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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 present paper analyzes the current state of the art X-ray sources of two different energies using a single RF linac, discusses a couple of proposed technical approaches, and then demonstrates the proof of concept experiments performed at SLAC and provides the results of those experiments. 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.

Analysis of the Current State of the Art

Many articles discuss a method of material discrimination by alternating X-ray pulses of two different energies using only one linac (see[2, 3] and references in these articles). For example, atomic numbers of cargo materials are identified using high- and low-energy profiles obtained through the irradiation of materials on an alternate pulse-by-pulse basis as described in [2]. Material discrimination is done using a bremsstrahlung beam with 10 MeV and 4 MeV dual boundary energies and using scintillating crystals coupled with silicon photodiodes as detecting elements. The experiments are carried out on a full-scale prototype of an 8 MeV customs inspection system. The linac is operated in an interlaced mode, where each even pulse generates a high-energy bremsstrahlung and each odd pulse generates a low-energy one. Such

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a scheme allows the forming of dual radioscopic images containing two transparency profiles with different energies. The scanning scheme expected to be used in customs inspection with 2.16 km/hr scan speed implies that the accelerator emits pulses with high and low energy couples, with a preset repetition rate.

Let us turn our attention to the current state of the art in the RF linac-based X-ray source that has rapid pulse-by-pulse accelerator control. Such an X-ray source contains an electron gun (particle source), an accelerating structure, and a converter (or target), where accelerated electrons are effectively decelerated producing the X-ray beam. Other components that control the X-ray generation are an RF system that feeds the accelerating structure by a pulsed RF power, a power supply for the electron gun, and an electronic system that controls the operation of the entire X-ray source. As an example, the recently proposed dual energy Mi linac structure produced by Varian Medical Systems, Inc. (VMS, Inc.) is shown in Figure 1 [4]. Although VMS, Inc. has other patents for the dual energy mode production, here we are considering the one most like our approach.

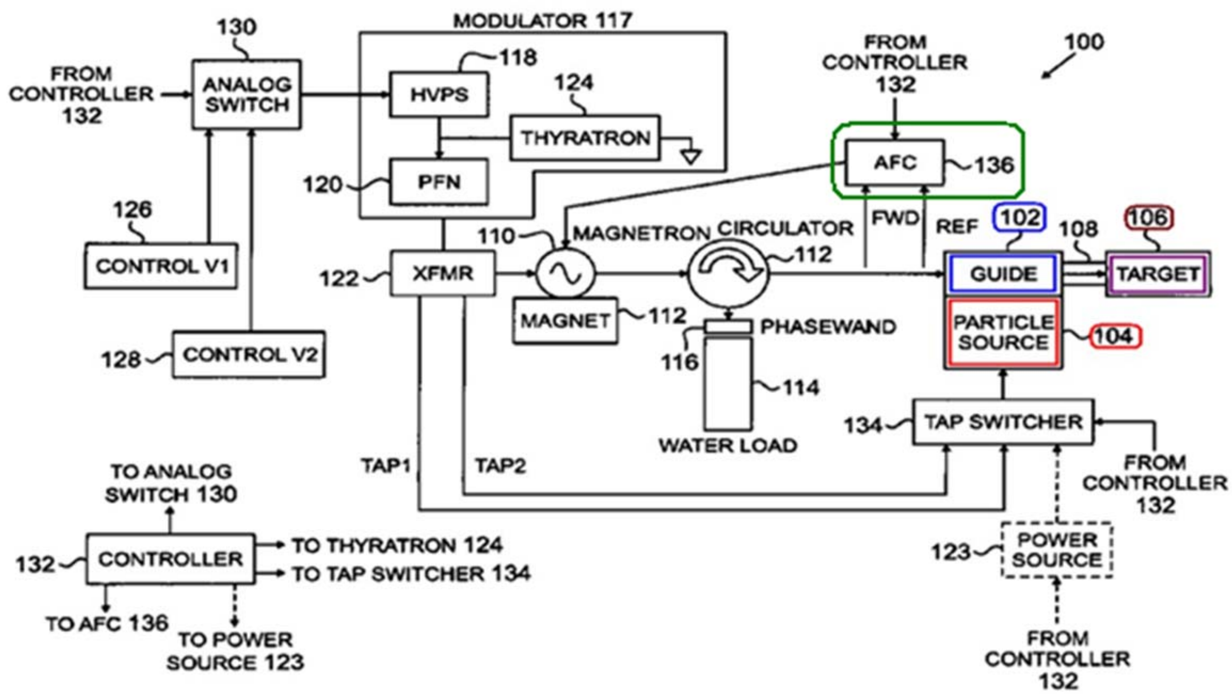

Figure 1 Components of Mi linac with a dual energy X-ray feature [4]: 104 is an electron gun, 102 is an accelerating structure, 106 is a converter, and 136 is "an automatic frequency controller" (AFC).

