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Preliminary Test Results of LGADs from Teledyne e2v for the LHC's High-Luminosity Upgrade

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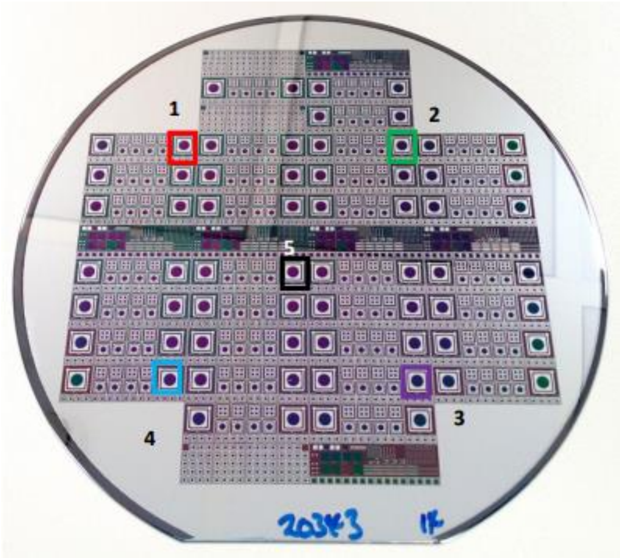
- Collaboration between the University of Birmingham, University of Oxford and the Open University
- We are working closely with the UK foundry at Teledyne e2v whom already have a large production volume set up for CCDs

- We are currently testing our first batch of 22 wafers, which come in triplets of the same implant energy and dose
- Each wafer contains sets of LGADs and PiNs, with and without the gain layer implant respectively
- There are 4 different size configurations: 1 mm, 2 mm, 4 mm, and 2x2 arrays of 1 mm
- Each size also has different “flavours” where properties such as the distance from the pad to the guard ring is varied



Wafer code	Normalised Dose (D)	Normalised Energy (E)
A	1.07	1.11
B	1.07	1.05
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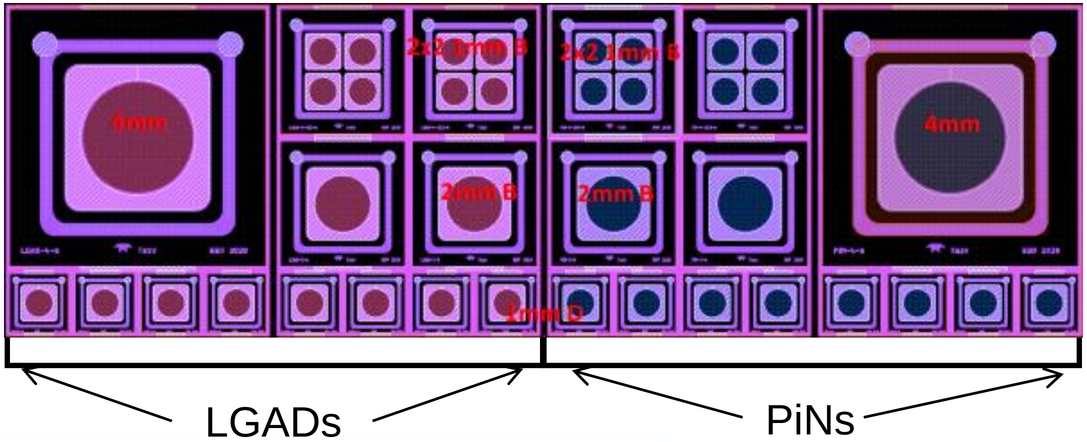

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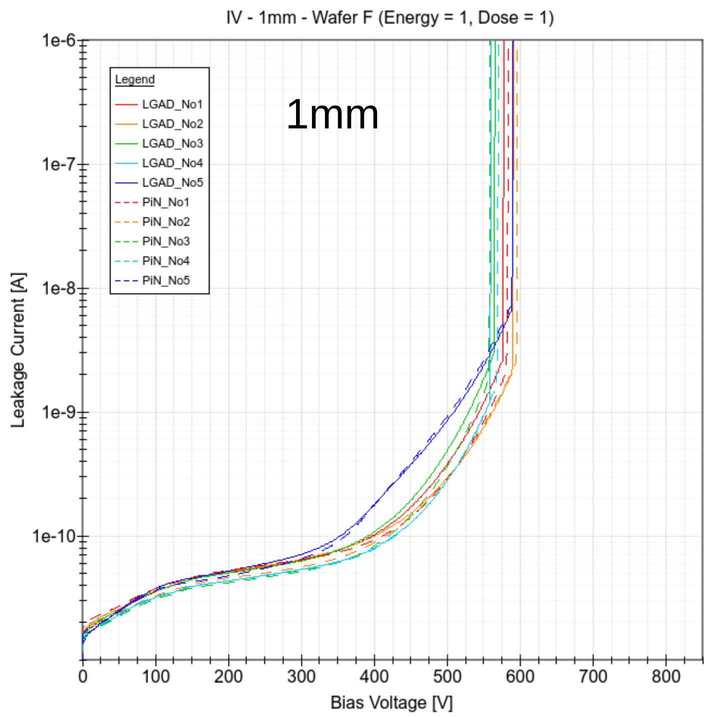
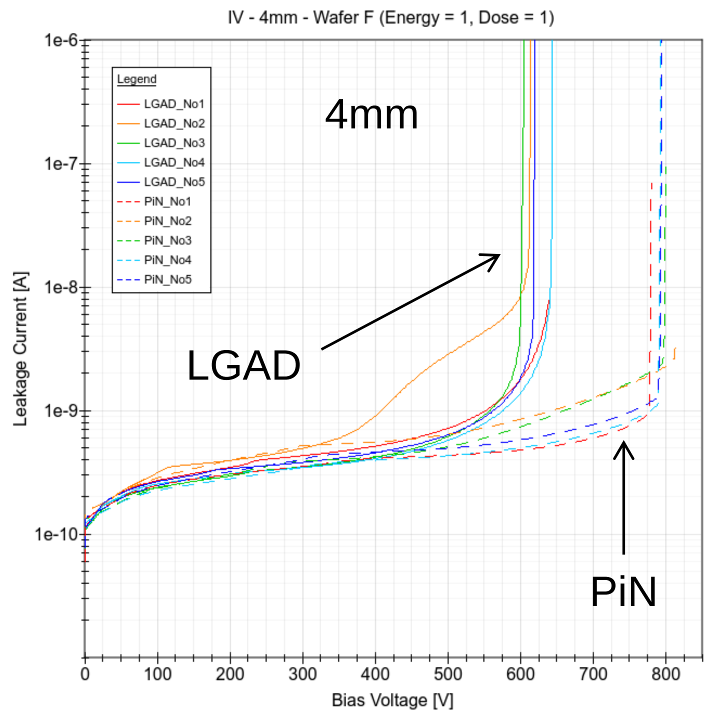
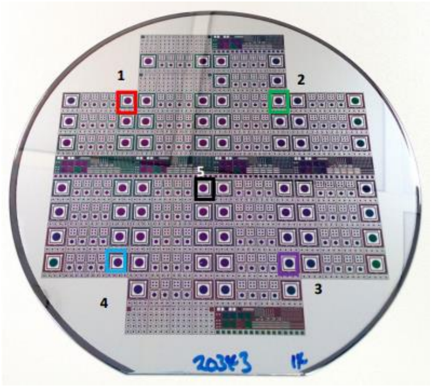


