Fabrication and first full characterisation of timing properties of 3D diamond detectors

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WORKSHOP ON PICO-SECOND TIMING DETECTORS FOR PHYSICS

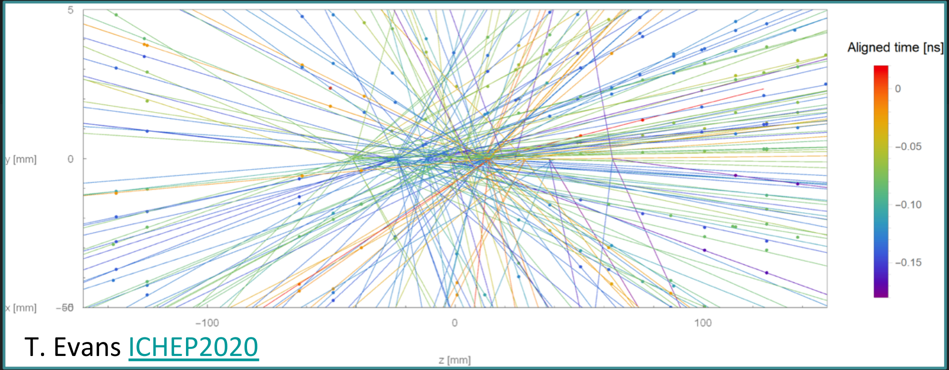
Zurich - September 9-11, 2021

Diamonds for timing

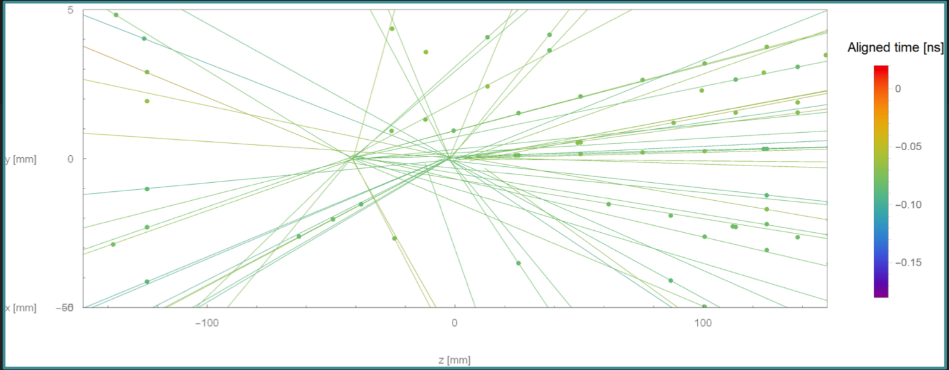
Detector challenges at future accelerators

- Very high luminosity experiments at HL-LHC (e.g. LHCb Upgrade 2) or at future colliders like FCC-hh will face severe detector challenges.
- Tracking detectors will be the most affected
  - ★ Very high radiation levels – O(10^{17}) 1MeV n_{eq}/cm^2 integrated over their lifetime
  - ★ Huge number of primary vertices and tracks
- Will require novel extremely radiation hard sensors/materials, e.g. diamond
- Timing capabilities with resolution ~10ps will be essential for efficient tracking – 4D tracking!

Reconstruction of Primary vertices at LHCb Upgrade 2



T. Evans ICHEP2020



Add timing

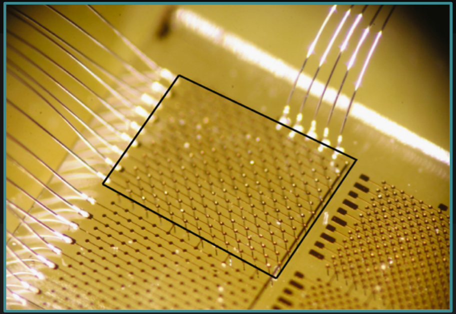
Diamond sensors

- Diamond is well known to be an excellent material for radiation detection
  - ★ very rad hard
  - ★ visible-light blind
  - ★ excellent heat transport ☞ no cooling needed
  - ★ very high mobility of charge carriers and large saturation velocities ☞ timing!

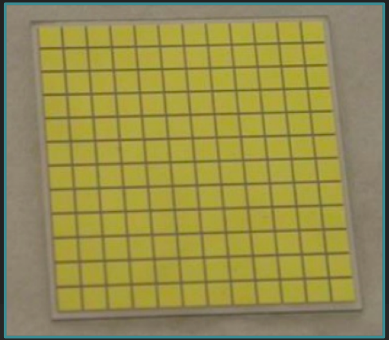
- Drawbacks
  - ★ Detector grade single crystals only available in small samples (typically ~4.5x4.5 mm^2)
  - ★ Fabrication process can be very slow
  - ★ Cost

- Long-lasting and well structured R&D on diamond sensors for HEP within RD42 collaboration
- R&D and applications also in other fields e.g.
  - ★ Dosimetry
  - ★ Neutron detection

Prototype of a 3D pixel sCVD tracking sensor (from F. Bachmair et at. NIMA 786 (2015) 97–104)



25x25 mm^2 pCVD segmented sensor for dosimetry (from A. Bartoli et al 2017 JINST 12 C03052)



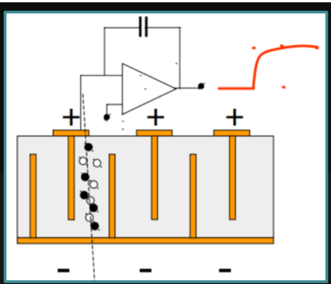
3D diamonds for timing

- 3D geometry enhances the above characteristics. With respect to classical planar geometry 3D sensors have:
  - ★ Very short charge collection time (~100 ps) -> timing!
  - ★ Smaller operating voltage (~20-100V vs ~500V)
  - ★ Short charge carrier path: reduces dramatically the effect of defects ☞ enhanced radiation hardness☞ try to keep the drift path shorter.
  - ★ e.g. 55 um pitch

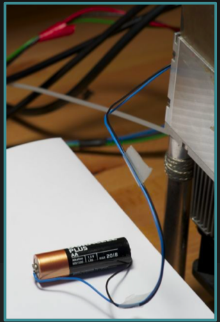
- 3D tracking diamond detectors studied at various sites (Florence, Manchester, Oxford, etc.)

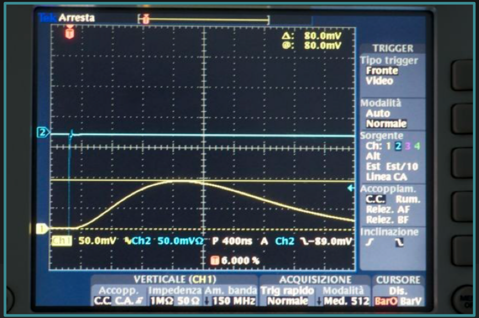
- Today: results on first systematic R&D of 3D geometry for timing in diamonds!

- Aiming at developing high time resolution 3D diamond sensors suitable for 4D tracking in very high radiation environment
  - ★ e.g. LHCb Upgrade 2
  - ★ FCC-hh

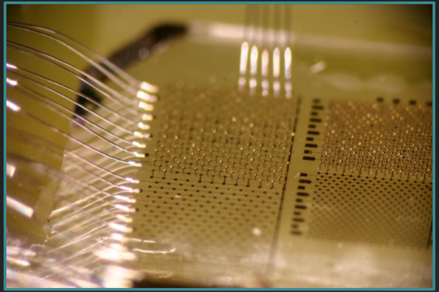


3D sensor principle





3D diamond sensor operated in Florence with 1.5V battery was demonstrated to have full CCE!



