

Single particle data – why it matters

Cold Spray Club 35
Dr. Jussi Larjo, Oseir Ltd.

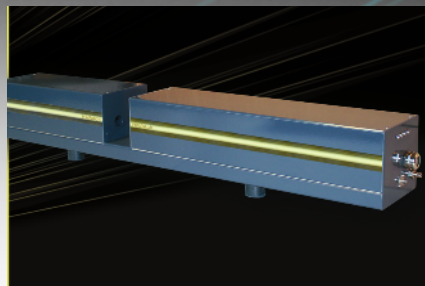
HiWatch line



HW Compact



HiWatch HR



HiWatch CS2



HiWatch CS-Q



HW



2011

2015

2017

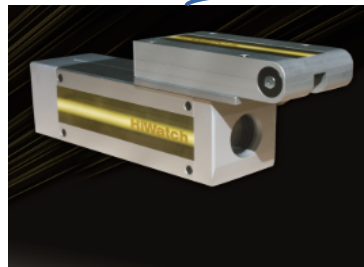
2018

2019

2024

2002

2005



HiWatch CS



ShotWatch



HiWatch HR2

Cold spray diagnostics

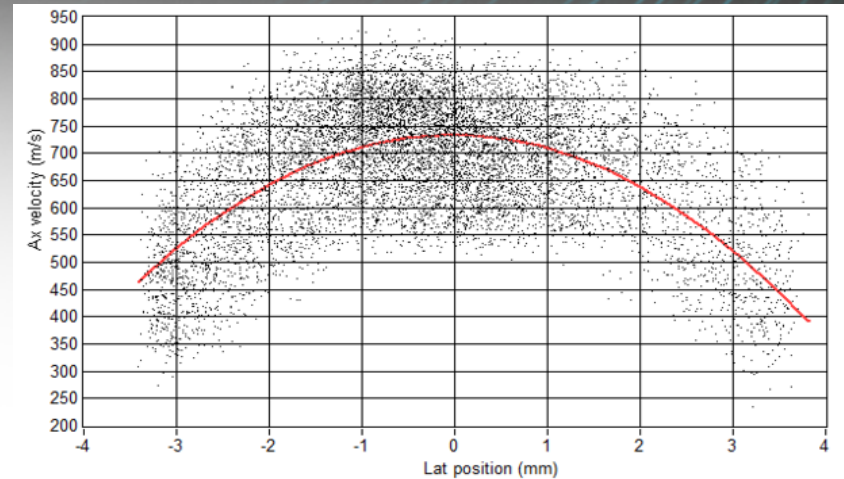


- ♦ Single point correlation signal
 - Fast, simple
 - velocity/intensity from one spot
 - Sample volume limits single particle data availability
 - ♦ Imaging PTV
 - Single particle data over plume diameter
 - 2D velocity, position + diameter
 - ♦ Gas density monitoring
 - Nozzle condition, no particle data
 - ♦ Spray spot imaging
 - Qualitative, no particle data
 - Thermal
 - photoluminescence
 - ♦ Plume acoustics
 - Qualitative, no particle data
 - Good results for delamination
- ◀ Oseir techniques

Why particle data?



