

# COMPACT, INEXPENSIVE X-BAND LINACS AS RADIOACTIVE ISOTOPE SOURCE REPLACEMENTS\*

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## Abstract

Radioisotope sources are commonly used in a variety of industrial and medical applications. The US National Research Council has identified as a priority the replacement of high-activity sources with alternative technologies, due to the risk of accidents and diversion by terrorists for use in Radiological Dispersal Devices (“dirty bombs”). RadiBeam Technologies is developing novel, compact, inexpensive linear accelerators for use in a variety of such applications as cost-effective replacements. The technology is based on the MicroLinac (originally developed at SLAC), an X-band linear accelerator powered by an inexpensive and commonly available magnetron. Prototypes are currently under construction. This paper will describe the design, engineering, fabrication and testing of these linacs at RadiaBeam. Future development plans will also be discussed.

## INTRODUCTION

Approximately 5,000 devices containing 55,000 high-activity radionuclide sources are in use in the United States today, in applications ranging from cancer therapy to oil exploration [1]. Such sources are classified by the International Atomic Energy Agency into five categories based on their relative danger. Category 2 devices can deliver a fatal dose if the unsafe exposure takes place over the course of hours or longer. Eighty percent of the radionuclide devices in the US are Category 2 gamma emitters (Ir-192, Cs-137, Co-60 and Se-75), used for industrial radiography, well logging, or in self-contained irradiators (e.g. blood irradiators).

RadiaBeam Technologies is developing inexpensive, compact accelerators to replace radionuclides in such applications. The accelerator, which we term the MicroLinac, is based on an X-band RF linac design developed at SLAC [2], and is powered by an inexpensive, commercially available magnetron RF source. While linacs are commonly used for industrial radiography and other applications, they are typically large and expensive. The innovation of the MicroLinac is the use of an inexpensive, low-power magnetron to power the structure, which not only greatly reduces cost compared to other linacs, but reduces the heat deposited and thus eliminates the need for water-cooling. The use of X-band power also allows the system to be relatively compact.

Two MicroLinac systems are currently in fabrication: a

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1 MeV version for industrial radiography, and a 2 MeV version for self-contained irradiators.

## INDUSTRIAL RADIOGRAPHY

Gamma-ray radiography is commonly used in industry for the nondestructive inspection of items such as pipes, boilers, vehicles, aircraft, and rebar reinforcements in concrete. The most common isotopes used for radiography are Ir-192, which produces an average gamma energy of 380 keV and has a half life of 75 days, and Co-60, with an average energy of 1.25 MeV and 5.3 year half life. Due to its short half-life, Ir-192 poses less of a threat than Co-60, however it has a higher risk of being diverted since it must constantly be replenished. We have chosen to start with a 1 MeV version of the MicroLinac for this application (see Fig. 1), which can achieve similar radiographic penetration to Ir-192 gamma-rays.

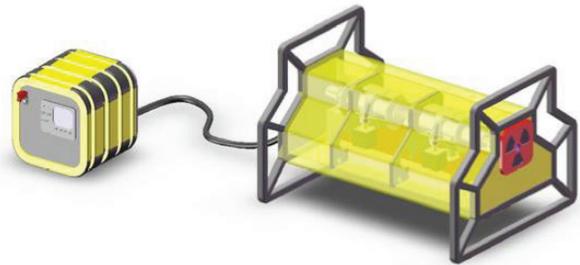


Figure 1: 1 MeV MicroLinac for industrial radiography.

Table 1: 1 MeV MicroLinac Parameters

Parameter	Value
Energy	1 MeV
Average current	10 $\mu$ A
Dose rate (at 1 m)	100 R/hr
Total length (both sections)	62 cm

## Linac Design

The original MicroLinac developed at SLAC consisted of two  $\pi$ -mode standing wave linac sections, each approximately 20 cm long, separated by a bellows for phase adjustment. A  $\pi$ -mode design was chosen due to easier fabrication. Electrons are injected into the first (anode) cell by an inexpensive 14 kV electron gun. The linac was designed to operate with power from a 50 kW peak-power fixed-frequency magnetron used for radar

applications. Due to the low average power, the structure does not need water-cooling; however a method of controlling the magnetron frequency is required. The basic parameters are shown in Table 1.

RadiaBeam has adopted SLAC’s linac design approach for the 1 MeV MicroLinac, however for both of the initial prototypes, in order to simplify initial testing, we will use a more powerful magnetron with tunable frequency over the range of 8.5 - 9.6 GHz (see Fig. 2). The peak power is 220 kW, and with a maximum 0.1% duty cycle, the average power is 220 W. The anode is air-cooled and the magnetic field is provided by integral permanent magnets. The RF output is coupled to WR-112 waveguide. After the linac is fully operational with this power system, we will transition to the less expensive regime.

