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Research within LGAD R&D by developing scientific tools for testing the samples and performing the experiments at the European Research Infrastructures: The case of the Montenegro RD50 group

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Due to a lack of scientific tools at the premises of the University of Montenegro, partially influenced by the COVID-19 pandemic, that coincided with our activities when we joined CERN RD50 Collaboration at the end of 2019, we set up the various R&D research activities on Low Gain Avalanche Detector (LGAD) at the different EU labs. While overviewing the projects in which we participated (study of the Single Event Burnout and study of the Gain Suppression), we will also review some findings and give new insights. The main result of this work is estimation of deposited energy by passing low-energy proton ions in the gain layer that insignificantly affects the gain in LGAD; we have also estimated the depth inside LGAD corresponding to the absorption length of the ion track after which further increase in absorption length (and deposited energy) will not significantly affect the further reduction of the gain. The corresponding number of MIP particles that would leave the equivalent charge is discussed too. What we have also noticed and what has not been previously published is that the reduction of gain also depends on charge generation and recombination rate. Strikingly, although the carbon ion (C(18 MeV)) deposits 14 times more energy than proton ion (H (0.745 MeV)) when passing the first 3.5 microns of device, their gains differ only by 20%. This can only be explained by faster recombination of electron and holes in the case of carbon ions; in the flat bias response, that is recorded for Carbon ions, the external field is unable to penetrate the dense charge cloud and high-injection level (over less spatial extent than for proton ions) results in shorter high-injection lifetimes due to Auger recombination.

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1. **Introduction**

Radiation sensors and detectors are widely used in fundamental physics, nuclear reactors, aerospace science, medicine, environmental monitoring, etc. One of the most important aspects of these application areas is the extremely harsh radiation environment, driven by the next-generation fusion energy reactors and future high-energy particle detectors. It is crucial to develop radiation-resistant, easy-to-operate, high-spatial/temporal-resolution devices that can survive in environments with high radiation fluences and high temperatures, as expected in plasma diagnostics and high-energy particle collisions. Solid-state sensors, especially wide-band gap semiconductors, are good candidates for these applications. To support the research and development of these new innovative solutions, further training in instrumentation techniques as well as the development of a new scientific tool that will support more advanced characterization of state-of-the-art sensor technologies are needed. In this paper, we report on three selected activities, all of which have a focus on LGAD, in which we have been involved over the past few years.

Table 1: The main activities, targeted aims we wanted to achieve, and experimental techniques we exploited.

Experimental technique	Motivations/Targets		
TCT	Fs-laser based SPA and TPA at the Extreme Light Infrastructure (ELI) Beamlines in Prague in Czech Republic		
	1. Development of a unique Experimental station with both SPA and TPA modalities	2.Study of the long-term stability of LGAD under the influence of Highly Ionized Particles with a main focus on the irreversible destructive mechanism, Single Event Burnout (SEB).	3. Study of the segmented LGAD: optimization of the peripheral unit and the determination of the interpixel distance (no gain region)
IBIC	Nuclear probe station at the Tandem Accelerator at the Rudjer Boskovic Institute		
	1. Feasibility study of LGAD's response to non-Minimum Ionized Particles (in this case we used ions)	2. The JTE effect on the fill factor and the interpad distance was studied.	3. Gain suppression mechanisms (quenching of impact ionization) due to charge screening of the local electric field.
Training of young researchers	**Training of young researchers at ELI Beamlines and at the Jozef Stefan Institute.**		
	an ongoing project with an aim to build the human capacity in Accelerator and Detector Instrumentation.		

Table 1. summarizes the main R&D research activities. The targeted aims we wanted to achieve and the experimental techniques we exploited are also given.

Firstly, we overview our research at the EU laser facility, ELI Beamlines in Prague, where a unique femtosecond laser-based experimental station has been developed. The setup is based on the technique of transient currents with two modalities: Single-Photon and Two-Photon Absorption (TCT-SPA and TPA-TCT). These techniques are very important tools for the characterization of a Si-based timing and tracking detector. In our research, we have been focused on the susceptibility of LGAD to rare, large ionization, the so-called "Highly Ionizing Particle" and irreversible damage recognized as a Single Event Burnout. LGAD is chosen as a timing technology for the ATLAS and CMS upgrade Timing Detector at the LHC-HL. The second case we will be overviewing is the ion microbeam study of the charge transport in LGAD. In this study, a few LGADs have been tested using the Tandem accelerator and low-energy ions (carbons and proton) at the Rudjer Boskovic Institute in Zagreb. The method of Ion Beam Induced Charge (IBIC) and ions with various energies were used to probe the different detector depths to study the LGAD's response. The gain suppression has been observed and systematically studied.

