ELECTRON BERNSTEIN EMISSION DUE TO NONTHERMAL DISTRIBUTIONS IN NSTX

***R.W. Harvey*[1]*, A.P. Smirnov*[1]*, E. Nelson-Melby*[1]*, G. Taylor*[2]*, S. Coda*[3]*, A.K. Ram*[4]**

[1]CompX, Del Mar, Calif., US [2]Princeton Plasma Physics Laboratory, Princeton, NJ, USA [3]EPFL, Lausanne, Switzerland [4]Massachusetts Institute of Technology, Boston, MA, USA

OUTLINE:

- GENRAY calculates electron Bernstein wave emission (EBWE) from thermal or nonthermal distributions (and is also an all frequencies ray tracing code).
  - Emission and absorption are calculated at each point along an EBW ray, and the radiation transport eqn is back-solved to the detector.
  - A hot plasma dispersion relation (Forest) and a relativistic calculation of the emission and absorption is used.
- The BXO (Bernstein-X-O mode conversion) emission window is found with a shooting algorithm to obtain the central ray angles for a given receiver (antenna) position, giving 100% transmission (Kopecky, Preinhaelter, Vaclavik, J. Pl. Phys., 1969).
  - Alternatively, efficient BX conversions is assumed.
- Following, we show calculated EBWE radial profiles for an NSTX experimental profile with thermal distributions, and compare to a case with EBWCD nonthermal distributions from a simulated OXB injection experiment. Both “low” and high beta cases are considered.

WHAT WE FIND:

- **EBW emission provides a flexible means to examine both thermal and nonthermal distributions. But calculations are required!**

Radiation Transport Equation

$I =$ Power per unit (area · radian free · steradian) flowing in direction $\hat{s}$

$$\boxed{\begin{array}{ccccc} n_r^2\ \hat{s}\cdot\nabla(n_r^{-2}I) & = & j & - & \alpha I \\ \Uparrow & & \Uparrow & & \Uparrow \\ \text{ray direction} & & \text{emissivity} & & \text{absorptivity} \end{array}}$$

$n_r =$ Ray refraction index (cold plasma)

$\hat{s} =$ Ray direction (cold plasma)

$j =$ Power radiated per unit volume, per (radian frequency, steradian)

$\alpha =$ Inverse damping length

<u>Multiple Reflections</u>

$$I_{0t} = I_0\ \left(1 + r\,e^{-\tau} + r^2\,e^{-2\tau} + \ldots\right)$$
$$= I_0\ /\ \left(1 - r\,e^{-\tau}\right)$$

CompX

▼

At each point along the ray:

$$\alpha = \frac{\omega}{4\pi}\,\frac{\underline{E}^{*}\cdot\underline{\underline{\varepsilon}}_{\mathrm{a}}\cdot\underline{E}}{|\underline{S}|}\,, \qquad j = \pi\, n_{\mathrm{r}}\left(\frac{\omega}{c}\right)^{2}\frac{\underline{E}^{*}\cdot\underline{\underline{G}}\cdot\underline{E}}{|\underline{S}|}\,,$$

$$\underline{\underline{\varepsilon}}_{\mathrm{a}} = -\,\pi\,\frac{\omega_{\mathrm{p}}^{2}}{\omega^{2}}\sum_{n=-\infty}^{\infty}\int d^{3}p\,U(f)\,\underline{\underline{S}}^{(n)}\,\delta\left(\gamma-\frac{k_{\parallel}u_{\parallel}}{\omega}-\frac{n\omega_{\mathrm{c}}}{\omega}\right)\,,$$

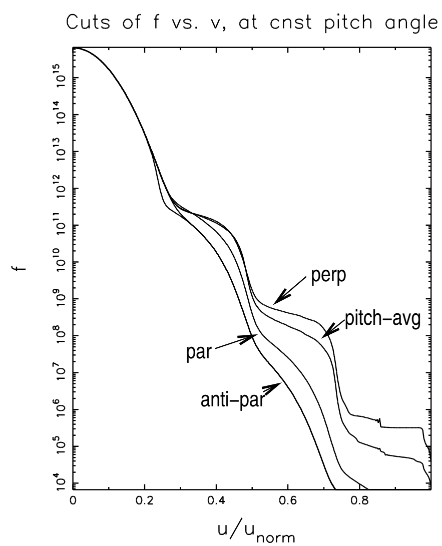
$$\underline{\underline{G}} = \frac{\pi}{(2\,\pi)^{5}}\,\frac{\omega_{\mathrm{p}}^{2}}{\omega^{2}}\,\frac{1}{m}\sum_{n=-\infty}^{\infty}\int\frac{d^{3}p}{\gamma}\,f\,p_{\perp}\,\underline{\underline{S}}^{(n)}\,\delta\left(\gamma-\frac{k_{\parallel}u_{\parallel}}{\omega}-\frac{n\omega_{\mathrm{c}}}{\omega}\right)\,,$$

$$U(f) \equiv \frac{1}{\gamma}\left[\frac{n\omega_{\mathrm{c}}}{\omega}\,\frac{\partial f}{\partial p_{\perp}} + n_{\parallel}\,\frac{p_{\perp}}{mc}\,\frac{\partial f}{\partial p_{\parallel}}\right]\,,$$

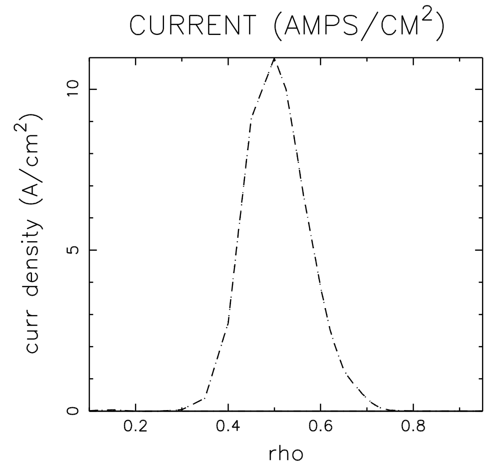
$$\underline{\underline{S}}^{(n)} \equiv \begin{bmatrix} p_{\perp}\left(\frac{nJ_{\mathrm{n}}}{b}\right)^{2} & -\,ip_{\perp}\,\frac{nJ_{\mathrm{n}}J_{\mathrm{n}}'}{b} & p_{\parallel}\,\frac{nJ_{\mathrm{n}}^{2}}{b} \\ ip_{\parallel}\,\frac{nJ_{\mathrm{n}}J_{\mathrm{n}}'}{b} & p_{\perp}\left(J_{\mathrm{n}}'\right)^{2} & ip_{\parallel}J_{\mathrm{n}}J_{\mathrm{n}}' \\ p_{\parallel}\,\frac{nJ_{\mathrm{n}}^{2}}{b} & -\,ip_{\parallel}J_{\mathrm{n}}J_{\mathrm{n}}' & \frac{p_{\parallel}^{2}}{p_{\perp}}\,J_{\mathrm{n}}^{2} \end{bmatrix}\,,$$

Comparison of EBWE from Thermal and Non–Thermal NSTX Shot (113544) [With next few slides]

