

# Coherent Radiation Spectrum Measurements at KEK LUCX Facility

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## Abstract

In this paper we demonstrate the detailed design concept, alignment and initial test of a Michelson interferometer for THz spectral range. The first coherent transition radiation spectrum measurement results and ultra-fast broadband room temperature Schottky barrier diode detectors performance are presented. The main criteria of interferometer beam splitter optimization, motion system high precision calibration and its linearity check as well as alignment technique are discussed.

*Keywords:* Coherent transition radiation, THz radiation, Michelson interferometer

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## 1. Introduction

In the last decade electromagnetic radiation in the terahertz frequency domain has started playing a key role in different applications ranging from material and biomedical science to quality control and national security [1, 2, 3, 4, 5]. Recent advances in these studies have encouraged an interest in investigation and development of THz radiation generation methods. One of the research directions in THz science and technology [6, 7, 8] is to generate short and high-brightness THz-frequency coherent radiation pulses

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9 using ultra-short electron bunches of a compact accelerator. The intensity  
10 of this radiation is proportional to the square of the beam current. For a  
11 stable THz emission one should consider generation of electron bunches with  
12 the duration smaller than 100 fs (about 30  $\mu\text{m}$ ) and the intensity stability  
13 of  $< 1\%$  rms. One possibility to obtain such short electron bunches is to  
14 illuminate a photo-cathode of an RF-Gun with a femtosecond laser pulse. In  
15 this case a well-established on-line diagnostics and control of both the laser  
16 and the electron beams are needed. Recent progress in laser technology and  
17 ultra-short laser pulse diagnostics [9, 10] gives promising results whereas re-  
18 liable methods for determination of femtosecond electron bunches still have  
19 to be developed. A streak camera [11] can provide about 300 fs resolution  
20 which is not applicable in this case. On the other hand deflecting cavity  
21 [12, 13, 14] can give required resolution but it makes an inadmissible prob-  
22 lem for a “table-top” accelerator based THz source design since the change  
23 related to accelerator high power RF distribution system and a significant  
24 beamline space allocation are required for the installation. Alternatively  
25 Electro-Optic methods for longitudinal bunch diagnostics [15] requires com-  
26 plex apparatus involvement and careful calibration.

27 Another promising technique for longitudinal bunch shape reconstruction  
28 is based on the coherent radiation spectral density distribution measurement  
29 [16, 17, 18, 19, 20]. Unfortunately this method is likely to have some restric-  
30 tions and limitations which should be considered in detail to push forward a  
31 progress in this direction.

32 As a potential candidate for spectrometry of the intense broadband radi-  
33 ation in THz and sub-THz frequency range and for longitudinal bunch shape  
34 reconstruction the Michelson interferometer (MI) was constructed as a part  
35 of a larger THz program launched at KEK LUCX (Laser Undulator Compton  
36 X-ray) facility [21, 22, 23]. The program aims to investigate various mecha-  
37 nisms for generating EM radiation including stimulated coherent diffraction  
38 radiation, undulator radiation, Smith-Purcell radiation and other types of  
39 polarization radiation.

40 In this paper we demonstrate a detailed design concept, alignment and  
41 initial MI test for the THz spectral range. The first coherent transition  
42 radiation spectrum measurement results and the ultra-fast broadband room  
43 temperature Schottky barrier diode detector performance are presented.

44 **2. Michelson interferometer for THz spectral range**

45 The MI is the most common configuration for optical interferometry  
 46 which can be extended to a long wavelength range including THz and IR  
 47 [16, 24]. Its design is much simpler than so-called Martin-Puplett interfer-  
 48 ometer [25, 26, 27, 28] since only one detector is required and no wire grid  
 49 polarizers are used. Also it does not require any special alignment techniques  
 50 what significantly increases measurements quality. Moreover the same inter-  
 51 ferometer can be aligned with optical wavelengths and used for THz spec-  
 52 troscopy with only beam splitter (BS) replacement. A general MI layout for  
 53 THz spectral measurements is given in Fig.1.

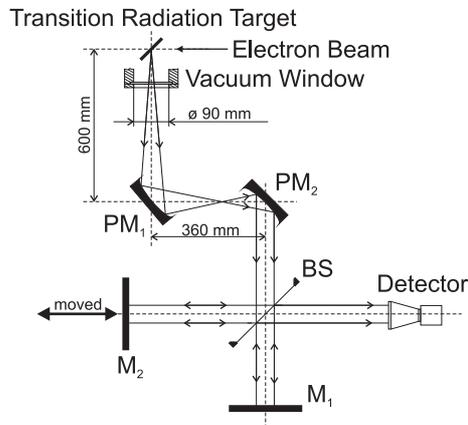


Figure 1: General layout of Michelson interferometer and THz radiation transport line.

