Effects of irradiation on leakage current in CMOS readout chips

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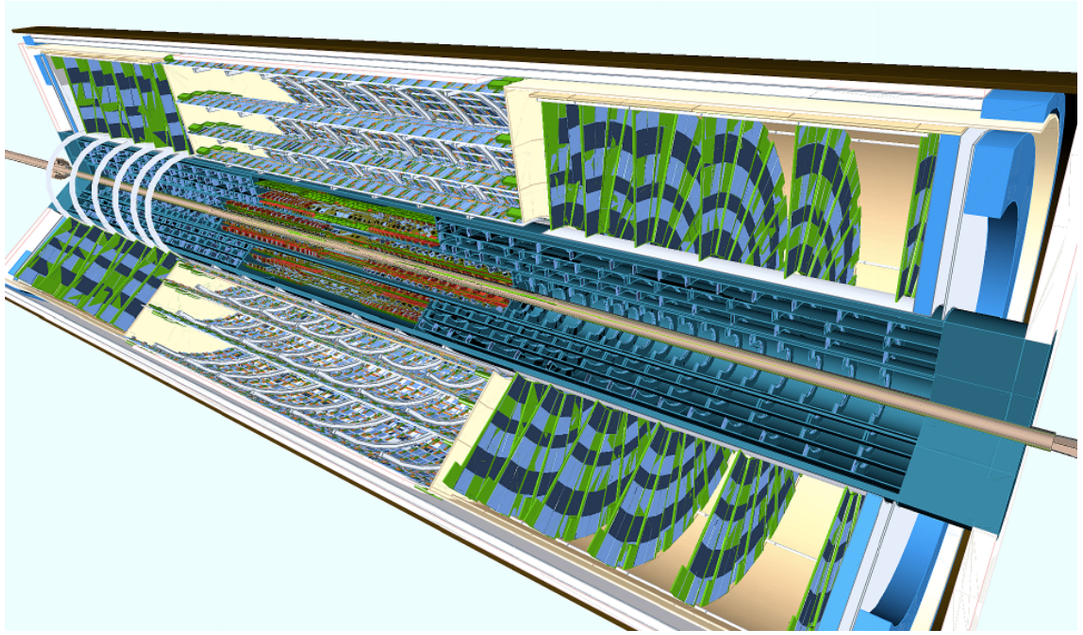
Atlas Inner Tracker

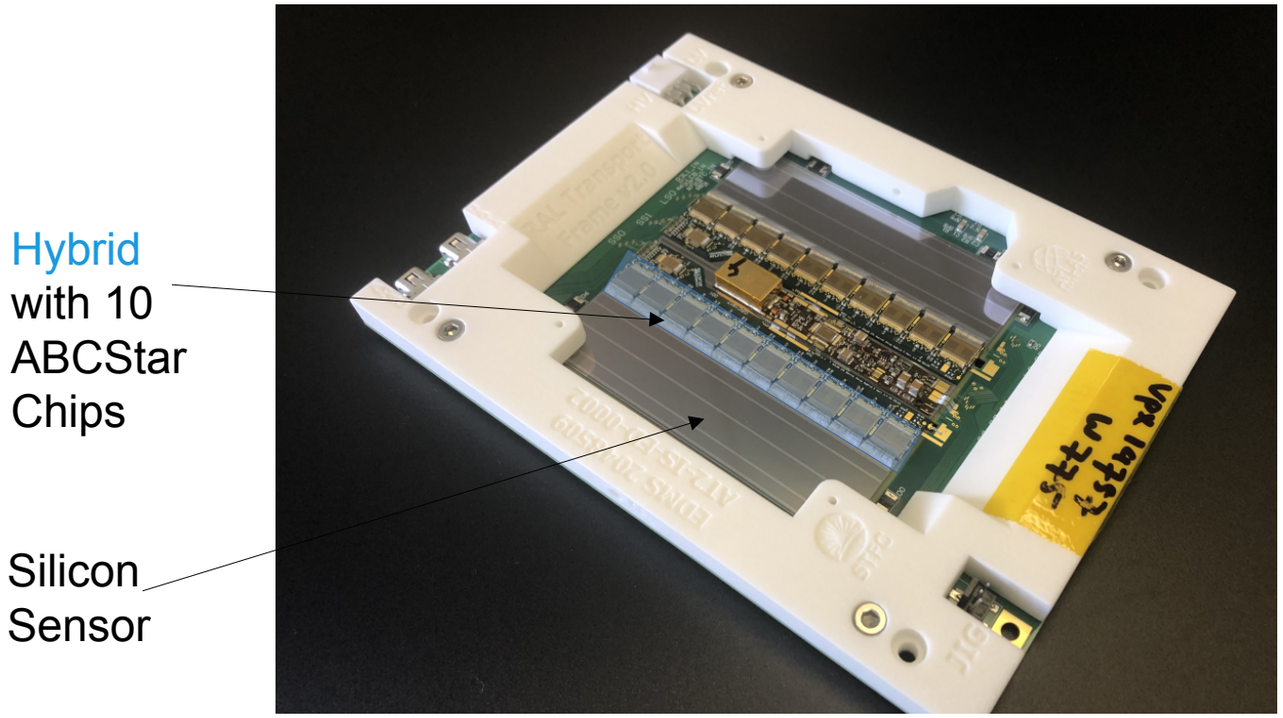
- ITk will be a complete replacement of the current inner detector for the High Luminosity LHC

- Designed to handle ten time larger luminosity and four times larger pileup
- Inner layer of high granularity “Pixel” detectors, outer layer of lower granularity “Strips” detector

- The ITk strip readout chip is called the ABCStar, Its prototype was the ABC130

- Manufactured in Global Foundries 130 nm technology



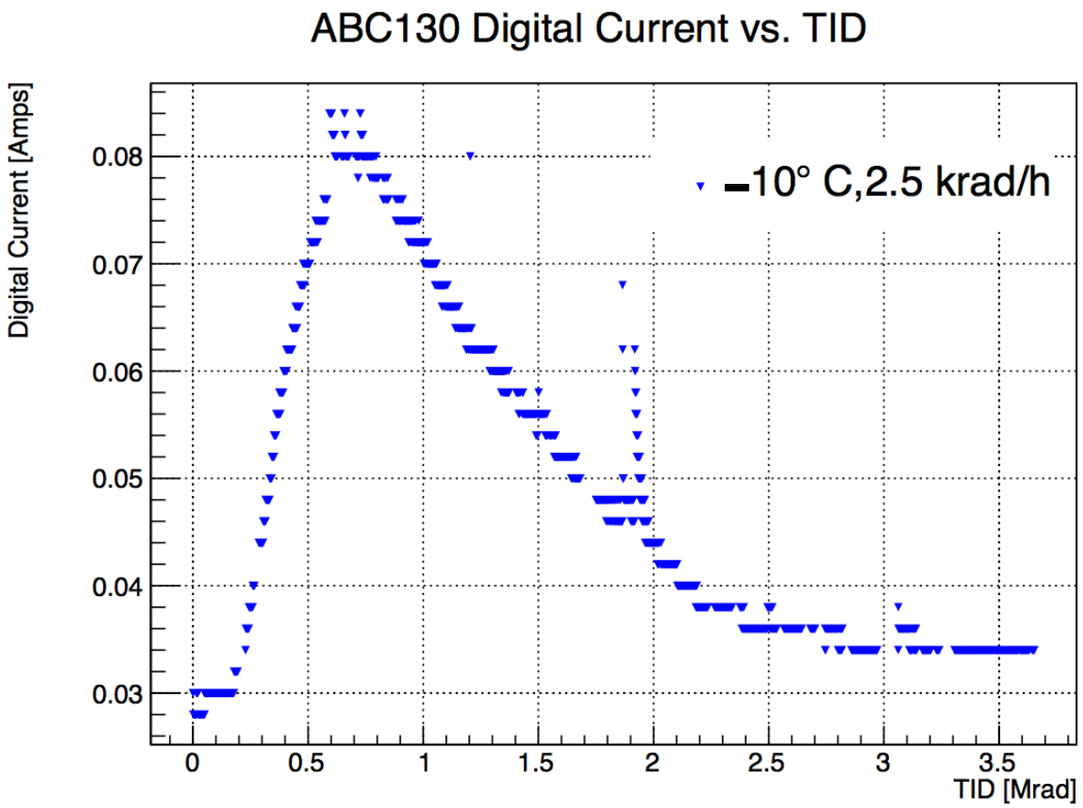


ITk Strip Module

Background to TID Bump

- A dramatic increase in the ABC130 digital current with Total Ionizing Dose (TID) has been observed In the ABC chips, up to ~600 krad, followed by a current decrease. This is known as TID bump

