REVIEW OF ENERGY VARIATION APPROACHES IN MEDICAL ACCELERATORS

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Abstract

Most of cancer treatment Radiation Therapy (RT) machines rely on a linac as the source of the treatment beam which can be an electron beam or an X-ray beam. In either case, an approach to vary the energy of the linac's output beam may be needed to target cancer tumors at different depths. Additionally, some of the Image Guide Radiation Therapy (IGRT) approaches use the linac as the source of both the treatment and imaging modes. This requires the linac to produce photon beams with different energies. Over the last two decades, multiple approaches for medical linac's energy variation were proposed and some of them have been developed and implemented clinically. In this paper, we review some of these approaches and discuss the advantages and disadvantage of each technique.

NEED FOR ENERGY VARIATION

A fundamental strategy in cancer Radiation Therapy (RT) is to deliver a sufficiently high dose to the tumor while minimizing the dose to the neighboring healthy tissue especially those in the critical organs. RT treatment plans take advantage of dependence of the dose depth distribution on energy. Additionally, many of RT treatment plans utilize multi-energy mixed photon beam modalities, where the patient is irradiated with photon beams of two or more different energies. For example, in a dual-energy treatment, [1, 2], one beam can be at 6 MV and the other at 18 MV, in the same treatment. By a selection of weighing of the two photon beams, a depth-dose characteristic for any energy between 6 and 18 MV can be obtained. An effective way of switching between the two energies of the generated X-ray beams is a requirement for such treatments.

ENERGY VARIATION APPROACHES

Varying Input Power

The simplest means of varying the linac's output energy is to change the RF power supplied to the accelerator and hence change the field strength in the accelerating cavities. The obvious advantage of this approach is simplicity. However, this approach provides only a narrow range of energy variation beyond which the energy spectrum degrades. Changing the field strength, especially in the beginning section of the linac, would cause electron bunches to slide in phase with respect to the RF, deviating from the optimum condition for narrow output energy spectrum. This results in broadening of the output energy spectrum and a decrease in efficiency.

Use of Beam Loading

In addition to varying the RF power, the linac's output energy can be varied by changing the injected beam current. The optimum bunching conditions, and hence the energy spectrum, are uniquely determined by geometry of the first few cavities, electric field strength in these cavities, and the energy of the electrons injected from the gun. Varying the field strength due to beam loading, would result in a deviation from the optimum condition and consequently, wider energy spectrum. Similar to the first approach above, the use of beam loading has the advantage of simplicity and reliability and the disadvantage of being restricted to narrow range of energy variation to avoid broadening of output energy spectrum.

Two-Section Linac

A straight forward approach for varying the linac's output energy over a wide range is to cascade sections of accelerators which are independently excited from a common RF source with independent control of phase and amplitude [3, 4]. Currently, this approach is implemented in the Mobetron using the X-band technology [5]. The Mobetron's linac system is composed of two collinear accelerators as depicted in Fig. 1. The energy of the electron beam is changed by varying the power to the second section. This is done through a phasing technique using movable shorts driven by motors controlled by the energy control system. Thus, the Mobetron can deliver multiple electron energies, namely, 4 MeV, 6 MeV, 9 MeV, and 12 MeV at two dose rate settings (250 cGy/min and 1000 cGy/min). Although this approach provides a wide energy range, the clear disadvantages are the cost, complexity, and the need to match the two sections precisely in frequency.

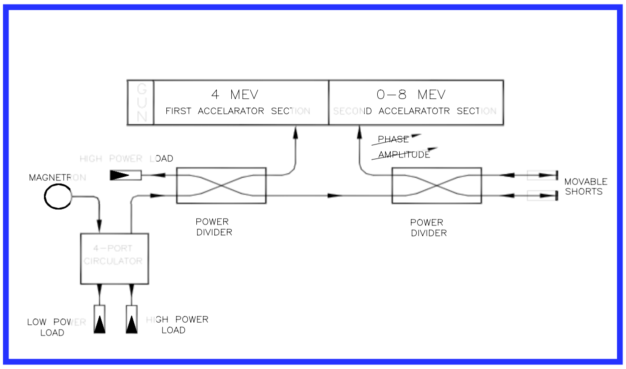

Figure 1: X-band linac and RF system for the Mobetron.

