Chapter 4

Remote Steering (RS) Launcher

4.1 Introduction to RS Launcher: In the tokamak, Electron cyclotron resonance heating (ECRH) is used to carry out breakdown start-up, heating and current drive experiments. The Electron cyclotron current drive (ECCD) have shown enormous importance in tokamak plasma like non-inductive heating, current drive [45,46] and suppression of neo-classical tearing mode [47,48] etc.. The ECCD is achieved by steering the microwave beam in in plasma. The ECCD along plasma current is called co-drive while opposite to plasma current it is counter ECCD. In conventional ECRH launcher, current drive is achieved by injection of the beam with a parallel k-component with respect to the magnetic field, which is usually performed by rotating the mirrors inside the tokamak. The mirrors movement inside ultra-high vacuum (UHV) machine close to plasma is a difficult task especially for long pulse operation when mirrors are actively cooled. The repair task of launcher is also difficult for mirrors kept inside the tokamak. An alternate to conventional ECRH launcher could be square/rectangular-corrugated waveguide [49] with a steering mechanism placed at remote end of waveguide (far from plasma).

The SCW shows image characteristic at a particular length. For a length of square corrugated waveguide (SCW) equal to $8a^2/\lambda$, the beam would emerge out at same angle as input. Where ‘a’ is cross section of waveguide and λ is wavelength of microwave. In such a case the mirror assembly can be kept away from the tokamak port. The beam exiting from the mirror launcher is used as input to the square corrugated waveguide. The output beam from the waveguide would emerge out at same input angle. Hence remote steering of the microwave beam could be achieved and the key issue of repair of launcher can be made easy as steering mirrors are placed far from the tokamak.

Theoretical and experimental work has already been carried out for remote steering launcher [49-54] for ECRH. High power test on remote steering antenna [55] has been already carried out and very encouraging results have been cited in the literature.A prototype of remote steering beam launcher with square corrugated waveguide (SCW) is made to study the behavior of remote steering launcher for Steady state Superconducting tokamak (SST-1). The frequency of SST-1 ECRH system is 82.6 GHz. The transmission line is terminated with circular corrugated waveguide of 63.5 mm diameter. Based on the dimension of circular waveguide and microwave frequency, a square corrugated waveguide based RS launcher is fabricated and experiments on remote steering launcher are carried out with low power microwave source.

4.2. Theory of RS Launcher:

Remote steering using square/rectangular corrugated waveguide is based on Talbot effect [49,50,56], which is discussed already in detail in references [49-55]. The theory of Talbot effect can be explained in short as follows:

The propagation constant $k_{(m,1)}$ for *HE (m,1)* mode in a square corrugated waveguide can be written as:

$$k_{m,1} = k_o \sqrt{1 - \left(\frac{m\lambda}{2a}\right)^2 - \left(\frac{\lambda}{2a}\right)^2} \qquad (4.1)$$

Where *k0* is propagation vector in free space and *a* is dimension of waveguide. If a beam is injected into the waveguide, a spectrum of waveguide modes is excited and at the exit of waveguide the output mode could be *(n,1)*. The phase difference Δψbetween two modes *(m,1)* and *(n,1)* after traveling a distance *L* in the waveguide can be written as:

$$\Delta\psi_{(m1,n1)} = L\Delta k = L(k_{m,1} - k_{n,1}) \qquad (4.2)$$

$$\Delta\psi_{(m1,n1)} \approx Lk_0 \frac{\lambda^2}{8a^2}(n^2 - m^2) \qquad (4.3)$$

$$\Delta\psi_{(m1,n1)} = L \times 2\pi \times \frac{\lambda}{8a^2}\left(n^2 - m^2\right) \qquad (4.4)$$

In order to get a replica of the input field at the exit of waveguide, the phase difference between any waveguide modes should be multiple of *2π*.

If we put $L = L_0 = 8a^2/\lambda$., the equation (4) will be simplified to:

$$\Delta\psi_{(m1,n1)} = 2\pi\left(n^2 - m^2\right) \qquad (4.5)$$

Thus at the length $8a^2/\lambda$, the phase difference between any two modes is integral multiple of 2π. It means the wave will emerge out at the same phase to the input of waveguide. Thus we get exact replica of input field i.e. if beam incidents at an angle φ to the waveguide, it would emerge out at same angle φ, which is symmetric beam steering.

