Design and Analysis of Steerable ECRH Launcher for SST-1 Tokamak

Hardik Mistry*, and *B K* Shukla

Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India -382428

Abstract. In the tokamaks ECRH system is used for pre-ionization, start up, heating, current drive and suppression of NTMs (Neo Classical Tearing Modes). A Standard ECRH system consists of high power microwave source Gyrotron, circular corrugated waveguide based transmission line and launcher. The Focused ECH power is launched into plasma through launcher. The microwave beam emerges out from circular corrugated waveguide and propagates freely in air with finite divergence. So focusing and plane mirror combination is used to launch focused beam in plasma. Thus an ECRH launcher consists of metallic profiled and plane mirror, UHV compatible vacuum barrier window and a UHV gate valve. One 42 GHz gyrotron capable of delivering 500 kW of power for 500 ms and other 82 GHz gyrotron capable of delivering 200 kW of power for 1000s are used for SST-1 ECRH system. The launcher design consists of mirror design, design of supports and design of steering mechanism to provide suitable movements with minimum backless error. The whole assembly is UHV compatible. The launcher is capable of steering the beams by ±20° in both toroidal and poloidal directions. Mirrors are given motion by means of one rotary and one linear feedthrough. For 82 GHz launcher active cooling is provided, whereas for 42 GHz launcher no active cooling is provided.

A detailed analysis is carried out for the mirrors of the high power launcher. The heat load for the 82 GHz launcher is 2 kW (~1% absorption) and for 42 GHz launcher it is 5 kW. For 82 GHz launcher, the maximum steady state surface temperatures of focusing and reflecting mirrors are 315K and 323K and von-mises stresses are within 10 MPa. Similarly for 42 GHz launcher maximum temperatures observed during 500 ms pulse are 301K and 303K for focusing and reflecting mirrors respectively. This paper explains the mechanical and thermal design and analysis of the launcher for the ECRH system.

1 Introduction

The ECRH offers the advantages of high coupling efficiency and fine control over power deposition. So, it is one of the attractive options for heating of tokamak plasma and it has been employed for many tokamaks. In SST-1, along with the ICRH (Ion Cyclotron Resonance Heating) and LHCD (Lower Hybrid Current Drive), the ECRH is used for pre-ionization, start up, heating and partially driving the current [1]. This system has two microwave sources, one 42 GHz gyrotron capable of providing 500 kW power for 500 ms and one 82 GHz gyrotrons capable of delivering 200 kW power for 1000s. This power is transmitted to tokamak through corrugated waveguide based transmission system which consists of matching optical unit (MOU), DC breaks, meter bends with bidirectional coupler, polarizer and vacuum window [2-3].

The microwave beam emerges out from the corrugated transmission line in TEM_{00} mode which has Gaussian profile and propagates in the vacuum with the finite divergence. In order to achieve desired beam radius at the plasma center, optimization is required. During the pulse, small part of the power (~ 1%) is absorbed by the mirror material and hence its temperature increases. In order to avoid the excessive heating of the mirror, the maximum temperature during the ECRH pulse has to be estimated and active cooling has to be provided as per the requirement.

2 Structure of the launcher

The launcher consists of two metallic profiled mirrors along with its support structure, steering mechanisms, UHV gate valves, vacuum barrier window and cooling arrangement. The mirror assembly of the launcher is shown in the figure 1.Two sets of focusing and reflecting (steering) mirrors are used for 42 and 82 GHz beams. The mirror assembly along with the cover plate is mounted on one equatorial port of the vacuum vessel. The focused beam then incidents on

* Corresponding author: hardik.mistry@ipr.res.in

the reflecting mirror (RM) which is parallel to the focusing mirror (FM). The RM steers the beam in two directions – poloidal and toroidal. The optimized dimensions of the focusing mirror for 42 GHz beam is 215 × 305 mm and for 82 GHz it is 125 × 175 mm.

