DESIGN OF A COMPACT, INEXPENSIVE LINAC FOR USE IN SELF-CONTAINED IRRADIATORS*

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Abstract

Self-contained irradiators 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. The US National Academy of Sciences has identified as a priority the replacement of such high-activity sources with alternative technologies, in order to prevent them from falling into the hands of terrorists for use in a Radiological Dispersal Device ("dirty bomb"). RadiaBeam Technologies is developing a novel, compact, low-cost linear accelerator – the MicroLinac – for use in self-contained irradiators in order to effectively replace Cs-137 in such devices. A previous version of the MicroLinac, originally developed at SLAC, was designed to produce 1 MeV electron energy and 10 μA of average current. RadiaBeam has redesigned the linac to produce 2 MeV and 70 μA current, in order to match the penetration and dose rate of a typical blood irradiator. This paper describes the new design of the MicroLinac and our future development plans.

INTRODUCTION

Blood irradiators belong to a class of devices called self-contained irradiators, 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 [1]. The source is transferred from a shielded storage area into the treatment compartment, and a container with blood products rotates near the source for even distribution. Apart from irradiation of blood products, self-contained irradiators are also used for biomedical and radiation research and calibration of detectors.

Cs-137, with a half-life of 30 years and 660 keV gamma energy, is the most common material used in these irradiators. The long half-life is advantageous for use in self-contained irradiators, since the source can last for the lifetime of the device without being replenished, however this also makes it a very dangerous component of an RDD. Furthermore, Cs-137 is usually supplied in a powder salt form (cesium chloride), which is soluble in water, highly dispersible and highly reactive. Thus it is an extremely dangerous material, as demonstrated by the infamous Goiania accident [2] in which 60 g of radioactive cesium chloride was accidentally spread throughout a city in Brazil, contaminating hundreds of people and requiring millions of dollars of cleanup.

In order to prevent future accidents and potential terrorist attacks, the National Academy of Sciences has appropriately identified the replacement of Cs-137 irradiators with safer alternatives as a priority [3]. There are some X-ray tube-based irradiators commercially available, most notably the Raycell from MDS Nordion, however they have seen very limited adoption due to low throughput, high capital cost, and high maintenance costs.

RadiaBeam is developing a novel type of accelerator, the MicroLinac, which was originally developed at SLAC as a cost effective, portable radiation source for the replacement of Ir-192 in industrial radiography. The MicroLinac is a compact, X-band linear accelerator, able to produce radiation that matches the penetration of the most common radionuclide sources and poses no proliferation hazards. While linacs are commonly used for industrial sterilization, they are very expensive (~ $1 million). 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 principle advantage of the MicroLinac over Cs-137 for irradiation is safety and security. Compared to the X-ray irradiators, the MicroLinac allows much greater throughput due to the higher photon energy and more efficient X-ray production. As the average photon energy is similar to that of Cs-137, new protocols and calibration to previous experiments will be easier. The Microlinac also uses low cost, commercially available components. So the MicroLinac should prove to have high reliability, as all of the components are comparatively low-power.

The goal of the project is to design a MicroLinac system with the output parameters required for self-contained irradiators (see Table 1), and a beam delivery/X-ray conversion system to produce sufficient dose uniformity on the irradiation volume. We will concentrate the initial efforts on designing a system for standard 3.7 L canisters of blood product however later efforts may be directed toward treating larger volumes.

Table 1: MicroLinac output parameters for blood irradiation.

Output Electron Beam Energy	2 MeV
Avg. Beam current	70 μA
Dose Rate (in 3.7L of blood)	4 Gy/min

DETAILED DESIGN

RF Power System

A block diagram of the RF system is displayed in Figure 1. There three major parts of the system are the magnetron, the modulator and the RF circulator.

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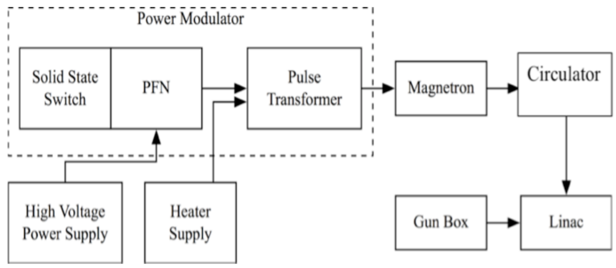

Figure 1: RF system diagram.

The magnetron that we have chosen for the blood irradiator MicroLinac system is a coaxial magnetron made by a local manufacturer. It is tunable over the range 8.5 – 9.6 GHz. The peak power is 220 kW, and with a specified 0.1% duty cycle, the average power is 220 W. The anode is air-cooled. The magnetic field is provided by integral permanent magnets. The RF output is coupled to WR-112 waveguide.