- The TID bump creates problems for cooling, power consumption and thermal simulations. It is thus necessary to conduct irradiation campaigns on the new ABCStar to characterize the TID bump



http://inspirehep.net/record/1665044/

Irradiation Setups

High dose rate irradiation at RAL

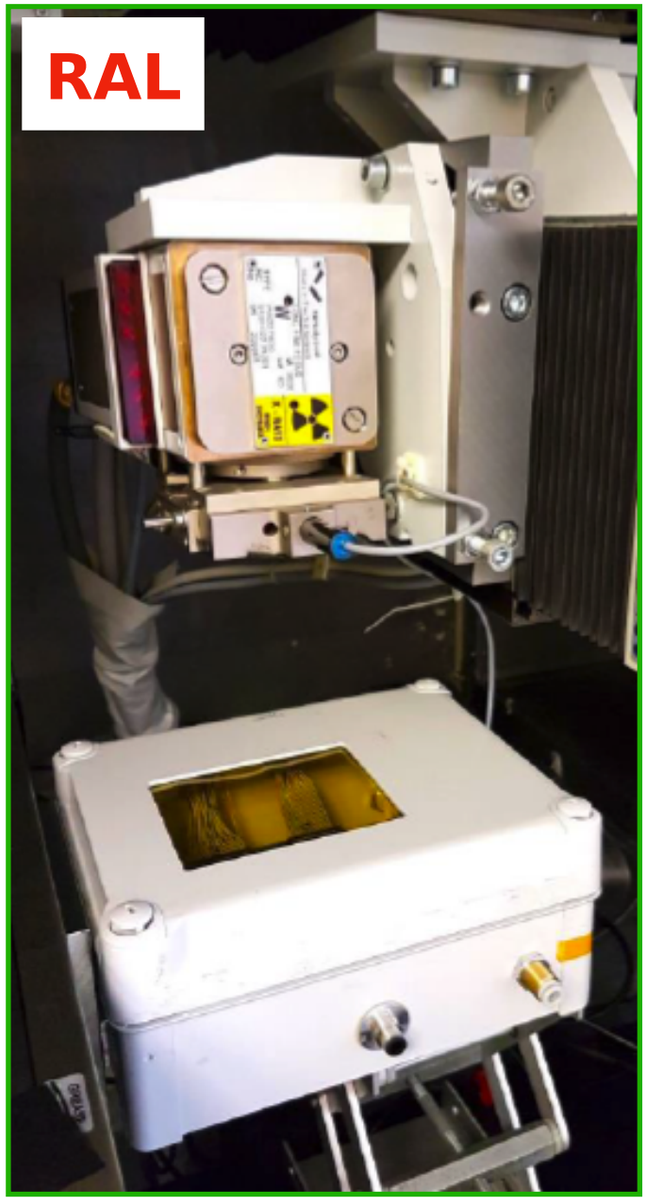
- 60 kV X-Rays
- Tungsten tube
- 1 Mrad/hr

Low dose rate irradiation at BNL

- 1.25 MeV Gamma Rays
- ^{60}Co source
- 0.6-2.5 Krad/hr

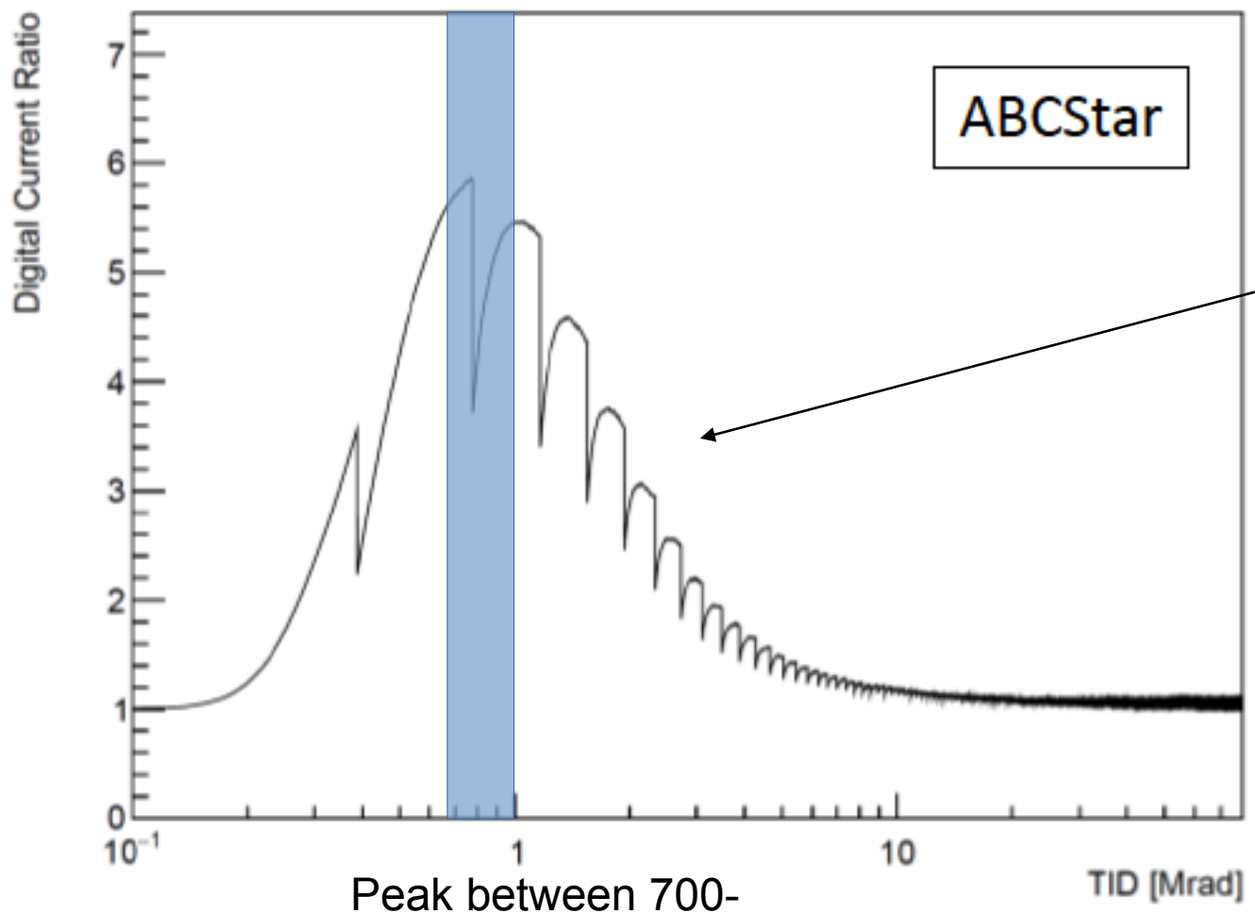
Pre-irradiation at INER

- ^{60}Co source
- 320 krad/hr



High dose rate irradiation results

RAL irradiation confirmed ABCStar TID bump (previously only studied with the prototype ABC130)



