SAND2007-1471P

Validation Techniques For Simulation of Radiation Effects in voltage regulators

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M.S. Thesis

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Motivation

- Maintain older electronic systems.
- Assessment of functionality, reliability, and safety using simulation rather than experimentation.
- Verification & Validation (V&V) is the primary method for gaining confidence in simulations.
- Validate current model’s radiation response.
- Simulate response to environments that are either too expensive or physically impractical to physically test with currently available facilities.

State of the Art

- Formalized V&V began with the US DoD.
- Validation integral to modeling and simulation according to IEEE Validation and Verification Standards dating back to the 1980's [7].
- IEEE holds simulation conferences including V&V discussion.
- Strong presence in simulation V&V at Sandia National Laboratories.
  - Division 1500 Mission: "Provide the facilities, research, diagnostic development, and experimental methodology to validate & accredit complex, multi-physics, computational models…"
- SNL is also a large contributor in the field of large-scale electrical simulations. Validation is important to this area and presents special challenges[2].

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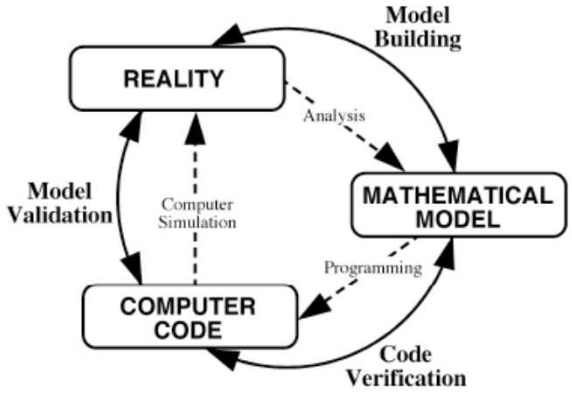
Novelty

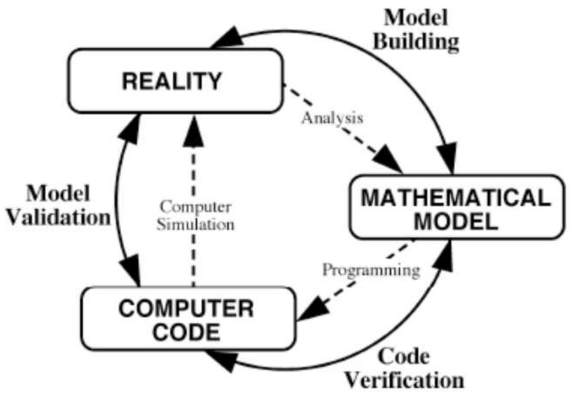
- Methodology is specific to an application and resource constraints.
- Radiation effects on power regulator circuits using a custom simulator.
- Methods
  - experimental procedure
  - measure of response (signal characteristic) identification
  - signal characteristic extraction methods
  - uncertainty quantification
- New hierarchical approach. Separates validation into device, sub-circuit, and full circuit levels.
- Validation at the sub-circuit level is the main focus of this research.
- Method for propagating the uncertainty through the hierarchical levels. Uncertainty quantification scheme.

Validation



Def: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

Verification



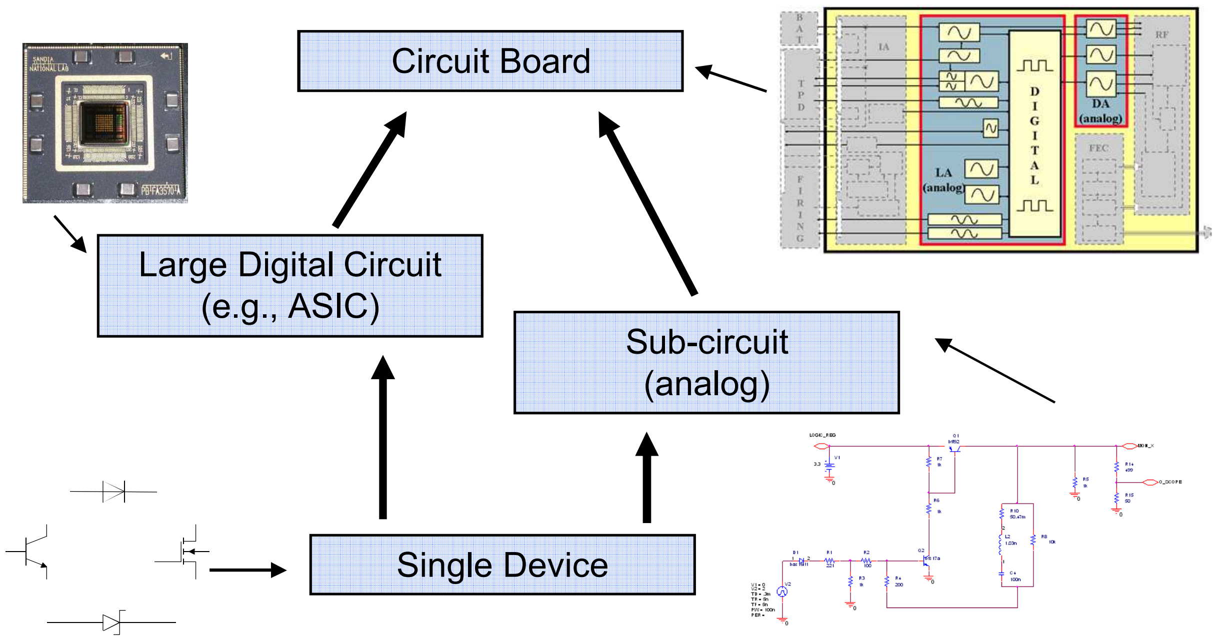
Def: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.

Validation Process Steps

- Identify application
- Create PIRT
- Perform Verification
- Identify Measures of Response
- Perform Validation Experiments
- Run Simulations matching experiments
- Identify metrics for, and perform comparison
- Perform Uncertainty Quantification
- Analyze results and consequences for predictions

New Validation concepts

- **Hierarchical Validation**



Device Level

- UQ: Sample uncertain parameter space and look at the outputs of the model.
  - Around 20 parameters per model.
  - Three levels, minimum, median, and maximum.
  - Sample the entire space: 3^20=3.4868e+009 samples.
- Use Orthogonal Arrays (OA) from collection of publicly available OA's [14].
- Naming convention:
  - Oa.(# of runs).(number of factors).(number of levels).(strength).txt
- Example,
  - 20 parameters
  - oa.243.20.3.3.txt
  - 243 samples required
  - Full UQ analysis time of 240runs*0.5s = 2 minutes.

Sub-circuit Level

- Calibration process not performed again at the sub-circuit level. UQ analysis is performed again.

- UQ analysis
  - 6 devices in circuit with 20 parameters each
  - Full factorial combinations: 3^(20*6) runs.
  - Use two levels and oa.240.120.2.3.txt [14]: 240 runs.
  - Coverage of the main effects has been severely reduced.

- As we go up the hierarchy, simulation run times increase exponentially.
  - Individual Device circuits run in under 1 s.
  - Sub-circuit simulations run in 10 seconds

- UQ analysis for the sub-circuit: 240*10s = 40 minutes

- Still two more levels at which the UQ analysis needs to be run. Clearly some other approach is in order.

Hierarchical Representations of Uncertainty

- 3 options for injecting the uncertainty in the device model parameters into the circuit
  - Vary device model parameters for each device
  - Relate device model parameters to internal device model currents (I1, I2, I3, I4, I5,…)
  - Relate device model parameters to external device model currents (Ib, Ic, Ie)

- UQ at sub-circuit level
  - 3^18 samples instead of 3^120.
  - oa.20.19.2.2.txt.
  - 20*10s =3mins 20s instead of 40 minutes

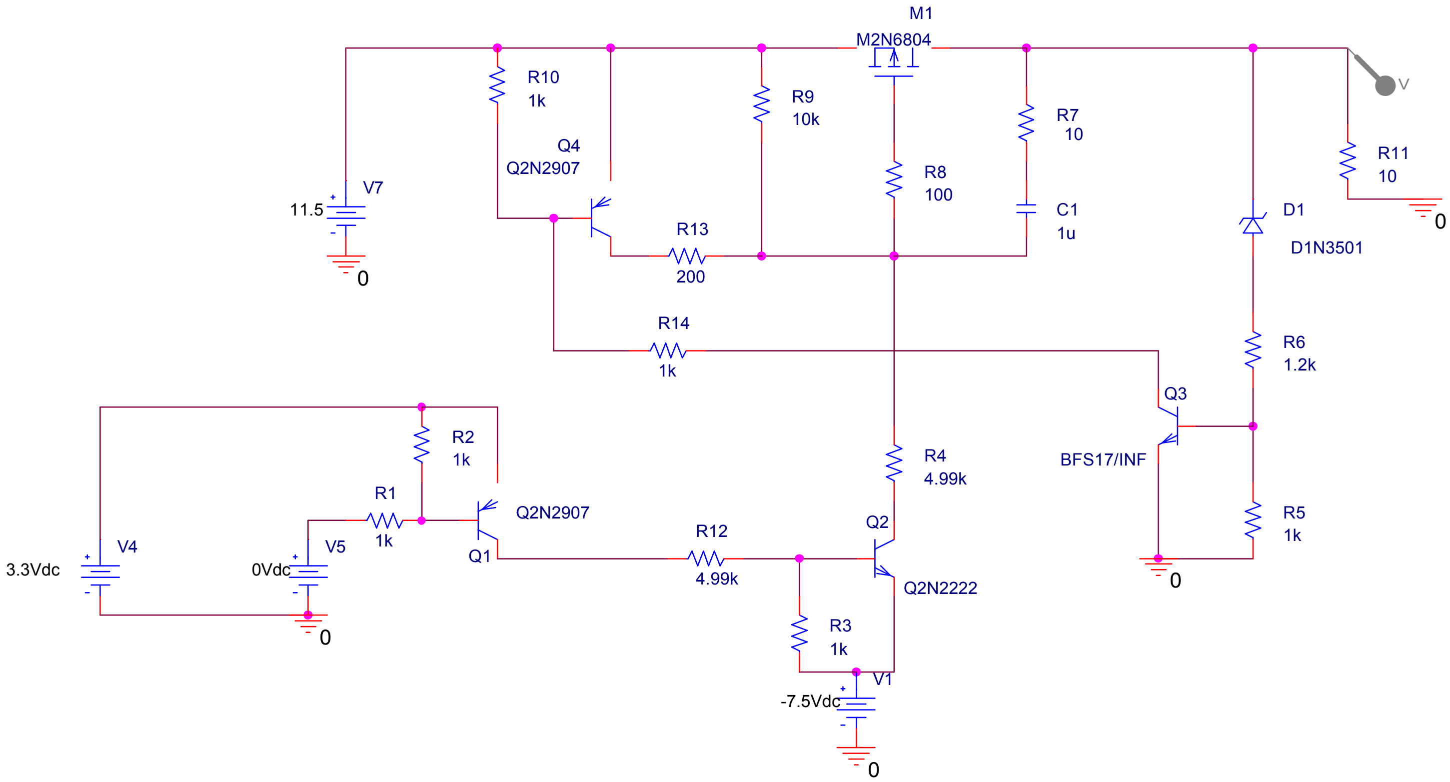
System Levels

- Non hierarchical representation of uncertainty,
  - 300,000 [transistors / ASIC] * 20 [parameters / transistor] = 6,000,000 parameters.
  - Full factorial at 3 levels: 3^(6*10^6)= Practically Infinite
  - Even using device terminal currents instead of parameters, it comes to 3^(9*10^5)=Practically Infinite

- Clearly a hierarchical representation of the uncertainty is required
  - Uncertainty range described by 3 levels of each ASIC standard-cell

Voltage Regulator Circuit

- Voltage regulation circuit intended to regulate the power supply voltage to approximately 9.0 volts at the output of the circuit despite varying load, noise on input power supply, or noise on the internal nodes of the circuit.

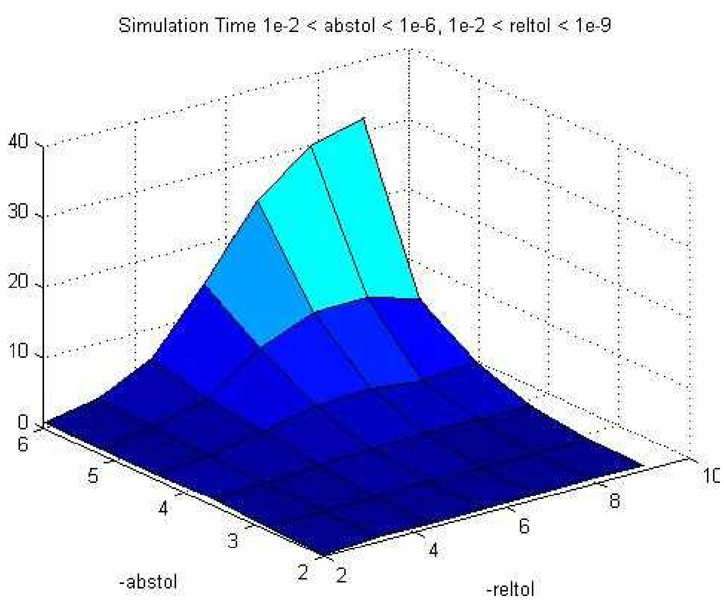


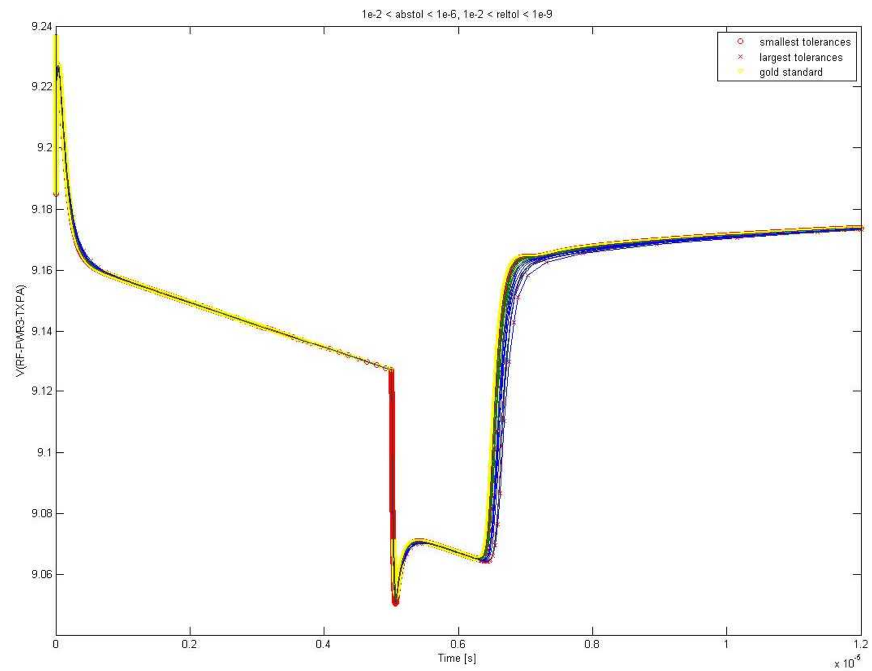
Test Circuit Solution Verification

- **Xyce simulator options and methods analyzed**
  - Time Integration Methods:
    - » BDF 1 (default)
    - » BDF 2
    - » Trapezoidal (fixed in 3.1.1 or 3.1.2)
    - » New DAE (variable order with maxorder=1…5).
  - Linear Solver:
    - » (.options linsol type=KLU, Ksparse, SuperLU, Aztec00)
  - Tolerances:
    - » Delta-x-tol is for the deltax in Newton method: $J^*\Delta x=-f$
    - » Right-hand-side-tol is for the f in the equation.
    - » RELTOL: Relative error – The error after each time step
    - » Absolute error – number of significant digits.
    - » RHSTOL: Maximum residual error for each nonlinear solution
    - » DELTAXTOL: Weighted nonlinear-solution update norm convergence
    - » MAXSTEP: Maximum number of Newton nonlinear steps for each nonlinear solve
  - Time Step Adjustment:
    - » Simulator adjusts so that the predictor corrector error is smaller than the tolerances

Test Circuit
Solution Verification

- **Tolerance Study**
  - Step log scale 6 pts1e-2 > ABSTOL < 1e-61e-2 > RELTOL < 1e-9





Radiation Experimental Data

QASPR (Includes 6 active devices)

- 3 replicates = A1, A2, A3
- 24 shots per board
- Temperature – 3 levels
  - » Ambient: 25
  - » Hot: 50
  - » Hotter: 75
- Dose rate – 6 levels
  - 1e9
  - 5e8
  - 1e8
  - 5e7
  - 1e7
  - 5e6
- Constant radiation pulse width.
- Bias
  - "on"(0V) and "off" (3.3V)

