



Novel electron source based on interaction between high power laser and metal wire

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Abstract: Electron source generates electron bunch and dominates the electron beam quality for an accelerator. We put forward a novel mechanism of electron source in this paper. A great amount of hot electrons with several hundred keV can be generated during the interaction process between high power laser and metal wire, and some of them fly forward along the wire, guided by EM field. We generate electron beam and measure beam parameters downstream the Au wire, W wire and Cu wire experimentally. 3 nC electrons can be collected by a Faraday-cup for a single shot. Electron energy spectrum is between 0–240 keV continually, and there is a density peak at 100 keV. RF buncher cavity can be used to compress the bunch length short enough for further RF acceleration in main accelerator. Start-to-end simulation has been done with ASTRA code. Electron beam with 55 ps length and 1 nC charge is injected into a 2-cell RF buncher cavity, it can be compressed into 27 ps long, which satisfies the general requirement of the main accelerator on the electron source.

Key words: electron beam; laser pulse; metal wire; bunch compression

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Electron beam has been playing an important role in the field of basic scientific research, industrial production, and medical treatment. Electron beams are all generated and accelerated in the accelerator. As we all know, electron source is an important component of the electron accelerator, which has two functions: One is to generate enough electrons, and the other is to accelerate these electrons to a certain speed immediately, better to a relativistic speed, which can effectively suppress the negative influence of space charge effect on the quality of the electron beam. For an accelerator, the quality of the electron beam is largely determined by the electron source^[1-3]. There are some kinds of electron sources according to the electron generation mechanisms: field emission^[4], thermal emission^[5], and photoelectric emission^[6]. We put forward a novel mechanism for electron source, which can produce high-quality electron beams. Hot electrons emit from the interaction between high power laser and solid density target, the behavior of these hot electrons is highlighted and significant to a lot of research field, such as fast ignition^[7-9], THz radiation^[10-12] and wake field particle acceleration^[13-15]. When a relativistic laser shines on a metal wire, plasma can be generated immediately at the laser focal spot. A great number of hot electrons escape from metal into vacuum and scatter in all directions. Along the wire, a radial electric field will be induced because of the charge separation effect. Meanwhile, a great number of cold electrons in the wire flow back to the interaction spot for supplement of the escaping electrons, and the induced current induces an instantaneous magnetic field around the wire. The electric field and the magnetic field act on those hot electrons flying along the wire, which guide them to the end of the wire. Experimentally, we have generated the electron beam and measured beam parameters, including energy spectrum, bunch charge, beam size and so on. We can select those hot electrons at peak of energy spectrum and compress them by an optimized RF buncher to short enough

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for further acceleration. Simulation results confirm that this mechanism can be developed into a potential electron source. Furthermore, this electron source is easy to transport the electron bunch to the experimental position by pulling the wire, which is beneficial for a lot of applications.

1 Experimental setup

The layout of the novel electron source is shown in Fig.1. Experiment was carried on the 200 TW laser facility in Shanghai Jiaotong University. A Ti:sapphire laser system provides the laser pulses, with 1 J per pulse, 800 nm, and 150 fs pulse duration. The maximum repetition rate is 10 Hz, and it can also operate in single-shot mode. In experiment, the laser pulse is finely focused on the wire at a spot size of 6 μm , resulting in a peak density of about 10^{19} W/cm². The experiment was conducted in a vacuum chamber, whose vacuum is about 10^{-2} Pa. Downstream of the wire target, we use imaging plates (IPs, Fujifilm SR2025) to measure the electron beam distribution, and a Faraday-cup can be used to measure the bunch charge. A uniform dipole magnet is put just behind of the wire end to rotate all electrons 90°, and the size of magnet is 150 mm×100 mm×10 mm. The magnetic field intensity in the central area of the two magnets is 0.139 T. An adjustable slit can be used to choose the bunch charge and energy spread by optimizing the position and width, as electrons in different velocity rotate at different radius. In the experiment, the slit width is 0.1 mm, and the horizontal distance between the slit and the end of the wire target is 8 mm. The chosen electron bunch downstream the slit is much long for RF acceleration, thus it enters an RF compressor to be compressed short enough for the main accelerator. We have measured three metal wires W, Cu and Ag with different diameter.

