The large helical device vertical neutron camera operating in the MHz counting rate range

メタデータ	言語: English
	出版者:
	公開日: 2021-07-13
	キーワード (Ja):
	キーワード (En):
	作成者: OGAWA, Kunihoro, ISOBE, Mitsutaka,
	Nishitani, T., KOBUCHI, Takashi
	メールアドレス:
	所属:
URL	http://hdl.handle.net/10655/00012570

This work is licensed under a Creative Commons Attribution-NoDerivatives 3.0 International License.



1	The Large Helical Device Vertical Neutron Camera Operating in the MHz Counting Rate Range
2	
3	K. Ogawa ^{1, 2} , M. Isobe ^{1, 2} , T. Nishitani ¹ , and T. Kobuchi ¹
4	
5	1. National Institute for Fusion Science, National Institutes of Natural Sciences, Toki, Japan
6	2. SOKENDAI (The Graduate University for Advanced Studies), Toki, Japan
7	
8	Email: kogawa@nifs.ac.jp
9	
10	Abstract
11	In the currently performed neutral beam (NB) -heated deuterium plasma experiments, neutrons are
12	
	mainly produced by a beam-plasma reaction. Therefore, time-resolved measurement of the neutron
13	mainly produced by a beam-plasma reaction. Therefore, time-resolved measurement of the neutron emission profile can enhance the understanding of the classical and/or anomalous transport of beam
13 14	mainly produced by a beam-plasma reaction. Therefore, time-resolved measurement of the neutron emission profile can enhance the understanding of the classical and/or anomalous transport of beam ions. To measure radial neutron emission profiles as a function of time, the vertical neutron camera
13 14 15	mainly produced by a beam-plasma reaction. Therefore, time-resolved measurement of the neutron emission profile can enhance the understanding of the classical and/or anomalous transport of beam ions. To measure radial neutron emission profiles as a function of time, the vertical neutron camera (VNC) capable of operation with a counting rate in the MHz range was newly installed on the Large
13 14 15 16	mainly produced by a beam-plasma reaction. Therefore, time-resolved measurement of the neutron emission profile can enhance the understanding of the classical and/or anomalous transport of beam ions. To measure radial neutron emission profiles as a function of time, the vertical neutron camera (VNC) capable of operation with a counting rate in the MHz range was newly installed on the Large Helical Device (LHD). This is the world's first neutron camera for stellarator/heliotron devices. The
 13 14 15 16 17 	mainly produced by a beam-plasma reaction. Therefore, time-resolved measurement of the neutron emission profile can enhance the understanding of the classical and/or anomalous transport of beam ions. To measure radial neutron emission profiles as a function of time, the vertical neutron camera (VNC) capable of operation with a counting rate in the MHz range was newly installed on the Large Helical Device (LHD). This is the world's first neutron camera for stellarator/heliotron devices. The VNC consists of a multichannel collimator, eleven fast-neutron detectors, and the digital-signal-

19	was made from hematite-doped heavy concrete, which has a high shielding performance against both
20	neutrons and gamma-rays. A stilbene crystal coupled with a photomultiplier having high-gain-stability
21	in the high-count rate regime was utilized as a fast-neutron scintillation detector because it has a high
22	neutron-gamma discrimination capability at high count rates. The DAQ system equipped with a field
23	programmable logic controller was developed to obtain the waveform acquired with a 1 GHz sampling
24	rate and the shaping parameter of each pulse simultaneously at up to 10^6 cps (counts per second).
25	Neutron emission profiles were successfully obtained in the first deuterium campaign of LHD in 2017.
26	The neutron emission profile was measured in tangentially co-injected NB-heated plasma with
27	different magnetic axies (R_{ax}). The neutron counts became larger in the inward-shifted configuration,
28	which was consistent with the total neutron rate measured by the neutron flux monitor. The radial peak
29	position of the line-integrated neutron profile which changed according to R_{ax} showed that the VNC
30	worked successfully as designed. The VNC demonstrated the expected performance conducive to
31	extending energetic-particle physics studies in LHD.
32	
33	Keywords: Large Helical Device, Neutron Camera, Fast-neutron Detection
34	
35	I. Introduction

36 Neutron diagnostics have been developed because neutron measurement is one of the key methods in

37	order to obtain the fusion output power directly from a fusion burning plasma. ¹ In deuterium plasmas,
38	2.45 MeV neutrons are produced as a result of the $d(d,n)^3$ He reactions. The spatially-resolved
39	measurement of fusion neutron emission from the currently performed plasma experiment supports
40	the theoretical modeling of the plasma, which preindicates the plasma behavior in a fusion reactor. In
41	most of the currently performed neutral beam (NB) heated plasma experiments, neutrons are mainly
42	created by the reactions between thermal plasma and beam ions. Therefore, neutron diagnostics have
43	mainly been utilized to study the energetic ion behavior. The measurement of the neutron emission
44	profile was reported for the first time in Princeton Large Torus (PLT) using nuclear emulsions in 1978. ²
45	The shot integrated neutron emission profile matched the theoretical model based on the Fokker-
46	Planck equation under the total neutron emission rate of 10 ¹² n/s. In the 1980s, the measurement of
47	the time evolution of the neutron emission profile was possible using neutron cameras mainly
48	composed of a multichannel collimator and fast-neutron detectors because the total neutron emission
49	rate increased by more than a factor of four with the increase of the plasma performance.
50	Neutron cameras were installed and have been working since the late 1980s in large tokamaks. The
51	vertical neutron camera (VNC) having the right cylinder type collimator was installed in the basement
52	of the Tokamak Fusion Test Reactor (TFTR). ^{3,4} The multichannel collimator was made of brick and
53	lead block stacked above the fast-neutron detectors. They used a zinc sulfide phosphor embedded in a
54	hydrogenous polymer matrix scintillator (NE451) operated in the current mode. The neutron camera

