Analysis of electron cyclotron emission measurements with radiation transport modeling in present and future fusion devices

by
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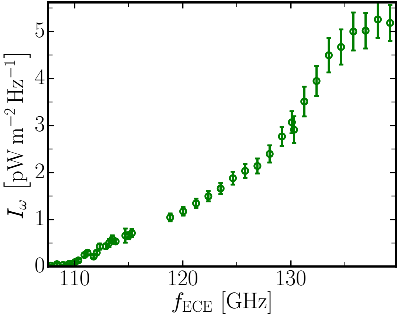
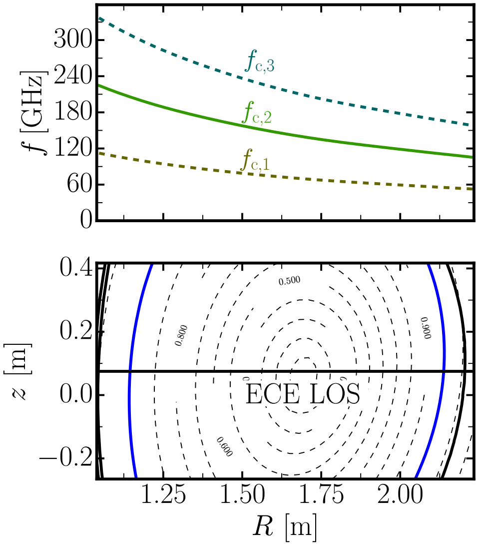
ASDEX Upgrade MIT PSFC Plasma Science and Fusion Center SPARC iter china eu india japan korea russia usa

In nowadays machines ECE can often be interpreted with the slab model





EC Resonance condition

$$f_{\mathrm{ECE}} = n \cdot f_{\mathrm{c}}(R) = n \cdot \frac{eB(R)}{2\pi m_{\mathrm{e}}}$$

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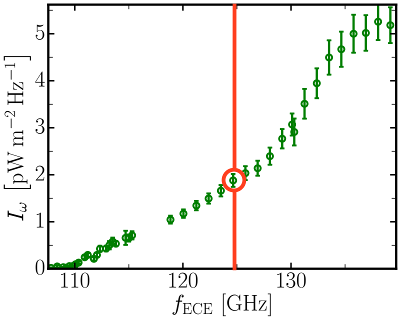

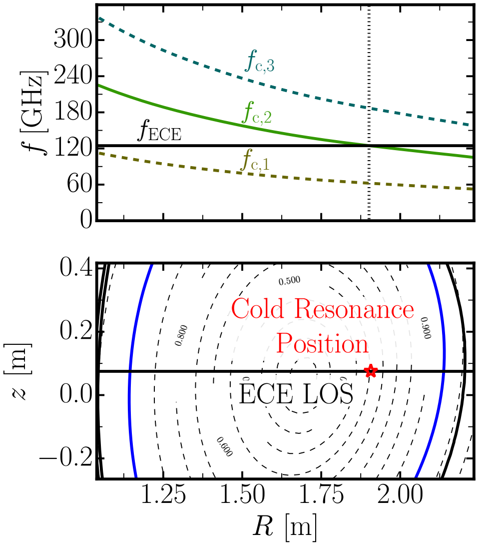

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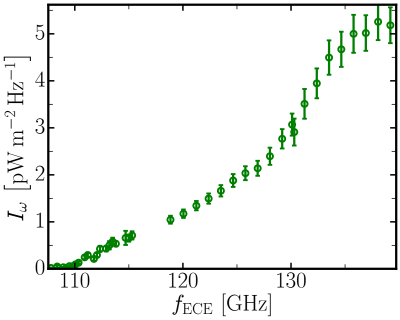

