INJECTOR PARTICLE SIMULATION AND BEAM TRANSPORT IN A COMPACT LINEAR PROTON ACCELERATOR *+

D.T Blackfield#, Y-J Chen, J.R. Harris, S.D. Nelson, A. Paul, B. Poole, LLNL, Livermore, CA 94551, U.S.A.

Abstract

A compact Dielectric Wall Accelerator (DWA)[1,2,3], with field gradient up to 100 MW/m is being developed to acclerate proton bunches for use in cancer therapy treatment. The injector must create a proton pulse up to several hundred picoseconds, which is then shaped and accelerated with energies up to 250 MeV. The Particle-In-Cell (PIC) code LSP is used to model several aspects of this design. First, we use LSP to obtain the voltage waveform in the A-K gap that will produce a proton bunch with the requisite charge. We then model pulse compression and shaping in the section between the A-K gap and the DWA. We finally use LSP to model the beam transport through the DWA.

PROTON INJECTOR

A conceptual compact proton dielectric wall accelerator (DWA) configuration has been designed[1] for cancer therapy. We use the PIC code LSP[4] to model the injector and accelerator regions. We model an azimuthally symmetric injector, 18 cm in length and 5 cm in radius. Figure 1 shows the 2-D geometry (r,z) that LSP uses for the proton injector section. We will examine scenarios using three different voltage waveforms launched from the emission gap radial boundary (A). The anode surface (S) is shaped so that the path lengths on either side of the channel, where the voltage pulse propagates, are nearly equal to reduce reflections.

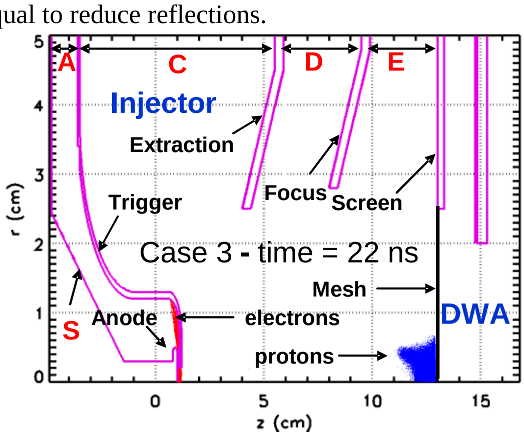

Figure 1: LSP model of the injector. The DWA begins beyond the metal mesh located at z=13.1 cm.

In the injector the smallest gap of 1.0 mm occurs between the anode surface and the trigger electrode. This small gap, shown in figure 2, and the assumed radius of particle emission of 1.0 mm on the anode surface restricts the LSP grid to 0.1 mm x 0.1 mm with a resulting time step of 0.2 ps. A metallic mesh, that shorts out the electric field while allowing particles to pass through without loss is located at z = 1.2 cm. We assume that both protons and electrons are created on a flat anode surface at z = 1.0 cm with Child-Langmuir emission. Additional voltage pulses are launched at the radial boundary between the trigger and extraction electrodes (C), extraction and focus electrodes (D) and focus and screen electrodes (E). These time-varying voltages shape and compress the proton bunch that leaves the emission gap. A similar lossless metallic mesh, is located at z=13.1 cm, the entrance to the DWA. The LSP particle data is collected at this location to be used when LSP simulates the beam dynamics of the DWA.

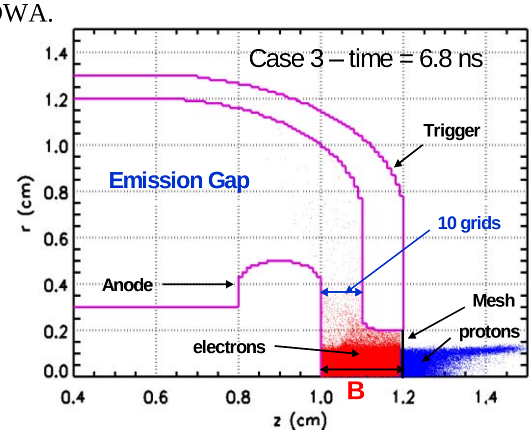

Figure 2: LSP model of the emission gap showing electrons cannot travel beyond the mesh.

