Analog SiPM R&D for High Energy Physics

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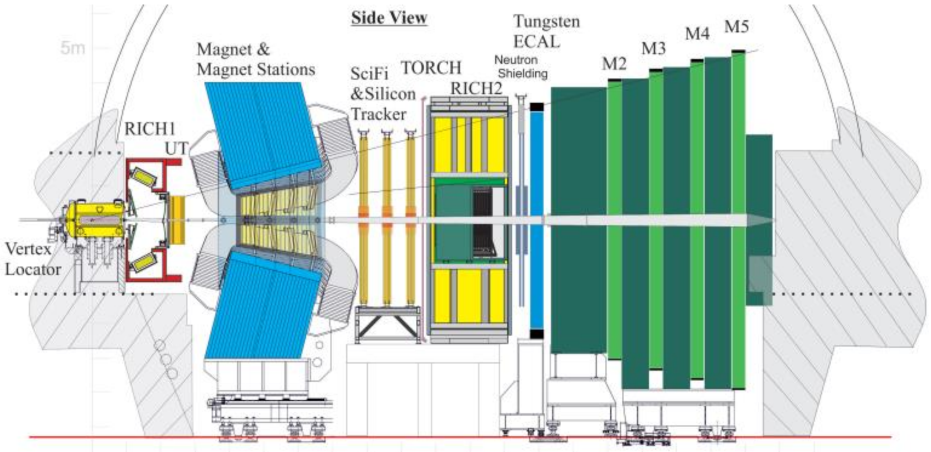
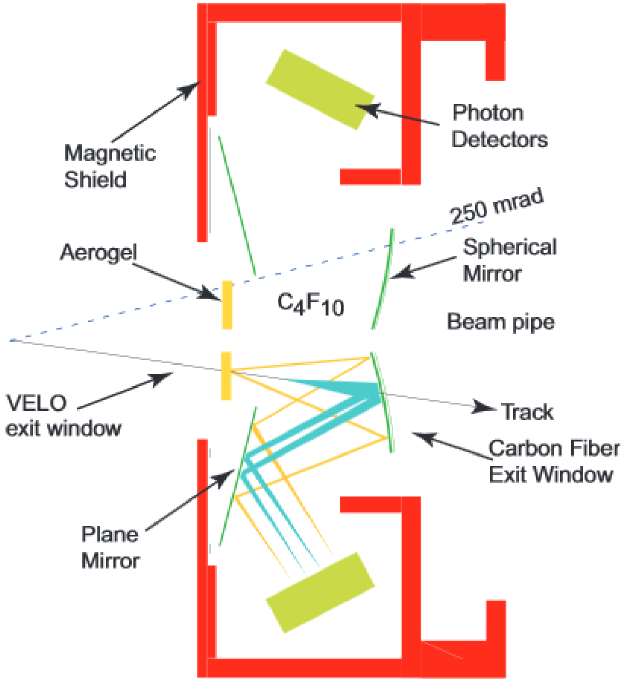
LHCb Upgrade II

The LHCb experiment is planning a major detector upgrade for the LHC RUN5 (2035) to cope with the foreseen instantaneous peak luminosity of $\sim 1.0/1.5 \times 10^{34}$ $cm^{-2}s^{-1}$ (increase of 5 with respect to actual value). For the Ring Imaging Cherenkov (RICH) Upgrade-II detectors, the present MaPMTs cannot stand the high particle flux in the central high occupancy region in a very harsh environment and thus new photosensors are needed. The main driving requirements are:

- Single photoelectron sensitivity and large Quantum Efficiency;
- Fast time response, ideally <100ps r.m.s. for single photon;
- Fine granularity to keep occupancy below 30%;
- Radiation hardness.





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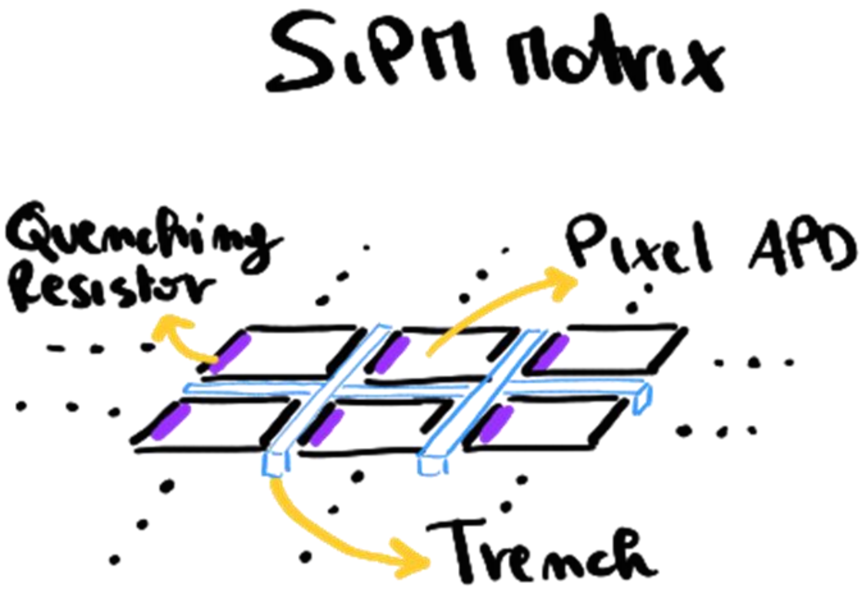
SiPMs

Silicon Photomultipliers are solid state photodetectors that work in the Geiger region: incident photons trigger high gain avalanches . They are matrices of small size single cells with a quenching resistor and connected in parallel. Widely used in many applications (Calorimeters, TPC, Cherenkov, PET, LIDAR,...).



Important features:

- Compact detectors
- Single p.e. detection
- High gain
- Large UV-VIS PDE
- Simple & low voltage
- Cryo resilience
- Magnetic field immunity
- Good fill factor
- High dynamic range
- Low cost

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R&D program on SiPMs

We are highly motivated to pursue an R&D program to develop photodetectors for the LHCb RICH Upgrade II that are capable of performing in the challenging high luminosity LHC environment ($L \sim 1.5x10^{34} cm^{-2} s^{-1}$);

SiPMs have the potential to meet all the the requirements after a strong R&D program targeted to:

- Improve intrinsic radiation hardness of the devices (different design);
- keep dark count rate under control (operation of SiPM at low temperature);
- Improve sensor efficiency and performances;

We started our test campaign with commercial HPK sensors:

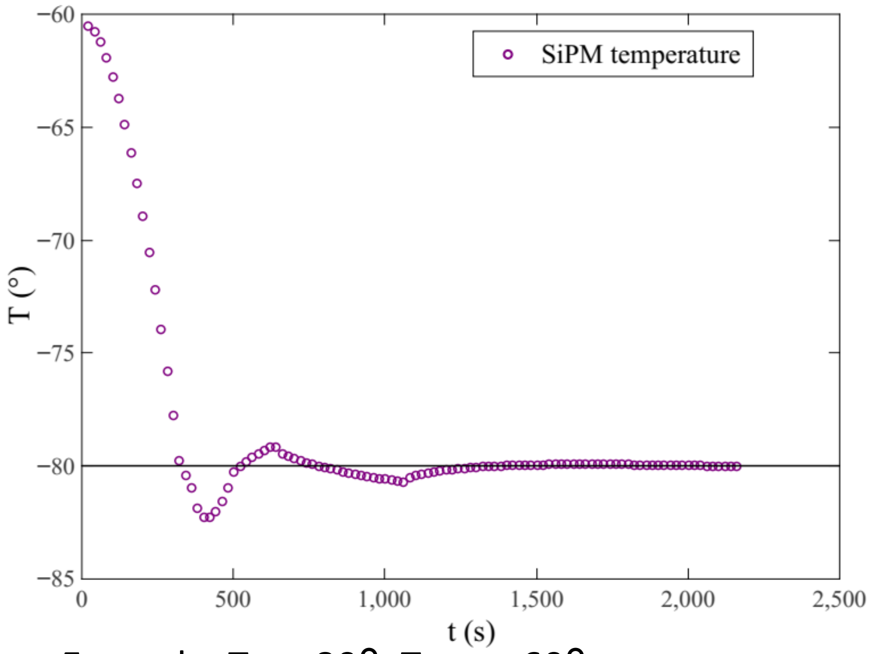
SiPM model	Pitch (um)	Area (mm^2)	Packaging	Window	V_{bd} room (V)	Fill factor %
S13360-1325PE	25	1.3x1.3	SMD	epoxy	53	47
S13360-1350PE	50	1.3x1.3	SMD	epoxy	53	74
S13360-1375PE	75	1.3x1.3	SMD	epoxy	53	82
S13360-2050VE	50	2x2	SMD	epoxy	53	74
S14160-3050HS	50	3x3	SMD	epoxy	38	74

Ferrara setup

Multipurpose setup for SiPM characterization in a wide temperature range (from -150° to 25°)

Setup:

- Liquid nitrogen cryostat (LN2) 14l;
- Source meter unit Keithley SM2450 resolution <1pA, triaxial cables ;
- Stabilized power supply Keysight E3630;
- Oscilloscope (Tektronix MSO 64) 12bit res., 4GHz bandwidth, sampling 25GS/s;
- Mechanical linear stage software controlled;
- Cold amplifier custom design by INFN MiB;
- Warm amplifier custom design by INFN MiB;
- Led system at 470nm;
- Pulsed UV laser Hamamatsu PLP10 @405nm, 50ps pulse width ;



Example: T_{set}=-80°, $T_{initial}$=-60°

PYTHON SCRIPT

MECHANICAL STAGE

PT100 TEMPERATURE SENSOR

SIMPLE FEEDBACK CONTROL

LN2 VAPOUR

Test procedure

- Measure of all the IV curve of the sensors as a function of the temperature for non-irradiated SiPMs;
- Measure the Gain, DCR and Time Resolution as a function of the temperature and for 3 values of OV (+2, +3, +4);
- Irradiation at Ljubjana JSI (250 kW TRIGA Mark II) reactor;
- Measure again IV curve after SiPMs irradiation;
- Measure the Gain, DCR and Time Resolution as a function of the temperature and for 3 values of OV (+2, +3, +4) after irradiation and without any annealing process;
- Different annealing procedure;
- DCR measure after annealing to test possible curing effects.

