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SpaceFibre Radiation Testing on Versal

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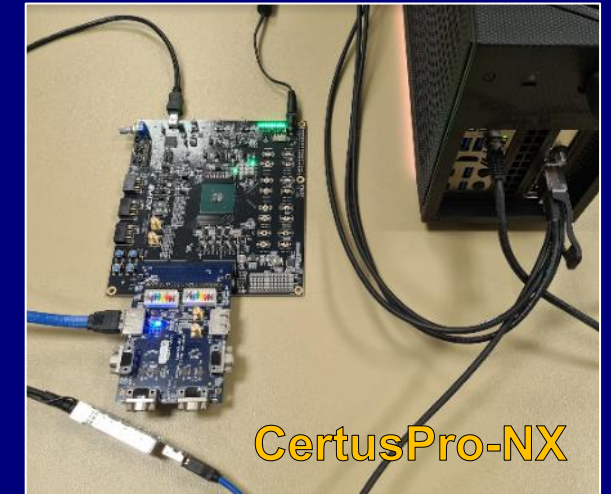
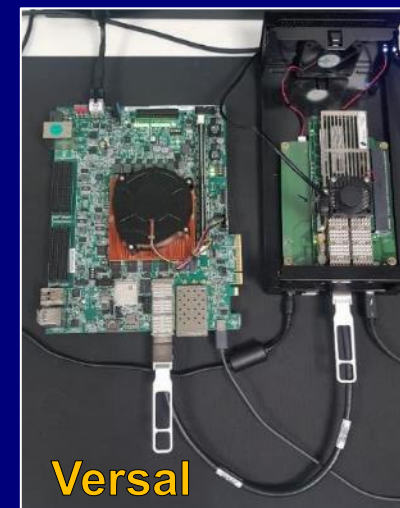
Introduction

Radiation Campaign Objectives

- Detailed measurement of radiation effects
 - A. Determine source of the event
 - Versal Transceiver
 - E.g. Datapath, PLLs
 - FPGA fabric
 - E.g. CRAM, Block RAM...
 - B. Effect of the event, consequences of the SEEs
- Evaluation of radiation mitigation measures
 - Distributed TMR (DTMR), Local TMR (LTRM), CRAM scrubber (XilSEM)
 - SpaceFibre Protocol and STAR-Dundee SpFi IP
 - Software-compatible with SpaceWire, over copper or fibre, integrated in SpaceVPX, ADHA and SpaceVNX+
 - Automatic error detection, isolation, and recovery in $< 4 \mu\text{s}$ (e.g. bit-flips, burst errors and loss of lock)
 - Automatic transceiver reset and link reconnection on persistent failures
 - Multi-lane operation
 - Arbitrary number of lanes with graceful degradation when a lane fails
 - Hot and warm redundancy