54 An interference pattern is produced by splitting a beam of light into  
 55 two paths, reflecting beams back and recombining them through the splitter  
 56 again. The setup consists of a THz radiation transport line (RTL), beam  
 57 splitter (BS), two interferometer arms formed by two flat aluminum mirrors  
 58 (M1 and motorized M2 mirror), alignment system, THz polarizer and the  
 59 detector. The incident THz wave propagates through the vacuum window  
 60 (VW) and RTL, which consists of two off-axis parabolic mirrors (PM1 and  
 61 PM2). After that it is divided by the BS so that one half of the incoming in-  
 62 tensity is transmitted through BS towards M1 and the other half is reflected  
 63 from BS towards M2. The BS was installed at the center of the interfer-  
 64 ometer at 45 degree with respect to the radiation beam axis. The radiation  
 65 beams are then reflected by the flat mirrors (M1 and M2) and reach the  
 66 beam splitter again. To acquire autocorrelation dependence (interferogram),

67 the mirror (M2) was moved along the optical axis of the interferometer per-  
68 pendicular arm back and forth. The flat optical-grade 100 mm diameter,  
69 15 mm thickness and  $\lambda/4$  surface flatness aluminum mirrors (Sigma-koki  
70 TFAN-100C15-4) were used along with optical mirror mounts (Sigma-koki  
71 MHA-100S [29]). The distance between the BS and the fixed mirror M1 was  
72 200 mm. The main MI components including BS, motion system, alignment  
73 system and the THz detection system will be presented in details below.

### 74 *2.1. Beam splitter*

75 Beam splitter determines the intensity and polarization features of the  
76 radiation for both arms of the interferometer which influences the quality  
77 of the interferogram. In modern MIs polyethylene terephthalate (PET or  
78 Mylar) beam splitters are widely used. The Maylar is commercially available.  
79 However, the efficiency of PET beam splitters strongly depends on thickness  
80 and radiation wavelength therefore for a wide-spectrum study usually a set of  
81 Maylar splitters is needed [30]. Recently it has been shown that the Silicon  
82 splitter efficiency is much higher than for the PET splitters in terahertz  
83 region [31]. Silicon is a well-known material. It has a negligible absorption  
84 coefficient and high refractive index in broadband THz range [32, 33]. It is  
85 important to point out that the theoretical efficiency for a beam splitter is  
86 given by  $\varepsilon = 4R_0T_0$ , where  $R_0$  and  $T_0$  are the reflectance and transmittance  
87 of the beam splitter which are the functions of incident angle, refractive index  
88 and a thickness of a splitter [34]. The maximum efficiency can be obtained  
89 when  $R_0 = T_0 = 0.5$ , in this case  $\varepsilon = 1$ .

90 The main criteria of beam splitter optimization in our case were the high  
91 efficiency for both components of polarization in THz range and splitter  
92 handling simplicity. In order to simplify alignment of the interferometer the  
93 radiation incidence angle was chosen to be 45 degree. In Fig.2 the dependence  
94 of the beam splitter efficiency for both components of polarization on the  
95 radiation frequency is presented.

96 As can be seen from the figure in case when the silicon splitter thickness  
97 is several hundred micrometers, the beam splitter efficiency curve has many  
98 closely spaced cycles (as shown on Fig.2). What affects spectrum measure-  
99 ments and should be taken into account for high resolution spectroscopy.  
100 In other words the frequencies which have very low beam splitter efficiencies  
101 are excluded from interference and hence do not appears in the reconstructed  
102 spectrum. However, if the spectrometer resolution is less than the cycle's pe-  
103 riod, the only average beam splitter response will be observed. So the best

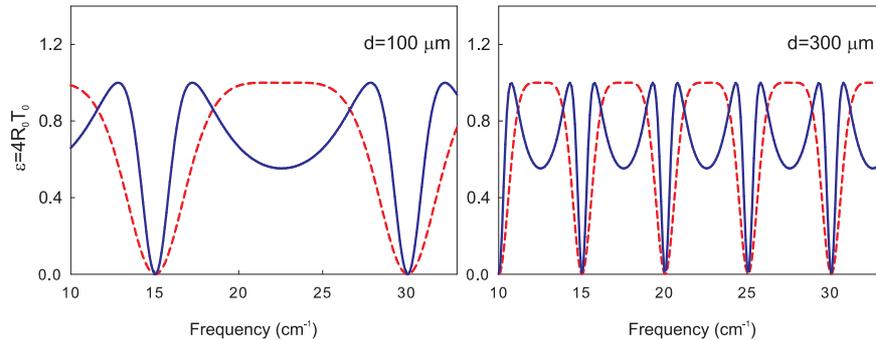


Figure 2: Variation in the efficiency of 100  $\mu\text{m}$  and 300  $\mu\text{m}$  silicon beam splitters as a function of wavenumber for s- and p-polarized radiation (solid and dashed curves, respectively).

104 way to measure broadband spectrum with high resolution is to have a set of  
 105 splitters with different thickness.

106 In our experiment we have used commercially available  $300 \pm 10 \mu\text{m}$   
 107 thick,  $150 \pm 0.5 \text{ mm}$  diameter n-type (Boron doped) Si plate, which has  
 108 two polished surfaces. The chemical polishing technique provides the surface  
 109 roughness much less than a radiation wavelength, what is far below tolerance  
 110 requirements. The splitter smooth edges allows to decrease influence of the  
 111 diffraction effect onto measured autocorrelation dependence.

