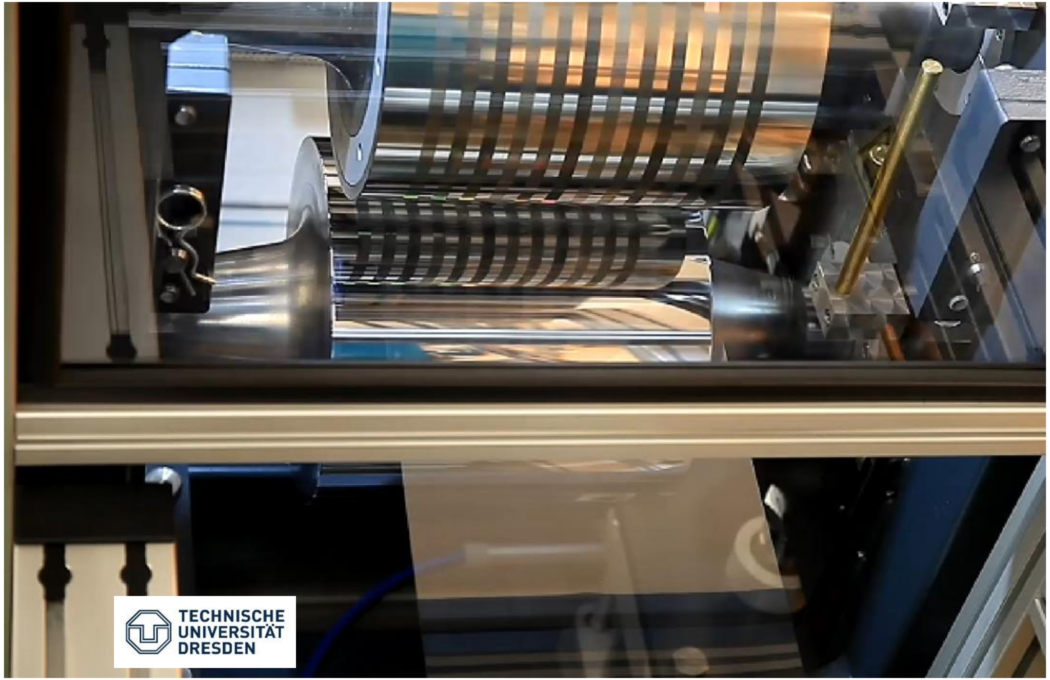


Coatema UV-NIL and Hot embossing in one unit

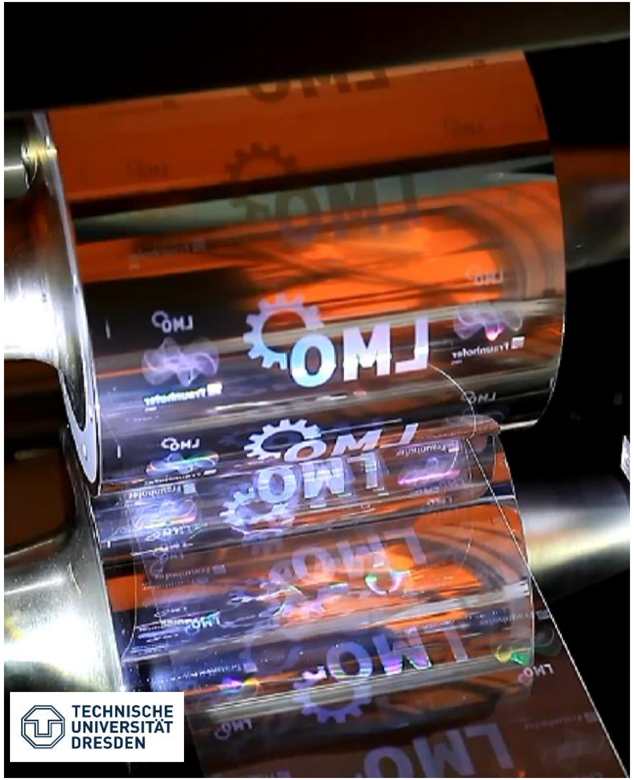
Hot embossing parameters:

Pressure up to 6bar, Temp. up to 170°C, web speed up to 50 m/min, foils up to 250 mm in width

Nanoimprint lithography – technologies and processes



Rank, A., Lang, V. & Lasagni, A. F. High-Speed Roll-to-Roll Hot Embossing of Micrometer and Sub Micrometer Structures Using Seamless Direct Laser Interference Patterning Treated Sleeves. *Adv. Eng. Mater.* **19**, 1–8 (2017).

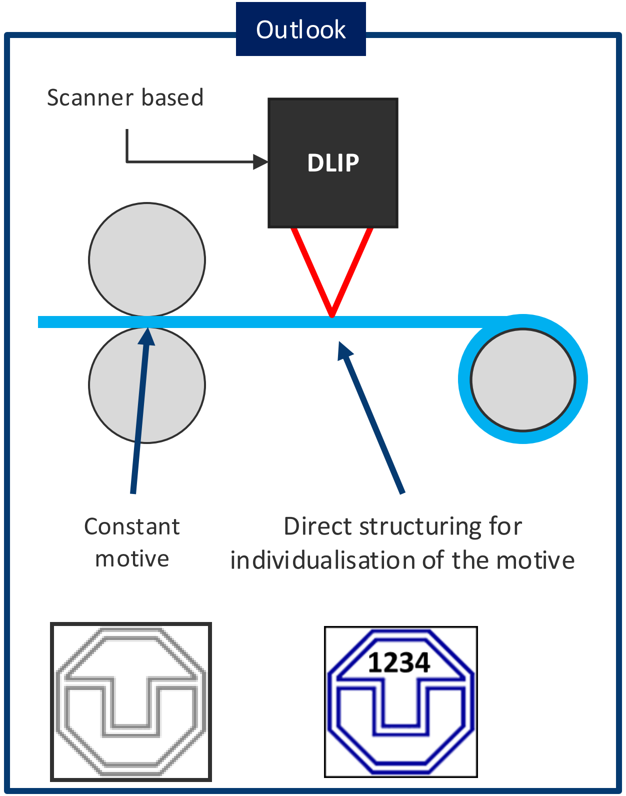


web-speed

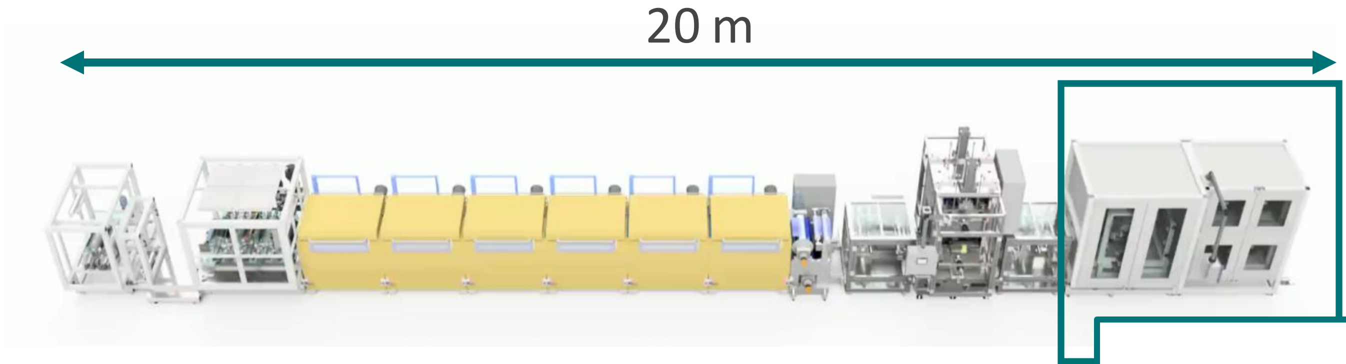
3 m/min

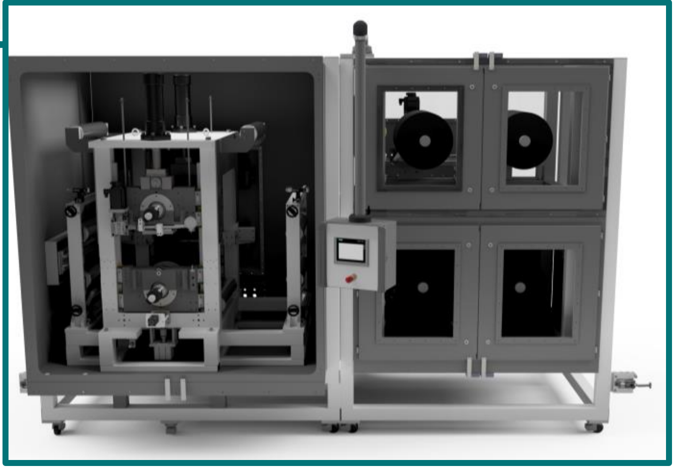
20 m/min

50 m/min



Nanoimprint lithography – technologies and processes



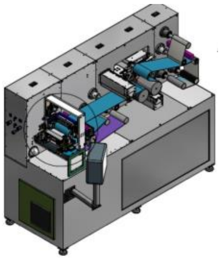


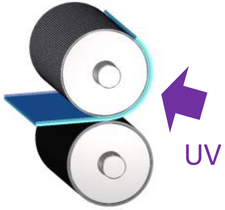
- ✓ 500 mm working width & 100 m/min
- ✓ 9m high performance Drying (Convection + IR)
- ✓ Multi Coating Unit
- ✓ Turret-winder for continuous production
- ✓ 200kN/m imprint pressure

State of the art UV-NIL technology / machinery

R2R

NIL 300 R2R



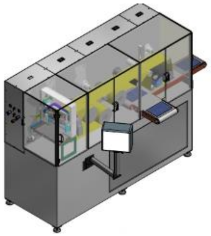


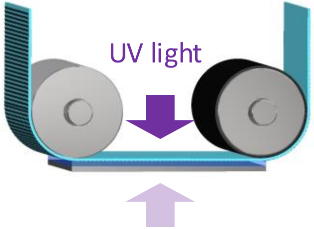
?

