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SOLID-STATE DRIVEN X-BAND LINAC FOR ELECTRON MICROSCOPY

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Abstract

Current transmission electron microscopes (TEM) accelerate electrons to 200-300 keV using DC electron guns with a nanoamp of current and very low emittance. However at higher voltages these DC sources rapidly grow in size, often times several meters tall for 1 MeV microscopes. Replacing these electron guns with a compact linac powered by solid-state sources could dramatically lower cost while maintaining beam quality, thereby increasing accessibility. 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 which power each cavity directly with solid-state amplifiers which can now provide up to 100W of power at X-band frequencies. We present a demonstrator design for a prototype low-cost CW RF linac for high-throughput electron diffraction 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 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 (SSA) which can now provide up to 100W of power at X-band frequencies [5]. This work presents our progress on the design of the solid-state driven linac demonstrator system. The linac will utilize X-band cavities operating at 11.424 GHz, each individually driven by 100 W SSAs to produce a 200 keV beam.

SYSTEM OVERVIEW

An schematic of the overall system is shown 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. Steering magnets will be use to align the beam with the rest of the system, with a gate valve to protect the electron gun's vacuum during downstream configuration

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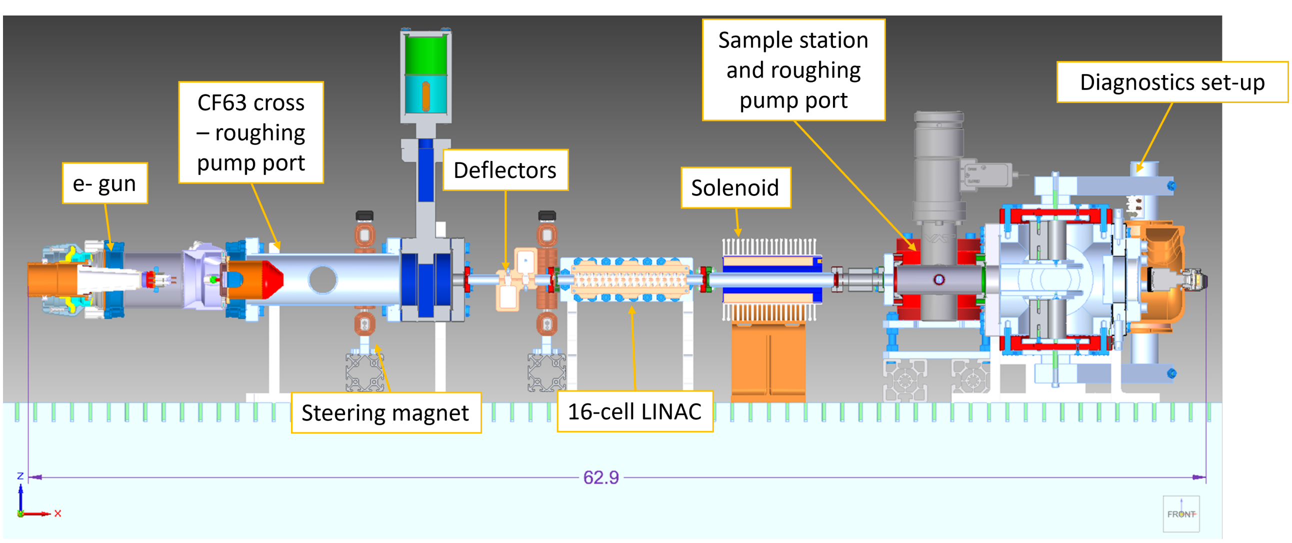

Figure 1: Mechanical model of the full electron diffraction system as designed.

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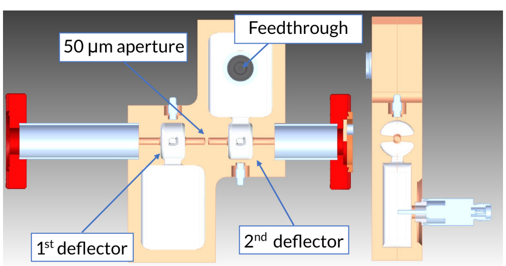
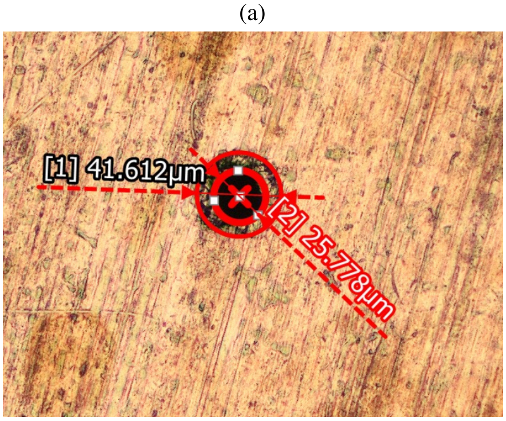
changes. This 30 keV beam then passes through a deflector formed from two TM_{12} cavities to ensure only electrons synchronized with the accelerator are passed through [6]. This also limits the bunches to a few electrons per cycle, maintaining spatial coherence. From there the beam is accelerated up to 200 keV through 16 X-band cavities, each one powered with 100 W and individually tuned to ensure maximal acceleration. At this stage the beam is gently focused onto a sample station, which can hold a series filtering apertures or diffraction samples. Finally the beam enters a diagnostic station, where beam profile, energy, and charge can be monitored.

