## Chapter 35

# Radiation Safety & Regulatory Aspects of Gemstone Colouration using EB Accelerators

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## 35.1 Introduction

Industrial electron accelerators which produce beams in the energy range of 100 keV to 10 MeV with average power from 1 kW to 500 kW are finding important radiation processing applications [164–166] in the fields: a) plastic modifications, b) medical products sterilizations, c) food preservation, and d) water and air pollution control. The main advantage of electron beam over gamma rays is the availability of very high power, energy and nuclear radiation free processing. Electron accelerators can handle large throughputs as compared to gamma ray sources. Table 35.1 lists various non-thermal applications of electron accelerator produced beams.

Table 35.1: Applications of Electron Accelerators.

| **Applications** | **Energy (MeV)** | **Power (kW)** | **Dose (kGy)** |
|---|---|---|---|
| Cross-linking of PE | 0.3-10 | 10 | 50-300 |
| Lubrication property of Teflon | 2 | 10 | 100-500 |
| Food preservation | 05-10 | 10-100 | 0.1-10 |
| Sterilization of medical products | 01-10 | 10-50 | 25-50 |
| Polymerization & curing of surface coatings, adhesives & paints | 0.15-0.5 | 10 | 20-500 |
| Purification of exhaust gases | 0.3-1.5 | 100 | 10-15 |
| Vulcanization of rubber | 0.5-1.5 | 30-100 | 20-500 |
| Exotic colors in Gemstones | 04-07 | 10 | >1000 |

Over the last several decades, enhancement of value of gemstones by inducing exotic colors has been a topic of interest for researchers as well as jewelers who design new trends in fashion industry. Several experiments have been carried out with radiation induced color enhancement in several gemstones. In today's world, irradiation is routinely used to change the color of gemstones. Irradiation has been around since the early 1900's when radium salts were used to change the blue sapphires and diamonds into green. Gemstones such as Diamonds, Beryl, Pearls, Topaz, Yellow Sapphire, Amethyst and Tourmaline that were exposed to radiation causes electrons to be knocked off from some of the atoms within the gemstones, leaving them free to be absorbed by others. This creates color centers which alter the light absorbing pattern of the gemstones and eventually its color. Due to availability of intense radiation sources, commercial exploitation of gemstone coloration has started. There are 305 different varieties of gemstones. Out of which 32 are being radiation processed for color enhancement by different kind of radiation sources. Table 35.2 shows some examples of color inducements in gemstones and its color centers. Figure 35.1 shows results of some experiments carried out at ILU6 facility at BRIT, Vashi and also at EBC, Kharghar, BARC. Many accelerators in 1.5 MeV to 3 MeV range have also been doing color enhancement in Gemstones in the cable manufacturing industry in India.
Several gemstones contain atoms of material that can produce radioactivity. This induced radioactivity can be a serious health concern for the user of the gemstones and also public at large. In this note, we analyze the impact of radiation produced when electron beam is used as a radiation source for gemstone coloration. For this purpose, all 305 varieties [164] are classified based on the composition.

## 35.2 Radiation Sources

Radium salts were first used to change the color of gemstones. However, all kinds of radiations sources like, neutron, ion, electron, Gamma rays and X-rays have been employed.

Table 35.2: Radiation Induced Colour Centers in Gemstones.

| **Material** | **Starting Colour** | **Ending Colour** | **Colour Center** |
|---|---|---|---|
| Beryl | Colourless or pale blue | Green | $Fe^{2+} \rightarrow Fe^{3+}$ |
| | Colourless or pale blue | Yellow | $CO_3{}^{2-} \rightarrow CO_3^-$ |
| Corundrum | Colourless | Yellow | $Fe^{2+} \rightarrow Fe^{3+}$ |
| | Pink | Orange, Pink | $Fe^{2+} \rightarrow Fe^{3+}$ in presence of Cr |
| Pearl | Pale Colour | Gray, Black | $Mn^{2+} \rightarrow Mn^{3+}$ |
| Qartz | Colourless, yellow, Pale Green | Yellow, Brown, Smoky | $Al^{3+}$ impurity related |
| | Colourless, yellow, Pale Green | Purple (Amethyst) | $Fe^{3+} \rightarrow Fe^{4+}$ |
| | Colourless, yellow, Pale Green | Pink (Rose) | Unknown |
| Spodumene | Colourless to Pink | Green | $Mn^{3+} \rightarrow Mn^{4+}$ |
| | Colourless to Pink | Pink | $Mn^{4+} \rightarrow Mn^{3+}$ |
| Topaz | Colourless, yellow, Orange | Red, Yellow | Unknown |
| | Colourless or pale blue | Blue, Brown, Green | Unknown |

Figure 35.1: Diamonds irradiated at ILU6: (a) Before Irradiation, (b) After Irradiation; and (c) Gemstones irradiated at EBC Kharghar.

a) **Neutrons** –

- Spontaneous Fission Source: Cf-252 emits neutrons. Also ($\alpha$,n) Reactions are used to produce neutrons. Plutonium-beryllium (PuBe), americium-beryllium (AmBe), or americium-lithium (AmLi) are some of the sources available. However, they are uf very low Intensity and are suitable for experiments.
- Nuclear Reactors: Thermal and Fast Neutrons of very intensity are available. They produce long term radioactivity.
- Plasma Sources: DD and DT fusion reactions produce CW and pulse neutrons in plasma sources. They are also of low power.
- Light Ion Accelerators: neutron are produced when D, T impinge on D, T, Be, Li

ions with more than 1 MeV energy.
- Photo neutrons: When high energy (more than 30 MeV) electrons impinge on high Z targets, and resulting X-rays fall over Be-6 targets (Energy $>$ 1.7 MeV photon) or on D target (Energy $>$ 2.26 MeV photon) or on Li-9 targets (Energy more than 4 MeV), photo neutrons are produced. Neutrons usually produce short and long term radioactivity while interacting with gemstones.

b) **Ions** –

- Ion accelerators from 0.1 MeV to 20 MeV are used for ion implantation in gemstones. They are usually low power ($<$ 1 kW) and can penetrate only a few microns on the surface.
- They can induce long term radioactivity

c) **Gamma Sources** –

- Co-60, Cs-137 emit 1.17 MeV, 1.3 MeV and 0.667 MeV intense Gamma rays. High intensity sources are available and also provide high depth penetration.
- They do not produce any radioactivity in the gemstones.

d) **Electron Beam** –

- Electron accelerators with 1-10 MeV and with 1 kW to 100 kW beam power are available and widely employed. They penetrate 1-10 mm deep.
- They produce short term radioactivity (up to 2 hrs Quarantine) when operated at more than 3 MeV in some cases.

e) **X-Ray Beams** –

- Electron accelerators with Tantalum X-ray converter in energy range of 1-7.5 MeV are available and employed. They have high penetration (10-75 mm) depth.
- They have low efficiency and radioactivity is similar to electron accelerators.

