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Wave Polarization Control of KSTAR ECH System*

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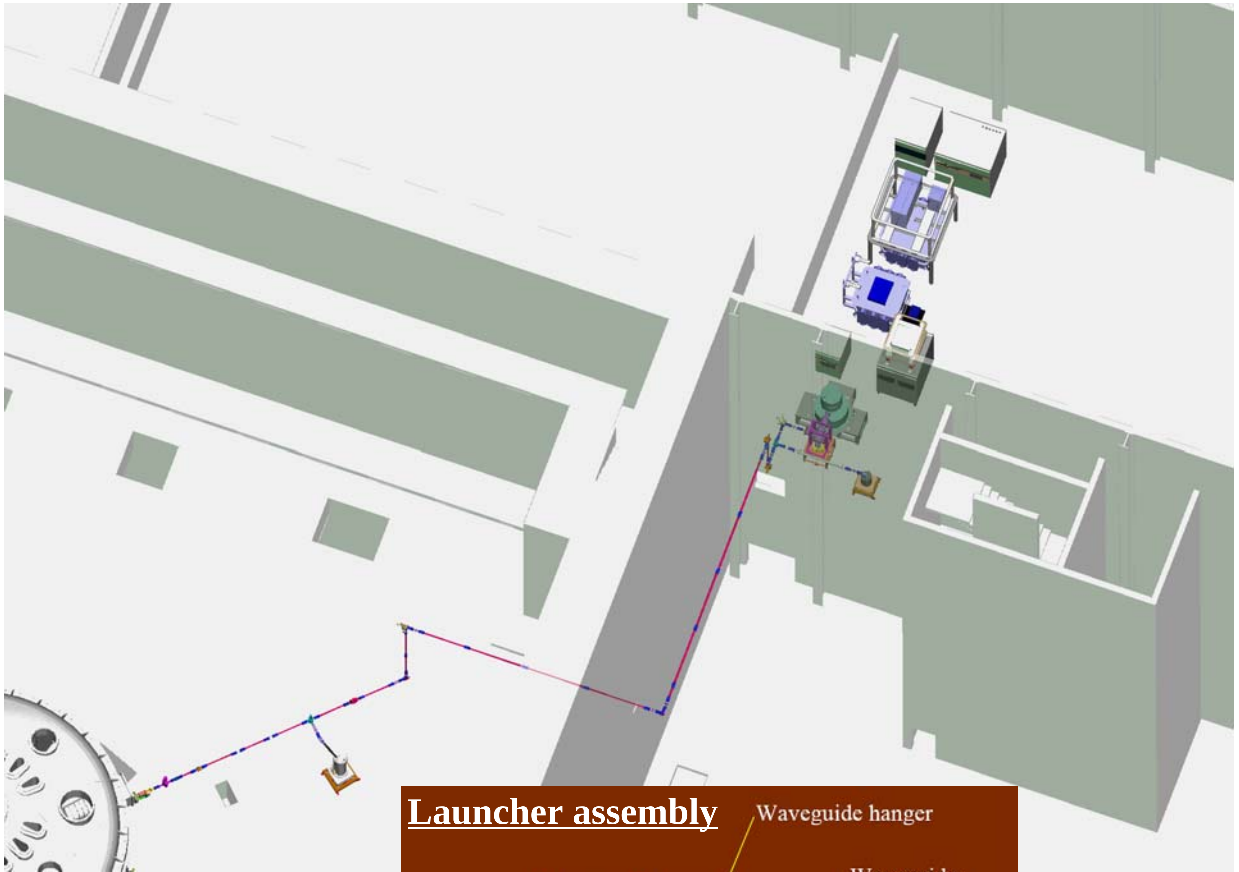
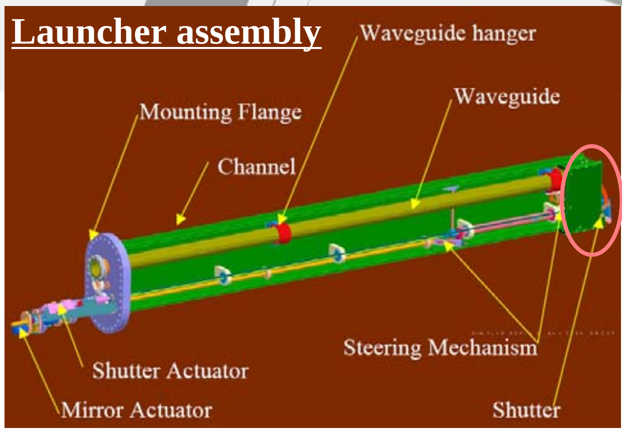
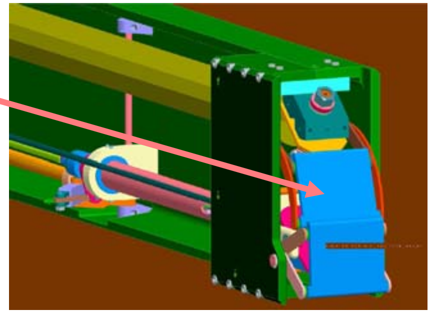
Abstract

- The high-power 84 GHz microwave wave is used for the Electron Cyclotron Heating (ECH) and Current Drive (ECCD) for KSTAR tokamak.
- The heating and the current drive efficiencies depend on the plasma mode. The selective coupling into the plasma mode is controlled by the polarization and the ellipticity at the wave launching antenna.
- Since the wave polarization changes with plasma density and the toroidal magnetic field as it propagates into the plasma, the tokamak plasma parameters should be considered for a particular plasma mode.
- The KSTAR ECH system will use two polarizer miter bends for the polarization control: a polarization rotator miter bend and a circular polarizer miter bend. The polarization rotator miter bend just rotates the incident polarization, and the circular miter bend makes the circular polarization. The combination of two polarizers makes a elliptically polarized wave.
- In this paper, an ellipticity map with respect to the mirror angles of the polarization rotator and the circular polarizer is presented. Also, the plasma mode map is investigated for the KSTAR plasma parameters and the mirror angles of two polarizers.

