Overview, Status, and Plans of the Plasma Liner Experiment (PLX)

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F. Douglas Witherspoon (HyperV Technologies), Jason Cassibry (Univ. Alabama-Huntsville), Mark Gilmore (Univ. New Mexico), David Hwang (U.C., Davis)

& The PLX Team

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November 11, 2010

PLX is supported by a national collaboration
PLX plans to merge 30 high Mach number plasma jets in spherically convergent geometry to create HED plasmas

**Goal**: generate μs/cm-scale plasmas with 0.1–1 Mbar peak pressure using ~1.5 MJ of initial stored energy

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**Attributes of the PLX Research Program**

- **Achieve both HED and lower-density plasma regimes**
  - Large, simply-connected chamber for engineering simplicity, good diagnostic access, and minimal boundary effects
  - Relies on spherical convergence to reach high temperatures and densities
  - Lower densities are easily achieved by lowering initial jet densities ➔ collisionless regimes are possible
  - Innovative method is proposed for “standoff magnetization”

- **Exciting potential applications**
  - Platform for conducting fundamental HEDLP scientific studies (including HED hydro, nonlinear optics of plasmas, and magnetized HED)*
  - Laboratory astrophysics (e.g., disk-jet dynamics, collisionless shocks, ...)
  - Potential path to IFE with magnetic fields: magneto-inertial fusion (MIF)

*Priority research areas as described in the HEDLP Research Needs Workshop (ReNeW) report, 2010
Motivation: PLX can provide a unique low-cost platform for experimental HEDLP science

<table>
<thead>
<tr>
<th>Facility</th>
<th>Shots/day (max)</th>
<th>Cost/shot</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIF</td>
<td>2</td>
<td>$250k</td>
</tr>
<tr>
<td>Omega</td>
<td>10</td>
<td>$12k</td>
</tr>
<tr>
<td>Shiva Star (AFRL)</td>
<td>2 per week</td>
<td>$150k</td>
</tr>
<tr>
<td>PLX</td>
<td>several dozen</td>
<td>&lt;$1k (based on &gt;2000 shots/yr @ $2M/year budget)</td>
</tr>
</tbody>
</table>

Motivation: Convergent plasma jets could be an attractive approach to inertial fusion energy (IFE) using magnetic fields

- Composite DT (yellow) and high-Z (purple) jets are imploded to $\rho_f r_T \sim 0.01\ g/cm^2$
- DT is magnetized via lasers just before peak compression
- Implosion speed $\sim 100\ km/s$
- Dwell time $\sim 1\ \mu s$
- Batch burn with $\sim 10\%$ fuel burn-up
- Peak pressures $\sim 50\ Mbar$
PLX has three key science & technology objectives in the next several years

1. Form dense high Mach number high Z (Ar, Xe) plasma jets with required density (~$10^{17}$ cm$^{-3}$), mass (~few mg), and velocity (>50 km/s)

2. Demonstrate imploding plasma liner formation and predictive physics understanding of underlying steps:
   - jet expansion from chamber wall to “merging” radius $r_m$
   - liner formation via jet merging (plasma penetration, shock dynamics, uniformity)
   - liner convergence (pressure amplification, atomic physics effects, liner stability)
   - stagnation (peak pressure scaling, conversion of liner kinetic energy to thermal/radiation energy, confinement time)

3. Standoff magnetization via laser generated beat wave current drive

PLX construction & facility view

PLX is situated in a ~3000 ft.$^2$ high-bay with a 10-ton overhead crane and shielded control room.
PLX facility status: construction phase 1 on track for completion with first experiments in early 2011

Phase 1 (by mid-FY11):
- Spherical vacuum chamber under $10^{-6}$ T vacuum
- Five plasma guns installed
- Plasma gun power supply (~300 kJ) and control system operational for up to 5 plasma guns
- Multi-chord interferometry, visible spectroscopy, and schlieren operational
- Single jet propagation and two jet merging studies to begin early 2011

Phase 2 (by late-FY12):
- Elevate vacuum chamber (likely in 2011)
- Increase to 30 guns and 1.5 MJ capacitor bank
- VUV spectroscopy, soft x-ray bolometry operational

We will use a refurbished, robust, oil-free 3200 l/sec turbo-molecular vacuum system

- Roughing to <1 T in ~1.5 hours
- High vacuum from rough vacuum in minutes
- Base pressure $<1 \times 10^{-6}$ T expected

Leybold MAG W 3200CT turbo pump & VAT Series 12 aluminum ISO320 gate valve

Edwards iQDP80 dry (fore-)pump (56 cfm, 8 mTorr)

PLX vacuum chamber (9’ diameter, 10,800+ liters, stainless steel)

MKS 972 DualMag (10$^6$ T to 1 atm) & PDR900 controller
Labview/PXI/MDS+ based control/DAQ system is being implemented that makes use of ~200 available CAMAC ADC channels

