Chapter 17

Titanium Foil Exit Window for Electron Beam Accelerators

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17.1 Introduction

Accelerators which produce electrons of energies from few hundreds keV to a few MeV are extensively in use for industrial and medical applications [86, 87]. 1 MeV DC and 10 MeV RF accelerators with a beam power upto 100 kW are being planned in BARC for waste water treatment and other industrial applications. In such accelerator, the electron beam usually comes out into atmospheric air through a window. This electron beam exit window is made with thin foil of typical materials such as stainless steel, beryllium, aluminum, titanium and its alloys which has a thickness in range of 10-100 μm. It is a critical part of beam-line and most fragile part of vacuum system. The window can be failed due to sputtering away of material by continuously exposure with radiation and corrosion on foil due to abnormal ambient conditions. When beam passes the window it excites the atoms of window and a part of energy is transferred into the window material. The foil window should have minimum thickness, a low mass density, and high strength to weight ratio, large creep strength, excellent transparency & permeability for large kinetic energy electrons due to its Z-properties [88]. It also should provide sufficient mechanical performance to take care of static differential pressure and occasional pressure cycling when vacuum system is vented for maintenance.

A planer scanning system is used to scan the beam for uniform distribution of electron beam on foil exit window. An air blower for forced convection on foil window is used to flow air with some velocity, tangential to bent concave surface of foil to provide efficient cooling to foil. To find out temperature profile on surface of foil in steady state during operation of accelerator, thermal analysis with conduction, radiation & forced convection at different air velocity, heat transfer mechanisms are taken into consideration [89, 90]. In structural analysis stresses come due to air pressure difference across the foil & temperature rise on foil surface are considered as a load. Deformation & maximum stress are calculated in foil by Ansys FEM methods. The knowledge of stress & deformation in foil is essential for avoiding of breakdown of foil during operation condition of accelerators. The breakdown of foil window can cause cathode (LaB_6) poisoning in electron gun by allowing air particles to enter in the beam cavity which ultimately damages the performance of accelerator.

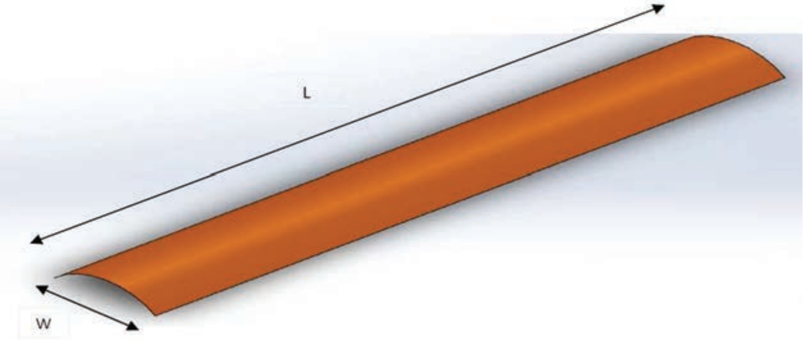

Figure 17.1: Geometry and Shape of Ti foil.

17.2 Geometrical Design and Material of Foil

The shape of foil should be bent as part of a cylinder as shown in Fig. 17.1 to increase the effective surface area for increasing mechanical strength & permitted temperature of foil for the bombardment of electrons which comes in direct contact of electron beam having high average power. The selected material of window should have a low atomic number due to desirable Z-properties, low mass density to reduce its interaction with beam, maximum diffusivity which increases heat transfer from source to sink and high mechanical reliability [91]. Beryllium has many desirable properties but it is toxic and if it fails, it contaminates the entire beam-line. Its cleanup costs can be significantly very high [92]. Stainless steel which is very dense and aluminum cannot endure the differential pressure and energy deposition induced by beam passage due to their low mechanical reliability. Ti Grade 2 unalloyed is often used titanium quality in 10 MeV linac accelerators with perfect permeability for high energy electrons and easily deformable. It has moderate strength, excellent resistance to oxidation and corrosion at low temperature. However for 1 MeV energy DC accelerators with higher power there are few problems with windows due to large temperature on foil surface during operating condition of accelerators. Pure Ti is chemically active at elevated temperatures ($\geq$ 200 ℃) and will oxidize in air, resulting in formation of a scale & degraded mechanical strength. Hence the foil undergoes severe corrosion damage by reaction with atmospheric gases. To overcome this, Ti alloy called Ti_6Al_4V/Grade 5 has excellent thermo-mechanical properties at elevated temperature (upto 400 ℃) and considered for better choice of window material.

