Microdosimetry and the Single Neutron

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Outline

- Background
- Radiation transport models
- Device physics models
- Issues relating to interfacing the two and some results
- The M^{2}EDUSA (Microdosimetry in Micro-Electronics Devices for Upset Simulation using ATLAS) framework
- Conclusions

Background

- SEEs may become a major factor limiting the reliability of future microelectronics
- The increasing susceptibility and range of single event effects is driven by:
  - Trends in microelectronics towards smaller feature sizes
  - Increase bandwidth of electronics (transients are now amplified and latched)
- Effects are now observed in avionic systems and at sea-level
- SEE in the atmosphere are driven by the neutron flux induced by cosmic-rays and solar flare particles, which undergo nuclear interactions in the active semiconductor or nearby materials

Background

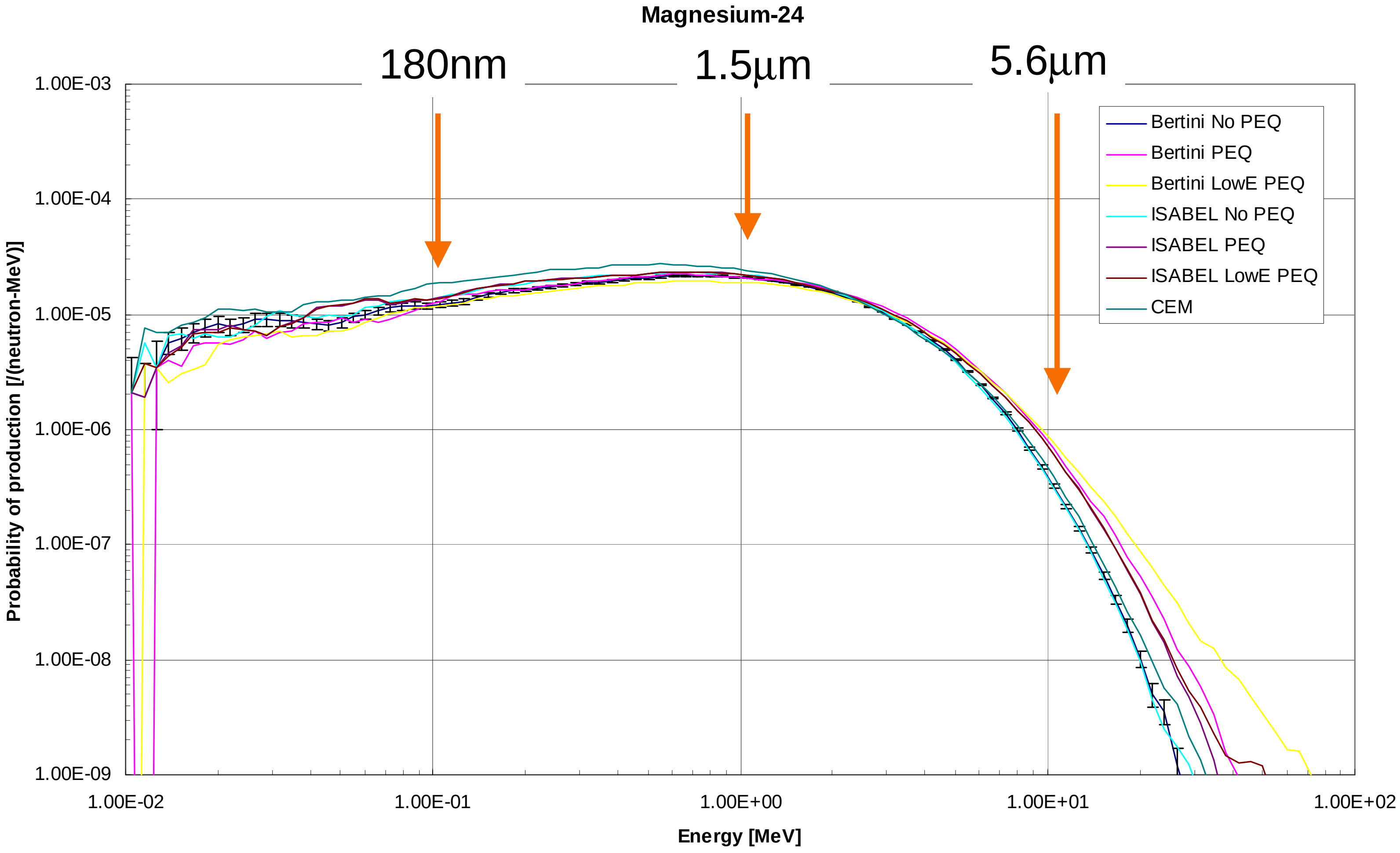
- Currently, the only accurate way to quantify device susceptibility is to use particle beam facilities
  - Expensive
  - Conditions for irradiation may not relate directly to operational conditions (bias, frequency, *etc*)
  - Does not lead directly to understanding of key physical processes driving effect

Most common models for SEE predictions rely on approximating device feature to parallelepiped, but still require experimental data

