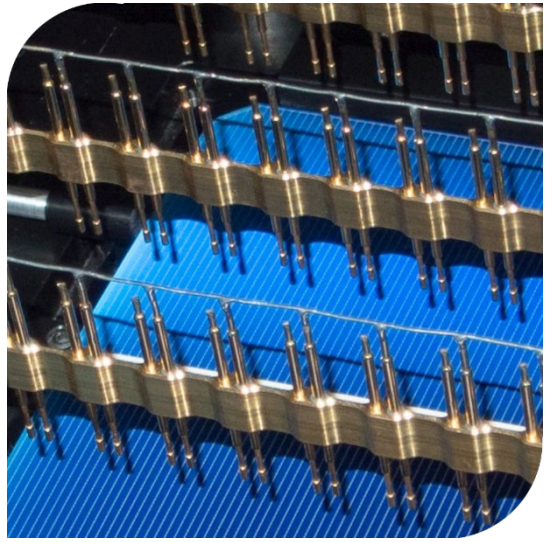
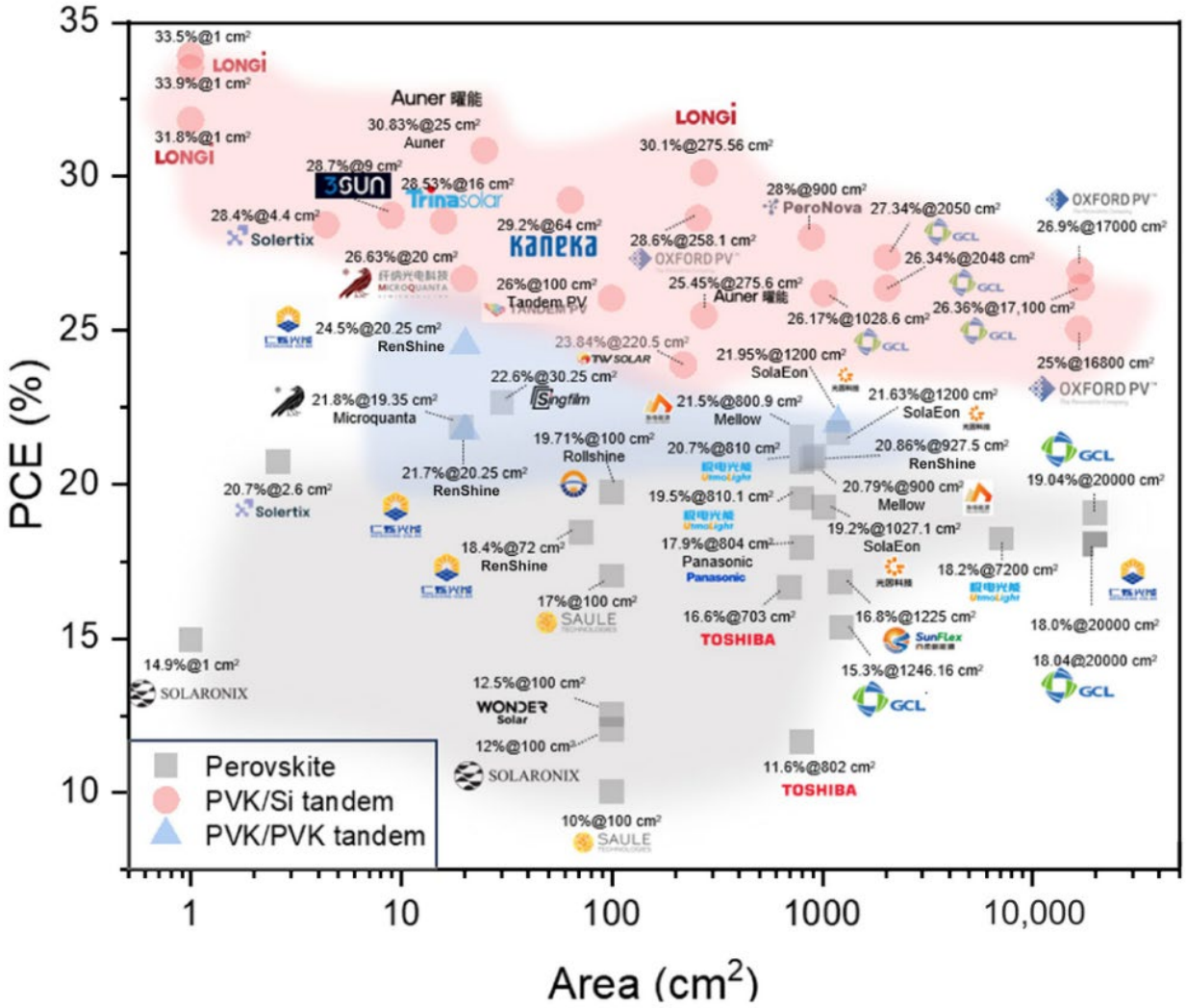



