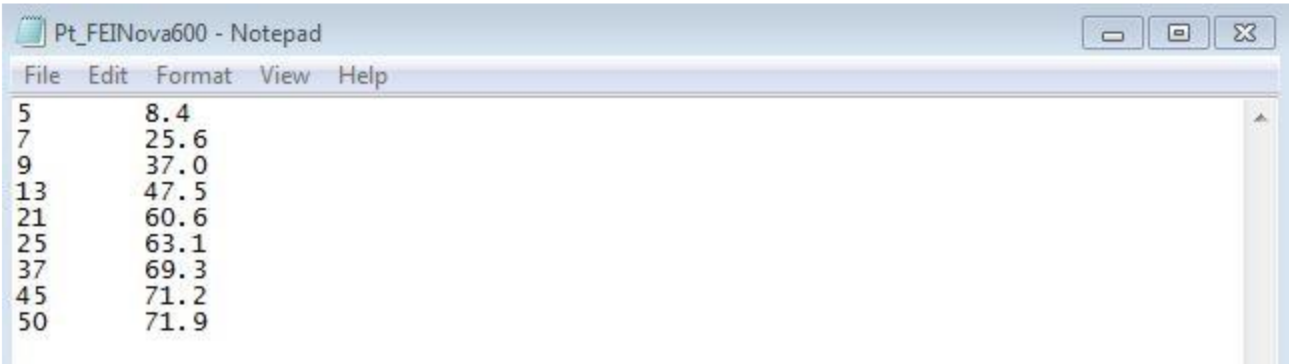
Method #1: Basic CAD use

Video: Method #1 (Basic CAD use)

The program is contained in the folder named \EBiD 3D (CAD). The program name is FEBiD_CAD_v9p0.m. The calibration files are located in \EBiD 3D (CAD)\FEBiD 3D CAD (Supporting Files). There are two required calibration files per calibration curve. In this case I have named the calibration file "Pt_FEINova600". The two files must have the format of (1) *name*.txt and (2) *name*_Parameters.txt. Therefore, the two required files in this case are;

(1) Pt_FEINova600.txt
(2) Pt_FEINova600_Parameters.txt

The first column of Pt_FEINova600.txt contains a list of the primary electron beam dwell times used to deposit the segment portion of a simple pillar + segment geometry. In this case the pillar for each experiment was always 400 [nm] tall with an attached segment. The segment angle determined from scanning electron microscope images for each deposited structure is provided in the second column in Pt_FEINova600.txt.



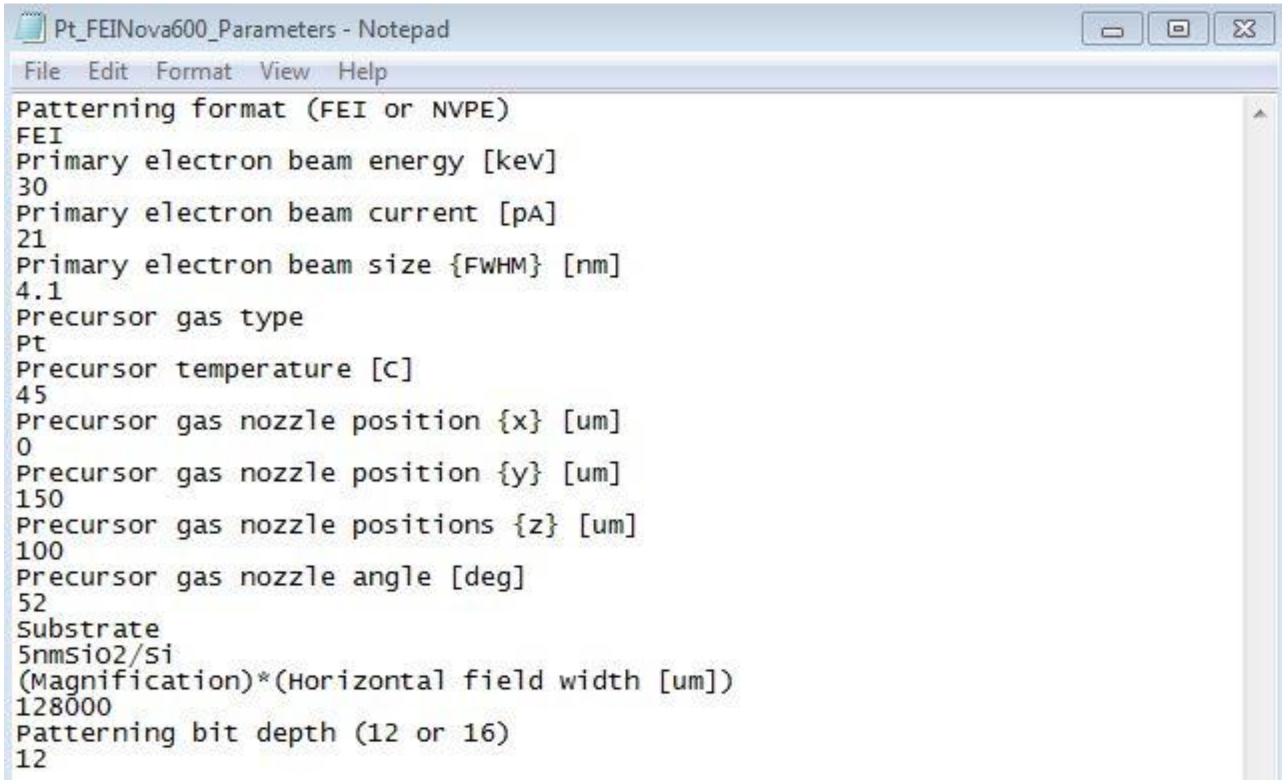
5	8.4
7	25.6
9	37.0
13	47.5
21	60.6
25	63.1
37	69.3
45	71.2
50	71.9

The units of the first column are in milliseconds and the units in the second column are in degrees.

The second file contains information critical to exposure file creation including the patterning bit depth (12 or 16 bit), the type of patterning capability (FEI or NVPE), and the value of the magnification multiplied by the horizontal imaging field width.

Importantly, in the case that the User has a microscope other than the FEI or NVPE options listed, a general exposure file is created that can be later converted to the required format by the User.

The second file appears with the following format;




```
Patterning format (FEI or NVPE)
FEI
Primary electron beam energy [keV]
30
Primary electron beam current [pA]
21
Primary electron beam size {FWHM} [nm]
4.1
Precursor gas type
Pt
Precursor temperature [C]
45
Precursor gas nozzle position {x} [um]
0
Precursor gas nozzle position {y} [um]
150
Precursor gas nozzle positions {z} [um]
100
Precursor gas nozzle angle [deg]
52
Substrate
5nmSiO2/Si
(Magnification)*(Horizontal field width [um])
128000
Patterning bit depth (12 or 16)
12
```

The program reads only the even numbered lines during the file read procedure. Information directly used by the program includes the lines;

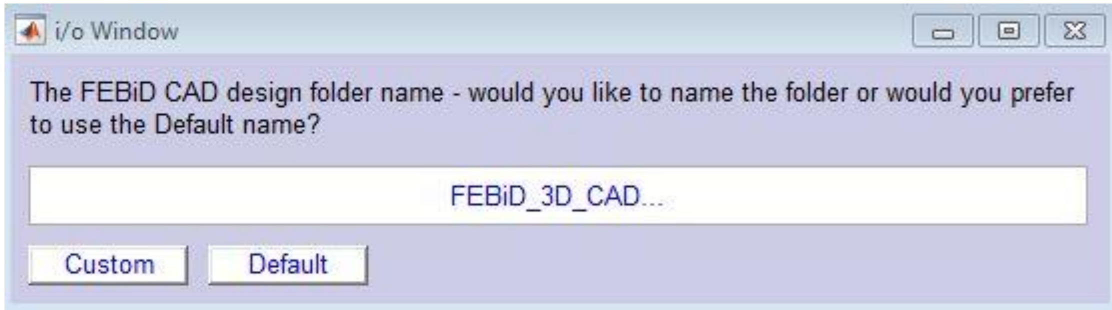
(1) "Patterning format (FEI or NVPE)"
(2) "Primary electron beam size {FWHM}"
(3) "(Magnification)*(Horizontal field width [μm])"
(4) "Patterning bit depth (12 or 16)"

Selection (2) is used during the fitting of the calibration curve (see Method #3 (Calibration data fit)). (1, 3-4) are directly used in exposure file creation.

The remaining information is displayed in the GUI when the calibration file is selected and represents key experimental parameters that strongly influence the magnitude and shape of the calibration curve. In this Method, this calibration file information is used. In a later Method, calibration file creation is demonstrated but simply requires creating new versions of these files (see Method #2 (Calibration file creation)).

Action #1: The program FEBiD_CAD_v9p0.m is executed from the Matlab Command Window.

This launches a window used the name the current design folder. This figure window is shown below.



The design folder, once named, is automatically saved in the directory \EBiD 3D (CAD). There are two options for naming a folder. The “Custom” option requires that the User type the name into the input box and press “Custom”. The second option consists of pressing “Default” only. In this case, the folder will be named \FEBiD_3D_CAD_*number* where the *number* is an integer that is automatically advanced by a value of +1 each time the program is executed. The current value is stored in the uID.mat file, located in \EBiD 3D (CAD)\FEBiD 3D CAD (Supporting Files), as the Matlab variable {UniqueID}.

Previously created design folders cannot be loaded from this window but rather must be opened once the main GUI has loaded.

Pressing either “Custom” or “Default” launches the main GUI figure window.

Action #2: A folder named “Simple Pillar and Segment” is created.

The main GUI window launches.

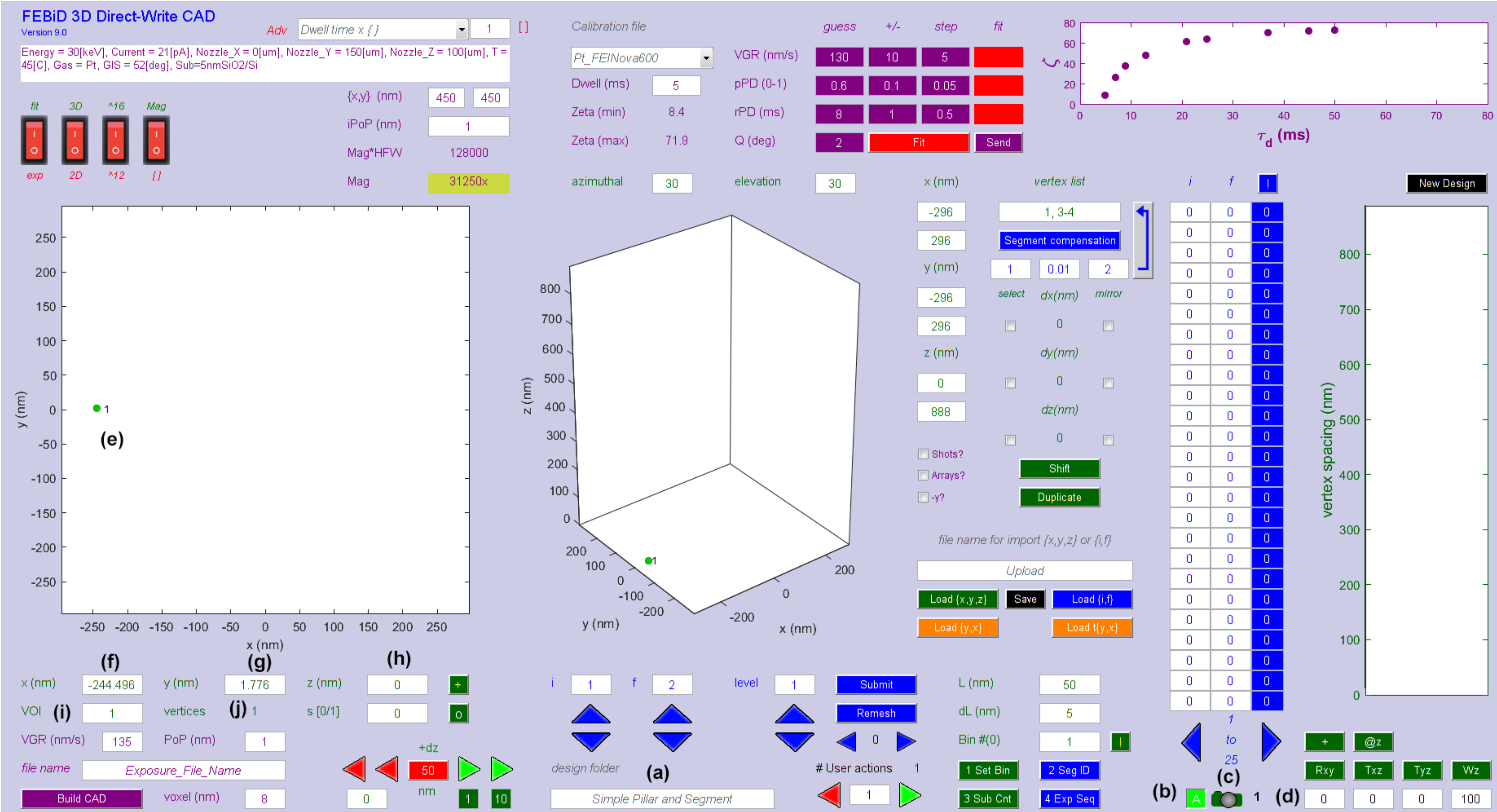


Figure 1

Note that a past design folder can be loaded in the “design folder” GUI textbox (figure 1a) by highlighting the text box, deleting “Simple Pillar and Segment”, typing the name of the previous design folder and pressing the enter key.

