Investigation the properties of Low Gain Avalanche Diodes (LGADs) on 60 MeV proton beam from AIC-144 cyclotron

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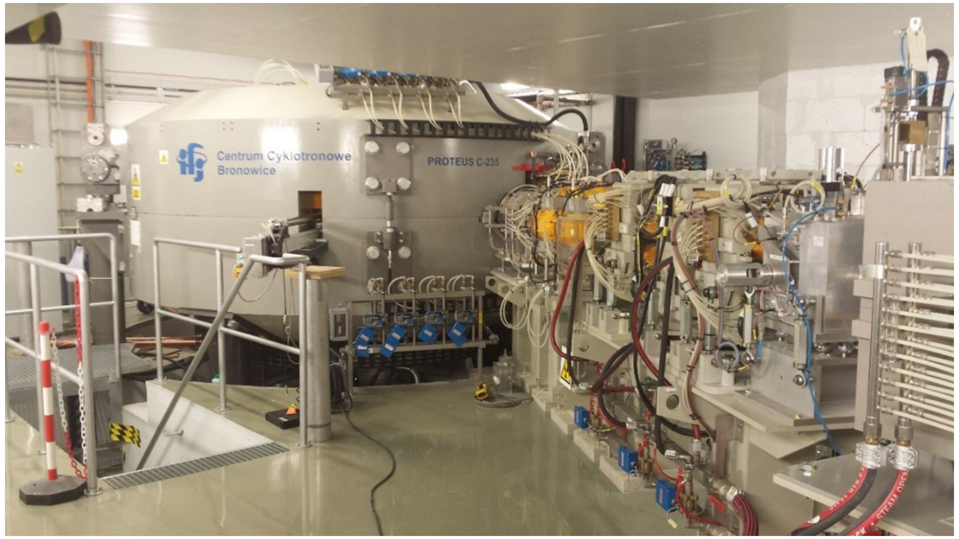
WP 4.3 Access to Research Infrastructures for Detector R&D

Two proton cyclotron facilities at IFJ PAN

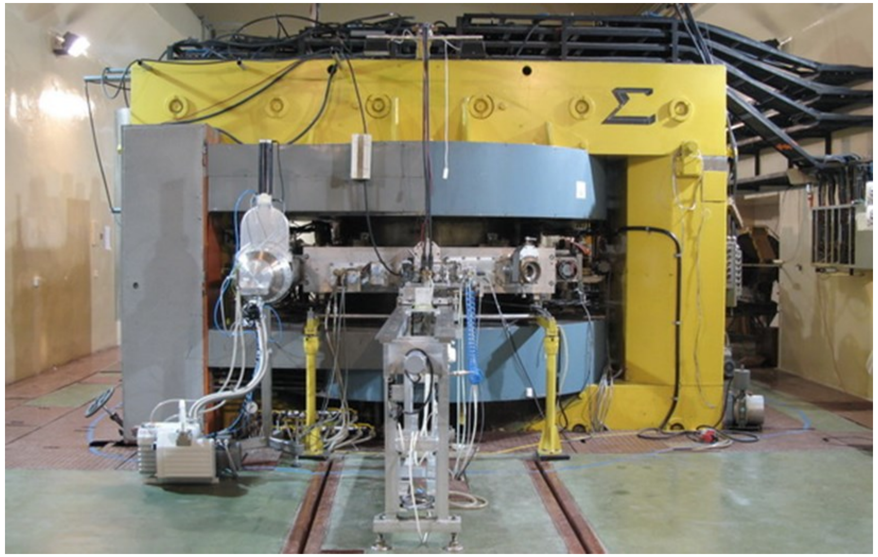
Cyclotron Centre Bronowice at IFJ PAN
230 MeV proton cyclotron + experimental room
+ proton therapy (2 proton gantries + 1eye-line)



Research in nuclear physics and Transnational Access in EURO-LABS (WP2) coordinated by Prof. A. Maj

AIC-144 at IFJ PAN

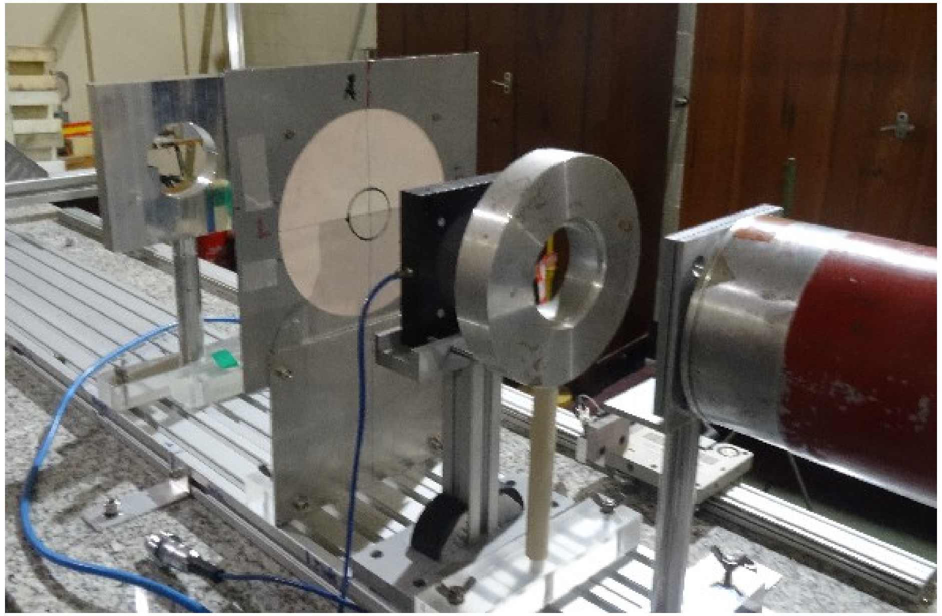
60 MeV proton cyclotron + 2 irradiation lines



Transnational Access in EURO-LABS (WP4.3) coordinated by P. Olko

60 MeV proton irradiation lines at the AIC-144

Exp. Room I */High dose-rate horizontal beam line/*



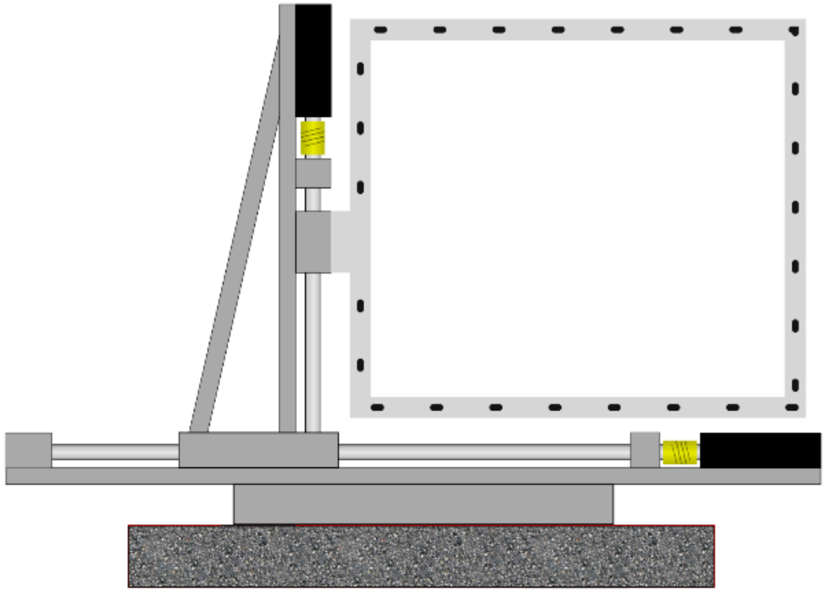
Dose rate: up to 50 Gy/s
Beam field size: ≤ 100 mm;
Proton beam current: 2nA – 100nA;
Flexibility in beam configuration

