Silicon-Germanium (SiGe) Technology for Low Temperature Environments for Europa and Enceladus Missions

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Outline of topics

- Overview of environmental conditions at the targeted sites (Europa and Enceladus).
- SiGe technology for implementation of electronics for extreme environments.
- What do simulation models tell us about the radiation environments of Europa and Enceladus ?
- Validation and testing of avionics for such environments
- Testing the radiation effects on SiGe electronics at low temperatures
- Summary and description of work-in-progress.

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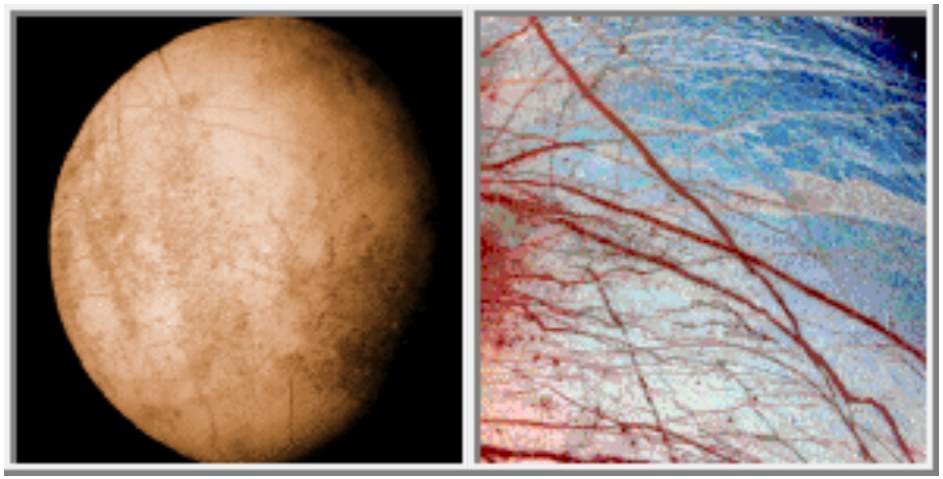
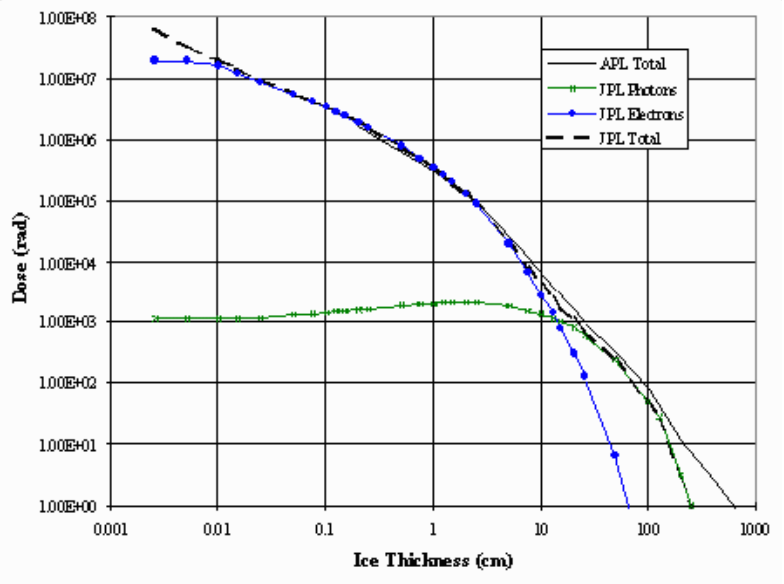
Overview of Environmental Conditions on Europa

Europa Geophysical Explorer has been designated by the Decadal Study as the highest priority flagship mission for planetary exploration, other than Mars.
NASA is currently conducting a study for a Europa Orbiter mission,



Credits: NASA



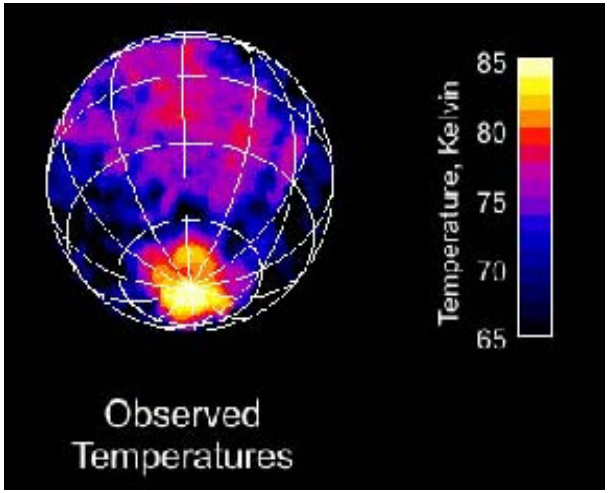
<u>High radiation environment</u> at surface of Europa: 20 Mrad per month at the surface; dropping to 10-cm depth in europan ice is ~5 krad per month. The radiation dose is dominated by electrons and bremsstrahlung over depth values down to approximately 1 meter, below which protons dominate. http://www7.nationalacademies.org/ssb/europach2.html

<u>Low Surface Temperature</u>, varying from a low of 50 to 125 Kelvin, with a mean of about 100 Kelvin

Overview of Environmental Conditions on Enceladus

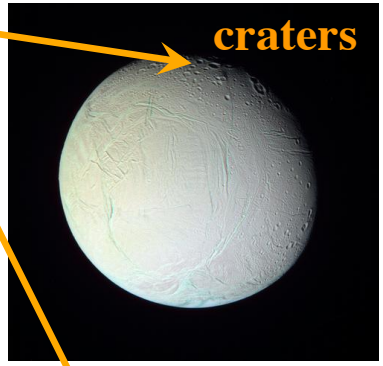
Temperatures in the areas of interest go as low as 65 deg. K (South Pole Tiger Stripes, geological features away from the pole)

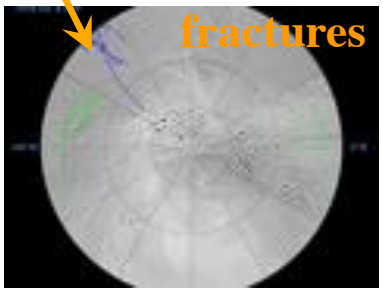
Narrow angle camera images
http://saturn.jpl.nasa.gov



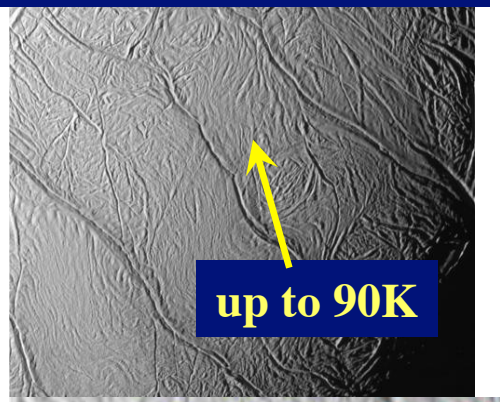
Enceladus temperature map IR spectrometer data from the Cassini 3-rd flyby
NASA/JPL/GSFC
www.nasa.gov/mission_pages/cassini