Processes on non-transparent substrates

R2P

NIL 300 R2P

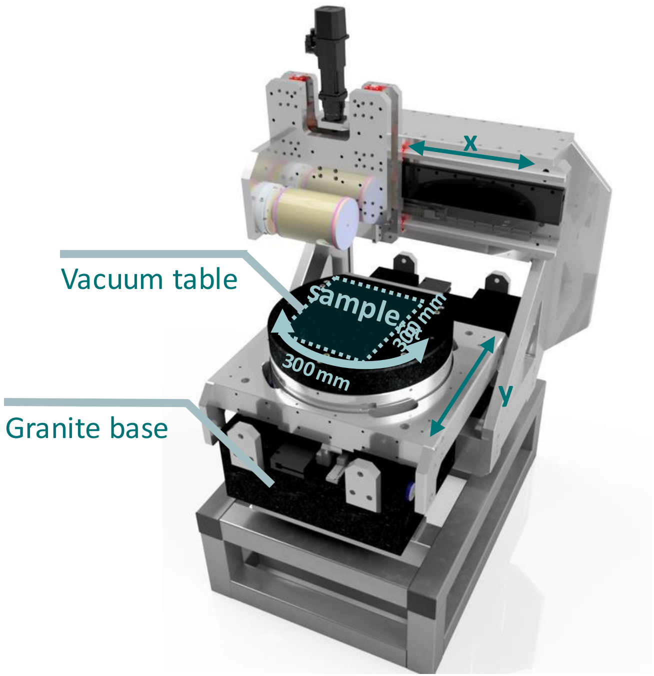




?

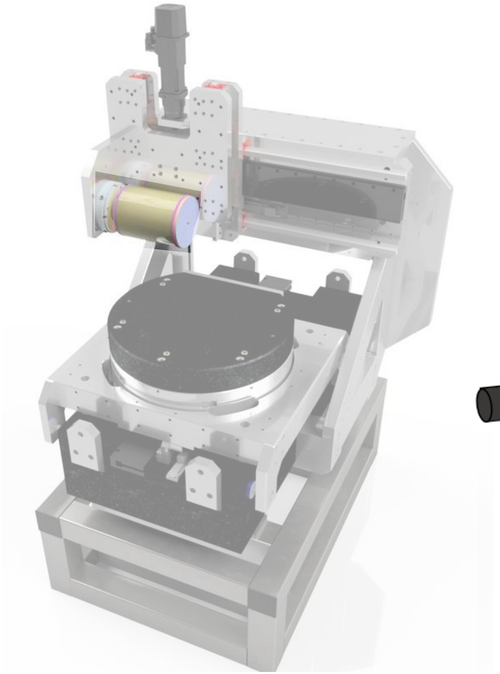
Seamless patterning of large (non-transparent) samples with a small stamp

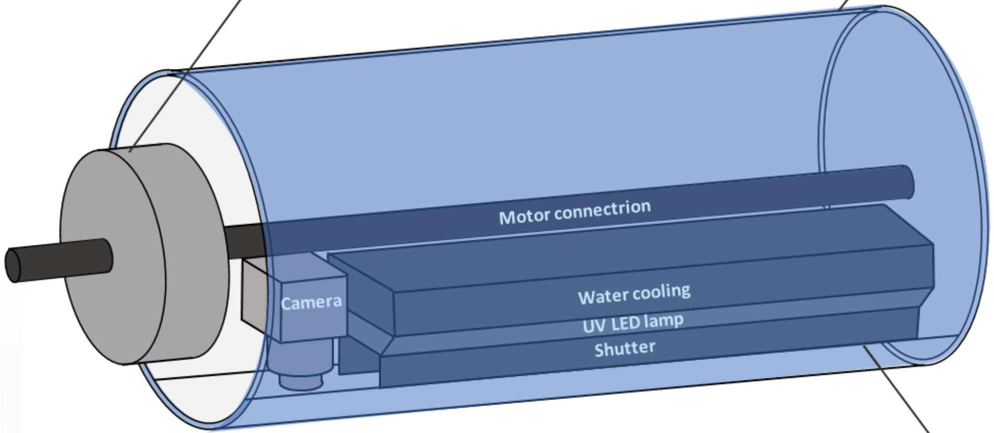
Design concept – high precision R2P S&R tool for UV-NIL



- ✓ R2P Vacuum table for samples up to 300 x 300 mm^2
- ✓ Granite base and vacuum table with 1 µm precision
- ✓ Magnetic linear drives + air gearings + interpolated high resolution linear encoders (resolution in <500 *nm* in xy and ±60 *mas* Rotation)
- ✓ Dust free housing with constant temperature
- ✓ Transparent acrylic based imprint roller with sub *µm* flatness
  - ✓ Integrated high power UV LED-lamp
  - ✓ Integrated interferometric high resolution camera system

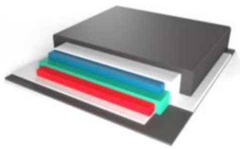
Design concept – high precision R2P S&R tool for UV-NIL





SOLID: Innovative solid-state batteries based on sol-gel materials with Li-metal anode and implemented 3D structuring

- ✓ R2R manufacturing of solid-state thin film batteries
- ✓ Innovative cell concepts
  - ✓ Implementation of a lithium metal anode
  - ✓ Sol-gel cathode and electrolyte
  - ✓ 3D patterning of battery layers



- Li metal
- Interface
- $Li_{1+x}Al_xTi_{2-x}(PO_4)_3$
- Interface
- $LiMn_2O_4$
- Interface
- Steel foil

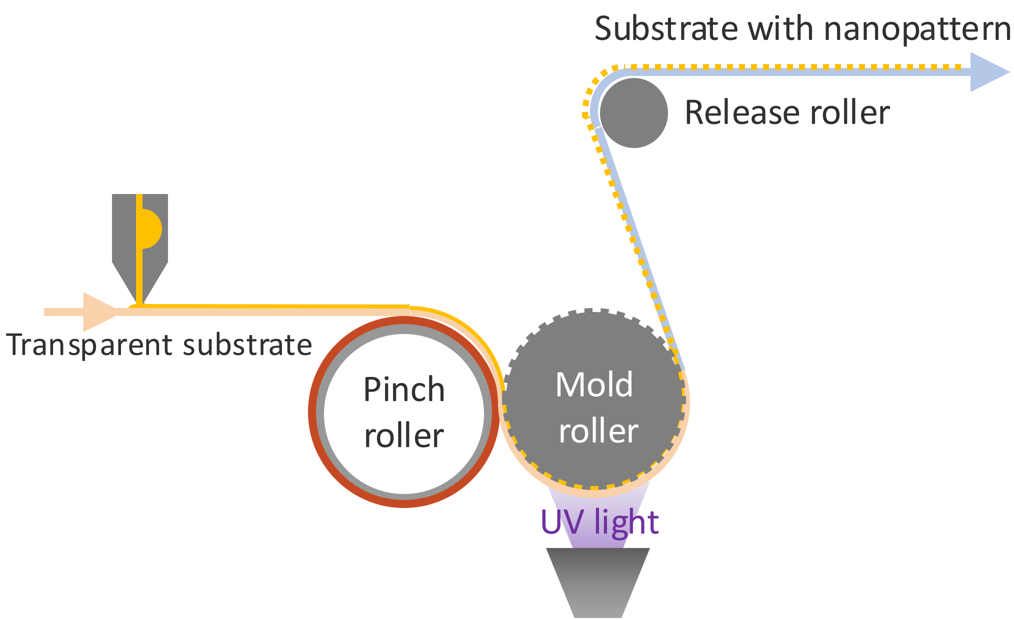
Partners:

Fraunhofer ISE
Fraunhofer ISC
LUNOVU Integrated Laser Solutions
APPLIED MATERIALS make possible
VARTA THE BATTERY EXPERTS

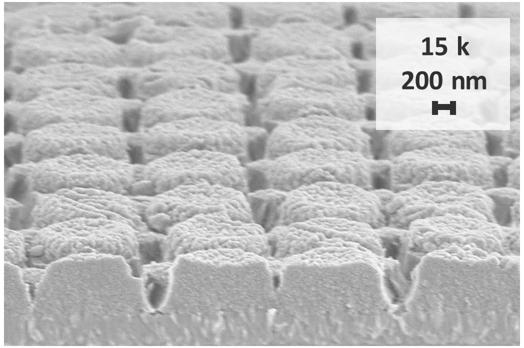
Funding:

Federal Ministry of Education and Research
FKZ: 03XP0129C

Upscaling of the UV-nanoimprint process

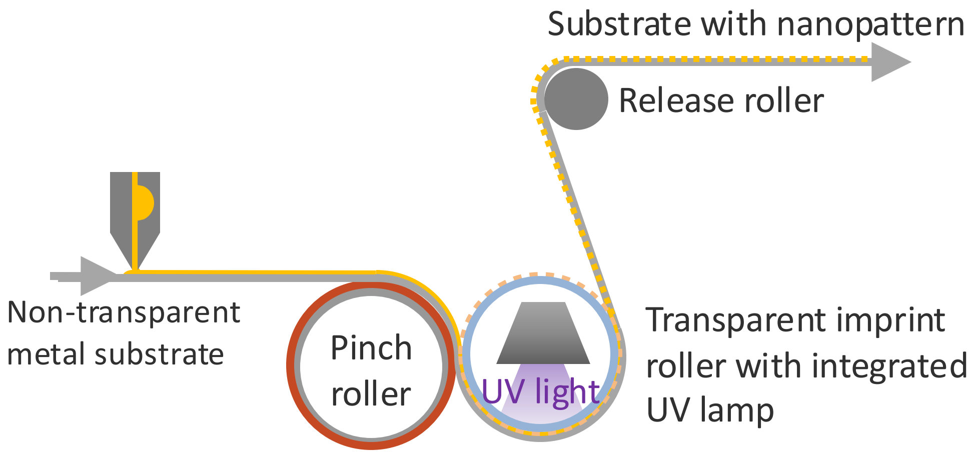


- ✓ Transfer from lab scale R2P → pilot scale R2R process
- ✓ Feature size 300 nm – 1 µm

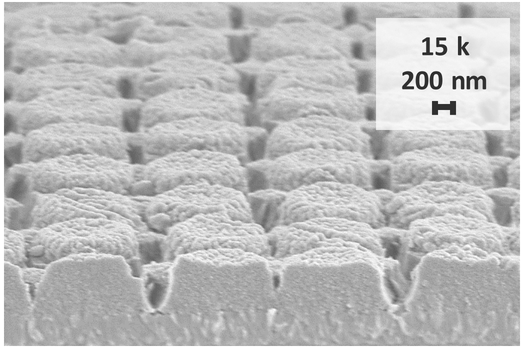


Reference sample prepared using nanoimprint lithography (Fraunhofer ISE)

Upscaling of the UV-nanoimprint process



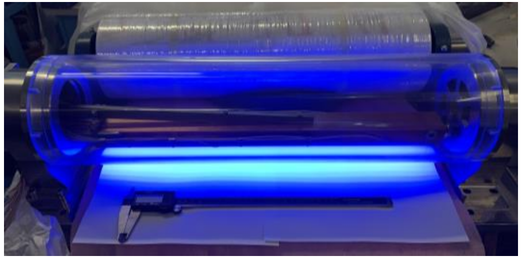
- ✓ Transfer from lab scale R2P → pilot scale R2R process
- ✓ Feature size 300 nm – 1 µm
- ✓ Process must be suitable for non-transparent substrates



Reference sample prepared using nanoimprint lithography (Fraunhofer ISE)

- ✓ **Implementation of a transparent imprint roller on 500 mm working width**

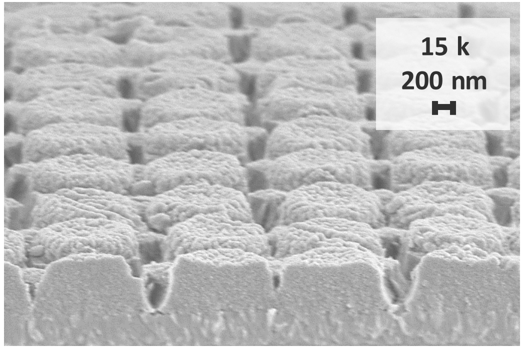
Upscaling of the UV-nanoimprint process



Transparent imprint roller with 500 mm working width

Design concept of the Click&Coat™ module with the transparent imprint roller

- ✓ Transfer from lab scale R2P → pilot scale R2R process
- ✓ Feature size 300 nm – 1 µm
- ✓ Process must be suitable for non-transparent substrates



Reference sample prepared using nanoimprint lithography (Fraunhofer ISE)

- ✓ **Implementation of a transparent imprint roller on 500 mm working width**
- ✓ **Integration into the modular Click&Coat™ pilot line**

8.

Drying technologies

Introduction thermal drying – Coating parameters

Coating chemistry	Coating processes	Process control	Drying
✓ Rheology ✓ Viscosity ✓ Viscoelasticity ✓ Type of solvents ✓ Solid content ✓ Van der Waals force ✓ Sheer ratio ✓ Adhesion/Cohesion	✓ Coating systems ✓ Single or multilayer coatings ✓ Direct coatings ✓ Transfer (indirect) coatings ✓ Substrate speed ✓ Layer thickness ✓ Coating accuracy	✓ Process layout ✓ Tension control system ✓ Material guiding system ✓ Inline parameter control ✓ Quality control	✓ Convection drying ✓ Contact drying ✓ Infrared drying ✓ Sintering ✓ NIR ✓ High frequency ✓ UV crosslinking systems

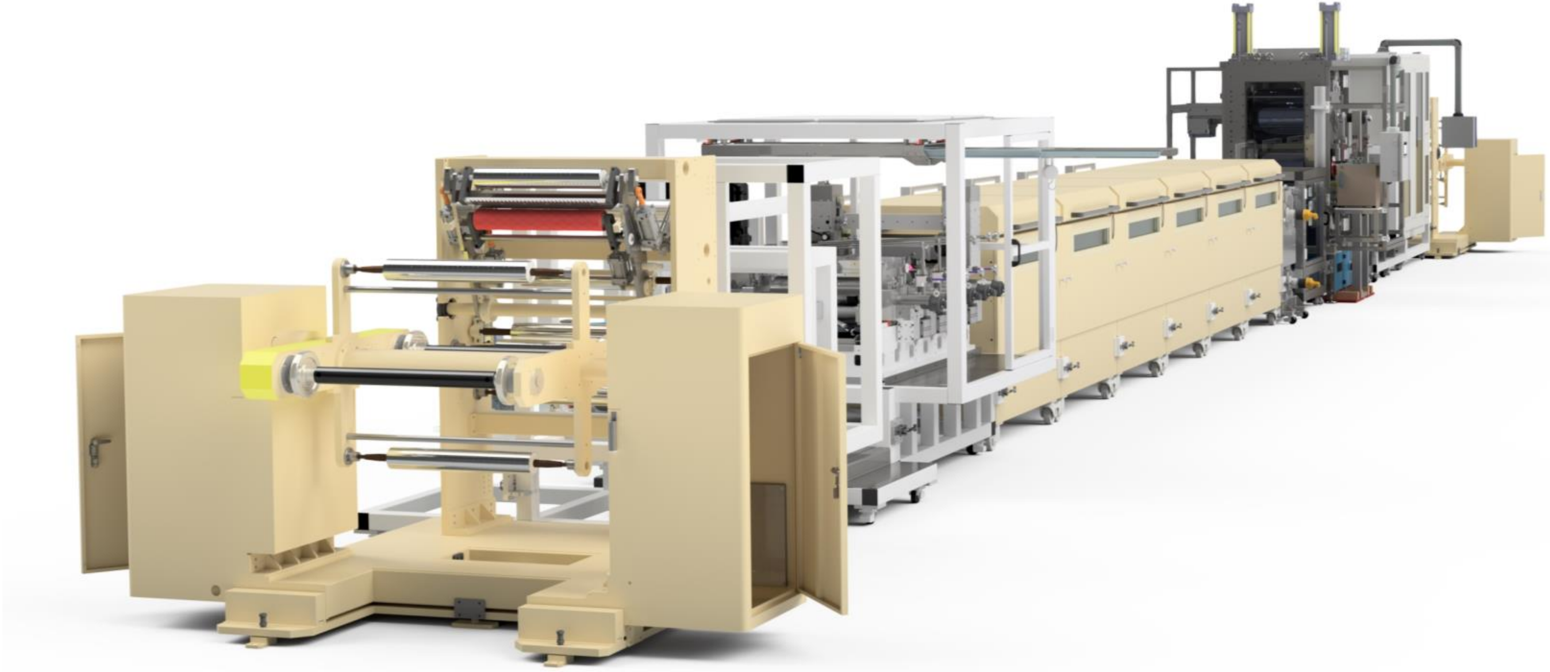
Substrate	Pretreatment	Environment	Finishing
✓ Surface tension ✓ Dimension stability ✓ Surface structure ✓ Contact angle	✓ Corona ✓ Plasma ✓ Cleaning	✓ Humidity ✓ Temperature ✓ Inert conditions	✓ Calendaring ✓ Embossing ✓ Slitting

Dryer specs needed for the layout

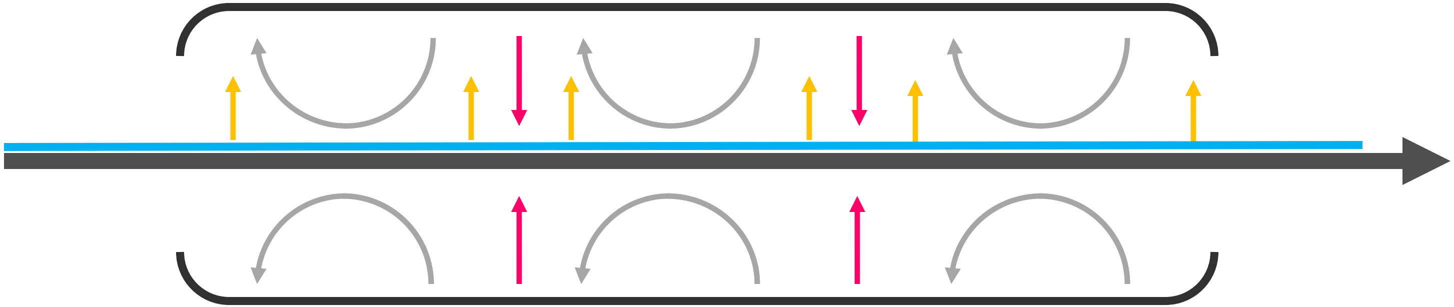
Information about the substrate

- ✓ Web weight – weight per unit area
- ✓ Web material
- ✓ Specific heat of web
- ✓ Temperature limitations
- ✓ Operating web tension – tension sensitivity
- ✓ Special characteristics

The Click&Coat^{TM} in production scale



Introduction thermal drying – As general as possible(!?)



