SEFUW: SpacE FPGA Users Workshop

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STAR-Barcelona

A STAR-Dundee Company

20 Years of Spacecraft Networking Innovation

AMD

Evaluating AMD Versal FPGAs and SpaceFibre Under Heavy-Ion Radiation

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Introduction

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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 µs (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

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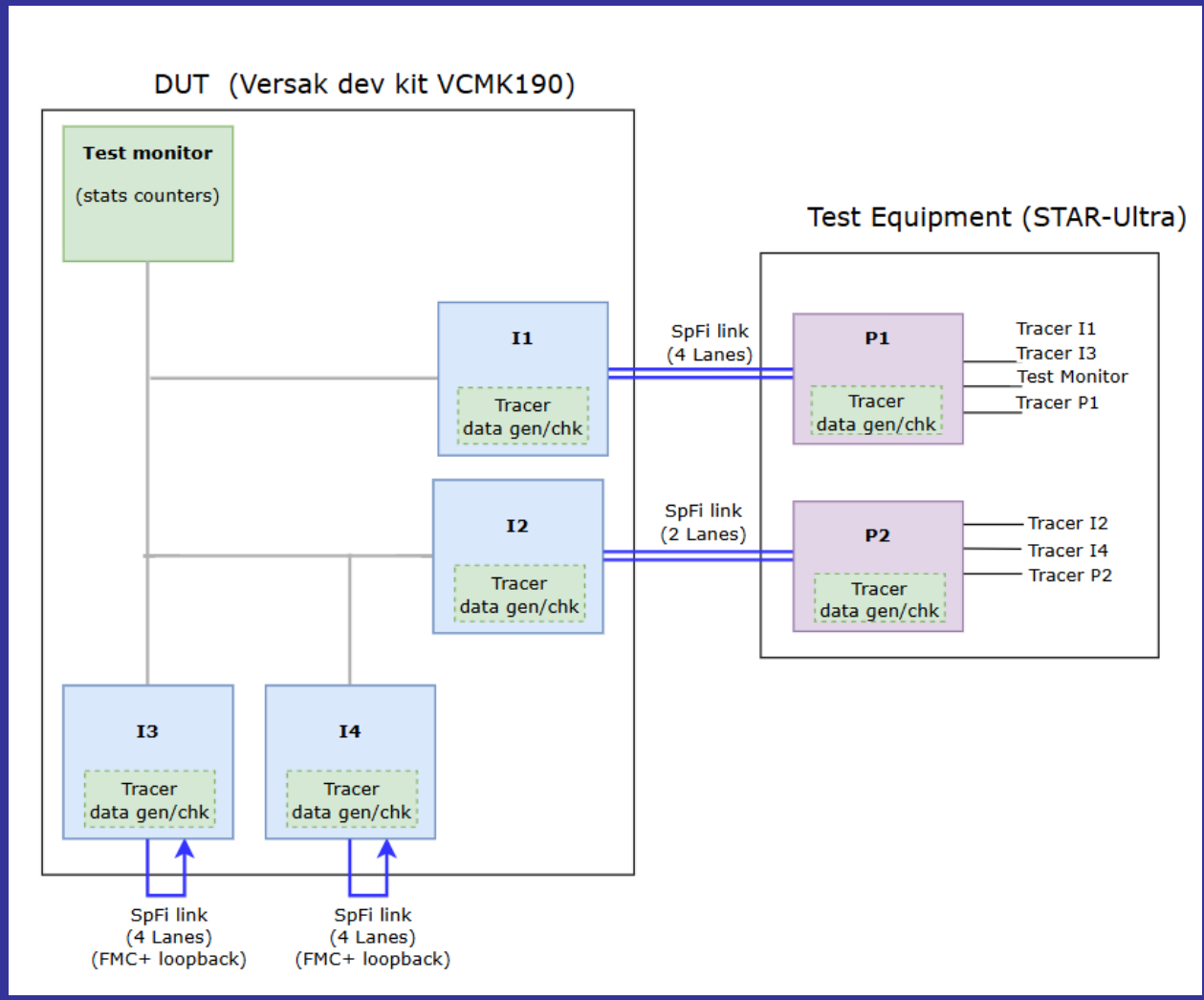
STAR-Dundee SpaceFibre Interface IP

- 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



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Radiation Test Facilities

- Test campaign carried out at GANIL (Caen, France) facility
  - Two separate 8-hour runs on the 25th and 26th of September 2024
  - In-air testing, plus several Aluminium foil thickness available to modify the effective LET
  - LETs tested were 28, 32 & 43 MeV·cm^2/mg (^{129}Xe – 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)

