Pulse Line Ion Accelerator for NDCX-II

C. Y. Ling[1], S. S. Yu[1,2], E. Henetroza[2], A. Friedman[3], W. L. Waldron[2], J. J. Barnard[3]
The Chinese University of Hong Kong
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory

Abstract

The Pulse Line Ion Accelerator (PLIA) (proposed by R. Briggs) produces a traveling EM wave by applying a voltage pulse to one end of a helix that accelerates and axially confines the heavy ion beam pulse. An anomalous flashover phenomenon has been observed on the vacuum-insulator surface which limits the amplitude of the accelerating field. It has been suspected that a small component of high frequency modes in the input pulse may be the cause of the breakdown. Simulation using MAFIA (MAxwell's equations by Finite Integration Algorithm) was conducted to investigate the fields on the insulator surface. A scaling law was proposed to reduce substantially the computational time in simulation. On the basis of these numerical simulations, we conclude that high frequency modes, even at very low amplitudes, may indeed lead to the observed insulator flashover.
Moreover, PLIA is a possible low-cost accelerator concept which prepares the heavy ion beam for the experiments of high energy density physics and warm dense matter. WARP was used to simulate the beam dynamics of PLIA and it shows that PLIA may accelerate the beam to meet the NDCX-II requirements by using relatively simple input voltage waveform.

Introduction

Basic Principle of PLIA

The pulse line ion accelerator (PLIA) provides a low-cost possibility to accelerate and confine heavy ion beams to regime of interests for the studies of high energy density physics and warm dense matter. A voltage pulse is applied to the front-end of PLIA and generates a traveling electromagnetic wave pulse moving down a helical structure.

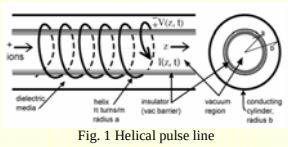


Fig. 1 Helical pulse line

The velocity of the wave pulse is determined by the impedance of the helix tube and the waveform of the pulse depends on the waveform of the applied voltage pulse. The ion beam can be accelerated and confined by specific waveforms and velocity of the wave pulse.

Scaled Helix Expt' and Insulator Breakdown

Figure2 shows the scaled PLIA used in experiments performed in Lawrence Berkeley National Laboratory. It shows a vacuum pumping on the right side while the direct drive high voltage feedthrough is on the left side. The dielectric oil is filled between the glass insulator and the tank. The length of the scaled PLIA is 51cm and the helix wire-spacing is 1.27mm.

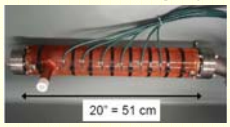


Fig. 2 The scaled helix used in the proof of principle test

A proof-of-principle test was done on PLIA successfully. But partial discharges were observed on the insulator surface for a relatively low input voltage (several tens kV) in further tests. 50MHz ringing was observed on the pulser output current and therefore high frequency modes in PLIA produced in the spark gap of the voltage pulser were suspected to be the cause of the anomalous flashover. The partial discharges result in distortion of the traveling EM field pattern. Simulation using MAFIA (MAxwell's equations by Finite Integration algorithm) was conducted to model scaled PLIA and to investigate the strength of the fields of high frequency modes on the insulator surface.

Simulation result

Simulation results indicate that there are high fields on insulator surface at high frequencies. High frequency components, even at very low amplitudes, MAY lead to insulator flashover.

MAFIA Simulation on Insulator Breakdown

PLIA model in simulation

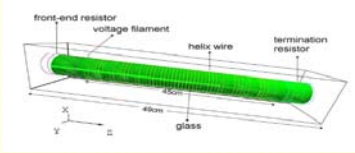


Fig. 3a Dimensions of PLIA model

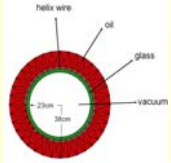


Fig. 3b Cross section of PLIA model

Figure 3a and b show the dimensions and the circuit of the scaled helix used in MAFIA. The helix wire connects between the front-end and termination resistive dividers and the voltage filament connects directly to the beginning of the helix wire. All the wires wind around the glass insulator. The inner radius of the glass insulator is 23cm and the radius of the tank is 38cm. The wire spacing of the scaled helix is 6.35mm, which is 5 times larger than the wire-spacing in the scaled helix experiment. Larger wire-spacing was used in simulation in order to model the PLIA in an efficient way. A scaling relation was proposed to compare the simulation results with experiment the measurements when they have different wire-spacings.

Scaling Law

For the sake of simulation efficiency, a scaling relation was proposed here to make the simulation faster. It is hypothesized for the scaling law that

if $\lambda_{\text{EM field}}$ is kept invariant, the EM field pattern should remain unchanged for different wire-spacings

Consistency check of the Scaling law

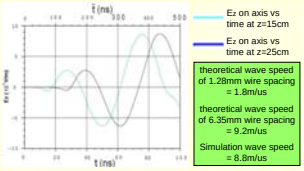


Fig. 4 Speed check after scaling

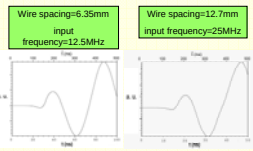


Fig. 5 Ez against time on axis at z=25cm for wire-spacings and frequencies differ by same factor

Result

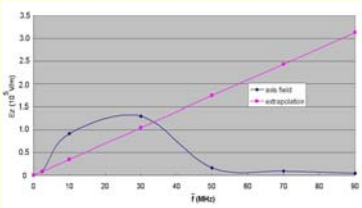
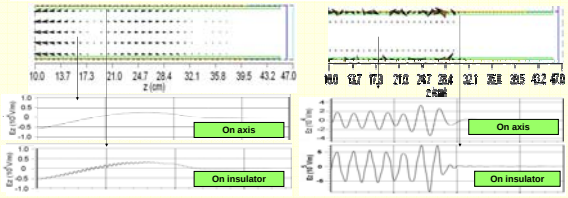


Fig. 6 Ez on axis and linear extrapolation from low frequency. When ka>>1 (k is the wave number and a is the pipe radius), the field on axis decreases with frequency due to the ka decaying in Bessel Function.



