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Performance of CVD diamond detectors for single ion beam-tagging applications in hadrontherapy monitoring

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Abstract

In the context of online ion range verification in particle therapy, the CLaRyS collaboration is developing Prompt-Gamma (PG) detection systems. The originality in the CLaRyS approach is to use a beam-tagging hodoscope in coincidence with the gamma detectors to provide both temporal and spatial information of the incoming ions. The ion range sensitivity of such PG detection systems could be improved by detecting single ions with a 100 ps (σ) time resolution, through a quality assurance procedure at low beam intensity at the beginning of the treatment session. This work presents

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the investigations that led to assessment of the Chemical Vapor Deposition (CVD) diamond detectors performance to fulfil these requirements. A ^{90}Sr beta source, 68 MeV protons, 95 MeV/u carbon ions and a synchrotron X-ray pulsed beam were used to measure the time resolution, single ion detection efficiency and proton counting capability of various CVD diamond samples. An offline technique, based on double-sided readout with fast current preamplifiers used to improve the signal-to-noise ratio, is also presented. The different tests highlighted Time-Of-Flight resolutions ranging from 13 ps (σ) to 250 ps (σ), depending on the diamond crystal quality and the particle type and energy. The single 68 MeV proton detection efficiency of various large area polycrystalline (pCVD) samples was measured to be $>96\%$ using coincidence measurements with a single-crystal reference detector. Single-crystal CVD (sCVD) diamond proved to be able to count a discrete number of simultaneous protons while it was not achievable with a polycrystalline sample. Considering the results of the present study, two diamond hodoscope demonstrators are under development: one based on sCVD, and one of larger size based on pCVD. They will be used for the purpose of single ion as well as ion bunches detection, either at reduced or clinical beam intensities.

Keywords: CVD diamond, hadrontherapy, ion range verification, time resolution, detection efficiency, particle counting, beam monitoring

1. Introduction

Hadrontherapy is an external radiotherapy modality based on light ion beams [1, 2]. Even though the ballistic properties of ions and the enhanced relative biological effectiveness represent essential advantages of particle ther-

5 apy compared to conventional X-ray radiotherapy, it is still facing limitations
6 due to ion range uncertainties arising at every stage of the treatment pro-
7 cedure [3]. They currently lead physicians to set ion range specific safety
8 margins that limit the dose conformation and prevent them to plan irradiation
9 fields where organs at risk are located close beyond the targeted volume.

10 In this context, several experimental approaches have been developed to
11 build an online ion range verification system [4, 5]. Among them, prompt-
12 gamma-based verification techniques [6] propose to retrieve the actual ion
13 range from the emission profile of prompt-gamma photons (PG) that are
14 emitted along the ion path by excited target nuclei or ion fragments right
15 after inelastic collisions between incoming ions and target nuclei. To get rid
16 of the inherent and substantial neutron-induced background also produced
17 during these nuclear interactions, PG detection systems use a Time-Of-Flight
18 (TOF) based gamma-neutron discrimination. It is generally carried out by
19 coincidence measurements between the gamma camera trigger and the ion
20 bunch time of arrival given by the accelerator radio-frequency signal (RF).
21 Provided the body-camera distance is set to a few tens of centimeters, an
22 overall TOF resolution of 1 ns (σ) is sufficient to achieve this purpose.

23 Instead of using the accelerator RF as a START signal, the CLaRyS
24 collaboration proposes to set up a beam-tagging hodoscope upstream from
25 the patient at reduced intensity (~ 1 ion/bunch). It will also provide an
26 ion transverse position that is useful for PG vertices reconstruction with PG
27 imaging systems (PGI). The direct detection of incoming ions also makes
28 the TOF measurement independent of the beam time structure and/or any
29 potential RF phase shift as has been observed [7]. According to this idea, the

30 collaboration has developed a $12.8 \times 12.8 \text{ cm}^2$ scintillating-fiber hodoscope.
31 It has been tested and characterized on proton and carbon ion beams [8] and
32 the results highlighted a 0.7 ns (σ) time resolution and a detection efficiency
33 up to 98%.

34 Considerable improvements can be achieved in the sensitivity of potential
35 ion range shift determination by improving the TOF resolution down to a few
36 hundred picoseconds. This holds for PGI and prompt gamma timing (PGT)
37 [9, 10, 11] and is thoroughly discussed in [12]. Different detector technologies
38 could enable the development of a beam monitor with a 100 ps (σ) time
39 resolution for single ion detection [13, 14, 15]. The collaboration has chosen
40 to focus on Chemical Vapor Deposition (CVD) diamond technology in order
41 to develop a beam hodoscope upgrade combining an excellent time resolution
42 [16],[15] (and references therein) and high radiation hardness guaranteeing
43 long-term stability in clinical conditions.

44 The current work presents investigations led on diamond detectors, at
45 first, to evaluate polycrystalline (pCVD) single proton detection efficiency.
46 Then, experiments were carried out to assess single crystal (sCVD), pCVD
47 and Diamond On Iridium (DOI) detector ability to perform TOF measure-
48 ments with a 100 ps resolution, using 68 MeV single protons in ARRONAX
49 (Saint-Herblain, France), 95 MeV/u carbon ions in GANIL (Caen, France),
50 short pulses of 8.53 keV X-rays at ESRF (Grenoble, France) and minimum
51 ionizing particle (MIP) with a ^{90}Sr laboratory source. Finally, the sCVD and
52 pCVD diamond detectors single particle counting capabilities have been eval-
53 uated with the 68 MeV proton beam delivered by the ARRONAX cyclotron
54 at low intensity (6 pA \sim 1 proton/bunch).

55 **2. Material and methods**

56 *2.1. Detectors assembly and generic experimental set-up*

57 The detector-grade diamond samples used in the present work are com-
58 mercially available and produced by Chemical Vapor Deposition (CVD). The
59 sCVD diamonds were purchased from Element6 [17], pCVD diamonds from
60 Element6, II-VI [18] and Diamond Delaware Knives (DDK) [19], and DOI
61 diamonds from Audiatic [20] and Augsburg University. The tested samples
62 ranged from 300 μm to 500 μm in thickness, and from $4.5 \times 4.5 \text{ mm}^2$ to 20
63 $\times 20 \text{ mm}^2$ in area. In particular, large pCVD are foreseen for the assembly
64 of a large size hodoscope. Diamond samples were assembled as pad detec-
65 tors as described in [21, 22]. A thin aluminum disk-shaped metallization
66 was performed either by physical evaporation [23] (50 nm) or by sputtering
67 (100 nm). The diamonds were sandwiched between two 50Ω -adapted printed
68 circuit boards (PCB), allowing bias of both polarities and signal readout con-
69 nections on both sides.

70 For the different tests presented in this work, diamond detectors were
71 systematically tested by pair. Figure 1 illustrates the general configuration
72 used during the tests. Two diamond detectors are exposed to a particle
73 beam. The detector under test is positioned upstream from a smaller size
74 reference detector (a sCVD sample, unless stated otherwise). For each beam
75 test, both detectors were enclosed together in an aluminum shielding box
76 with front and rear apertures covered with 12 μm -thick aluminized Mylar
77 films [21, 22]. The output channels of the detectors were coupled to broad-
78 band amplifiers (CIVIDEC C2-HV [24] or Greenstream DBA III and IV-R)
79 and analog signals were digitized using fast digitizers (a 500 MHz, 3.2 GS/s

Table 1: Summary of the various diamond samples tested within this work. DE = Single proton detection efficiency, TOF = Time-Of-Flight resolution, C = counting, σ_t = intrinsic time resolution.

