IMPELA: AN INDUSTRIAL ACCELERATOR FAMILY

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Summary

The IMPELA family of industrial accelerators is being developed by AECL to complement its isotope-based irradiators. These 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.

Introduction

The use of electron accelerators in industry has grown rapidly over the past two decades and it is estimated that in excess of 40 MW of electron beam power is now installed in the world for industrial applications. This growth in demand has been accompanied by an increase in the power of individual units. Accelerators already exist with beam powers in the 100-200 kW range; however, the technologies commonly in use for these high power machines limit their energy to less than 5 MeV and therefore limit the penetration of beams to thicknesses equivalent to 2-3 g/cm^2. The rf linear accelerator, which has had many years of development for research and medical therapy applications, is the only technology tested in diverse applications that is capable of producing higher energy beams at the power and reliability levels required.

A small number of rf linacs have been operated in industry over the past 20 years but the power levels available from these have generally been less than 10 kW. Atomic Energy of Canada Limited, the world's largest supplier of industrial irradiators, has recognized this need for higher power accelerators in the energy range above 5 MeV [1,2] and is developing a family of rf linacs engineered specifically for the industrial market.

Accelerators used in industry place special demands on their designers. The need for a small energy spread and good emittance normally placed on research machines is replaced by requirements of high reliability, ruggedness, simplicity of operation, high dose uniformity and economy. The IMPELA (Industrial Materials Processing Electron Linear Accelerator) family of linacs is designed specifically to address these requirements.

This family of accelerators, controlled by industrial computers, is based on standing wave, L-band, on-axis coupled linacs operated in the long pulse mode. A modular design approach is used to achieve beam powers in the range of 20-500 kW at various energies, with the same basic components coupled to the required power supply and klystron. The long pulse approach with modest accelerating gradients has been chosen as the most appropriate for industrial applications. This approach is intermediate to the high-gradient short-pulse systems used in the medical field and the lower gradient systems used in research accelerators. The desired range of power can be achieved using the same components by increasing the duty factor from 1-2% to cw operation while maintaining the same beam loading and peak stress levels from one accelerator to the next.

The first member of this accelerator family, IMPELA-10/50 (10 MeV, 50 kW) is now being constructed at the Chalk River Nuclear Laboratories in the shielded enclosure that formerly housed the 4 MeV, 80 kW Electron Test Accelerator (Fig. 1). The 50 kW average beam power is achieved by operating the accelerator at a nominal duty factor of 5% (200 µs pulses at a pulse repetition frequency of 250 Hz). This paper describes the major sub-systems and reports the construction status. A companion paper at this conference describes the control system for the prototype accelerator in greater detail [3].

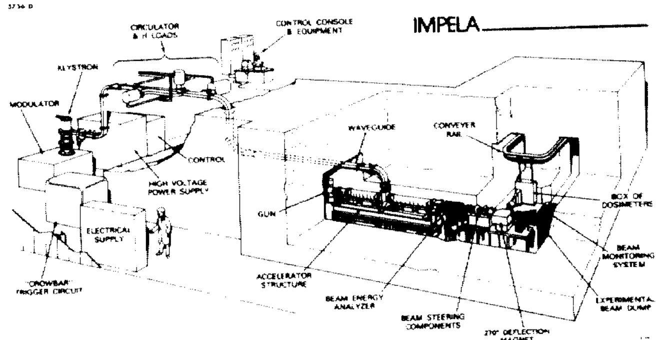

Fig. 1: Cut-away artist's conception of IMPELA-10/50

Accelerator Design

Injector

The IMPELA family is designed for direct injection at a relatively low voltage, 40 kV, from an electron gun with triode geometry, mounted directly on the accelerating structure. To achieve the rf system simplicity essential for industrial applications no prebunching of the beam is used. Commercially available 0.5 cm^2 dispenser cathodes are used in the electron gun. Both gridded and ungridded cathodes are being tested.

The cathode is held at the dc injection voltage and beam pulses are formed by pulsing the control element voltage relative to the cathode. Fine control of the beam current is achieved by adjusting the bias of the control element pulse-to-pulse. The pulse length and repetition frequency can be readily adjusted to meet the duty factor required of the accelerator. The pulser and dc power supply are located in a high voltage cabinet outside the accelerator vault away from high radiation fields.

The gun housing design facilitates rapid replacement of the cathode and maximizes vacuum pumping speed in the cathode region. A short gap lens and a set of steering coils are incorporated in the gun assembly. The total drift distance from the cathode surface to the centre of the first accelerating cell is only 20 cm.

