Speckle-based X-ray Phase Contrast Imaging at Free-Electron Lasers

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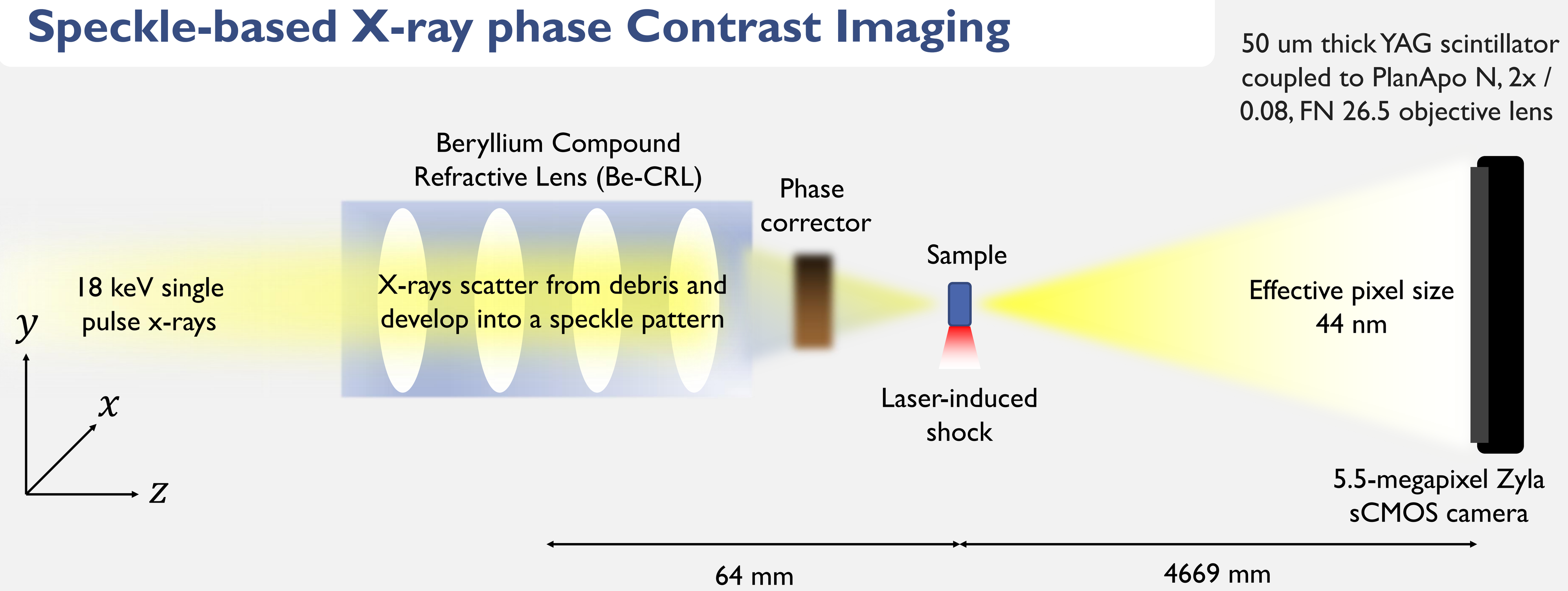
The Problem with Free Electron Lasers

Free-electron lasers (FEL) provide researchers unprecedented ultra bright, coherent, monochromatic single pulse x-rays for x-ray phase contrast imaging at the submicron scale. This has accelerated our understanding in quantum physics, material science and chemistry that underpin many of our present-day endeavors in fusion energy, biotechnology and engineering materials.

