Application of Diamond Detectors to proton beam measurements and ultrafast timing

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Outline

- *Diamond detectors for particle detection and TOF measurements*
- *Specifications of two cyclotrons operating at IFJ PAN. Requirements for measurement systems to be used with CVD Diamonds.*
- *Performance and challenges for front-end electronics for Diamonds. Emphasis on low-noise performance and wide bandwidth (>1GHz).*
- *Multiple particle detection (pile-up)*
- *TOF measurement preliminary results*
- *Outlook and future plans*

Diamond material as particle detector.

Mostly created artificially by Chemical Vapor Deposition process. Single (scCVD)- and poly (pcCVD)- crystaline. CCE ~ 100% for scCVD.

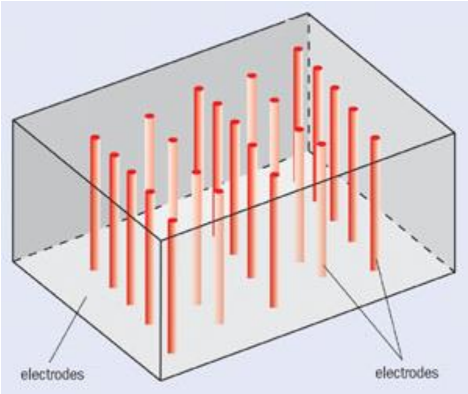
Parameter	Diamond	4H-SiC	Si
Bandgap eV (nm)	5.5	3.26	1.1
Dielectric constant	5.7	9.7	11.8
Thermal conductivity W/um*K*1e-6	22	4.9	11.8
electron mobility um2/V*ns	450	100	150
Hole mobility um^2/V*ns	380	11.5	45
Saturated electon mobility um/ns	270	220	100
Saturated hole mobility um/ns	270		90
Dielectric breakdown field V/um	1000	250	30
electron-hole pair creation [eV]	13.6	3.26	3.6
intrinsic carrier ni concentration at 300 K cm-3	~1e-27	~1e-5	1.07E+07
atoms/cm3	1.77E+23		5.01E+22

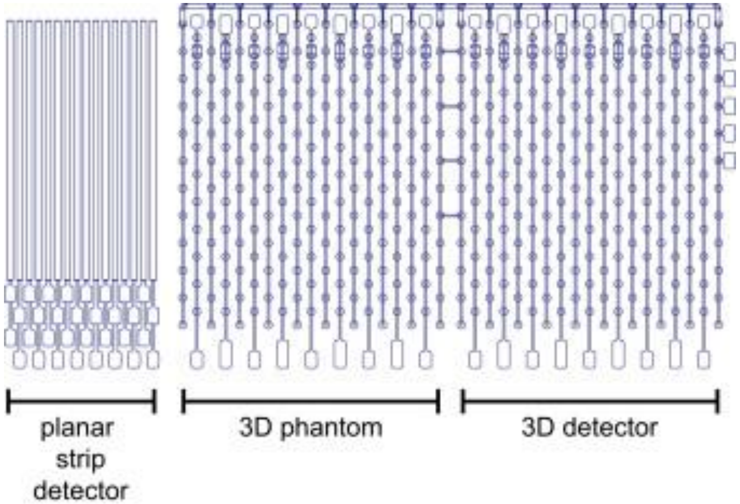
Element Six (main material supplier) scCVD diamond material:

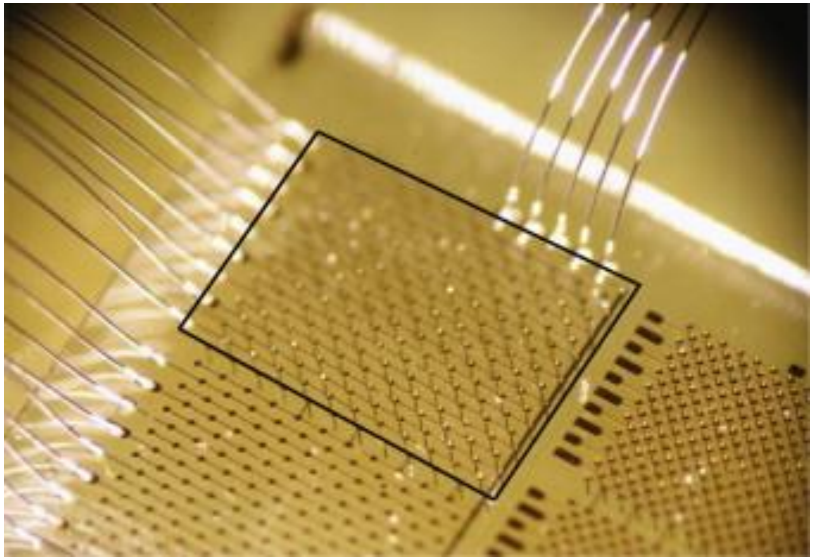
Typically 100% single sector {100},
[N] < 5 ppb,
[B] < 1 ppb
Orientation {100} faces, <110> edges (+/-3° crystallographic orientation)
Surface finish Ra<5nm on two polished {100} faces.

Diamond detectors offer high radiation resistance, especially working in transmission mode (no Bragg peak in the material)

From planar detectors to 3D diamonds







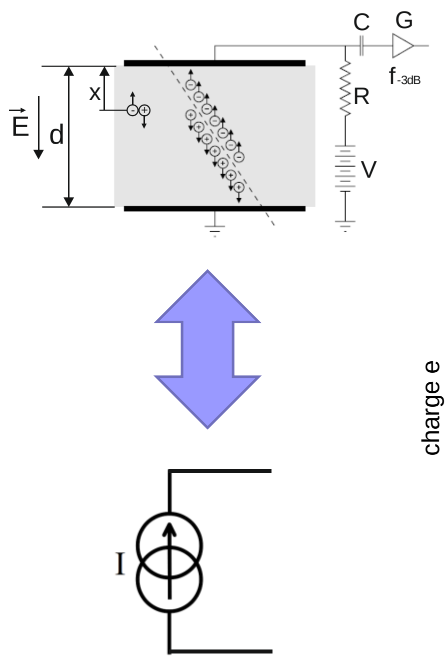
3D technology advantages:
- even higher radiation resistance
- higher S/N
- signal pulse duration depends on distance between electrodes rather than detector thickness

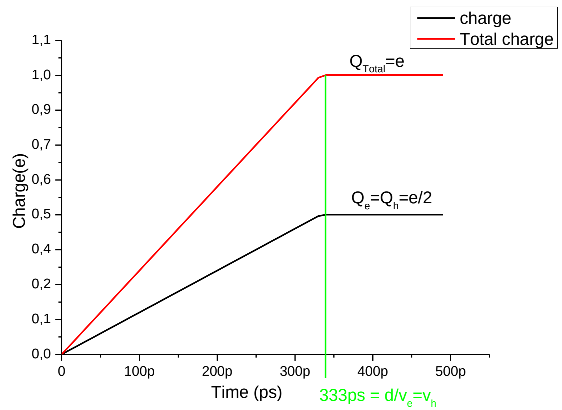
F. Bachmair et al. A 3D diamond detector for particle tracking,
NIM A Volume 786, 21 June 2015, pp. 97–104

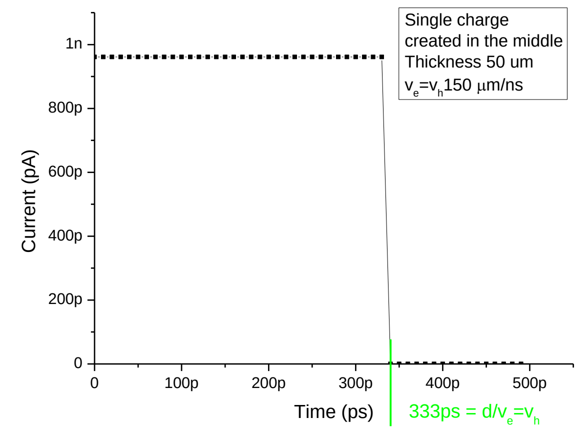
Signal generation in Diamond Detector

1. **Single e-h pair** generated in the middle of det. volume

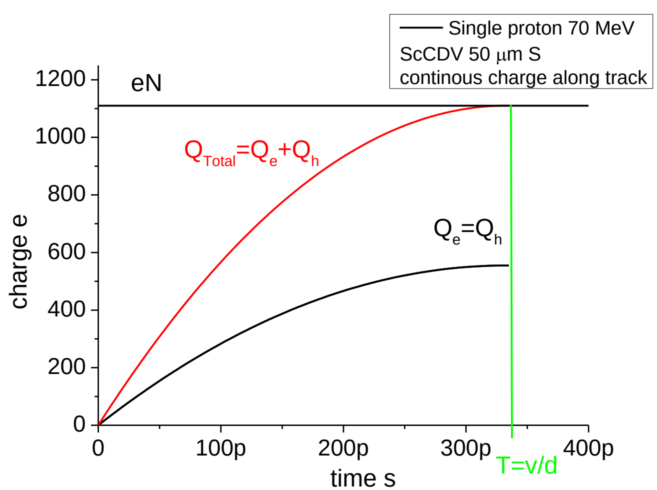
Typical E ↑: 1V/µm of det. thickness. Carrier drift velocities however saturate only at ~ 10 V/µm ($v_e=v_h$).

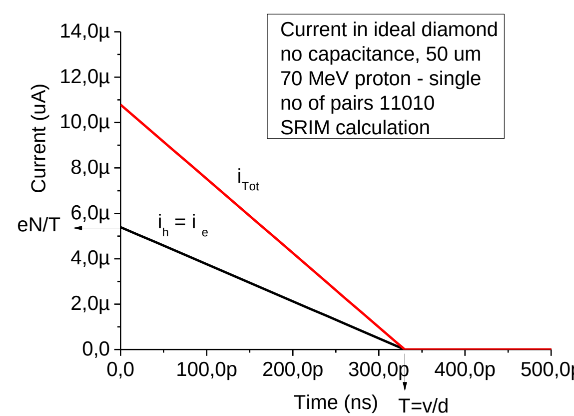






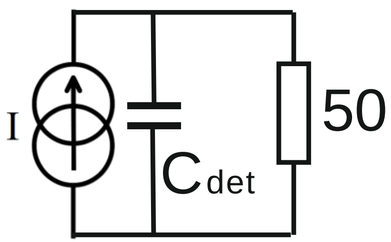
2. **Continuous** charge distribution **along particle track**

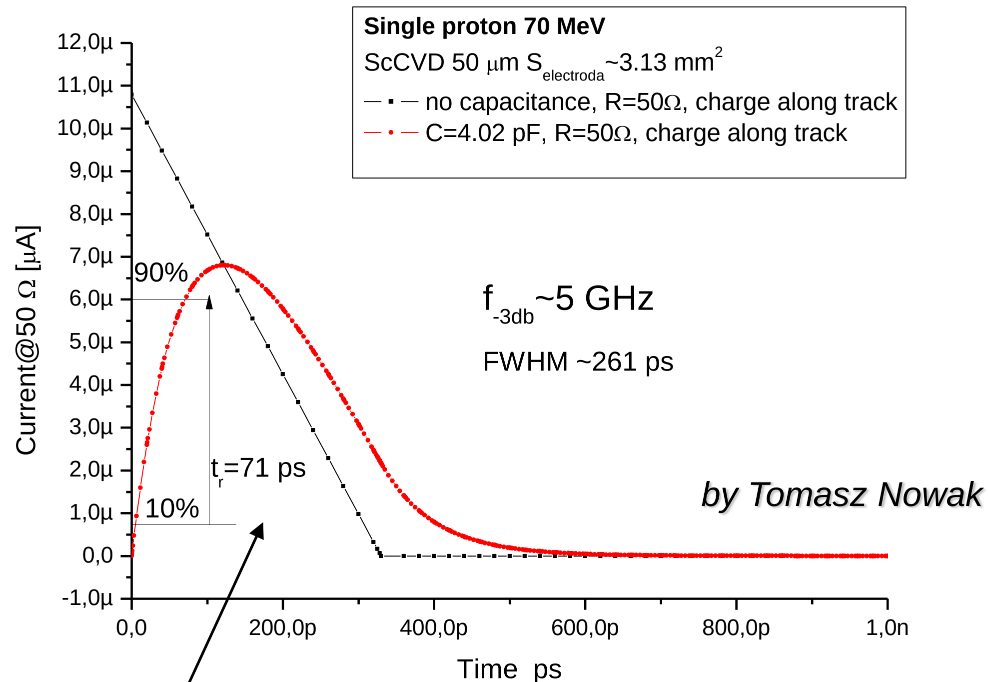




Diamond detector signal. The effect of the detector capacitance.