Back-contact technology for tandems

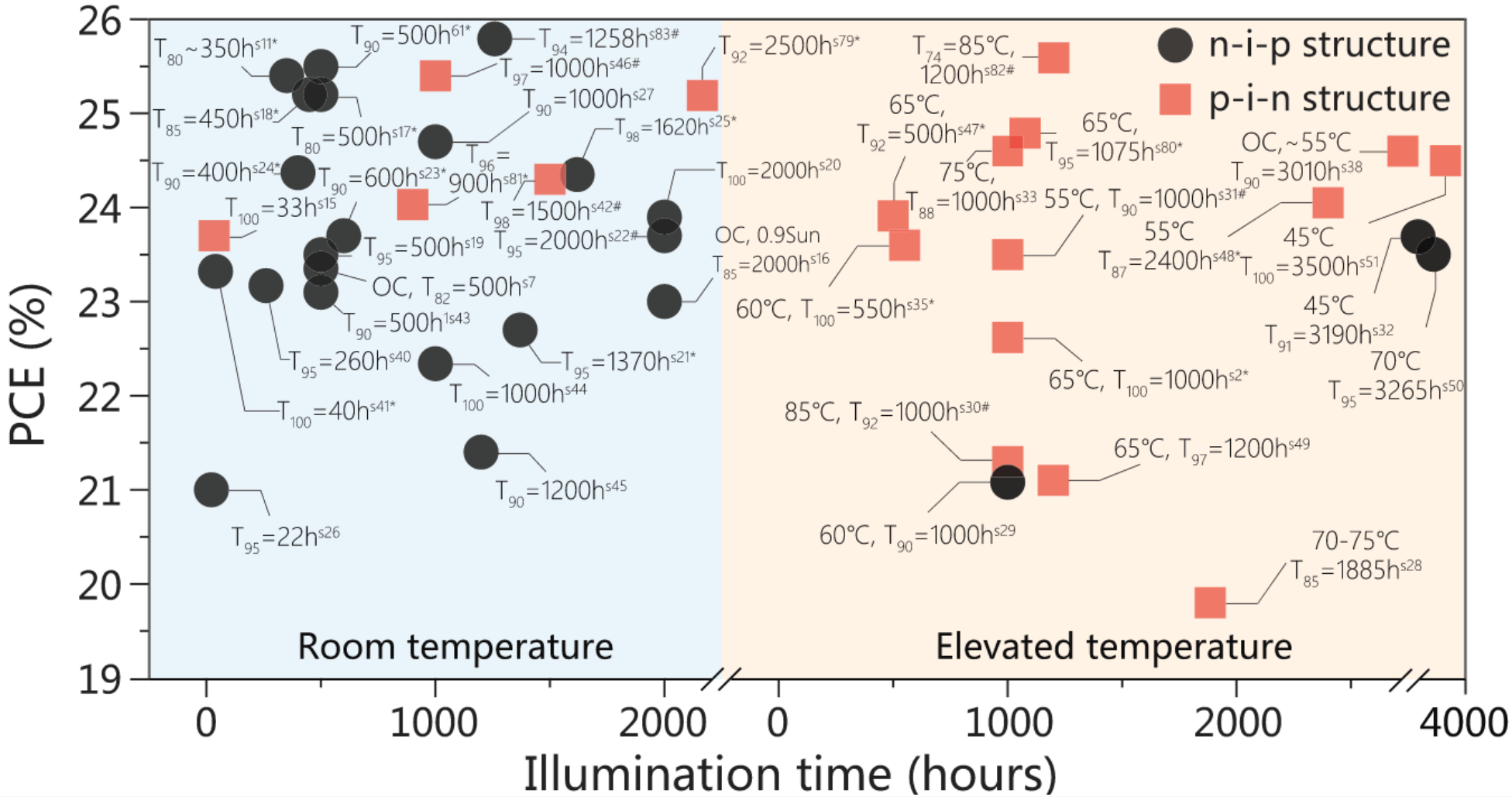
Daniel Tune

ISC research
for a sunny future

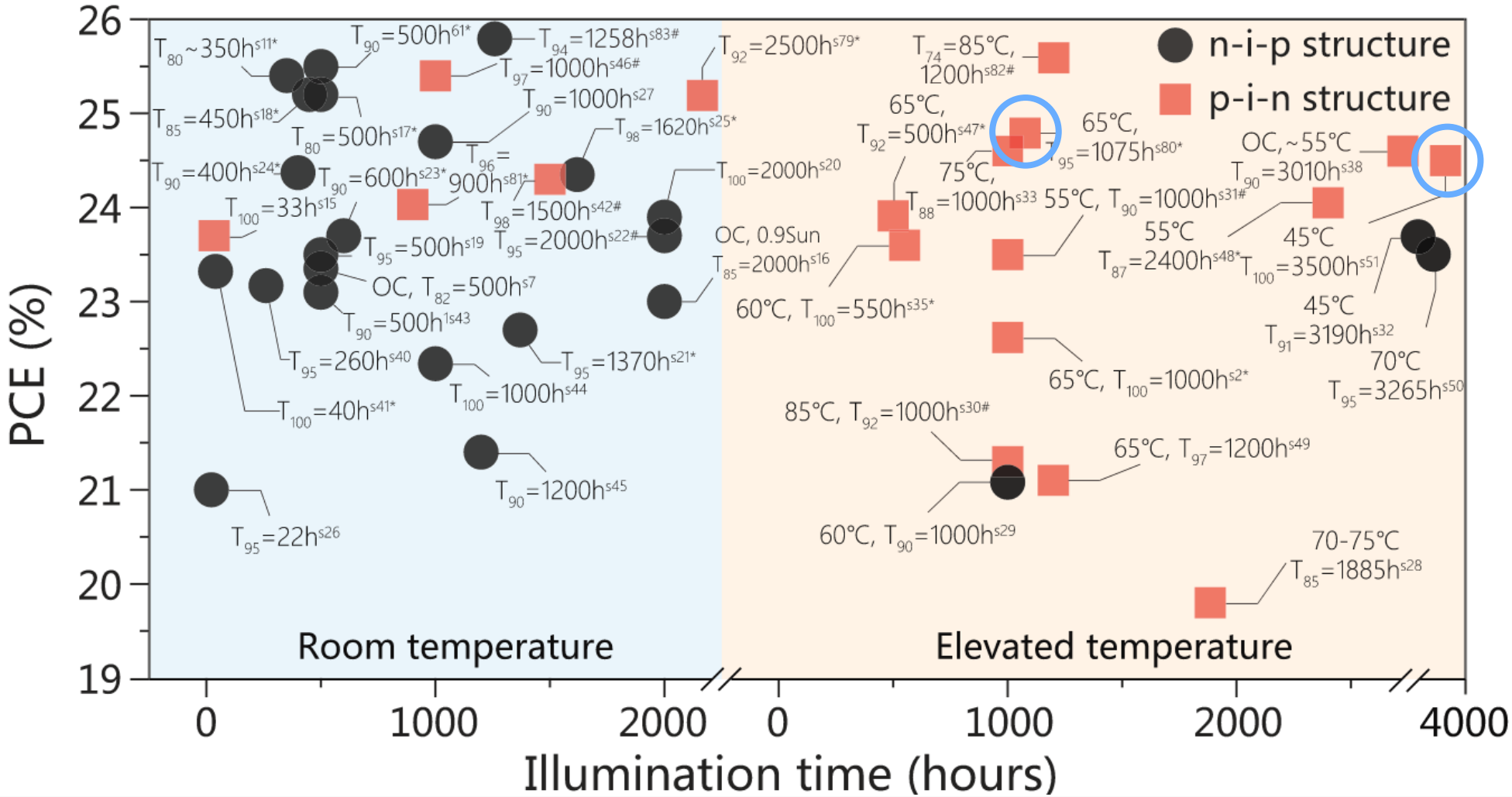
Overview - tandem efficiencies



Background – Perovskite stability



Background – Perovskite stability



A benchmark reliability test for tandems?

- How to measure and compare stability like we do efficiency?
- What should be the benchmark test?
- “Consensus statement on stability and reliability testing of perovskite-silicon tandems”
- ‘LeTID’ test – 1 Sun, 85°C, T_{80}, rigorous reporting

Daniel Tune[1], Ivona Kafedjiska[2], Erkan Aydin[3], Delfina Munoz[4], Mark Khenkin[2], Ulrich Paetzold[5,6], Quentin Jeangros[7], Solenn Berson[4], Carolin Ulbrich[2], Kaining Ding[8], Ivan Gordon[9,10,11], Juliane Borchert[12,13,14], Stefan Glunz[12], Michael Saliba[15], Bahram Abdollahi Nejand Asl[16], Stephan Abermann[17], Urs Aeberhard[18], Tom Aernouts[9,19,20], Steve Albrecht[2], Thomas G. Allen[21], Antonio Cabas Vidani[18], Pietro Caprioglio[22], Chris Case[23], Bin Chen[24], Gianluca Coletti[25], Stephane Cros[4], Ed Crossland[23], Stefaan De Wolf[26], Aldo Di Carlo[27,28], Barrit Dounya[29], Ewan Dunlop[30], Giles Eperon[31], Sascha Esefelder[32], Lingyi Fang[33,34], Fabian Fertig[22], Fan Fu[35], Gorkem Gunbas[36,37], Andreas Halm[1], Charlie Hasselbrink[38], Jens Hauch[39], Bo He[40], Martin Hermle[12], Anita Ho-Baillie[41,42], Yi Hou[43,44], Jinsong Huang[45], Marko Jost[46], Eugene Katz[47], Hans Köbler[22], Marcel König[16], Lars Korte[2], Anurag Krishna[9], Joel Li[48], Nengxu Li[43,44], Monica Lira Cantu[49], Jiang Liu[50], Adam Lorenz[51], Andrei Los[52], Mike McGeehee[53], Blagovest Mihaylov[30], Harald Muellejans[30], Peter Pasmans[54], Robby Peibst[55,56], Ralf Preu[12], Hari Radhakrishnan[9], Klaus Ramspeck[57], Stefan Roest[54], Nick Rolston[58], Edward Sargent[24], Rutger Schlatmann[2,59], Joel Smith[22], Bernd Stannowski[2], Martin Stolterfoht[60], Hairen Tan[61], Marko Topic[46], Kristofer Tvingstedt[22], Azhar Fakhar Uddin[22], Esma Ugur[62,63], Christian Wolff[64], Selcuk Yerci[36,65], Eugenia Zugasti[66]

A benchmark reliability test for tandems?