The modulator provides the energy pulse to drive the magnetron. It will output 20 – 24 kV pulses, with 28 A current, a pulse width of 1 μsec and a repetition rate of 1000 pps. In the initial SLAC MicroLinac project used an inexpensive, solid-state modulator, based on NLC technology, to drive both the magnetron and the diode gun. The modulator was powered with single-phase 120 VAC, and produced 15 kV, 7 A, 1 μs pulses at 1 kHz. The total cost of parts was < $5k. We will adapt this technology for the new MicroLinac.

The circulator for this blood irradiator system will be the XC3 series from the Ferrite Company. The Ferrite X-band circulators have been widely used in conjunction with many types of magnetrons.

Linac Design

The original SLAC design for the MicroLinac was a π mode standing wave structure. The mode frequency separation in π mode is much smaller than in π/2 mode. With a given cell-to-cell coupling, when the number of cells increases, the mode separation becomes smaller. So the SLAC prototype of MicroLinac was limited to 18 cells per section. For our application, at least two sections would have to be used to reach the intended energy level for the SLAC design with π mode structure. That increases the system complexity and the cost of linac because of the two separate RF feeds.

The π/2 mode standing wave guide (SWG) is the most popular design for medical and industrial linacs, due to its relative insensitivity to thermal and input power variations. To illustrate why, we draw the readers attention to Figure 2, which displays the resonances (i.e. S21) of a linac guide versus RF frequency. In an *N*-cavity RF structure, where *N* is the number of coupled cavities, there are *N* possible operational modes. Regardless of the number of cells, the π/2 accelerating mode offers the largest frequency separation between adjacent modes (mode separation), as can be seen in Figure 2. This makes a π/2 accelerating structure robust to frequency shifts due to thermal and/or RF power fluctuations, which is why π/2 structures are the most commonly used for industrial linacs. By using π/2 mode, the energy can be achieved with one section of linac, thus reducing the system cost.

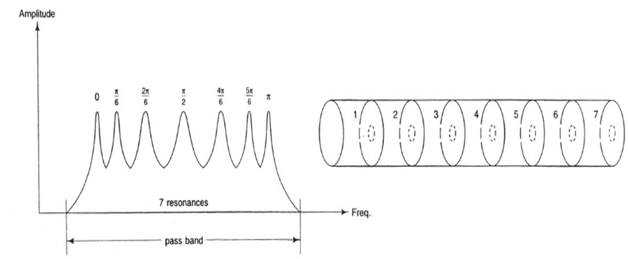

Figure 2: Layout of papers.

Since each alternative cell is idle when operating at π/2 mode, they can be moved off the beam line, as long as they keep the same frequency. This is called a side-coupled structure.

The cavity optimization was be achieved by running SUPERFISH code, which is an electromagnetic field solver. The following picture is a quarter of a full cavity from a typical SUPERFISH calculation.

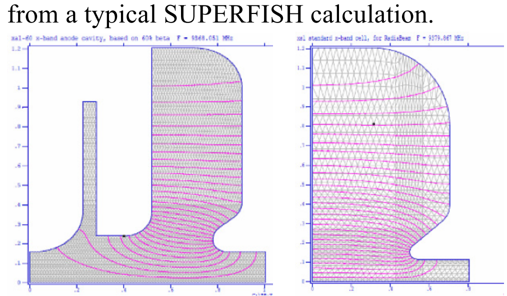

Figure 3: Typical SUPERFISH Output graphs for Cavity Optimization. LEFT: first half cavity. RIGHT: Standard cavities

For an X-band, π/2 mode, side-coupled standing wave structure, the length of each standard cavity (where β≈1) is half of the wavelength. Thus, with a 9300 MHz RF source, the standard cell length is about 1.6 cm. The length of the buncher cells, where β<1, will be shorter.

To understand the effect of the side-cell and accurately simulate the frequency and cell to cell coupling, a 3D calculation has been studied with the code HFSS. The simulations have confirmed that the frequency of the accelerating mode in the finalized structure is 9300MHz and cell to cell coupling is 5% with proper geometry of the side cells.

Beam dynamics is simulated with code PARMELA. EGUN output. The input RF field profile is from the SUPERFISH output. Only the main cell fields are considered during calculation. The fields in the coupling cells are small in the operation mode, thus they have little effects on electron beam. A solenoid with peak field of 900 gauss is also included.

