Design of robust microlinacs for wide replacement of radioisotope sources

A V Smirnov¹, R A Agustsson², S Boucher¹, M Harrison¹, K Junge², E Savin³ and A Yu Smirnov²

¹RadiaBeam Systems, LLC, Santa Monica, CA 90404, USA; ²RadiaBeam Technologies, LLC, Santa Monica, CA 90404, USA; ³National Research Nuclear University “MEPhI”, Moscow, 115409, Russian Federation

asmirnov@radiabeam.com

Abstract. To improve public security and prevent the diversion of radioactive material for Radiation Dispersion Devices, development of an inexpensive, portable, easy-to-manufacture linac system is very important. The bremsstrahlung X-rays produced by relativistic electron beam on a high-Z converter can mimic X-rays radiated from various radioactive sources. Here we consider development of two designs: one matching a Ir-192 source used in radiography with ~1-1.3 MeV electrons, and another one Cs137 source using 3.5-4 MeV electrons that can be considered for borehole logging. Both designs use standing wave, high group velocity, cm-wave, accelerating structure. The logging tool conceptual design is based on KlyLac concept combining a klystron and linac operating in self-oscillating mode and sharing the same vacuum envelop, and electron beam.

1. Introduction

Linear accelerators of electrons are employed in a wide variety of applications, including radiography and sterilization, radiolysis and imaging, modification of materials and borehole logging as well as testing of semiconductor electronic components for space applications. Among emerging applications is driving table-top sub-mm wave sources [1] and replacement of radionuclide sources [2] to improve public security and prevent the diversion of radioactive material for radiation dispersion devices. A challenging specific of such a replacement is inexpensive, portable, easy-to-manufacture linac system delivering relativistic electrons. The bremsstrahlung X-rays produced by the electron beam on a high-Z converter at the end of the linac may match the penetration and dose rate of a radionuclide source to be substituted using beam energies, e.g., ~-(1-1.3) MeV for Ir192 and ~-(3-3.5)MeV for Cs137.

As a rule classical linac system is rather expensive and not portable. MicroLinac technology originally proposed at SLAC [3] employs a compact X-band linear accelerator powered by an inexpensive, low power, magnetron [4,5]. However, to make the MicroLinac concept suitable for a wider scope of applications, the compact linac technology needs to be advanced to reduce further cost, weight, and dimensions. One such modification may employ of a light-weight, compact modulator, using, e.g., a transformer-free Marx scheme with array of isolated gate bipolar transistors (IGBTs).

However, fabrication of a multi-cell, tapered MicroLinac structure (usually side coupled periodic or circular disk loaded) remains rather expensive and time consuming. It includes high precision
machining, cold-testing and re-machining of the cells, testing of the clamped assembly, multi-step brazing, and individual tuning of the cells and of the brazed assembly.

A relatively unexplored candidate for a slow wave structure of a robust MicroLinac is a so-called cross-bar (“jungle-gym” or “loaded easitron”) structure. Such an accelerating structure have been first considered among variants for the SLAC two-mile accelerator [6] and analysed later numerically [7].

Among attractive features of this structure for MicroLinac is a high group velocity (>0.2c), possibility for simplified fabrication (including low-beta cells), and compactness (transverse dimensions are about half a wavelength).

In this paper we focus solely on resonant, standing wave (SW) mode of operation as being more effective for implementation in miniature RF linacs, though the cross-bar structure can be employed in a traveling wave mode as well.

A single section is a preferable option for a MicroLinac to avoid problems of inter-section detuning and RF network complexity. On the other hand, requirements imposed by cost, weight, or compactness may seriously limit the RF power available. That dictates a significant number of cells of linac section. For a SW single-section linac the solution is high enough group velocity which also determines the structure robustness in terms of sensitivity to tolerances related to production cost.

For borehole logging the conventional linacs with their automatic frequency control (AFC) system, ferrite-based circulator, and magnetron are not suitable because of very limited borehole diameter (3.5” is of practical interest), temperatures as high as 150°C at the depths ~kilometre, and vibrations with accelerations ~2G. KlyLac concept [8,9,10,11] offers an alternative, rugged approach to this problem. Both KlyLac and KlyNac [12,13] concepts are based on a combination of klystron and linac sharing the same vacuum envelop and electron beam.

Below we discuss some of the developments related to ~1 MeV MicroLinac and 3.8 MeV KlyLac with emphasis made to performance of the long “jungle-gym” accelerating structure.

2. Linac section of 1 MeV for Ir192 replacement

A 36-cell, cross-pin, X-band structure shown in Figure 1 has been designed using CST Suite™ [14] frequency domain solver and SolidWorks. The structural design takes into account specifics related to brazing of the 1.75 mm pins (which are available from third parties).

![Figure 1](image)

**Figure 1.** Cut-view of linac design with elliptical RF coupler, two vacuum ports, electron gun, and three-section alternating solenoid focusing.

S11 curves and the operating mode profile along the section are shown in Figure 2 and Figure 3 respectively. The results are obtained with a very high degree of confidence due to fast and stable convergence relatively insensitive to meshing (vs., e.g., DaR [15] or circular disk loaded structures).

Note as large as ~(70-100) MHz separation between adjacent modes exceeds by about two orders that for conventional circular disk loaded cavity having a comparable number of cells and resonant frequency.

