Low Dose-rate Irradiation of RD53A Chip//Update

Weekly instrumentation meeting

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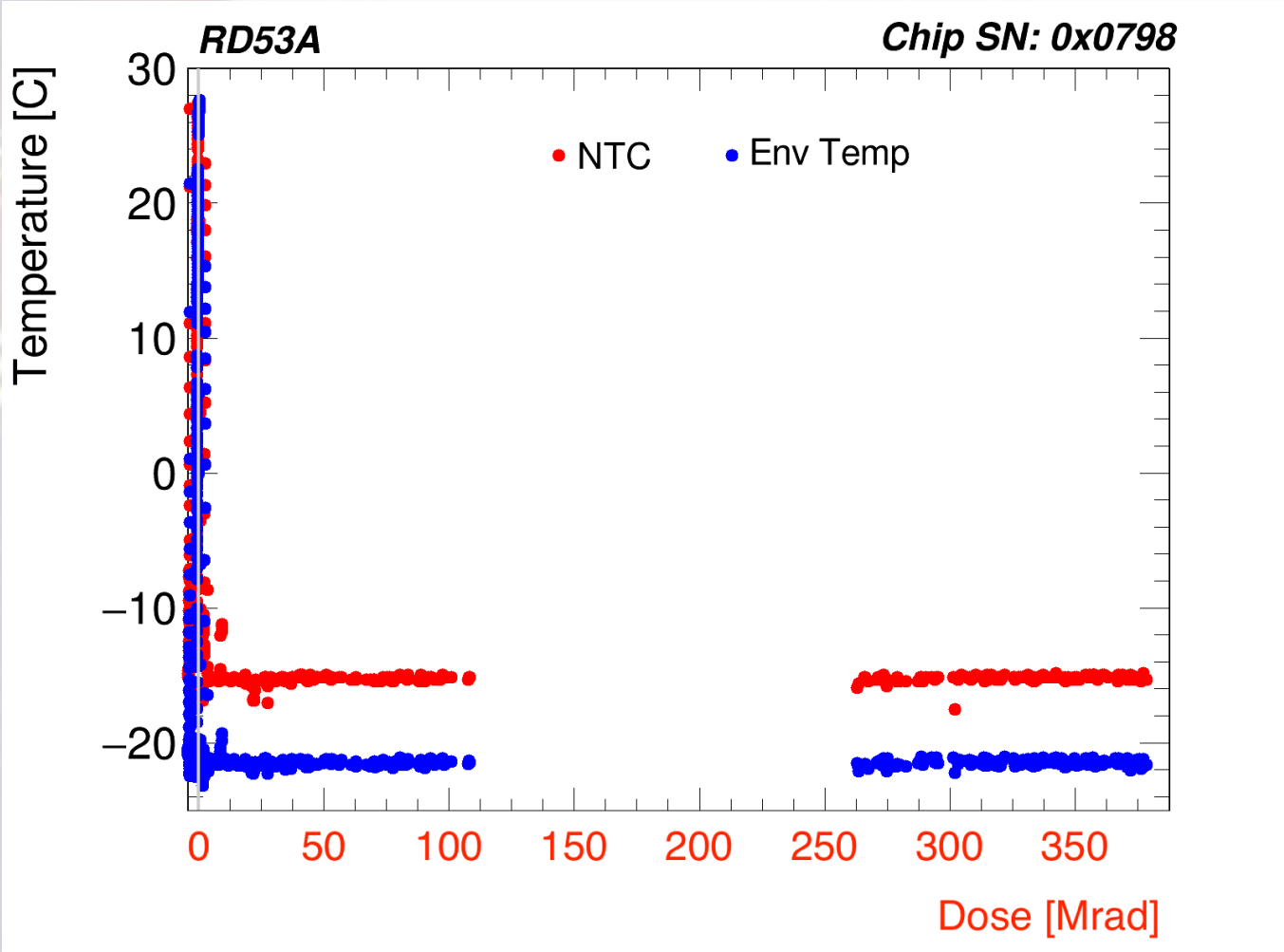
Aleksandra Dimitrievska, Maurice Garcia-Sciveres,
Timon Heim, Simone Pagan Griso

Lawrence Berkeley National Laboratory

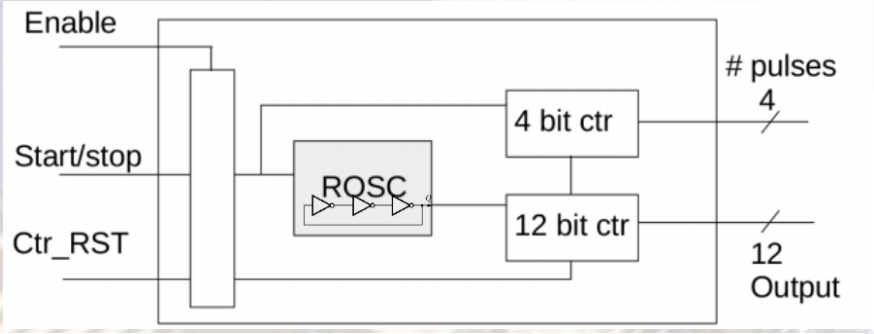
SLIPPER: SLow Irradiation of Phase-II PixEl Readout

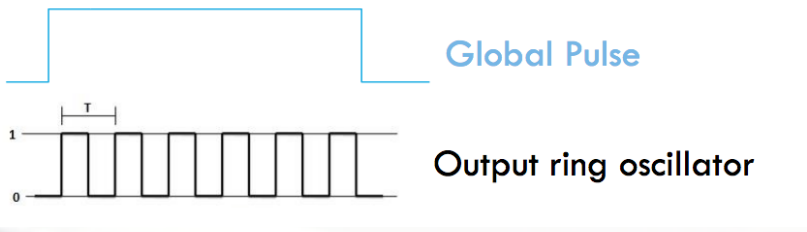
- Environmental conditions: -21 C (-15 C measured on the NTC)
- Ring Oscillator frequency/delay is measured every hour
- Noise scans are running all the time
- Additional scans: Tuning (once a day), digital/analog/threshold scans every hour

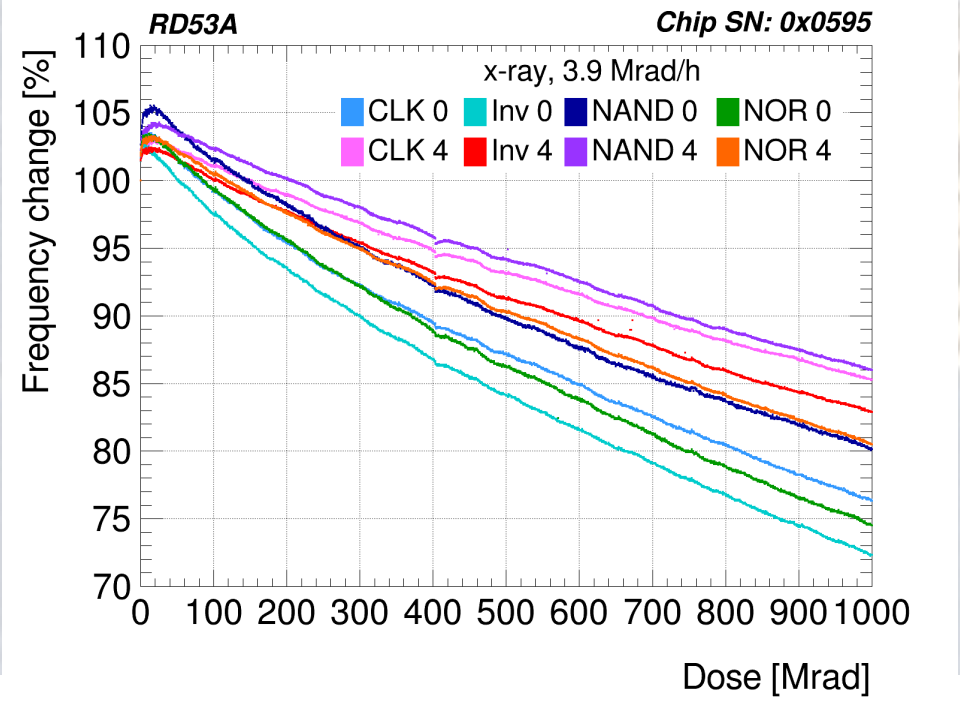


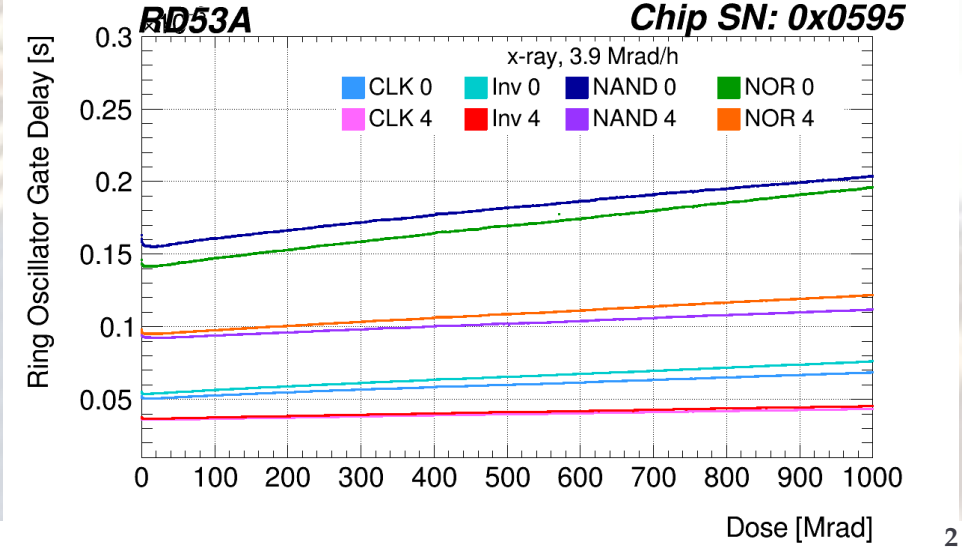
Ring oscillators

- Eight ring oscillators (bottom right corner of the chip)
- Each oscillator drives a 12-bit counter, enabled for a known amount of time set by configuration, dependence on temperature and Vddd
- Calculate the frequency ν or delay $T_D = 1/(N \cdot \nu)$ (N - number of cells)