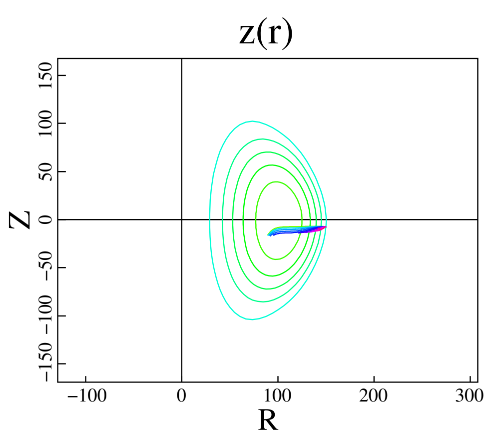
Non–Thermal Dististributions used for calcs vs rho (here = 0.59)

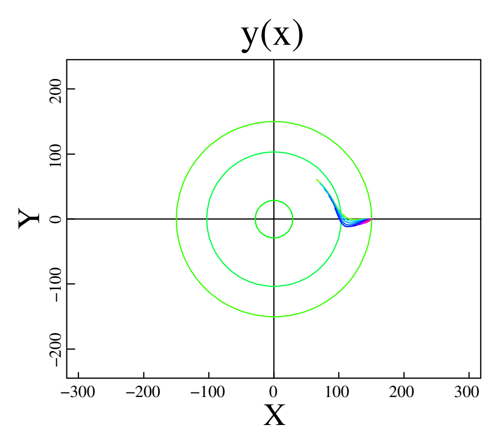


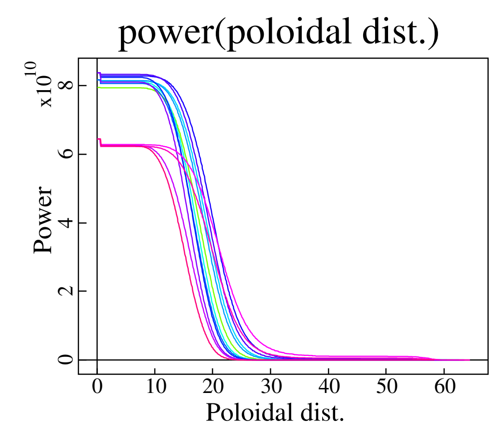
Radial variation of EBWCD vs rho. 1MW EBW, 47 kA.



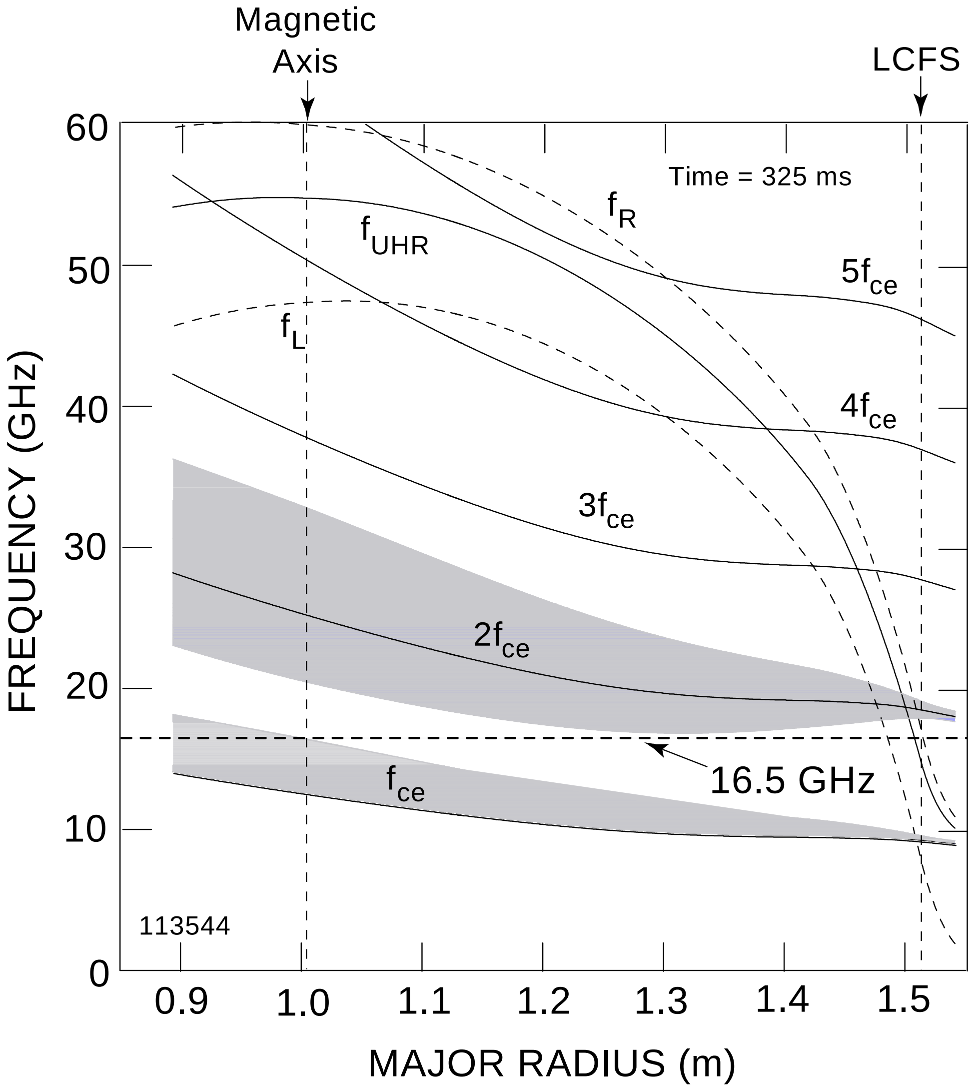
Good penetration of 16.5GHz, EBW with OXB launch