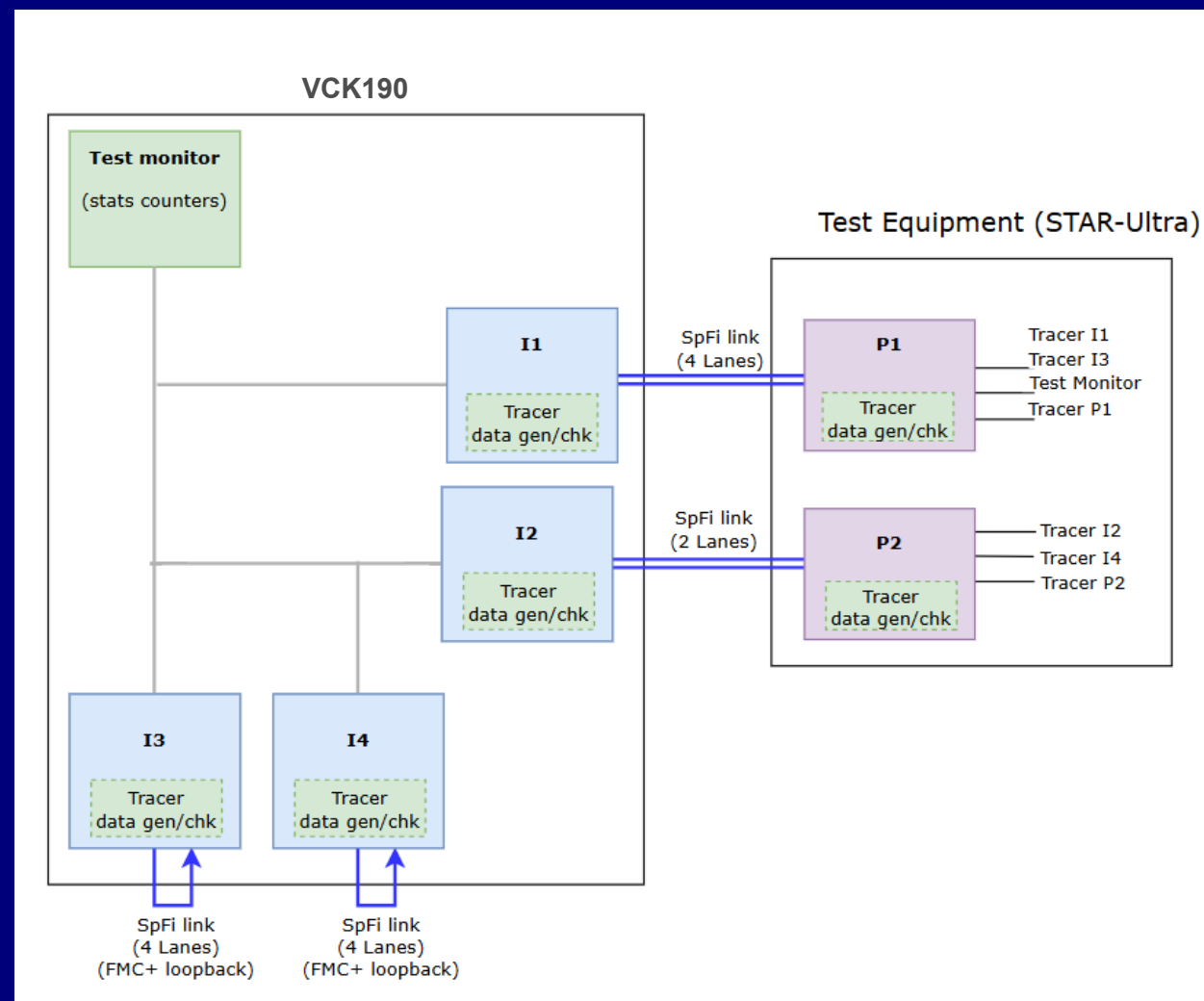
STAR-Dundee SpaceFibre Interface IP

- Small footprint and highly optimised
 - Enables using LTMR or **DTMR**, and **100G** links
- Flexible
 - Lanes can be mapped to different transceiver quads simply using a configuration file
- Easy to use
 - AXI4-Stream interfaces support arbitrary packet length
 - No specialized knowledge of SpFi standard required
 - **Transceiver is encapsulated** within IP Core
 - No specialized knowledge of FPGA transceiver is required
 - Reference designs for space-qualified FPGAs
- **TRL-9**
 - 6+ operational missions
 - 60+ under design



Radiation Test Design

- Four SpaceFibre links
 - A quad-lane link and dual-lane link connected to test equipment
 - Two quad-lane links in loopback
- All links except one loopback link at 6.25 Gbps per channel (25G)
- One loopback quad-lane link at 25 Gbps per lane/channel (100G)
- Each link has a “Tracer” and a data generator/checker
- A Test monitor block contain status and control registers with counters to gather statistics

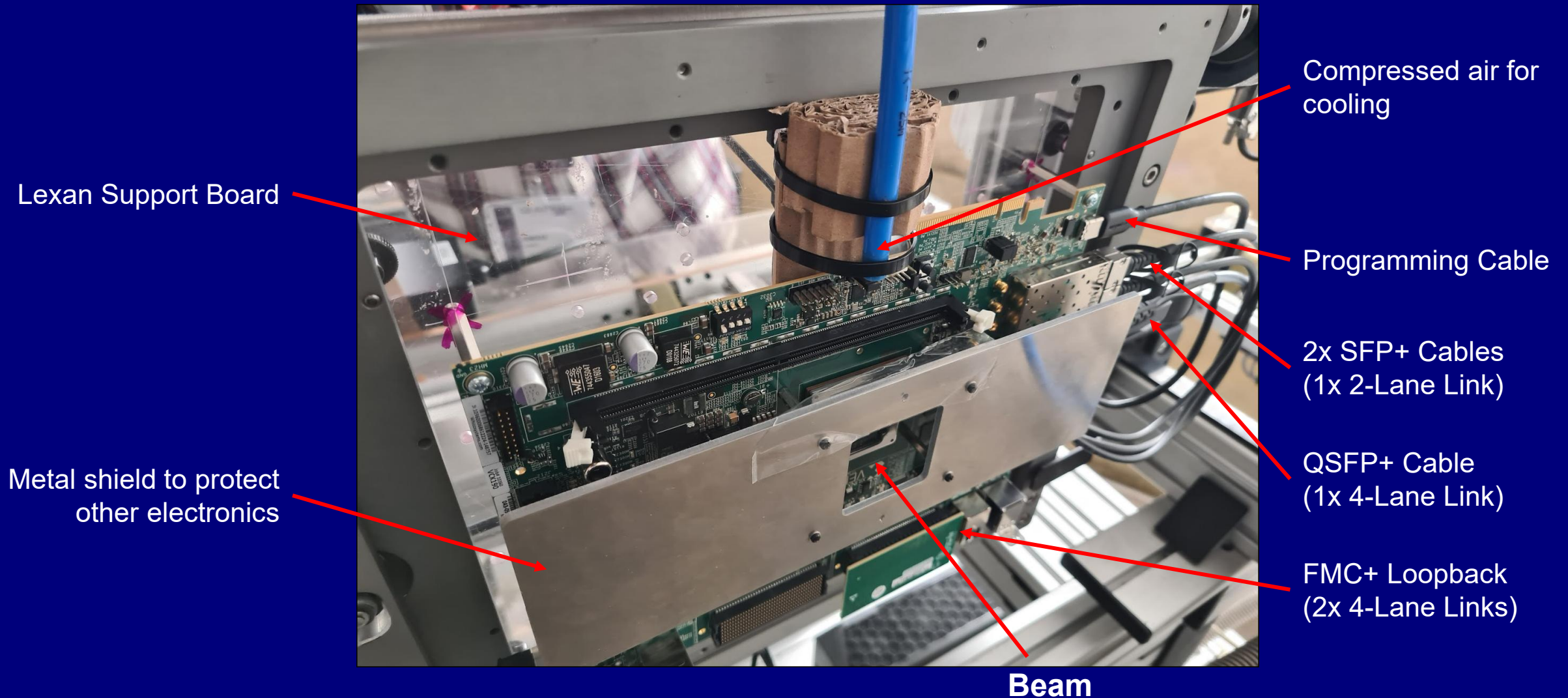


Radiation Test Facilities

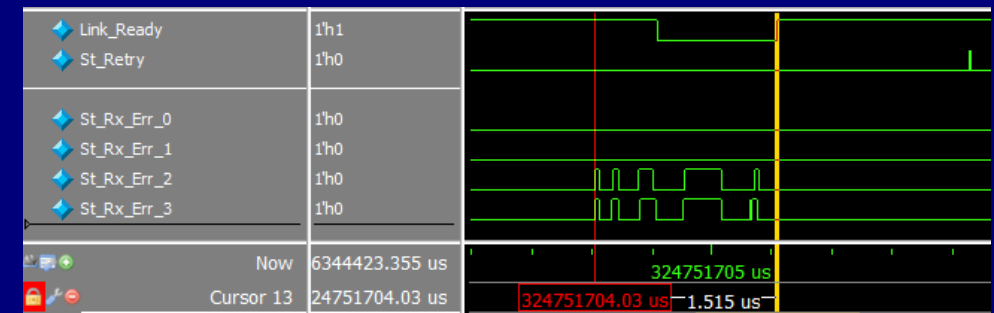
- Test campaign carried out at GANIL (Caen, France) facility
 - Two separate 8-hour runs on Q4 2024
 - In-air testing, plus several Aluminium foil thickness available to modify the effective LET
 - LETs tested were 28, 32 & 43 MeV·cm²/mg (¹²⁹Xe - 46.77 MeV/u)
- STAR-Barcelona were responsible for the tests
 - STAR-Dundee's wholly-own subsidiary based in Barcelona
 - Team has extensive radiation test experience (e.g. VHiSSI ASIC, RTG4, PolarFire)



