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Dommert, M.; Reginatto, M.; Zbořil, M.; Lutz, B.;

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## 2 **Dead time corrections for Bonner sphere measurements** 3 **of secondary neutrons at a proton therapy facility**

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4 **Martin Dommert,<sup>a</sup> Marcel Reginatto,<sup>a</sup> Miroslav Zbořil,<sup>a</sup> Benjamin Lutz<sup>b,1</sup>**

5 <sup>a</sup>*Physikalisch-Technische Bundesanstalt, Braunschweig, Germany*

6 <sup>b</sup>*Helmholtz-Zentrum Dresden - Rossendorf, Institute of Radiation Physics, Dresden, Germany*

7 *E-mail:* [b.lutz@hzdr.de](mailto:b.lutz@hzdr.de)

8 **ABSTRACT:** Radiation therapy with proton beams allows the deposition of high doses to the tumour  
9 while minimising dose to the surrounding tissue. During such treatment the patient is also exposed  
10 to secondary radiation which produces an out-of-field dose that affects healthy tissue. The largest  
11 contribution to this out-of-field dose comes from neutron radiation; therefore, it is of interest to fully  
12 characterise the neutron field in the therapy room with measurements. This is usually done with  
13 Bonner sphere spectrometers using active detectors, typically <sup>3</sup>He-filled proportional counters, as  
14 central thermal neutron sensors. Under the experimental conditions encountered in proton therapy  
15 facilities, a proper analysis of the measurements is impossible unless dead time corrections are  
16 implemented. In this paper, we present a method using a paralyzable dead time model for carrying  
17 out such corrections for Bonner sphere measurements with <sup>3</sup>He-filled proportional counters and  
18 apply it to data taken at the University Proton Therapy Dresden (UPTD) facility in double scattering  
19 mode. The neutron events were recorded with time stamps and, based on this time-resolved data, the  
20 measured neutron rate distribution was sampled. Since the neutron flux is proportional to the proton  
21 flux, the integral neutron flux is directly related to the proton dose. Hence, we were able to estimate  
22 the detector dead time from the measured rate distributions recorded for a set of measurements with  
23 different proton dose rates. Experimental measurements with different intensities of the proton  
24 field show that the corrections are in agreement within 0.5% for measured signal rates smaller than  
25  $15 \times 10^3$  counts per second and do not exceed 1% at  $25 \times 10^3$  counts per second.

26 **KEYWORDS:** Neutron detectors, Instrumentation for hadron therapy, Data processing methods,  
27 Radiation monitoring

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<sup>1</sup>Corresponding author.

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## 38 1 Introduction

39 The use of proton beams in radiation therapy has the advantage, when compared for example  
40 to photon therapy, that the tumour can be exposed to high doses while minimising the dose to  
41 surrounding tissue [1]. The treatment typically involves protons with energies in the range of 70 to  
42 250 MeV. During treatment with proton beams the patient is also exposed to secondary radiation,  
43 in the form of neutrons, photons and charged particles, which produces an out-of-field dose which  
44 affects healthy tissue. The determination of the additional dose from secondary radiation is of  
45 importance in order to assess the risk of secondary cancers [2, 3]. Neutron radiation provides the  
46 largest contribution to this out-of-field dose [4] and it can be of concern in the case of paediatric  
47 treatments and the treatment of pregnant patients.

48 Estimates of the out-of-field dose require accurate information about the quality and extent  
49 of the neutron radiation component for specific facilities, as a function of beam delivery and  
50 for particular patient configurations. Therefore, it is important to carry out measurements to  
51 characterise the neutron field in the therapy room under conditions that reproduce those that are  
52 used in clinical treatments. Such measurements are not straightforward. One critical issue is  
53 that proton therapy facilities operate with time varying beam settings. As a result, the secondary  
54 neutron field exhibits a complex time variation which makes the accurate correction of detector  
55 dead time effects difficult when measuring at high absolute rates, which are precisely the ones that  
56 are required for clinical treatment. A proper analysis of neutron spectrometric measurements with  
57 active detectors is impossible unless dead time corrections are implemented.

58 We have carried out Bonner sphere measurements at the facility of the University Proton  
59 Therapy Dresden (UPTD) using the extended-range Bonner sphere spectrometer of the Physikalisch-  
60 Technische Bundesanstalt (PTB). For the analysis of these measurements, we have developed a dead  
61 time model that is applicable to the system for the given measurement conditions. The validity of  
62 the approach has been tested with a series of measurements carried out with different beam currents.  
63 The focus of this paper is on this dead time analysis.

64 The paper is structured as follows. In the next two sections, we describe the spectrometer used  
65 for the measurements and show examples of the distortion of the pulse-height spectra that occurs  
66 due to dead time and pile-up effects. We then discuss dead time models and present the method  
67 developed for the dead time correction. We end with a discussion and conclusion. An appendix  
68 describes the time structure of the neutron flux in double scattering mode.

