Experimental Validation of Fault Injection Analyses with the FLIPPER Tool

M. Alderighi, F. Casini, S. D'Angelo, M. Mancini, S. Pastore, G.R. Sechi, G. Sorrenti

INAF/IASF Milano, Italy

Acknowledgments

C. Poivey, R. Harboe-Sørensen
ESA/ESTEC, Noordwijk, The Netherlands,

W. Hajdas
PSI, Switzerland

E. Mattaini,E. Sant'Ambrogio
INAF/IASF Milano, Italy

Motivations

- FLIPPER is FI tool to study SEUs in SRAM-FPGAs
  - ESA/ESTEC contract 18559
- SEUs in SRAM-FPGAs affect not only flip-flops and user memory, but also the device configuration memory and thus the logical function of the circuit as well
- The fault model in FLIPPER is the bit-flip of configuration memory cells

CAN WE RELIABLY USE FLIPPER FOR PREDICTION PURPOSES???

Accelerator validation is needed!!!!

FLIPPER

- FLIPPER injects bit-flip faults within the FPGA configuration memory by means of partial re-configuration
- The system consists of a hardware platform and a software application running on a PC
- DUT device is an XQR2V6000 device hosted on a piggy-back board, stacked on the control board
- Test vectors and reference values for the functional test of implemented designs are imported by the software application from an external HDL simulator

FLIPPER Boards

Sample design

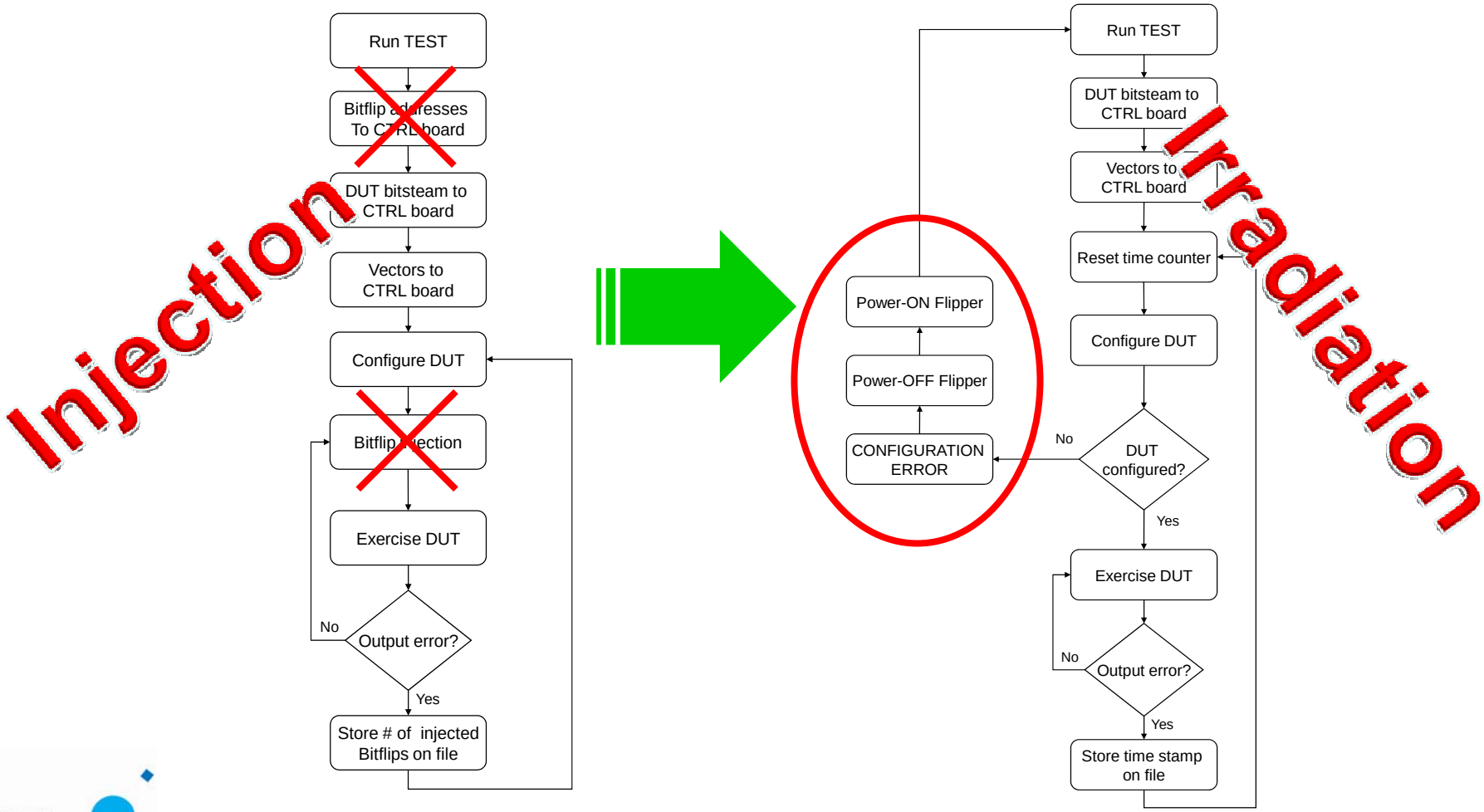
- ESA benchmark design consisting of modules
  - FFT: Fourier Transform of a data matrix
  - MULT16_LUT: 2-stage 16x16 bit multiplier instantiated twice
  - MULT16_MULT18: 10-stage 16x16 bit multiplier instantiated twice (embedded)
  - FFmatrix: two identical copies of a shift register chain (480 bits each)
  - ROMff: two copies of a shift register (256 bit each); the former is loaded and holds the stored values, the latter reads the values stored by the former
- V1 and V2 design variants
  - V1 is derived from the unprotected design by straightly applying the TMRtool.
  - In V2 a dummy feedback path, controlled by a multiplexer, is inserted for each flip-flop (the TMRtool is forced to instantiate a voter for every flip-flop in the design)

