Designing the Matching Section using Electrostatic Quadrupoles in a Compact Linear Accelerator

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ABSTRACT

In our group we designed a compact linear accelerator that uses radio frequency acceleration units and electrostatic focusing elements (ESQ). A matching section is being designed to avoid the loss of beam current between the ion source and the acceleration section. Optimizing the transport from the source to the acceleration section is also known as matching the beam to the acceleration section. We simulate the optimization of this section by developing a Python program and using an existing Java program, and solving the Kapchinsky-Vladimirsky (KV) equations that describes the radial evolution of the beam profile. Following these computationally inexpensive tests, a more rigorous analysis is done using simulations in WARP, a Particle-in-Cell framework. Results presented here include matching sections designed with the Python and Java programs, as well as simulations of these designs for emittance or perveance dominated beams. The results are then compared to full 3D-Warp simulations of the same design. Anticipated results will be presenting a comprehensive comparison of different designs with the known beam parameters for existing ESQ geometries. Future improvements involve comparing all results in a single graph and implementing an interactive user interface that allows easy exploration of the parameter space. Future work will verify the simulation results experimentally, as well as performing tests on wafers to determine breakdown voltage to determine the maximum allowable ESQ voltage.

BACKGROUND AND RESEARCH GOALS

- Multiple Electrostatic Quadrupole Array Linear Accelerator (MEQALAC) uses RF acceleration and focusing elements called electrostatic quadrupoles (ESQs).
- Kapckinsky-Vladimirsky (KV) differential equations to estimate the beam behaviour along the length of the accelerator.
- Goal of the group is to develop a 100 keV, 1 mA multi-beam linear accelerator prototype.
- Project goal is designing the matching section to transform the beam from the initial conditions to a matched beam solution to decrease beam loss

METHODS OF SIMULATION

Fast 1D Simulations:
Python and Java
- Optimize the beam envelope, with an interactive user interface

3D Simulation:
WARP
- Verifying KV equation results

ACCELERATOR AND BEAM PARAMETERS

- Source Temperature: 0.5-2eV
- Beam energy: 7-10keV
- Emittance: 1.58E-5 m-rad (unnormalized)
- Beamlet current: 10 µA

Pre Matching
- Last grounded aperture: 1 mm radius
- Diverging angle: 30 mrad

Pre Accelerator
- Extraction aperture: 0.25 mm radius
- Diverging angle: oscillating at ~ 5/-5 mrad

Matching
- Transforming beam from cylindrically symmetric to matched beam conditions, converging in one plane and diverging in the other

MATCHING SECTION DESIGN

- Beam limited by physical aperture of 0.55mm radius
- Ideal to have small amplitude oscillations
- Limit is the breakdown voltage of the ESQs (~500V)
- Distance between wafers = 0.3-1mm
- Aiming for matching section be 20% of the length of the accelerator

