WEPAB067

High duty cycle EUV radiation source based on inverse Compton scattering

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ABSTRACT ***Inverse Compton scattering (ICS) can obtain quasi-monochromatic and directional EUV radiation via a MeV-scale energy electron beam and a μm-scale wavelength laser beam, which makes it an attractive technology in research, industry, medicine and homeland security. Here we propose an EUV source based on high duty cycle ICS system. The scheme exploits the output from the laser-electron interaction between a MW-ps laser at MHz repetition-rate and a high quality electron beam with an energy of a few MeV at MHz repetition-rate.***

Introduction

Extreme Ultraviolet radiation (13.5 nm) is significant for advanced lithography technologies. Accelerator-based EUV sources such as FELs and synchrotron radiation sources are attracting attention for high power characteristic. But both their size and cost are enormous. A more economical way is inverse Compton scattering (ICS) source, which can obtain quasi-monochromatic and directional EUV radiation via a MeV-scale energy electron beam and a micron-scale wavelength laser beam. In order to meet the practical flux requirements, a high repetition-rate low emittance electron beam is required as well as a high repetition-rate high pulse energy laser beam.

We propose a high duty cycle ICS-based EUV scheme, and give a brief view on its possible technologies.

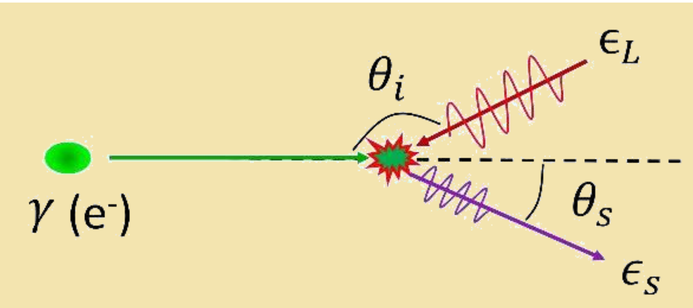
Inverse Compton Scattering

Scattered photon energy ϵ_s and wavelength λ_s

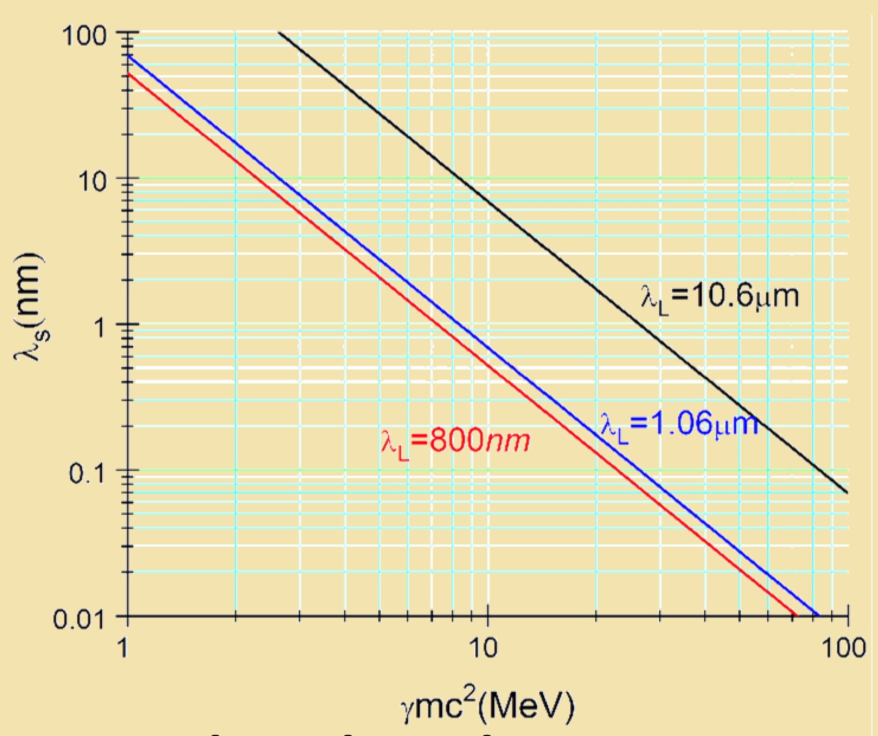
$$\epsilon_s = \frac{(1-\beta\cos\theta_i)\epsilon_L}{1-\beta\cos\theta_s + (1-\cos(\theta_s-\theta_i))\epsilon_L/\gamma mc^2},$$

