International Solar Energy Research Center Konstanz

How many Finger-Interruptions should we tolerate?

Jan Lossen, Dominik Rudolf, Adrian, Lejo Koduvelikulathu

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Motivation

High rejection rate

Failure catalogs often allow only a low number of finger cuts (e.g. 5, 7)

1. Innovation, like ..
- Ultra fine line screens
- Novel printing technique

Increased efficiency, but also … increased risk for finger cuts

2. Dispute in lab and production:

When must we clean/exchange the screen?

➡ What would be a sensible criteria on the number of finger cuts?

General considerations

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Power loss of a finger cut depends on

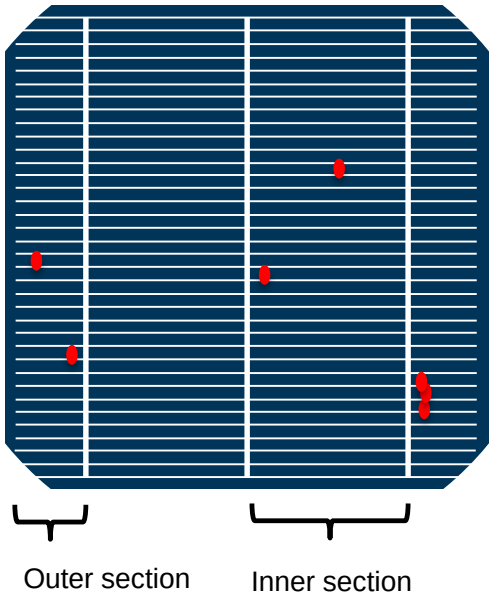
- Layout: finger length, redundancy features
- Individual position of the cut
- Position of further cuts in the neighborhood

Definition of standard PERC cell for this study

- Layout: 100 fingers, 45 µm, M2 Wafer
- R_{line} 0.55 Ω/cm (0.5, 0.7, 0.9 Ω/cm)
- R_{sheet} (Emitter) 90 Ω/□
- No redundancy line
- 3BB / 5BB / 18BB

IV-parameters the standard cell (5BB)

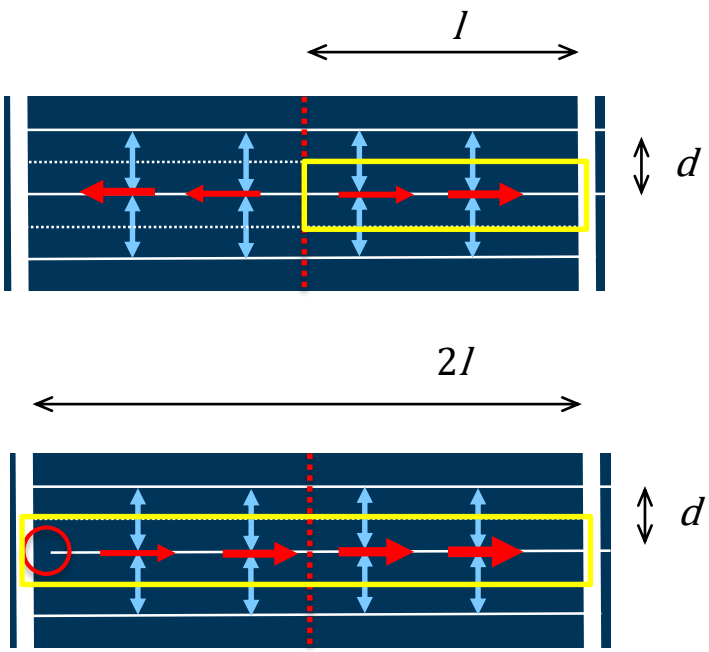
- η = 21.4%, FF = 80.5%,
- V_{oc} = 670 mV, J_{sc} = 39.7 mA/cm^2



Loss of cut in inner section

For a cut in an inner section (between BBs):

- No loss if cut is in the middle between BBs
- Maximum loss for cut close to one BB



Power loss of finger in symmetry element (SE) [1]

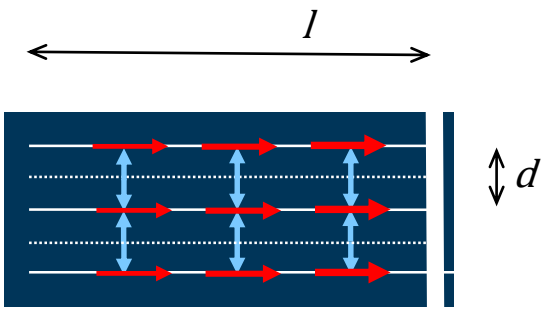
$$\Delta P_{line}\,(SE) = \frac{1}{3} l^3 {j_{mp}}^2\, d^2 R_{line}$$

Max. additional loss of one cut in inner section

$$\Delta P\,(inner\ cut) = \Delta P_{line}(2l) - 2 * \Delta P_{line}(SE)$$
$$= 6\,\Delta P_{line}(SE)$$
$$= 0{,}68\,mW\ (3BB)$$
$$\Delta\,eta\,(inner\ c., 3BB) = 0.0028\,\%$$
$$\Delta\,eta\,(inner\ c., 5BB) = 0.00056\,\%$$

[1] A. Goetzberger, et al., Sonnenenergie: Photovoltaik, B. G. Teubner Stuttgart, 1997