Diamond	Provider	Size (mm ³)	Metallization		Computed capacitance (pF)	Tested with	Involved in measurements:
			Diam. (mm)	Thick. (nm)			
sCVD	E6	4.5 × 4.5 × 0.517	3	50	0.7	X, β , p, ¹² C	DE, TOF, C
sCVD	E6	4.5 × 4.5 × 0.517	3	50	0.7	β	TOF
pCVD	E6	10 × 10 × 0.3	7	50 - 100	6.5	X, p, ¹² C	DE, TOF
pCVD	E6	20 × 20 × 0.5	16	50	20	¹² C	TOF
pCVD	IL-VI	10 × 10 × 0.5	7	100	3.9	p	DE, TOF
pCVD	DDK	5 × 5 × 0.3	3	100	1.2	p	DE, TOF, C
DOI	Augsburg Univ.	5 × 5 × 0.3	3	50 - 100	1.2	X, p, ¹² C	TOF, σ_t
DOI	Audiatec	5 × 5 × 0.3	3	50	1.2	X	σ_t

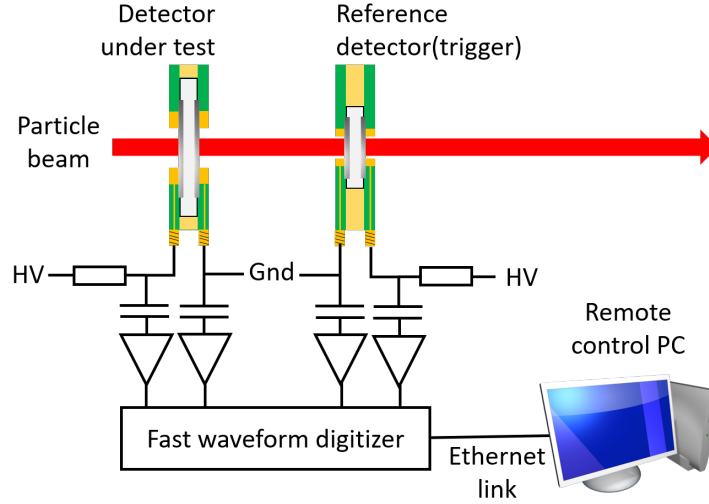


Figure 1: Generic experimental set-up used for detection efficiency, timing and counting measurements presented in this work. Specific dedicated additions in the set-up are presented in the corresponding subsections.

80 WaveCatcher digitizer [25] or a 2 GHz, 20 GS/s LeCroy Digital Storage Os-
 81 cilloscope (DSO)).

82 *2.2. Side-to-side signals summation*

83 During the interaction of a ionizing particle in a diamond detector, the
 84 same signal S (absolute value) is induced on both electrodes by the elec-
 85 tron/hole pairs drift. In practice, each side is read by a single preamplifier
 86 generating an output signal of amplitude S^{side_i} (with $i=1,2$) with a corre-
 87 sponding noise level $\sigma_n^{side_i}$ resulting in a signal-to-noise ratio $S^{side_i}/\sigma_n^{side_i}$.
 88 First, we assume that the intrinsic noise generated by the diamond itself is
 89 negligible at 300 K compared to that induced by the wide-band preamplifier.
 90 Then, the noise of each preamplifier is assumed to be an independent Gaus-
 91 sian white noise. Therefore, the resulting noise on the sum-signal σ_n^{sum} can
 92 be expressed as follows:

$$\sigma_n^{sum} = \sqrt{(\sigma_n^{side_1})^2 + (\sigma_n^{side_2})^2} = \sigma_n^{side_1} \oplus \sigma_n^{side_2}. \quad (1)$$

93 A sum signal $S^{sum} = S^{side_1} - S^{side_2}$ (the two side signals are of opposite
 94 polarity) can be derived as well as a sum-signal-to-noise ratio:

$$S/N_{sum} = \frac{S^{side_1} - S^{side_2}}{\sigma_n^{side_1} \oplus \sigma_n^{side_2}}. \quad (2)$$

95 If one supposes now that the two preamplifiers are strictly identical, Equation
 96 2 becomes:

$$S/N_{sum} = \frac{2S^{side}}{\sqrt{2\sigma_n^2}} = \frac{2S^{side}}{\sigma_n\sqrt{2}} = \sqrt{2} \cdot S/N_{side}. \quad (3)$$

97 Using the sum signal, the signal-to-noise ratio (SNR) can be increased by a
 98 factor $\sqrt{2}$. By doubling the amplitude of the signal, the slope in the rising
 99 edge of the sum-signal can become up to twice as much as the one measured

100 on each electrode signal improving the time resolution of the detector con-
101 sequently. This technique was used for the detection efficiency and timing
102 measurements presented in Sections 2.3.1 and 2.3.2. Note that this technique
103 requires identical preamplifiers (same pulse shape), a strict adjustment of the
104 pulses risetime and a null delay between both side signals.

105 *2.3. Experimental tests and data analysis procedures*

106 *2.3.1. Single proton detection efficiency of pCVD detectors*

107 The single proton detection efficiency has been evaluated with 68 MeV
108 protons during a dedicated experiment at ARRONAX IBA C70 isochronous
109 cyclotron, Nantes (with a fixed Radio-Frequency of 30.45 MHz) [26, 27]. In
110 order to restrict the incoming beam to bunches containing at most one single
111 proton, the beam intensity was lowered down to 50 fA. Three different pCVD
112 detectors presented in Table 1 and based on samples coming from different
113 providers were tested one-by-one during the experiment in reproducible con-
114 ditions. Each pCVD sample was tested in coincidence with the same sCVD
115 reference detector. The detectors box was set up and aligned between two
116 2.5 cm-thick aluminum collimators with 5 mm gaps. The upstream one was
117 used to constrain the proton incidence to the sensitive surface of the smallest
118 detector. The downstream one reduced the beam halo caused by the scatter-
119 ing of protons in the PCBs. Behind the second collimator, a PTW T34058
120 gas ionization chamber (IC) and a 5 mm-thick plastic scintillator coupled to
121 a photomultiplier tube (PMT) were aligned with the beam. The IC was
122 coupled to a PTW Unidos electrometer to measure the beam current while
123 the scintillator was used to get a redundant spectroscopic information of in-
124 coming ions that was used for the efficiency measurement. The applied bias

125 voltage was +300 V for the Element6 and DDK pCVD detectors, +500V for
 126 the II-VI pCVD detector and +300 V for the sCVD detector, according to
 127 the scheme presented in Figure 1. The applied biasing was +400 V for the
 128 IC and -800 V for the PMT. The two pCVD output channels were coupled
 129 to Greenstream DBA IV-R preamplifiers [28] while CIVIDEC C2-HV pream-
 130 plifiers were used for the sCVD sample. Analog signals from the diamond
 131 detectors and the scintillator were sampled using the WaveCatcher digitizer.

132 To assess the single proton detection efficiency of pCVD samples, mea-
 133 surements in coincidence with the two reference detectors (the sCVD and
 134 the scintillator) were used. First, recorded events that corresponded to a
 135 double coincidence between the two reference detectors were identified using
 136 a coincidence window of duration $\delta t = 1.25$ ns, as well as low and high volt-
 137 age thresholds selecting single proton events. Among the $N_{double}(\delta t)$ events
 138 that corresponded to these criteria, triple and random coincidences were
 139 tested event-by-event on the pCVD samples using two coincidence windows
 140 and a voltage threshold scanning. The triple coincidence window was the
 141 same as the one applied on the reference detectors. The random coincidence
 142 window was delayed by 15 ns, between two consecutive bunches (32.84 ns).
 143 Using the voltage threshold sweep, a voltage comparison is performed on
 144 the pCVD signal between the threshold level V_{th} and the waveform segments
 145 contained within the coincidence windows. For each V_{th} value, we counted
 146 $N_{triple}(V_{th}; \delta t)$ triple coincidences between the pCVD and the two reference
 147 detectors and $N_{random}(V_{th}; \delta t)$ random coincidences triggered by noise fluctu-
 148 ations in the pCVD signals. Thus, we can define a true coincidence detection
 149 efficiency $\epsilon(V_{th}; \delta t)$ at a given threshold value V_{th} (δt is a fixed parameter)

150 as follows:

$$\epsilon(V_{th}; \delta t) = \frac{N_{triple}(V_{th}; \delta t)}{N_{double}(\delta t)} \times \left(1 - \frac{N_{random}(V_{th}; \delta t)}{N_{double}(\delta t)}\right). \quad (4)$$

151 Equation 4 can be understood as the product of the probability to detect
152 a true triple coincidence and the probability not to detect a random coin-
153 cidence. As δt is fixed, the single proton detection efficiency ϵ_{det} was here
154 defined as the maximum of the obtained $\epsilon(V_{th})$ function.

