Theme Article - 2

T.2 : Industrial Electron Accelerators

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A program of development of accelerators for industrial applications was taken up at RRCAT. Under this, a 750keV, 20kW DC accelerator was developed and made operational in Nov. 2002. A 300keV, 6kW low energy accelerator is in advanced stage of development for curing of materials. In addition, development of a 2.5 MeV, 100 kW high power accelerator has been taken up in collaboration with Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia. Accelerator based irradiation facilities are becoming more popular in the world as compared to facilities based on isotopes (mainly Co-60) as : i) accelerator based facilities are more safe since the radiation from the accelerator can "switched on" or "switched off" by the user, ii) the accelerators provide tunable energy for desired penetration to suit the products, iii) the accelerator based facilities provide very high throughputs, iv) there is no need of isotope source replacement in the accelerator based facilities and hence no problem of nuclear waste disposal, and v) the systems can be made compact for specific applications.

This article describes 1) recent applications of the 750 keV system, 2) development of high power industrial accelerator, and 3) development of a self shielded low energy accelerator.

1. 750 keV DC Accelerator

The DC Accelerator developed at RRCAT [1] is an accelerator producing electrons in the energy range 300-750 keV. Electrons from an electron gun, having maximum energy of 10 keV are injected into the acceleration column. The electrodes of the column are provided with a uniform voltage gradient by suitable equalizing resistors. Electrons from the gun are accelerated during the course of passage of about 1 meter long acceleration column and they gain energy of 750 keV. Two focusing coils are provided in the beam line to control the beam divergence and beam size in the beam transport line. The electron beam is scanned using a scanning magnet to the desired width and is then extracted out in air through a thin titanium foil, for irradiation purpose. The system has been operational since Nov. 2002 upto maximum rating of 500kV / 5 kW and is now being modified to reach 750 kV / 20 kW. It has been used for a variety of industrial applications like de-polymerization of paper pulp sheets, surface irradiation of potatoes, disinfestations of seeds, sterilization of sanitary napkins, curing of coatings on wood, curing of rubber tiles, grafting of polypropylene sheets for extraction of uranium from seawater, etc. Some recent applications of this accelerator are described in section 1.3

1.1 Electrical Scheme for high voltage generator

The power supply for the 750keV system is based on a Cockroft -Walton multiplier operating at a frequency of 40 kHz. Initially the multiplier stack was designed using a 15-stage symmetrical Cockcroft-Walton circuit with maximum stage voltage of 60 kV DC. A nonlinear buildup of voltage due to stray capacitances in the structure resulted in voltage multiplication ratio of 11 against a theoretical value of 15 as compared with the 1st stage voltage. The multiplier stack has been redesigned with a maximum stage voltage of 90 kV DC keeping a safety margin of 33% in the component ratings. The details about modifications to the power supply are given in this edition of RRCAT Newsletter in News item A.1 by R.Banwari [2].

1.2 Material handling system

The material handling system is a slat type conveyor. It is capable of handling paper pulp sheets, wooden laminates, iron sheets, FRP sheets, etc. kept in trays. It consists of four stainless steel slat conveyors, each of a width 90 mm. The positions of the central two conveyors are fixed and the outer two conveyors are movable such that the conveyor width can be adjusted from 500 mm to 1000 mm. Length of the conveyor is 2.6 meters having a load capacity of 200 kg at 10 m/min. The speed is continuously variable from1 m/min to 40 m/min and is reversible. The conveyor height from the ground level is adjustable from 1400 mm to 1500 mm. It is driven by an a.c. servo-motor of 6.5 N-m. torque capacity at 2000 rpm. A gear box reduces the speed by a factor of 24. The drive from the gear box to a spline shaft (which drives the slat chain sprocket) is through chains. A speed sensor is mounted on the ground support and senses a rotating disc on the main drive shaft. There are four servo drives, one each for the four servo-motors and one variable frequency drive for the two induction motors of side conveyors. The entire system is in radiation shielded area and is controlled from the control room. A programmable logic controller (PLC) based on RS 500 Logix software is used for controlling the complete system.

