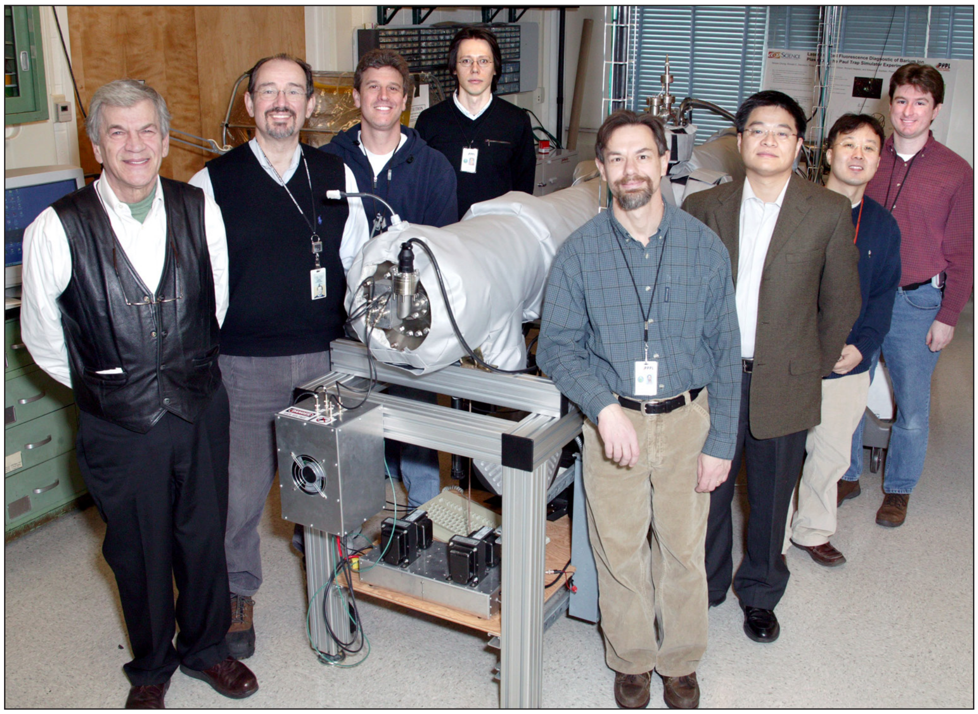
PRINCETON PLASMA PHYSICS LABORATORY

fact sheet

PPPL PRINCETON PLASMA PHYSICS LABORATORY

U.S. DEPARTMENT OF ENERGY

Small is Big for PPPL's Paul Trap



From left at the Paul Trap Simulator Experiment are Ron Davidson, Phil Efthimion, Andy Carpe, Ed Startsev, Dick Majeski, Hong Qin, Moses Chung, and Erik Gilson.

The Paul Trap Simulator Experiment (PTSX) at the U.S. Department of Energy's Princeton Plasma Physics Laboratory doesn't trap people named Paul or simulate the trapping of Pauls. Its mission is much grander.

"We are trying to answer big physics questions that have costly implications in a small, compact relatively inexpensive device," notes PPPL physicist Erik Gilson. Research by Gilson and his colleagues, led by Principal Investigator Ron Davidson, could have a significant impact on several areas of science and technology, including particle physics, heavy ion fusion, nuclear waste transmutation, and high-energy-density physics — wherever charged particle beams are used as tools.

"The next generation of particle accelerators needs to transport more charge than before. The more particles in the beam, the more energy you can deliver to a target, or the more interactions and the better statistics you'll have. But when there is too much charge, the beam will blow itself up because of the electrical interactions. This is not a problem in present day experiments, but it is becoming more important to think about," said Gilson. Thus the PTSX team is trying to determine the properties of intense charge particle beams as they travel through transport systems. Experiments began in spring 2002.

Charged-particle transport systems use quadrupole magnets, which confine the beam along a path. As the beam travels, it passes the magnets, which are equally spaced along the way. At any given time, the beam is focused in one direction perpendicular to the flow and defocused in another direction perpendicular to the flow of the particles. Gilson likens the beam to a water balloon, which if squished from the sides, will leak out the top and bottom. When pushed from the top and bottom, will leak out the sides. "That's exactly what the alternating gradient quadrupole magnets do. As the beam passes one set of quads, it's focused in one direction and defocused in the other, the next set of magnets reverses the situation. The pattern is repeated over the length of the accelerator, which may have several hundred or even a few thousand quadrupoles," he said.