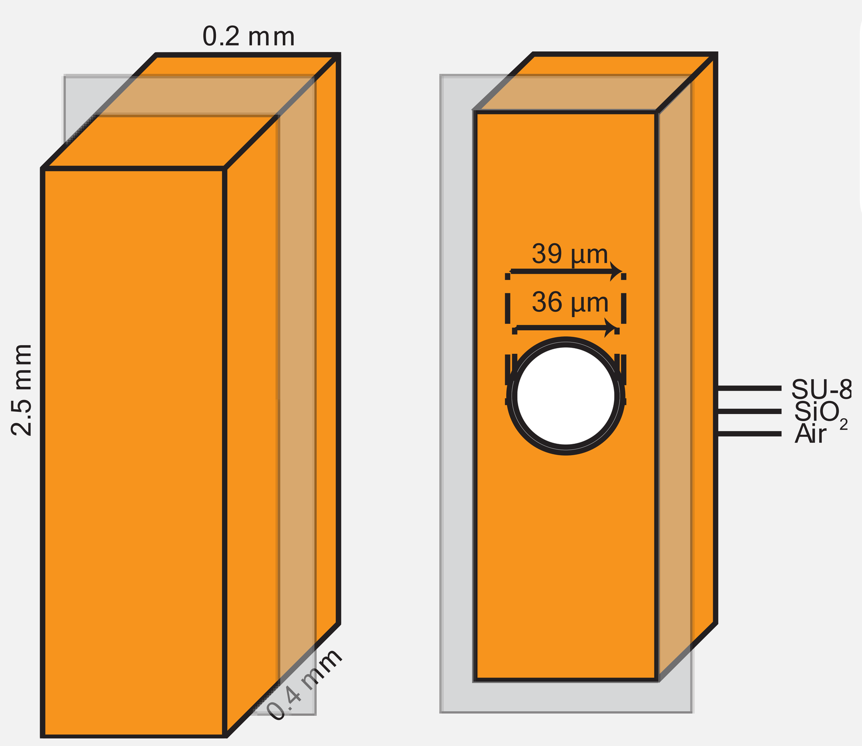
The problem is that tiny particles (debris) in the way of the x-ray beam optics scatter the x-rays and produce a speckle pattern that obscures the image. The speckle pattern and low frequency structure fluctuate on a pulse-to-pulse basis due to the stochastic nature of FEL and is distorted by the sample. This prevents the extraction of quantitative information. Consequently, simply dividing out the speckle pattern using a sample-free image does not eliminate the image artefacts (this is the conventional method for flat field correction).

Our solution is to reconstruct from the distorted speckle pattern the sample phase [1]. The speckle pattern acts as a reference pattern like in wavefront sensing. As the speckle pattern traverses the object, the object is imprinted onto the speckle pattern through distorting it. We present a speckle-based phase retrieval algorithm to transform the speckle pattern and into a phase map.

Speckle-based X-ray phase Contrast Imaging



Imaging setup for performing x-ray phase contrast imaging at MEC-LCLS [3]



SiO_2 shell embedded in epoxy
Left: Dimension of SU-8 pillar
Right: Slice through SU-8 pillar

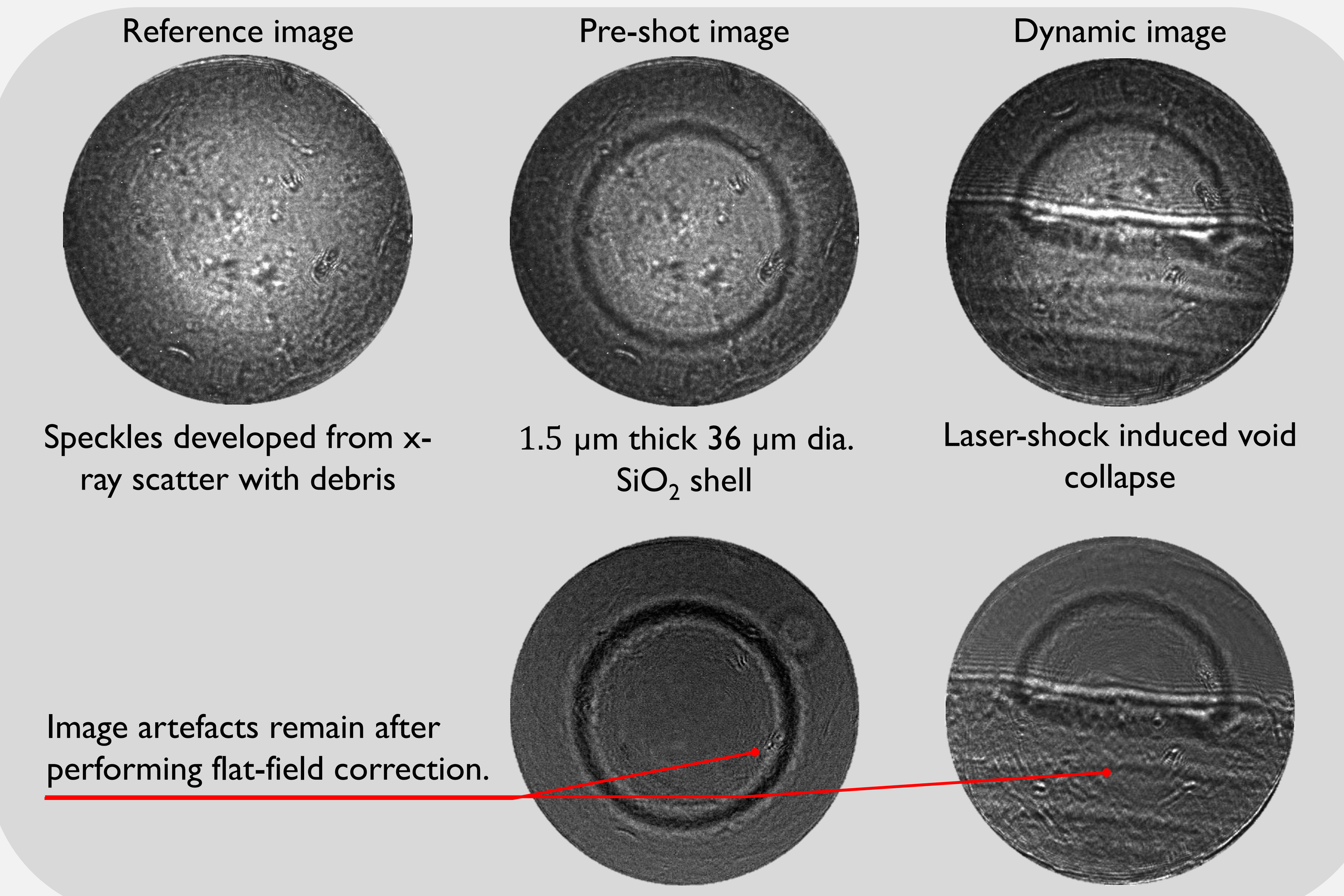
Step 1: Capture images
- Record single x-ray pulse images with (sample) and without (reference) the sample.

