MODULE

User Manual

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1 introduction

Welcome! Module is an easy to use finite-element simulation program for solar panels. Module session files are ZIP files, which packages the module layout and reduced cell models. It may also package the original Griddler cell models. To start, you can download models for a wide variety of common solar cell types, for different wafer sizes and cuts, at

http://griddlersolar.com/index.php/cell-and-module-files-library/

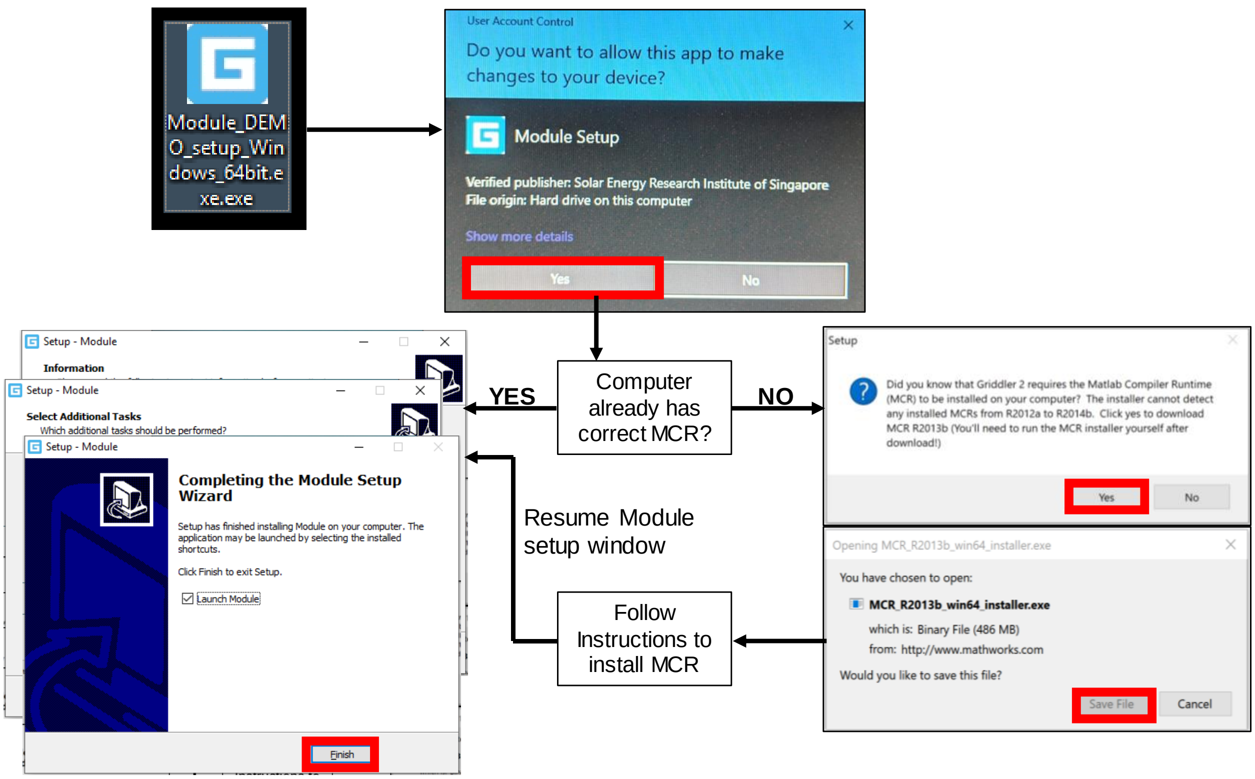
Wafer Size	Cut	Multicrystalline PERC	Mono SE PERC	n-type TOPCON	multiwire HJT	n-type IBC
125 mm	Full					Griddler IBC model
125 mm	Full					Module cell model
125 mm	Half Cut					Griddler IBC model
125 mm	Half Cut					Module cell model
M1 (156 mm)	Full	Griddler model	Griddler model	Griddler model	Griddler model	Griddler IBC model
M1 (156 mm)	Full	Module cell model	Module cell model	Module cell model	Module cell model	Module cell model
M1 (156 mm)	Half Cut	Griddler model	Griddler model	Griddler model	Griddler model	Griddler IBC model
M1 (156 mm)	Half Cut	Module cell model	Module cell model	Module cell model	Module cell model	Module cell model
M1 (156 mm)	6th cut top	Griddler model	Griddler model	Griddler model		
M1 (156 mm)	6th cut top	Module cell model	Module cell model	Module cell model		
M1 (156 mm)	6th cut middle	Griddler model	Griddler model	Griddler model		
M1 (156 mm)	6th cut middle	Module cell model	Module cell model	Module cell model		
M1 (156 mm)	6th cut bottom	Griddler model	Griddler model	Griddler model		
M1 (156 mm)	6th cut bottom	Module cell model	Module cell model	Module cell model		
M2 (156.75 mm)	Full	Griddler model	Griddler model	Griddler model	Griddler model	Griddler IBC model

The file links called "Module cell model" are zip files that you can directly load into Module via File → Open Session, or in the Cell Library of Module via "Add cells from another zip".

The file links called "Griddler model" and "Griddler IBC model" can be opened in Griddler 2.5 PRO and Griddler IBC, respectively. If you have the software bundle, then you can launch these cell simulation programs to load these files, edit them, and load them into Module for cell reduction.

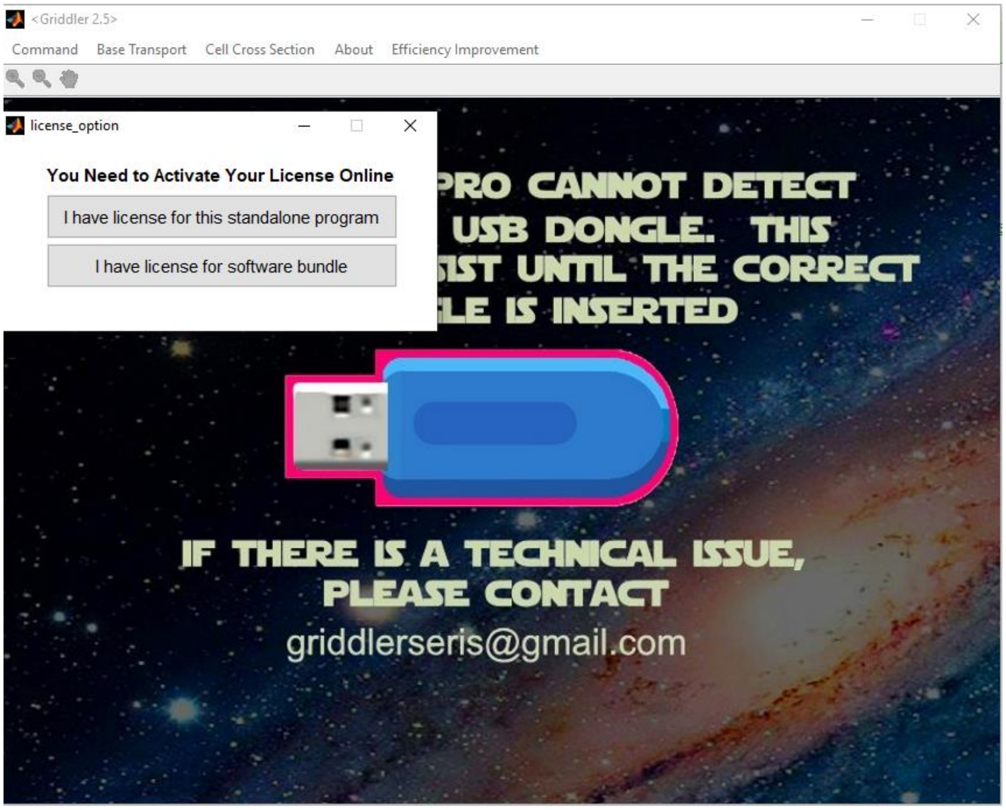
2.1 Installation

After you have downloaded the installer, double click it to initiate installation. The installation process is automatic and easy to follow and is described by the diagram below. Module is written in MATLAB and requires the Matlab compiler runtime (MCR R2013b) to run. The installer will autodetect the presence of the correct MCR version and download it if it is missing, but you will need to install the MCR separately. Once setup is complete, hit finish with the "Launch Module" checkbox checked, and Module will launch.

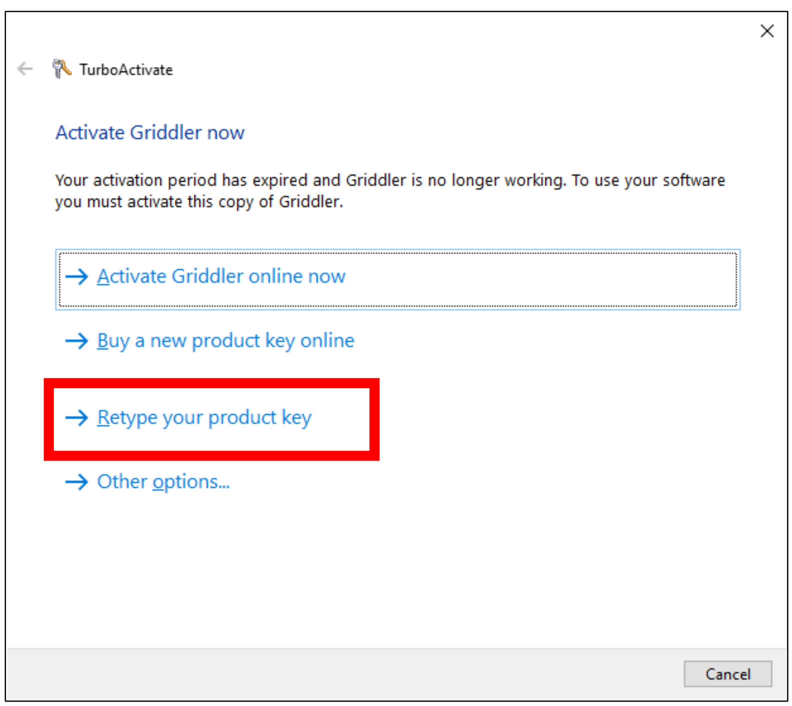


Module needs <u>either</u> a physical USB dongle provided by us or online activation to run. Either method requires periodic internet connection (for USB dongle about once a month; for online activation about once a day). The USB dongle looks like the one shown below and needs to be plugged into the computer while the program is running.

When you run the program for the first time, if it doesn't detect the USB dongle, then a pop up screen will show up with the following options. Select the appropriate (software bundle = Griddler 2.5 PRO + Griddler IBC + Module simulation program purchase; standalone = Module only).

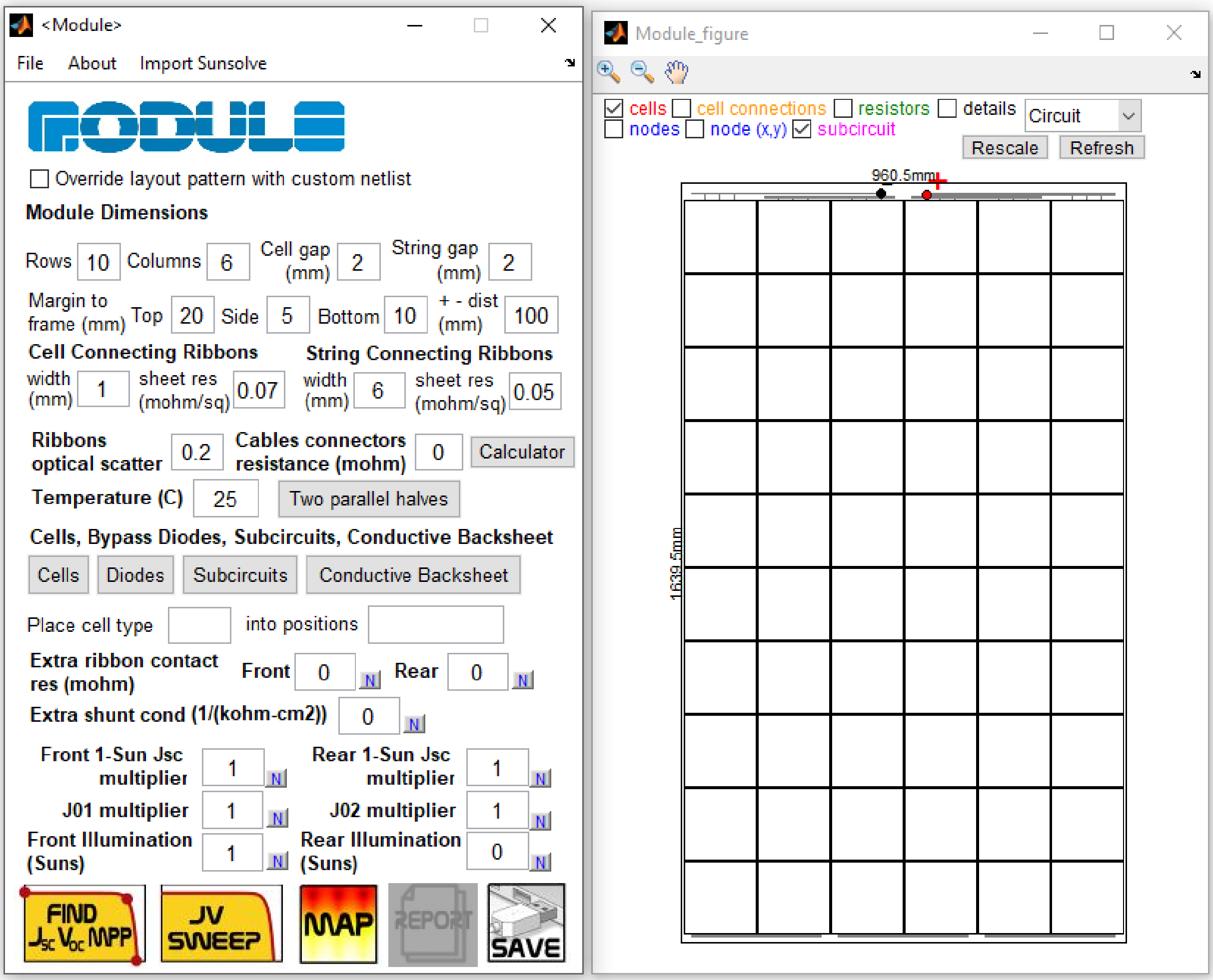


Then you will be give the option below to enter a product key. Use the one provided to you and you can then continue to use the program.

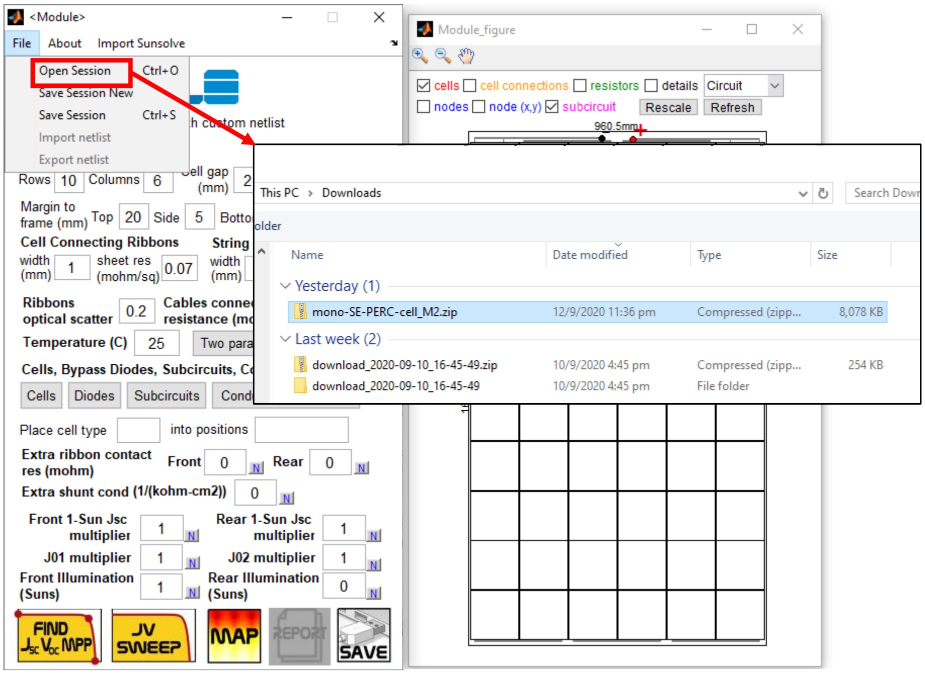


2.2 Module Quick Guide

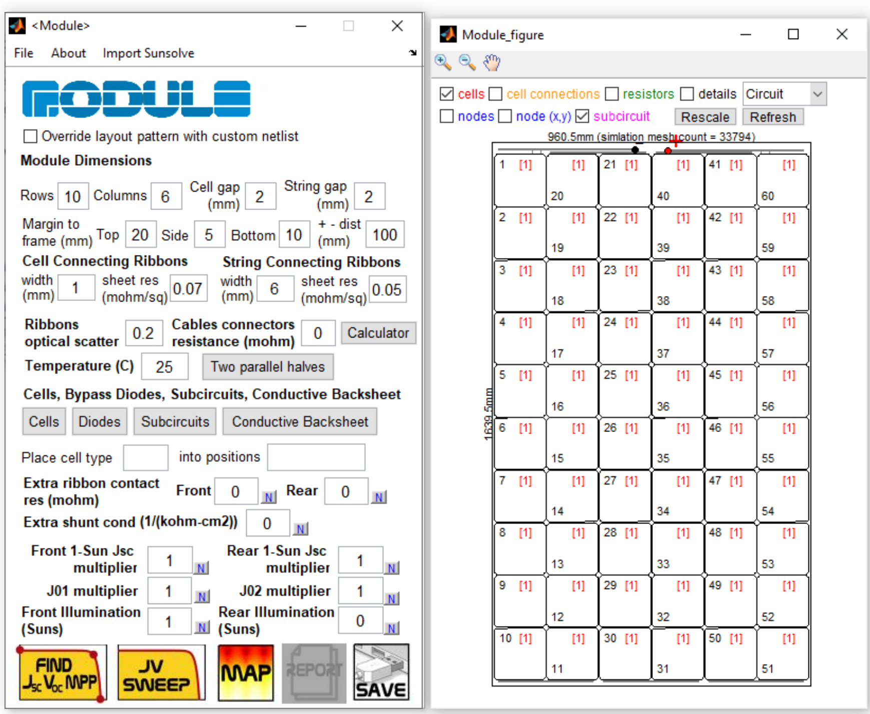
Here's Module's main screen. In it, you can define the module layout, set the temperature, access the cell and diode libraries, subcircuits library, conductive backsheet, and coarsely adjust the cell parameters of the cells inside the module. Of course, you can also run simulations.



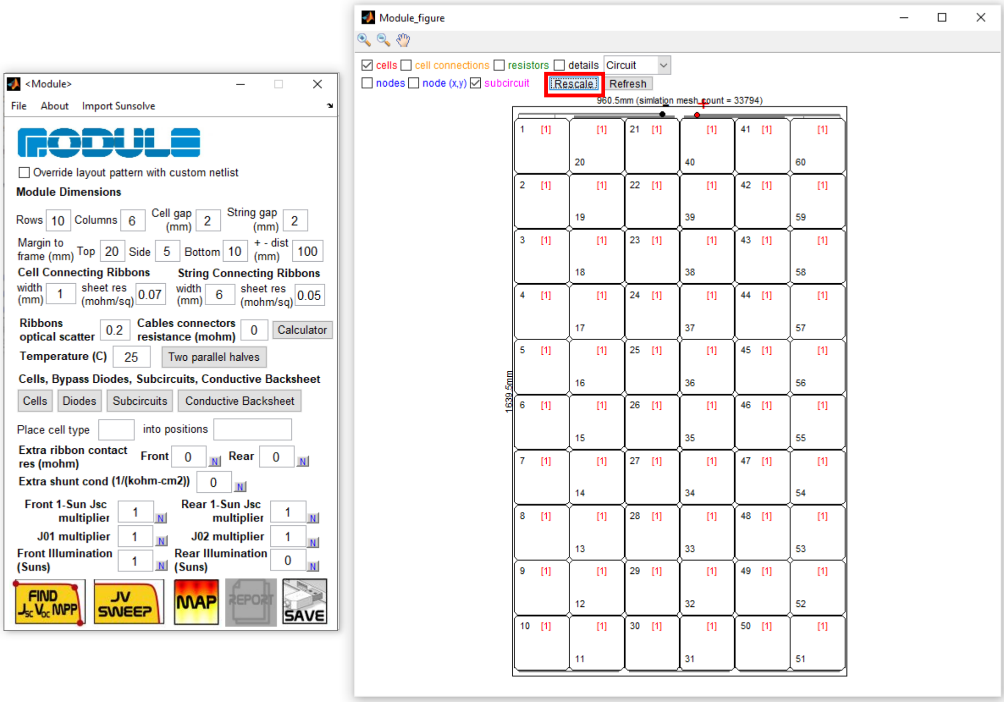
Let's start by choosing File → Open Session, and then choosing mono-SE-PERC-cell_M2.zip downloaded from the online library.



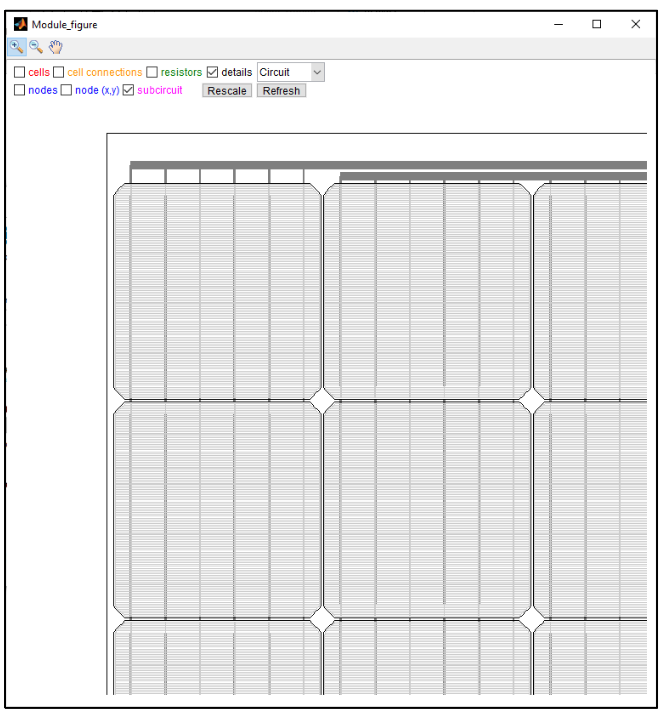
As soon as the zip file has been loaded and there is information of the solar cell, the module shown in the Module_figure will be populated by the first solar cell type by default. You can make a lot of changes---populating the module with different cell models, changing the details of the cell (if user has access to Griddler 2.5 PRO or Griddler IBC), etc. These will be explained later on in the manual.



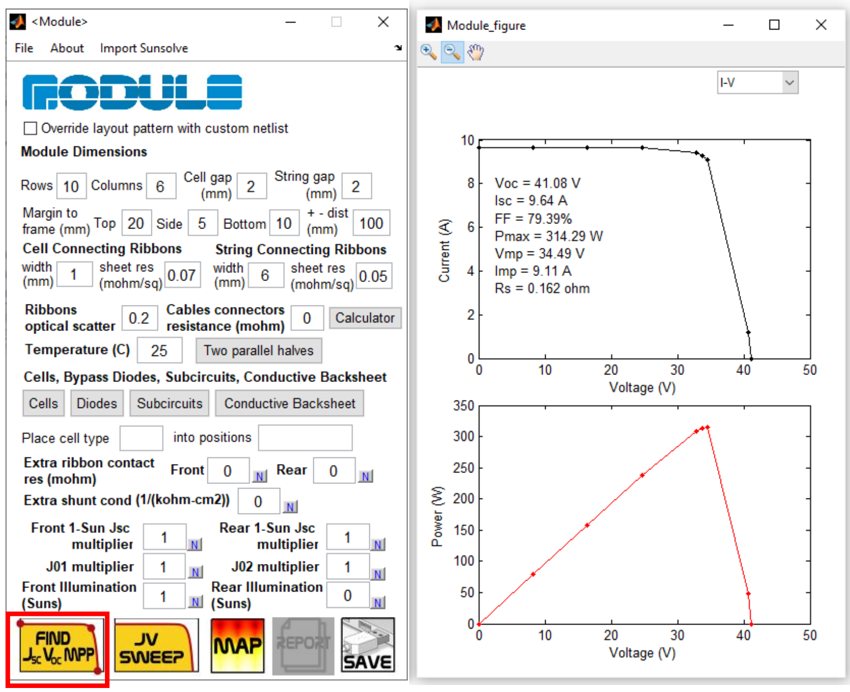
The Module_figure window can be resized. After resizing the window, pressing “Resize” will cause the program to redraw the module in the correct aspect ratio.



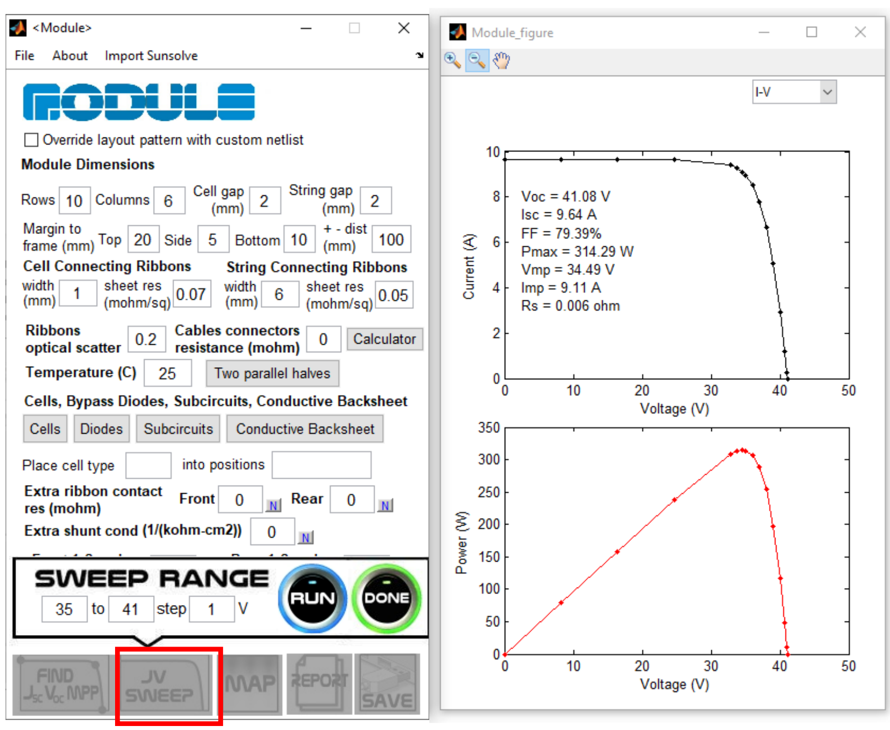
There is a variety of options of what to display for the module, which will be explained later in the Subcircuit Library section because that is where these options become useful. For now, we demonstrate for instance, if you press “details”, then the full details of the module down to cell ribbons and fingers will be displayed, and then you can use the zoom tool to look closely at sections of the module.



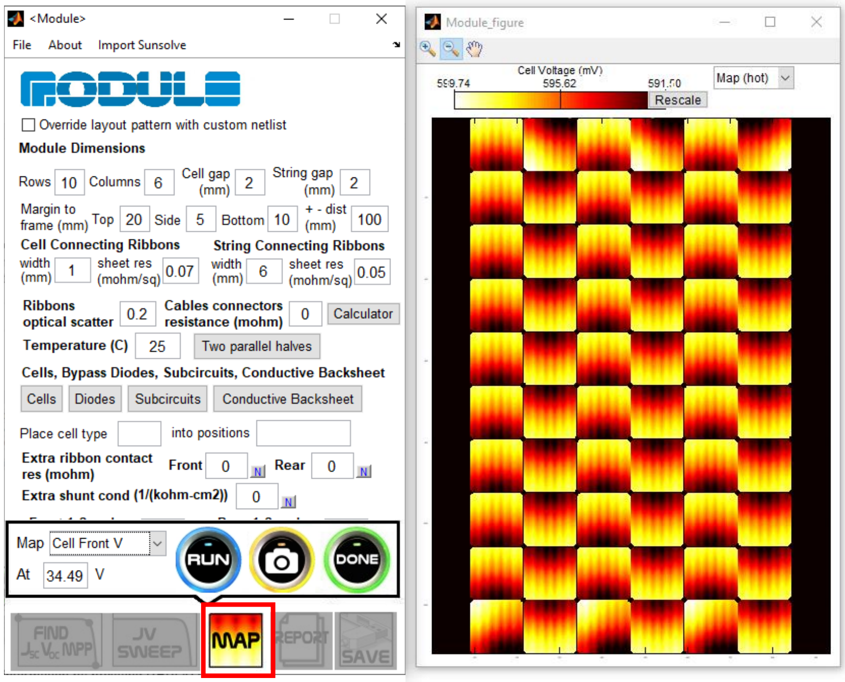
To run simulations, the Module interface resembles Griddler and Griddler IBC. Click “Find Jsc Voc MPP” and Module will run the I-V curve, focusing on finding the main I-V parameters.



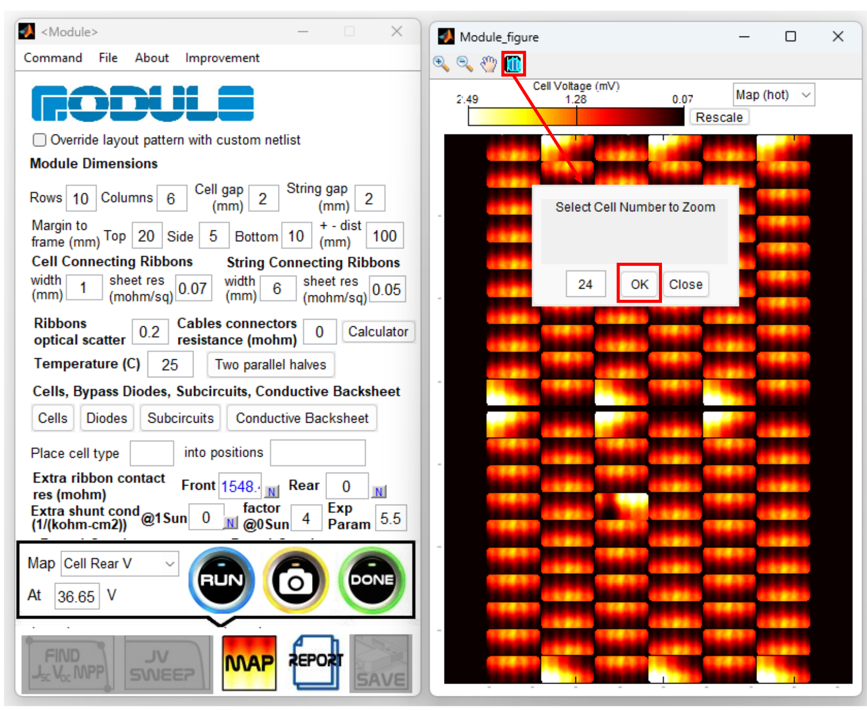
Find Jsc Voc MPP stops after the maximum power point has been found, so the I-V curve might not look very smooth. If you want the I-V curve to be smooth, you can press “JV sweep”, and specify additional voltages to run the simulation. As long as you have not made changes to the module simulation parameters, Module will add the newly simulated I-V points onto the existing I-V curve.



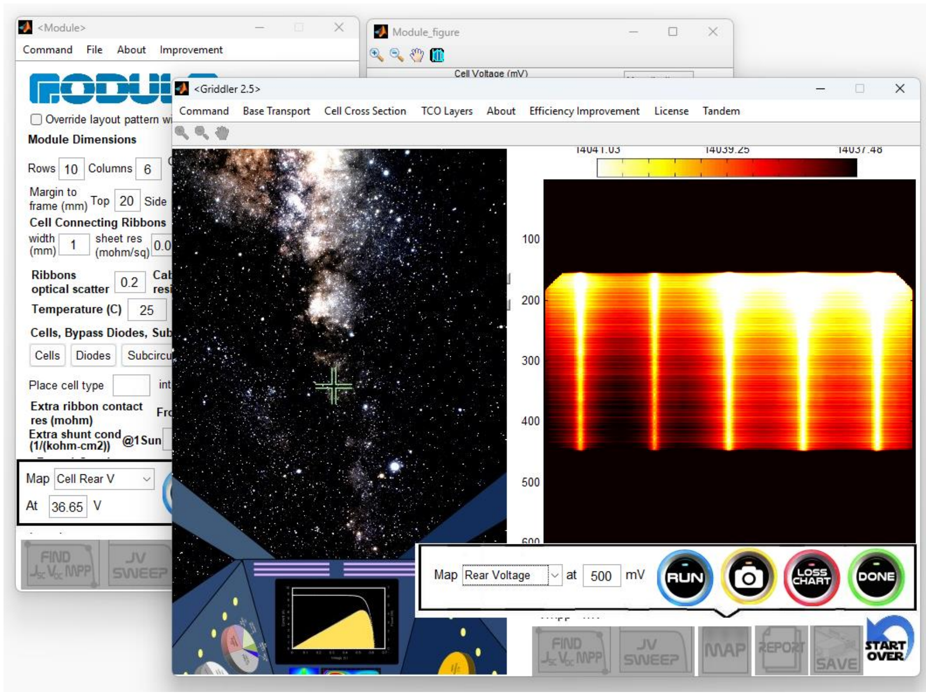
To visualize the voltage distribution, you can press “MAP” and then specify what to map (here we chose Cell front voltage) and what operating condition to map (here we chose 34.49V which is the maximum power point. You can also enter “OC” to simulate open circuit condition).



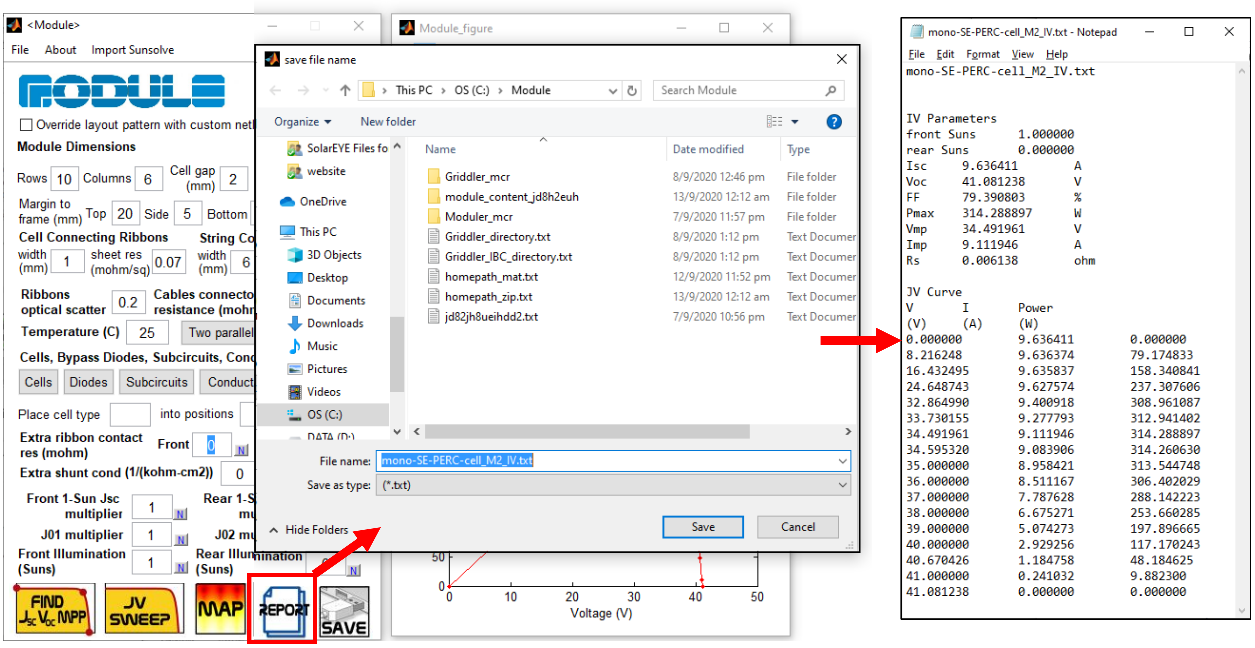
(New Since March 2023) For detailed simulation of a cell inside the module, after a MAP simulation, press the icon in the Module Figure and enter the cell number to zoom. Press OK and Griddler will launch to calculate the detailed voltage distribution for that particular cell inside the module.



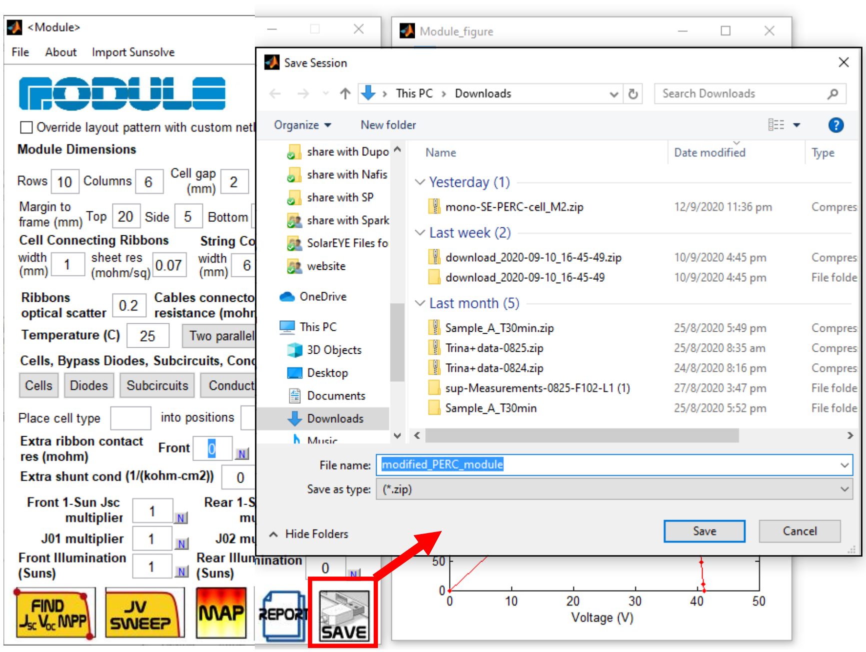
Note: user needs to choose the right map inside Griddler (e.g. Rear voltage).



You can save the I-V curve and I-V parameters information by pressing REPORT.

