DEAR Technical Note IR-6

Improved Detectors and Target Geometries for the DEAR Experiment

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1 Introduction

During the LNF Scientific Committe meeting of April, 1998, Professor Cabibo posed the following question: given that beam time on a facility such as DAΦNE is extremely expensive, why shouldn't the DEAR experiment at least double its total efficiency by doubling the number of detectors? At nearly any price, this should still be an economical decision.

Of course, the DEAR experiment, as it was originally conceived, was to have been carried out quickly with materials and detectors that were (more or less) in hand. The availability of readout electronics was the factor that restricted the number of CCD chips to eight, and thus placed the ultimate limitation on the efficiency of the experiment.

Now that DEAR has evolved into a long-term project, we have the luxury to seriously consider methods whereby we can increase the experimental efficiency by a factor of two or more. The purpose of this note is to suggest such methods.

2 Monte Carlo

Before entering the main discussion, we will give a brief overview of the Monte Carlo techniques used for these studies. The target simulations were carried out using the CERN software package GEANT 3.21.

Kaons were generated monochromatically (a simplifying assumption) with a momentum of 127 MeV/c and a $\sin^2\theta$ distribution relative to the beam axis. The starting points were sampled from a three-dimensional Gaussian distribution about the interaction point with $\sigma_X = 0.21$ cm, $\sigma_Y = 210$ microns, and $\sigma_Z = 3$ cm.

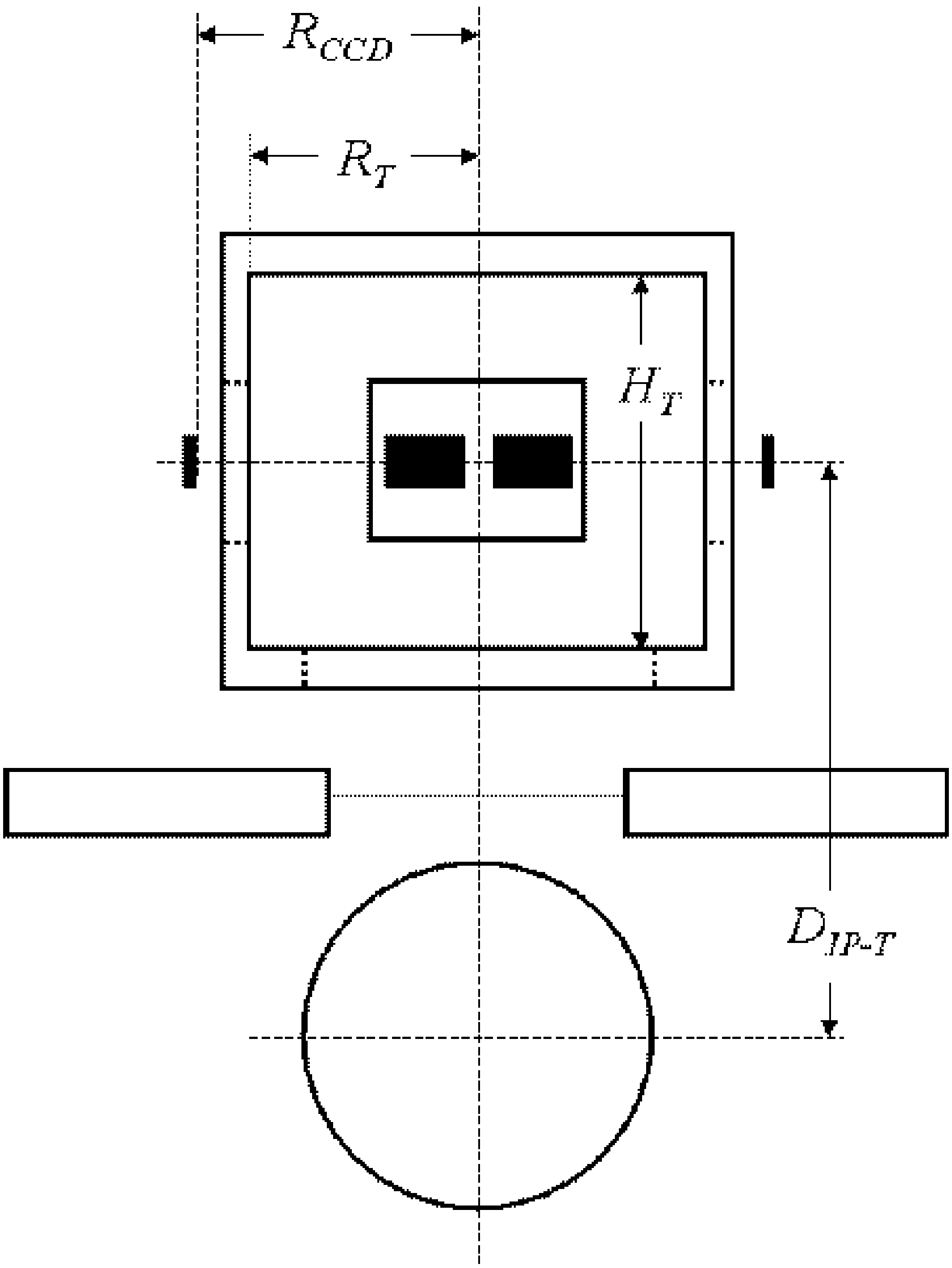

Figure 1: General target and detector geometry.

A general geometry of the type we encoded is shown in figure 1. All windows and apertures were simulated, with the exception of the target windows (since the transmission efficiency of a target material for a monoenergetic low-energy photon can be fairly accurately calculated). For critial regions such as the degrader and the target hydrogen, the medium parameter STEMAX (the maximum step size allowed) was set to 0.01 cm and the medium parameter DEEMAX (the maximum fractional energy loss in one step) was set to 1%.

For every kaon that stopped in the hydrogen volume, a 6 keV photon was istropically generated and followed until stopping.

The CCD detectors were simulated by thick (100 micron) silicon wafers, so that the stopping efficiency would be 100% for the generated photons. The CCD efficiency, which has already been well measured and modelled [1], is included at a later stage of the rate calculations.

3 Proposal Efficiency

If the subject at hand is an efficiency increase, the first question to be answered is, an increase relative to what? The original DEAR proposal [2] is perhaps a logical starting point. There are many details in this proposal that have since changed - for example, the beam pipe was assumed to be made of beryllium, with a radius of 53 mm - that nevertheless have little effect on the projected efficiency. Some items - for example, the operating conditions of 25 K, 3 atm ($\simeq 32 \cdot \rho_{STP}$) - remain unchanged. The critical geometry assumptions of the proposal (the relevant dimensions are defined in figure 1) are the following:

- distance from interaction point to target center (D_{IP-T}) = 19 cm
- target inner radius (R_T) = 7.2 cm
- target height (H_T) = 12 cm
- CCD radius (R_{CCD}) = 7.75 cm
- CCD type = 8 $\times$ CCD-05

We should point out that the proposal assumed that the active area of a CCD-05 chip was 2.7×1.7 cm^2; a better estimate of the area is 2.6×1.7 cm^2, which is the area assumed in this report.

The above geometry was encoded into a GEANT simulation in which one million negative kaons were generated. The simulation resulted in 1557 CCD hits, which is converted to a rate by the following

$$\frac{1557 \text{ hits}}{10^6 \text{ kaons}} \times \frac{7.92 \cdot 10^5 \text{ kaons}}{\text{hour}} \times 0.03 \times 0.94 \times 0.59 = \frac{20.5 \text{ hits}}{\text{hour}} \tag{1}$$

where 0.03 is the assumed kaonic hydrogen K_α yield, 0.94 is the transmission efficiency of a 25 micron Kapton foil for 6.1 keV X rays, and 0.59 is the CCD detection efficiency for said X rays. Note that $7.92 \cdot 10^5$ kaons/hour corresponds to 220 kaons/second or a luminosity of 10^{32} cm^{-2}s^{-1}.

So, this geometry is the origin of the oft-quoted rate of 20 K_α /hour. Note that this value assumes a K_α yield of 3%, which is put into doubt by the most recent KEK analysis, which claims to have measured 1.5%[3], and a luminosity which is likely to be somewhat higher than our starting luminosity. Nevertheless, we will continue to make these assumptions for the sake of comparison.

4 Present Efficiency

Of course, the target design, and indeed the entire experimental setup has changed considerably since the writing of the first proposal. For example, the beam pipe is no longer beryllium, but rather thin aluminum with a carbon-fiber reenforcing layer and the beryllium target entrance window has been replaced by mylar. It is necessary to examine the consequences of these changes. The present target geometry is characterized by the following:

- distance from interaction point to target center (D_{IP-T}) = 20 cm
- target inner radius (R_T) = 6.75 cm
- target height (H_T) = 13 cm
- target window = 25 μm Kapton
- CCD radius (R_{CCD}) = 9.0 cm
- CCD type = 8 $\times$ CCD-05

This geometry was encoded into a GEANT simulation in which one million kaons were generated. The simulation resulted in 973 CCD hits, which is converted to a rate by the following

$$\frac{973 \text{ hits}}{10^6 \text{ kaons}} \times \frac{7.92 \cdot 10^5 \text{ kaons}}{\text{hour}} \times 0.03 \times 0.94 \times 0.59 = \frac{12.8 \text{ hits}}{\text{hour}} \tag{2}$$

This rate is almost 40% smaller than that discussed in the proposal, and it is important to understand why this is the case.

It turns out that the details concerning pipe and window materials have only a minor effect on the detection efficiency and thus, the projected rate. The overwhelming effects are purely geometrical and simply reduce to the acceptance of the target for kaons and the acceptance of the CCDs for X rays. The difference between the proposal geometry and the present geometry is given by two numbers: first, the distance from the interaction point to the target center, and second, the effective radius at which the CCD detectors are placed. The first distance can be compared directly (19 cm versus 20 cm). The effective CCD radius cannot be compared directly, so we attempt to compare a CCD radius that is scaled by the target radius, which leads to the following prediction:

$$\left(\frac{19}{20}\right)^2 \times \left(\frac{\left[\frac{6.75}{7.2}\right] \cdot 7.75}{9.0}\right)^2 \times 20.5 = 12.1 \tag{3}$$

which is close to the simulated value of 12.8. Thus, we believe that the rate differences are essentially understood in terms of these geometrical effects.

There are several reasons why our present setup differs from the original proposal. Regarding the effective CCD radius, the original proposal underestimated this distance in two ways. First, the full extent of window deformation was not taken into account, and second, the amount of clearance necessary to safely insert the target without endangering the CCDs was not considered. Regarding the distance from the interaction point to the target center, at the time of the first proposal we were not aware that 1) we would require a good deal of lead shielding between the CCD vacuum housings and the table, which increases the required distance between the CCDs and the interaction point, and 2) we would required additional space between the target and the target isolation vacuum housing for the insertion of a calibration source.

5 Improved Efficiency

There are two strategies for improving the efficiency of our experiment: improved detectors and improved target geometries. These improvements will be discussed separately in the following subsections, but our ultimate recommendation will involve both types of improvements.

5.1 New CCD Detectors

It has long been known that the deep-depletion CCD-05 is no longer produced by EEV and new detectors are unavailable. After long deliberations and negotiations, a suitable new chip has been found in the CCD-22, also from EEV. Four of these chips have been ordered by the collaboration, but have not yet been delivered. A comparison of the CCD-22 and the CCD-05 can be found in table 1.

From our perspective, the CCD-22 has many advantages over its predecessor. First, the greater depletion depth means a increased efficiency in our energy region. The exact number depends on the real effective depth (which for example is closer to 25 μm than 30 μm for the CCD-05), but by conservatively estimating an effective

Table 1: Essential characteristics of two CCD detectors.

	CCD-05	CCD-22
Depletion Depth	$\leq$ 30 μm	$\leq$ 40 μm
Pixel Size	22.5 x 22.5 μm ^{2}	40 x 40 μm ^{2}
Number of Pixels	1152 x 770	600 x 600
Effective Area	2.6 x 1.7 cm^2	2.4 x 2.4 cm^2

depletion depth of 35 μm , we expect an efficiency improvement of approximately

$$\frac{1-\exp(-\frac{35}{27.8})}{1-\exp(-\frac{25}{27.8})} \simeq 1.2 \tag{4}$$

where 27.8 μm is the attenuation length for 6.1 keV photons in silicon.

The next clear advantage of the CCD-22 is its effective area, which leads to an efficiency improvement of

$$\frac{2.4\times 2.4}{2.6\times 1.7} \simeq 1.3 \tag{5}$$

Finally, the greatest advantage of all lies in a combination of two CCD-22 charateristics, one being that it is and EEV device and as such has operating parameters similar to the CCD-05, and the other being that, despite its larger effective area, thanks to the larger pixel size, it has fewer than half of the number of pixels of the CCD-05. These two traits have the beautiful effect of allowing the possibility of driving twice as many CCD-22 chips with the same readout electronics, compared to the CCD-05. In other words, the 16 independent readout channels, each of which originally read-out one half of a CCD-05, could in principle read-out an entire CCD-22 chip. This is worth a factor of two in our ultimate efficiency.

Of course, twelve additional CCD-22 chips represents a very substantial investment, on the order of one-hundred-thousand US dollars!

5.2 Improved Geometry

As we have already discussed, there are two major paths towards improving the DEAR geometry: get the target closer to the beam, and get the CCDs closer to the target.

At present, being closer to the beam is limited by three points. First, we need a thick table to support all the lead shielding. Second, we need some space in order to be able to insert the calibration source. Finally, we need some clearance for the bulging of the kaon entrance window of the target cell.

Let us start with the problem of the table. Not only does the table need to be thick, in order to support lead shielding, but it also limits the amount of shielding we can use by defining a plane, below which no shielding can be placed. Also, for accelerator safety, there must be some minimum clearance between the table and the beam pipe.

Our solution is radical: eliminate the table! What we propose instead is to have the target *next to* the beam pipe, rather than above it. This allows the target to be four or five centimeters closer to the pipe. The support structure for the setup, including shielding, would then be based on a platform considerably below the beam pipe.

We assume that the requirement of space for the calibration source cannot be avoided, so let us now consider the problem of window deformation. Bulging windows limit how close the target cell may approach the vacuum jacket, and how close the CCDs may approach the target cell. We propose to include a sort of thin wire mesh in the window structure, which would effectively limit the window deformation. Such a mesh would affect the transmission efficiency of a given window, but at the same time would allow for thinner windows with the same safety factor.

Given that the CCDs should be closer to the target cell (although still not as close as was envisioned in the original proposal), it is clear that, in order to allow safe insertion of the target, we require some kind of mechanical motion that allows the CCDs to slide into place after the cell in positioned. This requires a new design, but is certainly not an insurmountable problem.

5.3 A New Design

We propose a new design which incorporates both the advantages of the CCD-22 and an improved geometry, as suggested in the previous two sections. The improved target geometry is characterized by the following:

- distance from interaction point to target center (D_{IP-T}) = 14.5 cm
- target inner radius (R_T) = 8 cm
- target height (H_T) = 10 cm
- CCD radius (R_{CCD}) = 9.0 cm
- CCD type = 16 $\times$ CCD-22

This geometry was encoded into a GEANT simulation in which one million kaons were generated. The simulation resulted in 4734 CCD hits, which is converted to a rate by the following

$$\frac{4734\text{ hits}}{10^6\text{ kaons}} \times \frac{7.92 \cdot 10^5\text{ kaons}}{\text{hour}} \times 0.03 \times 0.85 \times 0.71 = \frac{67.9\text{ hits}}{\text{hour}} \tag{6}$$

Note that the window transmission efficiency has been reduced from 0.94 to 0.85, assuming a 90% reduction due to the wire mesh that prevents deformation of the window. On the other hand, the CCD efficiency has increased from 0.59 to 0.71.

Table 2: The predicted K_α rate for various target geometries. D_{IP-T} is the effective distance from the interaction point to the target center, and R_{CCD} is the radius at which the CCDs are placed, as shown in figure 1.

Geometry	Type/Number of CCDs	D_{IP-T} (cm)	R_{CCD} (cm)	K_α /hour
Proposal	CCD-05 / 8	19	7.75	20.5
Present	CCD-05 / 8	20	9	12.8
Improved	CCD-22 / 16	14.5	9	67.9

This rate represents more than a factor of five improvement over the present design. The contributions of various improvements can be broken down as follows:

CCD efficiency:	1.2
CCD area:	1.3
Number of CCDs:	2.0
Geometry:	1.7
TOTAL:	5.3

6 Conclusions

We first discussed the assumptions under which the rate of 20 K_α /hour found in the original proposal was obtained. We believe this rate to be overestimated, mainly because it assumed that the CCDs could be placed unrealistically close to the target. We then calculated the expected rate for the present target design, which is considerably lower than that in the proposal. Finally, we discussed how the rate could be improved, through changes in the geomtry and the CCDs used. A summary of the three situations is given in table 2.

In order to implement the improved design, we must make efforts on two fronts.

First, we need to demonstrate the feasibility of the CCD-22 as a low-energy X ray detector, in terms of efficiency, energy resolution, and background suppression. At the same time, we must show that these chips can be read-out by our existing electronics. This can only be accomplished after the first CCD-22 are delivered from EEV, which is expected in August of 1998. Other preparations for these tests, such as the design and construction of a CCD-22 camera head, are already underway.

If the CCD-22 proves to be the device we believe it to be, then we have strong reasons to believe that the purchase of twelve additional chips (for a total of sixteen) is strongly motivated and could increase our overall efficiency by another factor of three.

Finally, designs for a new target cell, vacuum chamber, support structure, and shielding should be started as soon as possible.

References

[1] B. Lauss, *Kaskade und Transfer von Myonen in Wasserstoff*, Ph.D. Thesis, University of Vienna, 1997.

[2] R. Baldini, *et.al.*, DAΦNE Exotic Atom Research: The DEAR Proposal, LNF-95/055 1995.

[3] T. Ito, *et.al.*, *Observation of Kaonic Hydrogen Atom X Rays*, in preparation.