155 2.3.2. Timing resolution with single ions

156 The experimental set-up presented in Figure 1 was used in various beam
157 test configurations as listed in Section 1 in order to evaluate the TOF reso-
158 lution achievable between two diamond detectors of various crystalline qual-
159 ities. Within the scope of this article, the TOF resolution σ_{TOF} of a pair of
160 independent detectors with respective time resolution σ_{t_1} and σ_{t_2} is defined
161 as:

$$\sigma_{TOF} = \sqrt{\sigma_{t_1}^2 + \sigma_{t_2}^2}. \quad (5)$$

162 Timing measurements were carried out on the digitized waveforms using
163 a normalised threshold algorithm, as defined in [29]. Once the amplitude
164 of a pulse is detected, a constant fraction of this value (between 20% and
165 50%) is computed. The pulse time stamp is finally obtained by means of
166 a linear interpolation between waveform samples, thus emulating an ana-
167 log Constant Fraction Discrimination (CFD). Unless stated otherwise, the
168 timing resolution is derived from the statistical dispersion measured on the
169 timing difference between the sum signals of the two detectors involved. Fur-

170 thermore, a pair of diamond detectors composed of a $5.0 \times 5.0 \times 0.3 \text{ mm}^3$
171 DOI detector produced at Augsburg University and a $4.5 \times 4.5 \times 0.517 \text{ mm}^3$
172 sCVD detector produced by Element6 were tested together in the different
173 beam tests presented in this work. They were systematically tested to pro-
174 vide a common reference for comparison purposes and are referred as the
175 sCVD-DOI reference pair, later on in this article.

176 At ARRONAX, the timing measurements were carried out on the wave-
177 form datasets we acquired for the single proton detection efficiency assess-
178 ment. We could therefore measure the TOF resolution for the three pCVD-
179 sCVD couples, as they are presented in Table 1 and Section 2.3.1. For each
180 V_{th} value, the events subset which fulfilled the triple coincidence criterion and
181 did not trigger random coincidences was selected. On this subset, the pulse
182 discrimination was performed using the normalised threshold algorithm on
183 the pCVD and sCVD sum signals. The distribution of the timing difference
184 between the discriminated pCVD and sCVD signals was then stored in a his-
185 togram. Since some distributions demonstrated non-gaussian tails on each
186 side, the root mean square (RMS) value of the histogram was chosen as an
187 estimator of the TOF resolution for all histograms (*i.e.* for each V_{th} value).

188 The timing measurements at GANIL were carried out with single 95
189 MeV/u carbon ions and the standard bench presented in Figure 1. Yet,
190 one noteworthy difference is that only one CIVIDEC C2-HV preamplifier
191 could be used for each diamond detector during this test, preventing us from
192 using the signal summation technique introduced in Section 2.2. The wave-
193 forms were digitized with the 3.2 GS/s WaveCatcher system. Two pairs of
194 detectors were tested. The first one is the sCVD-DOI reference pair and the

195 second one is composed of two Element6 pCVD detectors, $20 \times 20 \times 0.5 \text{ mm}^3$
196 and $10 \times 10 \times 0.3 \text{ mm}^3$ respectively. They were metallized as pad detectors,
197 with disk-shaped 50nm-thick Al electrodes and respective diameter of 16 mm
198 and 7 mm.

199 *2.3.3. Timing resolution with a pulsed X-ray beam*

200 At ESRF, the combined use of a X-ray micro-beam and various atten-
201 uators set up upstream from the detectors enabled us to study the time
202 response of a pair of diamond detectors as a function of the energy depo-
203 sition. The test beam took place in ID21 beamline [30] that delivered a
204 8.53 keV X-ray micro-beam while the ESRF synchrotron was running in 4-
205 bunch mode. In this configuration, the pulsed beam RF was $f_{RF} = 1.42 \text{ MHz}$
206 ($T_{RF} = 704 \text{ ns}$) and the bunch duration was 100 ps. With the maximum elec-
207 tron beam current (32 mA) circulating in the synchrotron, the primary X-ray
208 flux was $\phi_{32mA} = 1.79 \cdot 10^9 \text{ photons/s}$ [31], which corresponds to $1.26 \cdot 10^3 \text{ pho-}$
209 tons/bunch . The absorption length of X-rays with an energy $E_X = 8.53 \text{ keV}$
210 in diamond is $1/\mu_{diam} \sim 790 \text{ }\mu\text{m}$ [32]. As a result, the energy deposition is
211 almost uniformly distributed over the thickness of the tested samples (300 -
212 500 μm) thus mimicking the passage of single charged particles.

213 The two detectors used here were a $4.5 \times 4.5 \times 0.517 \text{ mm}^3$ Element6 sCVD
214 detector and a $5.0 \times 5.0 \times 0.3 \text{ mm}^3$ Audiatec DOI detector. Both were metal-
215 lized with aluminium disk electrodes of 3 mm diameter. For each attenuator
216 used (Al and Ti foils with various thicknesses), an acquisition of the signals
217 coming from the two detectors as well as of the RF signal was performed.
218 Each side electrode of the Audiatec sensor was coupled to a CIVIDEC C2-HV
219 preamplifier while only one was used on the sCVD detector. For a given at-

220 tenuous type and thickness, the energy deposits of a X-ray bunch in the DOI
 221 and sCVD detectors (thereafter noted ΔE_{DOI} and ΔE_{sCVD}) are computed
 222 using Beer-Lambert law as follows :

$$\begin{aligned} \Delta E_{DOI} = E_X \cdot \frac{\phi_{32mA}}{f_{RF}} \cdot \exp(-\mu_{att}x_{att} - \mu_{PET}x_{PET}) \\ \cdot [1 - \exp(-\mu_{diam}d_{DOI})] , \end{aligned} \quad (6)$$

$$\begin{aligned} \Delta E_{sCVD} = E_X \cdot \frac{\phi_{32mA}}{f_{RF}} \\ \cdot \exp(-\mu_{att}x_{att} - \mu_{PET}x_{PET} - \mu_{diam}d_{DOI}) \\ \cdot [1 - \exp(-\mu_{diam}d_{sCVD})] , \end{aligned} \quad (7)$$

223 where μ and x are respectively the attenuation coefficient at 8.53 keV and
 224 the thickness of the considered material (att = attenuator, PET = Mylar,
 225 diam = diamond) while d is the thickness of the detector. In this set-up, the
 226 attenuation ($< 0.7\%$) of the beam in the air path between the detectors was
 227 neglected. For each acquisition, the signals have been processed using the
 228 normalised threshold algorithm at 50%, as defined in Section 2.3.2.

229 A previous experiment with the DOI detector from Augsburg University
 230 had been carried out with only a few number of attenuators. During this
 231 test, the Augsburg DOI sample was coupled to two preamplifiers while the
 232 sCVD detector was equipped to only one preamplifier. In this case, we had
 233 measured the side-to-side time difference between pulses generated on the
 234 two electrodes of the DOI detector. We performed the same measurement
 235 with the Audiatec sample and compared the timing performance obtained in
 236 both cases.

237 *2.3.4. Timing resolution with MIP electrons*

238 Using MIP-like electrons allowed us to determine a lower bound of the
239 timing resolution that could be obtained for the detection of single particles.
240 In this case, two Element6 sCVD diamond detectors ($4.5 \times 4.5 \times 0.51 \text{ mm}^3$
241 each) were used. They were exposed to a collimated beam of electrons from a
242 ^{90}Sr source, with an energy up to 2.28 MeV. The source, the collimators and
243 the detectors were all enclosed in a U-shaped rail ensuring the mechanical
244 alignment of the set-up. An assembly of four scintillating fibres coupled to a
245 common PMT was added downstream from the diamond detectors. It was
246 used as an external trigger to detect electrons in the higher energy part of
247 the β spectrum. Both electrodes of the two diamond detectors were coupled
248 to CIVIDEC C2-HV preamplifiers via 10 cm coaxial cables. The signals
249 produced by the four preamplifiers were digitized using a LeCroy HDO9404
250 DSO (4 GHz, 20 GS/s, 10 bits). The applied bias voltage was -500 V on the
251 two diamond detectors.