1.3 Recent applications of 750 keV DC Accelerator

i. Curing of rubber tiles for Ship Building Centre, Visakhapatnam:

Ship Building Centre at Visakhapatnam has requirement of surface treatment of rubber tiles using electron beam. Using an imported electron accelerator, rubber tiles were irradiated at their premises. Dosimetry study and process evolution was carried in their facility by us. Based on these parameters, irradiation trials were conducted on few rubber tiles at our Centre. Fig.T.2.1 shows a sample rubber tile being arranged over the conveyor prior to its irradiation treatment. The tiles are irradiated in two stages : first with polyester resin and then with a glass cloth over it. The required dose in these stages varies from 100 kGy to 250 kGy. Dose variation for this experiment was within ±10%. After the radiation treatment and aging, 'bond pull strength test' was carried out. In this test, the glass cloth which was spread over rubber tile and treated with electron beam is peeled off using a peeler machine. The glass cloth rubber tile joint should withstand a minimum stress level of 15 Kg/cm^2 before peeling. The desired results were obtained after few trial irradiations.

Fig.T.2.1: Irradiation of rubber tiles

ii. Experiments on radiation grafting of polypropylene sheets for uranium recovery from sea water:

Radiation grafted polypropylene (PP) sheets are used for uranium recovery from sea water. Experiments on grafting of PP sheets are being carried out using the accelerator (Fig.T.2.2). This application requires a dose of 200 kGy which is given in multiple passes. The sheets are first irradiated and then immersed in an acrylonitrile solution at a predefined temperature after a fixed interval. The number of passes and the duration of waiting time were varied to optimize the results. Dose variation was found to be within ±10% over the scanning width. Necessary changes have been made in the conveyor system of the accelerator and the trial irradiation is in progress.

Fig.T.2.2: Radiation grafting of PP sheet

iii. Sterilization of sanitary napkins:

Sterilization of sanitary napkins was carried out (Fig.T.2.3) using this accelerator at the dose level of 25 to 30 kGy. The napkins were checked to be sterile by direct inoculation techniques at Alpha Labs, Indore.

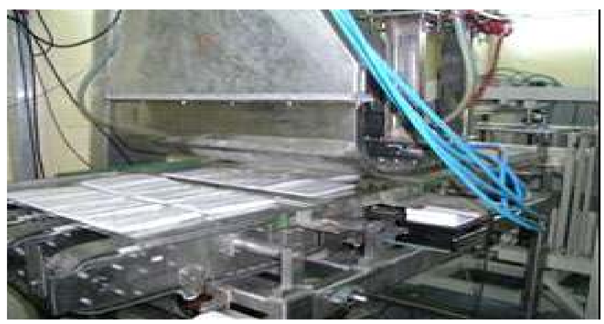

Fig.T.2.3: Sterilization of sanitary napkins

For routine dosimetry, thin radiochromic dosimeters (FWT-60 films) are used. Dosimetry of the accelerator at an energy of 500 keV was also carried out using $CaSO_4$:Dy phosphor by Bakshi et. al. [3] It was reported that in the dose range 10 kGy to 200 kGy, $CaSO_4$:Dy phosphor gave good results within experimental accuracy.

2. High Power Industrial Accelerator

Development of a 2.5MeV/ 100 kW air-core transformer type high power industrial accelerator (HPIA) is in progress at RRCAT pursued in collaboration with Budker

Institute of Nuclear Physics, Russia. Energy of the accelerator can be varied from 1 to 2.5 MeV with electron beam current up to 50 mA and maximum beam power up to 100 kW. It is to be used for long term, round the clock continuous operation under industrial conditions. Table T.2.1 shows the design specifications of the system. A schematic diagram of the HPIA is given in Fig.T.2.4

Operating Voltage	1-2.5 MeV Max.
Beam Current	50 mA at 2.5 MeV
Max. Beam Power	100 kW
Energy Dispersion	0.5 % at 2.0 MeV
Electron Gun	Indirectly heated triode electron gun with LaB_6 as emitter.
Maximum heater power	60 W
Accelerating Tube	PVA glued accelerating tubes from BINP
HV Scheme	Air core transformer. Secondaries rectified and series connected
Beam Scanning width	50 cm-140 cm
` Scanning frequency	50 Hz along the scanner and 1 kHz in transverse direction.