Although the block diagram shows a multiple component structure, the dual energy mode is attained by the feedback loop. The loop involves readout of forward (FWD) and reflection (REF) RF powers. The automatic frequency controller takes these signals and creates a correcting control signal for the magnetron as necessary. During the delivery period (during a pulse width), the feedback system keeps the RF power constant for a given constant of the beam current. For the next pulse, the feedback system does the same for the next level of the RF power and beam current. The possibility of changing the electron beam (and the X-ray endpoint energy as well) from pulse to pulse is based on control of the magnetron RF power level. The pulse-to-pulse repetition rate in this approach is rather low (<400 PPS). That is why it is not difficult to realize the pulse-to-pulse beam energy modulation. As the magnetron RF power varies from pulse to pulse, the magnetron frequency may also change. A difference between the accelerating structure resonance frequency and the magnetron frequency would be a disadvantage for this X-ray source. That is why the proposal provides an improved frequency control by mechanically and electrically tuning the "magnetron-guide" system.

A similar dual energy X-ray source concept and pulse-to-pulse feedback system has been described (and realized) by NucTech (China) [5]. As shown in Figure 2, one can find standard accelerator components: e- Gun (402), accelerating structure (406), and target (407).

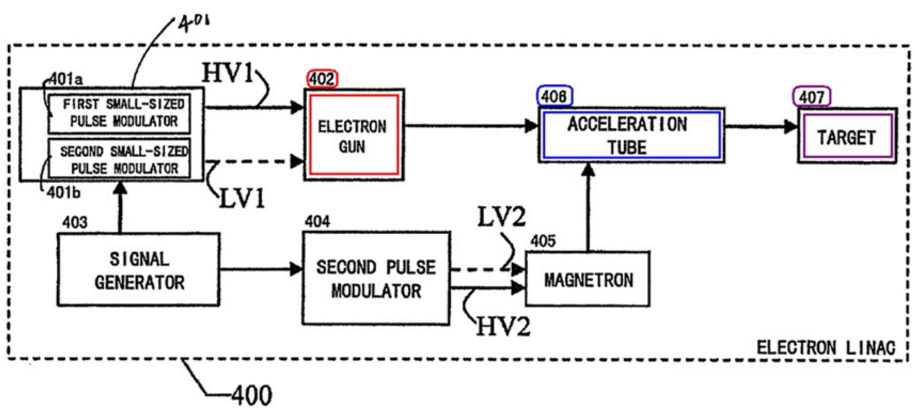

Figure 2 Components of the NucTech dual energy X-ray source [5]: 400 is the entire electron linac system, 401 is the power supply of the e- gun, 402 is the diode-type e-gun, 403 is the "signal generator," 404 is the magnetron modulator, 405 is the RF source (magnetron itself), 406 is the accelerating structure, and 407 is the converter (target).

The pulse-to-pulse mode of operation and the X-ray source follow a timing diagram shown in Figure 3. One can see that lower beam current from the gun is produced during the delivery of higher X-ray energy. During this period, the RF power in the accelerator structure (and electron beam energy accordingly) is maximal. The beam energy is a constant during a given pulse. One can see also that the beam current from the gun is higher for the next pulse and the RF magnetron power is reduced to produce lower X-ray energy at the converter. Again, one can see that the beam energy at the converter stays constant during the second delivery pulse. Two following pulses with different end point X-ray energies allow the discrimination of the cargo material. One can see that the needed time to switch from the first energy set to the next is proportional to the repetition rate.

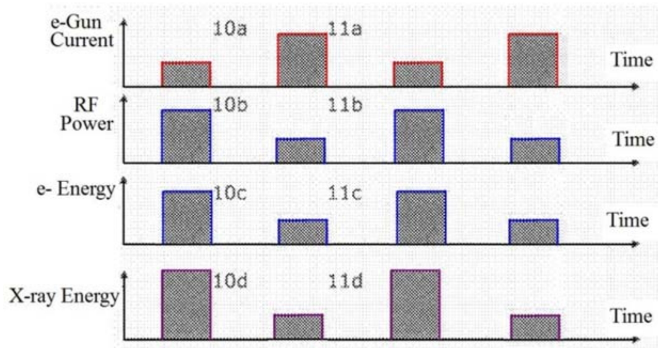

Figure 3 From top to bottom: electron beam current (e-Gun current), RF power in the accelerating structure (RF Power), electron beam energy on the converter (e-Energy), and X-ray energy vs. time [5].