Table 17.1: Comparison of properties of different window materials.

Properties	**Be**	**SS**	**Al**	**Ti Grade 2**	**Ti Grade 5**
Density (g/cc)	1.844	8	2.670	4.500	4.500
Yield Strength (MPa)	240	215	7-11	345	882
Thermal Diffusivity (mm^2/s)	60.850	4.050	87.390	7.155	2.820
Thermal conductivity (W/mK)	216	16.200	210	17	6.700
Specific heat (J/g ℃)	1.925	0.500	0.900	0.528	0.526
Atomic number (Z)	4	26	13	22	22

Table 17.2: Size of Ti windows used in accelerators.

Accelerator Energy (MeV)	**Length of foil (L, mm)**	**Width of foil (W, mm)**	**Arc radius (R, mm)**
1	1500	100	66
10	1000	80	53

17.3 Cooling Mechanism and Heat Load on Foil

To estimate the current and energy losses of electron in accelerator window consisting of titanium foil, we have studied the calculation for energy loss of the electron beam in titanium window which gives tables of values of fractional power loss $[f_e(t_f)]$ for variable thickness of foil (t_f = 10-50 μm) for normally incident energies 0.1-3 MeV [88]. This study describes related empirical equations that can accurately reproduce experimental results. The geometrical condition in this study treated is the case of the beam normally incident on the exit window of beam.

Table 17.3: Values of fractional power loss $[f_e(t_f)]$ of electron beam in titanium sheets.

T$_0$ (MeV)	$f_e(t_f)$ (%)				
	$t_f = 10\ \mu m$	$t_f = 20\ \mu m$	$t_f = 30\ \mu m$	$t_f = 40\ \mu m$	$t_f = 50\ \mu m$
0.1	47.7	82.5	98.5	100.0	100.0
0.2	15.6	31.6	47.1	61.3	73.3
0.3	8.1	16.6	25.1	33.8	42.3
0.4	5.2	10.6	16.0	21.6	27.2
0.5	3.7	7.5	11.4	15.3	19.4
0.6	2.8	5.7	8.7	11.7	14.7
0.8	1.9	3.8	5.7	7.6	9.6
1.0	1.4	2.8	4.2	5.6	7.0
1.2	1.1	2.1	3.2	4.3	5.4
1.4	0.9	1.7	2.6	3.5	4.4
1.6	0.7	1.5	2.2	2.9	3.7
1.8	0.6	1.2	1.9	2.5	3.1
2.0	0.5	1.1	1.6	2.2	2.7
2.5	0.4	0.8	1.2	1.6	2.1
3.0	0.3	0.7	1.0	1.3	1.6

