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Physics and Technology Considerations for Electron Bernstein Wave (EBW) Heating and Current Drive on NSTX*

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The in-plasma mode conversion (MC) of electron cyclotron (EC) waves to electron Bernstein waves (EBW), offers the possibility of greatly extending the useful density range over which high frequency ECH type heating techniques and capabilities can be utilized. Thus, EBW would enhance high beta operation in NSTX. The localization of power can enable localized current and flow drive. At low density, ECH can be used for noninductive startup assist. Recent studies of EBWs, via MC to X-mode electromagnetic radiation on the CDX-U and NSTX spherical torus (ST) plasmas, indicate that high mode conversion efficiency may be possible. New EBW emission antenna designs for X-mode and O-X-B and dedicated experiments are focused on achieving > 80% MC on NSTX during the next experimental campaign.

A multi-megawatt EBW heating and current drive (H&CD) system is under consideration for NSTX that could assist plasma startup, locally heat electrons, drive non-inductive current and suppress tearing modes or other MHD that limit high β operation. There are number of physics and technology considerations and tradeoffs that influence the design and application of EBW H&CD and startup assist on NSTX. EBWs have better radial access at fundamental resonance frequencies than at higher EBW harmonics, especially at high β. Also, since the fundamental X-B and O-X-B mode conversion layer is at densities that lie in the NSTX plasma scrape off, fundamental launch would potentially allow the use of a local limiter to control the density scale length at the mode conversion layer and hence maximize the tunneling and mode conversion efficiency. The emission measurements will be used to guide the launcher antenna/plasma interface and to decide whether the antenna should be designed to accommodate both X-B (normal incidence) and O-X-B (oblique incidence). Fundamental launch at 8, 12 or 15.3 GHz and second harmonic launch at 28 GHz are all under consideration. There are high power tubes available at both 8 and 28 GHz. The possibility exists to modify the 28 GHz tubes to operate at 15.3 GHz, but likely at somewhat reduced efficiency. Further tube development would be required for optimized high power tubes at either 12 or 15 GHz.

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EBW heating, CD and NTM stabilization roles

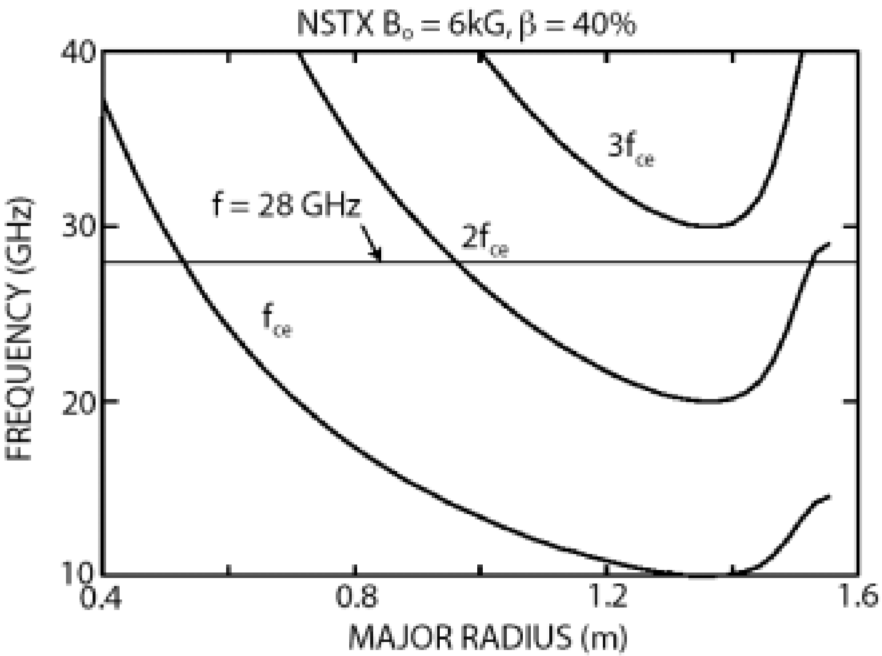
- **Core Heating**
- **ECH or EBW Startup**
- **EBW CD ~ 400 kA with ~ 5MW**
- **NTM Stabilization at β ~ 40% ~ 5MW ?**

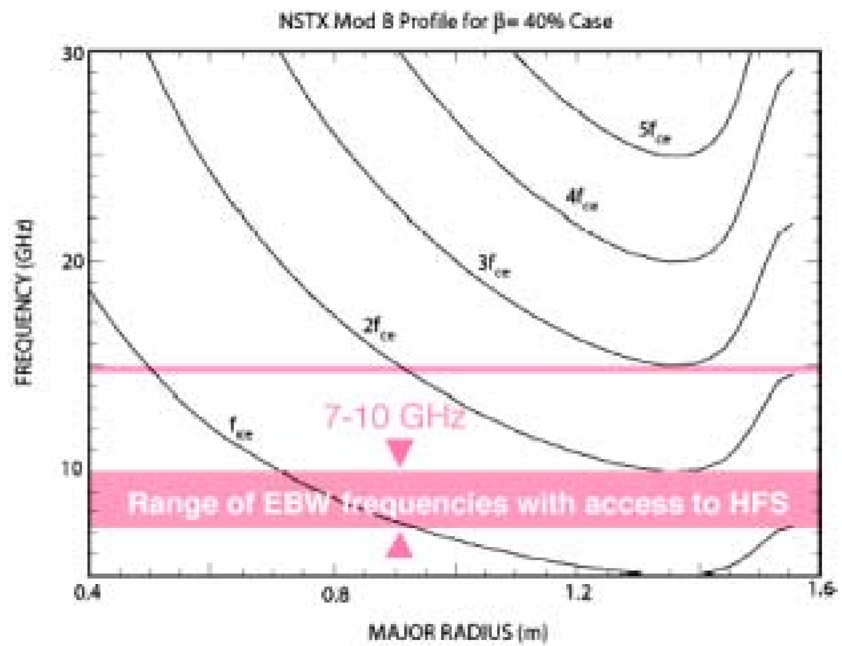
Requires efficient coupling, high power localization, efficient CD

EBW frequency choice for heating, CD and NTM stabilization involves a complicated set of tradeoffs

- **Coupling** **(X-mode, O-X-B, density scale lengths, limiters, fluctuations, profile evolution)**
- **Resonant location** **(center, profile, NTM, edge, harmonics)**
- **Power localization** **(launch aperture, acceptance angle)**
- **Critical density** **(ECH startup, EBW coupling)**
- **CD target density** **(> critical density, < 4 x 10^{13} cm^{-3})**
- **High β effects** **(Shafranov shift, B field scale lengths)**
- **Source power** **(MW/ unit)**
- **Nonlinear effects at edge** **(parametric, ponderomotive)**