A practical system for delivering high and low current from the electron gun modulation from pulse to pulse is shown in Figure 4 [5].

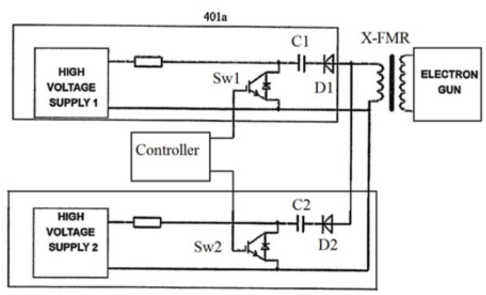

Figure 4 Circuit diagram for beam intensity modulation in a pulse-to-pulse manner [5].

Two independent high voltage (HV) power supplies with different voltage levels (HV1 and HV2) charge capacitors C1 and C2, respectively. The controller creates a trigger pulse width for switch Sw1. The capacitor C1 partially discharges the stored energy in C1 to the e-gun through a pulse transformer (X-FMR) and a diode stack D1. The electron gun produces current amplitude proportional to HV1 voltage. The same process takes place for the next trigger pulse width, when the controller generates a trigger signal for switch Sw2. Diodes D1 and D2 decouple HV1 and HV2 circuits allowing them to work independently on the electron gun.

A similar voltage modulation concept can be employed in the magnetron modulator where HV1 and LV1 levels vary in a pulse-to-pulse manner (see Figure 4).

Rapiscan Labs, Inc. reported on the completion of IMAXS source where a beam current from the e-gun is varied on a pulse-to-pulse basis [6]. The key idea is to anticipate the needed intensity for each X-ray pulse by evaluating the signal strength in the cargo inspection system detector array for the previous pulse. A magnetron-based system with a standing wave accelerating structure is employed in the IMAXS.

One disadvantage of the magnetron based X-ray sources is their sensitivity to RF power frequency, amplitude, and phase jitter, as well as power supply and temperature stability, causing beam energy and beam position instabilities at the output of the RF linac, especially in the case of low beam energy operation. These facts can result in inappropriate material recognition. A root cause analysis shows that the problems are associated with the type of accelerating structure employed in the present state of the art X-ray sources. In the common cases, standing wave (SW) structures are used. The next problematic component is the type of RF source. In most cases, it is a cost effective magnetron. This RF device is hard to control, even with the use of rather sophisticated feedback loops. The next generation of modern dual energy X-ray sources is based on traveling wave accelerating structures that are driven by klystron RF sources.

For example, the block diagram of a multi-energy traveling wave linac for X-ray source is shown Figure 5 [7].

This block diagram was reproduced from [7]. This diagram shows the RF linac subsystems and functional connections between them. The Frequency Controller (1) and Programmable Logic Controller (PLC) or PC Controller (shown on the left side of the diagram) makes it possible to track the phase and tune the Oscillator (2). These components are part of the pulse-to-pulse X-ray energy modulation. The beam intensity modulation takes place through the following chain: PLC or PC Controller, Grid Drive Level and Current Feedback Control, Gun Modulator (9), e-Gun.

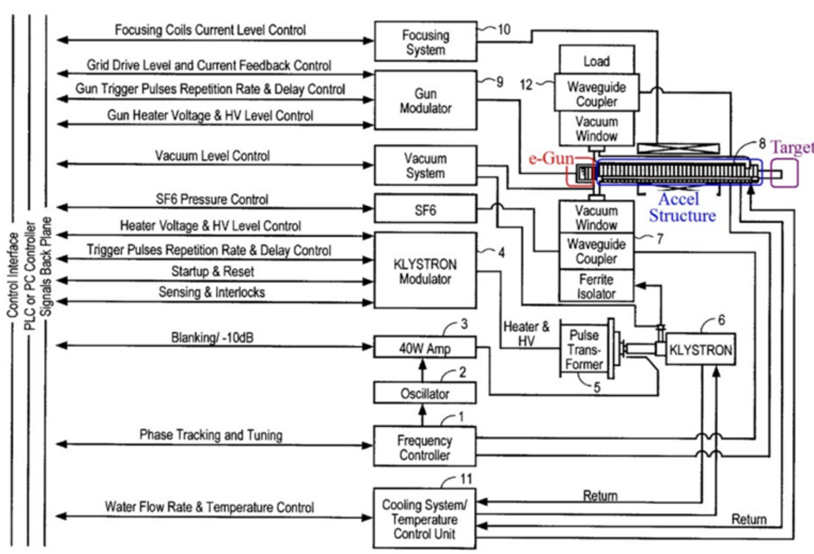

Figure 5 Block diagram of TW RF linac X-ray source [7]: the red colored box is the electron gun, the blue box is the TW accelerating structure, and the magenta colored box is the target.

