The Basic Plasma Science Facility – Upgrade for the next decade and beyond

Walter Gekelman, Troy Carter, George Morales, Chris Niemann
Department of Physics and Astronomy, University of California, Los Angeles

Overview:

Laboratory studies of the fundamental properties of the plasma state of matter is critically important to the future progress of pure and applied science. The resolution of frontier problems in basic plasma science such as magnetic reconnection, collisionless shocks, turbulence, and wave manipulation of energetic particles, have profound consequences for astrophysics, energy research and national security. The study of these challenging topics require sizeable, state-of-the-art facilities, capable of accommodating a wide range of user groups from academia, national laboratories and industry, each with diverse interests and backgrounds. The funding required to ascertain worldwide leadership by the U. S. over the next 15 years, in this area, does not require the $100M level targeted by the present facilities prioritization exercise. Instead, expenditures in the range of $20M may be adequate and can have major impact, in particular, if judicious investments are made that capitalize on existing technical expertise and infrastructure.

The U. S. plasma science program currently enjoys a leadership position in the worldwide effort in basic plasma physics research; the Basic Plasma Science Facility (BaPSF) at UCLA is widely recognized as a jewel in the crown of this program. This position, however, was not achieved overnight. It required steady and relatively significant support by various government agencies. But advances in this area urgently require infrastructure upgrades to meet the challenging problems that the plasma science user community needs to solve. It should be noted that significant investment is being made in basic plasma science internationally. In particular, there is an effort underway in China to develop a laboratory facility dedicated to the study of fundamental space physics processes; funding on the order of $30M is planned to build that facility.

Future BaPSF:

The core of the BaPSF is the Large Plasma Device (LAPD), which was constructed 12 years ago and has been used to make seminal contributions to the understanding of a number of plasma physics processes including waves, instabilities, turbulence and transport. A modest investment at this time could significantly enhance the LAPD and multiply the future opportunities for experimental discovery using the device over the next 15 years. Areas of upgrade include increasing the strength of the confinement magnetic field, implement auxiliary heating and modernizing the plasma sources. This would expand the range of achievable plasma density and temperature and thus encompass a wider ranger of users. Additionally, BaPSF would expand the choice of device configurations available to the user community by transforming the former Electric Tokamak into a high-repetition, toroidal basic device (ETPD) akin to the existing linear device LAPD. Additional investment is needed to make this facility ready for world-class research; this investment would be used, e.g., to expand the size of the plasma source (in order to fill the large volume), enhance the magnetic field capability, provide additional heating sources and add infrastructure for diagnostics and data acquisition. With these investments, the BaPSF would be poised to address a range of frontier topics including:

1. **Collisionless shocks**: There is great interest in the astrophysics community on collisionless shocks in plasmas. Ion acoustic shocks have been studied for many years, in fact the first experiments were done at UCLA close to 40 years ago. Work on shock waves has gone on ever since and attention has been turned to the use of high power lasers. In a recent publication a shock was observed to propagate in a background plasma and, by scanning proton imaging data, the shock structure determined to be in accord with solutions of the KDV equation. Both the LAPD and ETPD devices have Alfvénic plasmas, which raises the possibility of studying this type of shock. Prof. Chris Niemann has initiated experiments using a 20-100 Joule laser incident upon a target in the

LAPD. Intense Alfvén waves ($\frac{B_{wave}}{B_0} \approx 0.2$) were observed as well as structures which propagated faster than the Alfvén speed . The laser will soon operate at 500 J. The ETPD plasma is far denser and longer than LAPD and would offer a much better target background plasma for upcoming experiments.

2. Gradient-driven turbulence and transport in a high-beta toroidal plasma: The edge region of toroidal magnetic confinement devices plays a critical role in establishing performance through, e.g., setting the pedestal temperature and providing an edge momentum source. Understanding turbulence and transport in the edge is therefore critical and we have much work to do in order to establish a validated predictive capability for edge and scrape-off-layer plasmas. ETPD provides a platform for studying, in detail, turbulence and transport in a large volume, toroidal plasma with the unique capability of varying beta to significantly large values while remaining magnetized. This capability will allow studies of fusion-relevant edge beta values, but also allows for pushing to the unexplored region near unity beta. This will allow investigating, for example, the transition from electrostatic to electromagnetic transport in edge turbulence. At low beta, particle transport in the edge of confinement devices is largely due to convective transport of coherent electrostatic structures or "blobs" . As beta is increased, a transition to electromagnetic structures might be expected, similar to edge localized modes or ELMs. Momentum transport and flow-turbulence interaction studies could also be carried out using bias-driven flows which have been observed to cause a confinement transition in LAPD (as well as in toroidal devices).

