New diamond detector structure and related front-end electronics for sub-nanosecond TOF application

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Sub-nanosecond TOF technique for small area (few cm^2) and very high radiation hardness

- A sub-nanosecond Time Of Flight detector is necessary for the very forward region of various experiments at very high luminosity accelerators.

- This application is very demanding for the present detector technology.

- We present a very simple and promising crystal (polycrystalline diamond) detector with sub-nanosecond time resolution and very high radiation hardness.

Present situation of TOF with diamonds

Present diamond sensors are very promising:

- High carriers mobility.
- High granularity.
- High radiation hardness.

But they also show intrinsic limits for application as sub-nanosecond TOF detectors:

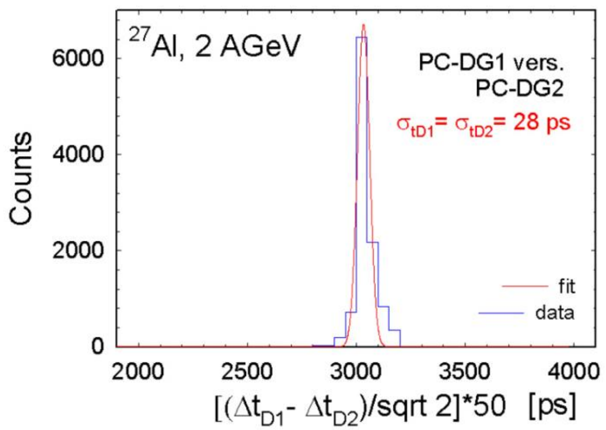
- Low charge collection (13 eV/couple, small c.c.d. for polycrystalline diamond).
- Non-uniformity of response (polycrystalline diamond).
- Reproducibility of detector parameters from production process.
- Difficult to achieve full efficiency and good time resolution for MIPs with polycrystalline diamond sensors in high radiation environment.

Diamond detectors timing performance

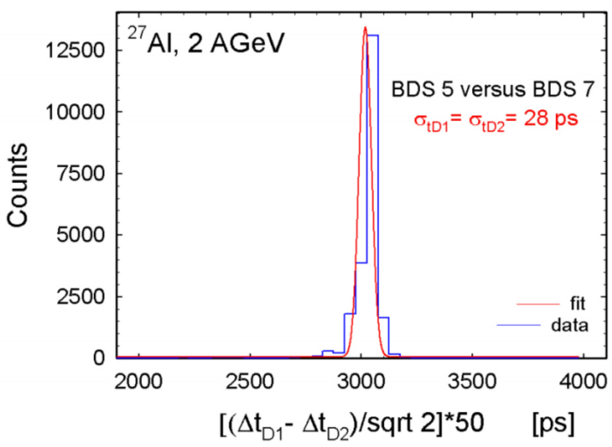
Why is it interesting to study the possibility to use diamond sensors for time of flight?

- The diamond detectors are successfully used in measurements of time of flight in nuclear physics for medium-heavy ions, where the signal intensity is high, obtaining temporal resolution of about 28 ps for both single crystal and polycrystalline diamond detectors.

ToF measurement using Polycrystalline Diamond Detectors on ^{27}Al beam.



ToF measurement using Single Crystal Diamond Detectors on ^{27}Al beam.



E. Berdermann et al, Radiation-Hard Detectors for Spectroscopy and Timing, for the NoRHDia* Collaboration

- This proves that the limit in time resolution for MIPs is only due to the small signal to noise ratio. **The charge collection time jitter is negligible in the few tens picosecond scale.**

Diamond detectors timing performance

		silicon [a]	natural diamond [b]
electron mobility	$[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$	1450	1500.. ..2400
hole mobility	$[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$	≈ 440	1000.. ..2100
electron saturation velocity	[cm/s]		2×10^7
hole saturation velocity	[cm/s]		10^7
energy to create *eh*-pair	[eV]	3.6	13
radiation length	[cm]	9.4	12.03
specific ionization loss	[MeV/cm]	3.9	6.2
ave. no. of *eh*-pairs/*mip*	[pairs/100 μm]	9000	3600
ave. no. of *eh*-pairs/*mip*	[pairs/300 μm]	27000	11850

What is limiting time resolution in our application. → Signal to Noise ratio with minimum ionizing particles.

Signal charge for a polycrystalline diamond with 100 μm collection distance is ~3600 e^-!

Time Resolution vs Signal to Noise ratio

For a particle detector whose time resolution is limited by the S/N ratio:

$$\sigma_t \propto \frac{Rise\ Time}{Signal\ to\ Noise\ ratio}$$

Using a charge-to-voltage amplifier:

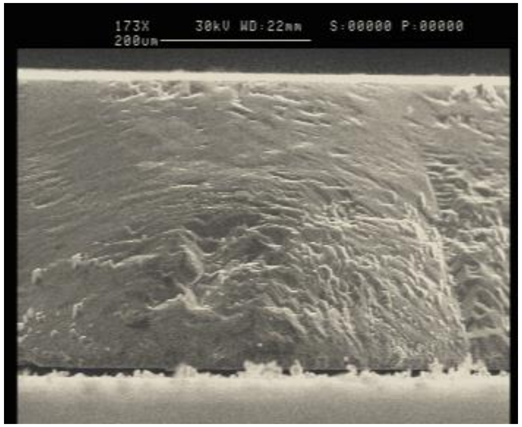
$$\sigma_t \propto \frac{Rise\ Time\ \left(= \frac{\cancel{\lambda}}{v_s}\right)}{Q_{ind}\ (= k\cancel{\lambda})} \cdot\ Noise$$

$k \rightarrow produced\ charge\ per\ unit\ lenght$
$v_s \rightarrow saturated\ charge\ drift\ velocity$
$\lambda \rightarrow detector\ charge\ collection\ distance$

The time resolution does not depend on:

- Detector thickness.
- Detector charge collection distance.

Single Crystal vs polycrystalline diamond sensor



Single Crystal CVD diamond.

- High charge collection efficiency.
- High cost per unit area.

Polycrystalline CVD diamond.

- Lower cost for a large area detector.
- Low charge collection efficiency.
- Lower uniformity of response.

Despite its lower charge collection efficiency, the polycrystalline diamond sensor is expected to have the same time resolution as the single crystal diamond due to the compensation effect between rise time and charge collection described before (detector efficiency, noise and uniformity not considered so far).

We choose the polycrystalline diamond sensor for its lower cost.

