Focusing Laser Wakefield Produced Betatron Radiation with a Spherically Curved Crystal

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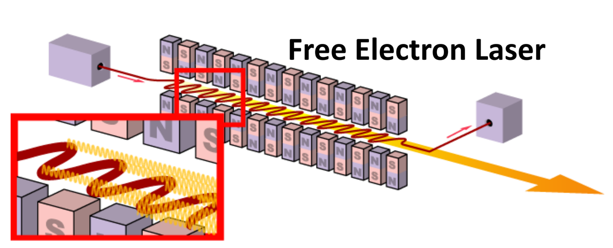
Abstract

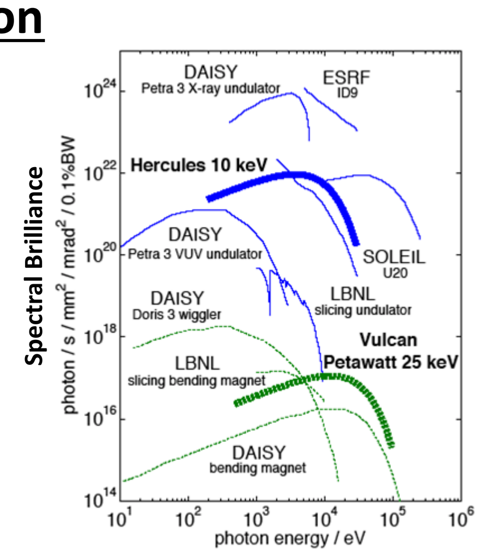
Laser Wakefield Acceleration can be used to accelerate electrons to GeV energies while simultaneously acccelerating them transversely to produce a synchrotron like X-ray radiation called Betatron radiation. Using HERCULES, a 300TW 800 nm TiSapphire laser, ~30fs pulses are focused above a 5mm gas jet to accelerate electrons in the bubble regime. The Betatron X-rays produced by the transverse motion of the accelerated electrons are focused onto a photo-stimulable detector by a spherically curved quartz crystal. This result shows the feasibility of dynamic studies of crystal diffraction, with femtosecond level time resolution, using pump probe techniques.

Background

Motivation

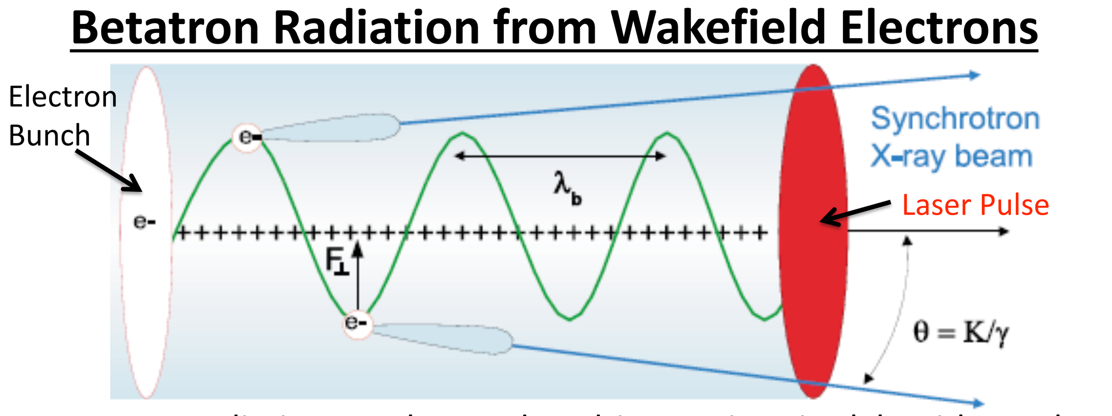
The current sources of coherent X-ray pulses for use in ultrafast structural dynamics are free electron lasers (FEL). These consist of a permanent magnet undulator placed at the end of a large electron accelerator facility. They are typically large and expensive user facilities (e.g. LCLS, FLASH).





