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CONCEPT OF RF LINAC FOR INTRA-PULSE MULTI-ENERGY SCAN*

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Abstract

A material discrimination based on X-Ray systems is typically achieved by alternating photon pulses of two different energies. A new approach relies on the ability to generate X-ray pulses with an end-point energy that varies in a controlled fashion during the duration of the pulse. An intra-pulse multi-energy X-ray beam device will greatly enhance current cargo screening capabilities. This method originally was described in the AS&E patents [1]. This paper addresses a linac concept for the proposed scan and describes some proof of concept experiments carried out at SLAC.

INTRODUCTION

The idea of the intra-pulse multi-energy X-ray scan proposed in AS&E is based on the possibility of a controllable incensement of X-ray endpoint energy during each pulse and a resolution of the time-energy structure of the X-ray pulse via the fast detector system. This concept provides the information needed for material discrimination in a single X-ray pulse. We are considering the classical architecture of the X-ray source, which contains an electron beam gun, an accelerating structure driven by an RF source, and an electron beam-to-X-ray converter. However, in order to achieve the desired variation in beam energy, several components of the accelerator (gun, buncher, accelerating structure, control system) need to be modified. The current state of the art X-ray sources of two different energies using a single RF linac the reader can find in [2 and 3]. Dual beam energy concepts limit the speed of the cargo inspection. If we will require scanning each cm of cargo length, then a cargo velocity has to be less than 0.4 cm/sec (i.e. v<14.4 km/hr). Requirement for advanced cargo inspection may include a resolution of 5 mm. Maximum X-ray penetration in dual energy approach is realized with only the high energy pulse. There is a probability that an irradiation of a heavy density material will be in a period of the low energy pulse. One can see that the cargo velocity will be too low and a material identification process will take a long time because: (1) there is the pulse mode of operation; (2) the dual beam energy is needed for material identification; and (3) one target (X-ray converter) is used. We do not discuss the fast detector system for the intra-pulse multi-energy X-ray scan. Rather, we focus on the RF linac, its subsystems, and its mode of operation. The present paper focuses on major issues of the proposed technical approach and proof of concept experiments performed at SLAC.

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PROPOSED TECHNICAL APPROACH

We consider an adjustable X-ray source for use in different scan scenarios. The different scan scenarios were discussed in [2]. Our fundamentally new approach relies on the ability to generate X-ray pulses with an endpoint energy that varies in a controlled fashion during the pulse interval. The dual energy approach cannot perform material identification for items which are smaller than the distance of the cargo moved during the pulse separation. The repetition rate in the intra-pulse multi-energy case is not increased. However: (1) the number of X-ray converters (e.g., targets) can be more than one [3] and (2) a controllable beam energy and intensity sweep can be realized on each target (converter). Basically the idea looks like the employment of an array of linacs. They are controllably working as a system on the separated targets. However the idea is embodied as a single X-ray source. Varying and controlling the electron beam current and energy during the duration of the pulse would allow the truly rapid scanning of cargo while it is in normal motion. The proposed X-ray source will rely on the classical architecture of an electron beam gun, an accelerating structure driven by an RF source, and an electron beam to X-ray converter. However, in order to achieve the desired variation in beam energy, several components of the accelerator (gun, buncher, accelerating structure, control system) need to be specifically designed to be conducive to the rapid electron beam energy changes. As has been mentioned above, typical commercially available MeV X-ray sources are based on standing wave accelerating structures with magnetron RF sources. For the implementation of intra-pulse energy control, a traveling wave (TW) accelerating structure fed by a klystron based RF source is better suited. The required intra-pulse, multi-energy capability can be achieved by varying the amplitude of the RF source during the pulse by varying the frequency of the source during the pulse, thus causing the klystron output to slide up or down on the resonance curve, or by ramping the drive level of the klystron by adjusting the output of the Solid State Sub-booster of the klystron. Either method requires us to vary the phase relation between the electron bunch and the RF source during the pulse to compensate for the resulting side effects. Our proposed intra-pulse variation of the beam energy, therefore the X-ray energy, by the intra-pulse variation of the RF amplitude is a huge advantage over the pulse-by-pulse X-ray energy variation described in [4]. Basically the idea of our novel approach is illustrated by the following simplified diagram (see Figure 1).