SiPM	Fluence
3	$3x10^{11}$
3	$3x10^{12}$
3	$6x10^{12}$
3	$3x10^{13}$
3	$6x10^{13}$

fluence in 1MeV neutrons equivalent per cm^2

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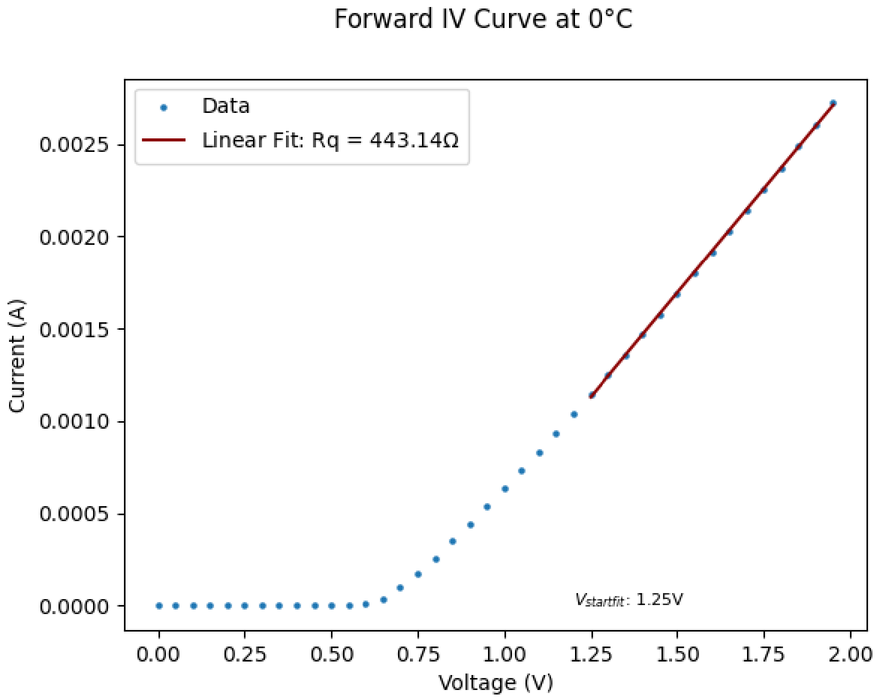
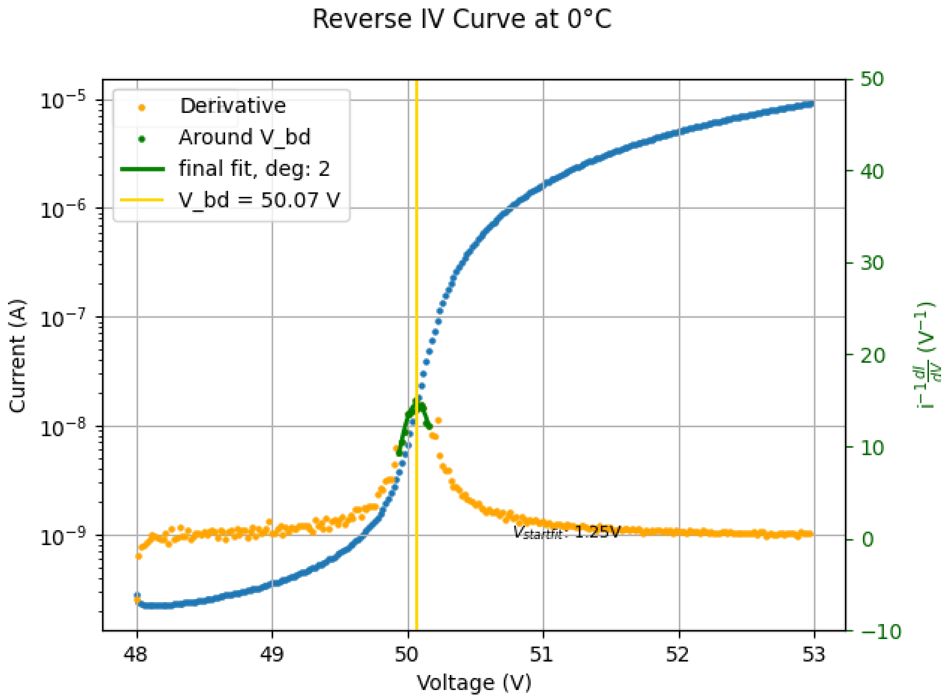
IV curves procedure

IV curve in reverse (REV) and direct (FW)

- Automated SMU measurement
- 20mV/50mV step curve
- Quenching resistor from the linear curve fit in FW region
- Breakdown voltage from the maximum of the normalized derivative in REV





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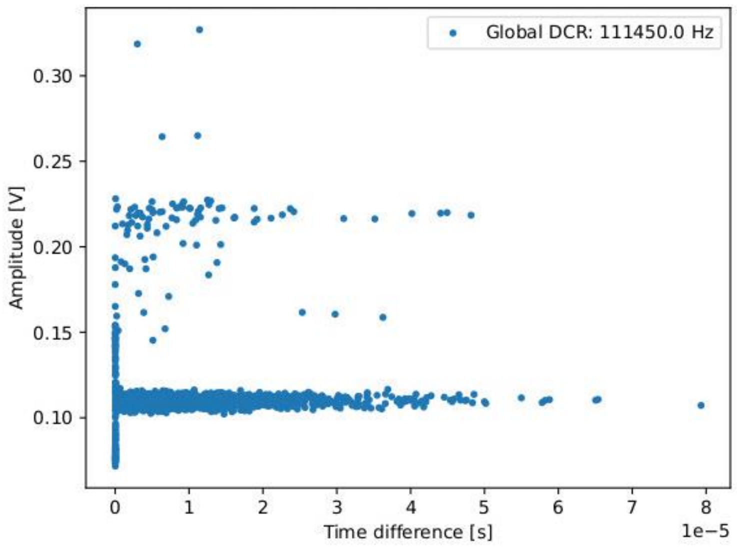
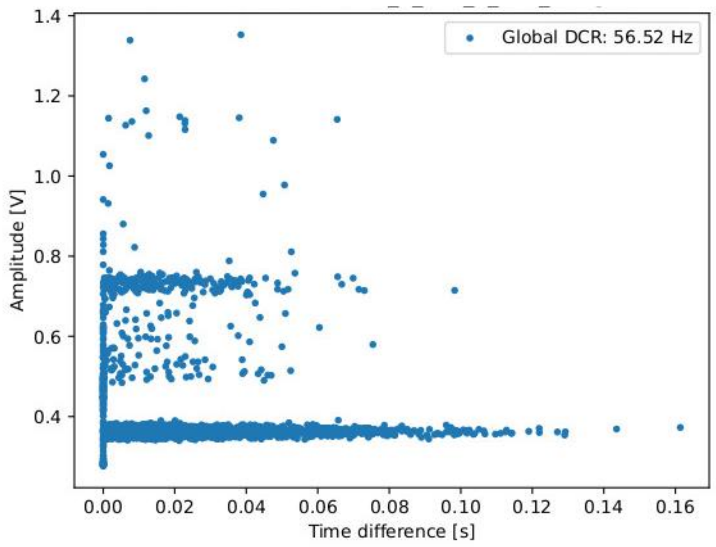
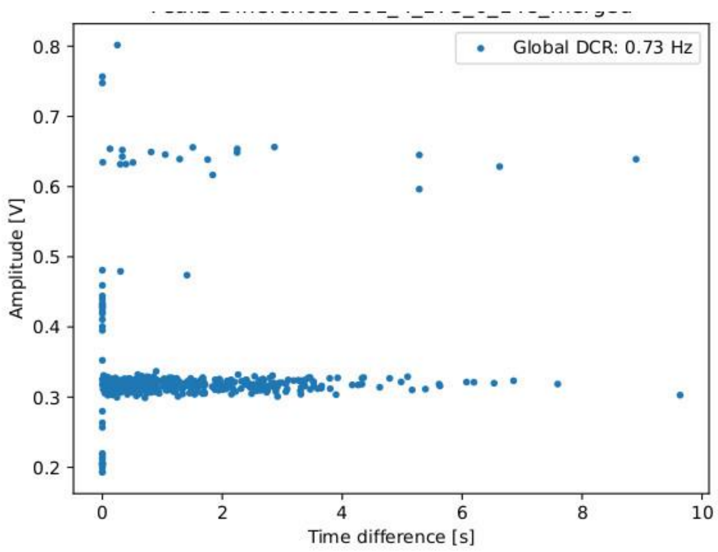
DCR and gain procedure

Global dark count rate (DCR)

- Linear power supply for bias + raw data acquisition from oscilloscope
- Counts of every signal above a certain threshold (0.5p.e.) without distinguish between primary pulses and correlated noise
- Temperature and OV dependencies







