X-rays simulation via interaction of laser-produced electrons with targets

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INTRODUCTION

X-rays have been generated by different techniques from ordinary x-ray generator tubes, and expensive huge accelerators, to recently developed laser-plasma accelerators based on development of Chirped-Pulse Amplification (CPA) in laser systems. In comparison with conventional accelerators, desk top size and low cost facilities of laser-plasma accelerators can produce high quality electrons with higher energy and less beam divergence, which can be transported and focused, easily. Besides of compactness and flexibility, the combination of high power and short pulse durations makes it possible to extend the emission of these sources to the high photon energy, easier than synchrotrons and conventional x-ray tubes. Interaction of ultra intense, short pulse lasers with plasmas can produce energetic electrons with quasi-monoenergetic distributions. These energetic electrons can directly produce x-ray beams for example by Thomson scattering, betatron, or high harmonic generation, etc. Here, the produced electrons interact with secondary targets, passing through various solid materials such as Pb with different geometries such as slab and cone, to produce bremsstrahlung and characteristic x-ray beams. It is shown that energy distribution of electrons, electron beam size, and target geometry can affect on the x-ray generation. The simulated results by MCNP code based on Monte Carlo method, represent that for small electron beam sizes, by choosing the geometry of small angle cone targets instead of slabs, the efficiency of x-ray generation grows significantly. Furthermore, for quasi-monoenergetic (q-monoenergetic) profiles of electrons, the spectrum with less band-width generate more efficient x-ray photons at greater thicknesses.

LASER-PRODUCED ELECTRONS-TARGET INTERACTION

Following the interaction of the focused high intensity laser with supersonic He nozzle gas, plasma is produced and after interaction process, the accelerated electrons are emitted. Then, because of the interaction of the MeV relativistic electrons with a solid target, they are converted to x-ray photons.

Laser-plasma based accelerators are capable to provide q-monoenergetic distribution of electron beams under special conditions of plasma and laser pulses [1]. During ultrashort intense laser-plasma interaction, plasma electrons are trapped and accelerated to a single energy in a plasma bubble generating an extremely collimated and q-monoenergetic electron beams. We focus on the production of x-ray photons via the interaction of q-monoenergetic electrons with solid targets of lead (Z=82, p=11.342 gcm-3) in slab with various thicknesses, and in cone with various heights and angles, and we also consider two electron spectra with different pulse-widths. The produced x-ray fluxes are determined in energy domain of 10 KeV to 100 KeV by using MCNP-4C simulation code [2] and compared at Kα energy.

EXPERIMENTAL SETUP TO BE SIMULATED

A 20 TW, 30 fs Ti-Sapphire CPA pulsed laser system at 10 Hz repetition rate is focused onto a He gas jet with a 2 mm cylindrical shape hole via a f/5 off-axis gold-coated parabolic mirror to generate a laser acceleration wake field, see Fig.1(a) based on reference [3].

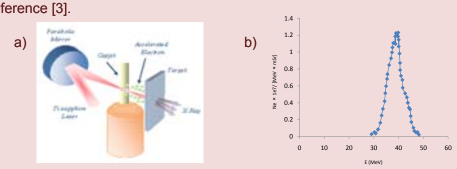

Fig.1 a) Schematic experimental setup, b) Experimental q–monoenergetic electron distribution, [3].

For the laser power of 16.6 TW (500 mJ) and the maximum plasma density of 14×1019 cm-3, by laser focusing point in about 250 μm from the nozzle edge and one millimeter above it, the q-monoenergetic electron spectrum is observed. The experimentally obtained q-monoenergetic electron spectra is indicated in Fig. 1 (b).

RESULTS & DISCUSSION

I. Target geometry

For study of the target geometry influence on x-ray generation, Pb targets with slab and cone shapes are considered. For q-monoenergetic electrons with 1500 μm beam size, the optimum angle for a lead cone with height of 1500 μm (equal to the optimum slab thickness) is illustrated in Fig. 2. It is found that the optimum angle depends on the electron beam size and the cone height. Our simulations reveal that for electron beam size of 1500 μm, the optimum angle of 45 degree generates more x-ray flux.

For the q-monoenergetic electron beam size of 1500 μm, a comparison between x-ray generated by two target geometries of slab and cone with equal height and thickness of 1500 μm, and cone angle of 45 degree is represented in Fig. 3. As it can be observed, the generated x-ray flux by the slab shows %33 increase compared with the cone. It can be explained that for the mentioned magnitudes, by using slab geometry, more target material can interact with the electrons and create more x-ray photons.

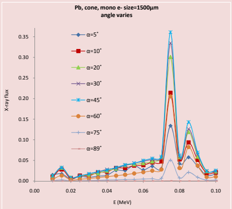

Fig.2 X-ray flux for a lead cone with height of 1500 μm at different angles, with electron beam size of 1500 μm.

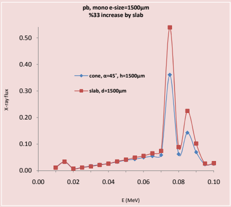

Fig. 3 Geometry comparison for electron beam size of 1500 μm, showing a gain of %33 by using slab compared with cone.

By reducing the q-monoenergetic electron beam size to 9 μm (closer to the bubble diameter), for lead cones with height of 1500 μm, the results show that more x-ray fluxes can be produced by using smaller angles; see Fig. 4.

