EPFL

Investigation of high frequency modes generated by runaway electrons in TCV

Olivier Panico

J. Decker, W. Bin, M. Hoppe, K. Klein, I. Muzio, Y. Poels, U. Sheikh, A. Van Vuuren, D. Verscharen

Swiss Plasma Center

EUROfusion

Runaway Electron Meeting

17.06.2026

RE driven modes are routinely observed in TCV

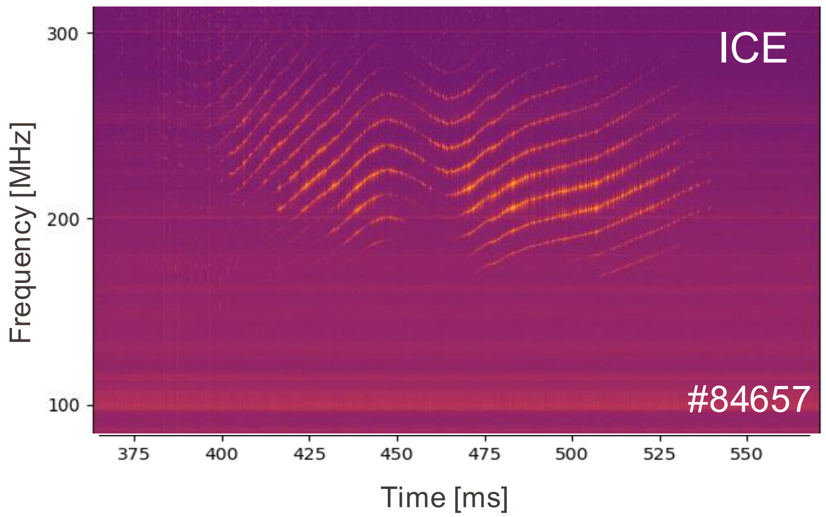
- Electromagnetic (EM) waves observed during RE experiments

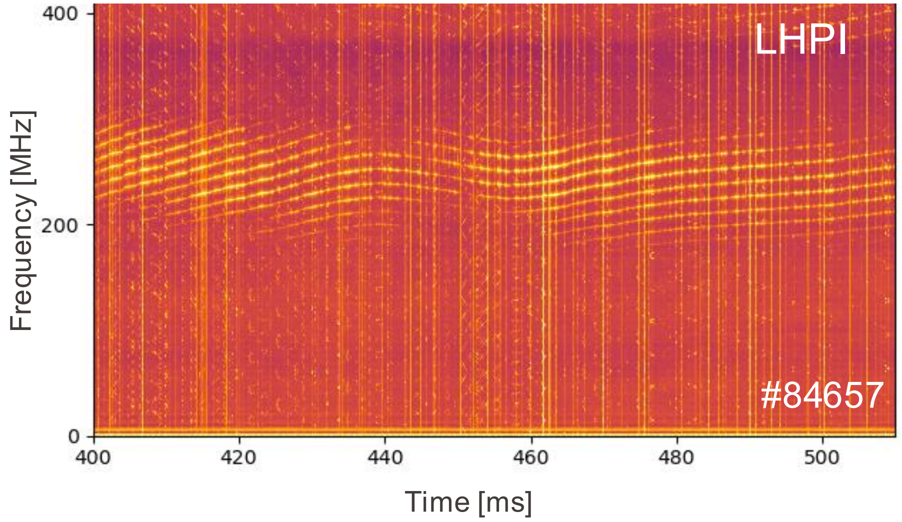
  Also observed in other tokamaks:
  - DIII-D: [Spong 2018, Heidbrink 2018, Lvovskiy 2019]
  - FTU: [Bin RSI 2022, PRL 2022]

  Both in LH frequency range $\omega_{ci} < \omega < \omega_{ce}$
  And Alfven frequency range $\omega < \omega_{ci}$

- Theory suggests:
  Whistlers [Fülöp 2006], Extraordinary electron mode [Pokol 2014], Bernstein waves [Castaldo 2024]

- Can increase transport and pitch angle scattering of RE [Fülöp 2006, Pokol 2006, Choudhury 2025]





Objectives

☞ What can the RE driven modes tell us about the underlying RE distribution?

☞ Can those modes be leveraged to limit maximum energy of RE or expel the seed RE?

I. **Identify TCV RE driven modes**

- Cross-diagnostic comparison & parametric dependences
- Forward modelling with Linear solver & Fokker Planck simulations

