Performance tests of the ATLAS Inner Tracker Pixel detector opto-electrical conversion system

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Following on from Lucas' talk…

- Crucial period for verification of data transmission and mechanical performance of Optosystem

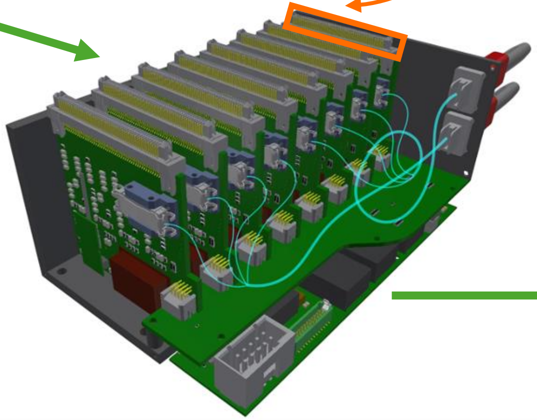
- Mechanic:
  - Optopanel fibre bundle fitting, mounting

- Data transmission:
  - Optoboard performance under intense radiation
  - Optoboard testing for Optosystem construction ("production")

Mechanics of the Optosystem

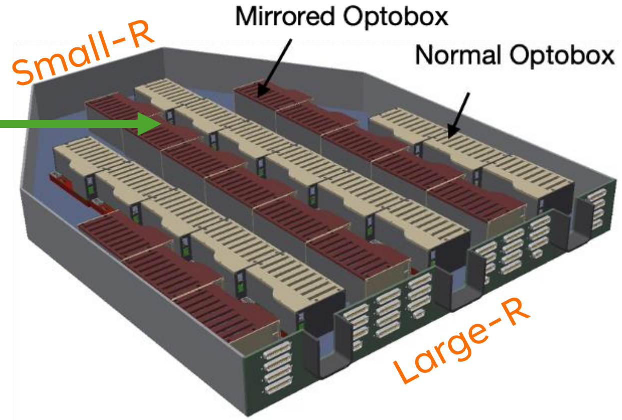
Optoboard

Optobox



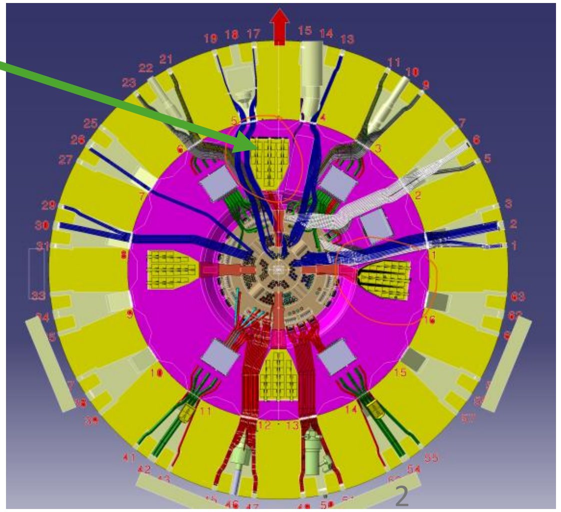
Termination board

- Interface between Optoboard (ERF) and electrical signal cables (twinax)



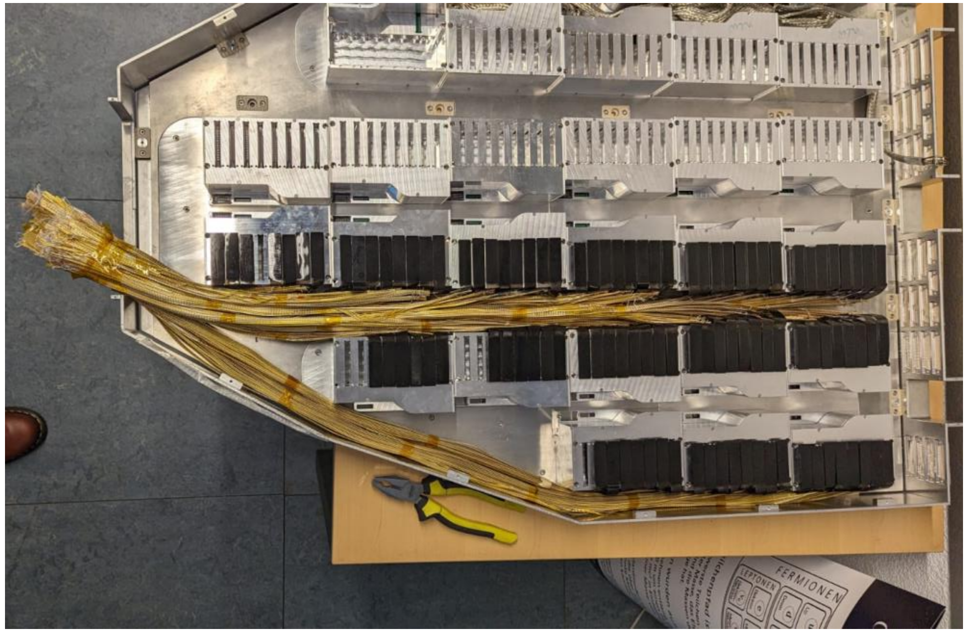
Optopanel

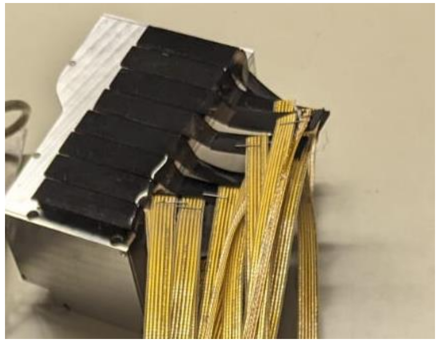
Position in ATLAS

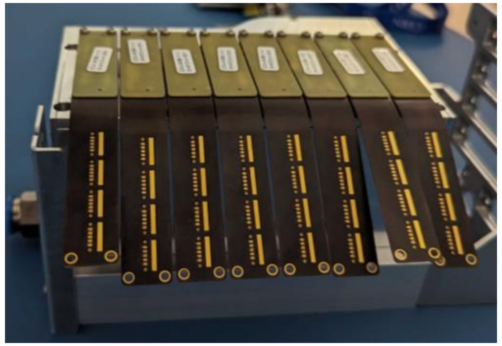


Twinax fitting

- What was done?
  1. Electrical signal cables (twinax) attached to 3D printed "termination boards" that fit onto Optoboxes
  2. Each Optobox with twinax placed into Optopanel, half chosen is one of the most populated (~1700 twinax)







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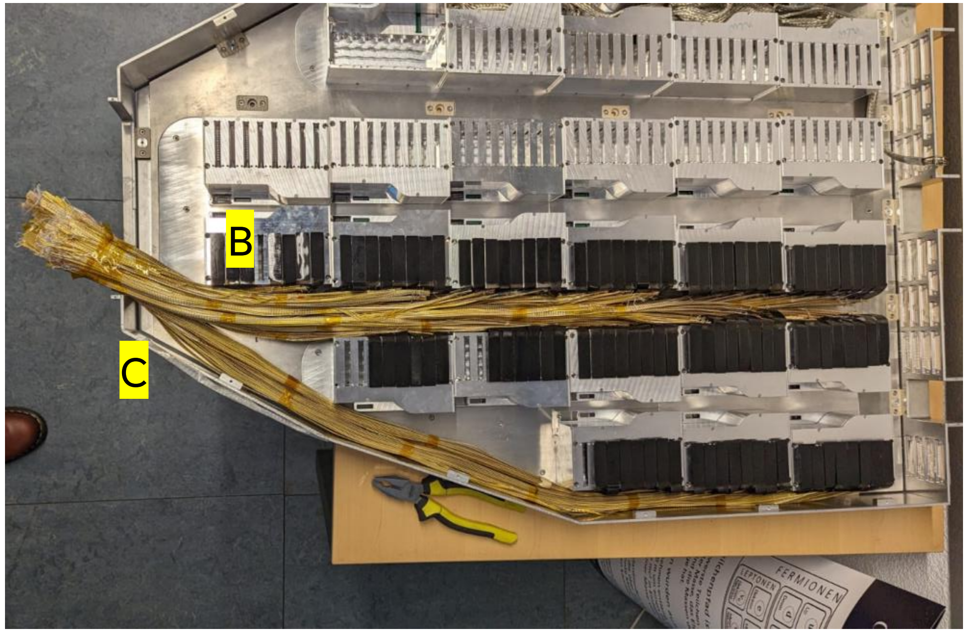
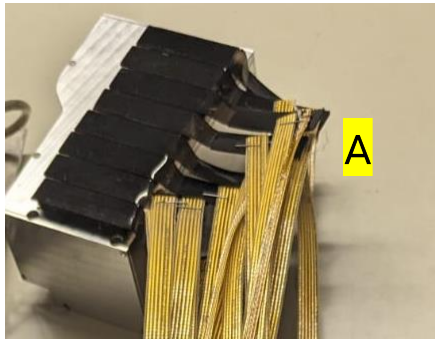
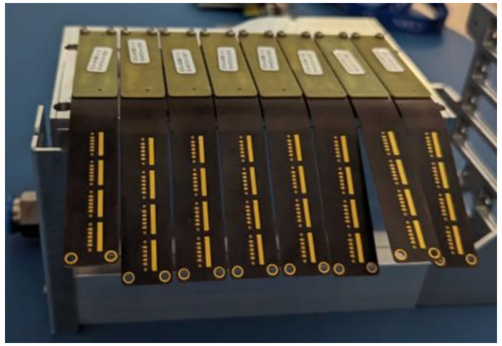
- What was noticed?
  1. "Termination boards" curling upwards (A) once twinax attached
  2. Corner of box closest to entry (B) very crowded, twinax laying on top of each other
  3. Small R corner of panel (C) has wasted empty space







