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Bi-resonant klynac

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A B S T R A C T

Here we present the first analysis of a new device called the bi-resonant klynac, which is a combined klystron and linac. In a bi-resonant klynac, all RF cells, except for the cell that acts as the input for the klystron section, belong to a single resonant circuit. This resonant coupling configuration leads to increased operational stability and can tolerate significant temperature variations. In this paper, a basic analysis of this device is presented, including discussions of how it operates and of the advantages of resonantly coupling the RF generation directly to the linac. We additionally describe the approach used to numerically model the klynac and we include detailed simulations of a 50-kV, 10-A klynac that produces a 1-MeV, 0.1-A output beam. This type of device may be especially useful for situations where an electron beam is needed at low cost.

1. Introduction

Klynac is a term that has been coined for a klystron and linear accelerator (linac) combined into a single structure [1]. Specifically, the klystron output cell is resonantly coupled to a short linac section and some portion of the klystron beam is transported into the linac section and accelerated. The intended purpose of a klynac device is to provide a compact and less expensive alternative to a conventional 1 to 6 MeV accelerator by eliminating much of the hardware associated with having a separate RF source to drive the accelerator. For example, this configuration eliminates the needed for RF windows, a circulator or isolator, possibly SF_6 to suppress breakdown, a second high-voltage electron gun to drive the linac, and separated temperature controls. Typical applications for compact 1 to 6 MeV electron beams are medical radiation therapy, nondestructive testing, and special nuclear material interrogation [2], all based on gamma-ray production from bremsstrahlung radiation from a conversion target at the end of the accelerator. For medical applications, the reduced size and weight of a klynac may significantly reduce the complexity and size of the cost-dominating gantries required for moving the radiation source about the patient. For other applications, a compact, man-portable unit may be required for field operation. Also, this type of device can be used to provide an electron beam for laboratory experiments at the fraction of a cost of a conventionally installed accelerator and only requiring a pulsed high-voltage source.

A klynac-like device was first described in a patent by Nygard in 1960 [3]. He considered a klystron directly driving a traveling-wave accelerator, with a portion of the klystron beam being accelerated in the linac section. In 1978, another klynac-type device was described by Schriber [4], where the output cell of a klystron formed a resonant structure with a standing-wave linac section. In this device, several of these klystron/linac combinations would be concatenated to form a high-energy accelerator, with the electron beam injected from a separate electron source. More recently in 2003, Xie [5] demonstrated another klynac-like device where a linac section was directly attached to the output of a klystron. Some portion of the klystron beam was accelerated in the linac cells. An iris in the klystron collector was followed by a bending magnet, which served as an energy filter for the electron beam prior to acceleration. The RF output of the klystron externally fed the linac section. Xie demonstrated 10 MeV acceleration with a 5 MW klystron. In 2013, Potter [1] designed a resonant coupling cell with the same functionality as in Schriber's concept but where the klystron and linac are collinear and a small iris would allow some fraction of the klystron electron beam to be accelerated in the linac as in Xie's device.

The RF power generation section in Schriber's, Xie's, and Potter's designs all assumed a standard klystron architecture, where the klystron input cavity is driven by an external, low-power RF source, and sequential gain cavities are driven by current modulation in the beam from previous cavities, as a convective instability. As in conventional standing-wave linacs, the accelerator cells were resonantly coupled. Smirnov [6] has also introduced a related "klylac" concept, where a klystron is operated as an oscillator (through internal feedback) driving a separate linac structure.

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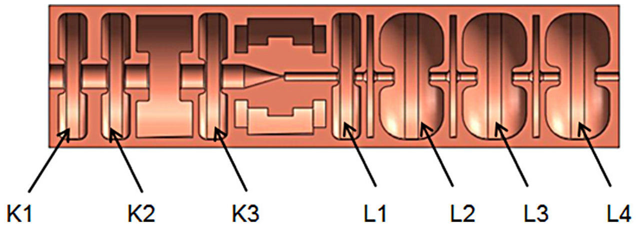

Fig. 1. Layout of a 7-cell, bi-resonant klynac structure. K1 is the klystron input cell which is independent of the other cells. Klystron gain and output cells K2 and K3 and linac cells L1, L2, L3, and L4 form the second resonant circuit. The unlabeled cells are coupling cells.