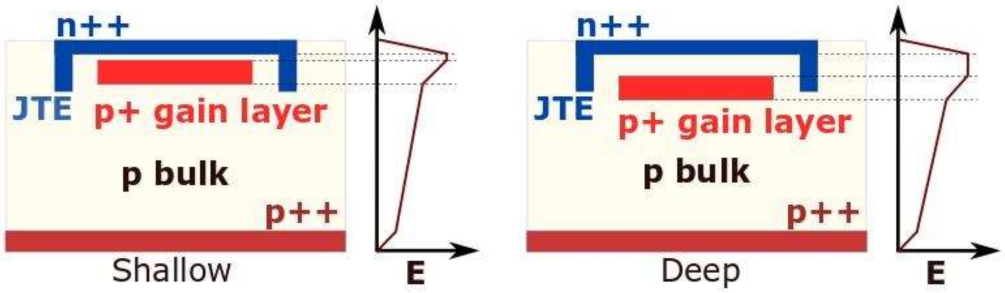
1.1 Methods

TCT: In the field of detector development for High Energy Physics, the so-called Transient Current Technique (TCT) is used to characterize the electric field profile and the charge trapping inside silicon radiation detectors where particles or photons create electron-hole pairs in the bulk of a semiconductor device, as PiN diodes. TCT allows for the inspection of the electric field profile inside the diode bulk. This is possible by analysing the waveform of the transient current induced by drifting free charges.

IBIC: Ionising radiation can generate electron-hole pairs in a semiconducting material, and photons and keV electrons are used to image device active regions using this effect, but their use is limited by the low penetration of thick metallisation and passivation layers present. In addition, keV electrons suffer from large scattering in the sample which severely degrades the spatial resolution. However, the high penetrating power of MeV light ions allows them to generate electron-hole pairs from deeply buried active areas within intact devices with a very little loss of spatial resolution of the beam size on the sample surface. In this paper, we will provide an overview of the use of the nuclear microprobe technique IBIC (Ion Beam Induced Charge) for tests of non-irradiated LGADs. By using a 0.7–4 MeV proton microbeam with a current of less than 1000 protons per second, images and profiles of charge collection efficiency in radiation detectors can be produced. We describe the generation, limitations, and capabilities of the ion beam-induced charge technique (IBIC) for imaging the active regions of devices through the passivation and metallisation of the layers.

1.2 Materials

Low Gain Avalanche Detectors (LGAD) [1] are presently the technology of choice for track timing detectors in particle physics. It is a baseline technology used for upgrades at the HL-LHC in the High Granularity Timing Detectors (HGTD) in ATLAS and the Endcap Timing Layer (ETL) in CMS.



a) b)

Figure 1: LGAD structure with two different gain layer designs: a) shallow gain layer and b) deep gain layer.

A highly doped p layer (Figure 1) is implanted between the p-bulk and n-implant (n^{++}-p^{+}-p -p^{++} structure) leading to a high enough electric field for impact ionization upon an applied sufficiently high bias voltage (see Fig. 1a). Gain factors typically between 10 and 100 have been obtained. The use of thin LGADs (few tens of µm) with high gain allows for the superior timing resolution of these devices of several tens of ps. LGADs are characterized by an extremely good time resolution (down to 17 ps), a fast rise time (~500ps for 50 µm thickness), and a very high repetition rate (~1ns full charge collection). In a broad array of fields, including particle physics (4D tracking) and photon science (X-ray imaging), LGADs are a promising new sensor option. However, as is shown in the next section, some limitations restrict the application of LGAD.

The Single Event Burnout (SEB) study and Gain Suppression (GS) were investigated on Hamamatsu HPK W36 and W28 (common CMS and ATLAS production in 2020) destructive breakdown. The SEB is an event, often accompanied by a visual crater in the surface of the device and presents the irreversible breakdown of the device. This damage is generally understood to be due to thermal runaway due to positive feedback between impact ionization (after the passage of Highly Ionized Particle (HIP)) and lattice heating at high fields in the silicon devices. The Gain Suppression is the response of a silicon device with internal gain to a large charge density when the gain is not felt anymore by the generated charge since the local electric field is screened and the charge cannot gain enough energy to undergo impact ionisation.