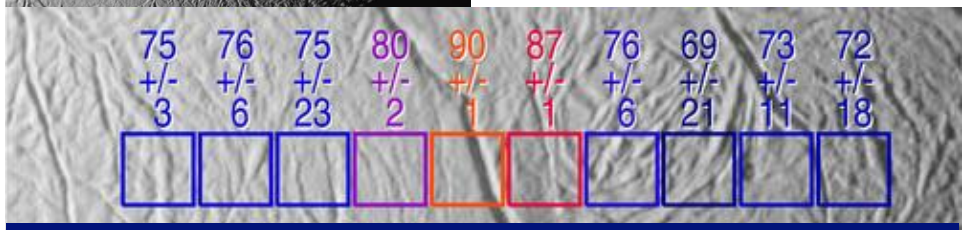
Older features away from the South Pole





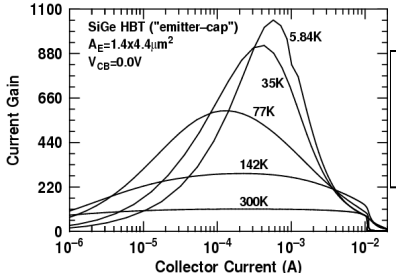
Tiger stripes at South Poles



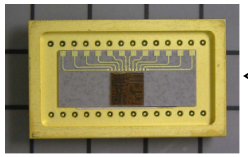


Temperature readings superimposed on narrow angle camera image - http://saturn.jpl.nasa.gov

Silicon-Germanium (SiGe) Integrated Electronics for Extreme Environments

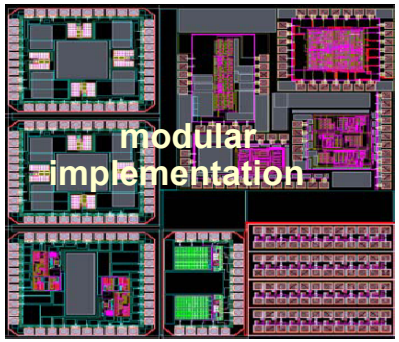


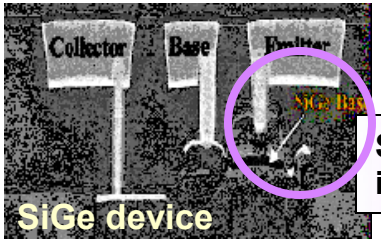
SiGe transistor demonstrated to operate at 5.8 degK



System on a chip

SiGe REU





SiGe transistor is intrinsically RadHard

Silicon-Germanium Electronics for Extreme Environments funded by NASA under the RHESE program.
Managed by NASA MSFC
Dr. M. Watson / Dr. A. Keys

Rationale: There is a 4% difference in the lattice constants of Si and Ge; and so if one is grown on the other, the layer is strained. This strain may be used to vary the semiconductor properties of SiGe (ex: bandgap energy) resulting in a versatile material which is low-cost and compatible with standard Si manufacturing processes.

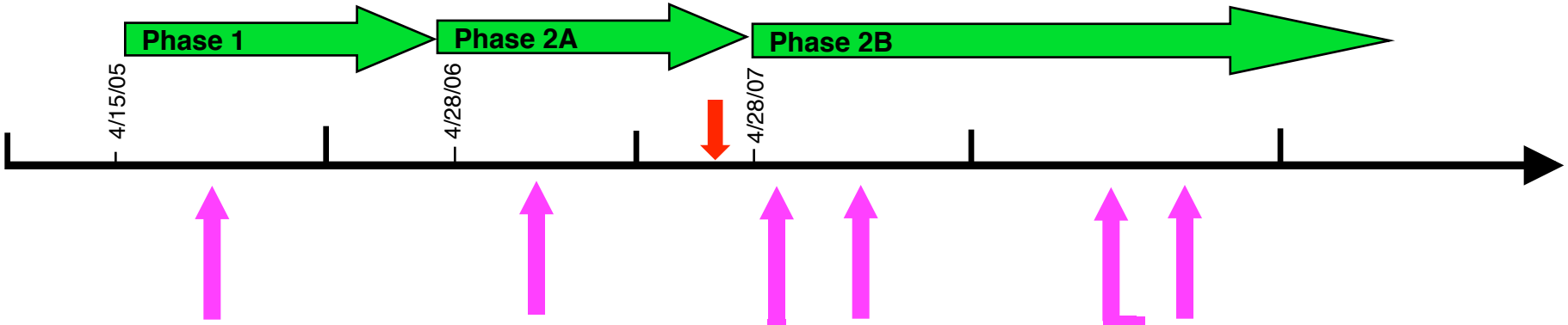
Objective: Develop and demonstrate SiGe Electronics for Extreme Environments for distributed architecture for Moon and Mars.

SiGe REU is a System-on-a-Chip that can operate at 43K without heaters. Also, SiGe HBTs are intrinsically Rad-Hard for TID.

Applications:
- distributed sensor and IVHM modules.
- adaptive control for MAGGI motors and actuators.
- penetrators.

Addressing the Technological Challenges through Design, Implementation And Validation Tests

device physics; circuit design and modeling; fabrication; packaging; environmental effects; reliability; physics of failure; environmental testing



CRYO-1
- proof of concept
- V references
- op amps
- DAC
- VGA
- HV device
- digital blocks
- test structures
- modeling
- MUXs

CRYO-2
- refined CRYO-1
- 2 ADCs
- more op amps
- drivers
- T sensors
- bus interface
- refined modeling
- radiation evaluation
- low power variants
- ramp generator
- REU components

CRYO-3
- refined CRYO-2
- REU paths
- more digital
- more sensors
- actuation
- RF blocks
- bus interfaces
- RHBD evaluation
- low power ckts

CRYO-4
- refined CRYO-3
- REU-on-a-chip(s)
- library enhancements
- RHBD enhancements
- modeling enhancements
- low power variants