Development of Multi-Layer Crystal Detector

Necessary to increase detector thickness in order to improve collected charge! → Higher rise time: then no gain in signal and timing performance.

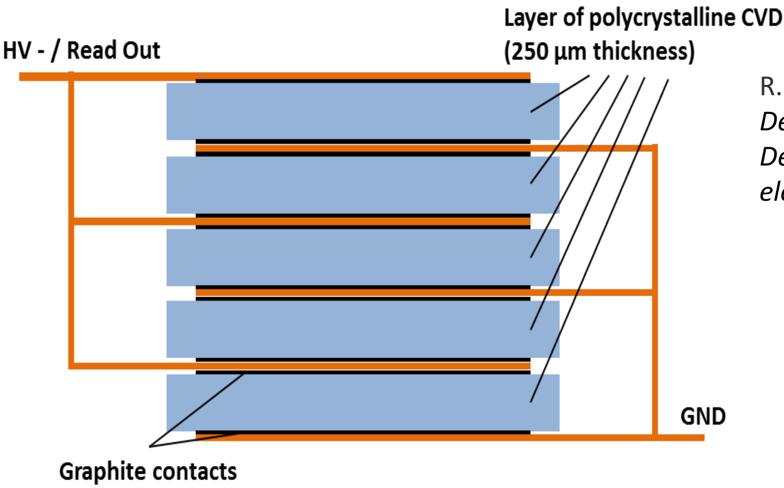
Non-uniformities of polycrystalline diamond may lead to a large spread on collected charge distribution. → Critical response in terms of efficiency.

These are intrinsic limits to the time resolution of the monolithic diamond detector.

Conclusion:
Proposal of a detector structure optimized for Time of Flight.

Development of Multi-Layer Crystal Detector

Possible solution: **Multi-Layer Crystal Detector (MLCD)**



R. Cardarelli, A. Di Ciaccio and L. Paolozzi, *Development of Multi-Layer Crystal Detector and related Front End electronics*; NIM A 745, 82–87 (2014)

The MLCD is based on the principle to divide the total detector thickness in a number of sub-layers read out in parallel with plane geometry, in order to maximize the total induced charge without increasing the rise time of the signal. With a charge-to-voltage amplifier, the expected time resolution of the MLCD is

$$\sigma_t \propto \frac{1}{kv_s} \cdot Noise \cdot \frac{1}{n}$$

$k \rightarrow produced\ charge\ per\ unit\ lenght$
$v_s \rightarrow saturated\ charge\ drift\ velocity$
$n \rightarrow number\ of\ layers\ of\ MLCD$

The MLCD can improve the time resolution of a crystal of a factor proportional to the number of layers (n).

Charge-to-Voltage amplifier for MLCD

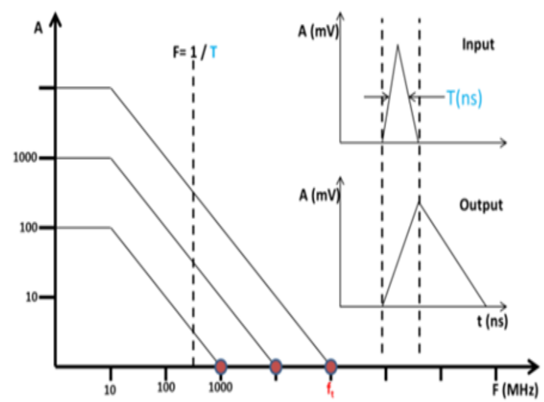
A custom charge-to-voltage amplifier in BJT technology was purposely developed for this application.

An important feature of this preamplifier for particle detector applications in high radiation, high temperature environment is that the input impedance can be matched to a 50 Ohm transmission line, thus allowing to put the preamplifier far from the diamond MLCD at a distance up to 100 m.

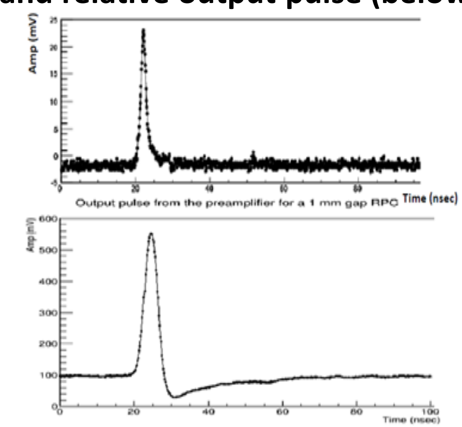
Properties of the preamplifier

Voltage supply	3-5 Volt
Sensitivity	2-4 mV/fC
Noise (up to 20 pF input capacitance)	1500 e^- RMS
Input impedance	100-50 Ohm
B.W.	10-100 MHz
Power consumption	10 mW/ch
Rise time $\delta(t)$ input	300 – 600 ps
Radiation hardness	1 Mrad, 10^{13} n cm^{-2}

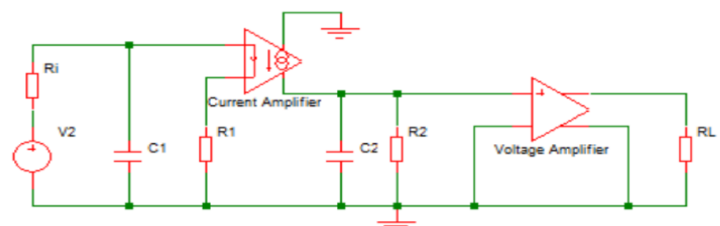
Working principle



Example of Input pulse (above) and relative output pulse (below)