Resource	Plain	V1	V2
Slice FF	2,926 (4%)	8,778 (12%)	8,778 (12%)
LUT	3,806 (5%)	13,437 (19%)	29,217 (43%)
IOB	87 (10%)	264 (32%)	267 (32%)
MULT 18x18	32 (22%)	96 (66%)	96 (66%)
GCLK	1 (6%)	3 (18%)	3 (18%)

FI campaign

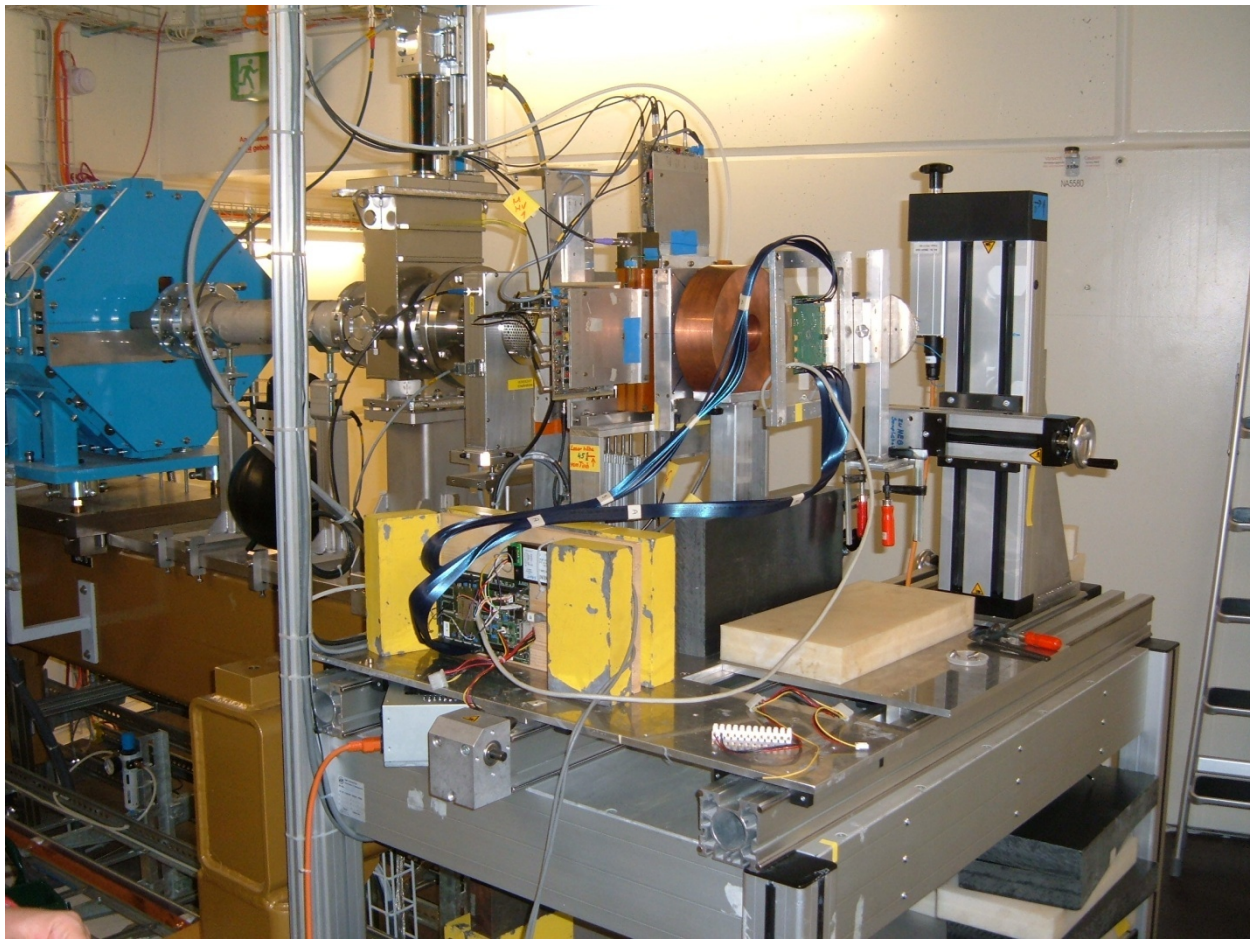
- Accumulation mode
  - the altered bit is NOT restored before the successive injection is performed
  - mimics the irradiation exp (without scrubbing)
- Configuration memory bits are flipped according to a random list of memory locations
- About 1000 runs for each variant; predefined maximum number of inj. = 100,000