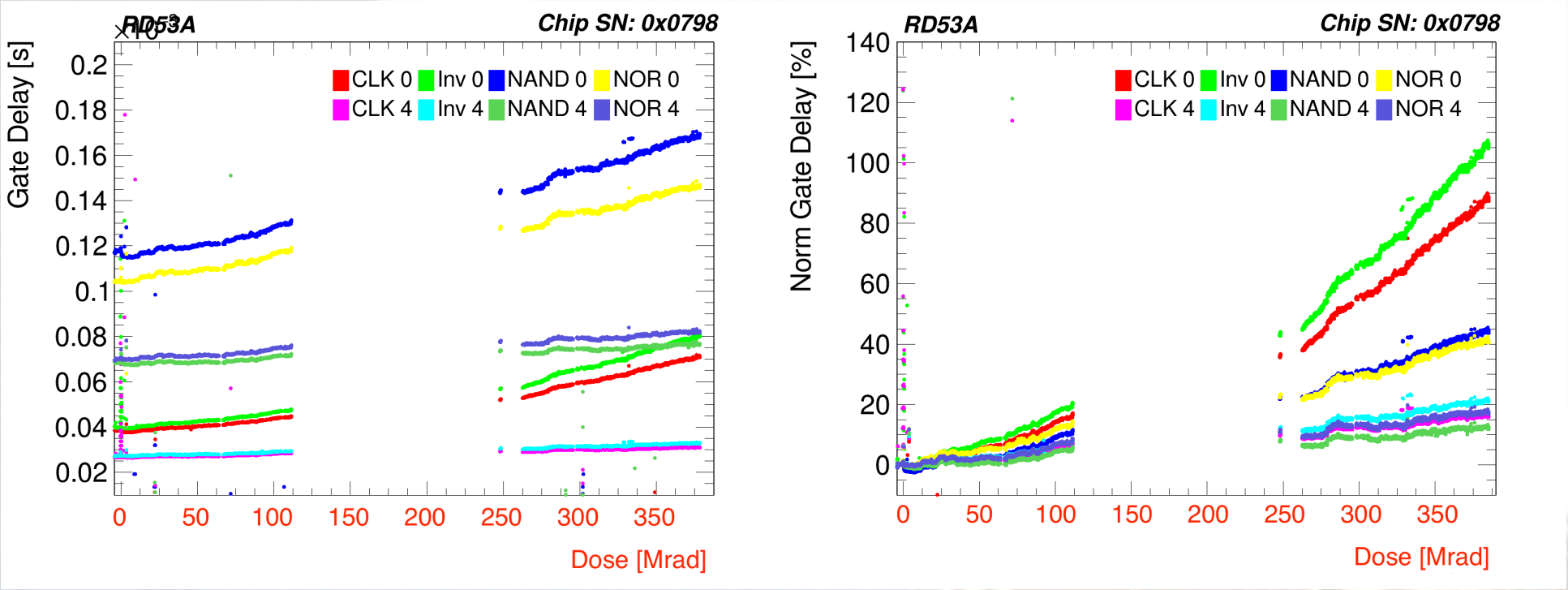




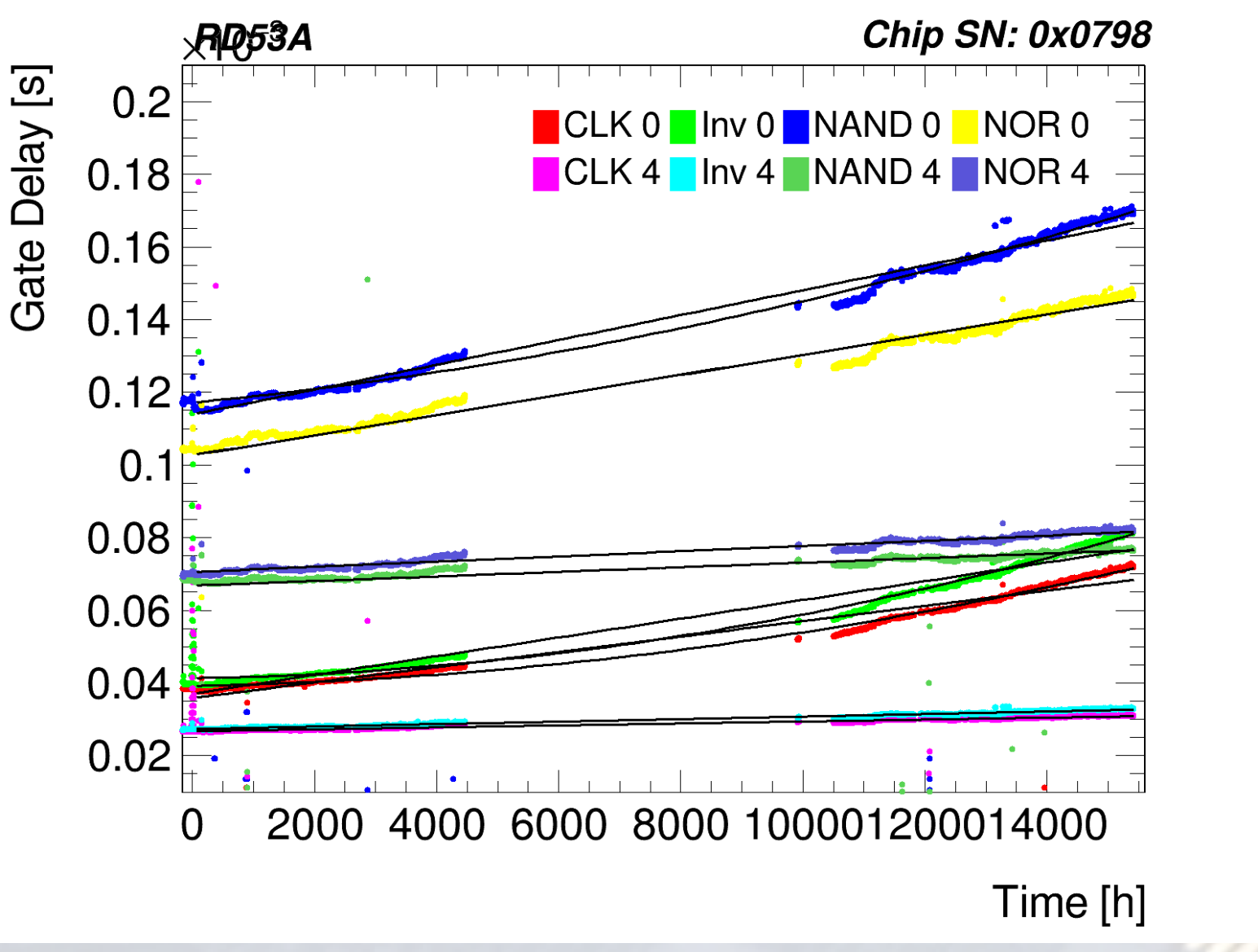




- Latest results: 385 Mrad total (15410 h), dose rate: 25 krad/h
- Ring oscillator delay