## 112 2.2. Motion system

113 Motion system directly affects spectral measurements quality. It should  
 114 have sufficient mechanical resolution, stability, repeatability and compatibil-  
 115 ity with modern hardware and software controllers. Moreover it should be  
 116 calibrated and its linearity should be checked with high precision.

117 To estimate mechanical resolution and travel range of the motion system,  
 118 required to measure a certain frequency spectrum with a MI, one should  
 119 consider target spectral resolution and radiation spectral bandwidth. To be  
 120 able to determine radiation spectrum in a range of  $0.1 - 4 \text{ THz}$  with  $10 \text{ GHz}$   
 121 resolution one need to consider a motion system with  $19.2 \mu\text{m}$  resolution and  
 122  $15 \text{ mm}$  minimal travel range

123 The ultra-high precision Kohzu YA16A-R1 stepping motor-powered,  $0.1 \mu\text{m}$   
 124 resolution linear stage based on cross-roller guide with ground-screw lead  
 125 mechanism [35] was chosen to design a movable arm of the interferometer.  
 126 The stage was equipped with a non-contact incremental optical linear en-

127 coder (Renishaw RGH24 [36]) with 50 nm resolution. Such high resolution  
 128 has enabled us to control the mirror M2 position even when we perform  
 129 alignment of the interferometer with the 632 nm wavelength laser.

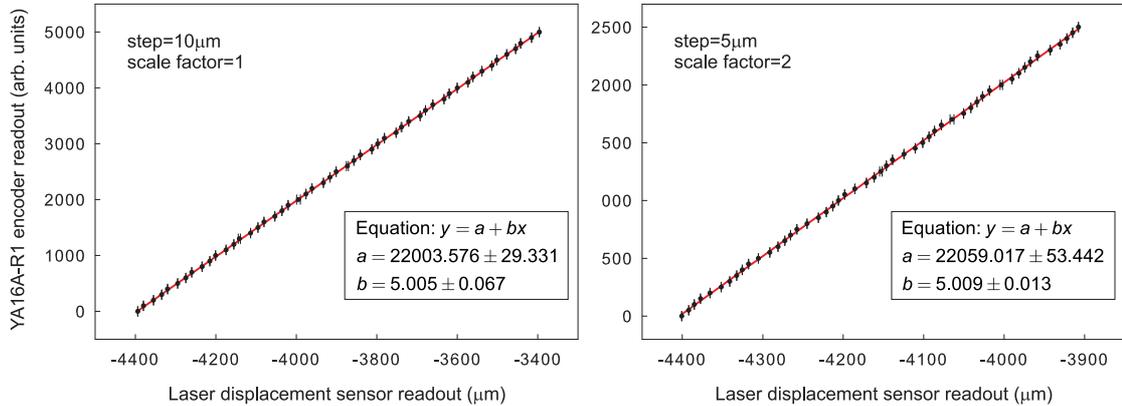


Figure 3: Typical calibration curves of motorized stage for different steps and scale factors.

130 The motor was controlled by an industrial-grade Oriental Motor CRK-  
 131 series controller [37] in the open-loop mode (i.e. with no feedback). It has  
 132 a simple programmable interface via RS-485 communication protocol and  
 133 allows daisy-chain of up to 32 motion controllers, what makes it unifying  
 134 solution for the LUCX THz program where many other motion mechanisms  
 135 are foreseen. The controller supports micro-step motor operation mode so  
 136 it is possible to change the real motor step angle by changing number of  
 137 micro-steps per step. In this case the motor's base step angle should be di-  
 138 vided by a corresponding scale factor. If the base step angle of the motor  
 139 is 0.72 degree/step the value of the scale factor could be changed from 1 to  
 140 250 that corresponds to 0.72 degree/step and 0.00288 degree/step respec-  
 141 tively. In this case the actual resolution of the motion system is determined  
 142 by a combination of mechanical resolution of the linear stage, stepping motor  
 143 quality/grade and electrical noise in the motion controller/driver. In order  
 144 to verify resultant resolution, stability and backlash the constructed mo-  
 145 tion system was cross-calibrated against Keyence LK-G30 [38] high-accuracy  
 146 CCD-laser displacement sensor, which has 0.01  $\mu\text{m}$  absolute resolution and  
 147  $\pm 0.05\%$  linearity. The results of the high precision motorized stage calibra-  
 148 tion for different scale factors are presented in Fig.3.

149 As expected, the linearity of the calibration curves does not change for dif-  
 150 ferent scale factors. The 0.2  $\mu\text{m}$  resolution in micro-step mode was observed

151 when the scale factor was equal to 20. The backlash value was measured to  
152 be less than  $0.5 \mu\text{m}$ .

### 153 *2.3. Alignment system*

154 The microwave interferometers are rather sensitive for alignment, espe-  
155 cially when they are operated in THz frequency range. In this case the  
156 alignment accuracy scales with the radiation wavelength and the intricacy  
157 level of alignment is increased. Inaccurate adjustment of any element could  
158 cause to variation of the light path. It implies the quality degradation of  
159 the recorded autocorrelation. There are two effects that tend to degrade the  
160 modulation intensity: mirror misalignment and non-parallel incoming radi-  
161 ation beam, i.e. when two beam splitting take place at different positions  
162 on the BS causing degradation of the phase map of the wavefront and, as  
163 a result, the measured autocorrelation. The combined effect also leads to  
164 interferogram asymmetry as well as to a degradation of modulation intensity  
165 [39].