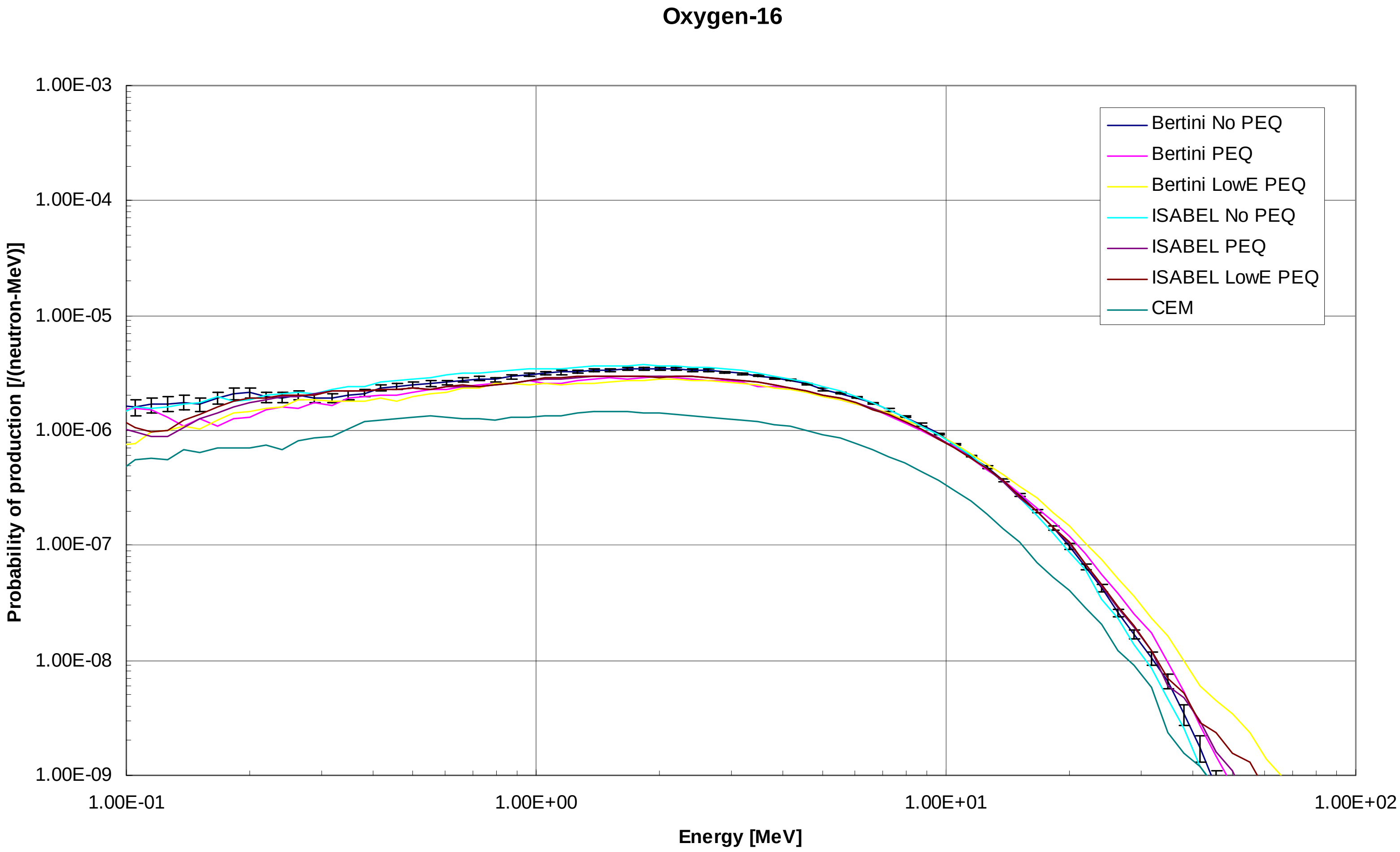
Application of Radiation Transport

- Initial work undertaken using:
  - MCNPX intranuclear cascade models to treat neutron-nuclear interaction
  - Ionisation from these nuclear events then treated using low-energy EM
- Extensive data-base of neutron-nuclear events built-up over 1 MeV to 10GeV for silicon and SiO_2
- Then we got G4BinaryCascade / G4ClassicalCascade ….

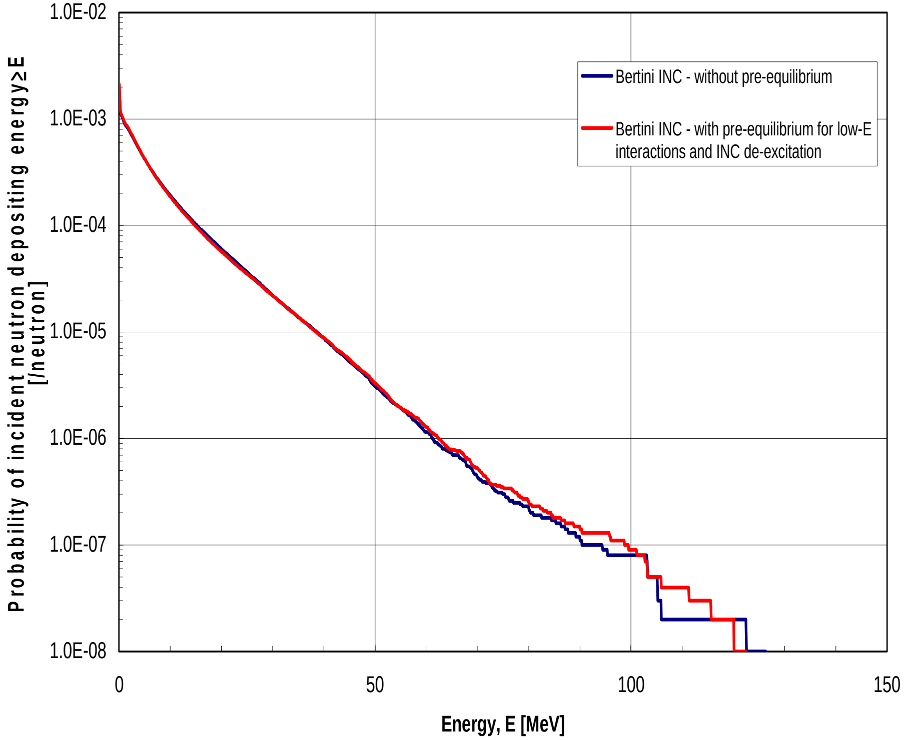
Results from MCNPX for ^{24}Mg energy spectrum from n-Si interactions



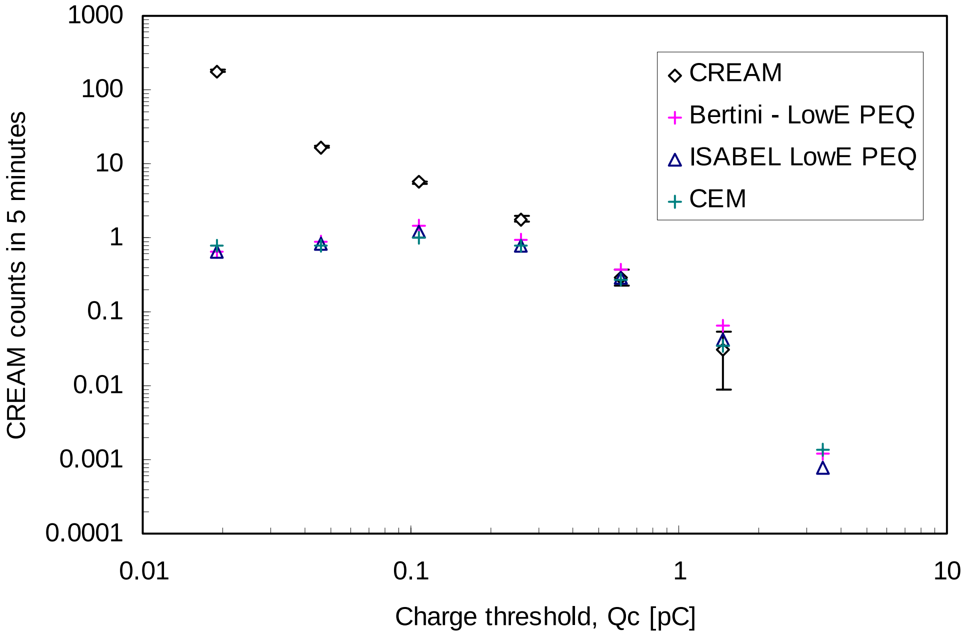
Results from MCNPX for ^{16}O energy spectrum from n-Si interactions