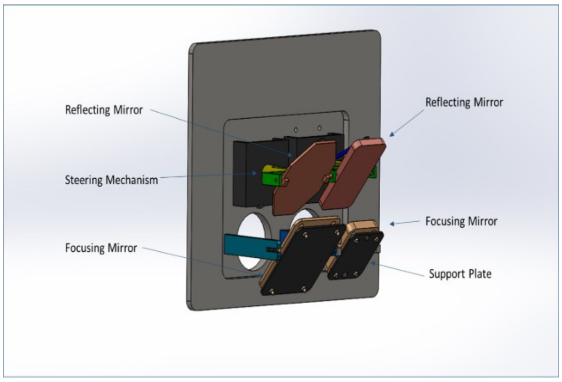

Fig 1. Model of the Launcher

The dimensions of the mirrors are optimized in such a way that more than 99% of the Gaussian beam power incidents on the mirror. Both the reflecting mirrors are connected to UHV compatible motion feedthroughs which facilitate the mirror to move along the poloidal and toroidal directions.

3 Beam optics and RF considerations

The HE_{11} wave when emerges out of the corrugated waveguide it travels in the free space with finite divergence and hence needs to be focused [4]. The beam emerging out of the waveguide has a Gaussian profile i.e. the intensity is maximum at the center and it falls rapidly as the distance from center increases. The intensity (I) and divergence (θ) of the beam can be written as

$$I = I_0 e^{-\left(\frac{x^2}{a_0^2}\right)} \quad (1)$$

and

$$\theta = \frac{1}{ka_0} \quad (2)$$

where,

I_o = peak intensity
x = radial distance
a_0 = beam radius at which intensity falls to its 1/e value
k = wave propagation vector.

The angle θ is the characteristic divergence of a Gaussian beam for the beam waist a_0. The divergence of a Gaussian beam transmitted in space is shown in the figure 3. The general expressions for the beam radius and the radius of the wave front are given by

$$a(z) = a_0 \sqrt{\left[\left(1+\frac{z}{R_o}\right)^2 + \left(\frac{z}{ka_o^2}\right)^2\right]} \quad (3)$$

and

$$R(z) = z \frac{1+\left(\frac{ka_0^2}{z}\right)^2\left(1+\frac{z}{R_0}\right)}{1+\left(\frac{ka_0^2}{z}\right)^2\left(\frac{z}{R_0}\right)\left(1+\frac{z}{R_0}\right)} \quad (4)$$

Where a_0 and R_0 are the beam radius and the radius of the incident wave front at z = 0.

The microwave beam emerging from the circular corrugated waveguide in the HE_{11} mode is Gaussian in nature. At the exit of the waveguide, the radius of the wave front $R_0=\infty$.

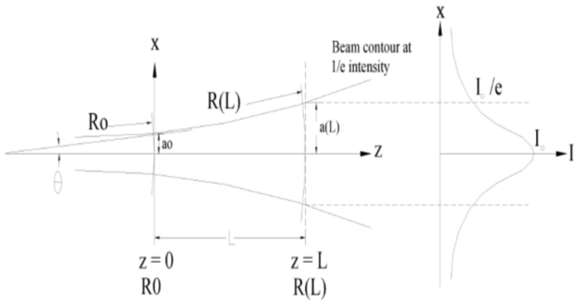

Fig 2. Beam divergence and intensity profile

The schematic diagram of the launcher system is shown in the Fig 3. Here, D_0 is the distance between waveguide end and focusing mirror, D_v is the vertical distance between two mirrors and D_p is the distance between reflecting mirror and plasma center. Here, axial distance between waveguide end and plasma center ($D_0 + D_p$) is fixed for the given layout. Positions of the mirrors can be varied within certain range. However, as the beam comes out of the waveguide it starts diverging.