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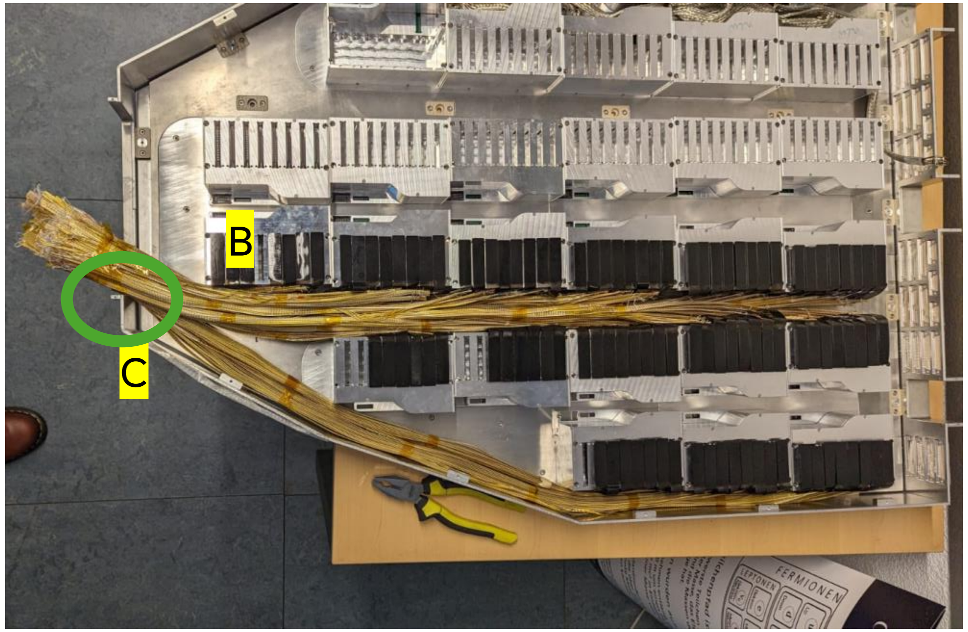
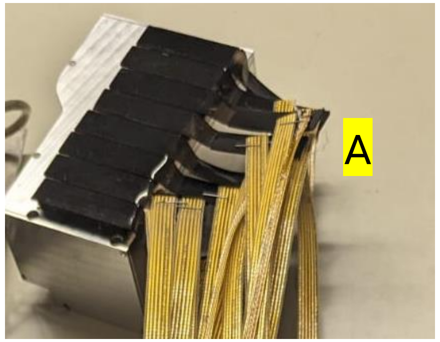
  2. Corner of box closest to entry (B) very crowded, twinax laying on top of each other
  3. Small R corner of panel (C) has wasted empty space
- Solutions:
  1. Small R side of panel redesigned to make entry wider
  2. Real termination boards are stiffer (D) – but curling should still be something to keep in mind when filling panel



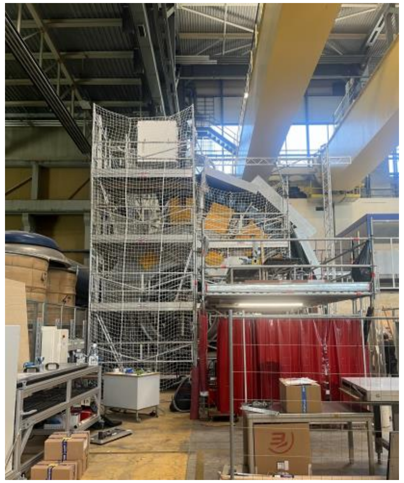


Mounting at CERN

- Aim: start to devise a plan of how to install the Optosystem in the ATLAS cavern

Mounted Optopanel

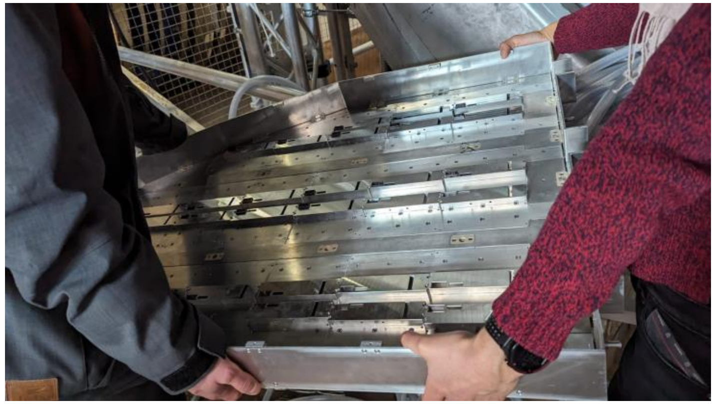
Mounted adapter plate



Inner services mock-up, B180@CERN

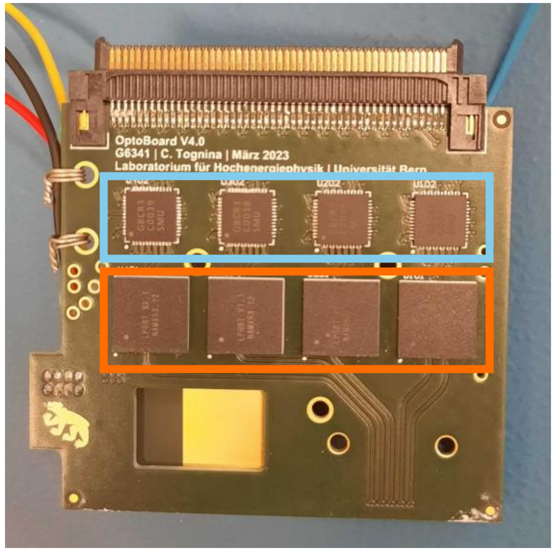
Proposal:

1. Attach adapter plate to endplate and cover screws with kapton tape
2. Mount Optopanel onto adapter plate without Optoboxes (manouvre ~30 kg instead of 60 kg)
3. Fill Optopanel with Optoboxes from small-R to large-R



Optopanel with Optoboxes removed

The Optoboard



- Around 1600 of these boards will read out the full ITk pixel detector

    - GBCR

    GigaBit Cable Receiver used for signal recovery and equalisation

    - lpGBT

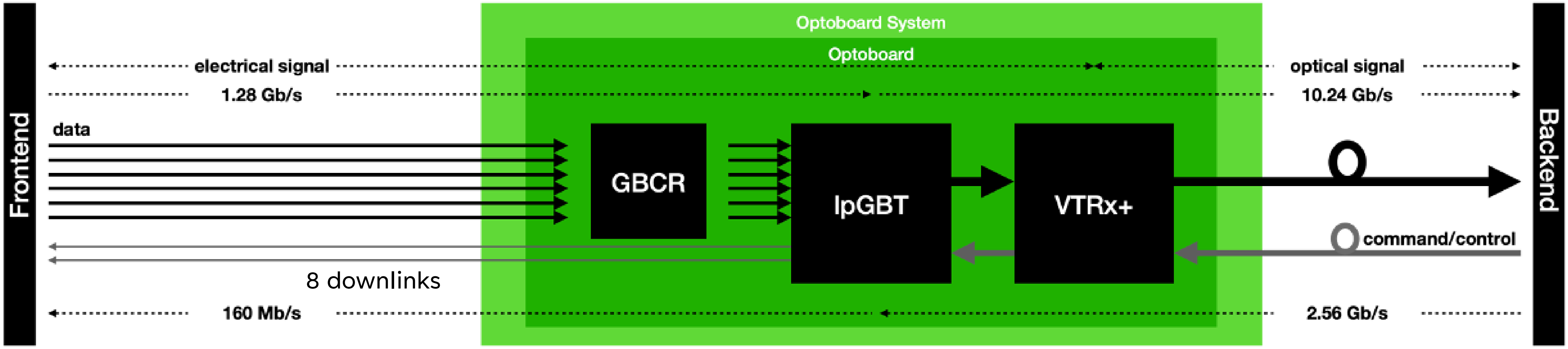
    Low Power GigaBit Transceiver used for serialisation

    - VTRx+

    Versatile Link Plus Transceiver used for opto-electrical conversion

On FELIX: S. Ryu (ATLAS TDAQ Collaboration) 2017 *J. Phys.: Conf. Ser.* **898** 032057

Data transmission chain

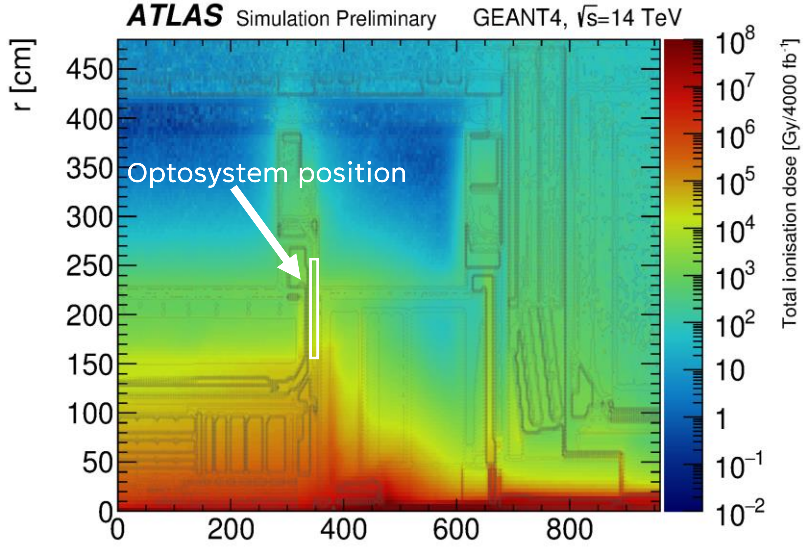


Pixel detector

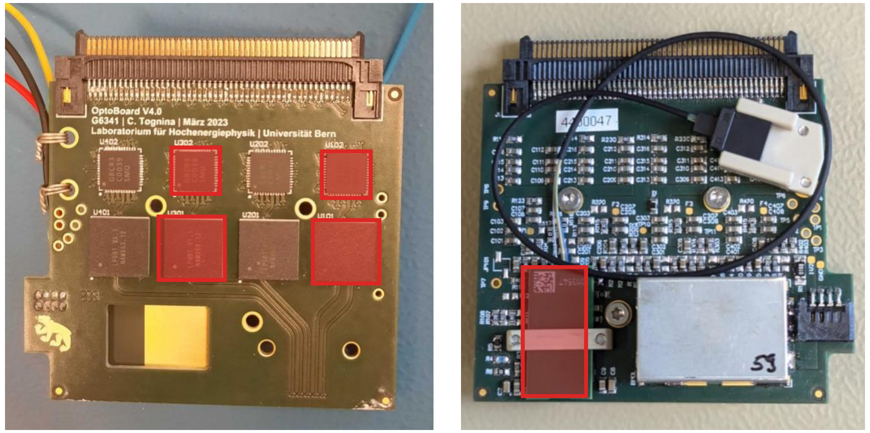
Counting room

Optoboard irradiation

- At Inselspital Bern cyclotron
  - Irradiations by day, radiopharmaceutical production by night
- Expected dose (10 years): 50 kGy (see plot), we irradiate to: 150 kGy* (40 mins, safety factor=3)
- Optoboard connected with an ITk Pixel module via adapter boards



ATLAS radiation simulation public results



Irradiated components

lpGBT	GBCR	VTRx+
• Bit Error Ratio Test (BERT) with PRBS7 • Single Event Upset (SEU) counter	• Bit Error Ratio Test (BERT) with PRBS7 • Single Event Upset (SEU) counter	• Bit Error Ratio Test (BERT) with Aurora 64/66b

*Same dose as in 2021 Bern irradiation campaign

Bit Error Ratio

lpGBT/GBCR: BERT with PRBS7
VTRx+: Soft Error (BERT) with Aurora

- Tests data transmission quality

Sent signal $\stackrel{?}{=}$ Received signal

- BER limit = 95% confidence interval
  - Industry standard is limit of O(10^{-12})

$$\text{BER} = \frac{\text{erronous bits}}{\text{total bits}}$$

$$\lim(\text{BER})95\%(x) = \frac{P^{+}(x)}{1.28 \cdot 10^{9} \cdot \text{efficiency} \cdot t}$$