One can see that the magnetron-based source is replaced by a klystron. The klystron is a high gain amplifier, and its output power and phase are precisely controllable by a low level RF (LLRF) subsystem.

One can also see that the standing wave accelerating structure is replaced by traveling wave (TW) accelerating structure. Usually linacs, which are configured to generate multiple energies, should be tuned at each energy level to provide maximum efficiency at the highest energy level and maximize stability at each energy level. The TW accelerator sections (or so called TW disk loaded waveguides) can be tuned at multiple energy levels to provide highly stable and highly efficient X-ray beams.

A pulse-to-pulse klystron feedback system enables the bunches to remain at the desired phase of the accelerating electromagnetic wave by shifting the phase of the beam to compensate for shifting the frequency of the klystron to achieve amplitude modulation.

A result of the current state of the art analysis shows that modern X-ray sources are based on controlling the low level RF drive of the klystron, which then controls the high power RF from the klystron fed into the traveling wave accelerating structure. This concept allows dual energy mode operation on a pulse-to-pulse basis. The X-ray beam intensity can be pulse-to-pulse modulated at the electron gun source. An X-ray imaging specification requires material identification at full speed (up to 60 km/hr) over a wide range of attenuation. This requirement translates to a linac repetition rate of up to 1 kHz with electron beam energy up to 10 MeV.

Proposed Technical Approach

We consider an adjustable X-ray source for use in different scan scenarios. The source can produce ramping and controllable end-point energy during each pulse. The end point X-ray energy and flux intensity is controllable in such a way that a detector system can resolve the time-energy structure of the ramping pulse. This technical approach is based on fast detectors that can resolve the time-energy structure of the pulse. This approach provides the information needed for material discrimination in a single X-ray pulse. A single detector channel records the energy-dependent attenuation in the course of a single X-ray pulse. Not only is there no penalty in penetration or in scan speed as in traditional dual energy systems, but also the method provides a new flexibility in the choice of the energy bins. Thus, for instance, when in a traditional 4/6 MeV interlaced dual energy system the 4 MeV pulse incident on the cargo is attenuated to a level which no longer allows material discrimination, our ramping pulse system could use a 5/7 MeV energy bin combination for material discrimination. Relying on the relation of three energy bins for material discrimination is also possible. Furthermore, in the case of less attenuating cargo, the ramping energy pulse can be stopped as soon as a sufficient signal has been recorded, thus minimizing the radiation created by the source to the amount needed for the radiograph.

If highly attenuating cargo is detected, the X-ray pulse energy will be increased to a maximum value, which ensures the best possible penetration. If the maximum end-point energy is chosen to be high enough to induce photofission in special nuclear material (SNM), the resulting prompt neutrons and delayed gammas can be detected and activate a real-time alarm resolution. This is especially important for rail scanning as a secondary inspection when alarm resolution is not practical. Note that this approach generates neutrons only during the very short time when the system calls for high-Z alarm resolution. Other scan scenarios could be realized with the proposed X-ray source. However, this article focuses on the linac system. 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. None of the current state of the art cargo scanning RF linacs have the capability to vary the electron beam during the pulse. 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 SW accelerating structures with magnetron RF sources. For the implementation of intra-pulse energy control, a traveling wave 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 [7]. Basically the idea of our novel approach is illustrated by the following simplified diagram (see Figure 6).

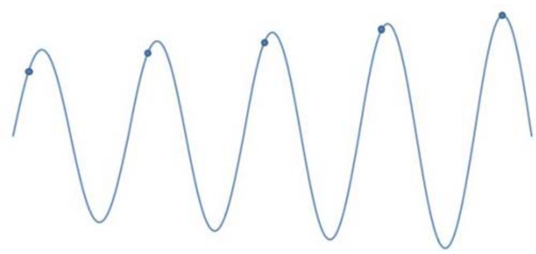

Figure 6 Several RF cycles of the pulse with varying RF amplitude and phase with electron bunches on each RF cycle. The dots represent the electron bunch on the RF wave. In the proposed technical approach, the bunch separation is one RF period and the pulse length is 4 to 10 microseconds (~9000 to 28000 RF periods).

During a long RF pulse, many bunches will be accelerated, each at an energy according to the amplitude of its RF cycle. Figure 6 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 6.

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 block diagram of the linac will be similar to the diagram shown in Fig. 5. However the LLRF control subsystem will be reprogramed for intra-bunch energy variation.

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. 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.

