Phase Contrast Imaging with Betatron Radiation from Laser Wakefield Accelerated Electrons

Michael Vargas, Will Schumaker, Zhaohan He, Vladimir Chvykov, Victor Yanovsky, Anatoly Maksimchuk, Karl Krushelnick, and Alec Thomas

Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI, 48109

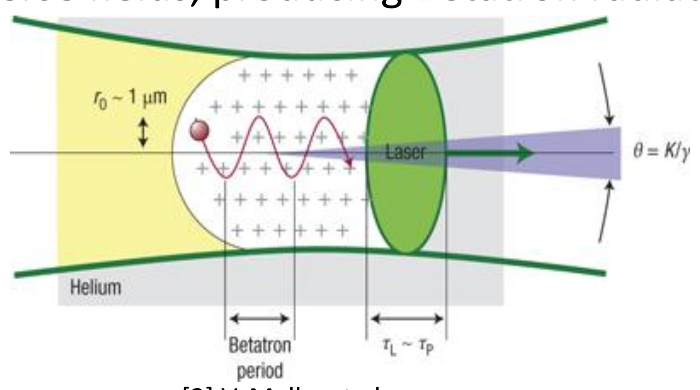
Abstract

Laser Wakefield Acceleration can be used to accelerate electrons to GeV energies while simultaneously wiggling them to produce a synchrotron like X-ray radiation called Betatron radiation. Using HERCULES, a 150TW 800 nm Ti-Sapphire laser, 35fs pulses were focused with an f/20 parabolic mirror on a 5mm gas jet to accelerate electrons. The Betatron radiation was used for phase contrast imaging of fabricated samples, while varying e⁻ injection and x-ray detection methods.

Background

Laser Wakefield X-Ray Source

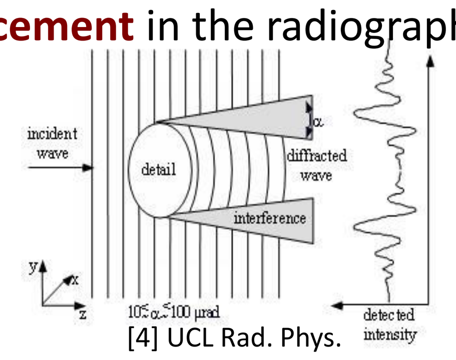
1. Intense laser pulse is focused into a gas jet producing a plasma.
2. Electrons in the immediate vicinity of the laser are expelled via the ponderomotive force.
3. This creates a plasma wake behind the laser pulse accelerating electrons to relativistic energies [1].
4. The electrons are simultaneously wiggled by transverse fields, producing Betatron radiation.



[2] V. Malka et al.

Phase Contrast Imaging

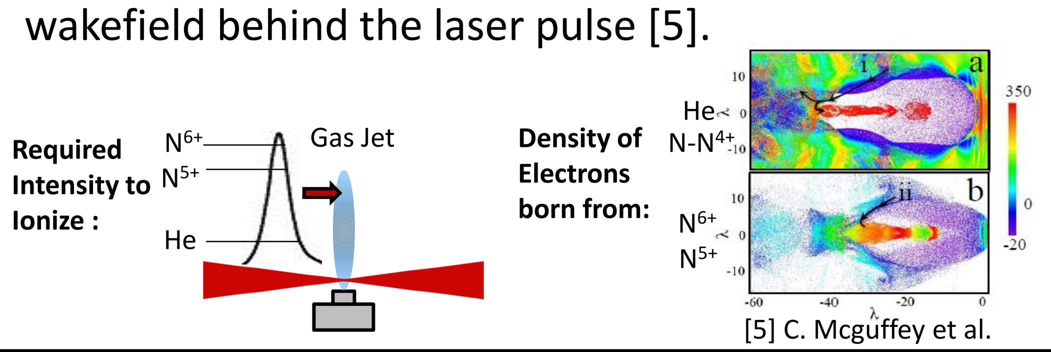
In this method a highly coherent polychromatic x-ray beam is sent through a sample. The phase front of the x-ray beam is diffracted, causing interference near the edges after propagation. This provides an **edge enhancement** in the radiograph [3].