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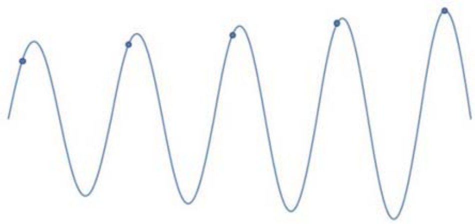

Figure 1 Several RF cycles of the pulse with varying RF amplitude and phase with electron bunches on each RF cycle. The dots represent the electron bunch positions on the RF wave. In the proposed technical approach, the bunch separation is one RF period and the pulse length is 4 to 10 microseconds.

During a long RF pulse, many bunches will be accelerated, each at an energy according to the amplitude of its RF cycle. Figure 1 shows only a portion of that long pulse. The amplitude sweep during the pulse (4 to 10 μs) is slow compared to the RF cycle itself. In an ideal case at the linac output, each bunch will possess its own energy during the pulse width. Modulation of the phase can be used as a veneer for additional amplitude variation by sliding up and down on the RF pulse itself in the vicinity of the crest. This will cause some phase shift between the bunch and the RF from one cycle to the next inside the pulse. Thus we can amplify or reduce the bunch-to-bunch beam energy control achieved only from amplitude variation by using the phase control. A simple schematic of a portion of the pulse train, which employs both amplitude and phase variation to control the intra-pulse beam energy, is shown in Figure 1. The range of the phase sweep is programmable and can be varied. The possible X-ray flux drop can be compensated for by varying the beam intensity from the gun using a feedback on the grid voltage. Beam loading effects on the bunch train pulse will be compensated with feedback loops on the RF phase-amplitude controller. The LLRF block diagram of the linac will be similar to the tradition SLAC diagram and adopted for example in [3]. However the control subsystem will be reprogramed for intra-bunch energy variation according to scenarios discussed in [2]. In order to take advantage of bunch-by-bunch energy variation amplification or reduction with the "phase knob," we need bunches to be as short as possible so that the energy spread when they are not at the crest of the RF is minimized. Requirements for the beam focusing system and the linac acceptance are not considered here but apparently these issues will not be a stopper. Also to assure a controlled transmission through the accelerator to the target, we would like bunches to be as short as possible. Additionally, the very low electron beam energy from the gun has to be increased to a level where the beam is traveling at nearly the speed of light in order for it to be synchronized with the RF in the main accelerator section. For the proposed X-Ray source, we will use a bunching system upstream of the speed of the light accelerator structure to achieve short bunches that can be fed into the accelerator structure.

PROOF OF CONCEPT DEMONSTRATIONS

Several key issues are used in the proposed concept. The first is a question of the current state of the art concerning beam stability at the output of the RF linac based on the klystron source and traveling wave accelerating structure. The next question is whether amplitude and phase modulation can be achieved in a klystron and traveling wave accelerating structure, and what the bandwidth of these RF components should be? Although the answer to these questions will require a detailed analysis for the optimal machine for cargo inspection, our preliminary evaluations and experiments shows that the accelerating electromagnetic wave amplitude can maintain electron energy gain through the structure with 0.03% accuracy and a 0.06 degree of 2856 MHz standard deviation phase stability [2]. The bandwidth of the traveling structure (a parameter that relates to a speed of a scan) actually is smaller than the klystron bandwidth. Our evaluations of the SLAC linac TW bandwidth [2] show that the bandwidth is 60 MHz, i.e. an electromagnetic field can be changed within a 30 nsec period (in principle). However, we shall take into account the group velocity, i.e. the speed of RF energy flow along the accelerating structure. Although parameters of the SLAC linac TW accelerating structure are not optimized for intra-pulse multi-energy mode, the given structure is suitable for the pilot experiments. Such experiments have been carried out at SLAC's sector 24-8 klystron station [2]. The klystron output power is propagated through the S-Band structure and dumped into a matched load. There is a coupler (i.e. RF view ports) between the output structure and RF load. The RF amplitude and phase at the output coupler ports are detected. They are shown in Figure 2.

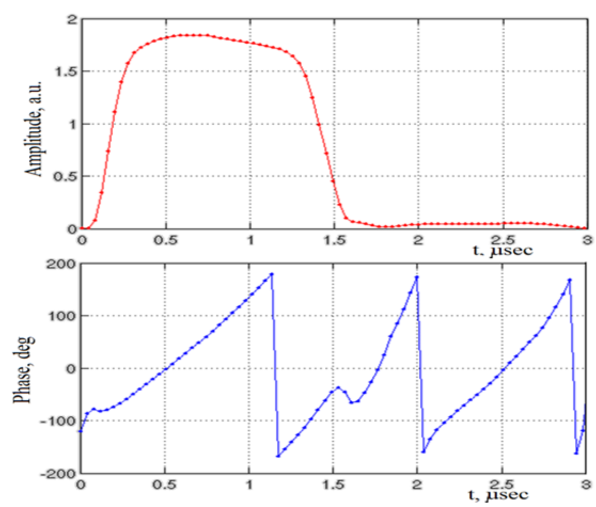

Figure 2 PAD/PAC controlled propagated RF amplitude and phase vs. time.