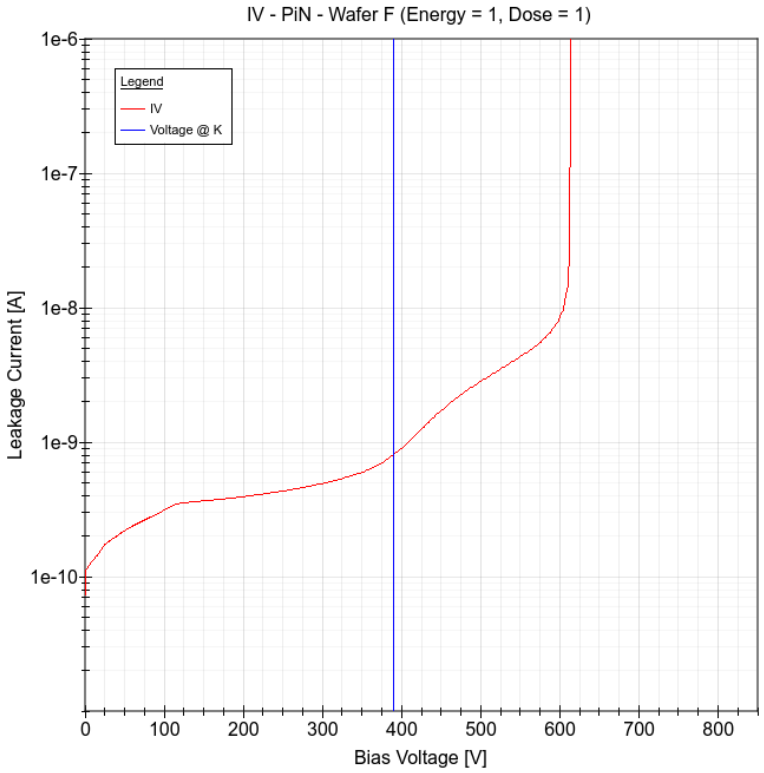


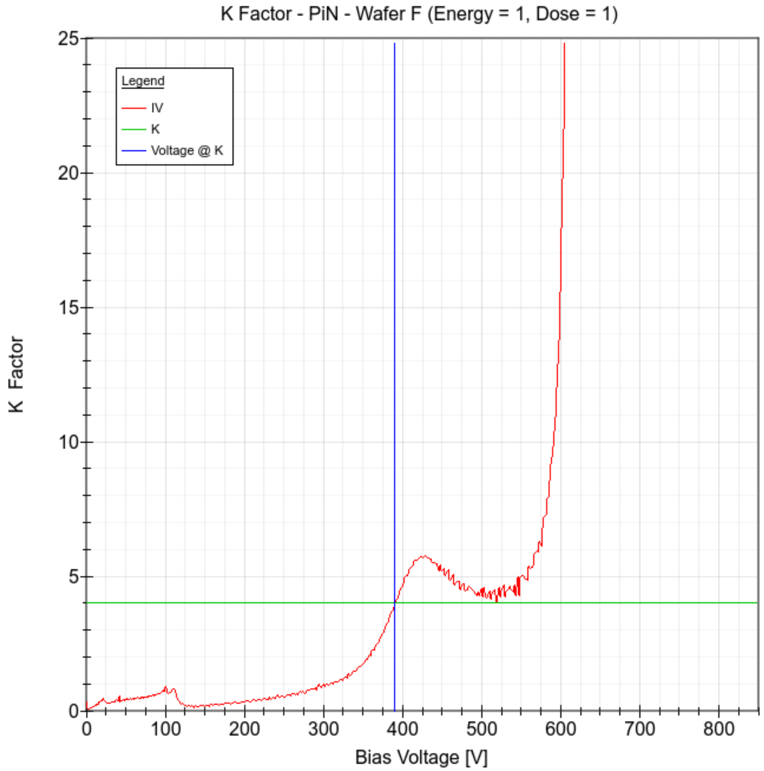
- While the devices are still on the wafer, we conducted IVs on a sample of locations across the wafer to check wafer uniformity (Typically, only 3 of the 5 locations were used to speed up the process)

- In the figure we have a sample of IVs for both PiN and LGAD from a wafer with an implant of Low Energy and Medium Dose

- There is clearly some differences within the same wafer LGAD to LGAD, but this nothing unusual. We also see a difference between LGAD and PiNs for 4mm devices





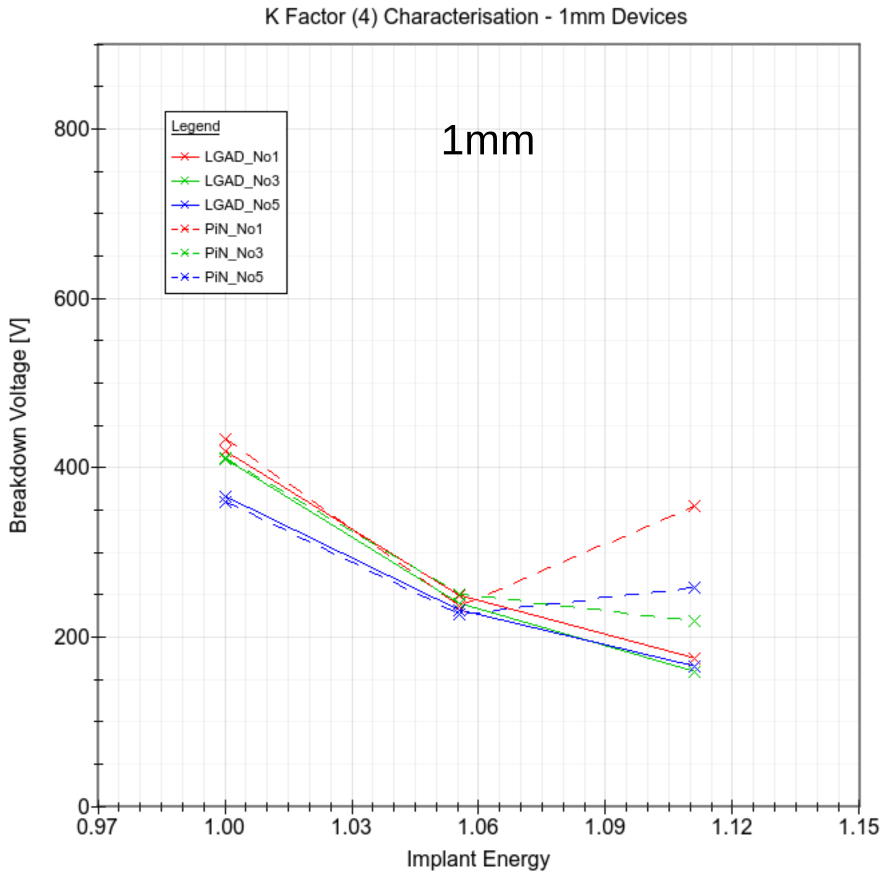


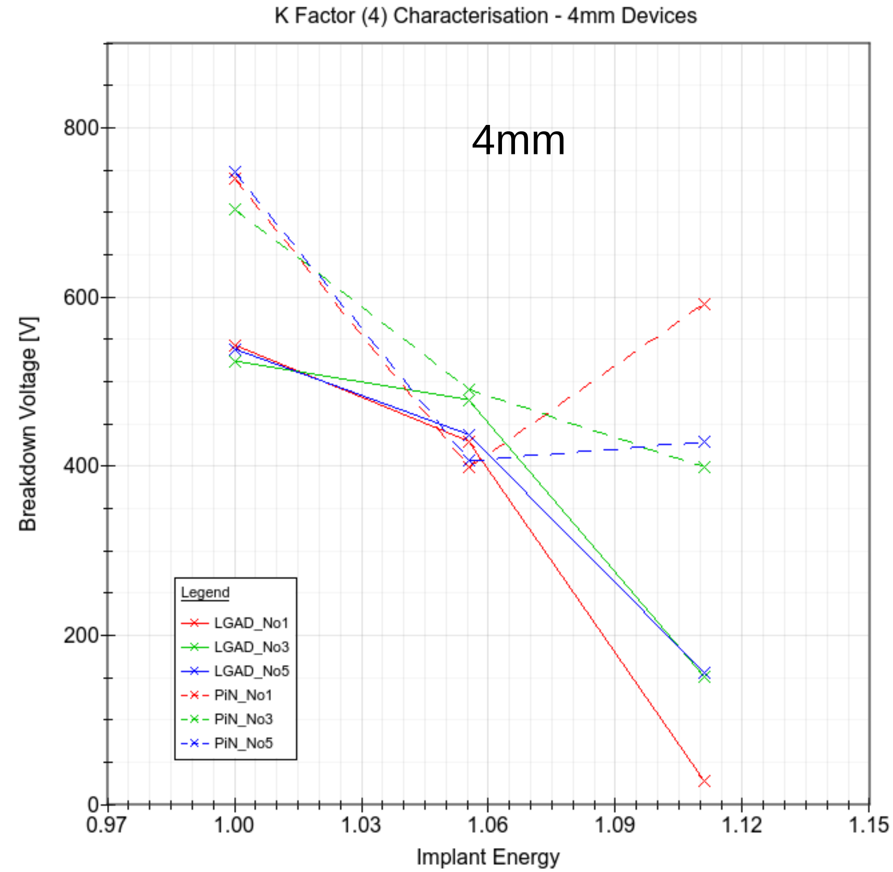
- For better comparison between wafers, we do a breakdown characterisation of the IVs
- We do this using the 'K-Factor' method, with formulae shown below.

$$K(I,V) = \frac{\Delta I}{\Delta V}\frac{V}{I}$$

https://doi.org/10.1016/S0168-9002(00)01207-9

- The K-Factor gives an indication to breakdown which is defined as a significant increase in the leakage current as function of voltage.
- We define a threshold of K = 4 as a 'soft' breakdown, and as soon as the K-Factor reaches this value, we record the voltage.





