Chapter 11

Techno-Commercial Aspects of Electron Accelerators

– Nishant Chaudhary, P. C. Saroj & Archana Sharma

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Radiation processing technique with electron accelerators is vast growing field because of safety and operational controllability of accelerators. It prevents to use of any radio-isotope like cobalt-60 (Co-60) or cesium-137 (Cs-137) which has no command on utilization view-point and lack of public acceptability. As per user demand the operation of Electron beam (EB) accelerators can be started and stopped without wasting any source or energy. Additionally EB accelerator can produce dose in order of'kilogray (kGy)' within few seconds and thus the throughput of the system is very high [47]. It leads to very less exposure time to the product as compared to the radio-isotope based facility. The product can be irradiated using continuous moving conveyor system (having one directional motion) or bidirectional conveyor system which enables batch wise processing. The product size (also batch size) can be adapted as per user obligations and the beam energy. Moreover electron accelerator is capable to deliver X-ray radiation as per demand to meet the radiation processing goals. X-ray beam is produced by impinging energetic EB on a high Z target like Tungsten or Tantalum [44]. Therefore the dosimetry of accelerator systems, to be used in both modes EB and X-ray, should be standardized in both the forms. The beam power efficiency is compromised in case of X-ray operation as the major EB power will be lost in form of thermal energy within the X-ray converter material. Also electron beam accelerators can be employed for cargo scanning applications to interrogate cargos at ports/borders to prevent the transport of contraband objects. The positive aspects and applicability of electron accelerators act as driven force and hence BARC has developed different electron accelerators indigenously at Electron Beam Centre (EBC), Kharghar, Navi Mumbai site. The layout of EBC building is shown in Fig. 11.1. The developed electron accelerators are majorly categorized as RF linear accelerator (Linac) which operates in pulsed form and direct current (DC) accelerator, operational in continuous fashion. This chapter contains about developed electron accelerators at EBC, their technology, purposes, foot print with radiation shielding barriers and commercial aspects.Comparative commercial status with radio-isotope based counterpart is also highlighted along with recent technologies transferred for actual production. It also highlights the respective responsibilities of BARC and competent team in situation of collaboration for set up of EB facility.

11.1 Accelerators at EBC

11.1.1 1 MeV DC Accelerator

A high power DC electron accelerator has high throughput for radiation processing applications, viz waste water treatment, flue gas treatments, cable irradiations etc. BTDG, BARC has developed a 1 MeV DC electron accelerator and demonstrated for Electron Beam Waste Water Treatment (EBWWT) using simulated test facilities.This accelerator is based upon Cockcroft-Walton voltage multiplier principle and using a pressure vessel with nitrogen gas at 6.0 atm, the pressure for insulation. Electron beam is generated by thermionic electron gun and accelerated under high vacuum in accelerating tubes.The accelerated beam is transported, steered, scanned and is extracted in atmosphere through a titanium foil window of size 1500 mm×100mm. The extracted beam falls on product to carry out various industrial radiation processing applications. The photograph of 1 MeV DC accelerator subsystems and waste water treatment set up are given in Fig. 11.2. The process flow diagram EB based waste water treatment set up is depicted in Fig. 11.3 located at EBC & table 11.1 as electrical power requirement.