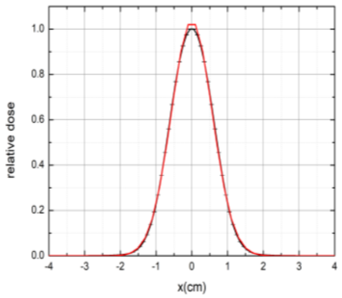
Exp. Room II */Former eye treatment room/*

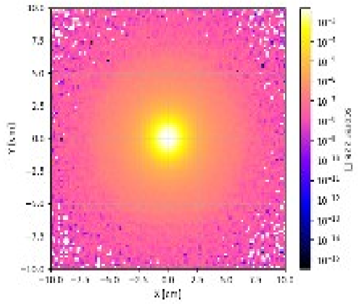
128 eye melanoma patients treated 2011-2016

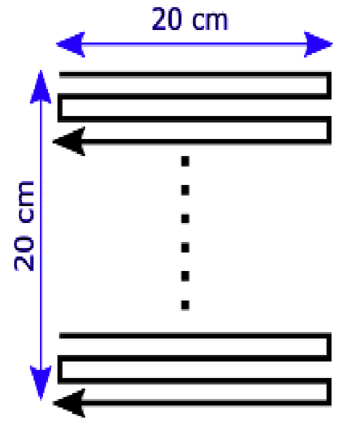
Dose rate: 0.001 – 1 Gy/s
Beam field size: ≤ 40 mm;
Typical flux: 5e5 – 1e9 p/cm2·s;
Spread Out Bragg Peak available;
Sample positioning precision (> 0.1 mm);

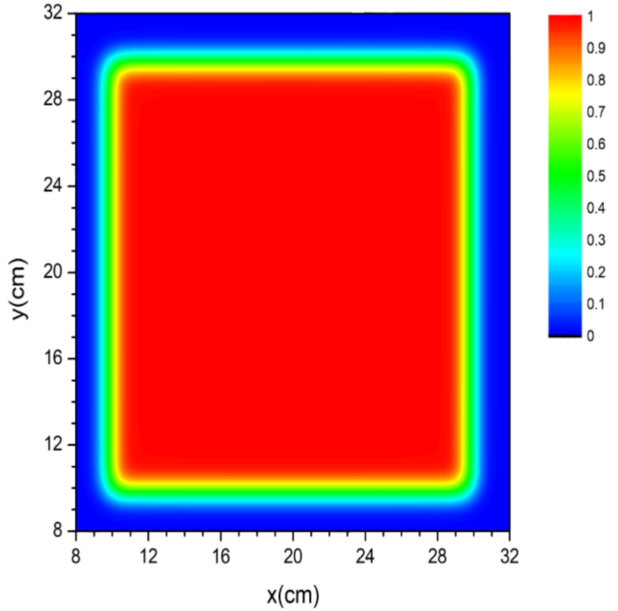
2D irradiation line at AIC-144 cyclotron at IFJ PAN











Remote controlled 2D moving table is used to uniformly irradiate objects up to 40 cm x 40 cm

WP 4.3.4 AIC-144 cyclotron –Transnational Access (TA)

- Sept. 2022 – August 2024 hosted 8 experiments
- An hour of facility operation - 1 Access Unit (AU)
- Delivered 272 hours i.e. 113% of the primary goal (30% out of 800h)

Project Title	LGAD for dosimetry
Project TA Identifier	IFJAIC-2022-01 10 -10 - 2022
PI name and affiliation	Ronan McNulty (University College Dublin)

Project Title	Dosimeters for FLASH proton therapy
Project TA Identifier	IFJAIC-2023-04 25-07-2023
PI name and affiliation	Ronan McNulty (University College Dublin)

Participating teams

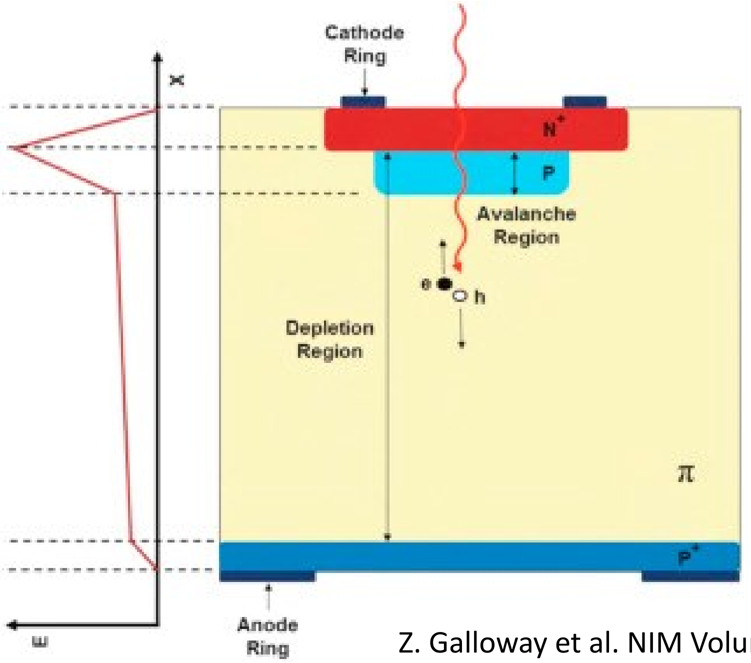
Participants in the TA experiments

Ronan McNulty (Dublin)
Nicola Minafra (Kansas)
Andrea Bellora (AGH)
Krzysztof Misan (AGH)
Piotr Rzeznik (AGH)
Christina Zacharatou (Dublin)
Timea Szollosova (Prague)

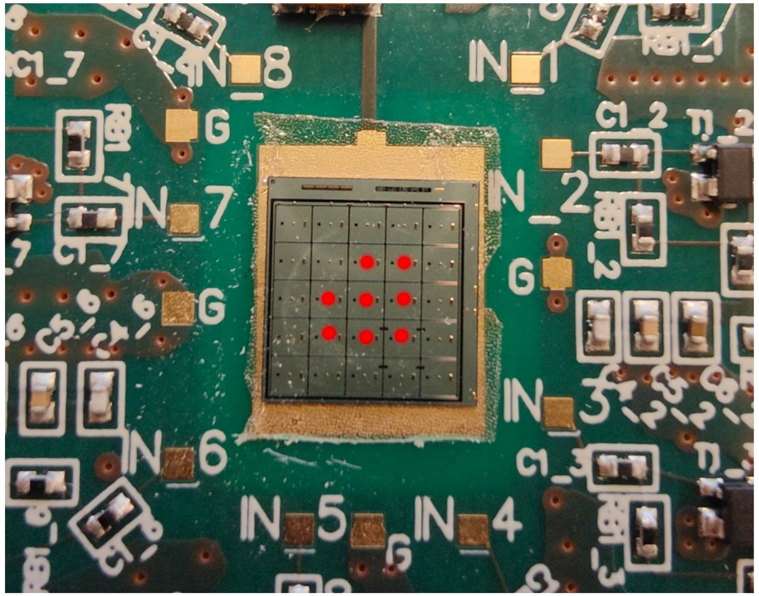
Supporting team from IFJ PAN

Jan Swakoń, Leszek Grzanka, Tomasz Nowak, Damian Wróbel, Sebastian Kusyk, Piotr Płatek, Wojciech Fryt

Low Gain Avalanche Detectors (LGAD)



Z. Galloway et al. NIM Volume 923, 2019,doi.org/10.1016/j.nima.2019.01.050



The LGAD pixel sensor mounted on the readout board (the front-end board was designed by N. Minafra at the University of Kansas, University of Turin provided the sensor)

