7.5 MeV High Average Power Linear Accelerator System for Food Irradiation Applications

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Abstract
In December 2004 the US Food and Drug Administration (FDA) approved the use of 7.5 MeV X-rays for irradiation of food products. The increased efficiency for treatment at 7.5 MeV (versus the previous maximum allowable X-ray energy of 5 MeV) will have a significant impact on processing rates and, therefore, reduce the per-package cost of irradiation using X-rays. Titan Pulse Sciences Division is developing a new food irradiation system based on this ruling. The irradiation system incorporates a 7.5 MeV electron linear accelerator (linac) that is capable of 100 kW average power. A tantalum converter is positioned close to the exit window of the scan horn. The linac is an RF standing waveguide structure based on a 5 MeV accelerator that is used for X-ray processing of food products. The linac is powered by a 1300 MHz (L-Band) klystron tube. The electrical drive for the klystron is a solid state modulator that uses inductive energy store and solid-state opening switches. The system is designed to operate 7000 hours per year.

Keywords: Rf Accelerator, Solid state modulator, X-ray processing

1. Introduction

Irradiation of food products has been regulated in the United States by the Food and Drug Administration (FDA) since 1958 [1]. In December 2004 the FDA amended the regulation to allow the use of 7.5 MeV X-rays from machine sources using tantalum or gold as the target material [2].

X-ray processing combines the advantages of the other energy sources approved for food irradiation. X-rays provide the penetrating power of gamma sources, and like electron beam sources they are generated by machines that can be turned on and off. However, before the amendment to 21 CFR Part 179 was enacted, X-ray processing of food products at 5 MeV was not economically competitive with other sources.

When all factors that affect energy efficiency (i.e. photon utilization, conversion efficiency and self-absorption) are considered, an overall efficiency of 4% can be achieved from a 5 MeV machine source and 8% can be achieved from a 7.5 MeV machine source. A 7.5 MeV X-ray machine source is comparable in efficiency to that of a gamma source [3].

An economic model was developed based on cost and performance data from an X-ray facility in Canada. Using this model the cost per tonne for irradiation of food product was estimated to decrease by one third when the energy of the source was increased from 5 to 7.5 MeV. In this case beam power (100kW) and absorbed dose (2.5 kGy) were held constant [3].

A 5 MeV X-ray processing facility in Vietnam uses a ~100 kW accelerator with X-ray converter to process approximately 2.5 tonnes of frozen seafood per hour and the facility routinely processes 20 tonnes of product per day. However, daily volumes up to 40 tonnes are available for processing [4]. A 7.5 MeV accelerator of the same average power would substantially reduce the time and therefore the cost to process 20 tonnes daily, and would allow for increased daily production rates and additional profitability.

Titan Pulse Sciences Division (TPSD) is developing a 7.5 MeV high average power (100 kW electron beam power) X-ray system that uses a linear accelerator with tantalum converter. The linac is an RF standing waveguide structure that is tuned for 1300 MHz operation and powered by a Thales 2104D klystron tube. An inductive store modulator with opening switches provides the electrical drive for the system.

The 7.5 MeV accelerator is extrapolated from a 5 MeV accelerator developed by SureBeam Corporation in 2002 [5]. A picture of the 5 MeV standing waveguide structure with vacuum pumps attached is shown in Figure 1. The structure consists of 6.5 accelerating cells and 6 coupling cavities with axial tuning slots in the cavity walls.

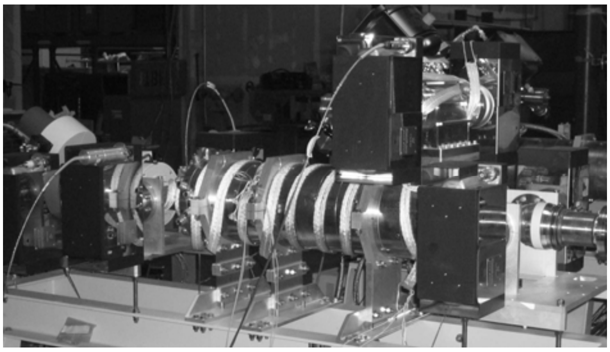

Fig 1. 5 MeV Linac Structure

Herein we describe the design of the 7.5 MeV accelerator structure, the RF system and the inductive store solid-state switched modulator that will drive the klystron and electron gun of the accelerator.

7.5 MeV Linerra Accelerator System :

A block diagram of the 7.5 MeV linear accelerator system (with the three subsystems that are discussed below highlighted) is shown in Figure 2.