- Linear and polynomial fits for ring oscillator delays

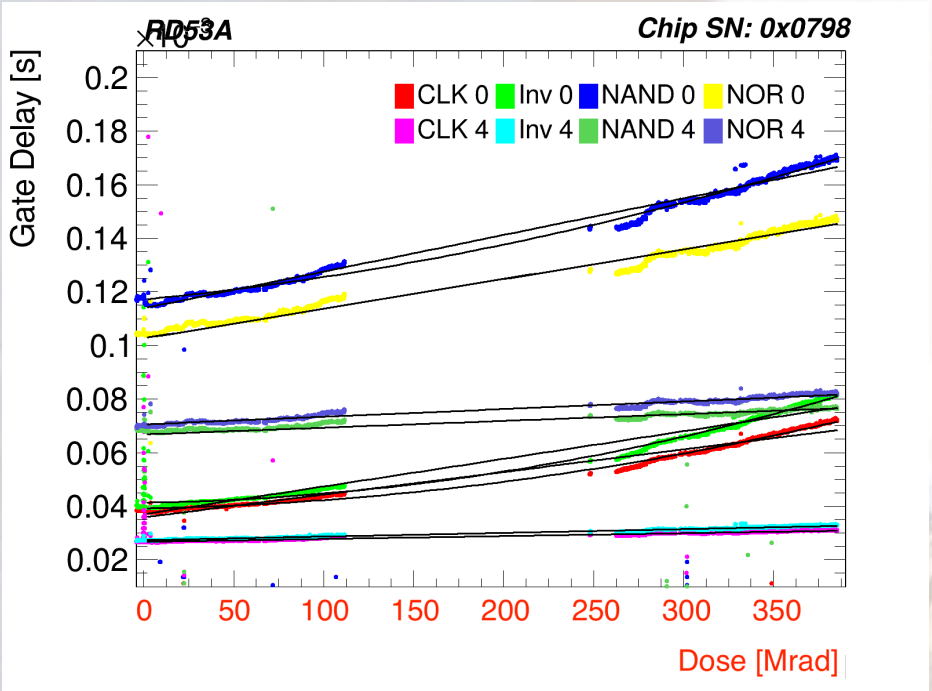


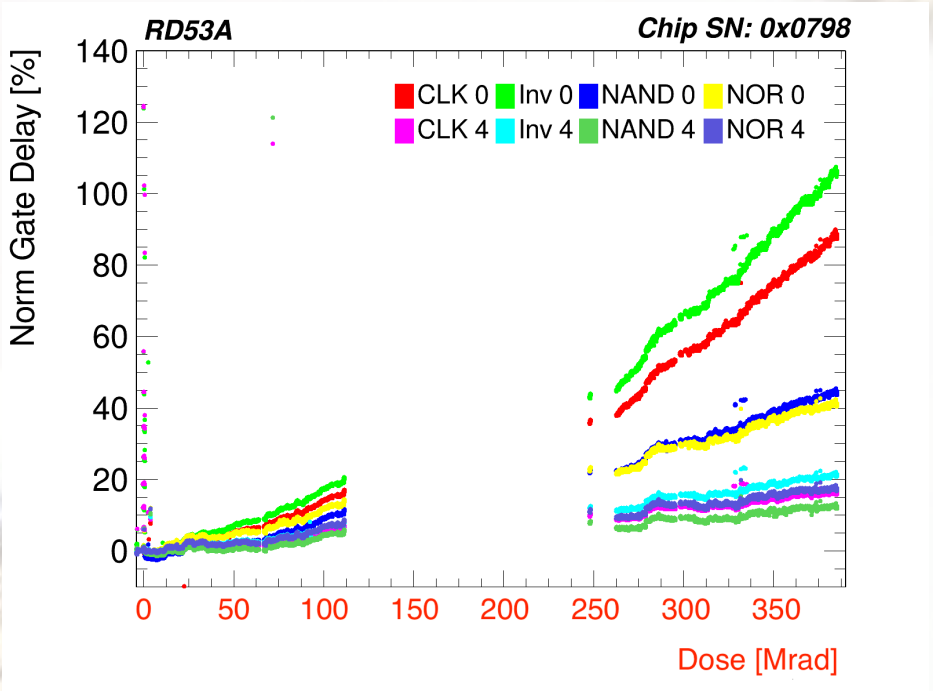
- Extrapolating ring oscillator delay degradation to 500 and 1000 Mrad total dose

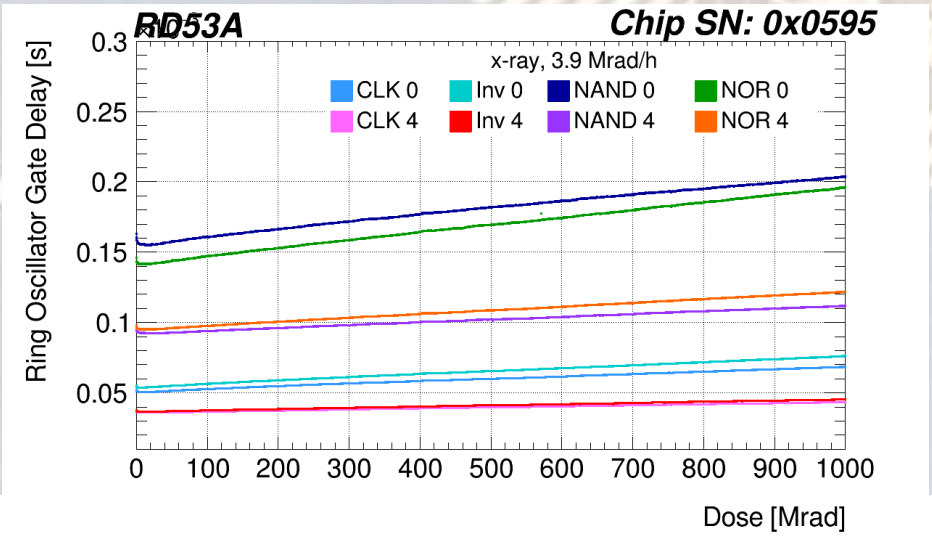
Gate	Measured [%] 385 Mrad	Fit [%] 385 Mrad	Fit [%] 500 Mrad	Fit [%] 1000 Mrad
CLK4	16	15.5	20.1	40.2
CLK0	87	90.5	117.5	235.0
CLK0 (pol)	87	82.6	134.5	506.5
INV4	21	19.5	25.3	50.6
INV0	104	107.3	139.3	278.5
INV0 (pol)	104	95.9	158.0	609.0
NAND4	12	14.6	18.9	37.8
NAND0	44	46.2	60.0	120.0
NAND0 (pol)	44	44.9	67.2	212.8
NOR4	17	15.6	20.3	40.5
NOR0	41	41.5	53.9	107.8
NOR0 (pol)	41	41.5	53.9	108.3

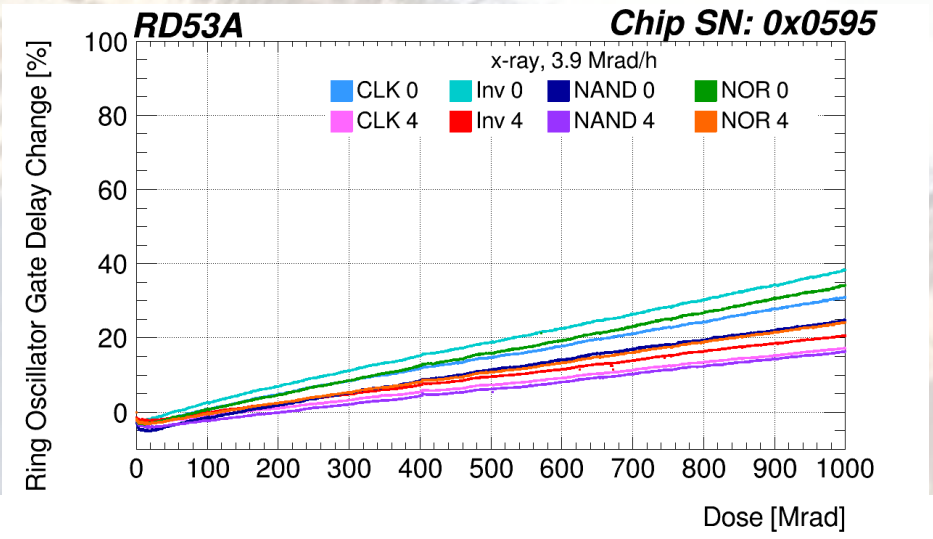
SLIPPER: SLow Irradiation of Phase-II PixEl Readout

- Comparing to high dose rate x-ray irradiation









- Extrapolating ring oscillator delay degradation to 500 and 1000 Mrad total dose

Gate	Meas [%]	Fit [%]	Fit [%]	Meas [%]	Fit [%]	Fit [%]
Total Dose [Mrad]	385	385	385(1000)	1000	50(1000)	100(1000)
Dose Rate [krad/h]	25	25	25	3900	100	756
Temp [C]	-15	-15	-15	-15	-10	-10
CLK4	16	15.5	40.2	17	52	26
CLK0	87	90.5	235.0	31	141	67
CLK0	87	82.6	506.5	31	141	67
INV4	21	19.5	50.6	20	67	32
INV0	104	107.3	278.5	38	178	80
INV0	104	95.9	609.0	38	178	80
NAND4	12	14.6	37.8	18	43	24
NAND0	44	46.2	120.0	25	97	53
NAND0	44	44.9	212.8	25	97	53
NOR4	17	15.6	40.5	24	61	34
NOR0	41	41.5	107.8	34	118	57
NOR0	41	41.5	108.3	34	118	57

- Compared to high dose rate x-ray (same temperature):
  - about 2 times more degradation for gates with strength 4
  - 7 times more degradation for CLK0 and INV0 (linear extrapolation)
  - 5 times more degradation for NAND0 (linear extrapolation)
  - 3 times more degradation for NOR0 (linear extrapolation)

- Extrapolating ring oscillator delay degradation to 500 and 1000 Mrad total dose (compared to Kr-85)