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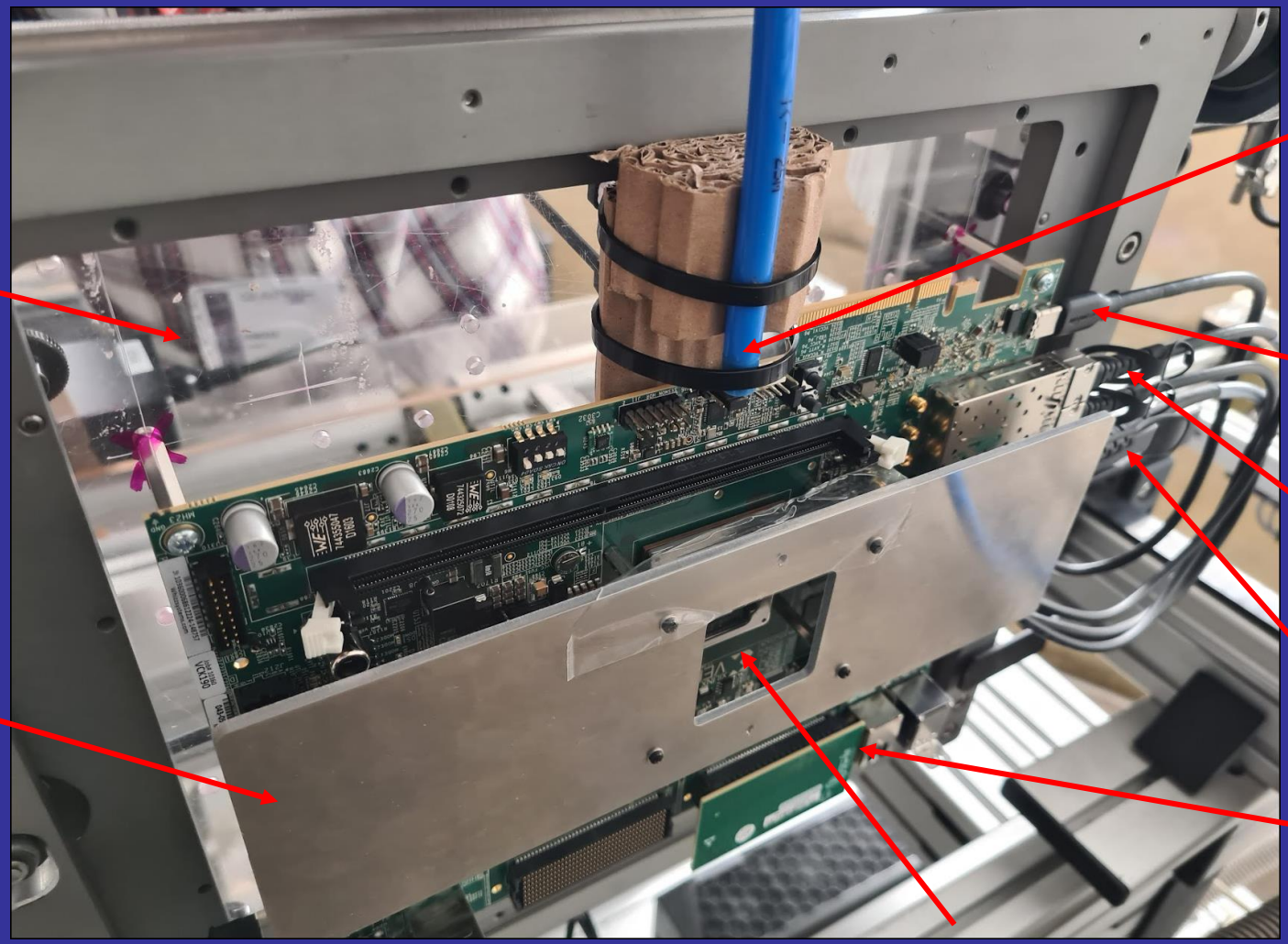
Hardware Set-up at GANIL



Lexan Support Board

Metal shield to protect other electronics

Compressed air for cooling

Programming Cable

2x SFP+ Cables (1x 2-Lane Link)

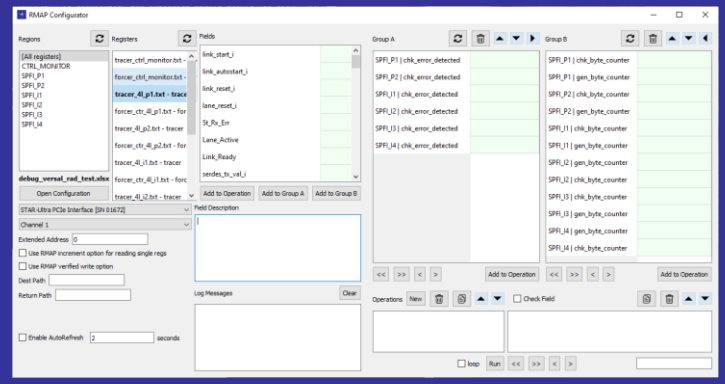
QSFP+ Cable (1x 4-Lane Link)

FMC+ Loopback (2x 4-Lane Links)

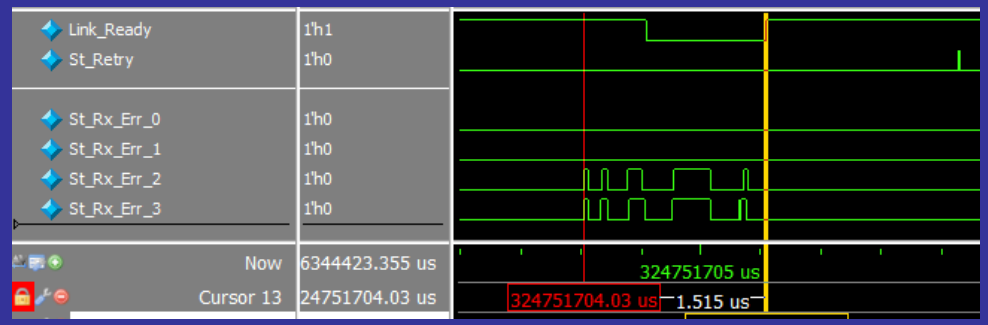
Beam

In-House Radiation Tools

- They are not specific to SpaceFibre/transceiver radiation testing. Can be used for other FPGA blocks
- They enable SEU event classification by source and effect



- Data acquisition (two independent measurements)
  - "The Monitor app"
    - SW that reads/writes status registers with counters
  - "The Tracer"
    - Embedded logic analyser within the FPGA
    - Stores samples with timestamps only when signals change
    - Nanosecond accuracy