[4] UCL Rad. Phys.

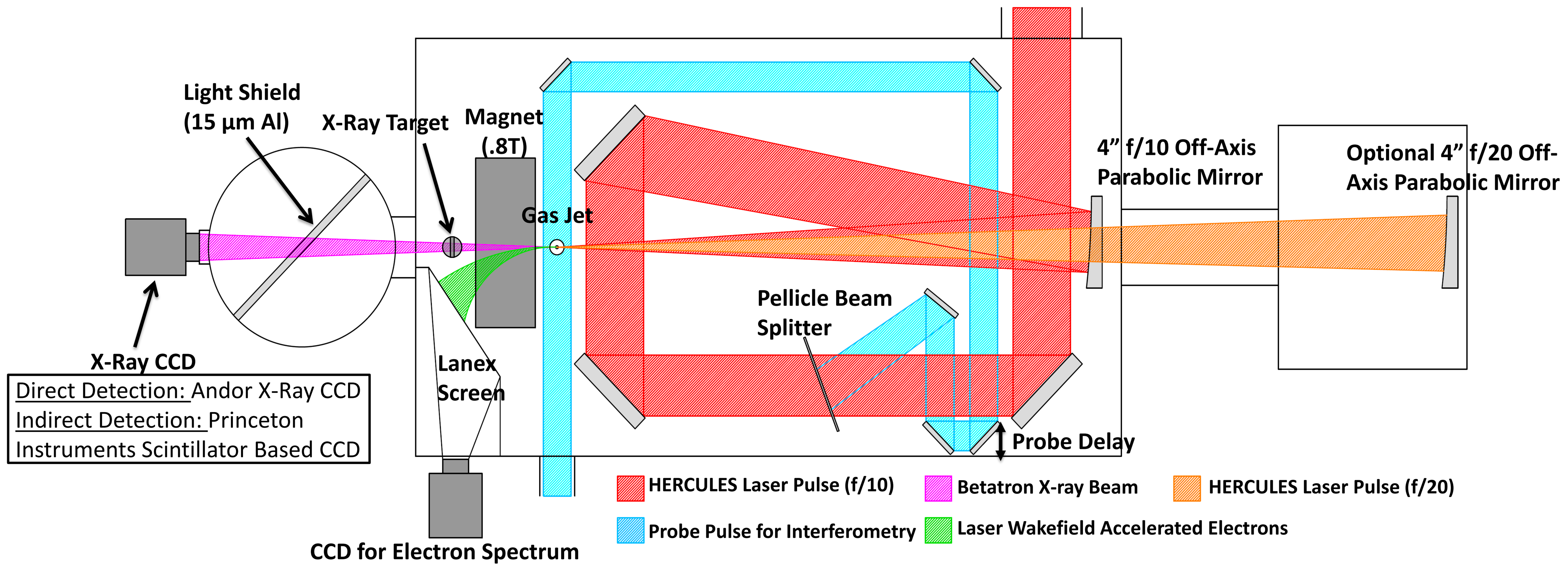
Ionization Induced Injection

Ionization induced injection relies on doping the acceleration gas (Helium) with a higher Z dopant (Nitrogen) to **increase the trapped electron charge**. The dopant gas provides additional seed electrons in the high intensity region of the laser pulse, which are at an ideal location to be injected into the wakefield behind the laser pulse [5].



[5] C. Mcguffey et al.

Experimental Setup



X-Ray Phase Contrast Targets

Overview

The targets were designed so they could isolate the phase contrast abilities of the Betatron radiation, while highlighting its resolution. They were produced using an Objet 3D printer (low-res), or a Viper SLA system (high-res). The small target size challenged each system, showing imperfections visible in the radiographs.

Target Descriptions

1.) Absorption: Produced with a low-res. 3D printer. Cut-out M shows absorption with some edge enhancement.
2.) Phase Contrast + Absorption: High-res. target with ~300μm thick extrusions for mostly phase contrast.
3.) Pure Phase Contrast: Ultra high-res. target with 80μm feature cut and extruded to eliminate absorption.