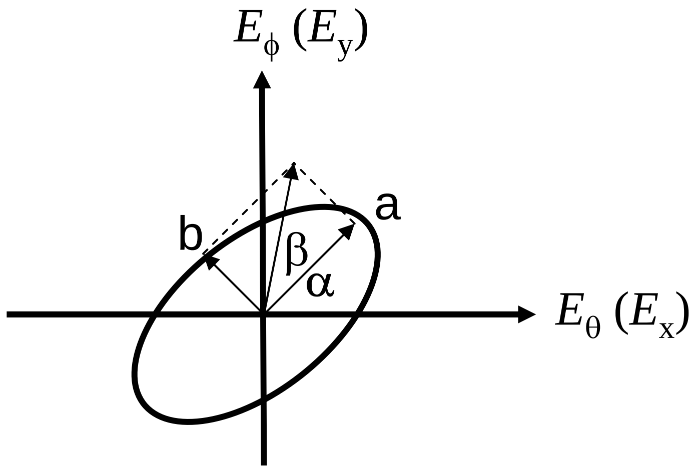
Transmission line of 84 GHz ECH system





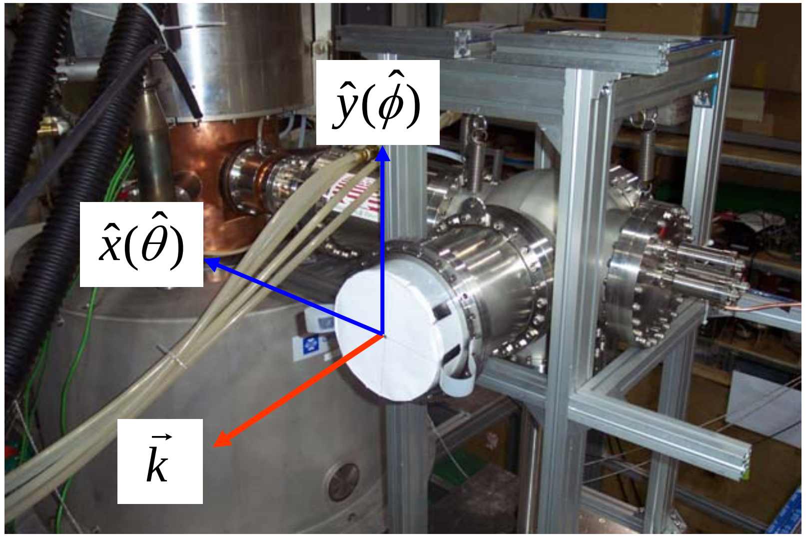


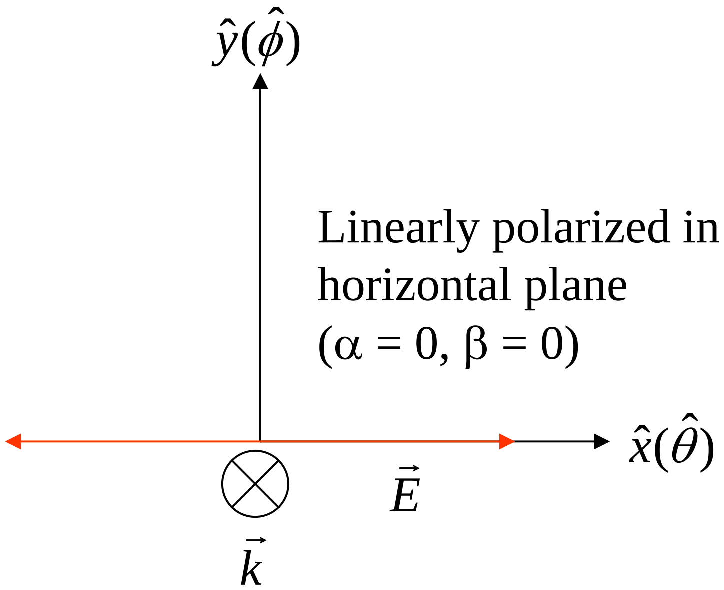
Polarization of output beam from gyrotron



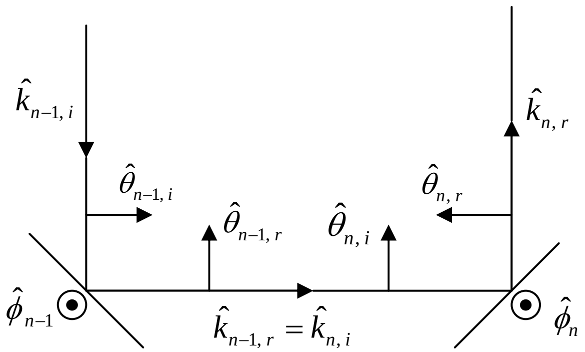
The relation between [E_x, E_y] and [α, β=arctan(b/a)]

$$E_x = [\cos\alpha \cos\beta - i\sin\alpha \sin\beta]\exp(i\theta)$$
$$E_y = [\sin\alpha \cos\beta + i\cos\alpha \sin\beta]\exp(i\theta)$$





Transformation matrix of waveguides from miter bend rotation angles



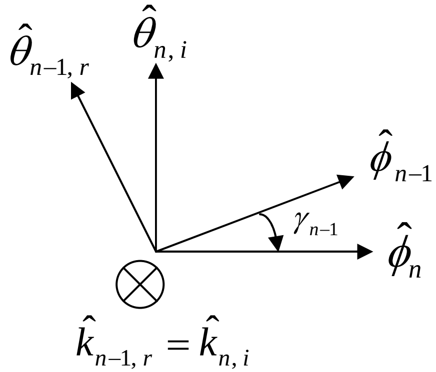
Propagation constants and local coordinates at fixed mirrors