252 *2.3.5. Proton counting*

253 The counting and monitoring capabilities of the diamond samples were
254 also tested at ARRONAX. The DDK pCVD detector and the Element6
255 sCVD detector presented in Table 1 were selected for this test. Only one
256 output channel per detector was used here and the biased electrodes of the
257 pCVD and the sCVD detectors were coupled to one preamplifier. In order to
258 acquire 2 μs -long waveforms (corresponding to 60 RF periods at 30.45 MHz),
259 the sampling rate was lowered down to 2.5 GS/s. A 2.5 cm-thick aluminum
260 collimator with a 1 mm gap was set up in front of the detectors to constrain
261 the beam to a section smaller than the sensitive diameter of the detectors.

262 Typical signal waveforms acquired simultaneously on the two detectors are
263 shown in Figure 2.

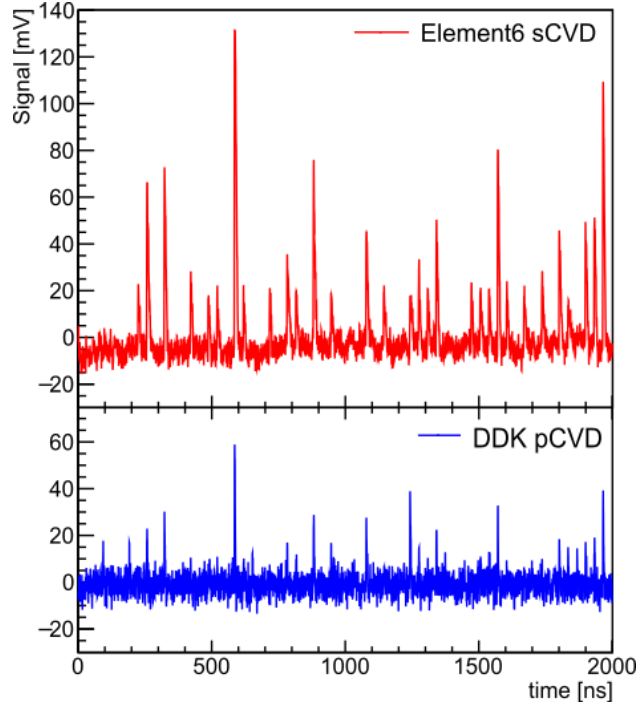


Figure 2: Compared waveforms acquired simultaneously on the Element6 sCVD detector (top, red) and the DDK pCVD detector (bottom, blue) using a 2.5 GS/s sampling rate.

264 In order to count the number of protons contained in the bunches, charge
265 measurement was performed by numerical integration of the waveforms on
266 both detectors. First, a baseline correction was achieved by projecting all
267 the waveform samples voltage values in an histogram. Considering that some
268 RF periods do not contain protons at this beam current level (~ 5 pA) and
269 that the signal duration is short compared to the RF period, the histogram
270 exhibits a dominant Gaussian noise peak that can be fitted to derive its mean

271 and standard deviation parameters. They are then defined as estimators of
 272 the baseline offset value and the noise level σ of the considered waveform,
 273 respectively. After subtraction of the obtained offset, each waveform is sub-
 274 divided in 60 33ns-long segments (corresponding to the 60 RF periods). For
 275 each RF period, the numerical integration is done by summing up the sam-
 276 ples contained in the corresponding segment. The charge response of both
 277 detectors can thus be compared on a bunch-by-bunch basis, as presented in
 278 Section 3.3.

279 From the counting statistics, it is possible to derive a mean beam current
 280 value. Later on in this paper, we will consider that at a given beam current
 281 I_{beam} , the number of protons contained in a bunch is a discrete random
 282 variable X according to Poisson law, with a λ parameter such as $\lambda \propto I_{beam}$.
 283 The probability $P(X = k)$ of having k protons in a bunch is therefore:

$$P(X = k) = \frac{\lambda^k}{k!} e^{-\lambda}. \quad (8)$$

284 In the case of an ideal beam delivering exactly one proton per bunch ($Q_{bunch} =$
 285 e) with a period $T_{beam} = 32.84$ ns (corresponding to the period of the AR-
 286 RONAX cyclotron RF signal), the average beam current I_{ref} is given by:

$$I_{ref} = \frac{Q_{bunch}}{T_{beam}} = \frac{1.602 \cdot 10^{-19}}{32.84 \cdot 10^{-9}} = 4.872 \cdot 10^{-12} \text{ A s/s}. \quad (9)$$

287 Then the average beam current I_{beam} can be derived as follows:

$$I_{beam} = \lambda I_{ref}. \quad (10)$$

288 This expression will be used later on in this work to estimate the average
 289 beam current during the counting experiment. Since λ is the parameter of

290 the Poisson law describing a bunch's proton multiplicity, this analysis carried
291 out on time windows corresponding to 60 consecutive bunches results in a
292 standard deviation $\sigma_\lambda = \sqrt{\lambda/60}$.

293 **3. Results**

294 *3.1. Single proton detection efficiency*

295 The results of the analysis presented in Section 2.3.1 and carried out on
296 the sum signals of the three pCVD samples presented on Table 1 are com-
297 bined in Figure 3 (dashed lines). The three pCVD detectors highlight the
298 same behaviour according to the V_{th} value. If V_{th} is close to zero, the proba-
299 bility of a random coincidence triggered by noise fluctuations is comparable
300 to the probability to trigger on the true event pulse. As a consequence, ϵ
301 remains low. If V_{th} increases, the noise-triggered random coincidence prob-
302 ability decreases and ϵ increases. Beyond an optimal V_{th} value for which
303 ϵ is maximized, the threshold starts rejecting true events resulting in the
304 degradation of the detection efficiency.

305 Following Section 2.3.1, the single 68 MeV proton detection efficiency ϵ_{det} is
306 here defined as $\epsilon_{det} = \max(\epsilon(V_{th}))$. For the three pCVD detectors, ϵ_{det} is
307 obtained at $V_{th} \sim 13$ mV and reaches 98% for the Element6 sample, while
308 97% is obtained in the case of the II-VI and DDK samples. These results are
309 in good agreement with measurements carried out in similar conditions in a
310 previous study [33] and bring an additional information on random triggering
311 probability. As these results depend on the δt parameter, one should note
312 that they could be improved by reducing the coincidence window, which is
313 in principle possible due to the shortness of the analog pulses. In our case,

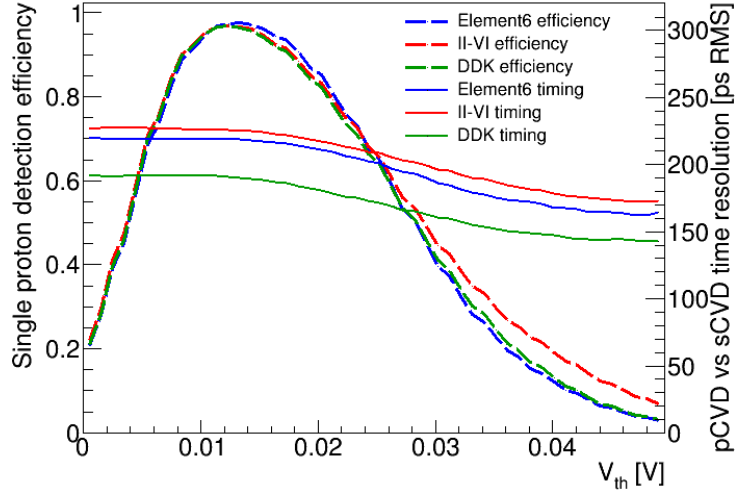


Figure 3: Single 68 MeV proton detection efficiency (dashed lines) and TOF resolution (solid lines) of three pCVD detectors as a function of the threshold value V_{th} used for the pCVD sum signal discrimination. The coincidence window duration is $\delta t = 1.25$ ns.

