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Optics for E951 Target Tests in the A3 Beamline

1 Introduction

In experiment E951 [1] we will conduct studies of the interaction of intense proton pulses with liquid metal targets.

In the initial studies we plan to use a 24-GeV proton beam of up to 1.5×10^{13} per pulse, with a pulse width of about 30 ns FWHM, and a spot size of 1 mm rms radius. A candidate liquid target material is mercury, whose density ρ is 13.6 g/cm^3, and whose minimum de/dx is 1.1 MeV gm^{-1} cm^2. The density of energy deposition u due to ionization of the protons is about 33 J/gm. Additional ionization due to secondary particles from interactions of the protons in the target raises this to a peak of about 100 J/gm at 10 cm into the target, according to a MARS calculation [2], as shown in Fig 1.

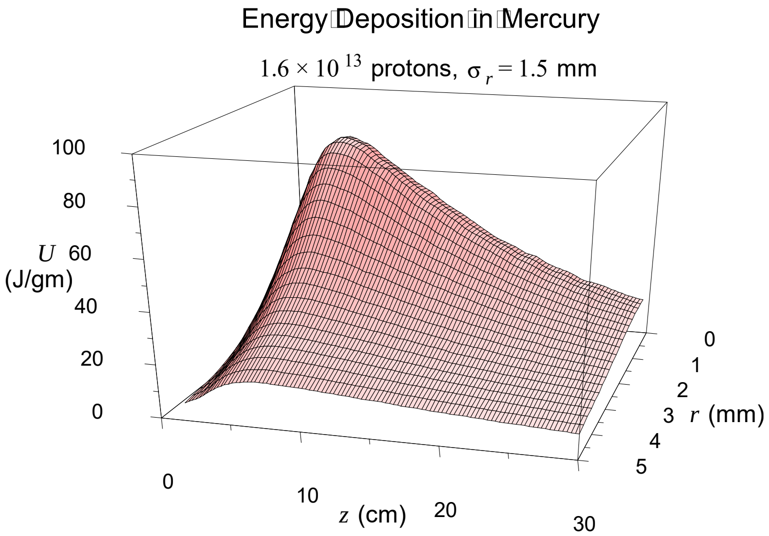


Figure 1: A MARS calculation of the profile of energy deposition by 24-GeV protons in a 30-cm-long mercury target [2].

The energy deposition u leads to pressure waves of peak stress P that can be estimated as,

$$P \approx \frac{\alpha_V E_V u}{C}, \tag{1}$$

where $\alpha_V = 3\alpha$ is the volume coefficient of thermal expansion, E_V is the bulk modulus (inverse of compressibility) and C is the heat capacity per unit mass. Mercury is a candidate target material, for which $\alpha_V = 180 \times 10^{-6}$ K^{-1}, $E_V = 25$ GPa, and $C = 138$ J K^{-1} kg^{-1} [5]. A peak value of $u = 100$ J/gm then corresponds to peak stress of about 3000 MPa, many times the tensile strength of steel.

In addition, the energy deposition heats the mercury target close to its boiling point (which differs from that at atmospheric pressure due to the pressure wave in the target [3]).

These effects make it probable that the mercury target will be disrupted by the proton beam, possibly leading to breakup into droplets. An estimate of the velocity of the droplets is given by the radial increase of the liquid mercury, $\Delta r \approx \alpha u r/C$, due to the energy deposition u, divided by the time of propagation r/v_s of the pressure wave over the target radius [4]. The speed of sound in mercury is $v_s = 1300$ m/s, which gives about 50 m/s in the present example. The characteristic time for the onset of droplet formation is $r/v_s \approx 6$ μs for a target of radius $r = 1$ cm.

The disruption of a liquid metal target by the proton beam will be somewhat reduced by magnetic damping associated with the eventual placement of the target inside a 20-T solenoid. However, the initial target studies in E951 will be performed in zero magnetic field.

2 Optical Diagnostics

A high-speed camera system is being designed as the primary diagnostic of the effects of the proton beam on liquid targets in E951. Since the minimum time scale is of order a few μs, the camera must have a frame rate of up to about 10^6 fps. We have purchased a model 64K1M camera from Silicon Mountain Design [6], whose properties are given in Fig. 2 and Table 1.

The sensor is a 960 × 960 pixel CCD of total area 1.34×1.34 cm^2. An electronically controlled mask on the surface of the CCD obscure 15 out of 16 pixels in each 4 × 4 group at any given time, so that a single frame actually consists of 240 × 240 pixels. The active pixel can be switched in 1 μs, leading to the possibility of recording 16 frames in as little as 16 μs. The entire CCD is read out in the usual "bucket-brigade" fashion in 1/30 s, *i.e.*, at usual NTSC video rate.