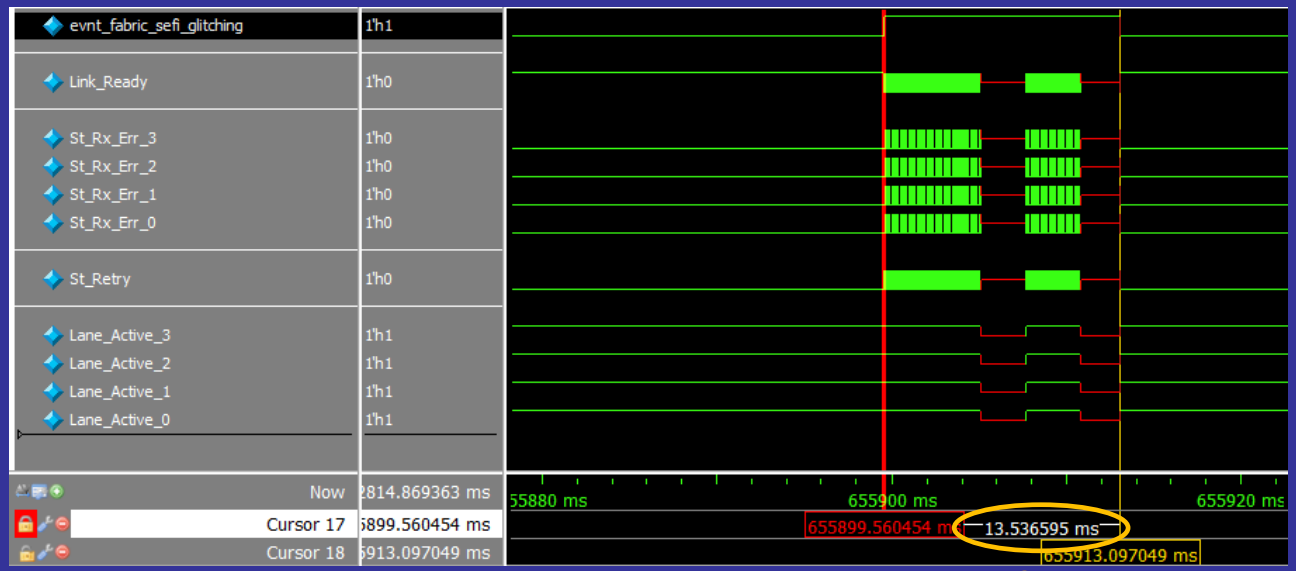
- Data processing
  - Event classifier
    - Executes scripts defining signal patterns for specific radiation events
  - Scientific python libraries tailored to radiation data

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

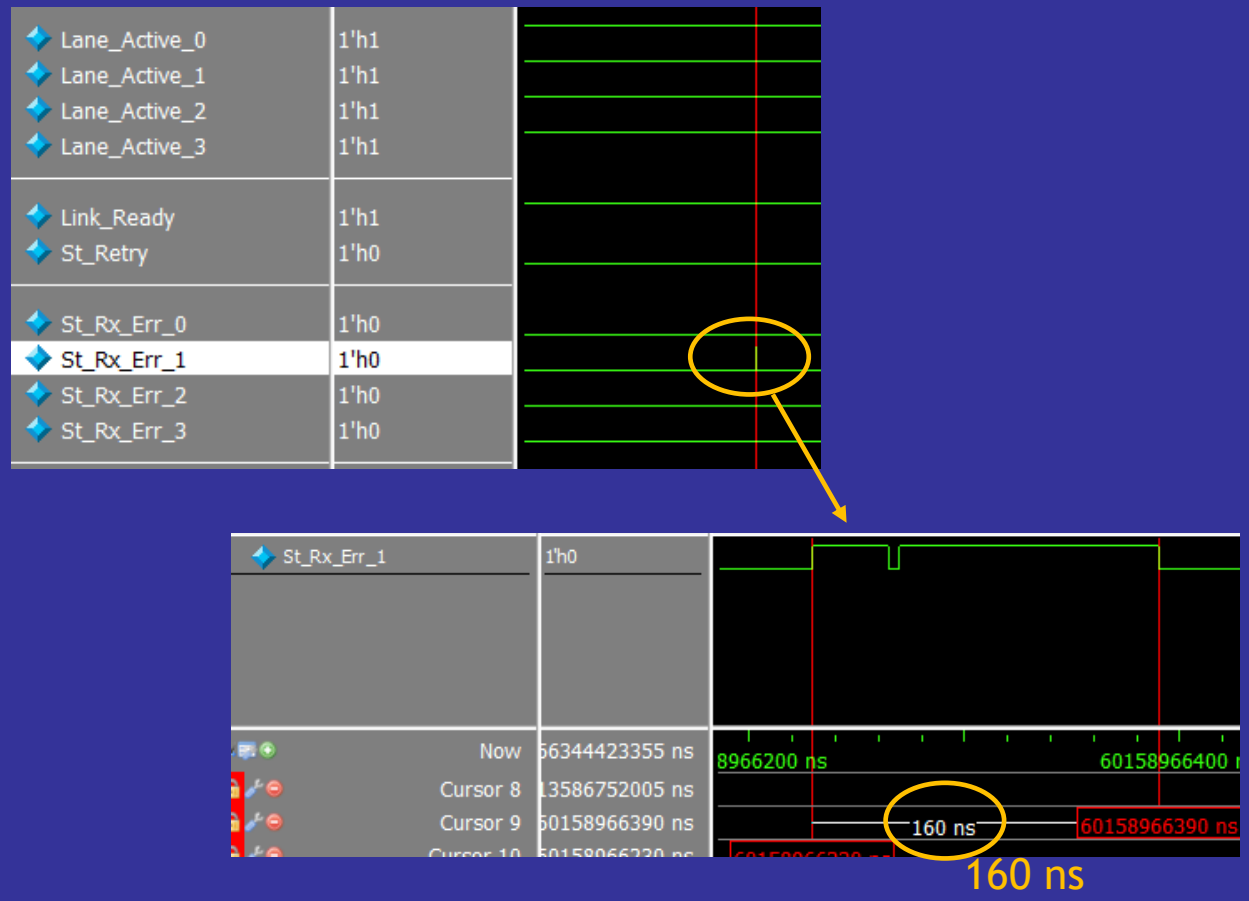
- Example that causes multiple signals to flicker, overflowing the Tracer buffer (in red)



