

Experimental investigation of a pulse line ion accelerator in Lanzhou^{*}

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Abstract: In order to put the Pulse Line Ion Accelerator (PLIA) concept to its practical application, a small experimental platform was built. It was found that the actual axial electric field is smaller than the theoretical calculation, so the accelerated ions will enter into the deceleration zone before leaving the helix, which will seriously affect the acceleration process. Based on the improved parameters, the He⁺ with 24 keV is accelerated to 55 keV, and the proof-of-principle experiment is completed on this platform.

Key words: PLIA, accelerator, beam experiment

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1 Introduction

With the unique advantages of High Energy Density Physics (HEDP) and Warm Dense Matter (WDM) experimental research driven by an intense heavy ion beam, the intense heavy ion beam has gradually become an important means of HEDP and WDM research. The Pulse Line Ion Accelerator (PLIA), which is a new accelerator concept [1], potentially offers high-gradient ion beam acceleration at high line charge density that is able to meet the need of these studies. The PLIA consists of a helix wound over an evacuated beam tube, an outer dielectric layer and an outer conductor. A ramped voltage waveform is applied to a helical pulse line creating a traveling wave, which produces an accelerating electric field to the ions over the length of the helix. The flexibility and modest cost of this kind of accelerator makes it of great interest for HEDP and WDM. In addition, it also has the flexibility of bunching and controlling the longitudinal phase space of the beam by applying a velocity tilt to counteract the longitudinal spreading due to space-charge forces and emittance.

The principle of the PLIA was first proposed by the Lawrence Berkley National Laboratory (LBNL), and the proof-of-principle experiment had been performed on the LBNL Neutralized Drift Compression Experiment (NDCX). In the initial beam experiment a 350 keV, 1 mA, 19 μ s K⁺ pulsed beam was accelerated to 500 keV

[2], which have demonstrated the ability of PLIA to accelerate ion bunches. However, a vacuum surface flashover limits the ion accelerating gradient to around 150 keV/m. Experimental and theoretical efforts are currently focused on understanding the origin of the flashover that limits this helix voltage.

2 Structure design and electric field measurement

A simple prototype of PLIA for a proof-of-principle experiment was designed and constructed. The basic parameters of the prototype are listed in Table 1. The wave velocity of the traveling wave is simulated by CST and measured by an array of capacitive pickups that are set along the helix structure. The simulation and measurement results better matches the calculated results [3].

To fully understand the real value of electric field excited from helical line in PLIA, an optical electric integrated electric field measurement system was adopted. The axis electric field at different locations along the helix is shown in Fig. 1. The real waveforms of axial electric field are consistent with the calculation and simulation results, but the real magnitude is smaller than that of the calculation, probably due to the actual pitch of the resistor column, which is much less than that of the helix [4].

The simulation and measurement results of wave

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Table 1. The basic parameter of PLIA in Lanzhou.

parameter	symbol	value
vacuum insulator radius/mm	r_0	26
helix radius/mm	a	30.6
ground return radius/mm	b	44
helix pitch/(turns/m)	n	783
effective helix length/mm	l	700
relative permittivity(oil)	ε_r	2.3
capacitance/(pF/m)	C_0	351
inductance/(\(\mu\text{H}/\text{m}\))	L_0	1160.8
impedance/\(\Omega\)	Z_0	1820
wave velocity/(m/s)	v_c	1.57×10^6

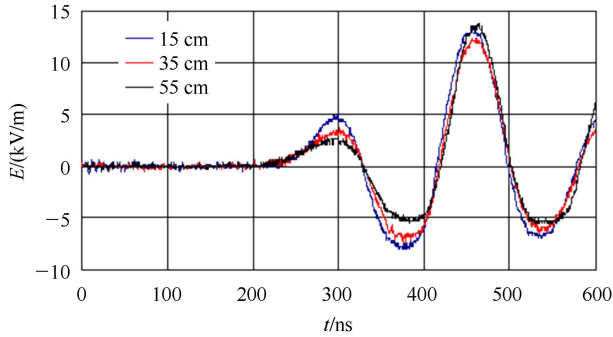


Fig. 1. (color online) The axis electric field at different locations along the helix.

velocity and electric field will provide an important reference for subsequent beam acceleration experiment.

3 Initial experiment design

Figure 2 shows the experimental scheme. It consists of an ECR ion source, a focusing system, a PLIA accelerating structure, and a beam measurement system etc. The synchronizer is used to ensure that the ion is only accelerated by the electric field of PLIA when it arrives. The beam measurement system consists of an electrostatic analyzer and an electron multiplier. The beam current is measured by varying the DC voltage of the electrostatic dipole and collecting the beam current at the exit of the electrostatic energy analyzer with the electron multiplier. The best choice of beam in this experiment is a mA, μs pulsed ion beam, but this is less demanding of emittance.

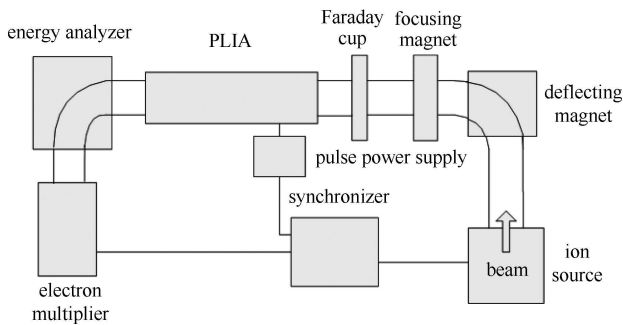


Fig. 2. (color online) The experimental scheme.

Based on the existing experimental conditions and funding constraints, it is difficult to achieve ideal experimental conditions in a short time. Consequently, existing equipment is planned to be used in the preliminary experiment, and the choice of beam parameters must be based on the existing ECR ion source. In order to facilitate the experiment, the He^+ is selected as implanting ions.

