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Radiation Transport Tools for Space Applications: A Review

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Mission Environments Group
February 16, 2008

5th Geant4 Space Users' Workshop

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Introduction

- A brief discussion of nuclear transport codes widely used in the space radiation community for shielding and scientific analyses:
 - Overview
 - What it can do
 - What it can not do
 - One or two examples of application

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Radiation Environments:

Particles that should be considered

- Electrons
 - Trapped, solar wind
- Photons
 - Bremsstrahlung, Reactor, RTG, RHU
- Protons
 - Trapped, Solar Energetic Particle Events, GCR
- Heavy Ions
 - GCR, Solar Energetic Particle Events
- Neutrons
 - Reactor, RTG, RHU

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Primary Use of Radiation Transport Codes

- Total ionizing dose
 - Cumulative long term ionizing damage
- Displacement damage dose
 - Cumulative long term non-ionizing damage
- Single event effects
 - Event caused by a single charged particle (heavy ions and/or protons) traversing the active volume of microelectronic devices
 - Deep charging
- Particle detector simulation
- Device Simulation

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National Aeronautics and Space Administration Ames Research Center California Institute of Technology Radiation Transport Codes that will be Covered in this talk

- CREME96
- TRIM
- Integrated Tiger Series (ITS) 3.0
- NOVICE
- MCNP
- MCNPX
- Geant4

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General Methods

Monte Carlo Method	Deterministic Method
<ul style="list-style-type: none"> • Does not solve explicit transport equation • Obtain answers by simulating individual particles and recording their average behavior 	<ul style="list-style-type: none"> • Solve transport equation for average particle behavior
<ul style="list-style-type: none"> • Pros: <ul style="list-style-type: none"> – Can handle complex geometries – Can handle physically accurate cross sections • Cons: <ul style="list-style-type: none"> – Slow – Results are statistical – Not efficient for deep penetration problems and for space applications 	<ul style="list-style-type: none"> • Pros: <ul style="list-style-type: none"> – Can obtain results throughout problem geometry in one run – Relatively fast even for deep penetration problem • Cons: <ul style="list-style-type: none"> – Systematic errors result from discretization of phase space (space, energy, angle) – Only works for geometries for which transport equations can be solved numerically – Must use multi-group cross sections; thus results in inherently less accurate results
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National Aeronautics and Space Administration Jet Propulsion Laboratory California Institute of Technology Monte Carlo Methods

- Forward vs. Adjoint methods
 - Forward: follows particles from source to target
 - Adjoint: follows particles from target to source
 - When are forward calculations more efficient?
 - When we require a large number of responses across the problem geometry from a source confined in relatively small volume
 - When are adjoint calculations more efficient?
 - When we require responses over the small volume from a source distributed over large volume or surface

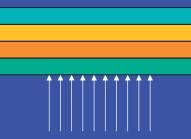
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Forward vs. Adjoint (1)

- We want to compute energy deposition at each slab (different material) from mono-directional particle source.



The forward method is more favorable in this situation because every particles simulated will contribute to the results for all 4 slabs.

If we use the adjoint method, this problem implies we have to run 4 separate runs.

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Forward vs. Adjoint (2)

We want to compute energy deposition at the small target region located at the center of spherical shell shield.

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Target region

Shielding medium

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Preview

	Electron	Photon	Proton	Neutron	Ion ($Z \geq 2$)
CREME96			Yes		Yes
TRIM			Yes		Yes
ITS	Yes	Yes			
NOVICE	Yes	Yes	Yes		Yes
MCNP	Yes	Yes		Yes	
MCNPX	Yes	Yes	Yes	Yes	Up to $Z=2$
Geant4	Yes	Yes	Yes	Yes	Yes

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CREME96 LET Spectra for ISS LTM/PF for different aluminum shielding thicknesses

500 km/51.5 degree Solar Minimum

LET, MeV-cm²/mg

Differential Flux (m⁻² sec⁻¹ sr⁻¹)

Energy (MeV)

