Update on FSC Activities at the U. of Texas: Laser interactions with cone and micro-sphere targets

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These experiments were conducted with the "Texas High intensity Optical Research laser" (THOR)

Present performance specs:
~ 35 fs pulsewidth
0.75 J energy @ 10 Hz
→ ~ 20 TW peak power
Our contribution to the FI FSC is in the study of hot electron generation in cone targets.

Proposed approach:
Study x-ray source size and brightness from cone targets in silicon with x-ray converter layers.

The spot from which x-rays originate is found to be considerably larger than the laser spot.

Many hot electrons, high energy conversion efficiency, small K-shell spot, bright K-shell emission.
Based on modeling at UNR, we have begun a study of hot electron generation in cone targets.

Incident & reflective electric fields
- Surface current
- Magnetic field
- Push electrons out to the interior of the cone

Simulations indicate that electrons are accelerated along the cone surface toward the tip of the cone.

Electrons are driven back by the sheath field

- Forces are balanced
- Electrons are trapped on the surface

Sheath field ($E_s$)

Magnetic field ($B_2$)

Electron guiding in cones could lead to electron focusing near the tip of the cone.

Combination of laser E-field and self generated B-fields guide electrons toward the tip.
With this Si etching method, pyramidal shaped cones with tips ~ 1 µm can be produced.

Pyramids:

The tip of the pyramid is sharper than 1x1·µm²

SEM images of Pyramid target
We use the fact that the KOH etching rates in Si are strongly affected by the crystallographic orientation.

<table>
<thead>
<tr>
<th>Crystallographic Orientation</th>
<th>Etching Rate (μm/min)</th>
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</thead>
<tbody>
<tr>
<td>(100)</td>
<td>0.797 (0.548)</td>
</tr>
<tr>
<td>(110)</td>
<td>1.455 (1.000)</td>
</tr>
<tr>
<td>(111)</td>
<td>0.005 (0.004)</td>
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@ 70°C, 30% KOH

Surface Orientation

\[
\begin{align*}
\langle 111 \rangle & \quad 54.74° \\
\langle 100 \rangle &
\end{align*}
\]
30% KOH solution is used to etch the Si 100 plane at a 1\(\mu\)m/min etching rate

The tip of pyramid goes to the reverse side as close as possible

Immerse in KOH solution

KOH etching done

Si\(_2\)N\(_3\) Deposition
Furnace @ 950°C

Optical Lithography
PR coat, UV, Develop

Reactive Ion Etching
Vacuum @ 10\(^{-5}\) torr

KOH Etching
~ 7 hours @ 60°C

Metal Layer Coating
Low Z material (Ti, Cu)

11-25 mm Ti foil layer
The silicone cones were backed with a Ti K-alpha converter layer.
We have investigated polarization effects by creating wedge shaped targets.

A wedge is a 1 dimensional pyramid. Due to laser absorption mechanisms and plasma heating, polarization effects should be observable with wedge-shaped targets.
We utilized a weak parabolic focusing optic for cone experiments

Alignment imaging system

Silicon cone targets

f/3 parabola

Peak intensity in vacuum > 2 x 10^{19} \text{ cm}^{-3} \ @ \ 20 \text{ TW}

Imaged focal spot of 800 nm light in vacuum
Targets were diagnosed with von Hamos and spherically bent crystal spectrometers

X-rays in the vicinity of $K\alpha_1$ and $K\alpha_2$ are focused by an off-axis spherically bent crystal which is fine-tuned to give spatial resolution in 1 dimension

**Spherically Bent Mica Crystal**
- Bragg reflection, 7th order
- Oriented to reflect $K\alpha_1$ and $K\alpha_2$
- Spatially images horizontal direction
- Demagnification of 1.15

**Kodak RAR 2492 Film**
- Directly exposed by Ti $K\alpha$ x-rays
- High (5um) resolution
- Requires ~30 shots integrated
A von Hamos spectrometer was designed to survey Ti K-α as well as He-like line emission.