- Having identified the breakdown voltage, we can plot this against wafer implant energy and see a general decrease in breakdown voltage

- We can see some variation within wafers as well as the difference between PiN and LGAD, which is less apparent for the 1mm devices

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E	1.15	1.05
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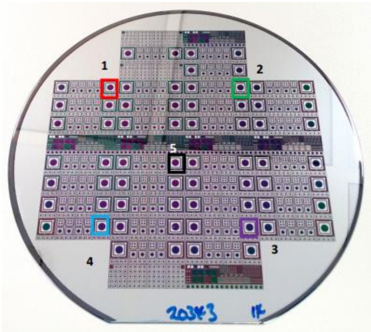

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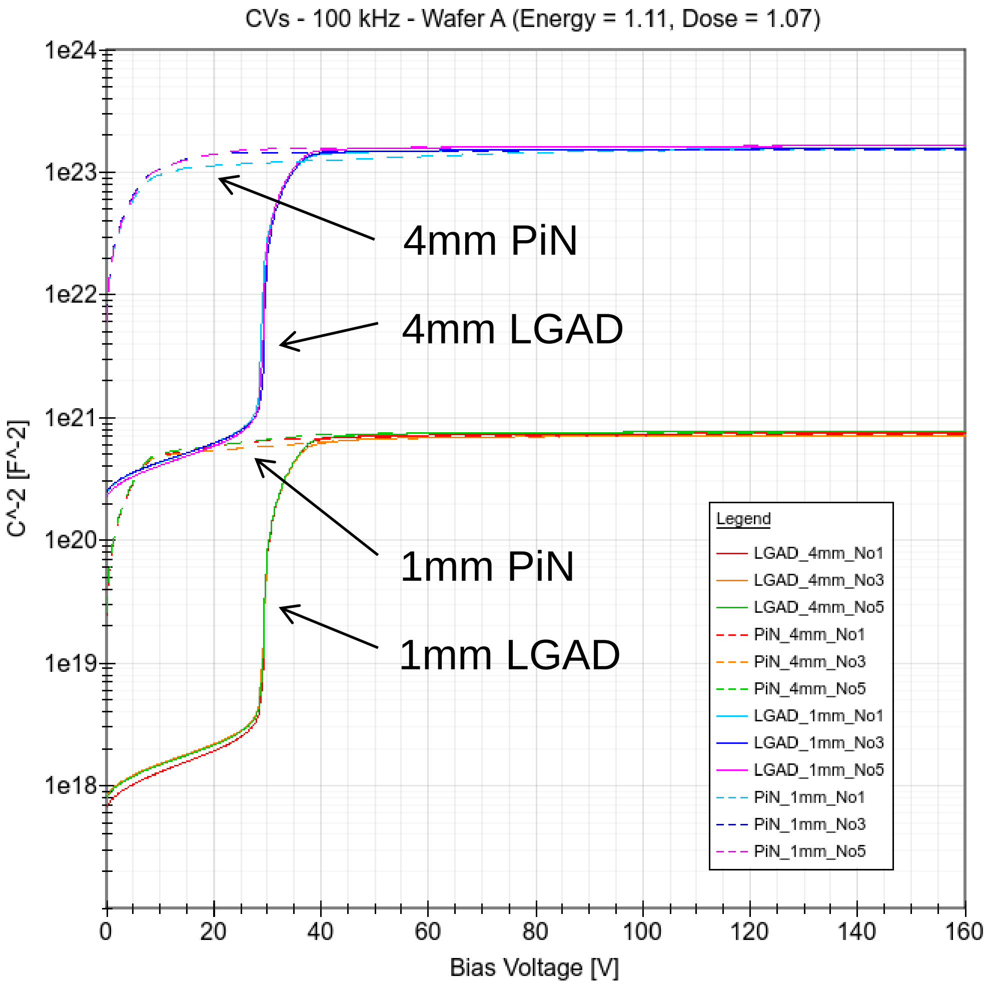
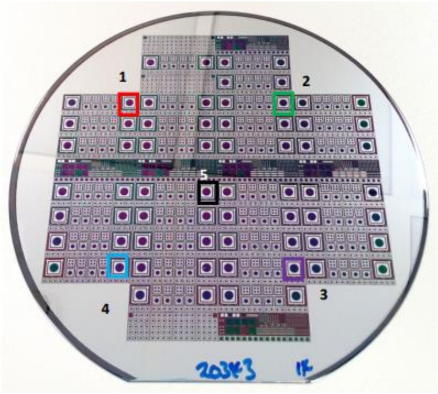
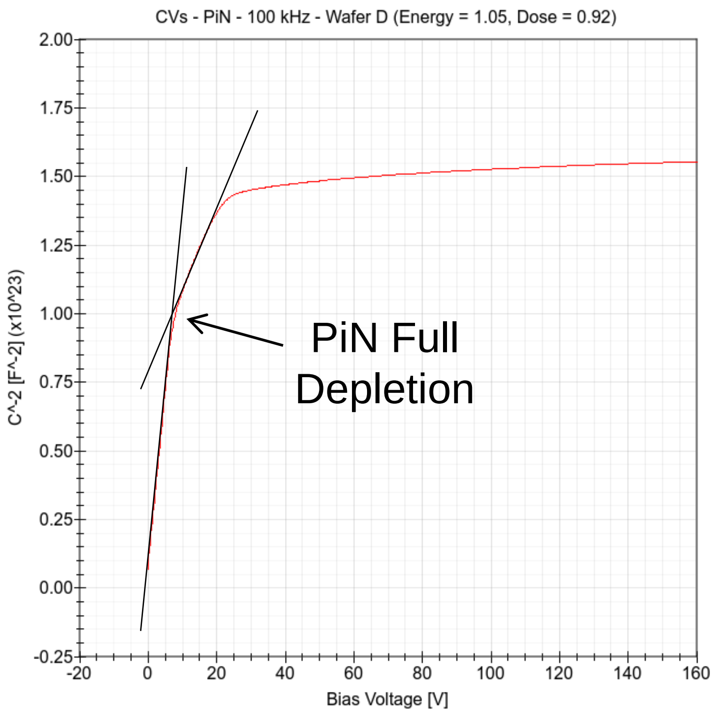
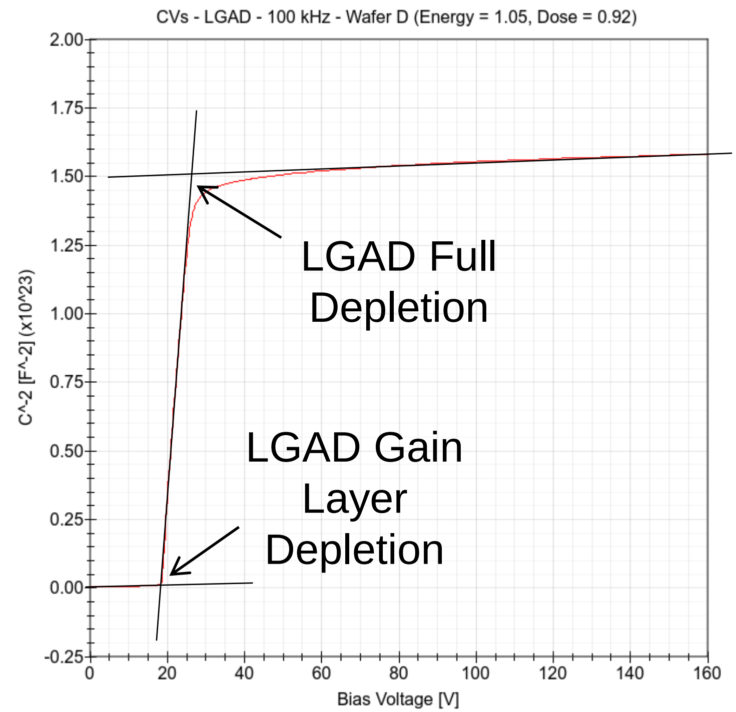
- Similarly to IVs, we measured CVs for a sample of locations across wafers.
- In the figure we have a sample of CVs for both PiN and LGAD from a wafer with an implant of Low Energy and Medium Dose
- We were also able to test multiple frequencies (10 kHz, 100 kHz and 1 MHz). Just 100 kHz is shown here
- Here, we see much better wafer uniformity. We also see a clear impact of the gain layer in the form of an offset of around 30V in this case