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CREME96 Proton Diff. Spectra for different aluminum thicknesses

Differential Flux (m⁻² sec⁻¹ sr⁻¹)

Energy (MeV)

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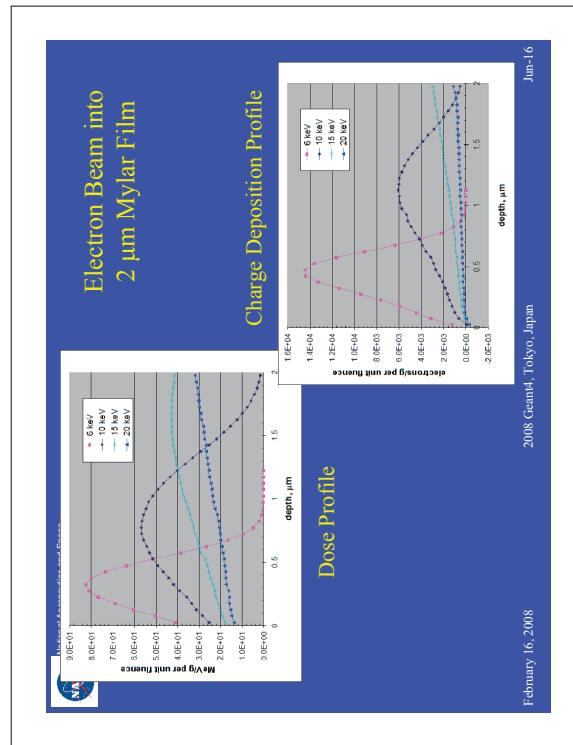
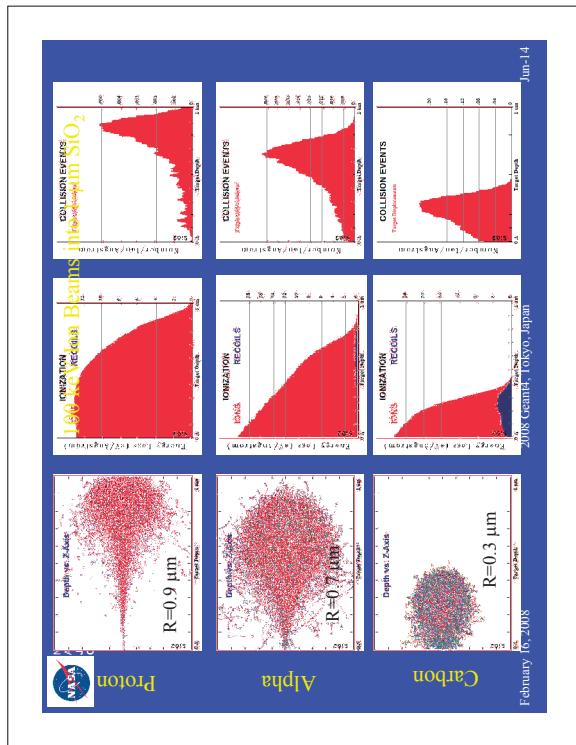
CREME96: <https://creme96.nrl.navy.mil>

- Developed by Naval Research Lab (NRL)
- TRANS module
- 1-Dimension for aluminum
- Particles: All particles treated in CREME96 (protons and heavy ions)
- Primary application at JPL:
 - Proton energy spectrum or heavy ion LET spectrum for SEE evaluation of microelectronics
- Pros:
 - Easy web-based user interface
 - Simple physics models for energy loss and nuclear fragmentation
- Cons:
 - Limited to aluminum shielding and 1-dimensional
 - Is the physics accurate?