Mechanical Energy Switch

This approach has been successfully implemented in several RT machines using standing-wave side-coupled linacs [6-8]. It utilizes one of the off-axis coupling cavities (cavity S in Fig.2), downstream from the RF input, to act as a switch that causes the relative magnitude or phase of the accelerating fields in the accelerating cavities downstream from the switching cavity to vary. A schematic for a linac with a switching coupling cavity is depicted in Fig.2, below. A view of a 20MeV linac with an energy switch built by BMEI in cooperation with Tsinghua University and BVERI is shown in Figure 3, below [9].

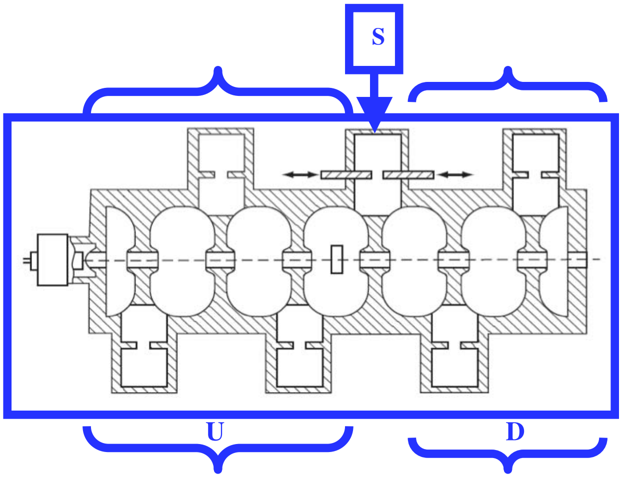

Figure 2: Concept of the mechanical energy switch.

Figure 3: A 20MeV SW medical acceleration with an energy switch [9].

By using the energy switch, the fields in the accelerating cavities in section D (Figure 2) may be varied in a controlled amount relative to the fields in the cavities in section U (Figure 2) which can be kept close to the optimum bunching conditions. Since the energy spread of the output beam is principally dependent on how tightly the electrons are bunched in that section, which is closer to electron gun, the mean output energy can be varied by changing the field strength in section (D) without compromising the energy spectrum.

<u>*Concept of Operation of Energy Switch:*</u>

In order to simply explain the above approach of changing the fields in the accelerating cavities, we employ Fig. 4. It shows a representative section of a side-coupled, SW linac and its equivalent circuit. From which one can readily deduce [1] that,

$$\frac{E_2}{E_0} = -\frac{K_{01}}{K_{12}} - \frac{2}{K_{01}*K_{12}*Q_0*Q_1} \tag{1}$$

Since,

$$K_{01}*K_{12}*Q_0*Q_1 \rangle\rangle 1$$

Then, the ratio of fields can be approximately equal to ratio of couplings,

$$\frac{E_2}{E_0} \approx -\frac{K_{01}}{K_{12}} \tag{2}$$

By moving a plunger inside the side-cavity, one can make the coupling unsymmetrical and hence reduce or increase the fields in the accelerating cavity downstream. This is realized by using radial (perpendicular to the beam axis) or transverse (parallel to the beam axis) plunger intruding in the switching side-cavity. It is clear that the motion of these plungers in the vacuum inside the linac proper requires the use of a relatively complex arrangement of bellows and water-cooling provisions

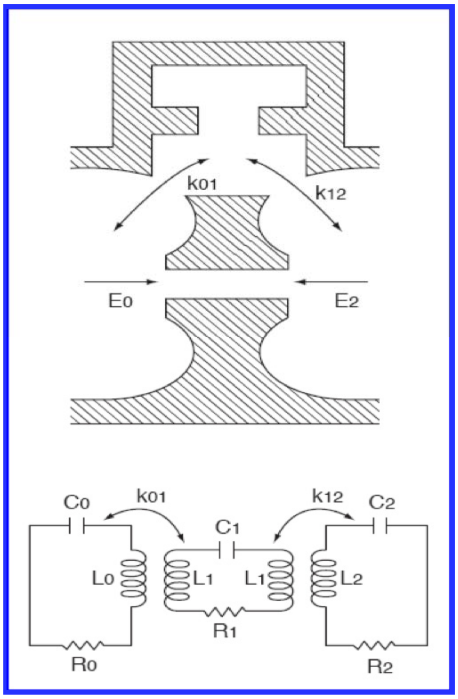

Figure 4: A schematic for a section of a side-coupled SW linac and its equivalent circuit [1].