2. Stability of Irradiated LGAD

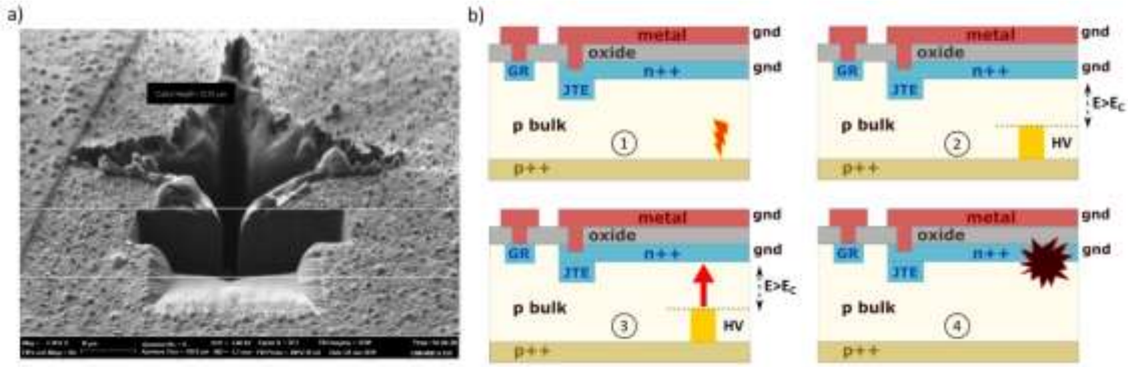


Figure 2: SEB damage (on the left) and stages of SEB that lead to irreversible damage [2].

The loss of gain in LGAD due to the acceptor removal mechanisms when exposed to high radiation doses (tested mainly by neutrons) was mitigated by increased applied voltage. However, LGAD, like other silicon detectors shows vulnerability and susceptibility to a rare, large ionization event, the so-called "Highly Ionizing Particle". Those events produce an excess charge that leads to a highly localized conductive path, namely a large current in a narrow path, the so-called "Single Event Burnout". Figure 2 [2] shows different stages of SEB: (1) a large amount of energy is deposited in the sensor; (2) the large carrier density leads to the collapse of the field; (3) the High Voltage is brought closer to the pad leading to very high field strength and (4) the avalanche breakdown leads to irreversible destruction of the sensor. The RD50 group from Montenegro was actively involved in SEB tests on LGAD where a fs-laser from the laser infrastructure ELI Beamlines with a 800 nm wavelength was used to mimic HIP particles. The main findings of those R&D activities can be summarized as follows:

- Understanding of single-event burnout mechanism is now greatly improved - caused by single-particle interaction (HIP).
- Susceptibility driven by thickness and bias voltage is identified and those parameters are seen as the crucial parameters to determine a safe operating voltage.
- Most likely SEB is caused by a collapse of the electrical field.

Regarding the operational conditions, the most important message is that these destructive events begin to occur when the average electric field in the sensor becomes larger than 12 V/µm meaning that not higher than High Voltage = 550 V should be applied to 50 µm LGAD to keep its safe operational mode when irradiated to a fluency of 2.5×10^{15} n_{eq}/cm^2; by the end of LGAD's lifetime at HGTD the most exposed sensors will have received a 1 MeV neutron equivalent fluence of around $\Phi_{eq} = 2.5\times10^{15}\ n_{eq}/cm^2$.

The fs-laser-based TCT setup is described in detail in [2].

3. The Gain Suppression

It is important to keep in mind that LGAD is originally designed to deal with Minium Ionizing Particles (MIP). It is not calibrated to non-MIP particles such as ions, alpha, and other highly ionized particles. However, LGADs are also proposed as candidates for the Active Stopping Target (ATAR) in the PIONEER experiment. PIONEER is a next-generation rare Pion decay experiment to measure Re/μ and Pion beta decay branching fraction with unprecedented precision. PIONEER's active target (ATAR) is a very ambitious detector and requires high granularity, high density, and good timing capabilities; it needs a large dynamic range and good energy resolution; baseline technology for sensors is AC-LGADs, but other high-density LGADs are being evaluated (TI-LGAD, DJ-LGAD). However, for large energy deposition from particle injection, where the generated e/h pairs density is large, the gain of LGADs can be significantly reduced (as seen in avalanche diodes).