- ✓ Heat Conduction/ Heat Diffusion
- ✓ Heat Convection/ **Mass Transfer**
- ✓ Radiation

Substrate
Coating
Heat transfer
Evaporating solvent
Solvent vapor transfer

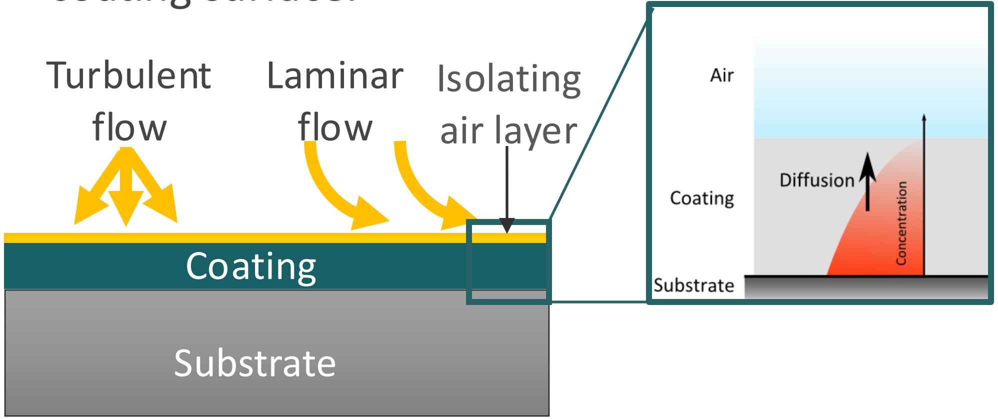
Mass Transfer

Basics mass + heat transfer – Drying dynamics: The Boundary Layer

An isolating air layer forms just on top of the coated film

✓ Without convection mass+heat transfer is limited to diffusion and therefore slow.

✓ Convective (laminar or turbulent) flow needs to be applied without sacrificing the coating surface.

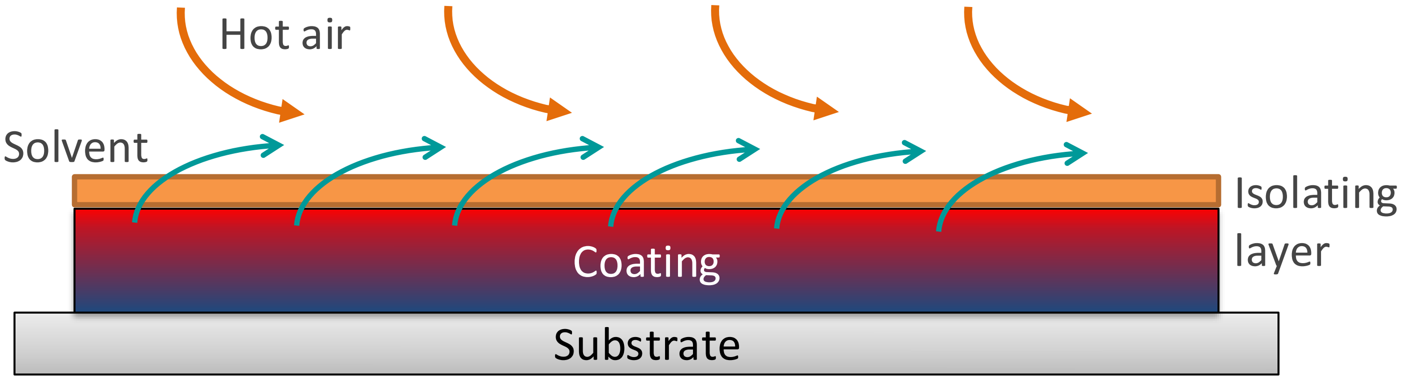


Usually there is a trade-off:

effective fast heat/mass transfer
or
gentle mild slow drying

Basics mass + heat transfer – Drying dynamics: Hot air drying

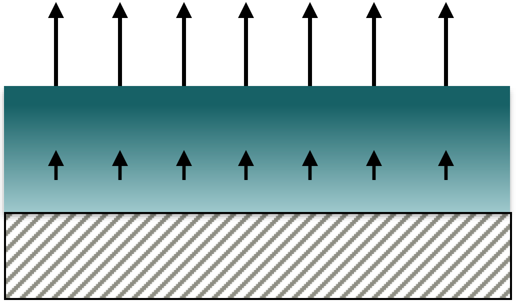
- ✓ Heating and vapor transport combined
- ✓ Bulk heating by thermal conductivity from surface
- ✓ Isolating layer to be overcome by air flow
- ✓ High air flow deteriorates surface
- ✓ Temperature easy to limit
- ✓ Slow



Basics mass + heat transfer

Nothing is as easy as it seems: Diffusion limit and skinning

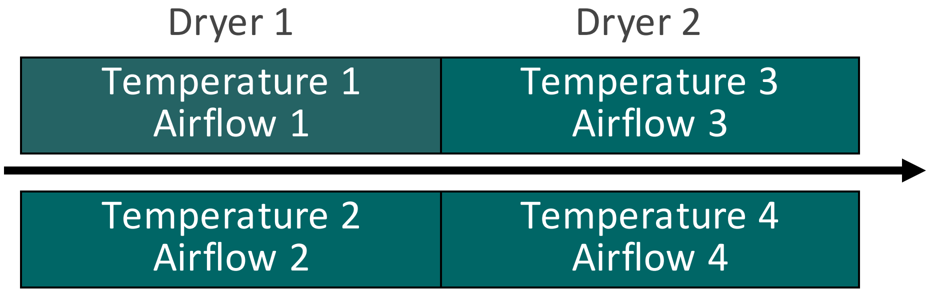
- ✓ Drying is also limited by solvent diffusion (at least in the final state of low residual solvent content).
- ✓ If the internal diffusion is slower than the evaporation from the surface, then a skin may be created.
- ✓ The skin acts as a barrier. The remaining diffusion through the skin may be slower than the wet diffusion by many orders of magnitude.



So the initial evaporation must be reduced by low temperature and/or by partially saturated atmosphere. Despite reduced evaporation the total drying time then may be shorter than at full initial evaporation.

Basics mass + heat transfer – Drying dynamics: Drying zone design

- ✓ Downweb temperature profiles can be realized by partitioning the dryer in different zones with different drying parameters.
- ✓ But temperature uniformity is difficult.
  Possible cause: Mixing of hot and cool air at unintended leakages by Venturi effect.
- ✓ Experience shows, that there is always a compromise:
  Good temperature uniformity requires low homogeneous air flow. High air flow results in less temperature uniformity.



Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

Industrial drying systems

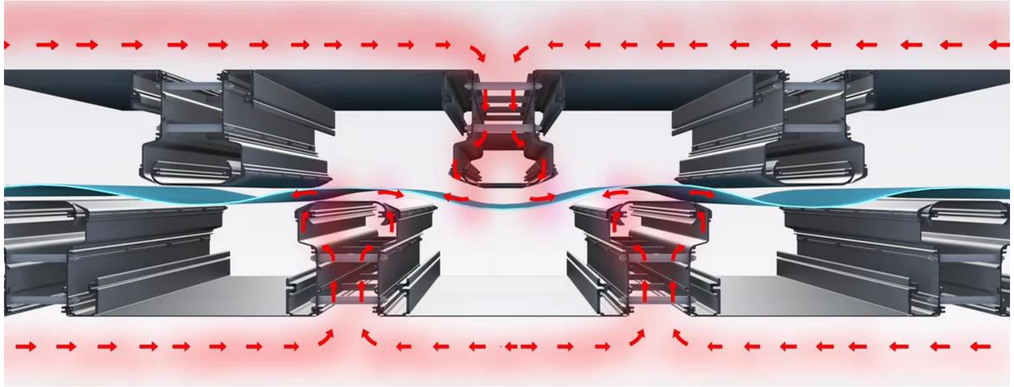
Coatema slot nozel and circulation dryer on small scale