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48 Cosmos Innovation, Singapore
49 Catalan Institute of Nanoscience and Nanotechnology (ICN2), Campus UAB Edifici ICN2, Bellaterra (Barcelona), Spain
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A benchmark reliability test for tandems?

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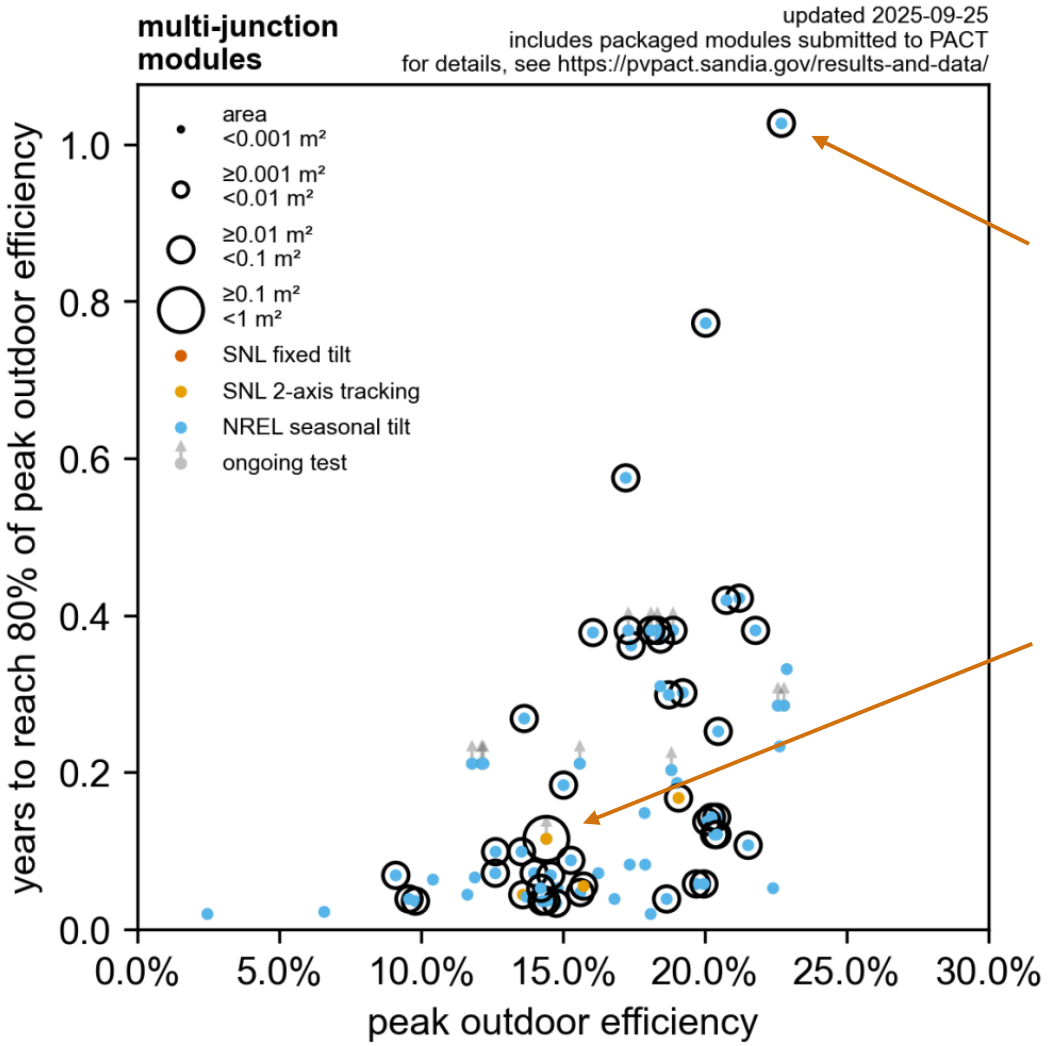
Outdoor testing at PACT

“Years to fall to 80% of original efficiency for 3 consecutive days”

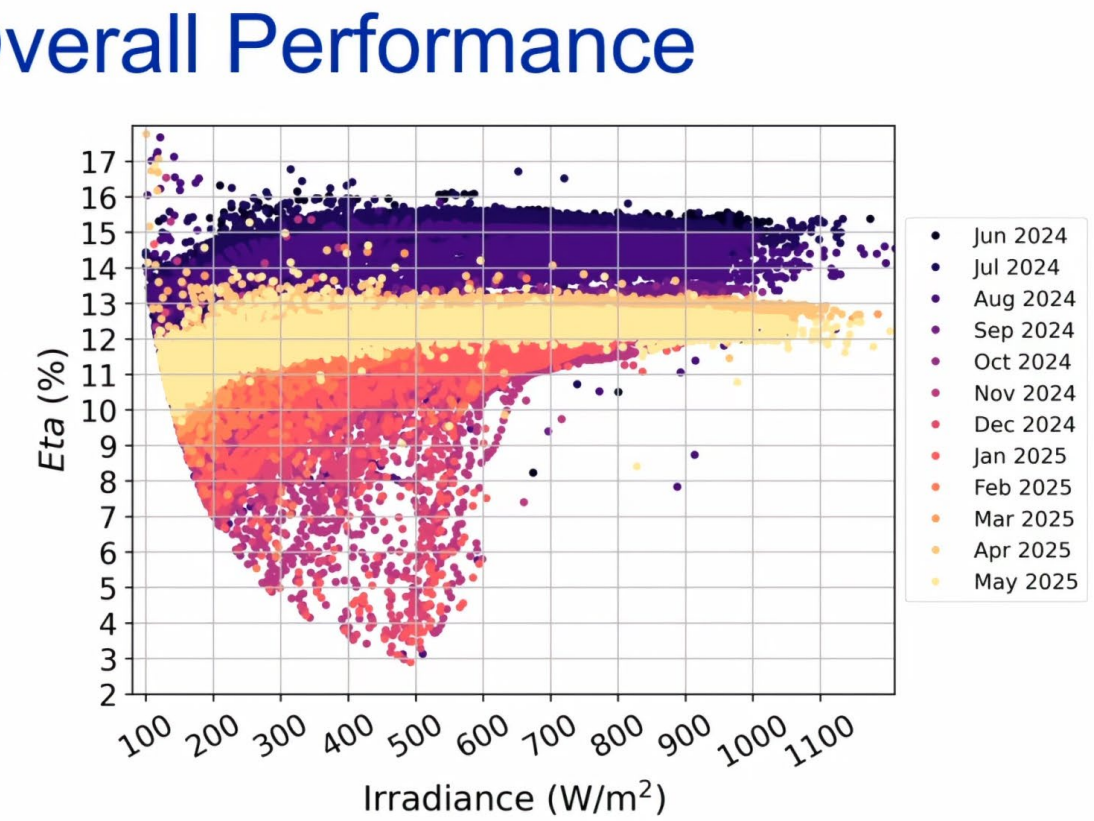


NREL site, seasonal tilt, 1-10 cm²

Sandia site, 2-axis tracking, 10 cm² - 1 m² (ongoing test)

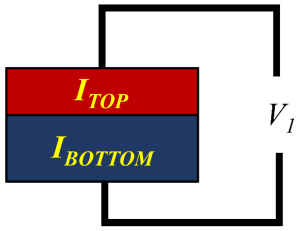
Outdoor testing results of SJ perovskite modules

- **Perovskites perform worse in colder months with low daily irradiance**
- Compare silicon which performs better in cold
- Opposite temperature coefficients
- Bad for e.g., Germany