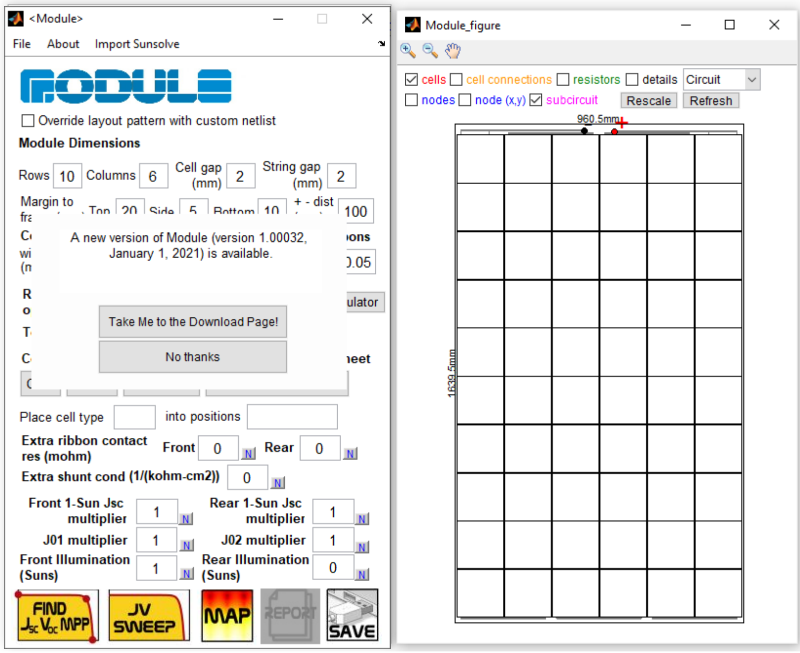


After changes have been made, you can also save the session back into a zip folder, either through the SAVE button in the main screen, or via File → Save New or File → Save.

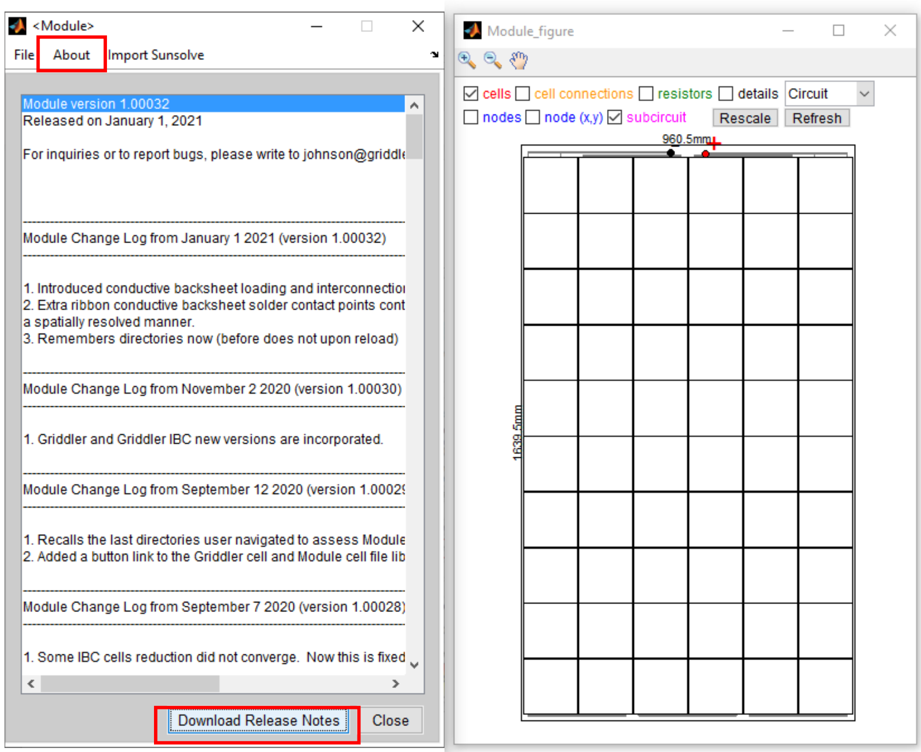


2.3 Update Notifications

We roll out periodic updates, and you'll be notified of one upon program start (below). Please be diligent, and click "Take Me to the Download Page" and download the latest installer. You can simply run the installer and it will overwrite the previous version from your computer.

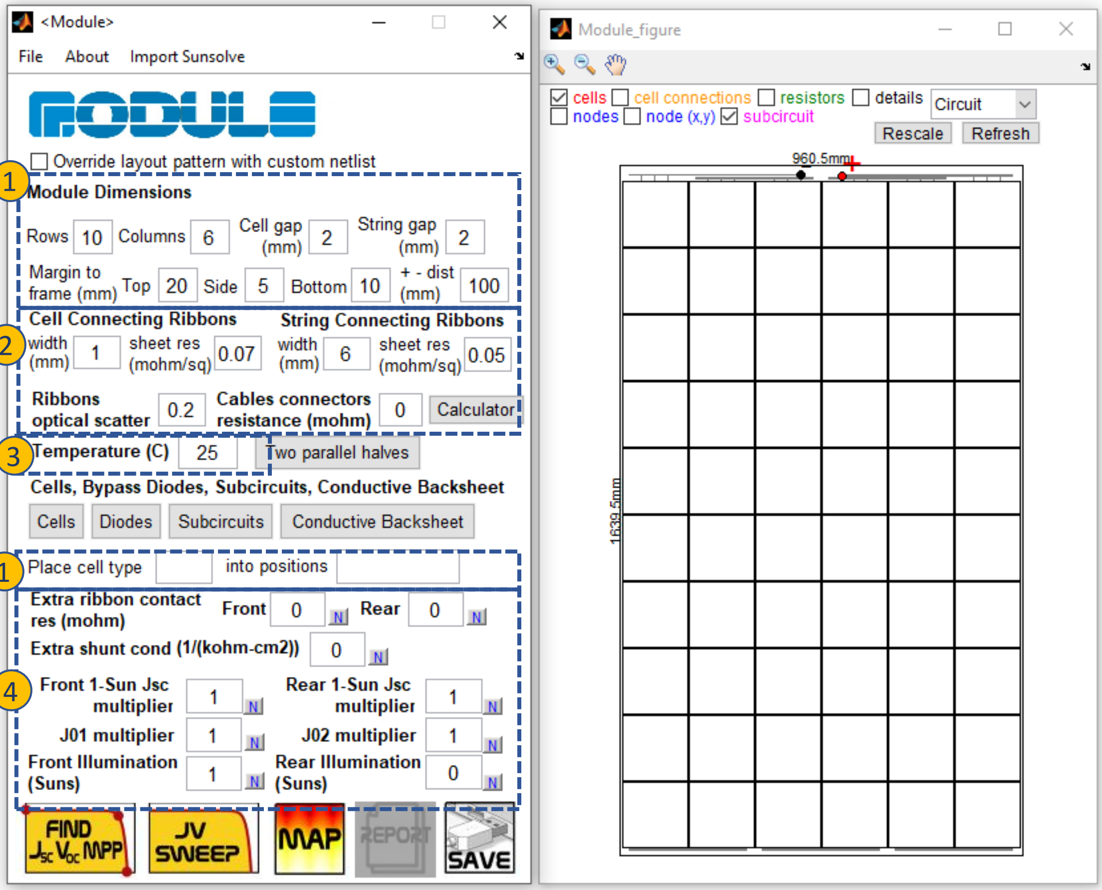


You can always check your version numbers by clicking "About" on the top menu bar. Hit "Download Release Notes" to see the changes made in each version.



3 Detailed Operations on the Main Screen

3.1 Introduction

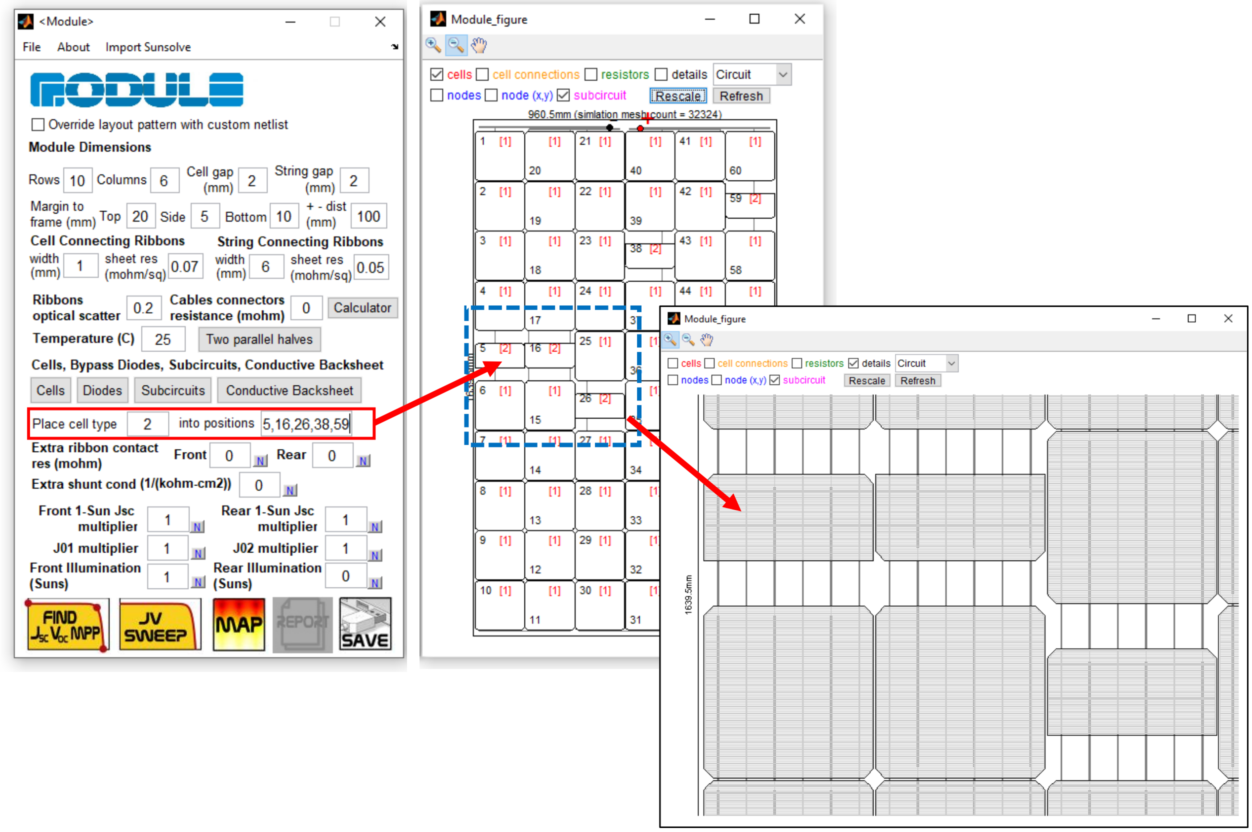


The main screen has the above categories of option groups 1) module layout options (for commonly encountered, rectangular patterns; for arbitrary patterns see Subcircuits Library Section), 2) Ribbons and cables connectors, 3) Temperature, 4) Illumination and cell diode properties.

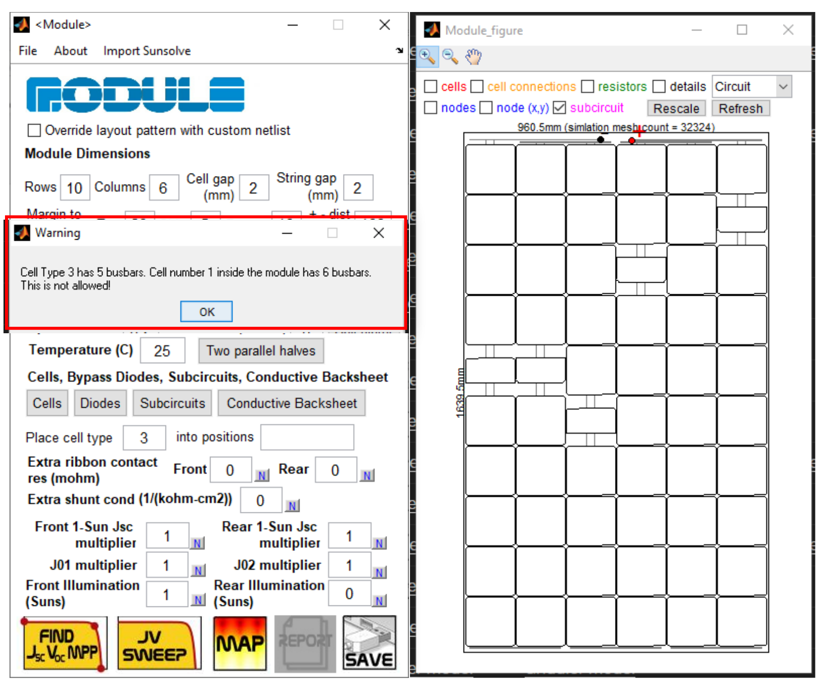
3.2 Module Layout Options

This group of options allows you to quickly change the layout of a rectangular module. For more arbitrary layouts, see the subcircuits library section.

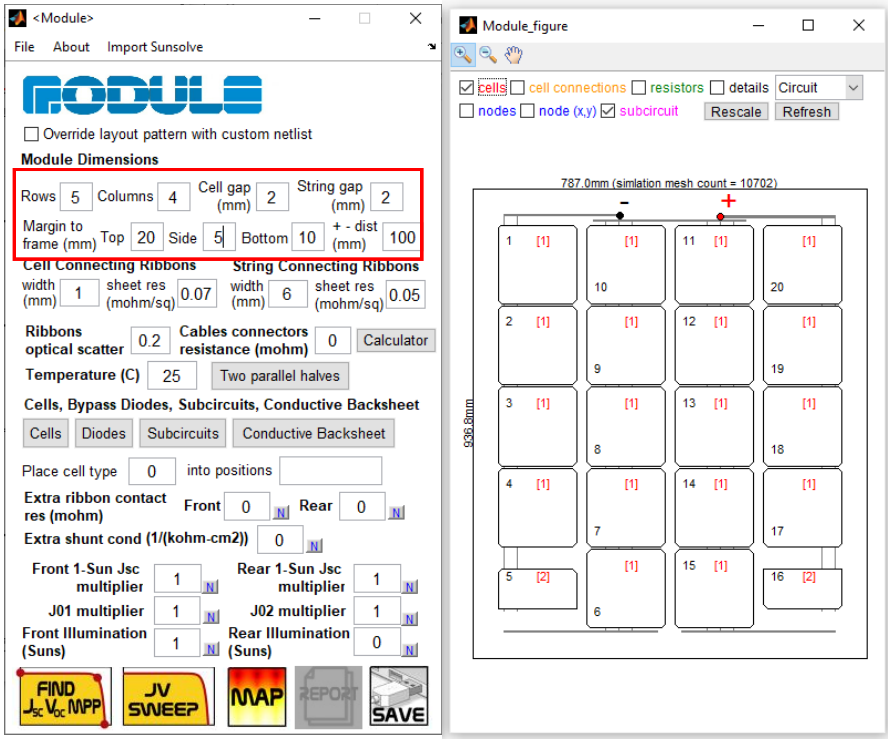
Here we show for illustrative purposes a module that consists of two cell types. To show this clearly we create a module that is a mixture of full size cells and half cut cells, but of course usually you want to create module with similar sized cells. For this to work, your module session has to have more than one cell type in the cell library (see Cell Library). To repopulate parts or all of the module with another cell type, see below. Enter the cell type number and positions of the module (which can be seen in the Module_figure) you wish to insert that cell type. If you want to place that cell type into all the positions, enter “all”.



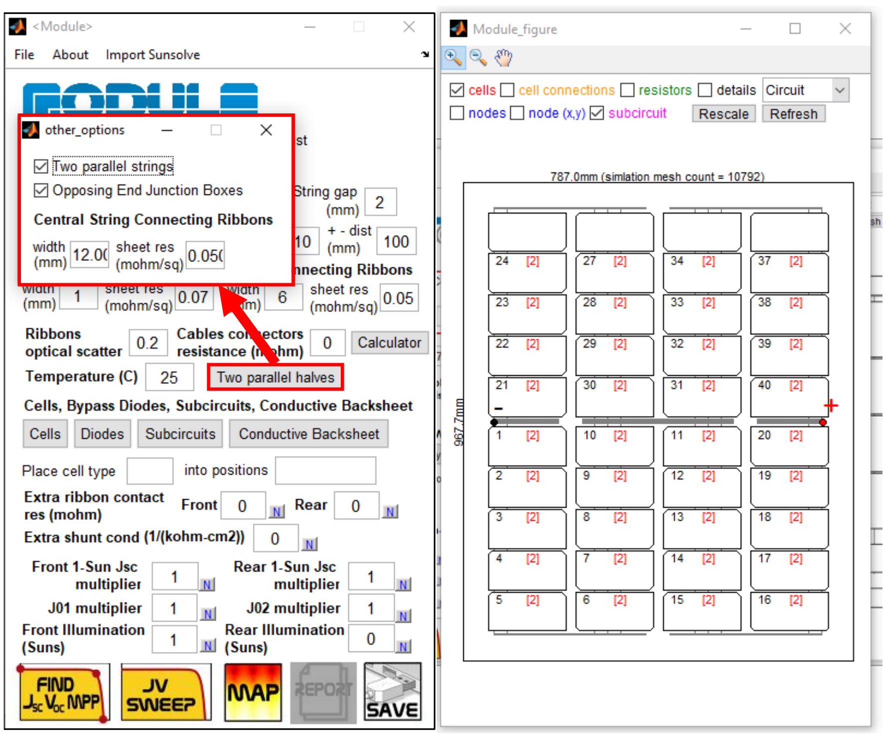
Note that all the cells within the module must have the same number of ribbons. Here we show what happens, for example, if we have a third cell type that has 5 busbars, when the existing cells inside the module have 6 busbars. If we try to place cell type 3 into certain positions of the module, an error message will appear and you won't be able to do it.



For rectangular layouts, you can easily change the dimensions of the module via the options in red below.



Because it is common to layout half cut cells into two symmetrical, parallel/series connected halves of the module, we have also added this as a quick option. Here we show for an example, a module consisted of entirely half cut cells. Press “Two parallel halves” and then check “two parallel strings” and module will layout the cells as shown in the Module_figure below.

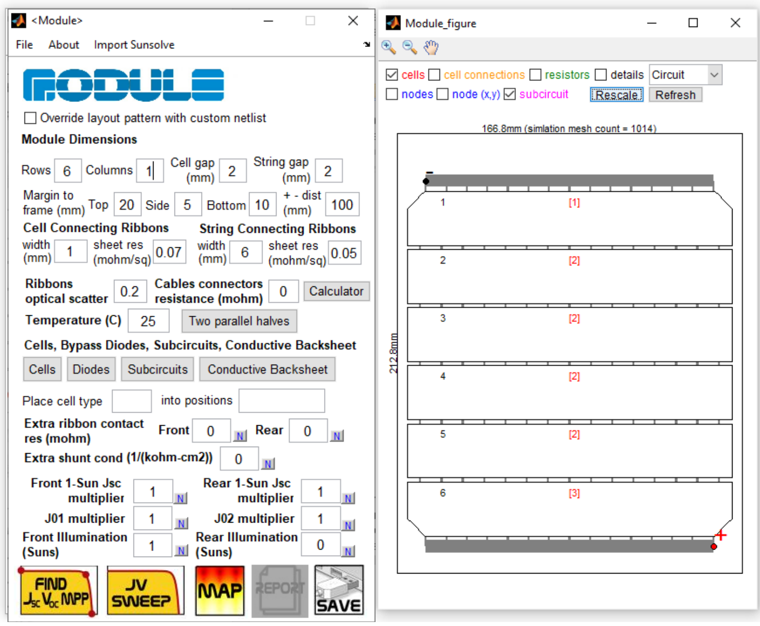


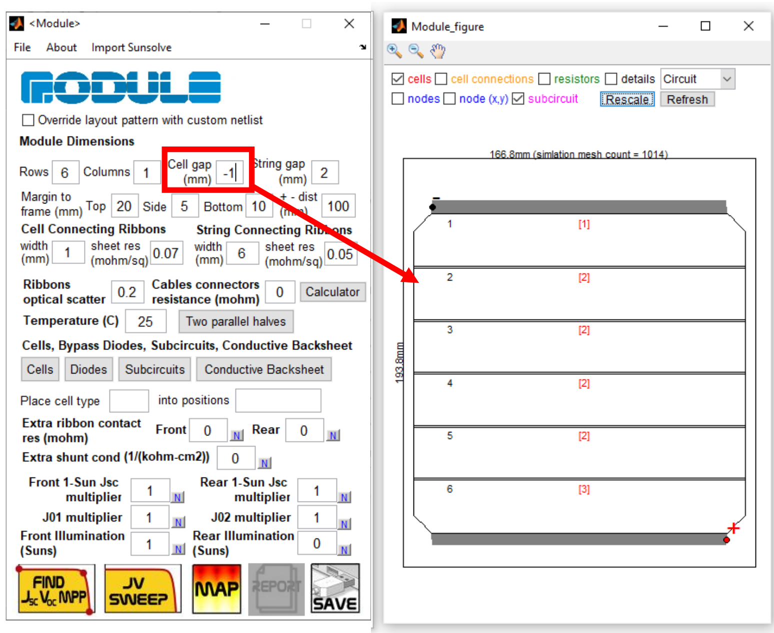
3.3 Shingled Cells Module

Shingled cells can easily be defined by simply setting the cell gap value to a negative number. To give ane example, we will start from scratch and build a module that consist of 6th cut mono-PERC cells laid out as shingles.

We download from the online Module cell library the following Module cell files: mono-SE-PERC-cell_M2_6THCUTTOP.zip, mono-SE-PERC-cell_M2_6THCUTMID.zip, mono-SE-PERC-cell_M2_6THCUTBOTTOM.zip and load them into Module via Cell Library → Add cells from another zip

Below we show the difference between arranging these cells with positive cell gap versus negative cell gap (shingling).

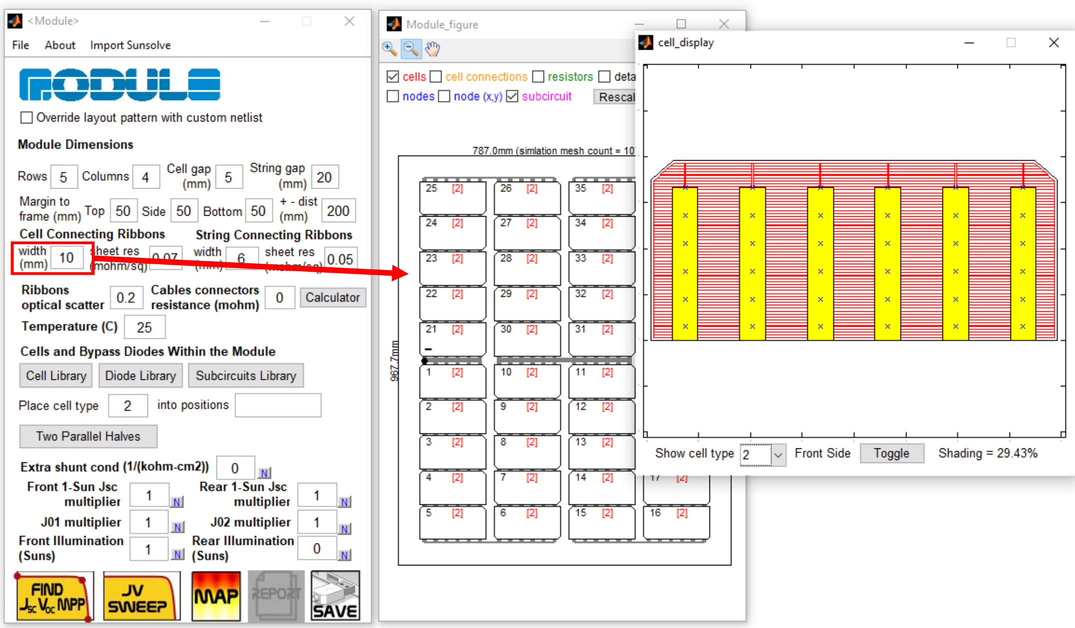




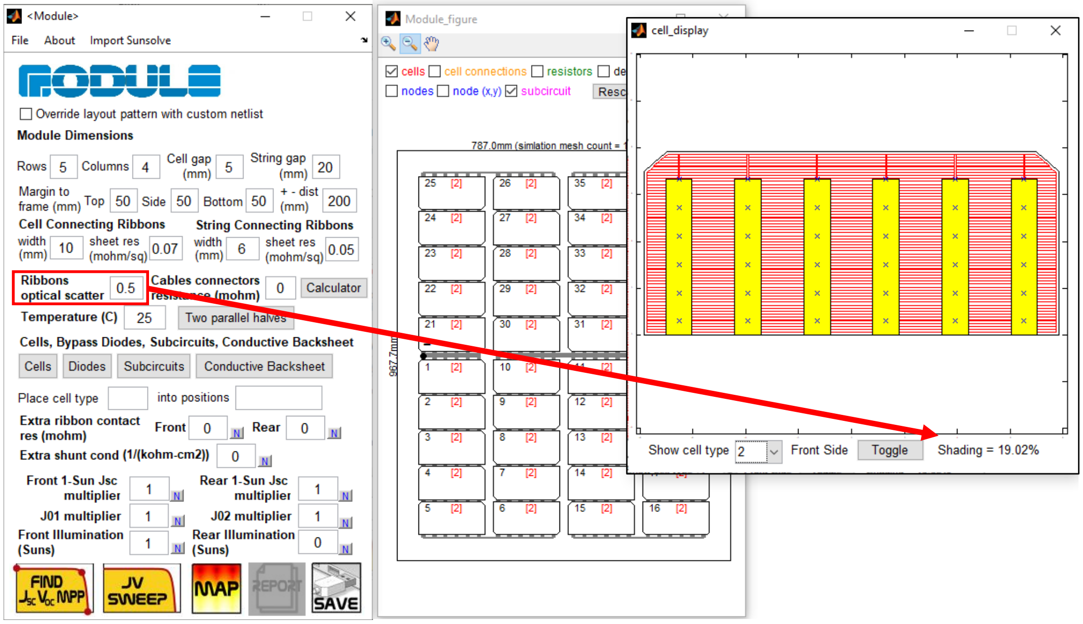
Firstly, the Griddler cell design page enables shingle cell type of grids to be defined. See Griddler_and_PRO_manual section 2.4. Assuming that you have the right kinds of shingled cells in the cell library of Module, simply set the Cell gap to a negative number, and you're all set. Now the cells are shingled with an overlap equal to the magnitude of the cell gap. The decrease in current of any cell due to the overlap shading is automatically calculated, for both front and rear illumination cases.

3.4 Ribbons and Cable Connectors

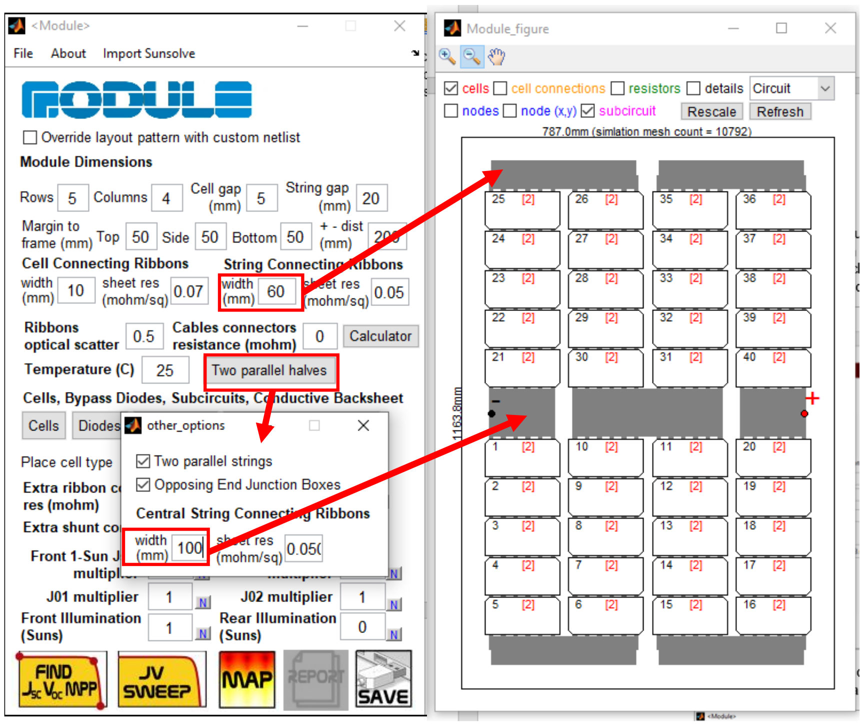
You can adjust both ribbon width and sheet resistance in the options below. Here we show what happens if you adjusted ribbon width to 10mm. The module figure will be updated, and there will also be a window that shows you the shading on the cell. You can choose which cell type to show. Here for cell type 2 the shading is 29.43%.



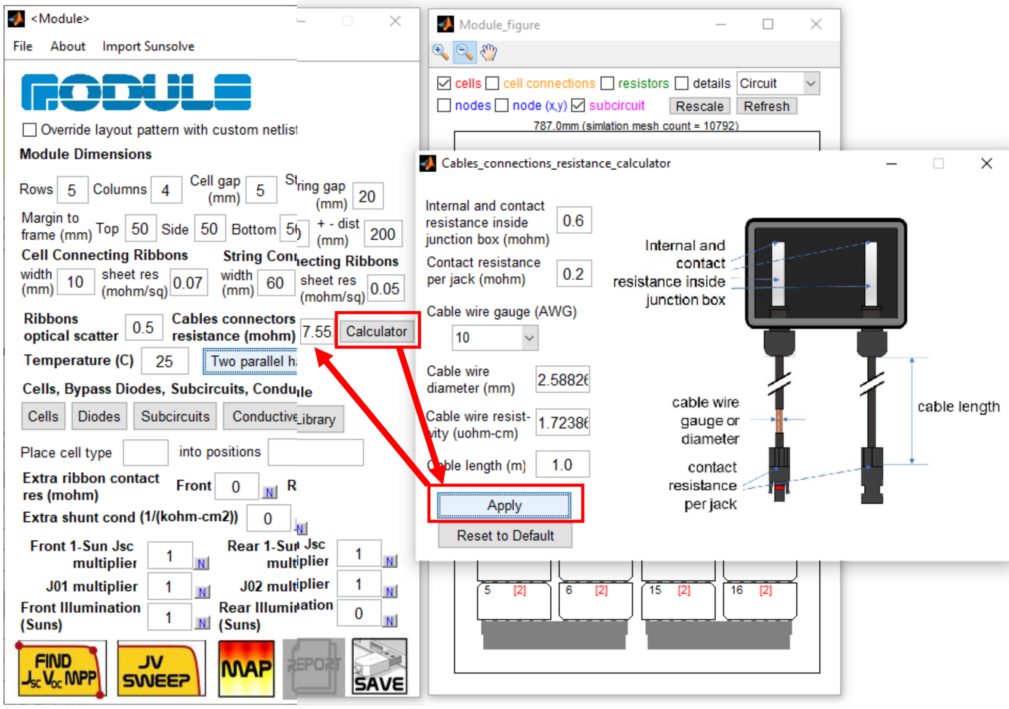
The shading depends not only on the ribbon width, but also on the ribbon optical scattering properties. Some ribbons are designed to scatter more light inside the module, resulting in higher cell light absorption. To reflect this, you can adjust "ribbon optical scatter". Value of 0 means that any light falling on the ribbon is not scattered back into the cell. Value of 1 means that all light falling on the ribbon scatters back onto the cell. You can see that adjusting this number results in a different shading percentage.



Similarly you can adjust the width and sheet resistance of string connecting ribbons. To illustrate an exaggerated example, below we adjust them to really large values.

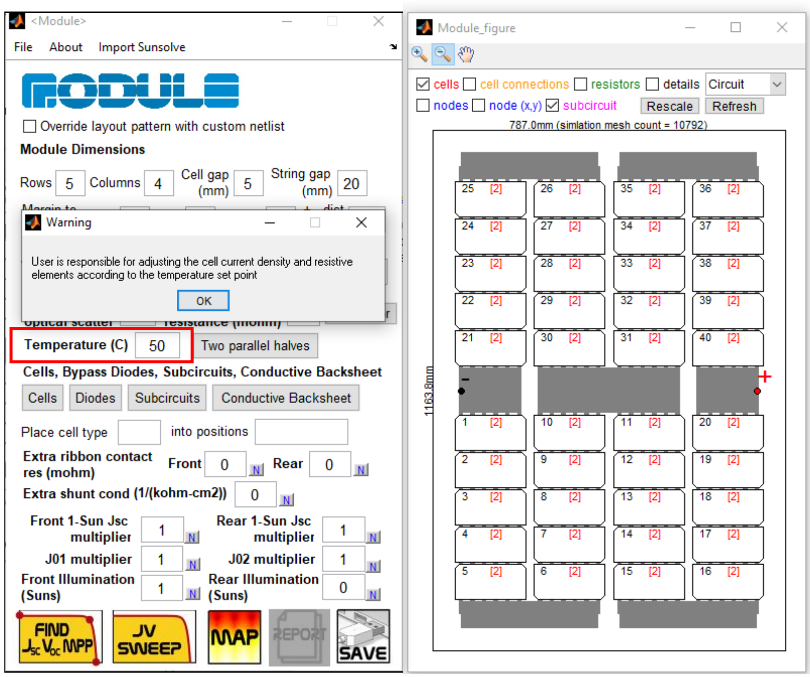


By default, cables and junction box related resistances are zero. If you wish to simulate their effects, you can click "Calculator" next to this field and a screen pops up which allows you to calculate the wire resistance for all kinds of copper wire gauge and lengths, as well as junction box resistance. Hitting "Apply" will enter the total resistance into the cable connections resistance field.



3.5 Temperature

The temperature can be adjusted from the default value of 25°C as shown below. Module will adjust the diode recombination parameters in the cell but the user will be reminded to adjust cell current density and resistors (if there is any temperature dependence) manually.



Module makes adjustments to the cell recombination parameters (expressed by the two diode model) according to

$$J_{01}(T) = J_{01}(25°C) \times (n_i(T)/n_i(25°C))^2$$

$$J_{02}(T) = J_{02}(25°C) \times (n_i(T)/n_i(25°C))^1$$

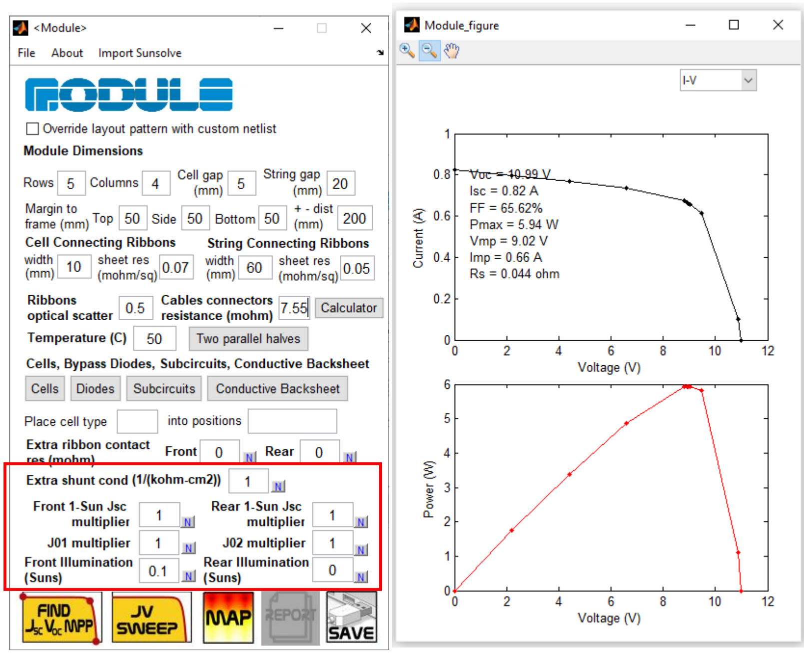
$$n_i(T) = 9.15 \times 10^{19} \left(\frac{T + 273.15}{300}\right)^2 exp\left(\frac{-6880}{T + 273.15}\right)$$

Where J_{01} and J_{02} are the saturation current densities of the n=1 and n=2 diodes respectively (saturation current per area values from the I_{01} and I_{02} explained in section 1.2), T is temperature in Celsius, n_i is the intrinsic carrier concentration in silicon. The above equations basically mean that the thermal equilibrium carrier concentration, and therefore recombination currents, increase with temperature. This leads to open-circuit voltage (V_{oc}) and efficiency drops as temperature rises. The above equations capture most of the negative temperature coefficient in solar cell V_{oc} and efficiency. However Module does not model the comparatively minor temperature coefficient in short-circuit current density (J_{sc}) that is due to increased absorption of infrared photons as the silicon bandgap decreases with increasing temperature.

3.6 Illumination and cell diode properties

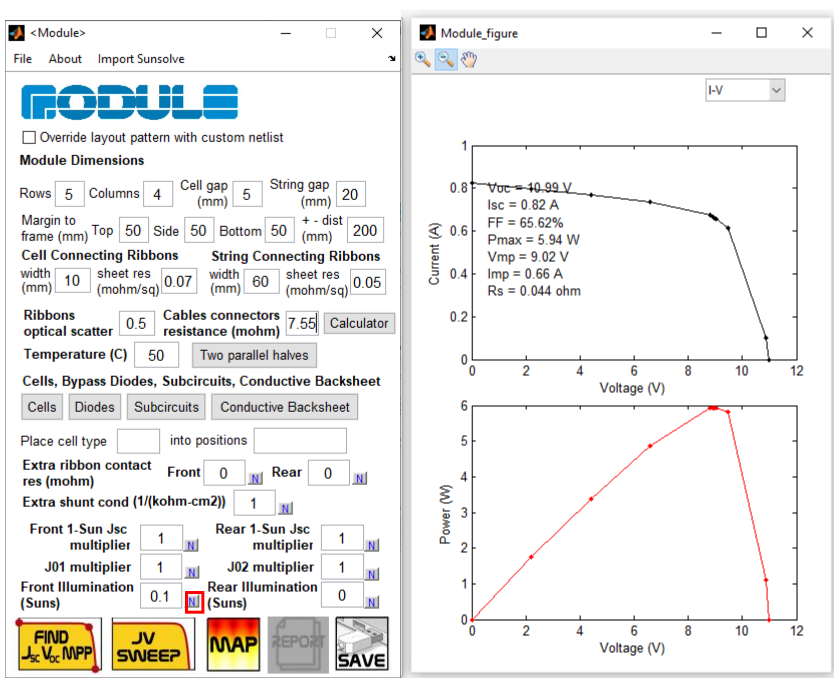
The illumination condition from the front and the rear (in units of Suns) can be adjusted in this option group. As well, without needing to access the original Griddler cell model, you can make adjustments to the cell diode properties by setting multipliers for the front and rear 1 Sun short-circuit current density (J_{sc}), and the diode recombination current densities J_{01}, J_{02}. You can also add additional cell level shunt conductance. For more details on the definition of these parameters and the two diode model of solar cells, refer to the Griddler and PRO manual, section 1.2 Griddler Core Model. By default, all multipliers are set to 1 and the extra shunt conductance is set to zero, meaning that there is no alteration to the diode properties of the cell model.

Below we illustrate the case where we set the extra shunt conductance to 1 (inverse kohm-cm^2) and plot the I-V curve under low light condition of 0.1 Sun from the front.