LGAD is also considered in astrophysics experiments where high injection levels may be prevalent during ion strikes in semiconductor devices resulting in large space-charge screening effects (SCSE) whose duration in an optoelectronic sensor, for example, depends on several parameters including device type and structure, the length of the track and the ambipolar properties of the generated electron-hole pair (EHP) plasma. The latter depends on the injected carrier density and therefore the radial structure of the thermalised ion track. However, since drift currents in the screened plasma depend on the minority carrier diffusivity and length of the ion track inside of the junction, the largest factor determining the charge collection dynamics is the sensors' geometries and type.

RD50 group from Montenegro was actively involved in understanding the gain suppression mechanisms on LGAD. Those experiments, in which the Montenegro team participated, have been performed at the Rudjer Boskovic Institute using ions from the nuclear microprobe station and the IBIC method. The other set of experiments was performed using alpha sources at the RBI and the laser beams at the ELI ERIC. For the tests with alpha radiation, we used a triple alpha source: Pu-239 (5.115 MeV), Am-241 (5.486 MeV), and Cm-244 (5.805 MeV) with corresponding absorption depths in LGAD of 25.3 μm, 28 μm, and 30.4 μm, respectively. The laser study on GS on LGAD was part of our study on SEB where we used a fs-laser with a wavelength of 800 nm. The gain suppression has been already seen in a SEB study as we did a SEB study on both regions: on the interpad region with no gain (the interpad region in segmented LGAD behaves as a PIN diode) and on the pad region (which has an internal gain layer). In the experiments at the RBI, the proton ions had energy from 0.56 MeV (corresponding to 7 μm of penetration depth) up to 4 MeV (150 μm of penetration depth), while the carbon ions covered the energy range from 2.88 MeV to 18 MeV which correspond to the penetration depths between 3.18μm and 17.7 μm.

3.1 The Impact of Recombination and Diffusion

In this article we will review a few selected cases from [3] and a new insight will be offered. The main features of conducted experiments are:

- The ionization pattern of probed ions is different from that of the minimum ionizing particle (MIP) usually encountered in tracking applications. This leads to the different ionization densities: from thousands e–h pairs/μm3 for protons and ions to tens e–h pairs/μm3 for minimum ionizing particles, assuming the ionization is typically contained within a lateral radius of as given by the Bethe–Bloch calculation. The lateral dimension of the generated e–h cloud increases due to multiple-scattering and diffusion of the drifting charge, but even for low energy beta electrons in thin sensors it reaches typically only a few μm.

- An external field separates the free carriers, but a large density of free carriers leads to a field screening effect after multiplication in the gain layer. That affects the impact ionization, and hence the gain of the LGADs. The gain of the LGADs thus becomes dependent not only on the gain layer design, applied voltage and temperature, but also on the particle that is being detected.

The most striking observation of the outcomes from the conducted experiments was the shape of gain curves (gain vs bias). After reaching a maximum at the depletion bias voltage, gain significantly drops (almost 15 times when compared to the tests with Sr-90 or with ps-laser whose intensity is adjusted to 1 MIP particle).

In what follows, we will firstly discuss the case where the charge was generated by different ion species, chosen so that the Brag peak is released at the same LGAD's depth; in the case considered it was 10.2 μm. H (0.745 MeV) having a range of 10.8 μm in Si and He (3 MeV) having a range of 12 μm in Si and C(14 MeV) having a range of 13.4 μm are studied. As we will see, the ratio of total charge (according to SRIM simulation) generated, for instance by C(14 MeV) and H(0.745), does not follow the ratio between the corresponding measured gains. If we assume a LET for the MIP of 30 keV/100 μm, which corresponds to a LET(MIP)=0.3 keV/μm so, in 50 μm of Si the energy deposited by one MIP it is assumed to be 0.015 MeV per MIP in 50 μm of Si. Using SRIM software, the energy deposited (E_{dep}) can be calculated for the different ion beam species and the energies in a 50 μm sample of Si. Comparing the total deposited energy by ion species to the deposited energy by 1 MIP, we can estimate what number of MIPs would produce such a charge in LGAD. The ratio between the number of MIPs corresponding to the generated charge by the passage of C(14 MeV) and H(0.745 MeV) was 18, while the gain measured using H(0.745) increased only by 70% compared to the measured gain from C(14 MeV). The measured gain for C(14 MeV) and He(3 MeV) was almost the same (1.3 and 1.4, respectively) while the charges converted to the number of minimum ionizing particles were 972 MIPs and 208 MIPs, respectively (bringing the ratio of 4.67). So, while the charge was increased almost 5 times, the gain decreased only by 7%. When only carbon ions are compared, a less significant change is recorded. For instance, by increasing energy from 11 MeV by 64 %, using C (18 MeV) instead of C(11 MeV), the absorption length in the device was increased by 60%, from 11 μm to 17.7 μm. This was followed by an increase of total generated charge (converted to the number of MIP particles) by about 56% bringing the change in gain only by 54%.