Uplink bitrate

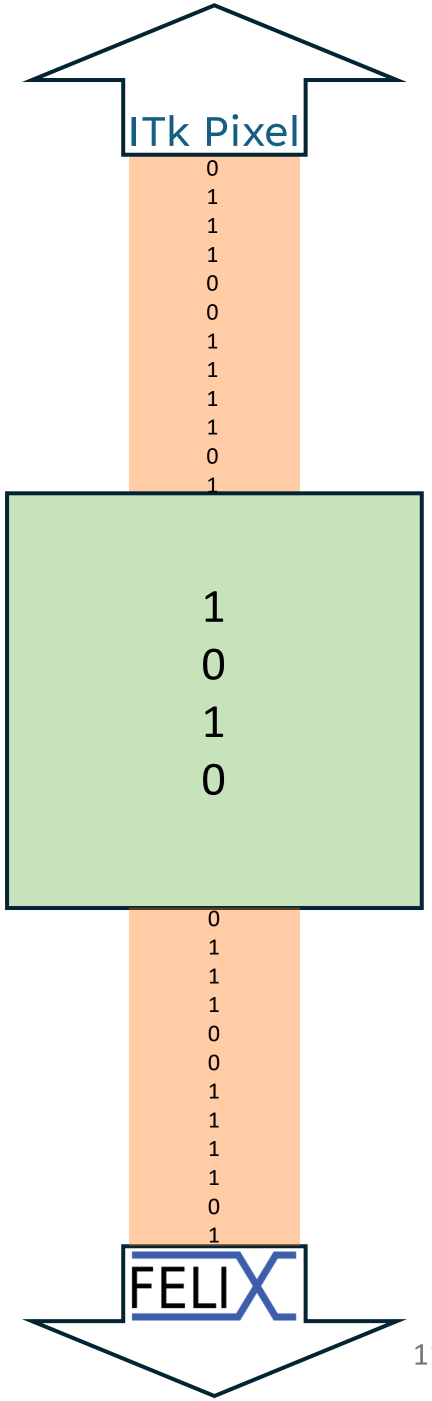
where:
- P+ - Poisson upper limit for x errors
- t– measurement time

- Two protocols used:
  - PRBS7: known pattern, 100% efficiency, tests quality between front-end and lpGBT
  - Aurora 64/66b: emulates real datastream, 62% efficiency, tests quality between front-end and FELIX

Single Event Upsets (SEUs)

- Does not cause permanent damage
- Caused by radiation: ionising particle causes bit flip in datastream
- Monitored by lpGBT

- How are SEUs recorded in our case?
  - lpGBT registers are triplicated and compared

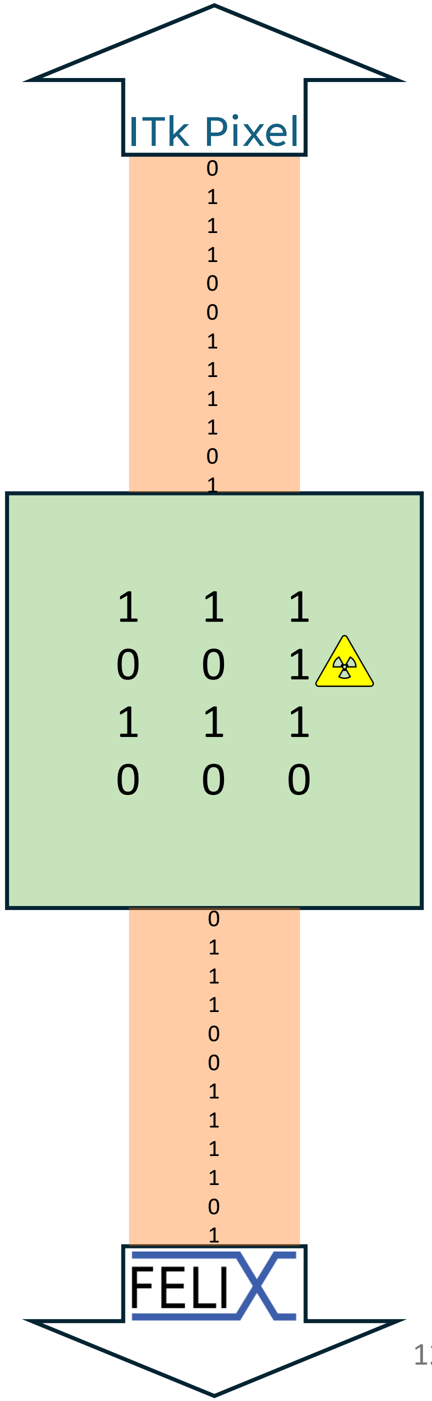


R. Müller CERN-THESIS-2023-214

Single Event Upsets (SEUs)

- Does not cause permanent damage
- Caused by radiation: ionising particle causes bit flip in datastream
- Monitored by lpGBT

- How are SEUs recorded in our case?
  - lpGBT registers are triplicated and compared
  - Any mismatch results in the recording of an SEU



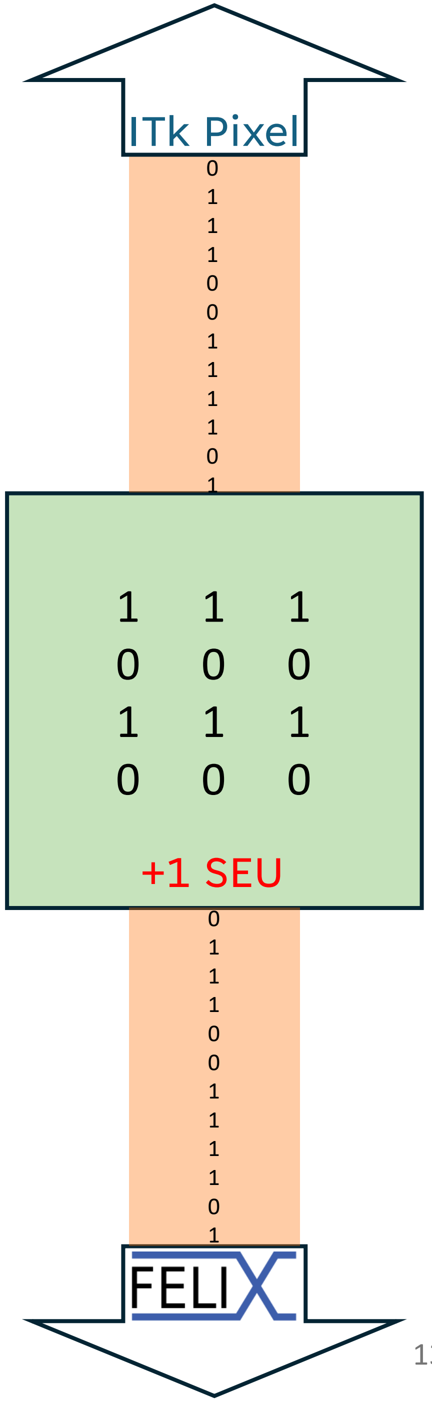
R. Müller CERN-THESIS-2023-214

Single Event Upsets (SEUs)

- Does not cause permanent damage
- Caused by radiation: ionising particle causes bit flip in datastream
- Monitored by lpGBT

Not done for VTRx+:
Optoboard too thick to let particles from beam through to lpGBT!

- How are SEUs recorded in our case?
  - lpGBT registers are triplicated and compared
  - Any mismatch results in the recording of an SEU
  - The incorrect register copy is corrected



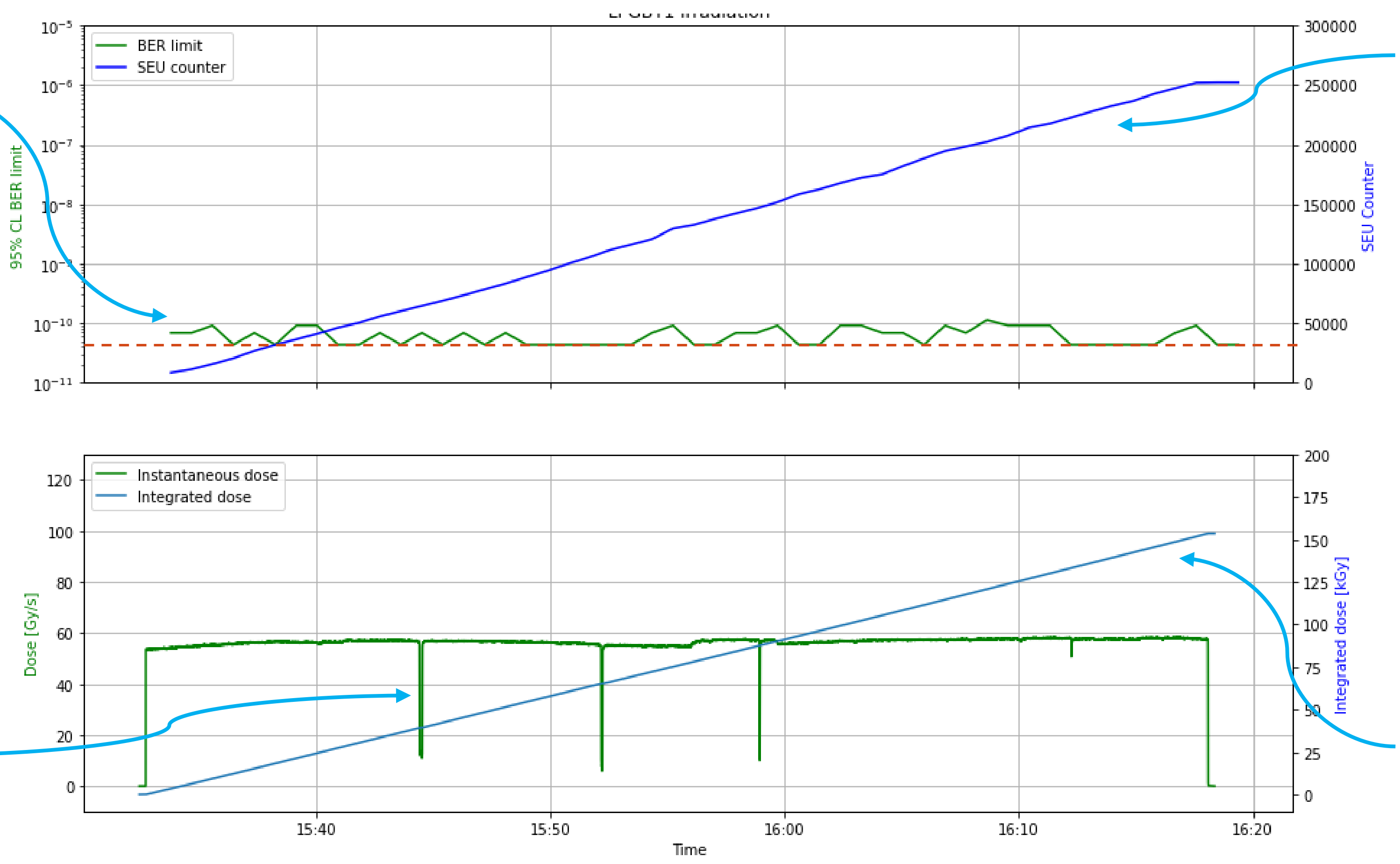
Irradiation results summary

- Measurement time = 54 s
- $\lim(BER)_{95\%}(0) = 4.34 \cdot 10^{-11}$

lpGBT 1 irradiation

Fluctuations in BER limit:

- Instantaneous flux is many times higher than what is expected – probability of bit error occuring is significantly higher



SEU counter:

- Increases as dose increases (expected cumulative behaviour)

Drops in dose:

- Feature of cyclotron source
- Does not affect results in any way

Integrated dose:

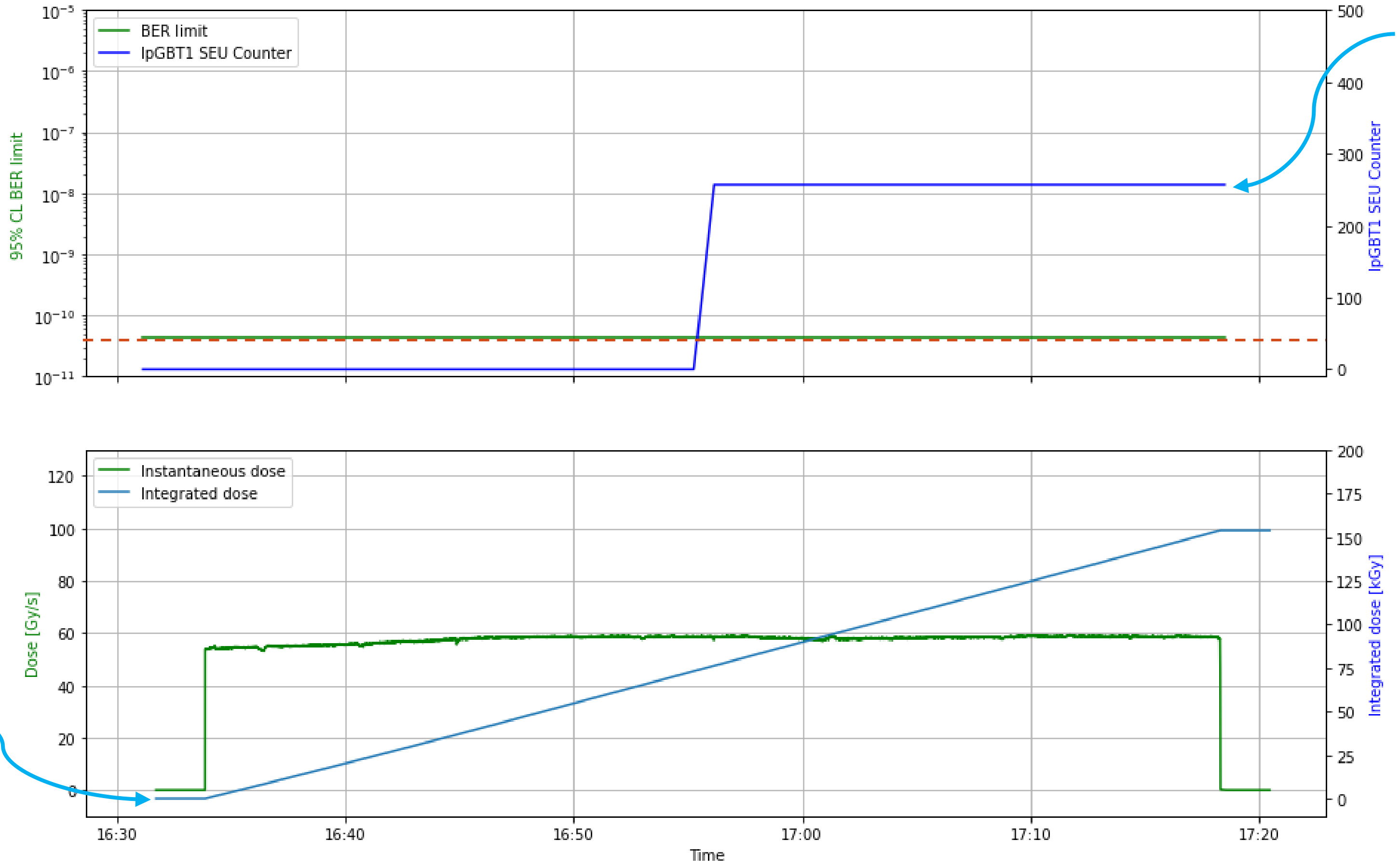
- Reaches 150 kGy

---- BERT 95% CL upper limit for 0 errors

Irradiation results summary

- Measurement time = 54 s
- $\lim(\text{BER})_{95\%}(0) = 4.34 \cdot 10^{-11}$

GBCR 1 irradiation



SEU counter:

- No SEUs expected here (SEUs not monitored by GBCR)
- Most probable explanation is showers of particles caused by beam interactions with air, which manage to hit nearby lpGBT

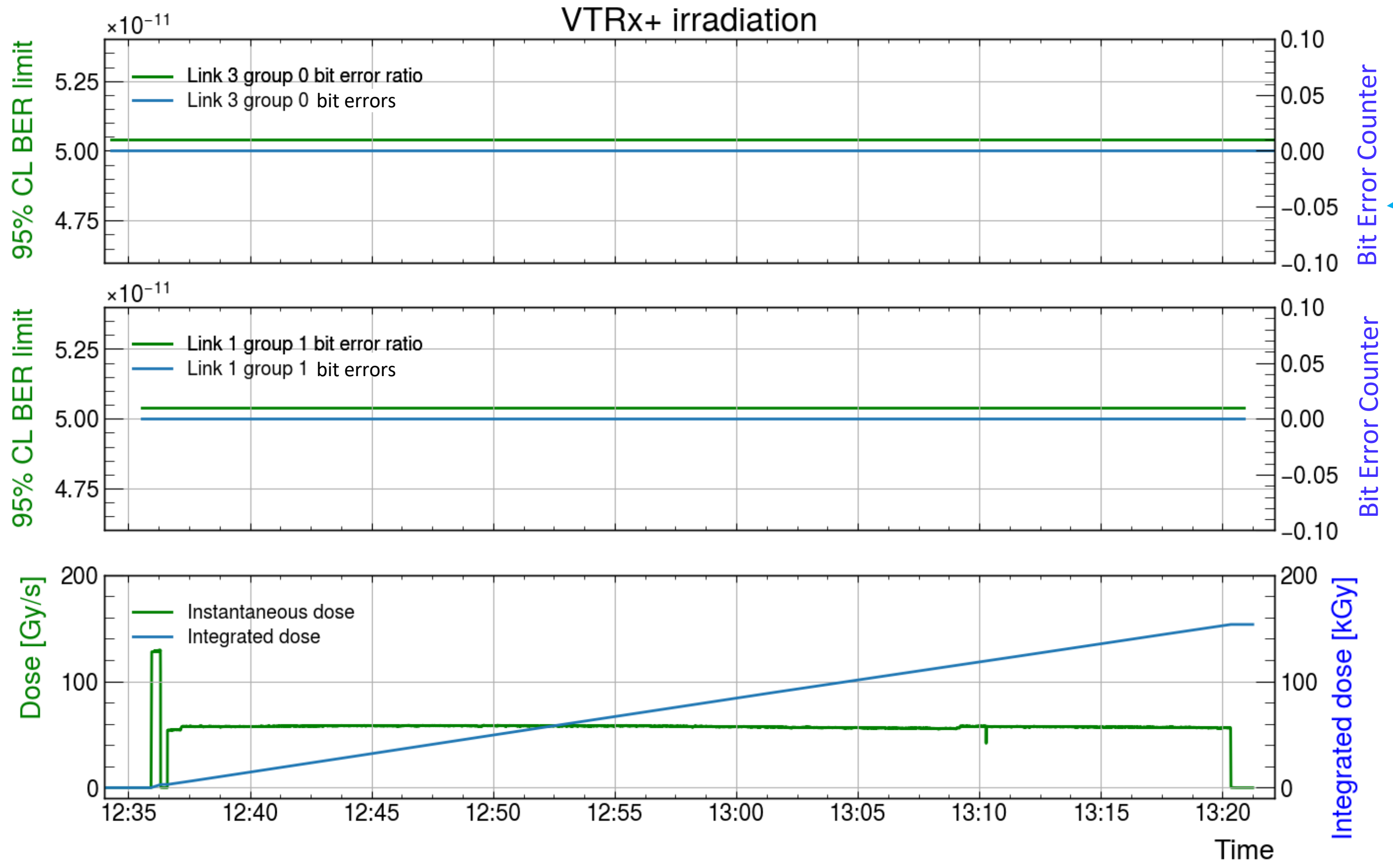
Integrated dose:

- Reaches 150 kGy

---- BERT 95% CL upper limit for 0 errors

Irradiation results summary

VTRx+ irradiation



Two uplinks monitored:

- Uplink 0 of lpGBT3
- Uplink 1 of lpGBT1

Spike in dose:

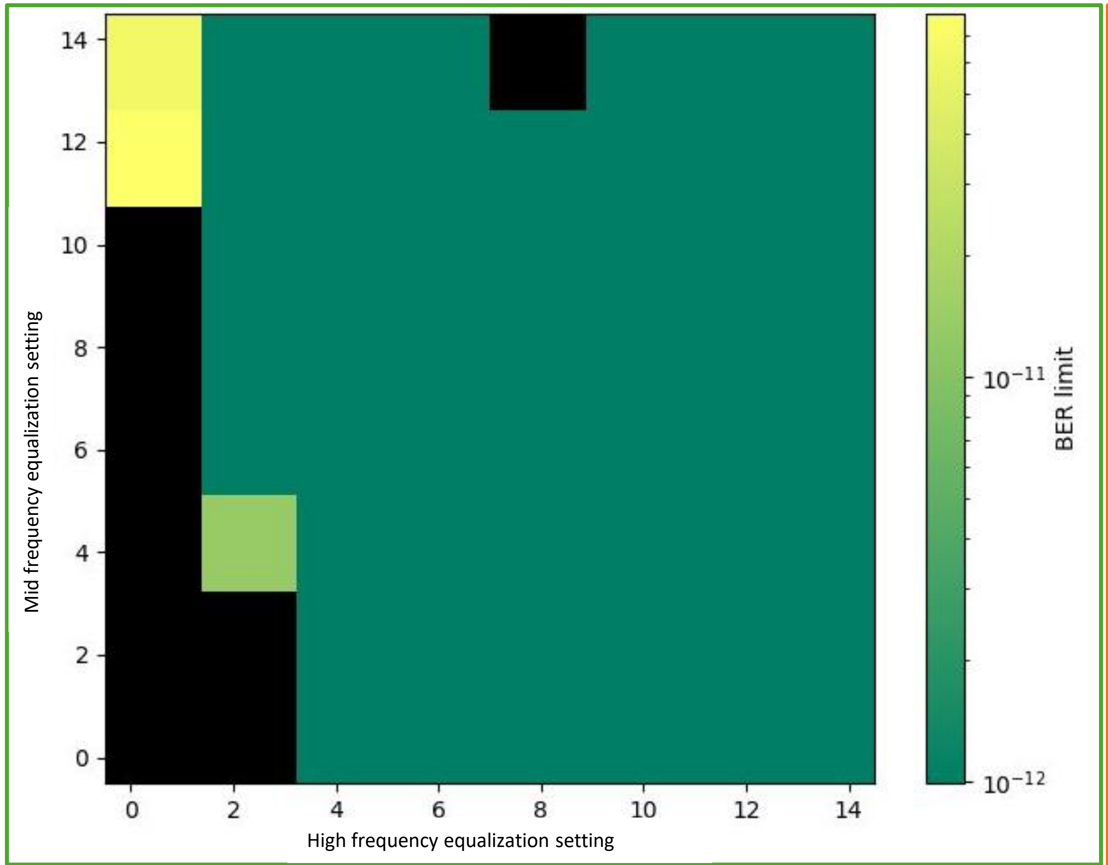
- Human error! Two sources available, stronger one chosen by accident – no effect on results