166 There are two common alignment techniques which are widely used for  
167 opto-mechanical systems alignment and can be directly applied for THz in-  
168 terferometer: geometrical referencing and “cold-test” alignment. First one  
169 includes just geometrical alignment of the optical elements (or its holders)  
170 with respect to known mechanical references with the help of a standard  
171 alignment tools like levels, scales, measures, etc. The “cold-test” is in fact  
172 more accurate technique which requires to substitute an actual radiation  
173 beam with the test source beam to perform alignment or even calibration of  
174 the system. Unfortunately THz test sources are quite expensive and require  
175 additional care significantly increasing overall system complexity. Also it is  
176 always preferable to have compact and build-in alignment system for a quick  
177 and high quality system justification.

178 We decided to use helium-neon laser (NEC GLG 5240) as a primary align-  
179 ment tool. A special interferometer splitter base magnetic mounting pairs  
180 were ordered to be able to replace Si splitter with an optical splitter (Sigma-  
181 koki CSMH 40-550) without disturbing its angular alignment with respect  
182 to interferometer axes. The additional periscope and a defocusing system  
183 for alignment laser were also introduced. The unpolished side of the optical  
184 splitter (OS) was used as a screen for visual control of the interferometer  
185 alignment.

186 The goal of the high precision alignment was to observe the interference  
187 fringe pattern produced by the He-Ne laser light on the unpolished side of the

188 OS. Similar to the description in the beginning of the section, alignment laser  
 189 beam was splitted in two path and the splitted beams were directed towards  
 190 the screen, interfered and produced a fringe pattern [40]. This pattern was  
 191 used for precise interferometer axis and mirrors angular misalignment checks,  
 192 Fig.4.

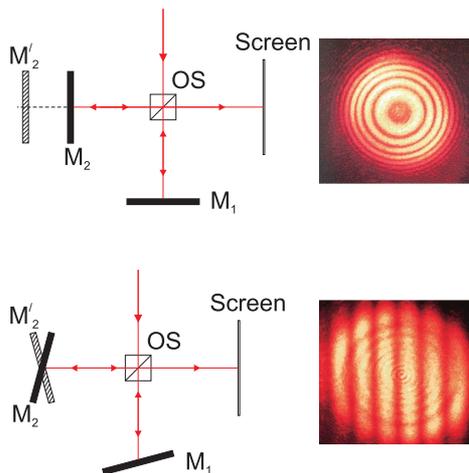


Figure 4: Formation scheme of fringes in MI (left) and the obtained fringe pattern photograph (right).

193 A half of the initial alignment laser beam returns back from the inter-  
 194 ferometer and travels through the THz transport line and vacuum window  
 195 of the LUCX electron beam line. Thus the alignment scheme also allows to  
 196 verify that main interferometer optical axis is parallel to the emission axis of  
 197 the THz radiation generated by the electron beam.

198 After that OS with half of the magnetic mount was replaced with Si  
 199 splitter on another half of the magnetic mount and reflection path was re-  
 200 checked.

#### 201 2.4. Schottky-barrier diode detectors

202 To detect the far-infrared coherent radiation, two different ultra-fast highly  
 203 sensitive room-temperature detectors were used. The first was a Schottky  
 204 Barrier Diode (SBD) detector with the rated frequency response range of  
 205 60 – 90 GHz [41]. The second was a Quasi-Optical Broadband Detector  
 206 (QOD) based on Schottky Diode with folded dipole antenna with the fre-  
 207 quency response range of 100 – 1000 GHz [42]. The basic parameters of  
 208 these detectors are listed in Table 1.

209 The Schottky diode detectors have a long history in electromagnetic ra-  
 210 diation detection in the range from millimetre to THz waves. These are the  
 211 rectifier-type detection devices, which normally consist of metallic contact  
 212 layer deposited on a lightly doped semiconductor material grown on a heav-  
 213 ily doped conducting substrate [43]. At incoming EM wave the electrons  
 214 of the epitaxial layer can cross the depletion barrier formed in the vicinity  
 215 of the metal, causing current to flow in the device by two processes: ther-  
 216 mal activation over the barrier or quantum-mechanical tunneling through  
 217 the barrier. For Schottky-barrier diode detectors operated at room temper-  
 218 ature, thermionic effects are dominant [44]. By its nature, such a devices  
 219 have very short response time because it uses majority-carrier current flow  
 220 and the recovery time associated with minority-carrier injection is absent  
 221 [45, 46]. Detectors have rather flat frequency response, as their sensitivity  
 222 shows minor variation over the entire wave band. As already mentioned, a  
 223 detector operation at ambient temperature and an extremely fast response  
 224 time make Schottky-barrier diode detectors more attractive in comparison  
 225 with other room temperature detectors, such as Golay cells or pyroelectric  
 226 detectors[47, 48, 49].