Industrial drying systems

Coatema slot nozel and circulation dryer on small scale

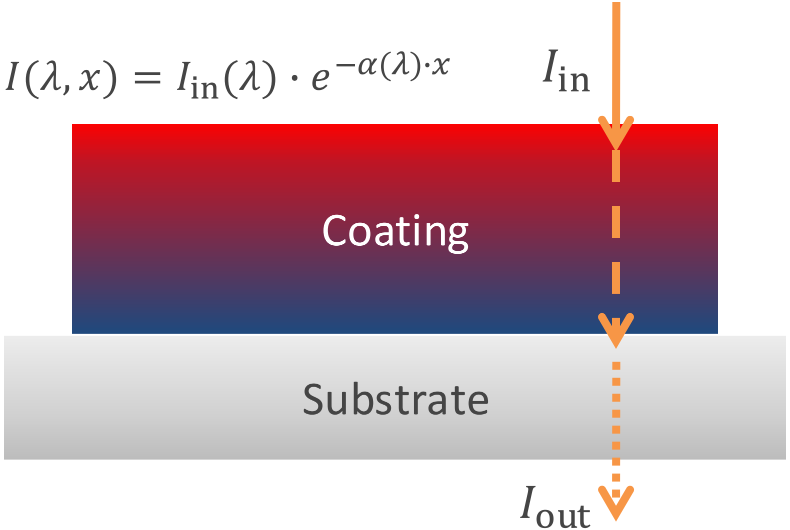
Flotation Click&Coat™ dryer prinziple

Drytec Click&Coat^{TM} dryer prinziple



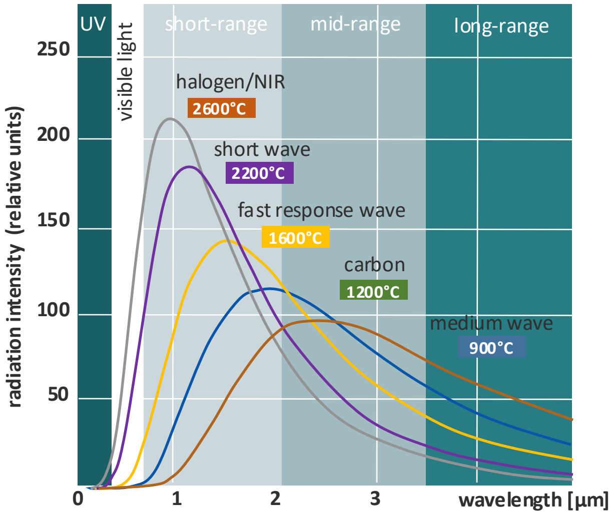
Basics mass + heat transfer: (N)IR technology

$$I(\lambda, x) = I_{\text{in}}(\lambda) \cdot e^{-\alpha(\lambda) \cdot x}$$



$I_{\text{in}}(\lambda)$	Intensity in
I_{out}	Intensity out
$\alpha(\lambda)$	Absorption coefficient
d	Layer thickness

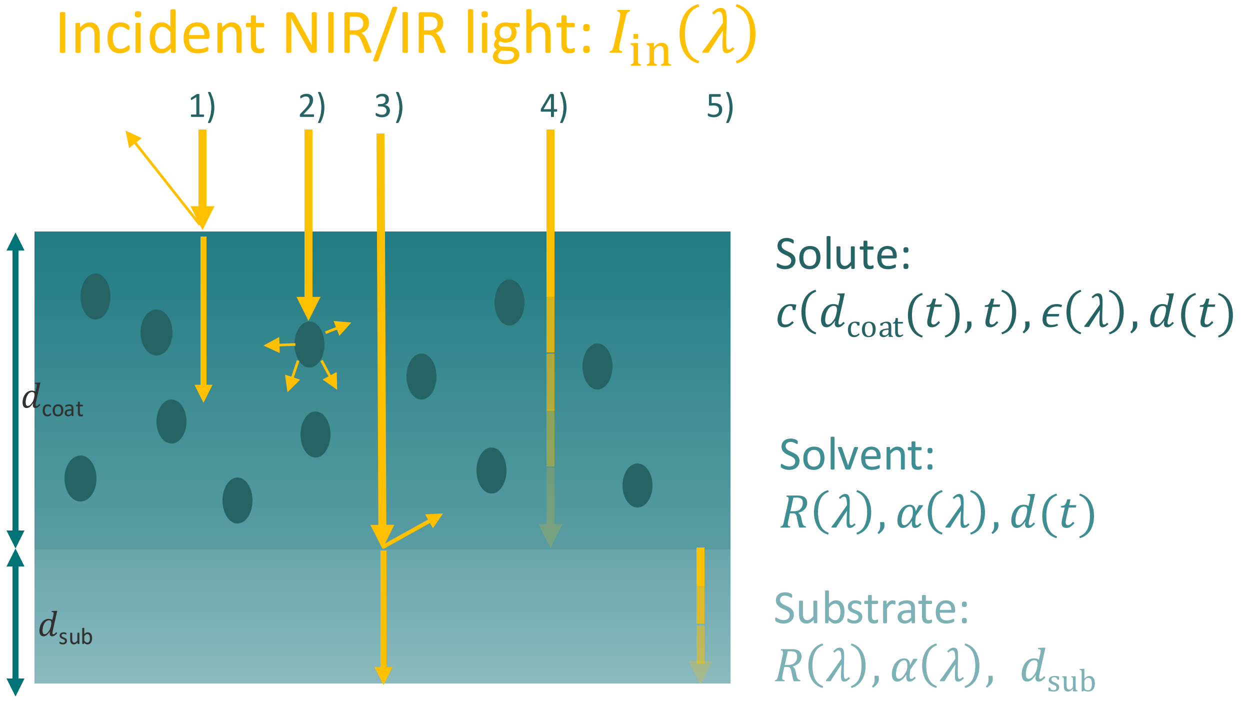
High absorption | Optimum absorption | Low absorption



Relative intensity of radiators at different wavelengths

Light-Structure interaction

1) Surface reflection R
2) Solute absorption α and scattering ϵ
3) Internal reflection R
4) Solvent absorption α
5) Substrate absorption α

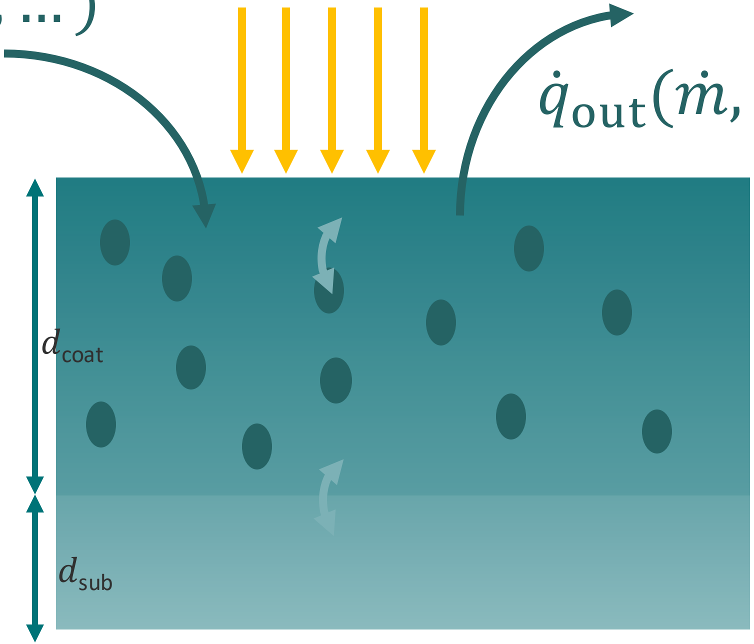


Thermodynamic Model

$$\dot{q}_{\mathrm{in,conv}}(\mathrm{Re}, \mathrm{Pr}, \ldots)$$

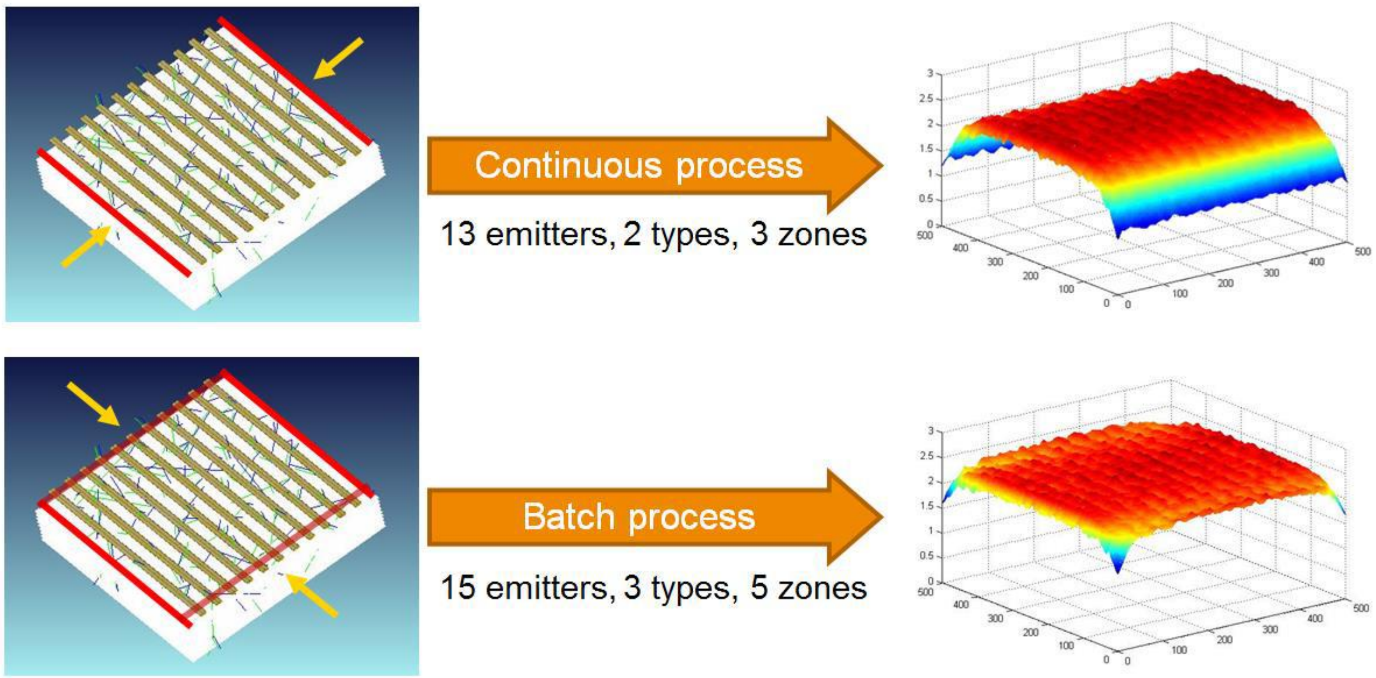
$$\dot{q}_{\mathrm{in,opt}}(\lambda)$$

$$\dot{q}_{\mathrm{out}}(\dot{m}, \mathrm{Re}, \mathrm{Sc}, D_{\mathrm{mass}}, T, \phi, \ldots)$$