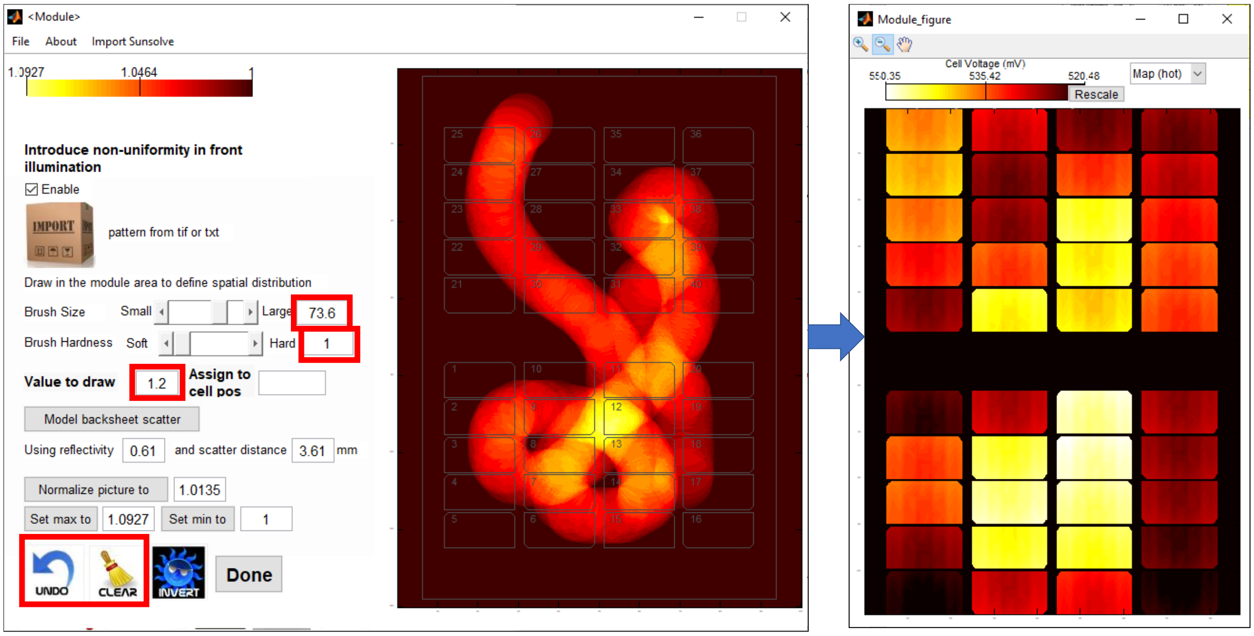


3.7 Non-uniform Cell Parameters

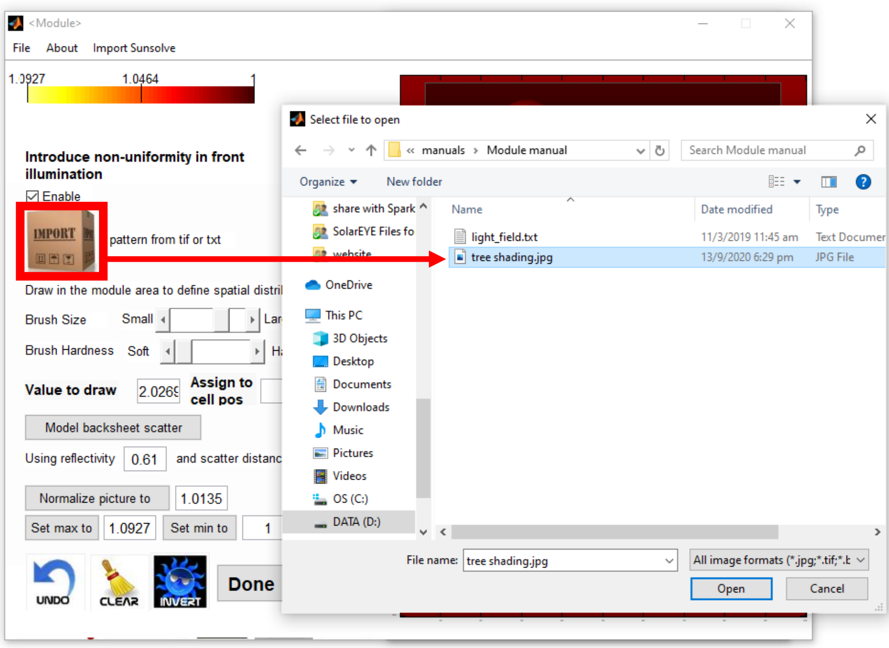
If you have used Griddler the solar cell simulation program before, you will recognize that next to certain parameters there are blue N buttons (shown below). That means that for these parameters you can define spatially non-uniform distributions. Let's click on the blue N button next to "Front illumination". An interactive screen pops up with tools that allow you to create a non-uniform light field.



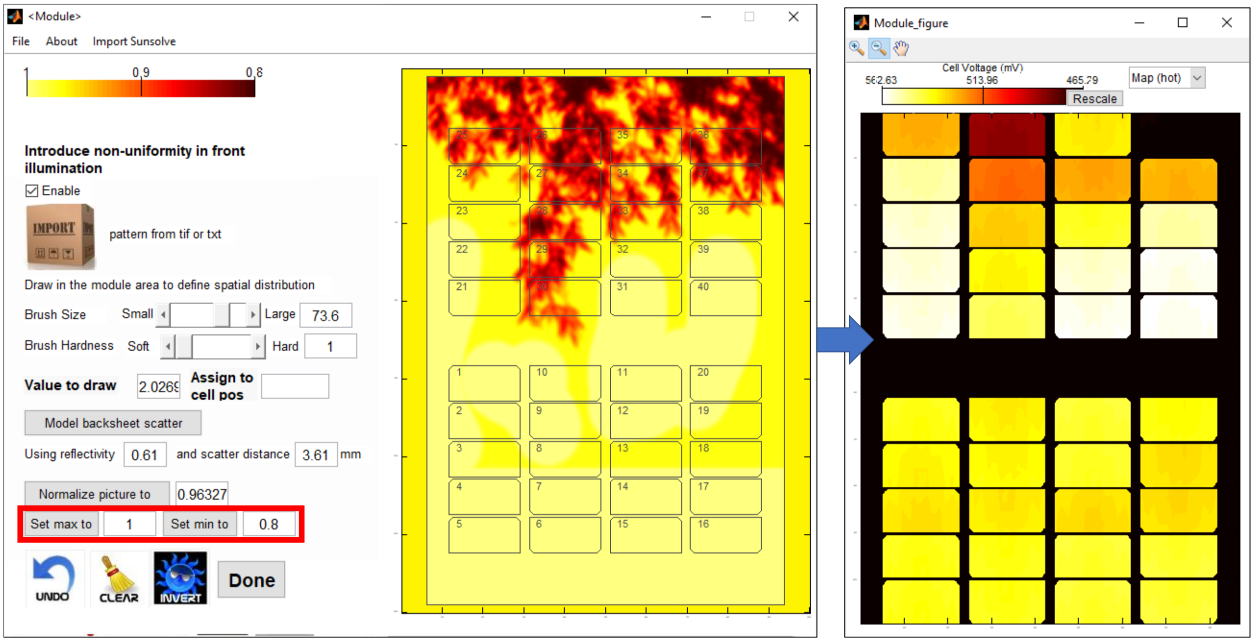
You can directly draw the light field by selecting the value to draw (specified in Suns), and then painting over the module schematic just like using paint tool. Below we show an example of such a free style illumination field definition and the resultant simulated front cell voltage near MPP:



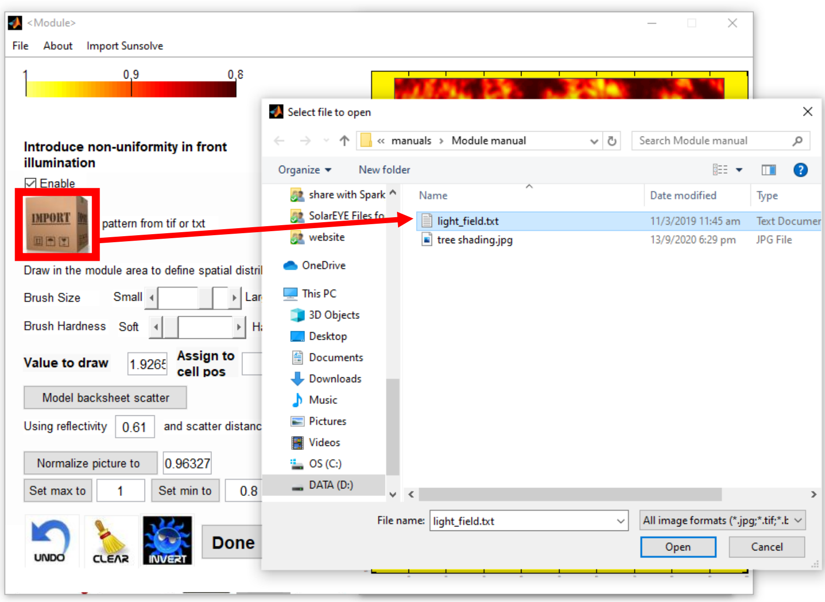
You can also select "Import" to load a picture that represents the light field. The picture is always resized to fit right inside the module frame. If you select a greyscale tif, the grey scale will be translated into numbers representing the nonuniform parameter; if you select an RGB jpg, the R, G, B values will be translated into numbers according to number = sqrt(Rvalue^2 + Gvalue^2 + Bvalue^2).

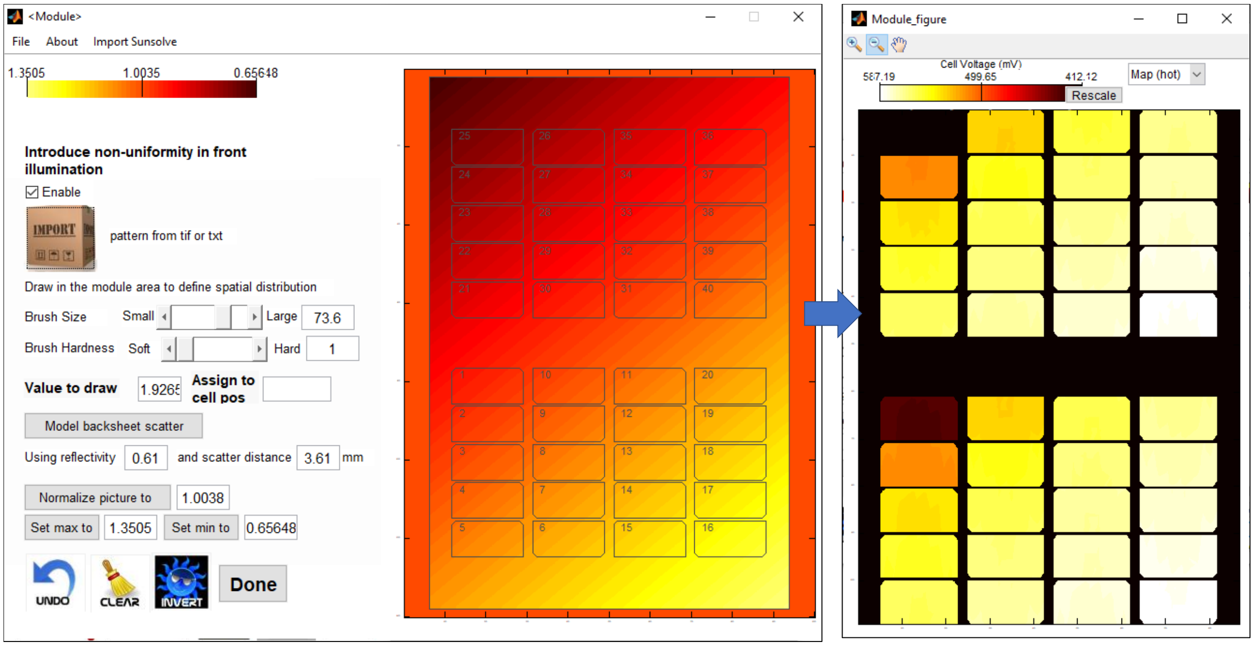


After loading the picture, you can make adjustments to the intensity by setting the maximum and minimum levels of the imported image as shown below. Here we set the maximum to 1 (Sun) and minimum to 0.8 (Suns). To the right is the resultant simulated front cell voltage near MPP:

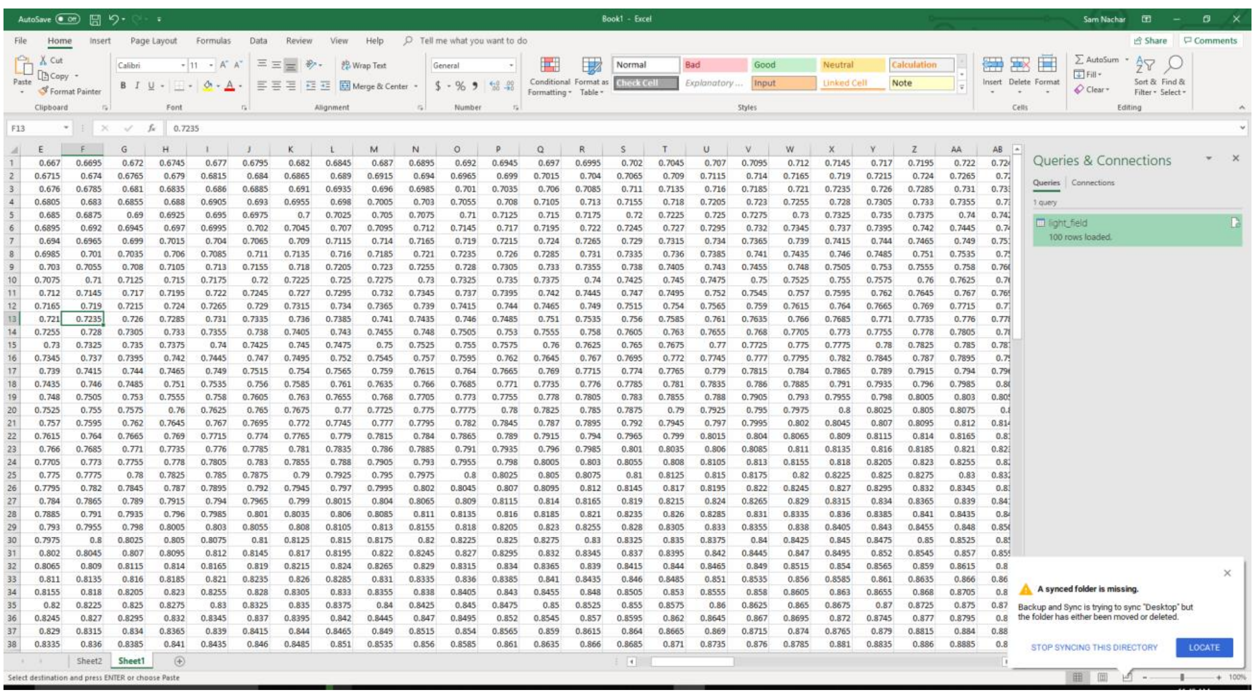


There is a more precise way to import picture representing a nonuniform pattern, by importing a text file that has within in an N x M matrix of numbers. In this case, Module will assign these numbers exactly to the nonuniform picture inside the module frame.

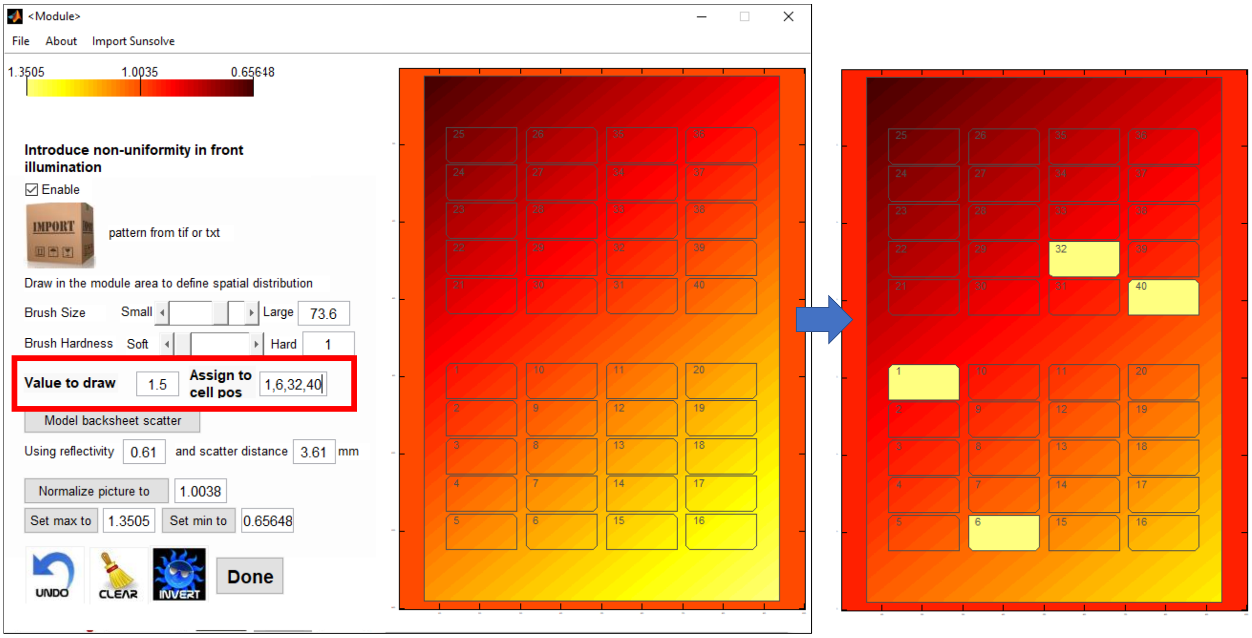




In this example we imported a text file called light_field.txt. If we open it in excel, we see that it is a 100 x 100 array of numbers. The upper left corner of the matrix has a value of 0.657. This is exactly the number which has been assigned to the upper left corner of the module frame.

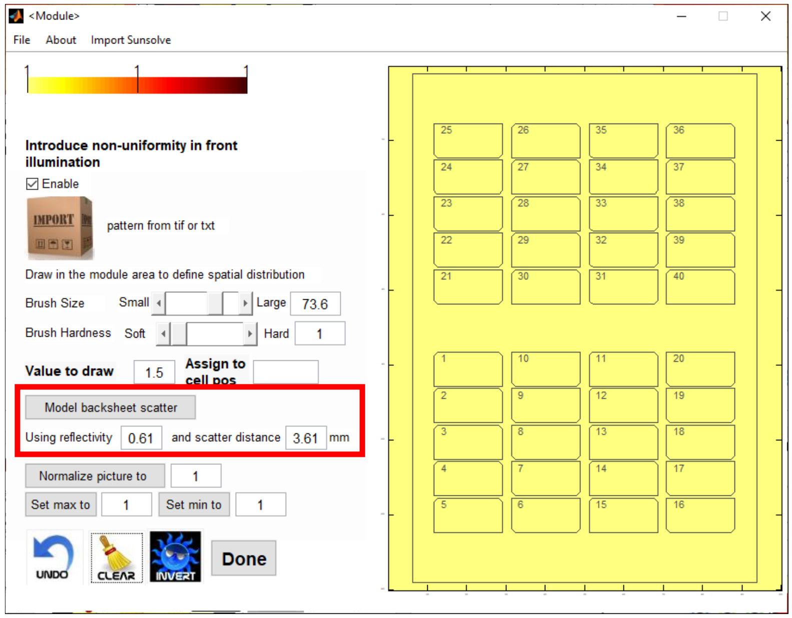


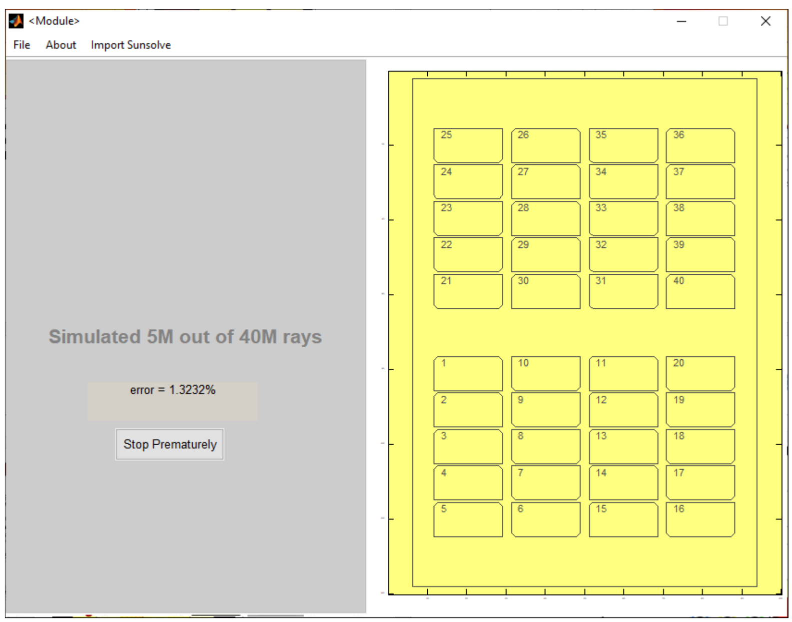
Besides using the brush, you can also set the value to draw, and then put the cell numbers to assign the value to. In this example we assign 1.5 to cell positions 1,6,32,40:

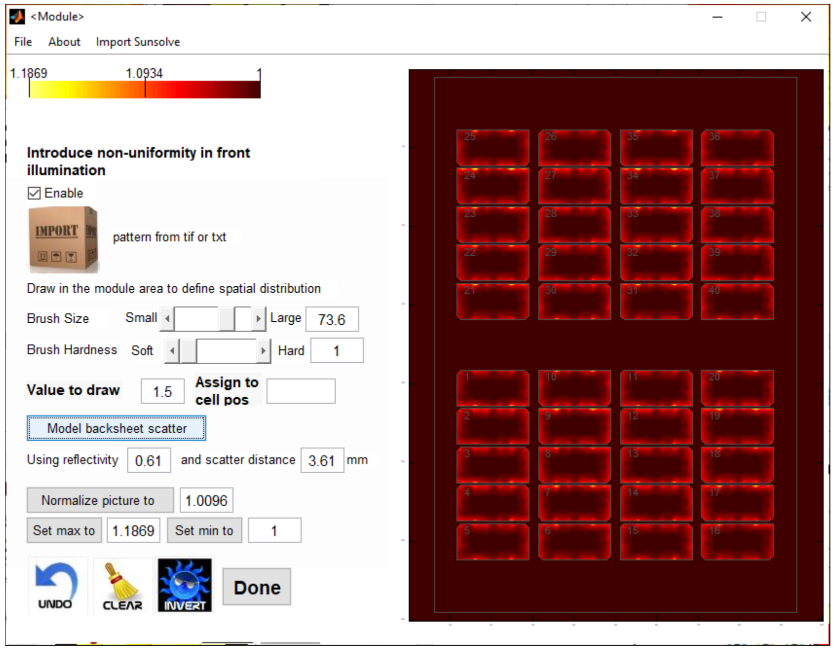


Let’s go back to the example where we imported a jpg representing leaf shading. We hit “Done” to go back to the main screen, and we can hit MAP to run a simulation (at this example at 37V) to see the impact of the shading on the cell voltage near MPP condition. Of course, you can also re-run the I-V curve on your own.

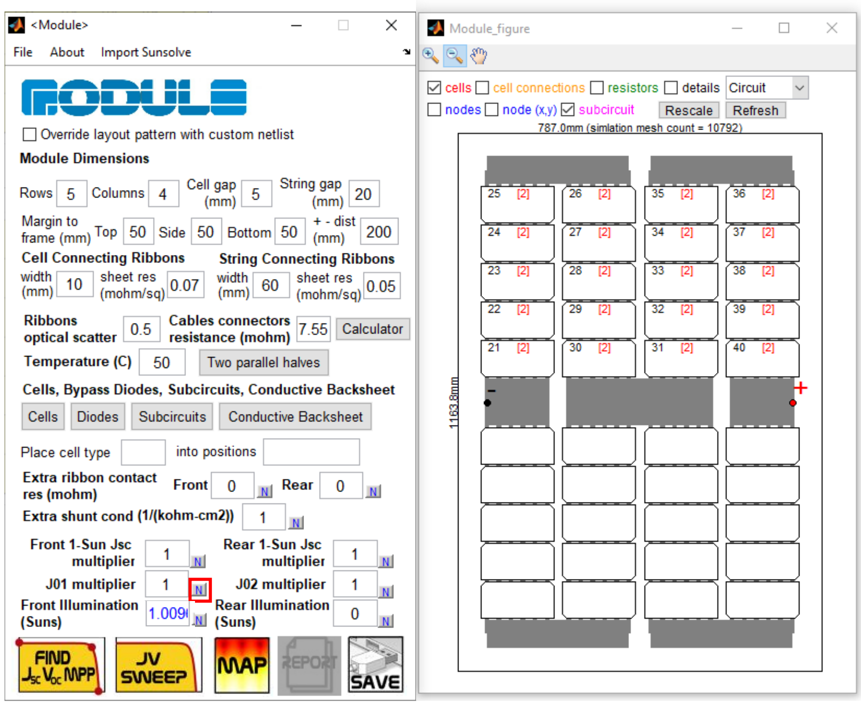
With illumination light fields, you’ll notice that there is an additional tool to define non-uniform light distribution, called “Model backsheet scatter”. This is a rough tool that calculates the enhanced light absorption in the solar cell due to light incident on the backsheet, in the gaps between cells or gap between cell and the module frame. The user must enter the backsheet total reflectance, as well as the scatter distance, which describes the point spread function of the light scattering laterally inside the module. Feel free to explore this calculator on your own and run some simulations. Here, first we clear the shaded pattern light field by pressing “Clear” in the non-uniform spatial distribution page for Front illumination, and then pressing “Model backsheet scatter” using the default reflectivity and scatter distance. You see that the light intensity falling near cell edges is enhanced because of the backsheet scattering.


<Module>
File
About
Import Sunsolve
Introduce non-uniformity in front illumination
Enable
pattern from tif or txt
Draw in the module area to define spatial distribution
Brush Size
Small
Large
73.6
Brush Hardness
Soft
Hard
1
Value to draw
1.5
Assign to cell pos
Model backsheet scatter
Using reflectivity
0.61
and scatter distance
3.61
mm
Normalize picture to
1
Set max to
1
Set min to
1
UNDO
CLEAR
INVERT
Done

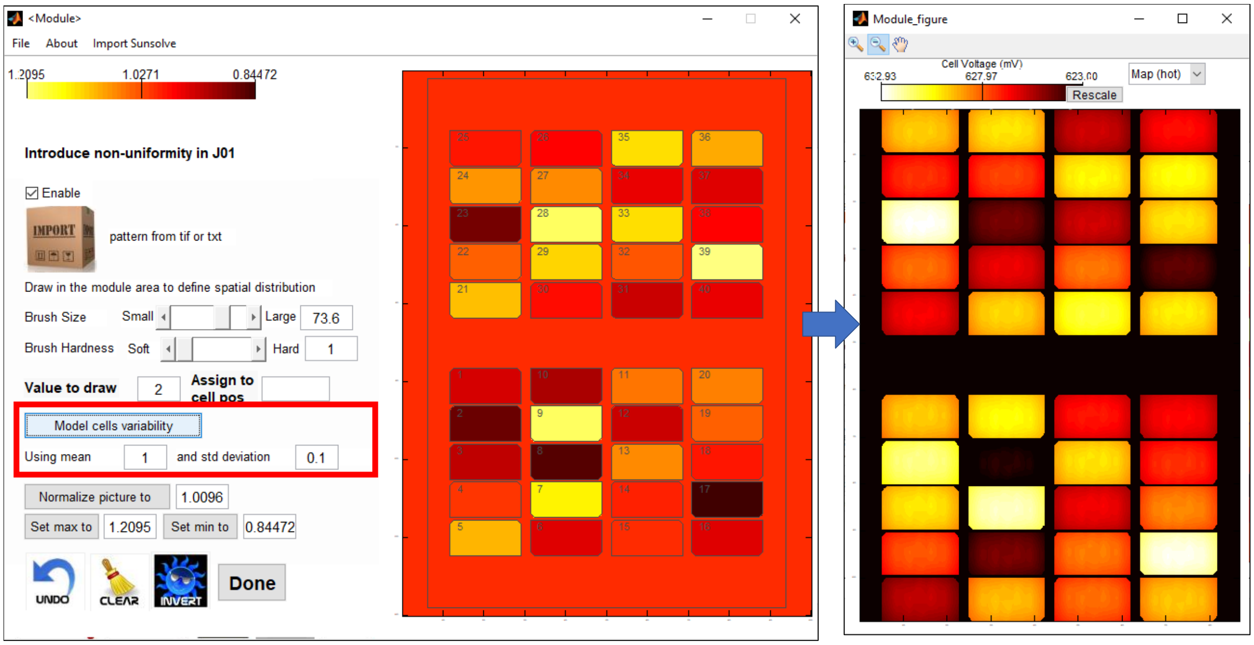

<Module>
File
About
Import Sunsolve
Simulated 5M out of 40M rays
error = 1.3232%
Stop Prematurely



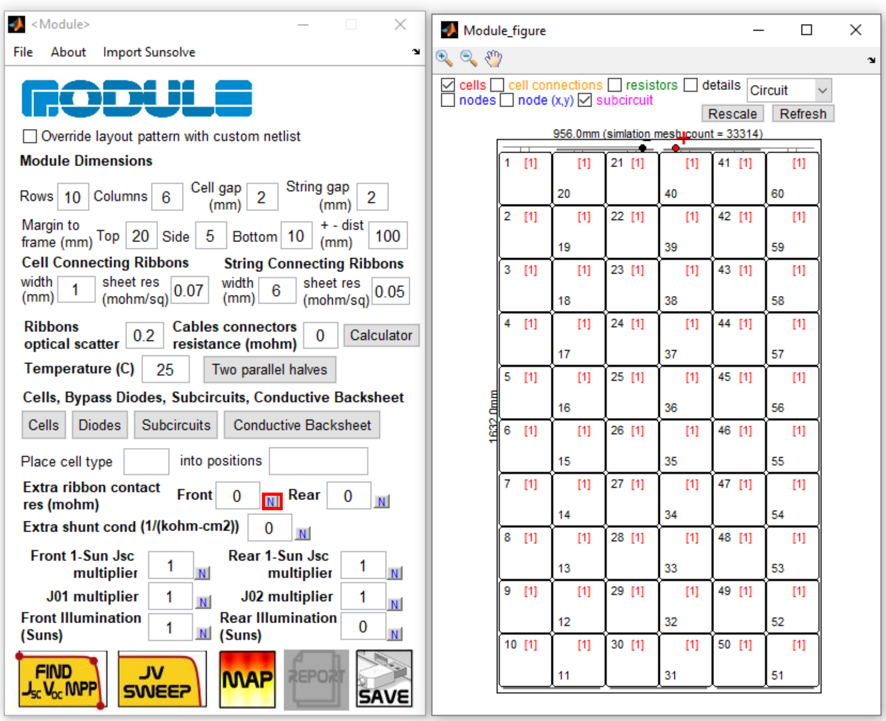
For the diiode parameter multipliers (1 Sun Jsc and J01, J02), one can also model cell to cell variability within the module. In this example below, press the blue N button next to "J01 multiplier", which is a modification factor to the J01 (recombination) of the cell type at the positions within the module.



In the window to define the spatial distribution of the J01 multiplier, press "Model cells variability" using mean 1 and standard deviation of 0.1. You can see that each cell will be randomly assigned a value according to normal distribution of mean 1 and standard deviation 0.1. Below we show this and the resultant front cell voltage at open-circuit conditions.



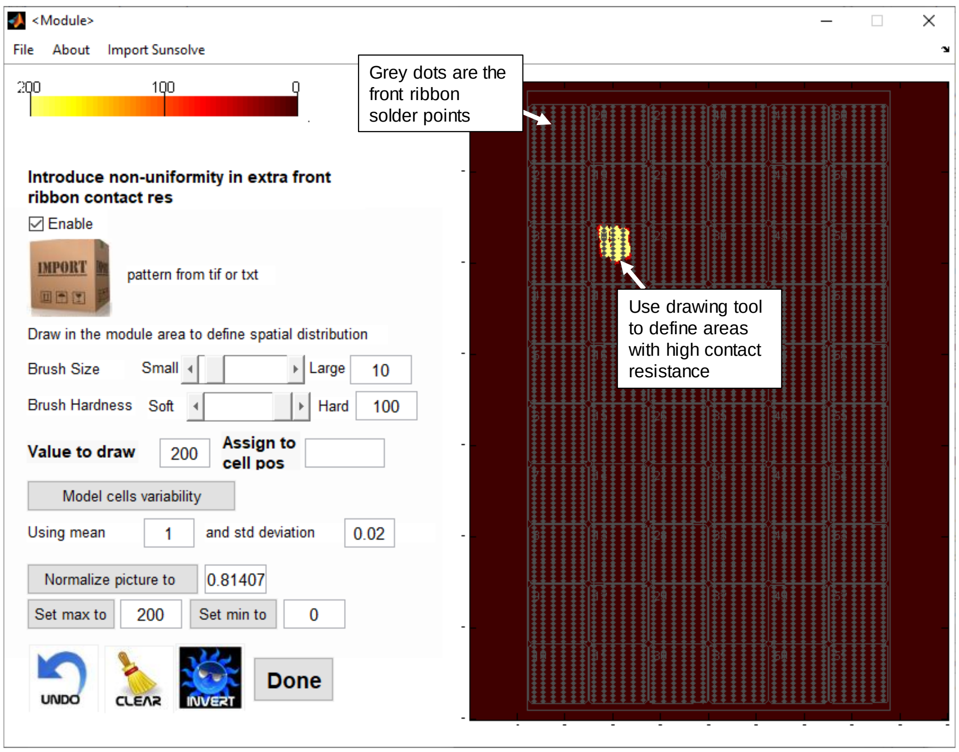
3.8 Extra Ribbon Solder Point Contact Resistance



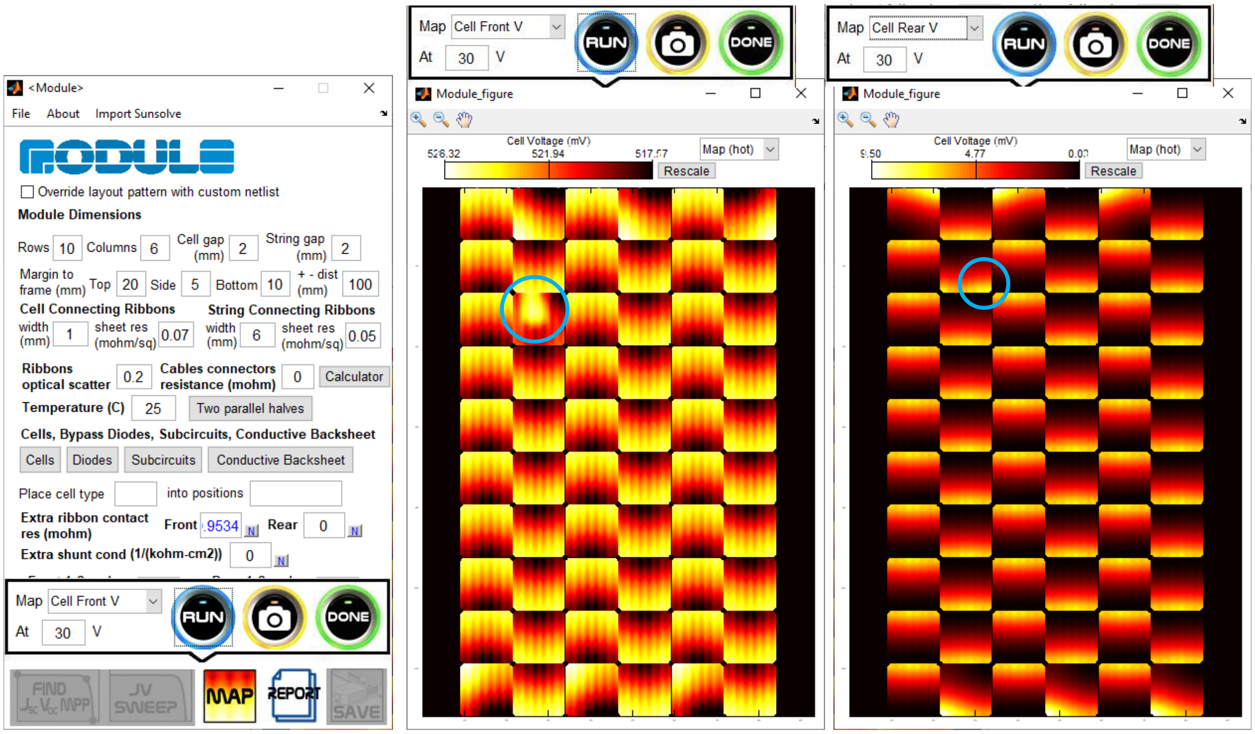
There is much interest in the investigation of whether a certain interconnection scheme is robust against imperfect solder joint/conductive adhesive joint contacts, or deterioration of contacts as the module is used in the field over time. In section 4.5, we will illustrate a very precise way of modelling nonzero ribbon joint contact resistance, by editing the Griddler cell model and then introducing the cell model into Module.

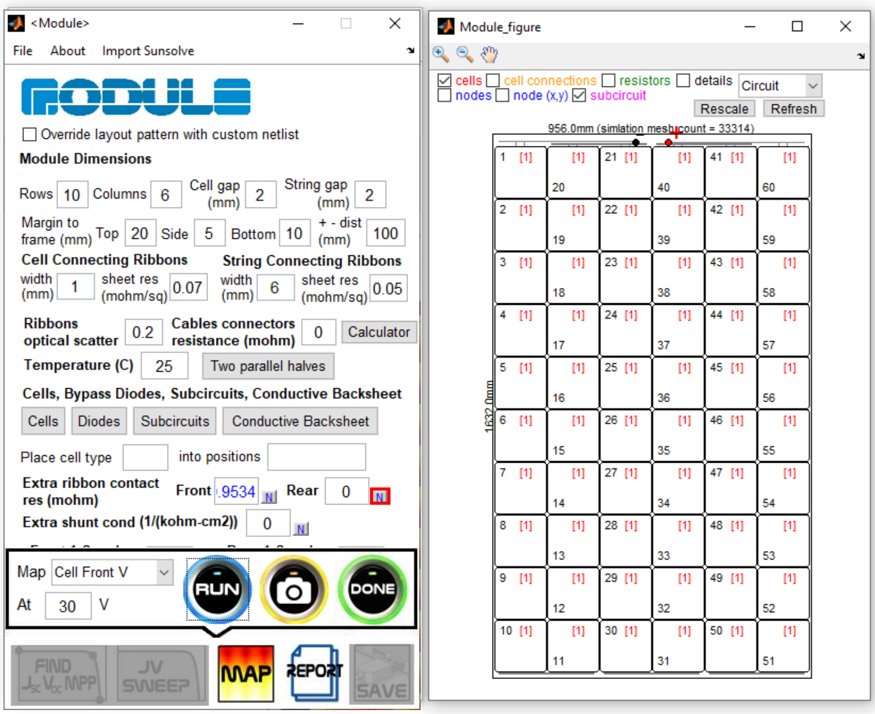
However, this method is time consuming because the cell analysis process takes a long time, and also, only users with software bundle license has access to Griddler 2.5 PRO for cell level editing. So, we have also introduced a much quicker way to allow the user to directly define joint contact point resistance in Module itself.