Results

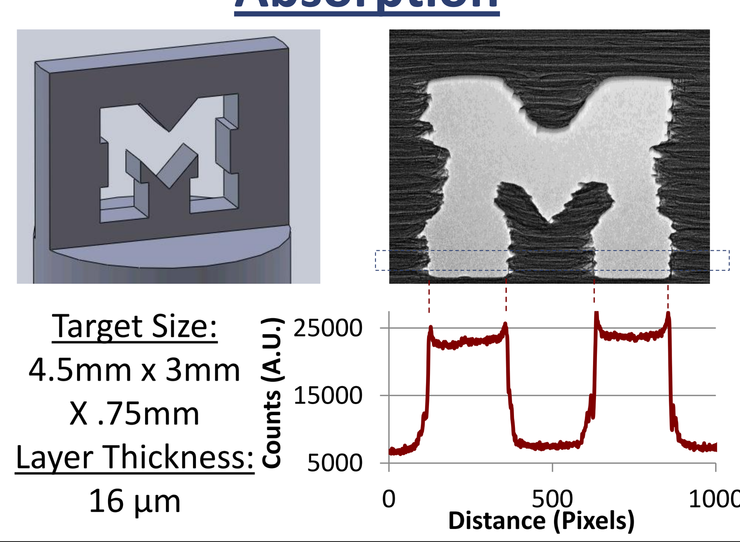
Experimental Parameters

- Laser: 150TW, 35fs, 800nm
- Focusing Optic: f/20
- Spot Size: 20μm
- Gas Jet: 5mm supersonic nozzle
- Gas Mix:

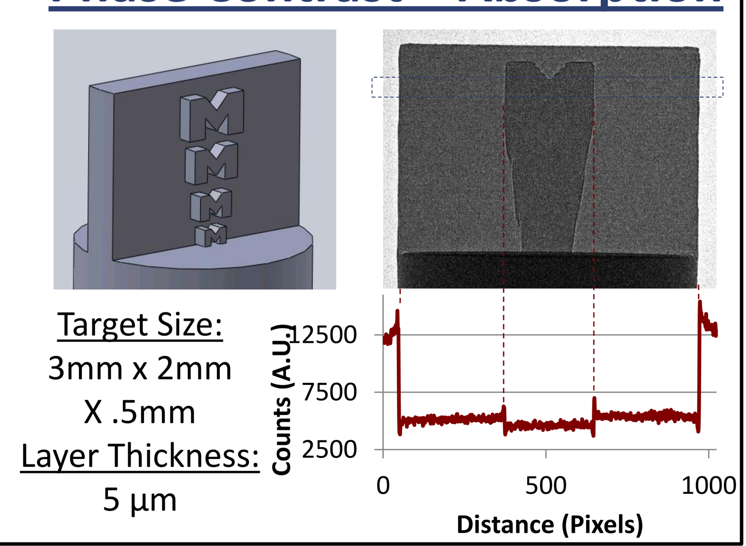
Self Injection- Pure He
Ionization Injection- 2.5%N 97.5%He

