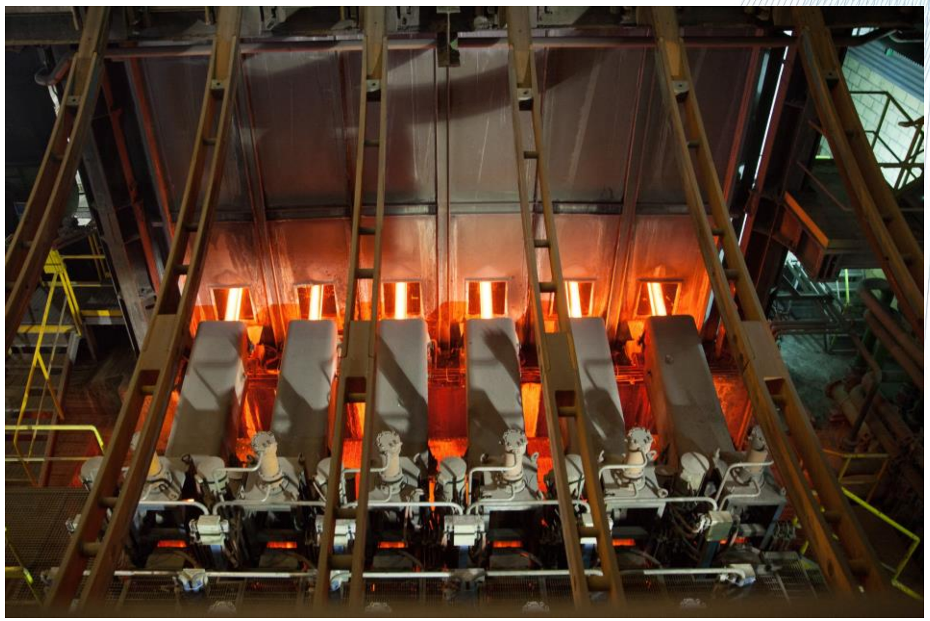
Measurement and model-based control of solidification in continuous casting of billets

M. Köster, M. Schlautmann, W. Krieger — VDEh-Betriebsforschungsinstitut GmbH
M. Groll, R. Schuster, J. Bellmann — ESF Elbe Stahlwerke Feralpi GmbH
P. Frittella — Feralpi Siderurgica S.p.A.



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BFI Excellence in Applied Research | VDEh-Betriebsforschungsinstitut GmbH

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Contents of presentation

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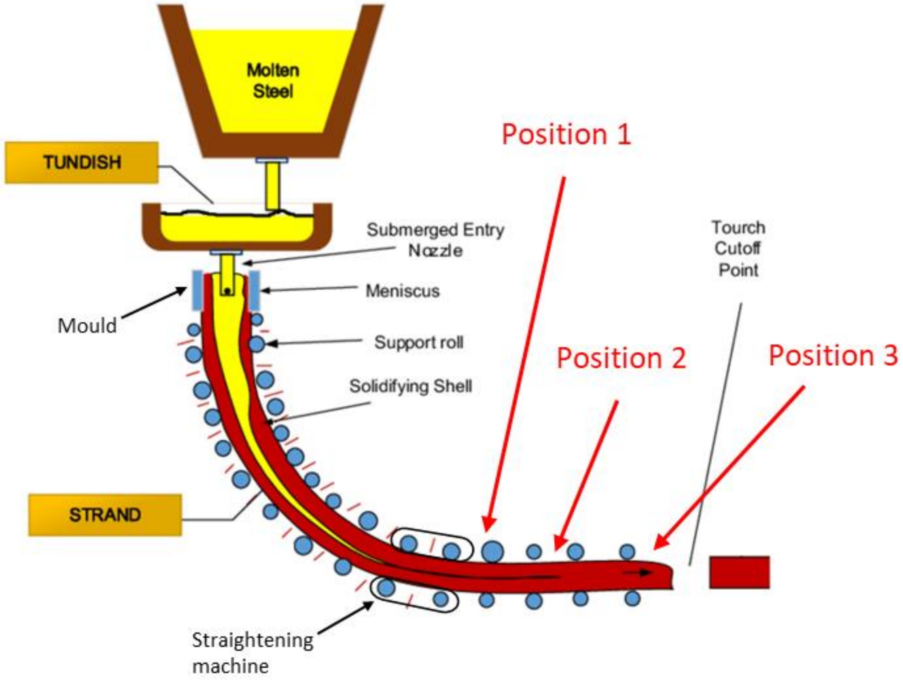
Main results from RFCS project ConSolCast at billet caster of ESF

- Laser-Vibrometry at the continuous caster
  - Stationary casting conditions
  - Varied casting conditions
- Real-time modelling, monitoring and control of continuous casting process
- Visualisation for operator
- Conclusions and outlook

Laser-Vibrometry at the continuous caster

- **Vibration excitations** of the strand by the casting machine itself
- Several measurements at different points of the strand
  to identify the **specific vibration characteristic**