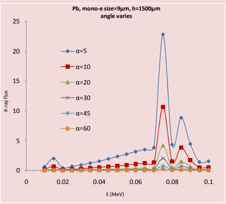

Fig. 4 X-ray flux for a lead cone with height of 1500 μm at different angles with small electron beam size of 9 μm.

Besides, for this electron beam size, a comparison between two geometries of slab and cone with equal height and thickness of 1500 μm, for two angles of 45 and 10 degrees, represent that x-ray fluxes are increased by using the cone targets compared with the slabs; refer to Fig. 5-a,b.

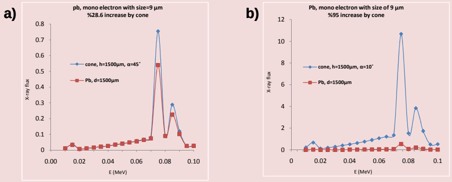

Fig. 5 Geometry comparison for electron beam size of 9 μm, showing: a) %28.6 gain for α=45˚, and b) %95 increase for α=10˚, by using cone shape.

As it can be observed, for smaller electron beam size of 9 μm, the generated x-ray flux is increased by using a cone compared with a slab, particularly for smaller angles. It is known that as energetic electrons propagate through matter they radiate bright x-ray beams in a highly directional cone. By the way, smaller radiating volumes emit brighter Kα radiation. It is revealed that although less material is engaged in x-ray production by using small angle cones, x-ray re-absorption is decreased [4]. It is also realized that more conformity between a beam and a target will increase the efficiency.

II. Electron spectra

The comparison between x-ray generated by q-Maxwellian and q-monoenergetic electrons has been done [5]. Here, to investigate the influence of pulse-width in q-monoenergetic electron profiles on x-ray efficiency, two distributions with similar maximum energy and different energy-widths are considered, Fig. 6.

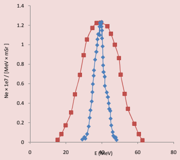

Fig. 6 Two q-monoenergetic electron profiles with different pulse-widths.

The percentage increase is defined as: $\Gamma=[(F_n - F_w) / F_n]\times 100$, where F_n and F_w stand for the x-ray fluxes produced by the narrower and wider q-monoenergetic electron spectra, respectively. X-ray fluxes are obtained by MCNP simulation code for two electron spectra at different thicknesses of slab lead targets, and then Γ is plotted versus thicknesses in Fig. 7.

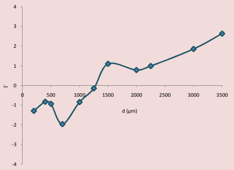

Fig. 7 percentage increase, Γ, (pulse-width comparison), versus target thickness.

From Fig. 7, the results reveal that for thinner samples, the wider profile acts better in x-ray generation ($F_w>F_n$, $\Gamma<0$), but towards thicker samples, more x-ray flux is generated by the narrower profile ($F_n>F_w$, $\Gamma>0$).

In general, electrons should have suitable energies proportional to the sample material and thickness, to be able to pass through the target to generate x-ray photons. Besides, they should interact with target in the same time and space, coherently, to enlarge x-ray efficiency.

As it can be seen from Fig. 6, the wider electron profile includes the narrow electron profile plus two extra parts of electrons with low energy trailing edge and high energy front edge. For less thickness, the wider spectrum prevails, because the electrons with lower energies located at the trailing edge of the wide spectrum have additional positive effect in x-ray generation, since they have enough energy to propagate throughout thin samples. While, for more thickness, the narrower spectrum overcomes, because electrons are concentrated around the maximum energy with approximately similar velocities and behave more coherently, which result in higher x-ray efficiency. Compared with the narrower profile, in the wider spectrum, electrons are spread more around the maximum energy and have wider range of various velocities, so there are more probability of collisions among high energy electrons, resulting in more scattering and fewer coherencies. Therefore, although the front edge electrons of the wide profile have enough energy to avoid stopping in thick targets, but because of their energy extension and various velocities, they can interfere with other electrons of the central part (similar to the narrow profile) resulting in unconstructive effect on x-ray production.

CONCLUSION

Laser produced electrons are employed for bombardment of high-Z lead targets for x-ray simulation. It is found that the electron beam sizes, energy distribution, and target geometry can affect on x-ray efficiency. Two target geometries of slab and cone are studied by using q-monoenergetic spectrum with two various electron beam dimensions. For the larger source beam size, the slab target is more effective, and for the small electron beam size, the cone target with smaller angle produce more efficient x-ray fluxes. It means that geometrical correspondence between a beam and a target has positive effect on x-ray conversion efficiency.

Also, the effect of electron profile pulse-width is studied in x-ray creation. It is found that in the wider profile, low energy trailing edge electrons have positive effect on x-ray generation for thin samples, but high energy front edge electrons have negative scattering effect in thick targets. In the narrower profile, electrons with similar energies and velocities represent more coherencies to produce more x-ray photons in thick targets.

REFERENCES

[1] A. Pukhov, J. Meyer-ter-Vehn, *Appl. Phys. B* **74**, 355–361 (2002).

[2] J. F. Briesmeister, Editor, *MCNP^{TM}- A General Monte Carlo N-Particle transport Code* (Version 4C, Las Alamos National Laboratory, LA-13709-M, 2000).

[3] R. Sadighi-Bonabi, H. A. Navid and P. Zobdeh, *Laser and Particle Beams* **27**, 223-231 (2009).

[4] *XioYa Li* et al., *Phys. Rev. E* ***83**, 046404 (2001).*

[5] L. Nikzad et al., *Phys. Rev. ST Accel. Beams* **15**, 021301 (2012).

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