The test pulse line ion accelerator in Lanzhou*

SHEN Xiao-Kang(申晓康)[1,2;1)] CAO Shu-Chun(曹树春)[1] ZHANG Zi-Min(张子民)[1]
ZHAO Hong-Wei(赵红卫)[1] ZHAO Quan-Tang(赵全堂)[1,2] LIU Ming(刘铭)[1]
JING Yi(景漪)[1] LI Zhong-Ping(李中平)[1] WAN Ming(万明)[1]
WANG Bin(王斌)[3] YANG Chun-Ming(杨春名)[3] XIAO Rong-Qing(肖荣庆)[1]
ZHANG Ying-Fa(张应发)[1] LI Ji-An(李继安)[3]

[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3] Lanzhou Kejin Taiji Co., Ltd, Lanzhou 730000, China

Abstract: To accelerate intense, short pulsed heavy ion beams to the energies of interest for studies of high energy density physics and warm dense matter, the Pulse Line Ion Accelerator (PLIA), of which the axial acceleration gradient can achieve several MeV per meter with realistic helix parameters at very low cost, was developed in recent years. A simple prototype of PLIA for a proof-of-principle experiment called the Lanzhou Test PLIA was designed and constructed at the Institute of Modern Physics in Lanzhou, and the test result matches the calculated result well. The pattern of the axial electric field Ez and the velocity of the traveling wave were simulated by CST.

Key words: PLIA, helix, accelerator, pulse power driver

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1 Introduction

Intense ion beams offer an attractive approach to heating dense matter uniformly to extreme conditions because their energy deposition is almost classical and shock-free. Simultaneous transverse and longitudinal beam compression in a neutralizing plasma medium, along with rapid beam acceleration, is being studied as a means of generating such beams for warm dense matter and high energy density (HED) physics experiments, as well as for heavy ion fusion (HIF). After the successful completion of the cooling storage ring project in China, research on the physics of HIF and HED is now available at the Institute of Modern Physics (IMP) in Lanzhou. The charge state distribution, energy loss of medium-energy heavy ion in matter, as well as the radiation from highly charged ions and low-dense plasma have been studied at HIRFL-IMP. Further activities will be concentrated on short, intense beam production, heavy ion beam-plasma interaction, and heavy ion driven fusion plasma and HED matter research with intense heavy ion beams [1]. So to complete the next work, we plan to build a special installation which should provide short beam pulses with the highest possible intensity and phase space density, strong beam compression and focusing.

The Pulse Line Ion Accelerator (PLIA), which is a new accelerator concept, potentially offers cost-effective high-gradient ion beam acceleration at high line charge density to meet the needs of these studies [2]. Compared with other types of accelerators, the major attraction of PLIA is the very low capital cost it promises. It should also be possible to achieve an axial acceleration gradient of several MeV per meter with realistic helix parameters [3], and in addition could provide axial focusing and confinement of the ion bunch.

2 Basic concept

The basic configuration of the PLIA is sketched

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1) E-mail: shenkang198@impcas.ac.cn

in Fig. 1. A helical pulse line with a radius of "a" is located inside a metallic cylinder with a radius of "b". Outside the helix is a dielectric media of permittivity of ε (e.g. oil), which prevents the breakdown between the helical windings and the metallic outer cylinder, and there is a vacuum inside the helix where the ion beam is transported. To provide continuous radial focusing of an intense ion bunch, the entire cylindrical structure can be inserted into a large bore solenoid magnet [4].

The wave velocity regime that we are considering for ion acceleration is of the order of 1%–10% of the light velocity in vacuum, and the axial wavelength spectrum of interest is large compared with the helix radius. So it is possible to model the PLIA as a transmission line with an equivalent capacitance and inductance per unit length of $C_0=2\pi\varepsilon/\ln(b/a)$; $L_0=\pi n^2a^2\mu_0(1-a^2/b^2)$, respectively [3], where n is the number of turns per meter of the helix, and μ_0 is the magnetic permeability of the vacuum. The wave velocity of the traveling wave is $v_t=(L_0C_0)^{-1/2}$, and the characteristic impedance is $Z_0=(L_0/C_0)^{1/2}$.