<table>
<thead>
<tr>
<th># channels</th>
<th>Model</th>
<th>purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital i/o</td>
<td>96 NI-7831R FPGA</td>
<td>Control &amp; shot sequence</td>
</tr>
<tr>
<td>Analog i/o</td>
<td>16 NI-7831R FPGA</td>
<td>Vacuum/HV monitoring</td>
</tr>
<tr>
<td>ADC 1 MHz, 10 bit</td>
<td>120 LeCroy 8210</td>
<td>Gun diagnostics</td>
</tr>
<tr>
<td>ADC 40 MHz, 12 bit</td>
<td>64 Joerger TR</td>
<td>Physics diagnostics</td>
</tr>
</tbody>
</table>

We are building a modular high voltage power supply for driving 30 plasma guns in groups of 6 (40–60 kJ/gun, ~1 MA/gun)

Maxwell model 32184 capacitors (6 µF, 60 kV) inherited

Hipotronics 875-335, 75kV, 335mA power supply, circa late 1970’s

Figure by Sam Brockington & David Van Doren, HyperV
Plasma guns are being developed and will be supplied by HyperV Technologies Corp.*

Diagnostics effort led by University of New Mexico* will be implemented in two phases with help from UNR

<table>
<thead>
<tr>
<th>Experiment Stage</th>
<th>Quantity</th>
<th>Diagnostic</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-5 Jets Merging</td>
<td>( n_e )</td>
<td>Interferometer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Schlieren Imaging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stark Broadening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visible Imaging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectral Line Intensity Ratios</td>
</tr>
<tr>
<td></td>
<td>( T_e )</td>
<td>Doppler Broadening</td>
</tr>
<tr>
<td>Imploded Plasma Liner</td>
<td>( n_e )</td>
<td>Interferometer</td>
</tr>
<tr>
<td>Region I (Outer Liner</td>
<td></td>
<td>Schlieren Imaging</td>
</tr>
<tr>
<td>at Stagnation)</td>
<td></td>
<td>Stark Broadening</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Visible Imaging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectral Line Intensity Ratios</td>
</tr>
<tr>
<td></td>
<td>( T_e )</td>
<td></td>
</tr>
<tr>
<td>Region II (Inner Liner</td>
<td>( n_e )</td>
<td>Stark Broadening</td>
</tr>
<tr>
<td>at Stagnation)</td>
<td></td>
<td>Spectral Line Intensity Ratios</td>
</tr>
<tr>
<td></td>
<td>( T_e )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( P(n_e, \tau, T_e) )</td>
<td>Bolometry</td>
</tr>
</tbody>
</table>

*See poster by D. Witherspoon for details on gun evaluation (mini-railgun vs. coaxial) and development status

*See poster by E. Merritt for details
Nine 29.5” diameter diagnostic ports with 15 windows will allow excellent and flexible diagnostic access

Theory/modeling effort led by UAHuntsville* is coordinating the efforts of many institutions using ten different codes

<table>
<thead>
<tr>
<th>Problem</th>
<th>Institution</th>
<th>Code</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>jet merging, liner formation/implision, peak pressure scaling</td>
<td>UAHuntsville</td>
<td>SPHC</td>
<td>3D smooth particle hydrodynamics (meshless Lagrangian)</td>
</tr>
<tr>
<td>liner implosion</td>
<td>LANL, Tech X</td>
<td>RAVEN, HELIOS, Nautilus</td>
<td>1D rad-hydro (RAVEN, HELIOS) &amp; 2D ideal hydro/MHD (Nautilus)</td>
</tr>
<tr>
<td>jet propagation/merging</td>
<td>Far-Tech, UAHuntsville</td>
<td>LSP, SPHC</td>
<td>PIC w/atomic physics, 3D smooth particle hydrodynamics</td>
</tr>
<tr>
<td>jet formation/acceleration</td>
<td>HyperV, Voss, UAHuntsville, RAC</td>
<td>MACH2, LSP, ePLAS</td>
<td>Rad-MHD (MACH2), PIC w/atomic physics (LSP), hybrid-PIC</td>
</tr>
<tr>
<td>effects of atomic physics on jet propagation and liner convergence</td>
<td>Prism, Far-Tech, Voss, LANL, UAHuntsville, Tech X</td>
<td>PrismSpect, LSP, HELIOS, Nautilus</td>
<td>DCA atomic physics (PrismSpect), others given above</td>
</tr>
<tr>
<td>predictions of spectral lines for diagnostics</td>
<td>UNR, LANL</td>
<td>PrismSpect</td>
<td>DCA atomic physics</td>
</tr>
<tr>
<td>laser beat wave generation</td>
<td>Voss, LANL</td>
<td>LSP, VPIC</td>
<td>PIC</td>
</tr>
<tr>
<td>fusion energy gain estimates</td>
<td>Stony Brook</td>
<td>FronTier</td>
<td>3D front tracking fluid code</td>
</tr>
</tbody>
</table>

*See poster by J. Cassibry (UAHuntsville) for overview and other posters for details
3D ideal hydrodynamics simulations guided original PLX design, and newer 1D imploding liner calculations give consistent results