55	indicates that the peak of the line-integrated neutron emission profile agrees with the plasma axis as
56	expected by transport code TRANSP. ³ Horizontal and vertical neutron cameras were installed in the
57	Joint European Torus (JET). ^{5,6} Two multichannel collimators, made from barite-doped heavy concrete
58	with a mass density of around 3.5 g/cm ³ , are placed on the upper side and the outboard side of the
59	plasma. The liquid scintillator (NE213) with the analogue-circuit-based pulse shape discrimination
60	circuit was used and recently upgraded to the FPGA-based pulse shape discrimination circuit. ⁷
61	Tomography of the neutron emission profile is performed using both horizontal and vertical cameras. ⁸
62	Neutron cameras with six sight lines were installed on the outboard side of the JAERI Tokamak 60
63	Upgrade (JT-60U).9 They used multichannel collimators made from polyethylene and lead. The
64	stilbene scintillator with the analogue-circuit-based pulse shape discrimination circuit was previously
65	used. The circuit was upgraded to the flash ADC modules. ¹⁰ The energetic ion transport due to the
66	energetic particle mode is observed with the neutron camera ¹¹ . In middle size tokamaks, the neutron
67	cameras are installed in FTU ¹² , MAST ¹³ , KSTAR ^{14, 15} , EAST ¹⁶ , HL-2A ¹⁷ , and MST ¹⁸ , and are used to
68	understand the energetic particle transport and losses. ¹⁹ In ITER, the installation of vertical and
69	horizontal neutron cameras is planned. ^{20,21} In helical devices and stellarators, no neutron cameras have
70	been installed because the neutron emission rate in previous experimental devices was too low to
71	measure the neutron emission profile. The deuterium operation of the LHD makes it feasible to obtain
72	time-resolved measurements of the neutron emission profile from the plasma because the expected

73	neutron emission rate from the NB-heated deuterium LHD plasma is 10 ¹⁶ n/s order which is equivalent
74	to the neutron emission rate of the deuterium operation of large tokamaks. The plan for installation of
75	the VNC was initiated during the construction phase of the LHD. ²² The height of the multichannel
76	collimator composed of polyethylene was studied by the MCNP5 code. ²³ It was reported that a sharp
77	peak of DD neutrons can be recognized when the collimator length is set to be 1.5 m. Through the
78	study of the multichannel collimator design, progress was made in fast-neutron detection systems. ²⁴ A
79	multichannel collimator made of heavy concrete and a Stilbene scintillation detector were suggested,
80	however the design of a fast-neutron detection system operating with 10 ⁶ cps was not completed. ²⁵
81	This paper describes the design and performance of the VNC stably operated with 10 ⁶ cps, which is
82	now used regularly to measure the time evolution of the neutron emission profile during LHD
83	discharges.
84	
85	II. Design of the vertical neutron camera
86	II-1 General outline
87	The VNC installed in the basement of the LHD torus hall sees the plasma from the lower side (Fig. 1).
88	The VNC mainly consists of three parts: a multichannel collimator, fast-neutron scintillation detectors,
89	and the digital-signal-processing-based data acquisition system. The VNC has a right cylinder
90	collimator type, similar to the neutron camera installed in TFTR and views the radial profile of neutron

91	emission with eleven sight lines. The geometry ensures that each individual collimator channel has the
92	same viewing efficiency. The distance from the plasma center to the multichannel collimator front and
93	the fast-neutron detector are 5.5 m and 8.5 m, respectively. Eleven ICF70 ports aligned to the axis of
94	the collimator were installed on the lower port of LHD. The thickness of the central part of the ICF70
95	flange is reduced to 2 mm in order to reduce the neutron scattering.
96	
97	II-2 Multichannel collimator
98	The multichannel collimator is installed in the LHD torus hall concrete floor with a thickness of 2000
99	mm (Fig. 2). The hole created in the concrete floor has a rectangular shape. The size of the bottom
100	opening is 1400 mm in depth (major radial direction) and 800 mm in width. The height of the
101	multichannel collimator was determined to be 1500 mm in order to implement sufficient shielding
102	ability as evaluated using the neutron transport calculation. ^{23,24} The collimator support was made using
103	angle bars made of SUS304A having a height of 250 mm, a width of 100 mm and a thickness of 10
104	mm for fixing the vertical rib plate. The structure of the collimator support was designed based on a
105	structural calculation. The collimator support is fixed with an M20 adhesive anchor and the gap
106	between the angle bars and the floor concrete is filled by shrinkage-compensating mortar in order to
107	avoid water and concrete falling to the understructure. The multichannel collimator is made using the
108	hematite (Fe ₂ O ₃)-doped heavy concrete. The mass density of heavy concrete is 3.5 g/cm ³ , which is

109	almost the same as the mass density of the heavy concrete used for the multichannel collimator of the
110	JET neutron camera. We used 210 kg of water, 380 kg of cement, 2100 kg of hematite with a particle
111	size of 2 mm, and 3700 kg of hematite with a particle size of 20 mm. The composition of heavy
112	concrete is shown in Table 1. Note that the reason for using the heavy concrete is that the heavy
113	concrete collimator has better performance in reducing unwanted gamma-rays compared with
114	collimators made of polyethylene and lead according to the Monte Carlo neutron and gamma-ray
115	transport calculation. ²⁴
116	The collimator consists of 3 sub-sections of 500 mm high stainless steel (SUS304A) pipes embedded
117	in heavy concrete. The three collimator units are stacked on the collimator support, and then the gap
118	between collimator units and the floor concrete is filled with heavy concrete. Here, we caulked the
119	small gap between collimator unit and collimator support to avoid water leakage. The reason for
120	making three collimator units is in order to avoid the bending of relatively long stainless steel pipes
121	due to the high pressure from the heavy concrete. Here, the size of the collimator unit placed on the
122	top is slightly smaller than that of the others in order to obtain easier access to the lower region during
123	the concrete placing work. The total weight of the heavy concrete used for the multichannel collimator
124	is approximately seven tons. In addition to the heavy concrete collimator, lead with a thickness of 150
125	mm (30 sheets of t of 5 mm lead plate) is placed under the heavy concrete collimator in order to reduce
126	the unwanted gamma-ray. Note that holes with a diameter of 30 mm are made in the lead sheets along

