



The HSX Hybrid Quasioptical Waveguide System

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Overview

- ECRH Transmission Line Upgrade
 - Oversized, mode-converting waveguide removed
 - Hybrid quasioptical line installed
 - Waveguide ECRH operation: July, 2006
- Hybrid Quasioptical Design
 - Vlasov mode converter: TE₀₂-to-TEM₀₀
 - Quasioptical units: beam direction and focus
 - Dual-mode (TE₁₁+TM₁₁) waveguide connects quasioptical units
- Beam Analysis
 - Launched power measured with a quasioptical water load calorimeter
 - Microwave beam patterns measured with a thermal camera and ceramic target

Oversized Waveguide

Microwave Source:

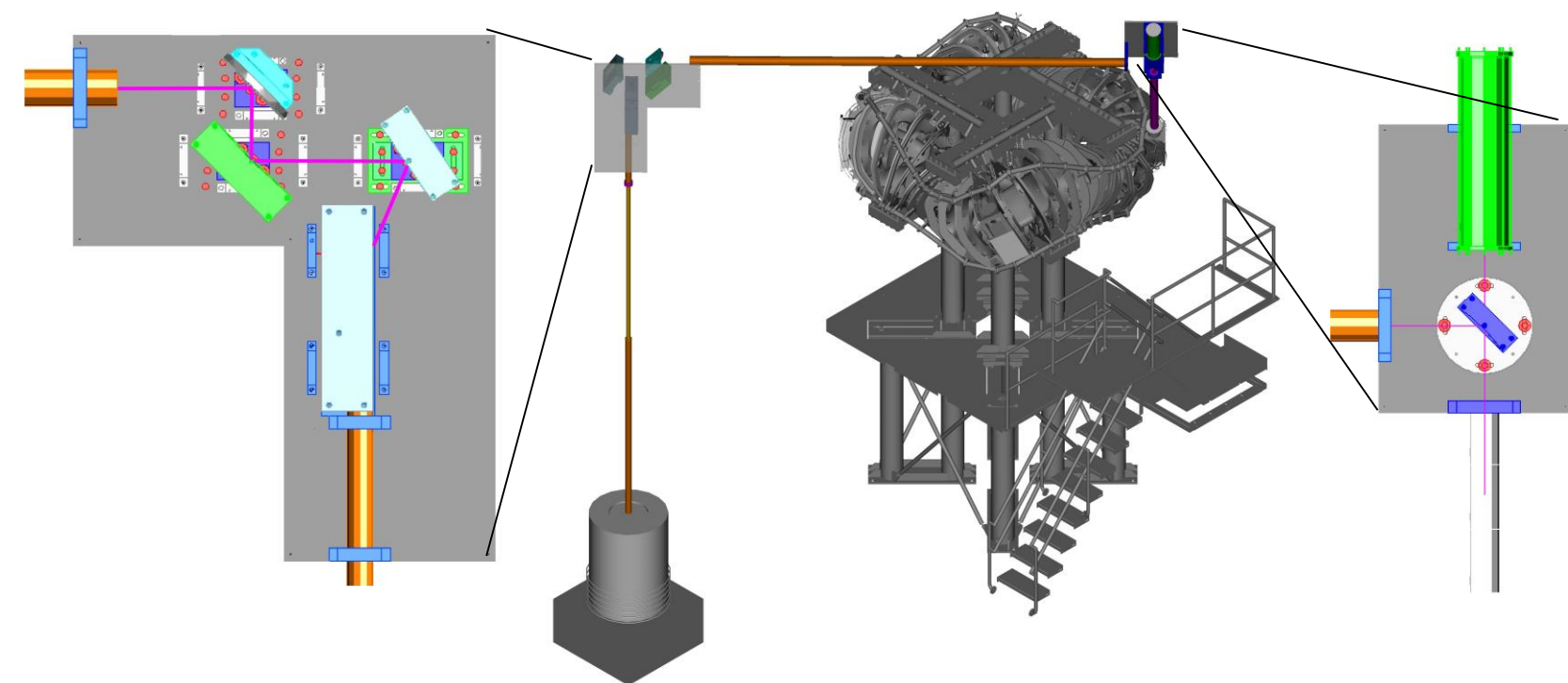
- 28 GHz Varian (CPI) Gyrotron
- TE₀₂ main output mode
- 200 kW (peak), 200 ms (max)

