MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Generation of energetic electrons during ECRH start up

Wendelstein 7-X

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EUROfusion

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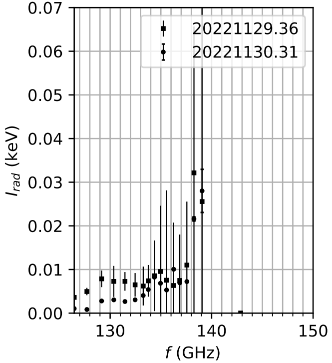
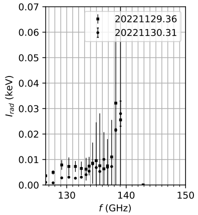
Experimental electron cyclotron emission spectrum

- Downshifted spectra are observed early on in experiments.
- Electron cyclotron emission occurs at $\omega = 2\frac{|q_e|B}{m_e\gamma}$.
- The downshift corresponds to electrons located at the magnetic axis with an energy of a few keV to 50 keV.
- The line-integrated density is low, thus precluding a change in B.
- How are such energetic electrons created during normal ECR operation?

Emission spectra at $6 - 8$ ms, line integrated density is less than $1 \times 10^{16}\,\mathrm{m}^{-2}$. $\int \mathrm{d}l \approx 1\,\mathrm{m}$



Outline



- Experimental spectra.
- Non–linear (and linear) cyclotron interaction.
- Analysis of non–linear ECR in the context of W7-X.
- Combine non–linear ECR with electron–orbits in W7-X.

Experimental spectra

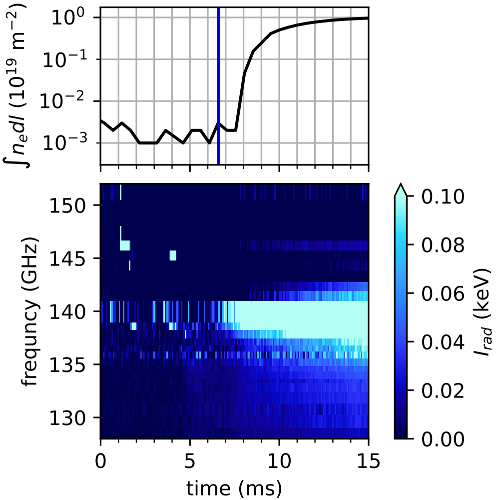
At what point in time are spectra taken?

1. The line-integrated density is low.
2. There's a noticeable downshift.
3. No up-shifted signal.

Only experiments with:

1. C1, D1, E1,
2. max one extra gyrotron,

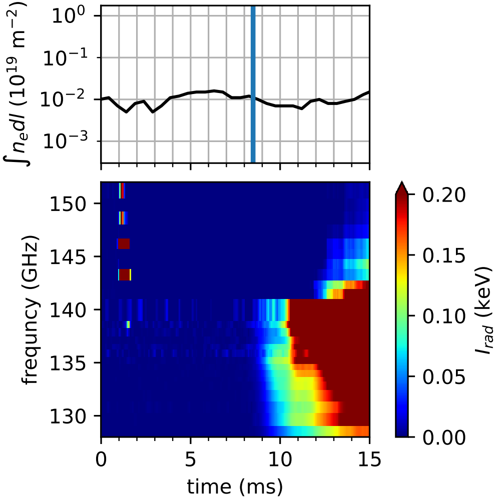
are considered.
(No experiment with only C1, D1, E1 and ECE exists in DB.)
Right figure shows experiment 20221129.36.



Experimental spectra

- Spectra are taken from Minerva.ECE.RadiationTemperatureSpectra/ relative_calibrated_signal_DATASTREAM.
- Errors are taken from RadiationTemperatureSpectra.StatisticalErrors
- Spectra are time averaged (again),
  - 20221129.36: for 0.4 ms ("20" datapoints),
  - 20221130.31: for 0.1 ms ("5" datapoints),

  to reduce noise.
- $\sigma^2 = \frac{1}{n^2} \sum \sigma_{stat}^2$
- Right figure shows experiment 20230316.20.



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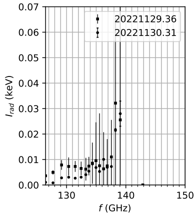

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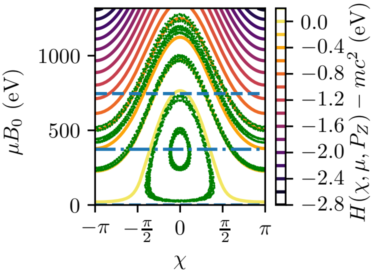
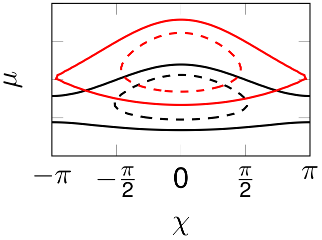
Cyclotron resonance theory

- Wave interaction can be written as a time-independent Hamiltonian $H = mc^2\gamma - \frac{\omega m}{ne}\mu + H_1$.
- The wave interaction term is $H_1 \propto E\mu\cos(\chi)$.
- The interaction angle is $\chi = n\zeta - \omega t + k_{\parallel} z$, where the gyro-angle is denoted by ζ.
- Electron kinetic energy oscillates due to wave interaction.
- The oscillations are associated with a resonance width.
- Multiple beams allow for resonance overlap in a contracted phase-space.