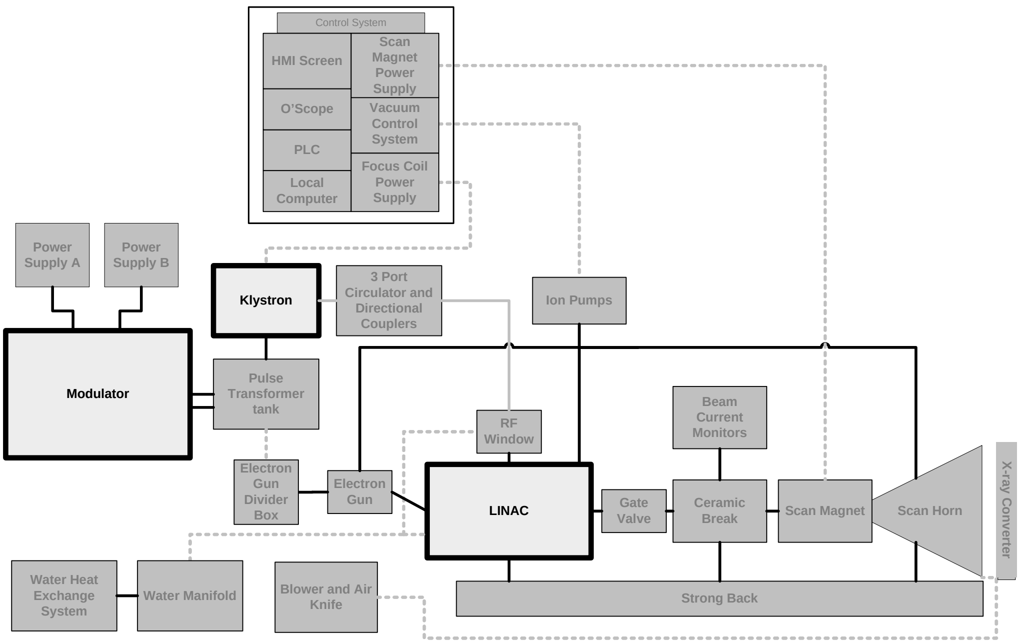

Fig. 2 System Block Diagram.

Specifications for the output of the accelerator system are summarized in Table 1.

Table 1. System Specifications

Parameter	Value
Kinetic Energy (MeV)	7.5
Average Power (kW)	100
Average Beam Current (Amps)	0.013
Duty Cycle	~0.04
Pulse Duration (μsec)	125
Repetition Rate (Hz)	325
Peak Beam Current (Amps)	0.33
Peak Beam Power (MW)	2.5
RF Efficiency (%)	60

Linear Accelerator :

The extrapolation of the 5 MeV accelerator design increased the number of accelerating cells from 6.5 to 10.5. This ratio results in a lower accelerating gradient by about 7%. With an rf efficiency of ~ 60% the copper power loss in the waveguide is approximately 1.7 MW. This sets the peak rf requirement for the klystron tube at 4.2 MW.

The results of a Klydyn simulation, a fixed-frame derivative of Parmela [6], of this increased length accelerator indicated the electron bunches tend to slip behind the rf phase, resulting in deterioration of the kinetic energy spectrum.

The phase slip can be mitigated by reducing the structural beta of the second (first full) accelerating cell from β=1.0 to β=0.89. Selected output frames from the simulation of this case are shown in Figures 3 and 4.

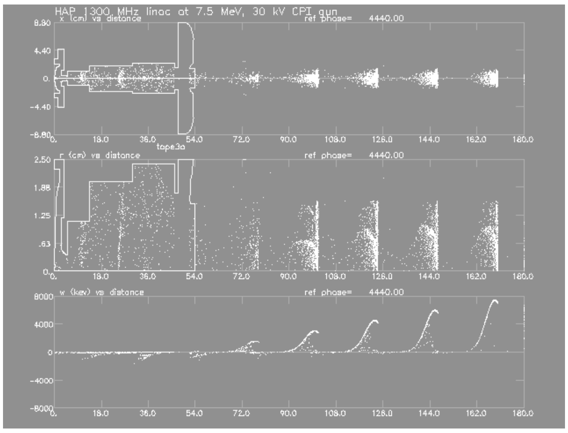

Fig 3. Klydyn Output Frame Showing Good Bunching with Kinetic Energy of 7.47 MeV.