Transmission Line:

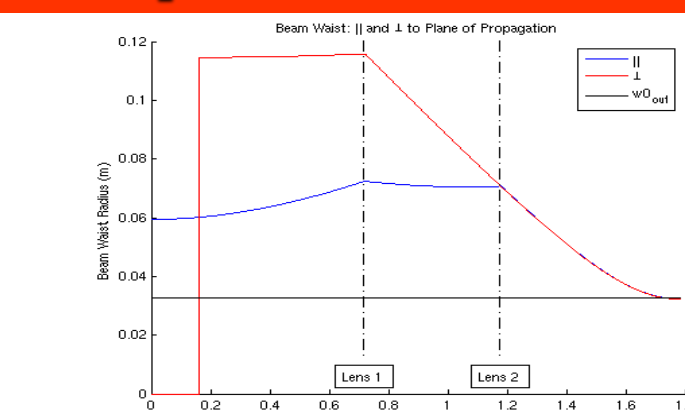
- TE₀₂-to-TE₀₁-to-TE₁₁-to-HE₁₁
- 50 kW (nominal), 50ms (nominal)
- Power limited by waveguide arcing

Gaussian Beam Propagation

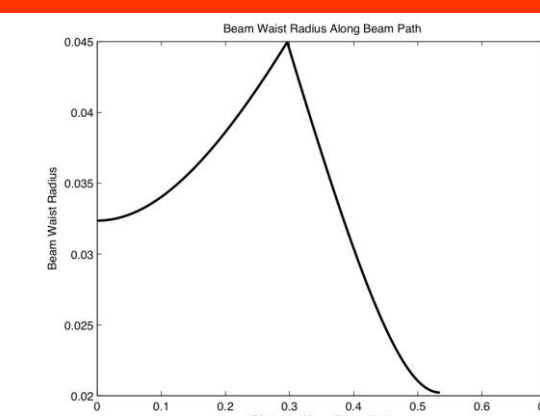
$$E(r, z) = \left(\frac{2}{\pi w^2} \right)^{0.5} \exp \left(-\frac{r^2}{w^2} - jkz - \frac{j\pi r^2}{\lambda R} + j\phi_0 \right)$$
$$M_{lens} = \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix}$$
$$M_L = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$$
$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & d_{out} \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & d_{in} \\ 0 & 1 \end{bmatrix}$$



Ellipsoidal Mirrors

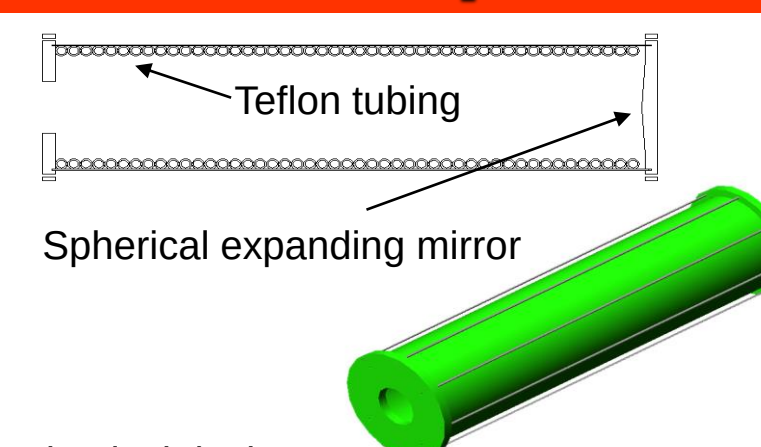


- Focus beam & correct astigmatism
- Integrated directional coupler
- Utilize quasioptical design techniques (Gaussian Beam Propagation)