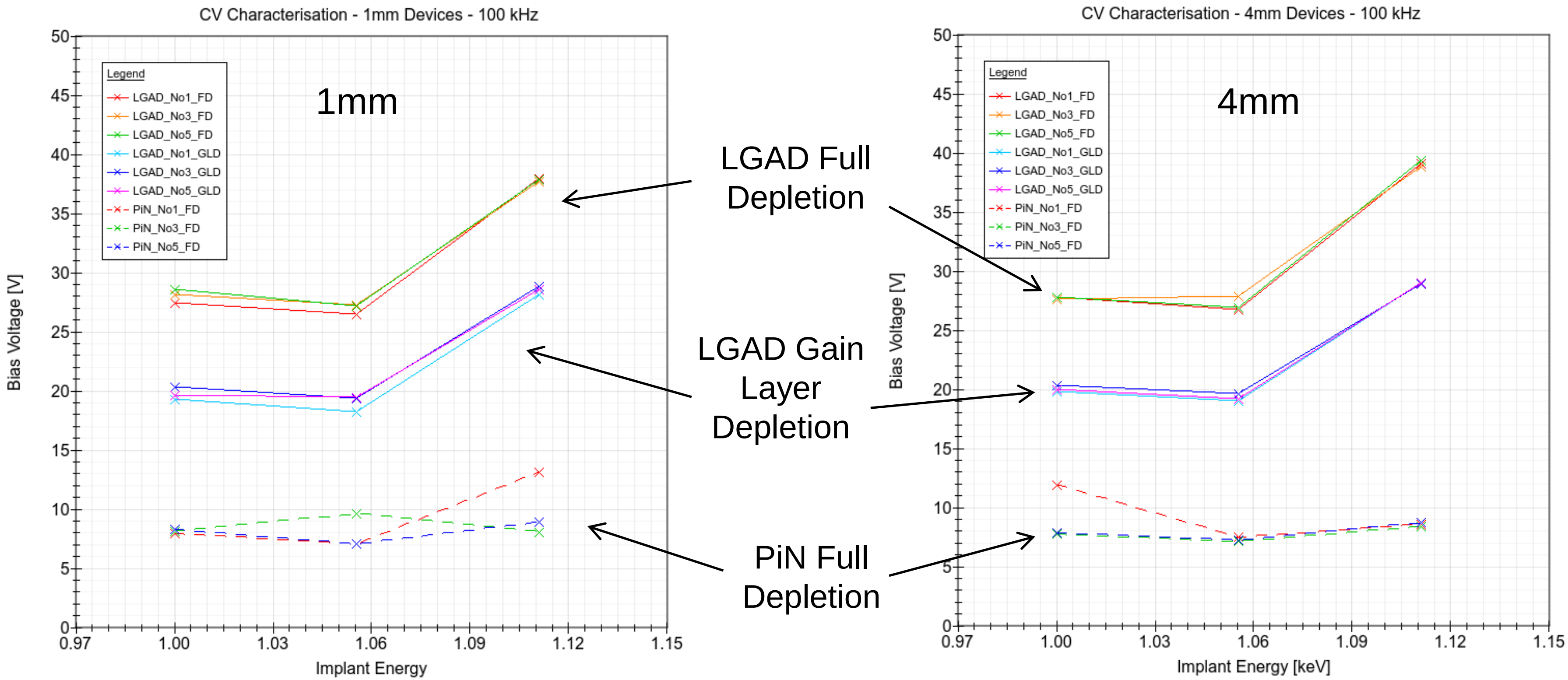








- To compare again across wafers, we can again identify specific voltages of interest.
- For the LGAD we have full depletion voltage and gain layer depletion voltage.
- PiNs only have the full depletion voltage.
- We identify these points by fitting straight lines to sections of the CV curve and finding the intercept.



- The depletion voltages can then be plotted against gain layer implant energy
- In all cases, we see really good wafer uniformity for LGADs with a clear increase in depletion voltages at higher implant energies.
- For the PiNs, the depletion voltage is unchanged by the gain layer implant energy as expected, but there is some variability.
- Here only results for 100 kHz is shown

Wafer code	Normalised Dose (D)	Normalised Energy (E)
A	1.07	1.11
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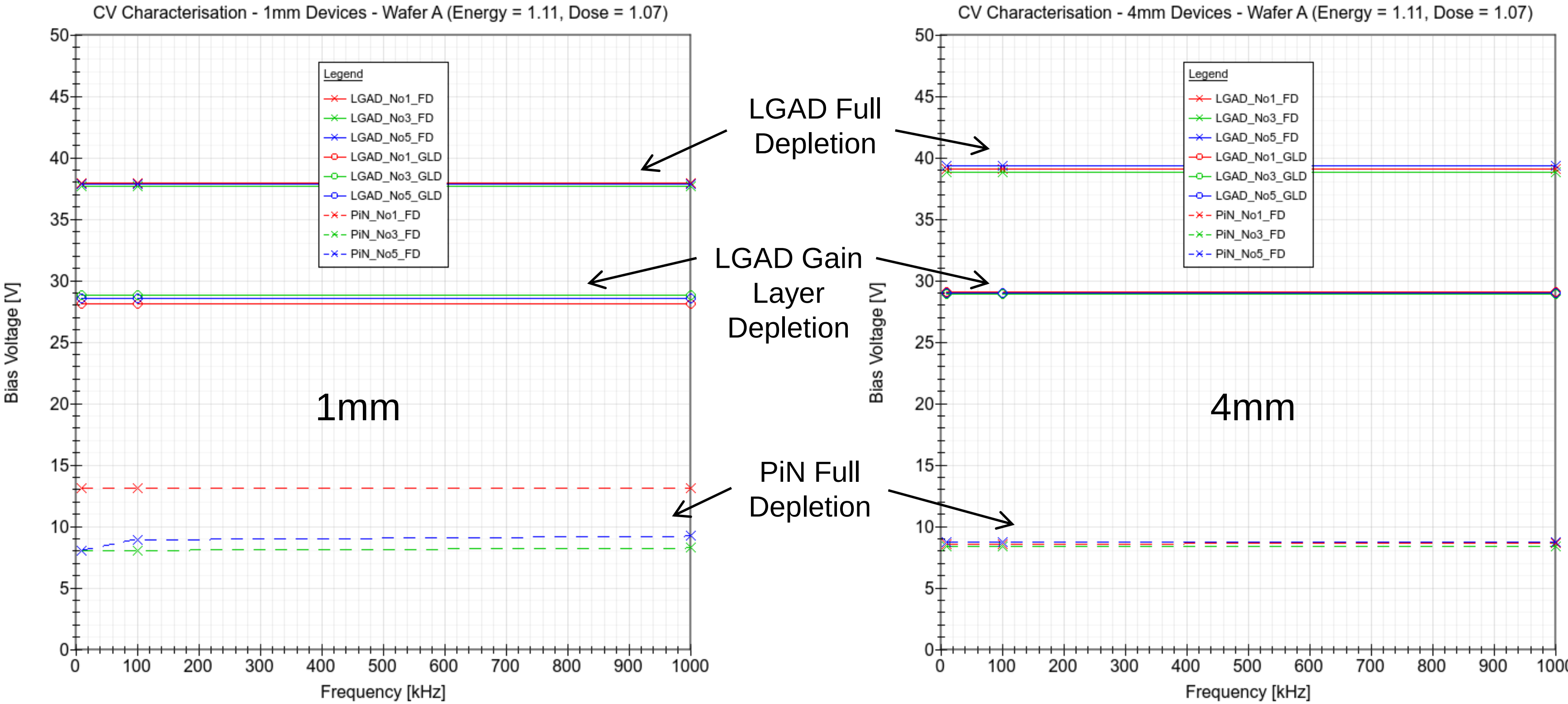
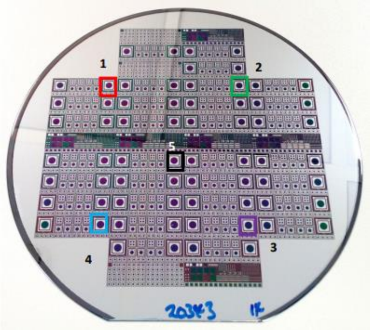