Action #3: The red press button labelled “M” is pressed (figure 1b).

This action automatically saves an image of the Main GUI in the design folder each time a major User action is executed, e.g., for documentation. “M” stands for manual. The button turns green and is labelled with an “A” in automatic mode when pressed. Each image is saved in the design folder at \EBiD 3D (CAD)\Simple Pillar and Segment as a .tiff file with the name “ImageUI_*number*” where *number* is automatically advanced.

Conversely, when the manual mode “M” is selected, the screen capture image must be executed on demand by pressing the camera icon (figure 1c). The total number of images taken is shown by the bold integer located beside the camera icon (figure 1d).

Action #4: The mouse is used to place a vertex on the x-y plot (figure 1e) by pressing the left mouse button.

The x–position (figure 1f) and the y–position (figure 1g) of the vertex appear in the respective edit text boxes. The z–position is not defined with the mouse (figure 1h). An index is automatically assigned to the vertex and is shown in “VOI”, or vertex–of–interest (figure 1i). The total number of “vertices” in the design is shown at figure 1j.

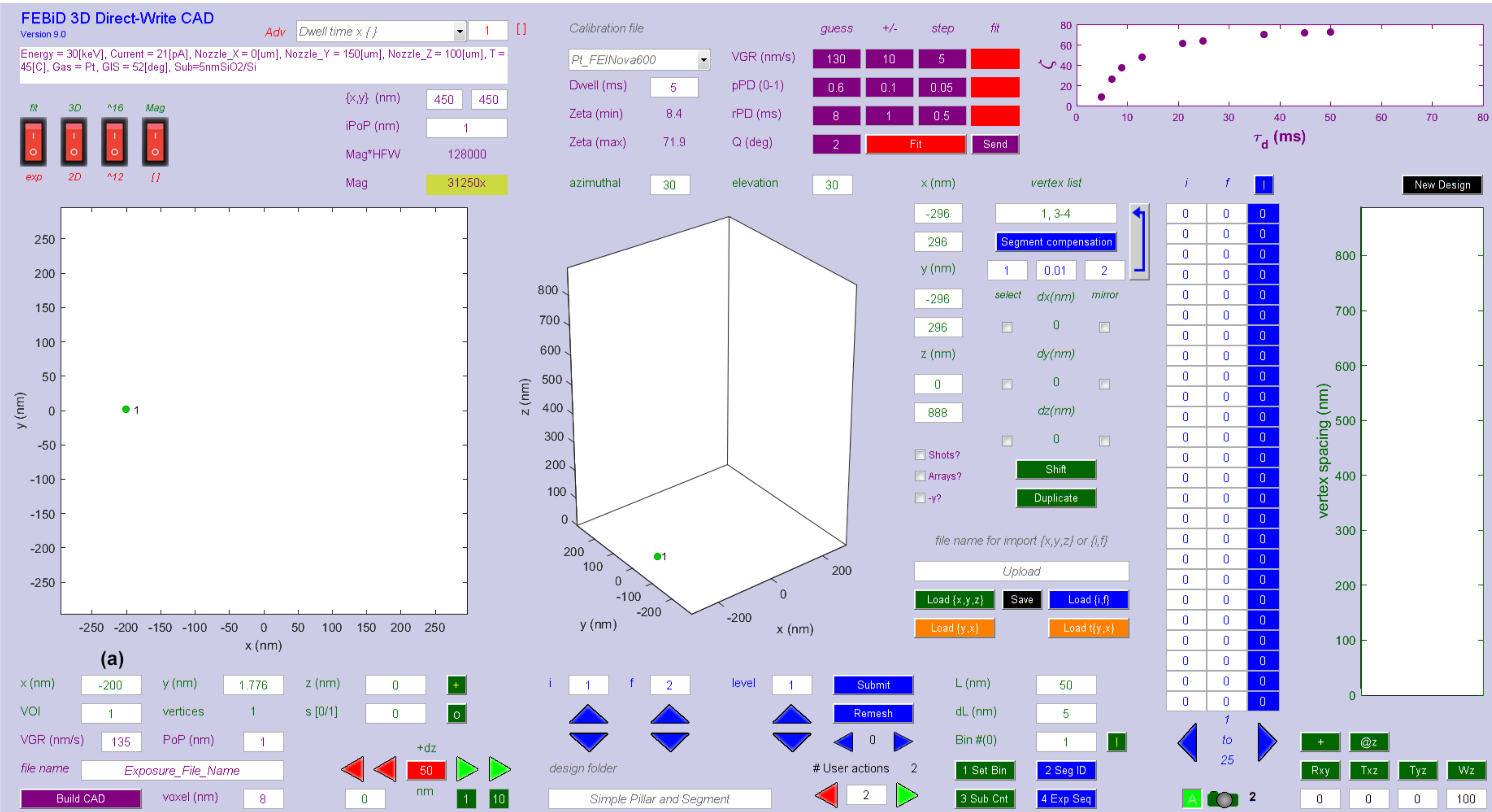


Figure 2

Action #5: The x–position is refined to a value of -200 [nm] using the edit text input box (figure 2a).

The vertex position and index labels update in both the (x,y) and (x,y,z) plots.

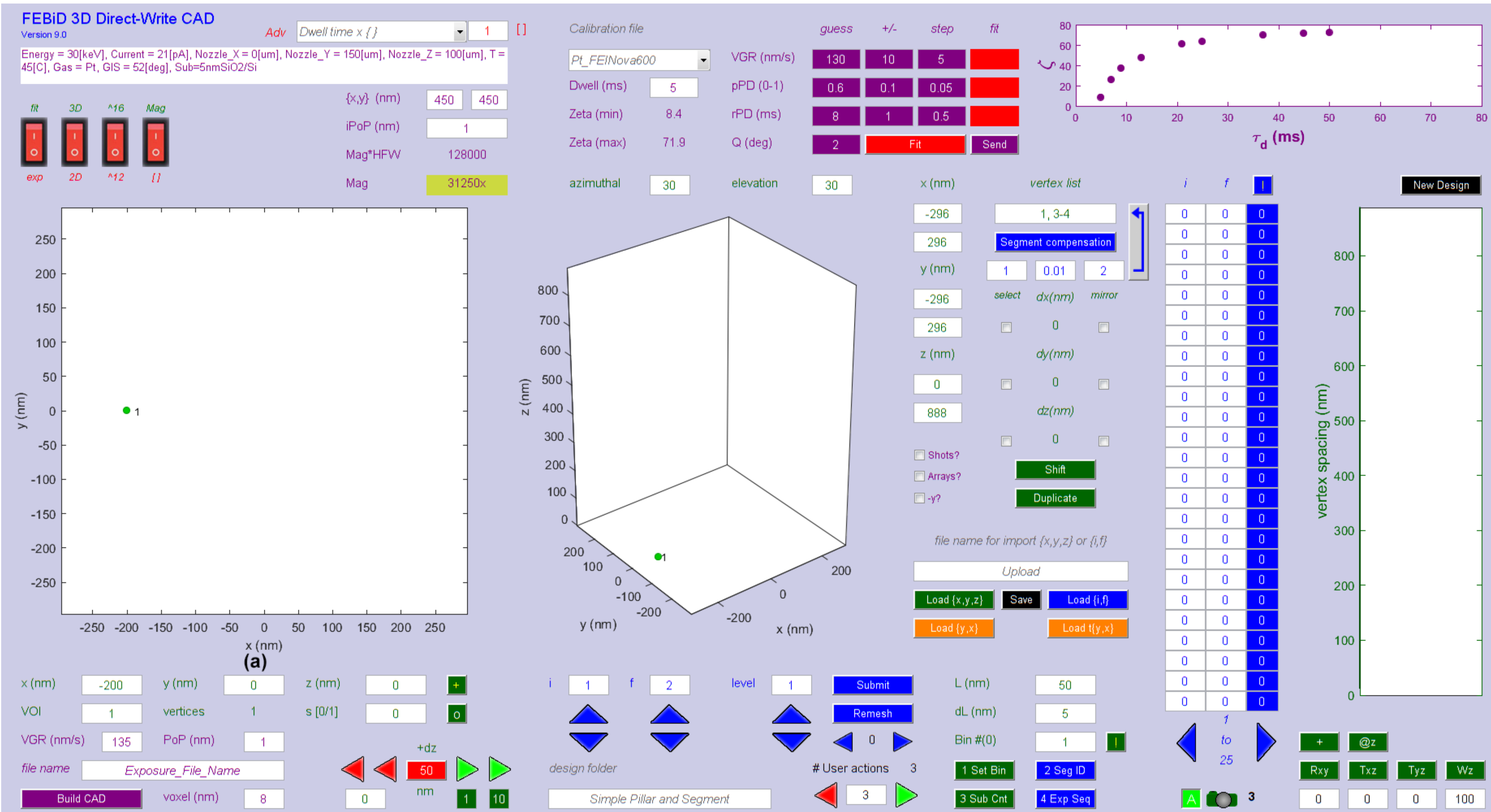


Figure 3

Action #6: The y–position is refined to a value of 0 [nm] using the edit text input box (figure 3a).

Again, the vertex position and index labels update in both the (x,y) and (x,y,z) plots.