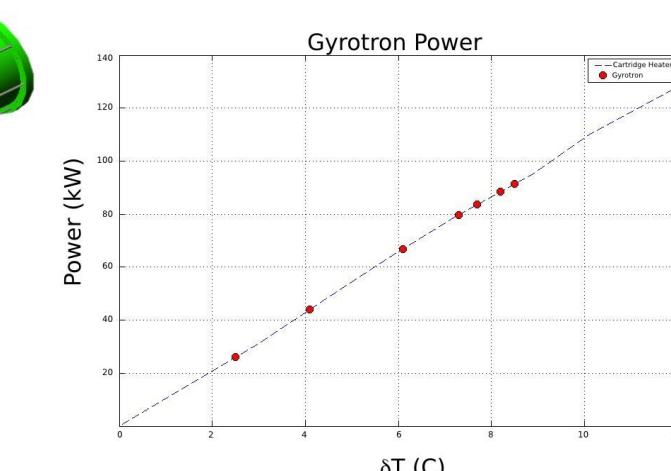


- Simplified waveguide bends
- Low loss (<1% per mirror)
- CNC machined aluminum

Quasioptical Calorimeter

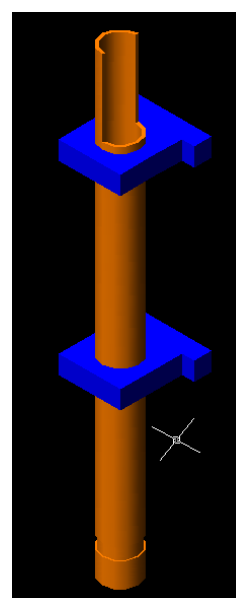


- Gyrotron test mode 24-96 kW
- ΔT calibrated with cartridge heater



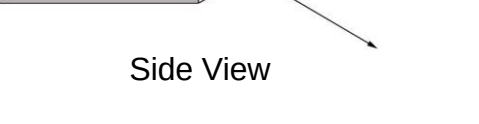
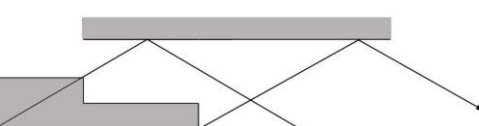
- Quasioptical design
- Calorimeter/dummy load operation
- Water load calorimeter
- Full power/Test pulse gyrotron operation

Vlasov Converter



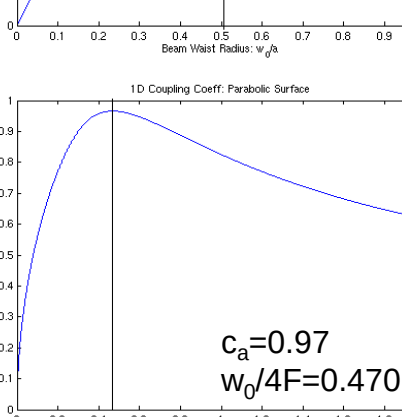
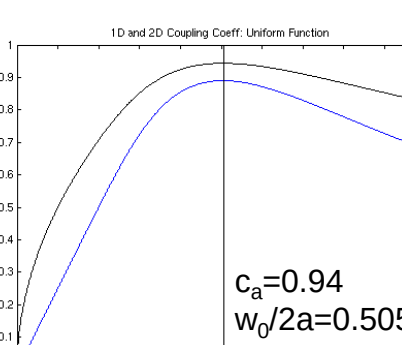
- Vlasov converter: stepwise cut + parabolic reflector
- Waveguide cut = L_B, bounce length
- TE₀₂-to-astigmatic beam

$$a = 1.25''$$
$$k = \frac{2\pi}{\lambda} \approx 587 m^{-1}$$
$$\theta_B = \sin^{-1} \left(\frac{\chi_{0.2}}{k} \right) \approx 22^\circ$$
$$r_c = \frac{m}{\chi_{0.2}} = 0$$
$$L_B = 2\sqrt{(a^2 - r_c^2) \cot(\theta_B)} \approx 6.15''$$