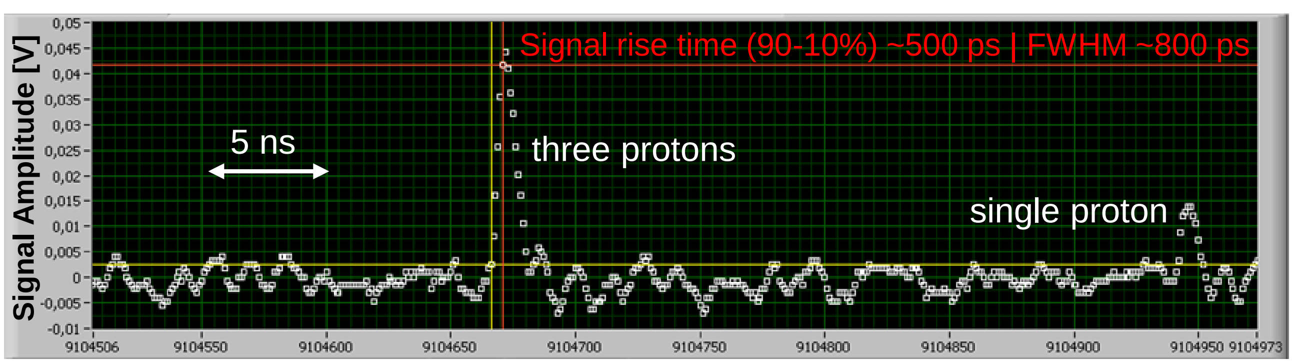
Capacitance C=e*S/d= 4.04 pF@50 um





Where is the limit in terms of rise time when the bandwidth f-3dB = 1 GHz is used? T_r =~ 350 ps.

50µm scCVD Diamond and **70MeV protons** registered with Tektronix DPO5104 **1GHz 10GS/s** oscilloscope



Sample no. (10 GS/s)

Two cyclotrons at IFJ: AIC-144 & IBA Proteus-235

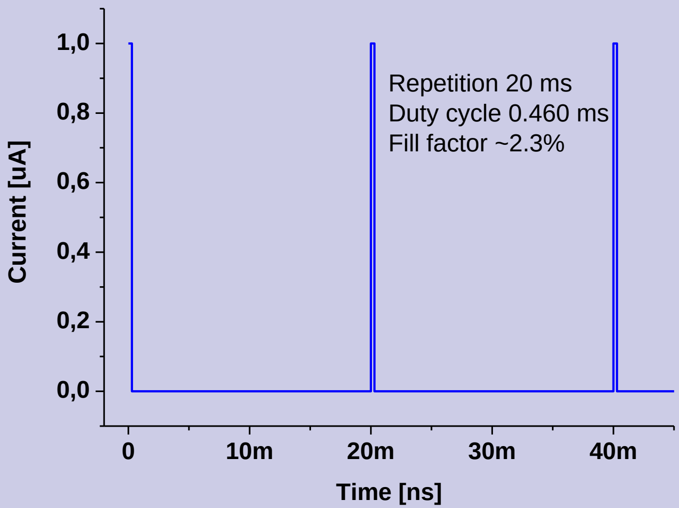
AIC-144

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=180°)
RF Generator Frequency	10 ÷ 27 MHz

IBA Proteus-235

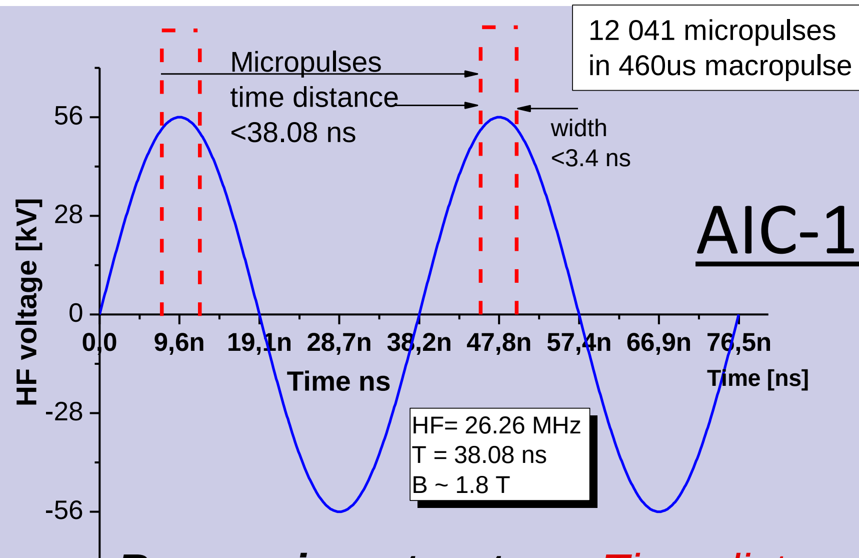
Beam energy	70 - 230 MeV
Ion beam current @ 230 MeV:	1 - 500 nA
Magnet yoke outside diameter	4,34 m
Magnet leg diameter	2,1 m
Magnetic structure	4 spiral sectors
Maximum magnetic field	3,1 T
Maximum current in main magnet coil	800 A
Number of dees	2 (45°)
RF system operation frequency	106 MHz
Dee voltage	50 - 100 kV
Extraction Factor	70%

The AIC-144 & IBA Proteus-235 beams: time structures.



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

AIC-144

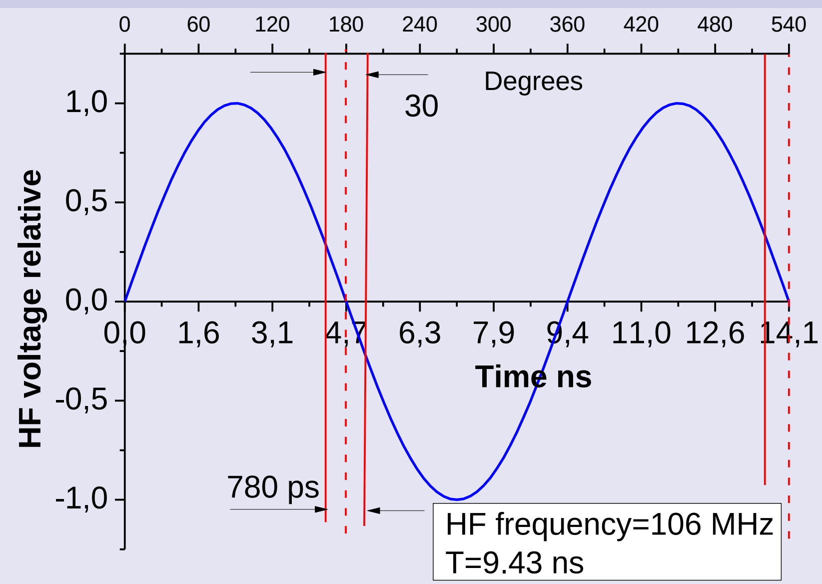


Beam microstructure: *Time distance between adjacent micropulses = 38.08 ns*

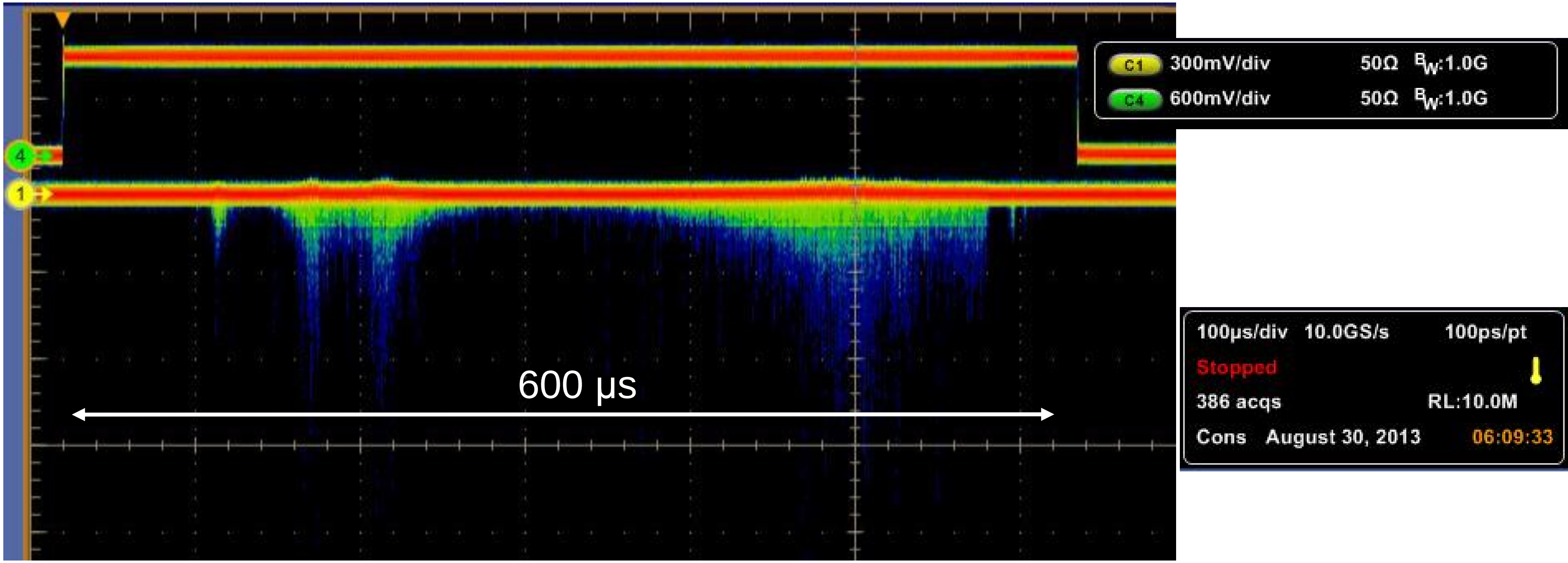
IBA Proteus-235

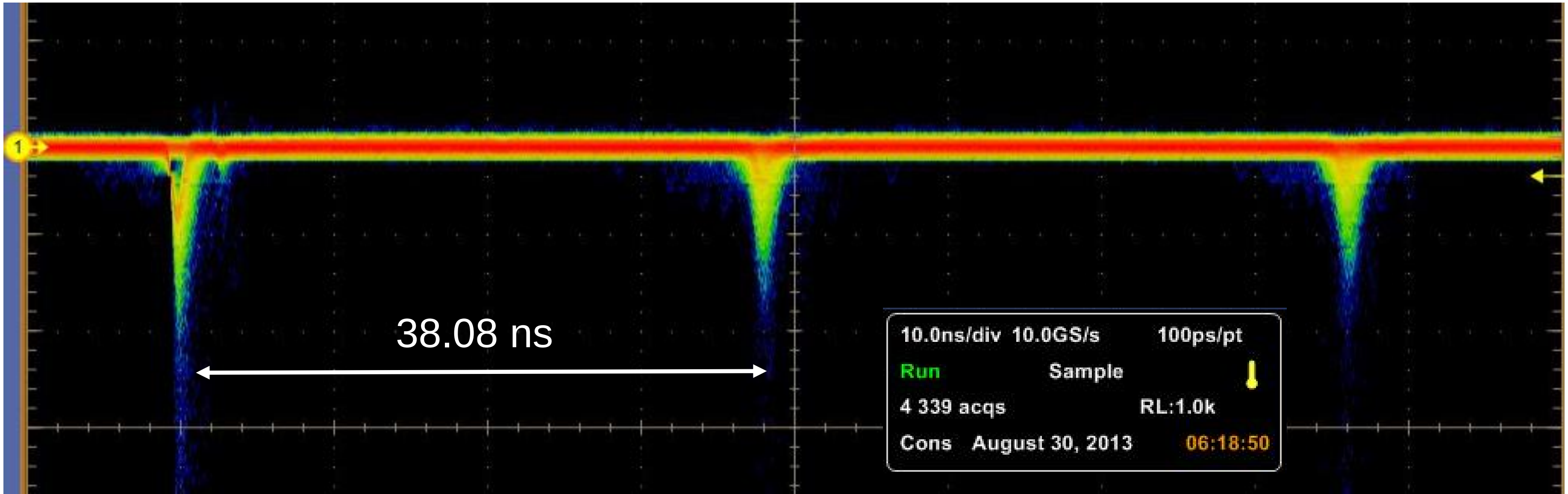
Beam microstructure: *Time distance between adjacent micropulses = 9.43 ns*

No beam macrostructure.
Quasi-continuous beam.