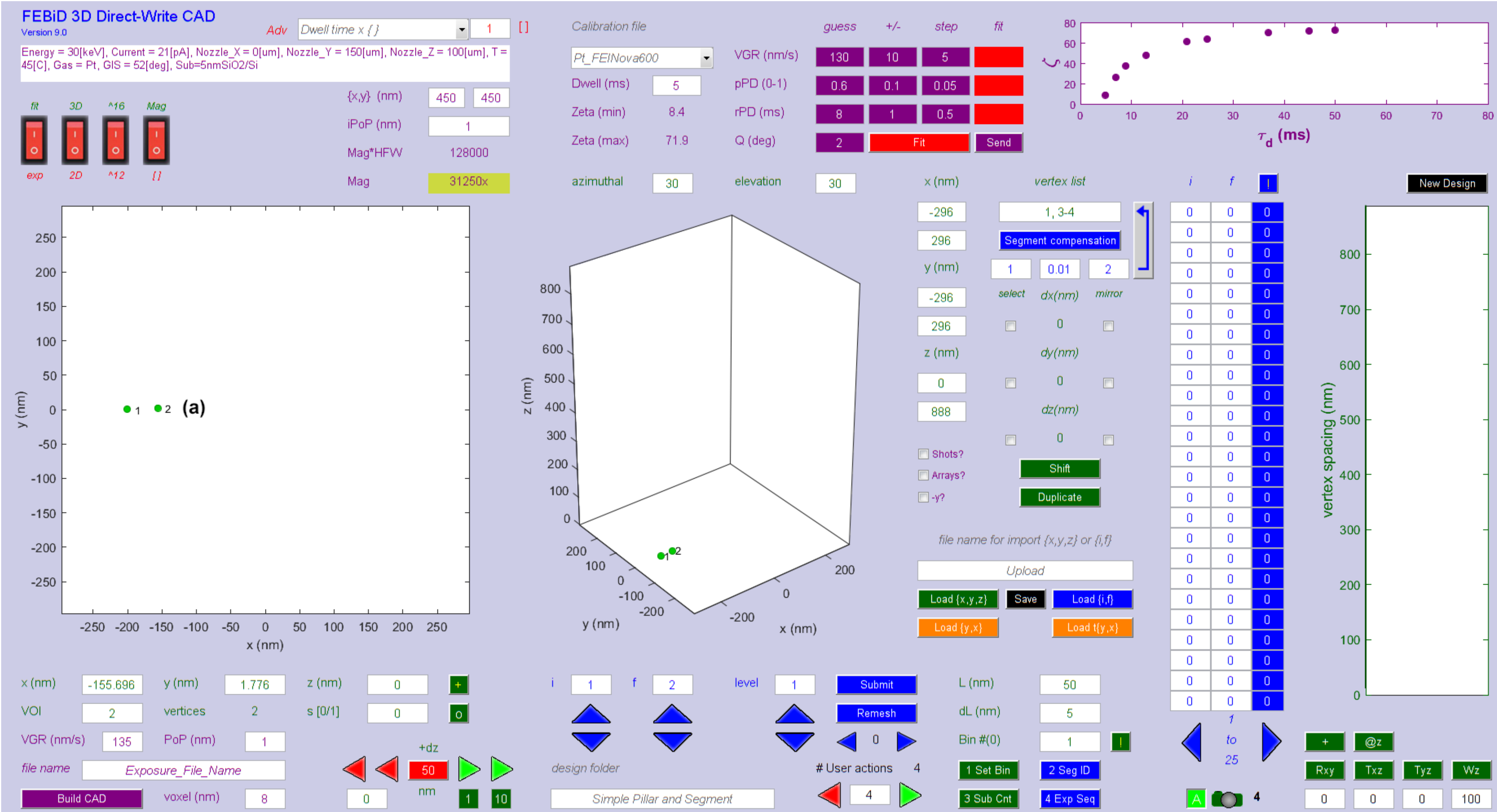


Figure 4

Action #7: The mouse is used to place a second vertex on the x-y plot (figure 4a) by pressing the left mouse button.

The vertex–of–interest is indexed as 2 and the total number of “vertices” is updated also to 2.

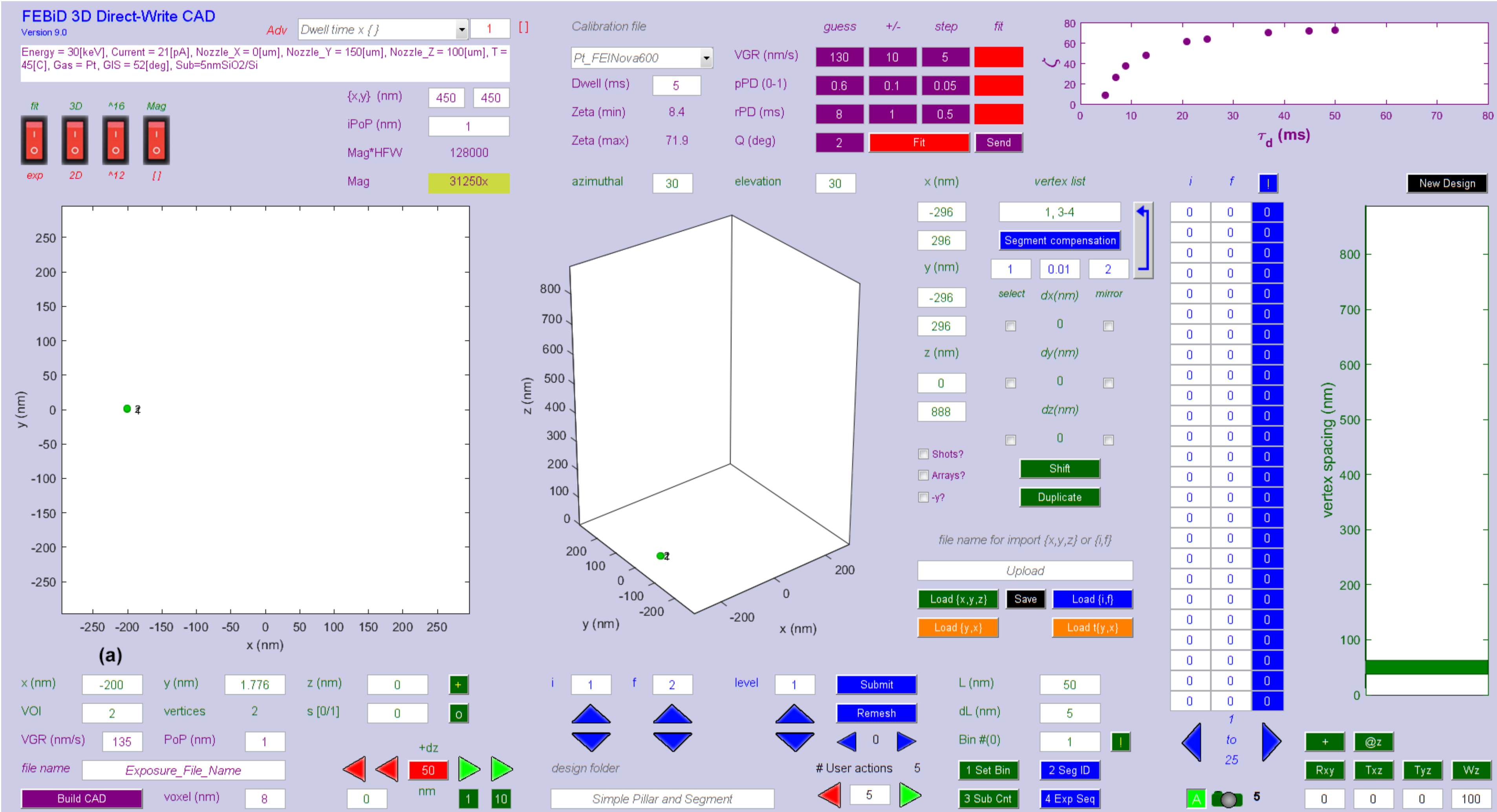


Figure 5

Action #8: The x–position is refined to a value of -200 [nm] for VOI = 2 using the edit text input box (figure 5a).

The vertex position and index labels update in both the (x,y) and (x,y,z) plots.

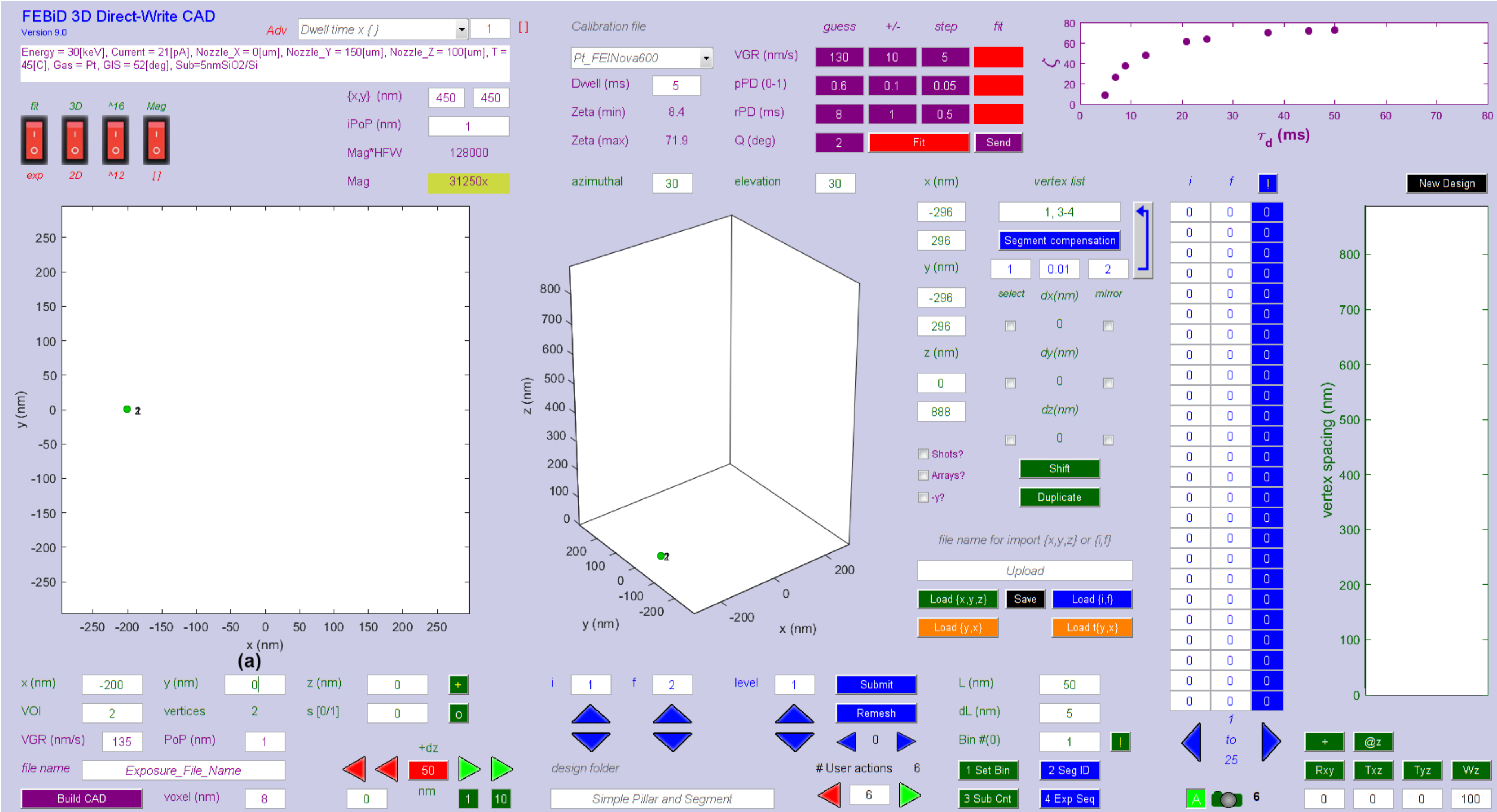


Figure 6

Action #9: The y–position is refined to a value of 0 [nm] for VOI = 2 using the edit text input box (figure 6a).

The vertex position and index labels update in both the (x,y) and (x,y,z) plots.