Peak between 700-900 krads

Source OFF to run electrical Functionality tests

Digital Current Ratio=

$$\frac{I_{dig}(\Phi(t))}{I_{dig}(\Phi(0))}$$

Φ=total dose

Current increase consistent with previous ABC130 results

Slow irradiation results

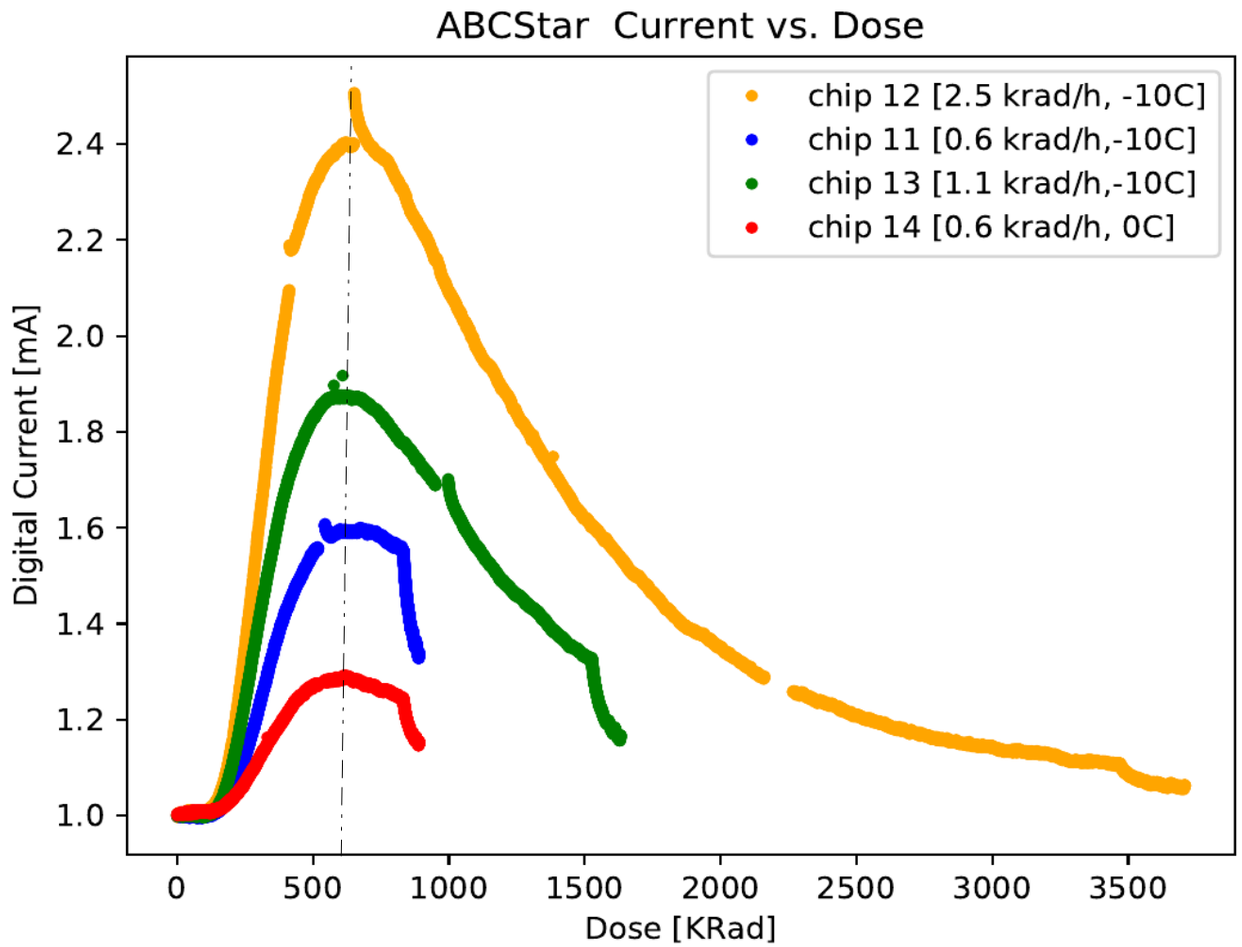
Study of the radiation-induced digital current of the ABCStar chip at HL-LHC-like dose rates

- Irradiation at BNL at different dose rates and temperatures

- Dose rates dependance studied at -10 C: 2.5, **1.1**, **0.6** krad/hr

- Temperature dependance studied at 0.6 krad/hr: **0** C and **-10** C

Results are in agreement from what expected from previous studies: http://inspirehep.net/record/1665044/



Current increase vs. Dose rate, peak is at 600 krad.

- At a given dose rate, a higher temperature results in a lower current increase
- At a given temperature, a higher dose rate results in a higher current increase

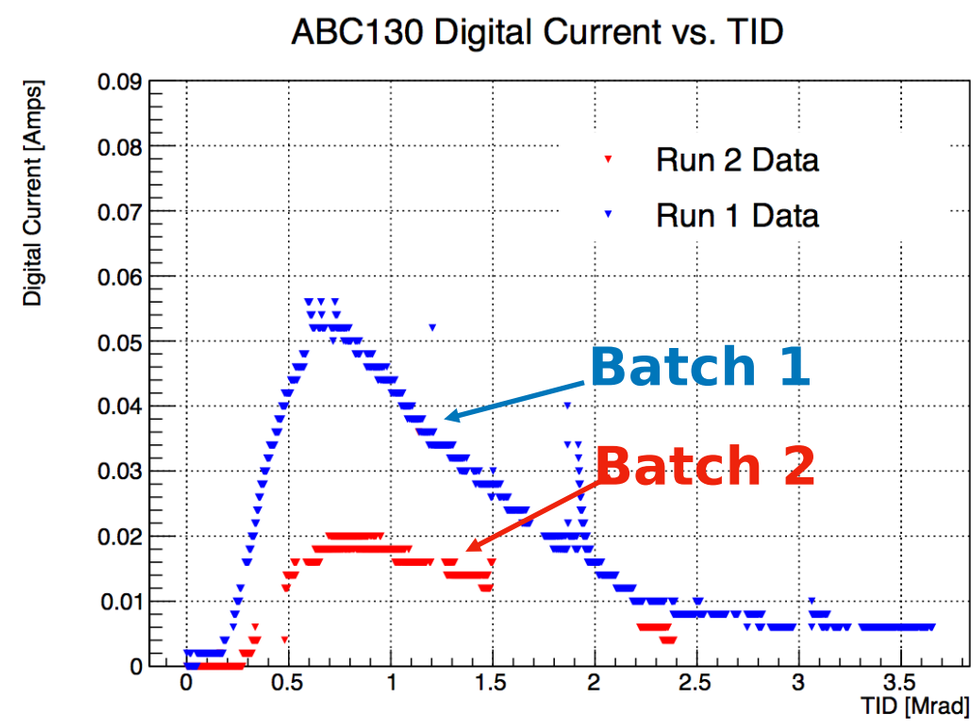
Batch-to-batch variations

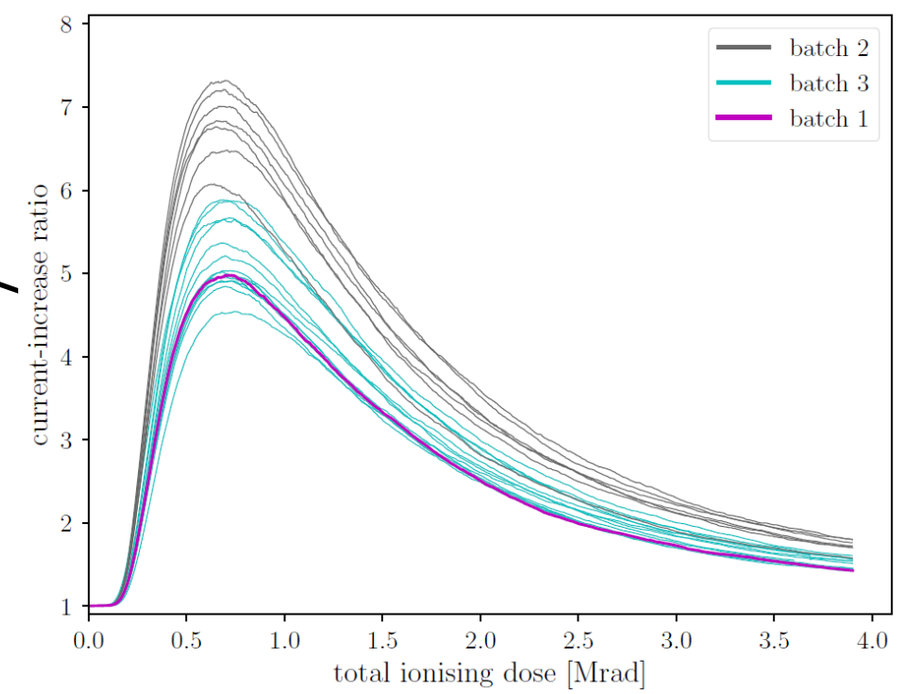
- Batch-to-batch variation observed during the ABC130 irradiation at BNL and later confirmed at RAL

