SIMULATION OF HIGH FREQUENCY MODES AND THEIR EFFECT ON INSULATOR BREAKDOWN IN THE PULSE LINE ION ACCELERATOR

C. Y. Ling[1], S. Yu[1,2], E. Henetroza[2]
1. *The Chinese University of Hong Kong*
2. *Lawrence Berkeley National Laboratory*

Abstract
The Pulse Line Ion Accelerator (PLIA) 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. It is based on the hypothesis that the pattern of 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. 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.

1. Introduction

The pulse line ion accelerator (PLIA) provides a low-cost option to accelerate and confine heavy ion beams to regimes of interest for the study 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. The velocity of the wave is determined by the impedance of the helix. The ion beam can be accelerated and longitudinally confined by a judicious choice of waveforms and wave velocities [1].

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 which corresponds to a low electric field of a few kV/cm. The partial discharges result in distortion of the traveling EM field pattern. 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 [2].

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.

2. Modeling in MAFIA

Figure 1 shows the scaled PLIA used in experiments performed in Lawrence Berkeley National Laboratory [2]. It shows vacuum pumping on the right side while the direct drive high voltage feedthrough is on the left side. Dielectric oil fills the region between the glass insulator and the tank. The length of the scaled PLIA is 51*cm* and the helix wire-spacing is *1.27mm*. All the wires wind around the glass insulator. The inner radius of the glass insulator is 23*cm* and the radius of the tank is 38*cm*.

In the scaled helix experiment, there were 6 capacitive pickups which measure the time derivative of the voltage at the corresponding positions. The output voltage at the termination resistive divider was also monitored.

Figure 2 and figure 3 show the geometry and dimensions of the scaled helix used in MAFIA. The helix wire connects between the front-end and the termination resistive dividers and the voltage filament connects directly to the beginning of the helix wire.

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 the simulation in order to model the PLIA in an efficient way. A scaling relation was proposed to compare the simulation results with experimental measurements when they have different wire-spacings. The details will be discussed in the next section.

Sensitivity tests on time steps and grid sizes were performed (Fig. 5-8). The sizes of the time steps and the grids satisfy the Courant condition. The waveform of the input voltage applied to the voltage pulser was shown in Figure 4.

Fig. 5 and Fig. 6 show that grid-size *1/4* of the

wire spacing gave a converging result. The same conclusion could be made with the high frequency voltage input (see Fig. 7 and Fig. 8).

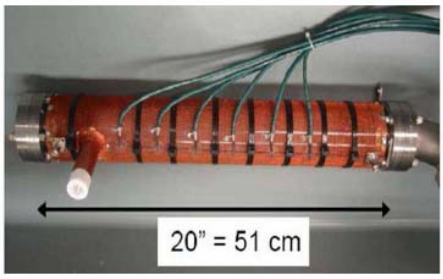

Figure 1: The scaled helix.

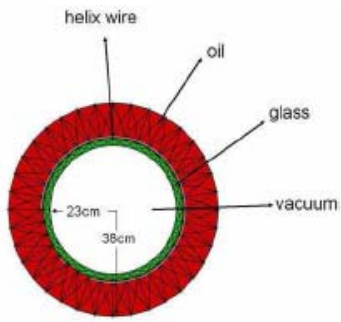

Figure 2: Cross section of PLIA model.

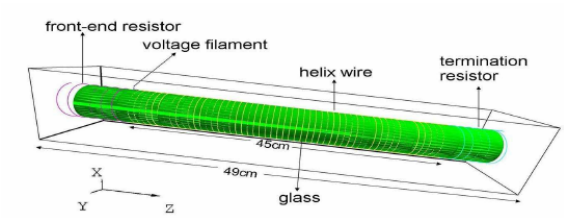

Figure 3: Dimensions of PLIA model.

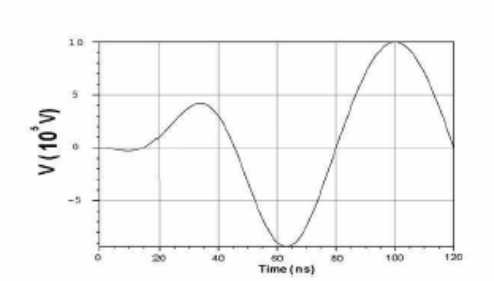

Figure 4: Input voltage for sensitivity tests.