To view perturbations to the target on a μs time scale, we must also have an intense light source.

The mask reduces the photosensitive area to 0.03 of the nominal pixel area. The quantum efficiency of the photosensitive area is 0.18 at 800 nm, and the pixel full well is 200,000 electrons. A full exposure of a frame of the CCD therefore requires $(960)^2 \cdot 2 \times 10^5/0.03/0.18 \approx 4 \times 10^{13}$ photons. For a uniform exposure over 1 μs, about 4×10^{19} photons would be required, or about 10 Watts for 800 nm photons. For "stop-motion" photography with illumination of, say, only 0.2 μs with 1 μs between frames, a 50 Watt, pulsable light source is required for full exposure.

These numbers are based on the use of shadow photography. Much higher powers would be required for reflective photography, which we consider impractical.

An isotropic light source that delivered 50 Watts into 1 cm^2 at 10 m distance would have 500 megawatt power. To be practical, we use a directed light source – a laser.

A convenient light source is an 808 nm, 15-Watt, fiber-coupled laser diode, such as model

Table 1: Specifications of the SMD 64K1M camera [6].

Imager	
Sensor	Custom Interline Transfer CCD
Format	240 × 240 pixels
Pixel size	56 μm × 56 μm
Active area	13.4 mm × 13.4 mm
Full Well Capacity	220 Ke^-
Fill Factor	3%
Camera Operating Parameters	
Frame Rate (max)	10^6 fps, in up to 15 bursts/sec
Sync	Internal/External
Video	12 bit RS-422 or LVDS (4 channels @ 10 MHz)
Remote RS-232 Control	Sync mode, trigger mode, electronic shutter, frame rate
Dynamic Range/Optical	
Dynamic Range	70dB
Read Noise	Less than 1.3 counts rms
Sensitivity	8 μV/e
Dark Current	300 e/pixel per second @ 25C
Quantum Efficiency	18% max. @ 740 nm
Mechanical & Environmental	
Lens Mount	C-mount
Dimensions (W × H × L)	$3.7'' \times 3.7'' \times 4''$
Power	30 Watts
Mass	30 oz (0.85 kg)

SMD 64K1M Camera • 240x240, 1,000,000fps, 12 bits

SMD has solved the problem of real-world interface to hyper-speed cameras

Features

- **Ultra High Frame Rate with Electronic Shutter.** Up to one million frames per second at 240x240 resolution from a custom-designed interline transfer sensor.
- **High Quality Images.** The custom sensor's electronic shutter allows crisp, clear images without smearing, even at maximum frame rate. True 12-bit dynamic range preserves superior image quality, even in low light conditions.
- **Flexible Data Readout.** The sensors's multiple parallel channels of image data are digitized, buffered, and output through four 12-bit wide ports at 10MHz each. Maximum readout is 15 bursts per second of 17 consecutive frames.
- **Compact and lightweight.** Small form factor to ease system integration.
- **Internal/External Sync.** Asynchronous-mode frame capture, externally triggerable to within 250 nanoseconds.
- **Extended Spectral Response.** Sensitive to UV and near IR wavelengths.

Figure 2: The SMD 64K1M camera that can record a 16-frame clip in as little as 16 μs [6].

SLI-CW-FCLD-B2-808-15M-F from Semiconductor Laser International [7], shown in Fig. 3, whose specifications are given in Table 2. This should provide a background illumination level of about 20% of full exposure, *i.e.*, about 800 counts out of 4192 per pixel. Even if absorption in various windows and mirrors amount to 50

To pulse this laser diode in as little as 150 ns, we use a model AVOZ-A1A pulser from Avtech [8]. To perform photography at any frame rate between 30 and 10^6 fps, the pulser must be triggered by a train of 16 pulses at the desired spacing. For this we use a model Compugen 1100 ISA-bus arbitrary waveform generator from Gage Applied, Inc [9].

The CCD camera, the diode laser and the various support electronics are all radiation sensitive, and will not be located inside the A3 target cave. Rather, they will be located outside the east wall of the cave, some 4 m upstream of the target position, as shown in Fig. 4. The optical path length from the target to the camera is about 8 m, with the optic axis folded by two mirrors.

The light from the laser diode will be transmitted into the target cave on an optical fiber, which terminates close to the target on the west side of the cave.

The conceptual layout of the optical system from the end of the optical fiber to the CCD

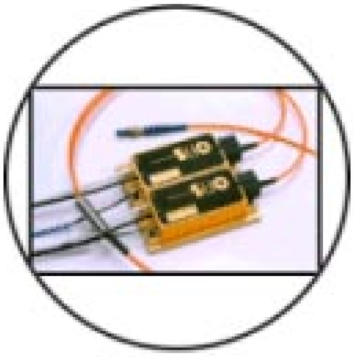


Figure 3: The 15-W, fiber-coupled, 808-nm laser diode [7].