$$\lambda_s = \frac{\lambda_L}{4\gamma^2}(1+a_L^2+\gamma^2\theta_s^2).$$

- $\boldsymbol{\epsilon_s}$ depends on interaction angle between laser and electron pulses, and their energies, which gives several tuning options.
- Incident laser behaves like a virtual undulator with an extremely short period $\lambda_u = \lambda_L/2$.
- For 13.2 nm EUV, an IR laser of 800 nm with an electron beam of 2 MeV, or an IR laser of 10.6 μm with an electron beam of 7 MeV, is required.
- $\boldsymbol{\epsilon_s}$ is maximal in e^- direction, and half angle of the emission cone ∝ 1/γ. Higher beam energy means narrower emission and higher brilliance.



Collision geometry



Wavelength Vs. beam energy

Radiation power

- Photon number per second $N_s = \dfrac{N_e N_L f_s \sigma_C}{\pi(\sigma_e^2+\sigma_L^2)}$,
- Cross section $\sigma_C = (8\pi/3)r_0^2 \approx 6.65\times10^{-29}\mathrm{m}^2$,
- $\boldsymbol{\sigma_C}$ is significantly low, actions should be taken.
- Effective ways: increasing electron bunch charge $\mathbf{Q_e}$ and laser pulse energy $\mathbf{E_L}$, focusing beam sizes at collision point $\boldsymbol{\sigma_e}$ and $\boldsymbol{\sigma_L}$, operating at a higher collision frequency $\mathbf{f_s}$ (high duty cycle).
- Engineering formula of radiation power

$$P_{avg}(\mathrm{mW}) \approx 0.1323\frac{\lambda_L(\mu\mathrm{m})}{\lambda_s(\mathrm{nm})}\cdot\frac{Q_e(\mathrm{pC})E_L(\mathrm{J})f_s(\mathrm{kHz})}{\sigma_e^2(\mu\mathrm{m})+\sigma_L^2(\mu\mathrm{m})},$$

$$P_{peak}(\mathrm{kW}) \approx 132.3\frac{\lambda_L(\mu\mathrm{m})}{\lambda_s(\mathrm{nm})}\cdot\frac{Q_e(\mathrm{pC})E_L(\mathrm{J})/\tau_e(\mathrm{ps})}{\sigma_e^2(\mu\mathrm{m})+\sigma_L^2(\mu\mathrm{m})}.$$

- For example, E_L=1 J, λ_L=10.5μm, Q_e=300 pC, $\sigma_e = \sigma_L$ = 50 μm, τ_e =2 ps, there are 4.2×10^8 EUV photons per bunch, P_{peak} could reach 3 kW.
- Radiation bandwidth is decided by the energy spread, the **beam emittance**, etc.

High Repetition Rate Electron Guns

DC guns

- DC schemes allow for arbitrary high repetition rates.
- High current and low emittance with photoemission.
- Cornell DC gun at 350 kV, 100 mA, ~77 pC, 1.3 GHz.
- DC gun is limited in energy and beam quality.

SRF guns

- SRF schemes potential for GHz repetition rate and MeV energy.
- Excellent vacuum performance, but technical challenges.
- BNL 700 MHz SRF gun outputs 500 pC beam to ~2 MeV in CW.

VHF guns

- Lower frequency increases the cavity size, reduces the power density on structure wall, contributes to a higher duty cycle.
- LBNL VHF gun 186 MHz CW, with beam energy of 750 keV.
- Proposed APEX-2 gun, comparable beam energy to SRF guns with a lower cost and complexity.
- Expected 2 MeV energy, 0.13 μm emittance at 100 pC, 162.5 MHz.
- **Demand by high duty cycle EUV ICS source attainable with VHF gun**

High Average Power Laser System

- High power laser system is a key portion of ICS source.
- Guiding both cathode laser and Compton scattering laser.
- IR laser with ~J energy, ps-MHz pulse not commercialized.
- IR laser with advanced amplification technology is required to enhance the laser power at collision.
- MW-ps laser at MHz repetition-rate is demanded for a mW average power EUV ICS source.

Conclusion

- EUV source based on high repetition rate ICS system is discussed, and a brief view on possible technologies of high repetition rate electron and laser sources is given.
- Upgraded VHF-gun and amplified IR laser are suggested.
- Proposed compact ICS scheme is efficient and may be used for EUV lithography and other potential applications.

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WEPAB067