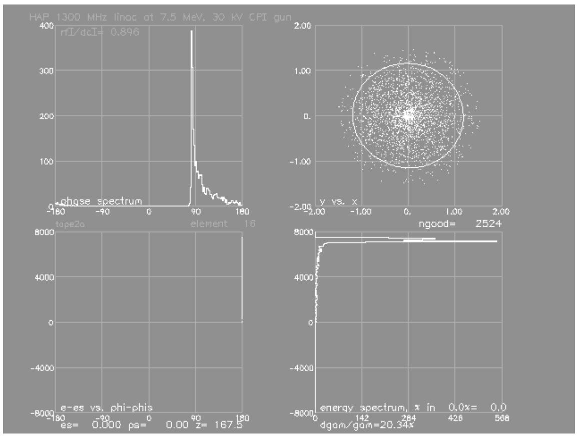

Fig 4. Klydyn Output Frame Showing Negligible Low Energy Tail.

The 7.5 MeV accelerators will have a reduced length second accelerating cavity. A cross section view of a solid model of the 7.5 MeV accelerating structure is shown in Figure 5.

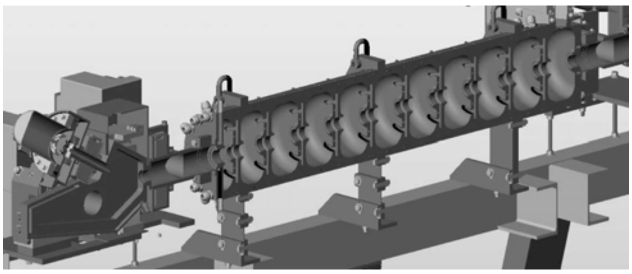

Fig 5. Cross Section View of 7.5 MeV Accelerator.

The electron capture efficiency into the first half-cell is on the order of 40%, which implies a total electron gun current of approximately 0.83 amps. The electron gun is oriented at a 30° angle with respect to the accelerator axis in order to protect the cathode emission surface from back bombardment. A dipole magnet deflects the beam into the linac (and deflects reflected electrons into a water-cooled collector). The voltage applied to the gun is in the range of 25 to 30 kV.

RF Drive :

The Thales TH2104D klystron tube meets the requirements of the 7.5 MeV accelerator. Key specifications for the tube are given in Table 2.

Table 2. Thales TH2104D Klystron Specifications

Parameter	Value
Frequency (MHz)	1300
Peak RF (MW)	5.0
Average RF Output (kW)	250
Efficiency	45%
Gain	46dB
Pulse Duration (μsec)	500
Nom. Voltage (kV)	125
Nom. Current (amps)	88

For 100 kW operation of the linac, the tube will be operating at approximately 85% of peak rf, 68% of average rf and 25% of the maximum pulse duration.

The klystron tube is protected by an arc detector and a three port circulator near the output window, and directional couplers that detect an increase in reflected rf. The transmission waveguide is WR650 that is insulated with pressurized SF_6 gas.

Modulator :

An inductive energy store modulator with solid-state opening switches powers the 5 MeV linac in operation at a food processing facility. Over the last 18 months improvements to prevent catastrophic switch failures caused by loss of control power have been implemented in the field as well as on three new modulators in test at TPSD. A simplified schematic of the inductive energy store modulator to power the 7.5 MeV linac is shown in Figure 6.

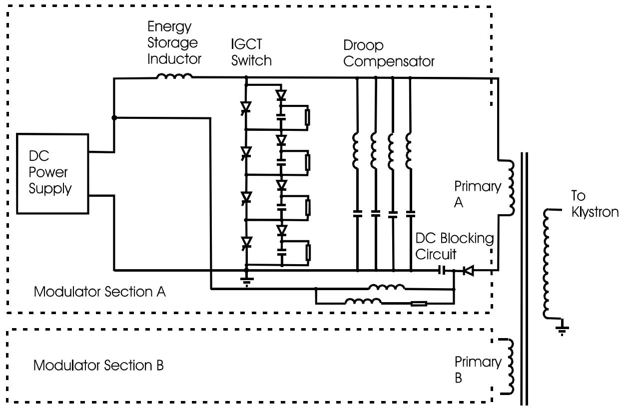

Fig 6. Schematic of Inductive Energy Store Modulator.

Two identical circuits power the primary windings of the pulse transformer. The main components of each circuit are the DC power supply, inductor, solid-state switch stack, droop compensator, and DC blocking circuit. Between pulses, controlled current from the DC power supply circulates in the inductor and solid–state switch. To start the pulse, the switch is turned off using its gate and the current transfers to the pulse transformer and then to the klystron. To end the pulse, the switch is turned on and current again flows through the switch.

During the pulse the current in the inductor decreases as energy transfers to the load. Four series inductor-capacitor tuned networks are used to compensate for this droop. The DC blocking circuit is on the low side of the primary winding and consists of a large capacitor, diode and inductor tied back to the power supply. This circuit forces the transformer magnetizing current to decay to zero between pulses.