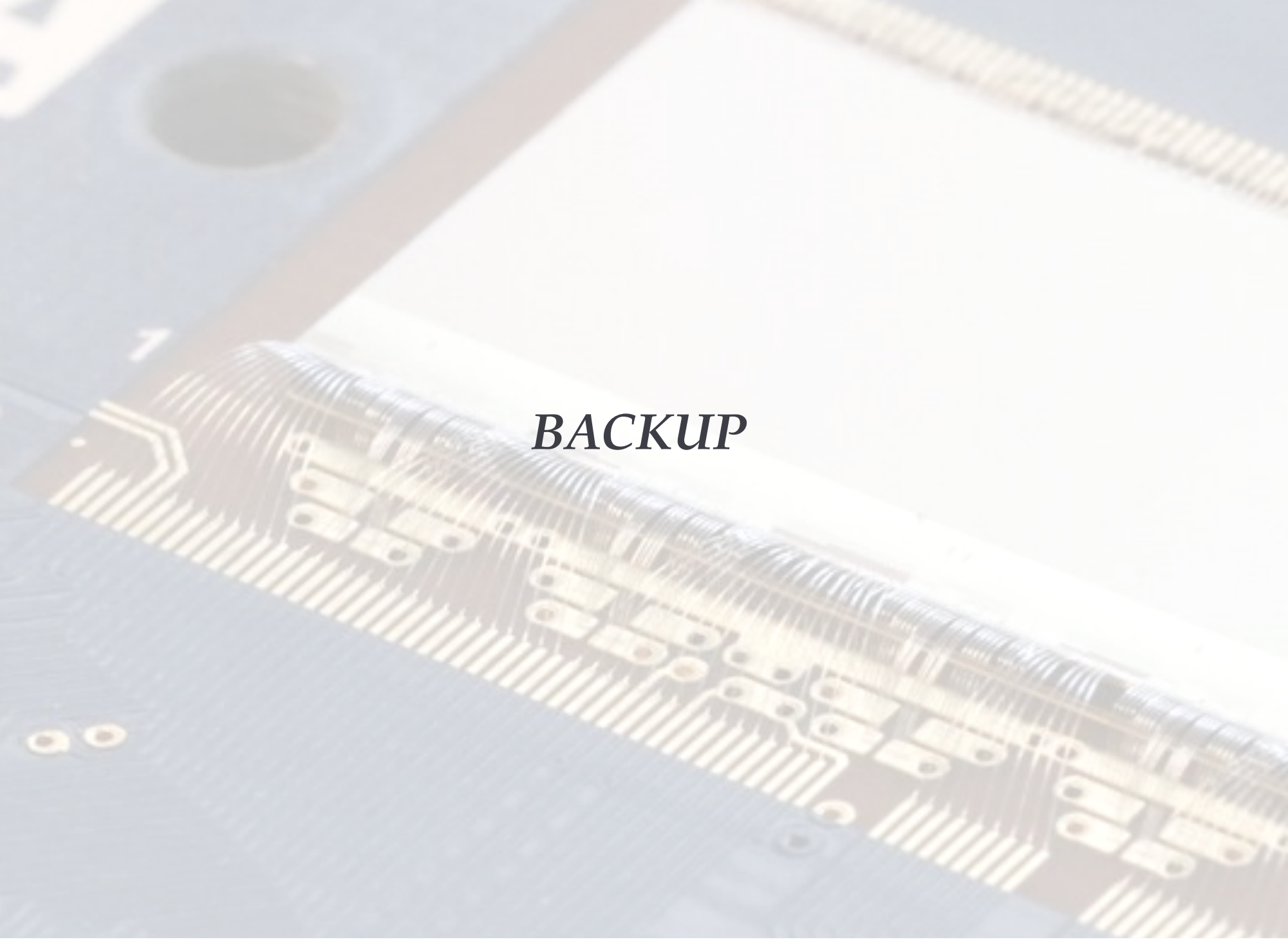
Gate	Meas [%]	Fit [%]	Fit [%]	Meas [%]	Fit [%]	Fit [%]
Total Dose [Mrad]	385	385	385(1000)	1000	50(1000)	100(1000)
Dose Rate [krad/h]	25	25	25	3900	100	756
Temp [C]	-15	-15	-15	-15	-10	-10
CLK4	16	15.5	40.2	2.4	0.8	1.5
CLK0	87	90.5	235.0	7.6	1.7	3.5
CLK0	87	82.6	506.5	16.3	3.6	7.6
INV4	21	19.5	50.6	2.5	0.8	1.6
INV0	104	107.3	278.5	7.3	1.6	3.5
INV0	104	95.9	609.0	16.0	3.4	7.6
NAND4	12	14.6	37.8	2.1	0.9	1.6
NAND0	44	46.2	120.0	4.8	1.2	2.3
NAND0	44	44.9	212.8	8.5	2.2	4.0
NOR4	17	15.6	40.5	1.7	0.7	1.2
NOR0	41	41.5	107.8	3.2	0.9	1.9
NOR0	41	41.5	108.3	3.2	0.9	1.9

- Compared to high dose rate x-ray (same temperature):
  - about 2 times more degradation for gates with strength 4
  - 7 times more degradation for CLK0 and INV0 (linear extrapolation)
  - 5 times more degradation for NAND0 (linear extrapolation)
  - 3 times more degradation for NOR0 (linear extrapolation)

Summary

- Low dose rate with Kr-85 with 25 krad/h @ -15C with 385 Mrad total dose collected
- Implementing corrections:
  – RO frequency/delay vs Vddd
  – Dose correction due to activity of the Kr-85 source: 0.75 % per month

- Compared to x-ray 3900 krad/h (- 15 C):
  – about 2 times more degradation for gates with strength 4
  – 7 times more degradation for CLK0 and INV0 (linear extrapolation)
  – 5 times more degradation for NAND0 (linear extrapolation)
  – 3 times more degradation for NOR0 (linear extrapolation)
- Compared to x-ray 100 krad/h (-10 C) - ETH:
  – about 20-30 % less degradation for gates with strength 4
  – 60 % more degradation for CLK0 and INV0 (linear extrapolation)
  – 20 % more degradation for NAND0 (linear extrapolation)
  – 10 % less degradation for NOR0 (linear extrapolation)



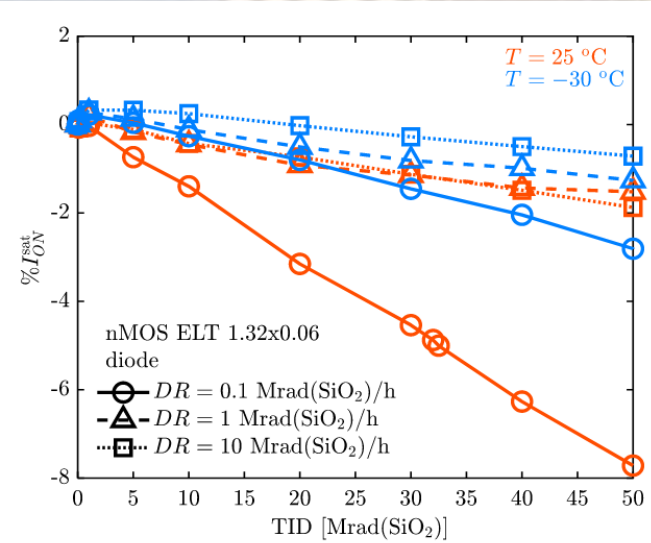
BACKUP

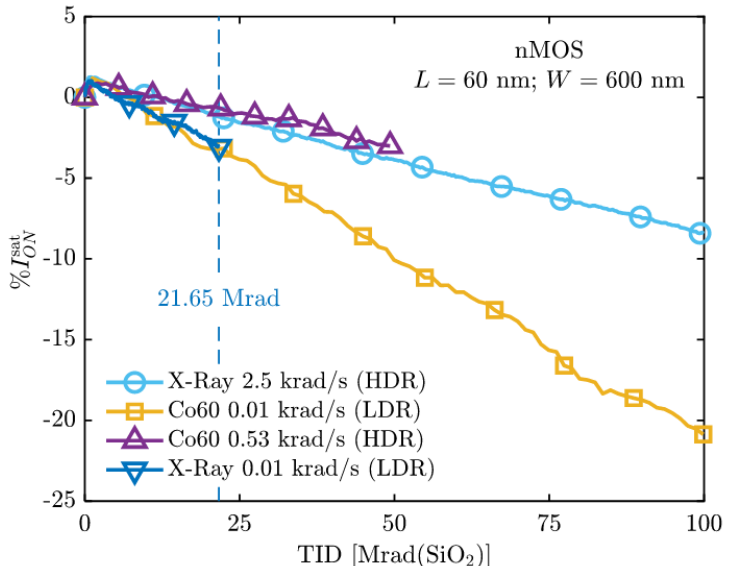
- Linear ($a + b \cdot x$) and polynomial ($a + b \cdot x + c \cdot x^2$) fits for ring oscillator delay vs time
- Parameter values

Gate	a	b	c
CLK4	2.67E-05	2.69E-10	-
CLK0	3.59E-05	2.11E-09	-
CLK0	3.92E-05	3.09E-10	1.16E-13
INV4	2.73E-05	3.45E-10	-
INV0	3.70E-05	2.58E-09	-
INV0	4.13E-05	2.38E-10	1.51E-13
NAND4	6.68E-05	6.32E-10	-
NAND0	1.14E-04	3.42E-09	-
NAND0	1.17E-04	1.64E-09	1.15E-13
NOR4	7.05E-05	7.15E-10	-
NOR0	1.03E-04	2.77E-09	-
NOR0	1.03E-04	2.76E-09	4.57E-16

Radiation Damage

- Radiation damage models:
  – RD53A: only standard threshold **single transistors models** irradiated at room temperature (200 Mrad)
  – RD53B: based on newer and more extensive cold irradiation and test data (100, 200, 500 Mrad at 25C, 0C, -30C)
- However the models work only for analog part
  (large transistors where the damage is independent of the dose rate)
- For the digital part (small transistors), the dose rate has a big impact
  – all models are for high dose rate
  – no data and no simulation to predict the high total dose damage at HL-LHC
  – from single transistor measurements (F. Faccio and G. Borghello) after 10-20 Mrad the damage at low dose rate is approximately twice worse than at high dose rate