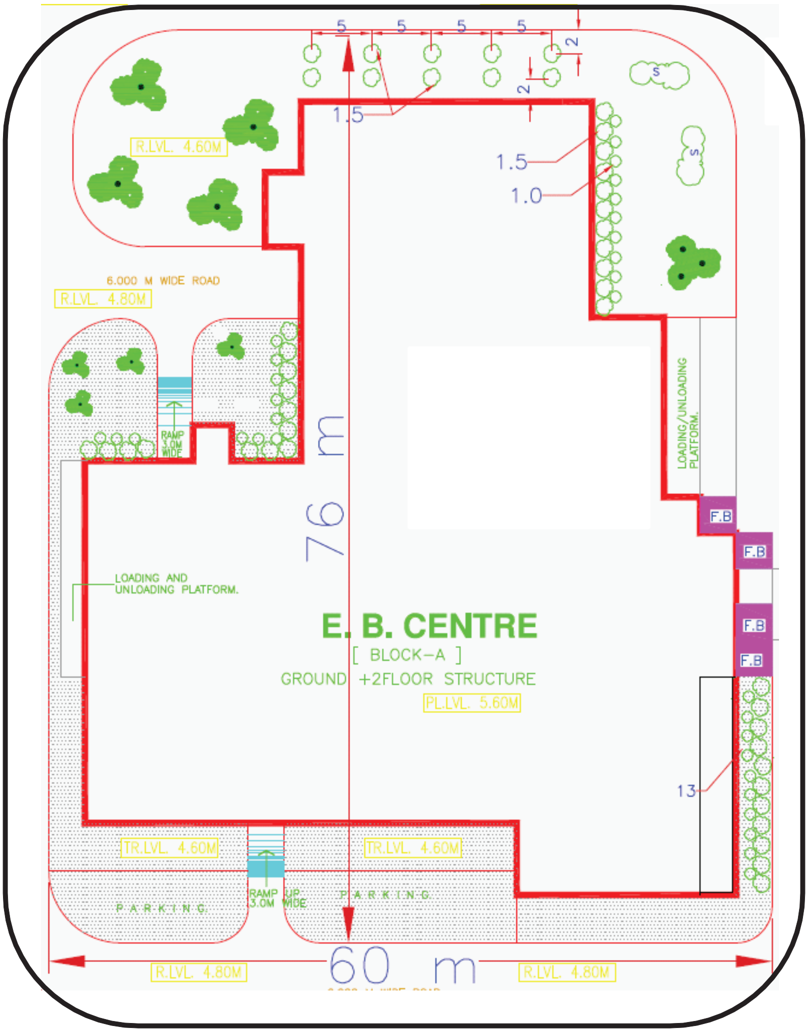

Figure 11.1: Layout of EBC main building.

11.1.2 10 MeV RF Linac

In case of RF Linear Accelerator (Linac) electron acceleration happens through establishing oscillating electric fields in a structure called cavity. This electric field is driven by microwave source either klystron or magnetron. The structure of Linac having a series of coupled cavities and those are driven at resonance, with the RF frequency, ultimately leading to acceleration in charged particle. A combination of modulator - pulse transformer is used to provide a high voltage pulse to function the microwave source in pulsed manner. This Linac has capability to generate 10 MeV EB in pulsed fashion with a certain repetition frequency and the beam is scanned over 1000 mm scan length with required dose uniformity [41, 47]. The output dose rate has been characterized through dosimetry experiments which were done using radio-chromic films. The dosimetry consists of in house calibration of dosimeters, EB energy verification and dose profile correlation with operating parameters (details discussed in chapter 14). All irradiation experiments have been carried out in open aerated conditions.

Figure 11.2: Subsystems and waste water treatment set up of 1 MeV DC accelerator.

Table 11.1: Electrical power requirement for 1 MeV DC accelerator.

Sr. No.	**Description**	**Electrical power (kW)**
1.	Input for HV generator	115
2.	UPS for vacuum, control, magnets, etc)	1.2
3.	AC, light, Fans	5
4.	Ozone exhaust blowers (10 HP motor), 1 No.	7.5
5.	20 HP x 2 Pumps for water feeder	30
6.	Foil cooling blowers, 1 No.	2.5
7.	Fresh air blowers (5000 CFM – 1.5 HP), 1 No.	1.1
8.	3 T EOT crane, 1 No.	∼5
9.	Chiller system, 30 TR,	36
10	Electrical Power Supply – Total (3 Φ, 415 V, 50 Hz)	203.3

The main purposes of this accelerator are food preservation, medical product sterilization,

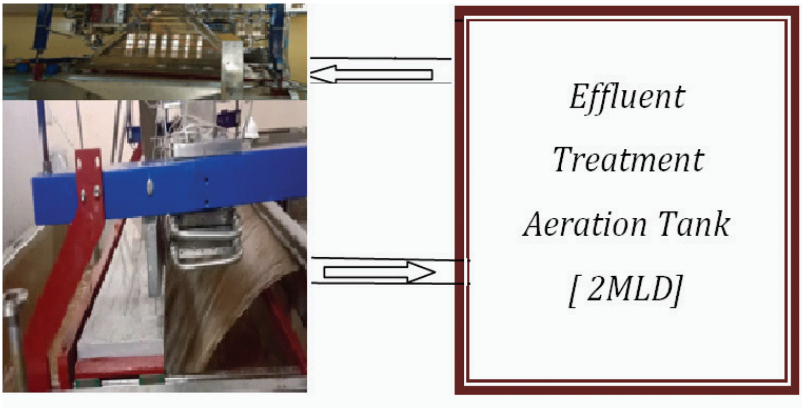

Figure 11.3: Process flow diagram of EB waste water treatment set up.

seed mutations, electronic-waste management, exotic coloration of gemstones, polymer irradiation, semiconductor modifications and applied research. Figure 11.4 exhibits the utility of 10 MeV Linac as food irradiator at EBC & table 11.2 as electrical power requirement.

