Coatema®

Coating Machinery GmbH

# Coating solutions for batteries
# lab 2 fab concept

# Overview

- Introduction
- Battery basics
- Coating systems
- Drying, curing & crosslinking
- Todays equipment
- Battery production lines
- The battery fab
- Proof of concept

# Summary

| | | | |
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# Overview

Quality
made in Germany

Innovations

Part of the ATH Holding

Working widths
from 100 mm
up to 5,400 mm

Coating

Printing

Laminating

Bespoke
equipment

Founded
1974

Printed electronics
Medicals
Membranes
Pharmaceutics
Renewables
Prepregs
Textiles

From lab 2 fab

R&D
projects & network

Worldwide
service

# Group of companies

ATH ALTONAER TECHNOLOGIE HOLDING

| KROENERT | DRYTEC | Coatema® Coating Machinery GmbH | ZAE ANTRIEBSSYSTEME |
|---|---|---|---|
| ✓ Founded 1903 | ✓ Founded 1995 | ✓ Founded 1974 | ✓ Founded 1919 |
| ✓ Approx. 200 employees | ✓ Approx. 50 employees | ✓ Approx. 50 employees | ✓ Approx. 140 employees |
| ✓ Located in Hamburg | ✓ Located in Norderstedt | ✓ Located in Dormagen | ✓ Located in Hamburg |

## Summary

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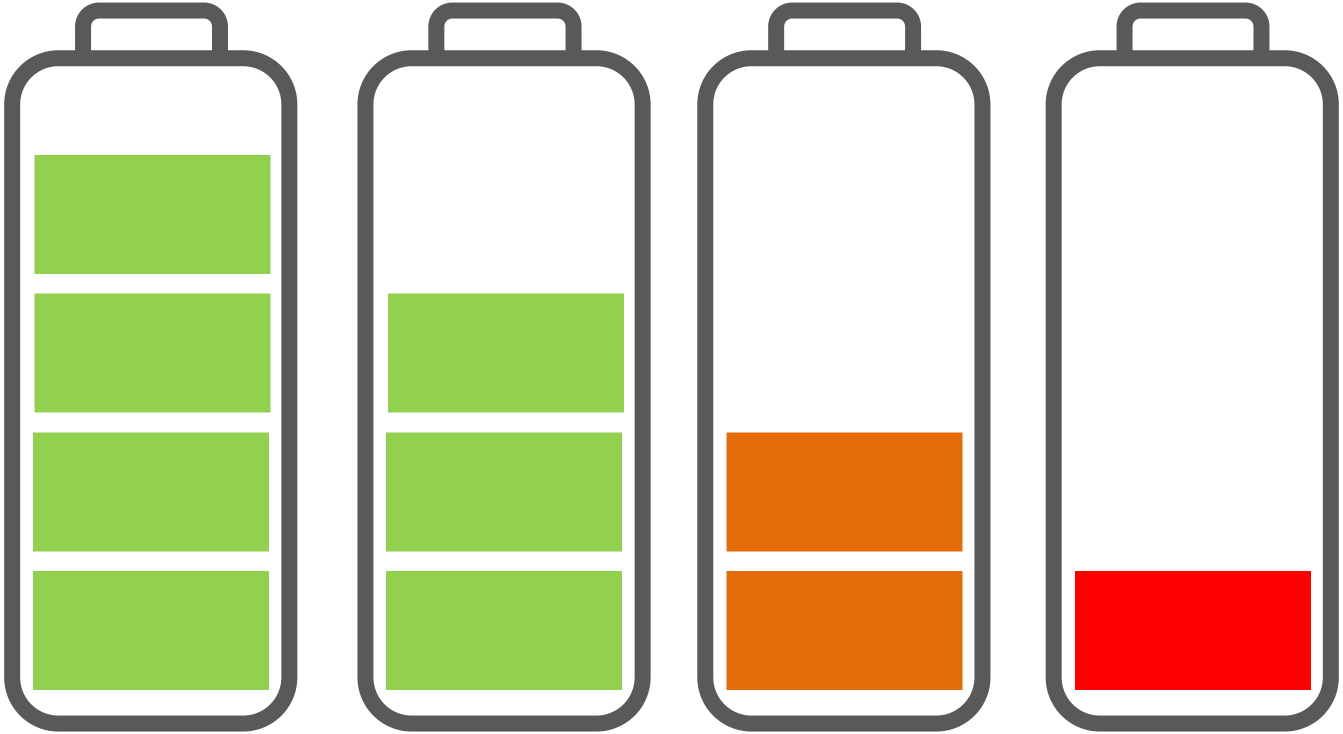
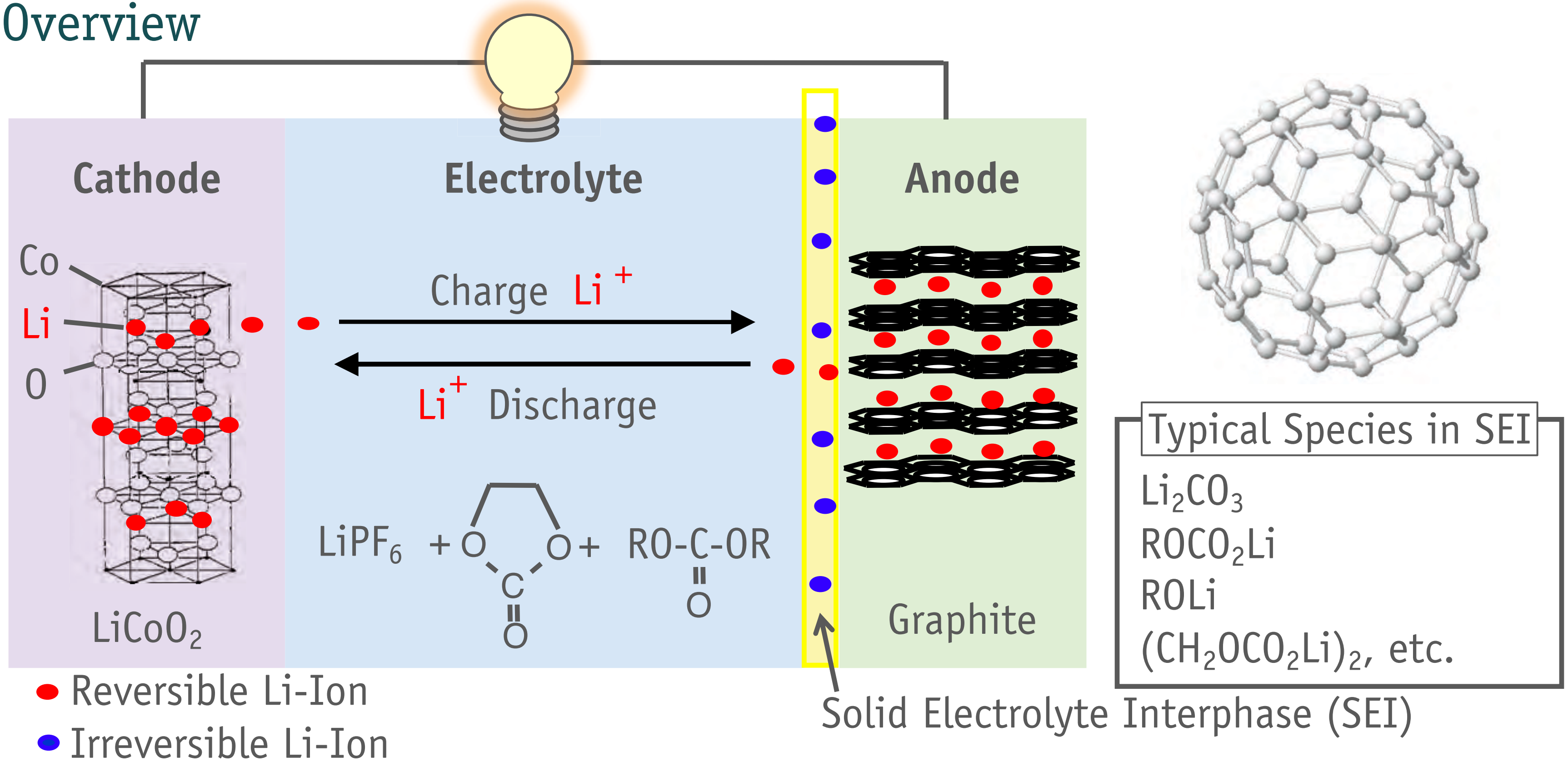
# Battery basics



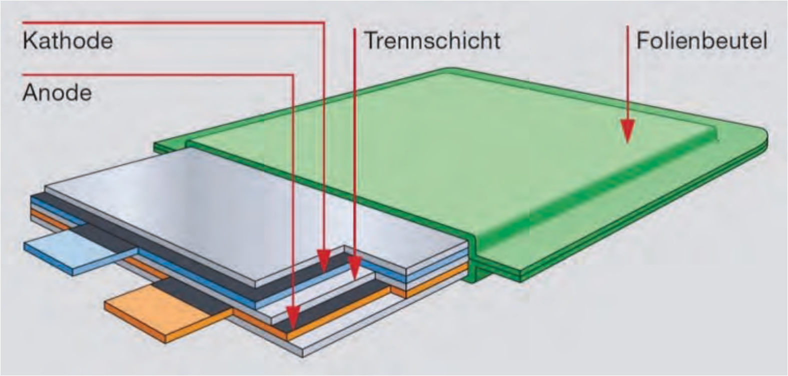
# Overview

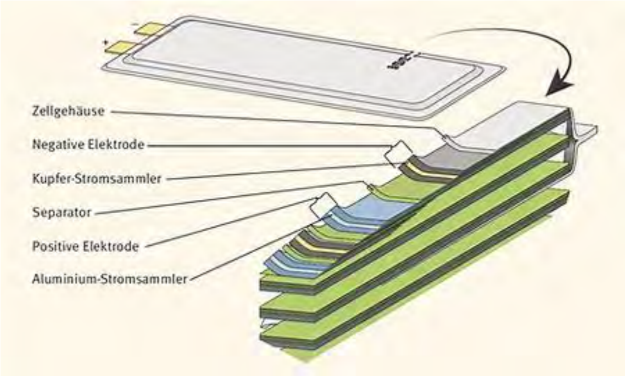
| Storage-systems | Energy-carrier | Energy-density | | Power-density | Lifetime / Cycles no. | Self-discharge |
|---|---|---|---|---|---|---|
| | | Wh/kg | Wh/l | | | |
| Capacitor | $e^-$ Super cap | 4 | 5 | ++ | + / ++ | -- |
| Primary cells | Zn-C | 60 – 100 | 100 – 150 | -- | o / -- | + |
| | $Zn-MnO_2$ | 100 – 150 | 200 – 300 | o | + / -- | ++ |
| | $Zn-O_2$ | approx. 300 | approx. 450 | + | o / -- | + |
| Secondary cells | Pb-PbO2 | 20 – 40 | 50 – 100 | o | o / o | + |
| | Ni-Cd | 40 – 60 | 100 – 150 | + | ++ / ++ | - |
| | Ni-MeH | 60 – 90 | 150 – 250 | + | ++ / ++ | -- (++) |
| | Ag-Zn | 80 – 120 | 150 – 250 | ++ | - / - | ++ |
| | Li-Ion | 100 – 200 | 150 – 500 | + | + / + | + |
| Fuel cells | $H_2$ (300 Bar) | 33.000 | 2400 | o | | ++ |
| | $H_2$ (liquid) | 33.000 | 750 | o | | o |
| | $H_2$ (MeH) | 600 | 3200 | o | | ++ |
| | Methanol | 5600 | 4400 | - | | ++ |
| Combustion engines | Petrol | 12700 | 8800 | ++ | | ++ |
| | Diesel fuel | 11600 | 9700 | ++ | | ++ |

# Overview

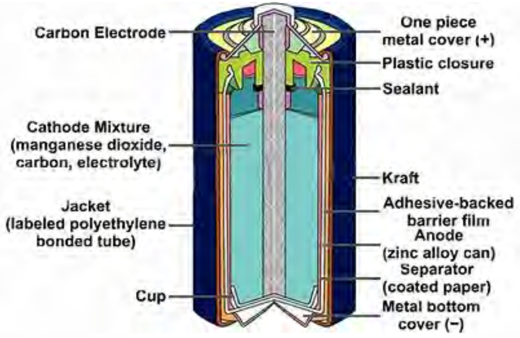

Cathode
Electrolyte
Anode
Co
Li
O
LiCoO2
Charge Li+
Li+ Discharge
LiPF6 + O O + RO-C-OR
C
O
O
Graphite
Typical Species in SEI
Li2CO3
ROCO2Li
ROLi
(CH2OCO2Li)2, etc.
Reversible Li-Ion
Irreversible Li-Ion
Solid Electrolyte Interphase (SEI)

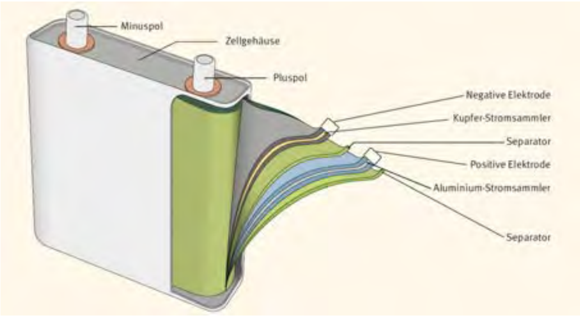
# Overview


Kathode
Anode
Trennschicht
Folienbeutel


Zellgehäuse
Negative Elektrode
Kupfer-Stromsammler
Separator
Positive Elektrode
Aluminium-Stromsammler


Lithium-Ion Battery Structure
Negative Tab
Positive Tab
Separator
"Jelly Roll"
Positive Electrode
Negative Electrode
Pouch


Carbon Electrode
Cathode Mixture (manganese dioxide, carbon, electrolyte)
Jacket (labeled polyethylene bonded tube)
Cup
One piece metal cover (+)
Plastic closure
Sealant
Kraft
Adhesive-backed barrier film
Anode (zinc alloy can)
Separator (coated paper)
Metal bottom cover (−)


Minuspol
Zellgehäuse
Pluspol
Negative Elektrode
Kupfer-Stromsammler
Separator
Positive Elektrode
Aluminium-Stromsammler
Separator

# Summary

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# Technologies & processes – process parameters

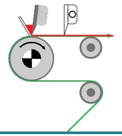
**Process parameters are:**

- ✓ 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

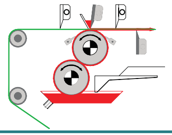
# Processes – definition of coating systems

| Category of coating methods | Examples of coating methods belonging to the category | Characteristics |
| --- | --- | --- |
| Self-metered | ✓ Dip roll<br>✓ Nip forward roll<br>✓ Reverse roll | ✓ Wet thickness is determined by the conditions of the coating meniscus |
| Doctored | ✓ Mayer rod<br>✓ Blade / Knife<br>✓ Air knife<br>✓ Dip & scrape | ✓ Post applicator device determines the wet thickness |
| Pre-metered | ✓ Slot die<br>✓ Slide curtain<br>✓ Spray | ✓ All the ink fed into an applicator is transferred to the web |

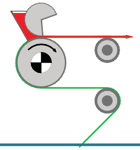
# Coating systems



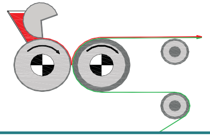
Knife system



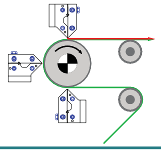
Double side system



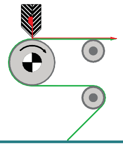
Commabar system



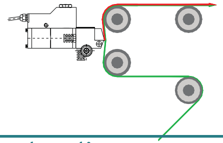
Reverse commabar system



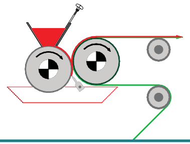
Slot die system



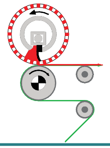
Curtain coating system



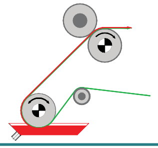
Hotmelt slot die system



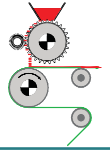
Case knife system



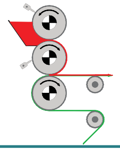
Rotary screen system



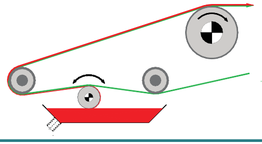
Dipping system (Foulard)



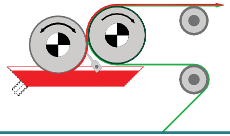
Powder scattering system



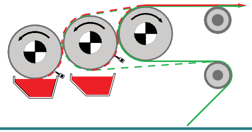
Reverse roll system



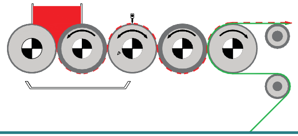
Micro roller system



2 Roller system

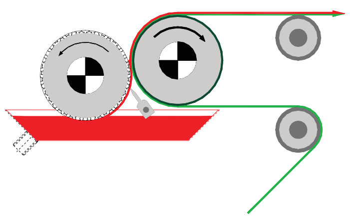


3 Roller combi system

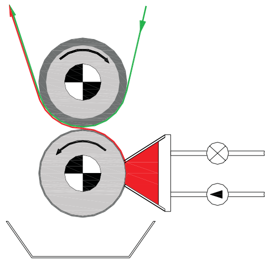


5 Roller system

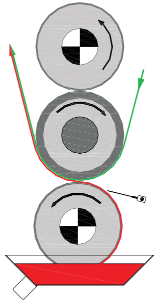
# Printing systems



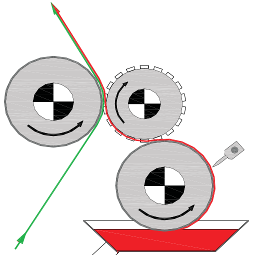
Engraved roller system



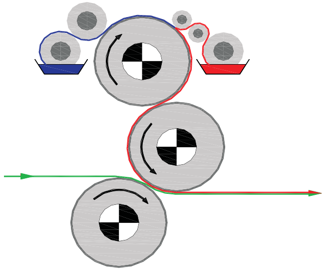
Gravure roller system



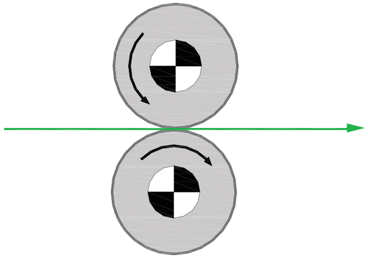
Gravure indirect system



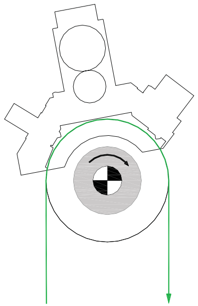
Flexography system



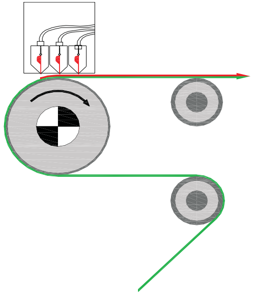
Offset lithography system



Hot embossing system



Nanoimprint system



Inkjet system

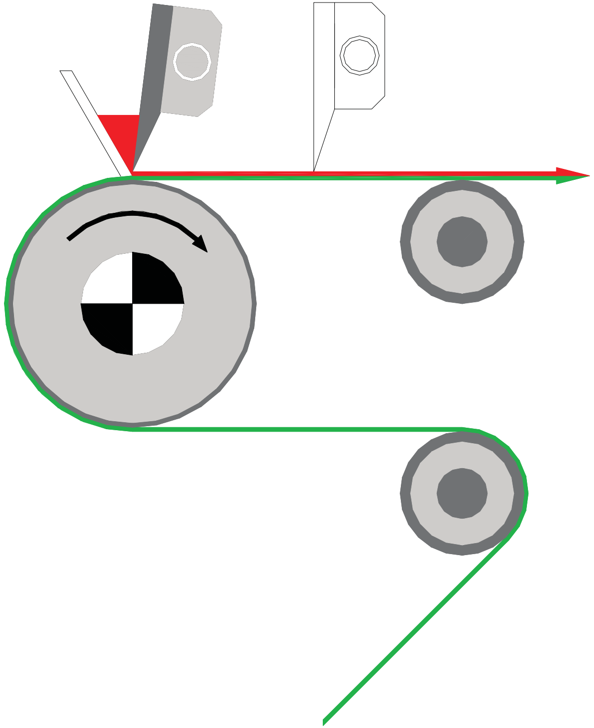
# Coating parameters

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

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

# Coating systems for battery application

# Knife coating



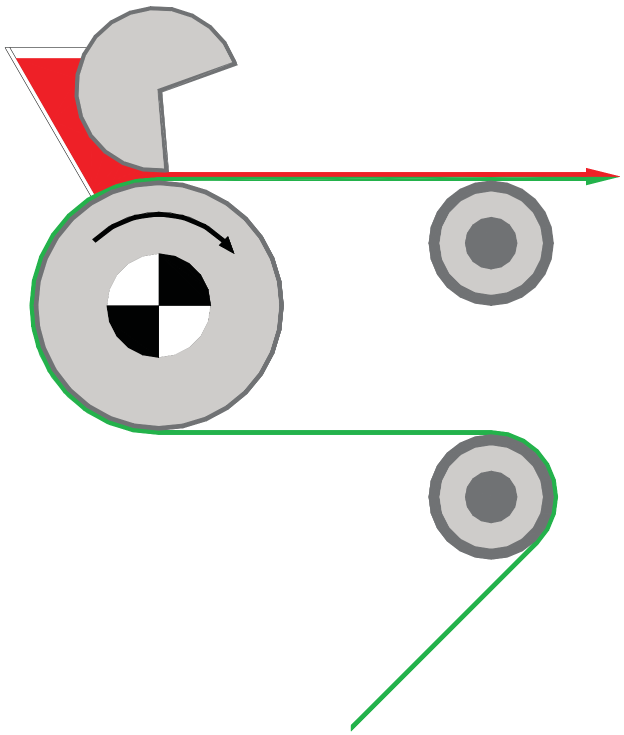
**Variation of the coating weight**

- ✓ Roller knife
  10 – 1.250 g/m²
- ✓ Air knife 5 – 6 to 60 g/m²

**Range of viscosity**

- ✓ Paste (1000)
  100 – 50 000 mPas
- ✓ Foam
  10 000 – 25 000 mPas
- ✓ Air knife
  5 – 10 000 mPas