Detector	Parameter	Value
Schottky Barrier Diode detector	Frequency Range	60 – 90 GHz
	Wavelength range	3.33 – 5 mm
	Response Time	~ 250 ps
	Antenna Gain	24 dB
	Input Aperture	30 × 23 mm
	Video Sensitivity	20 mV/mW
Schottky Diode Quasi-Optical detector	Frequency Range	0.1 – 1 THz
	Wavelength Range	0.3 – 3 mm
	Response Time	Sub-ns
	Antenna directivity	25 – 35 dB
	Video Sensitivity	500 V/W

Table 1: Parameters of Schottky Diode detectors.

227 The QOD is a relatively new product on the market. To our knowledge  
 228 this is its first experimental performance verification for short-pulse coher-  
 229 ent radiation detection. It is important to mention that the detector outer  
 230 dimensions and apertures were different since SBD was used with  $22 \times 14$

231 mm aperture gain horn antenna and QOD was, by default, equipped with a  
 232 10 mm diameter Si lens. Nevertheless custom detector holders were used in  
 233 order to keep both of them at the same centreline while testing.

234 The SBD and QOD signals were acquired synchronously with Inductive  
 235 Current Transformer signal by a 1 GHz bandwidth, 5 GS/s Tektronix 685C  
 236 Oscilloscope.

### 237 3. Experimental setup

238 For initial MI trial a test setup at KEK LUCX facility was constructed.  
 239 The interferometer was set to measure coherent transition radiation (CTR)  
 240 spectrum generated from one of the standard LUCX screen monitor. When  
 241 the electron beam with parameters summarized in Table 2 passes through  
 242 the center of the  $50 \times 50$  mm aluminium plate oriented at 45 degrees with  
 243 respect to the beam line it generates backward CTR with broad spectrum  
 244 [50, 51]. The radiation propagates through a 90 mm (clear aperture) z-cut  
 245 crystalline quartz vacuum window and is transported by a pair of the off-  
 246 axis parabolic mirrors to the MI as shown in Fig.1. The photograph of the  
 247 experimental setup is shown in Fig.5.

Parameter	Value
Beam Energy	8 MeV
Intensity/bunch, typ.	1 nC
Bunch length, max	10 ps
Bunch length, min	50 fs
Repetition rate, max	12.5 train/sec
Normalized emittance, typ	$4.7 \times 6.5 \pi$ mm mrad

Table 2: LUCX, RF Gun section beam parameters.

248 For infrared applications quasi-optical lenses made of low-loss materials  
 249 like polyethylene, polypropylene or Teflon are frequently used for the pur-  
 250 pose of focusing nearly parallel beams or for parallelizing light from a point  
 251 source. Parabolic mirrors have certain advantages over these diffractive ele-  
 252 ments that make them indispensable especially for the use with far-infrared  
 253 radiation. Firstly, a very good reflectivity of polished metal surface prevents  
 254 absorption losses that inevitably occur in any lens material. Secondly, chro-  
 255 matic aberration does not appear, so the focal point is the same for light of  
 256 all wavelengths [17].

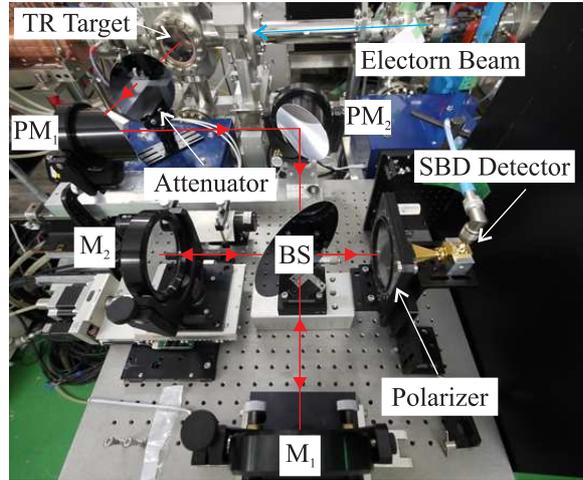


Figure 5: The photograph of the experimental arrangement.

257 In our case RTL consisted of a pair of 90 degrees off-axis parabolic mirrors.  
 258 It was designed to form a parallel THz radiation beam without introducing  
 259 any spectral distortions. The distance between parabolic mirrors defined by  
 260 the divergence of the initial beam was simulated by Zemax software which  
 261 allows to design, analyse and optimize different optical system for broad area  
 262 of applications [52]. The commercially available  $101.6 \times 76.2$  mm 90 degree  
 263 off-axis alumina parabolic mirrors [53] with 152.4 mm effective focal length  
 264 were used. The angle of transition radiation divergence is determined by  
 265 the charged particle beam energy as  $\gamma^{-1}$ , where  $\gamma$  is the Lorentz-factor of  
 266 the charge. The distance between radiation source and the first parabolic  
 267 mirror could not be shorter than 600 mm due to supporting equipment allo-  
 268 cation near the test setup. Thus we optimized only the distance between the  
 269 parabolic mirrors. The main simulation quality criteria were the dimension  
 270 of the final beam spot and its divergence throughout the RTL. The best re-  
 271 sult was obtained when the distance between off-axis parabolic mirrors was  
 272 equal to 360 mm (see Fig.1). Thereby the overall acceptance angle of the  
 273 spectrometer system is determined by the position of the first parabolic mir-  
 274 ror (PM1) against the radiation source which was about 0.1 rad for both,  
 275 horizontal and vertical directions.