Cut in outer section

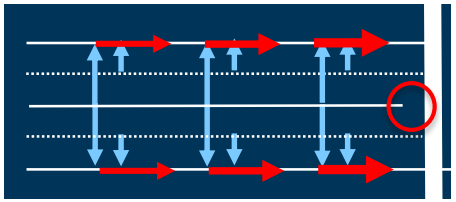


Cut in outer section

- Maximum loss for cut close to BB
- Loss = Additional loss in emitter
  + loss due to increased current in finger

Power loss in semiconductor in one symmetry element [1]

$$\Delta P_{semi}\,(SE) = \frac{1}{12} d^3 l\, j_{mp}{}^2\, R_{\square}$$



Max. power loss of one cut in out section:

$$\Delta P_{semi}\,(outer\ cut) = 6\,\Delta P_{semi}\,(SE) + 2\Delta P_{line}(SE)$$

In principal (max.) loss of a cut any position could be calculated in a similar way

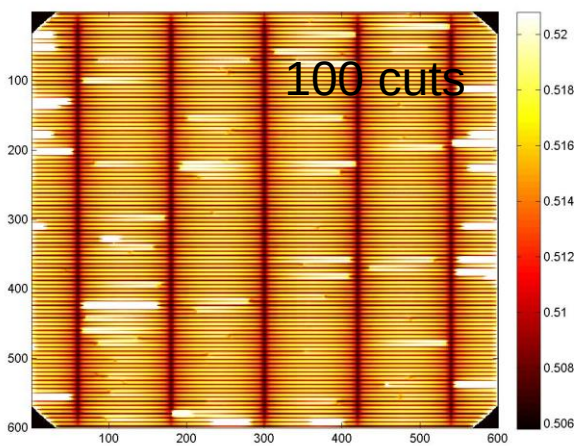
- However, for random positions and neighboring cuts things are getting very complicated
- And, in reality, current paths will slightly bend (emitter current not perpendicular to finger current)

Cuts in random positions

To investigate the impact of cuts in random positions we use the software Griddler 2.5 Pro [2]

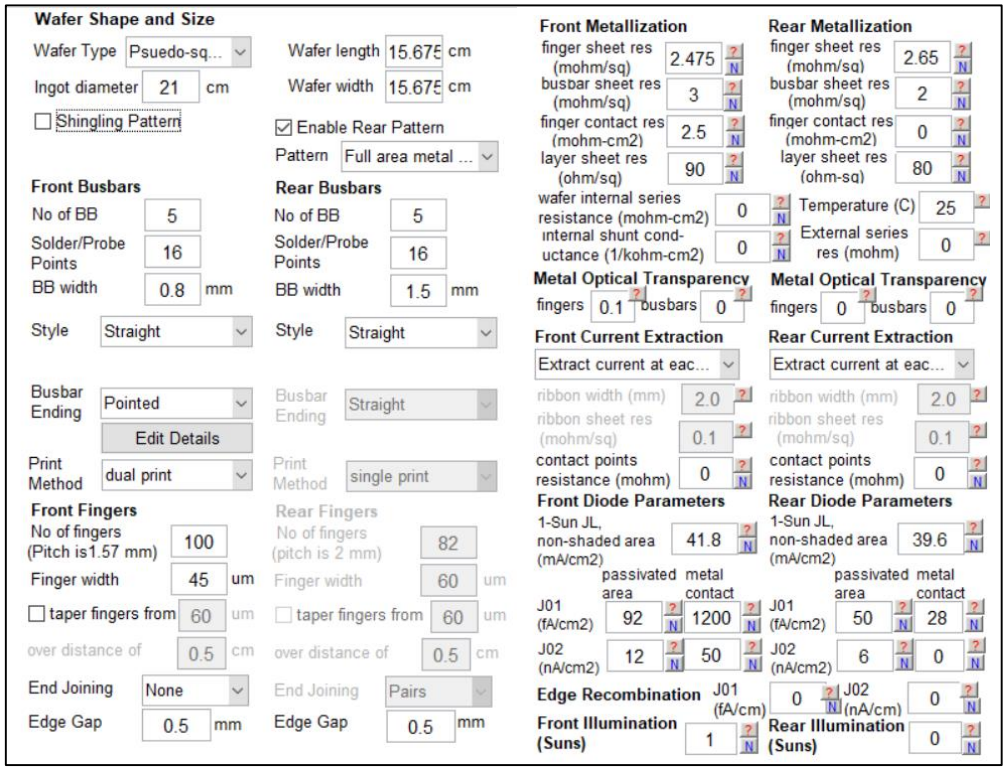
We wrote a script which creates finger cuts in random positions

