Ion acceleration with kHz ultra-intense laser interacting with thin liquid sheet target

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Outline

• AFRL Extreme Light Lab
• Motivation
• Precision liquid target development for high repetition rate application
• Relativistic electron generation @ kHz rep-rate
• Ion acceleration @ kHz rep-rate
• Outlook: Neutron generation @ kHz rep-rate
• Summary
10 kHz, 1 mJ 40 fs Laser system

Legend

Liquid Target Characterization Area

TOAC

Solid Chamber PC’s

Death Star Chamber

Red Dragon Laser System

Evolution

Probes Delay Line

Main Pulse Cmpsr

Pre-Pulse Cmpsr

SSA

Pockel’s Cell

Liquid Chamber

Solid Chamber
Laser Schematics

- Pulse Contrast:
  - ps < $6 \times 10^{-5}$
  - ns < $6 \times 10^{-8}$

450mW @ 65nm FWHM @ 80MHz

Griffin

Frequency Shifted SHG Pre-plasma Probe

YAG Pump Laser

25um Water Column/ few um droplets/sub-um liquid sheet

>10mJ, 35 fs 1 kHz, 780 nm

F/1.0 Off-axis Parabola
> $10^{18}$ Wcm$^{-2}$
Pulse contrast > 10$^5$-1

Stretcher

Pulse Picking Pockels Cell

Pulse @ 80MHz

200ps @ 1KHz

Multi-Pass Amp

2 Pulse Cleaning Pockels Cells

2mJ

Three-Pass Amp

70mJ

Compressor

24mJ

2 Separate YAG Pump Lasers
Motivation

- Advent of High Rep rate lasers
- Applications:
  - High rep rate sources
    - Ions (Cancer Therapy, HZDR)
    - Neutrons (Karsch, Kitagawa, DARPA Pulse NE-OSU-UT)
    - Electrons, x-rays, positrons (many groups)
- Experiments
  - FEL/XFEL rep-rate high (LCLS 120 Hz, European XFEL, SASE, and others)
Motivation: High Rep-rate

- kHz to multi-kHz mJ/pulse femtosecond lasers have the potential to be engineered in small, rugged, stable form factor with portable power source in near future
- Potential portable source for Multi-MeV x-rays/electrons/proton/ion beams All in one
- Potential application in DHS, Radiation damage, Material modification, photocathode, PIXE, etc.
- Need Cheap targets for ≥ kHz operation
Why liquid target?

**Pros**
- Cost effective
- Potential to go to Multi-kHz
- Alignment potentially easier than solid targets
- Debris evaporates

**Cons**
- Hard to produce very thin targets
- High vapor pressure for some liquids
- May cause corrosion inside chamber

**Liquid target type**

Liquid-jet target for laser-plasma soft x-ray generation
L. Malmqvist, L. Rymell, M. Berglund, and H. M. Hertz, RSI 67, 4150 (1996)

Ultrafast x-ray pulses emitted from a liquid mercury laser target

Individual solid target in Relativistic laser matter interaction cost $1 – $10,000 ea

Ultrashort 1-kHz laser plasma hard x-ray source

MBI+MPQ

Imaging Methanol Droplet Interaction in AFRL Dayton

Precision Liquid targets at AFRL

- Liquid targets produced in 0.9 – 20 Torr
- Target type
  - Jet column (30-200 µm),
  - droplets (> 5 µm),
  - Sheet (~300 nm)
- Positioning accuracy: 1 µm
- Healing time from 10 – 40 µs

Experiments at > $10^{18}$ Wcm$^{-2}$ intensities with liquid targets
Liquid target interaction Probing system

Single oscillator splits into pump (780 nm) and shifted probe amplifier (830 nm)

probe beam 420 nm polarization rotated

800 nm objective

Water target

pump beam 800 nm

OAP

Notch filter

Spatial filter

Hi-mag Camera

Low-mag Camera

Shearing Michelson Interferometer (Nees, UM)
Interferometry and shadowgraphy

- Pre-pulse generated pre-plasma detection with $10^{18}$ Wcm$^{-2}$ interactions in water
- Distinguish regions of plasma from vacuum and neutral regions

Feister et al.
A novel femtosecond-gated, high-resolution, frequency-shifted shearing interferometry technique for probing pre-plasma expansion in ultra-intense laser experiments
Experiment:
Relativistic electron generation with precision liquid targets
What we expected from Conventional Ultra-intense LPI mechanisms:
Ionized electrons accelerated in the laser field mainly propagates in forward direction with significant energy.