Concept schematics of the amplifier

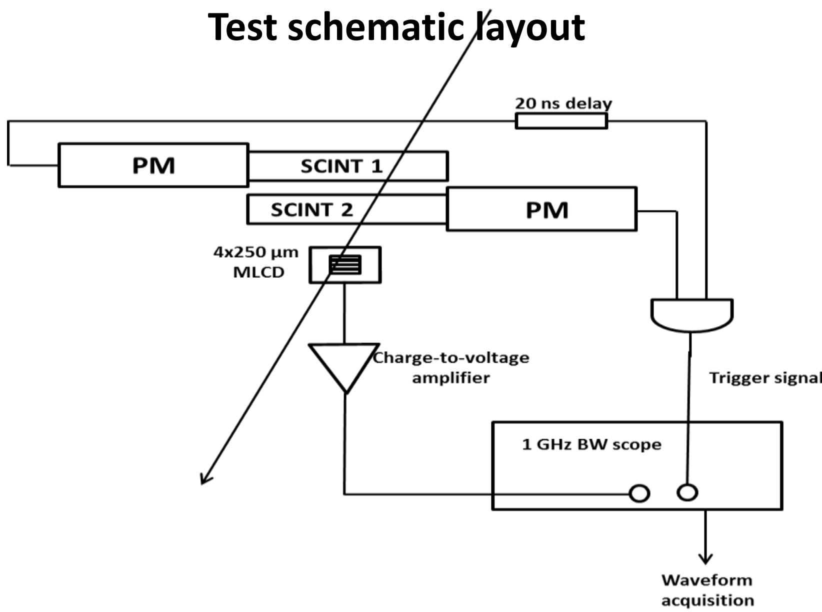


Test of MLCD with cosmic rays

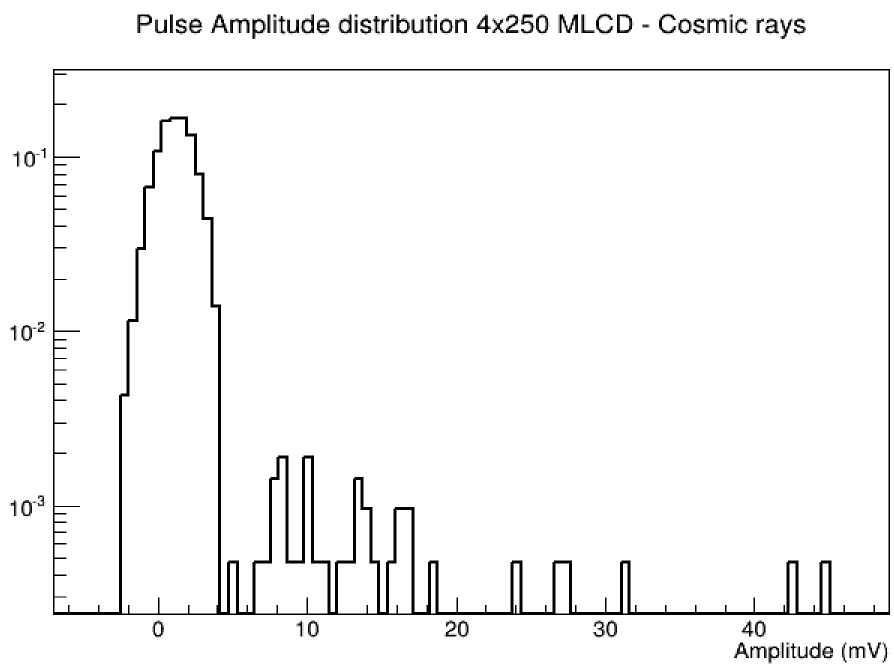
An first test of a 4x250 μm MLCD was carried out with cosmic rays.

- Time reference and trigger were given by two scintillators with ~250 ps time resolution.
- Signal of the MLCD was amplified by means of a custom charge to voltage amplifier.
- Read out of MLCD and one scintillator with 1 GHz BW, 5 Gs/s oscilloscope (TDS 7104 by Tektronix).

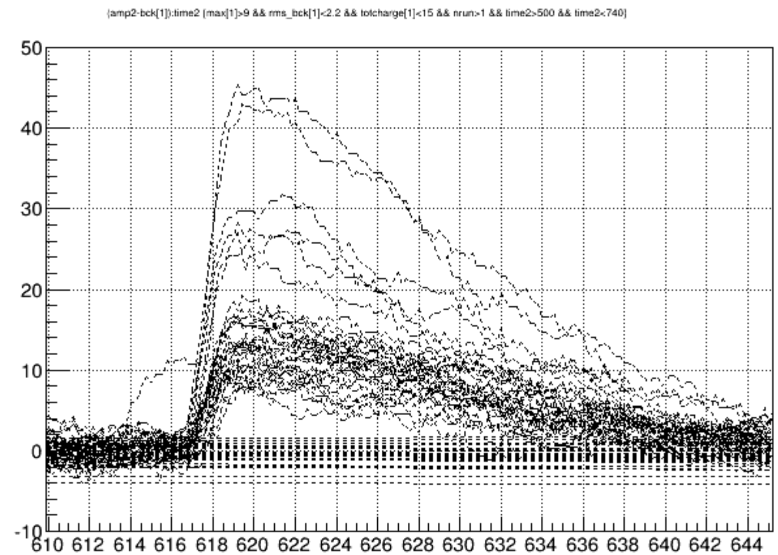
Test schematic layout



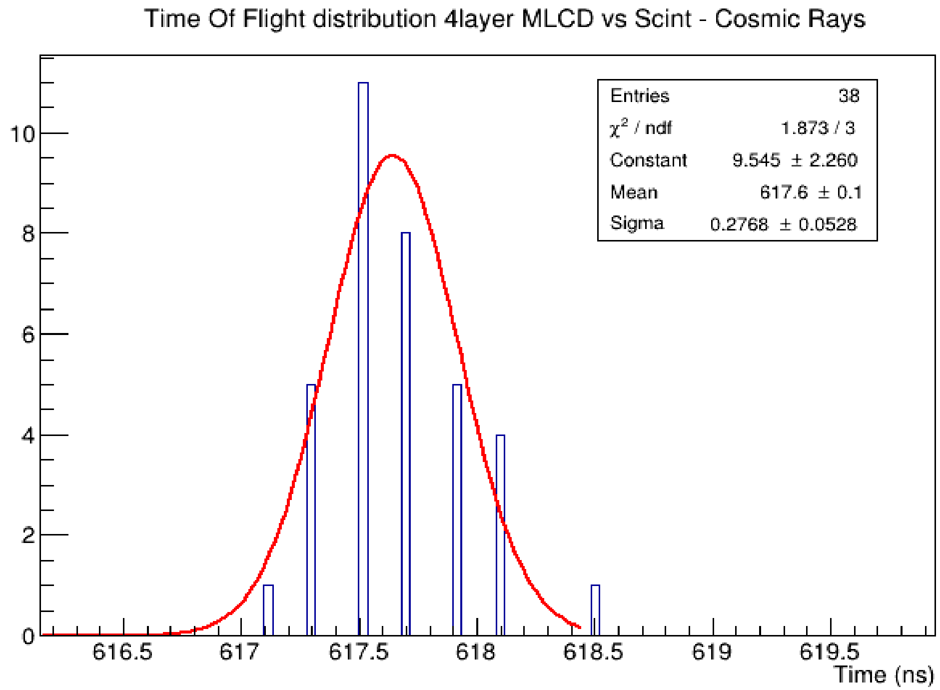
Results from cosmic ray test – charge distribution



Collection of pulses of the MLCD



Results from cosmic ray test – Time Of Flight



Time of Flight measurement 4x250 MLCD

The TOF measurement is dominated by the 250 ps trigger jitter.
Net time resolution of the MLCD is about 130 ps, compatible with the expectation for a 4 layer detector.