- Plotting the depletion voltages against frequency shows no trend
- We see the same non-uniformity for PiNs
- These results are from the higher implant energy only. Other implant energies behave very similarly against frequency



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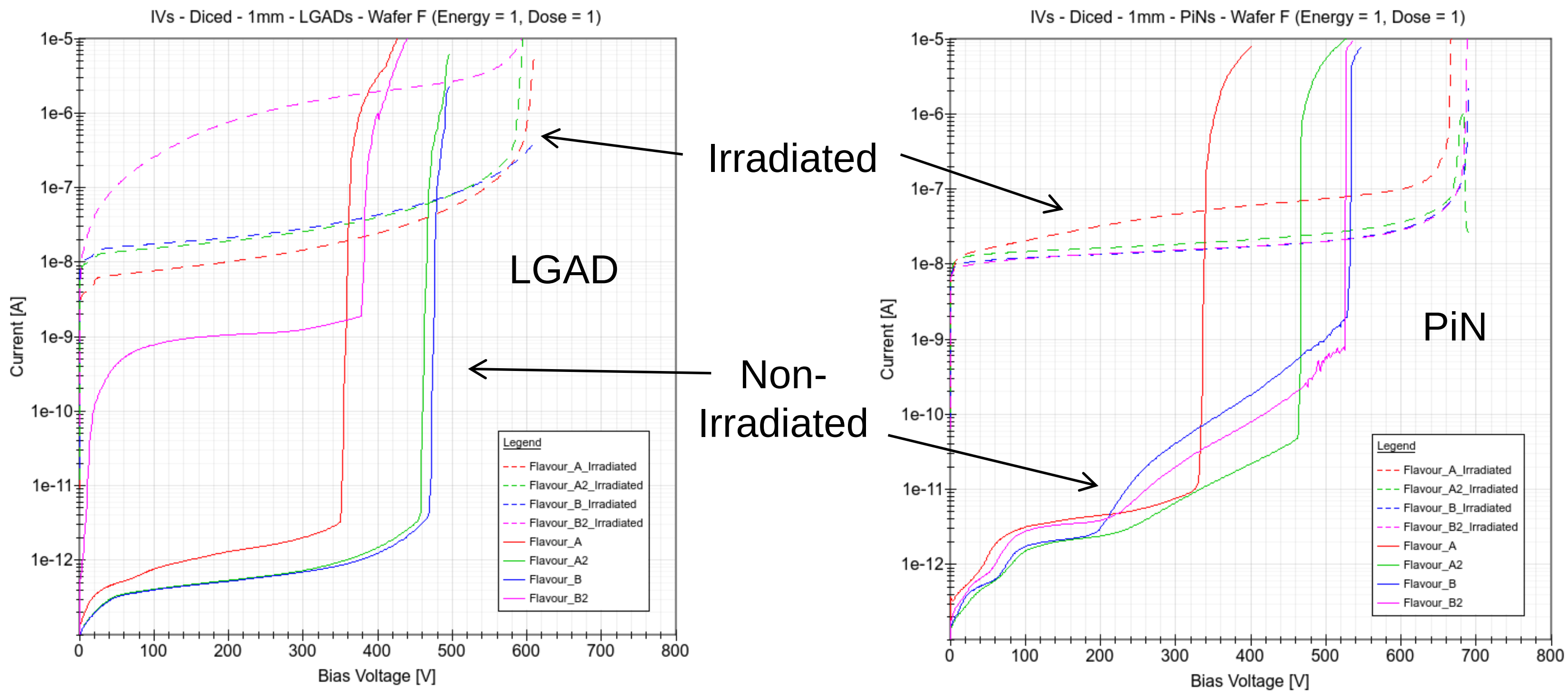
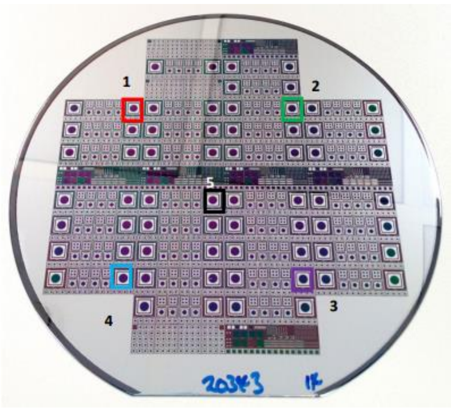


- Two diced devices were sent for irradiation at 5e14 1 MeV n_eq/cm^2.
- IVs were measured before and after irradiation and pre-annealing. The former were temperature corrected from 22 deg C to -20 deg C with the following formula:

$$I(T_{-20}) = I(T_{22})\left(\frac{T_{-20}}{T_{22}}\right)^2 exp\left(\frac{-1.2}{2k_B}\left(\frac{1}{T_{-20}} - \frac{1}{T_{22}}\right)\right)$$



- As expected, there is a clear increase in leakage current, but all devices which had a high breakdown voltages pre-irradiation, still have that high breakdown. Some devices were damaged by the laser dicing process

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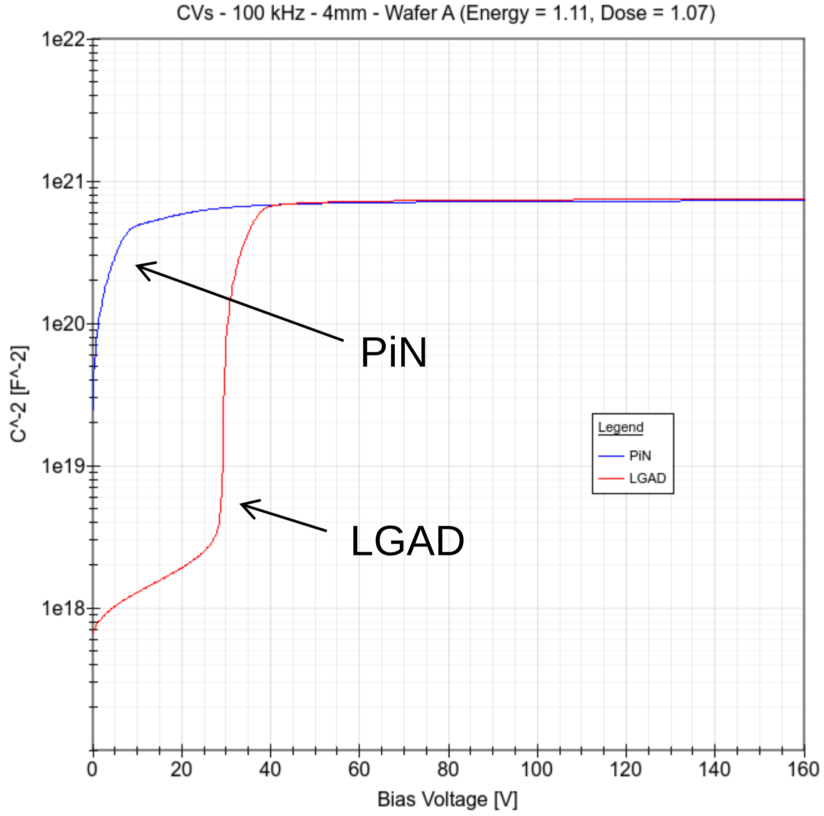
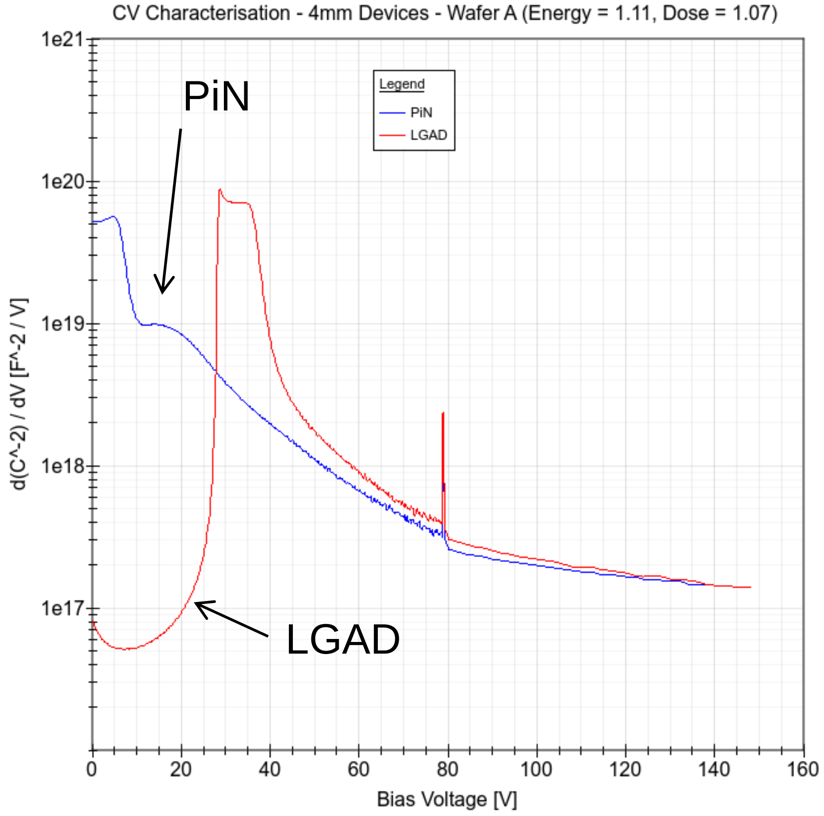




