BEAM DELIVERY SYSTEMS FOR INDUSTRIAL ACCELERATORS

V.A. Mason and R.W. Davis
Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J 1J0

Summary

AECL is well advanced in the development of two automatically controlled 10 MeV electron irradiators having beam powers of 1 kW and 50 kW. These irradiators use on-axis coupled standing-wave linac structures operating at duty factors of 0.1% and 5% respectively. Four beam transport arrangements have been designed for product irradiation; these are described.

Introduction

Industrial electron linear accelerators are being developed by AECL for new applications in radiation processing. One 10 MeV irradiator has been built[1] and is now in routine operation at a nominal power of 1 kW at the Radiation Applications Laboratory of the Whiteshell Nuclear Research Establishment (WNRE), Manitoba. A 50 kW machine, IMPELA-10/50[2] (Industrial Materials Processing Electron Linear Accelerator), will soon be ready for beam testing at Chalk River. Both these irradiators incorporate pulsed, on-axis coupled, standing-wave structures and are engineered specifically for industrial environments.

Four beam transport arrangements are being developed for this family of irradiators; these are described in this paper. Three use electromagnets to scan the beam pulses across a product conveyor as a series of overlapping spots. The fourth arrangement disperses each pulse across the entire width of the product without the need for scanning. In all of these systems the beam optics have been calculated using the TRANSOPTR[3] code.

I-10/1 Irradiator

I-10/1 is a 10 MeV, 1 kW electron beam irradiator which incorporates a 270° bend spot-scan beam delivery system with the beam scanned in the plane of the bend. The basic components of the irradiator are an electron gun, an accelerator structure and a beam delivery system.

The beam delivery system consists of all the beam transport components downstream from the accelerator structure, Fig. 1. It captures the electron beam leaving the accelerator, transports it to the product, and deposits the electrons over the product surface with the required exposure dose distribution.

After leaving the accelerator structure, the electron beam passes through a thin (1.0 cm) quadrupole singlet lens that constricts the beam in the 270° bend vacuum chamber to minimize beam loss. The beam passes through a current measuring toroid, a steering assembly and a quadrupole doublet lens. A 270° magnet then bends the beam from the horizontal to the vertical direction. Beyond the 270° bend, the beam passes through a second beam current toroid, a beam position monitor and then a scanning electromagnet. The current measured by the second toroid indicates the irradiator beam current and, with the energy defined by the bending magnet, the beam power of the I-10/1.

Finally the beam exits from the irradiator through a vacuum/air interface window at the base of the scan horn. The product surface is located 15 cm below the window.

Automatic operation of the I-10/1 beam delivery system is achieved using a GEC GEM 80/252 programmable industrial process controller with both open and closed control loops.

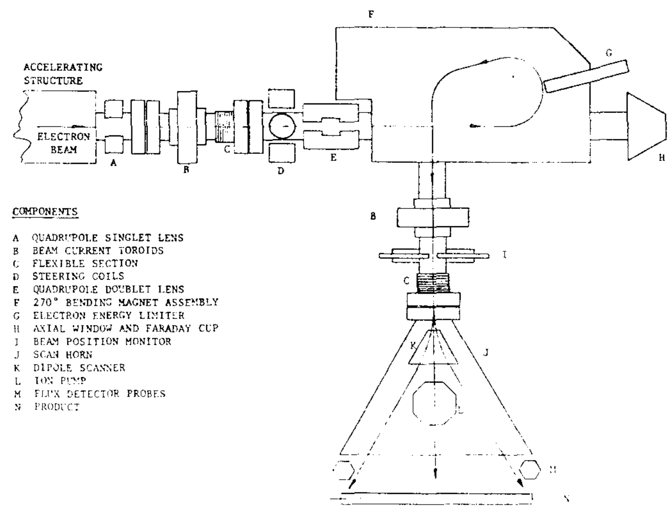

Fig. 1 I-10/1 beam delivery system.

Bending Magnet and Energy Analyzer: The 270° beam bending magnet has two main functions; these are to (i) deliver the beam, without energy dispersion, vertically downwards or sideways to the product from the horizontally mounted accelerator structure, and (ii) serve as an electron energy analyzer.