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NOVICE: tj@cnpc.com

- Monte Carlo (adjoint)
 - Specifically developed for space applications
 - Only adjoint code available for charged particle transport
- 3-Dimension
- Primary application at JPL:
 - Component level analysis with full spacecraft geometry
 - Routine TID/DDD calculations
- Particles:
 - Electrons, protons, photons, heavy ions
- Pros:
 - Fast
 - Versatile geometry, relatively easy to use
- Cons:
 - Neutrons, secondary particles?
 - User manual

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MER

HazCam

Small device in a box

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Los Alamos National Laboratory

MCNP: <http://mcnp-green.lanl.gov/index.html>

- Developed by Los Alamos National Lab (LANL)
- Monte Carlo (mostly forward)
- 3-Dimensional
- Particles:
 - Neutron, photons, and electrons
- Pros:
 - Primary application at JPL:
 - Neutron/photon transport for RTG and space reactor
 - Extensive history (since the Manhattan Project) and user base
 - Comprehensive physics
- Cons:
 - Versatile geometry and input/output options
 - Relatively difficult to learn
 - Slow for space applications

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Assessing the present and past habitability of Mars

1 MeV Et. Neutron Fluence Level for 1-Year Operation

1 MeV Et. 1-Year Operation

Neutron Displacement Damage, 25 cm grid

RDF=1

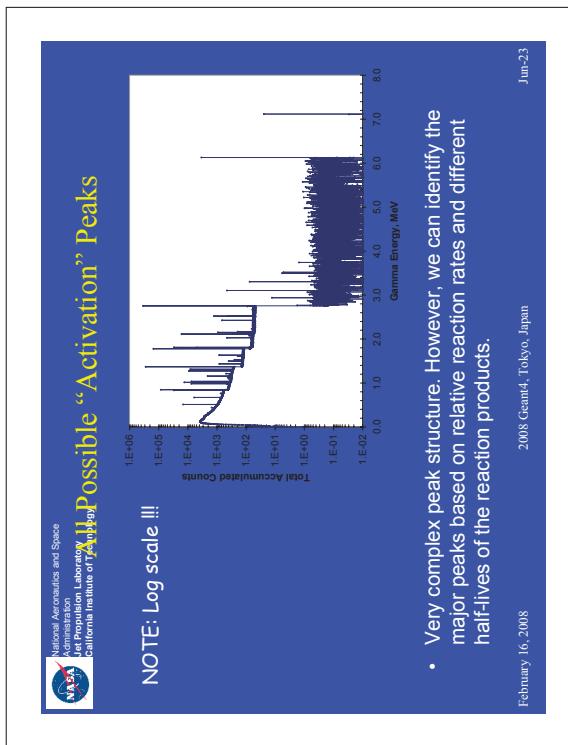
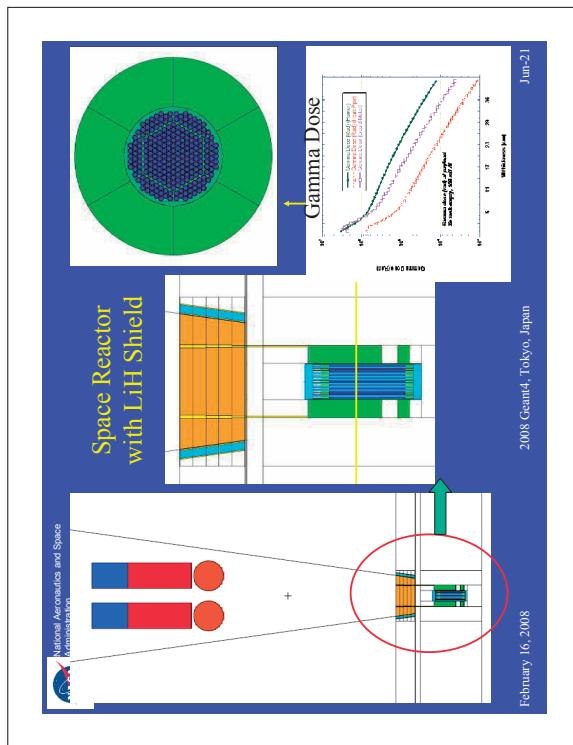
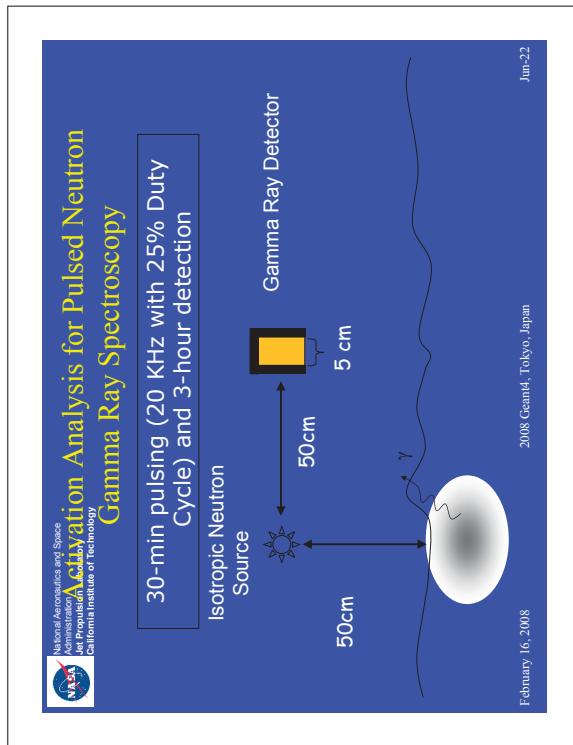
Red/Sy=1