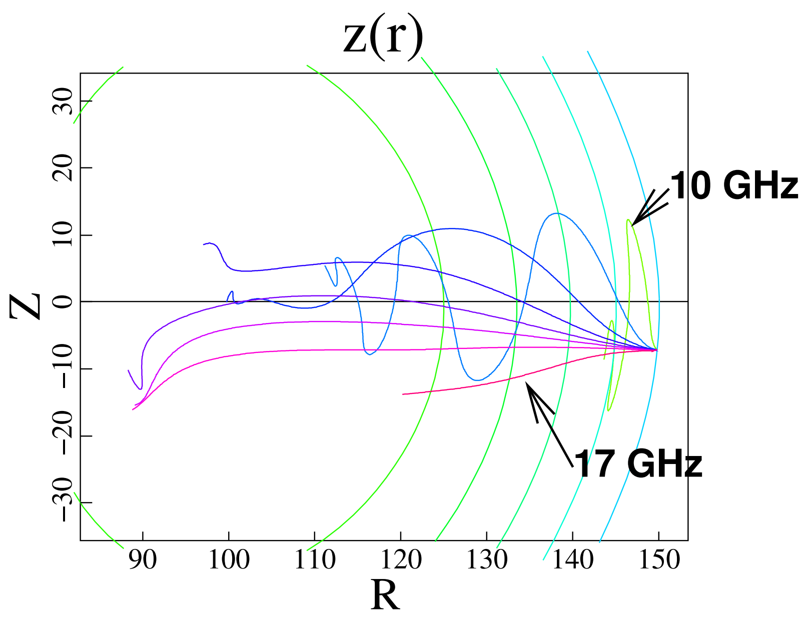
Critical Frequencies: Low Beta Case

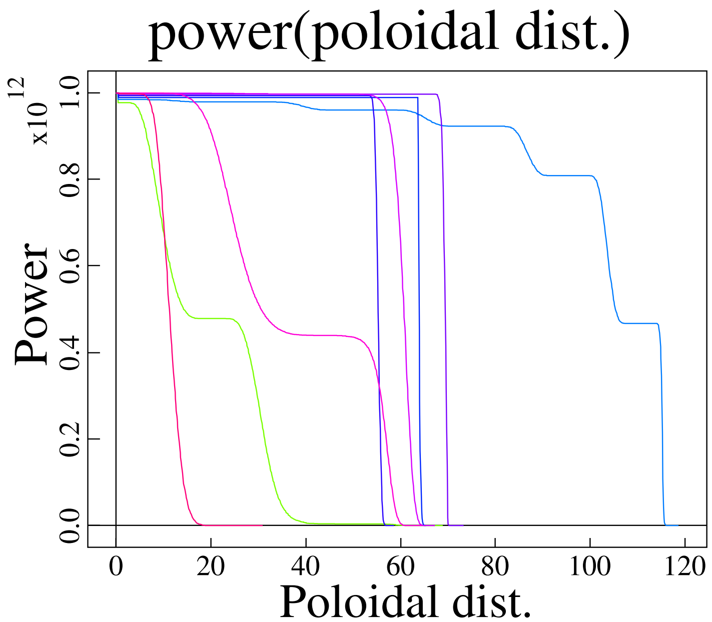


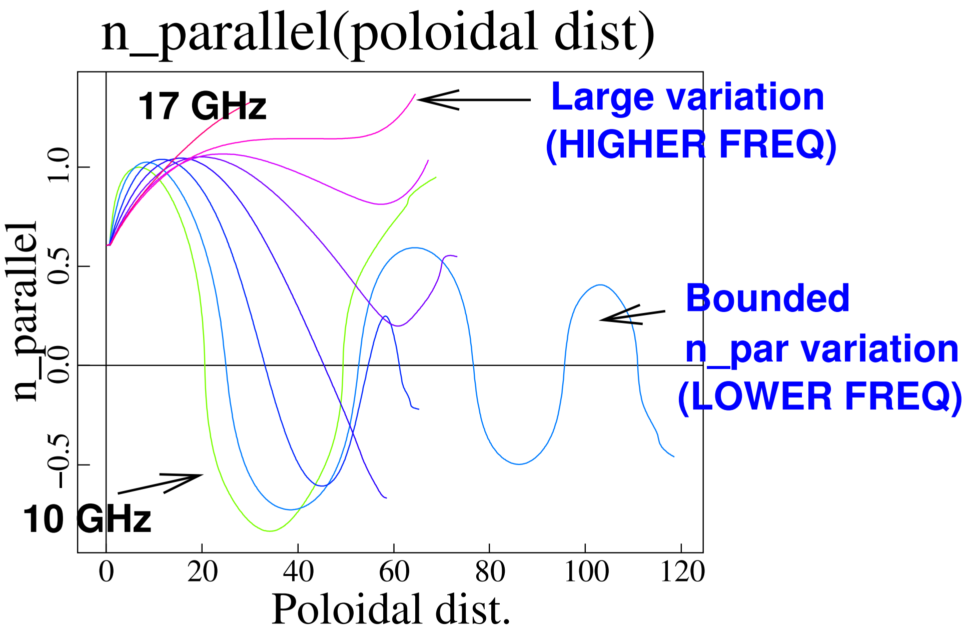
Examine emission between 1st and 2nd harmonic

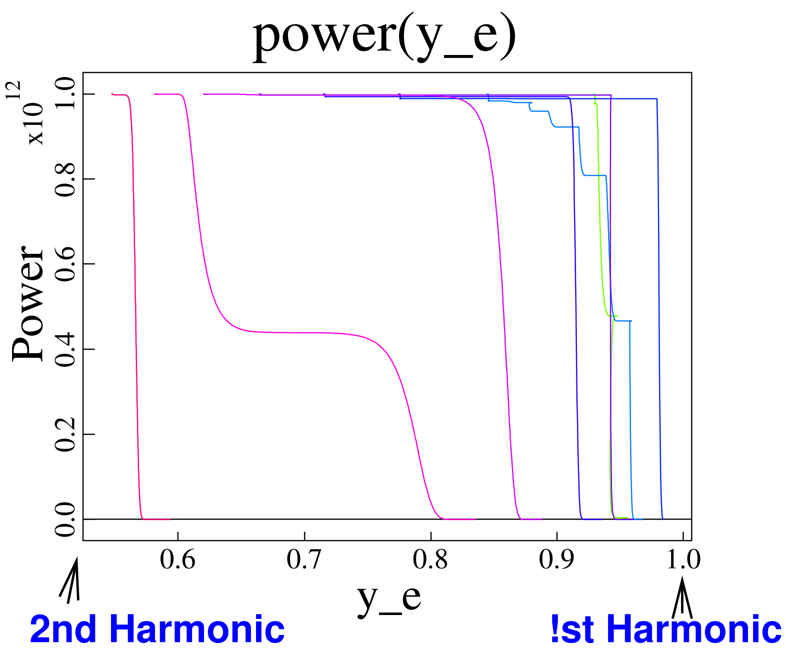
Figure 4

Ray Characteristics in 1st–2nd Harm Range (10–17GHz)





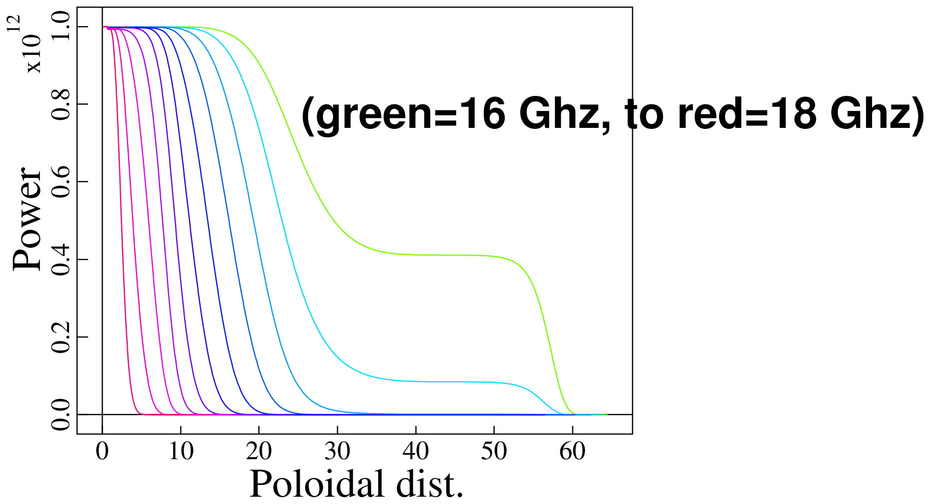




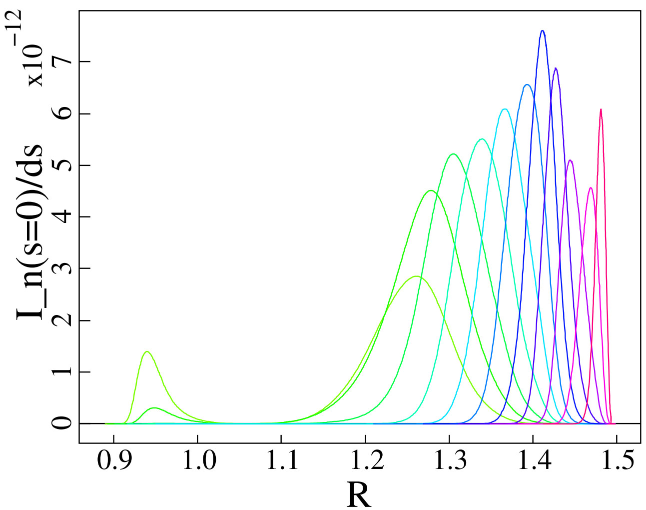
HIGHER FREQUENCY EMIS: Sensitive to NonThermals

Thermal

power(poloidal dist.)