Electron Accelerators and Gamma Sources are extensively used for Gemstone coloration. However, out of 305 varieties, only 32 are used for color enhancement.

## 35.3 Photo Neutron Production with Electron Beams

Electron Beams of 50 MeV to 100 MeV are employed for production of intense neutron sources where electrons produce $\gamma$ by (e, $\gamma$) reaction (bremsstrahlung radiation) and then neutrons are produced due to ($\gamma$, n) reaction. For high energy electrons, high Z targets are designed which are suitable for both the reactions. Neutron production by (p, n) reaction is more efficient than ($\gamma$, n) reaction. However for some applications like Accelerator Driven Subcritical System (ADS), proton beams are viable around 800 MeV where neutron yield saturates. In case of electron beam, neutron yield saturates at 100 MeV. Since the desired electron energy is low as compared to proton accelerators, electron accelerator systems are very compact and less expensive.

Figure 35.2 shows the neutron yield as a function of electron energy [167]. Here high Z materials are used as targets. These targets have Threshold energy from 6.74 MeV to 8.41 MeV. We can see that neutron yield increases rapidly as electron energy increases and saturates above 50 MeV. Therefore electron accelerator energy should be 50 MeV to 100 MeV. High Threshold energy nuclear reactions are shown in table 35.3. Typical neutron yield for 50 MeV beam with U, W, Pb and Ta targets at 100 to 200 mA beam current and 5 MW to 10 MW beam are tabulated in table 35.4.

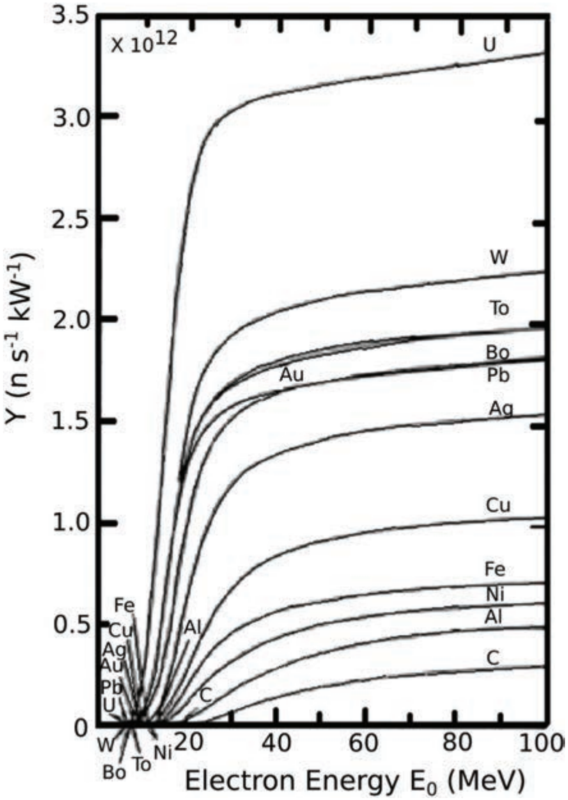

Figure 35.2: Electron Beam as an Intense Neutron Source (for ADS Applications) (Fig. ref. [167])

Here, Neutrons are produced via Photo nuclear and Photo fission reactions from Bremsstrahlung photons produced by the high energy electrons. Tungsten, Tantalum, Uranium, lead, Bismuth are normally employed as targets. In the photon energy range from threshold (few MeV) to about 30 MeV, neutron production is via Giant Dipole Resonance (GDR) mechanism.

Table 35.3: High Threshold Energy Nuclear Reactions.

| **Nuclide** | **Threshold (MeV)** | **Isotope Abundance (%)** |
|---|---|---|
| $^{206}$Pb | 8.09 | 24.10 |
| $^{207}$Pb | 6.74 | 22.10 |
| $^{208}$Pb | 7.37 | 52.40 |
| $^{181}$Ta | 7.58 | 99.99 |
| $^{180}$W | 8.41 | 0.12 |
| $^{182}$W | 8.07 | 26.30 |
| $^{183}$W | 6.19 | 14.28 |
| $^{184}$W | 7.41 | 30.70 |
| $^{186}$W | 7.19 | 28.60 |

## 35.4 Neutron Yield for High Intensity Low Energy Electron Beams

Here, we present an alternate approach using low energy electron accelerators to produce X-ray photons that are employed for neutron generations by low threshold energy ($\gamma$, n) reactions for injecting into sub critical system. Table 35.5 shows the nuclear reactions that

Table 35.4: Typical Neutron Yield for 50 MeV Electron Beam with Different Targets.

| **Beam Energy** (MeV) | **Neutron Yeild** (× $10^{12}$ n $\text{s}^{-1}$ $\text{kW}^{-1}$) | **Beam Current** (mA) | **Beam Power** (kW) | **Neutron Flux** (× $10^{16}$ n/s) |
|---|---|---|---|---|
| 50 (U-Target) | 3.25 | 100–200 | 5-10 | 1.625-3.250 |
| 50 (W-Target) | 2.17 | 100–200 | 5-10 | 1.085-2.17 |
| 50 (Pb-Target) | 1.97 | 100–200 | 5-10 | 0.985-1.97 |
| 50 (Ta-Target) | 1.91 | 100-200 | 5-10 | 0.955-1.91 |

Table 35.5: Low Threshold Energy Nuclear Reactions.