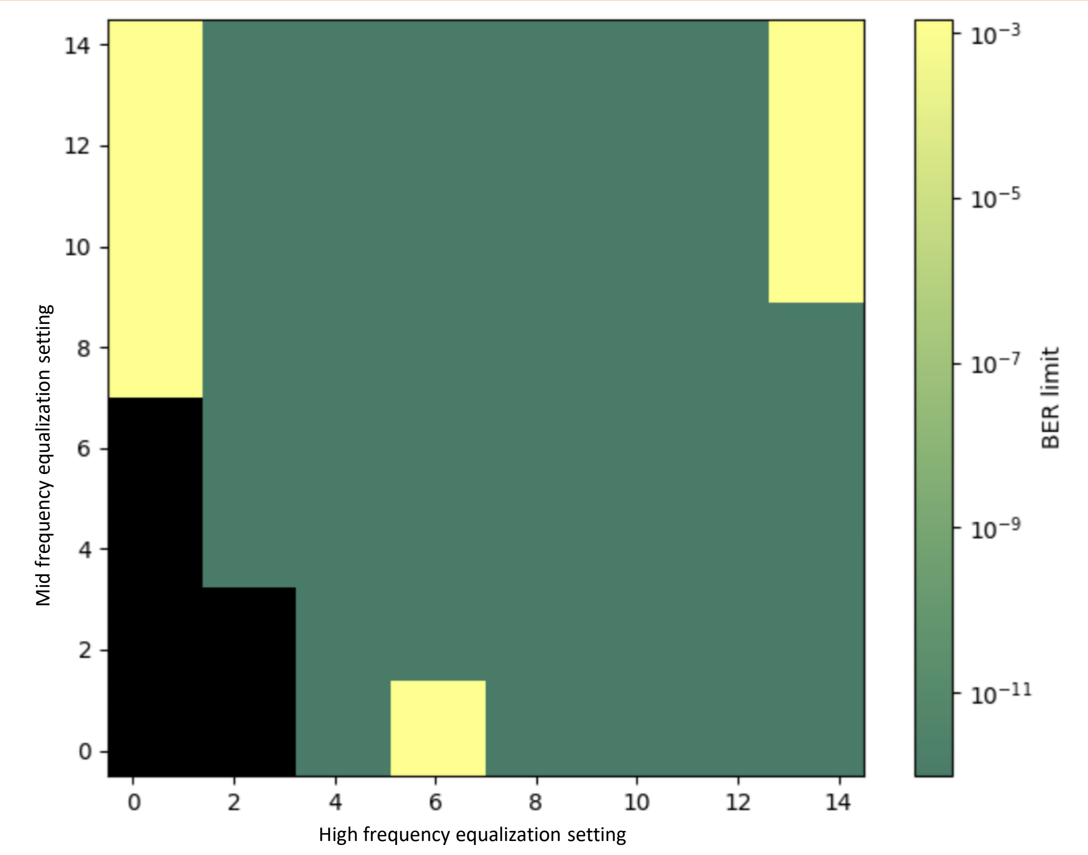
- Measurement time = 75 s
- $\lim(\mathrm{BER})_{95\%}(0) = 5.03 \cdot 10^{-11}$

Soft error scan pre- and post-irradiation

Note: Pre-irradiation plot is not for the irradiated board, but still v4

- Signs of damage:
  - Compromised data transmission where not expected (black)
  - Region of zero errors slightly 'shrinks' after irradiation (green)

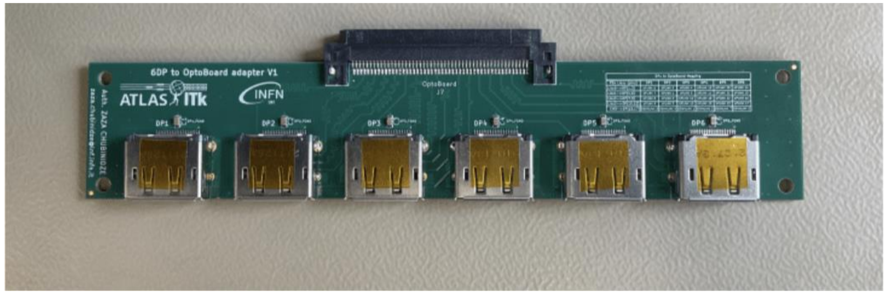


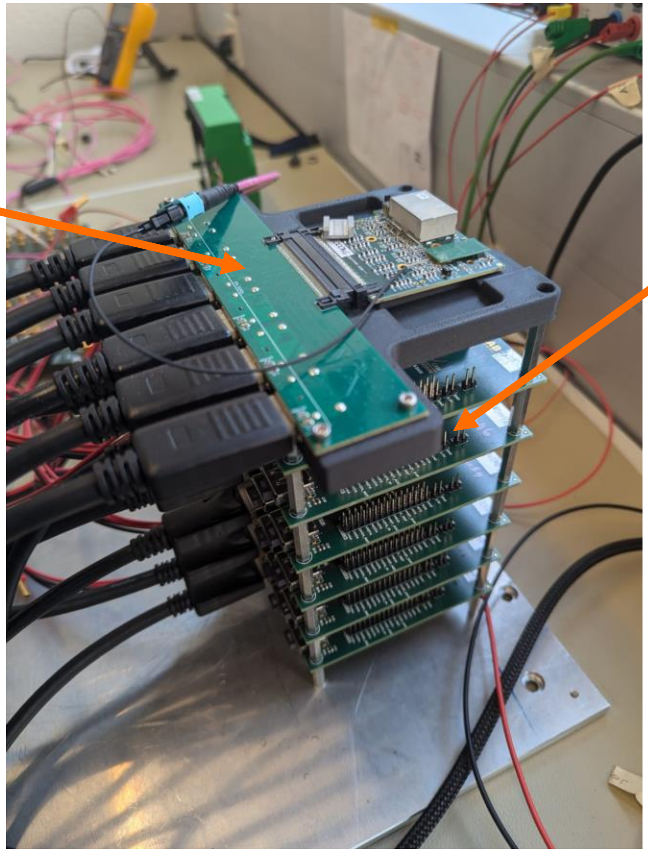


Test for Optoboard production

- Aim: design a quick and efficient way of testing Optoboards

6DP to ERF board
PCB designed specifically for Optoboard testing, and can access all uplinks and 6/8 downlinks

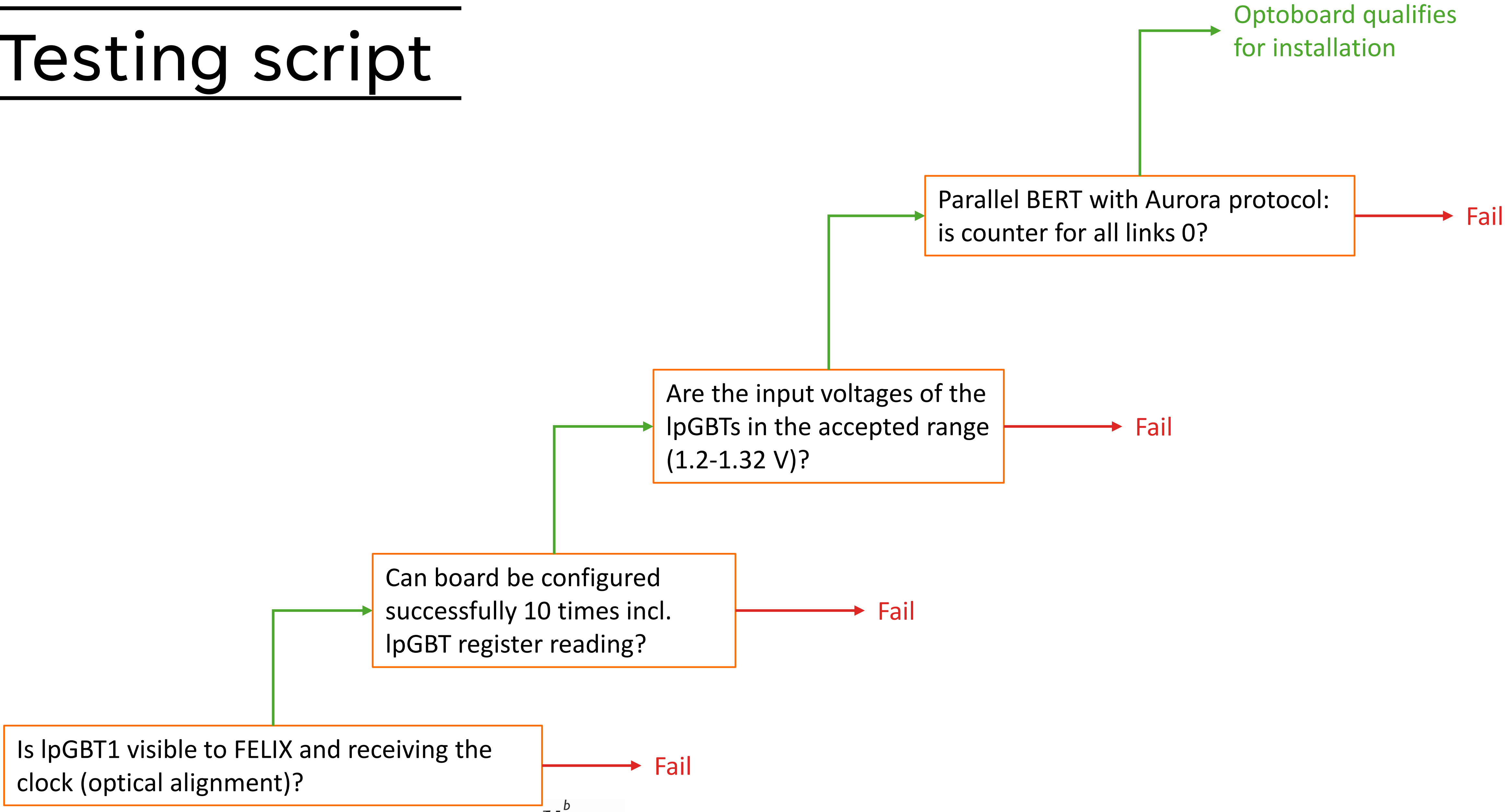




Optoboard test setup (prototype)

