

Single Event Effects in FPGA Devices 2015-2016

**Melanie Berg, AS&D Inc. in support of the
NEPP Program and NASA/GSFC**

Melanie.D.Berg@NASA.gov

Kenneth LaBel: NASA/GSFC

Jonathan Pellish: NASA/GSFC



Acronyms

- Advanced Encryption Standard (AES)
- Agile Mixed Signal (AMS)
- ARM Holdings Public Limited Company (ARM)
- Block random access memory (BRAM)
- Built-in-self-test (BIST)
- Cache Coherent Interconnect (CCI)
- Combinatorial logic (CL)
- Commercial off the shelf (COTS)
- Complementary metal-oxide semiconductor (CMOS)
- Controller Area Network (CAN)
- Device under test (DUT)
- Digital Signal Processing (DSP)
- Direct Memory Access (DMA)
- Distributed triple modular redundancy (DTMR)
- Double Data Rate (DDR3 = Generation 3; DDR4 = Generation 4)
- Edge-triggered flip-flops (DFFs)
- Equipment Monitor And Control (EMAC)
- Error-Correcting Code (ECC)
- Field programmable gate array (FPGA)
- Floating Point Unit (FPU)
- Global Industry Classification (GIC)
- Global triple modular redundancy (GTMR)
- High Performance Input/Output (HPIO)
- High Pressure Sodium (HPS)
- High Speed Bus Interface (PS-GTR)
- Input – output (I/O)
- Intellectual Property (IP)
- Inter-Integrated Circuit (I2C)
- Internal configuration access port (ICAP)
- Joint test action group (JTAG)
- Lightwatt High Pressure Sodium (LW HPS)
- Linear energy transfer (LET)
- Local triple modular redundancy (LTMR)
- Look up table (LUT)
- Low Power (LP)
- Low-Voltage Differential Signaling (LVDS)
- Memory Management Unit (MMU)
- Microprocessor (MP)
- Multi-die Interconnect Bridge (EMIB)
- MultiMediaCard (MMC)
- Multiport Front-End (MPFE)
- Not OR logic gate (NOR)
- Operational frequency (fs)
- Peripheral Component Interconnect Express (PCIe)
- Personal Computer (PC)
- Phase locked loop (PLL)
- Phase Locked Loop (PLL)
- Power on reset (POR)
- Probability of flip-flop upset (PDFFSEU)
- Probability of logic masking (Plogic)
- Probability of transient generation (Pgen)
- Probability of transient propagation (Pprop)
- Processor (PC)
- Radiation Effects and Analysis Group (REAG)
- Secondary Control Unit (SCU)
- Secure Digital (SD)
- Secure Digital embedded MultiMediaCard (SD/eMMC)
- Secure Digital Input/Output (SDIO)
- Serial Advanced Technology Attachment (SATA)
- Serial Peripheral Interface (SPI)
- Serial Quad Input/Output (QSPI)
- Single event functional interrupt (SEFI)
- Single event latch-up (SEL)
- Single event transient (SET)
- Single event upset (SEU)
- Single event upset cross-section (σ SEU)
- Spatial-Division-Multiplexing (SDM)
- Static random access memory (SRAM)
- System Memory Management Unit (SMMU)
- System on a chip (SOC)
- Transceiver Type (GTH/GTY)
- Transient width (twidth)
- Triple modular redundancy (TMR)
- Universal Asynchronous Receiver/Transmitter (UART)
- Universal Serial Bus (USB)
- Universal Serial Bus (USB)
- Universal Serial Bus On-the-go (USB OTG)
- Watchdog Timer (WDT)
- Windowed Shift Register (WSR)



Overview

- Review of field programmable gate array (FPGA) roadmap chart (previously presented by Kenneth LaBel).
- Work performed by NASA/GSFC:
 - Security and trust.
 - Heavy-ion radiation testing:
 - Xilinx Kintex-7,
 - Synopsys mitigation tools,
 - Altera Stratix-V, and
 - Microsemi RTG4.
- Plans for FY16 and out:
 - Microsemi, Xilinx, Altera, Synopsys.

Review of FPGA Roadmap Chart



Trusted FPGA

- DoD Development

TBD – (track status)

Altera

- Stratix 5 (28nm TSMC process commercial)
- Max 10 (55nm NOR based commercial – small mission candidate)
- Stratix 10 (14nm Intel process commercial)

Radiation Testing

Radiation Testing

Reliability Testing

Radiation Testing

Microsemi

- RTG4 (65nm RH)

Radiation Testing

Package Reliability Testing

Xilinx

- 7 series (28nm commercial)
- Ultrascale (20nm commercial – planar)
- Ultrascale+ (16nm commercial - vertical)
- Virtex 5QV (65nm RH)