276 **4. Experimental results**

277 Experimental investigation was done using a step-by-step approach and  
 278 pursues several goals: QOD signal check, QOD and SBD polarization sen-  
 279 sitivity and linearity tests, narrowband and broadband spectrum measure-  
 280 ments. SBD signal level, polarization sensitivity and linearity check were  
 281 previously performed in the course of a different experiment [22, 54] and  
 282 were repeated here for a reference.

283 The detector polarization sensitivity, linearity and the saturation thresh-  
 284 old are important parameters to obtain reliable experimental data. To inves-  
 285 tigate these detector characteristics the wire grid polarizers are usually used,  
 286 since they are simple and reliable components which responds to just one  
 287 polarization and are limited to radiation frequency which depends on size of  
 288 wires and grid period [55, 56]. To evaluate polarization sensitivity of these  
 289 detectors, 60  $\mu\text{m}$  wire spacing and 15  $\mu\text{m}$  wire diameter polarizer [57] with  
 290 a slight tilt with respect to the radiation propagation path was installed in  
 291 front of the detector. Using the same experimental setup and electron beam  
 292 condition the signal for both horizontal and vertical SBD detector orienta-  
 293 tions was observed. From the oscilloscope traces shown in Fig.6 it is clear  
 294 that the SBD detector is polarization sensitive. As expected QOD does not  
 295 show such strong polarization sensitivity since the folded dipole antenna is  
 296 much less sensitive for EM radiation polarization than the waveguide taper  
 297 transformer of the SBD [58].

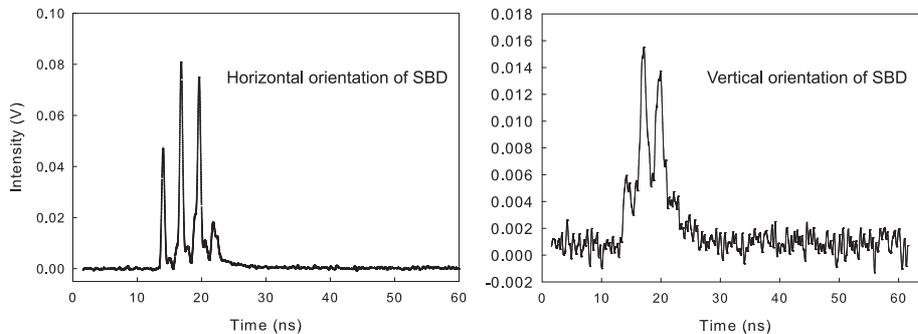


Figure 6: Observed signal for horizontal (right) and vertical (left) orientation of Schottky Barrier Diode Detector.

298 The QOD detector was equipped with an external RF circuit since it is  
 299 susceptible to damaging electrostatic discharge (ESD) from the peripherals.  
 300 However, the addition of an external protection device can slow the detector

301 responsivity, leaving researchers with a need to balance the safety of the  
 302 device and the measurement accuracy. To demonstrate the ESD protection  
 303 circuit effect onto the QOD signal two sets of data with and without the ESD  
 304 protection (see Fig.7) were taken for the same experimental conditions. The  
 305 QOD signal measured without external ESD protection shows much faster  
 306 response with almost the same signal intensity.

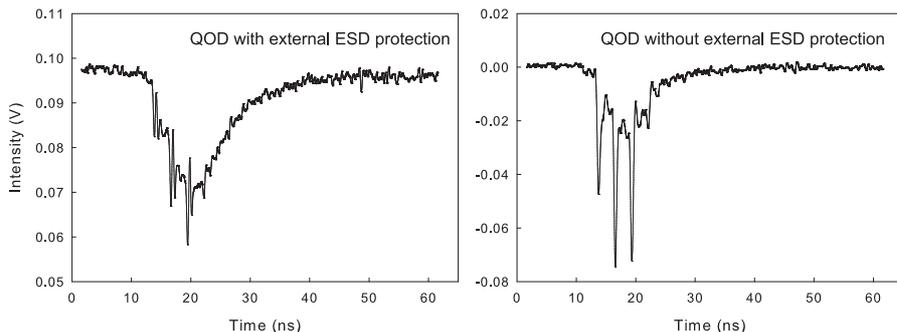


Figure 7: Observed signal of Quasi-Optical Broadband Detector with (right) and without (left) the ESD protection circuit.