314 the 3.2 GS/s sampling rate was the limiting factor since $\delta t = 1.25$ ns only
 315 corresponds to four consecutive waveform samples. Besides, we verified that
 316 reducing δt induced an increase of the true coincidence detection efficiency,
 317 particularly for low V_{th} values. An additional event selection criterion based
 318 on time-over-threshold (TOT) could be used to reject high frequency noise-
 319 generated triggers.

320 3.2. Timing performance

321 3.2.1. 68 MeV protons

322 Figure 3 also shows the results of the timing measurements that were
 323 carried out on the same acquired datasets. On Figure 3, the measured TOF
 324 resolution is plotted as a function of V_{th} for the three pCVD detectors (solid

325 lines). A similar evolution of the TOF resolution can be observed with the
326 three pCVD samples. It can be noticed that as long as the threshold level
327 remains below the value maximizing the detection efficiency, the measured
328 TOF resolution is rather constant. For higher values, as the threshold rejects
329 low amplitude signals, the SNR of the selected events increases. Since the
330 time resolution of diamond detectors is directly related to the SNR [15, 34],
331 the TOF resolution improves as well. In the case of the Element6 detector,
332 the TOF resolution ranges from 220 ps (RMS) to 162 ps (RMS) and 218 ps
333 (RMS) is obtained at best efficiency. The TOF resolution measured with
334 the II-VI samples ranges from 227 ps (RMS) to 172 ps (RMS) (225 ps at best
335 efficiency). The DDK provides the best results with a TOF resolution ranging
336 from 192 ps (RMS) to 139 ps (RMS) (191 ps at best efficiency).

337 The overall better performance obtained with the DDK detector is re-
338 lated to the capacitance of the devices. That plays a crucial role in timing
339 measurements [15, 34]. Using the geometries defined in Table 1 and the
340 relative permittivity of diamond ($\epsilon_r = 5.7$), the DDK detector's computed
341 capacitance is 1.2 pF compared to 6.5 and 3.9 pF for the Element6 and II-VI
342 detectors respectively. Despite that, the Element6 sample's timing response
343 appears to be slightly better than that of the II-VI sample. It therefore tends
344 to show the superior performance of the Element6 pCVD detector compared
345 to the II-VI one. As a comparison, in a previous beam test, the sCVD-DOI
346 reference pair of diamond detectors had been tested in similar conditions and
347 reached a 94 ps (σ) TOF resolution [11].

348 3.2.2. 95 MeV/u carbon ions

349 The results of the timing measurements carried out at GANIL are pre-
 350 sented in Figure 4. Due to the large energy deposition in the detectors (25
 351 MeV in DOI and 44 MeV in sCVD according to SRIM simulations [35]),
 352 the high SNR enabled us to lower the discrimination fraction down to 20%.
 353 Thus, the two detector pairs highlighted excellent results. In each case, the
 354 distribution could be fitted to derive the σ_{TOF} value. The measured TOF
 355 resolution of the sCVD-DOI pair is $\sigma_{TOF} = 13$ ps. In the case of the pCVD
 356 pair, the obtained TOF resolution was 66 ps (σ). The difference between the
 357 results obtained with the two pairs can be explained by the quality of the

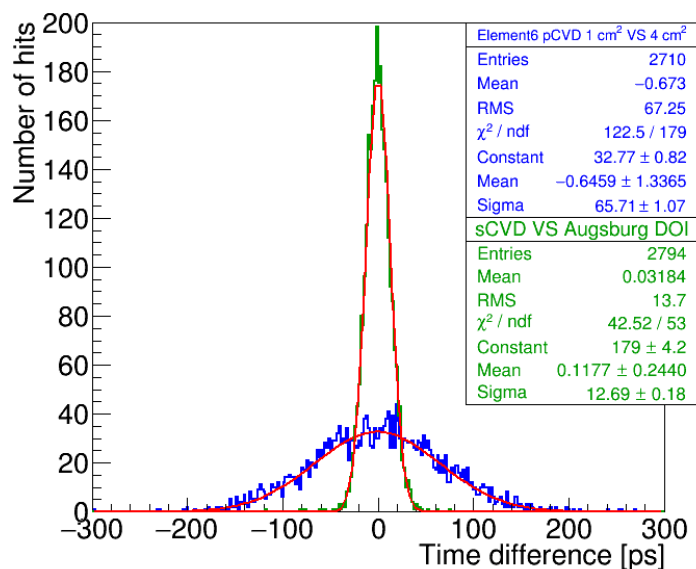


Figure 4: Time difference distributions obtained with two pairs of diamond detectors and single 95 MeV/u carbon ions at GANIL. The two pairs were the sCVD-DOI reference pair (green) and two large area pCVD detectors (blue).

358 involved samples and the large size of the pCVD detectors (with computed
359 capacitances of 20 pF and 6.5 pF). In any case, the two pairs demonstrated
360 excellent results nicely fitting with the objectives of the hodoscope.

361 3.2.3. Bunches of 8.53 keV synchrotron radiation X-rays

362 Figure 5-(Top) represents, for each energy deposition (each attenuator),
363 the TOF resolution measured between the two detectors (red) and between
364 each detector and the beam RF (DOI = blue and sCVD = green) as a function
365 of the deposited energy. The results are fitted with a function $\sigma_{TOF} = C/\Delta E$
366 with C a parameter to highlight the correlation between the TOF resolution
367 and the deposited energy. Due to the low jitter in the beamline RF signal,
368 the TOF measurements using the RF signal and a single diamond detec-
369 tor give better results than TOF measurements made between two diamond
370 detectors. It also provides a common reference allowing us to deduce that
371 the sCVD detector gives a better result than the Audiatic one. The re-
372 sults obtained with these two DOI detectors (Audiatic and Augsburg) are
373 compared in Figure 5 (Bottom). As the electronic channels used in both
374 cases were identical (1 CIVIDEC C2-HV per channel), the contribution of
375 the electronic jitter is the same for the two detectors. The better timing
376 response of the Augsburg DOI can therefore be related to the intrinsic better
377 performance of the detector, in comparison with the Audiatic one. While
378 the side-to-side jitter evolution measured on the Audiatic detector fits pretty
379 well with an inverse function, it is not the case of the Augsburg DOI sample.
380 The dashed line fit is drawn to show which correlation would be expected
381 with these measurements but they seem to be less sensitive to the energy de-
382 position. A possible explanation may rely on the surface heterogeneity of the

383 Augsburg DOI sample, already highlighted in [31], that could explain that
 384 the signal shape will depend on the hit position on the detector. Therefore,
 385 the jitter of the Augsburg sample could be dominated by other factors than
 386 the energy deposition.

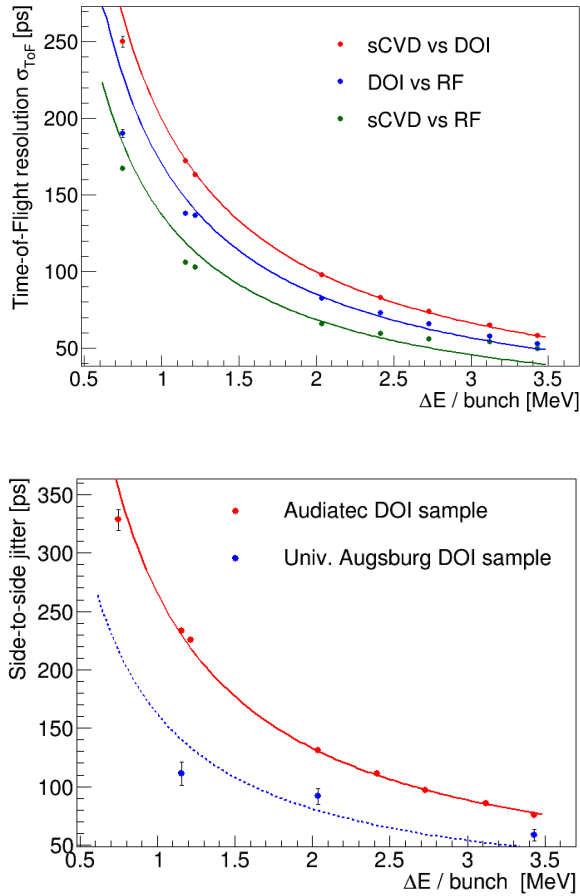


Figure 5: (Top) TOF resolution as a function of the energy deposited by a bunch of 8.53 keV X-rays in a pair of diamond detectors composed of a Element6 sCVD and a Audiatic DOI. (Bottom) Standard deviation of the side-to-side pulses time difference measured on the Audiatic DOI detector (red) and the Augsburg University DOI detector (blue) as a function of the energy deposition in the detectors.