Table T.2.1: Specifications of the HPIA

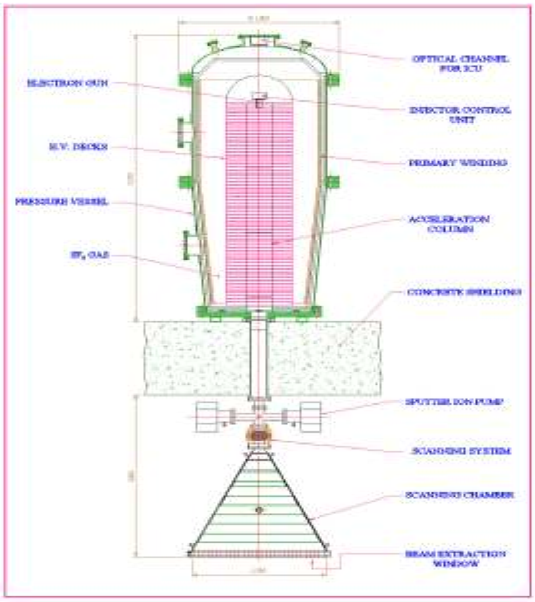

Fig.T.2.4 Schematic diagram of the high power industrial accelerator

Experiments have been performed at BINP for the measurement of beam energy using calibrated energy probe, measurement of beam current, measurement of linear density distribution of the beam current under the extraction device window and long time tests for its stable operation and are reported in Ref. 4. Fig. T.2.5. shows the assembly of the primary windings ready at RRCAT for tests with inverter.

Fig.T.2.5. Primary windings of the HPIA being tested at RRCAT

2.1 Development of inverter

The inverter required to feed power to the compensation network and the primary windings of the air-core transformer is rated for 150 kVA, 430 Hz output. Instead of single full-rated inverter, it is proposed to follow the modular approach for redundancy and availability. Six modules, each rated at 30 kVA, shall operate in parallel. In normal operation, when all the 6 modules are healthy, each module will operate at 25 kVA. In case one module fails, the remaining five modules will continue to feed power to the accelerator structure without de-rating. Each module will directly operate on 415V three-phase ac mains.

2.1.1 Inverter Scheme:

Various schemes are available for the development of inverter. Our inverter uses the dual half-bridge scheme [5]. Schematic diagram of the inverter is shown in Fig.T.2.6. A three-phase ac main is rectified and filtered using diode bridge rectifier and LC filter (Ldc-Cdc). The filter capacitors are split and the center point is used as the return of the following inverter stage. The inverting stage uses two active switches (IGBTs S1, S2) and two diodes (D1, D2). Since the active switches are not directly connected in series, the scheme is free from the shoot-through (i.e. accidental simultaneous conduction of both the switches in the same leg), which is a potential failure mode in half-bridge and full-bridge inverters. The dual half-bridge inverter can be viewed as two buck converters connected at the output through high-frequency filter inductors (Lf). Output inductor currents of two buck converters are opposite to each other, which double the effective output ripple frequency and reduce output ripple amplitude. In fact, there is a perfect ripple cancellation when the duty ratio of two buck converters is equal to 0.5. At this point, effective output is zero. Thus zero-cross-over distortion (experienced in conventional inverters) is eliminated. Further, the paralleled inverters can be suitably phase shifted reducing input/output ripple amplitude and increasing ripple frequency. High-frequency filtering requirement (Lf- Cf) is thus reduced.

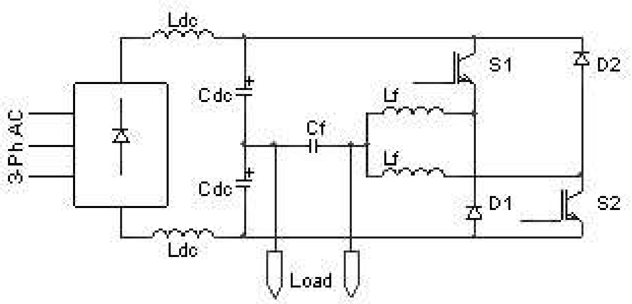

Fig.T.2.6: Schematic diagram of an inverter module.

2.1.2 Prototype 30 kVA Inverter

The first prototype inverter based on the dual half-bridge circuit has been developed. The inverter is rated for 175V/ 175A rms output at 430 Hz. The IGBTs are switched at 20 kHz in sinusoidal pulse width modulation (PWM) with unipolar voltage switching. Loss-less turns-off snubber is used to minimize the turn-off switching losses and stresses in the IGBTs. A photograph of the module is shown in Fig.T.2.7. The overall dimensions of the module are 0.7m (W) x 0.9m (D) x 8U (H). The module has been currently tested up to 9 kVA output (Ref. 6).