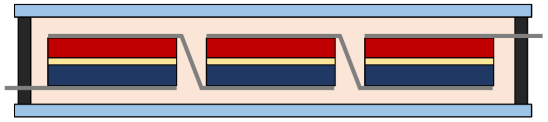


Tandem terminal configurations

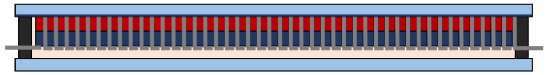
2-terminal (2T) tandems



perovskite – silicon (HJT or TOPCon)



perovskite – perovskite

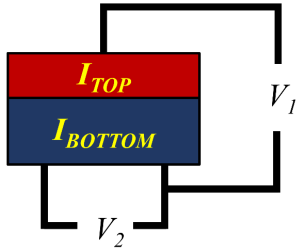


$I_{top} = I_{bottom}$

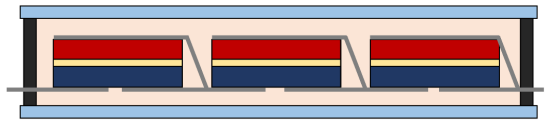
$V_1 = V_{top} + V_{bottom}$

- ✓ Highest STC efficiency
- ✓ Pero-Si drop-in replacement for silicon
- ✓ Pero-pero lowest cost
- ✗ Current-mismatch = lower annual yield

3-terminal (3T) tandems



perovskite – silicon (XBC back contact)

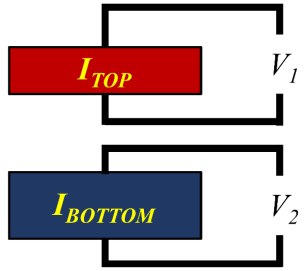


$I_{top} \neq I_{bottom}$

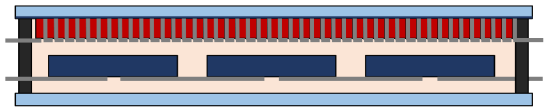
$V_{top} = n \times V_{bottom}$

- ✓ High annual yield
- ✓ Excellent bifaciality
- ✓ Similar manufacture to silicon modules
- ✗ String end losses depending on layout

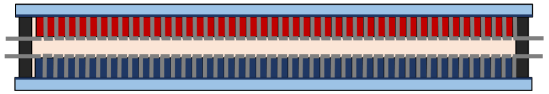
4-terminal (4T) tandems



perovskite – silicon (XBC back contact)



perovskite – perovskite / perovskite – other



$I_{top} \neq I_{bottom}$

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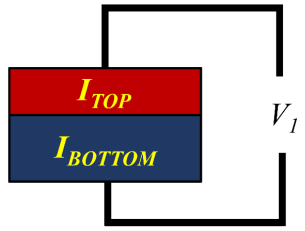
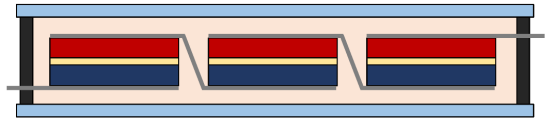
- ✓ Pero-glass drop-in replacement for glass
- ✗ Higher costs if power electronics used

Tandem terminal configurations

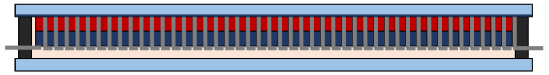
2-terminal (2T) tandems



perovskite – silicon (HJT or TOPCon)



perovskite – perovskite



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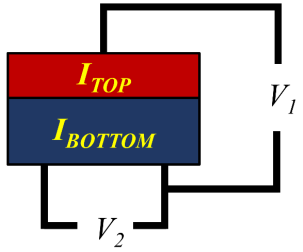
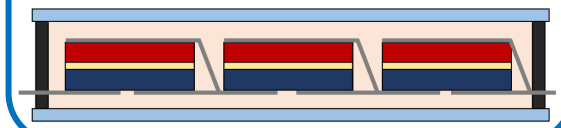
3-terminal (3T) tandems



perovskite – silicon (XBC back contact)



$I_{top} \neq I_{bottom}$
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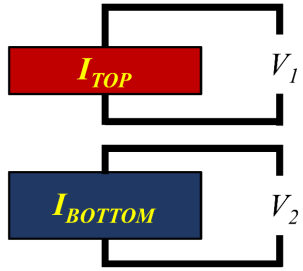
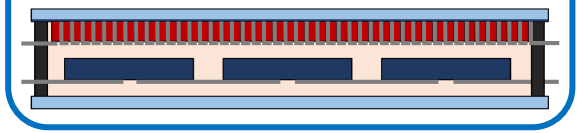
- ✓ Similar manufacture to silicon modules
- ✗ String end losses depending on layout

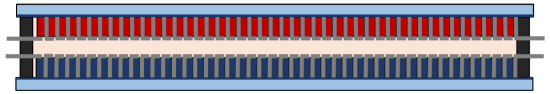
4-terminal (4T) tandems



perovskite – silicon (XBC back contact)



