Investigation of the Rayleigh-Taylor and Richtmyer-Meshkov instabilities

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1 Introduction

Some of the major difficulties encountered in the effort to achieve nuclear fusion by means of inertial confinement arise from the unstable behavior of the interface between the shell material and the nuclear fuel which develops upon implosion of the shell by direct or indirect laser drive. The fluid instabilities that develop are driven by the baroclinic generation of vorticity consequent to the non-zero cross product between the pressure and density gradients present at the interface. Depending on the time history of the driving laser pulse, the interface may be subjected to a nearly constant or nearly impulsive acceleration. The ensuing motions are termed the Rayleigh-Taylor (RT) or the Richtmyer-Meshkov (RM) instability, respectively. It is because of these instabilities that the gassified shell material ends up mixing with the nuclear fuel, causing a reduction in energy yield or no ignition altogether.

The present research program addresses the Rayleigh-Taylor and the Richtmyer-Meshkov instabilities with extensive laboratory and computational experiments.

2 Accomplishments

2.1 Laboratory experiments

2.1.1 Richtmyer-Meshkov instability

The RM experiments are performed in a vertical shock tube of large, square internal cross section. The shock tube is about 9 m long, with a 1.8 m driver section. A shock wave is generated by rupturing a steel diaphragm by gas overpressure. The driver section is at the top of the facility hence the shock initially travels downwards.

All RM shock tube experiments involve:
1) preparation of a gas interface;
2) acceleration of the interface by a shock wave;
3) measurement of relevant quantities at the interface, usually by optical diagnostics.

During the previous funding cycle (11/2000 - 11/2003) our group had developed a technique to prepare a continuous interface by initially separating a pair of gases using a thin, copper plate, with a sinusoidal shape imposed along one of its two dmensions. With the heavy and light gases above and below the plate, respectively, the plate was retracted out of the shock tube and, under the action of gravity, the RT instability started developing at the interface causing the initial amplitude of the sinusoidal perturbation of the gas interface to grow; a shock was released so that it would reach the interface when its shape was still single-valued. Planar Mie scattering images of the interface were recorded before and after the shock so as to always have precise information about the initial condition from which the RM instability developed. Planar imaging was peformed in a plane normal to the direction of plate retraction and both the pre- and post-shock images suggested that the flow was essentially 2-D.

The original plan for the current funding cycle was to continue using the retractable plate, and to build plates with cross sectional shapes containing more than one sinusoidal mode. But planar imaging experiments performed in a plane parallel to the direction of plate retraction showed that, superposed to the near 2-D flow caused by the RT instability observed before, other flows develop along that direction. These flows originate with the vortex shedding from the plate's trailing edge and then continue, similarly to the RT instability, under the action of gravity. From these side view experiments we concluded that:
1) the shape of an interface prepared by plate retraction is much more complicated than initially estimated;
2) for that interface to be a useful initial condition for a RM experiment, its shape must be quantified in 3-D, thus requiring experimental techniques which we have not yet developed.
We therefore set out to develop a new method to prepare an interface suitable for a RM experiment, pursuing two different approaches in parallel.

In a continued quest for a 2-D initial condition, tests were performed in a plexiglas box of the same cross section as the shock tube. The two gases were initially separated by a flat, retractable plate; this time, the configuration was gravitationally stable (light gas on top) so that, upon plate retraction, the RT instability did not develop. Instead, the flows consequent to the vortex shedding from the plate's trailing edge were dampened out by viscosity and the only flow driver was mass diffusion. Steady oscillations were then forced into the system by oscillating one of the box walls in a direction normal to that of plate retraction. The technique is promising but several issues still need to be worked out:
1) so far, only perturbations with small amplitude/wavelength ratio (¡ 0.05) were achieved; large initial values of this ratio are desirable to force the RM instability quickly into its non-linear (and most interesting) stages;
2) the shapes obtained so far were essentially single-mode sinusoids; higher modal composition is also very desirable in the initial conditions of a RM experiment to study post-shock mode coupling.

