Application of scCVD for proton beam diagnostics. New developments at IFJ-PAN

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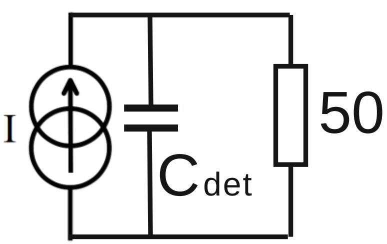
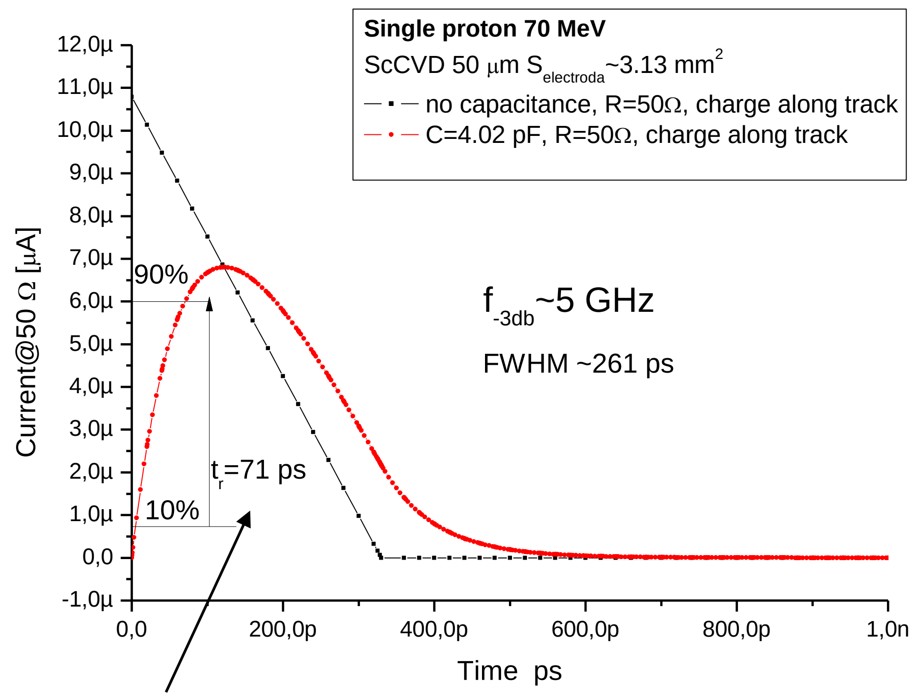
Outline

- Diamond CVD detector for particle beam measurements and diagnostics
- Characteristics and parameters of two cyclotrons at IFJ PAN: AIC-144 and Proteus-235 (IBA)
- Proton beam diagnostics in single-particle mode. Time structure and intensity (current) measurements.
- Performance and challenges of front-end electronics for CVD detectors. Emphasis on low-noise performance, wide bandwidth (>1GHz) and high gain.
- Results of measuremens with Proteus-235 and AIC-144 machines
- Outlook and future plans

Diamond detector signal. The effect of the detector capacitance.

Capacitance C=e*S/d= 4.04 pF@50 um

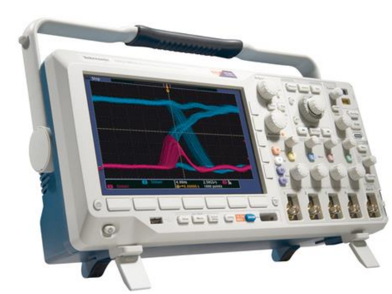




Where is the limit in terms of rise time when the bandwidth f-3dB = 1 GHz is used?

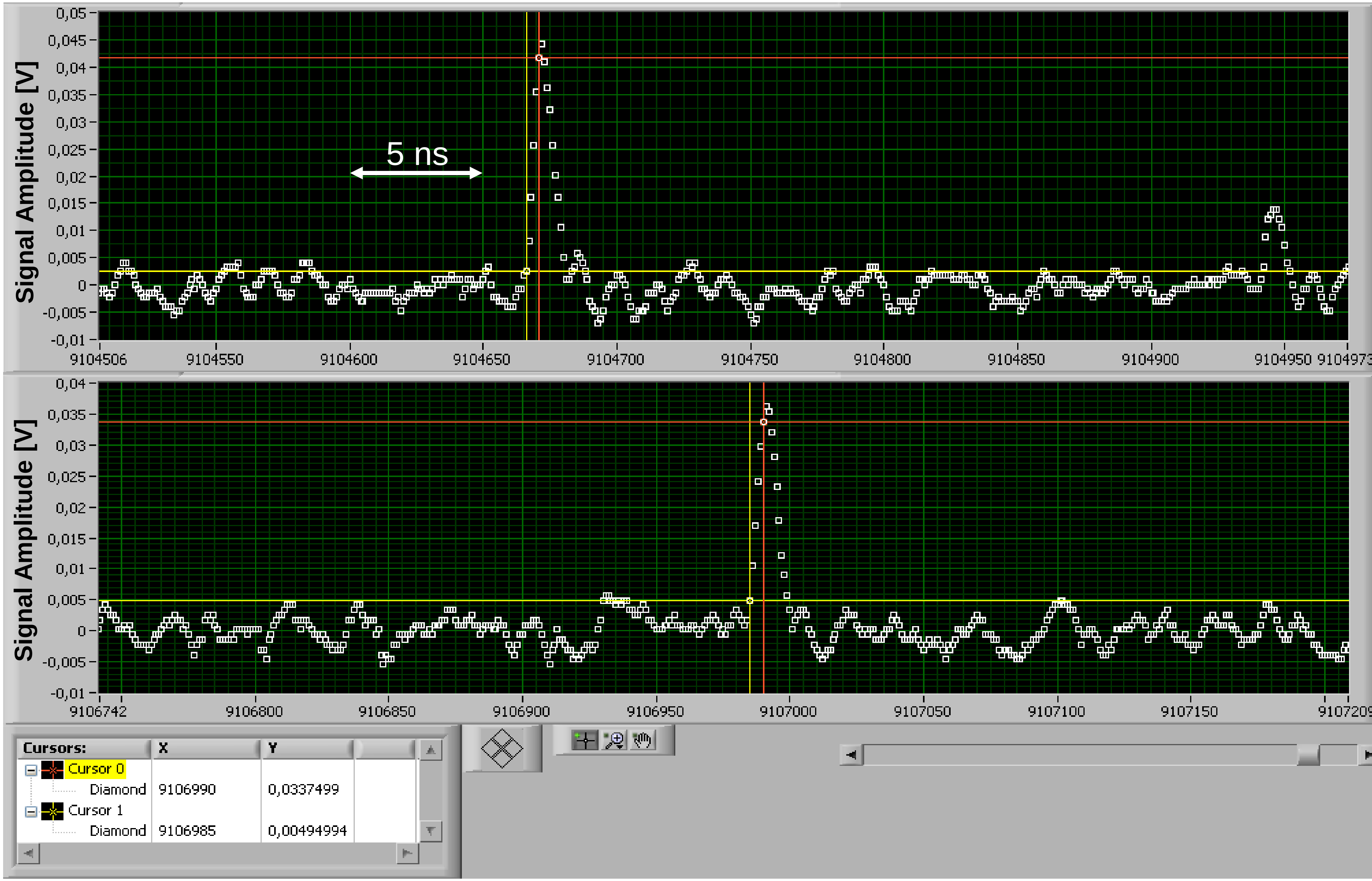
T_r =~ 350 ps

Most of the presented measurements were taken with Tektronix DPO5104 1GHz 10GS/s oscilloscope



by Tomasz Nowak IFJ PAN

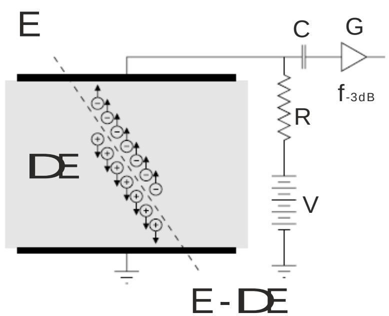
50um CVD det. exemplary signal @ 70 MeV protons



Rise time (90-10%) ~500 ps | FWHM ~800 ps

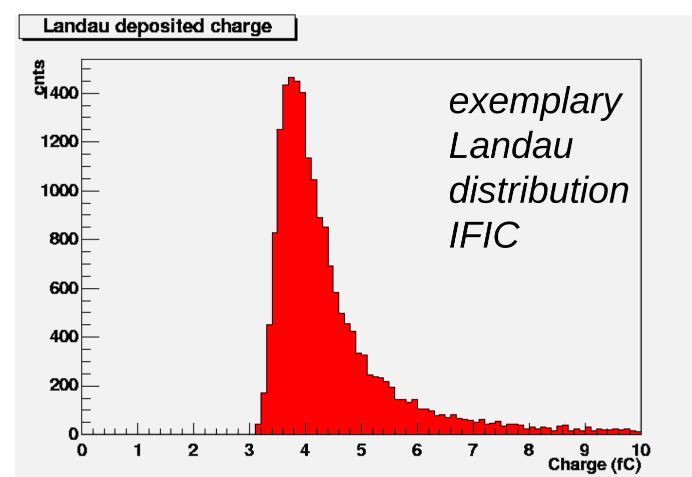
Energy loss in the detector – Landau distribution

dE/dx - Bethe-Bloch formula – the most probable signal value



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

K	$4\pi N_A r_e^2 m_e c^2$
Z	Atomic number of absorber
A	Atomic mass of absorber
m_e	Mass of an electron
r_e	Classical radius of an electron
I	Mean excitation energy
T_{max}	Maximum Kinetic energy which can be imparted to a free electron in one collision



Specifications of cyclotrons at IFJ PAN: AIC-144 and Proteus-235

Cyclotrons at IFJ: AIC-144 & IBA Proteus-235

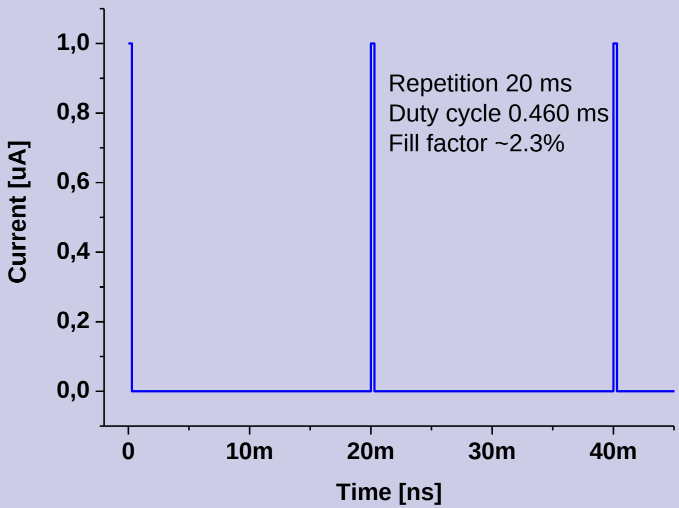
AIC-144

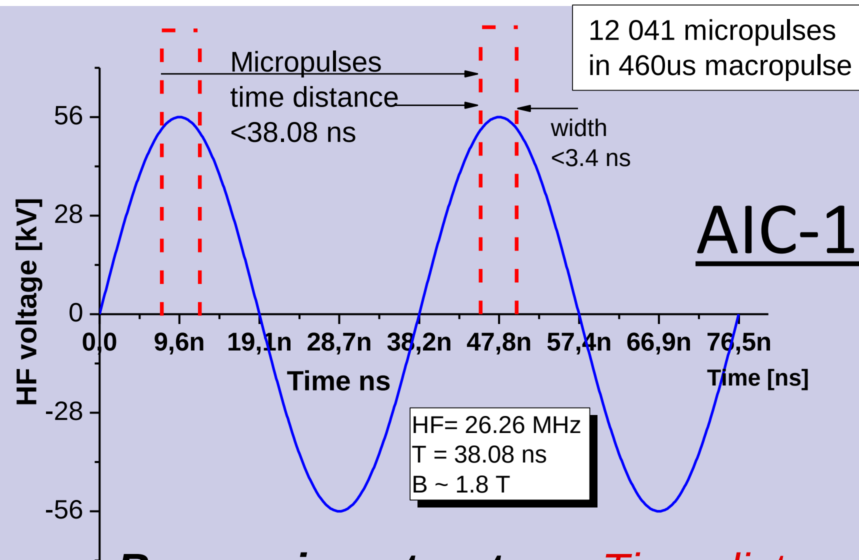
Beam energy	60 MeV
Beam current	up to 80 nA
Magnet Leg Diameter	144 cm
Magnetic Structure	4 spiral sectors
Magnetic Field	0,85 ÷ 1,8 T
Main Coil Current	0 ÷ 650 A
Number of Harmonic Coils	4
Trim Coils Current	±400 A
Number of Dees	1 (α=180º)
RF Generator Frequency	10 ÷ 27 MHz

IBA Proteus-235

Beam energy	70 - 230 MeV
Ion beam current @ 230 MeV:	1 - 300 nA
Magnet yoke outside diameter	4,34 m
Magnet leg diameter	2,1 m
Magnetic structure	4 spiral sectors
Maximum magnetic field	3,1 T
Maximum current in main magnet coil	800 A
Number of dees	2 (45°)
RF system operation frequency	106 MHz
Dee voltage	50 - 100 kV
Extraction Factor	70%

Cyclotrons at IFJ: AIC-144 & IBA Proteus-235





AIC-144

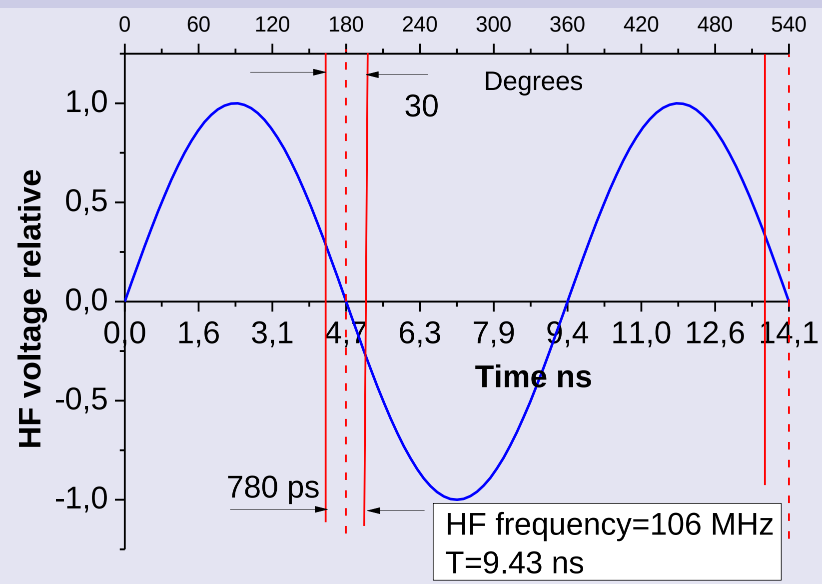
Beam macrostructure: *Time distance between adjacent macropulses = 20 ms*

Beam microstructure: *Time distance between adjacent micropulses = 38.08 ns*

IBA Proteus-235

Beam microstructure: *Time distance between adjacent micropulses = 9.43 ns*

No beam macrostructure.
Quasi-continuous beam.



