Method #3: Calibration data fit

Video: Method #3 (Calibration data fit)

Calibration curve fitting is demonstrated in this Method. In this example, the calibration curve is poorly represented at low segment angles. This situation could arise if FEBID yields poor segment take–off where it is desired to grow a segment with a relatively low angle. Fitting the sparse calibration curve makes it possible to quickly estimate dwell times to further refine the calibration data.

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

Action #2: The "Custom" file name of "CalibrationCurveFitting" was chosen for this Method.

The main GUI window launches.

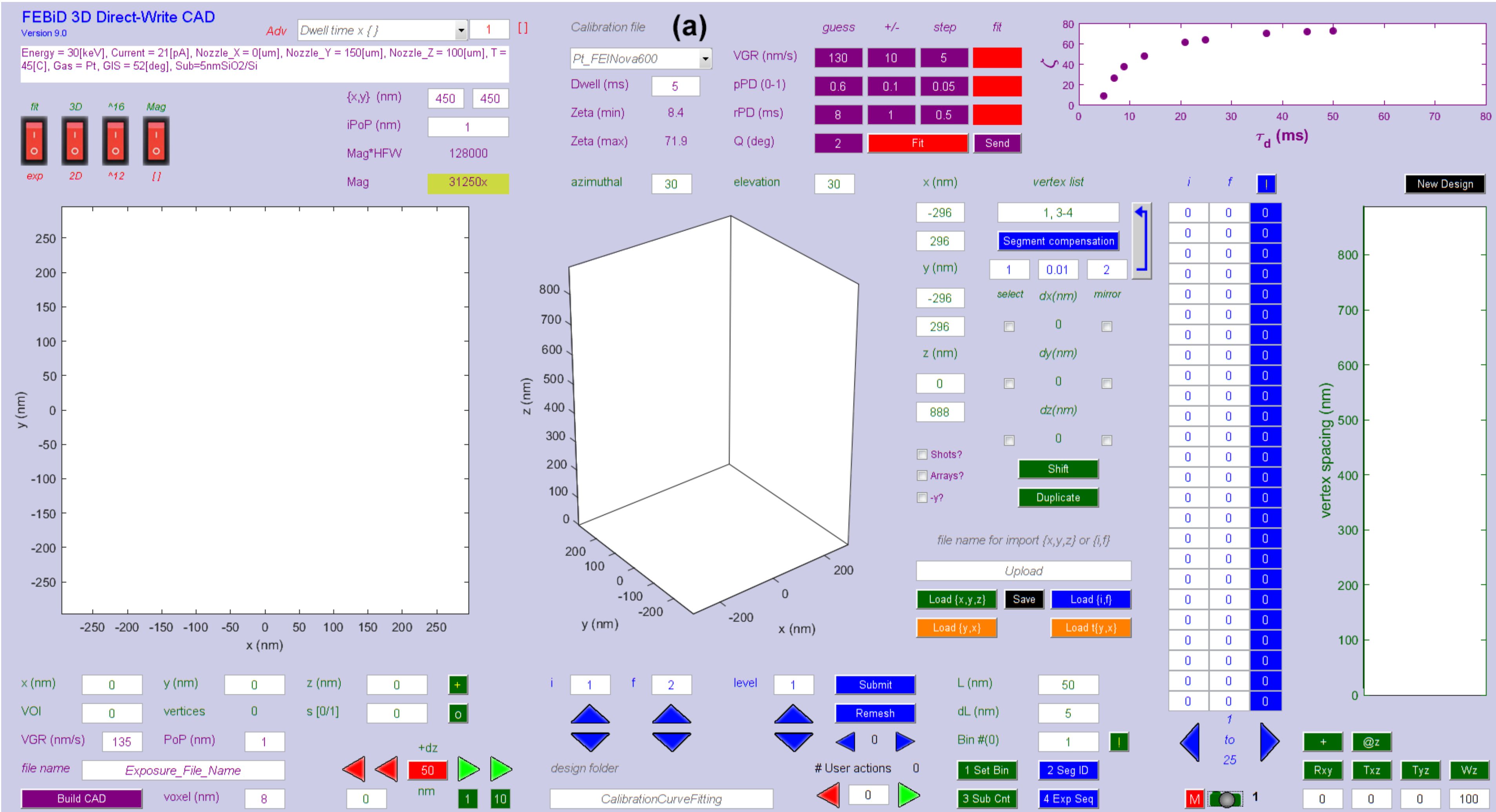


Figure 1

The calibration file "Pt_FEINova600" automatically loads as the default calibration file (figure 1a).

Action #3: The calibration curve “CalibFile2017” is selected from the dropdown menu options (figure 2a)