If the length of the waveguide is equal to $L_0/2$ i.e. $4a^2/\lambda$, the phase difference between input and output beam, would be π, which means anti-symmetric beam steering and the beam emerges out at $-\varphi$ angle. The benefit of anti-symmetric steering is the reduced length of the waveguide. Symmetric and anti-symmetric steering of the beam is shown in figure 4.1.

Thus square corrugated waveguide alongwith steering mirror can be used as remote steering launcher for ECRH system. The length of RS launchers ($8a^2/\lambda$ and $4a^2/\lambda$) is more for higher frequency and space is always a problem to accommodate such long RS launcher. This drawback can be further minimized by reducing length to half ($2a^2/\lambda$), and use an additional reflector at the exit of RS launcher. This launcher at $2a^2/\lambda$ length would be more advantageous, where space is not adequate to accommodate the launcher of length $8a^2/\lambda$ or $4a^2/\lambda$. Although experiment shows some limitation to this launcher as it is less efficient at smaller angle. The power cannot be diverted by the mirror at smaller angle as grazing angle of the beam is almost parallel to mirror or bigger size of plane mirror is needed, which would be not required for steering at higher angle.

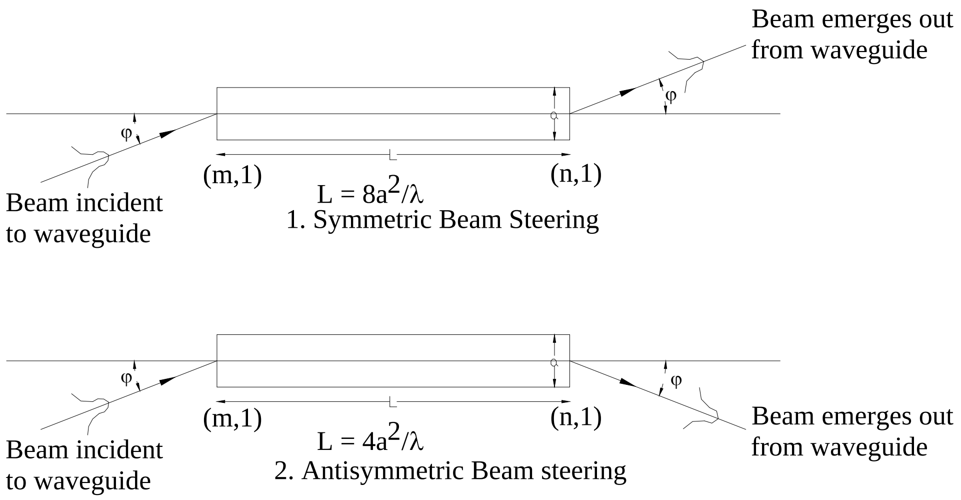

Figure 4.1 Symmetric and anti-symmetric Beam steering with square corrugated waveguide

It is also seen that if we reduce further the length of the waveguide i.e. $2a^2/\lambda$, the waveguide can be used as beam splitter[8] which is angle controllable. In this paper, this is observed experimentally in a low power experiment. The waveguide launcher with the length of

*$2a^2/$*ªcan also be used for remote steering by introducing a plane reflector at the exit of waveguide figure 4.2. This will reflect the remaining half part of the beam at the same angle and thus both the lobes of output beam from waveguide will be in one direction. The reflected beam will have a phase change, which can be written as:

$$(2\pi a \sin\alpha) / \lambda \qquad (4.6)$$

Thus the resultant beam would be interference of two beams and resultant steered beam would be in one direction with RS launcher at *$2a^2/$*ªand a plane mirror. A prototype experiment is carried out to verify the scheme of RS launcher at *$2a^2/$*ªand it is seen that at higher angle the entire power is reflected in only one direction and main peak in power appears at same angle to input of RS launcher.