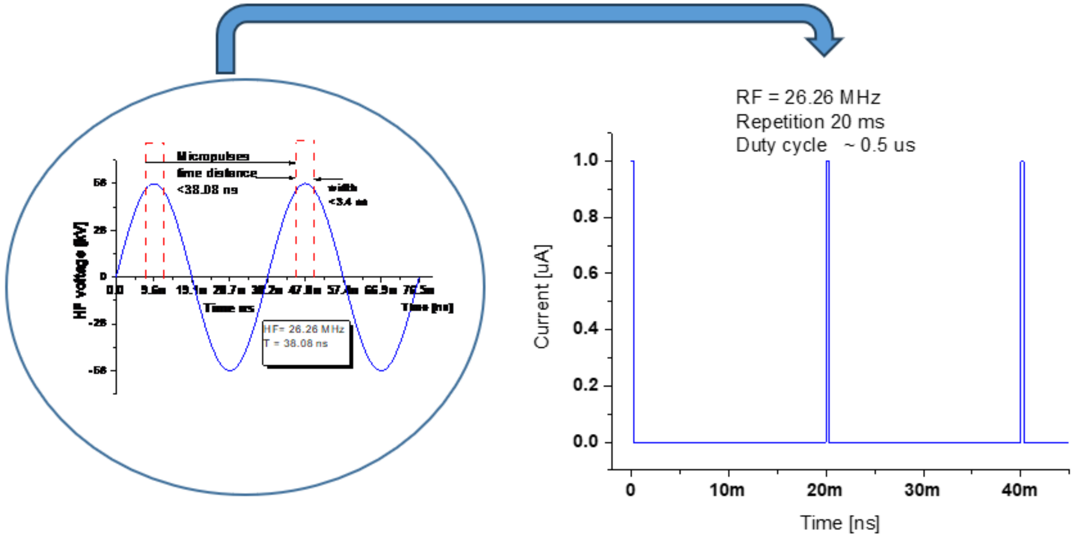
- The "P" region has significantly higher doping than the bulk π region, leading after depletion to an electric field large enough to provide amplification through multiplication of the signal

- LGAD are designed to measure charged particle fluences with high speed, spatial precision and timing capabilities

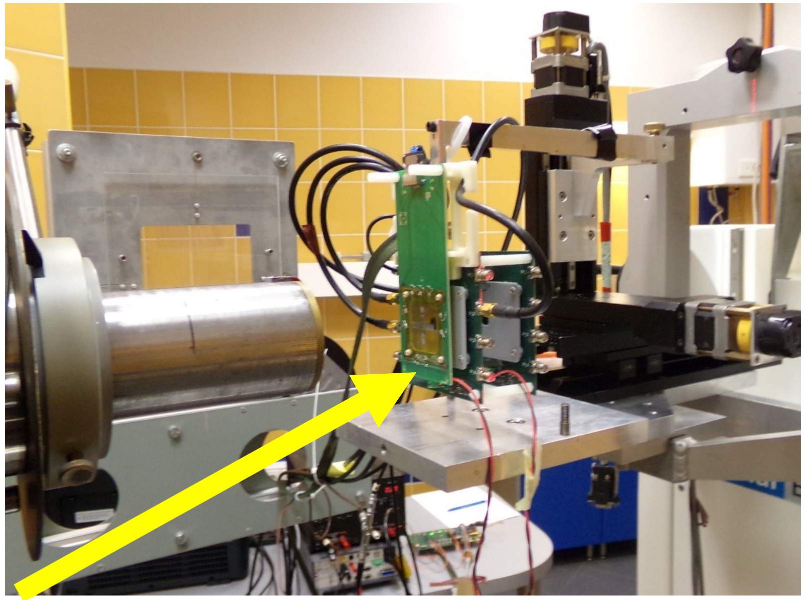
LGAD for determination of proton beam properties

Proton beam time structure:
Macro-pulses: frequency 50 Hz
pulse length ~ 0.6 ms
pulse period ~20 ms

Micro-pulses:frequency ~26 MHz
pulse length ~3ns
pulse period ~38 ns



Beam structure on AIC-144 cyclotron

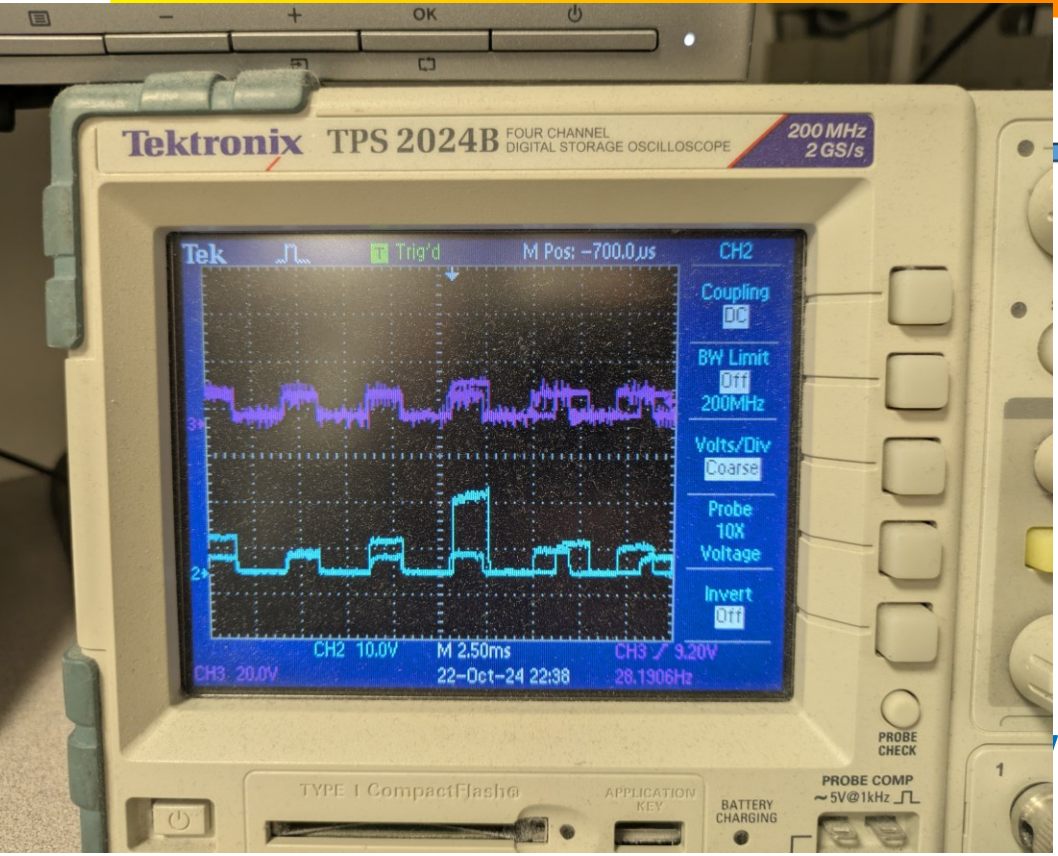


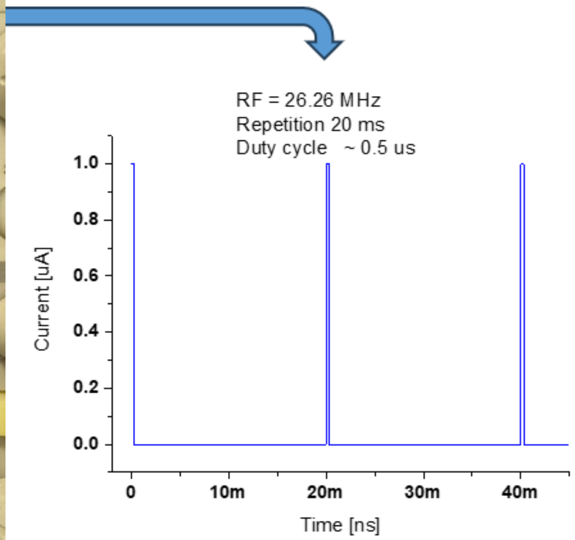
Beam Profile Monitor (IRRAD Team at CERN) and LGAD pixel sensor array at the irradiation facility