Here we consider an alternative klynac architecture where the klystron section gain and output cells are resonantly coupled with the linac cells, and the fields build up in the klystron gain and output cells and the linac cells all simultaneously as an absolute instability. This is a potentially significant improvement. Because the klynac is a single structure with a single thermal mass, it has the potential to be much less sensitive to temperature variations than a system with a separate RF source and linac, as temperature variations will lead to more-or-less equivalent frequency shifts in all the klystron and linac cells. This by itself should allow operation at low power without requiring active structure temperature control with a heated or cooled fluid flowing through the structure. Additionally resonantly coupling the RF source and accelerator greatly enhances the ability not require active temperature control because the frequencies of all cells are now locked together.

In Section 2, we present the basic klynac concept, including estimates on enhanced stability in the presence of temperature fluctuations. In Section 3, we describe our simulation approach and provide detailed simulations of a nominal bi-resonant klynac design which uses a 50-kV, 10-A electron gun to generate a 1-MeV beam at 0.1 A.

2. Klynac design concepts

This section presents the basics of klynac operation including the principles from which the physics design of a klynac can be completed. This section will encompass three parts: firstly, the klynac architecture and coupling will be described; secondly, the power balance is established; and thirdly, temperature stability is discussed.

2.1. Basics of klynac operation

A bi-resonant klynac is designed to have two standing-wave resonant circuits. The cells in each circuit (if there are more than one) are coupled via on-axis coupling cells, all operating in the $\pi/2$ mode which is a common configuration for accelerator linacs and has significant advantages for standing-wave operation in terms of mode amplitude stability and mode separation [7,8].

To illustrate the basic concept, we show the layout of the RF structure of a nominal 7-cell bi-resonant klynac in Fig. 1 The klystron input cell is K1 which forms an independent resonant structure. The other klystron cells, K2, and K3, as well as the four linac cells, L1, L2, L3, and L4, form a second resonant structure. K3 acts as a conventional klystron output cell, generating RF power that is then used to drive the linac cells and accelerate the electron beam.

This structure resonates in the $\pi/2$ standing-wave mode, therefore the fields in the coupling cells are negligible and are ignored in the following analyses. Note that this operating mode ensures that successive klystron cells are 180° out of phase with the previous cell, but does not constrain the cell amplitudes. The amplitudes of the different cells are determined numerically to maximize the extracted RF power and are controlled by the sizes of the coupling slots between the cells. Computer programs (e.g., DISPER [9]) can be used to determine the coupling coefficients needed between cells to achieve any desired amplitude ratios. Analytical formulas can be used to estimate the actual coupling slot dimensions [10] corresponding to these coupling coefficients, as a starting place for more accurate determination using 3-dimensional RF mode simulations with HFSS [11] or CST MicroWave Studio [12])

Similarly, successive linac cells are also 180° out of phase with the previous one. The axial separation between K3 and L1 is adjusted to optimize the bunch capture in L1 and an intercepting aperture between cells K3 and L1 reduces the beam current in the linac section to about 1% of that in the klystron section (the amount of beam interception is adjustable by pinching the beam at the location of the aperture with an external magnetic field). The coupling cell between K3 and L1 is unique in that it is not open to the axis (it is a toroidal cavity instead of a pillbox cavity). 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 cell 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.

Importantly, the input cell cannot be resonantly coupled with all the other cells as in a single resonant structure as that configuration will not turn on. Thus the klynac needs at least two separate resonant circuits to operate. This arises because the power loading in the linac section is linear with circuit voltage but the RF power generation is quadratic with circuit voltage so at small circuit voltages the RF power loading is always greater than the generation. Importantly, this same feature helps suppress mode competition in klynac's second resonant circuit. That circuit has 11 modes (for the design in Fig. 1), but only one will be driven by the input cell as long as it is driven at the correct frequency. The amplitudes of the other modes are suppressed because the linac section will load them down.

It is worth noting that a second klynac design approach would be to resonantly couple all the klystron section cells together except for the output cell and to have the output cell resonantly coupled with all the linac section cells [13,14]. In a manner similar to the klylac [6], that configuration would not need an input drive at all, but may suffer from frequency hopping because the resonant Q of the input circuit is larger than that of the power generation/linac circuit. Because of that issue, the configuration shown in Fig. 1 is considered superior and is presented here.

2.2. Klynac power balance

The klynac power balance can be approximated by

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

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 cells, V_L is the voltage of linac cells L2 through L4 (defined as the instantaneous line integral of E_z on axis), and Z_L is the impedance of linac cells 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 $Z_L T_L^2 = \left(V_L T_L\right)^2/P$, where we recognize $V_L T_L$ as the maximum energy gain of the electrons in the linac cells and P is the RF power dissipated in the cells. Additionally, in Eq. (1) we assume that L1 has the same impedance as L2, L3, and L4 with a relative amplitude of ε, and that the RF power dissipated in the klystron cells is negligible.

Eq. (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 cells 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