DEVELOPMENT OF A 500 KEV STANDING WAVE LINEAR ACCELERATOR FOR A TRANSMISSION ELECTRON MICROSCOPE

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Abstract

This paper demonstrates the versatility of using advanced 3D electromagnetic and particle dynamics simulation software for designing a 500keV side coupled standing wave linear accelerator, decelerator and RF chopper as part of a novel high energy transmission electron microscope (TEM). Side coupled accelerators require full 3D electromagnetic simulation. We show the optimization of single accelerator sections, the fine tuning of the field distribution along the beam axis and the calculation of beam dynamics. A simulation of different RF chopper designs shows the advantage of using the electric field for beam deflection instead of the commonly used magnetic field. A 500kV TEM has been successfully built and tested.

INTRODUCTION

High energy TEMs are an important tool commonly used in the life sciences since they allow observing thick samples with nanometer resolution. These machines typically use high voltage DC accelerators which have excellent beam stability but also drive up weight, size and cost. TEMs with beam energies of 500keV commonly exceed $10M and can weight over 10 tons. Using a standing wave linear accelerator reduces the cost substantially but great care must be taken to meet the stringent beam stability and emittance requirements needed for TEM. Therefore the new system replaces the photo cathode with an electron gun that emits 100keV electrons, a linear accelerator then increases the energy to 500keV while a 250 femtosecond RF chopper limits the energy spread to $\Delta E/E \leq 10^{-5}$. After passing the sample a decelerator decreases the energy to 200keV to protect the sensor chip. The accelerator, decelerator and RF-chopper are designed using state of the art 3D electromagnetic and particle dynamics simulation software from CST [1]. CST software is based on the Finite Integration Technique (FIT) [2] and calculates 3D electromagnetic fields in time and frequency domain on hexahedral and tetrahedral meshes. Simulation accuracy is greatly improved by the Perfect Boundary Approximation technique (PBA) [3] for hexahedral meshes and second order curved elements for tetrahedral meshes. A wide range of built in optimizers enables to meet design specifications with minimum effort.

SINGLE SECTION OPTIMIZATION

We use an S-band, side coupled standing wave accelerator to replace the static accelerator. The speed of the electrons along the accelerator changes from 0.55c to 0.86c forcing the accelerator to be non-uniform along the beam axis. To achieve the desired beam properties we first treat the single sections of the accelerator independently. A single section as shown in Figure 1 may be terminated with electric or periodic boundaries. We optimize the coupling slot lengths and nose gaps in the accelerator cavities and the nose gap in coupling cavity for each section. The goal is to obtain the desired E-field ratio in the accelerator cavities and remove fields from the coupling cavity while maintaining the π/2 mode frequency and dispersion. The optimization is performed with the Eigenmode Solver of CST Microwave Studio [1] on a second order curved tetrahedral mesh.

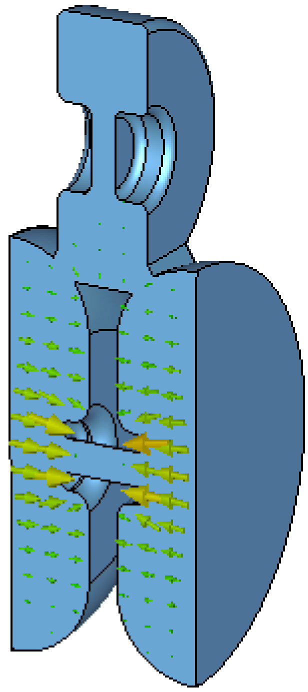

Figure 1: Vacuum internal of a single side coupled accelerator section and electric field of the π/2 mode.

ACCELERATOR TUNING

Since the boundary conditions of the single section do not accurately describe the alternating coupling cavities, varying geometry along the beam axis and termination of the accelerator it is necessary to fine tune all coupling slots and nose gaps again in the complete assembly as shown in Figure 2. The goal of the tuning is to obtain the desired field distribution along the beam axis, remove fields from the coupling cavities and maintain the π/2 mode frequency. Optimization of such a large model is feasible only with advanced 3D electromagnetic simulation software such as CST Microwave Studio.

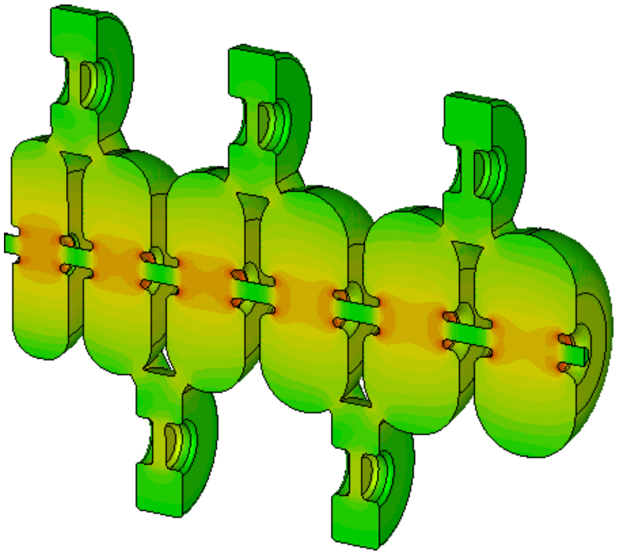

Figure 2: Contour plot of the electric field distribution of the π/2 mode in the tuned accelerator.