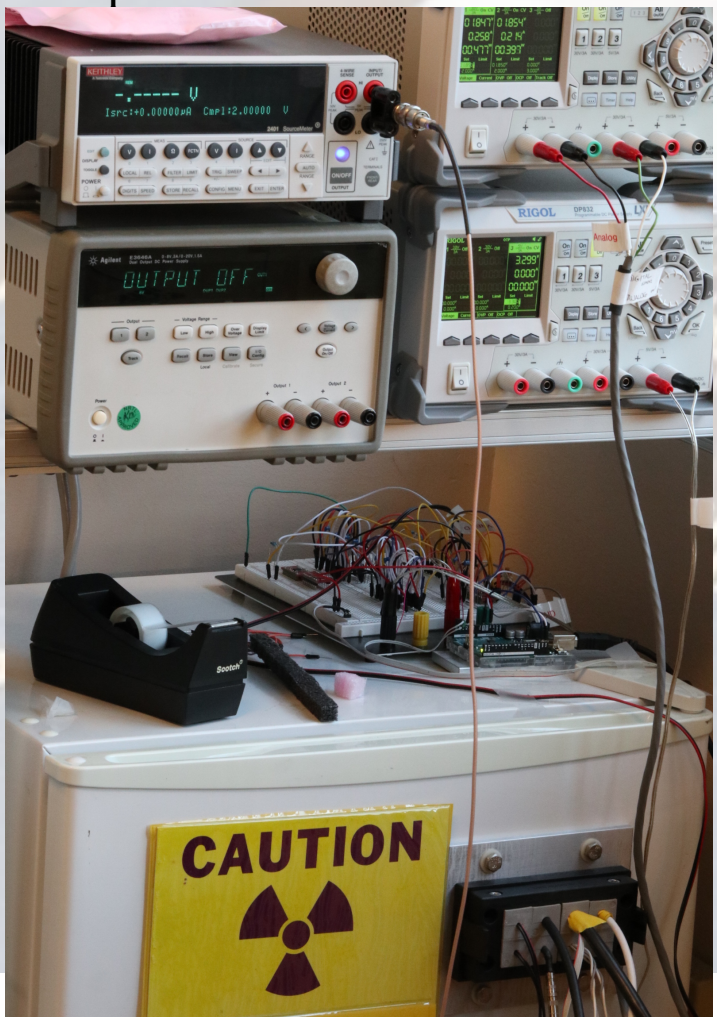


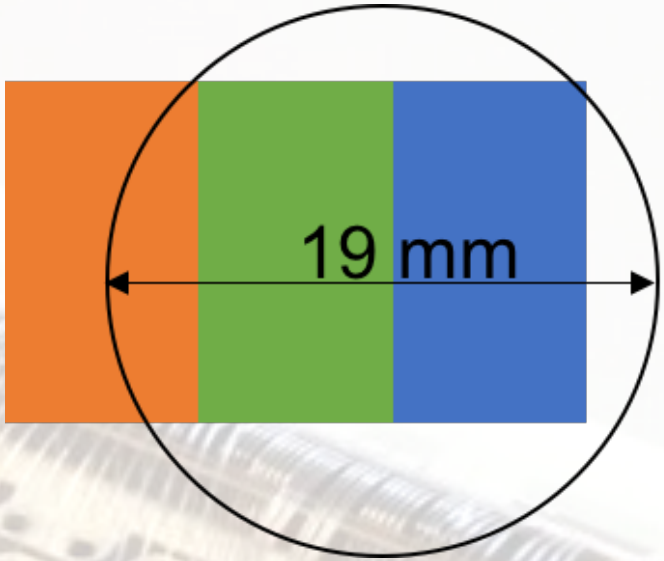


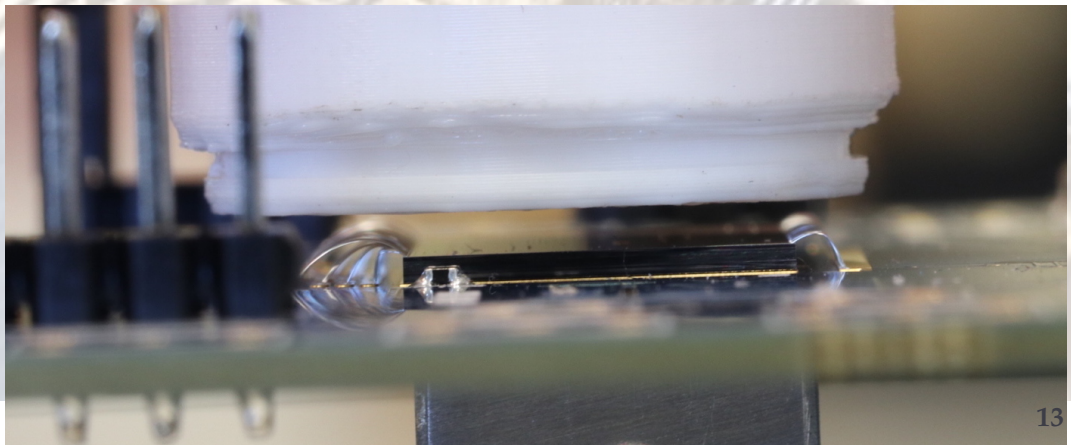
Slipper: SLow Irradiation of Phase-II PixEl Readout

- Beta Kr-85 sources: 60 mCi (2.22 GBq), the dose is about 7 rad/s.
- Irradiation with one RD53A chip started on September 6, 2018
- Total dose: about 285 Mrad
- Position of the source:

on top of the linear and differential FE, synchronous FE is not receiving the full dose







Software

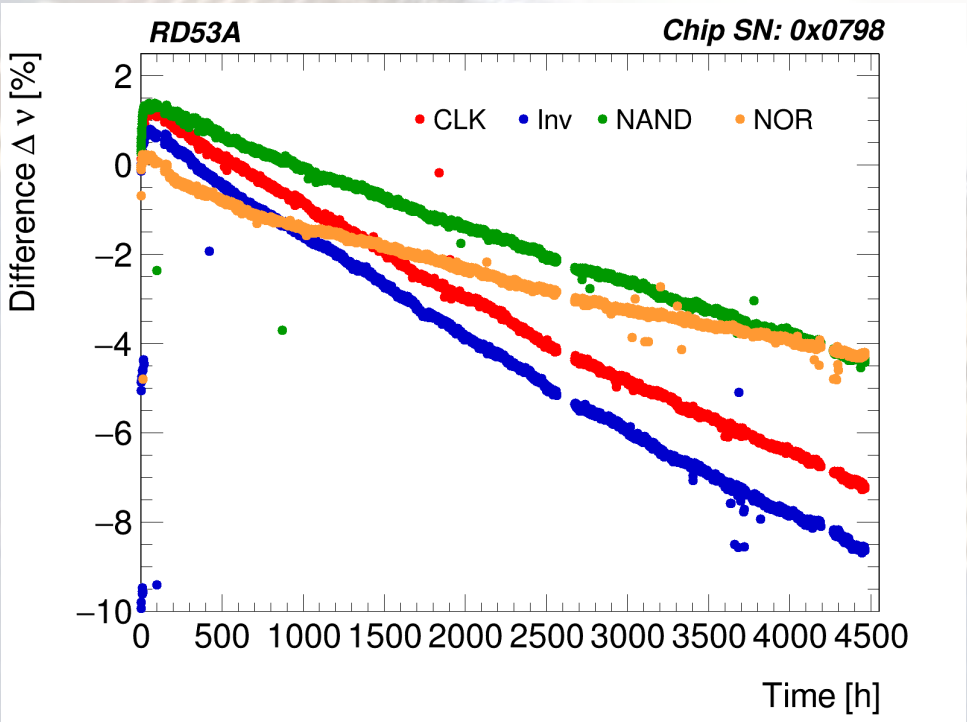
- Monitoring and data acquisition code:
  `https://gitlab.cern.ch/berkeleylab/slipper-monitoring-sw`
- Combines: Yarr, labRemote (control power supplies, multimeters), mysql