Gamma Dose in Silicon, 25 cm grid

Axial distance from the center of the RTG

Radius

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MCNPX (continues)

- Primary application at JPL:
 - Proton transport where secondary particle generation is important
 - Detector simulation
- Pros:
 - Charged particle capability
 - Capability of treating secondary particle generation
 - Extensive high energy physics
 - Versatile geometry and input/output options
 - Visual output
- Cons:
 - Relatively difficult to learn
 - Does not transport secondary particles (e.g., delta-rays)
 - Slow for space applications

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MCNPX (continues)

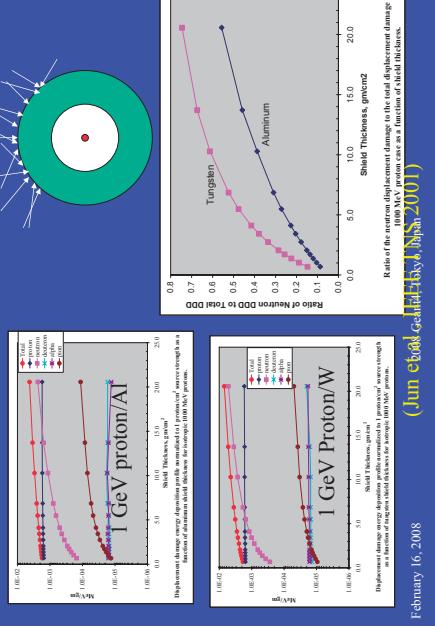


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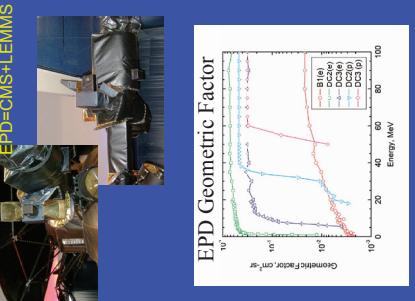
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Ratio of Displacement Damage Dose due to Secondary Particles Computed by MCNPX



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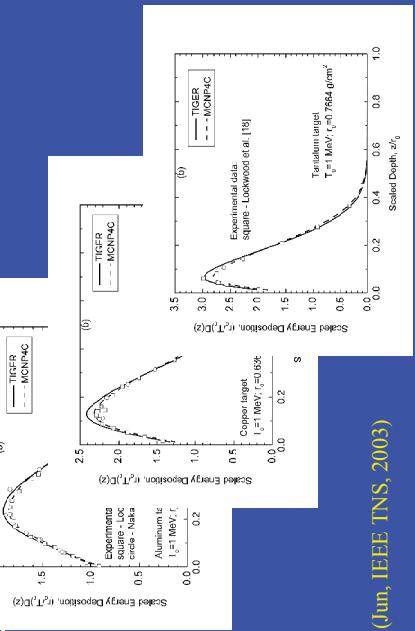
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Jun 27