II. **Quasilinear interaction between waves and particles**

- Interdependent Fokker Planck & wave simulations

Experimental set-up to measure RE and waves

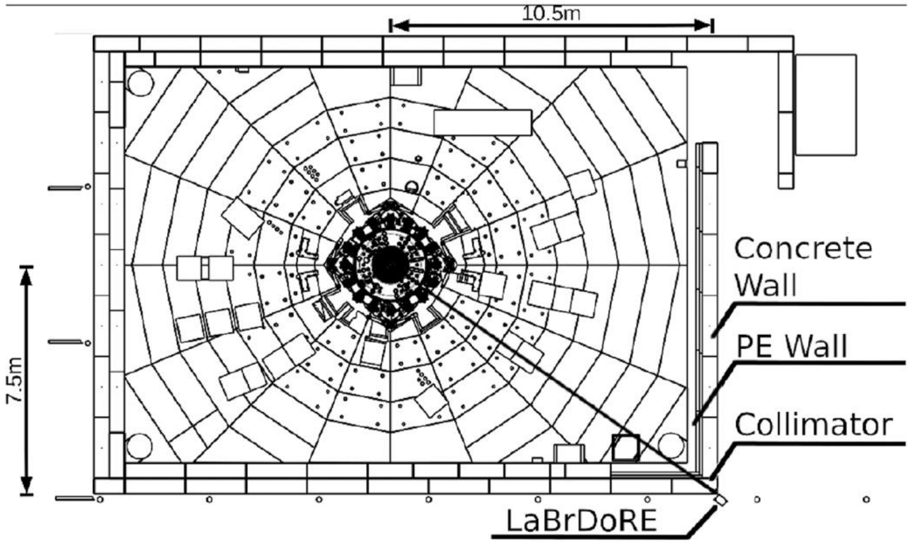
☞ **RE diagnostics**

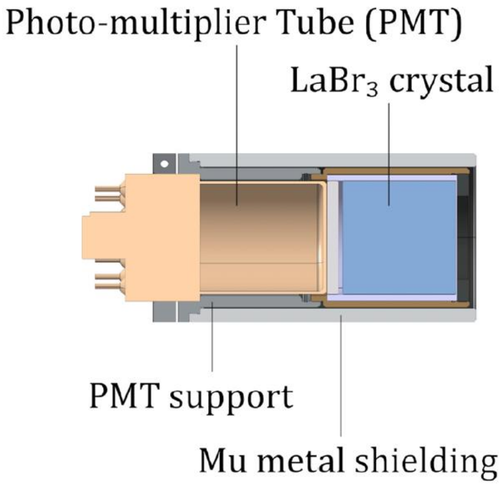
Hard X-rays

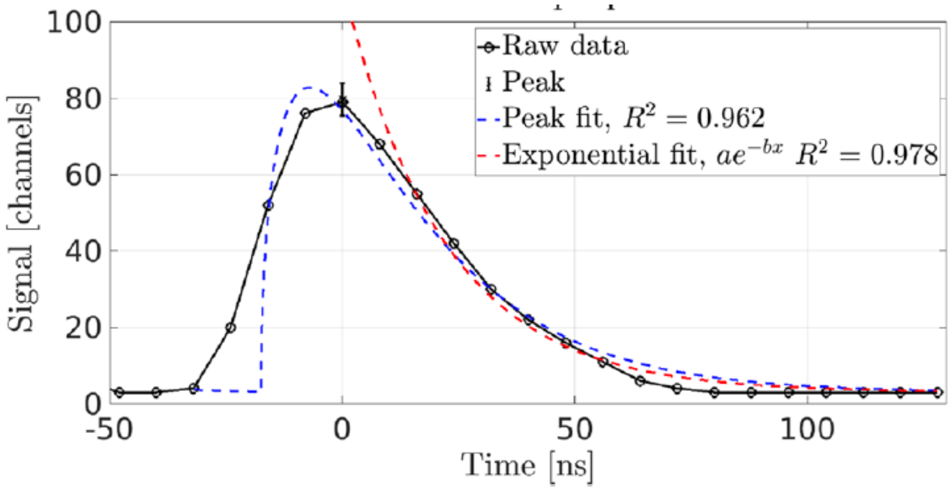
- LabrDoRE
  - Outside of tokamak hall

  ⇒ Identify single events & photonic energy

[Simons 2025]





