Evaluation of a cleaning robot on PV modules regarding its influence on electrical and optical module properties

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Task description

- To evaluate mechanical influences on photovoltaic (PV) modules, electrical and optical module properties are determined and compared before and after mechanical stress. This is done by power measurement and electroluminescence imaging - both under STC and low light conditions.
- For the evaluation of the influence of the PV cleaning robot, corresponding test modules are characterized accordingly before and after each test run of the cleaning robot and compared for evaluation.
- A corresponding horizontal test setup was installed for flat lying PV modules on a thin mounting structure over the ground to be passed over with the cleaning robot including brushes and activated water system.
- After initial module characterization, the cleaning robot makes 200 cleaning passes over the modules in direction of the module length. The modules are characterized again, and the robot makes another 200 cleaning passes perpendicular to the module length with subsequent final characterization of the modules.
- Performance measurements and EL images are analyzed for comparative evaluation of the influence of the cleaning robot.

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Sample overview

- Test samples (PV modules) brought by SolarCleanO on 08.07.2025

#	CSP-Number	Type	Comment	Used for test / measurement
1	CSP_SolOur_2_P01	TrinaSolar_TSM-500NEG18R.28	some minor dark spots in EL	**YES**
2	CSP_SolOur_2_P02	TrinaSolar_TSM-500NEG18R.28	one dark cell areas in EL	**NO**
3	CSP_SolOur_2_P03	JASolar_JAM60D41-500/LB	some minor dark spots in EL	**YES**
4	CSP_SolOur_2_P04	JASolar_JAM60D41-500/LB	some minor dark spots in EL	**YES**
5	CSP_SolOur_2_P05	Jinko_JKM440N-54HL4R-BDB	some minor dark spots in EL	**YES**
6	CSP_SolOur_2_P06	Jinko_JKM440N-54HL4R-BDB	some minor dark spots in EL	**YES**
7	CSP_SolOur_2_P07	Longi_LR5-54HTH_440M	some minor dark spots in EL	**YES**
8	CSP_SolOur_2_P08	Longi_LR5-54HTH_440M	one dark cell area and some dark spots in EL	**NO**
9	CSP_SolOur_2_P09	TrinaSolar_TSM-500NEG18R.28	some minor dark spots in EL	**YES**
10	CSP_SolOur_2_P10	Longi_LR5-54HTH_440M	some minor dark cell areas and minor dark spots in EL	**YES**

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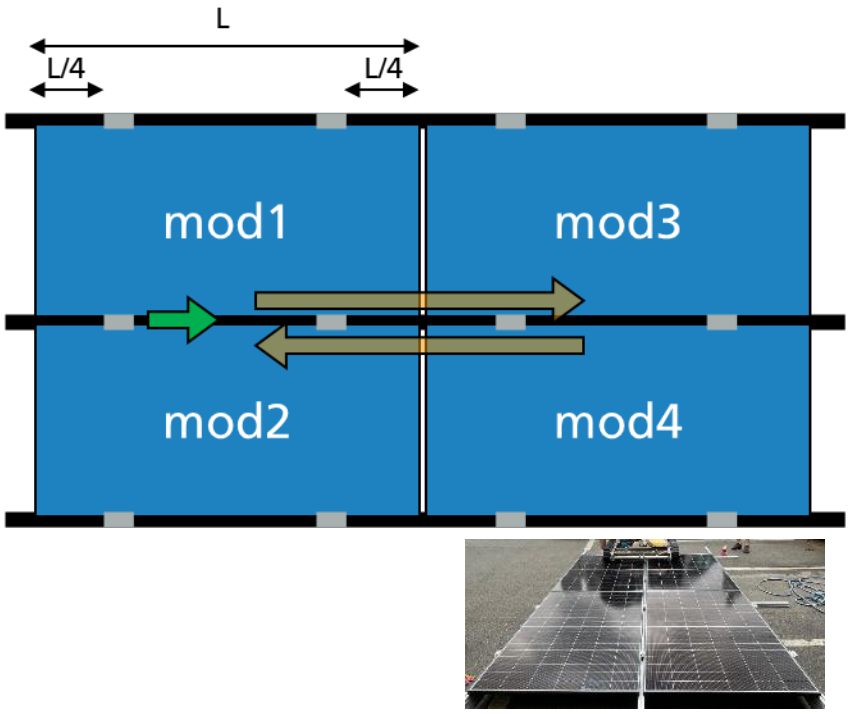
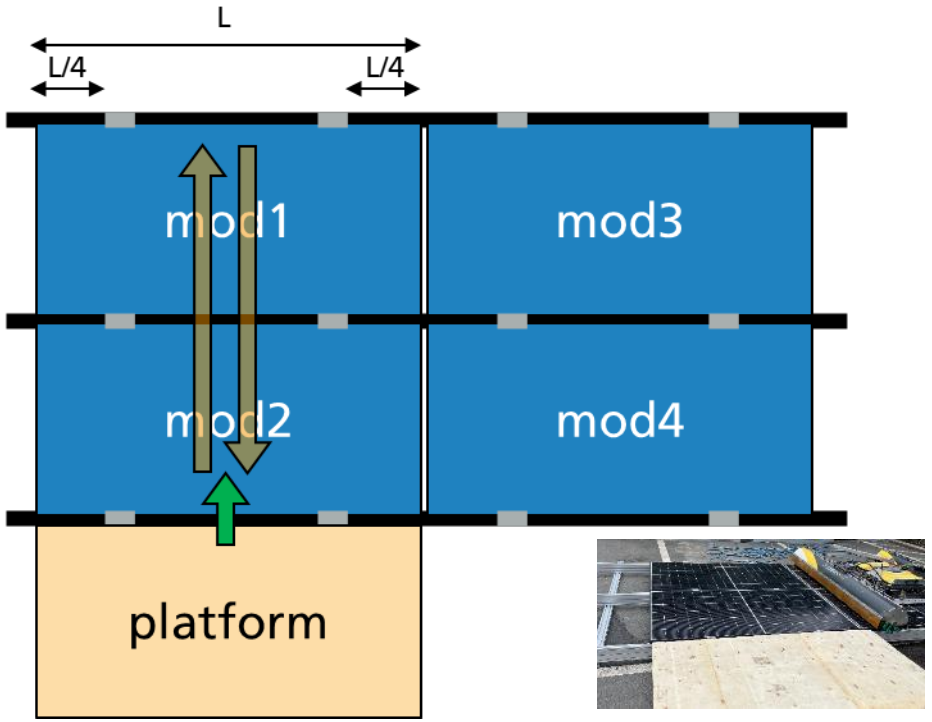
Test setup

- Two different test setups for testing of both driving directions were used with identical mounting (incl. clamp positions)



Setup 1 for passes in direction of module length



Setup 2 for passes perpendicular to the module length

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Module characterization methods

Performance measurement and electroluminescence

Equipment: Halm elektronik Solar Simulator cetisPV-Moduletest4
Parameter:

- STC (standard test conditions): (25±1)°C, irradiation 1000 W/m², Spectrum AM1.5
- Flash length : 85 ms
- Measurements are made without spectral mismatch correction
- Integrated EL measurement near I_{SC}

Technical Specifications	
Homogeneity	class A+ (<1 %)
Spectral match	class A+ (0.875 - 1.125)
Stability over time	class A+ (<0.8 %)
max. module size	2700 x 1700mm²
Flash length	10 – 145 ms
Irradiation	100 … 1300 W/m² (low irradiance with cetisPV-NDF2)
Repeatability	< 0.15 % für Pmpp
Measurement uncertainty without reference module	2.0 %

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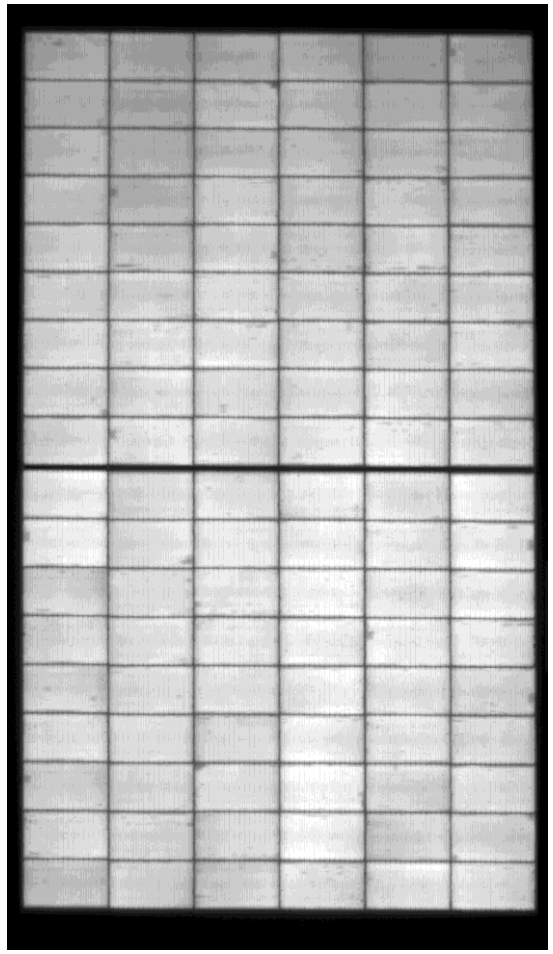
Results

Electroluminescence

- Manufacturer: TrinaSolar
- Type: TSM-500NEG18R.28
- CSP_SolOur_2_P01
  - EL image @ I_{SC} = 15.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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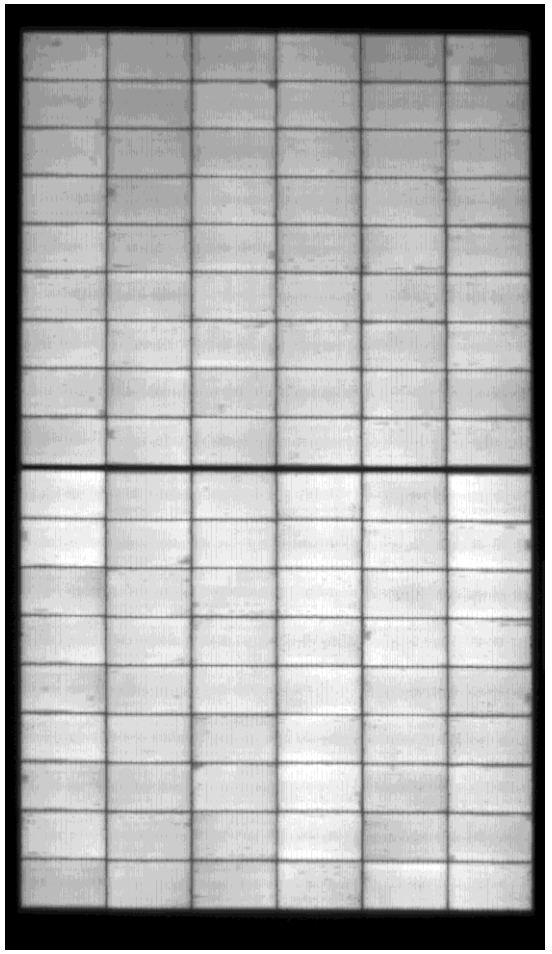
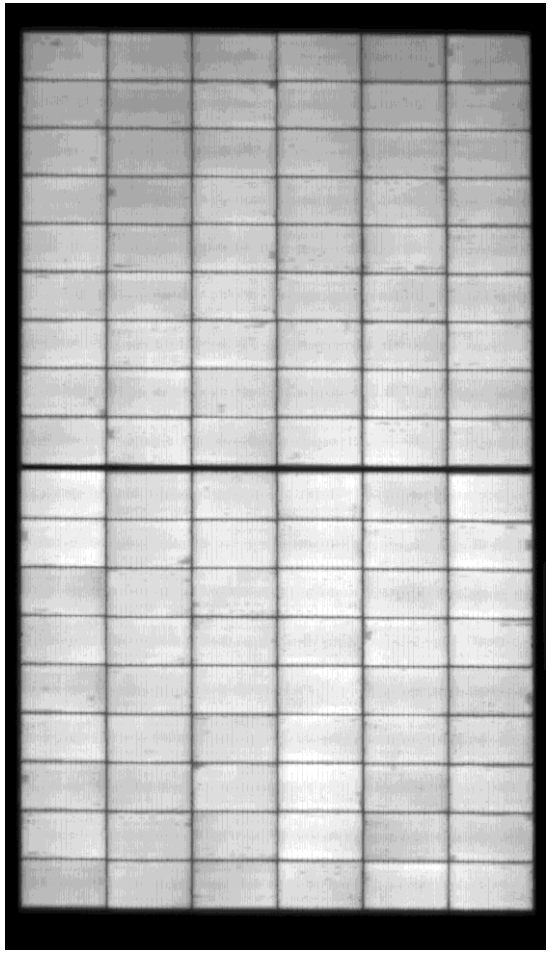