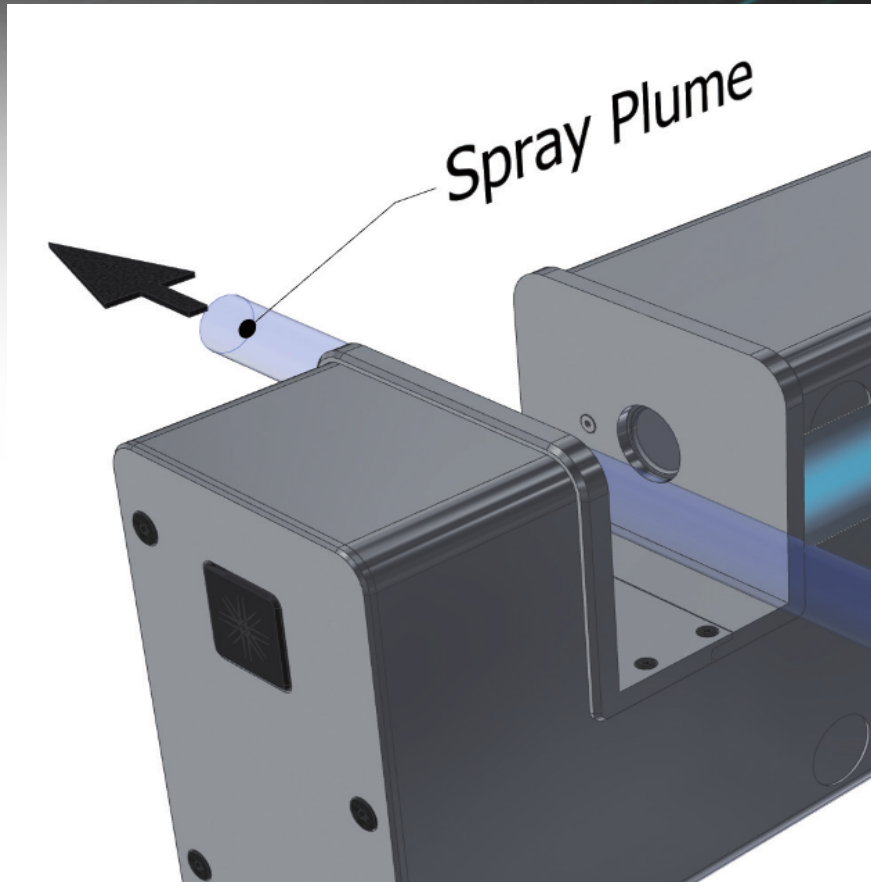
- Coating formation is determined by particle properties
- Always nonuniform
 - distributions
 - Usually radial symmetry assumed
- Large scale variation in velocity
 - Depending on particle size and lateral position
- Data collection: sampling
 - Finite sample volume
 - Low frame rate



Dissecting the plume: LM scan of a large particle dataset Oseir

- ♦ Jülich session Nov 2023
 - two powders
 - Coarse: Eckart TLS Ti, $-53/+20\text{ }\mu\text{m}$
 - Fine: Oerlikon Metco AE 10718, $-22/+5\text{ }\mu\text{m}$ (718-type Ni-base alloy)
 - 600–1100 °C process gas temperature
 - Statistical analysis of per-particle velocity, size and position data
- ♦ Sensor: HiWatch HR2
 - Analysis: per-run statistics and trends
 - plume-centred sectioning
 - instrument models (sizing bias, detection probability, axial uniformity)
 - corrected findings.

HW HR2: backlight measurement



- Particles detected by light extinction (shadow imaging)
- Results:
 - Velocity (2D)
 - Position (2D)
 - Diameter
 - Time point
- Measurement area 8x5mm²
- 12MP, 15fps (USB3.1)

Experimental details



Item	Value
Runs	14: 2 powders × 7 gas temperatures (600, 700, 800, 900, 950, 1050, 1100 °C)
Images / particles	~500 images per run; 95 446 tracked particles, 54 198 with a diameter
Measurement volume	0.5 mm light sheet through the plume centre plane; field ± 3 mm axial × ± 4.1 mm lateral
Per-particle data	speed, axial & lateral velocity, axial & lateral position, optical diameter (Z position discarded)
Feed rate	15 g/min, both powders
Reference sizing	Laser diffraction (LA-950 V2): D10/50/90 = 27.8/36.9/50.9 μm coarse, 9.6/14.1/19.5 μm fine
Cleaning	61 particles (0.06 %) outside 300–1400 m/s removed; size-class outlier gate applied where stated

This was the only input to the LM model besides the particle data.