But PTSX, measuring only three meters in length — much shorter than a typical particle accelerator — uses some interesting physics to simulate the conditions in an accelerator. "Imagine traveling along next to the beam with the magnets whizzing by. The beam would then appear to be a stationary cloud of charge with the magnets coming by periodically in time," according to Gilson. The charge cloud is a nonneutral plasma which experiences the alternating forces periodically in time. In PTSX, a stationary nonneu-

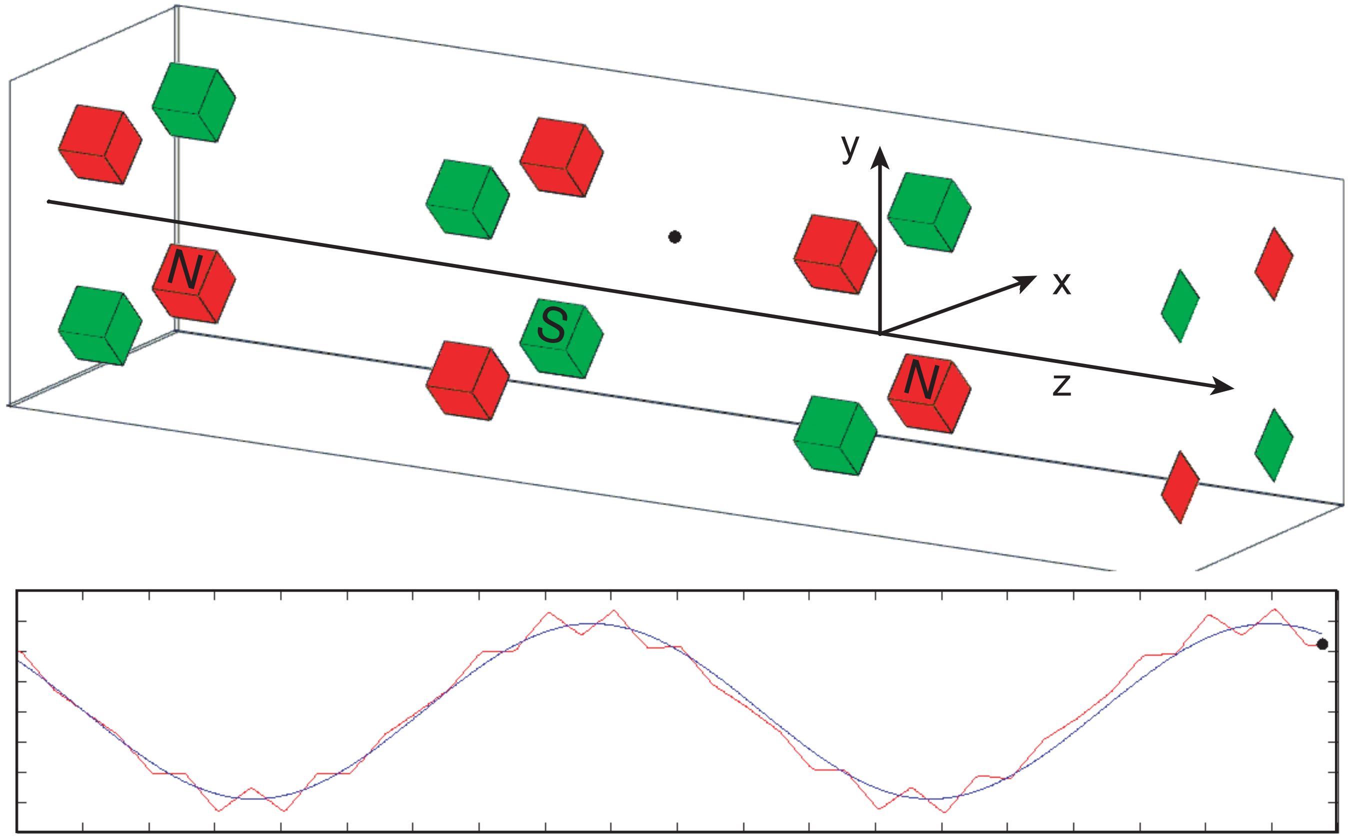


Figure 2. Top: A particle (black dot) moving through an infinite set of quadrupole magnets of an accelerator. Just over three sets of quadrupoles are shown. Each time the particle passes through a set of magnets, it feels a force that either focuses it towards the axis or de-focuses it away from the axis. Between magnets, the particle just drifts.