Diagrams of the dynamic frequency spectra of the strand

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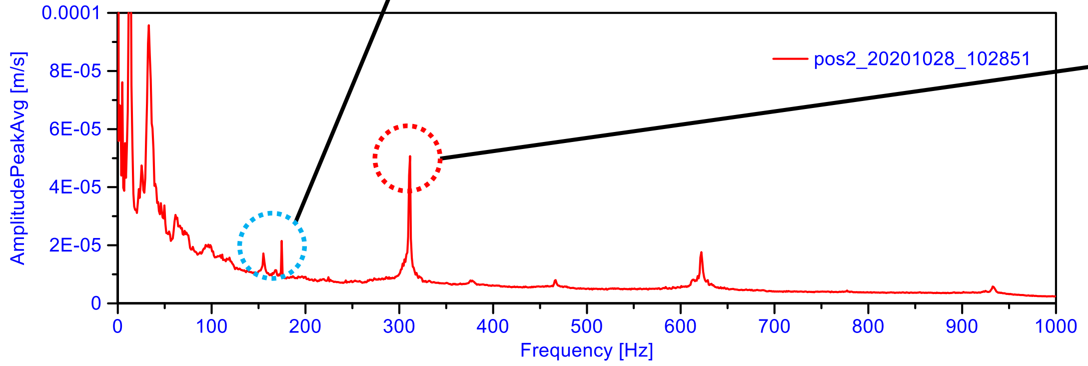
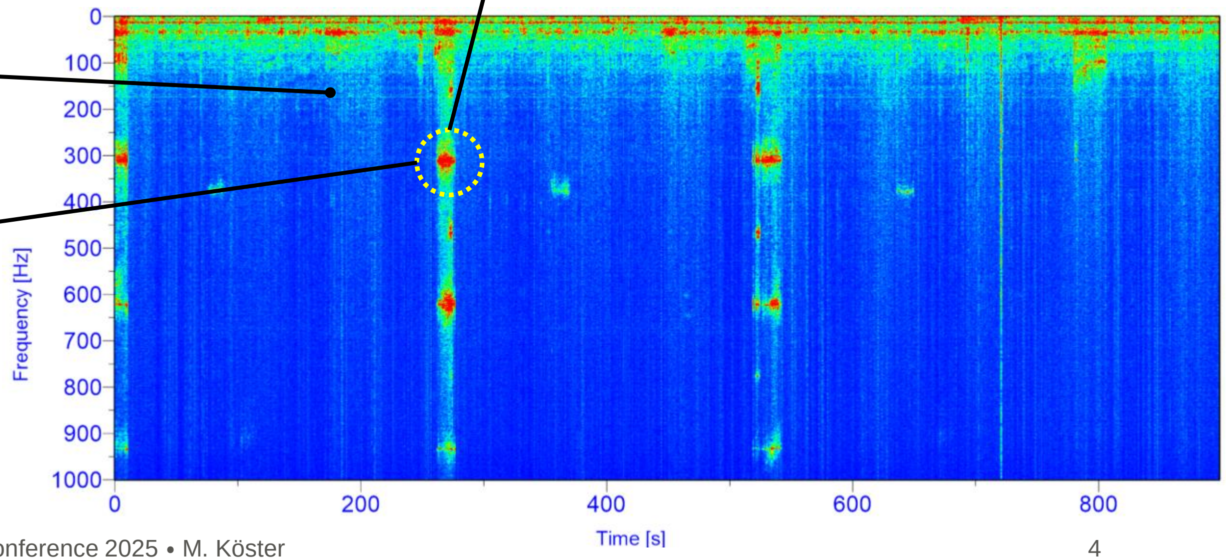
- Recording of vibration spectra with **laser Doppler interferometer**
  → **Fast Fourier Transformation** (FFT) for defined time intervals (e.g. 1 s, 10 s, 30 s)
- Time course of the frequency signature at a fixed measurement position
- Modulation of the frequency spectrum of the strand due to **periodic and continuous excitations by the continuous casting machine**
- ➢ **Characterization of the degree of solidification** of the strand based on the specific frequency signature**?**

Resonance frequencies
by continuous excitation

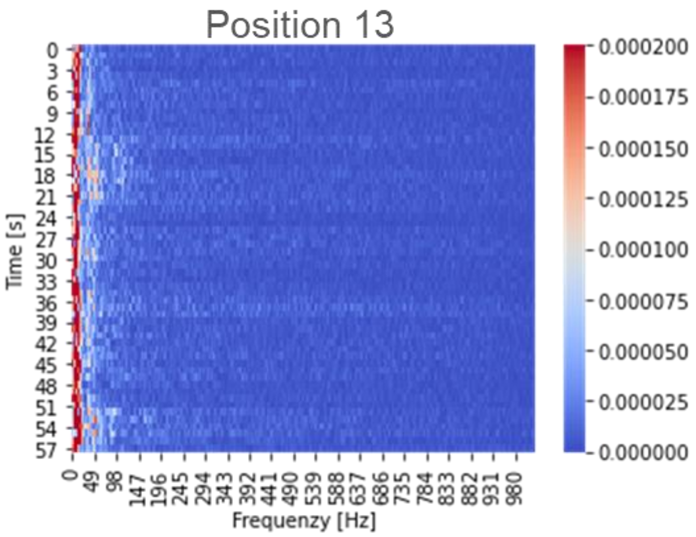
Periodic excitation by cutting torch

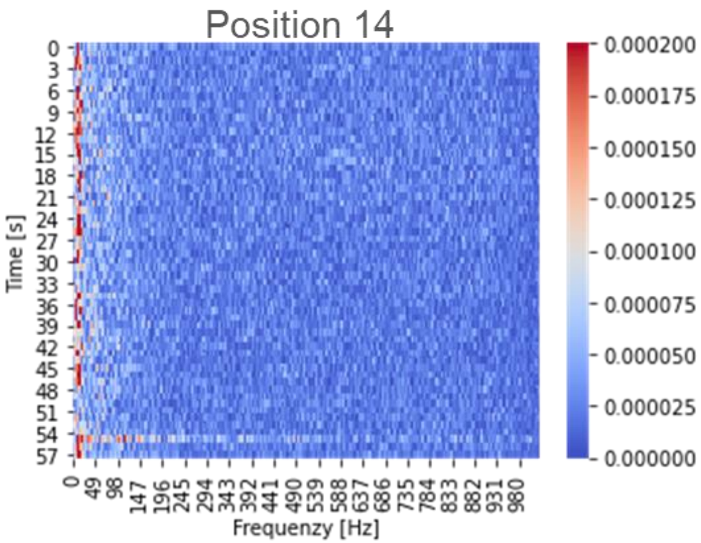




Measurements at different strand positions under stationary casting conditions

- Measurements at **20 positions over a range of 5 m** in front of the cutting torch
- For 60 s at each position
- FFTs of the measurement signals for intervals of 1 s
- ➢ **Significant differences of the spectra at the different positions** - also for the eye:

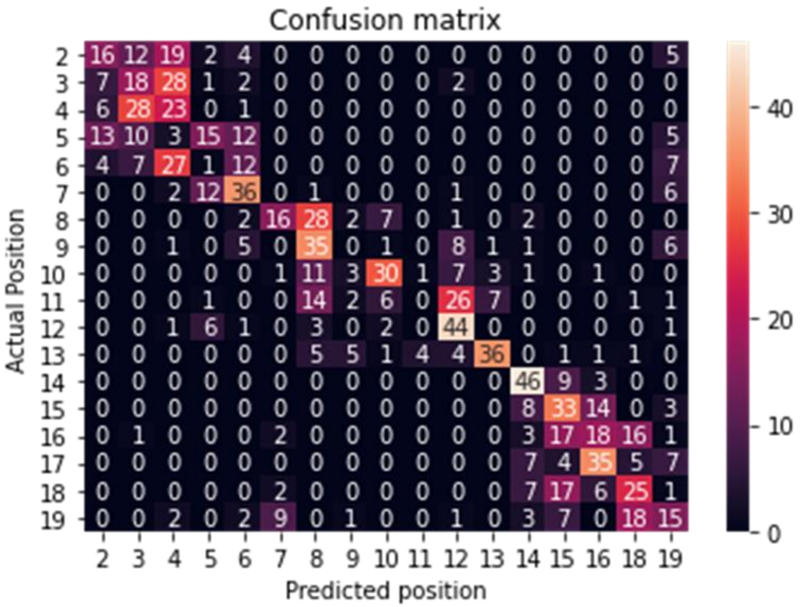




- However: the **influence of the position on the spectrum** is more noticeable, e.g. due to the water jet of the descaling system evaporating on the strand surface

Measurements at different strand positions under stationary casting conditions

- **Verification with supervised machine learning** using a **neural network**
  - Optimization of network parameters by tree-structured Parzen estimator
    - 2 hidden layers with 64 and 128 neurons
    - Rectifier activation function
    - Max. number of iterations: 500
- Splitting the data sets into training and test data



- ➢ Confusion matrix shows good prediction of measurement position from vibration spectra of test data set; confusion occurs mainly between adjacent positions
- ➢ Biggest difference between positions 13 and 14, there is no confusion → signature of descaling system
- ➢ **Position effects superimpose strand state effects**

Measurements at fixed strand position with varied casting conditions

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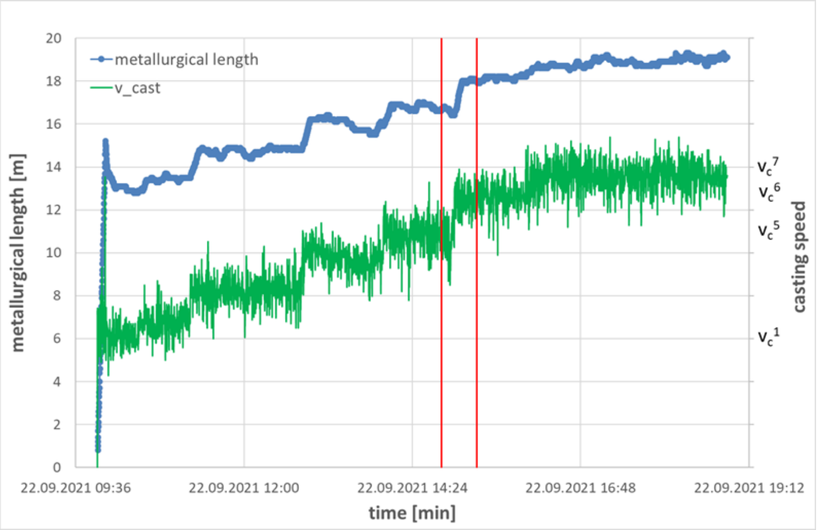
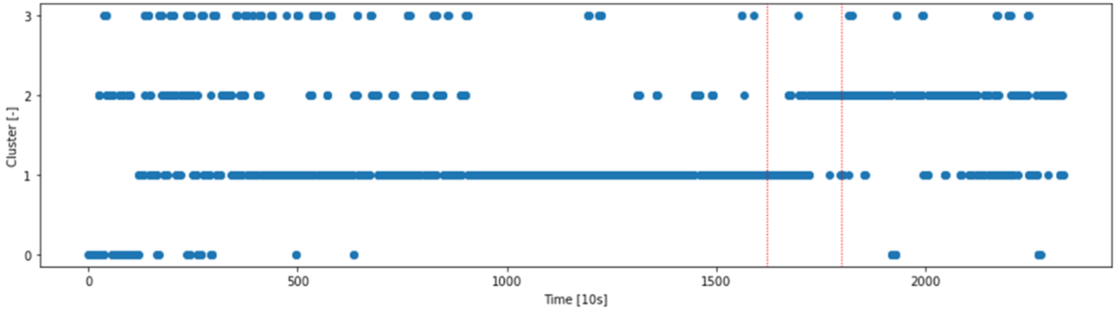
- **Measurement at fixed position** (17.5 m below mould level) **with stepwise increase of casting speed** → crater end moves forward
- Evaluation of spectra with **unsupervised machine learning** in the form of various **clustering methods** (e.g., k-Means, Gaussian mixture distribution, Ward method)
  - Optimal number of clusters via elbow method with k-Means: 4