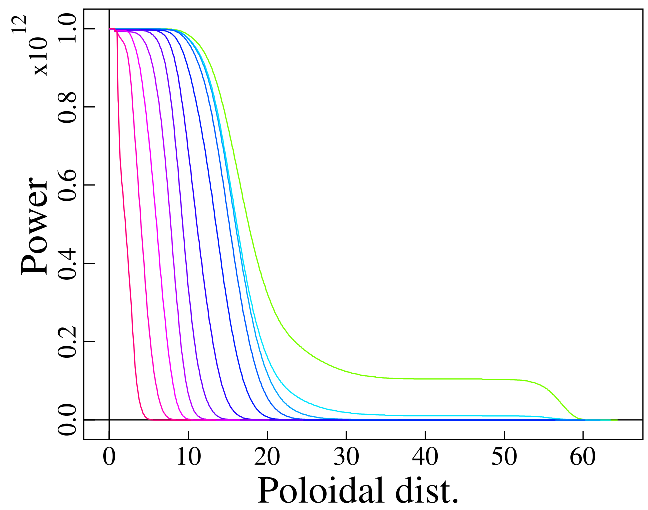


(Thermal specific intensity) dI/ds

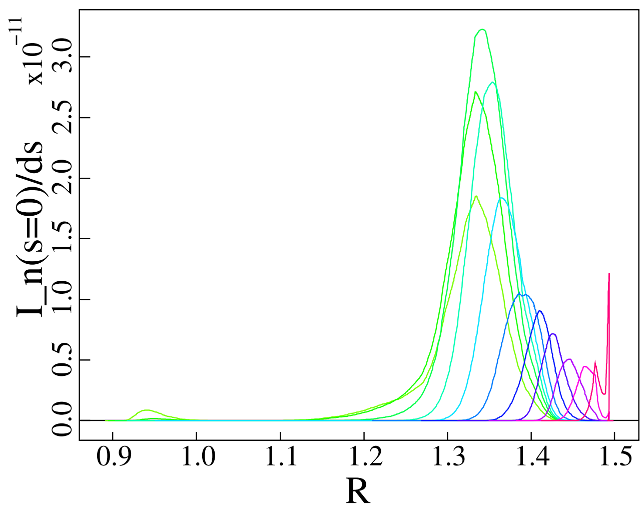


Non−Thermal

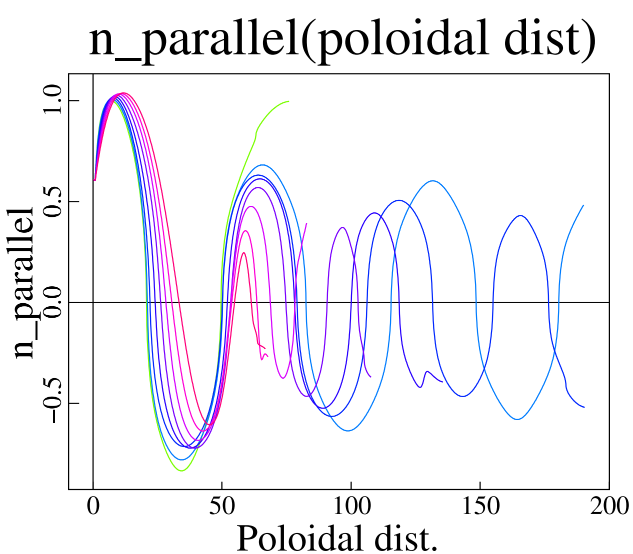
power(poloidal dist.)

