DUAL-ENERGY ELECTRON LINAC FOR CARGO INSPECTION SYSTEM

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Abstract

In today's turbulent and unsecure world, an X-ray radiographic image and a dual-energy Z-detection mapping of a container contents are needed to provide a reasonable level of port and border security. An interlaced dual-energy electron-beam linac has been developed for the use in cargo inspection systems to meet this growing need. Electron energy of the linac is software controllable from 3 to 15 MeV. Nominal operating energy levels of 4 and 9 MeV were chosen. The 9 MeV beam energy operating point is used for generating the X-ray radiographic image while 4 and 9 MeV beams are used for Z-detection mapping. The S-band linac has been calculated, designed, built and tested. Frequency repetition rate of alternating 4 and 9 MeV beams is 240 Hz. Pulse length is 10 usec. The beam energy in each beam pulse is over 10 J.

ACCELERATING SYSTEM

The accelerating system includes one section of standing wave on-axis coupled biperiodic structure. This section includes Ω-shaped accelerating and coupling cells. The first two accelerating cells are bunching cells with decreased phase velocity. The remaining accelerating cells have a constant relative phase velocity, which was set equal to 1. Computer simulation was used to predict the energy distributions of both the electric and accelerating field respectively. As depicted in Figure 1, the energy distribution in the first three and half accelerating cells has been approximated for both the electric field E as well as accelerating field E_a .

The total length of the accelerating section is 1 m, while the aperture diameter of the section is 5 mm. An optimal accelerating gap to period ratio is 0.6 for maximum shunt impedance in the biperiodic structure. However, this ratio was increased to 0.8 in this case, because the shunt impedance is reduced, and more importantly, there is a substantial increase in the electric strength of the accelerating structure.

The purpose of the accelerating system is to increase the velocity of electrons to two pulse-to-pulse alternating energy levels of 4 and 9 MeV. The desired maximum electron energy is 15 MeV. Two variables, the injected beam current and the klystron power controlled pulse-to-pulse, are used to vary the electron beam energies alternating pulse-to-pulse.

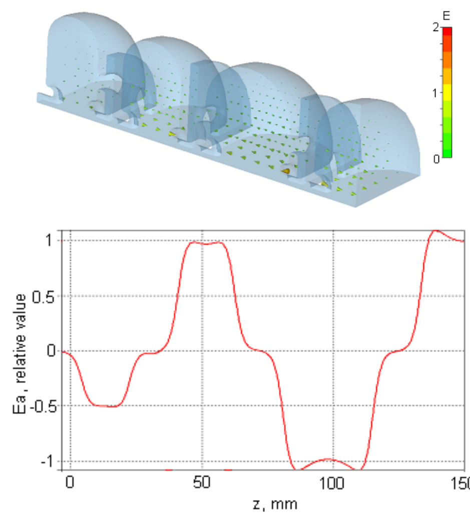
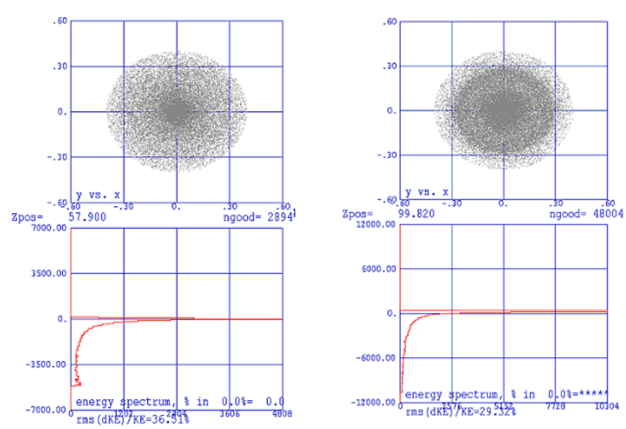


Figure 1: Calculation model and accelerating field distribution in first three and half accelerating cells.

A depiction of the calculated beam cross-section and electron energy spectra for 4 and 9 MeV are shown in Figure 2.



4 MeV 9 MeV

Figure 2: Beam cross-section and electron energy spectra for 4 and 9 MeV.

Since the RF electromagnetic fields inside the accelerating structure are designed to focus the electrons, there is no need for external focusing.