Transformation matrix of electric field E

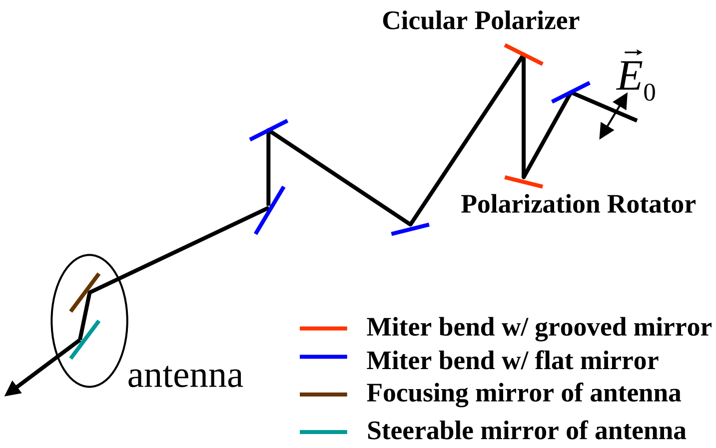
The rotation of coordinates due to miter bend rotation changes the input field E to the output field E' through

$E'_x = \cos\gamma_{N-1} E_x + \sin\gamma_{N-1} E_y$
$E'_y = -\sin\gamma_{N-1} E_x + \cos\gamma_{N-1} E_y$

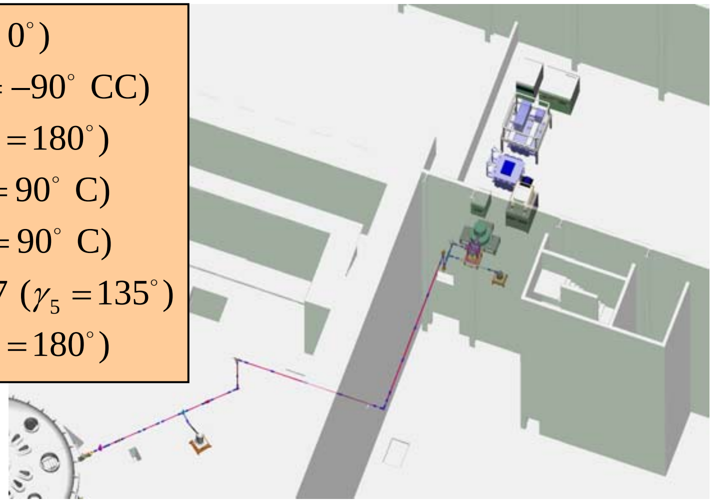
where, $\cos\gamma_{n-1} = \hat{\phi}_{n-1} \cdot \hat{\phi}_n$



Propagation directions along the transmission line are fixed.



$\cos\gamma_0 = \hat{\phi}_0 \cdot \hat{\phi}_1 = 1\ (\gamma_0 = 0^\circ)$
$\cos\gamma_1 = \hat{\phi}_1 \cdot \hat{\phi}_2 = 0\ (\gamma_1 = -90^\circ\ \text{CC})$
$\cos\gamma_2 = \hat{\phi}_2 \cdot \hat{\phi}_3 = -1\ (\gamma_2 = 180^\circ)$
$\cos\gamma_3 = \hat{\phi}_3 \cdot \hat{\phi}_4 = 0\ (\gamma_3 = 90^\circ\ \text{C})$
$\cos\gamma_4 = \hat{\phi}_4 \cdot \hat{\phi}_5 = 0\ (\gamma_4 = 90^\circ\ \text{C})$
$\cos\gamma_5 = \hat{\phi}_5 \cdot \hat{\phi}_6 = -0.707\ (\gamma_5 = 135^\circ)$
$\cos\gamma_6 = \hat{\phi}_6 \cdot \hat{\phi}_7 = -1\ (\gamma_6 = 180^\circ)$



Transformation matrix for grooved mirror rotation angles in polarizer miter bends

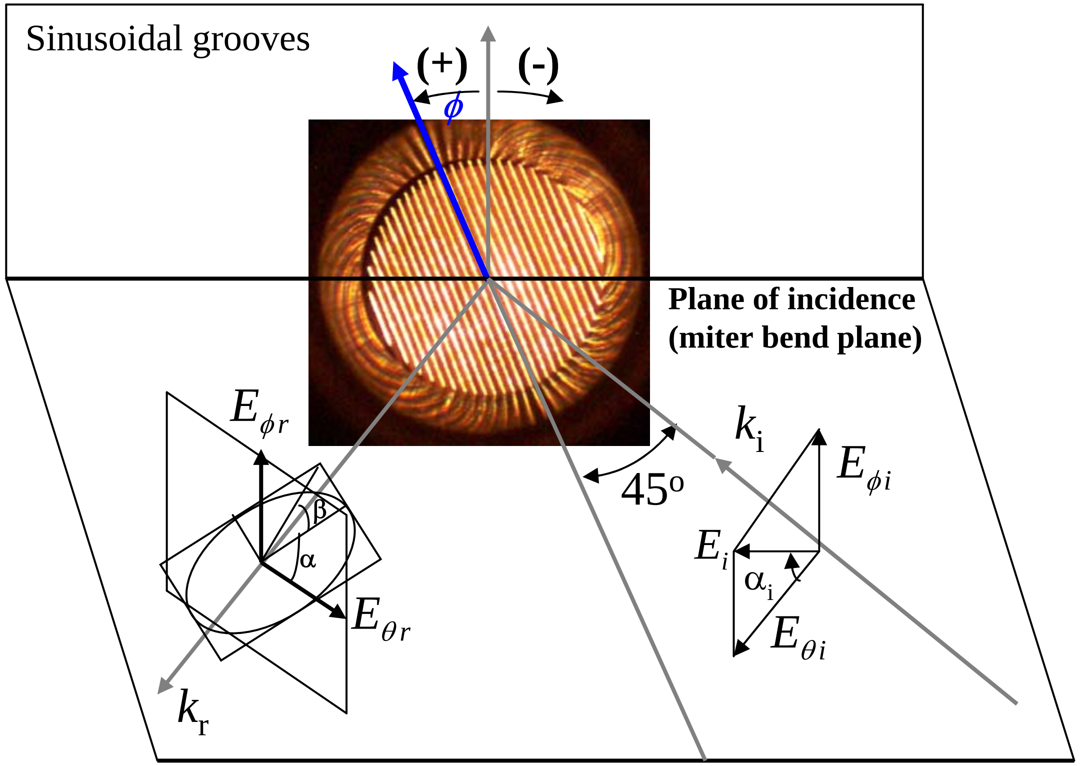
Transformation matrix of electric field E