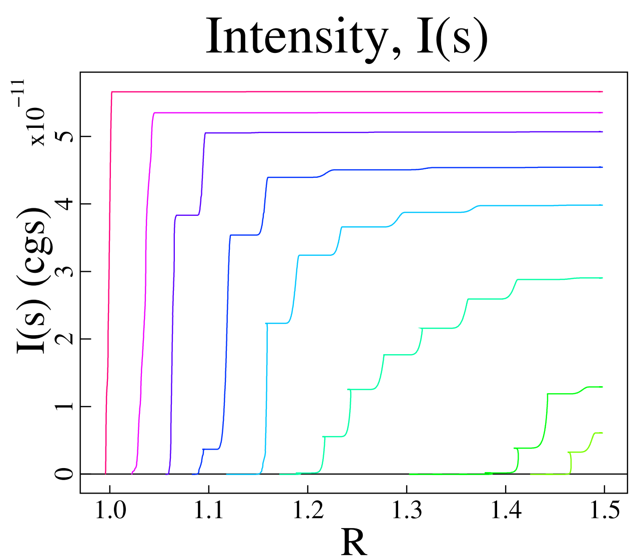


(Non−Thermal specific intensity) dI/ds

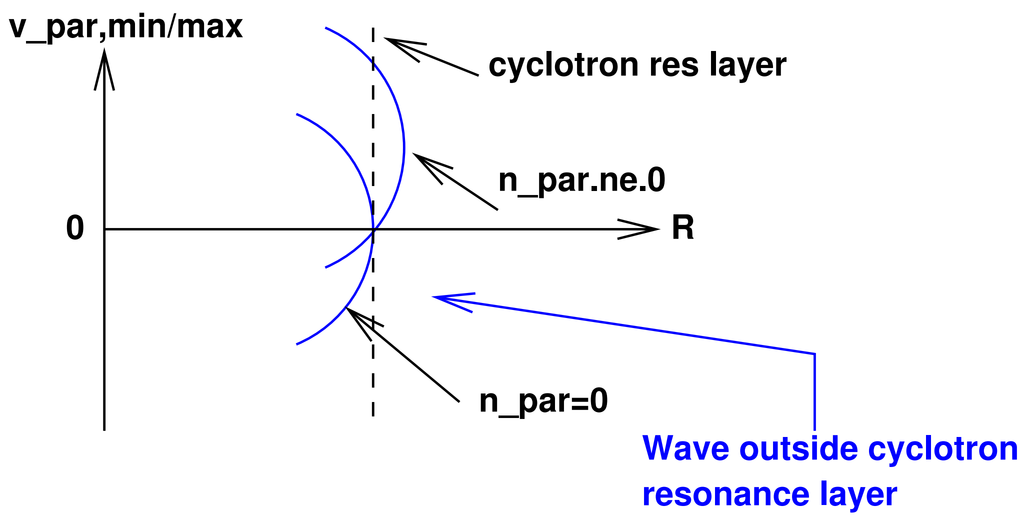


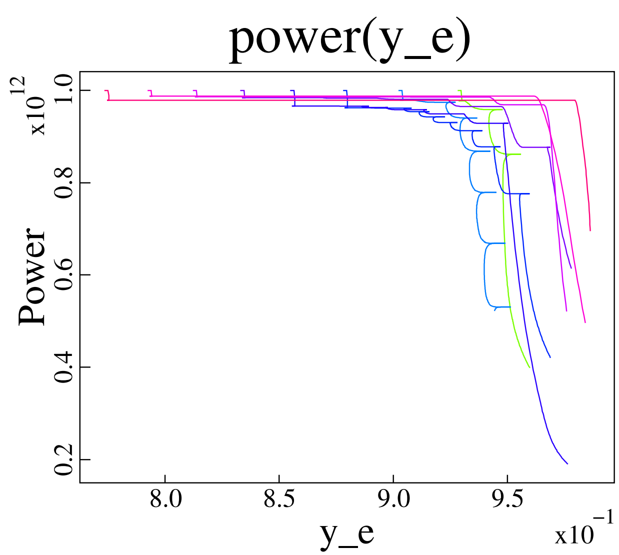
LOWER FREQENCY EMISSION: Maxwellian case
Absorp/Emission Controlled by n_par–Variation





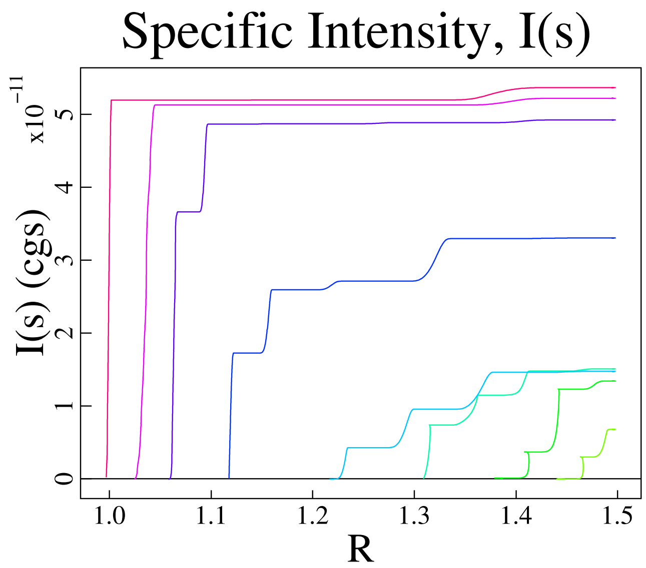
Relatvivistic Resonance Ellipse

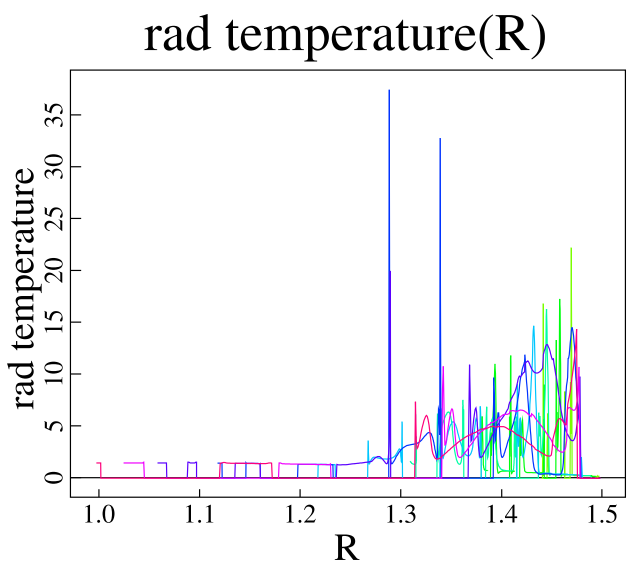


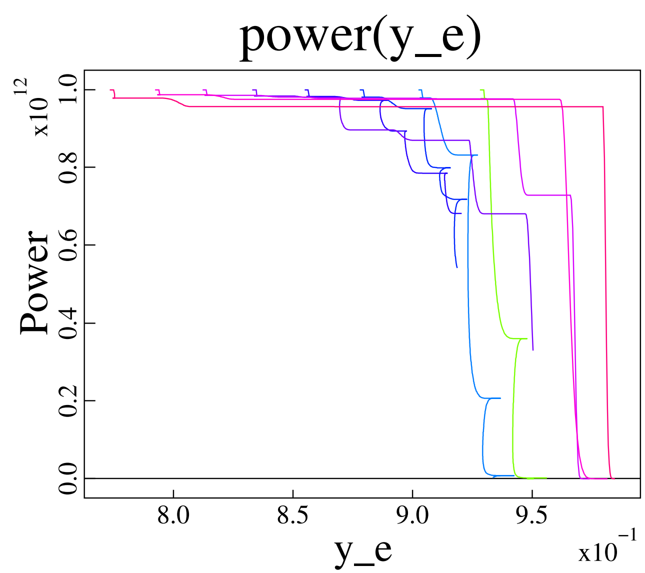


LOWER FREQUENCY EMISSION: Nonthermal case
Absorp/Emission Controlled by n_par–Variation

- **The power aborption and specific intensity have the same staircase effect as the thermal case.**
- **Therefore, expect an approx thermal temp measurement despite the high local radiation temperature, below.**