13.5ms

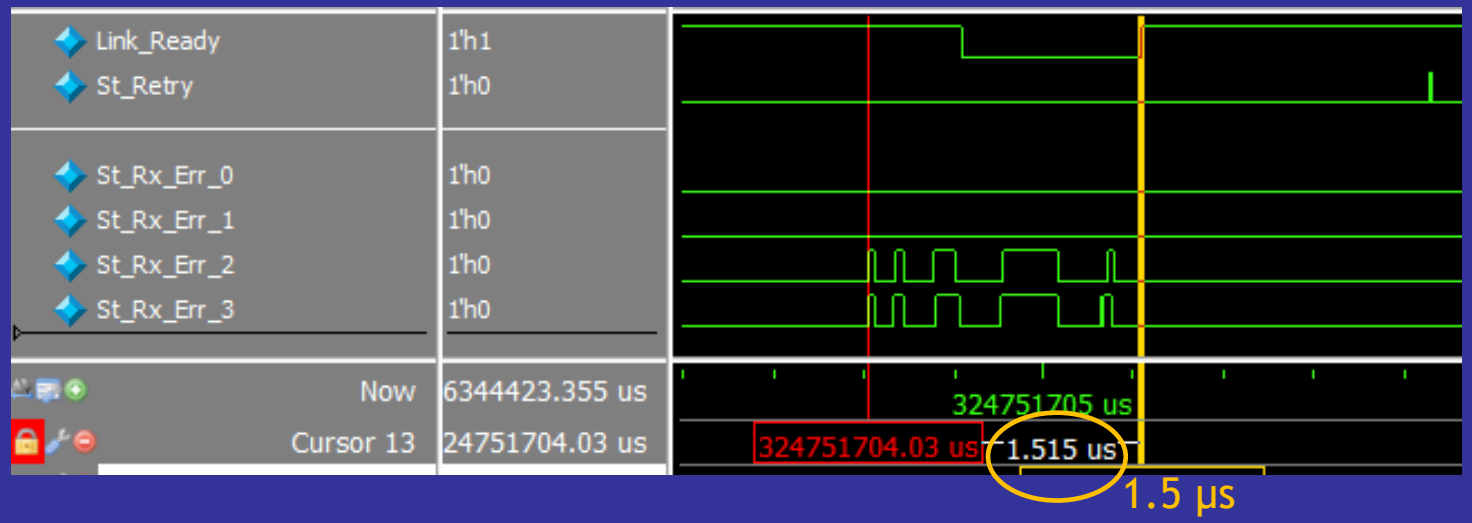
Datapath Transceiver Event

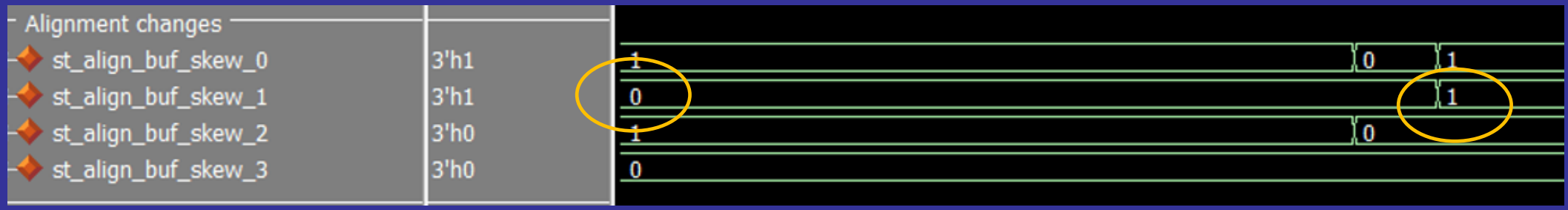
- Example of short error burst of 160 ns
  - SpaceFibre error recovery automatically resends the frames affected