(a) $\tilde{f} = 2.5MHz$ (b) $\tilde{f} = 50MHz$

Fig. 7 Comparison of Ez on axis and on insulator surface for the case (a) ka<<1 and (b) ka>>1.

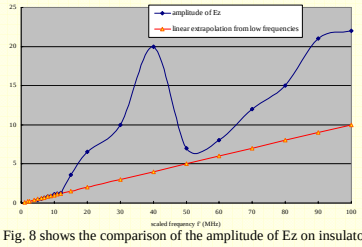


Fig. 8 Plot of amplitude of *Ez* on insulator surface against frequency $\tilde{f}$

Fig. 8 shows the comparison of the amplitude of Ez on insulator surface and the extrapolation from the low frequency data. Simulation shows that at low frequencies (ka << 1, where k is the wave number, and a the pipe radius) the field strengths on axis as well as on the insulator grow linearly with frequency. At high frequencies (ka >> 1), the field on axis nearly vanishes, while the field on the insulator continue to grow at a rate faster than linearly with frequency. At medium frequencies and above (ka >~ 1), we see clear signs of reflections from the terminating resistors, which are impedance matched only at low frequencies. These wave reflections, which are consistent with experimental observations, lead to further enhancements of the fields on the insulator surface.

NDCX-II design goals

Before the beam enters the Drift Compression Section, NDCX-II beam requires

Final beam energy = $2.8MeV$
Total charge = $30nC$
Normalized emittance = $0.48\pi - mm - rad$
$\delta p / p = 6\times10^{-4}$
$\delta v / v = 0.2$

The Basic Design Principle

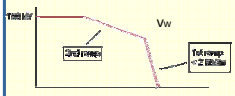


Fig. 9 The waveform used for the NDCX-II Design.

Strategy: Snowplow mode (The voltage waveform is faster than the beam and sweeps through it after the whole beam enters the PLIA tube) was used. The length of the 1st ramp is much less than the beam length and thus it has high gradient. The 2nd ramp is longer and has much gentle slope. The energy gain of the beam mainly comes from the 1st ramp. The 2nd ramp controls the expansion of the beam due to its intense space charge. Note that the gradient of the first ramp is limited to 2MV/m and the total voltage of the waveform is limited to 150kV.

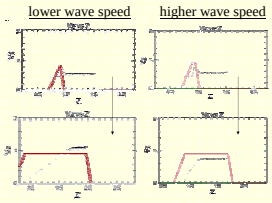


Fig. 10 Acceleration scenarios of the beam using wave with different speeds. Note that the lower the wave speed, the larger the energy gain.

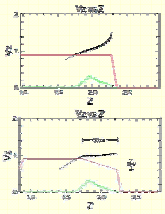


Fig. 11 The 2nd ramp cancels effectively the distortion of phase space of the beam due to space charge effect.

Beamline for Simulation

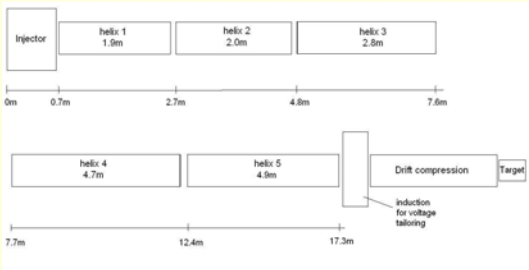


Fig. 12 Full Design for NDCX-II

Beam Dynamics: 3-D Simulation

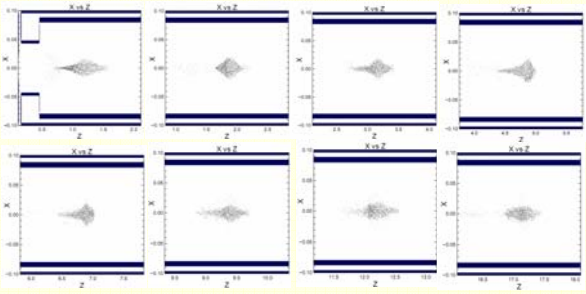
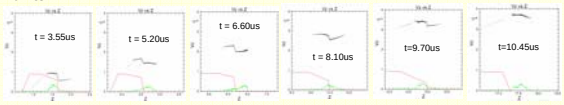


Fig. 13 Snapshots of the beam at different times



helix 1 helix 2 helix 3 helix 4 helix 5 the end of helix 5

Fig. 14 Phase Space of the beam at each helix and the final phase space with beam energy ~2.8MHz

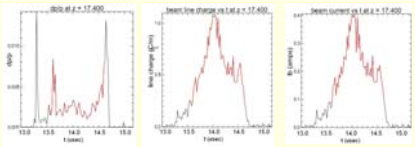


Fig. 15 Time-diagnostic before entering the Drift compression section

Finally, the beam has:
Energy ~2.8MeV
Total charge > 30nC
Normalized emittance ~ 1πmmrad
δv/v ~ 0.2