Radiation Testing

Radiation Testing

Radiation and Reliability Testing

Radiation Testing

Package Reliability Testing

FY=Fiscal Year

FY14

FY15

FY16

FY17

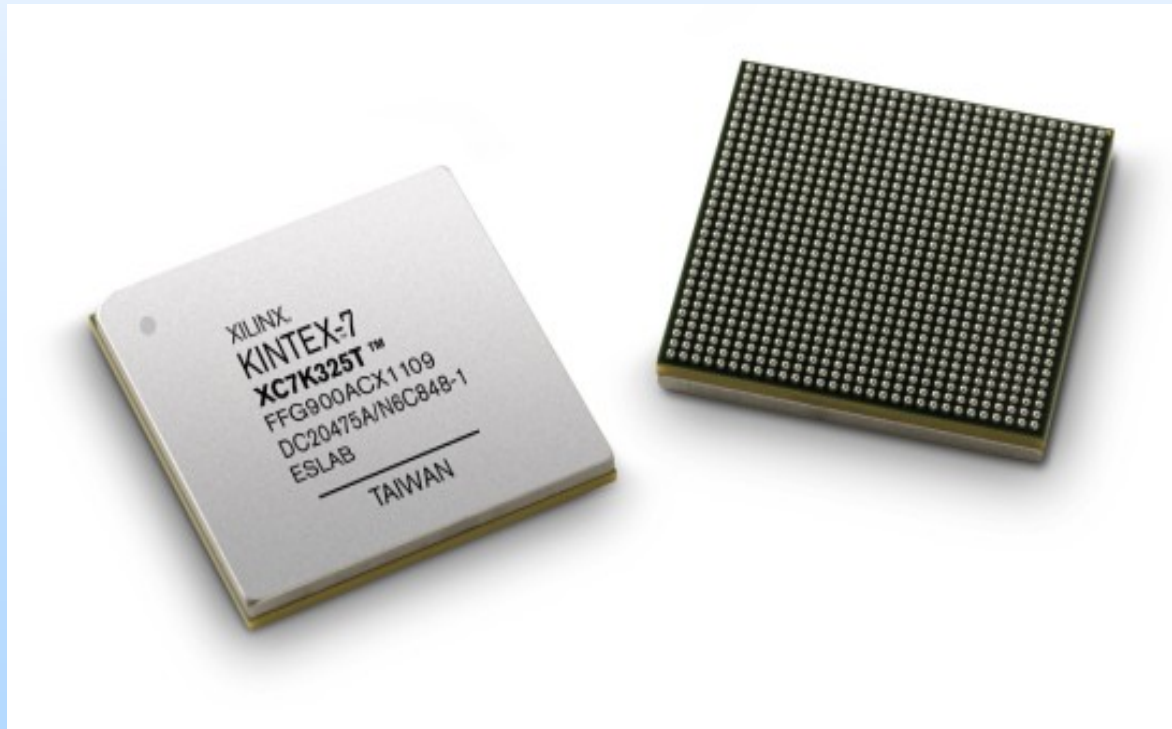


FPGA Security and Trust

- **Goal: Support the U.S. government concerns regarding security and trust in FPGAs.**
- **Conference participation:**
 - **Xilinx Security Working Group (XSWG) 2014 in Boulder/Longmont, CO.**
 - **Government Microcircuit Applications and Critical Technology Conference (GOMACTech) 2016 in Orlando, FL.**
 - **Hardened Electronics and Radiation Technology (HEART) 2016 in Monterey, CA.**
 - **Hardware-Oriented Security and Trust (HOST) 2015, McLean, VA.**
- **Collaboration with Aerospace Corporation and other agencies.**
 - **Meetings, consultations, and presentations.**

SRAM-based FPGA Mitigation Study using Xilinx Kintex-7 (XC7K325T- 1FBG900)

(1) Single event latch-up (SEL) and (2) Mitigation



Xilinx Kintex-7 Single Event Latch-up (SEL) Investigation



- This is an independent study to determine the SEL susceptibility of the Commercial Xilinx Kintex-7 device.
- Prior SEL testing has been performed by other groups. They have reported observing SEL in the Xilinx 7-series devices.
 - Lee, D.S.; Wirthlin, M.; Swift, G.; Le, A.C., "Single-Event Characterization of the 28 nm Xilinx Kintex-7 Field-Programmable Gate Array under Heavy Ion Irradiation," *Radiation Effects Data Workshop (REDW), 2014 IEEE*, vol., no., pp.1,5, 14-18 July 2014
- In 2015, NEPP decided to perform follow-up tests for validation.
 - NEPP test procedure was slightly different:
 - Real-time configuration memory scrubbing during irradiation.
 - Analog circuitry monitoring.
 - Custom DUT board was designed to connect with the NEPP LCDT.
 - Temperature variation.

Note: SEL is assumed when observing an increase of DUT current that can only be lowered by reducing the DUT power below threshold.



Summary of Kintex-7 during Single Event Upset (SEU)-Heavy-Ion Testing

LET: Linear energy transfer

- **Last year's data:** SEL results concur with other groups:
 - With real-time scrubbing.
 - However, on-set SEL was observed at a lower LET by NASA/GSFC (11.6 MeV*cm²/mg versus 19 MeV*cm²/mg).
- **NEPP Additional testing:** at elevated temperature.
 - Uncovered susceptibility as low as an LET = 8.6 MeV*cm²/mg with a SEU cross-section approximately equal to 1x10⁻⁷ cm²/device.
 - **NEPP is in discussion with Xilinx regarding whether the event should be classified as classical SEL (micro-SEL) or “something else.” More information to come after July 2016.**

Most importantly, no matter what this event is called, it needs a power cycle and has a fairly low probability of occurring.