- Gas Density: ~10^{19} cm^{-3}

Absorption



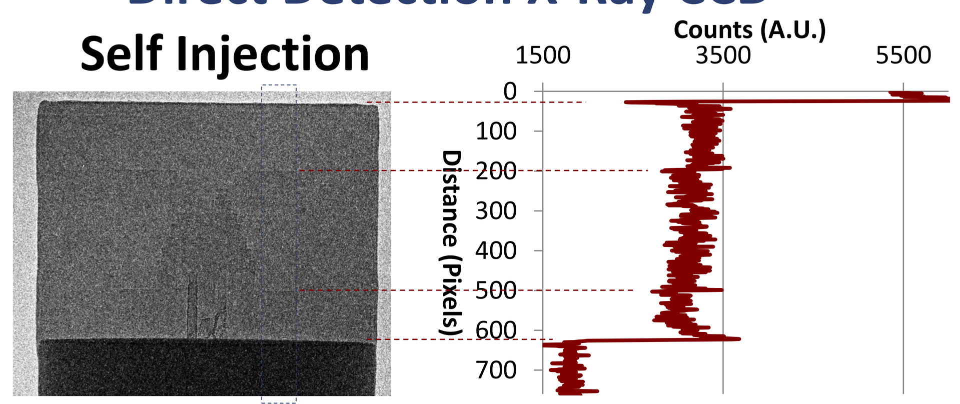
Phase Contrast + Absorption



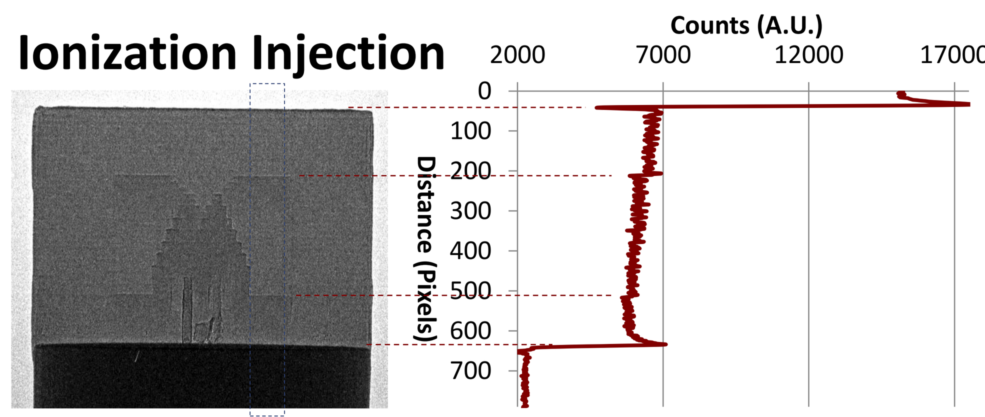
Pure Phase Contrast

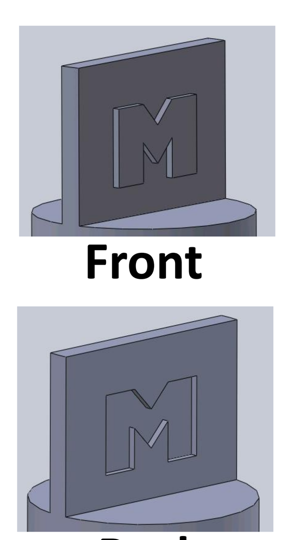
Direct Detection X-Ray CCD

Self Injection



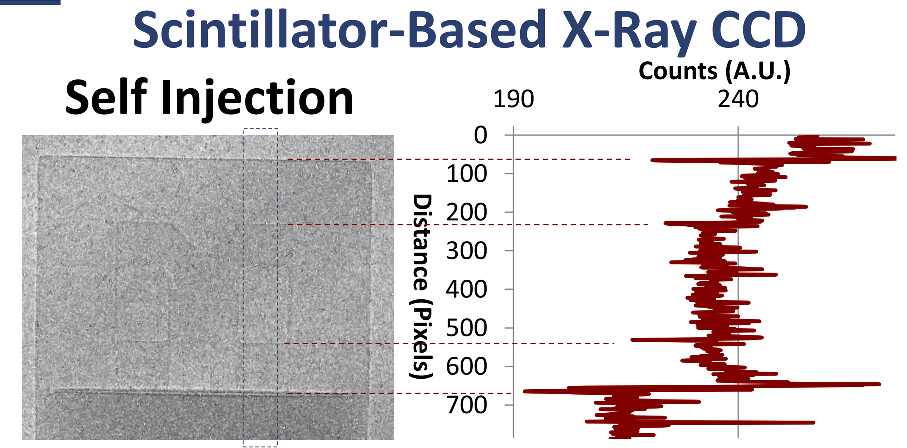
Ionization Injection



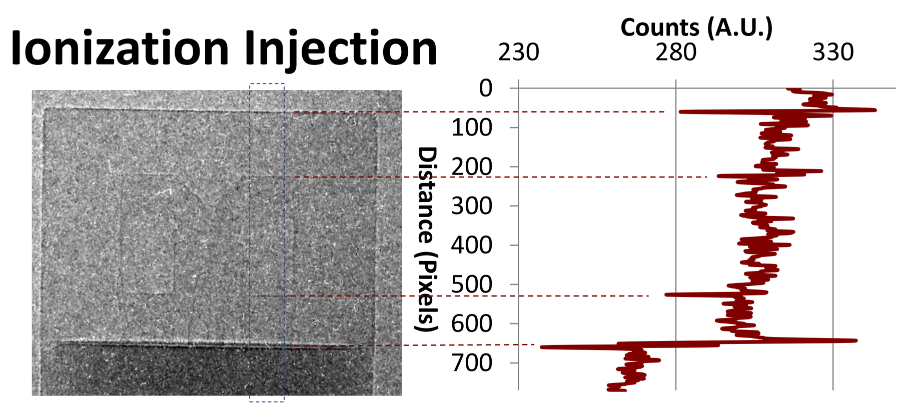


Scintillator-Based X-Ray CCD

Self Injection



Ionization Injection



*Scintillator-based Images were post-processed to reduce noise

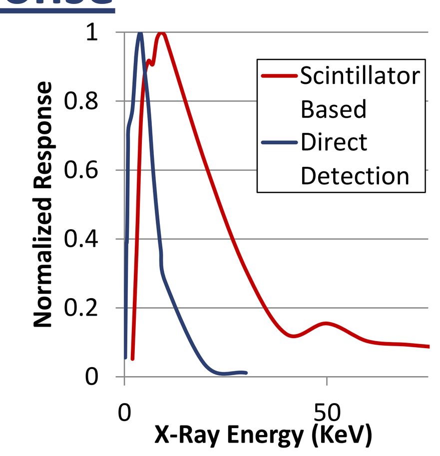
Discussion

Injection Mechanism

- Ionization injection showed higher x-ray flux, due to more trapped electrons to produce x-rays. This produced more phase contrast signal, increasing image quality.
- Self injection showed less attenuation through the target, which indicates the production of higher energy x-rays.

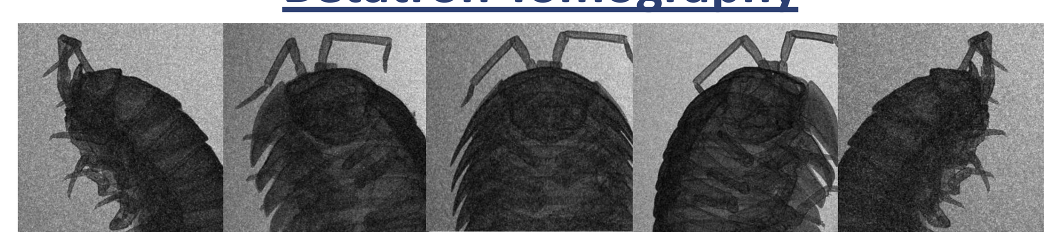
Detector Response

- Direct Detection: .1-10 KeV
- Scintillator Based: 3-50 KeV
- Indirect detection shown to be less efficient, as expected.
- Less attenuation through the target in indirect case due to low energy cutoff.