# Commabar coating



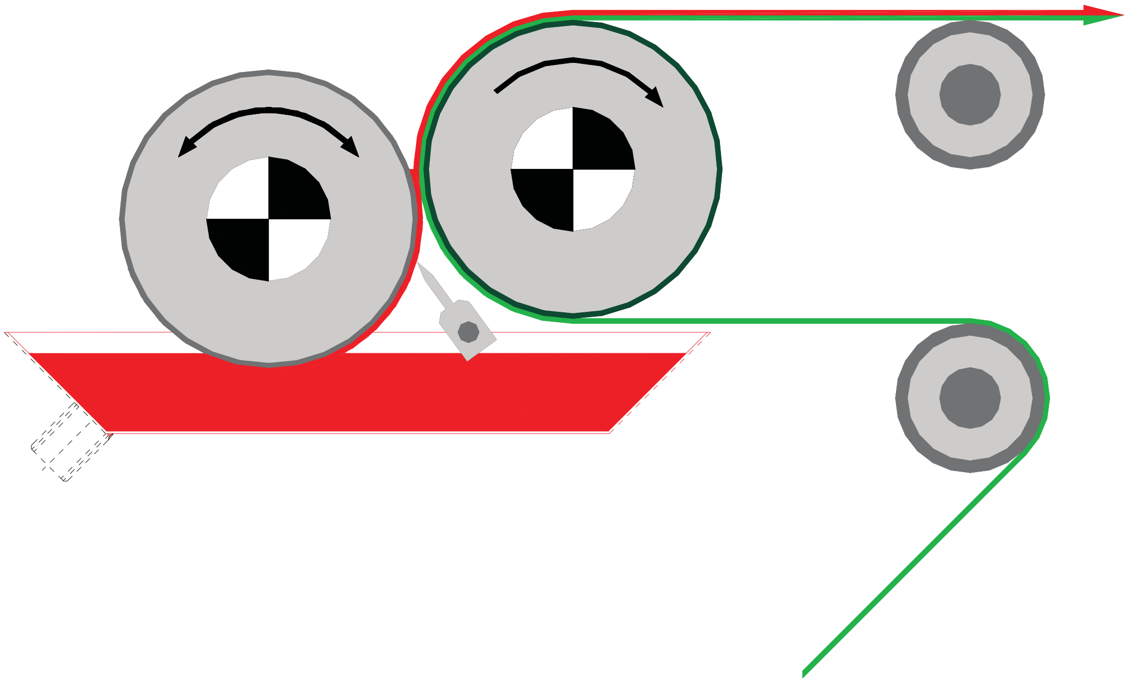
**Variation of the coating weight**

- ✓ Air knife
  5 – 6 to 1.250 g/m²

**Range of viscosity**

- ✓ Paste
  5 – 6 to 60 g/m²
- ✓ Foam
  10 000 – 25 000 mPas

# Gravur coating



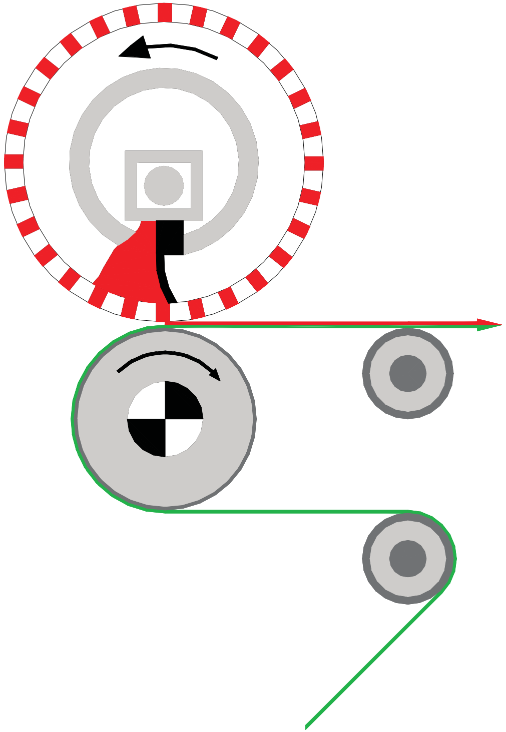
**Variation of the coating weight**

✓ 2 – 200 g/m²

**Range of viscosity**

✓ 1 – 15 000 mPas

# Rotary screen coating



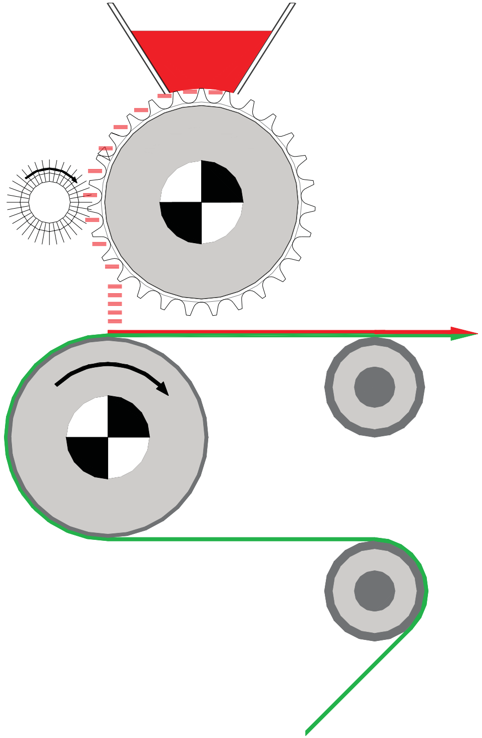
**Variation of the coating weight**

- ✓ 10 – 300 g/m²

**Range of viscosity**

- ✓ Paste
  10 000 – 80 000 mPas
- ✓ Paste
  10 000 – 25 000 mPas

# Powder scattering coating



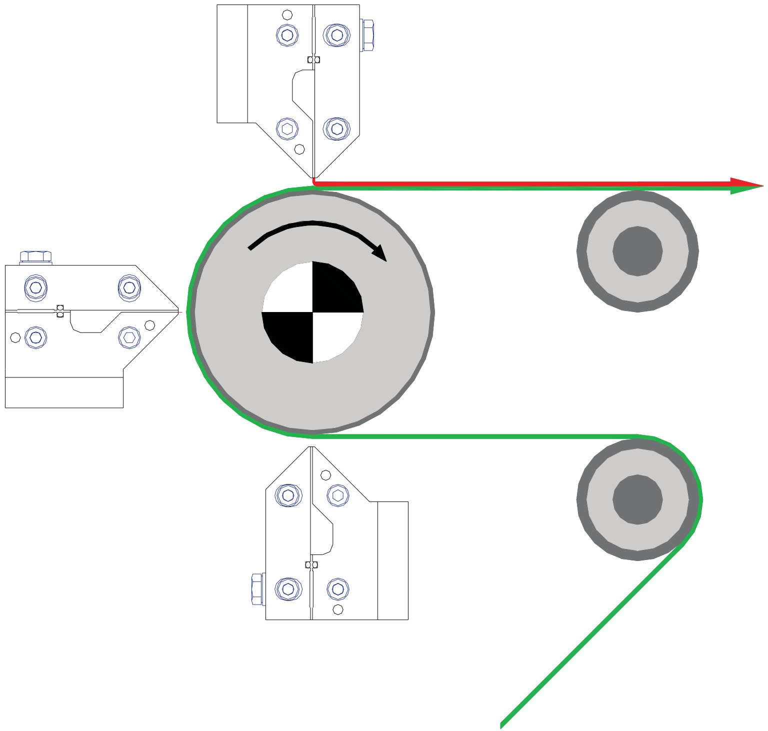
**Variation of the coating weight**

✓ 10 – 300 g/m²

**Range of viscosity** (mPas)

✓ Application of powdery materials

# Slot die coating



**Variation of the coating weight**

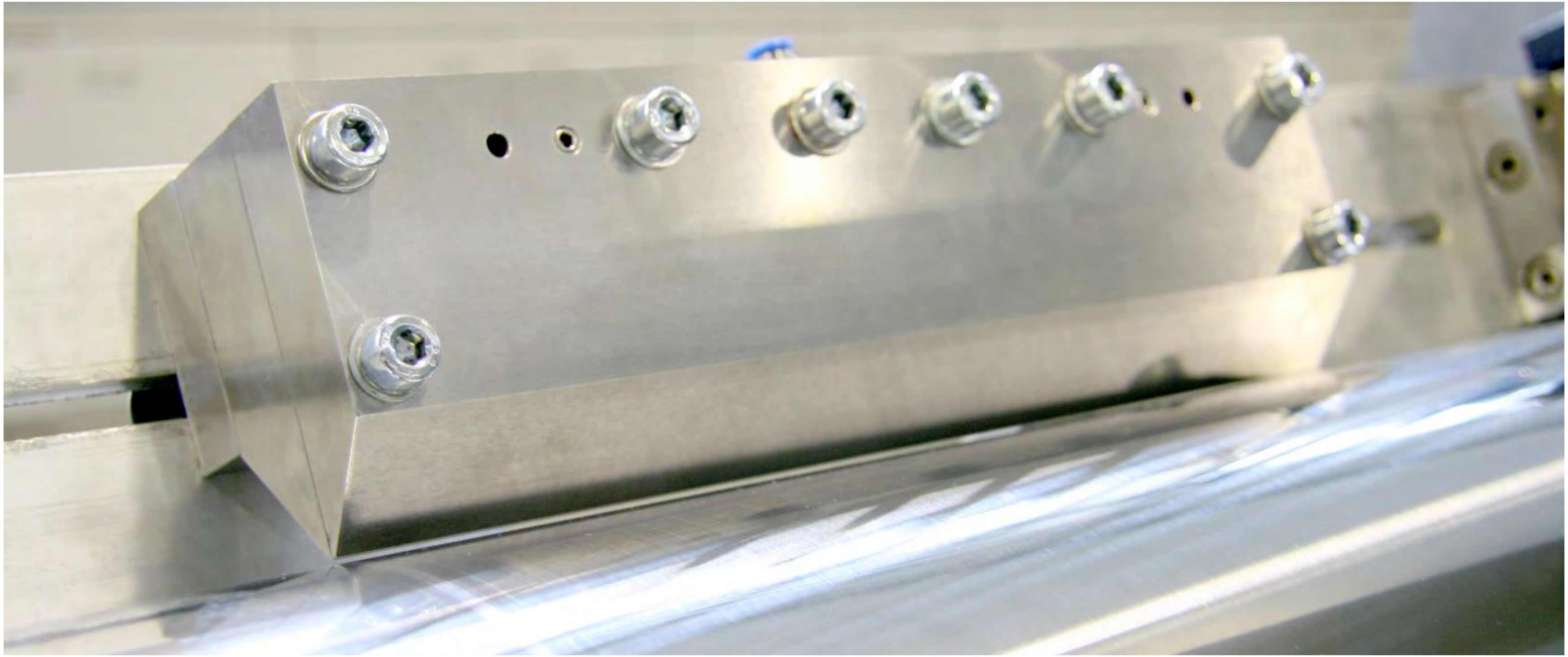
✓ 1 – 200 g/m²

**Range of viscosity**

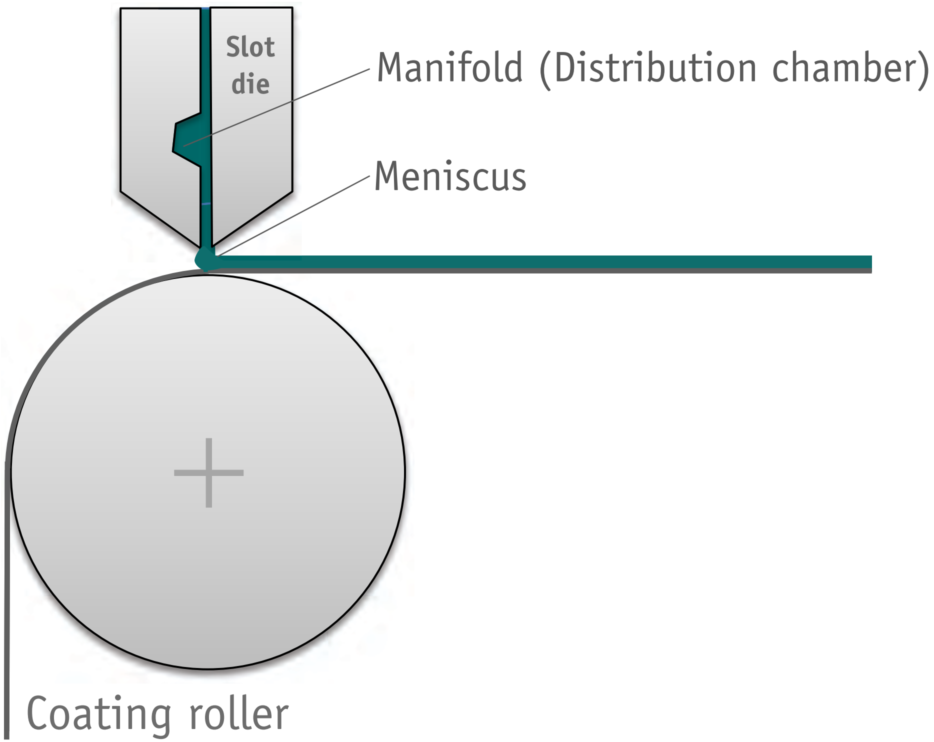
✓ 1 – 30 000 mPas

# New design principle

# Slot die system



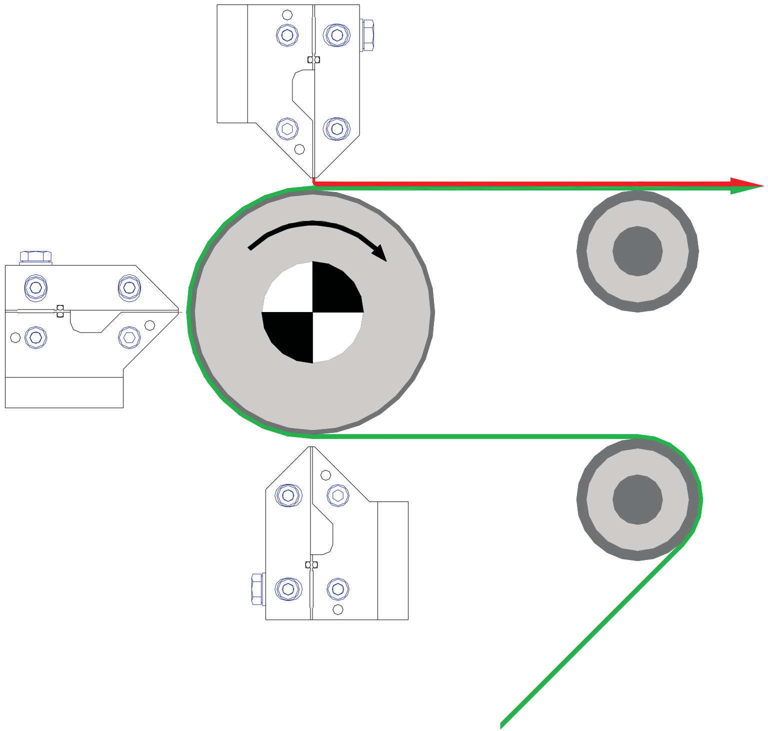
# Technologies & processes – slot die coating




**Operating a slot die**

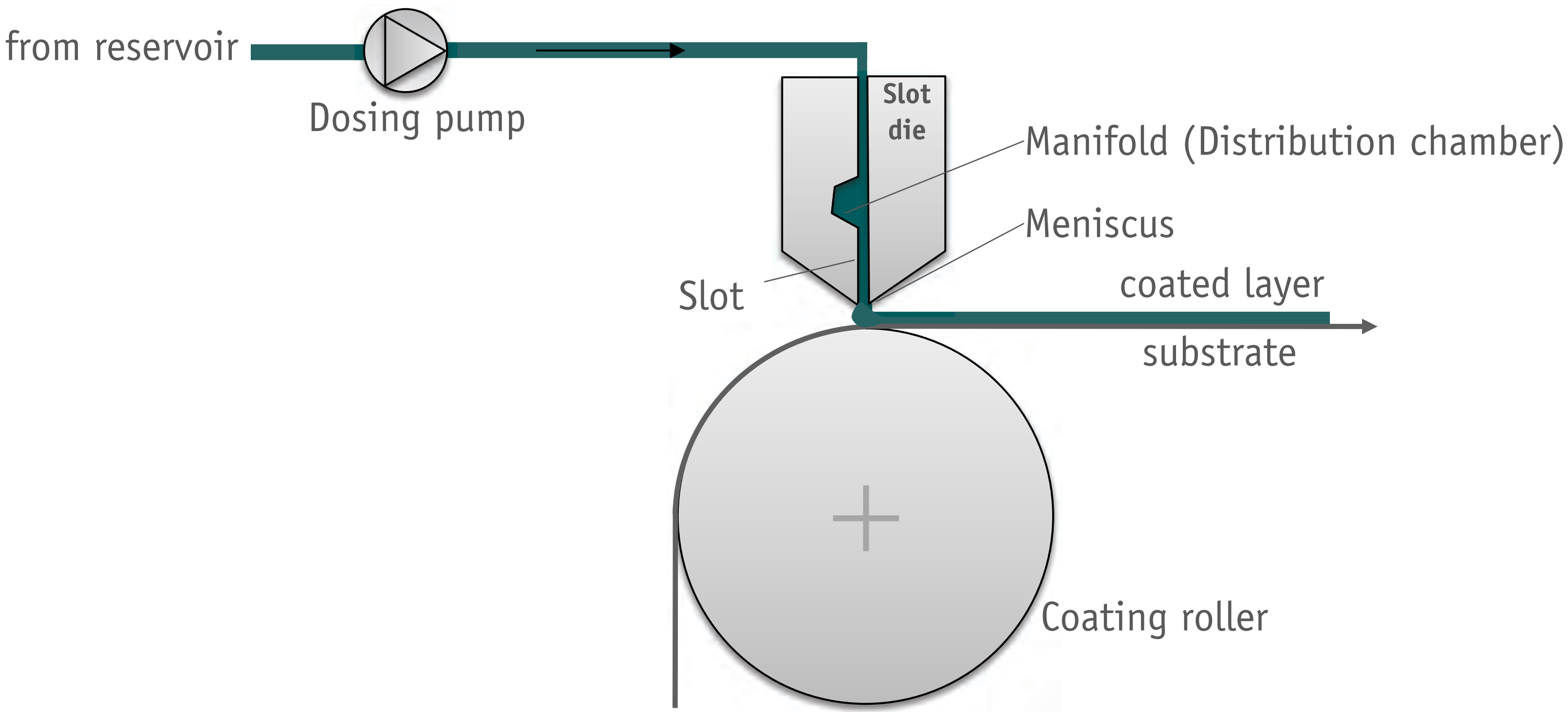
- ✓ Meniscus is formed between die lips and substrate
- ✓ Adhesive stabilization of meniscus by die lips
- ✓ Very low minimum flow rate possible
- ✓ For a stable process the range of rheological parameters is limited

# Basics of slot die coating – range of parameters

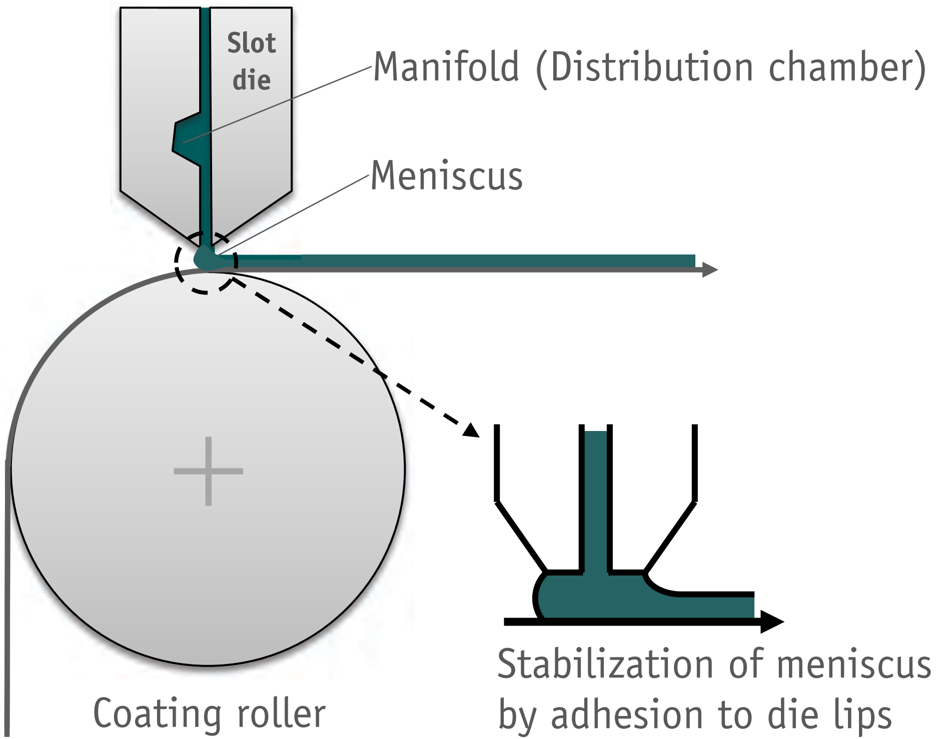


- ✓ Printing speed
  0.1 – >1000 m/min
- ✓ Ink viscosity
  1 – 30 000 mPas
- ✓ Layer thickness
  0,1 – >200 µm
- ✓ Coating accuracy
  <1% (2 – 5%)
- ✓ Coating width
  up to approx. 3 m

# Basic principle

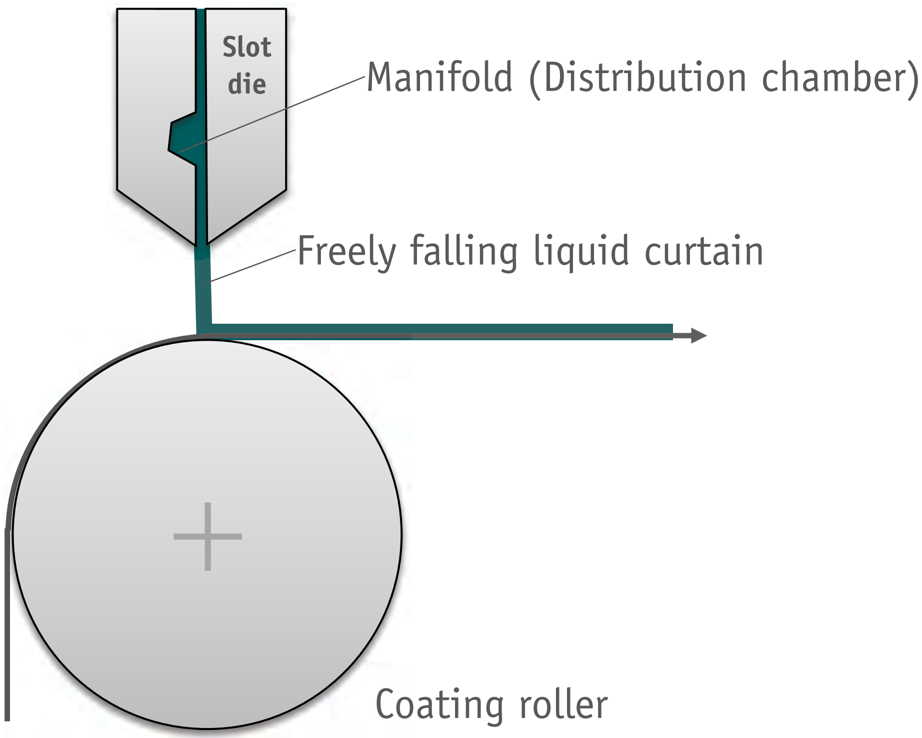


# Bead mode



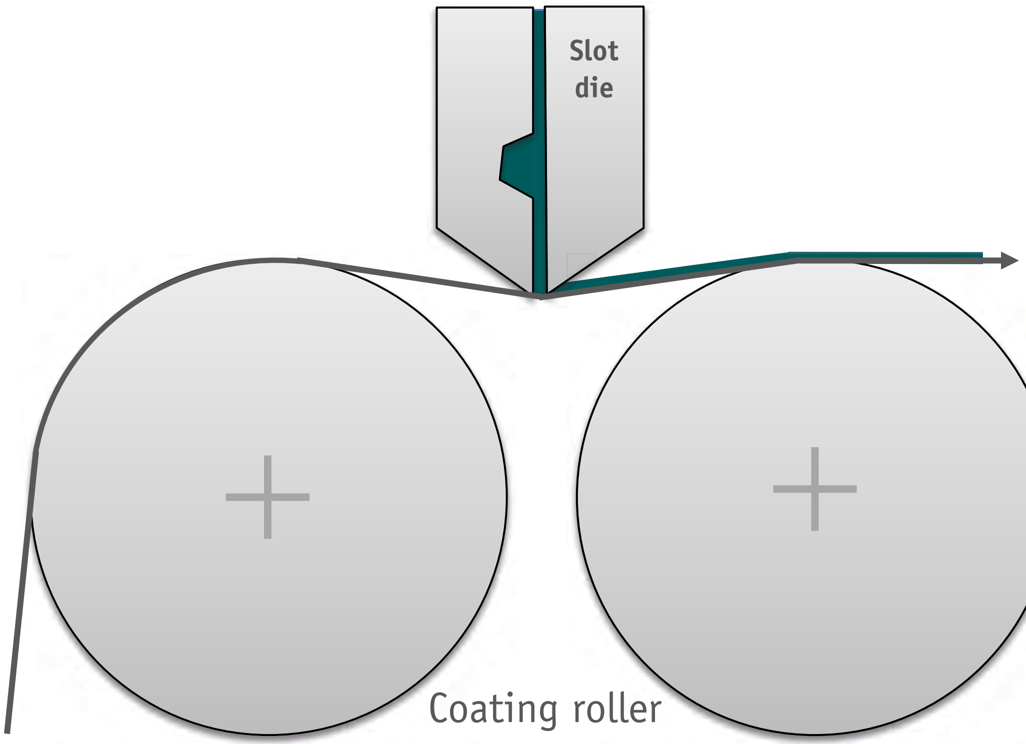

- ✓ Meniscus is formed between die lips and substrate
- ✓ Adhesive stabilization of meniscus by die lips
- ✓ Very low minimum flow rate possible
- ✓ For a stable process the range of rheological parameters is limited
- ✓ Preferrably for low coating speed

# Curtain mode



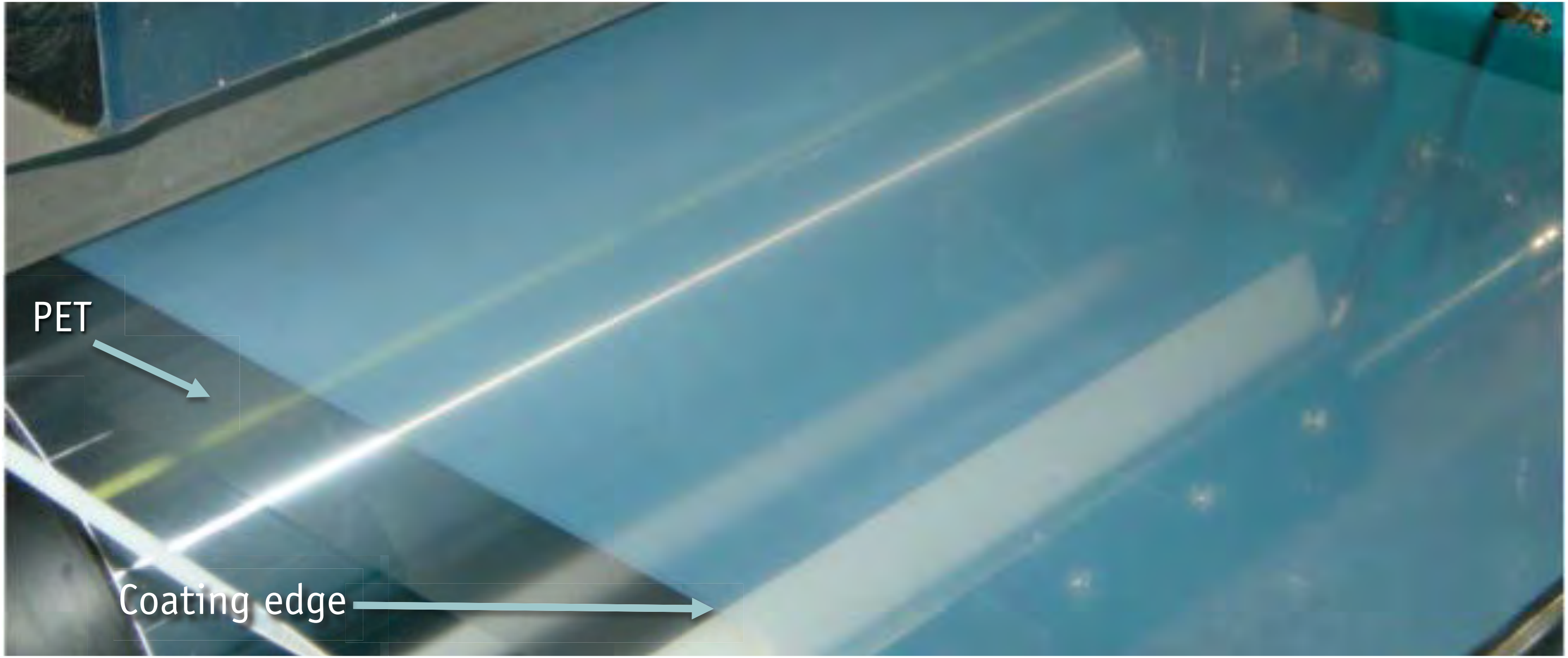

- ✓ Freely falling liquid curtain
- ✓ No adhesive stabilization of wetting line by die lips
- ✓ Curtain width shrinks while falling
- ✓ Minimum flow rate necessary for stable curtain
- ✓ Preferrable for high coating speed

# Impregnation mode




- ✓ Slot die acts as an impregnator with defined liquid release
- ✓ Sucking strength of web must be smaller than release strength of the slot die
- ✓ Slot die with high retention ability has to be used
- ✓ Preferrably for low porosity nonwovens

# Homogeneous coating with slot dies



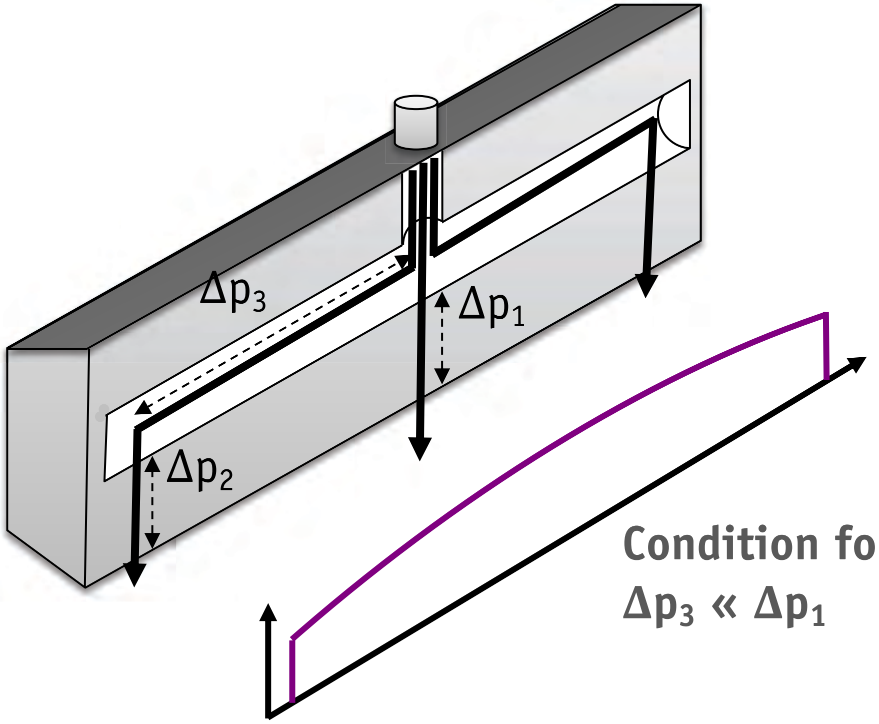
# Target of homogeneity

The target in thickness profile depends on the application.
E.g. window foils: target is determined by sensitivity of human eye.

- ✓ Standard optical density for window foils:
  $D = 0.6 – 0.7$ (absortion 75 – 80 %)
- ✓ In this range the human eye detects density variations of:
  $\Delta D = 0.01 – 0.003$
  (depending on the regularity of the variations)
- ✓ Density is proportional to layer thickness:
  $I = I_0 \cdot 10^{-ax}$ ; $D = -\log(I/I_0) = a\,x$ ; $\Delta D/D = \Delta x/x$

→ Target layer homogeneity: 1.7 – 0.4 %

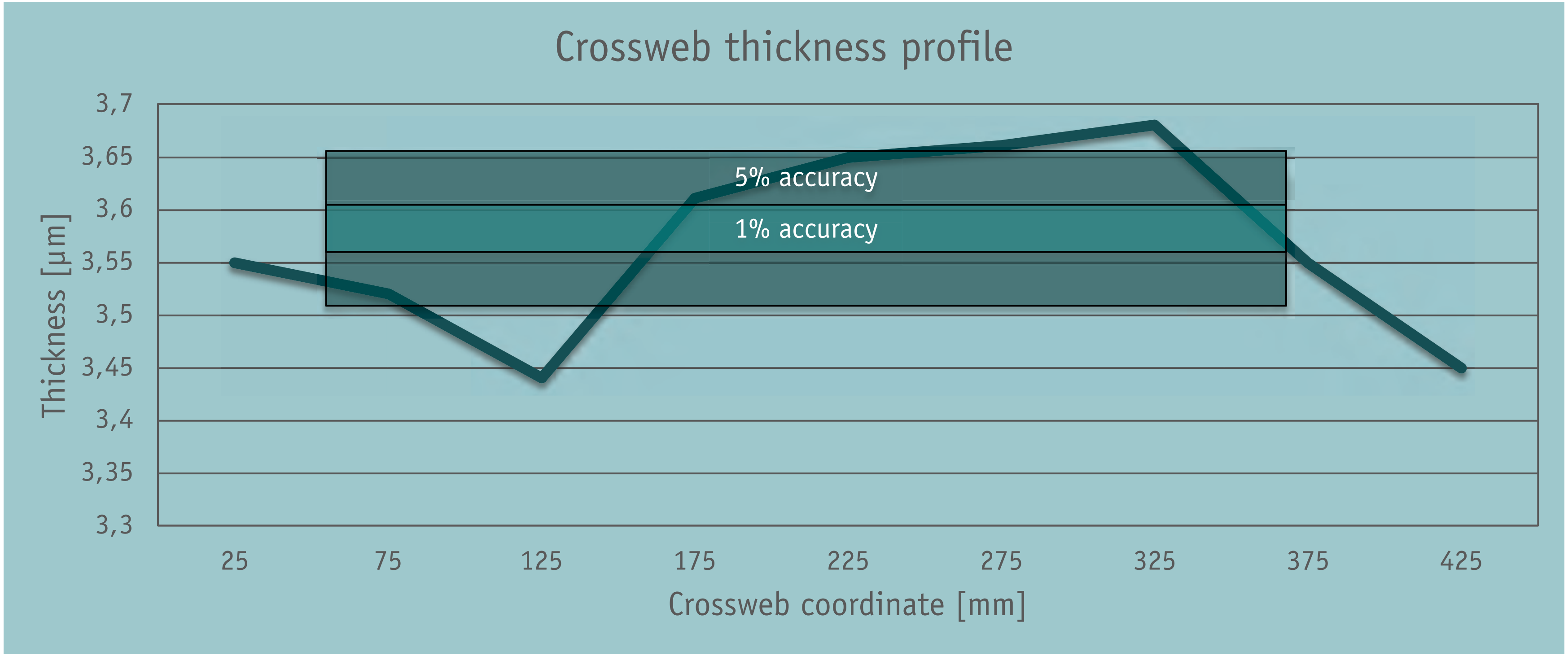
# Why should a slot die coat homogeneously?




Theoretical thickness profile

**Condition for good profile**
**$\Delta p_3 \ll \Delta p_1$**

# Experimental thickness profile



# Improving the coating profile

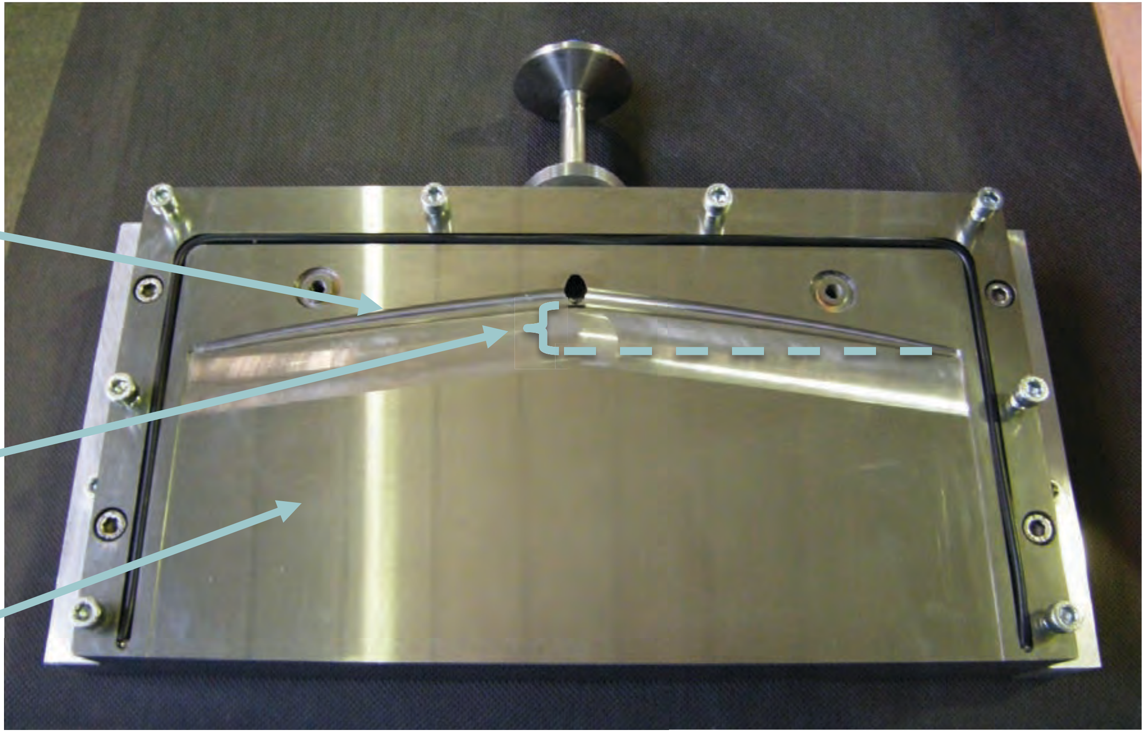
- ✓ Large manifold, long slot area, highly parallel lips (standard)
- ✓ Coat hanger design
  - ✓ Profile is compensated by a tilted manifold
  - ✓ Conical manifold cross section to keep flow speed constant (optional to prevent precipitation)
  - ✓ Works perfect for adequate rheology only
- ✓ Slot width adjustment
  - ✓ Slot width is locally narrowed or widened to adjust  the local flow resistence
  - ✓ Slot width can be modified by microns only. So despite adjustability the die has nevertheless to be highly precise and a sufficient manifold volume is necessary (the adjustment is a fine tuning only).