## 69 **2 The extended-range Bonner sphere spectrometer NEMUS**

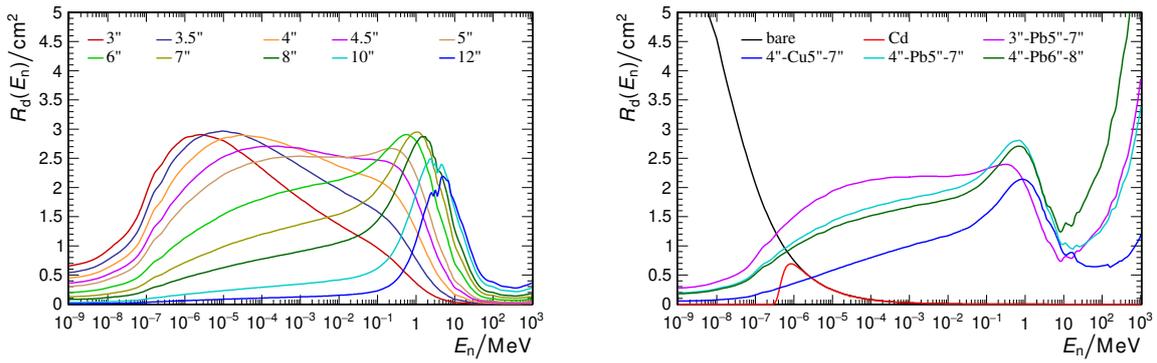
70 Spectral measurements of secondary neutrons in proton therapy facilities present a number of  
71 challenges. At a minimum, the spectrometer must be capable of covering a wide energy range that  
72 extends from thermal energies to a few hundred MeV and the resolution of the spectrometer must  
73 be sufficient to bring out the important features of the spectrum. These two basic requirements can  
74 be handled by extended-range Bonner sphere spectrometers, which have proven to be well suited  
75 for measurements in high-energy fields [5]. However, the measurements are not straightforward  
76 because proton therapy facilities are operated with time varying beam settings. The beam current  
77 is typically both pulsed as well as varying in current, and the beam energy is a function of  
78 time. Consequently, the secondary neutron field exhibits a complex time variation. This poses a  
79 challenge for the accurate correction of detector dead time effects when measuring with Bonner  
80 sphere spectrometers at high rates.

81 An extended-range Bonner sphere spectrometer consists of a set of moderating spheres of  
82 different diameters and a thermal neutron sensor that is placed at the centre of each sphere. A typical  
83 set has spheres made of polyethylene plus a few modified spheres with metal shells embedded in  
84 polyethylene spheres to increase the response to high-energy neutrons (i.e., at neutron energies  
85 above  $\sim 50$  MeV). In addition, it is usual practice to measure also with the thermal neutron sensor  
86 without a moderating sphere (i.e., the bare detector). Any combination of sphere and thermal  
87 neutron sensor is usually called a “sphere” and this terminology has also been extended to the bare  
88 detector. Each sphere plus thermal sensor combination has a different energy response to neutrons,  
89 which is what enables a determination of the spectrum from measurements with different spheres  
90 using unfolding methods.

91 PTB operates an extended-range Bonner sphere spectrometer known as NEMUS [6]. It consists  
92 of 10 standard polyethylene spheres with diameters 3, 3.5, 4, 4.5, 5, 6, 7, 8, 10 and 12 inches.<sup>1</sup>  
93 The set also contains a bare detector, a Cd-covered detector, and four modified spheres with lead  
94 or copper shells. The central thermal sensors are spherical  $^3\text{He}$ -filled proportional counters of  
95 type SP9 He3/152/Kr [7] manufactured by Centronic. For this particular set of measurements, we  
96 used proportional counters with partial  $^3\text{He}$ -pressures of  $\sim 200$  kPa and  $\sim 20$  kPa. The proportional

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<sup>1</sup>The convention of labeling each sphere by its diameter in inches has developed over the years and will be applied in this work (1 inch = 2.54 cm).

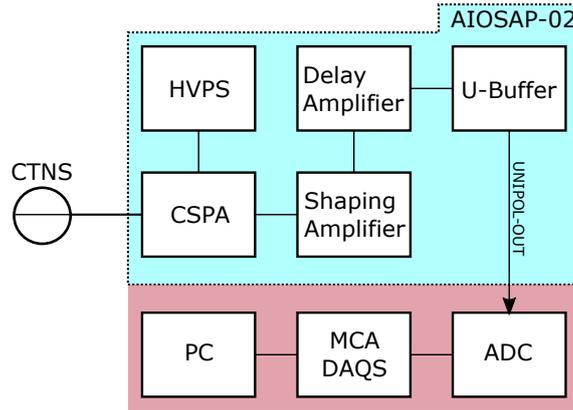


**Figure 1.** Response matrix of the NEMUS extended-range Bonner sphere spectrometer [6]. The response of the 10 polyethylene spheres are shown on the left side. The right side shows the response of the bare detector, the Cd-covered detector, and the four modified spheres with a lead or copper shell inserted. The names of the modified spheres indicate the outer radii of the polyethylene core, the metal shell, and the surrounding polyethylene shell.

97 counters with lower pressure are less sensitive to neutrons and thus less affected by dead time,  
 98 therefore, these are used at locations where the neutron intensity is higher. Figure 1 shows the  
 99 response matrix of the NEMUS spectrometer with the  $\sim 200$  kPa proportional counter. The readout  
 100 system of the NEMUS spectrometer consists of a shaping amplifier and a digitisation stage, as well  
 101 as a data acquisition system. The block diagram shown in figure 2 displays the main components  
 102 used for measurements with the NEMUS system. The shaping of the detector signal is performed  
 103 by an AIOSAP-02 (All In One Spectrometry Analogue Processor Version 2 [8]), a PTB in-house  
 104 development. The AIOSAP was specifically developed for the use with  $^3\text{He}$ -filled proportional  
 105 counters and combines a charge sensitive pre-amplifier, a shaping amplifier, and the detector  
 106 high voltage power supply. The shaping time of the detector signal is approximately  $2 \mu\text{s}$ . The  
 107 digitisation stage is a peak-sensing analogue-to-digital converter (ADC) of type Dual ADC Model  
 108 7072, ADC/SVA [9] manufactured by FAST Comtec GmbH. For data acquisition a multi-channel  
 109 analyser of type MPA4 Multiparameter Data Acquisition System (8 channel) [10] manufactured by  
 110 FAST Comtec GmbH is used. The MPA4 Multiparameter System is designed as an ultra fast list  
 111 mode system and allows for measurements of eight ADC input channels in parallel. In addition to  
 112 simple acquisition of the ADC pulse-height spectra, the system is able to save time resolved data  
 113 points, if operated in *list mode*; i.e., the pulse-height with a corresponding time stamp is recorded  
 114 for each detected event. The event time is recorded in units of 6.4 ns.

