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# CsI Calorimeter and low power PMT base for K<sup>O</sup>TO experiment

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KOTO is the first experiment in the world specialized in observing the decay $K_L \rightarrow \pi^0 \nu\bar{\nu}$. The decay is sensitive to new physics scenarios beyond the Standard Model. The most important detector of KOTO is the CsI calorimeter, which measures positions and energies of gammas from $K_L$, in order to reconstruct the vertexes of them. There are mainly three requirements for the calorimeter. First, dynamic range for each channel of CsI is more than 3 order of magnitude. Second, single counting rate is about 120 kHz comes from beam intensity. And linearity is required less than ±5% in order to discriminate the signals and backgrounds. Finally, to suppress the backgrounds, we will put the calorimeter at the vacuum level of 0.1Pa. So we must reduce its power consumption. That is why we plan to use the Cockcroft-Walton circuit as a high voltage supply for PMTs. It can reduce power down to about 150mW.

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## 1. K$^{\rm O}$TO experiment

K$^{\rm O}$TO is the experiment specialized in observing the decay $K_L \to \pi^0 \nu \overline{\nu}$. K$^{\rm O}$TO will start from JFY2011 in J-PARC. We plan to observe some $K_L \to \pi^0 \nu \overline{\nu}$ events in three years.

### 1.1 $K_L \to \pi^0 \nu \overline{\nu}$

The branching ratio of $K_L \to \pi^0 \nu \overline{\nu}$ decay predicted by standard model is presented as

$$Br(K_L \to \pi^0 \nu \overline{\nu}) = (2.20 \pm 0.07) \times 10^{-10} [\Im(V_{ts}^* V_{td}) X(x_t)]^2, \tag{1.1}$$

and current value is $(2.49 \pm 0.39) \times 10^{-11}$ [1]. Where $X(x_t) = 1.464 \pm 0.041$ is Inami-Lim loop function[2]. $x_t$ is squared mass ratio of a top quark and a W boson. Presented as Wolfenstein parameters, $\Im(V_{ts}^* V_{td}) = A^2 \lambda^5 \eta$, so there is the CP violation parameter $\eta$ representing the hight of Unitary triangle. Then, measuring the branching ratio of the decay $K_L \to \pi^0 \nu \overline{\nu}$, we can determine it.

### 1.2 CsI calorimeter

We plan to use CsI calorimeter to measure positions and energies of gammas from the decay $K_L \to \pi^0 \nu \overline{\nu}$, and the $\pi^0 \to 2\gamma$, in order to reconstruct the vertex of $K_L$ (Fig. 1). We reuse about 3000 blocks of CsI crystals used in KTeV experiment for the calorimeter at the Fermi National Accelerator Laboratory. There are $2.5 \times 2.5 \times 50$ cm crystals and $5 \times 5 \times 50$ cm crystals. We also reuse photomultiplier tubes used in KTeV.

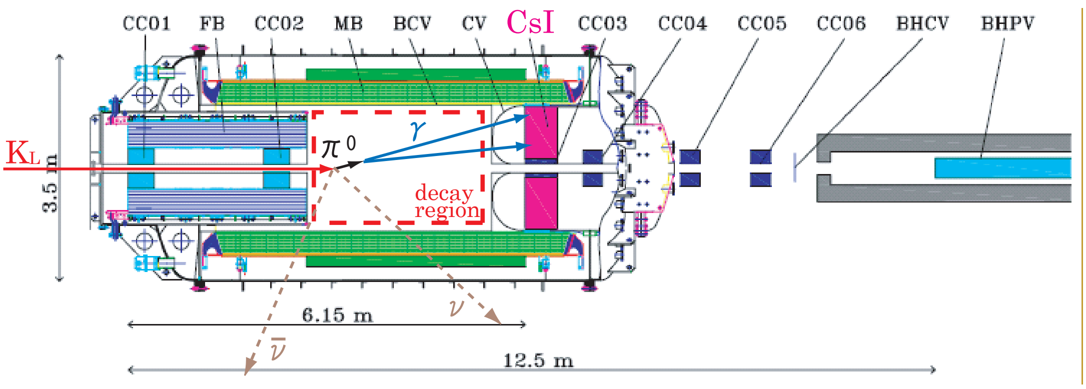


**Figure 1:** schematic view of detector setup

## 2. Requirements for CsI calorimeter

### 2.1 Single counting rate

The beam used in K$^{\rm O}$TO experiment will be neutral and sharply collimated pencil beam. All of particles entering into the calorimeter are generated from $K_L$ decays. So single counting rate of CsI calorimeter is not so high. Fig. 2 shows the single counting rate of each crystal simulated by Geant4. The hit rate is only 120kHz even in case of highest one.