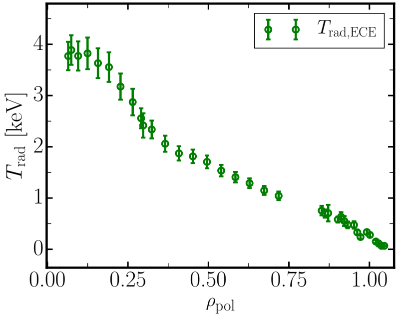

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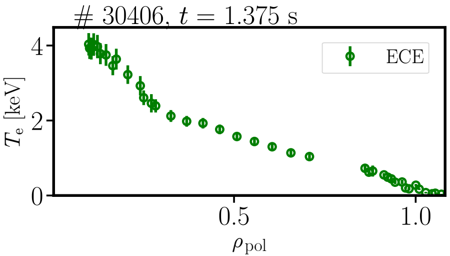
Radiation Temperature

$$T_{\mathrm{e}} \approx T_{\mathrm{rad}} = \frac{8\pi c_0^2}{\omega^2 k_{\mathrm{b}}} I(\omega)$$

However, some ECE spectra defy a classical interpretation



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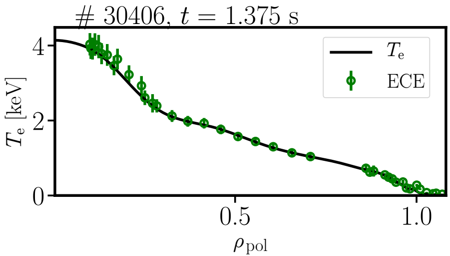

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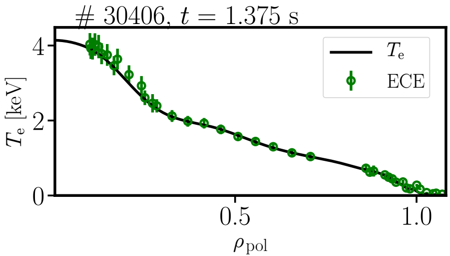

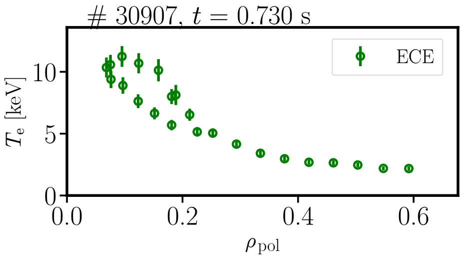

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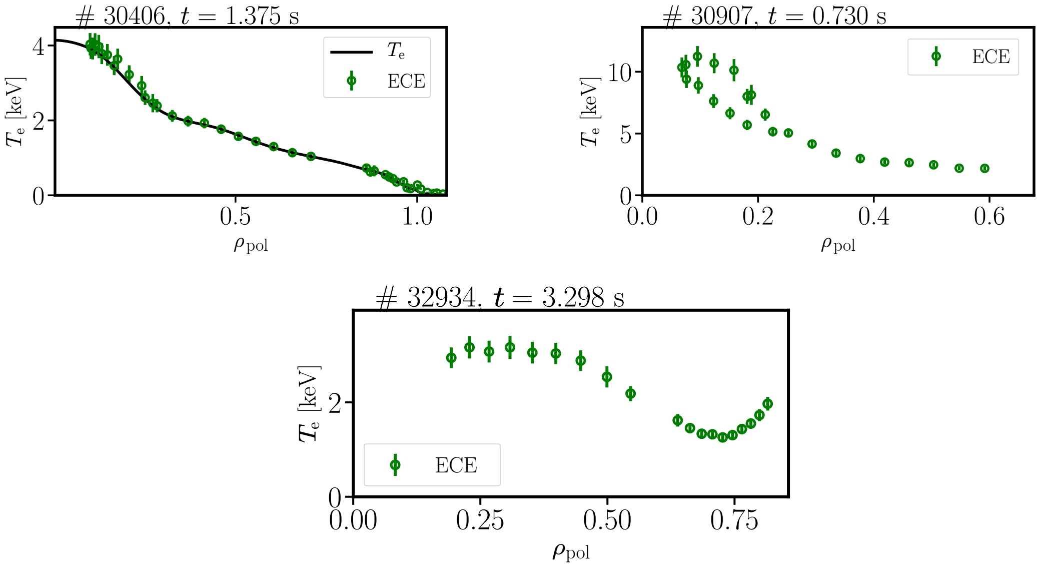