Comparison of the current coherent X-ray sources available.[2]

Betatron Radiation from Wakefield Electrons

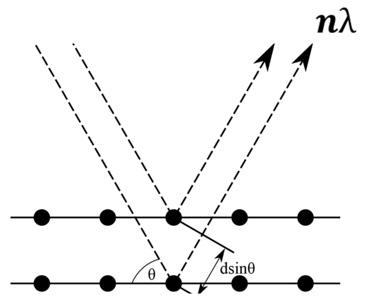


Betatron radiation can be produced in a university lab without the space and cost requirements of a traditional accelerator facility. [1]

Bragg Diffraction used to Focus X-Rays

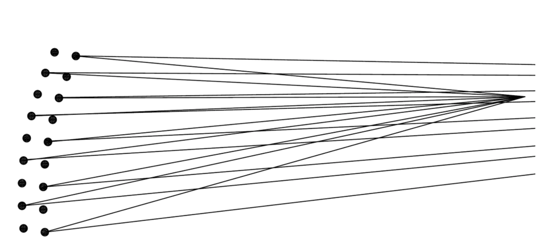
Normal Bragg Diffraction

$$n\lambda = 2d\sin(\theta)$$



Incident X-rays are scattered elastically due to Rayleigh scattering. These scattered X-rays can interfere constructively at a particular angle according to the above equation.