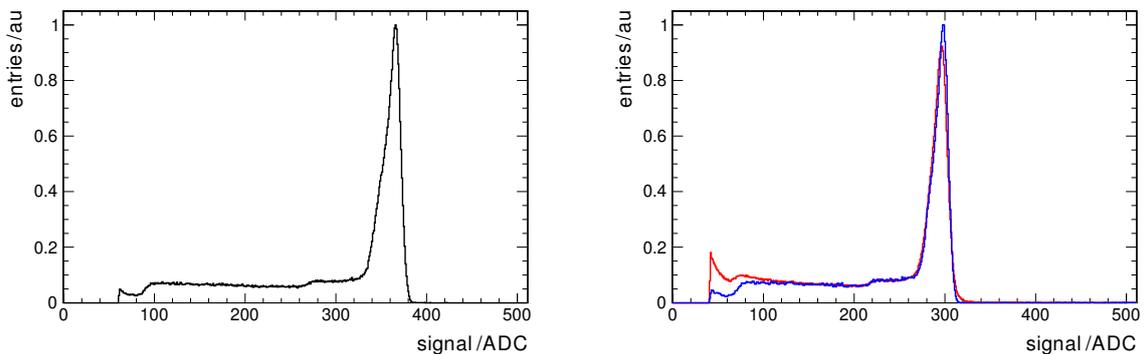
### 115 3 Pulse-height spectra of spherical $^3\text{He}$ -filled proportional counters

116 The data collected with a spherical  $^3\text{He}$ -filled proportional counter, used as a thermal detector in a  
 117 Bonner sphere, is in the form of a pulse height spectrum. The detection of neutrons takes place by  
 118 means of the reaction  $^3\text{He}(n,p)\text{T}$  (with a reaction Q value of +764 keV and a thermal neutron cross  
 119 section of 5321 barn). The counts in this spectrum are used to determine the number of neutron  
 120 induced events.



**Figure 2.** Block diagram of electronics used for measurements with the NEMUS Bonner sphere spectrometer and a  $^3\text{He}$ -filled central thermal neutron sensor (CTNS). Necessary components such as the detector high-voltage power supply (HVPS), charge sensitive pre-amplifier (CSPA), and further components used for the analogue processing of the detector signal are contained in a single AIOSAP-02 unit [8]. The output of the AIOSAP-02 is connected to a peak-sensing analogue-to-digital converter (ADC) which is read by a multi channel analyser data acquisition system (MCA DAQS).

121 The left plot of figure 3 shows a pulse height spectrum from a measurement made under  
 122 controlled conditions; i.e., good statistics, no noise or gamma-induced events in the lower channels,  
 123 and a rate that is low enough to exclude pile-up events and lead to negligible dead time. The  
 124 full-energy peak on the right part of the spectrum corresponds to the reaction energy of 764 keV.  
 125 The events in the lower channels are due to the partial escape of the proton and/or triton from the  
 126 active volume of the counting gas (wall effect). The lower limit of the neutron induced events, at  
 127 about channel 100, corresponds to the full escape of the proton (573 keV) implying the full energy  
 128 dissipation of the triton (191 keV) in the gas. In the case of measurements made under controlled  
 129 conditions as in the left plot of figure 3, the neutron signal can be determined in a straightforward  
 130 manner by setting appropriate thresholds summing the number of counts in the region-of-interest.

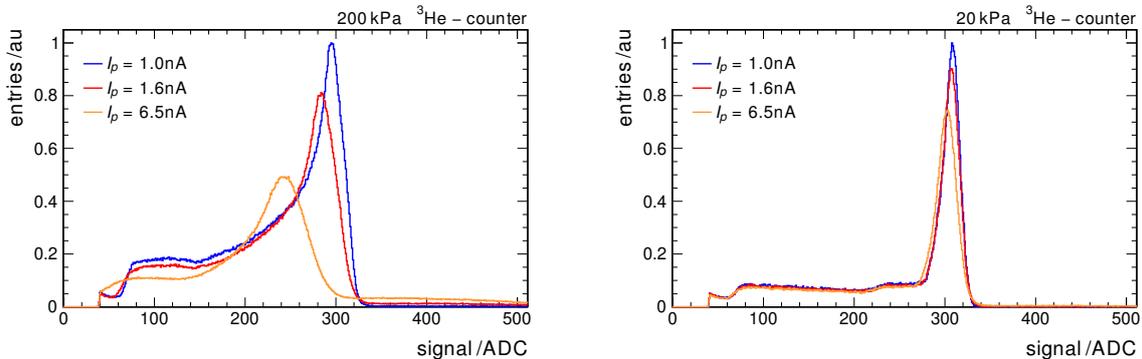


**Figure 3.** Left: pulse-height spectrum (PHS) of a  $^3\text{He}$ -filled proportional counter obtained from a measurement made under controlled conditions. Right: measured PHS with gamma induced events in the low channels (red) together with a fitted reference spectrum (blue).

131 Under more difficult measurement conditions, a number of corrections must be included in  
 132 the analysis. There are two main types of corrections, to account for non-neutron signals in the  
 133 lower channels of the pulse-height spectrum which are often induced by photons, and to account  
 134 for dead time and distortions of the spectrum caused by pile-up. Counts due to non-neutron events  
 135 will typically contribute to the dead time.

136 The right plot of figure 3 shows a measured pulse height spectrum that is distorted by gamma  
 137 induced events in the lower channels (red) together with a reference spectrum measured under  
 138 controlled conditions with the same proportional counter (blue) that has been fitted to the region  
 139 that is not affected by the gamma induced events. The correction is straightforward whenever the  
 140 gamma induced events do not extend past  $\sim 50\%$  of the maximum energy over which the neutron  
 141 deposits a signal (i.e., the full energy peak). After carrying out the fitting procedure, the reference  
 142 spectrum is used to determine the total number of neutron induced events.