CCB (Bronowice Cyclotron Centre) - therapeutic beam parameters

Beam parameters @ ocular therapy site (example)

~0.014 **protons**/mm^2/micropulse – flat intensity profile after scattering foil.

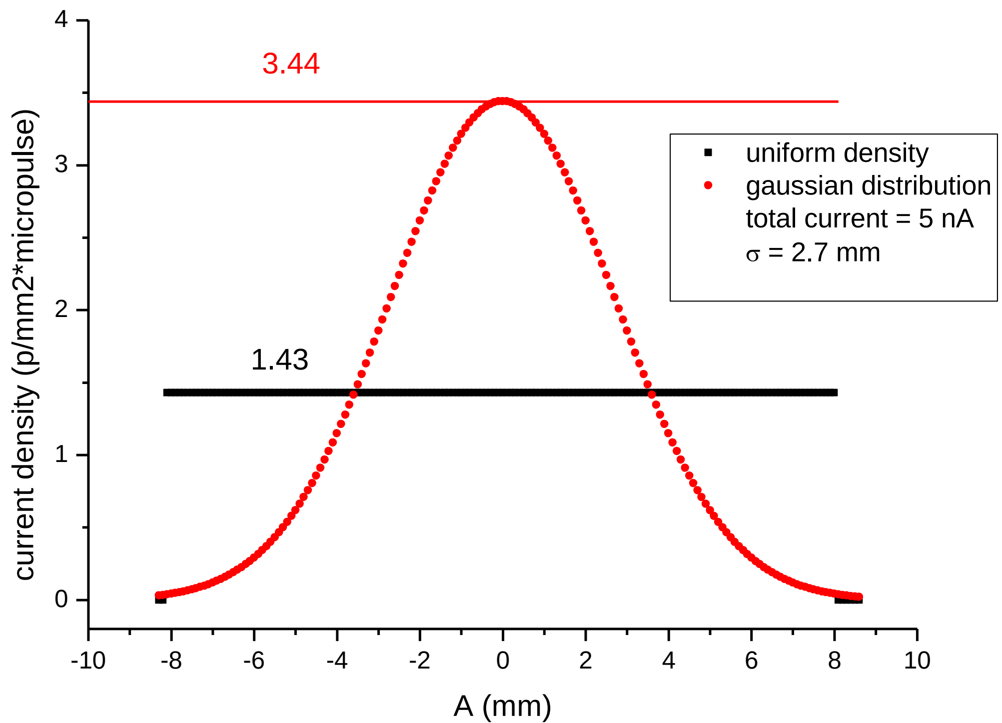
Beam parameters @ GANTRY site (example)

~2.4 **protons**/mm^2/micopulse at 5 nA – gaussian intensity profile.

Proteus-235 Gantry profile

(Normal Distribution

σ= 2.7 mm, 5 nA)



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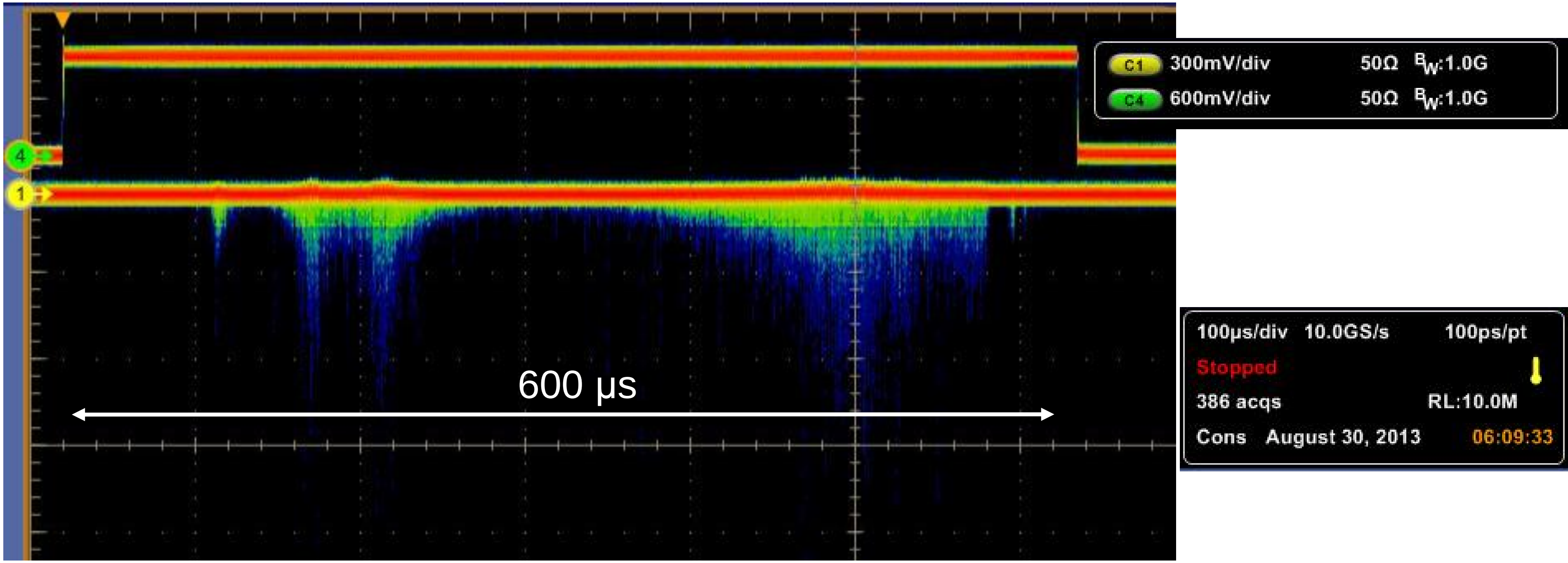
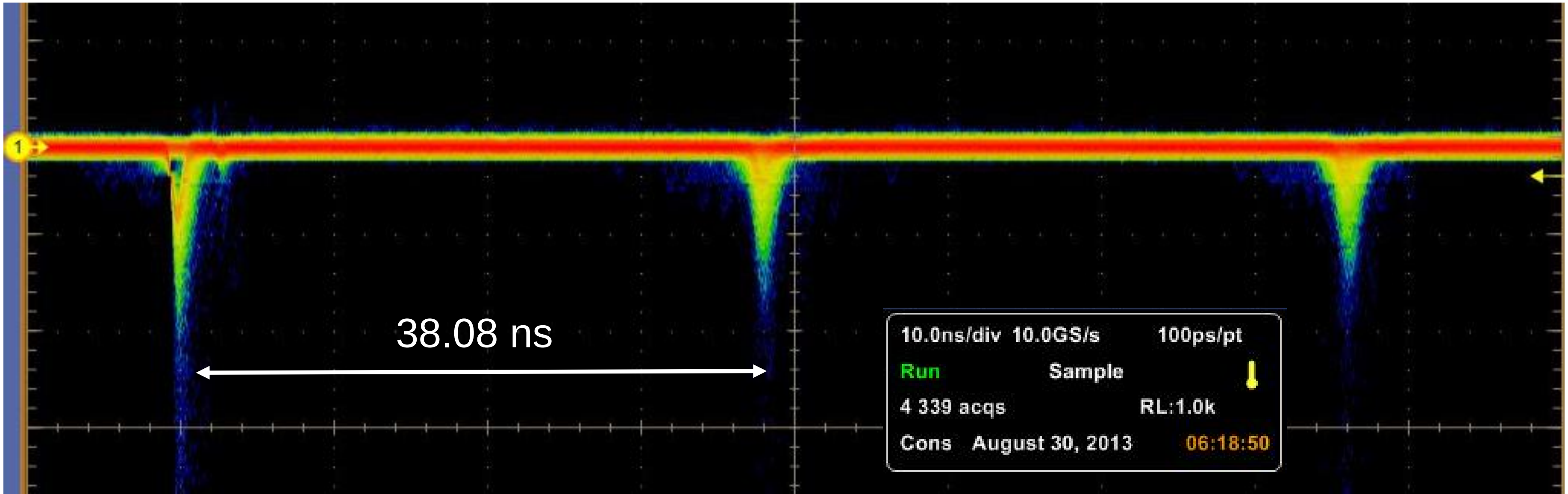
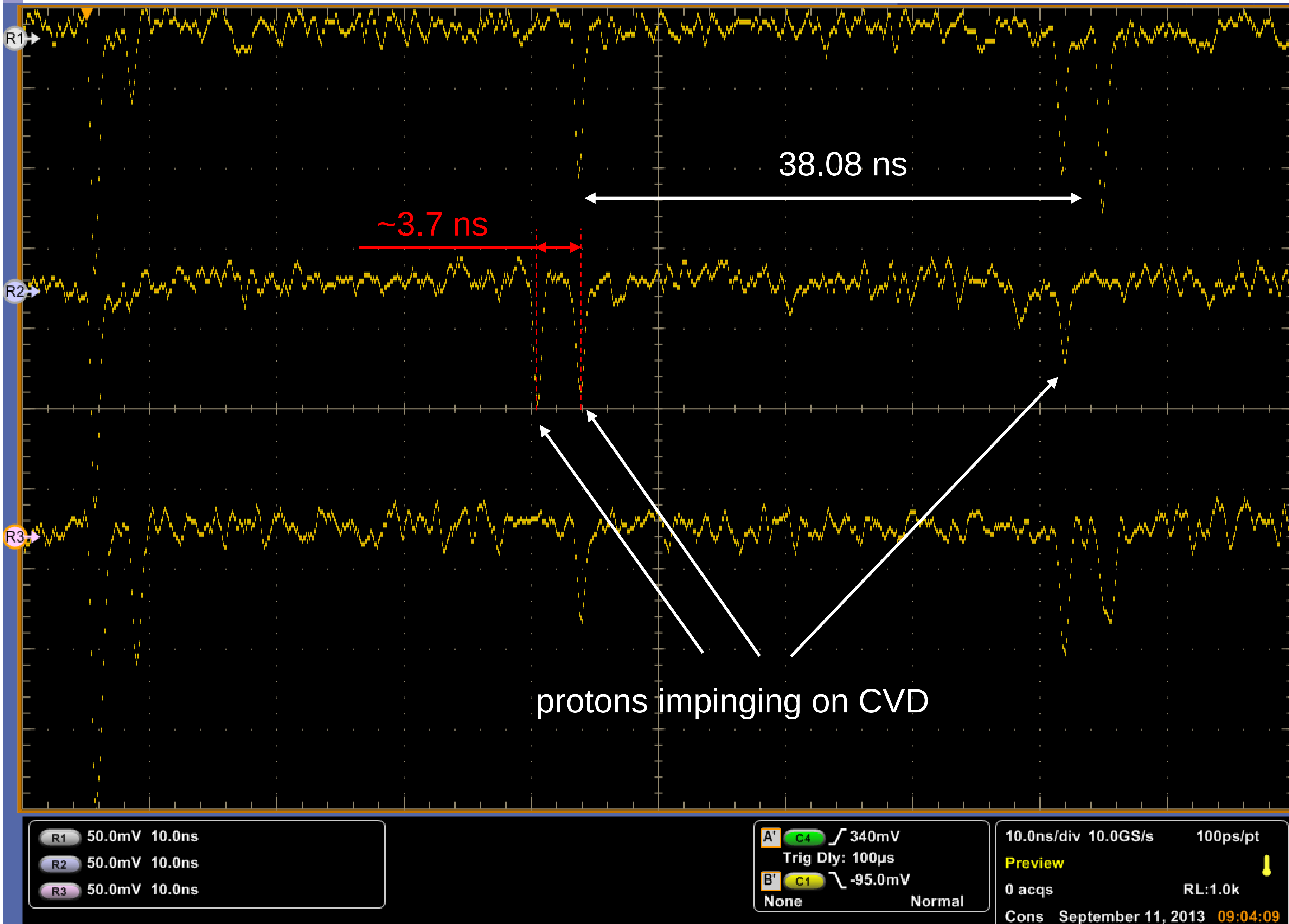
Proton beam diagnostics in single-particle (counting) mode