127	the sight lines to avoid the neutron scattering. The VNC has eleven sight lines whose inner diameter
128	is 30 mm aligned radially. A sight line is placed at each R of 3.36 m, 3.45 m, 3.54 m, 3.63 m, 3.72 m,
129	3.81 m, 3.90 m, 3.99 m, 4.08 m, 4.17 m, and 4.26 m. The distance between the centers of two sight
130	lines is 90 mm. Note that the inner diameter of the sight line can be changed to 10 mm or 20 mm using
131	an additional stainless steel pipe with the length of 500 mm. It should be pointed out that the relatively
132	short length of the additional stainless pipe is to avoid having a smaller pipe become stuck inside a
133	larger pipe. Fast-neutron detectors are placed at the bottom of the multichannel collimator. The support
134	of neutron detectors is designed to accept a supporting a weight of 500 kg. The crosstalk of the
135	multichannel collimator is experimentally obtained by using an intensive ²⁵² Cf neutron source. The
136	experimental results indicate that the crosstalk of the multichannel collimator is approximately 1 %. ²⁶
137	Figure 3 shows the sight line of the VNC together with the poloidal cross section of the plasmas having
138	the magnetic axis positions (R_{ax}) of 3.60 m and 3.90 m. The figure shows that the VNC is designed to
139	cover of the entire plasma region and obtain the information about the plasma axis position. Here, the
140	sight line with R of 4.26 m is designed in order to obtain the background counts. The plasma visible
141	region through sight line is approximately a cylinder with a 88 mm diameter at the bottom of the
142	plasma and a 110 mm diameter at the top of the plasma for the central cord (R of 3.63 m) and the
143	volume of the visible region is 0.05 m^3 .

145 II-3 Fast-neutron detection system

146 The block diagram of the fast-neutron detection system is illustrated in Fig. 4 (a). We choose a stilbene scintillator directly coupled with the PMT (H11934-100-10MOD²⁷ with a 3 m cable) having high gain 147 148 stability as a fast-neutron detector. The typical rise and transit time of the PMT are 1.3 ns and 5.8 ns, 149 respectively. The signal from the fast-neutron detector is directly fed into the data acquisition system. The length of the co-axial cable (3D-FB²⁸) from the detector to the data acquisition system is 18 m. 150 151 The length of the cable is decided by the possible locations for installing the Fast-neutron detection 152 system and the effect of the cable length on signal. We evaluated the effect of the cable length on the 153 pulse height and width using an LED emitting green light. Here, the pulse width of the LED light is 15420 ns. The data acquisition system should be placed away from the machine to prevent radiation 155 damage of the data acquisition system. However, the long cable causes a reduction of the signal height 156 and the broad signal. Therefore, the effect of the cable length on the pulse signal was investigated. Figure 4 (b) shows the pulse height and width measured by an Oscilloscope (DPO 7104C²⁹, Tektronix) 157 158 as a function of the cable length. The pulse height gradually decreases and the pulse width gradually 159 expended with the increase of the capacitance of the cable, as expected. The pulse height decreases by 160 25 % at the cable length of around 50 m and the pulse width becomes 30 % wider at the cable length 161 of around 40 m compared with a 3 m cable (no cable extension). It is found that on the VNC the pulse 162 height decreases by 10 % and the pulse width becomes wider by 11 % with an 18 m cable compared

163	with a 3 m cable. On the other hand, the pulse height decreases by 40 % and the pulse width becomes
164	wider by 50 % with a 100 m cable. The data acquisition system for the VNC is placed on the basement
165	level of the torus hall (cable length of 18 m) rather than in the data acquisition room located outside
166	of the torus hall (100 m) because 40 % smaller means that the signal to noise ratio becomes a 40 %
167	less and a 50 % wider signal induces a 50 % higher pile up rate. The data acquisition system
168	(APV8102-14MWPSAGb ³⁰ , Techno AP) composed of the fast digitizer, a leading edge technology
169	field programmable logic circuit, and synchronous dynamic random access memory (SDRAM), is
170	developed for the LHD VNC. High voltage is applied using an externally controllable high voltage
171	power supply with logging function (APV3304 ³¹ , Techno AP). We can obtain the information of both
172	applied voltage and supplied current every 1 ms to monitor the gain variation of the PMT. The
173	maximum voltage and current of APV3304 is 1 kV and 4 mA, respectively. In addition to the primary
174	high voltage module, external DC power supplies (P4K80H ³² , Matsusada Precision) are additionally
175	prepared in order to suppress the gain shift of the PMT in the high counting rate regime. The maximum
176	voltage, current, and power of P4K80H are 320 V, 0.5 A, and 80 W, respectively. The Ethernet outputs
177	of these modules are gathered to the high-speed Ethernet hub (XS712 ³³ , NETGEAR Corp.) equipped
178	with an SFP+ port. The SFP+ port is connected to the data acquisition PC through a 10 Gbps network.
179	Because the minimum operation interval of the LHD is approximately three minutes and the maximum
180	stored data of the DAQ is 11 GB, the required average transfer rate of the data acquisition system is

181	more than 500 Mbps. Therefore, we choose the 10 Gbps network for the data transfer. To acquire such
182	large data with high speed, we choose a relatively high performance data acquisition server equipped
183	with Xeon E5-2603v3 ×2 CPUs, 32 GB DDR4 ECC Registered memory, Intel Ethernet SFP+, and
184	SSD (SSDSC2KW240H6X1) ×3 RAID0. The specification of each component in detail will be
185	described in the next section.

187 III Experimental system

188 III-1 Magnetic shield for fast-neutron detector

189 The neutron detector must work under a relatively strong magnetic field environment, however the 190 effect of neutron scattering due to the magnetic shield should be reduced. The goal was to design the 191 magnetic shield surrounding the PMT without front and back sides in order to reduce the neutron 192 scattering. The fast-neutron detector shown in Fig. 5 is composed of the magnetic shield, the stilbene 193 scintillator, and the photomultiplier. Because the photomultiplier (PMT) is sensitive to the magnetic 194 field, we need the magnetic shield in order to reduce the magnetic field strength to an acceptable value. 195 The acceptable magnetic field for the PMT used for the LHD VNC is approx. 0.05 mT. Figure 6 (a) 196 shows the profile of the magnetic field strength at the standard configuration of the LHD experiment 197 at R of 3.60 m. Here, the toroidal magnetic field strength (B_t) is 3 T and R_{ax} is 3.60 m and Z = 0 198 corresponds to the plasma axis position. The figure shows that the magnetic field strength of the fast-

