KLYNAC DESIGN SIMULATIONS AND EXPERIMENTAL SETUP

K. E. Nichols, B. E. Carlsten, A. Malyzhenkov,
Los Alamos National Laboratory, Los Alamos, USA

Abstract

We present design simulations and experimental setup for the first ever experimental demonstration of a bi-resonant klynac; klynac is a term coined for a compact linear accelerator with integrated klystron source utilizing the same electron beam. This device is bi-resonant, one resonant circuit for the klyston input and gain cavities, and one for the klystron output and linac cavities, the schematic is presented in Fig. 1. The purpose of a klynac-type device is to provide a compact and less expensive alternative for an accelerator up to 6 MeV. A conventional accelerator requires a separate RF source and linac and all the associated hardware needed for that architecture. The klynac configuration eliminates many of the components to reduce the weight of the entire system by 60%. We have built an 8-cavity, 2.84 GHz RF structure for a 1 MeV klynac. A 50-kV, 10-A pierce-type electron gun provides the single beam needed. Numerical modelling was used to optimize the design. The separation between the klynac output cavity and the first accelerator cavity was adjusted to optimize the bunch capture and a pin-hole aperture between the two cavities reduces the beam current in the linac section to about 0.1 A. Standard high-shunt impedance linac cavity designs are used. We have fabricated the first test structure and present very preliminary results.

DESIGN PROCESS AND SIMULATIONS

Design

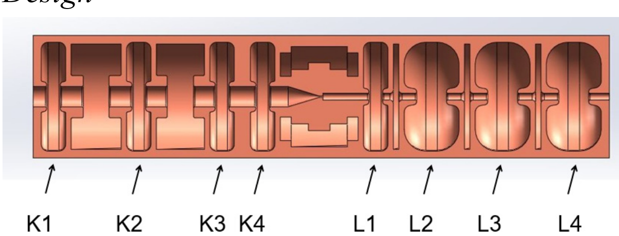

Figure 1: Schematic of the Klynac design. K1, K2, and K3 form one resonant cavity and serve the purpose of gain cavities. K4 is the gain output cavity and L1-L4 are the accelerating cavities, together they form the second resonant circuit. Unmarked cells are coupling cells and have 0 field in the π/2 mode.

The klystron input cavity is K1 which forms a resonant circuit with the two RF gain cavities, K2, and K3. The RF output cavity, K4, as well as the four linac cavities, L1, L2, L3, and L4, form a second resonant structure. Additionally, K4 acts as a conventional klystron output cavity, generating RF power that is then used to drive the linac cavities and accelerate the electron beam. This structure resonates in the π/2 standing-wave mode, therefore the fields in the coupling cavities are negligible and they can be ignored in the design analyses. Note that this mode ensures that successive klystron cavities are 180º out of phase with the previous cavity, but cavity amplitudes can be designed to maximize the extraction power. The cavity locations in the gain section are similarly chosen to maximize harmonic current. An efficiency of 38% was achieved for the gain section, we believe that could be improved upon. The separation between K4 and L1 is adjusted to optimize the bunch capture in L1. An intercepting aperture between cavities K4 and L1 reduces the beam current in the linac section to about 1% of that in the klystron section, this is the amount of beam current that can be accelerated with the power delivered by the gain section. The amount of beam current in the linac section is adjustable by pinching the beam with an external magnetic field. The coupling cell between K4 and L1 is special because it is not open to the axis, it is a toroidal cavity rather than a pillbox cavity [1]. Once the beam reaches L2, it is relativistic. Thus the separation between L2 and L3, and L3 and L4 are close to half the free-space wavelength of the klynac's operating frequency. Standard high-shunt impedance linac cavity designs are used. Both the gap in L1 and the center-to-center separation of L1 and L2 are shortened to provide for better capture of the initially low energy electron beam injected into the linac section.