Output: IV parameter, voltage maps



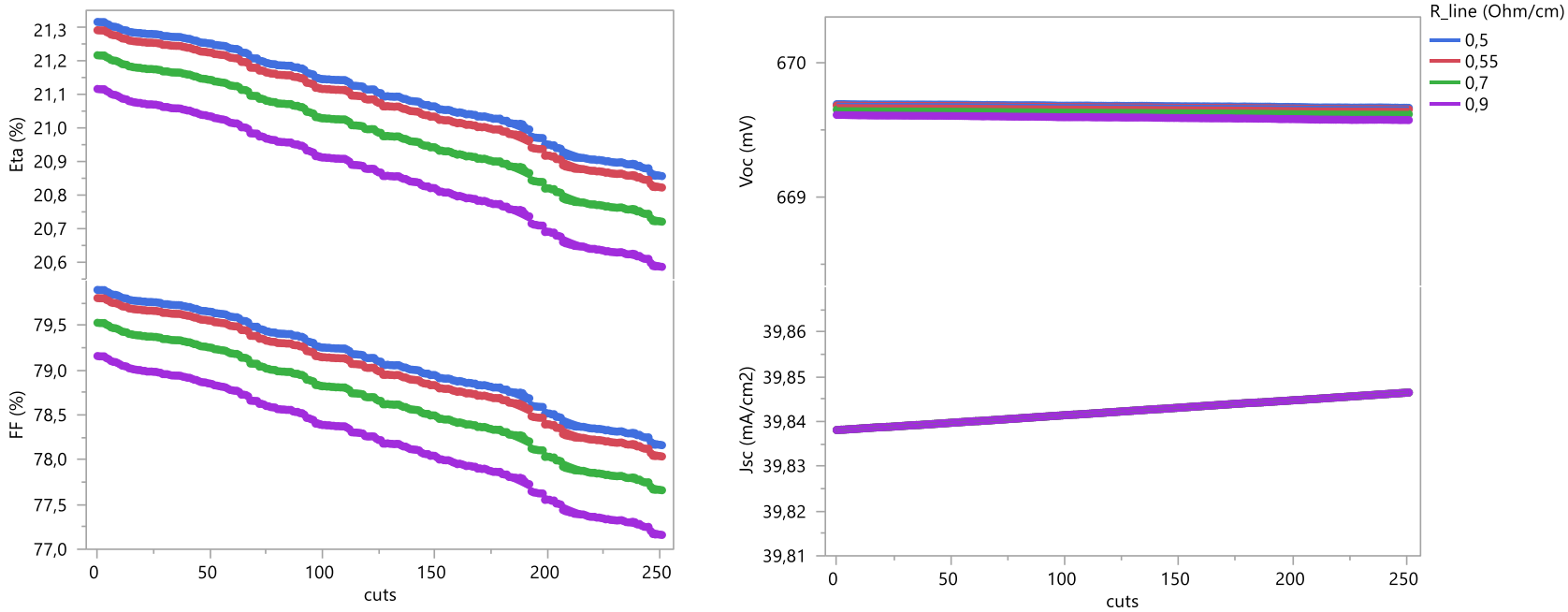
Diode voltage map at 500mV

Input parameter of Griddler 2.5 Pro Modell



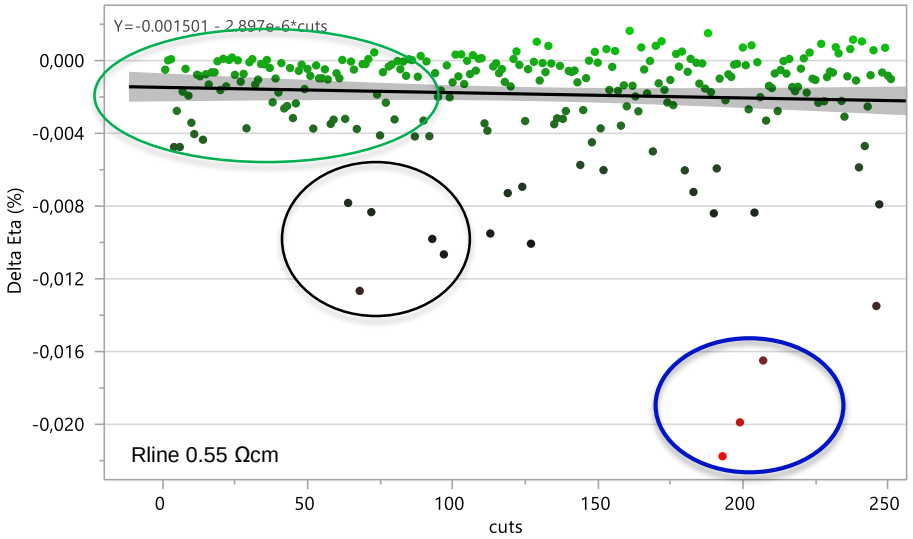
[2] Wong J., Griddler: intelligent computer aided design of complex solar cell metallization patterns. In Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th, 2013

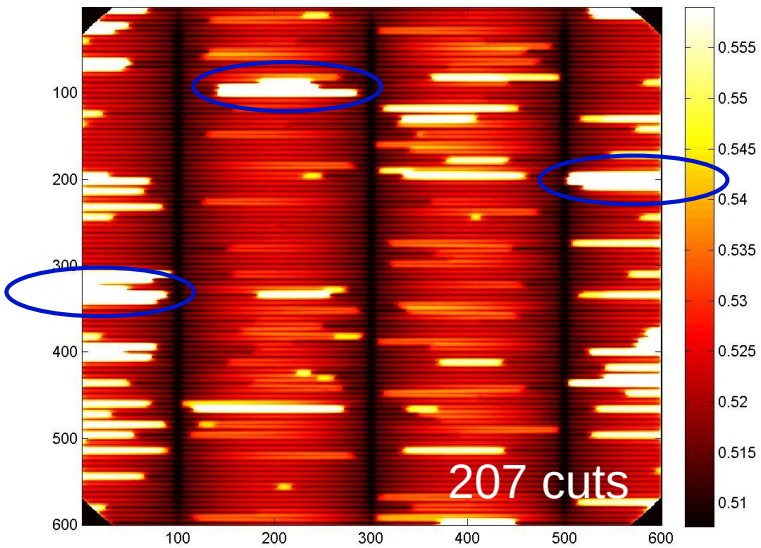
IV data – 3BB cell



- η decreases gradually with the number of cuts, such as FF
- V_{oc} and J_{sc} remain virtually unchanged
- Higher R_{line} reduces the FF severely, but the shape of the curves similar;
- However, for higher R_{line} the decrease gets slightly steeper