$E'_x = a\,E_x - c\,E_y$
$E'_y = c\,E_x + b\,E_y$

$$a = \cos(\tau/2) + i\cos(2\chi)\sin(\tau/2)$$
$$b = -\cos(\tau/2) + i\cos(2\chi)\sin(\tau/2)$$
$$c = i\sin(2\chi)\sin(\tau/2)$$

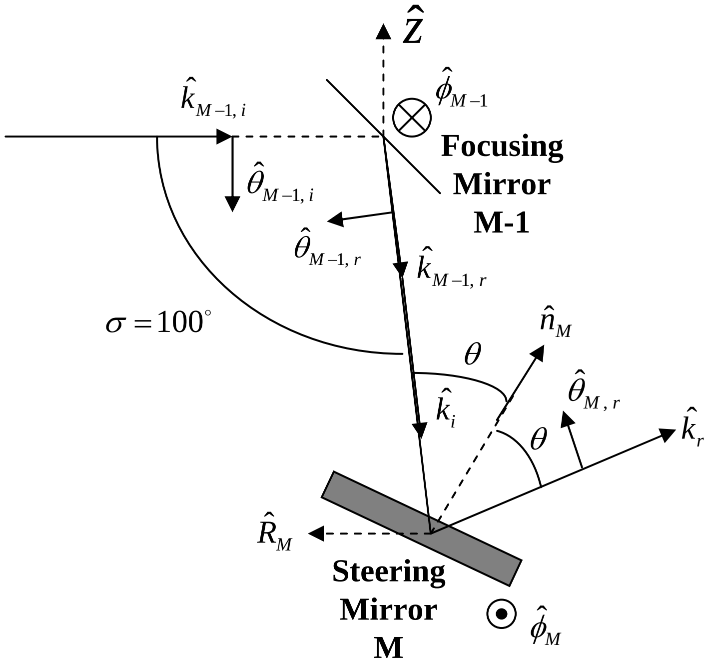
where,

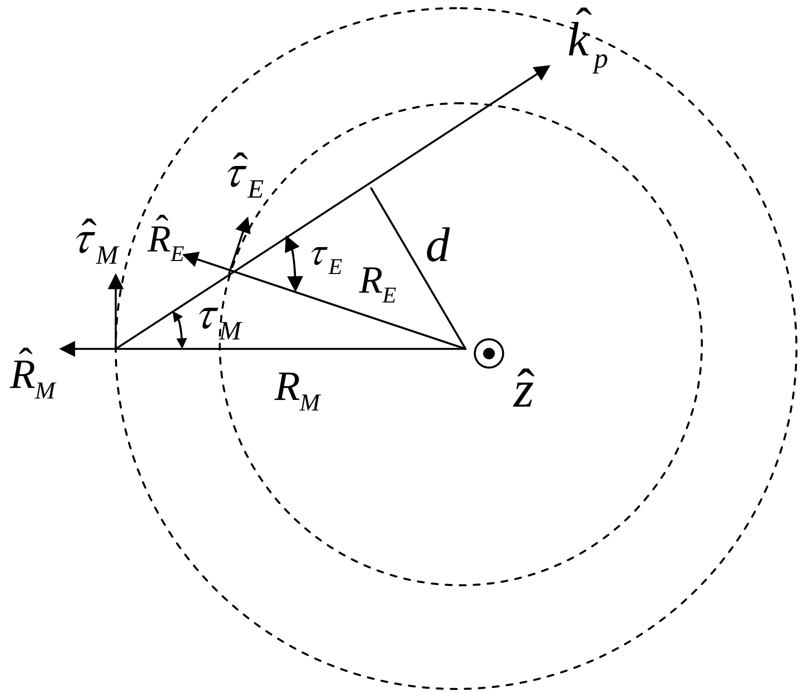
$$\chi = \arctan[\tan(\phi)/\sqrt{2}]$$
$$\tau = 2\sum_j c_j \cos[j2(\phi + \pi/2)]$$



The Cj are the Fourier coefficients of the phase delay functions.
The values of them depend on the groove design