Kintex-7 SEU Mitigation Study Overview

- This is an independent study to determine the effectiveness of various triple modular redundancy (**TMR**) schemes implemented in **SRAM-based FPGA** devices.
- TMR schemes are defined by what portion of the circuit is triplicated and where the voters are placed.
 - The strongest TMR implementation will triplicate all data-paths and contain separate voters for each data-path.
 - However, this can be costly: area, power, and complexity.
 - **A trade is performed to determine the TMR scheme that requires the least amount of effort and circuitry that will meet project requirements.**
- Presentation scope:
 - Block TMR (BTMR), Local TMR (LTMR), Distributed TMR (DTMR), and Global TMR (GTMR) .



TMR Descriptions

DFF: Edge triggered flip-flop;

CL: Combinatorial Logic

| TMR Nomenclature | Description | TMR Acronym |
|------------------|---|--------------|
| Block TMR | Entire design is triplicated. Voters are placed at the outputs. | BTMR |
| Local TMR | Only the DFFs are triplicated. Voters are placed after the DFFs. | LTMR |
| Distributed TMR | DFFs and CL-data-paths are triplicated. Similar to a design being triplicated but voters are placed after the DFFs. | DTMR |
| Global TMR | DFFs, CL-data-paths and global routes are triplicated. Voters are placed after the DFFs. | GTMR or XTMR |

Note: It has been suggested to separate (partition) TMR domains in SRAM based designs so that there are no overlapped shared resources. Shared resources become single points of failure.



Summary of Mitigation Application to Kintex-7 during SEU-Heavy-Ion Testing

SEFI: single event functional interrupt

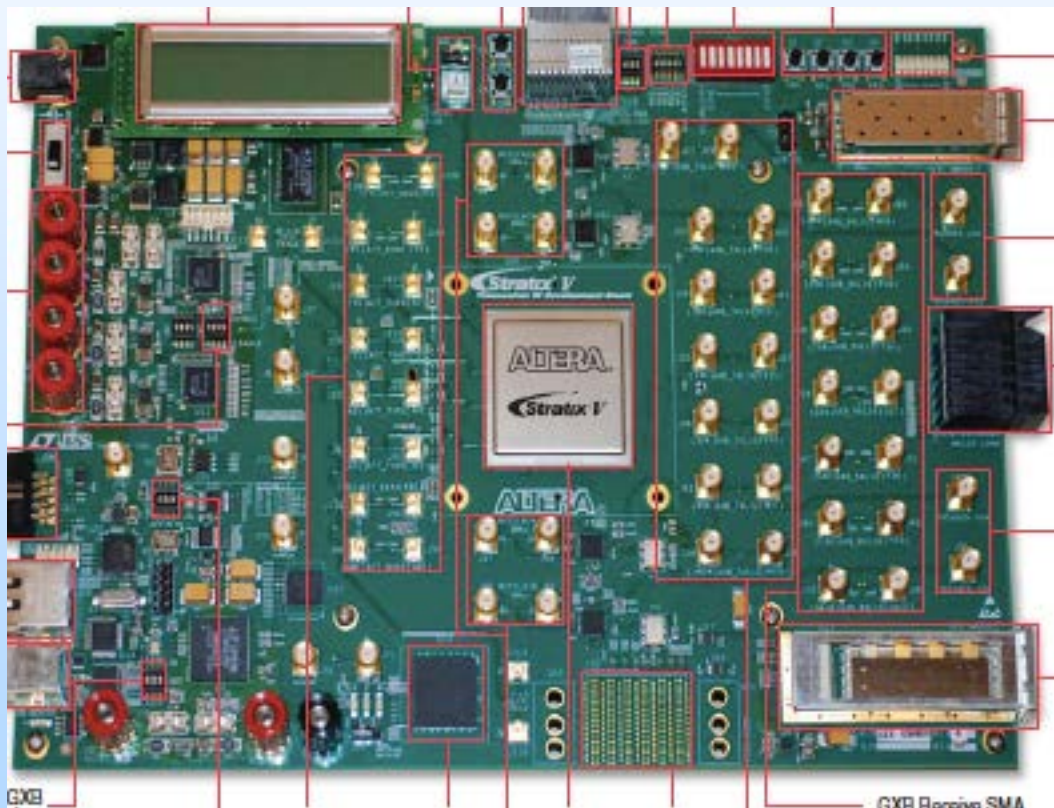
- Mitigation study proves DTMR is the strongest mitigation scheme implemented in an SRAM-based FPGA.
 - However, for flushable designs BTMR might be acceptable.
 - LTMR is not acceptable in SRAM-based FPGAs for any design.
 - Partitioning may not be necessary.
- Internal scrubbing will have a higher SEFI rate and may need further investigation for project usage.
- Although GTMR has been implemented in V5 families and earlier Xilinx device families, NEPP has suggested to avoid GTMR because clock skew is difficult to control.
 - In 2015-2016, via heavy-ion SEU testing, It has been observed in the Xilinx 7-series, that race conditions due to clock skew are unavoidable.
 - This is due to the speed of combinatorial logic and route delays in the 7-series versus earlier Xilinx FPGA device families.
- Synopsis is working on their tool. However, it is not ready.
- Mitigation and IP cores proves to be a major concern!!!!!!!!!!!!!!