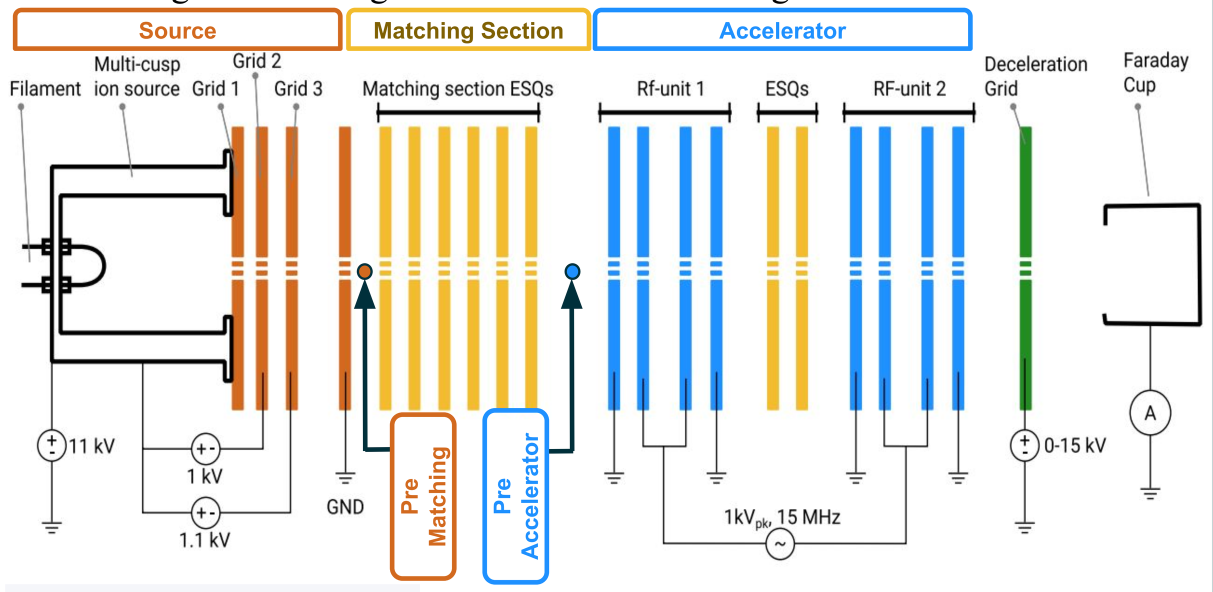
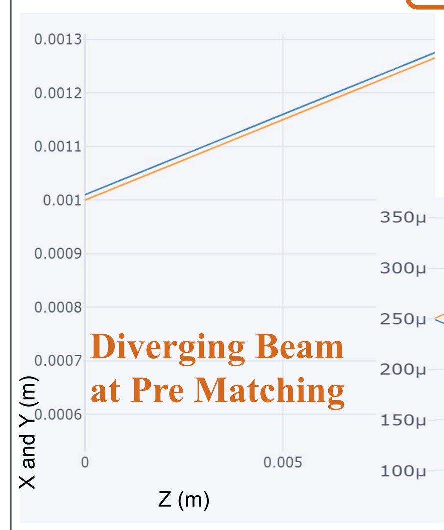


Figure 1: Overview of Accelerator Schematic



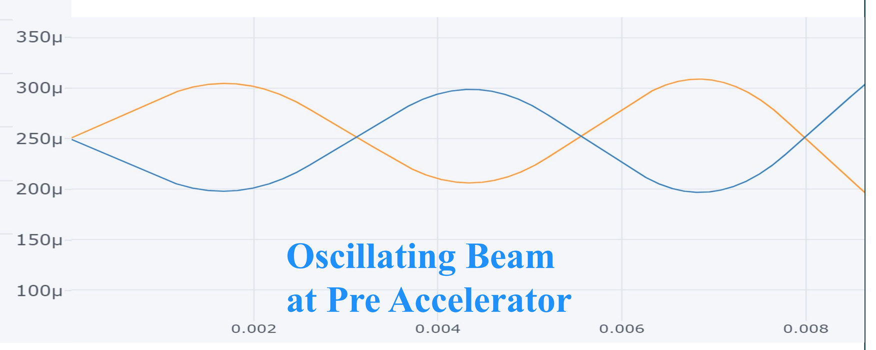


Figure 2: Diverging beam **Figure 3:** Oscillating beam

ESQ WAFER PARAMETERS

- ESQ thickness in Z direction = 1.59mm
- Electrode diameter = 1.3mm
- Aperture diameter = 1.1mm