Hardware Set-up at GANIL



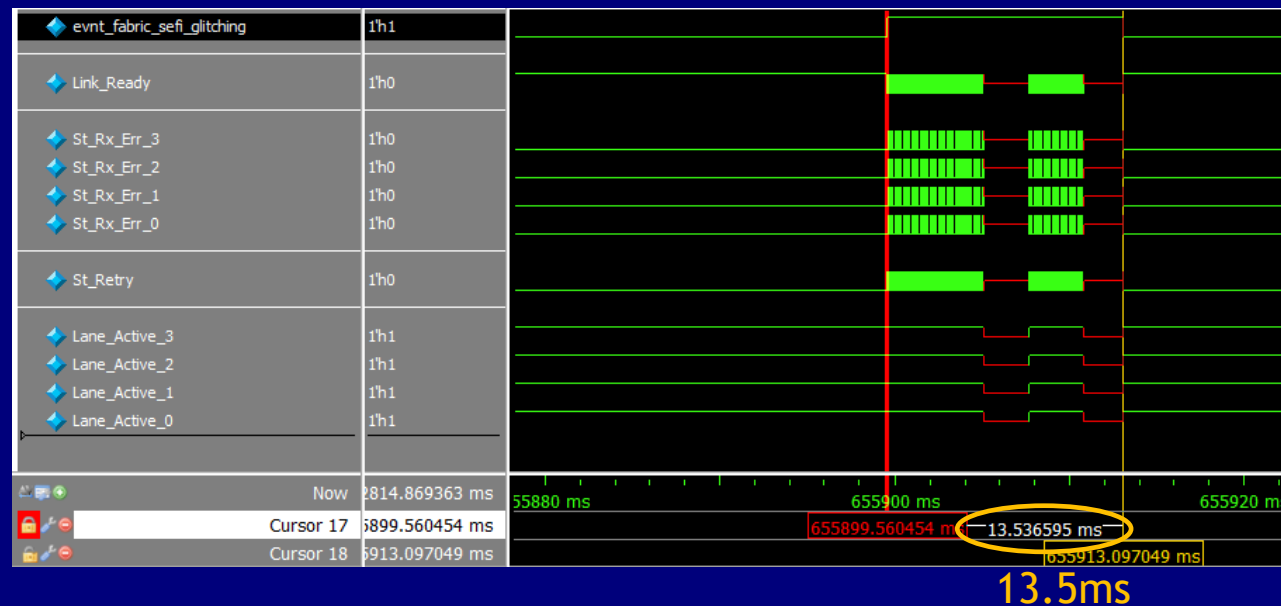
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- The screenshot shows the BMAP Configurator application. The interface includes a 'Registers' panel on the left with a list of registers and their values. Below this is the 'debug_vmsd_test_suite' section, which contains a 'Channel 3' dropdown menu, a 'Test Path' input field, and a 'Return Path' input field. To the right of the registers is a 'Field Description' panel showing a list of fields and their descriptions. At the bottom, there is a 'Log Messages' section with a 'Clear' button and a 'Run' button. The 'Run' button is highlighted in red.



Radiation Events

FPGA fabric events

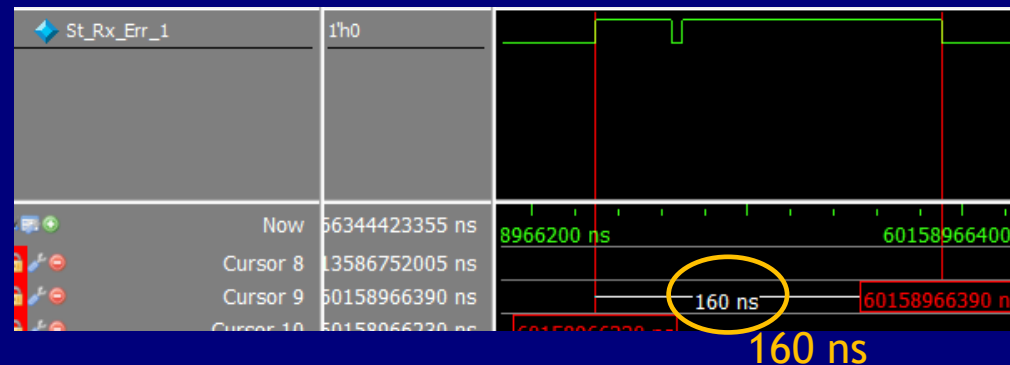
- FPGA fabric SEEs on a SpaceFibre link
 - Caused by SEUs in CRAM used by the SpFi link logic
 - Fixed by XilSEM in < 15 ms
 - Around **an order of magnitude less events** than the ones related with a transceiver Quad
- Example that causes multiple signals to flicker, overflowing the Tracer buffer (in red)