To introduce front side ribbon contact resistance, you can either directly enter a non-zero number into the box next to Extra ribbon contact res Front. This will assign that number in mohms to all front ribbon solder joint points in the module. Very frequently, one might want to investigate the impact of incidental bad contact resistance that occur locally in certain areas of the module. To do that press the blue N button next to “Extra ribbon contact res (mohm) Front”. As above, this will bring you to the interactive screen to define the nonuniform front ribbon contact resistance, where, as before, you can either import a picture describing the spatial pattern, or use the drawing tool to define areas with high contact resistance, as shown below.

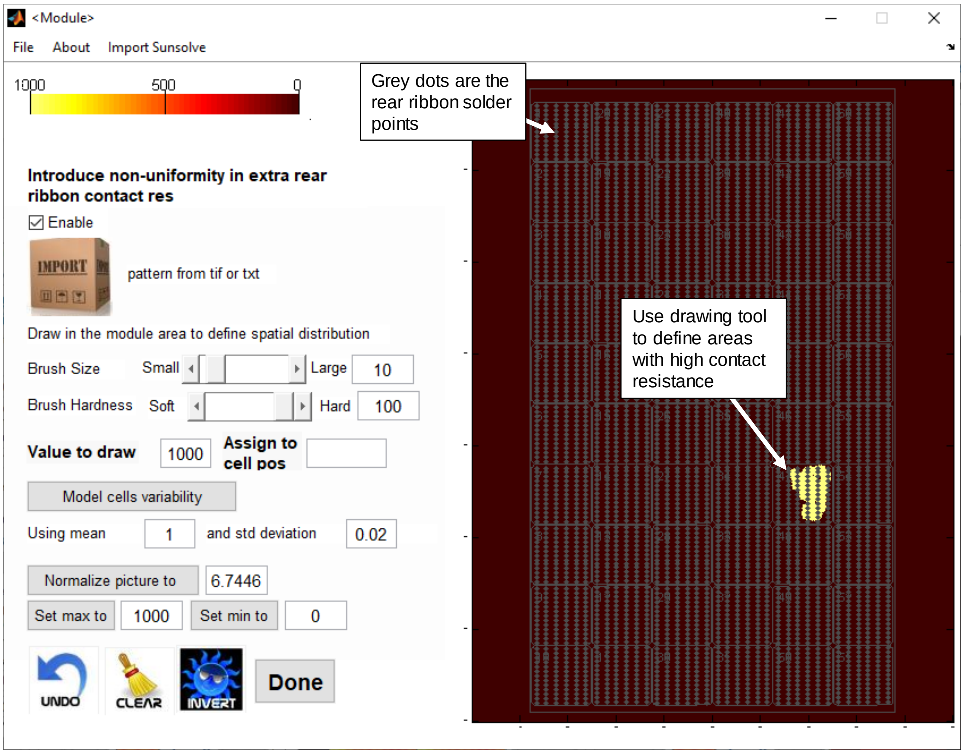


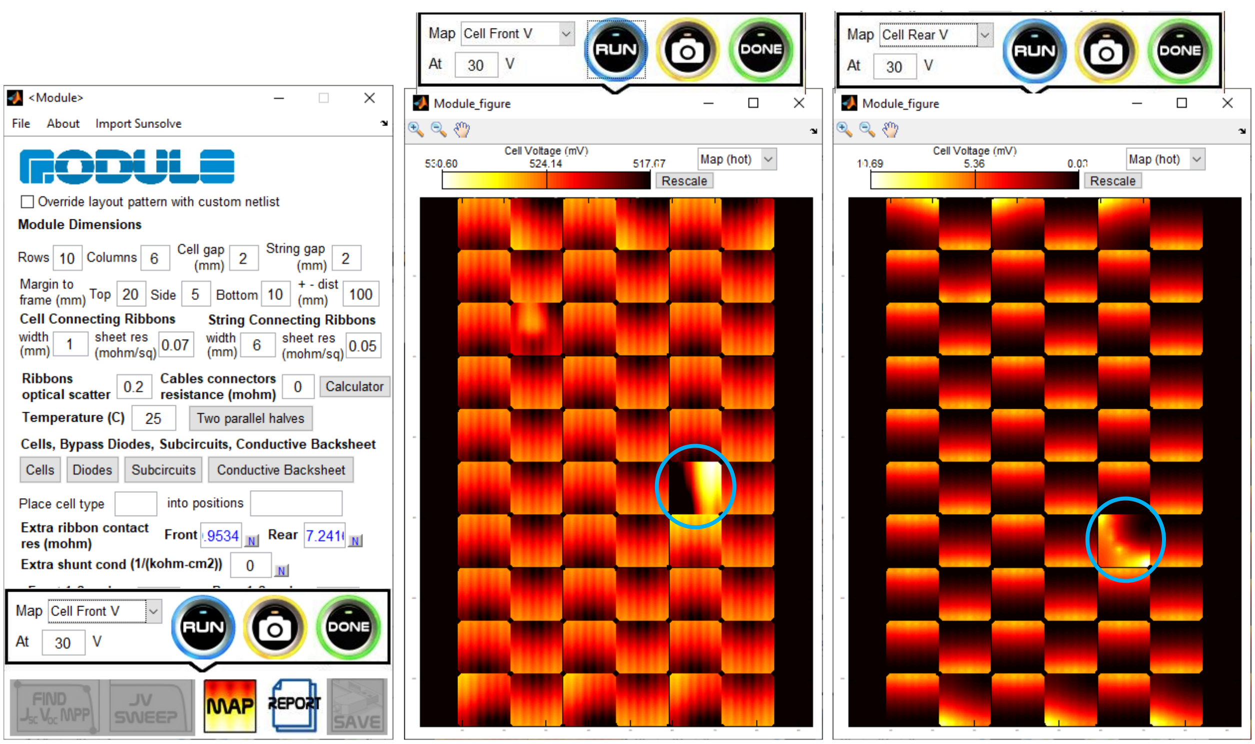
Once done, the average front ribbon contact resistance will be displayed as a blue number in the main screen, and the simulations will incorporate these additionally added contact resistance. In the example below, we show the cell front and rear voltage drops at 1 Sun illumination and 30V. One can see that the extra contact resistance has caused the voltage to swell locally, and has also slightly altered the rear side voltage pattern of the neighbouring cell.





Similarly, to introduce rear side ribbon contact resistance, you can either directly enter a non-zero number into the box next to Extra ribbon contact res Rear, or introduce a spatial pattern by pressing the blue N button next to “Extra ribbon contact res (mohm) Rear”. Once done, the average rear ribbon contact resistance will be displayed as a blue number in the main screen, and the simulations will incorporate these additionally added contact resistance.

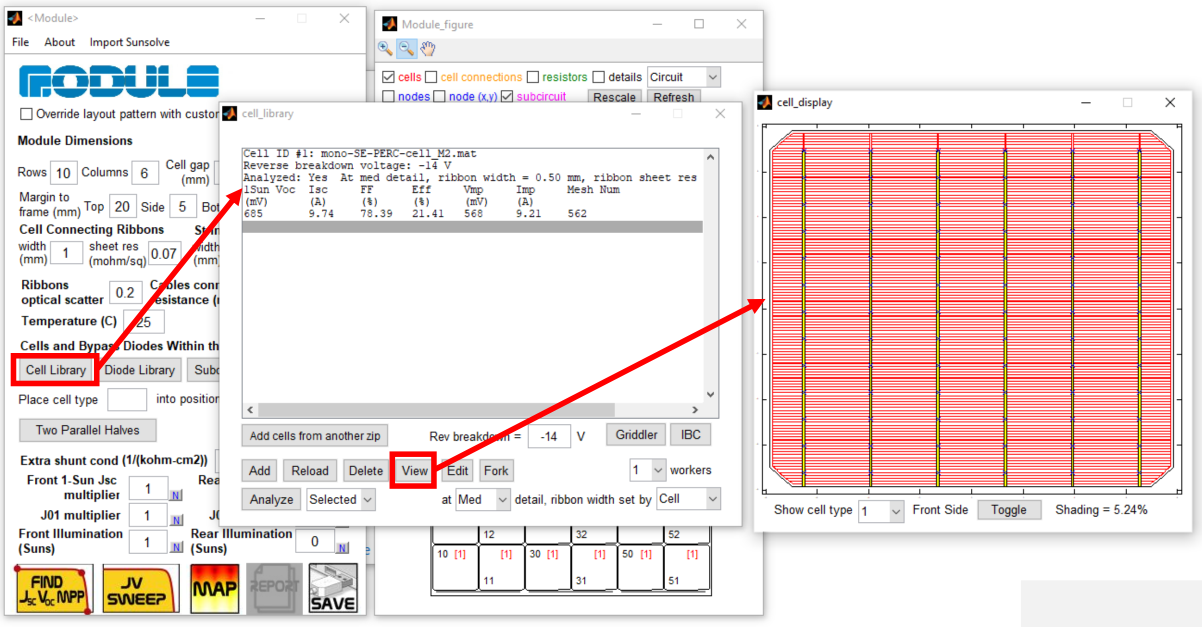

<Module>
File About Import Sunsolve
1000 500 0
Introduce non-uniformity in extra rear ribbon contact res
Enable
pattern from tif or txt
Draw in the module area to define spatial distribution
Brush Size Small Large 10
Brush Hardness Soft Hard 100
Value to draw 1000 Assign to cell pos
Model cells variability
Using mean 1 and std deviation 0.02
Normalize picture to 6.7446
Set max to 1000 Set min to 0
UNDO
CLEAR
INVERT
Done
Grey dots are the rear ribbon solder points
Use drawing tool to define areas with high contact resistance


<Module>
File About Import Sunsolve
Override layout pattern with custom netlist
Module Dimensions
Rows 10 Columns 6 Cell gap (mm) 2 String gap (mm) 2
Margin to frame (mm) Top 20 Side 5 Bottom 10 + - dist (mm) 100
Cell Connecting Ribbons
String Connecting Ribbons
width (mm) 1 sheet res (mohm/sq) 0.07
width (mm) 6 sheet res (mohm/sq) 0.05
Ribbons optical scatter 0.2
Cables connectors resistance (mohm) 0
Calculator
Temperature (C) 25
Two parallel halves
Cells, Bypass Diodes, Subcircuits, Conductive Backsheet
Cells Diodes Subcircuits Conductive Backsheet
Place cell type into positions
Extra ribbon contact res (mohm) Front 9534 Rear 7.241
Extra shunt cond (1/(kohm-cm2)) 0
Map Cell Front V
At 30 V
RUN
DONE
MAP
REPORT
SAVE
Map Cell Front V
At 30 V
Module_figure
Cell Voltage (mV)
530.60 524.14 517.67
Map (hot)
Rescale
Map Cell Rear V
At 30 V
Module_figure
Cell Voltage (mV)
10.69 5.36
Map (hot)
Rescale

4 Cell Library

4.1 Introduction

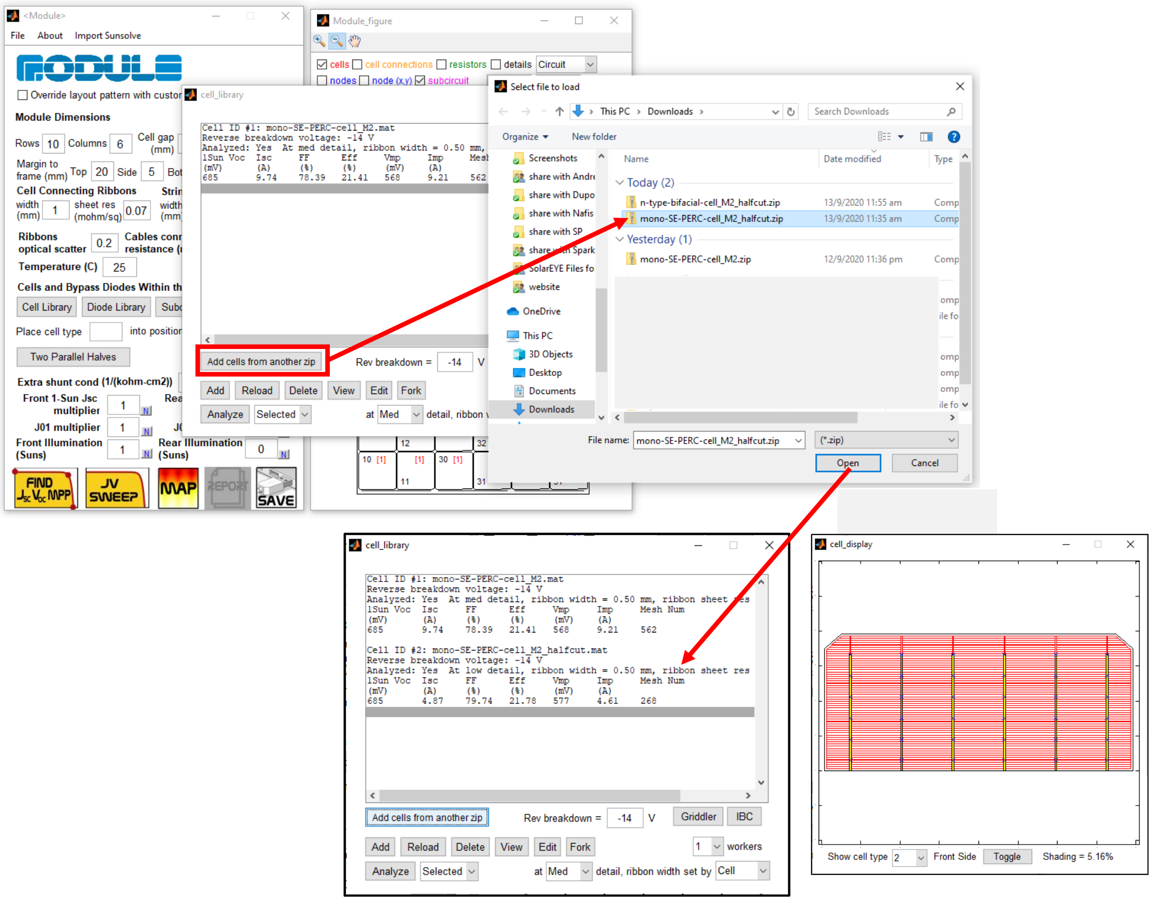
The cell library stores different cell models ready to be placed into the module. Here we start from the beginning and click File → Open → and load mono-SE-PERC-cell_M2.zip. Click Cell Library to open it. There is one cell type in the library. Click view to look at the schematic of this cell.



There are two ways to add more cell types into this session:

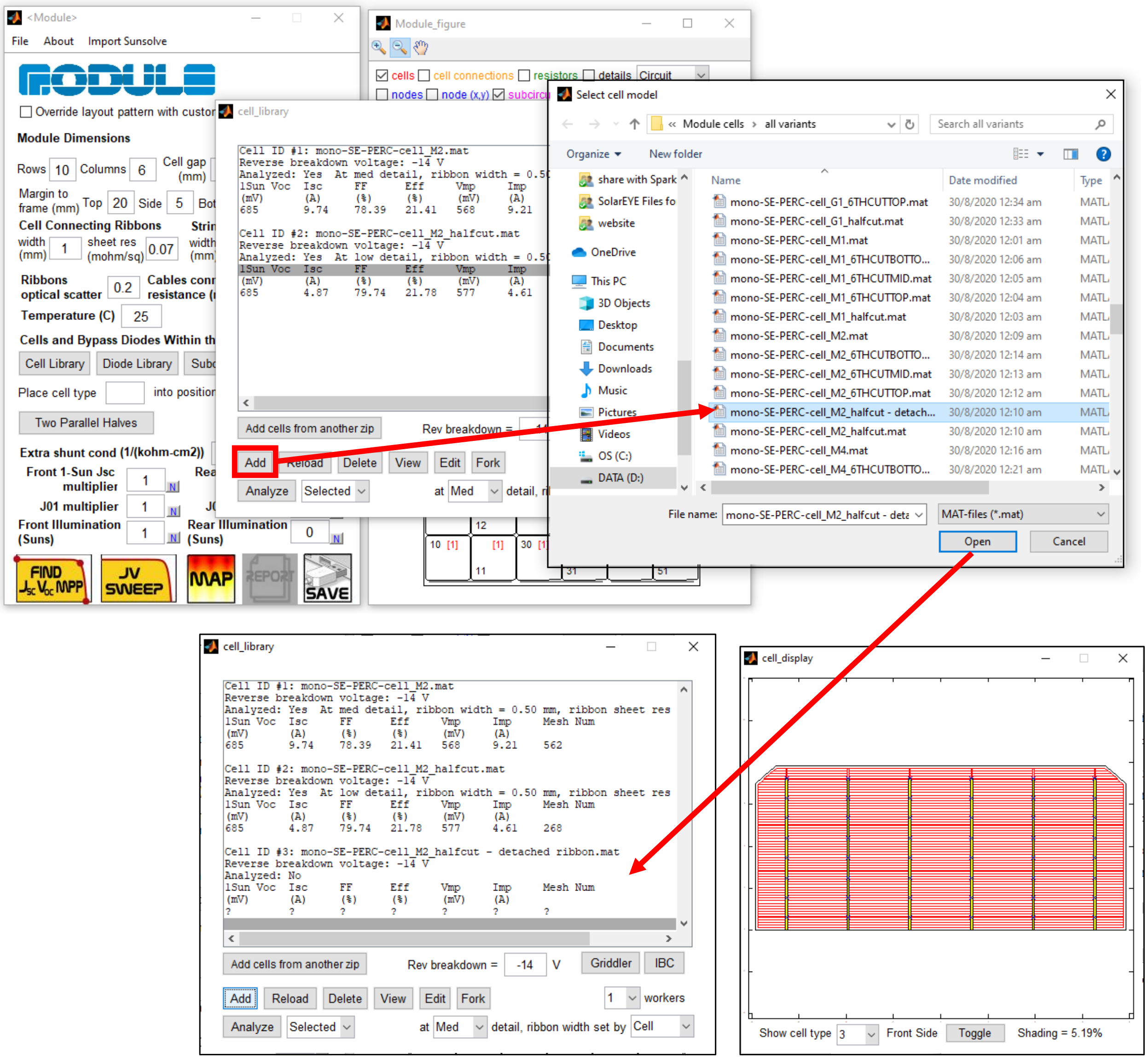
4.2 Adding Cells from Zip File

Clicking “Add cells from another zip” will load cell types that exist in other zipped session files. This cell type can be readily inserted into the Module and used in simulation.



4.3 Adding Cells from Griddler Files (For users with bundled software license)

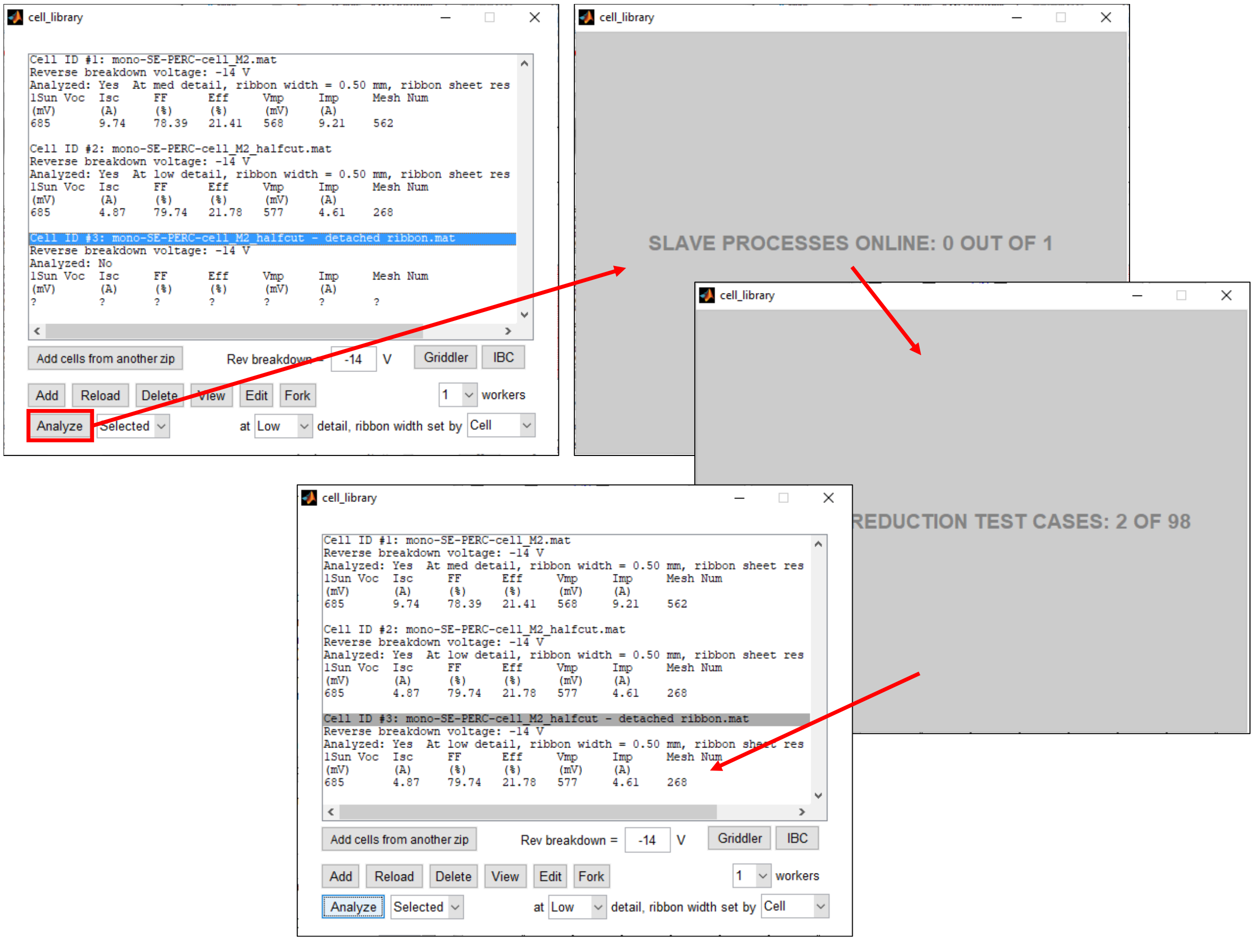
[For users with bundled software license] Clicking “Add” allows you to load Griddler cell models (multiple selection is permitted). Because the cell model is in the Griddler format with a high number of FEM nodes, this cell type cannot be immediately used in Module simulation. First it needs to go through a reduction process, where a smaller Module cell model with fewer number of FEM nodes is generated based on the Griddler cell model.



4.4 Analyzing Griddler Cells Files (For users with bundled software license)

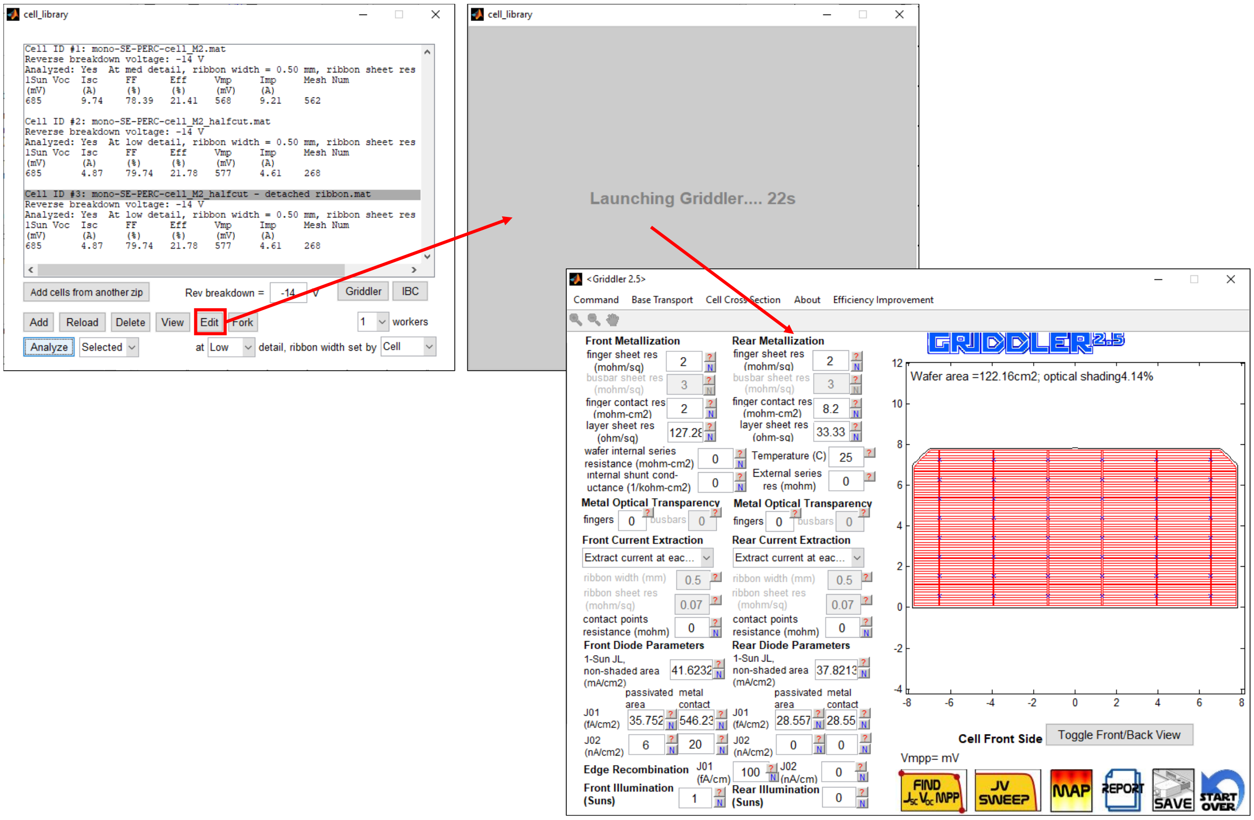
[For users with bundled software license] Choose the newly imported Griddler cell model. Choose the level of detail you wish to generate the reduced Module cell model. We recommend “Medium” for full size cell, “Low” for half cut cells, and “very low” for 5^{th} or 6^{th} cut cells. Click “Analyze” and a process of Griddler simulation and analysis will take place to generate the reduced Module cell model. This process will take a few minutes.

It is also possible to analyze multiple loaded Griddler cell models. To do so, in the popup menu that says “Selected”, choose “Cell #s” and then an edit box will appear allowing you to enter the Cell IDs in the library you wish to simultaneously analyze. In the popup menu that says “1” workers, you can choose up to 8 Griddler workers to run the reduction process in parallel.

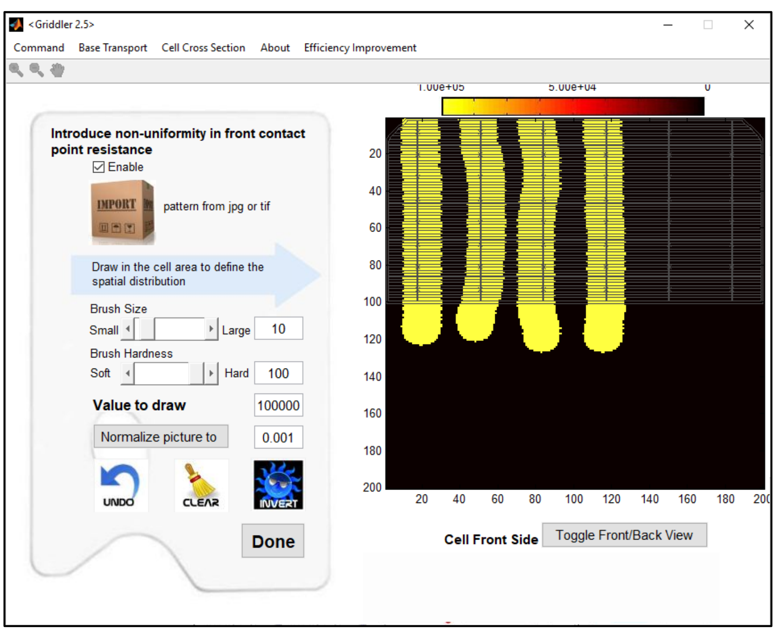


4.5 Editing Griddler Cell Files in Detail (For users with bundled software license)

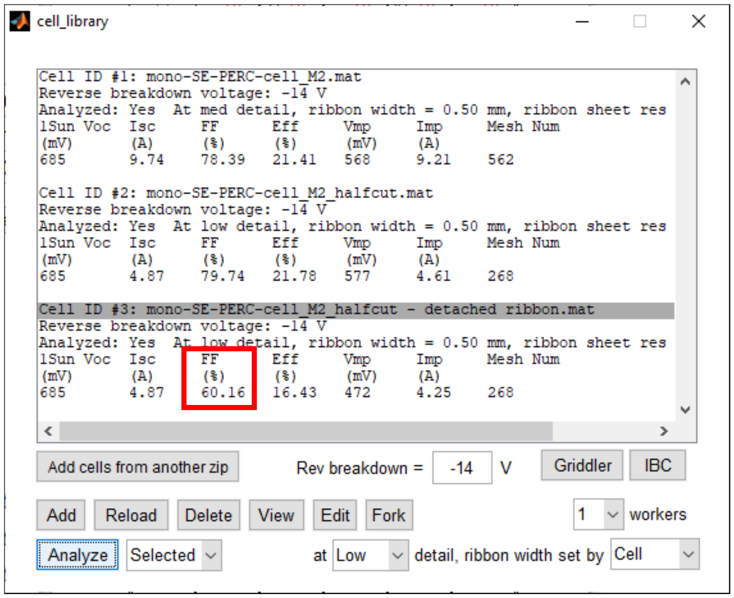
[For users with bundled software license] For cell types loaded from Griddler models, it is always possible to load the original Griddler model in Griddler 2.5 PRO (or if it is an IBC model, in Griddler IBC), edit it in great detail, save it and then re-analyze the cell type in Module. To do so, select the cell type you wish to edit in the listbox, and then press “Edit”.



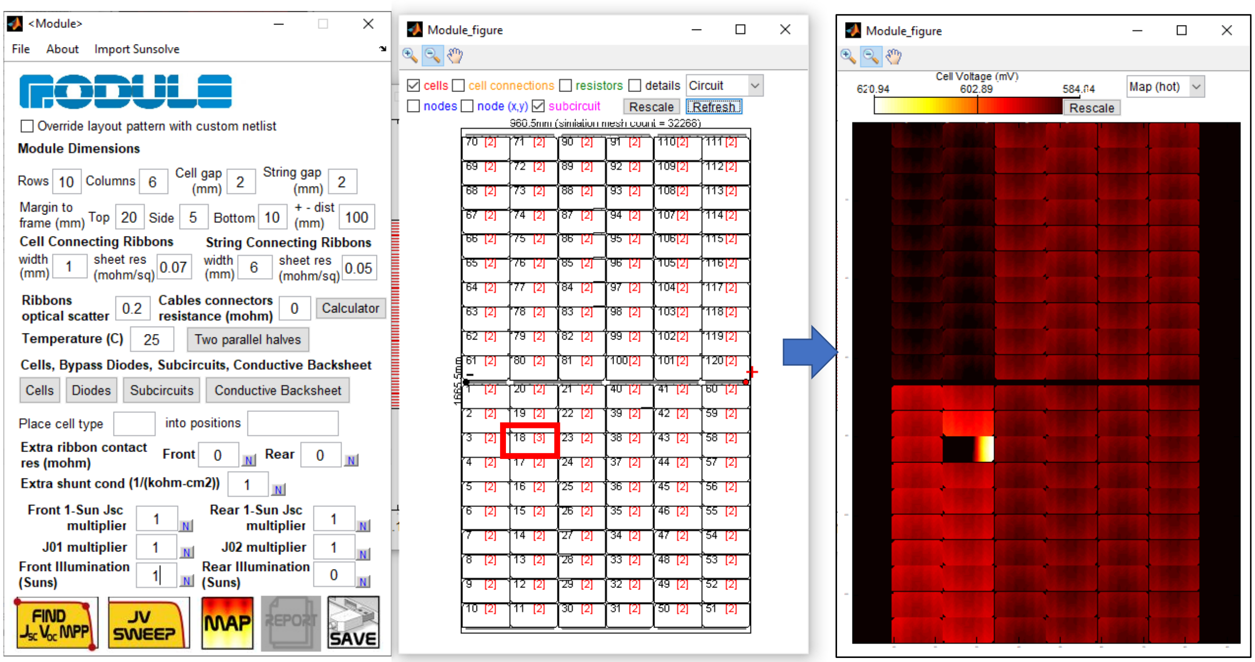
[For users with bundled software license] In this example, we edit the Griddler cell model at a level of detail not possible in Module: we introduce very large solder point contact resistance at 4 of the 6 busbars, thereby simulating 4 detached ribbons. After doing so, we resave the Griddler model



Back in Module, we click “Analyze” to re-analyze this cell type. You can see now the resultant cell FF has dropped from 79.74% (before simulating the detached ribbons) to 60.16% (after simulating the detached ribbons).

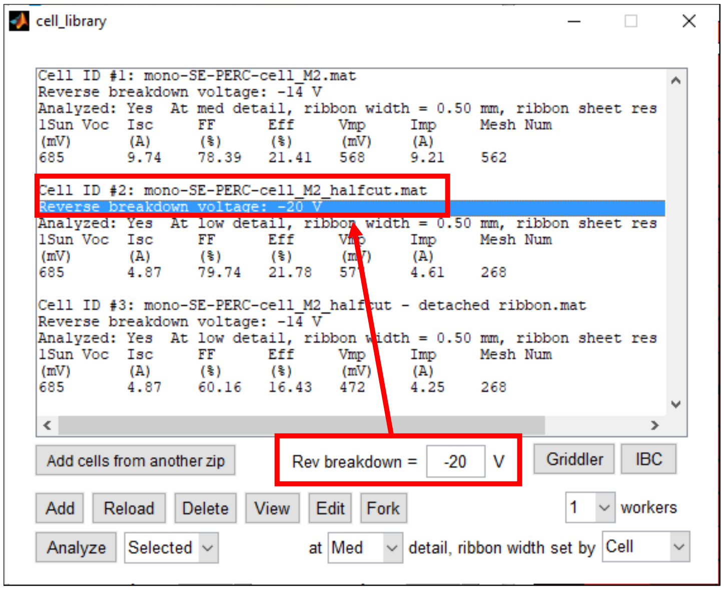


Now, if we created a module where every cell position is populated with cell type 2 (halfcut cell with no detached ribbon) except for position 18 which is populated with cell type 3 (halfcut cell with detached ribbon), we can simulate the effects of such a detached ribbon cell within the module. The picture to the right below shows the front cell voltage distribution near MPP.

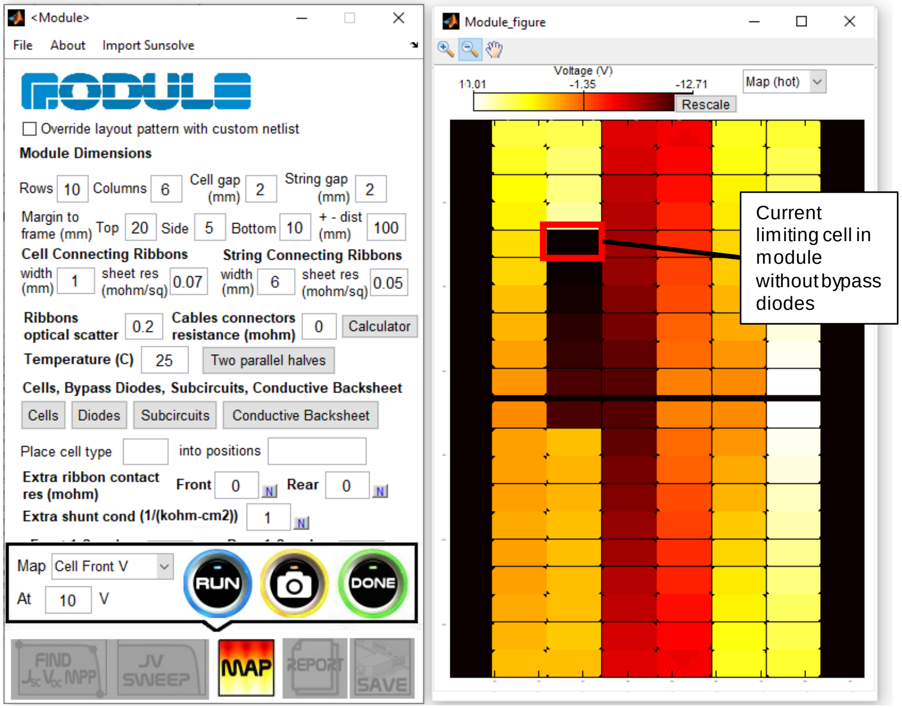


4.6 Reverse Breakdown Voltage

If the imported cell type does not have its own reverse breakdown behavior defined (i.e. hotspots and edge breakdown), you can add a reverse breakdown voltage in the process shown below. **If the imported cell type has its own reverse breakdown characteristics, then Module will emulate it during the cell analysis process (See next section 4.7)**

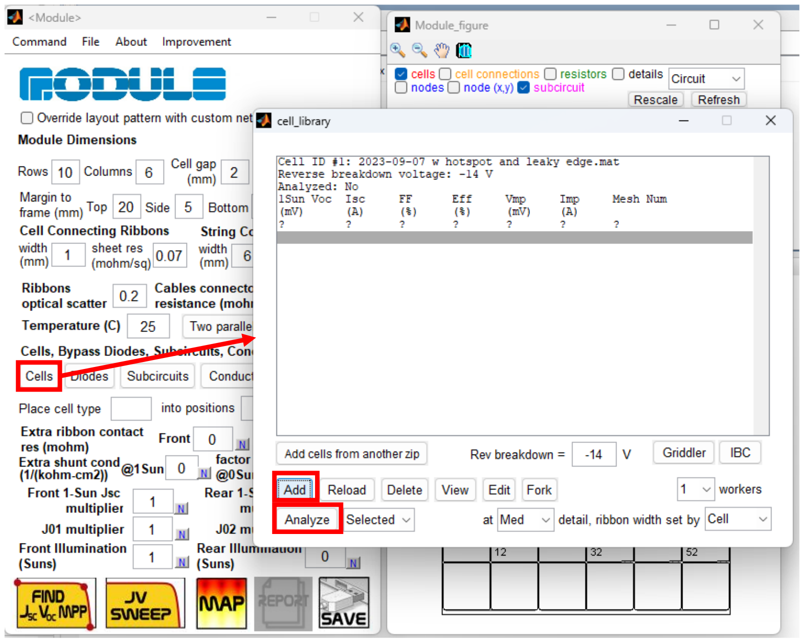


In the example above, we have set cell type 2 reverse breakdown voltage to be -20V. We can see the effect of this setting by running a simulation in which one of the cell is current limiting, and there are no bypass diodes in the module. Below, if we map the module front plane voltage, we can see a step at the current limiting cell, and the step in the voltage is about 20V, meaning that the current limiting cell is revers biased at approximately the breakdown voltage.