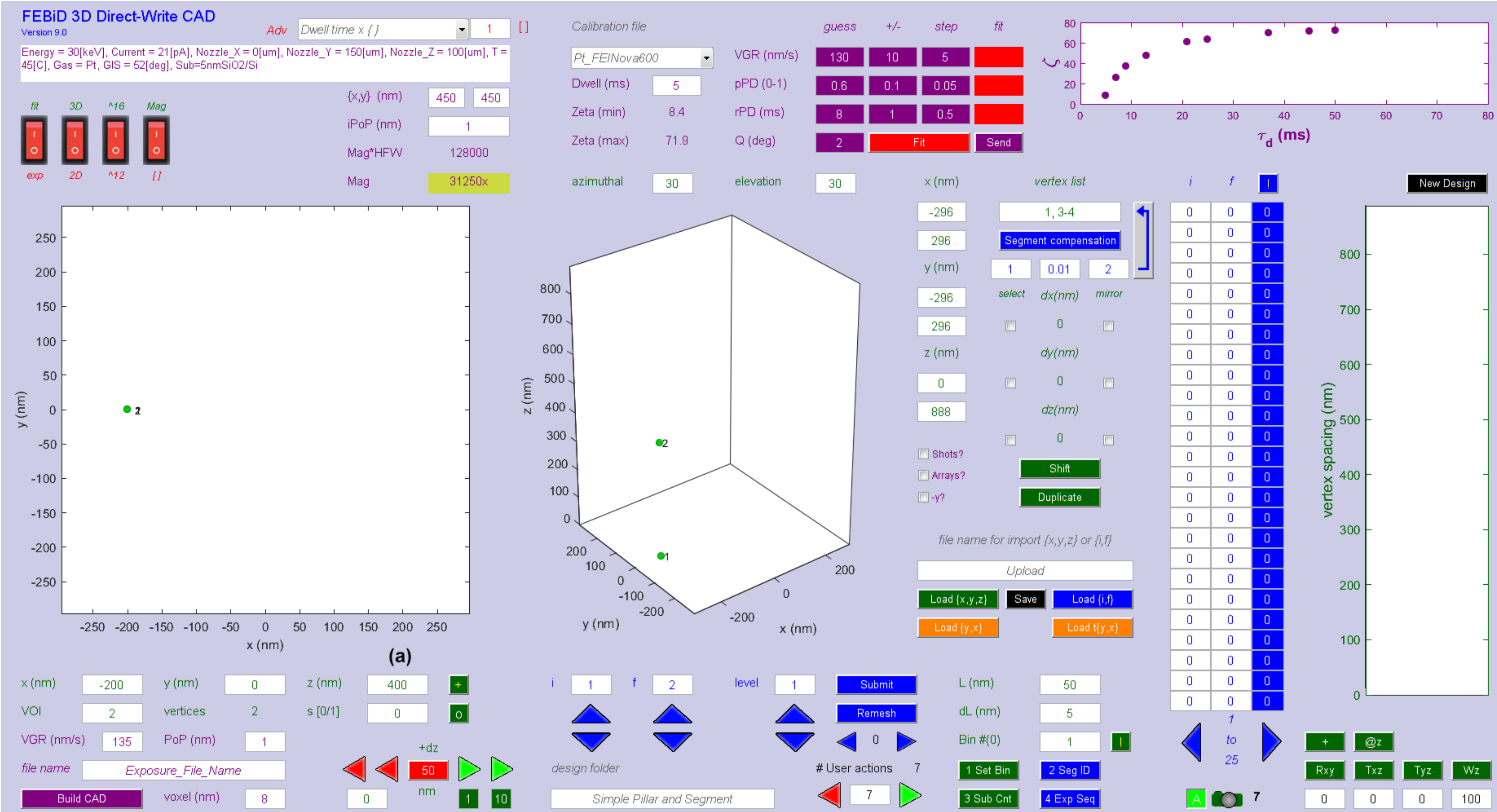


Figure 7

Action #10: The z–position is set to a value of 400 [nm] for VOI = 2 using the edit text input box (figure 7a).

The vertex position and index labels update in both the (x,y) and (x,y,z) plots.

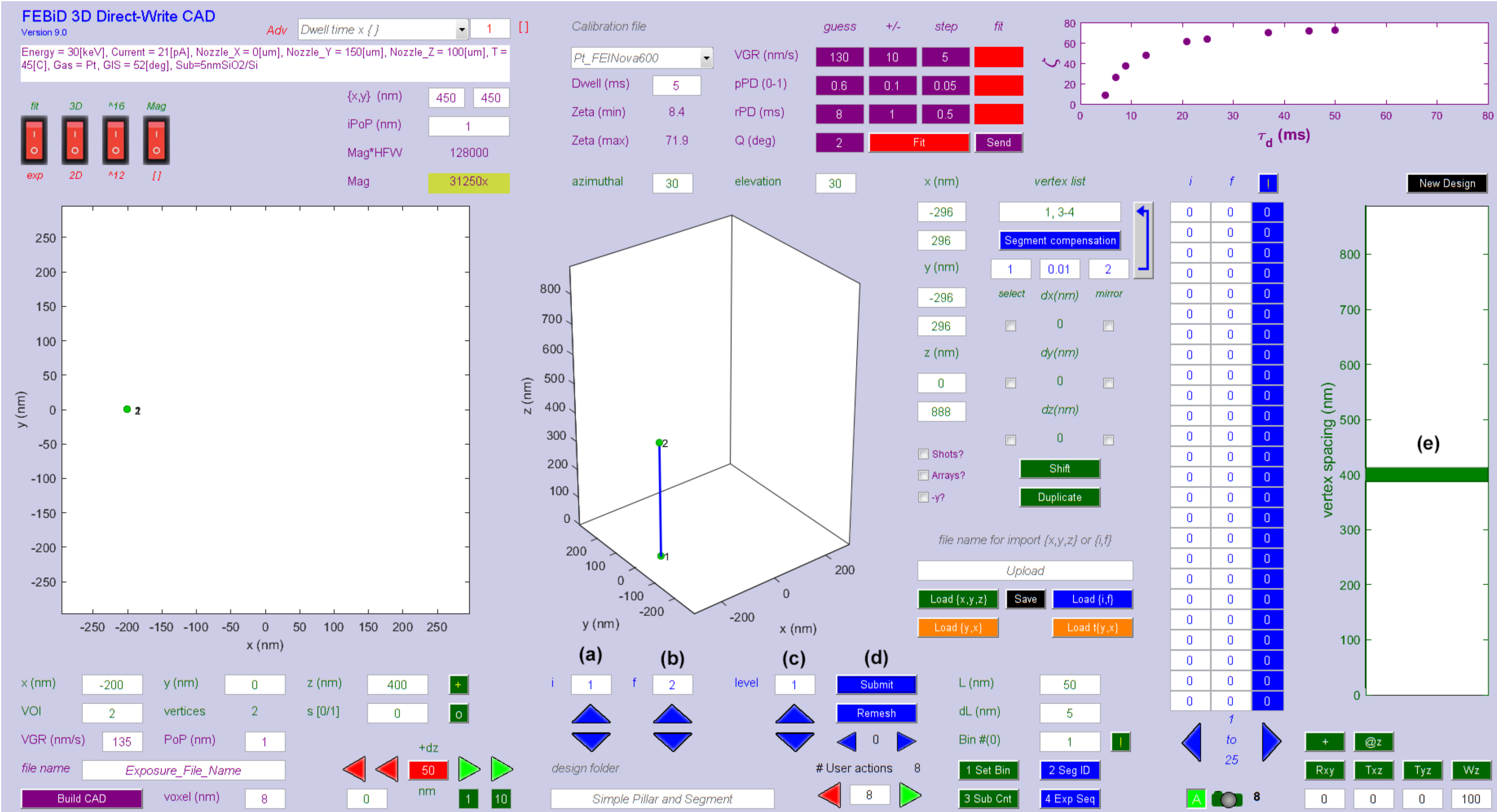


Figure 8

Action #11: The initial position of the pillar is defined by entering a value of 1 for the vertex index into the edit text input box labelled as "i" (figure 8a).

The value of "i" can also be incremented by a value of +1 by pressing the blue up arrow or by -1 by pressing the blue down arrow located below the edit text input box for "i".

Action #12: The final position of the pillar is defined by entering a value of 2 for the vertex index into the edit text input box labelled as "f" (figure 8b).

The value of “f” can also be incremented by a value of +1 by pressing the blue up arrow or by -1 by pressing the blue down arrow located below the edit text input box for “f”.

This defines the terminating vertex for the “pillar” type of element. This pillar represents the first exposure element of the 3D object.

Action #13: An exposure level of 1 is selected in the edit text input box labelled “level”(figure 8c).

The pillar must be formally submitted as an exposure level. This is accomplished by pressing the “Submit” button.

Action #14: “Submit” is pressed (figure 8d).

The exposure submission is presented as a linear element in the (x,y,z) plot spanning the vertices 1 and 2 as requested. A histogram of vertex spacing (vertical axis) versus counts (horizontal axis) is automatically populated as new vertices are added to the 3D object design (figure 8e). The histogram includes the spacings between all defined vertices, not just those vertices that define an exposure element such as a pillar or segment. As will be shown in an additional Method #4 (Auto segment detection), the histogram of vertex spacings can be used to automatically detect exposure elements in appropriate exposure order.

Green text in the GUI indicates a GUI element related to “vertices” while **blue** text in the GUI indicates a GUI element related to “segments”.

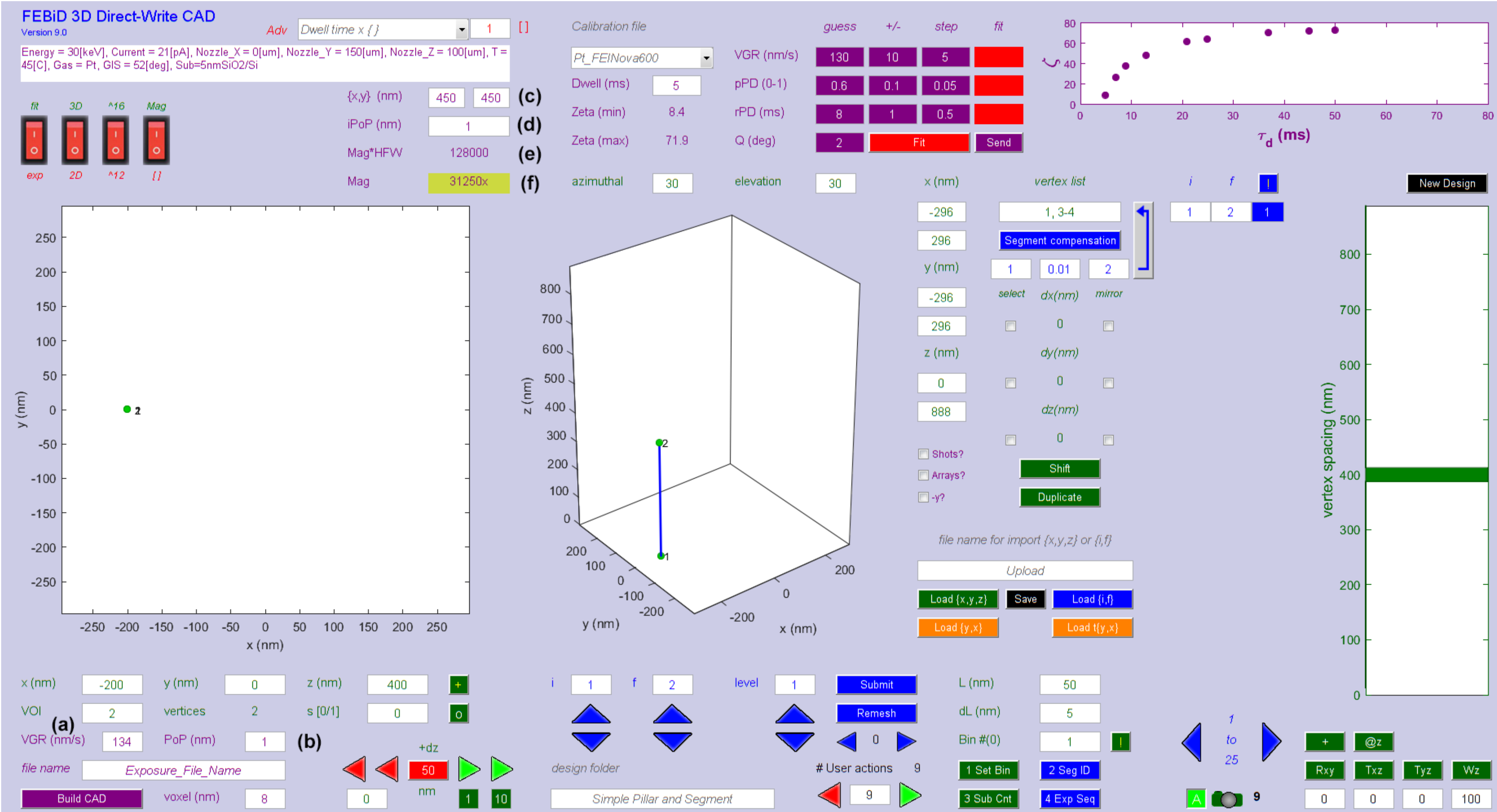


Figure 9

Action #15: The vertical growth rate is set to 134 [nm/s] in the edit text input box (figure 9a).