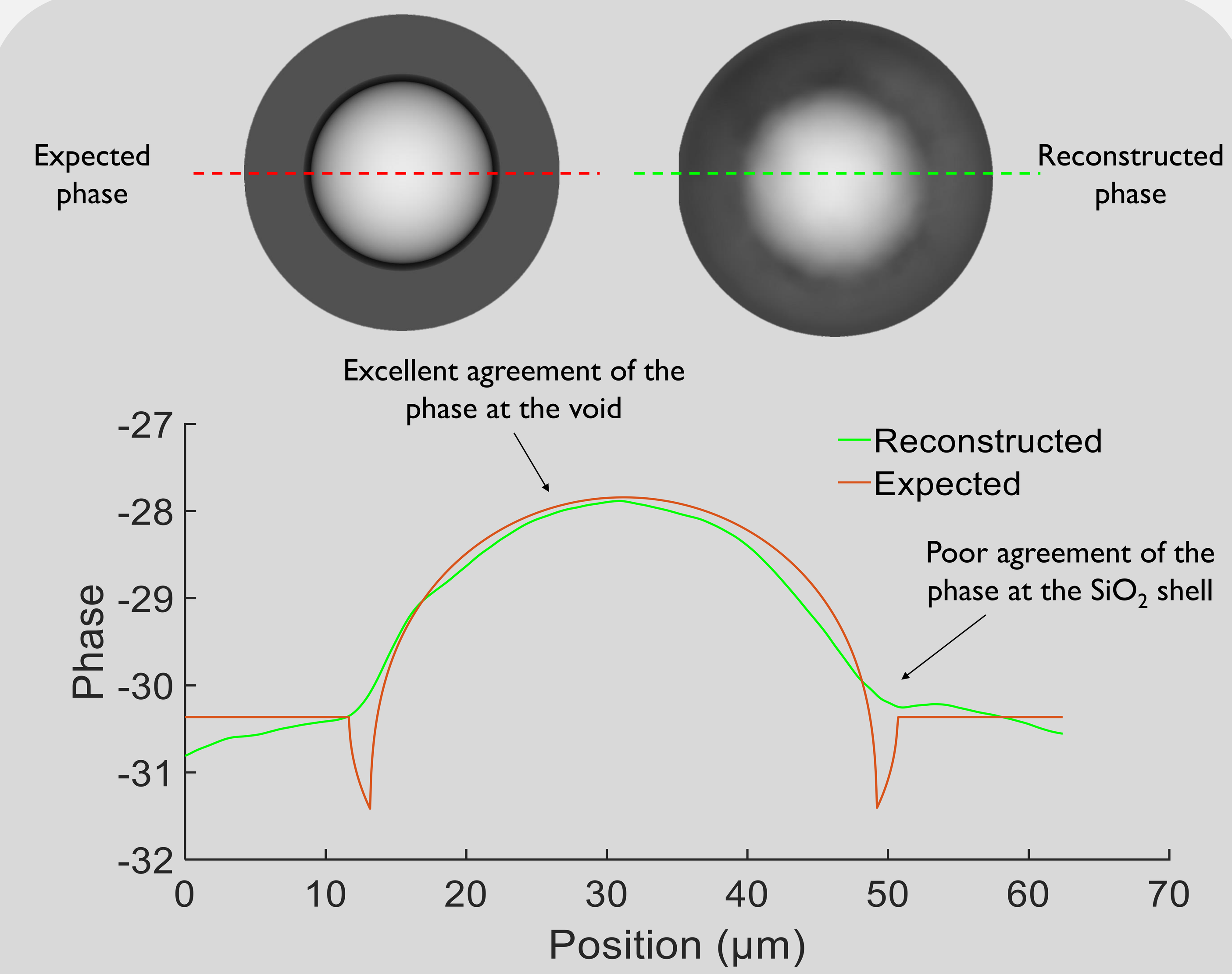
Step 2: Register images
- Align the speckle pattern in the sample and reference images using diffeomorphic Demon's image registration.
- Generate displacement fields in the x and y directions.