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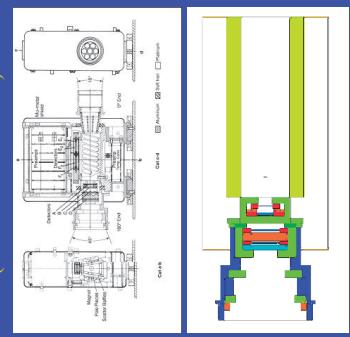
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**EPD-CMS+LEMMS
(LEMMS shown here)**



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Device Simulation – Extreme Events

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Source: 1GeV proton
Number of source particles simulated:
1,000,000
Number of secondary electrons ($1 \mu\text{m}^3$): 9,399

Secondary electron tracks simulated by
Geant4 (1 GeV proton incident from the
left)

Number of secondary electrons
Energy Bin, KeV (Upper Bound)

Energy Bin, KeV (Upper Bound)

Distribution of secondary electrons' energy. Secondary electrons from
extreme events are shown in the right panel.

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Carneio Heavy Ion Counter (HIC)

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HIC is composed of two solid-state
detectors called Low Energy
Telescopes (LETs): LET B and
LET E.

- The LETs are standard dE/dx
versus residual energy instrument
using a series of solid state
detectors to make measurements
over a broad energy range.
- Particle species are discriminated
by using energies deposited in each
detector.

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Device Simulation – Extreme Events

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- Developed by CERN
Monte Carlo (forward)
- 3-Dimension
Particles:
 - All particles relevant to space environment
 - Primary application at JPL:
 - Detector simulation
 - SEU simulation with TCAD
- Pros:
 - Charged particle capability including heavy ions
 - Ability of secondary particle transport
 - Extensive high energy physics
 - Versatile geometry and input/output options
 - Visual output
 - Extensive, and growing space user-base
- Cons:
 - Very difficult to learn
 - Slow for space applications
 - No error bar of results

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Device Simulation – Extreme Events