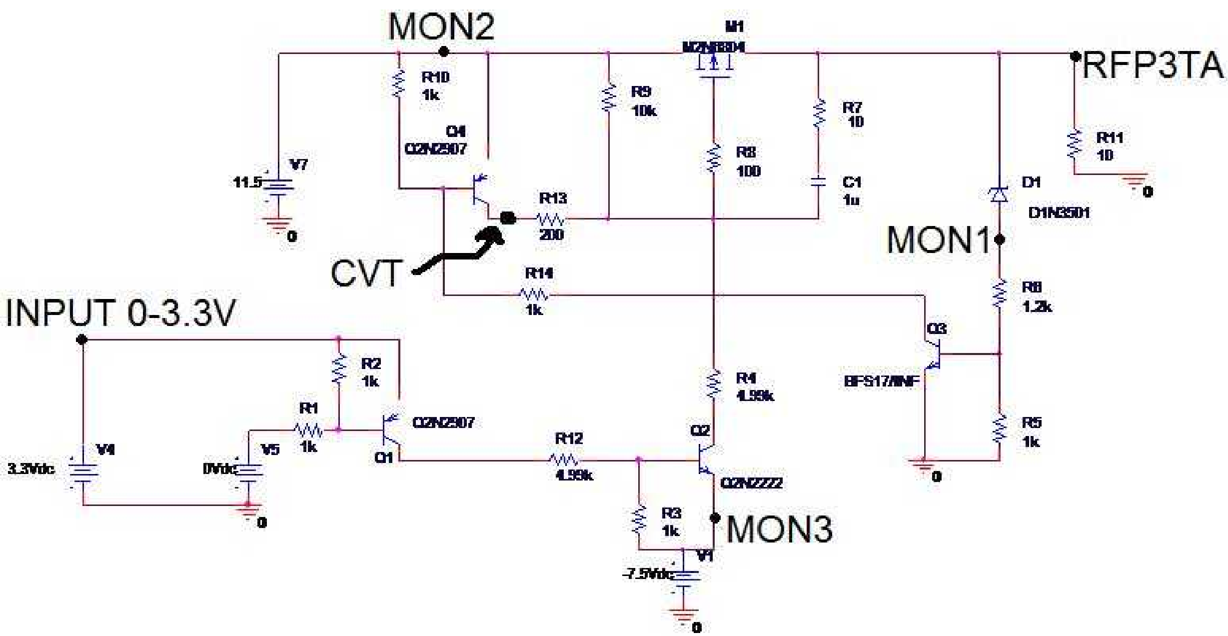
shot	temp in C	dose rate	bias (J11) RF_PWR 3_ENB_N in DC V
1	25	5.00E+06	0
2	25	5.00E+07	3.3
3	25	5.00E+08	0
4	25	1.00E+09	3.3
5	25	1.00E+09	0
6	25	1.00E+08	3.3
7	25	1.00E+07	3.3
8	25	1.00E+07	0
9	50	1.00E+07	3.3
10	50	1.00E+08	3.3
11	50	1.00E+08	0
12	50	1.00E+09	0
13	50	5.00E+08	3.3
14	50	5.00E+07	0
15	50	5.00E+06	3.3
16	50	5.00E+06	0
17	75	5.00E+06	3.3
18	75	5.00E+07	3.3
19	75	5.00E+07	0
20	75	5.00E+08	3.3
21	75	5.00E+08	0
22	75	1.00E+09	3.3
23	75	1.00E+08	0
24	75	1.00E+07	0

Characteristics of Interest

Decide which characteristics to extract from the signals measured on both boards.

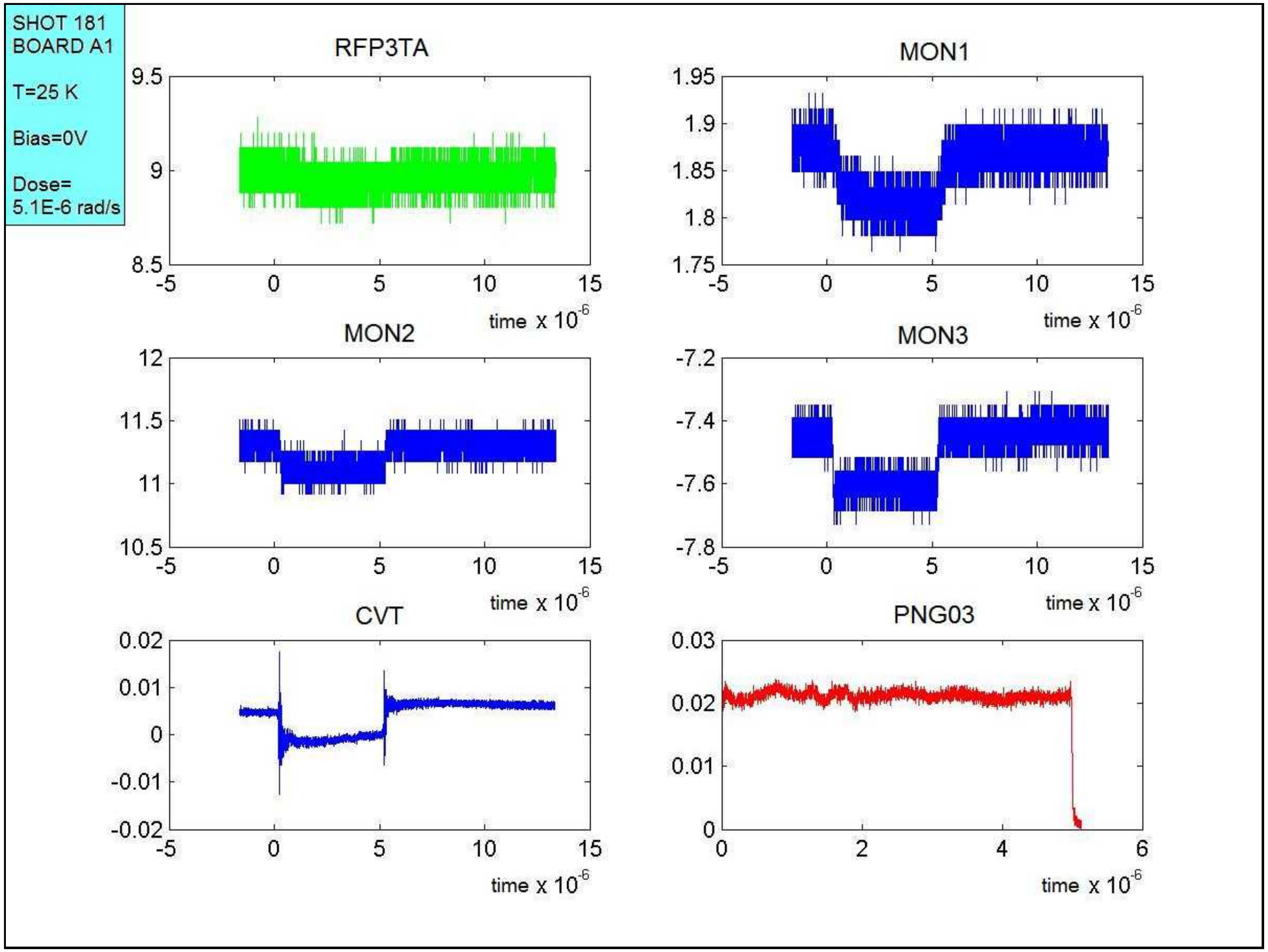
- Research circuits functions and designs
- Collect information from the experimenters about the setup, methodology etc.

Signals



Experimental Data Summary

- **MATLAB scripts used for extraction process.**



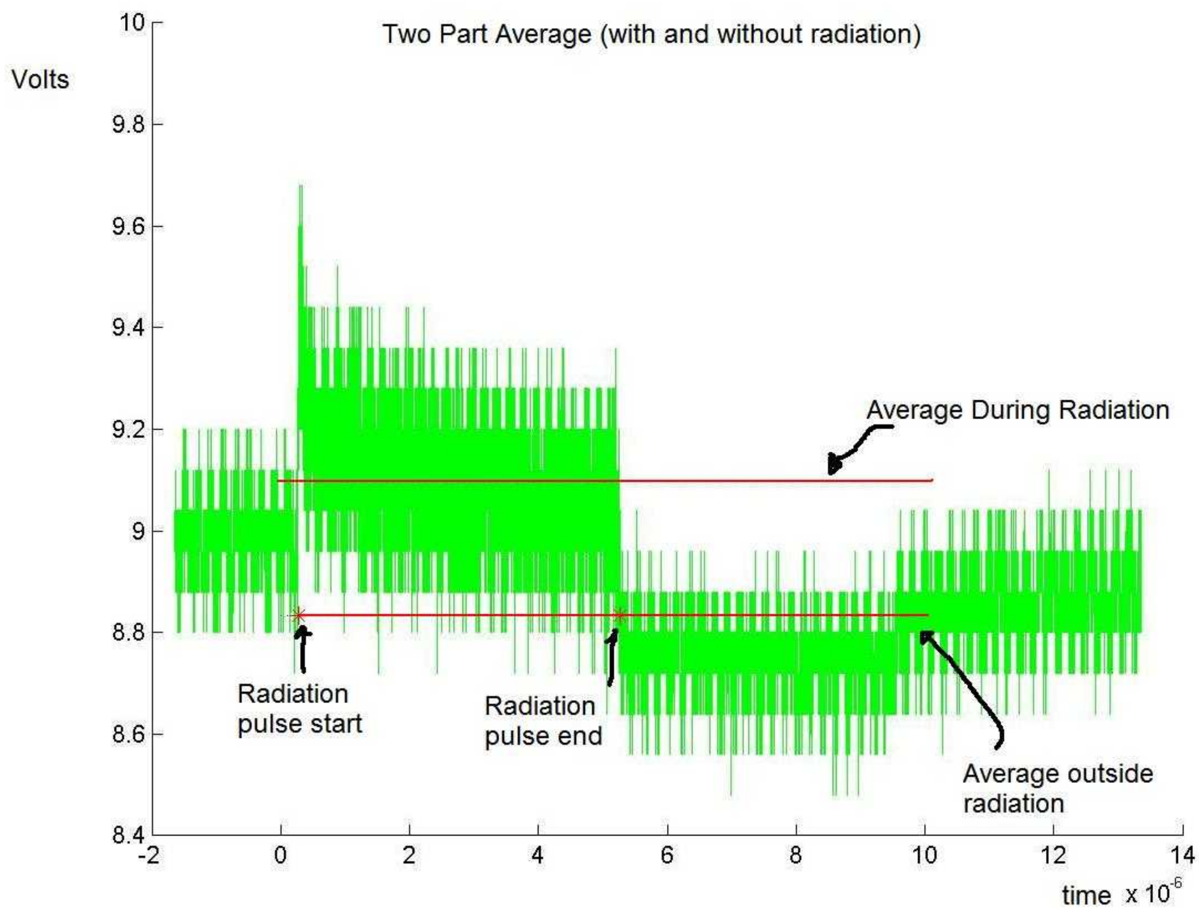
Chosen Characteristics

Signal Name	Identification	Characteristic
PNG03	radiation pulse	Amplitude/dose rate, rise time, fall time
CVT	Current through feedback path	Average magnitude difference between steady state and during radiation, delay time in returning to steady state value
MON1	Anode of zener regulator diode	Amplitude, rise time, flat top average, fall glitch length and amplitude
MON2	Positive power supply	Average magnitude difference between steady state and during radiation
MON3	Negative power supply	Average magnitude difference between steady state and during radiation
RFP3TA	Output signal	Average magnitude difference between steady state, during radiation, and during a short period after radiation

RFP3TA (Vout)

<u>Characteristic</u>

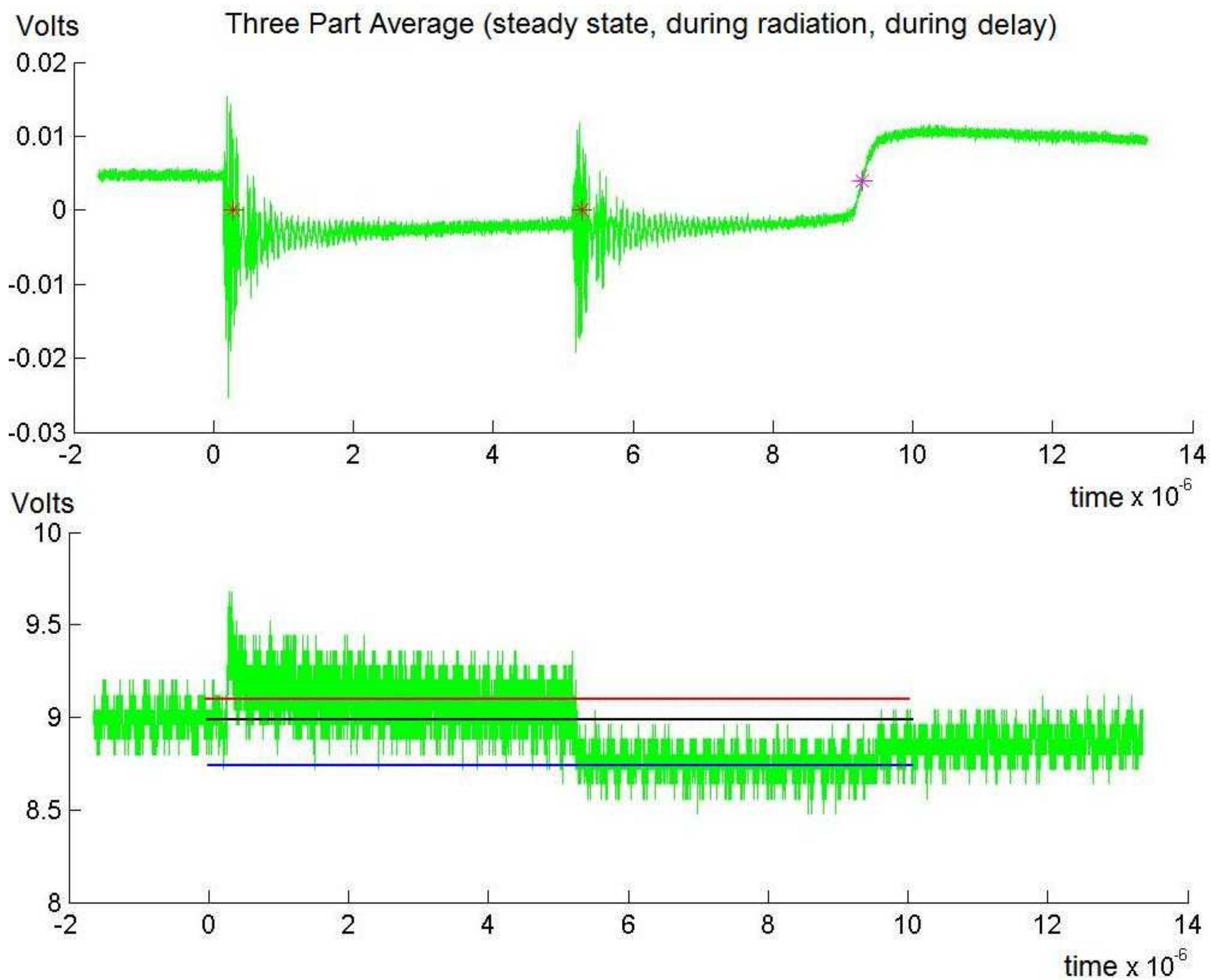
- Change in average voltage
- Change in amplitude of noise



SHOT 179

RFP3TA (Vout)

<u>Characteristic</u>
- Change in average voltages
- Change in amplitude of noise