DEFLECTOR DESIGN

In order to synchronize the CW beam from the electron gun with the RF frequency of the linac, a pair of deflector cavities were designed to use the TM_{12} mode to deflect the beam through a 50 µm aperture 1 mm thick. This would discard close to 99.9 % of the beam, leaving a small bunch of electrons in sync with the linac. As the beam current from the gun is decreased, this would eventually mean close to 1 electron per RF cycle is accelerated, allowing for sufficient coherence to potentially resolve electron images as well. A schematic of the deflector is shown in Fig. 2a



(a)



(b)

Figure 2: (a) Mechanical model of the defector cavities, with embedded aperture and welded vacuum feedthroughs. (b) Optical microscope image an laser drilled aperture. The target size was 25 µm in this case.

Each cavity is fed power via a coaxial vacuum feedthrough, which supplied around 0.1 W per cavity to deflect the beam. The aperture itself will be made via laser drilling, which recent tests have verified can be achieved with sufficient accuracy, as shown in Fig. 2b. Interestingly the accuracy and quality of the drilled apertures increased as the hole size decreases, suggesting that ablating too much material can form imperfections in the aperture. Smaller apertures could filter even more of the beam, but thermal analysis will be required to ensure the beam does not warp the aperture over time.

LINAC DESIGN

For the 16-cell linac, the accelerating cavities were designed with a shunt impedance of roughly 146 MΩ/m and quality factor of 6500. Each cavity is designed to be powered by an individual SSA, via a coaxial feedthrough similar to the deflector cavities. The linac from will be made from two copper slabs which will be brazed together, one of which is shown in Fig. 3.

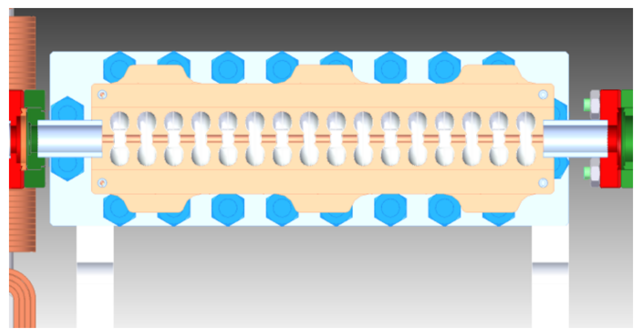


Figure 3: Cross section of the 16-cell linac.

The linac accelerates the beam from 30 keV up to 200 keV, with an energy spread close to 1 keV. This energy spread is radially dependent, so if finer energy spread is require the beam can be further filtered with apertures downstream. These could be made with the same laser drilling planning for the deflector.

SAMPLE HOLDER AND DIAGNOSTICS

After acceleration, the beam is gently focused with a solenoid onto a sample station, which can contain diffraction samples or the afore mentioned filtering apertures one a single arm. This sample station, as shown in Fig. 4 can hold three samples at a time, and is designed to easily retract and seal off from the main system vacuum in order to quickly swap samples and minimize pumping time. This is based on best practice for TEM sample holders, which have similar load-lock systems for exchanging samples.

Finally at the end of the beam line, we have the diagnostic station, containing a Faraday cup and two micro-channel plates (MCP). The in-line MCP is used for monitoring the beam profile, while the other diagnostics can be used by bending the beam with a solenoid driven parallel plate dipole magnet. The Faraday cup is in place to monitor beam charge, while the off-axis MCP can be used to measure the beam energy. In the future this station can be upgraded to include