Test of the MLCD at the Frascati Beam Test Facility (BTF)

The MLCD structure has been also tested at the Frascati BTF in order to measure the time resolution of the detector.

- The accelerator delivered 500 MeV electrons in single electron mode.
- Time reference was given by a 500 μm thick, 1 cm^2 polycrystalline diamond parallel to the beam (reference detector).
- Signal of both MLCD and reference detector was amplified by means of a custom charge to voltage amplifier.
- Read out with 1 GHz BW, 5 Gs/s oscilloscope (TDS 7104 by Tektronix).

Test beam schematic layout

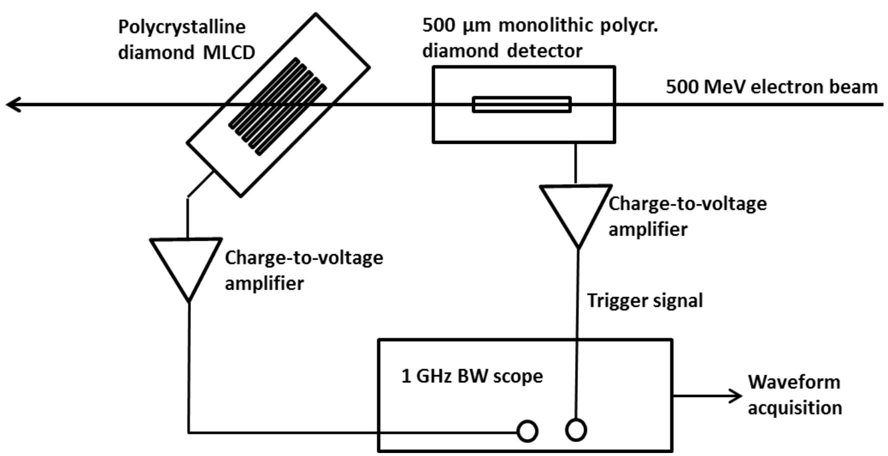
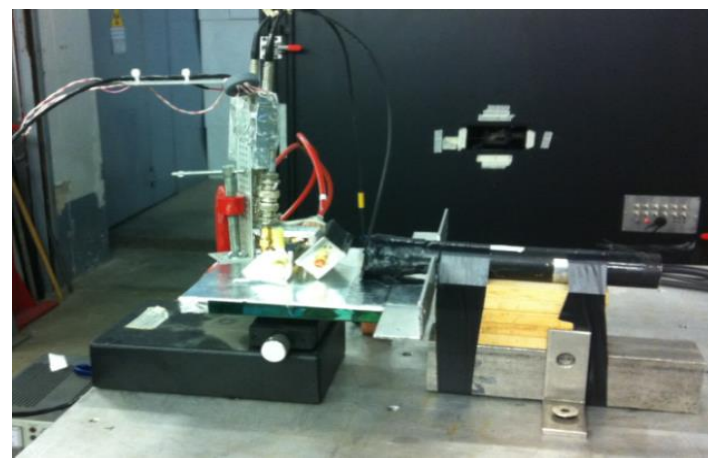
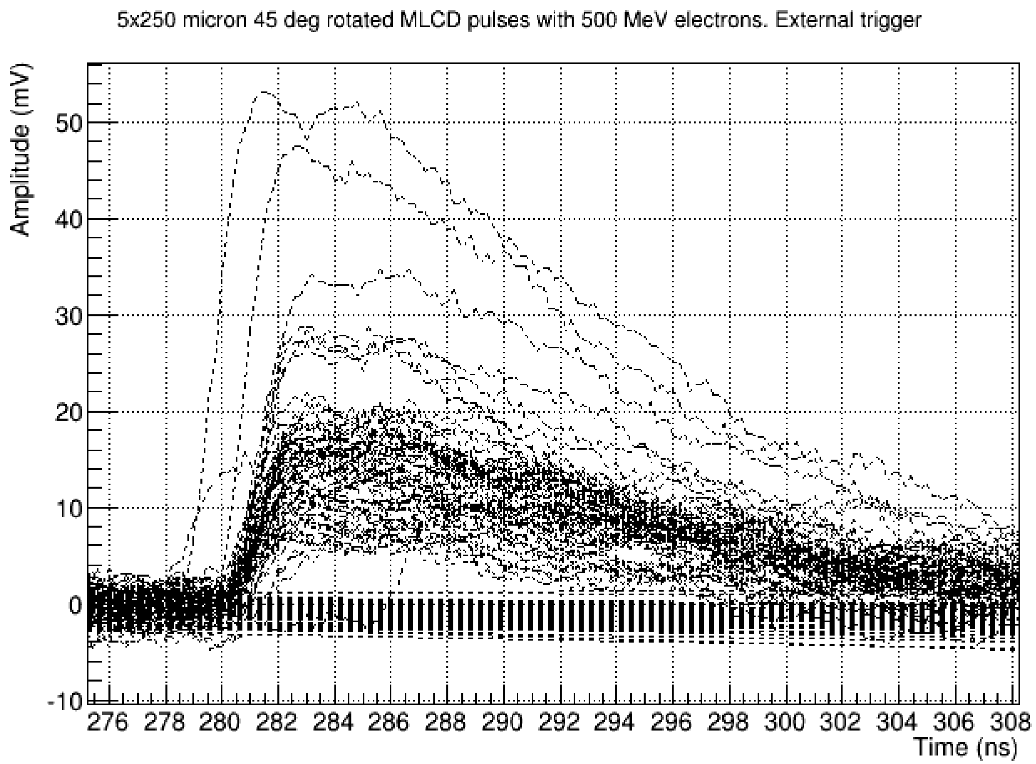