perovskite – perovskite / perovskite – other



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- ✓ Highest annual yield
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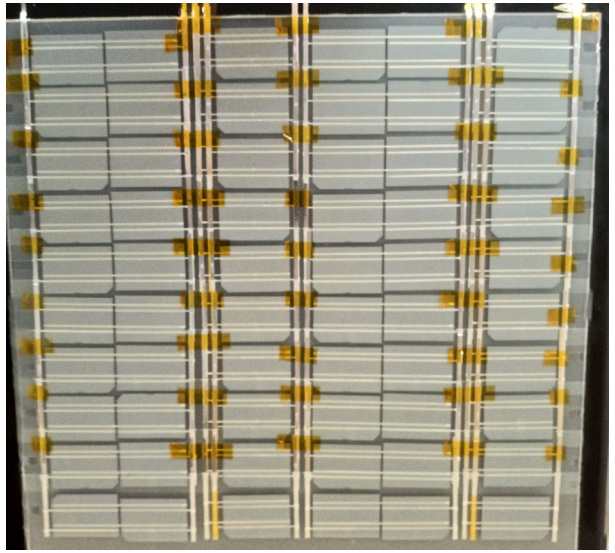
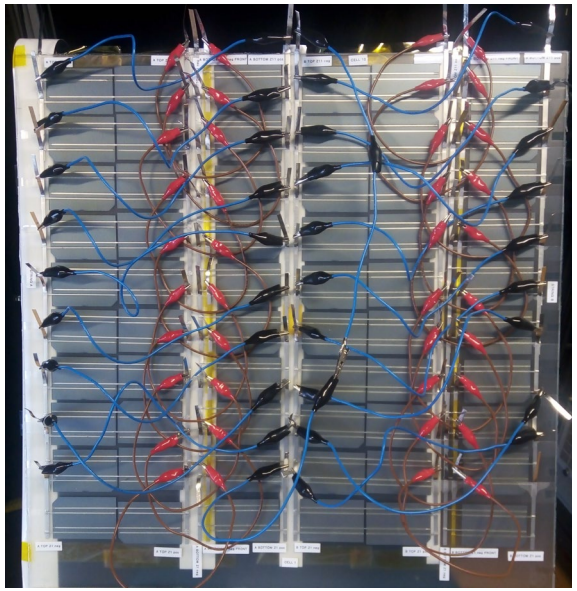
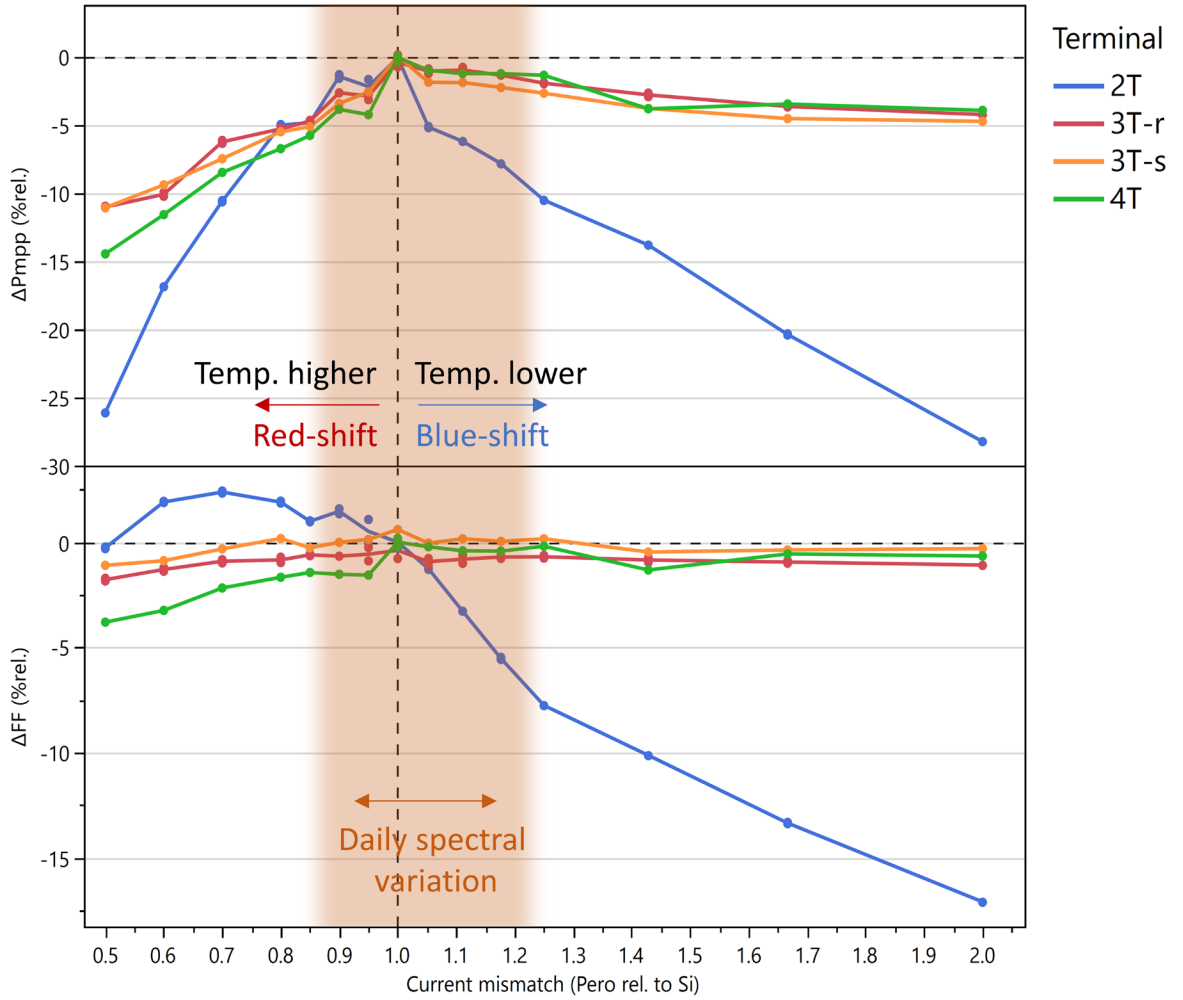
- ✓ Pero-glass drop-in replacement for glass
- ✗ Higher costs if power electronics used

Current mismatch vs. terminal configuration

- Simulation module using 3T Zebra IBC cells
- Fully reconfigurable into 2T/3T/4T
- Silicon only - no perovskite involved!