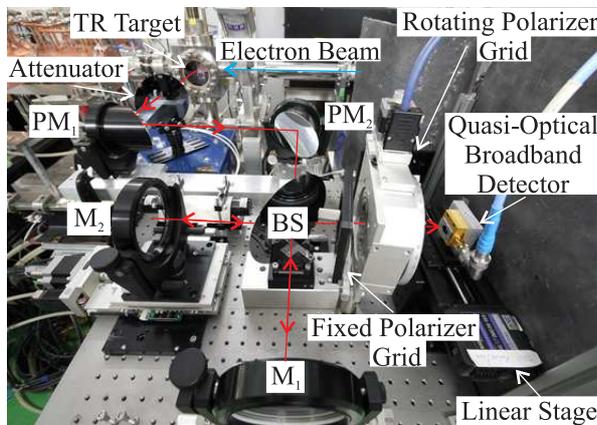


Figure 8: The photograph of the wire grid polarizers installation for linearity tests of SBD and QOD detectors.

307 The tests of the SBD and QOD detectors linearity were performed by  
 308 placing two wire grid polarizers in front of the transition radiation source.  
 309 The first polarizer was fixed and used to transmit one linear polarization

310 at a time. The second polarizer was installed into remotely controlled mo-  
 311 torized rotation stage (the arrangement of polarizers is illustrated in Fig.8).  
 312 To check detectors linearity the dependence of horizontally polarized radi-  
 313 ation intensity as a function of the motorized polarizer orientation angle  $\theta$   
 314 was acquired. The measured correlation was approximated by the sine-like  
 315 function. Figure 9 shows the linearity plot where the radiation intensity was  
 316 presented versus the approximation sine function. The linear fits show a  
 317 good linearity of both SBD and QOD detectors in the given response voltage  
 318 range. Here, the upper limit of the linear response region is dictated by the  
 319 detector saturation threshold. The lower limit of the linear response region  
 320 corresponds to the minimum detectable signal level. As can be found from  
 321 Fig.9 the SBD detector has a good linear response in the range from 0.02 V  
 322 to 0.09 V, while QOD from 0.01 V to 0.045 V what corresponds to 0.1 – 4  $\mu$ W  
 323 and 20 – 40  $\mu$ W input radiation power respectively. Thereby, the detectors  
 324 provide an output voltage which is directly proportional to the power level  
 325 of an RF signal without any external DC bias.

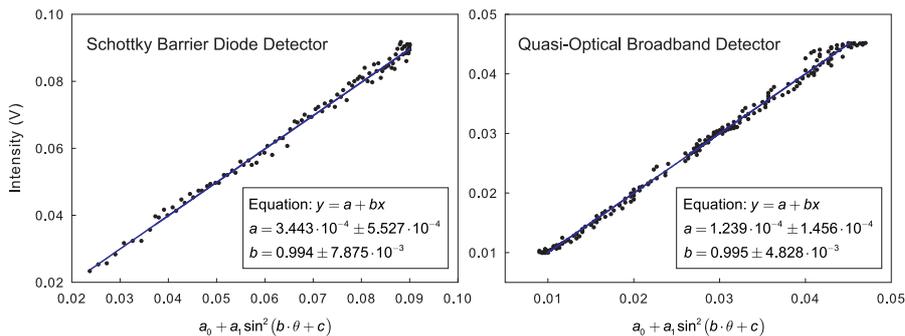


Figure 9: The measured linearity curves of the Schottky Barrier Diode detector (right) and Quasi-Optical Broadband detector (left).

326 After the input radiation power level was adjusted in order to avoid detec-  
 327 tors saturation, autocorrelation dependencies were measured for both SBD  
 328 and QOD detectors. To make interferograms from the raw oscilloscope traces  
 329 the method based on analysis of the signal peak integrals that corresponded  
 330 to an instantaneous transition radiation power of every electron bunch within  
 331 the train was used. In this case the applied method permits measuring in-  
 332 terferogram for any electron bunches in the train. To do so, the signal was  
 333 averaged over twenty successive pulses of second bunch in the train for each  
 334 M2 position set point. A typical SBD autocorrelation curve is presented in

335 Fig.10 (left). The M2 movable mirror translation step was  $200\mu\text{m}$ . A sym-  
 336 metric form of the interferogram and a clear presence of several oscillation  
 337 periods are a good evidence of a reasonable mirror alignment and motion  
 338 stability.

339 To reconstruct the CTR spectrum from the measured autocorrelation  
 340 data the method described in the reference [17] was used. As shown in Fig.10  
 341 (right), the restored spectrum is limited by the SBD spectral sensitivity range  
 342 (see Table 1) and shows only beginning of the co-called "coherent threshold"  
 343 around  $70 - 100\text{GHz}$ . Nevertheless obtained spectrum is consistent with our  
 344 expectations about SBD spectral response and LUCX bunch length.

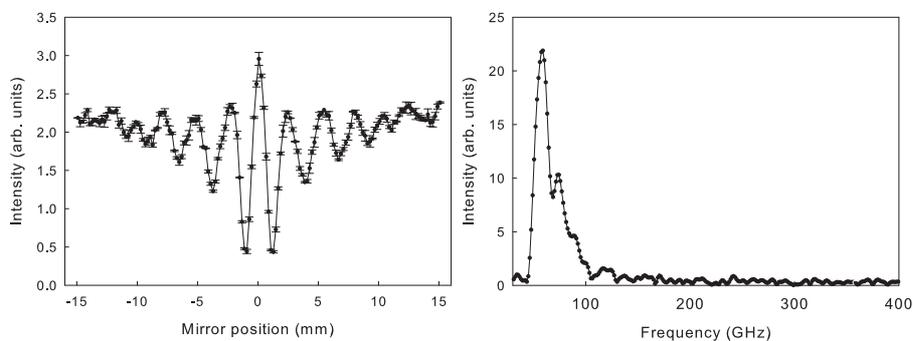


Figure 10: Schottky Barrier Diode detector intensity normalized by current as a function of the mirror position (left) and the restored spectrum (right).

