DESIGN, SIMULATIONS AND EXPERIMENTAL DEMONSTRATION OF AN INTRA-PULSE RAMPED-ENERGY TRAVELLING WAVE LINAC FOR CARGO INSPECTION*

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Abstract

Novel radiographic imaging techniques [1] based on adaptive, intra-pulse ramped-energy short X-ray packets of pulses, a new type of fast X-ray detectors, and advanced image processing are currently some of the most promising methods for real-time cargo inspection systems. RadiaBeam Technologies is developing the high-speed Adaptive Railroad Cargo Inspection System (ARCIS), which will enable better than 5 mm line pair resolution, penetration greater than 450 mm of steel equivalent, material discrimination over the range of 6 mm to 250 mm, 100% image sampling rate at speed up to 45 km/h, and minimal average dose.

One of the core elements of ARCIS is a new S-band travelling wave linac with a broad range of energy control. The linac allows energy ramping from 2 to 9 MeV within a single 16 µs RF pulse using the beam loading effect. RadiaBeam Technologies has designed, built and tested the ARCIS accelerator prototype. In this paper, we will discuss the linac design approach and its principal components. The results of the experimental demonstration of intra-pulse energy ramping will be presented. We will also provide a detailed comparison of beam dynamics simulations in Hellweg2D and CST Studio codes with experimental measurements, including transient beam loading effects.

INTRODUCTION

Adaptive Rail Cargo Inspection System (ARCIS) is an innovative X-ray cargo inspection technique being developed by RadiaBeam Technologies, LLC [1,2]. Conventional dual energy radiography systems cannot meet the requirements of the security market needs for high throughput rail cargo radiography inspection systems, which include:

- better than 5 mm line pair imaging resolution;
- penetration beyond 450 mm steel equivalent;
- maximum scanning speed with material discrimination (four levels of Z) 45 km/h;
- low dose and small radiation exclusion zone.

The ARCIS technical concept relies on linac-based, adaptive, ramped energy source of packets of short X-ray pulses sampled by a new type of fast X-ray detectors with rapid hardware processing for intelligent linac control, and advanced radiography image processing and material discrimination analysis.

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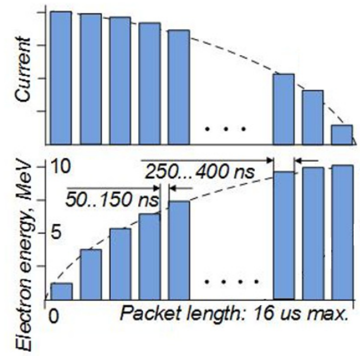

Figure 1: Energy and current temporal profiles of packet of short X-ray pulses.

To ensure ARCIS imaging performance a new S-band travelling wave linac with deep energy control has been designed. This linac will provide the packet of thirty-two 400 ns X-ray pulses separated by the 100 ns gap with pulse energy ramping within packet from 2 to 9 MeV and a total beam power of up to 2 MW (see Figure 1). The detailed description of the ARCIS system can be found in the paper [2].

LINAC DESIGN

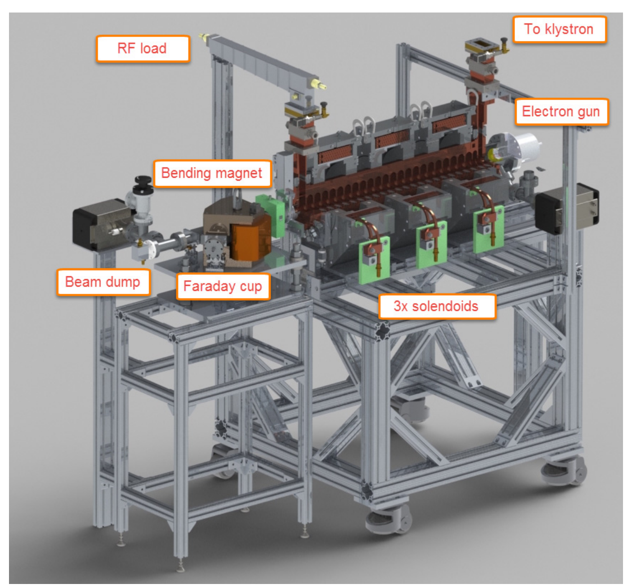

Figure 2: 3D design and physical layout of the ARCIS linac.