➢ Transient casting conditions at the beginning with approximately uniform population of all clusters; thereafter **formation of a preferred spectra class**

➢ Characteristic change in population of spectra classes after movement of point of complete solidification of the strand (i.e. crater end position) behind the measurement point



➢ **Conclusion from measured population of spectra classes to position of crater end in front of or behind the measurement position**

Real-time modelling of continuous casting process

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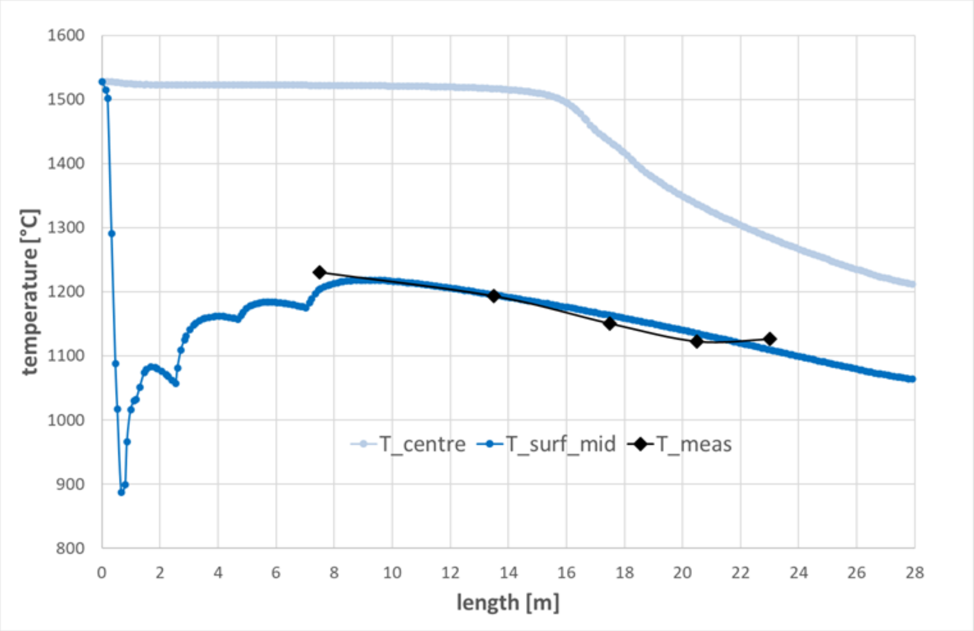
- **Dynamic 3D online temperature and solidification model** for continuous casting process (**DynSolidCC**)
  - Heat flow equation with boundary condition models for different cooling zones (mould, spray water and radiation zones)
  - Quality-dependent thermophysical material parameters as a function of temperature
  - Two approximations acceptable for the case of continuous casting:
    - neglection of heat conduction in casting direction compared to convective heat transport and other heat conduction
    - modelling of convective heat transport perpendicular to casting direction in fluid phase by an effective thermal conductivity
    - ➢ decoupling of the system of partial differential equations for fast numerical solutions

➢ **Continuous process monitoring** regarding strand temperature field and solidification front

Real-time modelling of continuous casting process

- **Object-oriented implementation** of model kernel with C++ and an application programming interface (API) for integration into online and offline applications
- Configuration of model for simulations of the billet casting processes at ESF
- **Validation** based on measurements with fibre-optical temperature sensors (FOTS) in mould walls, infrared camera-based measurements of surface temperatures behind the spray water zones and vibrometer measurements near to the crater-end position

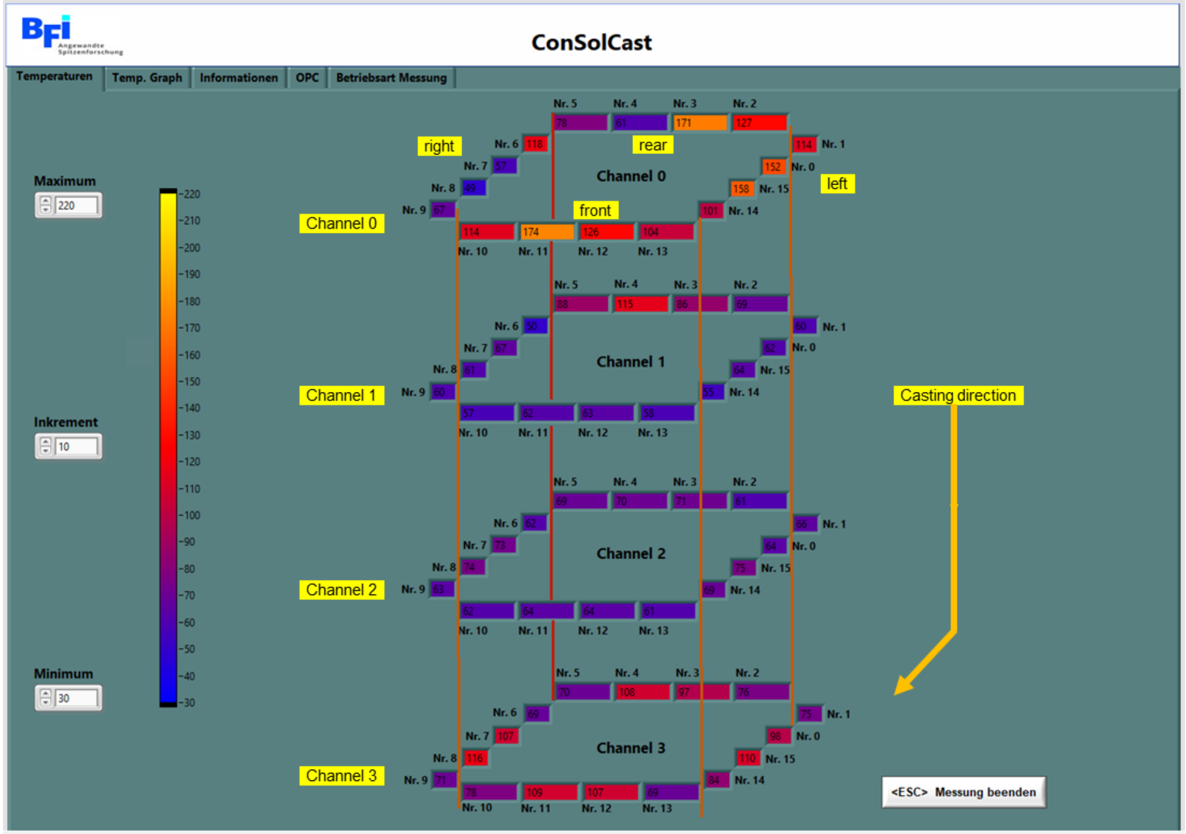
➢ **Tuning of related boundary condition model parameters**