| **Nuclide** | **Threshold (MeV)** | **Reaction** |
|---|---|---|
| $^{2}$D | 2.225 | $^{2}$H ($\gamma$, n) $^{1}$H |
| $^{6}$Li | 3.697 | $^{6}$Li ($\gamma$, n + p) $^{4}$He |
| $^{6}$Li | 5.67 | $^{6}$Li ($\gamma$, n) $^{5}$Li |
| $^{7}$Li | 7.251 | $^{7}$Li ( $\gamma$, n) $^{6}$Li |
| $^{9}$Be | 1.667 | $^{9}$Be ($\gamma$, n) $^{8}$Be |
| $^{13}$C | 4.9 | $^{13}$C ($\gamma$, n) $^{12}$C |

have low threshold energy for neutron production. Threshold energy for ($\gamma$, n) reaction is 1.67 MeV for Be, 2.23 MeV for $D_2O$ and 5.67 MeV for Li. Therefore Be, $D_2$/$D_2O$ and Li targets are evaluated for neutron production. Electrons are first converted (efficiently) into X-rays by impinging on high Z targets (W/Ta) and then the X-rays produced are employed for neutron production. Therefore, it is a two stage reaction. Figure 35.3 [165] shows the neutron yield for Beryllium and Deuterium targets as a function of Electron Energy. At any electron energy, neutron yield increases from Be to $D_2O$ to LiD and $CD_4$/$BeD_2$. Also for any target material, neutron yield increases from 8 MeV to 15 MeV and decreases at 20 MeV. Therefore, 15 MeV beam is ideally suitable for efficient conversion. However, depending on availability of accelerator facility, beam with 10 MeV to 20 MeV can be considered for ADS applications. Neutron Yield is estimated for 8 MeV to 20 MeV electron beam using Be, $D_2O$, LiD, $CD_4$/$BeD_2$ and W/Ta targets for 1 Ampere beam current. In comparison, neutron yield for W/Ta at 50 MeV/100 MeV with equal beam power is also estimated. For example, for 10 MeV beam, power at 1 A is 10 MW, then at 50 MeV/ 100 MeV, neutron yield is also estimated at 10 MW beam (0.2 A/ 0.1 A). The results are presented in the table 35.6. It can

Table 35.6: Comparison of Neutron Yield in 4 solid angles for different Targets-Low Threshold Energy & high Z (W/Ta).

| **S. No.** | **Beam Parameters** | | | **Targets and Neutron Yield (× $10^{16}$ n/s)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Energy (MeV) | Current (A) [a] | Power (MW) | Be | $D_2O$ | LiD | $CD_4(l)$ /$BeD_2$ | W/Ta | W/Ta [b] |
| 1 | 8 | 1 | 8 | 0.21 | 0.44 | 0.75 | 1.15 | - | - |
| 2 | 10 | 1 | 10 | 0.55 | 0.93 | 1.25 | 1.5 | 0.1 | 2.0 |
| 3 | 15 | 1 | 15 | 1.02 | 1.4 | 2.23 | 3.43 | 0.35 | 3.0 |
| 4 | 20 | 1 | 20 | 1.49 | 2 | 2.86 | 4.48 | 2 | 4.0 |

[a] Current varies for equal beam power experiments.

[b] Equal beam power with energy 50/100 MeV and varying currents.

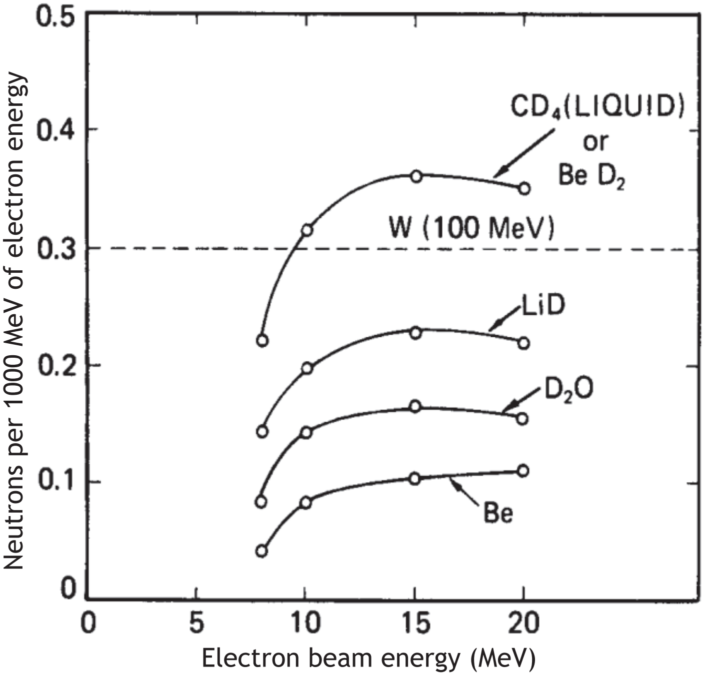

Figure 35.3: Neutron Yield for Beryllium and Deuterium targets as a function of Electron Energy [165].

be seen that neutron yield at 10 MeV to 20 MeV with low Z targets at 1 A is 1.5-4 × $10^{16}$ n/s which is comparable with high Z targets at 50 MeV/100 MeV with equal beam power. Therefore, it is proposed to consider 10 MeV to 20 MeV, 1 A electron accelerator for setting up micro reactors based on compact ADS for power production.

## 35.5 Classification of Gemstones based on Radiation Coloration

Tables 35.3 and 35.5 above show that Gemstones containing low Z materials Deuterium, Beryllium, Lithium and High Z materials Uranium, Tungsten, Tantalum, Lead can produce neutron activity which can be detrimental to health of personnel and equipment. Therefore, based on the chemical composition of all varieties, following classification is suggested. It is to be noted that the materials which are only some traces are not considered for classification.

a) Deuterium Family: Those varieties that contain deuterium atoms There is no known variety containing deuterium atoms

b) Beryllium Family (or Beryl Family): Those varieties that contain Be atoms. There are 19 varieties out of which 7 are processed with radiation

c) Lithium Family: Those varieties that contain Li atoms. There are 9 varieties out of which 2 are processed with radiation

d) High Z Components Family: Those varieties that contain Be atoms. There are 13 varieties out of which None is processed with radiation

e) All Others Family: Those varieties that contain other than D, Be, Li and High Z atoms like U, W, Ta, Pb etc atoms.

There are 264 varieties out of which 223 are processed with radiation

## 35.6 Color Enhancement by High Energy Electron Accelerators

Electron accelerator from 1 MeV to 10 MeV are employed for color enhancement. Beam energy is selected depending on the density and desired thickness of the gemstone employed for color enhancement. For various gemstone varieties, beam energy required for surface coloration (1 mm thick), medium (3 mm thick) and bulk coloration (5 mm thick) are calculated and tabulated in the tables 35.7-35.13 below.