Step 3: Integrate displacement fields
- Perform Fourier-based 2D integration on the displacement fields to retrieve the 2D sample phase map.

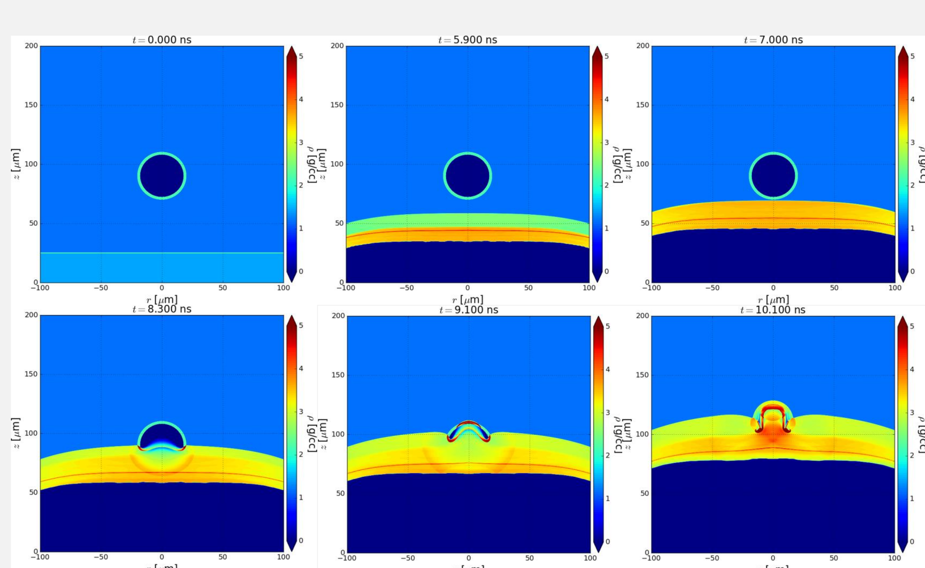
Speckle-based phase retrieval algorithm

Laser Shock-induced Void Collapse

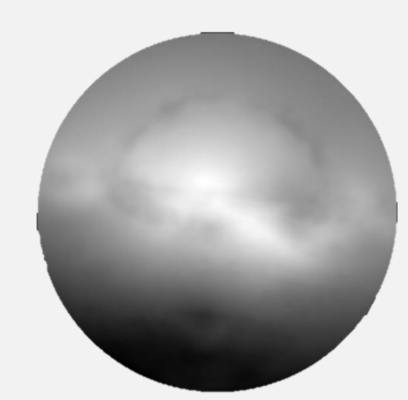




Line profiles of the expected and reconstructed sample phase



Hydrodynamic (xRAGE) simulations of laser-shock induced void collapse.