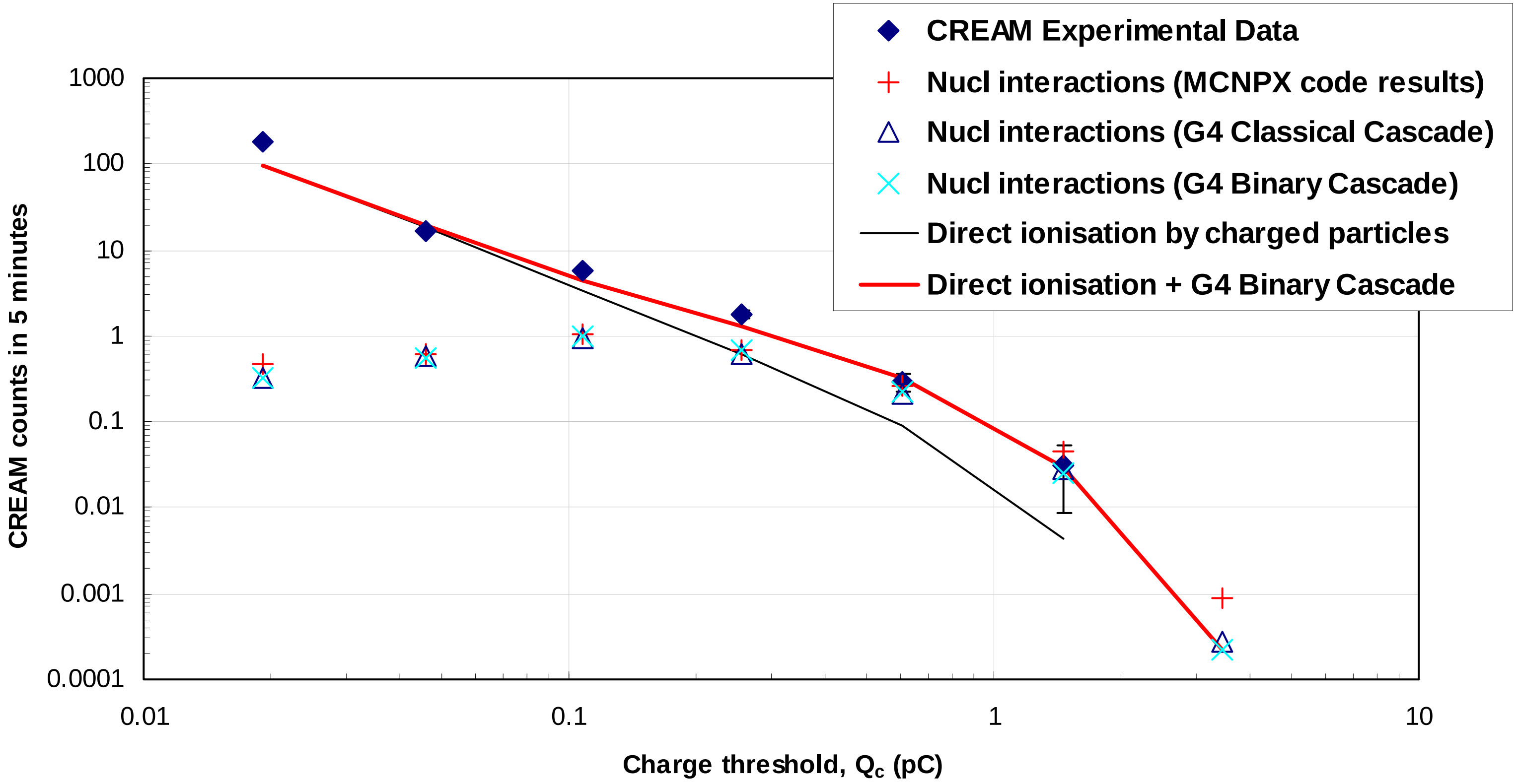
CREAM Boeing 767 Measurements vs Predictions (I)



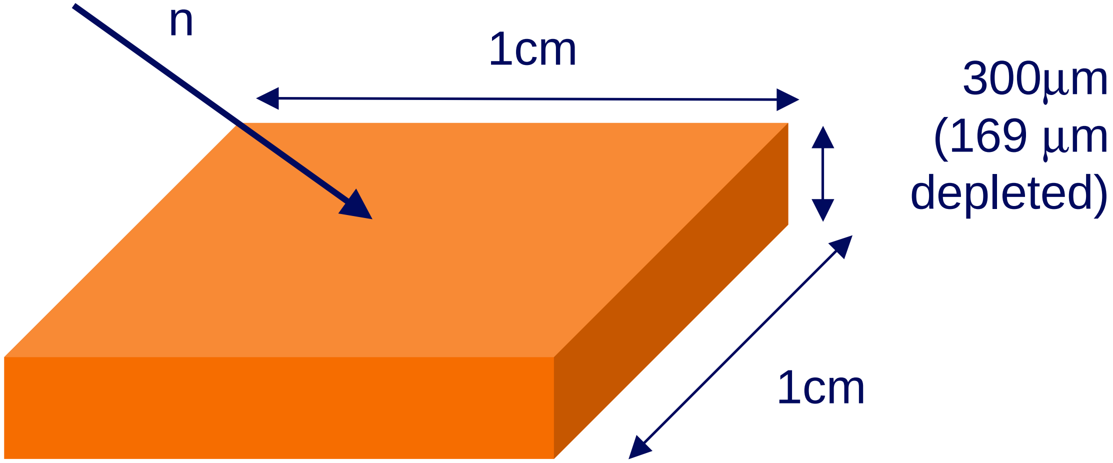
Is there a difference? Results from MCNPX for energy-deposition spectra shows surprising independence of model