Goal of experiments:

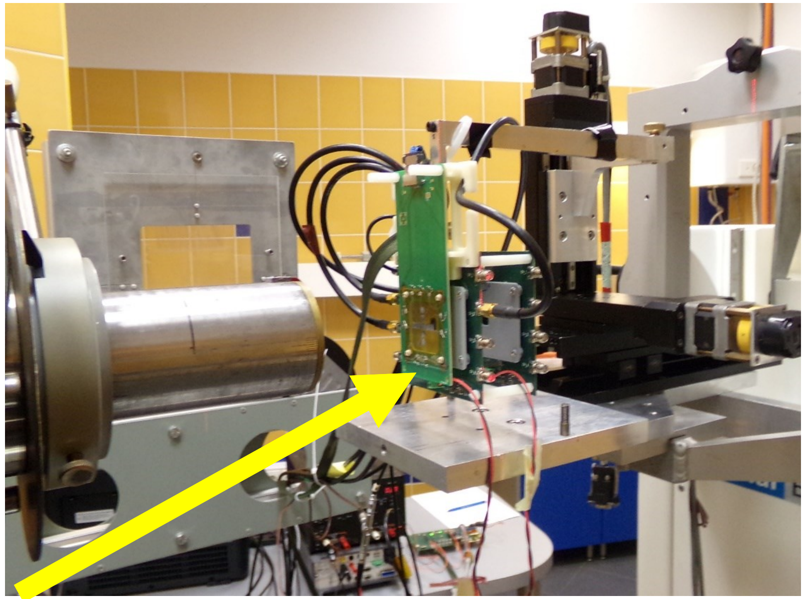
- Detection of single protons
- Measurement of energy deposited by 0 - 60 MeV protons
- Determination of beam fluence
- Measurement of the spatial and temporal beam profile

LGAD for determination of proton beam properties





yclotron



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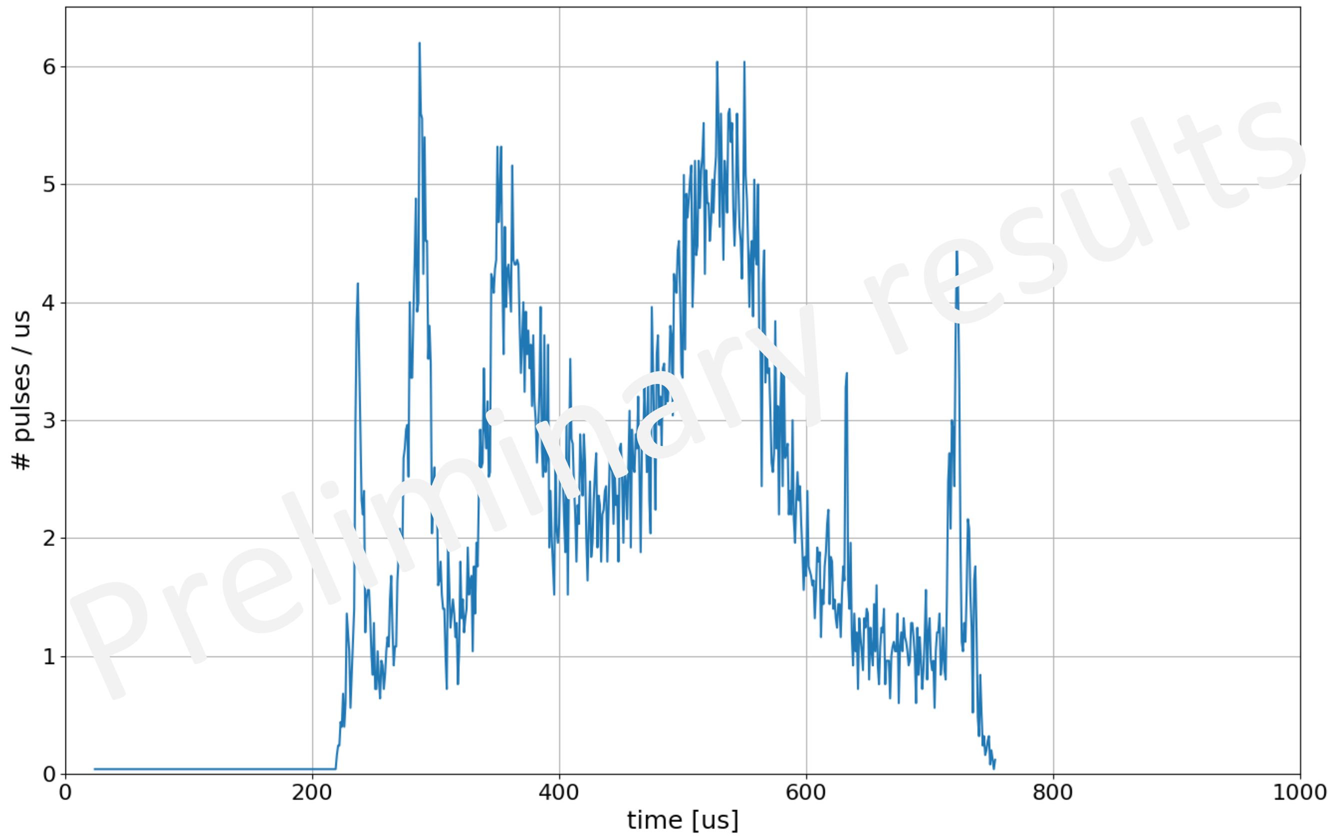
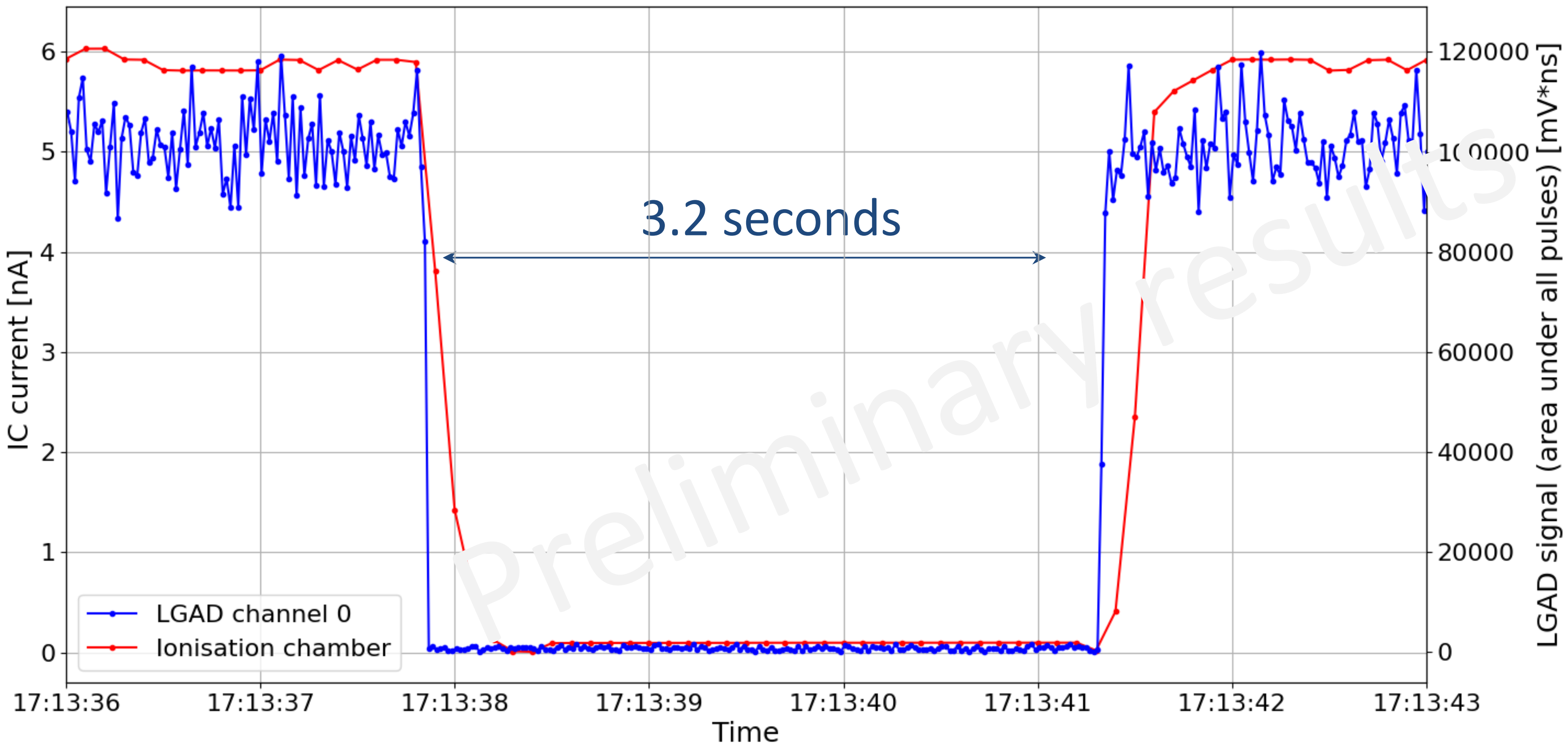
LGAD measurements of the AIC-144 beam – results (1)