Validation based on measurements with fibre-optical temperature sensors

- Comparison of strand surface temperatures in mould with related FOTS measurements: Position of fibres and sensors

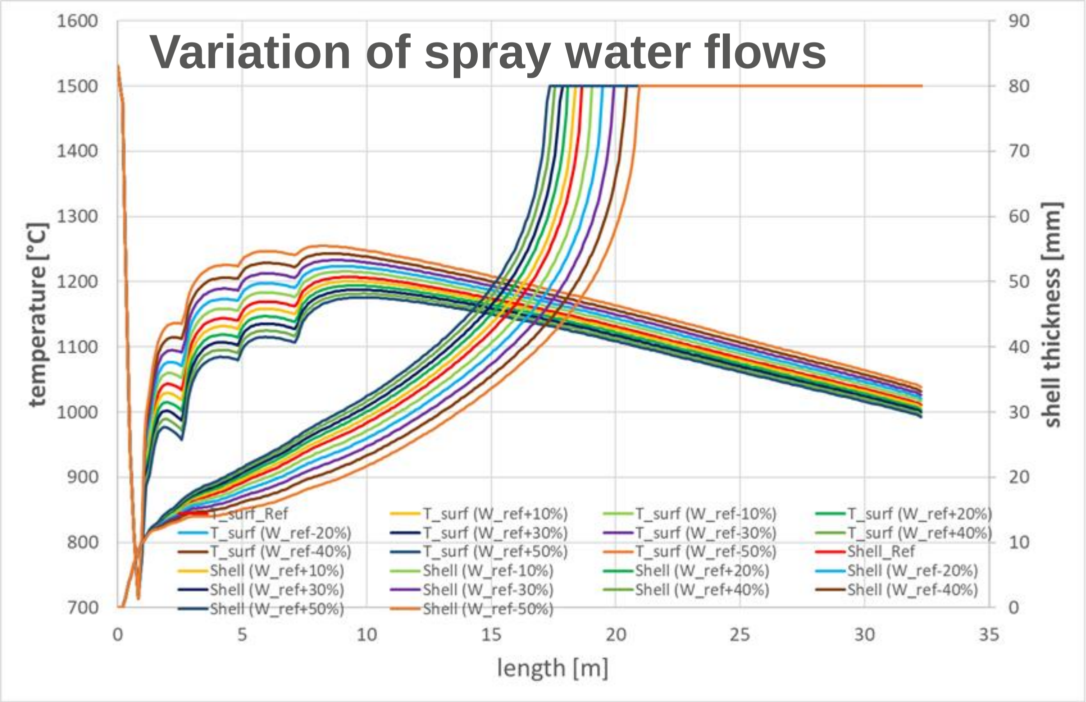
Example of instrumented mould (4 fibres; up to 80 measurement points)

