# Gamma-ray phase contrast imaging studies based on VIGAS


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## Introduction

With the rapid development of advanced manufacturing industries, there is an urgent need for high-resolution nondestructive testing (NDT) techniques applicable to metal materials. In this context, phase contrast imaging (PCI) in the gamma-ray energy region shows great promise, since a maximum cross-section ratio between the phase-shift and the absorption can be obtained for metal materials in the MeV energy region. Moreover, the intrinsic edge enhancement characteristics in the in-line PCI can help to discriminate the material interfaces, enabling the identification of invisible flaws like holes and cracks. Therefore, gamma-ray PCI presents a novel and powerful solution for high-resolution inspection of metal components.

To validate the feasibility of this technique, we have developed a simulation method for gamma-ray PCI of metal samples, based on the very compact inverse Compton scattering (ICS) gamma-ray source (VIGAS) facility[1] under construction at Tsinghua University. The simulation results confirm the capability of the system in imaging metal samples. This work paves the way for subsequent validation experiments and applications.

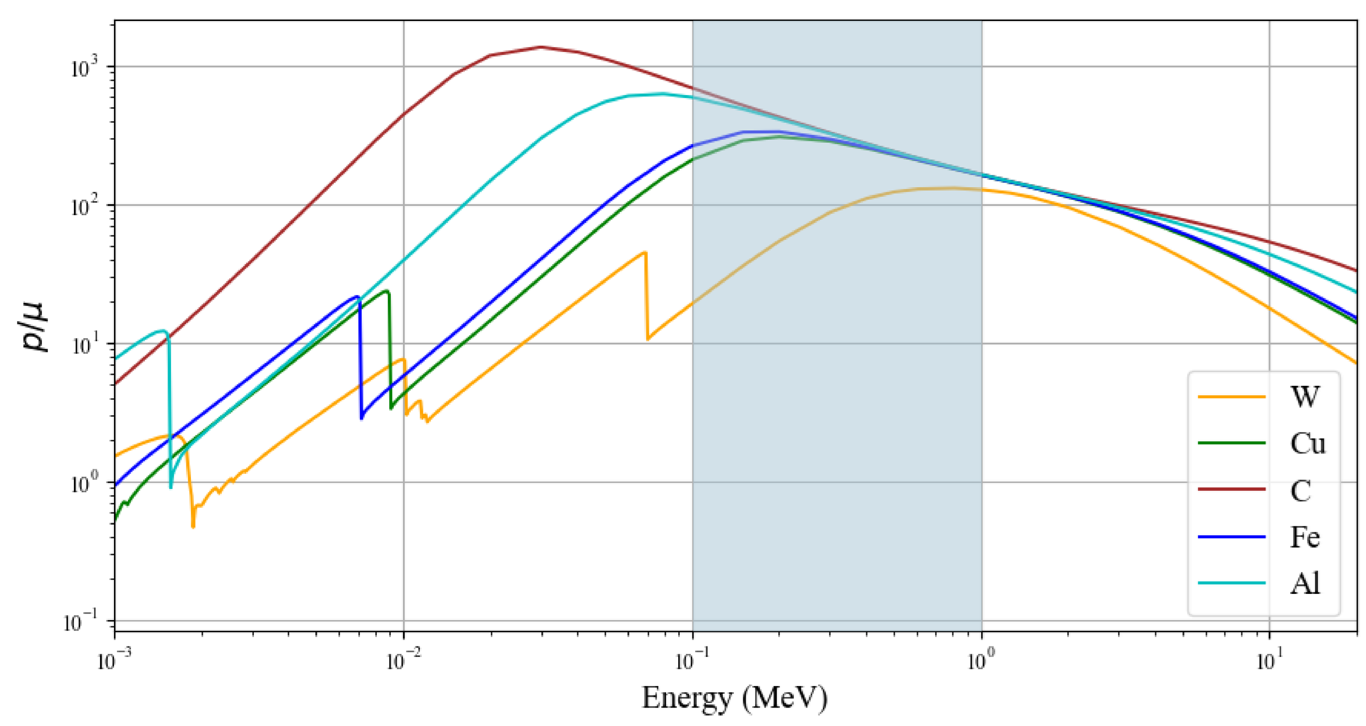
### Advantage of gamma-ray PCI

$$n = 1 - \delta + i\beta$$

The linear attenuation coefficient $\mu = 2k\beta$

The cross section of phase shift $p = k\delta$

A maximum cross-section ratio $p/\mu$ can be obtained for metal materials in the ~MeV energy region