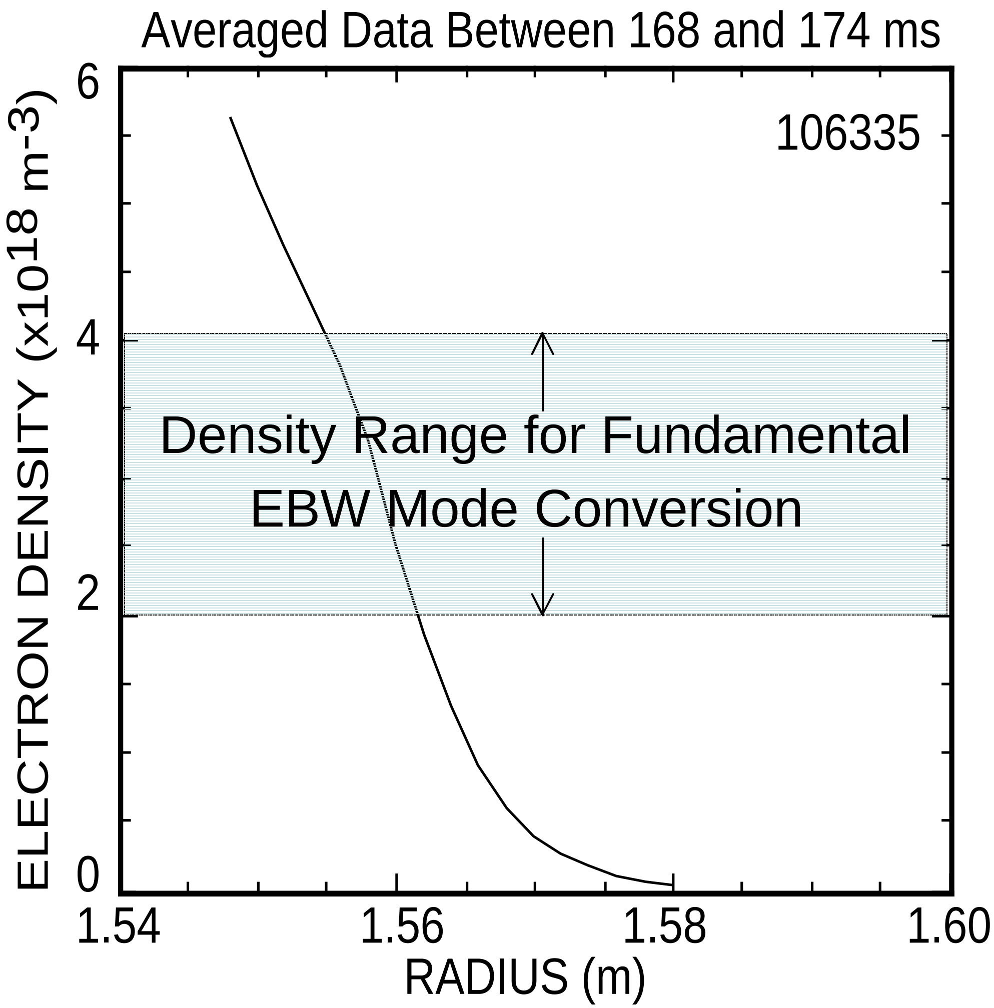
EBW heating, CD and NTM stabilization target plasma





Modeling 12 GHz, 1MW for β~12% NSTX gives dimensionless EBWCD efficiency ~ 0.5[0.08 A/W, T_{eo}=1 keV, n_{eo}=2x$10^{19}$$m^{-3}$]