143 A different type of corrections is required for the data in figure 4 which show distortions that  
 144 are due to pile-up effects and indicative of substantial amounts of dead time. The plots are for  
 145 measurements made for different primary proton beam intensities and counters with gas pressures  
 146 of  $\sim 200$  kPa and  $\sim 20$  kPa (the  $\sim 200$  kPa counters are more efficient than the  $\sim 20$  kPa counters due  
 147 to the difference in gas pressure and, therefore, more susceptible to pile-up). The pile-up leads to  
 148 significant shape changes of the pulse height spectrum for the 200 kPa pressure counters, shown on  
 149 the left, while the 20 kPa pressure counters, shown on the right, are far less affected at the same  
 150 beam current.



**Figure 4.** Pulse-height spectra obtained from measurements with varying primary proton beam intensity; i.e.,  $I_p = 1.0$  nA (blue),  $I_p = 1.6$  nA (red) and  $I_p = 6.5$  nA (yellow), with various types of distortion due to pile-up effects for counters with gas pressures of  $\sim 200$  kPa (left) and  $\sim 20$  kPa (right).

151 The changes of shape in the more distorted spectra of figure 4 are a clear indication of saturation  
 152 effects in the system. Such effects cannot be easily corrected (if at all). Thus, it is important to limit  
 153 measurements to count rates that cause only small distortions of the pulse height spectra, which can  
 154 then be corrected for pile-up and dead time. As an example, if you consider the plots on the left  
 155 side of figure 4, it turns out that reliable dead time corrections are possible for the cases of beam  
 156 currents of 1 nA and 1.6 nA but not for the case of a beam current of 6.5 nA. It is always important  
 157 to carry out a visual inspection of the spectra before attempting to carry out dead time corrections.

## 158 4 Dead time models

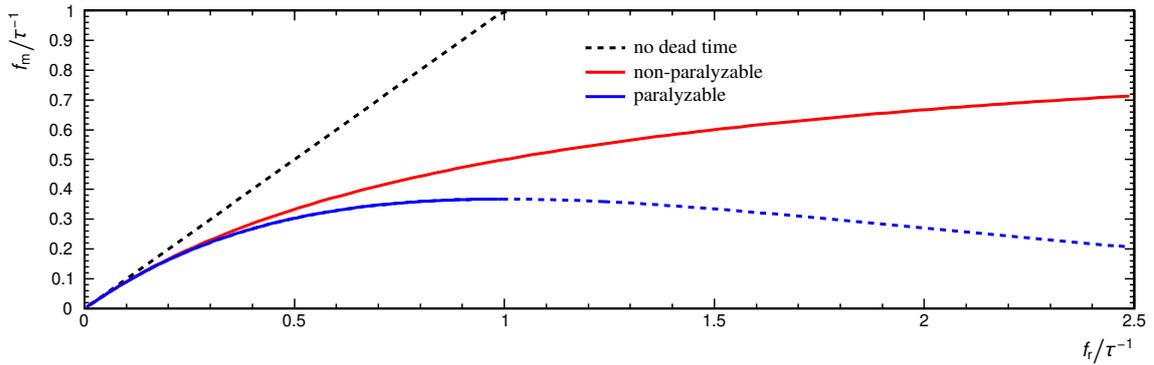
159 Detector dead time is defined as the minimum time interval between two consecutive events that is  
 160 needed for both events to be counted by a detector. Due to dead time effects, measured counting  
 161 rates will be lower than the actual counting rates; however, the real counting rate can be recovered  
 162 if the dead time of the detector can be determined and the measurements corrected.

163 It is useful to consider two different models of dead time effects [11], known as paralyzable and  
 164 non-paralyzable. In the first case, the time in which the system does not record a signal is extended  
 165 whenever another signal arrives while the system is busy. In the second case, the system is always  
 166 capable of recording the next signal after a time interval that is fixed. The two situations lead to  
 167 different equations relating the real signal rate  $f_r$  and the rate measured by the system  $f_m$ :

$$f_m^p = f_r e^{-f_r \tau}, \quad (4.1)$$

$$f_m^n = \frac{f_r}{f_r \tau + 1}, \quad (4.2)$$

168 where  $\tau$  is the dead time of the system. Equation (4.1) describes paralyzable systems while equation  
 169 (4.2) is valid for non-paralyzable systems. Figure 5 shows measured signal rate versus real signal  
 170 rate for paralyzable and non-paralyzable systems. The literature on dead time models is extensive  
 171 and there are a number of criteria for choosing between different models [11, 12] but a full discussion  
 172 of this issue lies outside of the scope of this paper.



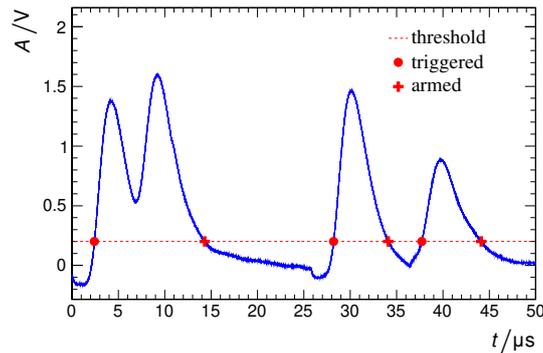
**Figure 5.** Measured signal rate versus real signal rate for paralyzable and non-paralyzable readout systems.

173 While the non-paralyzable dead time model is a monotonically increasing function and therefore  
 174 always invertible, the paralyzable model has a maximum measurable rate and the function is not  
 175 generally invertible: The relation between signal rate and measured rate is only unique for signal  
 176 rates smaller than  $1/\tau$ . In this case, the maximal measurable rate is given by  $f_{\max} = 1/(e\tau) \approx 0.37/\tau$ .

177 Most systems have dead times which are not truly paralyzable or non-paralyzable. This can  
 178 lead to a complex dead time behaviour which might not be easily correctable. However, in the case  
 179 in which one domain dominates the dead time behaviour, a correction with one of the two described  
 180 models can lead to reasonably good results. This is the case for the measurements carried out at  
 181 the proton therapy facility with the NEMUS Bonner sphere spectrometer, which can be corrected  
 182 using a paralyzable model, as we now discuss.