199	neutron detector position at $Z = 8$ m is around 12 mT in the radial direction and 6 mT in the vertical
200	direction. It is notable that the toroidal magnetic field component is negligibly small compared with
201	the radial magnetic field component. We designed the magnetic shield with a 1 mm thickness of
202	Permalloy C surrounded by a 10 mm thickness of SS400 using the finite element method. The length
203	of the magnetic shield is 300 mm and the photomultiplier tube is located at the center of the magnetic
204	shield. We designed a relatively long magnetic shield so that no magnetic shield component is located
205	on the front and the back of the fast-neutron detector in order to avoid the scattering of fast-neutron
206	due to the magnetic shield. We should keep in mind that the weight of the magnetic shield is
207	approximately 10 kg. The performance of the magnetic shield was checked by an experiment using a
208	light emitted diode (LED) in the magnetic field produced by HYPER-I. ³⁴ HYPER-I is the linear high-
209	density plasma device which can produce a linear magnetic field up to 250 mT. The PMT surrounded
210	by magnetic shield was placed parallel /perpendicular to the axis of HYPER-I. An LED fixed in front
211	of the PMT emits a light using a function generator (WF1946 ³⁵ , NF Corporation) with a pulse rate of
212	100 Hz and pulse width of 30 ns. We changed the magnetic field strength and recorded the pulse height
213	of the PMT signal measured by an Oscilloscope (DPO 7104C, Tektronix). The pulse height as a
214	function of the magnetic field strength is shown in Fig. 6 (b). Here, z is defined along the central axis
215	of the PMT and x and y are perpendicular to the z axis. The dependence of the pulse height as a
216	function of the magnetic field strength shows that the pulse height stays constant in the B_x and B_y cases,

whereas the pulse height decreases from *B* of 0.04 T in the B_z case. The design of a magnetic shield having minimal neutron scattering effect and working in the VNC position (B_R of around 12 mT and B_Z of 6 mT) was completed.

220

221 III-2 Gain stability of PMT in high-counting rate region

222 The understanding on the characteristics of the PMT in the high counting rate regime is one issue for 223 stable operation of the neutron measurement, especially in the neutron and gamma-ray discrimination. 224 In JT60-U, the gain shift of the PMT caused a disturbance on the neutron and gamma-ray 225 discrimination plot.³⁶ The goal of the PMT development is no gain shift in MHz pulse rate region. The 226 PMT used for the fast-neutron detector of the LHD VNC has a metal channel dynode structure and 227 consists of twelve stages. The maximum applied high voltage and typical gain are -1000 V and 4.8×10⁵, 228 respectively. High voltage cables and 0.01 F capacitors are connected to the last three dynodes of the 229 PMT. Each high voltage cable is connected to an external voltage module. In the high counting rate 230 region, these external DC power supplies supply the current in order to sustain the high voltage in the 231 latter phase of the dynodes for suppressing gain variation in the high counting rate condition. The gain 232 stability of the PMT was checked by using two LED lights emitting green light. The experimental 233 setup is shown in Fig. 7(a). Two LEDs were fixed in front of the PMT placed in a dark room. One 234 LED called LED1 emitted a light with 100 Hz, whereas the frequency of the other LED called LED2

235	was changed from 300 Hz to 10^{6} Hz. We measured the pulse height of the PMT signal created by
236	LED1 light by an Oscilloscope (DPO 7104C, Tektronix). Here, the pulse height and width created by
237	LEDs are around 200 mV and 30 ns, respectively in the case of a high voltage of 700 V, which is
238	similar to the pulse height of a 2.45 MeV neutron signal of the fast-neutron detector. Figure 7 (b)
239	shows the pulse height created by LED1 as a function of the pulse rate of LED2. The pulse heights in
240	the case of the high voltages of 700 V and 800 V are 200 mV and 600 mV, respectively. The gain of
241	the PMT at 700 V and at 800 V are 4.0×10^4 and 1.5×10^5 , respectively. It is worth noting that the gain
242	shift occurred at a different pulse rate in each case. The gain shift of the PMT occurred depending on
243	the ratio of the signal current on the dynode current. When the signal current becomes not negligible
244	with respect to the dynode current, a gain shift occurred due to the decrease of the voltage between
245	dynodes of the PMT. The signal current of the PMT increases nonlinearly with high voltage, whereas
246	the dynode current increases linearly with the high voltage. Therefore, the saturation level becomes
247	lower in the 800 V case compared with the 700 V case because the ratio of the signal current on the
248	dynode current is higher. In the case of a high voltage of 700 V, without external DC power supplies,
249	the pulse height increases from around the pulse rate of 10^5 Hz and then decreases starting from 3×10^5
250	Hz, whereas the pulse height is almost constant regardless of the pulse rate of LED2 with external DC
251	power supplies. In the case of a high voltage of 800 V, without external DC power supplies, the pulse
252	height increases at a pulse rate of LED2 of 10 ³ Hz and then decreases monotonically with respect to

253	the pulse rate of LED2, whereas the pulse height is almost constant irrespective of the pulse rate of
254	LED2 with external DC power supplies. The experimental results show that the external DC power
255	supplies works successfully to suppress the gain variation and the gain of the fast-neutron detector is
256	stable under the pulse rate of 10^6 Hz. The PMT suitable for the Stilbene fast-neutron detector stably
257	operated at a 10 ⁶ pulse rate without gain variation was developed.

- 258
- 259 III-3 Digital signal processing unit

260 The DAQ system (APV8102-14MWPSAGb) for the VNC is newly developed by combining a highspeed sampling rate analog to digital converter (1 GHz sampling, 14 bits and 2 or 6 V_{pp}) and a field 261 262programmable logic circuit (Fig. 8a) in order to accept the superior performance of fast-neutron 263 detector operating in the 10⁶ pulse rate regime. Figure 8 (b) is a block diagram of the DAQ board. The 264 signal acquired by the high speed ADC is transferred to the FPGA. The FPGA judges whether the 265 signal is above the threshold value. If the signal exceeds the threshold value, the time stamp is recorded 266 by using the constant fraction discriminator (CFD) function. Then, signal integrations Q_{total} and Q_{long} 267 are calculated. At the same time, the raw waveform consisting of 64 points is stored in the 1 GB 268 SDRAM. After the discharge, all the data is transferred to a PC through the Ethernet. Here, the data size of each pulse is 144 Bytes. Therefore, the expected data transfer rate at the 10⁶ cps counting rate 269 270 is ~ 1.2 Gbps per channel. Then we choose DDR2 SDRAM because of its high data transfer rate of

271	more than 3 Gbps. The DAQ only stored meaningful pulses. The acquisition time is not limited by the
272	duration of the acquisition but by the number of pulses. The maximum number of pulses stored in the
273	board is designed to be 3×10^6 per channel, because of the maximum expected neutron counts on an
274	LHD discharge (10^6 cps × 3 seconds).