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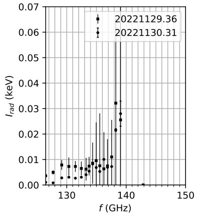
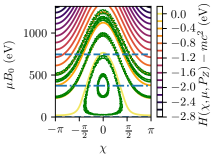
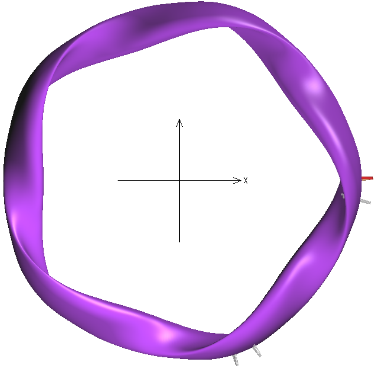


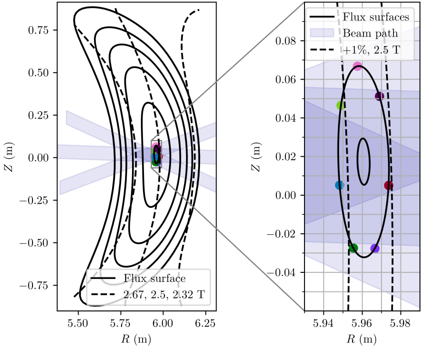


Resonance overlap due to rotational transform

- Electrons follow field lines.
- The rotational transform at the cold resonance is $\iota \approx 6/7$.

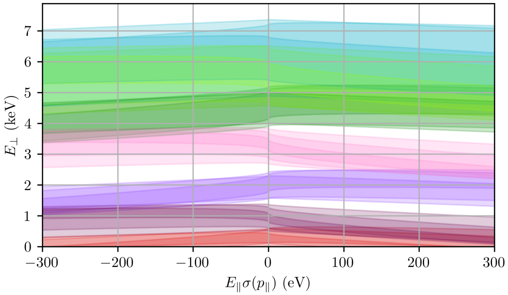
A field line crosses the gyrotron beams multiple times.



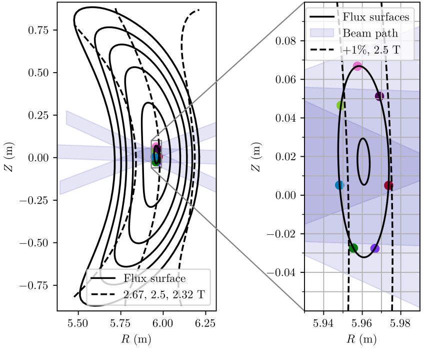


Resonance overlap due to rotational transform

Resonance width at the different points:



A field line crosses the gyrotron beams multiple times.



Resonance overlap! Chirikov criterion predicts chaotic orbits over many beam passages.

Detailed analysis of particle trajectories — Monte Carlo approach

Solve the equation of motion for different starting points to create a map from initial conditions to beam crossing positions.

↓

Apply map with random χ (random initial gyro-angle).

↓

Push electrons one time around the torus to next beam intersection. Assume they follow field lines.

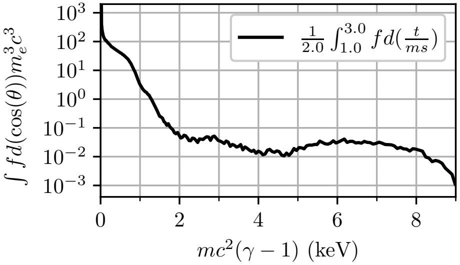
↓

Apply bounce averaged pitch angle scattering, and Bethe slowing down.