200 passes in direction of module length



200 passes perpendicular to module length

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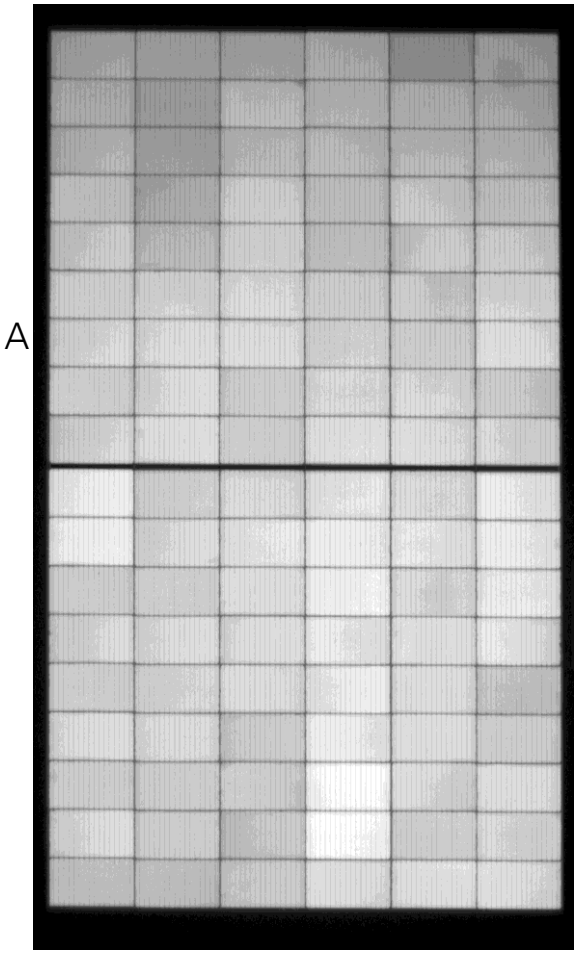
Results

Electroluminescence

- Manufacturer: TrinaSolar
- Type: TSM-500NEG18R.28
- CSP_SolOur_2_P01
  - EL image @ 1/10 I_{SC} = 1.5 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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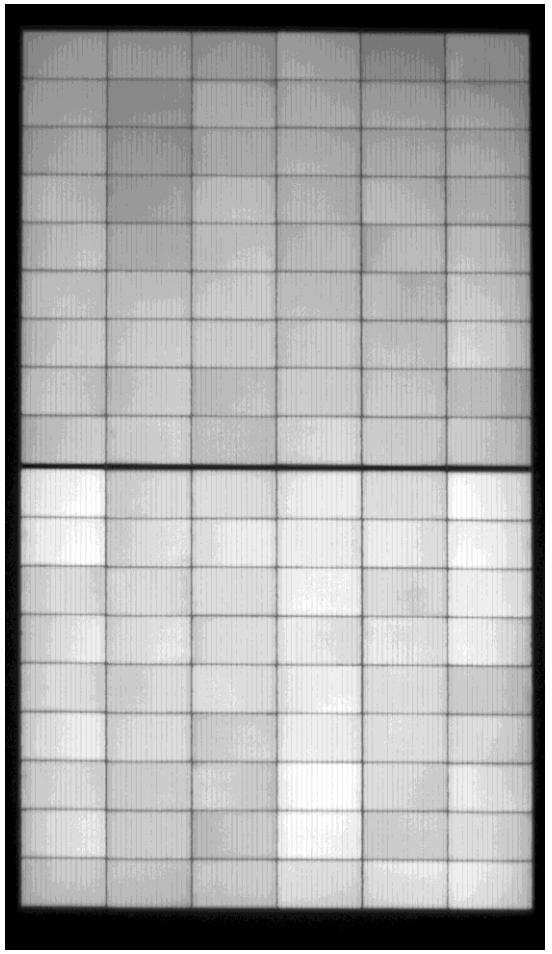
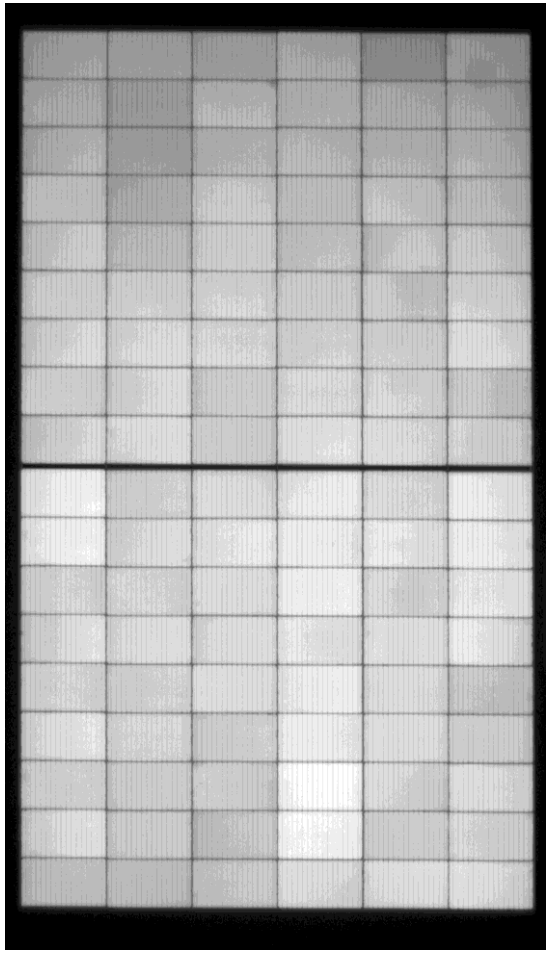


200 passes in direction of module length



200 passes perpendicular to module length

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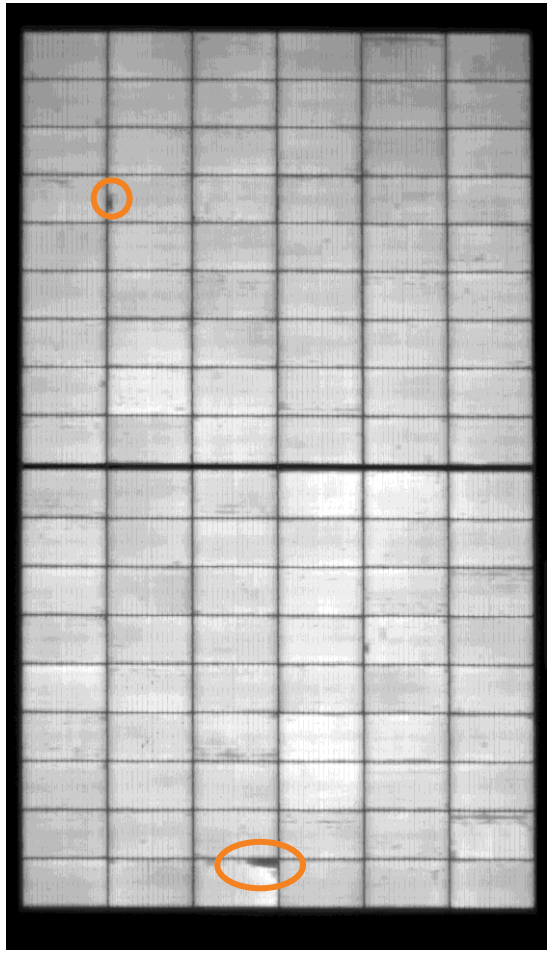
Results

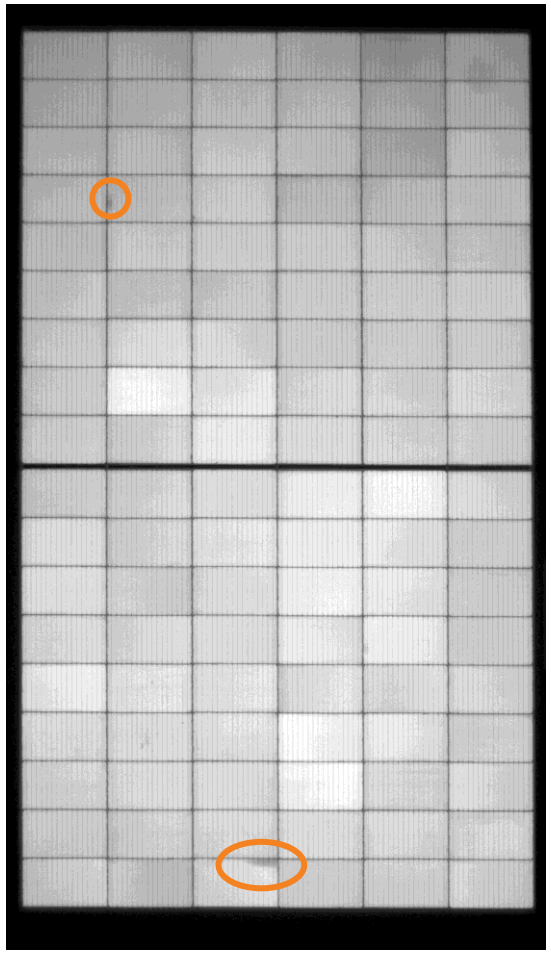
Electroluminescence

- Manufacturer: TrinaSolar
- Type: TSM-500NEG18R.28
- CSP_SolOur_2_P02
  - EL image
    - @ I_{SC} = 15.0 A
    - @ 1/10 I_{SC} = 1.5 A
  - Dark cell areas

    ➔**Excluded from the test**



Initial @I_{SC}



Initial @ 1/10 I_{SC}

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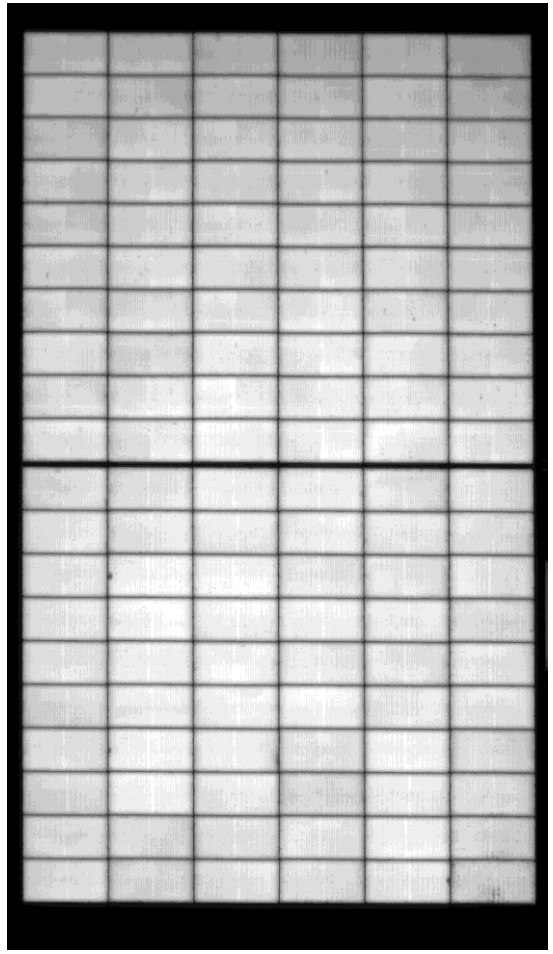
Results