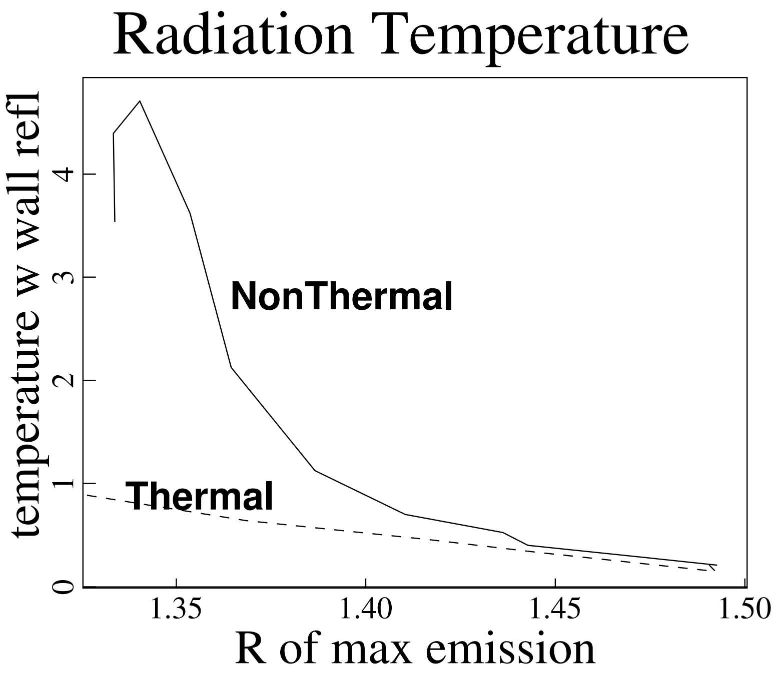




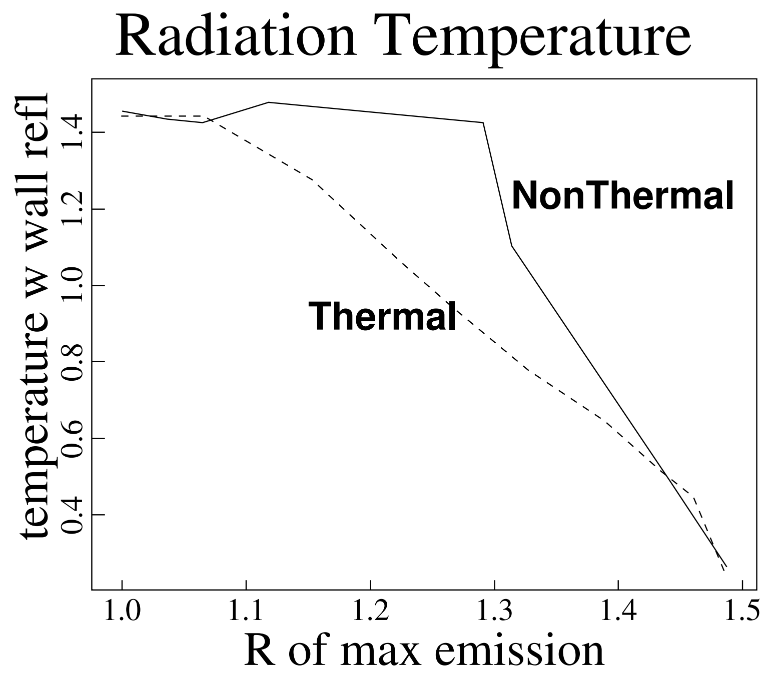
High Freq Radiation Gives Strong Nonthermal Trad, whereas, Low Freq Gives Near Thermal Trad (Low Beta case)

- **This result depends on whether there is large n_par (high freq), or small (low freq)**

High Frequency

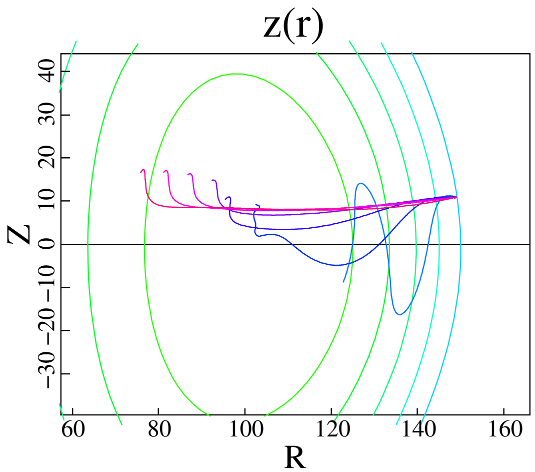


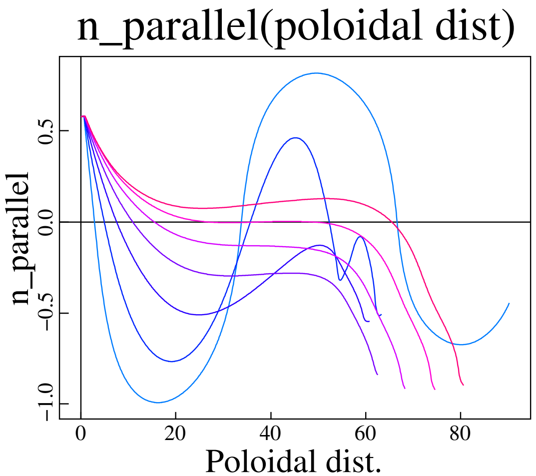
Low Frequency

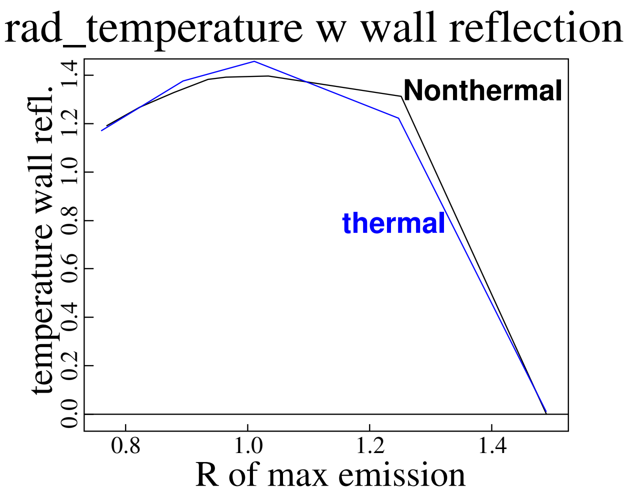


Effects of Poloidal Launch Location

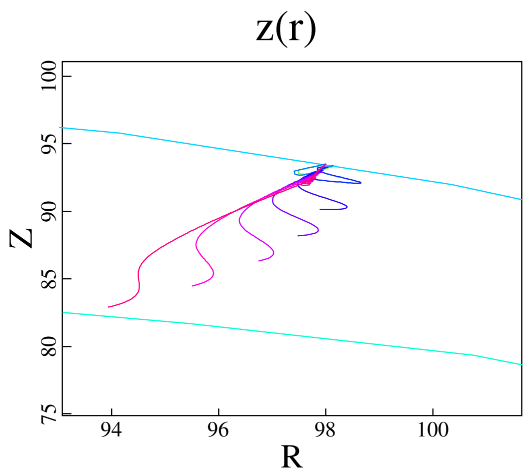
Launch from Z=+15 cms, low freq, gives less n_par–variation, more thermal Trad