INJECTOR

A three-electrode, grid-controlled, electron gun is used as an electron injector. The gun injects electrons at 40 kV with a current of 1.5 A. The calculated shape of the injector, the corresponding iso-potential lines (pink) and trajectories of the injected electrons (green) are shown in Figure 3.

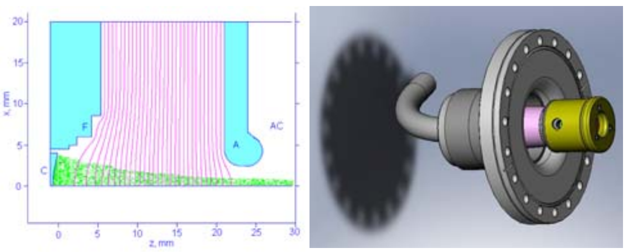


Figure 3: Shape of the injector. C is the cathode, F is the focusing electrode, A is the anode, which is the wall of first accelerating cell AC of the accelerating section. Z is the accelerating section axis.

X-RAY CONVERSION TARGET

The accelerated electron beam bombards the X-ray conversion target to produce Bremsstrahlung irradiation. The X-ray target consists of a thin Tungsten layer and Copper water-cooled radiator.

The temperature distribution as a function of time, is shown in Figure 4.

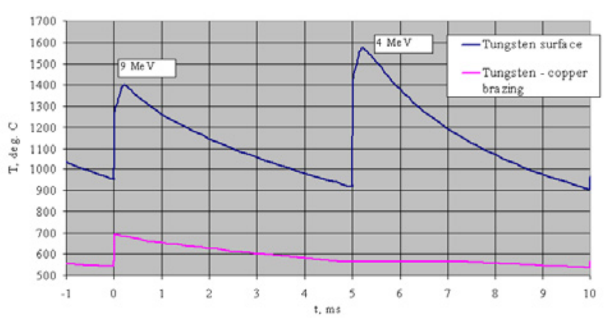


Figure 4: Temperature distribution versus time on the Tungsten (blue) and Tungsten-Copper brazing surfaces (pink).

The peak temperatures are 1700 and 700 °C in Tungsten and in Copper, respectively.

RF POWER SUPPLY

The RF power supply system includes the following components: a 5 MW peak and 10 kW average power klystron, ferrite circulator, waveguide load, waveguide ceramic window and vacuum unit connected to an ion pump.

RF power supply system is filled with Sulfur hexafluoride gas (SF_6) at 2.5 bar absolute pressure from the klystron to the window and with high vacuum from the window to the accelerating section.

MODULATOR

The solid-state modulator is used to feed the klystron and the injector by pulsed high voltage and by filament power. It includes a switch mode capacitor charger, capacitor, IGBT switch, pulse transformer, filament board, bias power supply, and oil tank and provides:

- 130 kV, 100 A, 0-10 µsec, 20 kW for klystron,
- 40 kV, 2 A, 0-10 µsec for injector.

The whole modulator is assembled in oil-tank.

VACUUM SYSTEM

The vacuum system provides high vacuum (quantified in torr) in the following areas: the accelerating section the injector and the waveguide. An oil-free vacuum system is used in the linac with several pumps being used in stages to maintain the desired operating conditions An 80 l/min dry scroll pump is used to achieve an oil-free fore-vacuum of 10^{-1} mbar, a 70 l/sec turbo-molecular pump is used to yield 10^{-6} mbar, while a 150 l/sec ion pump is used for final pumping to 10^{-8} mbar.

LOCAL SHIELDING

Local shielding is used to protect the operating personnel and the equipment of cargo inspection system from ionizing irradiation.

The local shielding consists of a cavity with the injector, the accelerating system, and the X-ray conversion target inside. There is a collimating slot in the local shielding for X-ray output. The Shielding itself is made of Lead and Tungsten. There are three Tungsten parts: the surrounding X-ray conversion target, the collimating output X-ray beam and shielding behind the injector. The calculated dose rate distribution in and out of the local shielding is shown in Figure 5.