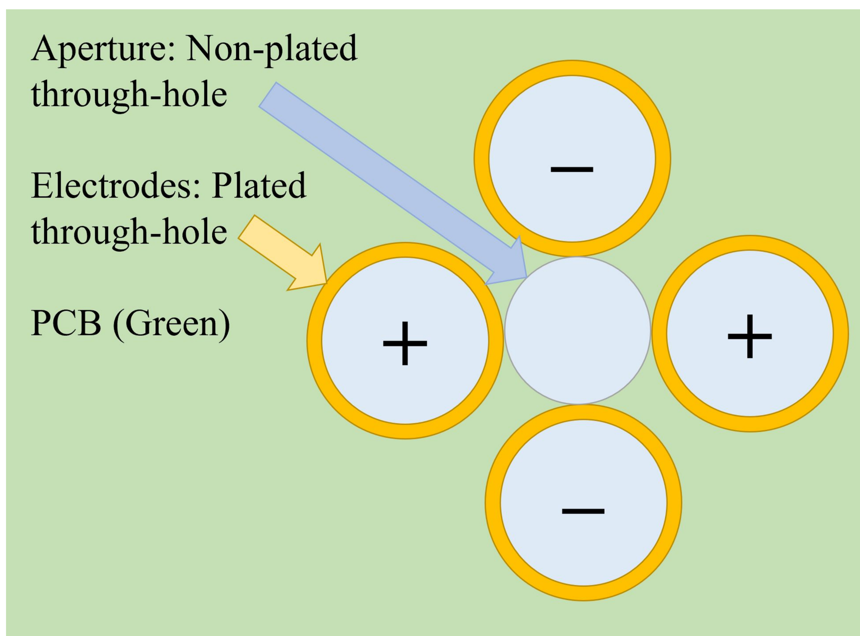


Figure 4: Oscillating beam

RESULTS

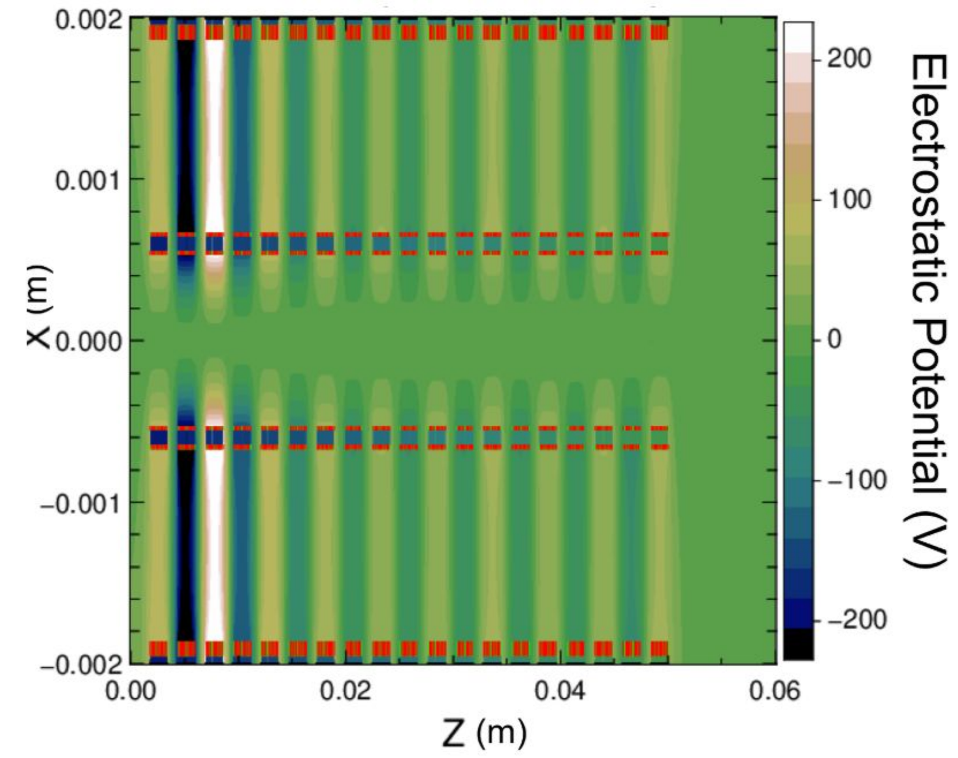


Figure 5: Electrostatic Potential in Z-X Plane

Table 1: Voltages and Center Positions of ESQs for Matched Solution from WARP

ESQ Wafer #	1	2	3	4	5	6	7	8	9	10
Voltage (V)	90.9	-227.3	227.3	-14.9	90.9	-72.7	63.6	-54.5	54.5	54.5
Position (mm)	2.59	5.18	7.77	10.36	12.95	15.54	18.13	20.72	23.31	25.9

ESQ Wafer #	11	12	13	14	15	16	17	18	19
Voltage (V)	50	-54.5	59.1	-54.5	50	-50	54.5	-59.1	59.1
Position (mm)	28.49	31.08	33.67	36.26	38.85	41.44	44.03	46.62	49.21

