Modular High Power RF Sources for Compact Linear Accelerator Systems

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Abstract: *SLAC is pursuing high efficiency, low cost RF source designs that are suitable for mass production, in order to enable the next generation of linear accelerators. These efforts have driven the development of compact linac systems with integrated modulators, klystrons, and accelerator structures, based on a modular, low voltage klystron topology. There is substantial demand for compact linacs for X-ray radiography with security applications, and for new radiation therapy machines that reduce treatment times by orders of magnitude and may yield beneficial biological effects. In this presentation, details and challenges for these new compact accelerator systems and the corresponding RF sources are discussed.*

Keywords: linear accelerator; linac; klystron; compact accelerator; radiography; radiation therapy.

Introduction

The development of efficient, inexpensive, high power microwave sources is essential for enabling the construction of next generation colliders and accelerator-based light sources. The high costs typically associated with klystrons and high voltage power supplies present a major budgetary obstacle for proposed science facilities around the world. As a result, the DOE Office of Science, High Energy Physics (HEP), through the General Accelerator R&D (GARD) program, has tasked the community with a price target of $2 per kW of RF output power, in mass production, encompassing the full capital and operating costs the modulator and klystrons together.[1]

In recent years, SLAC has pursued unique RF source designs with the goal of mitigating the high cost of RF power. The problem is approached from several angles:

1. Simplification of piece parts and assembly processes for klystrons
2. Optimization of RF cavities and circuit layout for peak DC-to-RF klystron efficiency
3. Lower voltage operation, enabling the development of inexpensive modulators using commercial off-the-shelf (COTS) components
4. Passive power combining of multiple low-voltage klystrons that are designed for mass production
5. Alternate approaches to conventional linear-beam devices, minimizing space charge and/or energy spread in the modulated beam
6. Novel alternatives to the major cost-driving components in conventional sources (*i.e.*, electron sources and focusing magnets).

SLAC is moving toward a simplified RF source and power supply topology suitable for high volume production. Multiple prototypes are being built and tested; an example is shown in Figure 1. The result is a modular "building block" klystron intended for a range of RF power systems, with each tube providing hundreds of kW peak power, and combining or distributing the output of multiple tubes as necessary for a given application.

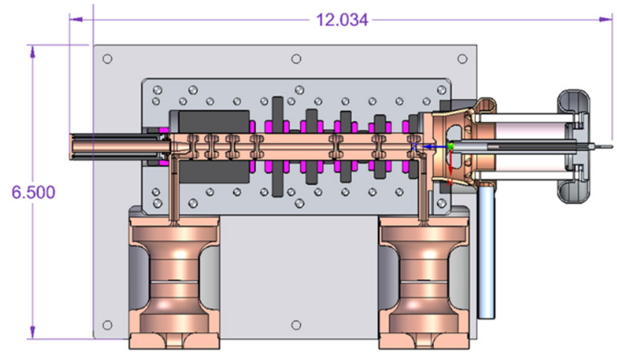

Figure 1. Example of an ultra-compact, permanent magnet focused, low-voltage 300 kW X-band klystron.

Applications for Compact Linac Systems

The creation of modular high power RF sources, when coupled with newly optimized accelerator structures, has positioned SLAC to develop fully integrated, state-of-the-art compact accelerator systems. There is substantial interest in these integrated machines for applications in national security, emergency response, and improved radiation therapy for cancer treatment.

X-ray radiography is a common method of non-intrusive inspection for the detection of special nuclear materials. Commercially available X-ray sources designed for radiography are limited, in that they do not deliver the X-ray intensity, repetition rate, or fast energy modulation required for high throughput scanning of cargo containers. Under development are two compact, efficient X-ray radiography machines based on SLAC's high gradient distributed coupling accelerator structures, low-cost modulators, and modular RF sources.

One such program intended for cargo scanning at ports is supported by DHS. The machine will deliver electron beam energies up to 10 MeV, with 10 times the beam power and twice the efficiency of commercially available systems, and repetition rates up to 4 kHz for high resolution imaging. An estimated footprint of the system is shown in Figure 2. Five modular, 300 kW klystrons are powered by a common 60 kV modulator and are used together to drive a single linac; individual drive controls for the klystrons allows for pulse-to-pulse adjustment of the accelerated electron beam energy from 2 to 10 MeV with up to 5 kW of average beam power.