Procedures


Injection
Run TEST
Bitflip addresses To CTRL board
DUT bitsteam to CTRL board
Vectors to CTRL board
Configure DUT
Bitflip injection
Exercise DUT
Output error?
No
Yes
Store # of injected Bitflips on file
Irradiation
Run TEST
DUT bitsteam to CTRL board
Vectors to CTRL board
Reset time counter
Configure DUT
DUT configured?
No
Yes
Exercise DUT
Output error?
No
Yes
Store time stamp on file
CONFIGURATION ERROR
Power-OFF Flipper
Power-ON Flipper

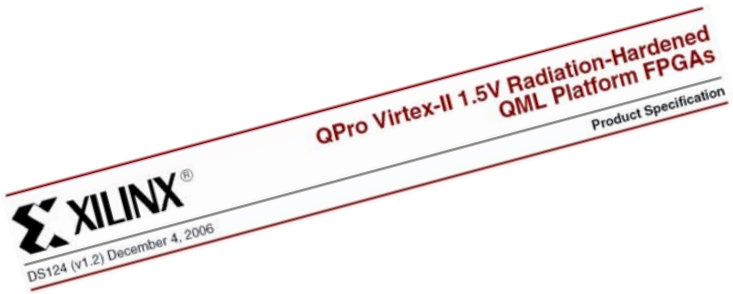
FLIPPER@PSI

PSI, Switzerland, November 23, 2008



Irradiation experiment

DUT Device: XQR2V6000



- 180 MeV proton beam (nominal)
- average flux : ~ $6.5 \cdot 10^{7}$ cm^{-2} s^{-1}
  - 1 CBU at most during test vector application
  - CBU_{rate}: ~ 80 s^{-1}
- stimuli: ~ 28,000 vectors@10 MHz
- total exposure time: ~ 12 hours
- Fluence: ~ $2.19 \cdot 10^{12}$ p/cm^{-2}
- TID: < 140 krad
- ~ 600 samples for V2, ~ 400 samples for V1

Radiation Specifications(1)

Table 3: **Minimum Radiation Tolerances**

Symbol	Description	Min	Max	Units
TID	Total Ionizing Dose Method 1019.5, Dose Rate ~50.0 rad(Si)/sec	200	-	krad(Si)
SEL	Single Event Latch-up Immunity Heavy Ion Linear Energy Transfer (LET)	160	-	(MeV-cm²/mg)
SEFI	Single Event Functional Interrupt GEO 36,000km Typical Day		1.5E-6	Upsets/Device/Day

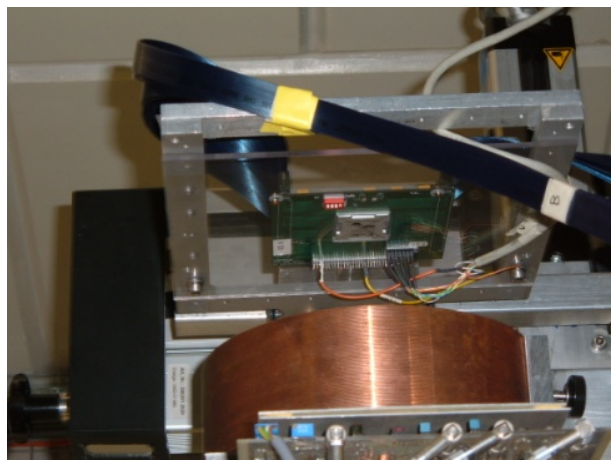
XQR2V6000 : device specification

Device static proton cross section (per bit)