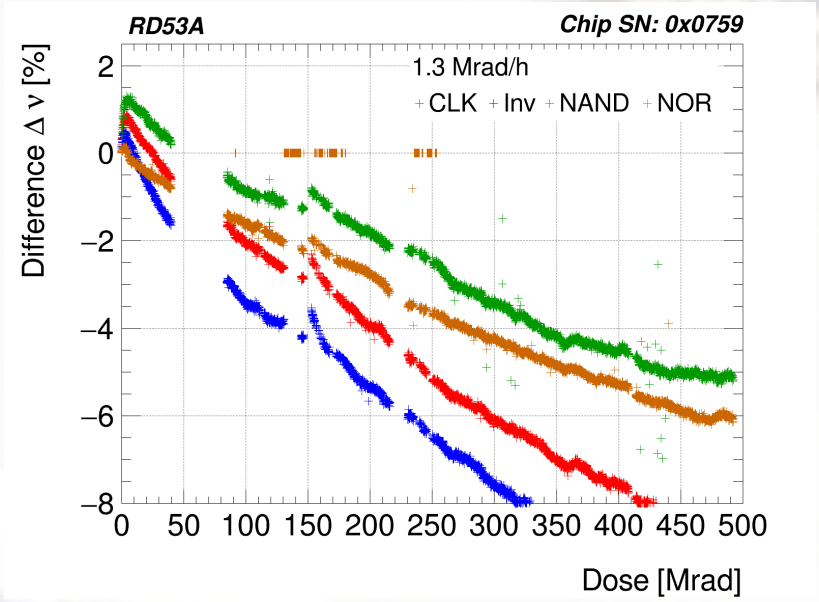
Testing Procedure

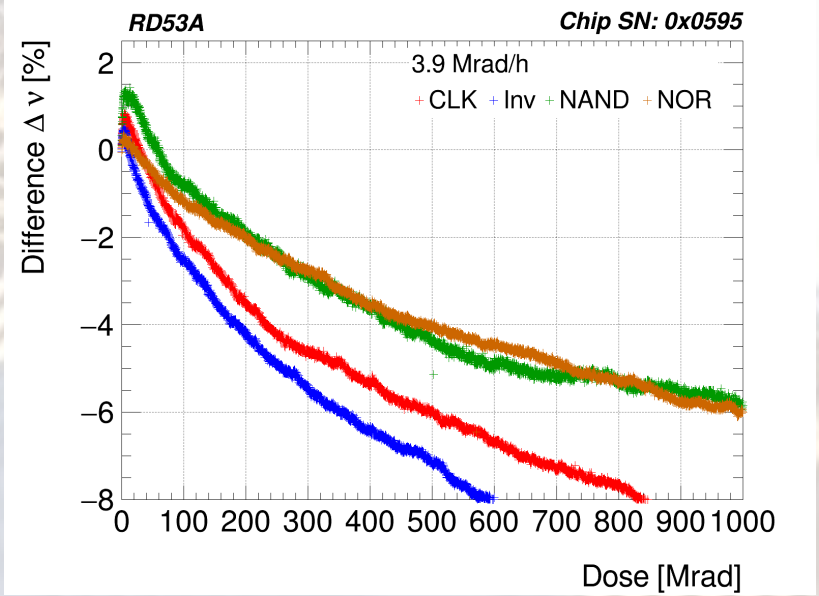
- Keep chip busy all the time (noise scans with global pulse for ring oscillators)
- Perform scans every hour (threshold, tot, MUX, ring oscillators)
- Tuning (1ke, 7 ToT at 10k e) once a day
- Monitor environmental conditions, humidity and temperature, voltage outputs from the chip every minute via Arduino
- Monitor input current of the chip
- The data is stored in database: Arduino, Chip and Log tables.

Dose Calibration

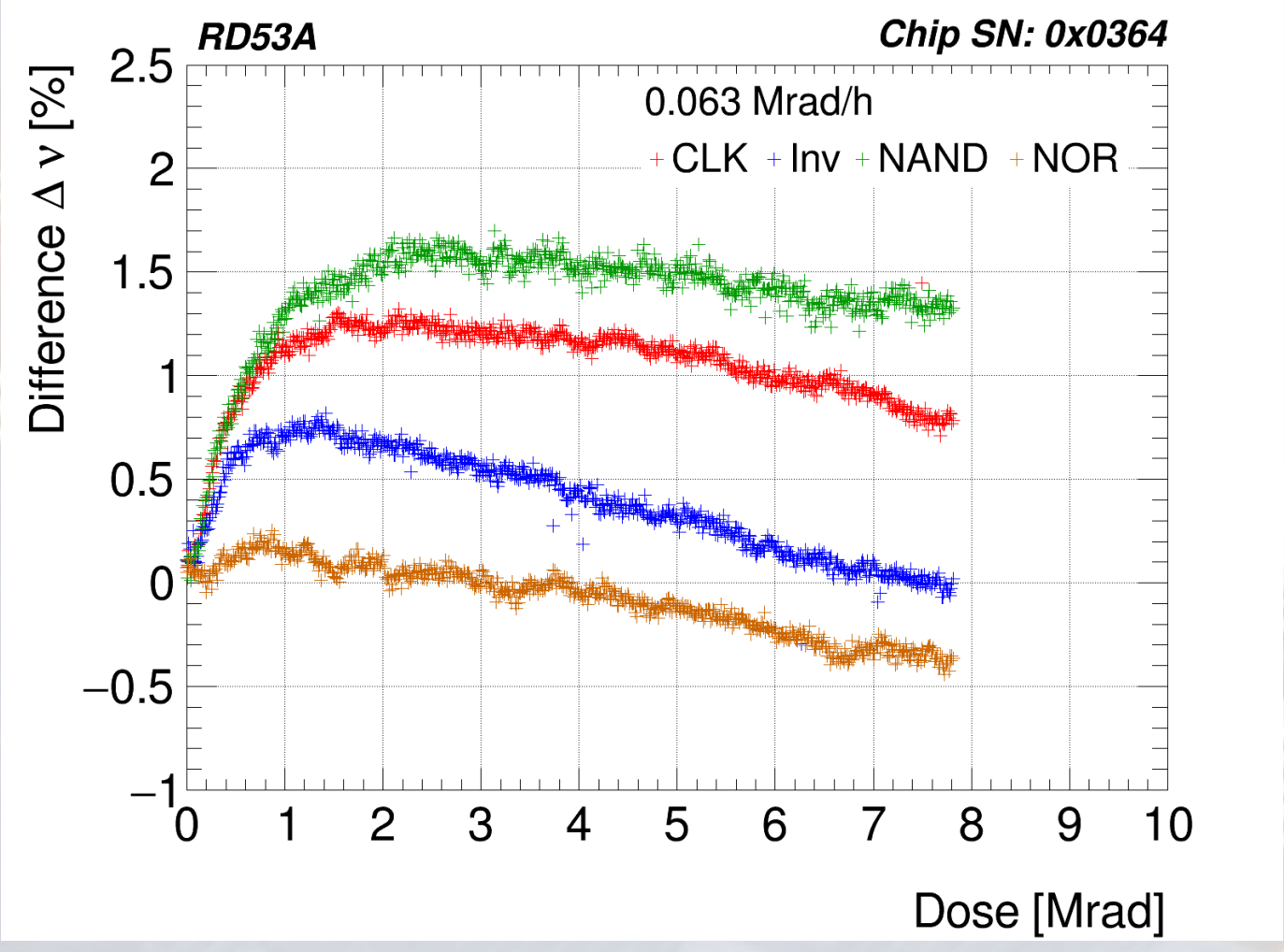
- Use Ring Oscillators as Dosimeters
- The **difference** between the gates with driving strengths 4 and 0
- Compare to X-ray irradiation results
  - Glasgow (high dose rate) 500 and 1000 Mrad
  - CERN (high dose rate) up to 80 Mrad
  - CERN (low dose rate) 8 Mrad





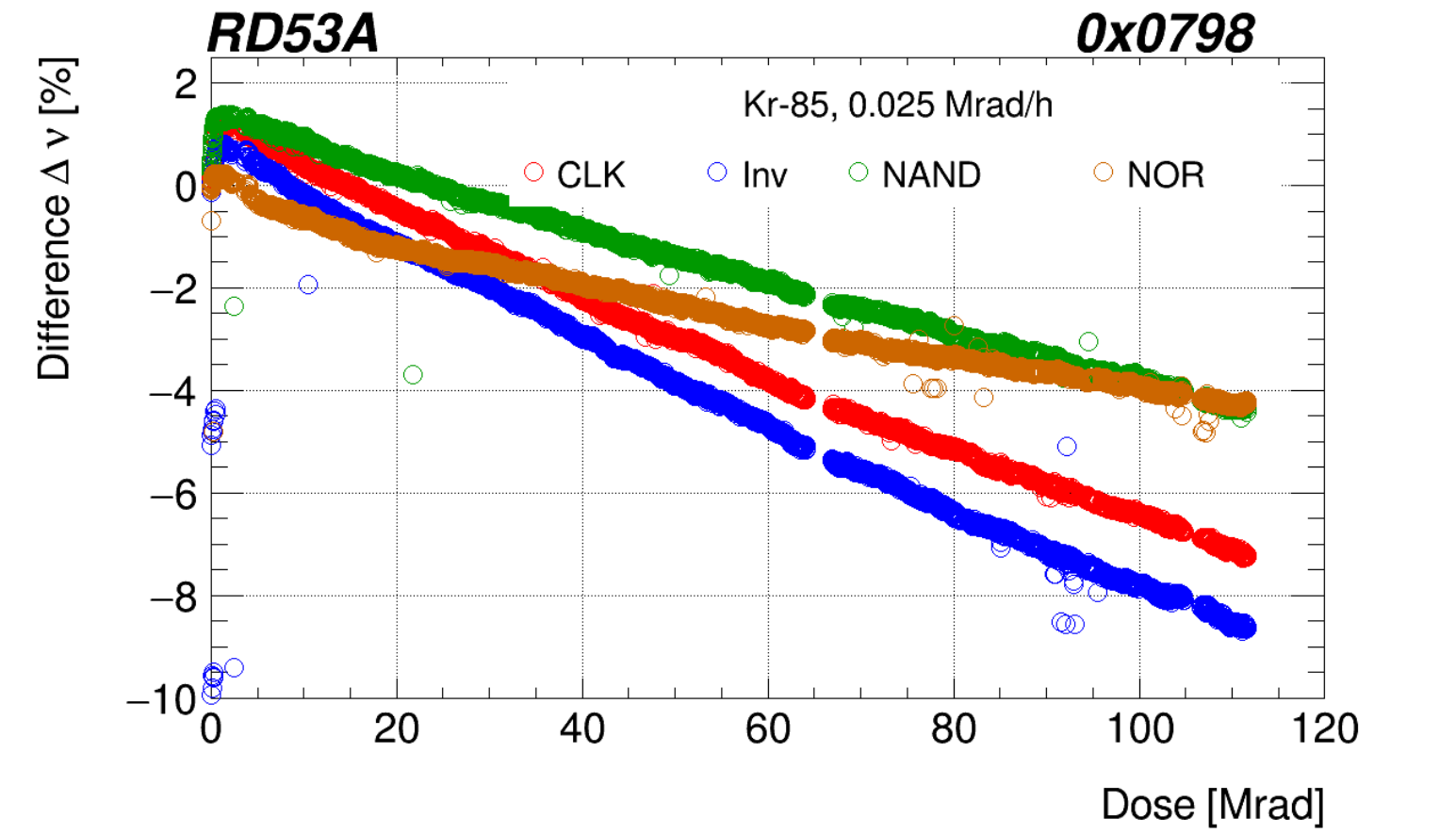


- Extract the values when the lines are crossing 0:
  when the irradiation effects are the same for the gates with driving strengths 4 and 0
  (when lines don't cross, linear fit after the peak and extract value when y=0)