Electroluminescence

- Manufacturer: TrinaSolar
- Type: TSM-500NEG18R.28
- CSP_SolOur_2_P09
  - EL image @ I_{SC} = 15.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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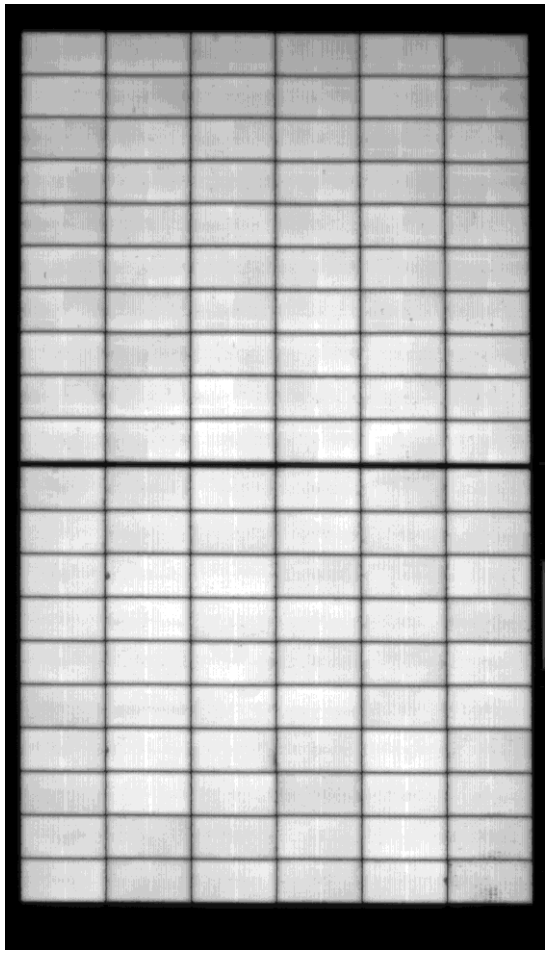
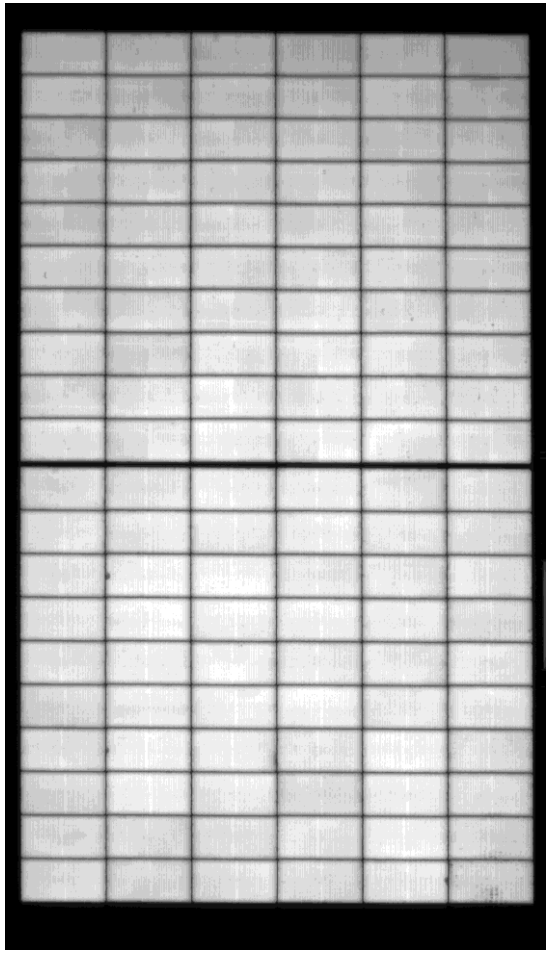


200 passes in direction of module length



200 passes perpendicular to module length

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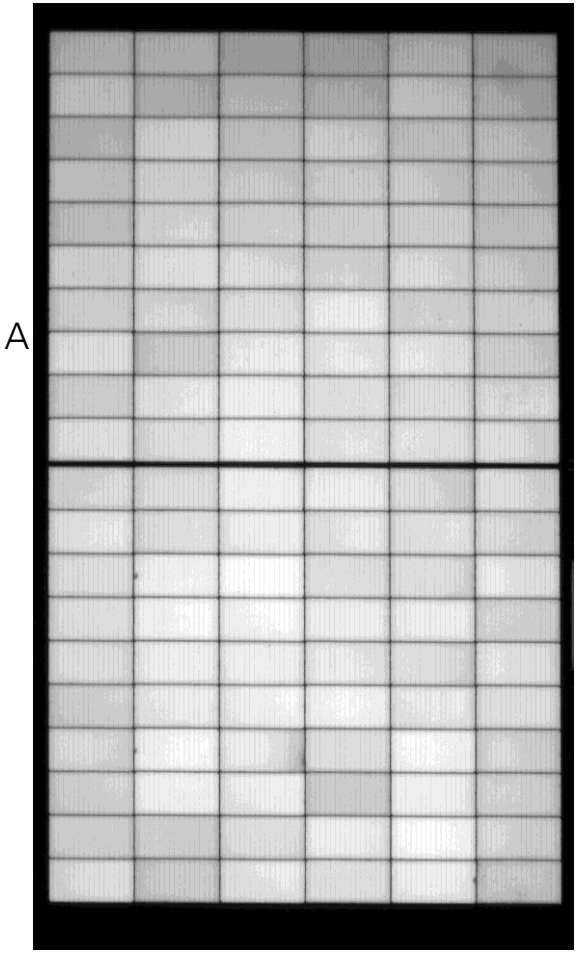
Results

Electroluminescence

- Manufacturer: TrinaSolar
- Type: TSM-500NEG18R.28
- CSP_SolOur_2_P09
  - EL image @ 1/10 I_{SC} = 1.5 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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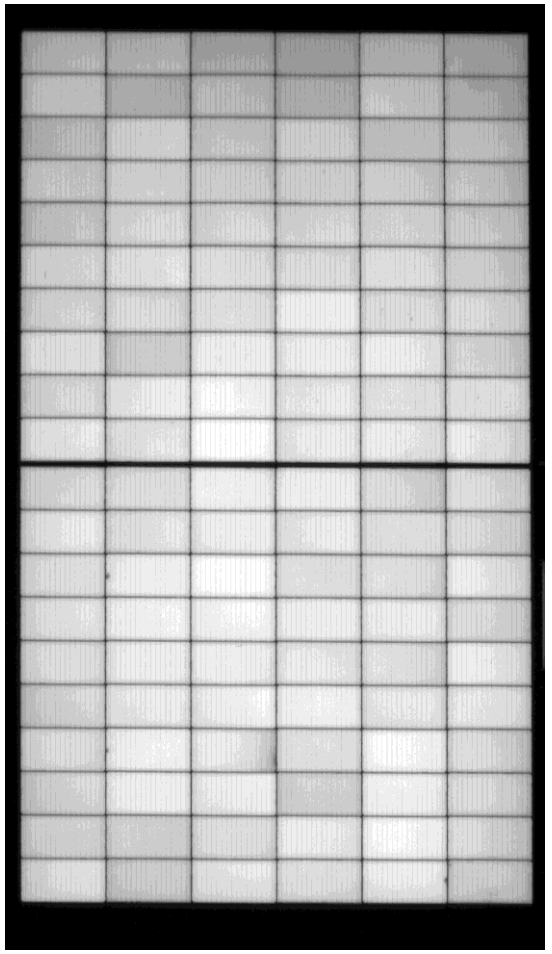
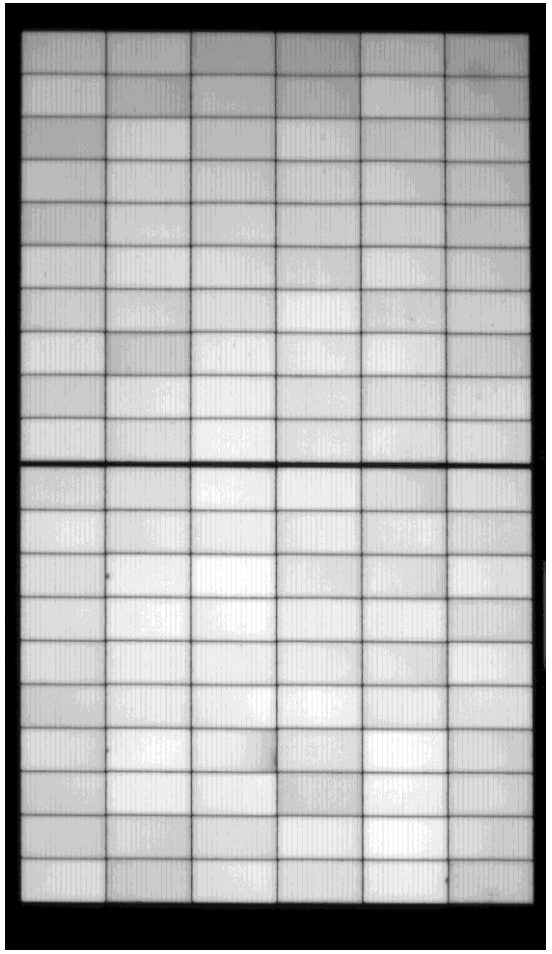


200 passes in direction of module length



200 passes perpendicular to module length

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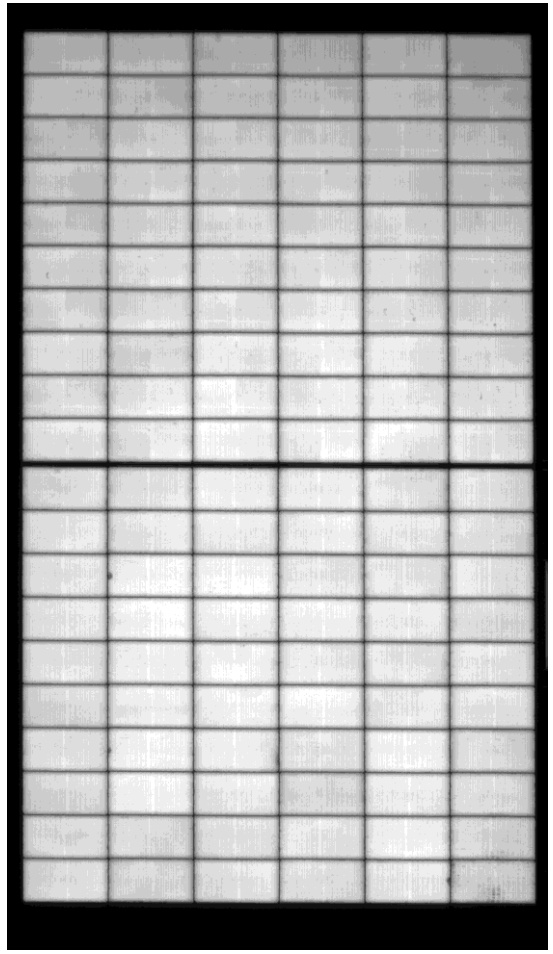
Results

Electroluminescence

- Manufacturer: JASolar
- Type: JAM60D41-500/LB
- CSP_SolOur_2_P03
  - EL image @ I_{SC} = 15.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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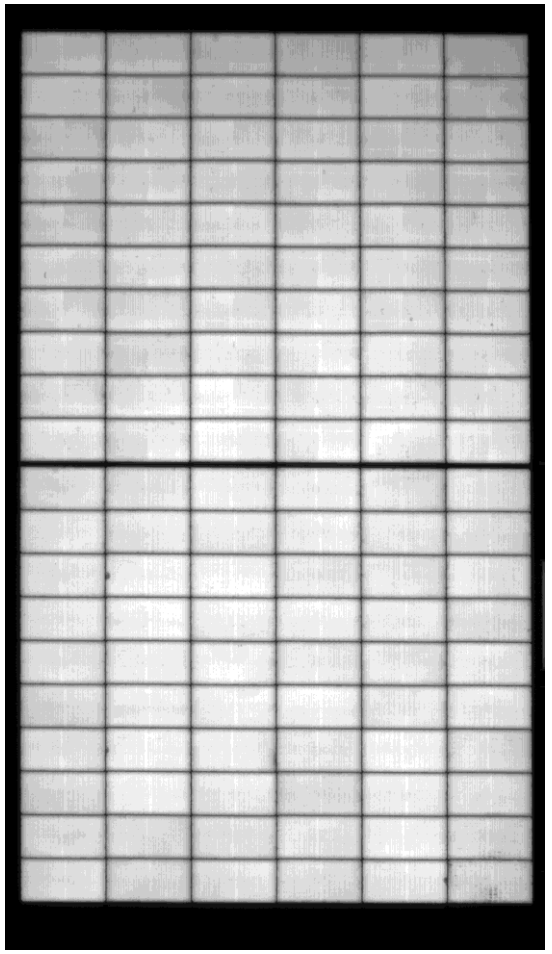
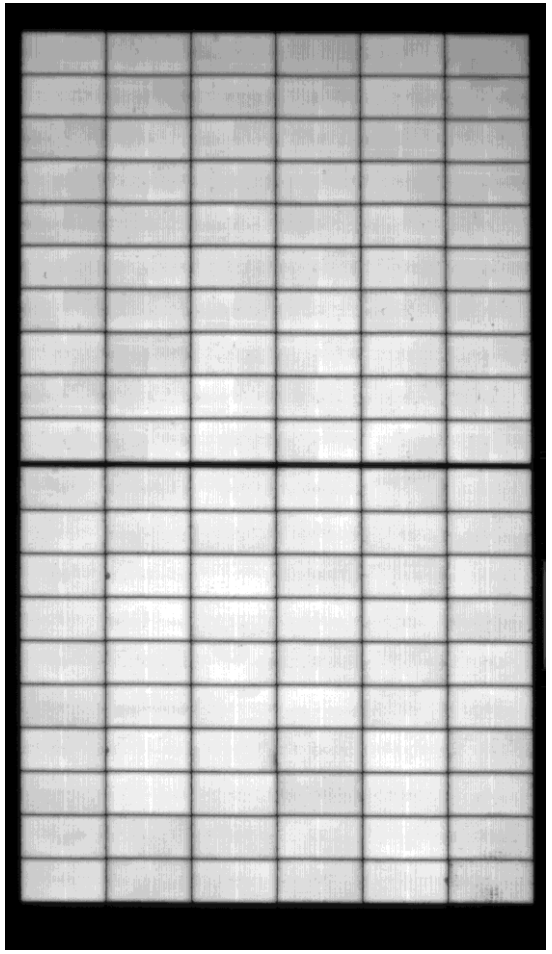