387 *3.2.4. Minimum Ionizing Particles (β source)*

388 Prior to the timing measurement itself, a preliminary analysis was per-
389 formed at LPSC. As the acquisition was triggered by the downstream scin-
390 tillator, it is shown in Figure 6 that one can assess the existing correlation
391 between the responses of the two diamond detectors. Each detector response
392 corresponds to the integral of the sum signals. The result mainly exhibits two

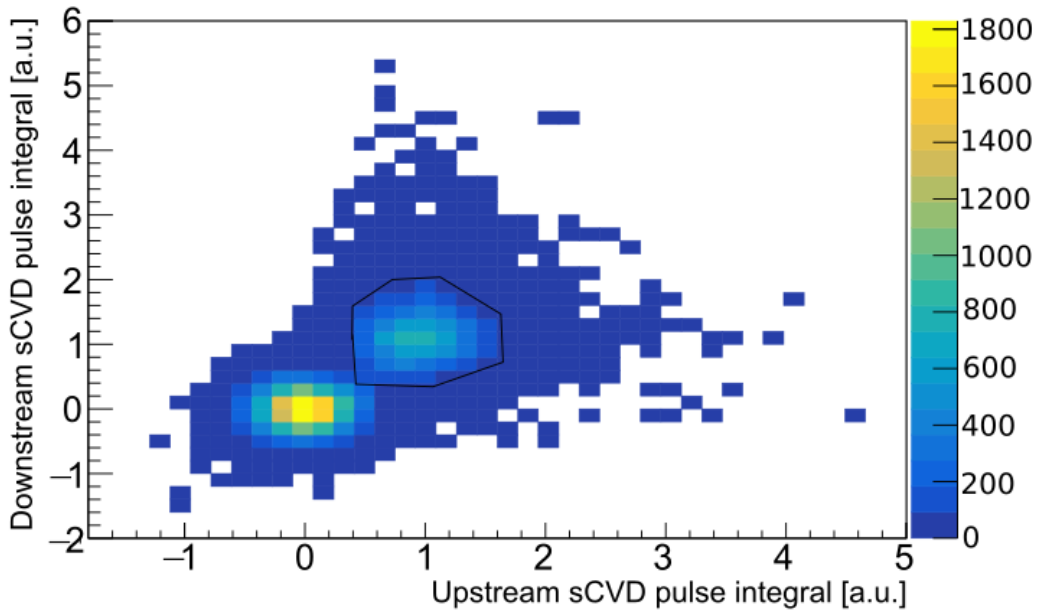


Figure 6: Correlation between the charge response of the two sCVD detectors used for the MIP timing measurement (the acquisition is triggered by the external downstream scintillator). The first peak centered on (0;0) is the noise peak. The second peak is due to single high energy electrons depositing the same amount of energy in the two detectors. The contour drawn on the distribution is the graphical cut applied on the data to measure the time resolution.

393 distributions. The first one is centered on zero and the second corresponds
 394 to a signal measured simultaneously on both detectors. The statistical pre-
 395 dominance of the distribution centered on zero is due to the trigger on the
 396 external scintillator which has i) a larger area than diamonds, and may then
 397 detect electrons outside the diamond active areas, and ii) a low detection
 398 threshold, enabling triggering on background.

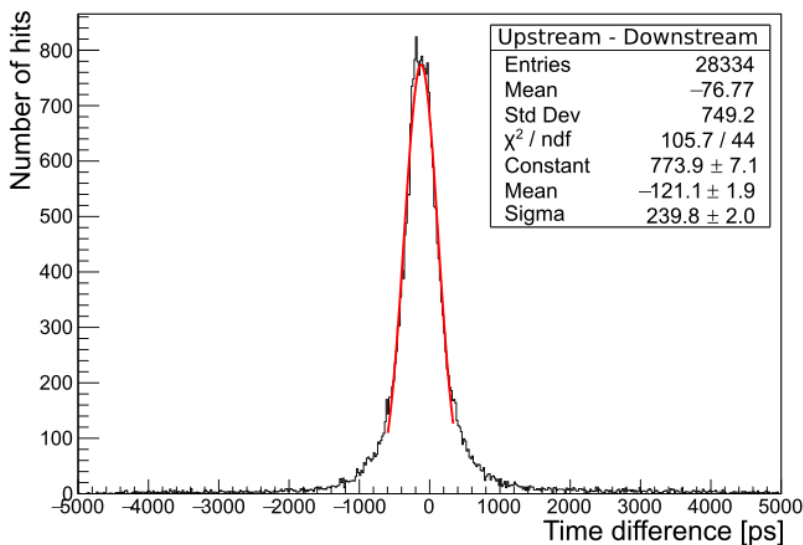


Figure 7: Distribution of the time difference between the sum signals of the two Element6 sCVD detectors detecting the same high energy β electrons.

399 In order to measure the time resolution of the detectors, a graphical selec-
 400 tion was performed on the data as illustrated by the black contour drawn in
 401 Figure 6. Since the electrons of highest energy are close to MIP, their energy
 402 deposition in the two detectors is expected to be almost constant. By se-
 403 lecting the events which exhibit the same charge response in both detectors,
 404 we can thus select electrons in the higher energy part of the beta spectrum.

405 The time difference measured on the sum signals of the selected events is
406 presented in Figure 7. Different estimators can then be used to derive the
407 TOF resolution in this case. An optimistic estimation would consist in using
408 the standard deviation given by a Gaussian fit. Choosing such a parameter
409 neglects the tails present on both sides of the distribution. Under these con-
410 ditions, $\sigma_{TOF} = 240$ ps is obtained, which corresponds to a timing resolution
411 of 170 ps for a single detector. A more objective estimator is the RMS of the
412 distribution. This one takes into account its tails that strongly degrade the
413 TOF resolution. Using this estimator, the TOF resolution is 749 ps (RMS),
414 *i.e.* a timing resolution of 530 ps (RMS) for one detector. However, these
415 values were obtained using a 10 ns coincidence window, which is of the same
416 order of the signal duration, and may contain random coincidences.

417 *3.2.5. Summary of Time-Of-Flight measurements*

418 The TOF resolution we measured at laboratory, at ARRONAX and
419 GANIL are summarized in Table 2 where D1 is the upstream detector and
420 D2 is the downstream one.

421 The correlation between time resolution and energy deposition (and there-
422 fore SNR) can be clearly observed. The measurements are better with the
423 sCVD-DOI reference pair. Using carbon ions at GANIL, the performance
424 of the pCVD pair is excellent. Considering the large energy deposition of
425 carbon ions with energies in the hadrontherapy range, developing a pCVD
426 hodoscope reaching a time resolution ≤ 100 ps (σ) is achievable in carbon ion
427 therapy. Finally, the measurement with beta electrons allowed us to define
428 a lower limit to these TOF resolutions.

Table 2: Summary of the different timing measurements presented. The energy deposition of single ions has been estimated with SRIM simulations. *Result from a previous study [11], given here for completeness purpose.

