COMPACT ELECTRON-LINAC DESIGN CONCEPT FOR A GAMMA RAY SOURCE

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Abstract

Gamma-ray sources, particularly sources that are easily transportable, are in high demand for different applications. We have carried out a review of commercially available electron-linac-based sources, and have investigated alternative compact electron-linac systems that use updated technologies compared with sources that are available commercially. As a result, we propose to develop a new source using an electron linac operating at 17-GHz. It uses a klystron, instead of a magnetron, and an IGBT-switched HV power supply. The source design takes advantages of the advances in X-band linac technology and solid-state HV technology. The higher frequency and upgraded technologies offer smaller size, lighter weight, better efficiency, easier operation, and higher reliability, compared with commercially available linacs. In this paper, we will describe the source design and our choice of technologies.

REQUIREMENTS OF AN ELECTRON-LINAC-BASED GAMMA-RAY SOURCE

For most applications, an electron-linac-based gamma-ray source is required to produce a dose rate up to 1500 cGy/min on axis one meter away from the source. The electron beam energy is typically between 6-10 MeV. The exact dose rate and energy will depend on the specific application and material to be penetrated. A pulsed linac is usually needed to allow for beam-off time for data acquisition. The typical pulse format is a repetition rate of 50 Hz, a 10-μs pulse length, and a nominal peak current of 70 mA. For some applications, a compact system is also required. A compact system provides transportability, ease of radiation shielding, and low cost. Ease of use and reliability will also be important.

STATUS OF TECHNOLOGY

We have carried out a study of electron-linac-based sources and associated technologies. The results are summarized in a report [1] and this paper is a summary of that report.

Presently, commercially available electron-linac-based gamma-ray sources are derived from medical linac technology. Such sources usually consist of a Linac Subsystem, a RF Subsystem, an HV Subsystem, and a Support Subsystem for cooling, vacuum, and control. The general features of presently available gamma-ray sources include:

- A S-band (3 GHz) linac
- Powered by magnetrons
- High-voltage modulated by a pulse-forming network (PFN) and a HV transformer
- Limited flexibility in energy and pulse format
- Dimensions of each component about a few feet on each side
- Weight of each component about 500-1000 pounds; with total weight about 1800 pounds.

AN GAMMA-RAY SOURCE WITH IMPROVED TECHNOLOGY

In our study, we concluded that using an electron linac at 17 GHz, a klystron as the RF source, and a solid-state Marx generator as modulator can make an improved electron-linac-based gamma-ray source. By updating the technology in these three aspects, the system will improve in efficiency, reliability, flexibility, size, weight, and cost. In this section, we will describe the subsystems using these updated technologies.

Linac Subsystem

The nominal parameters of the Linac Subsystem are given in Table 1. The linac will operate at an optimum frequency of 17 GHz. A higher-frequency linac operating at 17 GHz offers many advantages over the currently available S-band linacs because linac performance improves with linac frequency. The copper loss is reduced by a factor of 2.3. The linac is less prone to RF field breakdown with the breakdown limit higher by the same factor. The structure radius decreases linearly with frequency, resulting in a structure weight reduction by a factor of 25.

Table 1: Nominal Parameters of a Linac Subsystem

Linac frequency (GHz)	17
Beam energy (MeV)	8
Beam current (mA)	68.2
Beam Power (kW)	545
Structure power (kW)	1170
Total power required (kW)	1715
Length of structure (cm)	25
Acceleration gradient (MeV/m)	32
Diameter of structure (cm)	2.7
Number of cells	55
Ratio of mode spacing to mode width	3.2
Shunt impedance (MΩ/m)	219
Unloaded quality factor	5725
Cell to cell coupling coefficient	0.048

Our investigation shows that 17 GHz is nearly the optimum linac frequency for this application. Frequencies higher than 17 GHz, even better in linac efficiency, may lead us to linac operation with multiple RF-structure modes [2], and consequently unstable operation. A higher-frequency linac structure may also have such tight mechanical tolerances that fabrication of the structure may require more novel techniques than conventional machining. In the last ten years, Stanford Linear Accelerator Center (SLAC) has been developing electron linacs for the Next Linear Collider (NLC) at 11.5 GHz, close to our proposed 17 GHz. Results of their development in mechanical fabrication techniques and RF sources can readily be adapted for our application.

Our proposed linac structure, as shown in Fig. 1, will operate in the standing-wave mode for efficiency. The structure is a biperiodic structure operating in the π/2-coupled mode for best stability and efficiency. The buncher and main linac will be uncoupled to allow more flexibility in varying beam energy. Focusing will be provided by a periodic permanent-magnet (PPM) channel for compactness and high efficiency.

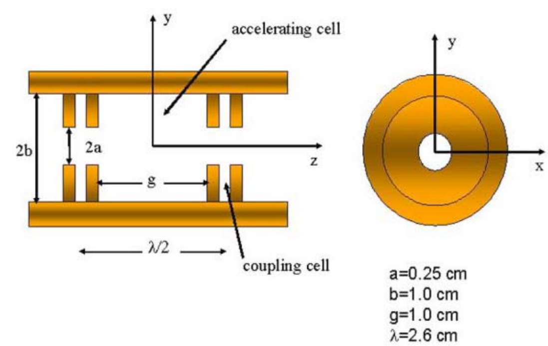

Figure 1: Cross sections of a 17-GHz linac structure.