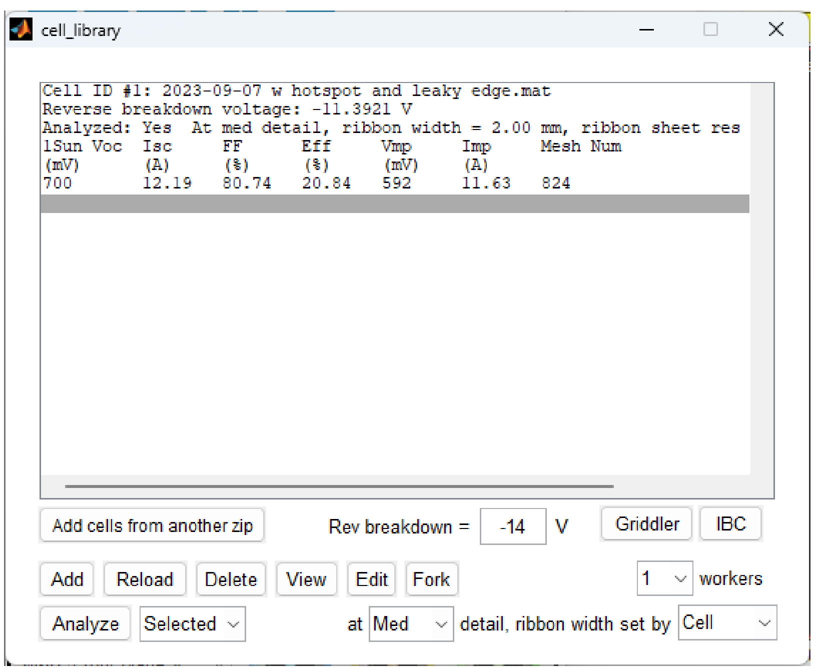


4.7 Detailed Reverse Breakdown Simulations

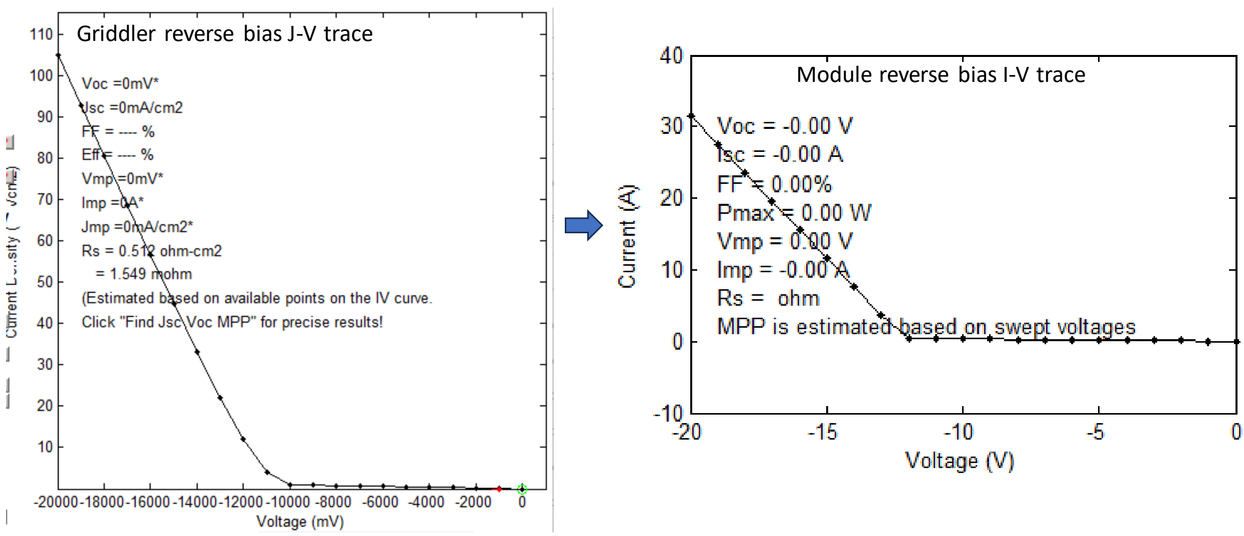
Griddler manual section 6.8 covers the definition of hotspots and wafer edge breakdown on the cell level. Once done, one can as usual add the cell model into the Module cell library to analyze it.



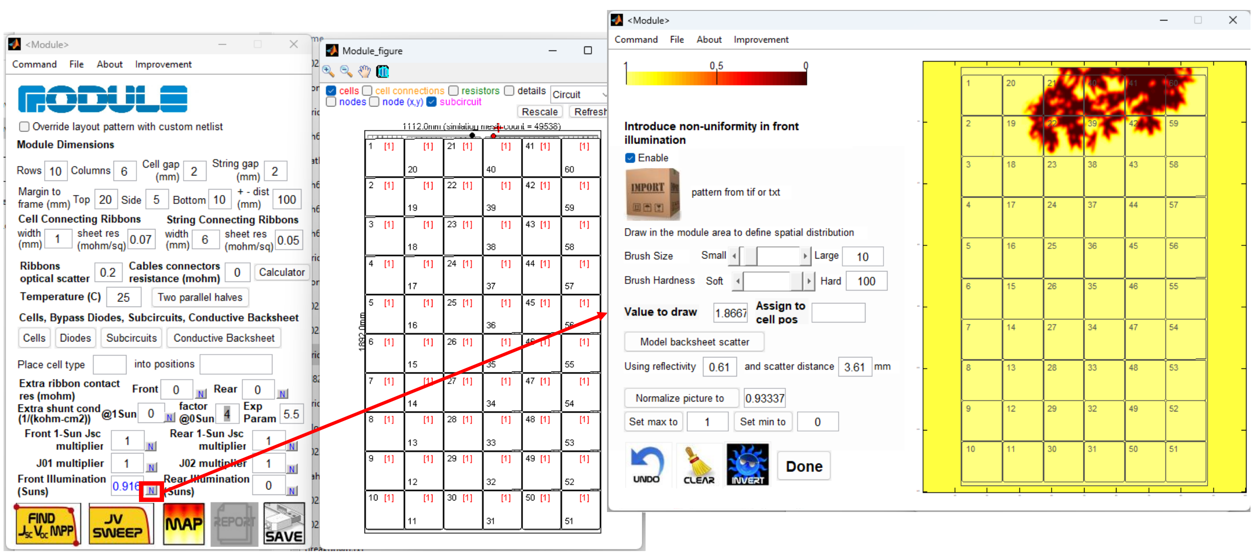
The analysis will result in a reverse breakdown voltage that is consistent with the cell level reverse bias characteristics.



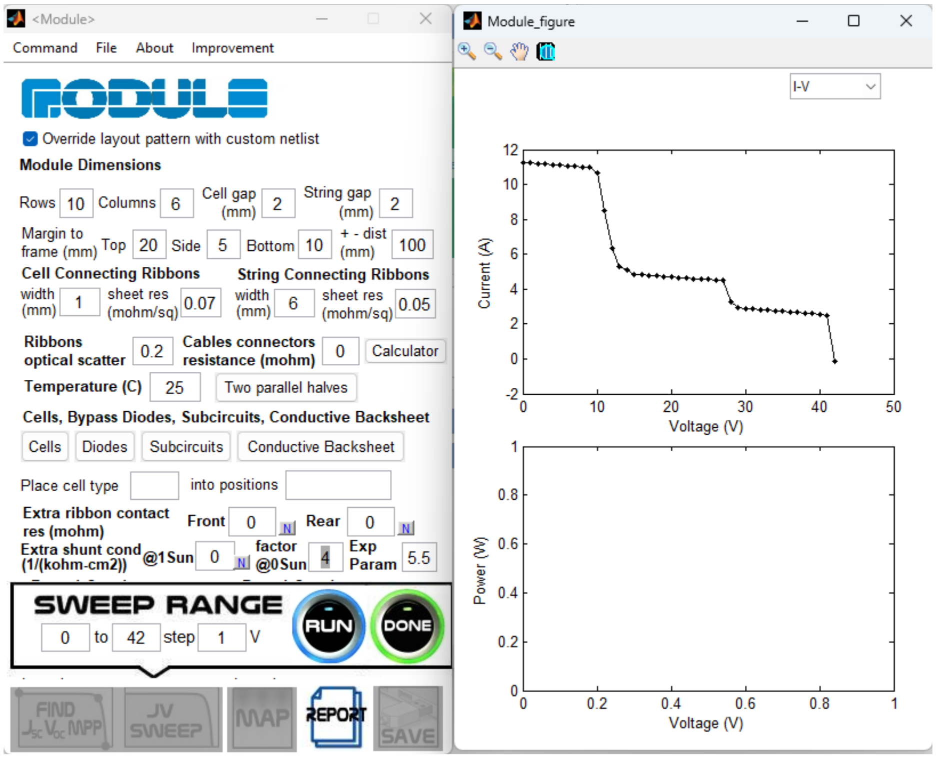
The module reduced cell will have the same reverse bias characteristics as the full Griddler model. Note in the below, the left J-V curve (Griddler, with current density in units of mA/cm^2 and voltage in units of mV) and the right I-V curve (Module, with current in units of A and voltage in units of V) have identical results, after accounting for the cell area of 330.69 cm^2.



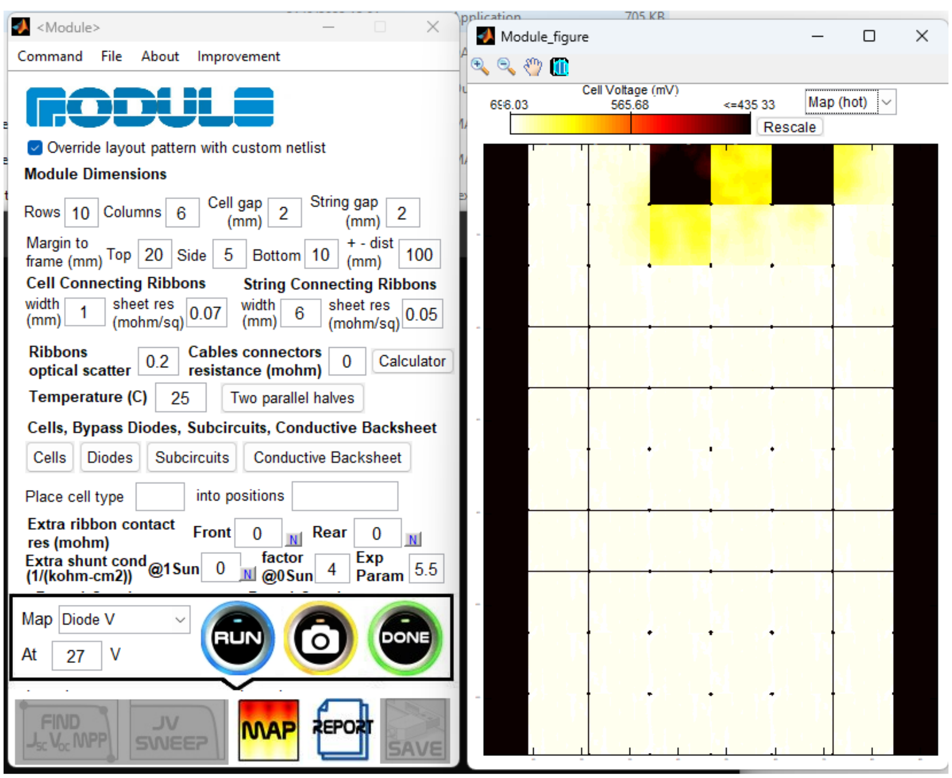
To illustrate a realistic module cell reverse bias condition, below we will simulate a partial shading condition where the front illumination pattern is 1 Sun except at the top section of the module where a few cells are partially shaded by a tree.

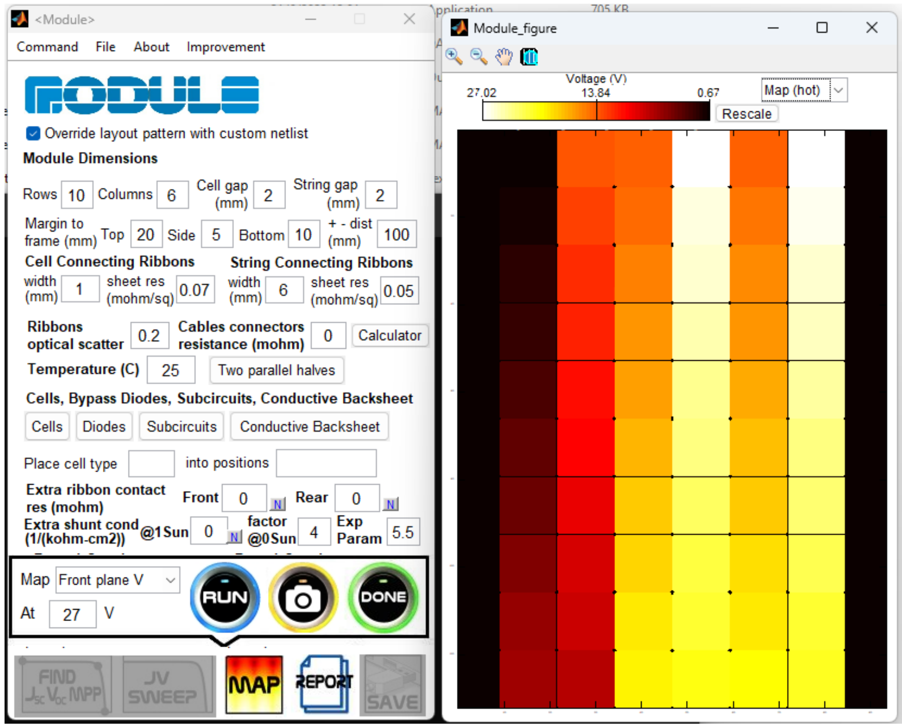


Below is the I-V characteristics under this partial shading condition (the module has three bypass diodes).

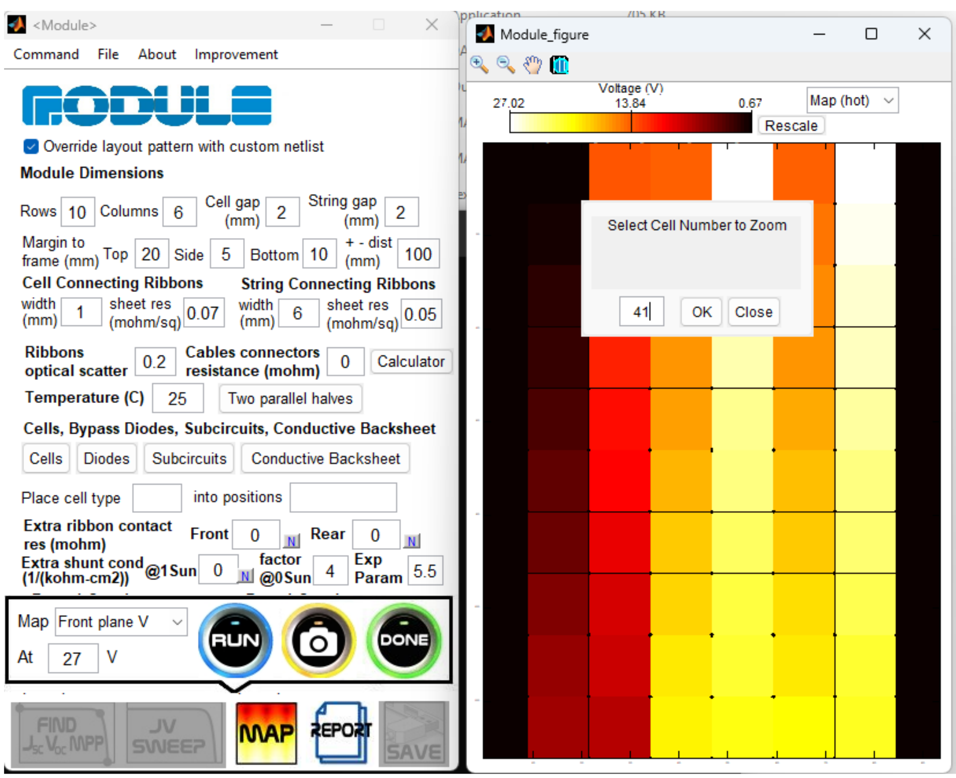


Below are the cell voltages and module cell voltage progression, at the voltage at MPP of 27V:

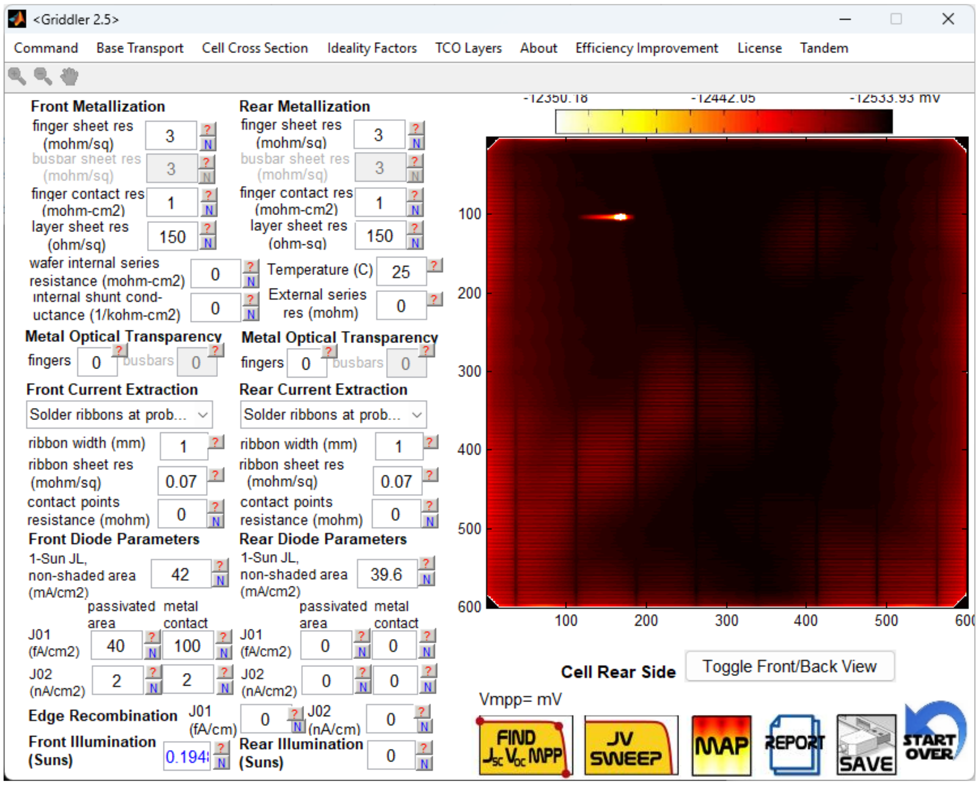


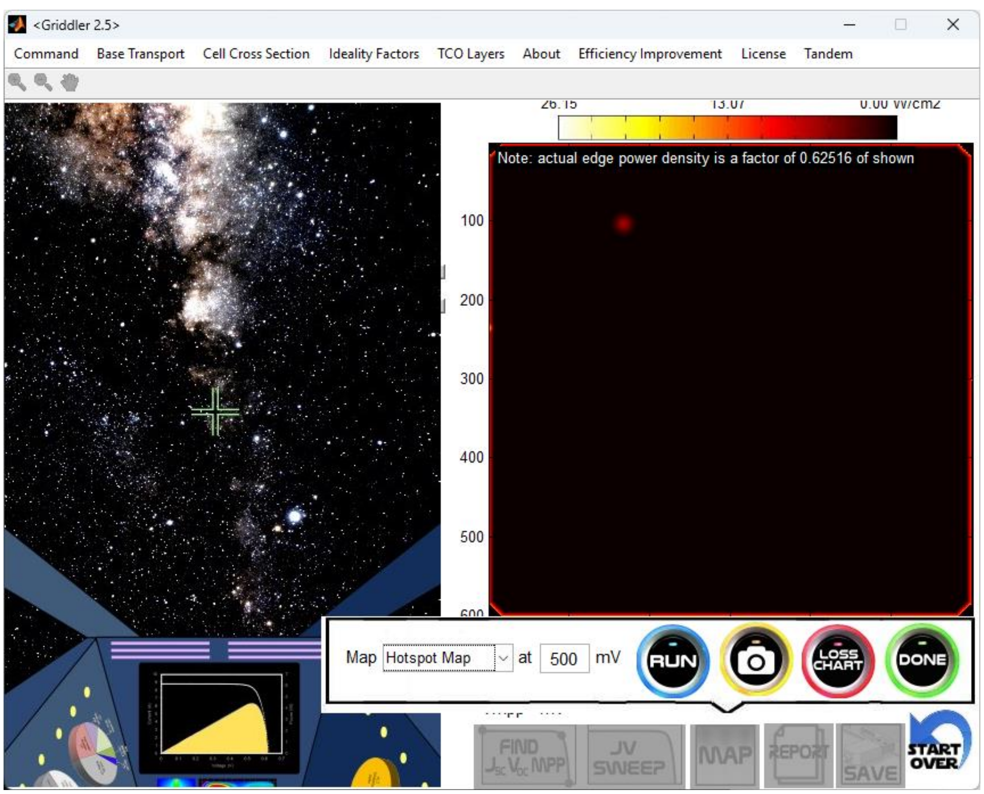


As in P.10 of section 2.2, one can select a cell to zoom in on with detailed Griddler simulation:

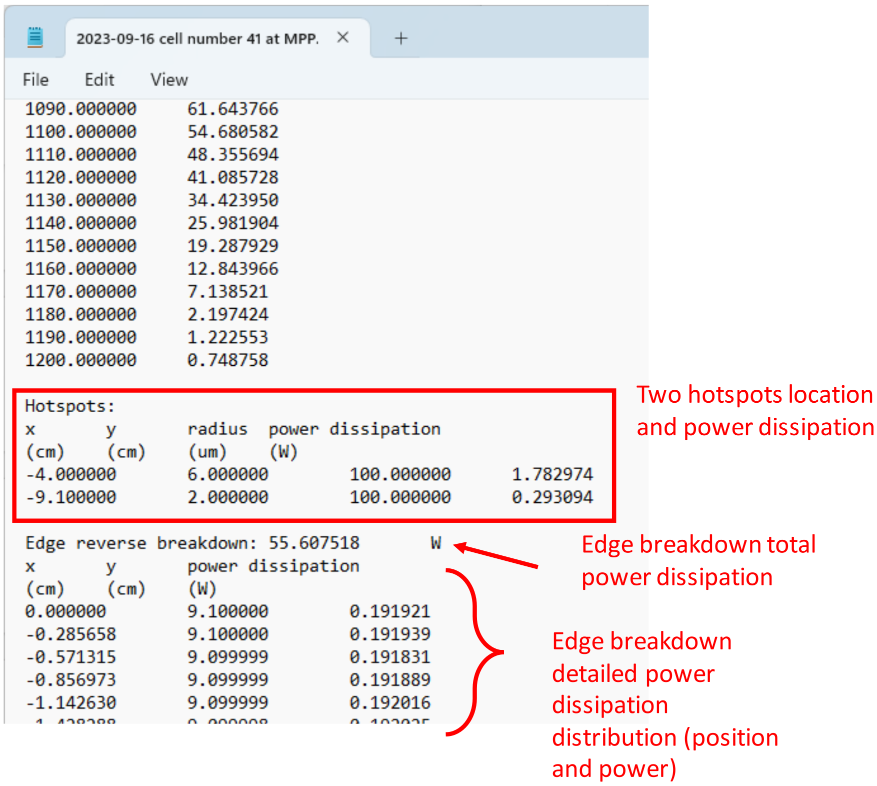


We pick on the shaded and reverse biased cell 41. Here are the detailed Griddler simulation of the shaded cell voltage and hotspot distributions:





Now, in Griddler, when one clicks on report, there will be a record of the hotspot and edge breakdown power dissipation information at the bottom of the report.

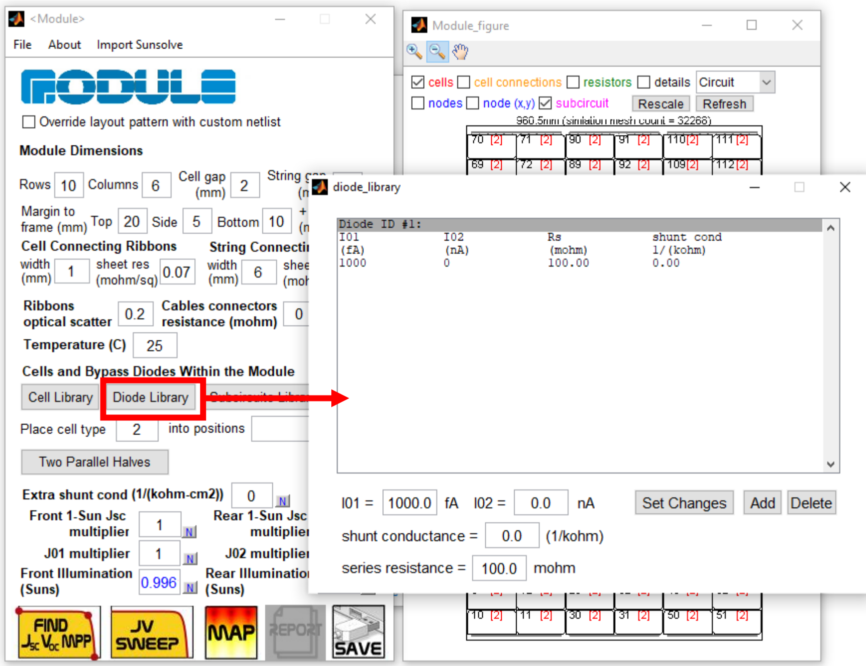


```
2023-09-16 cell number 41 at MPP.
File   Edit   View
1090.000000     61.643766
1100.000000     54.680582
1110.000000     48.355694
1120.000000     41.085728
1130.000000     34.423950
1140.000000     25.981904
1150.000000     19.287929
1160.000000     12.843966
1170.000000     7.138521
1180.000000     2.197424
1190.000000     1.222553
1200.000000     0.748758

Hotspots:
x         y         radius   power dissipation
(cm)      (cm)      (um)     (W)
-4.000000           6.000000          100.000000        1.782974
-9.100000           2.000000          100.000000        0.293094

Edge reverse breakdown: 55.607518        W
x         y         power dissipation
(cm)      (cm)      (W)
0.000000            9.100000          0.191921
-0.285658           9.100000          0.191939
-0.571315           9.099999          0.191831
-0.856973           9.099999          0.191889
-1.142630           9.099999          0.192016
```

5 Diode Library

The diode library lists the bypass diodes. By default there is one bypass diode type. The bypass diode is characterized by a two diode model with recombination currents I_{01}, I_{02}, series resistance R_s and shunt conductance in units of 1/(kohm). You can change these parameters and then click "Set Changes" to apply the changes, or Add to define more bypass diode types.

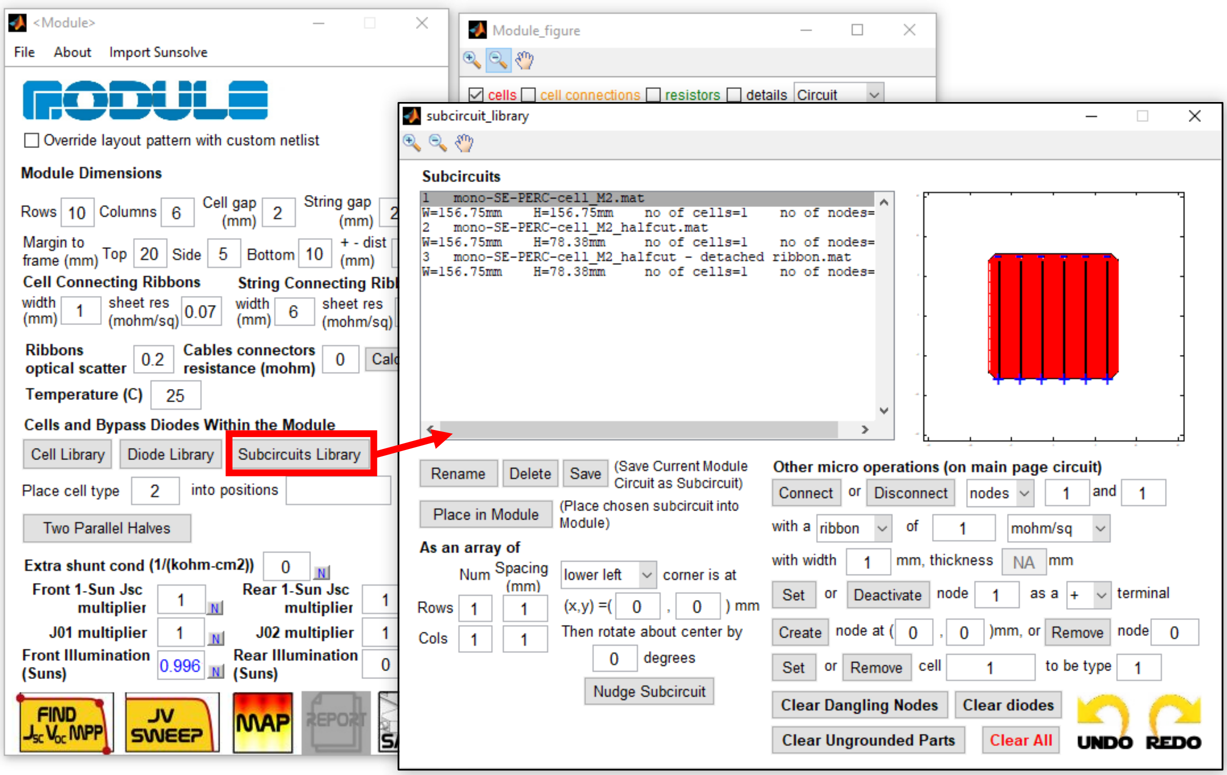
In the next section we will show how to insert bypass diodes into the module.



6 Subcircuits Library

6.1 Introduction

The subcircuit library offers the ultimate flexibility in defining cell layout patterns in the module, insertion and deletion of connections, and other micro operations. It is also the window in which you can insert bypass diodes. To access it, press Subciruits Library in the main screen. As a start, each cell type in the cell library is one subcircuit, as shown below.

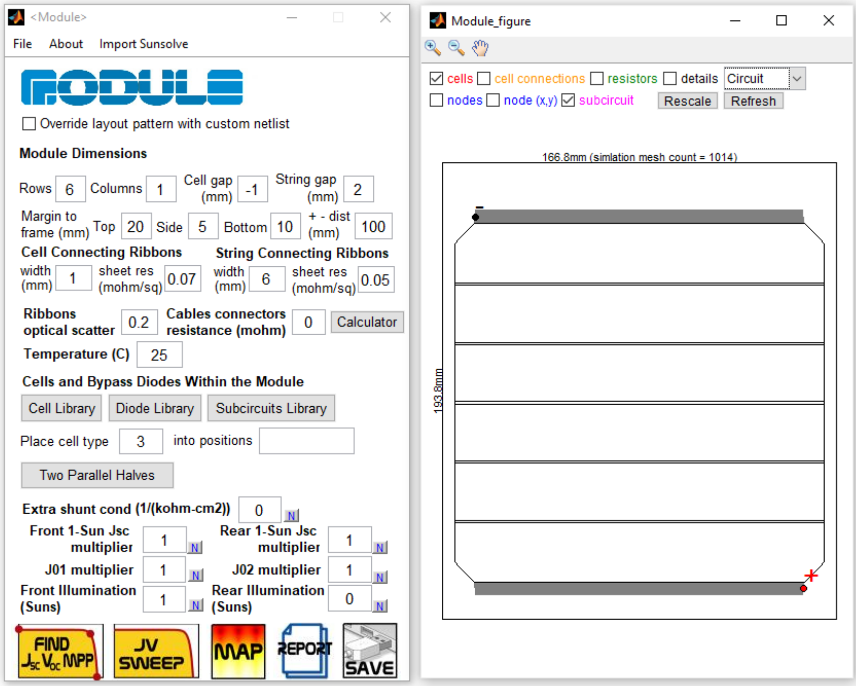


To illustrate the use of the various functions in the subcircuit library, we will start from scratch and build a module that consist of 6th cut mono-PERC cells.

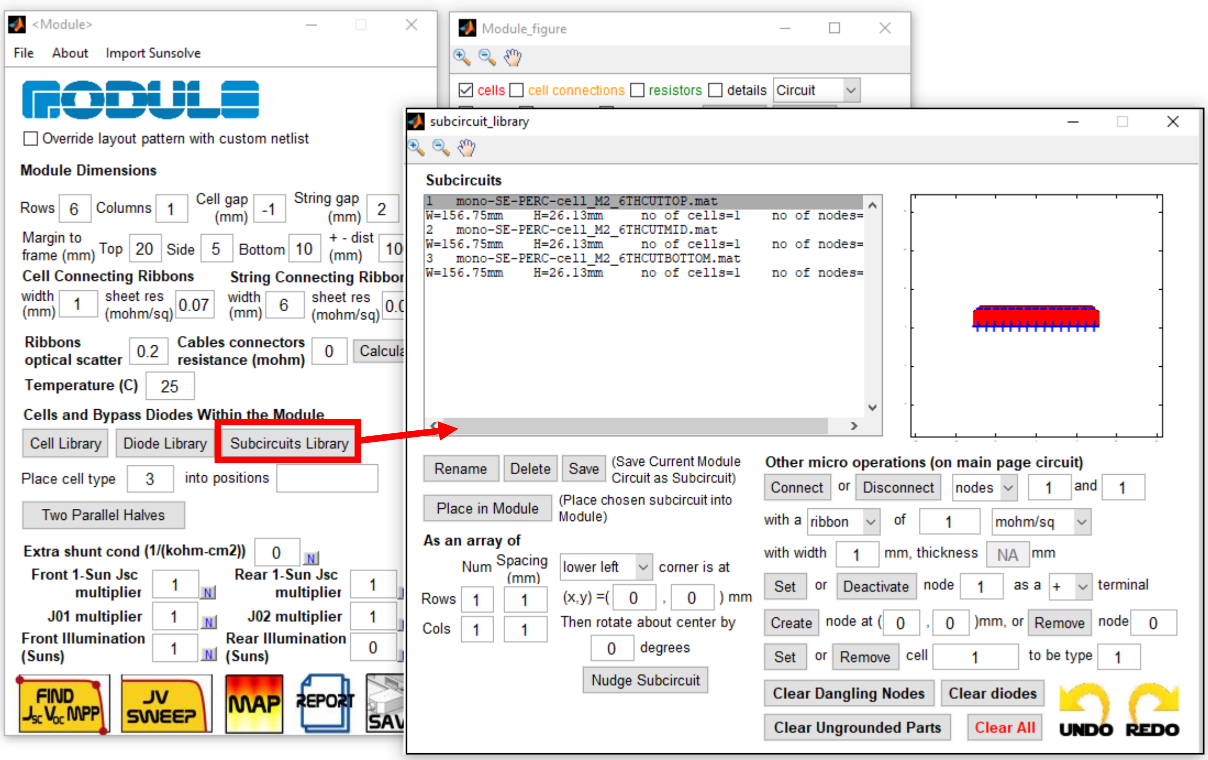
We download from the online Module cell library the following Module cell files: mono-SE-PERC-cell_M2_6THCUTTOP.zip, mono-SE-PERC-cell_M2_6THCUTMID.zip, mono-SE-PERC-cell_M2_6THCUTBOTTOM.zip and load them into Module via Cell Library → Add cells from another zip

6.2 Save Current Module Circuit As Subcircuit

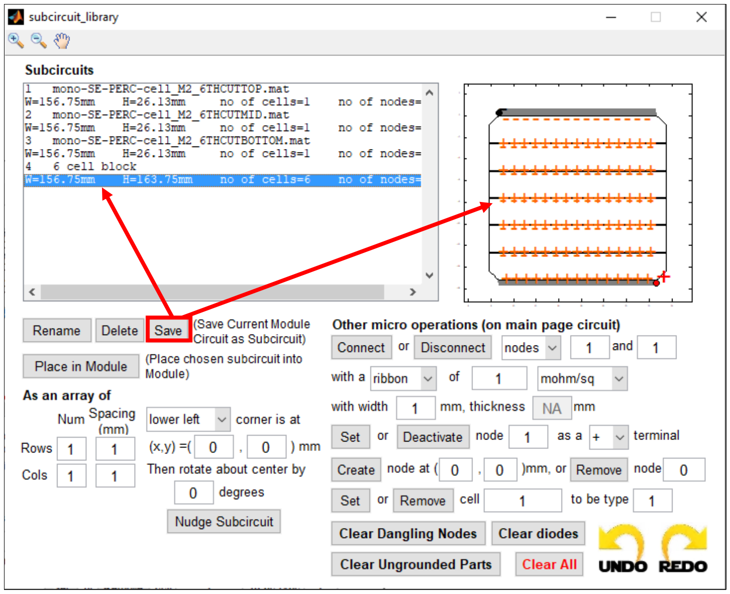
In the Module main page, we use the “Place cell type X into positions X” method, and adjust the module dimensions, to first create a 6 cell shingled module, as shown below.



Press Subcircuits Library to view it. You see that as a start, each cell type is a subcircuit.

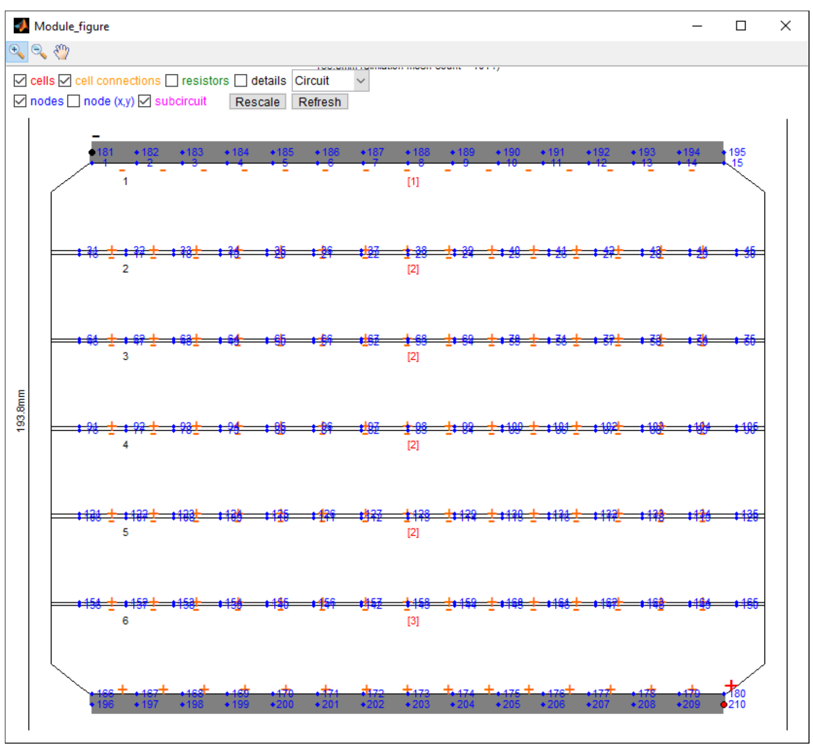


Press Save to save the current module layout as a subcircuit which you can edit and reuse as a part. A dialog box pops up asking you to give this subcircuit a name. We call it “6 cell block”.