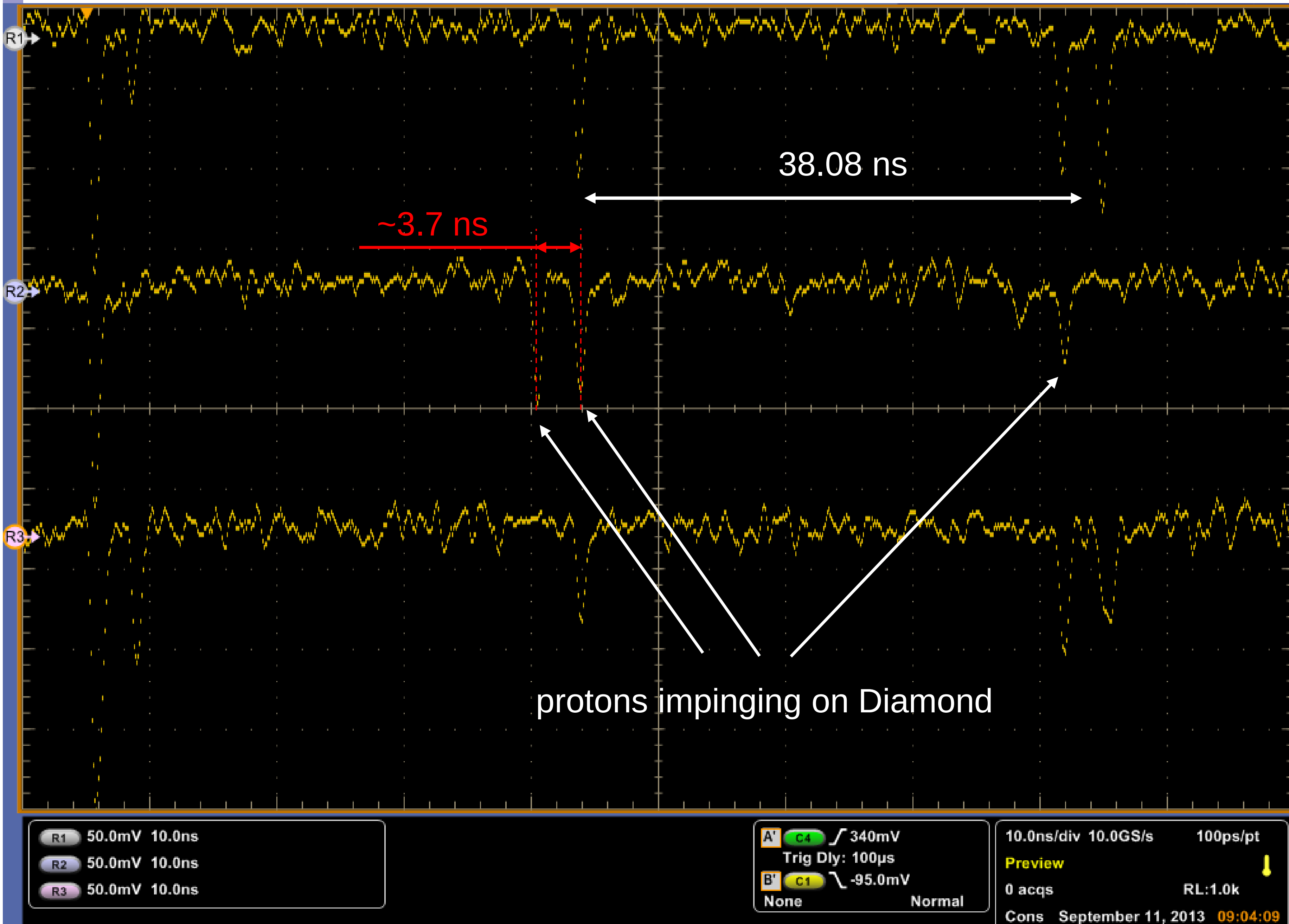


Time structure of the AIC-144 @ 50µm scCVDD

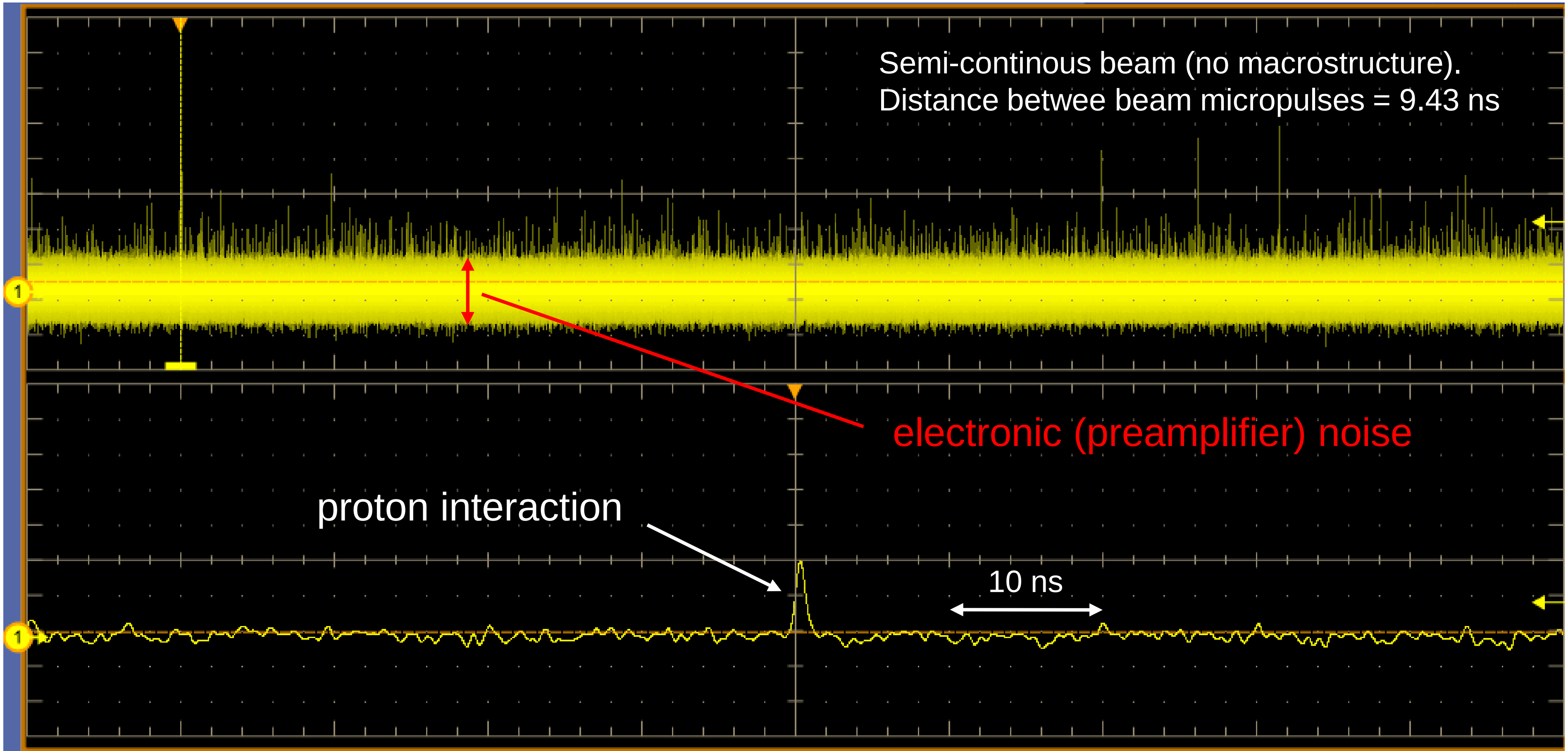




The AIC-144 beam time structure measured by scCVDD



The Proteus-235 beam time structure with 50μm scCVDD



	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	

Performance and challenges for front-end electronics for diamond detectors.

Diamond detector front-end electronics

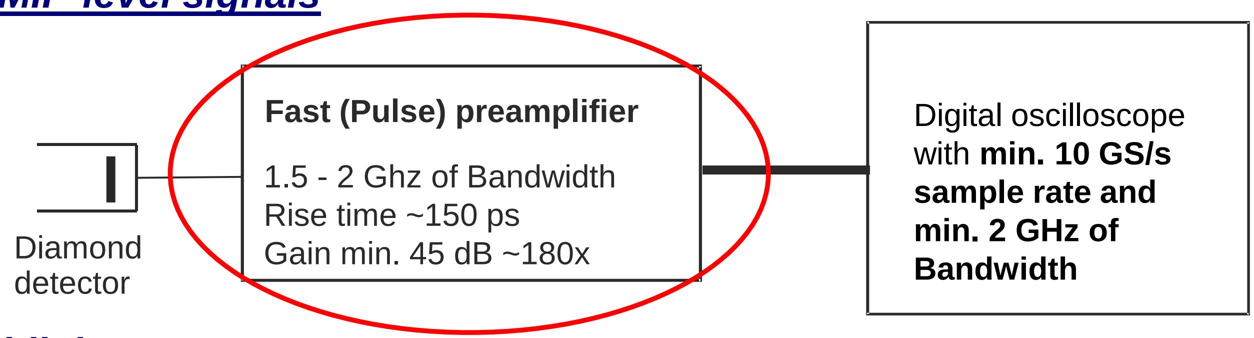
Applications at IFJ PAN

Particle counting and TOF measurements:

- **Single particle detection with high efficiency for each micropulse separately**
- **Mechanism of dealing with pile-up within micropulses. Is it possible to distinguish between multiple, contemporary protons within single micropulse?**
- **TOF resolution < 50 ps for measurements of beam monochromaticity**

Because of very low intrinsic noise of Diamond material, one of the most critical elements, often setting limits in performance of detection systems with CVD Diamond detectors is the preamplifier.

Wideband Electronics for MIP-level signals



Wideband Electronics Highlights:

- **RF technology >1.5 GHz bandwidth**
- **Signal amplification ~150-300 V/V for low-LET particles and/or thin detectors (single 70MeV proton loses (the most probable value) ~150 keV (~11 000 electrons) in 50µm scCVD, which turns into ~20 mV pulse amplitude after 45dB of amplification). This is very comparable to one MIP in 300µm (~10 800 electrons) in scCVD Diamond.**
- **Extremely low noise RMS requirement @ high amplification**

DBA IV – the reference preamplifier (2 GHz of bandwidth)

The reference broadband (2 GHz) preamplifier with the gain of up to 50 dB, designed and developed at GSI Darmstadt, was used. DBA IV was originally optimized for measurements of heavier ions with Diamond detectors.