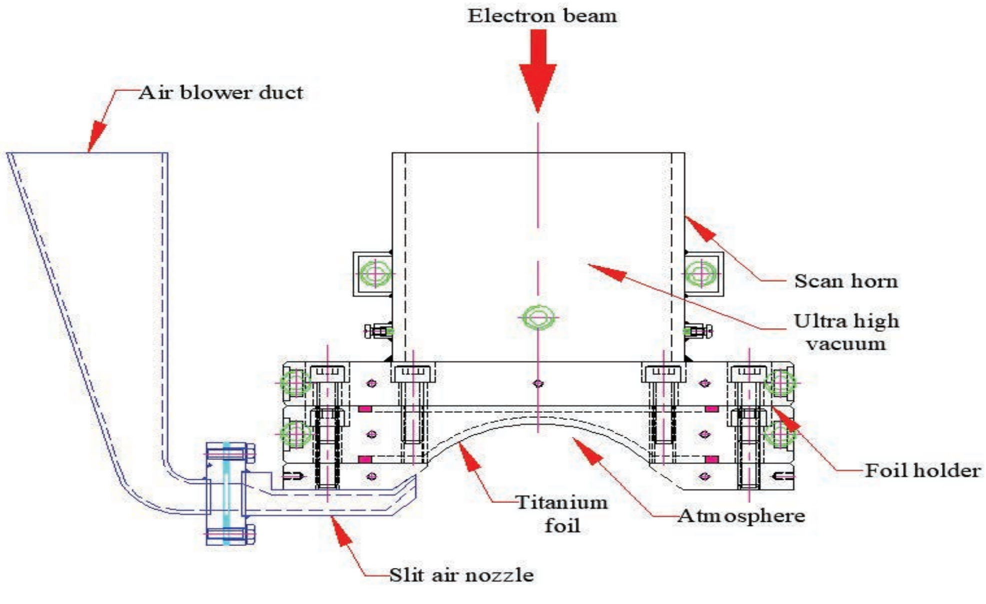

Figure 17.2: Cooling system for window foil.

17.4 Thermal and Structural Analysis

For the forced convection cooling, correlations given in Eqs. (17.1) & (17.2) are used where N$_u$ is Nusselt number, Re is Reynolds number and P$_r$ is Prandtl number.

$$N_u = 0.664 R_e^{0.5} P_r^{1/3}, \text{for laminar flow}, R_e < 500,000 \qquad (17.1)$$

$$N_u = 0.037 R_e^{0.8} P_r^{1/3}, \text{for turbulent flow}, R_e \geq 500,000 \tag{17.2}$$

Convection cooling,

$$Q_c = hA(T_f - T_0) \tag{17.3}$$

Generally in lower energy & higher power accelerators, the loss of electron beam power in Ti foil increases drastically which increases temperature of foil and thermal radiations are emitted from foil surface. To consider radiation Eq. (17.4) is used, where ϵ, T_f, T_0 & A are emissivity, foil temperature, ambient temperature and surface area of foil respectively.

$$Q_r = \epsilon \sigma_s A(T_f^4 - T_0^4) \tag{17.4}$$

Uniform distribution heat load in foil:

$$Q_d = f_e(t_f) \times P_b \tag{17.5}$$

where, P_b is beam power. The heat balance equation for heat transfer in steady state condition:

$$Q_d = Q_c + Q_r \tag{17.6}$$

To consider stresses in the foil it is considered as a long thin cylindrical pressure vessel with internal pressure. To calculate hoop stress (σ) due to air differential pressure (P) in the foil following mathematical equation is used:

$$\sigma = \frac{PR}{t_f} \tag{17.7}$$

17.5 Steady State Analysis of DC Accelerator Foil

In this study 1 MeV accelerator at different beam powers (25-100 kW) is taken for thermo-mechanical study of titanium foil in steady state. The power loss in Ti foil is considered as 7% of beam power as mentioned in table 17.3.

17.5.1 1 MeV, 25 kW

The Fig. 17.3 depicts the simulated result.

17.5.2 1 MeV, 50 kW

Figure 17.4 shows the simulated result.

17.5.3 1 MeV, 75 kW

The simulated result is shown in Fig. 17.5.

17.5.4 1 MeV, 100 kW

The result of simulation is shown in Fig. 17.6.

17.6 Steady State Analysis of RF Accelerator Foil

In this case 10 MeV accelerator at 20 kW beam power (Fig. 17.7) is taken for thermo-mechanical study of titanium foil in steady state. The power loss in Ti foil is considered as 1.6% of beam power for conservative side and equivalent to 3 MeV beam power loss as mentioned in table 17.3.