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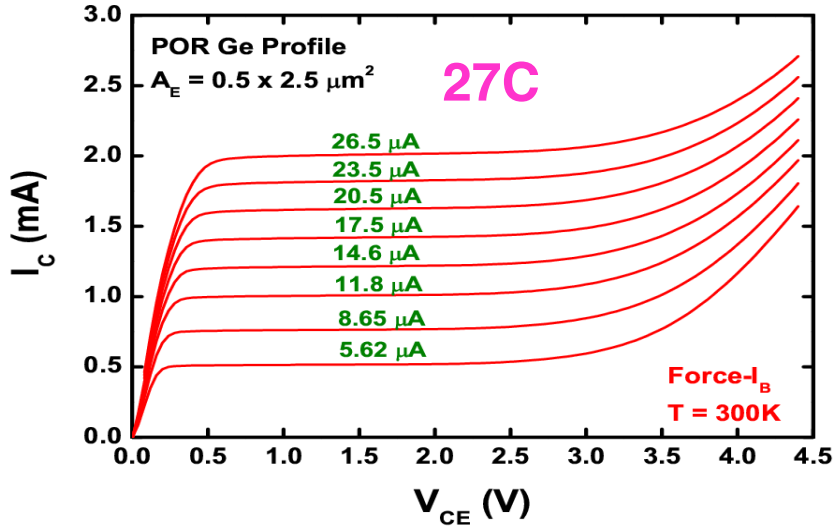
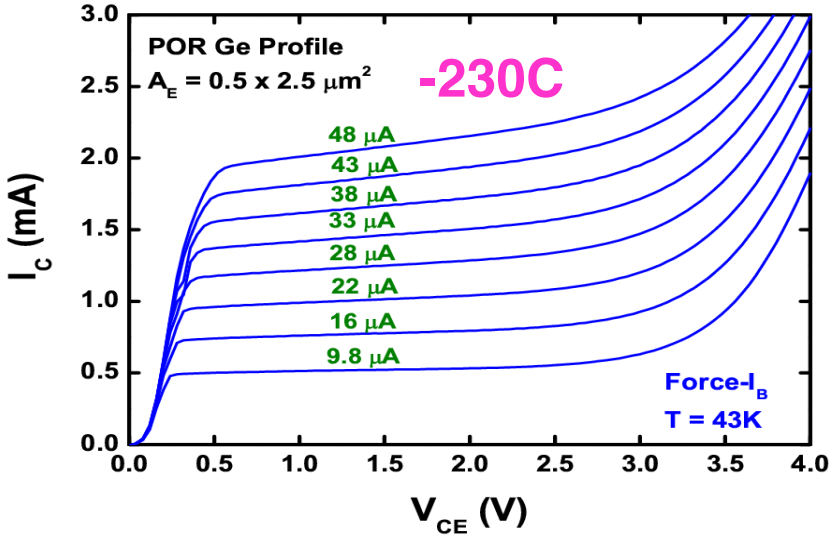
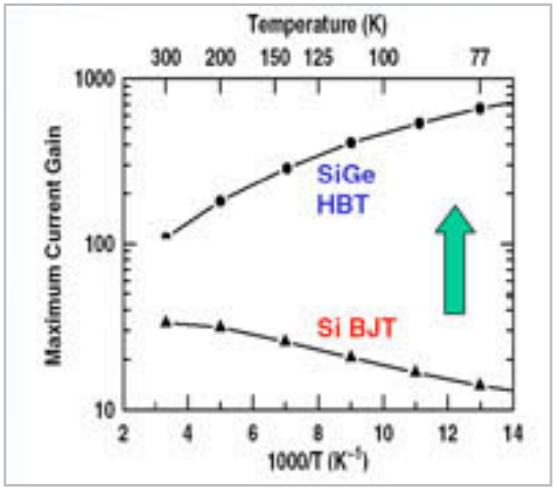
Silicon-Germanium (SiGe) Devices Operate Well at Low Temperatures





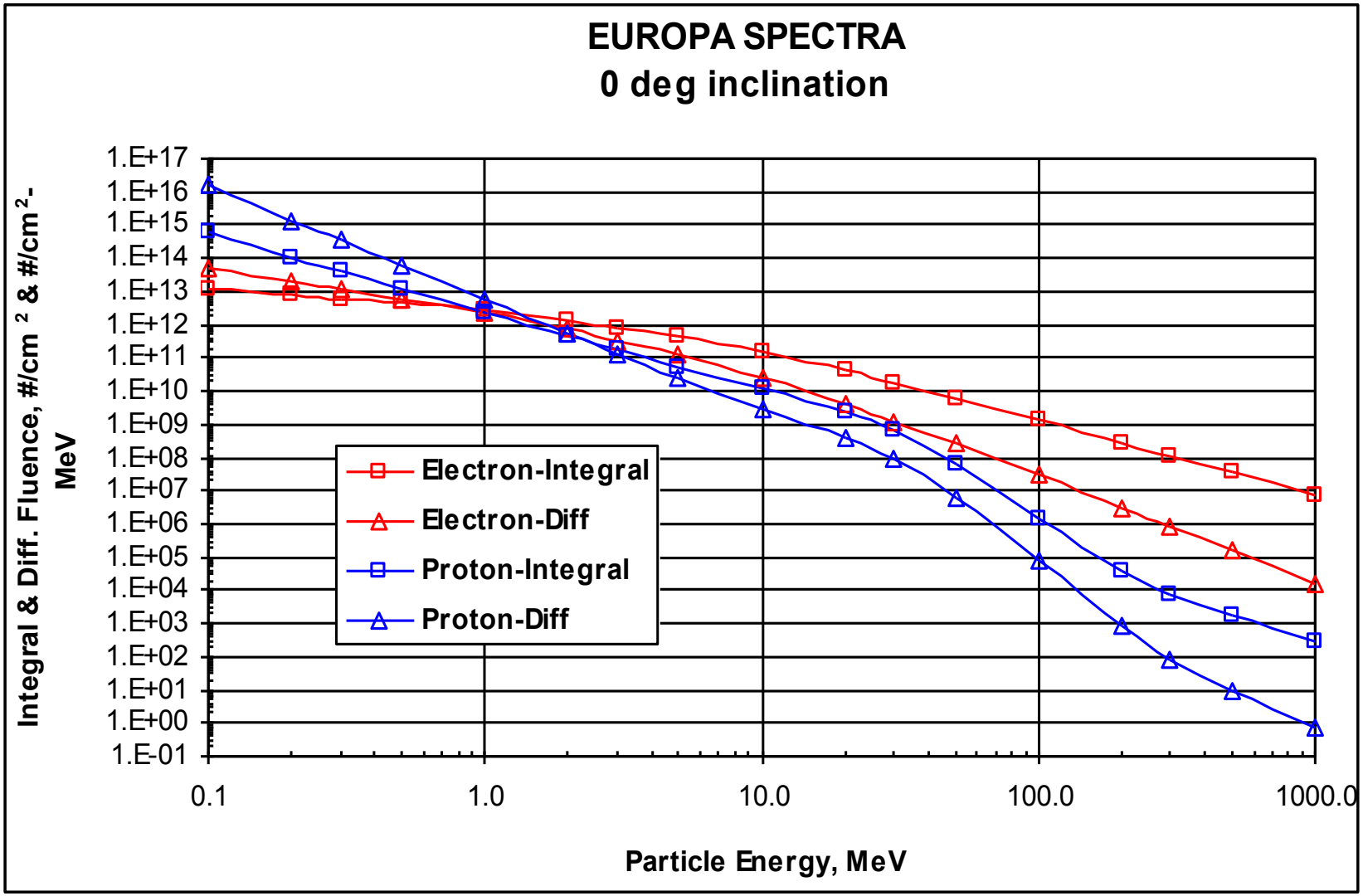
SiGe HBT can operate over a wide range of temperatures.



As temperatures drop lower, the SiGe HBT current gain increases (opposite of Si BJT).

What Do the Simulation Models Tell Us ?