Table 11.2: Electrical power requirement for 10 MeV RF Linac.

Sr. No.	**Description**	**Electrical power (kW)**
1.	Input for RF Linac	36
2.	UPS for vacuum, control, magnets, etc	1.2
3.	AC, light, Fans	5
4.	Ozone exhaust blowers (10 HP motor)	7.5
5.	Foil cooling blowers, 1 No.	2.5
6.	Fresh air blowers (5000 CFM – 1.5 HP), 1 No.	1.1
7.	1.5 T EOT crane	∼3
8.	Chiller system, 20 TR, 1 No.	21
9.	Electrical Power Supply – Total (3-Φ, 415 V, 50 Hz)	77.3

11.1.3 6 / 4 MeV Dual Energy RF Linac

Based upon Linac principle BTDG, BARC has also developed a dual energy accelerator operating in X-ray mode only. It facilitates to operate in either single energy mode or in dual energy mode with pulse to pulse energy variation. It can produce 6 / 4 MeV dual energy electron or any one in single energy vogue as per requirements. The main purpose of this EB accelerator based X-ray source is cargo scanning to restrict the movement of contraband articles. The machine ejects a focused X-ray beam, acting as point source (of size around 2 mm), to yield a good quality of internal image of cargo. A series of collimating units is applied to slice the X-ray beam in fanned profile to satisfy all the standards of image attributes (as demonstrated in Fig. 11.5). The cargo is divided into several slices, each slice is pictured and then they are integrated by software to generate a good quality image of the hidden object. The number of slices will determine the resolution of the object and hence it is required to have a small width collimating slit. The image quality will be better if the background radiation at the detector is minimal. Therefore it is necessary to provide adequate shielding

Figure 11.4: Onion irradiation on mass scale in 10 MeV electron accelerator at EBC.

around the target so that scattered radiation does not pass through the collimating system. Spectrum of X-rays generated with single energy EB is applicable to produce the image of object with size specific signature (not material wise discrimination). This is majorly used for radiography applications other than cargo scanning to identify the cracks or defects in a bulk material. The system has qualified the requisite ANSI standards for imaging with single energy.

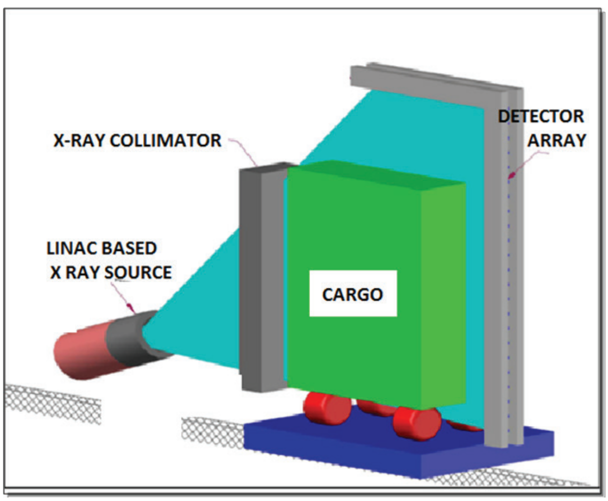

Figure 11.5: Schematic of Linac based X-ray source and cargo scanning.

Dual energy X-ray facilitates to discriminate the materials based upon atomic number identification which is not possible in case of single energy X-ray source [52]. The dual energy system qualifies the material discrimination standards IEC 62523 and four bands of materials viz. organic, light elements, inorganic and nuclear are identified clearly. To facilitate the system in mobile format (or truck mountable), the compactness and weight control are the major challenges. Therefore the design optimization of each subsystem including electronics is quiet imperative. In a compact box, electronic systems including the control unit are placed near the accelerator and so the shielding should be such as to ensure reliable performance of the electronics. The typical output dose rate received by this machine, to fulfill the demand, is up to 2 Gy/min at 1 m from source. This has qualified all the international standards related to image quality and successfully produced the internal image of cargo with material band identification.