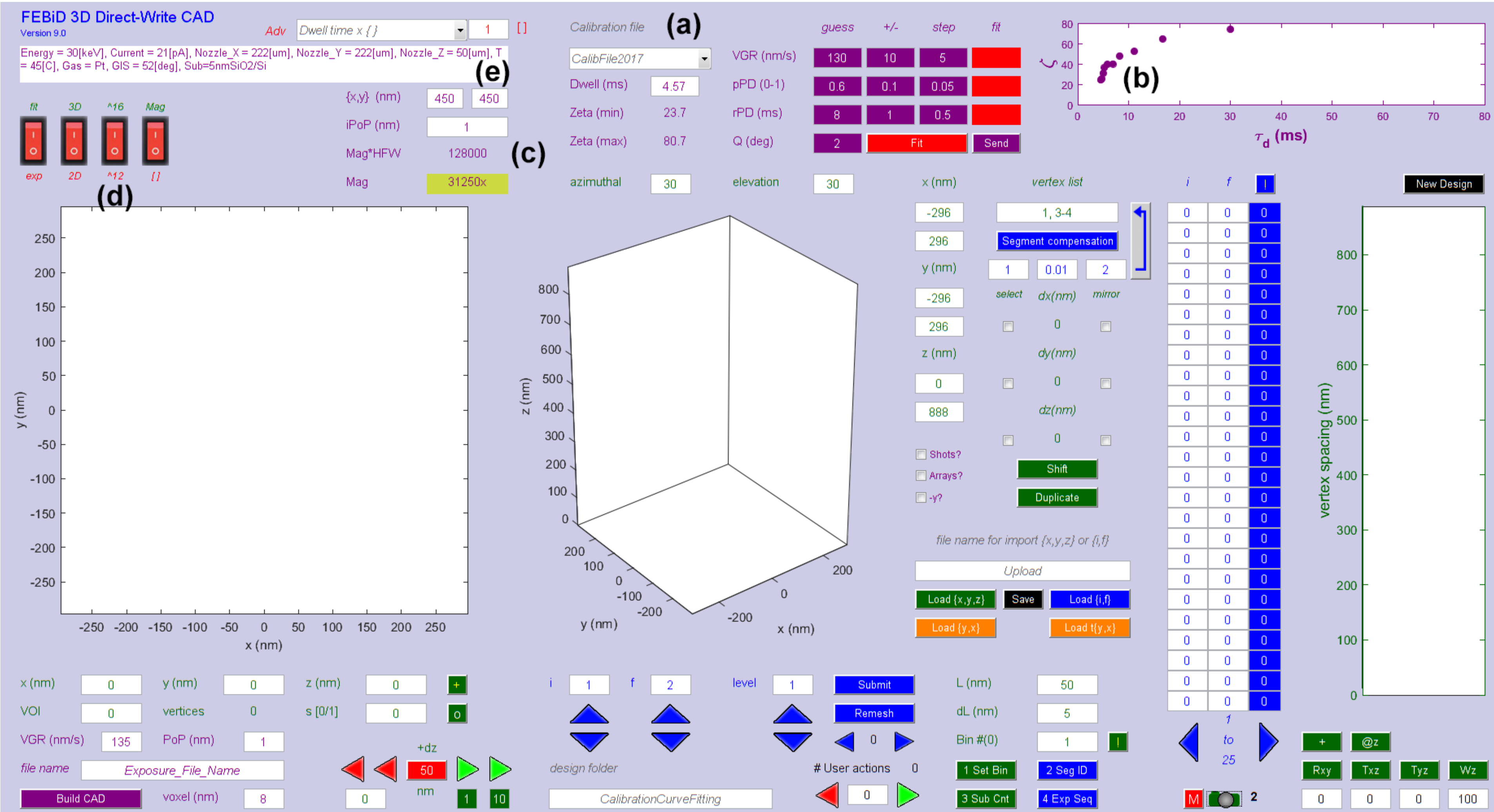


Figure 2

The segment angle versus dwell time curve updates in response to the change in calibration file (figure 2b). The magnification*HFW (figure 2c), patterning bit depth (figure 2d) and calibration file information text box (figure 2e) will update reflecting changes made to the file “CalibFile2017_Parameters.txt”. In this example however, there was no change for the parameters (c–e) between “Pt_FEINova600_Parameters.txt” and “CalibFile2017_Parameters.txt”.

Action #4: The range for the maximum vertical growth rate ("VGR" in the GUI, "v_n" in the main text) was set to ±30 [nm/s] (figure 3a).

Action #5: The step size for the range of v_n selected was set to 10 [nm/s] (figure 3a).

Action #6: The range for the percent precursor depletion ("pPD" on the GUI, "K_1" in the main text) was set to 0.3 (figure 3a).

Action #7: The step size for the range of K_1 selected was set to 0.1 (figure 3a).

Action #8: The range for the rate of precursor depletion ("rPD" on the GUI, "K_2" in the main text) was set to ±4 [ms] (figure 3a).

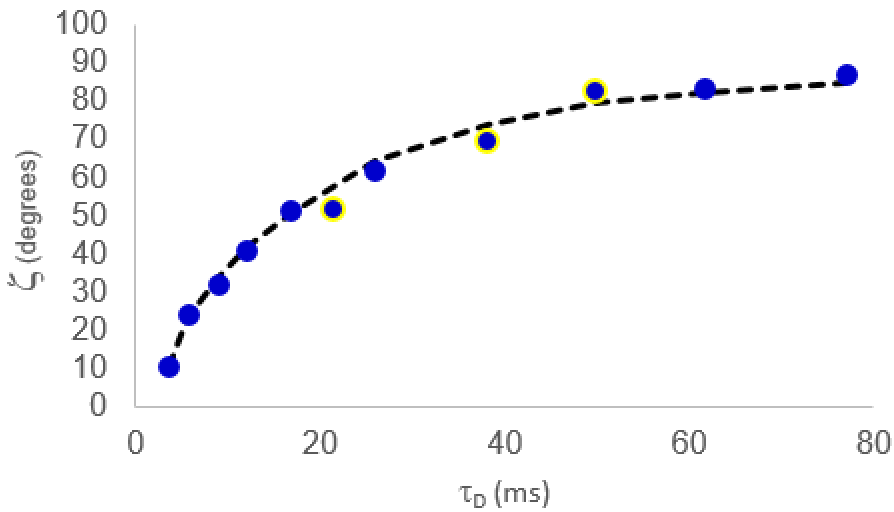
Action #9: The step size for the range of K_2 selected was set to 1 [ms] (figure 3a).

Action #10: "Q" was set to 3 [degrees] (figure 3a).

"Q" is the maximum allowable deviation, in degrees, between a fitted value of the segment angle and the experimentally measured value. This parameter works in concert with the parameter (F_2). F_2 specifies the number of data points where the "Q" constraint is relaxed. The location of this value on the GUI will be shown later in this Method.

Consider for example that Q = 3^o and F_2 = 2. A fabricated calibration curve and fit are provided below as part of the example.

$\tau_{D,exp}$ [ms]	ζ_{exp} [deg]	ζ_{fit} [deg]	ζ_{fit}-ζ_{exp} [deg]
3.6	10.9	10.3	-0.6
5.6	24.3	22.8	-1.5
8.9	32.4	33.4	1
12	40.9	41.7	0.8
16.7	51.4	50.4	-1
21.3	52.1	57.6	5.5
25.9	62.3	64.2	1.9
38.1	69.8	73.9	4.1
49.8	82.8	79.5	-3.3
61.5	83.7	82.3	-1.4
76.9	87.3	85	-2.3



The calibration curve (blue data points) consists of a total of 11 data points. Three data points (highlighted in yellow) exceed the allowable deviation of Q=3^o. This number of data points exceeds the allowable number of F_2=2. *Thus, even though the fit may yield the lowest minimization parameter, the fit is still rejected because the curve does not meet the fitting criteria.* See [S11: Calibration curve fitting rules].