Beam dynamics have been simulated for ~14 keV injection energy and ~0.15 T magnitude of on-axis longitudinal magnetic field. Complex RF fields (with magnitude shown in Figure 3) have been exported from CST Suite™ results into ASTRA code [16]. Simulation results are shown in Figure 4.
One can enhance capture if the pins are made from copper-plated mild steel. One configuration with the “passive” magnetic pins included into the full magnetic model with the focusing PM-based solenoid is shown in Figure 5. As it can be seen from Figure 5 presence of the iron pins results in two effects: a) magnetic field magnitude increase by ~16%; and b) strong derivatives of the local fields (i.e. local enhancement of transverse fields).

**Figure 2.** S11 curve simulated for the finalized RF model of Figure 1.

**Figure 3.** Magnitude for longitudinal RF electric field profile along the axis of RF model of Figure 1.

**Figure 4.** RMS Emittance (blue, right ordinate) and beam rms dimensions (red, left ordinate) (a) simulated with Astra code for the field profile of Figure 3. Beam energy gain plotted along the structure for ~100 kW RF power (b). Beam capture is ~17%.
**Figure 5.** Magnetic model with RF structure pins made from mild steel and copper plated inside the PM focusing system (a) and magnetic field profile along the axis perturbed by the pins (b).

Beam dynamics simulations results are given in Figure 6. The ASTRA results indicate significant increase of beam capture by 32% (at the expense of lower energy).

**Figure 6.** LEFT: RMS Emittance (blue, right ordinate) and beam rms dimensions (red, left ordinate) simulated with ASTRA code. RIGHT: Energy gain along the MicroLinac. Focusing field profile is given in Figure 5.

3. A conceptual design of a few MeV KlyLac

The results above are encouraging to apply the cross-bar type structure for a much longer section required for replacement of Cs137. The KlyLac concept using a sheet beam klystron (SBK) combined with the cross-bar structure is illustrated in Figure 7. A 1.3 m long linac section with about hundred cells is characterized in Figure 8 and Figure 9. It demonstrates excellent RF performance and rather uniform field distribution along the section at as large as 31 MHz separation between the adjacent modes.

**Figure 7.** A cut-view fragment of a KlyLac generating-accelerating conceptual design. SBK cavities are given in gray. The maximum diagonal dimension of the structure is 1.5". Sheet beam electron gun is not shown.

**Figure 8.** Field magnitude simulated along the 1.3 m long cross-pin linac section.

One variant of the linac focusing system we applied to the KlyLac is an alternating solenoid focusing system formed simply by three stacked focusing systems of Figure 1. To simulate and
analyse beam dynamics we applied the RF fields simulated above (see Figure 8). As it can be seen from Figure 10a,b the ASTRA simulations resulted in 3.72 MeV output energy and ~15% capture coefficient.

![Figure 9. S11-curve for two-port, 1.3 m long section.](image)

![Figure 10. Kinetic energy [MeV] (a), the beam rms size and transverse emittances (b) plotted along the linac section [m]. The pulsed microwave power is 575 kW at ~9.4 GHz frequency.](image)

### 3.1 Modelling of feedback operation

A number of CW and pulsed klystrons operate in a self-oscillating mode (some of them being employed even without circulator). However, to understand and design such a self-adjusted system a corresponding model is vital, because in general a positive feedback is vulnerable to instabilities. Such a transient model with delayed feedback loop starting from noise has been built. The model is based on classical Slater [17] and Vainshtein [18] theories of cavity excitation and includes a) feedback with adjustable gain; b) variable group delay Δt delay of the feedback; c) realistic modulator envelope with adjustable duration tHVpulse, raise Δraise, and fall times; d) realistic non-linear gain as a function of input power in a wide range imported from sheet-beam klystron simulations; e) variable attenuation Kprobe in the feedback loop; f) frequency detuning and loop phase shift; and g) a conservatively estimated noise level and noise figure as a seed triggering the self-oscillation. The model has been extensively benchmarked using known analytical solutions and experimental data (including RF compression setups such as SLED).

As it is shown in Figure 11, left improper choice of the feedback parameters may result in instabilities and bifurcations. One of the main limitations imposed on VSWR in ordinary high power RF sources is RF window. Since the KlyLac system does not employ circulator and RF windows we conservatively determined that the safe margin for the peak reflected power would be ~33% level of full power of (which corresponds to peak VSWR=3.7). We found several stable solutions with satisfactory moderate reflections (given in Figure 11 on the middle and right).
Figure 11. TOP: Waveforms for accelerating voltage at feedback loop (red, top) and HV envelope normalized to max energy gain (dashed blue). BOTTOM: Forward (dashed blue) and reflected (red) power waveforms. LEFT: \( \Delta \text{raise}=0.15\mu s, \ t\text{HVpulse}=3 \mu s, \ K\text{probe}=-50\text{dB}, \ \Delta \text{delay}=150\text{ns}. \) Cavity Rsh=25 M\text{Ohm}. MIDDLE: \( \Delta \text{raise}=0.075\mu s, \ t\text{HVpulse}=3 \mu s, \ K\text{probe}=-62\text{dB}, \ \Delta \text{delay}=(30-60)\text{ns}. \) RIGHT: \( \Delta \text{raise}=0.3\mu s, \ t\text{HVpulse}=5 \mu s, \ K\text{probe}=-62\text{dB}, \ \Delta \text{delay}=40\text{ns}. \)

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