- Information about the doping profile is extractable from the CVs
- Firstly, we calculate the gradient as a function of bias voltage
- From the gradient, the doping concentration can be estimated

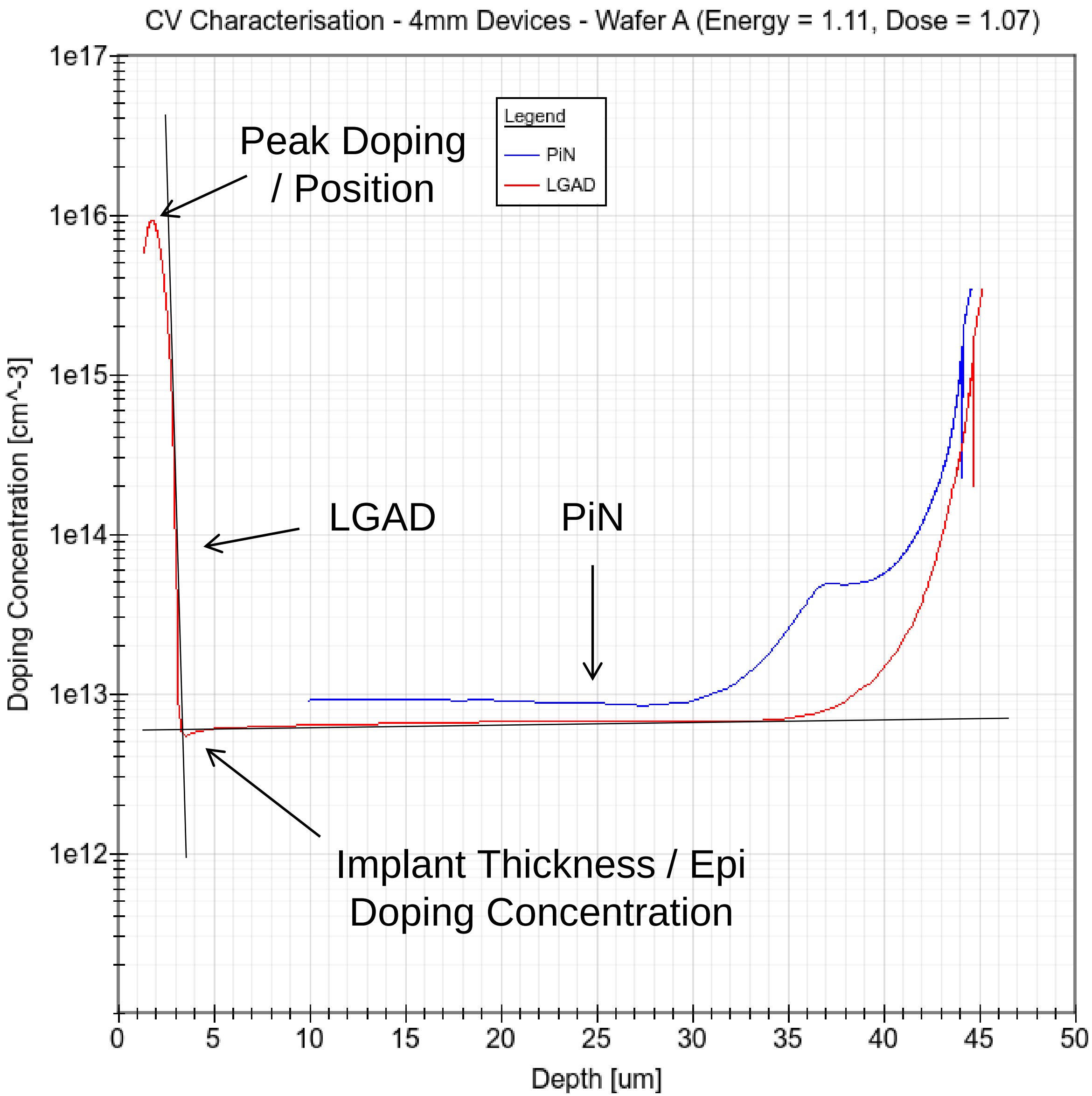
$$N = \frac{2}{\frac{d\left({}^{1}/_{C^2}\right)}{dV}} \cdot \frac{1}{\varepsilon q A^2}$$

$$x = \varepsilon\, A/C$$

N is the doping concentration and x is the depth

DOI:10.2139/ssrn.3433675

https://indico.cern.ch/event/273880/contributions/1614933/attachments/493731/682272/13_Genova_Doping_Profile_HFWS.pdf



- From the gradient, the doping concentration can be calculated
- An approximate depth can be mapped capacitance at each bias voltage
- As with the CVs, fittings can be made, and key features such as the peak doping, and gain layer depth can be extracted

$$N = \frac{2}{\frac{d\left(1/C^2\right)}{dV}} \cdot \frac{1}{\varepsilon q A^2}$$

$$x = \varepsilon\, A/C$$

N is the doping concentration and x is the depth

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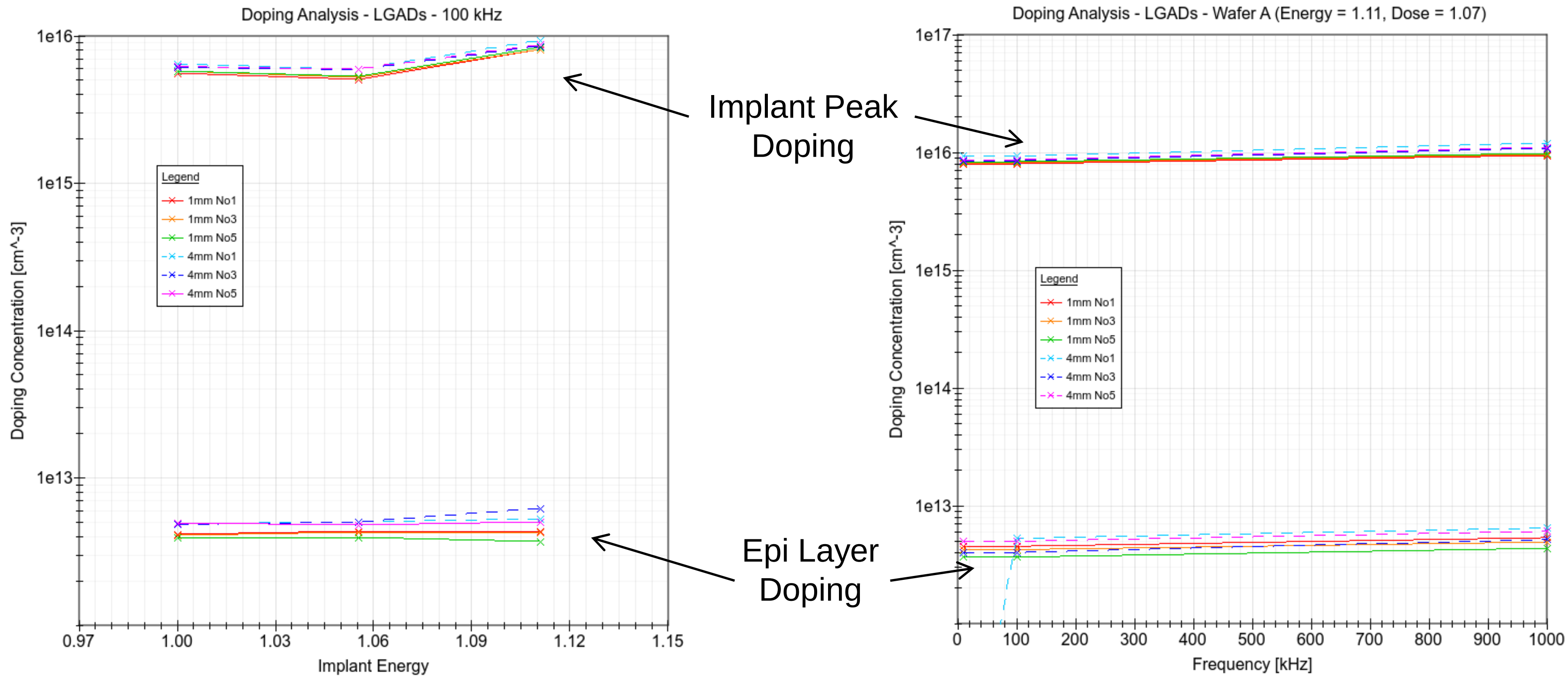