Transformation matrix for antenna



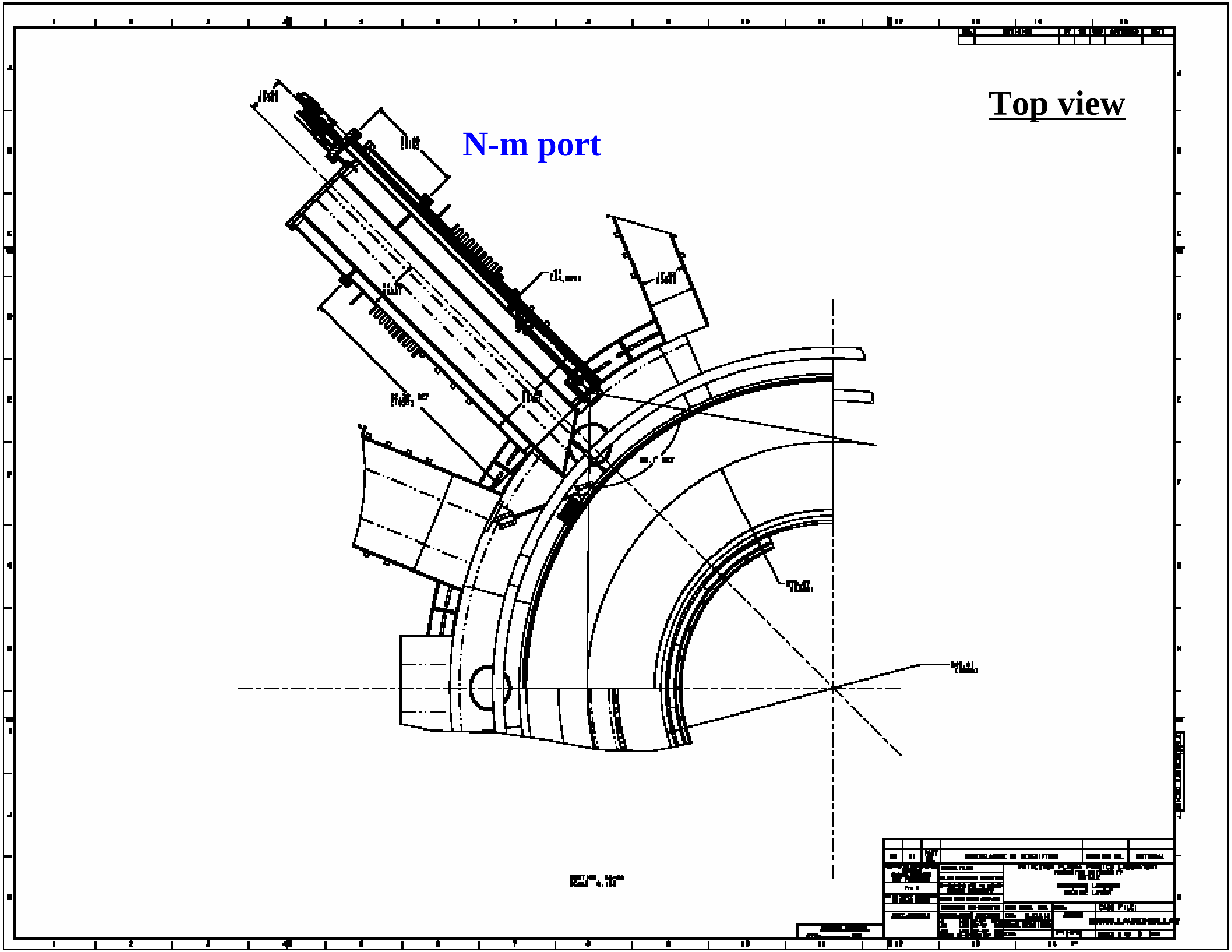


$$\hat{k}_r = \hat{\tau}_M \sin\tau_M - \hat{R}_M \cos\rho_M + \hat{z}\sin\psi_p$$

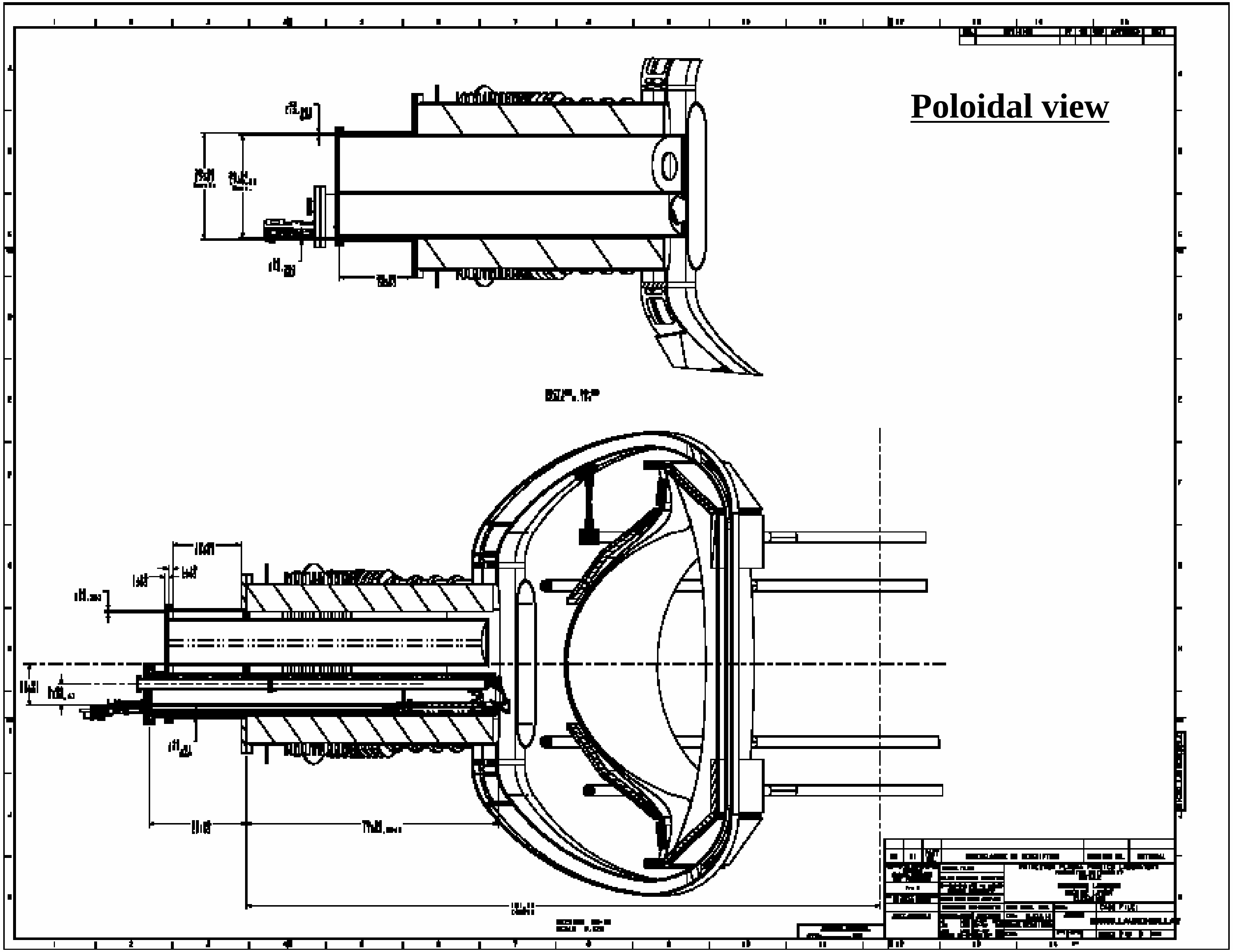
Given τ_M & ψ_p, $\sin\gamma_{M-1} = \dfrac{\sin\tau_M}{\sin 2\theta}$