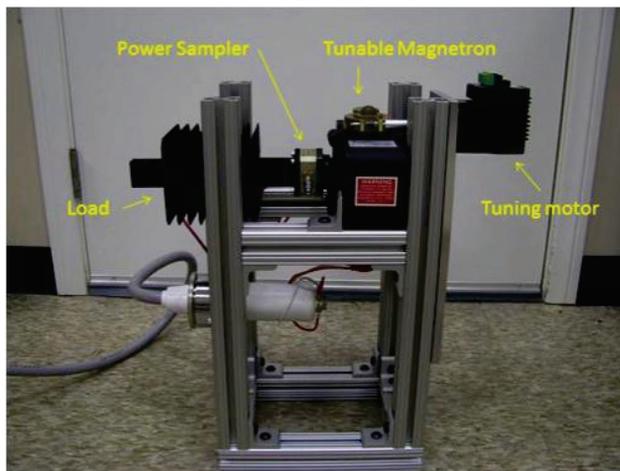


Figure 2: Tunable X-band magnetron being used for initial prototype testing.

Thorough RF and beam dynamics simulations were performed, and the mechanical engineering, machining, and brazing of the linac has been completed. An output plot from the PARMELA simulations is shown in Fig. 3.

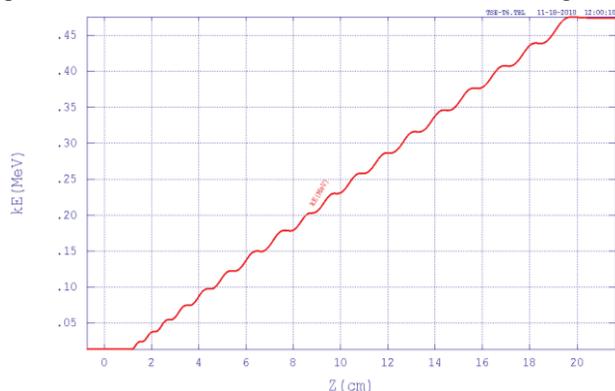


Figure 3: PARMELA simulation of the first section of the 1 MeV MicroLinac, showing 500 keV energy gain.

Full system testing has also been completed, with the gun voltage, grid voltage, gun current, and accelerated current monitored to evaluate gun and accelerator performance.

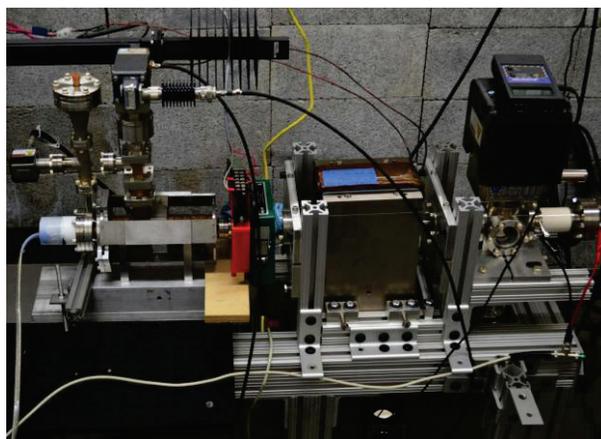


Figure 4: Current setup of the MicroLinac. From left to right: blue/white electron gun, accelerating structure with focusing magnet, orange steering magnet, green Pearson current transformer, spectrometer chamber with dipole, diagnostic cube and ion pump, dielectric break, and Faraday cup terminated into 50 Ohm load.

To characterize the beam energy and spread, the magnet field was first measured as a function of current. By sweeping the current passed through the dipole, we were able to deflect the electron beam onto the scintillator. The beam energy and spread could then be calculated from the strength of the magnetic field and relative intensity of the image. During commissioning of the spectrometer, we found it necessary to install a small steering magnet to properly align the beam with magnetic field.

With the spectrometer installed and working, we searched for the optimal set of operating parameters, varying the RF frequency, power and beam current. We just recently achieved peak energy of 520 keV (Fig. 5), which is higher than the design value. Although the energy spread appears to be quite large at this energy, we believe that this is due to the excessive RF power provided. These parameters will be further optimized in the near future.

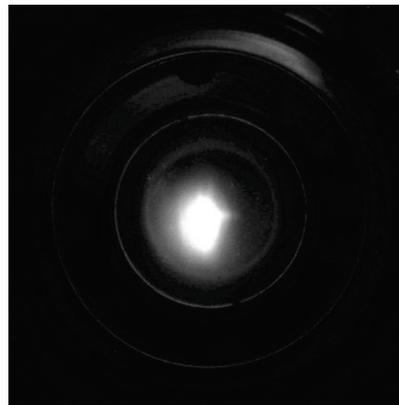


Figure 5: Beam image downstream of the 90° bend (6 in. radius) at 10 mA accelerated beam current and 520 keV energy.