The vertical growth rate, or VGR, is the critical GUI element used to set the exposure dwell time for the “pillar” type of element as explained in the main text. The displacement between beam exposures, or the pixel point pitch “PoP”, also determines whether the element is a pillar or segment. In the main text the variable (Λ) refers to the pixel point pitch.

Action #16: The pixel point pitch is set to 1 [nm] in the edit text input box (figure 9b).

The submitted element spanning from the vertex (1) to the vertex (2) is designated as a “pillar” because the following equality is satisfied;

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} < PoP$$

see also S1: Pillar versus Segment.

This value for the pixel point pitch will be applied to all elements in the final design when the final exposure file is created.

Action #17: The x–position and y–position for an initial and final dwell position is defined as (450,450) [nm] which is the default setting (figure 9c).

This information is only used if a 12 bit patterning engine is selected in the *name*_Parameters.txt file. In this case, a brief beam exposure dwell with a duration of 1.6 [μs] seconds is applied to the beginning and end of the FEBID exposure in order to avoid the introduction of an exposure artifact on the final 3D object which can degrade geometric fidelity.

Action #18: An exposure pattern pixel size of 1 [nm] is selected (figure 9d).

The exposure pattern pixel size, or “iPoP”, sets the lower limit for the pixel point pitch and, along with the value for “(Magnification)*(Horizontal field width [μm])” provided in the *name*_Parameters.txt file, sets the image magnification required during FEBID via;

$$Magnification = \frac{(Mag \times HFW)\ [\mu m] \cdot 1x10^3 \left[\frac{nm}{\mu m}\right]}{2^{bit}\ [pix] \cdot iPoP \left[\frac{nm}{pix}\right]}$$

The value for (Mag x HFW), which is imported from the *name*_Parameters.txt file, is displayed in figure 9e.

The magnification required during FEBID exposure is shown highlighted in yellow in figure 9f.

Also note that in this example it was not required to select the “Pt_FEINova600” calibration file from the “Calibration file” dropdown menu because this calibration recipe is the default calibration file when the program is executed.

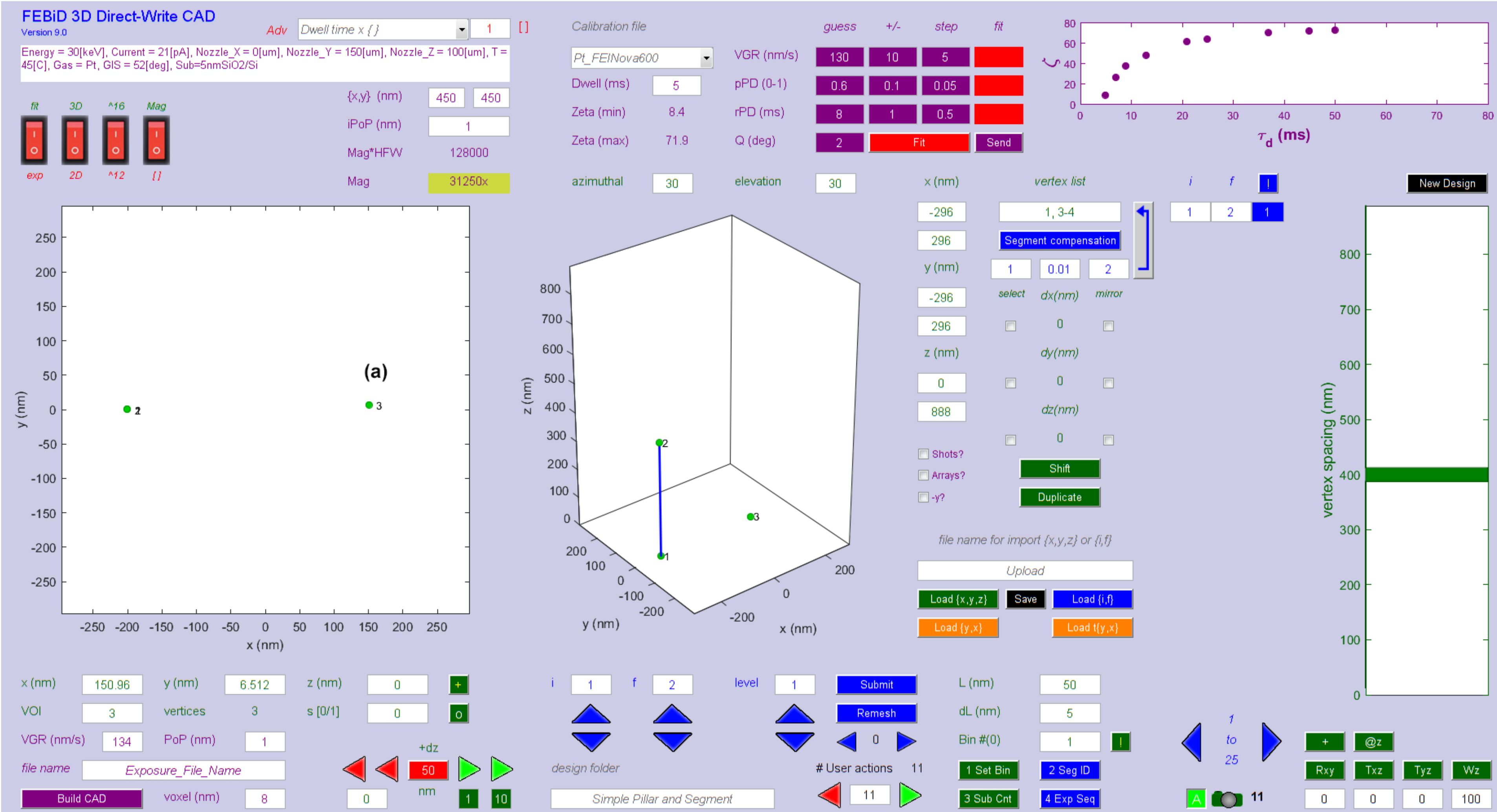


Figure 10

Action #19: The mouse is used to place a third vertex on the x-y plot (figure 10a) by pressing the left mouse button.

The vertex–of–interest is indexed as 3 and the total number of “vertices” is updated also to 3.

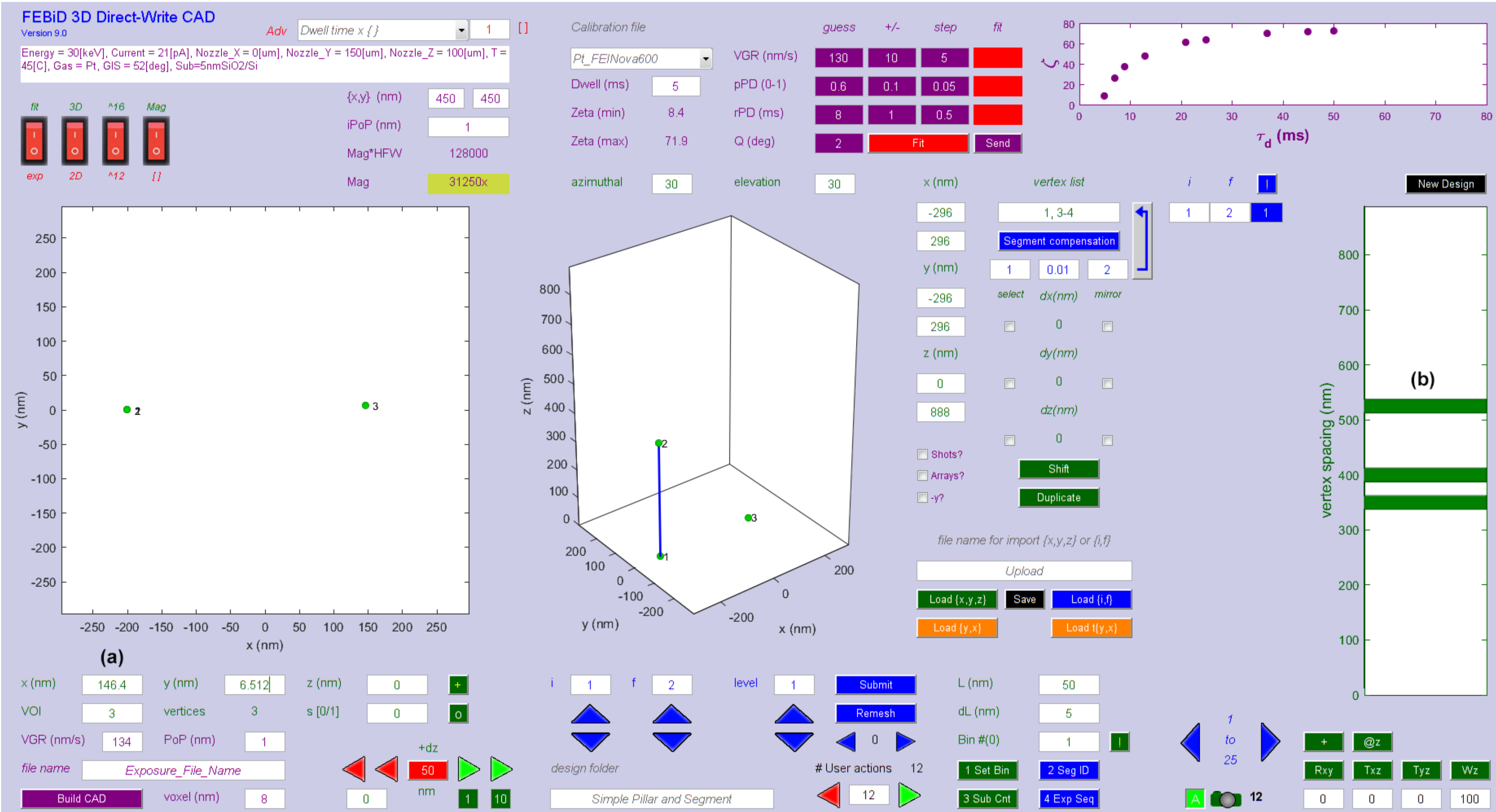


Figure 11

Action #20: The x–position is refined to a value of 146.4 [nm] for VOI = 3 using the edit text input box (figure 11a).

The histogram now displays three unique vertex spacings attributed to the distances between (1-2), (1-3) and (2-3).