Datapath Transceiver Event

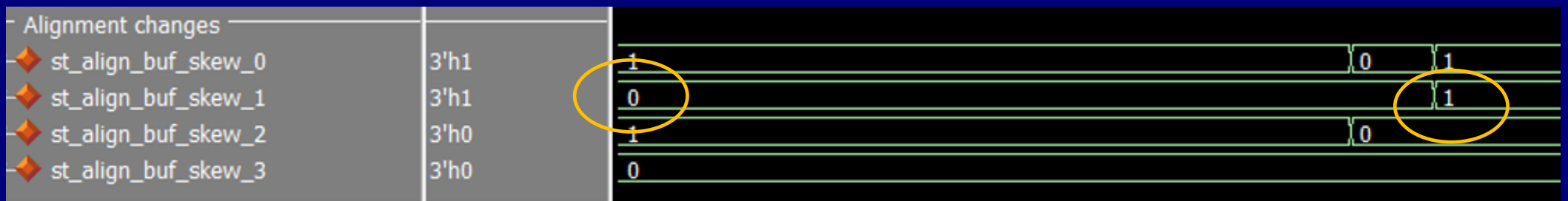
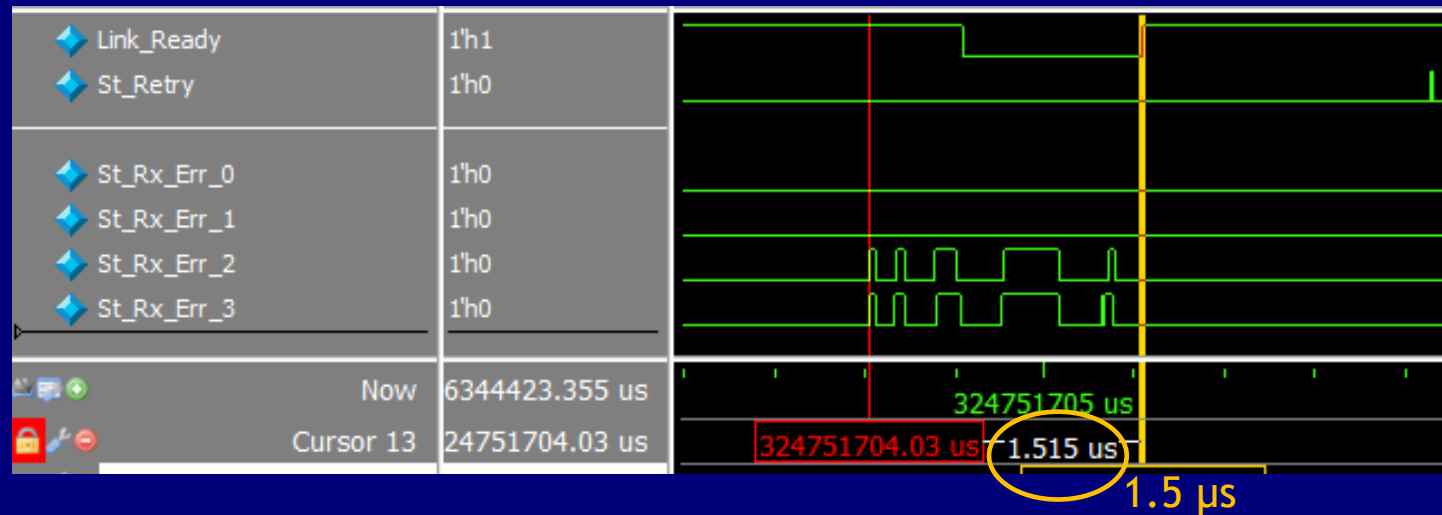
- Example of short error burst of 160 ns
 - SpaceFibre error recovery automatically resends the frames affected

◆ Lane_Active_0	1'h1
◆ Lane_Active_1	1'h1
◆ Lane_Active_2	1'h1
◆ Lane_Active_3	1'h1
◆ Link_Ready	1'h1
◆ St_Retry	1'h0
◆ St_Rx_Err_0	1'h0
◆ St_Rx_Err_1	1'h0
◆ St_Rx_Err_2	1'h0
◆ St_Rx_Err_3	1'h0