We consider an adjustable X-ray source for use in different scan scenarios. The source can produce ramping and controllable end-point energy during each pulse. The end point X-ray energy and flux intensity is controllable in such a way that a detector system can resolve the time-energy structure of the ramping pulse. This technical approach is based on fast detectors, which can resolve the time-energy structure of the pulse. The detector system is discussed in [1]. The adjustable X-ray source and the detector system provide the information needed for material discrimination in a single X-ray pulse. A single detector channel [1] records the energy dependent attenuation in the course of a single X-ray pulse. Not only is there no penalty in penetration or in scan speed as in traditional dual energy systems, but also the method provides a new flexibility in the choice of the energy bins. Thus, for instance, when in a traditional 4/6 MeV interlaced dual energy system the 4 MeV pulse incident on the cargo is attenuated to a level that no longer allows material discrimination, our ramping pulse system could use a 5/7 MeV energy bin combination for material discrimination. Relying on the relation of three energy bins for material discrimination is also possible. Furthermore, in the case of less attenuating cargo, the ramping energy pulse can be stopped as soon as a sufficient signal has been recorded, thus minimizing the radiation created by the source to the amount needed for the radiograph.

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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. To answer this question we would like to use several SLAC linac technical approaches and experiences that are suitable for the proposed concept. A block diagram of typical SLAC linac RF stations is similar to the block diagram shown in Figure 5. The LLRF electronic components at the SLAC linac can maintain amplitude and phase stability of 0.03% and 0.06 deg of S-band, respectively. This fact is illustrated in Figure 7 where RF amplitude and phase of a single klystron station is shown at the instant of time when a single bunch passes through the traveling wave structure.

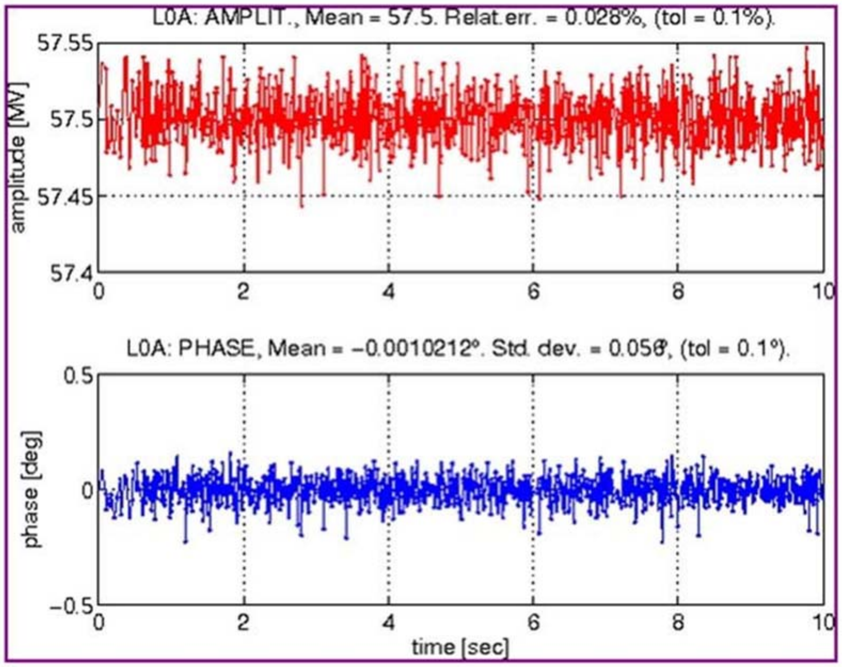

Figure 7 RF amplitude and phase stability on pulse-to-pulse basis during 10 sec continuous run of the SLAC 5045 klystron station feeding a single 10-ft-long S-band traveling wave accelerating structure. Each dot represents a simultaneous measurement of RF amplitude and phase at the instant of time when a single bunch passes through the structure. The repetition rate here is 120 PPS.

One can see that the accelerating electromagnetic wave amplitude maintains a 57.5 MeV electron energy gain through the structure with 0.03% accuracy and a 0.06 degree of 2856 MHz standard deviation phase stability. This achievement at SLAC is the current state of the art for LLRF subsystem control. Components of the LLRF control subsystem are available from industry, are not unique, and are controllable and programmable, with a good dynamic range in the signal-to-noise aperture. Basically digital signal processing with DAC and ADC is widely employed at SLAC with software control and feedback. Calculated digital samples are converted to voltage with the help of digital to analog converters. The amplitude and frequency of these signals are much less compared to the RF amplitude and frequency needed for the electron bunch acceleration. Analog signals can be converted back to high frequency and amplified to the desired amplitude and phase to drive the klystron.