3D diamond tracking detector prototype developed in Manchester

The TimeSpot initiative

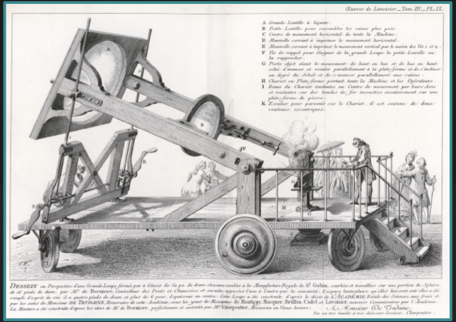
Timespot is an INFN-funded R&D aiming at the developing a demo timing tracker featuring:

- Rad-hard, trench-shaped, 3D silicon detectors optimized for timing
- Rad-hard, 3D diamond detectors optimized for timing
- Rad-hard 28-nm readout electronics with precise timing resolution
- Fast FPGA-based backend electronics to deal with unprecedented data throughput
- Highly parallel reconstruction algorithm operating on FPGAs to reduce data throughput towards CPUs

See the talk by A. Lai later today for more details and results on silicon detectors

Results presented here were obtained within the TimeSpot workpackage on diamond sensors

Fabrication of 3D diamond sensors in Florence



Fabrication of 3D diamond detectors with graphitic electrodes

- 3D diamond detectors are obtained by laser micro-fabrication of graphite columns in the diamond bulk
  - ★ Based on original ideas of Kononenko et al. [Diam. Rel. Mat., 14(8):1368 – 1376,2005].
  - ★ First 3D diamond detectors obtained by A. Oh, B. Caylar, M. Pomorski, and T. Wengler, P. Bergonzo [Diam. Rel. Mat., 38(0):9-13, 2013, Appl. Phys. Lett.,103(4), 2013].
  - ★ Fundamental input from B. Sun, P. S. Salter, and M. J. Booth introducing laser spherical aberration corrections dramatically improving the quality of beam focus [Appl. Phys. Lett. 105(23):231105, 2014].
  - ★ First characterization with MIPs by S. Lagomarsino, S. Sciortino et. al [Appl. Phys. Lett. 103, 233507 (2013)]

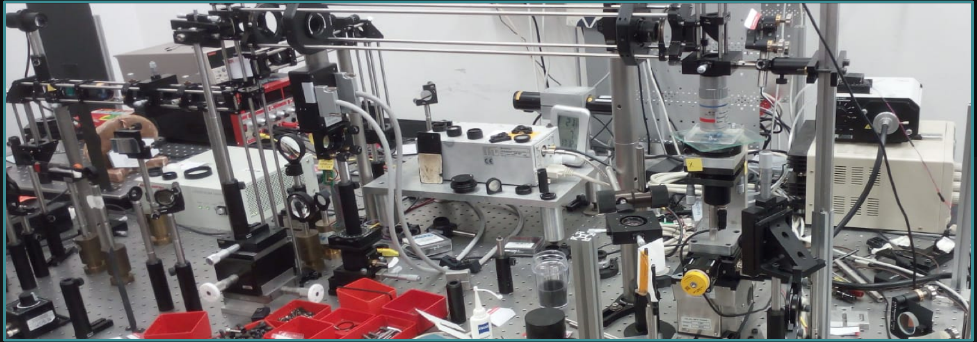

Angekohlte Diamanten; Foto: A. Schumacher, NHM Wien

Carbonized diamonds, Natural History Museum, Wien

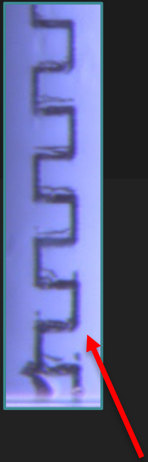
Attempt to graphitize diamonds by Kaiser Franz I, husband of Maria Theresa of Austria, who put diamonds in the focus of a powerful solar mirror around 1760 aiming at "soldering" diamond crystals

Sensor fabrication

- A 800 nm Ti:Sa laser with 50 fs pulses is focussed inside the diamond bulk.
- Diamond is transparent at 800 nm, but a sufficiently high light density allows for multiple-photon interactions, allowing energy absorption through large-bandgap transitions.
- Absorbed energy transforms diamond into a mixed carbon phase including graphite.
- Sufficiently short pulses prevent annealing of graphite into amorphous carbon (with higher resistivity)



Graphite columns in a 500um diamond crystal



Spherical aberrations due to the high diamond refractive index (2.42) are corrected with a Spatial Light Modulator (SLM). Here the laser beam modulated with the SLM to obtain the INFN logo

Thanks to the SLM the laser beam is focused with high precision allowing to ”draw” also complex patterns

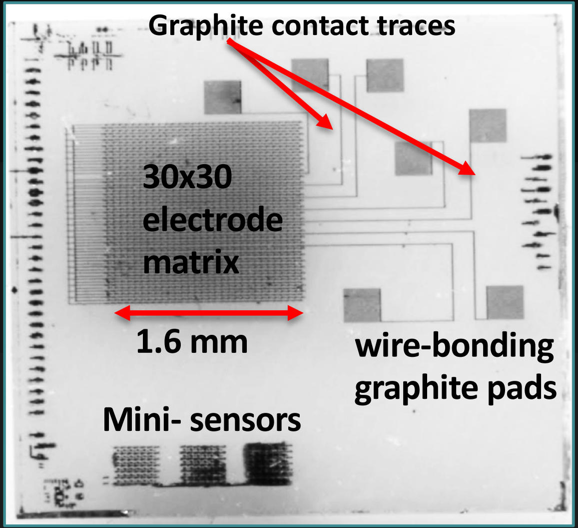
3D diamond sensors

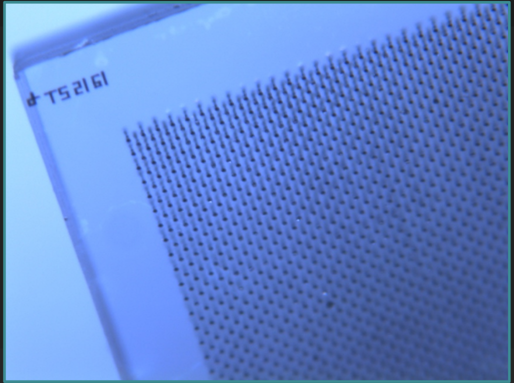
- For our prototypes we use 4.5x4.5 mm^2 500um thick detector grade single crystals by E6

- 3D sensors are obtained with graphitization of patterns of electrodes.
- Due to the small capacitance of the elementary cells it is possible to short-circuit many electrodes to get large sensitive areas, with good radiation hardness and few readout channels.
  - ★ Surface connections and bonding pads can be realised as well by graphitization (all carbon sensors!)

- Bump-bonding of single electrodes is also an option
  - ★ RD42 was the first to successfully bump-bond 3D diamond sensors to readout chips. [NIMA 436 (1999) 326-335]

- Our first bump-bonding (on TimeSpot 28nm ASIC) attempt planned with IZM in 2021.

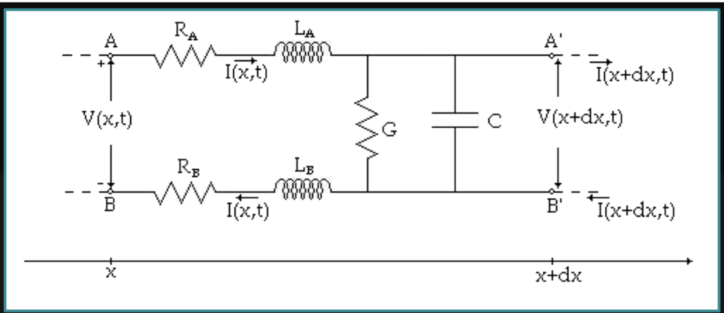




A sensor recently fabricated in Florence ready for bump-bonding at IZM 32x32 columns, 55x55 um pitch

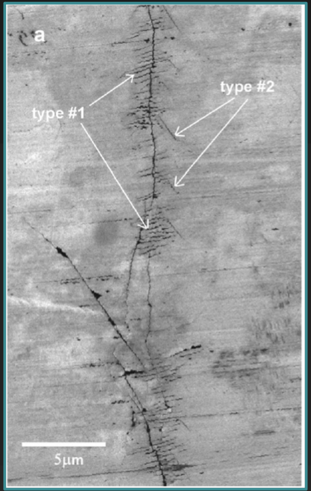
Timing optimization

- While the drift of charge carriers in diamond is significantly faster than in Silicon, the high resistivity of the electrodes increases the time-constant of the system, giving slower and smaller signals.
- To get faster sensors one needs more conductive electrodes.
- 2 ways:
  1. Optimise graphitization process
  2. Fabricate larger diameter electrodes



Resistive graphite columns behave like lossy transmission lines slowing down and attenuating the signals