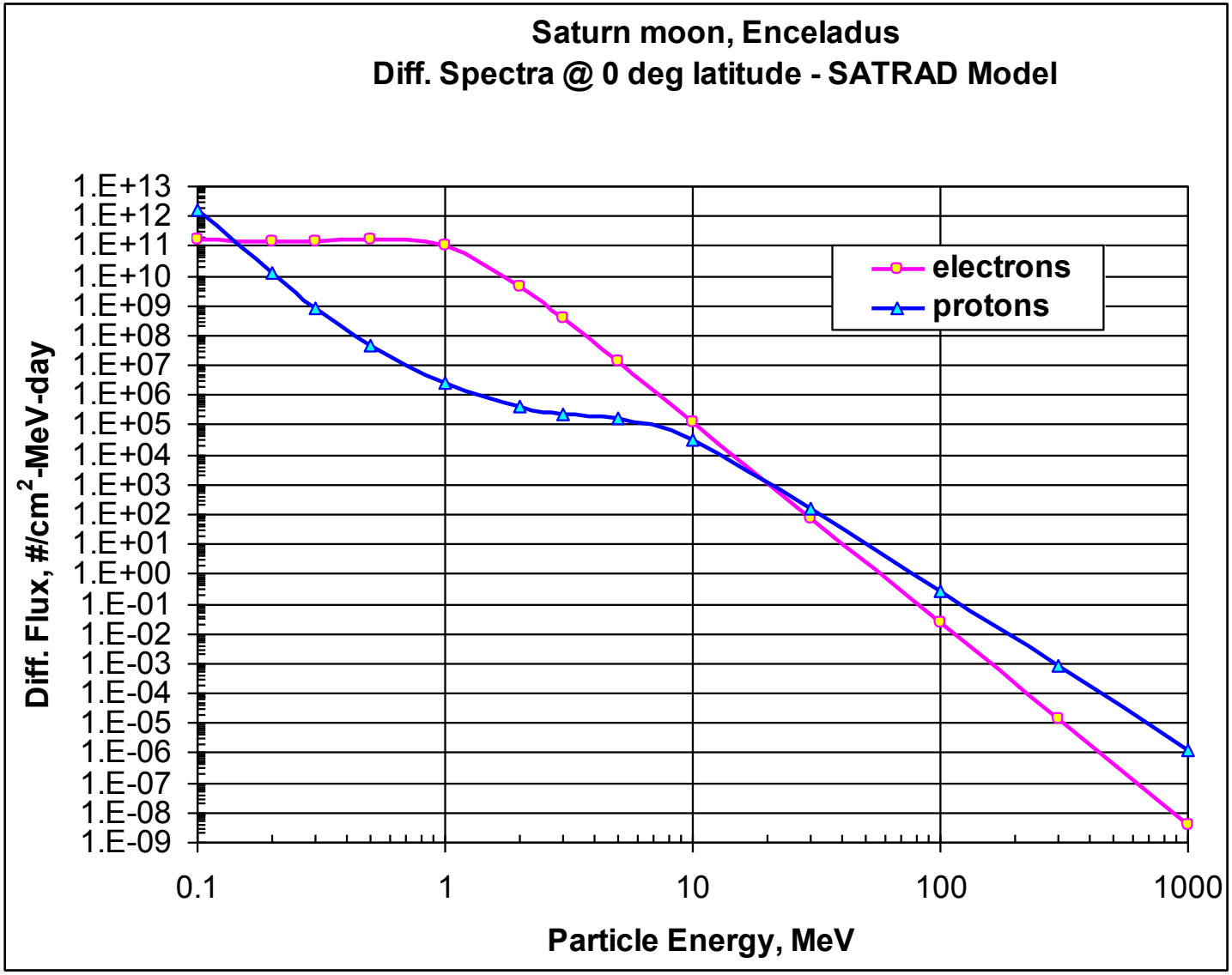
JUPITER – EUROPA SPECTRA, GIRE MODEL
(Galileo Interim Radiation Electrons model, developed at JPL / Caltech)



What Do the Simulation Models Tell Us ?

SATURN – ENCELADUS SPECTRA SATRAD MODEL

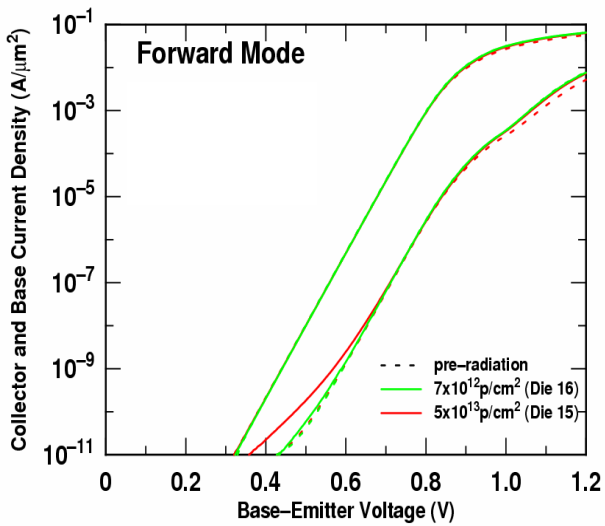
(

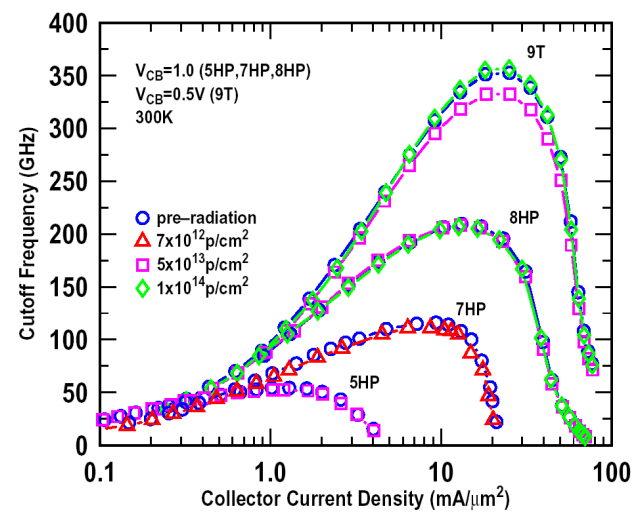


Radiation Effects on SiGe Electronics for Extreme Environments (HBT devices and CMOS devices for Analog and Digital Circuits)

- **Total Ionizing Dose (TID) – ionizing radiation**
  - TID is measured in "rads" (1 rad = 100 ergs per gram of energy absorbed)
  - 100-500 krad(Si) over 10 years for typical orbit *(300 rad(Si) is lethal to humans!)*
- **Single Event Upset (SEU) – high energy heavy ions**
  - measure data upset cross-section (σ) vs. Linear Energy Transfer (LET)
  - σ = # errors / particle fluence (ions/cm^2): LET = charge deposition (pC/μm)
  - **Goals:** low cross-section + high LET threshold

SiGe HBT has Multi-MRad TID hardness, with no intentional hardening, due to its epitaxial base structure.