Curved Crystal Bragg Diffraction

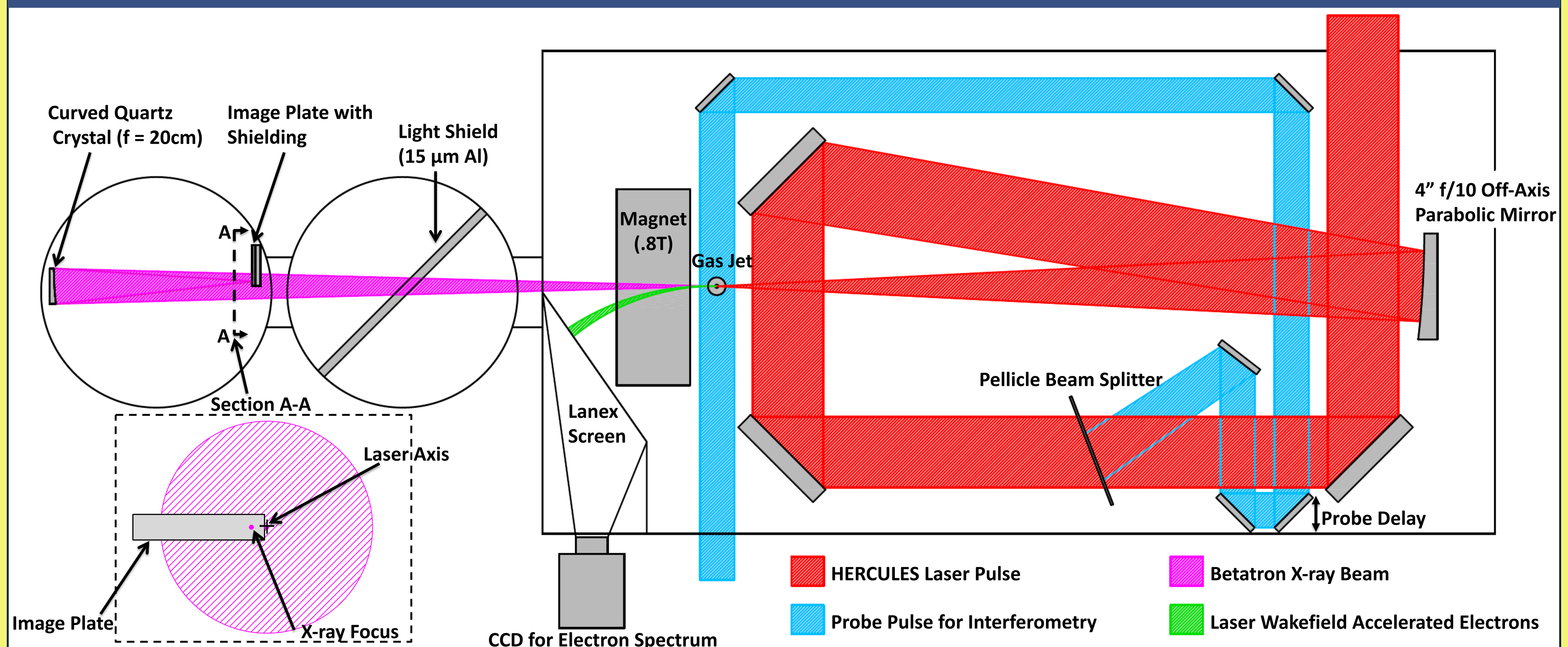


Traditional optics can't be used to focus X-rays. So, A quartz crystal is bent to produce a focusing geometry. Using the lattice constant and curvature of the crystal, as well as the frequency/ energy of the X-ray a focal position can be calculated.

Quartz Crystal Specifications

Index	Lattice Parameter	Diffracted Energy	Bandwidth
[211]	2d = 3.08A	4.2 keV for n=1 8.4 keV for n=2	~.1%

Experimental Setup

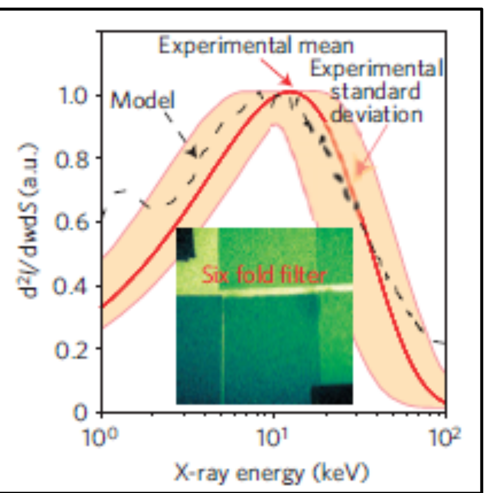


Shielding Considerations

- Laser wakefield acceleration produces scattered light and secondary electrons throughout the chamber that need to be filtered from the image plate (photostimulable phosphor plate which stores two-dimensional image of incident radiation).
- The accelerated electrons and secondary electrons can interact with the chamber walls to produce bremsstrahlung radiation.
- The image plate was wrapped in 15 µm aluminum foil to filter the visible, infrared light, as well as the 4.2 keV X-rays, and mounted on 1cm of Aluminum and 1cm of Steel to filter the X-rays from the rear.

Crystal Considerations

- Typical Betatron spectrum shown to the right measured with HERCULES in the same chamber setup with a peak at ~10 keV. Quartz[211] was chosen to focus 8.4 keV X-rays.[2]
- The crystal was placed in demagnifying geometry and aligned in the chamber using IR light reflected from the spherical mirror on which the crystal was mounted.



Results

Copper K-α Calibration Shots

A Copper target was mounted on the gas jet, and shot first to provide a calibration. The ~9 keV K_α X-rays produced in the interaction were focused by the spherically curved Quartz crystal.