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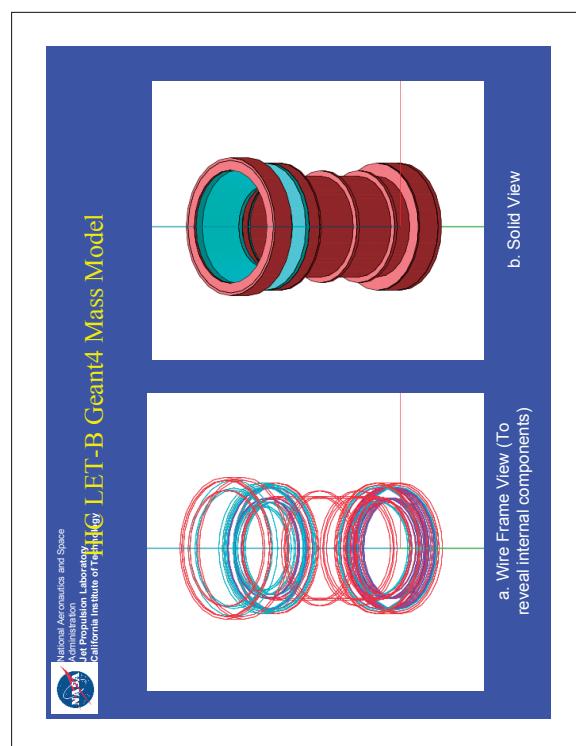
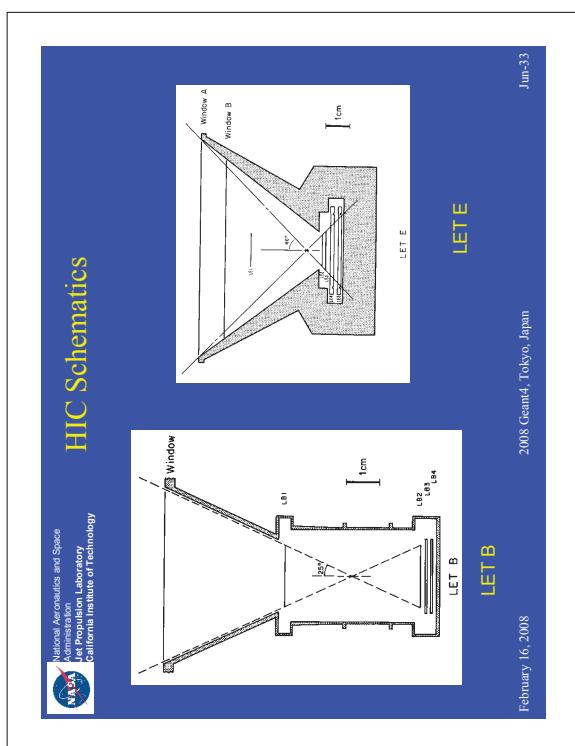
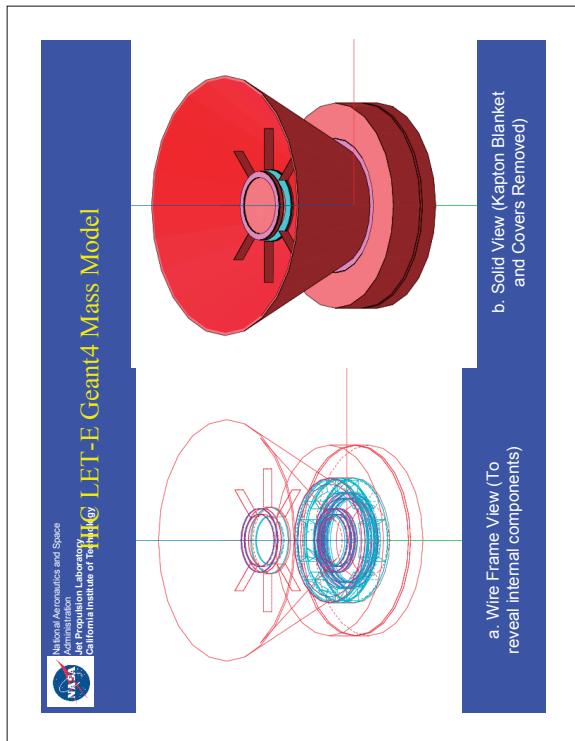
Transient current due to primary proton and
secondary electron simulated by TCAD using
the LET track information from Geant4,
On A Mesh

Linear energy transfer (LET) of a
secondary electron track was
modeled in this silicon diode block.
(Drift-Diffusion Equations Solved
On A Mesh)

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Summary			
National Aeronautics and Space Administration Ames Research Center Astrophysics Laboratory California Institute of Technology	CREME96	Primary Application	Particles
	1-D	Single Event Effects	Proton and all heavy ions
TRIM	1-D	Beam Simulation for dose and damage profile	Proton and all heavy ions (Coulomb only)
ITS	3-D	Beam simulation for dose and charging profile (TIGER)	Electron and photon
NOVICE	3-D	Component level analysis with complex spacecraft geometry	Electron, photons, and heavy ions
MCNP	3-D	RTG and space reactor simulation	Neutron, photon, and electron
MCNPX	3-D	Secondary particle simulation, science instrument simulation	>2000 particles
Geant4	3-D	Secondary particle simulation, science instrument simulation, device simulation	All particles relevant to space environment

Conclusion	
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• A careful code selection for a specific situation is required for the correct answer.	
– Some of the codes may be easy to learn and run, but may need correct interpretation of output.	
• My personal view of what we need to do in the future:	
– To develop an adjoint Monte Carlo code	February 16, 2008
– To expand to lower ($< 1 \text{ keV}$) energy	2008 Geant4, Tokyo, Japan
• Radiation transport codes not covered today:	Jun 37
– EGS4, CEPXS, HZETRN, SpaceRad, PENELOPE, FLUKA, MARS, PHITS.....	Jun 38