$3 \cdot 10^{-14}$ cm^2 @198 MeV

# of configuration cells

19.742.976

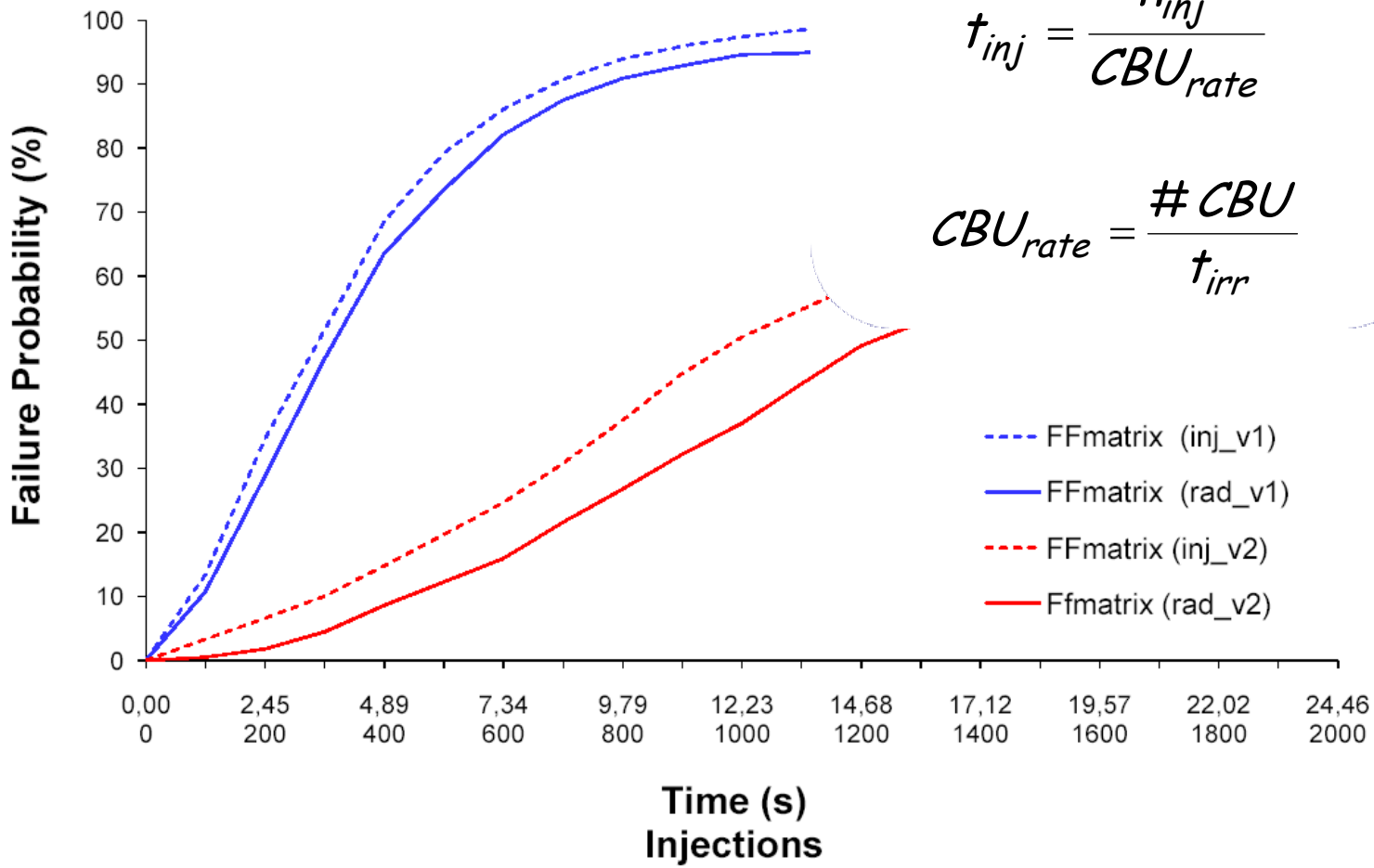