A pulsed power source connected at the input region of the helix creates an input voltage of the helix as shown in Fig. 2(a). Then it will generate a traveling wave, which is shown in Fig. 2(b) propagating along the structure of the helix. The ion beam can be accelerated and longitudinally confined by this voltage. In Fig. 2(b) an ion bunch is located in the ramp region, where the voltage goes from V_0 to $-V_0$ over the distance $l_t=v_t\tau_t$. The ions are accelerated by the axial electric field at a rate of the order $E_{\rm acc}=2V_0/l_t$, shown in Fig. 2(c) [5].

When the PLIA works, a few ions are initially located at the bottom of the ramp of the traveling wave (where $V=-V_0$), and move with a velocity v_i slower than the wave velocity by an amount Δv, $\Delta v=v_t-v_i$. So the ions initially move backwards relative to the traveling wave. To ensure that the ions are trapped by the wave, it must approximately satisfy:

$$\frac{1}{2}m(\Delta v)^2\leqslant 2qV_0. \quad (1)$$

With the increase in ion velocity, the ions begin to move forward relative to the traveling wave when the ion velocity is equal to the wave velocity, and will leave the traveling wave when the ion velocity reaches the maximum $v_{\max}$,

$$v_{\max}=v_t+\Delta v=v_i+2\Delta v. \quad (2)$$

The maximum velocity gain is where we reach the limit in Eq. (1), corresponding to a kinetic energy

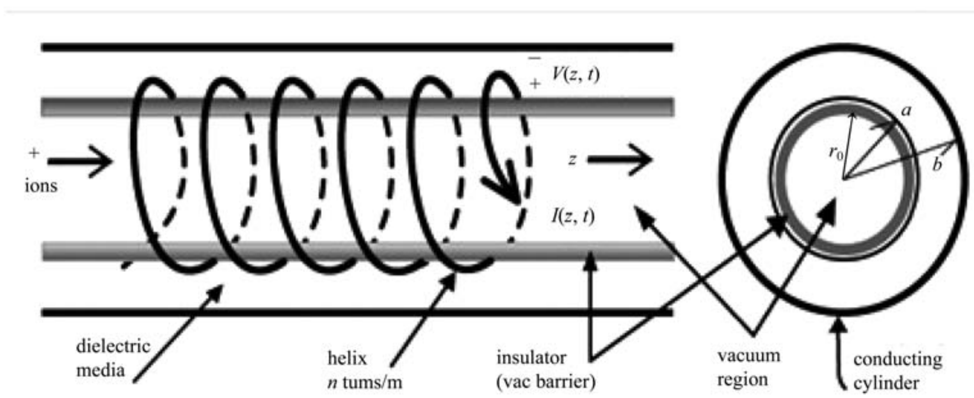

Fig. 1. The basic configuration of the PLIA.