- We can now plot the extracted doping concentrations for two key area: Peak doping in the implant layer and the baseline doping of the epi layer
- We see a slight dependency on implant energy for the peak doping, but not for the epi layer, as expected
- We see no real dependency on the size of the device, which is also to be expected
- We see in all cases a slight dependency on frequency. This is evidence that we can only crudely extract doping, showing the limitations of our approach

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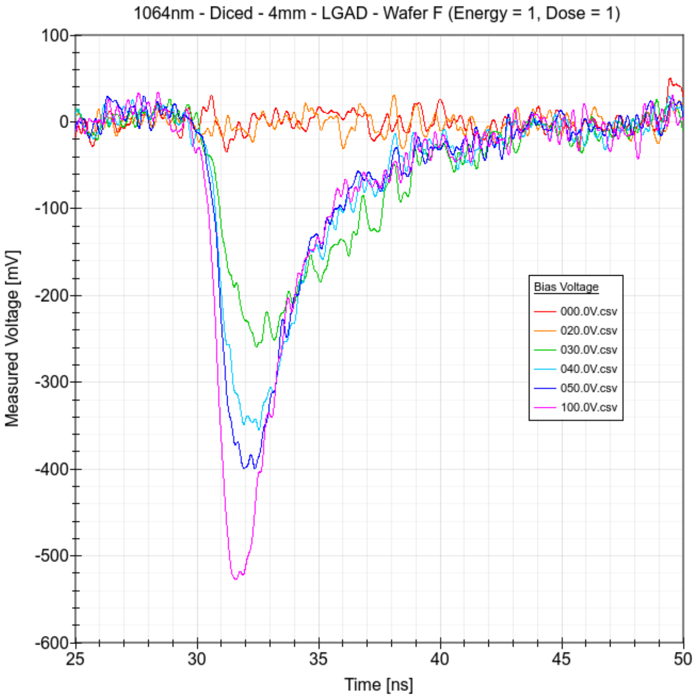
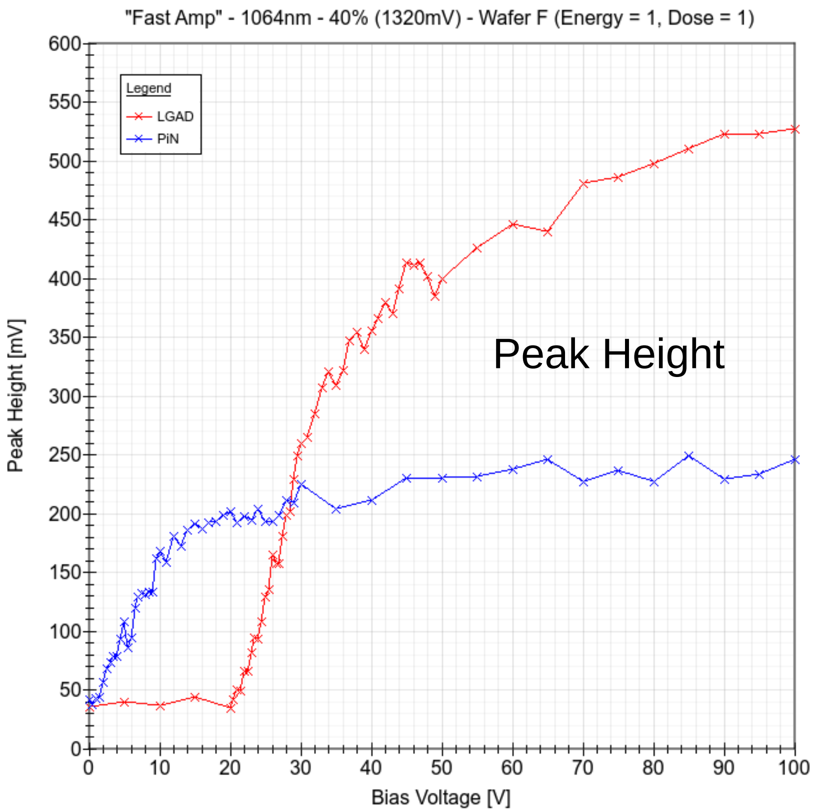
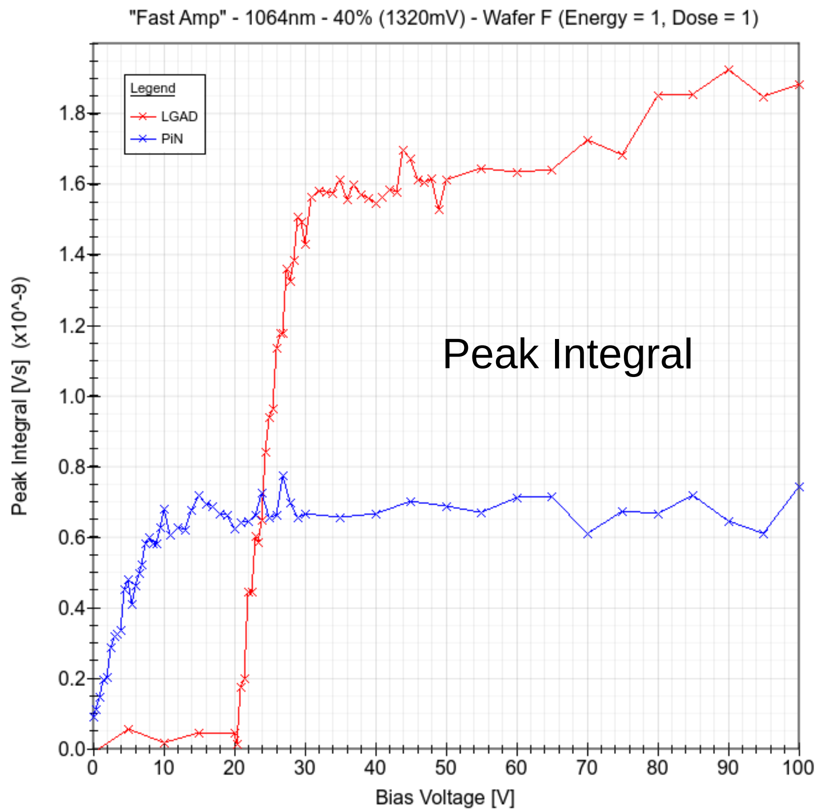
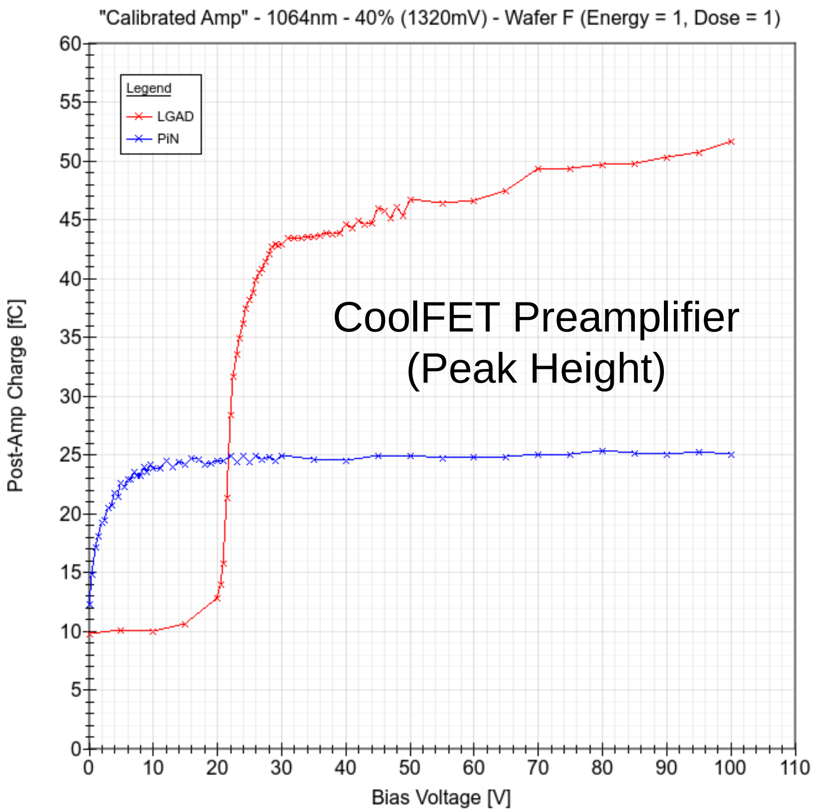