Now we will compare the results from measurements with proton ions, H(1.5) MeV and H(0.8 MeV). The gain of 4 was measured with the proton ion, H+(1.5 MeV); its range in Si is 30.8 μm. For the proton ion of 0.8 MeV having a penetration depth of 11.9 μm, the measured gain was 3 in the same device. If we convert the charge injected by 0.8 MeV into MIPs this would be equal to around 52 MIPs, while for 1.5 MeV, the total generated charge corresponds to 80 MIPs. This means that when increasing the energy of the proton ion by 87 %, the generated charge in LGAD (assuming no gain is there) increased by 54%; however, the gain changes only by 30%.

The above-given statements can be explained by the fact that recombining electrons and holes in by ions generated clouds of charges happens with different rates in denser or less dense charge clouds. The recombination rate also depends on the doping of silicon (the gain layer is more doped compared to the bulk region). Additionally, since the carbon ion is heavier than the proton ion, it also moves slower, producing a larger volume of the charge cloud compared to the proton ions, but also the cloud is denser, and recombination happens in a shorter time than in the case of proton ions. This also means that a larger portion of charge will be recombined before charge is diffused at low bias voltage or it drifts towards gain when bias is increased. The recombination is faster than the generation in the region where the silicon is more doped, while this is the opposite in the region with a less doped bulk (further from the gain layer). With diffusion, the situation is the opposite: diffusion is more pronounced in low-dopped regions and further facilitated by a lower bias; at a lower value of bias, diffusion happens sooner than the recombination takes place. Previous consideration also explains the overshoot of gain in the gain curve, observed at the depletion voltage; this overshot is more pronounced for proton ions than for the carbon ions.

What was said before also explains why the gain from the measurements with various proton ions (of different energies) differ the most at a lower voltage than at a higher one. As said, diffusion at a lower bias, in less doped bulk, overtakes the recombination of charge; less dense charge (wider cloud due to diffusion) is then reaching the gain layer, but it is not lost due to recombination. As a result, a higher gain is measured at a lower bias. This difference among results from measurements with protons of different energies is further reduced by increasing the bias since the drift of charge overtakes the diffusion and recombination. As more charge is reaching the gain layer the screening of the electric field becomes stronger, and as a result the gain drops. On the contrary, the gain from the measurements with different carbon ions (of different energies) differs more at a higher voltage than at a lower one. The higher bias reduces the probability of charge recombination, so less charge is lost by recombination, and the measured gain is more dependent on the absorption depth of the carbon ion.

Alpha particles not discussed in [3] showed a stronger gain suppression than proton ions with similar penetration depth due to their stronger ionisation power. The gain from alpha particles with smaller penetration depth was smaller compared to alpha particles with higher penetration depth as expected.

As a conclusion and as an extension to what was previously published, we emphasize here that the recombination should not be omitted from the explanation of reasons for the observed shape of gain curves published in [3] and for the observed ratio of gains measured for proton and carbon ions.

3.2 The recovery (relaxation) time of the electric field

To connect the gain suppression effects to the electric field within the gain layer, it is also important to consider the concept of recovery (relaxation) time of the electric field. Here we will consider the recovery time in relation to the creation of a plasma-like e-h cloud. The recovery (relaxation) time is the required time duration for the electric field within the gain layer to recover to a steady state after the impact ionization process. It is well known that the onset of high-injection conditions along an ion track (when we talk about high-injection conditions we compare charge density that is generated to the dopant level) can lead to a collapse in the local field. For times less than the dielectric relaxation time the field has yet to respond, and the width of the Quasi Neutral Region (QNR) is approximately the distance between the junction surface and the ion End of the Region. Once the dielectric response, the redistribution of excess carriers at the plasmas induces a fast displacement and drift current comprising of little charge which results in a dipolar field from the top of the track to the bottom. This induced field negates most of the applied field thereby creating a QNR with a length inside which the carrier populations are equal.