To ensure that the ions are always trapped by the wave, it must approximately satisfy [5]:

$$\frac{1}{2}m(v_c - v_{bi})^2 \leq 2qV_0. \quad (1)$$

Where v_{bi} is the initial velocity of ion, and V_0 is the peak voltage. Under 7.5 kV peak voltage (design value), the initial velocity of ion is calculated using Eq. (1) to be $v_{bi} \geq 0.72 \times 10^6$ m/s, and the corresponding initial energy is $E_i > 11$ keV. In order to obtain maximum energy gain under the existing parameters of the ECR ion source, the 20 keV He^+ is selected as implanting ions. The corresponding initial velocity of ion will be calculated by $v_{bi} = 0.98 \times 10^6$ m/s, and the final velocity of the ion will be calculated by $v_{bf} = 2v_c - v_{bi} = 2.16 \times 10^6$ m/s, which corresponds to the energy at the end of the acceleration process equal to $W_f = 96$ keV and energy increase is $\Delta W = V_0(8 + 4\sqrt{2W_{bi}/V_0}) = 76$ keV.

The length of the accelerating structure will be calculated by

$$L = \frac{4(mv_c^2/2q)(1 - v_{bi}/v_c)}{E_z} = 0.7 \text{ m}.$$

Due to technical reasons, the actual peak acceleration voltage is 6.2 kV, which is smaller than the design value. So, the final energy at the end of the acceleration process will be recalculated. By calculation, the final energy in fact should be $W_f = 87$ keV.

4 Beam experiment with the PLIA

As calculated above, 20 keV He^+ is chosen as the injected ions in the preliminary experiment. The beam intensity from the ECR ion source is relatively weak, the beam is only several μA at the entrance of PLIA, and the entrance of electrostatic energy analyzer is very small. So a focusing lens is used before the PLIA to constrain the size of the beam, which will ensure that the beam enters into the measuring system as much as possible.

Figure 3 is the measured signal of electrostatic energy analyzer with electrostatic dipole voltage of 3.7 kV. This illustrates that part of 20 keV He^+ is accelerated to 28 keV, which is much less than the theoretical calculated value of 87 keV. The reason for this is that the actual axial electric field is smaller than the theoretical calculation [4], so the accelerated ions will enter into

the deceleration zone before leaving the helix. To solve this problem, we increase the injected energy of the ions to avoid them entering into the deceleration zone before leaving the helix.

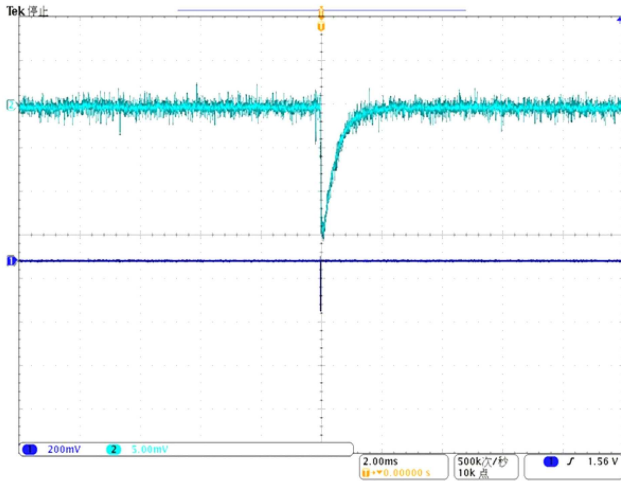


Fig. 3. (color online) The measured signal of electrostatic energy analyzer with electrostatic dipole voltage of 3.7 kV.

By calculation, we increase the injected ion energy to 24 keV. The final energy in this case should be $W_f = 46$ keV. Based on the improved parameters, the experiment was repeated. Fig. 4 is the measured signal of an electrostatic energy analyzer with an electrostatic dipole voltage of 7.7 kV, which corresponds to an ion energy of 55 keV. The experiment result is larger than the theoretical calculation value 46 keV. This is due to the presence of a fringe field at the front and rear ends of the helix, which will make the effective length of the accelerator a little longer than 0.7 m [6].

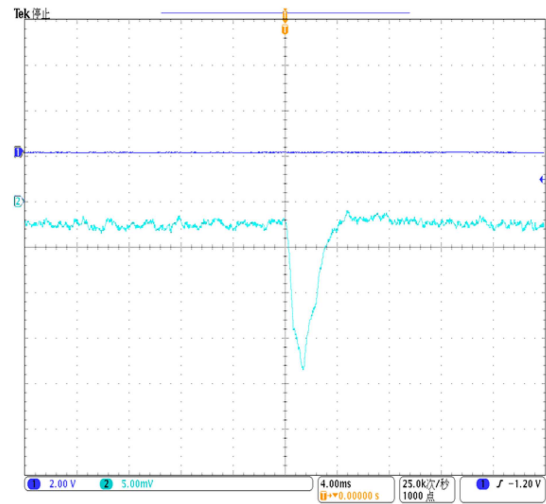


Fig. 4. (color online) The measured signal of electrostatic energy analyzer with electrostatic dipole voltage of 7.7 kV.

5 Conclusion

In the final beam acceleration experiment, the He^+ with 24 keV is accelerated to 55 keV after the improvement of the experimental scheme, which completes the verification of the proof-of-principle experiment of PLIA. Through the experiment, much experience can be summarized to provide guidance for subsequent experiments. First, the power supply and the helical line must be well matched to eliminate the reflected signal. Second, the electric field must be measured before the beam acceleration experiment because it will seriously affect the accelerating process.

Next, we will further optimize the structure of PLIA to improve the accelerating field, and upgrade the ion source to achieve pulsed acceleration.

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