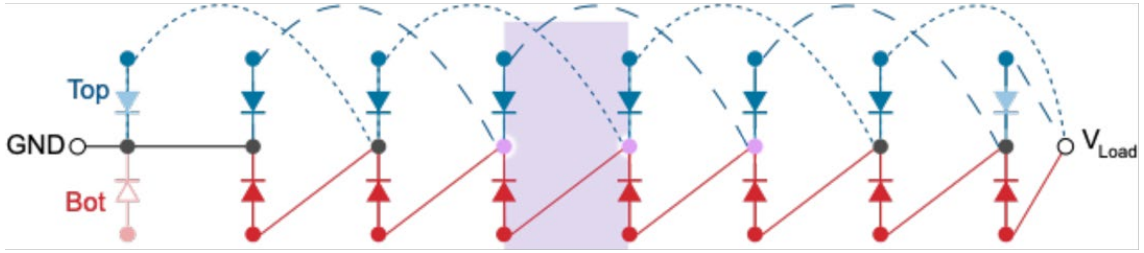




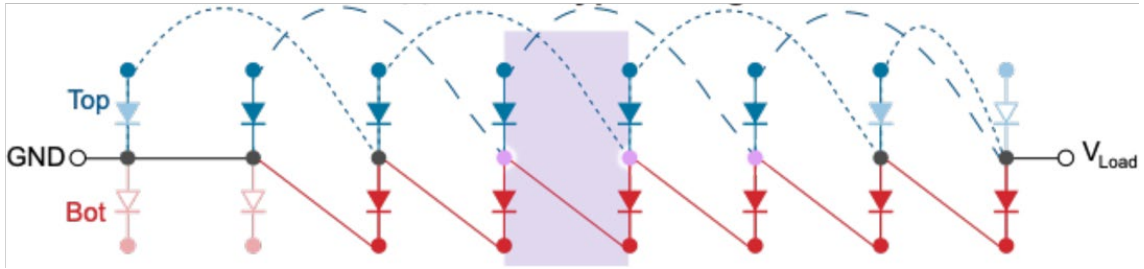


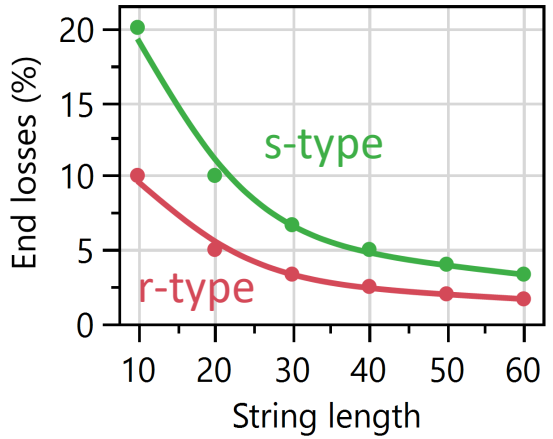
Industrial stringing of 3T cells

3T module in 2:1 voltage-matched r-type strings



3T module in 2:1 voltage-matched s-type strings





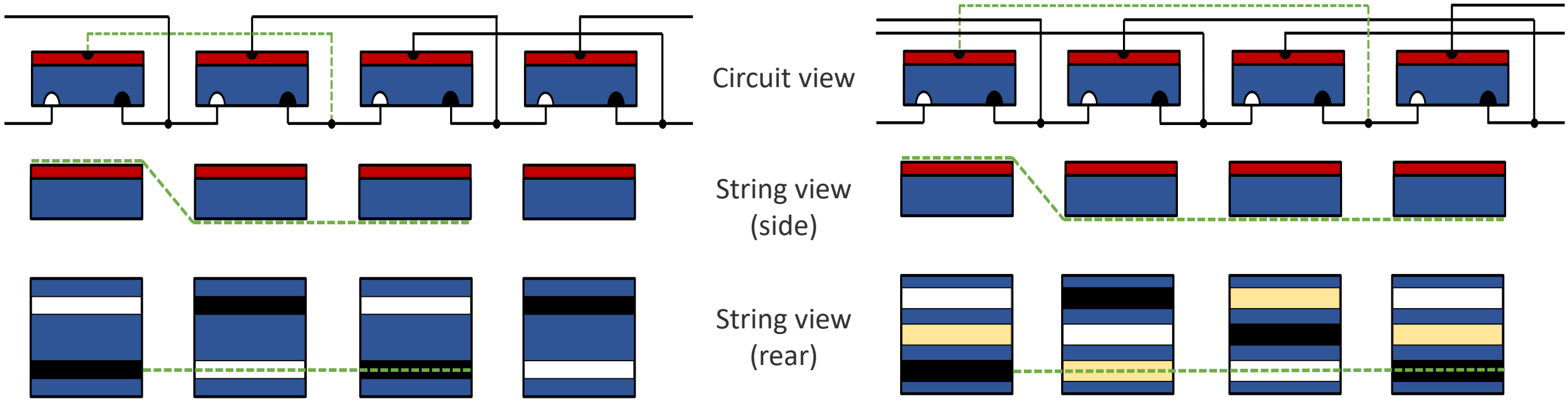
Longer strings = less losses

McMahon et al. (2021) IEEE J. Photovoltaics

Industrial stringing of 3T cells

r-type
(top/r/nuIBC)

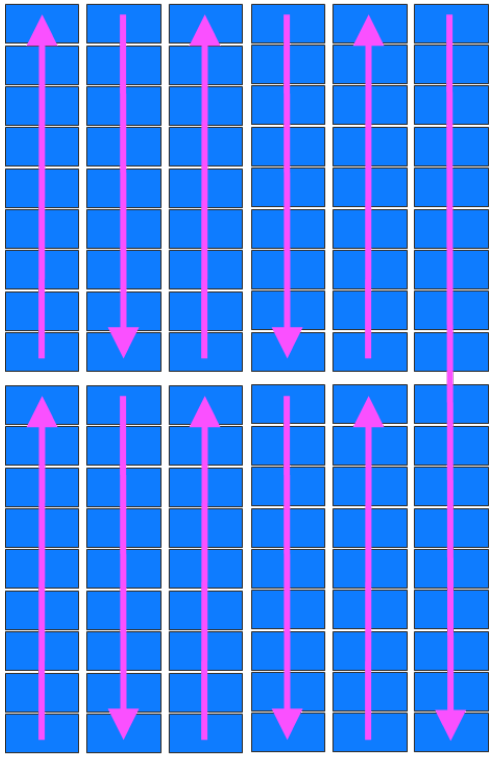
s-type
(top/s/nbIBC)



Industrial ribbon/wire stringing of ***r-type*** 3T strings is achieved by extending the existing bottom cell rear(+) busbar to rear(-) busbar connector over to the front side of the top cell that is next in the string

Industrial ribbon/wire stringing of ***s-type*** 3T strings instead requires the implementation of a floating third ‘busbar’ (shown here in yellow) that is isolated from the rest of the bottom cell

3T string end losses in the module



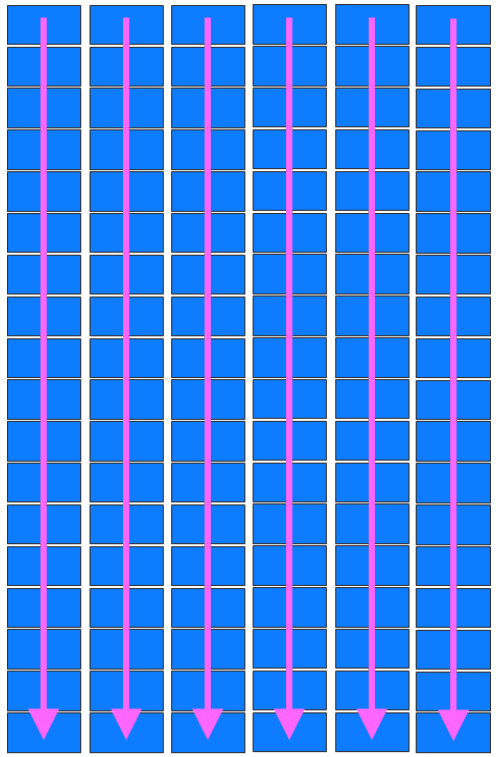
Voltage ~ 130 V

Classical long string approach

Cells
108 x M10 half-cell
(182 mm x 91 mm)

End losses
r-type: 1/108 = **0.93%$_{rel.}$**
s-type: 2/108 = 1.85%$_{rel.}$

Circuits per cell gap
r-type: 2
s-type: 3



Voltage ~ 20 V

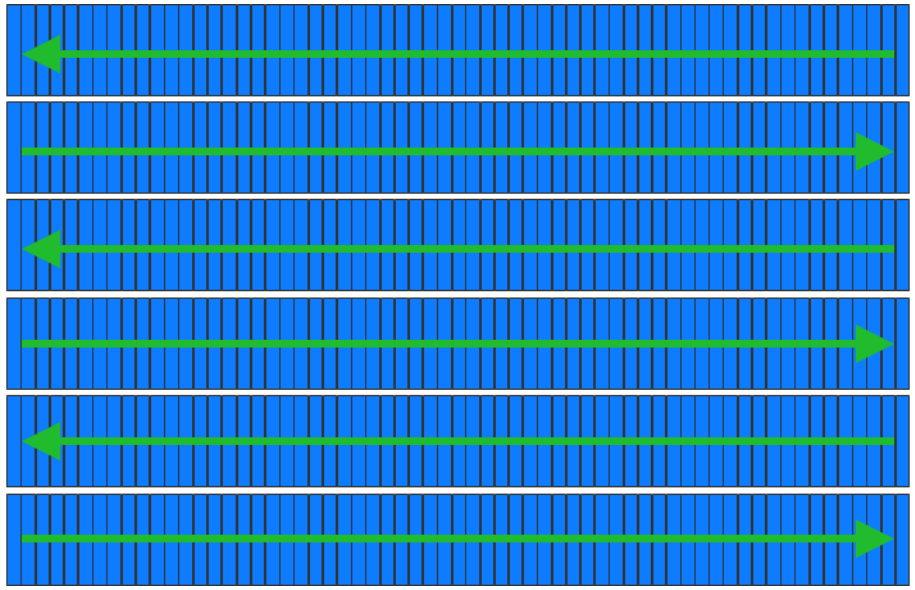
All parallel strings approach

Cells
108 x M10 half-cell
(182 cm x 91 cm)

End losses
r-type: 1/18 = **5.55%$_{rel.}$**
s-type: 2/18 = 11.1%$_{rel.}$

Circuits per cell gap
r-type: 2
s-type: 3

3T string end losses in the module

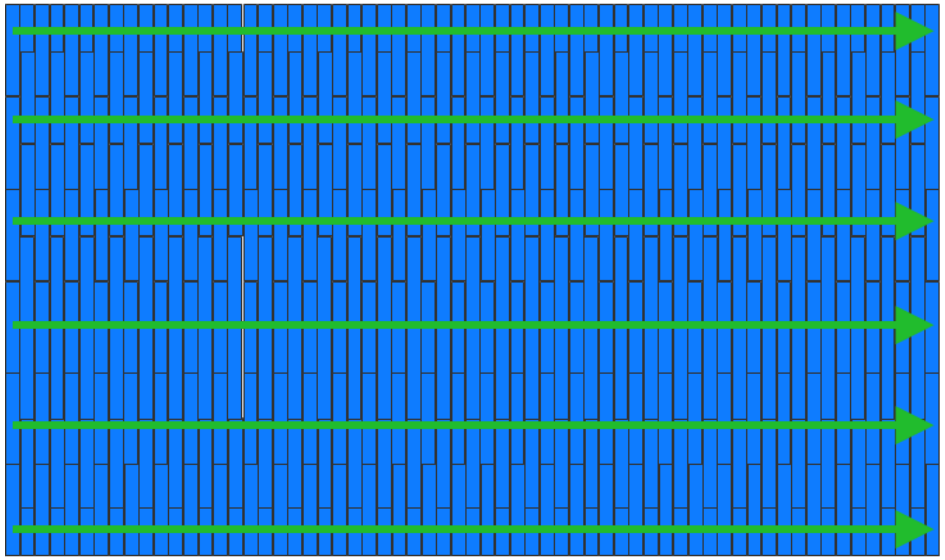


Classical shingling approach

Cells
378 x M10 1/7th shingles
(182 mm x 26 mm)