The other approach to interface preparation relies on the use of a soap bubble to contain the test gas. A soap film is more acceptable than a mylar or nitrocellulose membrane to set up an interface in that the bubble breaks up into much smaller fragments (droplets) than the membrane upon shock acceleration; hence the effects on the fluid flow and its observability are much smaller than the membrane's. The ultimate goal is to release a bubble inside the shock tube so that it can freely rise or fall, depending upon the test gas being lighter or heavier than the suronding driven gas. In either case, the bubble shape will not be perfectly spherical but it will be very nearly axisymmetric, making 2-D optical diagnostic techniques perfectly suitable to measure the quantities of interest (species concentration; velocity; vorticity). Two difficulties have been encountered in our attempts to achieve free bubble motion: the bubble often bursts before being released from the injector; and, once in free motion, the bubble wobbles from side to side (because of alternating vortex shedding from its rear surface) and it often breaks up against one of the shock tube walls.

While the technique for bubble release and free travel is being finalized, experiments have been performed with a bubble on an injector (the bubble sits on or hangs from the injector when the test fluid is lighter or heavier than the surrounding driven gas, respectively). Tests were performed with M=2.14 shocks; planar Mie scattering imaging was performed using a Nd:YAG laser sheet at λ =532 nm and by doping one of the gases with smoke with a 10% mass loading.

Examples of images of shock-accelerated bubbles are shown below.

Figure 1: Ar bubble in air, hanging from injector, before shock acceleration.

2.1.2 Rayleigh Taylor instability

A new experiment has been developed for the study of the RT instability. It is centered on the use of a magneto-rheological (MR) fluid as one of the two fluids at a perturbed interface. The property of the MR fluid that makes it ideal for a RT experiment is that the fluid can be "frozen" into any shape by applying a sufficiently large magnetic field. One can therefore impose an arbitrary shape on the free surface of a MR fluid, then apply a magnetic field thus forcing the MR fluid to retain the imposed shape; the "frozen" MR fluid can now be coupled with a different fluid (*e.g.* water) thus forming a pair of fluids of different densities speared by a perturbed interface; when the magnetic field is removed, gravity drives the RT instability. Use of an MR fluid thus allows for the preparation of interfaces of any desired shape (in particular, with any superposition of sinusoidal modes) and ensures that the experiment begins with both fluids at rest, without the extra velocity induced by, for example, a retractable plate.

The new experiment uses a plexiglas test section, 6.0 cm wide, 6.0 cm thick, 13 cm tall. The MR fluid in use is a dispersion of Fe particles (average diameter 4.5 μm) in mineral oil (98.2 % weight), with a small addiction of a surfactant (oleic acid) to prevent oxidation of the Fe particles. The "shaped" MR fluid sits on top of water and it is held in place by two sets of permanent magnets (1.5 T each) mounted in two plexiglas holders. To start the experiment, the magnet holders are retracted away from the test section by two pneumatic cylinders. The interface is illuminated with

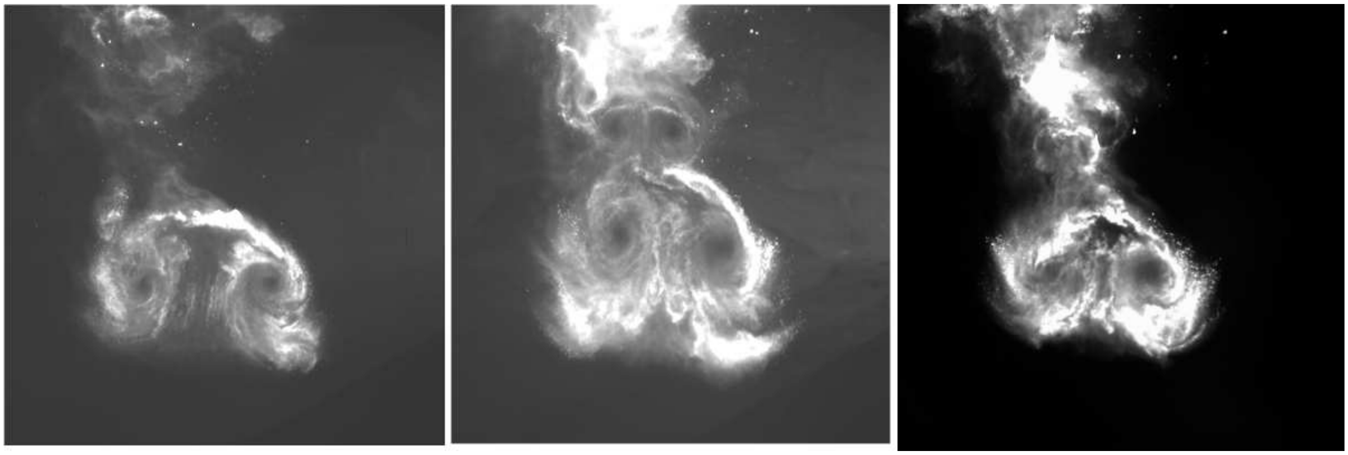


Figure 2: Ar bubble after interaction with M=2.14 shock wave. Images are from three different experimental runs, all at 1.2 ms after shock-bubble interaction.

diffuse, white light and it is imaged using a 512 $\times$ 512 pixel CCD camera, operating at 230 fps. Sample images from the experiment are shown below; data analysis algorithms have not yet been developped to measure growth rates from the images.