This is due to kinetic effects that broaden the resonance condition

Cyclotron frequency of a hot plasma:

$$\omega_\mathrm{c}(v_\perp, v_{||}) \neq \omega_{\mathrm{c},0} = \frac{eB_\mathrm{tot}}{m_{\mathrm{e},0}}$$

1) Relativistic mass shift:

$$\omega_\mathrm{c}(v_\perp, v_{||}) = \frac{eB_\mathrm{tot}}{\gamma(v_\perp, v_{||}) m_{\mathrm{e},0}}$$

$\Rightarrow$ frequency down shift

2) Doppler-shift

$$\omega_\mathrm{c}(v_\perp, v_{||}, \theta) = \frac{\omega_{c,0}}{1 - \frac{v_{||}}{c} N_\omega \cos\theta}$$

$\Rightarrow$ frequency up and down shift

$T_\mathrm{e} = 8\,keV$, $\theta = 80^\circ$ and $N_\omega = 1$
$2\omega_{\mathrm{c},0} = 140\,GHz$

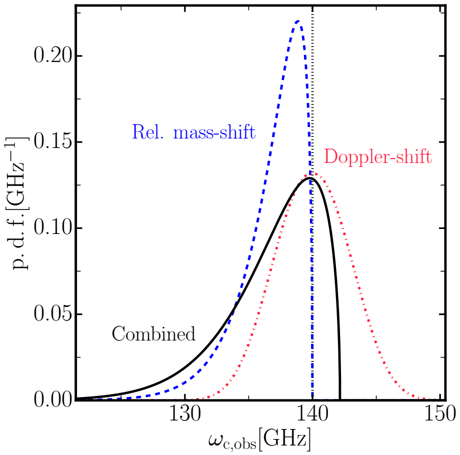


Table of Contents

Radiation transport modeling with the ECRad code

- Geometrical optics and radiation transport
- Birthplace distribution of observed intensity

Validation of ECRad against ECE spectra from ASDEX Upgrade

- ITER-like plasmas (from an ECE perspective)
- Third harmonic emission with harmonic overlap

Predictions for future machines

- ECE at high magnetic field: SPARC
- ITER ECE at half field

The Electron Cyclotron Radiation transport solver for Advanced Data analysis (ECRad)

Goal: Obtain synthetic $T_{\mathrm{rad}}(\omega)$ for given measured frequency, T_e and n_e profiles / a distribution function profile

Step 1: Obtain line of sight (LOS) in the cold plasma approximation:

$$\frac{\partial \vec{x}}{\partial s} = a \cdot \frac{\partial H}{\partial \vec{N}}, \qquad \frac{\partial \vec{N}}{\partial s} = -a \cdot \frac{\partial H}{\partial \vec{x}}$$

- $a = \left|\frac{\partial H}{\partial \vec{N}}\right|^{-1}$
- s LOS coordinate
- $\vec{x}$ position
- $\vec{N} = \frac{c\vec{k}}{\omega}$ normalized wave vector
- H Hamiltonian of the cold plasma