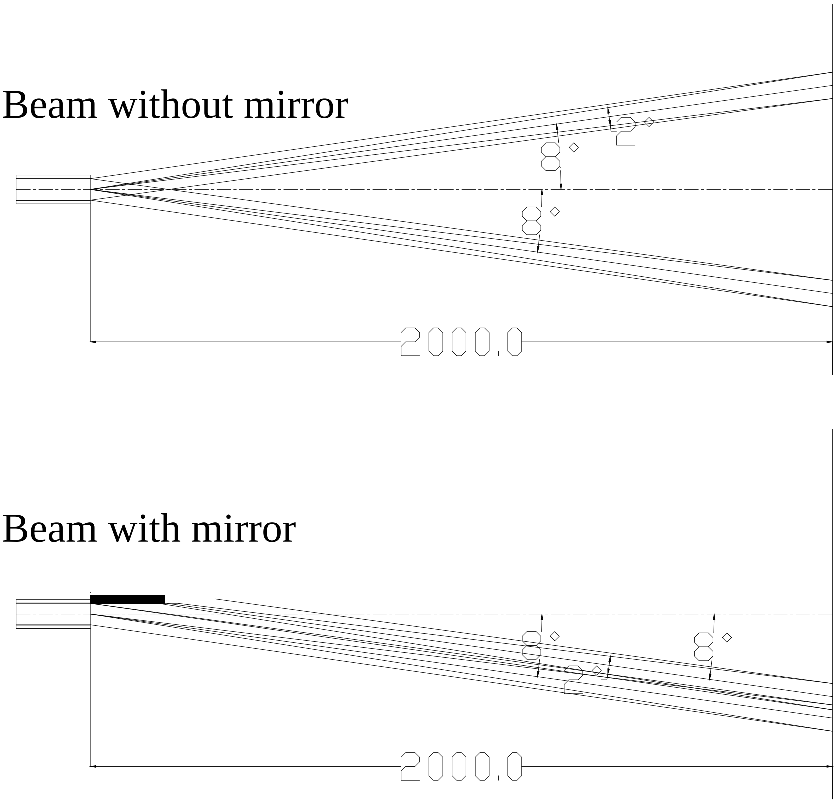

Figure 4.2 Microwave beam with and without mirror at a length of *$2a^2/$*ª

4.3 Experimental Set-up for RS Launcher

A low power microwave experiment is carried out to see the steering effect with square corrugated waveguide at a length of $2a^2/\lambda$ along with a fixed plane reflector. Experimental setup consists of a microwave source, attenuator, mode converter, square corrugated waveguide and microwave detector with horn antenna. The microwave source, isolator, attenuator and mode converter is mounted on a single platform, pivoted at the mouth of the SCW. This entire assembly is rotated about the pivot to change the input angle to the SCW.The schematic of the experimental set-up is shown in figure 4.3.

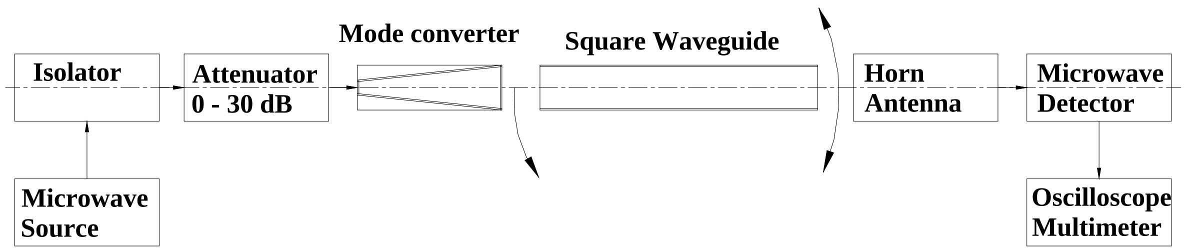

Figure 4.3 Block diagram for low power experiment with square corrugated waveguide

4.3.1 Microwave source: A Gunn oscillator, which delivers ~40mW (maximum) power at 82.6 GHz frequency is used as a microwave source. The output of the microwave source is TE_{10} mode, which is compatible for WR-12 waveguide. An isolator with built in load and a variable attenuator (0 dB to 30 dB) are used in microwave circuitry.

A HE_{11} mode converter is used to convert this rectangular TE_{10} mode to circular Gaussian beam of HE_{11} mode. The input of the mode converter is WR-12 connection in TE_{10} mode while output is ∅63.5mm corrugated waveguide.