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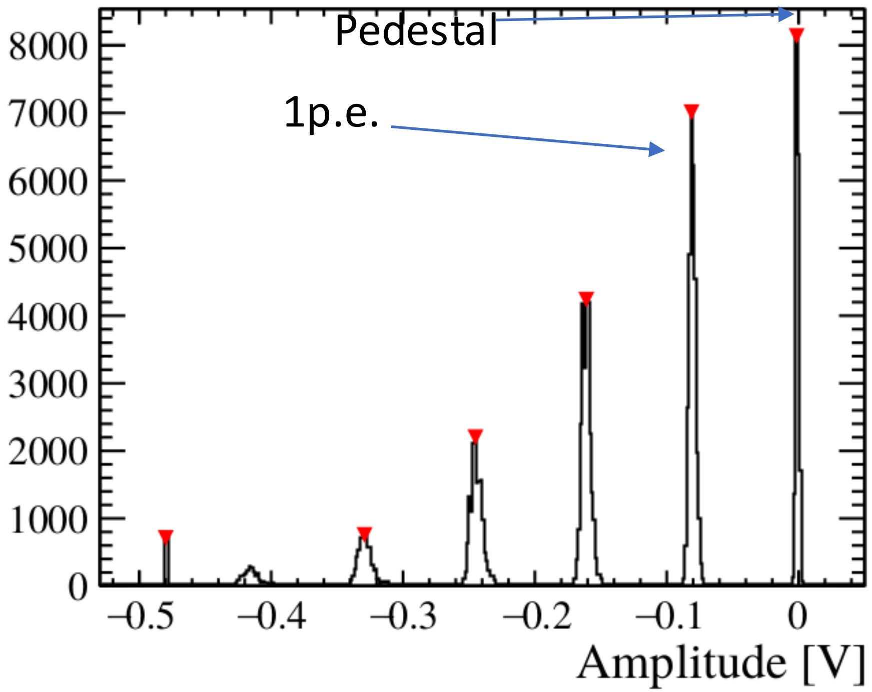
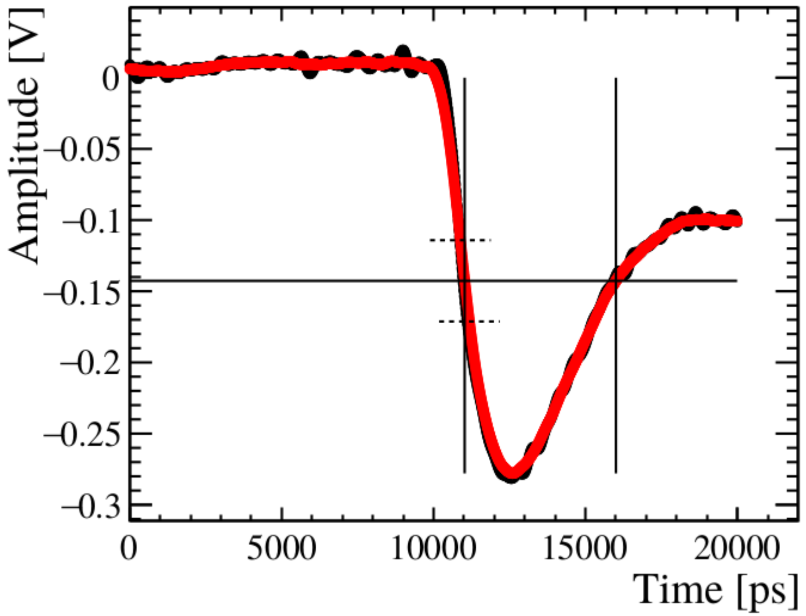
Time resolution procedure

Time resolution (TR)

- Linear power supply for bias + 405nm laser pulses (~50ps duration) + ray data acquistion from oscilloscope
- Offline selection 1 p.e. waveforms





- Time at a certain fraction of the 1p.e. peak (variable threshold)
- Baseline distribution determination
- Distributions of 1p.e. time jitter
- 40ns time window
- 10k waveforms

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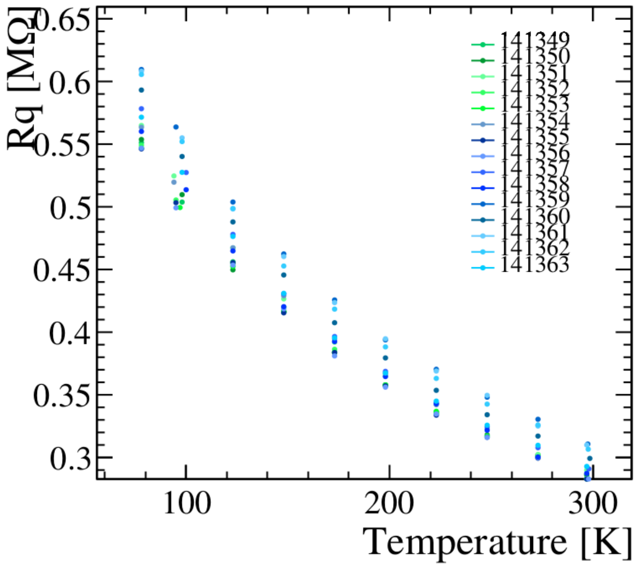
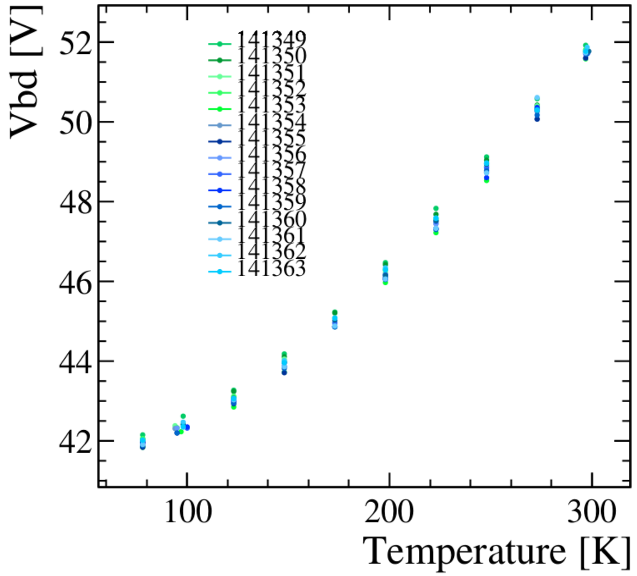
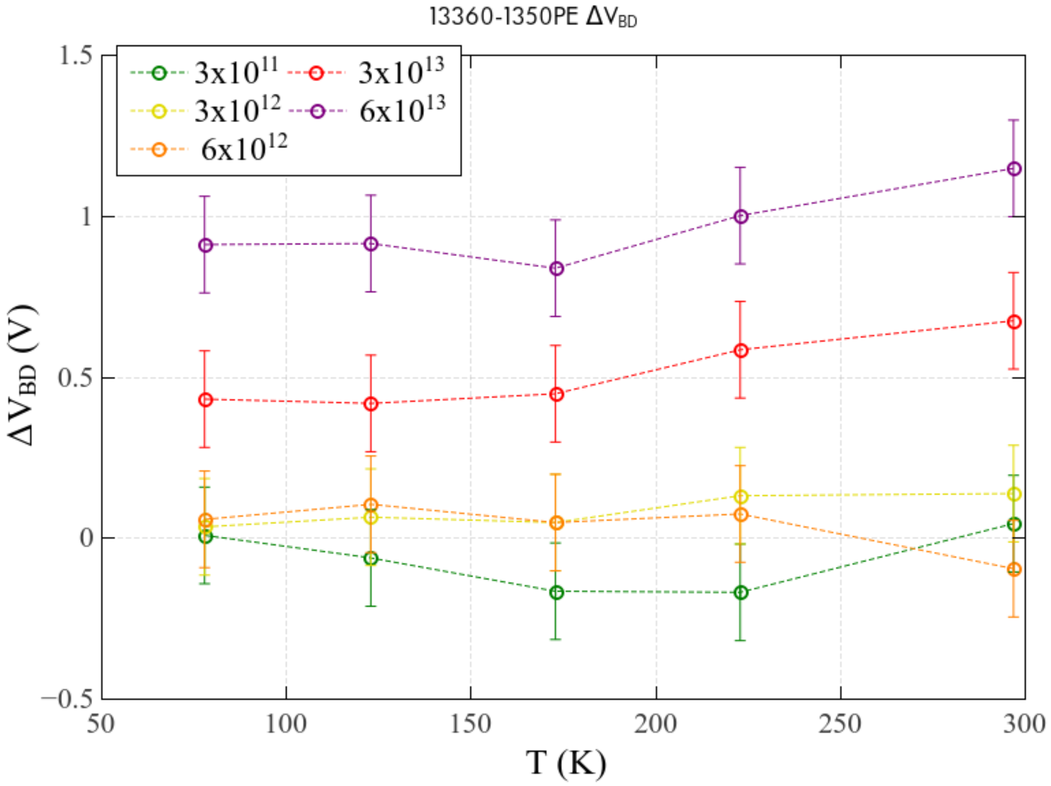
IV 13360-1350PE







- Standard Vbd and Rq behaviour as a function of temperature;
- Irradiation affects the breakdown voltage;
- Increase up to 1 V at $6x10^{13}$;
- Almost independent from temperature
- No increase in the Vbd spread

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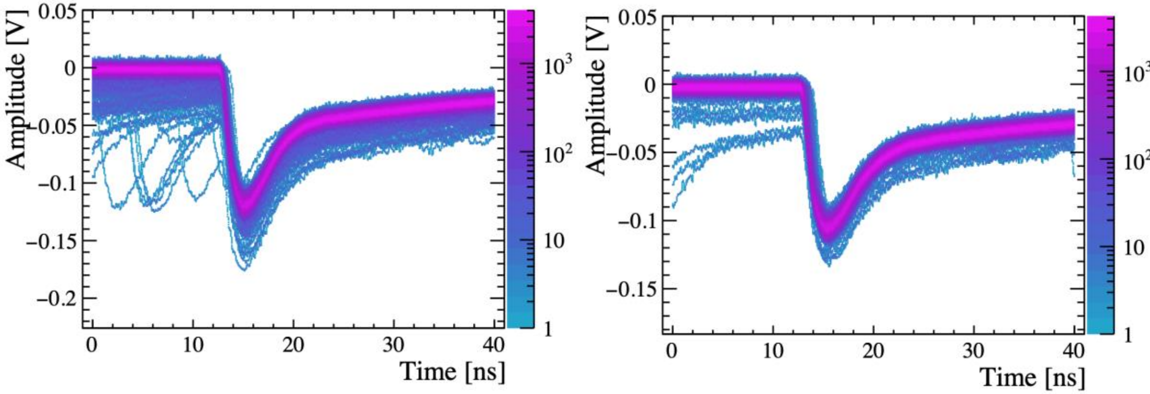
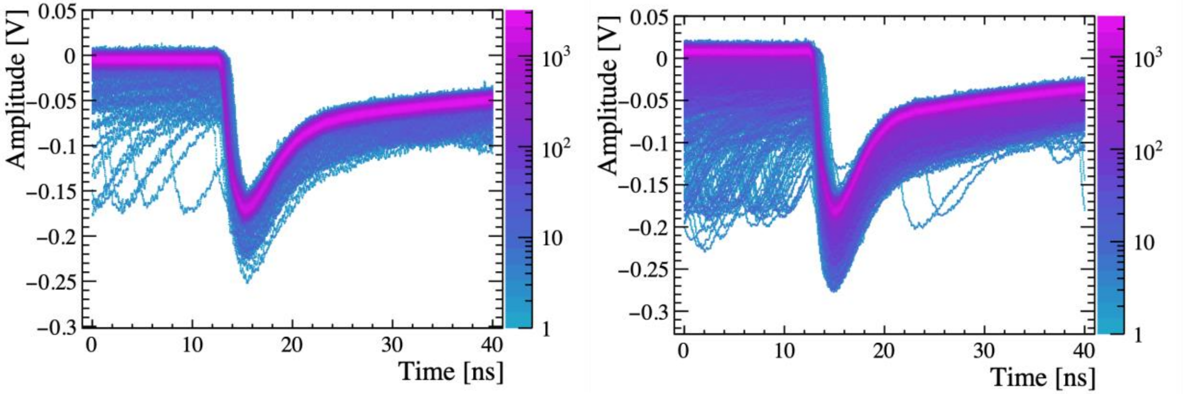
TR 13360-1350PE