## SELF-CONTAINED IRRADIATORS

A self-contained irradiator is a device in which the sealed radioactive source is kept shielded at all times and human access to the source and the volume undergoing irradiation is not possible during normal operation. They are used for a number of applications, such as blood irradiation to prevent Graft-Versus-Host-Disease, biomedical and radiation research, and detector calibration. They typically use a sealed Cs-137 source to irradiate an item within a treatment compartment. Cs-137 is a particularly dangerous radioisotope, as it has very long half-life (30 years) and usually comes in a powder salt form (cesium chloride), which is soluble in water, highly dispersible and highly reactive. Bremsstrahlung from a 2 MeV linac can approximate the penetration of the Cs-137 gamma-rays (660 keV). We calculated (and verified with Monte-Carlo simulations) that 70  $\mu$ A of average current is sufficient to approximate the dose rate of a small Cs-137 irradiator (see Table 2).

Table 2: 2 MeV MicroLinac Parameters

Parameter	Value
Energy	2 MeV
Average current	70 $\mu$ A
Dose rate (at 1 m)	30 cGy/min
Total length	48 cm

### Linac Design

Since the self-contained irradiator version of the MicroLinac must operate at higher energy and power, we decided to use a  $\pi/2$  mode design. The  $\pi/2$  mode standing wave guide is the most popular design for medical and industrial linacs, due to its relative insensitivity to thermal and input power variations. Coupling between cells will be achieved with side-coupling. RF design was performed with SUPERFISH and HFSS. Beam dynamics were modeled with PARMELA (output shown in Fig. 6).

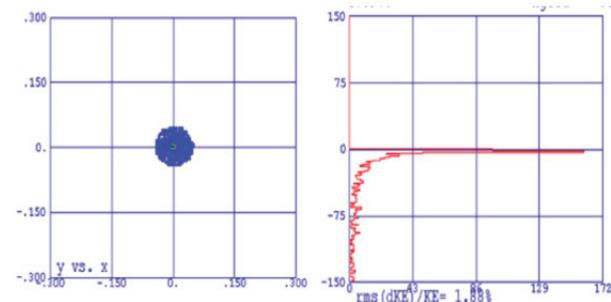


Figure 6: Output parameter of PARMELA. Left: electron position in x-y plane normal to the beam, units of cm. Right: energy spectrum at exit; units of keV vs. number of particles.

The linac has been fully designed, engineered, simulated, and machined (Fig. 7). It is now awaiting cold testing, which will be followed by brazing.

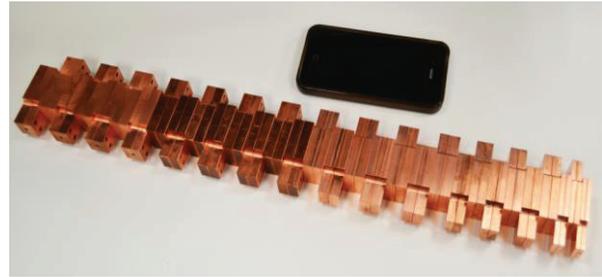


Figure 7: 2 MeV MicroLinac, with mobile phone shown for scale.

In addition to the linac, a full self-contained irradiator system will be fabricated. A dipole magnet will bend the beam and scan it across the X-ray target. The X-rays will be used to irradiate the material in a nearby chamber. RadiaBeam is working with a nearby manufacturer of such systems to design the shielded enclosure and controls. A conceptual rendering of a self-contained irradiator using the MicroLinac is shown in Fig. 8.

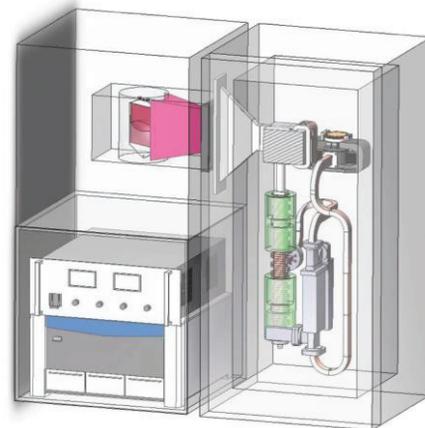


Figure 8: Conceptual design of the 2 MeV MicroLinac configured in a self-contained irradiator.

## ACKNOWLEDGMENT

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- [2] N. Ackerman et al., "MicroLinac – A Portable Accelerator for Radiography," The 12<sup>th</sup> Advanced Accelerator Concepts Workshop, (2006).