Cylindrically Bent PET Crystal
- Bragg reflection, 2nd order
- Oriented to detect 2.21Å - 2.79Å
- Line focus increases intensity of spectrum

Kodak RAR 2492 Film
- Integrate ~50 shots for good signal

X-rays in the vicinity of Ti K_α and K_β pass through a filter window and are diffracted and line-focused by a cylindrically bent crystal. Blue lines indicate path of detected x-rays.
We fielded a von Hamos spectrometer to survey Ti K-\(\alpha\) and He-like emission.
A bent mica spectrometer was used to image the Ti Kα in one dimension.
We observed hints of He-like and satellite lines from irradiation of Ti foil
We observe both K-α and He-like emission from irradiation of silicon targets.

An average of 70 shots has to be recorded on Agfa Structurix D7 film, revealing characteristic line radiation:

Heα  Li-like satellites (abcd, hkl and qr)  Kα₁ & Kα₂

Heα: 1s2p(1P₁)-1s2(1S₀) (Si XIII)

Li-like satellites are transitions (of high-n levels) of Li-like Silicon (Si XII), for example the so-called jk lines are 1s2p²(2D₅/₂)-1s²2p²(2P₃/₂) (1)

Cone targets exhibit lower yield but substantially smaller source size when compared to flat Ti targets.

Direct brightness comparison of cones vs. 0° flats

- Flat Ti, 11µm
- 71° square cones, 25µm Ti on back

Spatial extent in horizontal (polarization) direction [mm]

Ti Kα brightness [Kα photons/µm² shot/off film]

Flat Ti target

Si cone with Ti fluor layer target
The Ti K-alpha halo observed from flat targets was reproducible over many different runs.

Direct brightness comparison of runs 18 and 19, 0° on flats

- Higher noise levels from differences in shielding, wait time
- Slight spectrometer adjustment between runs
The spatial extent of $K_{\alpha}$ from cone targets showed no side peaks or plateau.

**Spatial Extend of $K_{\alpha}$ From 11\(\mu\)m flat Ti foil and 71° P-wedges and cones with 25\(\mu\)m Ti on Back Surface**

- 11\(\mu\)m Ti foil shot at 0°
- p-oriented Si wedge with 25\(\mu\)m Ti
- Si pyramid with 25\(\mu\)m Ti

**K_{\alpha} spatial from flats, p-wedges, and cones (offset):** Cones and wedges do not show a plateau or side peaks.

**Fountain screening:** In cones, electrons which “fountain” >50\(\mu\)m from center on the front side will be separated from Ti by enough Si to stop 100keV electrons. This could account for the lack of side peaks & plateau for cone and wedge targets.
We hoped to get info on electron acceleration by examining polarization effects in wedge targets.
Anisotropic etching of Si is used to produce shaped targets

A wedge is a “1-D” cone

“p” and “s” refer to wedge orientation relative to laser polarization
S-oriented wedges showed higher $K_\alpha$ yield than p-oriented wedges, but less than flat foils.

X-ray yield from 25$\mu$m foil for flat, s-wedge, and p-wedge Targets

Possible explanations

- Imperfect coupling between wedge and foil
- Mid-temperature (~10keV) electrons stopped by Si bulk material;
- Minimal surface guiding of electrons towards tip
- P polarized produced more hot electrons (>100 keV, which interact less with Ti) than s-polarized wedges

50 shots integrated for each target type
We measured hot electron production with NaI hard x-ray detectors

<table>
<thead>
<tr>
<th>Filter</th>
<th>Cutoff energy</th>
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<tbody>
<tr>
<td>32 mm Pb</td>
<td>600 keV</td>
</tr>
<tr>
<td>48 mm Pb</td>
<td>800 keV</td>
</tr>
<tr>
<td>95 mm Cu</td>
<td>1200 keV</td>
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Array of 6 detectors @ 4’ distance to chamber as used for flat targets

Array of 3 detectors @ 14’ distance to chamber as used for shaped targets
We used a multi channel hard x-ray detector array to derive some information on hard x-ray temps.