3D SPHC simulations using 30 discrete merging jets (2008)

1D RAVEN simulations of imploding liner starting at merging radius (2010)

Reference case: N=30 jets, $n_{jet} \approx 5.4 \times 16 \text{ cm}^{-3}$, $v=53 \text{ km/s}$, $E=10 \text{ kJ/jet}$, peak pressure $\sim 0.1 \text{ Mbar}$

*See posters by J. Cassibry (UAHuntsville) for scaling studies and T. Awe (LANL) for verification and new RAVEN results

First experimental campaigns in 2011-2012 will address jet propagation and 2–5 jet merging physics issues

Single jet propagation/evolution:
- Atomic physics corrections to adiabatic expansion model (see UP9.00122)
- Improvements needed for atomic physics models (see UP0.00119)
- Spreading out of jet edges

Two jet merging:
- Initial plasma penetration
- Shock formation/dynamics and heating
- Post-merge plasma properties

Five jet merging:
- Important differences with two jet merging
- Post-merge plasma properties
- Uniformity of leading edge of post-merged plasma

See posters UP9.00110 & UP9.00113 for preliminary jet merging studies at HyperV!
PLX project schedule

We plan to use laser generated beat waves to drive current and magnetize the plasma*

*See poster by F. Liu (UC, Davis) for details on refurbishment/testing of a CO\textsubscript{2} laser system

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Slide 19

Operated by Los Alamos National Security, LLC for NNSA

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Slide 20

Operated by Los Alamos National Security, LLC for NNSA

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Magnetized PLX plasmas could offer access to unique data on magnetized HED plasma transport and stability

PLX can potentially access both unmagnetized & magnetized HED regimes:

Instabilities such as magnetic Rayleigh-Taylor modes can be studied:

We will test the emergent phenomenon of jet formation in an astrophysics-relevant experiment at HyperV

Formation of extragalactic jets from black hole accretion disk

Idea proposed by D. Ryutov, LANL Plasma Jet Workshop, 2008; CAD by David Van Doren (HyperV).
A simple but cosmically-relevant collisionless shock experiment can be fielded by colliding two plasma jets head-on*

Table 1: Proposed reference experimental values, and evaluation of the resultant physics criteria against Drake's [Drake, 2000] criteria for a cosmically-relevant collisionless shock experiment. All speeds are for the laboratory frame of reference. W. P. Drake, Phys. Plasmas 7, 2690 (2000)

<table>
<thead>
<tr>
<th>parameter</th>
<th>jets at collision</th>
<th>jets initial</th>
</tr>
</thead>
<tbody>
<tr>
<td>species</td>
<td>H^+</td>
<td>H^+</td>
</tr>
<tr>
<td>density (cm⁻³)</td>
<td>3 x 10¹⁴</td>
<td>~ 5 x 10¹⁵</td>
</tr>
<tr>
<td>temperature (eV)</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>speed (km/s)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>magnetic field (G)</td>
<td>1000 (applied)</td>
<td>50 (decays quickly)</td>
</tr>
<tr>
<td>length L (cm)</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>radius R (cm)</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>background vacuum pressure (Torr)</td>
<td>10⁻⁴</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>shock speed V_s (km/s)</td>
<td>167</td>
<td>N/A</td>
</tr>
<tr>
<td>post-shock T_e (eV)</td>
<td>139</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Criterion (see Sec. 3.2) estimate for proposed experiment:

- DH/ps ≥ 1: 25
- post-shock β ≥ 1: 1.7
- M_a > 1: 2.1
- λ/ps ≥ 1: ~ 10 (quasi-L) and 2–3 (quasi-I)
- R_M ≤ 1: ~ 100
- λ_M > L: ≥ 2 (% neutrons in jet)
- ω_M/C_M ≥ 1: 20
- L/c/ω_M ≥ 1: 40

Legend for figure on right: 1–unshocked plasma of jet A, 2–left going shock, 3–shocked plasma of jet A, 4–where jets A/B collide, 5–shocked plasma of jet B, 6–right going shock, 7–unshocked plasma of jet B.

Imagine a full description of the proposed setup with various labeled elements.

Summary

- Imploding plasma liners have many potential applications
  - Assembling repetitive cm/μs scale Mbar plasmas for HEDLP scientific studies
  - Unique laboratory plasma astrophysics experiments of cosmic relevance
  - Innovative driver for IFE with magnetic fields
- PLX will explore/demonstrate formation of imploding plasma liners to 0.1–1 Mbar peak pressure using 1.5 MJ of initial stored energy
- Focus will be on predictive physics understanding of:
  - Plasma jet propagation, expansion, merging
  - Liner formation and convergence
  - Stagnation dynamics determining peak pressure and dwell time
  - Laser generated beat-waves for standoff magnetization of PLX plasmas
- There is a coordinated multi-institutional theory/modeling effort using ten different codes
- Facility construction phase 1 nearing completion with first experiments to begin in 2011!