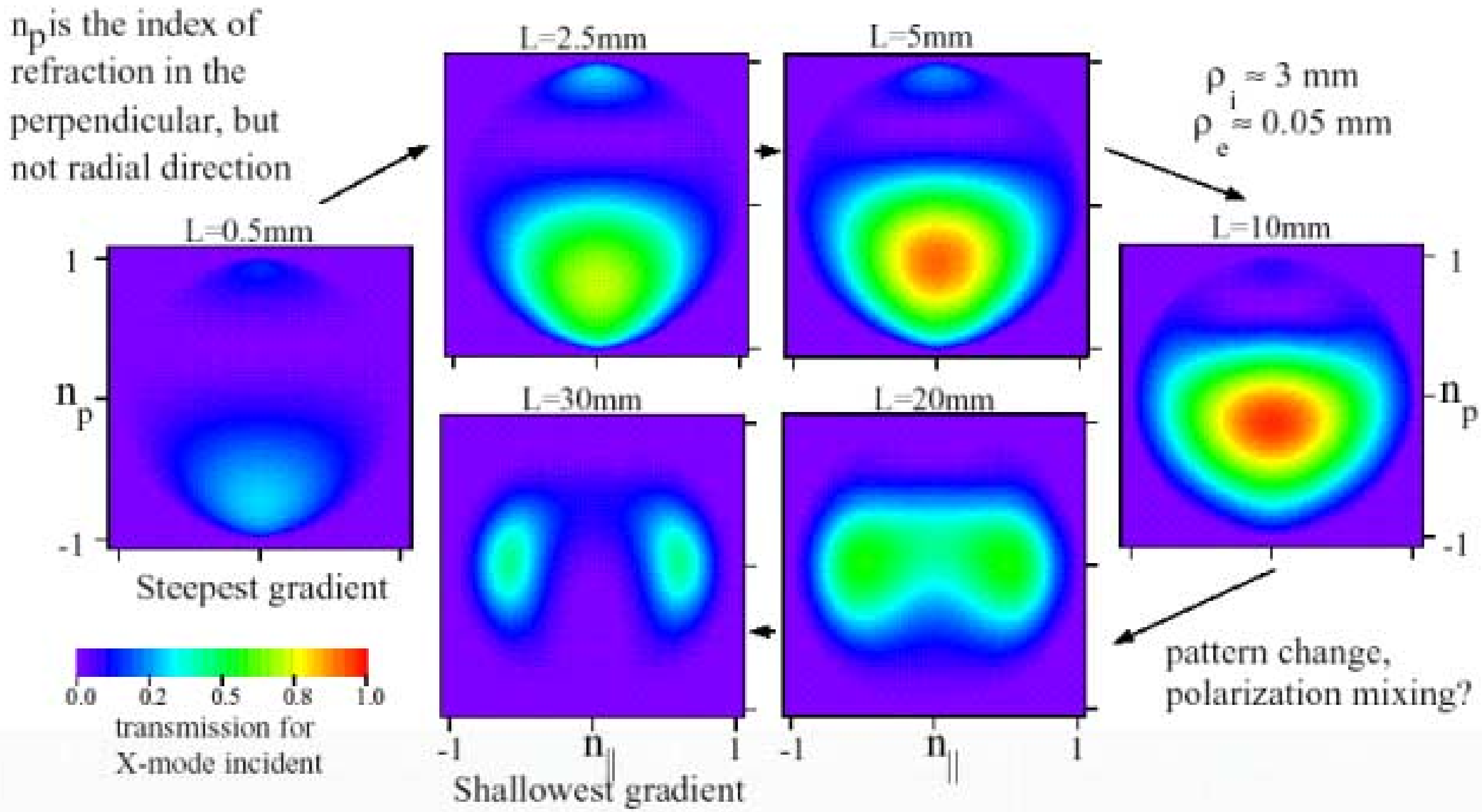
EBW mode conversion region



12-18 GHz

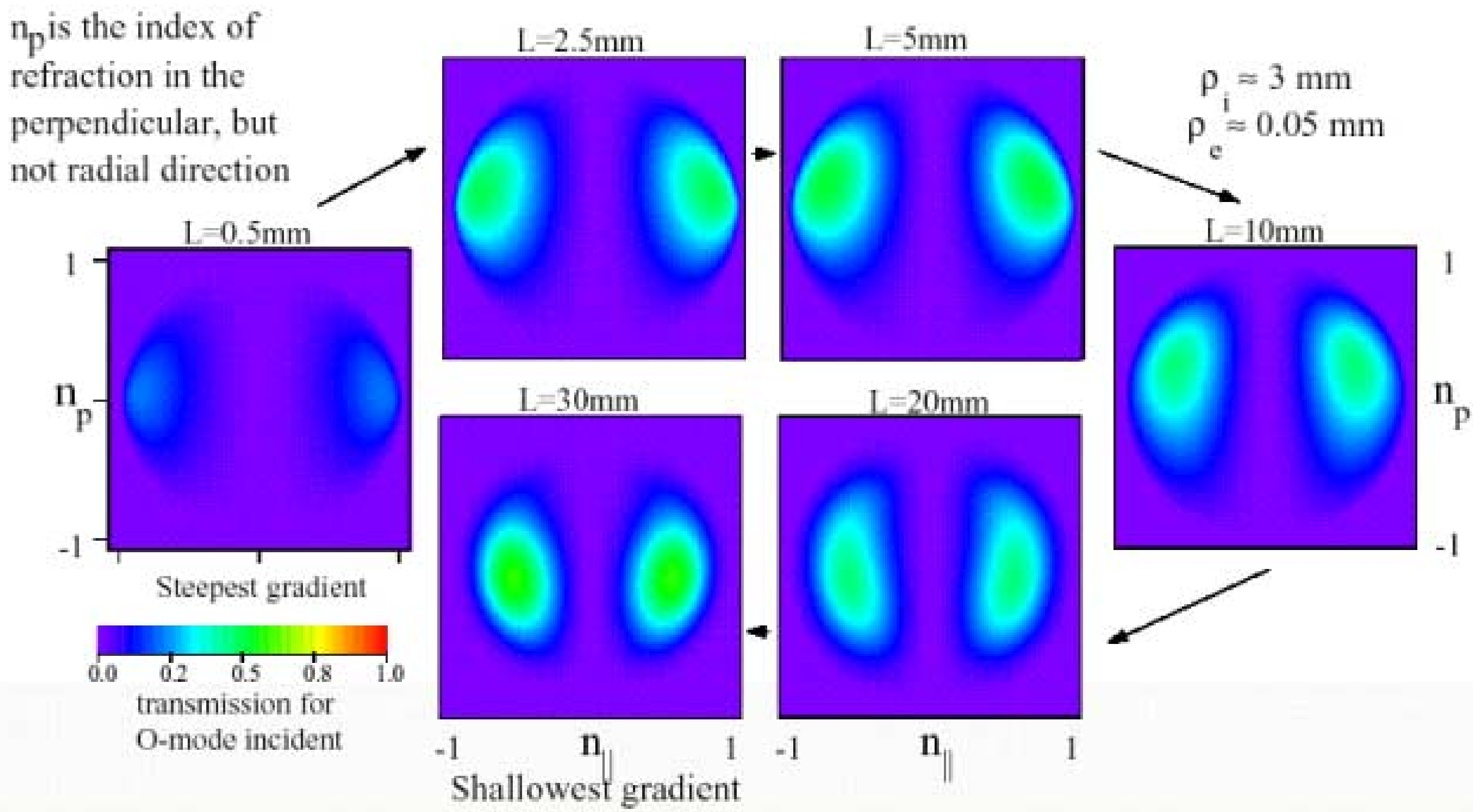
X-EBW

Transmission angle is a strong function of density gradient for $B_{rf} || B_0$ incidence



O-X-EBW

Optimum transmission angle depends weakly on density gradient for $B_{rf} \perp B_0$



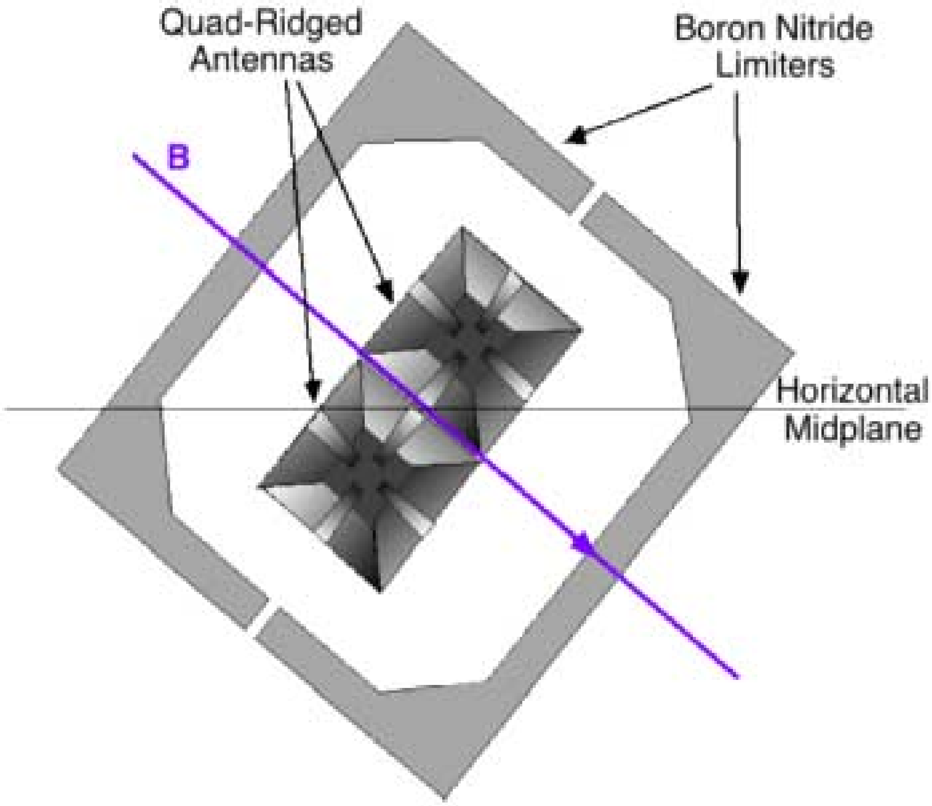
EBW emission, ST physics and high power tube technology impact the design