345 To measure the broadband CTR spectrum, the SBD detector was re-  
 346 placed by the QOD. The M2 movable mirror translation step was changed  
 347 to  $50\mu\text{m}$ . For each mirror position, the detector signals for twenty succes-  
 348 sive pulses were averaged again. Figure 11 shows an autocorrelation curve  
 349 measured by the QOD detector and corresponding reconstructed spectrum.  
 350 The autocorrelation curve has reasonable degree of symmetry with the slight  
 351 increase of detected intensity at the right-hand side of the interferogram.  
 352 This may come from the microwave reflections somewhere in the measure-  
 353 ment system and will be investigated in later experiments. Again, measured  
 354 spectrum shows only beginning of the CTR spectrum cut-off.

355 The reconstructed spectrum (Fig.11, left) shows agreement with the mea-  
 356 surements performed with SBD detector as no high frequency spectral com-  
 357 ponents were observed. That clearly means that the CTR spectrum thresh-  
 358 old is located at the beginning of the frequency response range of the QOD  
 359 detector. That gives a good chance to observe the full coherent radiation

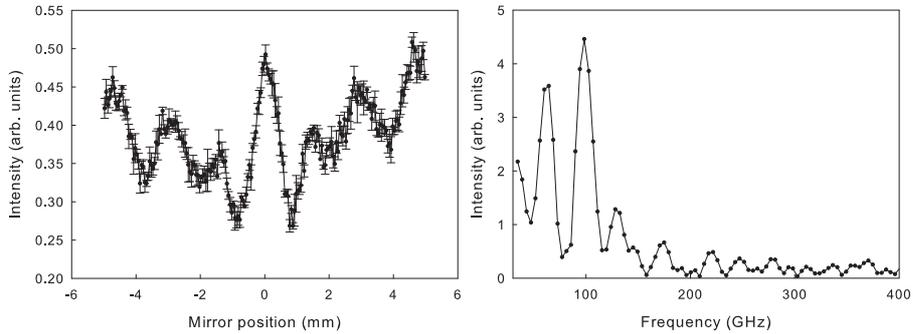


Figure 11: Quasi-Optical Broadband detector intensity normalized by current as a function of the mirror position (Right) and the restored spectrum (Left).

360 threshold for a much shorter electron bunches.

361 It is important to notice that both SBD and QOD detectors were used to  
 362 determine CTR spectrum produced by each bunch of the 4-bunch 357MHz  
 363 frequency train. This clearly shows that the constructed interferometer is  
 364 capable to resolve busts of radiations separated minimum by  $\sim 250$ ps (lim-  
 365 ited by detectors response), what can be used to determine bunch-by-bunch  
 366 profiles of the multi-bunch train or characterize beam of the high repetition  
 367 rate accelerators.

## 368 5. Conclusion and future plans

369 In this paper we present the initial Michelson Interferometer test and its  
 370 performance investigation in THz frequency range. This apparatus has been  
 371 constructed for intense THz radiation beams spectral measurements as a part  
 372 of the larger program on THz sources development at KEK LUCX facility.  
 373 The use of an ultra-fast highly sensitive Schottky Barrier Diode detector  
 374 and a new Quasi-Optical Broadband Detector based on Schottky Diode with  
 375 folded dipole antenna allowed for a detailed interferometer performance in-  
 376 vestigation. The QOD detector signal study shows that it has extremely fast  
 377 response with relatively high sensitivity.

378 The major advantages of this instrument over existing THz spectrometers  
 379 and commercial instruments is that it is capable to resolve busts of radiations  
 380 separated minimum by  $\sim 250$ ps (limited by detectors response), what can  
 381 be used to determine bunch-by-bunch profiles of the multi-bunch train or  
 382 characterize beam of the high repetition rate accelerators. Another advantage  
 383 is simplicity, what potentially leads to high level of upgradeability without

384 any special technical support and low price of the device. Also the large  
385 value of overall acceptance angle allows using interferometer for a numerous  
386 experimental investigations such as development of a wide angle THz sources  
387 and spectral-angular measurements.

388 For the first time the polarization response and linearity of the QOD  
389 in the pulsed mode was investigated. Also the simple and robust method  
390 to align Michelson Interferometer for THz spectral range using visual laser  
391 beam was implemented.

392 Our future plan is to produce a femtosecond micro-bunch train of elec-  
393 trons at KEK LUCX facility and use the MI as a main broadband spectra  
394 measurement tool for development of THz radiation source based on the dif-  
395 ferent types of coherent radiation [21, 59]. At the same time the coherent  
396 spectrum information can be used for longitudinal beam size diagnostic and  
397 for the bunch shape reconstruction using Kramers-Kroning analysis [16, 17].

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