11.2 Electron Beam Processing

The recent EB processing activities carried out at EBC are highlighted in chapter 14. In the present section we are going to focus on the radiation processing capacity of different accelerators existing at EBC. The suitable thickness of product (to be irradiated) is decided by EB energy whereas beam power concludes the throughput capacity (in terms of kg/h) of a particular product. Furthermore throughput depends upon the dose demand (or type of items to be treated) and the feasible conveyor moving system. Based upon the dosimetry and food as well as medical products irradiation experiments, carried out at EBC (on laboratory scale) in 10 MeV Linac, comparative charts have been prepared. Table 11.3 shows the conveyor speed (or process speed) variation with respect to beam power to treat different food items and medical products. Similarly table 11.4 summarizes the dependency of throughput on beam power. The capability of 1 MeV DC accelerator is summed up in table 11.5.

Table 11.3: Variation of conveyor speed with beam power of 10 MeV electron accelerator.

Items	**Dose demand (Gy)**	**Speed (m/min) at 1 kW**	**Speed (m/min) at 3 kW**	**Speed (m/min) at 5 kW**	**Speed (m/min) at 15 kW**
Onion	60	12	35	60	180
Pulses	660	1	3	5	15
Spices	6000	0.1	0.3	0.5	1.5
Medical Products	25000	0.03	0.09	0.13	0.4

11.3 Quality Assurance

In order to ensure reliability of the system, the ruggedness of EB accelerators have been proven by running the system round the clock on many occasions. The reproducibility of dose profile is periodically tested in–house to ensure that the desired modifications in the product will be achieved. Broad ranges of applications are concluded by delivering dose ranging from tens of gray to hundreds of mega gray order, as per demand [53–55]. The facility works under rigorous quality assurance processes to make available a quality of irradiation service for the users. Some of them are as follows:

1. In house calibration of dosimeter system to ensure the correct irradiation dose delivery.

Table 11.4: Throughput with respect to beam power of 10 MeV electron accelerator.

Items	Dose demand (Gy)	Ton/h. at 1 kW	Ton/h. at 3 kW	Ton/h. at 5 kW	Ton/h. at 15 kW
Onion	60	27	80	135	405
Pulses	660	2.25	6.75	11.25	33.8
Spices	6000	0.225	0.675	1.120	3.375
Medical Products	25000	0.065	0.21	0.35	1.0

[a] All the calculations/extrapolations given in tables 11.3 and 11.4 are based upon experiments done in 10 MeV Linac facility with existing infrastructure at EBC.
[b] Table 11.3 can be referred to table 11.4 for respective conveyor speed.
[c] Assumptions: One sided irradiation, density of food items 1 g/cc and that of medical products 0.15 g/cc.
[d] The dimension of product box can be tuned as per actual product density.

Table 11.5: Waste water processing capacity of 1 MeV DC electron accelerator.

Parameter description	Specifications
Typical output dose rate	18 kGy / min / kW
Throughput	2 million liters of water (MLD)
Size of water jet	1500 mm × 100 mm × 4 mm

2. Process monitoring dosimetry.
3. Selection of appropriate dosimeters depending upon applicable dose range.
4. Monitoring and logging of process critical parameters.
5. Periodic calibration and maintenance of the subsystems.
6. Safe preservation of irradiated dosimeter for reference and traceability for at least six months.

11.4 Commercial Merits of EB Accelerator

The economical aspects of EB machine is thoroughly analyzed and compared with its radio-isotope counterpart. It is well known that the beauty of accelerator system is On/Off provision. For example in case of food items most of the agriculture products are seasonal and therefore their demand to process in radiation facility is also be the same. Thus the high throughput demand in seasons can be fulfilled by EB only and also for off season it can be safely shut down without any economical drain. The same premise is not fit for radio-isotope based radiation processing units. It has to receive user demand continuously to avoid idle source loss. This feature makes electron accelerator more economically viable. Costing affairs of both the radiation processing sources are analyzed and a comparative chart is prepared, shown in table 11.6. Further iterations are also carried out upto per kg material processing charge and compared (table 11.7).

11.5 Collaborative Approach

In view of the massive applicability and a high power radiation source, the installation and operation of EB accelerator facility requires a collaborative approach. The major challenge in

Table 11.6: Costing comparison of 10 MeV EB and Co-60 radiation source.

Details	Pricing: 10 MeV EB of 3 kW power		Pricing: Co-60, 1 MCi	
		Running cost		Running cost
Material: Consumables, spares etc.	Rs. 10 Lakh per year	Rs. 500/- per h	Rs. 1 Lakh per year	Rs. 13/- per h
Machine Cost (Typical)	Rs. 6 Cr. > 20 years (2000 h/yr)	Rs. 1500/- per h	Rs. 10 Cr. > 4 years (7884 h/yr)	Rs. 3170/- per h
Direct Expenses (Electricity)	50 units per h (cost Rs. 10/- per unit)	Rs. 500/- per h	5 units per h (cost Rs. 10/- per unit)	Rs. 50/- per h
Direct Labor	One Nodal + Two operators	Rs. 1200/- per h	3 shifts	Rs. 3600/- per h
Total	Rs. 3700/- per h			Rs. 6833/- per h

[a] The actual cost of consumable/capital/operating given in table 11.6 may vary. The data shown are tentative.