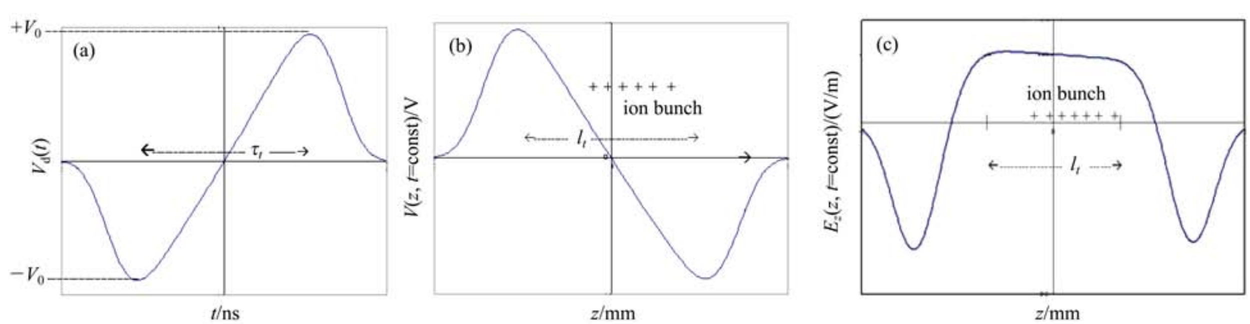

Fig. 2. (a) The voltage waveform at the helix input; (b) a snapshot of the voltage on the helix; and (c) a snapshot of the accelerating electric field $E_{\rm acc}$.

increase at the end of the acceleration process equal to:

$$W_{\rm f}=\frac{1}{2}mv_{\rm max}^2-\frac{1}{2}mv_i^2=V_0(8+4\sqrt{2W_i/V_0}). \quad (3)$$

Even in the early acceleration stages, where the initial kinetic energy of the ions W_i might be comparable to V_0, an energy gain of 15–20 times the peak voltage on the line can be obtained with a short bunch.

3 The design of the Lanzhou test PLIA

As the proof-of-principle experiment of PLIA, the main function of the Lanzhou test PLIA (LTP) is to verify the excitation of a traveling wave on the helix with capacitive pickups and other diagnostics to explore the voltage gradient limits and to implement ion acceleration.

During the primary design of LTP, the 100 keV O^+ with a velocity v_i of 1.1 m/μs was considered as the implanting ion. The helix wave velocity should be 1.57 m/μs so that the injected O^+ will be accelerated properly under an injection energy of 100 keV. At least 18 kV of the peak-to-peak voltage $V_{\rm p}$ of the traveling wave was required to "trap" the O^+ ions at 100 keV with a wave velocity of v_t=1.57 m/μs. Finally, a maximum $V_{\rm p}$ of 20 kV was adopted. Then the peak voltage axial gradient E_z was 2.0 kV/cm with a minimum ramp of pulse being about 70 ns. Based on the wave velocity, the input voltage and the limitation of materials on hand, the basic parameters of the LTP could be designed.

Recently, a simple prototype of PLIA for a proof-of-principle experiment, which is shown in Fig. 3, was constructed. The basic parameters of the prototype are listed in Table 1. In general, there are three methods to drive the helix-direct coupler, induction coupler and transformer coupler [6]. Here the direct coupler was chosen to drive the helix, and the high voltage pulse is coupled to the helix through a resistive column, as shown in Fig. 3.

Table 1. The basic parameters of LTP.

symbol/units	value
r_0/mm	26
a/mm	30.6
b/mm	44
n/(turns/m)	783
l/mm	700
ε_r	2.3
C_0/(pF/m)	351
L_0/(μH/m)	1160.8
Z_0/Ω	1820
v_t/(m/s)	1.57×10^6