The decelerator shown in Figure 3 consists of the last five section of the accelerator with opposite beam direction. Because of the changed length the decelerator requires fine tuning as well. After fine tuning the target frequencies for cold testing and mechanical tuning can be calculated accurately enabling to build highly efficient components.

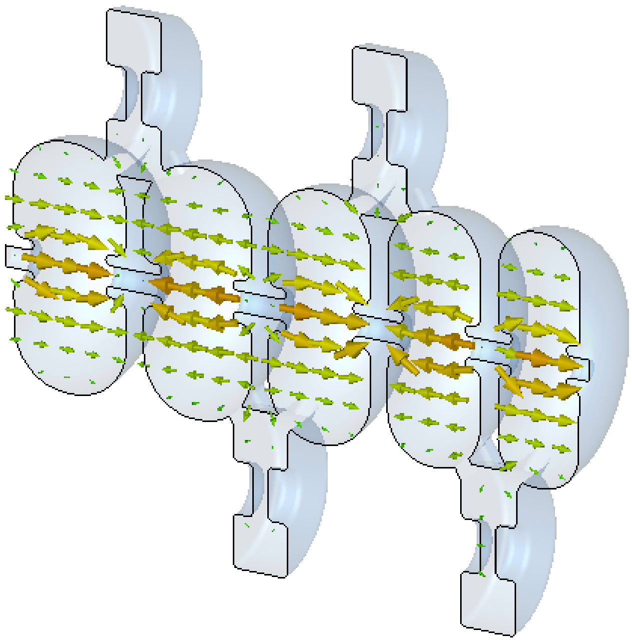

Figure 3: Arrow plot of the electric field distribution of the π/2 mode in the tuned decelerator.

BEAM DYNAMICS

A beam dynamics simulation determines the input power necessary to achieve the desired beam energy and reveals the energy spectrum. Beam dynamics are investigated with CST Particle Studio [1] which simulates charged particle dynamics in 3D electromagnetic fields including particle tracking, wake field and particle in cell (PIC) calculations.

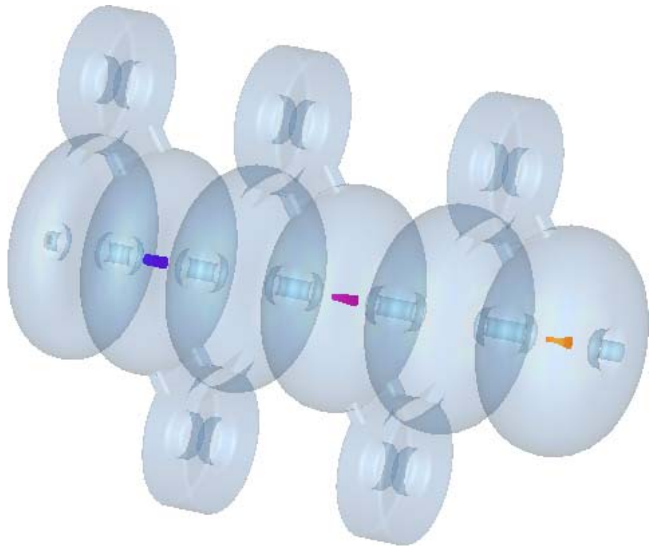

Figure 4: Snapshot of electron bunches in the accelerator. The diameter of the beam is scaled for better viewing.

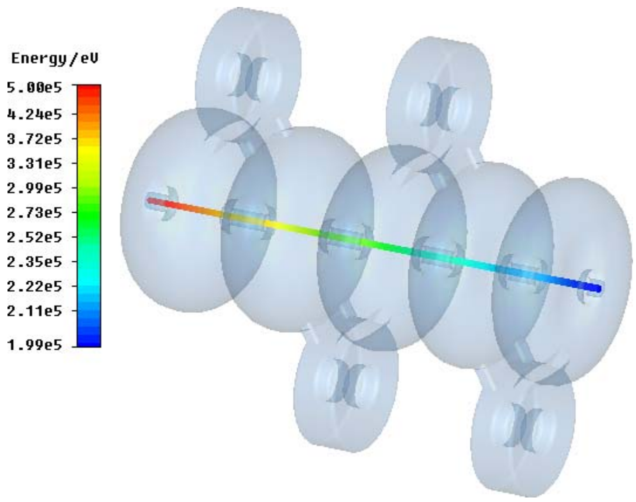

Figure 5: Electron trajectory in decelerator for the π/2 mode with injection at optimum phase. The diameter of the beam is scaled for better viewing.