### PCI exploits phase shift for enhanced contrast

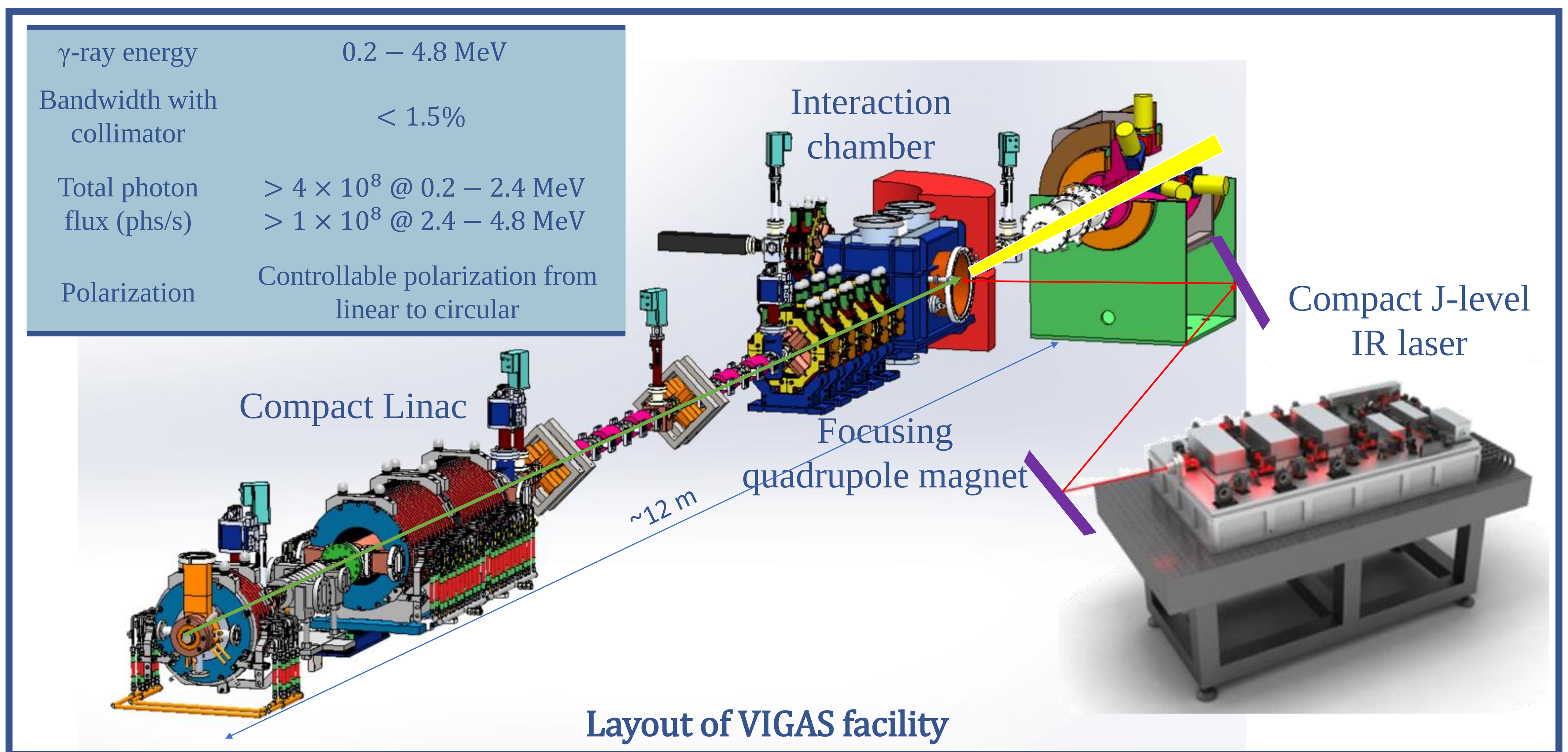
$$I(x,y,R_2) = I(x,y,0)\left(1 - \frac{\lambda R_2}{2\pi M}\nabla^2_{X,Y}\phi(X,Y)\right)$$

It can be seen that the greater the phase shift and intensity change, the greater the absolute value of the second term. Therefore, a strong edge enhancement are expected at the edge of the sample where the phase shift and intensity change are very sharp.