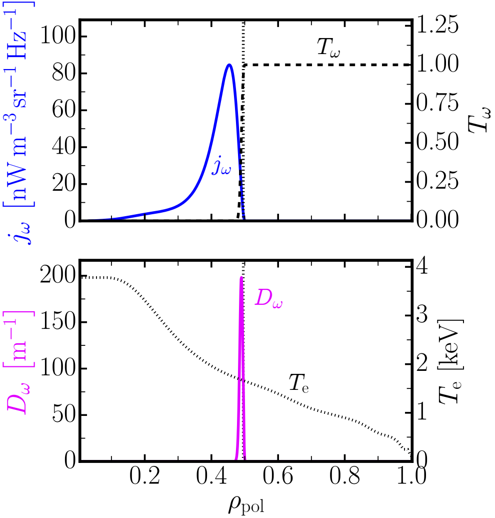
Step 2: Solve the radiation transport equation along the LOS:

$$\frac{\mathrm{d}}{\mathrm{d}s} \frac{I_\omega(s)}{N^2_{\omega,\mathrm{ray}}(s)} = \frac{1}{N^2_{\omega,\mathrm{ray}}(s)} \left(j_\omega(s) - \alpha_\omega(s) I_\omega(s)\right)$$

- s LOS coordinate
- $I_\omega(s)$ the intensity
- $j_\omega(s)$ emissivity[1]
- $\alpha_\omega(s)$ absorption coefficient[1,2]
- $N_{\omega,\mathrm{ray}}$ ray refractive index

[1] F. Albajar et al, PPFC (2006)
[2] D. Farina et al, Fusion Sci. Technol.

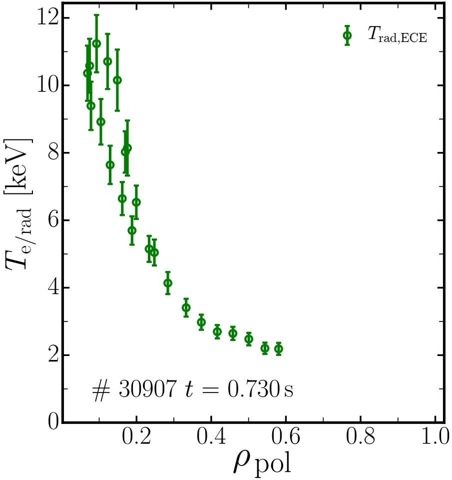
The Birthplace Distribution of observed Intensity is a powerful tool for understanding ECE physics

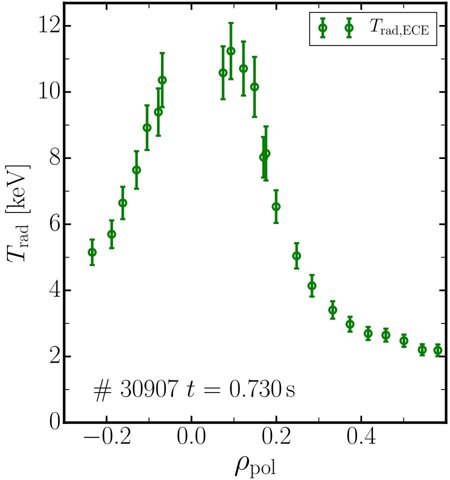


$$D_\omega(\rho_{pol}) \equiv \frac{j_\omega(\rho_{pol})\, T_\omega(\rho_{pol})}{I_\omega}$$

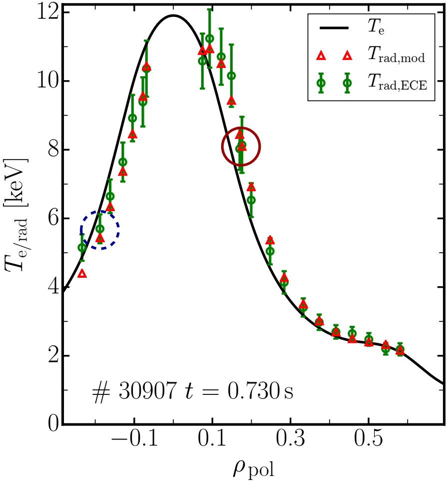
- Transmittance $T_\omega \rightarrow$ probability of emission reaching antenna
- Birthplace distribution D_ω gives direct break down of how each point on the LOS contributes