Time structure of the AIC-144 @ 50µm scCVD

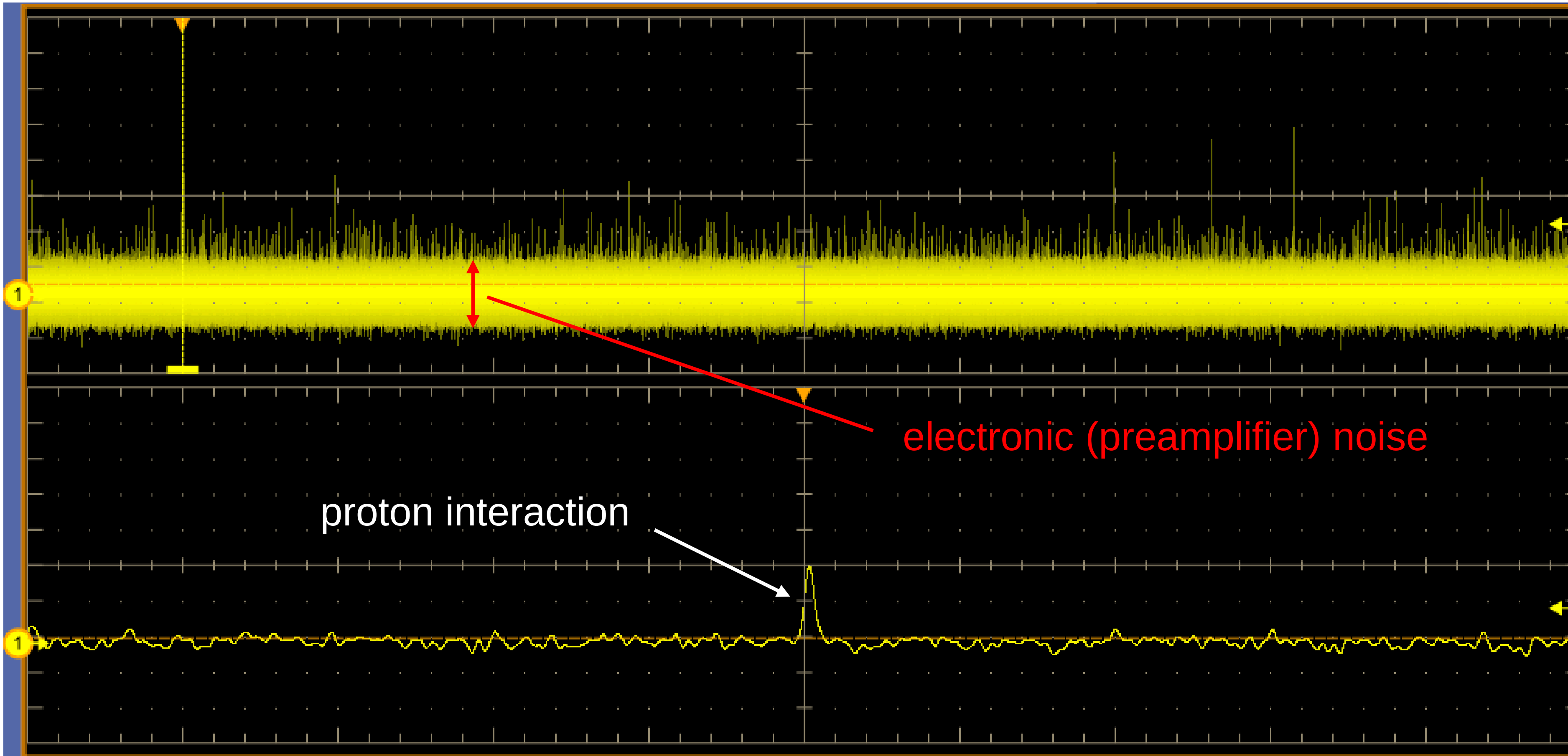




Time structure of the AIC-144 beam c.d.

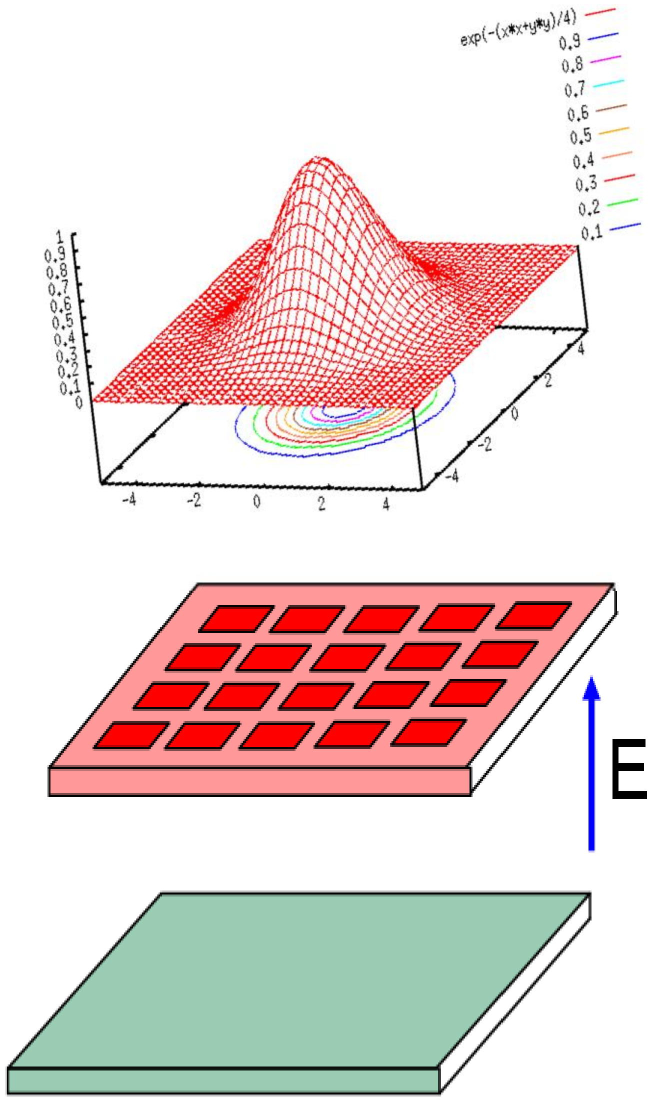


Time structure of the Proteus-235 @ 50µm scCVD



		Value	Mean	Min	Max	St Dev	Count	Info
C1	RMS	5.783mV	5.7904211m	5.739m	5.808m	6.057µ	146.0	
C1	AC RMS*	5.747mV	5.7554926m	5.706m	5.773m	6.025µ	146.0	

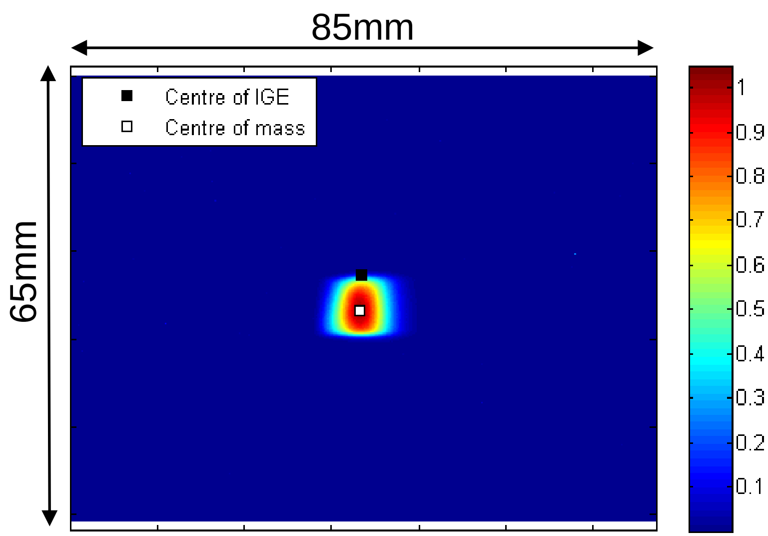
Concept of a segmented CVD detector for time- and space- beam profilometry



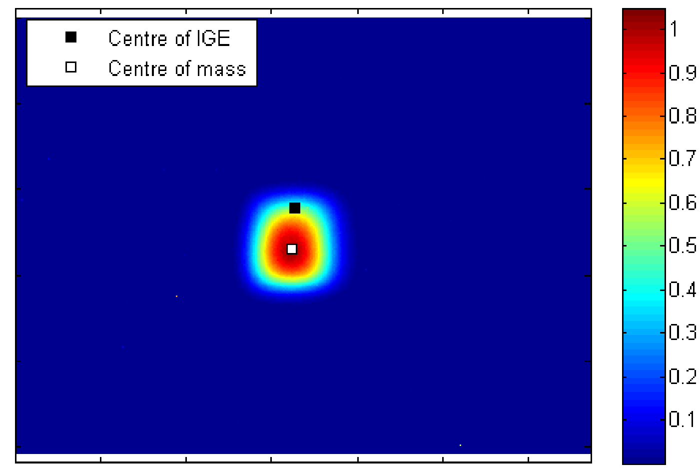
Main parameters to be defined according to application

- Spatial resolution
- Dimensions (total area)
- Fill Factor
- Signal (from single pixel) time duration
- Time resolution

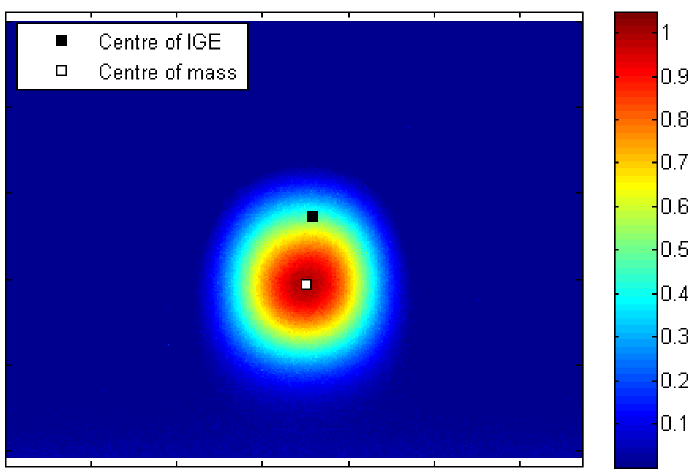
Proteus-235 beam profiles measured in Experimental Hall of CCB (Cyclotron Centre Bronowice).



Distance from Ion Guide End (IGE): Z=0



Distance from IGE: Z=0.7 m



Distance from IGE: Z=2 m

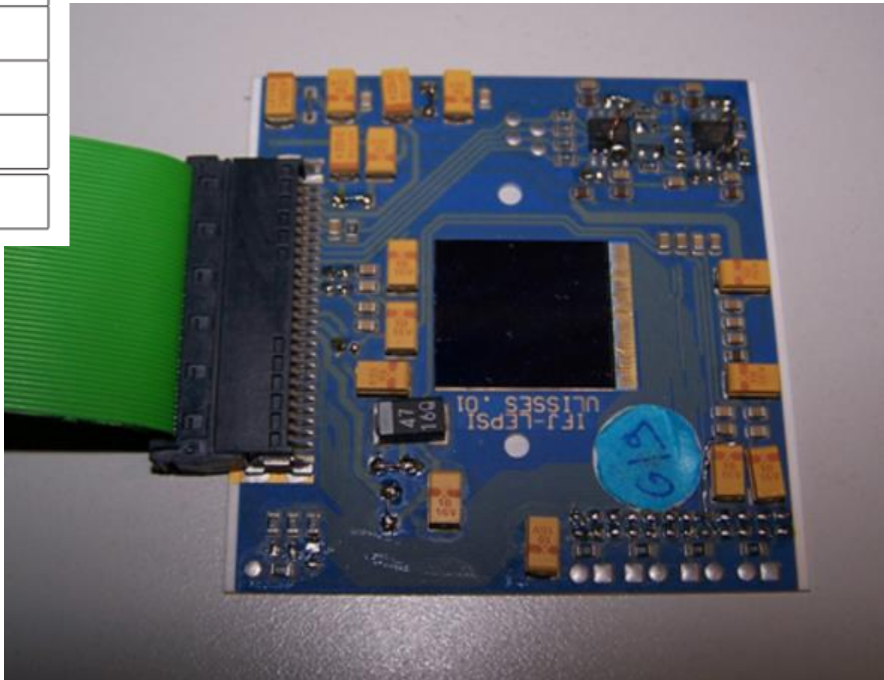
Measurements have been performed in the air by ProBImS measurement system developed at IFJ PAN and composed of scintillating screen and high-resolution ATIK 383 L+ digital camera.

by Marzena Rydygier IFJ PAN

Example of a silicon pixel detector capable of operating in single-particle detection mode

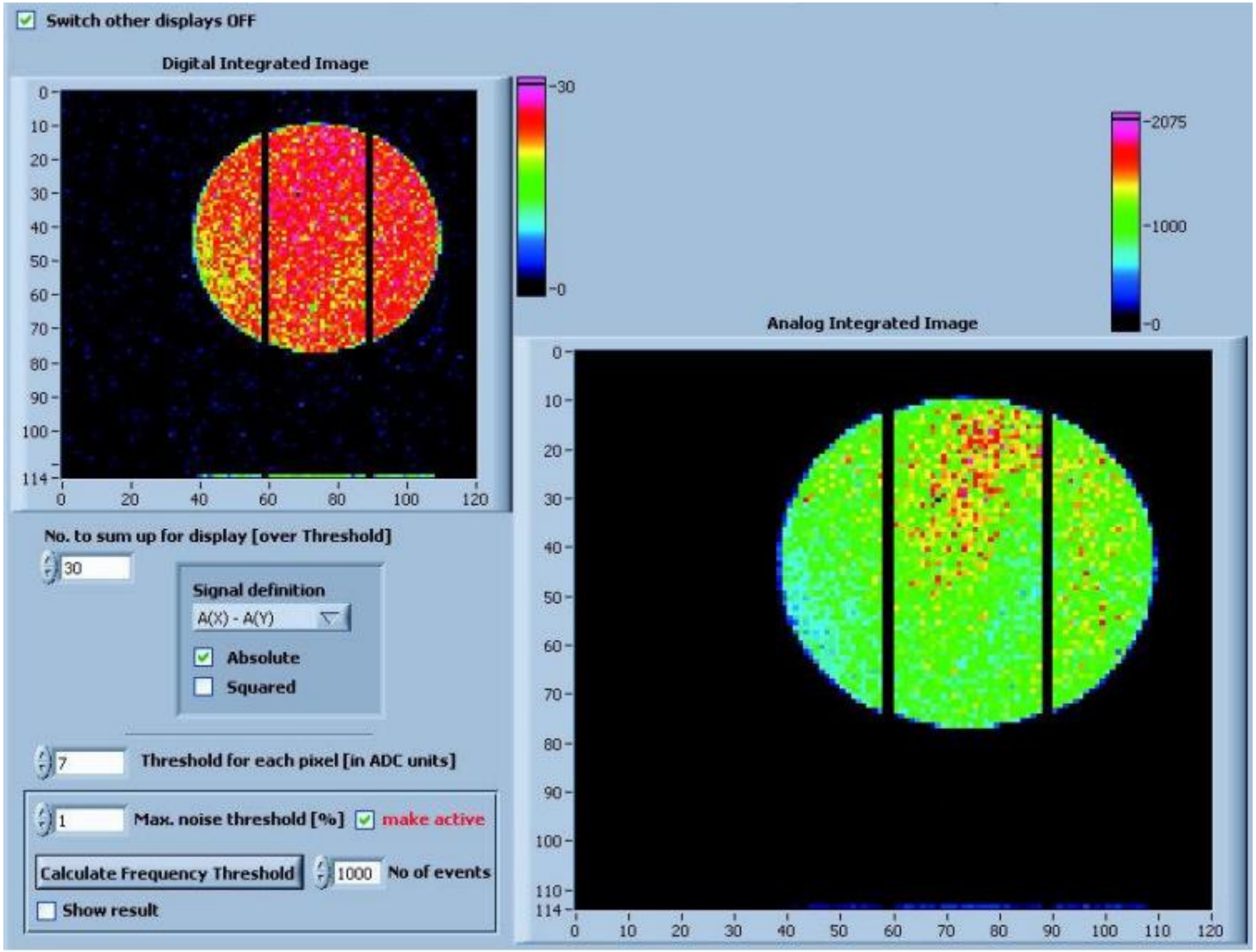
Ions: protons, energy: 1.2 MeV, nom. int. 8.8E6, collimator ϕ10mm			
Run no.	Run begin intensity $p/cm^2/s$	Run end intensity $p/cm^2/s$	Run mean intensity $p/cm^2/s$
1	8.8E6	9.2E6	9.0E6
2	5.9E6	5.5E6	5.7E6
3	1.5E6	1.1E6	1.3E6
4	6.15E5	5.5E5	5.83E5
5	2.04E5	1.5E5	1.77E5
6	4.1E4	2.6E4	3.35E4
7	1.0E4	8.9E3	9.45E3
DBM settings: 2.5 MHz, S0: NOT, ATT: NOT,			

MIMOTERA silicon detector 17x17 mm (pixel size – 155 μm)
SUCIMA project at IFJ PAN:
A. Zalewska, A. Czermak, B. Dulny, B. Sowicki, M. Jastrząb (PhD thesis)
Proj. coordinator: Massimo Caccia
Como University, Italy



One of the first application of the MIMOTERA was the profilometry of low-current, 1.2MeV proton beam at TANDEM accelerator at LARN (Laboratoire d'analyses par réactions nucléaires) in Namur, Belgium.