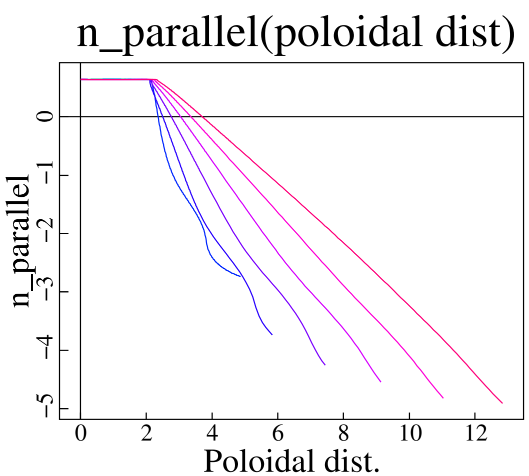


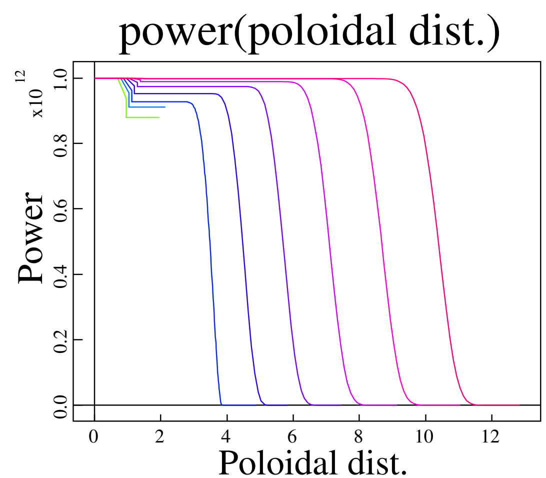




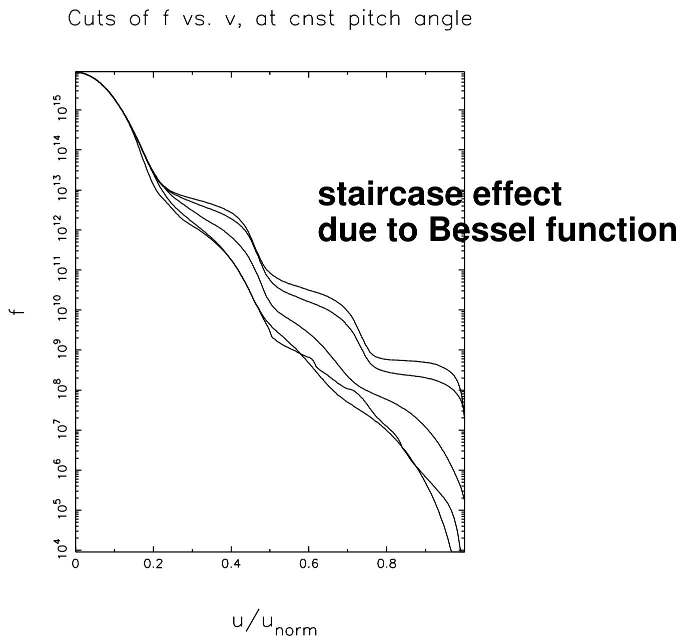
Near Top Launch gives large n_par–variation, poor penenetration (doesn't reach NTs)

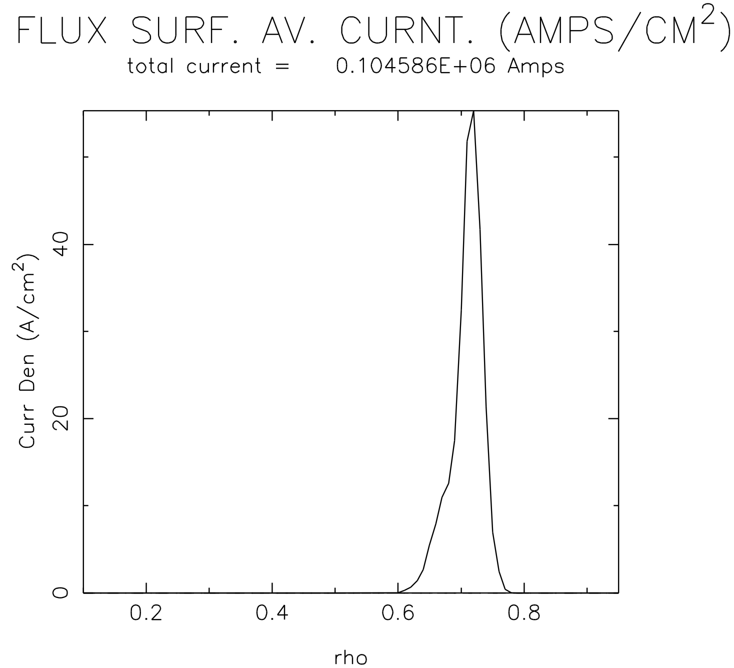




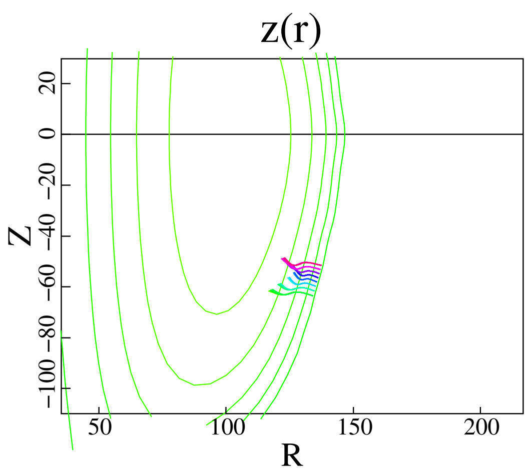


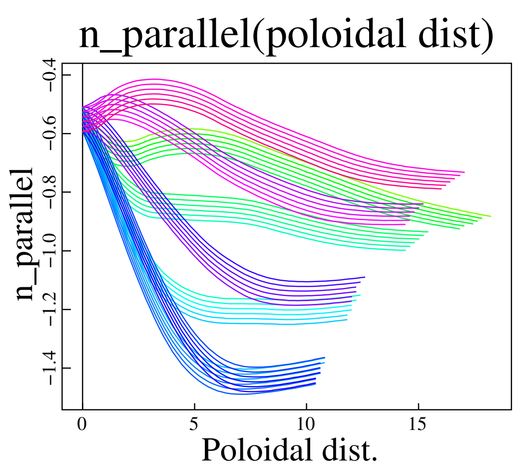
High Beta (41%) NonThermal Distribution, 4 MW