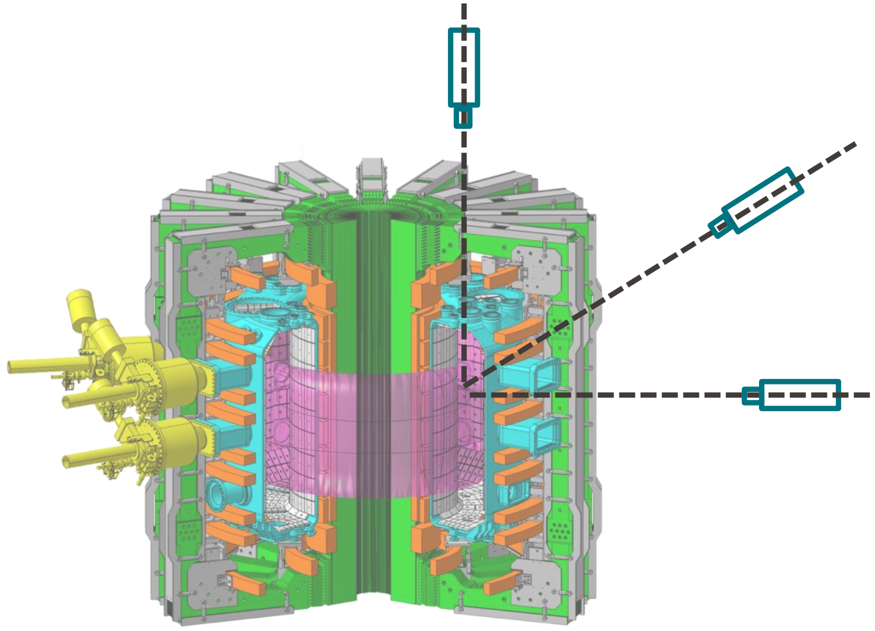


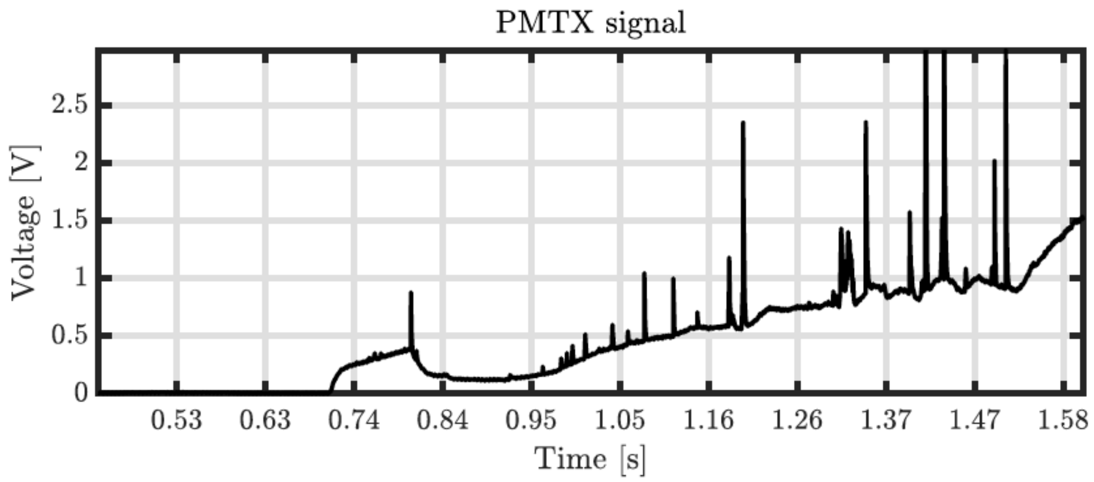
Experimental set-up to measure RE and waves

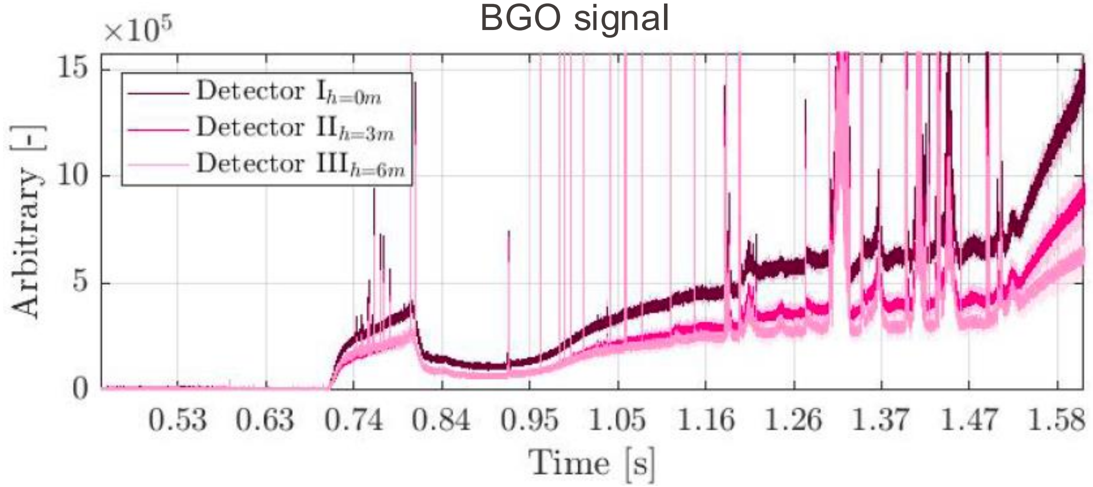
☞ **RE diagnostics**

Hard X-rays

- LabrDoRE [Simons 2025]
  - Outside of tokamak hall
  - ⇒ Identify single events & photonic energy
- BGO / PMTX [Khan 2024]
  - Current mode
  - Poloidal fan-like geometry
  - ⇒ spatial distribution of emission