Number of Varieties with density up to 4.0 = 271 (32 with Density 2.5 to 4.0 are used for coloration) Number of Varieties with density from 4 to 6.0 = 19 Number of Varieties with density more than 6.0 (up to 8) = 15

## 35.7 Estimation of Neutron Production with Gemstones containing Be/Li

Neutron production with high Z and low Z targets has been presented in Sections 35.3 and 35.4. As is known that neutron production is a two step process. Electron Beam produces Bremsstrahlung X-rays by (e, $\gamma$) reaction. Photons produced impinge on neutron targets producing neutrons. With high Z targets like U,W ,Ta or Pb, X-rays and neutrons are produced in the same target. Target thickness is adjusted such that beam produced X-rays are fully stopped to produce neutrons. At 10 MeV, optimum X-ray target thickness is ~2 mm for Ta and ~25 mm for photo neutrons. Figure 35.2 shows the source term for Be and LiD for calculation of neutron yield. However, the estimation is valid for High Z bremsstrahlung target and thick Be or LiD targets. In this estimation of neutron yield, gemstones of ~5 mm thickness containing a small fraction of Be or Li are are considered. X-rays are produced inefficiently with low Z Be or Li in the ratio of atomic number Z. A fraction of target material participates in neutron production by X-rays produced in Be or Li. Thickness of Be or Li target (5 mm) is much less than the thickness necessary for efficient neutron production. Suitable correction for this is necessary. Neutron Yield is therefore estimated in 4 steps as below:
For Beryllium – **Step-1** –
For an electron beam of 10 MeV, 1 kW with Thick Ta (2 mm) target for X-rays and infinite (80 cm) Be for neutrons (Ideal Condition). Source Term from Fig. 35.2 is 1000 MeV (100 electrons of 10 MeV) produce 0.08 n Therefore, 10 MeV, 1 kW Beam will produce $5.5 \times 10^{10}$ n $s^{-1}$ and 10 MeV, 3 kW Beam at EBC will produce $1.5 \times 10^{11}$ n $s^{-1}$.
**Step-2** – For an electron beam of 10 MeV, 1 kW with Thick Gemstone (5 mm) target for X-rays and infinite (80 cm) Be for neutrons – Average Z calculated in gemstone targets (32, 33, 98, 116,170,199) is 8. Neutron Yield will reduce in the ratio of Z: 8/74 = 0.11.
Therefore, 10 MeV, 1 kW Beam will produce $5.5\ (\times\ 0.11) \times 10^{11}$n/s $= 6.0 \times 10^{10}$ n/s.
10 MeV, 3 kW Beam at EBC will produce $1.8 \times 10^{11}$ n $s^{-1}$.
**Step-3** – For an electron beam of 10 MeV, 1 kW with Thick Gemstone (5 mm) target for X-rays and infinite (80 cm) Be for neutrons with fractional Be atoms –
Average Be fraction calculated in targets (32, 33, 98, 116, 170, 199) is 0.05;
Neutron Yield will multiply by this fraction: 0.05.

Table 35.7: All Gemstone Varieties Having Beryllium Atoms.

| No. | Name | Chemical Composition | Density (g/cc) | Energy (MeV) at depths | | Enhancement (Rad/Heat/ Coating/oil or resin) |
|---|---|---|---|---|---|---|
| | | | | Surface, 1 mm | Bulk, 5 mm | |
| 32 | Beryl | $Be_3Al_2Si_6O_{18}$ + Fe, Mn, Cr, V, Cs | 2.6-2.9 | 1.2 | 4.5 | Rad (Goshenite Yellow) |
| 33 | Beryllonite | $NaBePO_4$ | 2.84 | 1.2 | 4.5 | No known |
| 63 | Chrysoberyl | $BeAl_2O_4$ + Fe, Ti | 3.68-3.80 | 1.4 | 5.7 | Rad(rare) |
| 93 | Emerald | $Be_3Al_2Si_6O_{18}$ +Cr(+V) | 2.68-2.78 | 1.1 | 4.1 | Dip in Oil /resin |
| 96 | Epidote | $X_2Y_3Z_3$(O, OH, F)$_{13}$ X = Ca, Ce, La, Y,Th, Fe, Mn; Y = Al, Fe, Mn, Ti; Z = Si, Be | 3.33 | 1.3 | 5.3 | No |
| 98 | Euclase | $BeAlSiO_4(OH)$ | 2.99-3.10 | 1.2 | 4.5 | Rad (Green /Blue) |
| 106 | Gadolinite | $Be_2FeY_2Si_2O_{10}$ | 4.0-4.65 | 1.6 | 6.6 | No |
| 114 | Hambergite | $Be_2BO_3$ (OH, F) | 2.35-2.37 | 1.0 | 3.8 | No |
| 116 | Heliodor | $Be_3Al_2Si_6O_{18}$ + $Fe^{3+}$ | 2.68-2.72 | 1.1 | 4.1 | Heat/Rad /Dye |
| 119 | Herderite | $CaBePO_4$(F, OH) | 2.95-3.02 | 1.2 | 4.5 | No |
| 127 | Hurlbutite | $CaBe_2(PO_4)_2$ | 2.88 | 1.2 | 4.5 | No |
| 154 | Malaia Garnet | $A_3B_2Si_3O_{12}$; A = Mn, Mg, Fe; B = Al, Fe, V, Cr | 3.75-4.0 | 1.5 | 6.0 | No |
| 163 | Milarite | $K_2Ca_4Be_4Al_2Si_{24}O_{60}\cdot H_2O$ | 2,46-2.61 | 1.0 | 3.8 | No |
| 170 | Morganite | $Be_3Al_2Si_6O_{18}$ + Mn | 2.71-2.90 | 1.2 | 4.5 | Rad (but fades) |
| 199 | Phenakite | $Be_2SiO_4$ | 2.97 | 1.2 | 4.5 | Rad |
| 220 | Red Berryl | $Be_3Al_2Si_6O_{18}$ + traces (+ Mn, Ti, Li, B, Rb, Zr, Nb) | 2.66-2.70 | 1.1 | 4.1 | No |
| 221 | Rhodizite | (K, Cs)$Al_4Be_4$(B, Be)$_{12}$ $O_{28}$ | 3.44 | 1.3 | 5.3 | Rad |
| 282 | Tugtipite | $Na_4AlBeSi_4O_{12}Cl$ | 2.11-2.57 | 1.0 | 3.8 | No |
| 290 | Vayrynenite | $BeMnPO_4$(OH, F) | 3.18-3.32 | 1.3 | 5.3 | No |

Therefore, 10 MeV, 1 kW Beam will produce 6.0 (× 0.05) × $10^{10}$ n $s^{-1}$ = 3.0 × $10^9$ n $s^{-1}$ 10 MeV, 3 kW Beam at EBC will produce 9.0 × $10^9$ n $s^{-1}$.