- Higher statistics is needed to characterize variations between batches, wafer and chips in the same wafer

- The peak current changes significantly (up to a factor of ~2) according to the production batches

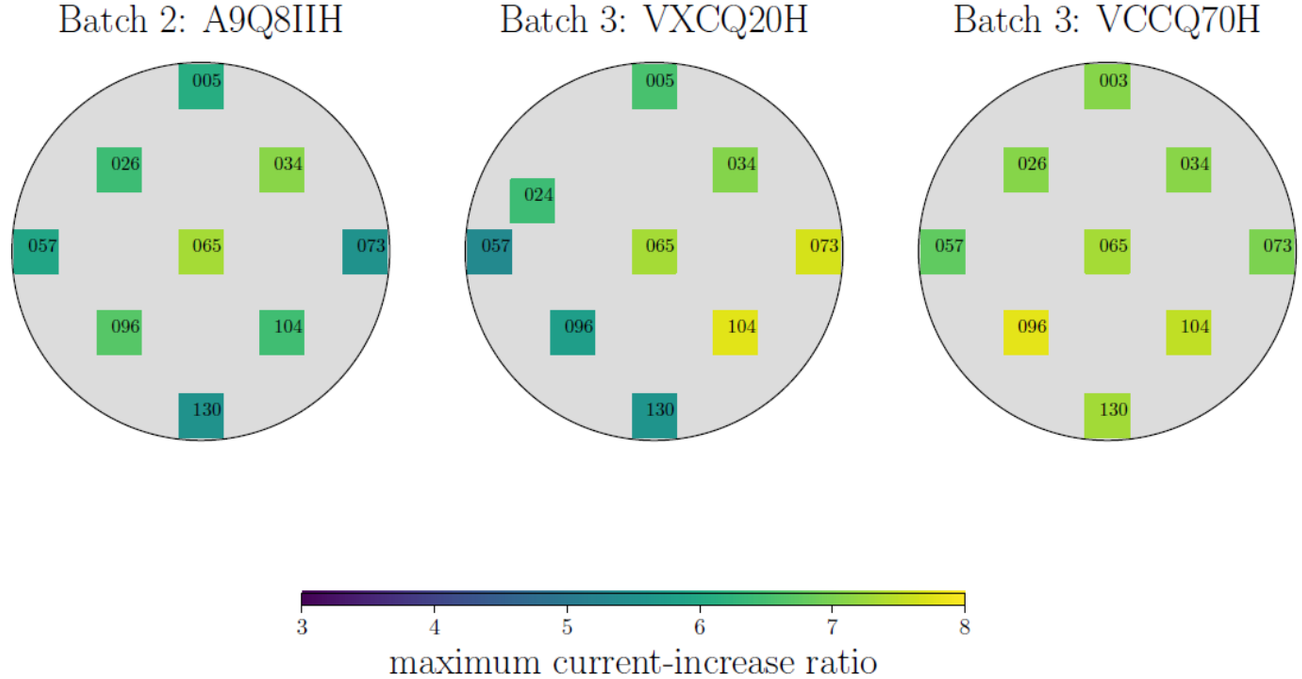
- These factors add serious complications on the prediction of the power consumption





Chip-to-chip variations

- X-rays studies on chips at a specific wafer positions made at RAL show similar variations as batch-to-batch (60 kV x-rays)
- No obvious pattern in the current peak relative to the chip position



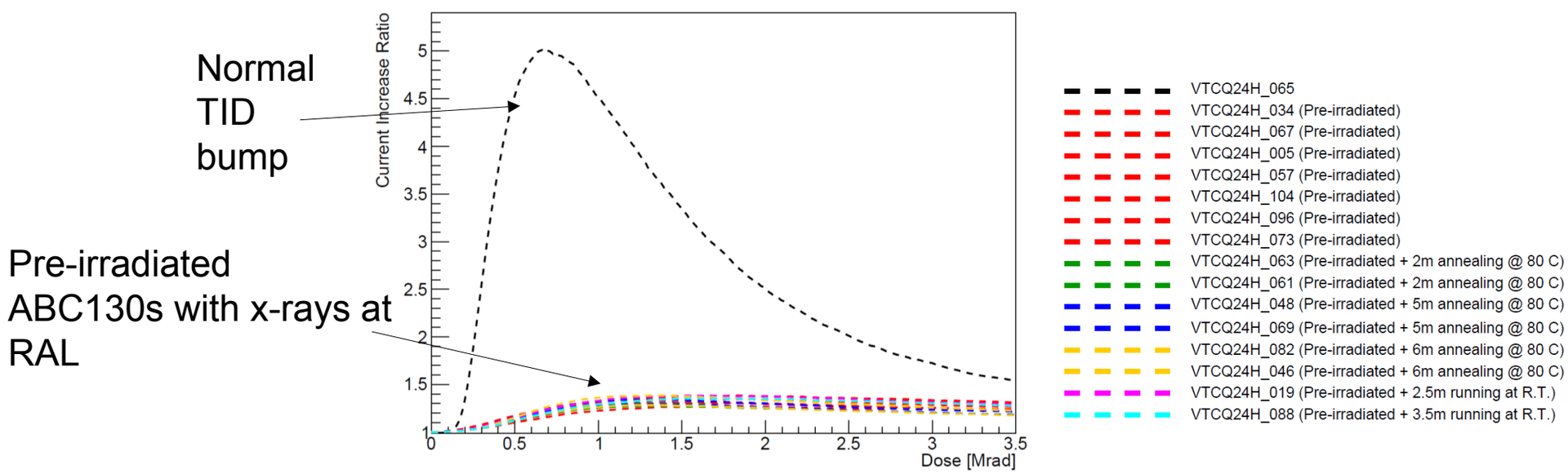
Pre-irradiation

Pre-irradiation at wafer level can be the way to eliminate radiation-induced leakage current and avoid the TID bump

- Initial results very promising (made with the chip prototype ABC130)
- Positive result was no significant change in digital current
- Pre-irradiation done with ABCStars unpowered, necessary for mass pre-irradiation of all ABCStars

Annealing studies were necessary:

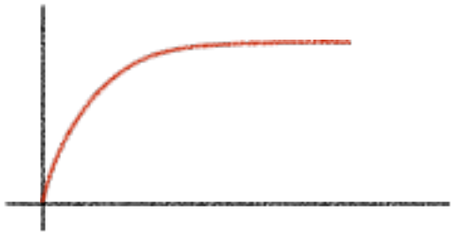
- Running ABC130s at room temperature continually (up to ~3.5 months)
- Keeping ABCs at 80 C (up to ~6 months) to accelerate potential electron annealing

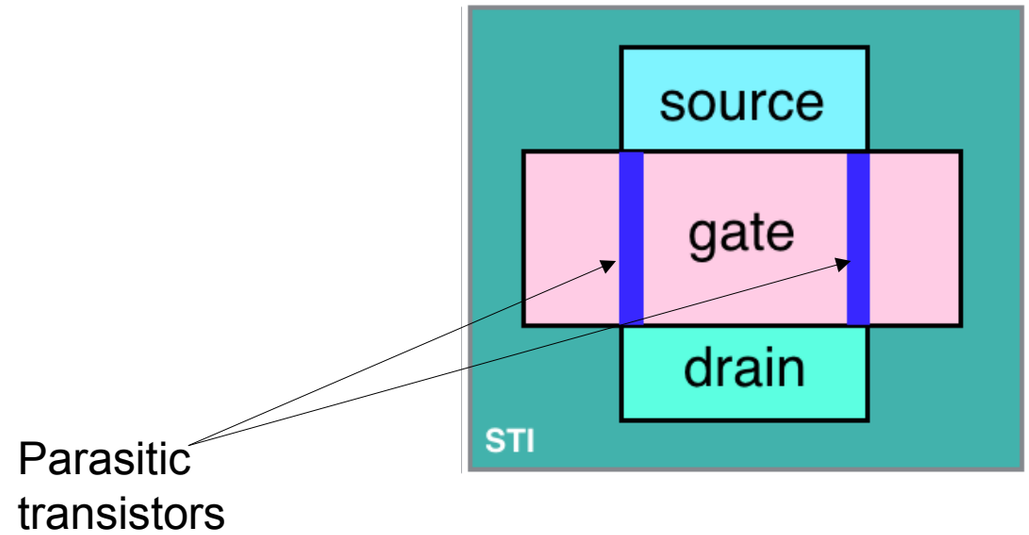


The ATLAS ITk collaboration is now considering pre-irradiation as the likely baseline