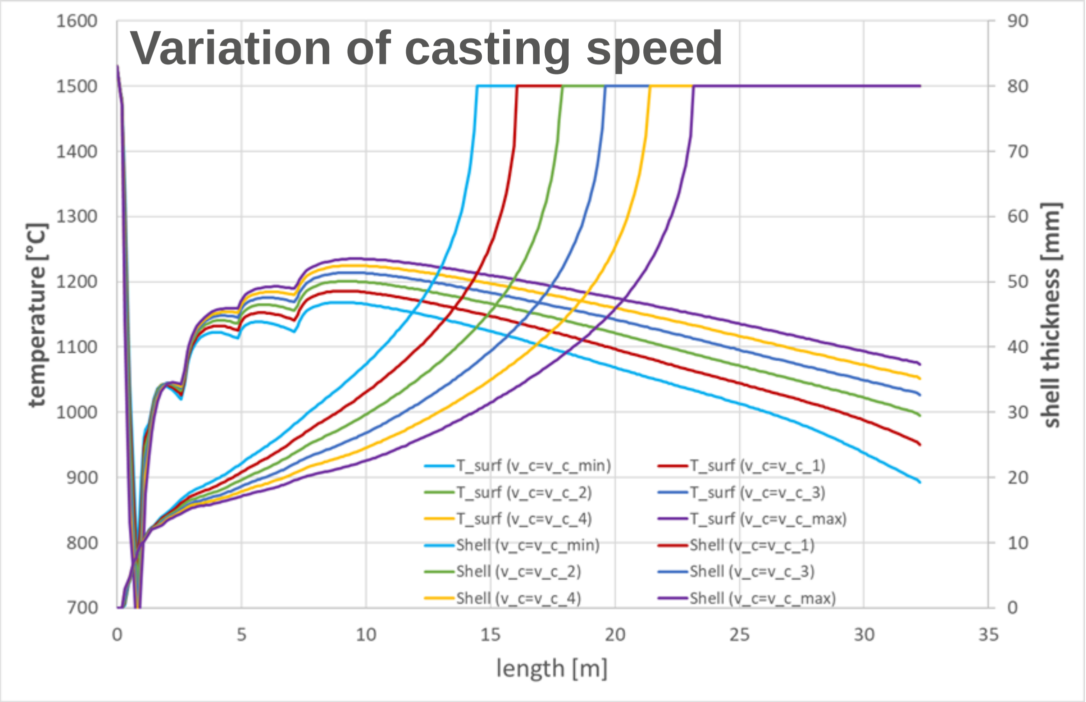


Model-based process control

- **Parameter studies** based on offline model simulations regarding influence of casting parameters
  - spray water flows in secondary cooling zone
  - casting speed and
  - initial superheat of steel

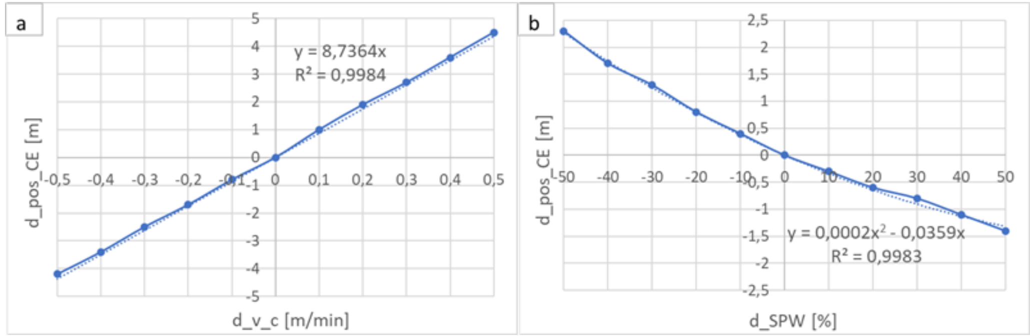
on the resulting temperature profile and solidification front in the billet caster at ESF