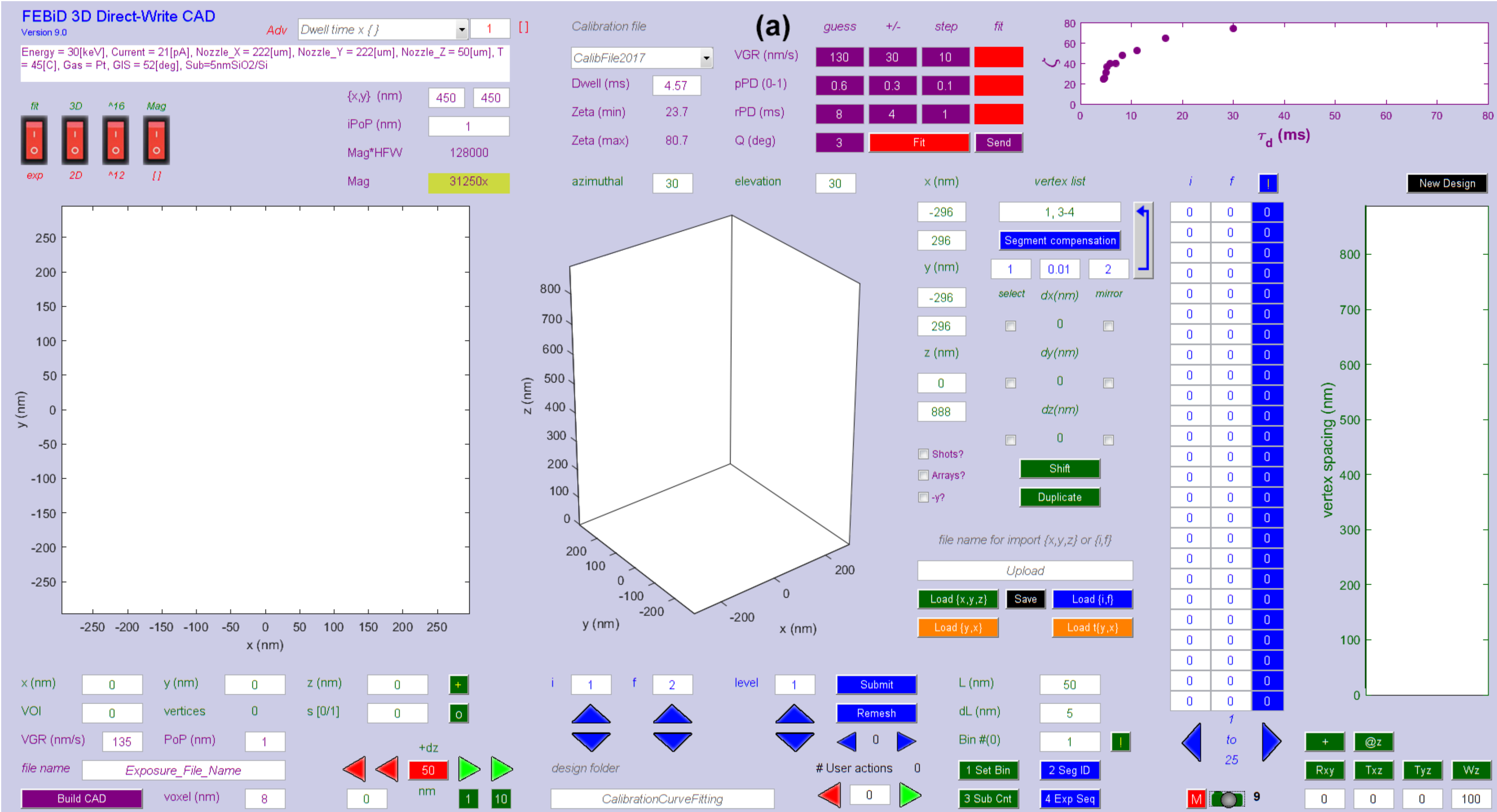

FEBiD 3D Direct-Write CAD
Version 9.0
Adv
Dwell time x { }
Energy = 30[keV], Current = 21[pA], Nozzle_X = 222[um], Nozzle_Y = 222[um], Nozzle_Z = 50[um], T = 45[C], Gas = Pt, GIS = 52[deg], Sub=5nmSiO2/Si
fit 3D ^16 Mag
exp 2D ^12 [ ]
{x,y} (nm) 450 450
iPoP (nm) 1
Mag*HFW 128000
Mag 31250x
Calibration file
CalibFile2017
Dwell (ms) 4.57
Zeta (min) 23.7
Zeta (max) 80.7
azimuthal 30
elevation 30
(a)
guess +/- step fit
VGR (nm/s) 130 30 10
pPD (0-1) 0.6 0.3 0.1
rPD (ms) 8 4 1
Q (deg) 3 Fit Send
τd (ms)
x (nm)
vertex list
1, 3-4
Segment compensation
y (nm)
select dx(nm) mirror
z (nm)
dy(nm)
dz(nm)
Shots?
Arrays?
-y?
Shift
Duplicate
file name for import {x,y,z} or {i,f}
Upload
Load {x,y,z} Save Load {i,f}
Load {y,x} Load t{y,x}
New Design
vertex spacing (nm)
y (nm)
x (nm)
z (nm)
x (nm) y (nm) z (nm)
VOI vertices s [0/1]
VGR (nm/s) 135 PoP (nm) 1
file name Exposure_File_Name
Build CAD voxel (nm) 8
+dz
nm
i f level
Submit
Remesh
design folder
CalibrationCurveFitting
User actions
L (nm) 50
dL (nm) 5
Bin #(0) 1
1 Set Bin 2 Seg ID
3 Sub Cnt 4 Exp Seq
to
Rxy Txz Tyz Wz

Figure 3

Action #11: Using the dropdown menu labelled "Adv", fitting parameter "Nuclei radius (fit)" was selected from the list displaying the value of 0.5 [nm] (figure 4a).

The value of 0.5 [nm] was left unchanged.