FFmatrix

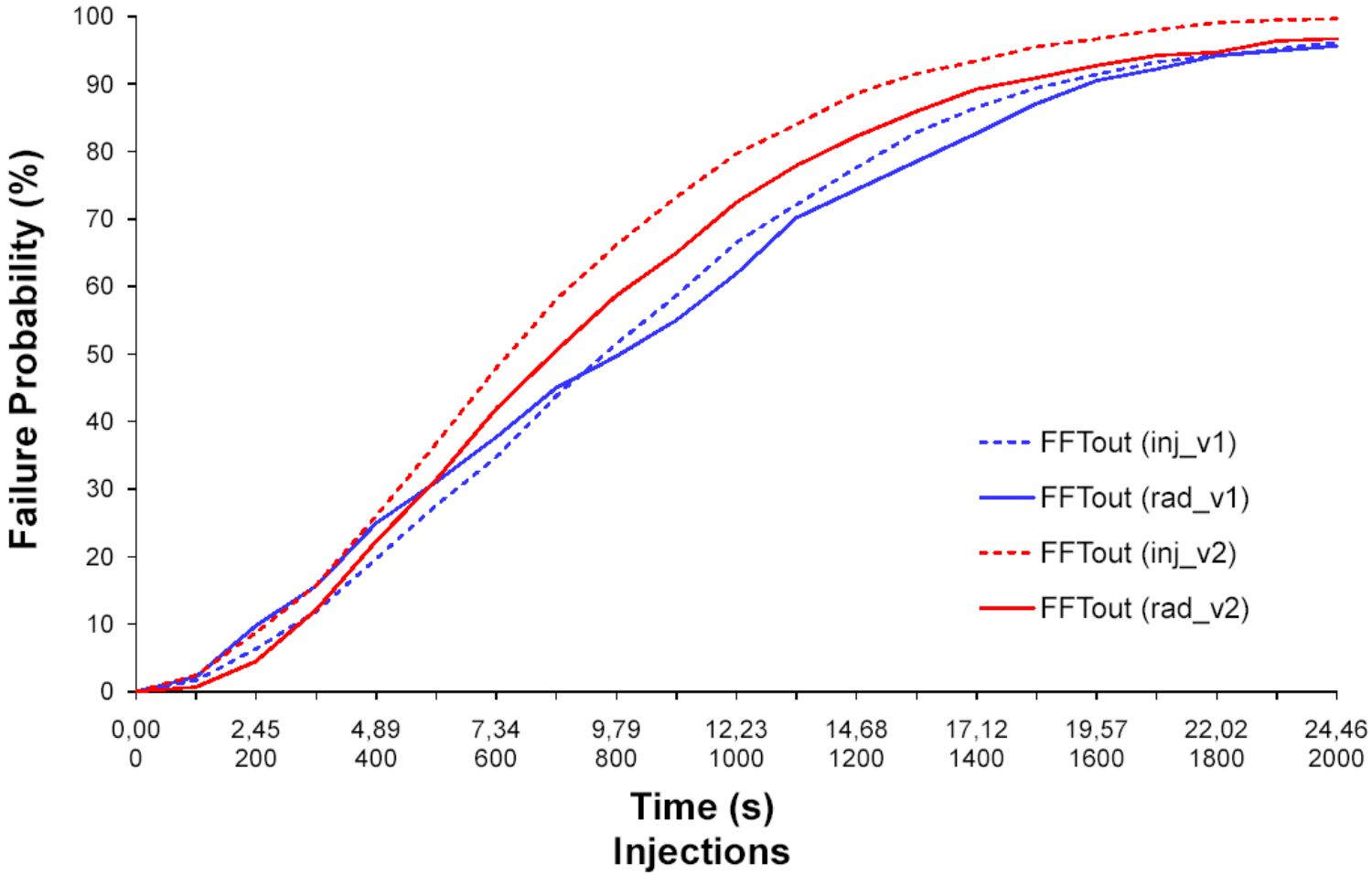
Time-injections correlation

$$t_{inj} = \frac{n_