1. Graphitization involves a multitude of graphitic domains, with resistance increased by the connections. Better laser focus enhance the “density” of domains and improves conductivity



K.K. Ashikkalieva et al., Carbon 102 (2016) 383e389

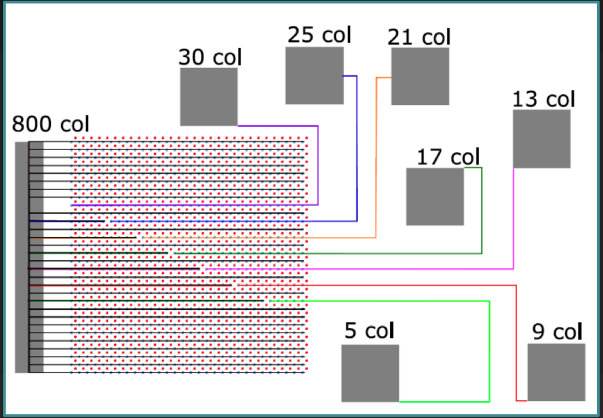
2. Graphite density is smaller than diamond density: graphitizing inflates and may crack diamond. This limits the column diameter especially for fine pitch

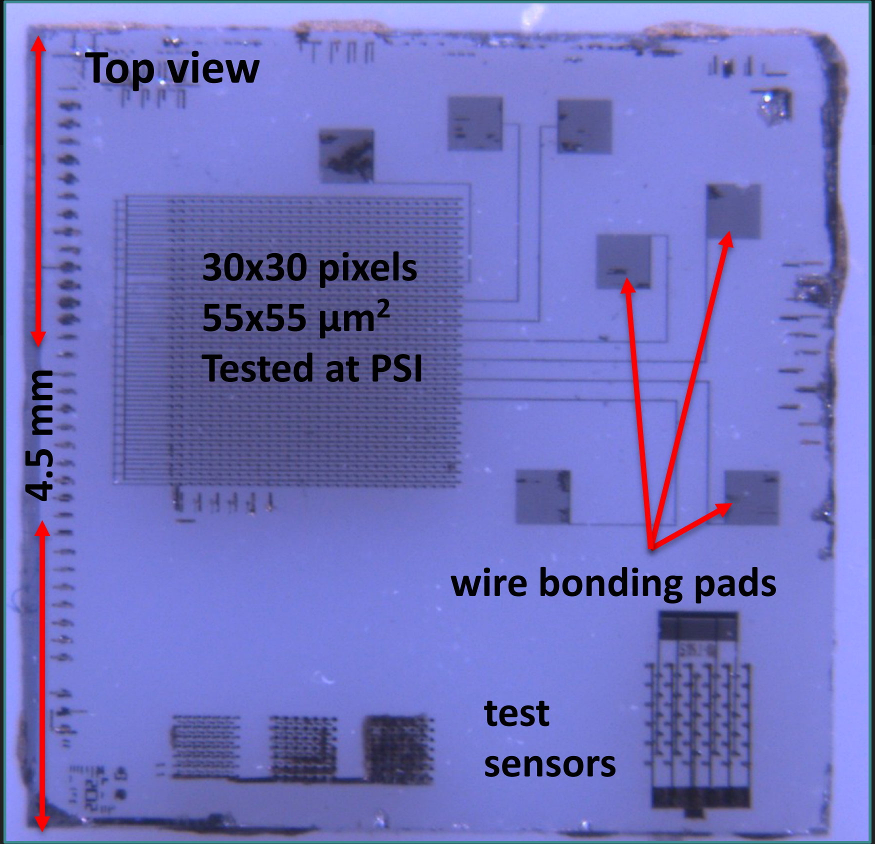
Results from first prototype 3D sensor

L. Anderlini et al., Front. in Phys.8(2020) 589844

Results from first prototype

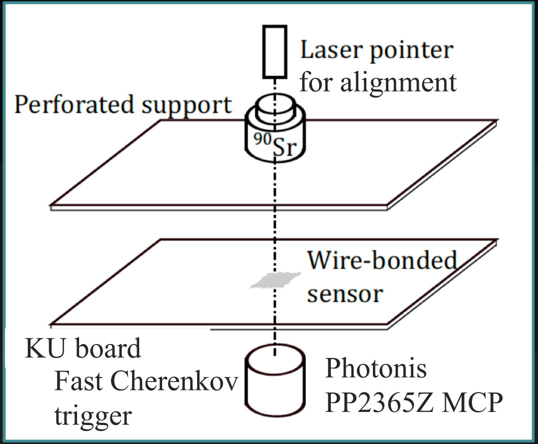
- First prototype sensor produced in 2019
- Fabricated with old optical setup
  - ★ No SLM for spherical aberration correction
  - ★ Column resistance ~100kΩ – 1MΩ
- Pitch 55μm, compliant with TimePix chip family (same as LHCb VeloPix)
- Electrodes grouped in various combinations
  - ★ Single strips of variable length
  - ★ More strips in parallel
  - ★ 7 «RO channels»

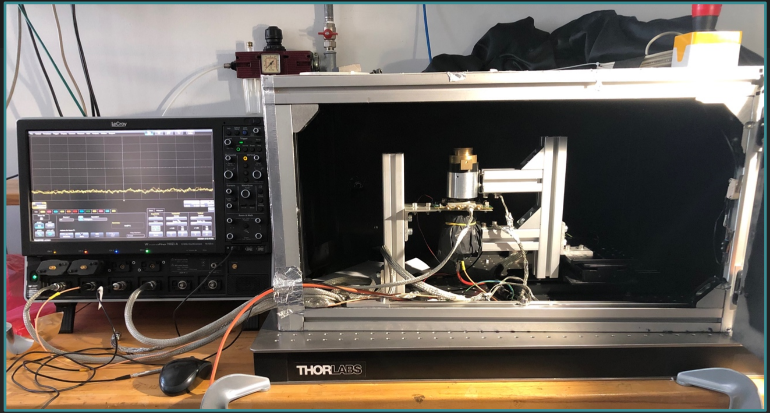


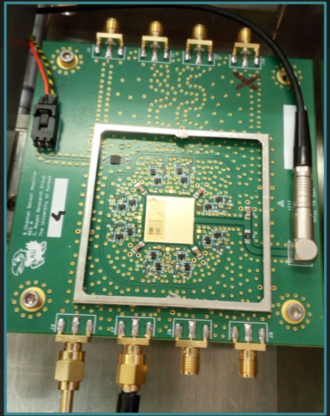


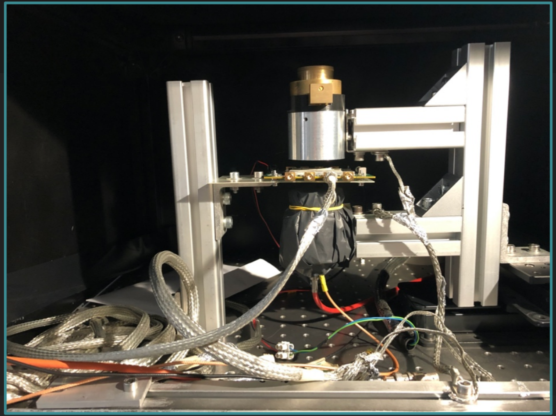
Timing characterization: test with ^{90}Sr β source

- The prototype first characterised in lab with a ^{90}Sr β source
  - ★ Electrons with 2.28 MeV endpoint
- Select MIPs by triggering on Cherenkov light generated in the entrance window of an MCP
  - ★ Provides also an extremely precise (σ_t ~40 ps) time marker!
- DAQ
  - ★ readout board by Kansas University (~600 ps risetime discrete component two stage amplifier, based of high BW SiGE transistors)
  - ★ board connected to a high BW (6GHz) Teledyne Lecroy digital oscilloscope
- Results obtained from waveform analysis
- Vbias = 80V