SHOT 179

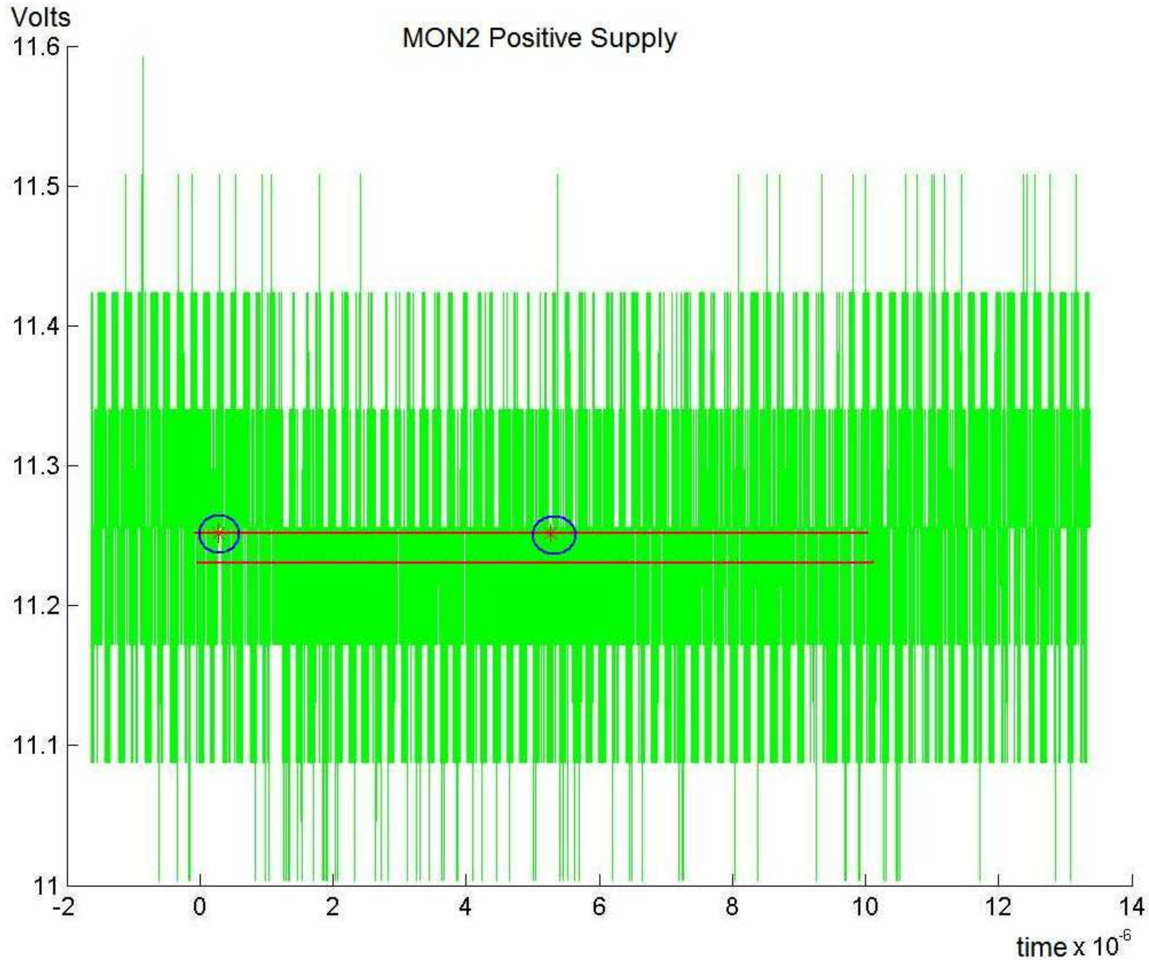
MON2 Positive Supply Voltage

Characteristic

•Change in average voltage

•Change in amplitude of noise

Digitizer/sampling noise comes from the 8 bit A-D converter. The signal was filtered previously by the testers.

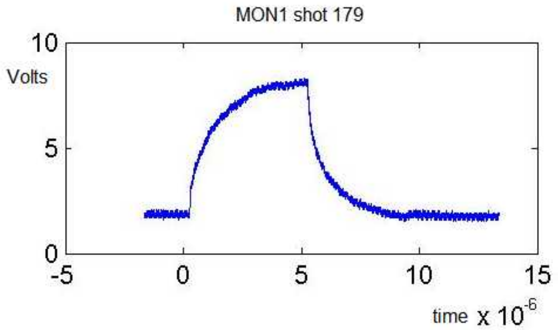


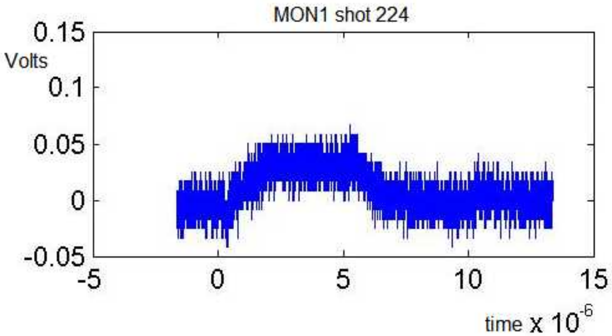
SHOT 179

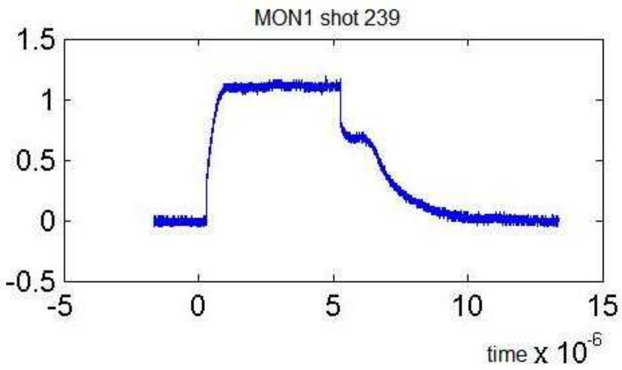
MON1

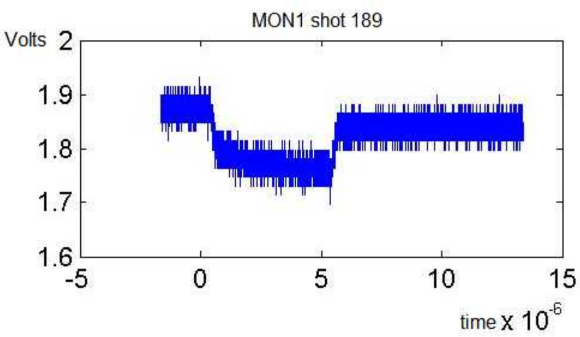
<u>Characteristic</u>

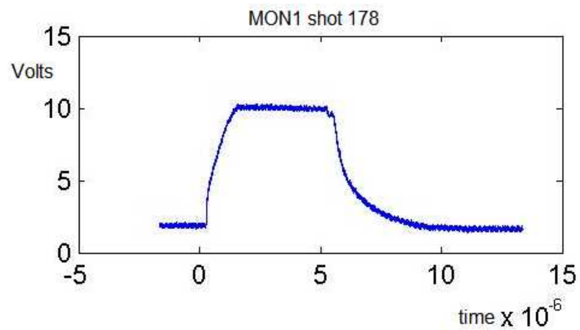
- (represents photocurrent magnitude through D1)
- Has the most variability:











MON1 Pattern?

Low doping outside depletion region causes photocurrent transport by diffusion. The rate is governed by the ambipolar transport equation. Excess minority carrier density *dp* in the *n*-doped region given by:

$$D_{ap}\frac{\partial^2(\delta p)}{\partial x^2}-\mu_{ap}E\frac{\partial(\delta p)}{\partial x}+G-U=\frac{\partial(\delta p)}{\partial t}$$

Explanation?

The “prompt” current density *Jdepl* is proportional to the width *Wdep* of the depletion region and to the rate of electron-hole pair generation *G*(*t*) in the semiconductor:

$$J_{dep}=qGW_{dep}$$

This current responds with a time constant given by the transport time

tdep = *W*/*v*

across the depletion region, where *v* is the carrier drift velocity.

Depends on:

Width of depletion region

Size of junction

Device terminal voltage

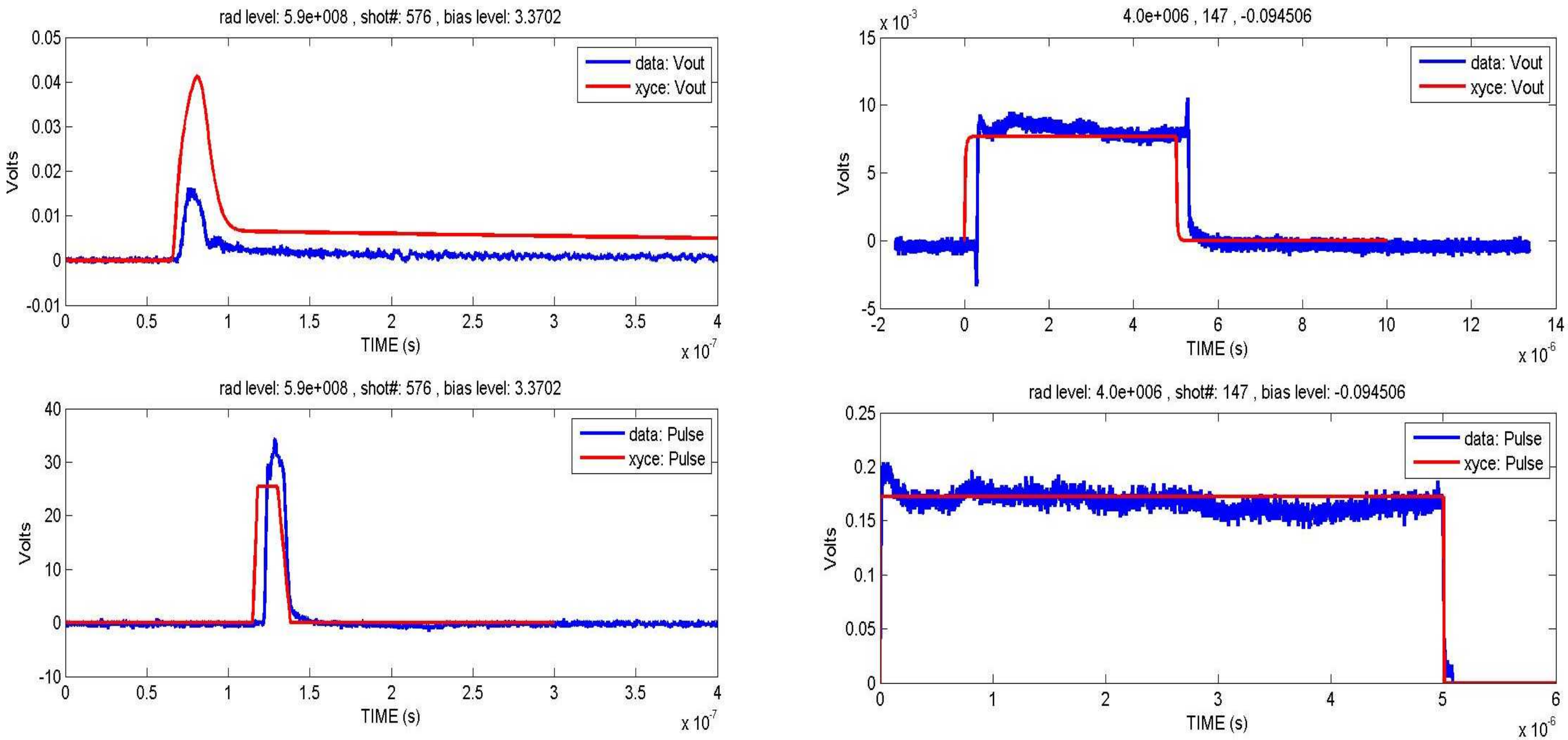
PNG	state	MON1 min	MON1 max	MON1 shape	Radiation s
0.025	off	0	0.3	Inoisy	
0.05	off	0	0.1	curved	
0.05	off	0	0.1	curved	
0.25	off	0	0.8	curved	
0.25	off	0	0.6	curved	
0.7	off	0	1	square	
0.7	off	0	1	square	
2.5	off	0	2	square	
2.5	off	0	2	square	
4.5	off	0	3.3	square	slanted
4.5	off	0	7.5	square	
0.02	on	2	2	line	
0.025	on	2	2	line	
0.05	on	2	2	line	
0.05	on	2	2	line	
0.24	on	2	2	square	
0.25	on	2	2	line	
0.25	on	2	2	line	
0.8	on	2	3	curved	
0.9	on	2	3	curved	
2.5	on	2	8	curved	
2.5	on	0	2	curved	
4.5	on	2	11	square	slanted
5	on	2	10	square	slanted

Phenomena Identification & Ranking Table (PIRT)

Physical Phenomena Description	Impact	Adequacy
Individual device photocurrent	H	H
Neutron, total dose, and other radiation effects	L	None
Parasitic effects	M	M
Temperature	M	M
Bias Condition	H	H
Experiment setup phenomena	L	M
Packaging, EMI, breadboard construction techniques	L	L