Although the field in the plasma is very low it cannot be zero due to the presence of the ambipolar field. Charge near the top and bottom interface is rapidly collected allowing the formation of a bottom, and later, top depletion region. The high conductivity of the track means the most potential is dropped at the top and bottom of the depletion region. However, due to the high injection level and remnant fields inside the plasma, this region still dominates the total drift current. Since the electric-field lines are almost perpendicular to the plasma along its length (the plasma is approximately an equipotential), carrier populations are also eroded from the side of the track which radially expands under ambipolar conditions. This period is referred to as the ambipolar, or phase in which SCSE (Space Charge Screening Effects) dominates charge collection. The charge is extracted from the vertical and radial limits of the QNR, shrinking its length until the excess carrier density can no longer sustain the dipolar field, and independent bipolar drift ensues. Obviously, the faster recovery time should reduce the gain suppression effects. The recovery time of the electric field depends on how fast the generated charges from the impact ionization process are “drained” away. We also found that higher saturated carrier velocities also mean the unscreened charge around the track edges disperses more rapidly. Below a threshold current, carrier transport enters the bipolar phase and carriers are rapidly collected as the dipolar field can no longer screen carriers; the ambipolar-phase gradient also decreases with increasing injection.

One mitigation approach to reduce gain suppression caused by high charge density and consequently to decrease the recovery time is to increase the conductivity of the gain layer profile configuration.

3.3 Discussion on GS saturation: Exploring the effect of ion interaction depth in correlation to ionisation profile

The first question we want to address here is whether there is a critical value for the absorption length of the ion above which its further increase will not noticeably increase the GS. To address this question, we compare the results on the gain from the measurements with proton ions of 0.56 MeV, 0.9 MeV, and 1.8 MeV (having penetration depths of 7µm, 14 µm, and 30 µm, respectively). The corresponding gains at full voltage depletion were 2, 3.8, and 4. However, when LGAD us over-depleted, the gain decreases faster for ions with Bragg peak that is realized further from the gain layer; with increased bias the size of cloud decreases and gain suppression increases. Nevertheless, all considered proton ions of energy above 0.9 MeV (>14 µm of absorption depth), reached a saturated gain value of 2 (that is 10-15 times lower than it would be measured with 1 MIP). So, we can conclude that for low—energy proton ions, with absorption length equal or above 14 µm (with corresponds to the deposited energy of 0.9 MeV in LGAD) no further GS is noticed.

Furthermore, in the context of the study of the increase in the number of MIPs on the measured gain, as a function of applied bias, the negligible difference is seen after the generated charge was equal to the passage of 50 MIPs. This is confirmed from the results on the gain measurements obtained by the carbon ion (14 MeV), He (3 MeV), and the proton ion H (0.745 MeV) having absorption lengths of 14µm, 12.5µm and 11µn, respectively. Notably, all those ions have a Bragg peak at the same penetration depth of 10.2 in silicon. For the considered case, the corresponding numbers of MIPs were 972, 268, and 52, respectively, while the measured gains were 2.3,1.39 and 1.4, respectively. Although the generated charge was four times higher for He(3 MeV) than for H(0.75), the significant change in the amplification is not registered.