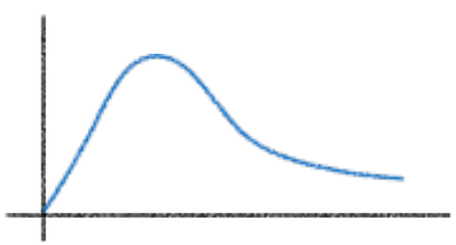
Theory

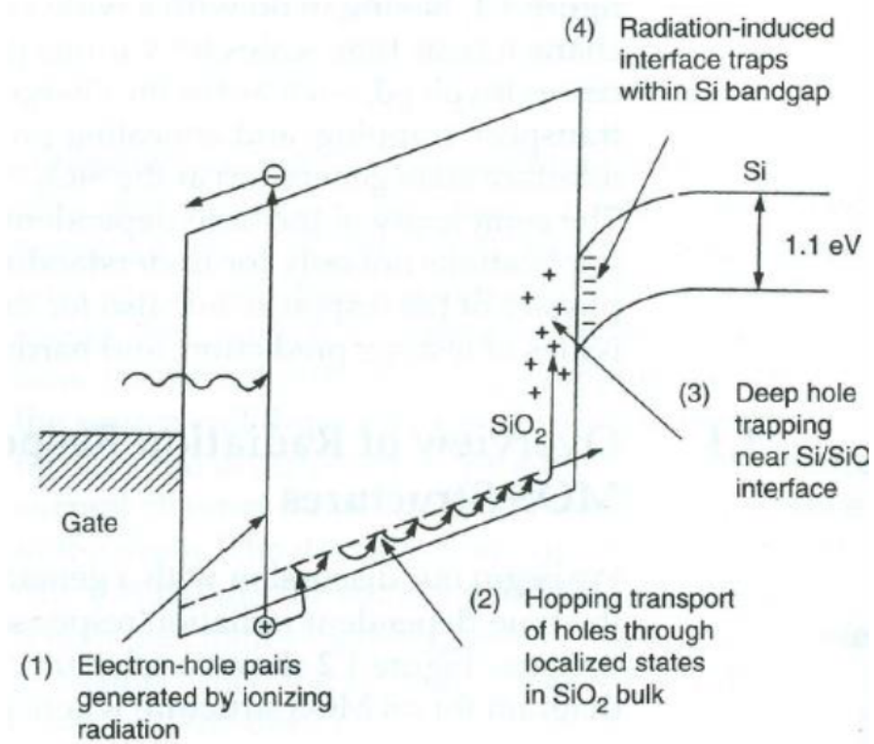
- TID gives origin mainly to two types of defects which contribute to the “TID bump”:
  - Trapped positive charges in the STI oxide (parasitic transistor gate) near the Si-SiO2 interface creates a source-drain channel → leakage current increases





  - Trapped electrons at the Si-SiO_2 interface compensate for the effect of trapped holes in the oxide → leakage current decreases





T. R. Oldham, *Ionizing Radiation Effects in MOS Oxides*. Page 4, Singapore: World Scientific, 1999.

Simplified Model

$$I_{leak} = (n_e - n_i - n_{thr})^2, n_e - n_i - n_{thr} > 0$$

I_{leak}: Leakage current

n_E: Number of trapped holes

n_i: Number of trapped electrons

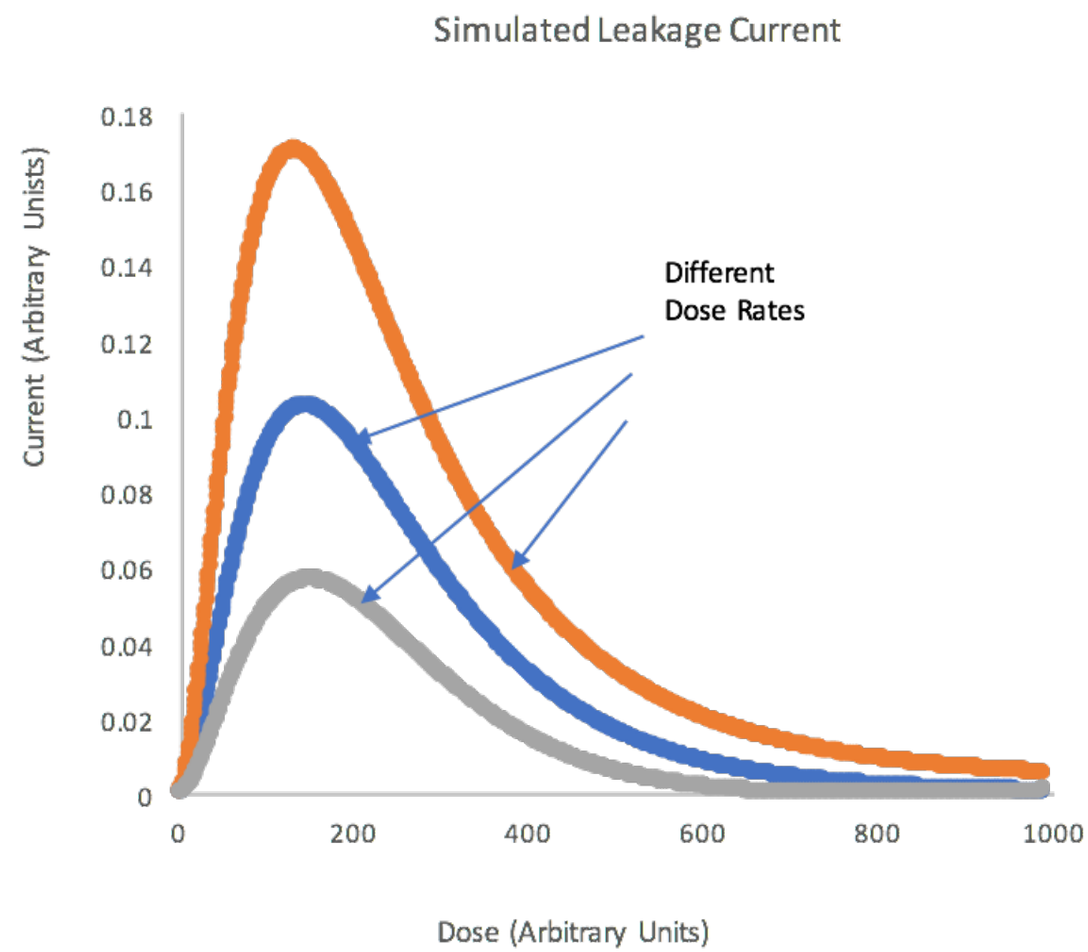
n_{thr}: Threshold

$$\frac{dn_E}{dt} = A_E(N_E - n_E) - P \cdot n_E$$

$$\frac{dn_i}{dt} = A_i(N_i - n_i)$$

Annealing term

Growth terms



$A_E(\phi)$: Rate holes created

$A_i(\phi)$: Rate electrons created

N_E: Number of available hole traps

N_i: Number of available electrons traps

$P(T)$: Probability per time that a hole is released from a trap (Temperature dependent)

Fit results

$$I_{leak} = K \cdot \left(\frac{N_e A_e}{A_e + P}(1 - e^{-x\cdot(A_e+P)}) - N_i(1 - e^{x\cdot A_i}) - n_{thr} \right)^2$$

- The Fit equation

$$y = \left(C_1(1 - e^{\frac{-x}{C_2}}) - C_3(1 - e^{\frac{-x}{C_4}}) - C_5 \right)^2$$