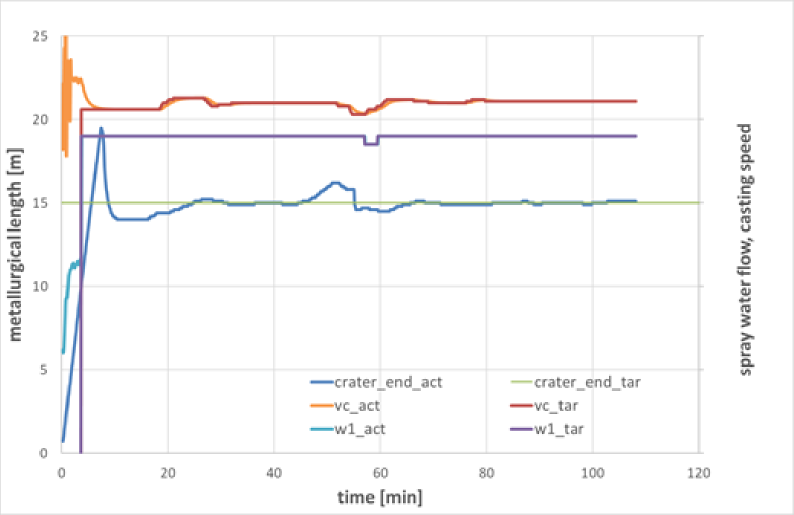


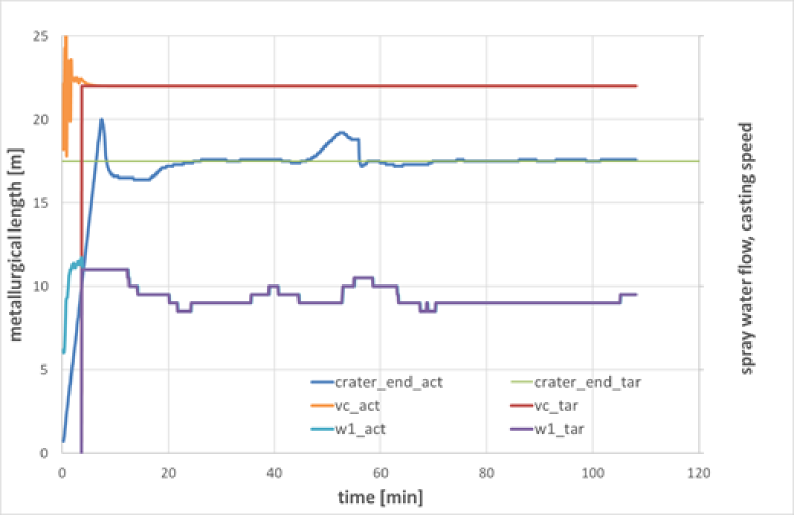


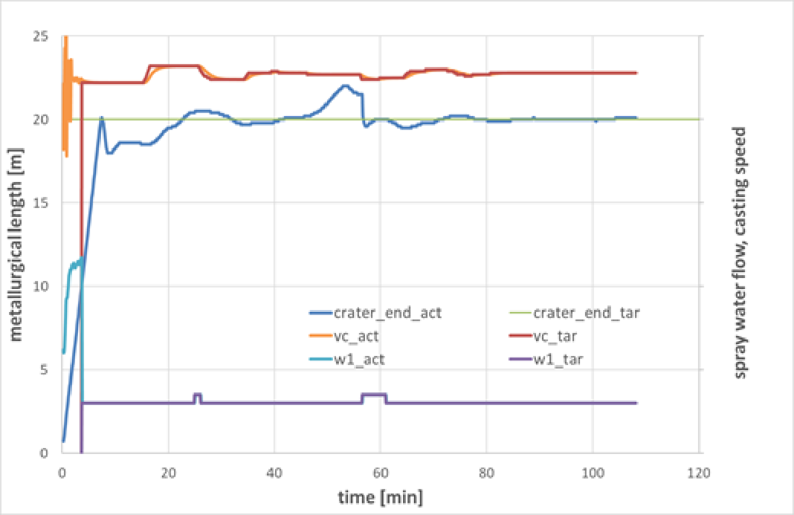
Model-based process control

- **Crater end position** with
  - Linear dependency from casting speed
  - Quadratic dependency from spray water flows
- **Dynamic online control of spray water flows and casting speed** to adjust specified target value for crater end position





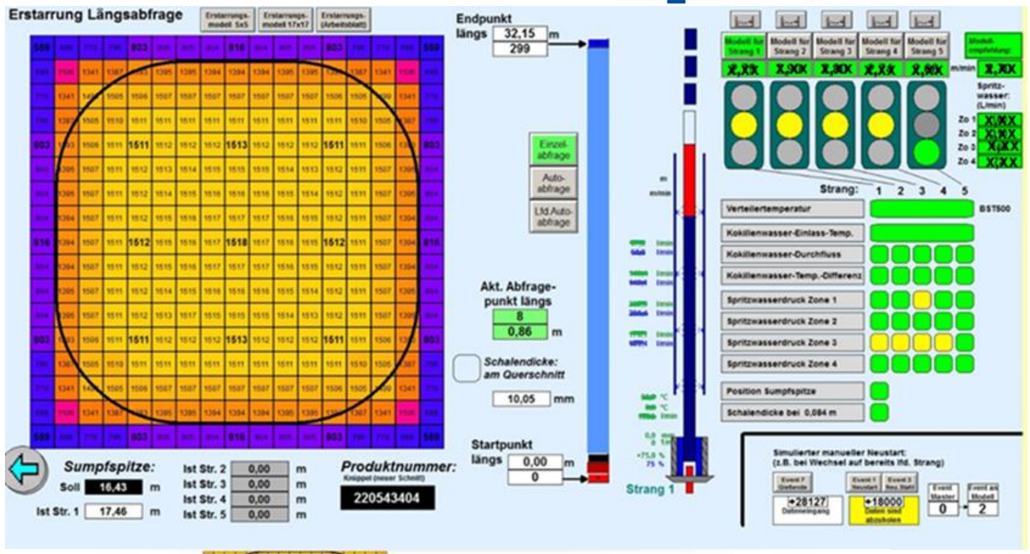


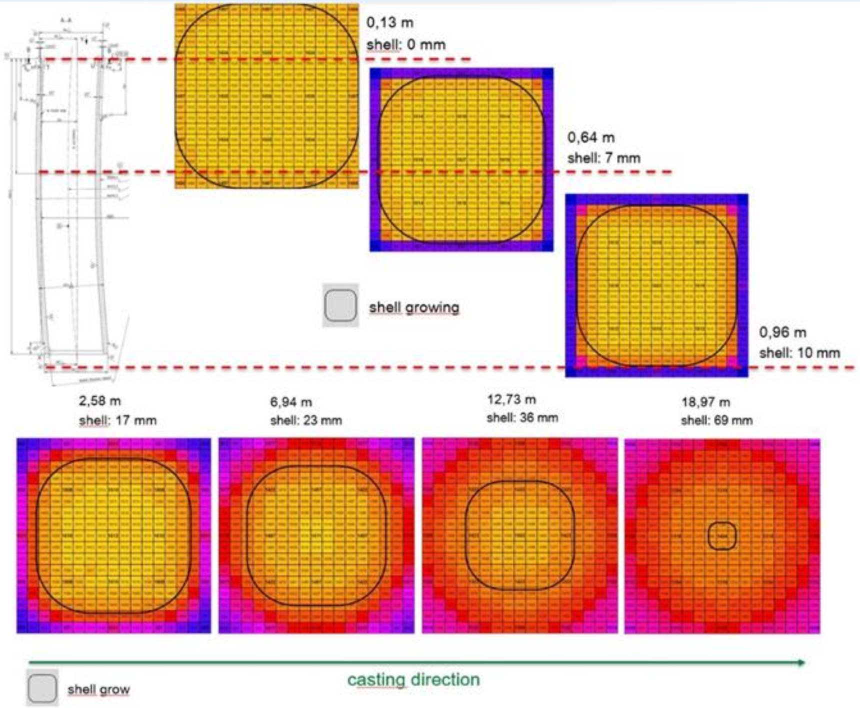


Visualisation for operator

- ESF

- API of the model kernel developed by BFI is used by a **model shell** developed by ESF for communication between the **ESF automation system** and the DynSolidCC model
- **Visualisation** of casting conditions and model results within suitable **HMI in operator control room**
  - Coloured cross section of the strand representing the **temperature field** for a selected distance from the mould level (to be chosen by a slider) as simulated by the model
  - containing the contour of the formed **strand shell**.
  - Numerical display of calculated actual and target **crater end position**
  - as well as **actual casting parameters** along the strand related to the primary cooling in the mould and the secondary cooling in the spray water zones
  - and **related recommendations** calculated by the model-based dynamic cooling control function.