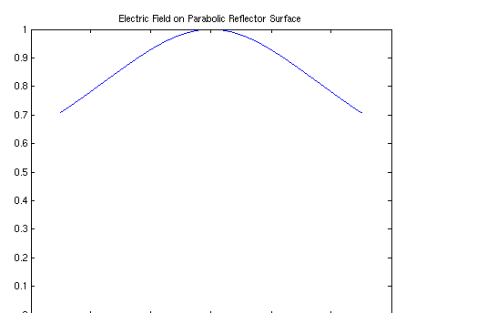


Coupling Coefficients

$$c_a = \frac{\int E^*(u) f(u) du}{\left[\int f^*(u) f(u) du \right]^{0.5}}$$

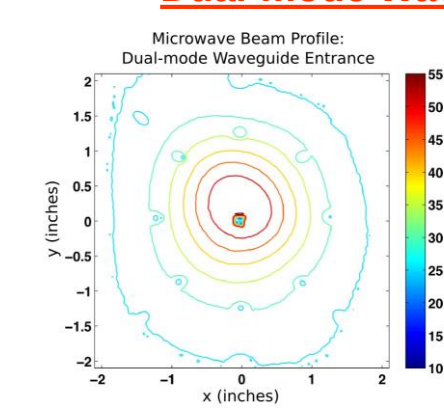


$$d = \frac{2F - r_c(\theta + \sin \theta)}{1 + \cos \theta}$$
$$= \frac{2F}{1 + \cos \theta}$$



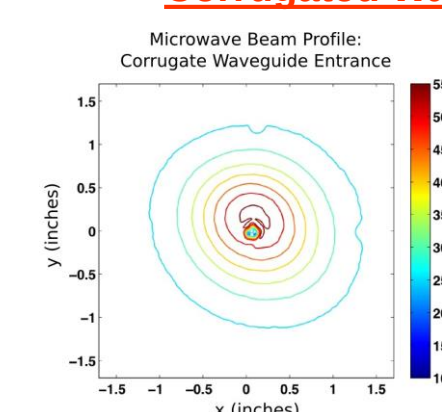
Thermal Beam Imaging

Dual-mode Waveguide Entrance



- Gaussian power profile
- w₀ ~ 3.25 cm
- Beam offset < 5mm

Corrugated Waveguide Entrance



- Gaussian power profile
- w₀ ~ 2.0 cm
- Beam offset < 5mm

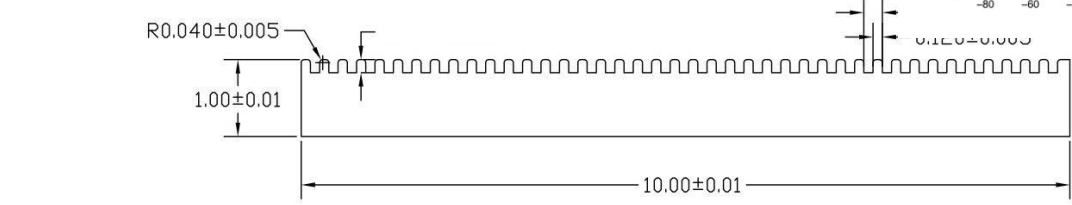
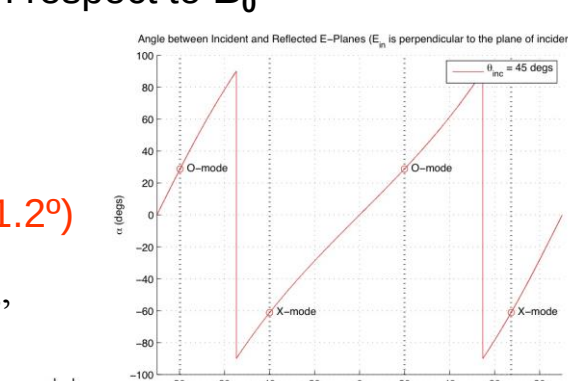
- Thermal camera + macor ceramic target
- Temperature profile ~ microwave power profile
- Analysis includes target thermal conduction