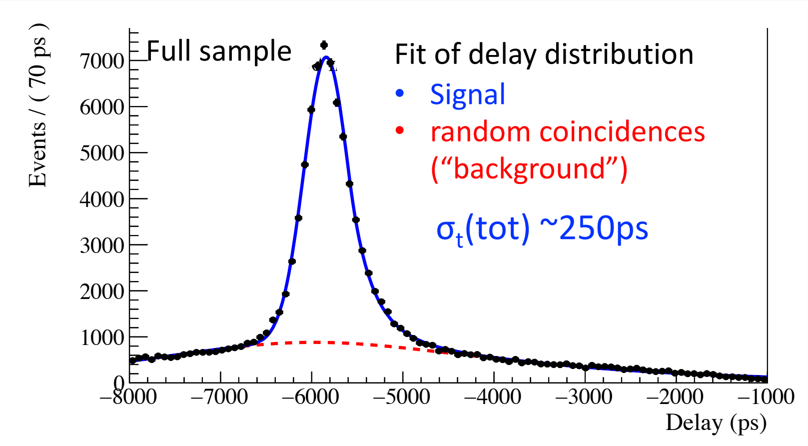


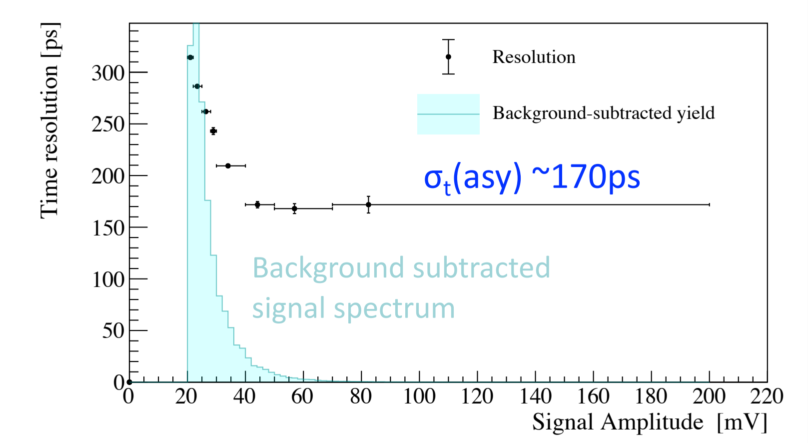




Timing characterization: test with ^{90}Sr β source

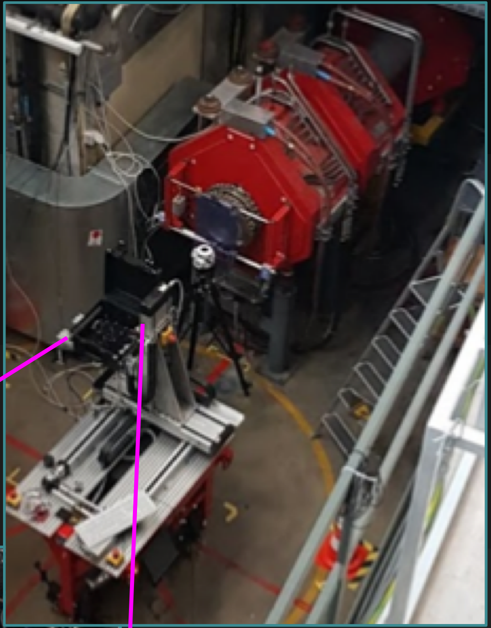
- Due to the very high resistance of the columns the signals are significantly attenuated
  - ★ no Landau peak visible
  - ★ Modest S/N ratio
  - ★ Slow signals
- Difficult to discriminate signal from noise
  - ★ Substantial background component in the delay distribution
  - ★ Use statistical separation (sPlot method) fitting a “signal peak” and a background continuum (random coincidences)
- Total time resolution σ_t(tot) ~250ps
- Asymptotic time resolution σ_t(asy) ~170ps

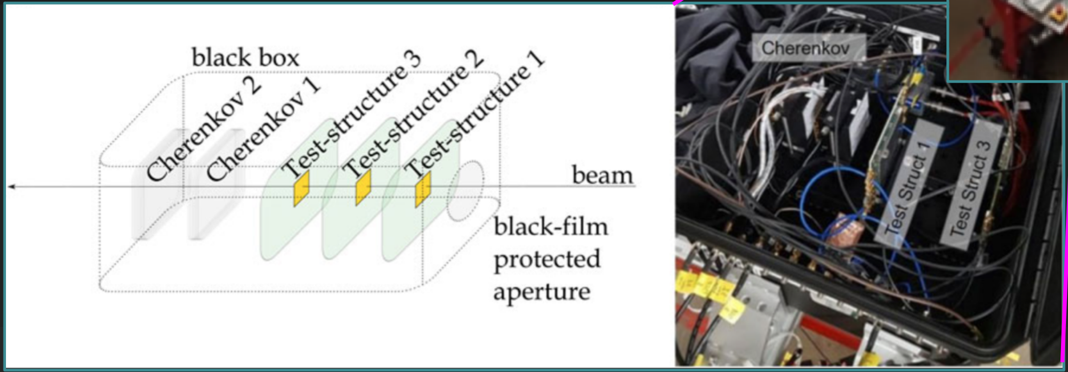




Timing characterization: 2019 test beam @PSI

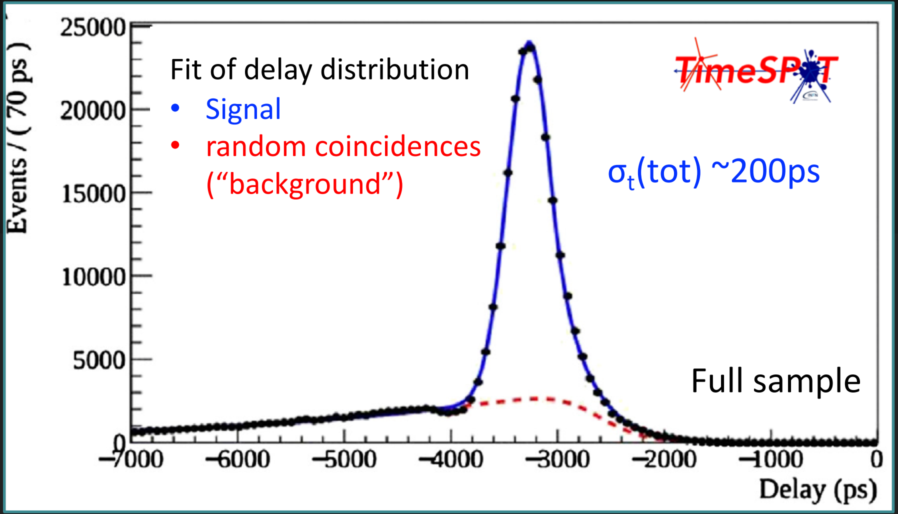
- The prototype was tested at PSI in 2019
  - ★ 270 MeV/c πM1 pion beam
- Trigger made with two Cherenkov counters used to reject non-MIP contributions (mainly protons) below Cherenkov threshold
  - ★ Obtained with two quartz radiators read out by MCPs
- Data read out with the Kansas University board connected to a high BW (6GHz) Teledyne Lecroy digital oscilloscope
- Results obtained from waveform analysis

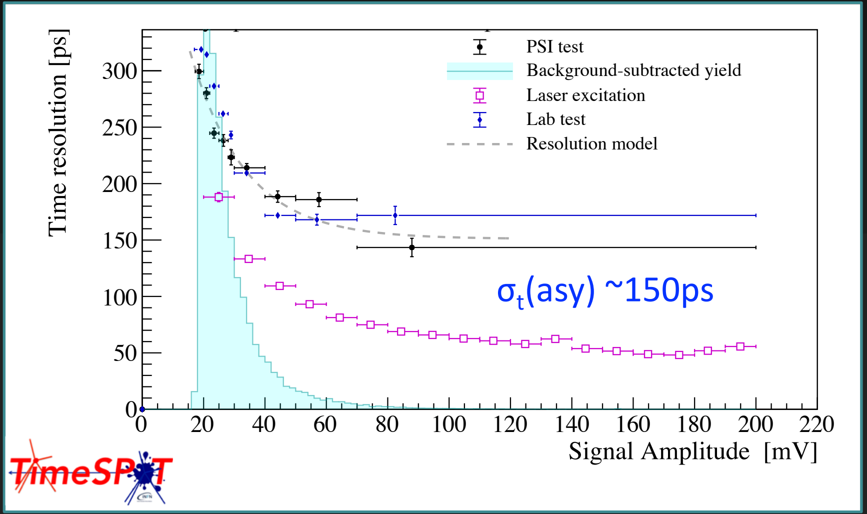




Timing characterization: 2019 test beam @PSI

- Results with the pion beam are very similar to those obtained with β source
- The time resolutions nicely match to each other
- (a test with a laser beam has also been made with unreliable results. Will not discuss these results)