Kintex-7 Test Report



- **The full Kintex-7 SEU dataset is still currently being analyzed and will be available by August 2016. Challenge is post processing software.**
- **A test report has been written but is missing some information. Can supply data by demand.**
- **Test report expected to be finished by end of 2016 (or before).**

SRAM-based FPGA Study using the Altera Stratix-V (5SGTMC7K3F40C2)





Stratix-V SEE Testing Overview and Goals

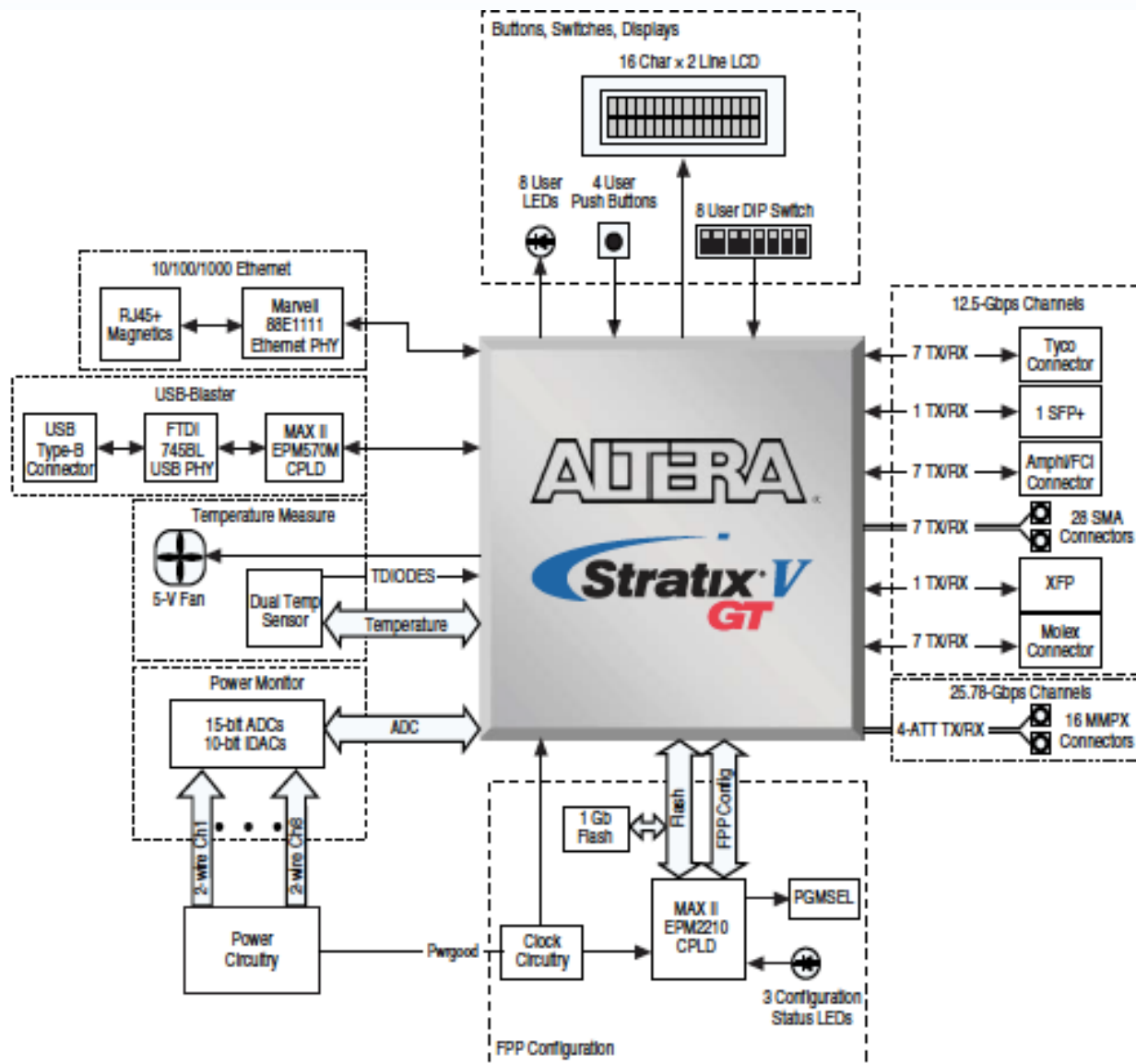
- This is a NASA Electronics Parts and Packaging (NEPP) investigation to determine the single event destructive and transient susceptibility of the Altera Stratix-V device under test (DUT).
- For preliminary evaluation: the DUT is configured to have shift registers as test structures to measure specific potential single event effect (SEE) susceptibilities of the device.
- Design/Device susceptibility is determined by monitoring the DUT for Single Event Transient (SET) and SEU induced faults by exposing the DUT to a heavy-ion beam.
- Potential SEL is checked throughout heavy-ion testing by monitoring device current.