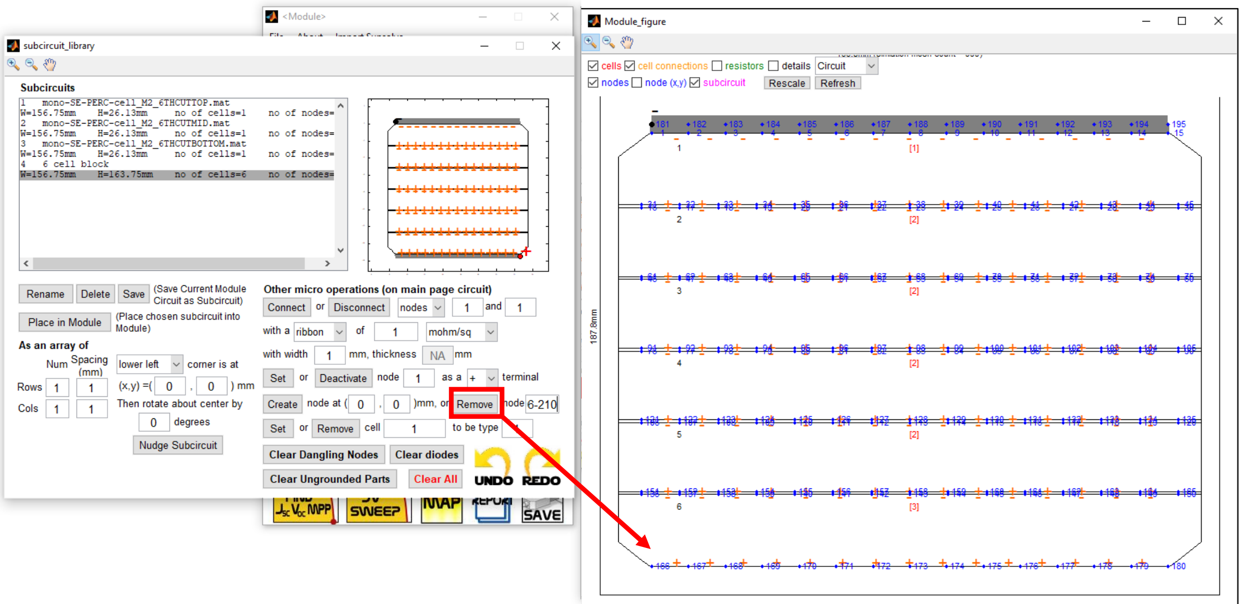


6.3 Removing nodes and deactivating terminals

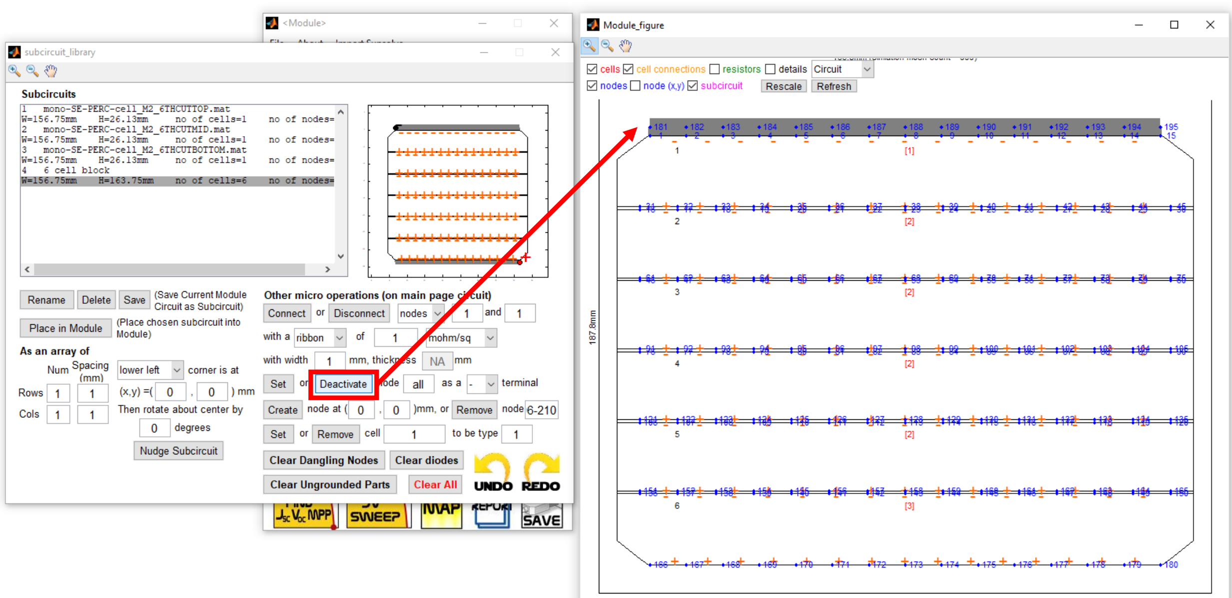
We can also make edits to the existing module layout before saving as a subcircuit. First, in the module figure, check “nodes” to show the ID of each node in the connection diagram. You can resize the window, use zoom, and hit “refresh” to get a clear view of the parts you would like to do editing on.



Let's remove the bottom ribbon from this circuit. To do so, in the subcircuit library window, type 196-210 next to "node" and click "remove". You can see now that these nodes, as well as all ribbon connections associated with them, are removed.

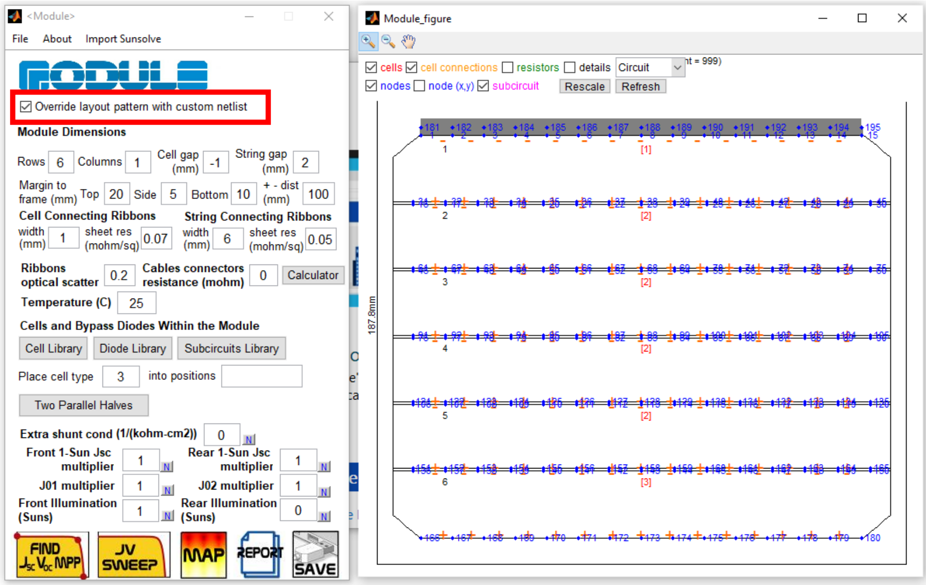


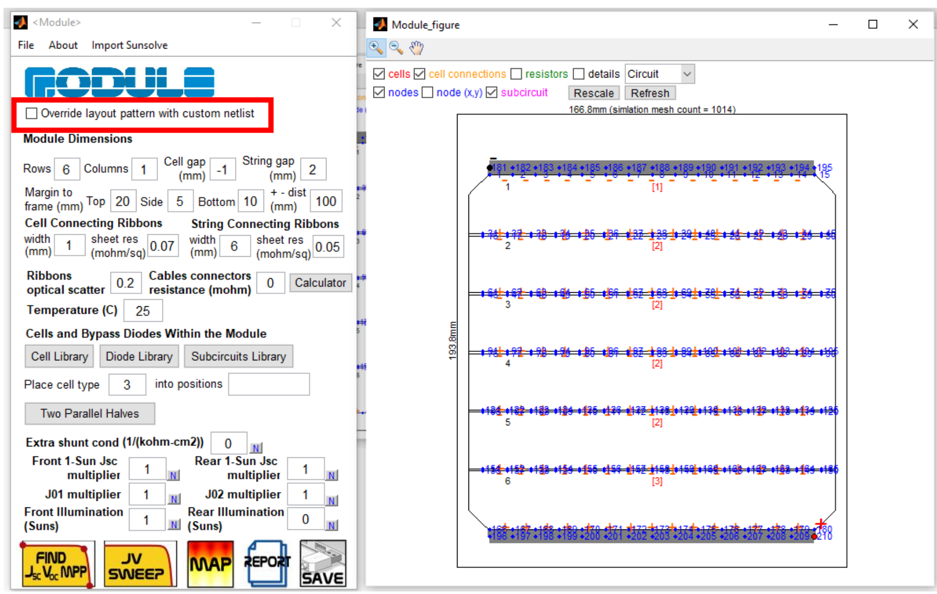
Let's deactivate also all terminal connections. To do so, set node to "All" and the popupmenu to "-" next to terminal, and click deactivate. You can see now the node 181 is no longer a negative terminal.



We can now save this circuit as a subcircuit called "6 cell block no bottom ribbon".

Note that as soon as you do any editing to the circuit, Module will check the box in the main page "Override layout pattern with customer netlist". This means that the edited circuit is shown in the Module_figure instead of the original rectangular layout as defined in the main page. If you uncheck this box, then the original rectangular layout (with terminals and the bottom ribbon) are displayed again, and you can then use this as a starting point to create other edited subcircuits.

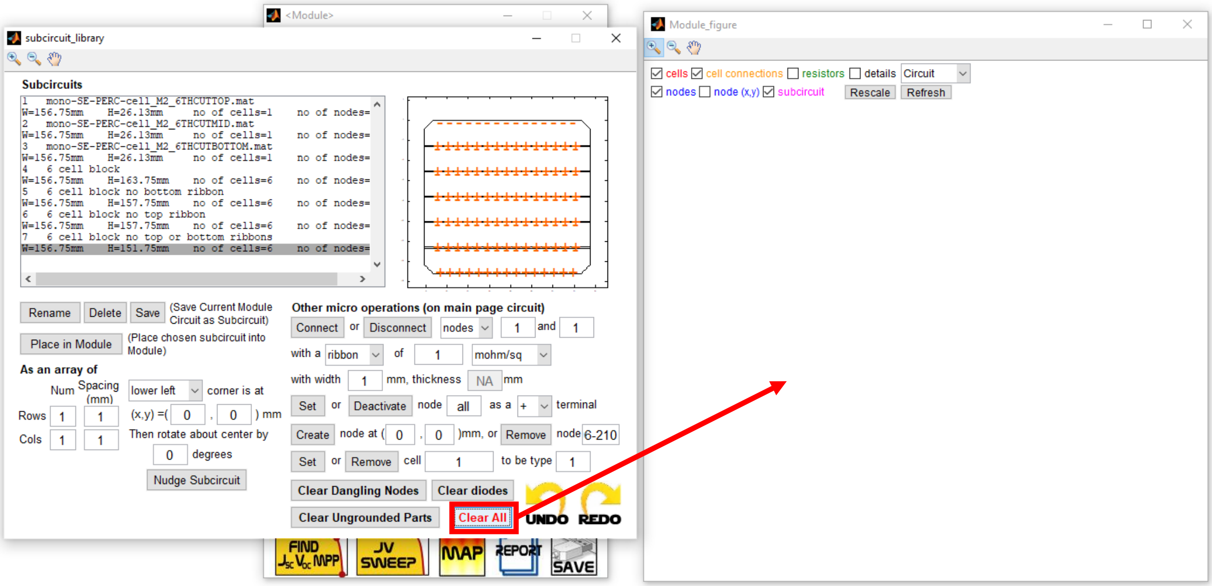




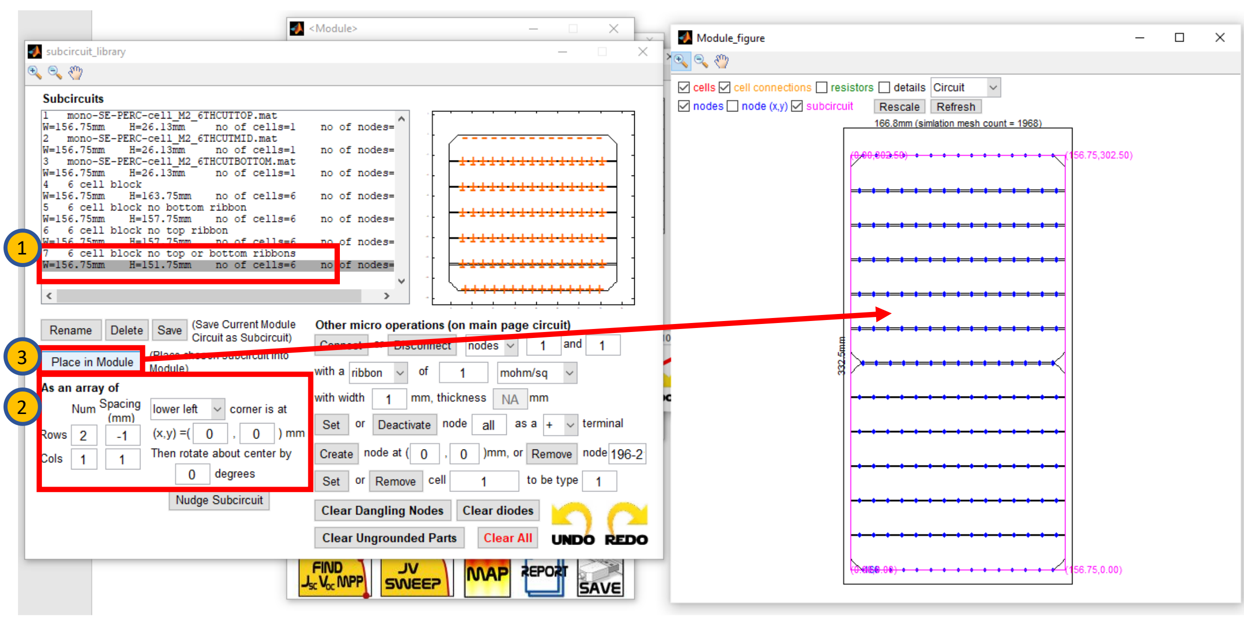
We do so and with more editing, create other subcircuits called “6 cell block no top ribbon” and “6 cell block no top or bottom ribbons”.

6.4 Place Subcircuits into Module

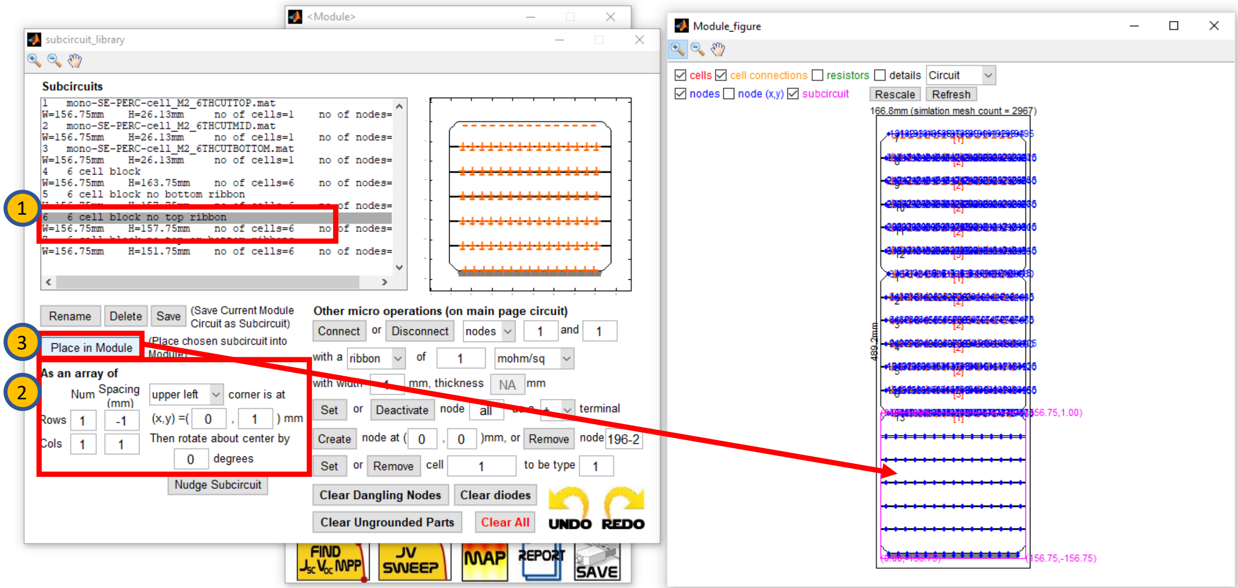
Now we are ready to layout the subcircuits we created into the module. To start, in the subcircuit library, press “Clear All” and the Module_figure becomes a blank canvas.



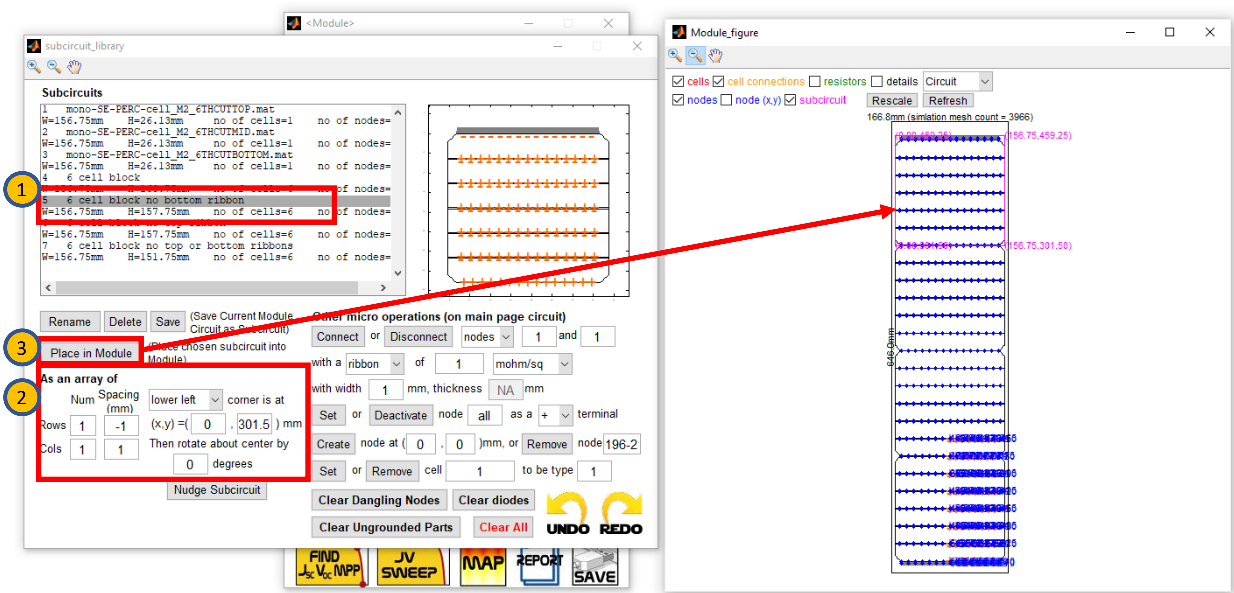
We select “6 cell block no top or bottom ribbons”, and then we create the right settings in the Array section, i.e. layout subcircuit as an array of 2 rows by 1 column, row spacing of -1 mm (for the shingling), and we place the lower left corner of the subcircuit at (x,y) = (0,0). Then we press “Place in Module”.



We select “6 cell block no top ribbon”, and then we create the right settings in the Array section, i.e. layout subcircuit as an array of 1 row by 1 column, and we place the top left corner of the subcircuit at (x,y) = (0,1). Then we press “Place in Module”. This will place this subcircuit below the existing laid out circuit with an overlap of 1mm. **Note that if you made a mistake, you can always click Undo, or enter new coordinates and press “Nudge Subcircuit” to re-place.**

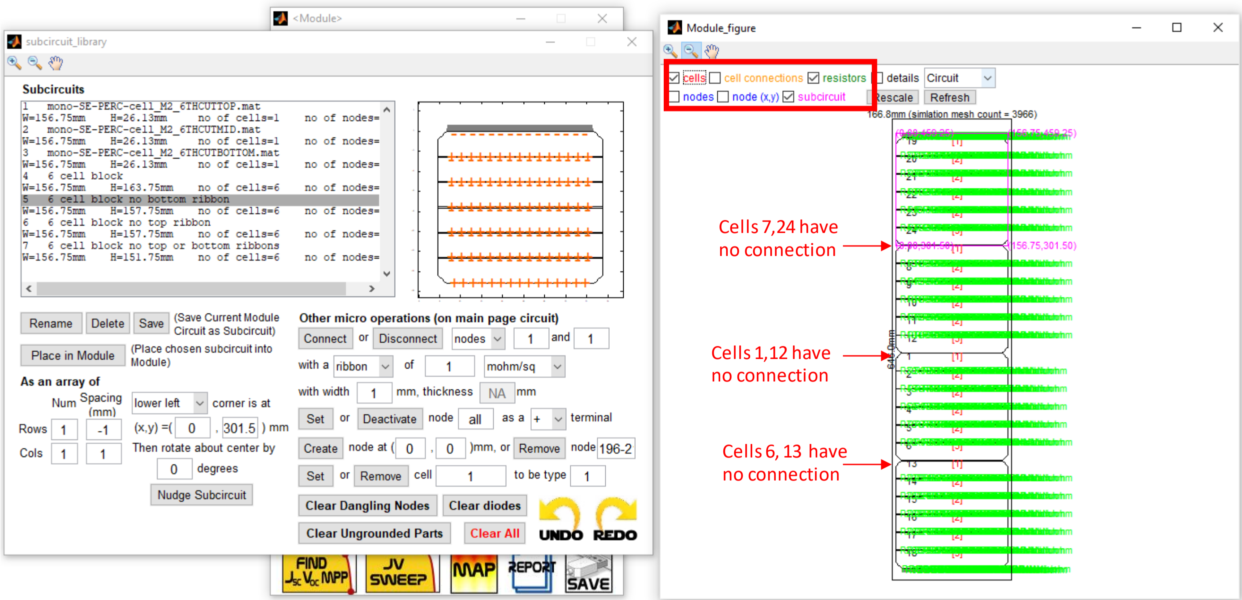


We select "6 cell block no bottom ribbon", and then we create the right settings in the Array section, i.e. layout subcircuit as an array of 1 row by 1 column, and we place the bottom left corner of the subcircuit at (x,y) = (0,301.5). Then we press "Place in Module". This will place this subcircuit above the existing laid out circuit with an overlap of 1mm. **Note that if you made a mistake, you can always click Undo, or enter new coordinates and press "Nudge Subcircuit" to re-place.**

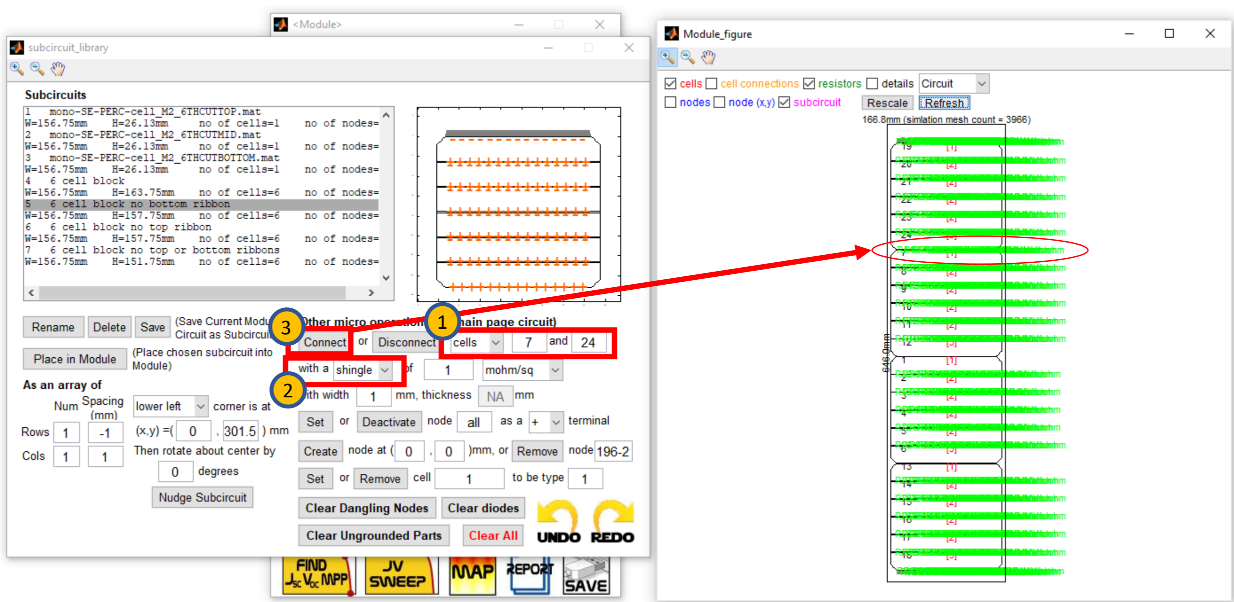


6.5 Making Connections

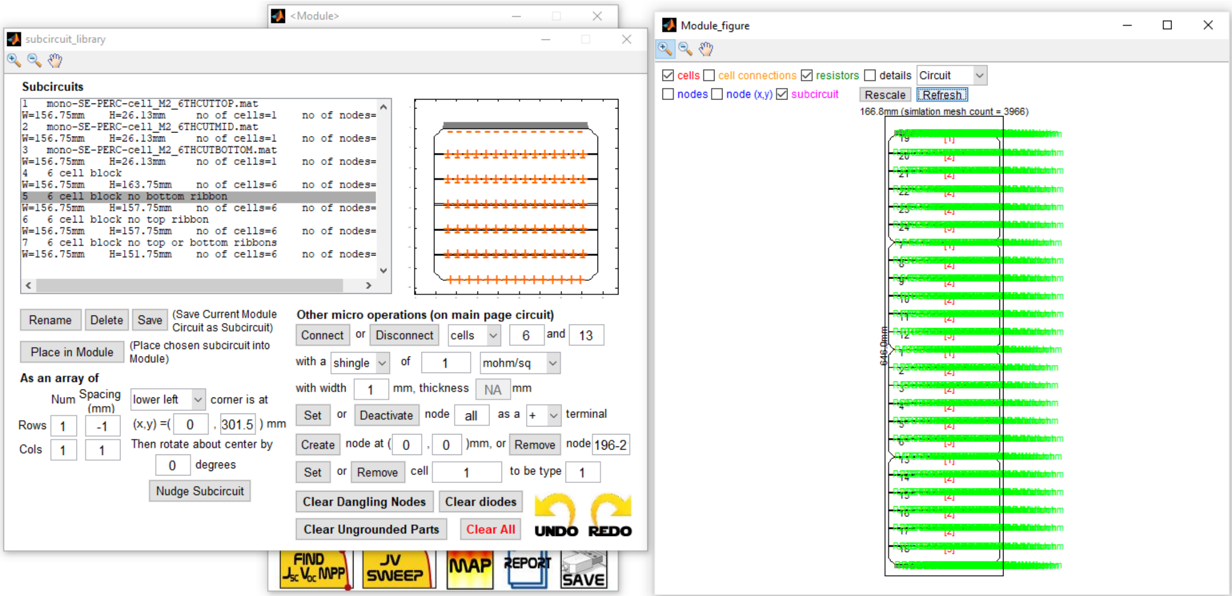
Now, if we go to Module_figure and check "resistors", we can see the resistor values of every connection in the circuit, shown in green numbers. We can see that there is no connection between cells 7,24, between cells 1,12, and between cells 6,13.



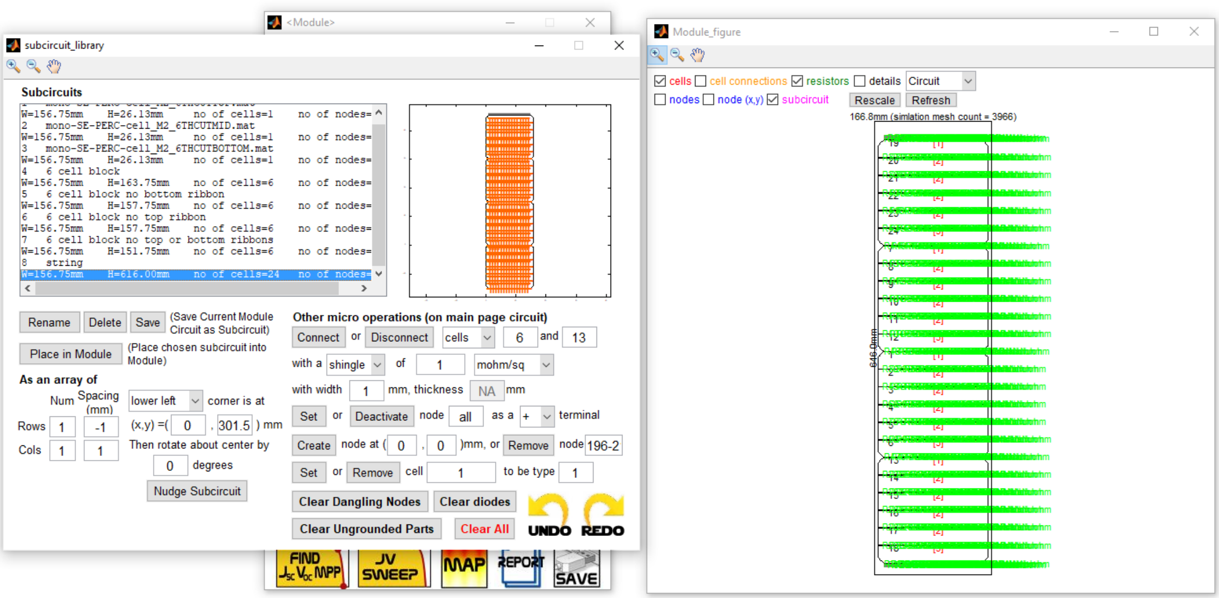
To connect cells 7,24, set "cells" to be 7 and 24, set connection to be "shingle" and then click "connect". Module will search for nearest neighbours of + and – cell terminals and connect them with shingle connections (which have near zero resistance).



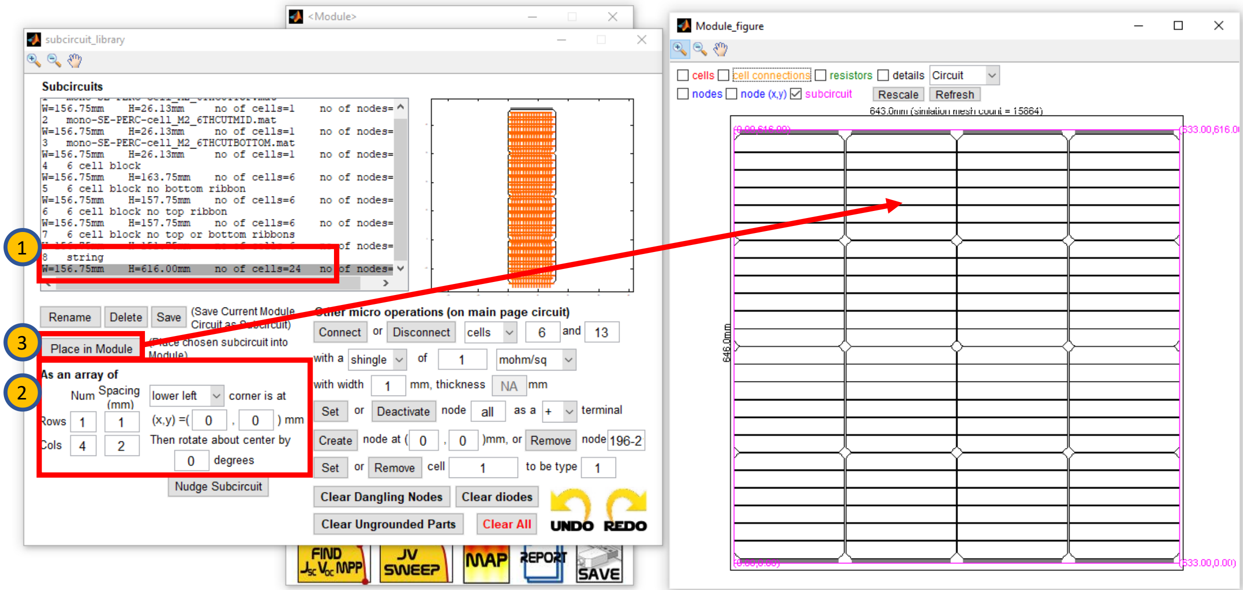
We continue on to connect all adjacent cells with shingle connections.



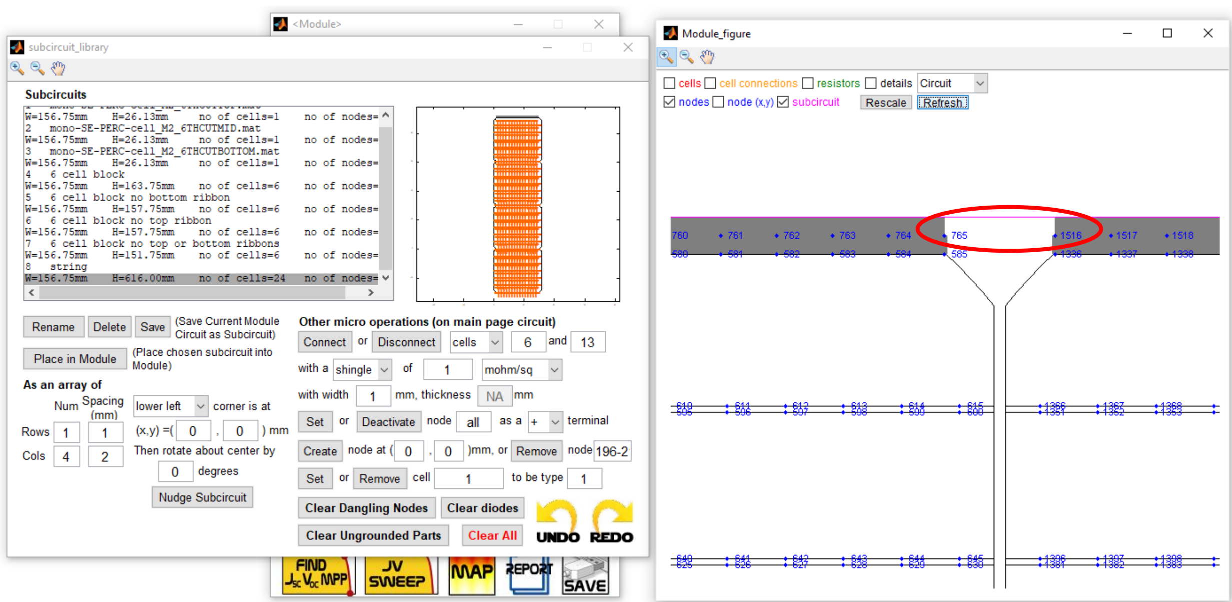
We save this entire subcircuit and call it “string”.



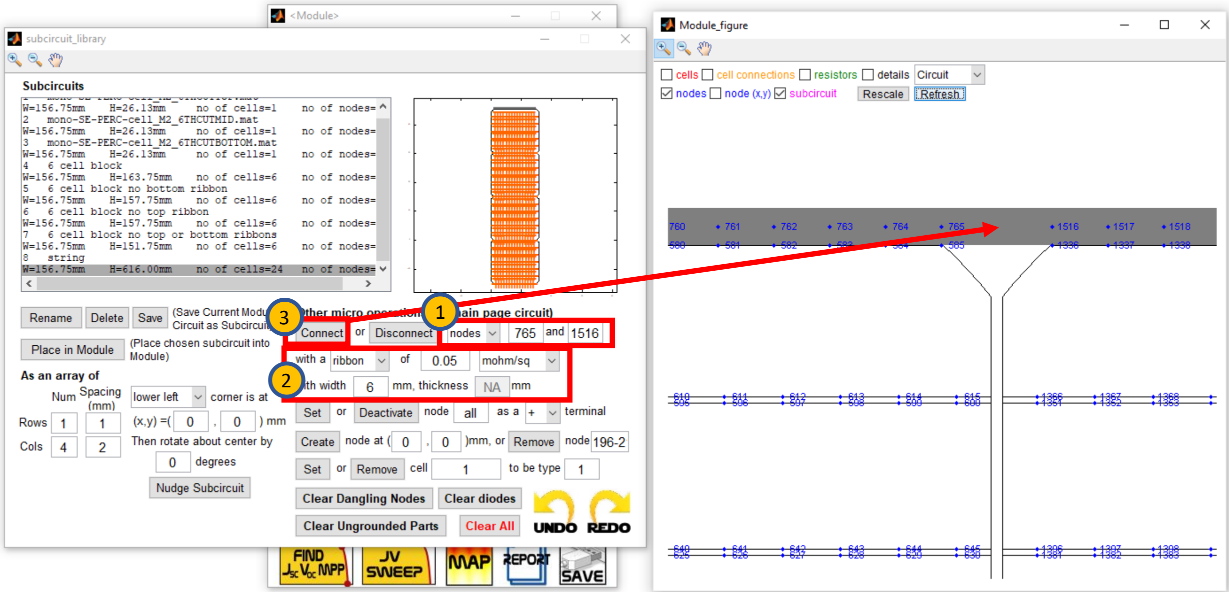
As before, we now press “Clear All” to start with a blank canvas, and then we layout an array of 1 row by 4 columns of “string”.



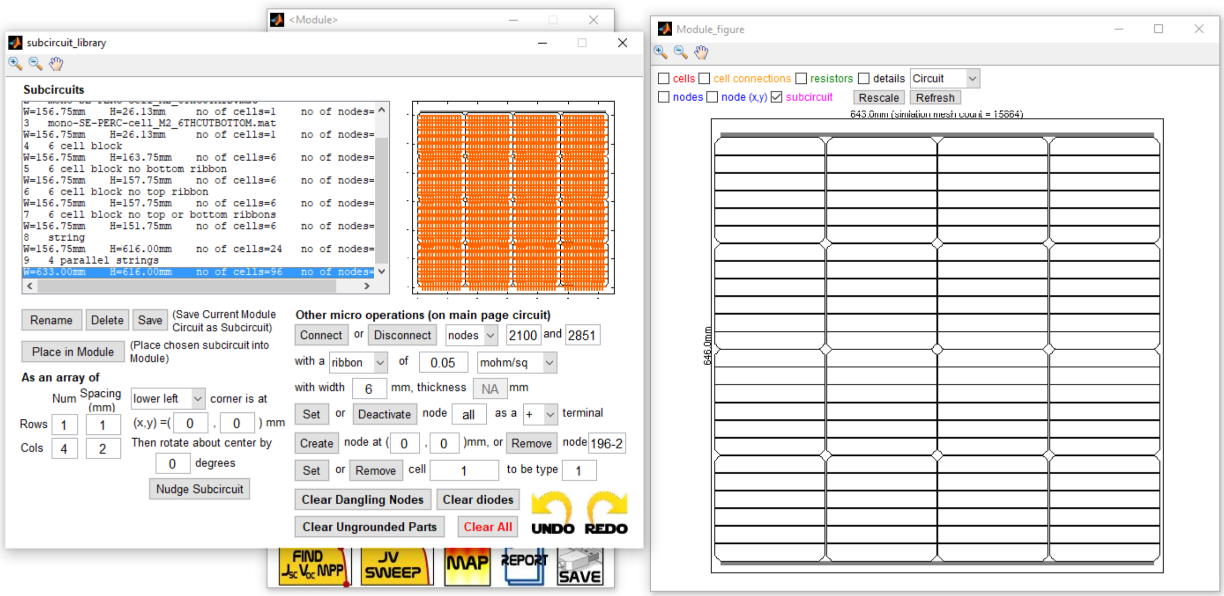
Again, there are no connections between the strings. For example, if you zoom into the top part, check “nodes” and click “refresh” to display the nodes, you’ll find there needs to be ribbon connection between nodes 765 and 1516.