183 The readout system consists of a shaping amplifier and a digitisation stage as described in  
 184 section 2. The amplifier turns the input signal into a pulse with an amplitude proportional to the  
 185 input charge and a pulse form defined by the integrated shaping. The shaped signal is then converted  
 186 to a digital value by a peak sensing analogue-to-digital converter (ADC). An ADC readout cycle is  
 187 triggered when the signal exceeds a certain amplitude threshold. By the operational principles of  
 188 the ADC, a consecutive readout cycle can only be triggered when the conversion and data transfer  
 189 times have passed and the signal has fallen below the trigger threshold. The ADC has a fixed  
 190 conversion time of 500 ns and a fixed data transfer time of 100 ns after the signal peak has been  
 191 reached [9]. Depending on the exact threshold setting, the shaped signal of a single pulse falls  
 192 below the threshold after roughly 4 times the shaping time of approximately  $2 \mu\text{s}$ .

193 Figure 6 shows the pulse shape of the signal after the amplifier, recorded with an oscilloscope.  
 194 Two consecutive signals start to overlap when the time difference is too short, as is visible for the  
 195 first two pulses. In this case, the ADC will not distinguish such nearby pulses as the signal does not  
 196 fall below the threshold between pulses. This is the classical case of a paralyzable dead time. As  
 197 the conversion and data transfer time are much shorter than the signal duration, they always pass  
 198 before the analogue signal has settled and do not contribute to the dead time. Consequently, the  
 199 overall system dead time follows a paralyzable dead time model.



**Figure 6.** Pulse shape at the amplifier output. The blue line shows the amplitude  $A$  of the AIOSAP output versus time  $t$ . The red dashed line indicates the trigger threshold. Points where the ADC triggers and rearms are marked with red circles and crosses, respectively.

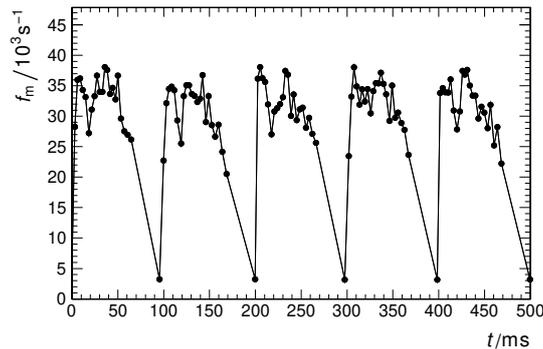
## 200 5 Dead time correction

201 In double scattering mode, the interplay of the different time variable components of the proton  
 202 therapy system generates a complex variation of the beam current in time and the irradiation  
 203 pattern (a description of the time structure of the neutron flux in double scattering is presented in  
 204 the appendix). Furthermore, the system uses different range modulator tracks and beam current  
 205 modulations for different range settings. Combined with the different settings for the modulation,  
 206 this means that the proton therapy system can generate several thousand different time patterns.  
 207 Therefore, a method that can estimate the dead time from the recorded data itself seems the only  
 208 feasible approach for the analysis of the measurements considered here.

209 **5.1 Correction method**

210 To estimate the dead time from the data, we take into consideration that the ADC used in the readout  
 211 systems has a count-rate capability of more than  $1 \times 10^6$  counts per second and the data processing  
 212 unit can record list-mode data with time stamps in units of 6.4 ns. This provides sufficient time  
 213 resolution to sample the measured signal rate several times during a single rotation of the range  
 214 modulator wheel. The samples can be used to estimate the distribution of the measured signal  
 215 rate. As there is no synchronisation between data acquisition and wheel rotation and to achieve a  
 216 constant uncertainty for the individual rate samples, the measured signal rate is calculated after a  
 217 fixed number of recorded events (every 100 triggers) rather than for fixed time intervals. Figure 7  
 218 is an example of the measured signal rate for a  $^3\text{He}$ -filled proportional counter inside a modified  
 219 sphere for irradiation using double scattering mode.

220 Under the assumption that the measured signal rate is sampled faster than it changes, it is  
 221 possible to apply the dead time correction to these individual sampling points. The real rate  
 222 is calculated for each sampling point using a numeric inversion of equation (4.1), assuming a  
 223 paralyisable dead time model. Figure 8 shows the distribution of measured signal rate  $f_m$  and  
 224 calculated real rate  $f_r$ . The peak at  $3 \times 10^3 \text{ s}^{-1}$  is an artefact and occurs when one sample is  
 225 composed from events both before and after the beam pause during the range modulator wheel  
 226 period. These entries are ignored in the calculations as they do not fulfil the requirement of  
 227 sampling the rate faster than it changes.



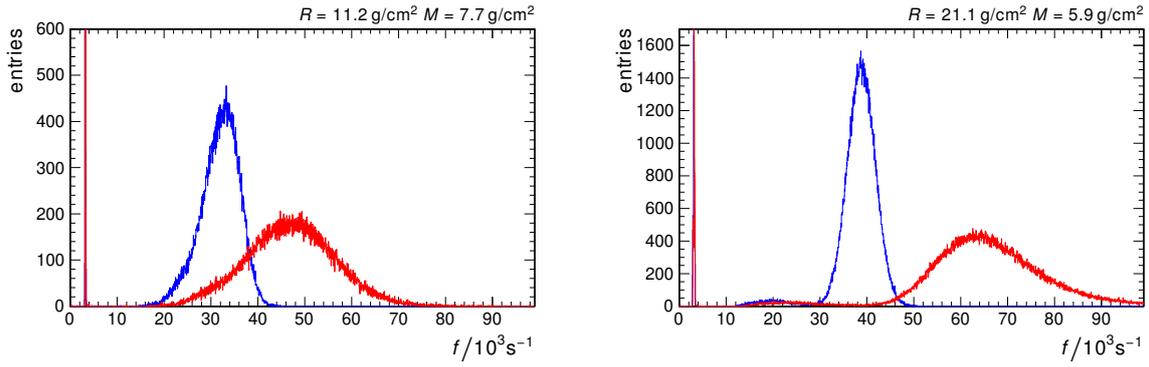
**Figure 7.** Measured signal rate  $f_m$  versus time  $t$  for a spherical  $^3\text{He}$ -filled proportional counter inside a moderator sphere of lead and polyethylene. The signal rate is computed every 100 triggers.

