OVERVIEW OF THE PULSE LINE ION ACCELERATOR*

R.J. Briggs, SAIC, Alamo, CA 94507, U.S.A.
F.M. Bieniosek, J.E. Coleman, S. Eylon, E. Henestroza, M. Leitner, B.G. Logan, L.L. Reginato, P.K. Roy, P.A. Seidl, W.L. Waldron, S.S. Yu, LBNL, Berkeley, CA 94720, U.S.A.
J.J. Barnard, G.J. Caporaso, A. Friedman, D.P. Grote, S.D. Nelson, LLNL, Livermore, CA 94550, U.S.A.

Abstract

An overview of the Pulse Line Ion Accelerator (PLIA) concept and its development is presented. In the PLIA concept a pulse power driver applied to one end of a helical pulse line creates a traveling wave pulse that accelerates and axially confines a heavy ion beam pulse The motivation for its development at the IFE-VNL is the acceleration of intense, short pulse, heavy ion beams to regimes of interest for studies of High Energy Density Physics and Warm Dense Matter. Acceleration scenarios with constant parameter helical lines are described which result in output energies of a single stage much larger than the several hundred kilovolt peak voltages on the line, with a goal of 3-5 MeV/meter acceleration gradients. The main attraction of the concept is the very low cost it promises. It might be described crudely as an “air core” induction linac where the pulse-forming network is integrated into the beam line so the accelerating voltage pulse can move along with the ions to get voltage multiplication.

INTRODUCTION

In the “Pulse Line Ion Accelerator” (PLIA) concept a ramped high voltage pulse is applied at the input end of a helical pulse line structure [1]. The resulting traveling wave pulse on the line can accelerate an ion bunch to energies much greater than the peak voltage applied to the line. It should also be possible to eventually achieve axial acceleration gradients of several MeV per meter with realistic helix parameters and appropriate insulator designs.

The development of the PLIA concept was originally motivated by a proposal to use moderate energy intense ion beams to heat matter to regimes of interest for studies of High Energy Density Physics (HEDP) and Warm Dense Matter (WDM) [2]. PLIA is an excellent fit to the accelerator requirements for the HEDP/WDM application. Typical beam parameters in the accelerator are singly charged Ne or Na ion pulses with total charge of order 0.1 micro-coulombs and an axial bunch length of 10’s of cm, accelerated to energies of 20 to 30 MeV. A helical pulse line with an outer radius of order 10 cm can be inserted into a large bore 5 to 10T superconducting solenoid to provide radial focusing of the intense ion pulse.

The HEDP/WDM application and the required beam parameters are described in the following section. The basic PLIA concept is briefly reviewed in the next section, and a summary of some initial experimental studies are presented in the last section.

ION BEAMS FOR HEDP/WDM STUDIES

The original motivation for the Pulse Line Ion Accelerator development came from the ion beam requirements for HEDP/WDM studies. The ion beam approach being emphasized at the LBNL IFE Virtual National Lab utilizes the Bragg peak to obtain uniform volumetric heating of foils or foam with < 5% target temperature variation and over 75% of the ion energy deposited in the target [2]. As an example of ion beam parameters that are a good match to the PLIA concept, we need ~ 0.1 microcolumbs of medium mass ions (Na+1) accelerated to an energy slightly above the Bragg peak (~ 24 MeV) in as short a pulse as possible. To heat the target to temperatures of one eV or more in times short compared to the hydro disassembly timescale, the ion beam pulse must be radially focused to ~ one mm spot sizes and axially compressed to pulse lengths of order 1-2 cm.

A system concept for a HEDP/WDM ion beam facility based on a PLIA accelerator is shown in Fig. 1. A short pulse injector is required that is capable of axially compressing the 0.1 microcolumb of Na+1 to lengths of (say) 20 cm and radii of 2 cm for transport through the PLIA in a 5 T solenoid field. An accel-decel injector with a resistive column, or a front end PLIA stage operating in the so-called “snow-plow” mode, are being considered for this function [3].