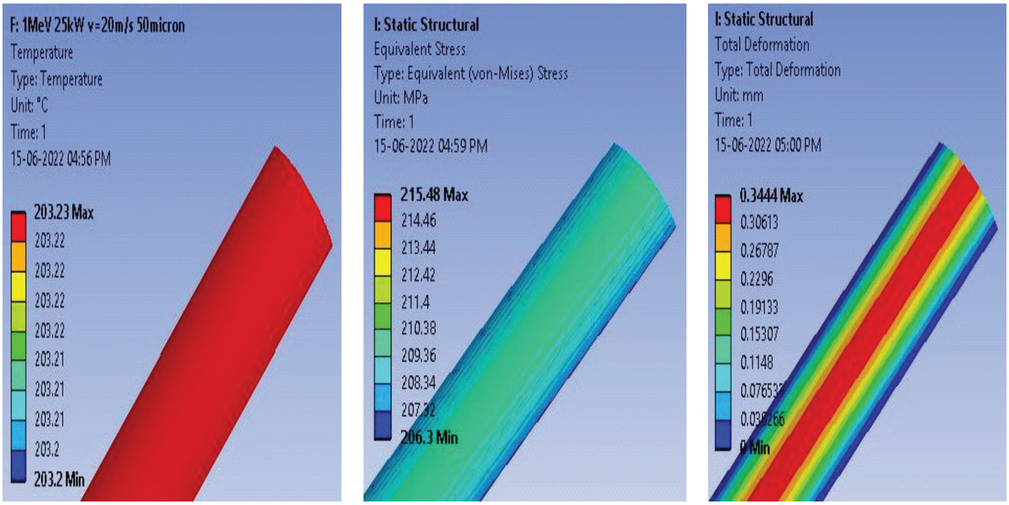

Figure 17.3: Temperature (L), stress (M) and deformation (R) profile for 25 kW beam at 20 m/s air speed.

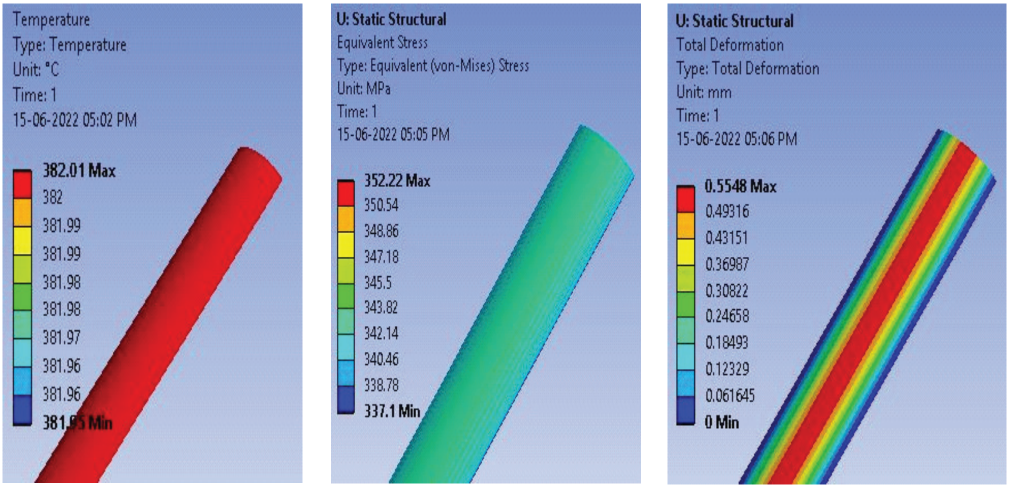

Figure 17.4: Temperature (L), stress (M) and deformation (R) profile for 50 kW beam at 15 m/s air speed.