What we observed:
Backward going MeV electron beam.

Conventional Wisdom: LPI
Added Panoramic Image Plate

800 nm beam

Water target

Cureved Image Plates & Pb filters

Flat Image of cylindrical detector
X-ray Dose Through Pb Filters

Beamlke dose through 4mm of Lead
Implies spectral components > 200keV

1 mm Pb  2 mm Pb  3 mm Pb  4 mm Pb

Central Feature 3-5° apparent divergence
Integrated over ~ $10^5$ shots
We then decided to observe single hit x-ray spectra


Target Normal Photon Spectra

Detector 10 m away
Collect back-scattered electrons using isolated OAP as Faraday Cup

800 nm beam

Water target

Cured Image Plates & Pb filters

~5 μA Current ->
~5 nC / pulse

Corroborated between Scope Potential Difference and Electrometer

Flat Image of cylindrical detector
Current Measurement Through 100 μm BK7 Glass

100 μm Cover Slip Stops ~120 keV e’s
~3.4 MeV p’s

800 nm beam

Water target

~2.5 μA Current ->
~2.5 nC / pulse w/ >120 keV

Cureved Image Plates & Pb filters

Flat Image of cylindrical detector
Backscattered electrons on Imaged Lanex Screen

800 nm beam

Water target

Image moves with introduction of magnetic field.

25um Al & Lanex phosphor

OAP

Light tight Al filter blocks
~< 55 keV e’s
~< 1.4 MeV p’s

Lanex Screen in 1” beam tube. 5 shot Integration

Camera
Direct Electron Measurement with H-OAP

- Hole is 3-mm, 10 degree cone.

The “Holey OAP”

- Energy calibrated using 2D particle-tracking code in conjunction with measured magnetic fields
- Electron angle of incidence at each energy can also be determined.

Electron diagnostics

- Deformable mirror
  Optimization of focal pot

“Best focus” optimization

- 10 shot integration
- working on absolute calibration this week at Notre Dame ion accelerator

Feister et al arXiv:1508.07374v2
Particle-in-Cell (PIC) simulations using the LSP code indicate strong electron beams if a pre-plasma is present. A scale length of $3 \times 10^{18} \text{ W/cm}^2$, 1.5 $\mu$m pre-plasma scale length is required. Without a pre-pulse, MeV electrons disappear.

Experiment:

Ion acceleration
Target Normal Sheath Acceleration (TNSA) Sketch

- Laser $\gtrsim 10^{18}$ W cm$^{-2}$
- Target thicknesses $\sim \mu m$’s
- Intensities $\sim 10^{18-20}$ W cm$^{-2}$
- Generate $\sim MeV$ electrons in a forward directed cone
- Laminar source of $\sim MeV$ ions, dominated by surface ions with the largest $q/m$
- The most energetic ions are typically within a $\sim 5-10^\circ$ cone around the target normal
Laser Based Neutron Production

Neutron production cross sections

- $^7\text{Li}(d,xn)$ – high neutron production cross-section
- $^7\text{Li}(p,n)$ – directional beam-like source


Coated w/ 1.2±0.2 μm D$_2$O Ice
500 mJ ~1x10$^{19}$ W/cm$^2$

≥3 MeV
0.5-1 MeV
Selective Deuterium Ion Acceleration Using the Vulcan PW Laser
AG Krygier, JT Morrison, S Kar, H Ahmed, A Alejo, R Clarke, J Fuchs, A Green, D Jung, A Kleinschmidt, Z Najmudin, H Nakamura, P Norreys, M Notley, M Oliver, M Roth, L Vassura, M Zepf, M Borghesi, RR Freeman