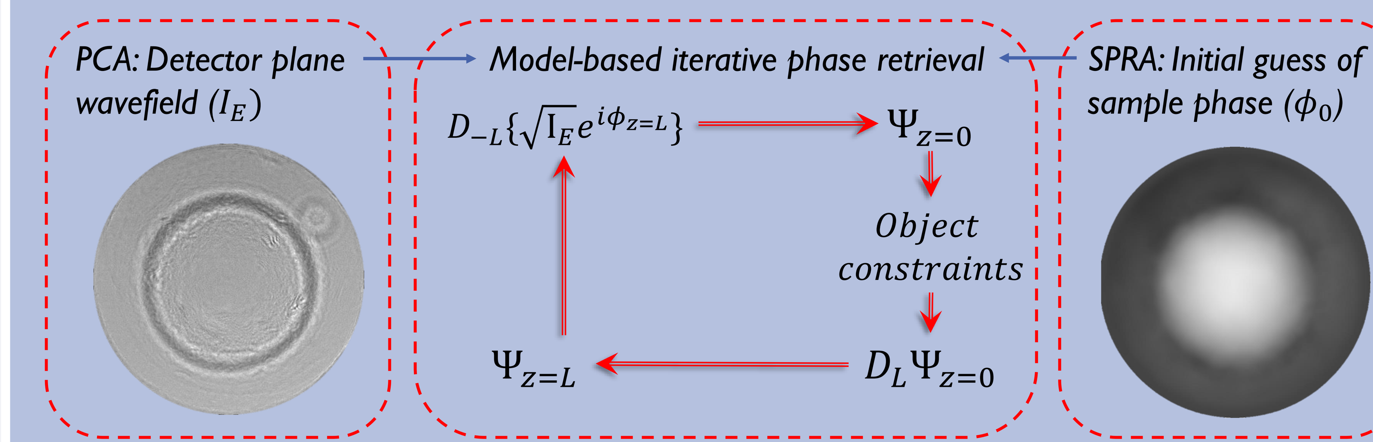
Reconstructed phase of laser-shocked induced void collapse. Matches closely to the t=8.3 ns xRAGE simulation.

Issues to Address in the Future

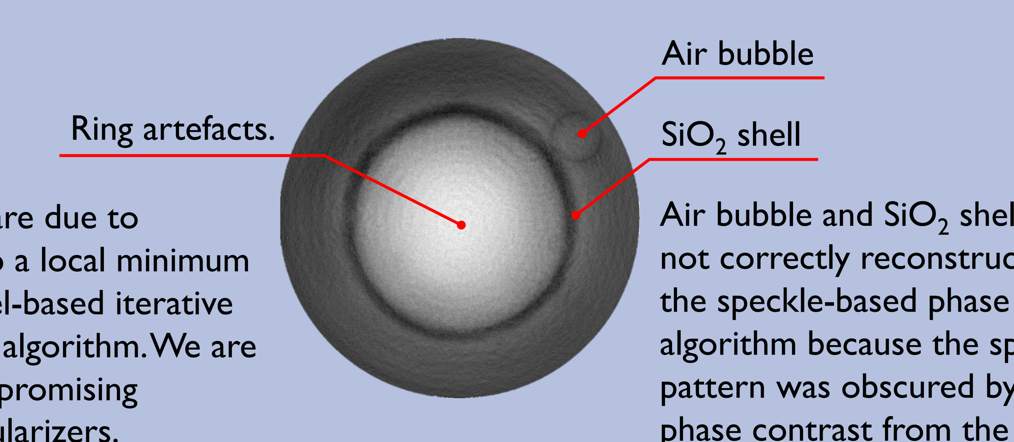
Issue 1: The stochastic x-ray pulse-to-pulse fluctuations in intensity, direction and energy introduces errors in the reconstructed sample phase. We are looking into possible solutions including principal component analysis (PCA) [3].

Issue 2: Strong phase contrast from the sample produces large distortions in the speckle pattern, particularly in regions around the SiO_2 shell. As a result, image registration is unable to accurately track the speckle pattern between the reference and sample image.

We plan to combine PCA, the speckle- and model-based iterative phase retrieval algorithms to address issues 1 & 2.



Reconstructed 2D phase map



Ring artefacts are due to convergence to a local minimum using the model-based iterative phase retrieval algorithm. We are testing several promising smoothing regularizers.

Air bubble and SiO_2 shell were not correctly reconstructed using the speckle-based phase retrieval algorithm because the speckle pattern was obscured by strong phase contrast from the sample.

Summary

Developed a speckle-based phase retrieval algorithm to recover the sample phase from x-ray phase contrast images recorded with free electron lasers.

Validated the speckle-based phase retrieval algorithm on a static image of a SiO_2 shell embedded in SU-8 epoxy. Comparisons with the expected object phase shows good agreement at regions of slowly varying phase.

Plan to employ in quantifying shock-induced void collapse related applications in inertial confinement fusion energy [4].

Acknowledgements & References

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