Table 1: Nominal 1 MeV Klynac Parameters from Simulations

Nominal Design Parameters 1 MeV Klynac	**Value**
RF power generated	160 kW
Number of linac cavities	4
Linac cavity impedance	8.5 MW
Linac cavity transit time factor	0.80
Linac cavity gap voltage	440 kV
Linac electron beam current	0.09 A
RF power dissipated in linac section	69 kW
RF power into beam power	91 kW
Final beam energy	1.00 MeV
RF power generated	160 kW

The cavity voltages in the accelerating cavities were determined from the klynac power balance, which can be approximated as:

ISBN 978-3-95450-169-4

$$0 = \eta I_0 V_0 - \left(3+\varepsilon^2\right)\frac{V_L^2}{Z_L} - \left(3+\varepsilon\right) I_L T_L V_L \qquad (1)$$

where I_0 and V_0 are the klystron section beam voltage and current, η is the RF power conversion efficiency of the klystron section, I_L is the electron beam current in the linac section, T_L is the transit-time factor for the linac cavities, V_L is the voltage of linac cavities L2 through L4, and Z_L is the cavity impedance of linac cavities L2 through L4. Note that here we are using the accelerator community convention of cavity impedance instead of the RF source community convention, defined by $Z_L T_L^2 = (V_L T_L)^2 / P$, where we recognize $V_L T_L$ as the maximum energy gain of the electrons in the linac cavities and P is the RF power dissipated in the cavities. Additionally, in (1) we assume that L1 has the same impedance as L2, L3, and L4, and a relative amplitude of ε and that the RF power dissipated in the klystron cavities is negligible.

Equation (1) states that power balance is established when the RF power generated in the klystron section is equal to the RF power dissipated in the linac cavities and the RF power that goes into the electron beam. Roughly speaking, we design the device to have about half the power going into the RF losses and half into the beam; if much less than half of the power goes into RF losses, the overall length can be shortened by increasing the gradient

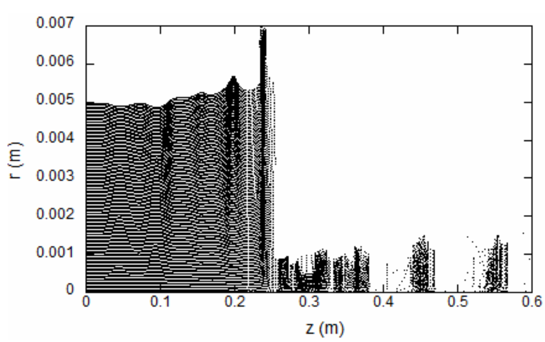

Figure 2: Radial-axial plot of simulation particles from start to end of klynac structure. The constricting aperture is at 25 cm, reducing the average beam current from 10 A to 0.14 A.

without too much performance degradation and if much less than half of the power goes into the beam, the beam power can be increased without a significant increase in overall length. Nominal klynac design parameters are presented in Table 1.

Simulations

Our numerical modeling of the klynac was done with the particle-in-cell, finite-different time domain numerical model TUBE [2]. In the following simulations, we modeled the beam transport in the klystron, aperture, and linac sections. We externally imported RF field profiles from SUPERFISH [3] and iterated the cavity gap amplitudes by hand when needed in order to match the required phase relationships.

100 radial emission points were used for initiating the 50-kV, 10-A, 0.5-cm radius electron beam and about 41000 simulation particles were used in the following simulations. All RF cavities used the same SUPERFISH field map, with a transit time of about 0.80.

The ohmic power losses in K2 and K3 are 276 W output 620 W respectively, leaving 159 kW for ohmic power losses in L1-L4 and for accelerating the beam. Scoping simulations showed that a relatively low L1 voltage (40 kV) was ideal for capturing the klystron bunch (i.e., it produced the highest harmonic current at the location where the harmonic current was in phase with the circuit voltage). Choosing L1 voltage of 40 V in turn required L2-L4 voltages of 420 kV to achieve a 1 MeV peak beam energy. Ohmic power losses in L2-L4 are about 62 kW, leaving 98 kW for the beam, or a current of 0.098 A at 1-MeV energy.