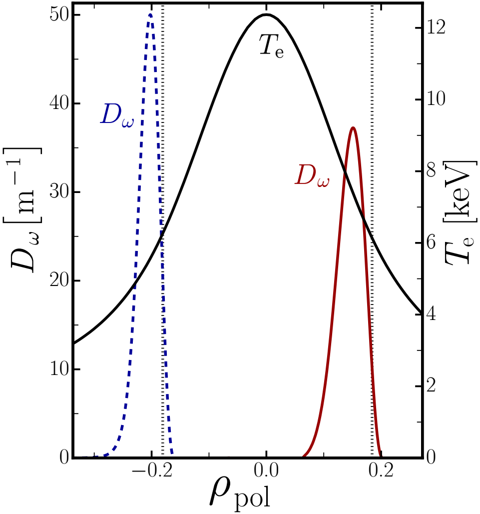
At high electron temperatures the ECE can exhibit an asymmetry between the LFS and the HFS



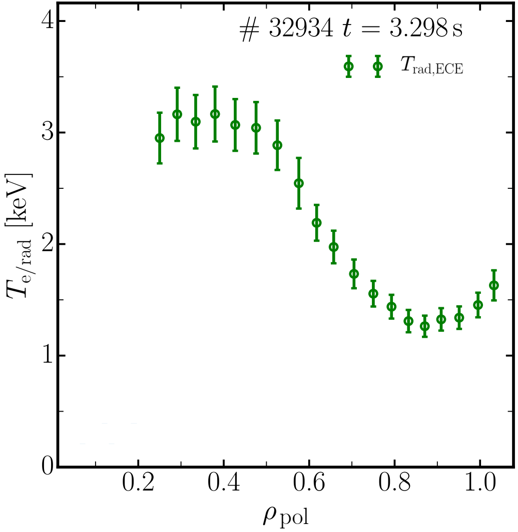


Under these conditions the relativistic mass-increase shifts the center of emission towards the HFS





Third harmonic ECE affected by harmonic overlap can be interpreted with ECRad and IDA



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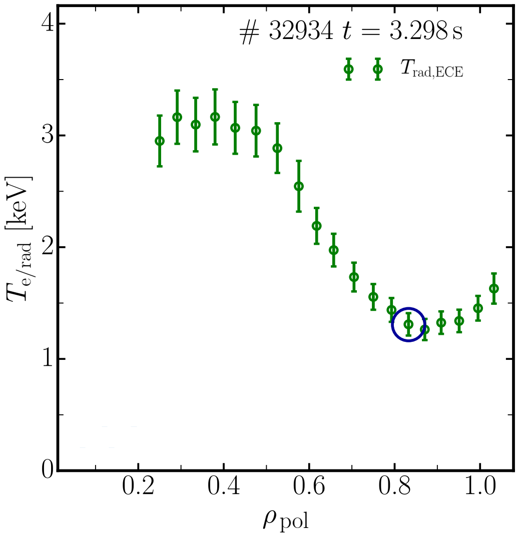