3. Reconnection in a high beta, collisionless, high Lundquist number plasma: Due to the large size and low collisionality of ETPD plasmas, Lundquist numbers exceeding 10^4 can be achieved. Extending the Lundquist number in this way will allow studies of current sheet stability and plasmoid formation, something that has been observed in natural plasmas like the magnetotail and recently predicted in numerical studies with a threshold of $L=10^4$. The large size of ETPD reduces the influence of boundary conditions on the reconnection and allows flexible reconnection geometry, such as studies of merging flux ropes and truly three-dimensional reconnection**.**

4. Basic properties of plasma waves in a high beta, toroidal plasma: Plasma wave research has been at the heart of the UCLA plasma physics research effort for many years, using novel experiments tightly coupled with theory to gain understanding. In particular for Alfvén waves, the experiments have been done in low-beta plasmas and ETPD provides an important opportunity to explore the properties of Alfvén waves at high beta. For example, ion Landau or Barnes damping of kinetic Alfvén waves can occur at high beta as $V_{alfven} \sim V_{thi}$. The toroidal geometry of ETPD allows studies of toroidicity-induced effects on Alfvén waves. Experiments on ETPD could become part of the ongoing successful fusion campaign on LAPD, which has studied Alfven waves in periodic structures and interaction between Alfven waves and fast particles. Beam injection or ICRF-driven fast particle excitation of Alfven waves could be studied in ETPD. The interaction between fast particles and Alfven waves is also important astrophysically (e.g. cosmic ray scattering).

5. Alfvénic turbulence and dissipation in a high beta plasma: Alfvenic turbulence is observed in the solar wind, inferred to be present in the interstellar medium (e.g. the "big power law in the sky") and is proposed to play a role in momentum transport and ion heating in collisionless accretion disks. Of particular interest are the shape of the turbulent spectrum and the nature of dissipation. Ongoing experiments on LAPD are investigating nonlinear interactions between antenna-launched shear Alfvén waves. Experiments in ETPD would seek to extend these studies to astrophysically relevant high-beta, large volume plasmas, with the ultimate goal of studying a driven Alfvénic cascade and associated heating.

6. Anisotropy-driven instabilities in a high beta plasma: Mirror and firehose instabilities have been invoked to explain the distribution of ion temperature anisotropy in the solar wind . These instabilities are also theorized to play an important role in the generation of small-scale magnetic fields in clusters of galaxies. Magnetic structures ("humps" and "holes") are observed in the solar wind and earth's magnetosphere and are thought to be nonlinear mirror-mode structures. Firehose and mirror instabilities may be observable in high beta ETPD plasmas with anisotropy in the ion velocity distribution with respect to the magnetic field. Anisotropy may be driven using RF heating (to access the mirror instability) or using field expansion (to drive the firehose). Field expansion would be enabled by the proposed flexible magnetic field capability and would mimic the firehose drive in the solar wind

7. **RF heating capabilities.** The proposed upgrade of RF-heating hardware for LAPD and ETPD opens new opportunities for studies of basic wave-particle interactions and wave propagation of significant impact to fusion and space plasma research. These are in addition to the new studies that will be made available by increasing the parameter space due to ion and electron heating by the RF waves. Basically, the upgrade will allow the launching of high-power compressional Alfven waves over a frequency band spanning harmonics of the ion cyclotron frequency. Since LAPD provides an ideal environment for the study of low-beta plasmas with field-aligned gradients, and ETPD complements these capabilities by permitting studies of high-beta plasmas with cross-field gradients, there are numerous topics that can be explored. In fact, an entire research program can be developed around these new capabilities.