Table 2: Specifications of the SLI 15-W, fiber-coupled, 808-nm laser diode [7].

Parameter	Min.	Typical	Max.	Unit
Power		15		W
Threshold Current	2	3	4	A
Operating Current	14	16	18	A
Numerical Aperture		0.22		
Operating Temperature		25		C
Voltage	3.6	4.0	4.2	V
Slope Efficiency	1.1	1.3	1.5	W/A
Wavelength Tolerance	±3.0	±5.0		nm
Connector Type		SMA 905		
Fiber Core Size		840		μm

camera is shown in Fig. 5, in which the vertical scale is expanded relative to that of the horizontal. A large Fresnel lens captures the output beam of the laser diode and focuses it through the field of view at the target onto the lens of the telescope. The CCD camera views the target through the telescope.

The distance c from the target to the telescope lens is 8 m. The aperture of the CCD sensor is $B = 0.0134$ m. The distance d from the telescope lens to the CCD is related to the

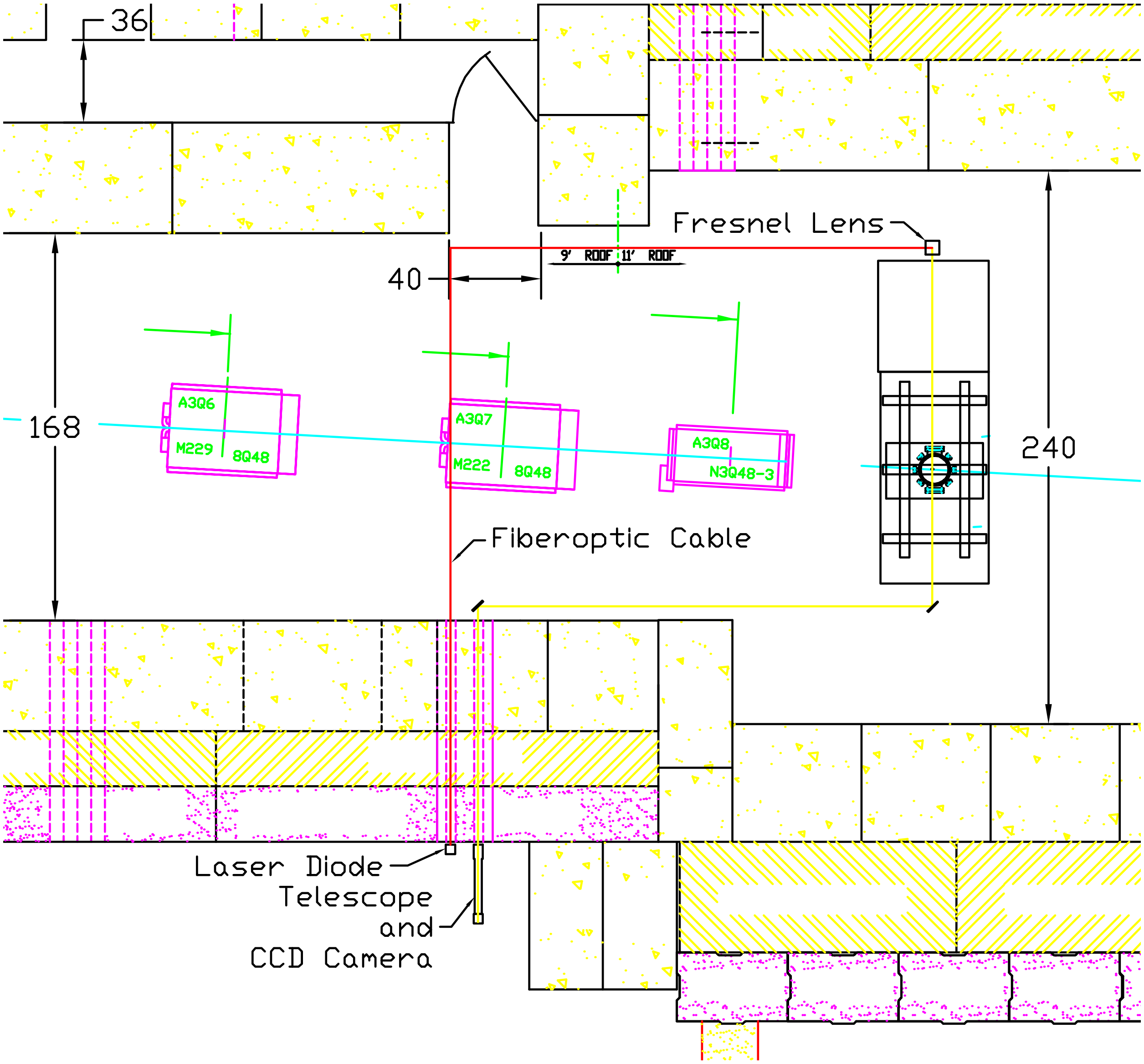


Figure 4: Layout of the optical transport between the laser diode and the high-speed camera in the A3 beamline for experiment E951.