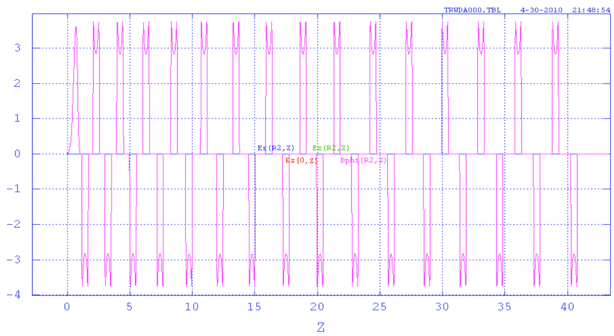

Figure 4: Field profile along the beam axis.

The on-axis electric field profile used by PARMELA is shown in Figure 4. While the output parameters, the beam profile and energy spectrum are shown in Figure 5.

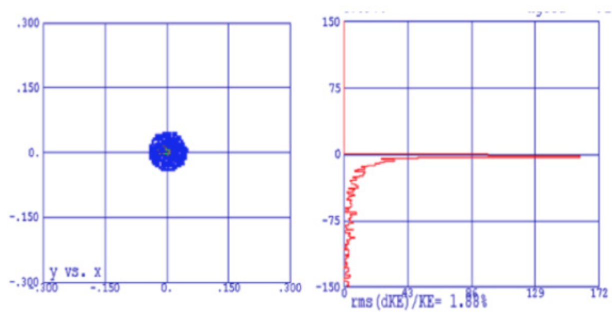

Figure 5: Output parameter of PARMELA. Left: electron position in x-y plane normal to the beam, units of cm. Right: energy spectrum at exit; units of keV vs number of particles.

The Monte-Carlo simulations of dose deposition within the canister were performed with the Integrated Tiger Series 3.0 code. The X-ray target itself will consist of a 240 µm thick tantalum foil welded onto a 2.2 mm sheet of aluminum. The assembly will be 15 cm tall by 2 cm wide. A scanning dipole is needed for bending and spread the beam on the target to reduce head and increase uniformity of the radiation.

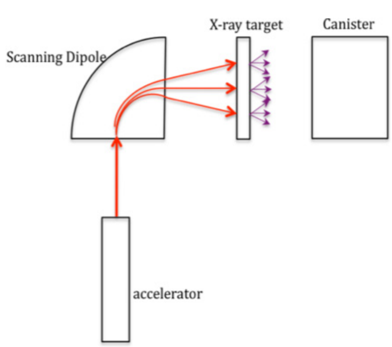

Figure 6: Scaning dipole system diagram

Irradiator System Design

In addition to the design of the MicroLinac itself, we have worked collaboratively with J.L. Shepherd & Associates, Inc. to design the complete irradiator system and prepare for integration. A conceptual drawing is shown in Figure 6.

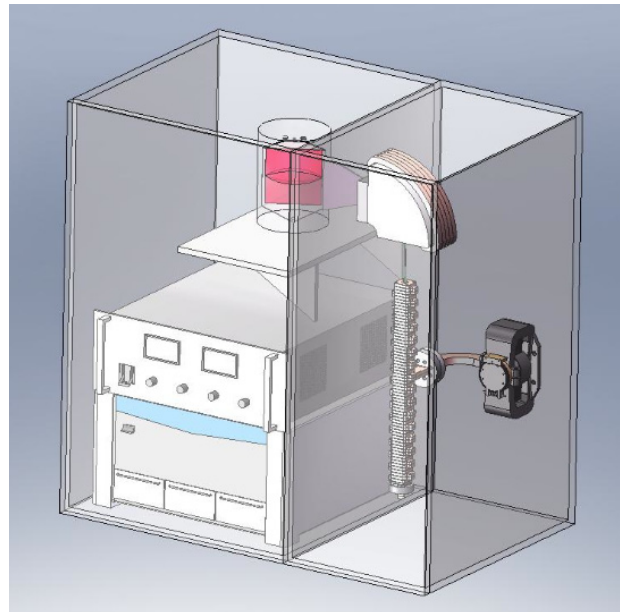

Figure 6: Conceptual design of the MicroLinac Blood Irradiator

CONCLUSIONS

In conclusion, the linac system was designed to produce a 70 µA, 2 MeV beam. The required RF drive power and input electron current were determined. The internal dimensions of the linac structure were optimized. The target and scanning dipole systems are also studied, and a design for the complete irradiator system was generated. We are currently applying for Phase II SBIR funding for the project. If funded, we plan to build and test the MicroLinac, as well as to integrate it into a blood irradiator system.

REFERENCE

[1] ANSI, 1977 ANSI, American National Standard N433.1 of the American National Standards Institute, Sub-Committee N43.3.4. NBS Handbook 127, U.S. Department of Commerce, Gaithersberg, U.S.A (1977).

[2] "The Radiological Accident in Goiânia", IAEA Report, (1988).

[3] "Radiation Source Use and Replacement: Abbreviated Version," Sciences Committee on Radiation Source Use and Replacement, National Research Council (2008)