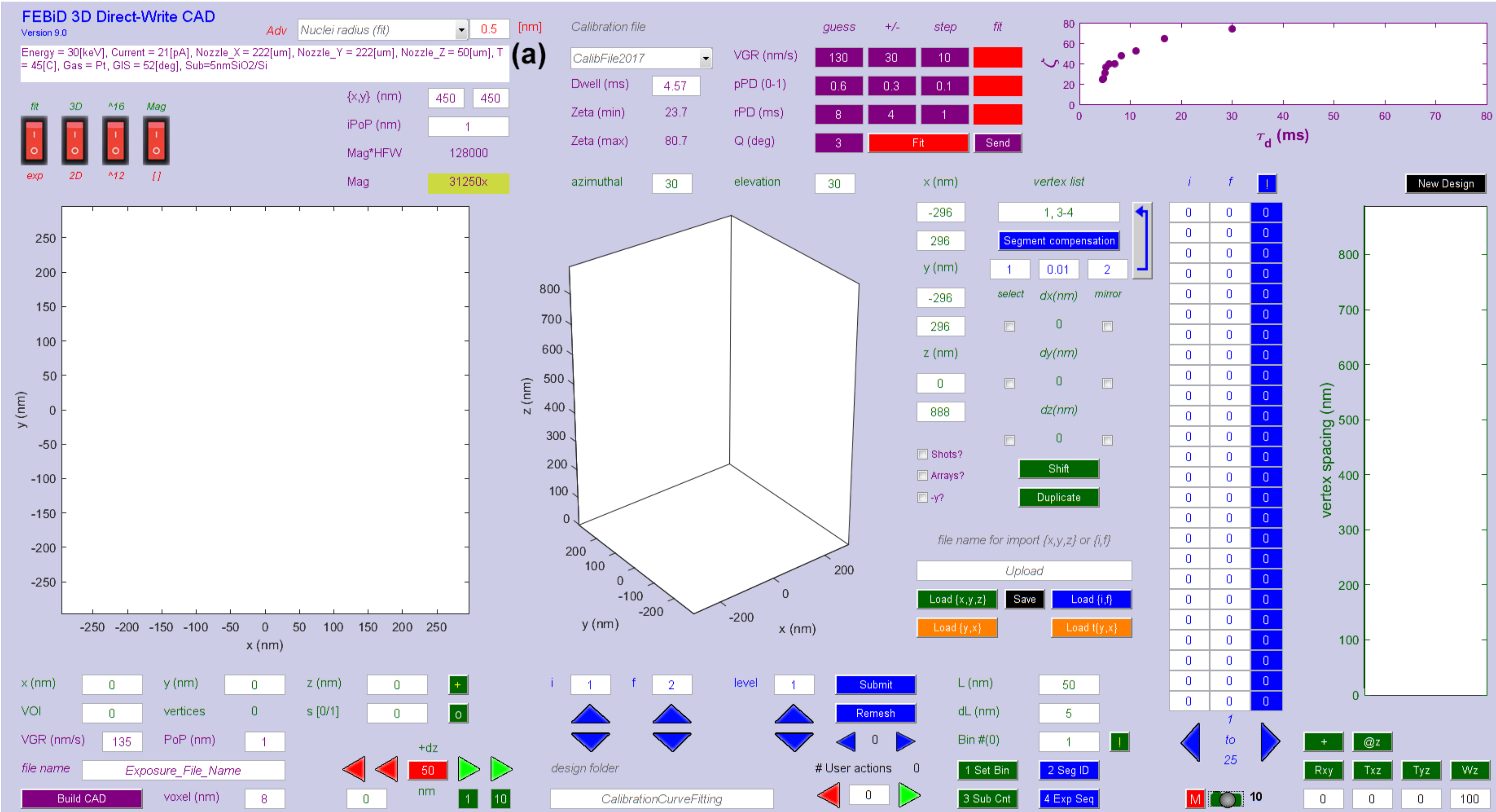


Figure 4

Action #12: Using the dropdown menu labelled "Adv", fitting parameter "Ignore (#) points in fit" was selected from the list and the value was changed to 3 (figure 5a).

The "Ignore (#) point in fit" parameter is the F_2 variable that was presented in the example above.

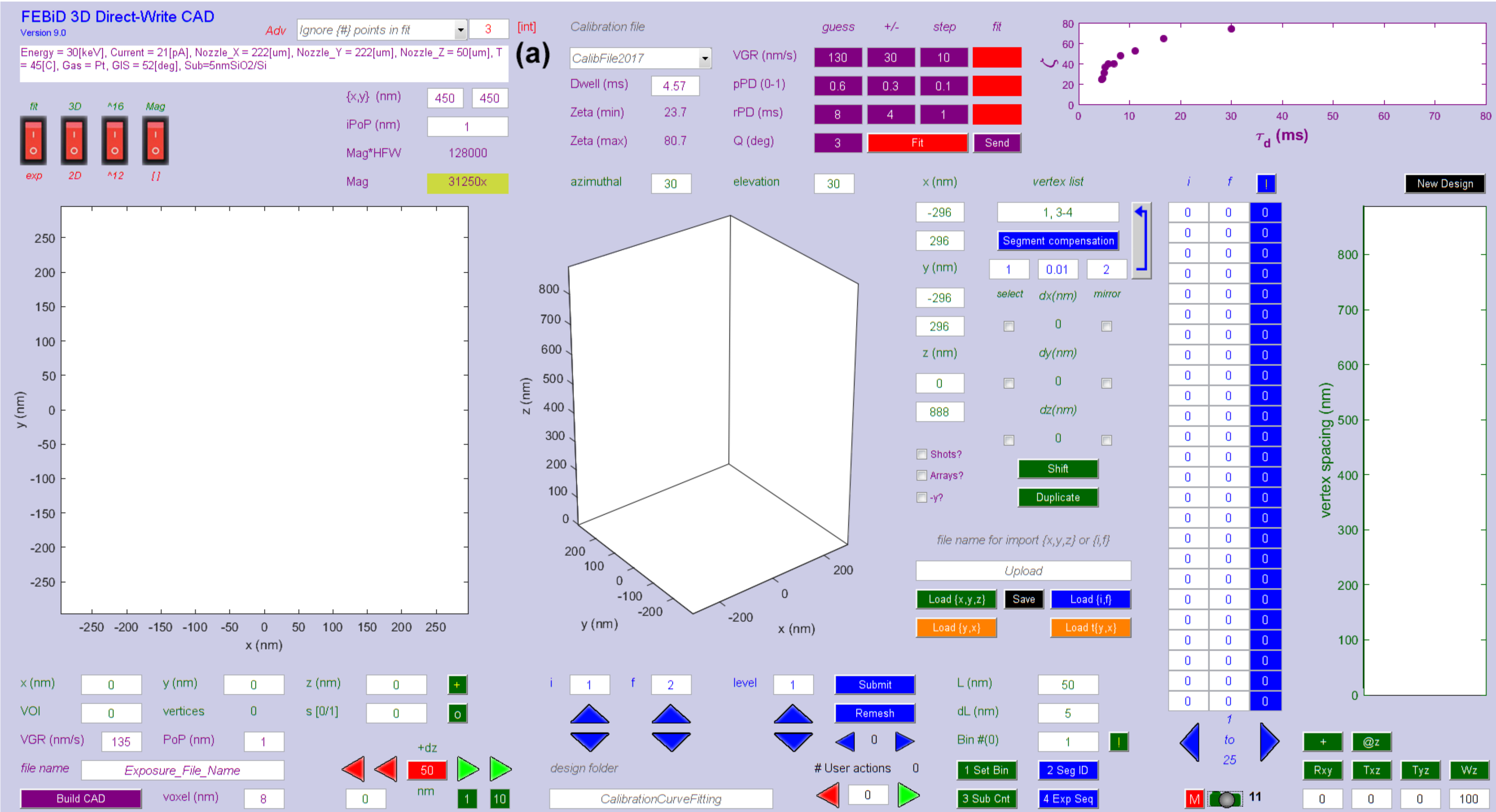


Figure 5

Action #13: Using the dropdown menu labelled "Adv", fitting parameter "FWHM" was selected from the list and the value was left unchanged at 4.1 (figure 6a).