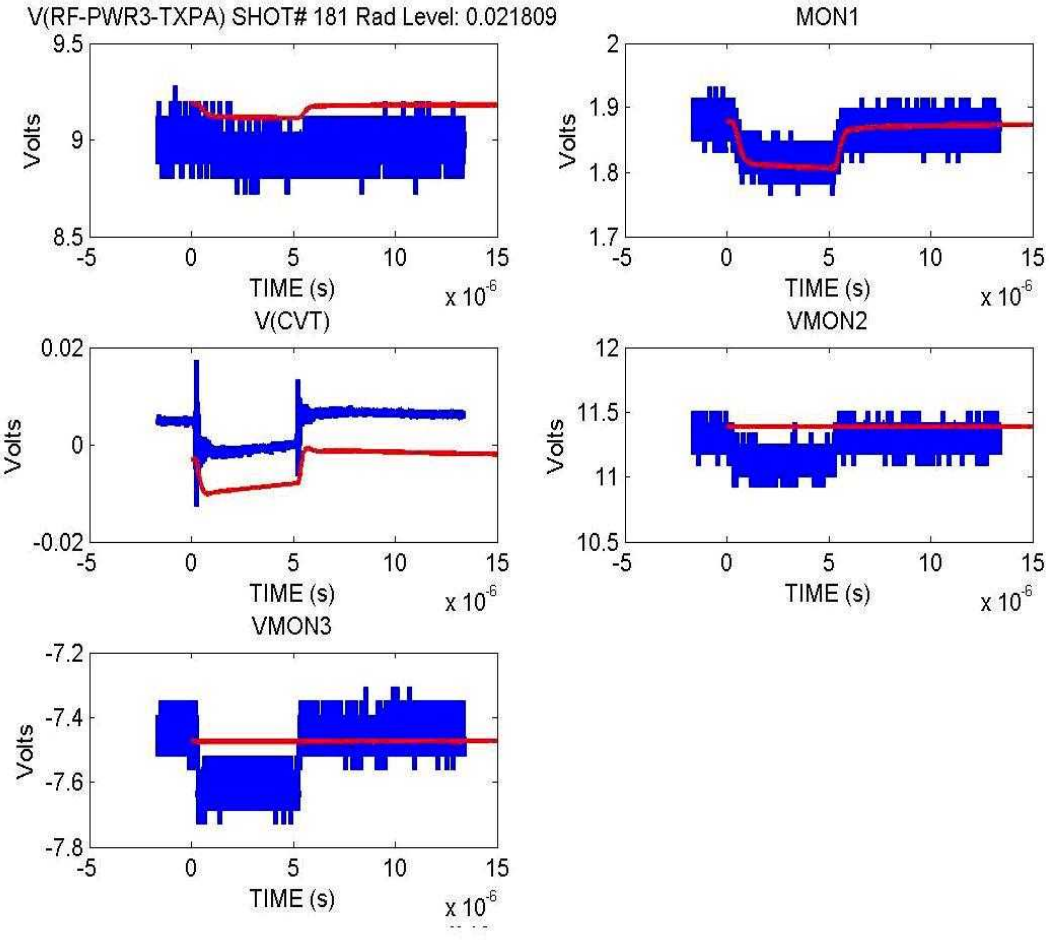
Xyce Simulations

- **Individual device circuit radiation photocurrent responses**



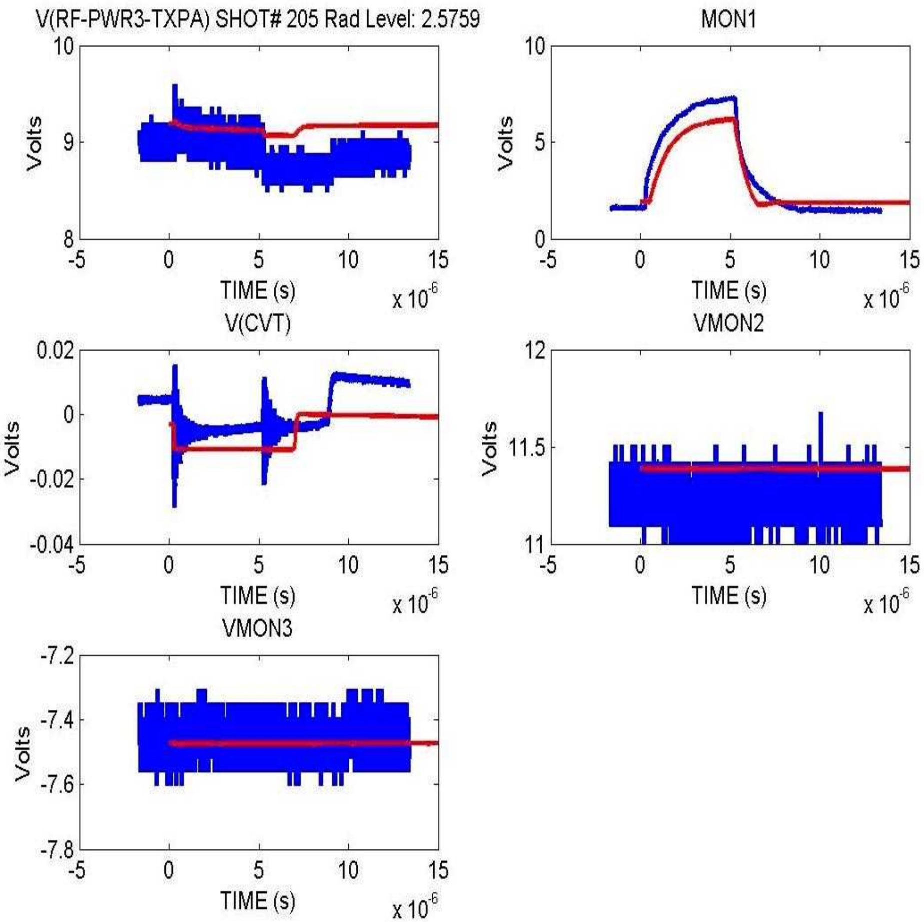
Xyce Simulations

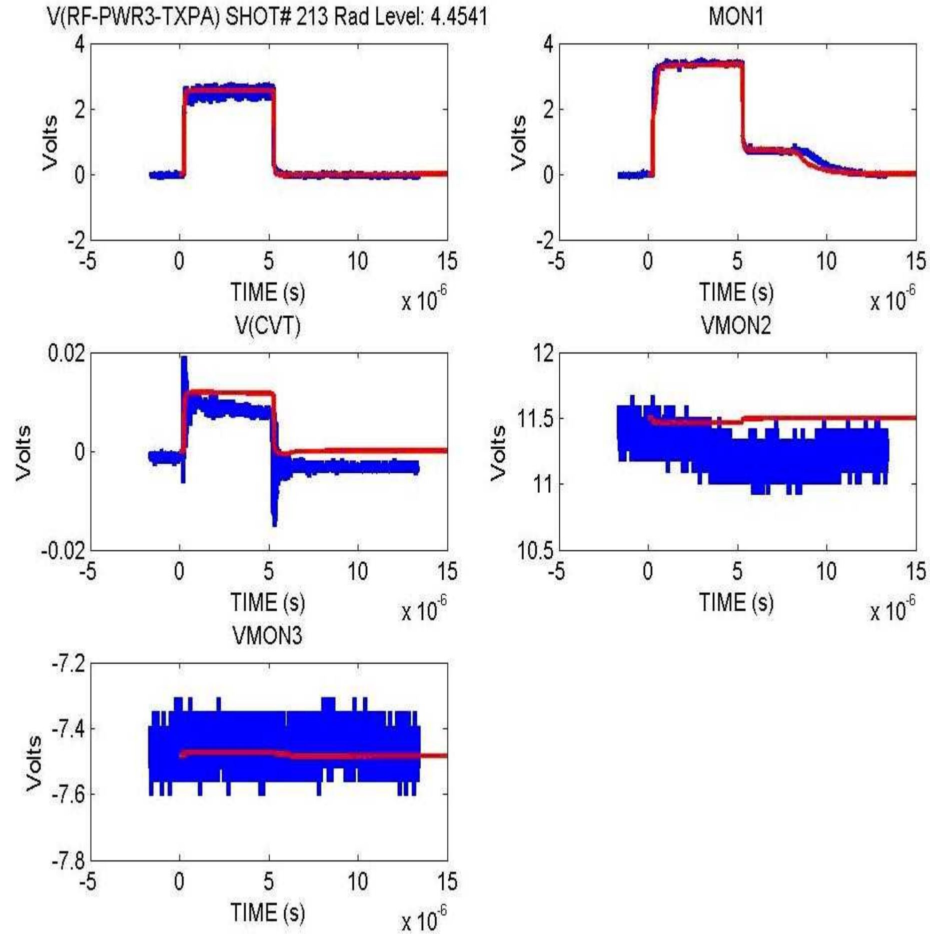
- Ran simulations and created batch files for processing and MATLAB files for plotting.
  - Compare previously mentioned characteristics to radiation test data.
- *Used Xyce functiontype* to input experimental PCD data points.



Functiontype 1

Xyce Comparison





Functiontype 1

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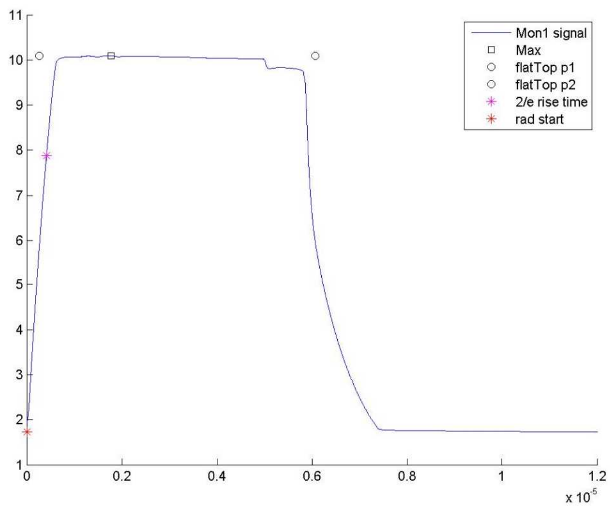
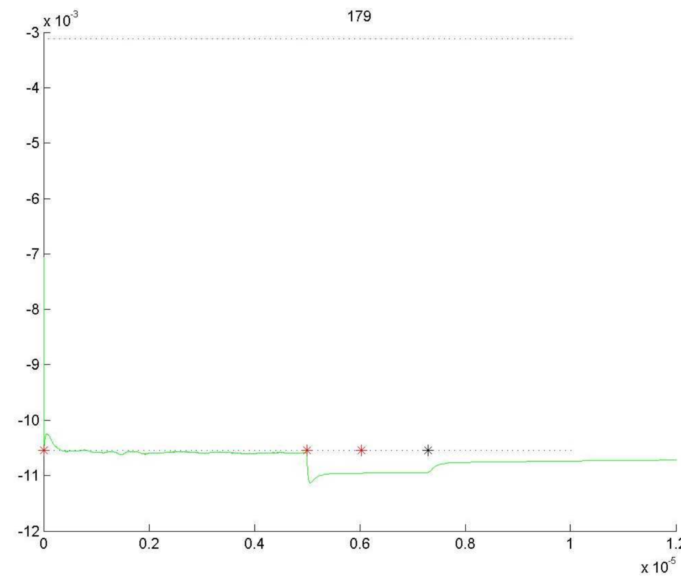
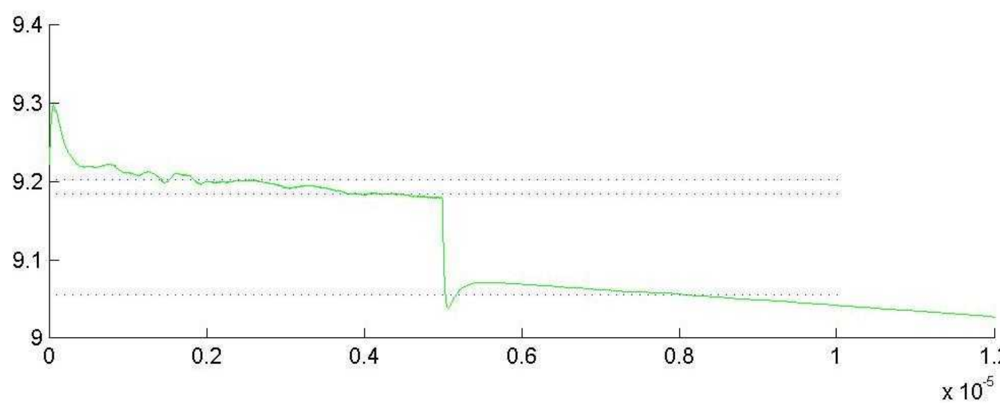
Characteristics of Interest



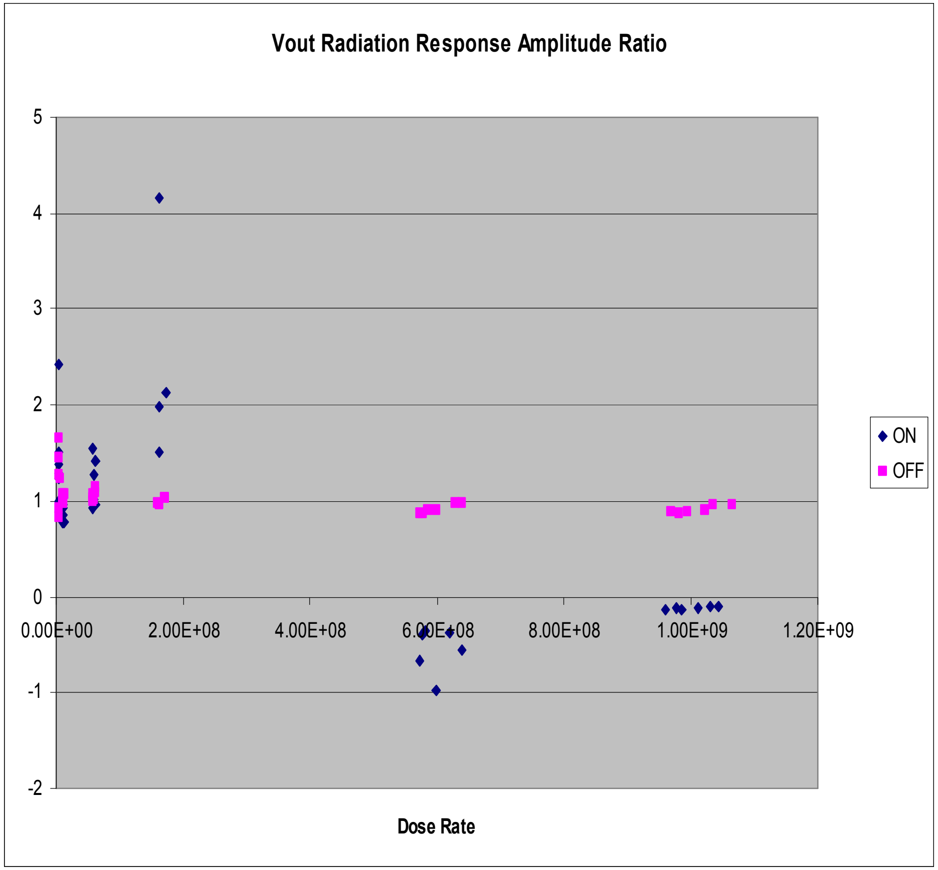


Same Characteristics and extraction techniques



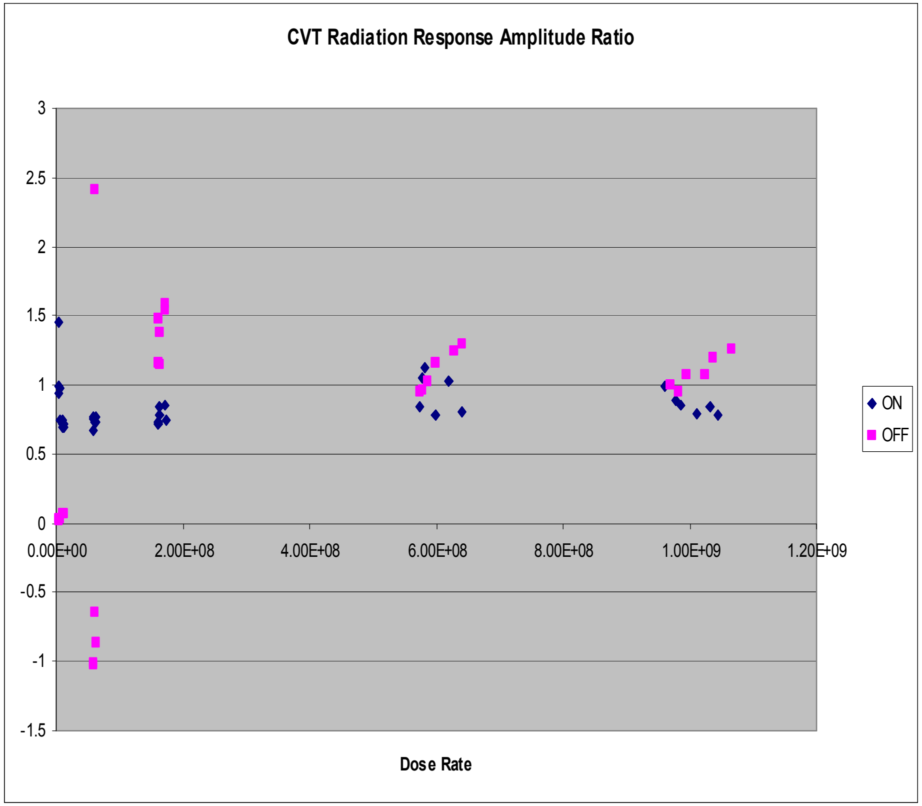
Sim. To Exp. Comparison Metrics

- **Ratio Simulated/Experimental**
- **indicates that the simulations match better for lower dose rates**
- **"ON" state matches better than in the "OFF" state, especially for lower radiation doses.**
- **Possible feedback effect.**



Sim. To Exp. Comparison Metrics

- **Ratio Simulated/Experimental**
- **When circuit is "ON", model over predicts the radiation response of MMBT2907 connected to CVT.**
- **Almost Uniform over prediction will be compensated by calibration**



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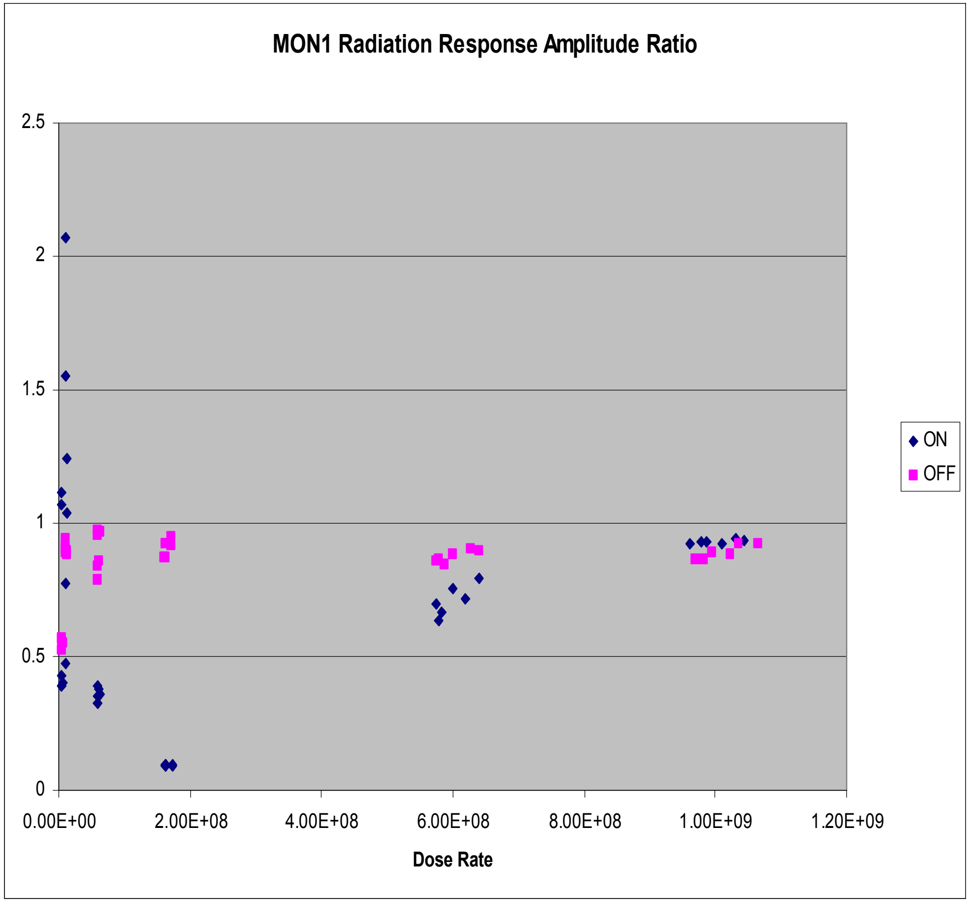
Sim. To Exp. Comparison Metrics

- **Ratio Simulated/Experimental**
- **Opposite correlation to dose rate**
- **Still has some mean error correctable by calibration**



Example Parameter Uncertainty Ranges

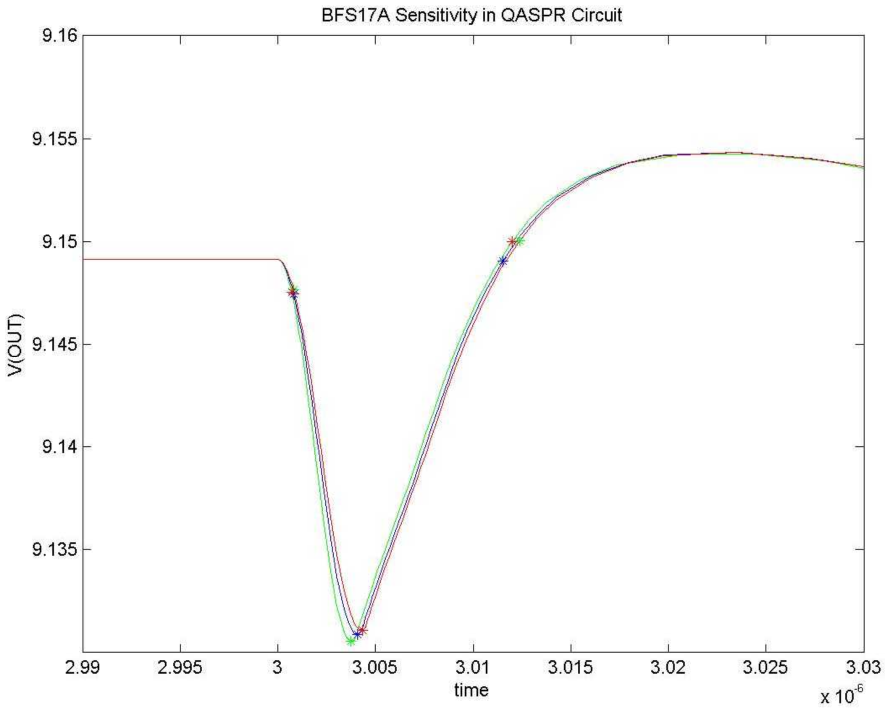
PARAMETER	DEFAULT	HAND OPT	LOW	HIGH
PERMITTIVITY	1.0443E-10	1.0443E-10	NA	
NI	1.45E+16	1.45E+16	NA	
RAUGN	1.10E-42	1.10E-42	NA	
RAUGP	3.00E-43	3.00E-43	NA	
ND	3.00E+25	1.00E+24	5.00E+23	2.00E+24
WN	2.00E-06	9.00E-07	8.00E-07	1.00E-06
NA	5.00E+20	1.00E+22	5.00E+21	2.00E+22
WP	5.00E-05	1.00E-05	1.00E-05	5.00E-05
NDN	1.00E-03	1.00E-03	2.50E-04	3.55E-03
NDP	7.00E-04	7.00E-04	1.00E-04	1.30E-03
TAUP0	2.00E-08	2.00E-08	1.00E-09	1.00E-05
TAUINFP	4.00E-08	4.00E-08	1.00E-09	1.00E-05
PDN	4.00E-03	4.00E-03	2.50E-04	3.55E-03
PDP	5.00E-04	5.00E-04	1.00E-04	1.30E-03
TAUN0	1.00E-06	1.00E-06	1.00E-09	1.00E-05
TAUINFN	2.00E-06	2.00E-06	1.00E-09	1.00E-05
DEVICEAREA	1	7.80E-06	6.60E-06	9.00E-06

All parameters for NTB5605P VDMOS

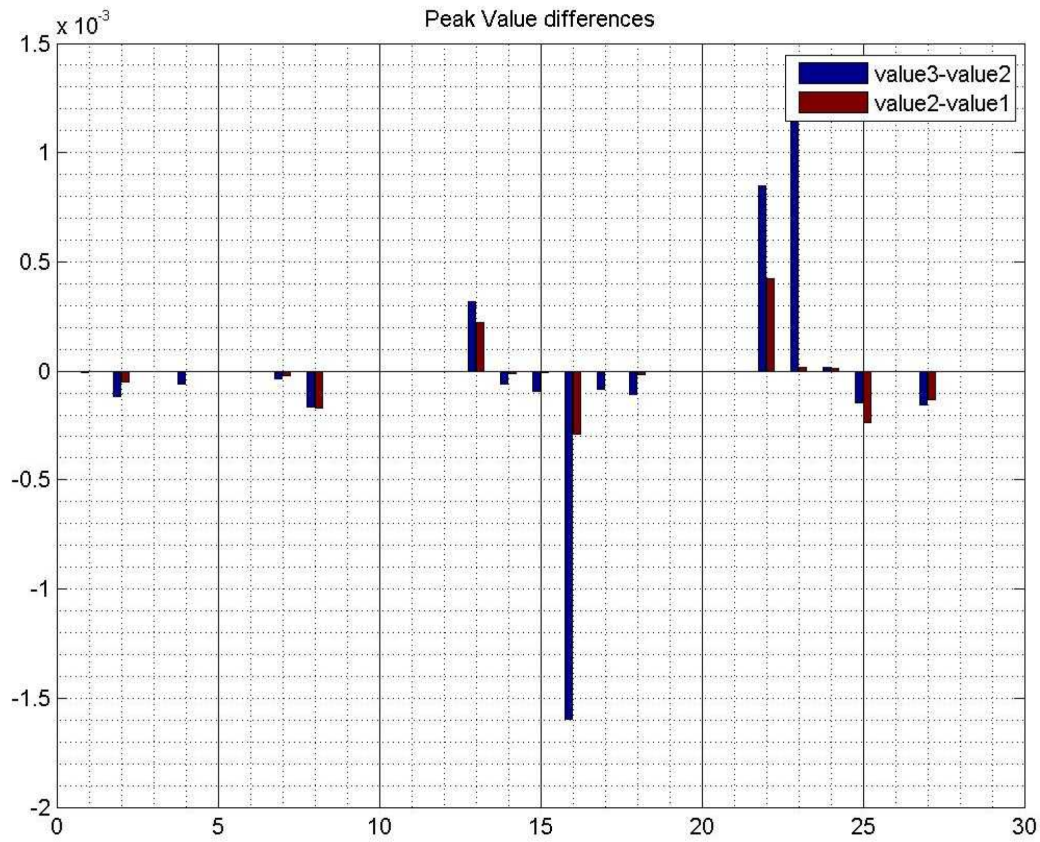
6-8 parameters are calibrated including lifetimes and minority carrier densities

Sensitivity Study

- **Determine the effects of the parameter uncertainty on the circuit output**
- **Worst case analysis for BFS17A device with simple adaptation of the regular validation script.**
  - **Input orthogonal array such that one device was varied at a time**

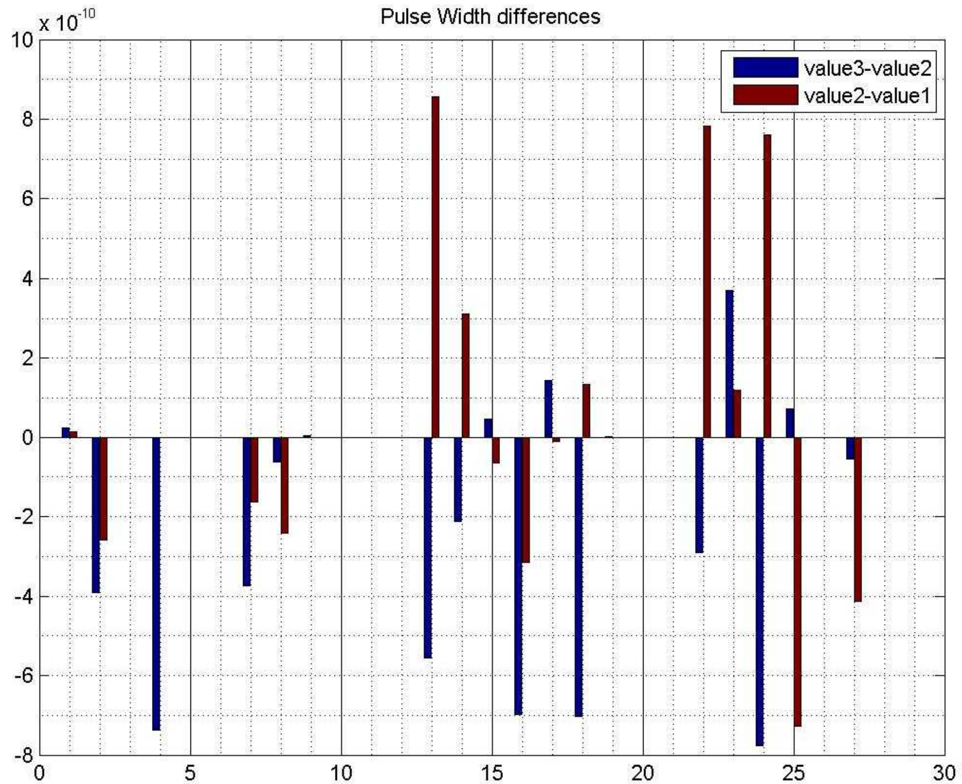


Sensitivity Study



Sensitivity Study

- The 26th parameter, the radiation pulse width, was kept constant
  - Note 26th parameter has zero effect
- The 27th, the radiation pulse magnitude was monotonically increased..
  - Note that the 27th parameter always has monotonic effect



New Experimental Approaches to UQ

- **Level zero, no simplifications**
  - UQ at the top level of the hierarchy is run with all of the model parameters of all of the devices varied as one sample space.
  - Sample space is much too large

- **Level one, hierarchical**
  - Each device UQ is run in isolation in the sub-circuit and bounding sets are those that yield the largest characteristic of interest on the sub-circuit. Sub-circuit UQ is run with only the bounding sets.
  - Assumes no interaction effects between uncertainty photocurrent responses of multiple connected devices.

New Experimental Approaches to UQ

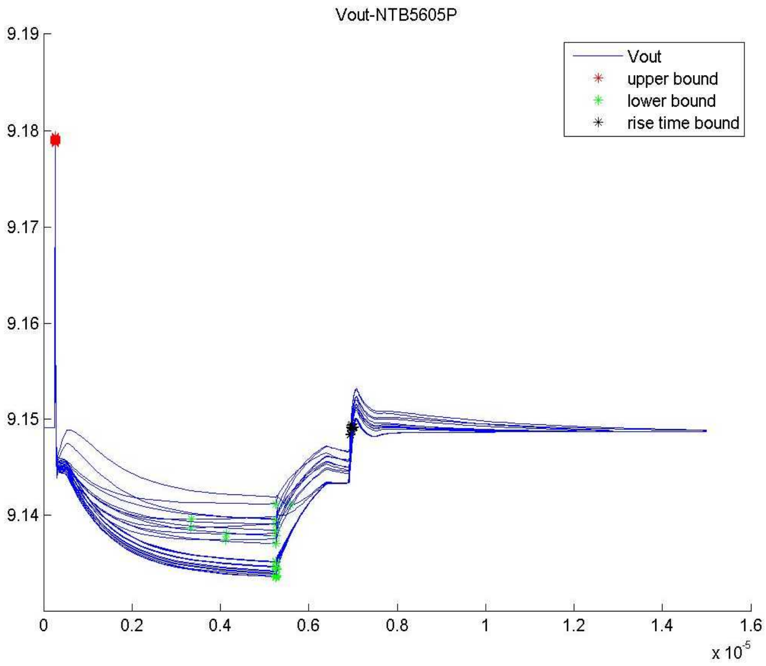
- **Level two, hierarchical individual bias**
  - The device UQ is run for each device in a separate circuit from the sub-circuit. Bounding sets are used to run the circuit level UQ.
  - More desirable because individual device circuits require much less simulation time
  - Also matches the experimental hierarchy.
  - Bias of individual circuit is different.

- **Level three, hierarchical individual bias injected as current sources**
  - Same as above assumptions plus photocurrent response is modeled as a current source injected in some configuration on the device, such as between the collector and base.
  - De-biasing can happen.
  - Circuits designed to avoid this behavior
  - Less useful is because the current source specifications are quite limited, they will not match the actual photocurrent response function well.

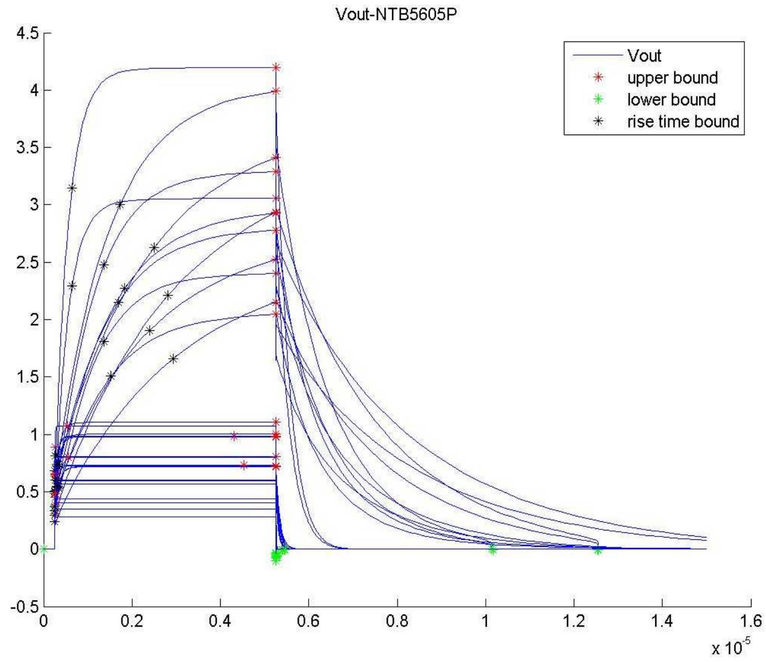
Level 1 and 2 Approaches

- **Voltage regulator circuit level one and two approaches compared with full parameter set approach**

Level 1 bounding set determination



Level 2 bounding set determination



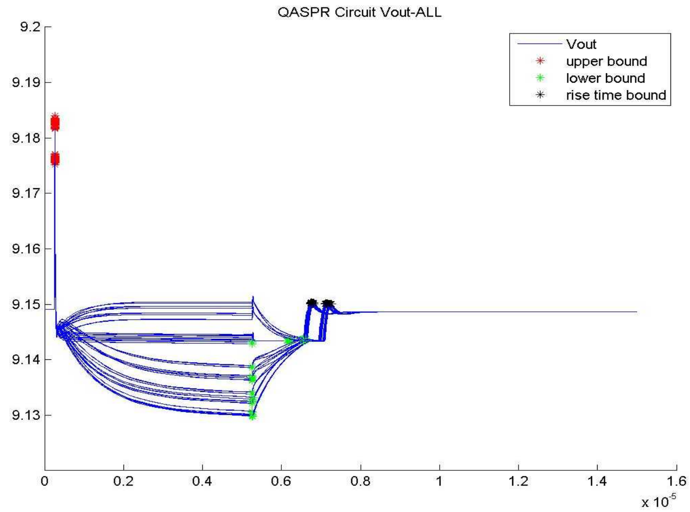
Level 1 and 2 Approaches

- **Resulting bounds**

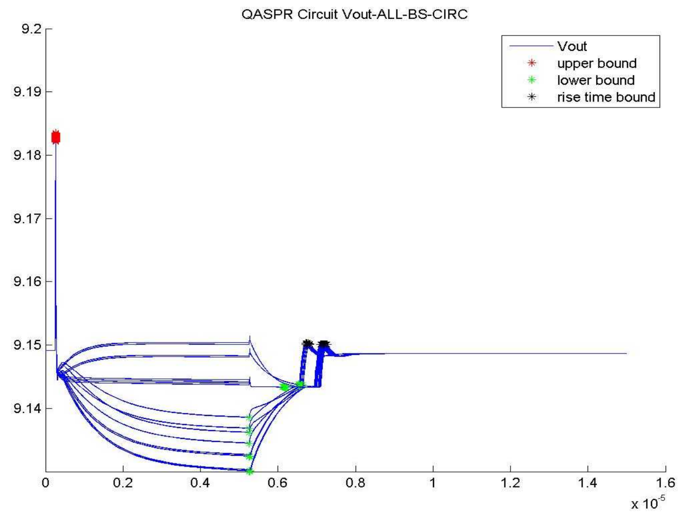
Device in Individual Circuit	Max	Imax	Min	Imin	Tmax	Itmax	Tmin	Itmin
BFS17A	2.36E-02	54	5.69E-11	16	5.10E-06	20	2.54E-07	33
MMBT2907ALT1	1.70E-01	52	8.07E-11	1	4.44E-06	50	2.54E-07	15
MMBT2222ALT1	3.01E-02	52	5.54E-11	1	6.90E-07	19	4.95E-07	48
NTB5605P	4.19E+00	1	-1.01E-01	3	2.93E-06	19	2.56E-07	17
MMSZ5236	5.80E-02	1	5.16E-09	4	3.34E-06	22	2.55E-07	3
Device In Voltage Regulator Circuit	Max	Imax	Min	Imin	Tmax	Itmax	Tmin	Itmin
BFS17A	9.18E+00	5	9.13E+00	40	1.38E-05	53	6.42E-06	20
MMBT2907ALT1	9.17E+00	33	9.13E+00	46	7.04E-06	31	6.98E-06	17
MMBT2222ALT1	9.18E+00	28	9.13E+00	11	7.01E-06	20	7.01E-06	14
NTB5605P	9.18E+00	25	9.13E+00	17	7.02E-06	10	6.94E-06	23
MMSZ5236	9.18E+00	10	9.13E+00	1	8.62E-06	15	6.73E-06	12

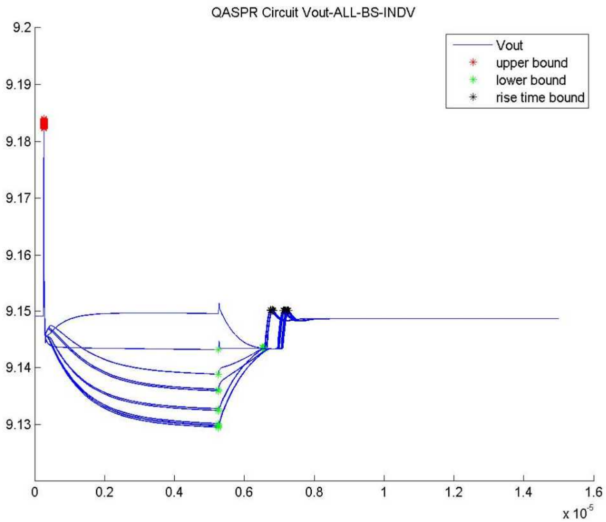
Using all parameters and oa.52.27.2.3.txt and oa.32.15.2.3.txt
Radiation level fixed

Level 1 and 2 Approches



- **Using only non-calibrated parameters**





Level 1 and 2 Approach

	max	Imax	min	Imin	Tmax	Itmax	Tmin	Itmin
Using all parameters	9.18396200	23	9.12973800	14	7.26629700E -06	48	6.72841900E-06	70
Bounding sets from circuit	9.18351300	57	9.13005200	985	7.26883000E -06	777	6.72563800E-06	653
Bounding sets from individual devices	9.18396800	569	9.12942900	641	7.27734100E -06	577	6.74983000E-06	53

Conservative

Most Accurate

- Arguably more important to have bounds that are conservative even if slightly less accurate.
- The level 2 method most desirable.

Uncertainties of comparisons

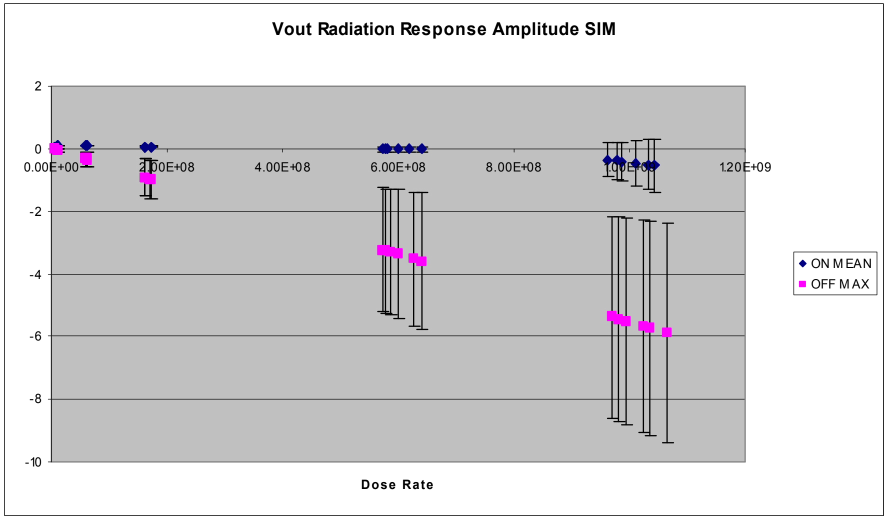
- The level zero and level one strategies for uncertainty quantification analysis were implemented

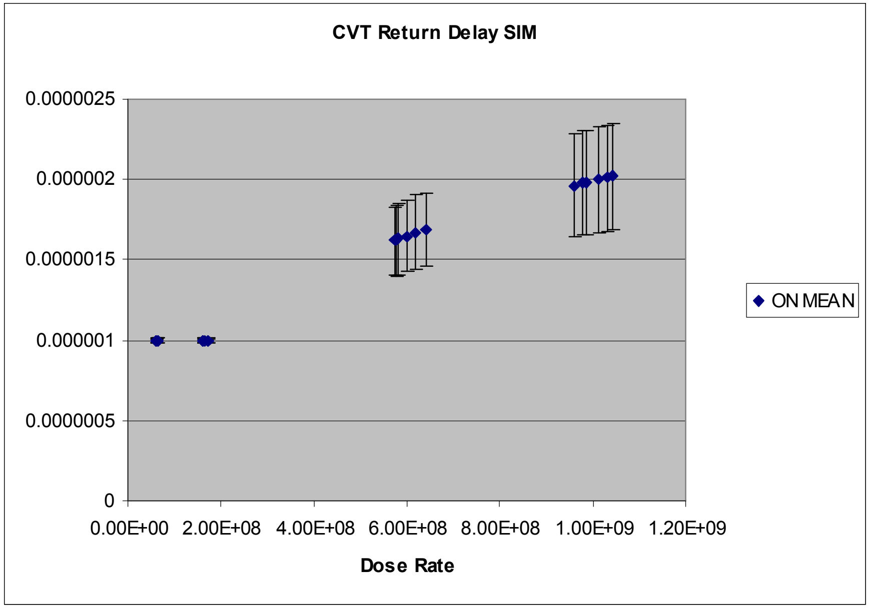
- Algorithm:
  - For each shot
    - » Set environmental variables
    - » For each row in the orthogonal array
      - Sample the parameter space from the orthogonal array and update the parameter library
      - Run transient simulation
      - Extract characteristics of interest
    - » End
  - End
  - The final step is to calculate all statistics of characteristics

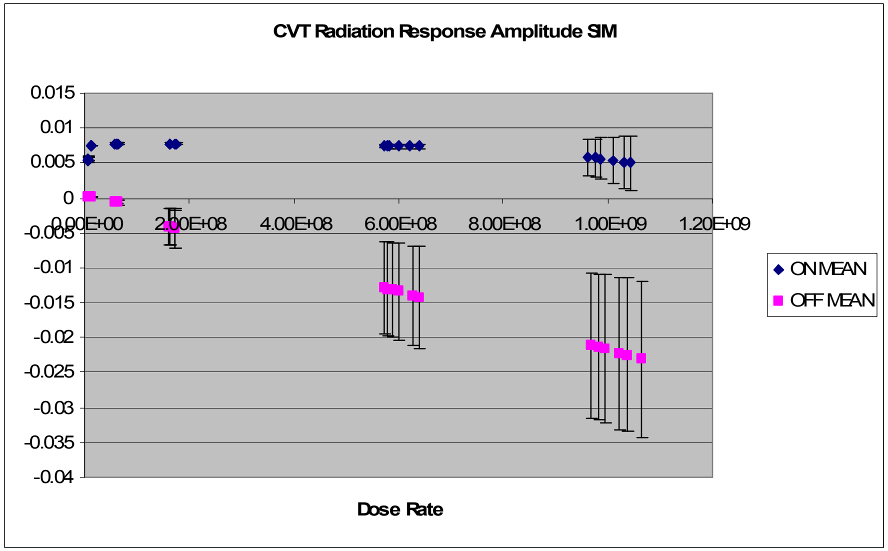
- In the case of level one or two, the orthogonal array is replaced by an enumeration of the possible bounding set combinations.

Uncertainties of comparisons

Results for level zero







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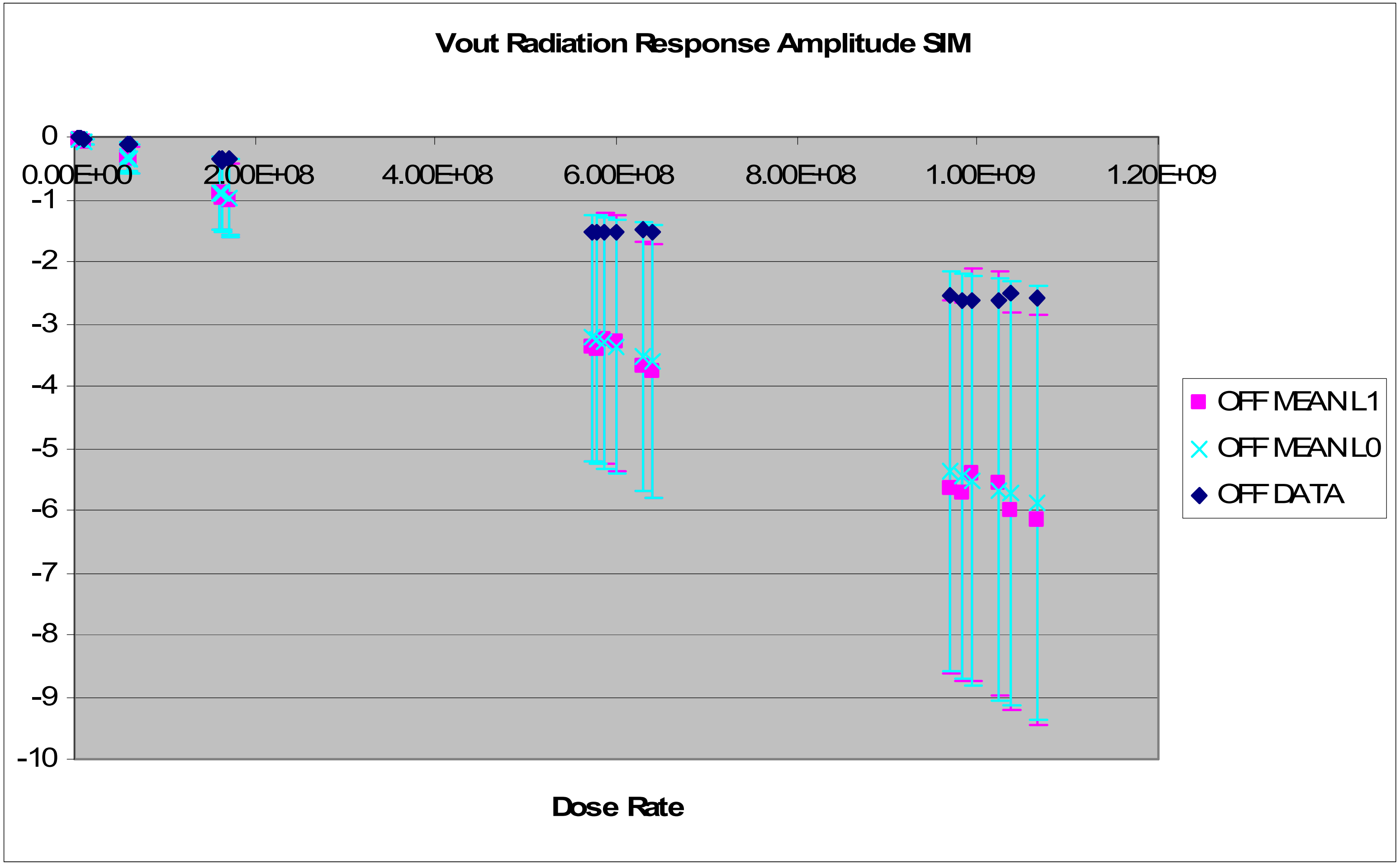
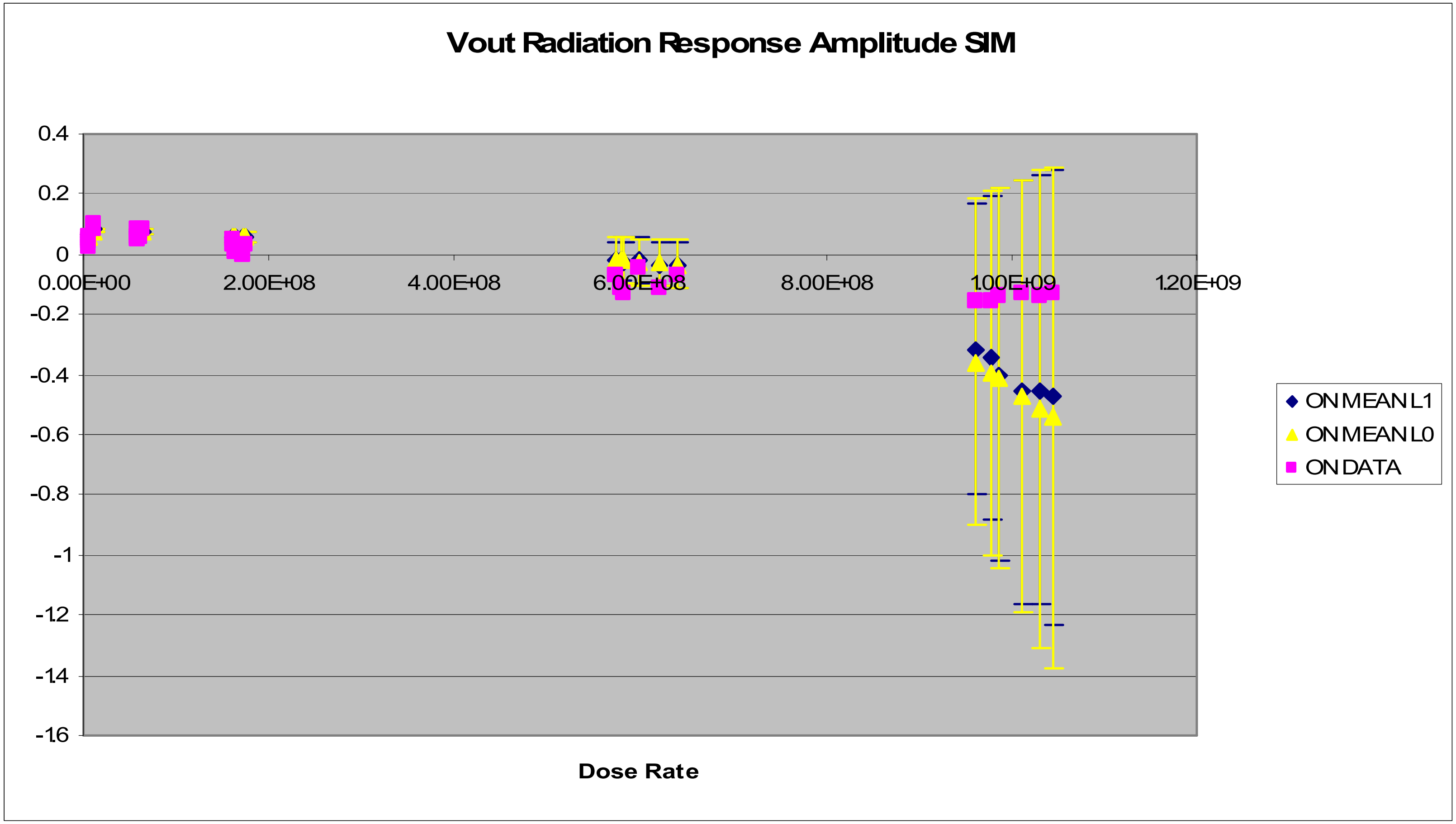
Uncertainties of comparisons

Comparison for level zero and one and data



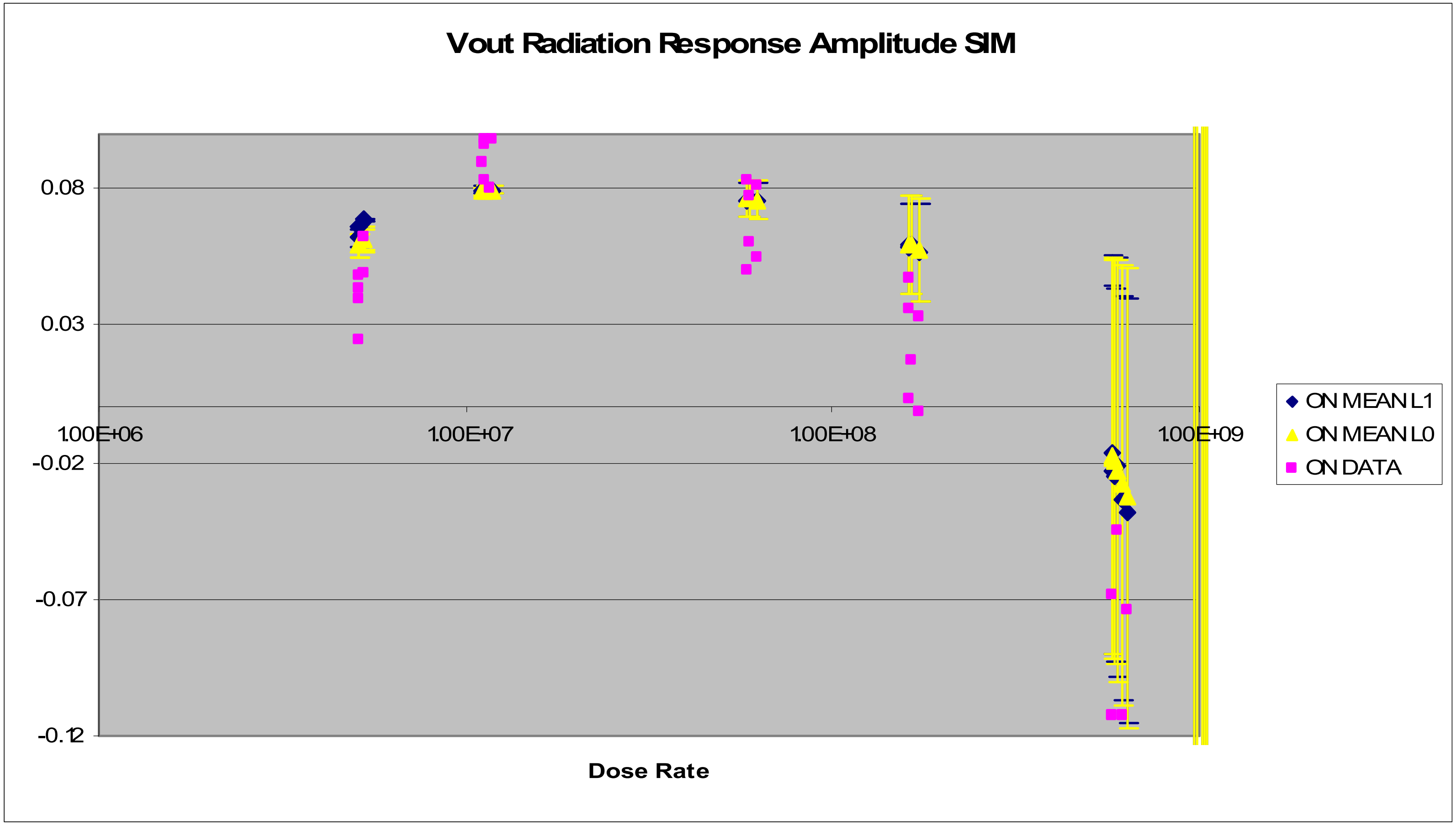
Uncertainties of comparisons

Comparison for level zero and one and data



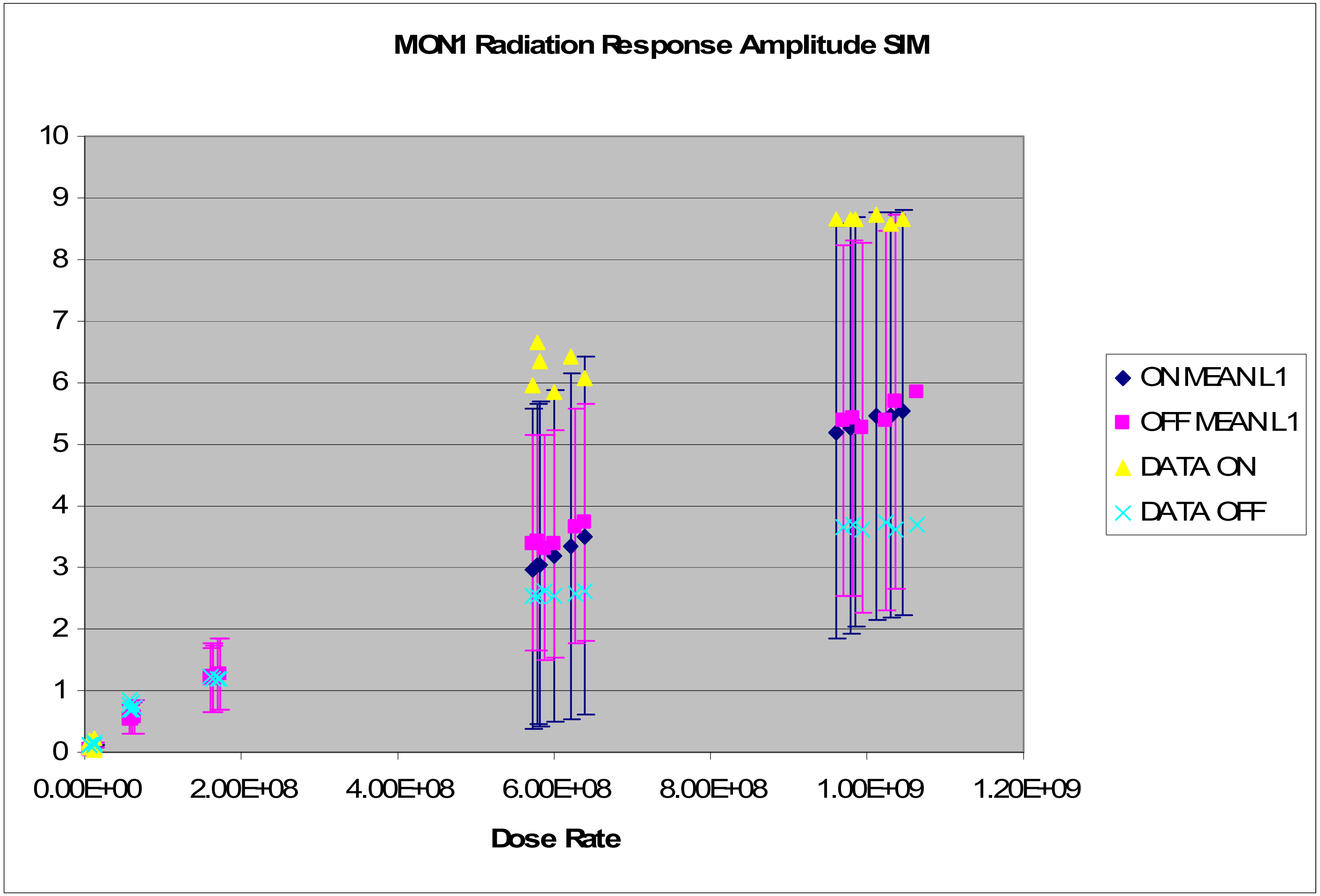
Uncertainties of Comparisons

Example comparison for level zero and one and data



Uncertainties of Comparisons

Example comparison for level one and data and circuit state (ON/OFF)

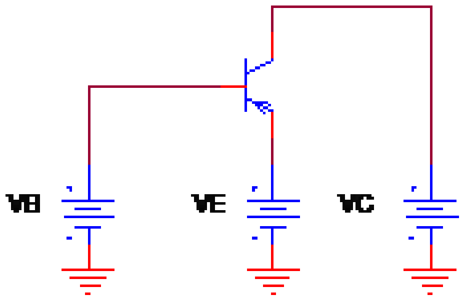


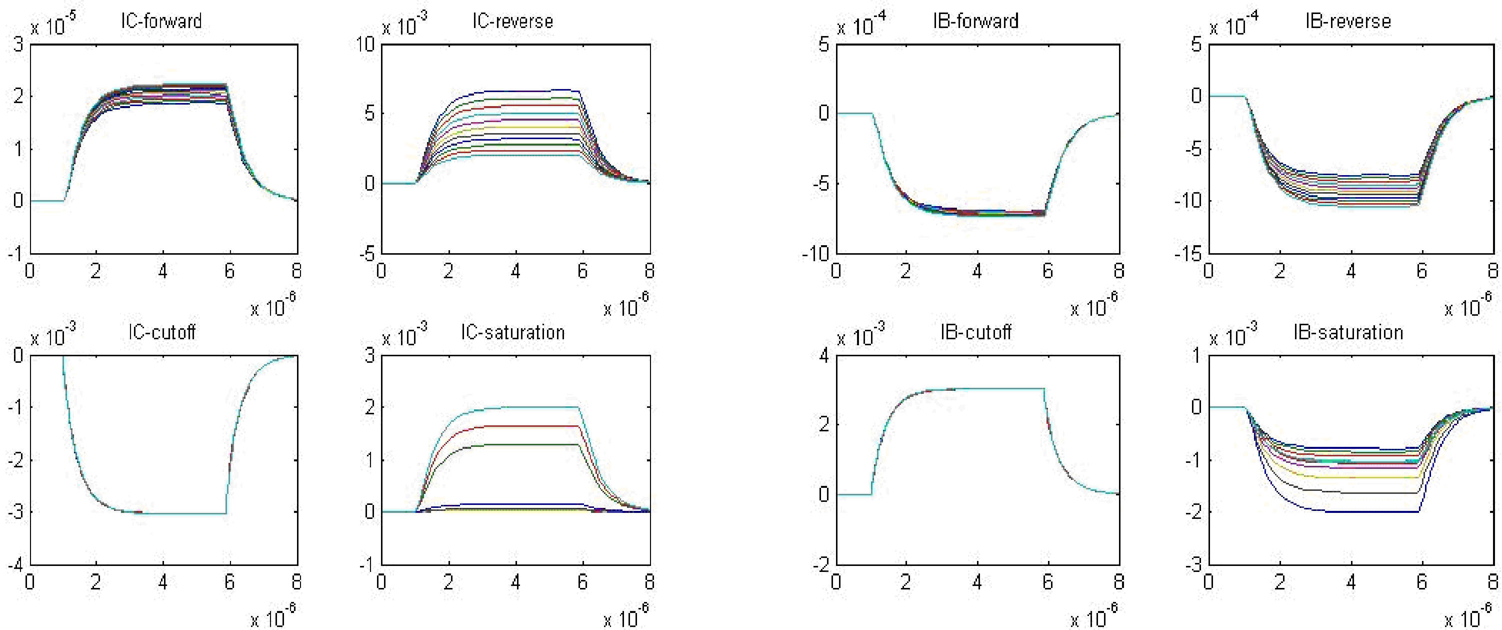
Questions?

Research Experiment 1

BFT92 Photocurrent for different bias regions:

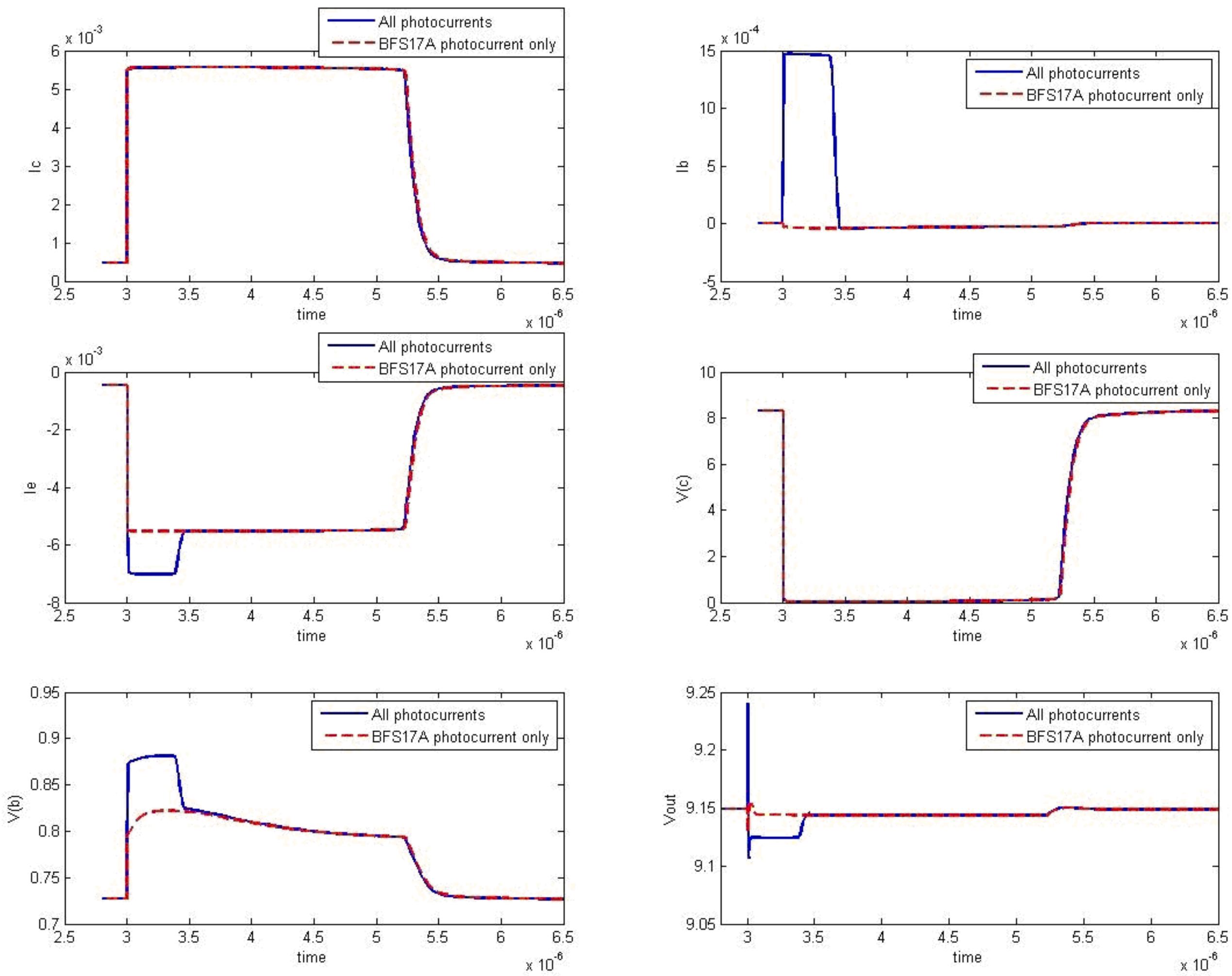
Active	Veb=-10	-10<Vcb<0
Cutoff	-10<Veb<0	Vcb=-10
Saturated	10<Veb>0	Vcb=10
Reverse	-10<Veb<0	Vcb=10





Research Experiment 2

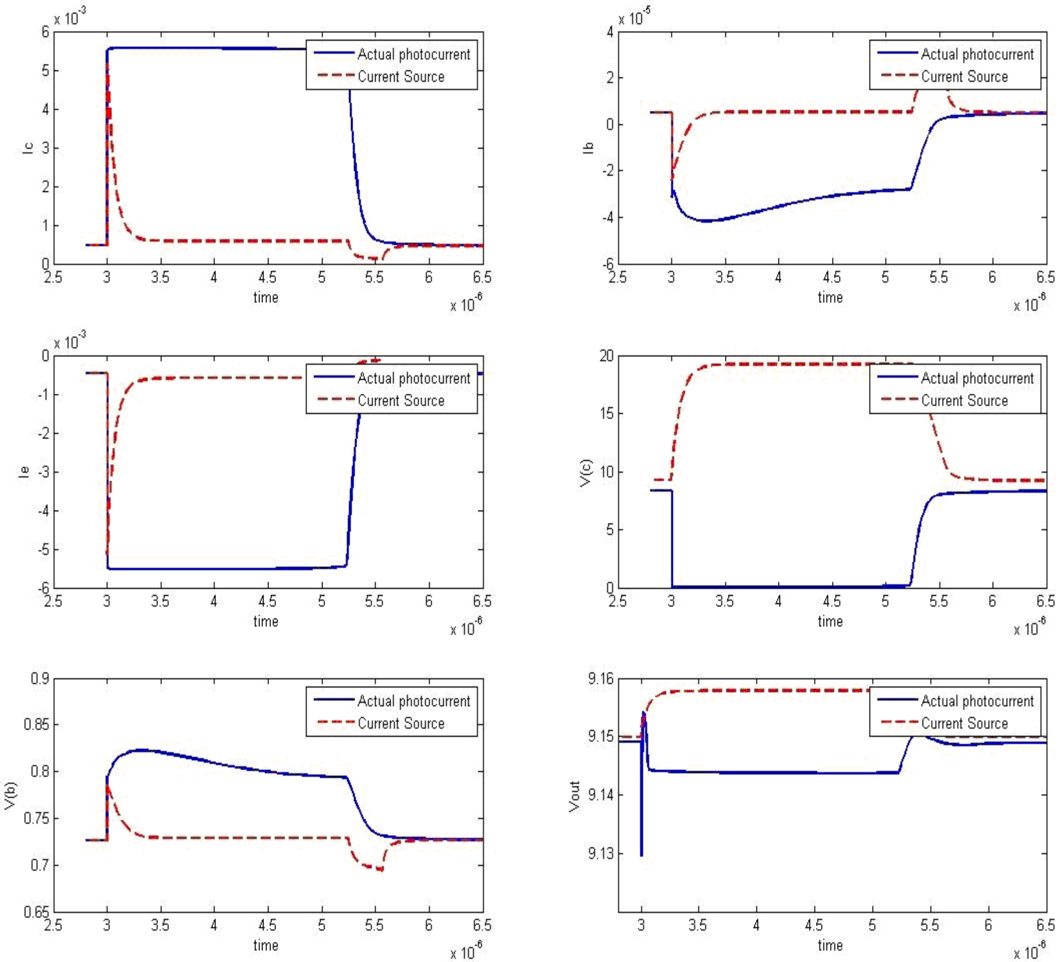
Isolated Photocurrent contribution of BFS17A



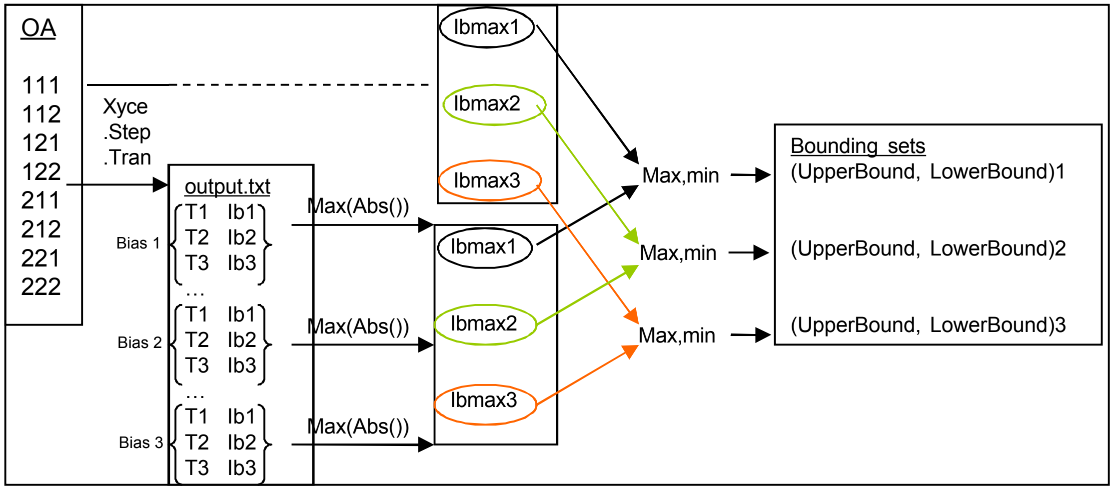
Photocurrent contributions from other devices in the circuit make their way to the terminals of the BFS17A device as well as the circuit output voltage.

Research Experiment 3

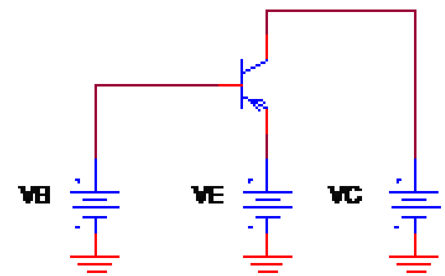
- **Photocurrent Source injection representation**
- **Inserted between collector and base**
- **Other configurations yielded worse results**



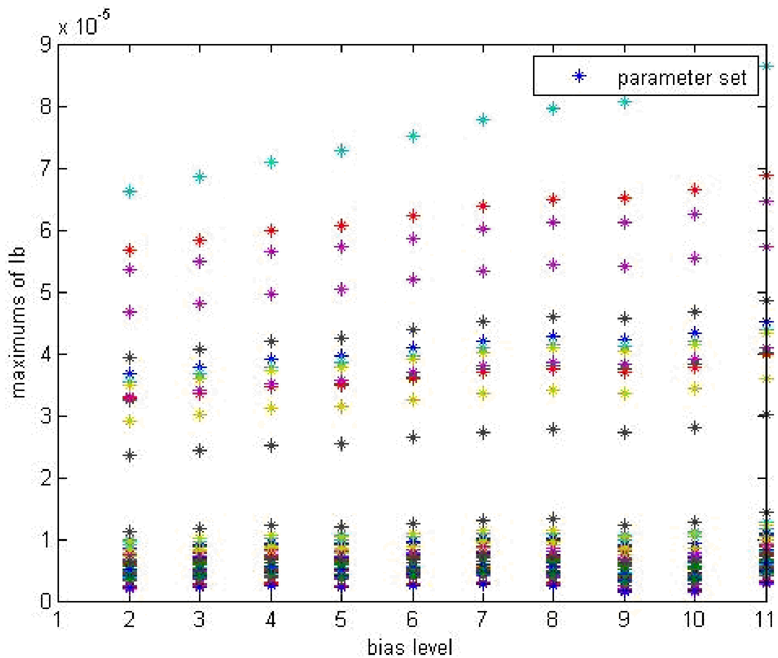
Research Experimental 4



BFT92 Device UQ over varying Biases in individual device circuit



Reverse	-10<Veb<0	Vcb=10



- The bounding sets are the same regardless of the bias level within the region.

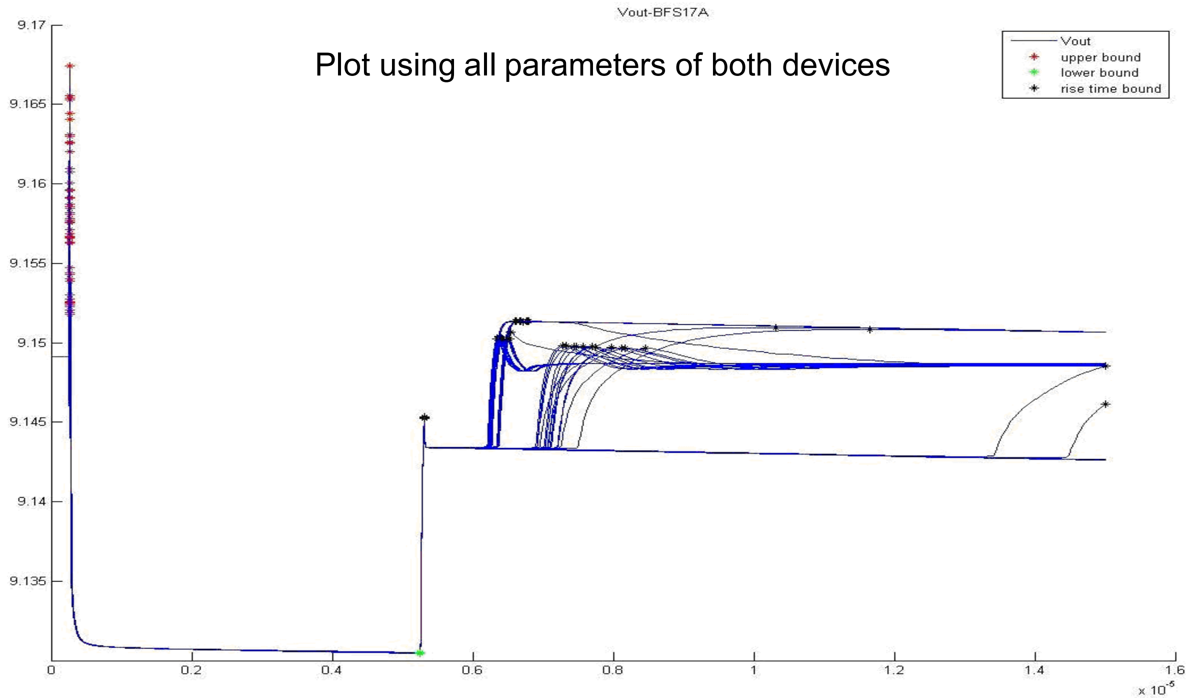
- Different for only the forward region and only on the collector current of the device, otherwise they are the same across the regions, for the terminal currents.

Research Experiment 5

- Voltage regulator UQ by all parameters vs. bounding sets for two devices
- Using all device model parameters (including those that will be calibrated), but with fixed radiation parameters
- Computationally less intensive UQ analysis at the sub-circuit level neglecting the interaction contributions of parameter uncertainties Using all parameters
- Bounding set determination
  - Maximum of maximums of output voltage
  - Minimum of minimums of output voltage
  - Earliest rise time of output voltage
  - Latest rise time of output voltage
- Enumeration of bounding set combinations

Research Experiment 5

- Tmax bound which moved to the end of the simulation
- Some combinations of both devices parameter uncertainties, than either individually.
- Synergistic effect: combination of the two devices yields bounding values ~ .01% beyond those of either device alone.
- Multiple OA's used, but both were two level and strength three



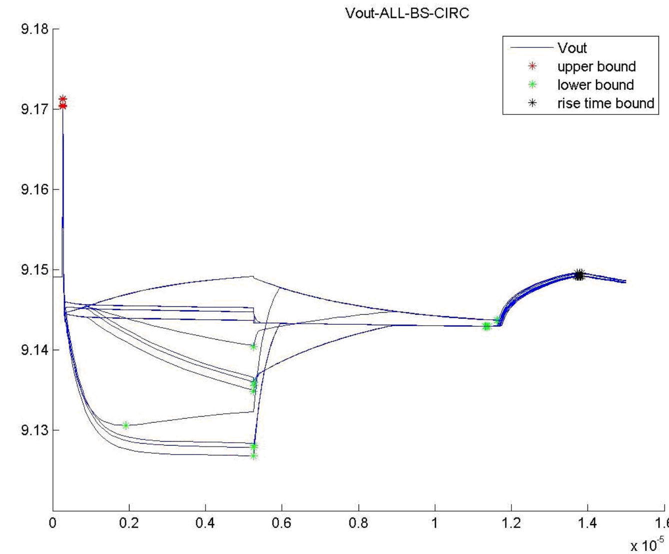
Bound Characteristic	Vout Upper Bound	OA row	Vout Lower Bound	OA row	Rise Time Earliest	OA row	Rise Time Latest	OA row
Run with bounding sets	9.168341	6	9.130448	1	1.392189e-006	15	5.312383e-006	7
Run with all parameters	9.167413	39	9.130454	3	1.5e-005	3	5.312214e-006	16

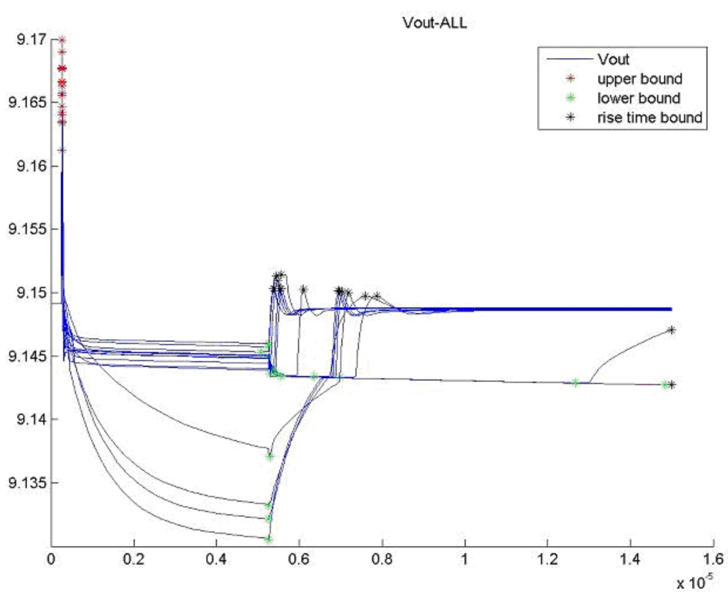
Results of all parameter and bounding sets approaches

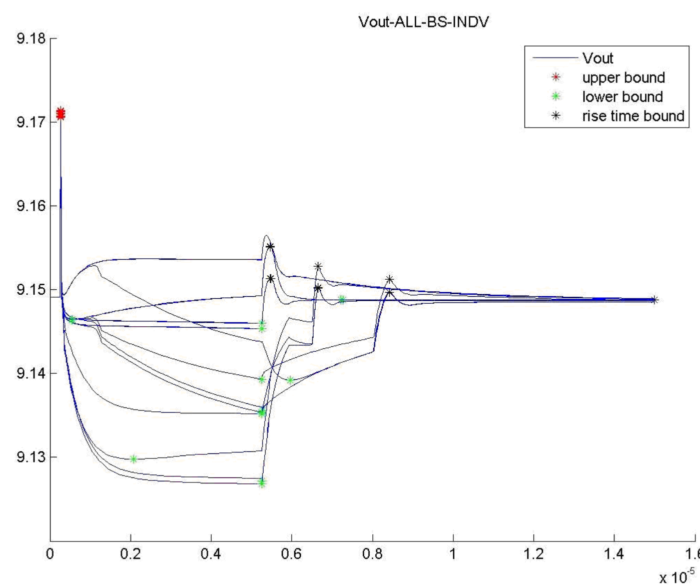
Research Experiment 6

<u>Voltage regulator UQ</u>

- All parameters of all devices using oa.208.103.2.3
- Bounding sets derived from isolated photocurrent response uncertainty in voltage regulator circuit
- Bounding sets derived from individual circuit uncertainty







Research Experiment 6

Results

- Device bounds in each circuit type
- Output voltage bounds using both methods

Device in Individual circuit	max	Imax	min	Imin	Tmax	Itmax	Tmin	Itmin
BFS17A	2.36E-02	54	5.69E-11	16	5.10E-06	20	2.54E-07	33
MMBT2907ALT1	1.70E-01	52	8.07E-11	1	4.44E-06	50	2.54E-07	15
MMBT2222ALT1	3.01E-02	52	5.54E-11	1	6.90E-07	19	4.95E-07	48
NTB5605P	4.19E+00	1	-1.01E-01	3	2.93E-06	19	2.56E-07	17
MMSZ5236	5.80E-02	1	5.16E-09	4	3.34E-06	22	2.55E-07	3

Device, In voltage Regulator circuit	max	Imax	min	Imin	Tmax	Itmax	Tmin	Itmin
BFS17A	9.18E+00	5	9.13E+00	40	1.38E-05	53	6.42E-06	20
MMBT2907ALT1	9.17E+00	33	9.13E+00	46	7.04E-06	31	6.98E-06	17
MMBT2222ALT1	9.18E+00	28	9.13E+00	11	7.01E-06	20	7.01E-06	14
NTB5605P	9.18E+00	25	9.13E+00	17	7.02E-06	10	6.94E-06	23
MMSZ5236	9.18E+00	10	9.13E+00	1	8.62E-06	15	6.73E-06	12

Characteristic	max	Imax	min	Imin	Tmax	Itmax	Tmin	Itmin
Using all parameters	9.173797	36	9.130505	5	1.500000e-005	2	5.365621 e-006	34
Bounding sets from circuit	9.171267	6	9.126809	1	1.385160e-005	16	1.368721e-005	1
Bounding sets from individual devices	9.171337	2	9.126832	10	1.500000e-005	5	5.470677e-006	15

Conclusions

- Verification and Validation assessments depending on budget, time, and experimental facilities.
- Simulation testing is phasing out experimental testing
- For this work, V&V is a very significant part of the entire M&S of electronics of interest to Sandia
- Developed methodology based on some existing generalized standards modified for the specific application.
- Methodology is augmented with a hierarchical approach and is explored and applied in greater detail than any of the state of the art work.

Conclusions

- **Methodology is specific to M&S of radiation induced photocurrent of electronic devices**
- **Using Sandia's proprietary physics based electrical simulation software Xyce**
- **Two new methods for the hierarchical simulation techniques were explored in depth**
- **Developed a suite of automated V&V scripts**
- **Result is high quality set of accuracy and fidelity quantification metrics of the current models to facilitate confidence. As, the knowledge of the accuracy of the simulations is invaluable and quantifying the extent to which that knowledge is itself accurate is equally important.**

QUESTIONS?