{inj}}{CBU_{rate}}$$

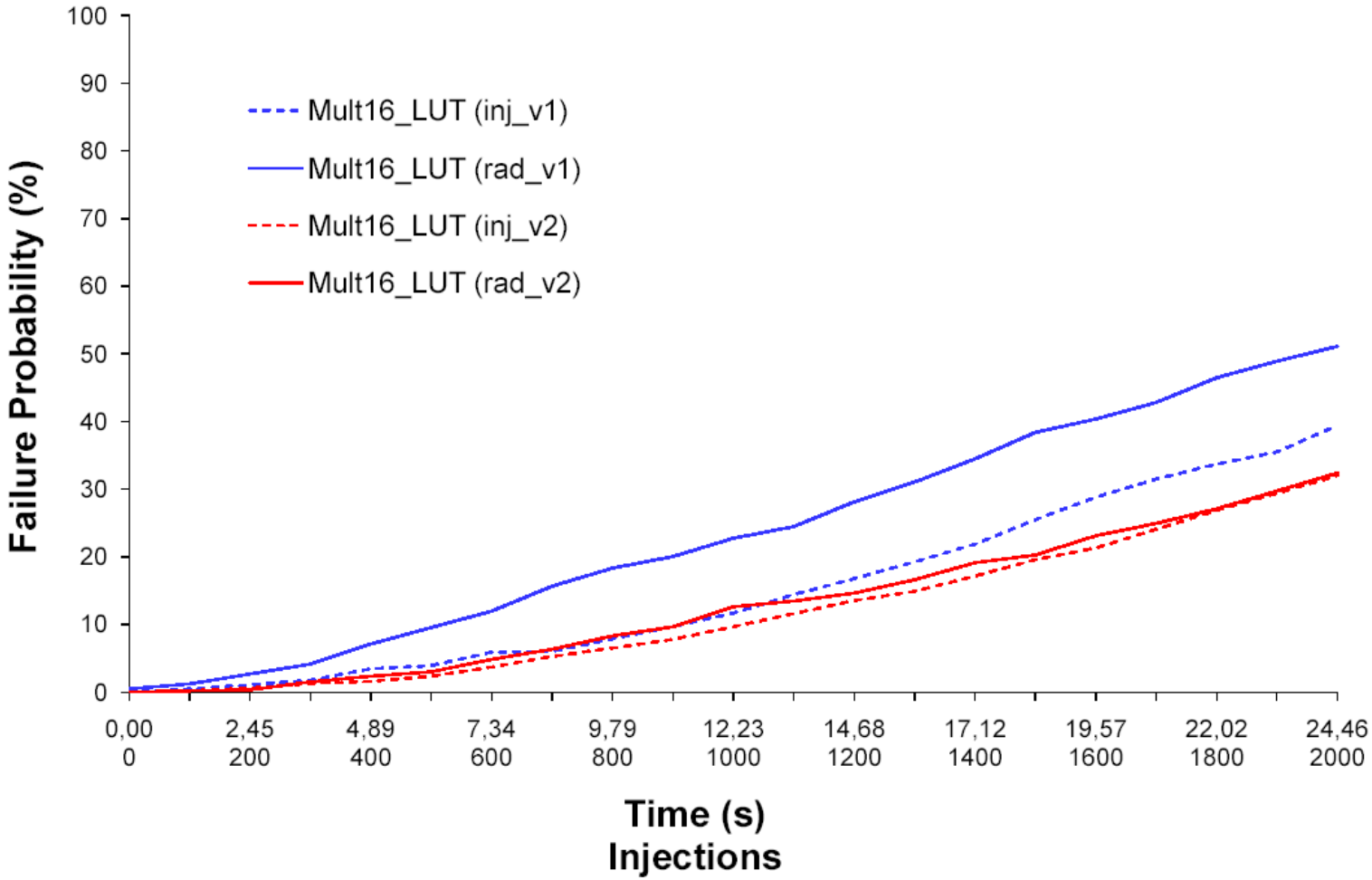
$$CBU_{rate} = \frac{\#\,CBU}{t_{irr}}$$