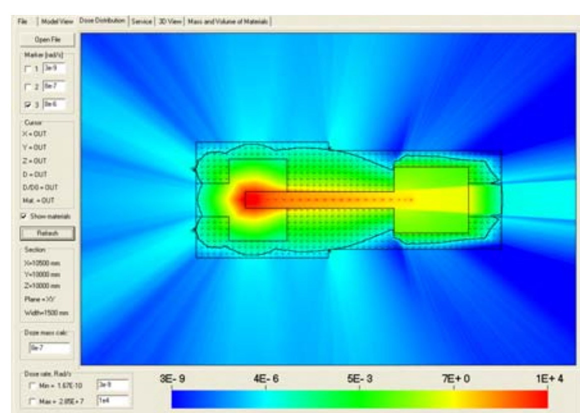


Figure 5: Calculated dose rate (Rad/sec) distribution (black line is $8\cdot10^{-6}$ Rad/sec isodose).

The local shielding is made of Lead and Tungsten assembled inside special frame (see Figure 6).

LINAC TEST

The linac system was tested remotely using real linac components assembled for prototyping purposes. The test stand is shown in Figure 7, and it includes the linac with X-ray conversion target inside the local shielding, X-ray detector array and control system.

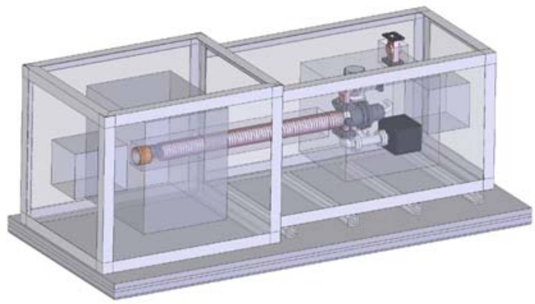


Figure 6: Local shielding.

Figure 7: Test stand.

The fully designed beam parameters were measured during this test. The beam current was determined to 300 mA at 9 MeV energy as shown in Figure 8.

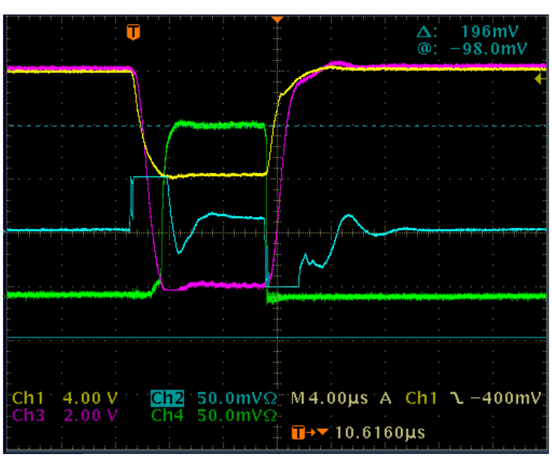


Figure 8: Operating point oscillogram.

A representative X-ray image measured at the stand is shown in Figure 9.

ENGINEERING DESIGN AND EQUIPMENT LAYOUT

The actual designed linac configuration is determined depending on its desired commercial application. In general, the linac should be compact, reliable, and safe.

The accelerator unit includes the accelerating system, injector, X-ray target and vacuum system inside the local

Figure 9: X-ray image measured at the stand.

shielding, klystron, circulator and modulator in one common box (see Figure 10). The Power supply and control equipment are located in separate cabinet.

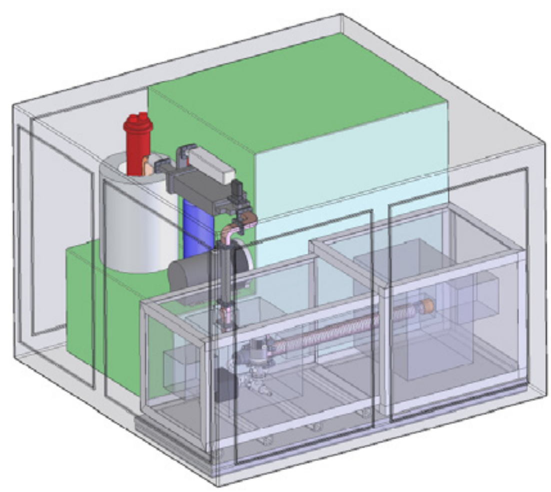


Figure 10: Accelerator unit.

Nominal operating energy levels of 4 and 9 MeV were chosen. The 9 MeV beam energy operating point is used for generating the X-ray radiographic image while 4 and 9 MeV beams are used for Z-detection mapping. The 15 MeV energy capability was included in the design for future development of high-Z fissionable material detection with neutron registration.

The linac has been developed, designed, manufactured and tested and is now ready for commercial application.