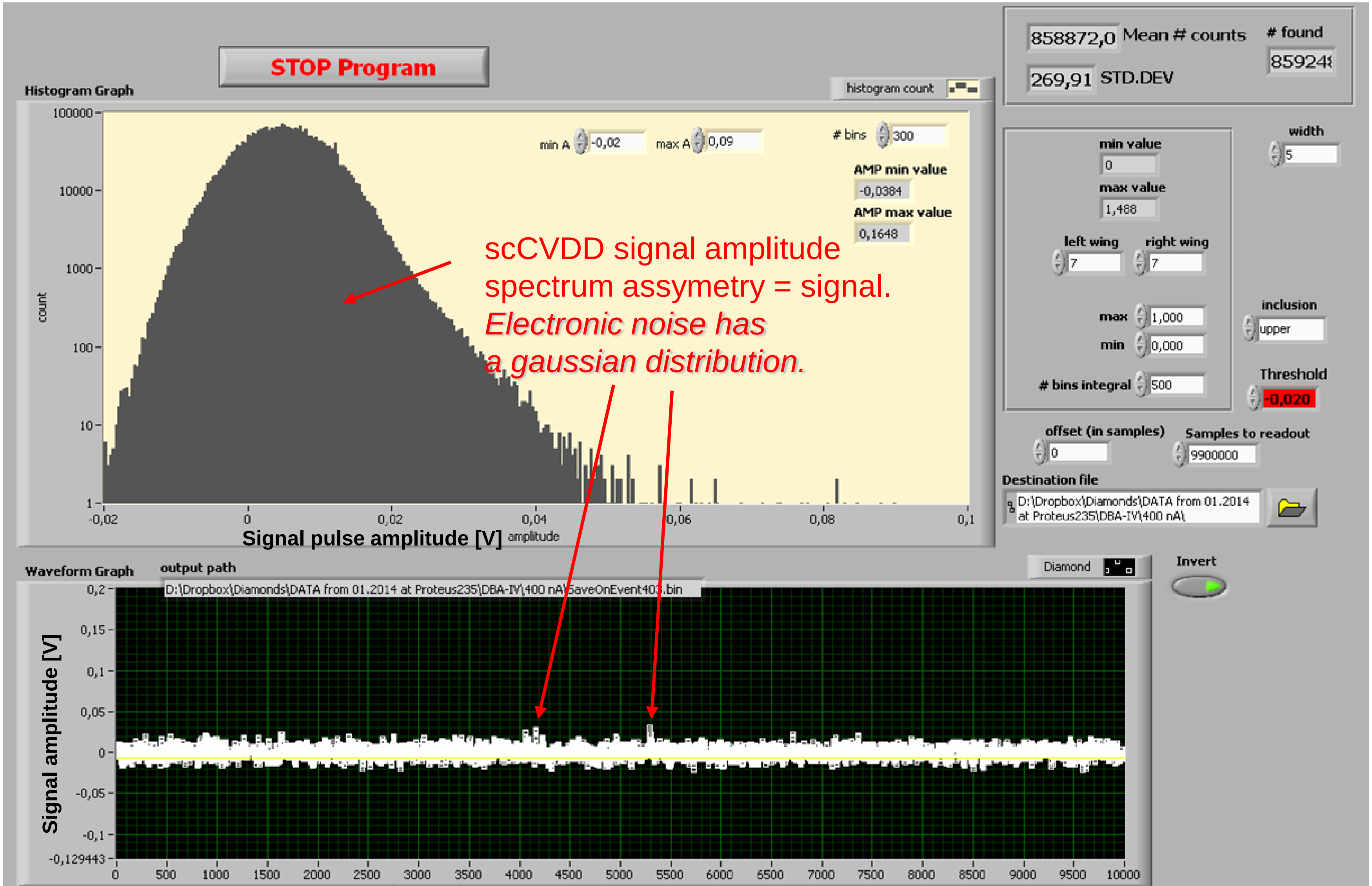
DBAIV main characteristics

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

GSI

The DBAIV preamplifier cont.

Signal spectrum of 70MeV protons measured @ Proteus-235 with 50µm scCVD detector by DDL (Diamond Detectors Ltd.)

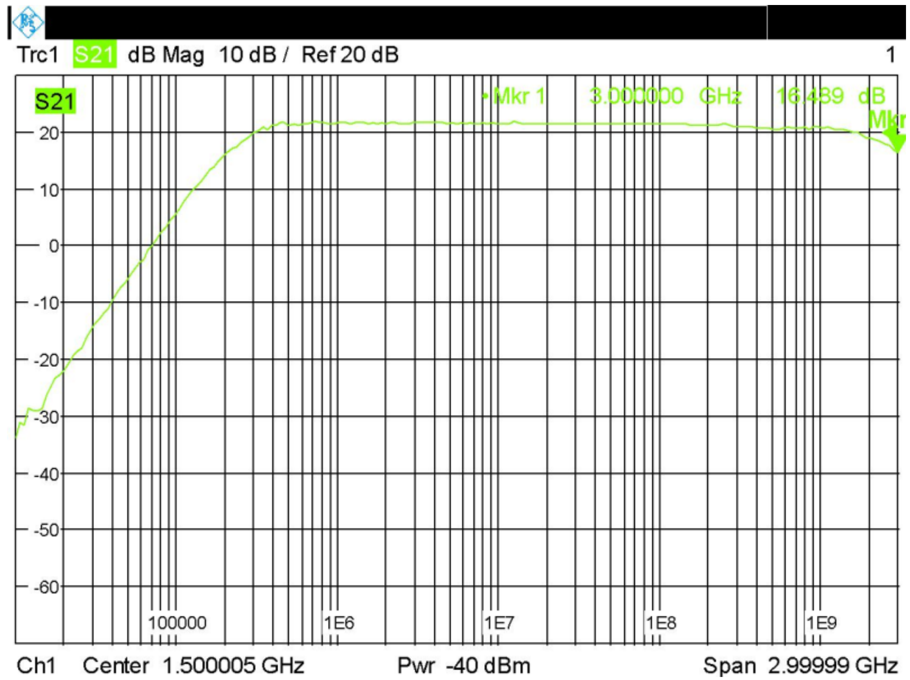


CVD front-end electronics design R&D: PA-10 preamp.

A new design of the low-noise and high-gain has been carried out in Krakow.
The design minimum requirements:
Improvement of S/N ratio @ minimum bandwidth of 1.5 GHz and gain >= 45 dB.

The result is the PA-10 wideband preamplifier.

The performance of the PA-10 allows to continue with signals by particles generating >~10 000 electrons of the signal as for single particle detection.

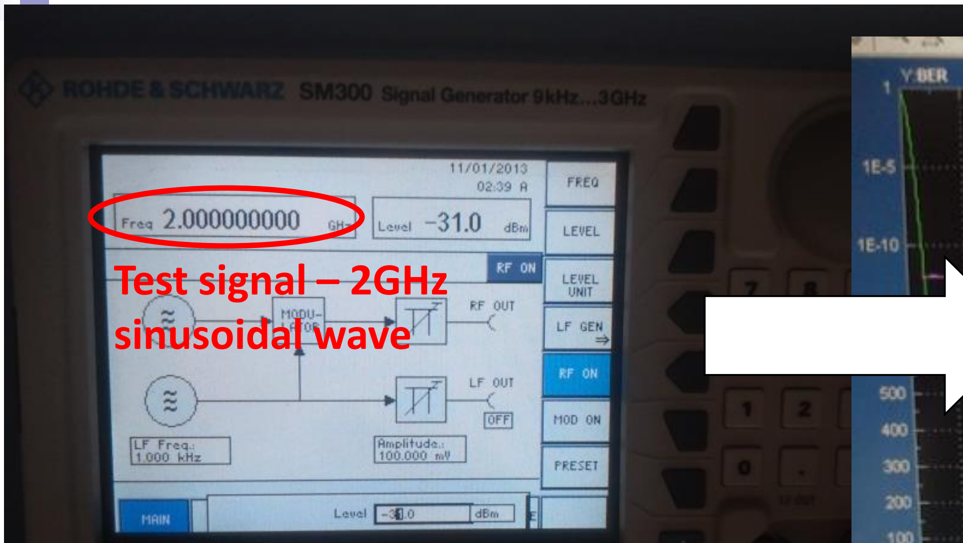


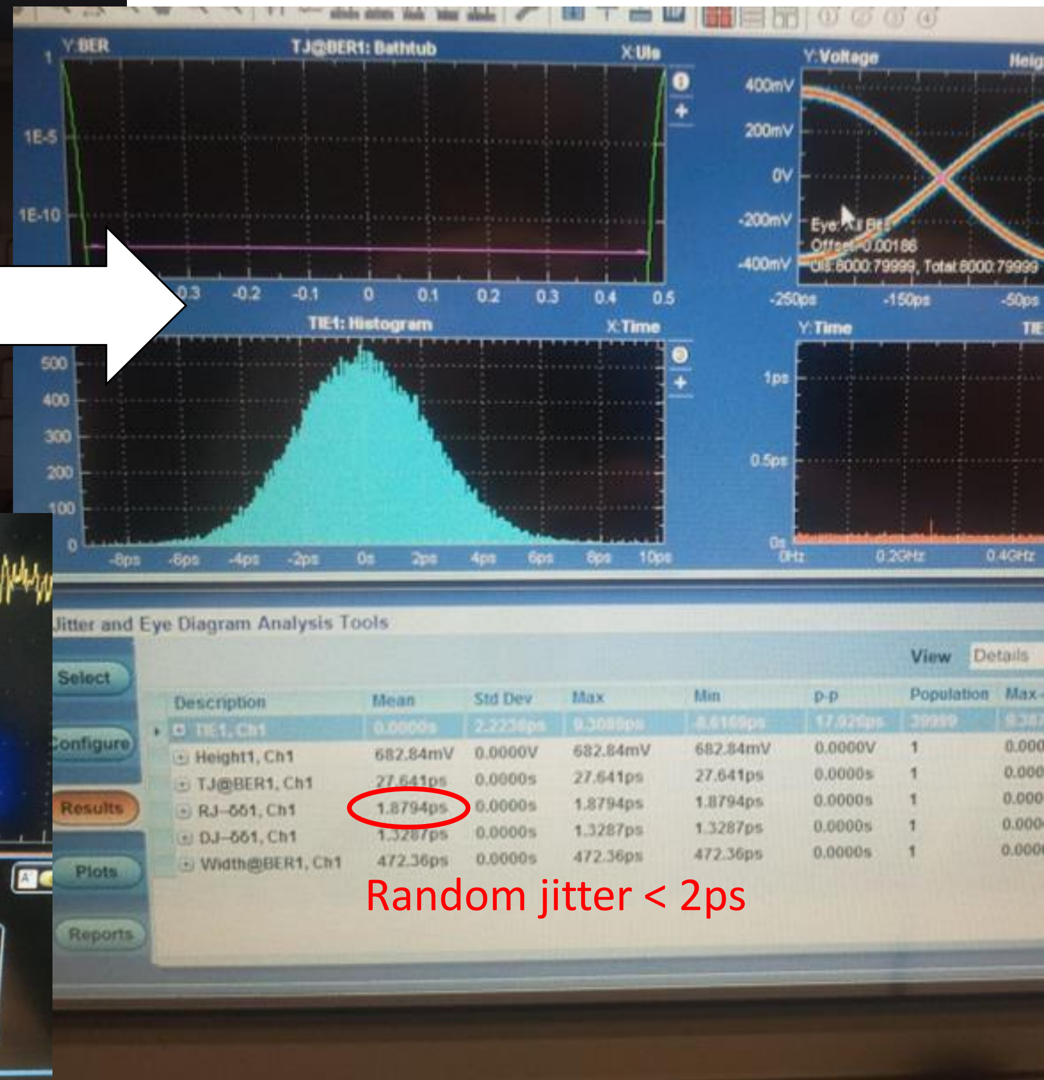
An exemplary gain measurement of a single stage prototype preamplifier by R&S network analyzer

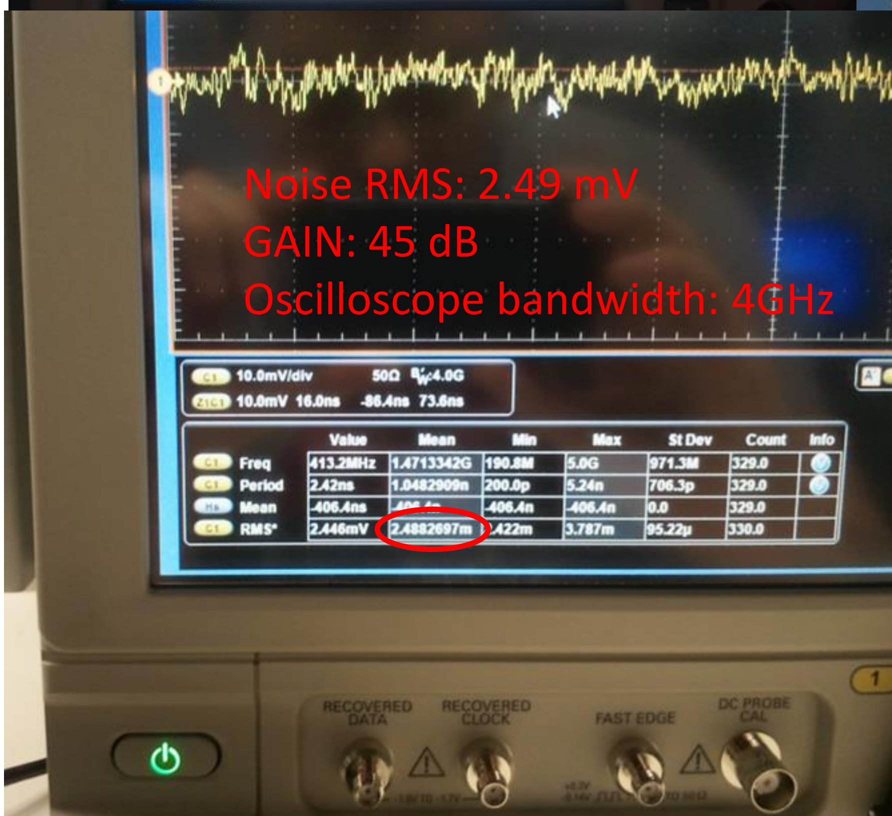
In terms of TOF performance, the improvement of the S/N may be required and optimized, depending on timing resolution needed in application.