THOR laser (Ti:S)
800nm: 35fs, ≈15mJ, ≈10^{18} \text{Wcm}^{-2}
400nm: ≈100fs, ≈15mJ, ≈10^{17} \text{Wcm}^{-2}

Glass or copper sphere-coated targets

Nal scintillation detectors (0.1 – 1 MeV)

<table>
<thead>
<tr>
<th>Filter</th>
<th>Cutoff energy</th>
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<tbody>
<tr>
<td>12 mm Cu</td>
<td>162 keV</td>
</tr>
<tr>
<td>12.5mm Al</td>
<td>450 keV</td>
</tr>
<tr>
<td>32mm Cu</td>
<td>500 keV</td>
</tr>
<tr>
<td>43mm Cu</td>
<td>600 keV</td>
</tr>
<tr>
<td>24mm Pb</td>
<td>700 keV</td>
</tr>
<tr>
<td>44mm Pb</td>
<td>900 keV</td>
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</table>
Hard x-ray detectors suggest higher hot electron temperature in P-polarized wedge targets

A set of three Hard X-ray detectors filtered with lead and copper filters was used to infer hot electron temperatures.

Filter 1: 3.3cm lead, cutoff 800KeV

Filter 2: 5.0 cm lead, cutoff 1000KeV

Filter 3: 9.3cm copper, cutoff 1200KeV

**Hard x-ray yield versus 1/e^2 cutoff energy for different shaped targets**

HXR(s-wedge) < HXR(pyramid) < HXR(p-wedge)
PIC simulations confirm that hotter electron temperatures are achieved with P-pol in wedge targets.

Higher absorption for P-wedge
but Energy is deviated from the tip for P-wedge \( \rightarrow \) less K\( \alpha \)

Less Absorption for S-Wedge
\( \rightarrow \) Pressure of Light Field \( \rightarrow \) Energy Flow towards tip \( \rightarrow \) Brighter K\( \alpha \) Source

Y. Sentoku, et al., PIC Simulations, private communication
We have some prepulse with the 800 nm pulses which create a pre-plasma of $\sim 2 \ \mu m$.

We measured hard x-ray yield as a function of angle for P-polarized irradiation of polished Cu targets.

Using the standard result for resonance absorption from Kruer (for a maximum absorption angle, $\theta_{\text{max}}$):

$$scale\ length \approx \frac{\lambda}{4 \pi \sin^3 \theta_{\text{max}}}$$

We find that we have a plasma scale length $\approx 2 - 2.5 \ \mu m$.
Our data indicate that we produce a large fraction of unredirected hot electrons from cones.

- More HXR for P than for S
- Highest Absorption for P
- Hottest Electron Temperatures
We have been conducting experiments on irradiation of mesoscale targets

Particles of Intermediate Size between Gas and Solid (Droplets, Cluster,…)

→ Droplet source: $T_{\text{hot}}$ higher than for planar target (700keV > 400keV)


→ Use electrons for bright K-alpha source:

0.1, 0.26, 0.36, 0.5, 2.9 µm diameter

~150fs, 10mJ, 400nm, $10^{17}$ W/cm²
Because of Mie resonance field enhancements, wavelength scale particles may be an interesting high field target.

- Large field enhancements expected (related to size parameter \( \pi \lambda / d \))
- Internal field is shielded
- Surface heating is inhomogeneous

Can we exploit these resonances to increase hot electron temperatures and hard x-ray efficiencies?
We created very simple targets by layering monolayers of polystyrene spheres in solution on a substrate.