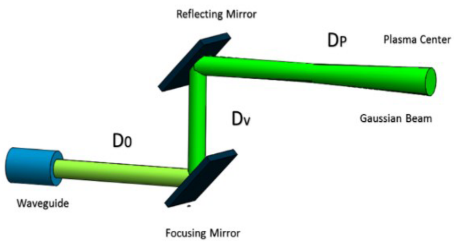

Fig 3. Schematic of Launcher system

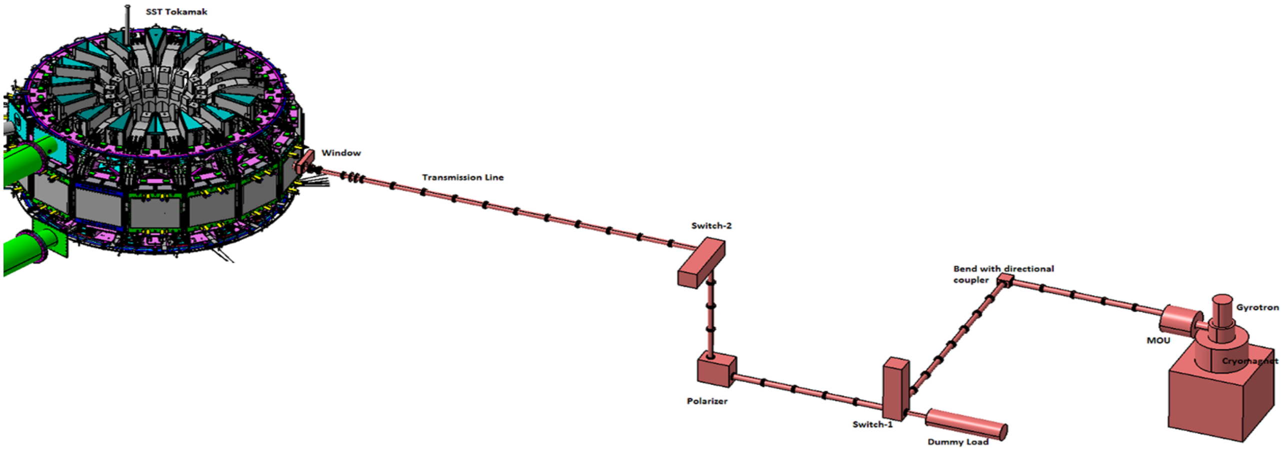

Fig 4. Present layout of ECRH system

So, if distance D_0 is increased the required mirror size will also increase. However, as the beam radius increases, the heat is dissipated on the larger area of mirror which reduces the heat flux for mirror. So, these dimensions can be optimized by proper selection of the parameters. The focal length f of the mirror can be calculated in terms of the radius of the curvature of the incident wavefront R and the reflected wavefront R', which is given in the following expression:

$$\frac{1}{f} = \frac{1}{R} - \frac{1}{R'} \quad (5)$$

In the launcher, the optimized beam radius at the plasma center is 25 mm for 42 GHz system and 20 mm for 82 GHz system. The focal length of the focusing mirrors are 0.41m and 0.54 m respectively.

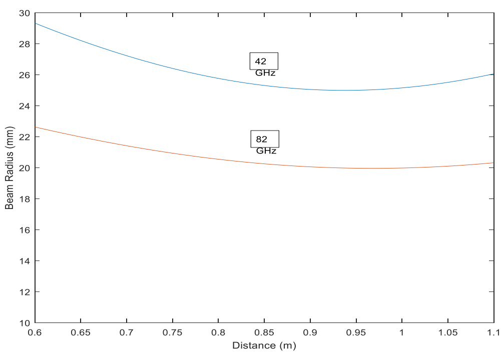

Fig 5. Calculated beam waists versus distance from focusing mirror

4 Thermal analysis and cooling scheme

For 42 GHz system which operates in pulsed mode mirrors are exposed to heat flux for short duration (500 ms). Hence no active cooling is required and heat can be dissipated in the thermal mass of the mirror material. However, it should be taken care that the temperature of the material does not reach near the melting point. So, transient thermal analysis is carried out for the mirrors. The maximum temperatures for 500 ms pulse are 301K and 303K for focusing and reflecting mirrors respectively. The temperature variation along with time for reflecting mirror is shown in the figure 6. However for 82 GHz system which can operate for 1000s, active cooling is mandatory. So, water flowing in the cavity absorbs the incident heat. The steady state thermal analysis is carried out for cavity like geometry for finding the distribution of temperatures on the mirror body in steady state.