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 us





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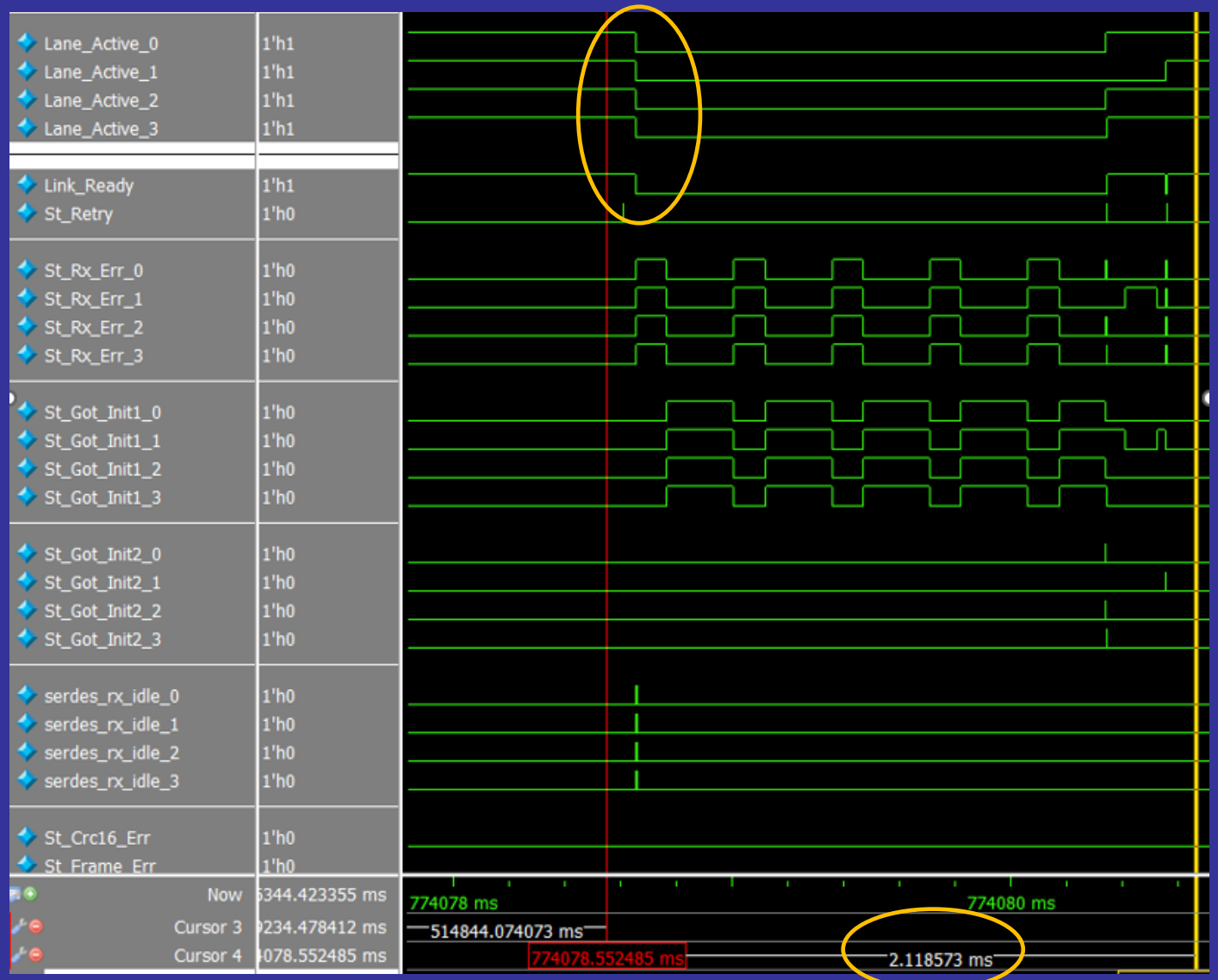
Quad Transceiver Event

- 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)

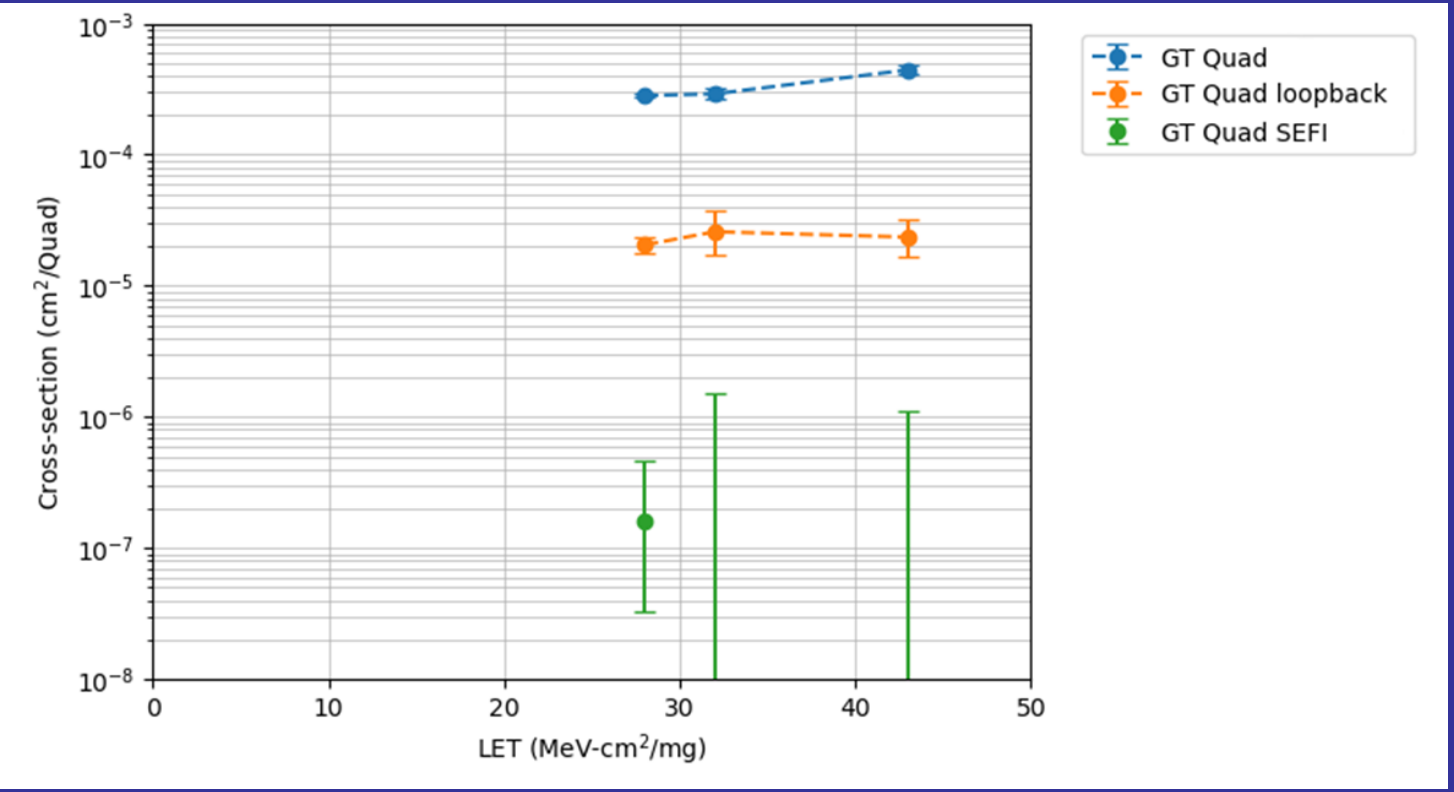


2.1 ms

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.