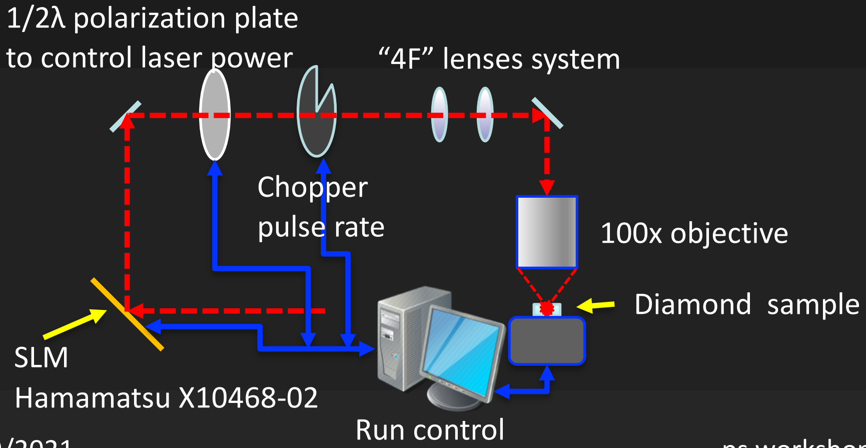
Front. in Phys.8(2020) 589844

Preliminary results on new sensors

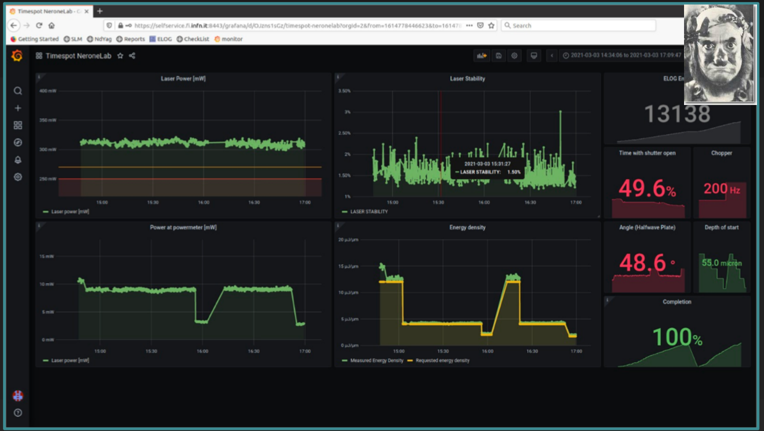
VectorStock.com/252476

Fabrication of 55x55um pitch sensors for bump-bonding

- A major milestone of TimeSpot is to test devices with a novel 28nm ASIC (see talk by A. Lai)
- To this goal we fabricated 10 new 32x32 55x55um pitch pixel sensors
- Before to go to the final production we validate the fabrication procedure with intermediate test sensors
- Beforehand, we significantly upgraded our optical system and optimised the fabrication procedure to obtain electrodes with lower resistance
  - ★ Introduction of an LCoS-SLM (Hamamatsu X10468-02) for aberration corrections
  - ★ new final focusing objective
  - ★ Systematic optimization studies to lower the column resistance
  - ★ Fully automatized fabrication process

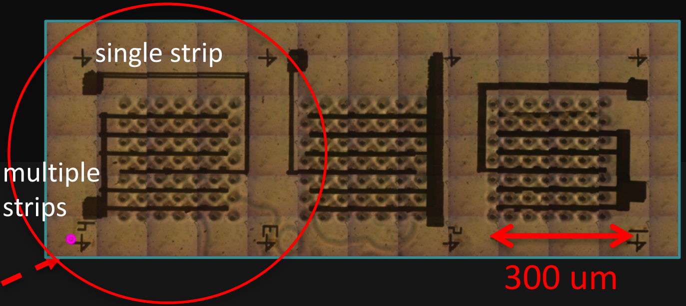


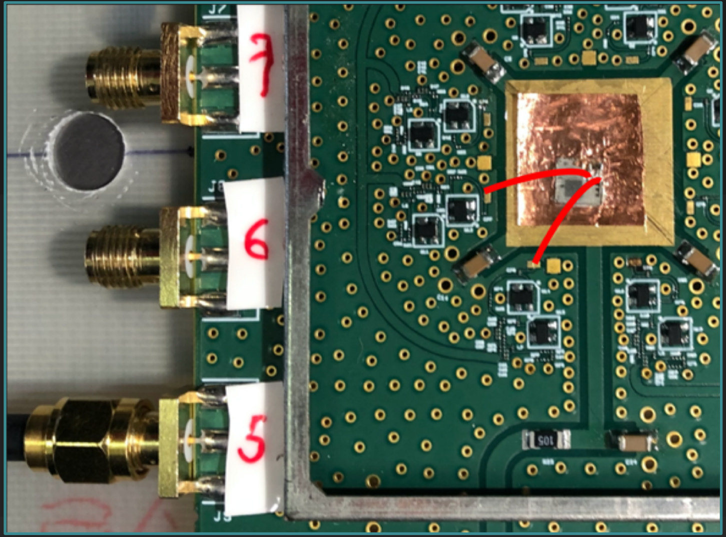
NeroneLab run monitoring



Results from test sensors 55um pitch

- 3 test sensors with 2 different electrode groupings
  - ★ multiple strip with 4 connected strips of 6 columns
  - ★ single strip of 6 columns
- Sensors fabricated with a procedure optimised for low resistance
  - ★ Column resistance estimated from test passing-through columns: ~30kΩ
  - ★ ~ an order of magnitude smaller than columns tested at PSI!
- Results from sensor 3 (in the circle)
- Single strip is a good proxy of a single pixel
- Multiple strips simulate clustering of more pixels
  - ★ Can study charge sharing effects
- Lab tests with the DAQ system discussed before
- Vbias = 70V



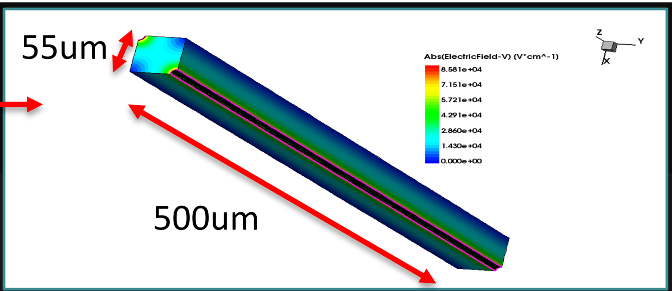


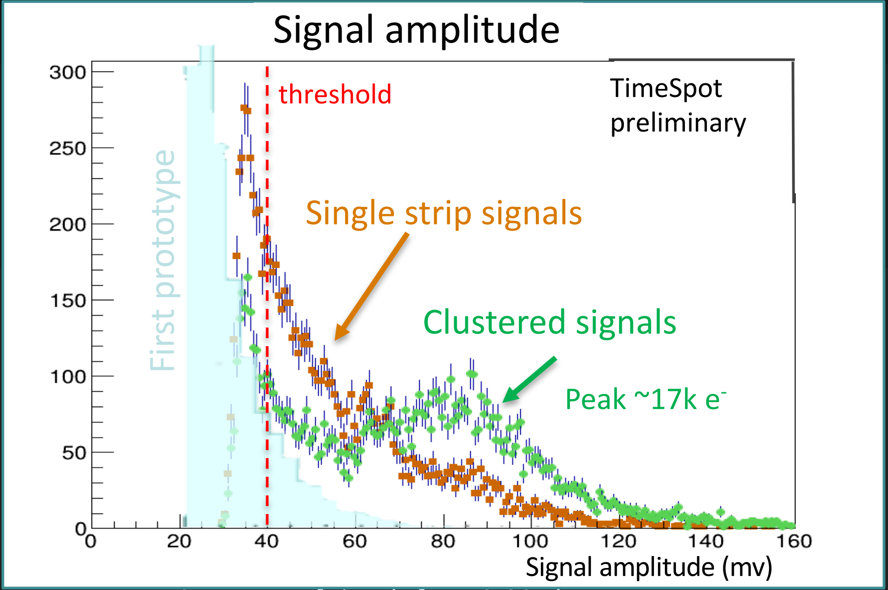
Diamond sample mounted on KU readout board