Heat diffusion between Solute, Solvent and Substrate

IR / NIR Drying – Infrared drying



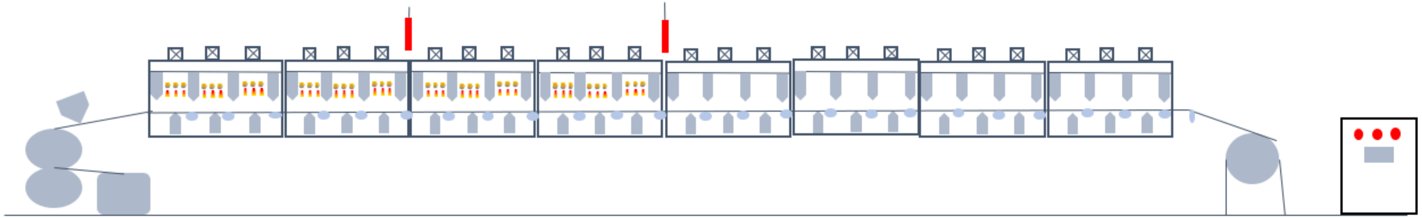
Source: Heraeus Noblelight

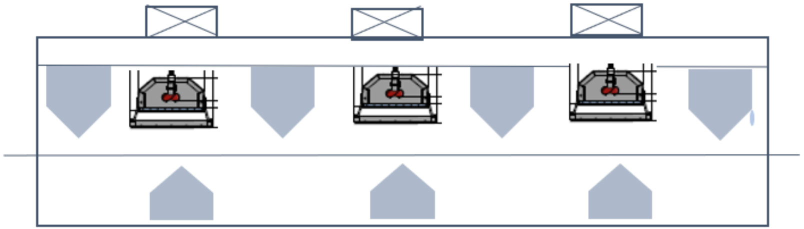
Heraeus

Coatema®
Coating Machinery GmbH

IR / NIR Drying – Infrared drying

Layout





Hotair oven: 50m (10 zone)

IR at first 25m (5 zone) for boost

Heating distance : 100mm

Qty of IR : 60 *3.1Kw = 186Kw

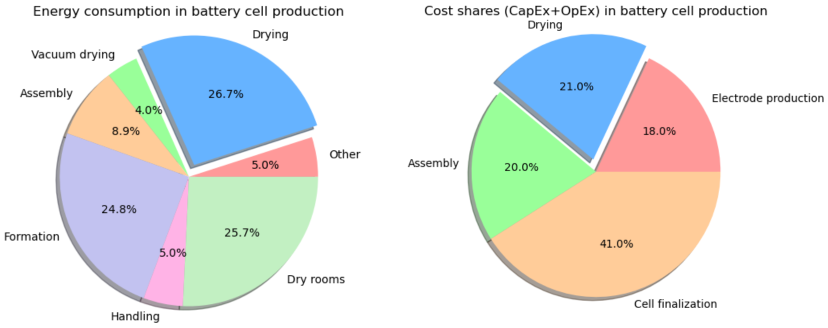
Source: Heraeus Noblelight

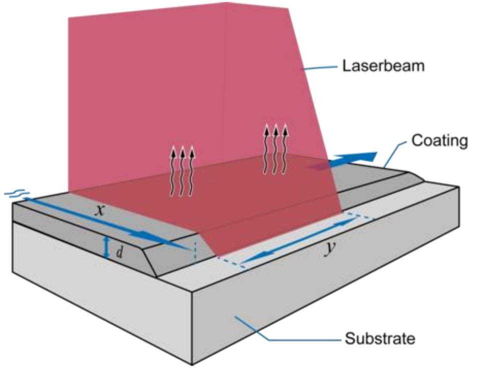
IR technology – combined hot air / IR dryer in 2010

FKZ: 03XP0414B

Laser drying of battery slurry

- ✓ Typically, a high-power laser, such as a diode laser o a fiber laser, is used for this purpose
- ✓ The laser passing through the optics is directed at a large
- ✓ The absorbed laser energy rapidly heats the solvent in the slurry, causing it to evaporate
- ✓ The quick drying might help preventing the formation of cracks or defects in the electrode
- ✓ Laser drying is **more energy-efficient** compared to traditional drying
- ✓ Laser drying can be adapted for use in high-volume battery manufacturing processes.





Source: Laserline

[1] Degen et al. (*Life cycle assessment of the energy consumption and GHG emissions of state-of-theart automotive battery cell production*) 2022
[2] Küpper et al. (*The future of battery production for electric vehicles*) 2018

Laser drying

Laser System: The laser should be capable of delivering the necessary energy for solvent evaporation without damaging the electrode material.

Temperature Control: Implement temperature control systems within the drying chamber to ensure that the slurry is dried at the suitable temperature.

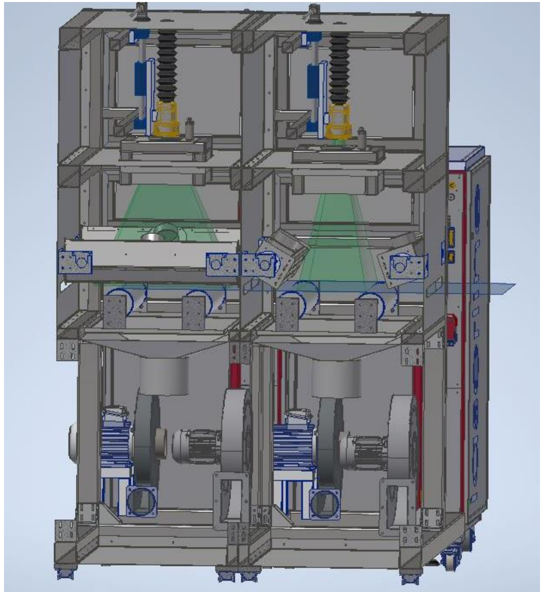
Gas Atmosphere: Consider the use of inert gases or controlled atmospheres within the drying chamber to prevent unwanted reactions or oxidation of the electrode materials during the drying process.

Monitoring and Control: Incorporate sensors and monitoring systems to continuously measure key parameters such as temperature, humidity, and laser power.

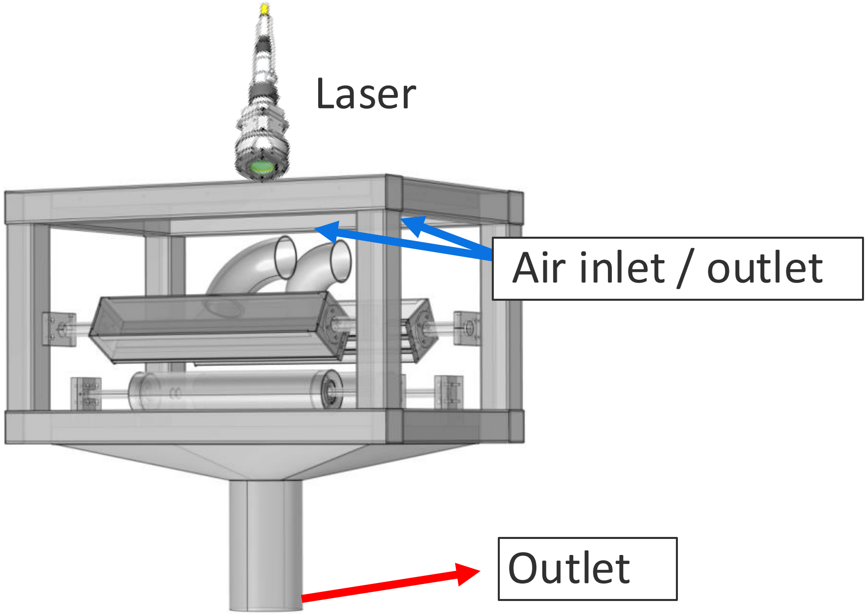
Drying Chamber: Design a drying chamber that allows for precise control of temperature, airflow, humidity, etc. to assure a **uniform and efficient drying.**