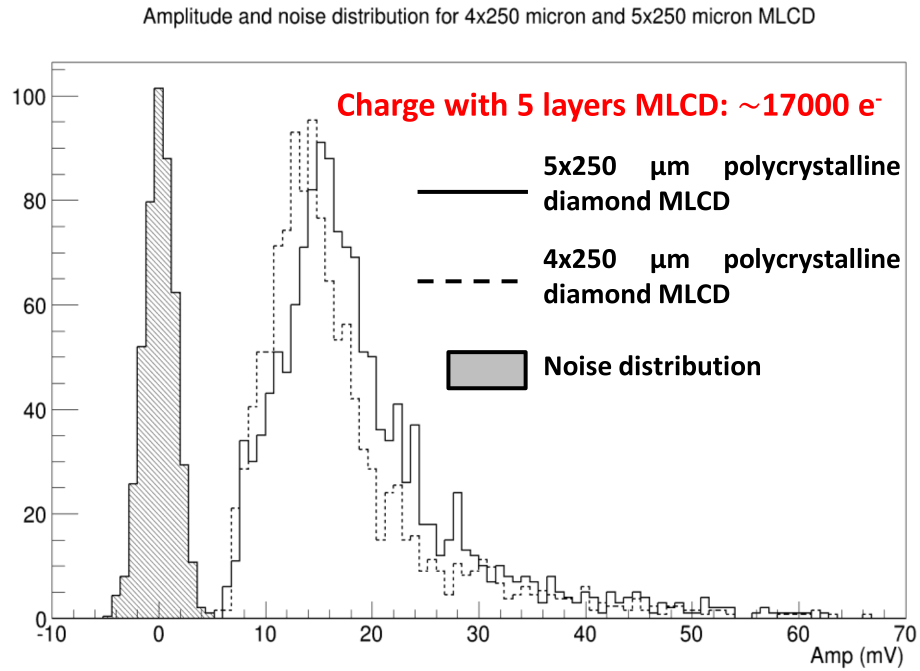
Photo of the test beam setup



5x250 µm polycrystalline diamond MLCD raw pulses



MLCD signal amplitude (charge) distribution

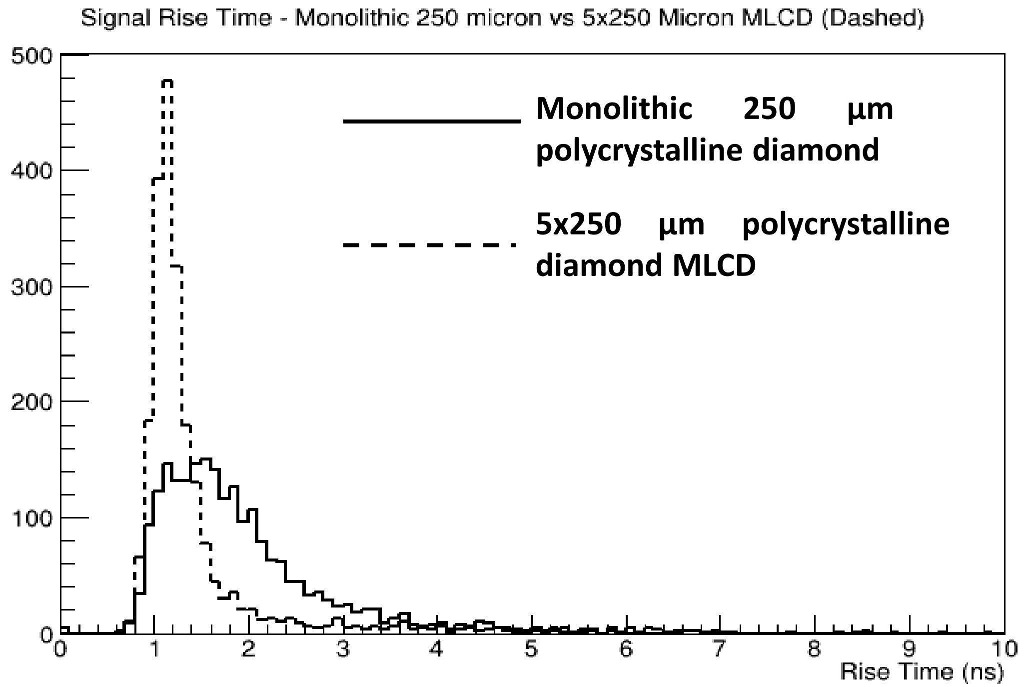


Adding a layer to the 4x250 µm MLCD allows to increase the average induced charge of about 25%.

The induced charge with 5 layers MLCD is about 17000 e^-, compatible with the expected value and with cosmic rays measurements.

The induced charge distribution, typically wider for polycrystalline diamonds, gets thinner thanks to the multilayer structure, thus granting better performance in terms of uniformity and efficiency.

Signal rise time of the 5x250 µm MLCD vs monolithic 250 µm diamond

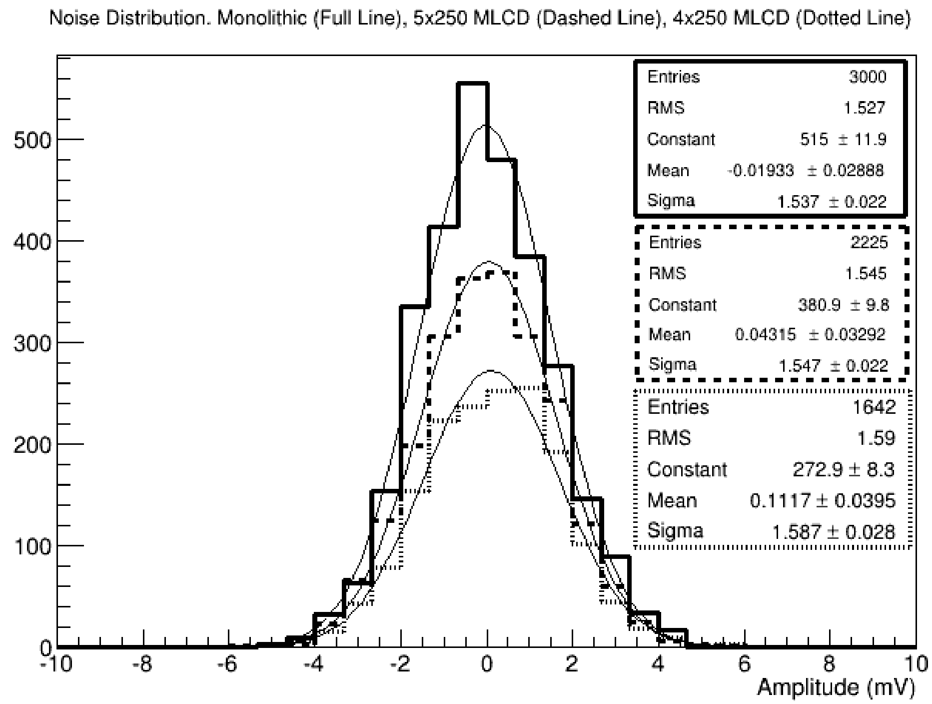


As expected the rise time depends only on the layer thickness. The multilayer structure does not deteriorate the rise time of the sensor.