Bottom: The distance of a particle from the axis is shown as a function of time as it passes through 40 sets of magnets. The red curve shows the exact trajectory — a bunch of straight lines (the drifts) connected by rapid changes in direction alternately towards and away from the axis (the passages through the magnets). The blue curve is a smooth approximation to the exact orbit. Since the entire beam is a collection of single particles, the overall shape of the beam is a pulsating ellipse, as Erik Gilson describes with his water balloon analogy.

tral cesium plasma, about two centimeters in diameter and two meters long, is subjected to a time-varying electric field, simulating the experience of a particle beam as it passes quadrupole magnets in an accelerator. The physics is comparable, providing researchers with a relatively inexpensive means to study properties of charged particle beams with greater flexibility than possible in an actual accelerator.

Initial Experiments Successful

First the PTSX team needed to determine if they could trap plasmas with enough space charge corresponding to really intense beams. In relative terms, they defined a parameter s, between zero (no space charge) and one (bursting at the seams).

"A place like SLAC might operate at 0.1, or ten percent of the limit, the Spallation Neutron Source needs about 0.2, and for heavy ion fusion, values of 0.95 or higher are sought. In the Paul Trap, we have been able to achieve values of 0.8, but we still have more to go," Gilson said. The plasma temperature in the Paul Trap must be kept as low as possible, a few tenths of an electron volt, because temperature also affects the amount of charge density achievable. "In absolute terms, the particle density in the Paul Trap is very low, but the s value is high, because we confine a small amount of charge in a relatively weak trap," he said.

The second test of PTSX's usefulness was its ability to confine a plasma long enough to simulate a beam traveling a meaningful distance in an accelerator. "We have been able to achieve about one-third of a second, not very long for a plasma experiment. But we use an electrode voltage with a frequency of 75 kilohertz. For one-third of a second, that's over 20,000 cycles. At SLAC the spacing between the magnets is about one meter, so we are able to simulate a beam that is propagating for over 20 km, and that's impressive," said Erik Gilson.

Unique Capabilities

A major advantage PTSX has over an accelerator is the arbitrary function generator that makes the voltage waveform for its electrodes. The amplitude of the waveform corresponds to the strength of the magnets in an accelerator and the frequency of the waveform corresponds to the magnet spacing. As Gilson notes with enthusiasm, “Can you imagine going to the people at SLAC and asking them to move every third magnet set? They would have to rebuild the machine! But we just take our computer and draw a different waveform. If we don’t like square pulse waves, we can draw a sine wave. We can even use a triangular waveform. So if someone has an idea to try with a different magnet configuration, we can just dial it up on the arbitrary function generator and see how it affects the plasma.” The generator also allows the PTSX team to simulate minor imperfections in the magnets that are unavoidable in accelerators. They inject random noise into their waveform and study its effects.

In addition to predicting the transport properties of intense beams over long distances, PTSX is studying the problem of halos. Gilson explains, “The beam is this egg-shaped object being squished, but individual particles are zipping around inside. If its orbit is chaotic, a particle could wander out somewhere unpredictably. Particles find their way out to a larger radius. If you were to look at the beam end-on, you would see a diffuse ring, or halo, around it. Particles in an accelerator can travel near the speed of light. They have a lot of energy. If they hit the wall of the accelerator pipe accidentally, the wall will become radioactive — something to be avoided.” Interactions of the halo with the wall can be eliminated by making the accelerator pipe larger, but such over-engineering is inefficient and expensive. Particles cost money to make, and physicists want the maximum number to hit the target. Consequently, studying how halos form and how they can be controlled is a high priority for PTSX during the next few years.

PTSX Team

In addition to Ron Davidson and Erik Gilson, other members of the PTSX team include Phil Efthimion, Dick Majeski, and graduate student Moses Chung. Ed Starsev and Hong Qin provide theoretical support. Paul traps are named after Wolfgang Paul, who invented them in the early 1950s, and received the Nobel Prize in Physics in 1989 for his research on them.