Integrated image of 30 readouts – proton beam profile at LARN



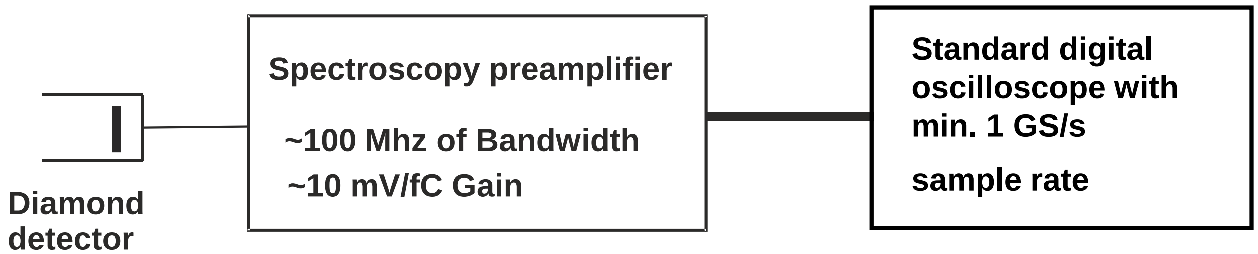
M. Jastrząb PhD thesis „Real Time Recognition of Sparse Data Patterns in Silicon Pixel Detectors”

Performance requirements for front-end electronics for CVD detectors

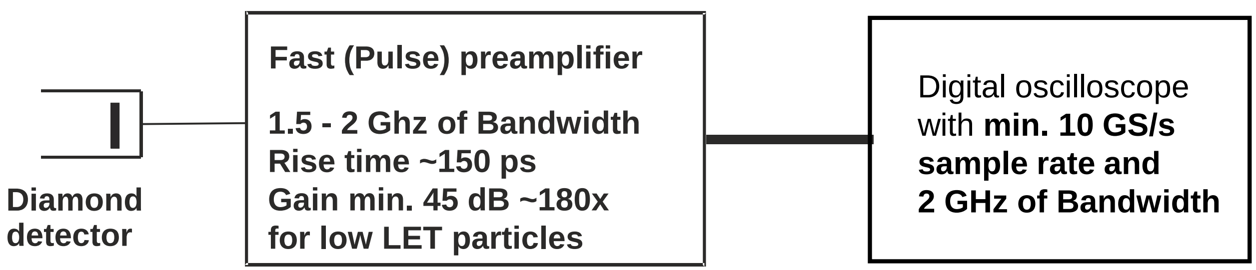
Diamond detector front-end electronics

Two general approaches:

Setup 1: for spectroscopy and precise amplitude measurements



Setup 2: for fast signal acquisition and timing measurements

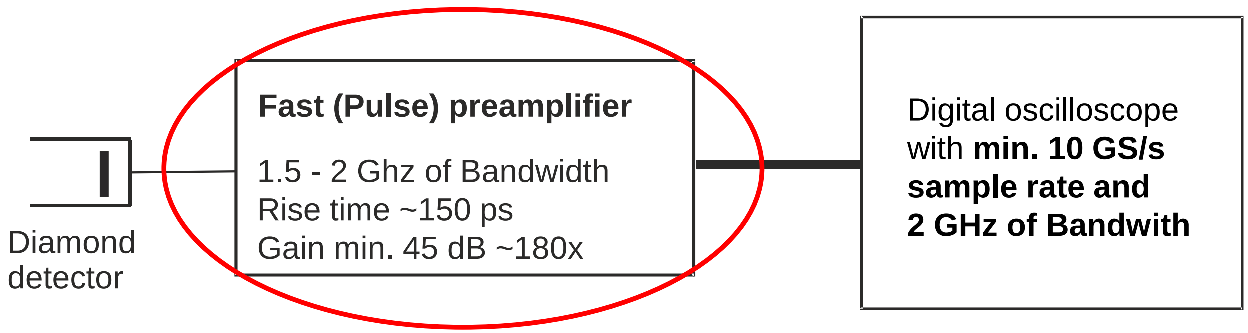


Diamond detector front-end electronics c.d.

The motivation for choosing the setup 2 - R&D for diamond detectors for high RF frequency accelerators applications:

- **Signal generation process in CVD (fast moving carriers)**
- **Signal shape and duration**
- **Capability of application of CVD detectors to ultra-fast, accelerator beam diagnostics**

One of the most critical elements, often setting limits in performance of detection systems with CVD detectors is the preamplifier.



Electronics Highlights:

- **RF technology because of >1.5 GHz bandwith (rapid signals)**
- **Signal amplification ~150-300 V/V for low-LET particles and thin detectors (single 70MeV proton releases (most probable value) in 50µm scCVD ~150 keV, which turns into ~20 mV pulse amplitude @ 180x amplification.**
- **Extremely low noise RMS @ high amplification**

The DBAIV preamplifier

The reference broadband (2 GHz) preamplifier with the amplification of up to 50 dB, has been designed and developed at GSI Darmstadt. DBA IV was originally optimized for measurement of heavier ions with diamond detectors.

DBAIV main characteristics

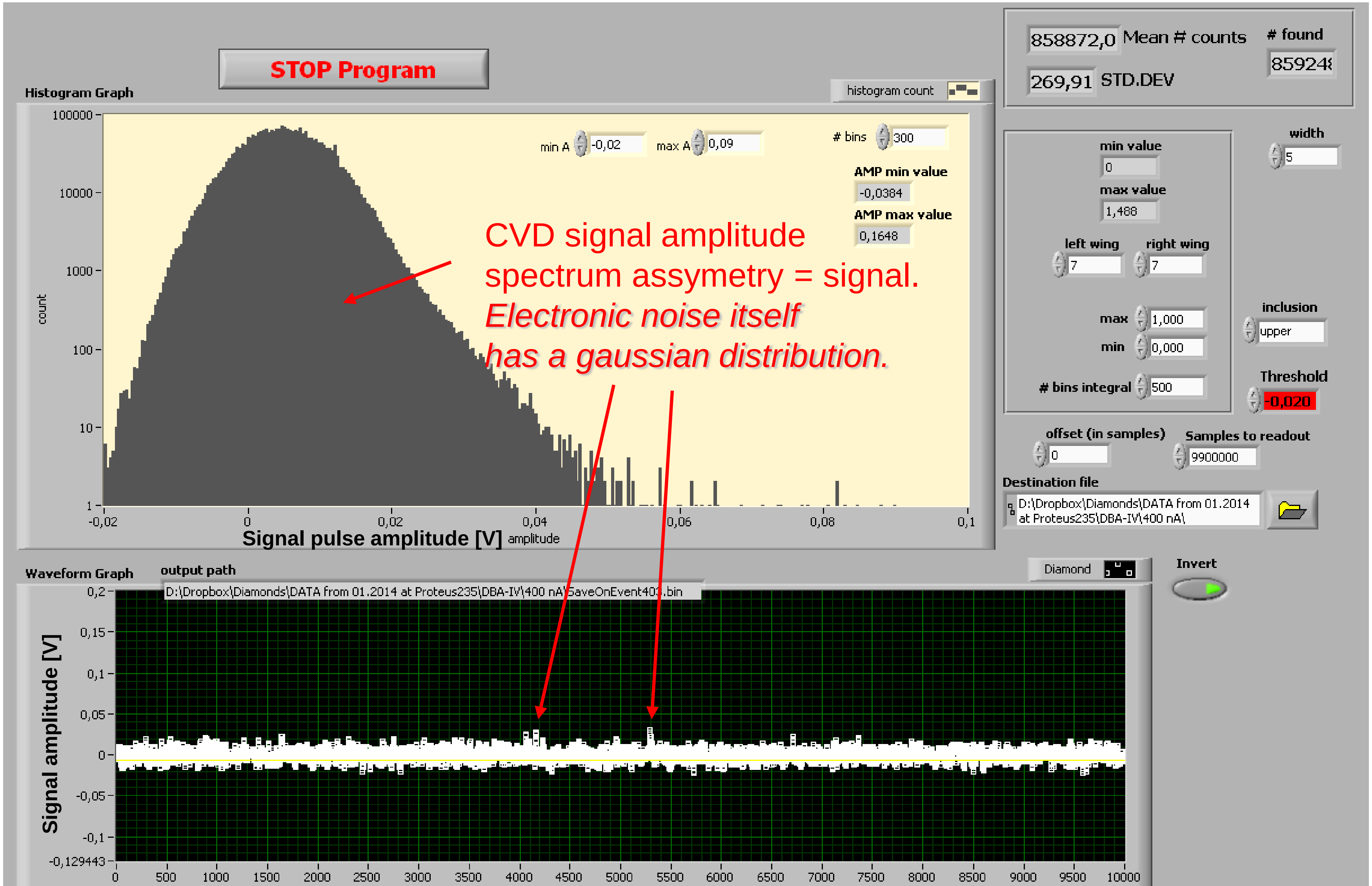
Type	DBA-IV
Description	GaAs 3-stage MMIC Non-Inverting Broadband Amplifier
Bandwidth (-3 dB)	0.003 - 2.0 GHz
Gain max.	+50 dB
Gain min.	+10 dB (Gain Remote Controlled 0-5V DC)
Input Impedance	50 Ohms, SWR <1.5
Output Impedance	50 Ohms, SWR <1.5
Noise Figure (Input terminated)	5 dB
Max. Input Voltage at min. Gain	1 V_{peak}
Max. Output Power Level	+18dBm / 2V_{peak}
Max. Bias Voltage for the Detector	+/- 2000V, no damage at Detector Input Shorts for -600V/+100V Bias Range
Power Supply	+12 V, 150mA
Dimensions	Length: 95mm, Width: 47mm, Height 25 mm
Connectors	RF in/out, Bias: SMA; Power/Remote Gain: LEMO 4pole

Goals to be achieved for beam diagnostics and profilometry at AIC-144 and Proteus-235 cyclotrons at IFJ PAN for scCVD detection system:

- ***Single particle detection with high efficiency for each micropulse separately***
- ***A mechanism of dealing with pile-up within single micropulses. Is it possible to precisely distinguish between multiple, contemporary protons?***

The DBAIV preamplifier c.d.

Signal spectrum of 70MeV protons measured @ Proteus-235 with 50µm scCVD detector by DDL.

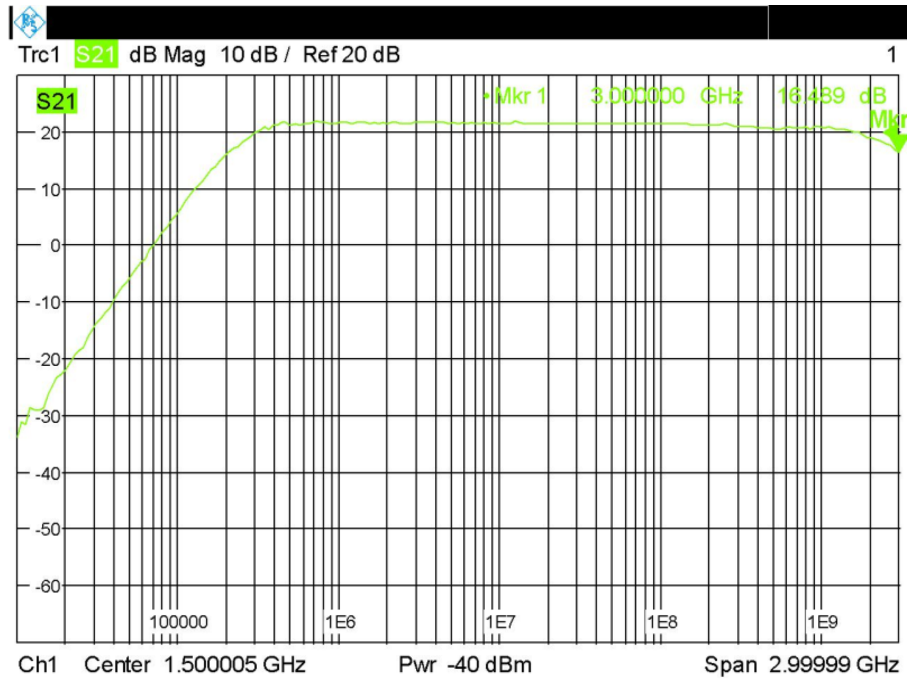


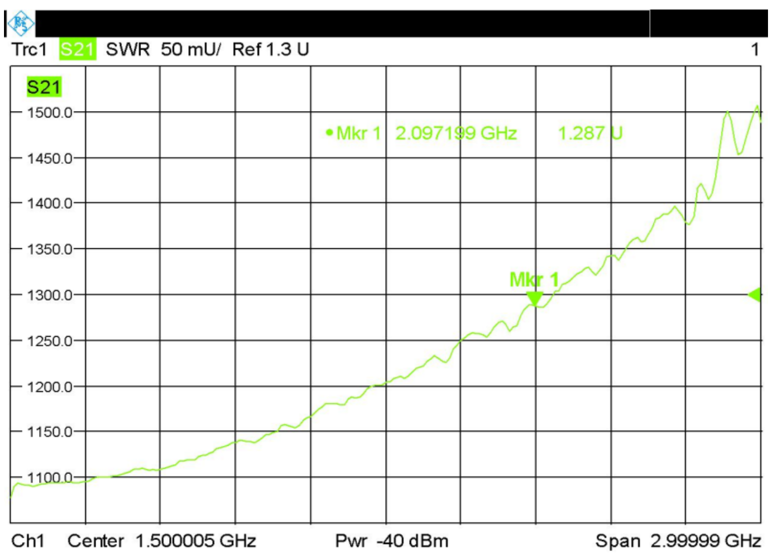
CVD front-end electronics design R&D: PA-10