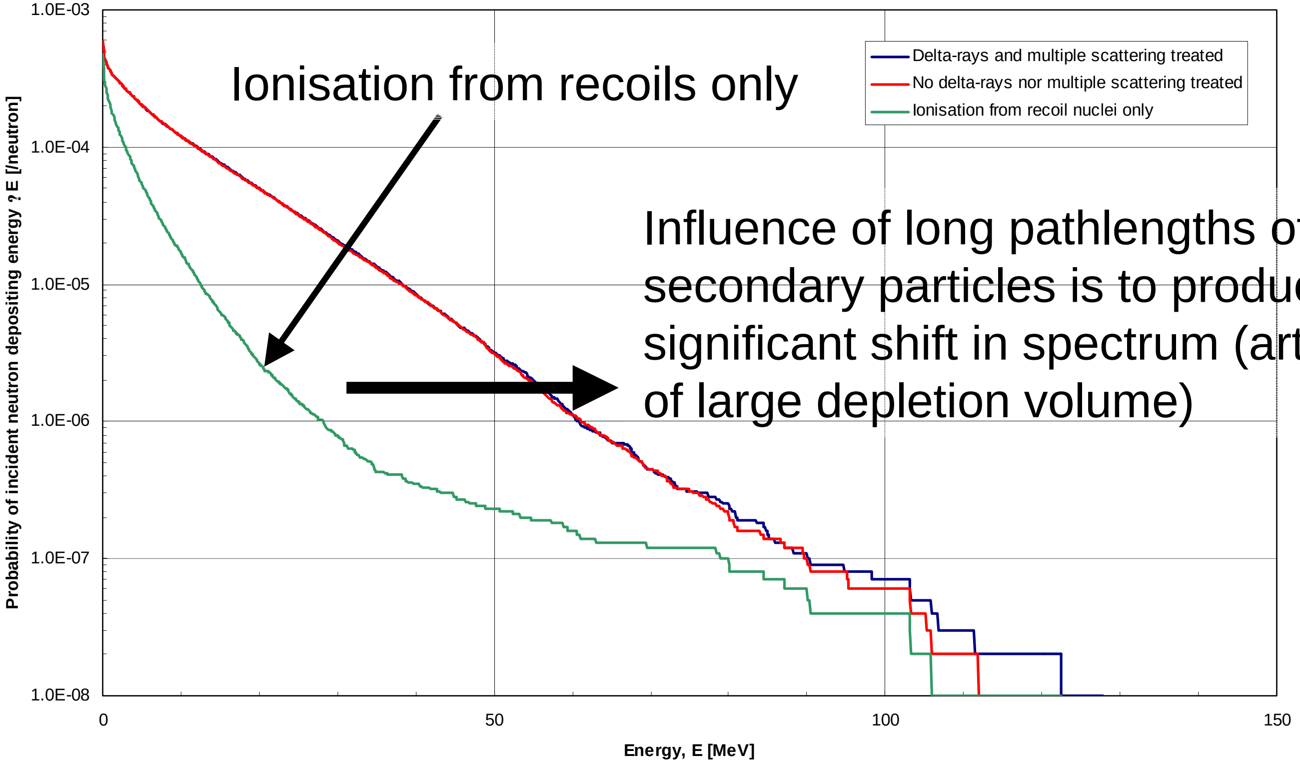


CREAM Boeing 767 Measurements vs Predictions (II)



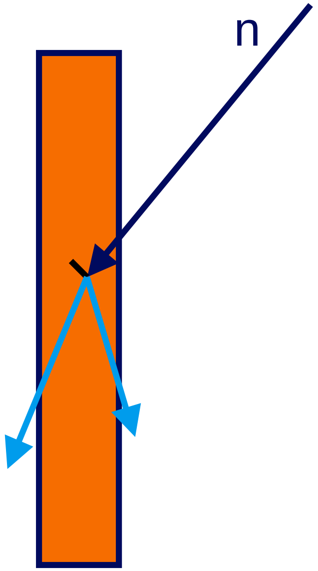
CREAM PIN diode chosen due to good, statistically accurate data from Concorde and Boeing 767 flights, simple geometry, and energy deposition spectra





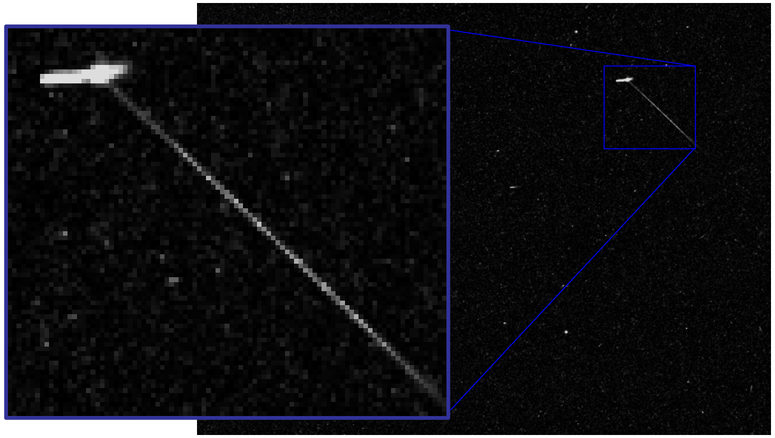
Ionisation from recoils only

Influence of long pathlengths of secondary particles is to produce significant shift in spectrum (artifact of large depletion volume)



CMOS Active Pixel Sensor

- APS with 5.4µm x 5.4 µm pixel interval
- Irradiated at TRIUMF with 63-352 MeV protons
- Initially results appeared anomalous until after correction for actual photo-diode area (~1/4 of “pixel” area) and calibration by pulse laser



CMOS Active Pixel Sensor

Energy	Experiment (provisional)	Geant4 Binary Cascade	MCNPX ISABEL
62.9 MeV	4.8×10^{-5}	5.5×10^{-5}	5.0×10^{-5}
105 MeV	4.9×10^{-5}	5.4×10^{-5}	
224 MeV	3.8×10^{-5}	4.8×10^{-5}	4.1×10^{-5}
352 MeV	3.6×10^{-5}	4.8×10^{-5}	4.1×10^{-5}

- Number of events in APS from nuclear interaction in Si or glass, per incident proton
- Note ~50% events from interactions in glass
- Mean track-lengths 40µm (measured) and 25-30 µm (model)

Categories of Device Simulator

- Finite element drift-diffusion & energy-balance, considered to accurately represent today's devices

  Slow
  - SILVACO ATLAS tools (S-PISCES and DEVICE-3D)
  - Synopsis (MEDICI and TAURUS codes)
  - ISE (DESSIS)
- Monte Carlo tools (not developed commercially)

  Slower
  - IBM DAMOCLES
- Quantum transport equation solutions

  Slowest?