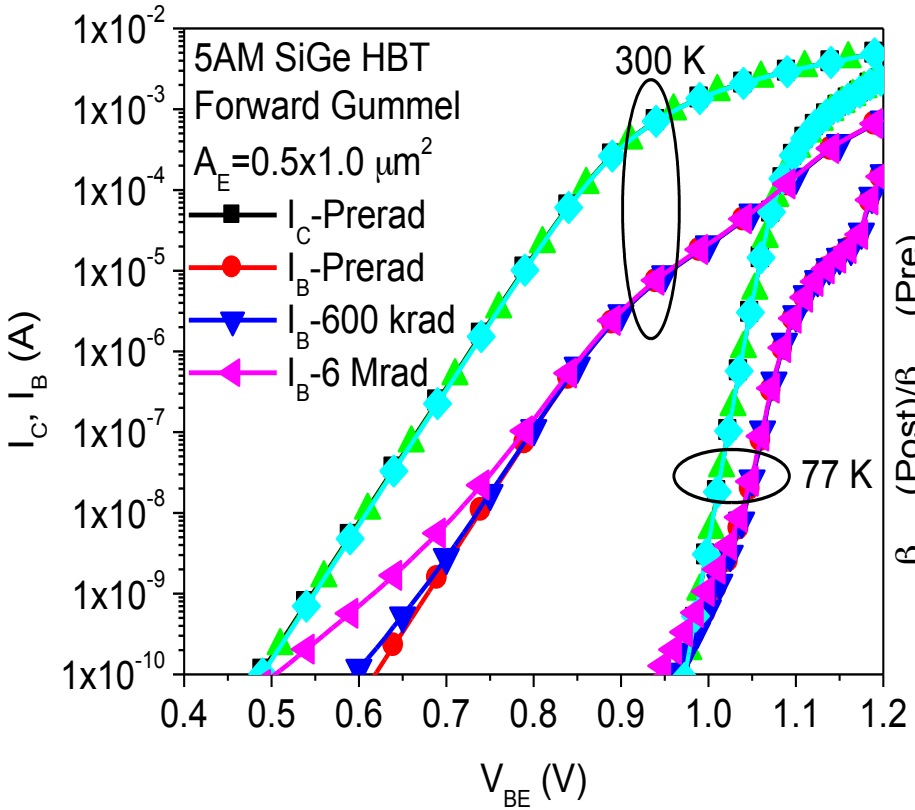


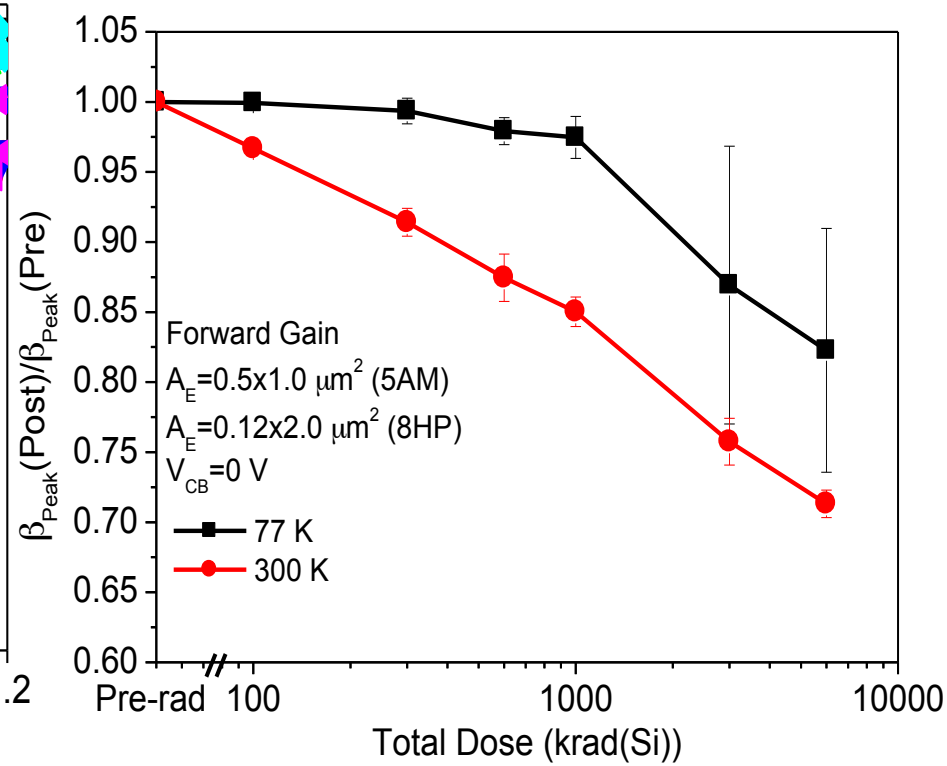
Radiation Effects on SiGe Electronics for Extreme Environments (cont). (HBT devices and CMOS devices for Analog and Digital Circuits)

First 77K Proton Irradiation Experiment in SiGe Technology

- 63 MeV protons at UC Davis (NASA-GSFC / DTRA collaboration)

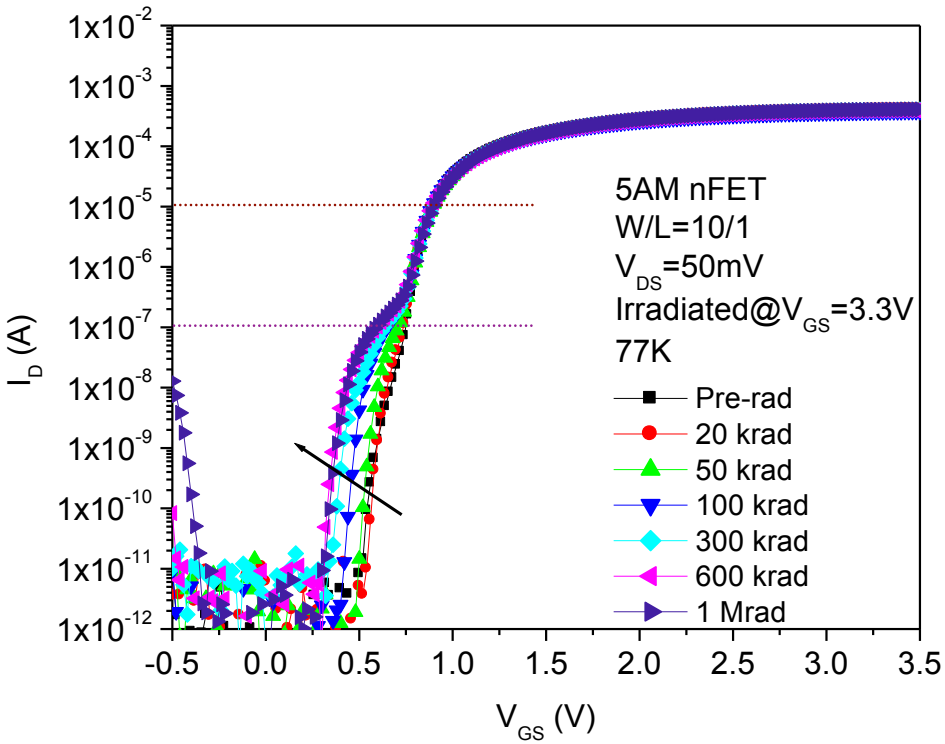
The TID radiation effects on SiGe are less pronounced at low temperatures.

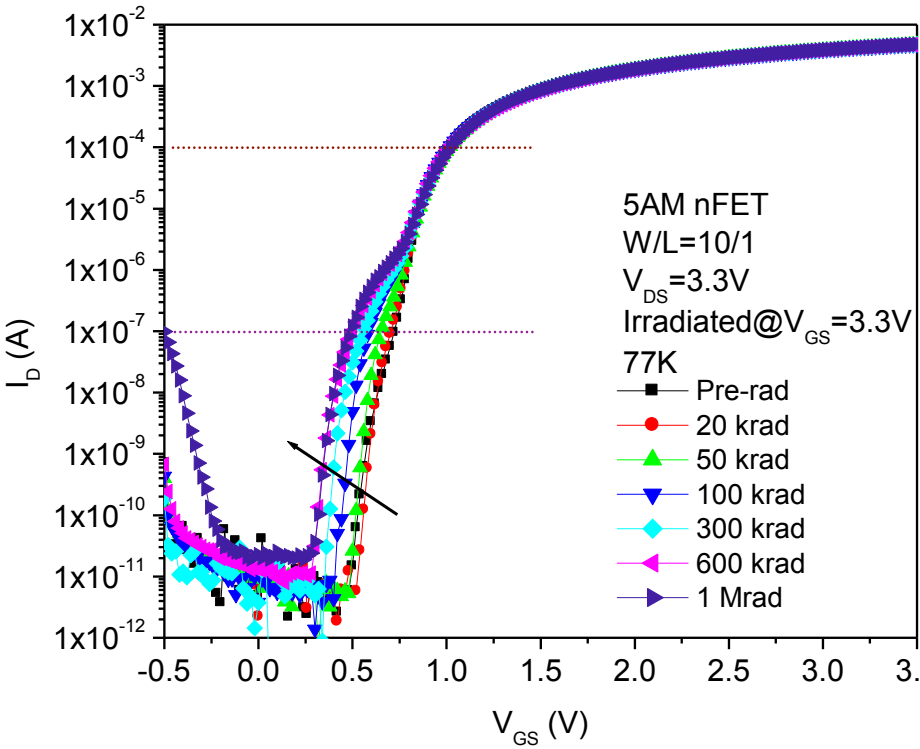




Radiation Effects on SiGe Electronics for Extreme Environments (cont). (HBT devices and CMOS devices for Analog and Digital Circuits)