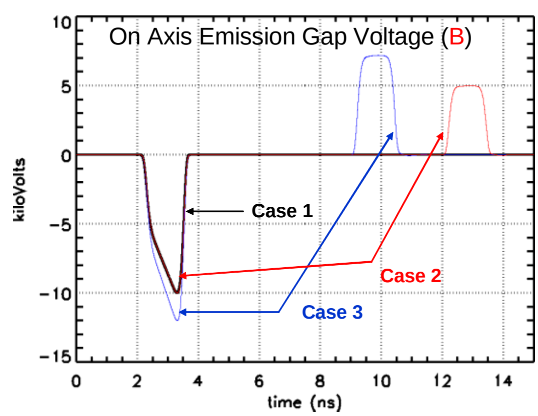

Figure 3: Voltages (kV) on axis in the emission gap (B).

Figure 3 shows the on axis voltages in the emission gap for three cases. For case 1 a single voltage pulse creates protons and propels them through the emission gap region. After 7.4 ns of emission, there is 96 pC in this proton beam. For Cases 2 and 3 an additional pulse with opposite polarity is used. In Case 2, the first voltage peak

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#blackfield1@llnl.gov

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is followed 6.0 ns later by a pulse with magnitude ½ the value of the first peak, resulting in a proton bunch of 67 pC reaching the DWA entrance. For case 3, by increasing the peak voltages and decreasing the time between pulses to 4.25 ns, 68 pC reaches the DWA entrance. All three cases use the same voltage ramps on the trigger, extraction, focus and screen electrodes.

When the anode emitting surface first sees a positive electric field, protons are pulled from the surface. However, once protons occupy the emission gap, electrons are emitted from the anode surface. These electrons cannot travel beyond the mesh at 1.2 cm due to the presence of a large repelling electric field produced by the voltage difference between the trigger and extraction electrodes. Figures 1-2 show these trapped electrons at t=6.8 ns and 22.0 ns for Case 3. Although electrons travel up the channel to the boundary (A) most remain in the emission gap. These gap electrons continue to pull protons from the anode surface well after the external voltage pulse has dissipated. In case 1, with only the single voltage pulse, a large proton tail is produced, with 29 pC of charge being contained in the tail. In cases 2 and 3, a second pulse, with opposite polarity, is used to prevent the formation of this proton tail. In case 3, higher voltage peaks are supplied, closer in time to produce a similar amount of charge within a shorter beam bunch.

The total proton flux at the metal mesh for each of the cases is shown in figure 4. Notice the absence of a tail for Case 2 and 3. The amount of charge and the initial bunch length can be modified by varying the two pulse heights and interval.

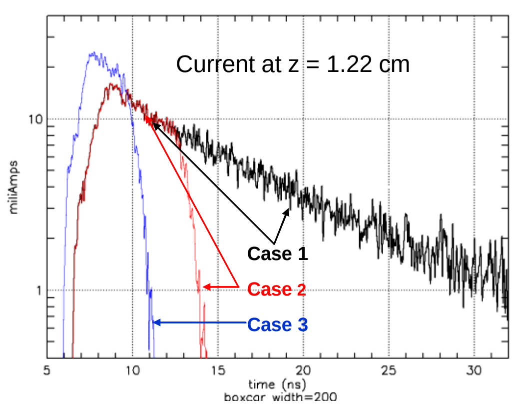

Figure 4: Total current just beyond the metal mesh.

We next follow those protons that travel beyond the metal mesh located at z=1.2 cm. The time-averaged voltages between the remaining sets of electrodes in the injector region are set to focus the beam towards the end of the DWA[1]. The electrode voltages are ramped linearly about these values so that the beam will be longitudinally compressed. The C voltage difference begins at -610kV. At 5 ns it takes 11 ns to ramp to its final value of -1190 kV. The D voltage difference starts at 1190 kV. After 10 ns it takes 9 ns to ramp to its final value of 610 kV. The E voltage difference starts at -610 kV. After 16 ns it ramps, using 7 ns, to its final value of -1050 kV. These linear ramps over compress the beam with later emitted protons passing earlier ones around 16.7 ns at a z location near 8.6 cm. Further refinements in electrode shapes and placements will improver both the beam bunch compression and focus. Despite being overly compressed, comparison between figures 4 and 5 show that the beam pulse width has greatly decreased.