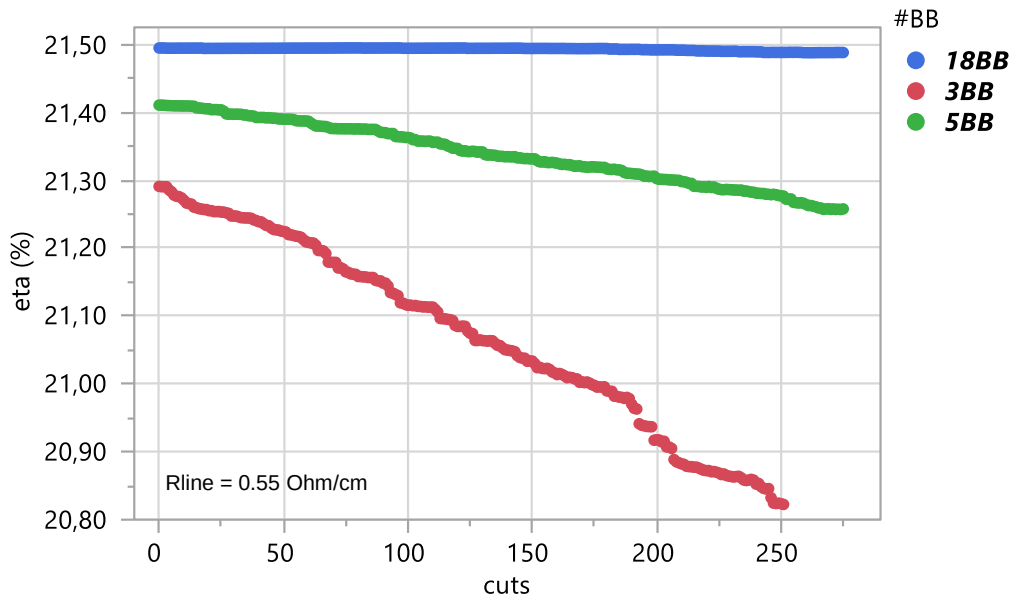
Loss per cut, 3BB cell

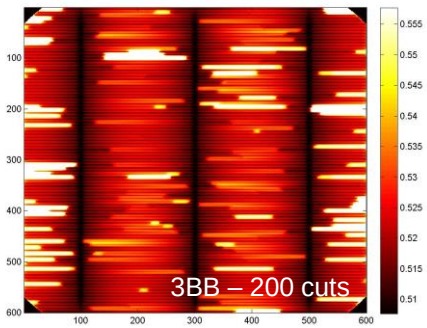


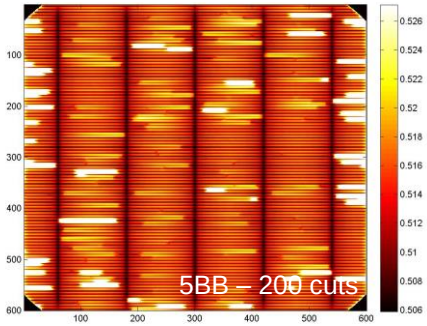


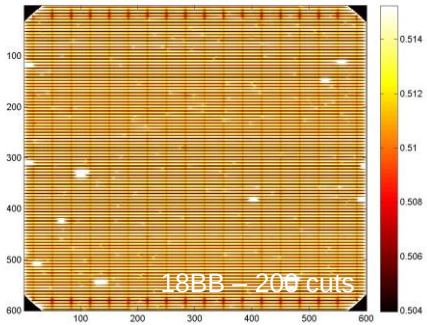
- Within the first 50 cuts, only losses < 0,005%
- First cuts with eta loss > 0,008% start ~70 cuts -> these correspond to cuts neighboring existing cuts in the outer sections
- Cuts with eta loss > 0,018% correspond to cluster with at least three neighboring cuts