200 passes in direction of module length



200 passes perpendicular to module length

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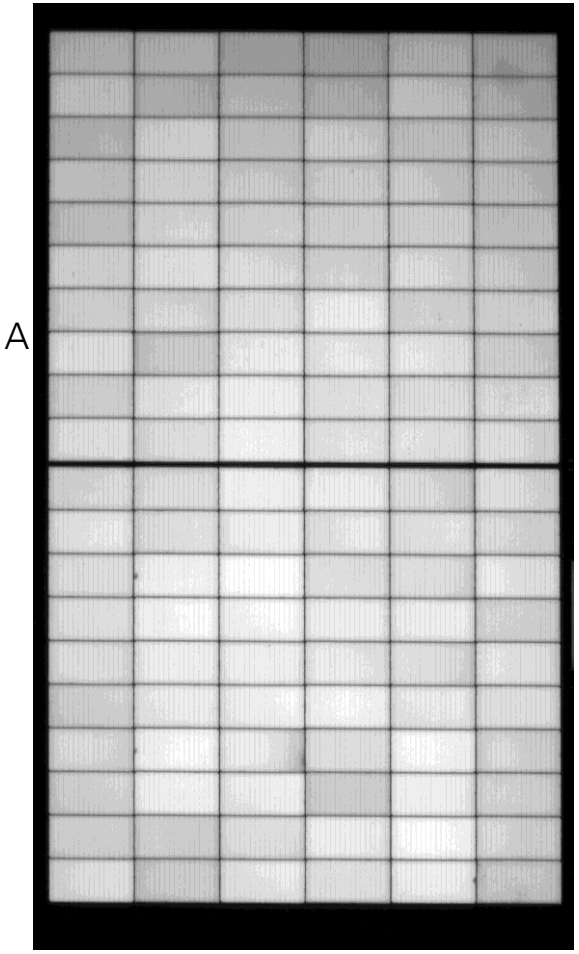
Results

Electroluminescence

- Manufacturer: JASolar
- Type: JAM60D41-500/LB
- CSP_SolOur_2_P03
  - EL image @ 1/10 I_{SC} = 1.5 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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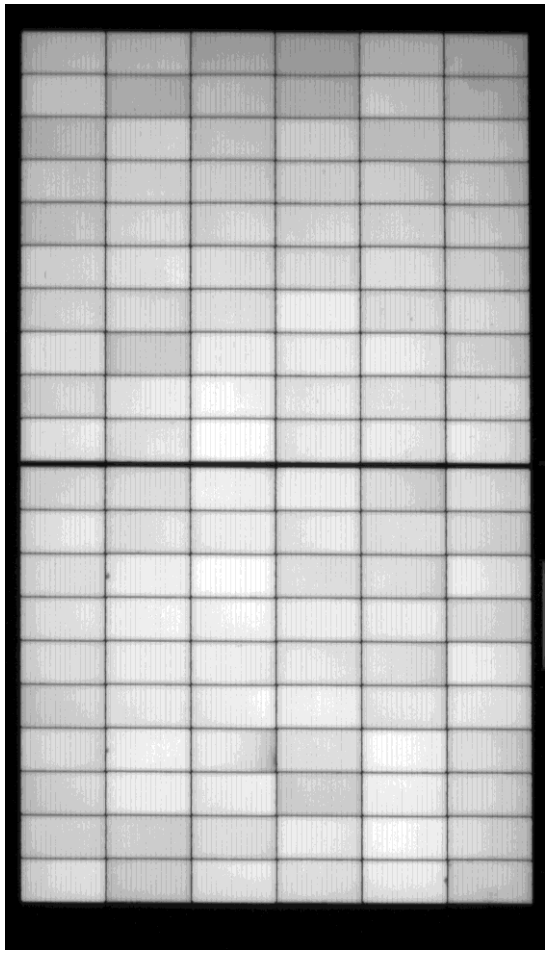
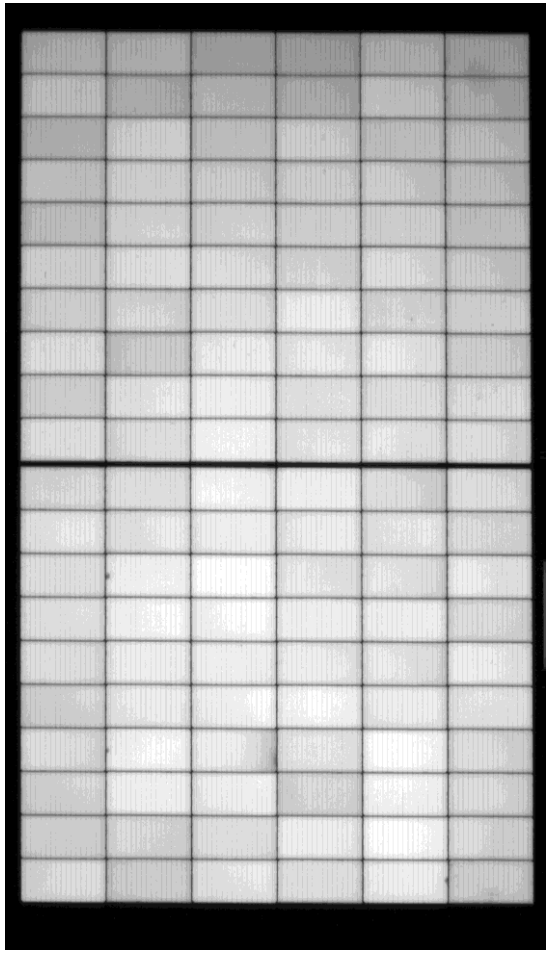


200 passes in direction of module length



200 passes perpendicular to module length

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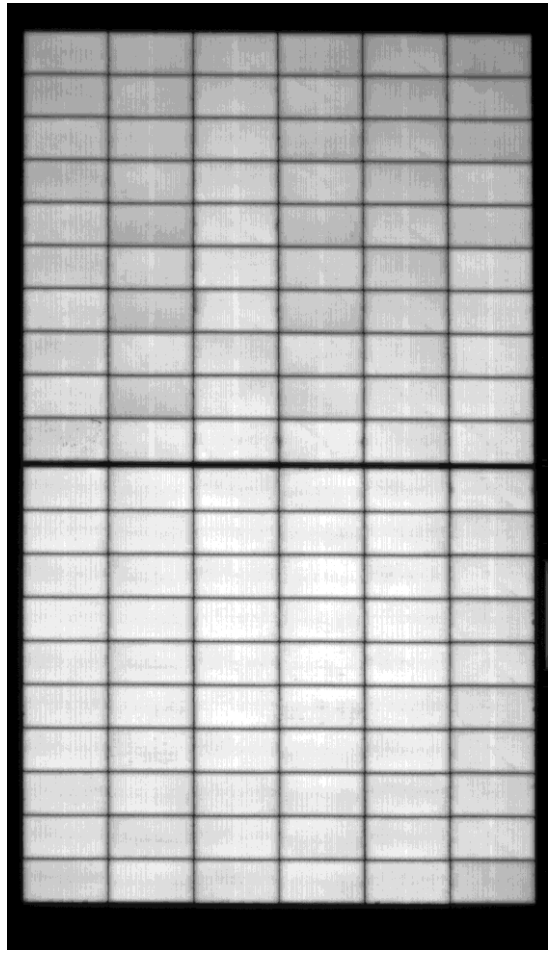
Results

Electroluminescence

- Manufacturer: JASolar
- Type: JAM60D41-500/LB
- CSP_SolOur_2_P04
  - EL image @ I_{SC} = 14.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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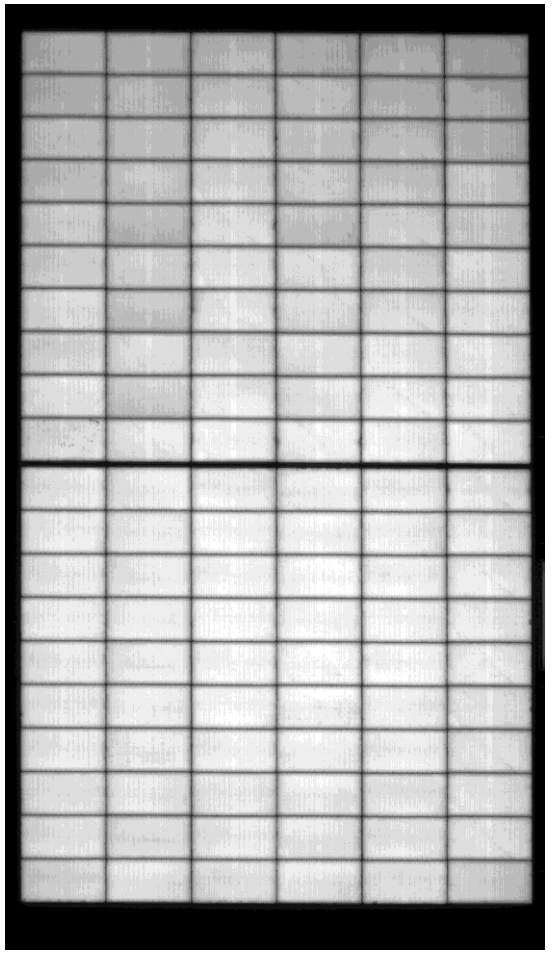
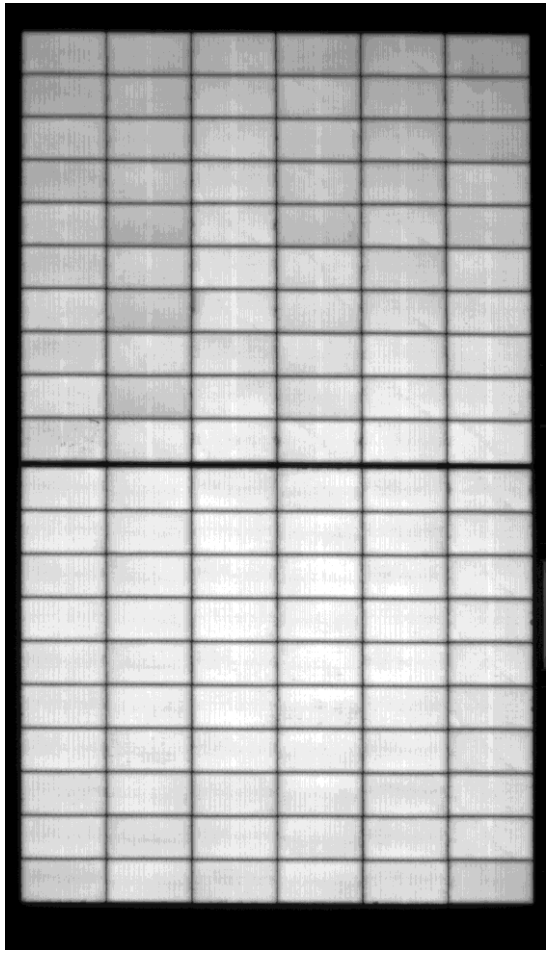