The beam requirements for the IMPELA family have been kept relatively conservative. IMPELA-10/50 will produce the rated power at a 5% duty factor with a beam current of only 100 mA. Using a typical beam transmission of 25% through an accelerator without a buncher translates to a modest injection current of

400 mA. A transmission of >40% has been achieved on a similar short pulse 13 MeV, 4 kW S-band linac at CRNL through the addition of a short focussing solenoid over the structure. A similar solenoid will decrease the gun current requirements on the IMPELA-10/50 below this estimate.

Accelerating Structure

The accelerating structure chosen for the IMPELA family is the on-axis coupled cavity, standing wave structure which has been developed and extensively investigated at the Chalk River Nuclear Laboratories [4]. A low duty factor, 3 GHz version of this structure is used on a 10 MeV, 1 kW industrial irradiator, the I-10/1, which is now in operation at the Whiteshell Nuclear Research Establishment [5].

A modular approach has been adopted for the accelerating structure. With this approach an optimum accelerating gradient and high beam loading can be chosen for any particular combination of energy and beam power. Three types of structure modules, graded beta, constant beta and rf coupling, are used. The modules terminate at the centre of an accelerating cell and are bolted together to form a single rf and vacuum cavity. The vacuum seal is made with conventional (ConFlat) flanges that are furnace-brazed to the structure modules during assembly. The flanges also provide the mechanical pressure for the copper-to-copper rf seal formed at the cell wall and are used as headers for the water cooling system. The MAMI accelerating structure at the University of Mainz [6] (2.45 GHz) which used this assembly technique has been operated successfully at 100% duty factor.

The prototype IMPELA-10/50 accelerator consists of 58 cavity segments, joined in four modules to form 29 accelerating and 28 coupling cavities. The injection module consists of four graded-beta accelerating cavities. It is followed by two constant-beta modules which are separated by the coupler module. The total length of the structure is 3.25 m corresponding to a conservative accelerating gradient of 3 MeV/m.

The accelerating cavity geometry has been optimized at 1.3 GHz for the large 19 mm diameter axial hole using SUPERFISH. The shunt impedance and Q for the structure, calculated neglecting the effect of coupling slots and pumping ports, are 67 MΩ/m and 24 500, respectively. Low-power rf measurements on the assembled structure indicate that ~85% of these theoretical values have been achieved. A relatively large cell-to-cell coupling constant of 7.6% has been used to ensure field flatness along the full length of the structure.

Based on the measured shunt impedance, the peak rf structure power for IMPELA-10/50 is 540 kW. With the nominal duty factor of 5% and a 100 mA beam current, the beam loading is ~65%. The coupling of the waveguide to the structure has been adjusted to an initial VSWR of 2.8 to achieve near-critical coupling at this loading level.

Extensive finite-element thermal analyses of the IMPELA structure with the computer code MARC have been used in the design of the cavity cooling to ensure stable, distortion-free operation up to a 100% duty factor. The integrated SUPERFISH and MARC calculations, lead to a design where the structure is cooled with a series of counterflowing circuits which are an integral part of the cavity segments. Two long web cooling channels are used in each segment to minimize the shift in the cavity frequency with power. The predicted shift in frequency over the range from zero to full rf power is less than 70 kHz for IMPELA-10/50.

The assembled structure is mounted on a strongback and vacuum manifold (Fig. 2). A vacuum manifold that provides a very high pumping capacity is used with this prototype structure to accommodate the wide range of experiments planned to investigate its operating limits. The vacuum manifold is connected to the structure at five points and is pumped by a 60 L/s ion pump supplemented by a titanium sublimation pump. An 8 L/s ion pump is mounted on the coupling module just below the rf window to ensure good pumping in this critical area.

Fig. 2: Assembled four-module IMPELA-10/50 structure.

Radio Frequency System

The IMPELA family is based on a long pulse rf system using modulated anode klystrons. With this approach the same low-stress design and efficient beam loading can be maintained across a wide range of average power by varying either the pulse length, the pulse repetition frequency, or both.

A simplified schematic diagram of the IMPELA-10/50 rf system is shown in Fig. 3. The main klystron is a 2 MW peak, 150 kW average TH2115 klystron developed for the IMPELA program by THOMSON-CSF. The drive for this klystron is provided by a 1 kW TH2437 klystron which acts as an amplifier for the voltage controlled oscillator and input control circuitry. The accelerating cavity rf field strength is chosen to set the beam energy and is controlled by independent loops to keep the field amplitude and frequency at a constant level.