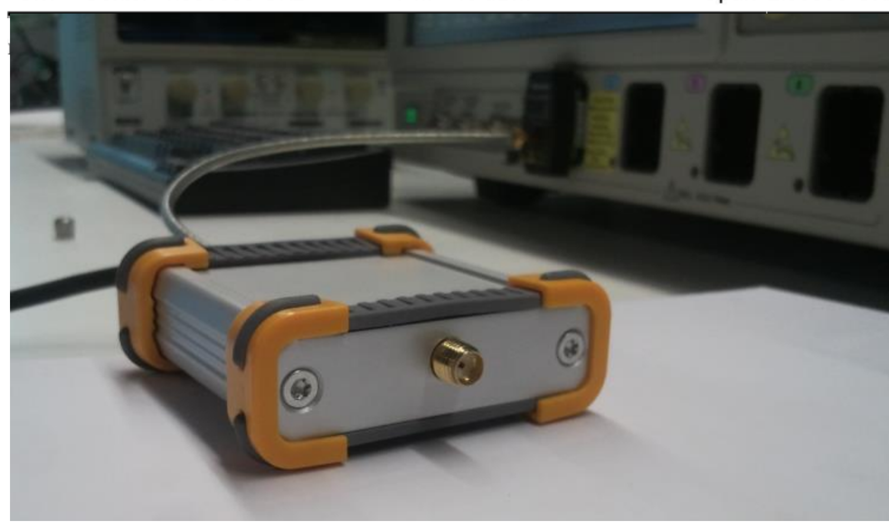
New design of low-noise and broadband PA-10 preamplifier.

The highest requirement:
Improvement of S/N ratio with minimum bandwidth of 1.5 GHz and gain >=45 dB.

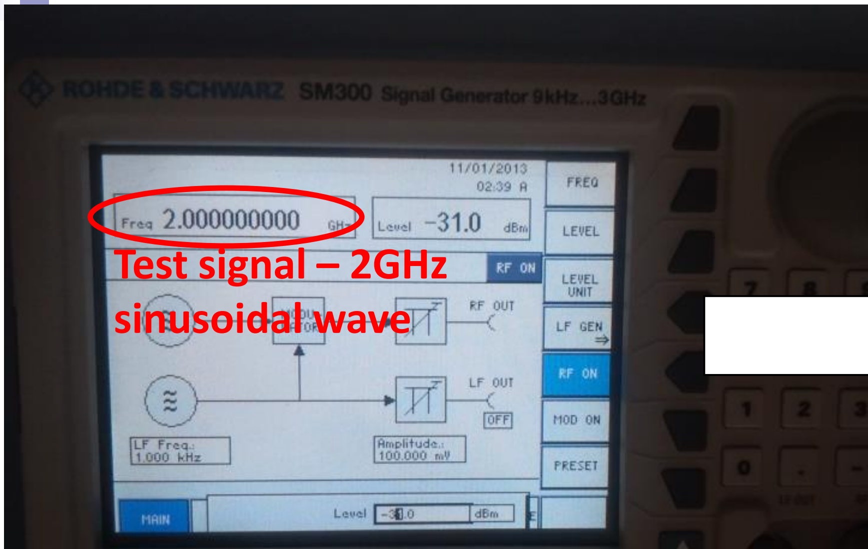
To accomplish the task a collaboration between the IFJ PAN and company with the RF Electronic Laboratory was set up.
The result is the design of PA-10 allowing to continue with high-energy proton beam measurements.
Eventually the front-end will be upgraded.

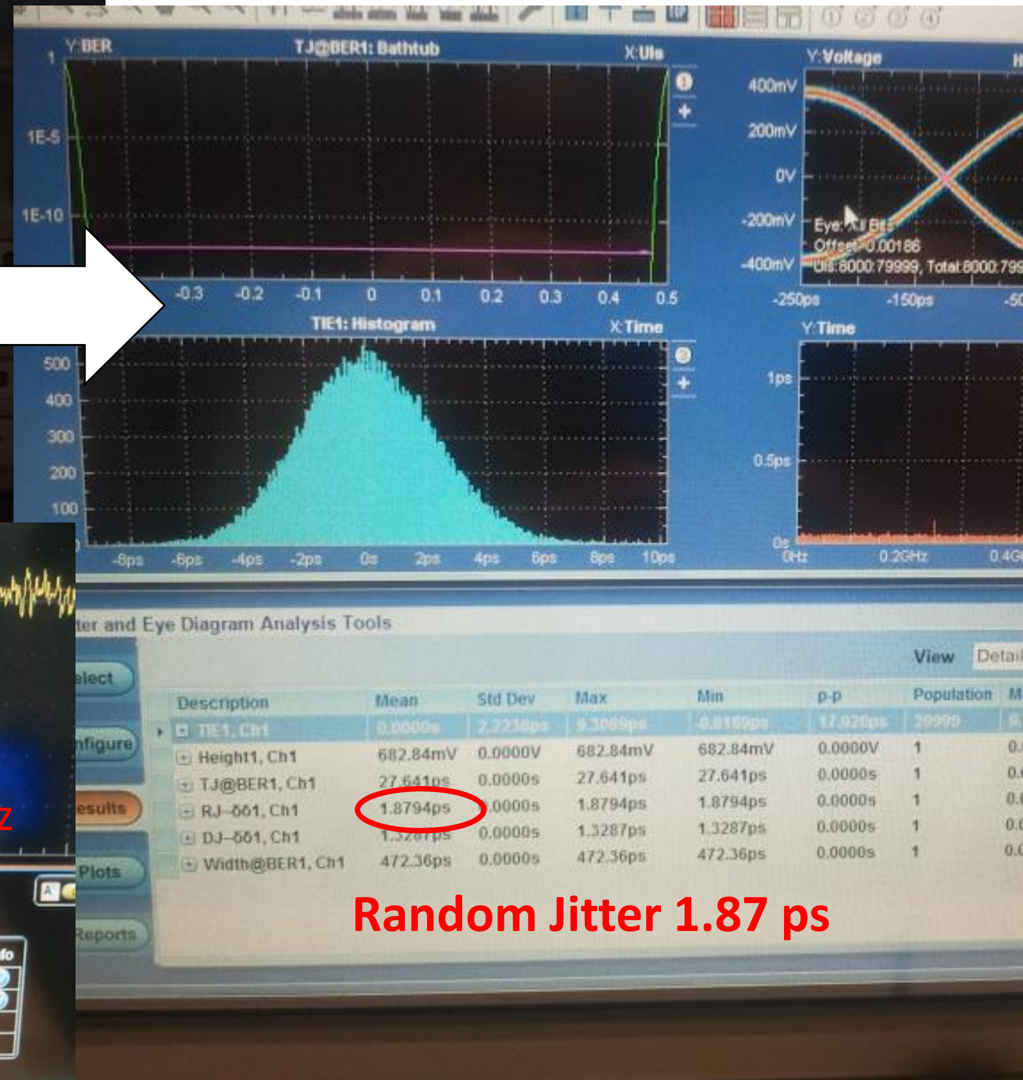


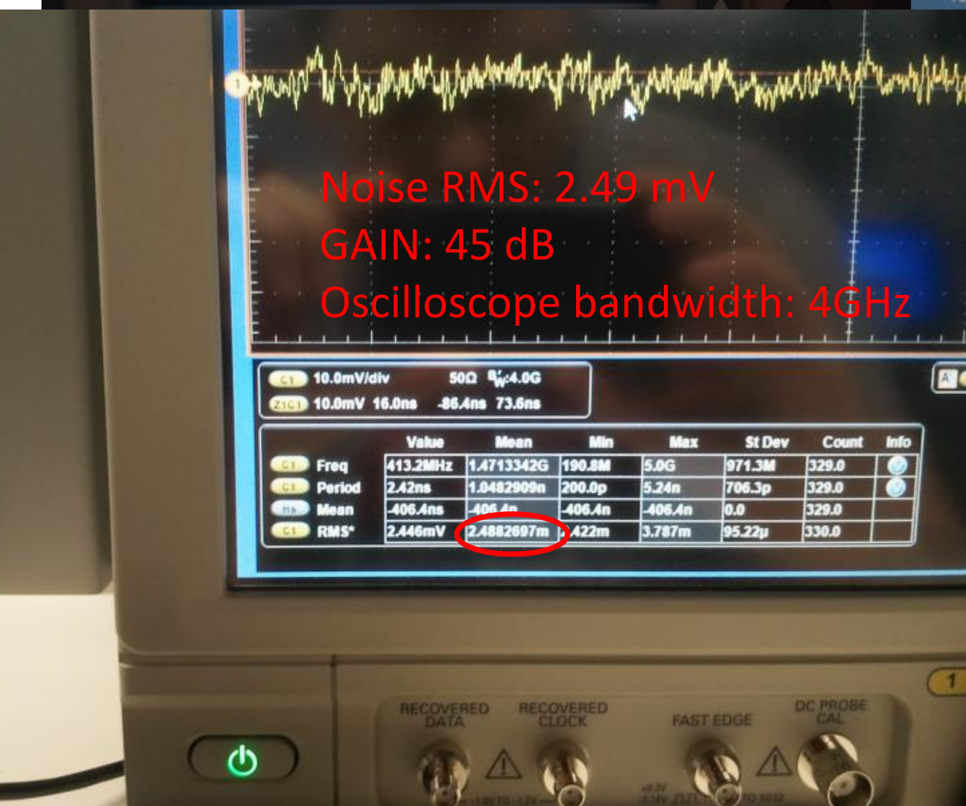




CVD front-end electronics: PA-10



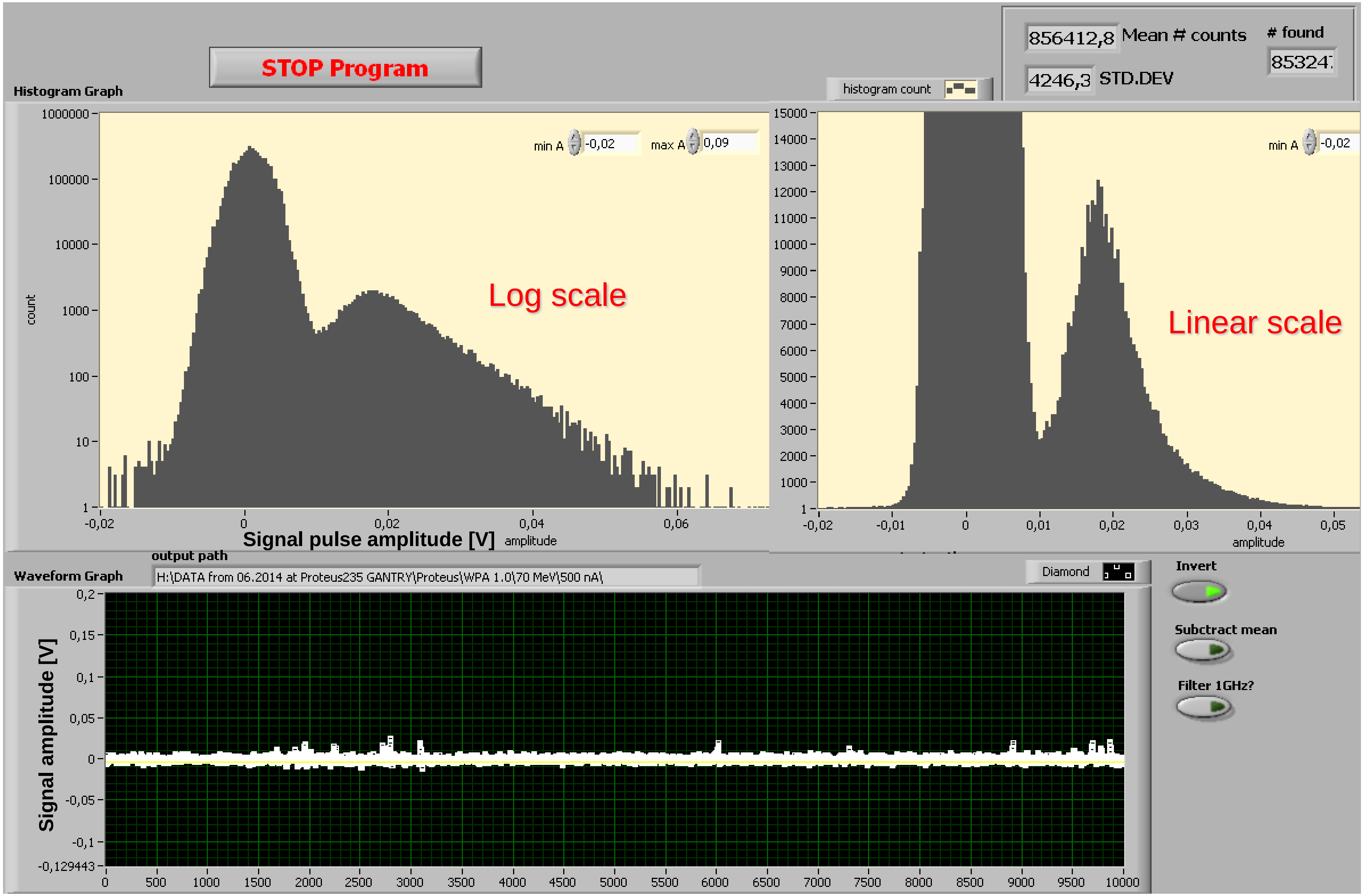




Wideband amplifier PA-10 tests and qualification.
<u>Noise</u> and <u>timing</u> performances.