Experimental set-up to measure RE and waves

☞ RE diagnostics

Hard X-rays

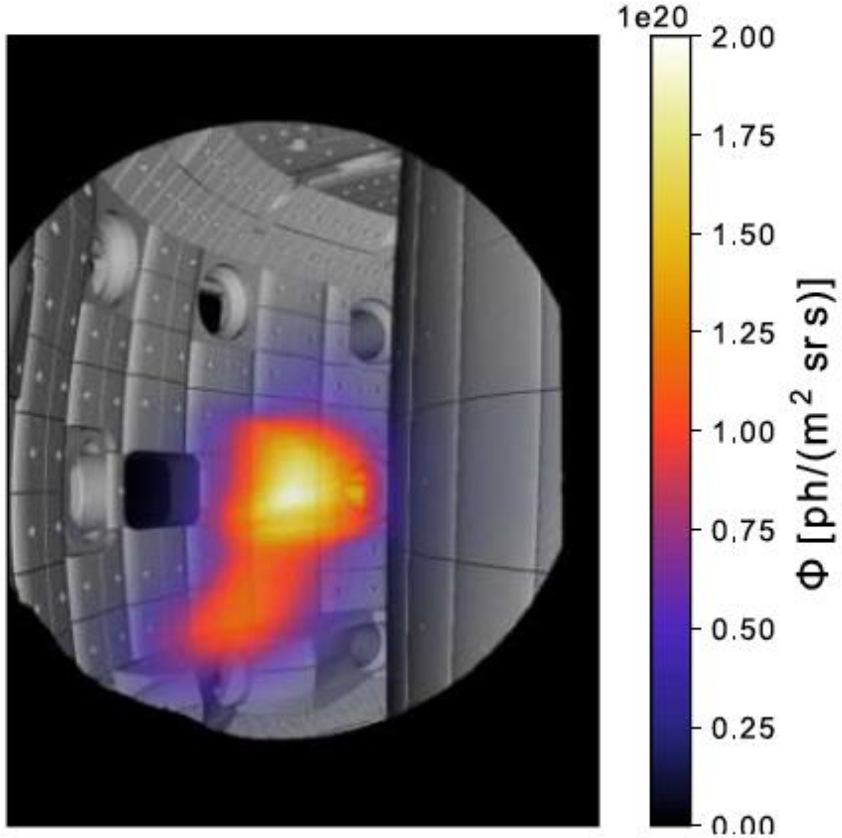
- LabrDoRE [Simons 2025]
    - Outside of tokamak hall

    $\Rightarrow$ Identify single events & photonic energy
- BGO / PMTX [Khan 2024]
    - Current mode
    - Poloidal fan-like geometry

    $\Rightarrow$ spatial distribution of emission

Synchrotron emission

- MANTIS



[Wijkamp 2024]

Experimental set-up to measure RE and waves

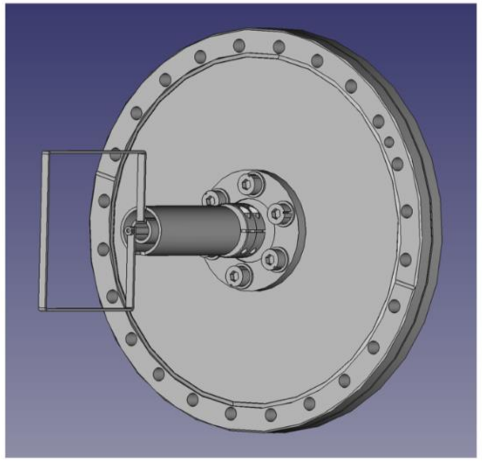
☞ Wave diagnostics

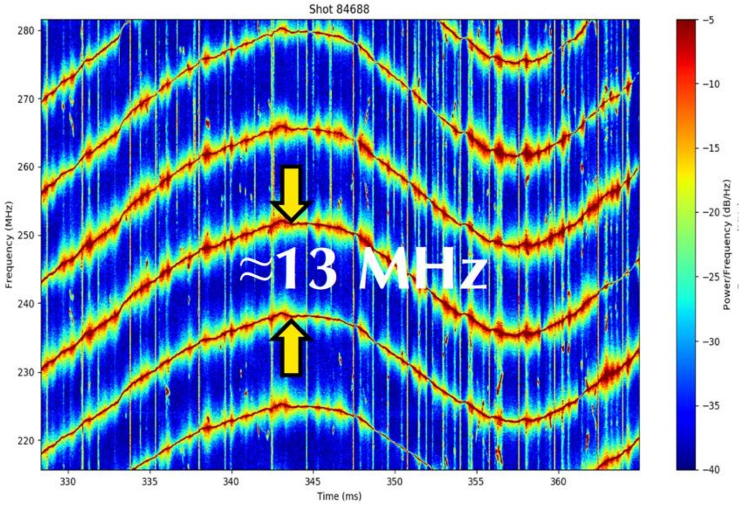
Ion cyclotron emission (ICE)

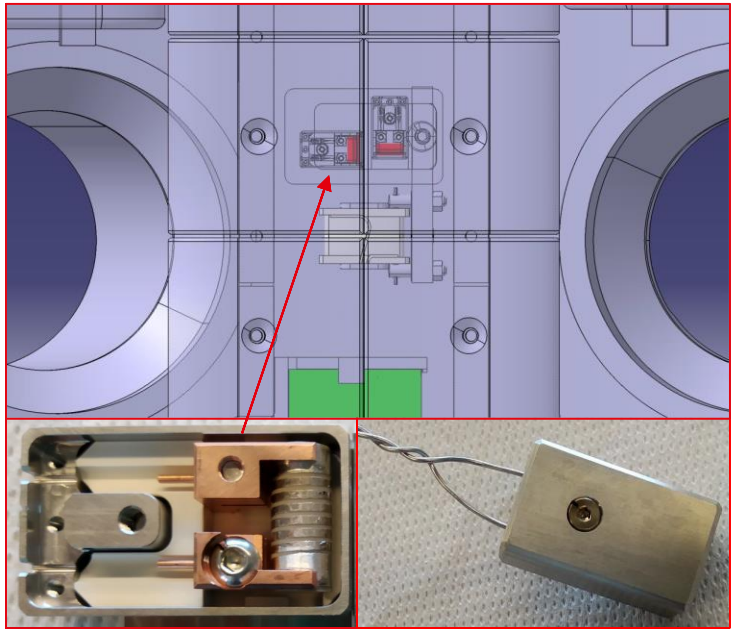
- 2 perpendicular coils
- 1 GSa/s acquisition card