Electronic Energy Switch

Some of the complexity of the mechanical switch described above can be alleviated by employing an alternative technique for detuning the switching side-cavity. The electronic switching technique proposed by Hanna [10] would eliminate the use of any moving parts in vacuum. In this approach, changing the frequency of the switching side-cavity is done by coupling this cavity to an external variable reactive circuit through a conducting-loop. Depending upon the phase of the reactive signal coupled back to the side cavity, the amount of detuning would change and hence the coupling of the RF power to the accelerating cavities downstream. There are multiple well known microwave techniques to realize the external variable reactance. One of these techniques is to use different sections of short circuited coaxial transmission lines connected to a microwave switch controlled by an electronic signal. In Fig. 5, we show schematically a representative configuration of an electronic switch using two transmission lines of different lengths. Representative field distributions at two different positions of the microwave switch are shown in Fig.6 (A and B).

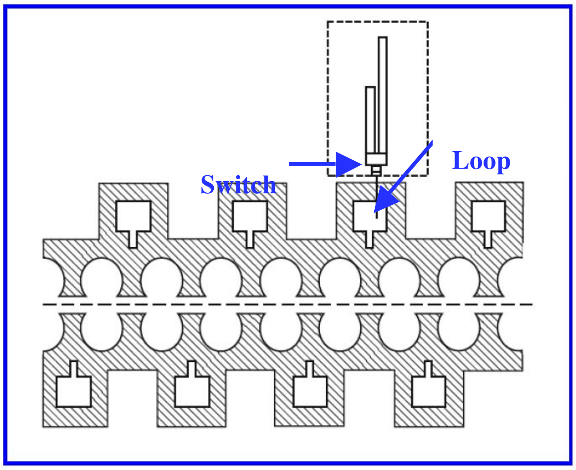

Figure 5: A schematic for an electronic switch [10].

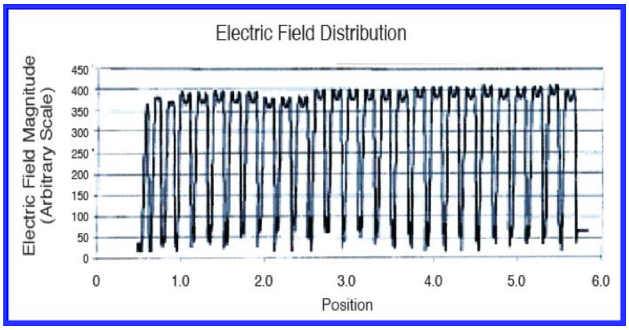

Figure 6A: Field distributions at one position of the electronic switch [10].

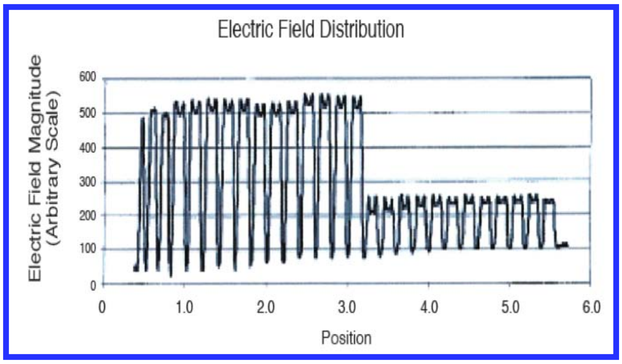

Figure 6B: Field distributions at one position of the electronic switch [10].

ACKNOWLEDGMENT

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