- Some examples **post-irradiation**
- There is a (expected increase in the background noise that makes difficult single p.e. selection

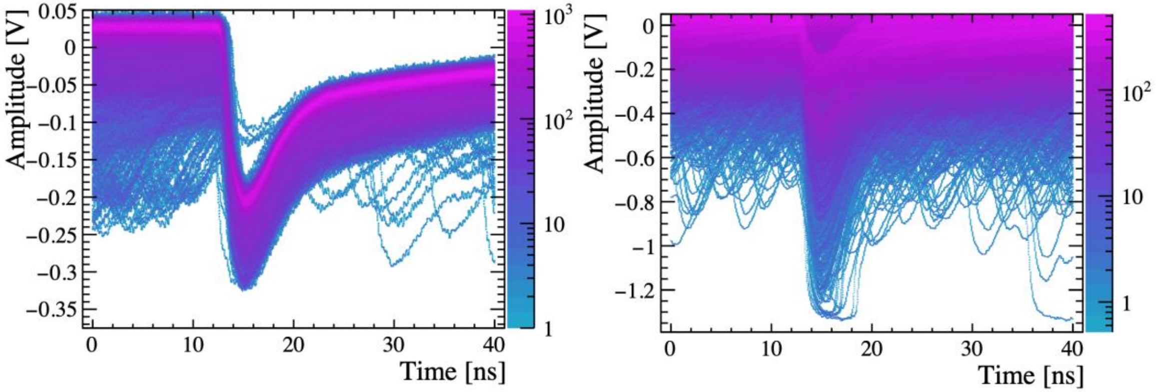
Examples OV=2V, 3x10^{13} @78K and 123K



Examples OV=3V, 3x10^{13} @78K and 123K



Examples OV=4V, 3x10^{13} @78K and 123K



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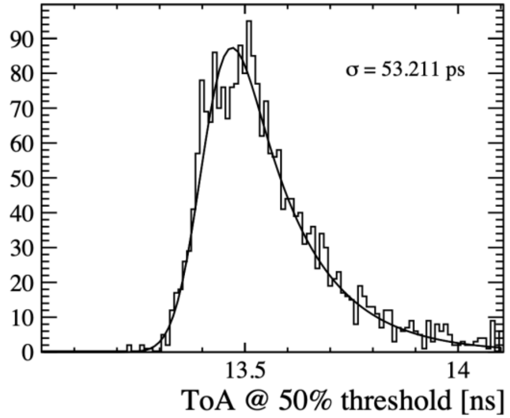
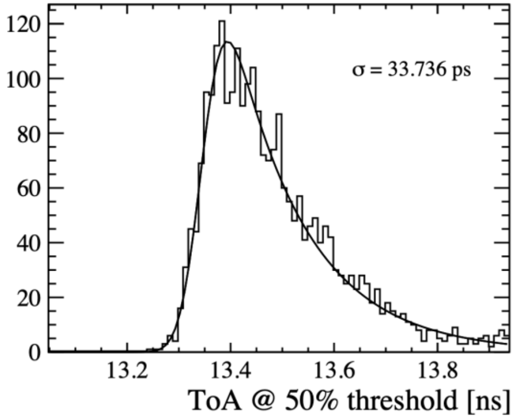
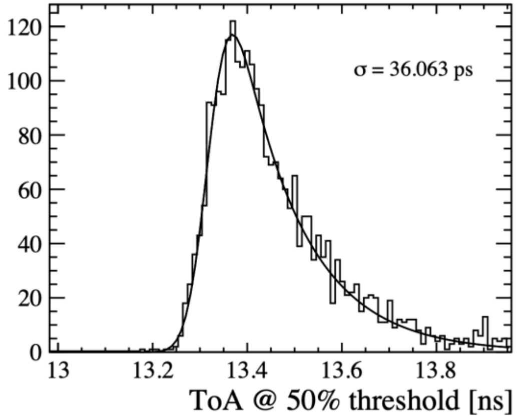
- Examples @ 3x10[12] ,78K at OV=2,3,4,V

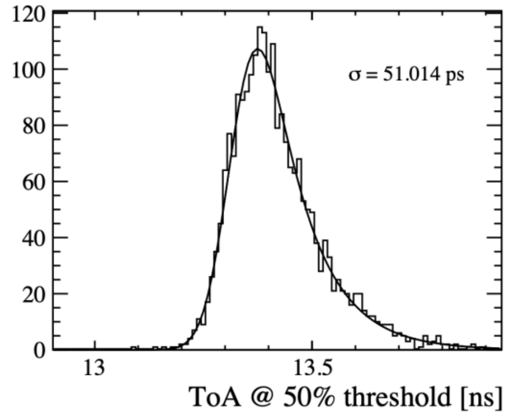


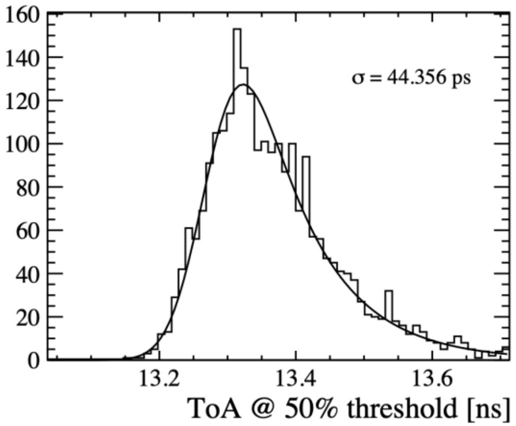


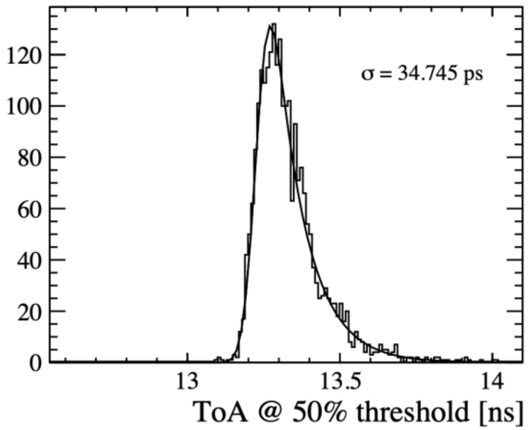


PRELIMINARY

- Examples @ 3x10[12] ,123K at OV=2,3,4,V







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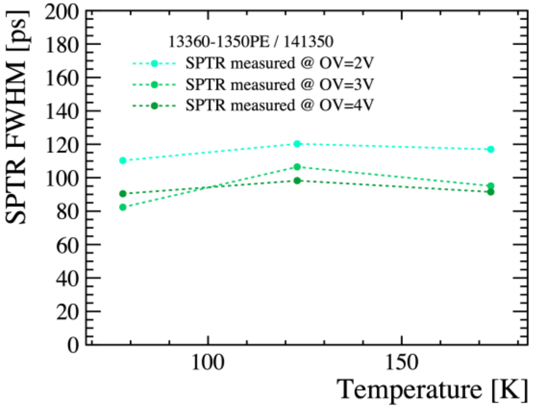
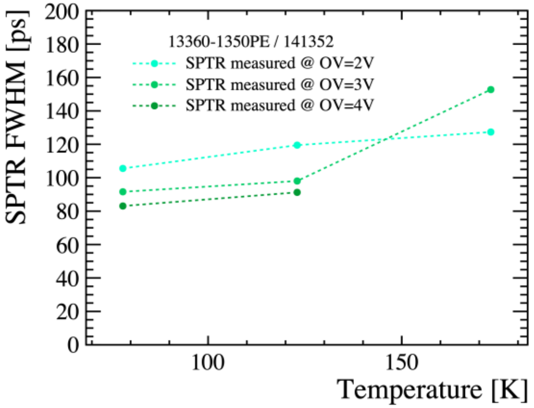
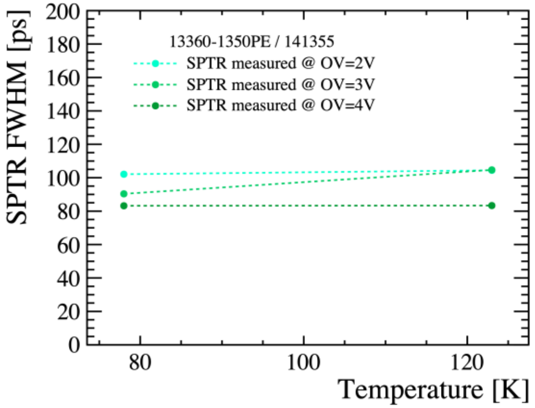
- FWHM of the Gaussian core Example @ $3x10^{11}$, $3x10^{12}$, $6x10^{12}$