- 275
- 276 IV Characteristics of Fast-neutron detection system
- 277 IV-1 Optimal *t*_{fast} for pulse shape discrimination

Pulse shape discrimination (PSD) is performed using the expression $PSD=Q_{long}/Q_{total}$. Here, Q_{total} 278 279 represents integration of the signal from the beginning to the end of the stored waveform of 64 ns 280length, whereas Q_{long} represents the integration of the signal from an arbitrary time in the middle of 281 the signal, t_{fast} , to the end. As shown in Fig. 9(a), neutron induced signal has a longer decay time, and 282 then the PSD becomes larger compared with the PSD of gamma-ray induced signal. We evaluated the pulse shape discrimination ability using a 252 Cf neutron source in order to obtain the optimal $t_{\text{fast.}}$ 283 284 Figure 9(a) shows the typical waveform acquired by APV8102-14MWPSAGb. Figure 9 (b) shows the pulse shape discrimination result of stilbene detectors at t_{fast} of 20 ns. We surveyed the pulse shape 285 286 discrimination ability as a function of t_{fast}. Here, we used the Figure of Merit (FOM) as an index of the 287 pulse shape discrimination ability. The FOM is defined as FOM= (PSD peak (neutron) -288 PSD peak(gamma-ray))/(FWHM(neutron)+FWHM(gamma-ray)), where FWHM indicates the full

width at half maximum. A non-zero FOM appears from t_{fast} of 17 ns, has a peak around 20 ns, and decreases from t_{fast} of 22 ns. It should be pointed out that no FOM was obtained when t_{fast} was less than 17 ns because only one peak appeared. Therefore, it is found that the optimal t_{fast} for this fast-

292 neutron detector is around 20 ns.

293

294 IV-2 PSD capability in high counting rate

295 The DD neutron measurement using the fast-neutron detector is performed using an accelerator-based neutron generator on the Fast Neutron Source (FNS) in the Japan Atomic Energy Agency³⁷. The DD 296 297 neutrons are generated due to the deuteron beam and the deuterium target reaction. The typical neutron emission rate from the target is 10⁹ neutrons per second. We used an x-axis stage (KXL06300³⁸, Suruga 298 299 Seiki CO.,LTD.) in order to change the neutron flux at the detector position by changing the distance 300 from the target to the detector. Note that the neutron flux at the detector position is from 2.5×10^6 cm⁻ 301 2 s⁻¹ to 2.2×10^{7} cm⁻²s⁻¹. The fast-neutron detector is placed in front of the DD neutron target. The energy 302 of the DD neutron is around 3 MeV. Figure 10 shows the two dimensional pulse shape discrimination 303 plot at the pulse counting rate of 108 kcps to 911 kcps. Here, the total number of pulses of each run 304 are 3×10⁶. Two peaks corresponding to the neutron and gamma-ray are clearly separated. It is 305 important to note that the pulse shape discrimination map does not change as expected from the 306 characteristics of the PMT gain stability reported in Sec II-2. Here, we can see several points on the

307	left and the right hand side of the two dimensional plot; this is due to the pile-up of pulses. The number
308	of these plots increases with the increase of the counting rate as expected by the simple pile up
309	calculation ($n/(1-nt_{pulse})$): <i>n</i> and t_{pulse} represent the counting rate of the pulse measured by the ADC and
310	the total width of the pulse, respectively. The larger PSD is obtained when the second pulse comes
311	after t_{fast} , whereas when the second pulse is coming before t_{fast} , the smaller PSD is obtained. The
312	number of pulses acquired by the DAQ as a function of the expected pulse counting rate evaluated by
313	the neutron flux is shown in Fig. 11. Here, we compared three different digitizers: DT5751 ³⁹ CAEN,
314	NI5772 ⁴⁰ +PXIe-7962R ⁴¹ National Instruments, and APV8102-14MWPSAGb Techno AP. DT5751
315	has 10 bits, 1 GHz, and 1 V_{pp} and only online analysis based on Q_{long} and Q_{short} is possible.
316	NI5772+PXIe-7962R reported in Ref. 23 has 12 bits, 1.6 GHz, equipped with 512 DDR2 SDRAM
317	memory and either online analysis or offline analysis (stored waveforms) is possible. It is should be
318	emphasized that those three DAQs acquire the periodic pulses with 10 ⁶ pulses per second without any
319	loss of pulses. The loss of pulses occurred when the expected counting rate was around 8×10^5 cps.
320	Here, the counting rate of the ADC compensates with simple pile-up theory. The pulse loss ratio of
321	DT5751, NI5772+PXIe-7962R, and APV8102-14MWPSAGb at 10 ⁶ cps are around 12 %, 16 %, and
322	8 %, respectively. It is found that the highest counting resistance among these three DAQs APV8102-
323	14MWPSAGb.

325 IV-3 Detection efficiency and detector response

326	The detection efficiency and the detector response of the fast-neutron detector are obtained at the Fast
327	Neutron Laboratory (FNL) ⁴² of Tohoku University, at FNS, and at the Intense 14 MeV Neutron Source
328	Facility (OKTAVIAN) ⁴³ of Osaka University. We used the p-Li reaction in order to produce neutrons
329	having an energy of 1.3 MeV in FNL, d-D reaction for 3 MeV neutrons in FNS, d-D reaction for 4.5
330	MeV to 5.7 MeV neutrons in FNL, and d-T reaction for 14 MeV neutrons in OKTAVIAN. Figure 12(a)
331	shows the pulse height spectra of the fast-neutron detector. Note that the threshold value in the case of
332	a neutron energy of 1.3 MeV and the threshold value in the other case are 10 mV and 30 mV,
333	respectively. The lower threshold value in the case of the neutron energy of 1.3 MeV is for observing
334	the response of the lower energy neutrons. Here, pulse height is evaluated by the waveform data. The
335	pulse height becomes larger with the increase of the neutron energy, as expected. Figure 12(b) shows
336	the maximum pulse height as a function of neutron energy. The plot shows that we can measure fast
337	neutrons having an energy of around 2 MeV if the threshold value is set to be 30 mV. We evaluated
338	the counting efficiency using an In foil in the FNS experiment. In this experiment, the In foil was
339	placed in front of the Stilbene detector and the time evolution of the neutron emission rate was
340	evaluated by a beam current monitor. Here, the distance between the deuterium target and the Stilbene
341	detector was 10 cm. It was found that the counting efficiency of the Stilbene detector is 0.06
342	counts/neutron/cm ⁻² , for 3 MeV neutrons with high voltage of 700 V and threshold setting of 30 mV.