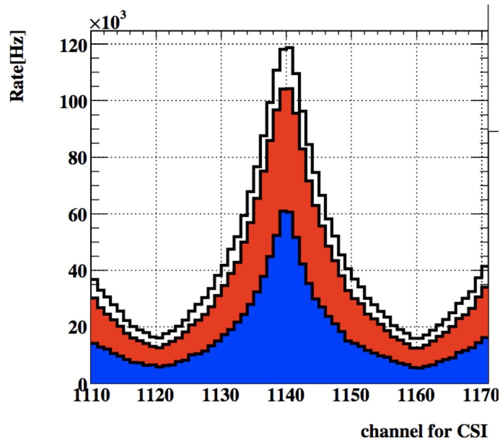


**Figure 2:** Single counting rate of each crystal. This graph shows only around hottest crystal which are located around beam hole. White histogram is all energy event, red one is over 0.1MeV event, blue one is over 1MeV event.

### 2.2 Linearity

Linearity is defined as the deviation of ratio between deposit energy and measured energy like,

$$\frac{E_{\text{measured}}}{E_{\text{deposit}}}, \tag{2.1}$$

when $E_{\text{measured}}$ is PMT output signal and $E_{\text{deposit}}$ is real energy deposited in CsI. If the linearity is worse, the number of signal and backgrounds change, because the $\mathrm{K_L}$ vertex and transverse momentum are not correctly reconstructed due to miss measured energy. Injecting into CsI calorimeter, $\gamma$ makes electro magnetic shower and deposits their energy to multiple crystals. In our analysis, we cluster those multiple energy deposits and reconstruct position and energy of $\gamma$. That is why, deviation of measured energy of each crystal changes clustering result and reconstructed vertex. Miss reconstruction of $K_L$ causes to mistake other decay modes for background. Fig 3 shows the quantitative estimation about it. According to this simulation result, CsI calorimeter linearity is required less than $\pm 5\%$.

### 2.3 Energy range

There is a necessity to estimate the energy range of deposit energy for each crystal. Fig. 4 shows maximum deposit energy of one gamma from the decay $K_L \to \pi^0 \nu \bar{\nu}$. Without any cut, deposit energies distribute over 2 GeV, but such high energy region is vanished by high energy kinematic cut which is for $K_L \to 2\gamma$. Finally we decided the energy range upper limit is 1.3 GeV. And also CsI calorimeter has a role as a $\gamma$ veto detector, so the energy range lower limit is 1 MeV.

## 3. Development of low power PMT base

As noted above, we reuse KTeV photo multiplier tubes(PMT). But there are some problems. One of them is heat problem. Major $\mathrm{K^OTO}$ detectors will be located in vacuum (0.1 Pa), because air and beam neutrons reaction makes $\pi^0$ which is background source. Then there is heat problem



PoS(KAON09)022

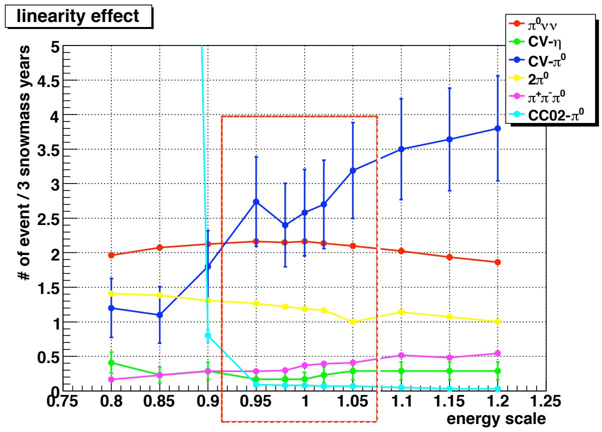


**Figure 3:** Linearity simulation result. Horizontal axis is defined in Eq. 2.1. Red line is the expected number of signal event with all runs, and other lines are that of background event. Under 0.95 and over 1.05, CV-$\pi^0$ and CC02-$\pi^0$ event increase.

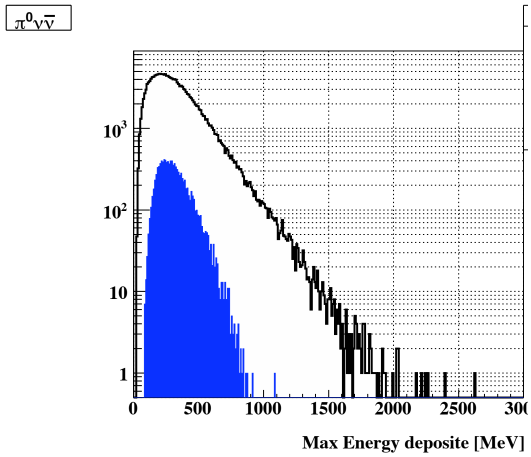


**Figure 4:** The deposit energy distribution from the decay $K_L \to \pi^0\nu\bar{\nu}$

caused by operation in vacuum using normal resistor-divided base. We must reduce PMT base power consumption to suppress heat. Other problem is quite small gain of KTeV PMT. The gain of KTeV PMT is only 5000, because average energy deposit in KTeV experiment was about 80GeV. In contrast, maximum deposit energy of K$^{\text{O}}$TO is only around 2GeV, so we had to increase its gain. That is why I planed to use Cockcroft-Walton circuit[4] as PMT base, and designed low power consumption preamp.

### 3.1 CW circuit

Cockcroft-Walton circuit consisting of diodes and capacitors bridge generates high voltage with low voltage supply. Using this circuit, we could reduce power consumption from 700mW/ch to 150mW/ch, that value is reasonable for cooling. In this experiment, we must reduce noise level in order to get 3 order dynamic range, so RC filters are attached to CW circuit between every dynode pins and diodes (Fig. 5).

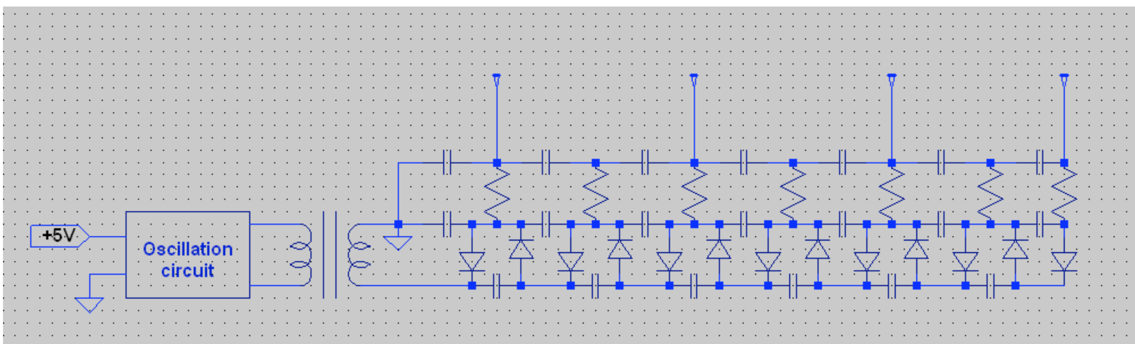


**Figure 5:** CW circuit diagram. There are RC filters between CW circuit and dynodes.

### 3.2 Preamp

The gain of KTeV PMT was about 5000. It is too low to detect 1MeV signal. So I designed a high-speed, low power consumption and low noise preamp to increase PMT signal enough to detect 1MeV signal.

## 4. Conclusion

K$^{O}$TO is the first experiment in the world specialized in observing the decay $K_L \to \pi^0 \nu \bar{\nu}$. The most important detector is the CsI calorimeter, which measures the positions and energies of gammas from $K_L$, in order to reconstruct the vertex of it.

There are several requirements for CsI Calorimeter in order to observe signal event with good S/N ratio. We designed new PMT bases which suffices them adopting filtered CW circuit and high-speed and low noise preamp. Table 1 shows major specifications and performance of our new PMT base. This one suffices all requirements noted Section 2 and power is enough low to cool.

**Table 1:** New PMT base Performance

| item | value | note |
|---|---|---|
| Power consumption | 150mW | KTeV base was 700mW |
| Signal level | $1.15\mathrm{mV_{p-p}/MeV}$ | |
| Noise level | $180\mu\mathrm{V_{rms}}$ | |
| Charge equivalent gain | $3.3 \times 10^5$ | KTeV base was 5000 |
| Linearity | less than 5% | 1MeV to 1.3GeV |
| rate stability | less than 5% | 0.1 to 500kHz at 700MeV |

## References

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[4] J. D. Cockcroft and E. T. S. Walton, *Proc. of Soc. London*, Vol. 137, No. 831, p. 229, 1932.

PoS(KAON09)022