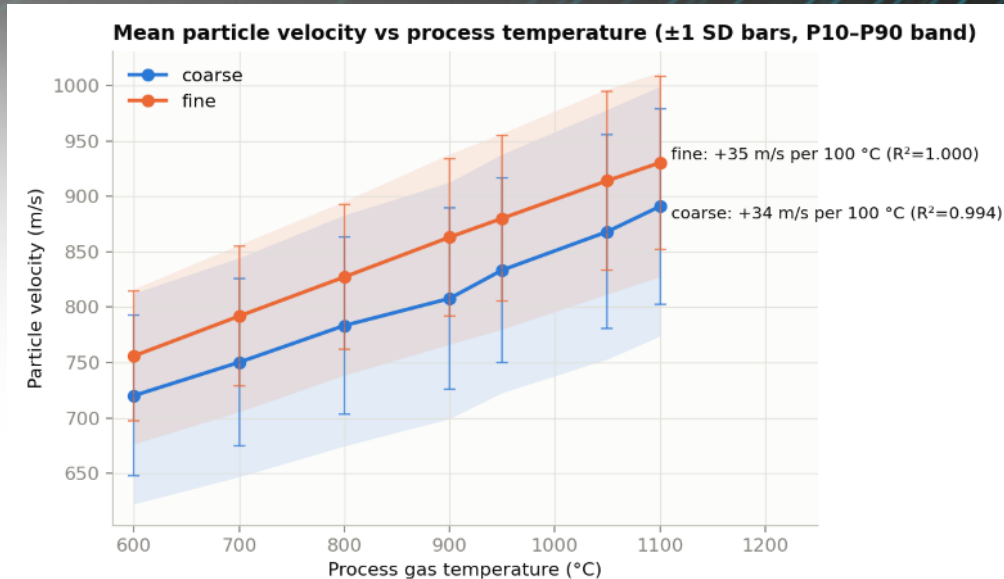
- Unmodified LM output in following slides: identified as **LM SLOP**

Particle velocity vs gas temperature



- +34 m/s per 100 °C (coarse) and +35 m/s per 100 °C (fine), $R^2 \geq 0.99$
- Coarse 720 → 891 m/s, fine 756 → 930 m/s over 600 → 1100 °C
- $v \propto T_K^{0.46}$ for both powders — close to the ideal-gas $\sqrt{T}$ scaling; $v/\sqrt{T_K}$ constant to ~2 %
- Per-run SEM ≈ 1 m/s: every step is a distinct population (Cohen's d 0.2–0.6)

LM SLOP

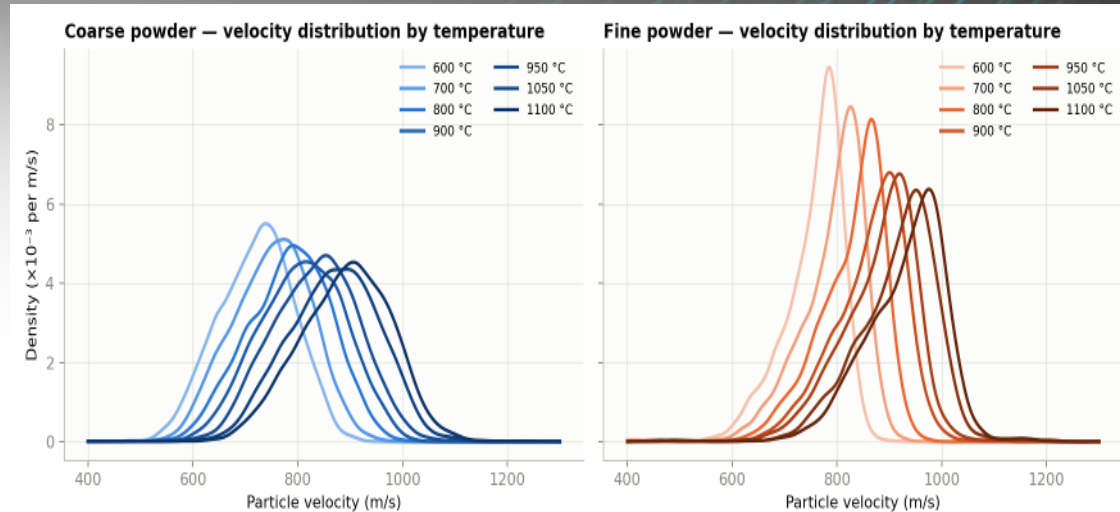


Velocity distributions



- Fine – coarse offset +36 to +55 m/s, Cliff's $\delta \approx 0.3$ –0.4; does not grow with temperature
- SD grows with temperature (73 → 88 coarse, 58 → 80 fine) but CV stays $\approx 10\%$ / $\approx 8\%$
- Fine distributions left-skewed (median – mean ≈ 14 m/s)
- Both powders accelerated by the same gas field with a size-dependent lag