344 V Typical data of the LHD experiment

345 Measurement of the time evolution of the neutron emission profile is performed in the LHD deuterium 346 operation (Fig. 13). In this discharge, B_t is 2.75 T and R_{ax} is 3.60 m. Electron cyclotron heating and a 347 negative-ion-based NB injection are started at the time t = 3.3 s. Thomson scattering diagnostics⁴⁴ 348 measure the central electron temperature and the line-averaged electron density is measured by an 349 interferometer⁴⁵. The total neutron emission rate (S_n) measured by the absolutely calibrated neutron flux monitor⁴⁶ gradually increases due to NB injections. Figure 14(a) shows the pulse shape 350 351 discrimination result of channel 4 (R of 3.63 m). The two peaks are clearly separated at a PSD of 0.175. 352 In this discharge, the number of neutron counts is 3500, whereas the number of gamma-ray counts is 353 17000. The time evolution of the line-integrated neutron profile shows almost a similar trend with S_n 354 as shown in Fig. 14(b). The neutron emission profiles are obtained in different $R_{\rm ax}$ configurations (Fig. 355 14 (c)). As R_{ax} shifts outward, neutron counts decrease due to the decrease of S_n . In addition, the peak 356 of the line-integrated neutron emission profile shifts outward with R_{ax} , as expected. We showed that 357 the VNC is installed with the desired performance. The VNC will be a powerful tool to measure the 358 neutron emission profile in LHD.

359

360 VI Summary

361	The vertical neutron camera characterized by high-counting rate capability is developed for LHD
362	deuterium operation in order to understand the beam ion behavior. A multichannel collimator was
363	constructed with hematite-doped heavy concrete. The magnetic shield is designed based on a finite
364	element method by considering the magnetic field strength at the VNC position. We experimentally
365	showed that the magnetic shield is manufactured according to the design requirements. The fast-
366	neutron detector composed of a stilbene scintillator characterized by high pulse shape discrimination
367	ability coupled with the PMT characterized by high gain stability equipped with external DC power
368	supplies for further improved gain stability were installed. The test of the high gain stability of the
369	PMT using an LED shows that external DC power supplies are effective for suppressing the gain
370	variation and the gain of the PMT is constant up to the pulse rate of 10^6 Hz. The DAQ composed of
371	the fast ADC and the novel logic circuit realized in the FPGA enable us to obtain data needed for
372	online and offline analysis simultaneously. The neutron measurement was performed on accelerators
373	using p-Li, d-D, and d-T reactions. It is found that the two dimensional pulse shape discrimination
374	map does not change even in the 10^6 cps region. The counting loss of the pulse under the 10^6 cps is
375	8 %, which is the smallest value compared with other digitizers like DT5751 and NI5772+PXIe-7962R.
376	The response of the fast-neutron detector shows that the detector can measure the neutron energy from
377	around 2 MeV when the discrimination level is set to be 30 mV. Initial measurement of the line-
378	integrated neutron emission profile was performed in LHD deuterium operation in order to check the

379	expected performance of the VNC. The time-resolved neutron emission profile has a time trend similar
380	to the total neutron emission rate. The typical neutron, gamma-ray ratio is 1:5 for the central channel.
381	The measurement of the neutron emission profile at R_{ax} of 3.60 m and of 3.90 m shows that the peak
382	of the line-integrated neutron emission profile shifts according to the R_{ax} position as expected.
383	
384	Acknowledgments
385	This research was supported by NIFS Collaboration Research programs (KOAH033), by the LHD
386	project budget (ULHH003, ULHH034, ULHH802, and ULGG801), and Japan/U.S. Cooperation in
387	Fusion Research and Development. One of the authors, K. Ogawa, is pleased to acknowledge the
388	assistance of LHD Experiment Group for assistance in installation and operation of the VNC;K.
389	Ochiai and the FNS team of National Institutes for Quantum and Radiological Science and
390	Technology, M. Miwa, S. Matsuyama, and the FNL team of Tohoku University, and I. Murata of the
391	OKTAVIAN team of Osaka University for assisting in obtaining the neutron detector response; H.
392	Tomita and A. Uritani of Nagoya University, S. Conroy, L. Giacomelli, and V. Kiptily of Culham
393	Centre for Fusion Energy, A. L. Roquemore and the late D. S. Darrow of Princeton Plasma Physics
394	Laboratory, G. Q. Zhong of the Chinese Institute of Plasma Physics, and T. Itoh of Kitano
395	Manufacturing Corp. in discussing the design of a multichannel collimator and detectors; T. Honda
396	and M. Goto of G-tech Corp. in discussing the PSD ability of the scintillator; A. Okada of

397	Hamamatsu Photonics K.K. in providing background knowledge of the photomultiplier; T. Takada of
398	National Institute of Technology, Ariake College and S. Yoshimura of National Institute for Fusion
399	Science in assisting with PMT test using LED; E. Takada of National Institute of Technology,
400	Toyama college, M. Riva, D. Marocco, B. Esposito, B. Francesco of the Italian National Agency for
401	New Technologies, Energy and Sustainable Economic Development in discussing the FPGA logic;
402	and Y. Endo, F. Watanabe, and Y. Arai of Techno AP for joint development of the FPGA circuit.

404 References

- 405 ¹O. N. Javis Plasma Phys. Control. Fusion **36** 209 (1994).
- ⁴06 ² J. D. Strachan, A. Bhattacharjee, D. J. Jassby, and H. H. Towner, Phys. Lett. **66A** 295 (1978).
- 407 ³A. L. Roquemore, R. C. Chouinard, M. Diesso, R. Palladino, J. D. Strachan, and G. D. Tait, Rev.
- 408 Sci. Instrum. **61** 3163 (1990).
- 409 ⁴A. L. Roquemore, M. Bitter, L. C. Johnson, and S. von Goeler, Rev. Sci. Instrum. **68** 544 (1997).
- 410 ⁵L. C. Johnson, Rev. Sci. Instrum. **63** 10 (1992).
- 411 ⁶J.M. Adams, O.N. Jarvis, G.J. Sadler, D.B. Syme, N. Watkins, Nucl. Instrum. Meth. A **329** 277
- 412 (1993).
- ⁴13 ⁷M. Riva, B. Esposito, D. Marocco, F. Belli, B. Syme, L. Giacomelli, Fus. Eng. and Design **86** 1191

414 (2011).