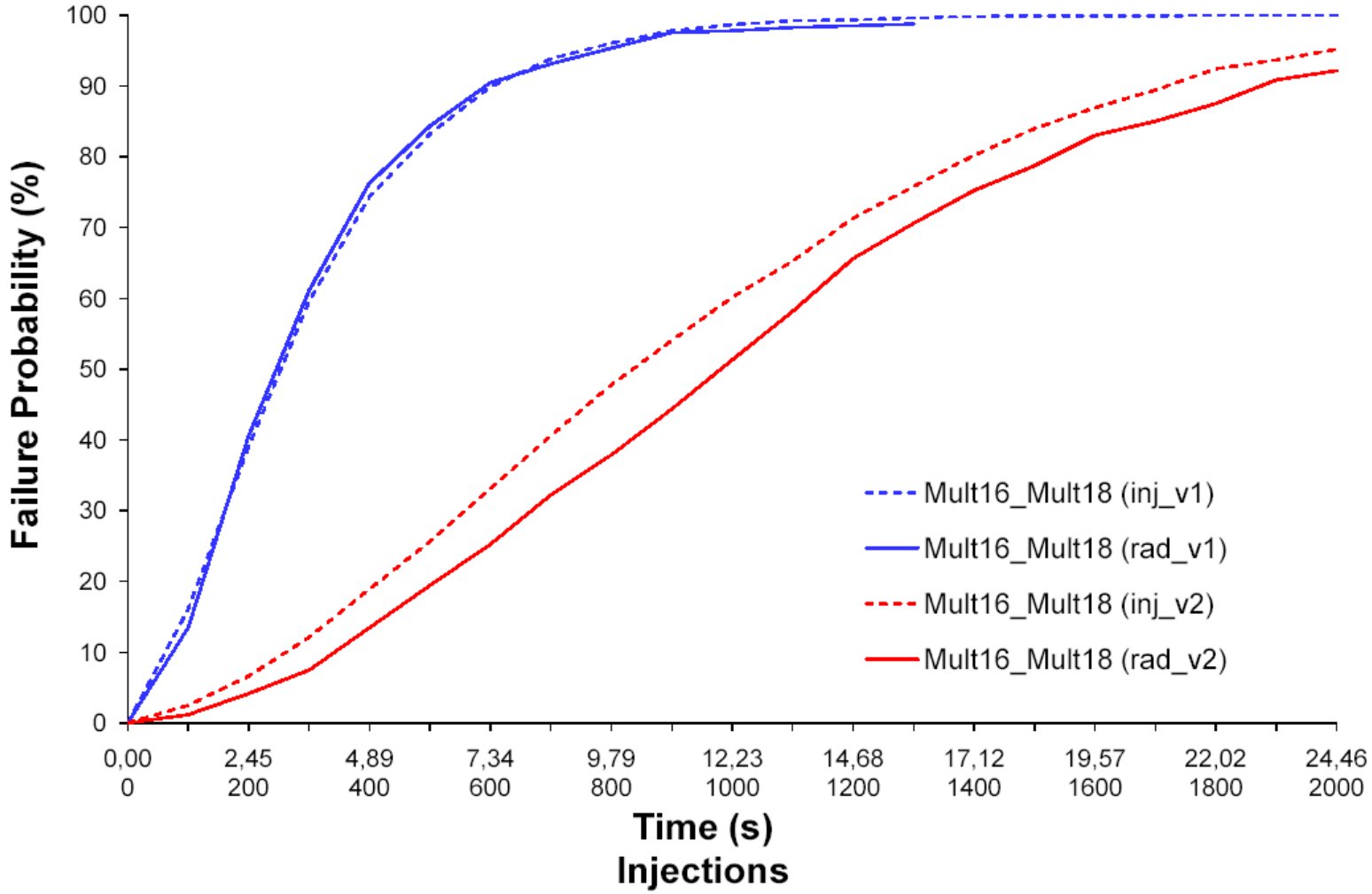
FFTout


Failure Probability (%)
100
90
80
70
60
50
40
30
20
10
0
0,00
0
2,45
200
4,89
400
7,34
600
9,79
800
12,23
1000
14,68
1200
17,12
1400
19,57
1600
22,02
1800
24,46
2000
Time (s)
Injections
FFTout (inj_v1)
FFTout (rad_v1)
FFTout (inj_v2)
FFTout (rad_v2)