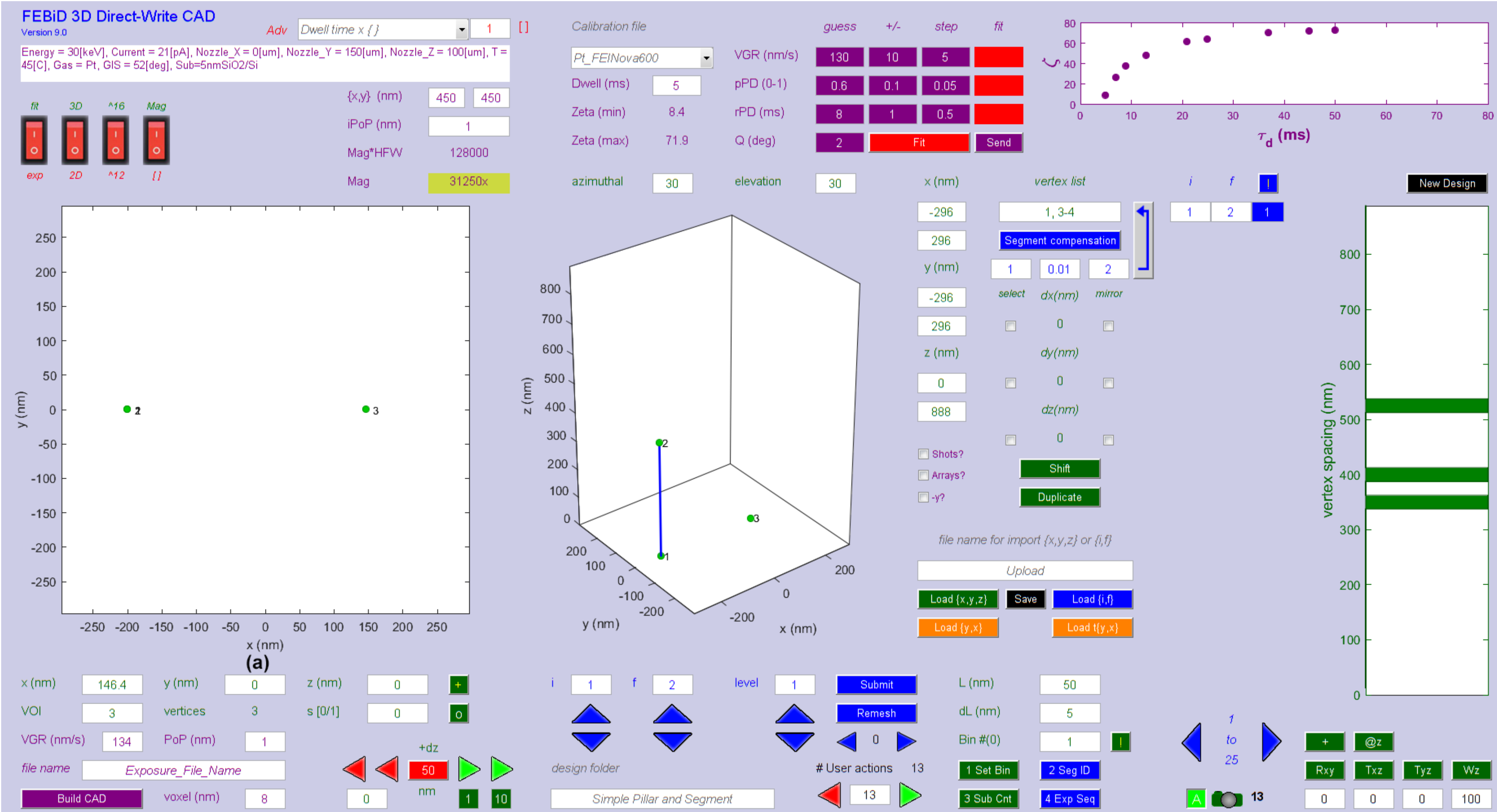


Figure 12

Action #21: The y–position is refined to a value of 0 [nm] for VOI = 3 using the edit text input box (figure 12a).

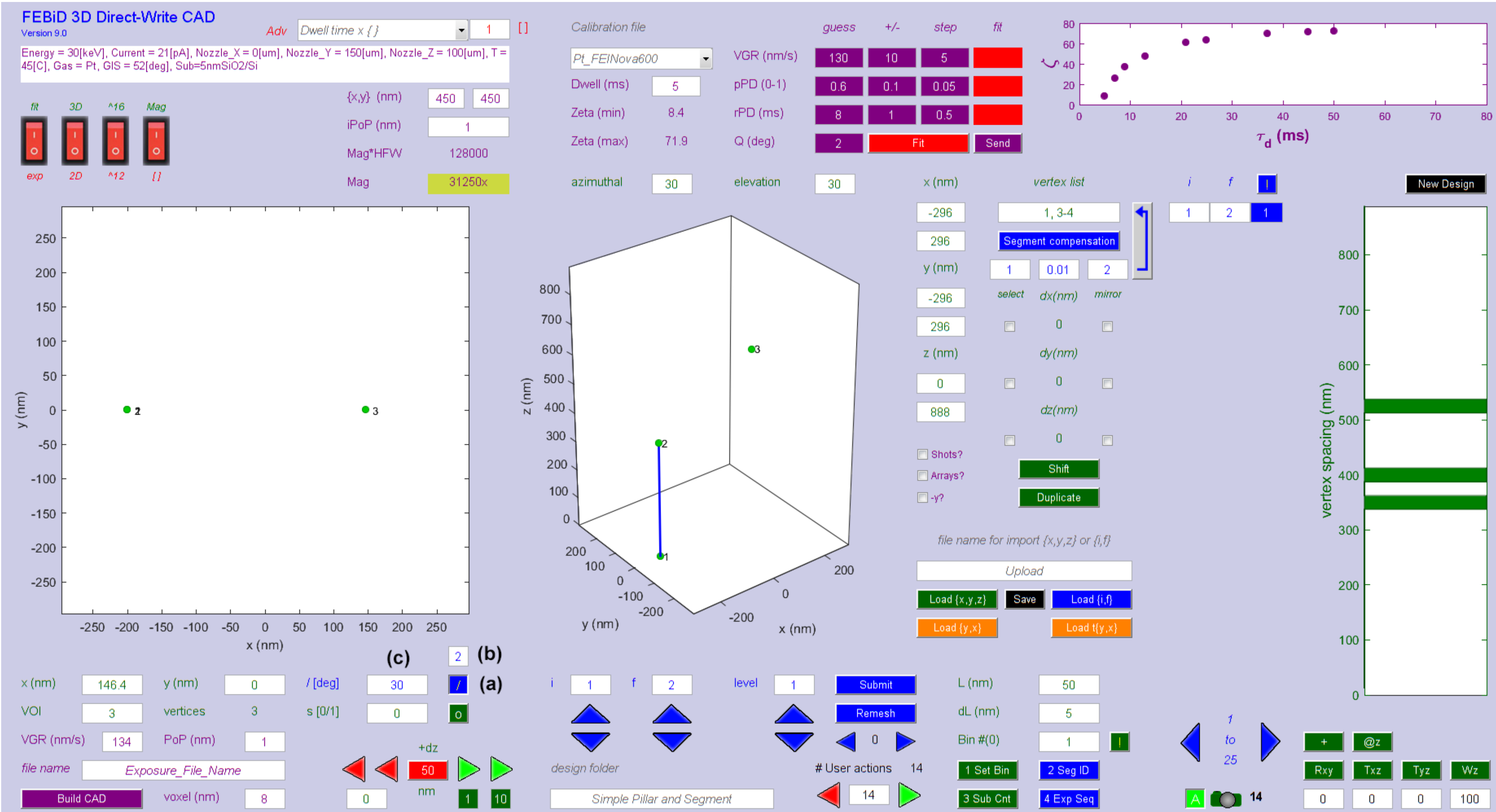


Figure 13

Action #22: The z-position input box if changed from the *absolute* input mode to the *relative angle* mode using the press button at figure 13a.

As a result, the edit input box will now receive input in the units of degrees. An additional edit text input box will appear when the relative angle mode is selected.

Action #23: A value of 2 is entered into the edit text box (figure 13b).

The angle to be specified in the z- position edit text input box will be relative to vertex number 2 based on this input.

Action #24: An angle of 30º degrees is entered into the z–position edit text box (figure 13c).

Pressing enter shifts the z–position of the “VOI” number 3 such that a linear segment, originating at vertex 2 and spanning vertex 3, has an angle of 30º with respect to the focal plane, or x–y, plane.

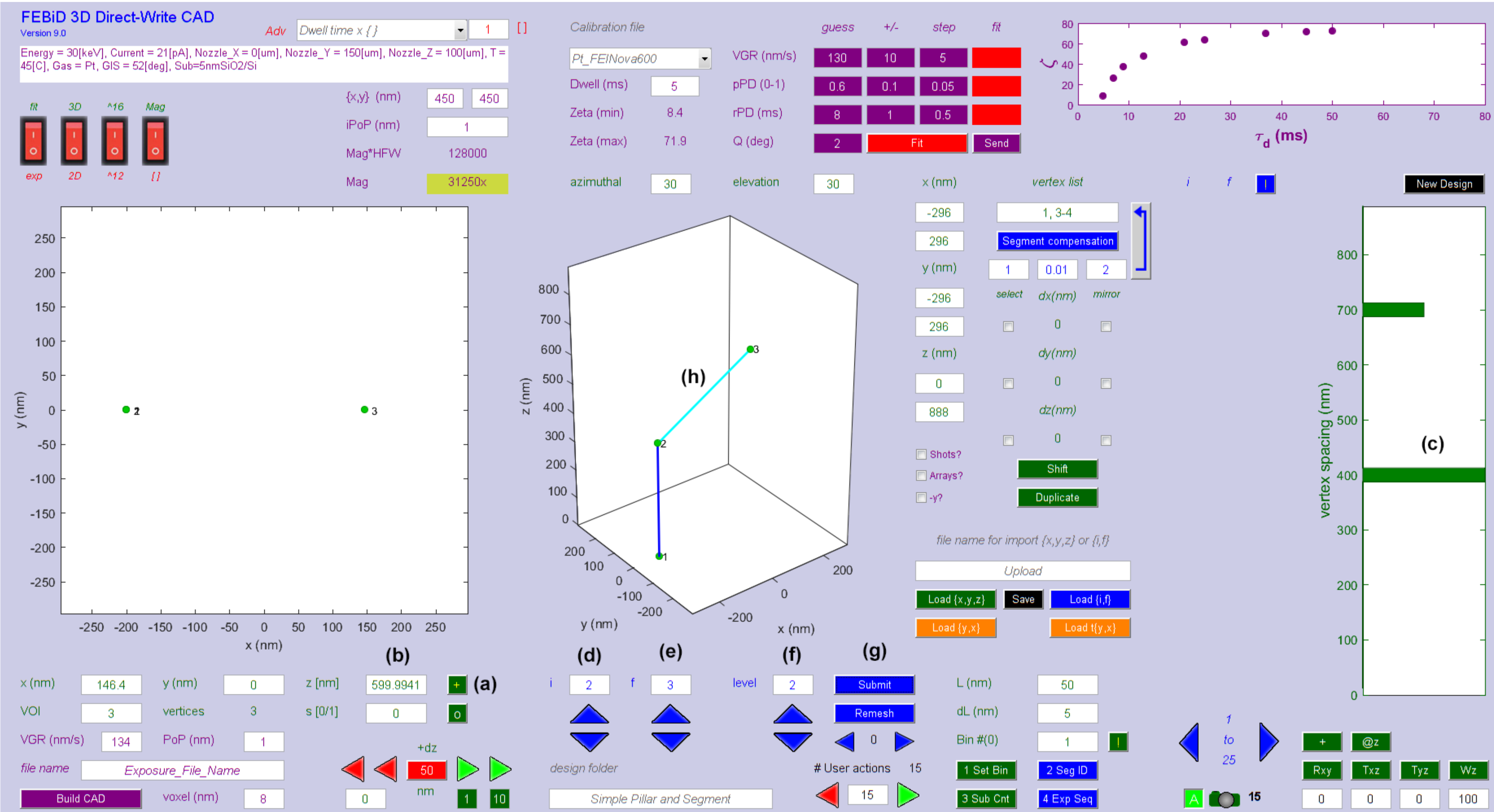


Figure 14

Action #25: Press button “+” is pressed (figure 14a).

The z–position edit text box input button returns to absolute coordinates (figure 14b) indicated by the symbol change back to “+”.

The vertex histogram is a normalized plot. The normalized units are not displayed on the horizontal axis. The bar located at 400 [nm] (figure 14c) is twice as long as the bar at 700 [nm] because two spacings have a distance of 400 [nm]; (1-2) and (2-3) while a single spacing characterizes 700 [nm]; (1-3).