desired field of view A at the target according to,

$$d = c\frac{A}{B}. \tag{2}$$

For the target to be in focus, we must also obey the lens formula,

$$\frac{1}{f} = \frac{1}{c} + \frac{1}{d}. \tag{3}$$

Hence, the focal length f of the telescope must be,

$$f = c\frac{B}{A+B}. \tag{4}$$

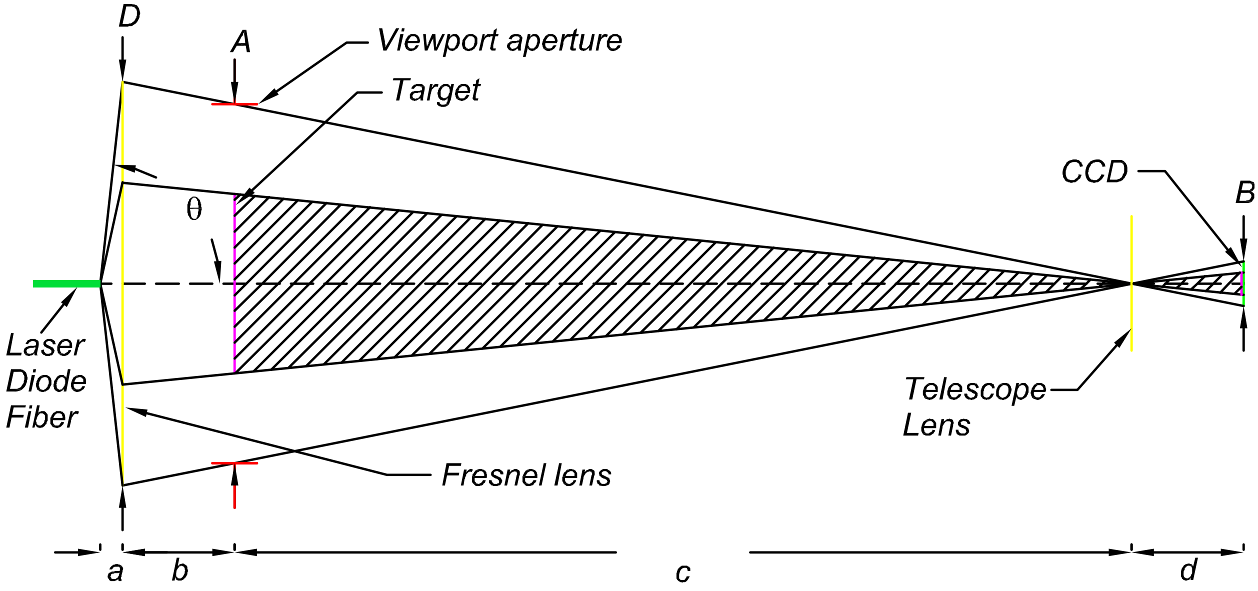


Figure 5: Plan view of the optical system for shadow illumination of the target in E951.

For example, a field of view of $A = 10$ cm requires $f = 0.95$ m. In this case, each pixel of the CCD image would correspond to a square of 400 μm at the target. A simple telescope with focal length close to this value is the Celestron C80-HD [10] with $f = 0.9$ m. Such a telescope is designed to focus on far objects, and its tube must be extended to focus as close as $d = 8$ m.

The output of the laser diode fiber has a numerical aperture of 0.22, corresponding to a half angle $\theta = 0.12$ rad. The distance a from the end of fiber to the field lens of aperture D is therefore given by,

$$a \approx \frac{D}{2\theta}. \tag{5}$$

To protect the field lens from radiation damage, it should be placed behind shielding blocks, and should view the target through a mirror, as shown in Fig. 6. Hence, distance b should be of order 3 m.

The aperture D of the field lens is then related by,

$$D = A\frac{b+c}{c} = 13.75 \text{ cm} \tag{6}$$

for $A = 10$ cm and $c = 8$ m. Distance a is therefore about 0.6 m according to eq. (5).

The focal length F of the field lens is related by,

$$\frac{1}{F} = \frac{1}{a} + \frac{1}{b+c}, \tag{7}$$

or $F \approx a \approx 0.6 \text{ m} \approx 24''$, since $a \ll b + c$.