CVD front-end electronics: PA-10 beam test

PA-10 preamplifier @ 70 MeV protons accelerated by Proteus-235 (50 μm)



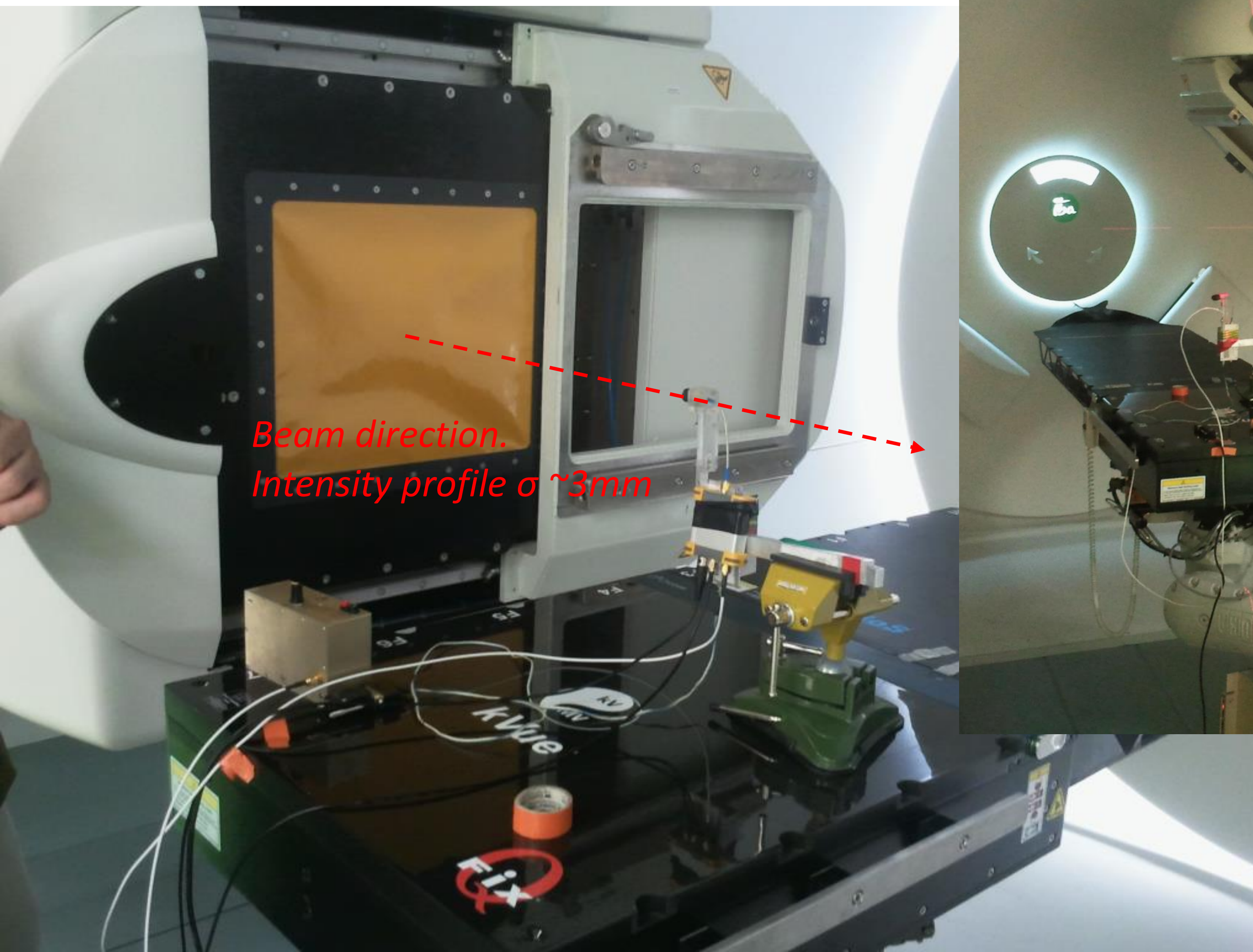
Preamplifiers for CVD detectors: DBAIV vs PA-10

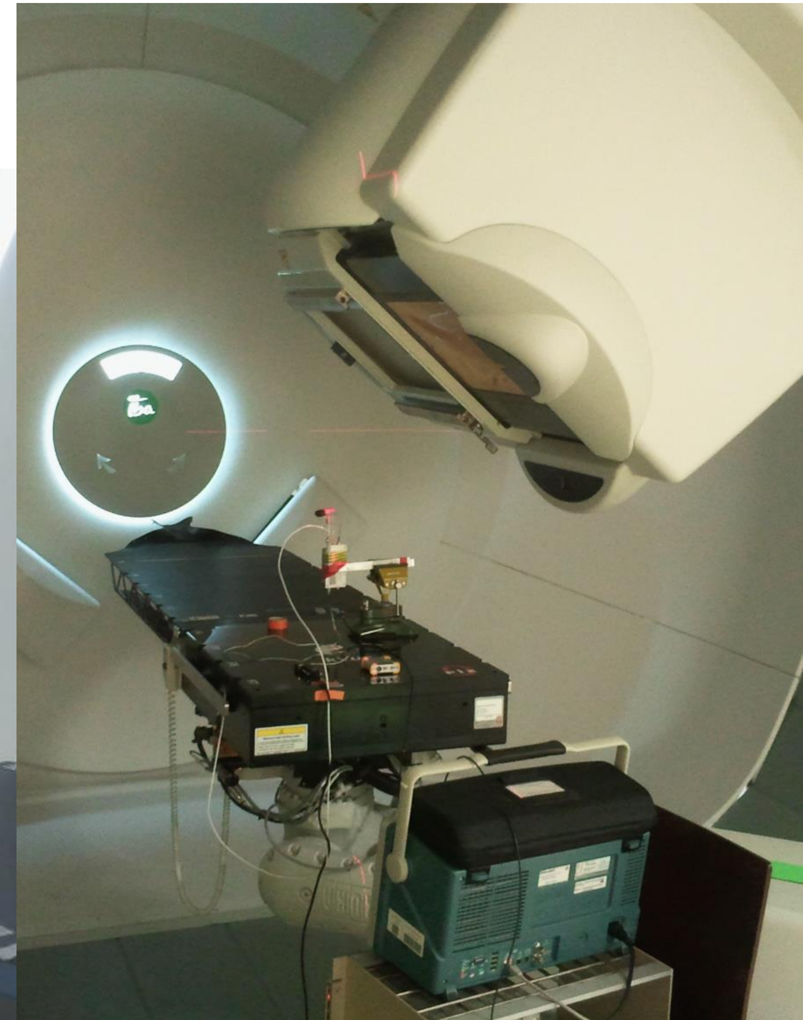
DBA IV & PA-10 technical summary

	DBAIV	**PA-10**
Bandwidth(-3db)	3 MHz - 2 GHz	1 MHz - 1.5 GHz
Gain	max. 50 dB (~316)	fixed 45 dB (~178)
Input inpedance	50 Ω	50 Ω
Output inpedance	50 Ω	50 Ω
Max bias voltage	+/- 2 kV	+/- 500 V
Power supply	+12 V, 150 mA	+12 V, 75 mA
Noise r.m.s.	**5.9 mV@45 dB**	**2.5 mV@45 dB**

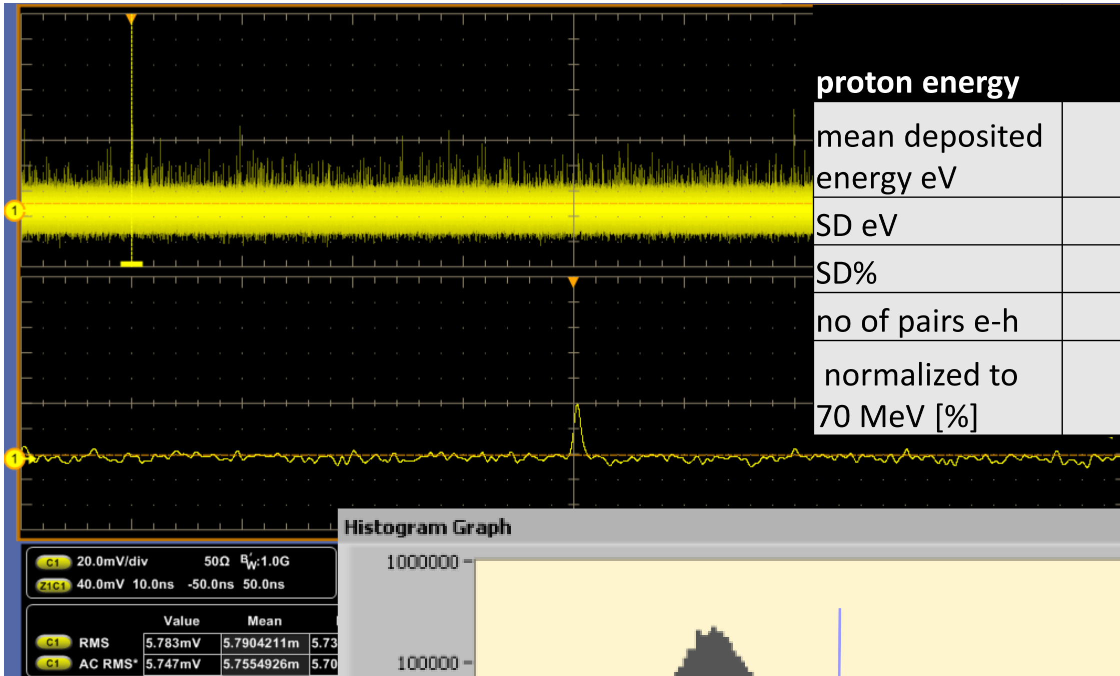
Results of measurements at Proteus-235 and AIC-144 cyclotrons