200 passes in direction of module length



200 passes perpendicular to module length

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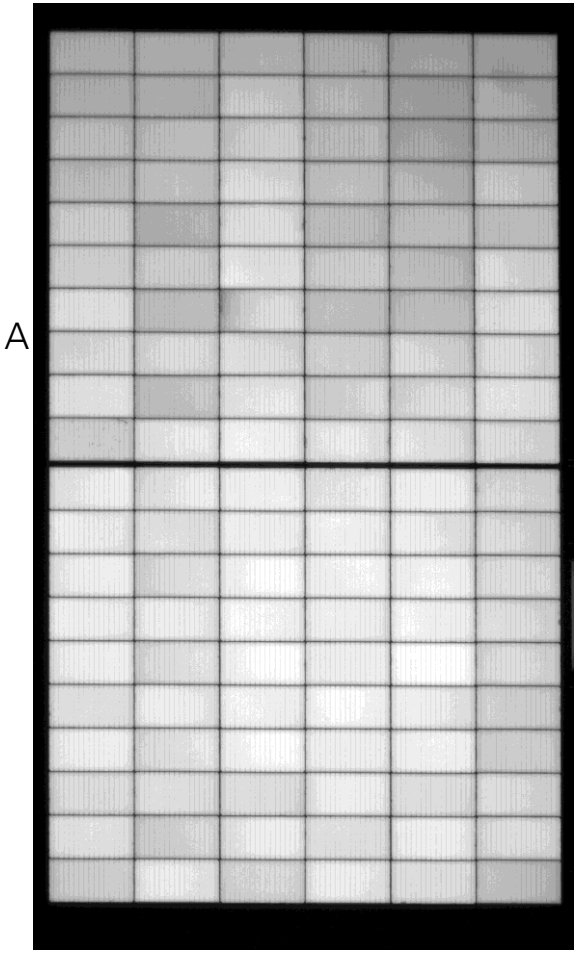
Results

Electroluminescence

- Manufacturer: JASolar
- Type: JAM60D41-500/LB
- CSP_SolOur_2_P04
  - EL image @ 1/10 I_{SC} = 1.4 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



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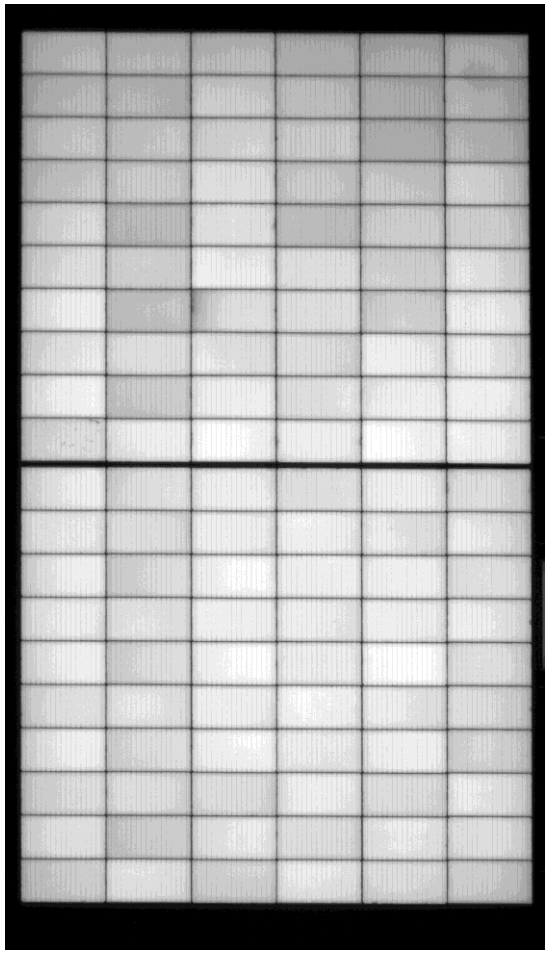
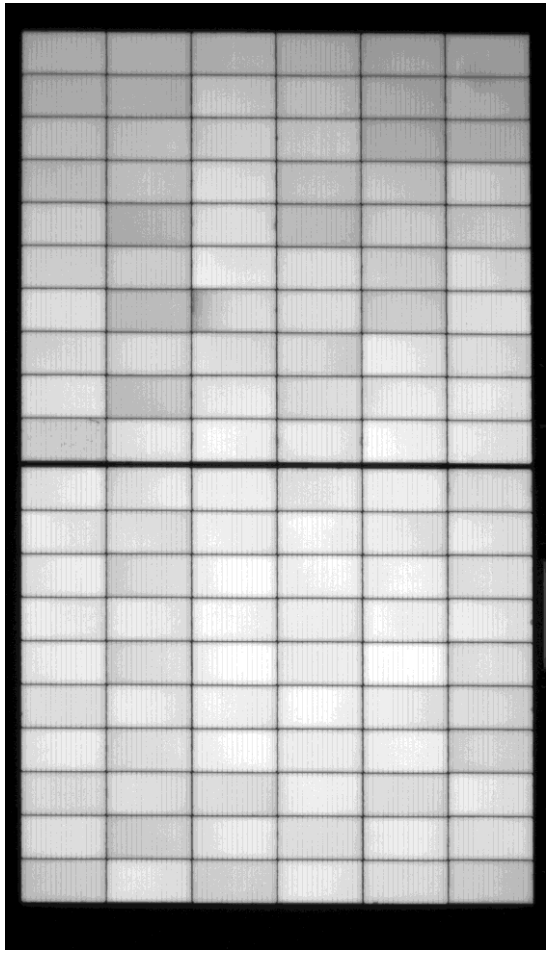


200 passes in direction of module length



200 passes perpendicular to module length

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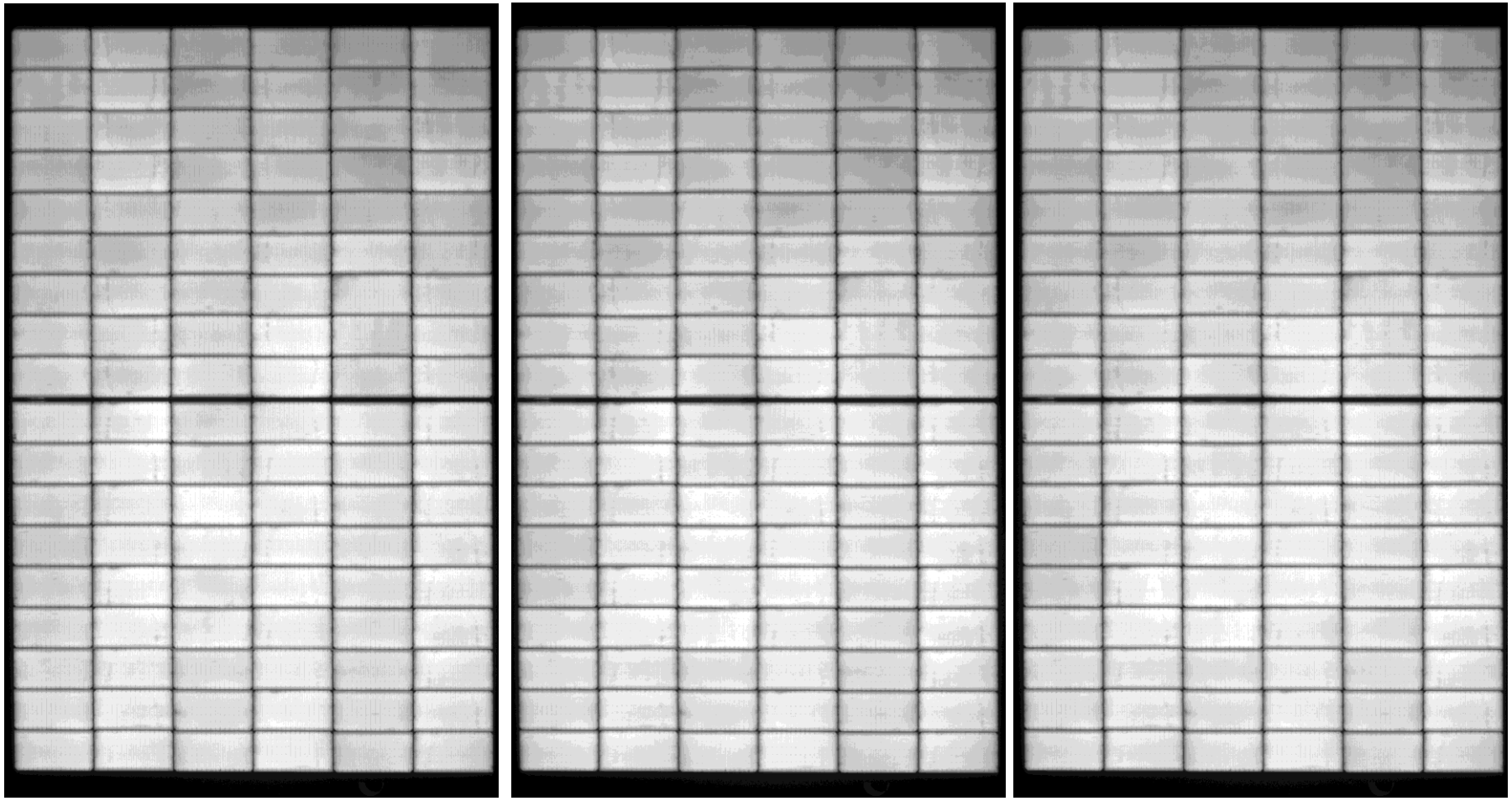
Results

Electroluminescence

- Manufacturer: Jinko
- Type: JKM440N-54HL4R-BDB
- CSP_SolOur_2_P05
  - EL image @ I_{SC} = 14.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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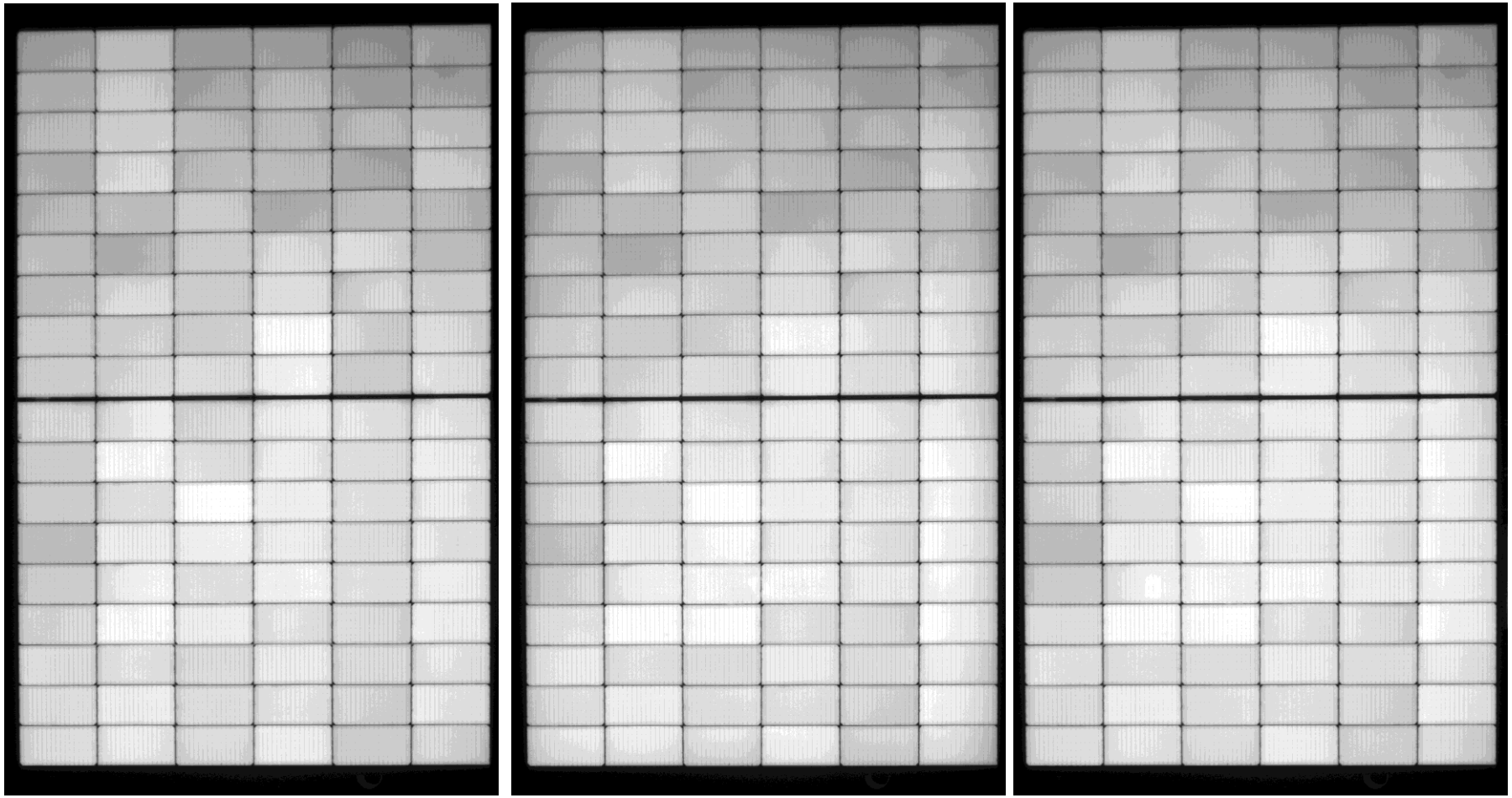
Results