In the PLIA accelerator section, the ion pulse is accelerated to 24 MeV keeping its physical length constant at 20 cm, to maintain a matched radii of the beam at 2 cm. (The duration of the pulse goes from ~ 100 ns to ~ 20 ns as it is accelerated to 24 MeV.) In the final PLIA sections, a “tilt” of order 10% in the axial electric field is required so the pulse can axially compress from 20 cm at the PLIA output to a ~ 2 cm length as it transits through the neutralized drift compression section.

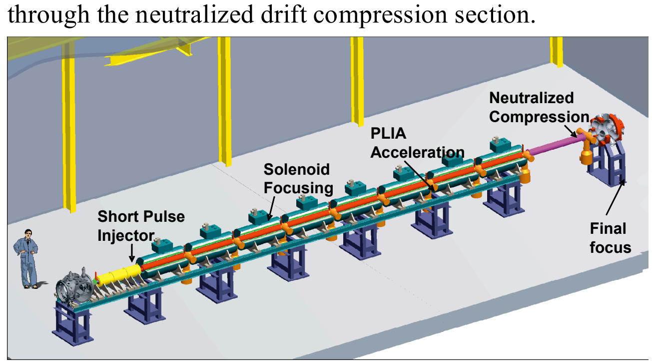


Fig. 1 System concept for HEDP/WDM ion beam facility.

PLIA CONCEPT

The basic configuration of the PLIA is sketched in Fig. 2. A helical pulse line of radius "a" is located inside of a conducting cylinder of radius "b". A dielectric media of permittivity ε is located in the region outside the helix, while the region inside the helix (where the ion beam is transported) is vacuum. A thin insulating cylinder inside the helix provides the vacuum barrier, and this insulator must sustain the desired pulsed axial voltage gradients of several MeV per meter along its vacuum interface without flashover.

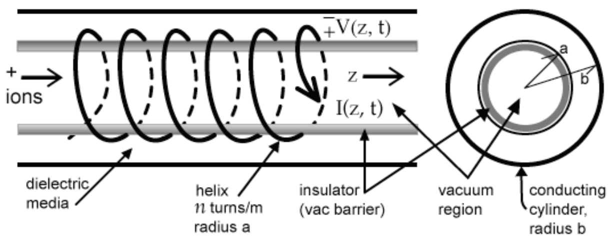


Fig. 2 Basic configuration of the PLIA

The wave speed regime we are considering for ion acceleration is the order of 1-10% of the speed of light in vacuum, and the axial wavelength spectrum of interest is large compared to the helix radius. In this regime, the helical line can be modeled as a transmission line with equivalent inductance and capacitance per unit length of $L_0 = \pi n^2 a^2 \mu_0 (1 - a^2 / b^2)$ and $C_0 = 2\pi\varepsilon / \ln(b/a)$ respectively, where n is the number of turns per meter of the helix.

A pulsed power source connected at the input region of the helix pulse line creates a traveling wave voltage of the form shown in Fig. 3. At any fixed location along the helix the voltage vs. time is as shown in Fig. 3a, while a "snapshot" view of the voltage vs. axial distance is as shown in Fig. 3b. In Fig. 3b an ion bunch of length l_b is shown located in the ramp region where the voltage goes from $+V_0$ to $-V_0$ over the distance $l_c = v_c \tau_c$, with v_c the propagation speed of the traveling wave on the pulse line. The ions are accelerated by the wave axial electric field, at a rate of order $E_{acc} = 2V_0 / l_c$.