L1 was located such that its induced current is 3π/4 out of phase with its voltage in order to provide both acceleration and bunching. L2 and L3 were located such that their voltages are in phase (π and 0) relative to the harmonic current at their respective locations. The location of L4 was chosen to cancel the out-of-phase contribution to the induced current produced by L1's location. Due to the circuit's induced current scaling favorably with cavity voltage, and the low voltage of L1, L4 was able to be located in very nearly the optimum location for acceleration.

The overall *r-z* plot of the beam is shown in Fig. 2. A 1-mm aperture located at *z*=25 cm reduces the beam current. Even with L1 acting as a bunching cavity, a large enough energy spread is produced in the linac (Fig. 4) so the linac can accelerator more current than initially indicated by the power balance, a total of 0.14 A with a harmonic current of about 0.18 A. L1 is located at 29.6 cm, and L2, L3, and L4 at 37 cm, 41 cm, and 45.7 cm respectively. Note the excellent bunching achieved by L1 by the location of L2 in Fig. 3. The peak accelerated electron energy is about 1.15 MeV. The final energy spectrum is shown in Fig. 4. The output rms beam size is about 6.4 mm, with an average electron energy of 0.98 MeV with an rms energy spread of 43 keV.

The final tuned voltage for L2-L4 was 439.5 kV, with induced currents of 0.134, 0.150, and 0.127 A respectively. The phases of the induced current are 2.376, -0.154, -3.114, and 0.258 radians in L1-L4 respectively.

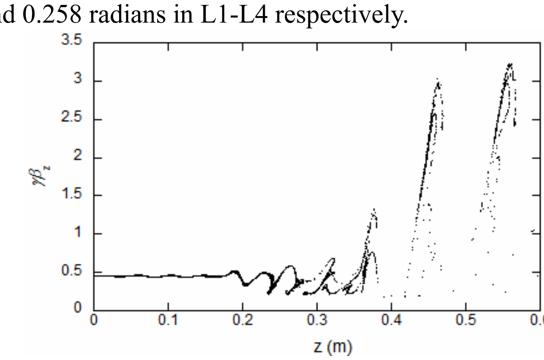

Figure 3: Axial momentum plot of the simulated particles as a function of axial position. Most of the accelerated charge has energy below the peak energy gain.

ISBN 978-3-95450-169-4

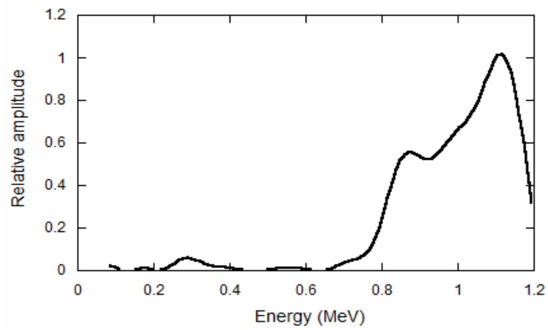

Figure 4: Final accelerator electron beam energy spectrum. The average electron energy is 0.98 MeV with an rms energy spread of 43 keV.

EXPERIMENTAL SETUP

The klynac is currently under test at LANL. The klynac is driven by a 50 kV, 10 A Pierce-type electron gun powered by a 48-stage solid-state diode-directed MARX modulator [4]. The high voltage transformer into the gun is protected in a lexan box using SF6 to supress breakdown. The modulator is pulsed at 50 kV for 5 μs, with a 100ns turn on, single-shot. The cathode is heated by 84 W floating at high voltage. Two solenoids are used to confine the beam, 300 G on the electron gun, and about 900 G, approximately three times the Brillion field, to confine the low energy beam in the RF gain section of the klynac. An input and pickup loop, inductively coupled are located in the third cavity, K3, in the gain circuit, the pickup loop is 30 dB down from the input loop. A similar pickup loop is located in the last accelerating cavity, L4. The accelerated beam hits a copper beam stop used as an x-ray converter and the photons are sampled with a scintillator and multichannel analyser. The experimental setup is shown in Fig. 5.