Proteus-235 at IFJ
- scCVD setup at Gantry

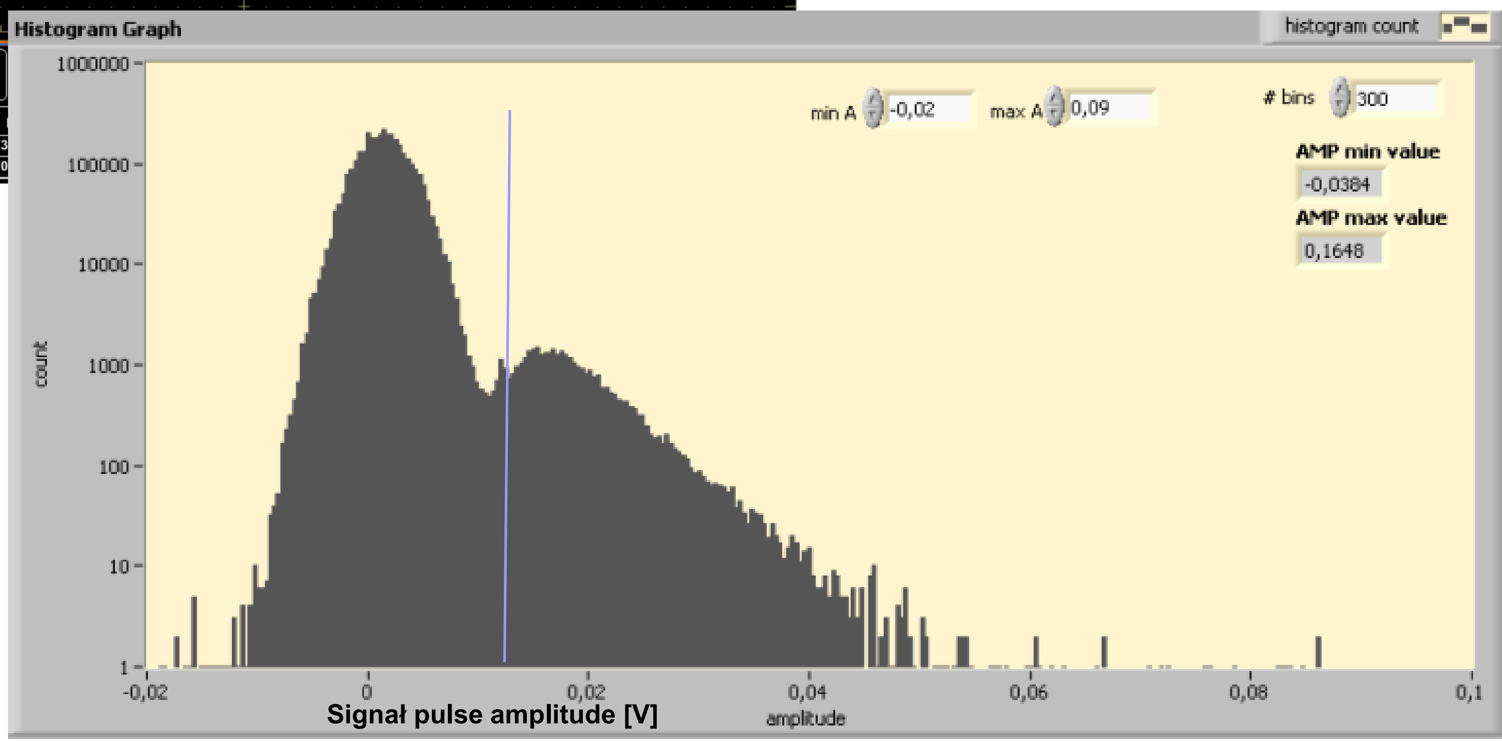




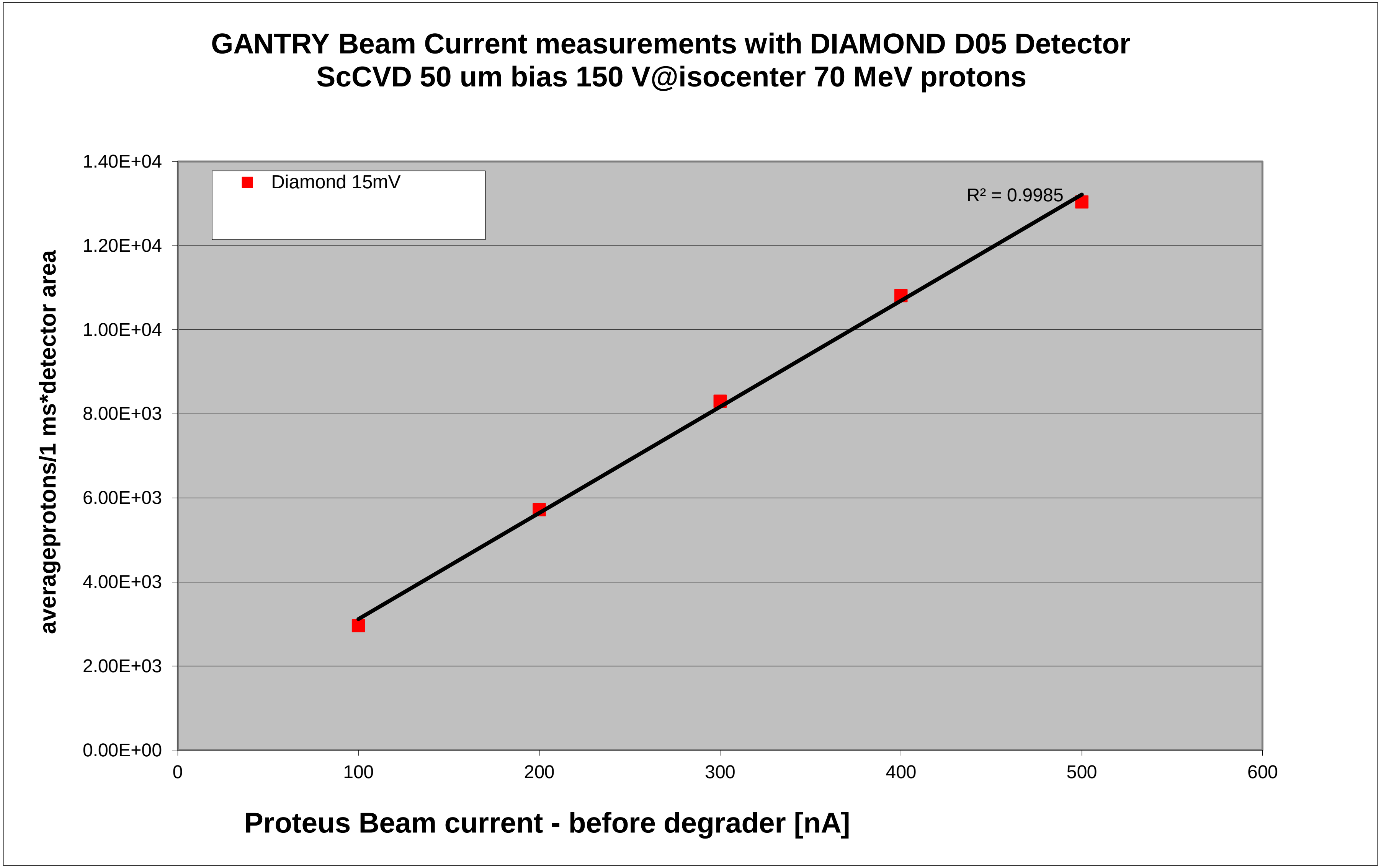
Proteus-235 - gantry measurements with 50µm scCVD



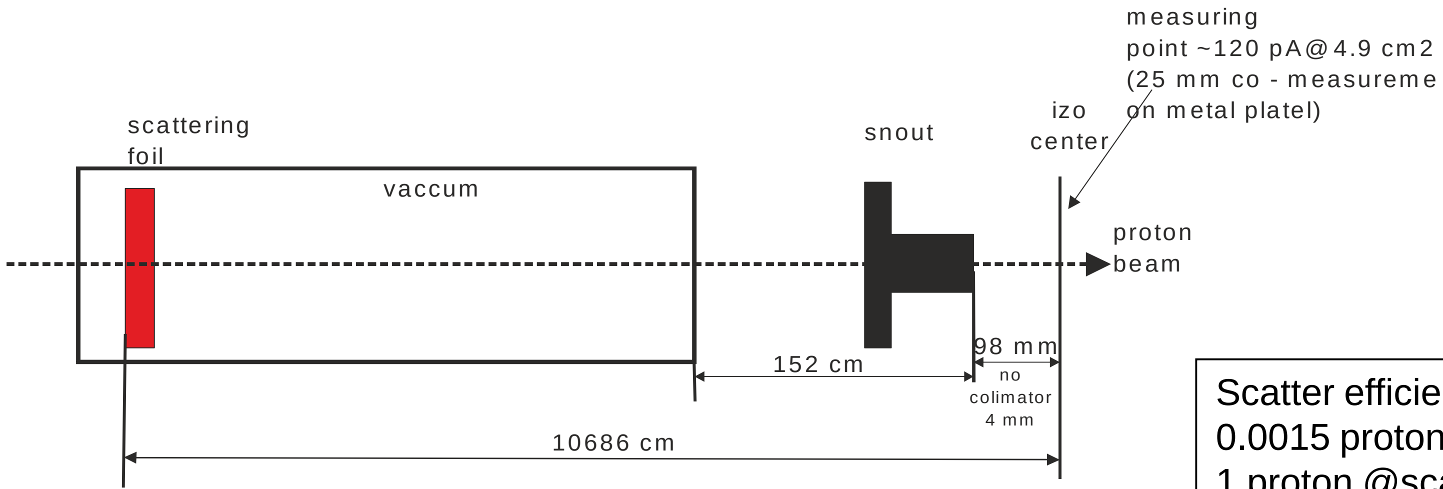
proton energy	70 MeV	150 MeV	225 MeV
mean deposited energy eV	151097	85900	66059
SD eV	39432	32644	28350
SD%	26.1	38.0	42.9
no of pairs e-h	11110	6316	4857
normalized to 70 MeV [%]	100	56.9	43.7



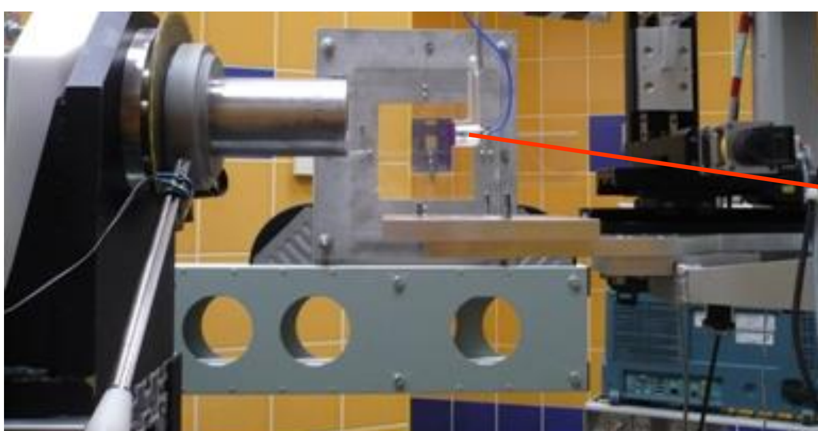
Proteus-235 - gantry measurements with 50μm scCVD



AIC-144 – melanoma eye handrontherapy room. 500μm scCVD detector mounted at isocenter.



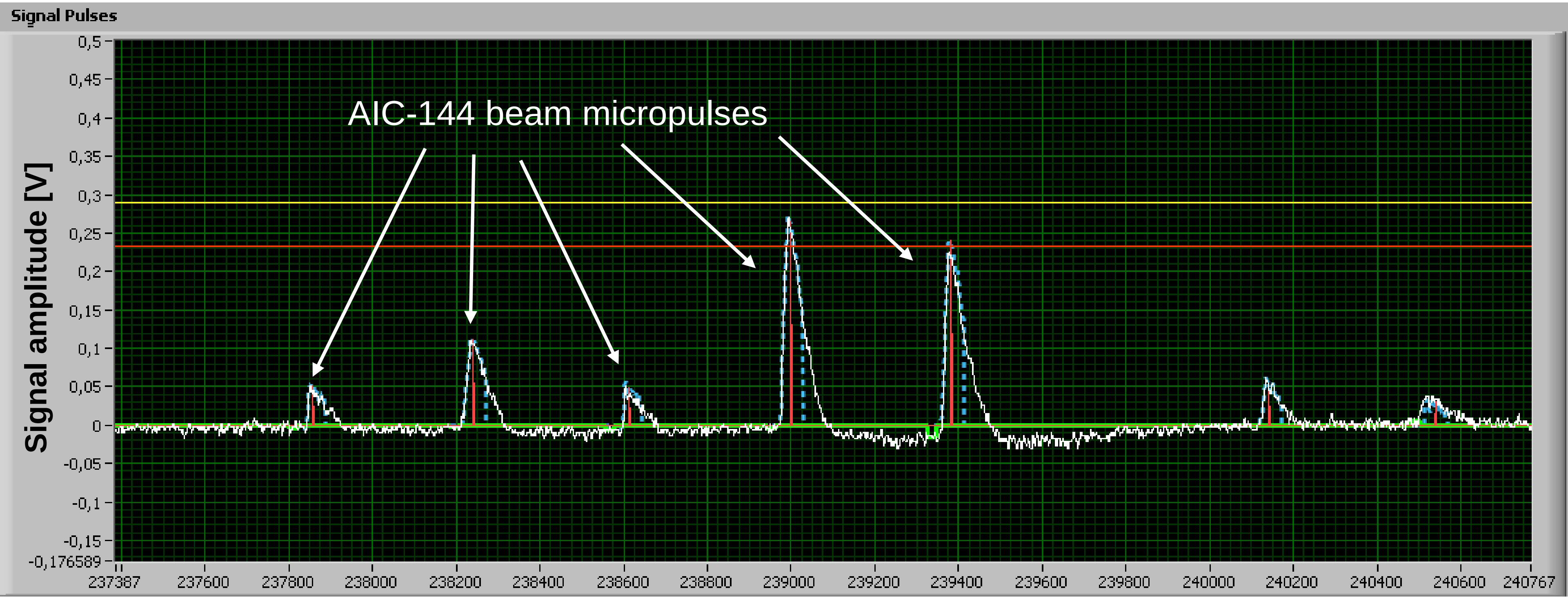
Scatter efficiency
0.0015 proton/
1 proton @scattering foil
(calculated)



scCVD Detector in special holder
mounted on 3D scanner

AIC-144: micropulse by micropulse proton beam diagnostics with 500µm scCVD.

Signal amplitudes from 60MeV protons with 500µm scCVD are ~ 3x higher than ones measured with 50µm scCVD and have a duration of ~4.5 ns FWHM instead of ~1.2 ns in the case of 50µm detector.