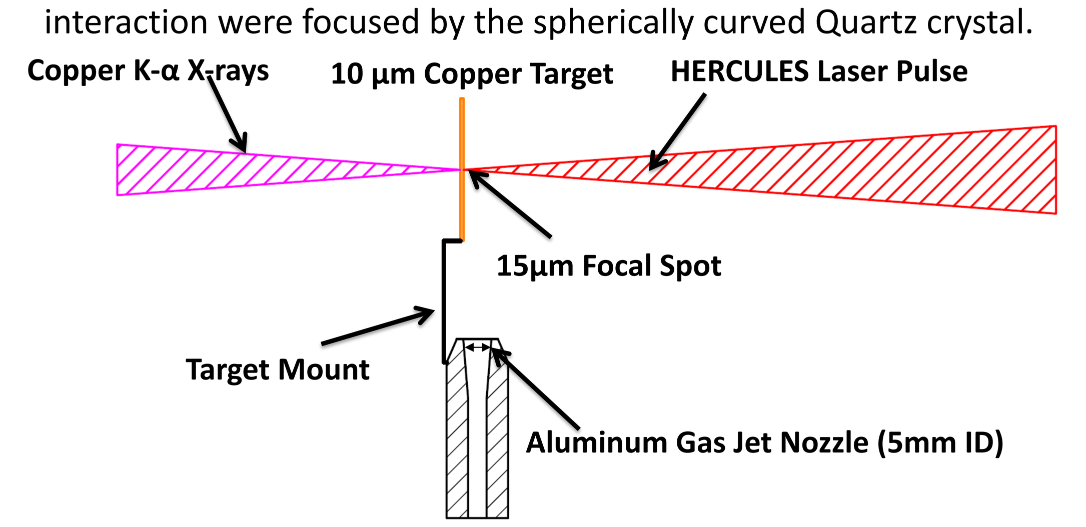
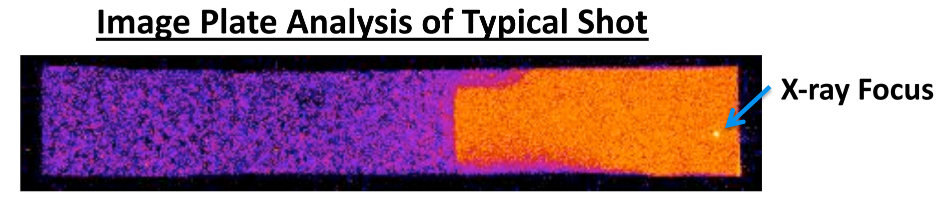
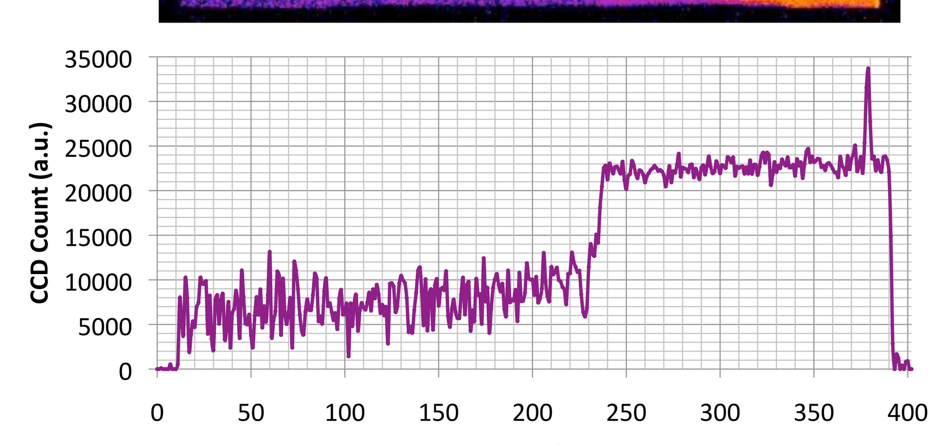


Image Plate Analysis of Typical Shot





Betatron X-Ray Shots

Once the K_α signal was seen, the nozzle was lowered in order to shoot an ionization injection gas mix (97.5% He, 2.5% N_2 by mass). The electron density here is on the order of $8X10^{18}$[cm^{-3}]. It is important to note that the copper is still in the vicinity of the laser and could potentially be a small source of K-α.