Altera Stratix-V Radiation Test Development



- New entry into the aerospace market with commercial off the shelf (COTS) expectation
 - 28nm bulk CMOS
- Accelerated SEE testing was performed on Altera Signal Integrity (SI) evaluation boards that contained one Stratix V GX FPGA .
 - Custom interface was designed to connect to the LCDT for increased visibility during accelerated radiation testing.
 - Voltage supplies are separated for accurate voltage monitoring.
- Phase I tests (dates: June 2015 and October 2015):
 - Tests were performed in collaboration with Cobham.
 - SEU evaluation of shift registers and internal scrubbing was performed.
 - **SEL evaluation was performed.**
- Phase II tests (TBD yet most likely cancelled):
 - Shift registers, counters, PLLs, and DSPs.
 - Use of Synopsis tool for mitigation insertion.
- Phase III tests:(TBD yet most likely cancelled):
 - High speed serial interfaces (TBD), instantiated processor(TBD).

Altera Stratix-V (5SGTMC7K3F40C2) Evaluation Board Schematic



Altera Stratix-V Configuration

Evaluation Limitations



- It is important to note that currently there is no independent method to evaluate Altera configuration memory.
- This is noted because the Stratix-V has a SRAM-based configuration.
 - From previous studies of SRAM-based FPGAs (e.g., Xilinx commercial devices), the configuration (SRAM) proved to be the most susceptible.
 - Outside of bit-interleaving and internal scrubbing, no radiation hardening of the Stratix-V configuration SRAM cells has been reported by Altera. This leaves Stratix-V SEU-characterization similar to a commercially available Xilinx device families.
- It is imperative to be able to perform a thorough and independent evaluation of the most susceptible portions of an FPGA that can potentially be targeted for critical applications.

Altera Stratix-V Radiation Phase I Test

Results: Questionable Power Cycle



- **The following data was obtained in collaboration with Cobham. Two evaluation boards were used: original used by NEPP (thinned to 110μm donated by Altera and LANL) and another thinned by Cobham to 50μm.**
- **There was one run at 80 MeV*cm²/mg, ~105°C, angle 60,(effective LET=102MeV*cm²/mg) where the device did not recover with a re-configuration after the beam was removed. After the test, the team cycled power.**
 - **Additional studies need to occur to determine what happened. The flux was 1x10⁴ particles/s*cm² and the goal was to demonstrate SEL immunity by reaching a fluence of 1e⁷particles/cm² .**
 - **The high-current condition occurred within ~4 seconds.**
 - **The flux was lowered to 1x10³particles/cm² and re-ran the test to a fluence of 1x10⁶particles/cm² (~20 mins). The test was run without any alarming anomalies. Whenever the beam was turned off, we could re-configure the device successfully.**

Altera Stratix-V Radiation Phase I Test

Results: Core Current Rise during Irradiation



- **NASA Goddard (NEPP) originally performed accelerated heavy-ion testing on shift registers with 100,000 flip-flop (DFF) stages.**
 - **Observed significant linear increase in core current while exposed to beam. Current rise is LET dependent and was observed to keep climbing. We stopped tests when current reached 10A-13A.**
 - **Core current stops increasing when beam is removed, and returns to pre rad values after re-program.**
- **Other teams tested with a significantly smaller number of shift register DFF stages and did not observe the current increase.**
- **Cobham decided to investigate the discrepancy and implemented a large shift register. Cobham was able to observe the same core current rises as NASA Goddard.**

Altera Stratix-V Radiation Phase I Test

Results: FPGA Fabric Shielding – I/O Isolation



- **Cobham specific test:**
 - A test was performed with the FPGA fabric shielded and only the GPIO sides of the die exposed.
 - The design was a high-fanout design using 300 I/Os. The DUT was irradiated at a 5×10^3 particles/s*cm² flux rate, at 80 MeV*cm²/mg and a DUT temp of 105°C.
 - A fluence of 1×10^6 /cm² was reached on this run, without any anomalies.