**Step-4** – For an electron beam of 10 MeV, 1 kW with Thick Gemstone (5 mm) target for X-rays and finite (0.5 cm) Be for neutrons with fractional Be atoms (Actual Conditions).

Figure 35.4 shows experimental energy distribution of photo neutrons produced in a 10 MeV 100 kW Electron Beam system (RHODOTRON TT200 IBA). Neutron Energy Range 0 to 4

Table 35.8: All Gemstone Varieties Having Lithium Atoms.

| No. | Name | Chemical Composition | Density (g/cc) | Energy (MeV) at depths | | Enhancement (Rad/Heat/ Coating/oil or resin) |
|---|---|---|---|---|---|---|
| | | | | Surface, 1 mm | Bulk, 5 mm | |
| 10 | Amblygonite | (Li, Na)Al($PO_4$)(F, OH) | 2.98-3.11 | 1.2 | 4.5 | Rad (Pale Yellow to Pale Green) |
| 122 | Holtite | $Al_6$ (Ta, Sb, Li)[(Si, As)$O_4$]$_3$. ($BO_3$) (O, OH)$_3$ + Fe, Be,Ti, Mn, Nb, | 3.9 | 1.5 | 6.0 | No |
| 148 | Lepidolite | K(Li, Al)$_3$ (Si, Al)$_4$ $O_{10}$ (F, OH)$_2$ | 2.8-3.3 | 1.2 | 4.5 | No |
| 171 | Nambulite | $NaLiMn_8Si_{10}$ $O_{28}$ $(OH)_2$ | 3.51 | 1.3 | 5.3 | No |
| 188 | Paraiba Tourmaline | $Na(Li_{1.5}Al_{1.5})O_{10}$ $(Si_6O_{18})$ $(BO_3)(OH)_3(OH, F)$ + Cu, Mn | 2.84-3.10 | 1.2 | 4.5 | Heat/Laser Drilling |
| 198 | Petalite | $LiAlSi_4O_{10}$ | 2.4 | 1.0 | 3.8 | No |
| 257 | Spodumene | $LiAlSi_2O_6$ | 3.0-3.21 | 1.3 | 5.3 | Rad (Pink/Green) |
| 280 | Triphylite | $Li(Fe^{2+}, Mn^{2+})PO_4$ + Mg | 3.42-3.58 | 1.3 | 5.3 | No |
| 302 | Zektzerite | LiNa(Zr, Ti, Hf) $Si_6$ $O_{15}$ | 2.79 | 1.1 | 4.1 | No |

MeV with maximum at 1 MeV is measured [168].
Refer to IAEA Technical Report Series 188, Fig 24 p-64 [166], for 1 MeV neutron, at 5 mm thickness, a factor of 0.025 is applied. Neutron Yield will multiply by this fraction: 0.025.

Therefore, 10 MeV, 1 kW Beam will produce 3.0 (× 0.025) × $10^9$ n $s^{-1}$ = 7.5 × $10^7$ n $s^{-1}$ 10 MeV, 3 kW Beam at EBC will produce 2.3 × $10^8$ n $s^{-1}$. In comparison, in an experiment at ECIL with 9 MeV, 3 kW (extrapolated) beam, a neutron yield of 1.8 × $10^8$ n $s^{-1}$ was reported (see Fig. 35.5).

For an electron beam of 10 MeV, 1 kW with Thick Gemstone (5 mm) target for X-rays and finite (0.5 cm) (Li) for neutrons with fractional Li atoms (Actual Conditions) Following the same procedure with different scaling factors for Li, we estimate below the neutron yield in Lithium family; Average Z = 9.5, Lithium fraction = 0.03 and neutron yield source term = 0.2 ($LiD_2$). Using Scaling, a factor = (9.5/8.0) × (0.03/0.05) × (0.2/0.08) = 1.78 more than yield with Be target. Therefore, 10 MeV, 1 kW Beam will produce 1.78 (7.5 × $10^7$ n $s^{-1}$ =1.3 × $10^8$ n $s^{-1}$ 10 MeV, 3 kW Beam at EBC will produce 3.9 × $10^8$ n $s^{-1}$.

Table 35.9: All Gemstone Varieties Having High Z Atoms.

| No. | Name | Chemical Composition | Density (g/cc) | Energy (MeV) at depths | | | Rad. (Y/N) |
|---|---|---|---|---|---|---|---|
| | | | | Surface, 1 mm | Depth, 3 mm | Depth, 5 mm | |
| 19 | Anglesite | $PbSO_4$ | 6.30-6.39 | 2.1 | 5.6 | 9.1 | N |
| 29 | Barite | $BaSO_4$ + Ca, Sr | 4.5 | 1.6 | 4.1 | 6.6 | N |
| 30 | Balydonite | $(Pb, Cu)_3(AsO_4)_2(OH)_2$ | 5.5 | 1.9 | 5.0 | 8.0 | N |
| 31 | Benitoite | $BaTiSi_3O_9$ | 3.64-3.68 | 1.4 | 3.5 | 5.7 | N |
| 34 | Bismuto-tantalite | $(Bi, Sb) (Ta, Nb)O_4$ | 8.84 | | | | N |
| 36 | Bolleite | $Pb_9Ag_3Cu_8Cl_{21} (OH).16H_20$ | 5.05 | 1.7 | 4.5 | 7.3 | N |
| 54 | Cerussite | $PbCO_3$ | 6.55 | 2.2 | 5.8 | 9.4 | N |
| 79 | Crocoite | $PbCrO_4$ | 5.9-6.1 | 2.0 | 5.4 | 8.7 | N |
| 92 | Ekanite | $(Th, U)(Ca, Fe, Pb)_2Si_8O_{20}$ | 3.28-3 | 1.3 | 3.2 | 5.0 | N |
| 100 | Euxenite | $(Y, Ca, Ce, U, Th) (Nb, Ta, Ti)_2O_6$ | 4.30-5.87 | 1.8 | 4.7 | 7.5 | N |
| 150 | Linarite | $PbCu(SO_4)(OH)_2$ | 5.3 | 1.8 | 4.8 | 7.6 | N |
| 165 | Mimetite | $Pb_5(AsO_4)_3Cl$ | 7.24 | 2.4 | 6.4 | 10+ | N |
| 230 | Samarskite | $(Y, Ce, U, Ca, Pb) (Nb,Ta,Ti,Sn)2O_6$ | 5.29-5.69 | 1.9 | 5.0 | 8.0 | N |