Preliminary test results with ^{90}Sr: signal spectrum

- Due to the large multiple scattering affecting electrons, significant amount of charge is released outside a single cell/pixel (see peculiar 1:10 cell aspect ratio !)
- (As we will see later, β electrons are not the optimal test probes…)
- Can study the charge sharing effect using coincidence signals between single and multiple column strips
- Summing the amplitudes of the two readout channels for coincidence signals is a proxy of a clustering procedure
- Single strip spectrum does not show any clear "peak"
- "clustered" signals show an evident Landau peak that can be well discriminated from the noise

- First clear result of substantially lower resistance of electrodes: much larger signals!
- Better S/N gives immediately significantly improved time resolution





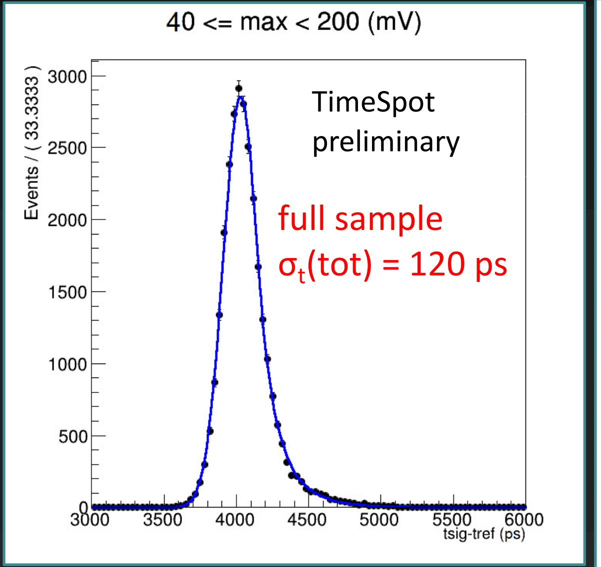
Spectrum of signals from Sr90 electrons

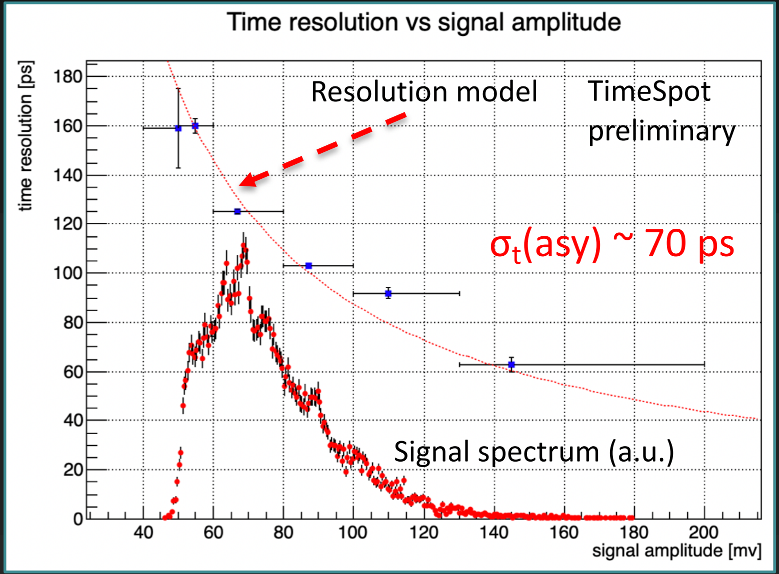
Preliminary test results with ^{90}Sr: time resolution

- Signal and noise can now be easily discriminated
  - ★ No need to perform statistical analysis
  - ★ Delay distribution is background free and shows only a moderate skewness
  - ★ Fit with a crystal-ball function (gaussian core + exponential tails)
- Time resolution (both total and asymptotic) a factor 2 better than first prototype
- Resolution follows nicely the simple model $\sigma_t \approx \sigma_{noise}$ x Risetime/Amplitude

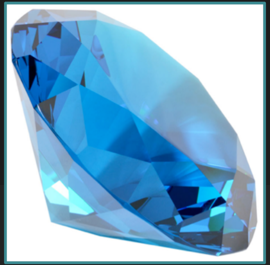
Results from sensor 3

- V_{bias} = 70V
- Trigger threshold = 40mV





Simulation of 3D diamond sensors

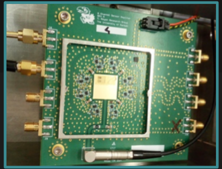


Simulation of 3D diamond sensors

- Started a simulation campaign to study the main features of 3D diamond sensors from timing point of view
  - ★ Detailed simulations with TCAD available by several authors (e.g. J. Inst. Met. (2016) 11:C12043, NIMA 845(2017)72–75)
- In this study we used the 3D detector Root-based simulator KDetSim (G. Kramberger IJSF Ljubljana)
- Simulation flow:

GEANT4 A SIMULATION TOOLKIT → KDetSim *

*



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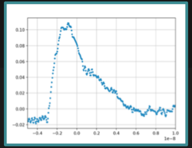


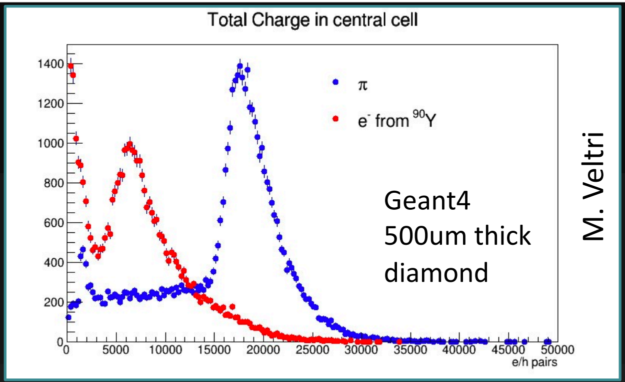
(following the recipe of W. Riegler and P. Windischhofer NIMA 980 (2020) 164471)

Simulated waveforms

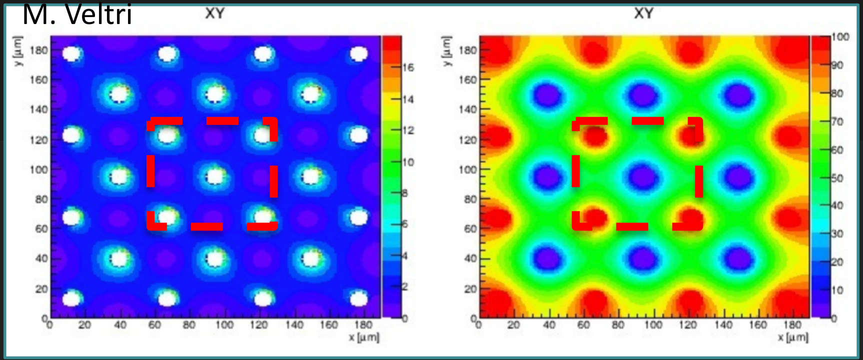
- The resistive electrodes are modelled as transmission lines with negligible L and G
  - ★ An alternative model with a “ladder”-like discrete set of series resistors and parallel capacitors gives largely compatible results
- As an initial step no noise simulation has been attempted: use real data noise waveforms superimposed to simulated signals
- The simulated waveforms are finally processed with the same algorithms used for data

GEANT4 and KDetSim simulation

- Realistic simulation of
  - ★ ^{90}Sr β source in air and lab test setup described before, including MCP trigger effects
  - ★ PSI πM1 pion beam including beam aperture
- Particle illuminate a 55um pitch 3x3 cell matrix
  - ★ **Only charge deposits inside the innermost cell are drifted with KDetSim**