LM SLOP

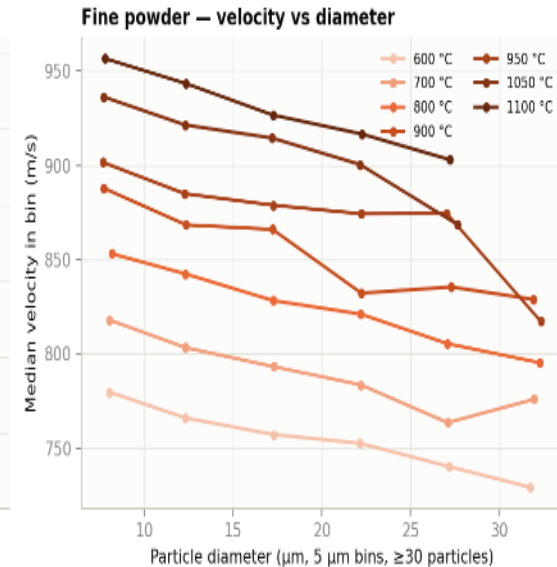
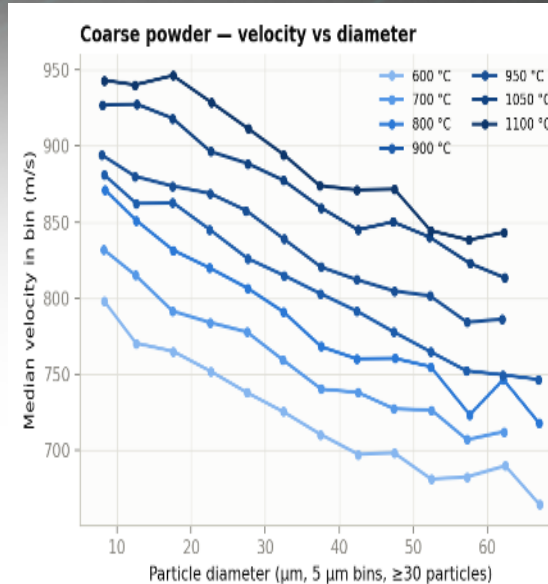


Velocity vs measured diameter



- Binned medians fall ≈ 2 m/s per μm (coarse) and 1.5–2 m/s per μm (fine)
- Log-log exponent only -0.07 (coarse), -0.04 (fine) vs $d^{-1/2}$ expected for drag-limited acceleration
- Curves for different temperatures are near-parallel: temperature shifts the whole curve