End losses
r-type: 1/378 = **0.26%$_{rel.}$**
s-type: 2/378 = 0.52%$_{rel.}$

Voltage ~ 450 V



Matrix shingling approach

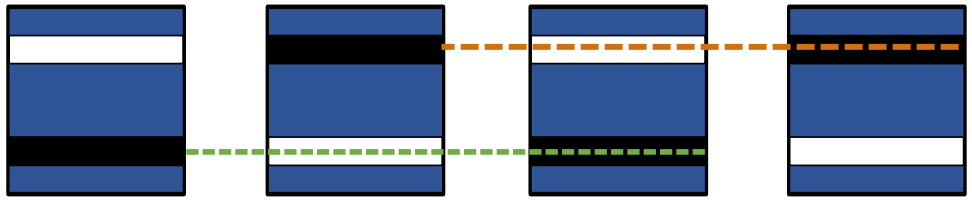
Cells
378 x M10 1/7th shingles
(182 mm x 26 mm)

End losses
r-type: 1/63 = **1.59%$_{rel.}$**
s-type: 2/63 = 3.18%$_{rel.}$

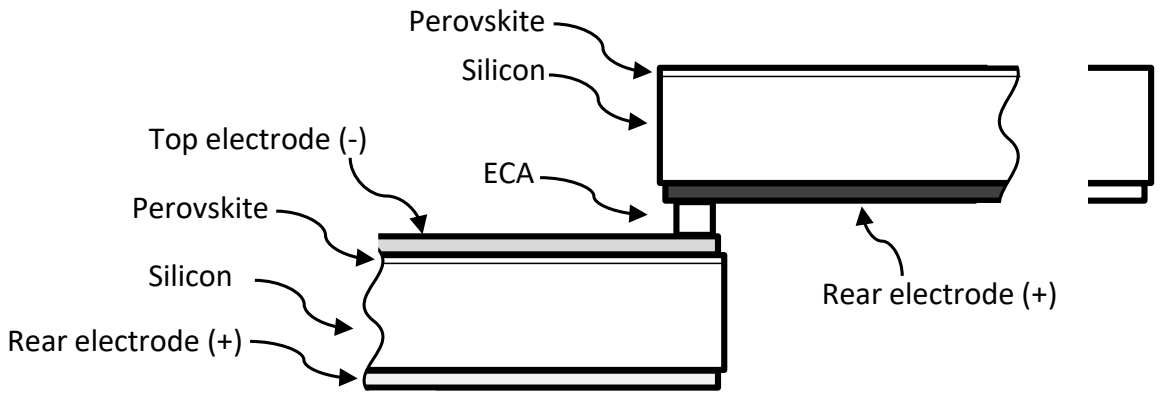
Voltage ~ 75 V

3T perovskite-xBC shingling?

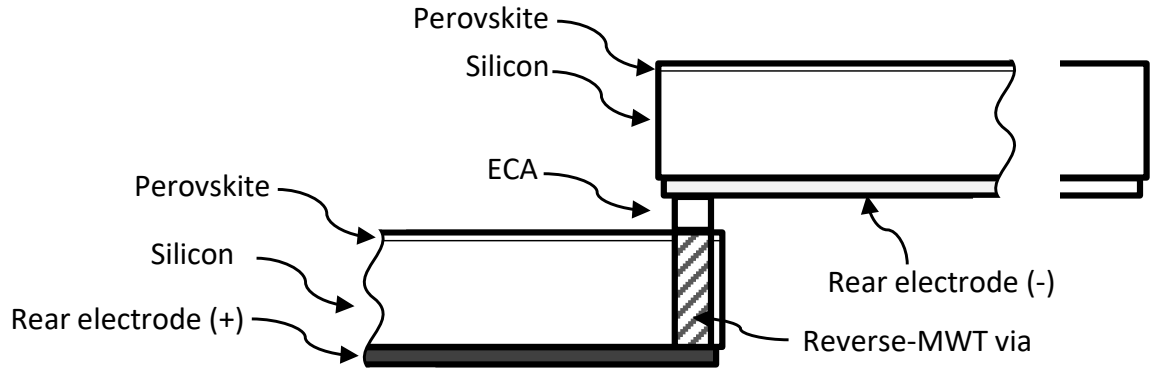
- How to string (shingle) 3T cells?
- No ribbon/wire interconnectors
  - No bonding to perovskite layer
- Both connections made in overlap
- Simplified string-end connections



Bottom cell to top cell connection

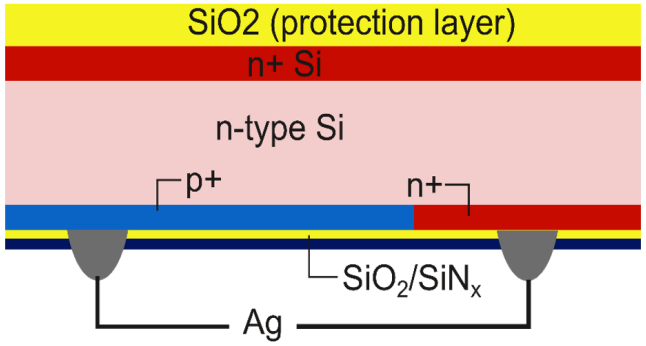


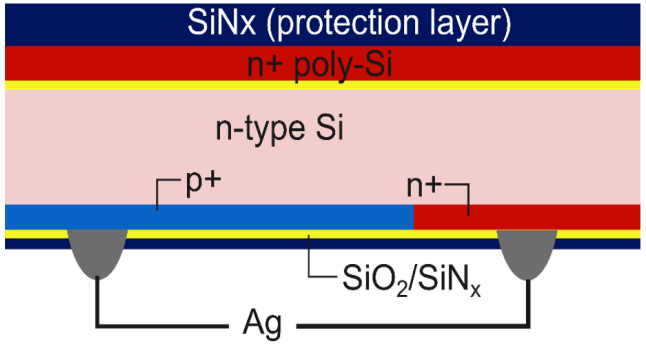
Bottom cell to bottom cell connection



***Patent pending**

3T cells @ ISC



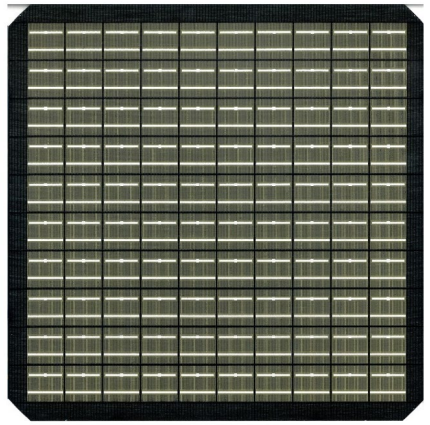


Gen1 features:

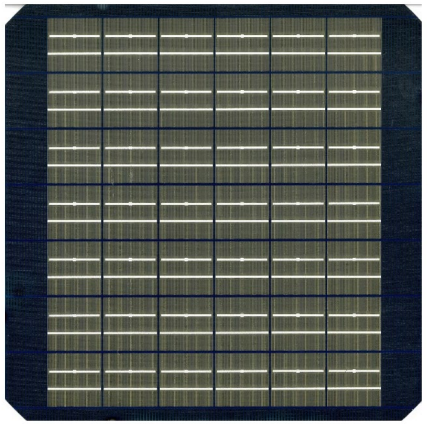
- Fully based on ZEBRA process
- n+ diffused FSF
- Flat front side with SiO2 capping
- Fully flat rear side
- Unpassivated front side after SiO2 removal!