# Coat hanger design

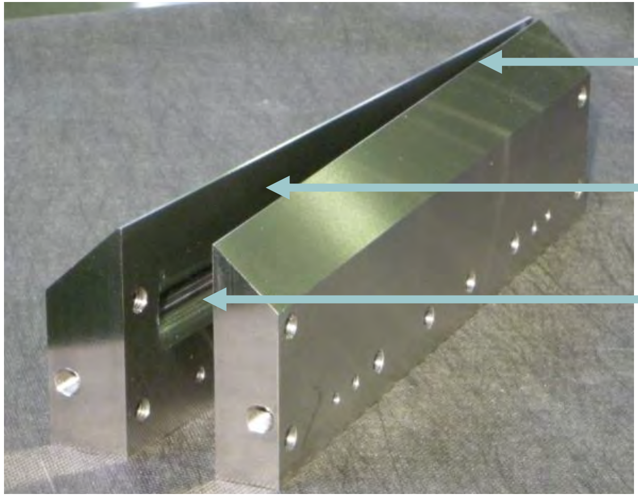
Manifold small to minimize dead volume (optional conical to prevent precipitation)

Tilted manifold to correct the pressure profile

Long slot area



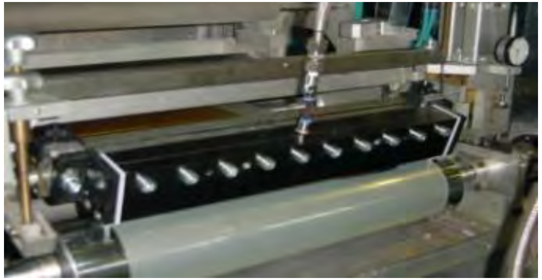
# Coatema standard layout – one design among many available



# Basics of slot die coating – slot die examples

100 mm, 11 o‘clock

300 mm, 9 o‘clock



500 mm, slightly tilted

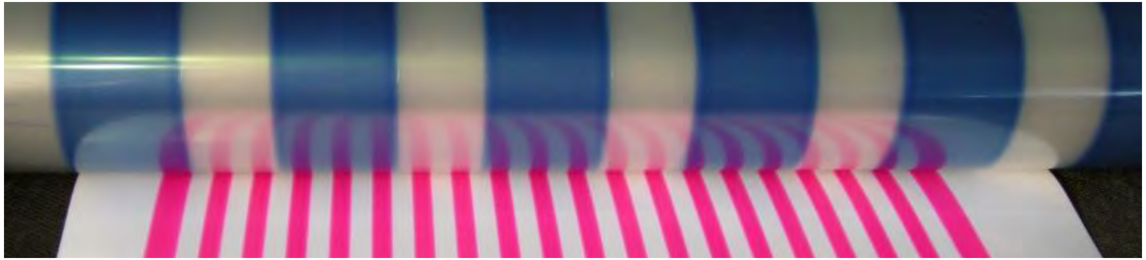
300 mm, double sided

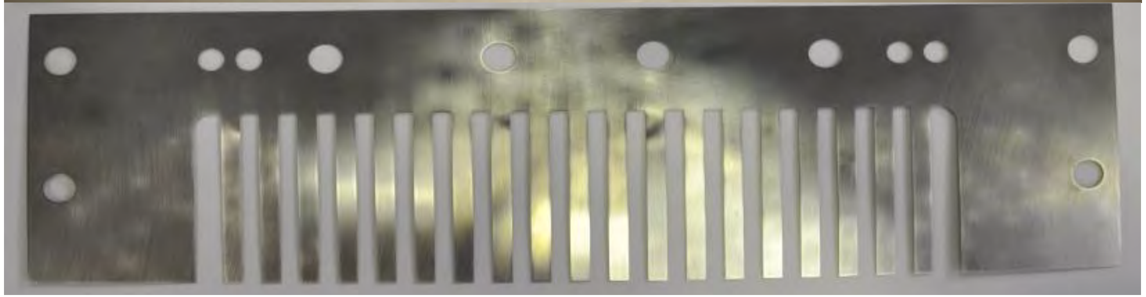
# Structured coating – levels of complexity

Web direction


| | | 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 |

# Structured coating – downweb stripes

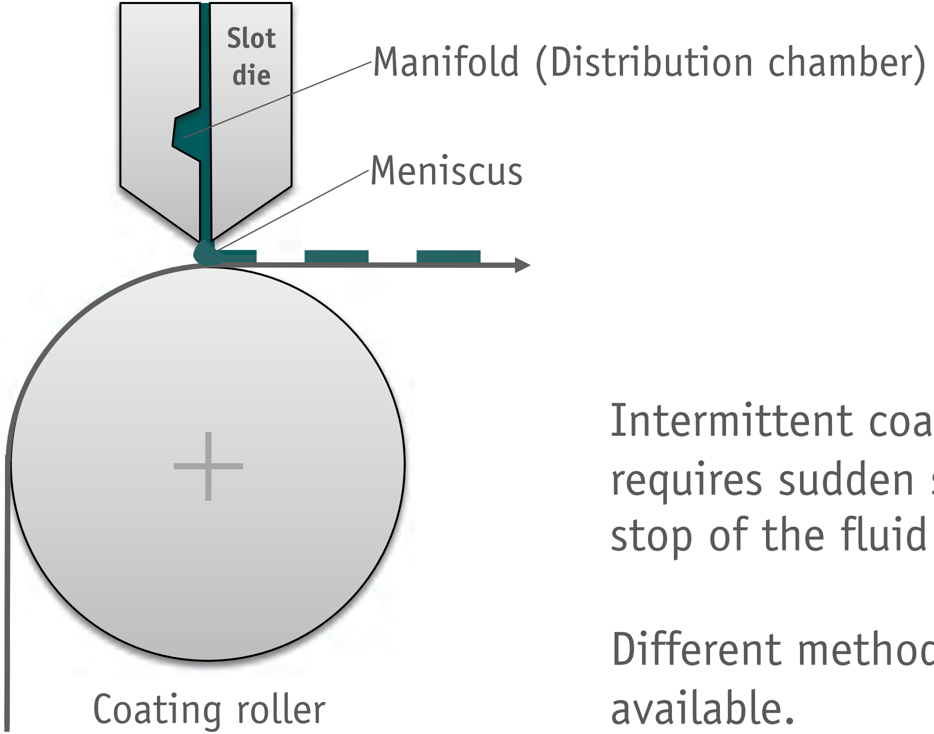




Downweb stripes of different width …

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

# Structured coating – crossweb stripes (intermittent)




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

Different methods are available.

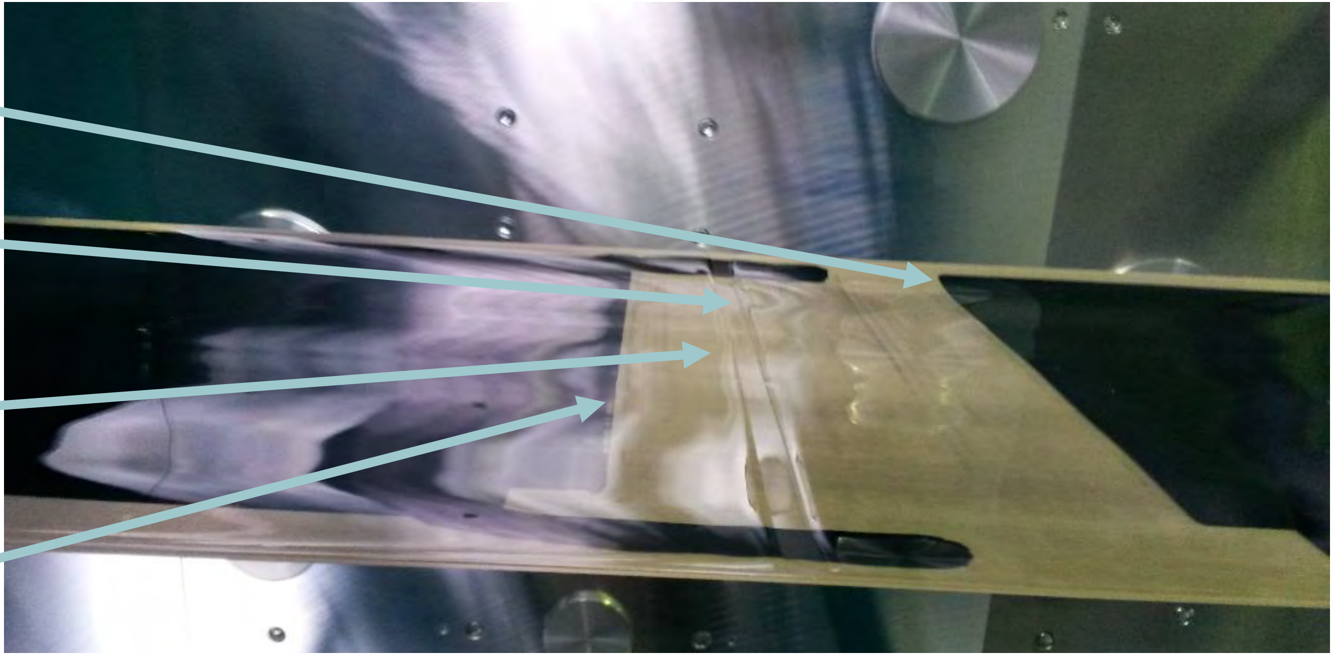
# Structured coating – well defined edges at high viscosity

Leading edge battery paste

Leading edge silicone

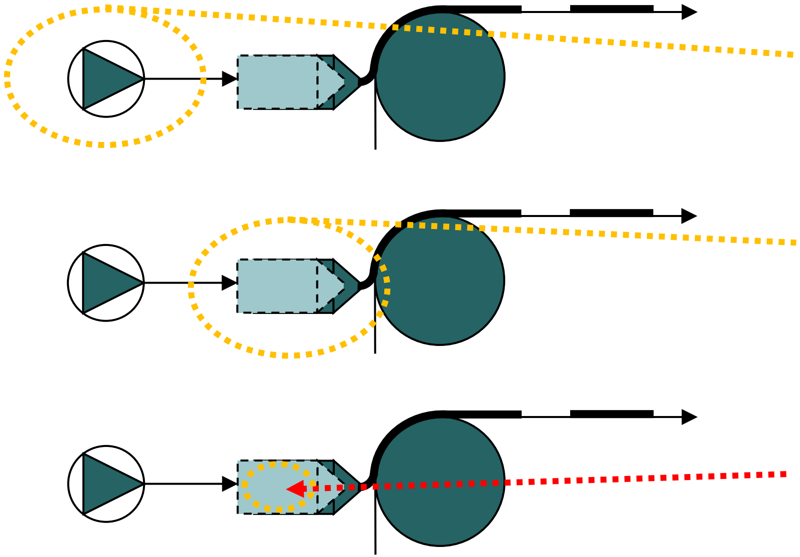
Trailing edge silicone

Trailing edge battery paste



Two different stripe patterns, one on top of the other

# Standard techniques for intermittent coating



**Pump:**
stop – reverse – restart

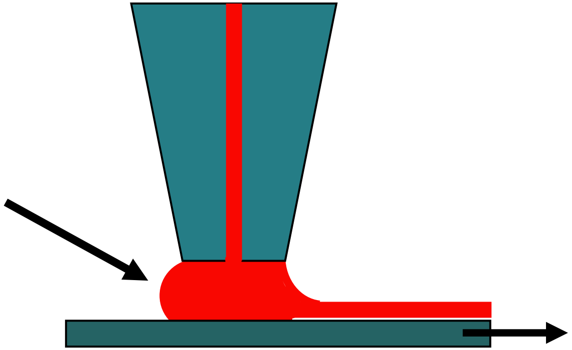
**Slot die body:**
move back – move forth to minimum gap – move back to working gap (wedge procedure)

**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

The mensicus volume between the slot die and the substrate has to be interrupted. Low viscous liquids do not break along a straight line. So the meniscus has to be sucked back and restored as fast as possible to achieve a clear defined edge.



If the viscosity is too low, all of the three before mentioned methods are too slow and too indirect to do this.

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Coatema®
Coating Machinery GmbH

# 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

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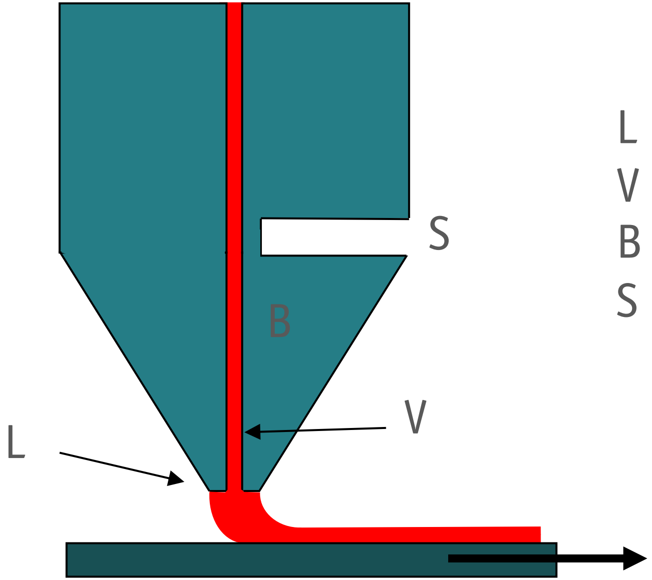
# Structured coating – the switching slot die lip

**Slot die with movable lips:**
**coating mode**




L lip
V slot volume
B bendable lip
S bending slot

coating works as usual

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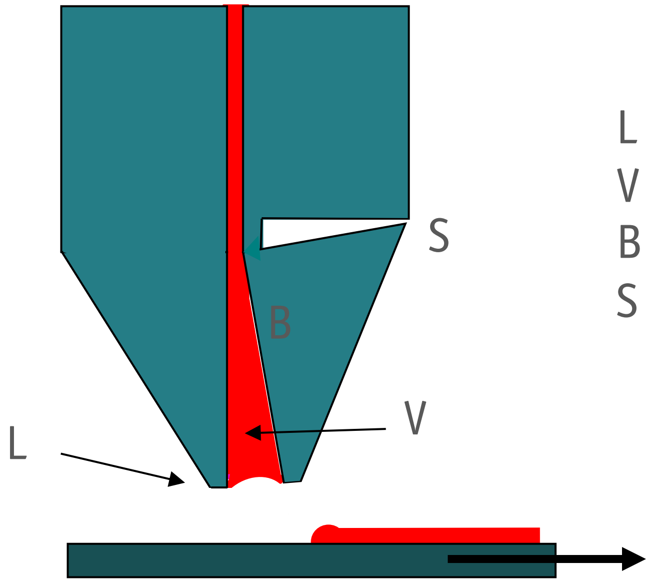
# Structured coating – the switching slot die lip

**Slot die with movable lips:**
**stop mode**




L lip
V slot volume
B bendable lip
S bending slot

Bendable lip B flips open
Volume V increases and
sucks away the meniscus

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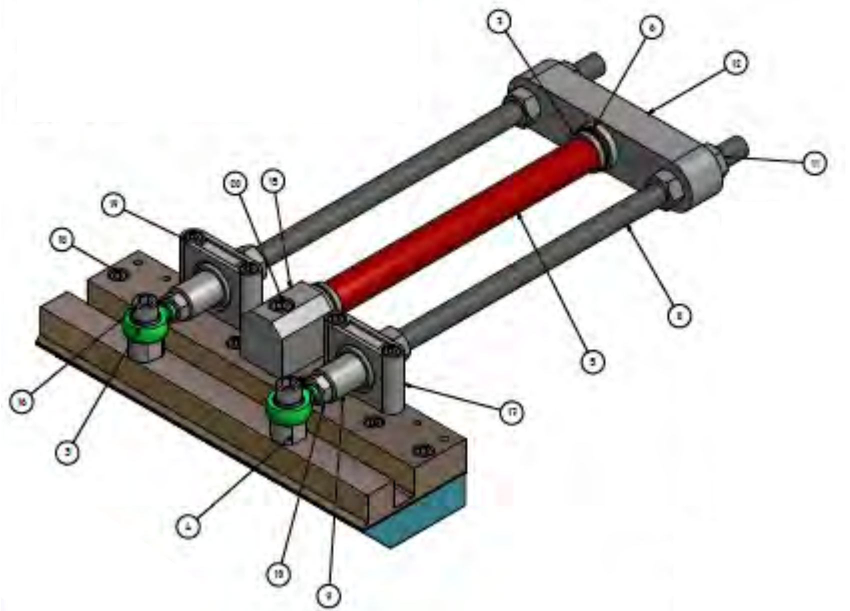
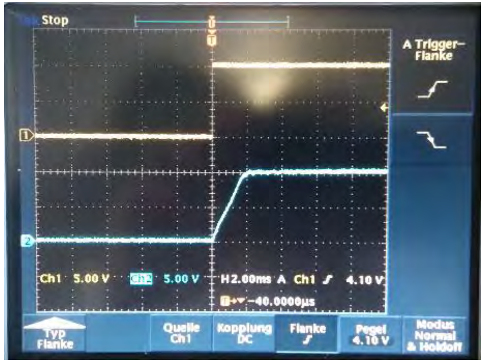
# Structured coating – technical implementation with Piezo-Drive

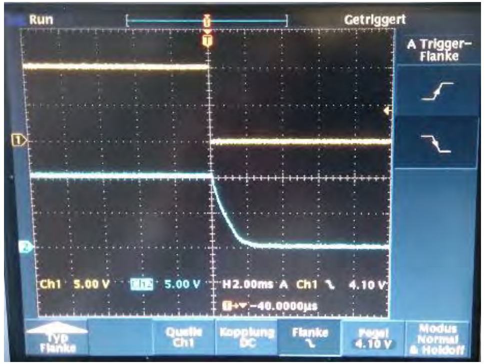


Extremely fast action:
within few ms from coating to stop mode and vice versa

Control
Response

Piezo
Response

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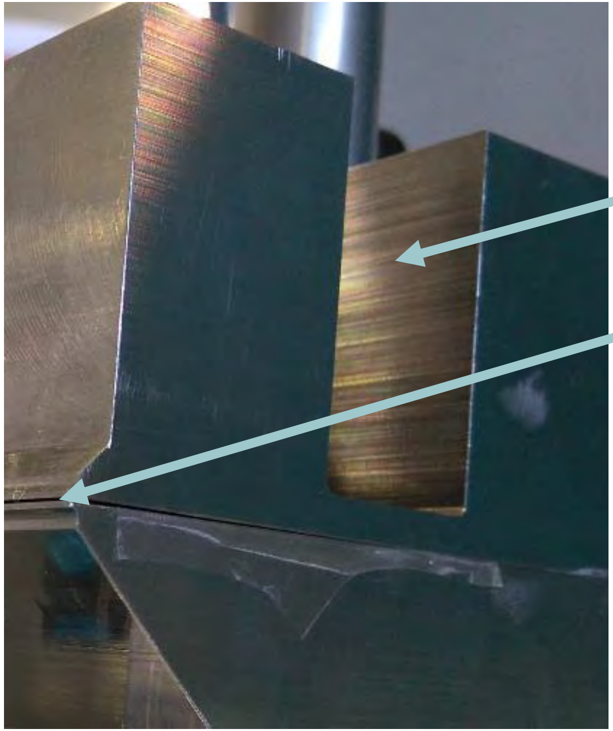
# Structured coating – technical implementation with bendable lips

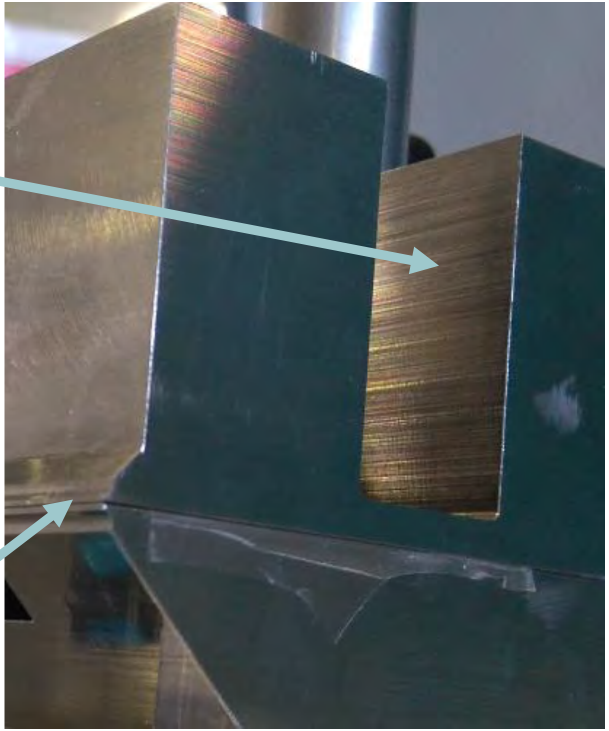


Bending slot

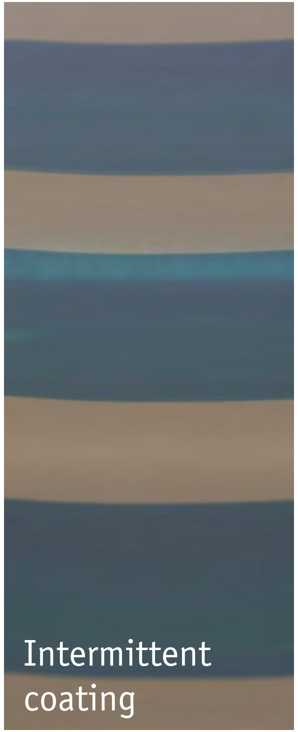
Lips open

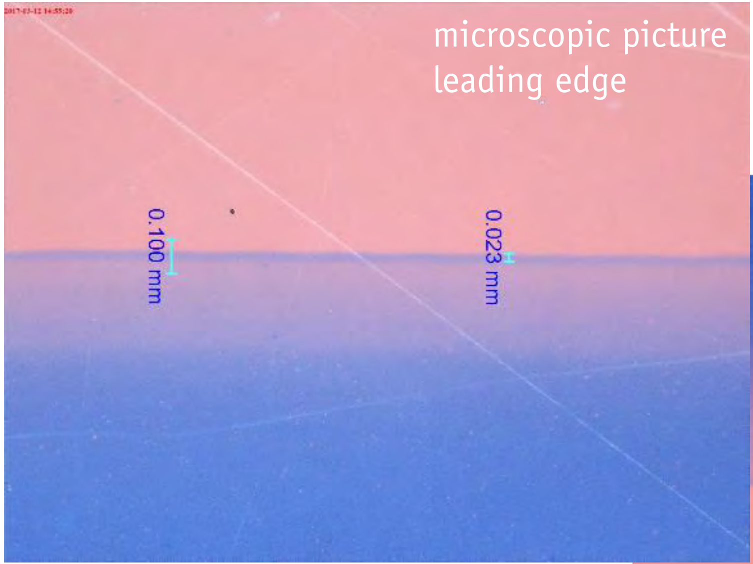
**Difference is 300 µm only**

Lips closed

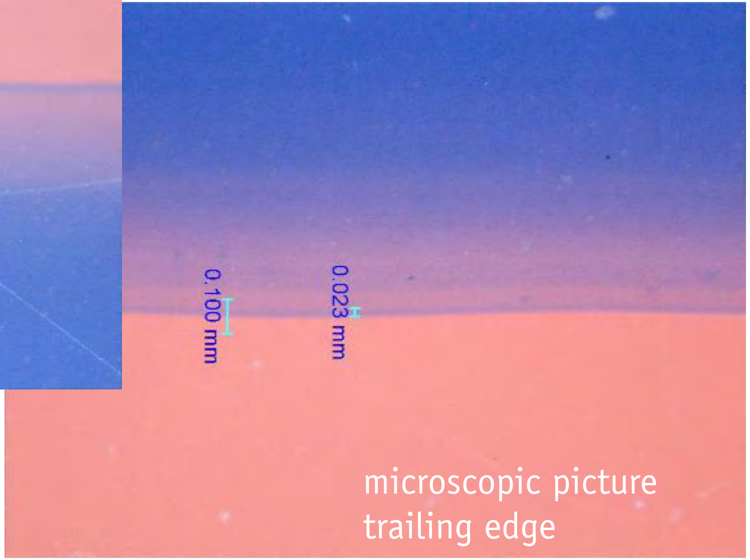


# Structured coating – switching slot die: first results

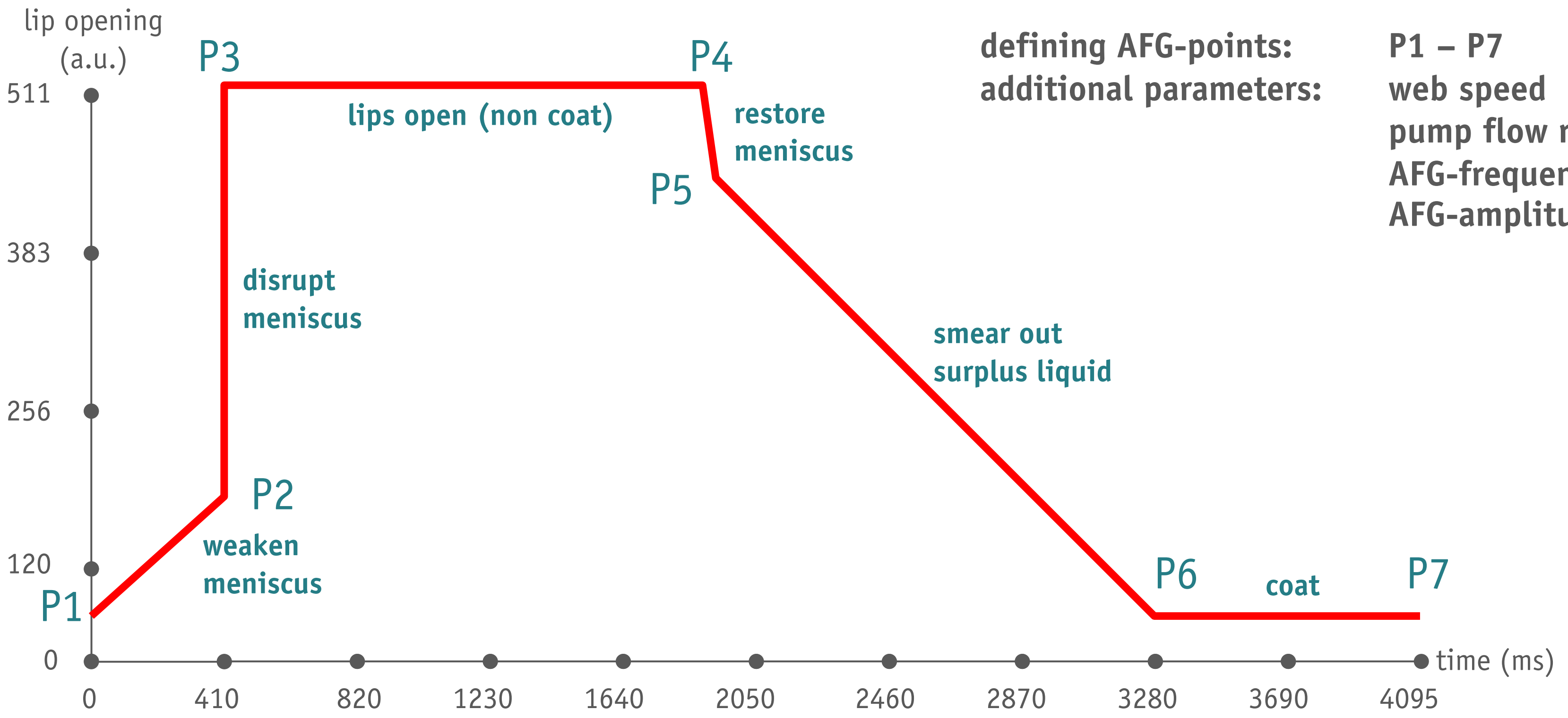



Straight edges well defined
within 20 µm



# 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

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## Theory

$$\frac{dV_p}{dt} = B \cdot v \cdot x$$

$$\Delta p = \frac{12 \cdot \eta \cdot l \cdot Vp}{D^3 \cdot B}$$

$$D = \sqrt[3]{\frac{12 \cdot \eta \cdot l \cdot vp}{\Delta p \cdot B}}$$

$$V_{max} = C(d) \cdot \left[\frac{\sigma \cdot h}{d-h} + \Delta p \cdot \frac{d}{\eta \cdot B}\right] \cdot \frac{h}{\eta \cdot b}$$

# Theoretical background

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

Continuity equation (conservation of mass)

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

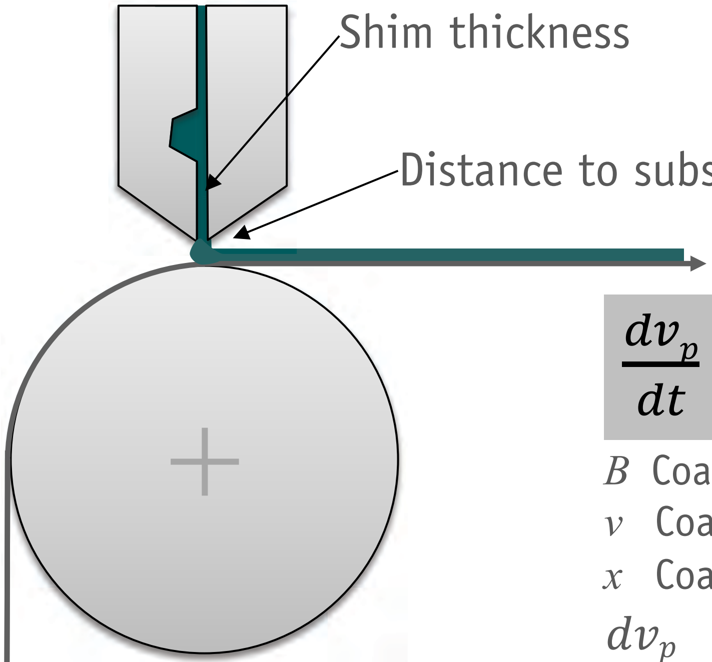
To describe the meniscus flow of a slot die means, to solve these differential equations for given boundary conditions.

Can be done by appropriate computer programs.