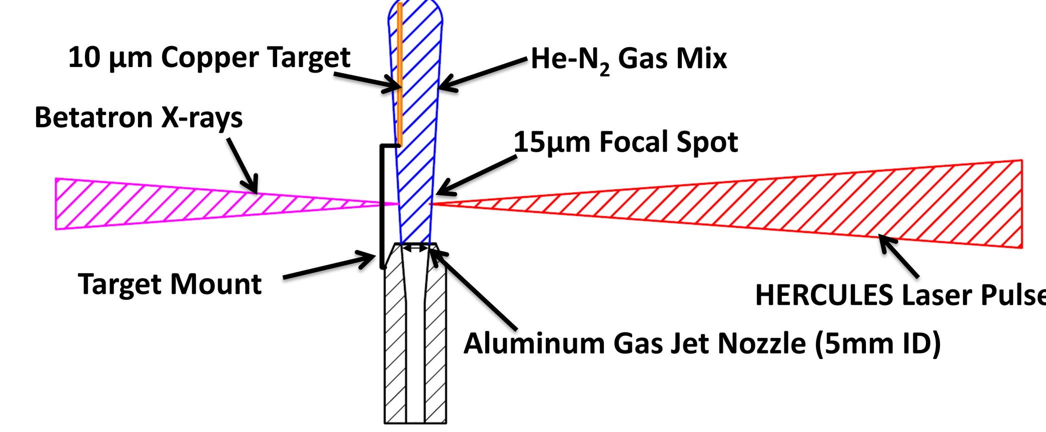
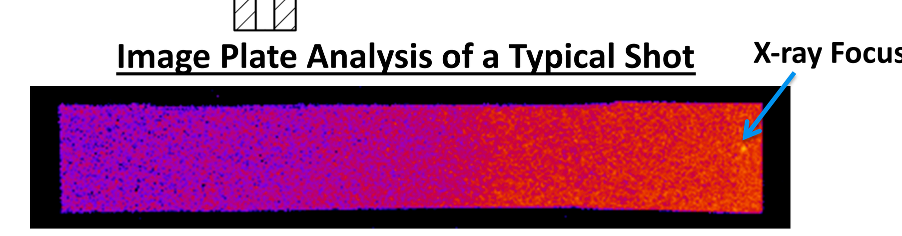
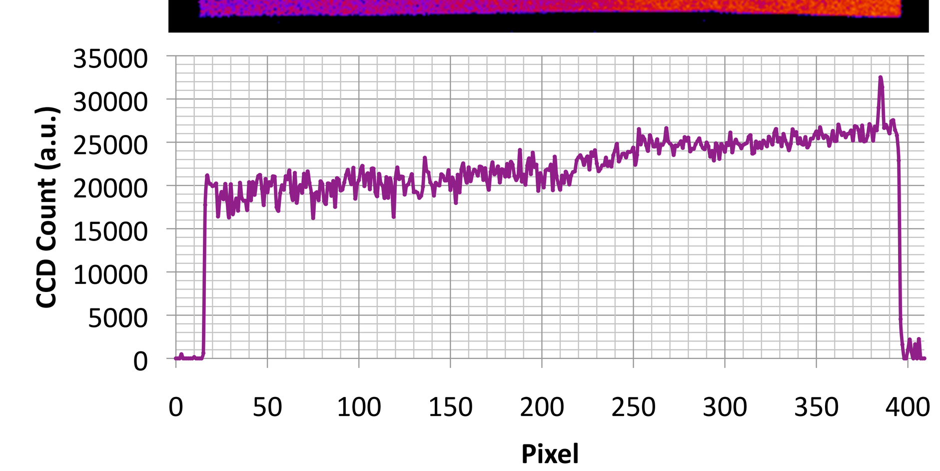