Applications

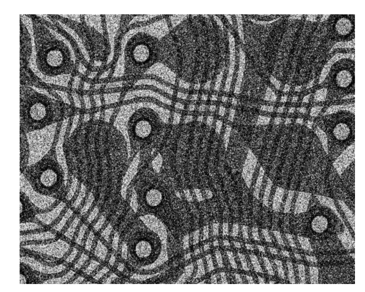
Betatron Tomography



- 3D reconstruction of biological samples (above)
- Useful for detection of edges in materials with similar absorption (tumors, clogged arteries, etc.)

Reverse Engineering

- Phase contrast imaging of micro SD card (right)
- Map electronics in order to reconstruct their functionality.
- Hard x-rays can probe denser materials found in chips.



Conclusions

Pure phase contrast imaging using Betatron radiation was observed with two injection mechanisms. A high efficiency direct detector showed clear phase contrast, while a low efficiency indirect detector showed imaging with high energy radiation. These results provided a basis for future experiments to map biological specimen.

References

[1] T. Tajima & J.M. Dawson *Phys. Rev. Lett.* **43** (1979).
[2] V. Malka et al. *Nature Physics* **4** (2008).
[3] S.W. Wilkins et al. *Nature* **385** (1996).
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[5] C. McGuffey et al. *Phys. Rev. Lett.* **104** (2010).

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