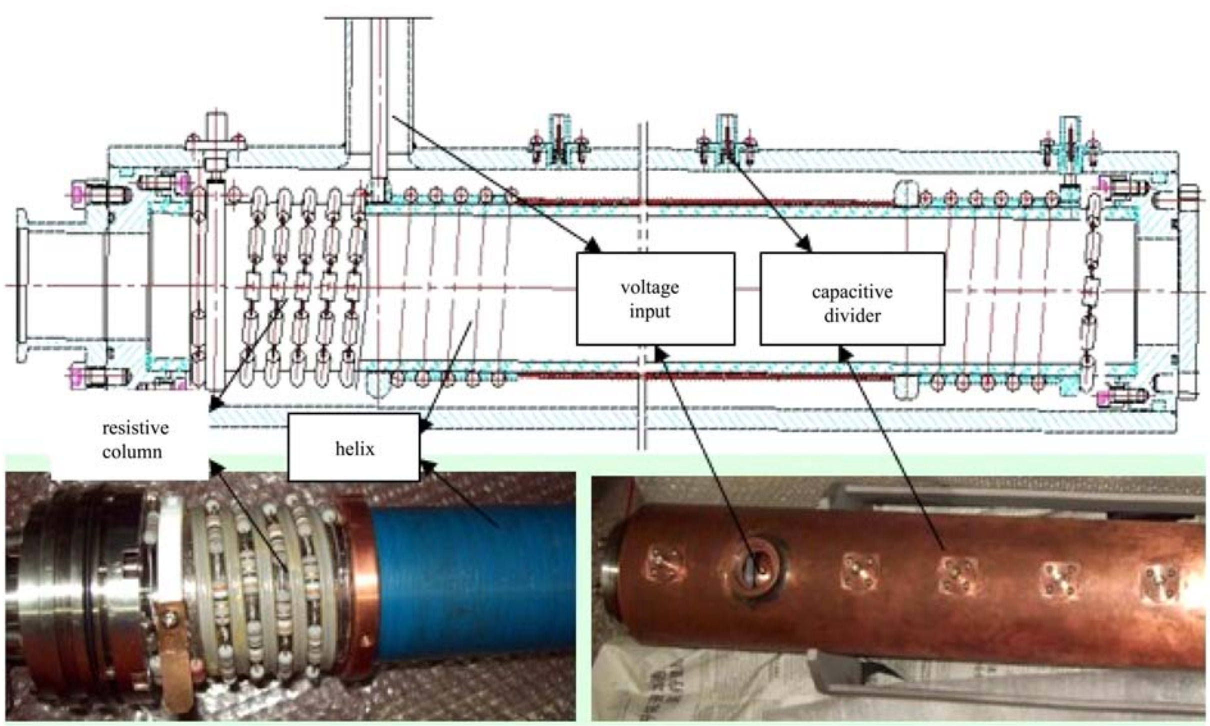

Fig. 3. A sketch and a photograph of the LTP.

4 The simulation of LTP

In order to understand how the PLIA works and to provide theoretical support for the design, some simulations were performed by CST to realize the pattern of axial electric field E_z and the traveling wave velocity excited along the helix structure. CST is a general-purpose electromagnetic simulator based on the finite integration technique. It can be estimated that numerical convergence requires the mesh size to be less than 1/4 of the wire spacing. The time-step should be no more than 0.6 ps to satisfy the Courant stability condition. The typical time scale for such a PLIA is several hundred ns, and the size of the time-step and mesh requires unreasonably long computational time. Therefore a scaling relation is proposed to make the simulation faster [7].

This is based on the hypothesis that the pattern of the electromagnetic (EM) field for a given wavelength is independent of the wire spacing as long as the wavelength is much longer than the inter-wire spacing, and the termination resistors are adjusted to maintain impedance matching. For LTP, $\lambda_{\rm EM}\gg d$ (d is the wire spacing) and the termination resistors can be changed to maintain impedance matching, so this scaling relation should be performed. The wire spacing used in the simulation is five times larger than that in the real experiment, and the velocity of the traveling EM waveform increases with larger wire spacing. Therefore, the theoretical calculation of the wave velocity should be 7.85×10^6 m/s.

Discrete sources and loads will be used directly, while the drive voltage waveform shown in Fig. 4(a) needs to be edited by VBA language. Fig. 4(b) is the corresponding accelerating electric field produced in the helix. The electric field has a large "bump" at 10 and 80 ns due to the fast voltage change rate at the leading and falling edges. This waveform is used for convenience, but in practice the leading and trailing