Diamond	Manuf.	Size (mm ³)	Computed capacitance (pF)	Particle type	Particle energy (MeV)	Energy deposition per particle/pulse (MeV)	Sum signals used ?	Measured TOF resolution (ps σ)
sCVD sCVD	E6	4.5 × 4.5 × 0.517	0.7	⁹⁰ Sr decay electron	~ MIP	~ 0.3	✓	240 ± 2
DOI sCVD	Augsburg	5 × 5 × 0.3	1.2	proton	68*	1.0 1.6	✓	94.1 ± 0.4*
	E6	4.5 × 4.5 × 0.517	0.7	carbon ion	1140	25 44	✗	12.7 ± 0.2
	Audiatec E6	5 × 5 × 0.3 4.5 × 4.5 × 0.517	1.2 0.7	X-ray pulse (no attenuator)	8.53 · 10 ⁻³	3.4 3.3	DOI only	58.3 ± 0.5
pCVD sCVD	E6	10 × 10 × 0.3	6.5	proton	68	1.0	✓	218 ± 1
	E6	4.5 × 4.5 × 0.517	0.7			1.6	✓	225 ± 1
	II-VI	10 × 10 × 0.5	3.9			1.6	✓	225 ± 1
	E6	4.5 × 4.5 × 0.517	0.7			1.0	✓	191 ± 1
	DDK E6	5 × 5 × 0.3 4.5 × 4.5 × 0.517	1.2 0.7			1.6	✓	191 ± 1
pCVD pCVD	E6 E6	20 × 20 × 0.5 10 × 10 × 0.3	20 6.5	carbon ion	1140	44 25	✗	65.7 ± 1.1

429 3.3. Proton counting

430 The monitoring and counting capabilities of sCVD and pCVD detectors
431 were evaluated at ARRONAX at a beam intensity around 1 proton/bunch.
432 The results of the bunch-generated ionisation charge Q_{bunch} as measured
433 simultaneously on the sCVD and pCVD detectors are presented in Figure 8
434 (Top). On the one hand, it can be clearly observed that the sCVD detector
435 has an energy resolution which is sufficient to distinguish a discrete number
436 of protons contained in each bunch. The 2D distribution therefore exhibits 6
437 peaks corresponding to bunches whose content ranges from 0 to 5 protons. On
438 the other hand, the pCVD detector's energy resolution is not good enough to

439 count the number of protons in the bunch, leading to an overlap of the charge
440 distributions corresponding to different numbers of protons. The different
441 charge distributions could be separated in this case thanks to the correlation
442 with the sCVD detector.

443 The sCVD Q_{bunch} distribution which corresponds to the X-projection of
444 the 2D histogram in Figure 8-Top is the convolution of a Poisson distribution
445 of parameter λ with the Gaussian response function of the detector. One
446 can fit the whole distribution with the sum of 6 Gauss functions. From the
447 obtained fit parameters and using the fact that $\lambda = (k + 1) \cdot P(k + 1)/P(k)$,
448 one can derive the actual λ value. From this analysis, an experimental value
449 of $\lambda = 1.26 \pm 0.02$ is obtained, thus resulting in a mean beam current $I_{beam} =$
450 6.16 ± 0.10 pA (using Equations 9 and 10). The error corresponds to the
451 RMS of the λ values obtained using the different k values. Moreover, the
452 I_{beam} uncertainty could be easily reduced by increasing the integration time.
453 Note that the method is only valid if the beam current is constant during
454 the acquisition.

455 Nevertheless, the bunch content separation provided by the sCVD detec-
456 tor can be used to assess the linearity of the pCVD detector's mean charge
457 response. Fixed thresholds can be set on the sCVD Q_{bunch} distribution so
458 that the response of the pCVD detector can be conditioned by the response of
459 the sCVD detector. For each peak in the sCVD Q_{bunch} distribution (ranging
460 from 0 to 4 protons), the histogram of the corresponding charge measured
461 on the pCVD is drawn and the obtained mean and RMS values are stored.
462 The correlation between the mean responses of the two detectors for each
463 number of protons can thus be plotted (Figure 8 Bottom). In spite of the

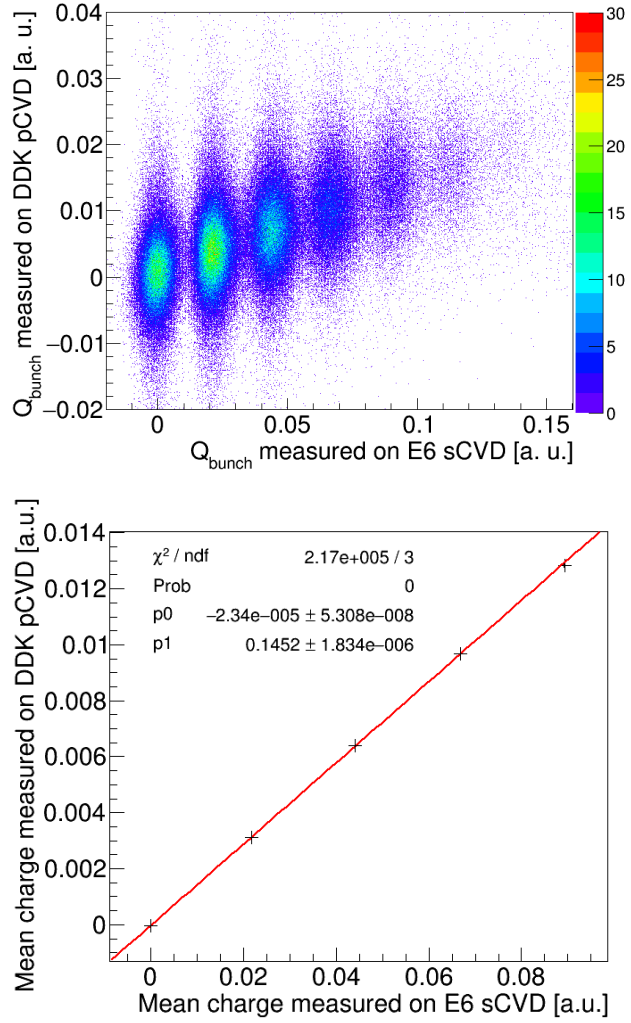


Figure 8: (Top) Bunch-generated ionisation charge measured on the Element6 sCVD detector as a function of the charge generated in the DDK detector. (Bottom) Mean charge generated in the sCVD detector as a function of the mean charge generated in the DDK detector, for a discrete number of protons in the bunch. Error bars are given in the figure but are hidden by the marker size. They correspond to the statistical error obtained for each number of protons.

464 poor pCVD energy resolution, one can note that its mean charge response
465 remains linear with the number of protons contained in the bunch. There
466 is no evidence of charge-saturation, and this suggests that pCVD detectors
467 could be used at higher beam currents (typically clinical beam currents) to
468 provide an efficient beam monitoring, where the proton bunch multiplicity
469 prevents from counting the protons individually.

470 **4. Discussion**

471 At first, measurements were carried out to evaluate diamond single proton
472 true coincidence detection efficiency, *i.e.* the probability to detect a proton in
473 a time coincidence window as short as possible (1.25 ns), without triggering
474 on the noise, in order to perform efficient TOF measurements on any incident
475 proton. They were done using 68 MeV protons in a single incident particle
476 mode (50 fA). In this way, we could make measurements independent from
477 the beam time structure. Three pCVD diamond sensors were tested. A pro-
478 ton coincidence detection efficiency $> 96\%$ is reached on the three diamond
479 samples. To perform such a measurement, diamond detectors were read out
480 on both sides which, in the case of an off-line data analysis, makes it possible
481 to increase the SNR by a factor $\sqrt{2}$ when using identical read-out channels.
482 If one is using this method online, particular care should be paid onto the
483 exact synchronization and identical pulse shapes on the two readout chan-
484 nels. Indeed, we could observe that if a slight delay between the two signals
485 is not corrected, the time resolution is degraded. Also, if the noise levels
486 are different on the two signals, the noise level of the sum signal is domi-
487 nated by the worse level as expected from Equation 1, which degrades the

488 performance obtained with the best readout channel. This has an effect on
489 both efficiency and timing resolution. In the case of a single channel reading,
490 data analysis has shown that the signal to noise ratio is less favorable. It is
491 obvious that in terms of efficiency, sCVD diamonds surpass the performance
492 of pCVD but the commercially available surfaces remain small, which would
493 imply combining several diamonds in the form of a mosaic to make a larger
494 detector.

495 The purpose of the hodoscope is to detect each incident ion while ensuring
496 intrinsic time resolution ≤ 100 ps. The best results were obtained with the
497 sCVD-DOI reference pair. The TOF resolutions obtained with this pair of
498 detectors are matching the objectives of the project, both with single protons
499 of 68 MeV and with carbon ions of 95 MeV/u. Indeed, the proton & PG
500 TOF resolution obtained during a past ARRONAX experiment [11] showed
501 the capability of our detectors to discriminate PGs with a TOF resolution of
502 101 ps (σ), making techniques such as ultra-fast PGT very promising. Such
503 results could not be obtained with pCVD detectors which exhibit a too low
504 SNR to be able to measure an equivalent timing resolution with 68 MeV pro-
505 tons. Moreover, the threshold-based study of their detection efficiency and
506 time resolution demonstrated that combining a detection efficiency $> 90\%$
507 and a time resolution at the 100 ps level was not achievable. A noteworthy
508 improvement of their time resolution could only be obtained for threshold
509 values that rejected most of the single-proton signals, thus dramatically de-
510 teriorating their detection efficiency.

511 It should be also considered that the energy deposition of a 68 MeV proton
512 is the highest we can get with a single proton in particle therapy. Indeed, the

513 protons energy range varies from 70 MeV to 250 MeV. The deposited energy,
514 and therefore the generated signal, is inversely proportional to the proton's
515 initial energy. The combination of these considerations makes difficult the
516 use of pCVD detectors for time tagging of single protons in the energy range
517 of proton therapy. We will therefore use sCVD detectors, with the limitation
518 on the commercially available area for this application.

519 However, the results obtained with carbon ions at GANIL are promising.
520 The 13 ps (σ) TOF resolution obtained between the sCVD Element6 detector
521 and the Augsburg DOI one is the best time performance we measured, in
522 all our experiments. This result is mainly explained by the large energy
523 deposition generated by each ion in the diamond and by the quality of the
524 two diamond samples. This energy deposit is so that a 66 ps (σ) resolution
525 between two pCVD detectors was obtained whereas they were metallized
526 with electrodes of 7 and 16 mm in diameter, respectively. Assuming that
527 this value is the quadratic sum of their respective timing resolutions, we can
528 estimate that their individual timing resolution is equivalent to or better
529 than 66 ps. Besides, in the case of carbon ion therapy, the energy of the
530 ions ranges from 95 MeV/u to 400 MeV/u. SRIM simulations show that in a
531 500 μm pCVD diamond with a charge collection efficiency of 30% (measured
532 on an alpha test bench at laboratory) generates a collected charge ranging
533 from 156 fC to 61 fC, respectively (see [36]). As a comparison, a 5.49 MeV
534 α particle (equivalent to 67 fC) generates a sufficient signal to measure an
535 intrinsic resolution of less than 100 ps [21, 22]. We can thus reasonably
536 assume that to obtain an intrinsic temporal resolution of 100 ps (σ) with a
537 large size (pCVD) detector remains a realistic goal for carbon ion therapy.

538 It should also be noted that in the configuration of our tests, pCVD sen-
539 sors were not optimized for timing measurements. An improvement of their
540 timing performance could be obtained by combining different approaches.
541 First, their thickness could be reduced down to their charge collection dis-
542 tance so that the applied electric field can be higher. By doing so, a seg-
543 mentation of the active surface would be necessary to over-compensate the
544 increase of the capacitance. Using two layers of thin pCVD sensors would
545 allow to improve the timing performance of the device by a factor $\sqrt{2}$ and
546 they could be inclined with respect to the beam axis to increase their effective
547 thickness.

548 Finally, concerning the particle counting performance, the measurements
549 carried out with 68 MeV protons at a beam intensity of ~ 6 pA can allow
550 us to conclude that a beam monitor equipped with sCVD diamond sensors
551 makes it possible to provide both fast timing and counting of protons inside
552 a bunch. In terms of hadontherapy beam monitoring, this makes it pos-
553 sible to count at the start of treatment at reduced beam intensity and, if
554 necessary, identify bunches where the proton multiplicity is greater than 1.
555 On the contrary, pCVD detectors are not able to achieve particle counting
556 at low proton rate. This result on the comparative performance of sCVD
557 and pCVD diamonds should however be qualified. Indeed, for higher beam
558 intensity, sCVD diamond sensor thickness is certainly to be optimized to
559 prevent long time drift which may result in a pile-up phenomenon at highest
560 RF frequencies (up to 106 MHz). pCVD may present an advantage relative
561 to sCVD. Since charge trapping occurs while charge carriers are drifting to
562 the electrodes, it results in a shorter signal as observed in Figure 9 at ~ 2 nA

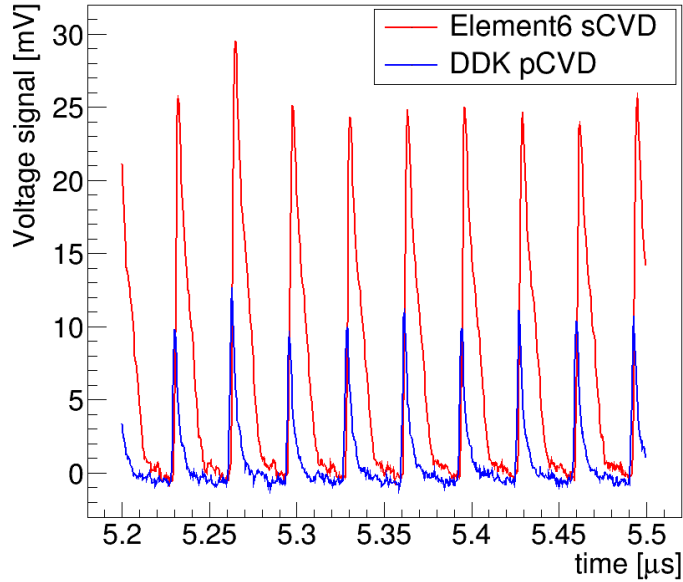


Figure 9: Compared time-domain responses of the Element6 sCVD and the DDK pCVD detectors, irradiated with the ARRONAX proton beam at $I_{beam} \sim 2$ nA (with an accelerator radio-frequency of 30.45 MHz). The induced currents produced by the detectors are converted into voltage signals through a 50Ω resistor.

563 (~ 400 protons/bunch at 30.45 MHz). Such a beam current is close to clinical
 564 conditions. Therefore, the two types of diamond could be used depending on
 565 the targeted intensity range.

566 5. Conclusions

567 The present results are encouraging the development of a beam-tagging
 568 hodoscope with TOF capabilities. For all the tests presented in this work,
 569 sCVD diamond detectors demonstrated characteristics that are in good agree-
 570 ment with the requirements of the hodoscope project. The detection effi-

571 ciency measurements highlighted that pCVD detectors can detect single ions
572 with a good efficiency but can not reach a timing resolution at the order of
573 100 ps (σ) when detecting single protons. At low intensity, their poor energy
574 resolution prevent them from counting the number of protons contained in
575 a bunch but their mean charge response remains linear with the deposited
576 energy. At higher intensity, the shorter pulses generated by pCVD detectors
577 can represent an advantage over sCVD for beam monitoring at 100 MHz
578 rates. Using carbon ions, both sCVD and pCVD demonstrated excellent
579 timing results.

580 Consequently, two solutions can be foreseen for the beam tagging ho-
581 doscope design. The first one may consist in using either four $4.5 \times 4.5 \times$
582 0.5 mm^3 commercially available sCVD diamonds arranged in mosaic or, later
583 on, large area sCVD diamonds. The second solution may consist in using 20
584 $\times 20 \times 0.3 \text{ mm}^3$ pCVD mainly dedicated for carbon ion therapy applications.
585 In both cases, the hodoscope will be made out of double-sided strip sensors.
586 It will provide the ion transverse position with a precision $\leq 1 \text{ mm}^2$ (X and
587 Y strips width). The influence of the segmentation of the metallic contacts
588 on the timing performance of the device will have to be evaluated while it
589 will not be possible to use the side-to-side signal summation method. The
590 next step of the hodoscope development is the assembling of the two selected
591 diamonds types with front-end electronics currently developed at LPSC for
592 TOF measurements of prompt-gamma in view of range verification in particle
593 therapy.

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