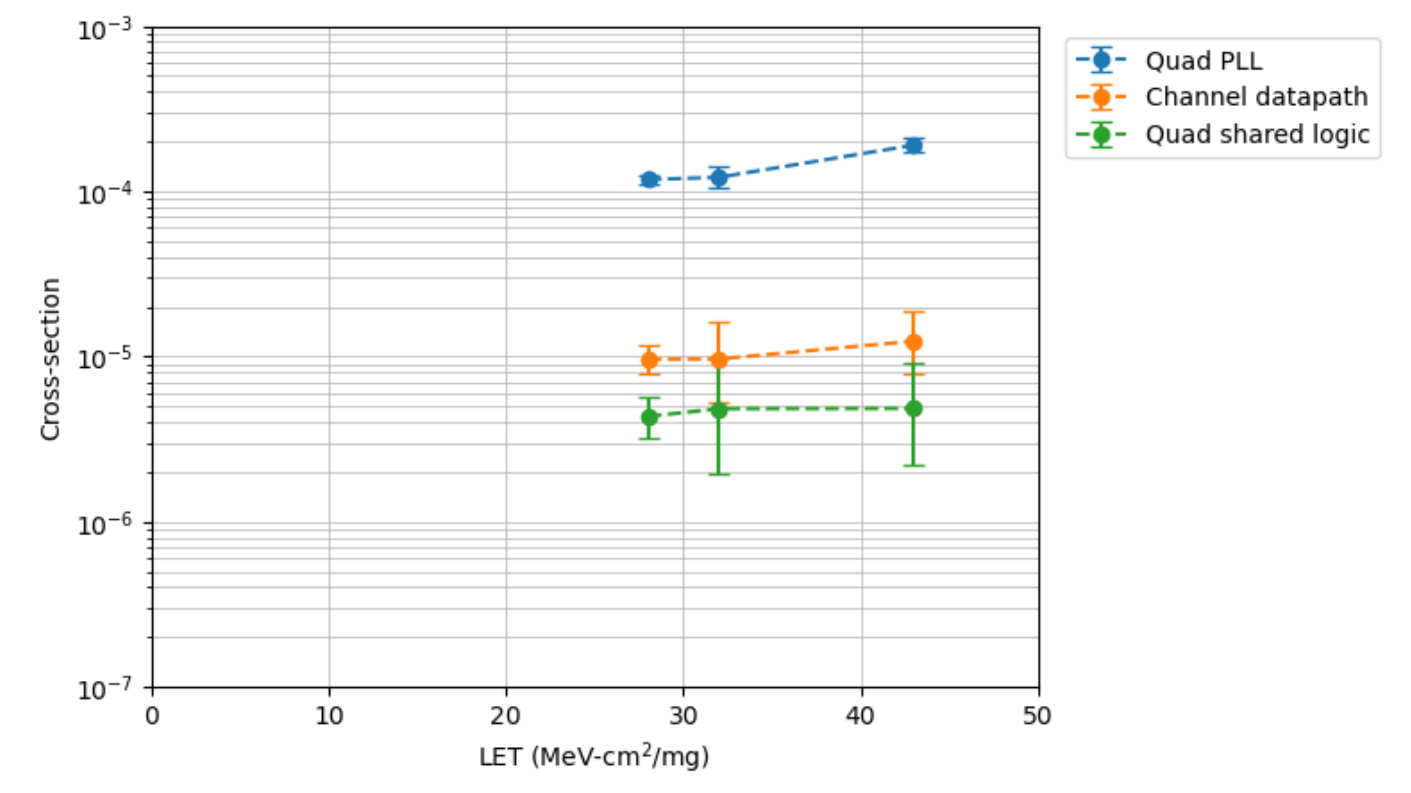


Loopback cross-section results are not relevant to real applications

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

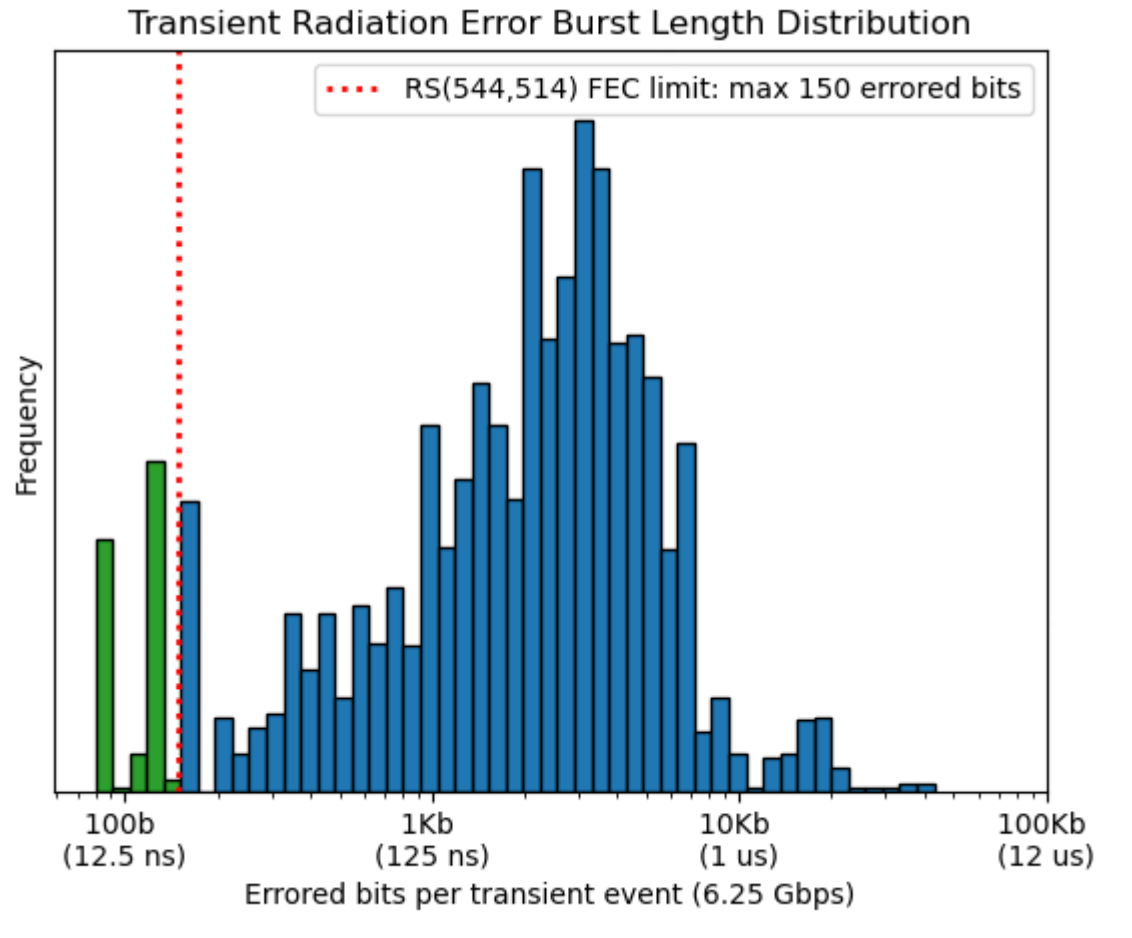