If $C_1(1 - e^{\frac{-x}{C_2}}) - C_3(1 - e^{\frac{-x}{C_4}}) - C_5 > 0$

- Where the parameters are

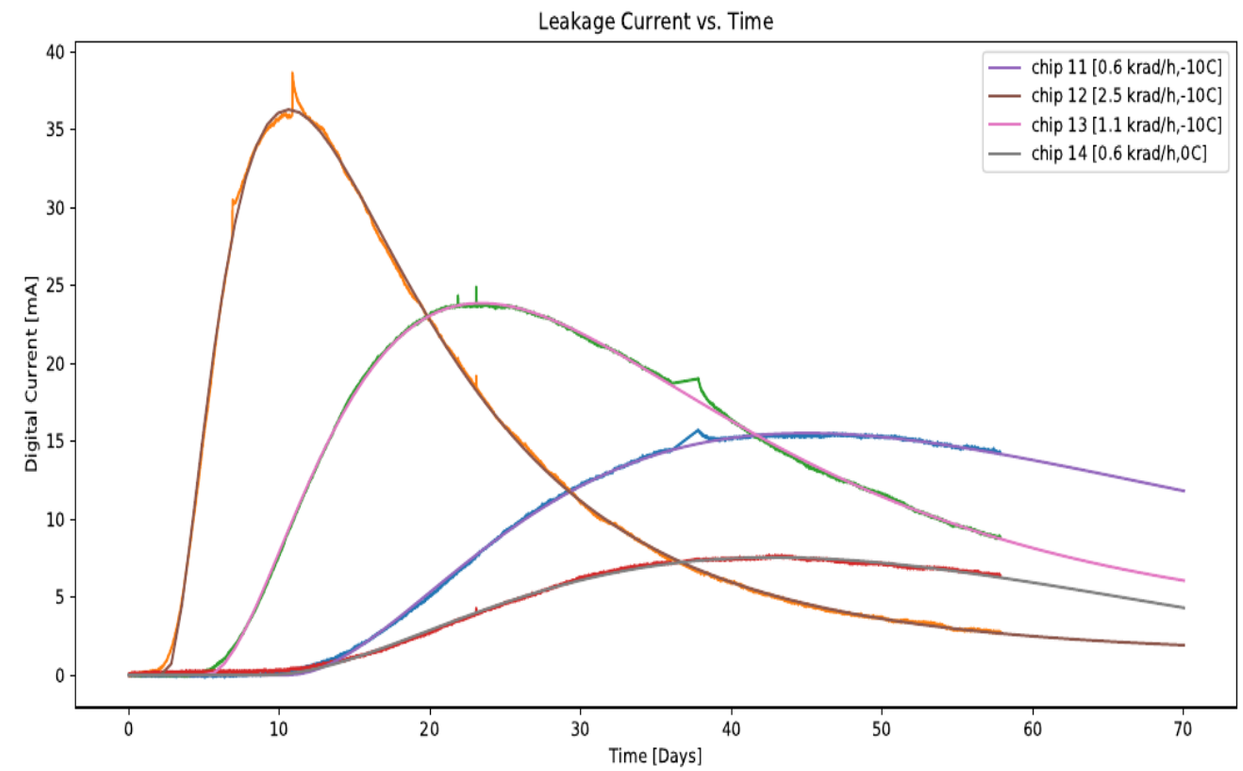
$$C_1 = \frac{K \cdot N_E \cdot A_E}{A_E + P}$$

$$C_5 = K \cdot n_{thr}$$

$$C_2 = \frac{1}{A_E + P}$$

$$C_4 = \frac{1}{A_i}$$

$$C_3 = K \cdot N_i$$



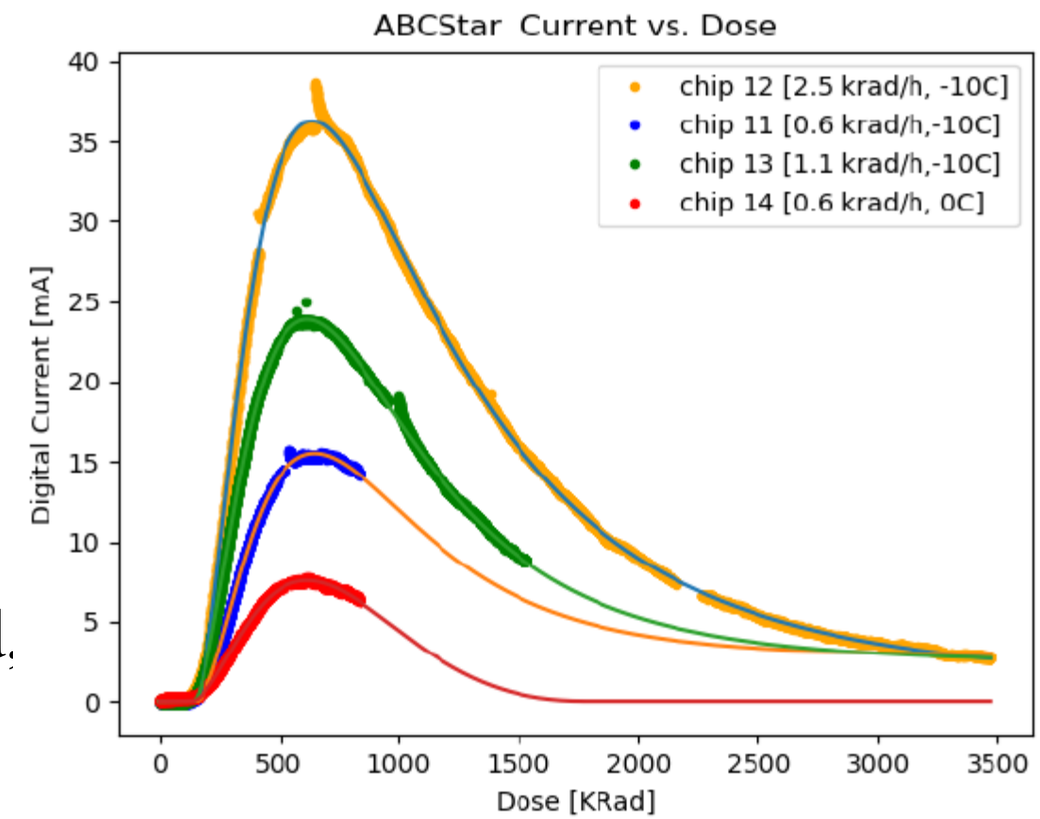
- Fit Results look good

Fit result

Chip	Dose Rate[krad/h]	Temperature [C]	C5 [√mA]	C1 [√mA]	C2[days]	C3[√mA]	C4[days]
12	2.5	-10	8.12	19.9	3.77	10.6	19.34
13	1.1	-10	5.74	21.02	10.445	13.71	25.88
11	0.6	-10	3.95	396.01	27.74	289.37	28.5
14	0.6	0	2.45	392.7	40.77	392.26	42.18

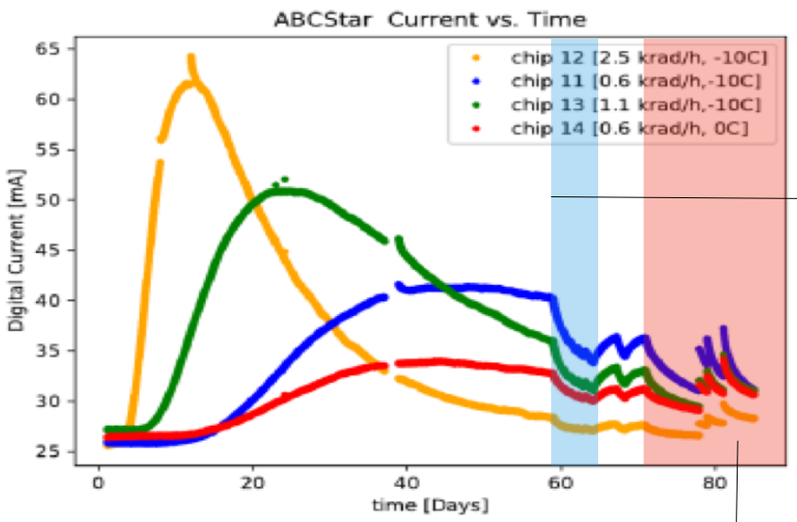
Fit results, Shared parameter

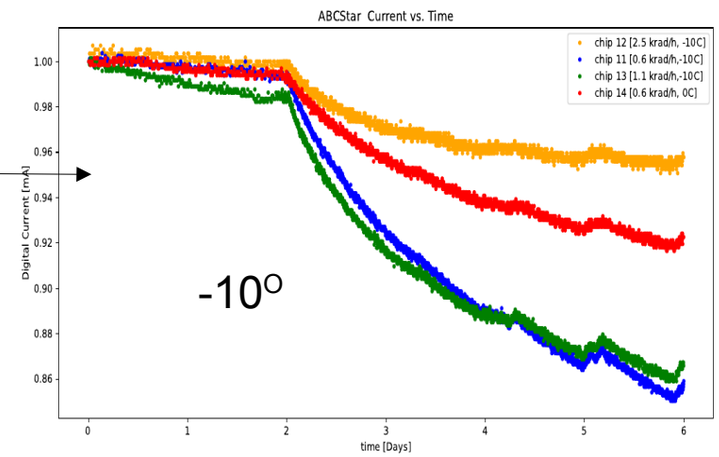
- Fit of the same formula but keeping the tau constant for negative states build up (C4) the same between the datasets
- C4 in the model only depends on total dose not the dose rate
- All the curves peak between 600 and 630 Krad, The peak moves to around 700 Krad with high dose irradiation