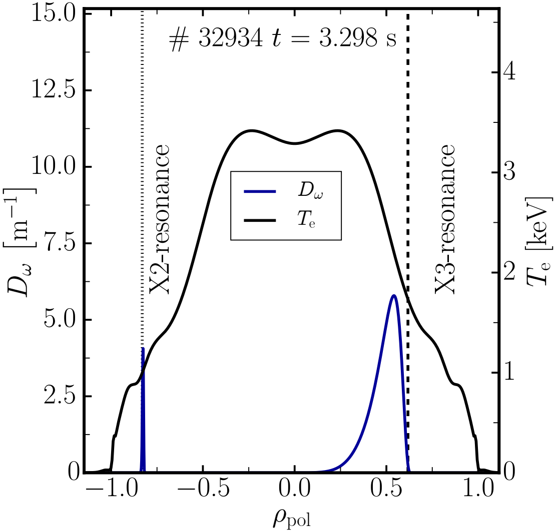

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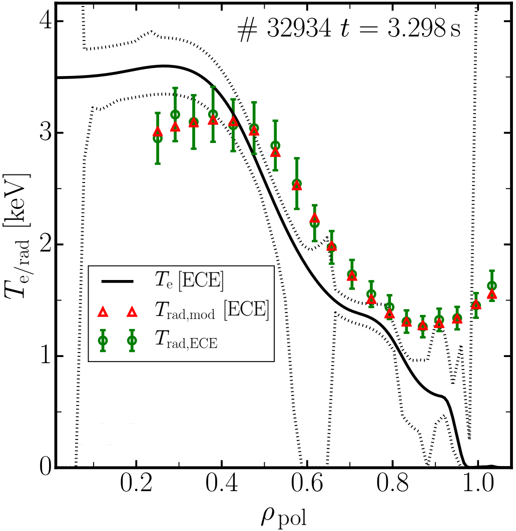

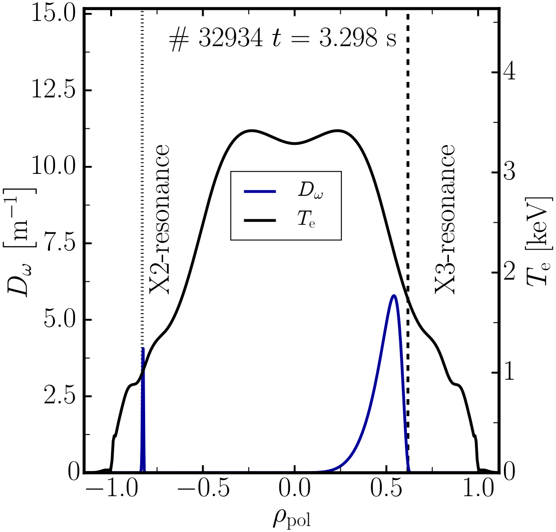

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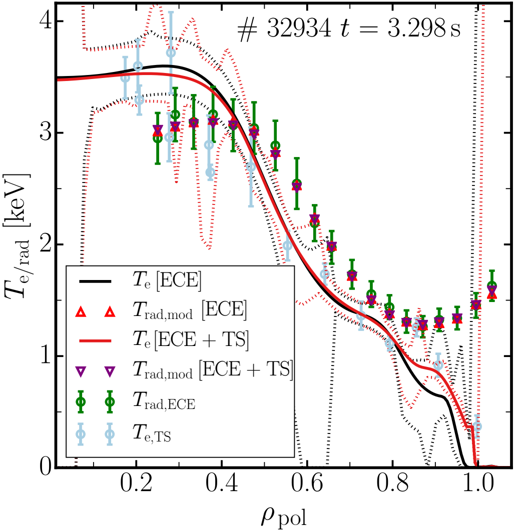
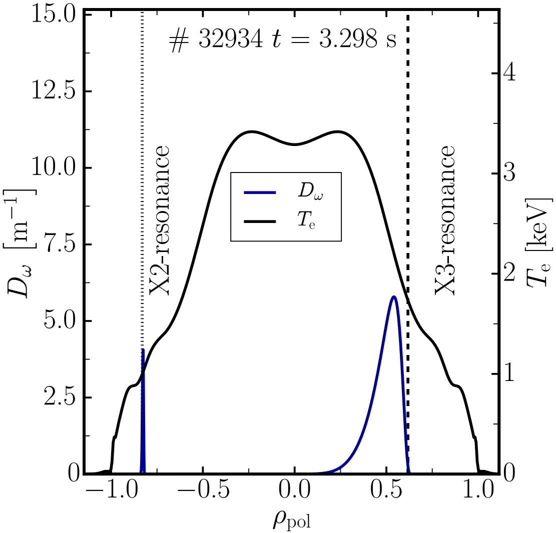
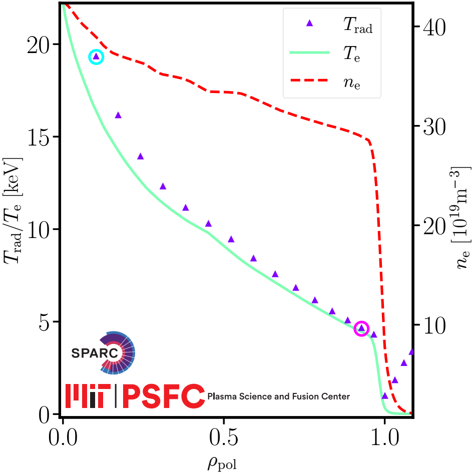
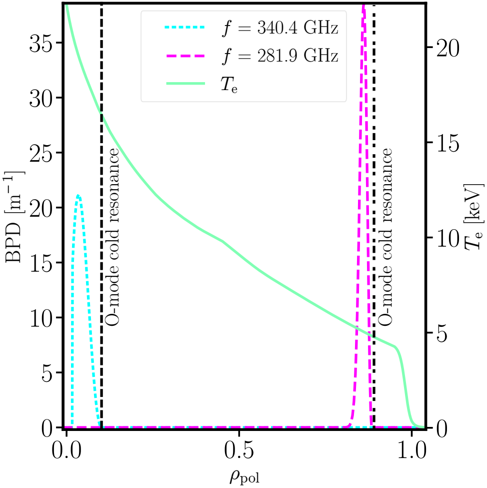




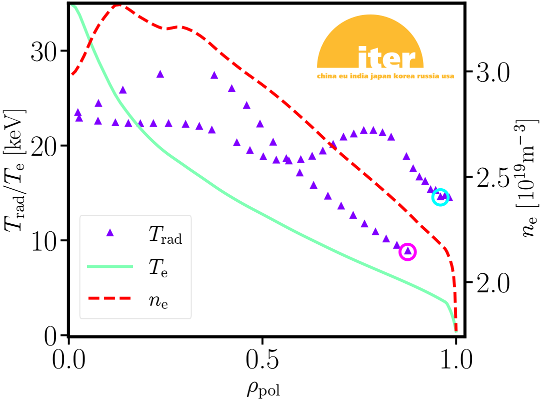
The SPARC ECE is planned to measure O-mode emission which is slightly broadened due to the high temperatures



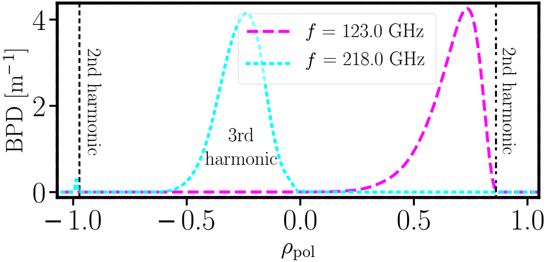


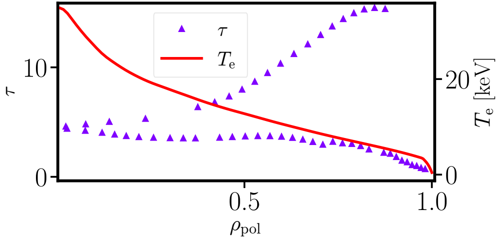
Courtesy of N. Howard

If the ITER ECE only covers the 2nd harmonic O-mode in the half field phase it will have poor spatial resolution



Courtesy of A. Medvedeva
More on this in two talks!





Summary

- ECRad is a fast radiation transport code suitable for integrated data analysis
- Accuracy of relativistically shifted ECE measurements successful
- Comparison against TS T_e profile validates ECRad for measurements subject to harmonic overlap
- At SPARC the high magnetic field reduces the overall optical depth of the ECE and radiation transport modeling is necessary
- At half field ITER will also require radiation transport modeling for the analysis of ECE measurements

Radiation transport modeling allows us to understand complicated ECE spectra and will be essential for future machines