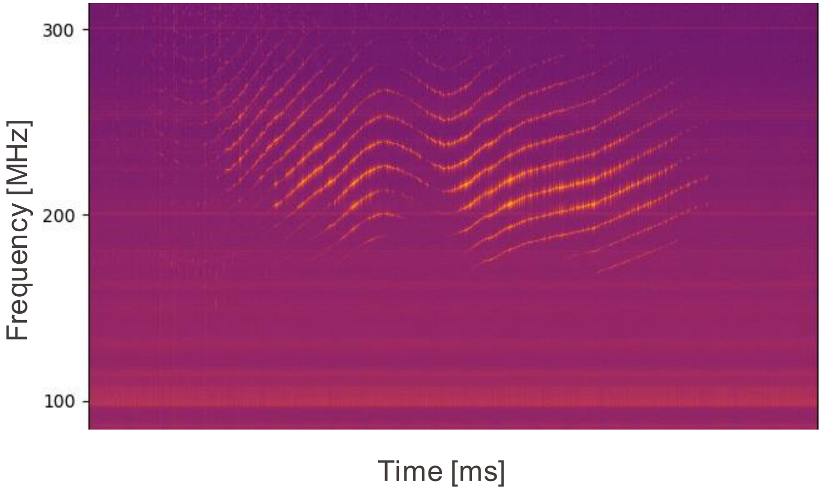
LHPI antenna

- Log-periodic antenna
- Full shot acquisitation at 2GSa/s







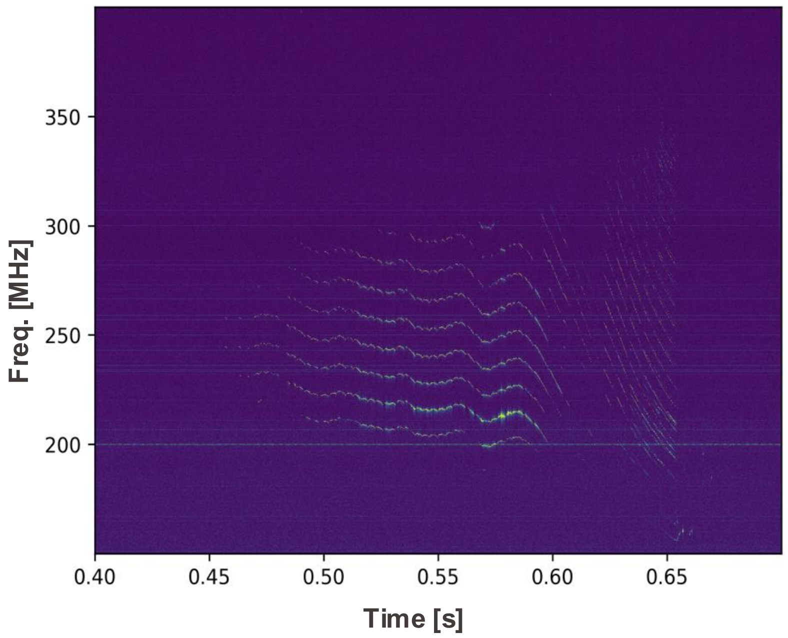


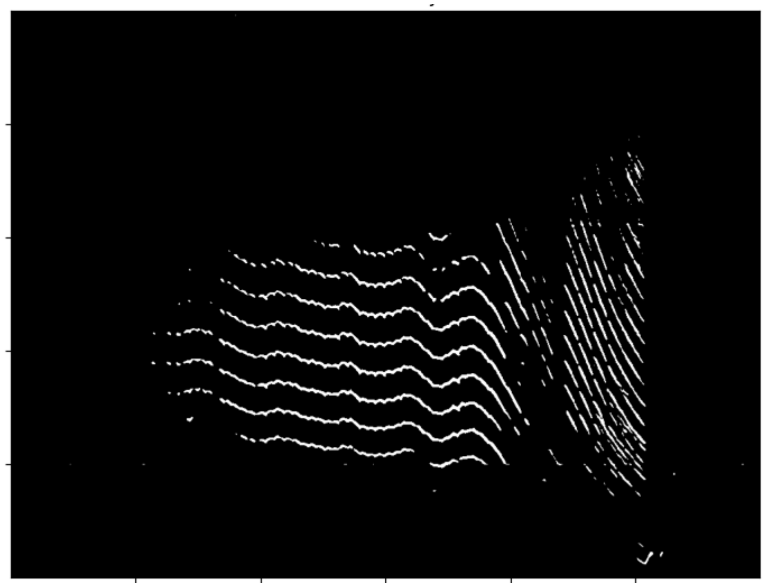
Automatic identification of high frequency modes