FWHM refers to the full–width at half–maximum of the primary electron beam. The "FWHM" variable was updated to the value specified in the calibration file CalibFile2017_Parameters.txt when "CalibFile2017" was selected in the dropdown menu named "Calibration file". This fitting parameter should be changed if it is suspected that the electron beam was defocused during the FEBID of segments that were used to derive the calibration file.

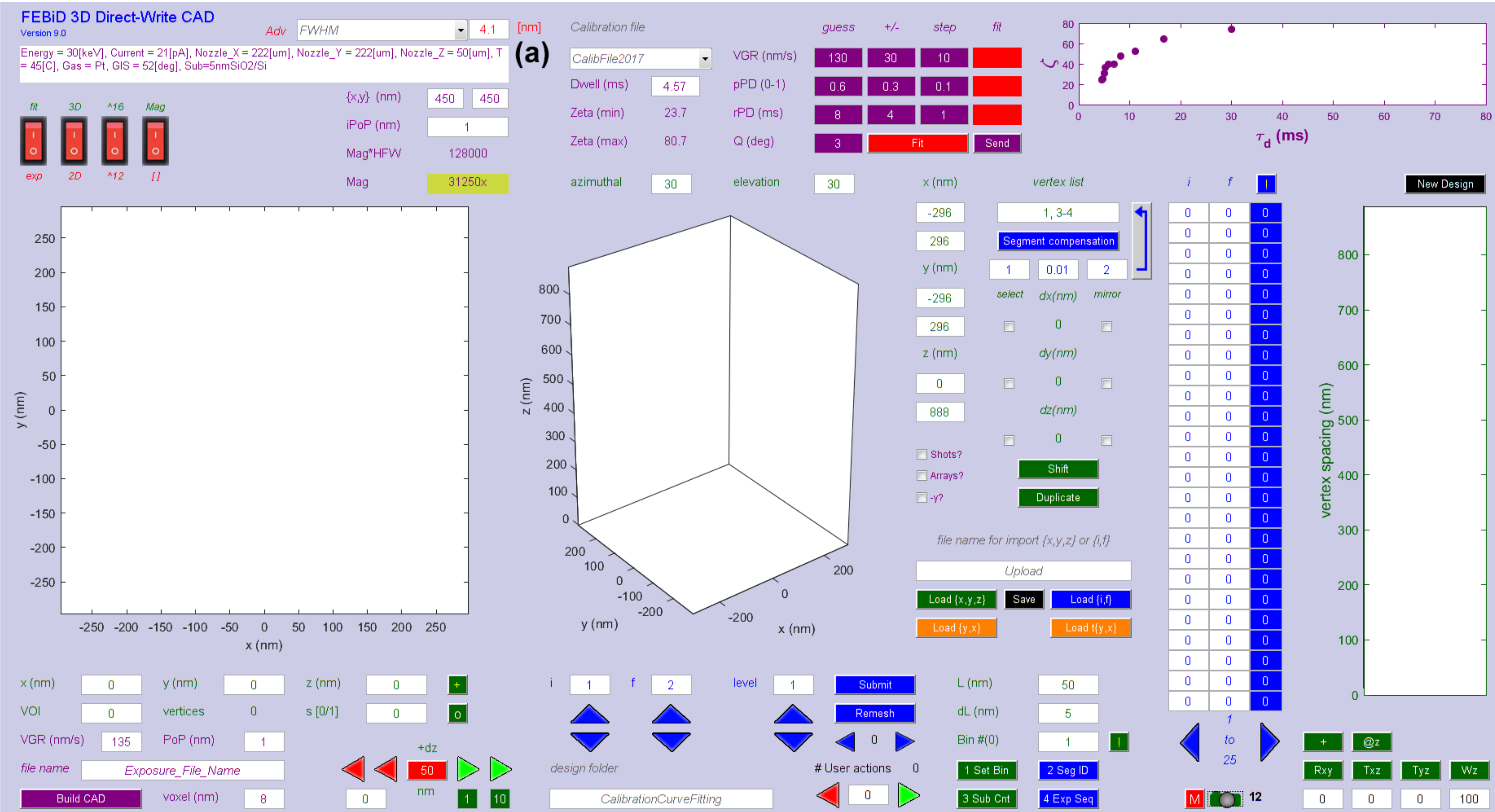


Figure 6

Action #14: The fitting procedure is executed by pressing “Fit” (figure 7a).

The fitted curve appears on the graph (red -. Curve, figure 7b) when both (1) a new fitting parameter minimum is achieved and (2) when the fitting criteria are satisfied related to the variables Q and F_2. The press button “Fit” executes the fitting procedure then dynamically displays the percent completion of the fitting algorithm in increments of 10% by replacing the word “Fit” with the percent completion value. The best fit values are shown the red static text boxes (figure 7b) and those values were VGR = 160 [nm/s], pPD = 0.5 and rPD = 10 [ms].