LM SLOP



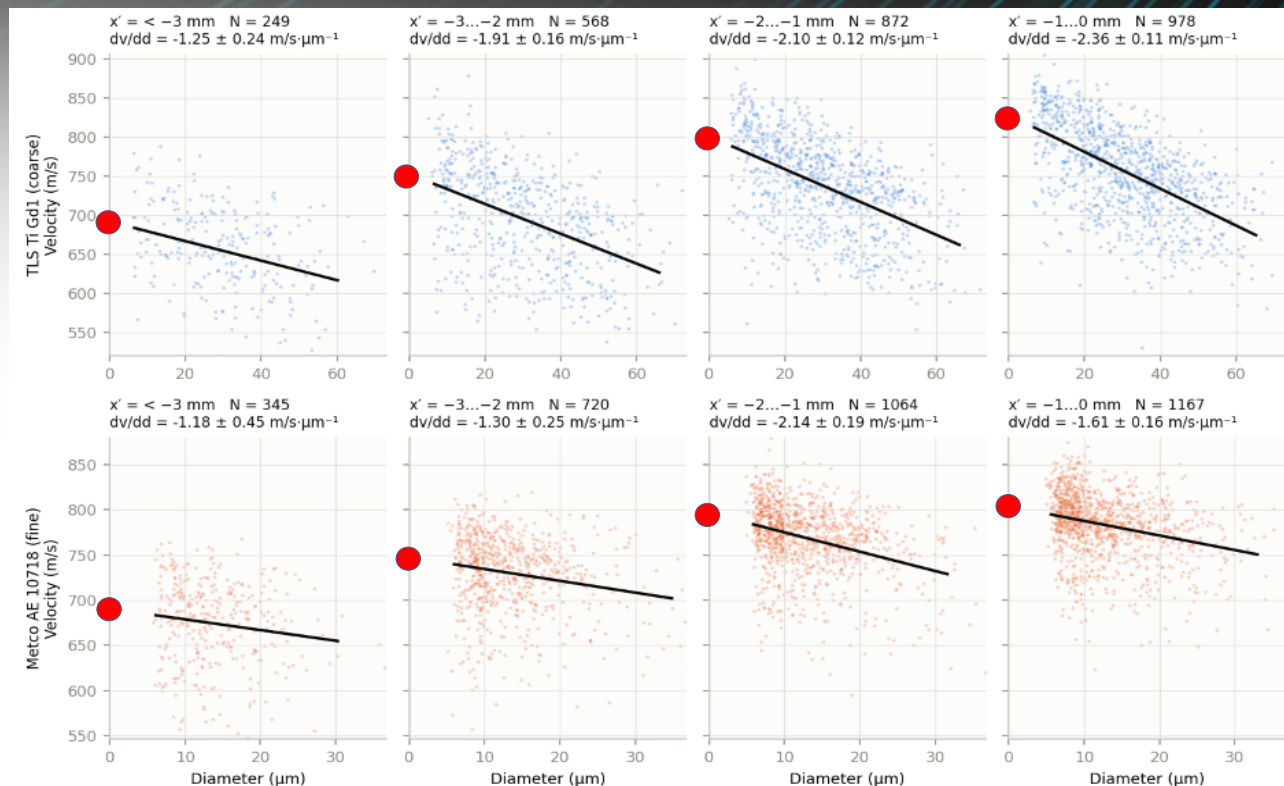
Axial dissection of the plume



Edge

Core

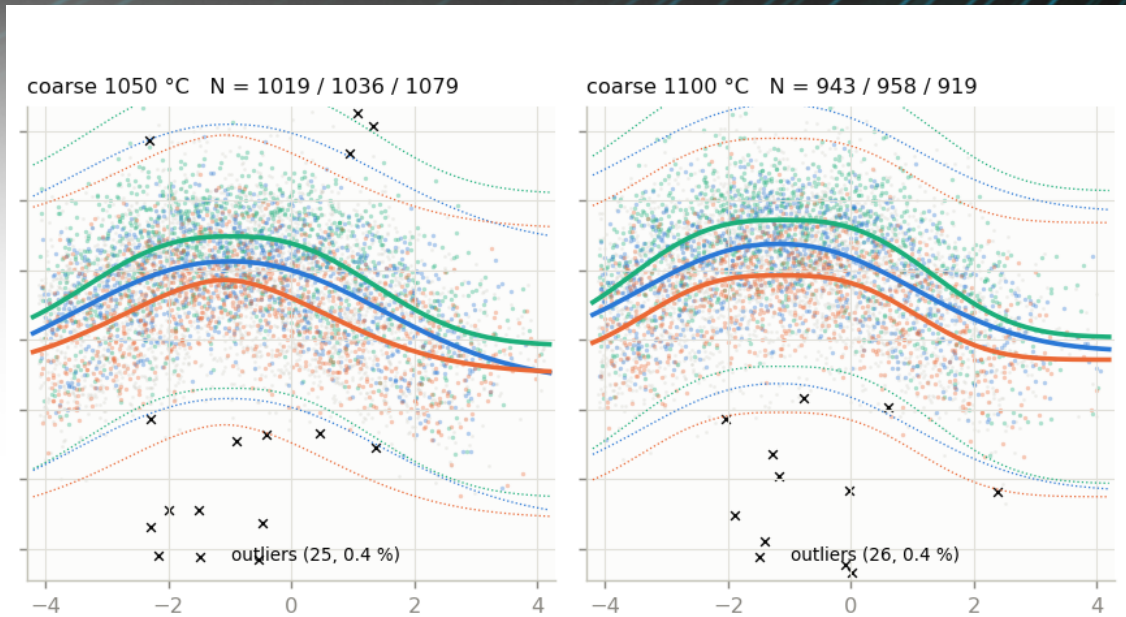
- v/D slope development from edge to core
 - Coarse: slope much steeper in core
 - Fine: nearly unchanged dependency
- gas-velocity ceiling for both powders:
 - Core ≈ 800 – 820 m/s
 - Edge 690 m/s