The diameter $D \approx 14$ cm of the field lens is large for a glass lens. As the quality of the field lens need not be high, it suffices to use a plastic Fresnel lens, such as available from

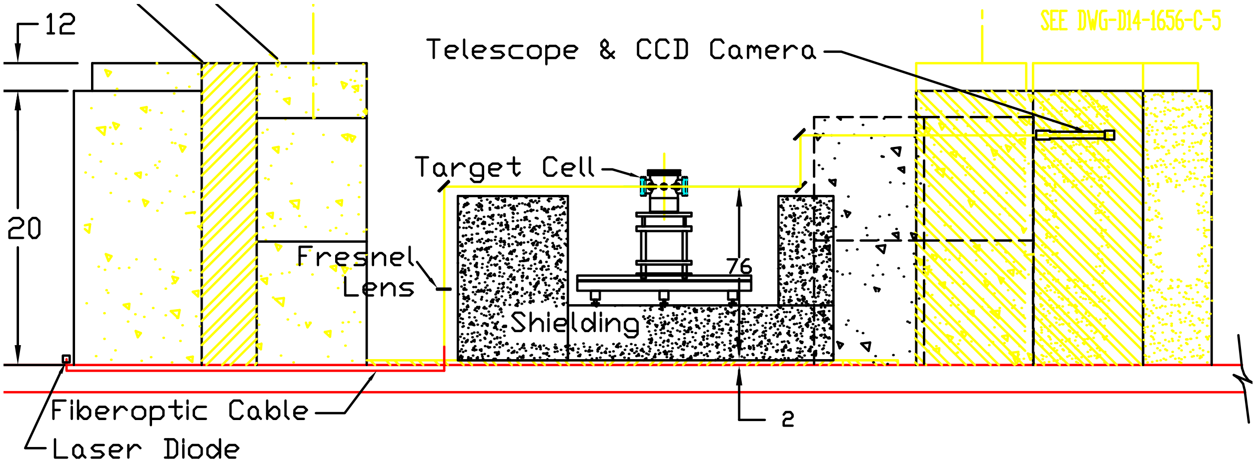


Figure 6: Elevation view of the schematic of the optical system for shadow illumination of the target in E951.

Edmund Scientific [11]. Model NT32-691 with a 24″ focal length and 11″ × 11″ area would suffice.

3 Optical Windows for the Liquid Metal Containment Vessel

The liquid metal targets to be tested in E951 will be viewed using the optical system described above through two pairs of windows, on the inner and outer containment vessels, respectively. These windows must contain any possible spray of hot liquid metal due to intense beam energy deposition, and remain reasonably transparent after the radiation dose of, say, 100 pulses of 1.6×10^{13} protons on target.

3.1 Required Impact Resistance

As discussed in the Introduction, the pressure wave induced by the proton beam energy depostion might lead to dispersal of the liquid jet into droplets of velocity $v \approx 50$ m/s (170 fps). If the entire liquid column that interacts with the jet were so dispersed, the total mass of the mercury droplets would be $\pi \rho r^2 l = \pi \cdot 13.6 \cdot 0.25 \cdot 15 = 160$ g, assuming that the jet radius is $r = 0.5$ cm and the interaction length is $l = 15$ cm.

A window of 5-cm radius at a distance of 16.5 cm from the beam axis has fractional solid angle of $\pi \cdot 5^2/4\pi 16.5^2 = 0.023$. Assuming isotropic dispersal of the droplets, the mass of mercury impacting on the window would be $m = 3.7$ g. The peak force on the window is $\Delta P/\Delta t$, where $\Delta P \approx mv$ and $\Delta t \approx r/v$. Then,

$$F \approx \frac{mv^2}{r}. \tag{8}$$

3.2 Temperature Requirement

The peak energy deposition in mercury from a pulse of 1.6×10^{13} protons with a radius of 1 mm is about 100 J/g. The heat capacity of mercury is 0.14 J/K-g, which suggests that the temperature of core of the jet would rise briefly by as much at 700C. If the pressure waves redistribute the energy such that a quasi-uniform temperature is attained before the jet disperses, the temperature rise of a 5-mm-radius jet would be $700/5^2 = 28$C.

The maximum temperature of the mercury that hits the window is somewhere between these values, but could well be over 100C. The window must retain mechanical integrity and optical transparency after being struck by mercury droplets of this temperature.

3.3 Radiation Dose

A MARS calculation of the radiation dose on a window at 16.5-cm transverse distance from the beam is shown in Fig. dose.