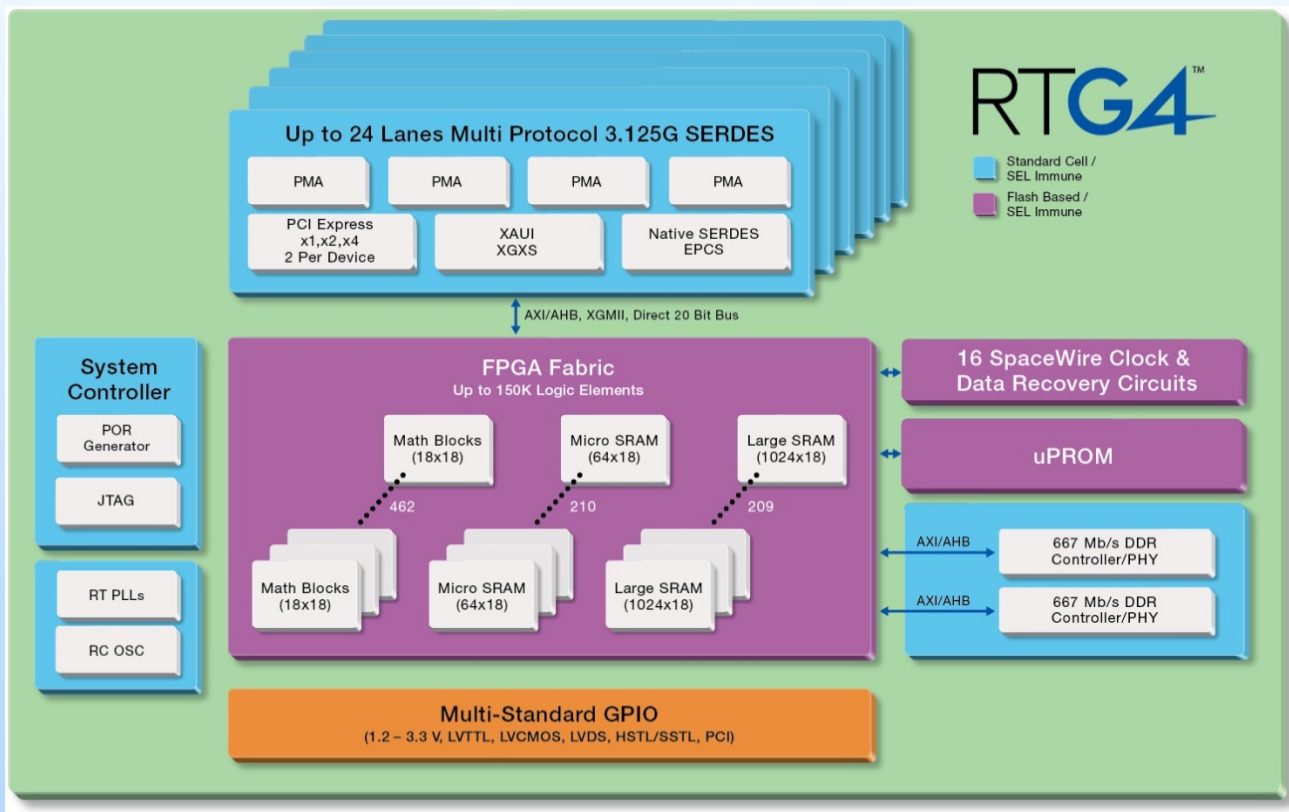


Altera Stratix-V Radiation Phase I Test

Results: Internal Scrubber

- **Internal scrubber failed during all tests.**
- **Flux was relatively high to draw conclusions. Flux was high because the primary goal of testing was SEL.**
- **The effectiveness of the internal scrubber needs more investigation.**
- **The level of mitigation of the internal scrubber is unknown.**

Flash-based FPGA Study using the Microsemi RTG4 (RT4G150-CG1657M)





Microsemi RTG4

- **New Entry into the Aerospace Market with Space-grade Expectation**
 - 65nm
- **Custom daughter DUT cards have been built.**
- **Phase I tests (date: Winter 2015 – Summer 2016):**
 - Shift registers and counters.
- **Phase II and Phase III tests (date Summer 2016-2017):**
 - PLLs and DSPs
 - High speed serial interfaces (XAUI, PCIe, Spacewire, and Spacefiber), instantiated processor (TBD).
 - Use of Synopsis tool for mitigation insertion.

RTG4 Data shown in the “NEPP Independent Single Event Upset Testing of the Microsemi RTG4: Preliminary Data” ETW presentation.