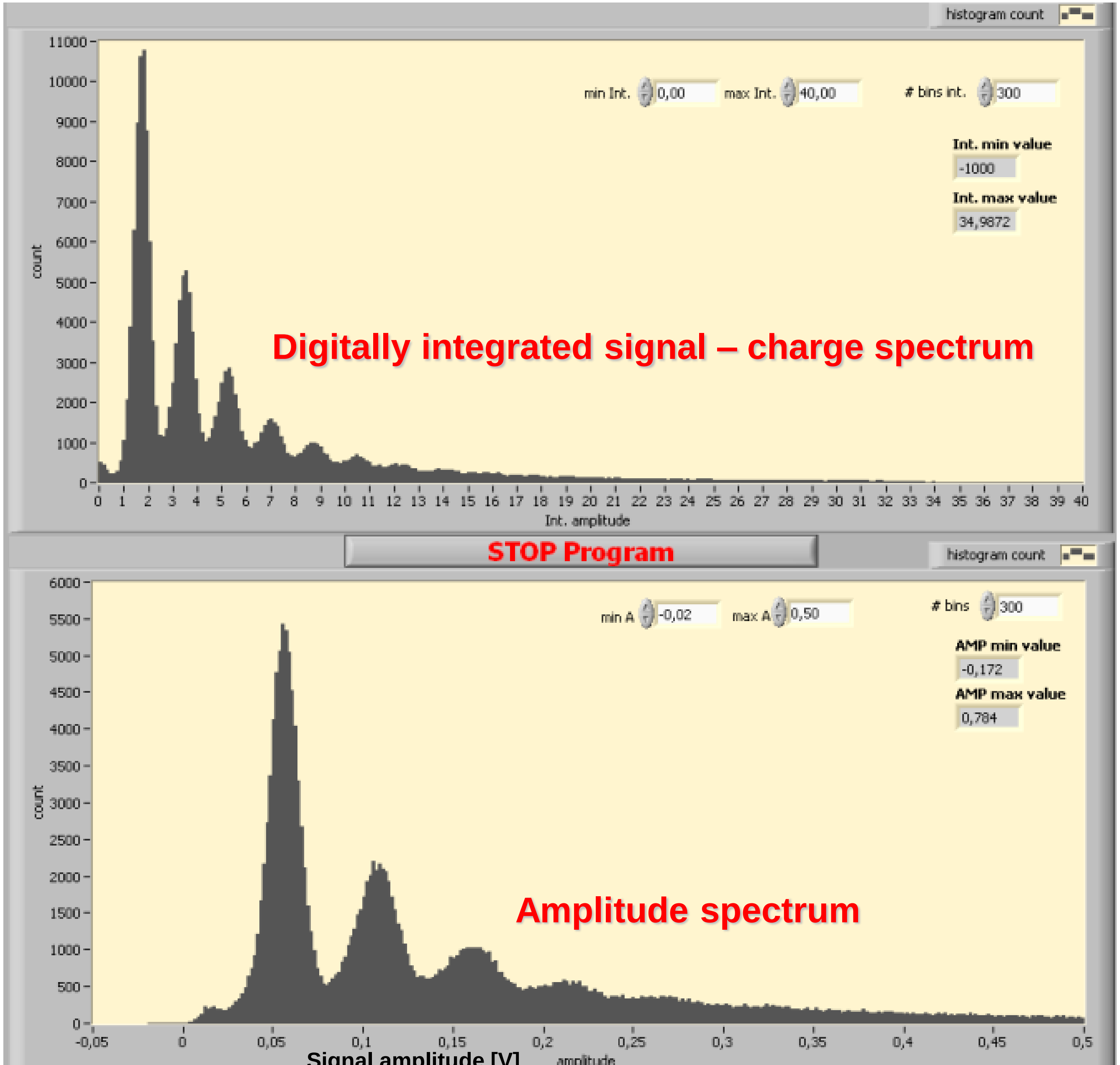


scCVD detector 500µm @ 350V bias voltage

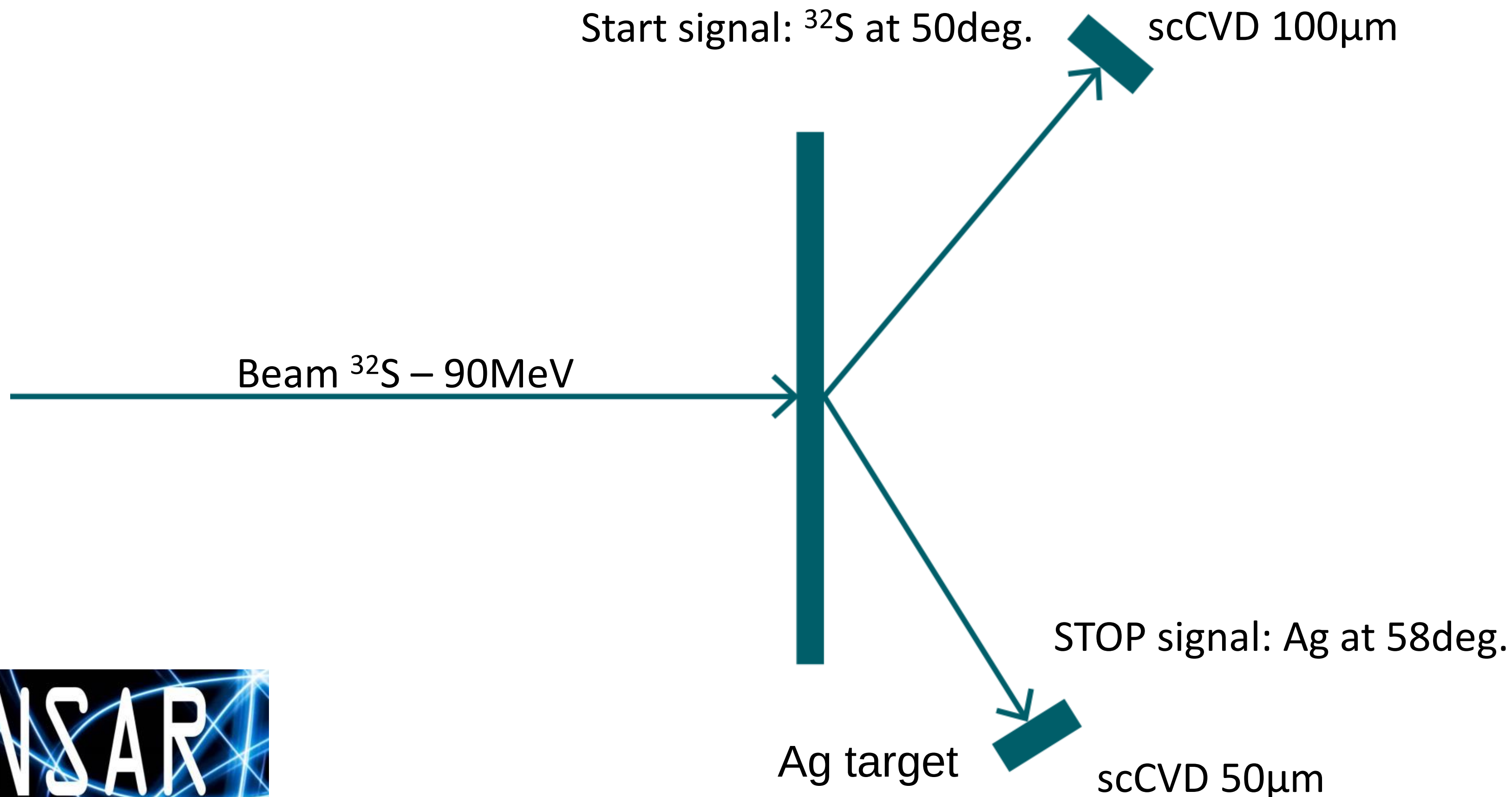
AIC-144: multiple (pile-up) proton separation within micropulse

500µm scCVD digital measu-rements with 10Gs/s sample rate.

The charge spec-trum (upper) profits from an increased S/N.

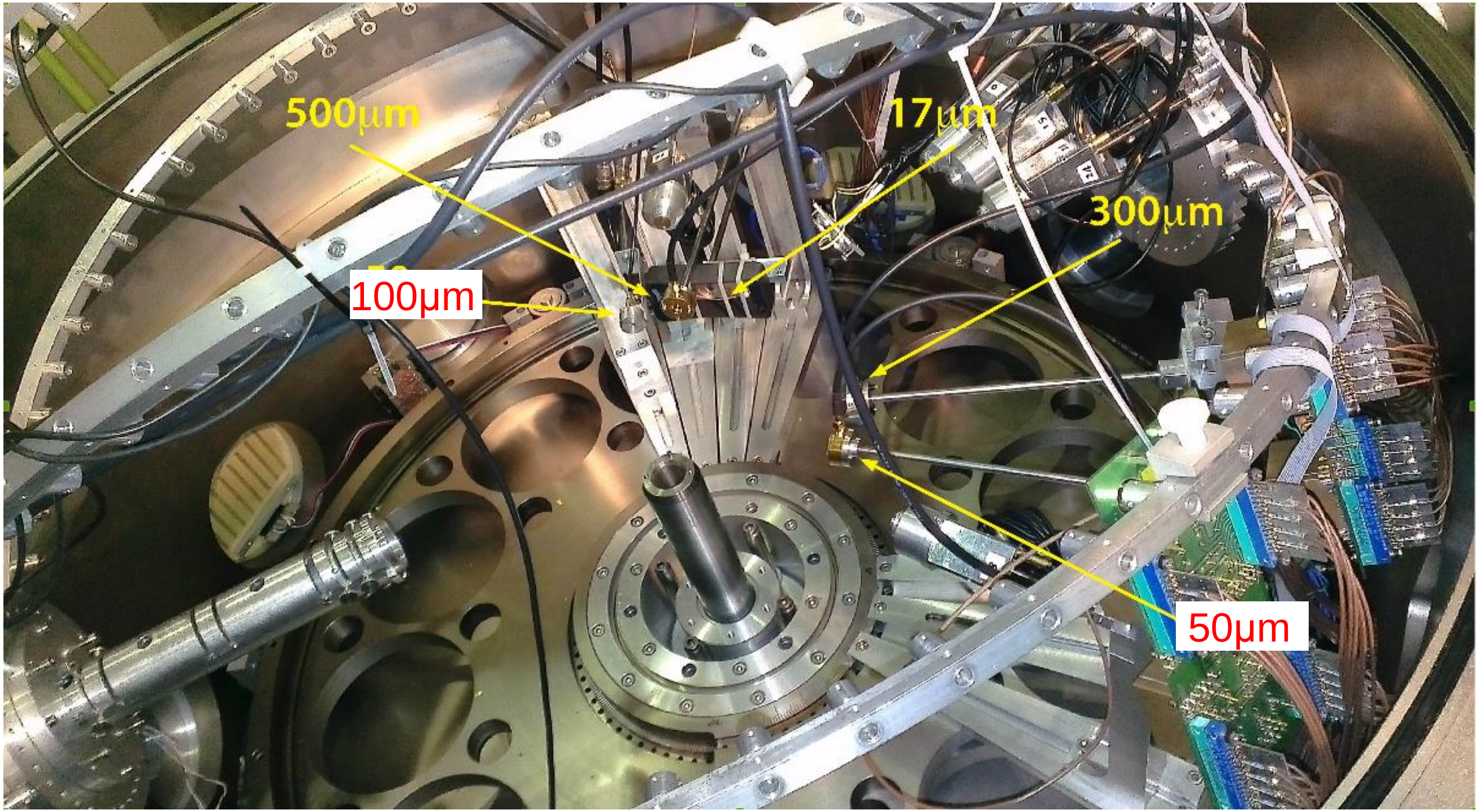


Test of timing performance of scCVD at Heavy Ion Laboratory (HIL), Warsaw in November 2014



Collaboration:
HIL UW, IFJ Krakow, CEA Saclay, Univ. of Huelva

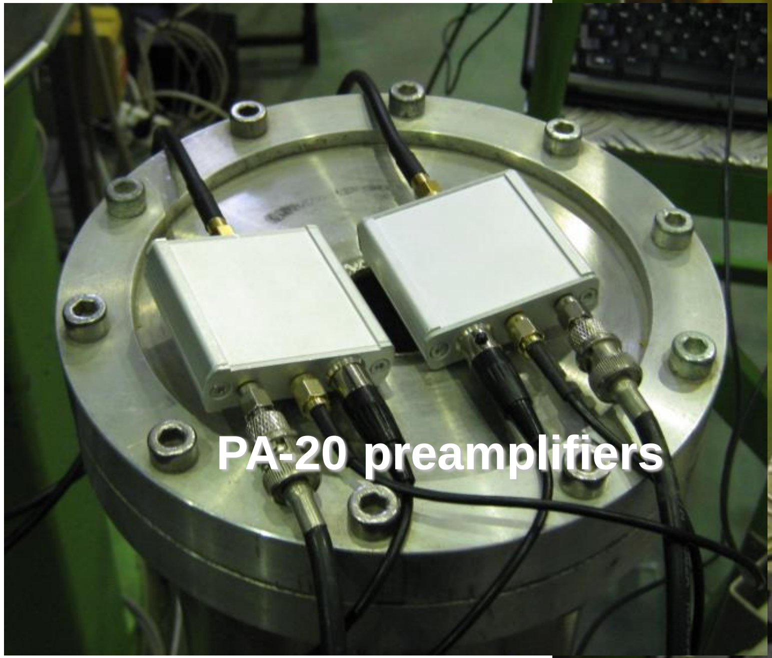
TOF test setup at HIL. Configuration of detectors during the experiment.



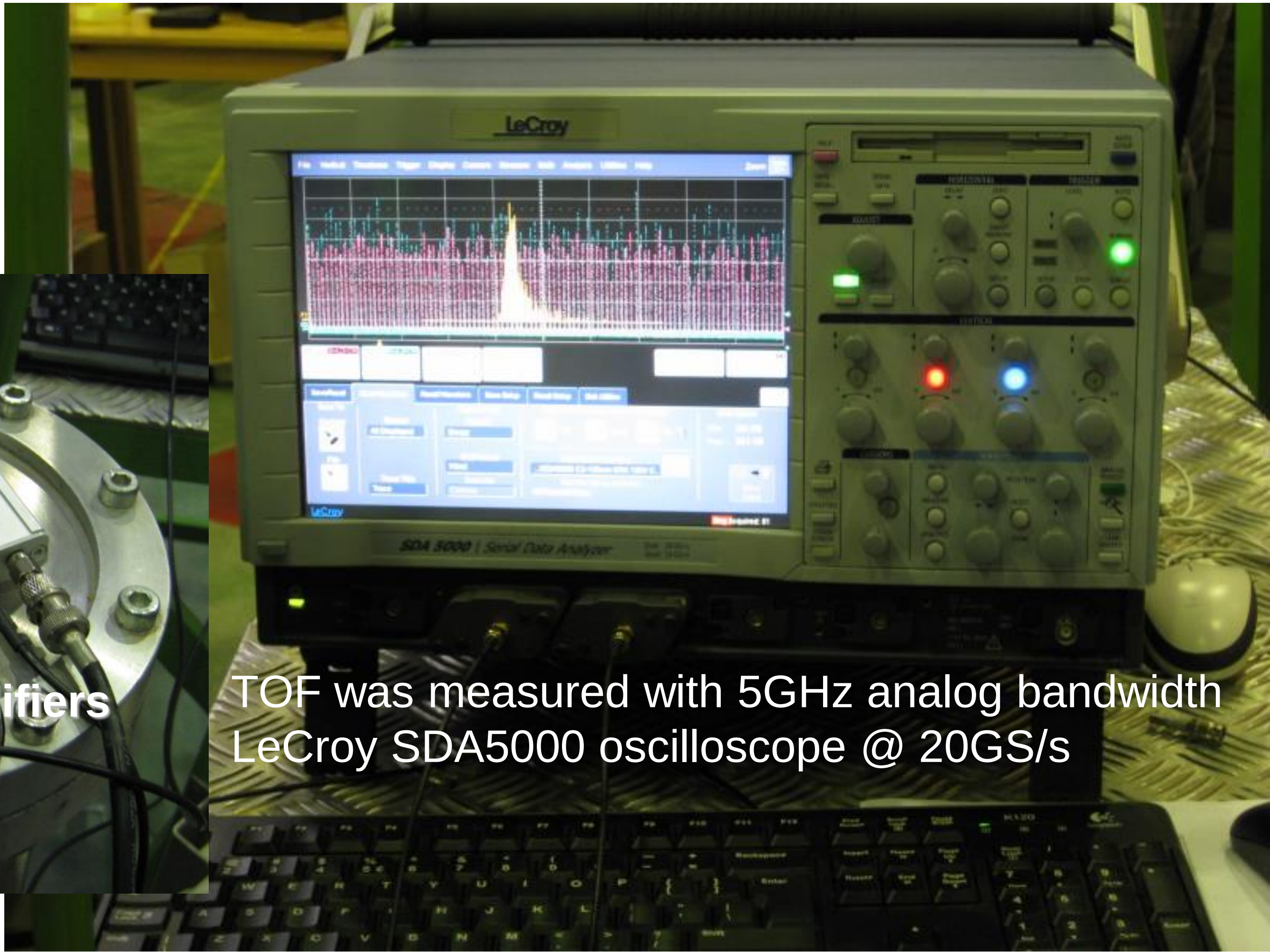
To measure the timing performace with heavy ions (up to 100 MeV) a new, low-noise, broadband preamplifier: PA-20 has been developed in Krakow.

PA-20 main specification:

Gain: 20 dB
Energy range: 100 MeV
Bandwith 1.5 GHz
Noise RMS: 190 μV



PA-20 preamplifiers



TOF was measured with 5GHz analog bandwidth LeCroy SDA5000 oscilloscope @ 20GS/s

Outlook and perspectives

- There is a possibility of performing the real-time proton beam diagnostics in single-particle mode with for ~10 pA/detector (pixel) in the case of Proteus-235, quasi-continous beam.
- Therapeutic protons (70-230 MeV) are challenging to detect, because of the low LET.
- State of the art electronics is capable of separating signal from the noise (for 50µm CVD) for proton energies up to ~100 MeV. New developments are necessary in order to be capable of dealing with higher energies.
- S/N ratio can be improved by using thicker detector. Signal timing performance deterioration has to be hovewer considered.

- We are interested in development of position-sensitive diamond detector for ion beam profilometry with resolution <0.1 mm for focused beams (σ ~= 3 mm) for physics experiments and medical applications.
- TOF performance of CVD detectors will be explored with fast electronics. Improvement of S/N ratio in new generation of preamplifiers should also affect the TOF performance.
- Measurement of energy of protons with TOF technique becomes feasible at Proteus-235 beam with TOF precision <50 ps

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Thank you for your attention!