The discussion on linac parameters justification and detailed linac design can be found in the paper [3]. The design of the ARCIS linac consists of the following components (see Figure 2):

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- Travelling wave accelerating structure
- RF power source
- DC triode electron gun
- Three focusing solenoids
- RF load
- Vacuum system
- Colling system with chiller
- LLRF control system

The high power RF system (Figure 3) is based on a CPI VKS-8262F2 S-band klystron. The tube is capable of 5 MW peak power, and 36 kW of average power. It is driven by a ScandiNova K1-P solid-state modulator. A Microwave Amps Ltd. model AMS10-2.85S- 52R provides the low-level RF source and preamp for the input of the klystron. The klystron is protected from reflected power via a ferrite based isolator from Mega Industries. We employ a dual directional coupler with -50 dB of nominal coupling to monitor the incident and reflected RF power. RF power levels are detected by fast Schottky diode detectors which in turn are calibrated using an Agilent E44117A peak power meter with a high-speed Agilent E9325A detector.

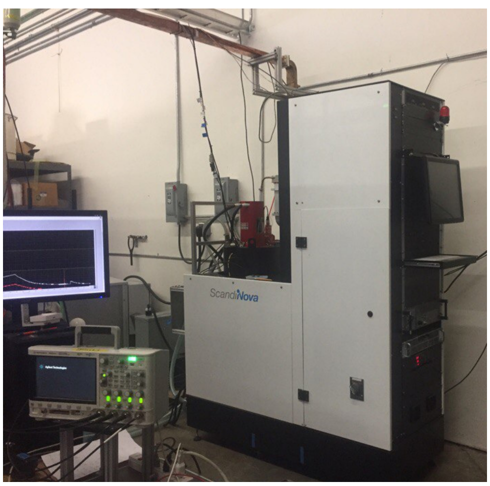

Figure 3: Klystron's collector visible from the modulator mounting and the high power isolator from Ferrite Inc. mounted to the wall directly behind it.

The gridded electron gun is used as an injector. The gun injects electrons with an energy of 30 keV at the currents of up to 3A. The gun was manufactured by Nano-Invest, LLC [4] and utilizes Eimac Y-646E cathode.

Three solenoids were designed and built by RadiaBeam Technologies and will be used for the beam focusing. The operation level at 1A beam is expected at 1000 Gs. However, it can be increased up to 1200 Gs in the case of beam-break-up effect observation. The cathode is shielded from the magnetic field by enclosing it in an iron box. Fully assembled system is shown in Figure 4.

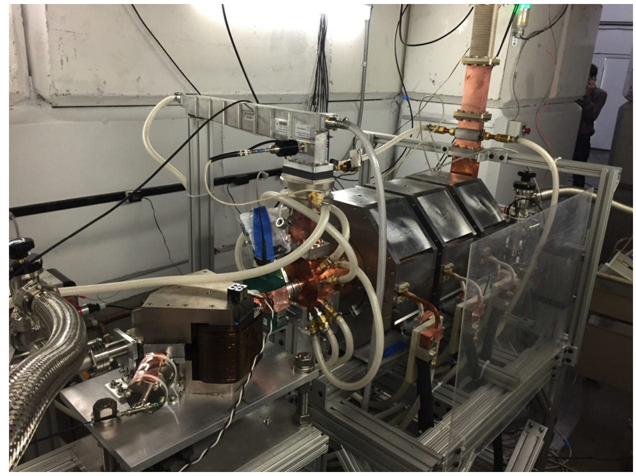

Figure 4: Assembled ARCIS linac.