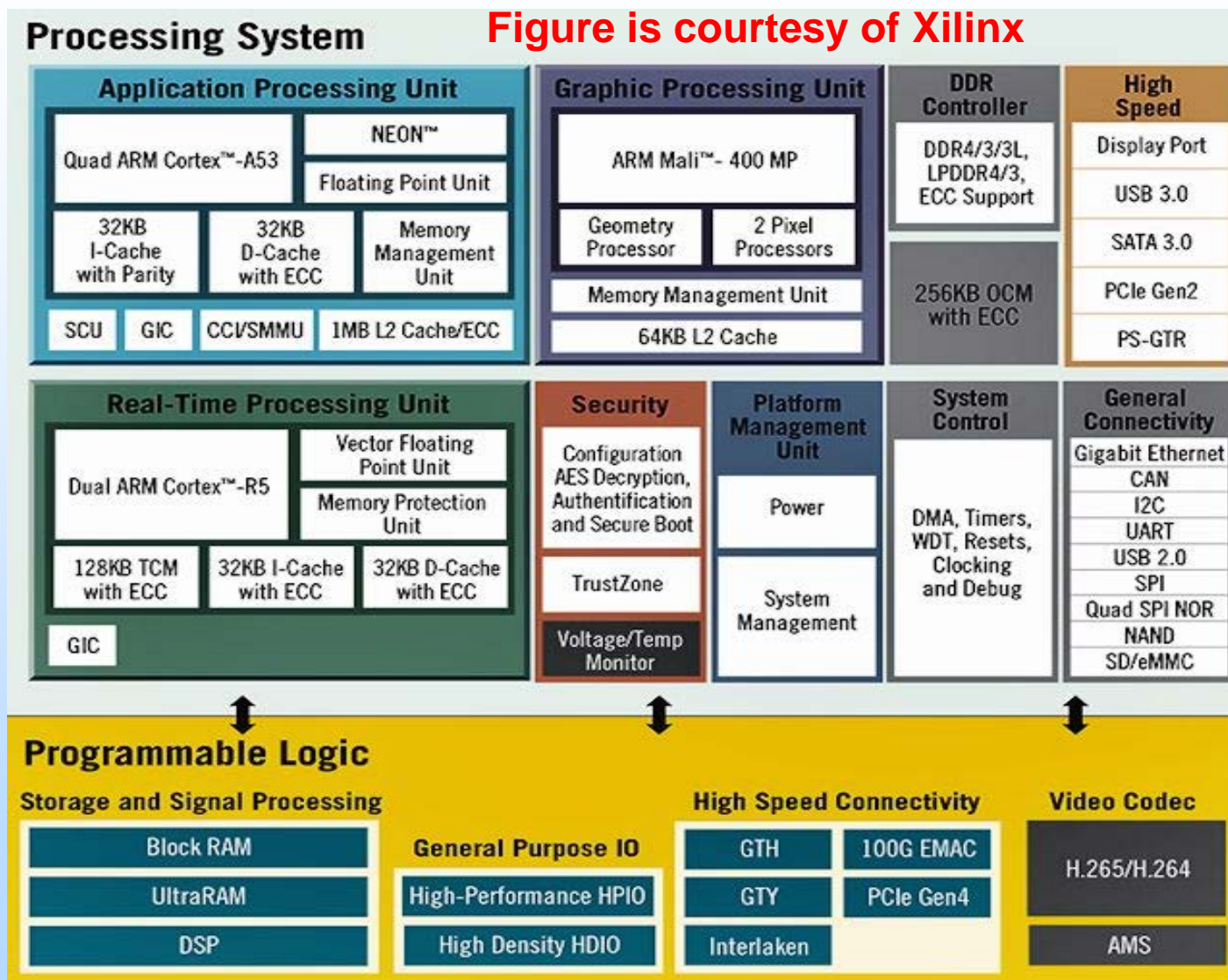
Plans for FY16 and out: Xilinx, Altera, and Synopsis. We Looking for Collaborators



Xilinx Kintex UltraScale

- **New Entry into the Aerospace Market with COTS Expectation**
 - 20 nm planar process (TSMC)
- **Prototype evaluation board will be purchased for early design development and early latch-up testing.**
 - Custom interface will be designed to connect to the LCDT for increased visibility during accelerated radiation testing.
- **Phase I tests (fall 2016):**
 - Evaluation board latch-up investigation.
- **Phase II tests (date TBD):**
 - Shift registers, counters, PLLs, and DSPs.
 - Use of Synopsis tool for mitigation insertion.
- **Phase III tests (TBD):**
 - High speed serial interfaces (TBD), embedded processors.