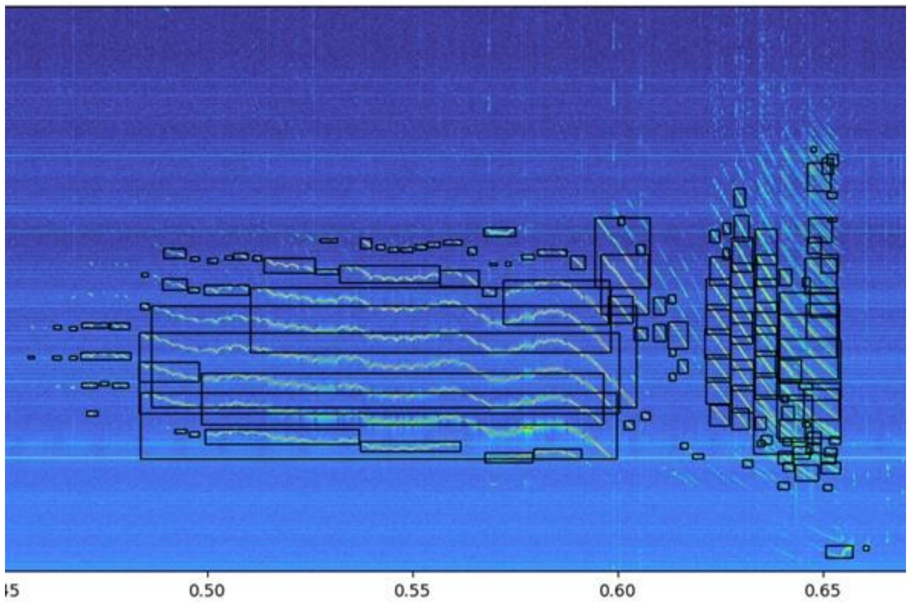
- Large database of RE shots built in the past few years (~600)
- Automatic detection of modes on this database
  - Filtering, thresholding, detection of continuous ridges

  => Get connected components

[Zapata-Cornejo 2024]

