MEASUREMENT OF BEAM DRIVEN HYDRODYNAMIC TURBULENCE

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Abstract

Cooling intense muon beams in liquid hydrogen absorbers introduces kW of heating to the cold fluid, which will drive turbulent flow[1]. The amount of turbulence may be sufficient to help cool the liquid, but calculations are difficult. We have used a 20 MeV electron beam in a water tank to look at the scale of the beam driven convection and turbulence. The density and flow measurements are made with schlieren and Ronchi systems. We describe the optical systems and the turbulence measured. These data are being used to calibrate hydrodynamic calculations of convection driven and forced flow cooling in muon cooling absorbers.

INTRODUCTION

The schlieren method was discovered in 1864 by August Toepler[2]. This qualitative test allows one to see density fluctuations in a fluid. The general setup involves an objective lens or mirror, point light source, and a knife edge at the focus of the lens or mirror. The object to be visualized is placed between the objective and knife edge. The image can be directed onto a screen or into a camera. This is a highly sensitive test, allowing for precision measurements. The image obtained consists of a light and dark pattern corresponding to the density fluctuations. The placement of the knife edge determines whether a higher density region appears light or dark compared to the average background. A vertical knife edge is used to view density variations in the horizontal direction and a horizontal knife edge shows vertical density variations.

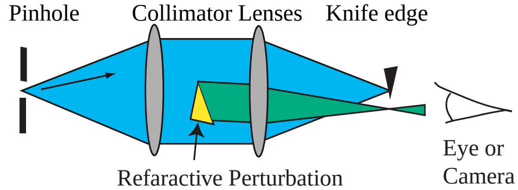

Figure 1. The Schlieren principle

In schlieren refraction, optical perturbations refract light in proportion to the gradients of refractive index in a direction perpendicular to the optical path. When the directly transmitted light is entirely or partially blocked, as in Fig. 1, the optical perturbations can be seen either with the eye or a camera.

The Ronchi method is an extension of the schlieren technique that can make quantitative measurements. Unlike the schlieren system, the Ronchi method is quantitative. Instead of a knife edge at the focus, a glass slide with closely spaced, parallel lines (ronchi ruling) is used. By knowing the spacing of these lines on the Ronchi ruling and the deflection of the lines in the image, it is possible to measure the magnitude of the refraction, and thus the density gradient in the sample.

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EXPERIMENTAL PROCEDURE

The electron linac used in this experiment is located at Argonne National Laboratory in the Chemistry Division. It delivers a beam of approximately 20 MeV. In our experiment, we used 50-200 pulses with approximately 30 nC per pulse. Pulse lengths ranged from 4-40 ns. During this experiment, we were the only users of the linac. The beam intensity was primarily a function of the pulse length, and the total beam power depended on the pulse repetition rate. Most of the data were taken at 30 to 60 Hz, which produced the scale of turbulence we needed for tuning up.

We used two setups, the first one with the beam perpendicular to the optical path and the second one with the beam close to colinear with the optical path. The collinear geometry was most relevant to checking the computational fluid dynamics models.

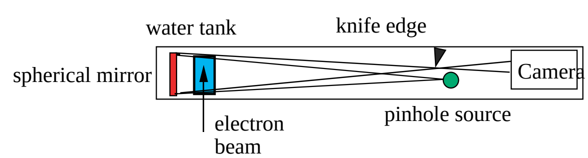

Figure 2, Transverse optical path and beam

In our first setup, we used a spherical mirror with a focal length of one meter, a knife edge, pinhole light source, and a digital camera to record the data, (Fig. 2). The water was placed in a rectangular tank with two optically flat 10 cm x 10 cm pieces of glass for the front and back windows. The optical depth was 5 cm and the sides were 0.8 mm thick aluminum. The top was open, but covered with a layer of G10, because evaporation at the surface produced eddies in the water after a period of a few minutes. The electron beam was directed into the tank through one of the aluminum sides. Behind the water tank was the spherical mirror. The placement of the knife edge and light source varied in different runs of this experiment but were always approximately one meter in front of the spherical mirror. The camera was placed about one and a half meters away from the mirror.

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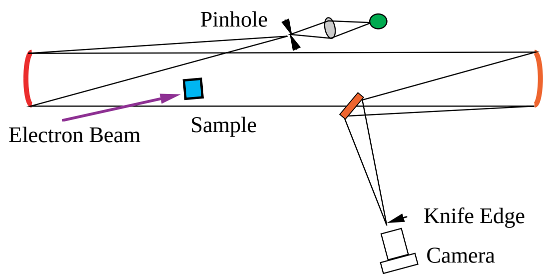

Figure 3, Colinear optical path and beam.