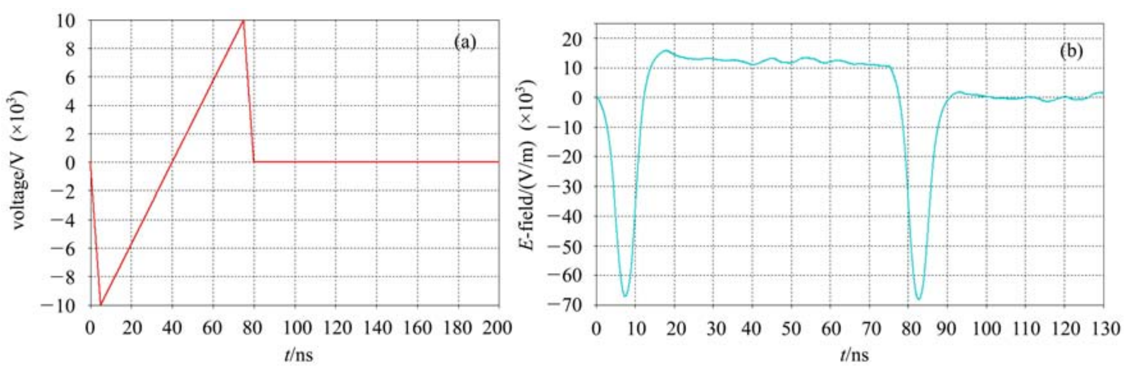

Fig. 4. (a) The drive voltage waveform used in the simulation, and (b) the accelerating electric field.

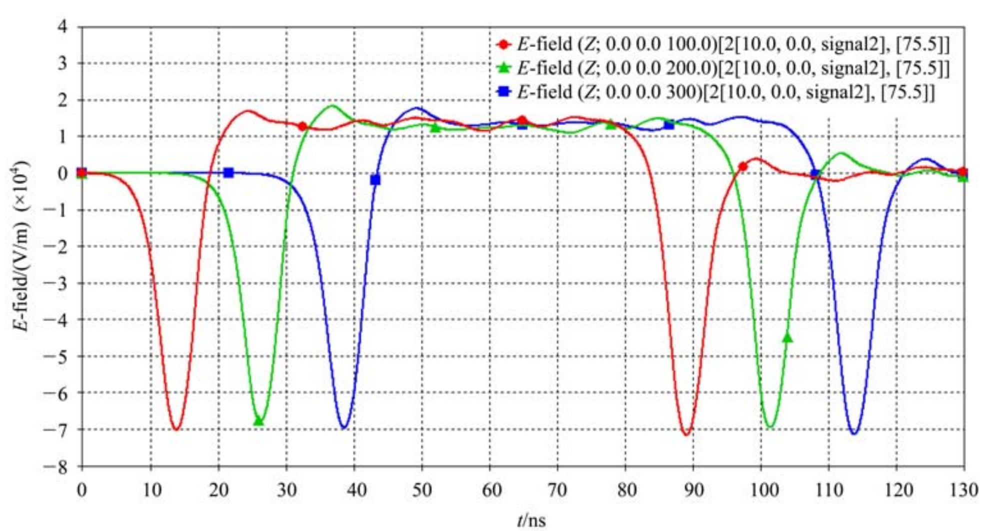

Fig. 5. The delay time simulation result.

edges should be slower than the main ramp-pulse in order to minimize the peak electric field in the structure.

To measure the wave velocity of PLIA, three probes were located every 100 mm along the structure. Fig. 5 is the delay time simulation result of about 12.6 ns. So the wave velocity v_t is 7.94×10^6 m/s, which shows good agreement with the calculated result.

5 Initial experimental results

The function of the transmission line is to transfer the pulse signal with high fidelity and a certain delay time. Fig. 6 shows the input and output signal waveforms of LTP, which were measured from the high voltage dividers on the two ends of the helix column. It is shown that the input and output signal waveforms are very consistent, and the delay time of 455 ns agrees with the calculated result of 446 ns very well. So it is feasible to model the LTP as a transmission line.

Furthermore, to measure the waveform and velocity of the traveling wave more accurately, an array of capacitive pickups was set along the helix structure (shown in Fig. 3). The distance between each capacitor is 210 mm. Fig. 7 shows the delay time measurement result of about 134 ns between each adjacent pickup. So the wave velocity v_t is 1.53×10^6 m/s, which better matches the calculated and simulation results.