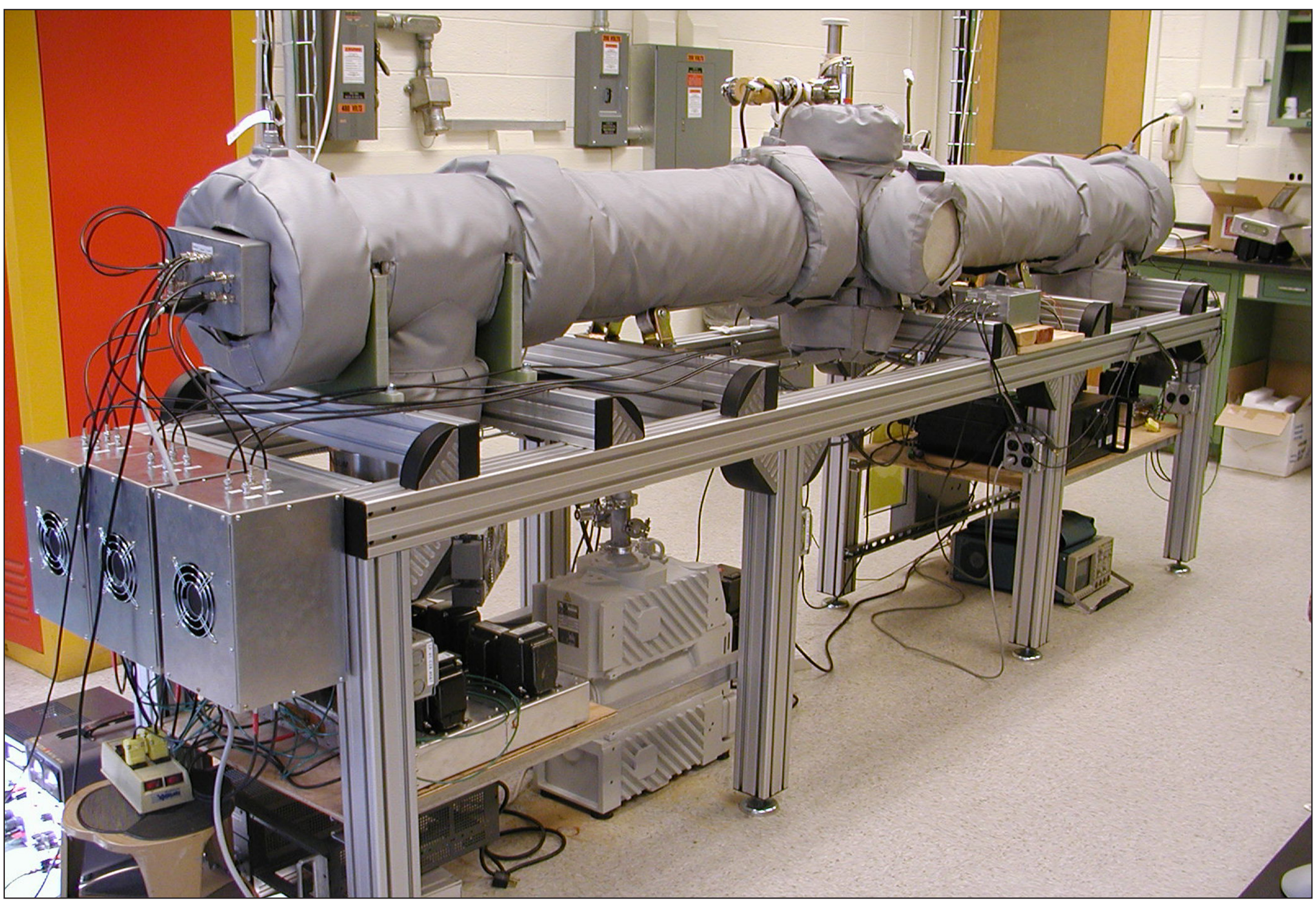


Figure 3. The Paul Trap Simulator Experiment (PTSX).

The Princeton Plasma Physics Laboratory is operated by Princeton University under contract to the U.S. Department of Energy. For additional information, please contact: Office of Communications, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543; Tel. (609) 243-2750; e-mail: **pppl_info@pppl.gov** or visit our web site at: **www.pppl.gov**.