In the second setup, two spherical mirrors with focal length 91 cm were mounted two meters apart, as shown in Fig. 3. A 5 cm diameter. cylindrical tank with 5 mm thick fused quartz windows was placed between the spherical mirrors. A pinhole light source was placed slightly off-axis and pointed toward one of the mirrors. A small flat mirror was used to direct light away from the axis of the spherical mirrors toward the knife edge, and the camera was set directly behind. When two paraboloids are used off axis in this way, the dominant aberration, coma, is minimized.

In this experiment, we used the SILICON VIDEO® 2112 CMOS digital camera for data acquisition. The software used in conjunction with this camera is XCAP (V2.1.010611) from EPIX, Inc. The initial frame for each run was triggered manually. After this, the software took additional frames automatically at regular time intervals ranging from 1-5 seconds each. These frames were initially stored as binary files in the frame buffer and later converted via XCAP to JPEG file format.

The primary experimental complication was due to electrical pickup in the camera from the charge in the beam. When the apparatus was carefully grounded with low impedance conductors, this problem disappeared. We also saw significant Cherenkov light from the beam in the second setup. The Cherenkov light can be minimized or eliminated by a mask in front of the camera lens, since all schlieren or Ronchi data would pass through an aperture of mm dimensions, as was done in the first setup.

Figures 4, 5 and 6, show the beam power, beam profile at the entrance window to the target cell, and the beam radius as it passed through the cell. The beam radius increased due to the initial divergence of the beam, and multiple scattering in the water and windows.

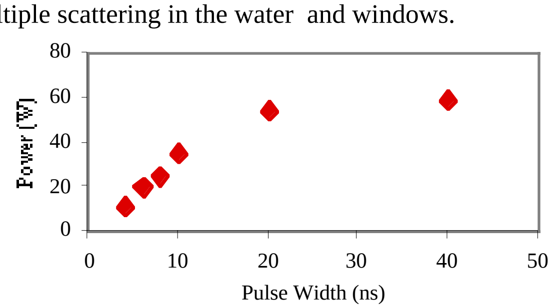

Figure 4, Beam power vs pulse length, at 30 Hz.

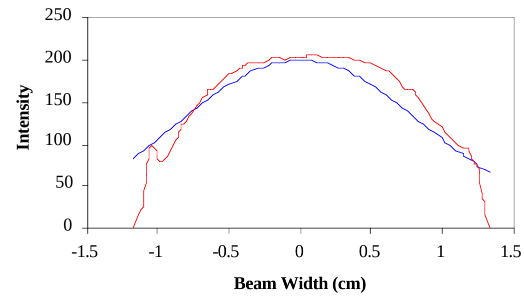

Figure 5, Beam profile.

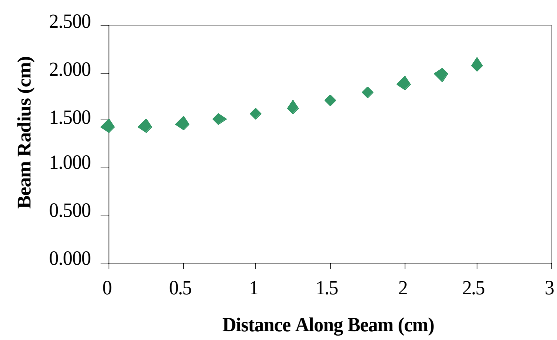

Figure 6, The beam size in the test cell

The second setup is shown in Fig. 7, which shows the two mirrors, test cell, camera and light source structure near the beam exit window of the linac.

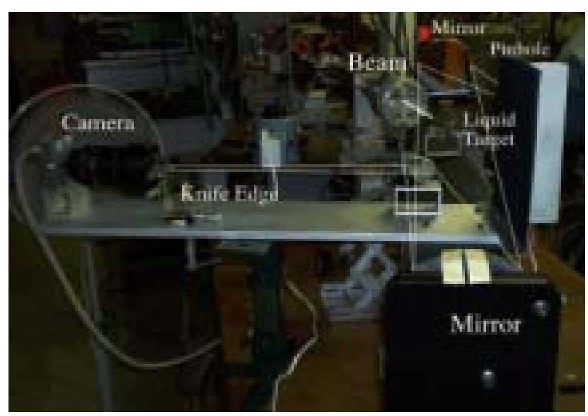

Figure 7, The colinear setup.