An energy analyzing scraper is located 100° into the bend. This limits the electron energy to less than 10 MeV which is necessary for food irradiation[4] and provides beam energy control via a feedback loop to the magnetron drive circuit. A quadrupole doublet focuses the beam to a waist, measured normal to the bending plane, at the high energy limiting scraper of the 270° bending magnet. The dispersion at the scraper provides good energy resolution. Beyond the scraper, the dispersion is reversed and the beam completes its achromatic bend[5]. The stigmatic properties of the quadrupole doublet compensate for those inherent in the 270° bending magnet. With the scraper positioned at 100° into the bend, the bremsstrahlung, emitted with energies up to 10 MeV, is directed away from the product to avoid activation problems.

The main coils of the electromagnet are wound around two sets of pole pieces. Trim coils are located around the second poles; these are used to centralize the beam after the 270° bend. The trim-coil current is controlled by feedback from a beam position monitor beyond the 270° bend. With no field in the bending magnet, the beam leaves the irradiator through a 0.075 mm thick titanium window located on the accelerator structure axis. A Faraday cup can be bolted over this window to measure the accelerated beam current for calibration of the beam current toroid.

Beam Scanner: After passing around the 270° bend, the beam passes between the poles of a beam scanning electromagnet. Here, four coils generate an oscillating dipole field between two pole pieces causing the beam to sweep from one side of the product to the other in the plane of the 270° bend. The scanner is magnetically shielded to avoid beam wobble upstream caused by stray oscillating fields. At 4 Hz scan frequency at full power (300 pulses per second), 38 overlapping pulses are laid across the product.

The beam scanner is located at the neck of an evacuated scan horn within which the beam sweeps back and forth before reaching the product. A scan horn is used on I-10/1 because it avoids (i) the production of excessive amounts of ozone and oxides of nitrogen, (ii) electron energy losses by collisions in air, (iii) unwanted beam spread by scattering in air and at a window remote from the product, and (iv) excessive heating at a single point on the window which could result in window failure at full power operation. A 60 L/s ion pump evacuates the scan horn and the beam delivery end of the irradiator.

Finally, the beam exits from the irradiator through a 0.25 mm thick aluminum window. Screened electron detector probes mounted outside the window sense the beam edges during scanning. Conditioned signals from the probes control (i) the scanner dc offset, to maintain the scanned beam central in the aluminum window, and (ii) the scan width to ensure a constant dose distribution across the product.

The computer model shows that the beam leaving the accelerator structure translates into an ellipse at the product having major and minor axes of 1.1 cm and 0.9 cm after full deflection in the scanner. Experiments during commissioning of I-10/1 have shown that scattering in the window and air gap can increase the beam radii to 2.7 cm and 2.5 cm at the product surface.

IMPELA Irradiator I-10/50

The IMPELA family of industrial electron accelerators use an on-axis coupled standing-wave structure and operate in the long pulse mode. The first member of the family, IMPELA-10/50 (10 MeV, 50 kW) is now being assembled.

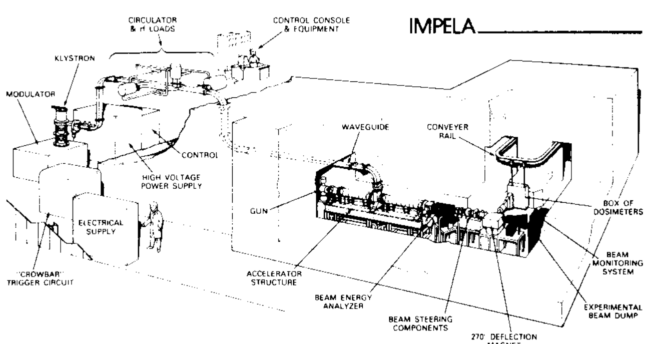

Fig. 2 Accelerator test facility at CRNL.

