ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB110

SOLID-STATE DRIVEN X-BAND LINAC FOR ELECTRON MICROSCOPY

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Abstract

We present an initial design for a prototype low-cost CW RF linac for high-throughput microcrystal electron diffraction (MicroED) producing 200 keV electrons with a standing-wave architecture where each cell is individually powered by a solid-state transistor. This design also provides an upgrade path for future compact MeV-scale sources on the order of 1 meter in size.

INTRODUCTION

Current transmission electron microscopes (TEM) typically accelerate electrons to 200-300 keV using DC electron guns with a nanoamp of current and very low emittance. These DC sources are used in order to ensure the high beam coherence required for electron microcopy. However at higher voltages these DC sources rapidly grow in size, often times several meters tall for 1 MeV microscopes [1]. Microcrystal electron diffraction is a novel technique used by chemists and biologists to image small molecules and protein crystals with cryo-electron microscopy (cryo-EM). However, cryo-EMs remain an expensive and logistical investment due to the specialized equipment required, limiting the number of labs that can utilize this technique. However the coherence requirements for MicroED are lower than standard TEM imaging, making it a suitable target for testing new electron sources.

One such source would involve replacing the DC source with a compact linac powered by solid-state sources. This could dramatically lower cost while maintaining beam quality, thereby increasing the accessibility of MicroED and other Cryo-EM techniques. Utilizing compact high shunt impedance X-band structures ensures that each RF cycle contains at most a few electrons, preserving beam coherence. CW operation of the RF linac is possible with distributed solid-state architectures [2–4] which power each cavity directly with solid-state amplifiers which can now provide up to 100W of power at X-band frequencies [5].

This work presents our progress on the initial design of the solid-state driven linac as well as characterization of the amplifiers to be used as sources. The linac will utilize X-band cavities operating at 11.424 GHz, each individually driven by 100 W solid-state amplifiers to produce a 200 keV beam.

LINAC OVERVIEW

An schematic of the overall linac design is shown below in Fig. 1. To create the electron beam we intend to use a standard 30 kV field emission gun (FEG) that is commonly used in electron microscopes. This 30 keV beam then passes through a deflector formed from two TM_{12} cavities to ensure only electrons in sync with the accelerator are passed through [6]. This also limits the bunches to a few electrons per cycle, maintaining spatial coherence. From there the beam is accelerated up to 200 keV through 32 X-band cavities, each one powered with 75 W and individually tuned to ensure maximal acceleration. Finally to ensure the energy spread, and therefore temporal resolution, is minimal, the beam is passed through an energy filter formed from crossed E and B fields. The effect of these elements on the beam energy and deflection can be seen in Fig. 2 as well, which was generated from simulations in GPT.

CAVITY DESIGN

As mentioned above, the accelerating cavities were designed to operate at 11.424 GHz, with a shunt impedance of

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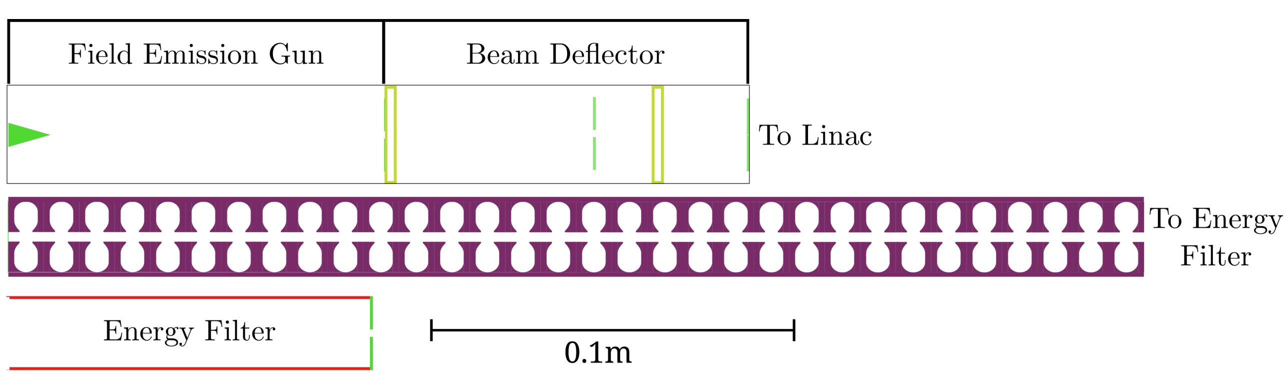

Figure 1: Schematic of the full linac as designed, starting with a field emission gun to generate 30 kV electrons, followed by a beam deflector to chop the beam into smaller pulses, and an accelerator and energy filter to ensure coherence.