ACCELERATING STRUCTURE

Travelling wave (TW) accelerating structure was preferred to the standing wave (SW) for several reasons. First, the filling times of TW structure are ~3 times faster than for the non-significantly over-coupled standing wave structure. This effect is critical for the beam loading effect to take place in 400 ns meso-pulse since we plan to use beam loading for the energy ramping. Second, the TW linac can be made as a single section without a pre-buncher due to the good bunching efficiency for wide input power and beam current ranges, because the beam loads the structure gradually from the beginning to the end.

The bunching section consists of two cells with β=0.7. Aggressive bunching allows the particles to fly through the region with weak magnetic field faster, which makes the buncher more robust and easy to manufacture. However, fewer phase oscillations lead to minor compression, lower capture and the existence of low-energy tail.

Figure 5 shows the 3D model of the accelerating structure with the beam shape evolution. Initially, ARCIS linac section was designed using Hellweg2D code [5]. Later, the full 3D EM and beam dynamics simulations including transient effects were verified in CST Particle Studio (PIC solver) for 0.25 mA and 2A injected currents. The comparison of the results can be found in Table 1 and shows excellent agreement between the codes.

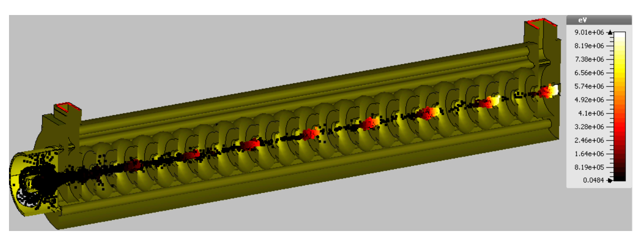

Figure 5: Beam dynamics simulations in ARCIS accelerating section.

CST Particle Studio allows doing full 3D self-consistent beam dynamics analysis in transient regime. The results of such simulations demonstrated the feasibility of the beam loading approach during the meso-pulse, as shown in Figure 6. Energy burst, observed in the plots is unavoidable in RF structures due to the filling time. In ARCIS it was minimized by choosing the proper group velocity and can be neglected completely in future by using an RF-power ramp

Table 2: Comparison of Hellweg2D and CST PIC solver simulations

Injected current, A	**0.25**		**2.0**	
Code	Hell-weg	CST	Hell-weg	CST
Beam current, mA	124	115	835	906
Max. energy, MeV	9.6	9.2	5.10	5.08
Load power, MW	1.73	1.72	0.22	0.50

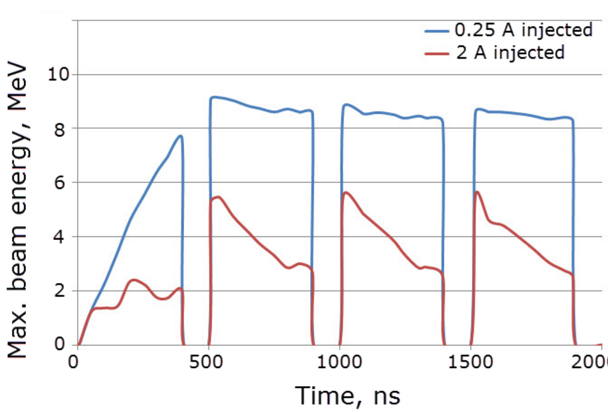

Figure 6: Temporal profile of the high (blue) and low (red) energy meso-pulses.

LINAC HIGH POWER TESTS

We have tested the linac with the full 5 MW peak power, and up to 12 µs pulse lengths. The primary conditioning phase took approximately 30 continuous hours of progressively increasing peak power and pulse length. To date, we have created beams with a variety of temporal profiles and energy profiles. These measurements are made using a dipole magnet based monochromator designed and built by RadiaBeam Technology. By accumulating many energy slices over multiple linac shots, we can generate energy profiles of our beams with high temporal resolution.