### Compact ICS source enables gamma-ray PCI

Realizing gamma-ray PCI requires a highly spatially coherent light source. The advent of an ICS light source, based on the interaction of relativistic electrons and high-intensity laser, provides an excellent prospect for the gamma-ray PCI, since it can provide quasi-monochromatic, energy tunable, high brightness, and high coherent gamma-rays.

| | |
|---|---|
| γ-ray energy | 0.2 – 4.8 MeV |
| Bandwidth with collimator | < 1.5% |
| Total photon flux (phs/s) | $> 4 \times 10^8$ @ 0.2 – 2.4 MeV<br>$> 1 \times 10^8$ @ 2.4 – 4.8 MeV |
| Polarization | Controllable polarization from linear to circular |




Layout of VIGAS facility

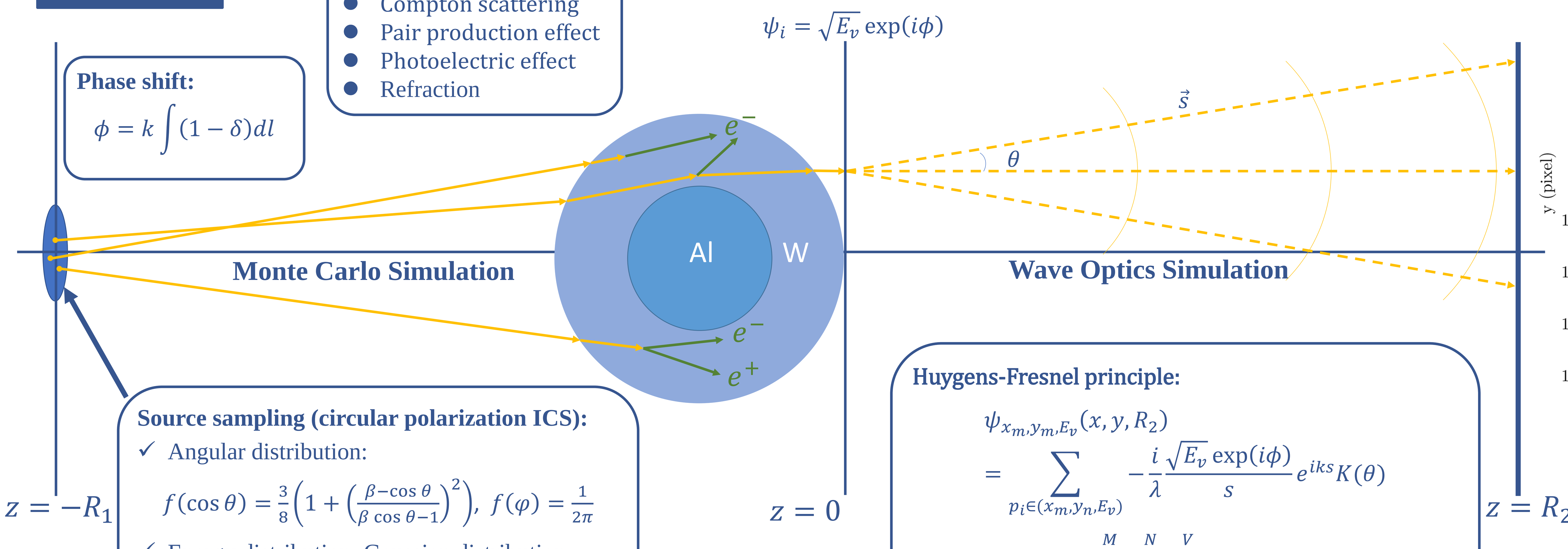
## Method

**Physical process:**
- Compton scattering
- Pair production effect
- Photoelectric effect
- Refraction

**Phase shift:**

$$\phi = k\int(1-\delta)dl$$

**Gamma-ray PCI Simulation method[2]**




**Source sampling (circular polarization ICS):**
- ✓ Angular distribution:

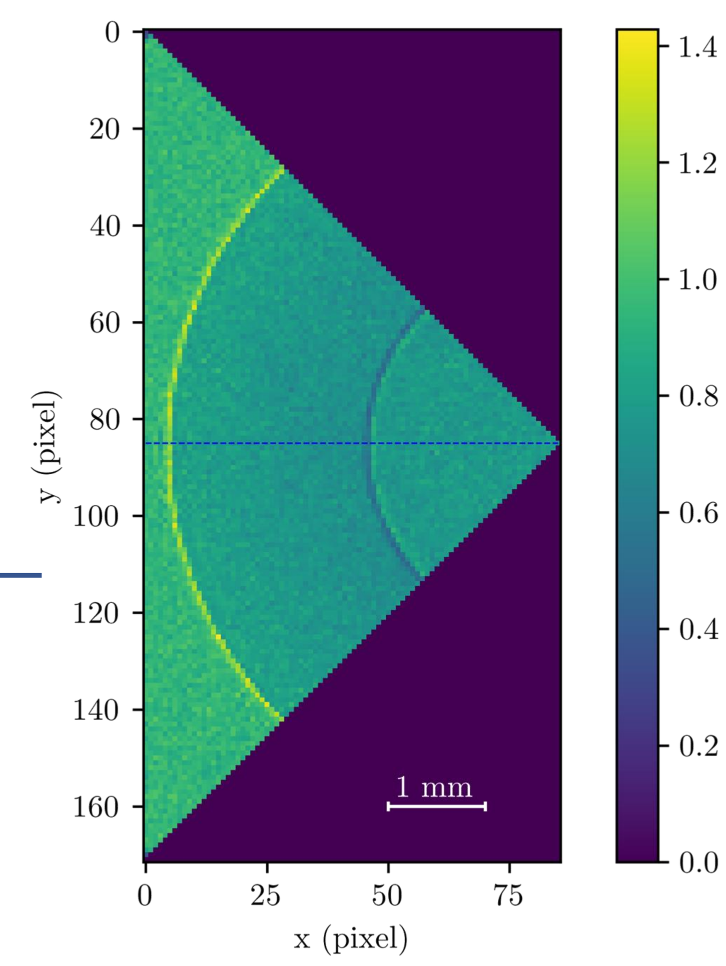
$$f(\cos\theta) = \frac{3}{8}\left(1 + \left(\frac{\beta - \cos\theta}{\beta\cos\theta - 1}\right)^2\right),\ f(\varphi) = \frac{1}{2\pi}$$

- ✓ Energy distribution: Gaussian distribution
- ✓ Initial photon position $(x_m, y_m)$: 2D Gaussian distribution

**Huygens-Fresnel principle:**

$$\psi_{x_m,y_m,E_v}(x,y,R_2) = \sum_{p_i \in (x_m,y_n,E_v)} -\frac{i}{\lambda}\frac{\sqrt{E_v}\exp(i\phi)}{s}e^{iks}K(\theta)$$