Impact of BB number



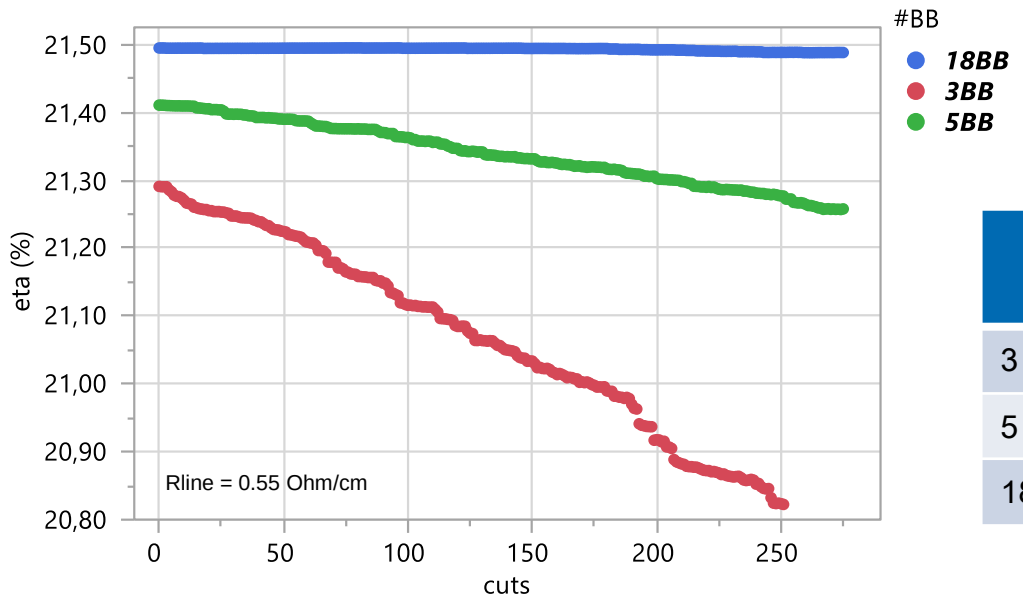






- A higher number of BBs reduces impact of cuts drastically
- Lower loss per cut and smaller risk for severe cuts
- For 5 BB more than 50 cuts are needed for decrease of ΔFF > 0.1%

Impact of BB number



	Δ η / 100 cut	#cuts for ΔFF = 0.1%
3 BB	-0.18 $\%_{abs}$	14 cuts
5 BB	-0.048 $\%_{abs}$	60 cuts
18 BB	-0.0040 $\%_{abs}$	>500 cuts

- A higher number of BBs reduces impact of cuts drastically
- Lower loss per cut and smaller risk for severe cuts
- For 5 BB more than 50 cuts are needed for decrease of ΔFF > 0.1%

Validation experiment

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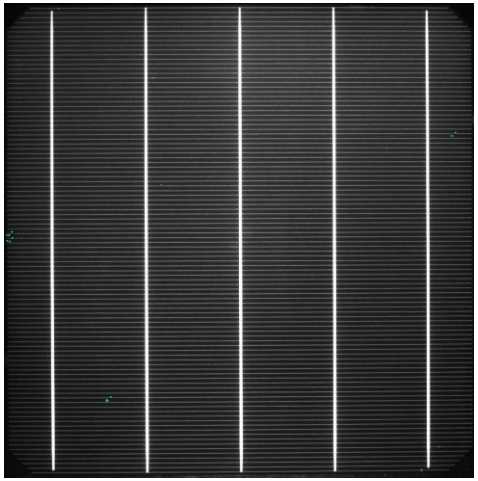
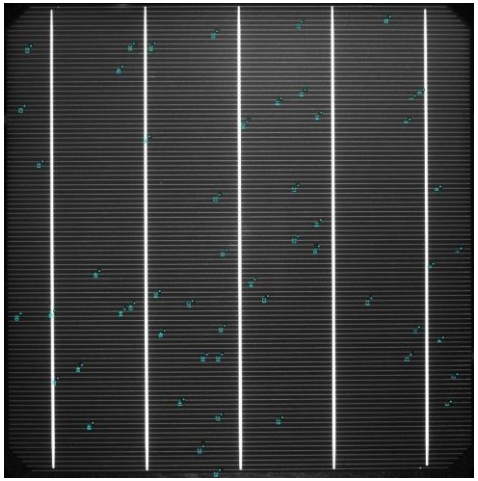
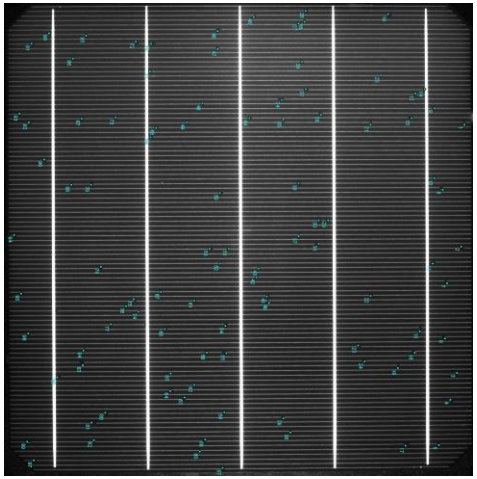
Experiment