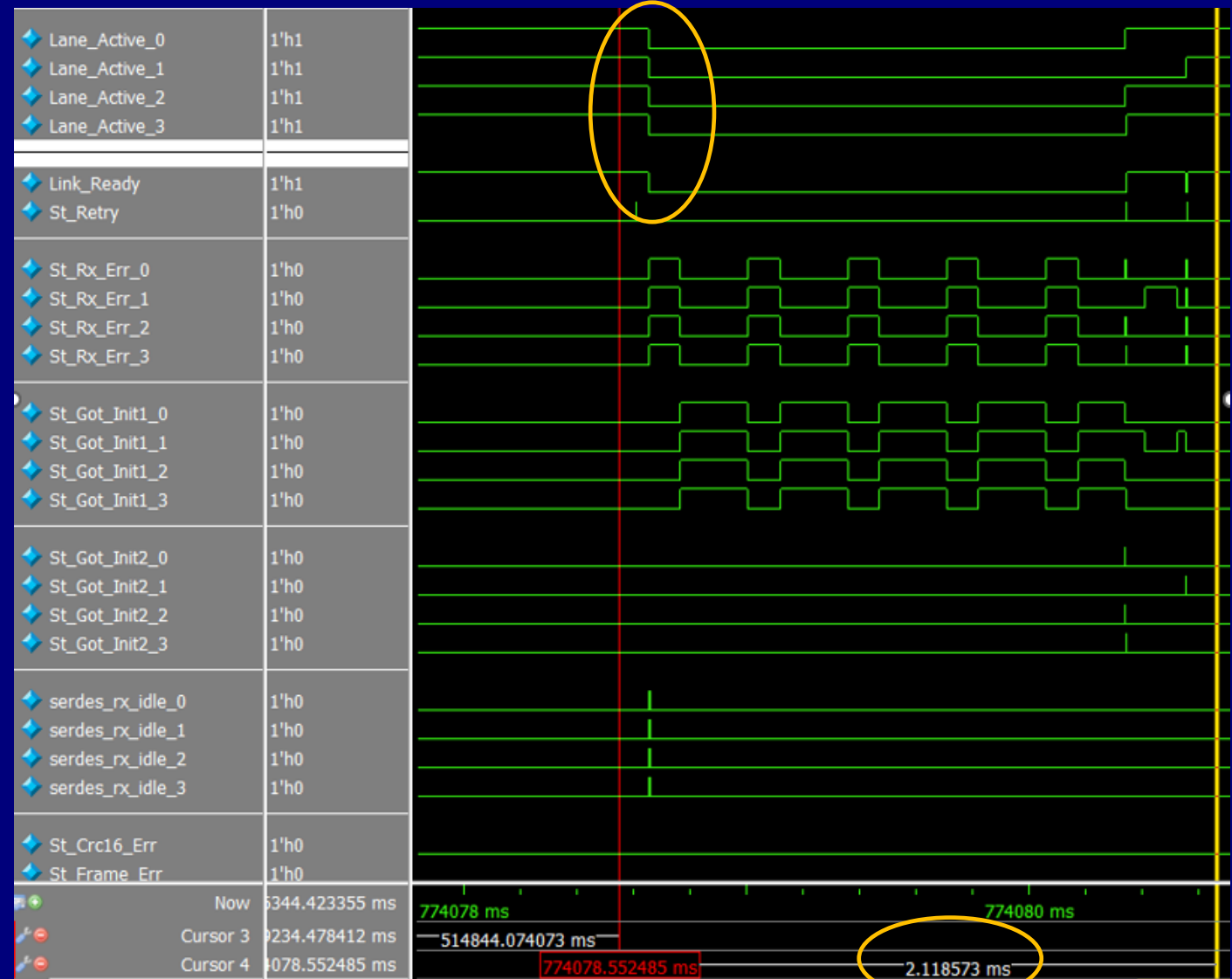
PLL Transceiver Event

- Errors on 2 lanes/channels used by the same PLL
 - Modification of skew between lanes requires lanes to be realigned again
 - SpaceFibre automatically executes link realignment in $< 2 \mu\text{s}$



Quad Transceiver Event

- Few events required the SpFi IP to execute a transceiver quad reset
 - A transceiver lane reset takes ~1.5 ms
 - Example of this event at the far-end of the link (Tester)