Energy gains much large than V_0 are possible even in a helix with a constant wave velocity. Consider, for example, a few ions initially located at the bottom of the ramp of the traveling wave (where $V = -V_0$), moving with a velocity v_{bi} slower than the wave speed by an amount Δv (Fig. 4). These ions will slide up the voltage ramp and back down it as the wave travels through the system, if the wave amplitude satisfies the inequality

$$\frac{1}{2} m (\Delta v)^2 \leq 2qV_0$$

The velocity of the ions when they return to the bottom of the ramp is $v_c + \Delta v = v_{bi} + 2\Delta v$. At the limit of the above inequality the gain in the ion energy is $V_0 (8 + 4\sqrt{W_{bi} / V_0})$ where W_{bi} is the initial ion energy. Even in the early stages of the PLIA where the initial ion energy is comparable to V_0, the maximum energy gain *in an untapered pulse line* can be 10 – 20 times the peak pulse voltage on the line.

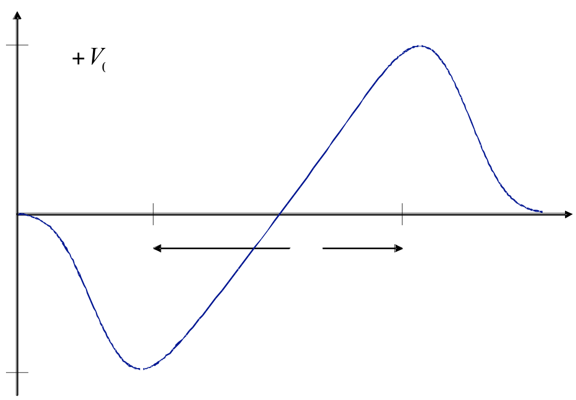


Fig. 3a Voltage waveform vs. time at fixed z

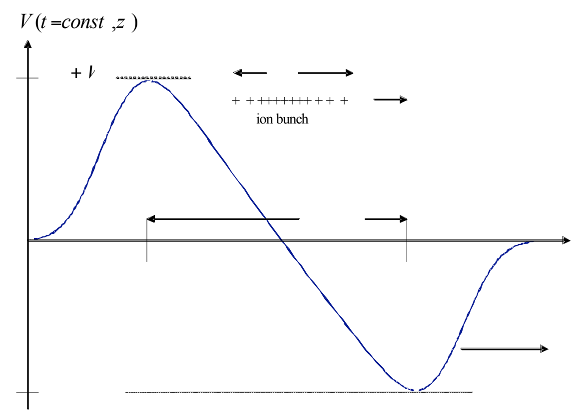


Fig. 3b Voltage waveform vs. z at a fixed time

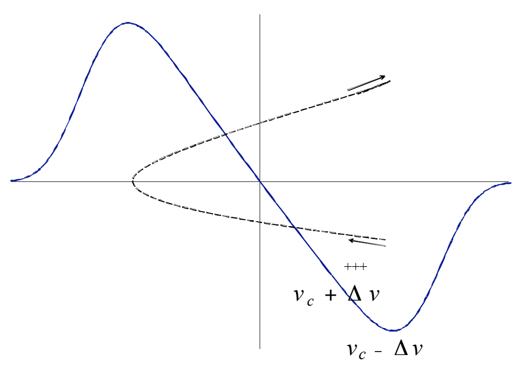
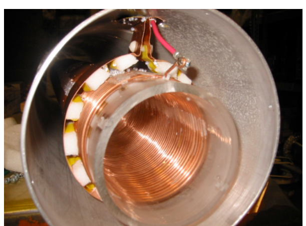


Fig. 4 Illustration of ion energy gain in an untapered line. The ion bunch slides up the potential hill and down again.

The ion bunch length must of course be long enough to transport the required total charge in the bunch, given the solenoidal focusing magnetic field and a maximum beam radius. The maximum energy gain in an untapered line will then involve tradeoffs *when the peak voltage on the line is limited by radial breakdown*, since the acceleration gradient is reduced as the wave ramp length is increased to fit the ion bunch. Simple models indicate that a single untapered PLIA stage can still add energies of 10 to 40 times the peak pulse voltage on the line (depending on the initial ion energy) without significantly compromising the average gradient [1]. Tapering the line wave speed in z can increase the maximum energy gain, but the flexibility and simplicity of the untapered line make it particularly attractive for initial experimental studies.