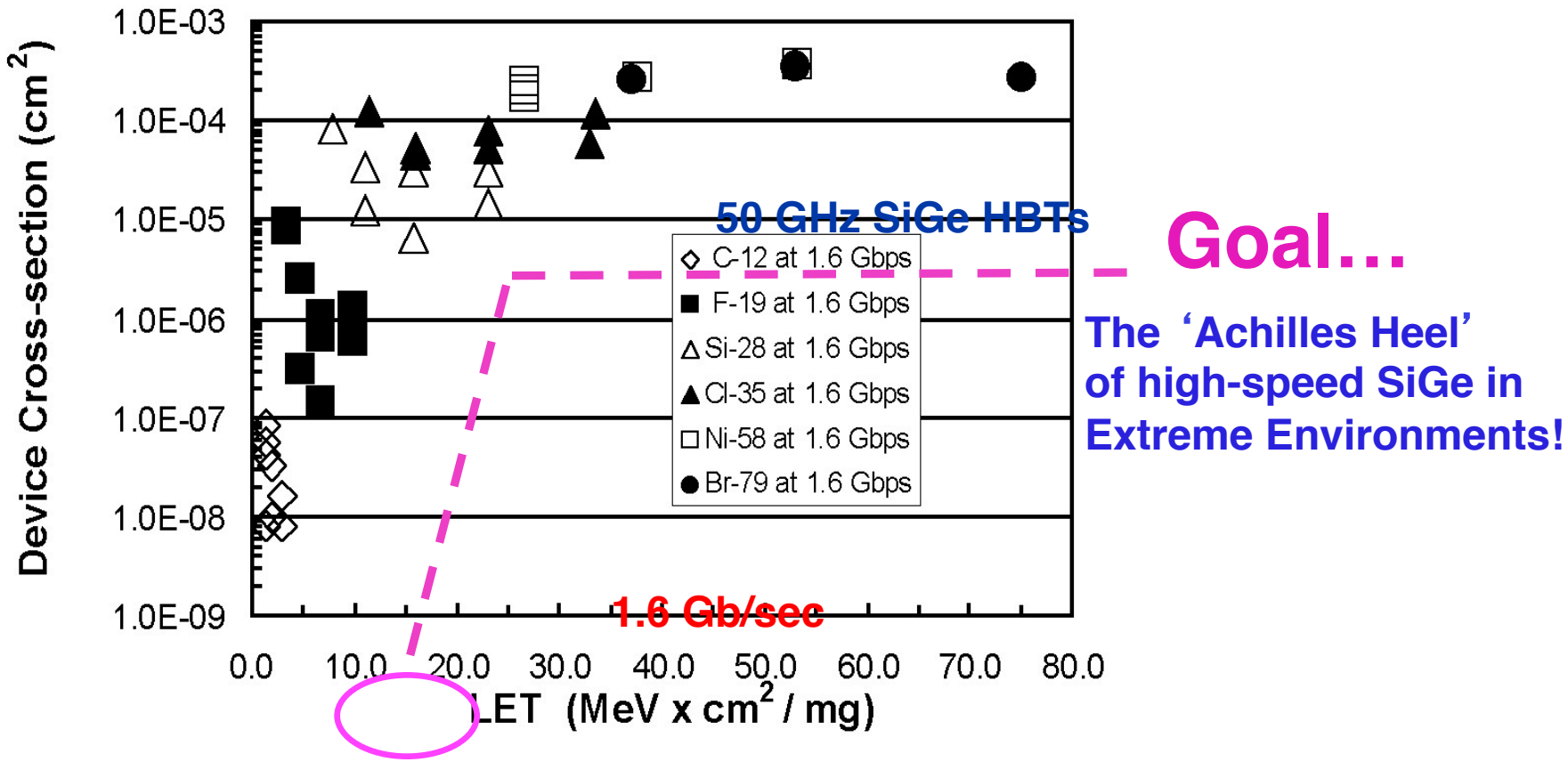
63 MeV Proton Irradiation Effects on SiGe 5AM nFETs at 77K





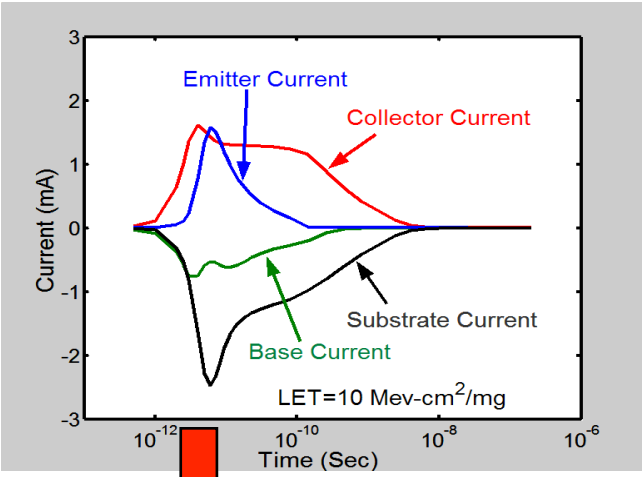
Radiation Effects on SiGe Electronics for Extreme Environments (cont). (HBT devices and CMOS devices for Analog and Digital Circuits)

Observed SEU sensitivity of SiGe Shift Registers operating at 50 GHz.

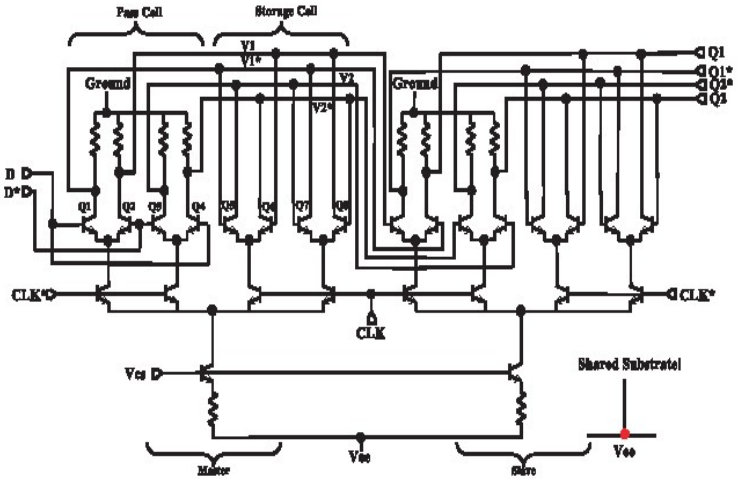


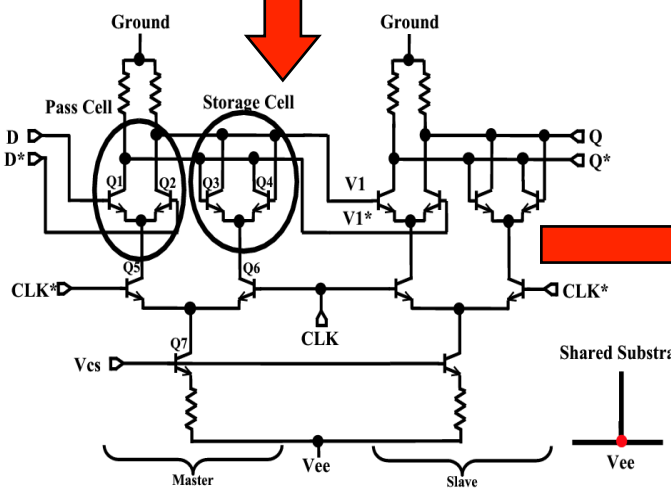
Design and Modeling Work to Develop SEU-tolerant SiGe High-Speed Digital Circuits (work in progress)