Action #26: Initial vertex index entered for segment (figure 14d).

Action #27: Final vertex index entered for segment (figure 14e).

Action #28: The exposure level for the segment is entered (figure 14f).

Action #29: “Submit” is pressed to formally submit the exposure level for the defined segment (figure 14g).

The (x,y,z) plot updates to show the new exposure segment. Exposure level is indicated by color; exposure level number 1 is blue while exposure level (2) is indicated by light blue (figure 14h).

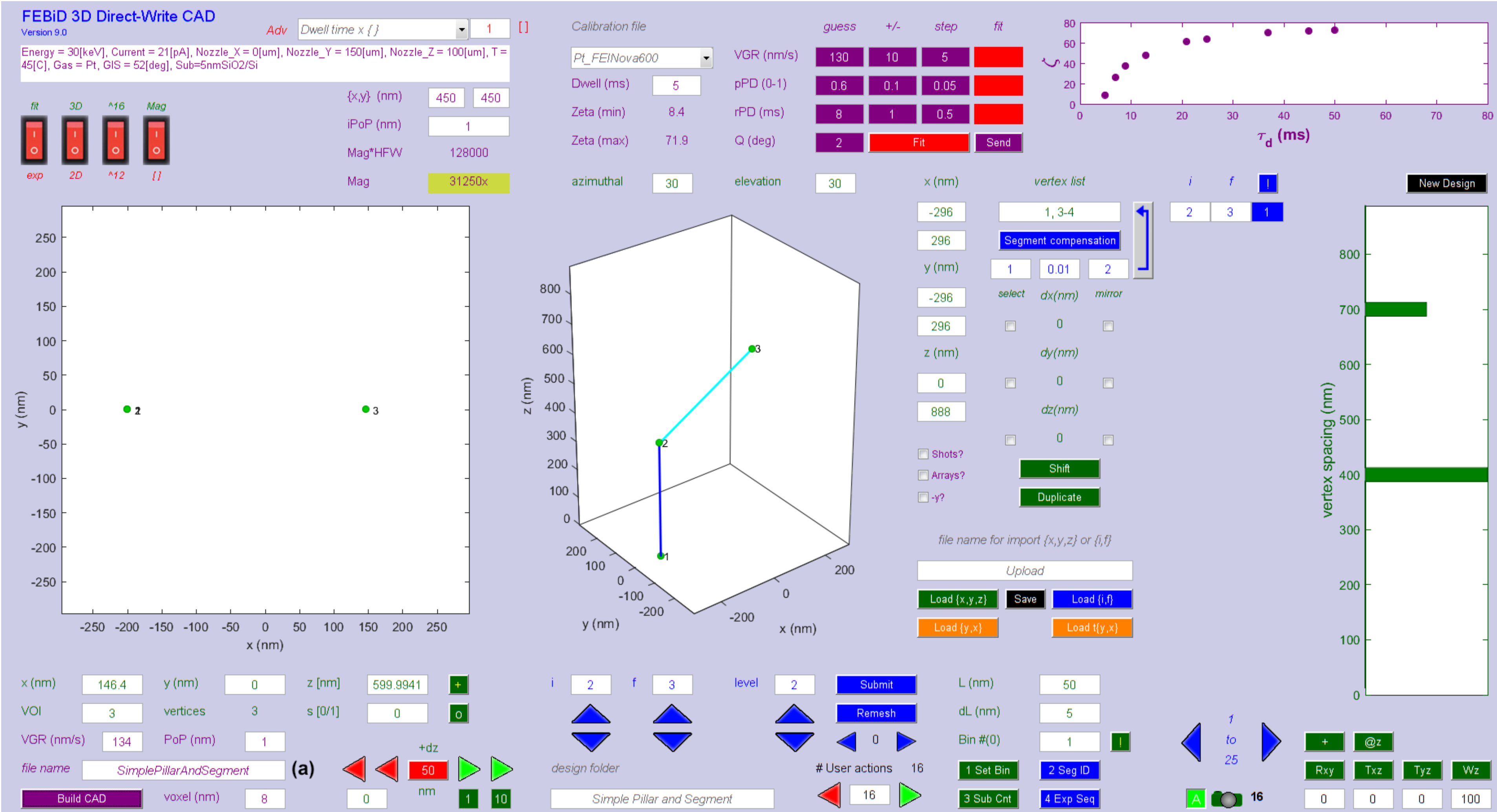


Figure 15

Action #30: The exposure file name “SimplePillarAndSegment” is entered into the “file name” edit text input box to name the exposure file soon to be created.

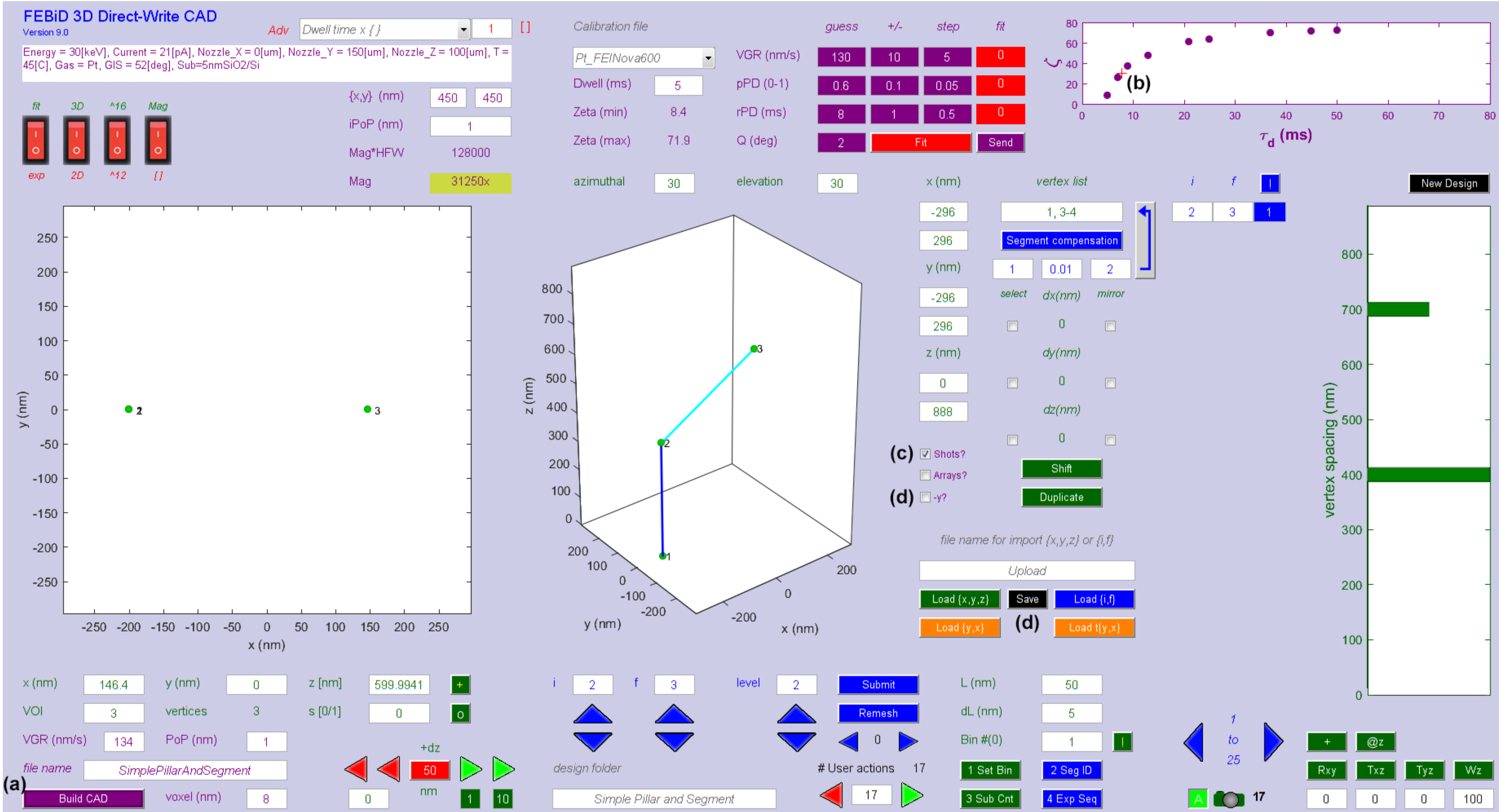


Figure 16

The exposure file is ready to be created.

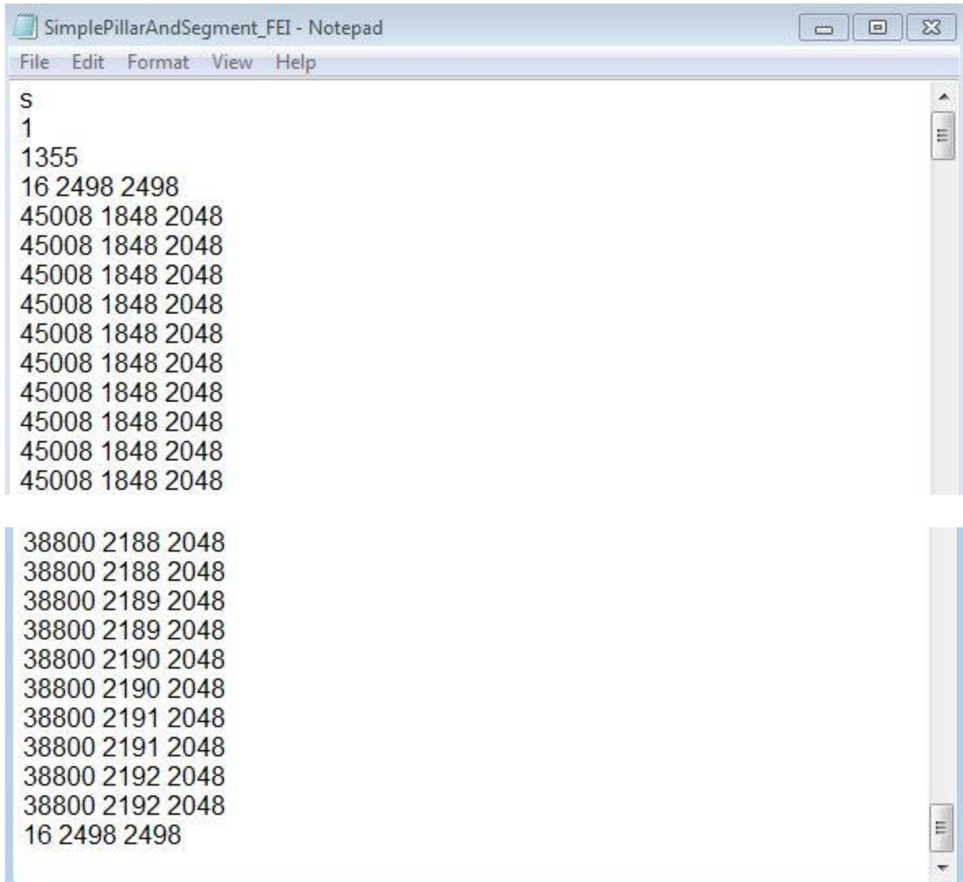
Action #31: Press "Build CAD" (figure 16a).

Exposure file creation is executed and the files are saved in the design folder which in this case is \EBiD 3D (CAD)\Simple Pillar and Segment.