RESULTS

The data presented here are preliminary, since we have just begun to process the graphics, and have not had a chance to fully understand the density and velocity gradients in the cell. We have looked at perpendicular and colinear geometries, horizontal and vertical knife edge data which produces vertical and horizontal density gradients. We have also produced horizontal and vertical Ronchigrams which can be used to generate numerical estimates of the density fluctuations. This data were taken with time intervals between pictures of 0.5 to 2 s, and using a range of beam powers. We will show some example data. Fig. 8 and 9 show vertical and horizontal gradients viewed from the side, and Fig. 10 and Fig. 11 show vertical and horizontal colinear gradients. Fig 12 is taken with a vertical Ronchi grid.

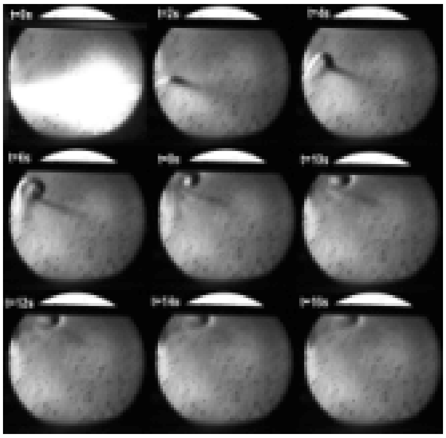

Figure 8, Transverse image, horizontal gradients

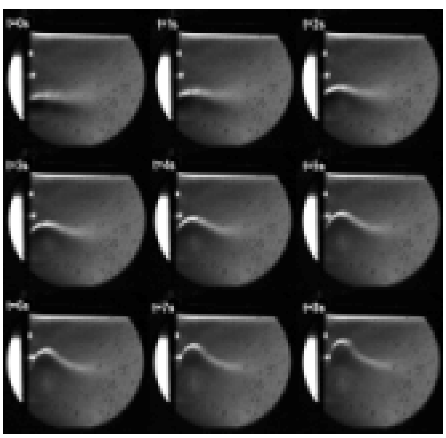

Figure 9, Transverse image, vertical gradients

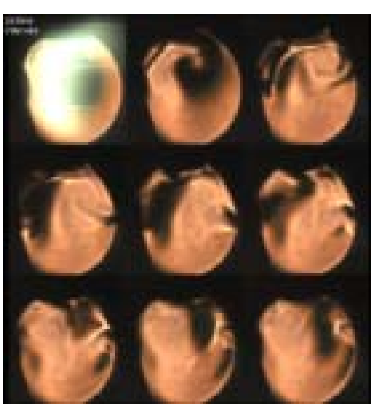

Figure 10, Colinear image, vertical gradient

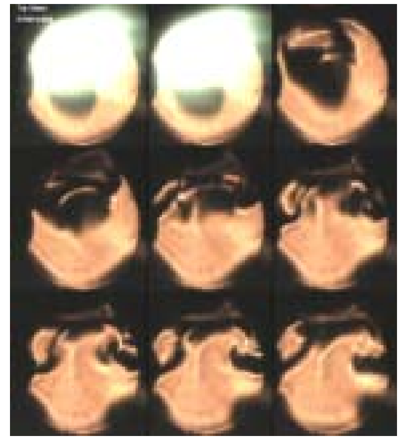

Figure 11, Colinear image, vertical gradients

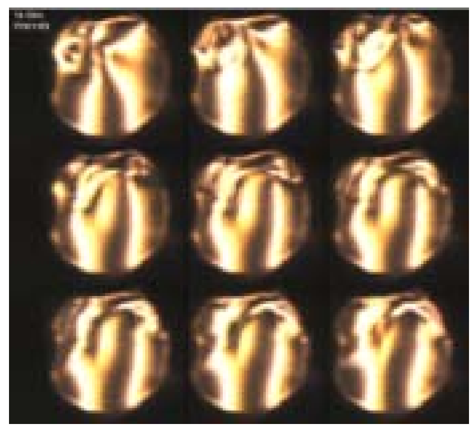

Figure 12, Colinear image, Ronchi pattern

This initial test of schlieren and Ronchi methods shows that density gradients in liquid targets are easily accessible. We plan to extend this work to quantitative comparison with predictions of computational fluid dynamics for high power beams in water and liquid hydrogen.

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[1] M. A. Cummings, et. al., in *Proceedings of NUFACT02*, London, (2002)

[2] Settles, G. S., *Schlieren and Shadograph Techniques* Springer-Verlag, New York, (2001)