4.3.2 Square Corrugated Waveguide: The waveguide size, for optimum coupling of a HE_{11} mode between a circular waveguide of radius R and width a of square waveguide is given as [52] :

$$a = \frac{2^{1/2} R\pi}{\chi_{01}} = 1.848R \qquad (4.7)$$

Where ¡$_{01}$ is first root of field function J_0. Thus for 63.5mm diameter waveguide, the cross section of square waveguide is taken 58mm x 58mm. The length of the waveguide is 1850mm. Two sides (top and bottom) of the waveguide are corrugated while other two are plane. All four side corrugated waveguide can also be used for same RS launcher. The HE_{11} mode is close to plane polarized with *Ey* and *Hx* as the main dominating field components. The *Ey* component interacts with top and bottom corrugated sides of square corrugated waveguides for propagation of microwave beam. Thus side plates does not matter too much whether it is plane or corrugated. The depth and period of corrugation of the waveguide are 0.9mm and 1.3mm respectively. The geometrical view of rectangular waveguide is highlighted in fig.4. The waveguide is fabricated in-house. Four plane sheets of aluminium (two corrugated and two plane) are screwed together to construct a square waveguide Figure 4.5. The dimension (length) of fixed plane reflector can be optimized with ordinary ray optics and the width can be calculated as a divergence of gaussian beam. The size of reflector (200mm x 150mm) is dimensioned to reflect the incident beam over a steering range from 6^0 to 18^0.

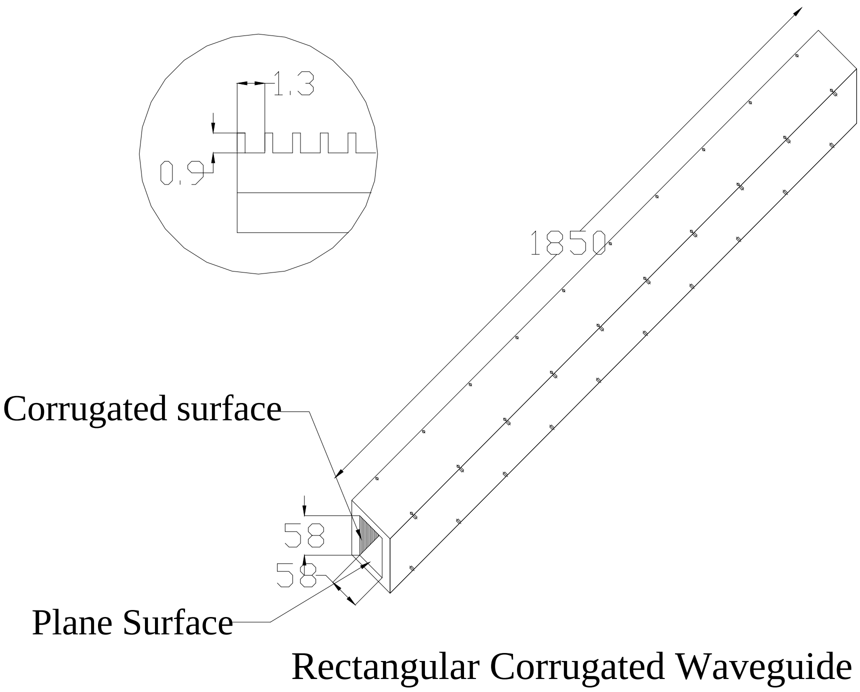

Figure 4.4 Square corrugated waveguide as a RS Launcher

Figure 4.5 Square corrugated waveguide

4.3.3 Microwave Detector with horn:A calibrated microwave detector is used for the power detection. Frequency range of this detector is 80-90 GHz with a central frequency of 82.6 GHz. This detector is compatible to WR-12 waveguide. The maximum continuous power to the detector should be less than 40 mW. The sensitivity of the detector is ~500 mV/mW. A horn antenna is used to enhance the signal level of the microwave. Photograph of the experimental set-up with Gunn oscillator and mode converter is highlighted in Figure 4.5 and 4.6.

