ABSTRACT

The Low Energy Accelerator Facility (LEAF) contains a low-energy linac with high average beam power, which was designed and built in the late 1960’s primarily for radiation-chemistry experiments. The maximum beam energy in that configuration was 21 MeV. Although, the installation is old, it is still reliable. The accelerator was repurposed for development of accelerator-based technologies for the production of $^{99}$Mo with funding provided by the National Nuclear Security Administration’s Office of Material Management and Minimization (M$^3$). An extensive scientific program on the production of radioactive isotopes demanded an upgrade of the accelerator to fit the experimental requirements. Several possible LEAF upgrades were proposed to increase the electron beam energy. The final design proposed the replacement of the old accelerating structures with new ones. In 2011-2012, the new structures were manufactured, installed, and tested with the beam energy up to 50 MeV and average beam power up to 20 kW. LEAF now is an attractive installation for performing research into medical isotope production.

KEYWORDS

Linac, high power beam, accelerating structure

1. INTRODUCTION

The Low Energy Accelerator Facility (LEAF) was commissioned in 1969 for radiation chemistry experiments. This accelerator had an electron beam energy range up to 21MeV. The injector of the linac is a DC electron gun with a BaO thermocathode. It produces electron pulses with amplitude up to 2.0A with length from 4 ns (in short-pulse mode) up to 5.5 µs (in long-pulse mode). The bunched system is composed of a single-cavity prebuncher, a five-cell traveling wave prebuncher, and a main buncher. All of them are operating at the frequency 1300.7 Mhz. The initial accelerating structure consisted of tapered traveling-wave sections with a shunt impedance 43 MOhm/m and a loading factor 1.93 MeV/A. Initially, two Litton model L 3661 klystrons were used as the RF power source [1].

The linac vault is located under ground level and consists of two rooms: accelerator and experimental areas separated by a 7-feet-thick concrete wall (Figure 1). Each room has a separate entrance closed by plug door. The beam line in the experimental area has two (prospectively three) branches, which are convenient for setting up a few different experiments in the same area. Increasing the maximum energy up to 40-50 MeV was seen as an interesting issue for photonuclear isotope production. After discussing a
few approaches [2], the next project was approved for the LEAF upgrade. Injector, buncher, RF, and beam transport system will stay the same, but the accelerating structures will be substituted by standing-wave sections, powered by an L-band RF system.

![Linac layout](image)

**Figure 1. Linac layout.**

### 2. NEW ACCELERATING STRUCTURES

Two standing-wave accelerating structures were designed and produced by MEVEX Corp. Each structure is composed of 21 coupled cells and is powered by a THALES TV2022A klystron. The main parameters of the structure are in the Table I:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>16 kW</td>
</tr>
<tr>
<td>Shunt Impedance</td>
<td>43 MOhm/m</td>
</tr>
<tr>
<td>Unloaded VSWR</td>
<td>5.48</td>
</tr>
<tr>
<td>Open Circuit Energy Gain</td>
<td>28.72 MeV</td>
</tr>
<tr>
<td>Breakdown Strength</td>
<td>32.12 MV/m</td>
</tr>
<tr>
<td>Filling Time (high beam load)</td>
<td>0.6 µs</td>
</tr>
<tr>
<td>Length</td>
<td>2.305 m</td>
</tr>
</tbody>
</table>

New accelerating structures were installed in 2012; after that, they were pumped down and backed up to 200°C for two days. A routine conditioning procedure was performed, and a vacuum level of 4×10⁻⁸ Torr was achieved.

### 3. RF SYSTEM

Klystrons and modulators are located in the modulator room right above the accelerator room. Two klystrons were replaced by THALES TV2022 klystrons with an ultimate peak power of 20 MW (50 kW average) for the first one and 24 MW peak (60 kW average) for the second one. The RF pulse from the first klystron travels through the waveguide to the splitter, and part of the power is directed to the bunched system. All power from the second klystron goes to the second accelerating structure.
Expected beam parameters, average power and average current, are presented in Figure 2. The maximum average beam power gain is corresponding to energy region between 21 and 37 MeV. The highest beam energy with reasonable average power up to 10 kW is equal to 50 MeV.

