Real-time Luminosity Monitor for a B-factory experiment

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Abstract

A luminosity as high as 10^{34} cm^{-2}s^{-1} is required for a B-factory experiment. It is crucially important to have a system that measures the luminosity in real time and continuously feeds it back to the accelerator control. The zero-degree luminosity monitor (ZDLM) has been developed for this purpose. It detects and integrates photons from radiative Bhabha scattering. The design and performance of the detector are reported.

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References

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1 Introduction

The BELLE experiment [1] at the KEKB collider [2] in KEK has started its data taking in June 1999. The main physics topic is a detailed study of CP violation in the B meson system. KEKB is an asymmetric energy e^+e^- collider (3.5 GeV e^+ and 8 GeV e^-) to enable measurement of time dependent CP violation phenomena. It has two rings whose circumferences are 3 km each. One is for the electron beam and called "HER" (high energy ring), and the other for the positron beam is called "LER" (low energy ring). They cross each other at two points and collide at one of them. The particles generated by the beam collisions are detected by the BELLE detector.

The BELLE experiment requires a high luminosity as much as 10^{34} cm^{-2}s^{-1}. Under such a high luminosity, a small fluctuation of the system causes a big change in the luminosity. Then, the system that measures the luminosity in real time and immediately feeds it back to the accelerator control is very desirable. For this purpose, Zero-Degree Luminosity Monitor (ZDLM) has been developed.

2 Design

2.1 Basic Design

ZDLM detects the γ-ray from the radiative Bhabha scattering,

$$e^+e^- \to e^+e^-\gamma \quad .$$

Its approximate differential cross section for the radiation to a single-beam side is expressed as

$$d\sigma = C \ln(\frac{E_{CM}^2}{m_e^2})\frac{dk}{k} \ , \ C \simeq 3.0 \text{ mb} \ ,$$

where k, E_{CM}, and m_e are the energy of the emitted γ-ray, the total energy in the center-of-mass system, and the mass of the electron, respectively. Under the target luminosity, the high rate of the reaction provides about 10^9 photons(k > 10 MeV)/s, and the total energy is expected to be 3.2×10^9 GeV/s that corresponds to 0.51 W. The e^+ and e^- beams in KEKB cross with a finite angle, 22 mrad, at the collision point. ZDLM is located between the two beam pipes and about 9 m downstream to the direction of the e^- beam from the point. The beam pipes where the signal photons pass were made of aluminum at first, but they have been replaced with copper ones to decrease X ray background backscattered into the BELLE detector in the summer of 1999. The thickness of copper beam pipe and the cooling water where photons pass through is 7.4 radiation length in total. The γ-rays are emitted primarily to the direction of the e^- beam at the collision point, and the angular spread is within about 0.4 mrad. Therefore it is possible to measure luminosity with little background by the detector located in the direction, where the e^- beam and e^+ beam are bent away.

The main backgrounds are X-rays emitted by the synchrotron radiation and γ-rays emitted through the bremsstrahlung process in collision with residual gas or accelerator materials along the straight section of 100 m in length. The critical energy for the former is about 30 keV, and the total energy is 2.5×10^{14} GeV/s (= 40 kW). It does not become a big background because the contribution can be reduced by placing a shield to less than 1 % of the γ-ray energy of the radiative Bhabha scattering. The latter background has essentially the same spectrum as that of the radiatively produced γ-ray. But it is possible to correct it empirically by measuring the background level without making the filled beams collide. The rate of the bremsstrahlung estimated for 1×10^{-7} Pa vacuum and for the length of the straight part of the e^- beam pipe is about 2×10^7 GeV/s (= 3.2 mW), which is about 1 % of that of the signal.

Since the dose rate expected at the detector is more than 100 krad/day, radiation hardness of more than 100 Mrad is needed for it. This is the main reason why a GSO (Gd_2SiO_5 : 0.5%Ce) scintillator has been chosen. Its properties are listed in Table 1 together with those of other scintillators.