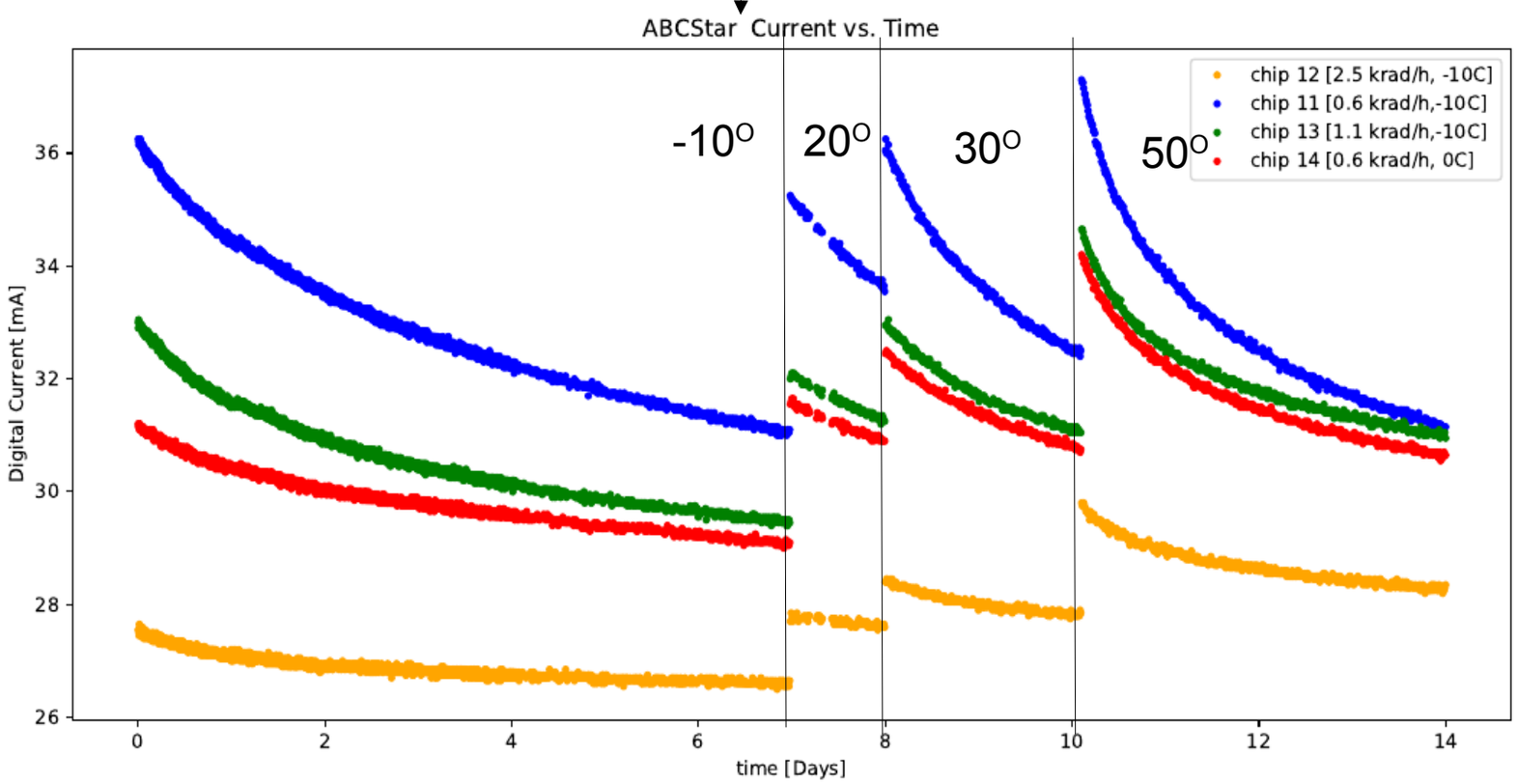


Chip	Dose Rate	Temperature	C5	C1	C2[krad]	C3	C4[krad]
12	2.5	-10	8.21	19.9	226.4	10.58	1161.7
13	1.1	-10	6.5	16.35	226.97	9.44	1161.7
11	0.6	-10	5.02	14.67	273.06	10.155	1161.7
14	0.6	0	2.06	27.63	575.32	32.4	1161.7

Annealing time







- Source was turned OFF in order to measure the time constant for the current to return to baseline
- Temperature was increased at the end of the run three times at 20 degree intervals
- For each fall off period, we fit a decaying exponential of the form

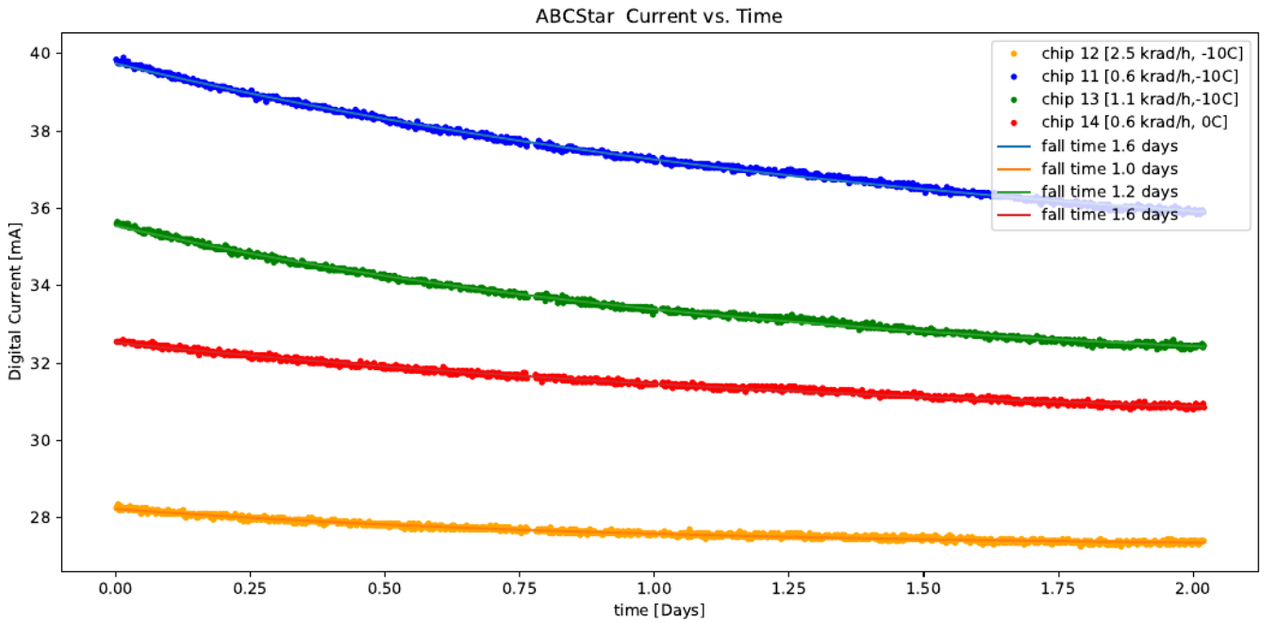
$$y = K \cdot e^{\frac{-x}{\tau}} + C$$

Annealing time

First two fits at -10 C, before any temperature changes, just the source was turned off for several days at two different times