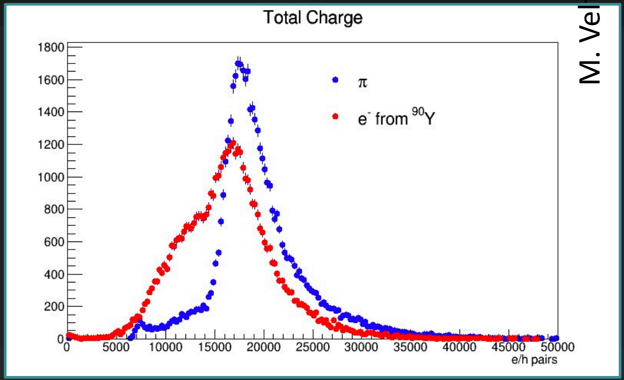


As expected in the case of electrons a lot of charge leaks outside the central cell. As a result no “peak” is visible in electron spectra
Pions show a typical tail on the left of the Landau peak



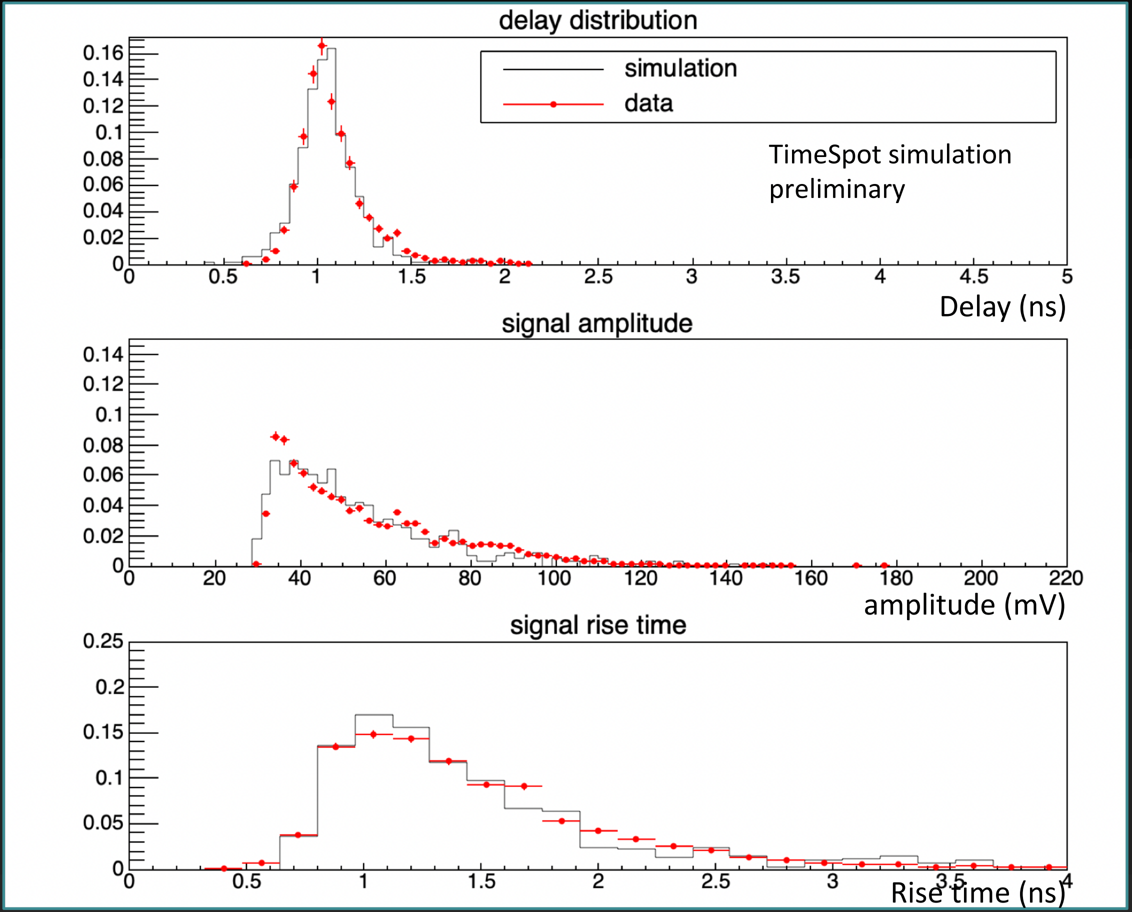
Electric field and potential calculated by KDetSim for the 3x3 55um pitch matrix

When clustering all the cells the full energy peaks are recovered. Notice that the electron spectrum (β spectrum!) has a more complex structure



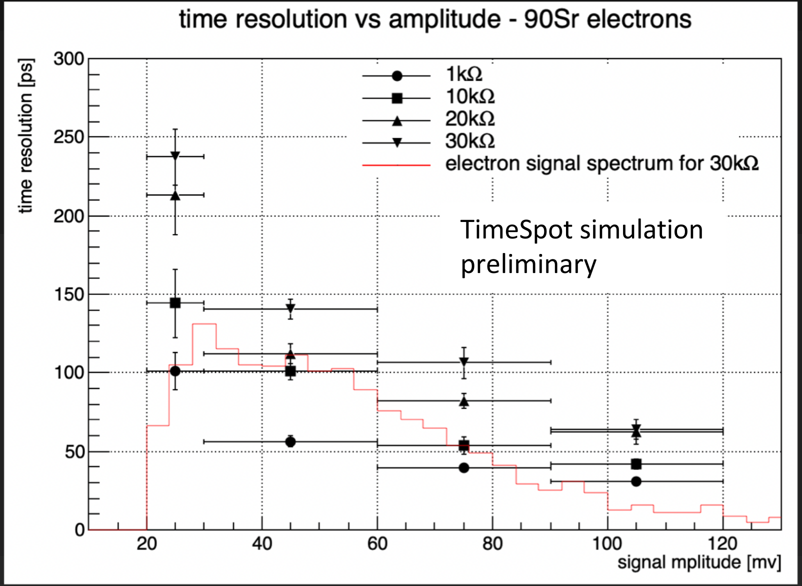
First preliminary simulation results: validation

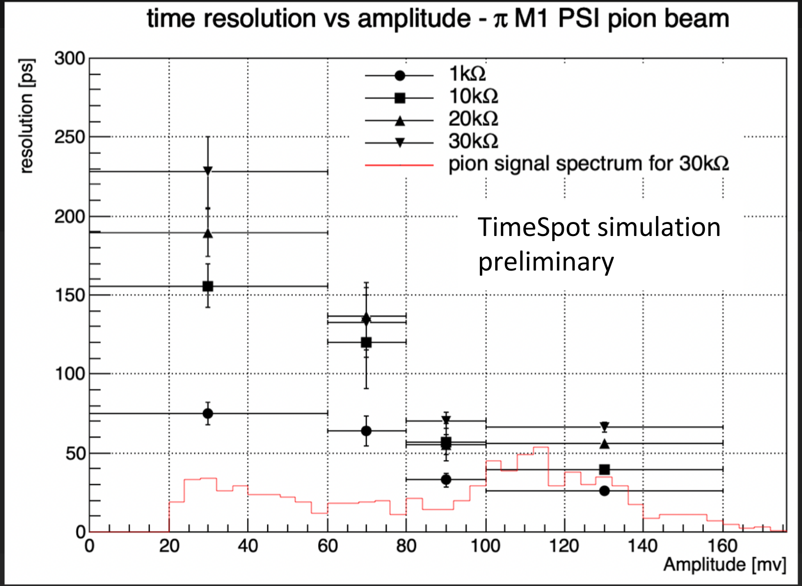
- The simulation flow has been validated with data obtained from the 55x55um test sensor – single strip channel
- In simulation, assumed column resistance of 30kΩ
- Compare delay, amplitude and rise time distributions
  - ★ All distributions normalised to 1
- Very nice agreement between data and simulation!