EBW emission measurements:
- **Can indicate viability of EBW heating and current drive**
- **Guide the launcher antenna/plasma interface**
- **Help decide whether the antenna launch is X-B, O-X-B or both.**

EBW "role" & coupling efficiency guide choice of launch frequency:
- **Fundamental launch at 8, 12 or 15.3 GHz**
- **Second harmonic launch at 28 GHz**

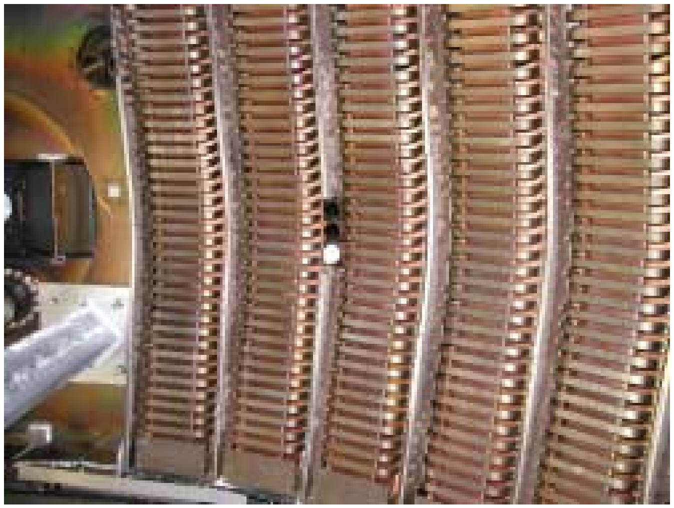
High power tubes:
- **Available at both 8 and 28 GHz.**
- **Possibility exists to modify 28 GHz tubes to 15.3 GHz**
- **Tube development required for optimized high power tubes at ~ 12-15 GHz.**

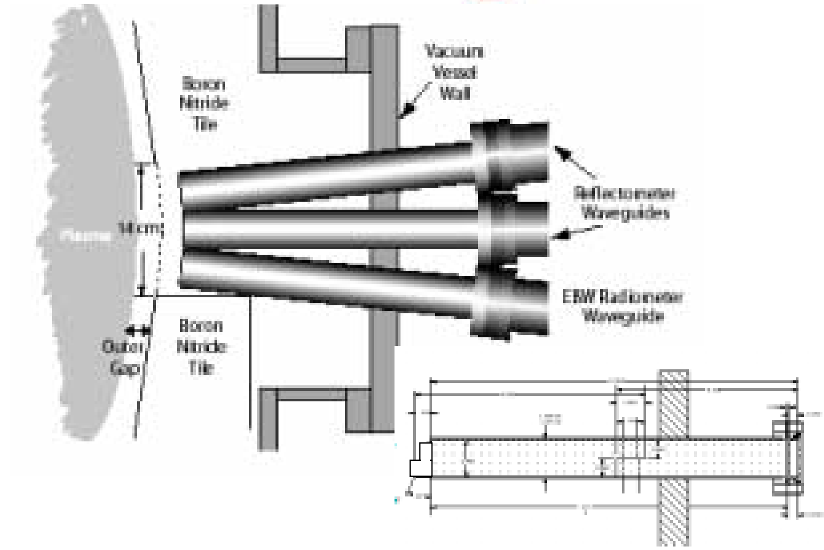
X-EBW quad-ridged antennas

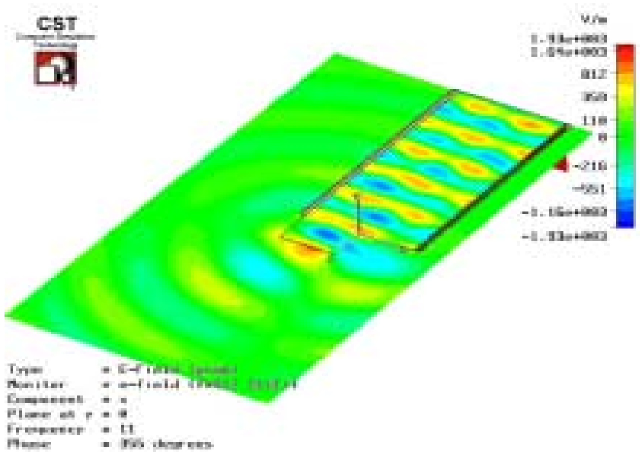


- Two radially movable boron nitride limiters
- Integrated with O-Mode reflectometer to measure local L_n
- local gas inlet valve to enable local density control

O-X-EBW boron nitride step antenna







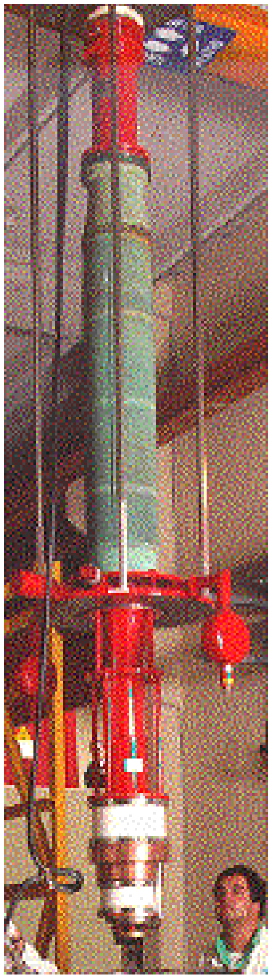
EBW frequency tradeoffs

H&CD, plasma startup, local heating, NTM suppression

Qualitative comments:

Frequency/ harmonic #	Resonant field (T)	Critical density $x10^{12}$ cm^{-3}	Scale length (mm) Coupling X O-X-B	Sources (MW)	Deposition spot size	Potential for driving edge parametric instabilities	Heating, CD, or NTM
28 GHz/fund	1	9.2	~ 1 ~10	0.3	++	1	H, CD?
2nd	0.5						H, NTM
3rd	0.33						NTM
18 GHz/fund.	0.64	3.8	~1.5 ~15	0.015	+	2 - 8 X	H, CD
2nd	0.32						NTM
15.3 GHz/fund	0.546	2.7	~ 2 ~20	0.2 Modified 28 GHz	+	4 - 16 X	H, CD, NTM
2nd	0.27						H, NTM
12 GHz/fund	0.43	1.3	~2.5 ~25	??	+	6 - 24 X	H, CD, NTM
2nd	0.21						?
8 GHz	0.29	0.95	~ 3 ~30	0.5	-	8 - 32 X	NTM
2nd	0.14						?