Polarization Twist Reflector



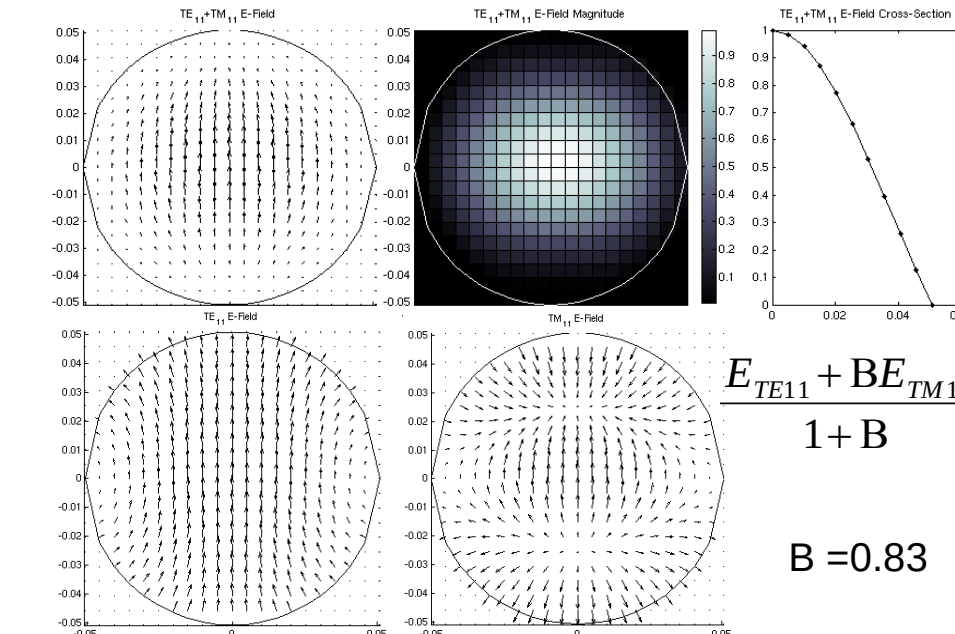
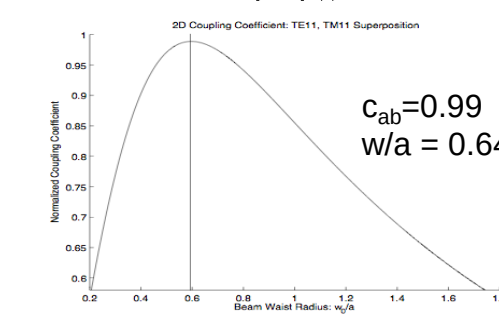
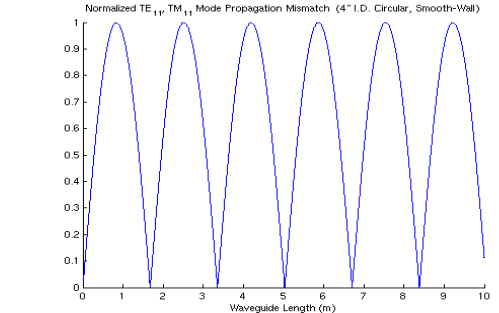
- Rotate beam polarization with respect to B₀
 - E || B₀ (O-mode)
 - E ⊥ B₀ (X-mode)
 - Low cross-polarization
- O-mode (28.8°) X-mode (-61.2°)
- φ₁ = -79.7° φ₁ = 67.3°
- d = 0.1473'' d = 0.1408''



Smooth-Walled (Dual-Mode) Waveguide

- Traverse long distances
- Low loss (<< 1%)
- Superposition TE₁₁, TM₁₁
- Efficient coupling to Gaussian beam modes

- Multiple of TE₁₁, TM₁₁ guided wavelength
- 2.5'' ID: ΔL = 0.065 m
- 4.0'' ID: ΔL = 1.676 m



Future Work

Hybrid Quasioptical Line #2

- 200 kW, 28 GHz CPI gyrotron
- Steerable launching mirror
- 0.5 T X-mode 2nd harmonic heating
- 1 T O-mode fundamental heating

Modulated ECRH (MECH)

- ECRH Power Deposition Profiles
- Electron Thermal Diffusivity, χ_e
- Heatwave & Heat pulse propagation

Summary

- HSX over-sized, mode converting waveguide was replaced with a hybrid quasioptical waveguide.
- Quasioptical design was utilized for mode conversion, astigma correction and beam bends.
- A dual-mode (TE₁₁+TM₁₁) waveguide eliminates mirror size/quantity trade-off in a quasioptical system.
- Measured microwave beam profiles exhibit good agreement with predicted profiles.
- Waveguide tested for 100kW X- and O-mode ECRH