- MICRO-PULSE : Individual protons were observed with a time resolution of 50 ps.
- MACRO-PULSE: In precise measurements of the macro-pulse it was seen that the dose delivered in one pulse is not constant and varies by a factor ~5 with time.
- A way for quick diagnosis of cyclotron operation and beam extraction



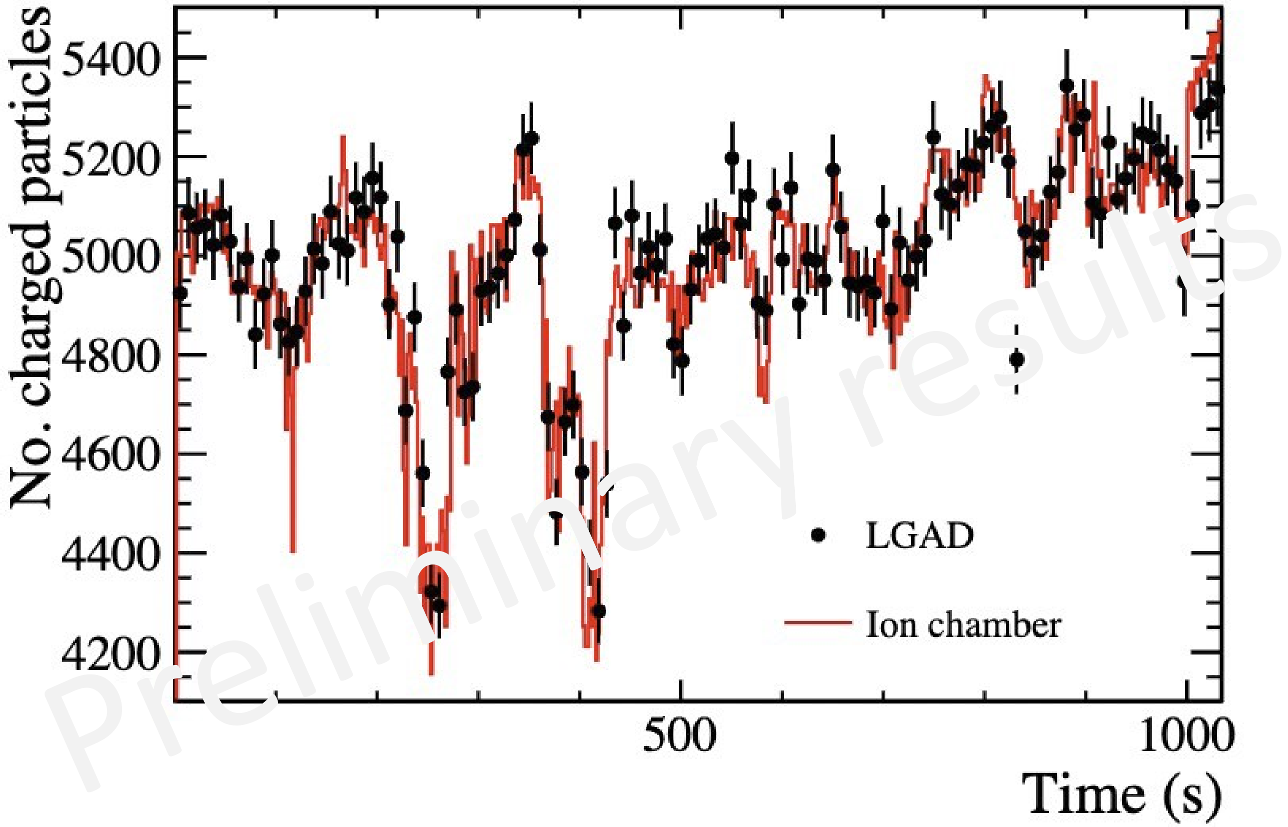
Macro-pulse structure of the AIC-144 proton beam:
mean mumber of registered particles in 25 consecutive macropulses

LGAD measurements of the AIC-144 beam – results (2)



Short (nanoseconds) reaction time of LGAD would allow much faster beam switch-on switch –off in proton therapy than ionization chamber with electrometer

LGAD measurements of the AIC-144 beam – results (3)



At low beam intensities an excellent correlation observed between the current recorded by the ion chambers and the number of protons recorded by the LGAD detector.

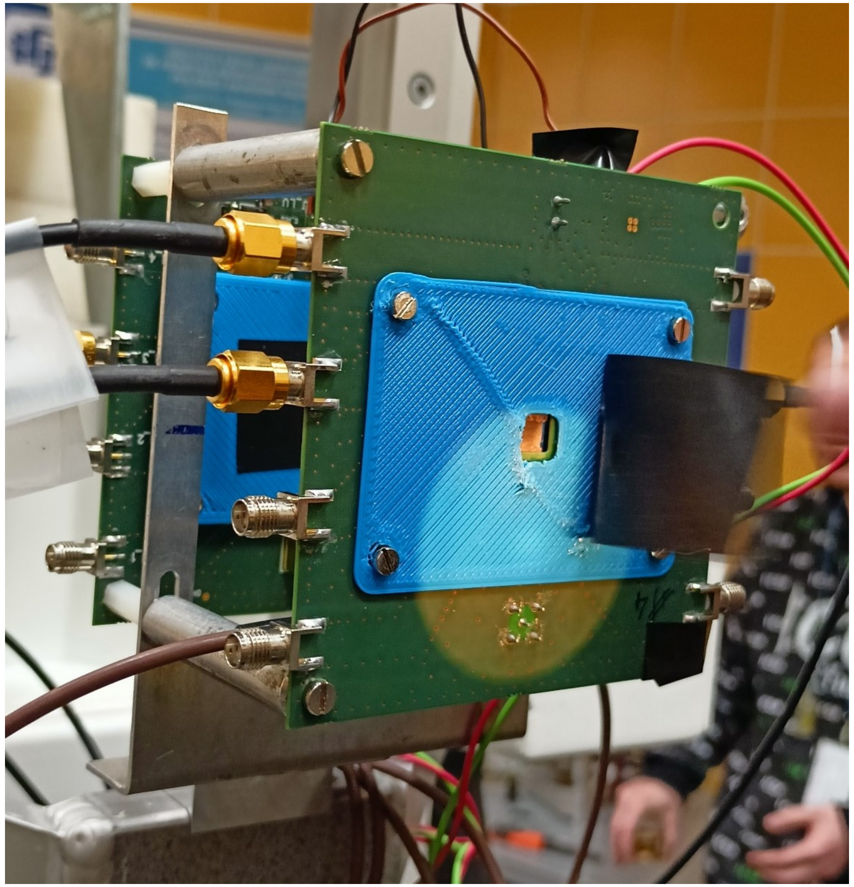
LGAD for determination of high intensity proton beams (FLASH)