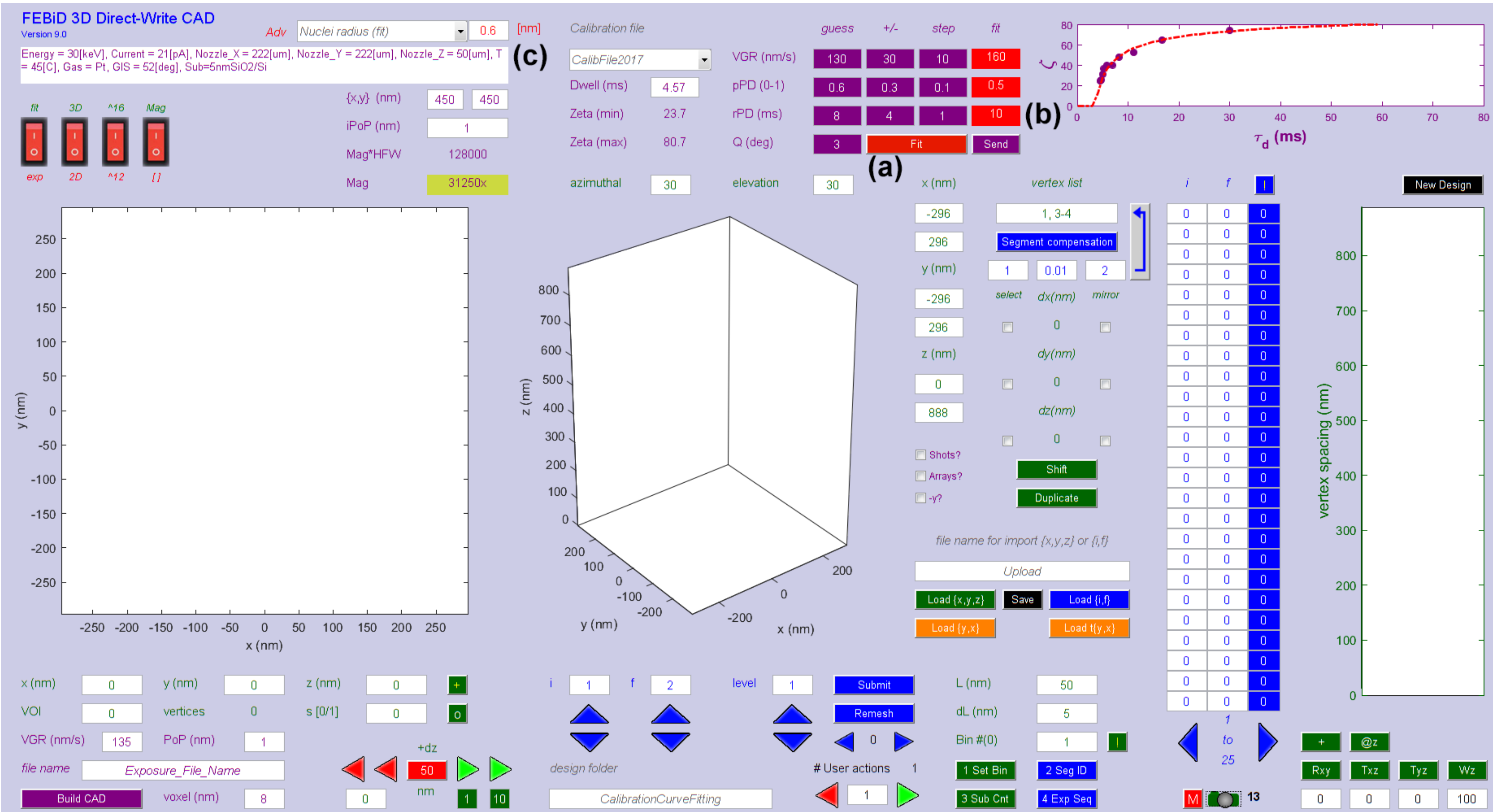


Figure 7

Action #15: The fitting procedure was repeated using an updated value of 0.6 [nm] for the “Nuclei radius (fit)” parameter (figure 7c).

Action #16: The second cycle of fitting was executed by pressing “Fit” (figure 8a).

A better fit was determined using the updated nuclei radius parameter. The best fit values are shown the red static text boxes (figure 8b) and those values were VGR = 140 [nm/s], pPD = 0.5 and rPD = 10 [ms].