Thales 8 GHz 1 MW Gyrotron



Cavity Oscillation Mode	TE_{511}
Nominal Output Frequency	8 GHz
Frequency Stability	+/- 1 MHz
Output Power (TE_{01})	1.1 MW
Peak Power @ VSWR = 4:1	700 kW
Frequency Pulling @VSWR=4:1	+/-2 MHz
Beam Voltage (typ)	84 kV
Beam Current (typ)	27 A
Efficiency	<= 46 %
Gun-anode Voltage (typ)	51 kV

The RF output is through a single disk, alumina (Al_2O_3) window, edge cooled by water flow.

Personal comment:
Basis for 1 MW 15 GHz design

28/15.3 GHz hardware available

- Utilize existing hardware to make experiments affordable
- Four 28 GHz, 200 kW, gyrotrons available at ORNL
- May be possible to retune and operate at 15.3 GHz
- Pulsed or cw tubes can be refurbished and generate 200-350 kW each (0.8-1.4 MW from 4 tubes)
- Four sockets and HV modulator/regulator are available at ORNL
- Utilize installed PPPL "NBI" power supply available at D-site (-90 kV at 40 A) or DNB supply (-90 kV, 30A)
- ATF beam launcher assembly

28 GHz to 15.3 GHz conversion

15.3 GHz TE01 mode:

Cathode Voltage = 80 kV

Mode Anode Voltage = 67 kV

Cathode to mod anode voltage = 13 kV

Cavity magnetic field = 0.60 T

Cathode magnetic field = 0.062 T

Beam magnetic compression = 9.7

Beam alpha (velocity ratio, $v_{\perp} / v_{\parallel}$) ~2.0

Beam size at cavity = 0.13 inch

Magnetic field profile optimization required

Proposed design for 1 MW 15 GHz

Waves and Beams Division

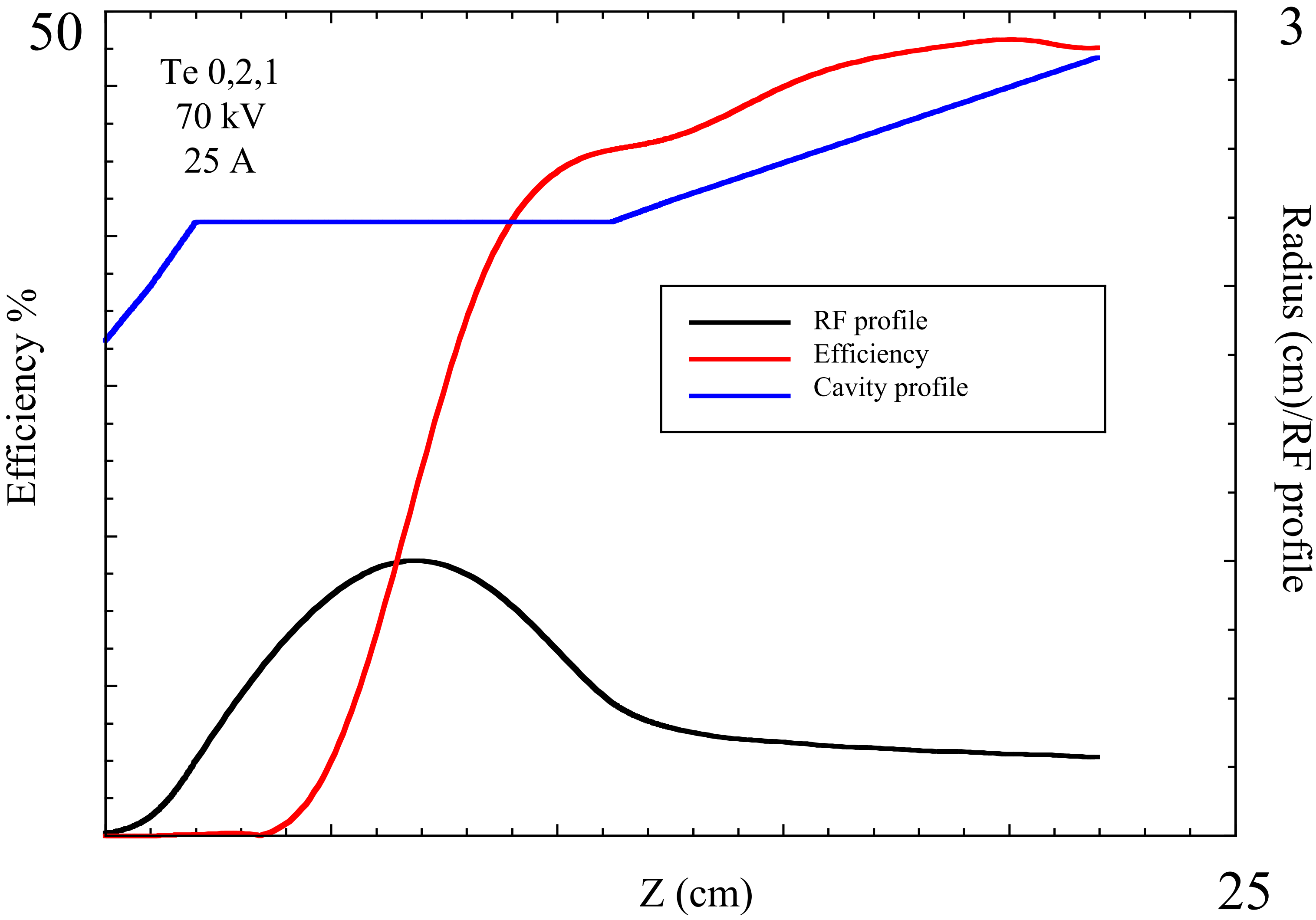
- Mode TE_{02}
- Frequency 15 GHz
- Magnetic field 0.58 T
- Beam current 25 A
- Beam voltage 70 kV
- Anode voltage 50 kV
- Body voltage 20 kV
- Beam radius at cavity 1.45 cm
- Beam pitch factor a 1.5
- Voltage depression in cavity 2.5 kV
- Cathode radius 4.5 cm