GOAL of measurements:

- to prove the linearity of the LGAD response in high intensity environment
- measure depth-dose profile
- employ time-of-flight method to deduce beam energy

Properties of the fast silicone sensor LGAD

- Gain of ~20
- Fast rising time ~500ps
- Short pulses ~1.5ns
- Small pixels 0.5x4 mm2 / 1.3x1.3mm2
- Operate at nominal beam current
- Sensors are radiation-resistant



Two LGAD boards at the irradiation unit

Data acquisition setup

Aim:
- operate LGAD in particle-counting mode
- register signal waveforms for offline processing
- capture data for couple of minutes

Continous data taking
10 GS/s sampling mode @ 2 bytes => 1.TB / min

Each macropulse registered
Trigger @ 50Hz and registering 1 ms => 60 GB / min

Scope buffering + SSD speed -> throttling
- save 25 macropulses (500 ms), dump data (7s), repeat
- save 1 macropulse (20 ms), dump data (1s), repeat

Data flow:
1. LGAD boards
2. Scope fast RAM memory
3. Fast SSD disk (over USB)
4. S3 storage @ Cyfronet (over Gigabit Ethernet)

In total gathered 2.7 TB of raw data

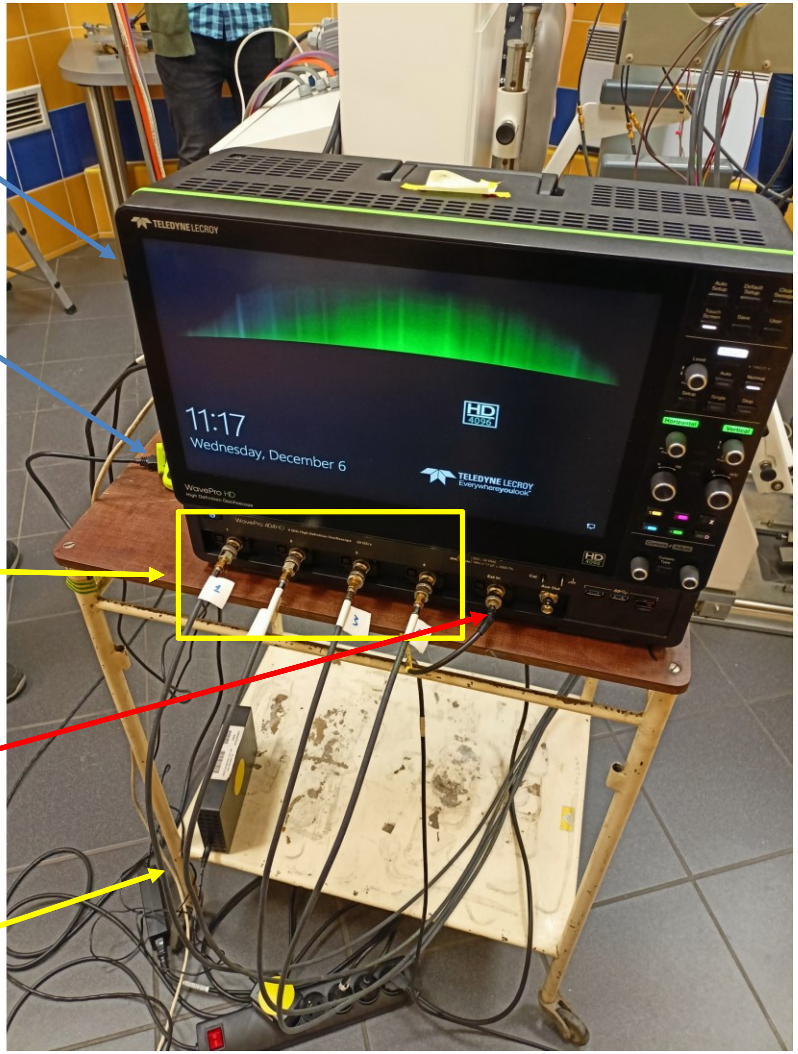
LeCroy scope
10 GS/s sampling

Fast USB 3.0 SSD

4 channels from
LGAD boards

trigger signal (50Hz)

Gigabit Ethernet
-> S3 storage @
Cyfronet



Data reduction – single proton identification

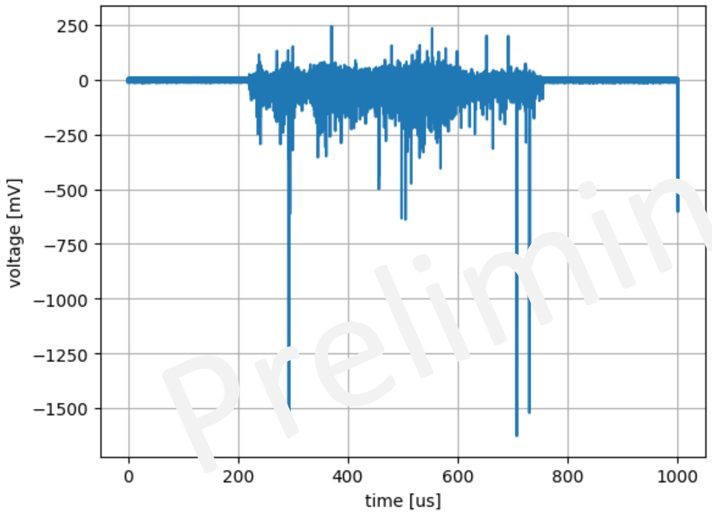
Peak finding:

Need to work under various conditions

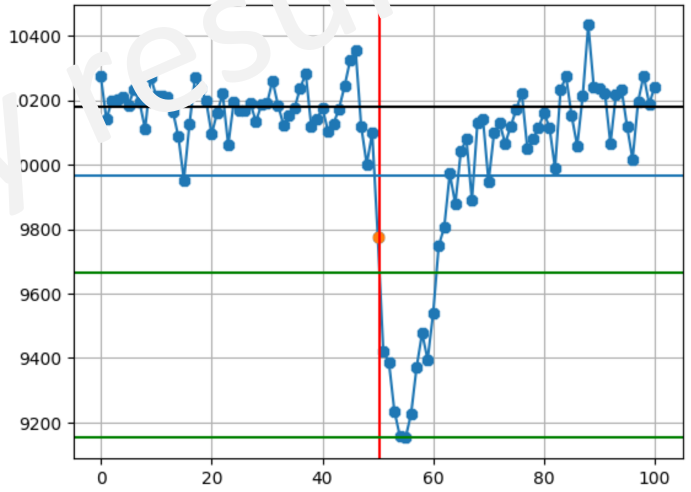
- Low and high multiplicity
- Various gain settings
- Different sampling

The method:

- base line analysis
- choosing correct threshold
- iterative procedure over ~ 2TB of data
- each iteration: ~2 hours on ~80 jobs