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

Navier-Stokes-equations (equations of motion for incompressible fluids, $\rho$ = const)
$\Delta, \nabla$ = differential operators

# Theoretical background



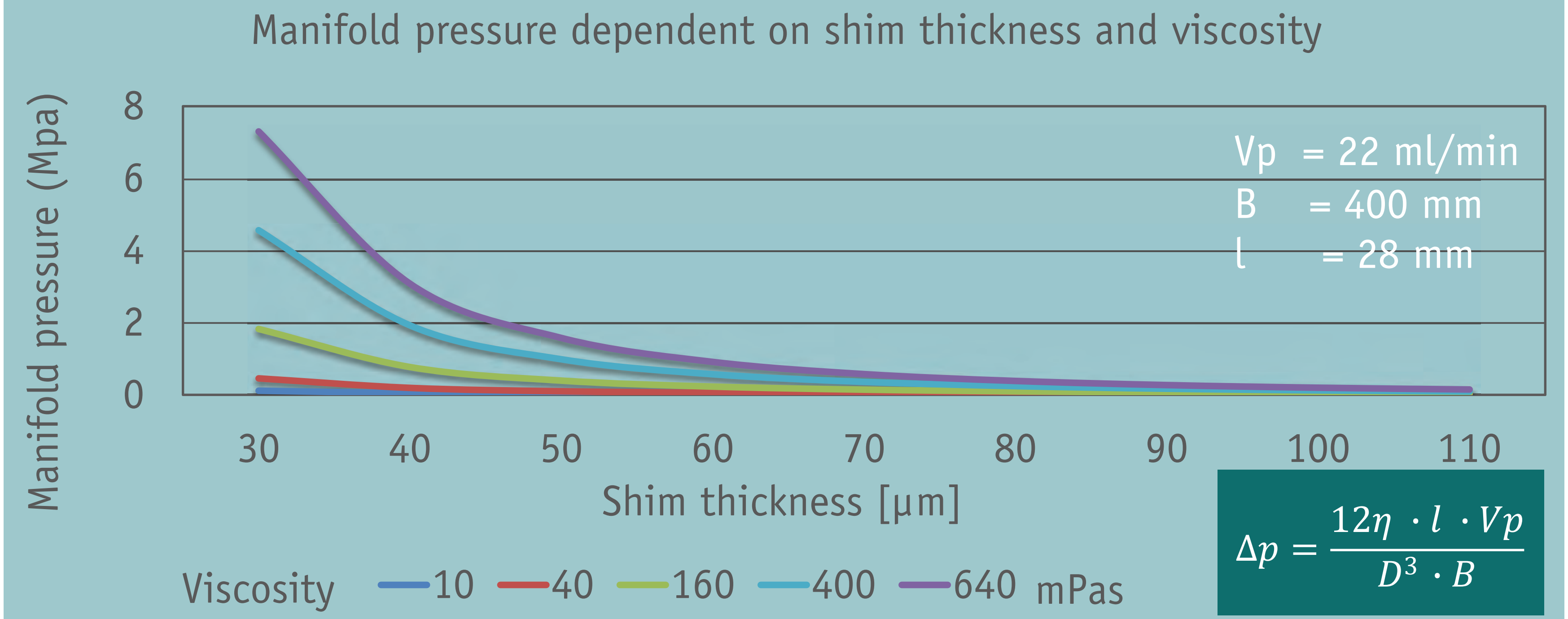

$$\frac{dv_p}{dt} = B \cdot v \cdot x$$

$B$ Coating thickness wet
$v$ Coating speed
$x$ Coating width
$\frac{dv_p}{dt}$ 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.

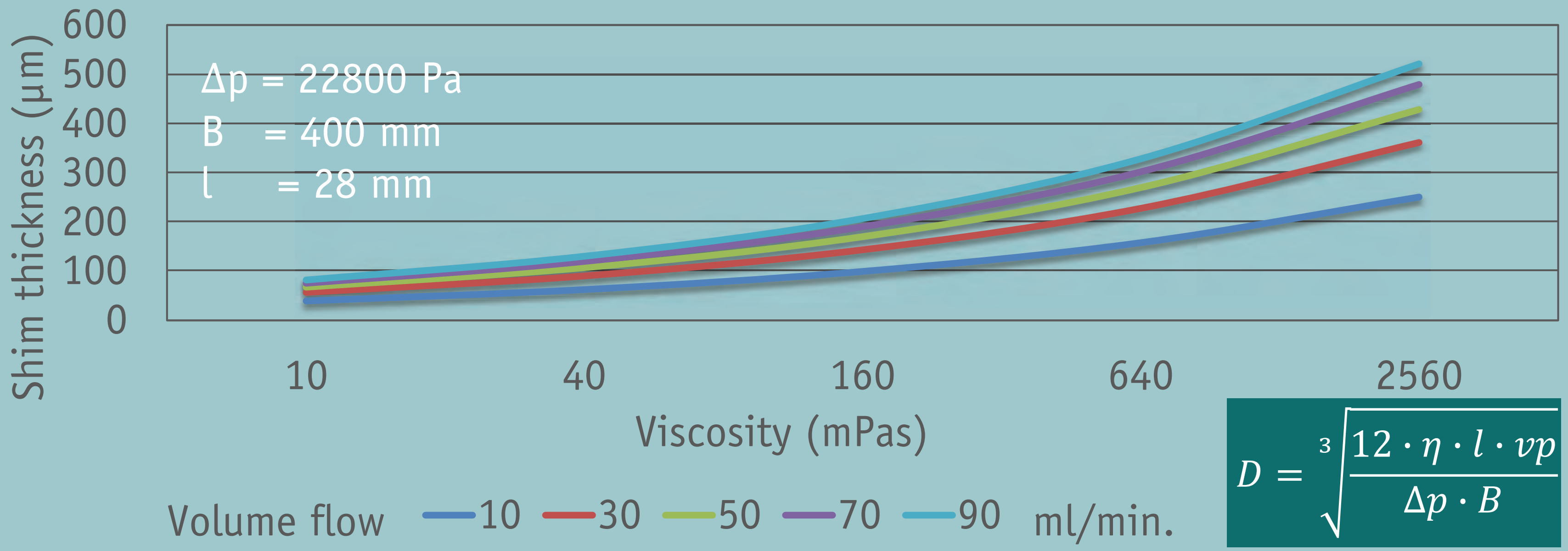
# Calculation of internal pressure




$$\Delta p = \frac{12\eta \cdot l \cdot Vp}{D^3 \cdot B}$$

# Calculation of shim thickness

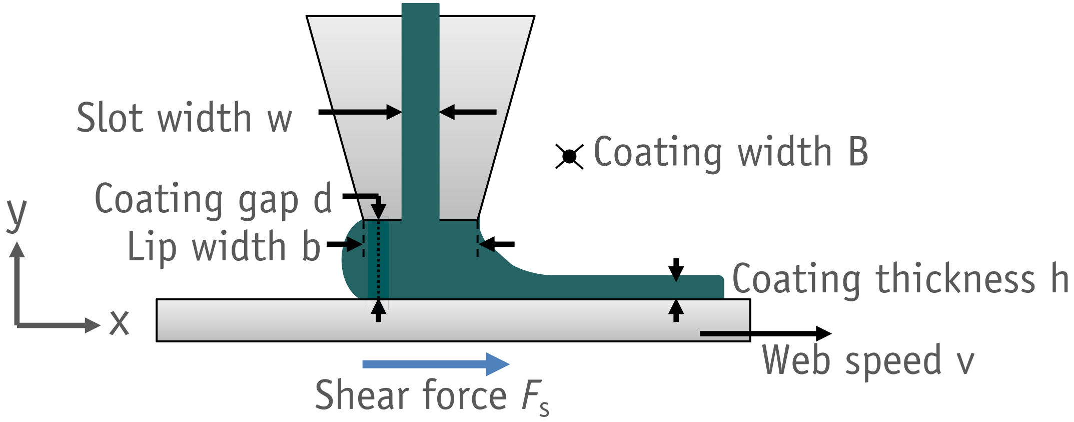
Shim thickness dependent on viscosity and volume flow



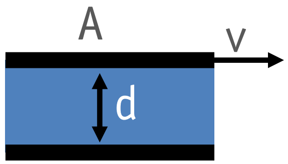

$$D = \sqrt[3]{\frac{12 \cdot \eta \cdot l \cdot vp}{\Delta p \cdot B}}$$

# Calculation of shear force on meniscus

Slot die mathematics




Force caused by shear: This force pulls the meniscus to the right

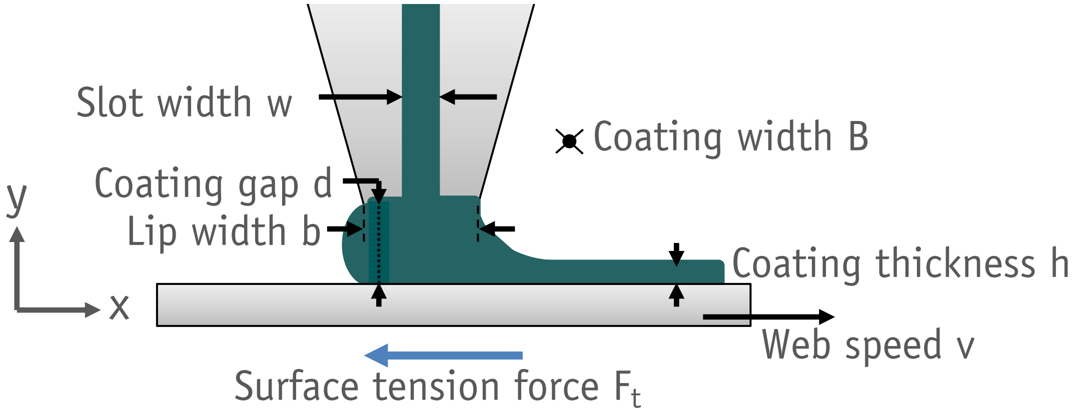



Shear force in general: $$F_s = \eta \cdot A \cdot \frac{v}{d}$$

The shear takes place mainly over the thickness h: $$F_s = \eta \cdot B \cdot \frac{v}{h}$$

# Calculation of surface tension force on meniscus

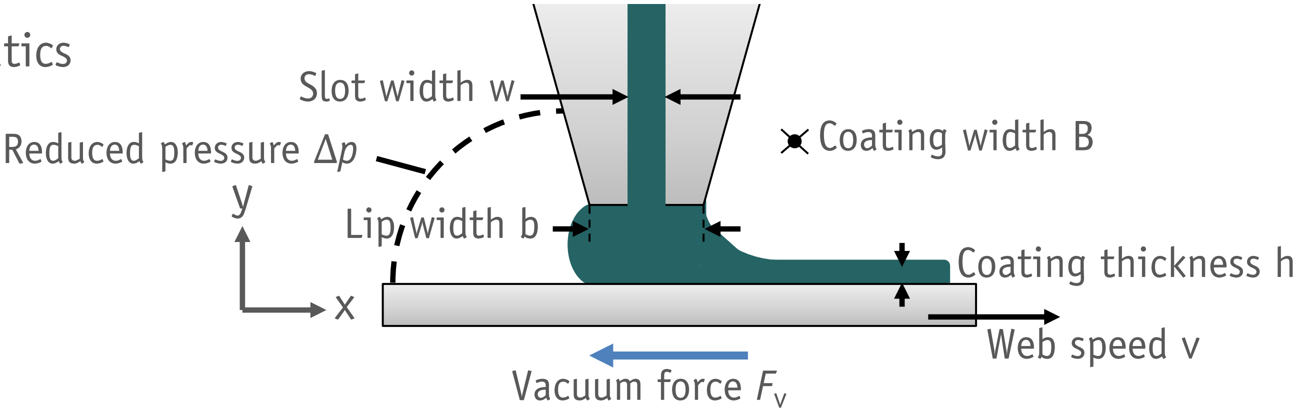
Slot die mathematics




- ✓ Force caused by surface tension: This force pulls the meniscus to the left
- ✓ Surface caused tension $\sigma$ caused pressure $p$ inside of a fluid sphere: $p = \frac{2\,\sigma}{r}$
- ✓ In the meniscus the pressure is approximately: $p = \frac{\sigma}{d-h}$
- ✓ The corresponding pressure force is: $F = p \cdot A = p \cdot B \cdot h = \sigma \cdot B \cdot \frac{\sigma}{d-h}$

# Calculation of vacuum force on meniscus

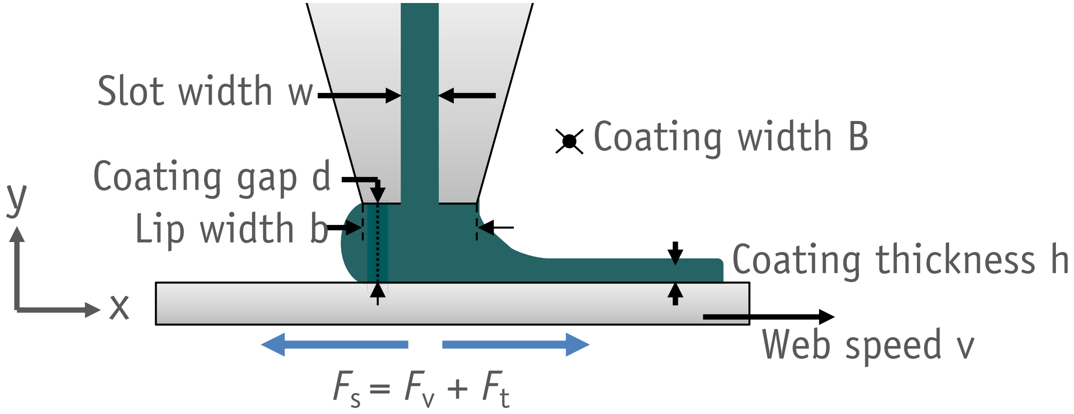
## Slot die mathematics




- ✓ Force caused by reduced pressure on the rear of the meniscus
- ✓ This force pulls the meniscus to the left
- ✓ $F_v = p \cdot A = \Delta p \cdot B \cdot d$

# Estimation of coating speed

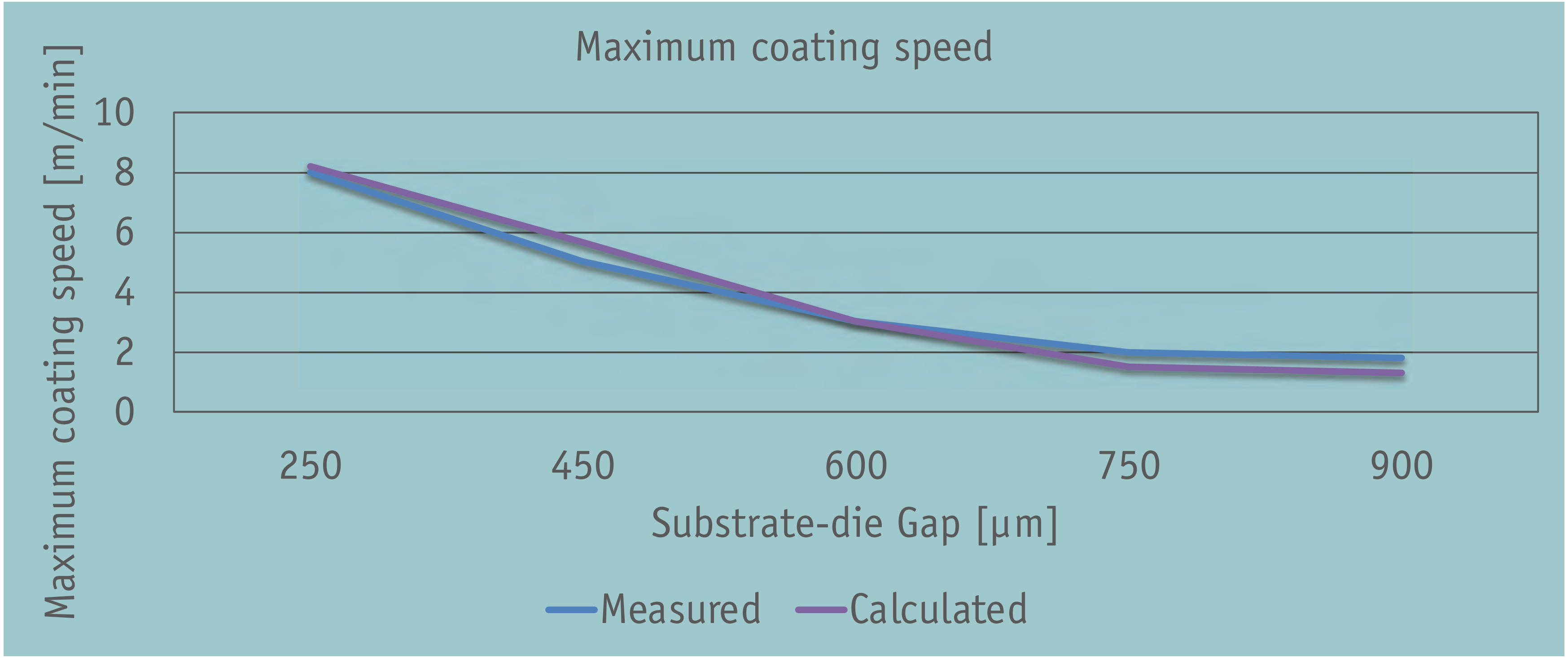
Slot die mathematics




✓ Stability of the meniscus:
The meniscus is stable as long as the right bound shear force is smaller than the sum of left bound forces. At maximum speed the forces are equal:

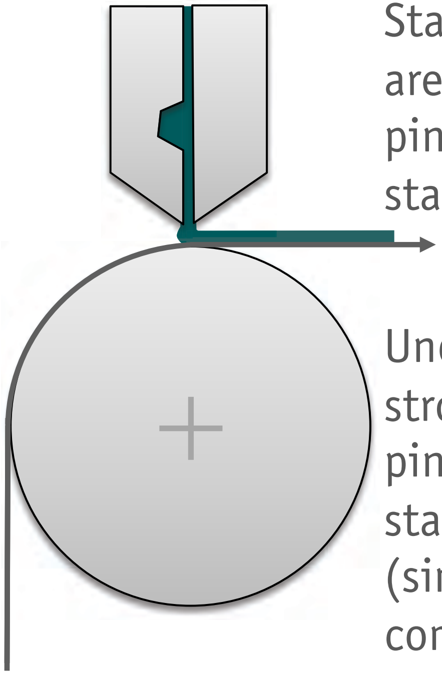
$$F_s = F_v + F_t \rightarrow v_{max} = C \cdot \left[\frac{\sigma \cdot h}{d - h} + \Delta p \cdot \frac{d}{\eta \cdot b}\right] \cdot \frac{h}{\eta \cdot b} \text{ with } C\ (d) \mathrel{\widehat{=}} \text{scaling factor\#}$$

# Comparison of theory and praxis



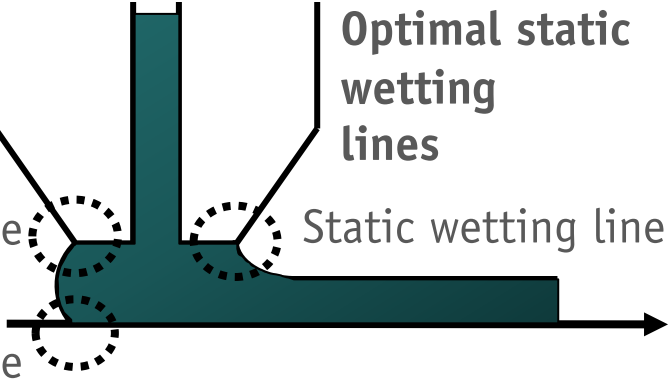
# Innovation: slot die types and concepts

# Modification of die lips

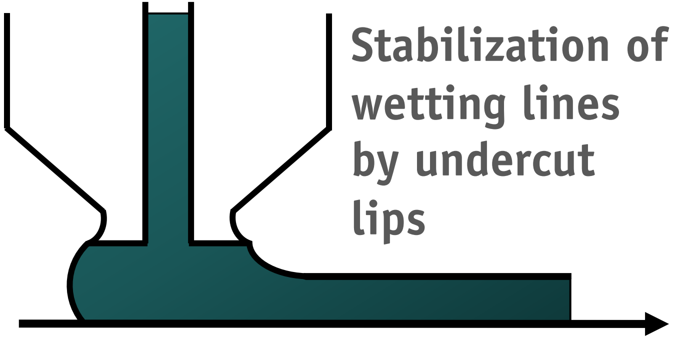


Standard die lips are only weakly pinpointing the static wetting lines

Undercut lips are strongly pinpointing the static wetting lines (similar to comma bar)



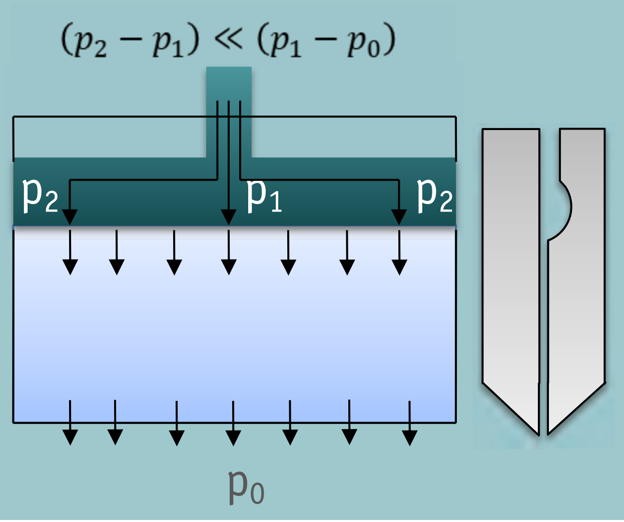

**Optimal static wetting lines**



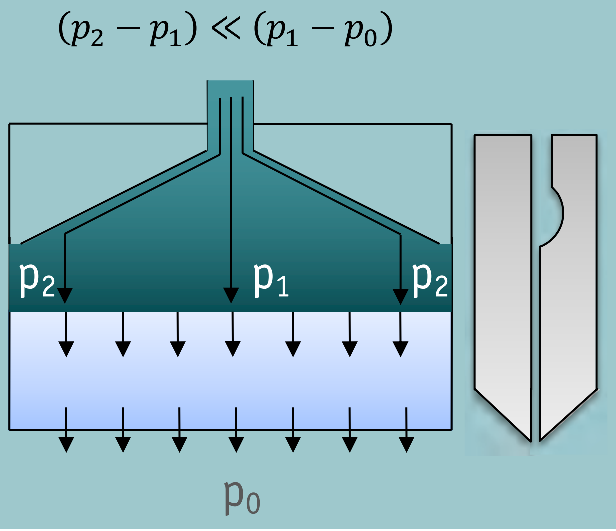
**Stabilization of wetting lines by undercut lips**

# Alternative design – types and concepts

## Standard



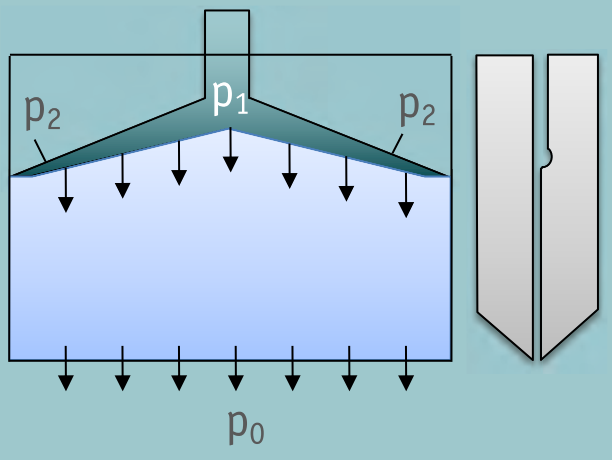

## Delta design for more uniform pathlengths



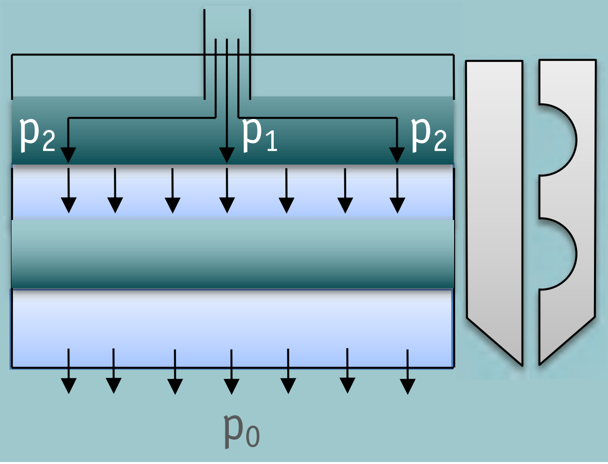
# Alternative design – types and concepts

## Coat hanger design for tiny manifolds

$$(p_1 - p_2) + (p_2 - p_0) = (p_1 - p_0)$$




## Double manifold for 2-fold uniformization

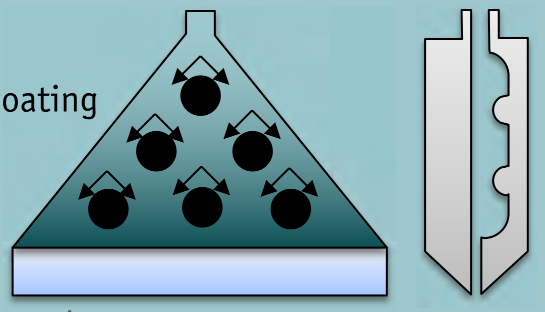


# Alternative design – types and concepts

## Randomized predistribution

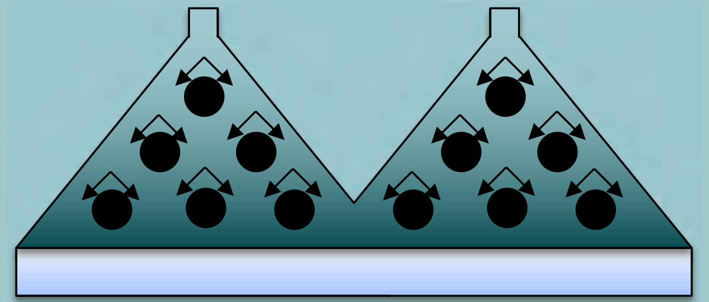
Predistribution by obstacles in the manifold
Reduced flow resistance by low σ coating
slot area remains uncoated or hard coated

Low σ coating



Uncoated
or hard coated

## Stackable version



## Summary

| | | | |
|---|---|---|---|
| Introduction | Battery basics | Coating systems | Drying, curing & crosslinking |
| Todays equipment | Battery production lines | The battery fab | Proof of concept |

# Drying, curing & crosslinking

# Coating parameters

## Coating chemistry
- ✓ Rheology
- ✓ Viscosity
- ✓ Viscoelasticity
- ✓ Type of solvents
- ✓ Amount of solids
- ✓ 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

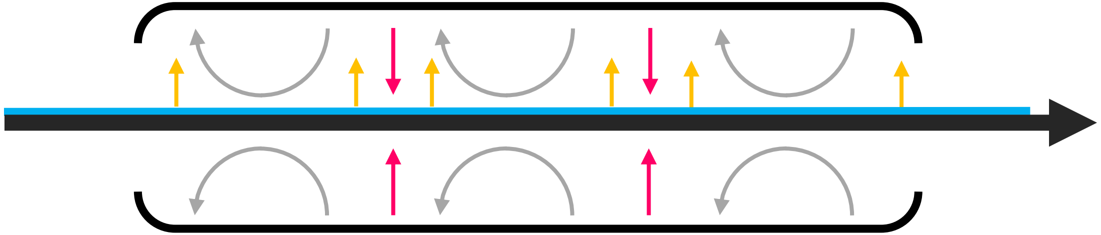
## Substrate
- ✓ Surface tension
- ✓ Dimension stability
- ✓ Surface structure
- ✓ Contact angle

## Pretreatment
- ✓ Corona
- ✓ Plasma
- ✓ Cleaning

## Environment
- ✓ Humidity
- ✓ Temperature
- ✓ Inert conditions

## Finishing
- ✓ Calendaring
- ✓ Embossing
- ✓ Slitting

# Motivation – general tasks of drying



Substrate
Coating
Heat transfer
Vapor removal
Evaporating solvent

Relevant parameters:

- ✓ Solid heat capacity
- ✓ Solvent heat capacity
- ✓ Solvent evaporation energy
- ✓ Solvent evaporation speed

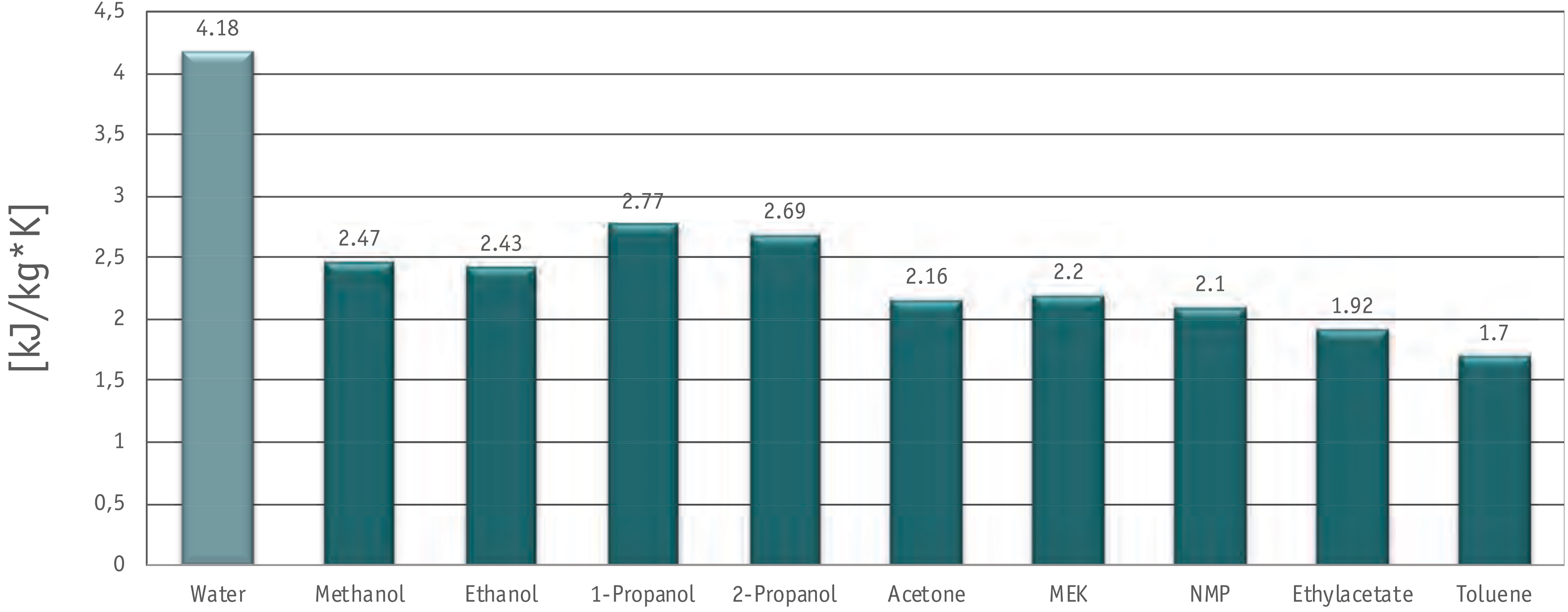
→ Seems to be trivial, but dryer technologies differ exactly in handling these tasks