CHOPPER

The RF-Chopper is used to limit the energy spread of the 500keV electrons leaving the accelerator to $\Delta E/E \leq 10^{-5}$ so a clear image can be obtained. RF-Choppers typically use magnetic fields to deflect the electron beam. A simulation based study of different deflectors shown in Figure 6 however shows that using the electric field is more efficient.

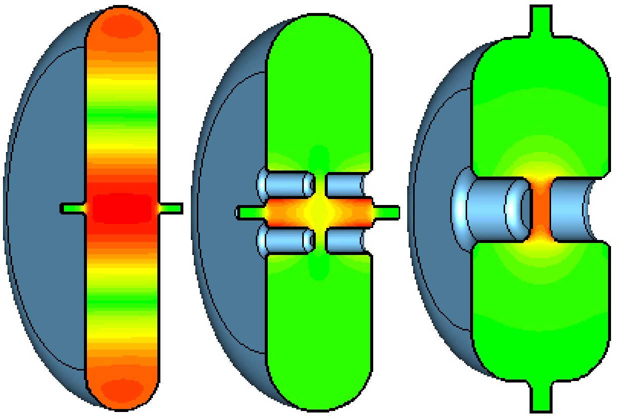

Figure 6: Contour plot of magnetic field in deflector A (left) and deflector B (centre) and electric field in chopper C (right). Sizes are scaled for better viewing.

Chopper A requires 5550W for a beam deflection of 9 degrees, chopper B requires 322W and chopper C 68W, making the electric chopper the most efficient. Deflector C shown in Figure 7 also has the lowest temporal energy spread while the spatial energy spread is similar in all deflectors.

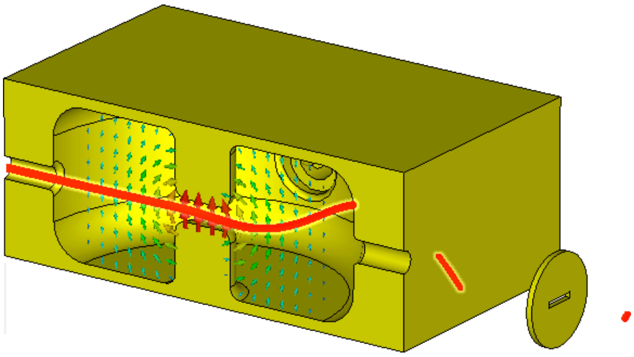

Figure 7: Deflector C with chopper iris showing the electric field and electron beam. The size of the beam and iris is scaled for better viewing.

EXPERIMENTAL RESULTS

A 500kV TEM as constructed in the National Institute for Physiological Science [4] is shown in Figure 8. The 100kV field emission electron gun (FEG) is installed on the top (silver part) of the main body, the 400kV linear accelerator and the 300kV linear decelerator are installed in the blue-painted parts. The object lens and the specimen holder are installed in the white-painted part between the accelerator and the decelerator. The chopper system is installed in the white-painted part between the FEG and the accelerator. A two-dimensional image sensor for the electron beam is installed at the bottom. The whole beam system is installed on a air-suspension system to isolate it from ground vibrations.

Figure 8: Main body (left) and microwave circuits (right) of the constructed 500kV TEM. The height of the main body is 3.75m.

We have performed first tests of the TEM. We obtained TEM images using only the linear accelerator. The beam energy is confirmed to be 200keV by an omega energy filter inside the TEM. We have also taken the first image of the 500kV TEM with both the linear accelerator and decelerator activated. A beam energy of 500kV is confirmed by the Au[100] incident diffraction pattern.

CONCLUSION

We presented the simulation based design of a side coupled standing wave accelerator and decelerator using advanced 3D electromagnetic and particle dynamics simulation software. We demonstrated the optimization of single sections and the fine tuning of the electric field distribution along the beam axis in the complete assembly as well as the calculation of beam dynamics and selection of the most efficient chopper design based on simulation results. The automatic optimization process enables to significantly reduce the development time and cost. The simulation results agree well with measurements. Finally, the successful first tests of the world first microwave TEM verifies the optimization techniques.

REFERENCES

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[2] T. Weiland, "A discretization method for the solution of Maxwell's equations for six-component fields", Electronics and Communication (AEÜ), vol. 31, p. 116, 1977.

[3] B. Krietenstein, R. Schuhmann, P. Thoma, and T. Weiland, "The Perfect Boundary Approximation technique facing

the challenge of high precision field computation", in Proceedings of the XIX International Linear Accelerator Conference (LINAC'98), Chicago, USA, 1998, pp. 860-862.
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