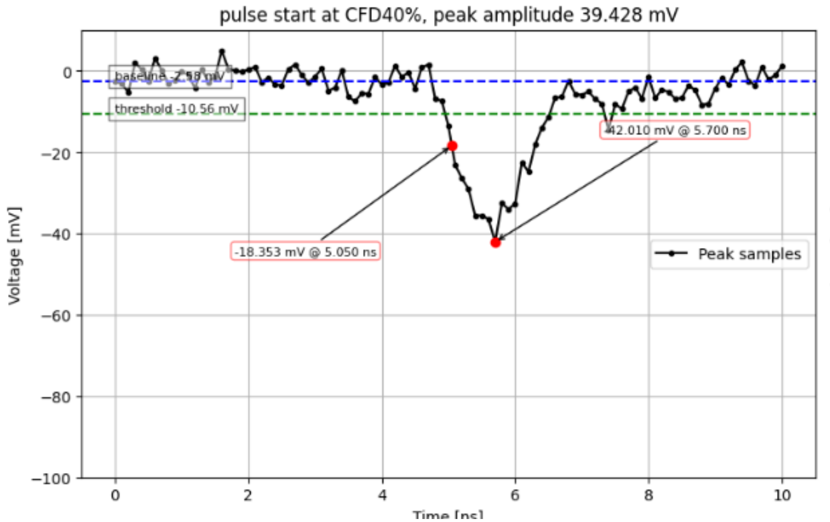


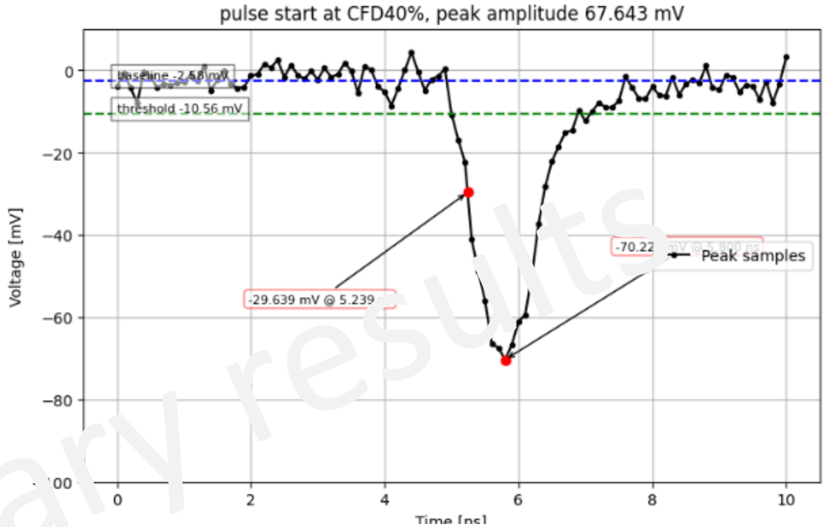
One macropulse : typically, few thousands protons.

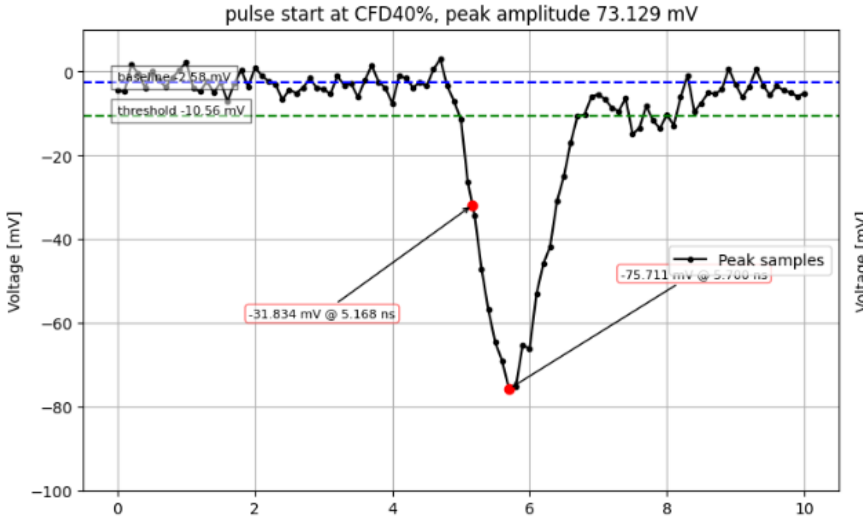


Negative peak – corresponding to detected single proton

Single proton identification of different energies



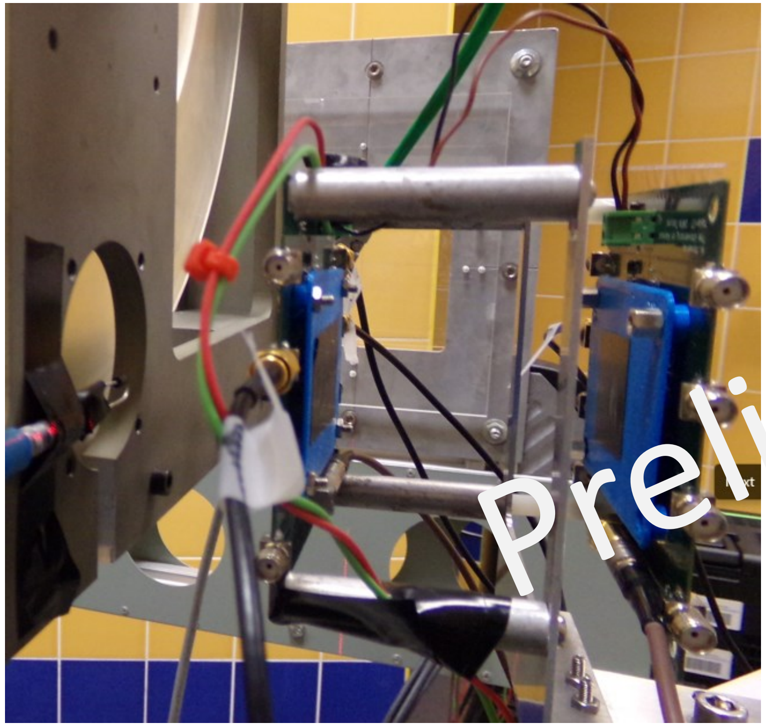




- Individual protons could be identified.

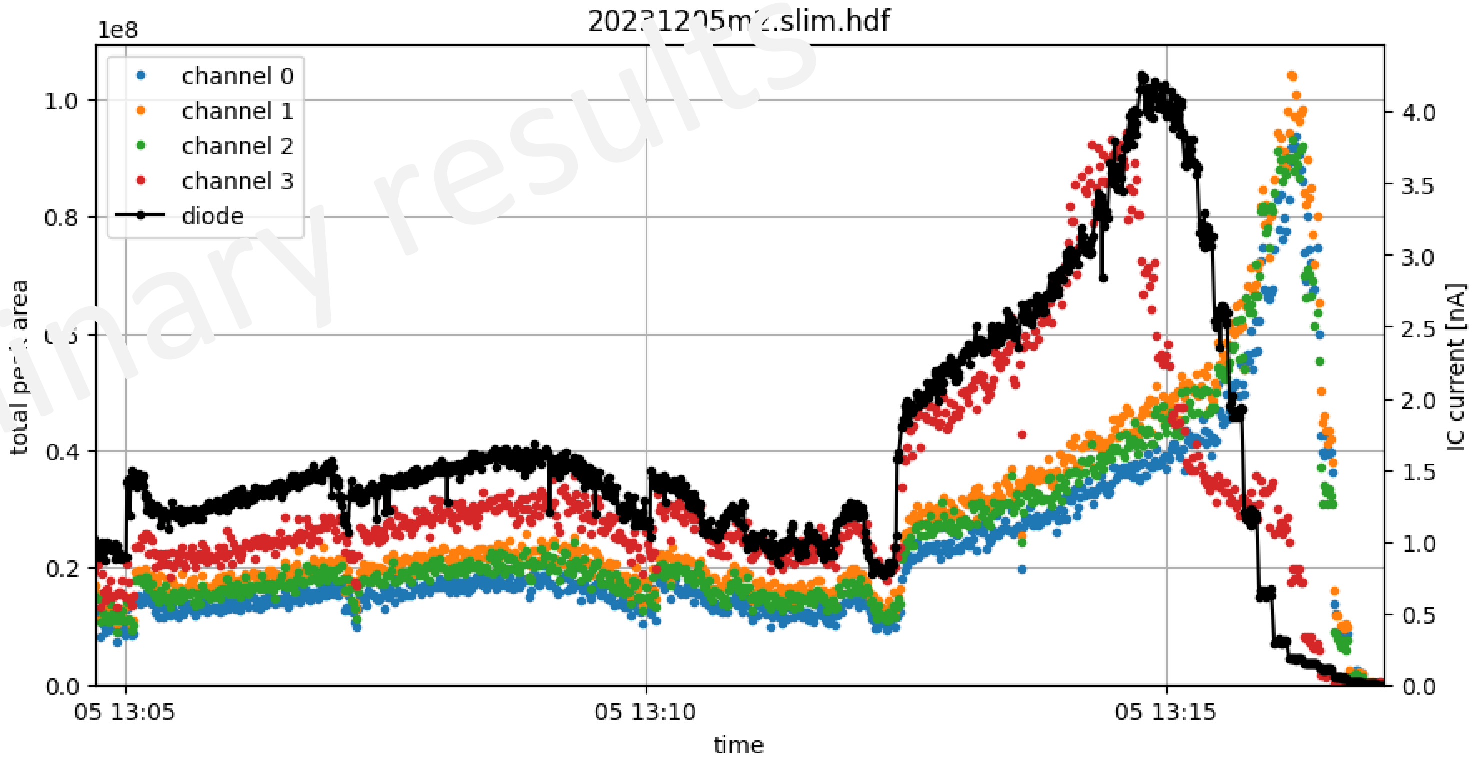
- The amplitude proportional to proton stopping power in Si, decreasing with proton energy