Fig.T.2.7: Photograph of the prototype 30 kVA inverter.

2.2 Pressure vessel

Table T.2.2 shows the specifications of pressure the vessel for the accelerator designed as per ASME code The details of design of the vessel are available in Ref.7. The pressure vessel is being fabricated at Vadodara and is expected to be delivered shortly.

Design parameters	Vessel for HPIA
Design pressure: Internal	 162 psi (1.1 MPa)
External	15 psi (0.1 MPa)
Design temp.: Minimum Maximum	 20°C 60°C
Inside diameter of cylindrical portion	1500 mm 1200 mm at small conical shell
Dimension of tori-spherical or elliptical head	Inside crown radius - 1350 mm Inside knuckle radius - 255 mm
Allowable leak rate	10^{-6} mbar-litres/sec

TableT.2.2: Pressure vessel specifications for HPIA

2.3 Potential applications of the 2.5 MeV / 100 kW electron accelerator in India:

- The 2.5 MeV system can be used in dual mode. The x-rays generated from 2.5 MeV, 100 kW electron beam using an optimized target (Tantalum 0.4 mm plus water plus SS) will be equivalent to cobalt-60 source strength of 300 kilo curie.
- Sterilization: Urine specimen cards can be sterilized at 25,000 cards per hour at 1 MeV, 50 mA. At 2 MeV, 20 kW, this system can sterilize disposable 2.5ml syringes at about 100,000 per hour.
- Irradiation of artificial leather for footwear production : using 1.5 MeV, 50 mA 300 kGy -1000 m^2/hour
- Irradiation of paper pulp sheet for viscose yarn production (10 kGy dose) at 50 kW power level : 250 tonnes/day or 25 truck-loads of material per day.
- Grains irradiation (to be located at port for export of grains) : A 50 truck-load of material can be irradiated per hour with this system at 0.2 - 0.3 kGy.
- Waste water treatment : At 0.4 kGy, about 15000 m^3/hr. throughput can be achieved.
- Cables : Insulation thickness of 1 mm to 5 mm and cable outer diameter of 100 mm can be cross linked using this system with a throughput of 100 - 1000 m/min.

In fact, in all these applications, the limitations will come from material handling point of view rather than the accelerator.

3. Self-shielded low energy electron Accelerator

A Self-Shielded Low Energy Accelerator (SLEA) is being developed in our Centre. The specifications are given in the Table T.2.3. Most of the components of this accelerator are ready. Installation is scheduled to begin shortly.

3.1 SLEA Power Supply

The high voltage generation is based on Cockroft-Walton multiplier scheme operating at high frequency. Fast diodes with reverse recovery time (t_{rr}) of 75 ns and 40 kV, 2nF capacitors are used in the voltage multiplier decks. A 30 kHz, 12.5 kV inverter unit will power the voltage multiplier stack The complete system is housed in a gas filled tank, to provide insulation.

Operating Voltage Range	200 - 300 kV
Max. Beam Current	20 mA @ 300 kV
Maximum Power	6 kW
Electron Gun	Planer diode gun with LaB_6 Cathode
Acceleration Column	Indigenously developed column
HV Scheme	Multi stage, N_2/CO_2 gas (at 5.5 bar) insulated balanced Cockroft-Walton multiplier with driver frequency of about 30 KHz
Beam Scanning width	50 cm - 125 cm on the product
Window Foil	25 micron or 10 micron with reinforcements in beam path
Scanning Frequency	100 Hz

Table T.2.3: Specifications of SLEA

A fast acting stabilization circuitry will operate the power supply in a constant high voltage. Constant emission current is achieved by controlling filament supply. Both functions can be remotely controlled and monitored from the control panel which will also indicate the output voltage and the emission current.

For safety considerations, the stored energy is kept at minimum and the unit is short circuit protected. The voltage ripple is kept at low level due to the high frequency operation. When connected to the load i.e. accelerating column along with cathode power supply, the voltage ripple will be further reduced because of added capacitance of high voltage dome.