The signal rise time with the MLCD is even better than for the monolithic structure. The structure reduces the non-uniformities also for detector timing.

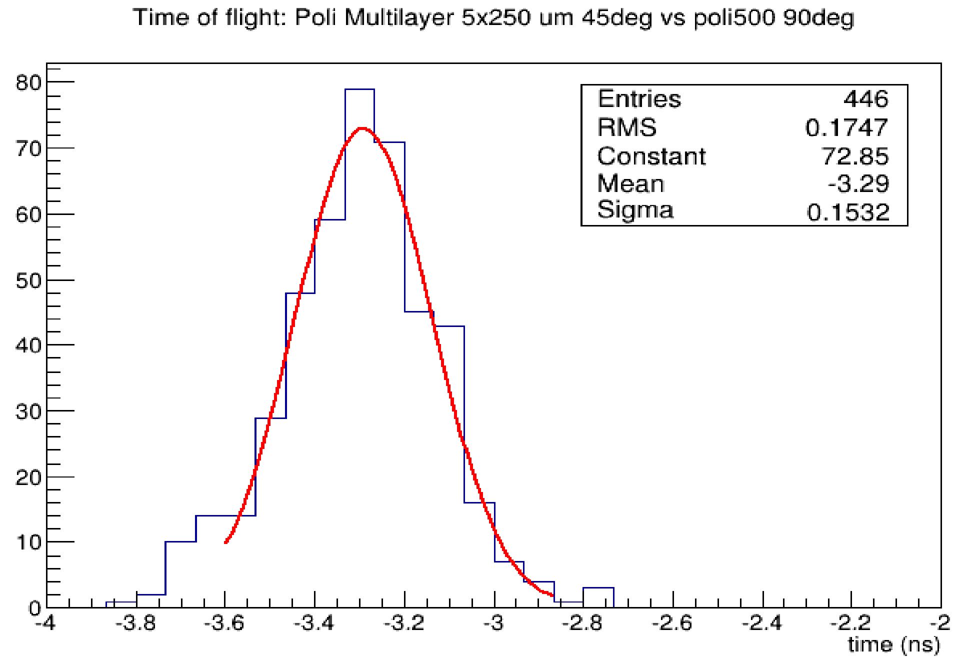
Front-end noise for different MLCD number of layers

Another critical point is to verify that the front end noise does not depend on the number of layers.



The 5 layers MLCD has exactly the same noise as the monolithic detector. The increase of detector capacitance did non affect the front end response.

Time of flight measurement with 5x250 µm MLCD



The ToF measurement is 150 ps.

- After the deconvolution from trigger jitter and readout systematics we estimated a time resolution of 100 ps for the polycrystalline diamond MLCD. As expected this value is better than the one obtained with cosmic rays for the 4x250 µm MLCD.

Possible future improvements of the MLCD

The time resolution obtained with polycrystalline diamond MLCD is about 100 ps.

What are the next steps?

- Still possible to reduce front end noise by using SiGe technology.

  → Very promising and already showing good possibilities.

  R. Cardarelli *et al,* 2013 *JINST* **8** P01003.

- Add layers to the MLCD and possibly reduce layer thickness.

  → So far the increase of detector capacitance did not affect at all the front end noise.

Conclusions

- Diamond sensors are a valid possibility for future Time Of Flight applications in high luminosity accelerators, thanks to their granularity, fast response and radiation hardness.
- Intrinsic time resolution of the sensor is very promising.
- A strategy to exploit this time resolution with MIPs using polycrystalline diamonds has been defined and allowed to obtain 100 ps time resolution.
- With the proposed detector structure there is a new improvement of performance at hand, so even better resolution is achievable.
- The MLCD structure, tested with diamonds, is an improvement for TOF measurements with any kind of crystal sensor, like silicon, germanium, etc…

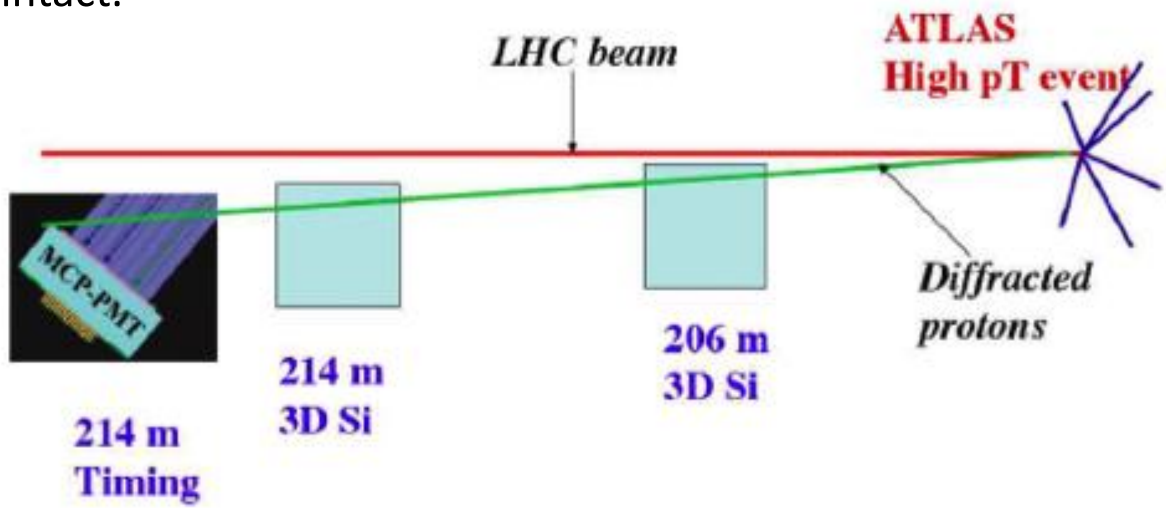
Thank you

Backup slides

A possible application: The AFP project

AFP (ATLAS Forward Proton) is one of the proposed upgrades for phase-I of the ATLAS experiment

The purpose of the project is to observe and measure processes where one or both protons remain intact.