The solid-state switches used are Integrated Gate-Commutated Thyristors (IGCTs) because of their low conduction loss and fast switching speed. A maximum peak current of 800 amps in each IGCT stack results in acceptable IGCT losses. The voltage at the primary of the pulse transformer is 7.5 kV. The pulse transformer has a turns ratio of 16.25:1.

Klystron voltage and current waveforms are shown in Figure 7. Peak klystron beam power is on the order of 11.0 MW. Average power delivered to the klystron is approximately 550 kW. Because of the relatively slow rise time of the electrical pulse and voltage variation at the end of the pulse, the RF drive to the klystron is limited to 130 μseconds.

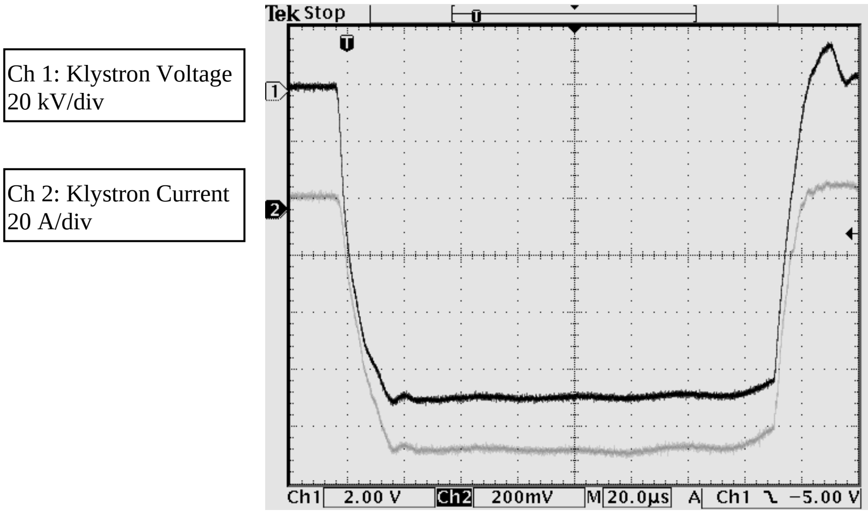

Fig 7. Klystron Voltage and Current Waveforms.

System Reliability :

In order to maximize profitability, a food irradiation system must be capable of reliable multi-shift operation every day of the year with some time allotted for preventive maintenance and periodic revalidation of the system.

A typical operating plan for a food irradiation facility includes 7000 hours of operation at 95% reliability, or approximately 6650 hours of available operation per year. Although 350 hours is a reasonable amount of time to allot for unscheduled maintenance, interruptions of more than a few hours at any one time have significant negative impact on the profitability of a processing facility as perishable product begins to stack up and contingency plans for alternative processing must be implemented.

Accelerator reliability can be affected by the combination of heat, radiation, moisture and ozone. However, ozone production is significantly reduced in X-ray facilities because of the relatively short distance electrons travel in air before being stopped in the converter. Maintenance schedules are intended to address normal wear and tear caused by the environment, however, occasionally, parts fail between scheduled maintenance. Therefore, maintaining a stock of critical spare parts on site is essential to minimize down time.

In the 7.5 MeV accelerator, reduced electron gun currents (approximately 2/3 of the current in the 5 MeV system) will result in less heating of the accelerator structure and therefore less mechanical stress on the vacuum joints in the system. Also, additional cooling is being designed into the accelerator and materials that transfer heat more efficiently will be used.

In-line gate valves are being incorporated into the design to isolate the accelerator from the scan horn. This is intended to minimize reconditioning time in the event that vacuum must be broken to replace parts.

Within the facility, the accelerator will reside in an enclosed area isolated from the process chamber to minimize the effects of back-scattered radiation. The combination of reduced mechanical and electrical stress and implementation of the improvements noted above will result in more reliable accelerator performance.

RF system reliability is also being addressed. Transmission waveguide flange and seal designs as well as waveguide materials are being tested to determine the combination of materials that yields the highest reliability by minimizing heating and arcing in the waveguide.

The modified modulator has operated reliably under test at TPSD’s accelerator test facility in Dublin, CA since July 2004.

Summary

TPSD is developing a 7.5 MeV 100 kW accelerator system for use in X-ray processing of food products in response to the recent amendment to 21 CFR Part 179.26. The design is based on a 5 MeV accelerator system that has been in operation in a food processing facility. The higher energy X-rays will increase throughput and profitability.

The system will incorporate a new standing waveguide and improvements to the RF system and inductive store modulator.

The first 7.5 MeV accelerator system for X-ray processing of food products will be deployed in the 4th quarter of 2006.

References

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[6] L.M. Young, “PARMELA”, Los Alamos National Laboratory Report LA-UR-96-1835, Revised 3 January 2003.