The reflected wave has been observed from the measured waveform shown in both Fig. 6 and Fig. 7.

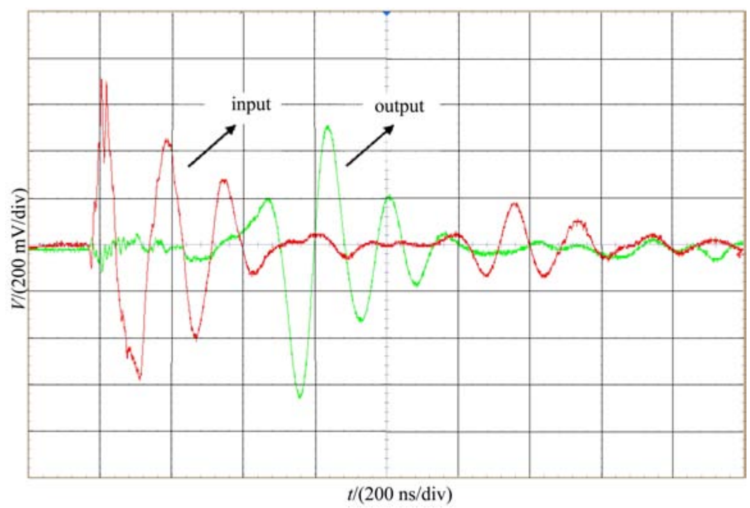

Fig. 6. (color online) The input and output signal waveforms of LTP.

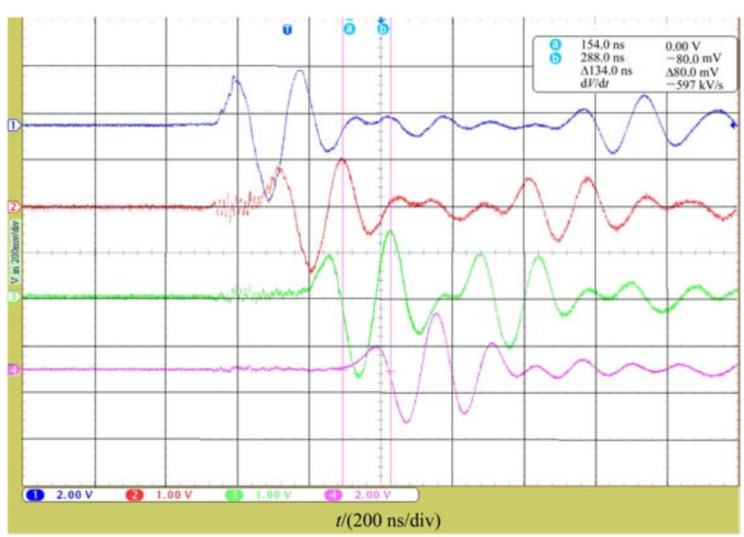

Fig. 7. (color online) The delay time measurement result.

Even if load impedance is changed on a large scale, the reflected wave remains. The possible reason for this is that the impedance mismatching between the helical line and the joint section (resistive column), which should also be equivalent to a transmission line and its characteristic impedance, is very small [8]. The pitch of the joint section is only 120 turns/m, which is about 1/6 that of the helix pitch. This leads to a much smaller inductance of the joint section than the helix structure, which is proportional to the pitch n^2. So the impedance of the joint section is too small to match the helical line. A new helix configuration in which the impedance of the joint section will be increased by increasing the inductance and decreasing the capacitance is being constructed to resolve this problem.

6 Conclusion

The principle of LTP has been demonstrated by both simulation and experiments. The accelerating electric field and the measured wave velocity show good agreement with the theoretical calculation results. A new helix configuration is being constructed to eliminate the reflected signal. In the future, the initial beam acceleration experiment will be delivered on LTP. The ion injector will be prepared by the modification of the existing ECR ion source, and a helical Blumlein transmission line designed as the extraction pulse generator, while an electrostatic energy analyzer is placed after the PLIA to measure the beam energy.

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