17.7 Transient State Analysis for RF Accelerator Foil (Beam Scanning Failure)

In this case study 10 MeV accelerator at 20 kW beam power (Figs. 17.8, 17.9, and , 17.10) is taken for thermo-mechanical study of titanium foil in transient state when scan magnet stopped to work and electron beam strikes the foil at a fixed position. The heat flux (ϕ) is defined with radius (r) as a Gaussian profile [Eq. (17.8)] of beam in transient study.

$$\phi = Ke^{-cr^2} \tag{17.8}$$

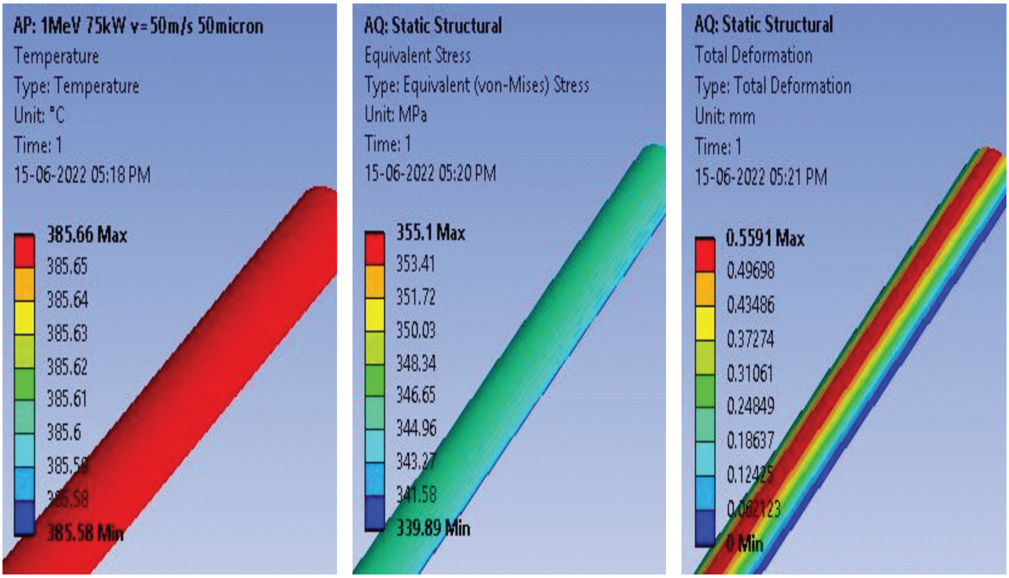

Figure 17.5: Temperature (L), stress (M) and deformation (R) profile for 75 kW beam at 50 m/s air speed.

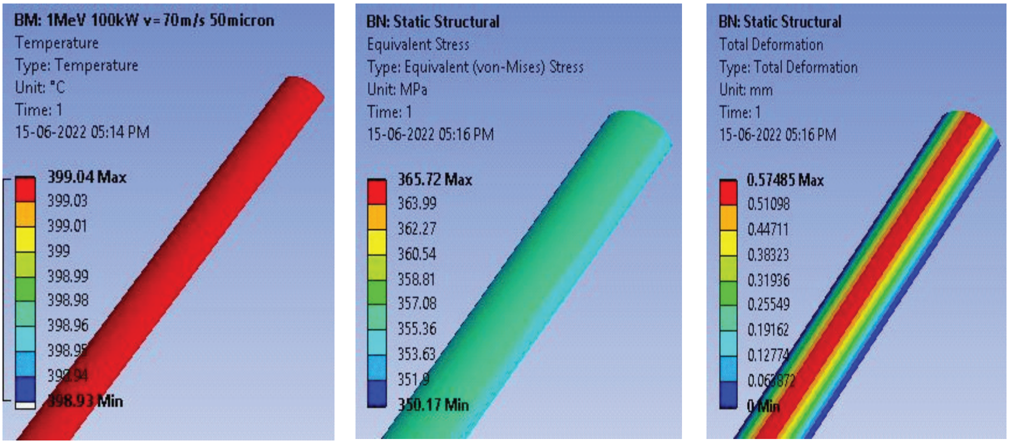

Figure 17.6: Temperature (L), stress (M) and deformation (R) profile for 100 kW beam at 70 m/s air speed.