228 We define the overall dead time correction factor  $c$  as the ratio of the measured number of  
 229 signals  $N_m$  to the real number of signals  $N_r$ . It can be computed from the means of the measured  
 230 signal rate  $f_m$  and the calculated real rate  $f_r$ :

$$c = \frac{N_r}{N_m} = \frac{\langle f_r \rangle}{\langle f_m \rangle} = \frac{\sum_i f_{i,r}}{\sum_i f_{i,m}} \quad (5.1)$$

231 **5.2 Determination of the detector dead time**

232 In order to derive the calculated real rate  $f_r$  from equation (4.1) and compute the dead time correction  
 233 factor  $c$  from equation (5.1), the dead time  $\tau$  of the detection system needs to be known. The value  
 234 of the dead time  $\tau$  depends on the shaping time and the chosen trigger threshold. Both properties



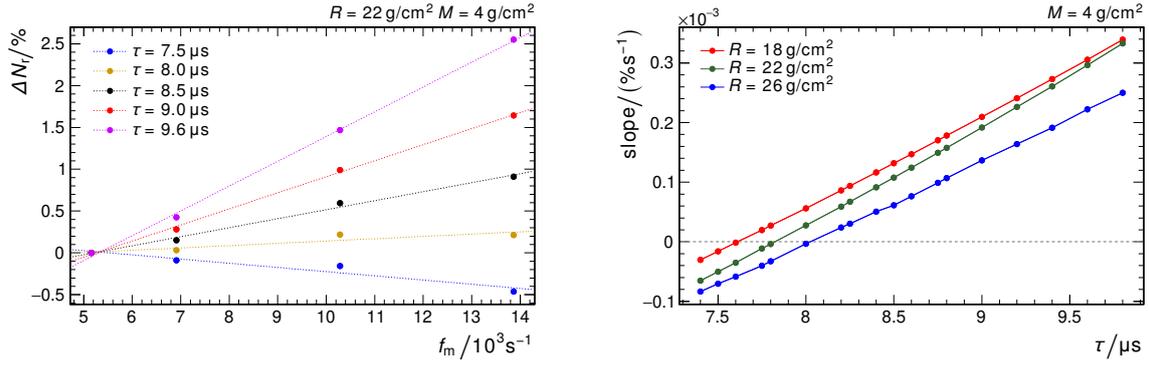
**Figure 8.** Histograms of measured and corrected rate over a long irradiation period for different settings for range  $R$  and modulation  $M$  (see the appendix for a discussion of the range  $R$  and the modulation  $M$ ). The measured signal rates  $f_m$  are drawn in blue. The red histogram shows calculated real rates  $f_r$  assuming a paralyzable dead time model with an optimised value for  $\tau$ .

235 can vary for different readout channels. Consequently,  $\tau$  has to be determined for each readout  
 236 channel individually.

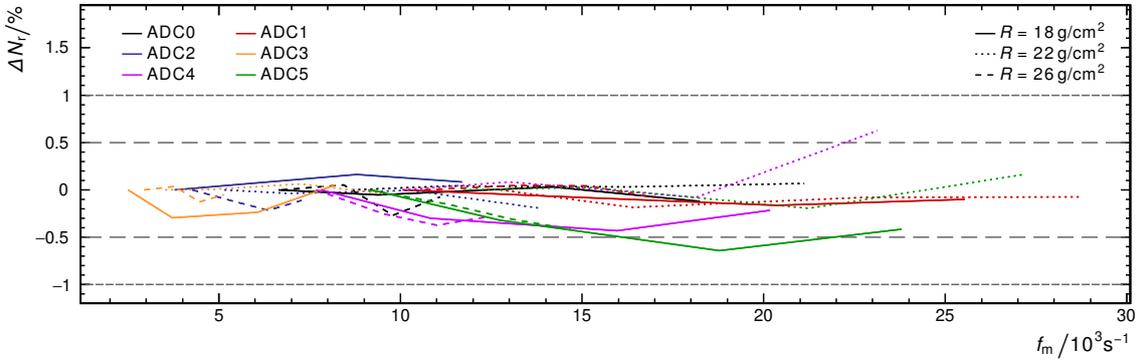
237 The neutron flux at proton therapy facilities is directly proportional to the proton flux, therefore,  
 238 the integral neutron flux is directly related to the proton dose. The proton therapy system is designed  
 239 to accurately deliver a prescribed dose to the patient. The reproducibility of the delivered proton  
 240 dose is better than 0.5% independent of the selected dose rate [13]. Hence, the calculated real rate  
 241  $f_r$  of a detection system is directly related to the applied proton dose rate and the real number of  
 242 signals  $N_r$  is related to the applied proton dose. This allows us to determine the dead time  $\tau$  with  
 243 the help of a dose rate scan where we change the primary proton current. We carried out three sets  
 244 of dose rate scans for different proton range settings (see the appendix for a discussion of the range  
 245  $R$  and the modulation  $M$ ). Each scan consisted of four different dose rate settings. For the different  
 246 dose rate settings, we calculated the corrected number of neutron signals  $N_r$  assuming different  
 247 values of  $\tau$  based on the procedure introduced in the previous paragraph.

248 The left plot of figure 9 gives an example of one such dose rate scan and how the residual  
 249 of dead time corrected number of signals varies assuming different dead time values. When the  
 250 correct  $\tau$  is chosen, the calculated number of neutrons  $N_r$  has to become independent of the dose  
 251 rate and the slope of the linear fit to the residual values will equal zero. The right side of figure 9  
 252 displays the variation of the slope of the linear fit versus  $\tau$  for the three recorded range settings.  
 253 The optimal dead time value, used to calculate the dead time correction factor  $c$  for each individual  
 254 readout channel, is determined as the mean of the three crossing points where the slope becomes  
 255 zero.