Table 11.7: Throughput comparison of 10 MeV EB and Co-60.

Applications	Dose Required (kGy)	10 MeV, 3 kW	Co-60: 1 MCi
Spices, Coriander, Onion powder etc	10 – 14	1 ton per h	1 ton per h
Cost		Rs. 3.7 per kg	Rs. 6.8 per kg
Onion, Potato, Mango, Rawa etc.	Up to 1	10 ton per h	12 ton per h
Cost		Rs. 0.37 per kg	Rs. 0.57 per kg

[a] All the calculations/extrapolations given in table 11.7 are based upon 10 MeV Linac facility and existing infrastructure at EBC.

this reference is technology, budget and space constraints. The collaboration with technology developer / designer smoothen the process. Its main part takes in radiation shielding which explains the space requirements, responsibilities of different teams and the experience of the designer to optimize all the hurdles including budgets, licensing, training and maintenance. This section deals with these points in brief with typical figures.

11.5.1 Radiation Shielding

Radiation shielding is the foremost criteria to conclude the space obligations. Also optimization of shielding barrier thickness is the most important confront to identify a dedicated site for the same. It includes radiation shielding as per regulatory guidelines and its estimation with design (discussed in details in chapter 15). The footprint with required concrete (as shielding material) wall thickness of 10 MeV RF Linac and 1 MeV DC accelerator are typically shown in Figs. 11.6 and 11.7 respectively.

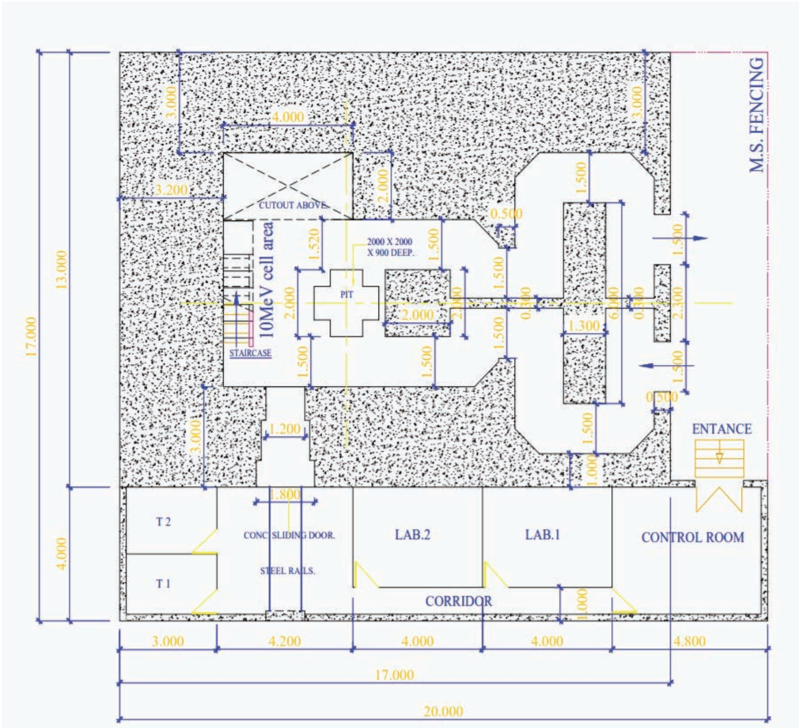

Figure 11.6: Typical footprint with shielding wall thickness of 10 MeV, 15 kW EB Linac, all dimension are in meters.

11.5.2 Responsibilities

The installation of EB accelerator facility demands a collaborative approach with designer and the actual user to process the product on industrial scale. In order to conceive the project successfully the responsibilities must be assigned explicitly to both. In the design and installation area are look after of BARC whereas site and infrastructure along with budget belongs to the user. Table 11.8 explicitly mentions the respective responsibilities of two collaborators.

Table 11.8: Collaborative responsibilities for EB facility to actual applications.