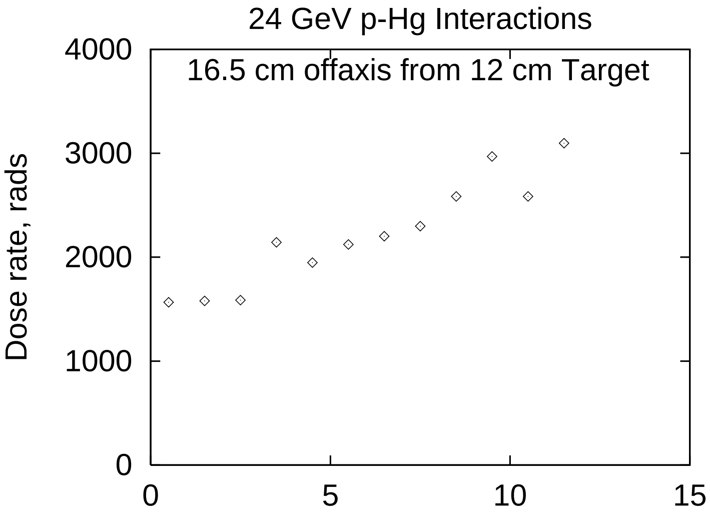


Figure 7: Radiation dose *vs.* longitudinal position on a window at 15-cm transverse distance to a pulse of 1.6×10^{13} 24-GeV protons hitting a mercury target, according to a MARS simulation.

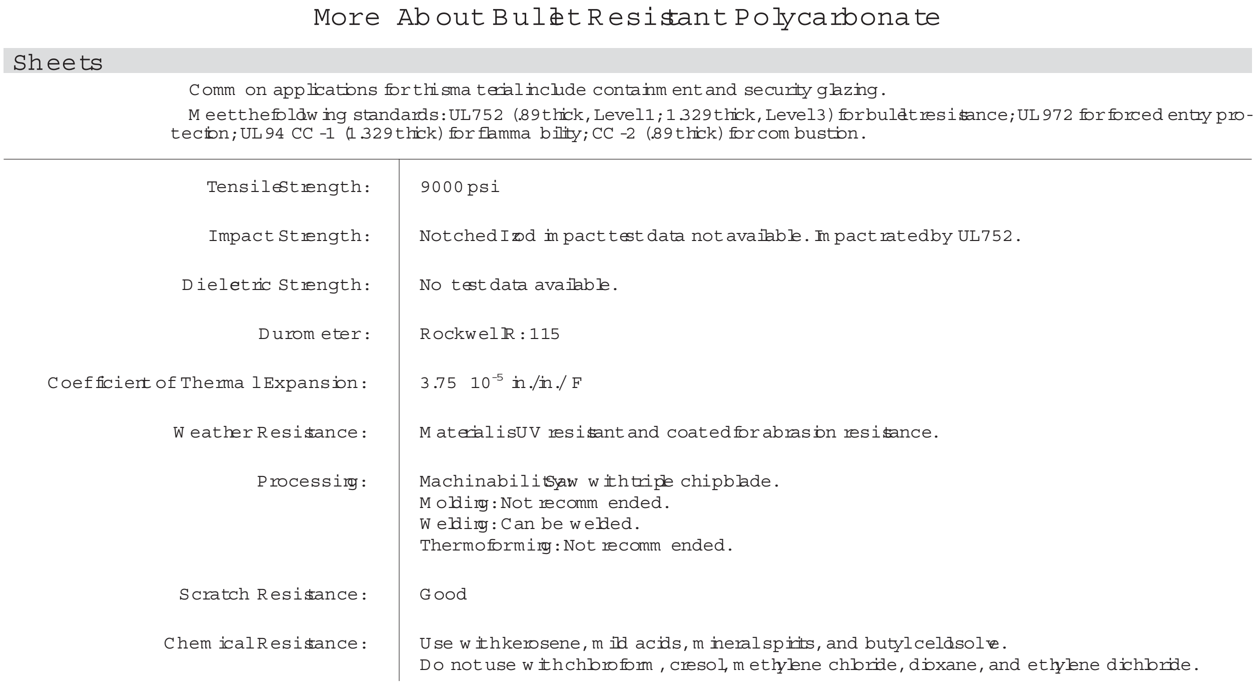
The accumulated dose after 100 pulses of 1.6×10^{13} 24-GeV protons would be about 200 kRad. The window must remain optically transparent at such dose.

3.4 Candidate Window Materials

1. Glass. A simple solution would be a glass window, 10 cm in diameter mounted in a 6″ conflat flange, such as MDC Vacuum part no. 450006. The window has a thickness of 1/4″.

2. Quartz. This material retains good optical transparency up to doses of order 1 GRad. A 10-cm-diameter quartz window mounted in a 6″ conflat flange, such as MDC Vacuum part no. 450024 has a thickness of 1/4″.

3. Lexan (polycarbonate). Polycarbonate sheets have much better impact resistance that glass or quartz. A 0.8″-thick 3-layer polycarbonate laminate with a UL 752 level I bullet resistance rating is readily availabe from McMaster-Carr. See Fig. 8.



More About Bullet Resistant Polycarbonate

Sheets

Common applications for this material include containment and security glazing.