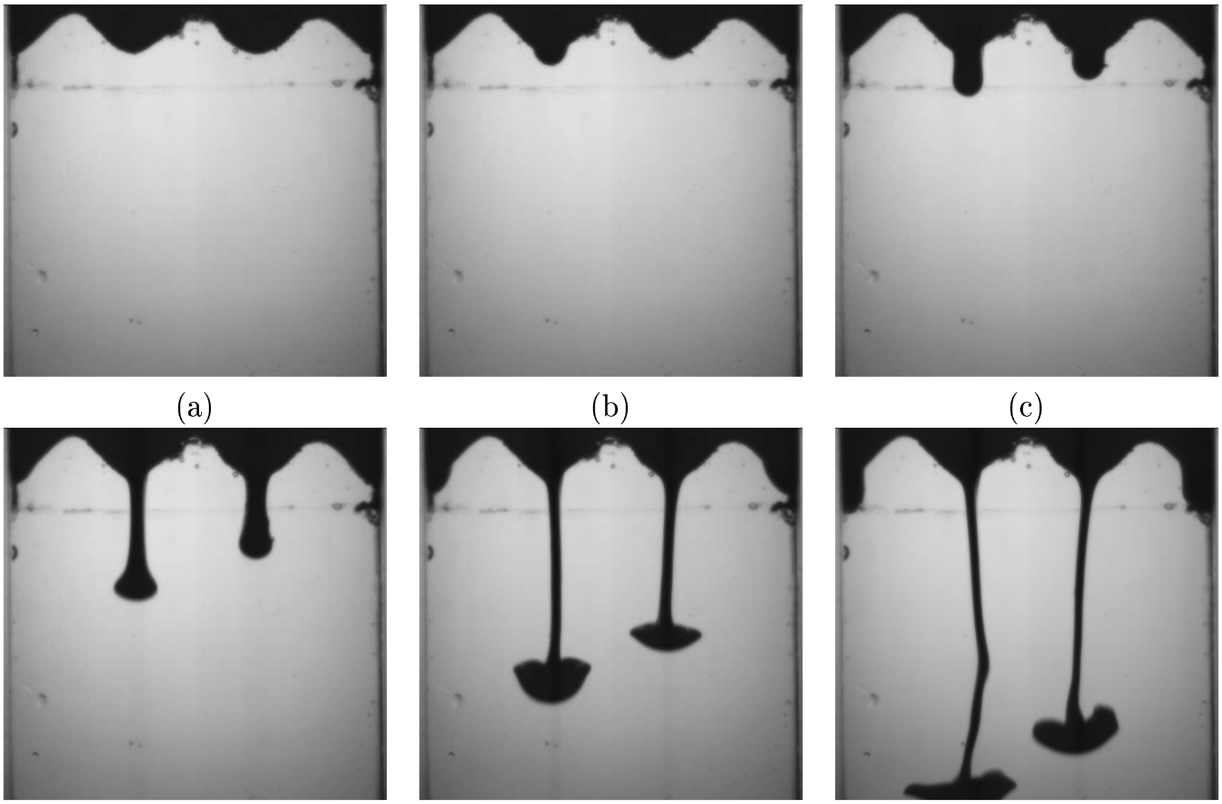
2.1.3 Intrumentation purchased

As originally planned, two pre-owned pulsed excimer lasers (Lambda Physik, model LPX210) were purchased at a cost of about $80,000 each. Combined with another pulsed excimer laser and three UV-sensitive CCD cameras already available, this investment gives us the capability of recording one pre-shock and two post-shock images during each experiment; and to perform both planar laser induced fluorescence (PLIF) and planar Rayleigh scattering experiments for the quantitative measurement of density and species concentration distributions.