- Perp. velocity spread 10 %
- Normalized cavity length L/l 4.4
- Cavity length 9.2 cm
- m parameter 8.15
- Cavity radius Rc 2.233 cm
- Limiting current 90 A
- Normalized detuning D 0.67
- Diffraction Q factor 360
- Efficiency w/o depressed collector 47 %
- Efficiency w depressed collector 65 %
- Power 820 kW
- Cavity wall loading 0.2 kW/cm^2

Personal comments:
MIT design; CPI engineering and fabrication. Guess; 1st tube ~ $1M 2nd tube ~ $.5M
Depressed collector likely not advantageous with PPPL power supplies
Thales would likely also bid with their own ~ 1 MW 15 GHz design

Self-consistent gyrotron design code

Waves and Beams Division

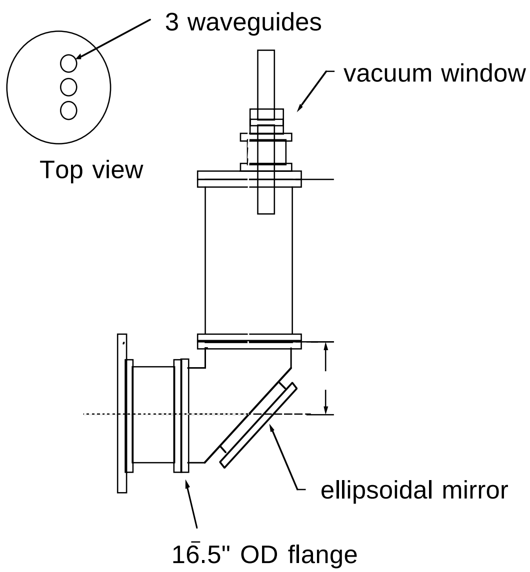


High power launcher requirements

- For EBW and current drive schemes, high beam quality and focusing is required
- Some beam steerability desired
  - Focusing mirrors close to plasma or
  - Phased array (4-8 waveguides)
- Polarization control can be provided by external waveguide or by mirror grooves
- Three options under consideration