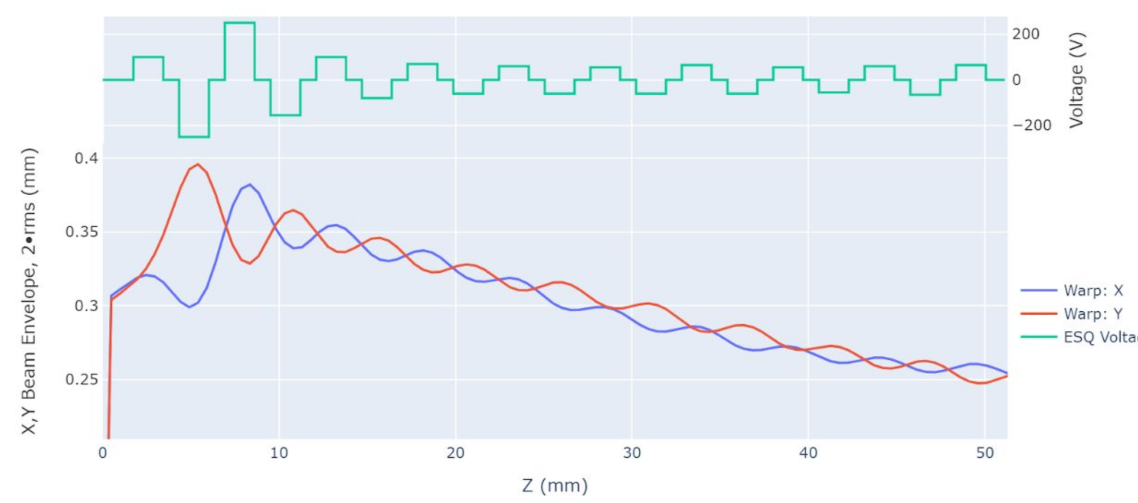


Figure 6: Beam Envelope (2•rms)

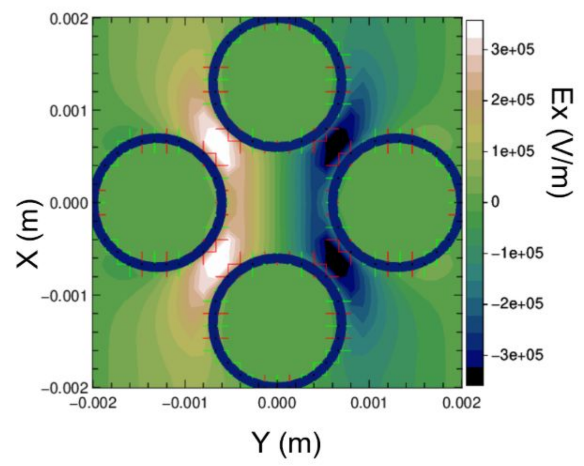


Figure 7: Electric Field (x component) at ESQ1

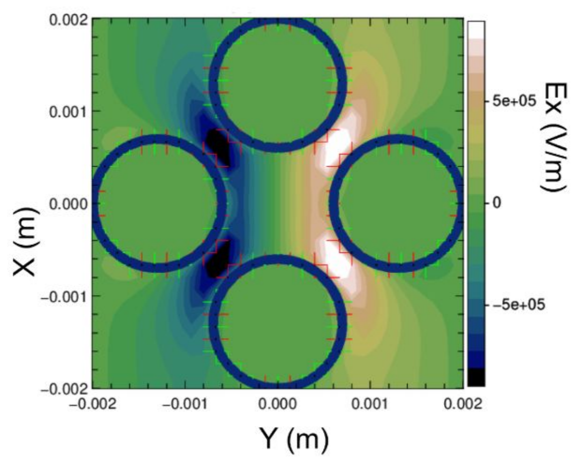


Figure 8: Electric Field (x component) at ESQ2

DISCUSSION

Differences between KV Equations (Python and Java) and WARP:
- KV equations assume hard edge fields, and no particles lost
- WARP more realistic representation, non-uniform fields and edge effects