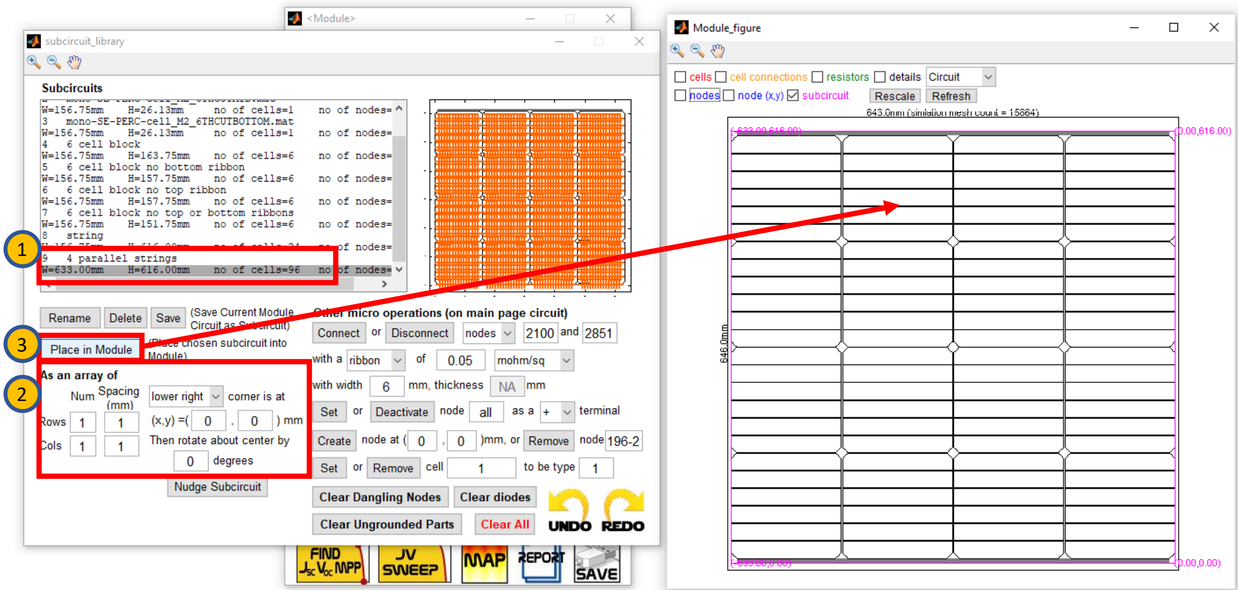
To establish the ribbon connection, set “nodes” to be 765 and 1516, then select “ribbon” of “0.05 mohm/sq” and width “6 mm”, then press Connect.



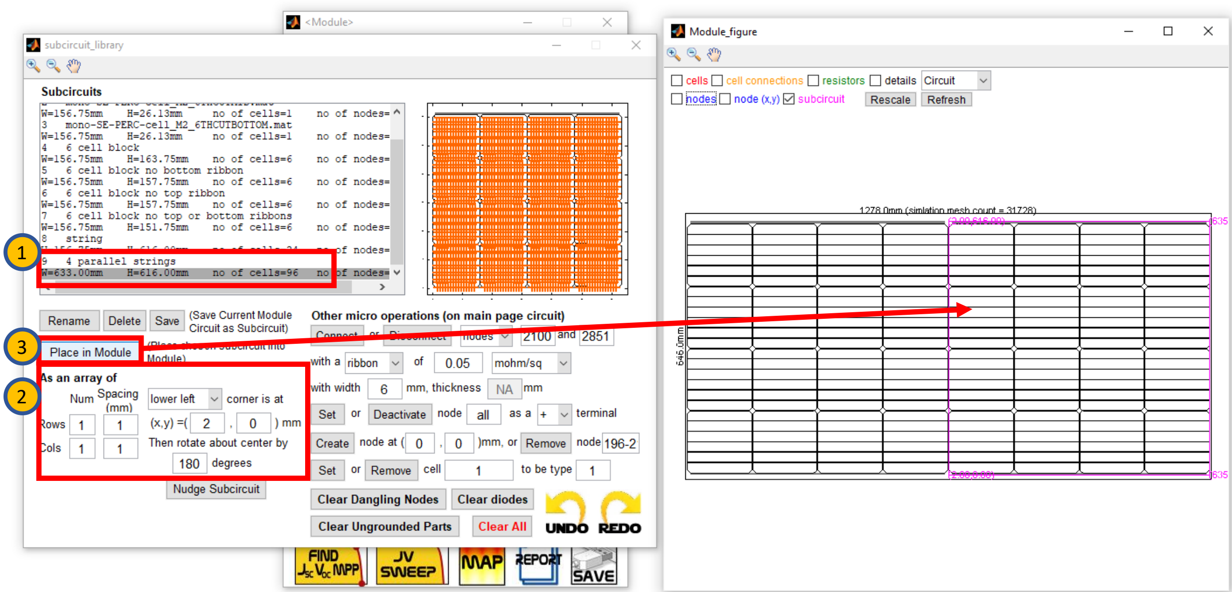
We finish off all the needed ribbon cross connections, then save this subcircuit with the name “4 parallel strings”.



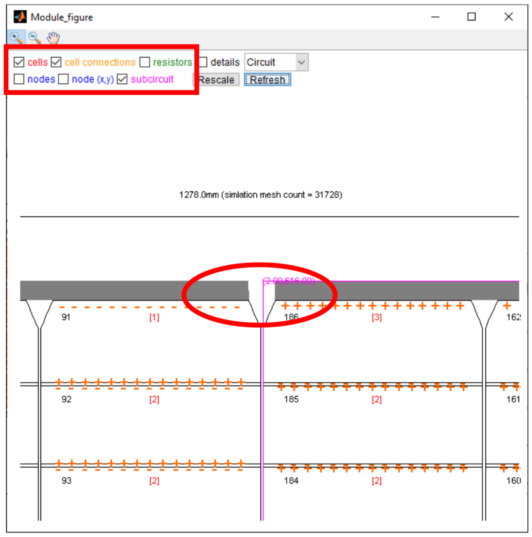
We press “Clear all” again to start with a blank canvas, and then we select the 4 parallel strings subcircujit, array of 1 by 1, and place the subcircuit with lower right corner at (x,y) = (0,0).



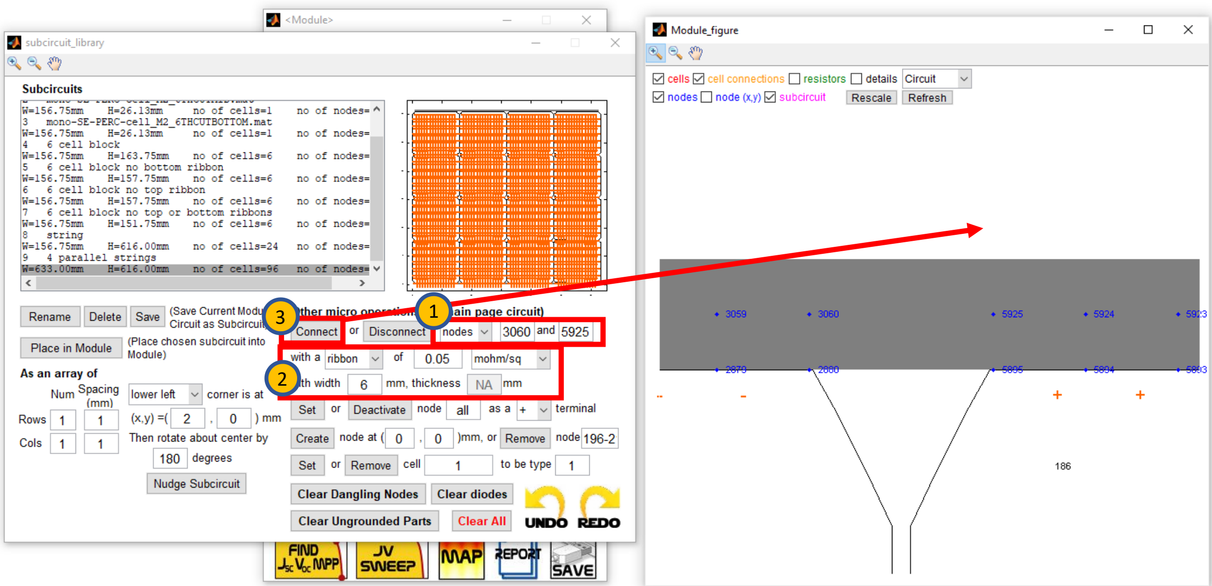
Then we again select the 4 parallel strings subcircujit, array of 1 by 1, and place the subcircuit with lower left corner at (x,y) = (2mm,0) then rotate subcircuit about center by 180 degrees. This places a 180 degree rotated instance of the 4 parallel strings next to the one already placed.



If we go to Module_figure, choose “cell connections” and “cells”, zoom into the upper part between the two 4 parallel strings and click refresh, we can see that establishing a ribbon connection in the red circled part below will create a series connection, as it connects the negative terminals of cell 91 to the positive terminals of cell 186.

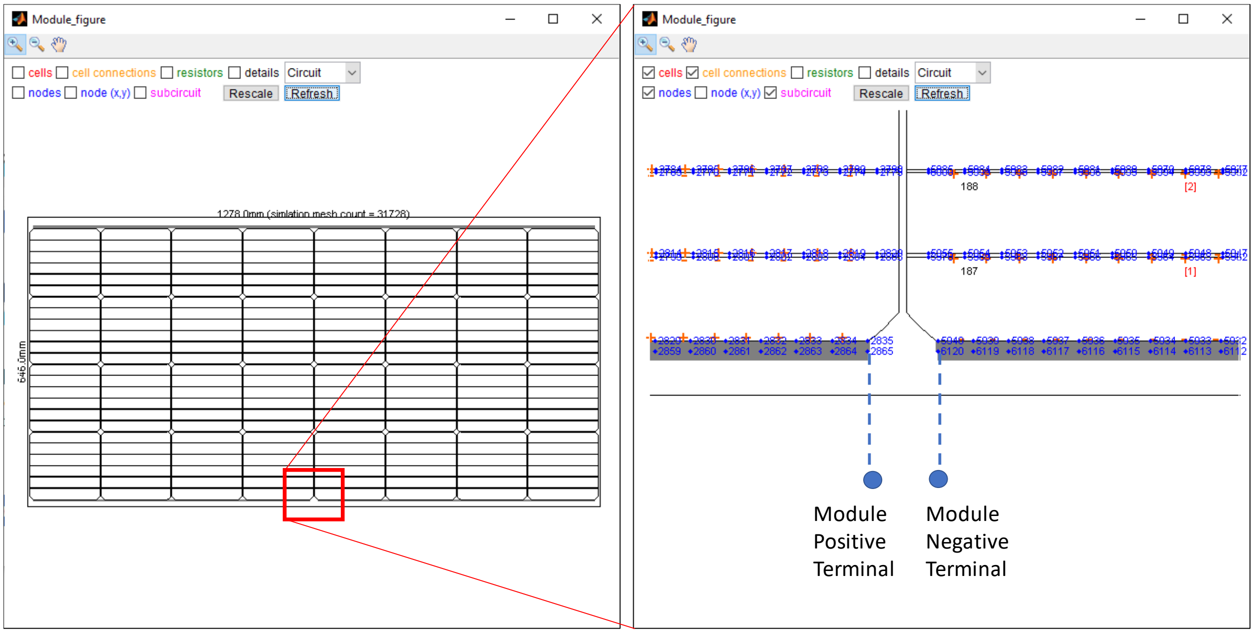


To establish the ribbon connection, we zoom in further and check "nodes" and hit "refresh" to see that the two nodes needing connection are 3060 and 5925. We set "nodes" to be 3060 and 5925, then select "ribbon" of "0.05 mohm/sq" and width "6 mm", then press Connect.



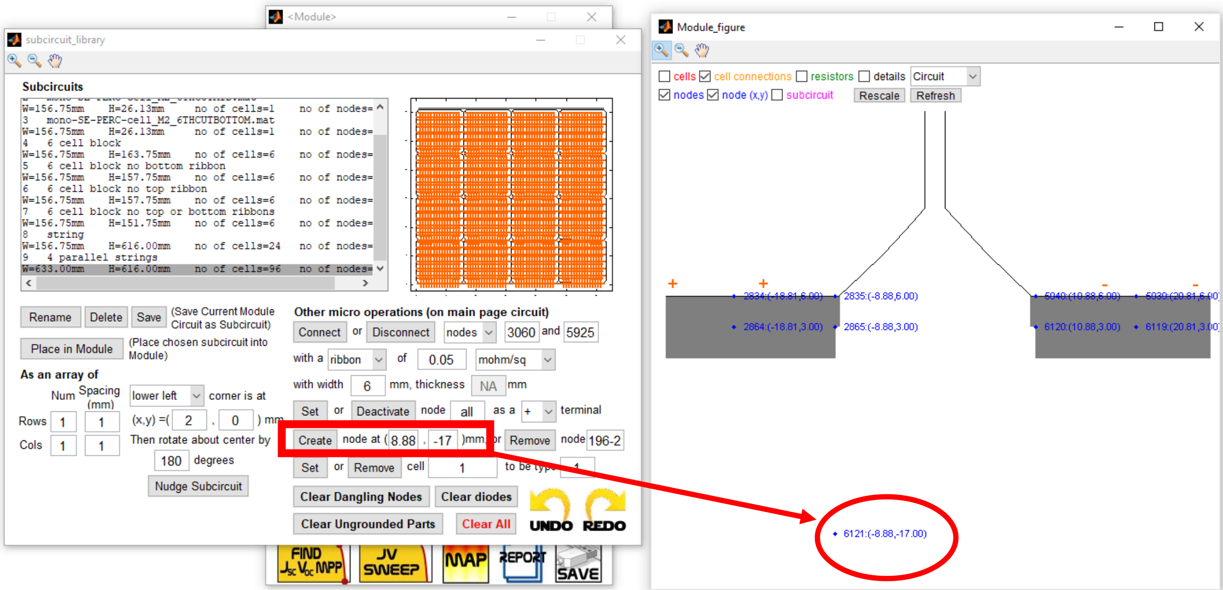
6.6 Creating New Nodes

Now, suppose we wish to Extend the ribbons as shown in the red rectangle region of the module to make the module positive and negative terminals, let's say 20mm.

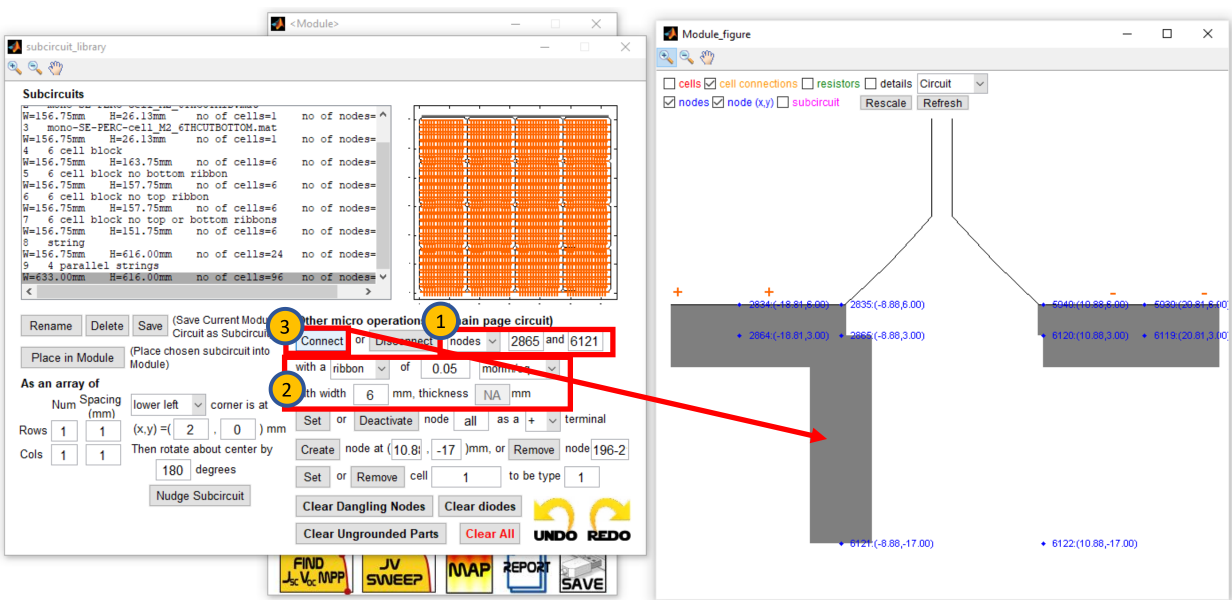


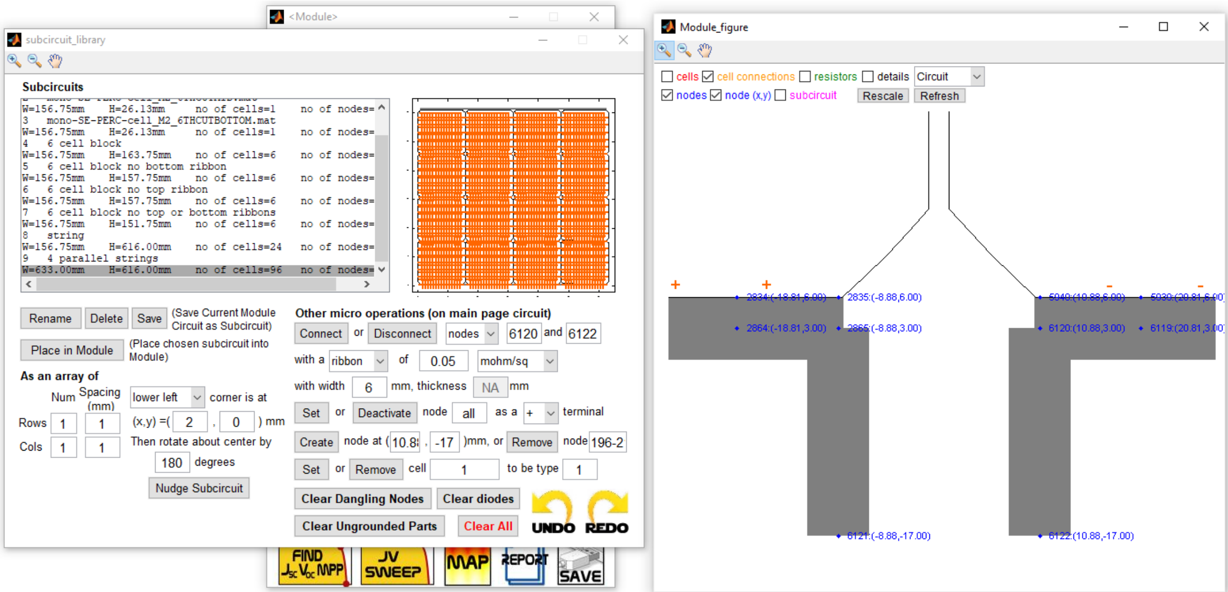
In Module_figure, we select "node(x,y)" and zoom in further, then click "refresh" to see that the two nodes we wish to extend the ribbons off of are nodes 2865 and 6120, with coordinates (-8.88, 3) and (10.88, 3) respectively.

In the subcircuit library, make the coordinates (-8.88, -17) and press “Create” (node) and a new node appears at the coordinate specified. We can also make another node at (10.88,-17).



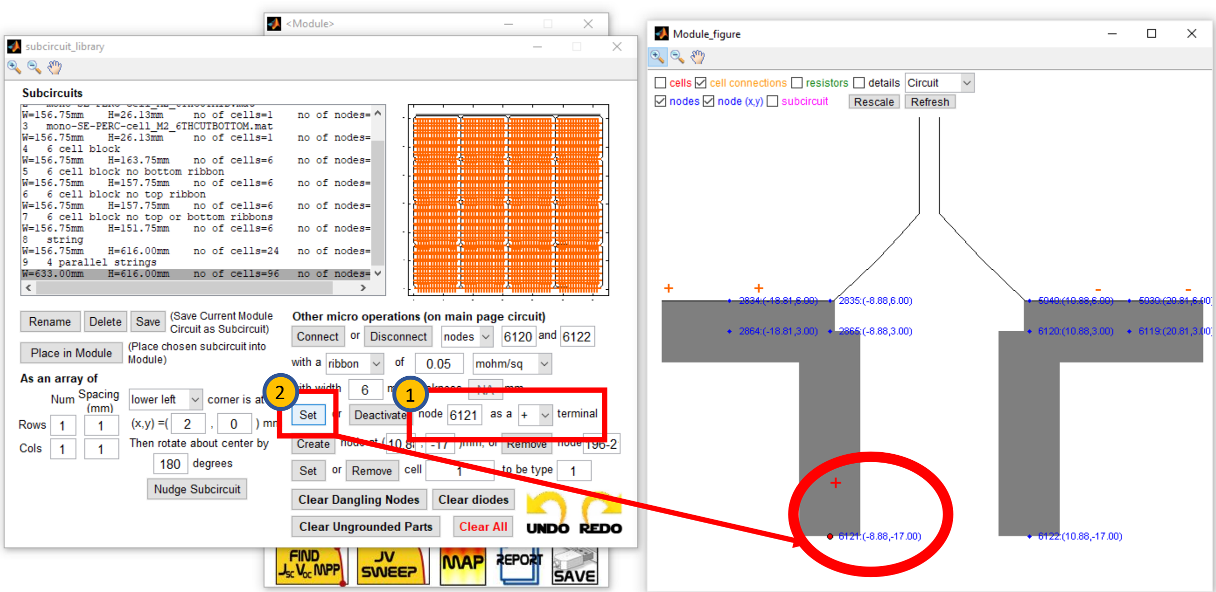
As before, we establish ribbon connections.

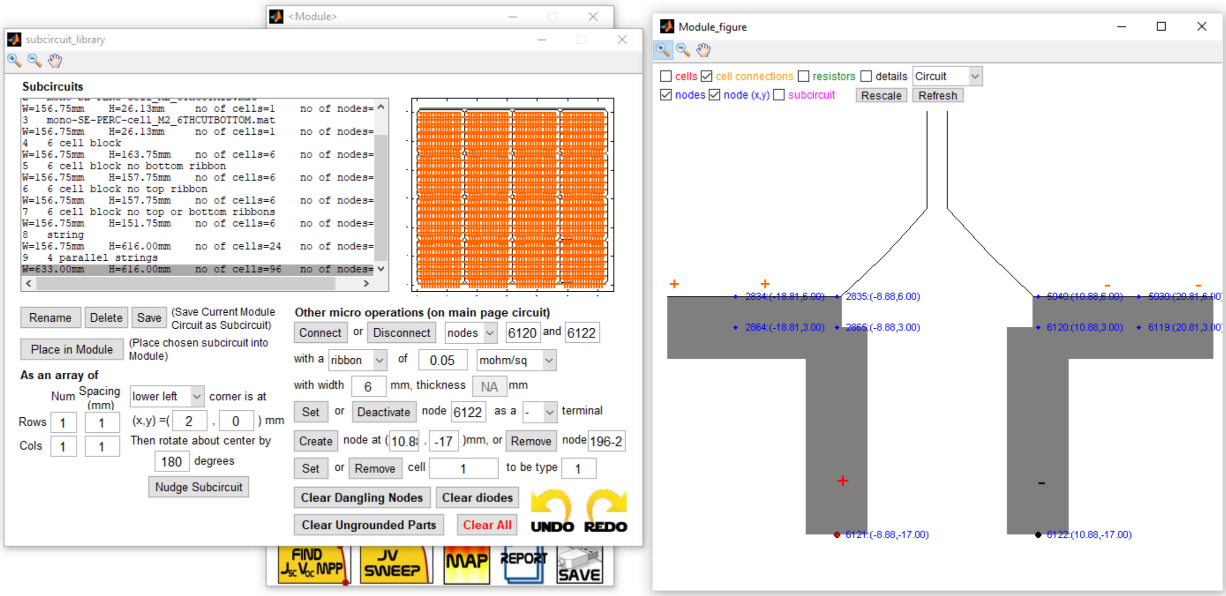




6.7 Setting Module Terminals

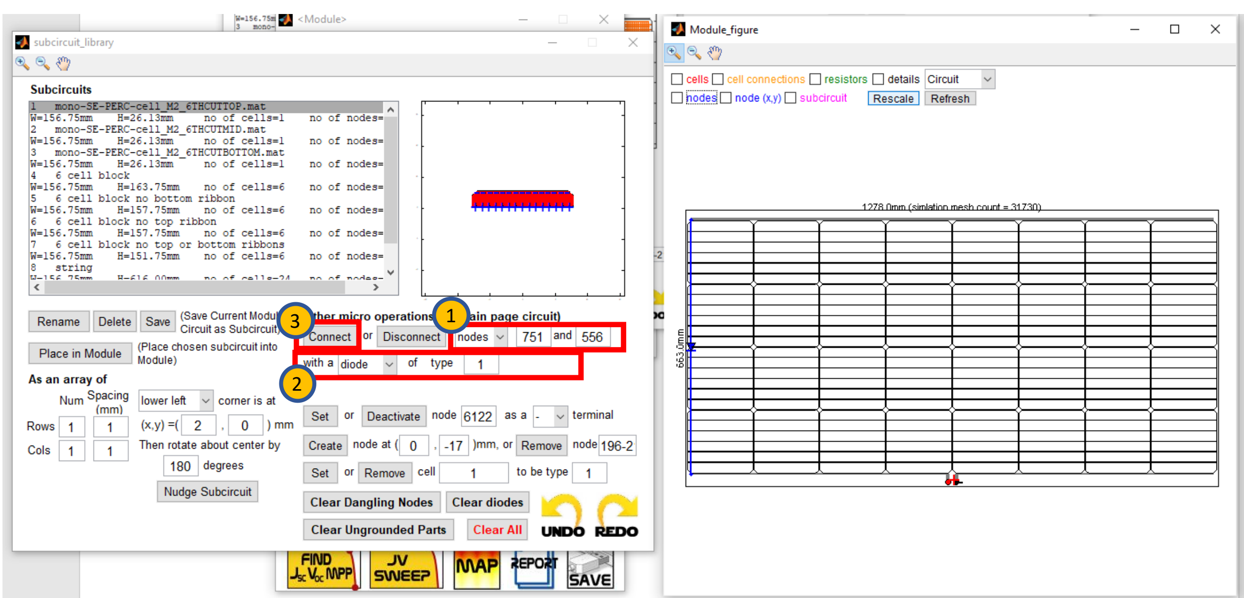
We select node “6121” as a “+” terminal, then press set. Similarly we select node “6122” as a “-“ terminal, then press set.



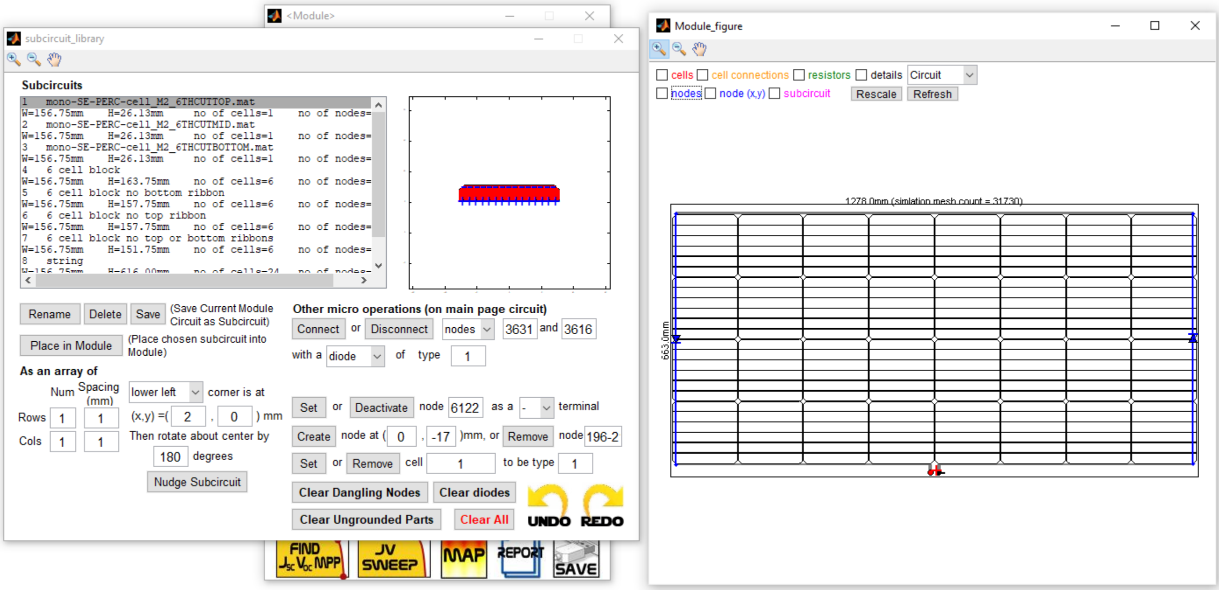


6.8 Setting bypass diodes

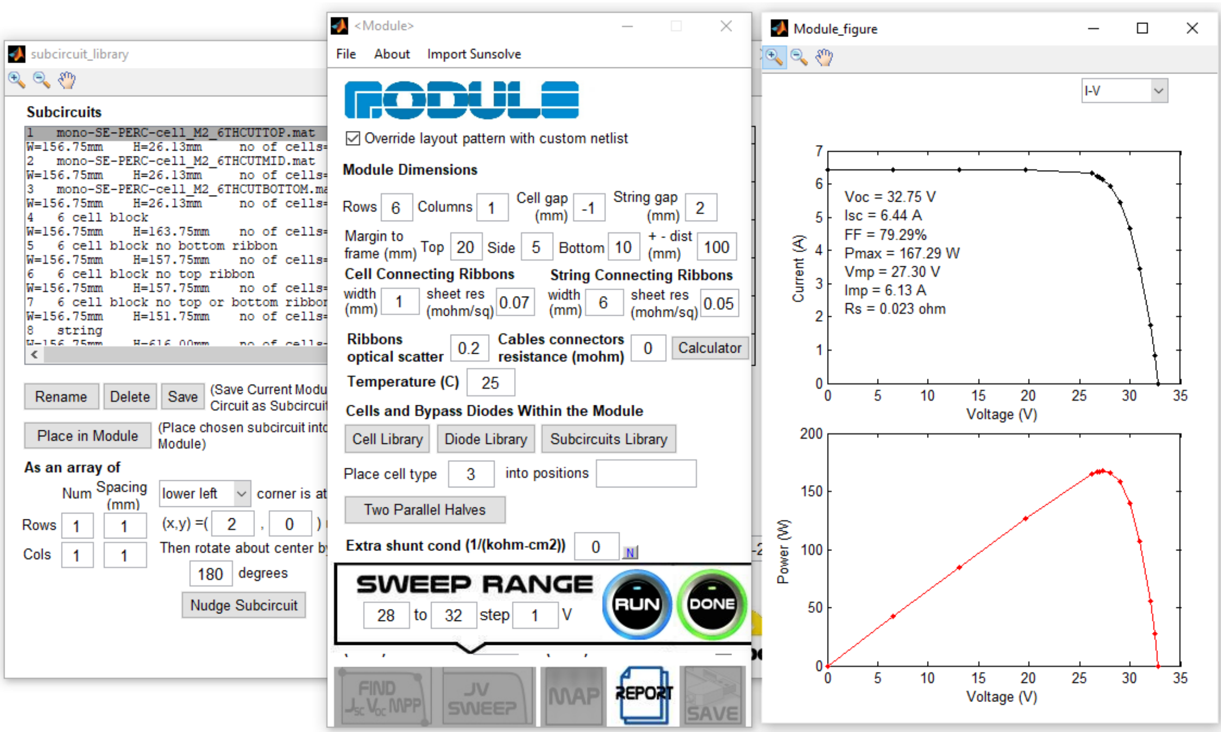
After identifying the nodes we want to connect with a bypass diode using the zoom, we enter the nodes to be connected (node 751 being the positive terminal of the bypass diode, node 556 being the negative terminal of the bypass diode), select “diode” and type “1”, then press connect.



Similarly we create another bypass diode for the other half of the module.



Once we're done, we can simulate the I-V characteristics of the module (this example required module backsheet scatter to be calculated in order for the simulation to converge well).



7 Conductive Backsheet

7.1 Introduction

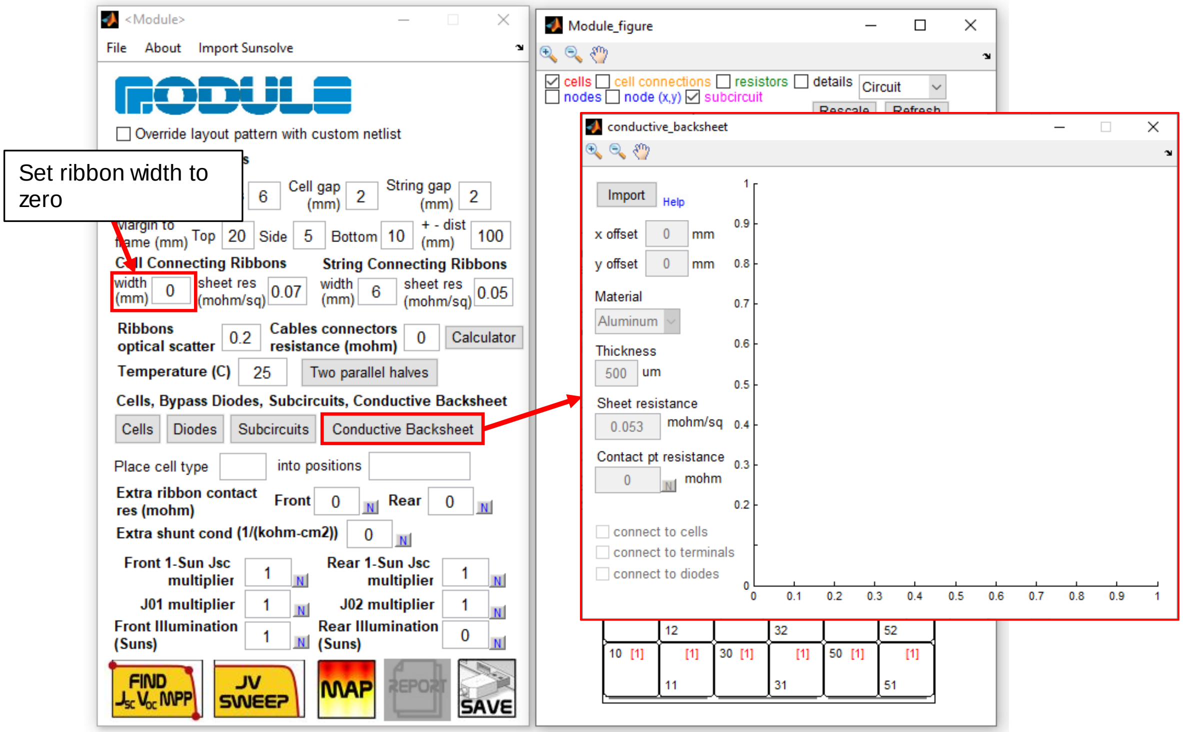
Interdigitated back contact (IBC) and metal wrap through (MWT) are two solar cell types where both cathode and anode metallization patterns are on the rear side of the solar cell. For these cell types, there is the possibility of creating advanced module concepts that use conductive backsheets for interconnection, much like surface mount components on a printed circuit board.

In Module, now there is the option to use conductive backsheet interconnection---and it is not limited to IBC or MWT cell designs. It is also possible to combine ribbon connection elements with the conductive backsheet, offering a wide range of possibilities in the research realm.

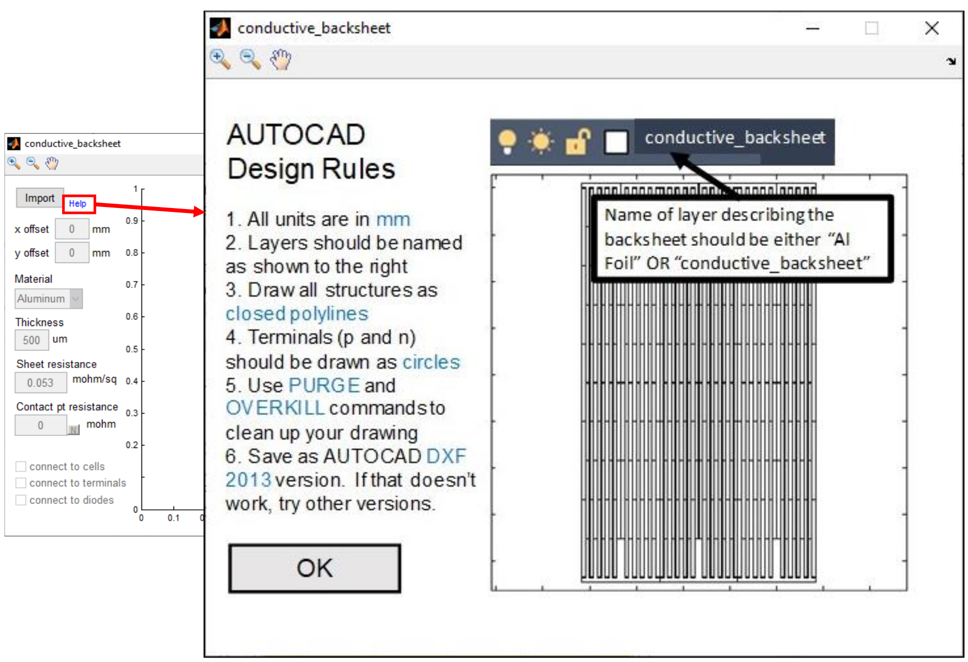
To illustrate the use of conductive backsheet in Module simulation, we load an IBC cell model where both cathode (positive) busbars and anode (negative) busbars are on the rear side, as shown below. The design is similar to the Zebra solar cell technology invented by ISC Konstanz.