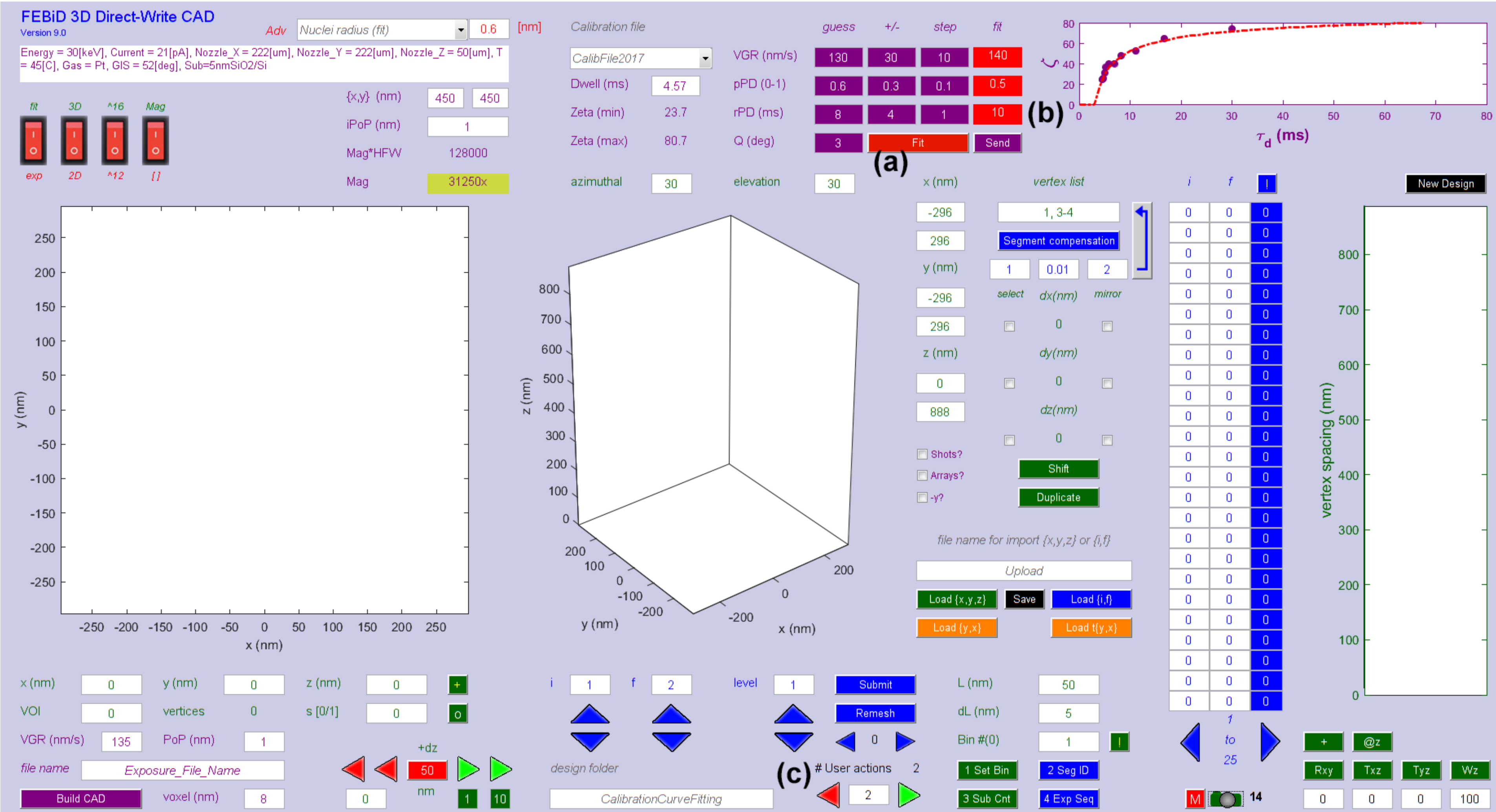
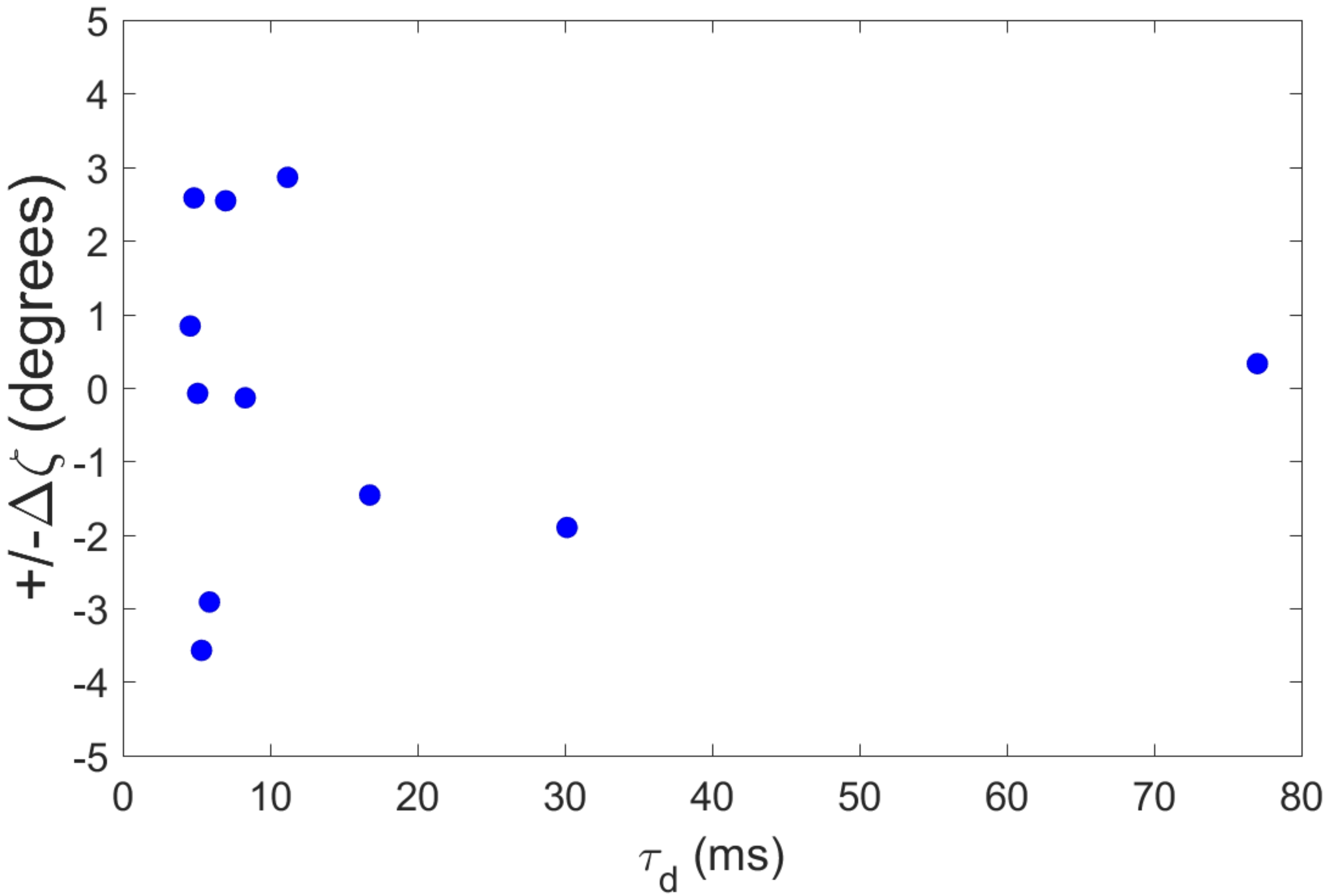


Figure 8

A plot of the deviation angle between the fitted curve and the experimental data is briefly displayed when the fitting algorithm concludes. This plot is also saved in the design folder as FitQuality.tif, in this case as \EBiD 3D (CAD)\CalibrationCurveFitting\FitQuality.tif. The file is replaced each time a name fit is executed so only the most recent fit is saved. The graph following the second fit is shown below.



Only a single data point exceeded the Q = 3° requirement where a maximum of $F_2 = 3$ were allowed. Additional information regarding fitting is also included in a file named CalibFit2017_Fit.txt located in the supporting file folder;

\EBiD 3D (CAD)\FEBiD 3D CAD (Supporting Files)\CalibFit2017_Fit.txt

The contents of this file are shown in the snapshots below. The fitted data for the calibration curve is provided at the bottom of the file where the dwell time list is indicated by "tau_d" and the segment angle list as "ζ". The dwell time list has a dwell time resolution of 1 [ms] and a maximum value of 100 [ms].

CalibFile2017_Fit - Notepad

File Edit Format View Help

```
----------------------------------------------------------
Calibration Fit & Parameters
----------------------------------------------------------
----------------------------------------------------------

Vertical Growth Rate (VGR) (nm/s)
------------------------------------------------
140.0

percent Precursor Depletion (pPD) (0-1)
------------------------------------------------
0.50

rate of Precursor Depletion (rPD) (ms)
------------------------------------------------
10.00

Nuclei radius (rN) (nm)
------------------------------------------------
0.60

Minimum dwell time index (ForbiddenTau) (1,2,3...)
------------------------------------------------
5.00

Minimization parameter
------------------------------------------------
1.921766e+01

tau_d  Zeta
 (s)  (deg)
---------------
0.000      0.000
0.001      0.000
0.002      0.000
0.003      0.000
0.004      17.650
0.005      29.737
0.006      37.066
0.007      42.247
0.008      46.278
```

The fitted values of the calibration curve can be used to create the final exposure file by pressing the "fit" press button switch (figure 9a). The fitted data for the calibration curve is interpolated in the same way as the experimental data as explained in [SX: Calibration data interpolation and extrapolation]. The minimum allowable dwell time updates in the "Dwell (ms)" text box (figure 9b) which represents the first non–zero dwell time detected in the fitted calibration data list in CalibFit2017_Fit.txt. In this case the minimum dwell time is 4 [ms]. The segment angle associated with this dwell time is also displayed on the GUI as "Zeta (min)" = 17.6503. "Zeta (max)" = 82.8255 is the segment angle at the maximum dwell time of 100 [ms]. If the "fit" switch is pressed again these parameters return to values based on the experimental calibration curve (figure 9c).