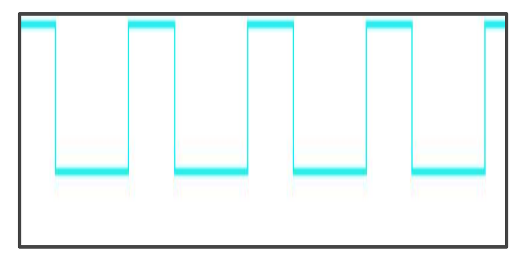


Figure 9: Hard edge fields with KV equations

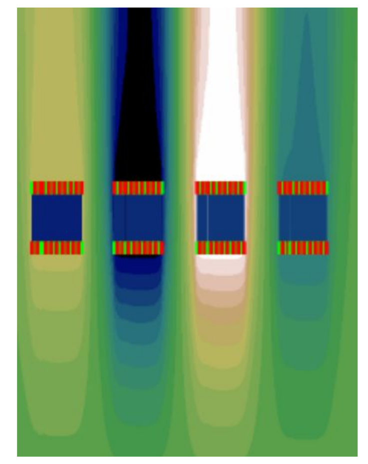


Figure 10: Edge effects in WARP

WARP geometry implementation, new ESQ singlet

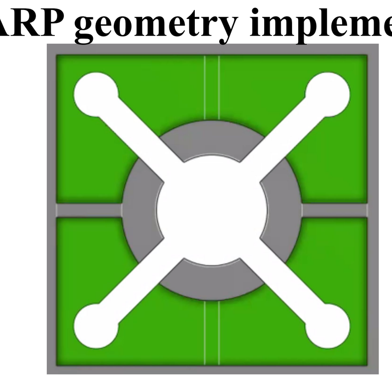


Figure 11: Original Geometry

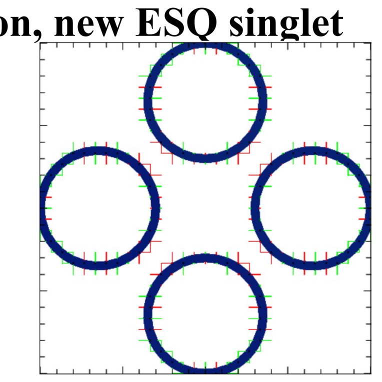


Figure 12: New Singlet Geometry

FUTURE WORK

Further Improvements
- Interactive interface for Python simulation using matplotlib, plotly, or streamlit.io
- Adapting Kapchinsky ENVelope (KENV) project to work with ion beams

Future experimental tests
- Confirming simulations
  - Add ESQs and test with actual accelerator to verify if simulation works. If the current increased then can assume the solution is an improvement
  - Use a knife edge scan to examine the beam profile
- Testing breakdown voltage of new ESQ wafers
  - Put wafer in vacuum and and increase voltage until breakdown occurs

CONCLUSION

- ESQs used for matching beam from source to accelerator
- Simulations using Python, Java, and WARP
- Resulting solution for matching section
  - ESQ voltages and positions
- Future experiments to confirm simulations

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ATAP ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

Poster Summary

My project was on a linear accelerator for positive ions, which has applications in medical devices, electronics manufacturing, and nuclear systems. The prototype for this project is a compact accelerator, meaning everything is scaled down so it can be cheaper and easier to build and test.

What I did was work on the matching section, which is between the plasma ion source and the accelerator section. This uses focusing elements called electrostatic quadrupoles or (ESQs).
The purpose of the matching section is to transform the beam to the desired conditions, and reduce the loss of particles from the diverging beam.
The beam from the source is diverging, and the beam going into the accelerator section needs to have a smaller radius, and needs to be oscillating.

I have been modeling the beam focusing using 1D simulations with Python and Java, as well as 3D simulations with a Particle in cell code called WARP.

The results include plots of electrostatic potential from the quadrupoles. The ESQs voltages and positions to a matched beam solution that I found are shown in the table here.The electric fields at the first and second ESQs indicate how the polarity is inverted, focusing the beam in one direction and defocusing in the other.

Future work can be done to experimentally confirm the results of these simulations.