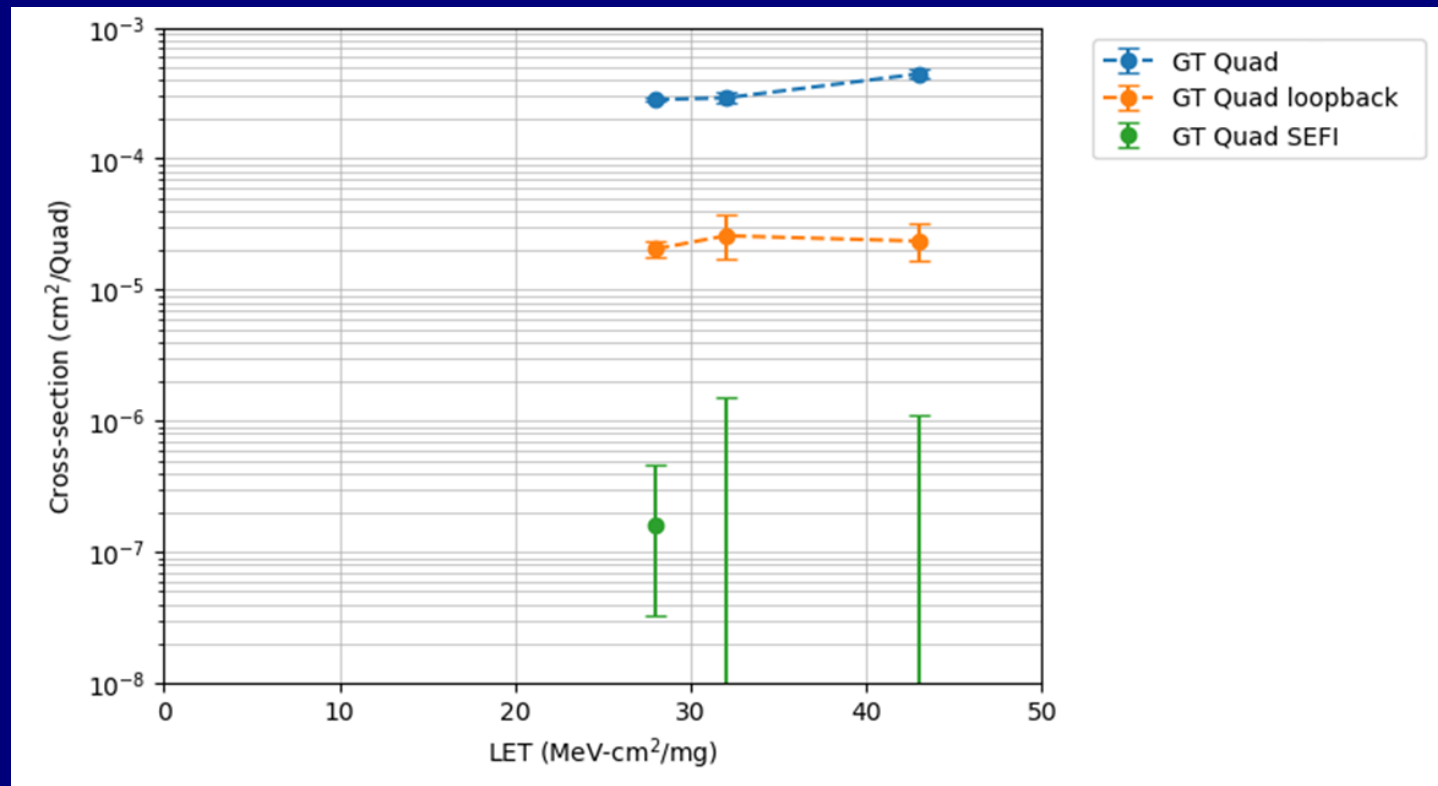


2.1 ms

Transceiver Cross-Sections

Versal Transceiver GT Quad

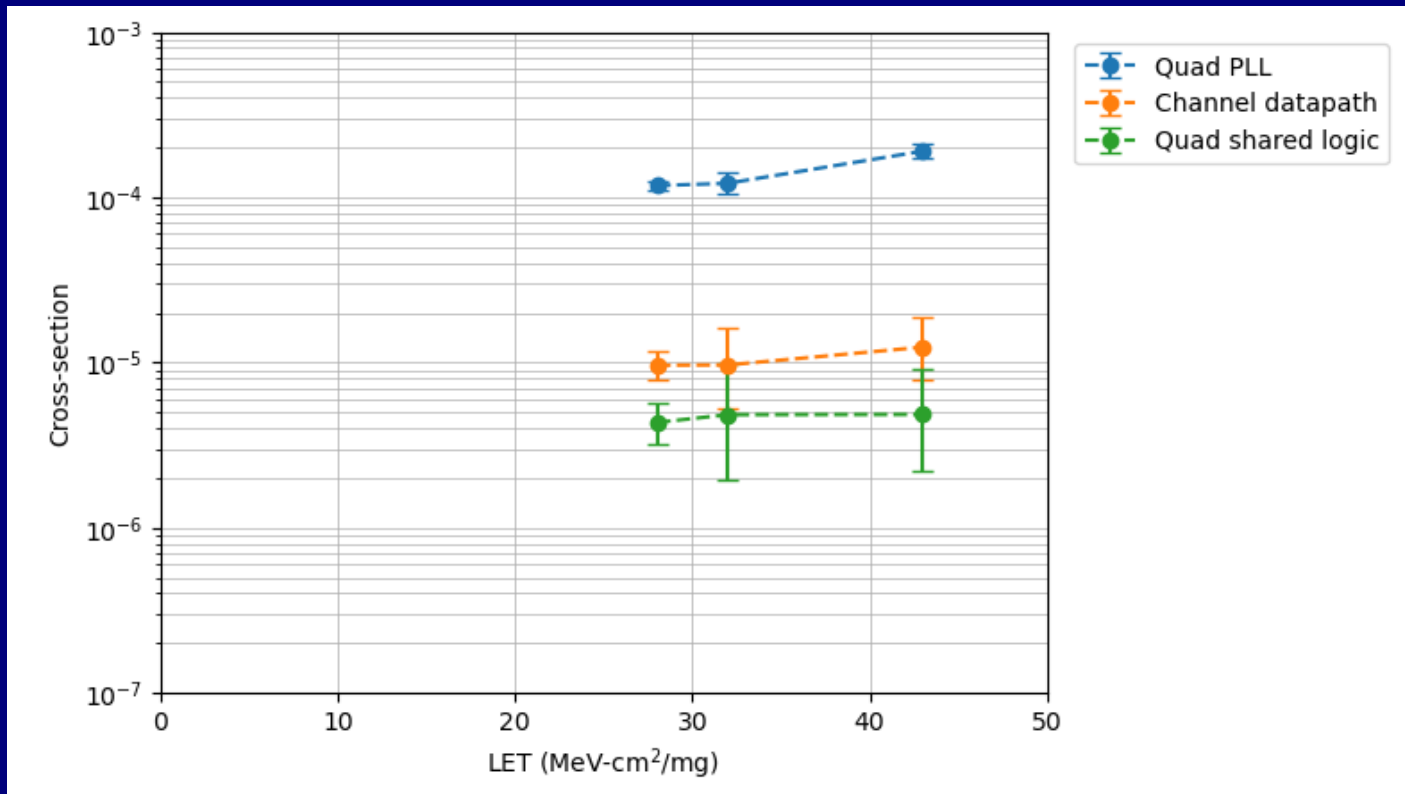
- When the transceiver is in loopback there are much less (~10x) SEUs
- A few transceiver SEFIs were observed, in which a full transceiver reset did not recover one or more failing lanes of the link, and reprogramming the FPGA was required



Loopback cross-section results are not relevant to real applications

Versal Transceiver GT Quad Elements (Non-Loopback)

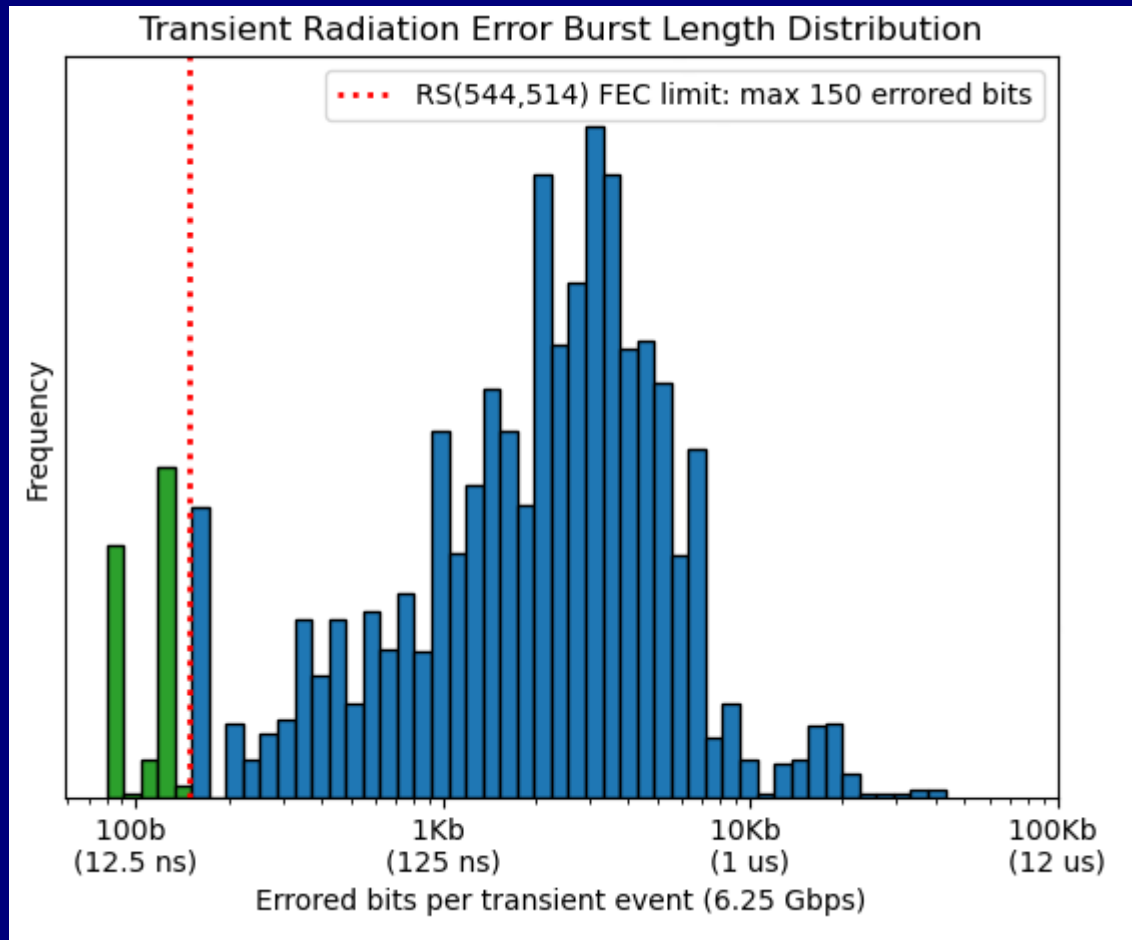
- The “Quad PLLs” (i.e. LCPLL) are the most SEU sensitive transceiver element when not in loopback
 - They are 10 times more likely than errors in the “Channel Datapath”
 - They produce small burst errors and may change the skew between lanes
- SEUs on “Quad shared logic” require full transceiver reset, which takes ~1.5ms