# Solvent

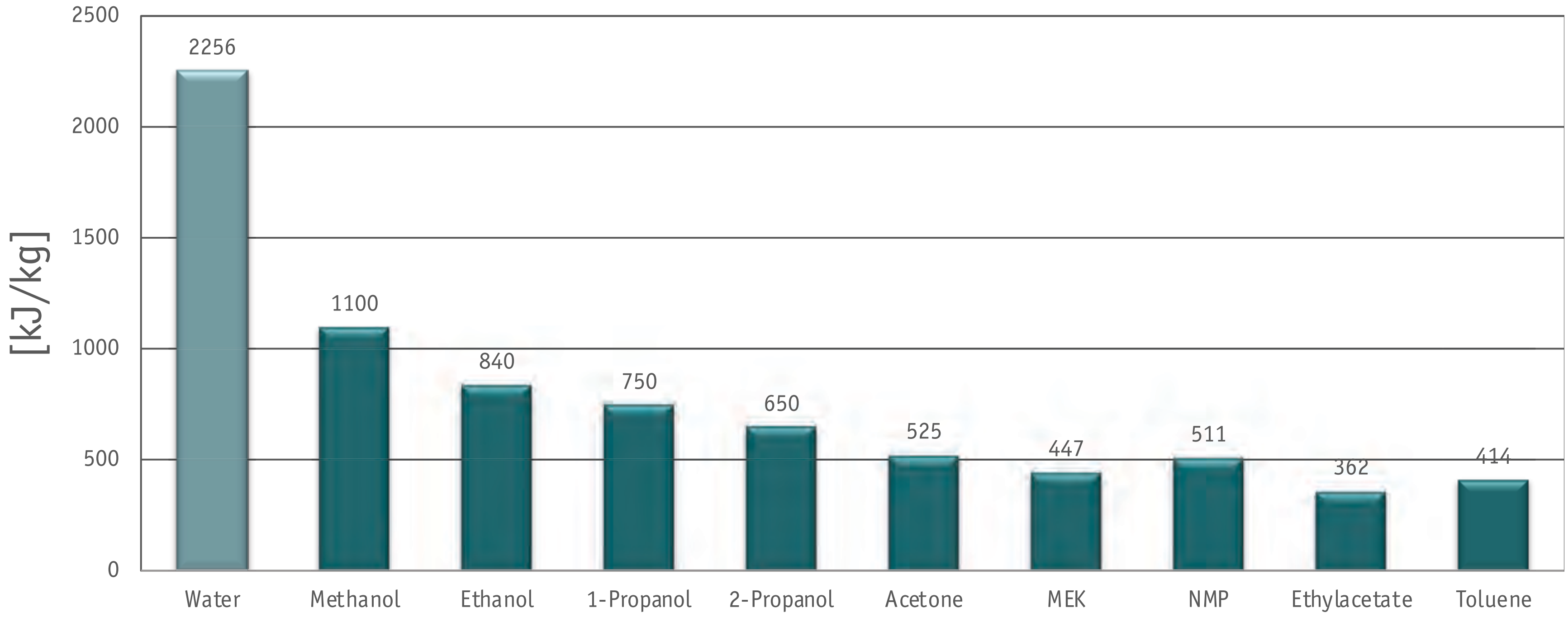
| Solvent | Molar mass (g/mol) | Boiling point (°C) | Vapor pressure at 20°C (mbar) | Vapor pressure at 50°C (mbar) | Evaporation energy (kJ/kg) | Heat capacity (kJ/kg*K) | Surface energy at 20°C (mN/m=dyn/cm) |
|---|---|---|---|---|---|---|---|
| Water | 18 | 100 | 23 | 123 | 2256 | 4.2 | 71.9 |
| Methanol | 32 | 65 | 129 | 535 | 1100 | 2.5 | 22.5 |
| Ethanol | 46 | 78 | 59 | 280 | 840 | 2.4 | 21.6 |
| 1-Proponol | 60 | 97 | 20 | 112 | 750 | 2.8 | 23.0 |
| 2-Proponol | 60 | 82 | 43 | 225 | 650 | 2.7 | 21.0 |
| Acetone | 58 | 56 | 246 | 830 | 525 | 2.2 | 22.8 |
| MEK | 72 | 80 | 105 | 373 | 447 | 2.2 | 24.6 |
| NMP | 99 | 203 | 0.3 | 2.9 | 511 | 2.1 | 40.9 |
| Ethylacetate | 88 | 77 | 98 | 380 | 362 | 1.9 | 23.0 |
| Toluene | 92 | 111 | 29 | 124 | 414 | 1.7 | 28.5 |

no guaranty

# Heat capacity



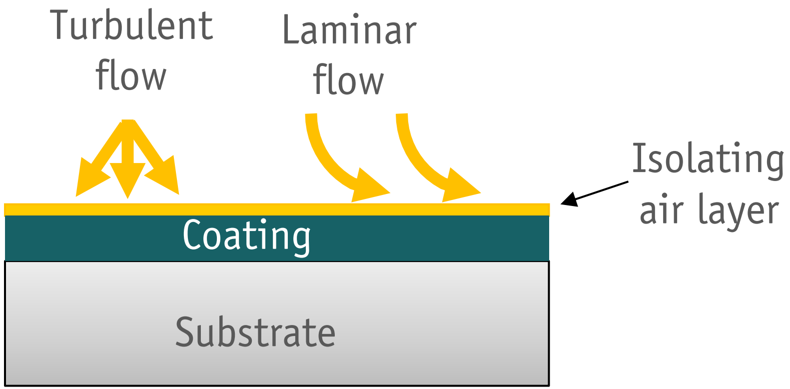
# Evaporation energy



# Drying time

An isolating air layer forms just on top of the coating layer.

- ✓ This layer is hardly moving and thereby hinders the heat transfer as well as the solvent evaporation.
- ✓ It has to be broken by sufficient air flow without sacrificing the coating surface.




**Usually there is a trade-off:**

effective fast heat transfer
or
gentle mild slow drying

# Drying time: heat transfer coefficient

- ✓ The heat transfer coefficient $\alpha$ describes energy transfer from hot air to liquid
- ✓ Energy transfer $\dot{Q}$ can be calculated in fair approximation from Reynolds number $R_e$ , Prandtl numer $P_R$ and Nusselt number $N_U$
- ✓ $\propto = \frac{\dot{Q}}{A\,(TD - TO)}$ $\quad R_e = \frac{wD}{v}$ $\quad P_r = \frac{v}{a}$ $\quad N_u = f\,(Re, Pr)$
- ✓ An empirical function Nu = f (Re, Pr) is given in the literature for single slot nozzle and slot nozzle arrays
- ✓ From $N_u = \alpha \cdot \frac{D}{\lambda}$ then derive $\alpha$ and $\dot{Q}$

# Drying time

- ✓ Drying time depends on the solvent evaporation rate at demanded temperature (sufficient energy transfer to achieve this temperature may be presupposed).
- ✓ A decisive factor for evaporation rate is vapor pressure. If drying is allowed near the solvent boiling temperature, there is no difference in vapor pressure for all solvents.
- ✓ But if by other reasons the drying temperature is limited, there are huge differences in vapor pressure.
- ✓ So the issue is to find the vapor pressure and evaporation rate for the given solvent at demanded temperature.

## Vapor pressure

- ✓ Vapor pressure can be calculated for any solvent at any temperature, if 2 pairs of pressure and temperature are known:

  Clausius-Clapeyron: $\log p = K_1 + \frac{K_2}{T}$

- ✓ Such pairs of p and T are available in the literature for any solvent e.g. p (20°C) and T (1013 hPa).

- ✓ Online excel-sheets are available to calculated the vapor pressure for any solvent at any temperature from two pairs (p/T).

## Drying time, calculation of evaporation rate

- ✓ Vapor pressure is one factor of evaporation rate, but not the only one.
- ✓ Other than for vapor pressure there is no simple way to calculate the evaporation rate for any solvent at the demanded temperature.
- ✓ Based on a modified Hertz-Knudsen approach, the evaporation rate of any solvent at any temperature can be estimated (Coatema IP).
- ✓ $Z \sim (P_s - Pp) \cdot \sqrt{\frac{M_r}{T}}$
- ✓ But still there are other influencing factors unknown (like the matrix of solids). Such factors have to be determined experimentally.

# Calculation example

This is a practical example of a real calculation of dryer length for a 900 µm wet coating based on solvent xylene at drying temperature 120°C.

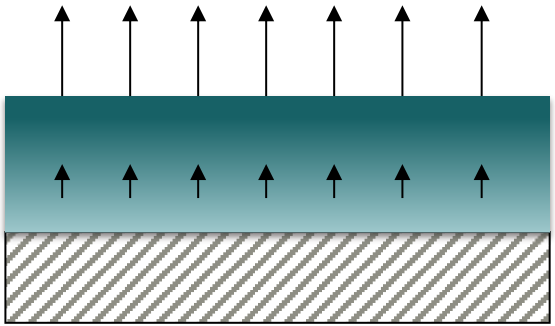
Sufficient energy transfer is supposed.

The result was verified by trial.

| **Coating data:** | |
|---|---|
| Coating thickness wet | 900 µm |
| Solvent xylene | 65% |
| Pure solvent thickness wet | 585 µm |
| Specific weight xylene | 0.88 g/cm³ |
| Solvent grammage | 514.8 g/m² |
| Web speed | 0.13 m/min |
| **Evaporation data:** | |
| Vapor pressure xylene at 20°C | 880 Pa |
| Boiling temperature xylene | 140°C |
| Vapor pressure at 120°C | 56180 Pa |
| Relative molar mass xylene | 106.17 |
| Evaporation rate (according to Coatema method) | 1.64 g/m²s |
| **Result (from web speed, grammage, evaporation rate):** | |
| Dryer length | 0.68 m |

# Diffusion limit and skinning

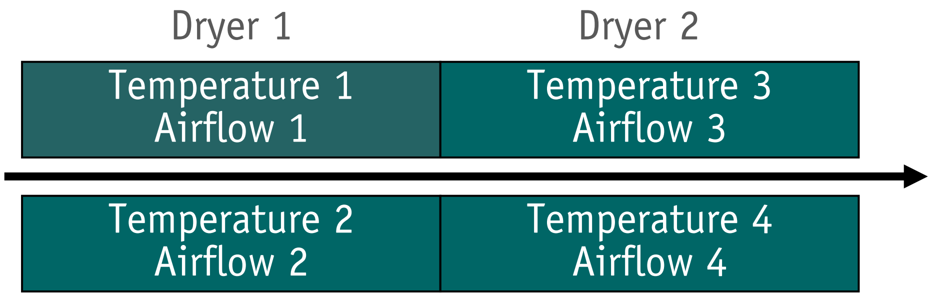
- ✓ Drying is limited by diffusion
  (at least in the final state of low residual solvent content).
- ✓ If the internal diffusion is slower than the evaporation from the surface, then a skin may be created.
- ✓ The skin acts as a barrier. The remaining diffusion through the skin may be slower than the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

# Dryer 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.



# Dryer design: surface deterioration

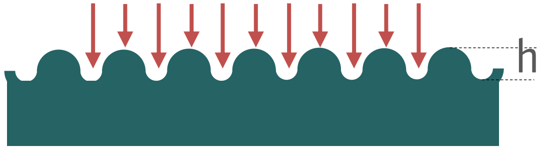
✓ Air flow removing the evaporating solvent may be laminar or turbulent.
Fluctuations of the flow may deteriorate the surface of a low viscous liquid causing wavy or stochastic structures.

✓ For rough estimation it may be assumed, that 10% fluctuations of the dynamic (impact) pressure of the air flow compensate the hydrostatic pressure difference caused by surface structures of the low viscous liquid:

$$10\rho_{liquid} \cdot g \cdot h = 1/2 \cdot \rho_{air} \cdot {v_{max}}^2 \qquad v_{max} = \sqrt{20\left(\frac{\rho_{liquid}}{\rho_{air}}\right) g \cdot h}$$

→ Result: orange skin of 1 µm deterioration depth would be created by an air flow of 0.5 m/sec with superimposed fluctuations of 10%.

Nonuniform air flow with 10% fluctuations




Coating with orange skin surface (exaggerated)

Dynamic effects being influenced by viscosity are not calculated. So the estimation holds for very low viscous liquids only.

# Dryer design

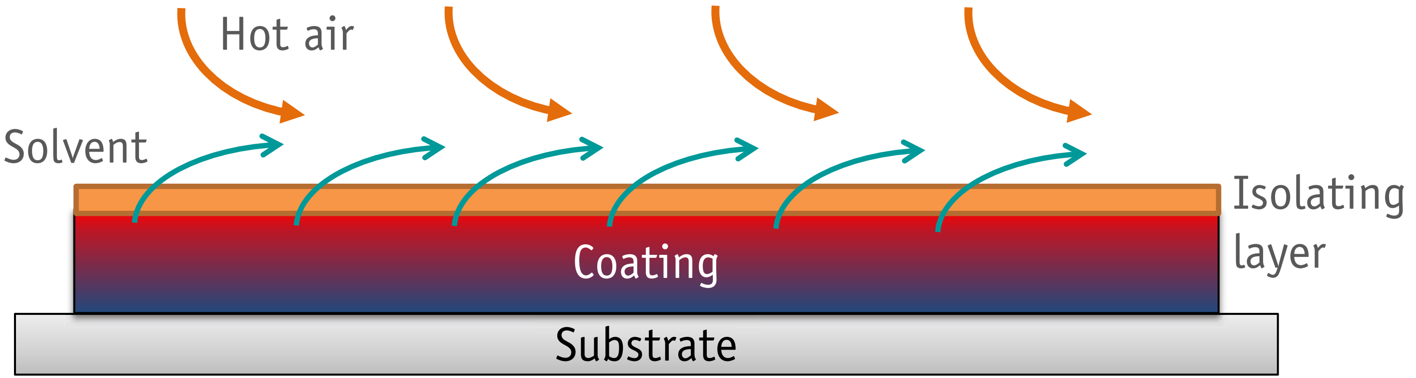
## Practical example: measured air speed in different dryers

| Dryer | Setting | $v_{air}$ at slot exit [m/s] | $v_{air}$ at web surface [m/s] | Remarks |
|---|---|---|---|---|
| **SC 12**<br>30 cm wide mini hot air dryer<br>with slots from above | 100% | 4.7 | 0.8 | 7 slots 260 x 7 mm²<br>Slot length = web width<br>Only from top values measure at first slot |
| **CC 08**<br>50 cm wide hot air dryer<br>with slots from above and below | 100% | 4.6 | 1.6 | 48 slots 83 x 5 mm²<br>24 from top<br>24 from bottom |
| **SM 21**<br>50 cm wide hot air floating dryer<br>with 180°-shifted air cusion<br>nozzles from above and below | 100% | 25 | | 8 nozzles from top<br>8 nozzles from bottom<br>3 slots for each nozzle<br>Center 800 x 7 mm²<br>Sides 800 x 4 mm² |

From the 100% setting the air speed can be reduced to any intended value by changing the ventilator settings and/or reducing the slot width. Surface deterioration thus can be avoided.

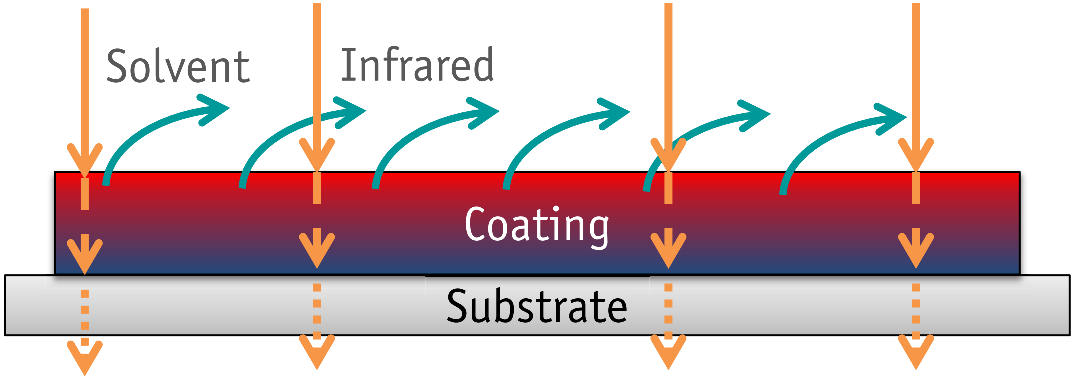
# Dryer design: hot air

- ✓ 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



## Dryer design: near-infrared (NIR)

- ✓ Heating and vapor transport separated
- ✓ Selective bulk heating by absorption
- ✓ Absorption dependent on λ
- ✓ Overheating and uniformity to be controlled
- ✓ Fast, if applicable
- ✓ Wavelength range 780 nm – 3 µm



# Dryer design

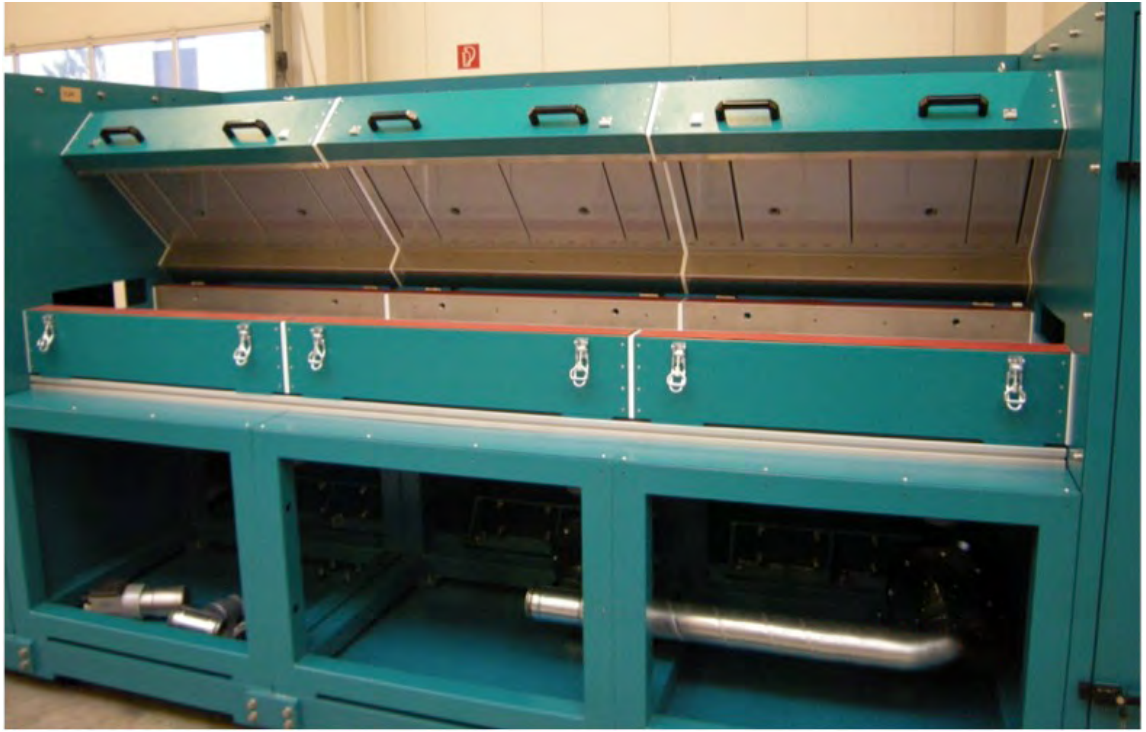
Wing shaped slot dryer

Wing shaped nozzle dryer with different nozzles

Simple slot dryer

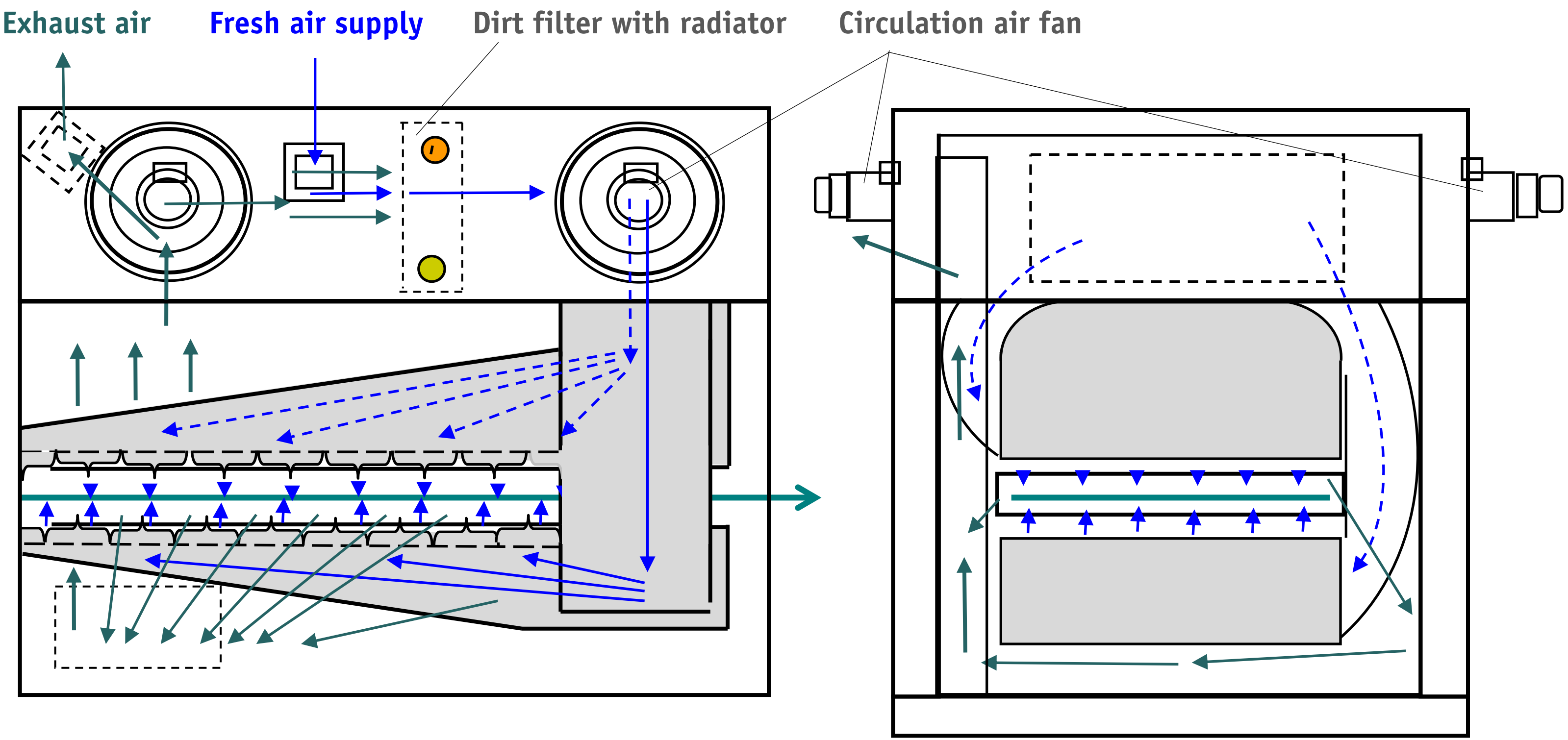
- ✓ Combined functions of heating and vapor transport
- ✓ Bulk heating by heat transfer from the surface
- ✓ Overheating easily avoided by limited air temperature

## Dryer design



Slot dryers with adjustable slots easy to clean

# Drying topics – drying technologies

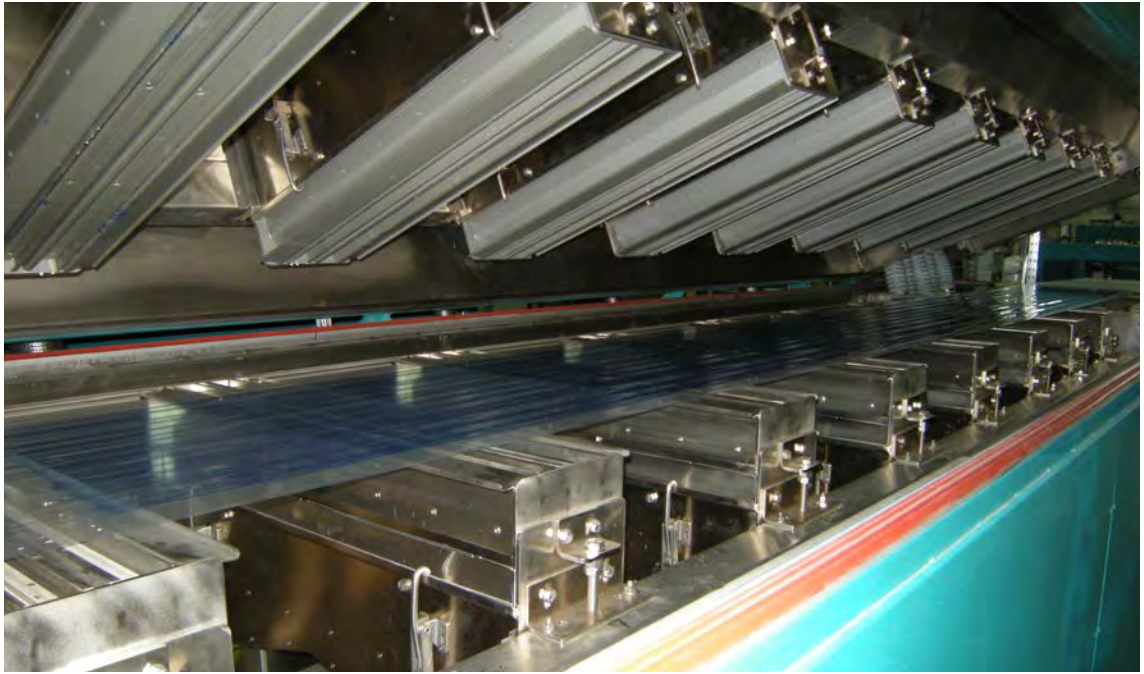


# Hot air technology

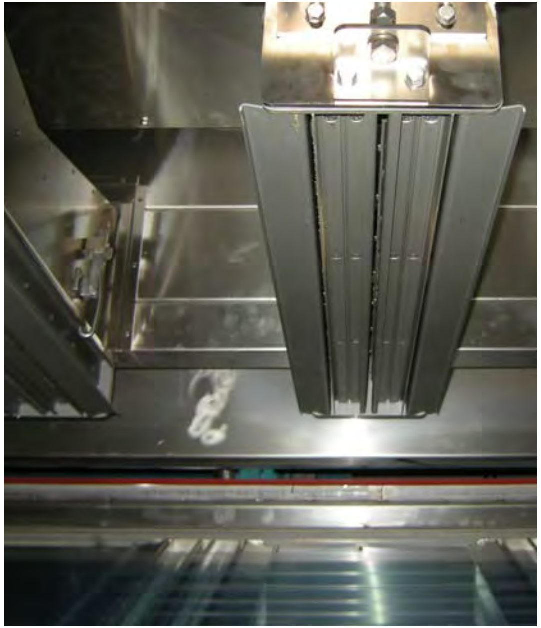
# Hot air technology

Nozzle dryers modul
Dry with shifted nozzles and wing shaped blow boxes

# Hot air technology



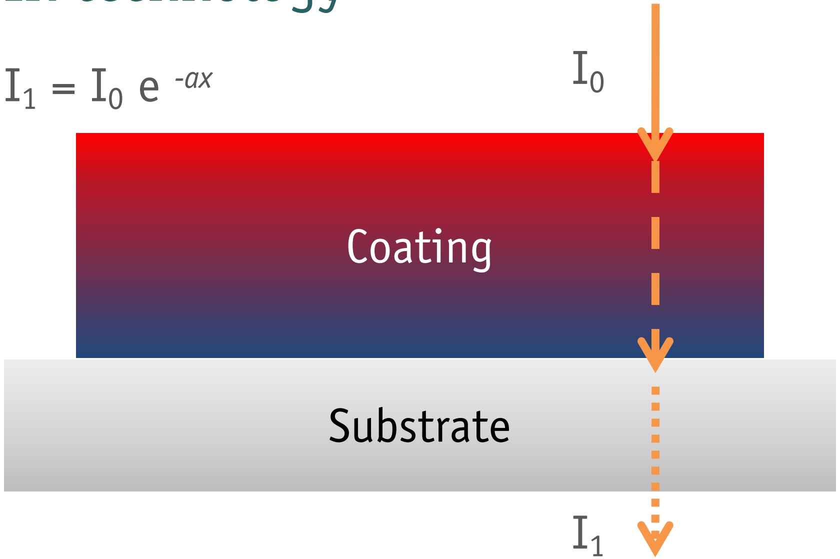
Floating dryer with 180°-shifted air cushion nozzles



Single 3-slot spoiler nozzle (option: venturi nozzle)

## IR technology

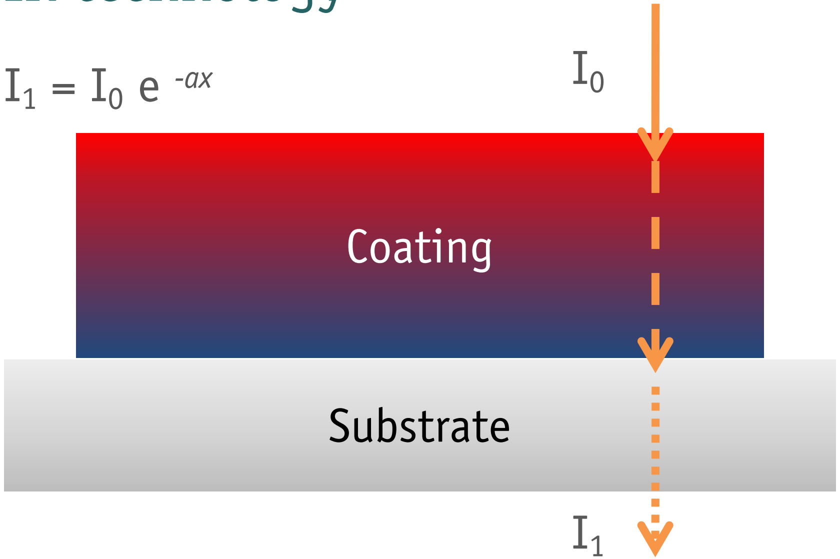
$$I_1 = I_0 e^{-ax}$$




$I_0$ Intensity in
$I_1$ Intensity out
a Absorption coefficient
x Layer thickness

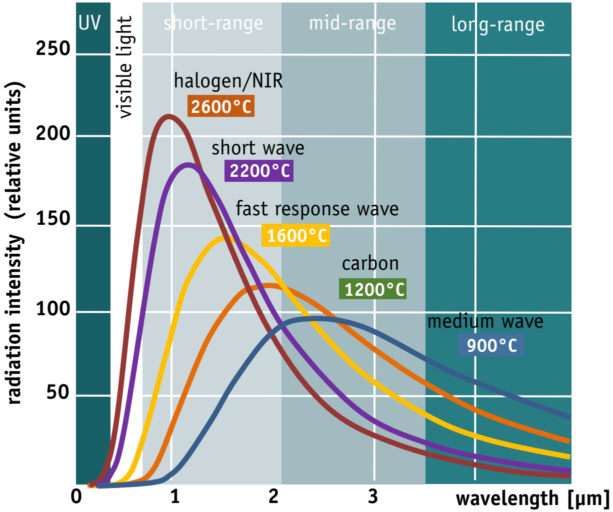
# IR technology

$I_1 = I_0 e^{-ax}$




$I_0$ Intensity in
$I_1$ Intensity out
a Absorption coefficient
x Layer thickness

High absorption | Optimum absorption | Low absorption




Relative intensity of radiators at different wavelengths

# IR technology – combined hot air / IR dryer

Coatema®
Coating Machinery GmbH

# Comparison

**Summary:**

Short wave NIR can be of great advantage, but only if applicable.

