Three parameterisation = 

- implemented in 0.35 μm SiGe BiCMOS technology node with 3 mW/channel power consumption;
- OMEGA – Microelectronics Center:

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- Three samples investigated using 35 MeV proton beam at JULIC:
  - cumulated total ionizing dose (TID) per each device of 200 to 600 krad (Si);
  - TID rate of about 30-170 rad/s;
  - proton flux: typically 1.3 \times 10^{10} p/cm^2/s to maximum of 7.8 \times 10^{11} p/cm^2/s;
  - proton fluence: 0.9 \times 10^{12} p/cm^2 to a maximum of 2.8 \times 10^{13} p/cm^2;
  - once beam stopped, annealing phenomena measured for one sample over 8.5 h continuously.

Conclusions
- Rapid annealing has mitigated the cumulative radiation-induced effects leaving no signs of permanent operation impairments on MAROC3 even at 600 krad(Si);
- Tested samples proved very resilient against TID effects.
- After Phase I Upgrade, in the LHCb-RICH sub-detectors environment dose rate is 7.8 \times 10^{-6} rad/s TID(Si), therefore it is a low probability for the cumulative effects to become visible.
- The MAROC3 behaviour should be investigated under particle beam with high linear energy transfer (LET) to measure the threshold for various Single Event Effects (SEE), e.g. Single Event Upset (SEE) in configuration bits, and especially Single Event Latchup (SEL).
- In radiation environments with low dose rate the rapid room-temperature annealing process overcome the effect of leakage current increase with TID, moreover for the target application the analytical toy model used indicate an insignificant current consumption increase in worst case scenario, so no major impact on detector power budget.

Data analysis and extrapolation
- TID effects induced by proton beam at high dose rate:
  - threshold found between 50 - 100 krad (Si), TID rate of about or greater than 30 rad/s for presented results;
  - the chip power consumption increased on both rails (analog and digital) once 50 krad (Si) value was exceeded;
  - leakage current within ASIC semiconductor structure increases sharply with TID.
- Analytical toy model for ASIC behaviour extrapolation:
  - worst case scenario when current increase is parametrized with an linear model;
  - the current increase was taken to be linear with TID rate, and overestimated the largest value of first derivative of current during irradiation to 200 krad(Si);
  - annealing phenomena was parameterised (yellow line) using a fit with a two exponential functions (formula 1):
    \[ y = y_0 + A_1 e^{-\frac{x}{\tau_1}} + A_2 e^{-\frac{x}{\tau_2}} \]
  - an analytical toy model was used for the ASIC current consumption parameterisation in given radiation environment;
  - added to the baseline value are two current components increasing with TID in time to a saturation plateau;
  - their amplitude ratio was found for the digital current to be 551 and for analog 127;
  - annealing timescales for the two currents in case of digital rail are \( \tau_1 = 1359.12 \) s and \( \tau_2 = 5497.37 \) s, while for analog rail are \( \tau_1 = 1749.8 \) s and \( \tau_2 = 8663.3199 \) s;
  - at end of irradiation, the digital current consumption increased severely to 190%, while the analog current with almost 35%;
  - the results of extrapolation procedure applied to irradiation plus annealing period show an increase with only 3.12 mA digital current from baseline, with purple is model extrapolation for 9.5 h irradiation time;
  - parametrisation applied for estimated RICH-LHCb radiation environment (200 krad (Si) TID over 7000 h of LHC operation in RUN3 and RUN4) show an increase for the digital current with 4 μA and for analog current with 8 μA.

Third sample was irradiated up to 600 krad (Si) and 170 rad/s dose rate had the Slow Control registers latched:
- beyond 400 krad (Si) the DACs configuration registers became stuck, but fully recovered through annealing.

Study motivation
- Readout Chips are exposed to high TID to assess their reliability in mixed-field radiation environment generated within Large Hadron Collider (LHC) experiments;
- ASICs and Commercial Off-The-Shelf COTS tolerant beyond 400 krad (Si) in hard hadron spectrums;
- Accelerated irradiation tests, behavior analysis and extrapolation to a given environment;
- Large Hadron Collider beauty (LHCb) detector Phase I Upgrade for RUN 3 and RUN 4 of LHC:
  - Sub-systems upgraded for data readout at 40 MHz, and integrated luminosity of 50 fb^{-1};
  - MAROC3 was considered as backup for Ring Imaging Cherenkov (RICH) sub-detector front-end chip, where TID level is estimated to 200 krad (Si) and expected High Energy Hadrons (HEH) fluence is 1.2 \times 10^{15} cm^{-2}.

Mult-Anode ReadOut Chip
3rd generation
- Application-Specific Integrated Circuit (ASIC) features:
  - implemented in 0.35 μm SiGe BiCMOS technology node with 3 mW/channel power consumption;
  - OMEGA – Microelectronics Center:

ASIC Test Bench


Proton-Induced Radiation Effects in MAROC3, a full readout 0.35 μm SiGe ASIC

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