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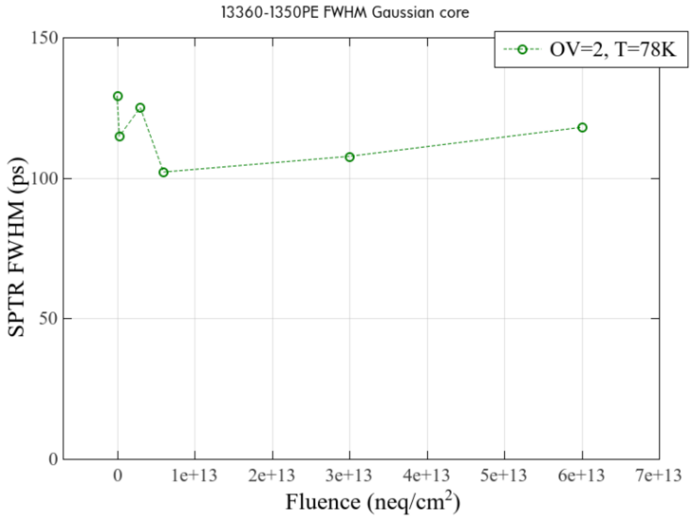
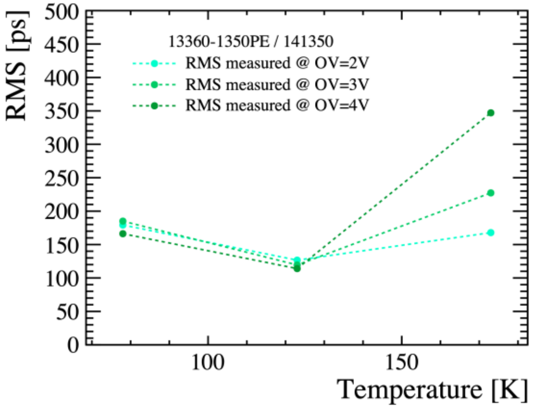
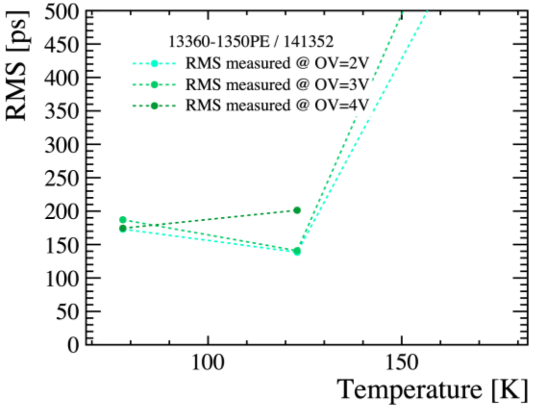
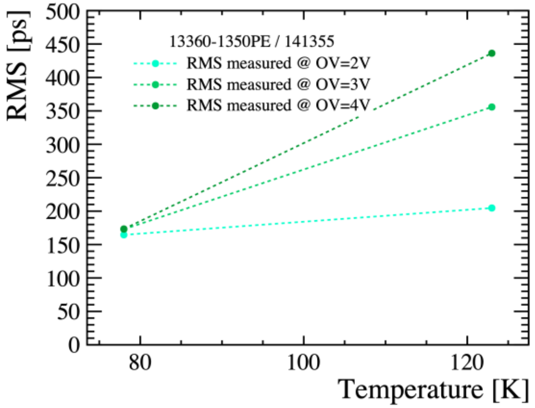


- RMS of the entire distribution Example @ $3x10^{11}$, $3x10^{12}$, $6x10^{12}$







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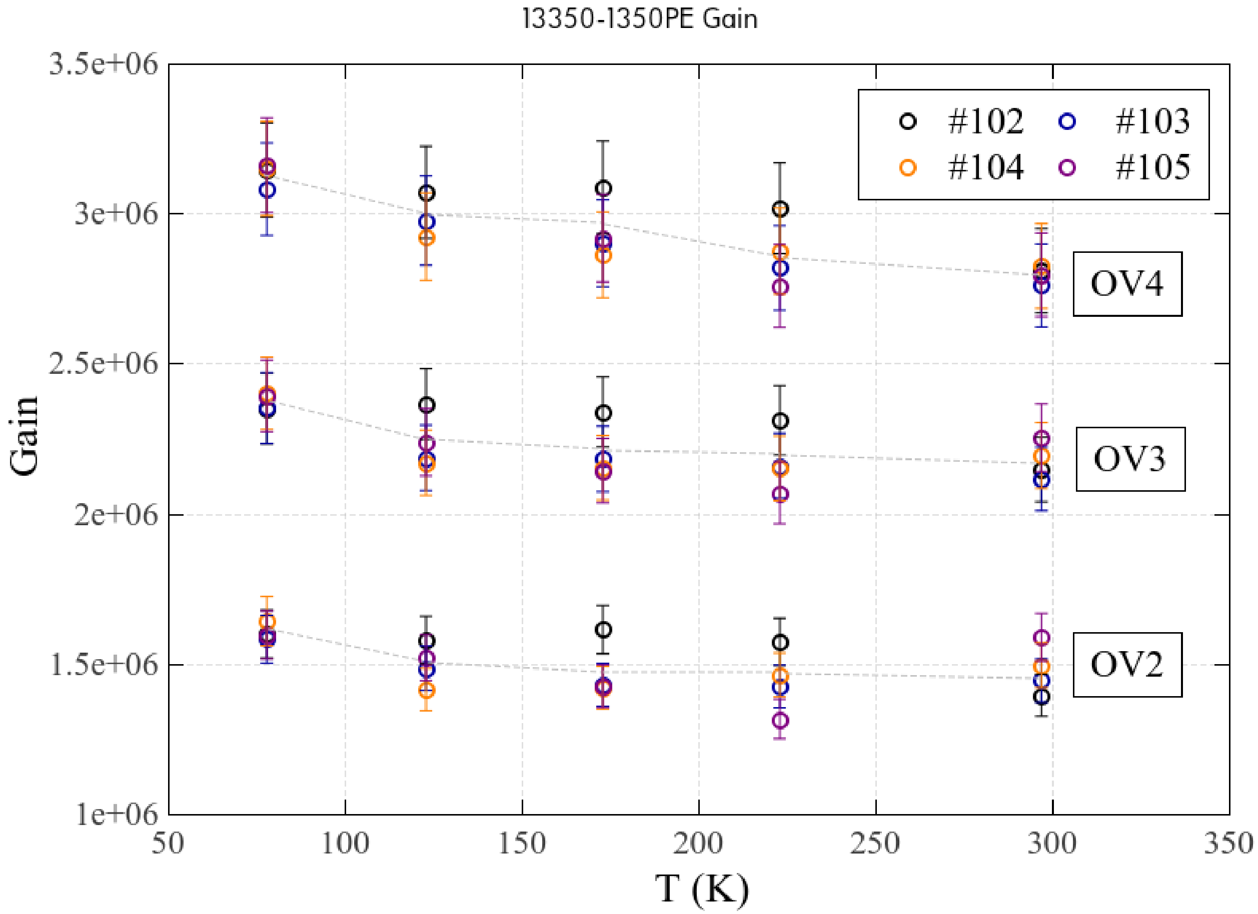
Gain 13360-1350PE

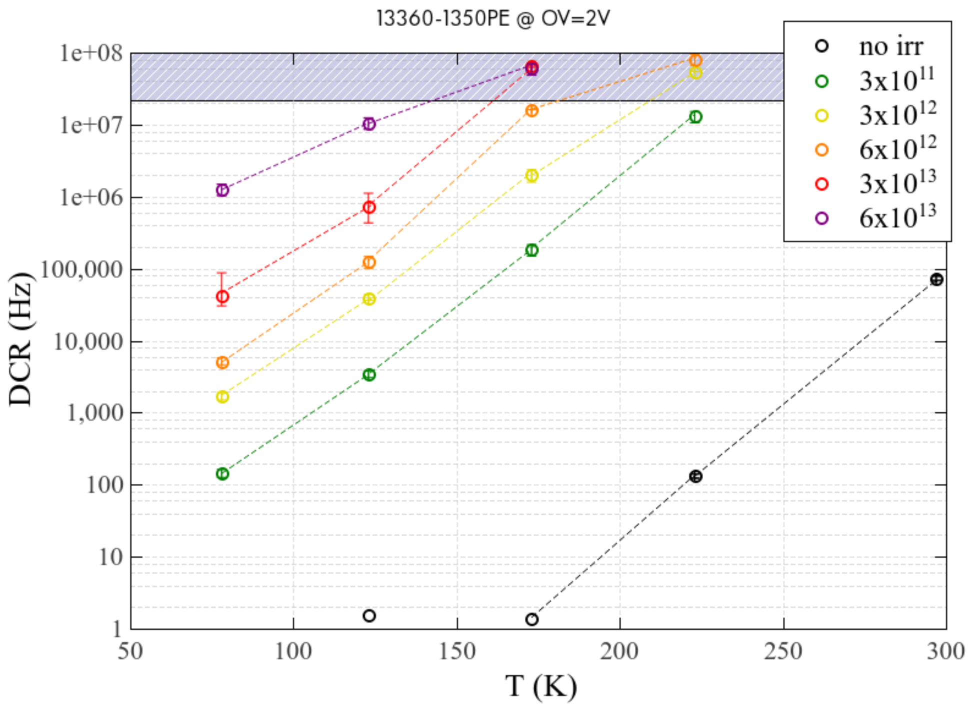


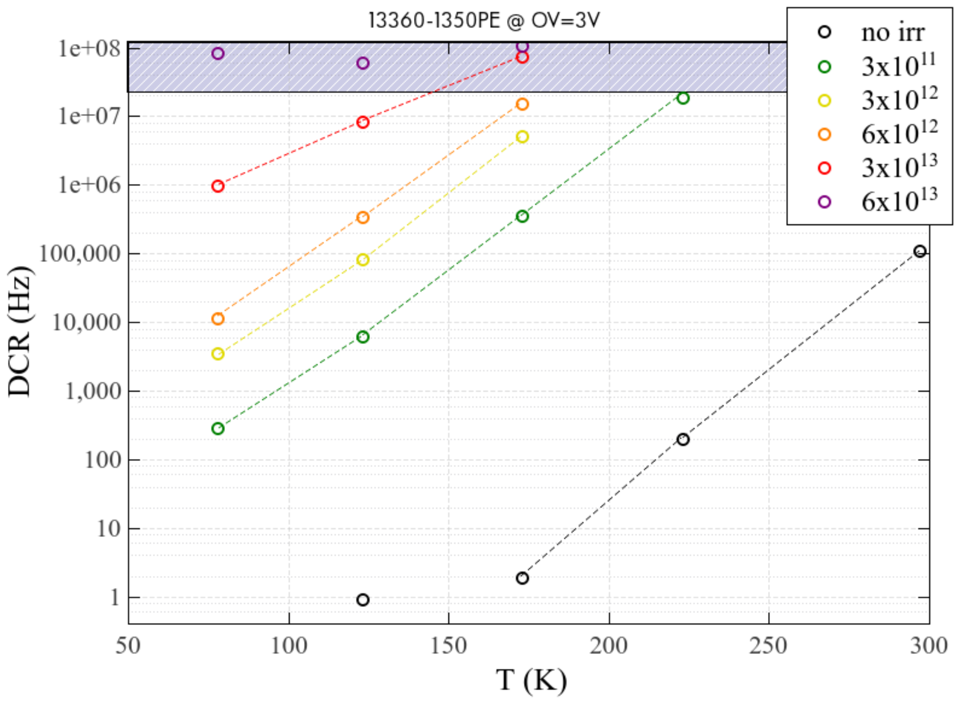
- Measured integrating the charge output signals from cold + warm amplification stages in the range [-20;580]ns
- Systematically higher (10%) that HPK
- Almost independent from temperature
- Seems to be independent to irradiation
- More tests with electronics are needed
- Check with data from other groups