Electroluminescence

- Manufacturer: Jinko
- Type: JKM440N-54HL4R-BDB
- CSP_SolOur_2_P05
  - EL image @ 1/10 I_{SC} = 1.4 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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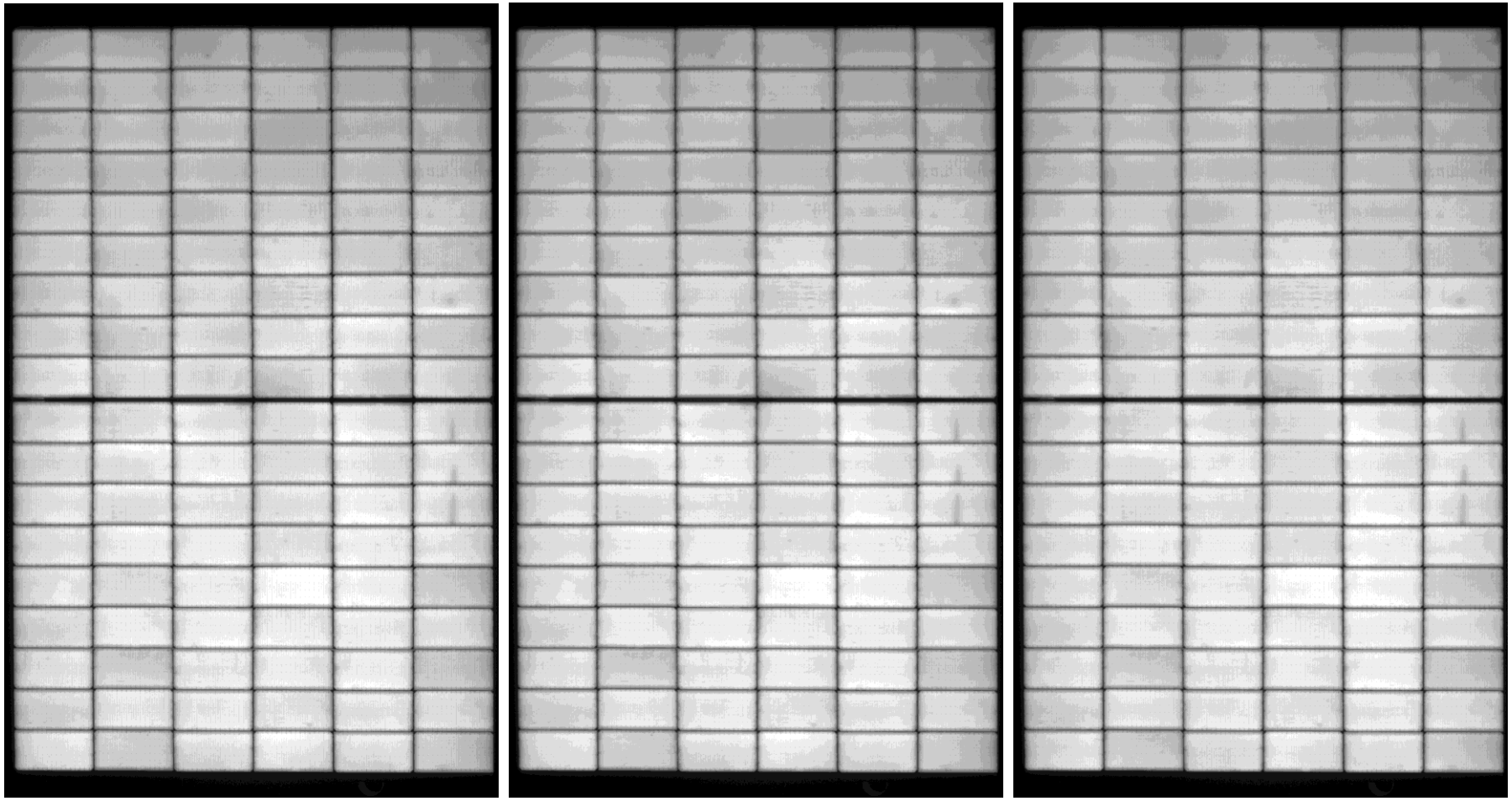
Results

Electroluminescence

- Manufacturer: Jinko
- Type: JKM440N-54HL4R-BDB
- CSP_SolOur_2_P06
  - EL image @ I_{SC} = 14.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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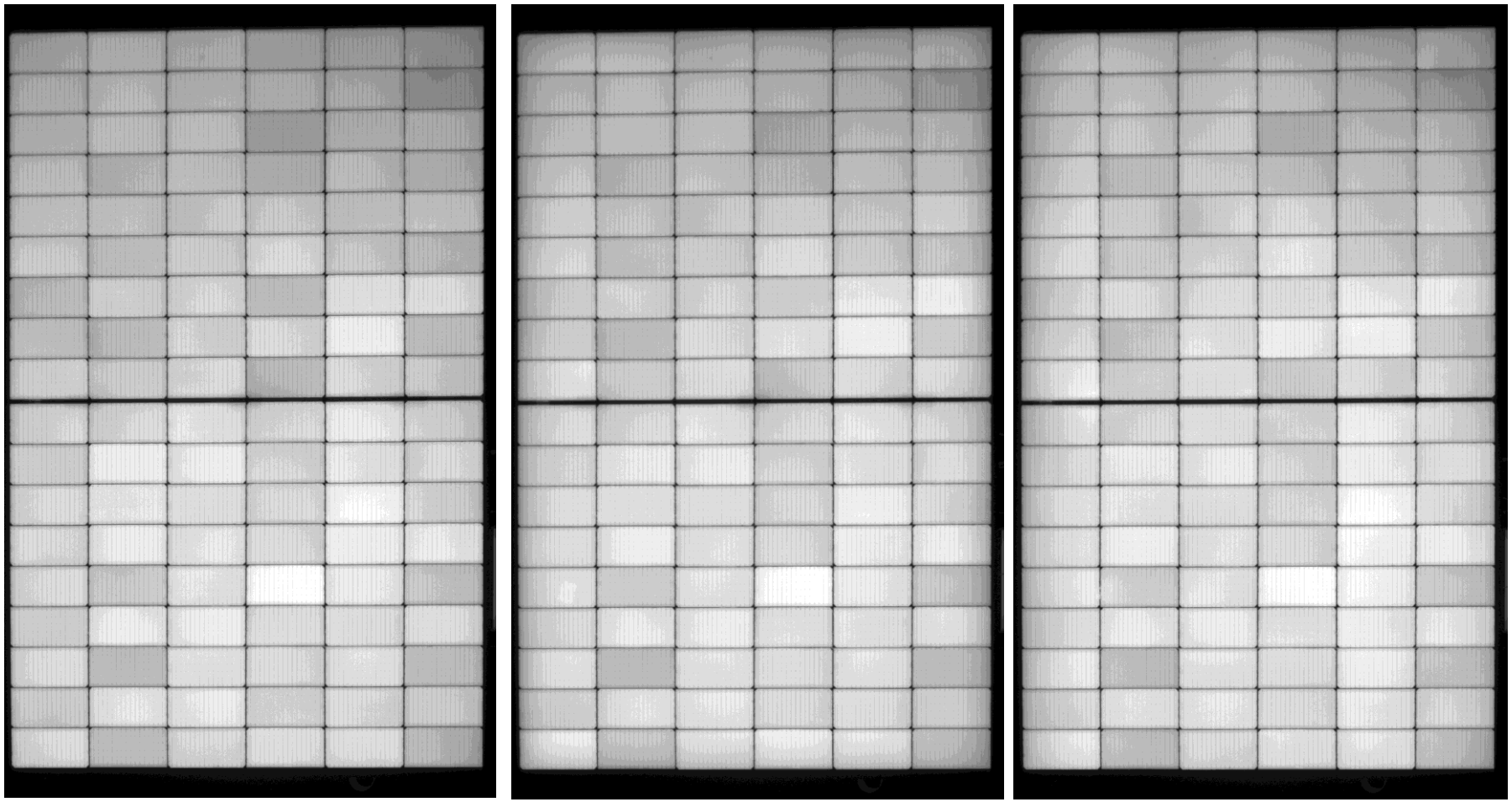
Results

Electroluminescence

- Manufacturer: Jinko
- Type: JKM440N-54HL4R-BDB
- CSP_SolOur_2_P06
  - EL image @ 1/10 I_{SC} = 1.4 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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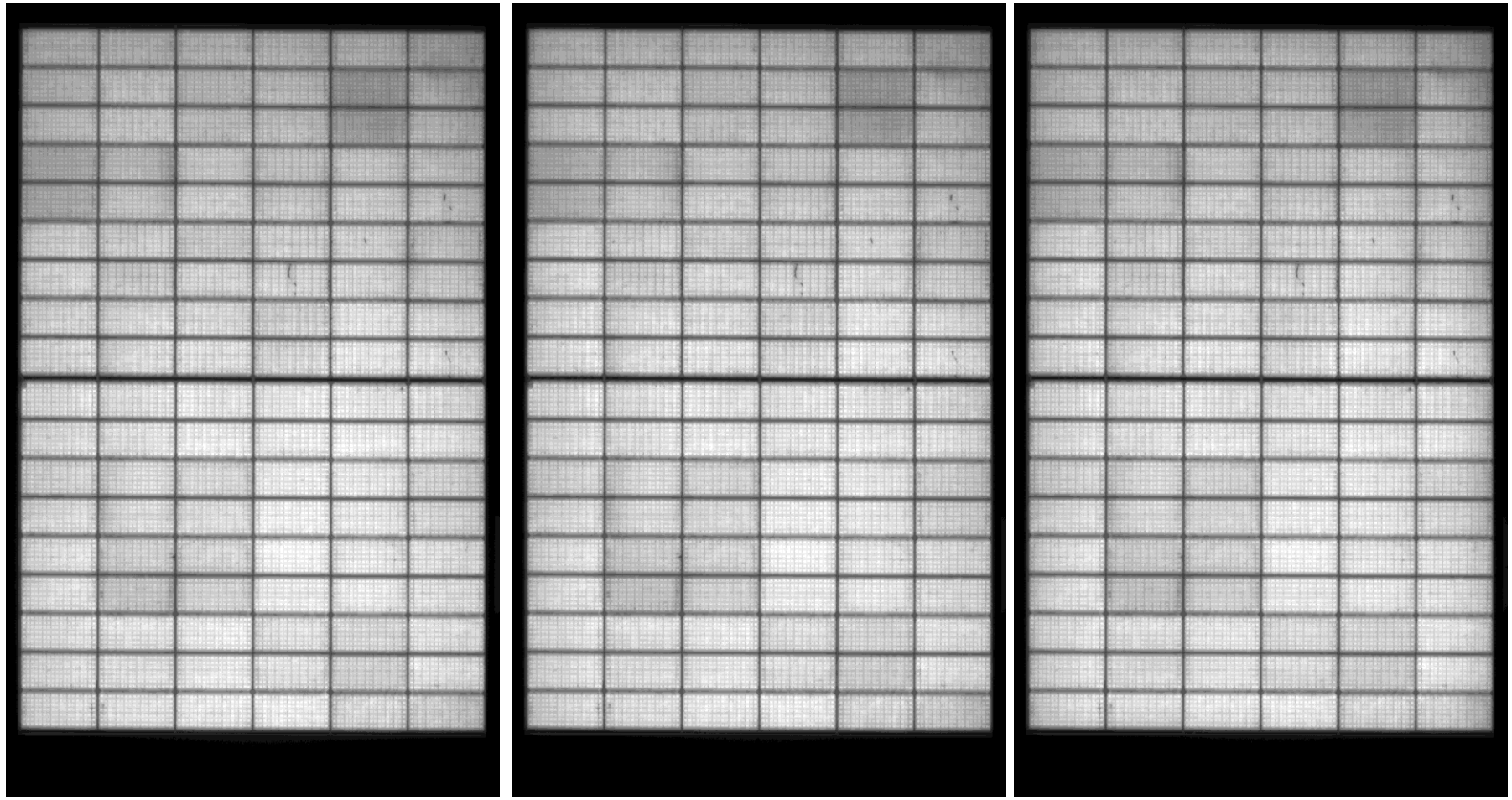
Results