Laser dryer

Coatema's design

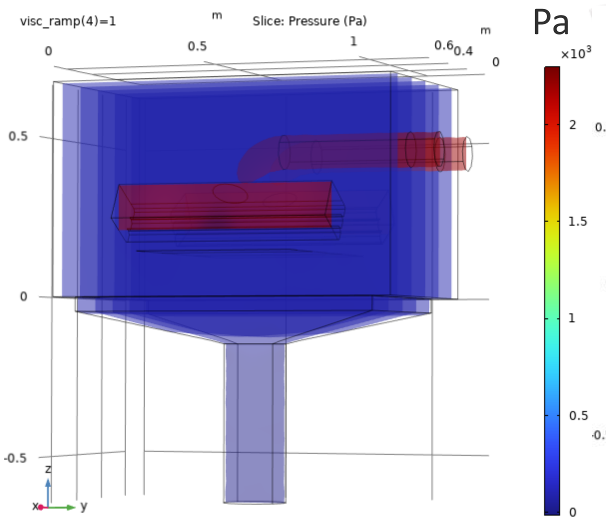


Geometry used for simulation

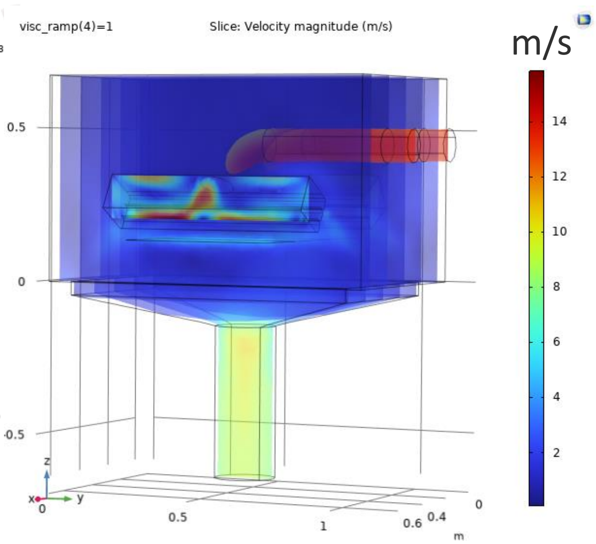


Web speed 30m/min, in -x direction

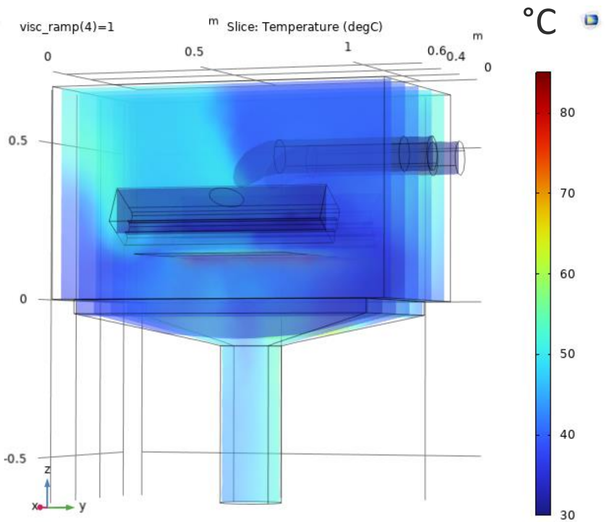
Pressure



Air velocity

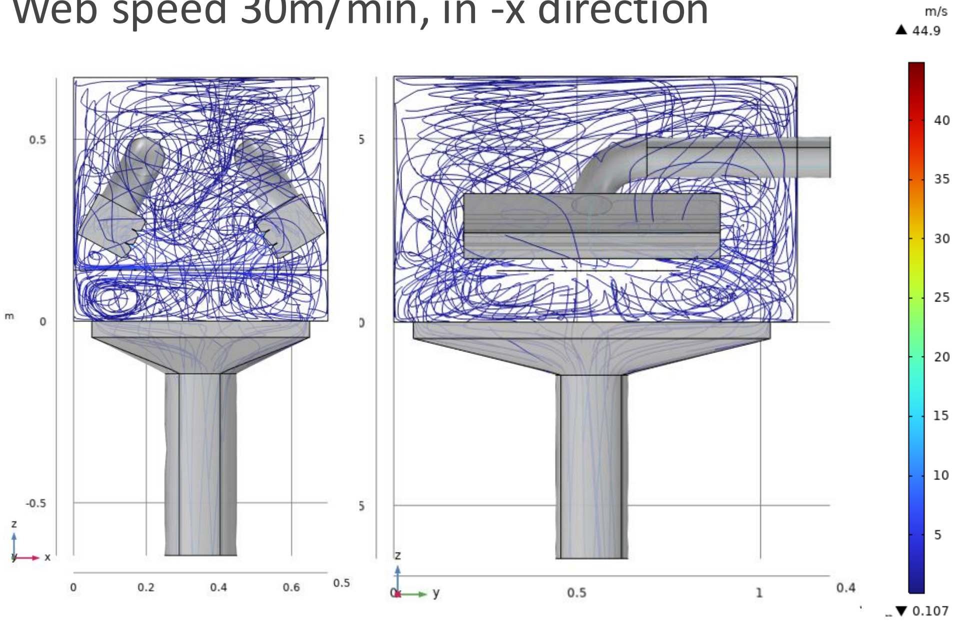


Temperature

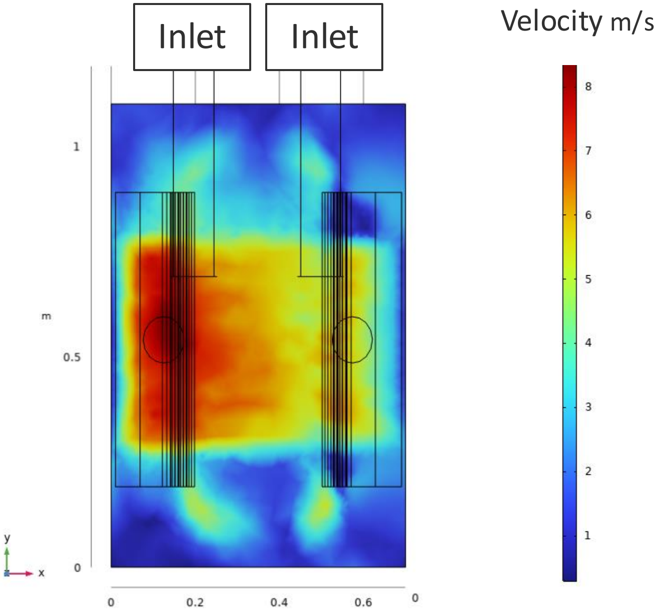


Airflow in 3D, testing different design possibilities

#1: 2 inlets, 1 outlet
Web speed 30m/min, in -x direction

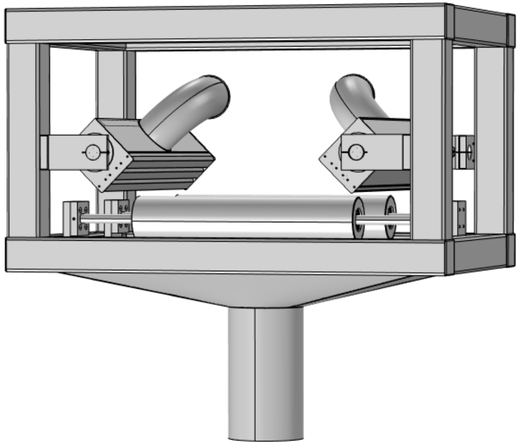


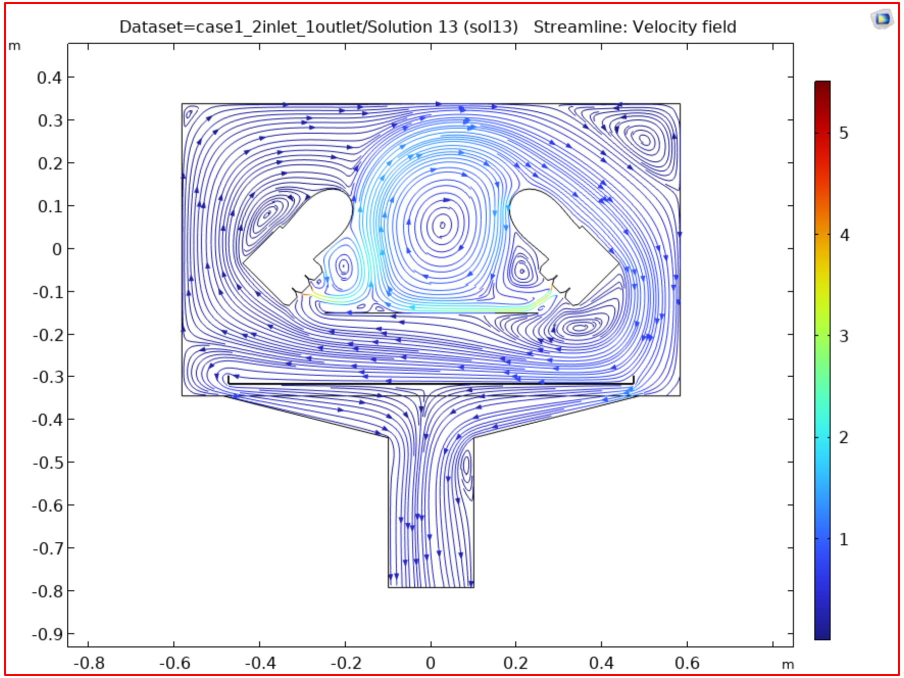
Volumetric air inflow~ 300 m3/hr



Airflow in 3D, testing different design possibilities

- ✓ The air is blown in a transverse direction to the web
- ✓ 280 mm x 350 mm laser area