Applicability depends on coating liquid and substrate.

(The table focusses on applicable cases)

| | Hot air dryer | Heated drum-based dryer | Infrared dryer | NIR drying technology | UV/EB curing |
|---|---|---|---|---|---|
| Drying time of physical drying | > 1.0–20.0 s | Depending on substrate thickness ~> 1.0 s | 0.3–10.0 s | 0.02–1.5 s | Not applied |
| Curing time of cross-linking section | 5.0–30.0 s | 3.0–15.0 s | 1.0–10.0 s | 0.1–2.0 s | 0.1–2.0 s |
| Dynamic capability | Preheating and standby operation while web stop required | Preheating and standby operation while web stop required | Mostly no preheating required | Fully instantaneous start/stop capability | Depending on system, extreme dynamic, often preheating required |
| Max. possible production speed | Mostly only up to 600 m/min (1969 fpm) | Mostly <100 m/min (328 fpm) | Max. up to <1000 m/min (3281 fpm) | At present no limit up to >2000 m/min (6562 fpm) | Mostly only up to 600 m/min (1969 fpm) |
| Risk regarding thermal damage | High, depending on air temperature especially at fast web stop | High, depending on drum temperature | Lower, but given depending on heat due to mass of dryer design | Low, due to working principle and dryer design | Low, due to working principle |
| Applied for thermal sensitive substrates | Limited to low air temperature (<80 °C/ 176 °F) results in strong reduced drying performance | Limited to low drum temperature (<80 °C/ 176 °F) results in strong reduced drying performance | Limited to low drying power due to resulting thermal stress | Possible up to high production speed due to working principle and dryer design | Possible up to high production speed due to working principle an dryer design |
| Risk regarding penetration of the coating materials in open substrates | Cannot be avoided due to long drying time required | Cannot be avoided due to long drying time required | Can be reduced slightly, but not completely avoided | Can be avoided, due to extreme short drying time and high energy density | Can be avoided, due to extreme short drying time and high energy density |
| Consumption of consumable material | High, especially due to penetration in the substrate | High, especially due to penetration in the substrate | Lower, because of low penetration | Lower, because of mostly avoided penetration in the substrate | Lower, because of mostly avoided penetration in the substrate |

courtesy Adphos

## Dryer design: microwave technology

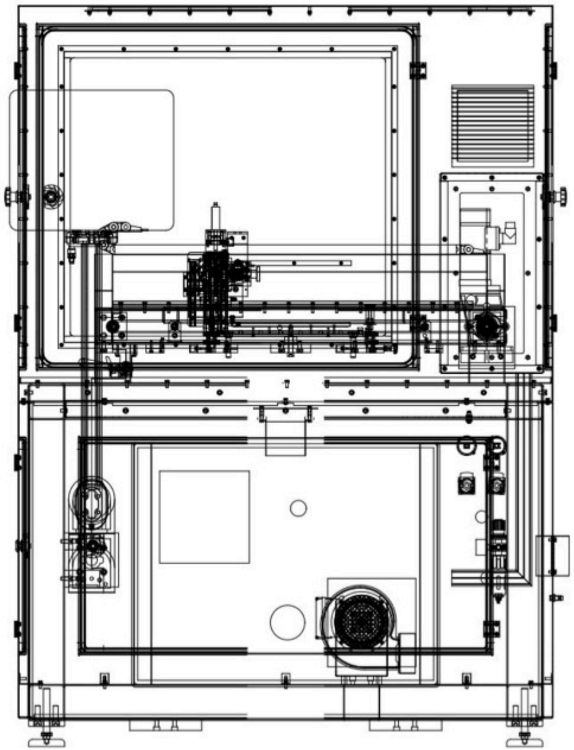
- ✓ Same pros and cons as IR, but even exaggerated
- ✓ Penetration depth approximately 2 cm,
  low absorption in thin layers (low absorption coefficient),
  resonator required for multiple passage
- ✓ Complex system
- ✓ Advantages for very thick layers only (e.g. foam blocks)

# Drying technologies – drying with hot air technology

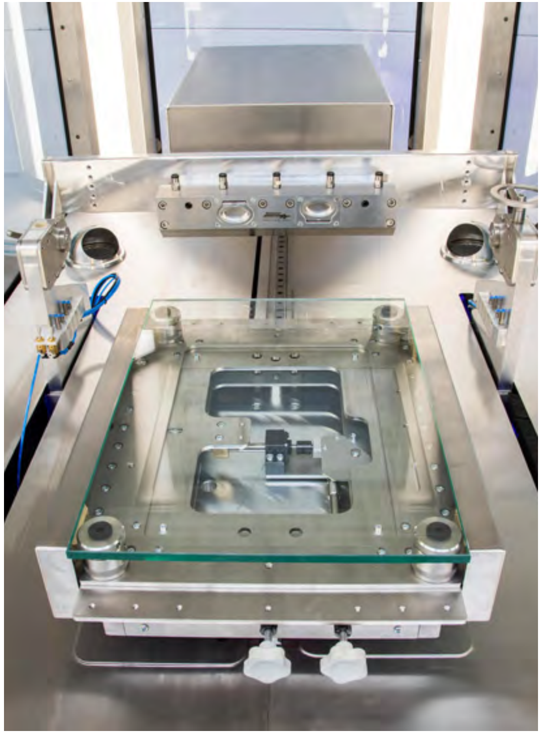
# Summary

| | | | |
|---|---|---|---|
| Introduction | Battery basics | Coating systems | Drying, curing & crosslinking |
| Todays equipment | Battery production lines | The battery fab | Proof of concept |

# The Easycoater

# The Easycoater



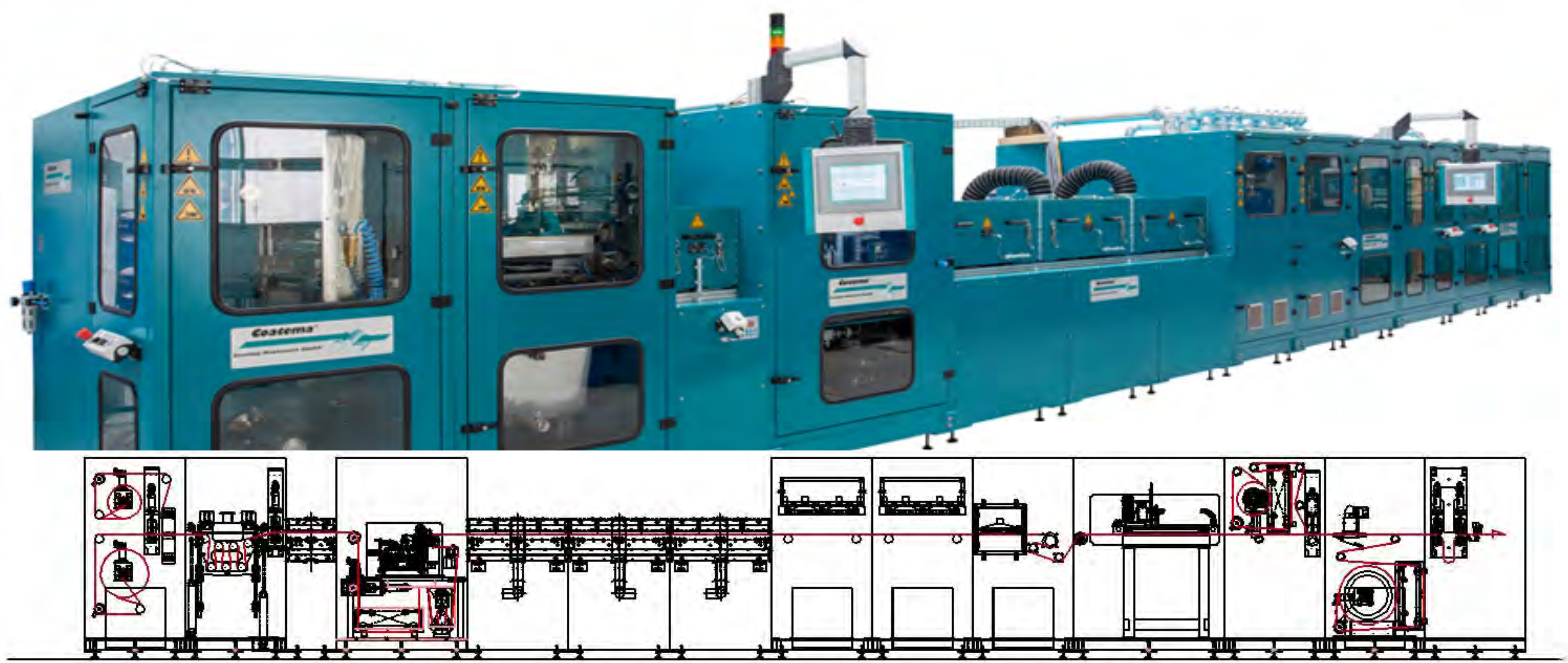

## Facts

- ✓ Knife system
- ✓ Slot die system
- ✓ Screen system
- ✓ Heated vacuum table
- ✓ Integrated air heating

# The Smartcoater

# The Basecoater

# The Basecoater 3rd Generation

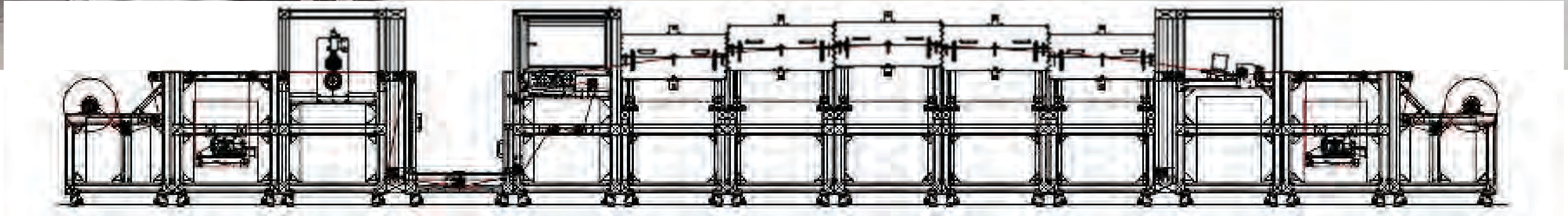


# The Basecoater 3rd Generation

## Facts

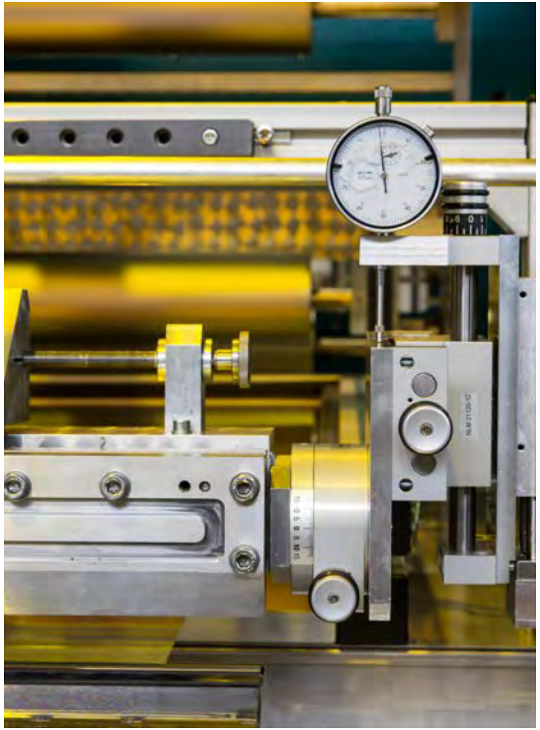
- ✓ Cantilever rollers
- ✓ Contact cleaning
- ✓ Corona station
- ✓ Rotary screen system
- ✓ Hot air dryer
- ✓ Edge sealing & glue application
- ✓ IR dryer
- ✓ UV unit
- ✓ Slot die system
- ✓ 2 Roller system
- ✓ Delamination/Lamination
- ✓ Cross-directional cutting system

# The Click&Coat™



# The Click&Coat™

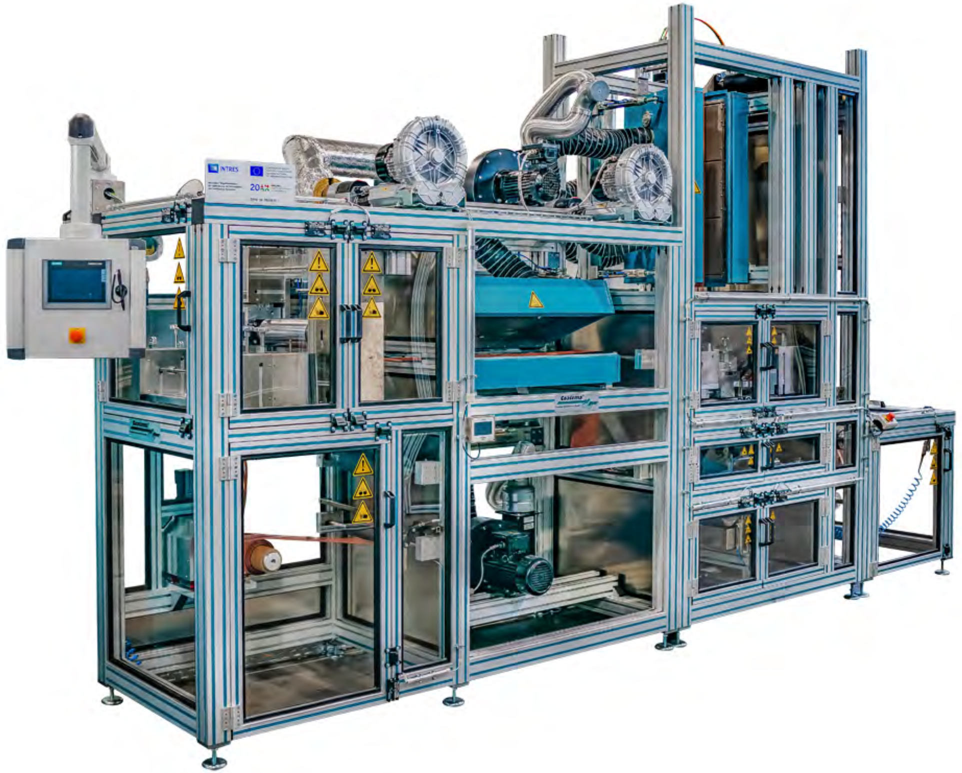
# The Click&CoatTM



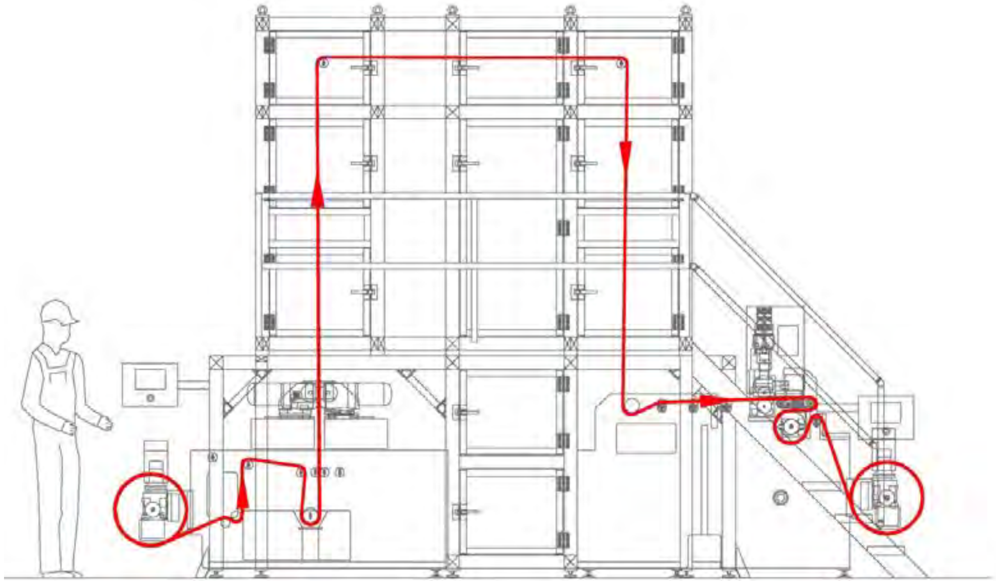
## Facts

- ✓ Working pedestral
- ✓ Edge control
- ✓ Corona unit
- ✓ Coating module
- ✓ Lamination
- ✓ Vacuum conveyor
- ✓ Dryer (with fan air supply heater)

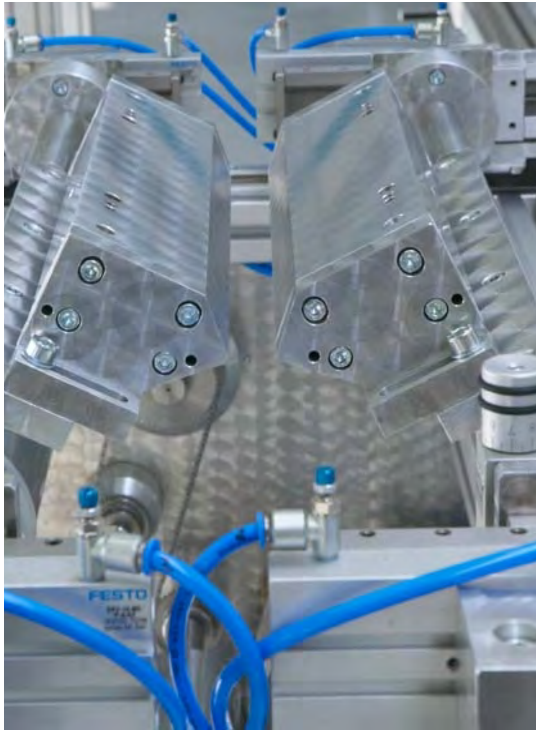
# The Verticoater



# The Verticoater



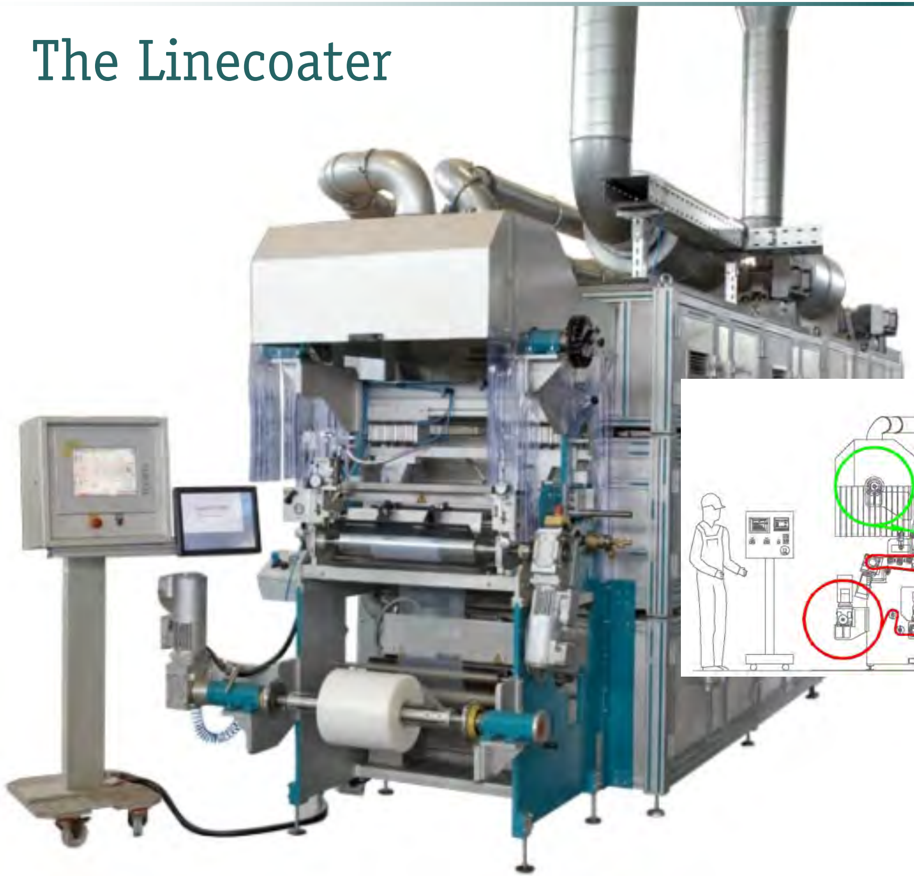
# The Verticoater

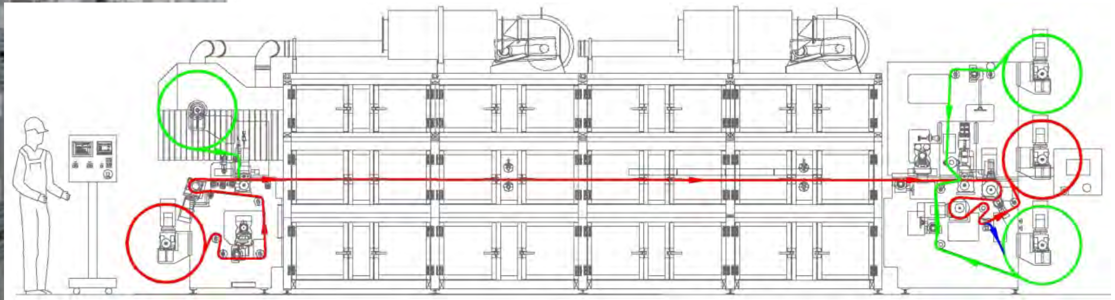



## Facts

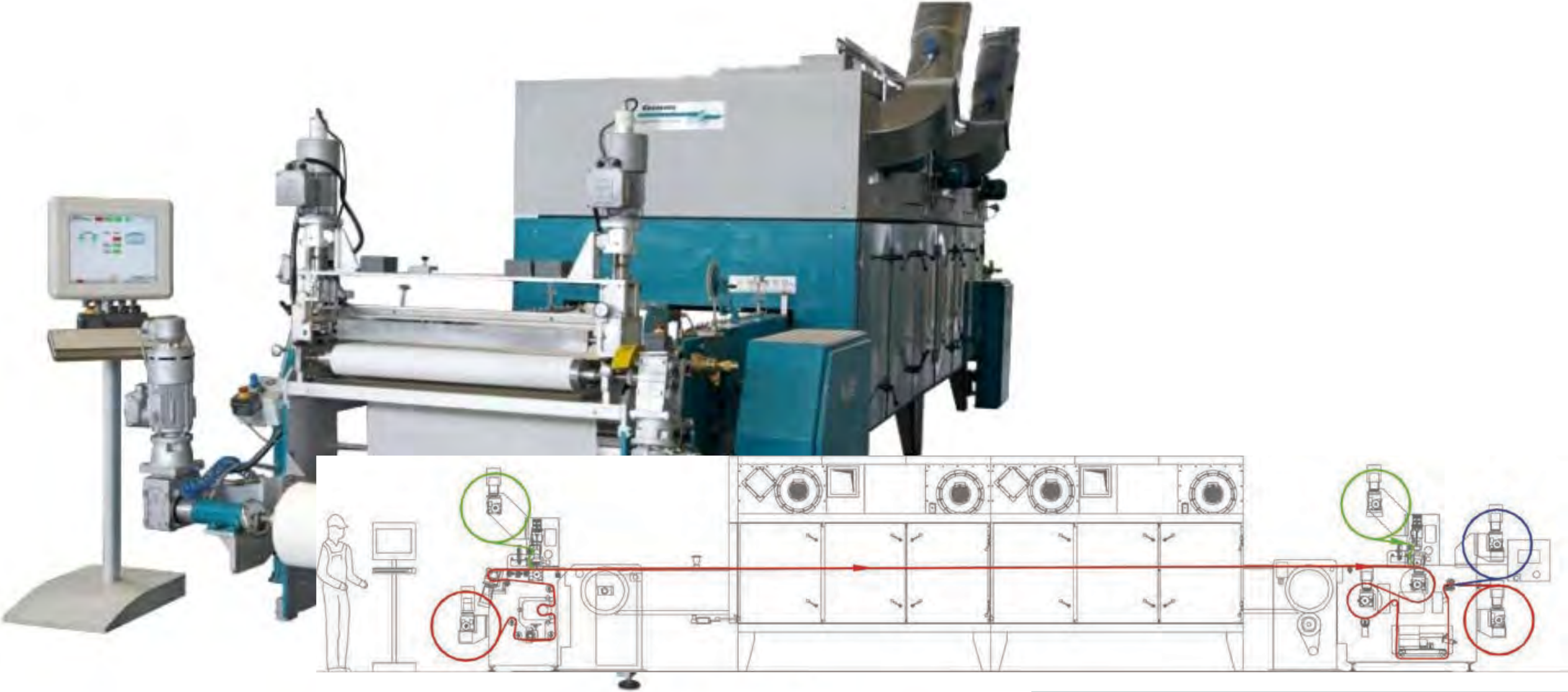
- ✓ Doubleside slot die coating
- ✓ Vertical drying
- ✓ Corona unit
- ✓ Exchangable coating modules
- ✓ Working width 300 mm, 500 mm, 1.000 mm

# The Linecoater





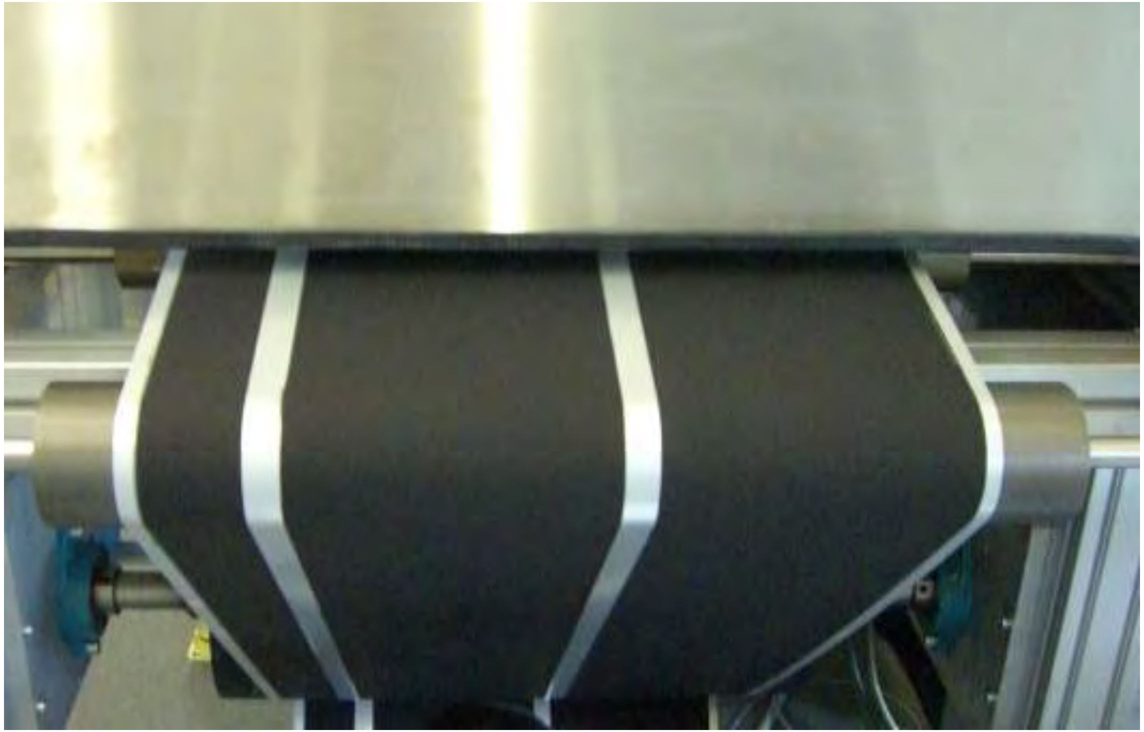
# The Linecoater



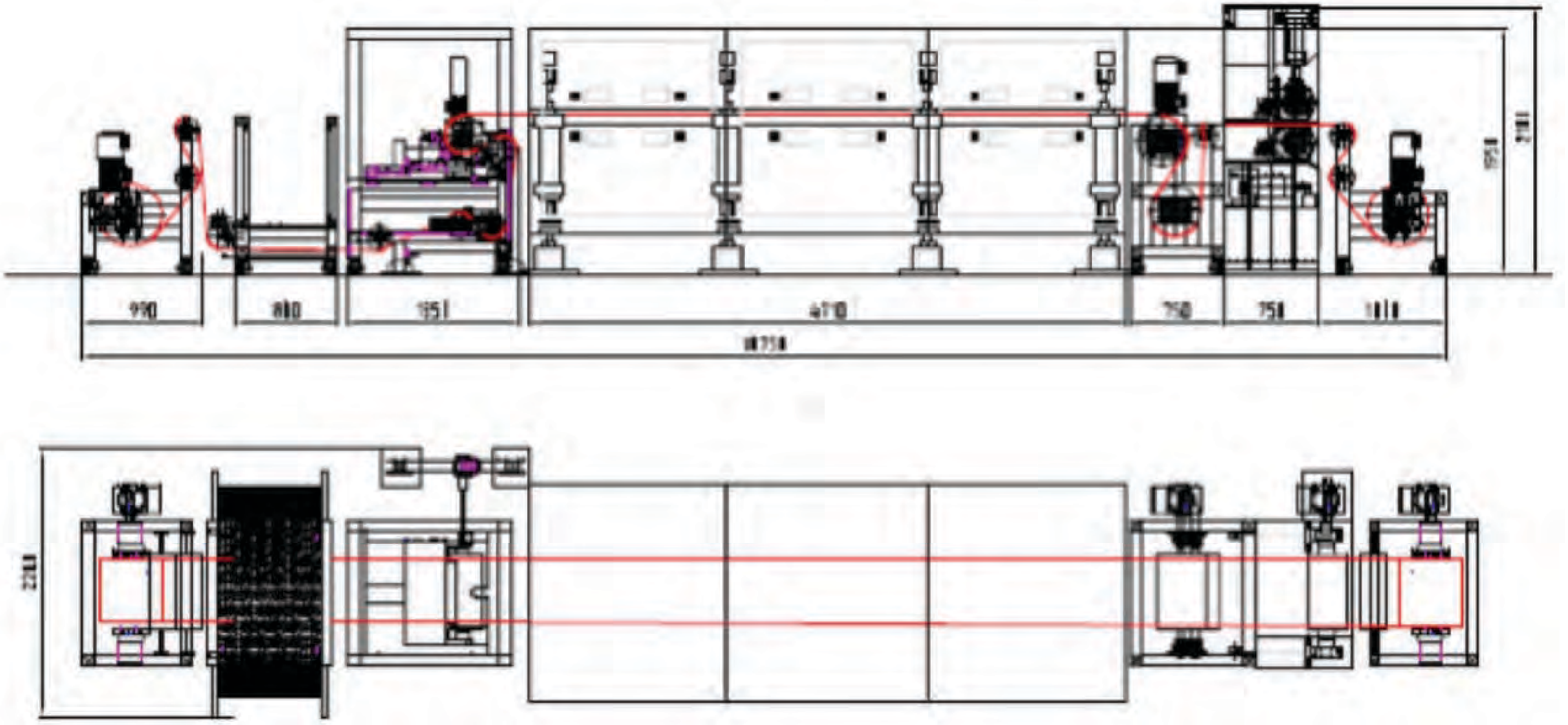
# Summary

| | | | |
|---|---|---|---|
| Introduction | Battery basics | Coating systems | Drying, curing & crosslinking |
| Todays equipment | Battery production lines | The battery fab | Proof of concept |