where, $\cos 2\theta = \left|\hat{k}_i \cdot \hat{k}_r\right| = \cos\sigma\cos\rho_M + \sin\sigma\sin\psi_p$

and $\cos\rho_M = -[1 - \sin^2\tau_M - \sin^2\psi_p]^{1/2}$


Top view
N-m port

Poloidal view



Total transformation matrix & electric field rotation

- $Q_1 = P_1 \cdot T_1 \cdot T_0$
- $Q_2 = P_2 \cdot T_2 \cdot Q_1$
- $Q_3 = T_6 \cdot T_5 \cdot T_4 \cdot T_3 \cdot Q_2$
- $Q_4 = S \cdot Q_3$
- $E' = Q_4 \cdot E_0$

  - T_n = Transformation matrix of waveguides through the miter bend rotation angles
  - $P_{1,2}$ = Transformation matrix for grooved mirrors of polarizer miter bends
  - S = Transformation matrix for antenna
  - E_0 = Input electric field from L-box
  - E' = Transformed electric field at the steering antenna

$$T_n = \begin{pmatrix} \cos\gamma_n & \sin\gamma_n \\ -\sin\gamma_n & \cos\gamma_n \end{pmatrix}$$

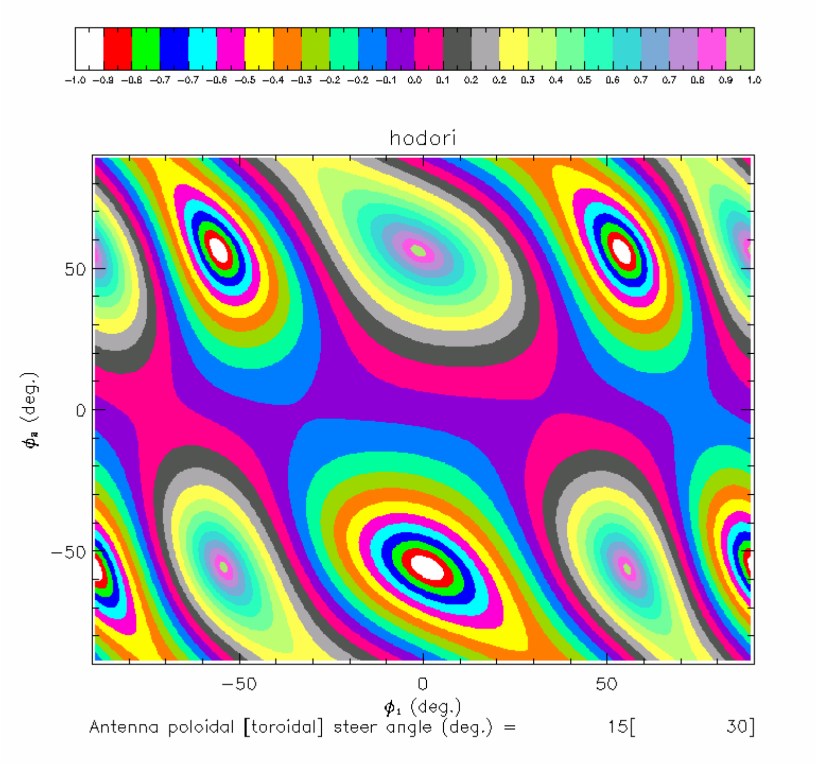
$$P_{1,2} = \begin{pmatrix} a_{1,2} & -c_{1,2} \\ c_{1,2} & b \end{pmatrix}$$

$$S = \begin{pmatrix} \cos\gamma_m & \sin\gamma_m \\ -\sin\gamma_m & \cos\gamma_m \end{pmatrix}$$

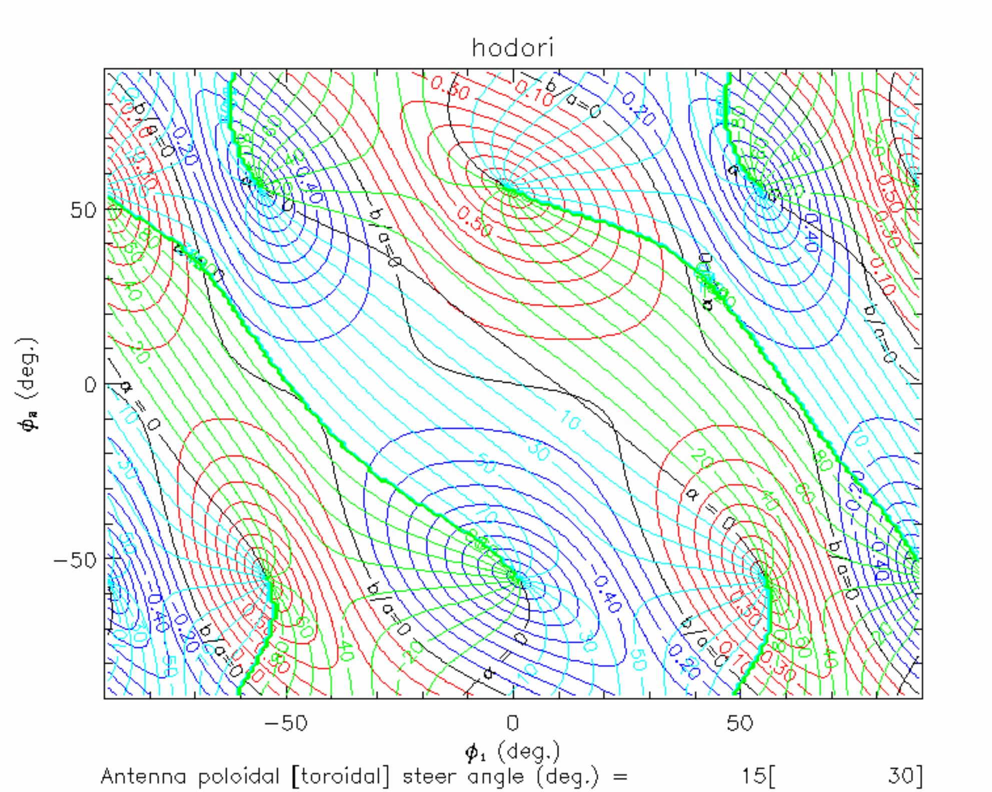
Polarizations and ellipticities at steering mirror cont’d