Small ITk Pixel module
Final version sensor chip on a PCB with dedicated ports for data transmission (DP) and powering (LV and HV)

Testing script



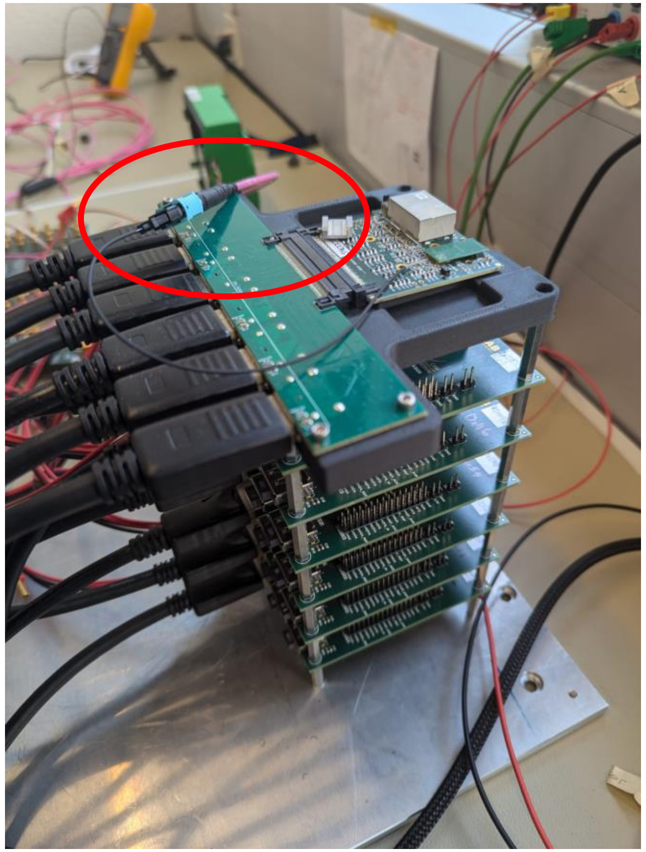
Upcoming improvements

- Current setup does not allow for all downlinks and uplinks to be tested simultaneously (2 downlinks not tested)
  - Proposed solution: reorganise 6DP board into 8DP board with 3 uplinks per port

DP Lines (pins)	ERF8					
	DP1	DP2	DP3	DP4	DP5	DP6
Line0 DP(1,3)	Uplink 6	Uplink 0	Uplink 4	Uplink 10	Uplink 20	Uplink 14
Line1 DP(4,6)	Uplink 7	Uplink 1	Uplink 5	Uplink 11	Uplink 21	Uplink 15
Line2 DP(7,9)	Uplink 8	Uplink 2	Uplink 12	Uplink 18	Uplink 22	Uplink 16
Line3 DP(10,12)	Uplink 9	Uplink 3	Uplink 13	Uplink 19	Uplink 23	Uplink 17
CMD DP(15,17)	Downlink 3	Downlink 0	Downlink 1	Downlink 2	Downlink 7	Downlink 5

GBCR1	Master LpGBT 1
GBCR2	Slave LpGBT 2
GBCR3	Slave LpGBT 3
GBCR4	Slave LpGBT 4

Table 1. The 6DP adapter card V1 mapping



Optoboard test setup (prototype)

- Difficulty connecting optical fibre ferrules without risk of damaging VTRx+ fibre

Summary

The time has come to build the Optosystem!

- Established initial Optopanel filling (Optoboxes and twinax) and mounting procedures
  - Next steps: Finish mechanical tests of Optopanel, including optical fibre fitting
- Optoboard v4 (final) passed irradiation test – even with a safety factor of 3!
  - Next steps: None
- Preparation of Optosystem component test setups including Optoboard test (others not mentioned: cables (CAN, power,...), fibres, Powerboard, Connectorboard, ...)
  - Next steps: Finalise all tests before we start to receive components, then TEST THEM ALL!

Thank you!

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Bern Optosystem presentations

Previous talk: Tests and results of the power components of the ATLAS Inner Tracker detector readout system (L. Mollier)

Next talk: Time-domain Reflectometer Measurements of the Optosystem Data Transmission Chain (U. Alberti)

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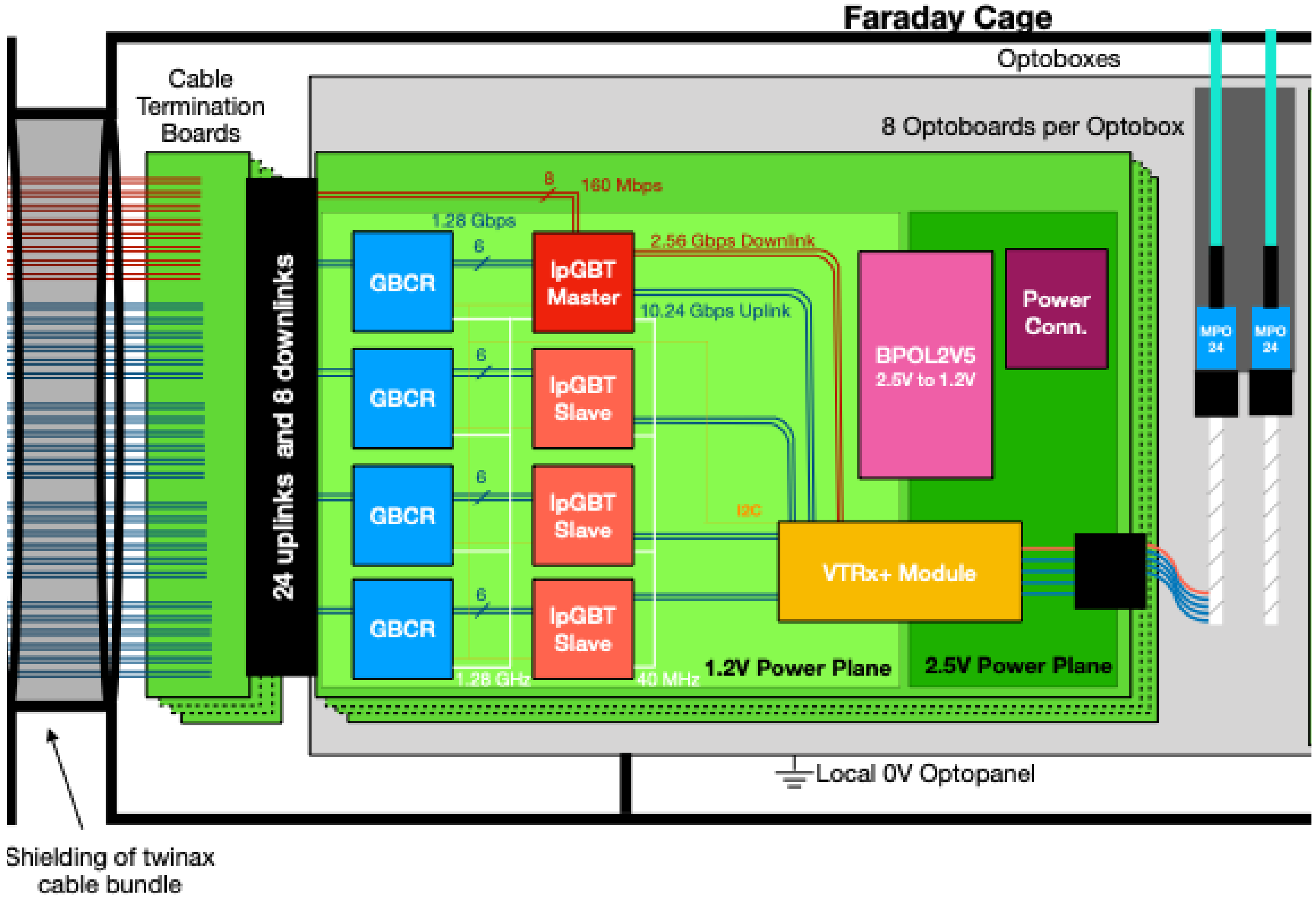
Optoboard data transmission



How to calculate P⁺

- Bit errors are all independent → Binomial distribution is suitable!
- <u>HOWEVER:</u> p << n → Poisson approximation!

Number of bits checked

Probability that bit is wrong

$$\sum_{r=0}^{N_{err}} P(r, N_+) = 1 - 0.95, \qquad P(r, N_+) = \frac{e^{-N_+} \cdot (N_+)^r}{r!} \qquad BER_{95\%} = \frac{N_+}{N_{bits}}.$$

- Above 10 bit errors, BER limit calculated using:

$$BER_{95\%} \approx \frac{N_{err} + 1.96\sqrt{N_{err}}}{N_{bits}}$$

Soft Errors (BERT)

lpGBT/GBCR: BERT with PRBS7
VTRx+: Soft Error (BERT) with Aurora

- Tests data transmission between front-end and FELIX
- Also BERT, but following 64/66b Aurora protocol
  - 64 bits of datastream scrambled into 66 bits (64 + 2 bit header)