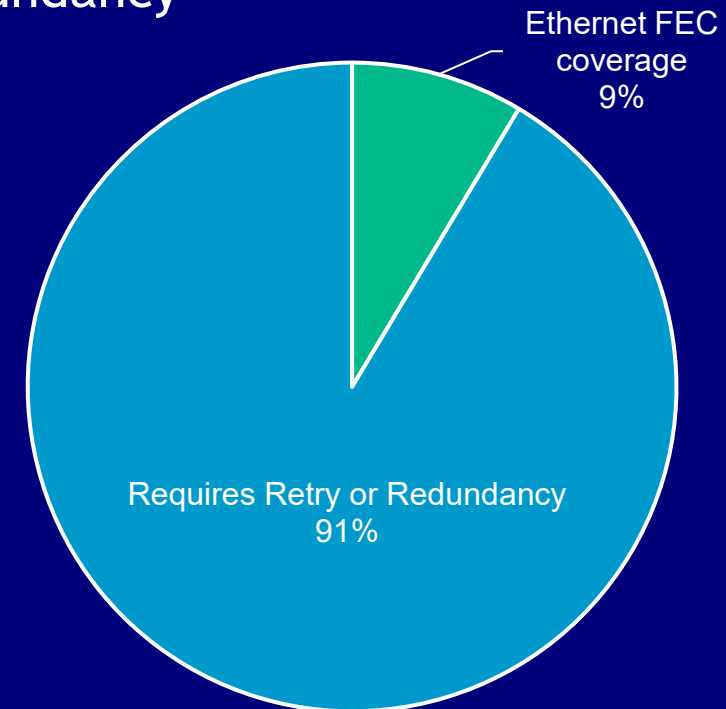
~99% of SEUs produce burst errors that last only a few microseconds.

Link Radiation Effects

Radiation-Induced Error Burst Length vs. RS FEC Capability

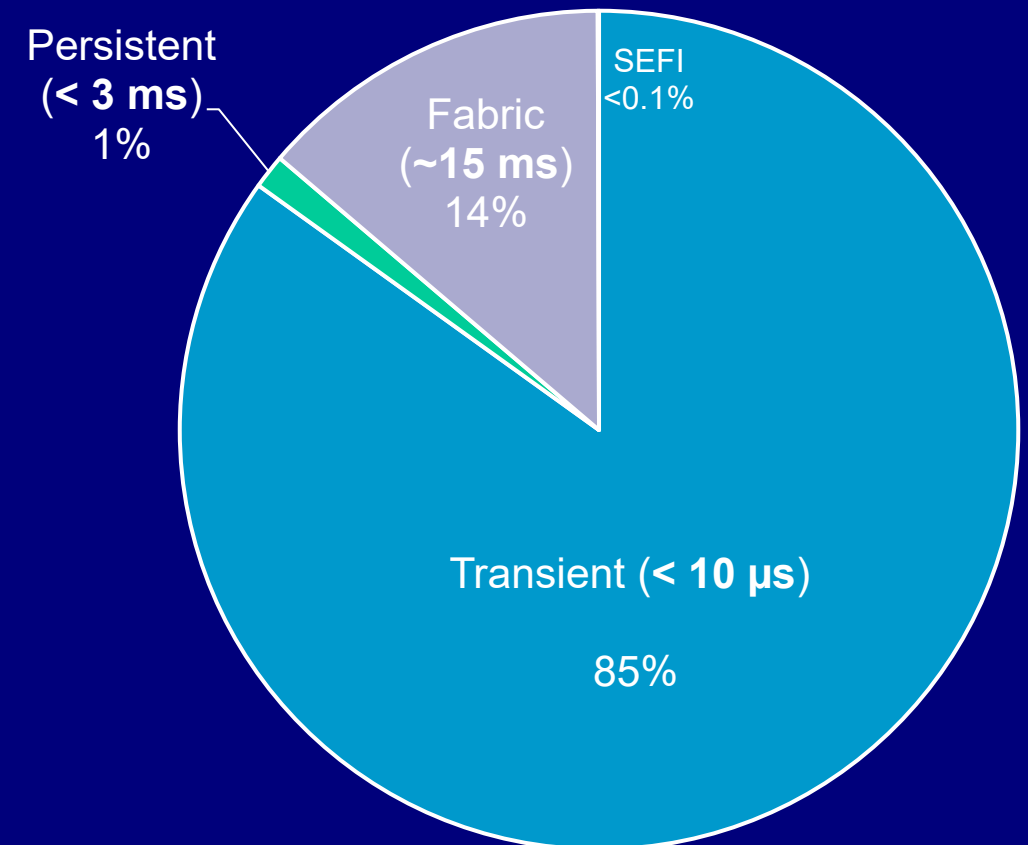
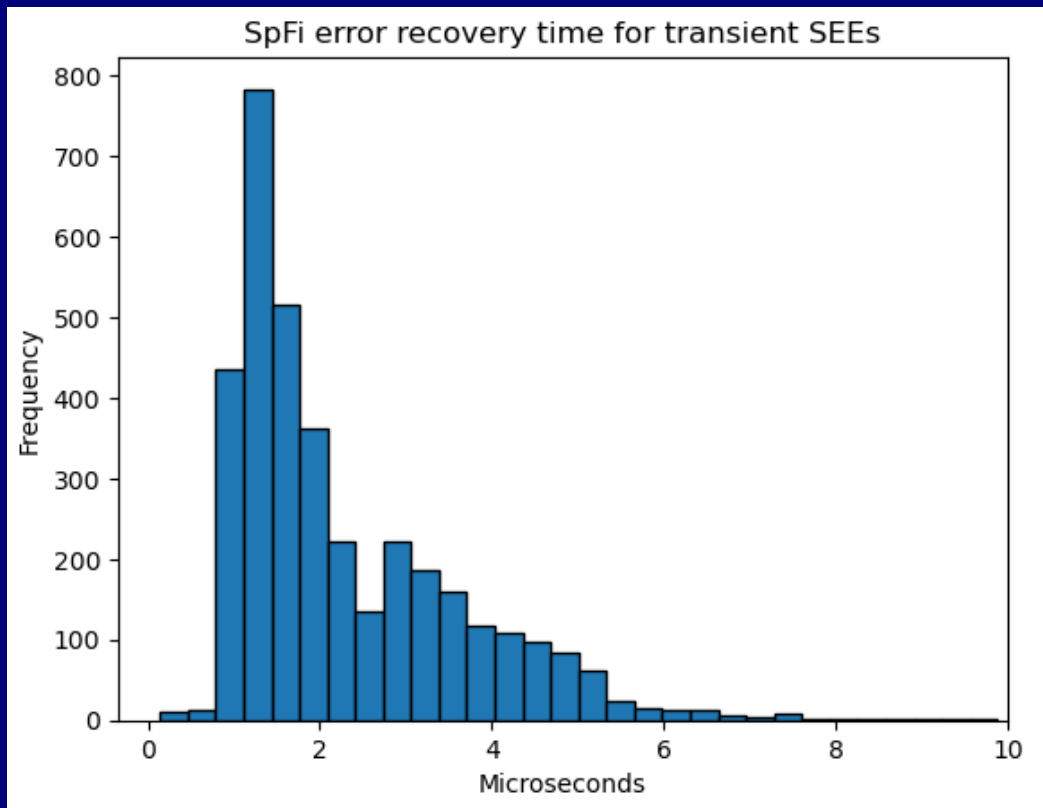