Radiation Transport versus Device Modelling

Radiation transport	***vs***	**Device physics simulators**
Geant4 - Monte Carlo		Finite element (commercial)
10^5 nuclear events in hours		one event in several hours
Infer from many events at a boundary or in a volume		Must calculate quantities at point in space and time

- There is a basic incompatibility of the two modelling approaches
- One approach to resolving this issue is compromise device physics (ignore Poisson's eq to increase speed) and implement as MC
- Otherwise - DON'T TRY TO INTEGRATE THE TWO

Ion-Track Modelling

- Models such as SILVACO’s ATLAS incorporate a number of models to simulate ionisation track, but reliant upon user providing correct parameters:
  - Extension of physics for photo-current generation
  - Radial dependence:
    - Radial step-function
    - Constant e-h density up to user defined radius, then radial Gaussian or exponential fall-off
    - Power law up to user-defined radius, then zero
    - (Note that a better fit is usually considered to be power-law at low radii, then Gaussian at large radii)

Ion-Track Modelling

- e-h density dependence on path-length, l:

$$\rho(l) \propto \rho_1\left(a_1 + a_2 l + a_3 e^{a_4 l}\right) + \rho_2 b_1 (b_2 + b_3 l)^{b_4}$$

  - We are more use to expressions for dE/dx as a function of energy, as reported by Zeigler and ICRU
- Temporal dependence:
  - Gaussian
  - δ-function
- Constructing a distribution of particles representing nuclear interaction of a primary with recoiling nucleus and several secondaries + multiple scattering and ionisation losses is non-trivial

Ion-Track Modelling

- Several analytical models and fits to models available to determine the dose distribution around an ion track, integrated over the secondary electron spectrum
  - Based on the expression:

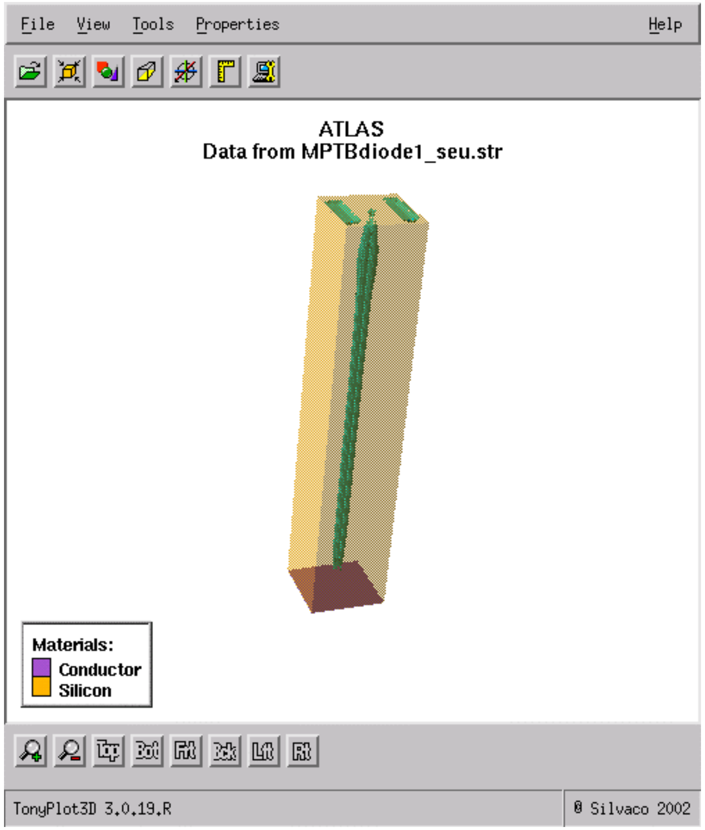
$$D = -\frac{1}{2\pi t}\sum_{i=1}^{j}\int_{w_i}^{\omega_m - I_i}\left[\frac{\partial W(t,w)}{\partial t}\eta(t,w) + W(t,w)\frac{\partial \eta(t,w)}{\partial t}\right]\frac{dn_i}{dw}dw$$

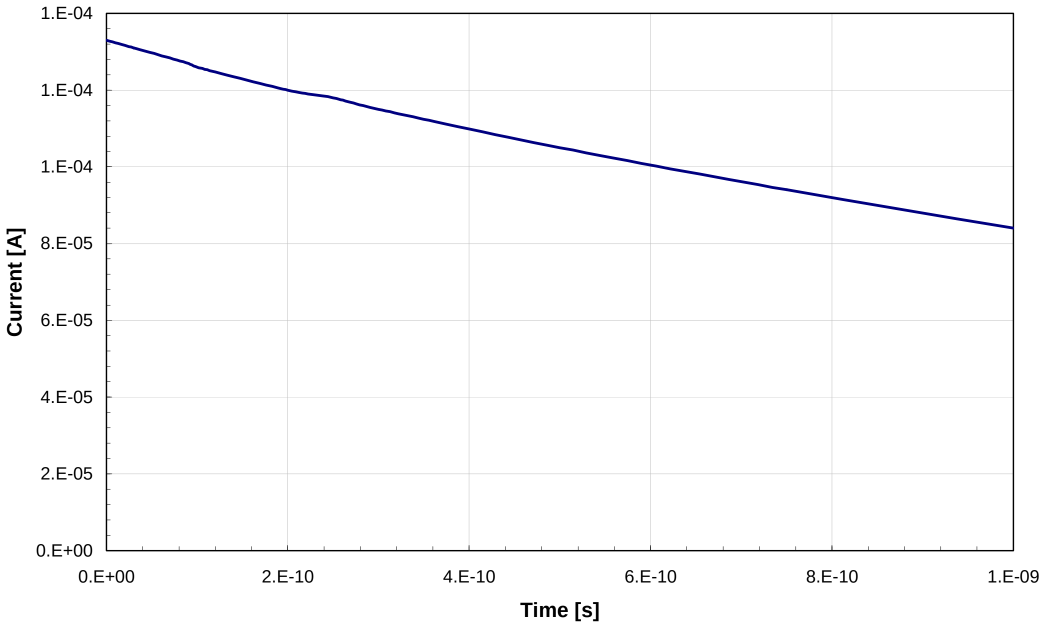
  - Original work undertaken by Kobetich and Katz, but many other algorithms & fits to data since then, with various merits

Ion-Track Modelling

- Obviously Geant4 produces 3D ion-tracks based on SOTA stopping power models and multiple scattering
- Geant4 can simulate ionisation of ions down to a few keV and electrons and photons to a few 100’s eV (this includes the production of δ-rays from ionisation)
- Use a mixture of both approaches to extrapolate the dose (and electron-hole production) from an Monte Carlo ion-track or nuclear interaction tracks to the required (x,y,z,t)
- Current model for e-h density from electron is crude (intend to improve this based on better expression of the δ-ray spectrum)

Simple α-particle interaction simulation to verify correct charge collection. α-particle energy 100 MeV, section of MPTB-type diode (500µm depletion depth)