Electroluminescence

- Manufacturer: Longi
- Type: LR5-54HTH_440M
- CSP_SolOur_2_P07
  - EL image @ I_{SC} = 14.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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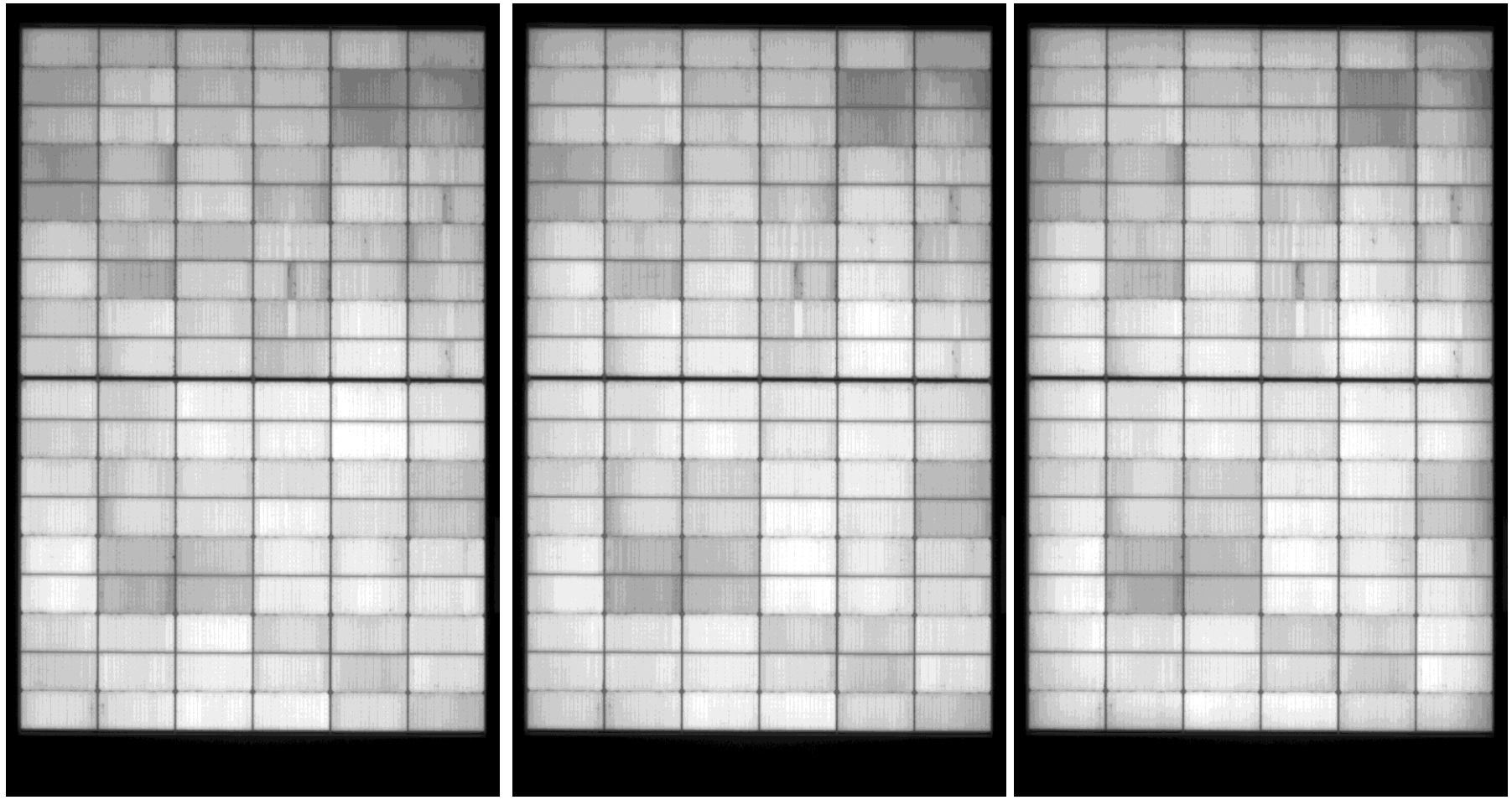
Results

Electroluminescence

- Manufacturer: Longi
- Type: LR5-54HTH_440M
- CSP_SolOur_2_P07
  - EL image @ 1/10 I_{SC} = 1.4 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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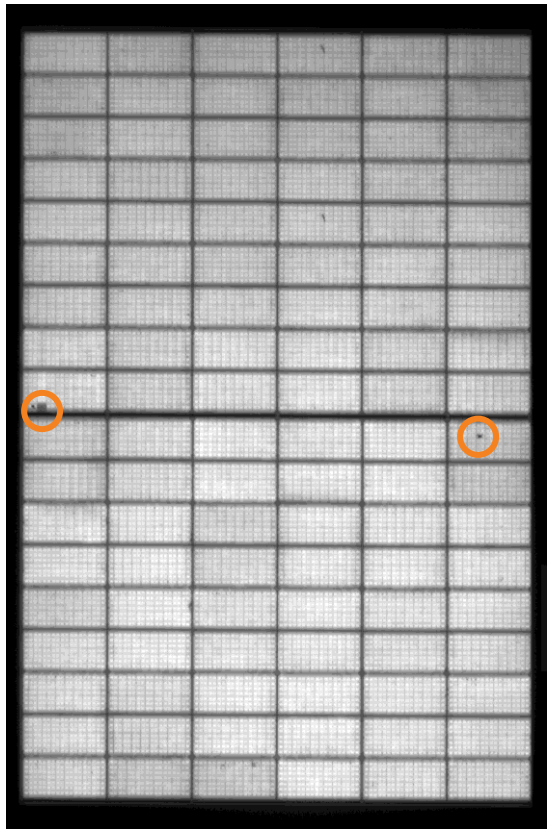
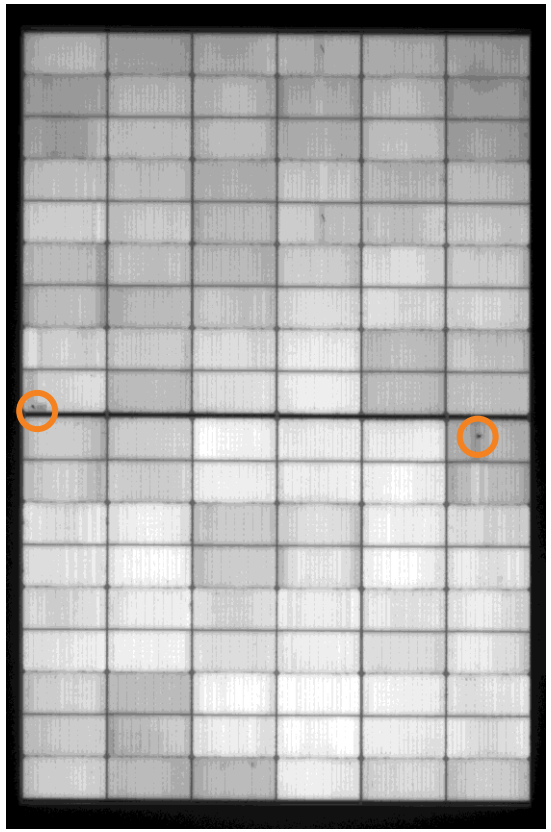
Results

Electroluminescence

- Manufacturer: Longi
- Type: LR5-54HTH_440M
- CSP_SolOur_2_P08
  - EL image
    - @ I_{SC} = 14.0 A
    - @ 1/10 I_{SC} = 1.4 A
  - Dark cell area and dark spots
    ➔**Excluded from the test**



Initial @I_{SC}



Initial @ 1/10 I_{SC}

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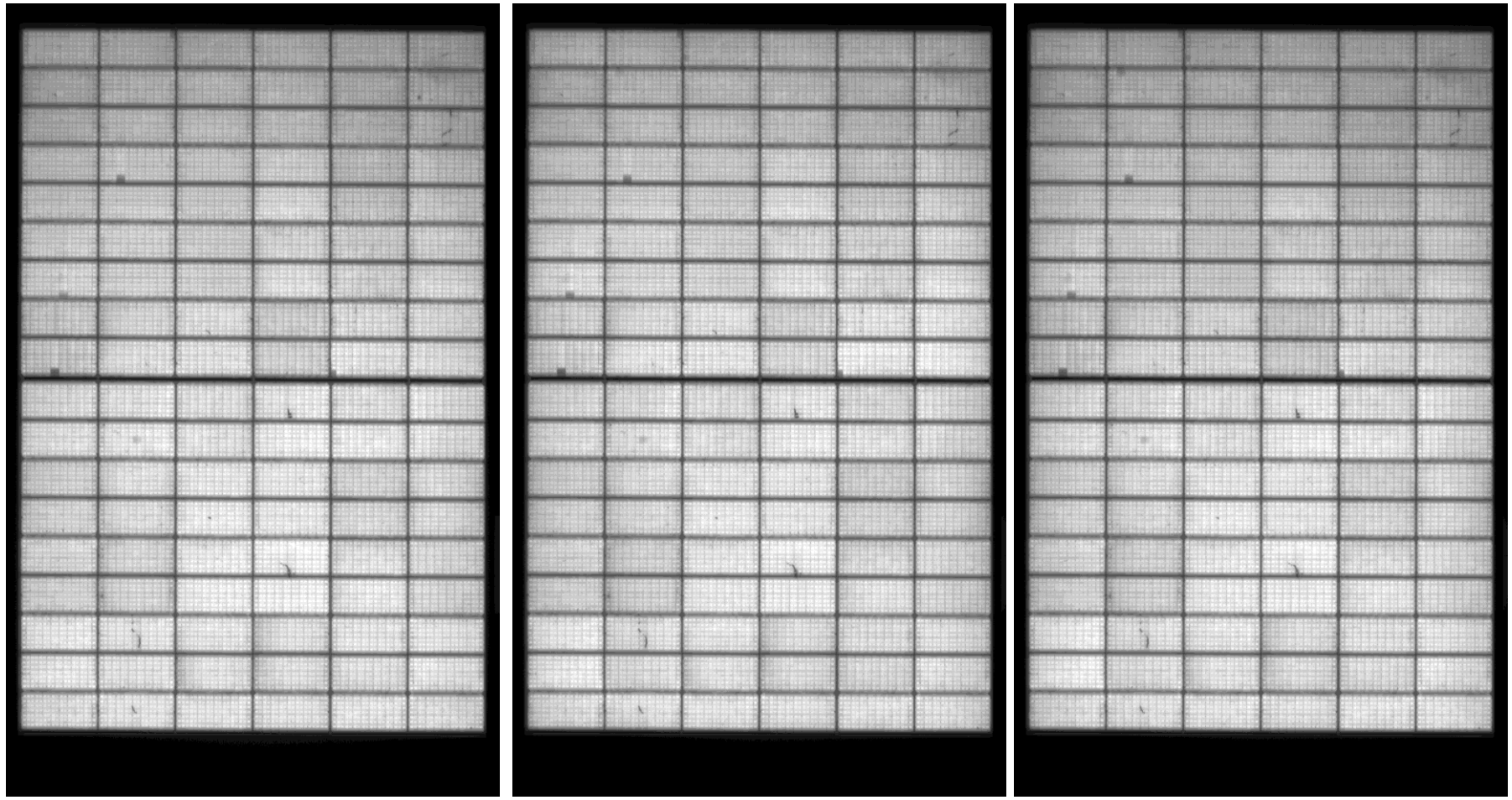
Results

Electroluminescence

- Manufacturer: Longi
- Type: LR5-54HTH_440M
- CSP_SolOur_2_P10
  - EL image @ I_{SC} = 14.0 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