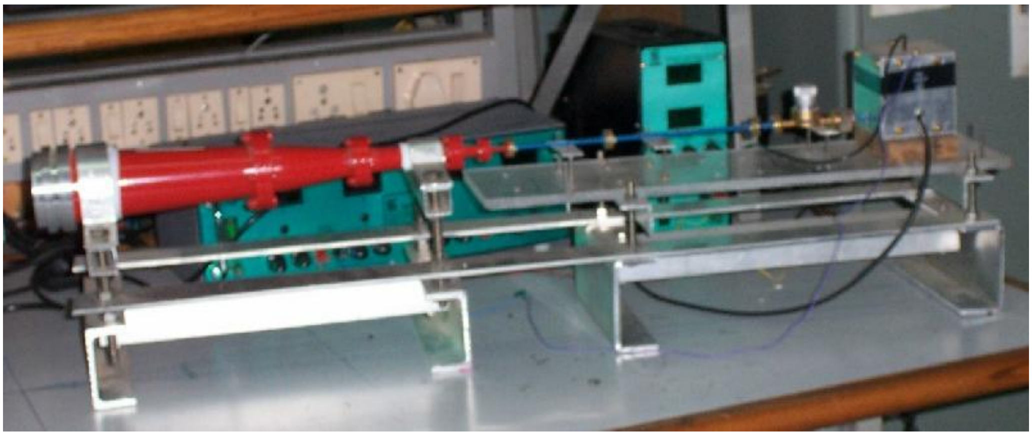

Figure 4.6 Microwave source with mode converter

4.4 Low power Measurements

The entire set-up is aligned on one horizontal plane. The detector alongwith horn antenna as shown in figure 4.7 is mounted at one end of aluminum rectangular channel, while other end is hinged at the exit of the waveguide. This arrangement gives flexibility to monitor the angular steering of the beam from -25^0 to $+25^0$ on the spherical wavefront. The measurements are taken at ~2 m away from the waveguide exit to monitor far field pattern. There is no steering reflector is used at the input of RS launcher. The circular corrugated waveguide (mode converter) is placed as close as possible to RS launcher and input angle is changed by rotating entire platform of circular waveguide mounted with the microwave source.

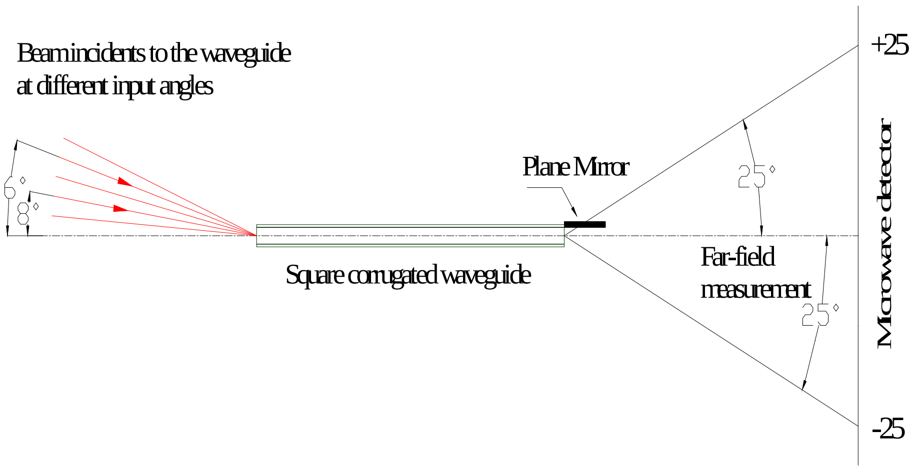

Figure 4.7 Schematic waveguide with reflector and measurement at far field

Initially the input angle of the beam to the waveguide is varied from 4^0 to 10^0 to check the performance of the launcher at $2a^2/\lambda$ without mirror and it is found that the beam is splitting in two lobes left (negative angle) and right (positive angle). This is checked for input angles from 4^0 to 10^0 as shown in figure 4.8. Beam splits in exact equal lobes for 8^0 and 10^0, however such symmetry is not achieved in 4^0 and 6^0. This may be due to imperfection in fabrication quality, as it is made within in-house workshop and limitations are in fabrication quality.

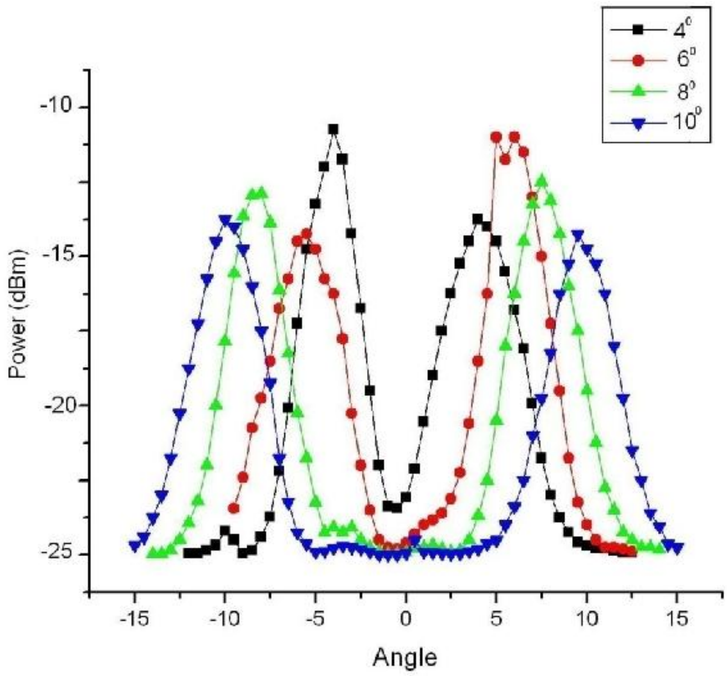

Figure 4.8 Beam split in two equal lobes at a length of waveguide $2a^2$/a (without mirror)