↓

Calculate next initial condition for the map. (→ back to "Apply map with random χ")

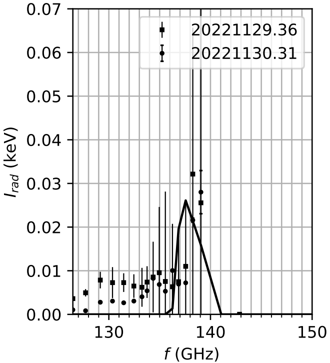
Distribution function — electron cyclotron emission spectrum



Emission spectra from experiment (squares and circles) and distribution function through TRAVIS (solid black)

[N.B. Marushchenko, Y. Turkin, H. Maassberg,

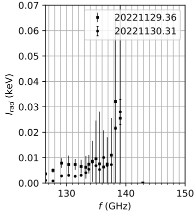
Comput Phys Commun. 2024;185(1):165-176]



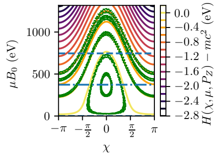
The spectrum (right figure) from the distribution function (left figure) from Monte Carlo modelling explains the peak of the experimental spectra (right figure).
How is the full tail created?

Outline

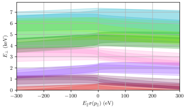
- Experimental spectra.



- Non–linear (and linear) cyclotron interaction.

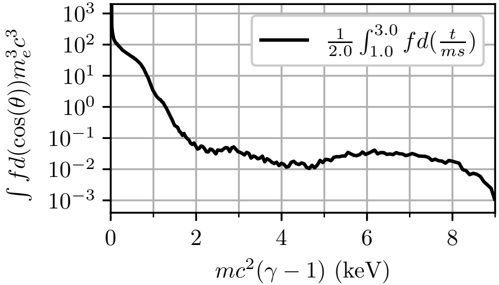


- Analysis of non–linear ECR in the context of W7-X.

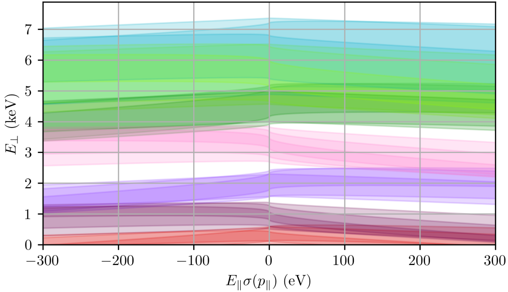


- Combine non–linear ECR with electron–orbits in W7-X.

Modelling the full tail by understanding the distribution function



Resonance widths:



- The distribution function is flat up to the maximum resonance energy.
- If an electron reaches a higher flux surface, assume the distribution function is flat up to the maximum resonant energy.

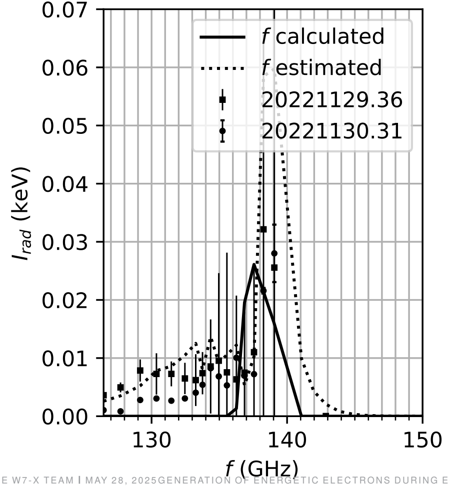
Using Neoclassical Transport to Model the Drift

- Drift is complicated by that the collisional time-scale is similar to the collisionless drift time-scale.
- Assume drift to come from the neoclassical diffusion.
- $D_{11} \approx 20\,\mathrm{m}^2\,\mathrm{Hz}$ for $\nu_* = 1.5 \times 10^{-5}$ at $\rho = 0.25a$ and $\rho = 0.5a$, a minor radius.

  [C.D. Beidler, *et.al.*, NF, 51(7):076001, 06.2011]
- Solve $\frac{\partial n}{\partial t} = D_{11} \frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial n}{\partial \rho} \right)$ with boundary condition $n = const$ at $\rho = \rho_{overlap}$.
- $\rho_{overlap}$ is the radius of flux surface overlap. The density is assumed constant at this radius because the distribution function quickly reached a steady state due to fast wave interaction.
- We assume the velocity distribution is constant up to the maximum resonance energy.

Full spectra explained by drifts

- Neoclassical drift and resonance interaction explain complete spectra.
- The energy needed to explain the 126 GHz signal is 25 keV.
- The only free parameter is the scaling parameter determining the density of fast electrons at the core.



Conclusions

- The ECE spectra reveal energetic electrons during early plasma formation.
- Such energetic electrons are not expected from the plasma bulk or from a wave-particle interaction at a fixed position.
- A resonance overlap structure becomes apparent upon consideration of the entire flux surface.
- This overlap enables the formation of a magnetically-trapped supra-thermal population of electrons, which subsequently drift radially.
- Following the process of collisional detrapping, electrons are once again able to interact with the wave, becoming magnetically trapped with a higher kinetic energy.
- The repetition of this process allows for the creation of high-energy electrons, which are sufficient to explain the observed ECE spectra.