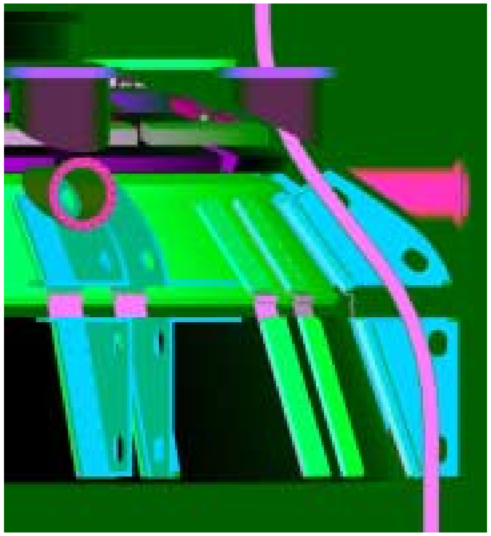
Three possible launcher schemes

External mirror



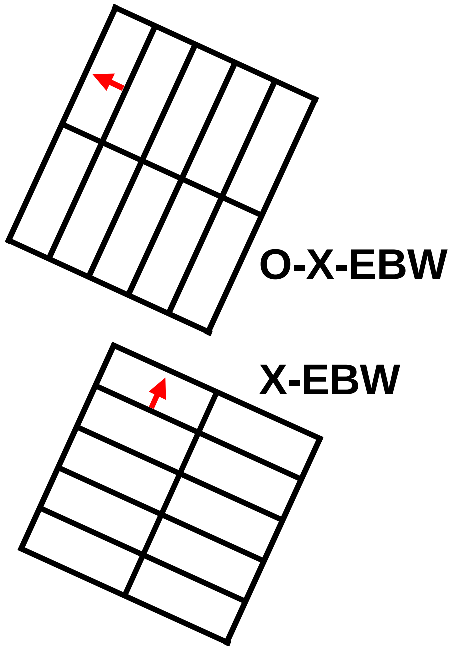
Multiple waveguide feeds

Internal mirror



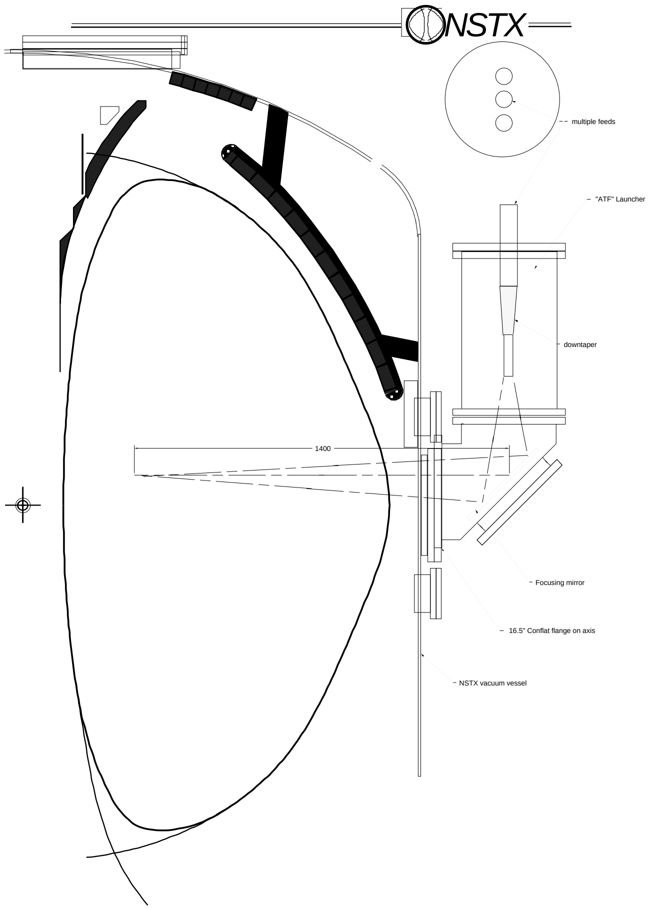
Curved waveguide through top port

Waveguide grill



8-10 elements

Multiple gyrotron outside-mirror launcher configuration

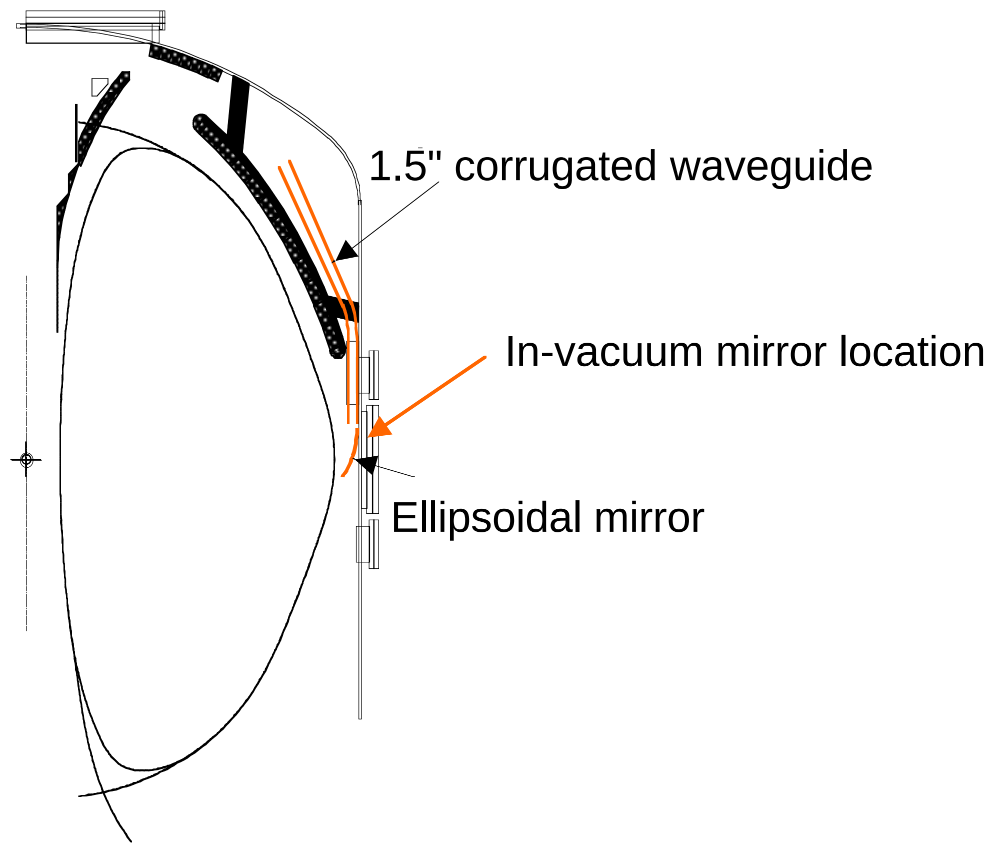


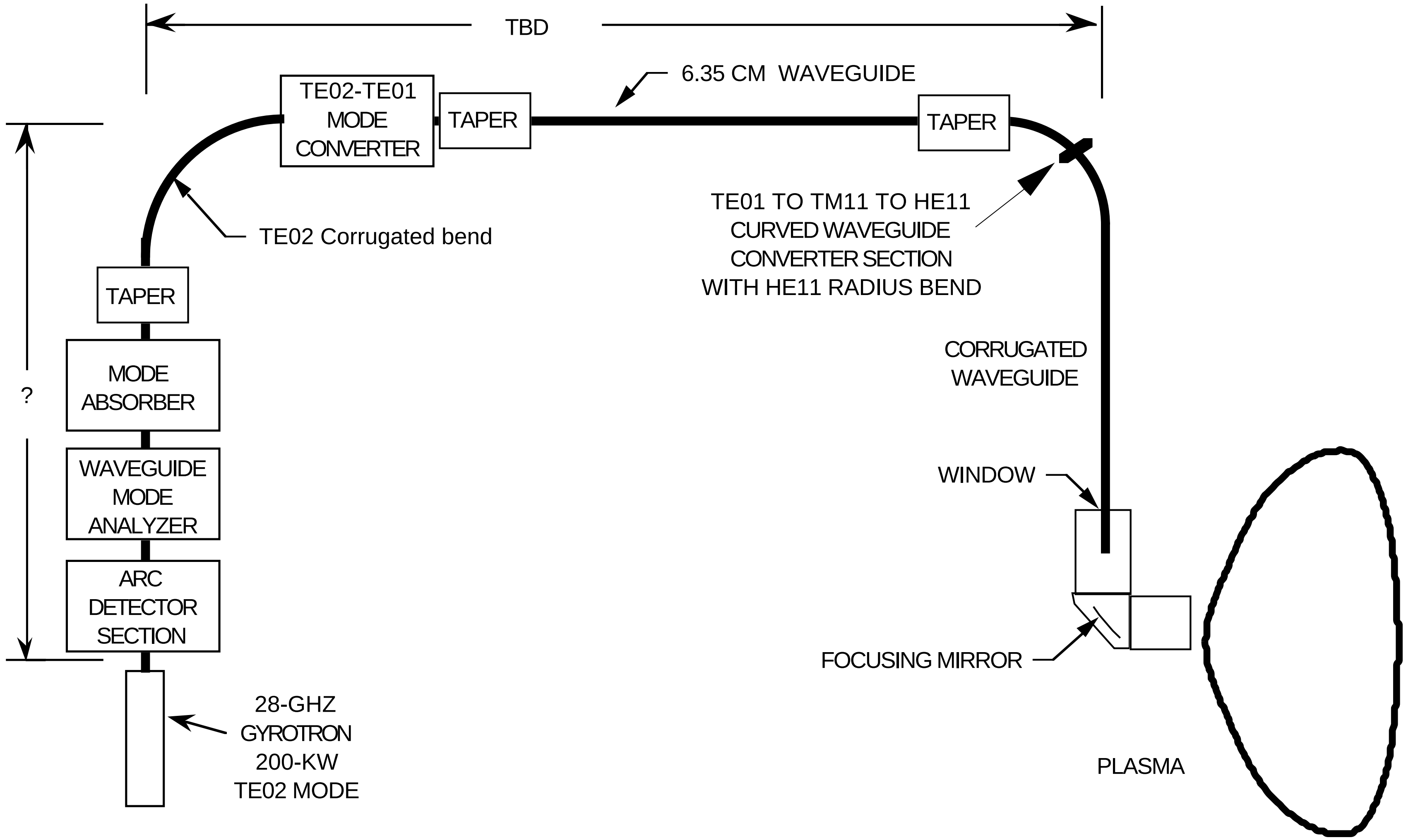
- Utilize existing launcher
- Need large midplane port
- Narrow focused beam
- Adjustable pointing angle
- Less beam steering possible

ECH launcher from ATF

Top port launch option

- **Use several available top ports**
- **Route curved corrugated waveguide to midplane behind stabilization plates**
- **Use inside focusing mirror for launch**
- **Advantages**
  - **Ports available**
  - **Better launch optics**
- **More difficult for installation & beam steering**