Characterisation of deuterium spectra from laser driven multi-species sources by employing differentially filtered image plate detectors in Thomson spectrometers

$\sim 10^{20}$ W cm$^{-2}$ interacting with 10um Au foils coated with 0.5-4um of heavy ice.
Why AFRL Dayton?

kHz Rep – rate & water Target - with comparable intensity

It is often argued that in application, high repetition rates will be employed but rarely are in practice.

On neutrons / sec this has the potential to match or exceed some of the largest lasers in the world in a much more manageable package.

<table>
<thead>
<tr>
<th>Laser</th>
<th>Energy (J)</th>
<th>Intensity (W/cm²)</th>
<th>Shot/sec</th>
<th>$^7$Li($D,nx$) n/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omega EP</td>
<td>2600</td>
<td>$2 \times 10^{19}$</td>
<td>$\sim 3 \times 10^{-4}$</td>
<td>$\sim 4 \times 10^{7}$</td>
</tr>
<tr>
<td>Vulcan</td>
<td>500</td>
<td>$3 \times 10^{19}$</td>
<td>$\sim 3 \times 10^{-4}$</td>
<td>$\sim 1 \times 10^{7}$</td>
</tr>
<tr>
<td>Titan/ Texas PW</td>
<td>150</td>
<td>$3 \times 10^{19}$</td>
<td>$\sim 3 \times 10^{-4}$</td>
<td>$\sim 4 \times 10^{6}$</td>
</tr>
<tr>
<td>Scarlet (OSU)</td>
<td>15</td>
<td>$1 \times 10^{20}$</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$3.5 \times 10^{7}$</td>
</tr>
<tr>
<td>Red Dragon (AFRL/RQ)</td>
<td>0.01</td>
<td>$5 \times 10^{18}$</td>
<td>$1.0 \times 10^{3}$</td>
<td>$6.5 \times 10^{7}$</td>
</tr>
</tbody>
</table>
Focal spot: 3 μm, Pulse energy: 8 mJ @ 1 kHz, Peak intensity 5 $10^{18}$ W cm$^{-2}$
The 5 cm x 5 cm CR-39 sheets were placed 2.5 cm away from interaction region, to capture evidence of “Target normal Sheath acceleration (TNSA)” of ions, and for energy calibration, had number of 6 um thick Mylar sheets covering it. The more energetic the ions would penetrate increasing number of Mylar sheets and leave their mark underneath, on the CR-39 etch pattern.
Ion Detection with CR-39

Mylar Cutoff Energy for Protons
- 1 sheet: 6µm - 425keV
- 2 sheets: 12µm - 690keV
- 3 sheets: 18µm - 910keV
- 4 sheets: 24µm - 1090keV

Saturated under 4 Sheets of Mylar
Radiochromic Film

Back of the water target (TNSA), 2 x 6 um Al foil light tight
Radiography
Our Liquid Scintillator Detectors

• In house design and construction
• Utilize same scintillator
• Use PMT’s and scopes for signal acquisition
• ToF detectors Use smaller cavities & faster PMT’s
• Future gate implementation uses custom voltage dividers similar to Pockel’s cell drivers
• AFIT contacts have shown interest in calibration efforts.
Summary

• AFRL Lab liquid target development for kHz rep-rate experiments
  – Jet
  – Droplet
  – Sub-micron sheet
• Experiment: Relativistic electron generation with precision liquid targets
  – Backward MeV electrons/x-rays with mJ-1kHz laser
  – Presence of pre-plasma crucial for backward propagating electron acceleration
• Experiment: Proton acceleration from thin liquid sheet at kHz rep-rate
  – Optimization for conditions
  – Multi MeV protons
• kHz neutron generation using pitcher-catcher techniques