A mirror is then added at the exit of SCW to reflect the right lobe into opposite direction and get total beam in one direction. The input angle to the square corrugated waveguide is varied from 6^0 to 18^0. The far field pattern of the microwave beam is scanned from -25^0 to $+25^0$. The detector output is plotted as a function of angle. For input angles of 6^0, 10^0, 14^0 and 18^0, anti-symmetric steering is observed. This phenomenon is highlighted in figure 4.9 to figure 4.12.

Since the output of RS launcher is the result of interference of two beams with finite phase differences. It can be seen from the results (figure 4.9 to 4.12) some side lobes adjacent to main lobe appear with some significant power. At lower angles 6^0 figure 4.9 two lobes appear one at -6^0 (left) and other at $+6^0$ (right) with reduced power. The right side branch is around –7dB down than left side, which shows significant steering effect but the entire power is not diverted in one direction at small angles. This is due to the fact that entire beam is not reflected by the mirror and results in some power appearing exactly at +6 degree. The reason is clear that at lower input angle, the mirror is not big enough to reflect entire power. However the size of mirror becomes adequate at higher input angles and almost no power appears in the positive direction. This is highlighted in figure 4.10 to figure 4.12. The power level is also low at low input angle and at higher input angle entire beam appears at same input angle with some spread. Figure 4.12 shows that the power level is further starts reducing and beam spread is more. This is due to fact that higher input angle, the phase difference is more and resultant beam spreads more. The power in side lobes is small and found to be less than 10dB than the main lobe. This could be a limitation of RS launcher at $2a^2/\lambda$ length. But the results confirm that, from 5^0 to 20^0 steering can be achieved with modified RS launcher at $2a^2/\lambda$ length.

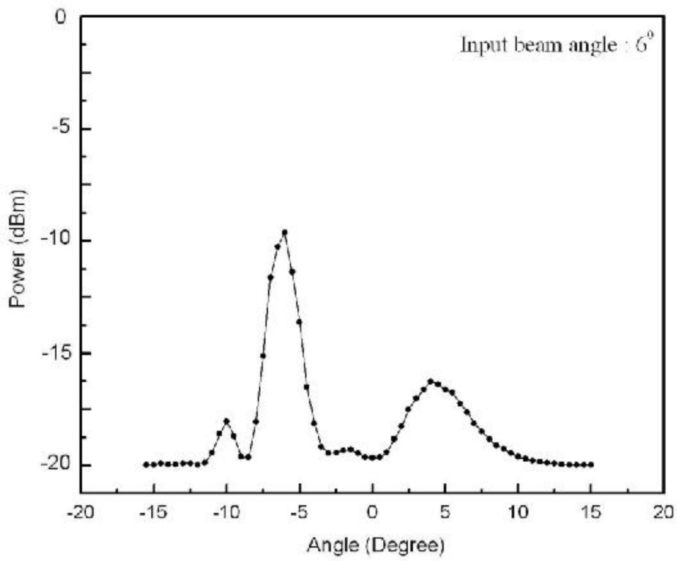

Figure 4.9 (Beam Steering at 6^0 input angle)

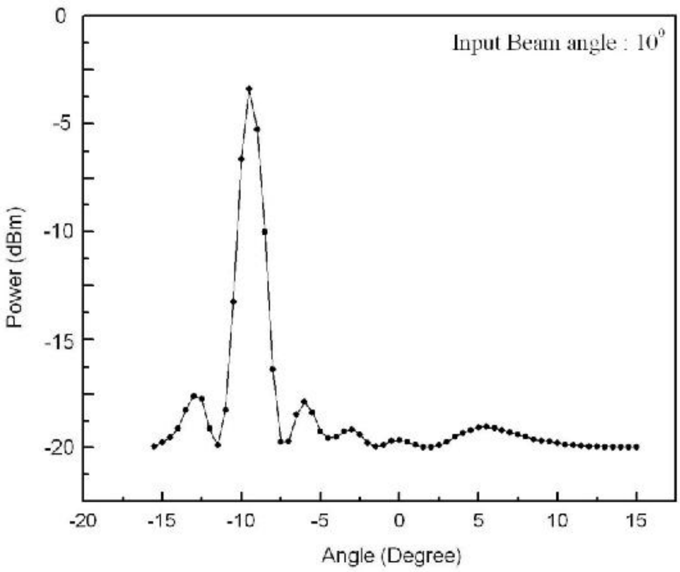

Figure 4.10 (Beam Steering at 10^0 input angle)