Klystron Subsystem

A klystron will be used to power the linac for excellent controllability and reliability. Nominal 17-GHz klystron parameters are given in Table 2. Klystrons, being amplifiers, amplify well-defined low-level input signals with high fidelity. By formatting the low-level input signals, a variety of pulsing schemes can be reliably provided. This is an improvement compared to magnetrons, which are oscillators starting by amplifying noise. Magnetrons also are not chosen because it is difficult to push magnetron technology to our required higher frequency of 17 GHz at high power.

Table 2: Nominal parameters of a X-Band klystron

Frequency	17.136 GHz
Peak RF Output Power	2000 kW
Pulse length	20 μs
Pulse repetition rate	50 Hz
Average Power	2000 W
High-voltage subsystem requirements	
Voltage	115 kV
Current	29.3 A
Diameter	16.3 cm
Height	53.4 cm
Weight	60 lb

Klystrons with peak power of 75 MW have been developed by industry for the NLC. Designs of such klystrons can easily be adapted for our need of 2 MW. A diagram of a proposed commercial 17-GHz klystron is shown in Fig. 2. It uses a PPM array for beam focusing and an air-cooled collector/beam dump to improve compactness and efficiency [3]. Similar design was also proposed by SLAC. Success of higher power X-band klystron at SLAC klystron indicates that the development of a 17-GHz klystron for our application will be of relatively low risk.

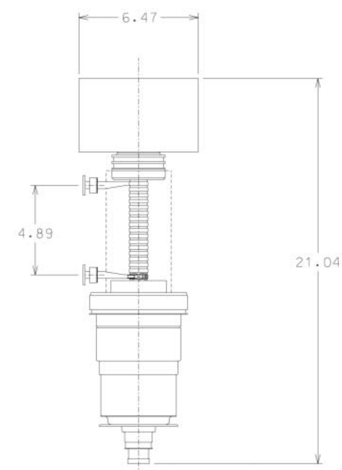

Figure 2: Schematic of a 2-MW 17-GHz klystron. Dimensions are in inches.

High-Voltage Subsystem

A solid-state Marx generator [4] will be used to provide the high-voltage to the klystron. The requirements of the HV subsystem are given in Table 3.

Table 3: Nominal parameters of a HV-Subsystem

Pulse width	10–40 μs
Pulse Voltage	130 kV
Peak Load Current	30 A
Peak Output Power	3.5 MW
Pulse Repetition Frequency	25–100 Hz
Pulse Droop	1–2 %
Energy per Pulse	70 J
Duty Factor	0.1%
Average Output Power	3.5 kW
Available Utility Power	3.3 kW (110 V, 30 A)

The advantages of a solid-state Marx generator are improved reliability, flexibility in pulse format, and compact size. As shown in Fig. 3, the solid-state Marx generator charges a collection of energy-storage capacitors in a parallel configuration at low voltage and uses solid-state switches to reconnect the capacitors into a series configuration to provide the required high-voltage. The switches are high-power IGBTs (Insulated Gate Bipolar Transistors), available only in the last five years. They will be operated by optical links that provide the high-voltage insulation. Although this is a relatively new technology, three designs at 50 to 500 kV have been proposed and one prototype is being built in Los Alamos [5] and at SLAC. A 2-μs, 11-kV device is presently in use driving a traveling-wave tube at SLAC.

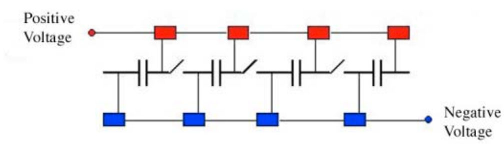

Figure 3: Schematic of a basic Marx-generator module.

The solid-state Marx generator offers many advantages compared to conventional modulator technology using a pulse-forming network and a high-voltage transformer. Its pulse format is flexible, tailored simply by sending on/off signals to quick-recovering IGBT switches. It is built by stacking identical Marx circuit boards that contain a few low-voltage capacitors (Fig. 4). Such a modular design allows the basic module to be well tested and the full unit easily reconfigured to different output voltages. With all solid-state components, the unit will share the long service life and high reliability typical for solid-state devices. Additionally, a solid-state Marx generator has small size (a fraction of a cubic foot) and is lightweight (about 50 pounds), compared to conventional units.

Figure 4: Photograph of a single Marx circuit board showing 4 IGBTs, 4 optical receivers, and 8 charging diodes.

Overall System

The proposed gamma-ray source design is very compact. Table 4 shows a comparison between our proposed system and a commercially available unit. Instead of the truck size of a commercial unit, our proposed design is approximately the size of a filing cabinet. The system can be designed to operate using electrical power supplied by readily accessible 110-220-volt household circuits. Portable power and a self-contained cooling system can also be considered.

Development Plan

The proposed design, although not based on off-the-shelf technology, is based on reasonable extensions of known technologies. We have proposed a 3-year development plan that will result in a demonstration of this new technology and would only require a minimal R&D effort. Our development plan would have three phases:

- Phase I: Review and optimize design parameters (six months)
- Phase II: Design, build, and test prototype subsystems (twenty two months)
- Phase III: Test prototype of full-unit (six months)

Industry should be brought in at the beginning of the technology development process. They can play a major role, particularly in Phase III, contributing to the integrated design of the full system. The system packaging is important for achieving a minimum overall size; an area where industry has significant experience and expertise.

Table 4: Comparison of sizes and weights of major subsystem of the proposed gamma-ray source design to a typical commercially available unit.

Subsystem	Commercial Unit	Proposed Design (Estimated)
HV Modulator	35 ft^3, 700 lbs	1.5 ft^3, 50 lbs
RF Source	8 ft^3, 350 lbs	2.5 ft^3, 60 lbs
Linac	21 ft^3, 1600 lbs	2.5 ft^3, 60 lbs

ACKNOWLEDGEMENT

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