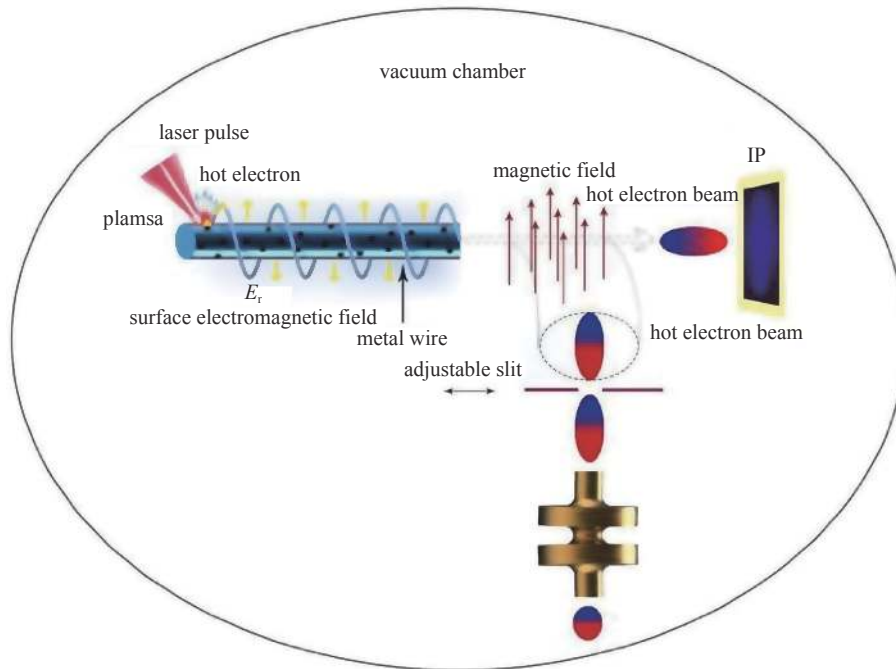


Fig. 1 Experimental layout

2 Results and discussion

2.1 Beam profile

Fig.2 is the electron image on IP board. In this case, W wire has the diameter 0.03 mm, the distance from the laser focusing point to the end of the wire L is 150 mm. The beam is in ring shape with the maximum diameter about 33 mm, which indicates the electrons propagate forward along the wire surface. The white area indicates the majority of the electrons are within this region that bring the IP board into saturation.

2.2 Electron emission from three metal wires

According to Schottky theory, metal material has a work function. When the electron energy in the material is higher than its work function, electrons escape off the material surface into the vacuum. Different metal has different work function. To find the good electron emission target, we tested three metal wires (W, Ag, Cu) wires with the same diameter and length ($d=$

0.3 mm, $L=150$ mm). Two similar IP board layers stack together to detect electron beam profile. Of course, all electrons arrive on the first IP board and imaging. Only those electrons with energy higher than 200 keV can pass through the first IP board layer and reach the second layer. Fig.3 shows the beam profiles on the first IP layer and second IP layer for the three different wire targets. As we know, the beam signal recorded in IP board decays with time due to IP character^[16]. Fig.3 (a) is beam image read out from IP board 120 min later after experiment, and Fig.3 (b) is beam image read out from IP board when signal decays much enough after experiment. Comparing these results, we can draw a conclusion: among the three wires, Ag wire is the best electron emitter, which generates the most electron charge, then followed by W wire, and then Cu wire. The electrons with more than 200 keV energy from Ag and W wires are almost same, but there are almost no electrons with high energy from Cu wire.

