OPERATING EXPERIENCE WITH THE IMPELA-10/50 INDUSTRIAL LINAC

J. Ungrin, S.B. Alexander, S.T. Craig, G. Frketich, V.A. Mason,
I.L. McIntyre, M.P. Simpson, D.L. Smyth, R.J. West, and B.F. White
AECL RESEARCH, Chalk River Laboratories
Chalk River, Ontario, Canada, K0J 1J0

ABSTRACT

AECL is building and marketing the IMPELA family of high-power linear electron accelerators designed specifically for the industrial market. The accelerators are built around an L-band on-axis coupled structure that is assembled in a modular fashion and is driven in the long-pulse mode with a modulating anode klystron. A wide range of average power is achieved with the same basic accelerator components by simply changing the beam duty factor and the size of the power supply. The control system for the IMPELA family is built around a simplified operator interface that incorporates automatic sequences, fast control loops, self-diagnostics and the instrumentation that is key to reliable, simple operation and rapid maintenance. The first member of the IMPELA family, the 10 MeV, 50 kW, IMPELA-10/50, is a highly instrumented industrial prototype that has been operating at full power since 1989 November. It is now undergoing prolonged testing at Chalk River Laboratories.

INTRODUCTION

AECL is building and marketing the IMPELA family of high-power electron linacs that has been designed specifically for the industrial irradiation market.[1] These accelerators are designed conservatively around an L-band standing-wave, on-axis coupled accelerating structure and are driven in the long-pulse mode by a modulated anode klystron. High beam loading (typically 60-65%) is achieved with a modest output current (typically 100 mA). This high beam loading, combined with an optimized rf cavity design, ensures good rf efficiency for the accelerator. A wide range of average power can be achieved with the same accelerator components by varying the duty factor while retaining the conservative energy gradients and beam current. The single-resonator, 1300 MHz structure is an assembly of modules that has been designed with adequate cooling for operation at duty factors up to 100%. The 10 MeV, 50 kW, IMPELA-10/50 (Fig. 1) under test at Chalk River operates at a 5% duty factor (typically 200 μs pulse lengths at 250 pps). This accelerator has been built as an industrial prototype and is being used as a fully instrumented test bed where a detailed characterization of the existing hardware and of several additional variants under development is possible. The prototype is equipped with a wide range of diagnostics to allow rigorous testing of both the physics and the engineering design aspects. It is in the process of undergoing extended lifetime testing to ensure that all systems can meet the high reliability required by industry.

Details of the IMPELA accelerating structure,[1] rf system[2] and the control system design[3] have been previously reported. This paper reports the operation at full power.

AUTOMATED CONTROL

The IMPELA family of accelerators have been designed for industrial use. The control system is built around a GE-FANUC Series-6 industrial programmable logic controller (PLC) and uses a simplified operator interface with automatic sequences, hardware and software-based control loops and self-diagnostic instrumentation that is largely transparent to the industrial user, who will generally lack the specialized skills or knowledge normally required to operate a high-power rf linac. The control system has been designed with the capability to operate with two redundant processors for those applications that require very high reliability. In addition to the PLC system, a set of high-speed hardware loops has been developed to provide the machine protection actions required to act on a microsecond timescale.[3] These high speed loops which act to trigger the high-voltage power supply crowbar or to disable the rf drive or the electron gun current are supervised and monitored by the PLC.