Meet the following standards: UL752 (.89 thick, Level 1; 1.329 thick, Level 3) for bullet resistance; UL972 for forced entry protection; UL94 CC-1 (1.329 thick) for flammability; CC-2 (.89 thick) for combustion.

Tensile Strength:	9000 psi
Impact Strength:	Notched Izod impact test data not available. Impact rated by UL752.
Dieletric Strength:	No test data available.
Durometer:	Rockwell R: 115
Coefficient of Thermal Expansion:	3.75 10^{-5} in./in./ F
Weather Resistance:	Material is UV resistant and coated for abrasion resistance.
Processing:	Machinability: Saw with triple chip blade. Molding: Not recommended. Welding: Can be welded. Thermoforming: Not recommended.
Scratch Resistance:	Good
Chemical Resistance:	Use with kerosene, mild acids, mineral spirits, and butyl cellosolve. Do not use with chloroform, cresol, methylene chloride, dioxane, and ethylene dichloride.

Figure 8: Specification of a polycarbonate laminate from McMaster-Carr.

4. Glass-lexan laminate. Better performance than lexan at high temperature can be obtained with an impact resistant glass-lexan laminate, such as provided by Ballistica (Fig. 9), where (perhaps surprisingly) the impact face is made of glass.

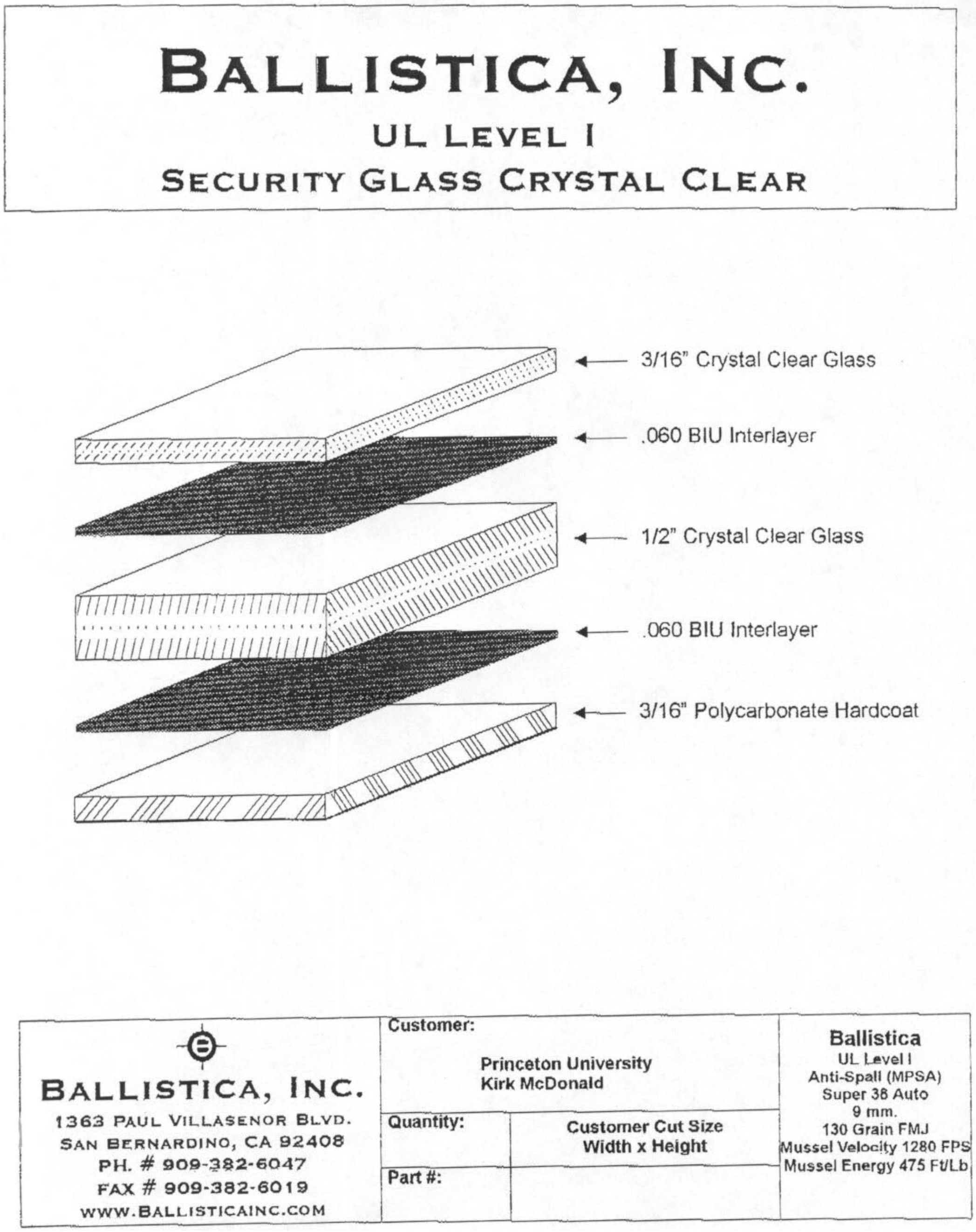
3.5 Impact Tests

We have tested several candidate window materials using a paintball gun. A paintball is a 2.75 g sphere of radius 8.6 mm (68 caliber) containing a colored gel that readily "splats" on impact. The muzzle velocity of paintball guns is about 300 fps.