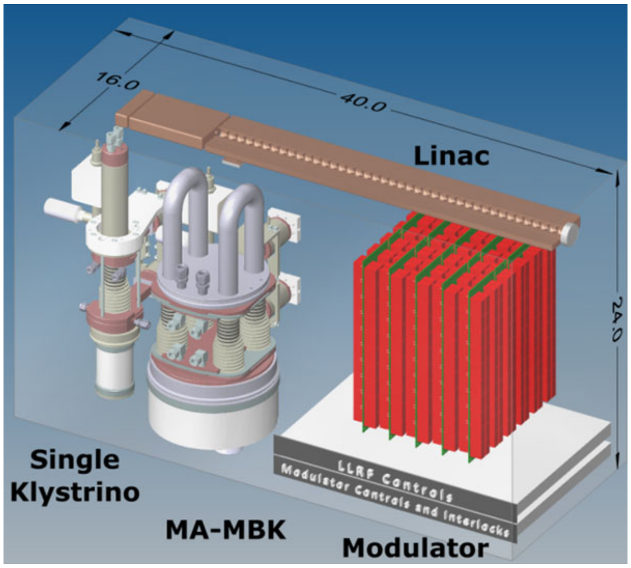

Figure 2. Estimated footprint of linac-based X-ray radiography system for high throughput cargo scanning.

Another machine under development at SLAC exchanges the high throughput capabilities discussed above for low weight and high efficiency in an extremely compact package. This effort, supported by the NNSA, will yield a portable linac-based radiography machine for emergency response applications that can be easily transported and powered by battery. Again, an electron beam is accelerated by a single linac, but here it is driven by two lightweight modular klystrons while still providing up to 10 MeV beam energy. The average power consumption of the system is less than 600 W, and the modulator itself can fit within a fraction of a standard sized rack.

A larger system utilizing SLAC's modular linac/klystron topology is being designed for state-of-the-art radiation therapy in collaboration with Stanford Medical School Dept. of Radiation Oncology – Pluridirectional High-energy Agile Scanning Electronic Radiotherapy (PHASER). The PHASER concept, shown in Figure 3, utilizes sixteen individual beamlines (fed by 16 individual klystrons), with electronic steering of each beam, and a unique drive-controlled power combining scheme which enables the delivery of X-ray doses exceeding 1 Gy/s to the patient. This dose rate is 300x higher than that of commercially available RT systems, allowing for freezing of organ motion and improved targeting precision, and with orders of magnitude improvement in treatment times. These extremely high dose rates have been shown to provide beneficial biological effects, wherein cancer cells are preferentially destroyed while healthy cells are able to recover, and unwanted side effects of the radiation treatment are partially mitigated.

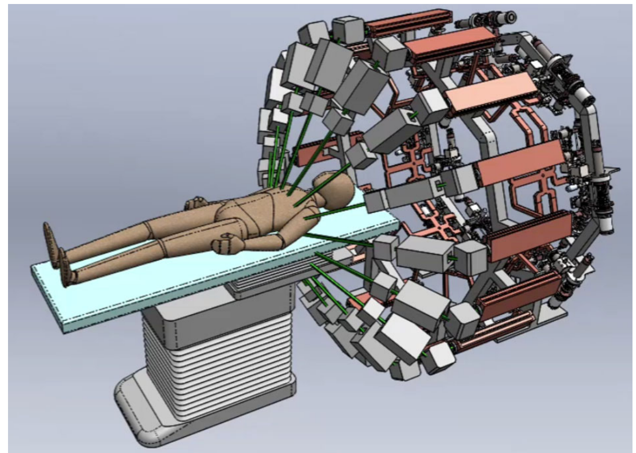

Figure 3. Layout of PHASER radiation therapy system, consisting of 16 modular klystrons and beamlines.

Future Steps

SLAC's Technology Innovation Directorate is actively engaged in finding novel applications for linacs and RF sources both within and outside of fundamental science. Fabrication and test of these prototype machines is imminent. If successful, there will be substantial demand for large volume production of these integrated compact accelerator systems.

Industrial partners will be essential for moving these technologies forward after the prototype phase. With each system requiring a few to tens of independent RF sources, it is no exaggeration to expect that hundreds or thousands of compact klystrons could be required. Industry will have a crucial role to play in minimizing build costs through standardization and automation. SLAC/TID certainly welcomes feedback and partnerships with industry – including magnet, cathode, and tube manufacturers – to identify and mitigate the major cost drivers associated with high volume RF source production.

Acknowledgements

We thank Diana Gamzina, Matthew Franzi, Richard Kowalczyk, and Aaron Jensen for their contributions to early stages of this effort. This work was supported by: U.S. Dept. of Energy, contracts DE-AC02-76SF00515 (HEP) and FY18-NA-PD3Jc (NNSA/NA-22); U.S. Dept. of Homeland Security (IAA HSHQDC18ITR0004); and the Dept. of Radiation Oncology, Stanford Medical School.

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[1] "Radiofrequency Accelerator R&D Strategy Report" DOE HEP General Accelerator R&D RF Research Roadmap Workshop March 8–9, 2017