Most errors can not be corrected by Forward Error Correction and require a reliable link (i.e. SpFi) or hot link redundancy



SpaceFibre Link Error Recovery Time

Measurements confirm that transient errors due to SEEs in transceiver's PLLs or Datapath are recovered automatically by SpaceFibre protocol in a few microseconds without user data loss.



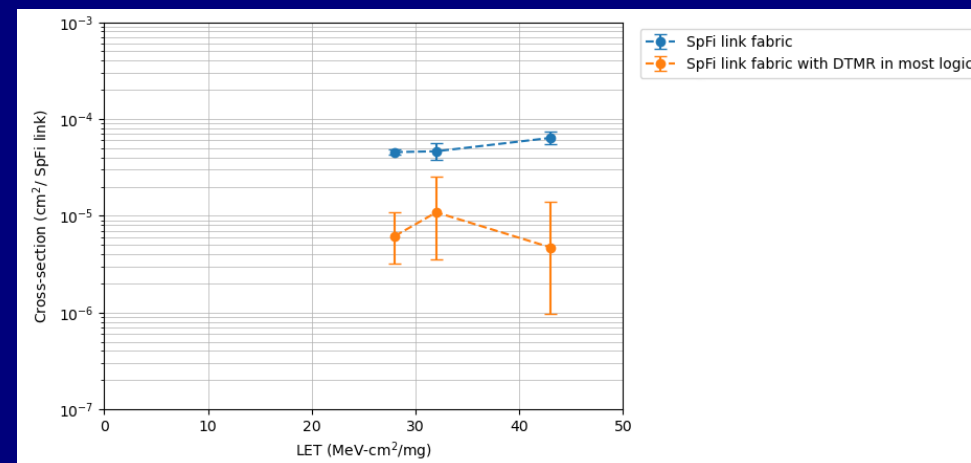
TMR on SpFi Link Fabric

- DTMR was applied in some runs using Synplify Elite
 - It did not cover the data generator/checkers (~12% of total logic)
 - Applying DTMR results in a significant resource penalty → small footprint is essential

- DTMR significantly reduced the cross section
 - The cross section was reduced by a factor of 10, similar as the expected cross section of logic without DTMR

- LTMR did not provide significant benefits

	XQRVC1902 – Nominal			XQRVC1902 – DTMR		
	LUT	DFF	RAMB36	LUT	DFF	RAMB36
Single-Lane 1 VC	1797 0.2%	2151 0.1%	4 0.4%	11555 1.3%	6459 0.4%	12 1.2%
Single-Lane 2 VCs	2164 0.2%	2604 0.1%	6 0.6%	14487 1.6%	7713 0.4%	18 1.9%
Quad-Lane 1 VCs	5456 0.6%	6726 0.4%	12 1.2%	42130 4.7%	23949 1.3%	36 3.7%
Quad-Lane 4 VCs	6980 0.8%	9375 0.5%	30 3.1%	61492 6.8%	31557 1.8%	90 9.3%



Conclusions

- High LET campaign was performed on Versal with nanosecond accuracy data collection
 - Allows to measure error bursts length precisely and identify the source of SEEs within the transceiver
- Versal with SpFi links is an excellent combination of robustness and high-performance
 - SpFi automatically recovers, without data loss, from all non-SEFI events affecting the transceiver
 - Vast majority of SEEs on transceiver last only a few microseconds
 - SpaceFibre link transparently deals with them in a few microseconds without user intervention
 - A SpFi link is mainly affected by SEEs on fabric
 - Embedded XilSEM recovers from CRAM SEUs in around 15 ms, with SpFi link self-recovering a few ms afterwards
 - Data loss may occur during this process as SpFi reset is required.
 - Applying DTMR to the SpFi IP prevents most fabric events caused by radiation and its associated data errors
 - Without DTMR, SpFi link cross-section is still an order of magnitude lower than when using Ethernet or other non-reliable protocols, which are highly affected by SEUs on transceiver
- Successful testing of a SpFi link running at 100 Gbps (4x 25 Gbps)

Acknowledgments

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- We would like to acknowledge GANIL's team for their support during the radiation test campaign.
- We would like to acknowledge Synopsys for their support with Synplify Elite, used to apply TMR to the SpaceFibre IP Core.