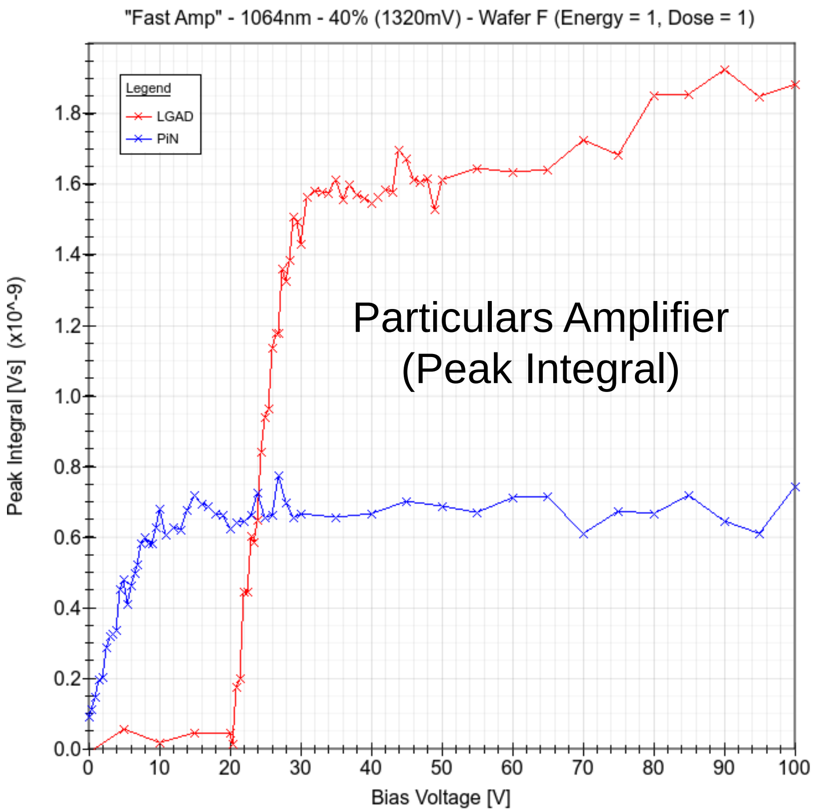
- In order to gain an understanding our LGADs intrinsic gain, we inject charges via a 1064nm IR laser
- We do this for a range of bias voltages, and the output signal is then amplified by a Particulars AM-02 A RF amplifier and the signal is recorded. (Examples of the recorded signal is shown in the figure)
- We can use the height of the signal to indicate the charge collected, but by integrating the signal, we extract all of the charge collected
- We can understand the gain of our LGAD by comparing it to a PiN (which we assume a gain of around 1)





- Both methods (peak height vs integration) show delay in full depletion for the LGAD, caused by the gain layer implant
- The integration method shows a more sharp rise charge collection similar to what we see in the CVs.
- After full depletion, the integration method suggests a gain of around 3, whereas the height method suggests a gain of around 2 – 2.5





- We also repeated the measurements using a much slower CoolFET A250CF Preamplifier.
- For this particular amplifier we have a calibration from output voltage to charge in fC
- We see a similarly sharp rise of the LGAD from both this slower amplifier and the integral of the faster amplifier.
- The relative gain also remains similar, closer to 2 for the CoolFET

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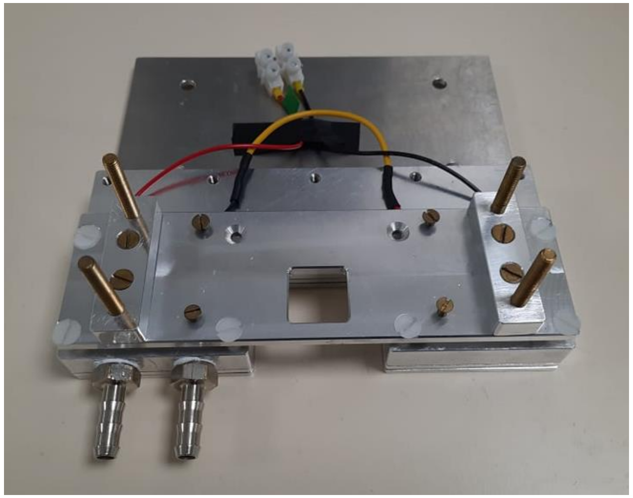

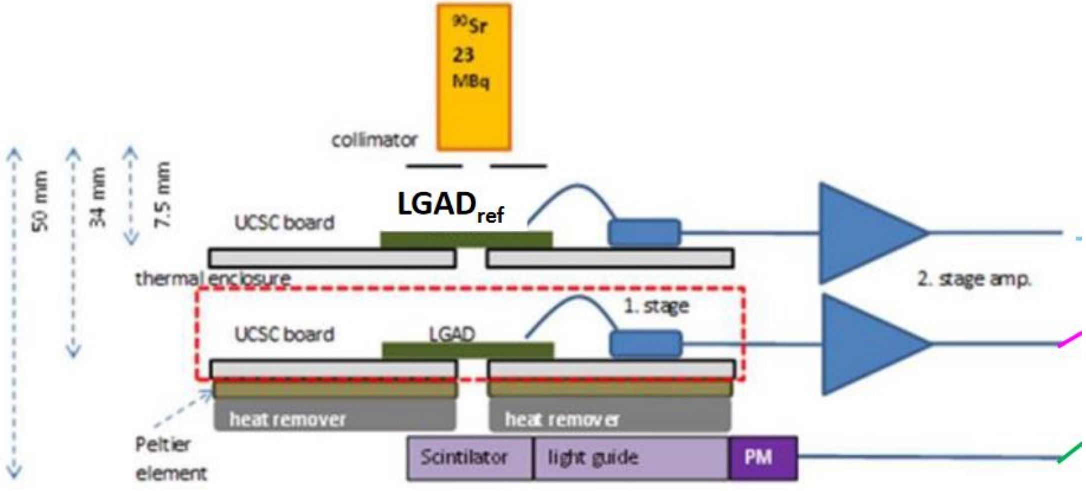

Timing setup from Ljubljana

- We are currently in the process of building a setup with will allow us to measure picosecond timing resolution.
- The setup will use a Sr-90 source along with a reference LGAD and PM & Scintillator for triggering.
- We hope to finish construction and begin the first measurements over the next few months
- We'd like to thank Gregor and colleagues at Ljubljana for allowing us to use their design for the setup, as well as their continuing help with its construction

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In Summary

- LGADs produced by Teledyne e2v exhibit expected behaviour for IVs and CVs
- Initial implant energy comparisons suggest correlation between implant energy/dose and depletion voltage
- Initial irradiation of diced devices did not affect the high breakdown voltage but as expected, the leakage current did increase overall
- Early gain measurements confirm that our LGADs do indeed have low gain.
- Work on the timing setup has started, and we hope generate plots with a picosecond scale very soon!

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Thank you for listening

Any questions?