Lateral dissection of the plume



- LM guided outlier removal
 - Dividing particles to 3 size classes
 - Large/mid/small
 - Plotting lateral v fit for each class
- Eliminating clear outliers by their size class



Findings after cleaning: coarse/fine



Finding	As measured	Corrected	Verdict
Mean velocity vs temperature	+33.7 / +35.0 m/s per 100 °C	+33.6 / +34.9	unchanged
Run mean velocity	720–891 / 756–930 m/s	+0.6 to +1.2 m/s	unchanged
Fine – coarse offset	+36 to +55 m/s	+35 to +55 m/s	unchanged

- Outlier content was too small to affect the mean findings
 - Standard HW software has similar feature
 - Size class based rejection is a bit more convincing

LM predicted DE models



Coarse

Run	$\bar{v}$ (m/s)	frac v > 700	DE-model (v_cr 700)	frac v > 800	DE-model (v_cr 800)
600 °C	720	0.62	0.58	0.14	0.25
800 °C	783	0.84	0.77	0.44	0.45
1100 °C	891	0.98	0.94	0.84	0.76

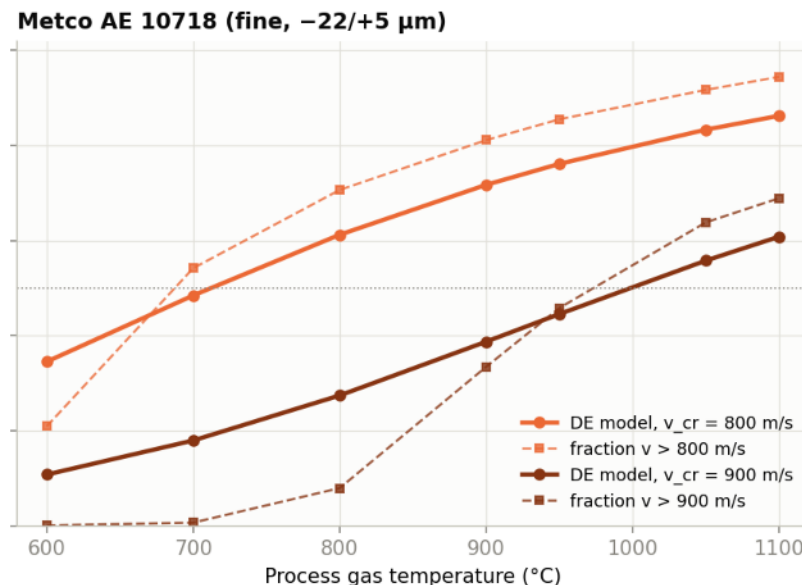
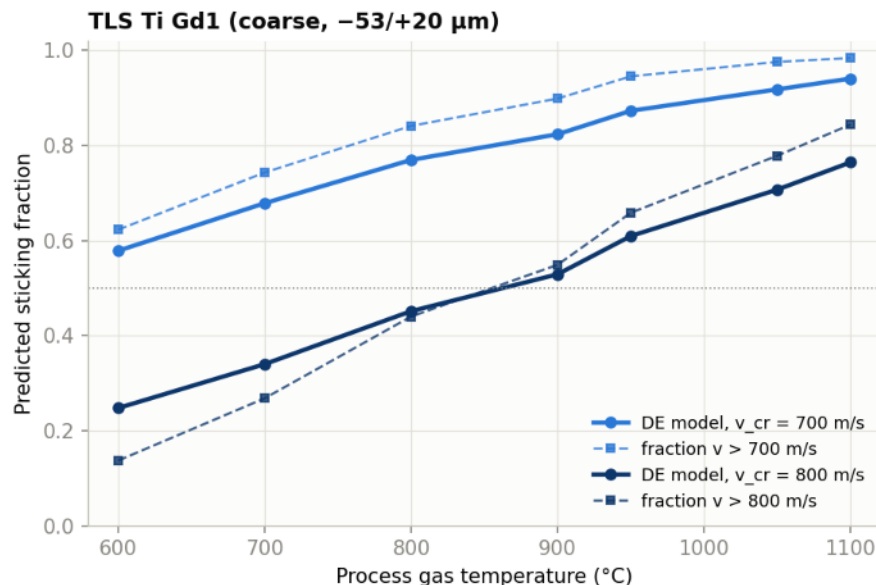
Fine