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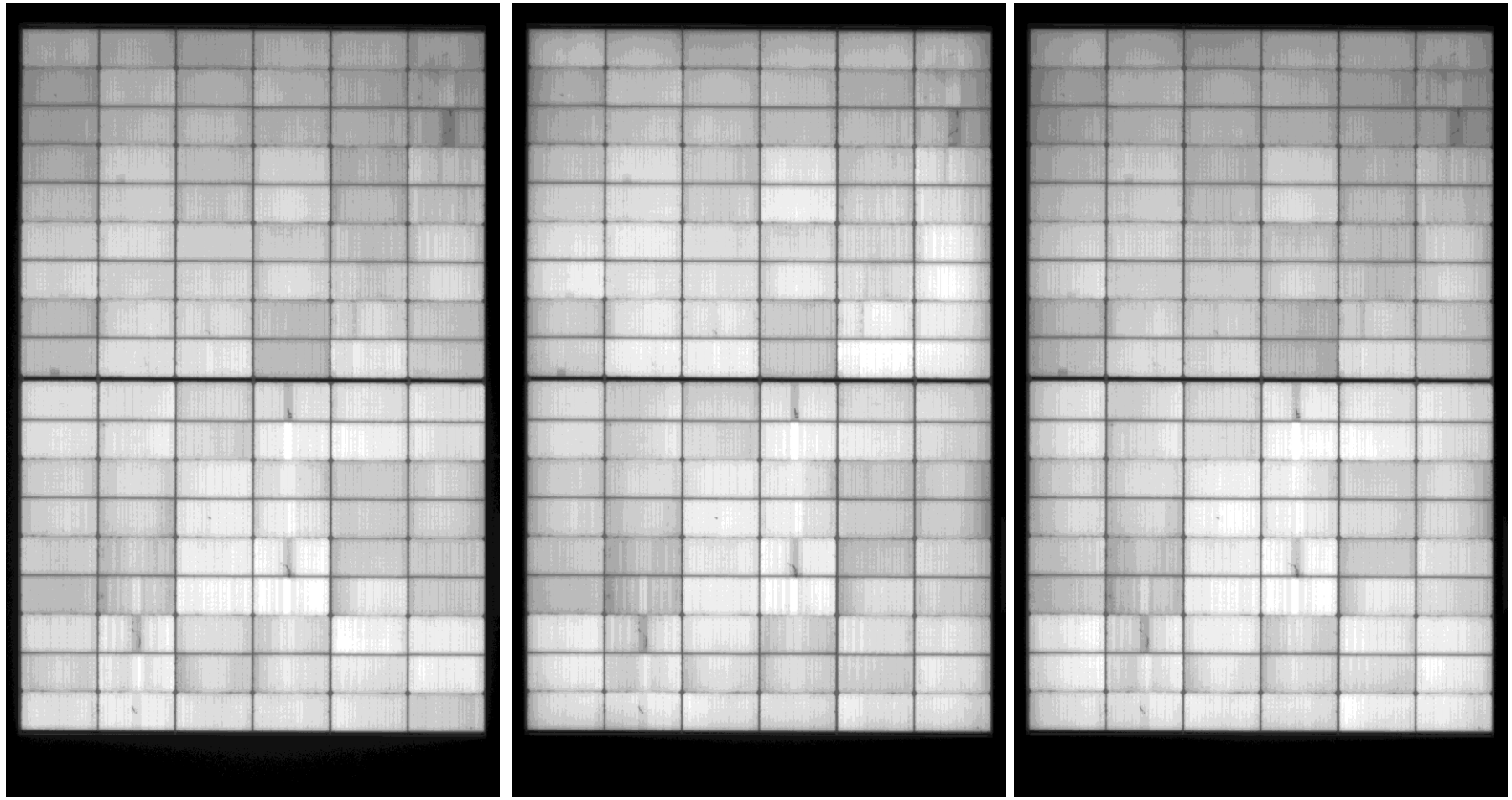
Results

Electroluminescence

- Manufacturer: Longi
- Type: LR5-54HTH_440M
- CSP_SolOur_2_P10
  - EL image @ 1/10 I_{SC} = 1.4 A
  - No significant changes detected like:
    - additional cracks
    - crack growth



initial

200 passes in direction of module length

200 passes perpendicular to module length

Confidential

Results

Performance measurement

- Manufacturer: TrinaSolar
- Type: TSM-500NEG18R.28

➔Slightly changed performance measurement values due to lowered cell temperature caused by cold water during cleaning drives

➔Stable performance characteristics after both cleaning runs

					STC measurement values							low light measurement values					
TestTimeDate	CellIDStr	Comment	Tcell	Tmonicell	Isc	Impp	Umpp	Pmpp	Uoc	FF		Isc	Impp	Umpp	Pmpp	Uoc	FF
			[°C]	[°C]	[A]	[A]	[V]	[W]	[V]	[%]		[A]	[A]	[V]	[W]	[V]	[%]
09.07.2025-09:21:24	CSP_SolOur_2_P01	initial	24,61	24,71	15,58	14,80	33,51	495,81	39,69	80,16		3,13	2,96	32,60	96,67	37,62	82,09
09.07.2025-13:57:39	CSP_SolOur_2_P01	200x setup 1	24,68	24,67	15,54	14,77	33,45	494,07	39,63	80,22		3,12	2,96	32,56	96,34	37,56	82,18
09.07.2025-14:52:20	CSP_SolOur_2_P01	200x setup 2	24,17	24,39	15,56	14,81	33,66	498,42	39,82	80,42		3,13	2,97	32,74	97,20	37,77	82,32
09.07.2025-09:55:52	CSP_SolOur_2_P02	initial	24,11	24,48	15,59	14,78	33,48	494,84	39,65	80,04		3,13	2,97	32,42	96,37	37,56	81,97
09.07.2025-11:50:37	CSP_SolOur_2_P09	initial	24,54	24,62	15,56	14,81	33,26	492,66	39,52	80,10		3,13	2,97	32,40	96,21	37,46	82,13
09.07.2025-14:03:24	CSP_SolOur_2_P09	200x setup 1	24,61	24,69	15,56	14,79	33,42	494,21	39,66	80,09		3,13	2,96	32,63	96,64	37,61	82,20
09.07.2025-14:38:52	CSP_SolOur_2_P09	200x setup 2	24,04	24,46	15,54	14,78	33,87	500,72	40,01	80,55		3,12	2,97	33,02	98,02	37,97	82,68

Note: The accuracy of the flash tests is affected by module temperature variations after cleaning drives with cold water and due to heating caused by solar radiation; Repeatability: 1 %

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Results

Performance measurement

- Manufacturer: JASolar
- Type: JAM60D41-500/LB

➔Stable performance characteristics after both cleaning runs

					STC measurement values							low light measurement values					
TestTimeDate	CellIDStr	Comment	Tcell	Tmonicell	Isc	Impp	Umpp	Pmpp	Uoc	FF		Isc	Impp	Umpp	Pmpp	Uoc	FF
			[°C]	[°C]	[A]	[A]	[V]	[W]	[V]	[%]		[A]	[A]	[V]	[W]	[V]	[%]
09.07.2025-10:35:11	CSP_SolOur_2_P03	initial	24,30	24,17	13,61	12,91	37,65	486,19	44,35	80,51		2,73	2,59	36,56	94,55	41,93	82,62
09.07.2025-15:34:52	CSP_SolOur_2_P03	200x setup 1	24,26	24,34	13,62	12,95	37,71	488,32	44,44	80,67		2,73	2,58	36,85	95,05	42,04	82,79
10.07.2025-07:14:10	CSP_SolOur_2_P03	200x setup 2	24,24	24,62	13,62	12,92	37,75	487,70	44,41	80,62		2,73	2,58	36,81	94,85	42,00	82,69
09.07.2025-10:48:39	CSP_SolOur_2_P04	initial	24,50	24,29	13,67	12,96	37,72	488,94	44,48	80,42		2,74	2,59	36,85	95,32	42,09	82,64
09.07.2025-15:28:57	CSP_SolOur_2_P04	200x setup 1	24,22	24,39	13,66	12,94	37,88	490,02	44,54	80,53		2,74	2,58	37,00	95,40	42,16	82,61
10.07.2025-07:22:25	CSP_SolOur_2_P04	200x setup 2	24,35	24,52	13,66	12,96	37,77	489,64	44,53	80,48		2,74	2,59	36,82	95,35	42,14	82,55

Note: The accuracy of the flash tests is affected by module temperature variations after cleaning drives with cold water and due to heating caused by solar radiation; Repeatability: 1 %

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Results

Performance measurement

- Manufacturer: Jinko
- Type: JKM440N-54HL4R-BDB

➔Slightly changed performance measurement values due to increased cell temperature caused by high sun irradiation on second test day

➔Stable performance characteristics after both cleaning runs

					STC measurement values							low light measurement values					
TestTimeDate	CellIDStr	Comment	Tcell	Tmonicell	Isc	Impp	Umpp	Pmpp	Uoc	FF		Isc	Impp	Umpp	Pmpp	Uoc	FF
			[°C]	[°C]	[A]	[A]	[V]	[W]	[V]	[%]		[A]	[A]	[V]	[W]	[V]	[%]
09.07.2025-11:23:22	CSP_SolOur_2_P05	initial	24,30	24,56	13,68	12,96	33,49	434,23	39,73	79,87		2,74	2,59	32,64	84,70	37,65	81,99
10.07.2025-12:37:03	CSP_SolOur_2_P05	200x setup 1	28,48	24,59	13,69	12,98	33,53	435,10	39,85	79,76		2,75	2,60	32,63	84,86	37,75	81,89
10.07.2025-14:18:34	CSP_SolOur_2_P05	200x setup 2	30,01	24,55	13,67	12,94	33,53	433,82	39,83	79,66		2,74	2,60	32,57	84,62	37,71	81,80
09.07.2025-11:34:06	CSP_SolOur_2_P06	initial	24,40	24,59	13,65	12,94	33,55	434,23	39,77	80,00		2,74	2,59	32,69	84,52	37,68	81,92
10.07.2025-12:30:09	CSP_SolOur_2_P06	200x setup 1	31,63	24,53	13,69	12,96	33,43	433,37	39,80	79,55		2,75	2,59	32,50	84,30	37,65	81,57
10.07.2025-14:12:09	CSP_SolOur_2_P06	200x setup 2	36,19	24,51	13,66	12,93	33,50	433,28	39,99	79,30		2,74	2,59	32,52	84,26	37,79	81,34

Note: The accuracy of the flash tests is affected by module temperature variations after cleaning drives with cold water and due to heating caused by solar radiation; Repeatability: 1 %

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Results

Performance measurement

- Manufacturer: Longi
- Type: LR5-54HTH_440M

➔Slightly changed performance measurement values due to increased cell temperature caused by high sun irradiation on second test day

➔Stable performance characteristics after both cleaning runs

					STC measurement values							low light measurement values					
TestTimeDate	CellIDStr	Comment	Tcell	Tmonicell	Isc	Impp	Umpp	Pmpp	Uoc	FF		Isc	Impp	Umpp	Pmpp	Uoc	FF
			[°C]	[°C]	[A]	[A]	[V]	[W]	[V]	[%]		[A]	[A]	[V]	[W]	[V]	[%]
09.07.2025-12:04:25	CSP_SolOur_2_P07	initial	24,46	24,59	13,70	12,99	33,20	431,17	39,37	79,93		2,74	2,60	32,14	83,63	37,25	81,97
10.07.2025-11:04:30	CSP_SolOur_2_P07	200x setup 1	26,86	24,27	13,73	13,02	33,14	431,44	39,37	79,83		2,75	2,62	32,21	84,36	37,26	82,37
10.07.2025-11:36:16	CSP_SolOur_2_P07	200x setup 2	31,54	24,47	13,71	12,99	33,04	429,22	39,41	79,46		2,75	2,62	32,05	83,90	37,24	82,06
09.07.2025-12:14:05	CSP_SolOur_2_P08	initial	24,39	24,56	13,72	13,00	33,05	429,74	39,35	79,62		2,74	2,61	32,01	83,50	37,20	81,79
09.07.2025-12:21:30	CSP_SolOur_2_P10	initial	24,62	24,58	13,71	13,00	33,15	431,02	39,39	79,82		2,74	2,62	32,07	83,99	37,26	82,31
10.07.2025-10:58:57	CSP_SolOur_2_P10	200x setup 1	31,23	24,24	13,74	13,01	32,97	429,02	39,37	79,33		2,75	2,62	32,10	83,96	37,21	82,12
10.07.2025-11:42:20	CSP_SolOur_2_P10	200x setup 2	30,14	24,52	13,72	13,02	33,14	431,40	39,50	79,62		2,75	2,62	32,24	84,34	37,35	82,27

Note: The accuracy of the flash tests is affected by module temperature variations after cleaning drives with cold water and due to heating caused by solar radiation; Repeatability: 1 %

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Summary

- The influence of the cleaning robot during operation in terms of mechanical and electrical stability of the investigated PV modules is not harmful to the module performance or the electrical-mechanical integrity with the applied test methods.

- The test drives of 400 passes over the modules (200 in direction of the module length and 200 perpendicular to it) show no significant changes in electroluminescence images and power measurement (considering the progressively increased module temperature and the associated increased measurement uncertainty).

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