The first beam measurements were done in September 2016. The current of ~8 MeV was achieved with ~ 200 mA beam current. We measured the temporal profile of train of 400 ns meso-pulses, as shown in Figure 7, which demonstrated the feasibility of the intra-pulse energy ramping method. Figure 8 shows the time resolved spectrum of the beam. Further conditioning and tests will be done to achieve the beam current of ~1A, measure the beam loading curve and demonstrate the energy ramp from 2 to 9 MeV within 16 µs pulse length.

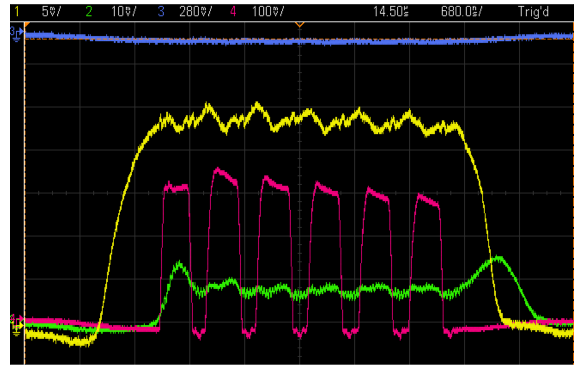

Figure 7: Oscillogram of six beam pulses injected into a single 5 us RF pulse. Yellow is the incident RF power (nominally 5 MW), green is the power transmitted to the load on the output coupler of the linac, and pink is the current accelerated and detected by a self-integrating current transformer.

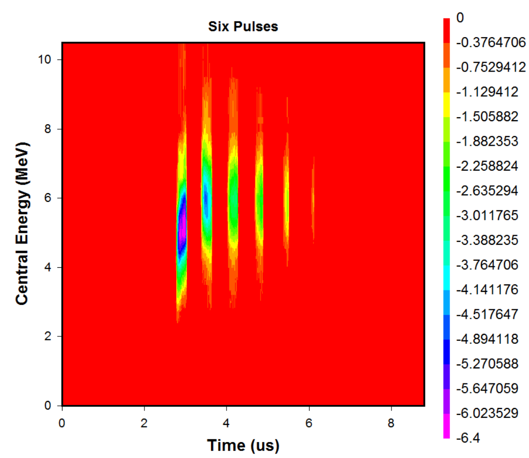

Figure 8: Time-resolved spectrum of the beam shown in Fig. 7. Color represents the beam intensity in a.u.

SUMMARY

We designed, built, and tested the travelling wave linac prototype for adaptive, an intra-pulse ramped-energy technique for cargo inspection system. The feasibility of the approach was demonstrated. The energy of 8 MeV with 200 mA current was achieved for 12 µs pulse length. Further tests are to be done at higher current regimes to demonstrate deep energy variation due to the beam loading effect.

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REFERENCES

[1] A. Arodzero, S. Boucher, A. Murokh, S. Vinogradov, and S.V. Kutsaev. "System and Method for Adaptive X-ray Cargo Inspection," US Patent Application 2015/1472051.

[2] A. Arodzero, S. Boucher, J. Hartzell, S.V. Kutsaev, R.C. Lanza, V. Palermo, S. Vinogradov, and V. Ziskin. "High Speed, Low Dose, Intelligent X-ray Cargo Inspection," *IEEE-2015 Nuclear Science Symposium proceedings*, N2B1-6.

[3] S. Kutsaev, R. Agustsson, A. Arodzero, S. Boucher, L. Faillace, J. Hartzell, and V. Ziskin, "Electron Linac with Deep Energy Control for Adaptive Rail Cargo Inspection System," *IEEE-2015 Nuclear Science Symposium proceedings*, N1CP-118.

[4] A. A. Zavadtsev, D. A. Zavadtsev, A. A. Krasnov, N.P. Sobenin, S.V. Kutsaev, D.V. Churanov, and M. O. Urbant, "A Dual Energy Linac Cargo Inspection System", *Instruments and Experimental Techniques*, 2011, Vol. 54, No. 2, pp. 241–248

[5] S.V. Kutsaev, "Electron dynamics simulations with Hellweg 2D code", *Nuclear Instruments and Methods*, 618(1), 2010, pp. 298-305.