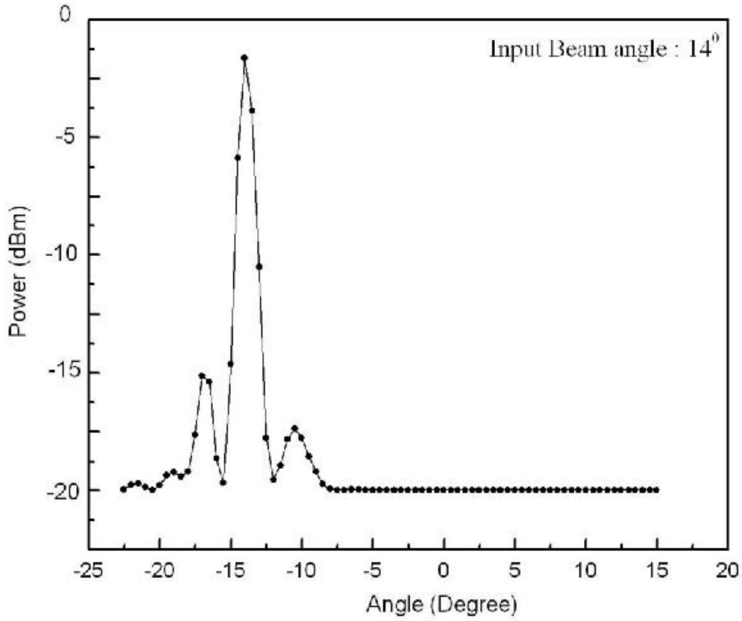

Figure 4.11 (Beam Steering at 14^0 input angle)

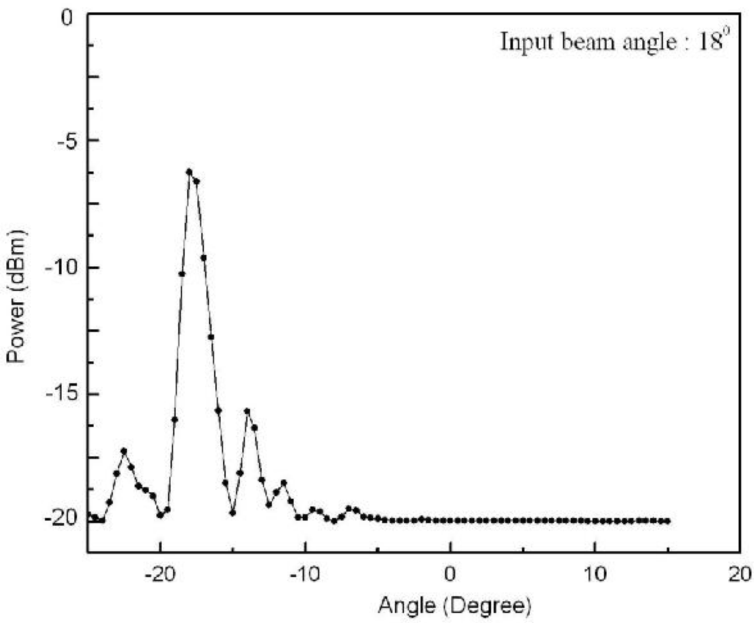

Figure 4.12 (Beam Steering at 18^0 input angle)

The nature of the steered beam is monitored in two planes (XX-horizontal and YY-vertical) and plotted in figure 4.13. From the figure it is found that the beam size is bigger in vertical mid plane (YY-plane) and small in horizontal mid plane (XX-plane). The 1/e intensity spread in XX-direction is ~2.2^0 (~75mm) and in YY-direction it is ~4.7^0 (~160mm). Hence the steered beam appears to be elliptical gaussian in nature. The exact polarization of the steered beam could not be measured. However information on field pattern of the beam is checked by rotating the detector through out 360^0. The detector out put is zero at 90^0 and 270^0 (when it is perpendicular to E field of beam) while maximum when detector is parallel to E field of beam i.e. 0^0 and 180^0 (figure 4.14). Thus it can be said that the beam is close to plane polarized.