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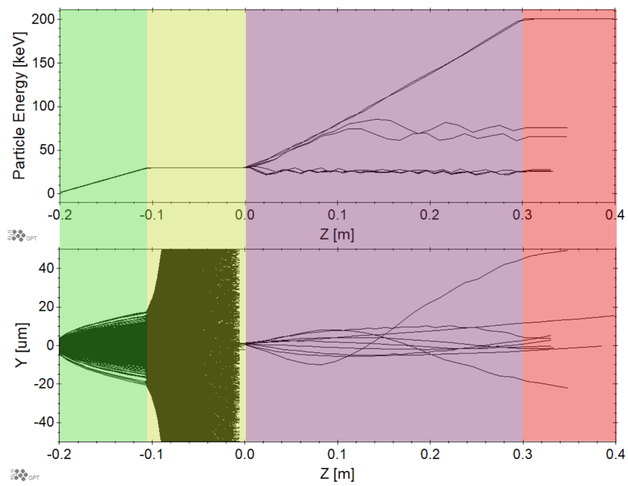


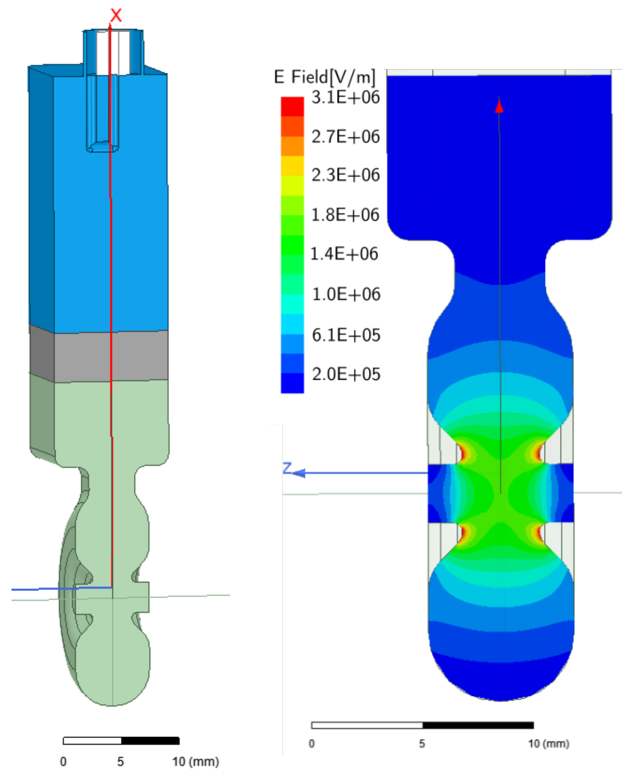
Figure 2: GPT simulations of full linac, including the FEG (green), beam deflector (yellow), accelerator (purple), and energy filter (red).

roughly 146 MΩ and quality factor of 6275. The initial design was refined using HFSS to simulate power coupling and field distributions [7]. Once the initial cavity was designed, further simulations were used to include a dielectric window and coaxial-waveguide transition to ensure power from solid-state sources could properly couple into the cavity, as shown in Fig. 3a. The fields generated from this simulation were produced by 75 W of input power from the coaxial line, producing gradients over 1 MV/m within the cavity, shown in Fig. 3b. These levels of input power are achievable with solid-state sources, and thus provided a target for our ongoing tests.