The TH2115 klystron typically requires an 82 kV 55 A pulse to produce the peak output of 2 MW. This pulse is provided by a 100 kV, 4 A dc power supply which is coupled to four 1 μF capacitors. The capacitors are located in a 2.7x1.5x1.3 m high oil tank that also contains the modulator, the klystron filament supply and supports the klystron. The stored energy in the capacitors at 90 kV is a relatively modest 16 kJ. The size of the capacitor bank was chosen as a compromise of size, stored charge and voltage droop during the long pulse.

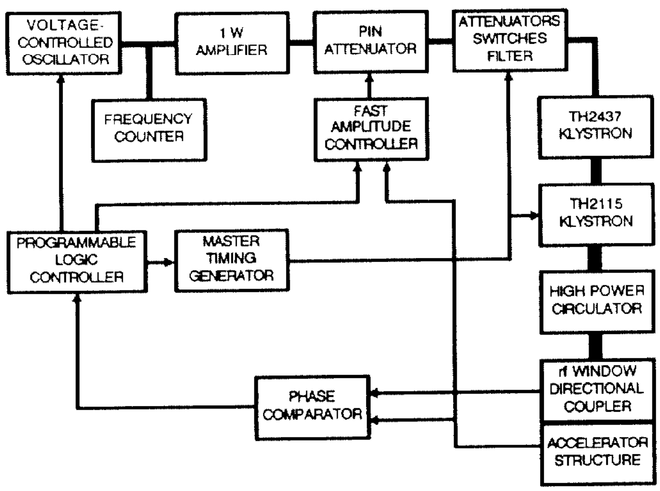

Fig. 3: Simplified diagram of 1.3 GHz, 2 MW rf system.

The design of the modulator follows closely that used on the Millstone Hill Radar Site [7]. One major difference is in the use of a single switch tube and a pull-down resistor instead of two switch tubes. The switch tube used is a TH5188 tetrode.

Power from the TH2115 klystron is fed to the accelerator through 15 m of WR650 waveguide pressurized with SF_6. The klystron is isolated by a high power THOMSON-CSF circulator which is designed to sustain a continuous VSWR of 3.0.

Two protective systems are used on the IMPELA-10/50 to ensure that the energy deposited in the klystron by a potential internal arc is kept below a damage threshold of 20 J. The first system uses a high-speed triggered crowbar to divert the energy from the klystron. The second uses surge resistors rated for high energy in series with the klystron to limit the fault current to 2 kA and thereby limit the arc voltage to <30 V [8].

Beam Delivery System

IMPELA-10/50 is designed to deliver the beam over an 80 cm wide zone 15 cm from the end of a scan horn with a dose variation, at a depth of 2 cm in water, not to exceed ±5%. The beam is scanned in a plane orthogonal to the accelerator axis and will be available either at 0° or at 90° after a bend through 270°. A 270° bending system ensures that high energy photons from the scraping of electrons with energy exceeding 10.0 MeV are directed away from the product as is required if the accelerator is used for food irradiation [9].

The initial beam delivery system will produce a spot scan at 0° at the end of a 1.3 m scan horn with a scan frequency of ~5 Hz. The optical design of this system has been developed using the TRANSOPTR code with phase-space parameters determined from modeling the beam dynamics through the linac with PARMELA. A 10 cm diameter beam spot is obtained at the air/vacuum window with careful matching of the dispersal and scanning magnets. The beam exits through a 0.13 mm thick titanium window. Heating effects and thermal stresses in the window have been modeled using the MARC code. The effects of scattering by the window and air are calculated with the COPSI code [10].

The modular approach for the IMPELA family has been incorporated in the physics and engineering design of the major components of the beam delivery system. The scan horn assembly can be used in both the 0° and 270° configurations.

The prototype accelerator differs from future production accelerators in that it incorporates a 45° analyzing magnet in the 0° line for measurements of the energy spectrum under various operating conditions. No provision is made in the present shielded cell for a product conveyor and maze but extensive diagnostics for on-line monitoring of exposure dose distributions has been incorporated.

Control System

The control system for IMPELA-10/50 is based on an industrial programmable logic controller with a distributed input/output system. Custom electronic modules have been developed for interfacing the sensors that are unique to pulsed accelerators, the machine protection systems and the fast rf feedback control loop. The hard-wired personnel safety system is fully separate from the control system.

A separate paper at this conference describes the control system in detail [3].

Status

As of 1988 June 01, the accelerator structure is fully assembled and ready for final installation in the shielded tunnel. The rf system is 90% assembled and delivery of the klystron is expected within several weeks. The PLC is installed and the programming required for rf testing of the klystron is essentially complete. Acceptance tests of the klystron are expected to be complete in August and first beam from the accelerator is scheduled in 1988 December.

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