- 415 ⁸T. Craciunescu, G. Bonheure, V. Kiptily, A. Murari, S. Soare, I. Tiseanu, V. Zoita, and JET EFDA
- 416 Contributors, Nucl. Instrum. and Meth. A **595** 623 (2008).
- ⁹M. Ishikawa, T. Nishitani, A. Morioka, M. Takechi, K. Shinohara, M. Shimada, Y. Miura, M.
- 418 Nagami, and Yu. A. Kaschuc, Rev. Sci. Instum. 73 4237 (2002).
- ⁴¹⁹ ¹⁰M. Ishikawa, T. Itoga, T. Okuji, M. Nakhostin, K. Shinohara, T. Hayashi, A. Sukegawa, and M.
- 420 Baba, Rev. Sci. Instrum. 77 10E706 (2006).

- 421 ¹¹M. Ishikawa, M. Takechi, K. Shinohara, Y. Kusama, C.Z. Cheng, G. Matsunaga, Y. Todo, N.N.
- 422 Gorelenkov, G.J. Kramer, R. Nazikian, A. Fukuyama, V.A. Krasilnikov, Yu. Kashuck, T. Nishitani,
- 423 A. Morioka, M. Sasao, M. Isobe and the JT-60 team, Nucl. Fusion **45** 1474 (2005).
- 424 ¹²P. Batistoni, B. Esposito, M. Martone, and S. Mantovani, Rev. Sci. Instrum. **66** 4949 (1995).
- 425 ¹³M. Cecconello, M. Turnyanskiy, S. Conroy, G. Ericsson, E. Ronchi, S. Sangaroon, R. Akers, I.
- 426 Fitzgerald, A. Cullen, and M. Weiszflog, Rev. Sci. Instrum. 81 10D315 (2010).
- 427 ¹⁴Joung-Gu Kwak, H. S. Kim, M. S. Cheon, S. T. Oh, Y. S. Lee, T. Terzolo, and KSTAR team,
- 428 Fusion Eng. Des. **109-111** 608 (2016).
- 429 ¹⁵ Y. Izumi, H. Tomita, Y. Nakayama, S. Hayashi, K. Morishima, M. Isobe, M. S. Cheon, K. Ogawa,
- 430 T. Nishitani, T. Naka, T. Nakano, M. Nakamura, and T. Iguchi, Rev. Sci. Instrum. 87 11D840 (2016).
- 431 ¹⁶G. Q. Zhong, L. Q. Hu, N. Pu, R. J. Zhou, M. Xiao, H. R. Cao, Y. B. Zhu, K. Li, T. S. Fan, X. Y.
- 432 Peng, T. F. Du, L. J. Ge, J. Huang, G. S. Xu, B. N. Wan, EAST Team, Rev. Sci. Instrum. 87 11D820
- 433 (2016).
- 434 ¹⁷Y. P. Zhang, J. W. Yang, Yi Liu, T. S. Fan, X. B. Luo, G. L. Yuan, P. F. Zhang, X. F. Xie, X. Y.
- 435 Song, W. Chen, X. Q. Ji, X. Li, T. F. Du, L. J. Ge, B. Z. Fu, M. Isobe, X. M. Song, Z. B. Shi, Q. W.
- 436 Yang, X. R. Duan, Rev. Sci. Instrum. 87 063503 (2016).
- 437 ¹⁸W. J. Capecchi, J. K. Anderson, P. J. Bonofiglo, J. Kim, S. Sears, Rev. Sci. Instrum. **87** 11D826
- 438 (2016).

- 439 ¹⁹M. Cecconello, S. Sangaroon, M. Turnyanskiy, S. Conroy, I. Wodniak, R.J. Akers, G. Ericsson and
- 440 the MAST Team, Nucl. Fusion **52** 094015 (2012).
- ²⁰L. Giacomelli, A. Hjalmarsson, H. Sjostrand, W. Glasser, J. Kallne, S. Conroy, G. Ericsson, M.
- 442 Gatu Johnson, G. Gorini, H. Henriksson, S. Popovichev, E. Ronchi, J. Sousa, E. Sunden Andersson,
- 443 M. Tardocchi, J. Thun, M. Weiszflog and Contributors to the JET-EFDA Workprogram, Nucl. Fusion
- **4**44 **45** 1191 (2005).
- ²¹D. Marocco, B. Esposito and F. Moro, JINST **7** C03033 (2012).
- 446 ²²M. Sasao, M. Isobe, M. Osakabe, A. Taniike, T. Iguchi, H. Takada, T. Iida, and M. Wada, Fusion
- 447 Eng. Design **34** 595 (1997).
- 448 ²³X-5 Monte Carlo Team, "MCNP A General N-Particle Transport Code, Version 5", Volume I:
- 449 Overview and Theory LA-UR-03-1987 (2003, updated 2005).
- 450 ²⁴M. Isobe, H. Yamanishi, M. Osakabe, H. Miyake, H. Tomita, K. Watanabe, H. Iwai, Y. Nomura, N.
- 451 Nishio, K. Ishii, J. H. Kaneko, J. Kawarabayashi, E. Takada, A. Uritani, M. Sasao, T. Iguchi, Y.
- 452 Takeiri, and H. Yamada, Rev. Sci. Instrum. **81** 10D310 (2010).
- 453 ²⁵K. Ogawa, M. Isobe, E. Takada, Y. Uchida, K. Ochiai, H. Tomita, A. Uritani, T. Kobuchi, and Y.
- 454 Takeiri, Rev. Sci. Instrum **85** 11E110 (2014).
- 455 ²⁶H. Kawase et al., accepted for publication in IEEE transaction of plasma physics
- 456 ²⁷https://www.hamamatsu.com/resources/pdf/etd/R11265U_H11934_TPMH1336E.pdf