The governing equation of heat balance in foil:

$$C_f \frac{dT_f}{dt} = Q_d - Q_c(t) - Q_r(t) - Q_t(t) \tag{17.9}$$

Heat deposition to the foil:

$$Q_d = (f_e(t_f)) \int_S \phi dA \tag{17.10}$$

Heat conduction in foil is governed by following equation:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial \phi}\right) + \frac{\partial^2 T}{\partial z^2} \tag{17.11}$$

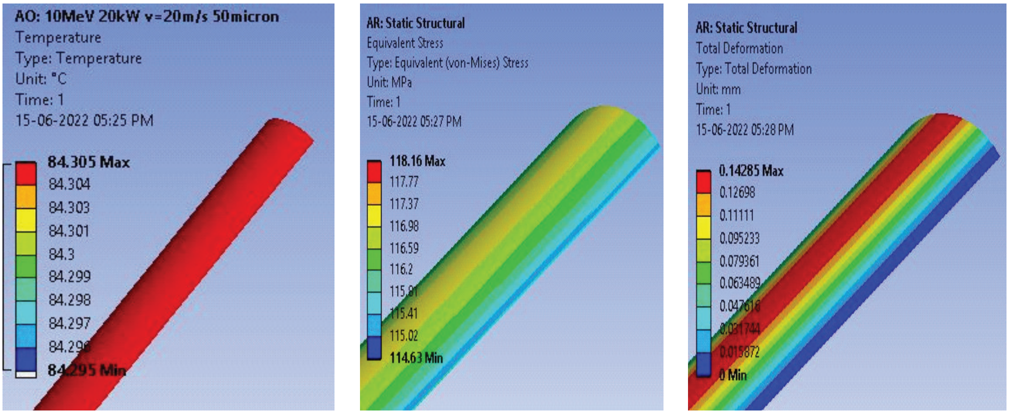

Figure 17.7: Temperature (L), stress (M) and deformation (R) profile for 20 kW beam at 20 m/s air speed.

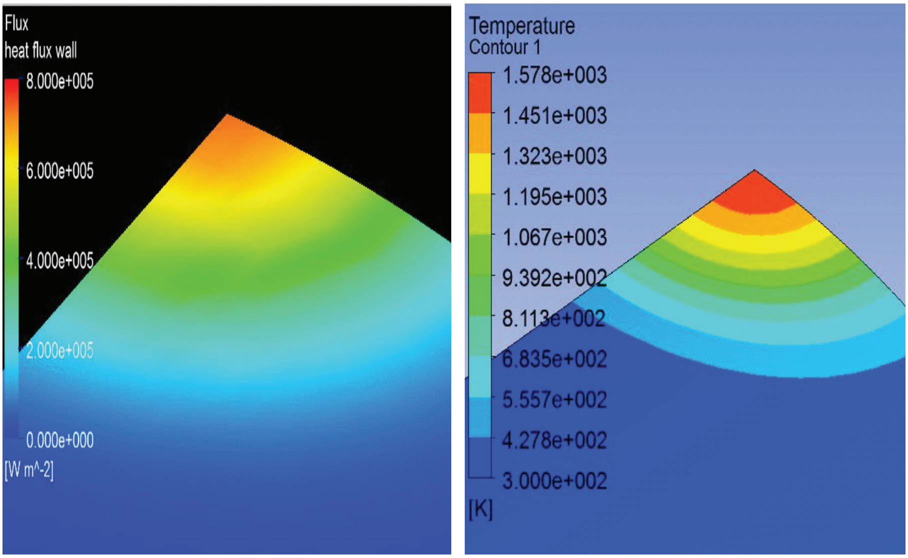

Figure 17.8: Heat flux (L), and temperature (R) profile for 20 kW beam at 20 m/s air speed (transient state).

17.8 Summary

This chapter gives a brief description of importance of exit foil window in DC and RF accelerators. For 1 MeV accelerator it is concluded that Ti Grade 2 foil can be used as an exit window up to 25 kW beam power when foil temperature is allowed up to 200 °C. For higher beam power ($\geq$ 25 kW), Ti Grade 5 foil should be used for 1 MeV beam when foil temperature is allowed up to 400 °C. In 10 MeV RF accelerator there is $\sim$1% of power loss in electron beam where as in 1 MeV accelerator it is $\sim$7% for the foil thickness of 50 μm.