First preliminary simulation results: time resolution

- Once validated, the simulation can be used to study the time resolution as a function e.g. of the column resistance (main driving parameter!)
- As expected the lower the resistance the better the resolution
    - ★ Notice also that there is a global larger improvement (not only asymptotic) as the signal amplitude increases with lower resistance
- Estimated resistance of the newly fabricated 32x32 55um pitch pixel sensors is ~15-20kΩ





Conclusions and outlook

Conclusion and outlook

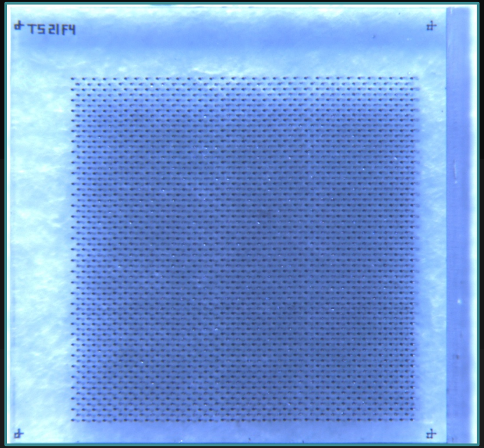
Conclusion

- An intense R&D program on 3D diamond detectors for timing has been going on in Florence in the framework of the TimeSpot initiative
- First beam test at PSI as a positive proof of concept
- Preliminary lab results with 55x55 um pitch recent 3D sensors show very encouraging results hinting at possible time resolutions in the ball-park of 60-70 ps
- These tests were a first validation of the fabrication procedure used to produce 10 32x32 55um pitch pixel sensors to be bump-bonded on 28-nm TimeSpot ASIC at IZM

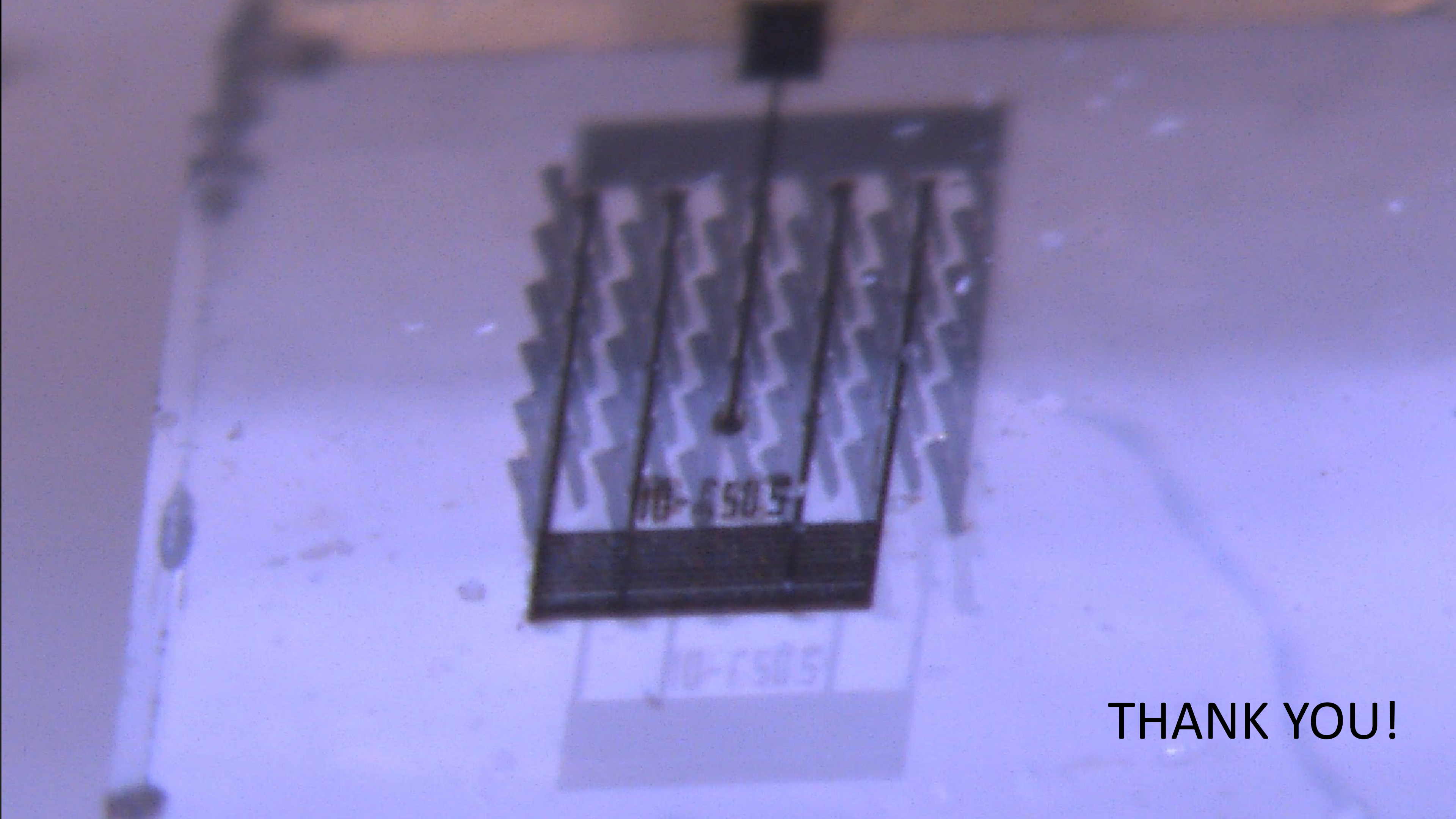
Outlook

- A beam test with the sensor+ASIC hybrids is planned for 2022
  - ★ Crucial to validate the encouraging lab results and simulation expectations!
- R&D on fabrication procedure and on column resistivity optimisation is still ongoing
- More detailed simulations with TCAD and the TCode suit developed within TimeSpot will be carried out in the next months

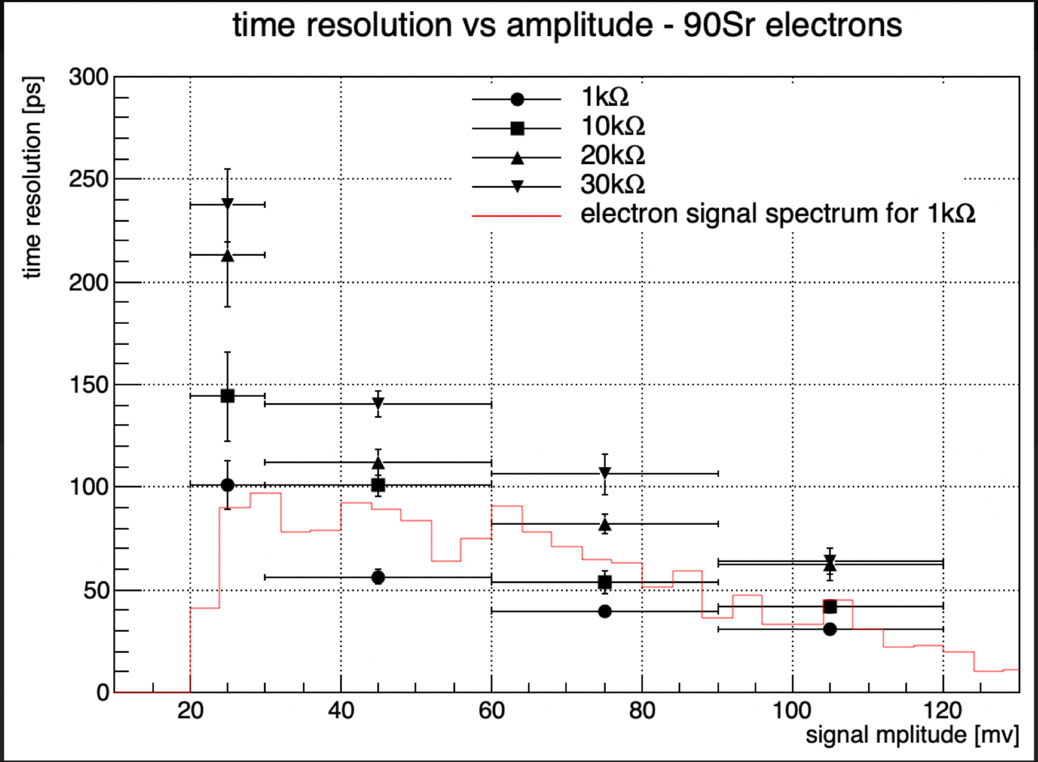
- The road for diamond timing detectors for 4D tracking is open !



32x32 55um pitch sensor on a 2.2x2.2 mm^2 E6 crystal to be bump-bonded at IZM on TimeSpot ASIC


THANK YOU!

Backup slides


time resolution vs amplitude - 90Sr electrons
time resolution [ps]
300
250
200
150
100
50
0
20
40
60
80
100
120
signal mplitude [mv]
1kΩ
10kΩ
20kΩ
30kΩ
electron signal spectrum for 1kΩ