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 this question will require a detailed analysis for the optimal machine for cargo inspection, we would like to demonstrate that the RF amplitude and phase can be controllable during the typical RF pulse at the SLAC linac. The bandwidth of the traveling structure is smaller than the klystron bandwidth. The bandwidth of the SLAC traveling structure was evaluated from a dispersion curve simulated by the SUPERFISH code. It is illustrated by Figure 8.

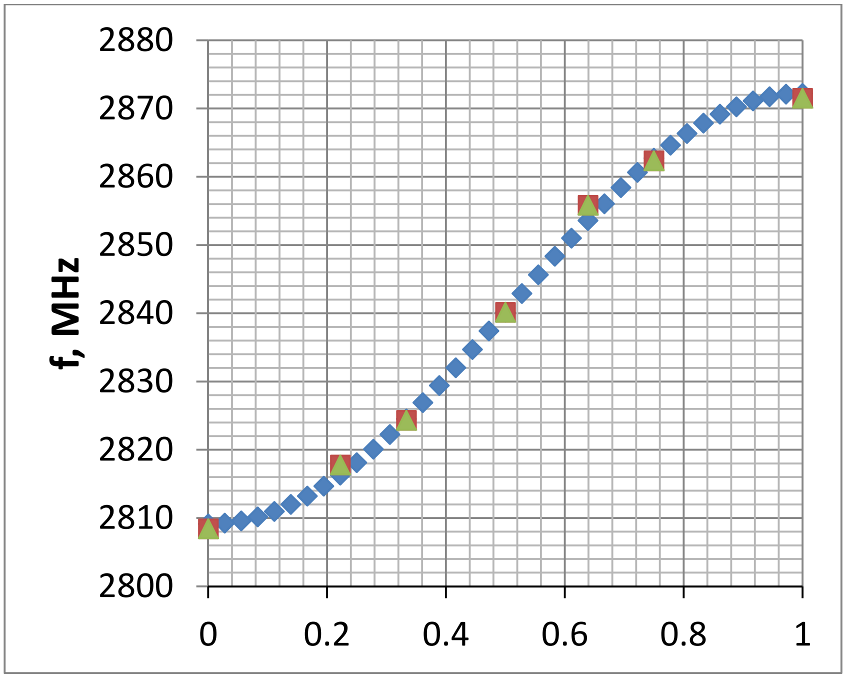

Figure 8 Dispersion curve for SLAC traveling wave accelerating cells. The horizontal scale is a normalized phase shift.

One can see that the bandwidth of the first SLAC linac cells of the traveling structure 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. This station is used for diagnostics of the LCLS bunch. The klystron station feeds one S-Band TW structure. The klystron power phase and amplitude are controlled by the Phase and Amplitude Controller (PAC) chassis, and the result is detected by the Phase and Amplitude Detector (PAD) chassis. The station uses a solid state sub-booster to dive the klystron. The SLAC PAC was programed to adjust the phase and amplitude of the RF signal using two analog outputs to run an I&Q mixer. The control board uses a MAX5875 two-channel, 16-bit, 200MSPS DAC to clock out waveforms, which are stored in a Xilinx Spartan 3 FPGA. The Coldfire microprocessor is memory mapped to two 2k, 16-bit sample waveforms in the FPGA. The FPGA-based RF processor enables the pulse-to-pulse and also intra-pulse feedback control. On a trigger the two waveforms are simultaneously clocked out of the dual DAC. Voltage waveforms of up to ±1.0Volts are sent to the I&Q modulator. The FPGA has an internal trigger mode to continuously write a waveform. The unit is calibrated by writing a cosine to one waveform and a sine to the other. In this mode the unit becomes a single sided band modulator. Figure 9Figure 9 shows the PAC window where one period of sin-like curve is shown.