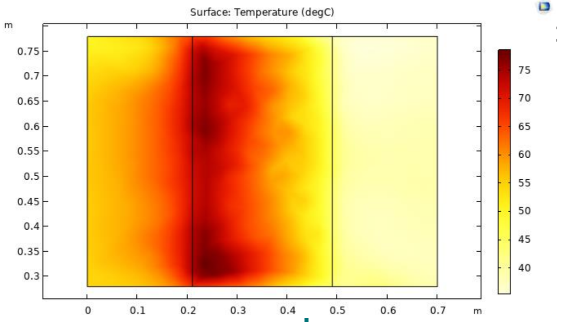




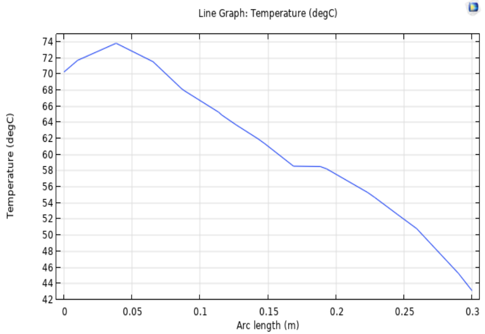
Airflow in 3D, testing different design possibilities

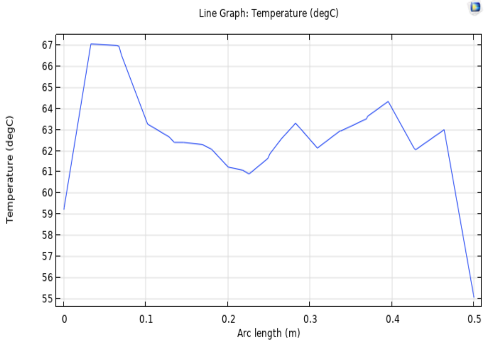
Evaporation is not included in the model!

From Simulation

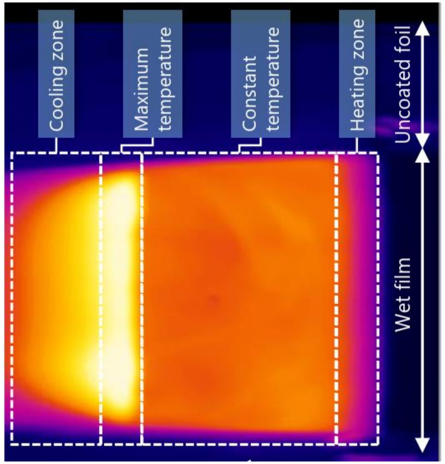


Direction of web





From thermographic camera



Thermographic analysis of the laser drying process

9.

Spatial ALD

Spatial ALD


SPATIAL ALD
INNOVATORS
Explore. Develop. Integrate. Together.

SALD BV

SALD BV is an Eindhoven (NL) based Spatial ALD-equipment specialist serving the following green growth markets:

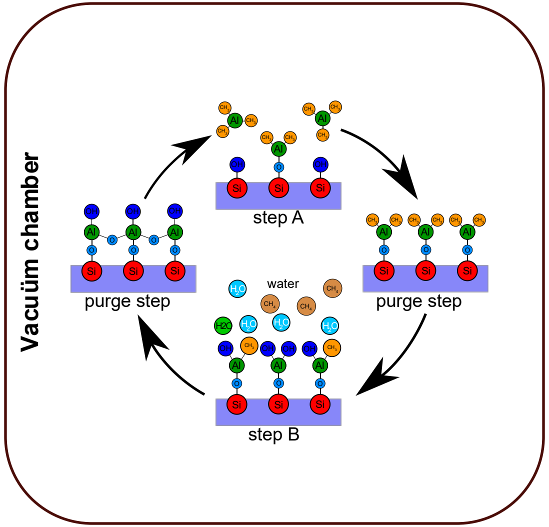
- ✓ Li-ion **batteries & SSB** coatings
- ✓ next-gen **thin-film solar** (OPV, perovskites)
- ✓ **fuel-cells** and **electrolyzers**
- ✓ Membranes & packaging **foils**
  - ✓ We have over 10 years industrial experience with Spatial ALD processes
  - ✓ We supply compact Spatial ALD machine for Research and small-scale production
  - ✓ Our technology is scalable from lab-scale up to 24/7 high-volume production

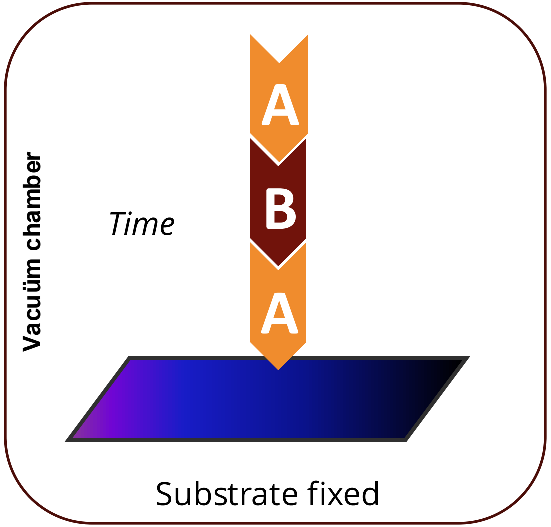
Classic ALD vs. Spatial ALD

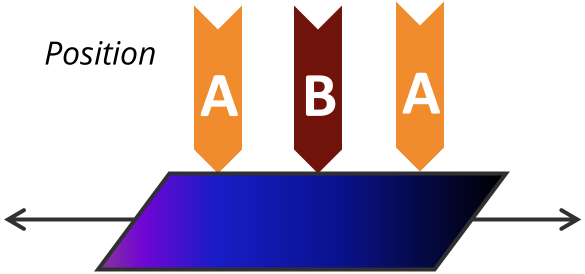
Temporal ALD:
Gas-phase self-limiting deposition process.
One atomic layer per cycle

Temporal ALD:
Precursor (A) and co-reactant (B) are **separated in time** in vacuüm

Spatial ALD (SALD):
Precursor (A) and co-reactant (B) are **separated in space** in atmospheric pressure





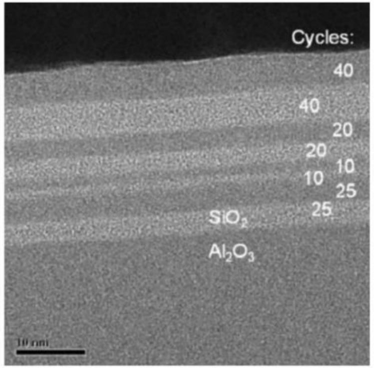


Substrate moves
(v_{max} = 1.5 m/s)

Temporal ALD vs. Spatial ALD & benefits ALD

	Temporal ALD	**Spatial ALD (SALD)**
Processing	Batch only	**In-line** / continues / R2R
Atmospheric pressure	No	Yes
Single-sided deposition possible	No	Yes
Typical deposition rate (Al_2O_3)	0.2 nm/min	60 nm/min

- ✓ High quality material
- ✓ Precise control in film-thickness
- ✓ Excellent uniformity
- ✓ Wide range of materials such as: metaloxides, metalnitrides, sulfides, fluorides, metals etc.
- ✓ Directly available: Al_2O_3, ZnO, ZnO:Al, SnO_2, TiO_2, SiO_2
- ✓ Low- and high temperature processing possible (50˚C – 350˚C)



Partners in Spatial ALD for Roll-to-Roll production

Spatial ALD for Roll-to-Roll production

Roll-to-Roll spatial ALD solution:

- ✓ 6 nm single pass coating at 60 m/min
- ✓ Substrate width on specification
- ✓ Demonstrator available from begin of December for demonstration / sampling

Contact us:

SPATIAL ALD INNOVATORS

Explore. Develop. Integrate. **Together.**

In Summary

- ✓ Thermal and Plasma enhanced Spatial ALD concepts for lab and scalable into high volume production
- ✓ SALD is the only company with field experience of Spatial ALD for high volume production
- ✓ Spatial ALD can be integrated in existing high volume production lines
- ✓ SALD has experience with: Al_2O_3, ZnO, ZnO:Al doped, SnO_2, TiO_2 and plasma enhanced SiO_2
- ✓ SALD systems can be equipped with a protective environment like N_2 or Ar.

SALD is an open and flexible company:

- ✓ Open for joint development programs
- ✓ Feasibility studies and sampling for new materials and/or applications
- ✓ Collaborate to find the best thin-film solution for your application
- ✓ Open for investments

10.

Summary

Bridging the gap

Needed for success:

- ✓ Reproducible results in every step of scale?
- ✓ Reality check if the approach is really scalable?
- ✓ Is the approach an approach for the real life production environment or is it rocket science?
- ✓ Are economies of scale reachable and when?
- ✓ Is durability really needed?
- ✓ Standardization of device manufacturing is the key for the industry
- ✓ Maybe small is the new big?

Do not hesitate to contact us!

Anything missing?

Let us know and we will make it happen!

Our R&D centre is worldwide the most versatile centre for coating, printing and laminating.

Sales department:
sales@coatema.de

Download broschures & presentations

Coatema

Thank you

Roseller Straße 4 ▪ 41539 Dormagen ▪ Germany
T +49 21 33 97 84 - 0 ▪ info@coatema.de

www.coatema.com

MEMBER OF ATH