One can see that the propagated phase is rotated in a $-180^{o}<phase<+180^{o}$ range during the RF pulse width. The FWHM pulse width is approx. 1.2 µsec. This experiment convinces us that the phase and amplitude can be modulated at low level RF power. This modulated power can be amplified without distortion in the klystron and passed through the accelerating structure practically without a distortion.

We also were able to carry out the beam based experiment at the front end of the SLAC injector with two bunches. SLAC linac typically operates in the single bunch mode. However the thermionic gun driver can operate in multi-bunch mode [5]. The nearest to the gun position is the K02 klystron station in Sector 0. A block diagram of experiment is shown Figure 3.

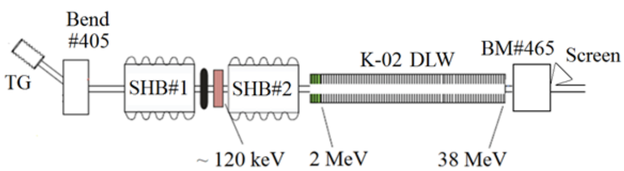

Figure 3 Block diagram of the beam-based experiment. SHB #1 & #2 are subharmonic buncher cavities.

A thermionic gun (TG) was used as a beam source. All beam optic and beam diagnostic components of the beam line up to the BM#465 magnet at 38 MeV were employed. This magnet is the beam spectrometer. The bend magnet directed the beam on to a screen. The beam image from the screen could be seen by the existing camera. We did the phase and amplitude modulation experiment with two bunches, which were separated by approximately 600 nanoseconds. The filling time of the 10 ft long SLAC accelerating section was approximately 850 nsec. During this period, the beam phases are different for the first and second bunch while they are passed through the buncher and the first accelerating section (K-02 DLW). The traveling wave buncher and first accelerator section are fed by the K02 klystron. The synchronization of other components of the K02 klystron station was carried out using the existing injector timing system. Figure 4 shows waveforms of the RF drive video signal (yellow trace), the klystron beam current (magenta trace), and the RF forward power envelope with a phase modulation.

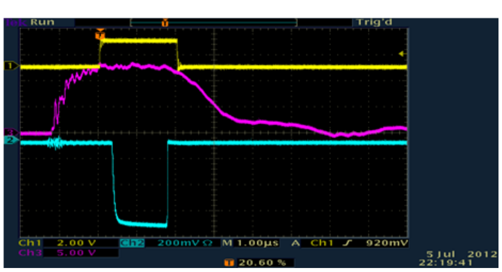

Figure 4 Synchronization of RF drive with the K02 klystron modulator.

The phase modulation was performed using the low level RF signal. A special phase amplitude controller (based on the existing PAC chassis) was integrated in the K02 station.

Figure 5 shows two bunch images on the spectrometer camera screen.

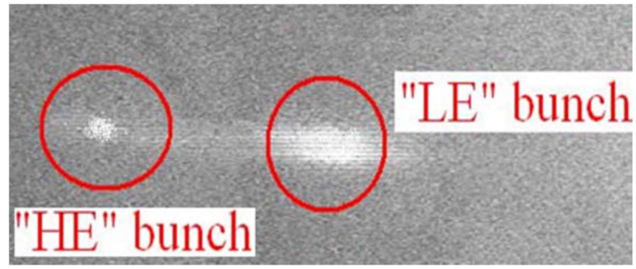

Figure 5 Two bunch images on the spectrometer camera screen

The horizontal separation between two bunches corresponds to the different beam energies during the same RF pulse. These images belong to low energy (LE bunch) and high energy (HE bunch) bunches that were placed in the same RF pulse but in different accelerating phases separated by more than 17,000 RF periods. Both bunches were accelerated in the same beam focusing channel.

CONCLUSION

Intra-pulse energy control will greatly improve the current cargo scanning scenarios by scanning cargo while it is in normal motion, thus reducing scanning time as well as increasing the accuracy of detecting cargo composition. Proof of concept experiments on varying the intra-pulse electron beam energy have been successfully conducted on the different parts/systems of the SLAC linac. It remains to be shown that an X-ray converter and detection system can take advantage of the varying energy beams within a pulse.

ACKNOWLEDGMENTS

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