The last question we want to address is whether there is an upper limit for deposited energy in the gain layer above which the gain in LGAD would not be insignificantly affected by a further increase in deposited charge. The deposited energy is correlated with the carrier concentration while non-irradiative losses, expansion of clouds, etc depend on the charge concentration and the local electric field. To address the question, we will look at the results from the measurements with a proton ion of energy 1.8 MeV compared to the results from measurements with a proton ion of energy 0.56 MeV. Proton ion of energy 1.8 MeV has a penetration length of 40 μm in silicon. Its deposited energy in the first 3.5 μm (covering mainly the gain layer), as it is obtained from SRIM simulation, is only 0.1 MeV, which is 18 times less than the total energy deposited in the device (over 40 microns of full absorption length). Moreover, the charge generated in the first 3.5 μm corresponds to the passage of 9 MIP particles (passing the whole device) while the charge generated until the proton ion of 1.8 MeV is completely absorbed in the device corresponds to the passage of 166 MIPs. Notably, for the same sample, the gain measured by beta particles and a ps-laser, which is adapted to correspond to one MIP particle, is around 4 at a voltage corresponding to the full charge depletion; this value is equal to what we measured. However, when the LGAD is over-depleted, meaning that the local electric field is proportionally increased all over the full volume of the device, the measured gain at 140 V drops significantly, almost 15 times. This means that when the charge equivalent to the passage of 166 MIPs reaches the gain layer, the measured value of gain is about 3.5 and does not change significantly when the voltage increases further. On the other side, although the carbon ion (C(18 MeV)) deposits 14 times more energy than the proton ion (H (0.745 MeV)) when passing the first 3.5 microns of the device, the amplifications are reduced equally (gain is about 2 at the full depletion voltage; this value is almost 2.5 times smaller than one measured for H(1.8 MeV)). The plausible explanation can be in the recombination that has a more significant impact when carrier concentration is high (in our case induced by carbon) and generated in the more doped region (in our case, it is gain layer). Moreover, charge screening also prolongs the charge collection thereby accumulating higher Auger losses. Furthermore, if lateral expansion overtakes the vertical one, then, more charge will be collected by JTE (the termination structure interfaced at the end of n++ layer in the periphery region of the pixel that isolates the two pixels) preventing electrons to undergo impact ionisation. So, to answer the question whether there is critical value for deposited energy which would indicate GS saturation we can say that this value can be set but only in corelation with the depth at which the energy is deposited by ion in LGAD. The more certain answer is that charge equal to passage of 9 MIPs will not significantly affect the gain.

3.4 Discussion on GS in correlation with the gain layer design

Here we looked at the results from measurements with proton ions of 0.56 MeV and 0.75 MeV. These had a penetration depth of 7 and 11 microns, and we performed experiments on two different sensors, HPK 28 2x2 IP5-SE3 and HPK 36 2x2 IP7-SE3, respectively. Strikingly, the gain vs bias seems to be almost equal. The only plausible explanation is that the difference in LGAD prototypes compensates for the difference in the ionisation profile of the probed ions. The difference between the two multipad samples is the nominal interpad distance (W29: 70 μm and

W36: 90 μm) and the depleted voltage of the gain layers (W28: 54.5 V, W36: 51 V). The effect of gain suppression can be used to estimate the width of the effective gain layer, while the difference when different sensors are probed with the same ion can be used to estimate the difference between the nominal and effective width of the gain layer.

4. **Conclusion**

Discoveries in frontier science depends on the progress in finding a new innovative solution for tracking and timing detectors. To support the research and development of those new innovative solutions, the RD50 group from Montenegro conducted a few R&D activities on the Low Gain Avalanche Detector.

LGAD is now mature technology for timing detectors at the CMS and ATLAS experiments. Its development lasted more than a decade. The loss of gain due to radiation was explained by the acceptor removal mechanism and the loss was compensated by increasing the bias since. The advantage of this mitigation approach was further seen in the onset of charge multiplication in the bulk region. However, the irreversible breakdown seen in tests with proton beams was later confirmed. The three different phases – stable, unstable, and irreversible damage have been defined. The V(SEB) dependence on thickness was found. The bias voltage of <550 V is defined as the safe operational voltage. When the local electric field is larger than 12 V/μm, the SEB happens.

Besides SEB study, we also overviewed and reviewed the results of GS study to which Montenegro RD50 group significantly contributed. New insights are highlighted. In this article, we paid the utmost attention to the study exploring a correlation between the rate of increase in carrier concentration at a certain depth inside LGAD and the rate of decrease in gain. The rate of decrease in the gain does not follow the rate of increase in carrier concentration; the reason is in difference in rate of expansion and recombination of charge in plasma like cloud which strongly depends on carrier concentration and on the position where the cloud is formed inside LGAD. Slicing the depth of the LGAD with different ions of different absorption depths and different stopping powers shows not only a significant dependence of the gain on probed ions but also that this difference (after careful calibration) could be utilized as a tool for particle identification (to distinguish MIP from HIP) and for the control of the lateral energy spread of the beams (useful for cancer therapy). For this, the best choice would be to use the multilayers of LGADs where different active widths of the sensor would be further explored.

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