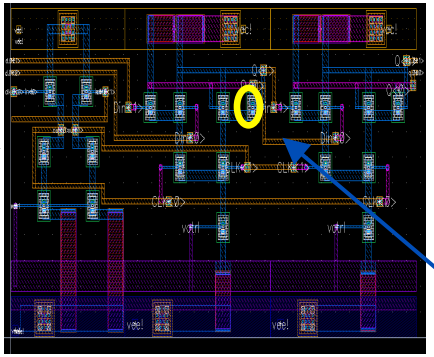
"TCAD Ion Strike"

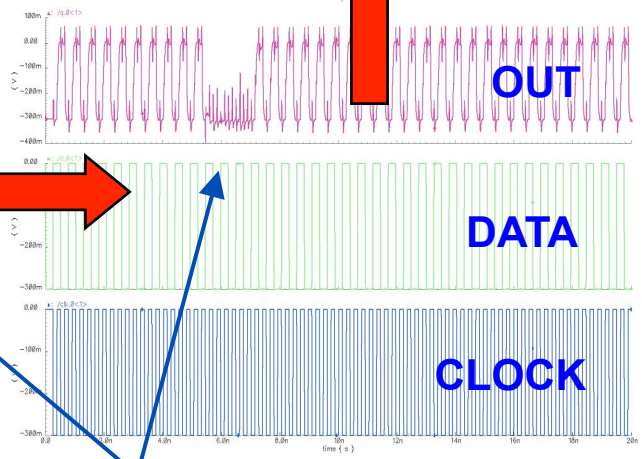


New RHBD SiGe Latch









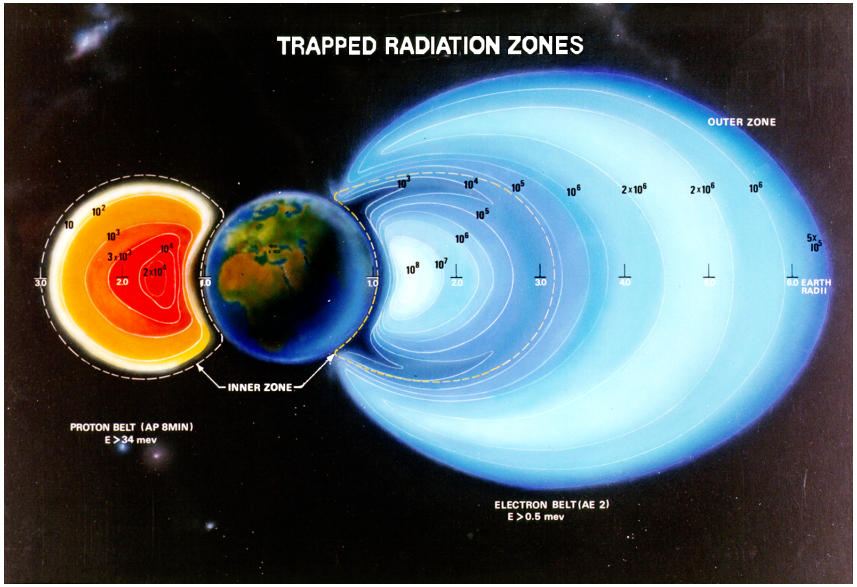
UPSETS

Standard Master Slave Latch

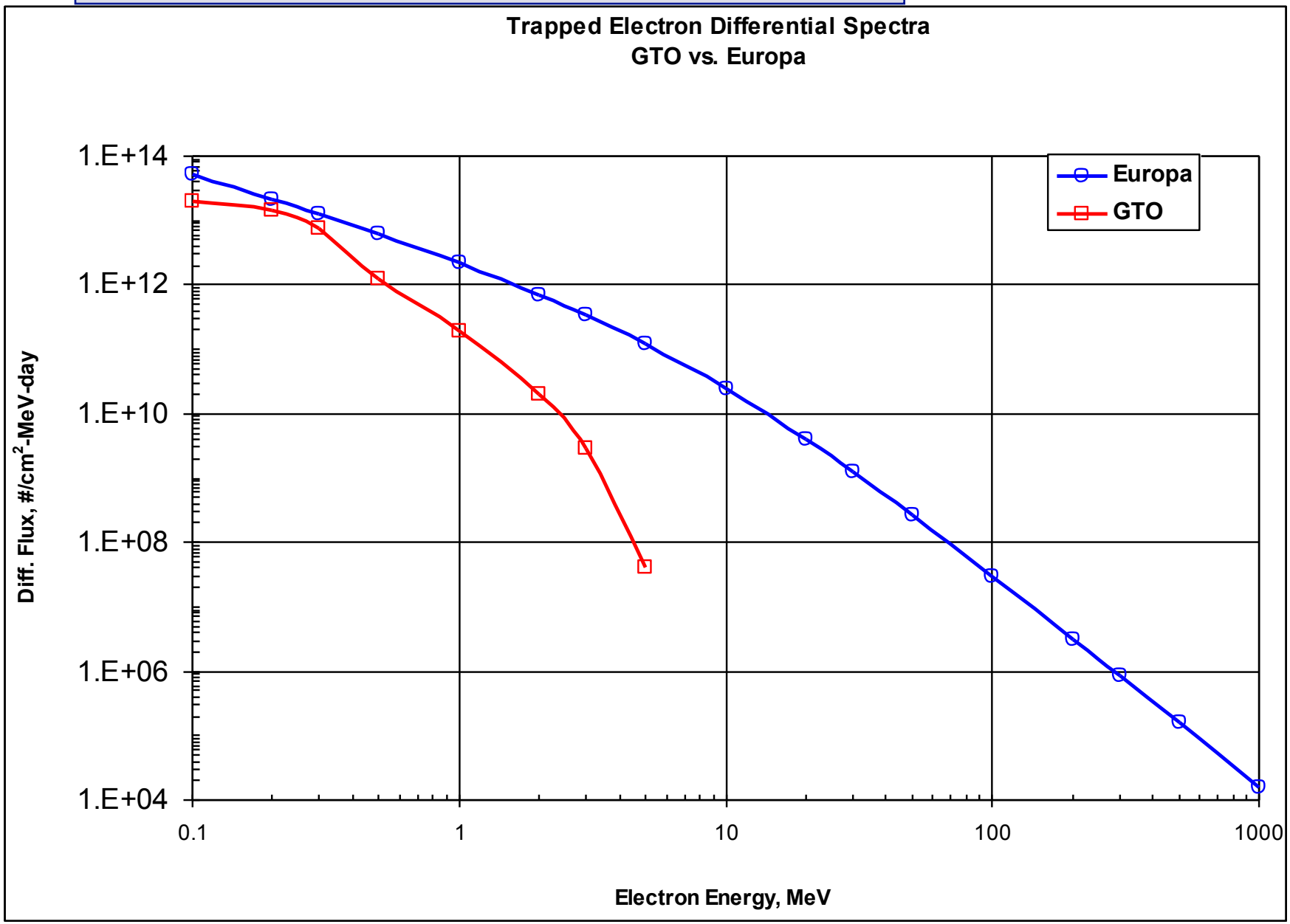
Platforms for Testing and Validation

- Brookhaven National Lab, New York
  - - Protons to 1 GeV
- Texas A&M, College Station, Texas
- UC Davis, CA
- Naval Surface Warfare Center , Crane, Indiana
  - - Electrons to 800 MeV
- Loma Linda University, Loma Linda, CA
  - - Protons, to 250 MeV
- Los Alamos National Lab, Los Alamos, NM
  - - High energy neutrons
  - - High energy electrons
- Spacecraft in GTO (Van Allen Belts)
  - - Protons to 400 MeV
  - - Electrons to 5 MeV