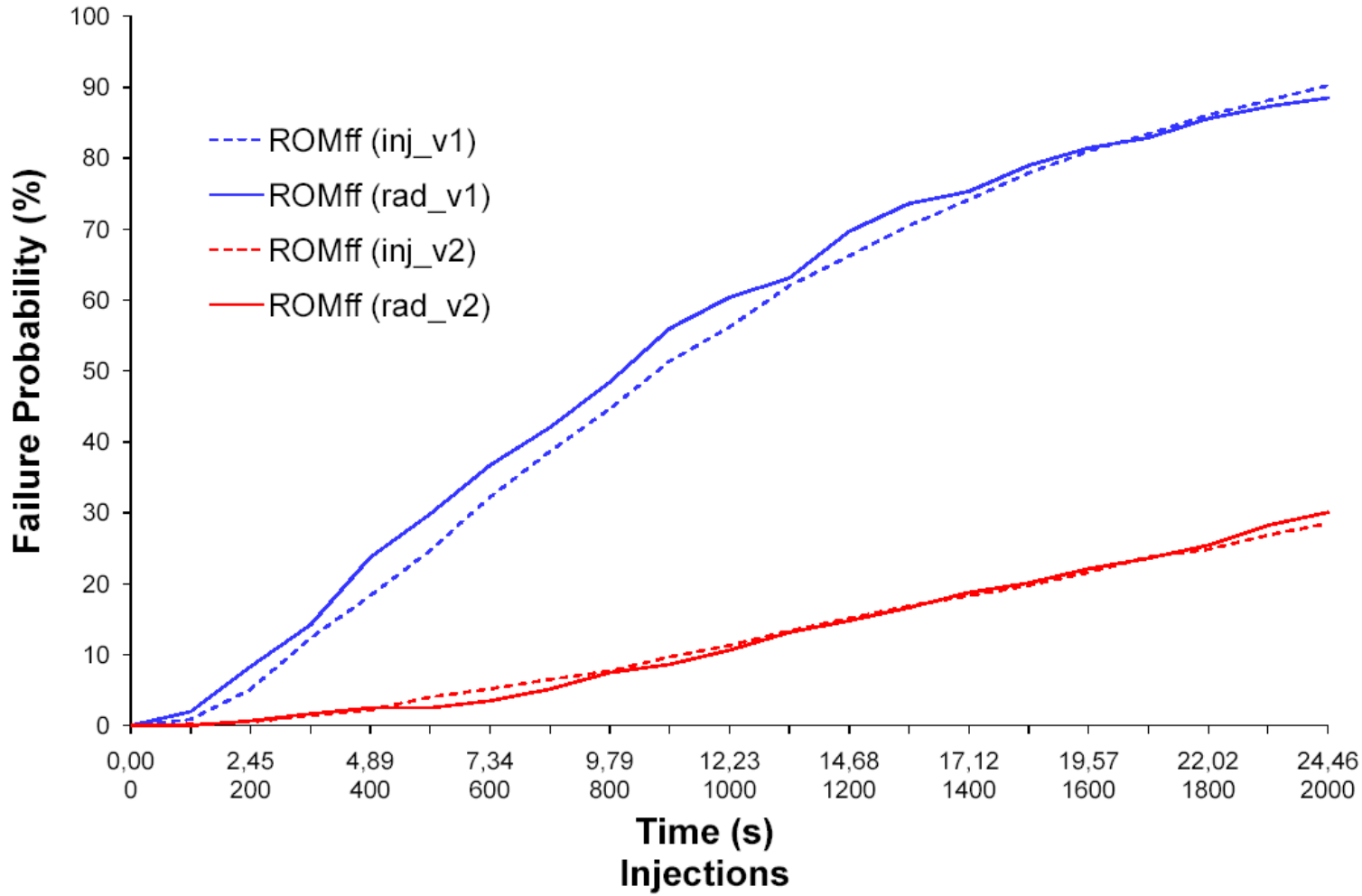
Mult16_LUT


Failure Probability (%)
100
90
80
70
60
50
40
30
20
10
0
Mult16_LUT (inj_v1)
Mult16_LUT (rad_v1)
Mult16_LUT (inj_v2)
Mult16_LUT (rad_v2)
0,00
0
2,45
200
4,89
400
7,34
600
9,79
800
12,23
1000
14,68
1200
17,12
1400
19,57
1600
22,02
1800
24,46
2000
Time (s)
Injections

Mult16_Mult18



ROMff


100
90
80
70
60
50
40
30
20
10
0
Failure Probability (%)
ROMff (inj_v1)
ROMff (rad_v1)
ROMff (inj_v2)
ROMff (rad_v2)
0,00
0
2,45
200
4,89
400
7,34
600
9,79
800
12,23
1000
14,68
1200
17,12
1400
19,57
1600
22,02
1800
24,46
2000
Time (s)
Injections

Conclusions

- Good agreement between injection and irradiation data
- Suitability of the fault model
- FLIPPER can be effectively used to predict proton data
- Tests of further protection techniques (developed by Politecnico di Torino) are being planned

Alderighi, M., Casini, F., D'Angelo, S., Mancini, M., Pastore, S., Sterpone, L., Violante, M. Soft errors in SRAM-based FPGAs: a comparison of two complementary approaches. IEEE Transactions on Nuclear Science, vol. 55, n. 4, pp. 2267-2273 (2008)
Alderighi, M., Casini, F., Citterio, M., D'Angelo, S., Mancini, M., Pastore, S., Sechi, G.R., Sorrenti, G., "Using FLIPPER to Predict Proton Irradiation Results for VIRTEX 2 Devices: a Case Study", Accepted for publication, IEEE TNS, 2009

Thank you!