The ratio of the force (8) from a paintball to that due to the possible dispersal of the entire mercury jet by the proton beam is,

$$\frac{F_{\rm paintball}}{F_{\rm mercury}} = \frac{m_{\rm paintball}}{m_{\rm mercury}} \frac{v^2_{\rm paintball}}{v^2_{\rm mercury}} \frac{r_{\rm mercury}}{r_{\rm paintball}} = \frac{2.75}{3.7} \frac{300^2}{170^2} \frac{5}{8.6} = 1.3. \tag{9}$$

That is, the impact of a paintball is very similar to that of a fully dispersed mercury jet.



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Quantity:

Customer Cut Size
Width x Height

Part #:

Ballistica
UL Level I
Anti-Spall (MPSA)
Super 38 Auto
9 mm.
130 Grain FMJ
Mussel Velocity 1280 FPS
Mussel Energy 475 Ft/Lb

Figure 9: A glass-polycarbonate laminate from Ballistica, Inc.

We use a Kingman Spyder Compact 2000 paintball gun, and a Competition Electronics Prochrono to verify the muzzle velocity of the gun, as shown in Fig. 10.

The 1″ glass-lexan laminate from Ballistica, the 0.8″ lexan laminate from McMaster-Carr, and even a single 1/4″ lexan sheet all survived paintball splats with muzzle velocities of 320 fps (Figs. 11-12. However, the MDC window no. 45006 broke from a splat of 300 fps (Fig. 13, after surving one with 280 fps. No quartz window has been tested yet.

Figure 10: The impact resistance test setup with a Kingman Spyder paintball gun and a Competition Electronics Prochrono timer. The distance from the gun to the window under test was about 2 m.

References

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[2] Harold Kirk, private communication.

[3] Nikoloas Simos, private communication.

[4] P. Sievers and P. Pugnat, *Response of Solid and Liquid Targets to High Power Proton Beams for Neutrino Factories*, CERN-NuFact Note035 (Oct. 12, 2000),
http://physics.princeton.edu/~mcdonald/mumu/target/Sievers/nf35.pdf

[5] Web-accessible tables of material properties are maintained by Goodfellow Corporation, 800 Lancaster Avenue, Berwyn, PA 19312-1780,
http://www.goodfellow.com/static/A/HG00.HTML

[6] Silicon Mountain Design, Inc., 5055 Corporate Plaza Drive, Colorado Springs, CO 80919. Camera model 64K1M: http://www.smd.com/products/64K1M.asp

Figure 11: Paintball splat (320 fps) on a 1″ glass-lexan laminate from Ballistica, Inc.

[7] Semiconductor Laser International Corporation, 15 Link Drive, Binghamton, NY, 13904. Laser diode model SLI-CW-FCLD-B2-808-15M-F, http://www.slicorp.com/main/products.html

[8] Avtech Electrosystems Ltd., PO Box 265, Ogdensburg, NY 13669-0265. Laser diode pulser model AVOZ-A1A: http://www.avtechpulse.com/laser/avoz-a1a/

[9] Gage Applied, Inc., 2000 32nd Avenue, Lachine, QC, Canada H8T 3H7, http://www.gage-applied.com/ftpsite/catalog/COMPUGEN/cg1100.pdf

[10] Celestron International, 2835 Columbia Street, Torrance, CA 90503. The C80-HD telescope is described at http://www.celestron.com/c80.htm

[11] Edmund Industrial Optics, 101 East Gloucester Pike, Barrington, NJ 08007-1380. Fresnel lens model NT43-018: http://www.edmundoptics.com/IOD/DisplayProduct.cfm?productid=2040

[12] E.A. Lee, *Dose and LET effects on optical density for electron or ion irradiated polymers*, to be published in the Proceedings of the 4th Int. Symp. on Ionizing Radiation and Polymers (IRAP2000).

Figure 12: Paintball splat (320 fps) on a 1/4″ lexan sheet.

Figure 13: A Paintball splat at 300 fps broke the 1/4″ glass window mounted in a 6″ conflat flange (MDC Vacuum no. 450006).