BARC	**USER**
Support in Subsystem Fabrications and Procurement	Budget
Installation and Integration of System	Site and Civil Construction
Shielding, Radiation Safety and Regulatory Clearances	Logistics and Manpower
Trial Operation	Electricity
Training of Operators, Dosimetry and Process Development for Applications	Operation of the System after Hand over

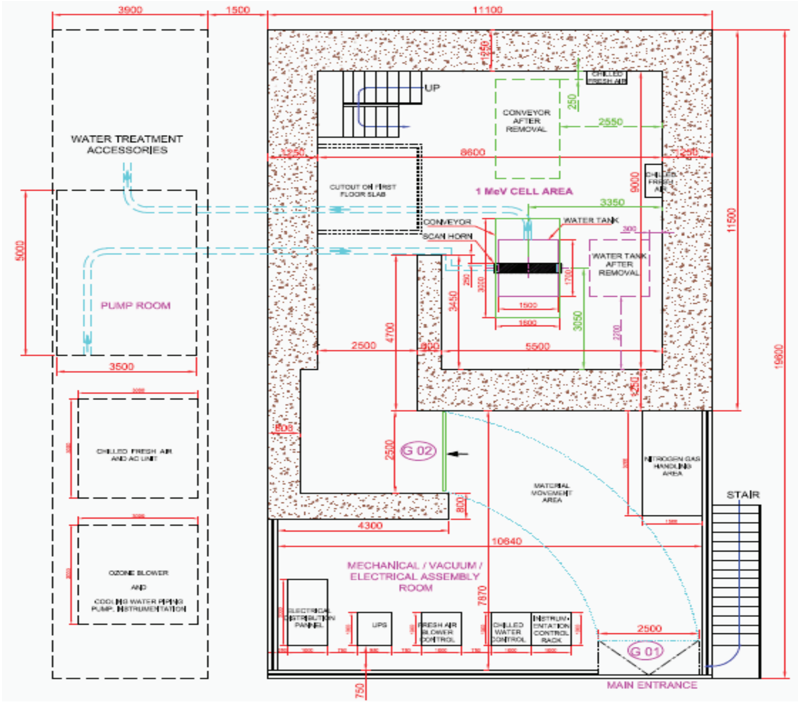

Figure 11.7: Typical footprint and shielding wall thickness of 1 MeV, 100 kW DC EB accelerator for waste water treatment, all dimension are in millimetres.

11.5.3 Technologies Transferred Recently

The technology of subsystems of electron beam accelerator and the accelerator system as a whole are developed in house at EBC/BARC. Therefore these are assets of BARC in full format and being a research organization these cannot be utilized for commercial aspects by BARC. But any technology without actual use is meaningless. To overcome this situation BARC has stream lined a process of technology transfer to the interested and competent users for commercial production of the units based upon transferred technology. It has already been discussed that EBC has developed many EB accelerators and their sub systems. In view of actual production and utilization many technologies have been transferred recently to the competent manufacturer and many more are in pipeline. Some of the important technologies transferred are:

1. Fast Current Transformer (FCT):

This unit provides inline measurement of electron beam current in vacuum. This is a non destructive measurement technique of electron beam current. This technology is handed over to M/s CG Power & Industrial Solutions Limited, Navi Mumbai, India

2. 10 MeV RF Linac:

10 MeV RF electron linear accelerator (Linac) technology as a whole is transferred to two competent outfits: (a) M/s Symec Engineers (INDIA) Pvt. Ltd., Navi Mumbai, India; (b) M/s Anandsparx Technology, Surat, India.

11.6 Conclusion

A range of EB accelerator development and their irradiation process advancements are briefed in the present chapter. The reliability, reproducibility and ruggedness of these are successfully demonstrated on the actual scale. Now it is time to transform these electron accelerator technologies from laboratory scale to industrial levels for concrete use. The economical aspects of EB technology are explained and results that 10 MeV EB accelerator with 3 kW beam power is sufficient to get the desired throughput of many products, say around 30 Ton/hr of onion irradiation and other similar applications including pulses and spices irradiations. Comparative charts on costing (capital and operational) of accelerator, conveyor speed constraints and throughput variation with beam power for food and medical products irradiation are emphasized. Normally the shielding cost and area footprint demand are more or less equal in EB as well as radioisotope facilities. Based upon the rigorous scrutiny, we are in the position to conclude that EB radiation processing is more economically suitable in contrast to radio-isotope based facility. It has also been verified that EB technology is a powerful tool to replace conventional approaches like chemical cross-linking, autoclave techniques, ozonolysis, even radiation process through Co-60, etc on technological angle [43].