4. TESTING OF THE SYSTEM

After installation of the new structures and circulators, the RF waveguides were reassembled. All directional couplers were calibrated before RF measurements. Waveguides were filled with SF$_6$ at a 12-15 psi pressure. Initially, low-power measurements were performed to estimate attenuation and power losses for all elements of the system: waveguides, circulators, power splitter, loads, and accelerating structures.
The next test of the structures was performed with beam load. The injector pulse current was from 100 mA up to 1.5 A. A load line plot was made for the full RF-power deposited to both structures. RF pulse length was 6.3 µs for the first accelerating structure and 7.0 µs for the second one. Beam pulse length in all measurements was 5.0 µs, the repetition rate was 2 Hz, and the beam energy spread was about 3%.

The first measurements showed that the power loss in the circulators was too high (Figure 3), so replacement circulators were ordered in 2013.

![Beam load line](image)

**Figure 4. Beam load line.**

At the end of 2013, new circulators were installed, structures were re-conditioned up to full operating pulse power up to 16 MW for the first one and 20MW for the second one, and new load line measurements were performed. The obtained measurements for the old and new circulator sets are presented in Figure 4. The beam energy measurement was restricted to 41MeV due to a magnetic spectrometer maximum current limitation.

5. EXPERIMENTAL AREA

The experimental area is located below ground level. Access to the area is through the linac room or a side gate. The side gate is closed by a 6-feet thick concrete plug door. Radiation-monitors are installed in all rooms around the experimental area where people may be present during an experimental run. The interlock circuit will trip the machine, if the radiation field reaches a level of 4.5 mR/h.

In addition to the installation of the new accelerating structure, the experimental area was upgraded and improved. The beam transport system now has two lines (Figure 5): “0-degree” and “10-degree”. The “10-degree” line is connected to the shielded box that protects the surrounding area from the target radiation field. The “0-degree” line has an alpha-magnet and two 45-degree bending magnets to have a possibility of putting an electron beam into the shielded box from opposite side, which is required for a double-side target irradiation experiment for NorthStar Medical Technologies [3]. Part of the beam line on the “0-degree” branch is easy to remove, and this place can be used for installing an additional target.
To process the liquid target from the shielded box, two glove boxes were installed in the experimental area. Gas analysis and gas collection systems are used to analyze and collect gases produced during target irradiation. The shielded box, glove boxes and enclosures for gas collection and gas analysis systems are constantly under negative pressure and are connected to the ventilation system with high-efficiency particulate arrestance (HEPA) filters, to prevent airborne contamination of the experimental area.

![Figure 5. Experimental area.](image)

6. SCIENTIFIC PROGRAM

The National Nuclear Security Administration’s (NNSA) in partnership with commercial entities and the US national laboratories, is working to accelerate the establishment of a reliable domestic supply of Mo-99 for nuclear medicine while also minimizing the civilian use of HEU. Argonne National Laboratory (ANL) is supporting NorthStar Medical Technologies and SHINE Medical Technologies in their efforts to become domestic Mo-99 producers. NorthStar Medical Technologies, LLC is utilizing the photonuclear reaction in an enriched Mo-100 target for the production of Mo-99. In this approach a high-power electron accelerator is used to produce the required flux of high energy photons through the bremsstrahlung process. SHINE Medical Technologies is developing SHINE, a system for producing fission-product $^{99}$Mo using a D/T-accelerator to produce fission in a non-critical target solution of aqueous uranyl sulfate. ANL is assisting SHINE in development Mo-99 separation and purification system using mini-SHINE experimental setup [3, 4, 5]. LEAF linac was used in number of experimental activities related to medical isotopes development program. Some of the experiments are:
- Mo-99 production via gamma/n reaction on Mo-100 (NorthStar).
- Mo-99 production in mini-SHINE experiments (SHINE)
- Cu-67 production experiments
- Radiolysis of uranyl sulfate solution “Bubble” visualization experiments
For the period of 2013-2015, multiple experiments were performed at the linac (Figure 6). Beam parameters used in irradiations depend on the specific experimental requirements presented in the Table II. In all experiments, the beam length was 5.0 µs, with a duty factor up to 0.1%.

<table>
<thead>
<tr>
<th>Repetition range</th>
<th>15-200 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>30-42 MeV</td>
</tr>
<tr>
<td>Average beam current</td>
<td>100-300 µA</td>
</tr>
<tr>
<td>Average beam power</td>
<td>up to 15 kW</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

The goal of this upgrade was to increase the electron beam power and energy to enable efficient production of medical isotopes. Tests of the structures with high beam load have shown what the actual parameters of the installation are close to design parameters. Multiple experiments have demonstrated that linac is very reliable tool for development of novel approaches in medical isotope production. High average power and energy make LEAF an attractive installation for experiments in the low energy region by using the $(\gamma, n)$ and $(\gamma,p)$ reaction.

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REFERENCES


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