7.2 Conductive Backsheet Window

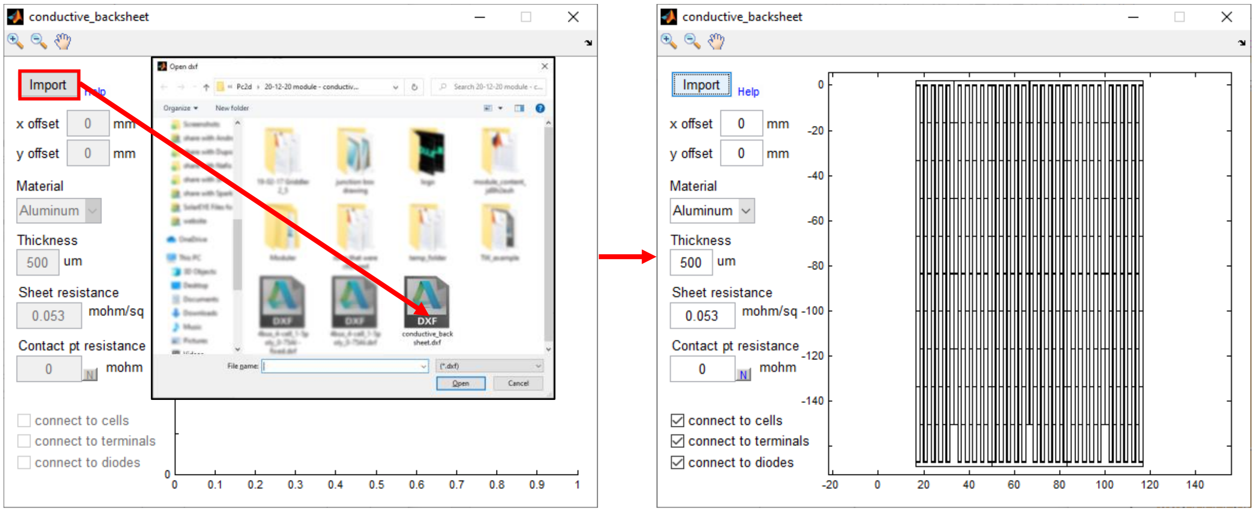
By default, Module always creates a rectangular module that is interconnected by ribbons. To replace that with conductive backsheet interconnection, set the cell connecting ribbons width to zero----this will remove any conducting elements along the busbars of the solar cell, other than the busbars themselves. Press "Conductive Backsheet" to open the conductive backsheet window.



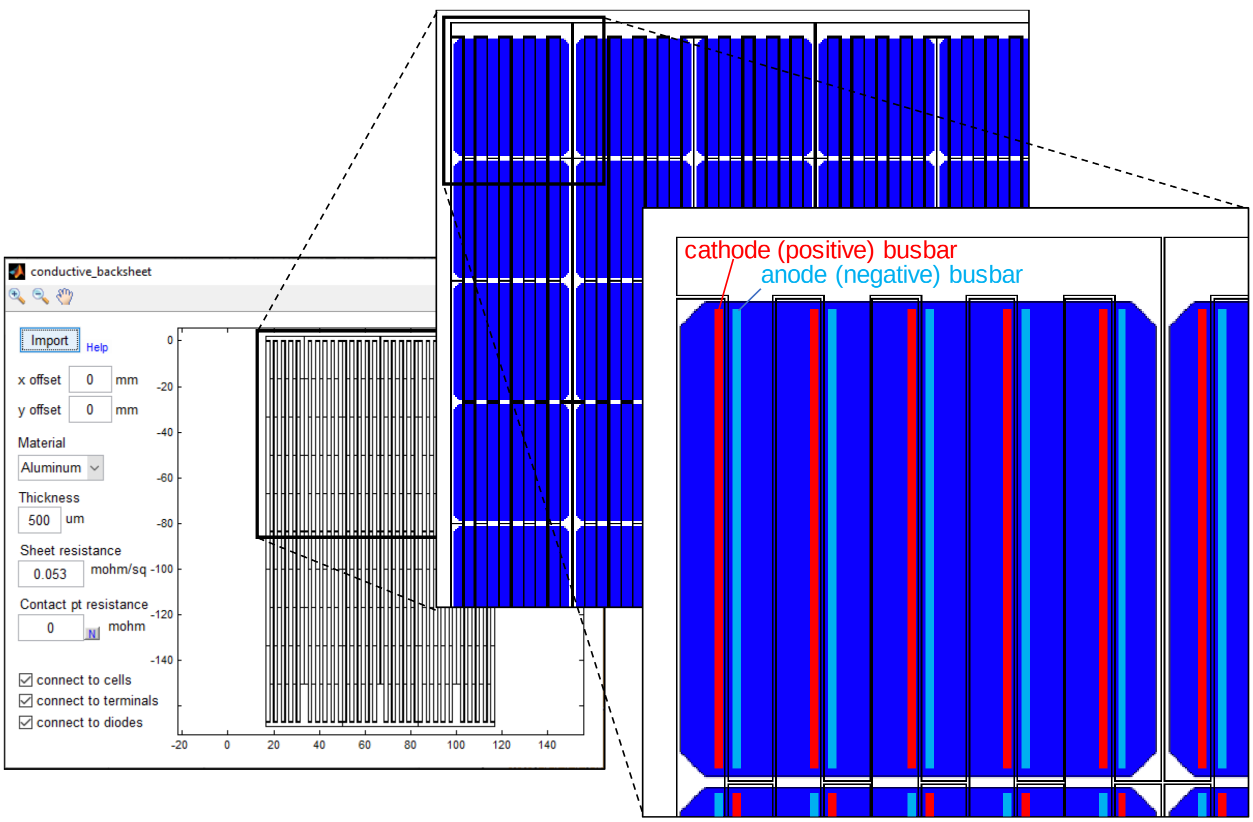
As of v33, Module does not have a native conductive backsheet design tool, so the user will have to import CAD designs (in dxf format) of the backsheet which are usually created in AutoCAD or Solid Works. You can press the “Help” button to view the design rules.



Press “Import” to load your conductive backsheet pattern.



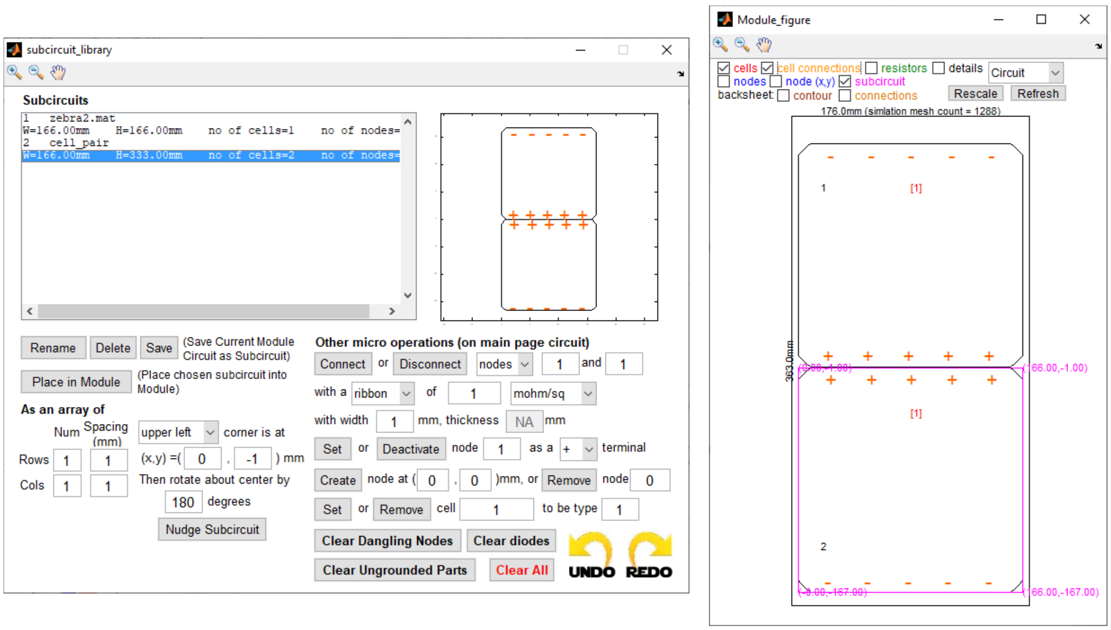
The conductive backsheet pattern deserves some explanation. Any shape within this pattern is considered to be a conductive foil. If we zoom in, we see that the backsheet consists of many interdigitated, but unconnected conductive foil sections. Here we show how the IBC cells are intended to be laid out on the conductive backsheet, showing the alignment of the busbars to the different foil sections. Notice that within a column, adjacent cells are rotated 180 degrees with respect to one another, so that a common foil section connects the anode busbars of one cell to the cathode busbars of the next cell.



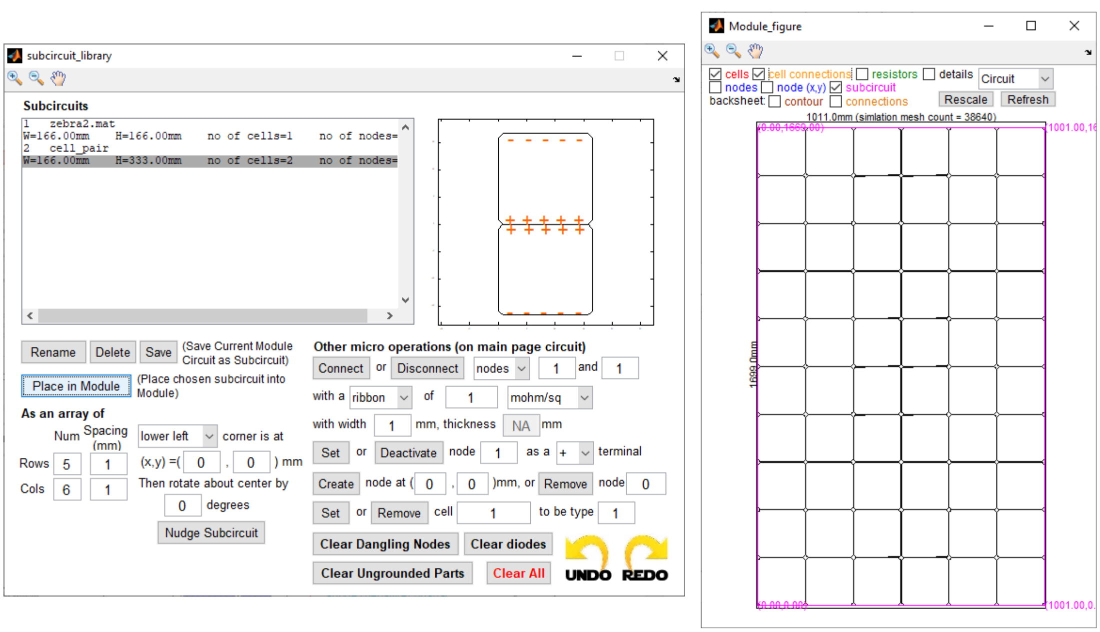
7.3 Conductive Backsheet Interconnection

The conductive backsheet pattern in this case requires that within a column, adjacent cells are rotated 180 degrees with respect to one another. We make use of the subcircuit library to make this kind of custom layout. See Section 6 Subcircuit Library for details. Here we simply show screenshots and brief descriptions of the steps.

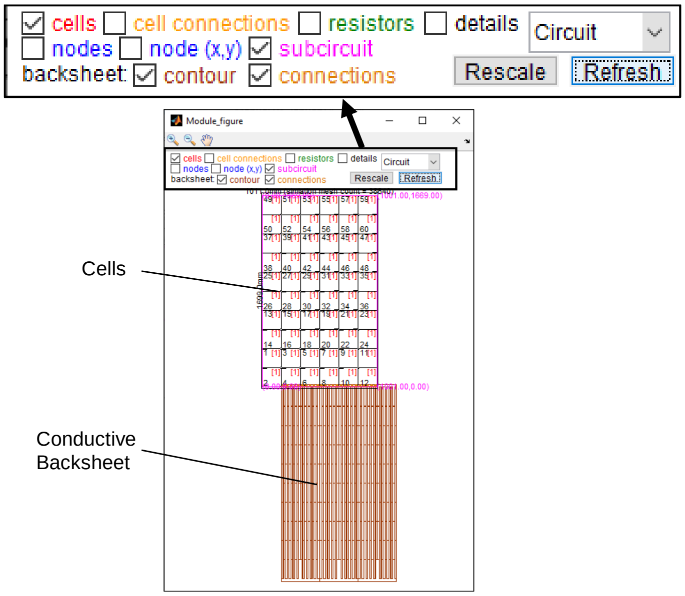
Step 1: Create a subcircuit that consists of a pair of cells, spaced 1mm apart. The lower cell is rotated 180 degrees (see 6.4 Place Subcircuits into Module and 6.2 Save Current Module Circuit As Subcircuit).



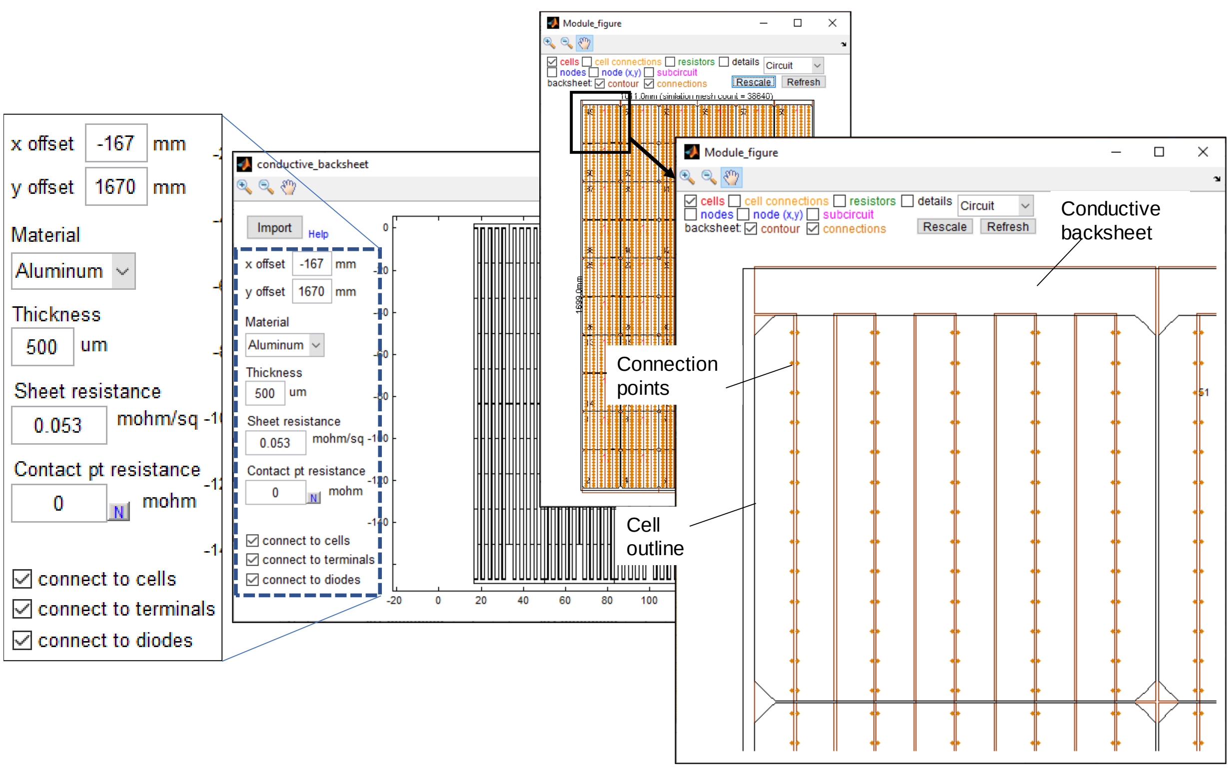
Step 2: Now insert a 5 rows x 6 columns array of the cell pair, with 1mm spacing. This creates the 60 cell module.



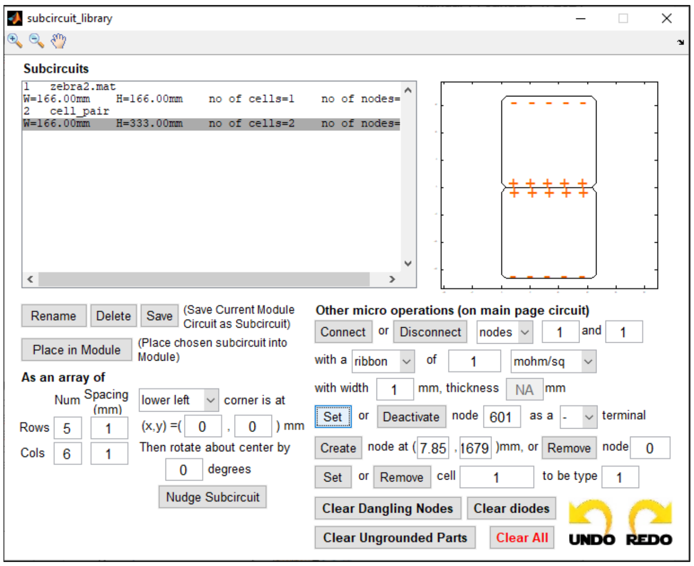
Step 3. When there is a conductive backsheet, the Module Figure allows you to select whether to view the backsheet contour or connections. Here we select contour and press "rescale". We can now see the conductive backsheet and also see that it is not at all aligned with the cells.

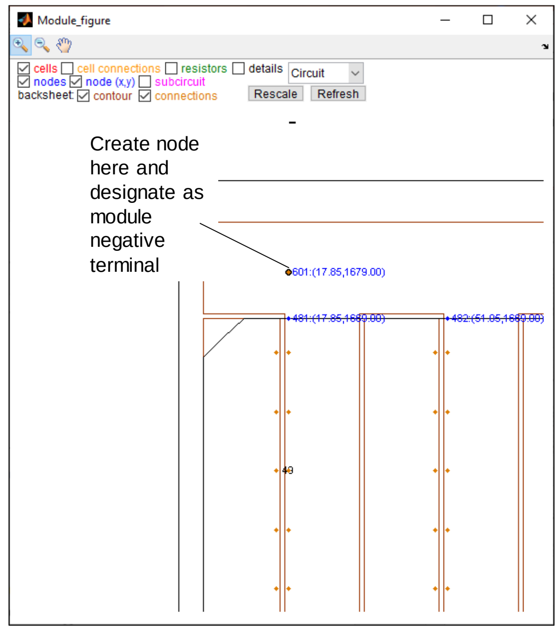


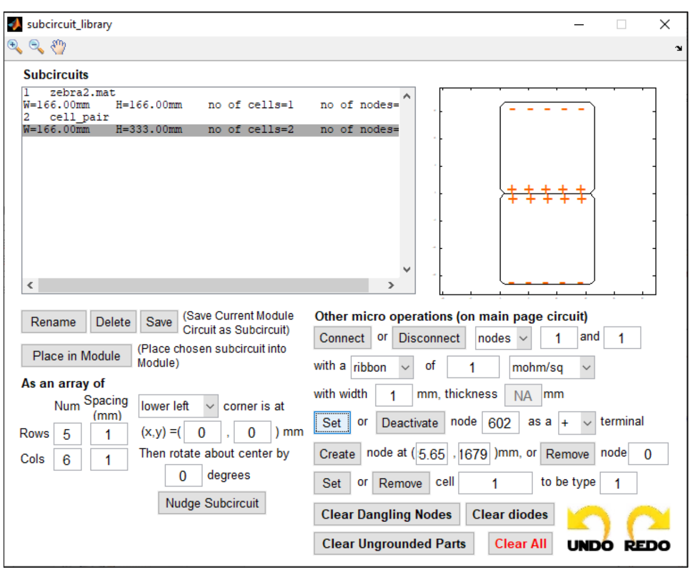
Step 4. Now open the conductive backsheet window. Adjust the x and y offset values to bring the conductive backsheet into alignment with the cells. If the box "connect to cells" is checked in the conductive backsheet window, then any solder point defined on the cell busbars which lie within the conductive backsheet, will be displayed as a connection points. In this design, we have perfect alignment when the positive busbar connection points and the negative busbar connection points are lying in different backsheet sections, as shown below.

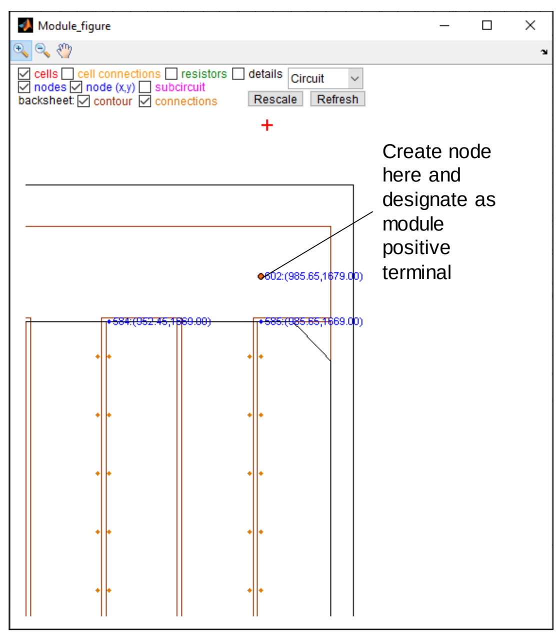


Step 5. Now that we have interconnected cells, we still need to define the module positive and negative terminals and connect them (see 6.6 Creating New Nodes and 6.7 Setting Module Terminals). If you go to the subcircuit library to create nodes and set them as positive/negative terminals, and these points are lying inside the conductive backsheet, and that the box “connect to terminals” is checked in the conductive backsheet window, then these points will be connected to the backsheet, as shown below.

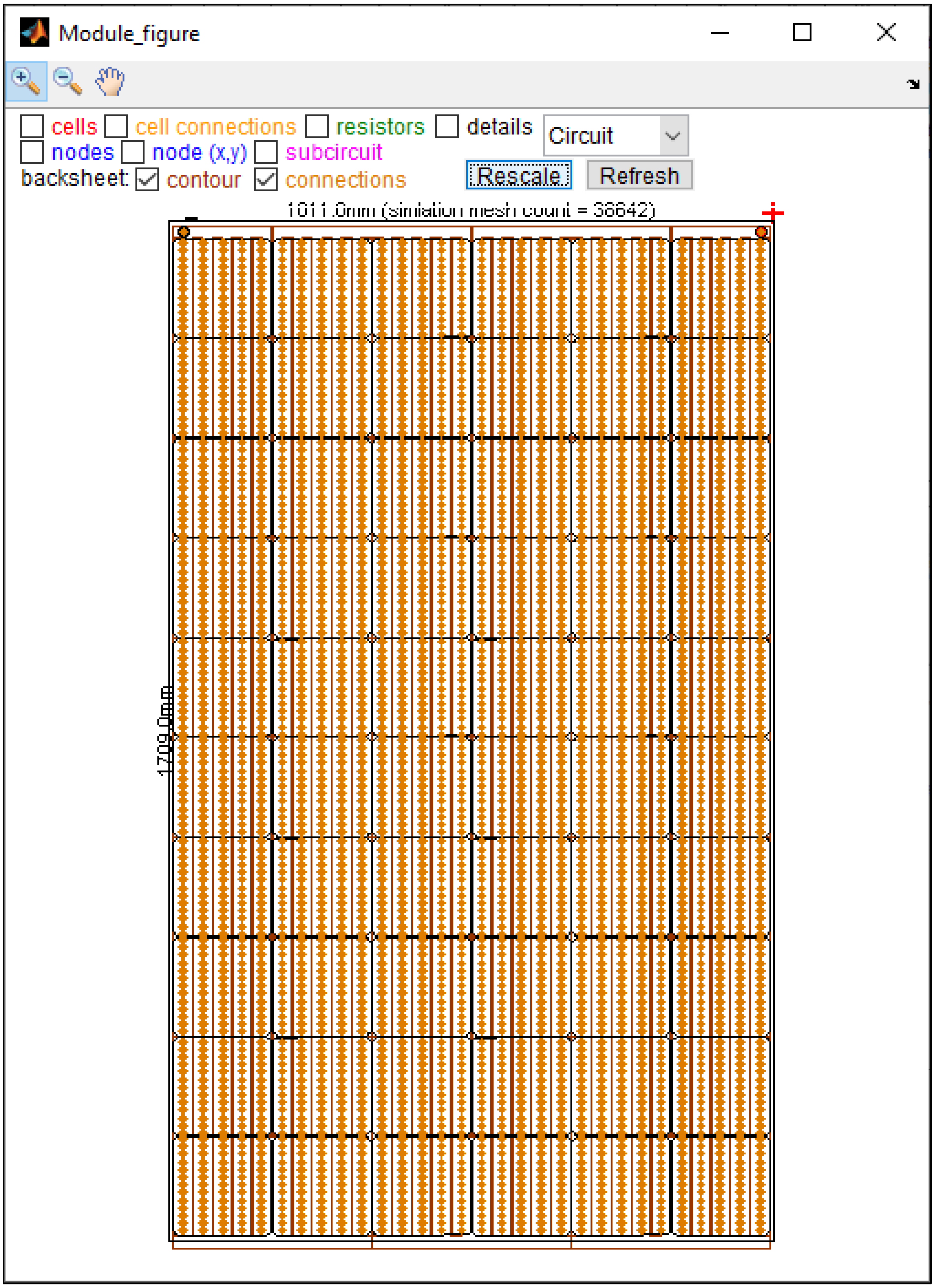




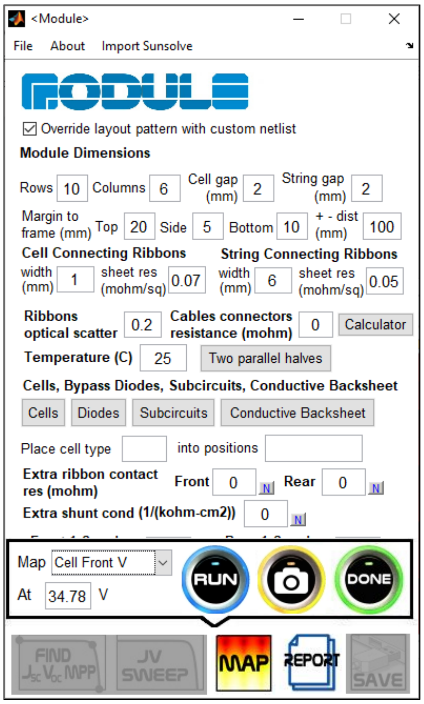


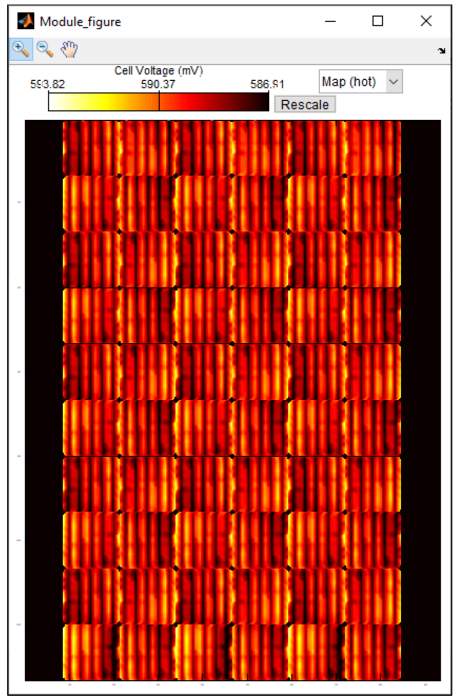


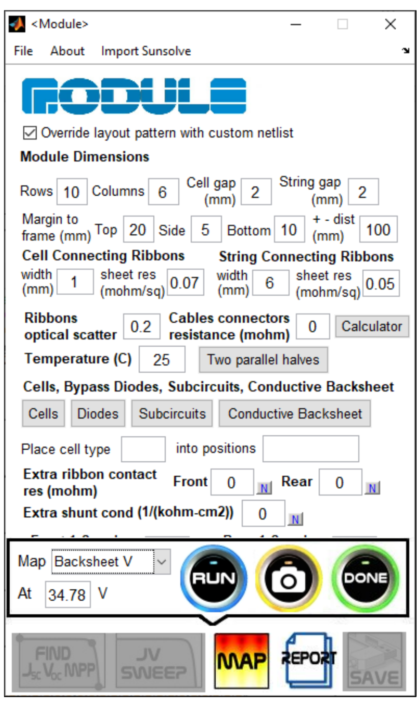
We can now review the entire schematics. This module is now ready for simulation!

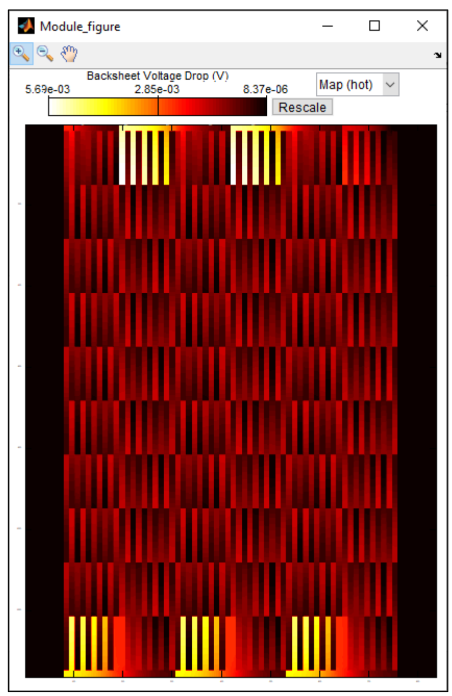


As with any module design, you can simulate the I-V characteristics, view the spatial distribution of cell voltages, etc. When there is a conductive backsheet, you can also choose to Map “Backsheet V” to see the voltage drop along each conductive backsheet section, as shown below.



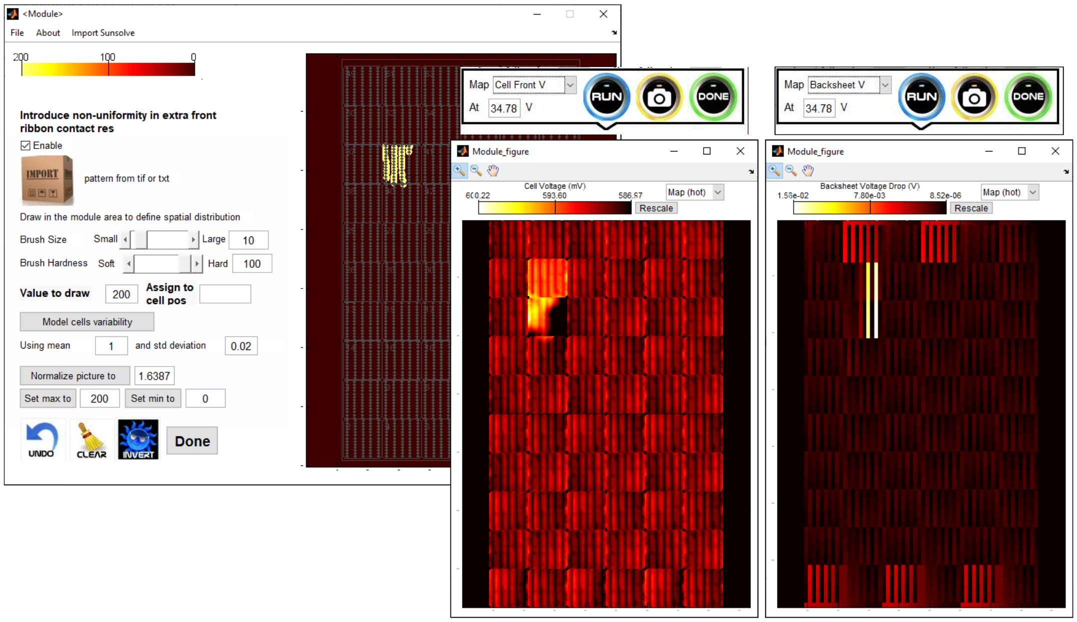




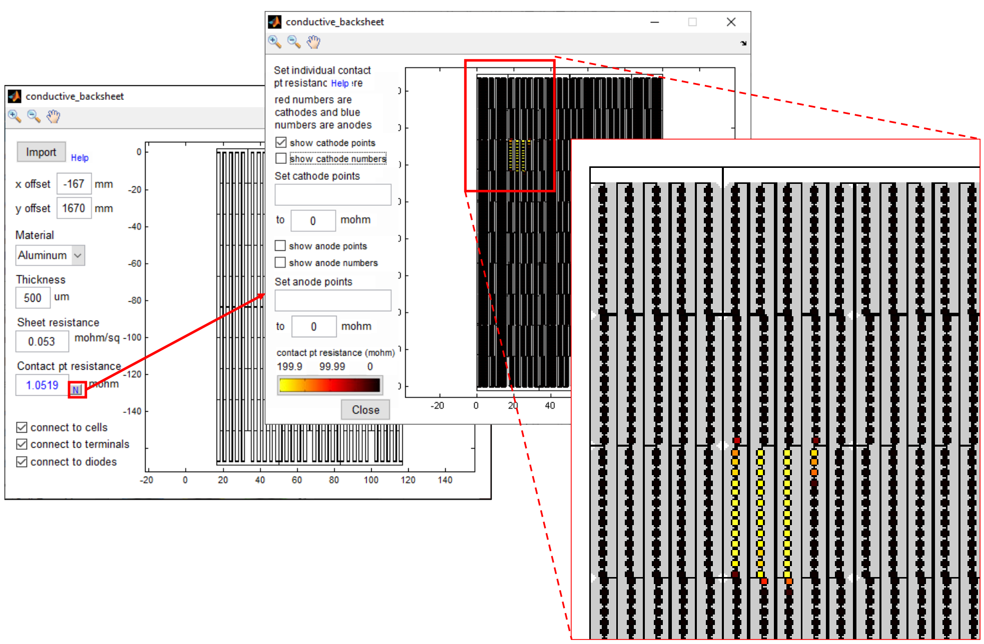


7.4 Conductive Backsheet Connection Point Contact Resistance

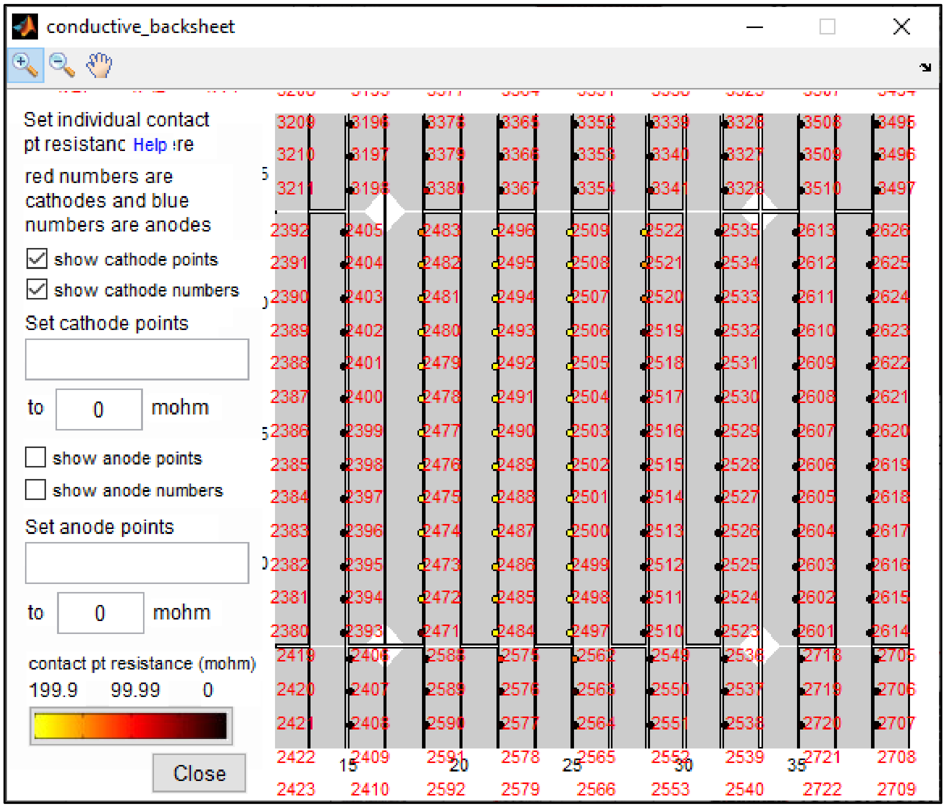
You can simply follow the steps in section 3.8 to define extra connection point contact resistance between the cells and the backsheet. In this case, “extra front ribbon contact res” means extra contact resistance between cell positive busbar connection points and the conductive backsheet, and “extra rear ribbon contact res” means extra contact resistance between cell negative busbar connection points and the conductive backsheet. An example is shown below.



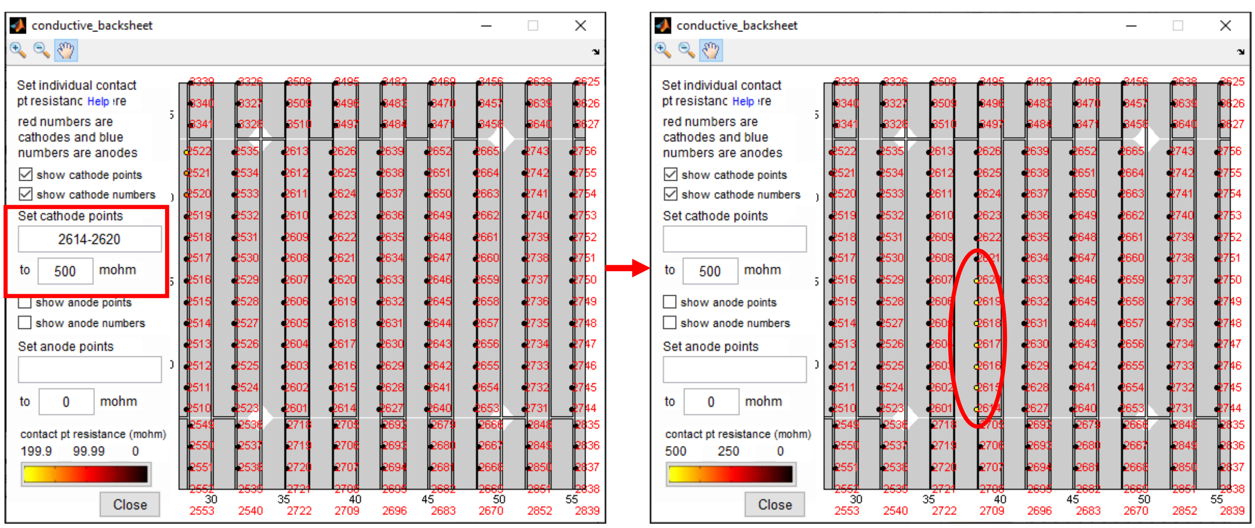
When there is conductive backsheet, an alternate way to view and edit the contact point resistance is in the conductive backsheet winow. Here, click on the blue N button next to “Contact pt resistance” to view the backsheet connections coloured by contact resistance. You can see that whatever spatial pattern was defined in the main screen, is displayed here as well.



If we check the box "show cathode numbers", then we can see the indices of the positive connection points to the backsheet as well.



To make edits, you can set the value for the contact point resistance in mohm, then type a series of cathode points (or anode points), e.g. if we want to set another series of points 2614-2620 to value of 500 mohm, we simply set 500 and type "2614-2620" and hit enter, as shown below.



Now we can see that the updated spatial pattern of contact point resistance is reflected in the simulations.