PRELIMINARY

DCR 13360-1350PE

PRELIMINARY





- Amplifier issues at rate higher than ~10MHz
- All pulses above ½ p.e. counted (not divided in primary and correlated noise): this is what our electronic will see
- Rate per sensor 1.7mm^2 area (not divided by area!): this is what our electronic will see

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DCR 13360-1350PE

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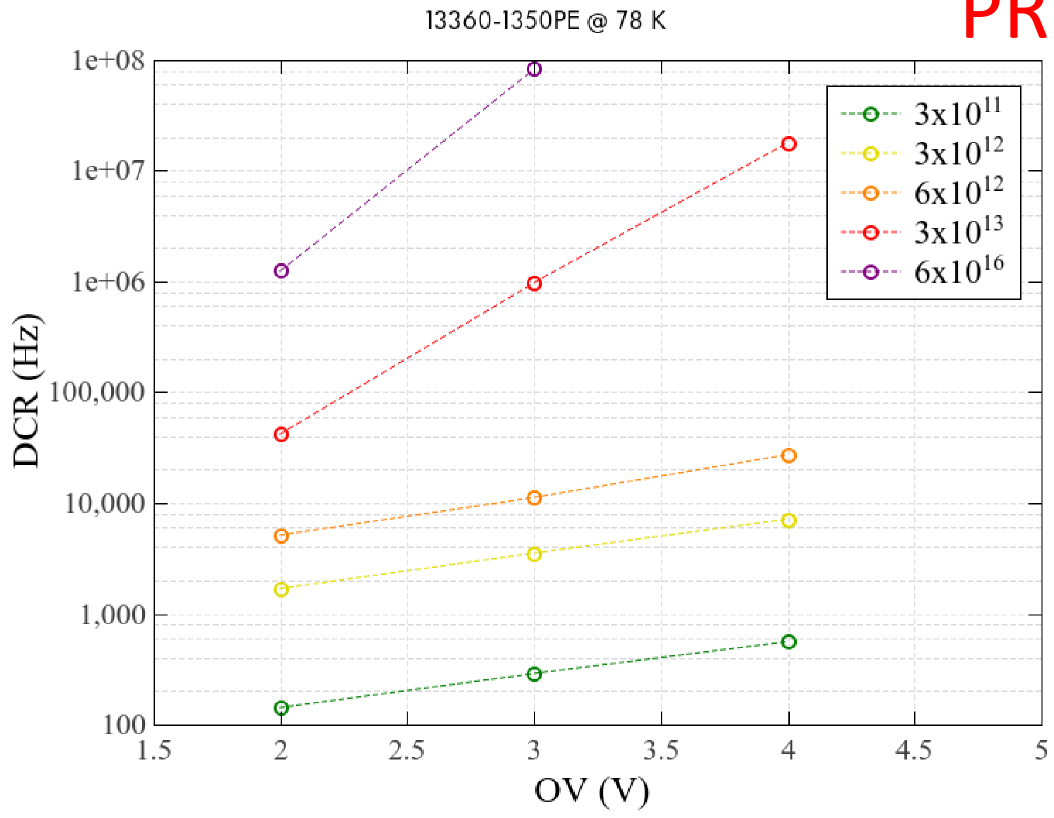

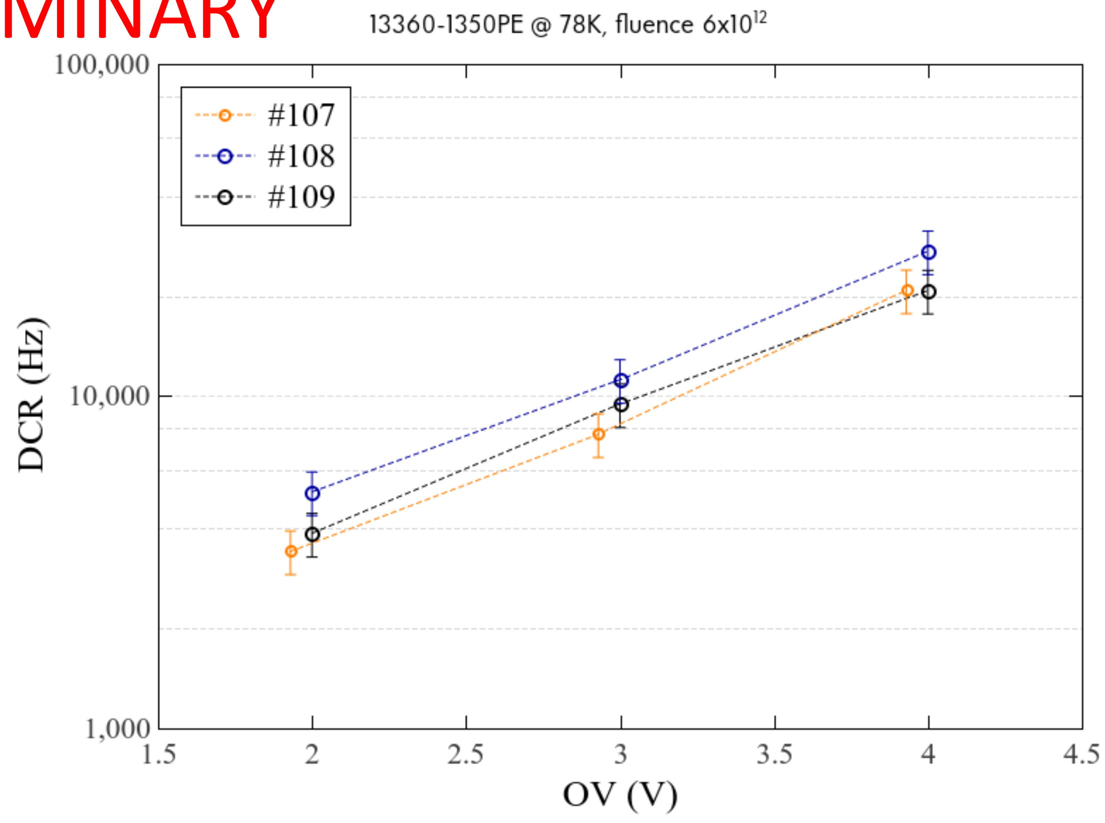

- Increase with overvoltage
- Good accordance among different samples

Conclusions

Untill now:

- IV curves for all models (14160-3050HS, 13360-1350PE, 13360-1325PE, 13360-1375PE, 13360-2050VE) pre-irradiation at all temperatures from room to LN2;
- Time resolution, Gain & DCR measurements for 13360-3050PE, 13360-1325PE, 13360-1375PE pre-irradiation;
- Time resolution, Gain & DCR measurements for 13360-3050PE post-irradiation;

General results:

- 13360-1350PE commercially available (1.7mm^2 area, 50um cell pitch, PDE at 450nm and 2OV is 32%)
  - Consistent change of breakdown voltage after irradiation;
  - Irradiatiation affects a lot the performance in terms of noise: at 3e13 only 78K remains under 100kHz rate (@ OV=2);
  - Irradiatiation seems not affect the core of the distribution for TR measurements, but the overall distribution is worst because of the numerous spurious signals and thus it can be an issue;
  - Irradiation seems not affect the gain of the sensors.

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The end

Thanks for your attention

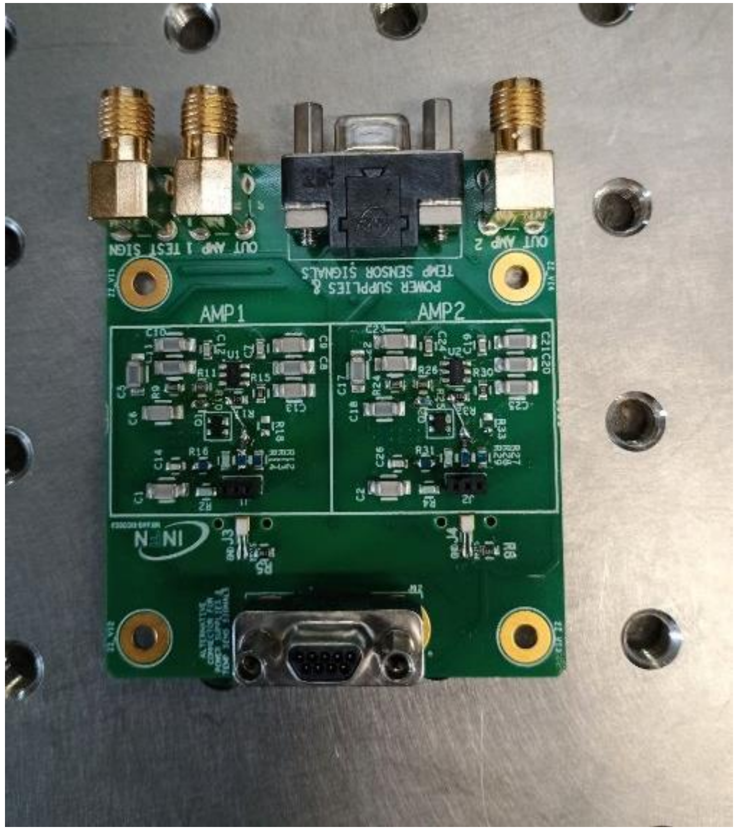
Backup slides

Measurements in Ferrara pre-irradiation

- **IV curve: reverse (REV) and direct (FW):** Breakdown voltage and Quenching resistor;
- **Time resolution (TR) measurements:** with pulsed laser;
- **Dark count rate (DCR);**
- **Gain (G):** with pulsed laser;