256 The dead time value  $\tau$  of the individual channels is approximated from dose rate scans for the  
 257 three different range settings. The success of the dead time correction can be tested by calculating  
 258 the residual variation between the measurements with different dose rates. Figure 10 summarises  
 259 the result for all readout channels. The remaining fluctuations are below 0.5% for measured signal  
 260 rates smaller than  $15 \times 10^3 \text{ s}^{-1}$  and do not exceed 1% for the maximally tested measured rate of  
 261 approximately  $25 \times 10^3 \text{ s}^{-1}$



**Figure 9.** Left: Difference of the dead time corrected number of signals  $\Delta N_r$  relative to the measurement with the lowest signal rate for one readout channel. The dotted lines show the linear fit for a specific value of  $\tau$ . Right: Slope of the linear fit versus  $\tau$  for three different proton range settings.



**Figure 10.** Difference of the dead time corrected number of signals relative to the measurement with the lowest signal rate. The line colour distinguishes the different readout channels. The three different proton range settings are differentiated by the line style.

## 262 6 Discussion

263 The method for dead time correction presented here is not restricted to proton therapy facilities. It  
 264 is designed to work with all systems that have a long enough pulse duration that the rate can be  
 265 sampled multiple times during one pulse. The choice to sample the rate every fixed number of  
 266 events is practical as it creates samples with the same relative error and is easy to calculate. By  
 267 discarding the samples that contain the beam pause, the bias from mixing very different rates in one  
 268 sample is kept to a minimum. An alternative would be to sample with fixed time intervals. But, a  
 269 good choice of the interval length would require an a priori knowledge of the rates as a minimum  
 270 number of events per time slot should be achieved to get numerically stable results.

271 A clear limitation of the method is the requirement of long enough pulses. For repetitive  
 272 signals, this might be overcome by sampling synchronised to the pulse start and collect statistics  
 273 over several repetitions. Of course, this would require some synchronisation between beam delivery  
 274 and data acquisition or a precise way to identify the pulse start in the recorded data. However, the  
 275 signal patterns generated at a proton therapy facility operating in double scattering mode are well

276 suited for the suggested method. The applicability to other operation modes like pencil beam  
277 scanning has to be studied.

278 The suggested in situ determination of  $\tau$  depends on an accurate knowledge of the applied  
279 amount of primary beam. This is readily available at therapeutic facilities, which are designed  
280 to reproduce an exact dose. At accelerators without such a precise beam control, an independent  
281 measurement of the applied amount of primary beam can be used to scale the measured counts.

## 282 7 Conclusion

283 The measurement of neutron fields at proton therapy facilities is technically challenging. One  
284 particular issue is the determination of the dead time for a measurement in a neutron field which  
285 is both pulsed and varying in intensity. This work describes a method to correct the dead time  
286 for complex rate distributions in case time-stamped data is available. Additionally, how the time  
287 constant  $\tau$  can be determined in situ with the help of a rate scan is explained. The method was  
288 applied to measurements conducted at the University Proton Therapy Dresden operating in double  
289 scattering mode. After the correction, residual variations of the reconstructed number of events  
290 below 0.5% for measurement rates smaller than  $15 \times 10^3$  counts per second (cps) and below 1% for  
291 rates up to  $25 \times 10^3$  cps are achieved.

## 292 Appendix: Time structure of the neutron flux in double scattering mode

293 A spread-out Bragg peak (SOBP) is typically described by its range  $R$  and its modulation  $M$ .  
294 Different conventions are in use for these quantities. Here, the definition used for the IBA system  
295 is adopted. The range  $R$  is defined as the distance between the entrance point of the beam and the  
296 point in depth where the dose falls to 90% of the plateau level. Similarly, the modulation  $M$  is  
297 defined as the distance between the point where the dose level reaches 90% of the plateau dose and  
298 the point where it falls below 90% of the plateau dose.

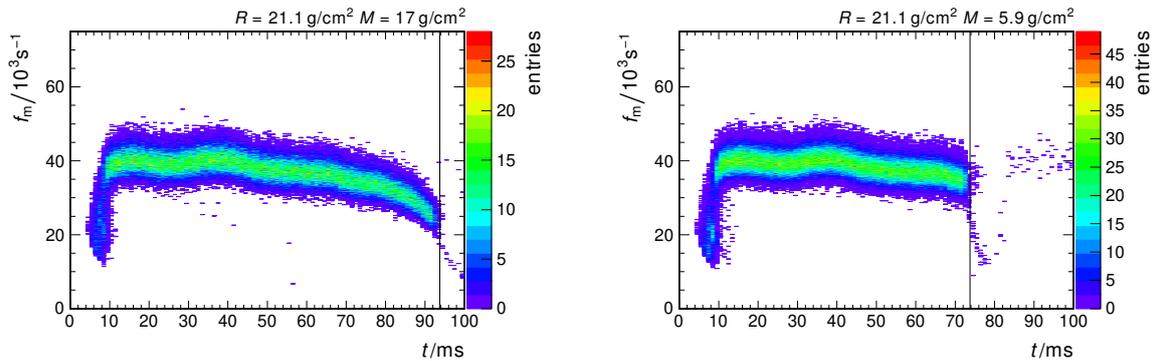
299 Double scattering uses a rotating wheel with steps of variable thickness to modulate the beam  
300 energy and consequently vary the penetration depth (range) of the protons in the target. The height  
301 and width of the steps are designed such that a spread-out Bragg peak is generated when the  
302 wheel rotates at constant speed. The design also permits varying the length of the SOBP plateau  
303 (modulation) by stopping the beam before the wheel has completed a full rotation. Finally, the  
304 beam current is modulated with the rotation of the range modulator wheel (RMW) to compensate  
305 for production imperfections. This results in three different components for the time structure of  
306 the neutron flux.

307 The most prominent feature is the switching of the proton beam to adjust the modulation.  
308 Figure 7 shows the rate in a  $^3\text{He}$ -filled proportional counter inside a moderator sphere versus time.  
309 The 10 Hz rotation of the wheel is clearly visible.

310 The varying proton energy leads to a second time component. The RMW always starts with  
311 an absorber that blocks the proton beam. The absorber is followed by modulator steps of increasing  
312 thickness. While the absorber is blocking the beam, neutrons are only generated in the RMW and  
313 upstream of it. This moves the neutron generation away from the target volume and reduces the  
314 neutron flux at the target location. Directly after the absorber, the neutron flux increases to its

315 peak as the protons reach the aperture of the scattering system with the highest energy. With the  
 316 increasing size of the steps, the protons lose more energy at the range modulator wheel and the  
 317 number of neutrons generated in the RMW increases while the neutron component generated by  
 318 protons absorbed in the aperture reduces. This results in a net reduction of the rate at the target  
 319 location.

320 The modulation of the beam current directly translates into a variation of the neutron flux and  
 321 overlays the time variations that comes from the rotation of the wheel.



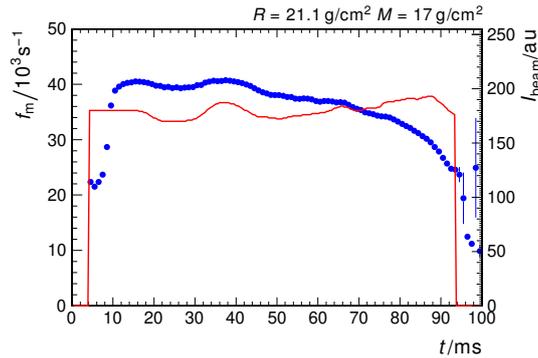
**Figure 11.** Measurements of the trigger rate of a  $^3\text{He}$ -filled proportional counter in a moderator sphere for a proton range  $R = 21.1 \text{ g/cm}^2$  and modulation of  $R = 17 \text{ g/cm}^2$  (left) and  $R = 5.9 \text{ g/cm}^2$  (right). The trigger rate is plotted against the time after the range modulator wheel zero-crossing. The black line indicates the time when the proton beam is switched off.

322 Another aspect of the variation of the neutron flux with time can be seen in figure 11. The  
 323 plot on the left shows the instantaneous rate in a  $^3\text{He}$ -filled proportional counter versus the time  
 324 calculated from the leading edge of the pulsed beam. The black line indicates the time when the  
 325 proton beam is stopped to adjust the modulation. The plot on the right shows the same quantity  
 326 with the same proton beam range setting but with decreased modulation. The shortening of the  
 327 neutron pulse is clearly visible.

328 Figure 12 compares the mean rate measured by the  $^3\text{He}$ -filled proportional counter with the  
 329 beam current setting used to modulate the proton beam intensity. The low rate before the 10 ms  
 330 point is due to the absorber block at the beginning of the range modulator. The variations in the  
 331 neutron flux between 10 ms and 50 ms are mainly due to the variation of the beam current. At later  
 332 times, the decrease of the neutron flux due to the reduction in proton range is dominant.

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**Figure 12.** Mean measured neutron rate  $f_m$  (blue points) and primary proton beam current setting (red line) versus time within one range modulator wheel rotation.

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### 343 References

- 344 [1] W. D. Newhauser and R. Zhang, *The physics of proton therapy*, *Phys. Med. Biol.* **60** (2015) R155.  
 345 [2] X. G. Xu, B. Bednarz and H. Paganetti, *A review of dosimetry studies on external-beam radiation*  
 346 *treatment with respect to second cancer induction*, *Phys. Med. Biol.* **53** (2008) R193.  
 347 [3] W. D. Newhauser and M. Durante, *Assessing the risk of second malignancies after modern*  
 348 *radiotherapy*, *Nat. Rev. Cancer* **11** (2011) 438.  
 349 [4] U. Schneider and R. Hälgl, *The impact of neutrons in clinical proton therapy*, *Front. Oncol.* **5** (2015)  
 350 235.  
 351 [5] D. J. Thomas and A. V. Alevra, *Bonner sphere spectrometers – a critical review*, *Nucl. Instr. Meth.*  
 352 *Phys. Res. A* **476** (2002) 12.  
 353 [6] B. Wiegel and A. Alevra, *NEMUS – the PTB neutron multisphere spectrometer: Bonner spheres and*  
 354 *more*, *Nucl. Instr. Meth. Phys. Res. A* **476** (2002) 36 .  
 355 [7] Centronic LTD., *<sup>3</sup>He Proportional Counters General Data*, 4, 2005.  
 356 [8] A. V. Alevra, *All-In-One Spectrometry Analogue Processor AIOSAP-02, Manual*.  
 357 Physikalisch-Technische Bundesanstalt, Braunschweig, 2008.  
 358 [9] FAST Comtec GmbH, Gruenwalder Weg 28A, 82041 Oberhaching, Germany, *Model 7072 Dual ADC*  
 359 *- Data Sheet*, 2006.  
 360 [10] FAST Comtec GmbH, Gruenwalder Weg 28A, 82041 Oberhaching, Germany, *Model MPA4, 8 ch*  
 361 *acquisition system with 6 ns time tagging*, 2011.  
 362 [11] V. Bécares and J. Blázquez, *Detector dead time determination and optimal counting rate for a detector*  
 363 *near a spallation source or a subcritical multiplying system*, *Sci. Technol. Nucl. Install.* **2012** (2012) .  
 364 [12] S. Usman and A. Patil, *Radiation detector deadtime and pile up: A review of the status of science*,  
 365 *Nucl. Eng. Technol.* **50** (2018) 1006 .

- 366 [13] C. Bäumer, B. Ackermann, M. Hillbrand, F.-J. Kaiser, B. Koska, H. Latzel et al., *Dosimetry*  
367 *intercomparison of four proton therapy institutions in germany employing spot scanning*, *Z. Med.*  
368 *Phys.* **27** (2017) 80 .