$$S \cdot T \cdot S^{-1} \stackrel{?}{=} \mathbb{1}$$

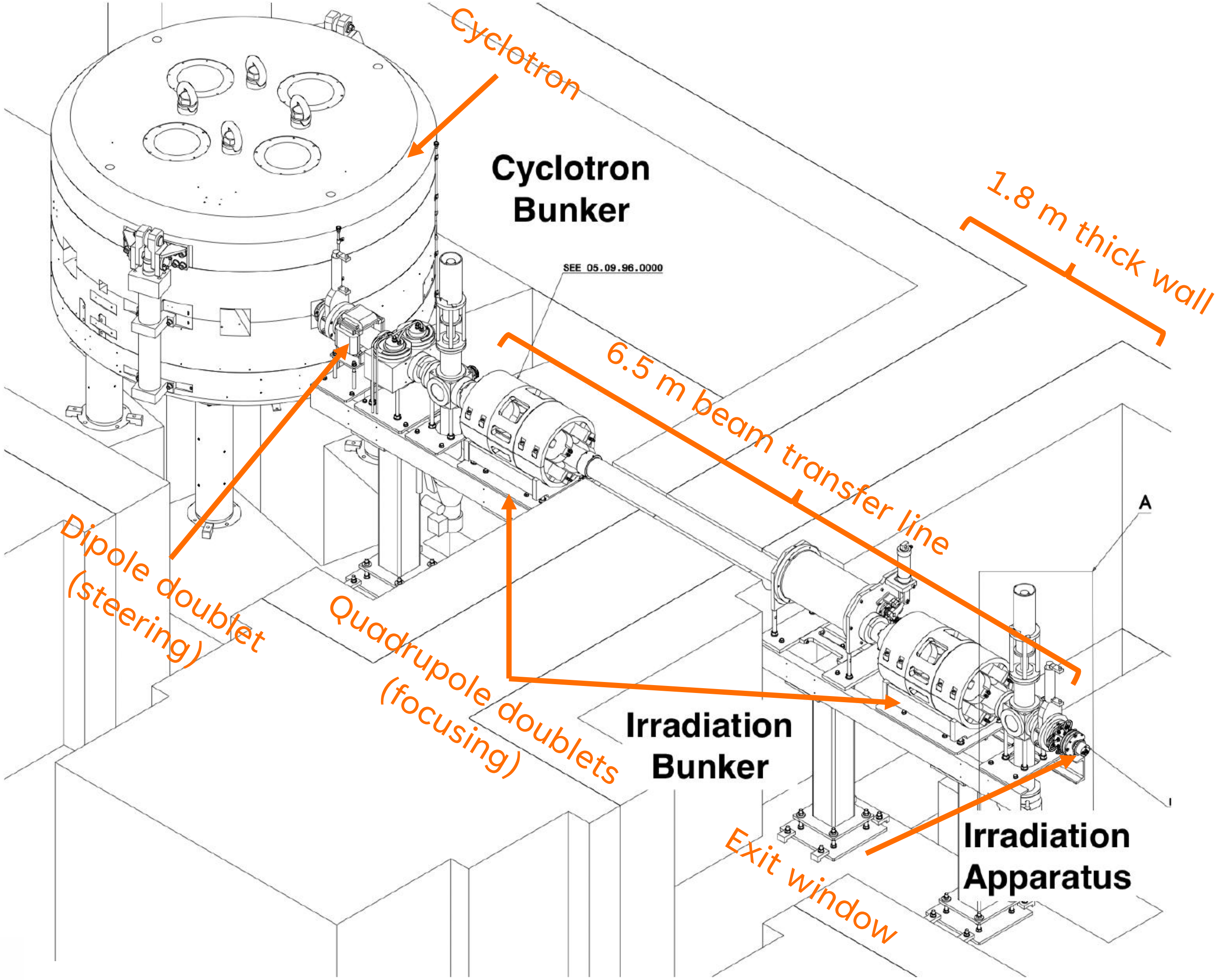
where:
- S – scrambling
- S^{-1} – unscrambling
- T - bitstream sent to FELIX (no header)

- Scrambling/unscrambling depends on three bits (i^{th},$(i-38)^{th}$,$(i-57)^{th}$)
  - After taking into account double counting, 62% of datastream covered

Further discussion in backup slides

Inselspital cylotron

- Cyclotron facility split into two bunkers: cyclotron and irradiation
- Bunkers separated by thick wall, and beam transer line passes through this wall
  - Safe to be inside irradiation bunker when cyclotron running and beam shutter is closed



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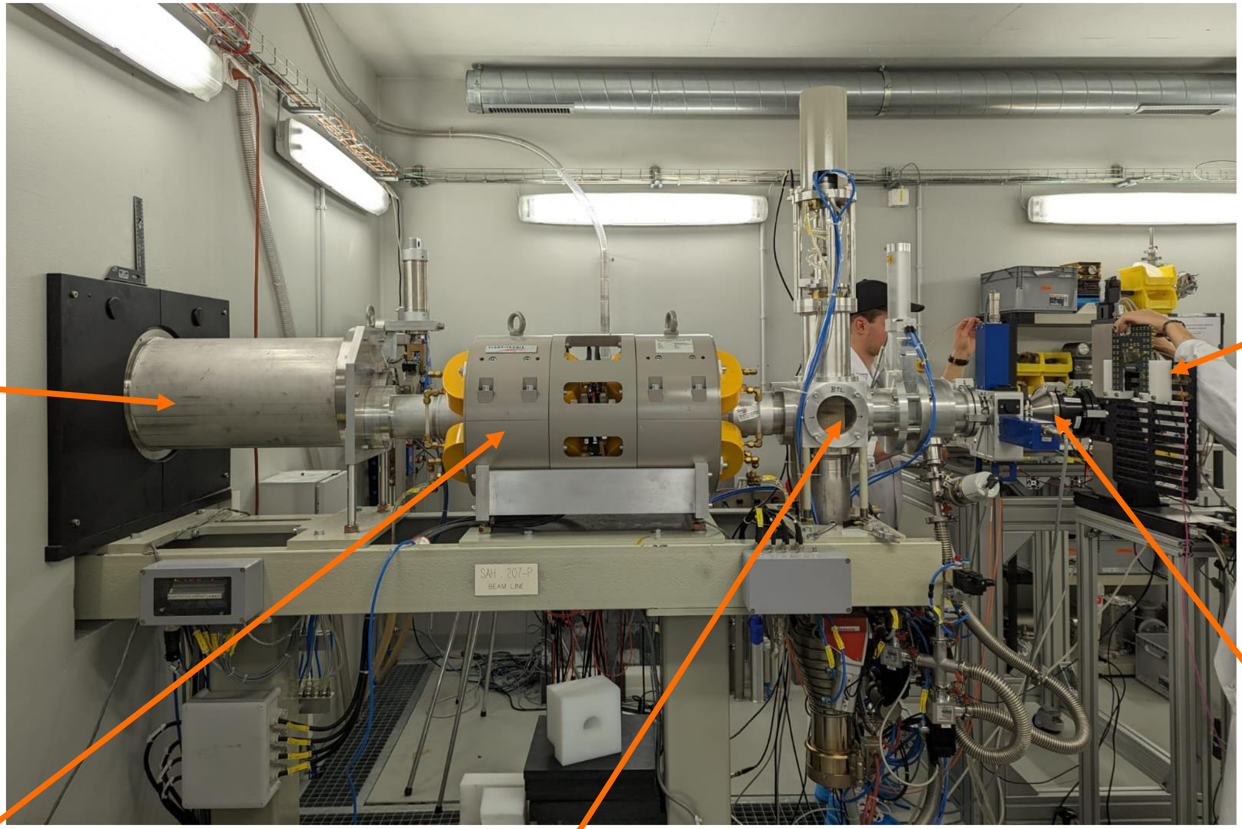
Inselspital cyclotron irradiation bunker



End of beam transfer line

Comes from cyclotron bunker

2D stage

At this point protons have 16.7 MeV energy

Quadrupole doublet

Used for beam focusing

Beam viewer

For beam current measurements, which are used to calculate doses

Collimator

Used 1x1 cm^2 as largest ASIC is 0.9x0.9 cm^2

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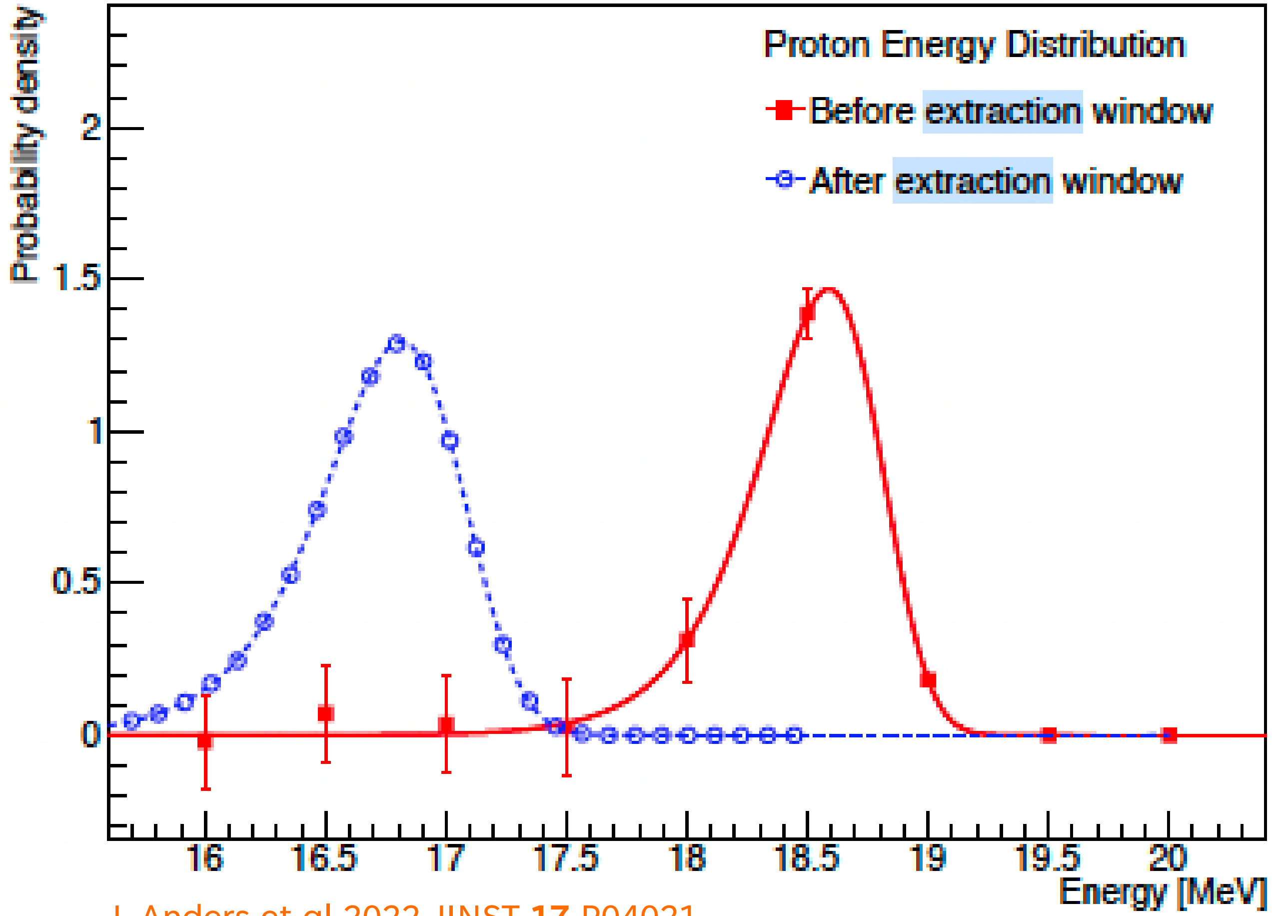
Cyclotron proton beam energy