BLOCK DIAGRAM PROPOSED NSTX 28 GHZ ECH SYSTEM

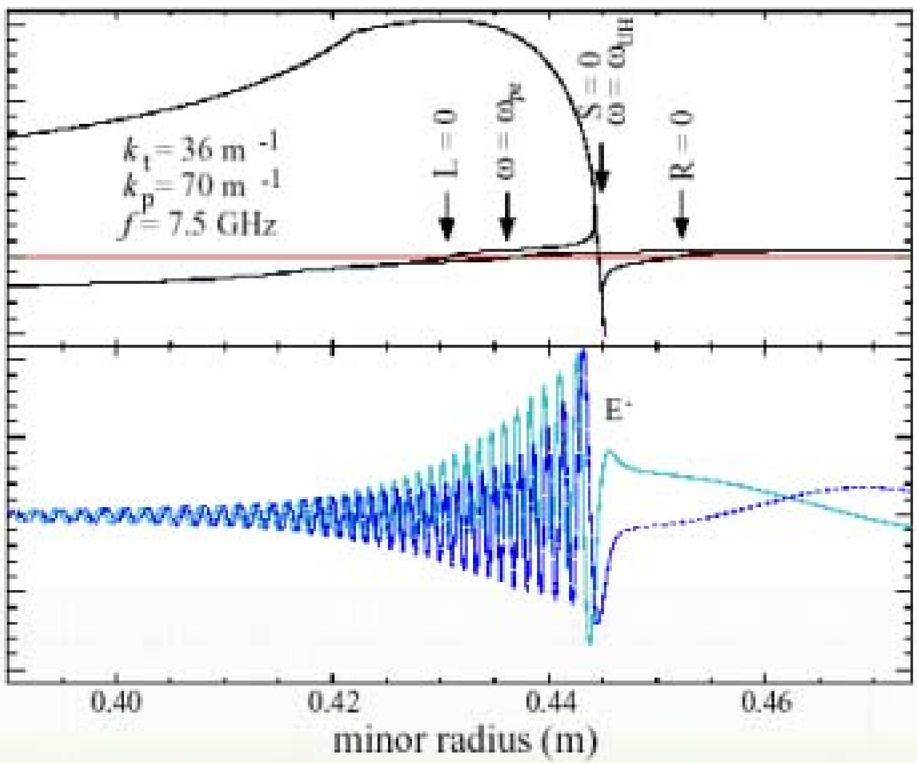
Strawman Schedule & Goals

- **Demonstrate >80% B-X conversion (local limiter, early 2003)**
- **Model EBW Heating & CD (early 2003)**
- **Demonstrate >80% B-X-O conversion (w or w/o local limiter, late 2003)**
- **Complete conceptual design for EBW heating and current drive system (early 2004)**
  - **Source frequency, f_{ce} or $2f_{ce}$?**
  - **Local limiter?**
  - **X-B or O-X-B**
  - **Power level? 1MW (2006), ~ 5MW (2008)**
- **Complete ~1MW installation (late 2006)**
- **Explore Core Heating (~ 1MW, 2006-7)**
- **Explore EBW Startup (~ 1MW, 2007)**
- **Complete ~ 5MW installation (2008)**
- **~ 400 kA EBW sustained current (~ 5MW, late 2008)**

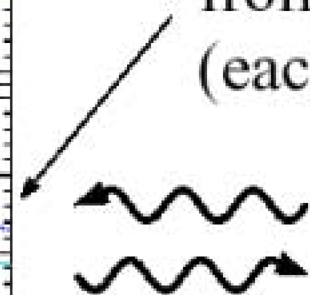
Backup

GLOSI solves for mode converted wave fields in plasma edge

- For each poloidal and toroidal mode, generates a 2x2 surface impedance for tangential components of the RF fields at the plasma/vacuum interface

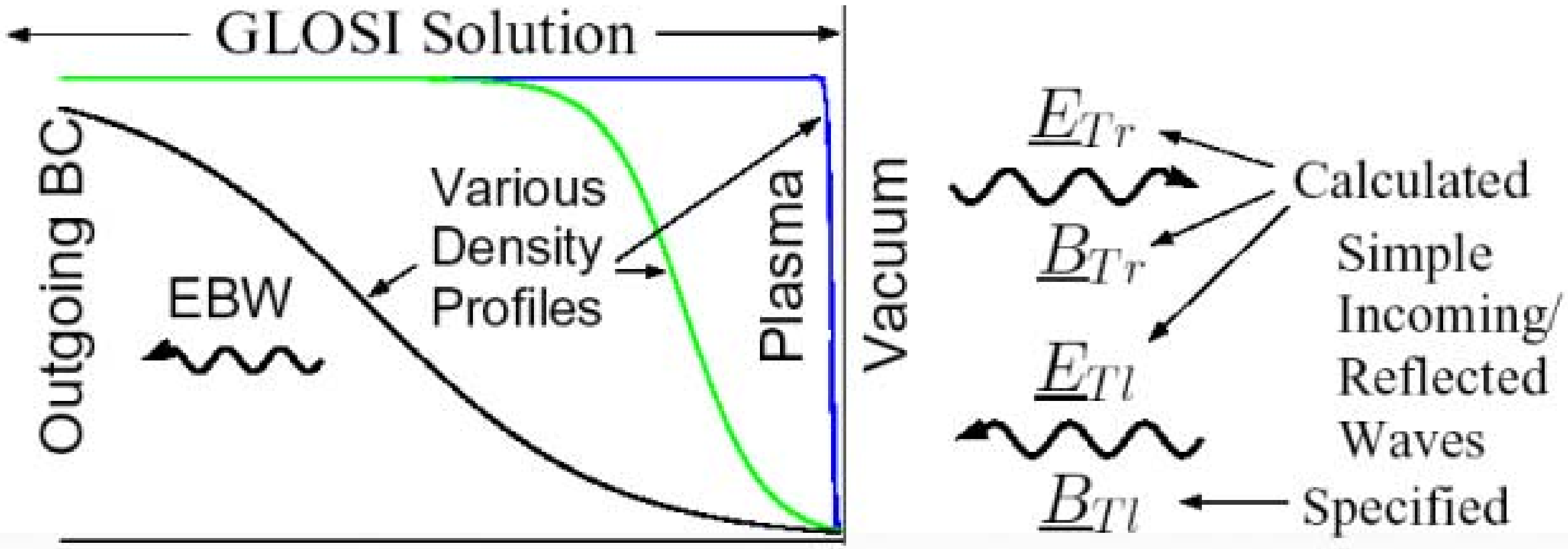


Surface Impedance from GLOSI (each *m,n*)



Systematic variation of density gradient near upper hybrid layer gives good idea about optimum angle for coupling

- Emission at same angles as absorption
- Te = Ti = 10 eV, B = 0.13 T, 7 GHz



$$n_e = 1\times 10^{18}\mathrm{m}^{-3}\left[1 - tanh\left(\frac{x - x_r + 2L}{L}\right)\right]$$