Figure 1 shows a cross sectional view of ZDLM. The main part of ZDLM consists of a GSO crystal scintillator, a concave mirror, and a photo-diode (Hamamatsu S3584-09). The GSO crystal is a columnar scintillator whose diameter is 30 mm and length is 150 mm. The sensitive area of the photo-diode is 28 mm $\times$ 28 mm and it is positioned 70 mm above the concave mirror whose minor axis is 30 mm. The low energy part of the incident photons are absorbed in the shield. A shield placed in front of the main part consists of 15 mm thick aluminum, 5 mm thick lead, and 3 mm thick copper whose total radiation length is 1.4. A shield placed in rear of the main part is 5 mm lead. Between the side of the main part and HER beam pipe, we put a lead plate with 11 mm thickness to stop the low-energy photons. The photons, electrons and positrons from electromagnetic showers that transmit through the shield are captured by the scintillator. The scintillation light is reflected by the concave mirror, and caught by the photo-diode and transformed to the direct current, which is immune to environmental noises. This current is proportional to the energy absorbed in the scintillator and is expected to be about 60 μA under the target luminosity.

2.2 Readout System

The signal from ZDLM is amplified after being transported by a 70 m shielded-twisted-pair cable and read by a digital-multimeter. A workstation takes the data from the digital-multimeter through an RS-232C cable. The digital-multimeter can take data from the photo-diode with the integration time of 120 msec and send the average of 10 readings to the workstation, so the workstation can read the data every 1.2 sec, while the data are saved every 2 sec. The workstation sends the data through a network to the BELLE data acquisition and monitoring system then to the KEKB control system.

3 Performance

3.1 Background

The commissioning of KEKB was started in the middle of December 1998. Photons detected by ZDLM are mainly from the bremsstrahlung process during that period. Figure 2 shows an example of data taken every 1 min. in March 1999. The ZDLM outputs are plotted together with the pressure near the collision point and the current of e^- and e^+ beams. It is found from this figure that the background signal from ZDLM and the pressure are well correlated with the e^- beam and independent of the e^+ beam. The reason why pressure depends on e^- beam current is that gas molecules which cling to the beam pipe are scattered by the beam when a halo part of the beam or synchrotron radiation hits the beam pipe. Because of this, the pressure becomes higher and the background from the bremsstrahlung increases. After the vacuum improved with continual beam-baking and pumping, background decreased. As a result, the background tends to increase faster than the beam current.

The data taken from March to April in 1999 are useful to calibrate the background because the ZDLM setup was little different from that in the BELLE first run started in June,1999 and the output of ZDLM was essentially all background because the beams were not in collision in this period. In Figure 3, the ZDLM outputs and pressure are plotted as a function of the e^- beam current. It is found that the ZDLM output and pressure are both linearly dependent on the e^- current, though The ZDLM output must be proportional to the square of the e^- beam current. It infers that the number of photons that are injected into ZDLM decreases because the beam becomes wider as the current gets higher.

3.2 Signals from radiative Bhabha scattering

The collision study started in June 1999. ZDLM caught the signals from the radiative Bhabha scattering. Figure 4 shows electron and positron beam currents, ZDLM output, and the Bhabha scattering rate detected by Extreme Forward Calorimeter (EFC) [3]. EFC can monitor the luminosity by detecting the electron and positron from Bhabha scattering in coincidence. It is found that even at 1 % of the full KEKB luminosity, the structure of ZDLM is well correlated with that of EFC and the S/N is about 2, with much smaller statistical fluctuation.

3.3 An example of its usefulness

While the accelerator was increasing the luminosity, ZDLM detected a fluctuation of luminosity with 40 sec period (Figure 5 (a)) while both e^+ and e^- currents were stable. It had prevented the precise accelerator tuning for about 6 months. Finally it was found recently that the oscillation was due to the heat cycle of a circuit which controled the temperature of cooling water for one quarter of the main ring machine components. The old circuit was replaced with a new one with much smaller temperature variation and the oscillation was mostly gone. This incident clearly demonstrates the power and usefulness of ZDLM.