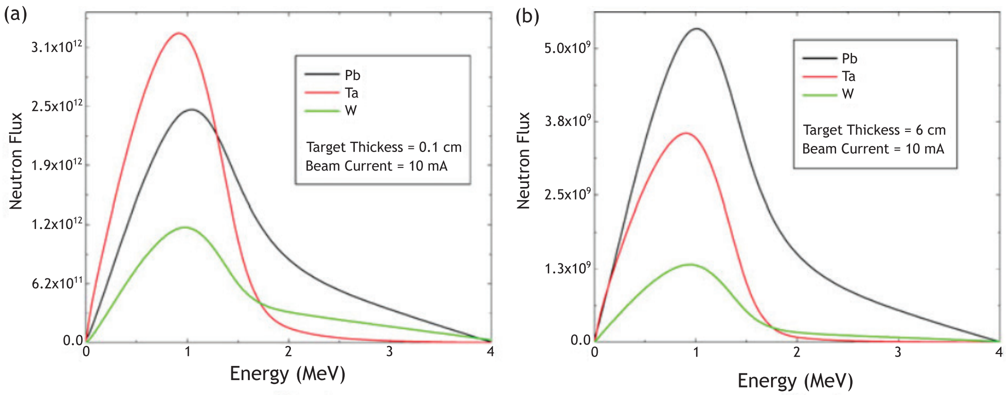

Figure 35.4: Energy distribution of photo neutrons in the target [168].

## 35.8 Dose Rate & Quarantine Time Estimations with Gemstones Containing Be/Li

a) **Estimation of Dose Rate [166]:**

For Be, 10 MeV, 1 kW Beam will produce 3.0 ($\times$ 0.025) $\times 10^9$ n $s^{-1}$ = 7.5 $\times 10^7$ n $s^{-1}$

Table 35.10: Gemstone Varieties with Beryllium and Lithium atoms employed for Radiation Coloration.

| No. | Name | Chemical Composition | Density (g/cc) | Energy (MeV) at depths | | Enhancement (Rad/ Heat/ Coating/ oil or resin) |
|---|---|---|---|---|---|---|
| | | | | Surface, 1 mm | Bulk, 5 mm | |
| 32 | Beryl | $Be_3Al_2Si_6O_{18}$ + Fe, Mn, Cr, V, Cs | 2.6-2.9 | 1.2 | 4.5 | Rad (Goshenite Yellow) |
| 63 | Chrysoberyl | $BeAl_2O_4$ + Fe, Ti | 3.68-3.80 | 1.4 | 5.7 | Rad (rare) |
| 98 | Euclase | $BeAlSiO_4(OH)$ | 2.99-3.10 | 1.2 | 4.5 | Rad (Green /Blue) |
| 116 | Heliodor | $Be_3Al_2Si_6O_{18}$ + $Fe^{3+}$ | 2.68-2.72 | 1.1 | 4.1 | Heat/Rad /Dye |
| 170 | Morganite | $Be_3Al_2Si_6O_{18}$ + Mn | 2.71-2.90 | 1.2 | 4.5 | Rad (but fades) |
| 199 | Phenakite | $Be_2SiO_4$ | 2.97 | 1.2 | 4.5 | Rad |
| 221 | Rhodizite | $(K, Cs)Al_4Be_4(B, Be)_{12}O_{28}$ | 3.44 | 1.3 | 5.3 | Rad |
| 10 | Amblygonite | $(Li, Na)Al(PO_4)(F, OH)$ | 2.98-3.11 | 1.2 | 4.5 | Rad (Pale Yellow to Pale Green) |
| 257 | Spodumene | $LiAlSi_2O_6$ | 3.0-3.21 | 1.3 | 5.3 | Rad (Pink/Green) |

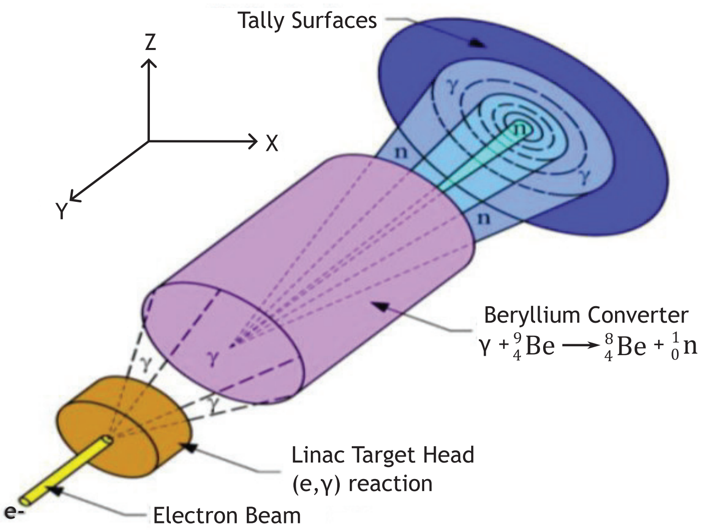

Figure 35.5: Neutron yield for Lithium.

Table 35.11: Gemstone Varieties without Be and Li atoms employed for Radiation Coloration.