SOLID-STATE AMPLIFIER TESTS

In order to test the viability driving accelerating cavities with solid-state amplifiers, we have started tests on Qorvo QPM1021 X-band amplifiers. These amplifiers can output 100 W of RF power, so to test this we operated the amplifiers with pulsed power on the drain, keeping the overall operation to 1 ms pulses with a 1% duty cycle. This was achieved by generating a 1 ms trigger and running it through a power modulator, as shown in Fig. 4. The RF output from the amplifier would then be fed to a directional coupler and calibrated diode in order to estimate the power generated.

By measuring the diode drop from the amplified pulse, as shown in Fig. 5, and accounting for the attenuation in the directional coupler, we estimate the power output from the amplifier to be about 50 W. This initial test of the amplifier's capabilities is promising, but more power would be required to drive accelerating cavities properly. As we continue to test higher power outputs, we also intend to do some initial tests of coupling this power into an RF test cavity, measuring the effective power coupled into the cell and reflected back from it. These tests will give us the operational parameters needed to finalize design of the linac and begin construction.



(a) Render of cavity (green), connected to waveguide transition (blue) via dielectric window (grey).

(b) Simulation in HFSS of electric field magnitude within accelerating cavity, showing an average field over 1 MV/m.

Figure 3: Overview of cavity and waveguide coupler design as rendered in HFSS.

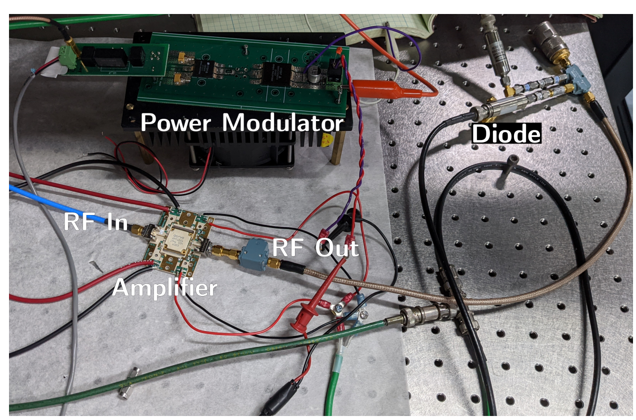


Figure 4: Picture of the test setup for solid-state amplifier. RF power is fed in from the left as the amplifier drain is pulsed with power in 1 ms pulses. The amplified signal is then fed into a directional coupler and diode which is read out to estimate the total power.

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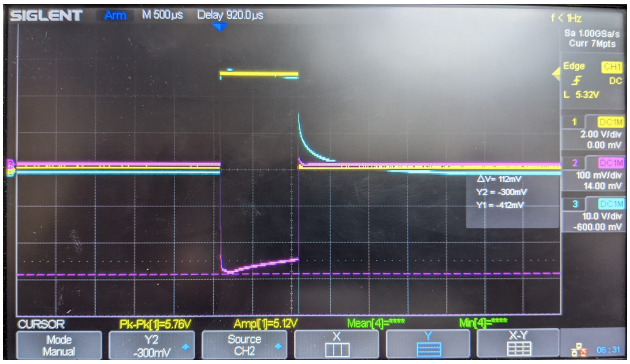

Figure 5: Picture of the oscilloscope trace showing the trigger pulse (yellow), the pulsed power on the drain(blue), and the diode reading (pink). The maximum drop in diode voltage corresponds to an output power of roughly 50 W.

CONCLUSION

We have presented here the initial designs for a solid-state driven linac to generate a 200 keV beam capable of electron diffraction. The accelerator uses high shunt impedance cavities that can generate 1 MV/m fields with 75 W of input power. This makes it possible to use 100 W solid-state amplifiers to power these cavities individually and ensure beam coherence for diffraction. Future work will include driving individual test cavities with solid-state cavities, finalizing the design and construction of the full linac, and characterising the output beam for electron diffraction.

ACKNOWLEDGEMENTS

We would like to thank E. Snively and B. Kuchhal for helpful discussions on HFSS, as well as A. Haase, E. Jongewaard, and C. Nantista for advice on mechanical design. This work was supported by the Department of Energy Contract No. DE-AC02-76SF00515.

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