Each side of the detector consists of:

- A momentum spectrometer made of 6+6 tracking stations (angular resolution ~1 μrad)
- **A high resolution Time of Flight, with 1 timing station (time resolution ~ 10 ps → ~ 3 mm on interaction vertex).**

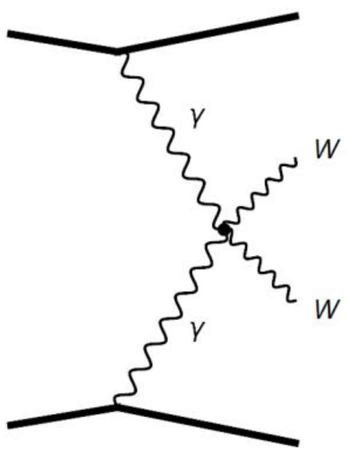
The detectors are contained in 2 beam interface stations at 206 m (tracking) and 214m (tracking and ToF).

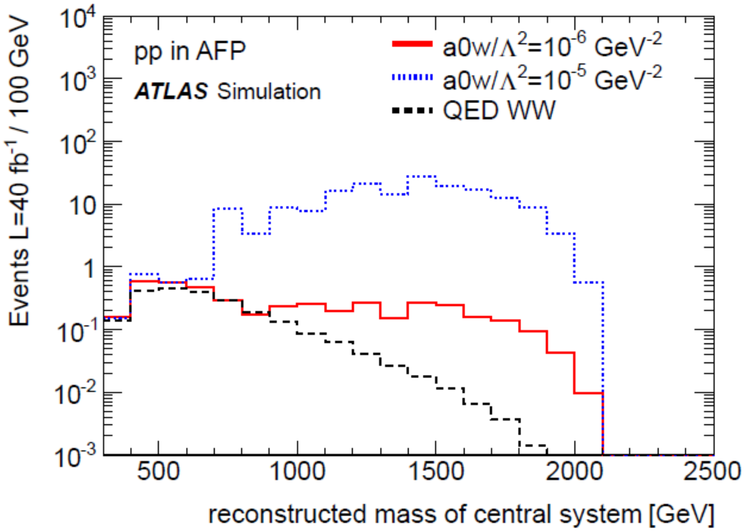
AFP: main physics objectives

Studies on diffractive QCD (DPE) and QED (γγ interaction)
https://cdsweb.cern.ch/record/1454194

- Search for anomalous couplings in the $\gamma\gamma \rightarrow WW$ process in high pile up environment. Two orders of magnitude better sensitivity using the AFP enhancement than with the main ATLAS detector alone.

Purely exclusive process





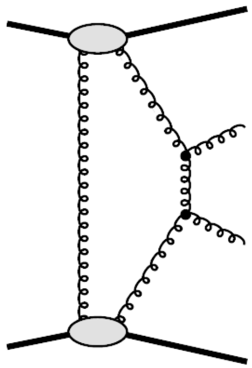
In double tagged events 5 GeV *per event* mass resolution.

AFP: main physics objectives

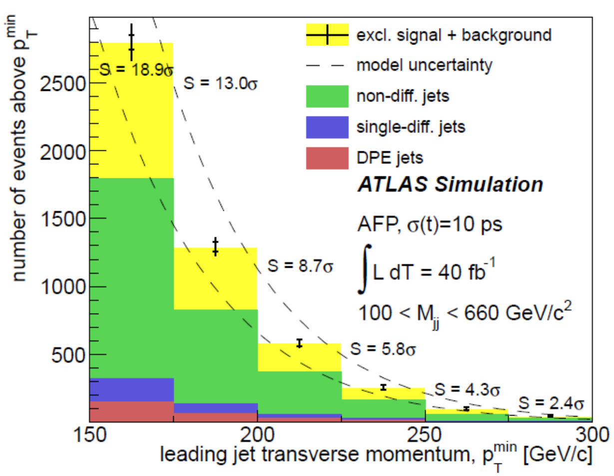
Studies on diffractive QCD (DPE) and QED (γγ interaction)
https://cdsweb.cern.ch/record/1454194

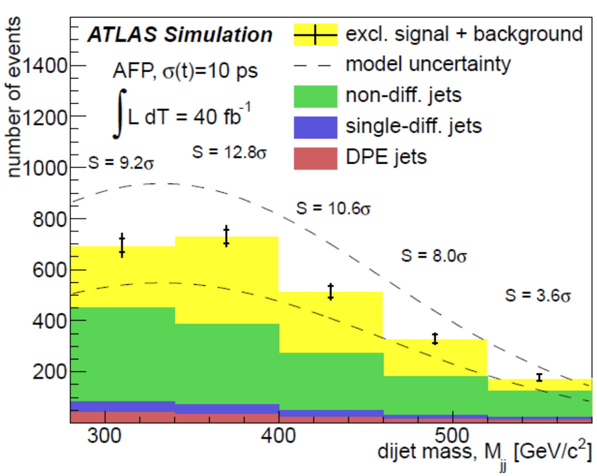
- Exclusive Jets Production (EJP) and Double Pomeron Exchange (DPE). Select events with two jets in the ATLAS detector and two protons tagged in AFP.

In the case of EJP:



Exclusive Production





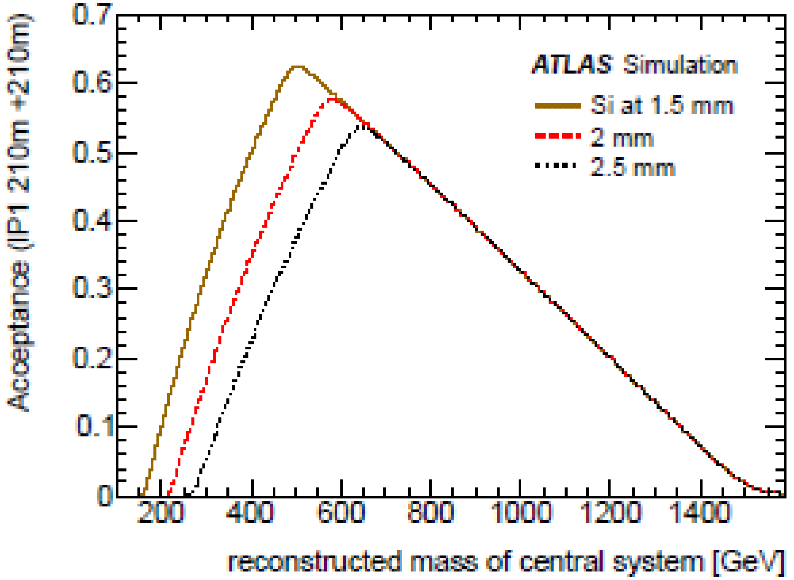
AFP: main physics objectives

Exotic searches: Magnet monopoles, SUSY particles

- Thanks to its excellent proton track reconstruction, AFP will be able to determine of central produced particles in the range

$$0.3\ TeV < M_{gg} = \sqrt{s x_1 x_2} < 1.2\ TeV$$

ξ is the proton momentum loss measured with AFP



Acceptance of AFP as a function of the reconstructed mass of the central system at different distances from the beam.