PA-10 - 45dB preamplifier

CVD front-end electronics: PA-10 laboratory tests



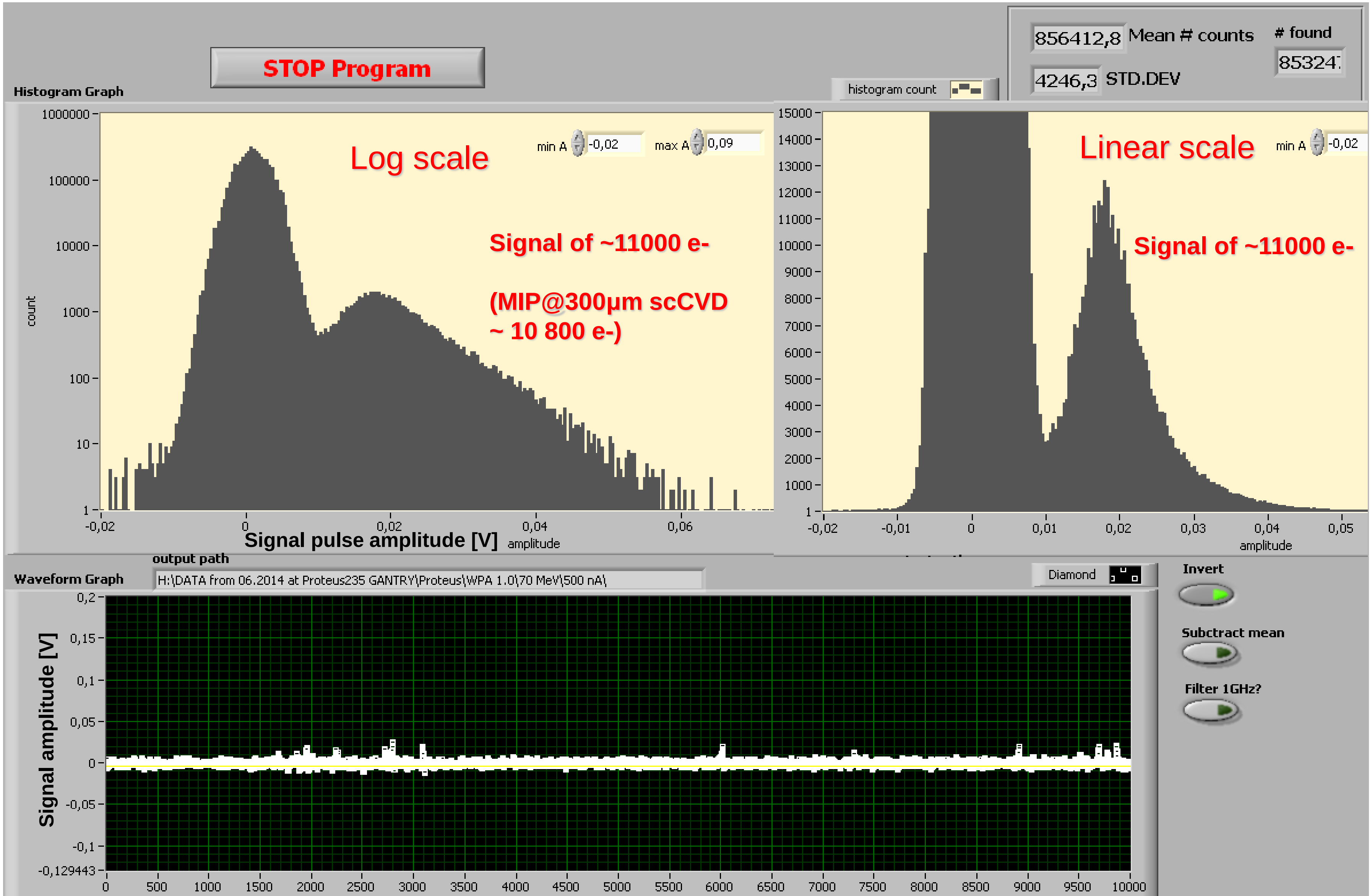




Wideband amplifier PA-10 tests and qualification.
<u>Noise level</u> and <u>jitter</u>.

CVD front-end electronics: PA-10 beam test

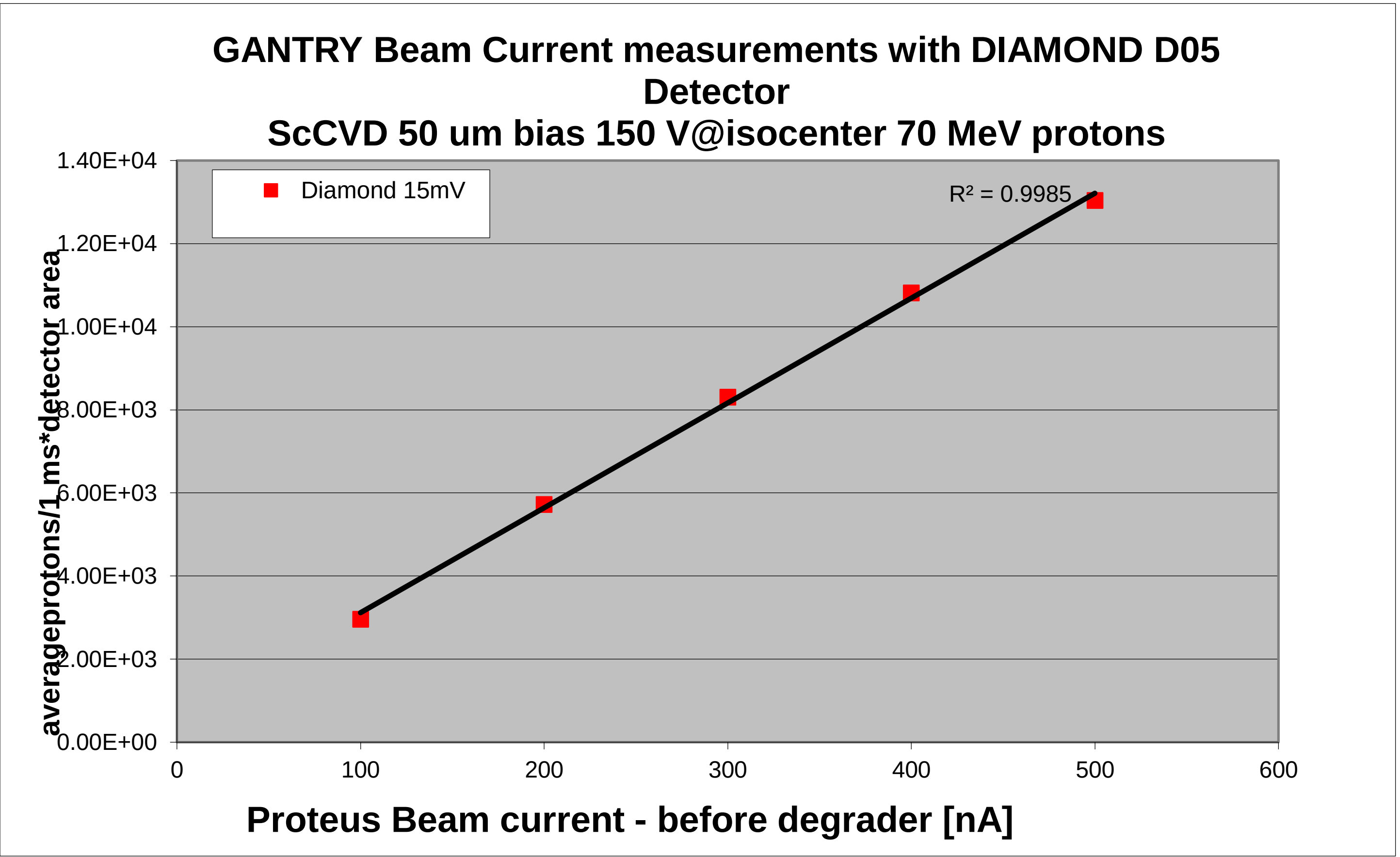
Signal spectrum of 70MeV protons measured @ Proteus-235 with 50µm scCVD detector by DDL (Diamond Detectors Ltd.)



CVD front-end electronics: PA-10. Beam intensity measurements.

Signal amplitude comparison for different proton beam energies

proton energy	70 MeV	150 MeV	225 MeV
average energy loss [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

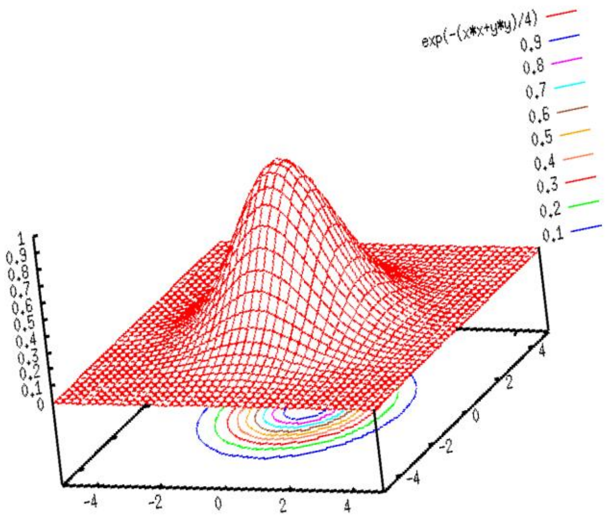


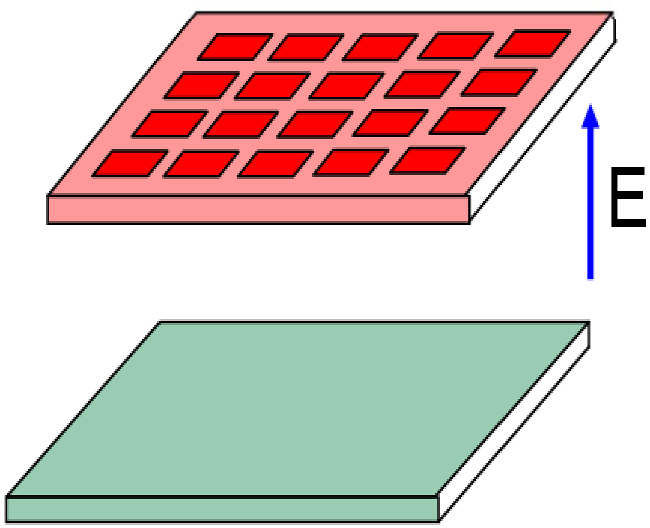
Preamplifiers for CVD Diamonds: DBAIV vs PA-10

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 impedance	50 Ω	50 Ω
Output impedance	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**

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

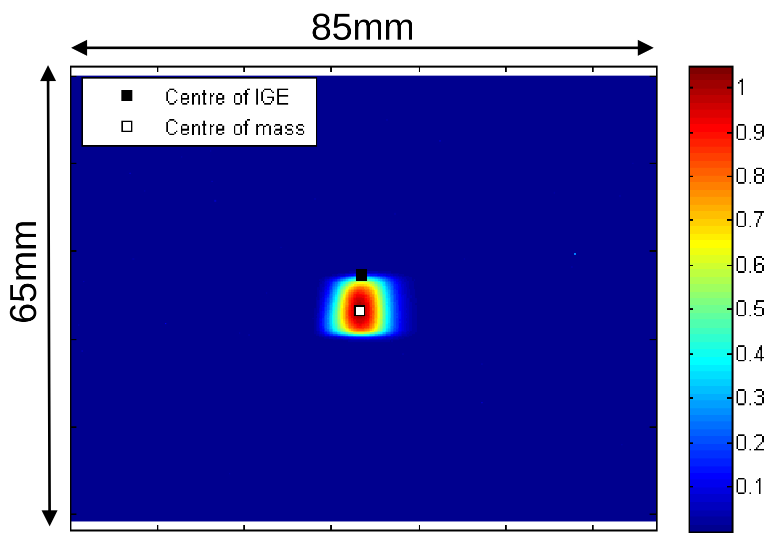




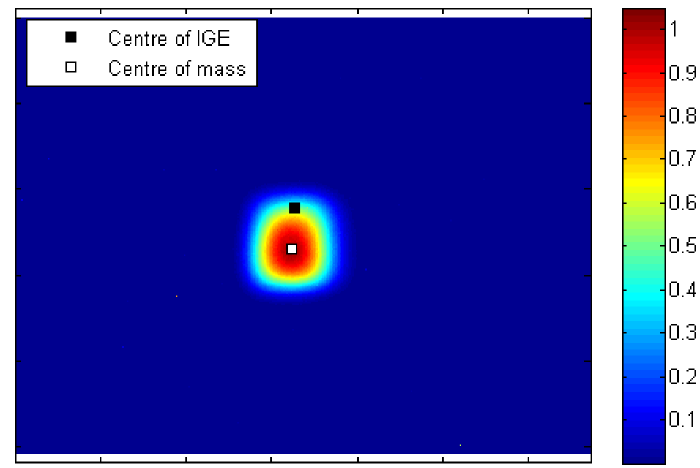
Main parameters to be defined according to application

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

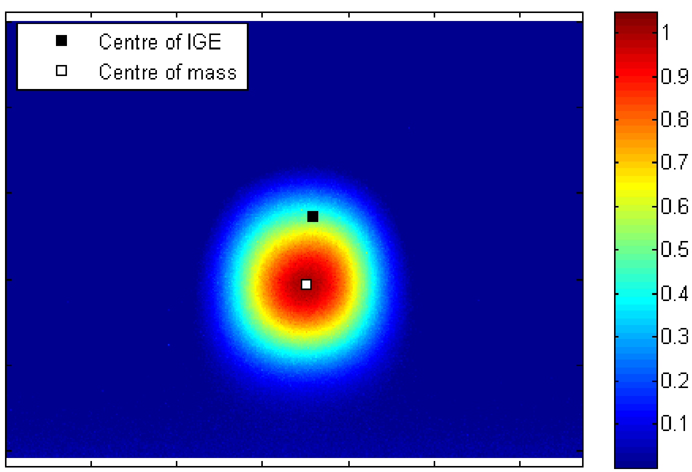
Proteus-235 beam profiles measured in Experimental Hall of CCB (Cyclotron Centre Bronowice).



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



Distance from IGE: Z=0.7 m



Distance from IGE: Z=2 m

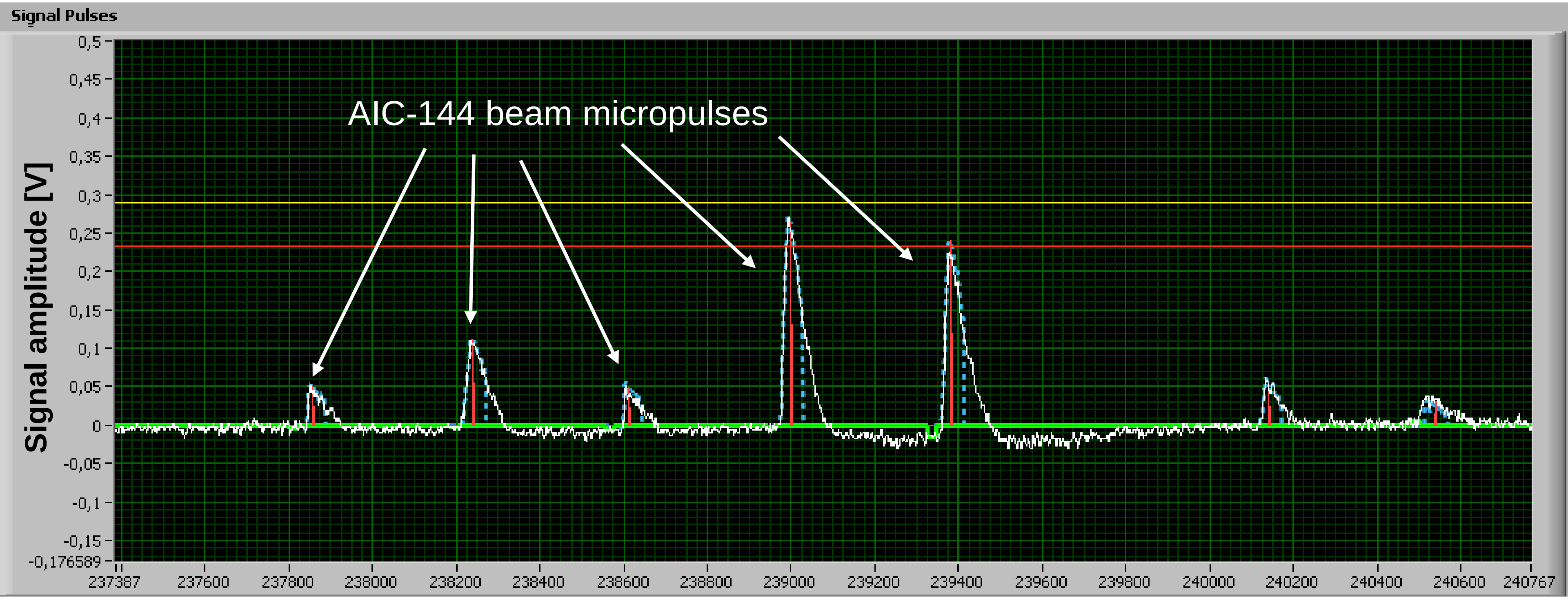
Measurements have been performed in the air by ProBImS measurement system developed at IFJ PAN and composed of scintillating screen and high-resolution ATIK 383 L+ digital camera.

by Marzena Rydygier

AIC-144 cyclotron beam diagnostics at IFJ PAN. Pile-up resolving.

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.

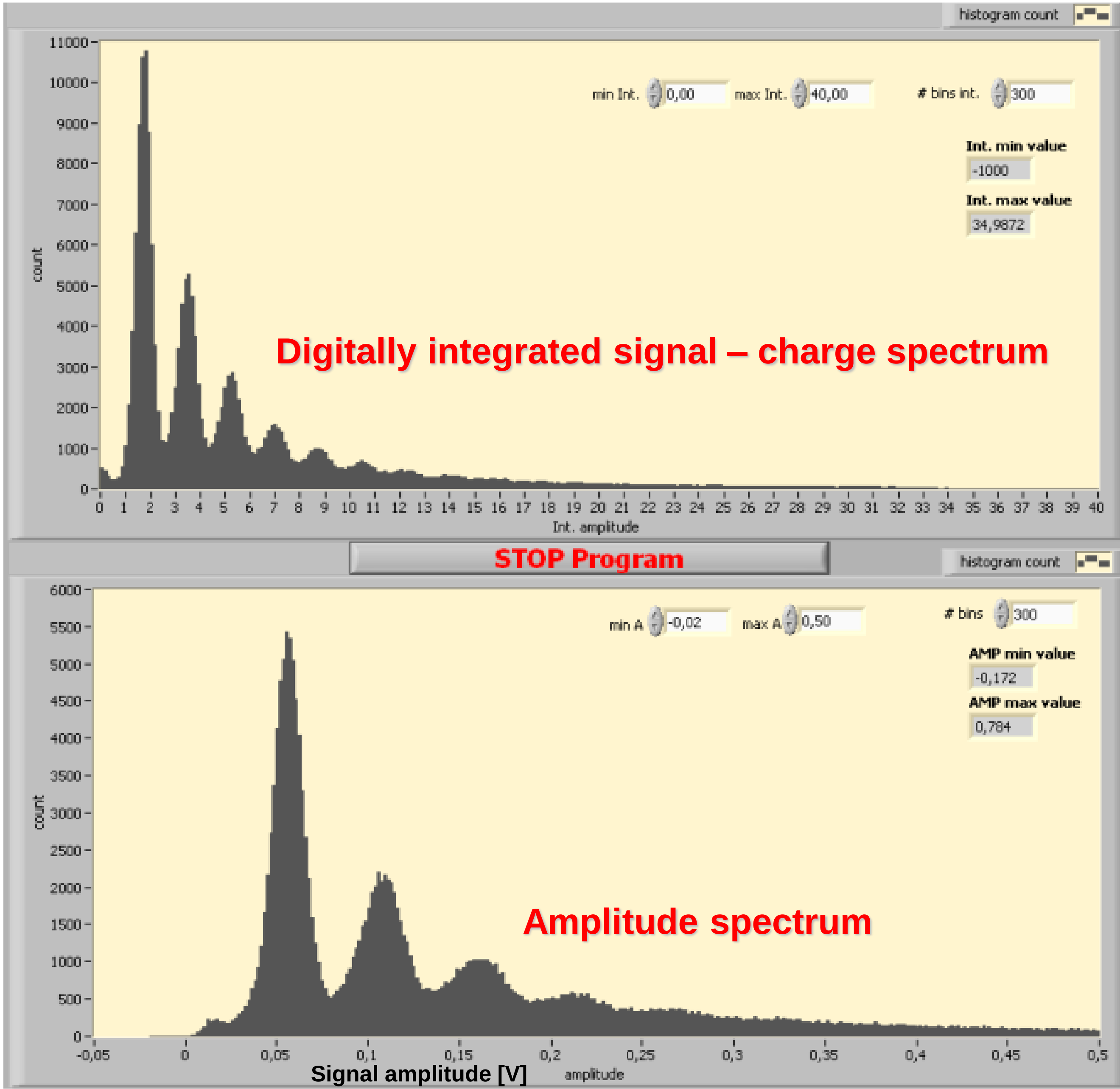


scCVD detector 500µm @ 350V bias voltage

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

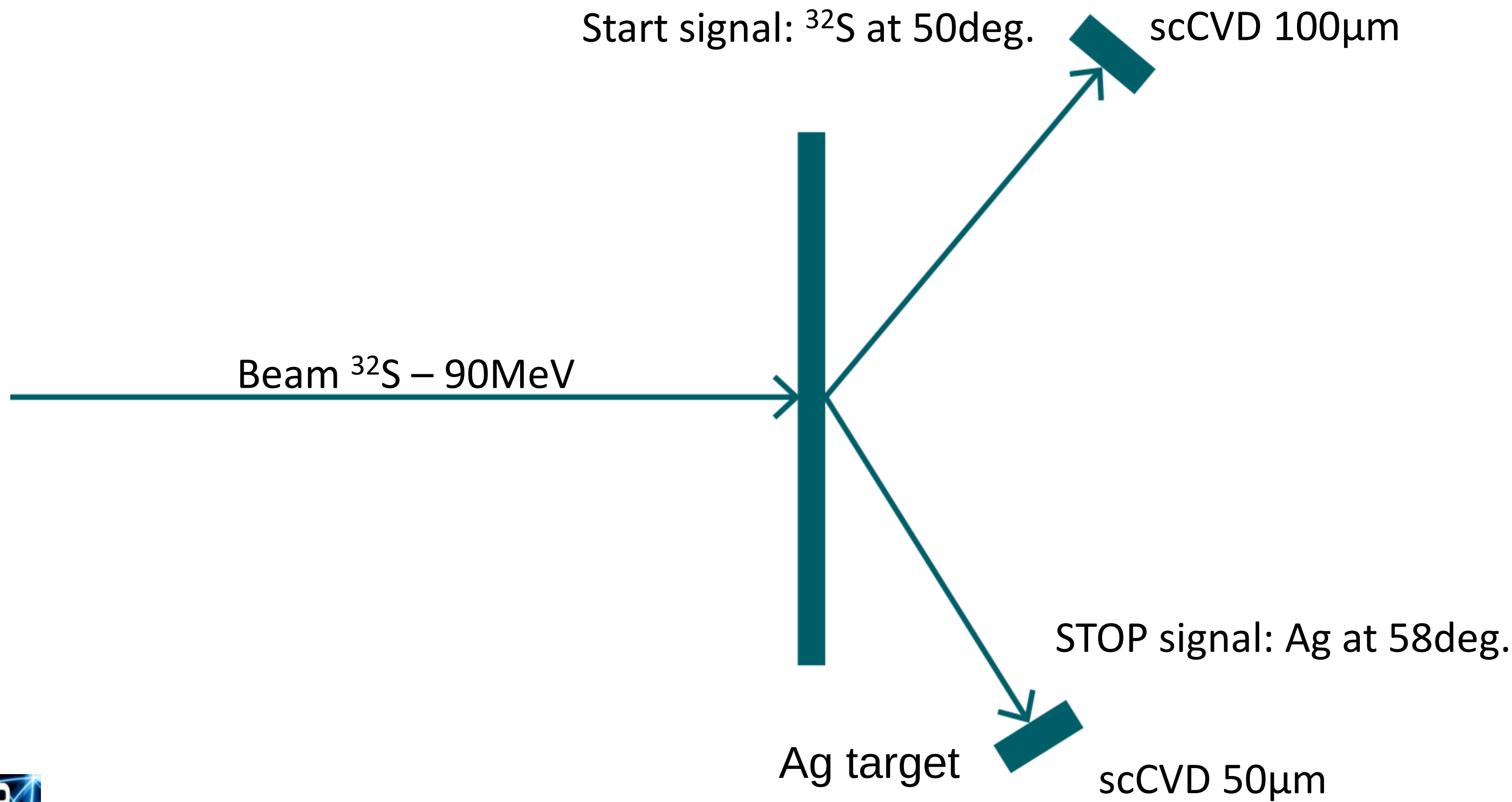
500µm scCVD digital measu-rements with 10Gs/s sample rate.

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



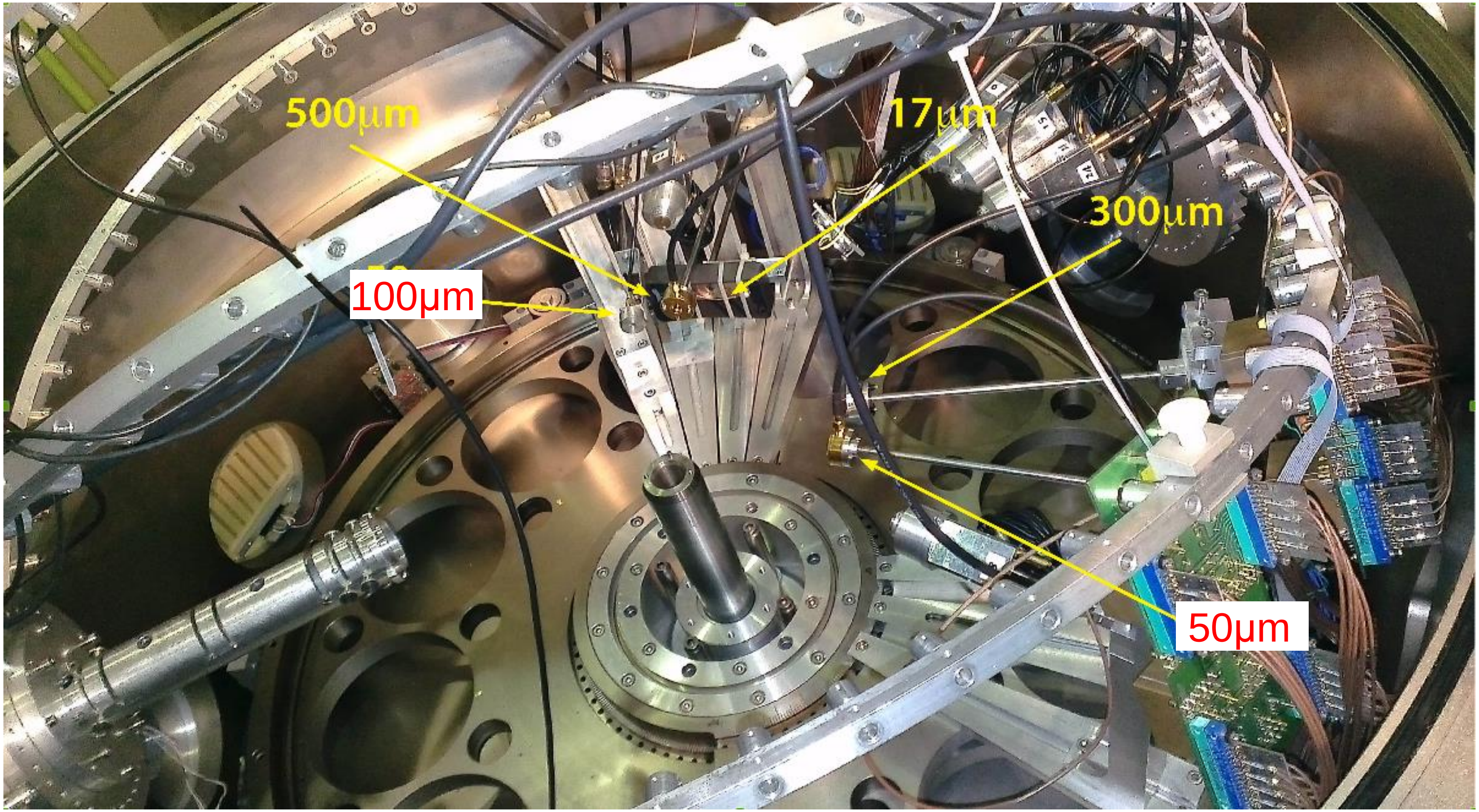
TOF preliminary measurements with heavy ions and 70MeV protons

Test of performance of scCVD at Heavy Ion Laboratory (HIL), Warsaw.

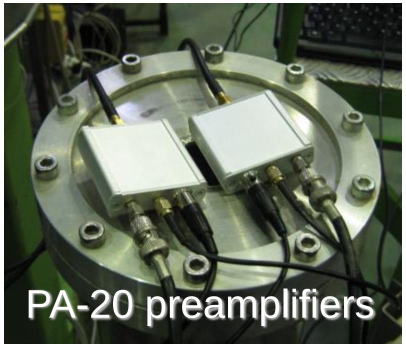


Collaboration:
HIL UW, IFJ Krakow, CEA Saclay, Univ. of Huelva

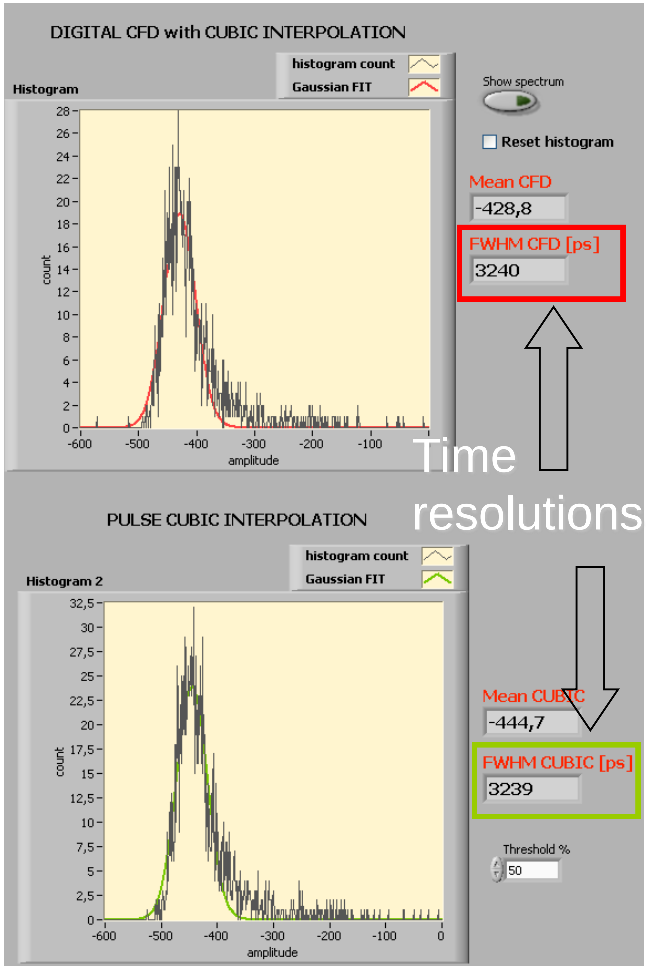
TOF test setup at HIL. Configuration of detectors during the experiment.



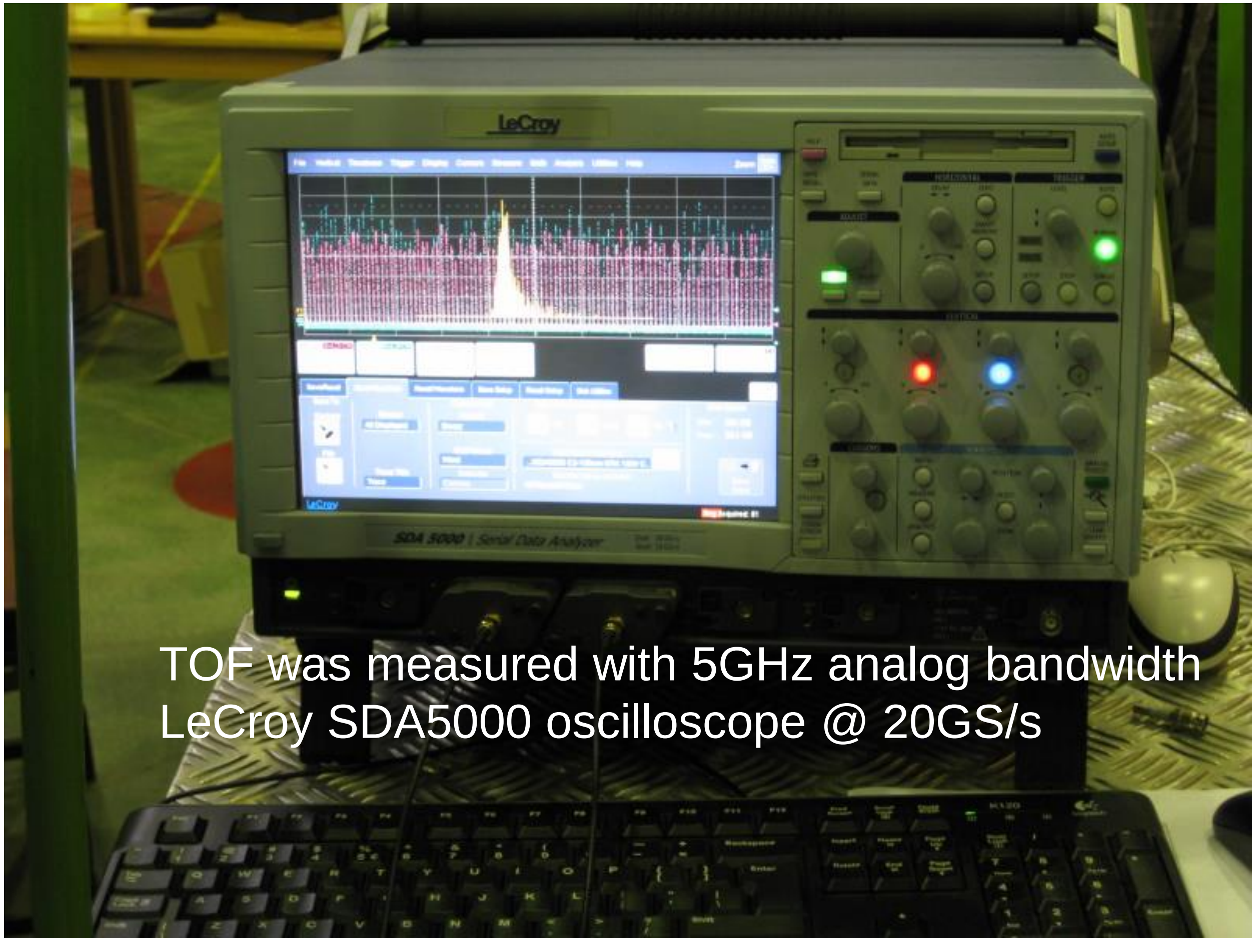
Measurement of kinematics with heavy ions (up to 100 MeV) at HIL.



PA-20 preamplifiers



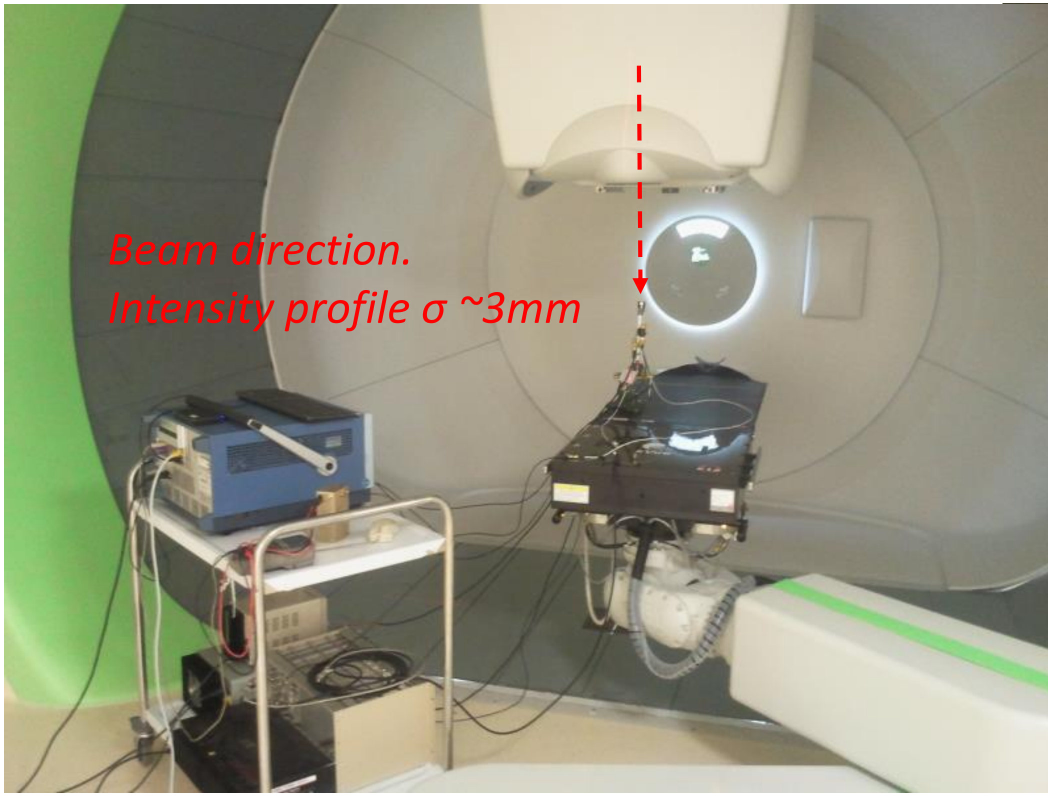
Time resolutions

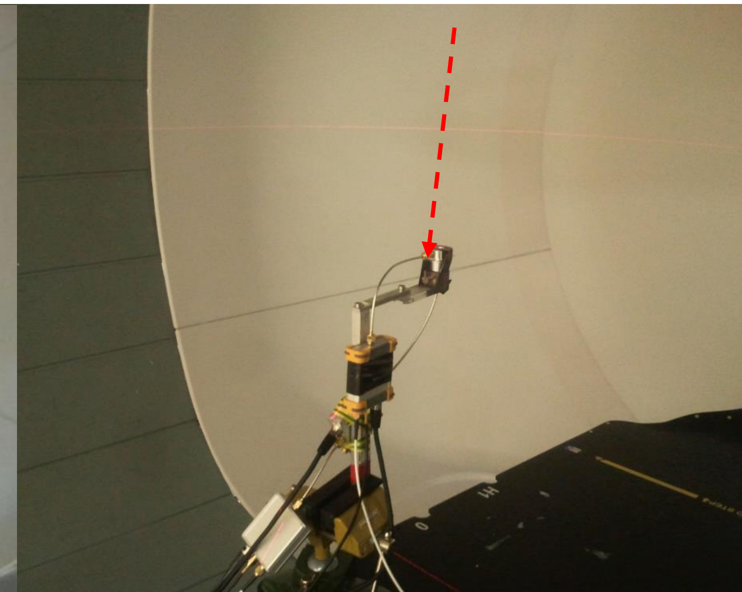


TOF was measured with 5GHz analog bandwidth LeCroy SDA5000 oscilloscope @ 20GS/s

TOF measurements in Krakow CCB (Bronowice Cyclotron Centre) – hadrontherapy site

TOF preliminary measurements with 70MeV protons at Gantry site with two scCVD's: 100μm and 300μm set in series (with respect to beam direction).

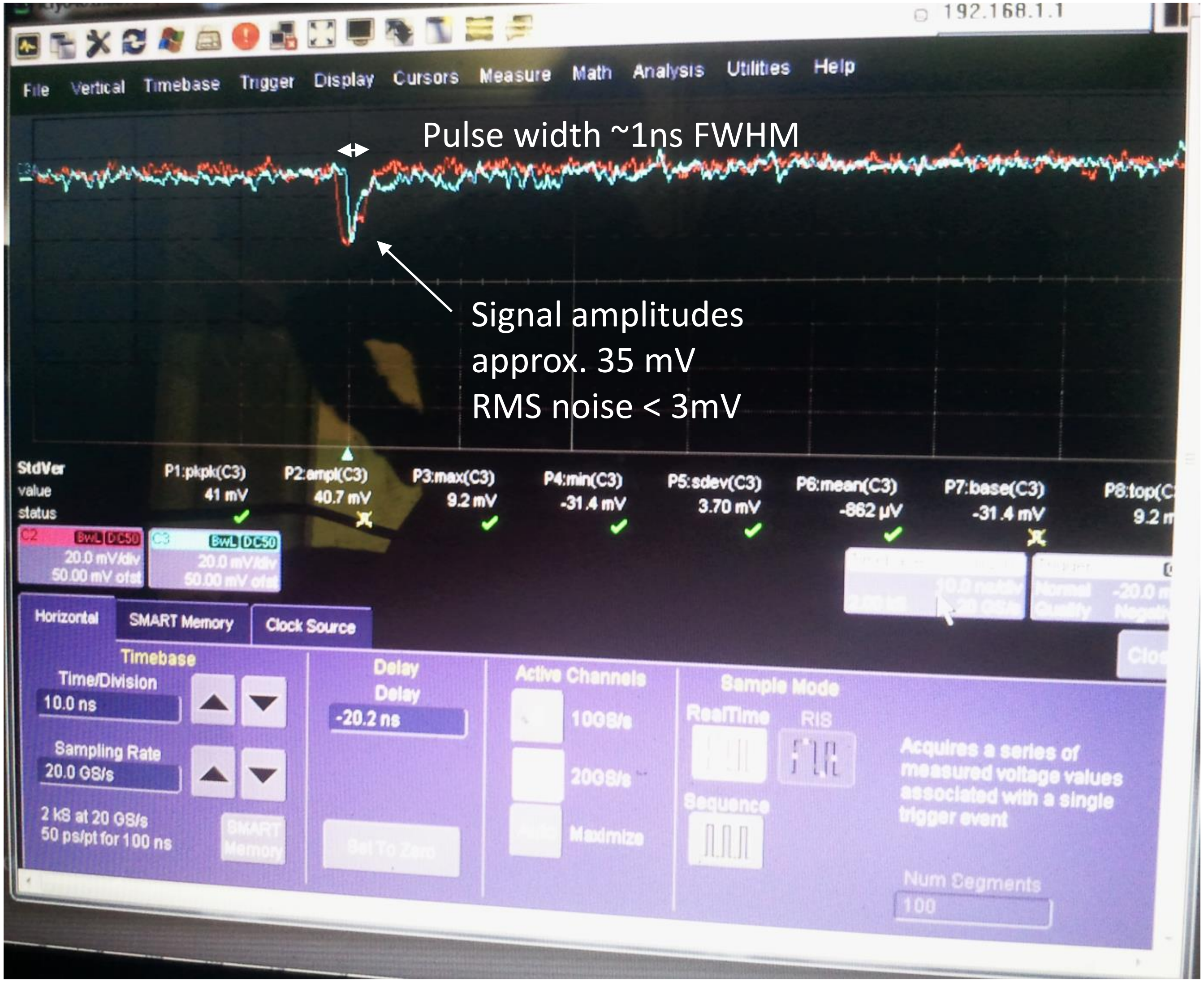




Wideband preamplifiers with 20dB gain

Detector's signals were measured and stored by 5GHz analog bandwidth LeCroy SDA5000 5 GHz (analog bandwidth) oscilloscope / SDA @ 20GS/s.

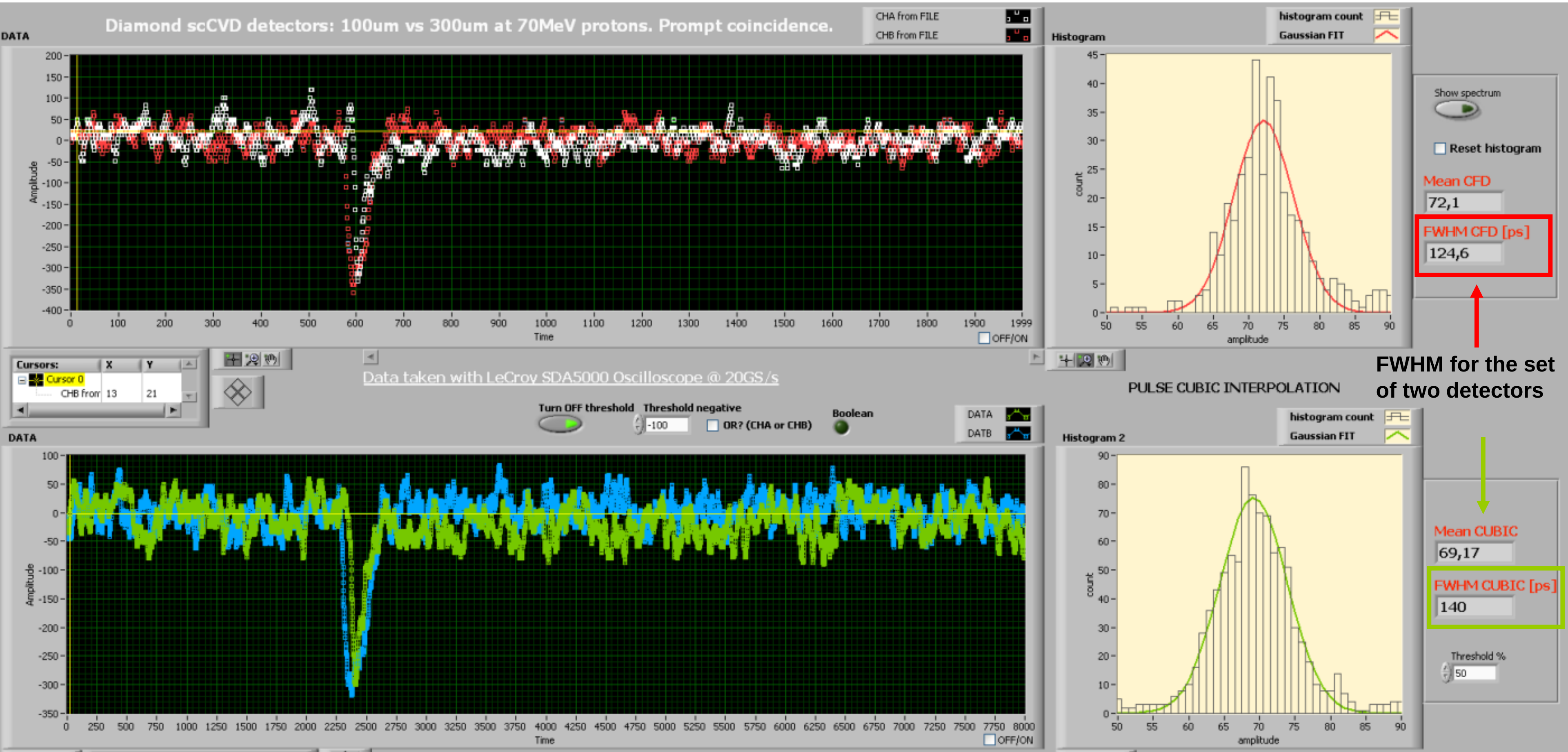
TOF preliminary results at Gantry: scCVD pulses.



Signals from 100µm and 300µm detectors were amplified by single PA-10 preamplifier and two PA-20 preamplifiers (in series) for the second detector.

TOF preliminary results with 70MeV protons at Gantry

DIGITAL CFD + CUBIC INTERPOL. OF ZERO CROSSING



$$\sigma^2_{time} = [t_{rise}/(S/N)]^2 + \sigma^2_{t,quantization} + \sigma^2_{t,CVDD}$$

TOF results with 70MeV protons is ~125 ps (FWHM) for the set of two detectors. Assuming both detectors equal (not actually the case) the distibution σ < 40 ps for single scCVD Diamond detector.

Summary and perspectives

- **Proteus 235 produced protons (70-230 MeV) are challenging to detect because of the low signal (~150 keV for 70 MeV) and high bandwidth.**
- **One of the most important Nuclear Physics (and medical) application at IFJ PAN is the precise measurement of Proteus-235 proton energies before they arrive to the „target". The required precision <0.3 % can only be reached by TOF technique. To accomplish the task, the system TOF precision has to be <50 ps, assuming the distance between detectors to be ~2m.**
- **Preliminary TOF test beam provide ~125 ps FWHM of resolution (σ < 40 ps per detector, assuming two identical scCVD's).**
- **For systems with diamond detectors, one of the major limiting factor is the front-end electronics. State-of-the-art preamplifiers are capable of separating signal from noise (for 50μm scCVD) for proton energies up to ~100 MeV. New developments may be necessary in order to cope with higher particle energies, thus lower energy loses.**

Our collaborators:

Heavy Ion Laboratory (HIL) Warszawa
Paweł Napiorkowski
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Katarzyna Wrzosek-Lipska
Jędrzej Iwanicki
Paweł Matuszczak
Agnieszka Trzcińska

IFJ PAN Kraków
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Tomasz Nowak
Marzena Rydygier
Michał Ciemała
Krzysztof Drozdowicz
Jan Dankowski
Witold Męczyński

CEA-Saclay
Michał Pomorski

University of Huelva
Ismael Martel Bravo