3. Scaling Law

As mentioned in the previous section, larger wire-spacing was used in the simulation for the sake of efficient computation. In the experiment, the wire-spacing of the scaled helix was 1.25*mm*. By the sensitivity tests above, it can be estimated that convergent results required the grid-size to be *1/4* of the wire-spacing. In order for the size of the time-step to satisfy the Courant condition, it has to be less than 0.6*ps*. The typical time scale for such PLIA is several hundreds *ns*. The size of time-step and grid requires unreasonably long computational time. Therefore a scaling relation is proposed here to make the simulation faster.

Consistency checks on the proposed scaling

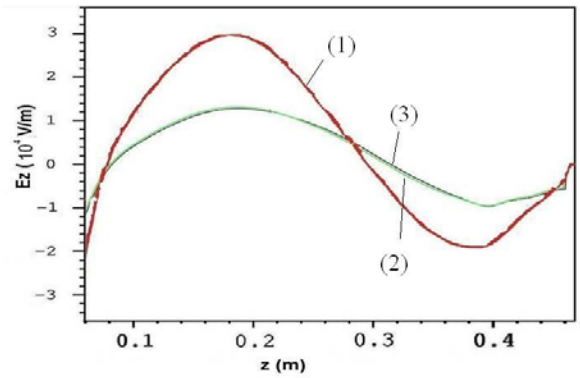

Figure 5: Sensitivity test for **low** frequency input: Snapshot of *Ez* **on axis** at *t=80ns* for grid sizes *4/5*(1), *2/5*(2) and *1/4*(3) of the wire-spacing.

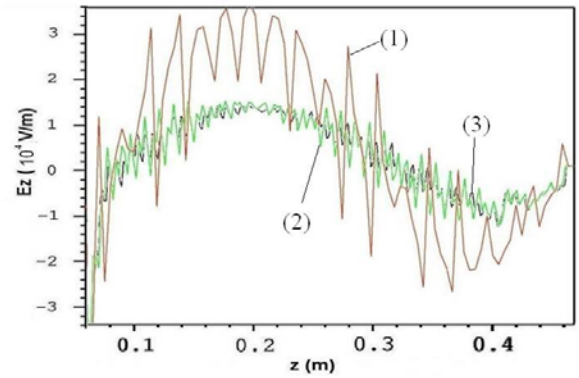

Figure 6: Sensitivity test for **low** frequency input: Snapshot of *Ez* **on insulator surface** at *t=80ns* for grid sizes *4/5*(1), *2/5*(2) and *1/4*(3) of the wire-spacing.

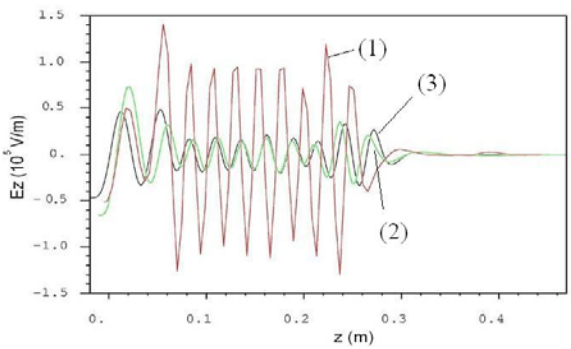

Figure 7: Sensitivity test for **high** frequency input: Snapshot of *Ez* **on axis** at *t=40ns* for grid sizes *4/5*(1), *2/5*(2) and *1/4*(3) of the wire-spacing.

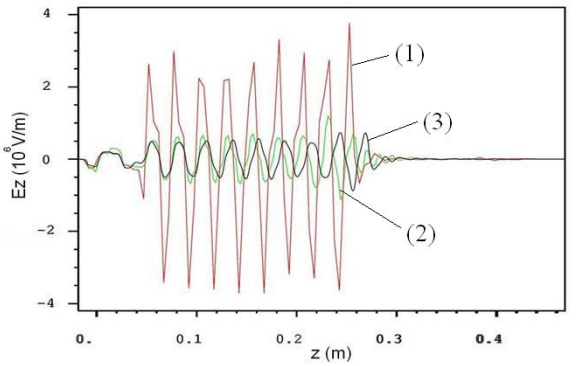

Figure 8: Sensitivity test for **high** frequency input: Snapshot of *Ez* **on insulator surface** at *t=40ns* for grid sizes *4/5*(1), *2/5*(2) and *1/4*(3) of the wire-spacing.

relation were performed. It is hypothesized that *if* $\lambda_{EM\ field}$ *is kept invariant, the EM field pattern would remain unchanged for different wire-spacings*, provided that 1. $\lambda_{EM\ field} >> d_{wire}$ and 2. termination resistors are changed to maintain the impedance matching. So the working principle of the scaling law is "*Simulation should be compared to data at the same wavelength of electric and magnetic field* $\lambda_{EM\ field}$ *inside the PLIA.*