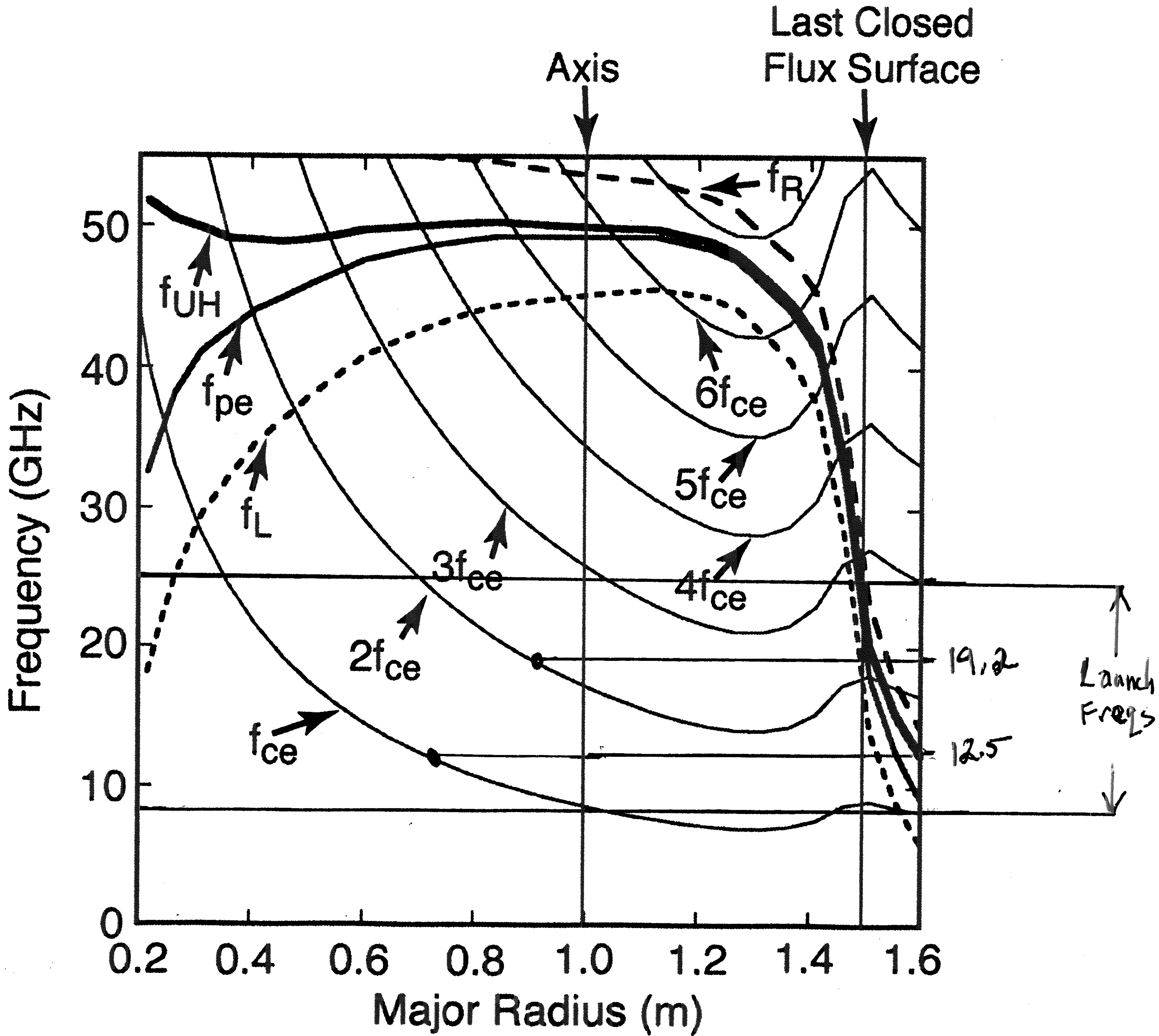


OXB Injection at 14 GHz, Taylor, PoP'04
(Gives amazing large n_par–variation with poloidal location)





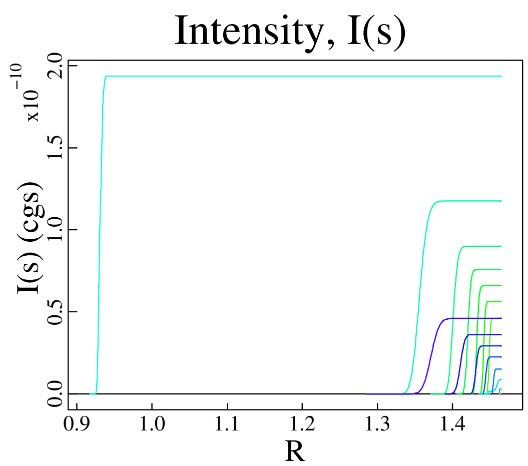
Critical Frequencies, High Beta (41%)

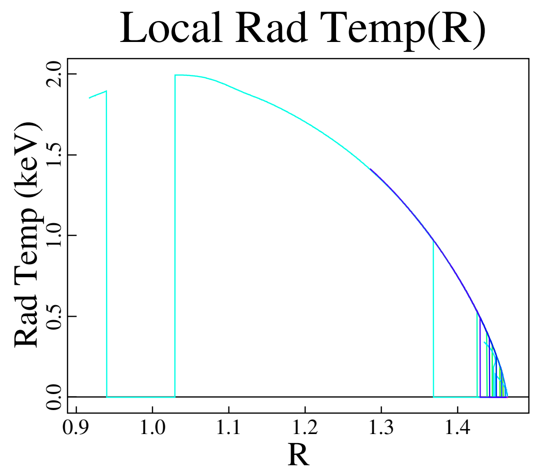


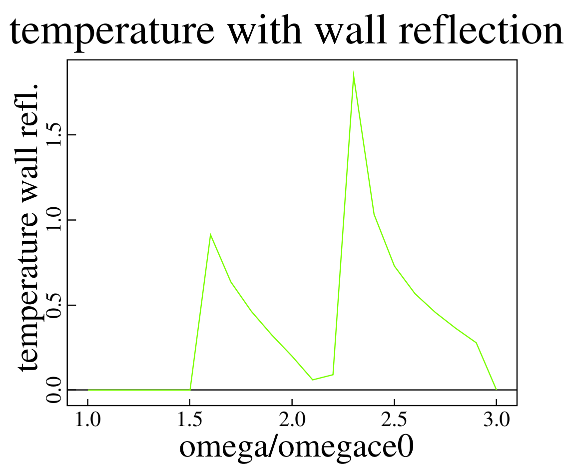
Taylor et al, PoP'04

Comparison of Rad Temp from Thermal and NonThermal

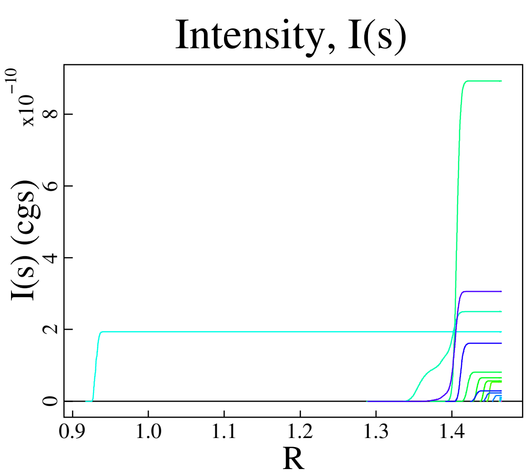
Thermal Distributions

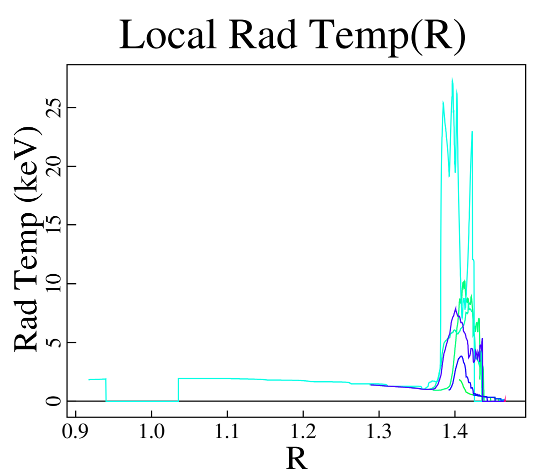


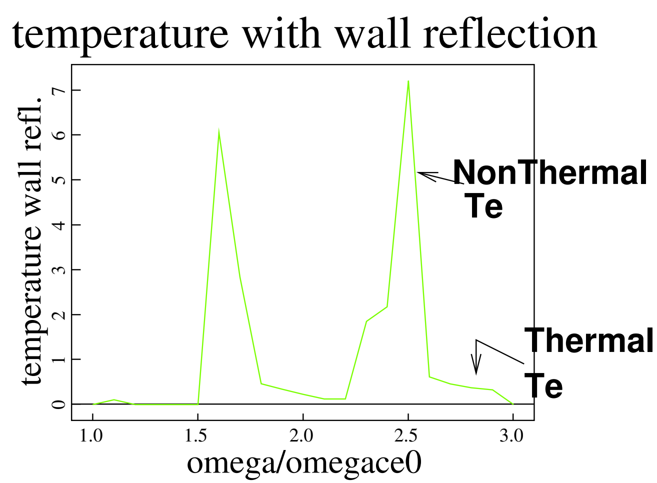




NonThermal Distributions







CONCLUSIONS

- EBWE provides a basis for flexible measurement of thermal and nonthermal electron distributions
- At low beta, central plasma thermal and nonthermal radiation temp measurements are accessible
- At high beta, central thermal measurements is more difficult, and may not be possible in presence of intervening nonthermal distribution
- There is substantial dependence on poloidal detector location, of penetration and as to whether themal or nonthermal electrons are detected
- Low n_par rays are necessary in order to be sensitive only to the thermal electrons
- Careful modeling is necessary, in order to interpret the measurement, in contrast to the usual perpendicular, X-mode in lower density plasmas