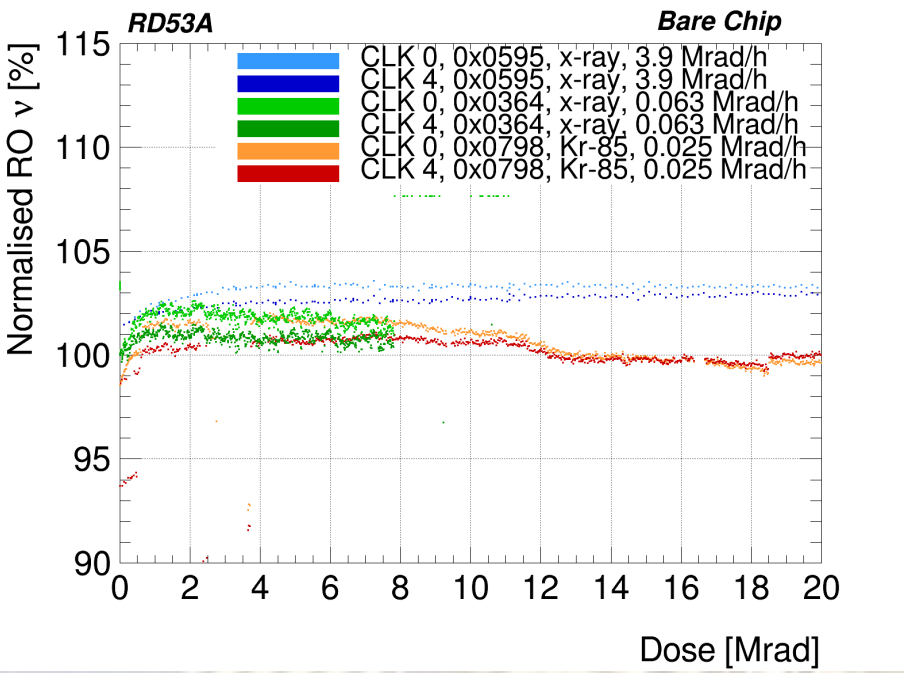


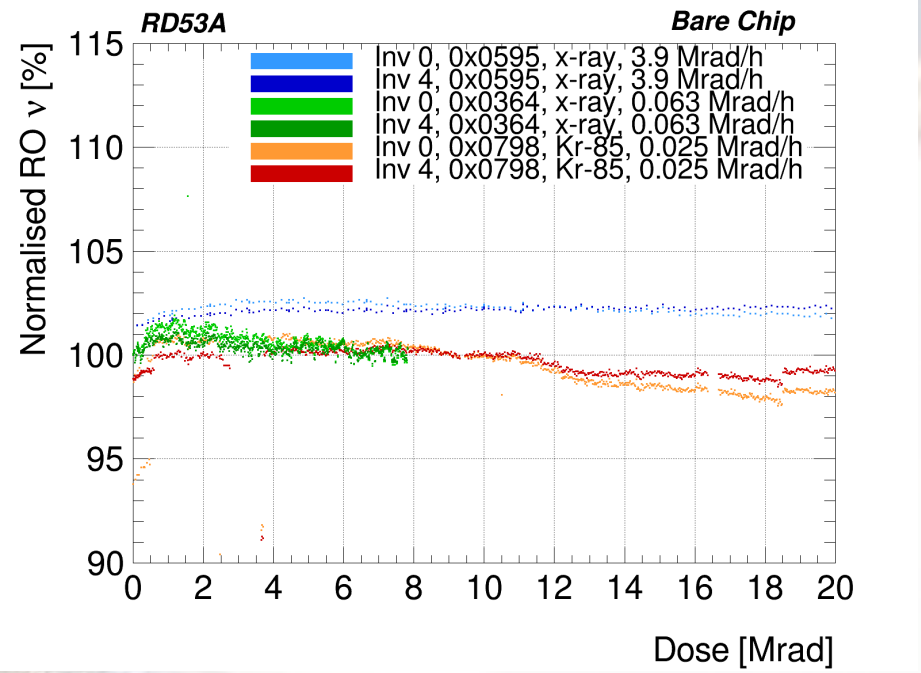
Estimation of the dose rate for Kr-85 source from x-ray irradiations

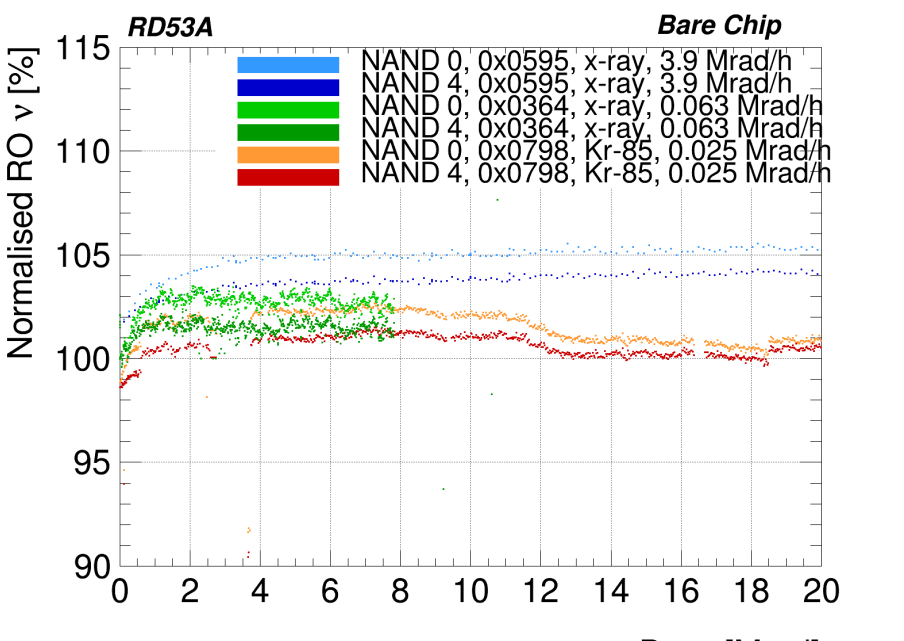
- Kr85 estimated dose rate is: 0.025 Mrad/h
  (back on the envelope calculation from the activity and opening window)
- Change due to activity of the source: 0.75 % per month
- Kr-85 dose rate estimation from the 0.063 Mrad/h x-ray irradiation:
  0.030 Mrad/h (Clock), 0.021 Mrad/h (Inverter),
  0.031 Mrad/h (NAND), 0.048 Mrad/h (NOR)