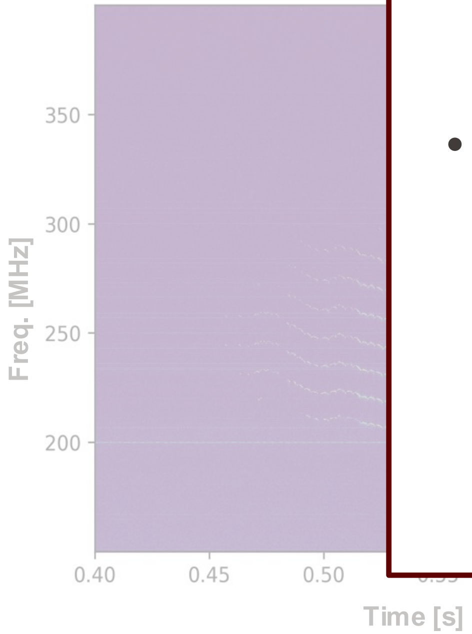




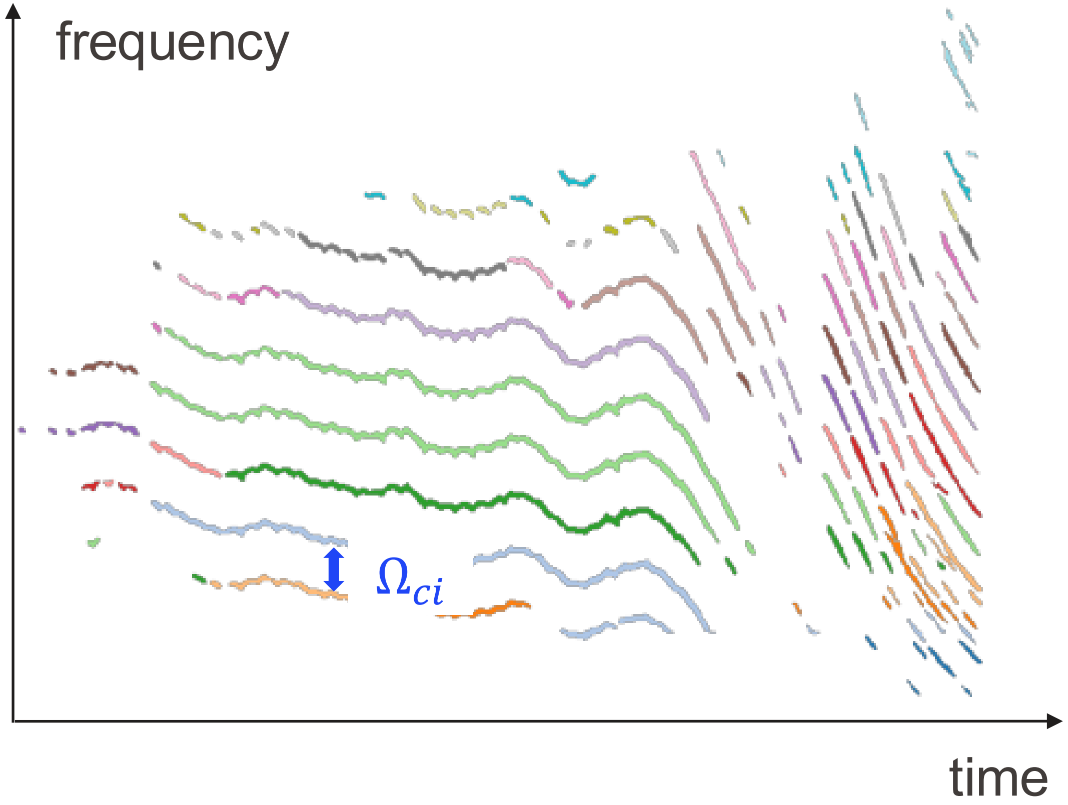


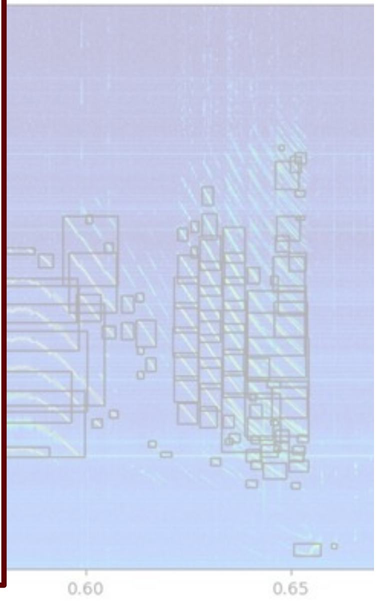
Automatic identification of high frequency modes

- Large database of RE shots built in the past few years (~600)
- Automa
  - Filt
  => Ge



- Cluster of waves separated by ion cyclotron freq. Ω_{ci}
- Parametric dependences of waves w.r.t. plasma parameters





Simulation of RE driven waves

☞ General dispersion relation for plasma waves

$$\det\left(\boldsymbol{kk} - k^2\underline{\underline{I}} + \frac{\omega^2}{c^2}\underline{\underline{\epsilon}}(\boldsymbol{k},\omega)\right) = 0$$

Dielectric tensor involves susceptibilities

$$\epsilon(\boldsymbol{k},\omega) = \boldsymbol{I} + \sum_s \chi_s(\boldsymbol{k},\omega)$$

$$\chi_s^{ij} = \frac{\omega_{ps}^2}{\omega}\int d^3v \sum_{-\infty}^{+\infty} \frac{T_s^{ij}(n,\boldsymbol{v})}{\omega - k_\parallel v_\parallel - n\,\Omega_{cs}}$$

Resonance

$z_s = \dfrac{k_\perp v_\perp}{\Omega_{cs}}$ $\quad J_n$: Bessel function 1st kind, order n

$$\underline{\underline{T}}(n,\mathbf{v}) = \begin{bmatrix} v_\perp\left(\frac{nJ_n}{z_s}\right)^2\hat{U}_{f0} & iv_\perp\left(\frac{nJ_nJ_n'}{z_s}\right)\hat{U}_{f0} & v_\perp\left(\frac{nJ_n^2}{z_s}\right)\hat{W}_{f0} \\ -iv_\perp\left(\frac{nJ_nJ_n'}{z_s}\right)\hat{U}_{f0} & v_\perp J_n'^2\hat{U}_{f0} & -iv_\perp J_nJ_n'\hat{W}_{f0} \\ v_\parallel\left(\frac{nJ_n^2}{z_s}\right)\hat{U}_{f0}) & iv_\parallel J_nJ_n'\hat{U}_{f0} & v_\parallel J_n^2\hat{W}_{f0} \end{bmatrix}$$

$$\hat{U}_{f0} = \frac{\partial f_0}{\partial v_\perp} + \frac{k_\parallel}{\omega}\left(v_\perp\frac{\partial f_0}{\partial v_\parallel} - v_\parallel\frac{\partial f_0}{\partial v_\perp}\right)$$

$$\hat{W}_{f0} = n\Omega_{cs}\frac{v_\parallel}{v_\perp}\frac{\partial f_0}{\partial v_\perp} + (\omega - n\Omega_{cs})\frac{\partial f_0}{\partial v_\parallel}$$

Requires careful handling of the poles

Requires distribution function for each species:

- Maxwellian assumption
- Decomposition $\chi_e = \chi_e^{bulk} + \chi_e^{RE}$ and analytical model
- Full numerical resolution with arbitrary distribution function

Simulations of RE driven waves

☞ Coupling of 2 codes

LUKE / DREAM: 3-D relativistic guiding-center Fokker-Planck code
- Kinetic equation for electrons
- Electric fields, collisions, avalanche generation, radiation losses, **wave-particle interactions / partially ionized collision operator**