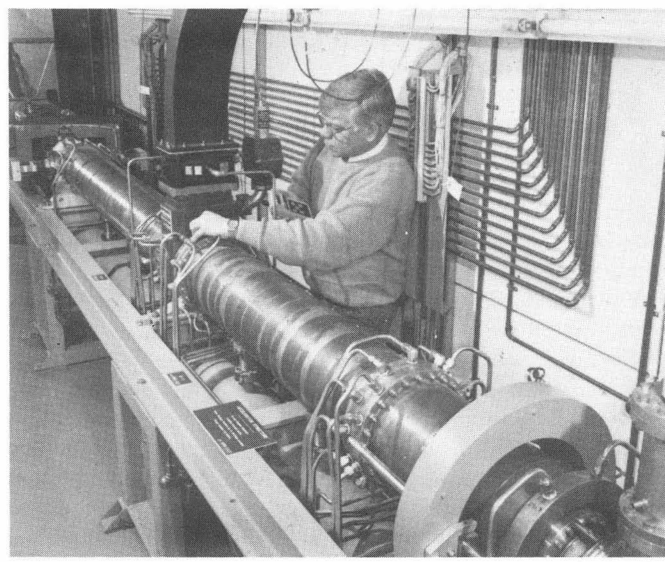

Fig. 1 View of IMPELA-10/50 from the injector end.

A set of automatic sequences controlled by the PLC have been developed to provide an industrial operator with a reliable and convenient means of starting and stopping the irradiator operation. These sequences have been based on the commissioning and operating experience gained with the prototype accelerator. They provide an orderly path through turn-on of cooling systems, warm-up of the filaments and other devices that require time to stabilize, application of high voltage to the electron gun and rf systems and finally the turn-on of all the accelerator systems at low beam power with all the applicable control loops closed. The set points for the control loops and all the controlled devices are derived from a set of parameters previously saved in the PLC memory. The sequences have reverse paths to control shutdown through to a full power-off condition.

All the normal interlocks and alarms are active during the execution of the automatic sequences. A sequence action that is inhibited by an interlock or alarm causes the sequence timer to fail and to abort the sequence. An aborted sequence generates an alarm to the operator. In addition to the alarm, the sequence state is indicated on the operator display, which shows the state of each sequence: inactive, executing, complete or aborted.

The automatic sequences have become a routine means of operating the accelerator and subsets of the full sequence are regularly used to control operation during tests of various procedures or of equipment performance.

CONTROL LOOPS

The operation of IMPELA is greatly simplified by the use of a number of automated feedback control loops. Seven independent loops have been developed to control key accelerator parameters. These include the conventionally-controlled accelerator parameters, beam energy (structure field amplitude), output beam current, rf drive frequency, klystron high voltage and temperature control of the cooling circuits both for the water-cooled accelerator and for the oil-cooled rf modulator. In addition, a control loop has been developed to regulate the filament heating in the electron gun to compensate for power deposited in the cathode by off-phase electrons reflected to the electron gun by the accelerator. This latter effect, normally absent on most research linacs, is significant on IMPELA, which uses a simple low-voltage electron gun that is closely coupled to the accelerator and does not use an independent buncher with its associated rf drive and control requirements. The filament control loop maintains a constant cathode temperature by adjusting the filament power to maintain a fixed filament resistance.

Dedicated high-speed electronics have been developed to control the field amplitude to $\pm$ 2% of setpoint on an intra-pulse timescale. Intra-pulse control has been introduced to reduce the energy spectrum and to provide a more uniform dose distribution from the accelerator. Control of the structure rf field on this timescale is particularly significant for a long-pulse accelerator where significant gain change will occur in the klystron due to power supply droop. Additional important factors affecting the design of the loop are the wide variation in duty factor (pulse lengths of 50-500 μs at repetition rates from 1 to 500 pulses per second), long loop lengths at relatively high Q ($\approx$4000) and a wide range of operating temperature.

The block diagram shown in Fig. 2 illustrates the amplitude control feedback circuit. Temperature controlled crystal detectors convert structure rf signals into an average amplitude envelope that is compared with a setpoint supplied by the PLC. A gated Proportional-Integral (PI) controller processes this amplitude error signal to produce the required attenuation for a PIN modulator which is in-line with the drive chain. Thus, the drive power is automatically adjusted to bring the structure fields to the desired amplitude independent of beam current, pulse length or frequency tuning errors.