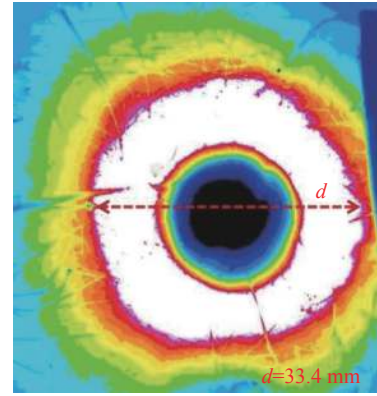
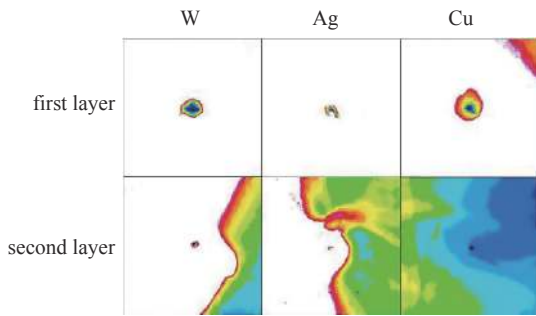
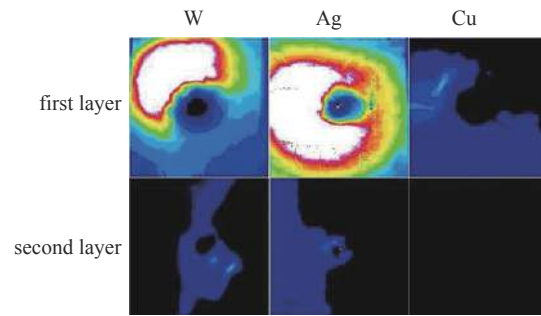


Fig. 2 Electron beam image on IP board. W wire target with $d=0.03$ mm, $L=150$ mm



(a) from IP board 120 min later after experiment



(b) from IP board when IP signal decays much enough after experiment

Fig. 3 Electron beam profiles on two-layer IP board for three wires

2.3 Guiding effect on electrons from metal wire

Hot electrons propagate forward along the wire. As discussed above, the electric field and magnetic field around the wire limit and guide the electrons along the wire. We stack three layers of IP board together and put them downstream the W wire end to detect the beam space distribution and energy distribution in the beam bunch. Fig.4 shows beam profile on the three-layer IP board for $L=10, 20, 30$ cm respectively. If the distance from the laser focusing spot to the wire end L is longer, the beam can be guided better, thus the beam profile is smaller. Long wire has a better guiding effect on electron beam than short one. Another finding is that the beam size on the first layer is much bigger than that on the second layer. Similarly, the beam size on the second layer is bigger than that on the third layer. This means that the electrons with high power is inside the beam, and the lower energy electrons is outside the beam. There are a few electrons with energy higher than 400 keV from the W wire.

2.4 Energy spectrum

From the beam profile on IP board, we can deduce the energy distribution of the beam from the metal wire. To get energy spectrum exactly, we insert a dipole magnet just behind the wire to make all electrons rotate 180° , and hit on the IP board. From the beam position, distribution, and magnetic field, we can calculate the energy spectrum of the beam. Fig.5 shows the beamlet

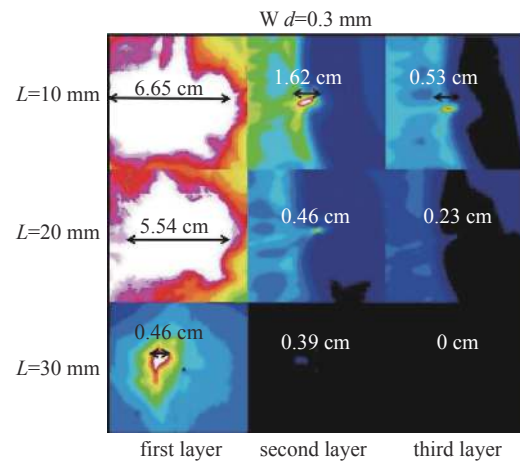


Fig. 4 Electron spatial distribution on three-layer IP board for tungsten wire of different length

and energy spectrum. In this case, the laser intensity is about 10^{19} W/cm², the Cu wire is 150 mm in length and 300 μ m in diameter. The electron energy is mostly between 40–240 keV, and an energy peak is at 100 keV. For the same wire, we use a Falady-cup to collect and measure the total charge. 3 nC electron charge can be generated totally in a single shot.