- Focus laser onto a solid target coated with microspheres
  - Commercially available in solution
  - Sizes are variable and well defined (3%)
  - High-Z substrates

Enhanced field around spheres increases $T_{\text{hot}}$

$\Rightarrow$ Improved hard x-ray yield
We constructed targets of monodisperse spheres deposited on copper or fused silica substrates

Monolayers of spheres were deposited on Si wafer
Duke Scientific, monodisperse solutions
0.1, 0.26, 0.36, **0.5, 2.9 μm** diameter

![Image of 0.5 μm spheres](image_url)
We could achieve close packed monolayers of spheres over sizes greater than the laser focal spot

- Monolayer regions are near-perfect although coverage is not 100%
- Sphere diameters of:
  - 0.26µm
  - 0.5µm
  - 1.0µm
  - 2.9µm

Hope to see different strength res (related to size parameter $\pi$)
Focusing of the low energy 400 nm pulses for microsphere experiments yielded intensity $\sim 5 \times 10^{17}$ W/cm$^2$.
Irradiation with $2 \omega$, 400 nm light indicates that the plasma scale length is very short, $< 100$ nm

Peak in hot electron production with incidence angle $\sim 55^\circ$ suggests Brunel heating at a very sharp surface

scale length $\approx \lambda / (4 \pi \sin^3 \theta_{\text{max}})$

scale length $\sim 100$ nm $< \lambda$

Angular dependence of $>22.7$ keV x-ray yield for glass irradiated with 400nm laser beam
Si K-alpha yield shows a very distinct dependence on the size of spheres coating the silica.

- Yield depends on Sphere Size
- Resonance for 0.26 $\mu$m
- Lowest yield for 2.9 $\mu$m
- 45 degree gives more K$\alpha$ than 0 degree (2.9 $\mu$m is only exception)
Sphere coated targets show a significant enhancement in K-α yield, even over P-polarized flat irradiation.

- Spheres give >10x more Kα
- Measured repeatedly

- Spheres give ~3x more Kα
- Rough silicon better than polished
- Measured repeatedly

- More electrons around 5-7 keV created with spheres
Line broadening on Si He-\(\alpha\) from silica targets coated with spheres indicates a denser thermal plasma

**He-\(\alpha\), 0.26 \(\mu\)m spheres, 45°**

**He-\(\alpha\), Flat Target, 45°**

Line Width \(\Rightarrow\) Information about Plasma Density \(\Rightarrow\) broad = high density

Spectroscopy integrates over Density Gradient

\(\Rightarrow\) Fast rising edge corresponds to longer density scale length
Si K-alpha yield peaks with sphere sizes of 260 nm

Integrated K-alpha yield (arb. units)

Sphere diameter (µm)

70 shots integrated @ 45°

70 shots integrated @ 0°
Field structure around a plasma sphere depends dramatically on the ratio of sphere size to wavelength.

Intensity of Electric field in a plane parallel to the polarization of incident laser:

- Internal field is shielded
- Surface heating is inhomogeneous

Max intensity vs. diameter (in Microns) for plasma
Field enhancements around ionized, over critical spheres are sizable

Calculated field structure around a sphere in an EM field

1) Field structure around a sphere in free space

Value of $|E|^2$ compared to vacuum value

2) Field structure around a sphere sitting on a dielectric substrate
Very large field enhancements occur between two closely spaced ionized spheres.

Value of $|E|^2$ compared to vacuum value

Intensity enhancement of over 20 may exist in the interstices between spheres in an array.
Field enhancements around spheres are very dependent on sphere size.

Calculated maximum enhancement of the vacuum field around ionized spheres.

- Single sphere in vacuum
- Single sphere on a substrate
- Close packed array of spheres

Sphere diameter (nm) vs. $|E|^2$ maximum enhancement.
Both K-\(\alpha\) and hard x-ray yields show order of magnitude enhancements with the coating of 260 nm spheres.

Ka and Hard X-Rays show same resonance-like behavior for 0.26 \(\mu m\)

HXR spectrum gives Maxwellian \(T_{\text{hot}} = 20 \text{ keV} \gg U_{\text{pond}} = 2 \text{ keV}\)

\(\rightarrow\) Mie-Resonance?

\(\rightarrow\) Multi-pass Vacuum Heating / Stochastic Heating