4 Measurement of transmittance of GSO crystal

The transmittance of the crystal was measured with a spectrophotometer before and after placed in the beam line in order to examine the radiation damage during the operation at the KEKB accelerator. Light was injected into the side of the crystal to transmit the diameter of the cross section in this measurement because the equipment is small. Figure 6 shows the transmittance of the crystal versus wavelength. The line plotted with "×" is the transmittance when the crystal had never received radiation, and "+" line shows the one after 11 Mrad deposit during five months when the background had been high. The crystal had not been exposed for two weeks since then, and the transmittance was recovered ("◯"). "□" line is the data measured after three months. In this period the crystal received only 22 krad (low background), so that the transmittance had recovered. So far, no decrease of the transmittance at the wavelength above 700 nm was reported [4] for 10 Mrad level, but in this case it dropped slightly. So we measured the transmittance through the axis direction with a red LED in order to decrease the uncertainty due to the reflection and to emphasize the absorption effect by letting light run through a longer distance in the crystal. The decrease was confirmed.

5 Summary and conclusion

A Zero-degree luminosity monitor has been developed to measure the luminosity of the e^+e^- collider in real time. Photons from the radiative Bhabha scattering are detected by a GSO crystal scintillator placed 9 m downstream of e^- beam from the interaction point. The signals are read out by a photo-diode in DC current. GSO crystal is used for this detector because of its excellent radiation hardness. It is shown that ZDLM can measure the luminosity in real time and is quite useful for a quick feedback to the collider.

The deterioration of transmittance of the crystal by the radiation damage during the operation and recovery were measured, and it is proved that GSO crystal can stand a severe radiation level.

6 Acknowledgment

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Table 1
Properties of GSO and other crystal scintillators

Crystal	NaI:Tl	BGO	CsI	GSO
Density (g/cm^3)	3.67	7.13	4.53	6.71
Radiation length (cm)	2.59	1.12	1.86	1.38
Decay constant (ns)	230	300	101000	30-60
Peak emission (nm)	415	480	305, 400	430
Radiation hardness (rad)	10^3	10^4	10^4	$> 10^8$
Light yield (NaI:Tl=100)	100	$7 \sim 10$	~ 1	18
Hygroscopicity	strong	no	slight	no
Hardness (Mohs)	2	5	2	5.7
Index of refraction	1.85	2.15	1.80	1.85
Melting Point (^{o}C)	651	1050	621	1950

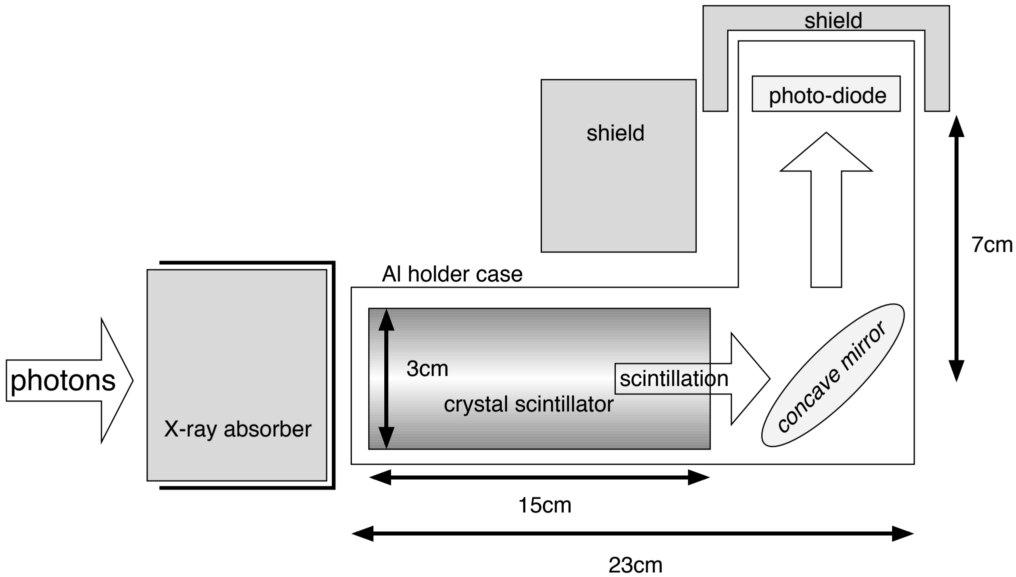

Fig. 1. Schematic view of ZDLM

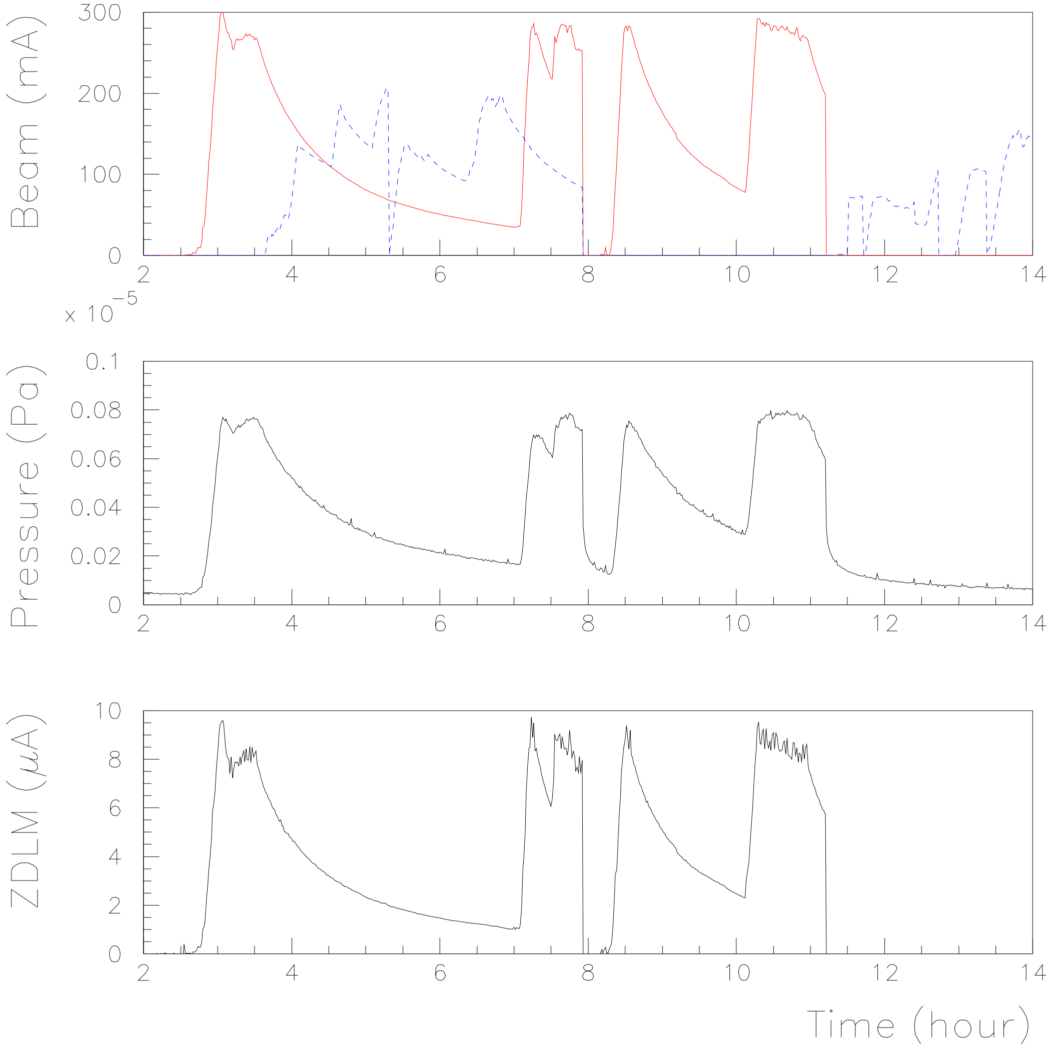

Fig. 2. The line of the top graph is the e^- and the broken line is e^+ beam current. The next graph shows the change of pressure in the e^- ring, and the bottom one shows ZDLM output.

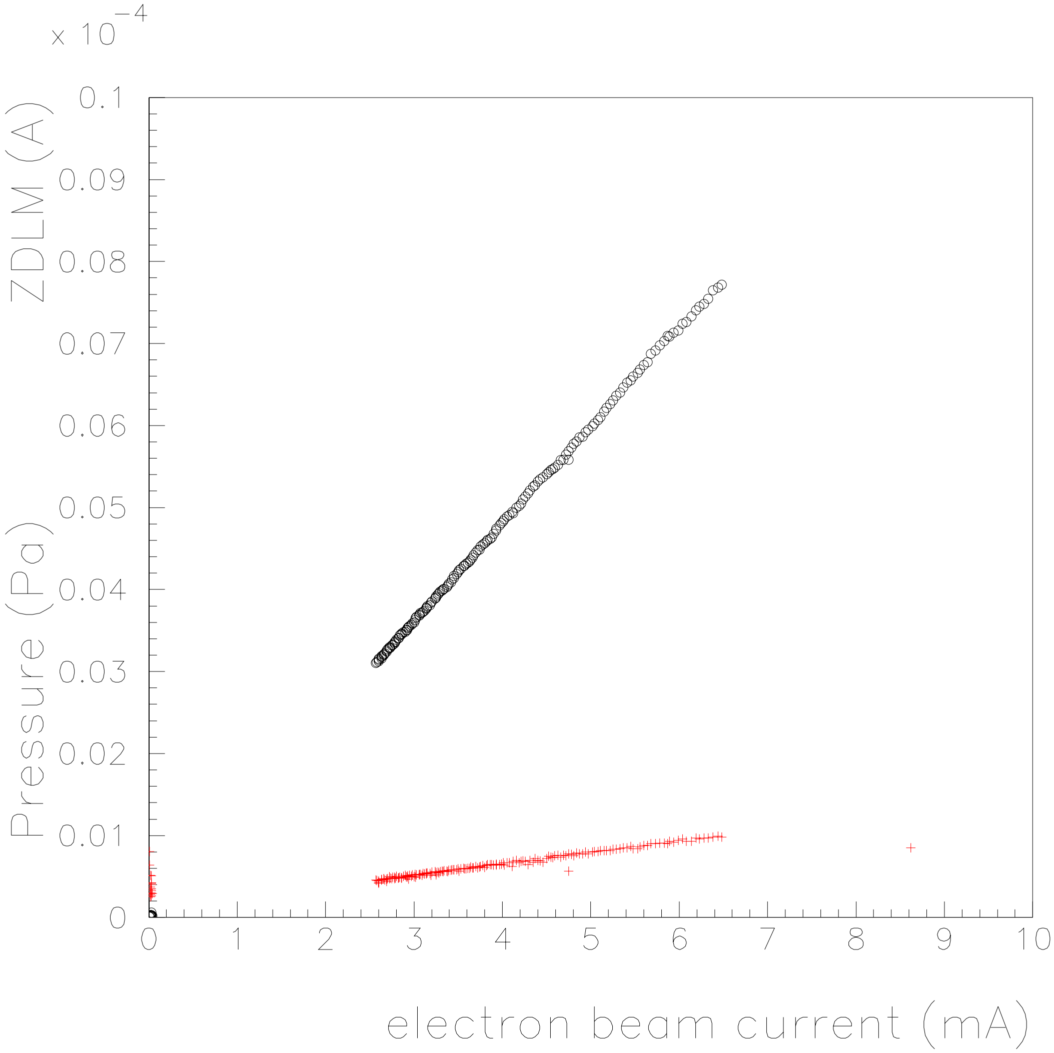

Fig. 3. The pressure (+) and the ZDLM output (◯) versus electron beam current

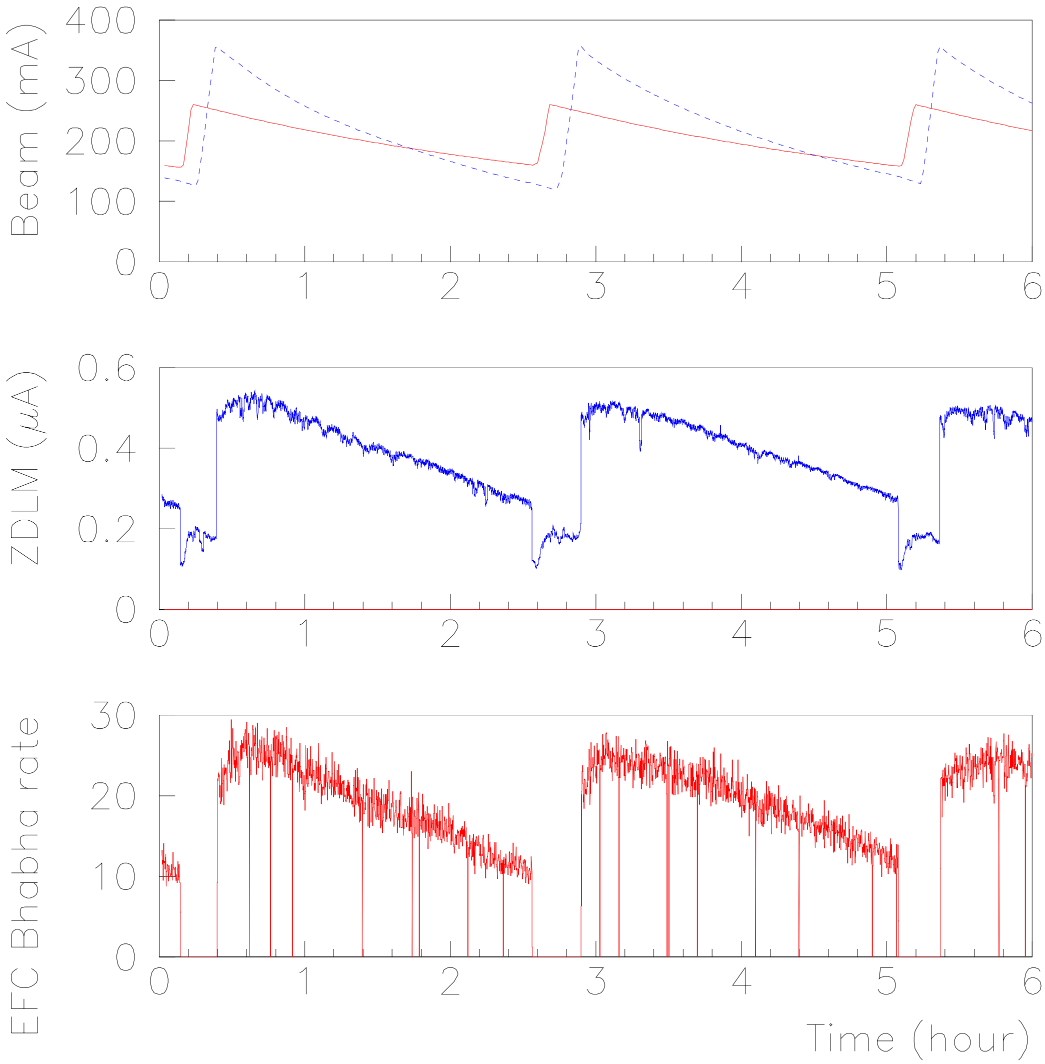

Fig. 4. Beam currents (the notation for lines is the same as that of Fig. 2), ZDLM output, and EFC's Bhabha rate are plotted by every 2 sec.

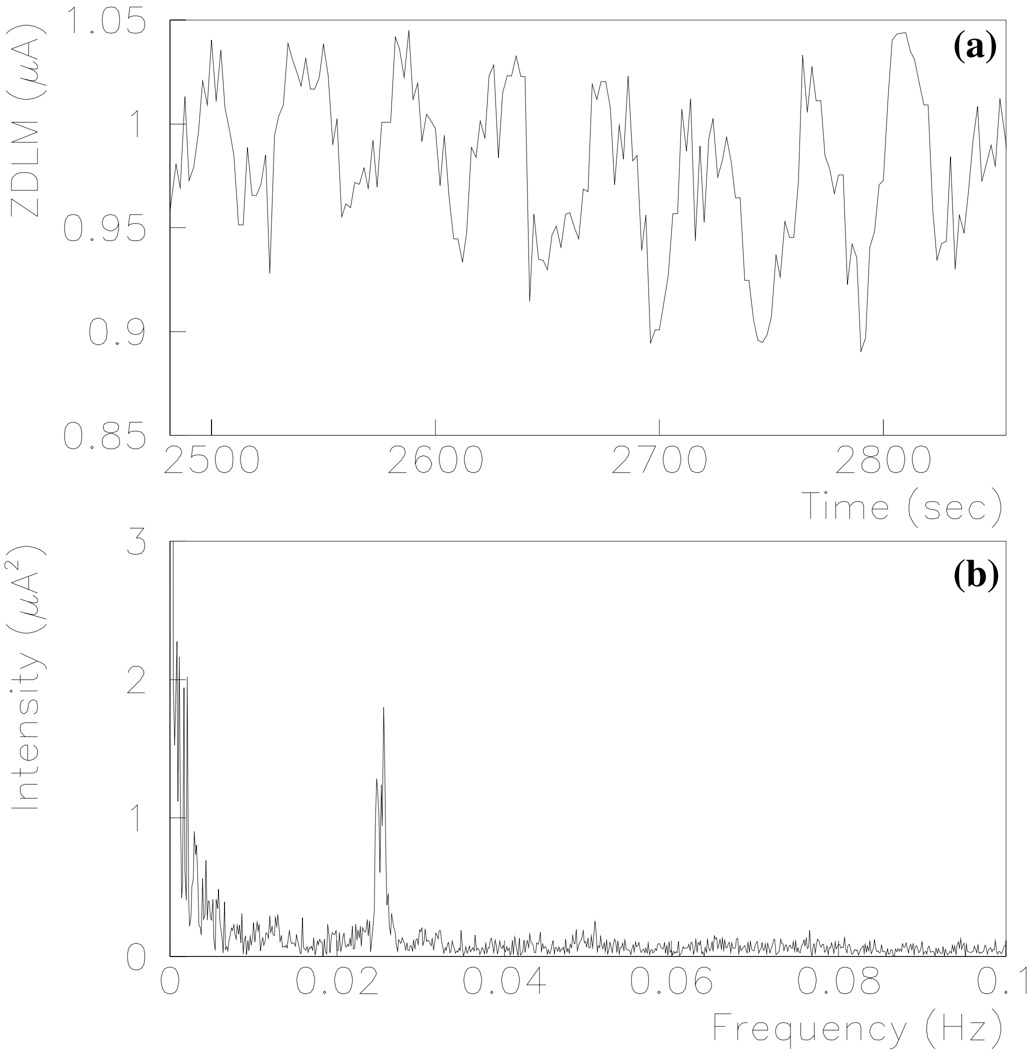

Fig. 5. (a) : An oscillation pattern in the measured luminosity due to the rise of water temperature in the accelerator
(b) : Fourier transformation of (a)

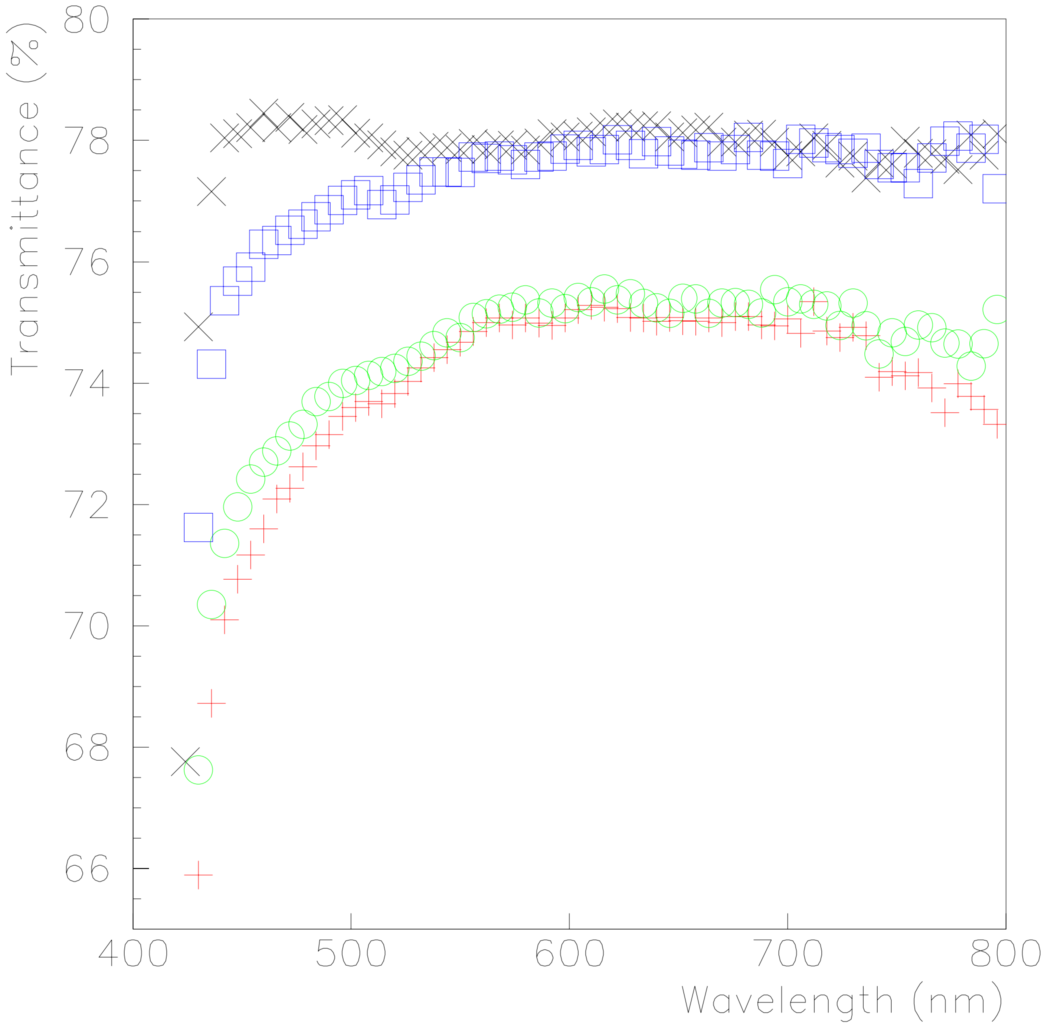

Fig. 6. The change of transmittance of the crystal by the radiation damage and its recovery.
"×" : before irradiation
"+" : after 11 Mrad during 5 months
"◯" : after 2 weeks without radiation
"□" : after 22 krad during 3 months