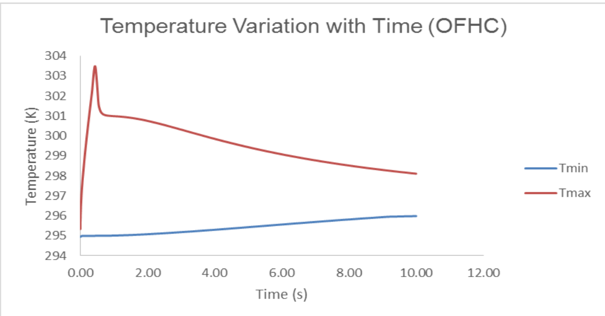

Fig 6. Variation of maximum and minimum temperature (K) of reflecting mirror with time (s)

The maximum steady state surface temperatures of focusing and reflecting mirrors with active cooling at flow rate of 6.8 liter per minute are 315K and 323K respectively. The contours for focusing mirror are shown in the figure 7.

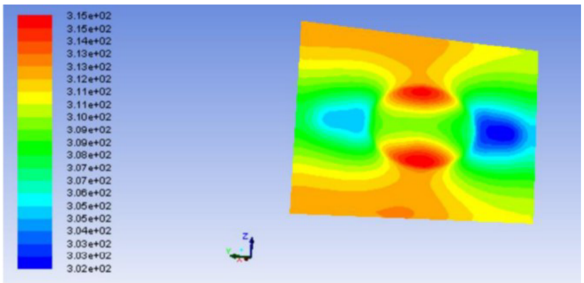

Fig 7. Contour of steady state surface temperature (K) of focusing mirror

5 Structural analysis

The main loads acting on the mirrors are internal fluid pressure, dead weight of the mirror, load due to thermal expansion and electromagnetic forces during plasma disruption. Among these, internal fluid pressure and dead weight are significant and they are applied simultaneously in static structural analysis. The maximum von mises stress is around 10 MPa and hence well below the fatigue strength limit of OFHC. The stress contour for focusing mirror of 82 GHz system is shown in figure 8.

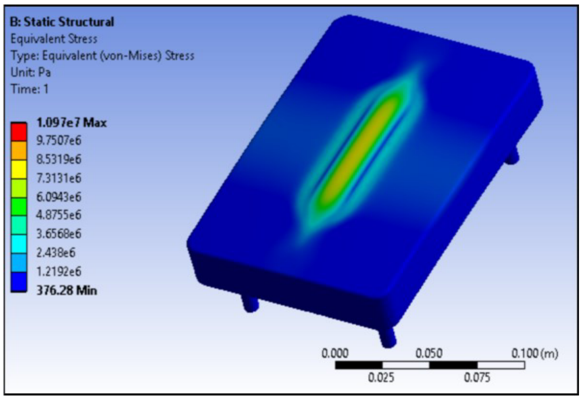

Fig 8. Von Mises stress (Pa) of focusing mirror

6 Conclusion

As per this design, the launcher consists of two focusing and two reflecting mirrors. The beam radii for 82 GHz and 42 GHz system at the resonance layer of plasma are 20 mm and 25 mm respectively. The thermal aspects of the launcher are studied and the maximum temperatures of focusing and reflecting mirrors with active cooling are 315K and 323K respectively for 82 GHz system. Since 42 GHz system is pulsed system, heat load is not critical for 500 ms operation. Hence design is able to withstand the thermal loads of SST-1 and it is safe. Similarly, to ensure the structural integrity the structural analysis is carried out considering the significant forces and design is found safe.

Further study is being carried out on the dynamic aspects of the system and optimization of the various parameters to reduce the response time of the mirror.

References

1. D. Bora, K. Sathyanarayana, B.K.Shukla et. al., Nucl. Fusion **46**, 3 (2006) pS72 - S84
2. D. Bora, K. Sathyanarayana, B. K. Shukla, P. Chattopadhyay, Y S S Srinivas, et al., Journal of Physics **25**, 1 (2005) p96-102
3. B. K. Shukla, P. Patel, J. Patel, R. Babu et. al., IEEE trans. on plasma sci., **vol. 43**, no. 1, (2015) p 485-488
4. B. K. Shukla, K. Sathyanarayana, P. Biswas et. al., Fusion Sci. and Tech., **v. 45(4)**, (2004) p. 549-55