The gated PI controller forms the heart of the loop. Wideband, 6 MHz, proportional control provides rapid correction for small disturbances while, over a microsecond timeframe, a gated integrator corrects larger disturbances and drift. Bandwidth constraints imposed by the rf drive chain and by the loop transit time prohibit use of a large proportional gain. The controller employs inter-pulse memory and sequential deployment of controller terms to achieve the necessary integral gain without overshoot. A portion of the mid-term pulse integral term is stored for use as the initial value with the next pulse. Fast yet smooth pulse turn-on is accomplished by first applying the drive power as stored in the integrator memory and engaging the proportional control action. After a delay of $\approx$4 μs the integral term is engaged. Thus the integrator acts only when the field is close to the desired strength and upsets at the leading edge of each pulse are avoided.

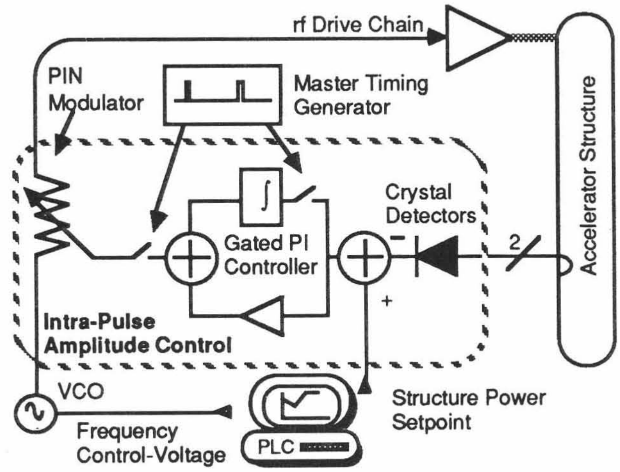

Fig. 2 Block diagram of the field amplitude control circuit.

A comparison of intra-pulse performance with and without feedback control is shown in Fig. 3. Operating experience has shown that the controller can be readily tuned to regulate the field within $\pm$ 0.5% (voltage) following a 6 μs pulse rise and settling time.

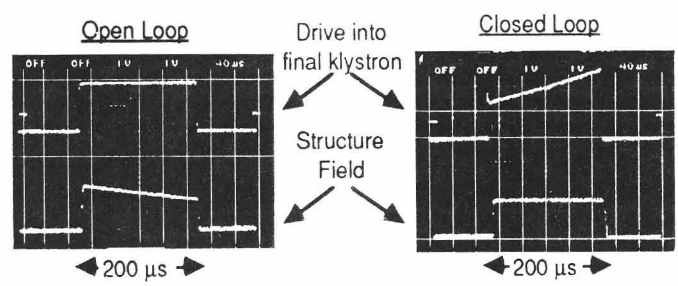

Fig. 3 Structure field level control.

The remaining six control loops are implemented by Proportional-Integral-Differential (PID) controllers via the software in the PLC. The beam current, drive frequency and klystron voltage loops employ zero-droop sample and hold circuits which sample the process variable at a predetermined time in the pulse and hold this value for asynchronous input to the PLC. Conventional PLC algorithms are then used to control these pulsed variables on a timeframe of a few seconds. Coolant temperatures and electron gun filament power are not pulsed variables and the PLC PID controller is applied directly to these loops. The operation of the six PID loops are summarized in Table I.

EXPOSURE DOSE UNIFORMITY AND ASSURANCE

The industrial application of radiation from a high-power electron linac requires distributing the beam power through a product volume. In most cases the beam power is spread over an exposure area and the product is conveyed in a direction normal to the major axis of the exposure pattern at a carefully controlled rate.

Table I
Software-Based Control Loops

Loop	Control Variable	Response Time	Regulation
Current	Wehnelt Voltage	2 s	±0.1%
Frequency	VCO	2 s	±0.5°
Klystron HV	SCR Firing Angle	10 s	±0.3%
Cathode Temperature	Filament Current	10 s	±0.3%
Water Cooling	Secondary Flow	20 s	±0.3°C
Oil Cooling	Secondary Flow	60 s	±0.3°C

The processing of a specific product requires a uniformity of dose delivered throughout the product volume. To obtain the volume uniformity with good electron economy a variety of measures may be applied, including the use of "tailored" beam exposure distributions, external scattering surfaces or the use of a dose build-up layer.