2.2 Computational experiments

Use of the *Raptor* code has been made available to our group by colleagues at Lawrence Livermore National Laboratory (Dr. Jeff Greenough). The code solves the full Navier-Stokes equations with an algorithm based on Phil Colella's Piecewise Linear Method and with automated mesh refinement capability. One of our graduate students has been working full time with the code since July and has performed extensive runs, using initial conditions very similar to those set up in the shock tube. Differences between the computational and the laboratory experiments include: perfectly spherical *vs.* near-spherical, axisymmetric shape; diffuse interface with no soap film *vs.* soap interface with no diffusion; absence *vs.* presence of an injector to hold the bubble in place.

Despite these differences, the qualitative agreement between the computational and laboratory results is good, as shown in the figures below.



(a) (b) (c)

(d) (e) (f)

Figure 3: Rayleigh-Taylor instability at a magnetorheological fluid/water interface. (a) 0^{-} ms, (b) 75 ms, (c) 150 ms, (d) 225 ms, (e) 300 ms, (f) 375 ms.

3 Path Forward

In the RM experiments, during the next year, the technique for bubble release will be finalized; the PLIF diagnostic will be set up and implemented for one pre-shock and two post-shock image captures per experiment; shock strengths of $M \geq 3.0$ will be used to accelerate the bubbles; various test/driven gas combinations will be used to scan a rnage of Atwood numbers.

In the RT experiment, the magnet withdrawal procedure will be improved to ensure no residual field is left that may delay the motion of the MR fluid. A data analysis algorithm will be developed to extract velocity and growth rate data from the images.

4 Publications and presentations

Our work was presented at the Annual Meetings of the Plasma Physics and Fluid Dynamics divions of the American Physical Society. Further progress will be reported at the 24th International Symposium on Shock Waves (in Bejing, China) and the 9th International Workshop on the Physics of Compressible Turbulent Mixing (in Cambridge, England) in the summer of 2004.

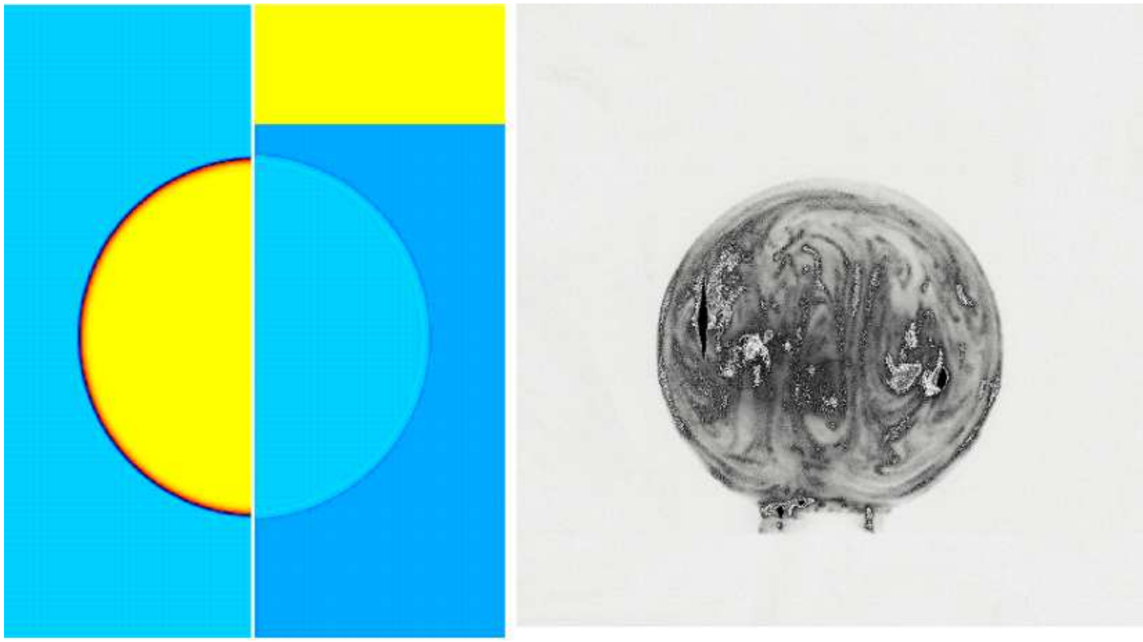


Figure 4: Computational and laboratory experiments. Air bubble in Ar; pre-shock initial conditions. Air mass fraction and total density are on the left and right of the computational image, respectively.