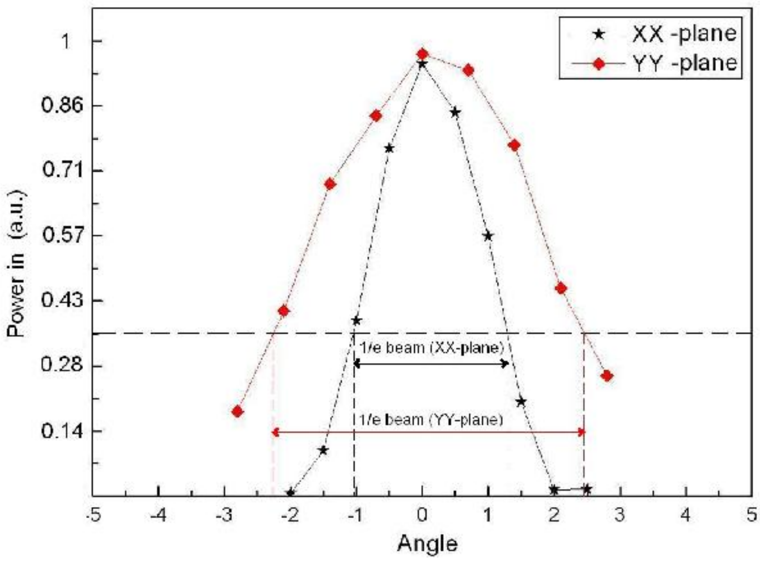

Figure 4.13 Microwave beam in two planes (input angle to the SCW is 10^0)

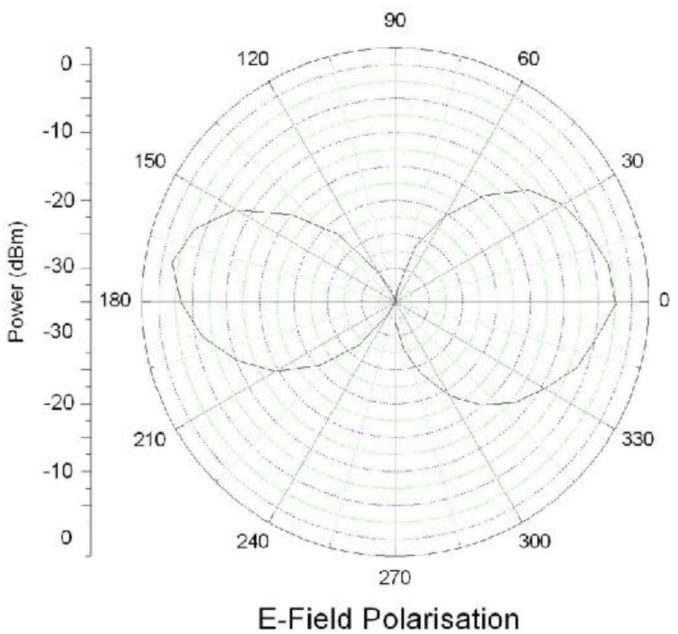

Figure 4.14 Detector output during the rotation

4.5 Observations on RS Launcher:

The aim of low power microwave test of remote steering antenna is to check the steering effect with the smaller length of the corrugated waveguide alongwith a fixed plane mirror. This is a new work carried out in the field of RS launcher to make it compact and feasible. Results show that the effective beam steering can be achieved from 6^0 to 20^0. Since the resultant beam is interference of two beams with some finite phase difference and this phase difference is more at higher input angle. So the steering is limited up to 20^0 for a RS launcher at $2a^2/a$ length. Also at very low input ingle like 2^0 to 4^0, this RS launcher in not very efficient as at very small input angle, the size of plane mirror would be very large as the beam would be almost parallel to mirror and this large size mirror would be redundant for higher input angle. The depth and period of corrugation was difficult to maintain within the accuracy of 0.1mm. In spite of poor fabrication quality and imperfections in the corrugations, the phenomenon of steering the beam could be established with smaller waveguide length and experimentally verified at low power. Symmetric or anti-symmetric steering of the beam is also possible with smaller waveguide at a length $2a^2/a$, which depends on the position of fixed plane mirror installed at the exit of waveguide.