We introduce a scaled time $\tilde{t}$ and scaled frequency $\tilde{f}$ which are related to the time t_{sim} and frequency f_{sim} used in the simulation.

$$\tilde{t} = t_{sim}\frac{v_{sim}}{v_{\exp}}$$

$$\tilde{f} = f_{sim}\frac{v_{\exp}}{v_{sim}} \qquad (1)$$

The scaled parameters $\tilde{t}$ and $\tilde{f}$ are used when comparing simulation to experiment. Note that v_{sim} and v_{exp} are the velocity of the traveling EM field in the PLIA in the simulation and experiment respectively. They are directly proportional to the wire-spacing of the helix [1] and are constant along the PLIA if the dispersion of the traveling wave is ignored. By increasing the wire-spacing of helix in the simulation, larger grid-size (and hence larger time-step) could be used. However, the velocity of the traveling EM waveform is increased with larger wire spacing, and so t_{sim} should be decreased by a factor of v_{exp}/v_{sim}. At the same time the f_{sim} has to be increased by the same factor.

The wire-spacing used in the simulation for the investigation of the anomalous flashover was 5 times larger than those in the real experiment, that is, 6.35*mm*. For condition 1 to be satisfied, $\tilde{f}$ should be less than *300MHz*.

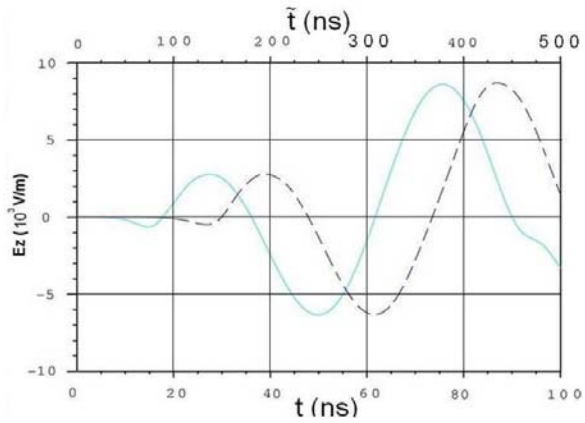

Figure 9: *Ez* on axis versus time at *z=15cm* (solid line) and *z=25cm* (dotted line), the speed of wave measured from this graph is *8.8m/µs.*

Consistency tests were performed for this scaling law. First of all, the voltage wave speed was checked in the simulation. For 6.35*mm* wire spacing, the theoretical wave speed is 9.2*m/µs* while it was measured to be 8.8*m/µs* in simulation (Fig. 9). Secondly the waveform of electric field was also compared in the simulation using different scaling factors (Fig. 10). The result is also consistent with the scaling law

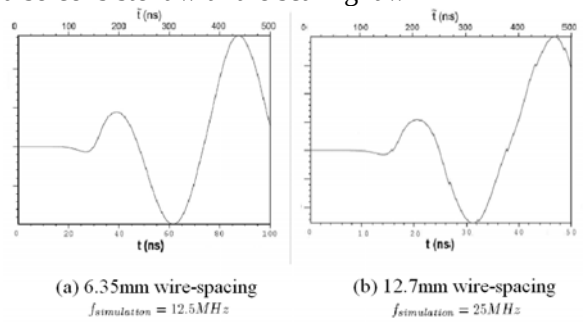

Figure 10: Consistency test of scaling law with different wire-spacings, *Ez* on axis versus time at *z*=25*cm* with arbitrary unit.

4. Investigation of different frequency modes near insulator surface

The ratio of *Ez* on axis and on insulator surface differs from low and high frequency. Figure 11 shows that the amplitude of *Ez* on axis is similar to those on insulator surface for the frequemcy in the range of *ka<<1*, where *k* is the wave number and *a* is the helix radius. However, when the frequency is high (*ka>>1*), the amplitude of *Ez* on insulator surface is much higher those on axis, as shown in Figure 12. This can be explained by the

ka decay of the Bessel function [1].