3 Start-to-end simulation for bunch compression

As Fig.5 shows, the charge of the electrons with 95–100 keV energy is estimated at nC level, and the bunch length is estimated about 55 ps after drifting a 150 mm distance from the laser focusing spot. To the main accelerator generally, bunch charge is high enough, but bunch length is too long. For example, we suppose the main accelerator is S-band, 2856 MHz, one RF duration is 350 ps. We put forward a compression scheme: Firstly, selecting the electrons by a magnetic field and an adjustable slit, and then injecting them into an RF cavity. Fig.6 shows the electric field in a 2-cell RF cavity. When an electron bunch with a certain length enters the microwave electric field, electrons at different position of the bunch experience different electric field. We can choose a proper time to inject the electron beam into the RF cavity, so that the head electrons of the bunch feel low electric field and gain a small amount of energy, but the tail electrons of the bunch feel high electric field and gain a lot of energy. After the bunch passed through the cavity, the tail electrons move faster than the head electrons. After drifting a distance, the tail electrons catch up with the head electrons gradually. As a result, the bunch length is compressed. The required RF peak power is estimated only 10–30 kW.

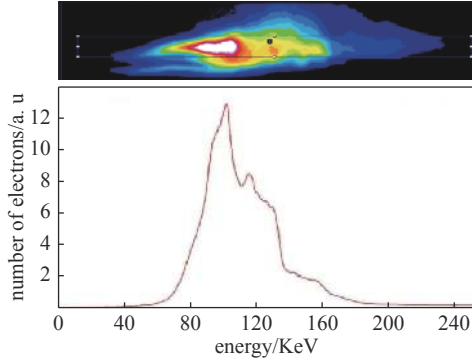


Fig. 5 Beamlet and energy spectrum

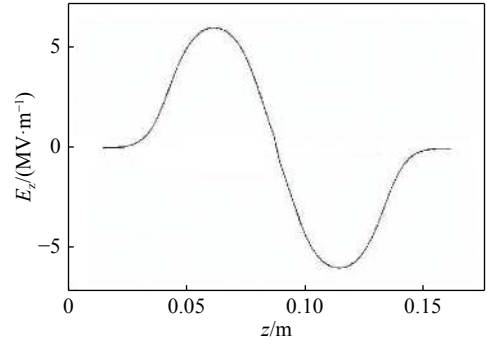


Fig. 6 E_z field in the 2-cell RF cavity

We simulated the compression effect of the RF cavity on the electron bunch with ASTRA (A Space Charge Tracking Algorithm) code. ASTRA is a beam dynamics simulation software. User defines the initial distribution of particles and external electromagnetic field; it can track the particles under the influence of external fields and space charge effect. It is assumed that all electrons are generated from the laser focal point of 6 μ m diameter at the same time, then they drift along 150 mm wire. Arriving at the end of wire, the electron bunch length of 95–105 keV increases to about 9 mm (RMS) in space, about 55 ps in time, as shown in Fig.7. The first step is to find the optimized injection phase for electron beam into RF cavity. Fig.8 shows the relation between bunch length and the injection phase.