Xilinx Zynq UltraScale+ Figure



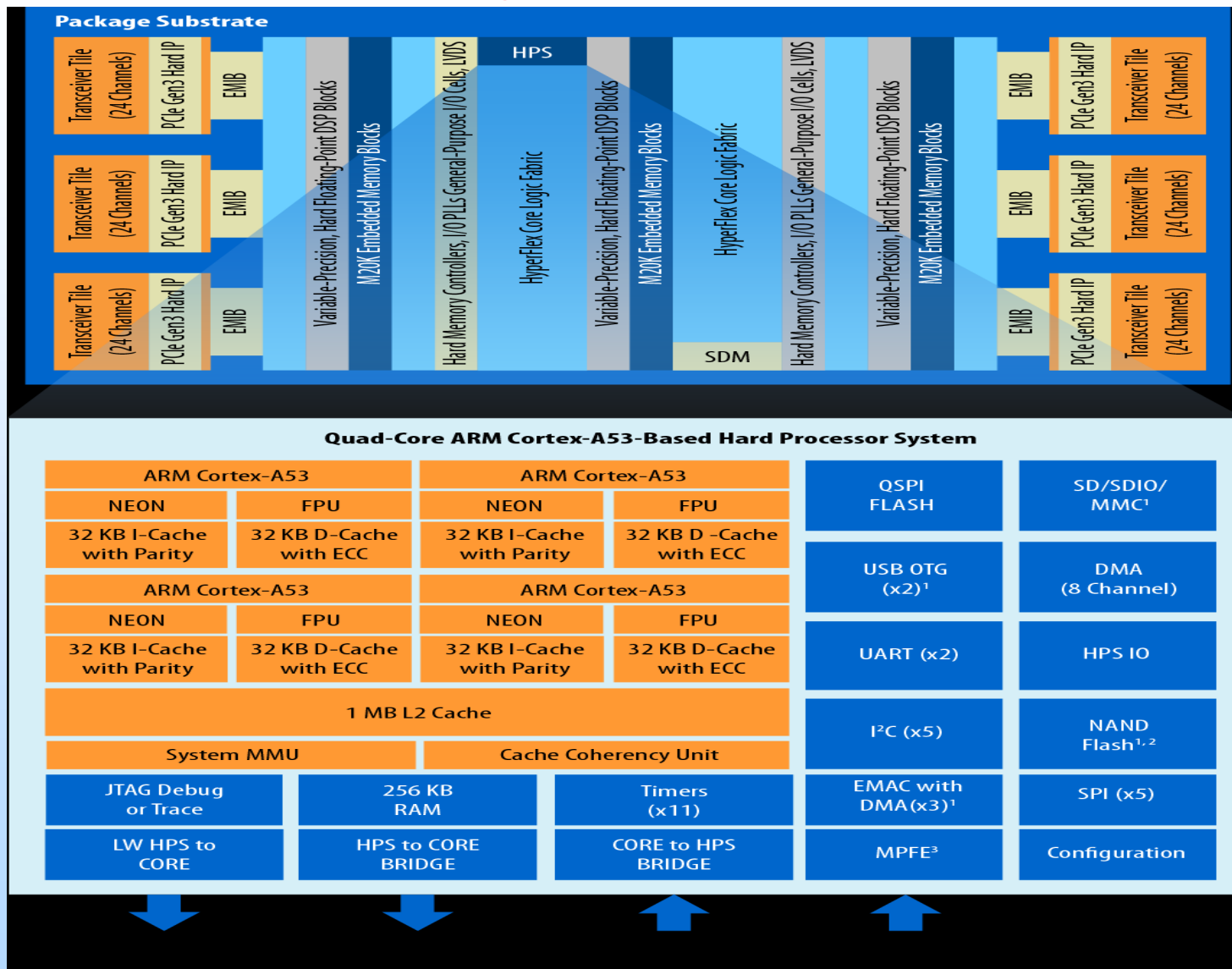
Xilinx Zynq UltraScale+



- **New Entry into the Aerospace Market with COTS Expectation**
 - 16nm vertical process (TSMC)
- **Multi-Processor System on a Chip (MPSoC) family.**
- **Prototype evaluation board will be purchased for early design development and early latch-up testing.**
- **Planning to receive parts in fall of 2016.**
- **Custom daughter (DUT) cards will be built (date TBD).**
- **Phase I tests (date TBD):**
 - Evaluation board latch-up investigation.
- **Phase II tests (date TBD):**
 - Shift registers, counters, PLLs, and DSPs.
 - Use of Synopsis tool for mitigation insertion.
- **Phase III tests (TBD):**
 - High speed serial interfaces (TBD), embedded processors.

Altera Stratix-10 Figure

Figure is courtesy of Altera





Altera Stratix-10: The Entire Study is TBD

- **New Entry into the Aerospace Market with COTS Expectation**
 - Intel 14 nm Tri-Gate process.
- **Integrated quad-core 64 bit ARM Cortex-A53 hard processor system.**
- **Prototype evaluation board will be purchased for early design development and early latch-up testing.**
- **Planning to receive parts (TBD).**
- **Custom daughter (DUT) cards will be built (date TBD).**
- **Phase I tests (date TBD):**
 - Evaluation board latch-up investigation.
- **Phase II tests (date TBD):**
 - Shift registers, counters, PLLs, and DSPs.
 - Use of Synopsis tool for mitigation insertion.
- **Phase III tests (TBD):**
 - High speed serial interfaces (TBD), embedded processors.



Conclusions

- **NEPP has provided and will continue to investigate:**
 - **New accelerated-radiation test methodologies for FPGA devices and embedded hard-IP (e.g., processors).**
 - **Mitigation strategies specific to FPGA types and how to measure their efficacy for meeting project requirements.**
- **NEPP continues independent investigation of various FPGA devices:**
 - **Destructive mechanisms and SEL.**
 - **SEU characterization.**
 - **Total Ionizing Dose (TID) characterization.**



Acknowledgements

- **Supporters:**
 - Defense Threat Reduction Agency (DTRA)
 - NASA Electronics Parts and Packaging (NEPP) Program
- **Current Collaborators:**
 - Xilinx,
 - Microsemi,
 - Altera,
 - Synopsis,
 - Cobham,
 - Harris,
 - Honeywell,
 - Aerospace Corporation,
 - NASA Space Launch System (SLS) mission, and
 - NASA Transiting Exoplanet Survey Satellite (TESS) mission.