(τ_M = 30 deg, ψ_p = 15 deg)

Ellipticities (b/a)



Ellipticities (b/a) & Polarization (α)

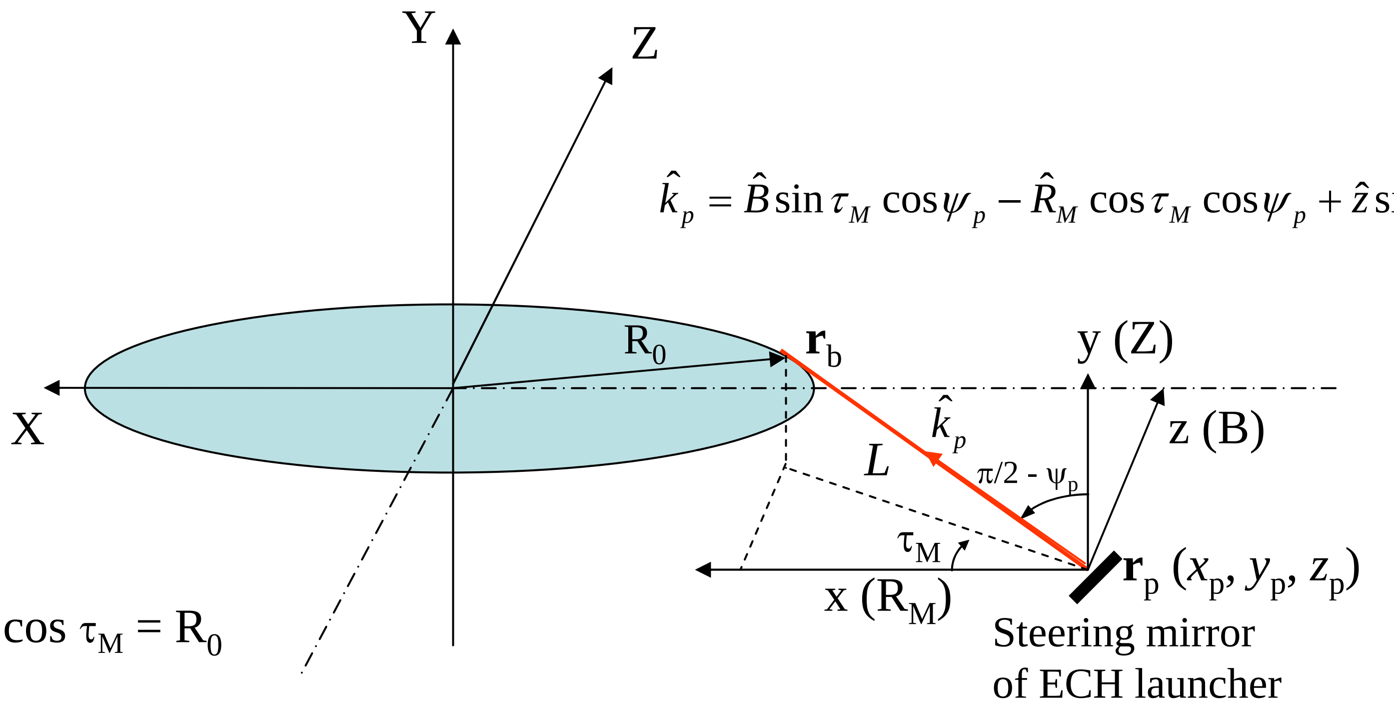


b/a = 0 & α

b/a > 0 : red lines, b/a < 0 : blue lines

α > 0 : light blue lines, α < 0 : green lines

Crossing point at major radius for $N_{\|} = 0.5$



$$\hat{k}_p = \hat{B}\sin\tau_M \cos\psi_p - \hat{R}_M \cos\tau_M \cos\psi_p + \hat{z}\sin\psi_p$$

$x_p - L \cos\psi_p \cos\tau_M = R_0$

$L \sin\psi_p = y_p$

For $\tau_M = 30^0$ ($N_{\|} = 0.5$), $\psi_p = 15^0$.

Thus, $L = |\mathbf{r}_p - \mathbf{r}_b| = 1176$ mm

Total distance of beam from focusing mirror:

$Z = L + y_p/\cos 10^0 = 1481$ mm

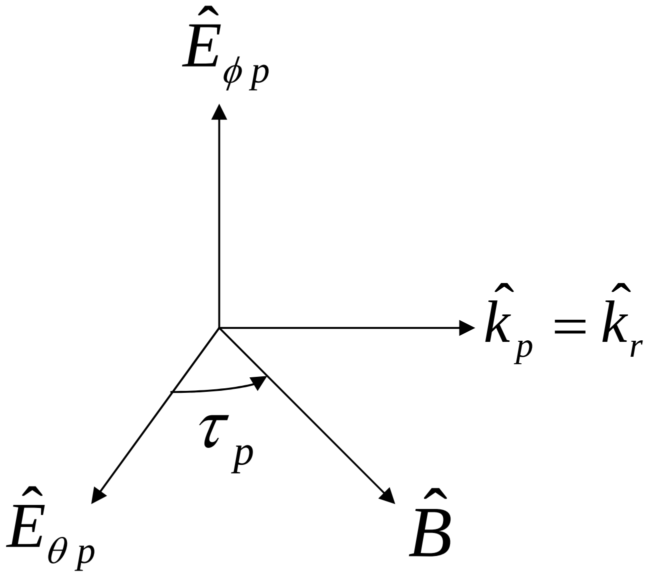
Steering mirror pivot position:

$\mathbf{r}_p$ = (-2785 mm, -300 mm, -270 mm)