The IMPELA prototype employs a low frequency (5 Hz) magnetic spot scanner that deflects the electron beam to produce a pattern of overlapping spots, each 8-10 cm in diameter, at the exposure plane[4]. The scanner uses a simple iron magnetic circuit for the magnet. To overcome the non-uniform distribution that results with such a magnet due to eddy-current and hysteresis effects when driven with a simple triangle-wave drive current, the scan magnet drive system applies an appropriately corrected, deformed current excitation, which produces a linear deflection of the beam. A dose uniformity within ± 5% across an 80 cm wide distribution has been achieved using this method (Fig. 4). This method can equally be used to tailor an appropriate non-uniform exposure dose that will result in improved beam usage and dose uniformity for specific products.

The performance of the beam scanner is dependent on the stability of the beam energy and the scan drive electronics. Probes positioned at the ends of the scan pattern sense the maximum deflection for each scan cycle. A control loop that regulates scanner operation on the basis of these signals is being developed. This loop will regulate both the position of the centroid of the beam and the scan width.

Many industrial applications require continuous monitoring of a number of key accelerator parameters to demonstrate the stability of the radiation pattern delivered at the end of the accelerator. All the parameters essential to characterize the stability of the delivered beam are logged and archived by the PLC via a dedicated data logger and a Cimstar computer (an industrial IBM-AT compatible) with a FIX software package.

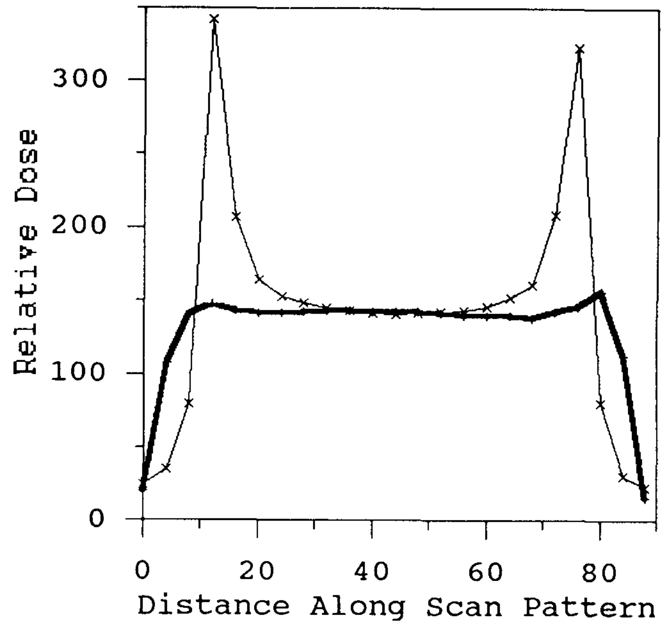

Fig. 4 Exposure dose distribution 15 cm beyond the linac with triangular (light line) and shaped (dark line) wave form.

ACCELERATOR PERFORMANCE

The IMPELA-10/50 prototype has been operating at full power at Chalk River since 1989 November. Extensive testing has been carried out with the automatic sequences, feedback control loops and exposure dose control system and significant operating experience has been gained. Several minor improvements have been incorporated to further simplify operation. The degree of automated control has reached a point where the accelerator will routinely operate uninterrupted at full specifications for periods of up to 10 h with no operator intervention. This operating simplicity combined with the excellent regulation of the energy and current loops and the ability to tailor the exposure dose at the exit of the linac make IMPELA a powerful, user-friendly accelerator for the non-expert industrial user. Extended lifetime-testing of the machine hardware and software systems continue on this unique industrial prototype.

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