As described in [SX: Calibration data interpolation and extrapolation], when the segment angles calculated in the design are less than "Zeta (min)" the dwell time per pixel for that segment are forced to 4 [ms]. If a segment angle is calculated that exceeds "Zeta (max)" then extrapolation is used to estimate the dwell time.

Notice that the minimum dwell time "Dwell (ms)" can be edited by the User. For example, this limiting value can be increased beyond detected minimum is necessary in order to set a larger threshold segment angle for the design.

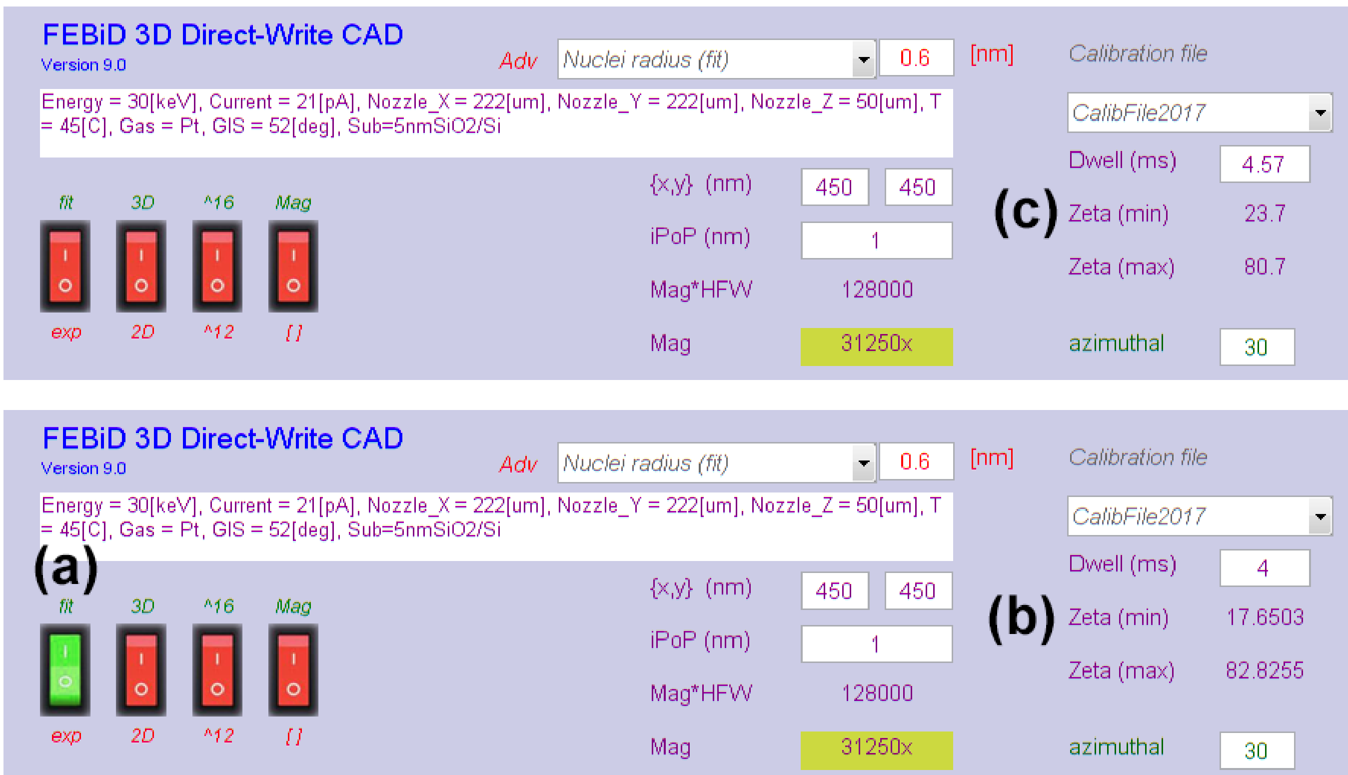


Figure 9

Each time that a “Calibration file” is selected from the drop down menu the program checks for the existence of the fitted data text file. If such a *name*_Fit.txt exists, the curve is plotted on the τ_d versus ζ axis and the display boxes with the best fit values are updated (see again figure 7b).

At this point, the undo/redo option for the program is introduced because this can affect the fitted values used. Figure 8c shows the undo/redo option which is labelled “# User actions”. A User action is registered each time a major action is taken by the User, e.g., a new vertex is defined, a new segment is created, etc. For example, when a new best fit is discovered, a new User action is registered. In the example in figure 8c, the value of 2 indicates that only 2 major User actions have been executed. The red (undo) and green (redo) arrows can be used to cycle through the values. Or, the past action can be directly entered in the white text input box.

Importantly, if it is desired to use fitted data for exposure file creation, **<u>it is best practice just prior to exposure file creation to</u>**;

(1) Select again the “Calibration file” from the dropdown menu to confirm your choice
(2) Activate the “fit” toggle button
(3) Press “Build CAD”

This is a prudent action because each time a major User action is registered a file is saved that contains the current status of the design. The fitted calibration curve is saved as part of this procedure which is independent of the name_Fit.txt file. This makes it possible to revert back to a previous 3D object design and fit but can cause problems if it is desired to apply a new fit to an older 3D object design state.

For example, consider the follow sequence of general design steps

(1) 3D object is defined (3D object state #1)
(2) Calibration curve is fitted (Arbitrary Calibration #1a)
(3) The 3D object is modified (3D object state #2)
(4) Calibration curve is again fitted with a better result (Arbitrary Calibration #1b)
(5) The User uses “Undo” to return to (3D object state #1)
(6) “fit” toggle button is selected
(7) Exposure file is created by pressing “Build CAD”

The result is that exposure conditions were specified for (3D object state #1) with (Arbitrary Calibration #1a). However, if the User wanted to expose (3D object state #1), but with (Arbitrary Calibration #1b), then the following sequence should occur;

(1) 3D object is defined (3D object state #1)
(2) Calibration curve is fitted (Arbitrary Calibration #1a)
(3) The 3D object is modified (3D object state #2)
(4) Calibration curve is again fitted with a better result (Arbitrary Calibration #1b)
(5) The User uses “Undo” to return to (3D object state #1)
(6) Calibration curve “Arbitrary Calibration” again selected from the “Calibration curve” drop down menu
(7) “fit” toggle button is selected

(8) Exposure file is created by pressing “Build CAD”

The additional step is red replaces the old fitted values with the most recent values stored in *name*_Fit.txt.