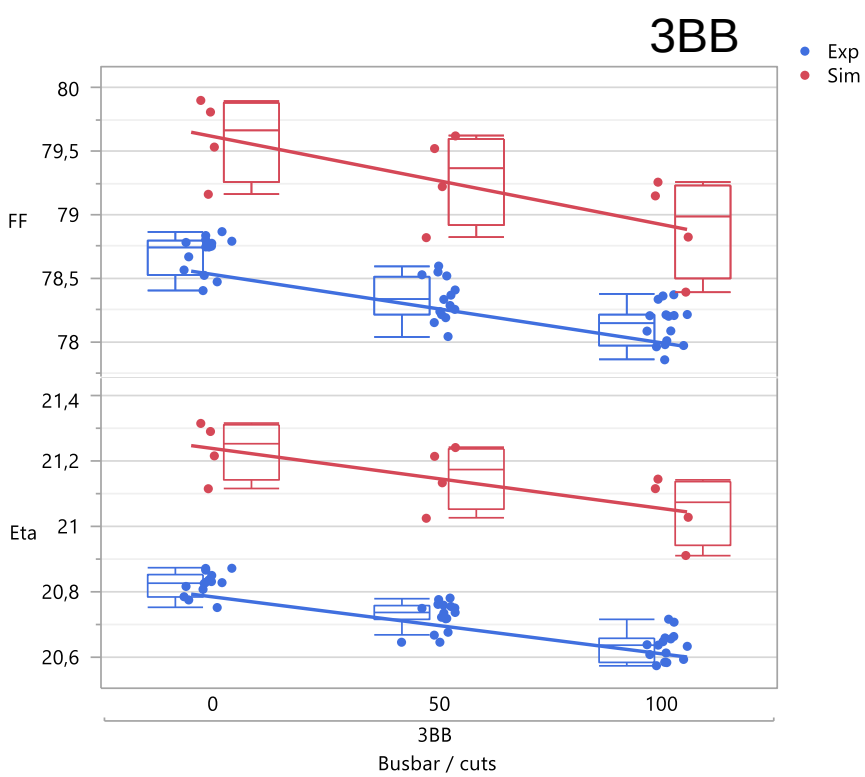
- 150 CZ- PERC precursors from industrial production line,
- We deliberately introduced 50/100 cuts into a printing screen by screen filler
- Combined this screen with print of 3BB / 5BB / 0BB resulting in ~15 per group

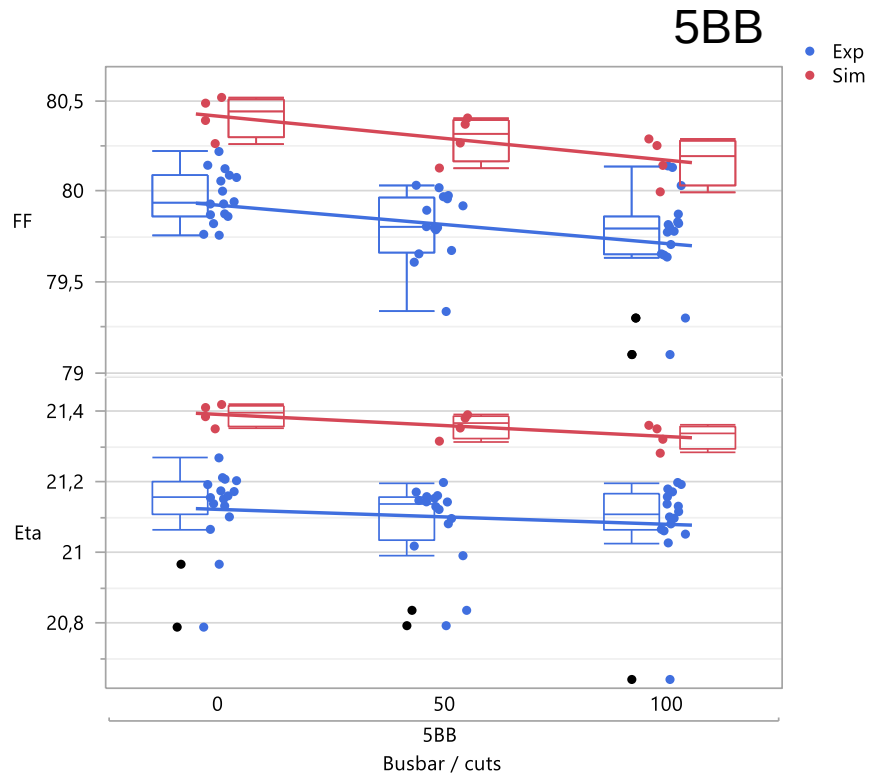






Validation Experiment: IV Data





Experiment: ~15 solar cells per group with deliberately introduced finger cuts

Simulation: cuts at similar positions as in screen, variation of R_line from 0.5Ω/cm to 0,9 Ω/cm

-> Experiment and Simulation match reasonable well

Validation Experiment

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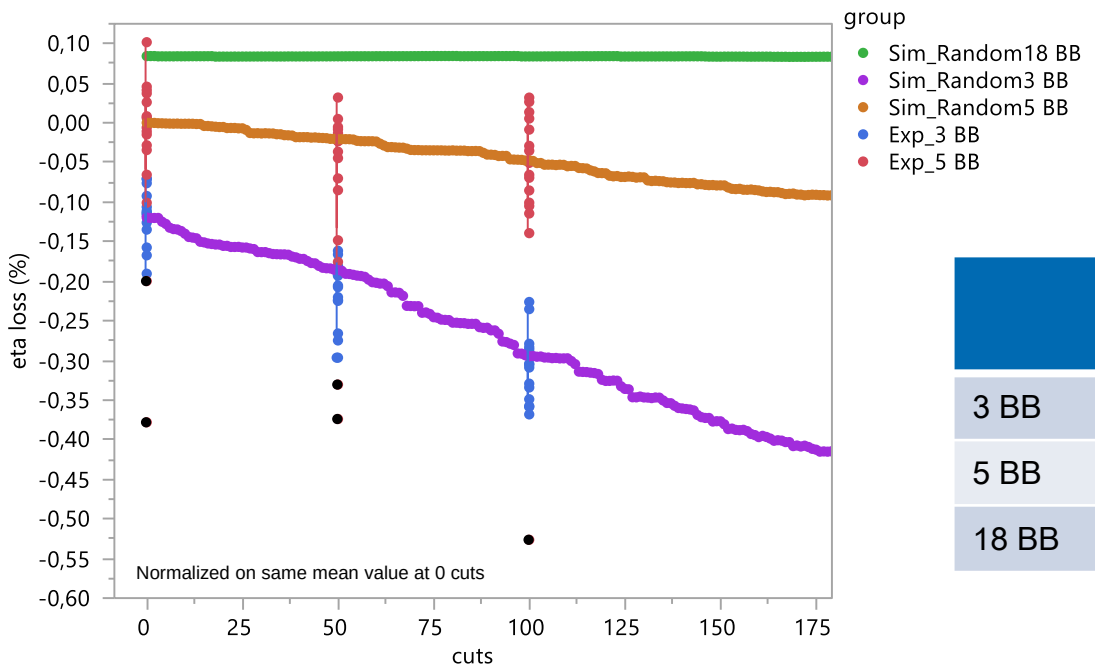