To minimize the corona, the high voltage terminal will be provided with suitable size aluminium dome and the multiplier decks will have equi-potential rings to control the external field.

The power required for the cathode will be generated through a capacitive isolation column, which is driven by a low power high frequency inverter. The beam current will be stabilized by controlling this inverter in a closed loop with respect to emission current. The systems are being assembled in the Industrial and Medical Accelerator building, RRCAT.

The major subsystems of the power supply are : rectifier and chopper unit, driver inverter, high voltage transformer, multiplier stack assembly, filament power supply and control system as shown in Fig.T.2.8. Fig.T.2.9 shows a photograph of the multiplier stack assembly with the high voltage dome. Details of these are available in Ref.6.

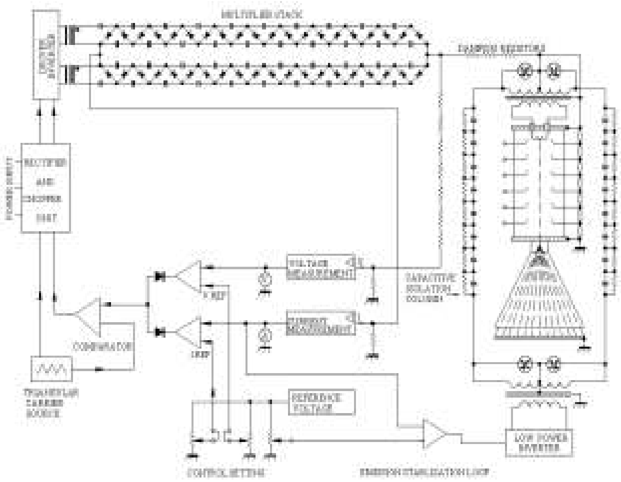

Fig.T.2.8. Schematic of the 300 kV, 6 kW power supply for the Self-shielded Low Energy DC accelerator

Fig.T.2.9: 300 kV multiplier stack assembly for SLEA

3.2 Pressure vessel

Table T.2.4 shows the specifications of the pressure vessel for the accelerator, designed as per ASME code The details of the design of the vessel are given in Ref. 7. The vessel has been received at RRCAT and the photograph is shown in Fig.T.2.10.

Design parameters	Vessel for SLEA
Design pressure: Internal External	 88 psi (0.605 MPa) 15psi (0.103 MPa)
Design temp.: Minimum Maximum	 20°C 60°C
Inside diameter of cylindrical portion	1200 mm
Dimension of tori-spherical or elliptical head	Inside crown radius 1210 mm Inside knuckle radius 75 mm
Allowable leak rate	10^{-6} mbar-litres/sec

Table T.2.4: Pressure Vessel specifications

Fig.T.2.10.: The pressure vessel for SLEA

3.3 Development of Acceleration Column

Fig.T.2.11 : The acceleration column for SLEA

An acceleration column rated 300 kV as shown in Fig.T.2.11 has been successfully developed. Ceramic to metal sealing was achieved by polyvinyl acetate (PVA). The column has 28 ceramic to metal joints and has overall height of 400 mm and diameter of 150 mm. The column was subjected to leak test after thermal and pressure cycles and leak rate was found to be less than 10^{-10} mbar-litre/s. Individual ceramic rings were tested for high voltage insulation under pressure. The column will be tested for its full high voltage rating using the 400kV power supply in the high voltage lab.

3.4 Potential Applications of SLEA:

A self shielded low energy accelerator can be used for the following industrial applications:

- Curing of opaque materials such as laminates, printing inks, paints, and coatings as well as transparent films.
- Sterilization of food packaging materials.
- Curing of wooden materials.
- Manufacturing of heat shrink film.
- Electron beam curable silicone coatings for a wide variety of paper and film applications.
- Surface irradiation of fruits, vegetables, cut-flowers, seeds etc

4. Conclusion

A wide range of industrial accelerators developed / being developed at RRCAT, with energy ranging from 200 keV to 2.5 MeV are covered in this article. These systems are basic tools for R & D in the field of radiation processing, which is one of the six "Key Drivers" identified by the Department of Atomic Energy. These accelerators will be deployed for societal use, that includes large scale radiation processing of food, industrial and medical products.

Acknowledgements

Contribution of all our colleagues in Industrial and Medical Accelerators Section and Power Supply Division is acknowledged.

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