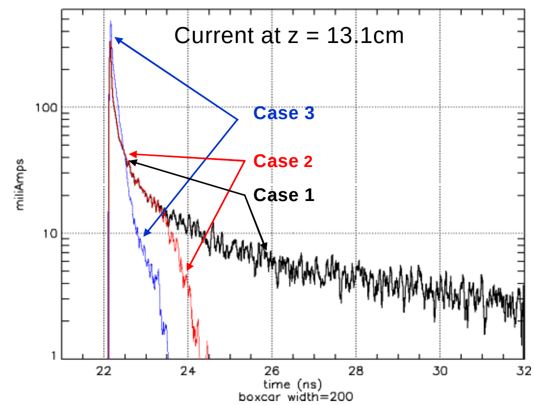

Figure 5: Total current at the end of the injector region

For case 3, the beam pulse has decreased from 5 ns to less than 2 ns with most of the current within 300 ps. The beam energy at the end of the injector for Cases 1 and 2 is the same, the beam energy rising slowly from 890 to 995 keV. For Case 3, the beam energy is fairly uniform, varying from 870 to 890 keV. For the tail in Case 1, the energy rises from 995 keV to 1500 keV over a 5 ns interval before leveling off around 1570 keV. We now follow the 300 ps beam bunch from Case 3 through a subscale prototype DWA.

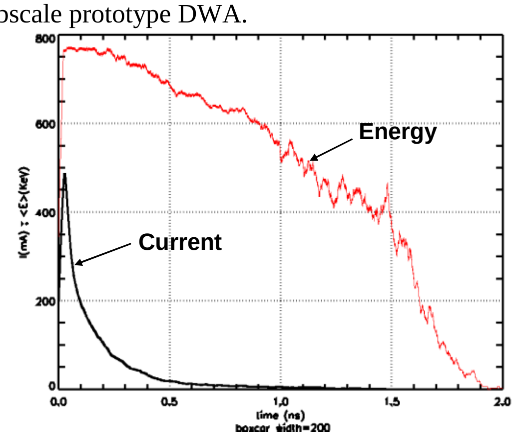

Figure: 6 Injected proton current (mA) and averaged energy (keV) from Case 3.

PROTON ACCELERATOR

Our most recent simulations involve a subscale prototype DWA. We expect this machine to achieve field gradients similar to the full scale DWA but will be only 40 cm long. For these simulations we use an azimuthally symmetric LSP model of a set of stacked radial transmission lines. The model begins with a conducting boundary representing the mesh at the end of the injector. Beyond this boundary, the DWA is represented as 100 sets of 0.2 mm thick electrodes, each set separated by 3.8 mm. The radial boundary is at 3.0 cm with a wall radius at 2.0

cm. Finally there is a conducting, boundary at z=40.4 cm. We inject the 68 pC of protons with the radial positions and velocities that LSP collected on a plane at the end of the injector, at z=13.1 cm. The current and energy of this bunch are shown in figure 6.

The shapes and timing of each pulse launched from the 100 boundary inlets are obtained from XFTD[2]. With the inlets only 4 mm wide, even small timing changes can have a great impact on the beam dynamics since the EM fields generated in many adjacent lines overlap within the beam tube. Besides the timing between the voltage pulses, the time when the bunch enters the DWA also has a large impact on beam dynamics. We present two scenarios (Case 4 and 5) where identical pulse timings are used, but the time when the bunch enters the DWA differs by 0.8 ns. The timing between the bunch and the on axis E_z 2 mm beyond the start and 2 mm before the DWA exit for these cases are shown in figures 7 and 8.