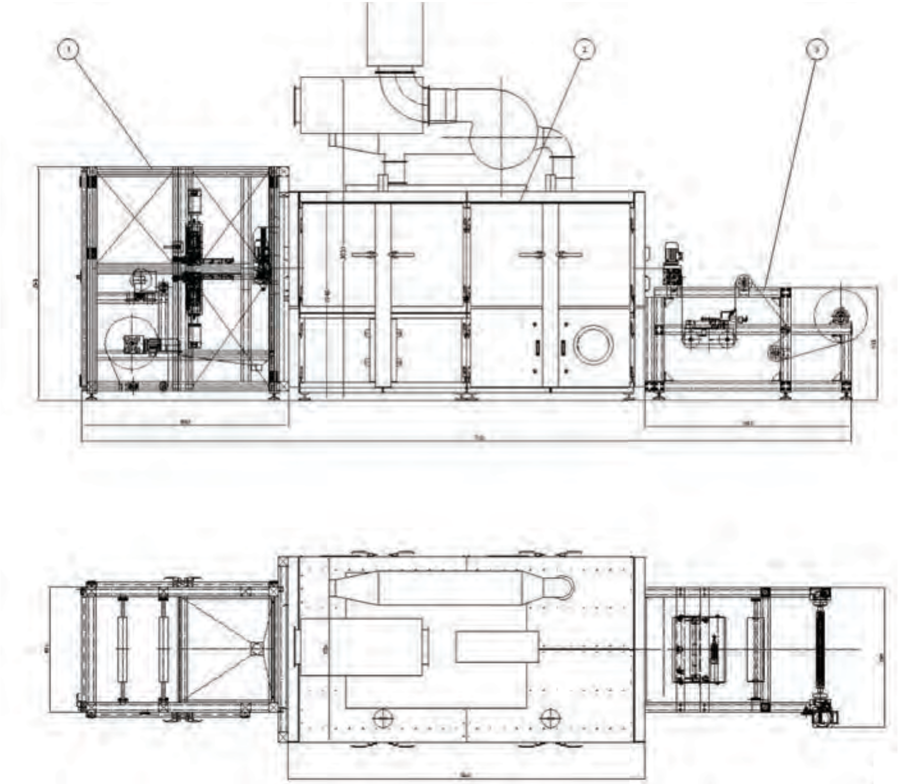
# Production line for batteries



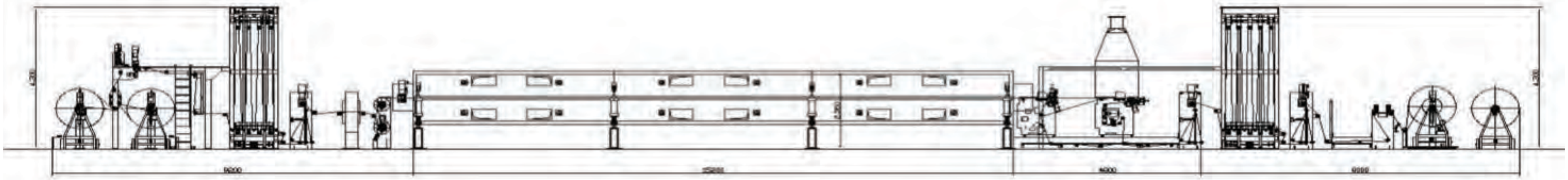
# Flotation dryer in pilotcoater concept



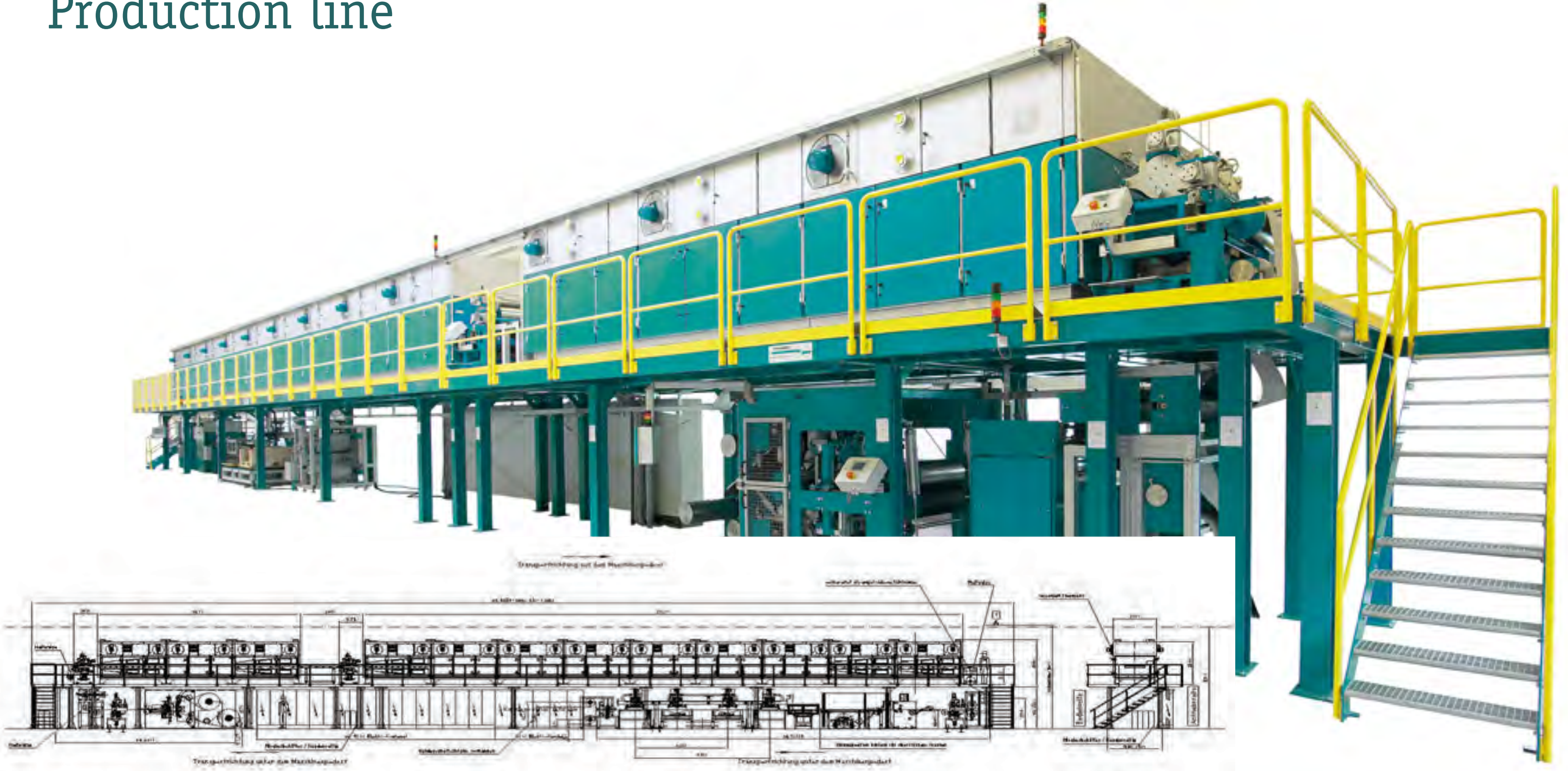
# Flotation dryer in pilotcoater concept



# Production line



# Production line



# Production line

# Production line

# Production line

# Production line

# Summary

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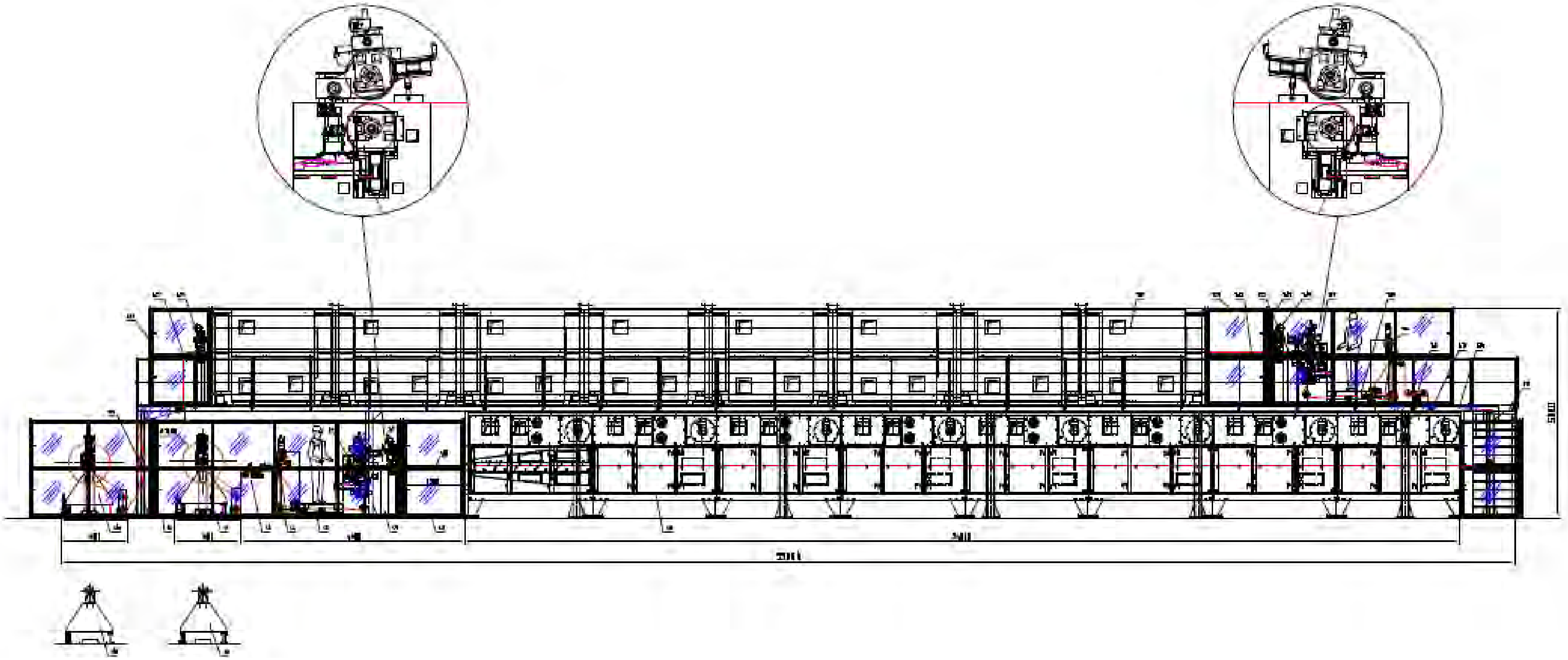
# Overview


Cathode Coating
Drying
Press & Slitting
Slurry
Anode Coating
Drying
Press & Slitting
Drying
Charge / Discharge
Stock
Formation
Electrolyte Filling
Assembly

# Coatema battery fab concept



# Lithium battery markets

## Transportation

### HEV / PHEV / EV

### Heavy-Duty hybrids

## Electric grid services

### Grid stabilization

### Uninterrupted power supply

## Facts

- ✓ Fuel economy
- ✓ Reduced emissions
- ✓ Energy independence

- ✓ Increase plant efficiency
- ✓ Increase grid reliability
- ✓ Energy independence

# Production process Li-Ion batteries

**Cathode** ⟩⟩⟩ Material preparation ⟩ Mixing ⟩ Coating ⟩ Pressing ⟩ Slitting, notching ⟩ Drying

**Anode** ⟩⟩⟩ Material preparation ⟩ Mixing ⟩ Coating ⟩ Pressing ⟩ Slitting, notching ⟩ Drying

Tab alignment and welding ⟩ Winding/ Lamination ⟩ Cell-stack assembly ⟩ Canning / Packaging ⟩ Sealing ⟩ Second drying

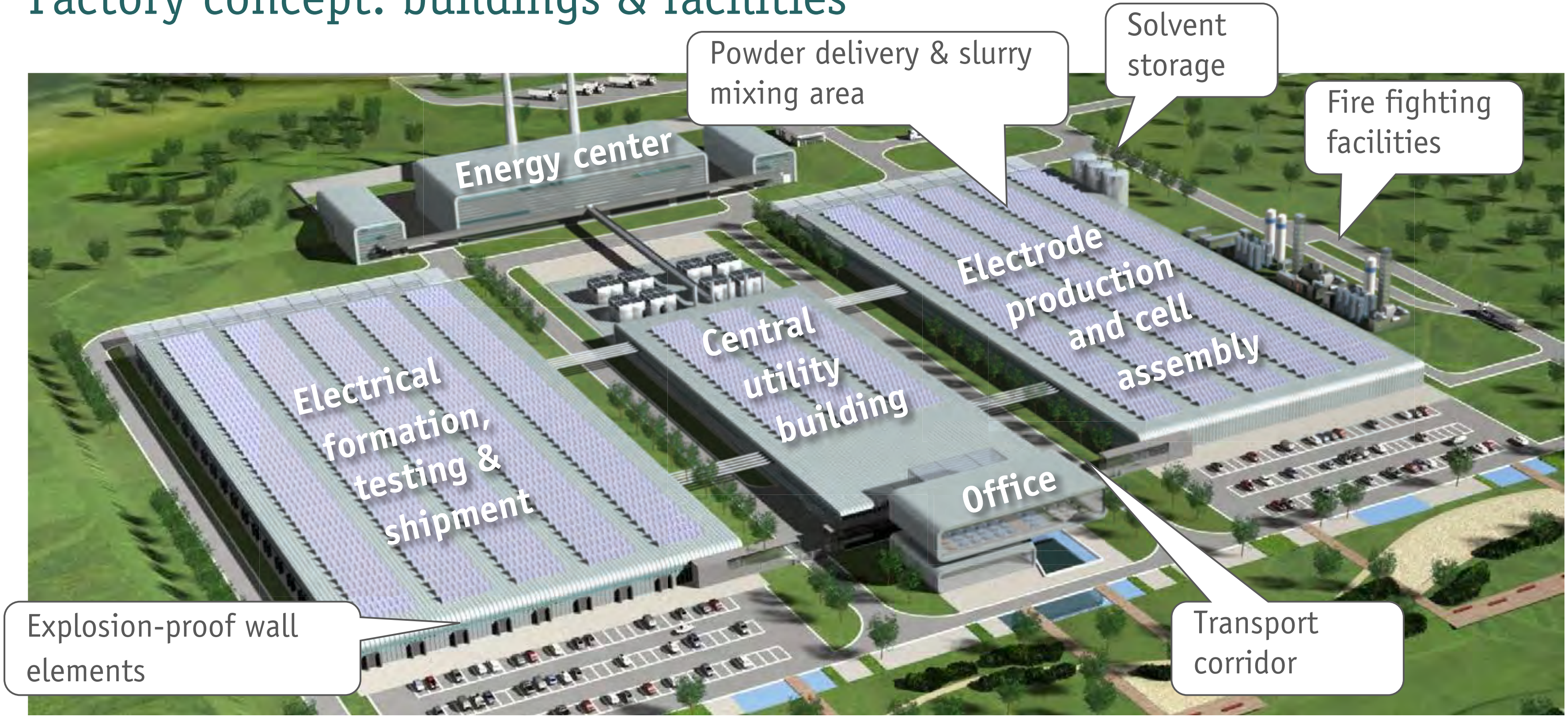
X-Ray ⟩ Electrolyte injection ⟩ Rest ⟩ Pre-Formation

X-Ray ⟩ Aging ⟩ Degassing ⟩ Formation

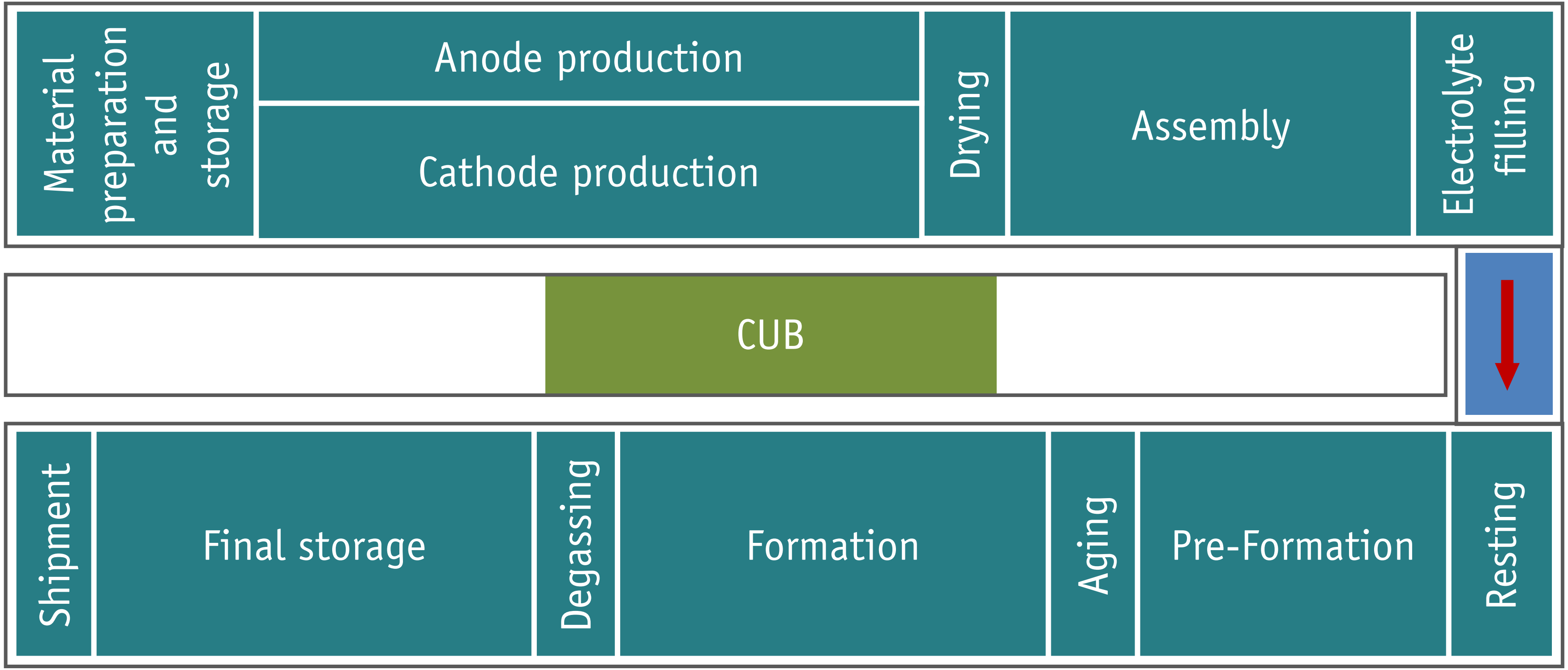
Final storage

# Factory concept: master site plan

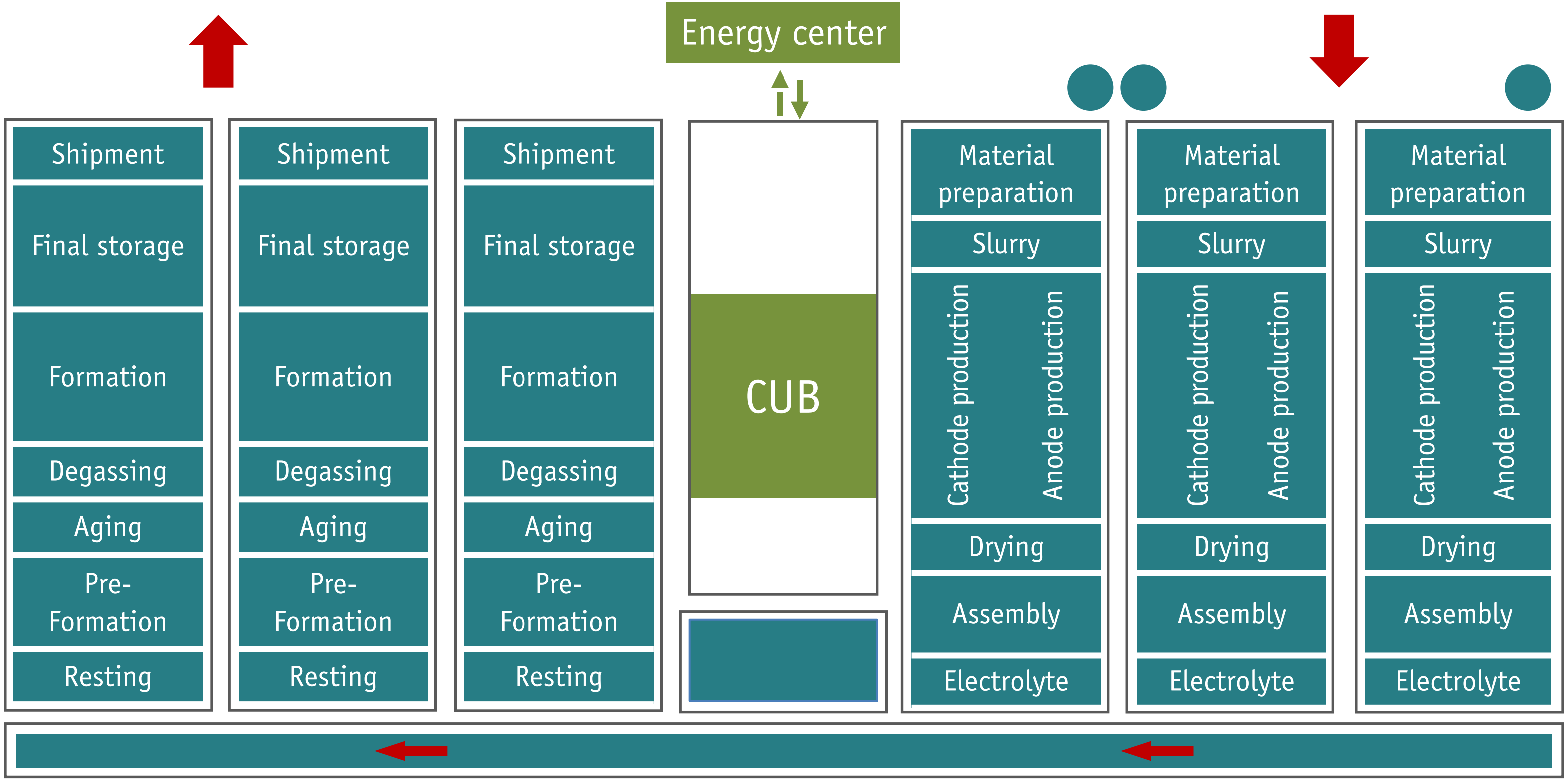
# Factory concept: buildings & facilities



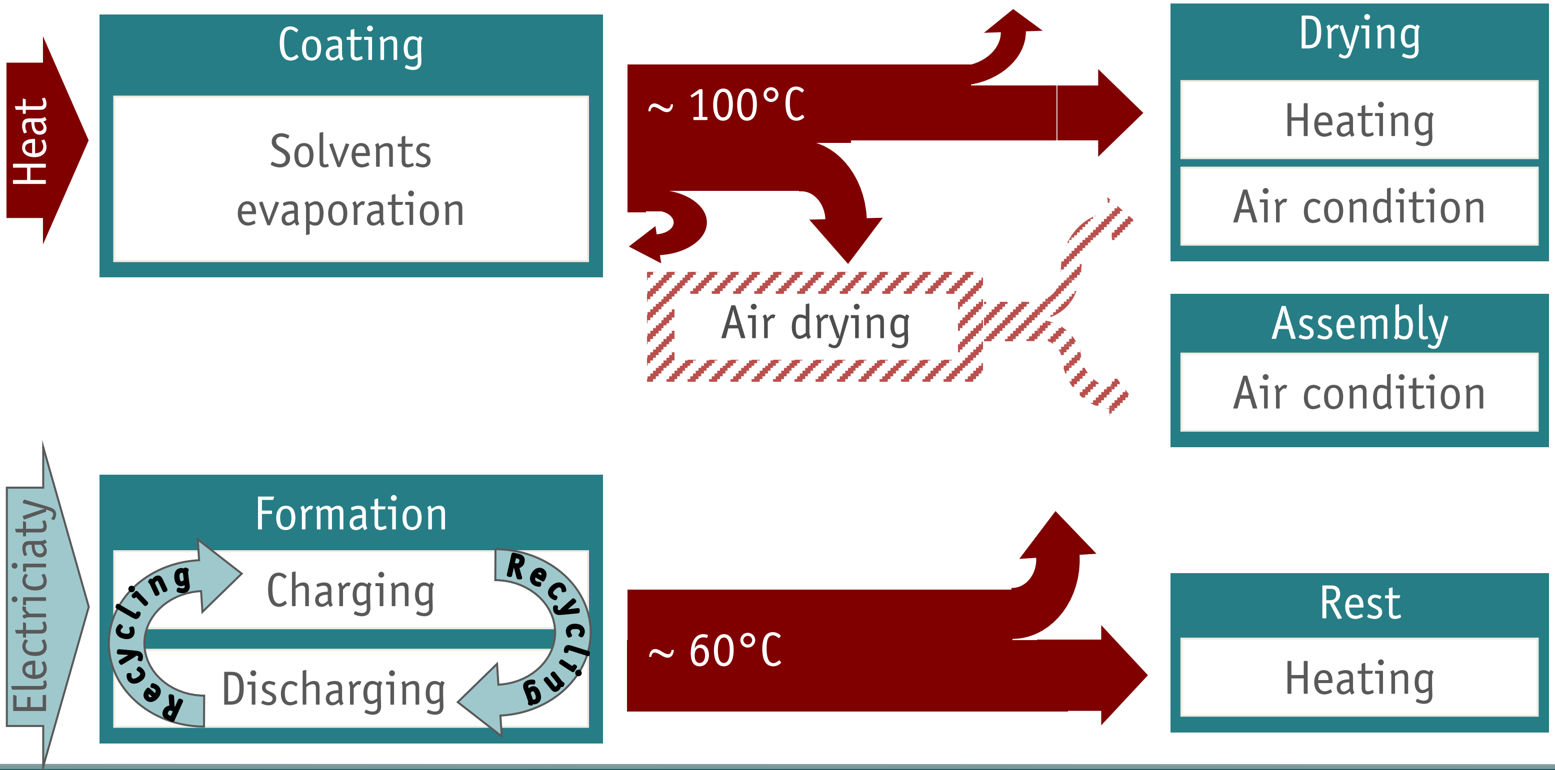
# Concept – phase I



## Concept – phase II: capacity 1200 – 1800 MWh/a



# Most relevant energy flows



# Summary

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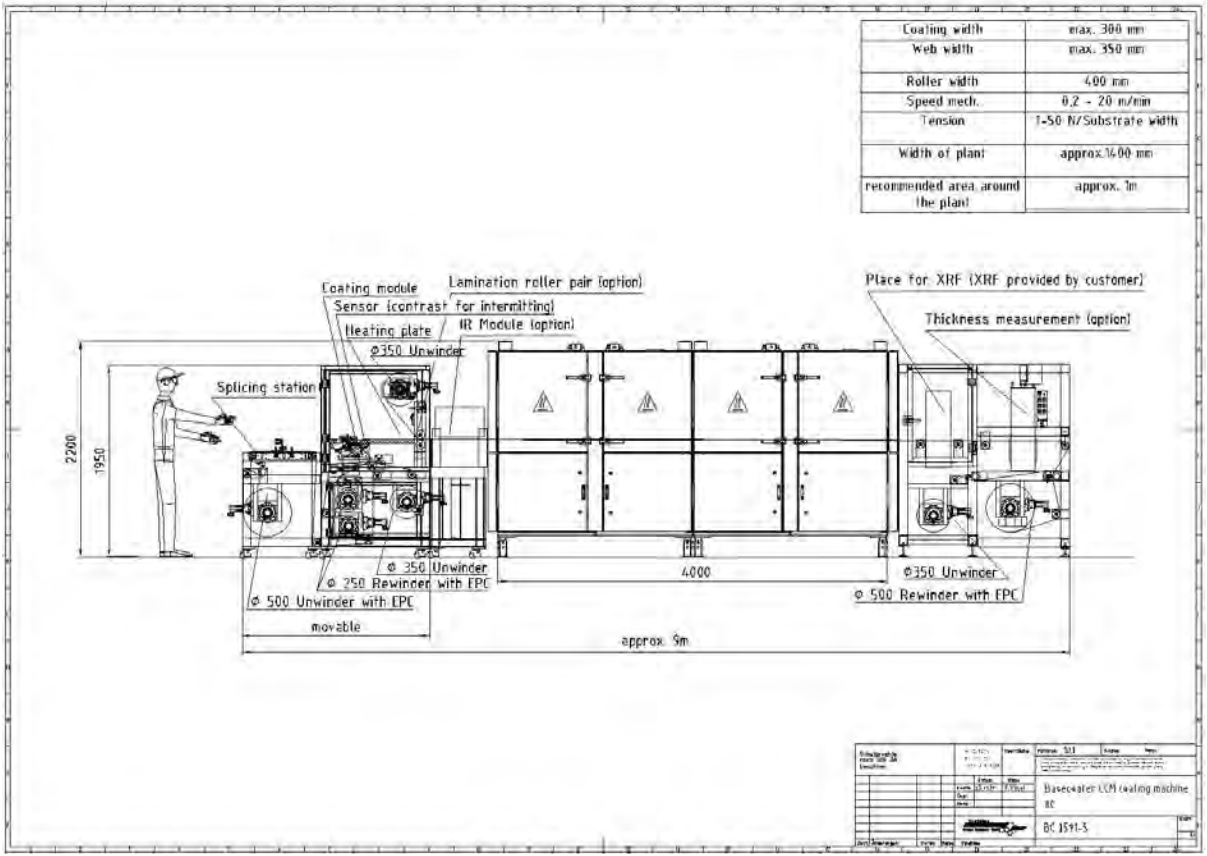
# Production steps