- SEUs on “Quad shared logic” require full transceiver reset, which takes ~1.5ms



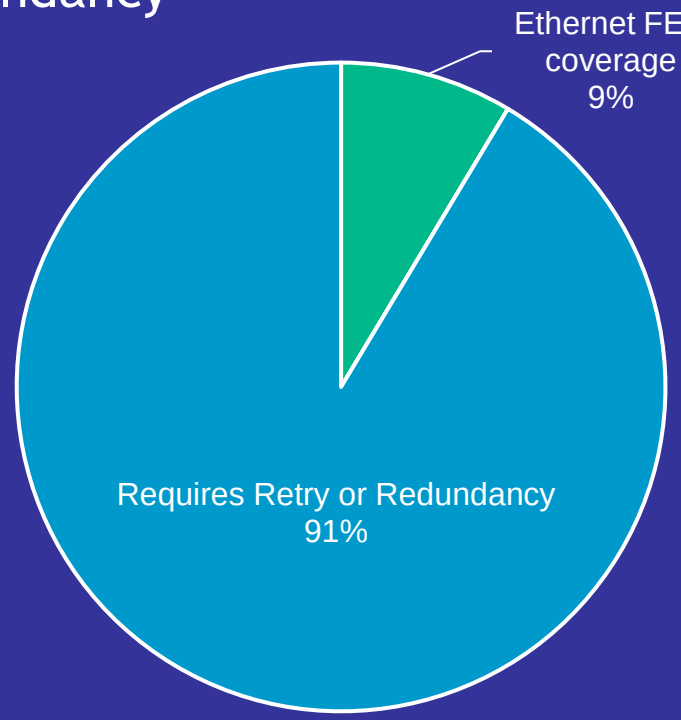
~99% of SEUs produce burst errors that last only a few microseconds.