INITIAL EXPERIMENTAL STUDIES

Many aspects of the input coupler design, the wave propagation and dispersion, matching, etc. were tested first on very inexpensive full scale models operating at low voltages [5]. For example, the first studies of transformer coupling and wave propagation were made using the air dielectric helix shown in Fig. 5 (6 cm radius helix, 0.9 m long, 0.25 cm diameter wires with 2 turns/cm, 10 cm radius conducting tube, terminated in a 1.5 K ohm matched load).



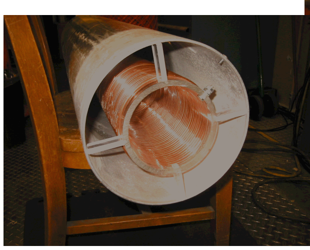


Fig. 5 Low voltage air dielectric model. The helical line on the left was driven directly by a voltage source connected to the input tap, while the right figure shows a test of transformer coupling with a one-turn primary strap.

The dispersion characteristics of the wave propagation on this helical line were measured with a Network Analyzer, recording the phase of the output voltage on the termination resistor as a function of frequency. The result is shown in Fig. 6 as a traditional $\omega - k$ plot, with the frequency normalized as $\omega a / v_{c0}$ and the wavenumber normalized as ka, where $v_{c0} = 4.6x10^6 \ m/\sec$ is the measured low frequency limit of the wave velocity. A theoretical calculation of the dispersion [1], [4} is also shown in Fig. 6. The bending away from the dispersionless straight line shown in the figure of both the theory and experiment is in good agreement. The dispersion can also be minimized by an appropriate choice of dimensions and dielectric constant [4].

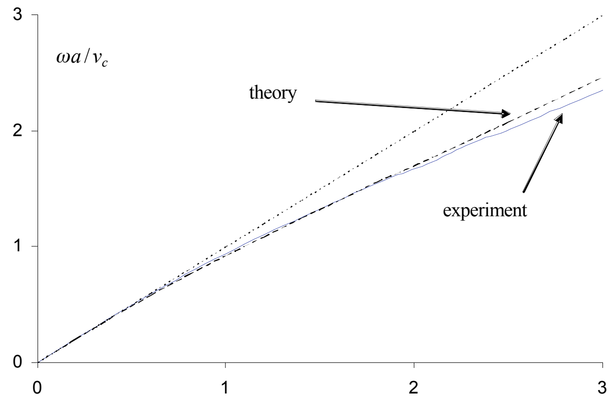


Fig. 6 Dispersion curve measured on the low voltage air dielectric model, compared to theory and a dispersionless straight line (upper broken line)

The transformer coupler shown in Fig. 5 is an attractive method for driving the helix. In this approach, the input end of the helix is shorted to the outer cylinder (ground). The primary strap with (typically) only one or two turns is driven by a low impedance pulse power source placed a short distance from the grounded input end of the helix. A fraction of the flux created by the primary strap links the helix, and this flux launches a traveling wave in much the same fashion as if we had connected a direct drive voltage source at that point.

A useful feature of the transformer coupler is the large voltage step-up from the primary to the traveling wave with a corresponding reduction in the feed-through voltage. The ½" wide single turn strap in the air dielectric model shown in Fig. 5 produced a 5:1 step up, for example.

The oil dielectric helix shown in Fig. 7 has been used for most of the high voltage testing [5], and for the initial ion acceleration experiments [6].

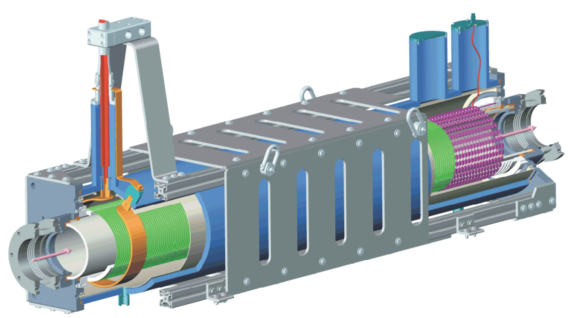


Fig. 7 Drawing of oil dielectric helix (in green). The primary strap is at the left, and the helical termination resistor is on the right.