Gen2 features:

- Thin n+ poly-Si FSF
- Flat front side with SiNx capping
- Fully flat or fully textured rear side
- Passivated front side after SiNx removal!



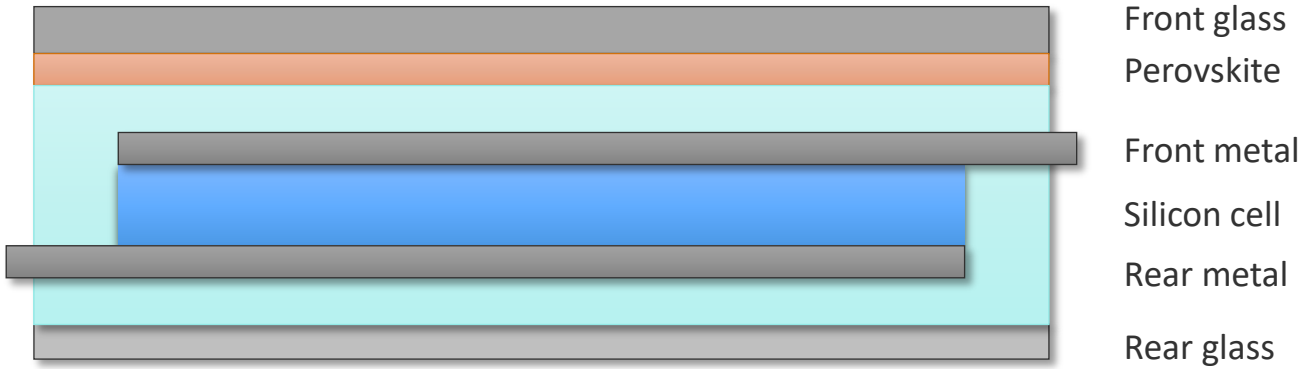
14.3×14.3 mm^2 (100 pieces)



20.9×20.9 mm^2 (42 pieces)

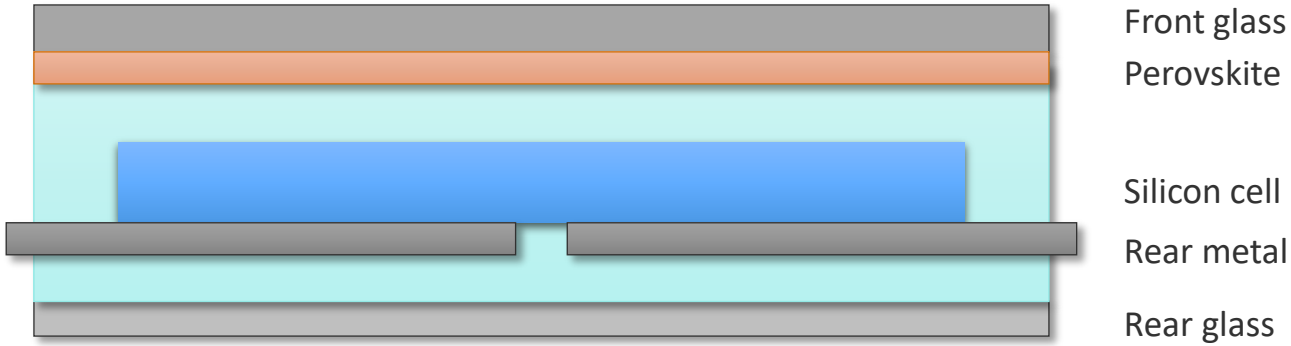
Why 4T-perovskite xBC?

- Ideal ≠ production realities
- High potential for punctures
  - Yield losses
  - Field failures
- Thicker front encapsulant
  - Optical losses



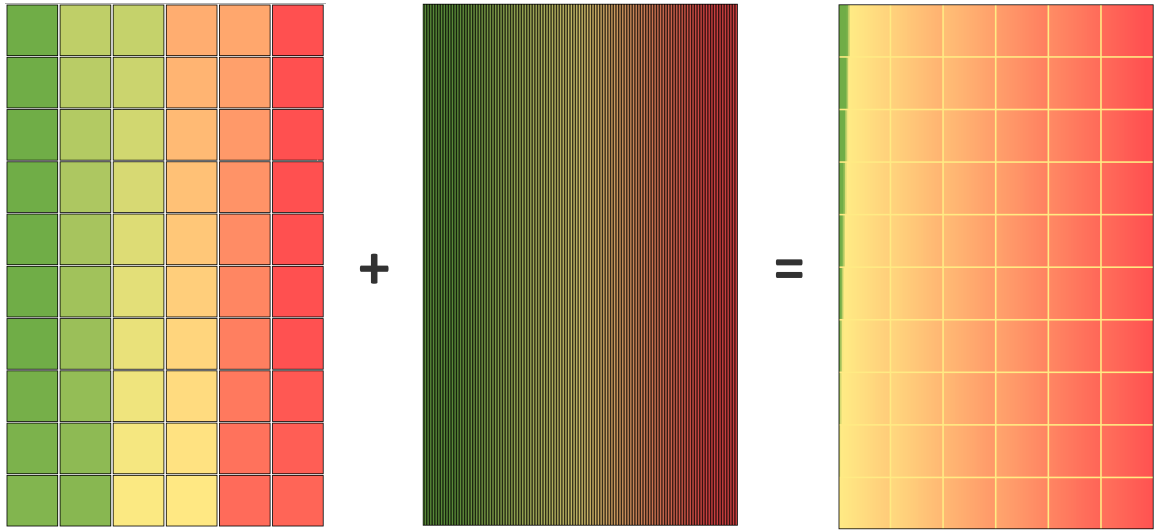
Why 4T-perovskite xBC?

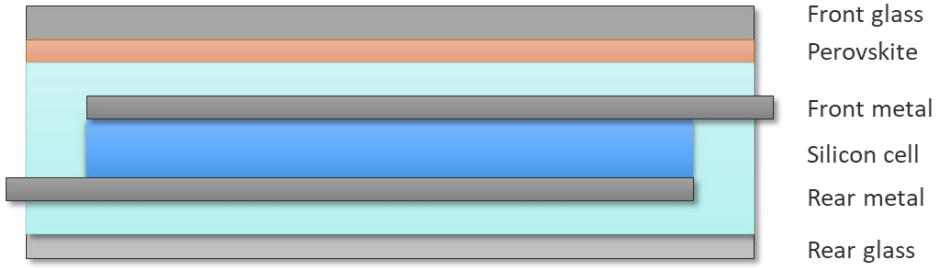
- More ideal structure
- Reduced potential for punctures
- Thinner front encapsulant



Why 4T perovskite xBC?

- Silicon ≠ perovskite layout
- Spatial differences in voltage
- Exacerbates front metal issues





Summary

- Perovskite (tandem) reliability indoors improving
- Outdoors not so convincing yet
- xBC in 3T tandems
  - Not complex to string
  - End losses can be managed
  - Concepts for shingling without ribbons/wires
- xBC in 4T tandems
  - Optical advantages due to lack of front side metalisation shadowing
  - Practical advantages due to flat front surface – less risk of puncturing / shorting

ISC research for a sunny future

Thank you