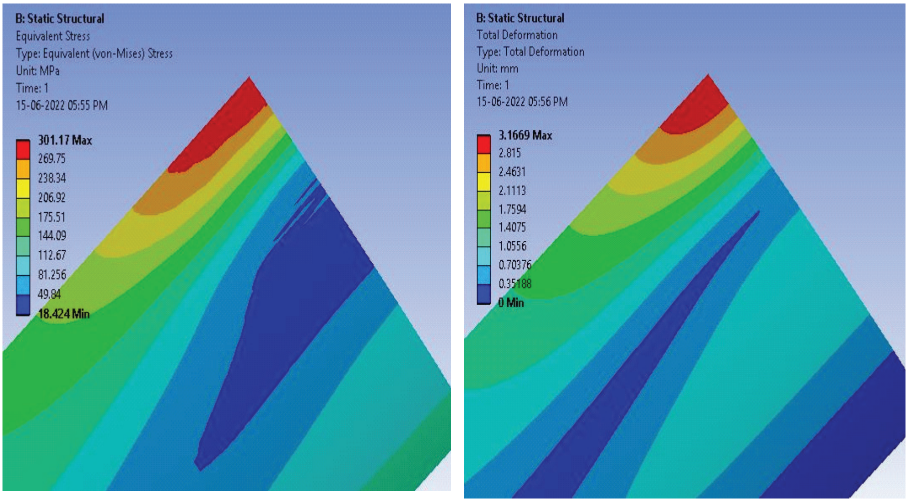

Figure 17.9: Stress (L), and deformation (R) profile for 20 kW beam at 20 m/s air speed (transient state).

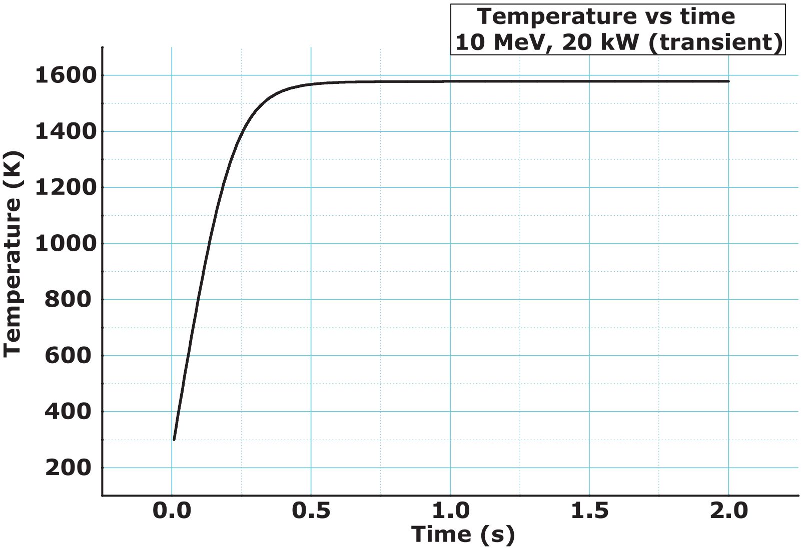

Figure 17.10: Variation of temperature of Ti foil with time in transient state for 10 MeV beam at 20 kW.

Ti grade 2 can be used as an exit window in 10 MeV accelerators for 20 kW beam power. From transient state study of 10 MeV energy accelerator when scan magnet stops to work and beam incidents at a fixed position it is observed that heat flux is very high in the order of 5 due to which temperatures rises drastically at a local position. The rise in temperature of foil in the range of 1000 °C is observed within 120 ms which can cause foil to be punctured. For the safety purpose of electron gun to stop its poisoning by air particles an electronic circuit should be incorporated in accelerator which can activate a trip of beam in less than 100 ms for ensuring safety of foil.