| No. | Name | Chemical Composition | Density (g/cc) | Energy (MeV) at depths | | | Rad. (Y/N) |
|---|---|---|---|---|---|---|---|
| | | | | Surface, 1 mm | Depth, 3 mm | Depth, 5 mm | |
| 8 | Amazonite | $KAlSi_3O_8$ | 2.54-2.63 | 1.1 | 2.5 | 3.9 | Y |
| 20 | Anhydrite (Angelite) | $CaSO_4$ | 2.90-2.98 | 1.2 | 2.9 | 4.5 | Y |
| 23 | Apophyllite | $KCa_4Si_8O_{20}(F, OH). 8H_2O$ | 2.3-2.5 | 1.0 | 2.4 | 3.8 | Y |
| 52 | Celestite | $SrSO_4$ | 3.97-4.0 | 1.5 | 3.7 | 6.0 | Y |
| 76 | Corundum | $Al_2O_3$ + Fe, Ti, Cr | 3.99-4.1 | 1.5 | 3.7 | 6.0 | Y |
| 85 | Diamond | C | 3.515 | 1.3 | 3.3 | 5.3 | Y |
| 101 | Feldspar | $KAlSi_3O$; $NaAlSiO_3$ $O_8$ | 2.54-2.77 | 1.1 | 2.6 | 4.1 | Y |
| 103 | Fluorite | $CaF_2$ | 3.18 | 1.3 | 3.1 | 4.8 | Y |
| 104 | Fresh Water Pearl | Variety of pearl $CaCO_3$ | 2.6-2.78 | 1.1 | 2.6 | 4.1 | Y |
| 112 | Grossular Garnet | $Ca_3Al_2Si_3O_{12}$ | 3.4-3.71 | 1.3 | 3.3 | 5.3 | Y |
| 161 | Microcline | $KAlSi_3O_8$ | 2.54-2.58 | 1.0 | 2.4 | 3.8 | Y |
| 184 | Padparasdscha Saphire | $Al_2O_3$ + Fe, Ti, Cr, $Al_2O_3$ + Fe, Ti, Cr | 3.99-4.0 | 1.5 | 3.7 | 6.0 | Y |
| 191 | PEARL | $CaCO_3$ | 2.6-2.78 | 1.1 | 2.8 | 4.2 | Y |
| 217 | Quartz | $SiO_2$ | 2.65 | 1.1 | 2.6 | 4.1 | Y |
| 225 | Rose quartz | $SiO_2$ | 2.65 | 1.1 | 2.6 | 4.1 | Y |
| 226 | Rubellite | $Na(Li, Al)_3Al_6B_3Si_6$ $O_{27}$ $(OH)_3(OH, F)$ | 3.01 3.06 | 1.2 | 2.9 | 4.5 | Y |
| 229 | Salt water Pearl | $CaCO_3$ | 2.61-2.78 | 1.1 | 2.6 | 4.1 | Y |
| 232 | Sapphire | $Al_2O_3$ + Fe, Ti, Cr | 3.99-4.1 | 1.5 | 3.7 | 6.0 | Y |
| 235 | Scapolite | $3Na(AlSi_3)O_8.NaCl$<br>$3Ca(Al_2Si_2)O_8.CaCO_3$ | 2.5-2.8 | 1.1 | 2.6 | 4.1 | Y |
| 251 | Sodalite | $Na_4Al_3(SiO_4)_3Cl$ | 2.14-2.40 | 1.0 | 2.3 | 3.5 | Y |
| 259 | Star Sapphire | $Al_2O_3$ + Fe, Ti, Cr (sapphire) | 3.99-4.1 | 1.5 | 3.7 | 6.0 | Y |
| 277 | TOPAZ | $Al_2SiO_4(F, OH)_2$ +Cr | 3.50-3.57 | 1.3 | 3.3 | 5.3 | Y |
| 278 | Touramaline | $Na(Fe_3)Al_6(Si_6\ O_{18})$ $(BO_3)_3O_3$ F | 2.82-3.9 | 1.2 | 2.9 | 4.5 | Y |

Table 35.12: Gemstone Density Data for Radiation Coloration.

| No. | Name | Density (g/cc) | No. | Name | Density (g/cc) |
|---|---|---|---|---|---|
| 32 | Beryl | 2.6-2.9 | 103 | Fluorite | 3.18 |
| 63 | Chrysoberyl | 3.68-3.80 | 104 | Fresh Water Pearl | 2.6-2.78 |
| 98 | Euclase | 2.99-3.10 | 112 | Grossular Garnet | 3.4-3.71 |
| 116 | Heliodor | 2.68-2.72 | 161 | Microcline | 2.54-2.58 |
| 170 | Morganite | 2.71-2.90 | 184 | Padparasdscha Saphire | 3.99-4.0 |
| 199 | Phenakite | 2.97 | 191 | PEARL | 2.6-2.78 |
| 221 | Rhodizite | 3.44 | 217 | Quartz | 2.65 |
| 10 | Amblygonite | 2.98-3.11 | 225 | Rose quartz | 2.65 |
| 257 | Spodumene | 3.0-3.21 | 226 | Rubellite | 3.01 3.06 |
| 8 | Amazonite | 2.54-2.63 | 229 | Salt water Pearl | 2.61-2.78 |
| 20 | Anhydrite (Angelite) | 2.90-2.98 | 232 | Sapphire | 3.99-4.1 |
| 23 | Apophyllite | 2.3-2.5 | 235 | Scapolite | 2.5-2.8 |
| 52 | Celestite | 3.97-4.0 | 251 | Sodalite | 2.14-2.40 |
| 76 | Corundum | 3.99-4.1 | 259 | Star Sapphire | 3.99-4.1 |
| 85 | Diamond | 3.515 | 277 | TOPAZ | 3.50-3.57 |
| 101 | Feldspar | 2.54-2.77 | 278 | Touramaline | 2.82-3.9 |

Table 35.13: Beam Energy Necessary for Different Density of Gemstones.

| Density (g/cc) | Energy (MeV) at depths | | | |
|---|---|---|---|---|
| | Surface, 1 mm | Depth, 3 mm | Depth, 5 mm | Depth, 10 mm |
| 1.5 | 0.75 | 1.6 | 2.4 | 4.5 |
| 2 | 0.9 | 2 | 3.1 | 5.9 |
| 2.5 | 1 | 2.4 | 3.8 | 7.3 |
| 3 | 1.2 | 2.9 | 4.5 | 8.8 |
| 3.5 | 1.3 | 3.3 | 5.3 | 10.1 |
| 4 | 1.5 | 3.7 | 6 | 11.5 |
| 4.5 | 1.6 | 4.1 | 6.6 | 10+ |
| 5 | 1.7 | 4.5 | 7.3 | 10+ |
| 5.5 | 1.9 | 5 | 8 | 10+ |
| 6 | 2 | 5.4 | 8.7 | 10+ |
| 6.5 | 2.2 | 5.8 | 9.4 | 10+ |
| 7 | 2.3 | 6.2 | 10 | 10+ |
| 7.5 | 2.4 | 6.6 | 10.0+ | 10+ |
| 8 | 2.6 | 7 | 10.0+ | 10+ |

10 MeV, 3 kW Beam at EBC will produce $2.3 \times 10^8$ n $s^{-1}$

For Li, 10 MeV, 1 kW Beam will produce $1.78\ (7.5) \times 10^7$ n $s^{-1} = 1.3 \times 10^8$ n $s^{-1}$
10 MeV, 3 kW Beam at EBC will produce $3.9 \times 10^8$ n $s^{-1}$

Refer to IAEA Technical Report Series 188, Eqn 22 p-65 [166], D is given by:
Dose Rate $D = 1.4 \times 10^{-4} \times \varphi$, where $\varphi$ is in n.cm$^{-2}$.s$^{-1}$
Refer to Table XI p. 62, $\varphi$ at 1 MeV = 8.5 n.cm$^{-2}$.s$^{-1}$ per mRem.hr$^{-1}$
Beam Area = 100 cm × 10 cm = 1000 cm$^2$