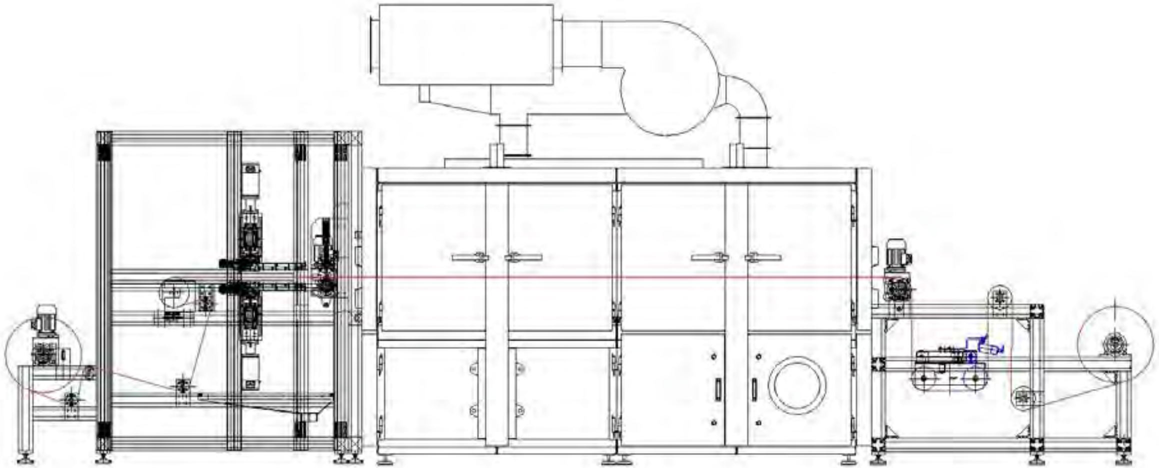
**Single side step:**
**coating / drying / cooling**

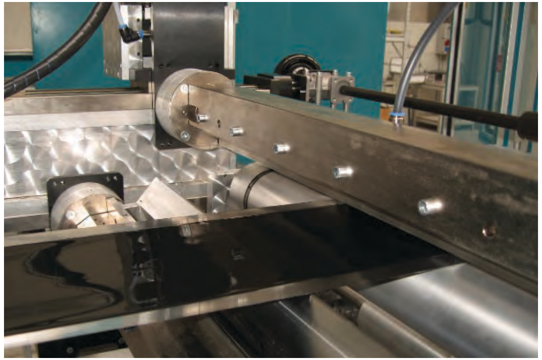
# Overview on layouts

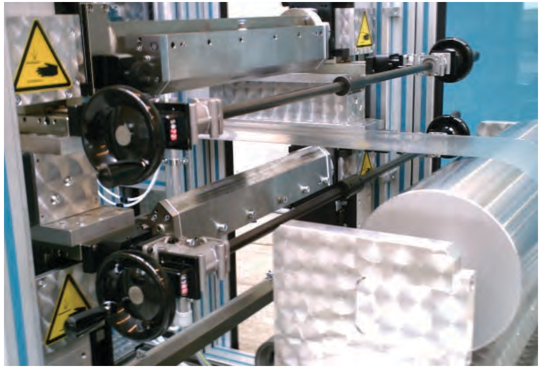


# Production steps

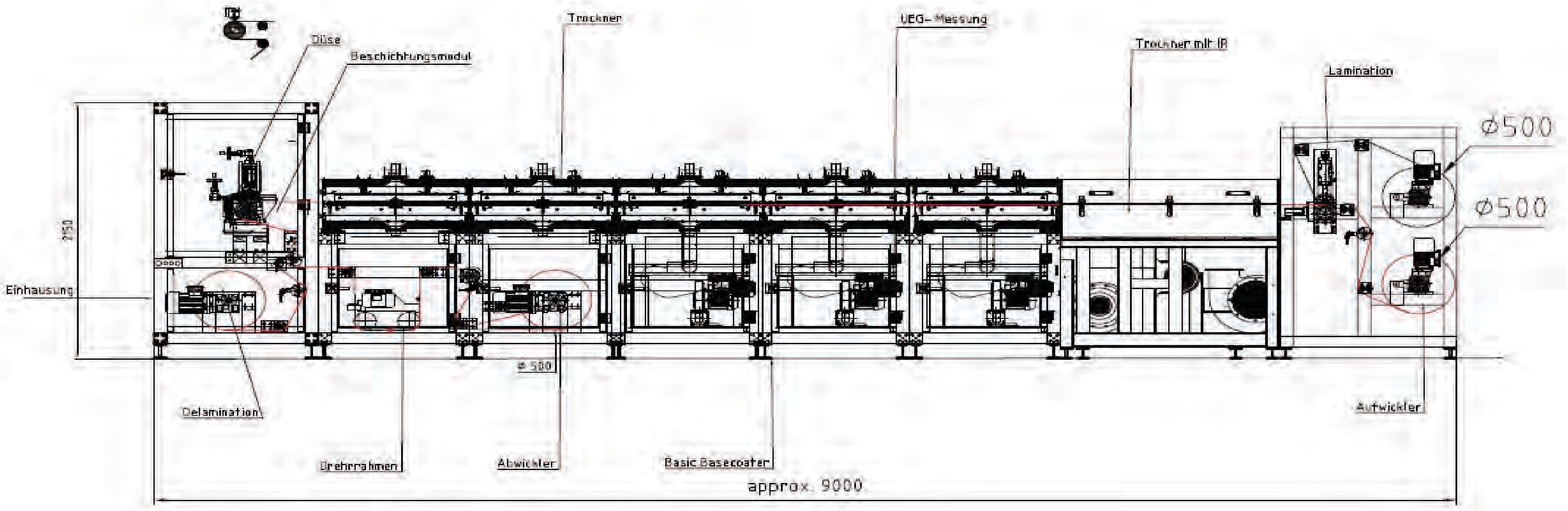
**Double side step:**
**coating / drying / cooling**







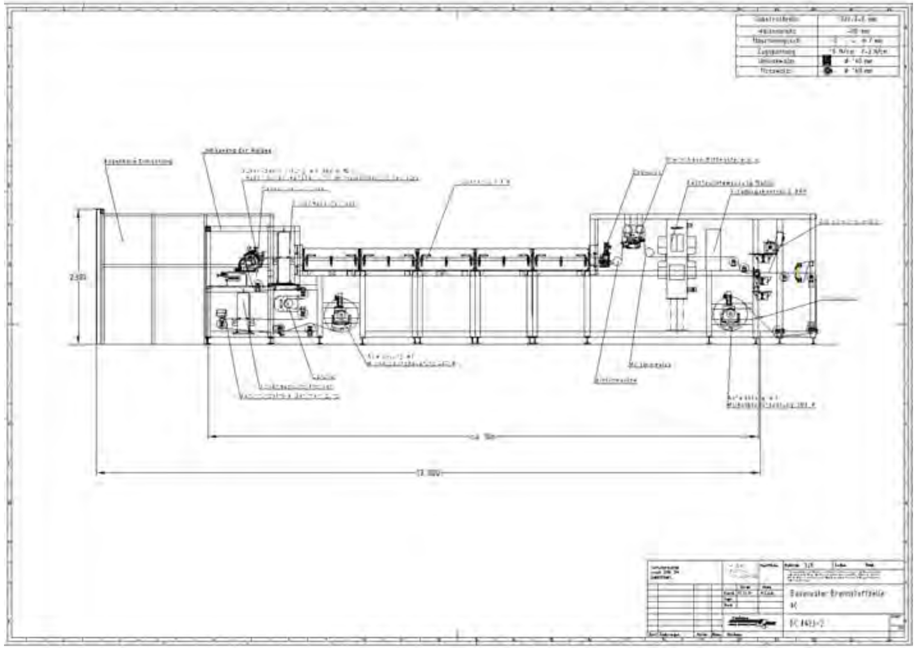
# The Basecoater



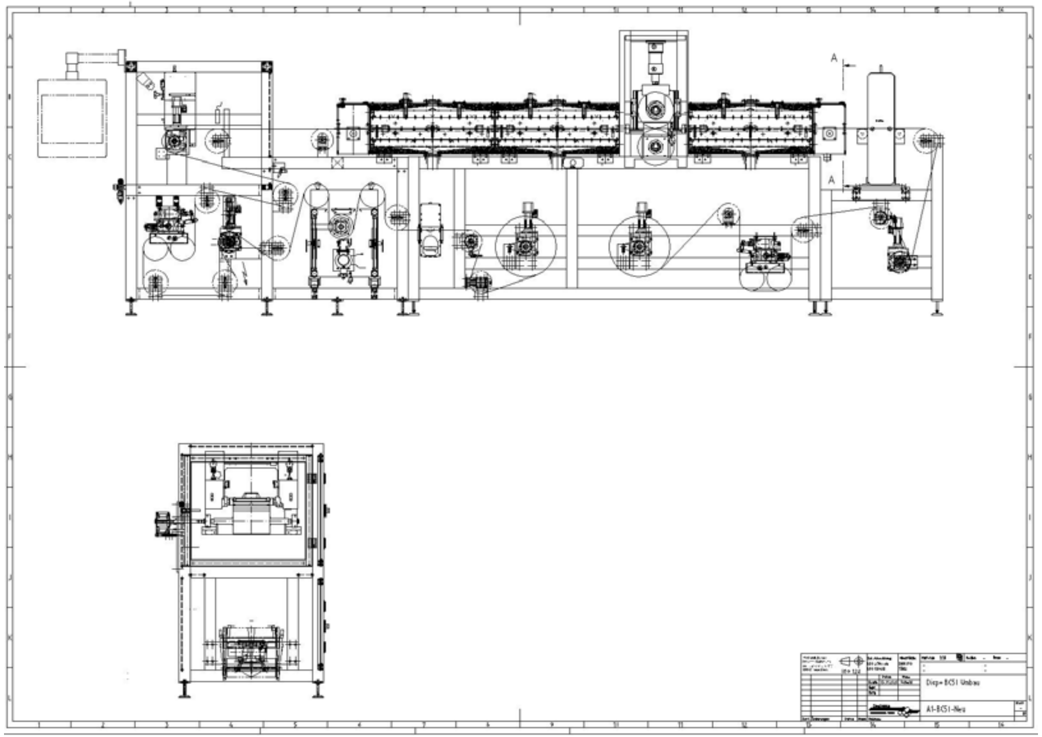
# The Basecoater

# Proof of concept

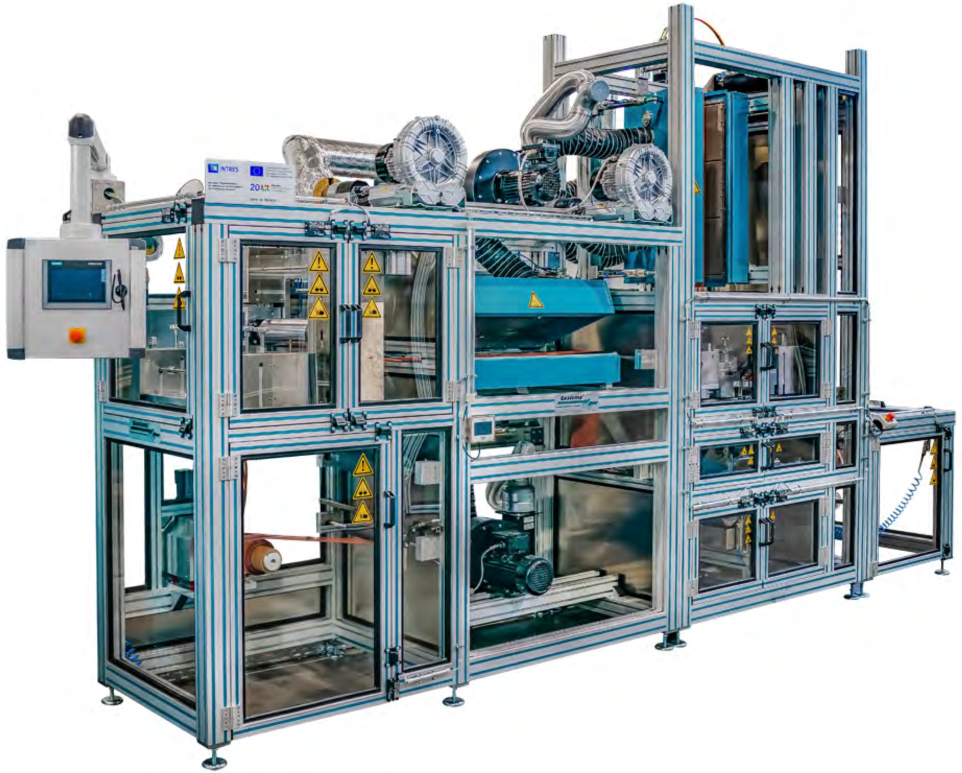
# Overview on layouts



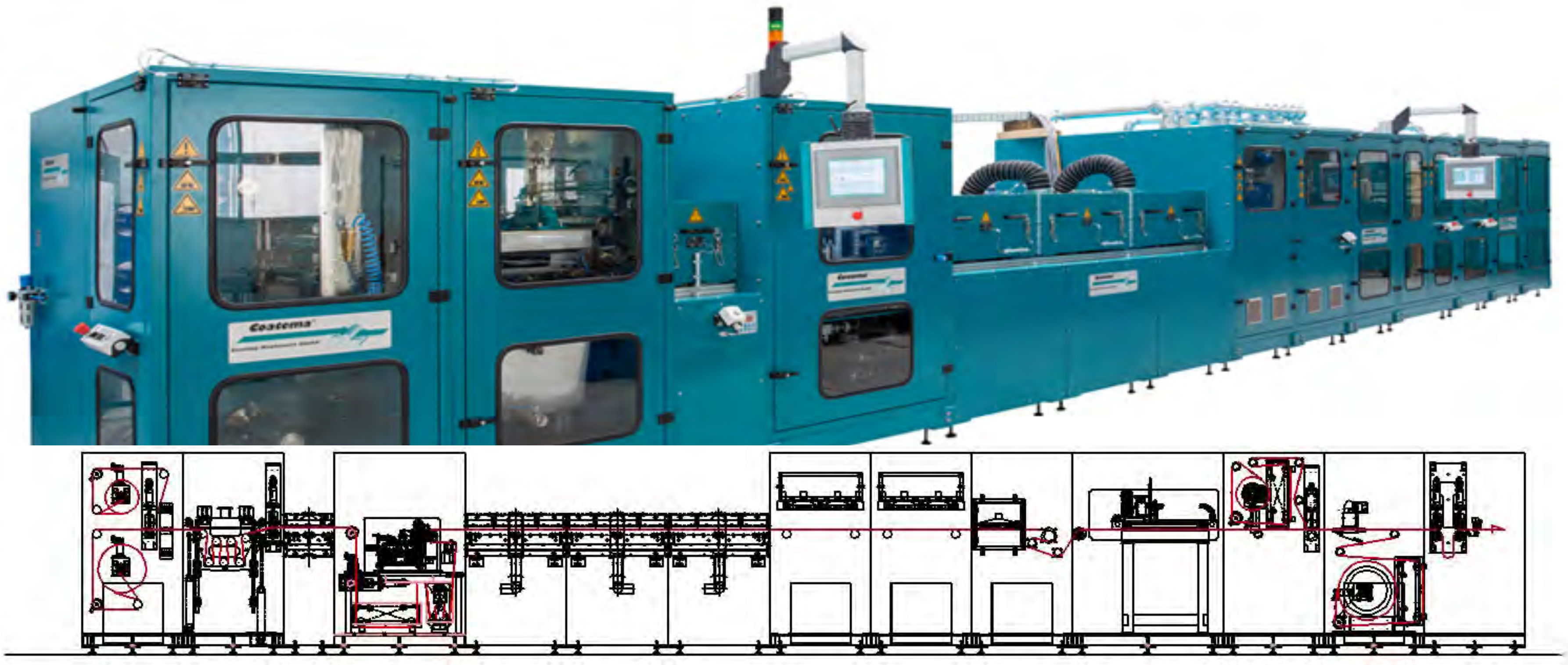
# Overview on layouts



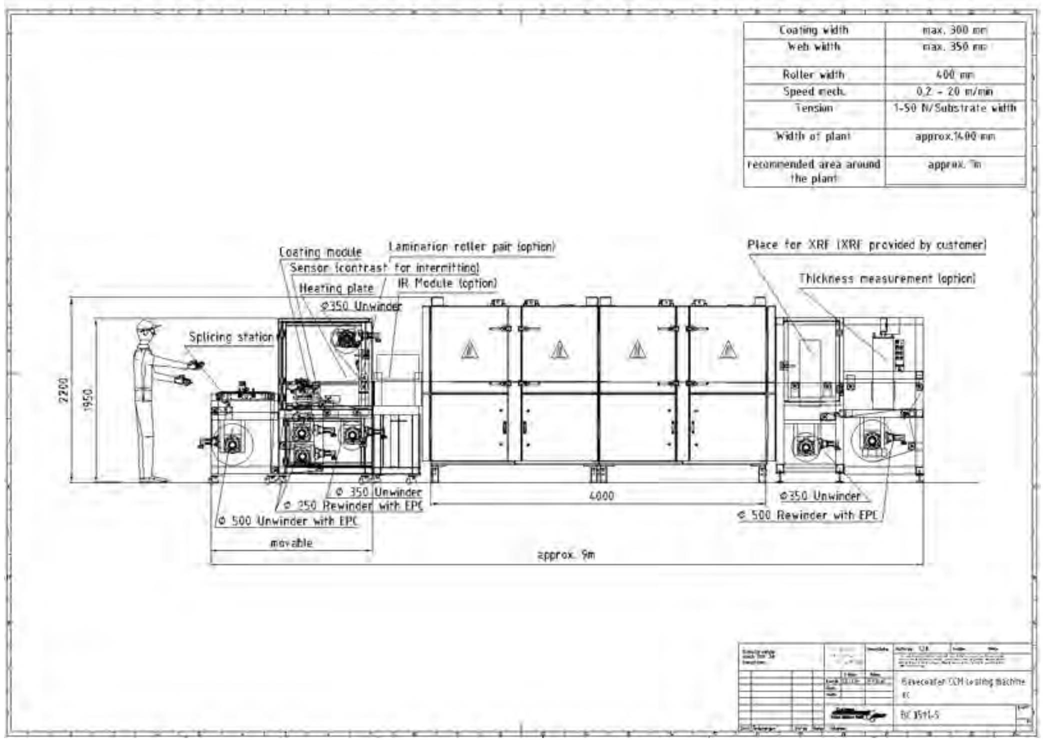
# The Basecoater



# The Basecoater 3rd Generation

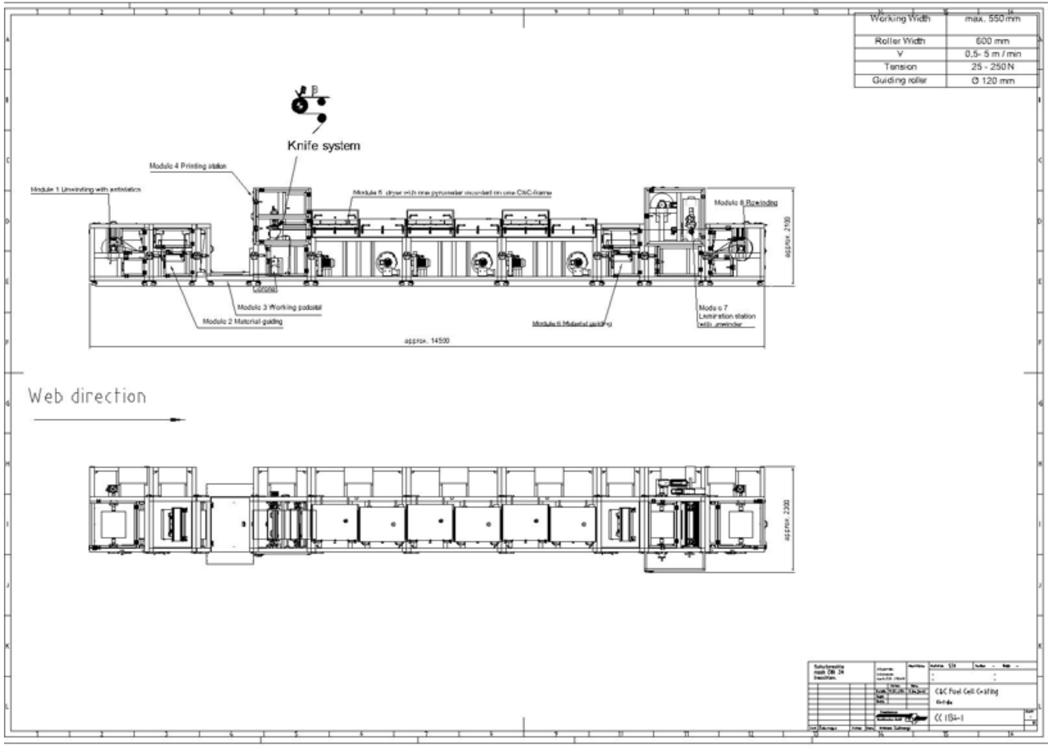


# The Linecoater

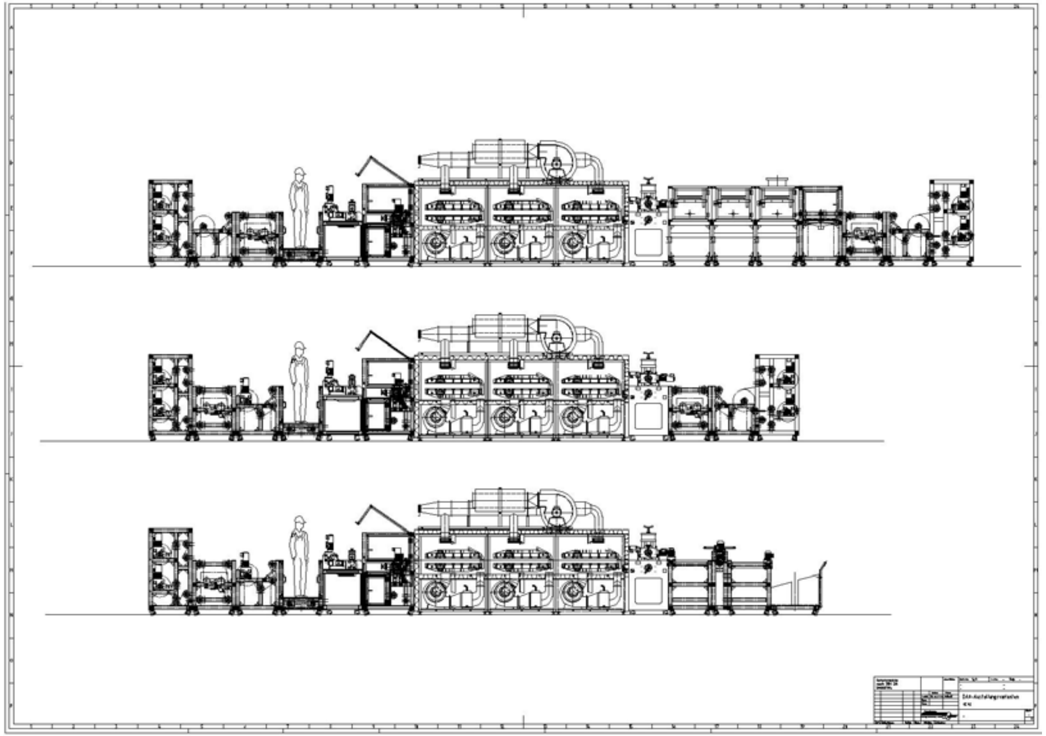


# The Click&Coat™

# The Click&Coat™ – overview drawing



# The Click&Coat™ – overview drawing



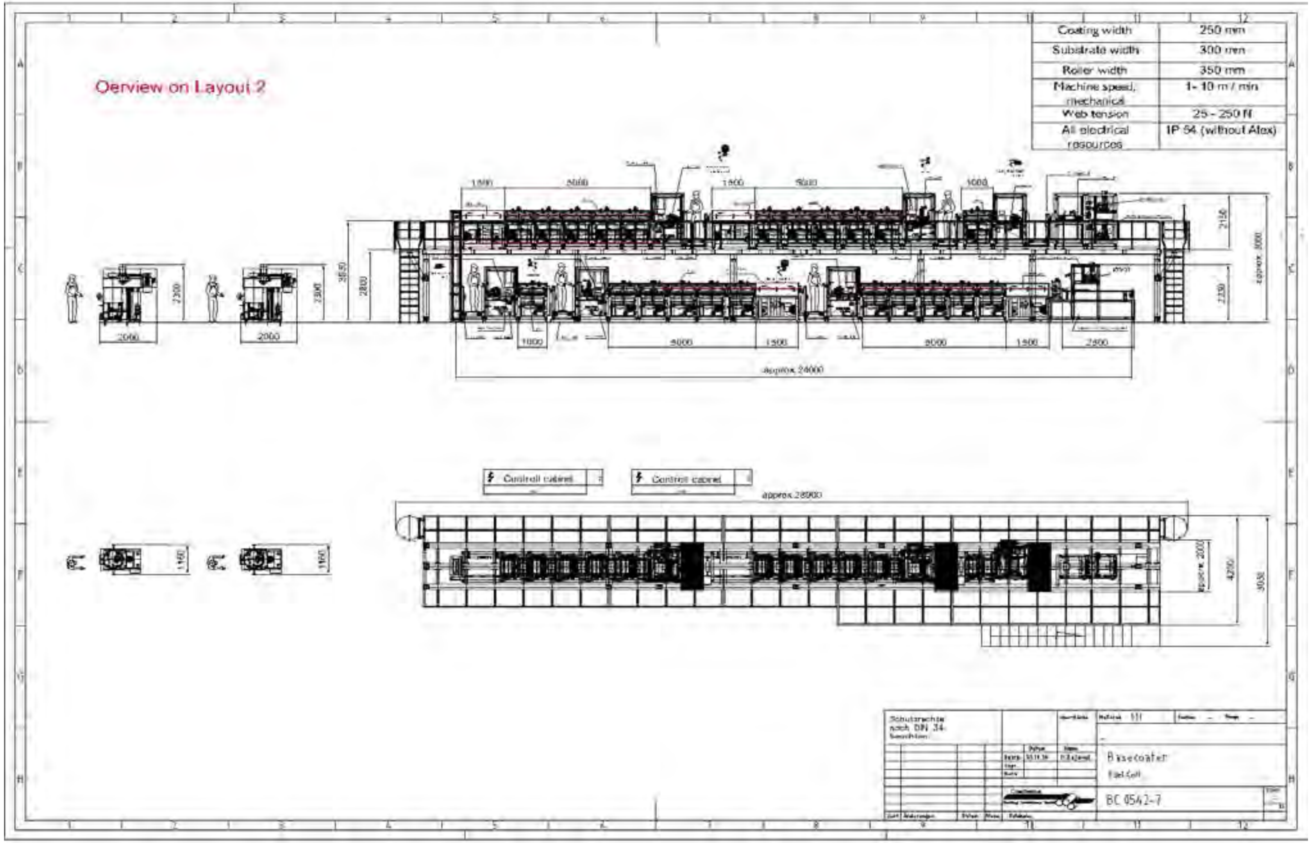
# The Click&Coat$^{TM}$ Steel layout

# The Click&Coat™ Steel layout

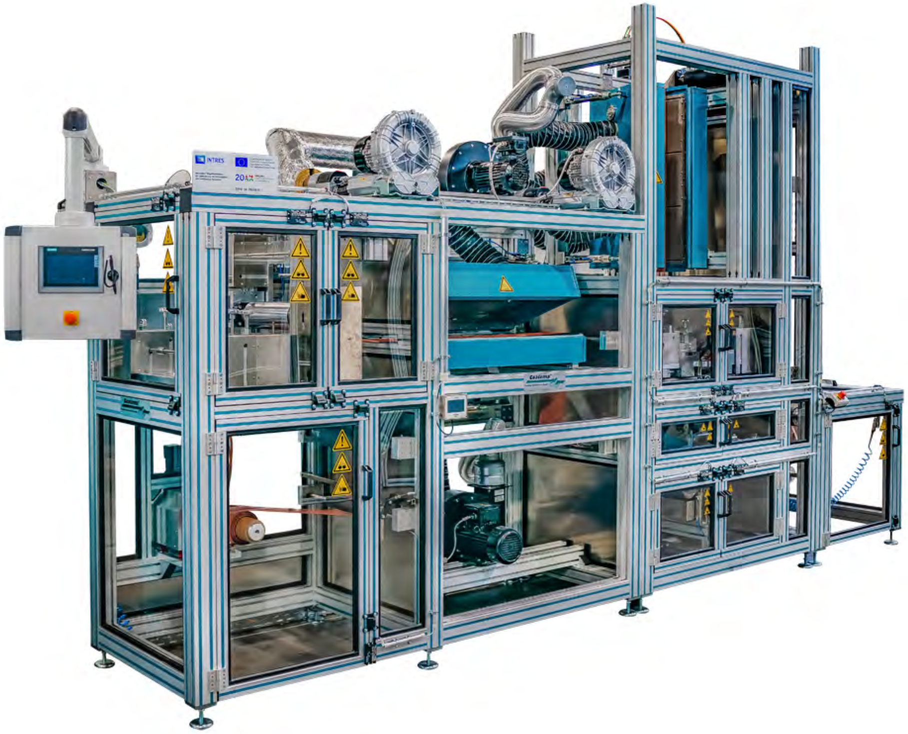
# The Click&Coat™ Steel layout

# Production line for fuel cells – 1000 mm working width

# Proof of concept



# Basecoater for batteries



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# Custom made solution

# Do not hesitate to contact us!

**Anything missing?**

Let us know and we will make it happen!

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