	297K (roomT)	223K (-50°)	173K (-100°)	123K (-150°)	78K (-196°)LN2
S13360-1325PE	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested
S13360-1350PE	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested
S13360-1375PE	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested	IV: 15 samples tested TR, DCR, G: 5 samples tested
S13360-2050VE	IV: 15 samples tested	IV: 15 samples tested	IV: 15 samples tested	IV: 15 samples tested	IV: 15 samples tested
S14160-3050HS	IV: 15 samples tested	IV: 15 samples tested	IV: 15 samples tested	IV: 15 samples tested	IV: 15 samples tested

Ferrara setup II



Cold amplifier developed by Milano Bicocca

The setup can perform:

- **IV curve through the source meter unit SM2450**

Quenching resistor R_q;

Breakdown voltage V_{bd};

- **DCR analysis through power supply + MiB amplifier + oscilloscope**

Primary DCR;

Afterpulses;

Cross-talk;

Burst effect;

- **Temporal study through power supply + aMiB amplifier + oscilloscope + Laser source**

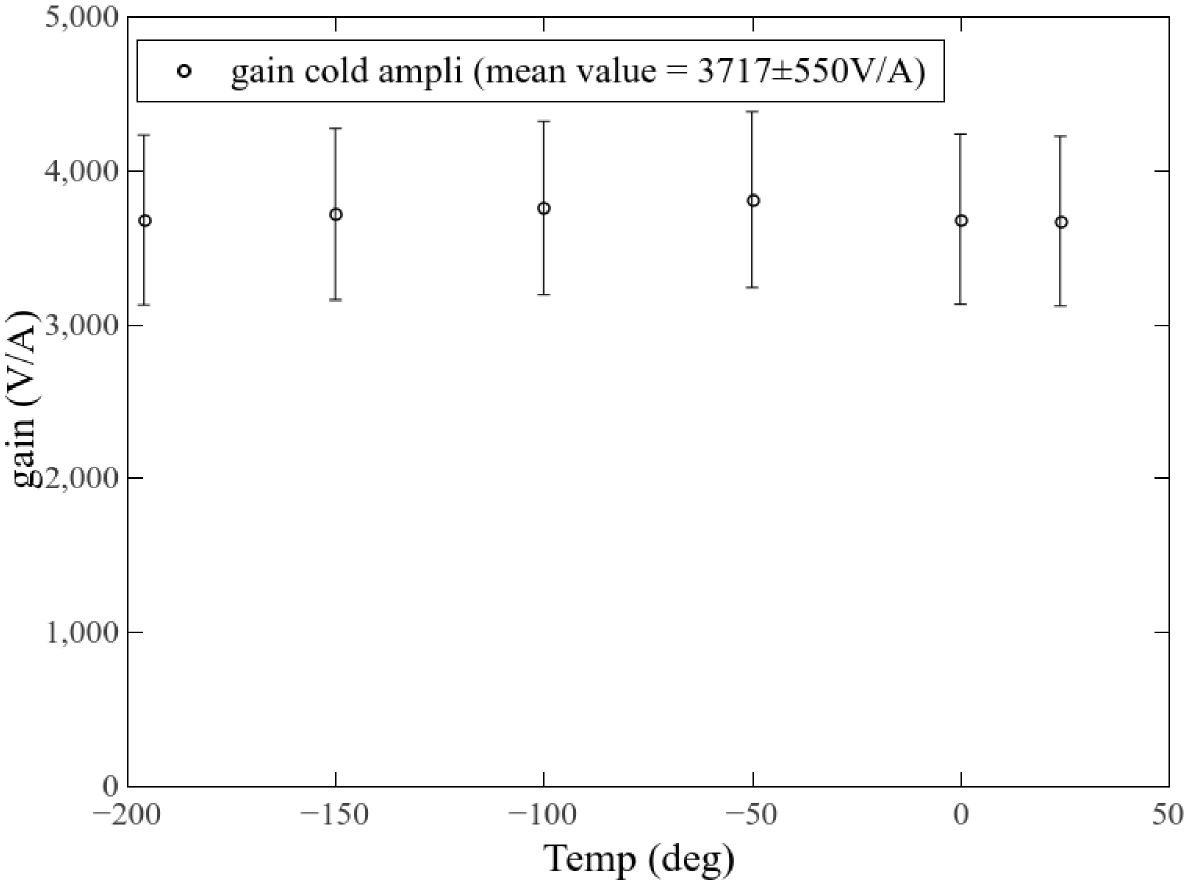
Time resolution

Analysis through Python Scripts:

- Linear fit direct IV;
- Polynomial fit normalized derivative reverse IV;
- Peak amplitude and time search;
- Peak shape;
- Hystograms;

Ferrara setup

Cold amplifier gain



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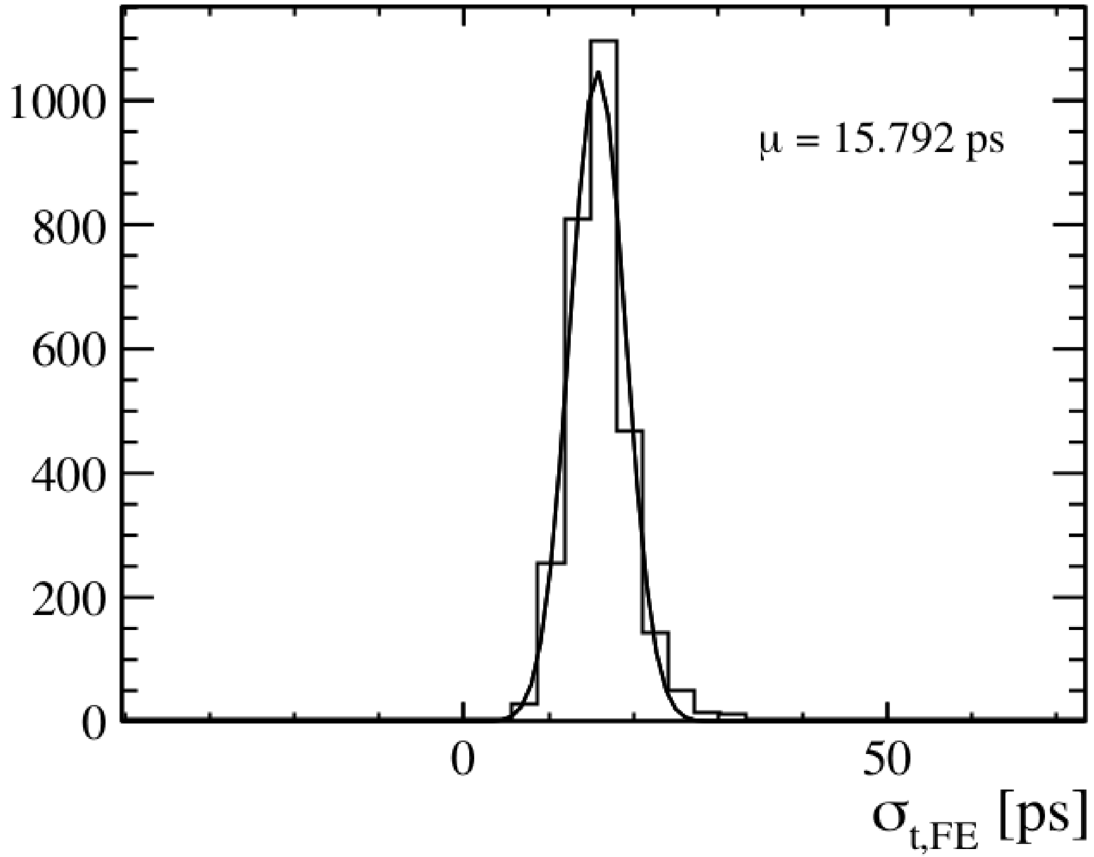
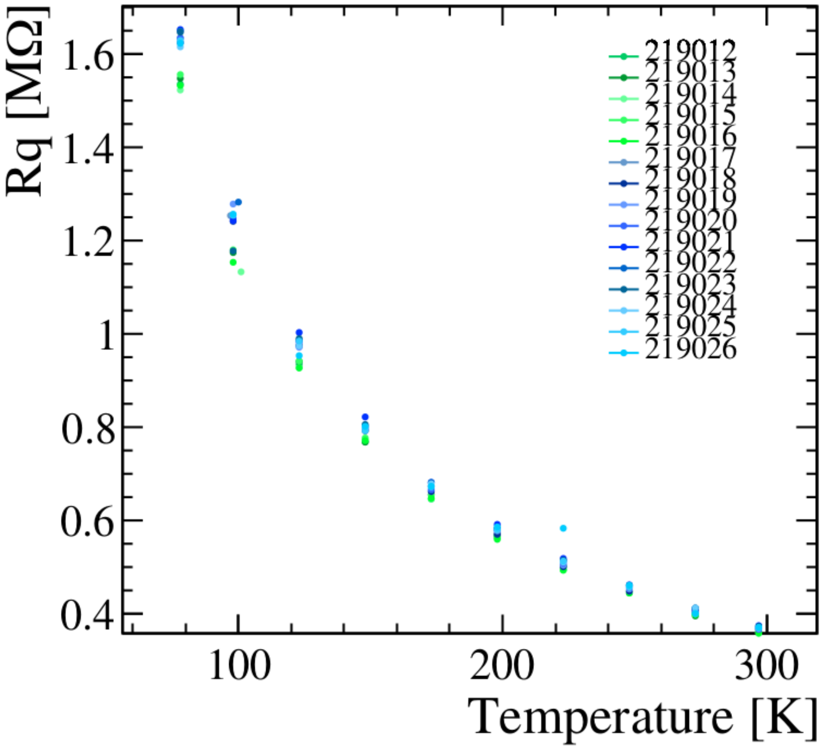
Ferrara setup

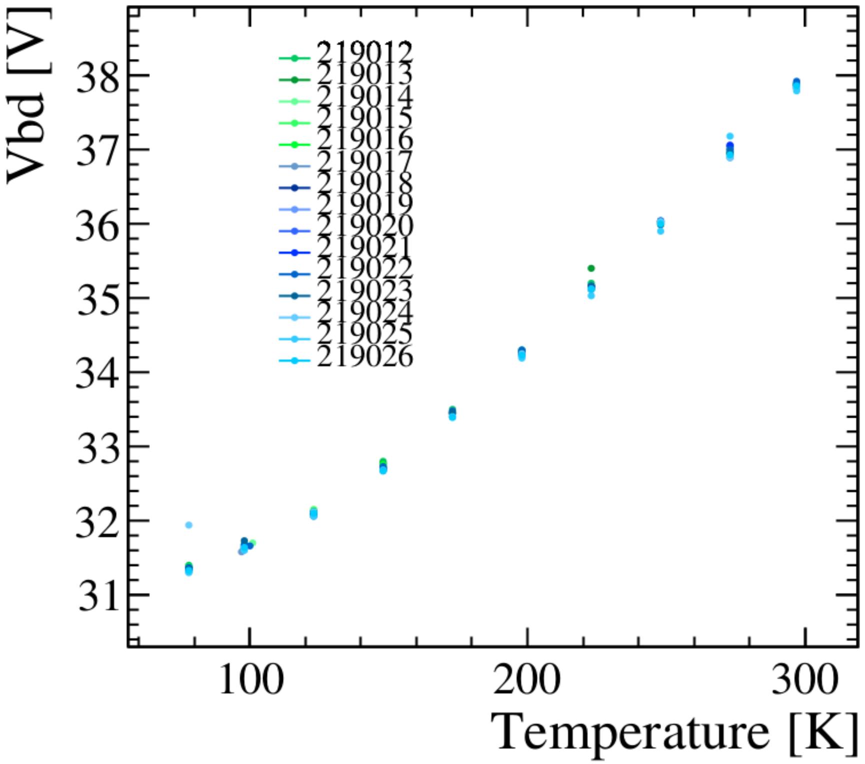
Cold amplifier time jitter



14160-3050HS Ferrara

- 15 samples already tested: min-max operation spread 100mV
- Rq increases at low temperature: from room T to LN2 4 times
- Vbd decreases at low temperature: 30mV/°C





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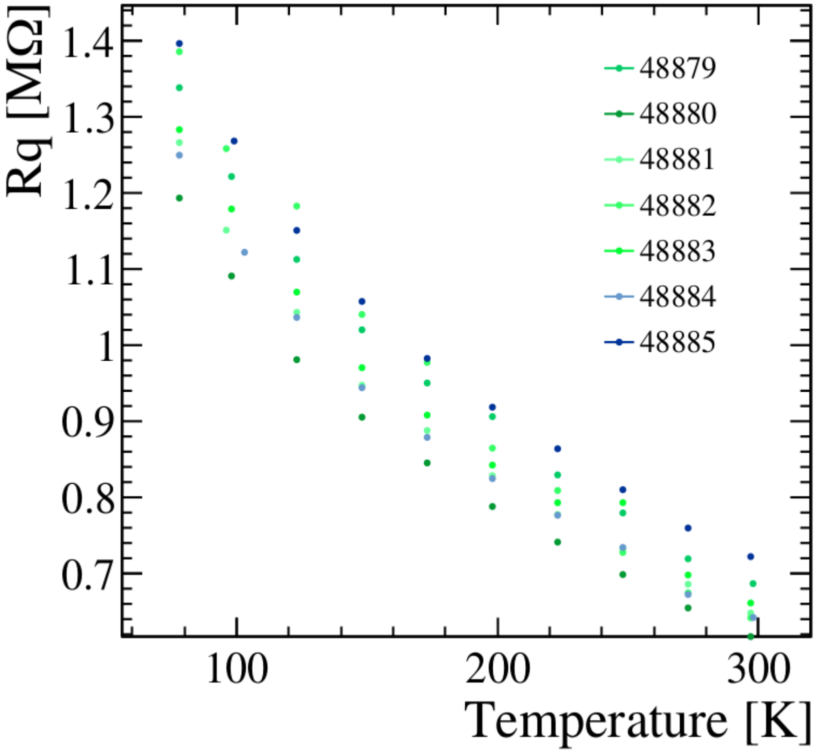
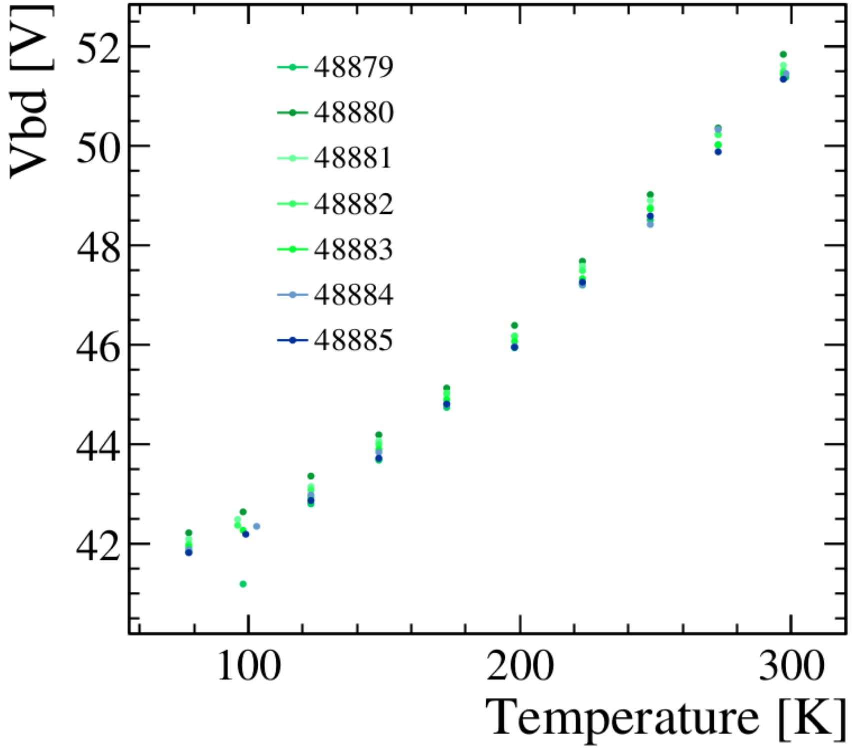
13360-1325PE Ferrara





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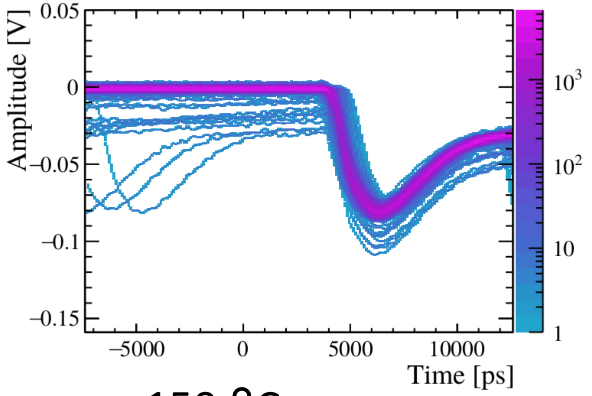
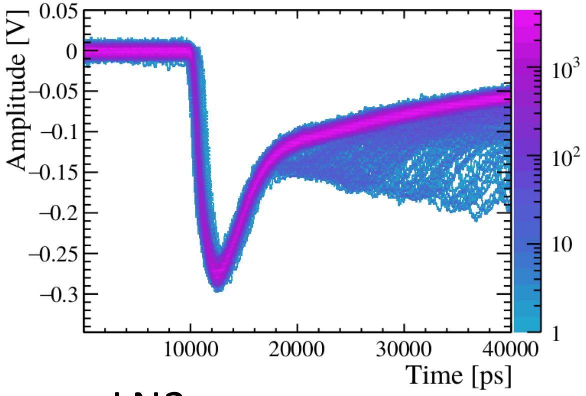
Time resolution 13360-1350PE

- Examples of samples **pre-irradiation**

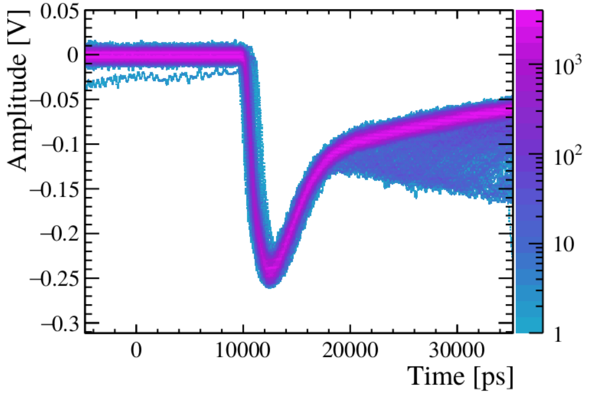
Room T



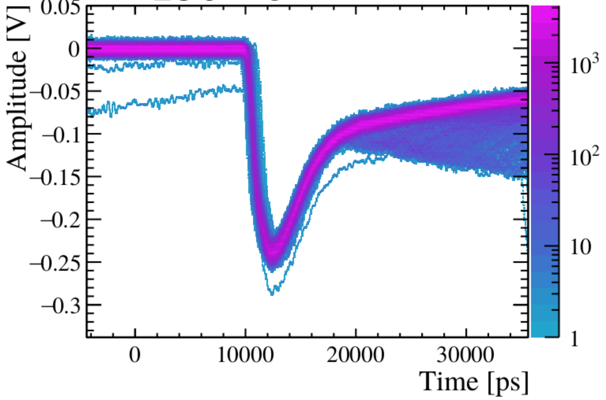
-50 °C



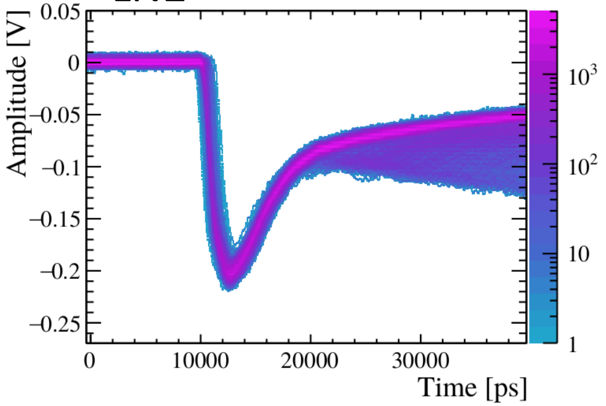
-100 °C



-150 °C



LN2



An increase in the afterpulse probability seems to occur going to low temperatures