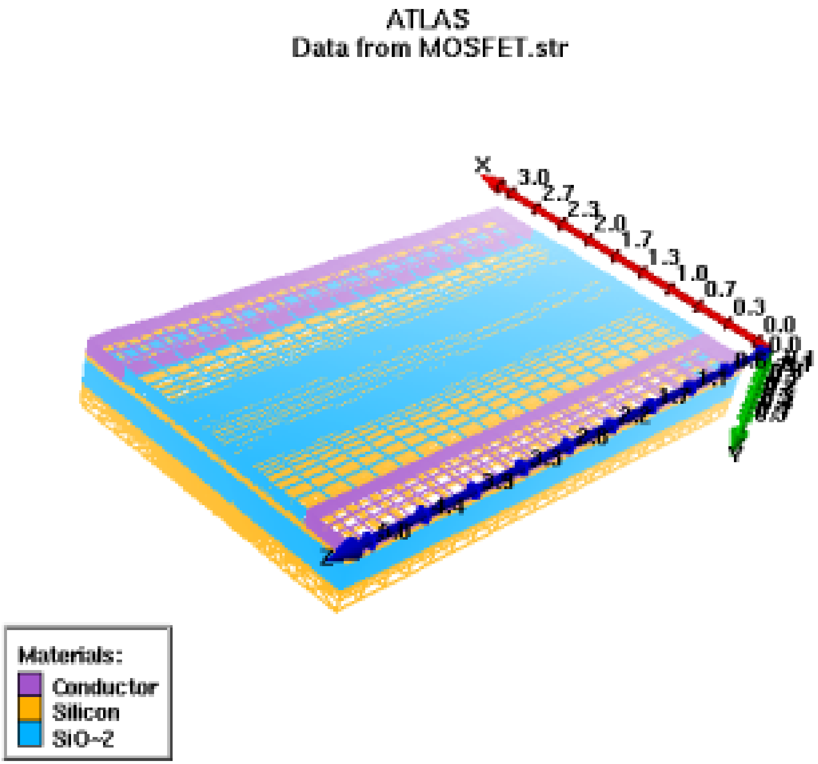
Integral of current = 0.31 pC
Expected charge generated = 0.37 pC

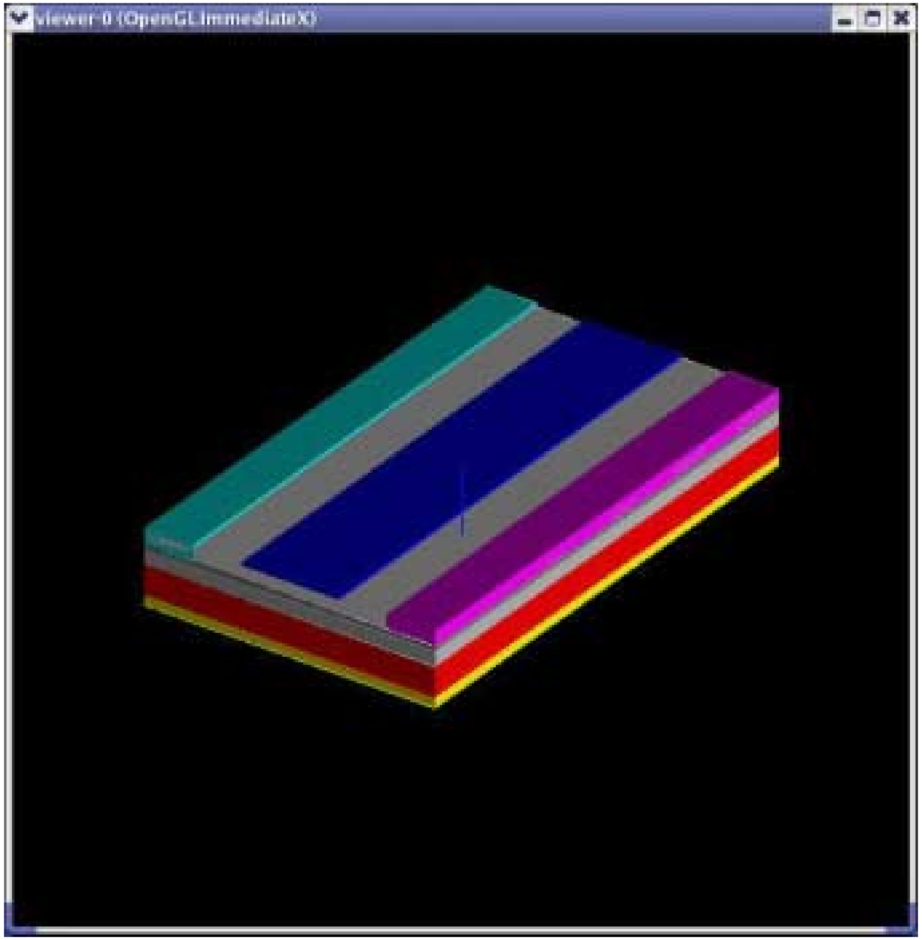
Geometry Input

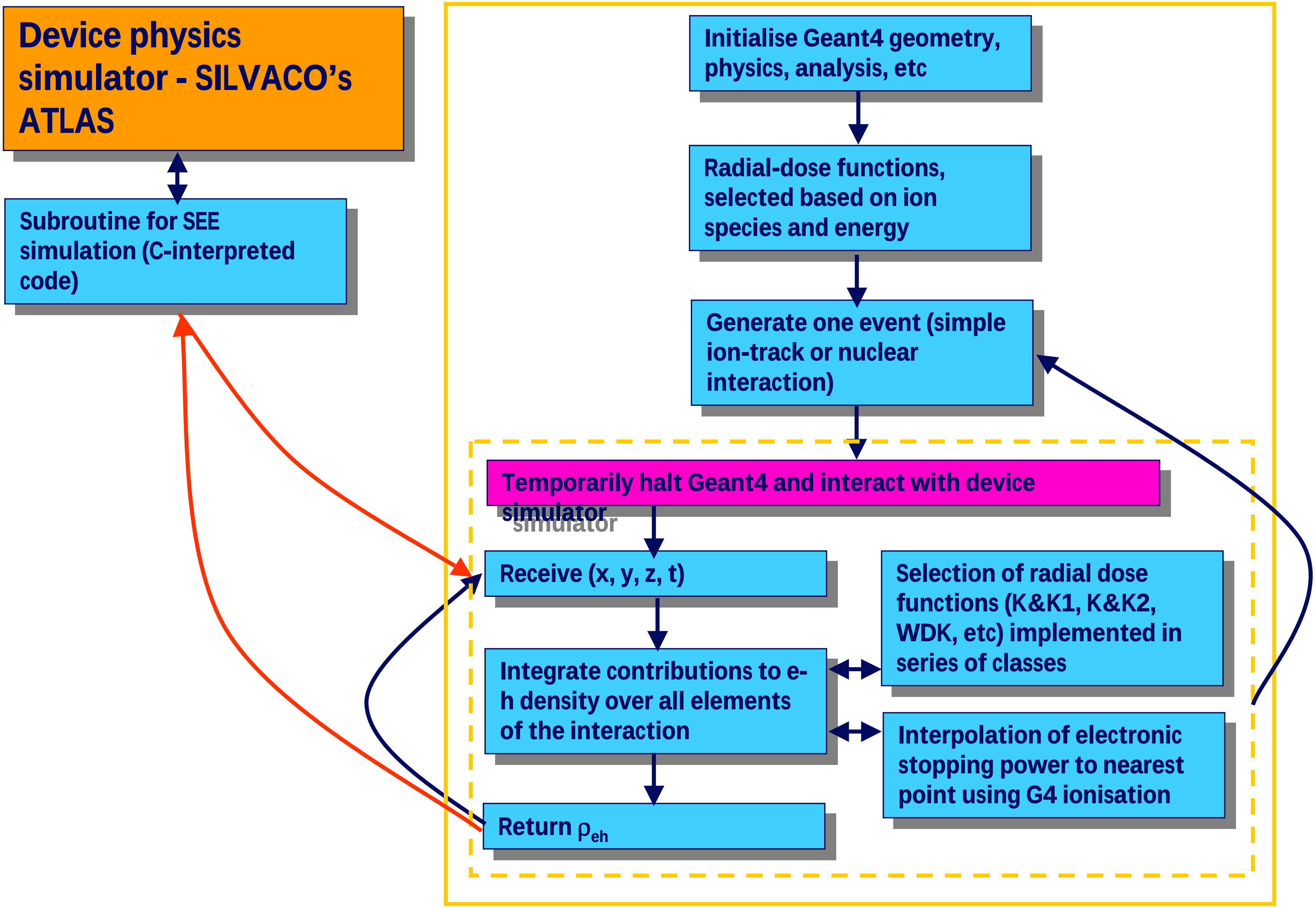
- Geometry input is in terms of mesh-file
- ATLAS-geometry interpreter established in Geant4
- Includes data-base of typical materials used for semiconductors

```
#
#  SECTION 1:  Mesh  Specification  for  simple  MOSFET
#
#
mesh  three.d  space.mult=1.0
#
x.mesh  location  =  0.0     spacing  =  0.25
x.mesh  location  =  1.15    spacing  =  0.02
x.mesh  location  =  1.5     spacing  =  0.05
x.mesh  location  =  1.85    spacing  =  0.02
x.mesh  location  =  3       spacing  =  0.25
#
y.mesh  location  =-0.12     spacing  =  0.025
y.mesh  location  =  0.00    spacing  =  0.025
y.mesh  location  =  0.025   spacing  =  0.2
y.mesh  location  =  0.05    spacing  =  0.005
y.mesh  location  =  0.3     spacing  =  0.01
y.mesh  location  =  0.5     spacing  =  0.1
#
z.mesh  location  =   0.0    spacing  =  0.25
z.mesh  location  =   5.0    spacing  =  0.25
#
#
#  SECTION 2:  Structure  Specification
#
region  num=1  y.min=-0.12  y.max=0.0   material=SiO2
region  num=2  y.min=0.0     y.max=0.05  material=Silicon
region  num=3  y.min=0.05    y.max=0.3   material=SiO2
region  num=4  y.min=0.3     y.max=0.5   material=Silicon
#
electrode  num=1  name=gate  x.min=1  x.max=2.0  y.min=-
0.15  y.max=-0.12  z.min=0.0  z.max=5.0
electrode  num=2  name=source  x.min=0.0  x.max=0.5
y.min=-0.15  y.max=0.0  z.min=0.0  z.max=5.0
electrode  num=3  name=drain  x.min=2.5  x.max=3.0
y.min=-0.15  y.max=0.0  z.min=0.0  z.max=5.0
electrode  num=4  name=substrate  bottom
#
doping       uniform  conc=1.75e17  p.type   reg=2
doping       gauss  n.type  conc=1e20  char=0.2
lat.char=0.05  reg=2  x.r=1.0
doping       gauss  n.type  conc=1e20  char=0.2
lat.char=0.05  reg=2  x.l=2.0
doping       uniform  conc=1e15  p.type  reg=4
```

Geometry Input







Device physics simulator - SILVACO's ATLAS

Subroutine for SEE simulation (C-interpreted code)

Initialise Geant4 geometry, physics, analysis, etc

Radial-dose functions, selected based on ion species and energy

Generate one event (simple ion-track or nuclear interaction)

Temporarily halt Geant4 and interact with device simulator

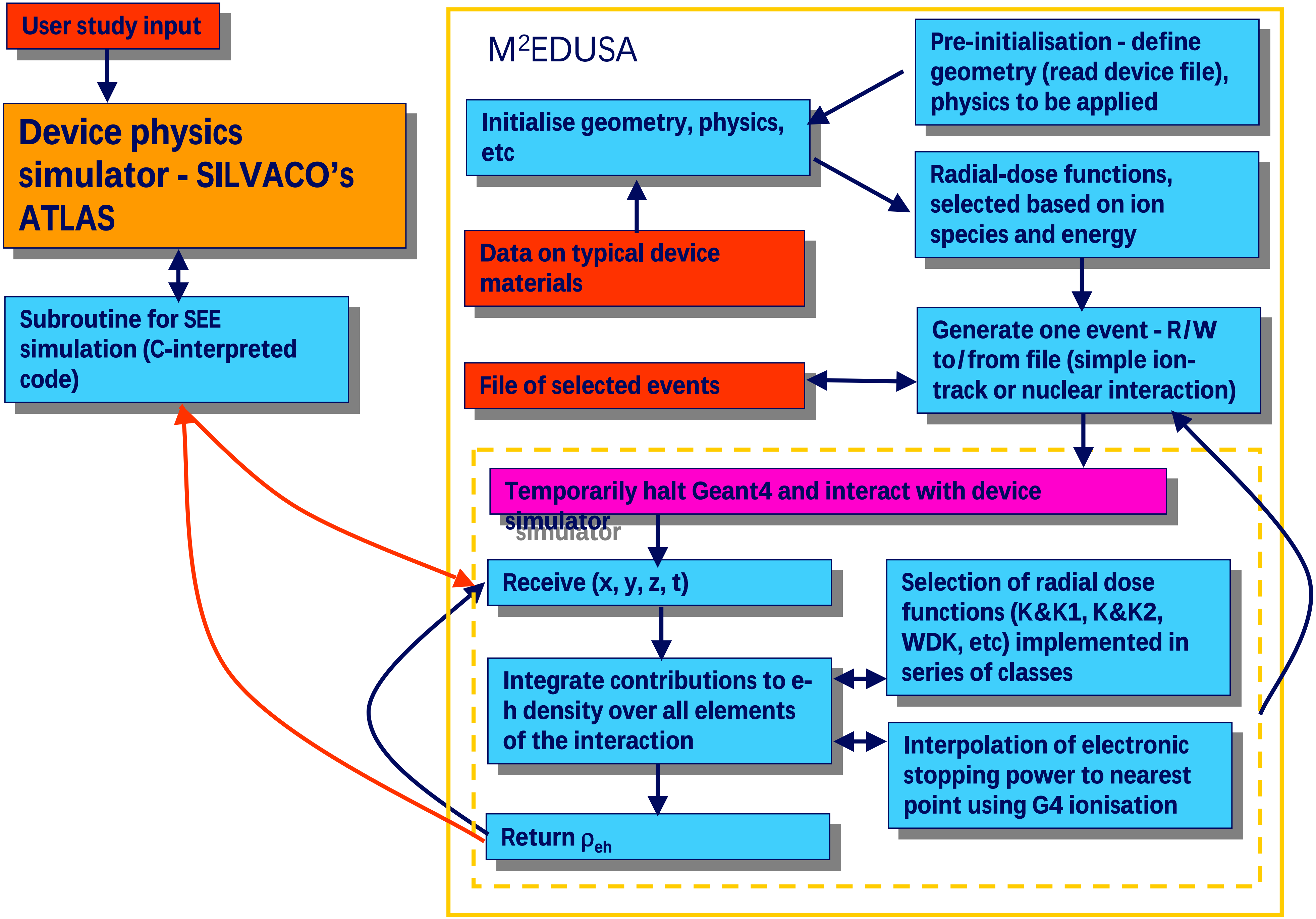
Receive (x, y, z, t)

Integrate contributions to e-h density over all elements of the interaction

Return ρ_{eh}

Selection of radial dose functions (K&K1, K&K2, WDK, etc) implemented in series of classes

Interpolation of electronic stopping power to nearest point using G4 ionisation



User study input

Device physics simulator - SILVACO’s ATLAS

Subroutine for SEE simulation (C-interpreted code)

M^{2}EDUSA

Pre-initialisation - define geometry (read device file), physics to be applied

Initialise geometry, physics, etc

Data on typical device materials

Radial-dose functions, selected based on ion species and energy

Generate one event - R/W to/from file (simple ion-track or nuclear interaction)

File of selected events

Temporarily halt Geant4 and interact with device simulator

simulator

Receive (x, y, z, t)

Selection of radial dose functions (K&K1, K&K2, WDK, etc) implemented in series of classes

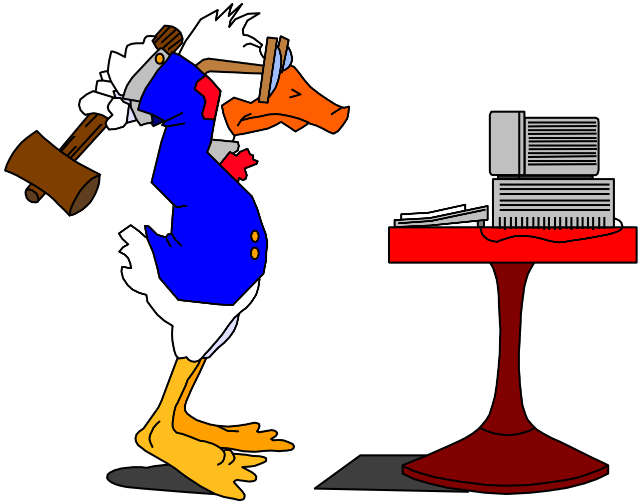
Integrate contributions to e-h density over all elements of the interaction

Interpolation of electronic stopping power to nearest point using G4 ionisation

Return ρ_{eh}

Beware of Trends with Device Feature Size

- Device simulation is the bottleneck in the process
- Solutions: Parallel processing ⇒ application on computer farm or grid computer systems, alternatives??



- Decrease in feature size compared with particle ranges could mean greater number of nodes required for finite element model ($N \propto f_{old}/f_{new} \rightarrow f_{old}^2/f_{new}^2$) ; execution time scales as O($N^{1.5}$); computer speeds scale as f_{old}/f_{new}

Therefore, rather than improving execution times, we may find Moore's law working against us

Conclusions

- Much of the physics to perform detailed single-event simulations are in place
  - High-energy nuclear interactions
  - Electromagnetic interaction, with δ-ray production down to 100eV
- For the applications considered so far, Binary Cascade with Low-E EM is in reasonably good agreement with experiment (10-25% for APS data), although MCNPX/ISABEL appears better
- By-product of these studies has been data-bases for neutron-nuclear interactions of atmospheric neutrons in silicon, silicon oxide, etc

Conclusions

- Decision taken to use commercial device physics simulators - probably the least challenging approach!
- Classes implemented to extrapolate e-h density from Monte Carlo tracks
  - Hybrid between MC and analytical
  - May not be essential for large device feature sizes, but investment for future
  - More accurate treatment of ionisation tracks than previous models
  - Seamless treatment of Geant4 nuclear/ionisation interaction events
  - Further improvements in radial-dose models to be implemented
- M^{2}EDUSA framework established interfacing Geant4 with SILVACO’s ATLAS simulator

Conclusions

- Includes an interpreter-class in Geant4 to allow it to read geometry defined in ATLAS input file
  - Note that the similarity of commercial simulators means a similar approach could be taken for other device physics models
- Preliminary applications at O(100µm) - next need to apply to µm and sub-µm scales
- Remaining challenges are significant, but I don’t believe insurmountable
  - Trends with device feature-sizes means that eventual will need to move away from finite element models for device physics
  - Even for current commercial device models significant differences in simulation speeds … is this going to get worse?

Backup slides

Objective

- Develop modelling capability to simulate high-energy interaction processes, charge production, and semiconductor device response
- In doing so:
  - Reduce the reliance on repeated recourse to experiments to determine device susceptibility
  - Enable better understanding of dominant physical processes driving observed effects
- Provide an ***engineering tool*** to assist in cost-effective selection of current/future components for aerospace and general safety-critical projects

Relevance of physics to future systems

- As device feature sizes shrink, drift-diffusion becomes inaccurate, therefore use energy-balance to treat velocity overshoot of electrons
- Finite element solutions should remain accurate, perhaps for 10 years, if “patched-up” using Monte Carlo results