- 457 ²⁸http://www.hongsencable.com/pdf/01714670.pdf
- 458 ²⁹https://www.tek.com/datasheet/digital-phosphor-oscilloscopes
- 459 ³⁰http://www.techno-ap.com/img/APV8102_14MWPSAGb.pdf
- 460 ³¹http://www.techno-ap.com/img/APV3304.pdf
- 461 ³²https://www.matsusada.com/product/psel/dcps/handy/000002/
- 462 ³³http://netgear.com/business/products/switches/smart/XS712T.aspx
- 463 ³⁴M. Y. Tanaka, M. Aramaki, K. Ogiwara, S. Etoh, S. Yoshimura, and J. Varanjes., AIP Conference
- 464 Proceedings **1061** 57 (2008).
- 465 ³⁵https://www.nfcorp.co.jp/english/sup/dl/manual/mi/e_wf1946b.pdf
- 466 ³⁶K. Ishii, K. Shinohara, M. Ishikawa, M. Baba, M. Isobe, A. Okamoto, S. Kitajima, and M. Sasao,
- 467 Rev. Sci. Instum. **81** 10D334 (2010).
- 468 ³⁷C. Konno, Compendium of Neutron Beam Facilities for High Precision Nuclear Data
- 469 Measurements IAEA-TECDOC-1743 (Vienna: IAEA) pp 110–18 (https://www-
- 470 nds.iaea.org/publications/tecdocs/iaea-tecdoc-1743/) (2014).
- 471 ³⁸https://eng.surugaseiki.com/Products/spec/Motorized+Stage/Motorized+Linear+Stage/X-
- 472 Axis+Motorized+Stage/KXL06300/KXL06300-N2-F3C/pkey:X-
- 473 Axis%20Motorized%20Stage%20%E2%96%A160
- 474 ³⁹http://www.caen.it/csite/CaenProd.jsp?parent=14&idmod=632

- 475 ⁴⁰http://www.ni.com/ja-jp/support/model.ni-5772.html
- 476 ⁴¹http://www.ni.com/ja-jp/support/model.pxie-7962.html
- 477 ⁴²M. Baba, M. Takada, T. Iwasaki, S. Matsuyama, T. Nakamura, H. Ohguchi, T. Nakano, T. Sanami,
- 478 and N. Hirakawa, Nucl. Instrum. Methods Phys. Res. A 376 115 (1996).
- ⁴³I. Murata Compendium of Neutron Beam Facilities for High Precision Nuclear Data Measurements
- 480 IAEA-TECDOC-1743 (Vienna: IAEA) pp 110–18 (https://www-
- 481 nds.iaea.org/publications/tecdocs/iaea-tecdoc-1743/) (2014).
- 482 ⁴⁴I. Yamada, K. Narihara, H. Funaba, T. Minami, H. Hayashi, T. Kohmoto and LHD Experiment
- 483 Group, Fusion Sci. Technol. **58** 353 (2010).
- 484 ⁴⁵T. Akiyama et al., Fusion Sci. Technol. **58** 345 (2010).
- 485 ⁴⁶M. Isobe et al., Rev. Sci. Instrum. **85** 11E114 (2014).

Chemical composition	Weight ratio (%)
H ₂ O	3.3
SiO ₂	1.2
Al ₂ O ₃	0.28
Fe ₂ O ₃	91
CaO	3.8
MgO	0.084
SO ₃	0.17
Na ₂ O	0.015
K ₂ O	0.022
Cl	0.00029

487 Table 1 Weight ratio of heavy concrete material



491 Fig.1 Schematic drawing of LHD vertical neutron camera

LHD center -0 ICF70 port (thickness of 2 mm in central part) 1 m Floor concrete Heavy concrete (>3.5 g/cm³) (~2 g/cm3) Stainless pipes (inner diameter of 30 mm) 1.5 m Collimator units filled with heavy concrete 2 m -8 æ Collimator support Lead Hole (h of 150 mm) Scintillation detectors ΗL H Н

495 Fig.2 Schematic of the ports, the multichannel collimator, and the detector support of LHD VNC.

496



498 Fig.3 Sight lines of VNC and poloidal cross section of plasma with R_{ax} of 3.60 m and 3.90 m with zero

499 beta. The diameter of each sight line is 88 mm at Z of -0.9 m and 110 mm at Z of 0.9 m.





502 Fig.4 (a) Electronic schematic of VNC. All the electrical components are externally controllable. (b)

503 Pulse height and pulse width as a function of cable length.



506 Fig.5 Schematic drawing of the fast-neutron detector.



Fig.6 (a) Typical profile of magnetic field strength at the vertically elongated cross section in LHD where B_t , R_{ax} , Z, and R represent the toroidal magnetic field strength, the plasma major radius, the height from the plasma plane, the major radius from the machine center, respectively. The dashed line shows the location of fast-neutron detectors. (b) Test of the magnetic shield in HYPER-I. The dashed line shows the magnetic field strength at the fast-neutron detector position. The magnetic shield has sufficient performance as designed.



516 Fig. 7 Result of gain stability. The gain of PMT is not changed even at 10^6 cps with external DC

517 power supplies.







521 stored in the internal memory and transferred after the discharge.

(a)



Fig. 9 (a) Typical signal of the fast-neutron detector induced by fast-neutron and gamma-ray. The
decay time of the signal is longer in the fast-neutron case compared with gamma-rays. (b) Typical
one-dimensional histogram of pulse shape discrimination for stilbene detector. (c) Pulse shape

527 discrimination ability as a function of t_{fast} . The highest FoM is obtained at a t_{fast} of around 20 ns.



529 Fig. 10 Two dimensional pulse shape discrimination plots in different counting rates obtained in the





533 Fig. 11 Pulse counting rate obtained with DAQ as a function of expected counting rate evaluated by

the neutron flux at the detector position in the FNS. The counting loss ratio of APV8102-





537 Fig. 12 (a) Pulse height spectra obtained at the neutron energy of 1.3 MeV, 3.0 MeV, 4.5 MeV, 5.7

538 MeV, and 14 MeV. (b) The maximum pulse height as a function of neutron energy. The pulse height

539 monotonically increases with neutron energy as expected.

540

536



543 Fig. 13 Typical time trace of electron cyclotron heated (ECH) and negative-ion-based neutral beam

544 (N-NB) injected plasma discharge.



547 Fig. 14 (a) Typical two-dimensional pulse shape discrimination plot obtained in the LHD



- 549 integrated neutron emission profile obtained at R_{ax} of 3.60 m and 3.90 m. Number of neutron count
- be decreases with the outward shift of R_{ax} which is consistent with the total neutron emission rate
- 551 measurement. The peak position of the profile shifted outward with R_{ax} as expected.
- 552

553 Appendix1

(a)





554

555 Fig. 15 (a) Three multichannel collimator units. (b) The multichannel collimator made in the LHD

556 torus hall.