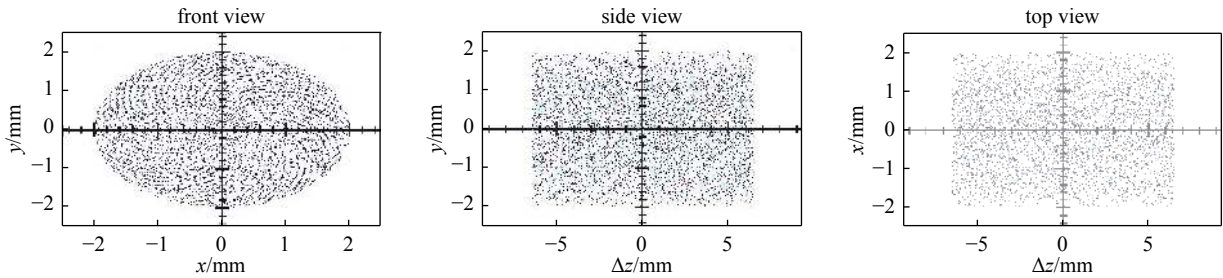


Fig. 7 Initial distribution of electron bunch

In simulation, the space charge effect is included. Fig.9 (a) shows that the average energy of the electron bunch increases to about 240 keV. The bunch length can be compressed successfully to around 50% of the original length, from 55 to 27 ps in time, which can be captured and accelerated by the main accelerator.

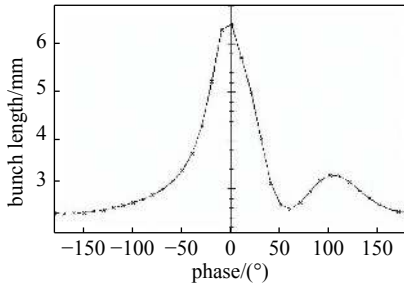


Fig. 8 Bunch length vs injection phase

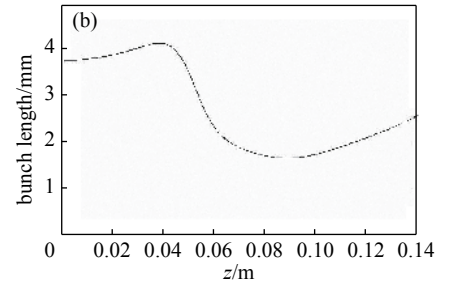
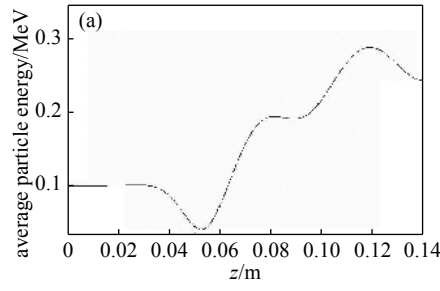


Fig. 9 Average beam energy in the RF cavity and bunch length (RMS) in the cavity

4 Conclusion

We have generated electron beam by the interaction between relativistic laser and metal wire target experimentally. The beam energy covers 40–240 keV, and the total charge is more than 3 nC. We propose to choose the electrons with energy between 95–100 keV into the buncher cavity, and to compress electron bunch short enough for the main accelerator. We have done start-to-end simulation to optimize the performance of electron beam and successfully compressed bunch length to 27 ps, meanwhile beam energy up to 240 keV. This scheme is a potential electron source for further acceleration in the following main accelerator. Furthermore, this wire source is easy to guide the electron bunch to the experimental position only by pulling the wire, which is beneficial for a lot of applications, such as low energy electron diffraction.

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新型金属丝靶电子源实验研究

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摘 要: 电子束在基础科学研究、工农业生产和医疗领域发挥了重要作用。提出了一种新型的电子源技术方案: 高功率激光脉冲轰击金属丝靶, 可以产生大量能量在百 keV 量级的热电子, 一部分热电子在丝靶表面自生电磁场的作用下沿着丝靶运动, 丝靶后方可以获得指向性良好的电子束。实验上成功在金、钨和铜丝靶后方获得了电子束团, 测量了束团束斑、电荷量和能谱。铜丝靶单发实验收集到的电子束团总电荷量可达 3 nC, 能量分布在 0~240 keV 区间内, 能谱在 100 keV 附近呈现峰值。提出了微波压缩方案, 设计了 2 腔微波聚束腔, 利用 ASTRA 对微波腔压缩过程进行了模拟计算。结果显示, 可以将电荷量 1 nC、长度 55 ps 的束团压缩至 27 ps, 满足后续微波加速器对电子源的要求。

关键词: 电子束; 激光脉冲; 金属丝; 束团压缩