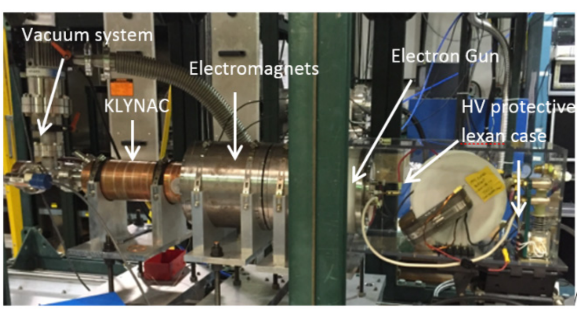

Figure 5: 8-cell KLYNAC undergoing tests at LANL. The 50-kV, 10-A electron gun is about 20-cm long and the KLYNAC structure is about 60-cm long.

PRELIMINARY RESULTS

Very preliminary results are currently presented. RF build-up is demonstrated in the gain section of the klynac. The pickup loop shows 80 mW of RF power at approximately 20 dB down from the beam location as can be seen in Fig. 6. Initially, the spectrum shows that most of the power is in the π-mode, not the π/2 mode as operation was intended. Results were only obtained up to a beam operating voltage of 45 kV, as significant breakdown issues in the gun region were occurring above that voltage. Simulations show that operation in the π/2 mode at voltages less than 46.5 kV show negative efficiency in the gain section. Π-mode operation at approximately 6.7 GHz has positive efficiency at this beam energy. We do not expect RF at this frequency to drive the accelerator section, no photon energy spectrum was measured above background at this beam energy.

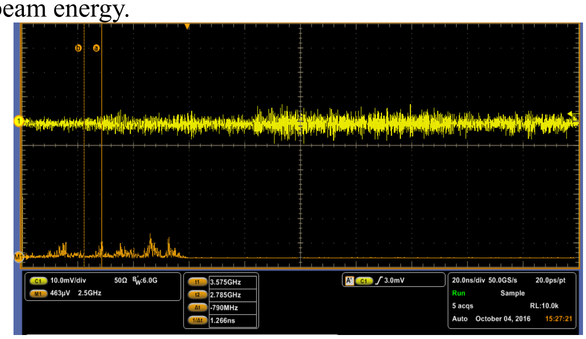

Figure 6: Oscilloscope data from RF pickup loop demonstrating build-up of RF power. Orange curve is FFT of the frequency spectrum plotted linearly, with a peak at 6.7 GHz. Beam power of 44.6 kV.

CONCLUSION

Through analysis and numerical simulations, we have shown that a resonant klynac device is stable and will accelerate electrons up to 1 MeV. In particular, our approach has the potential for excellent gain and extraction efficiency. A prototype has been built and is being experimentally studied. Preliminary experiments have demonstrated RF power produced by the beam.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the US Department of Energy through the LANL/LDRD Program for this work. In addition, we would like to thank Gregory Dale and Dale Dalmas for their hard work and solutions putting the experiment together.

REFERENCES

[1] J. M. Potter, D. Schwellenbach, and A. Meidinger, "The klynac, an integrated klystron and linear accelerator," presented at CAARI, Aug. 510, 2012, in *AIP Conference Proceedings* 1525, 2013, p.178.

[2] B. E. Carlsten, R. J. Faehl, M. V. Fazio, W. B. Haynes, R. D. Ryne, and R. M. Stringfield, "Beam cavity interaction physics for mildly relativistic, intense beam klystron amplifiers," *IEEE Trans. Plas. Sci.*, 22, 730 (1994).

[3] The Los Alamos Accelerator Code Group, `http://laacg.lanl.gov/`

[4] G.E. Dale, H.C. Kirbie, W.B. Haynes, C.E. Heath, T.A. Lopez, F.P. Romero, and R.M. Wheat Jr., "Performance of a diode-directed solid-state marx modulator," IEEE International Pulsed Power Conference, Monterey, CA, 2005.