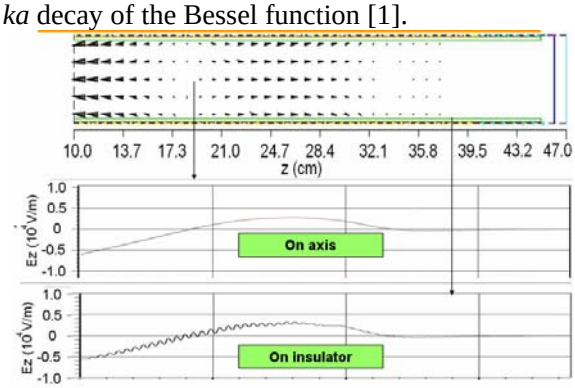

Figure 11: The vector plot of the electric field inside the PLIA tube and the comparison of *Ez* on axis and on insulator surface for $\tilde{f} = 2.5MHz$ (***ka<<1***). The amplitudes of the *Ez* are similar on axis and on insulator surface.

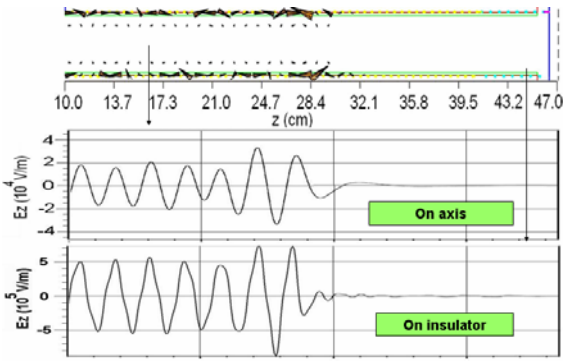

Figure 12: The vector plot of the electric field inside the PLIA tube and the comparison of *Ez* on axis and on insulator surface for $\tilde{f} = 50MHz$ (***ka>>1***). The ratio of amplitude of *Ez* on axis and on insulator is around 1:50.

The amplitude of *Ez* **on axis** was plotted against frequency as shown in figure 13. At low frequency, it is expected theoretically that the amplitude of *Ez* is linear with frequency. Therefore the on-axis field was compared to its extrapolation for different frequencies. Result shows that the electric field on axis is much stronger than the extrapolation at intermediate frequency (*ka~1*). The enhancement of the field at intermediate frequency can be explained by the mismatch of the termination resistive divider with the impedance, which is matched only at low frequencies. This mismatch leads in turn to the reflection of the voltage wave and associated standing wave patterns. At high frequencies, the on-axis field decays, as mentioned previously, and the decay rate is consistent with Bessel function arguments.

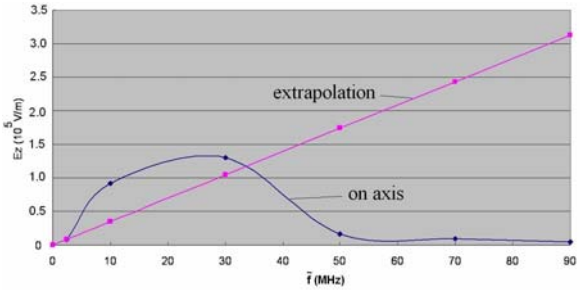

Figure 13: The amplitude of *Ez* **on axis** and its extrapolation from low frequency versus frequency.

Figure 14 shows the frequency dependence of the frequency, as shown in the graph, the amplitude grows linearly with the frequency. Afterwards the field increases with frequency, at a rate that is somewhat faster than the linear extrapolation. It is evident that high frequency modes can indeed generate high electric fields on the insulator surface.

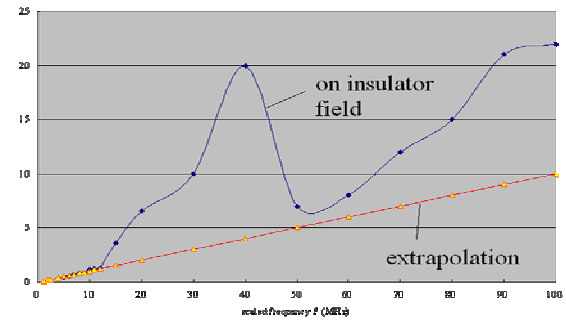

Figure 14: The amplitude of *Ez* **on insulator surface** and its extrapolation from low frequency versus frequency.

5. Conclusion:

The proposed scaling law made the simulation of scaled PLIA more efficient. Simulation results show that the high frequency modes, even at very low amplitudes, generate high field and may lead to the observed insulator flashover. The theoretical predictions must of course be confirmed experimentally, and an ensuing campaign to suppress the high frequency modes will hopefully lead to the elimination of the observed anomalous flashover.

References

[1] R. J. Briggs, "Pulse Line Ion Accelerator Concept," PRST-AB 9, 060401 (2006).

[2] W.Waldron et al., in Proceedings of the 2007 Particle Accelerator Conference, 2007, p. 852.