Image Plate Analysis of a Typical Shot



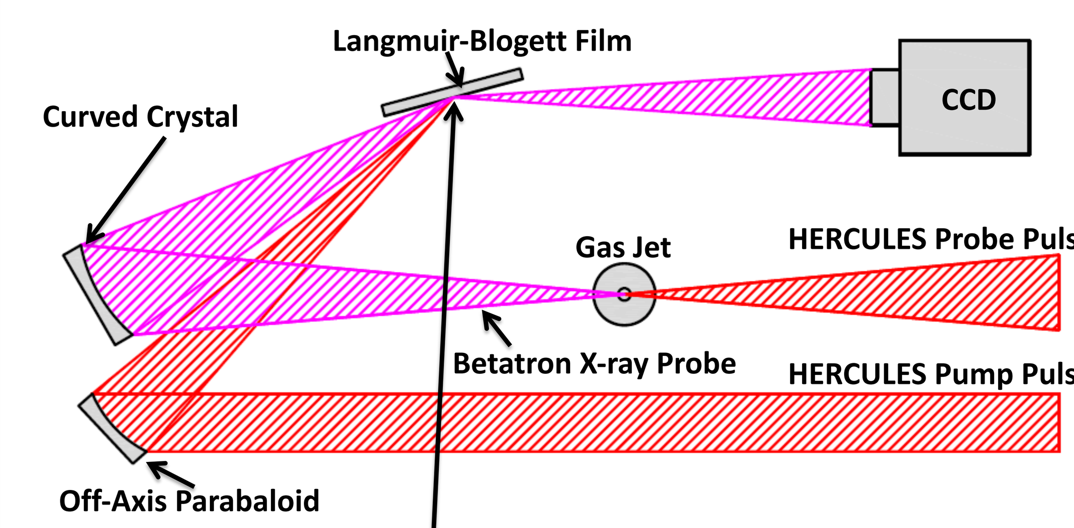


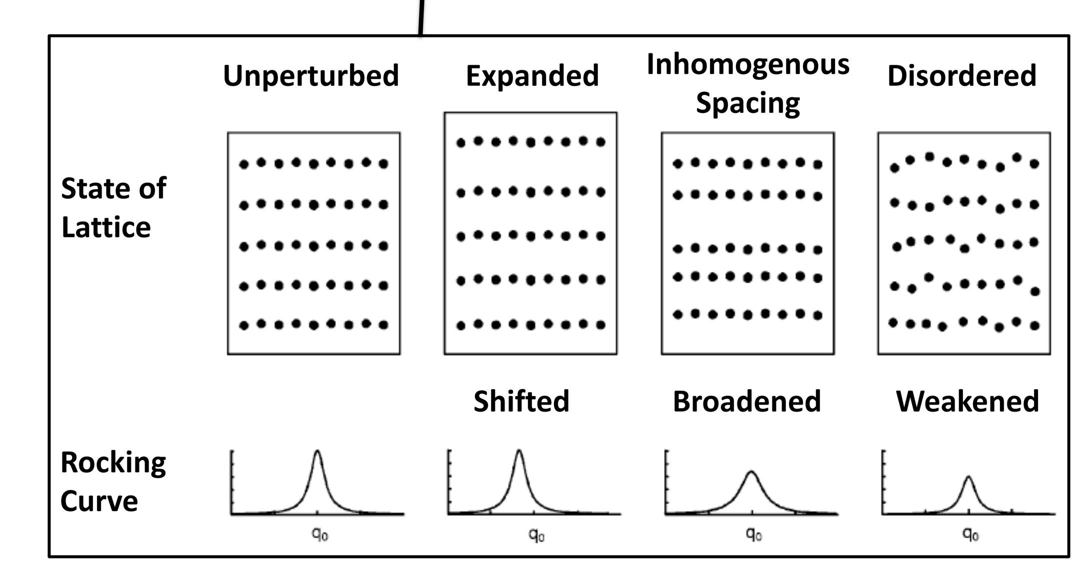
Future Research

Improvements

- The background signal is approximately 75% of the peak signal of Betatron X-rays. This is not an acceptable signal to noise ratio. In the future additional shielding and plastic collimators will be added to reduce the unwanted radiation incident on the CCD.
- The source of the X-rays needs to be confirmed definitively. The copper used for the calibration remained in the close vicinity of the laser in this experiment and could have contributed K_α. However It will be removed completely in future experiments.
- Different spherically curved crystals should be considered as the signal level could be improved if the X-ray energy is shifted towards the peak of the energy spectrum (e.g. Si [111]~2KeV, or Quartz [1010]~1.5keV).
- In the future a CCD will be used instead of the image plate. This will reduce the time between shots and increase resolution.

Proposed Ultrafast Pump-Probe Experiment





Rocking curve measurements used to study ultrafast structural dynamics in.[3]

Summary

The results shown provide a proof of principle for pump-probe experiments using Betatron radiation. Copper K_α and Betatron radiation was produced by laser wakefield acceleration from a 5mm gas jet. The X-rays were then focused using a quartz crystal adhered to a spherical mirror. In the future, additional shielding and different crystals will be employed to study ultrafast structural dynamics. If successful, this could increase the accessibility of such experiments which are vital to a number of fields.

References

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