	Simulated Δ η (100 cuts)	Experimental Δ η (100 cuts)
3 BB	-0.18 %	-0.19 %
5 BB	-0.048 %	-0.046 %
18 BB	-4.0 E-06 %	~ 0

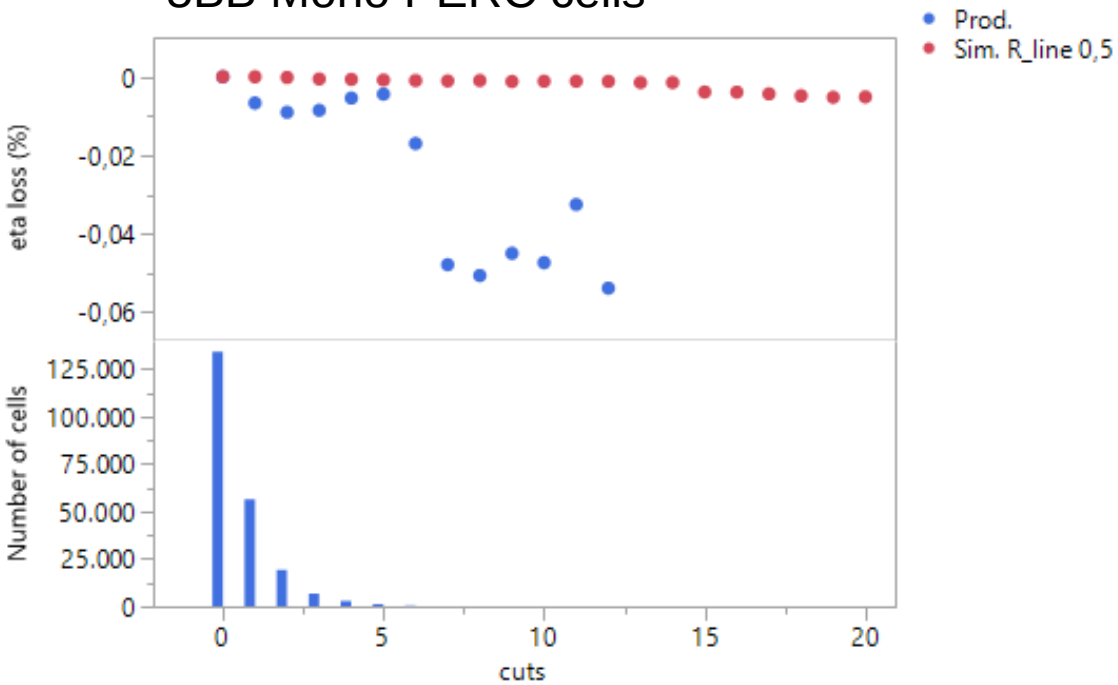
- Data plotted normalized to simulated value at 0 cuts
- Simulation and experiment match well, however statistical error is significant

Analysis of Production Data

H.A.L.M. provided an analysis of 220.000 PERC cells:
(#cuts / Mean(eta_loss) / frequency)

- #cuts were derived from EL picture by an algorithm
- Eta Loss < 0.01% for 1-5 cuts, eta loss ~0.05% for 7-12 cuts
- However, very low count >5 cuts (<0,5% of all cell have >5 cuts)

5BB Mono PERC cells



Data and simulation do not match well ! -> Further effects?

Analysis of Production Data

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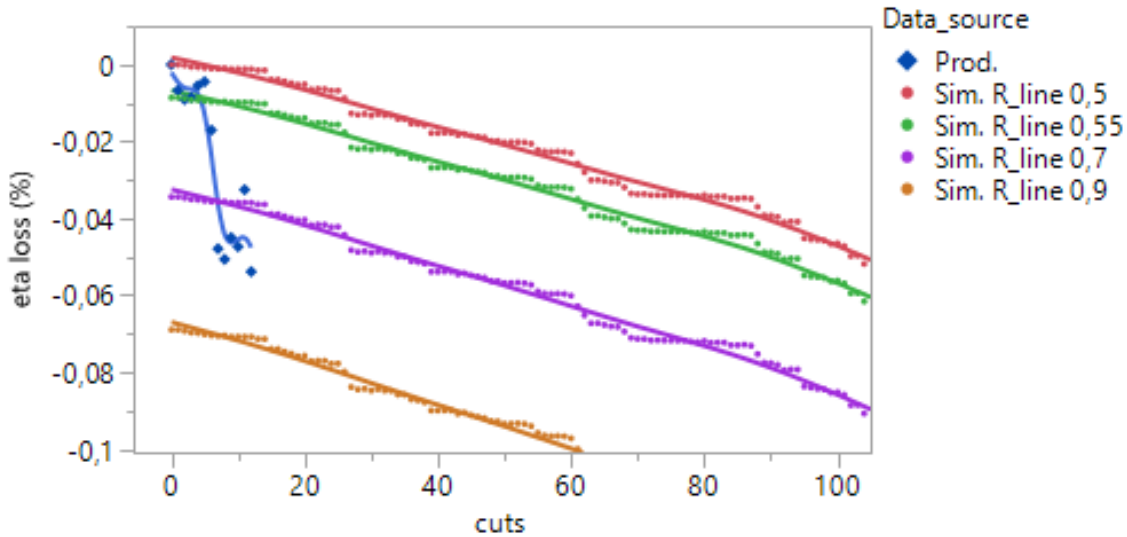
Hypothesis:

- This line probably operates with rejection criteria of 5 cuts
- Before number of cuts increases gradually towards 5 cuts, operators take action (e.g. cleaning or exchange of screen)

-> The few cells with >5 cuts originate from another mechanism than clogging of screen. E.g. they might be the first prints after a stop, or after screen cleaning procedure

-> most likely these cell suffer on further problems, e.g. a reduced cross section

5BB Mono PERC cells



Increased line conductivity could easily explain eta loss in observed range!

Analysis of Production Data II

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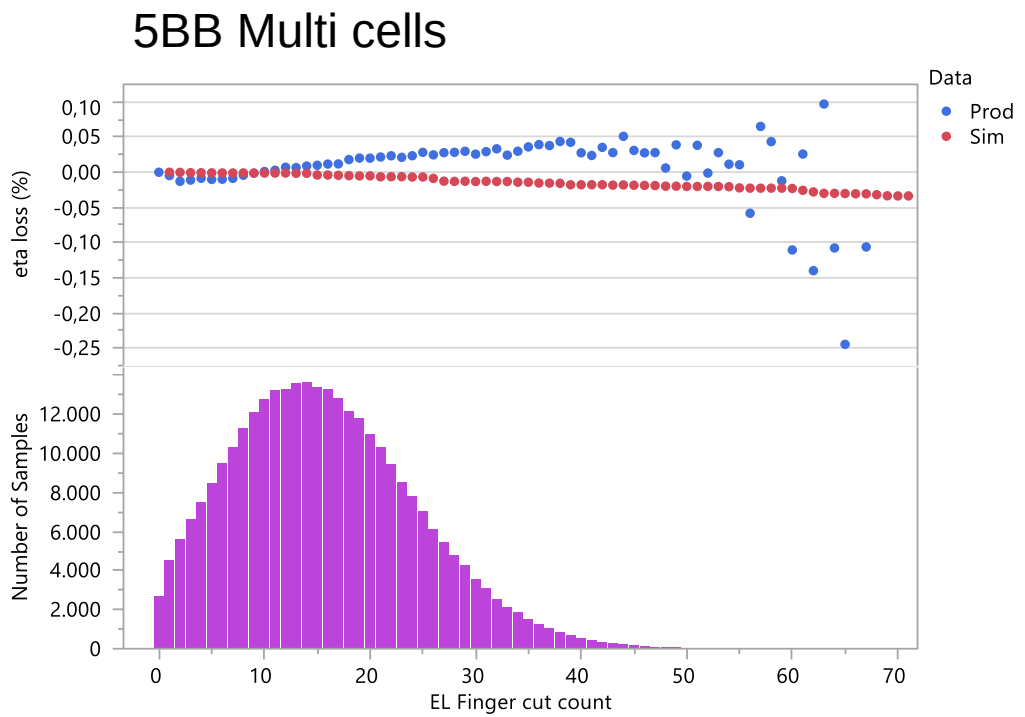
Further, H.A.L.M. provided an analysis of ~300.000 mc-Si 5BB Al-BSF cells:
(#cuts / Mean(eta_loss) / frequency)

– This data set features brought distribution with maximum at 15 cuts



Data show a slight increase of η with number of cuts!

-> must also arise from another effect, e.g. a reduction of line width

-> however, data compatibly with low loss by cuts

Conclusions

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- Finger cuts are detrimental, but the losses produced by random cuts are very small
- A higher number of BBs reduces impact of cuts drastically
  - For 5BB about 50 cuts are needed for ΔFF = 0.1%
  - For 18BB more than 500 of cuts are needed for ΔFF = 0.1%

	Sim Δ η (100 cuts)	Exp Δ η (100 cuts)
3 BB	-0.18 %	-0.19 %
5 BB	-0.048 %	-0.046 %
18 BB	-4.0 E-06 %	~ 0

- Single digit rejection criteria (e.g. < 7 cuts) are not justified by physics.
  For 5BB cells, it would be prudent to allow at least 50 cuts.
- Reduced finger cross section has a bigger impact -> better to monitor paste laydown or R_{line}
- No reliability problems due to finger cuts are known to us
- A relaxed criteria on the number of finger cuts would allow for:
  - Lesser cleaning and lower consumption of screens -> higher productivity
  - More headroom for further reduction of line width -> potential for higher efficiency

Have “Mut zur Lücke”!

(Dare the gap)

Acknowledgements

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We would like to thank…

- Stefan Schenk and Stefan Dauwe of H.A.L.M. for providing the analysis of production data, and for valuable discussions
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