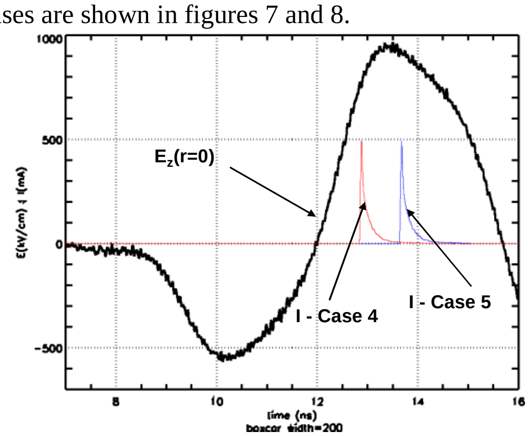

Figure 7: E_z (kV/cm) on axis and current (mA) 2.0 mm beyond the DWA entrance.

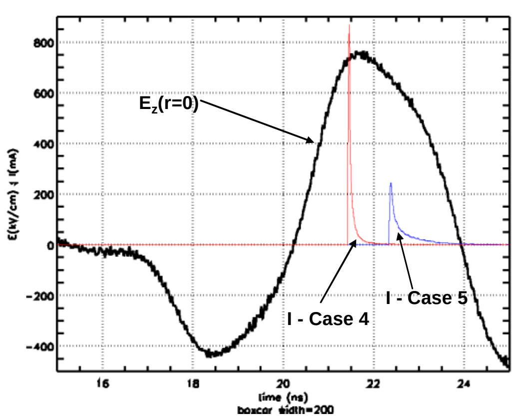

Figure 8: E_z (kV/cm) on axis and current (mA) 2.0 mm before the DWA exit.

The beam may either compress or expand longitudinally depending upon the time the bunch enters the DWA. In Case 4, the protons longitudinally compress but radially expand as they transport through the DWA. For Case 5, the bunch is lengthened but radially it focuses as it travels through the DWA. While these cases have similar beam energies, figure 9 shows that Case 4 has a shorter beam bunch.

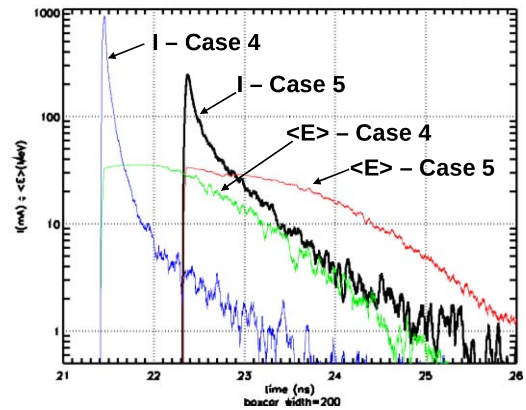

Figure 9: Current (mA) and energy (MeV) 2.0 mm before the subscale DWA exit.

We have simulated the transport of 300 ps proton bunches, with uniform density, radius of 1.0 cm and an initial energy of 1.0 MeV through a 250 cm long full scale DWA[5] using identically shaped boundary voltage pulses in all the lines from XFTD simulations. A bunch charge of 80 pC was injected 1 cm beyond the end of the injector. At the end of the DWA, the beam energy varied slightly, from 256 to 257 MeV and while no longer uniform in density, the beam pulse had shortened to 150 ps

CONCLUSION

In this paper we have demonstrated that we can adjust the bunch charge by varying the magnitudes and the timing between the two emission gap pulses while also eliminating the electron produced ion tail. We can compress and focus this bunch by changing the injector electrodes voltages and ramps. Besides transporting a 68 pC proton bunch from the injector through the subscale DWA without beam loss, we can adjust the bunch shape by varying the DWA voltage pulse timing. By adjusting the timing between pulses and the time when the protons enters the DWA we should be able to longitudinally and radially compress the bunch as it transports through the DWA. The energy spread at the DWA exit will be at most a few percent. We expect that further simulations will produce a shorter more tightly focused beam bunch.

REFERENCES

[1] Y-J Chen, A.C. Paul, “Compact Proton Accelerator for Cancer Therapy”, these proceedings.

[2] B.R. Poole, D.T Blackfield, S.D. Nelson, “Particle Simulations of a Linear Proton Dielectric Wall Accelerator”, these proceedings

[3] G.J. Caporaso, et al., “High Gradient Induction Accelerator”, these proceedings

[4] LSP is a software product Copyright (C) 1997-2005 Mission Research Corporation

[5] G.J. Caporaso, S. Sampayan, Y-J Chen, et al., private communications

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