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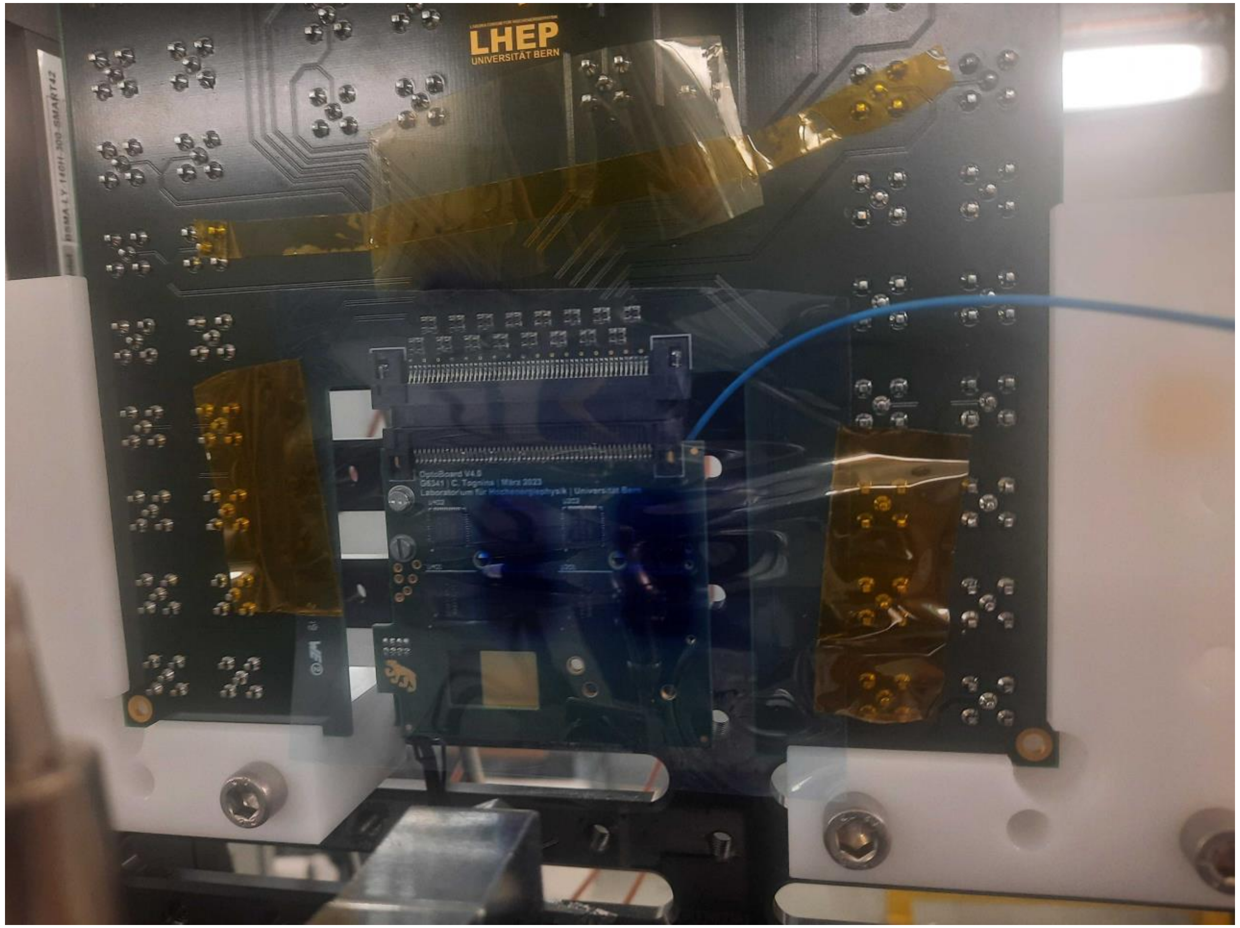
Calculating dose

$$\text{Dose} = \frac{I \times \left\langle -\frac{dE}{dx} \right\rangle}{A_{beam} \times e}$$

- **Current (I)** is known (files provided by Isidre Mateu)
- **Stopping power (dE/dx)** calculated using electron charge (e) and energy of 16.7 MeV
- **Beam area (A_{beam})** calculated assuming beam is circular with 1.5 cm radius, and removing collimator area (1 cm^2) – this is area hitting collimator

Aligning Optoboard with beam

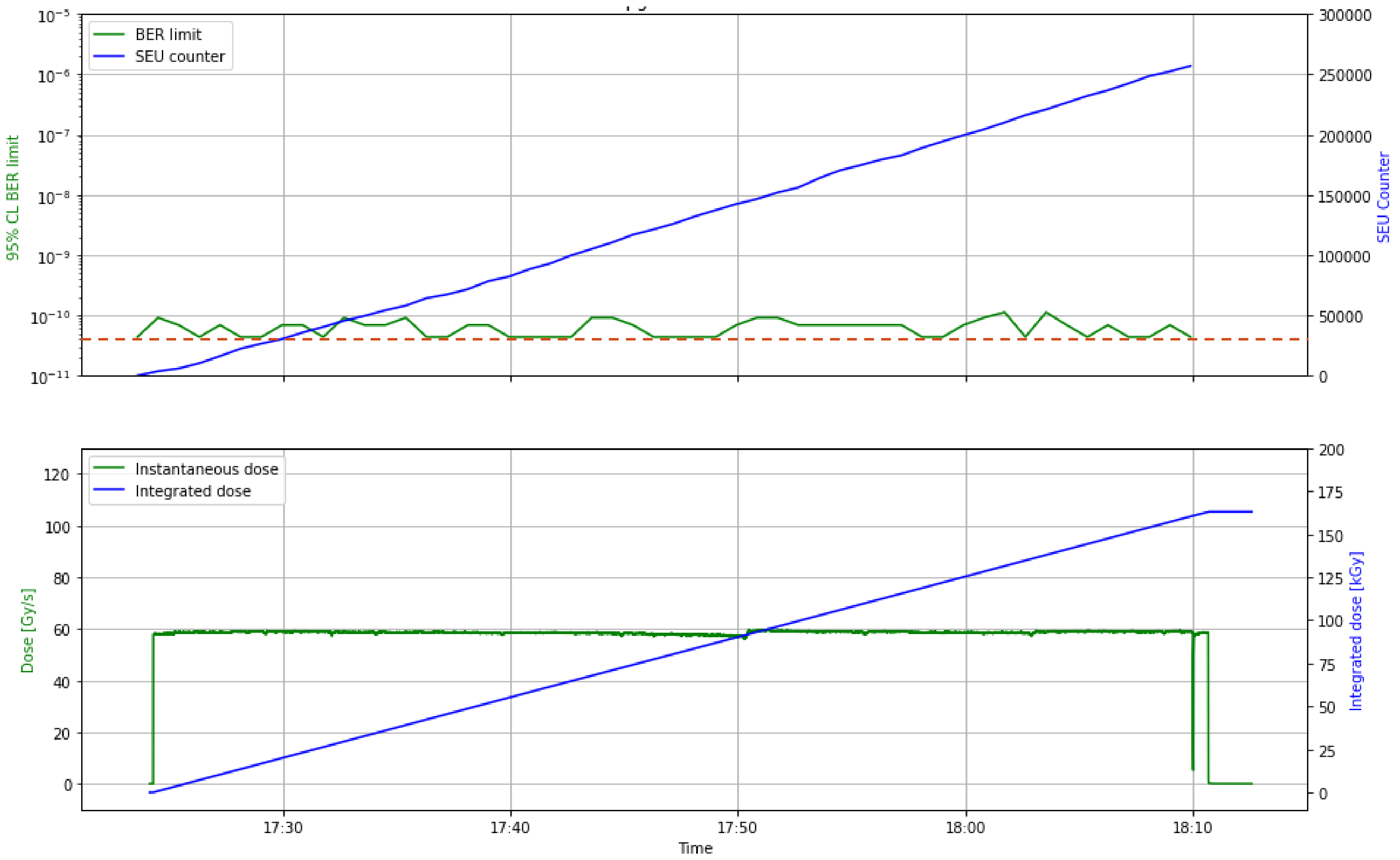


- Using photochromic film, one can see where the beam hit the Optoboard
  - Size of spot should be the same as size of collimator used

Irradiation results summary

- Measurement time = 54 s
- $\lim(\text{BER})_{95\%}(0) = 4.34 \cdot 10^{-11}$

lpGBT 3 irradiation



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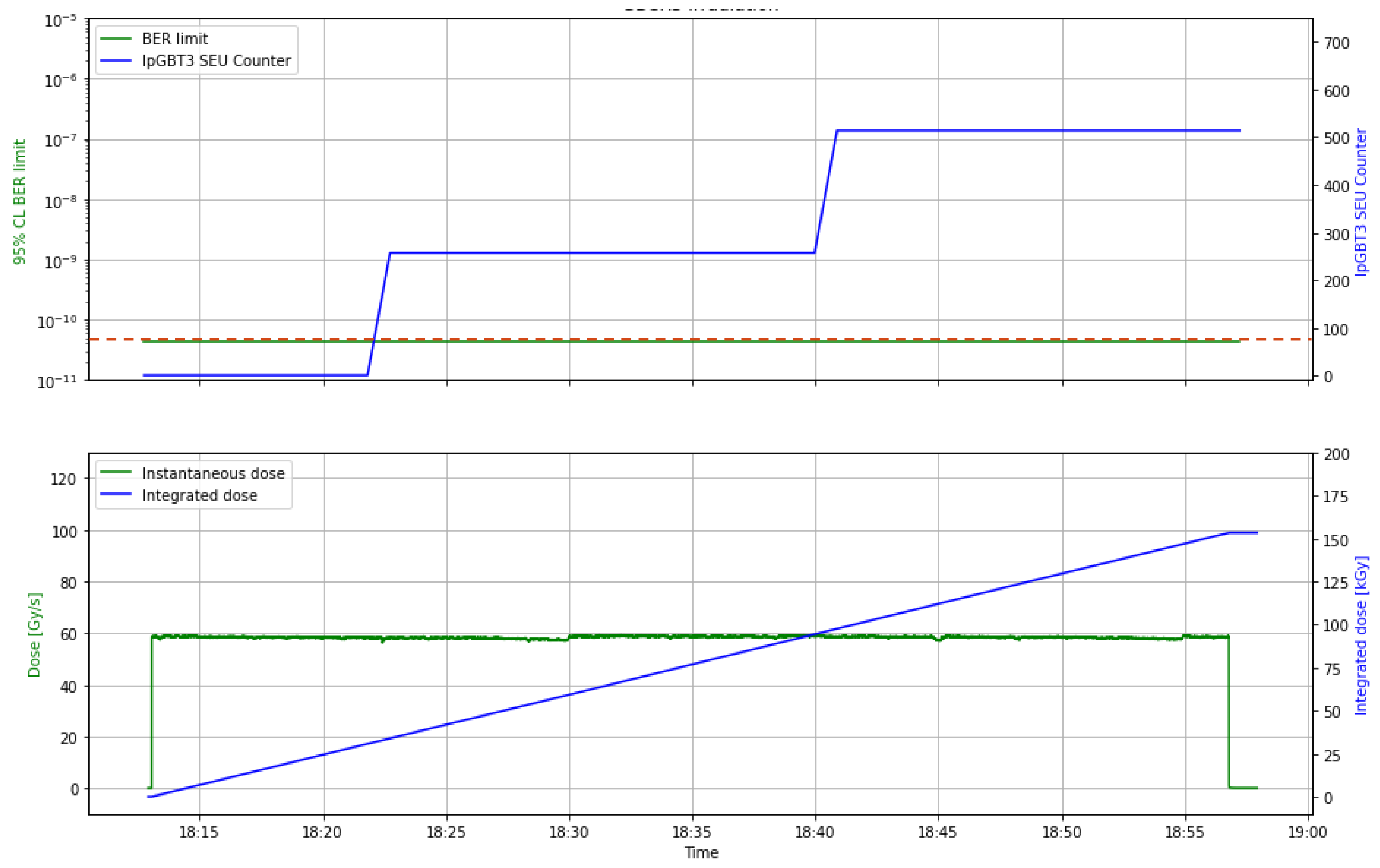

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