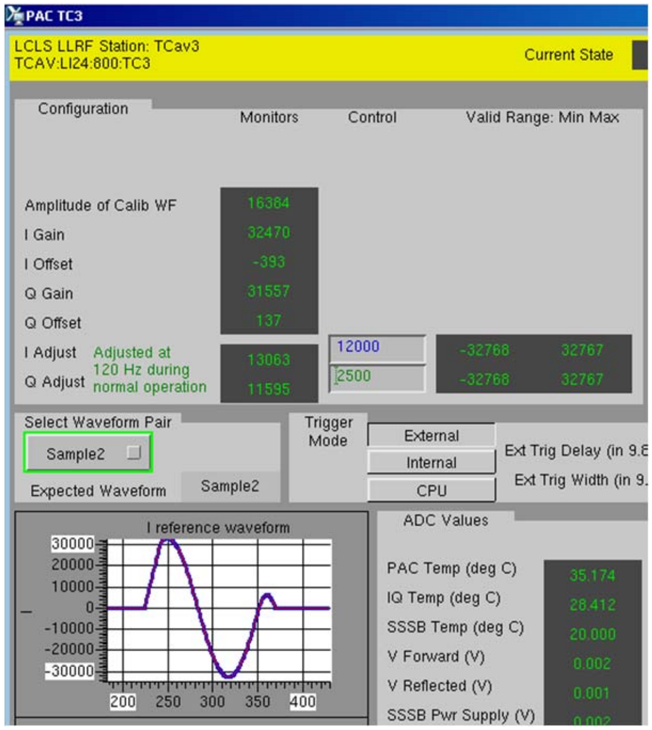

Figure 9 PAC window to control SLAC's sector 24-8 klystron station. One period of sinusoidal curve represents a 360^{o} phase variation signal to drive the 5045 klystron.

The RF amplitude of the klystron forward power is shown in Figure 10. A shape of the drive amplitude signal has the rise and fall intervals with an almost flat top between.

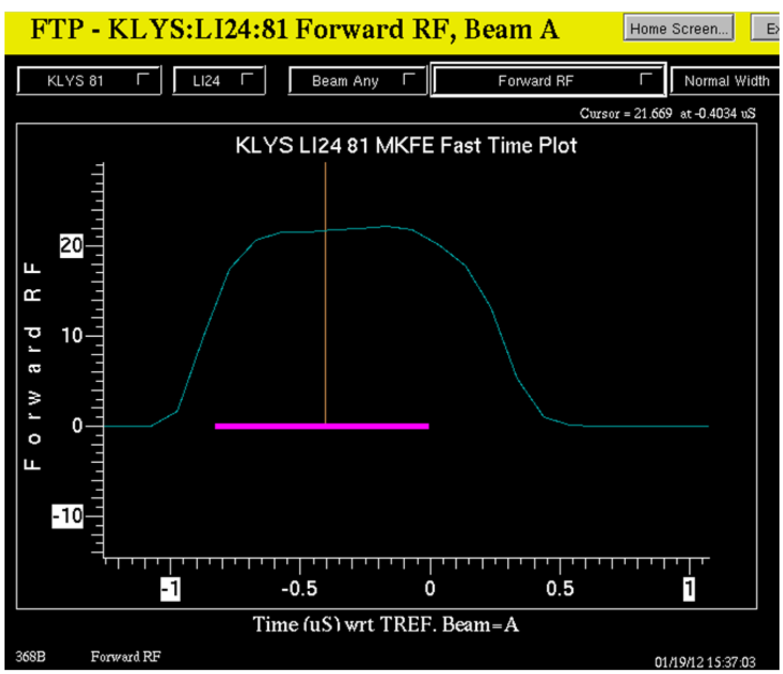

Figure 10 Output klystron power vs. time.

The drive signal with phase modulation is amplified in the solid state sub booster and applied to the input of the 5045 klystron. The klystron output power (see Figure 10) 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 11. 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 approximately 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.

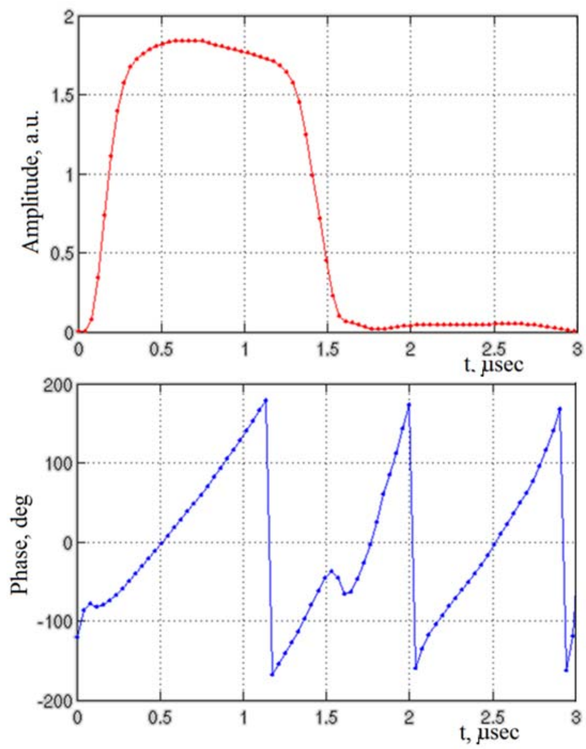

Figure 11 PAD/PAC controlled propagated RF amplitude and phase vs. time.

We also were able to carry out the beam based experiment at the front end of the SLAC injector with two bunches. It was a separate experiment with a separate klystron station. The nearest to the gun position is the K02 klystron station in Sector 0. A block diagram of experiment is shown in Figure 12.