Run	$\bar{v}$ (m/s)	frac v > 800	DE-model (v_cr 800)	frac v > 900	DE-model (v_cr 900)
600 °C	756	0.21	0.35	0.00	0.11
800 °C	827	0.71	0.61	0.08	0.27
1100 °C	930	0.94	0.86	0.69	0.61

LM predicted DE models



Temperature vs predicted deposition efficiency — raw velocities; DE = logistic, 50 % at v_{cr} , 95 % at $1.2 \cdot v_{cr}$



- Finally something testable!
 - Critical velocity estimates after "Schmidt, Gärtner, Stoltenhoff, Kreye, Acta Materialia 54 (2006) 729–742"

Summary



- Cold spray diagnostics: individual particle data allows deep analysis of plume
 - Reveals complex inter-dependencies and hidden relations
- Imaging PTV
 - Provides rapidly enough data for good representation of plume
 - Sampling must be understood
- LM models
 - Provide fast and thorough overview of the data
 - Models must be vetted and verified
 - Refined by continuous process, sample analysis
- For production use
 - Particle data is overwhelming for shop floor
 - LM models may be used to generate simple indicators for process quality and efficiency
 - Plume health indicator: symmetry, stability
 - DE prediction

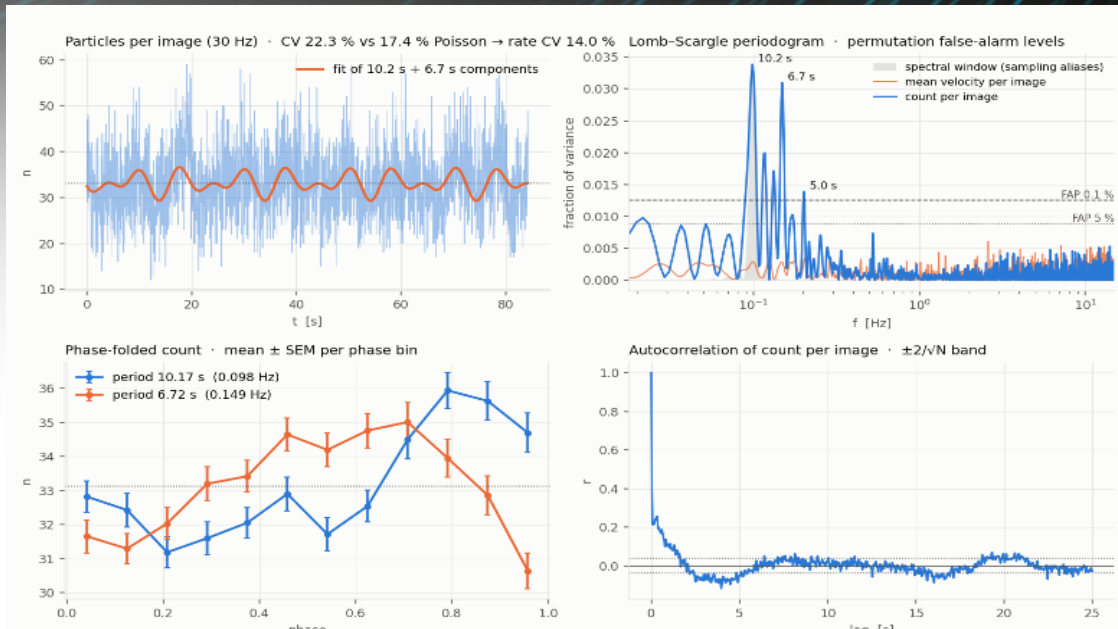
Bonus slide: feed analysis



- CS-Q data from real coating run "B"

- Monitoring particle detection rate
- Filtering reveals periodic variation in feed

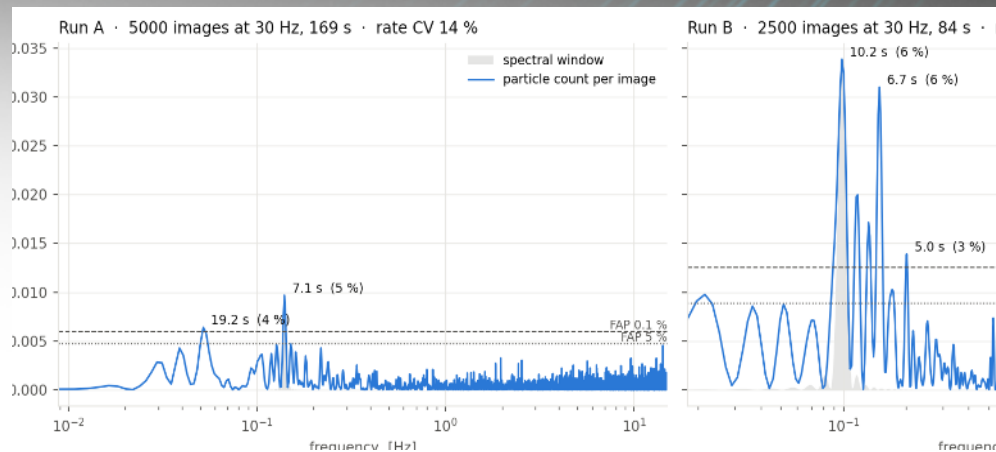
- Compute frequency analysis of the particle density



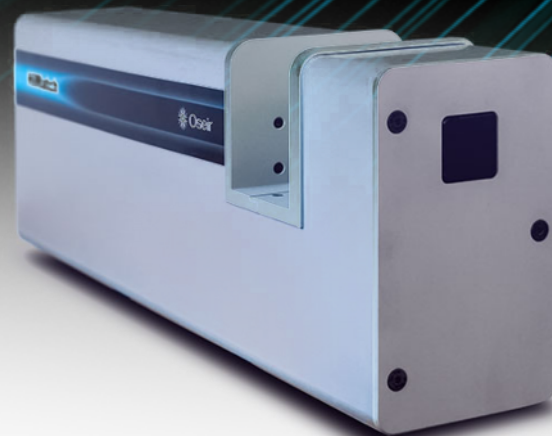
Feed: frequency analysis



- Run B: feed shows two distinct periods
 - 10.2s and 6.7s
 - Feeder rate was 3 RPM
 - Peaks at 1/2 and 1/3 rotation time
- Previous run A with same feeder and powder had no significant structure
- Oscillating powder feed may result in nonuniform growth
 - And may happen anytime!



Thank you!



Acknowledgements

FSZ Jülich:

- Georg Mauer, Johannes-Christian Schmitt, Karl-Heinz Rauwald
- Anthropic Claude Fable 5.1