LAPD upgrades: The main elements to the upgrade for the LAPD device would allow operation at several times larger magnetic field and five times larger density. The typical present experimental magnetic field is 1 kG with operation up to 1.8 kG possible. The field is limited by the end magnets which were acquired from a retired Tokamak and not designed for continuous operation. The end magnets will be replaced by superconducting magnets allowing for 1 T operation. (New technology allows for magnet cooling provided by the same type of helium refrigerators used on cryogenic pumps. No Helium delivery or storage is necessary.) The central magnets can operate at 5-7 kG in steady state operation. At 5 kG the ion gyroradius in Hydrogen is 0.02 cm. A 60 cm diameter column would be 3000 gyro-radii across, very highly magnetized. Lab6 cathodes will power the device at both ends. These have a higher emissivity and will result in plasma densities in the mid 10^{13} cm^{-3} range. The ion inertial length will be of order 4 cm, roughly 1/10 of what it presently is. This places the LAPD plasma solidly in the MHD regime, perfect for the validation of codes. The LAB6 cathodes are not as sensitive to contamination as the present BaO cathode. Probes are presently introduced into the LAPD through interlocks which have to be evacuated to $P = 4 \times 10^{-6} Torr$. This necessitates the use of turbomolecular or cryopumps and takes 2-3 hours. When LaB6 cathodes are used the pressure in the interlock station can be 10 mT and mechanical pumps are all that is needed. Introducing a probe would take 5 minutes vastly increasing the time available to users who must often wait for their probes to be installed. The plasma discharge length (on time) can be increased from 10-15 ms to 100 ms allowing end states of plasma edge turbulence to evolve. Of course, all of the parameters currently available on the LAPD will still be accessible; it is the range of parameters, and possible experiments, that will be greatly increased. Finally, recent experiments on ETPD show that the cathodes can be placed on the floor of the machine allowing for probe and camera access along the entire length of the device. Both machines will run at 1 Hz allowing for volumetric collection of data.

Facility operation: The goal is to bring two complementary and highly flexible devices up to standards of operation never before seen in basic plasma science. The project will result in a world-class research facility that will broadly impact the development of the field and the training of students for the next 15 years. Researchers from universities, national laboratories and industry will be able to use the upgraded machines following the well-established user protocols developed by BaPSF. The upgraded infrastructure will impact frontier developments in several communities by greatly expanding the range of plasma parameters and conditions available for basic plasma research. The proximity of the devices and common mode of operation will contribute significantly to the exchange of research findings across complementary areas.

Summary of upgrades:

<u>LAPD</u>

a) Superconducting end magnets, 5 kG continuous magnetic field in main discharge. Plasma 70 cm in dia., L = 18m long , $n \le 8 \times 10^{13} cm^{-3}$

b) Replacement of BaO plasma source with two Lab6 cathodes, and much larger discharge supplies and switches, for double ended operation.

c) Addition of microwave and Thompson scattering diagnostics for high field operation.

<u>ETPD</u>

a) Replace present 20 cm diameter test plasma source with 75cm diameter LaB6 cathode. This includes fabrication of large bank and transistor switch for high power operation. Plasma 75 cm dia., L = 120 M, $n \le 4 \times 10^{13} cm^{-3}, 0.01 \le \beta \le 1.2$

b) Acquire power supplies and water cooling to allow for up to 1 kG magnetic field programmable in 8 quadrants

c) Build a 3D probe drive, increase number of access ports and add a data acquisition system.

d) Construct platforms, safety systems and machine computer control to allow 24/7 operation.

Conclusion: The upgrade to the LAPD and completion of construction of ETPD will make the BaPSF the most versatile basic plasma facility in the world. No other laboratory dedicated to basic plasma science will have the range of available parameters, state of the art diagnostics and data acquisition, round the clock operation, and rapid experimental turnaround time.

Timelines for projects.

We are confident that the BaPSF technical staff can order and fabricate the items outlined in the time frame (36 months) of the proposal. To do this we will hire three machinist/technicians for the duration of the project and a part time computer programmer. The programming for ETPD will be a straightforward translation of what was done on LAPD , but specialized to the geometry and different sub-systems of the larger device. We have spent the past few years in cathode research and development and can immediately proceed with the project.

Proposed Budget

The Large Plasma Device was constructed with an NSF major instrument award and completed in 2000. The cost of construction (it was done entirely by the UCLA group) was about 2M. Since then there have been continual upgrades for about 1.5 M more. ETPD was repurposed from the UCLA tokomak, which cost approximately 6 M to construct. This was funded by DOE. UCLA has put a considerable amount of resources into the facility. It occupies nearly an entire building with 30 MW of available electricity and water cooling. For the last ten years UCLA has paid the lion's share of the electrical costs. There are no scientific challenges in this construction project. It can be done by our group, mostly in house.

A tentative budget for the items mentioned above (superconducting magnets, power supplies, large cathodes, diagnostics) is of order 17M. If the project takes off UCLA will make a substantial contribution including investment in faculty. The project will take 3 years to complete. We estimate the facility operations budget would be a total of 2.7 M/year, 20% higher than at present.