The time constants range between 1-3 days

Larger dose rate have smaller time constant



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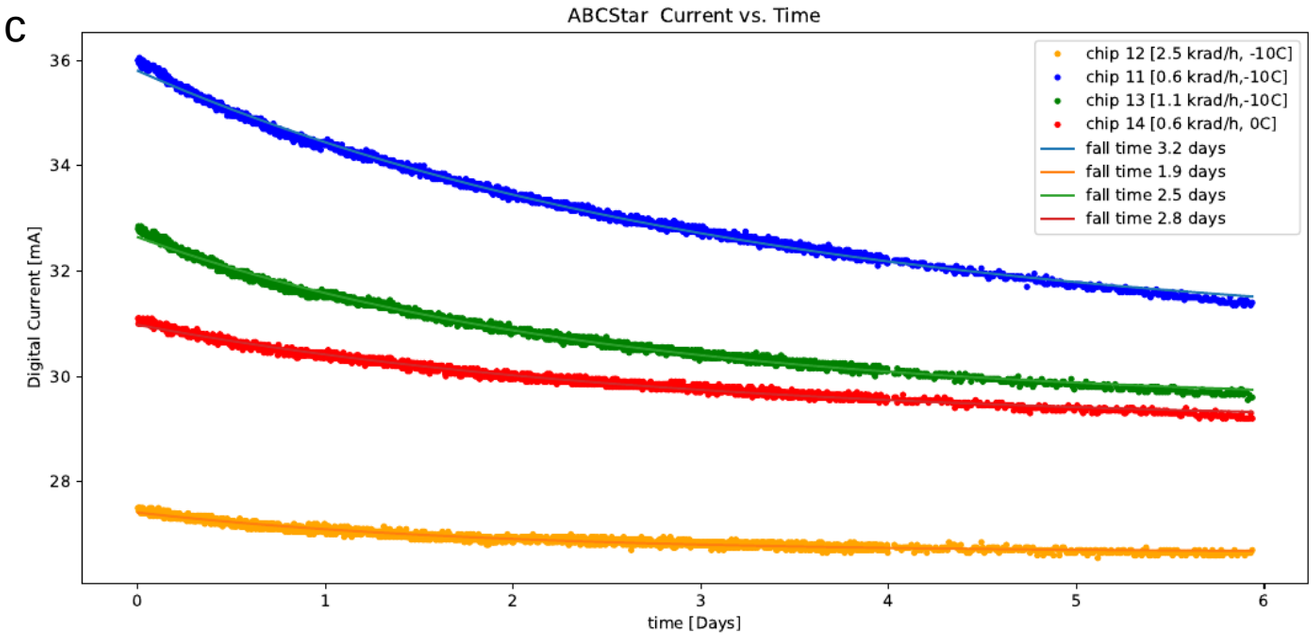


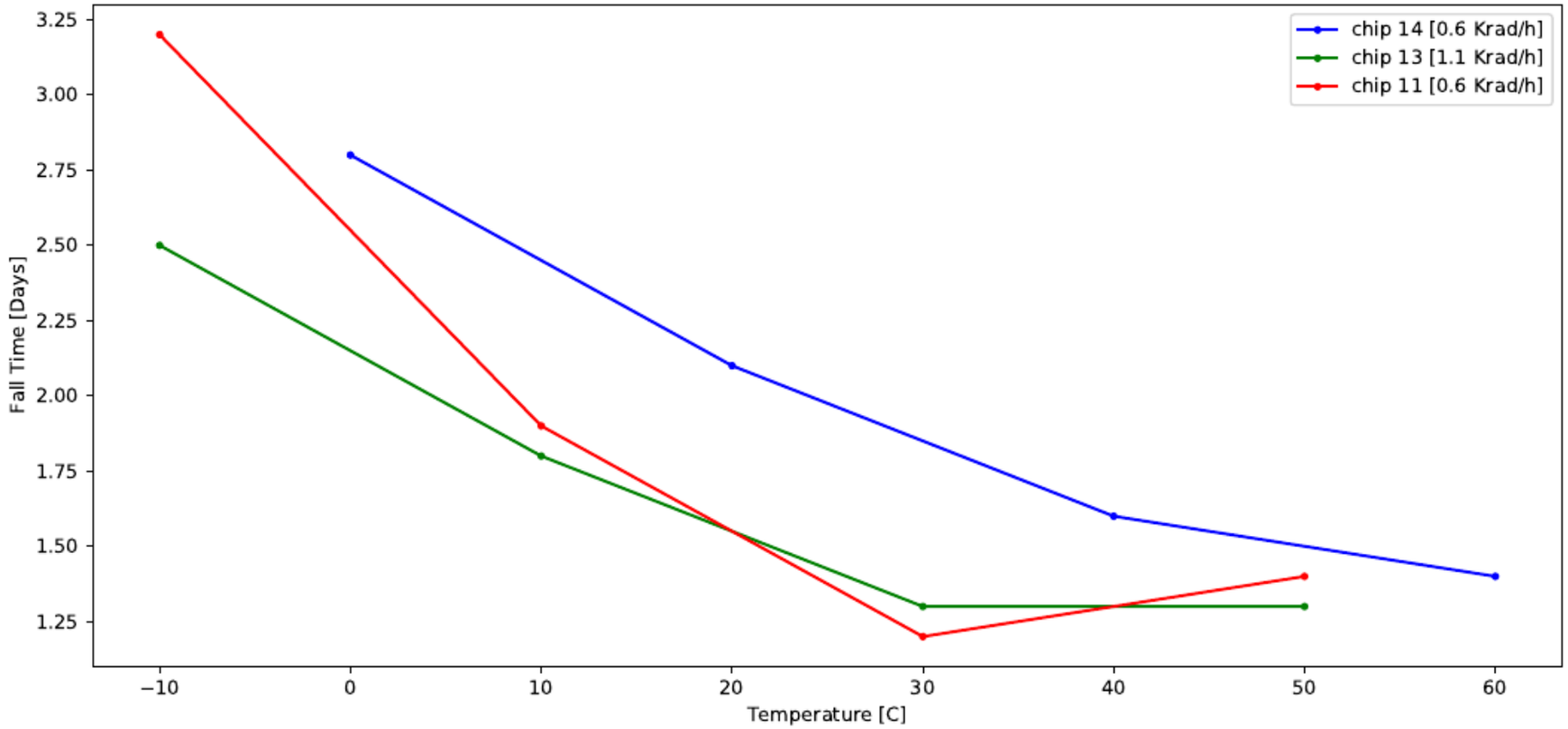
Chip	Dose Rate	Temperature	Tau 1 [days]	Tau 2 [days]
12	2.5	-10	0.96	1.9
13	1.1	-10	1.22	2.5
11	0.6	-10	1.61	3.2
14	0.6	0	1.64	2.8

Annealing time Vs. Temperature

Temperature was increased in 20 C intervals to measure the fall time constant dependence on temperature

The data shows a small dependence but need more statistics

Excluded Chip 12 because it already returned to baseline



Conclusions

- The first irradiation campaign on the ABCStar was done at RAL with x-rays to confirm that the TID bump exists on the new chip.

- Gamma irradiations were done on the ABCStar at BNL with conditions in terms of dose rate and temperature being close to what will exist at the HL-LHC. Some findings are:

  - The peak of the TID bump occurred at about 600 MRad and showed no clear dose rate dependence. The peak of the chips at RAL with about 1000 times higher dose rates occurred at only slightly higher doses, between 700 and 900 Mrad.

  - As expected, the TID bump is larger for higher dose rates, and lower for higher temperature.

  - A simple model to explain the TID bump was presented and a fit equation was developed. The resulting fits were very good. We are just beginning to attempt to interpret the resulting fit parameter values.

  - Direct measurements of the annealing time constants were obtained by turning the source off. The ABCStar temperatures were varied to ascertain the temperature dependence of the time constants. In general, as expected, annealing time constants were shorter for higher temperature. In all cases the time constants were on the order of 1-3 days.

- Batch-to-batch variations in the TID bump make predictions of the magnitude of the TID bump for each module difficult. A solution in the form of pre-irradiation has been shown at RAL and BNL to be very promising.

- Pre-irradiation does not require the chips to be powered to be effective. Therefore pre-irradiation of large batches of ABCStar chips with ^{60}Co gammas is possible. It is expected that pre-irradiation will soon become the baseline for ATLAS,