FEI

If “FEI” was selected in the *name*_Parameters.txt file then the file SimplePillarAndSegment.str will be created and will be located in \EBiD 3D (CAD)\SimplePillarAndSegment. The dwell times in the stream file, for each exposure, will be determined according to [S2: Final exposure dwell time]. The per row format is;

$$[\tau_d(100\,ns)\quad x(pixel)\quad y(pixel)]$$


SimplePillarAndSegment_FEI - Notepad

File Edit Format View Help

```
s
1
1355
16 2498 2498
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048
45008 1848 2048

38800 2188 2048
38800 2188 2048
38800 2189 2048
38800 2189 2048
38800 2190 2048
38800 2190 2048
38800 2191 2048
38800 2191 2048
38800 2192 2048
38800 2192 2048
16 2498 2498
```

In the first three lines of the stream file, ‘s’ indicates a stream file, ‘1’ indicates 1 loop only through the stream file and 1355 is the total number of electron beam dwells. The first and last exposure pixels, set at [16 2498 2498], were set using **Action #17** above. Lastly, the sign of the y–axis is inverted in the FEBID CAD program relative to the y–axis on some FEI instruments. Prior to exposure file creation, select the “-y?” checkbox to make the 3D object in-plane (x,y) orientation match the orientation of the FEI instrument User Interface.

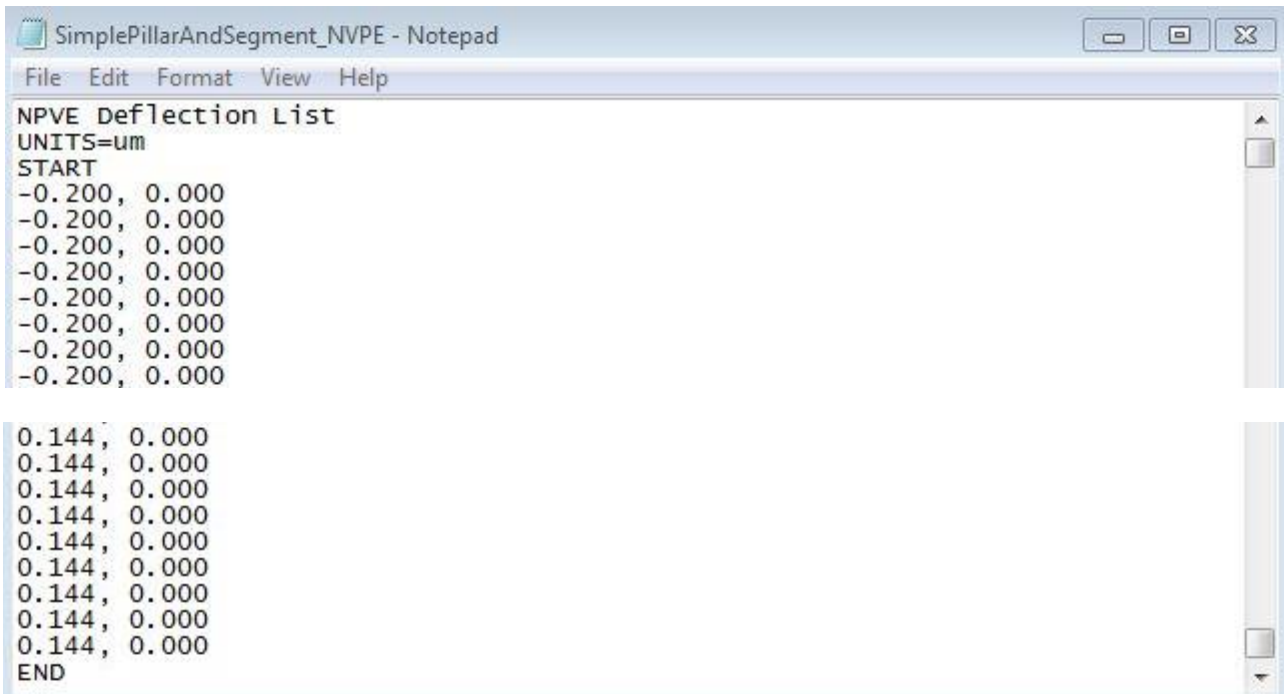
NVPE

If "NVPE" was selected in the *name*_Parameters.txt file then the file SimplePillarAndSegment_NVPE.txt will be created and will be located in \EBiD 3D (CAD\SimplePillarAndSegment. The dwell times in the stream file, for each exposure, will all be set to the value indicated in the "adv" dropdown menu under the listing "NPVE dwell". The default value is 0.2 [ms]. Thus, if an exposure per pixel exceeds 0.2 [ms] then multiple exposures numbering;

$$ceil\left|\frac{\tau_d\ [ms]}{\tau_{d,NVPE}\ [ms]}\right|$$

will be executed at the pixel to accumulate the correct integrated dwell time. The maximum value that can be selected in the GUI is 1 [ms]. Exceeding this value could lead to mass transport limited conditions. The per row format is;

$$[x(\mu m)\quad y(\mu m)]$$


SimplePillarAndSegment_NVPE - Notepad

File Edit Format View Help

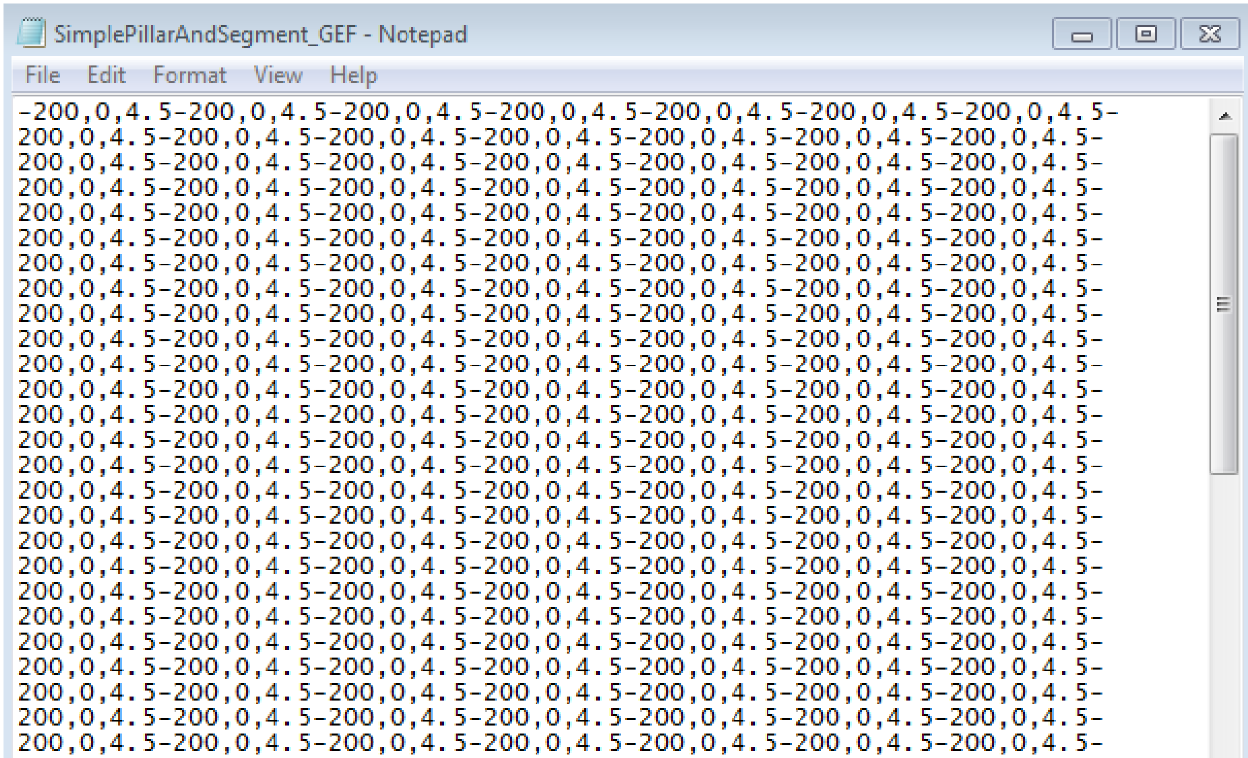
```
NPVE Deflection List
UNITS=um
START
-0.200, 0.000
-0.200, 0.000
-0.200, 0.000
-0.200, 0.000
-0.200, 0.000
-0.200, 0.000
-0.200, 0.000
-0.200, 0.000

0.144, 0.000
0.144, 0.000
0.144, 0.000
0.144, 0.000
0.144, 0.000
0.144, 0.000
0.144, 0.000
0.144, 0.000
0.144, 0.000
END
```

The NVPE software requires that the User input the constant dwell time independent of the stream file generated here. A text file is written when "Build CAD" is executed called NVPE_DwellTime_ms.txt which is located in the CAD design folder that provides the dwell time in units of milliseconds.

GEF (General Exposure File)

A general exposure file SimplePillarAndSegment_GEF.txt is created for all cases which can later be converted into the appropriate stream file input if a microscope is used that is not currently supported by this program. The per row format is;

$$[x(nm)\ \ y(nm)\ \ \tau_d(ms)]$$




```
-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-200,0,4.5-
```

The dwell time per pixel required to expose the segment element type is determined by interpolation of the calibration curve. The interpolated value is superimposed on the calibration curve with the “+” symbol following exposure file creation (figure 16b).

In the supporting video, “Build CAD” was pressed twice. Prior to exporting the exposure file the second time in the video, the check box “Shots?” was selected (figure 16c). This demonstrates visually the order of exposure shots in the (x,y,z) plot in sequence using a red circle data point and serves only this purpose.

The z–position shown for each exposure is the anticipated z–position during FEBID, but is not the guaranteed position, because this depends on the quality of the calibration curve and careful control of experimental conditions. For example, a poor or out dated calibration curve could potentially lead to a loss of beam–deposit intersection resulting in a poor replication of the 3D object during actual EBID.

Nonetheless, the “Shots?” option can be a very slow process especially for the case of a large number of exposures ~10^4. Options are provided in the “Adv” dropdown menu which allows the User to skip an integer number of exposures to more rapidly view the exposure sequence. For example, the default setting in the “Adv” menu, for the dropdown selection “Shots? (all shots?)”, the default value is 1. In this case, when the “Shots?” checkbox is activated, all exposure shots are shown in the (x,y,z) plot when “Build CAD” is pressed. If “Shots? (all shots?)” is set to 0 then exposure pixels are skipped in the rendering according to the settings of “Pillar acq every” and “Seg acq every”. Both options are also located in the “Adv” dropdown menu. If “Pillar acq every” is set to a value of 10 then an exposure with be shown every 10th dwell for every pillar located on the current exposure level. If “Seg acq every” is set to 10 then an exposure pixel is shown every 10th dwell for every segment located on the current exposure level

Lastly, the black “Save” button was pressed near the end of the video. Execution of this press button leads to the generation of two text files. The first text file contains the current vertex list and is saved as xPort_Verts_*number*.txt. The *number* is automatically advanced +1 integer each time that “Save” is pressed. This variable in contained in the uID.mat file which is located in the directory \EBiD 3D (CAD)\FEBiD 3D CAD (Supporting Files). The variable name is {i_xPort}. The tab delimited file for the current example (xPort_Verts_21.txt), opened via Microsoft Excel is;

xPort_Verts_21.txt

	A	B	C
1	-200	0	0
2	-200	0	400
3	146.4	0	599.99

The vertex index is indicated by the row. The column (A) contains the x–coordinate, the (B) column contains the y–coordinate and the (C) column contains the z–coordinate. The units are in nanometers for xPort_Verts_*name*.txt.

The second text file created using the “Save” button is the segment list. This file is also saved in the current design folder. The file is given the name xPort_Segs_*number*.txt.

xPort_Segs_21.txt

	A	B	C	D	E
1	1	2	2	3	
2					
3					
4					
5					

Exposure level #1 is represented by columns (A) and (B). The number of segments per exposure level is indicated by the number of rows. Therefore, there is one segment on exposure level #1. Column (A) contains the index into the vertex list representing the initial position of the segment. Column (B) contains the index into the vertex list representing the final position of the segment.

Similarly, exposure level #2 is represented by columns (C) and (D). There is one segment on exposure level #2. Column (C) contains the index into the vertex list representing the initial position of the segment. Column (D) contains the index into the vertex list representing the final position of the segment.

The same file format is used to upload coordinates and segment lists into the GUI environment as is shown in an additional Method #4: Auto segment detection.