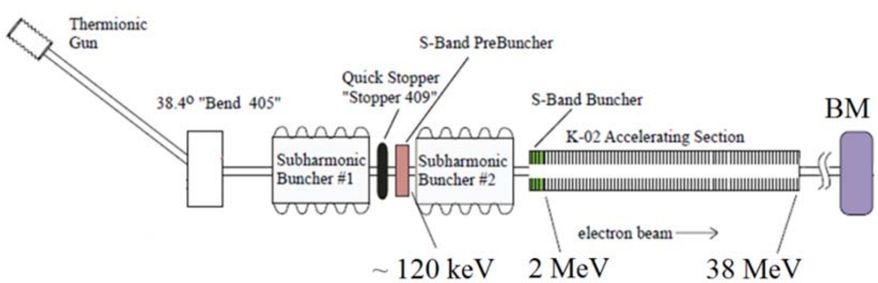

Figure 12 Block diagram of the beam-based experiment.

A thermionic gun was used as a beam source. All beam optic and beam diagnostic components of the beam line up to the TRIM BEND 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. The traveling wave buncher and first accelerator section are fed by the K02 klystron. 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. Setup of the K02 klystron station is shown in Figure 13.

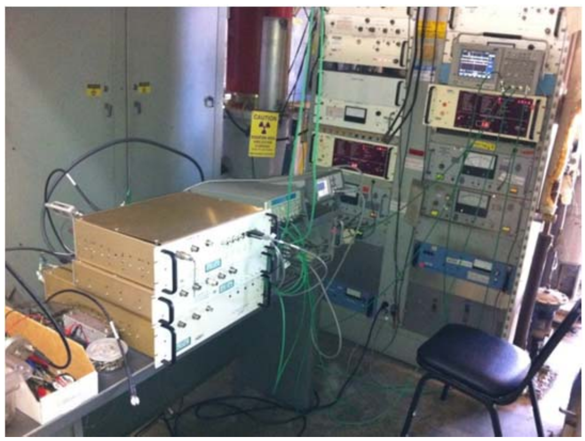

Figure 13 Temporary layout of K02 LLRF subsystems for the Intra-Pulse Multi-Energy Experiment.

The synchronization of other components of the K02 klystron station was carried out using the existing injector timing system. Figure 14 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.

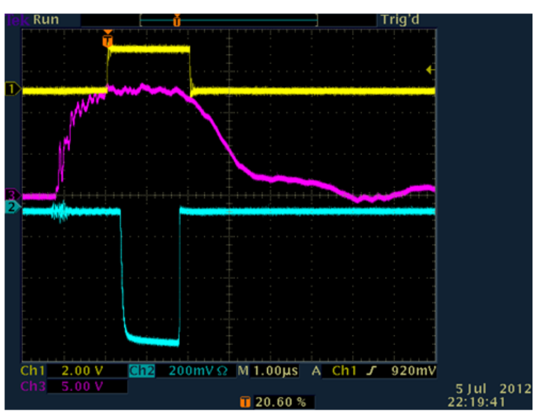

Figure 14 Synchronization of RF drive with the K02 klystron modulator.

The PAC control (read and write) was integrated in the LCLS computer network accordingly to tune the modulation setup. Figure 15 shows 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.

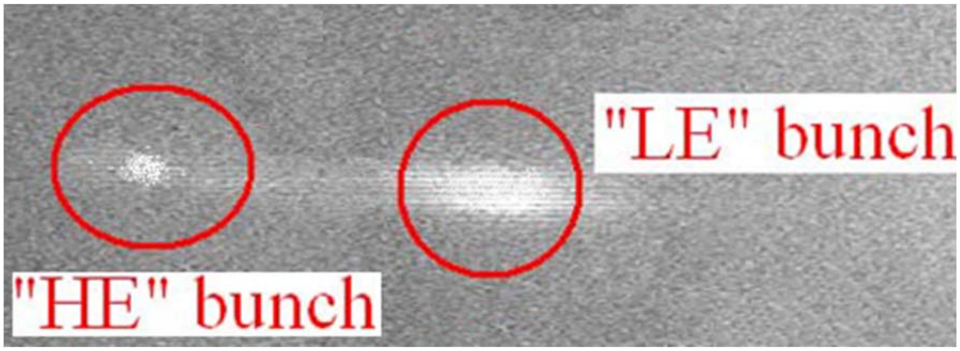

Figure 15 Two bunch images on the spectrometer camera screen.

These images belong to "low energy" and "high energy" 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. Such proof of concept experiment can be conducted inside one of SLAC's experimental linac bunkers; however a small accelerator suited specifically for those experiments needs to be built and installed there. Some existing parts at SLAC can be devoted to the cause.

Acknowledgments

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