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



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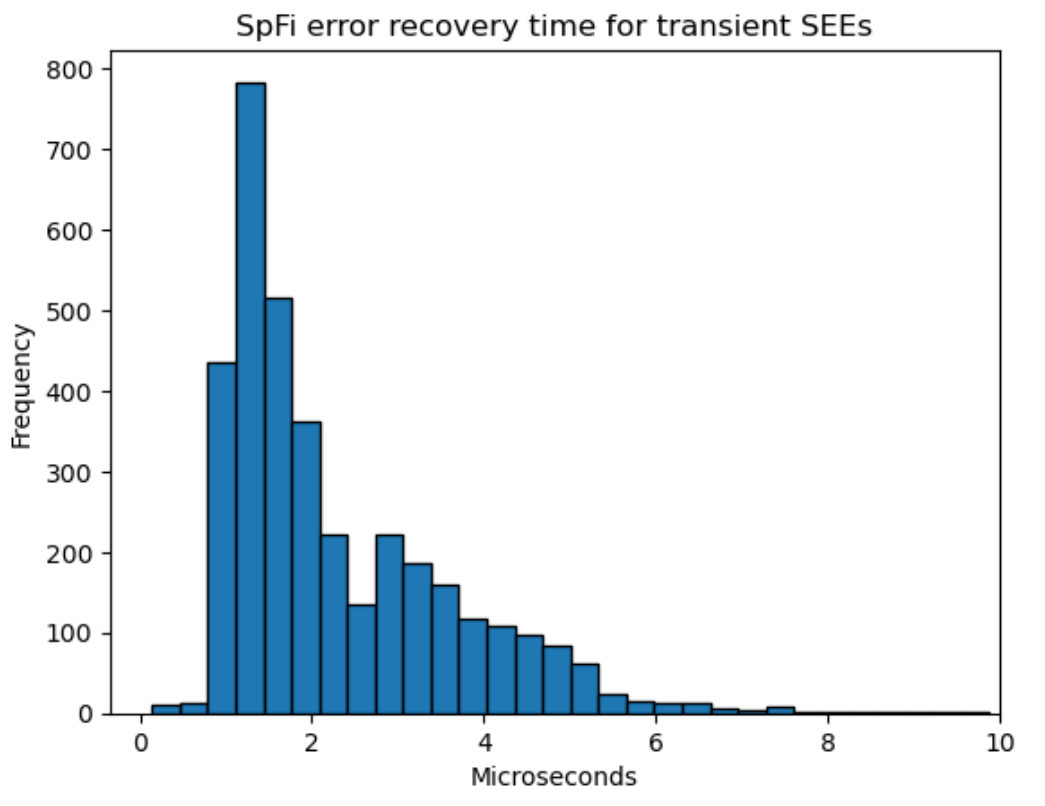
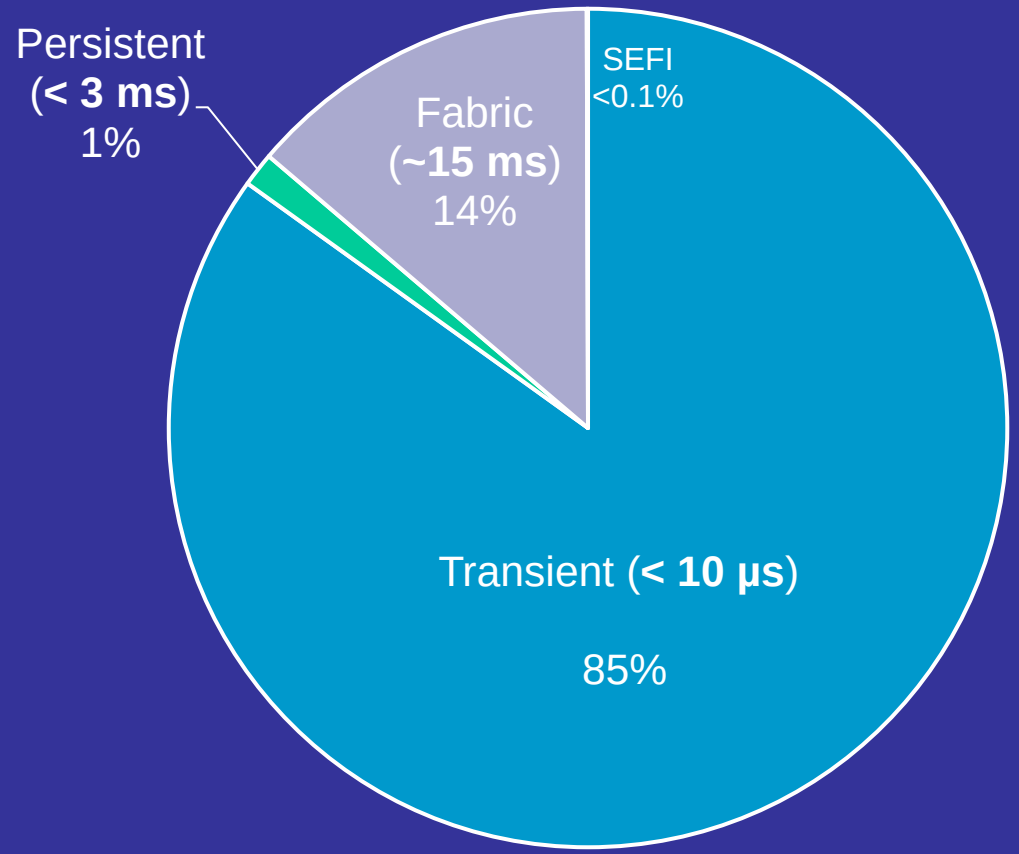
SpaceFibre Link Error Recovery Time

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.





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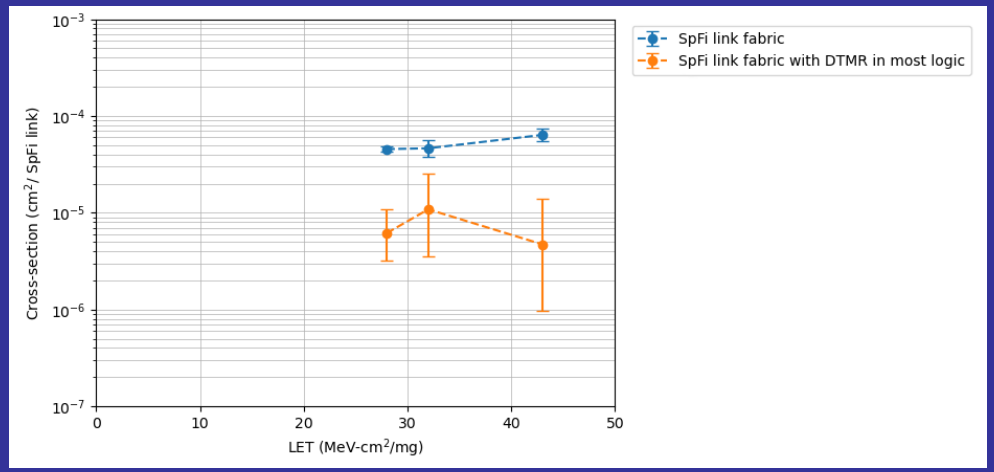
TMR on SpFi Link Fabric

- 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 errors 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.