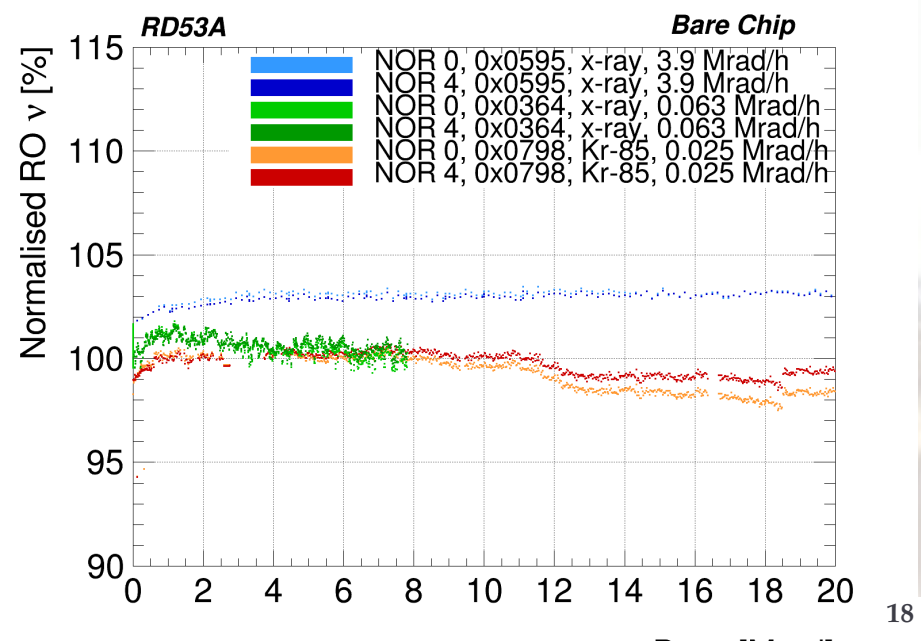


Comparing high and low dose rate

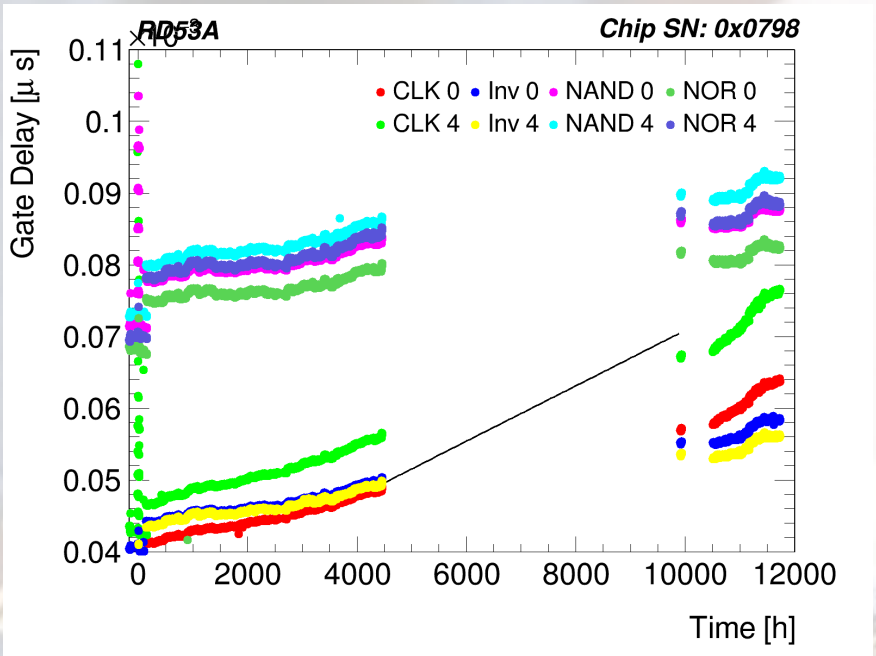


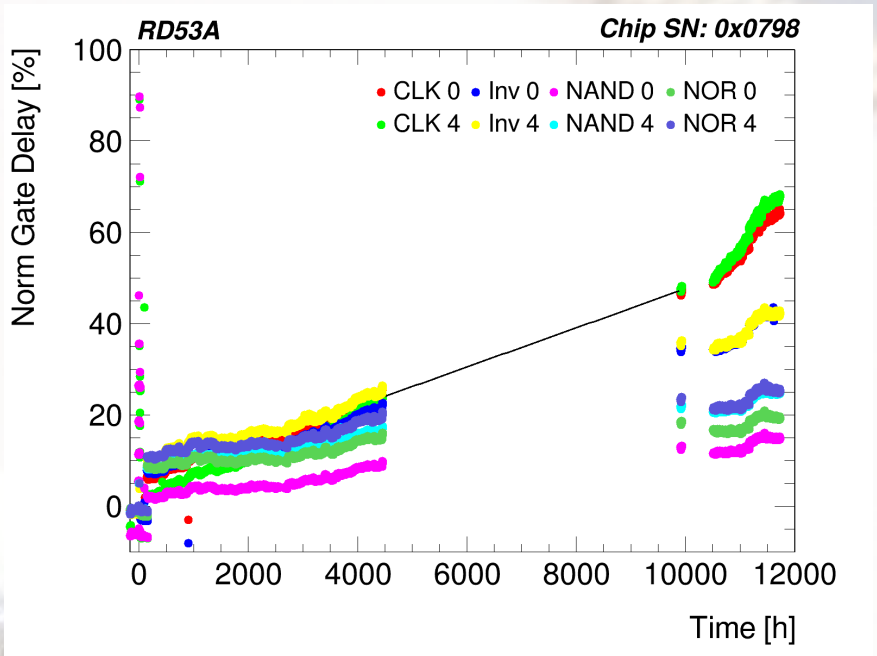


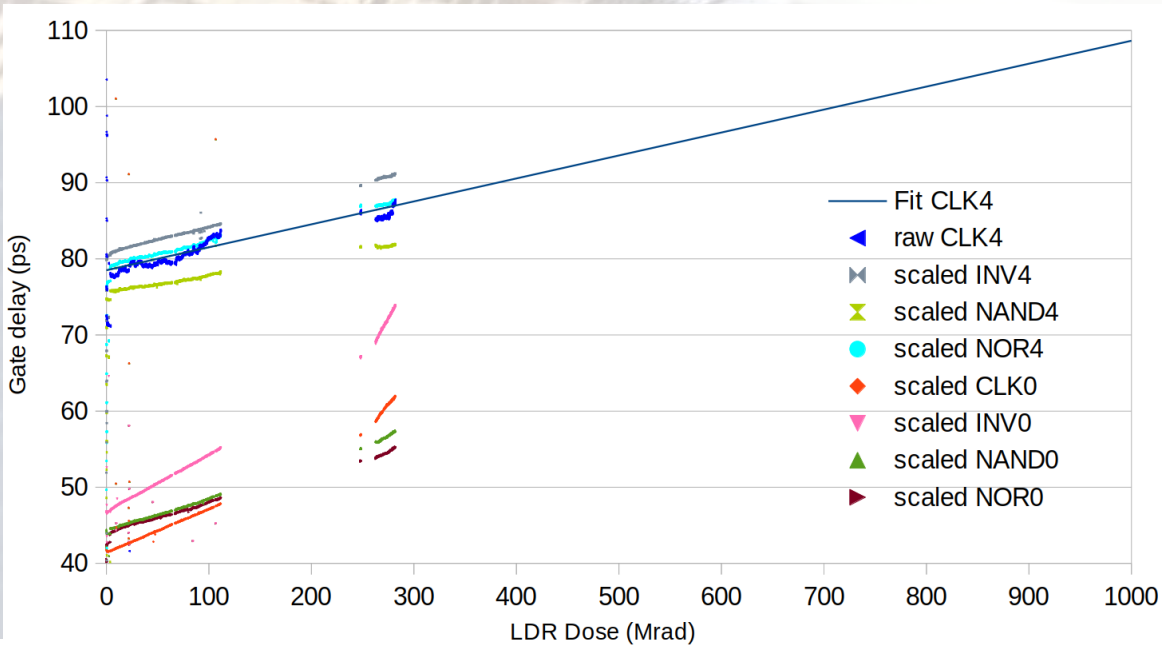




Comparing high and low dose rate - extrapolating the value of the delay

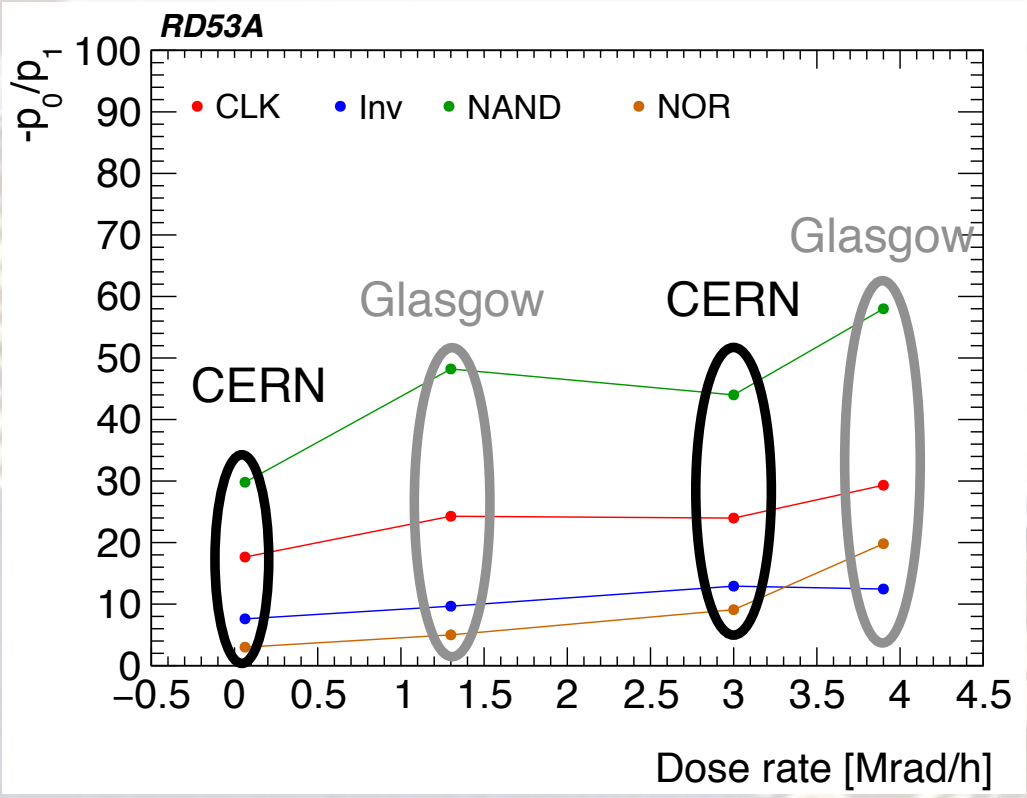






High Dose Rate vs Low Dose Rate

- Zero crossing of the difference 4- and 0- strength gates vs dose rate



- Correction of the 10 % drop
- Same change for all gates: