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Study of Magnetic Shielding Configurations for the ICD Photo-multiplier Tubes in The DØ Upgrade

Abstract

We have studied the variation of gain in intercryostat detector photomultiplier tubes as a function of magnetic field strength in a variety of both magnetic shielding configurations and magnetic field/tube orientations. The magnetic field strengthes studied exceeded that expected in the DØ upgrade environment by a factor of three. We found that the combination of a 1020 steel block combined with one layer of μ-metal exceeds the requirements of the upgraded detector. We also find that obvious extensions of the run 1 ICD shielding configuration and a combination of commercial steel pipe with μ-metal are extremely sensitive to the axial angle of the tube and field. We also discovered that when the tubes are exposed to magnetic fields they experience a history-dependent change of gain with a relaxation period of many minutes.

1. Introduction

The run 1 InterCryostat Detector (ICD) is a device which resides between the central (CC) and end (EC) cryostats of the DØ Detector in the pseudo-rapidity range: $0.8 < \eta < 1.4$ [1]. The purpose of the ICD is to provide energy sampling for deposits in the cryostat wall. The ICD consists of scintillator tiles of size $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ which are read out by wave-shifting fibers embedded in the tiles. The tiles and fibers are housed in steel boxes mounted on the EC. The light exiting the polished ends of the fibers is measured by photomultiplier tubes (PMTs) which are located onboard in the steel box attached to the EC. For run 2, the ICD will cover $1.1 < \eta < 1.4$ and, with the addition of the central solenoid, will be in a magnetic field with strength of order 2 kG [2]. Since we cannot realistically expect to shield conventional PMTs from fields of this magnitude, and since budget constraints prevent us from replacing the run 1 ICD PMTs, the upgraded ICD will have its wave-shifted scintillation light piped out from between the cryostats to the "pig-troughes" where the

PMTs and associated electronics will be housed. The pig-troughes are along the side of the EC where the magnetic field strengthes will be less than 350 G.

In a PMT photons are incident on a cathode which is followed by a series of dynodes and, ultimately, an anode. The relevent process is the photoelectric effect: a photon hits the cathode which kicks an electron off and is then accelerated through a succession of very large electric fields between the dynodes. As this occurs, more electrons are emitted from the dynodes resulting in an avalanche of current at the anode. The total amount of charge observed at the anode is proportional to the number of photons which struck the cathode during the interval that the device is read out. This interval is usually less than 50 ns. Since the trajectories of electrons are bent in the presence of magnetic fields (recall $\mathbf{F} = q(\mathbf{E} + \beta \times \mathbf{B})$) common PMTs will not function in an appreciable magnetic field.

We report here a series of measurements of the relative gain of the ICD PMT [3] in a variety of magnetic field strengthes, shielding configurations, and geometric orientations. In section 2 we review the physics of shielding and describe the experimental apparatus and levels of precision of the various quantities measured; in section 3 we present our results for four different shielding configurations: extension of current ICD shielding, combination of commercial steel pipe and μ-metal, a 1020 steel tube plus μ-metal, and a 1020 steel block plus μ-metal; and, in section 4, we conclude with a summary and recommendation for the Run 2 ICD.

2. Experimental Technique and Sources of Uncertainty

The ICD PMTs are Hamamatsu model R-647. In our studies, the base we used was a simple DC coupled voltage divider chain. We ran the PMT at -800 V. This gave a potential between the cathode and the first dynode of -73 V, a drop of -58 V between each of the first eight dynodes and drops of -73 V and -90 V across the last two dynodes and -104 V between the last dynode and the anode. The last two dynodes and the anode had 10 nF capacitors across them to maintain plenty of potential even for large avalanches of charge. Assuming a quantum efficiency of 20% and a typical secondary emission coefficient of four, the gain of this base is about 10^6. It should be noted that the base used in the Run 1 ICD were low gain and AC coupled. Since the gain of the tubes drops abruptly when the magnetic field permeates the PMT, we are confident that there is no qualitative base dependence in the gain of the shielded PMTs as a function of magnetic field. Further, since we've tested tubes at magnetic fields more than three times the expected field in the Run 2 PMT environment any small quantitative differences can be accomodated.

We used a high powered electromagnet designed for condensed matter studies in electron and nuclear magnetic resonance. The magnet was capable of maintaining fields as low as 100 G and as high as 15000 G. A Hall probe is used to set the value of the magnetic field. That is, one chooses a field value by turning a knob on the magnet's power supply, a feedback loop then sets the current in the magnet so that the field at the Hall probe is within 0.2% of the value chosen by the user.

In media, the magnetic field is defined by $\mathbf{H} = \mathbf{B} - 4\pi\mathbf{M}$ where $\mathbf{M}$ is the moment density of the media and $\mathbf{B}$ is the magnetic flux density (up to this point we have referred to $\mathbf{B}$ as the magnetic field, we will return to this inexcusably informal syntax after this paragraph). The magnetic permeability, μ, is given by $\mathbf{B} = \mu\mathbf{H}$ for non-ferromagnetic materials, or ferromagnets at low fields. For ferromagnetic materials in large fields, the relation between $\mathbf{B}$ and $\mathbf{H}$ depends on the history of the media and therefore is nonlinear, $\mathbf{B} = \mathbf{F}(\mathbf{H})$; the definition of permeability, in general, depends on the field, $\mu = \mu(\mathbf{H})$. In discussing magnetic shielding, it is convenient to restrict reference of μ to unprepared materials where, at least initially, $\mathbf{B} = \mu\mathbf{H}$ is a fair approximation. For the ideal case of a spherical shell of permeability μ in the presence of an external flux density $\mathbf{B}$, the field inside the shell is proportional to μ^{-1} [4]. Thus, magnetic shielding media have large magnetic permeability. In this study we used combinations of four different materials for shielding:

- commercial μ-metal with $\mu_{\max} \sim 10^5$,
- transformer shield steel with $\mu_{\max} \sim 5000$,
- 1020 steel (i.e. 99.8% Fe) with $\mu_{\max} \sim 3500$, and
- cold rolled steel with $\mu_{\max} \sim 2000$.

The premeability varies over the range of field strengthes in this study, we quote values for $\mu_{\max}$ as a qualitative indication of the relative shielding properties of the various materials.

The shielded tube was flashed by a green LED within a light tight enclosure. The enclosure was a rectangular box which sat on the magnet's base rising into the space between the magnetic poles. The PMT base sat at the bottom of the box, the PMT/shielding sat on a platform between the poles, and the LED was easily placed near the tube cathode anywhere in the box. In measurements with 1020 steel shielding, the PMT/shielding was bolted to the platform to resist the torque of the magnet-iron interaction. A ten pound weight was set on top of the enclosure to help hold it steady – at very large fields the system moved, this concluded the set of measurements for that given configuration.

The LED was flashed by a pulser [5] with a time width of 30 nsec and a frequency of 1-10 kHz. The amplitude of the pulse was tuned so that about 50 photo-electrons were observed in the PMT. This was estimated by integrating the PMT pulse by eye from an oscilloscope trace assuming the PMT gain of 10^6. The anode signal from the PMT was amplified [6] and readout by a charge integrating ADC provided by a qVt multi-channel analyzer [7] using a charge resolution of 1.0 pC. The qVt was projected onto an analog oscilloscope as a histogram of the charge emitted from the PMT anode. The peak value of the charge was recorded. The relative gain of the PMT under various conditions was measured by comparing the various measurements with those observed with no magnetic field.

The electromagnet was free to rotate on its mount which had angles in degrees marked off. Thus, it was simple to measure the PMT gain as a function of both magnetic field strength and axial angle. We define the axial angle to be the angle between the axis of the cylindrically shaped PMT and lines of magnetic flux. We are not concerned with the slight dependence of the gain on the azimuthal angle.

First, we centered the tube between the magnetic poles with its axis perpendicular to the field; second, we took sets of readings with increasing magnetic fields; third, when the gain of the tube was seriously depleted we backed the magnetic field off to 100 G, rotated the electromagnet to another axial angle and took another set of readings.

The uncertainties in this study came from six areas:

1. spatial variation of the magnetic field;
2. reproducibility of the light output of the LED;
3. hysteresis effect in the PMT;
4. error in the axial angle of orientation of the PMT with respect to the magnetic field;
5. variation of the PMT gain in magnetic fields with azimuthal orientation; and,
6. statistical error in estimating the peak of the charge histogram from the qVt.

<u>Spatial Variation of the Magnetic Field</u>

The length of the tube was 7 cm, including pins and socket about 10 cm. The distance between the magnet's pole faces was 6 cm. Thus, we removed the magnet's pole faces to allow space to measure the tube gain as a function of both the field strength and the angle of the field with respect to the axis of the tube. In this configuration we had ample space to vary the tube configuration, but at the cost of field uniformity. With the pole faces removed, we measured the spatial variation of the field in the area where the PMT was suspended with a hand held Hall probe. The magnetic flux spread out in this region such that the net field decreased a maximum of 15% of the nominal value. Over most of the region where the measurements were made the field decreased by about 5%. This was used to correct the nominal values in the measurements reported below. We assign an error of 10% to the field for these spatial variations.

<u>Variation of the Light Level in the LED</u>

In the early stages of the study we encountered problems with the light intensity of the LED. First, we observed a 'double peak' in the charge distribution which was caused by light reflecting off of the inner layer of μ-metal shielding onto the cathode. This was fixed by installing a felt tube to channel the light properly from the LED to the cathode of the PMT. We also observed an overall drift in the peak value observed at the qVt which was erradicated by leaving the main power supply on all the time. Evidently the drift was caused by temperature variations in the NIM equipment.

Ultimately we were left with a systematic error in the LED light intensity due to inconsistencies in the positioning of the tube with respect to the LED between measurements with different shielding configurations. Since we are concerned here with relative measurements, this error is not so important as long as our plots of gain vs field are restricted to sets of measurements with a given shielding configuration. In comparing different sets of measurements we've seen errors of the order of 5%.

Hysteresis Effect in the PMT

We observed that the gain of the PMTs depends on their history of exposure to magnetic fields, hysteresis. Early in the study we had serious trouble reproducing our measurements. For example, the PMT gain at a given field strength, say 500 G, was recorded, then the field was increased to 1400 G and decreased again back to 500 G. Following this sequence with a second measurement at 500 G, we found that the two measurements were inconsistent. An interesting effect signalled that the PMT was 'infected': the gain *increased* with increasing field until reaching a threshold where it began to decrease with increasing field; the magnetic field threshold was a lower value for the given PMT after being infected than before. We found that in order to reproduce the original measurment, the PMT had to be isolated from magnetic fields for about an hour before the gain returned to a steady-state reading. The inability to reproduce measurements invalidated many of our early measurements. Evidently the problem was due to magnetic hysteresis effects in the PMT. We excluded that the effect could have been caused by hysteresis in the shielding because the effect was observed with and without shielding and with both multiple layers of μ-metal shielding as well as for 1020 steel shielding. In the measurements presented here, we attempted to avoided this problem by preventing magnetic saturation of the PMT. That is, as soon as we saw a drop in the gain of about 40% we backed off the magnetic field. With this procedure, the time required for the PMT to come back to normal gain was about 20 minutes. This allowed us to complete the measurements. With these precautions we were able to beat the variations back to about 3% discrepancy.

Error in the Axial Angle of the PMT With Respect to the Magnetic Field

For shielding configurations involving only μ-metal, it turns out that the PMT is highly sensitive to the axial angle of the PMT in the magnetic field. In this respect the design of our light tight enclosure was flawed. It was very difficult to set the initial orientation with an accuracy better than a few degrees. By comparing repeated similar measurements we estimate a flat error of about 8% in the gain due to error in the measured axial angle. It should be noted that this is a rough approximation because the error is not flat: it depends strongly on how sensitive a given shielding configuration is to axial angle.

Non-measurement of the Azimuthal Angle of the PMT

The design of the PMT is not azimuthally symmetric. Thus there is a slight dependence of the gain on the azimuthal angle of the PMT relative **B**. This variation is given in the vendor's documentation [3]. We made an effort to keep the azimuthal orientation the same throughout our measurements, but since we cannot reasonably expect this to be done in the Run 2 ICD, we assign the manufacturers measured azimuthal variation of about 10% as a systematic error in this study.

Source of Error	Value of Error
Magnetic Field Variation	10% in **B**
Variation of the Light Level in the LED	5%
Hysteresis Effect in the PMT	3%
Mismeasurement of Axial Angle	8%
Non-measurement of azimuthal angle	10%
Statistical	3%
Total Error in the PMT Gain	15%

Table 1: Summary of errors.

Statistical Error

The multi-channel analyzer yielded by the qVt provided histograms of the amplified charge deposited at the anode of the PMT for all of the orientations/values of **B**. These histograms had a Gaussisan peak with a low-edge trail due to the PMT's dark current. The peak level, in pC, was read off by simply taking enough readings to form a nice peak. Most of these measurements required about 10^4 LED flashes. The amplification of the PMT signal was set so that the full scale of 256 pC was used. Thus, with $\mathbf{B}=0$, the peak was usually around bin 220, and for gains depleted by 40% the peak was around bin 132. The ambiguity in reading off the peak value was less than, but about, 4 bins. Therefore we assign a statistical error of 3%.

The total error in the PMT gain is given by the sum of the errors in quadrature because none of the errors are obviously correlated. Since, in what follows, we plot the PMT gain as a function of the magnetic field strength, the error in the field strength is orthogonal to the error in the PMT gain.

3. The Dependence of PMT Gain on Magnetic Field Strength and Orientation

In what follows, let the axial angle be defined by θ. We expect the shielding to be most effective for $\theta = 90°$ where the flux cannot easily penetrate the shielding; and least effective for $\theta = 0°$ when the flux is parallel to the axis of the cylinder and so can pass straight through. The Hamamatsu specifications for an unshielded ICD PMT [3] show a 50% loss of gain for fields of ~ 6 G at $\theta = 90°$ and ~ 30 G at $\theta = 0°$. Thus, the PMT is more sensitive to, and the shielding is most effective for, transverse fields.

We made four separate sets of tests. Each set is with different geometries and shielding media. We have summarized the geometry of the various shields in Table 2.

3.1 Extension of Run 1 Shielding

In the ICD implementation of Run 1, the ICD PMTs are shielded from stray magnetic

Shield	Geometry	Dimensions (cm)
μ-metal	Cylinder	$l = 8.9$, $r_o = 1.7$, $t = 0.05$
Transformer Shield	Thin Rectangular Sheet	$l = 8.9$, variable widths
Soft Steel	Rectangular Block	$l = 8.9$, $w = 3.8$, $t = 3.8$, $r_i = 1.0$
	Thick Cylinder	$l = 8.9$, $r_o = 1.75$, $r_i = 1.13$
Cold Rolled Steel Pipe	Cylinder	$l = 7.8, r_o = 2.4, r_i = 2.28$
Hamamatsu R647 PMT	Cylindrical Symmetry	$l = 7.1, r = 0.65$

Table 2: Geometry of various shields, l = length, w = width, t = thickness, r_i = inner radius, and r_o = outer radius.

fields by one thick layer of μ-metal shielding [8] and three thin layers of transformer shield steel. The μ-metal is a thick cylinder which fits loosely around the PMT. The three thin layers are formed by wrapping thin sheets of transformer shield steel around previous layers separated by insulating tape.

The simplest approach to the problem of shielding the PMTs in the upgraded detector is to recycle the shielding from Run 1. In Fig. 1 we have plotted the relative gain of PMTs as a function of magnetic field strength with different symbols for different θ and with different shielding configurations. In Fig. 1a we measure the gain for the Run 1 shielding: three layers of transformer shield steel around a central layer of μ-metal (denoted $3+1$ in the figure). In Figures 1b-d we increase the shielding by successive layers of transformer shield steel. The gain in these figures is given as a fraction of that with no external field. The most prominant feature of the plots in Fig 1 is the abrupt, dramatic loss of gain for all shielding configurations with θ less than about 85°. The loss of gain demonstrates a less sharp threshold effect for increasing θ. That the gain depletes so rapidly over just 10° from the perpendicular demonstrates extreme sensitivity to the axial angle with these shields. In the upgraded detector the tubes will not be perpendicular to the field. At the time of this study, the precise angle was not known, though we expect it to be larger than 40°. Thus recycling the Run 1 shielding would not seem to be an option.

3.2 Soft Steel (1020) Block

An alternative to the extended Run 1 shielding is to use a large soft steel block as an external shield with an air gap between the block and a single layer of μ-metal. The highly permeable thick soft steel sucks up the magnetic flux and the single layer of μ-metal shields the tube from leakage. We used a rectangular block of 1020 steel (i.e., 0.2% carbon, 99.8% iron) $9.0 \times 3.5 \times 3.5$ cm with a hole of radius 1.0 cm bored through the face in which the μ-metal shield easily fit. The PMT fit into the μ-metal shield and soft steel block up to the socket connection of the PMT pins to wires extending down into the light tight enclosure to the PMT base. This left about 2 cm of steel beyond the photo-cathode.

In Fig. 2 we present the relative gain as a function of magnetic field strength for a variety of different axial orientations, θ. Notice that for the tube perpendicular to the field,

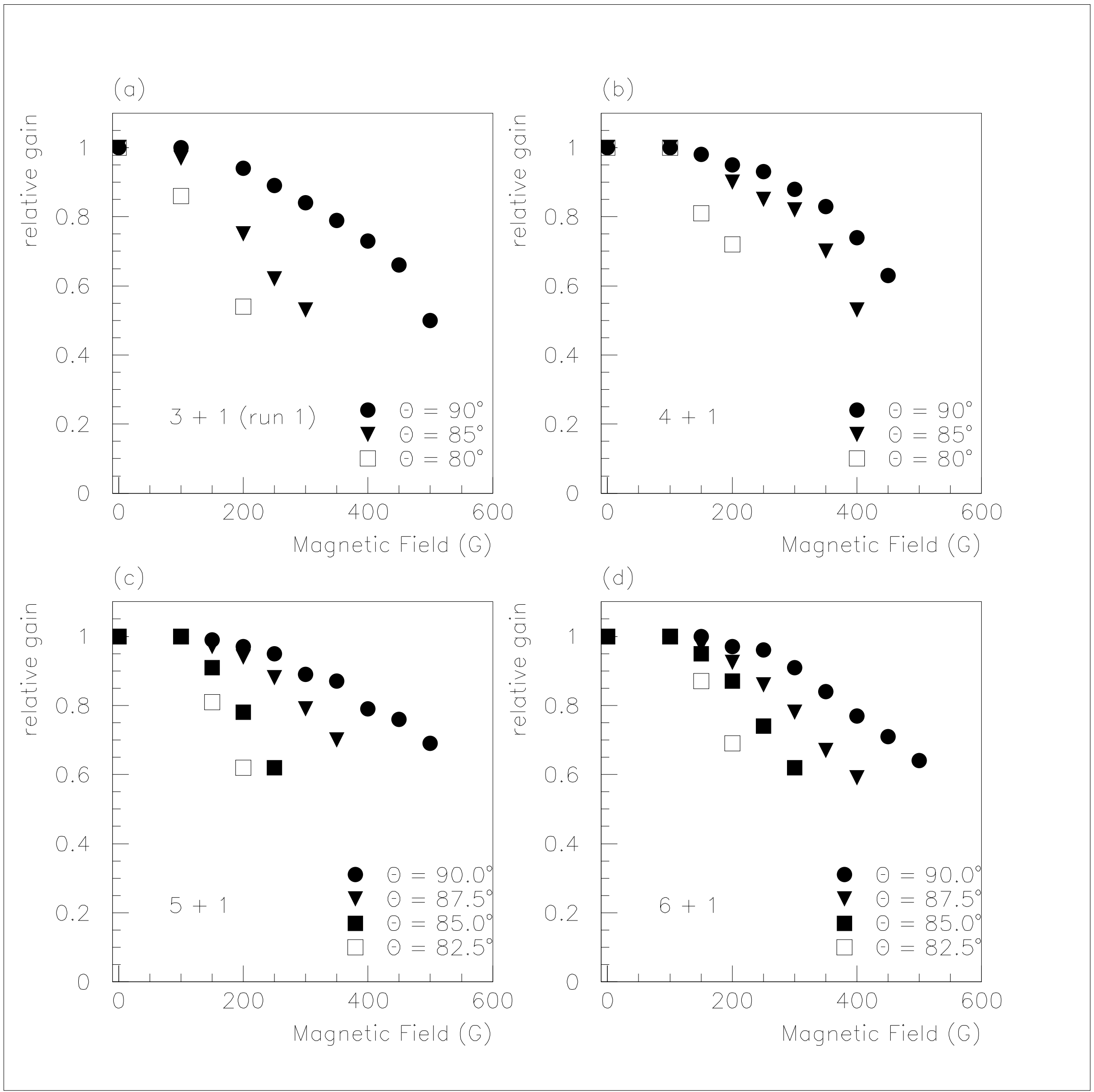

Figure 1: The relative PMT gain as a function of magnetic field strength for various angles of orientation using different combinations of the Run 1 shielding: (a) 3 layers of transitional steel + 1 layer of μ-metal — the run 1 configuration; (b) 4 layers of transitional steel + 1 of μ-metal; (c) 5 transitional steel + 1 μ-metal; and, (d) 6 transitional steel + 1 μ-metal.

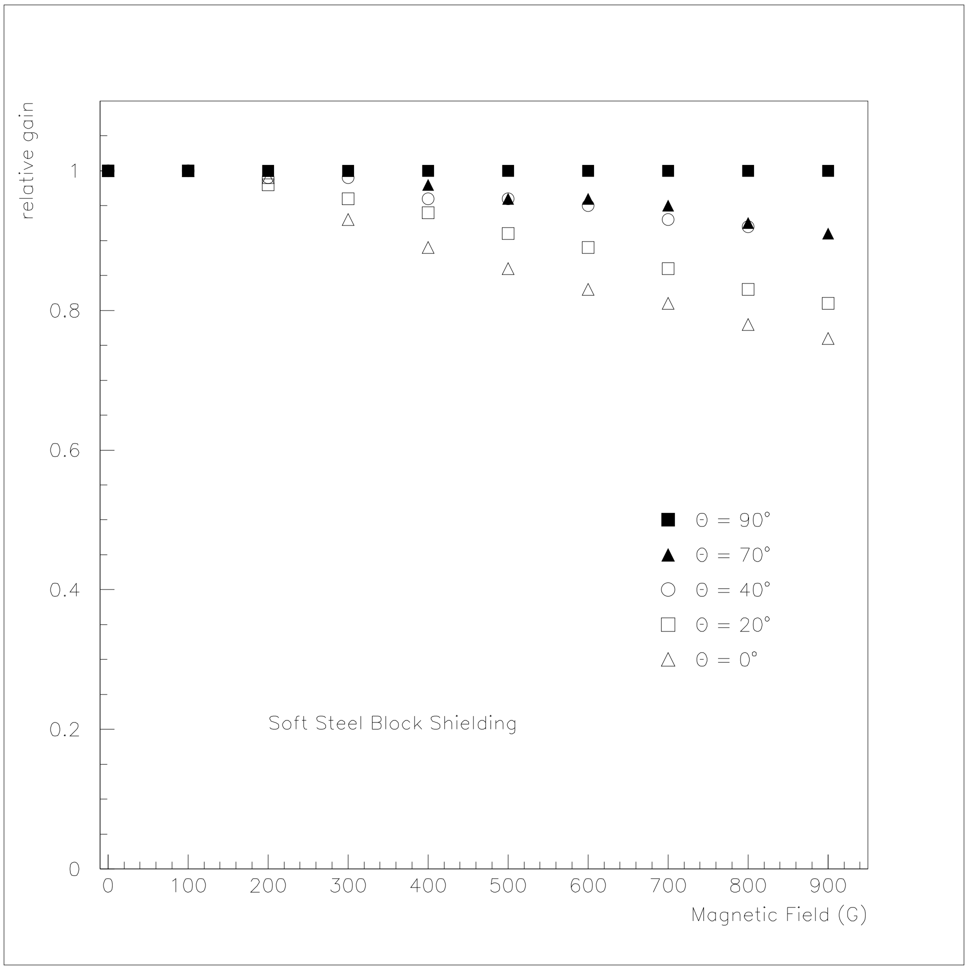

Figure 2: The relative PMT gain as a function of magnetic field strength for various angles of orientation using a soft steel block for shielding plus a single thick μ-metal shield.

$\theta = 90°$, there is no loss whatsoever. This was the case for all field values we measured – up to $B = 2000$ G. At the opposite extreme, for the tube parallel to the field, $\theta = 0°$, the gain drops slowly with increasing field. The dependence of the PMT gain as a function of $\mathbf{B}$ for intermediate angles, $40° < \theta < 70°$, is smooth and only weakly dependent on the specific angle.

3.3 Commercial Steel Pipe Shielding

The cheapest alternative to extending the Run 1 shielding is to use a piece of cold rolled steel pipe around the central μ-metal shield with an air gap between them. Our steel pipe was of cylindrical symmetry, 7.8 cm long with an inner radius of 2.28 cm and outer radius of 2.40 cm. Figure 3 gives the relative PMT gain as a function of magnetic field for three

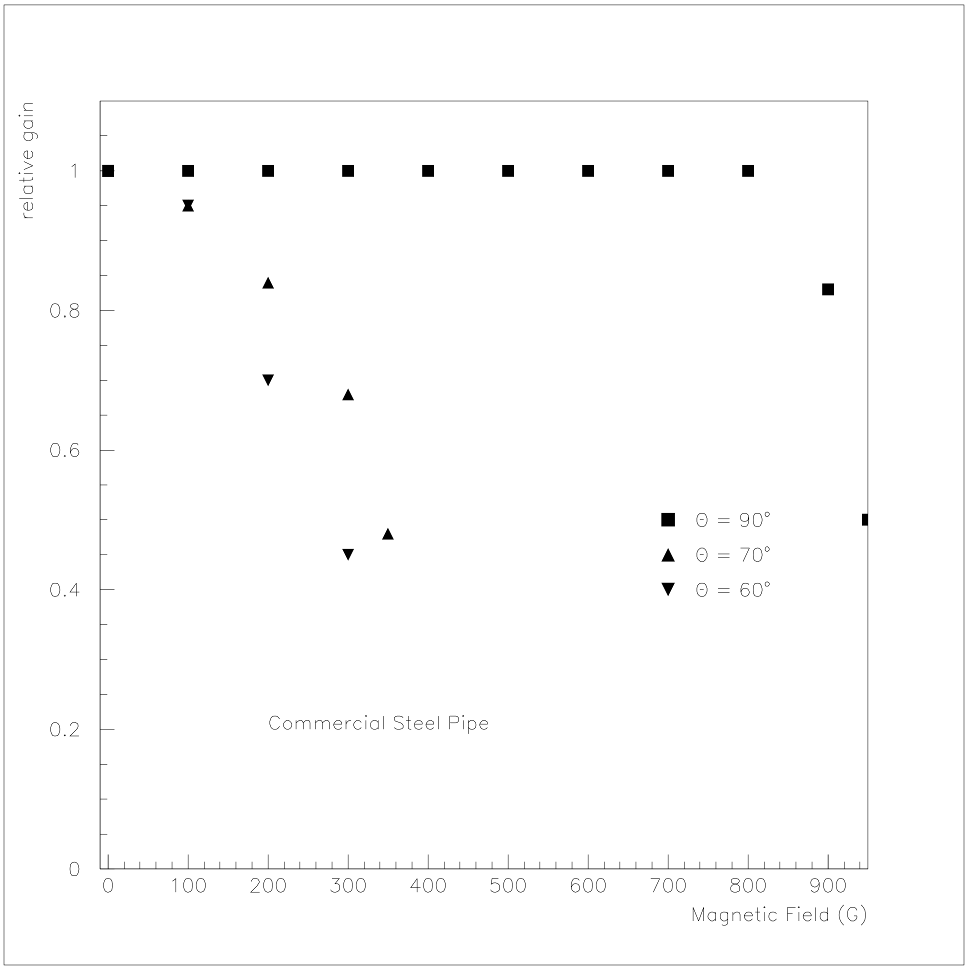

Figure 3: The relative PMT gain as a function of magnetic field strength for various angles of orientation using a commercially available cold rolled steel pipe plus an inner layer of μ-metal.

angles. At 90° the gain is unaffected by the field until $\mathbf{B} = 800$ G where it drops abruptly, exhibiting sharp threshold behavior. As the PMT is rotated and $\mathbf{B}$ obtains a component parallel to the PMT axis, the gain drops at much lower field values, though with a less abrupt threshold. From the perspective of PMT shielding for the Run 2 ICD, this situation does not meet our shielding specifications.

3.4 Soft Steel (1020) Tube Shielding

We tested a soft steel cylinder 9 cm long with outer radius 1.75 cm and inner radius 1.13 cm (i.e., 6.2 mm thick) around the central μ-metal shield with an air gap between them. Before performing the measurement we were confident that this situation would reproduce the results of the soft iron block, after all it's the same media and it is still quite thick.

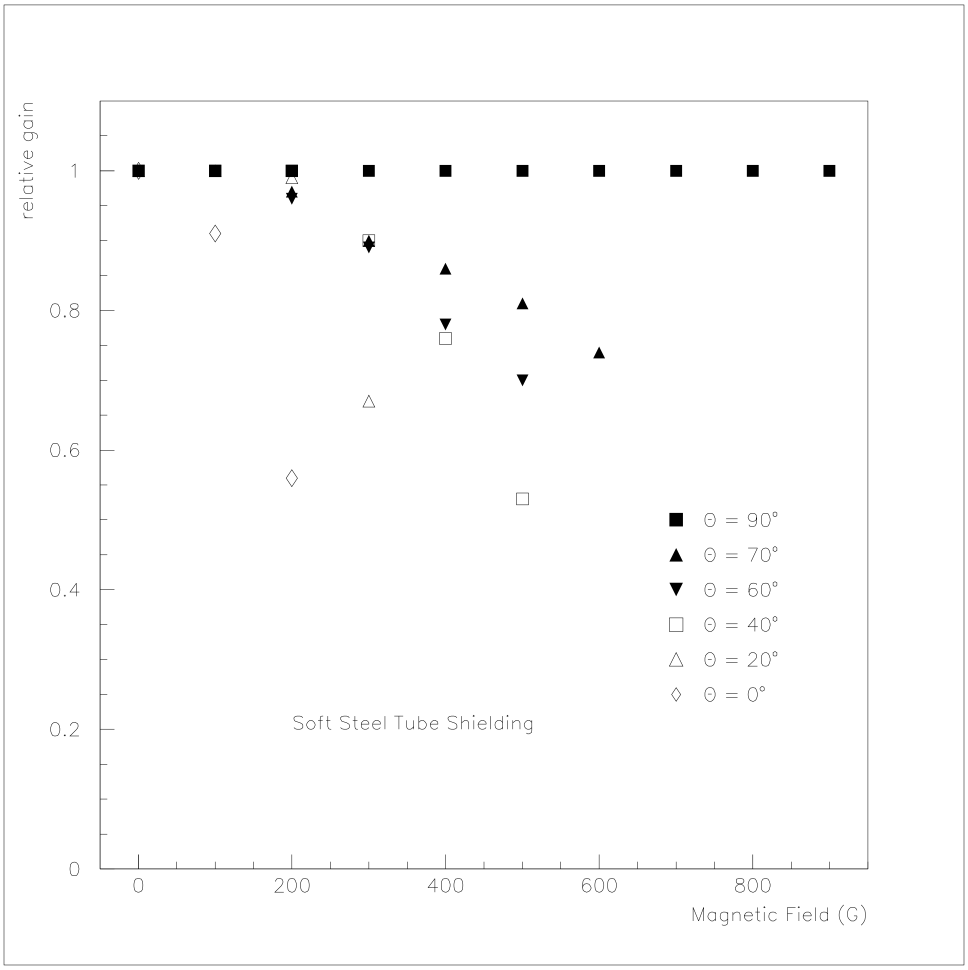

Figure 4: The relative PMT gain as a function of magnetic field strength for various angles of orientation using a thick soft steel tube plus an inner layer of μ-metal.

The results are given in Fig. 4. The gain is much more dependent on the axial angle for the tube than for the block (Fig. 2). This is probably caused by a combination of the decrease in the volume of iron in going from a rectangular block to a thick cylinder and the larger inner radius of the tube. That these qualitatively small geometric changes resulted in such huge differences in shielding effectiveness was quite a surprise. Evidently the increased volume of the rectangular block geometry provides substantial permeability for containing the magnetic flux.

4. Recommendation for the Run 2 ICD

We have studied the dependence of the ICD photomultiplier tube gain on magnetic field strength and axial angle with four distinct methods of magnetic shielding. We tested shielding configurations for a single PMT in a field ranging from 100 to 2000 G to determine the optimum design for a field of less than 350 G. At the time this is written we don't know what the axial angle will be when the ICD readout drawers are mounted in the pig troughs.

As a mechanism for summarizing our results we arbitrarily define effective shielding to be gain reduced less than 20% at 300 G: With a combination of transformer steel and μ-metal shielding, available from the Run 1 ICD, the gain exhibits a strong axial angle dependence rendering the shielding ineffective for axial angles less than 85°; a piece of commercially available cold rolled steel piping around a layer of μ-metal proved highly effective at 90° but was ineffective by 70°; a thick soft steel tube around a layer of μ-metal was effective out to about 60°; and, a rectangular block of soft steel with a hole bored through combined with an inner layer of μ-metal maintained effective shielding even with the PMT axis parallel to $\mathbf{B}$.

Based on our measurements we recommend that each PMT have a rectangular block of soft (less than 0.2% carbon content, i.e., 1020 or less) steel of dimensions consistent with that we tested ($9.0 \times 3.5 \times 3.5$ cm with a 2 cm diameter hole). The large qualitative difference between this geometry and our measurements for the same material but with thick cylindrical geometry indicate that the volume of highly permeable media is a crucial element in the shielding effectiveness. Therefore we cannot endorse variations on the shielding scheme beyond our recommendation of block geometry, except to use iron of greater purity, without further testing.

Acknowledgements

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   Hamamatsu Photonics K.K., "Photomultiplier Tubes and Assemblies For Scintillation Counting and High Energy Physics," (Hamamatsu, Japan, 1994). The Hamamatsu Corporation Main Office phone number in the USA is (908)231-0960.

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5. BNC Pulse Generator, Model 8010.

6. LeCroy 612AM photo-multiplier amplifier, 200 MHz bandwidth, 2.5 - 40× gain, 5 V linear range.

7. LeCroy qVt 3001, Multichannel Analyzer for Charge, Voltage, or Time. The Maximum charge resolution of this device was 0.25 pC, for our measurements it was most convenient to separate the scale into four partitions each with resolution of 1.0 pC.

8. Magnetic Shield Corporation, 6P35, "co-netic" shielding.