Three beam delivery systems have been designed for IMPELA-10/50 as part of a staged development program. The first, which is currently under construction, is a spot-scan arrangement with no bend in the beamline. A 270° bend spot-scan delivery system will be assembled next for applications where a more stringent energy definition is required. This beam transport system is similar to that used on the I-10/1 irradiator; however, in this case the scan plane will be normal to the 270° bending plane. Finally, a beam dispersal arrangement will be developed. This will transport the beam around a 270° bend and then spread each pulse, using quadrupole lenses and edge-folding magnets, across the whole width of the product without the need for scanning.

IMPELA-10/50 Spot-Scan Beam Delivery Systems

The 0° bend and 270° bend beam delivery systems are at present being installed in the IMPELA-10/50 prototype facility at Chalk River, as shown in Fig. 2.

Zero Degree Bend Beam Delivery System: This is essentially a spot-scan arrangement similar to that used on the I-10/1 irradiator but without the 270° bend in the beamline. A quadrupole triplet lens focuses the beam to a waist near an electromagnetic scanner beyond which the beam spreads to a spot approximately 10 cm diameter in the product plane. In the prototype, an electron energy analyzing magnet is included after the accelerator structure to provide beam diagnostics. A beam position monitor located immediately before the scanner will be used to ensure the analyzing magnet field is set to zero by current reversal. A second set of beam position monitors outside the scan horn window will control the scan amplitude and bias off-set for a uniform dose distribution at the product.

A toroid mounted around a ceramic section of the vacuum assembly will measure beam current. Total beam power and delivered current will be measured using an instrumented water-cooled beam dump. The quadrupole lens and scanner poles have been designed to maintain a constant spot size at the product independent of scan angle.

270° Bend Beam Delivery System: The 270° bend spot-scan beam delivery system is similar to that used on the I-10/1 irradiator. However, in this case the scanning plane is normal to the 270° bending plane. The physical sizes of all beamline components in IMPELA-10/50 will be roughly twice the linear dimension of those on the I-10/1. Also, on the prototype, the vacuum system walls will be protected and cooled to avoid beam contact damage.

A quadrupole doublet lens, immediately after the accelerator structure, focuses the beam near the analyzing slits which are located in a region of high dispersion. Steering coils beyond the quadrupole lens, controlled by a beam position monitor, guide the electron beam into the electromagnetic dipole scanner located after the bending magnet. Trim coils will be used near the second pole of the bending magnet to ensure the beam leaves the magnet along the design trajectory.

Two quadrupole lenses positioned after the 270° bending magnet control the size of the beam spot at the product and confine the beam between the poles of the scanner. Toroids will be used to measure the beam current as it enters and leaves the bending magnet. Again, the characteristics of the beam dispersal quadrupoles and scan magnet poles provide a constant beam spot size at the product independent of scan angle. The major axis of the 0.13 mm thick titanium foil window of the horn will be oriented vertically with the 270° bending plane horizontal. Flux monitor probes located outside the scan horn window will sense the position and scan width of the beam aimed at the product. All beam monitor signals will be used for automatic control of the beam delivery system.

TRANSOPTR calculations in Fig. 3 show the beam width along the beam delivery system. The beam current density at the window will be similar to that in the I-10/1 which operates satisfactorily without cooling.

Changes to the beam envelope during the life of the prototype have been anticipated. These can be accommodated by magnetic field adjustments in the quadrupole assemblies to provide a constant beam spot size at the product. Because mechanical adjustments are unnecessary, compensation for these changes can be achieved automatically by the control system.