Visualisation for operator

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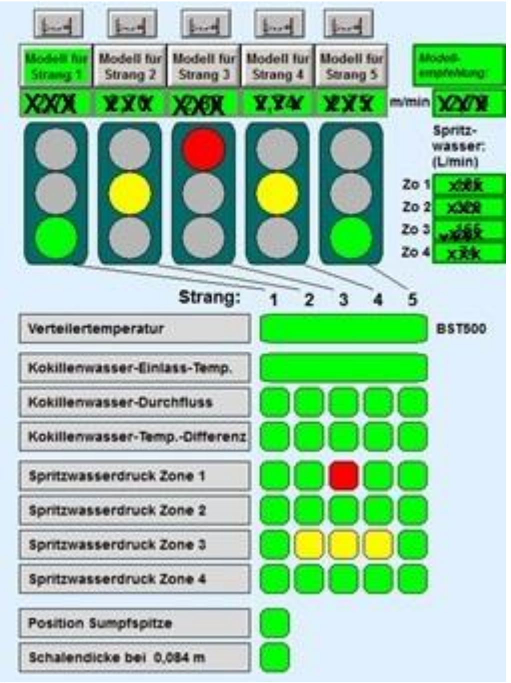
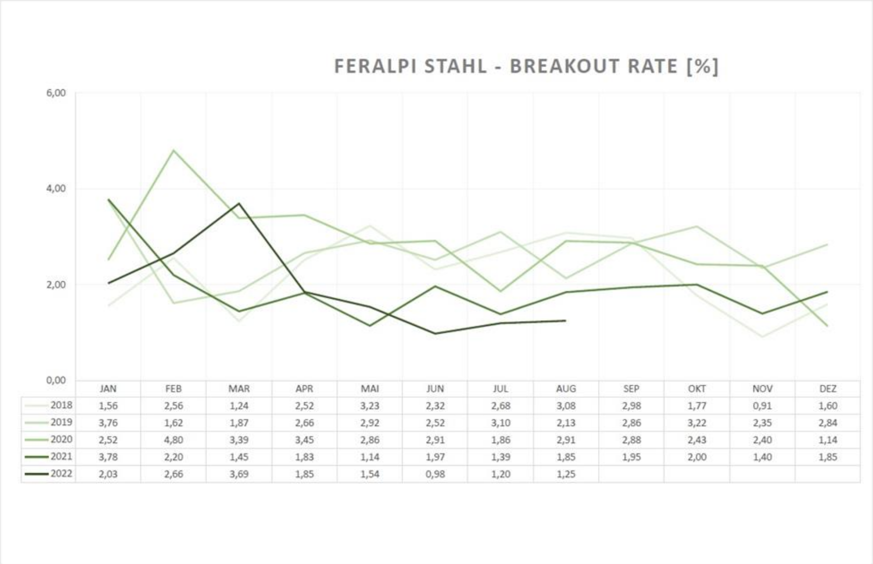
- **Traffic light system** compares defined casting and strand state data with specified limit values
- Parameters analysed and visualised by the traffic light system include
  - temperature in tundish
  - temperature of mould cooling water inlet
  - flow rate of mould cooling water
  - temperature increase of mould cooling water
  - pressure of spray cooling water (loops 1 – 4)
  - shell thickness at mould exit
  - and crater end position calculated by model
- Intervention of operator may result in a **shutdown of irregularly running strand**

➢ **Reduction of strand breakout events**





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2018	1,56	2,56	1,24	2,52	3,23	2,32	2,68	3,08	2,98	1,77	0,91	1,60
2019	3,76	1,62	1,87	2,66	2,92	2,52	3,10	2,13	2,86	3,22	2,35	2,84
2020	2,52	4,80	3,39	3,45	2,86	2,91	1,86	2,91	2,88	2,43	2,40	1,14
2021	3,78	2,20	1,45	1,83	1,14	1,97	1,39	1,85	1,95	2,00	1,40	1,85
2022	2,03	2,66	3,69	1,85	1,54	0,98	1,20	1,25				

Conclusions and outlook

- **Innovative laser vibrometry** method for non-contact measurement of the degree of solidification in the strand
- in combination with **dynamic online temperature and solidification model**
- and **traffic-light observation** of relevant casting parameters

➢ **Comprehensive monitoring** of casting conditions and strand quality in terms of temperature profile, shell growth and crater end position

➢ Model-based **dynamic cooling strategy** for reliable adjustment of specified target values for these quality variables

➢ **Reduction of strand breakout** events and **increase in product quality and productivity** of continuous casting process

- Planned **next steps**: Further development and validation of the presented methods for **other casting machines with other strand formats and steel grades**

Acknowledgements

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Thank you very much for your attention!

Contact: Dr. Marc Köster
VDEh-Betriebsforschungsinstitut GmbH
Sohnstraße 69 · 40237 Düsseldorf
Phone +49 211 98492-894
E-Mail Marc.Koester@bfi.de

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Coming up: **METACAST Webinar**

The pivot role of modelling in problem-solving issues in continuous casting of steel: a project clustering experience in the European programmes frame! 🚀

We are excited to invite you to our upcoming webinar dedicated to showcasing the pivotal role of modelling 👨‍💻 🎓 👩‍💻 in continuous casting industrial 🏭 problem solving.

This webinar will highlight experiences 🤝 from other ongoing RFCS and EU funded projects: SUNSHINE and SHELLCRACK

📅 Date: 16th of June

🕑 Time: 14.30-17.00 CET

📍 Location: online (Link will be provided upon registration)