The first configuration was designed for a wave speed of $2.9x10^6 \ m/\sec$; it had the parameters listed in Table 1. It was later modified for a wave speed of $1.9x10^6 \ m/\sec$ to better match the ion beam parameters for the initial ion acceleration experiments, the main change being an increase of the helix pitch to 240 turns/m.

wave velocity	**2.9 x 10^{6} m/s**
helix radius	**8.1 cm**
ground return radius	**11.75 cm**
dielectric permittivity	**2.3**
capacitance	**344 pF/m**
inductance	**345 mH/m**
impedance	**1000 ohms**
helix pitch	**160 turns/m**
effective helix length	**1 m**

Table 1 Oil helix parameters (first version)

A low voltage pulse was applied to the primary strap to measure the wave speed with an axially oriented B-dot loop that could slide along the axis of the helix. The measurements on the first oil helix configuration are shown in Fig. 8. The measured velocity of $2.8x10^{6}\ m/\sec$ is in good agreement with the design value of $2.9x10^{6}\ m/\sec$.

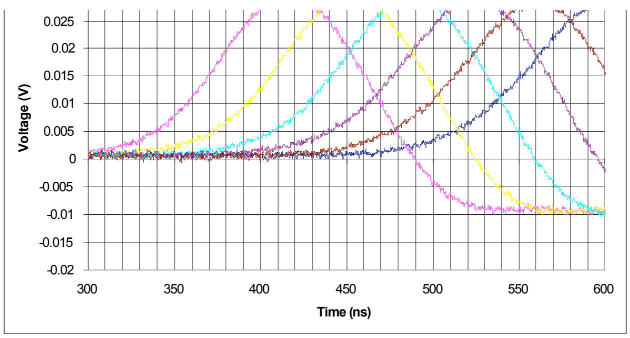


Fig. 8 B-dot loop signals at 10.16 cm intervals.

The oil helix pulse line was installed in the LBNL NDCX facility for the initial K+1 ion acceleration experiments (Fig. 9). The PLIA exhibited puzzling flashovers at relatively low voltages (less than 20 keV on the helix), so the ion acceleration tests were limited to gradients of around 150 keV/m for good shot-to-shot reproducibility. Even at these low levels, flashovers (light emission) on the interior of the beam tube insulator were observed, but the waveforms were reproducible. With optimal timing the ion energy increased from 350 keV to 500 keV passing through the PLIA. The details of the energy modulation and bunching as a function of the timing were in good agreement with beam dynamics modeling with the WARP3D simulation code [6]. It is noteworthy that the 150 keV ion energy increase was achieved with a 15 kV pulse applied to the 2 turn primary drive.

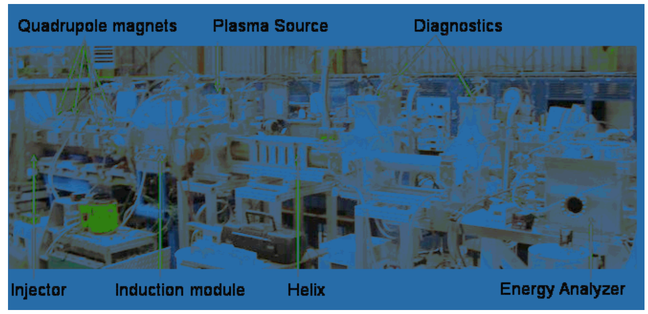


Fig. 9 PLIA installed in the LBNL NDCX facility

Experimental and theoretical efforts are currently focused on understanding the origin of the flashover that limits the helix voltage. One new helix configuration that will be tested has the helix wires protruding inside the vacuum dielectric barrier. Another configuration involves the insertion of shorting rings along the outside of the vaccum insulator to exclude the pulsed magnetic field. This test is motivated by the speculation that the pulsed magnetic field may help recycle secondary electrons back into the insulator.

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