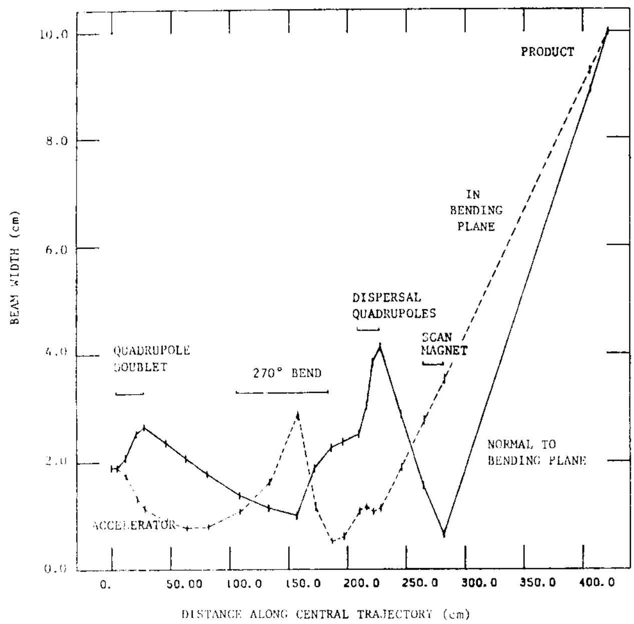

Fig. 3 Beam width along the 270° bend spot-scan beam delivery system.

IMPELA Beam Dispersal Arrangement

Spot scanning, as used in the three beam delivery systems described above, is only feasible for a 50 kW machine when high product doses are required. The most versatile beam delivery system for IMPELA-10/50, which has been designed to accommodate a wide range of products, is beam dispersal. Here, after energy analysis, the beam is spread by static magnetic fields to provide the required dose uniformity across the product conveyor. Unfortunately, dispersal of the IMPELA-10/50 beam would, by itself, lead to an elliptical irradiation patch at the product plane where the electron intensity along both axes would be approximately Gaussian. If laid across the conveyor, the dose distribution to the product would far exceed the surface uniformity target of ±3%. To avoid this, the dispersal system over-spreads the beam and folds back the edges, using dipole magnets, so that the electron distribution across the moving conveyor is flat.

General Description: A quadrupole doublet lens focuses the electron beam leaving the accelerator structure at the energy analyzing slits of a 270° beam bending assembly that are set to transmit 5% of peak energy at the reference point. Steering coils beyond the lens, controlled by a beam position monitor, guide the electrons into a static magnetic field beam dispersal arrangement positioned after the bending magnet. Toroids measure the current in the beam as it enters and leaves the bending/analyzing magnet field.

The dispersal system spreads the beam, now travelling vertically upwards, in an evacuated horn. Steering coils, located at the neck of the horn, centre the defocused beam in a titanium foil window below a product conveyor. In the current design, the beam spot size at the product is 0.12 m wide by 0.65 m, measured across the conveyor. A beam dump mounted beyond the conveyor stops any portion of the beam transmitted by or missing the product.

Again, computer control of the beam delivery system has been considered throughout the optical design. After the commissioning phase, mechanical adjustment of beam transport elements to cope with changes in beam characteristics will be unnecessary; full control will be achieved electrically.

Beam Dispersal and Folding: The beam dispersal arrangement must spread the beam into an irradiation patch, projected onto the product plane, of 0.12 m by 1.95 m. Before reaching the product, however, the width is reduced to 0.65 m by the beam edge folding magnets. Two electromagnetic quadrupoles of the same polarity will be used to disperse the beam in the IMPELA-10/50 prototype.

The first element of the quadrupole pair conditions the beam for a more extreme expansion in the second. If too great a beam divergence occurs after the first quadrupole, the second element must be made very large to prevent beam contact with the vacuum chamber. In addition, the quadrupole design provides for moderate electrical power consumption and versatility in coping with a wide range of beam envelope values.

Computer calculations have shown that the dose distribution is acceptably flat when the beam edges are folded to the opposite sides of the conveyor (67% folding). This represents the maximum level of folding attainable using only two edge dipoles without the loss of electrons from the beam. If the folding is greater than 67%, peripheral electrons will miss the product conveyor resulting in inefficient use of the beam. Alternatively, if the folding is significantly less, then the field flatness of the dose distribution suffers. The use of 67% folding therefore represents the "elegant solution" for IMPELA in both field flatness and electron economy.

Status

Irradiator I-10/1 has been operating successfully at WNRE for over 6 months. The IMPELA-10/50 zero degree and 270° bend beam delivery systems are being assembled at CRNL at present. The optical design of the IMPELA beam dispersal arrangement is complete and detailed design is in progress.

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