For Be, Neutron Yield for 10 MeV, 1 kW = $(7.5 \times 10^7)/1000 = 7.5 \times 10^4$ n $s^{-1}$ cm$^{-2}$

Neutron Yield for 10 MeV, 3 kW = $2.25 \times 10^5$ n $s^{-1}$ $cm^{-2}$
For Li, Neutron Yield for 10 MeV, 1 kW = $(1.3 \times 10^8)/1000 = 1.3 \times 10^5$ n $s^{-1}$ $cm^{-2}$
Neutron Yield for10 MeV, 3 kW = $3.39 \times 10^5$ n $s^{-1}$ $cm^{-2}$
Using the Dose Rate Equation, above,

For Be, Dose Rate for 10 MeV, 1 kW = $7.5 \times 10^4 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 90 mR/hr
Dose Rate for10 MeV, 3 kW = $2.25 \times 10^4 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 270 mR/hr
For Li, Dose Rate for 10 MeV, 1 kW = $1.3 \times 10^5 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 160 mR/hr
Dose Rate for10 MeV, 3 kW = $3.9 \times 10^5 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr =480 mR/hr

b) **Estimation of Quarantine Time [166]:**

No moderators are used to thermalize neutrons in the gem coloration process. Therefore, neutrons produced are fast and they are free neutrons. Free neutrons decay with a Half-life of 10.2 minutes. Therefore, a number of half-lives should elapse before neutron activity comes below the safe level of 0.1 mR/hr.
For Be, Dose Rate for 10 MeV, 1 kW = $7.5 \times 10^4 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 90 mR/hr
Dose Rate for10 MeV, 3 kW = $2.25 \times 10^4 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 270 mR/hr
For Li, Dose Rate for 10 MeV, 1 kW = $1.3 \times 10^5 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 160 mR/hr
Dose Rate for10 MeV, 3 kW = $3.9 \times 10^5 \times 1.4 \times 10^{-4} \times 8.5$ mR/hr = 480 mR/hr
Estimation of Quarantine Time is basically calculation of number of Half Life required to bring the activity to safe level.
For Be, 1 kW beam requires 9 Half Lives = 92 minutes
For Li, 1 kW beam requires 10 Half Lives = 102 minutes
For Be, 10 kW beam requires 12/13 Half Lives = 125 minutes
For Li, 10 kW beam requires 13 Half Lives = 135 minutes
Neutron Dose and Quarantine Time for different Beam Powers are listed in table 35.14.

Table 35.14: Neutron Dose and Quarantine Time for different Beam Power

| **10 MeV Beam with Power (kW)** | **Gem Family - Be (Li)** | **Neutron Yield for Be/Li** ($\times 10^8$ n/sec) | **Dose (mR)** | **No. of Half-lives** | **Quarantine Time (min)**[a] |
|---|---|---|---|---|---|
| 1 | Be | 0.75 | 90 | 9 | 92 |
| | Li | 1.3 | 160 | 10 | 102 |
| 3 | Be | 2.25 | 270 | 10 | 102 |
| | Li | 3.9 | 480 | 11 | 112 |
| 10 | Be | 7.5 | 900 | 12 | 125 |
| | Li | 13 | 1600 | 13 | 135 |
| 20 | Be | 15 | 1800 | 13 | 135 |
| | Li | 26 | 3200 | 14 | 150 |

[a] Quarantine Time is estimated based on Beam Area = 1000 $cm^2$; Actual Covered area is ~150 $cm^2$ which reduces time by ~30 min; For 3 kW to 10 kW Beam, a time of 70 min to 100 min is considered adequate.

## 35.9 Results and Conclusions

Results of this study can be summarized as follows:

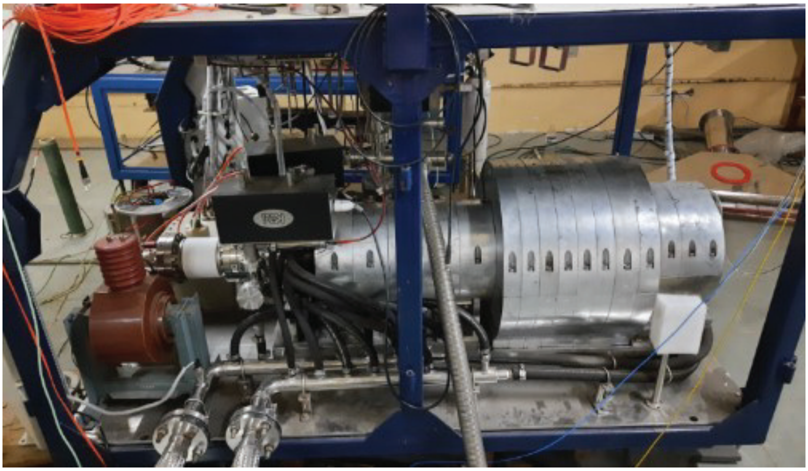

Figure 35.6: Cargo Scanner 6/4 MeV Linac.

i. Be and Li containing varieties only can produce neutron radioactivity. Hence out of 32 varieties, 9 varieties containing Be and Li need to be evaluated for radioactivity.

ii. Surface Irradiation (up to 1 mm): Beam Energy required is between 1 MeV to 1.5 MeV. Since this energy is below the threshold for any neutron producing reaction, no radioactivity is produced for any of the 32 varieties. Hence no quarantine is necessary for any of the gem variety.

iii. Bulk Irradiation (up to 5 mm): Beam Energy required is between 4 MeV to 6 MeV. 5 mm+ (up to 12 mm) can be processed by double side irradiation. Short lived neutron activity can be produced with 9 varieties containing Be and Li. Estimated Quarantine time of 70 to 100 minutes (max) may be needed.

iv. Remaining 23 varieties do not produce any activity and hence no quarantine is necessary.

v. Since most of the gemstones up to 5 mm (single sided and up to 12 mm (double sided) can be processed at 6 MeV, it is suggested to set up a 6 MeV, 1-3 kW Electron Linac by a consortium of Gem manufacturers or by Indian gem Society to cater to need of its members. Electron Beam Center of BARC can develop this 6 MeV Linac based on the Cargo Scanning 6/4 MeV dual energy Linac (shown in Fig. 35.6) already developed.

vi. Cooling of the Gemstones while irradiation is ON is very essential. It is suggested to employ Liquid Nitrogen cooled Gemstone support structure. This can be developed at very nominal cost.

vii. AERB should be approached for any radiation related issues and necessary permissions should be obtained by presenting all relevant data.