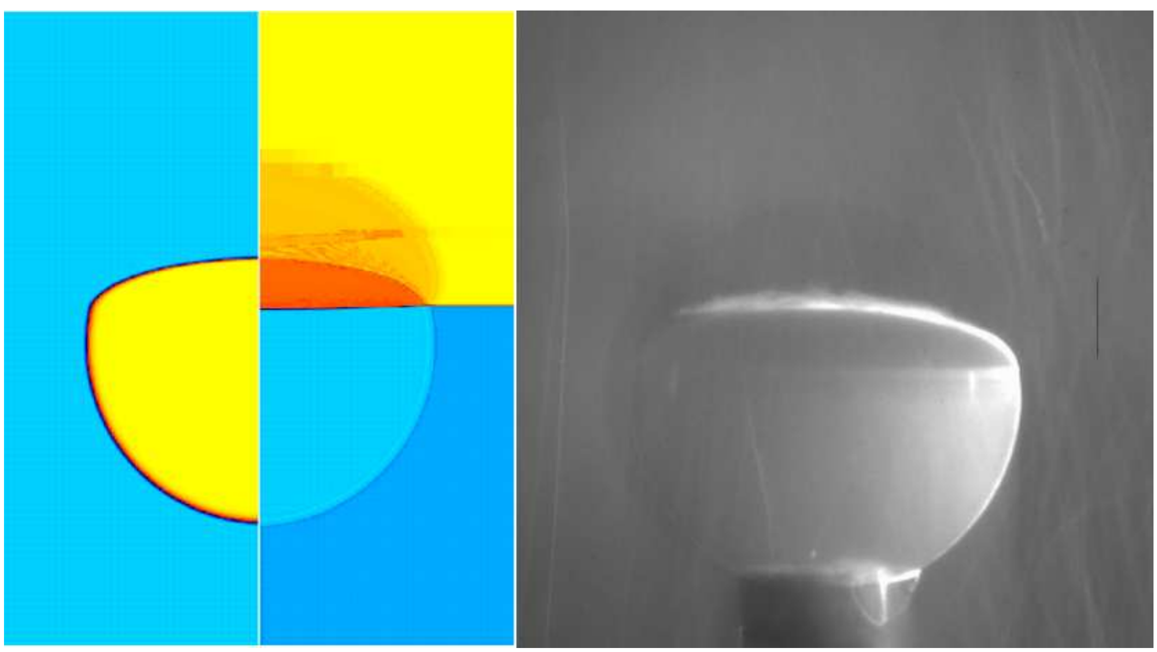


Figure 5: Computational and laboratory experiments. Air bubble in Ar; M=2.14; shock has traversed 36% of the bubble volume. Air mass fraction and total density are on the left and right of the computational image, respectively.