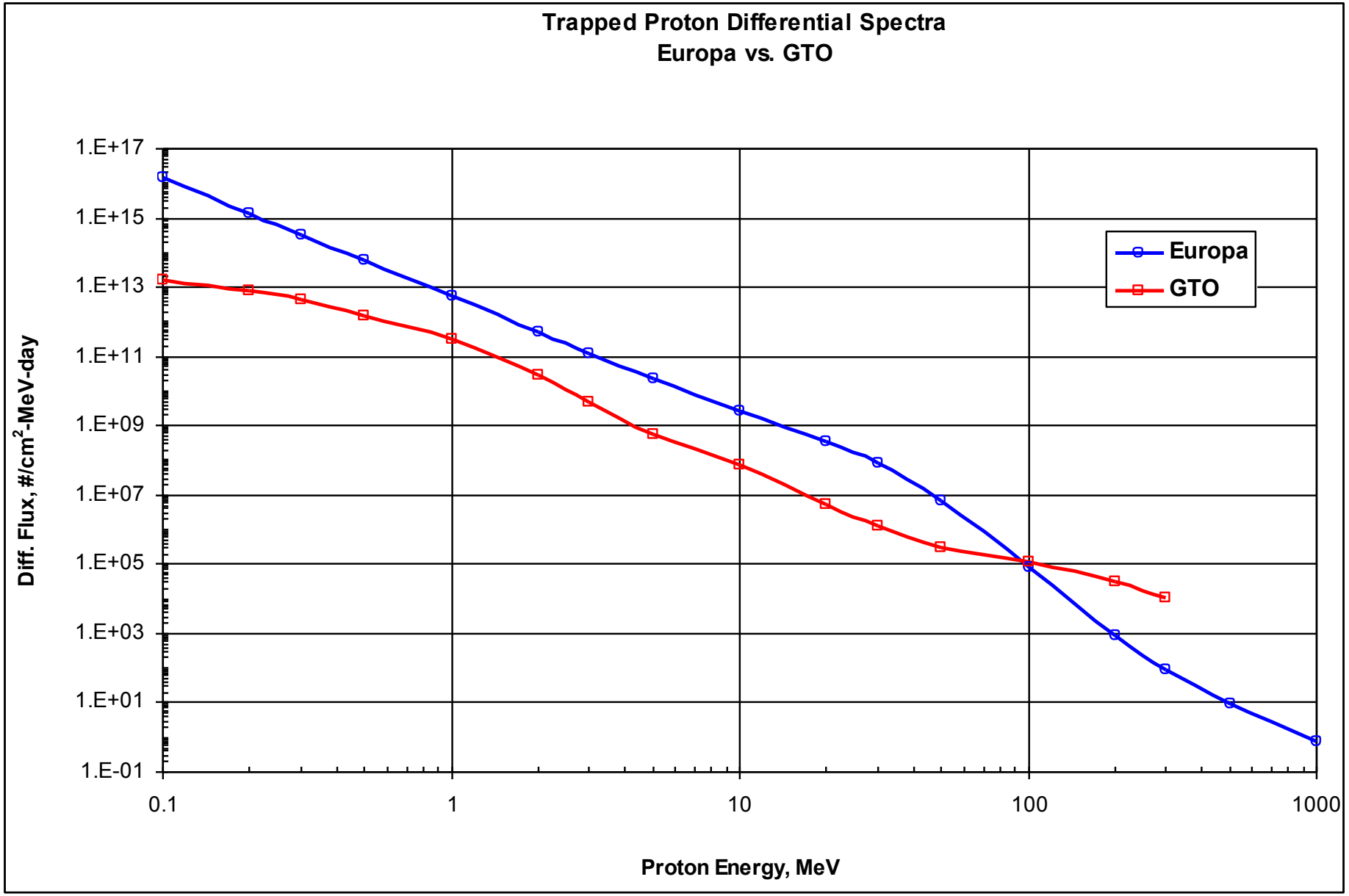
The Van Allen Belts:
Are these effective test-beds ?



Platforms for Testing and Validation (cont.)



Platforms for Testing and Validation (cont.)



Acknowledgments

* Co-authors
* The SiGe Team
* The NASA RHESE program, managed by Dr. M. Watson / Dr. A. Keys, MSFC.

References and Publications:

1. H.B. Garrett, J.M. Ratliff, and R.W. Evans, "Saturn Radiation (SATRAD) Model," NASA Jet Propulsion Laboratory JPL Publication 05-9, Pasadena, CA, October 2005.
2. H.B. Garrett, I. Jun, J.M. Ratliff, R.W. Evans, G.A. Clough, and R.W. McEntire, "Galileo Interim Radiation Electron Model," NASA Jet Propulsion Laboratory JPL Publication 03-006, Pasadena, CA, February 2003.
3. J. Allison, et al., "GEANT4 Developments and Applications," IEEE Transactions on Nuclear Science, vol. 53, issue 1, part 2, pp. 270-278, Feb. 2006.
4. Information about MCNPX development can be found on the web site http://mcnpx.lanl.gov/.
5. Information about FLUKA development can be found on the web site http://www.fluka.org.

Silicon-Germanium (SiGe) Integrated Electronics for Extreme Environments

• Publications

- J.D. Cressler, "On the Potential of SiGe HBTs for Extreme Environment Electronics," *Proceedings of the IEEE*, vol. 93, pp. 1559-1582, 2005. (invited)

- J.D. Cressler, "Using SiGe HBTs for Extreme Environment Electronics," *Proceedings of the 2005 IEEE Bipolar/BiCMOS Circuits and Technology Meeting,* October 2005. (invited)

- J.D. Cressler, "SiGe HBT Reliability Issues Associated with Operation in Extreme Environments," *Proceedings of the 2006 IEEE Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems*, Jan. 2006. (invited)

- T. Chen *et al.*, "CMOS Device Reliability for Emerging Cryogenic Space Electronics Applications," *Proceedings of the 2005 IEEE International Semiconductor Device Research Symposium,* December 2005.

- L. Peltz *et al.*, "Silicon-Germanium Integrated Electronics for Extreme Environments Applied to the Design of a Lunar Hopper," *Proceedings of the 7th International Conference for Lunar Exploration and Utilization*," October 2005.

- C. Zhu *et al.*, "Assessing Reliability Issues in Cryogenically-Operated SiGe HBTs" *Proceedings of the 2005 IEEE Bipolar/BiCMOS Circuits and Technology Meeting,* October 2005.