$$I(x,y,R_2) = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{v=1}^{V}\left|\psi_{x_m,y_n,E_v}(x,y,R_2)\right|^2$$




| | |
|---|---|
| γ-ray peak energy | 1 MeV |
| Bandwidth | 1.5% |
| Focal spot size | 10 μm |
| $R_1$ | 200 m |
| $R_2$ | 600 m |
| Pixel size | 50 μm |

## Conclusion

A simulation method combining Monte Carlo and wave optics has been developed. This simulation method simultaneously takes the particle and wave characteristics of gamma-rays into account, and reflects particle scattering, absorption process and the coherence effect at the same time.

To demonstrate the potential of gamma-ray PCI of metal samples, a simulation of concentric tungsten–aluminum spheres is performed, and the edge enhancement characteristic of PCI has been clearly observed from the simulation result. These results prove the feasibility of gamma-ray PCI for metal samples.


1. Y.C. Du, H. Chen, H.Z. Zhang, Q. Gao, Q.L. Tian, Z.J. Chi, Z. Zhang, H. Zha, J.R. Shi, L.X. Yan, R. Qiu, C. Cheng, T.B. Du, R.K. Li, H.B. Chen, W.H. Huang, C.X. Tang, A very compact inverse Compton scattering gamma-ray source, *High Power Laser and Particle Beams* 34(2022) 104010–104011.

2. J.Y. Sun, Z.J. Chi, Y.C. Du, R.K. Li, W.H. Huang, C.X. Tang, A simulation method of gamma-ray phase contrast imaging for metal samples, *Nucl. Instrum. Methods Phys. Res. A* 1053 (2023) 168321.