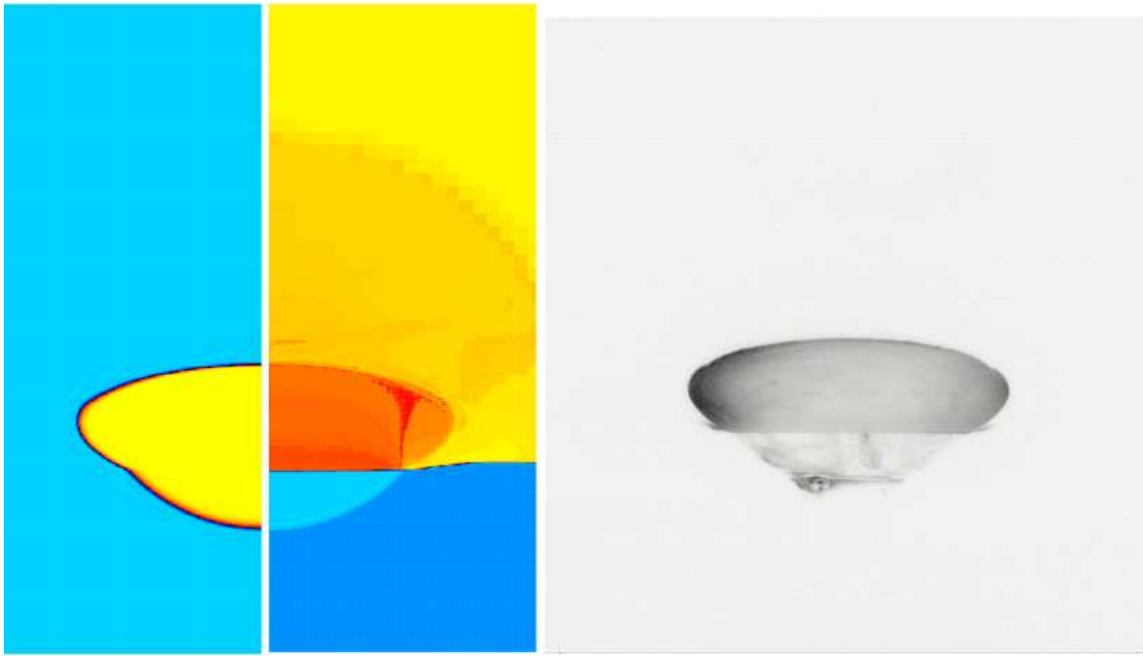


Figure 6: Computational and laboratory experiments. Air bubble in Ar; M=2.14; shock has traversed 80% of the bubble volume. Air mass fraction and total density are on the left and right of the computational image, respectively.

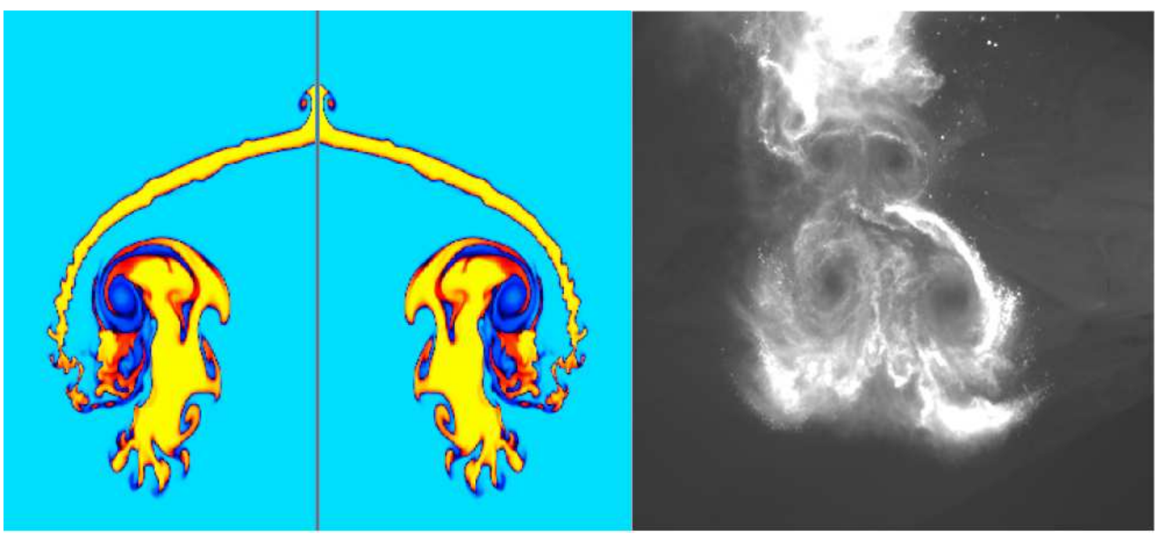


Figure 7: Computational and laboratory experiments. Ar bubble in air; M=2.14; t=1.2 ms after shock-bubble interaction. Left: air mass fraction from computations. Right: planar Mie scattering image.

5 Personnel

Faculty and staff involved in and supported by the program include:

Prof. Riccardo Bonazza, Associate Professor, Dept. Engineering Physics; supported for 2.7 months.
Dr. Mark Anderson, Associate Scientist, Dept. Engineering Phsyics; supported for 7.1 months.
Dr. Jason Oakley, Assistant Scientist, Dept. Engineering Physics; supported for 10 months.
Mr. Paul Brooks, Instrumentation Specialist, Dept. Engineering Physics; supported for 4.5 months.

Graduate students supported by and fully involved in the program in the past year include:

Mr. Alec Bates (USA; completed a Master's degree); supported for 2.1 months.
Mr. Brad Motl (USA; pursuing a Ph.D. degree); supported for 2.5 months.
Mr. John Niederhaus (USA; pursuing a Ph.D. degree); supported for 1.8 months.
Mr. Devesh Ranjan (India; pursuing a Ph.D. degree); supported for 3 months
Mr. Chaine Selig (USA; pursuing a Master's degree); supported for 5.3 months

About 6 undergraduate students were also involved in and supported by the program at various levels and for different lengths of time.