Linearity achieving of high sensitivity laser energy measurement at pre-amplifier system in SG-III laser facility

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Linearity of laser energy measuring is necessary for high laser power facility used for Inertial Confinement Fusion (ICF) approach because of power balance among beams. Due to large dynamic range and high sensitivity, pyro electric detector is the only option. However, the linearity of the measuring is hard to obtain due to high responding speed and response ration's variation. Therefore, in this paper, the temporal characteristics of pyro electric detectors to laser pulse, sensitivity ratio's variance to different energy are studied. RC filtering and high speed AD are adopted to shield the electromagnetic interference and to capture the real amplitude of the output curve, respectively. Least square fitting is introduced to correct the response ration's variation. The experimental results show that, by correcting the factors leading to nonlinearity in the measuring, a linearity of 99.26% is obtained @5 mJ~350 mJ with a measuring sensitivity of no less than 1 mV/mJ. And they perform well at Pre-Amplifier Diagnostics Package in SG-III facility.

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1. Introduction

The Shenguang-III (SG-III) Laser Facility at Laser Fusion Research Center (LFRC) in Mianyang is designed to achieve an Inertial Confinement Fusion approach. It contains 48 square shaped laser beams having a section of 360 × 360 mm^2. The wavelength during amplification process is 1053 nm (1ω). The amplified 1ω beams are frequency converted to 351 nm (3ω) before reaching the target. The first shot on SG-III Laser Facility was operated at the beginning of 2011[1]. By the end of 2016, SG-III has already been finally completed and providing regular shots for various experiments [2].

The energy measurement is a key point to describe the performance capability and safety status of the pulsed laser systems [3,4]. In SG-III applications, during a shot on target, energy measurements are performed independently on each beam at four locations: Pre-amplified beam, Beam-reversed beam, Main-amplified beam, and 3ω beam. To perform non-invasive diagnostics, beam splitters reflect small parts of the pulse in sensor packages called Pre-amplifier Diagnostics Package (PADP), Beam-Reversed Diagnostics Package, Main Amplifier Diagnostics Package and Tripled Beam Diagnostics Package [5].

An energy meter in application has to be designed taking into account these laser characteristics: wavelength, power or energy, pulsed or continuous, and laser beam size. In Pre-amplifier Diagnostics Packages, such demands on energy measuring are put forward: 5 mJ~350 mJ at 1053 nm with the measuring sensitivity not less than 1 mV/mJ and the linearity not less than 98.78%, measuring in an aperture of 45 mm × 45 mm in a duration of 3 ns with a surface uniformity of measuring results not bigger than 1.5% [6,7], different with other diagnostics packets, higher sensitivity (1 mV/mJ)and wider dynamic range (70 times) are needed in the Pre-Amplifier system.

Commonly, there are three different kinds of energy meter: calorimeter based on volume absorbing glass and thermopile [8], integrating photon-detectors [9] and calorimeter based on pyro electric sensors [10]. Volume calorimeter is known for their stability and high damage threshold while its respond sensitivity is much smaller due to larger thermal capacity [11]. Integrating photon-detector is sensitive enough and is used in the Input Sensor Package of National Ignition Facility [12], however, its dynamic range is very restricted, at most about 20 times. Therefore, to satisfy the pulse energy measuring requirement of high sensitivity and wide dynamics at the same time, calorimeter based on PE sensors becomes the only option in the Pre-amplifier Diagnostics Package.

Robert W. Astheimer and Robert E. Buckley [10] introduced a kind of pyro electric calori- meter which could be subject to ten successive measurements under 75

MW power conditions with an absolute accuracy better than +-5%. In our application, the most severe condition is about 333 MW and the energy is all absorbed in 3 nanoseconds, causing extremely transient temperature which could degrade the black absorbing layer, furthermore, a high nonlinearity of 1.22% is needed. Therefore, in this paper, the time profile of the response of our pyro electric sensor (which we call it cal. H) is demonstrated, a circuit improving an algorithm are introduced to ensure the nonlinearity below 1.22%.

2. Characteristics of PE sensors

2.1. Theoretical basis of measuring

Pyro electric (PE) sensor is a kind of fast responding thermal detector. When it is heated by laser radiation or the additional absorber is heated, causing the thermal-electric dipolar to change (the potential changing rate is as fast as ps) to produce net charges, hence electric field and corresponding pyro electric voltage related to temperature changing. The whole process is called PE effect.

After the absorbers are heated by the incident pulse, under ideal thermal conducting conditions, the maximum temperature rise and the peak voltage can be expressed as [13]

$$\Delta T = \eta E / C_T \qquad (1)$$

$$U_{max} = \eta \xi E C_s / AC \qquad (2)$$

where η is the percentage of the absorbed incidence radiation, C_T is the thermal capacity of the crystal, E is the energy of the incident beam, $\xi = \lambda / \varepsilon C_p$ is the PE constant, also named calibration constant, λ is the temperature changing rate of the PE crystal's polarization intension, which is a constant independent of crystal's geometrical dimension, $\varepsilon = \varepsilon_r \varepsilon_0$ is the dielectric constant, C_p is the volume thermal capacity and C_s is the inter-electrode capacitance of the thermal-electric element. Equation 2 is the theory base of measuring which means the output peak voltage is proportional to the incident laser energy.

The thermal time constant of the additional absorber determines the sensor response time, which is,

$$\tau_{thm} = \rho C_r d^2 / K_r \qquad (3)$$

where ρ, K_r and d are the density, heat conductivity and thickness of the additional absorber respectively. Equation 3 means that, the sensor's response time is totally determined by the physical characteristics of the sensor, independent of ether input laser pulse width or energy.

2.2. Experimental installation

In the measuring process, to guarantee the accuracy and linearity, such factors have to be considered, first, the output signal's peak value's relativity with the energy, equation 2 shows that, the maximum of the output voltage is proportional to the incident energy, however, in the practice, this has to be verified, or, if it is NOT true, then it is necessary to find out the relationship. Second, the real peak value of the sensor's output voltage has to be caught, which means that, in the sampling process, enough sampling points are needed and interfering signal has to be filtered if there was any.

Based on the two demands as mentioned above, peak value's relativity with the energy and response time profiles of PE detectors to different pulse widths are researched. An experimental set as Fig. 1 was built. A laser beam of Φ 42 mm from an Nd: YAG pulsed laser (λ = 1064 nm) operating from 20mJ to 70J is directed to beam splitter. It is placed on the laser path to direct a small part of the laser energy (and the ratio is known and adjustable) to a standard calorimeter which provides the value of the energy injected in the PE sensor. Input energy and pulse width are altered to research the temporal profile with the input pulse width, and amplitude characteristics the input energy, respectively.

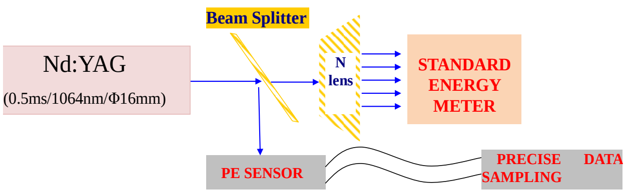
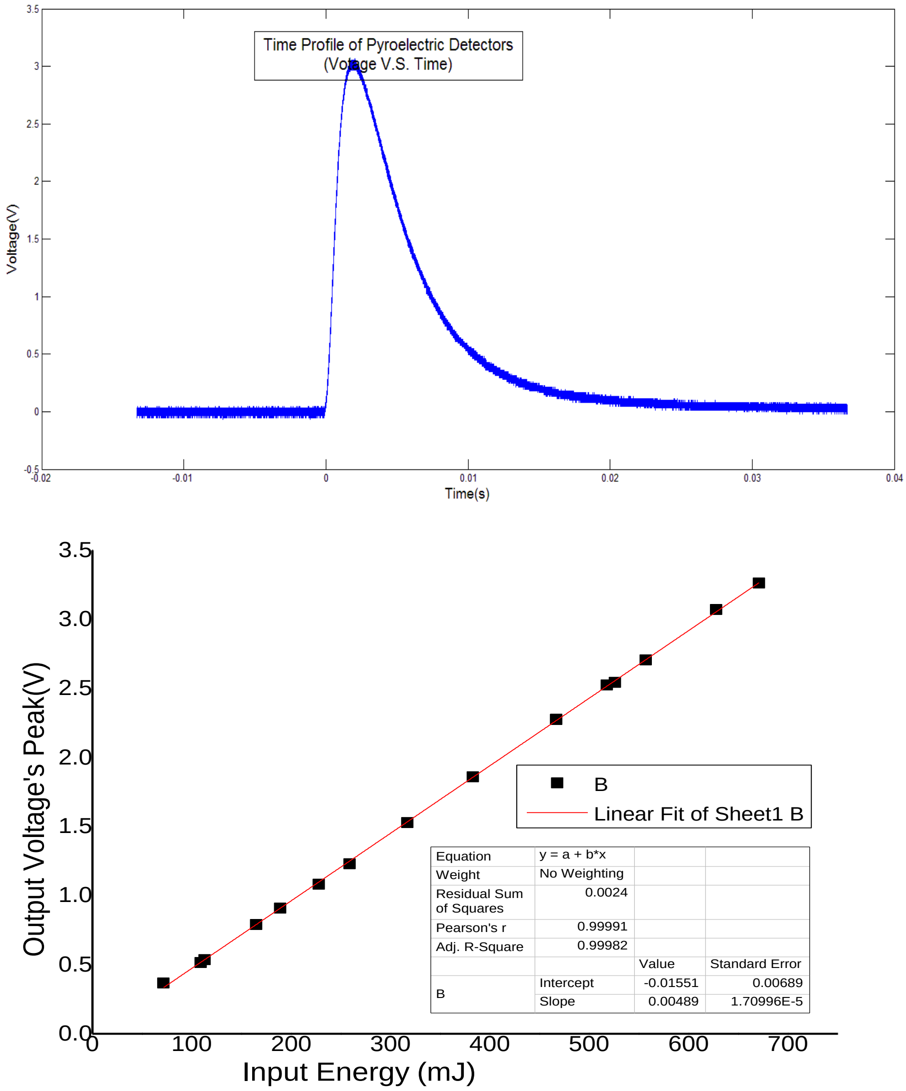


Fig. 1. Installation in the characteristics test experiment

2.3. Peak value's relativity with the energy and pulse width

As mentioned in Equation 2, output peak voltage is proportional to the incident laser energy. It is necessary to verify it as it is the theory base of measuring.



a) time profile of the output pulse b) Output Voltage's Peak Value versus Input Energy

Fig. 2. Peak value's relativity with the energy and pulse width

Fig. 2 shows that, in the measuring range, as the incident laser energy increases, the response sensitivity (which is the ration of the output voltage peak value to the input energy) increases rather than exactly proportional. It doesn't conform to equation 1, and a single sensitivity coefficient in the whole measuring range is not enough. Instead, an optimized algorithm is needed to guarantee the linearity.

2.4. Response profiles of PE detectors to different pulse widths

As mentioned in Equation 3, the sensor's response time is totally determined by the thermal time constant, independent of either incidence beam's pulse width or the energy. It's necessary to find out the time constant in order to develop proper circuit to get the peak value of the output pulse. Using the installation in Fig. 1, a 0.5 ms-pulse-width laser beam and a 3ns-pulse-width laser beam with the same energy are directed to the detectors, respectively. The experiment is executed for 17 shots with different pulse energy, and the response time and voltage profile are shown in Fig. 3.

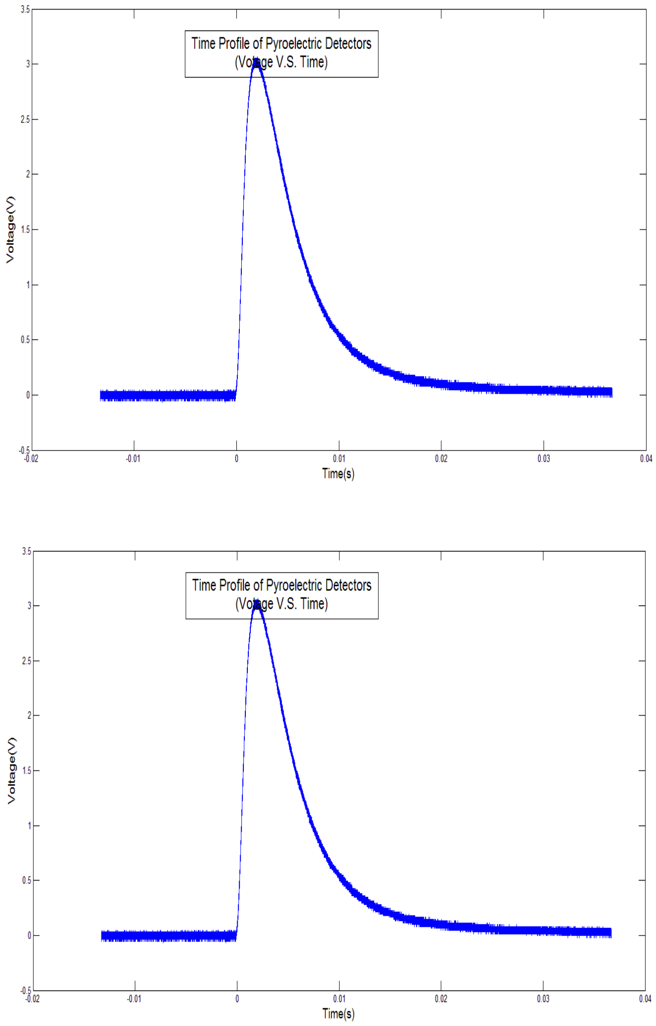


Fig. 3. Response curves of the PE detectors to different pulse width a) a 6 ns incident beam b) a 0.5 ms incident beam

As shown in Fig. 3, the detector responds to a 0.5 ms pulse the same as a 3ns pulse. It rises to the top at about 1 ms, descends slowly and the full width at half maximum is about 4 ms, the profile of pulse is independent of the incidence laser beam pulse width. Also, in the measuring process, there is some electromagnetic interference.

3. Circuit improving and algorithm optimization

Based on the study on the characteristics of PE detectors, for our use, there are three troubles for PE sensors: firstly, the response profile of the PE detector is too fast to get the real peak of the signal unless AD converter is fast enough. Secondly, sometimes, there is some electromagnetic interference mixed in the response signal unless the interference signal is shielded; thirdly, under the measuring range, the output signal is not exactly proportional to the incident energy which means the measuring linearity cannot be assured.

The Analog to Digital Conversion (ADC) module as Fig. 4 is designed [14] as follows: analog signal amplifier is configured as a follower to achieve an impedance transformation. After two stages of RC filtering, then the signal is converted to digital signal by a MCU, to make sure the signal DO NOT distort, before all the circuit module are assembled to the detectors, a standard voltage DC(with a significant voltage about 10 μ V) is used to calibrate the circuit modules.

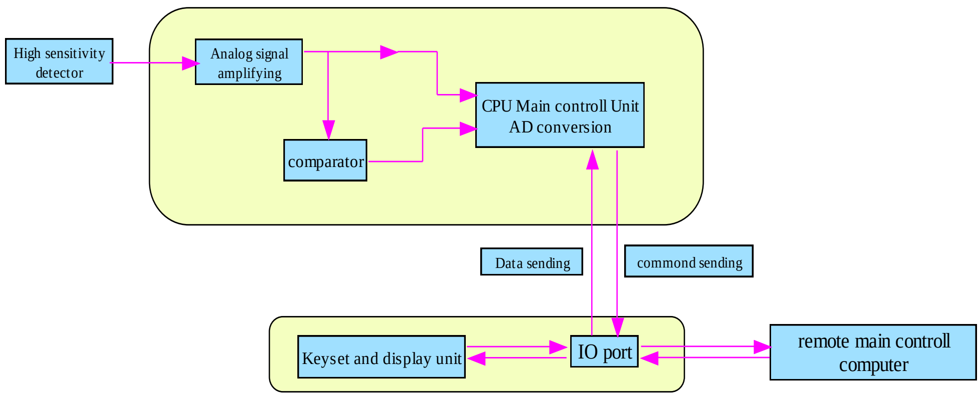
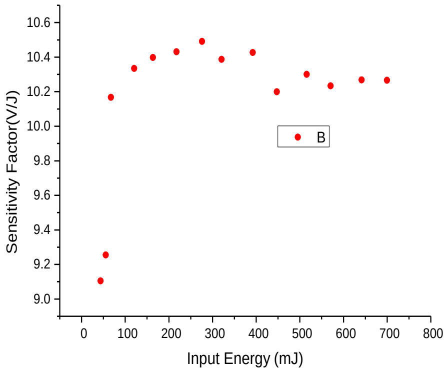
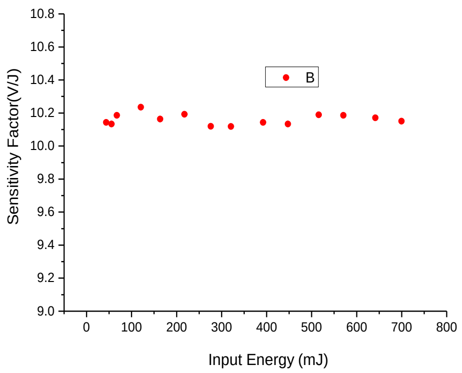


Fig. 4. Schematic circuit diagram of Analog to Digital Conversion (ADC) module

In order to overcome the troubles mentioned above, three corresponding measures are adopted. First, to obtain the real peak of the electric signal voltage, the sampling frequency of ADC is decided as, so that we can get 30 to 40 points in the rise time of PE detectors. Secondly, two stages of RC filtering are used to shield the space electromagnetic interference. Thirdly, a set of calibration procedure is executed using the experiment set as Fig. 2. There are two steps of the standard calibration structure and can be described as follows: First, by comparing the input energy value (given by the standard calorimeter) with the output voltage's peak value, the first stage correcting factor (V/J) is obtained, then, the sensor and circuit module is assembled as an integrated measuring suit. The second calibration step on the integrated measuring suit is made using segmented calibration [15], which divides the input energy range into several individual sections according to the first step correctors. In each section, the input energy is varied to get more recording pairs about the input energy and output peak value, then, least square [6] fitting is used to get the specialized correcting factor in this section. The correcting factors of a suit used in the facility obtained in the two steps are shown respectively in Fig. 5. And as it shows, after the second calibration, the correcting factor becomes more concentrated.



a) sensitivity factor before correcting in A1-YF-N1



b) equivalent correcting factor after correcting in A1-YF-N1

Fig. 5. Sensitivity factors before and after correcting

By designing the proper circuit and calibration algorithm (segmented calibration and least squares), real peak value of the signal is obtained and measuring linearity. All of the 48 laser energy measuring suits in the Pre-Amplifier Diagnostics Packages are tested in the experimental laboratory. Response linearity was our focal point. All of them present a linearity of no less than 99.26%, and one of the measuring results is shown in Fig. 6.

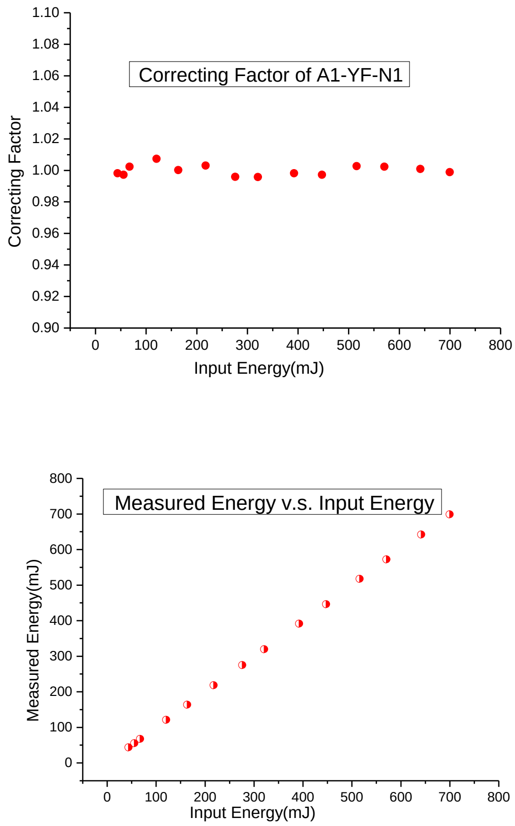


Fig. 6. Correcting Factor and Linearity of A1-YF-N1

4. Summary

For ICF laser facility applications, the need to perform accurate and linear laser pulse energy measurements is important because of power balance among beams. Due to large dynamic range and high sensitivity, pyro electric detector is the only option. To make linear calorimeters, the response characteristics of pyro electric detectors have been experimentally investigated. In this research, it is proved that the time constant of response voltage profile is about 4 ms and independent of the incident beam laser's pulse width (whatever it is 0.5 ms or 3 ns), which warrants a sampling interval time of 30 μs to get the real peak value of detectors' output signal. Moreover, the output voltage's peak value in not exactly proportional to the input energy, which violates against the known theory and brings troubles to linear measuring. In the algorithm, segmented calibration and least squares are used to overcome the sensitivity ration's variation. For all of the measuring suits used in the PADP, a linearity of 99.26% is obtained, and all of the measuring suits in PADP in SG-III facility work well.

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