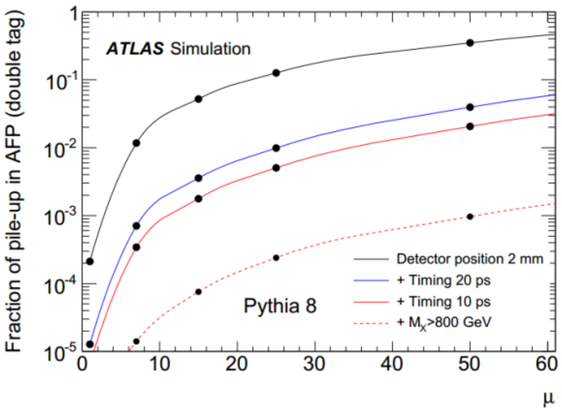
Importance of timing station in the experiment (1)

The leading background originates from the non-diffractive events overlapping with two intact protons from pile-up events. The AFP timing detectors contribute in reducing the background.

Requirements for the timing station:

- 10 ps or better resolution to cope with the high pile up (μ≥50). → 2.1 mm vertex position resolution, with ∼5 cm width of the luminous region gives a rejection factor of ∼20. **Essential for very challenging channels.**

- High efficiency



- Acceptance that fully covers the proton tracking detectors → 2 cm^2 area covered.

- High rate capability (O(5) MHz/pixel) → Constraint on maximum pixel size.

Importance of timing station in the experiment (2)

Requirements for the timing station:

- Pixelated detector: for multi-proton timing and to Identify tracks in the Si Detector. → average of one proton/crossing on each side with μ=50, pixel size $\sim mm^2$ to have full efficiency.

- Level 1 trigger capability

- Radiation tolerant → The maximum flux is around $4 \cdot 10^7$ protons $cm^{-2}s^{-1}$ at a luminosity of 10^{34} $cm^{-2}s^{-1}$. In a year this corresponds to $4 \cdot 10^{15}$ protons cm^{-2}.

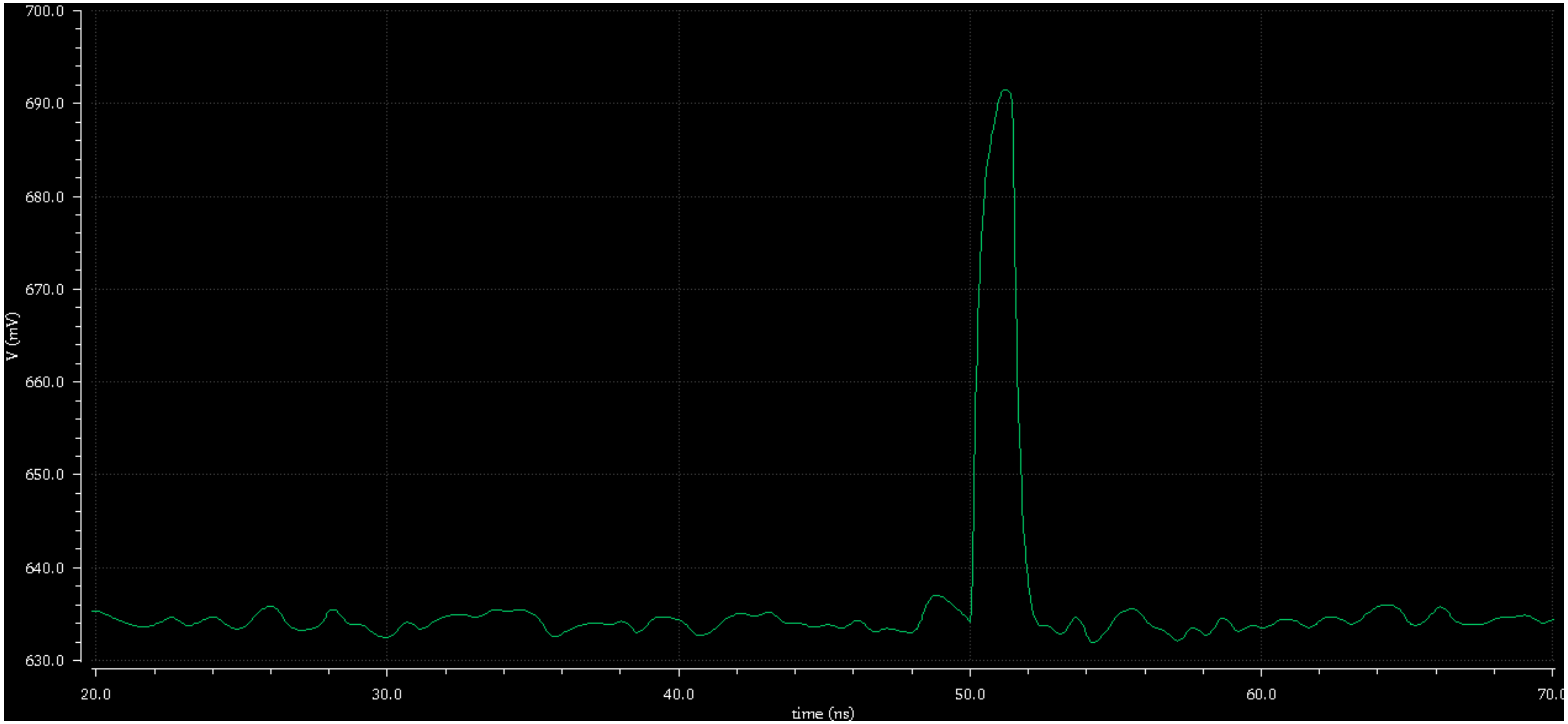
- Robust and reliable

- Additional need: cheap. → In the scenario of $1\ mm^2$ pixel size: 400 channels.

Improvement in progress on front end preamplifier

From Cadence simulation of the preamplifier in SiGe technology:

Simulated amplified pulse for a 2 fC input triangular signal



Noise ≅ 200 electrons RMS