* Note $\mathbf{r}_b$ is on the XZ-plane

Polarization at plasma edge

- The specific coupling mode to the fundamental ordinary and extraordinary mode in the KSTAR plasma is considered here.
- When the propagation direction is not perpendicular to the DC magnetic field in the plasma, the required polarization is elliptic.



$$\hat{k}_p = \hat{\tau}_p \sin\tau_p - \hat{R}_p \cos\rho_p + \hat{z}\sin\psi_p$$
$$= \hat{B}\sin\tau_p - \hat{R}_p \cos\rho_p + \hat{z}\sin\psi_p$$

X-mode polarization at the plasma edge (assuming the plasma edge density drops to zero):

$$E_{\phi p}/E_{\theta p} \equiv i\tan\beta_X = \frac{2i\tan\tau_p}{B_N\cos^2\tau_p + \sqrt{(B_N\cos^2\tau_p)^2 + 4\sin^2\tau_p}}$$

O-mode polarization at the plasma edge:

$$E_{\phi p}/E_{\theta p} \equiv i\tan\beta_O = \frac{2i\tan\tau_p}{B_N\cos^2\tau_p - \sqrt{(B_N\cos^2\tau_p)^2 + 4\sin^2\tau_p}}$$

where, $B_N = f_c/f = 28R_0B_0/Rf$

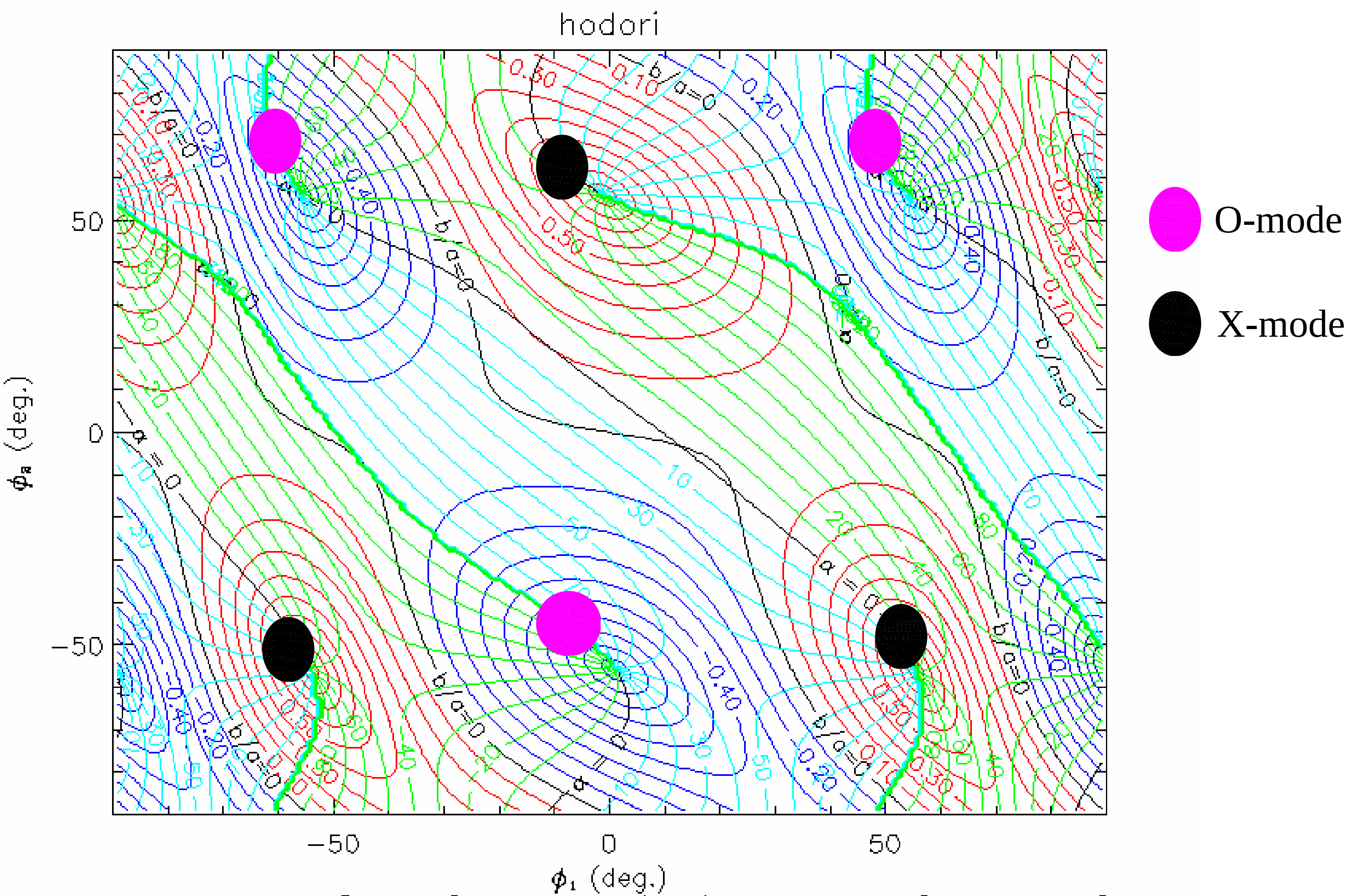
and $\tau_p = \sin^{-1}[\sin\tau_M\cos\psi_p]$

For $\tau_M = 30^0$ ($N_{\|} = 0.5$) and $\psi_p = 14.8^0$, $\tau_p = 28.9^0$

Elliptical polarization required O&X-mode low field injection

B at plasma center (tesla)	B at plasma edge (tesla)	Launch angle τ_p (deg)	Required Ellipticity $\tan\beta_X$	Required Polarization, α_X (deg)	Ellipticity $\tan\beta_O$	Required Polarization, α_O (deg)
1.5	1.17	28.9	0.84	0	-0.64	90
3.5	2.74	28.9	0.58	0	-0.45	90

Calculated output polarization



Antenna poloidal [toroidal] steer angle (deg.) = 15[30]