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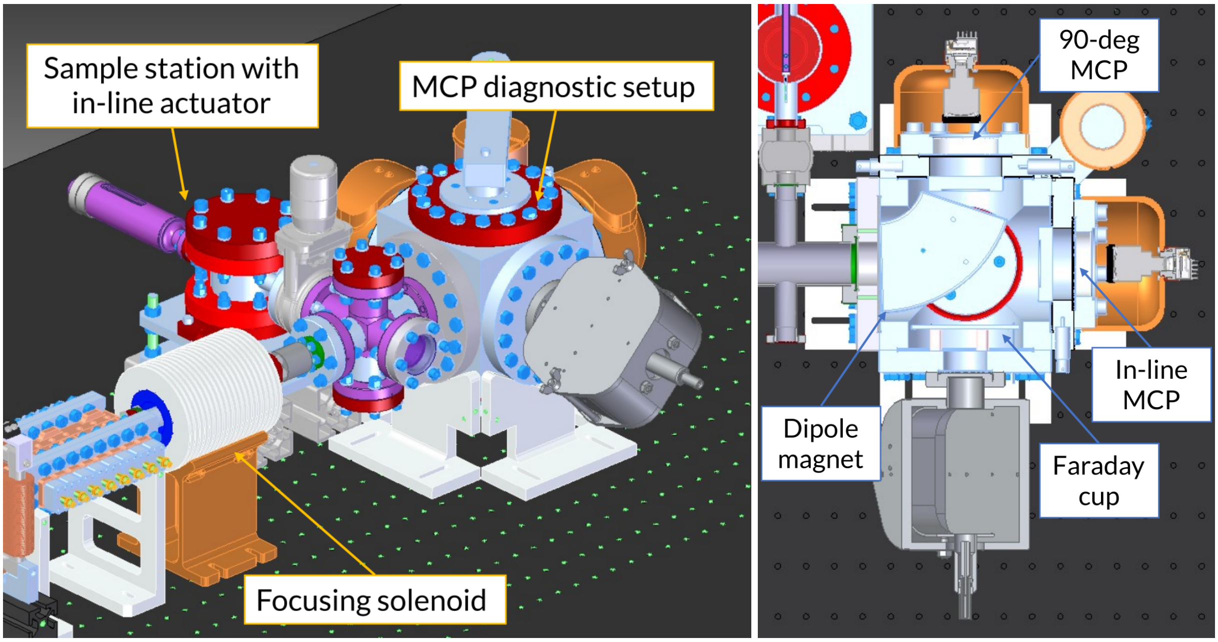

Figure 4: Mechanical views of the diagnostics section, with sample station and diagnostic cube. The cube contained a Faraday cup and two MCPs for monitoring beam charge, profile,and energy.

detectors for imaging, once beam characteristics are understood.

SOLID-STATE AMPLIFIER TESTS

As continuing development from previous work, we have continued to develop the necessary hardware to operate these 100 W SSAs reliably [7]. Recent work has determined that in order to avoid thermal runaway in the SSAs, the drain needs to be pulsed on the order of a few microseconds. This allows for stable operation up to 60 Hz and a peak output power of 103 W. Figure 5 shows the recent test sending this power into a resonant cavity, confirming the operational requirements for each SSA. Work is ongoing to development a compact modulator for these SSAs, with the goal of creating a compact 100 W RF source for testing and power smaller scale system such as this electron diffraction setup.

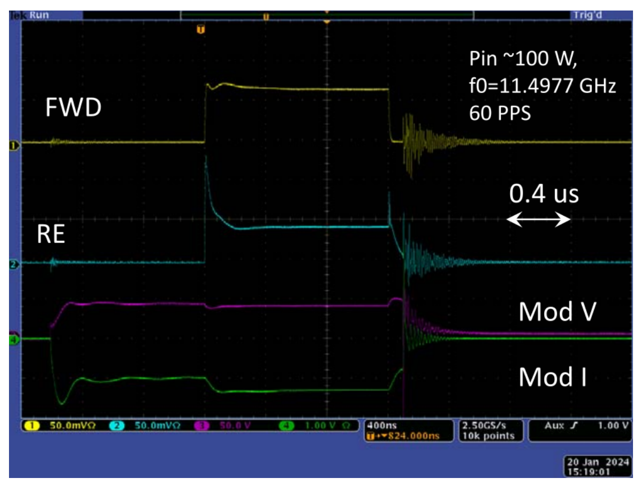

Figure 5: Measurements of the 100 W SSA under test into resonant cavity, utilizing pulsed RF and drain voltage to operate .

CONCLUSION

We have presented here designs for a system utilizing solid-state driven linac to generate a 200 keV beam for electron diffraction. The accelerator uses high shunt impedance cavities that can generate 1 MV/m fields with <100 W of input power per cavity. 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 finalizing the power modulators required for pulsed operations of the SSAs, and construction of the full linac.

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