Measurements of the depth dose (Bragg peak)



Channel 3 is on 2nd board,
protons loose energy
crossing 1st board, stops "earlier"

Protons loose energy on **diode** envelope,
stopping earlier than on 1st board

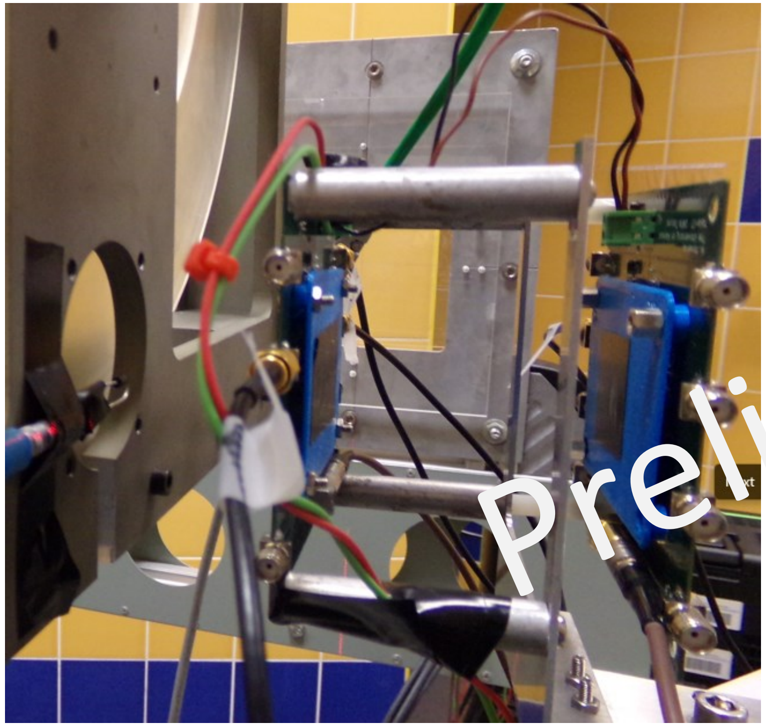


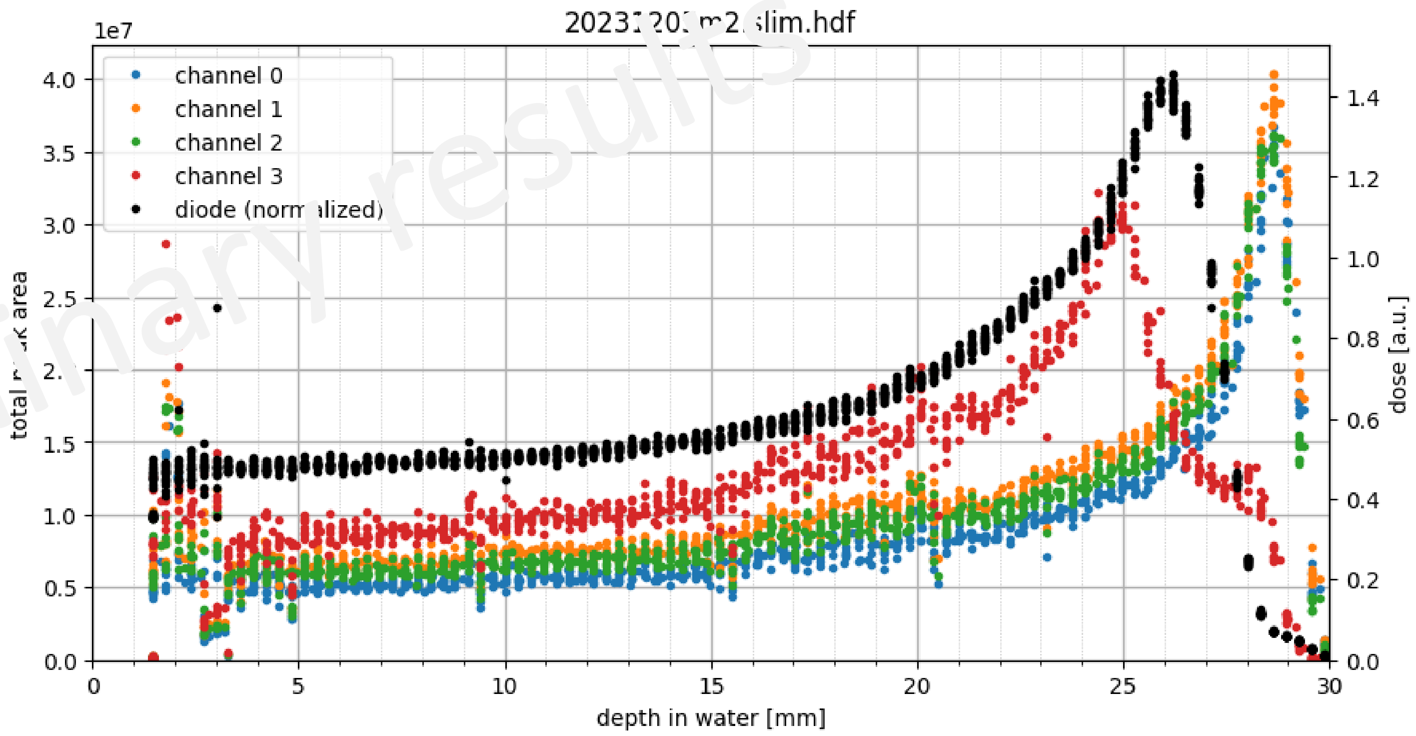
Direct (not normalized) correlation of LGAD signal (total area under all peaks) and signal from diode measured behind PMMA wheel

Measurements of the depth dose (Bragg peak)

Channel 3 is on 2nd board, protons loose energy crossing 1st board, stops “earlier”

Protons loose energy on **diode** envelope, stopping earlier than on 1st board





Correlation of **normalized** LGAD signal (total area under all peaks) and **normalized** diode measured behind PMMA wheel **gives correct Bragg peak**

Summary

The experiments performed within the two EURO-LABS TA experiments demonstrated the usefulness the use of LGAD detectors for accelerator control and beam monitoring:

- LGAD very well reproduced the signal of ionization chamber used to beam monitoring
- LGAD detectors were proven to be useful in the analyses the time structure of proton beam
- Due to microsecond reaction time can be used for fast switch on – switch off proton beam
- LGAD can work with high beam intensities, which is requested in radiation therapy (FLASH)
- We are working on publication of the first results (to be submitted to Physics in Medicine and Biology this autumn).