Provide electron distribution function as a function of $p_\perp, p_\parallel$

Provide waves parameters: frequency, polarisation

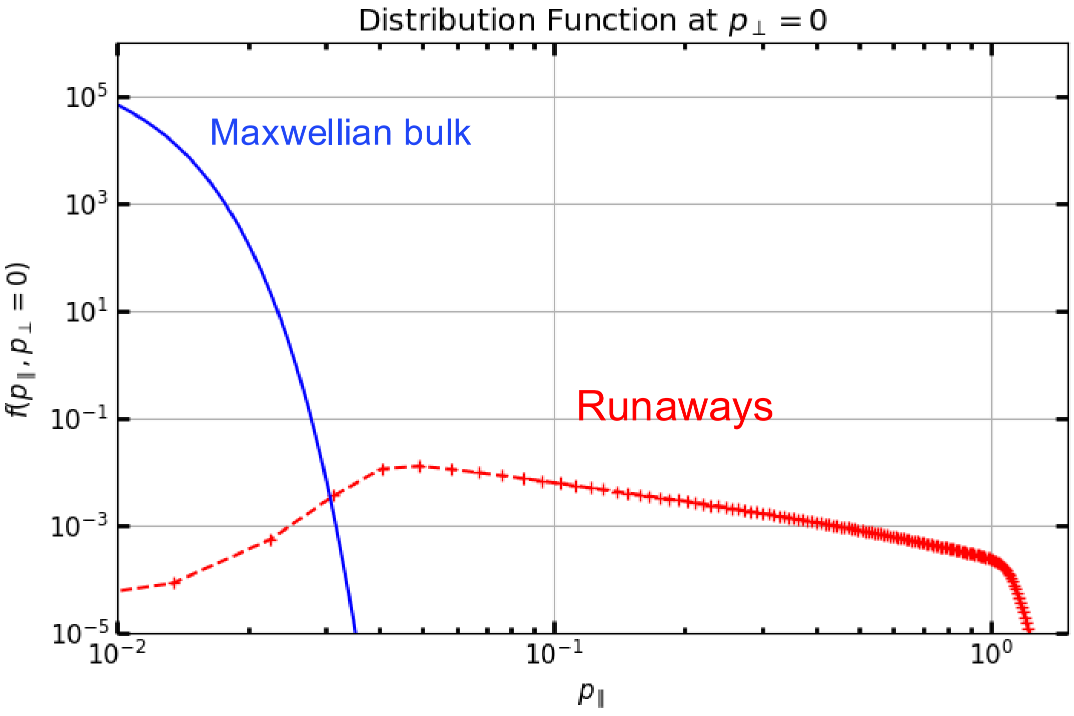
Arbitrary Linear Plasma Solver (ALPS)
- Solves relativistic dispersion relation for hot plasmas
- Arbitrary distributions

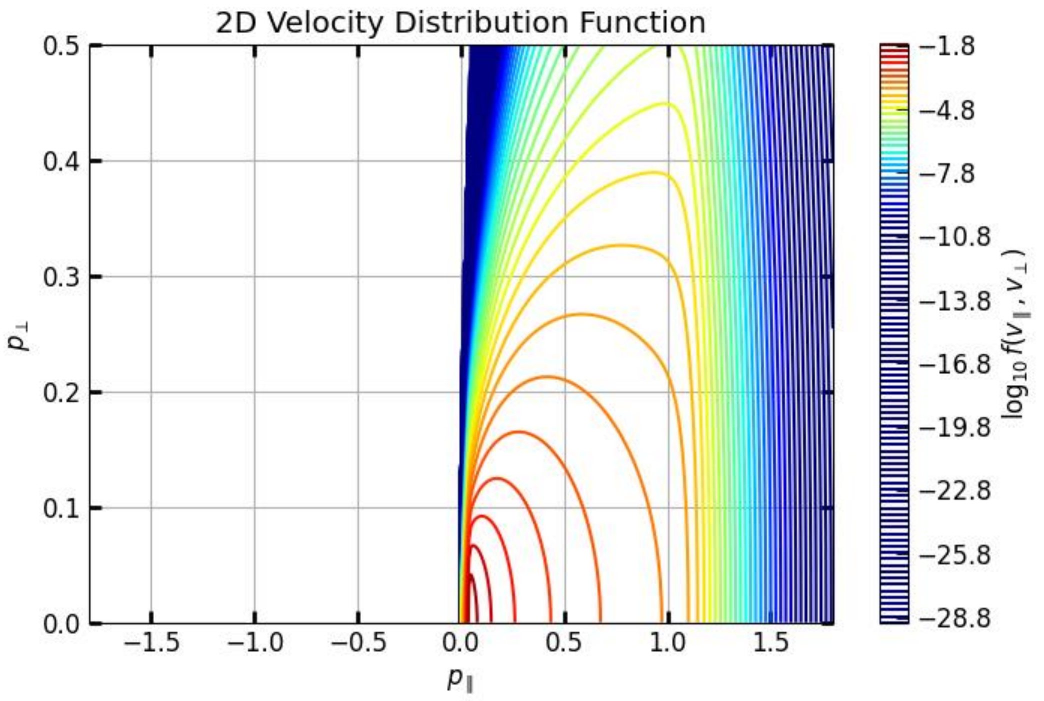
Benchmark ALPS on prescribed distributions

☞ Analytical distribution from [Fülöp 2006, Pokol 2014]

$$f_0(p_\parallel, p_\perp, t) = \frac{n_{r0}\alpha}{2\pi c_Z p_\parallel} \exp\left(\frac{(E-1)t/\tau_c - p_\parallel}{c_Z} - \frac{\alpha p_\perp^2}{2p_\parallel}\right)\left(\exp\left(\frac{p_\parallel - p_{\max}}{\sigma_p}\right) + 1\right)^{-1}$$

- $B = 2\ T$
- $n = 5.10^{19}$
- $T = 0\ eV$
- $Z_{eff} = 1$
- $n_{RE}/n = 6.10^{-3}$





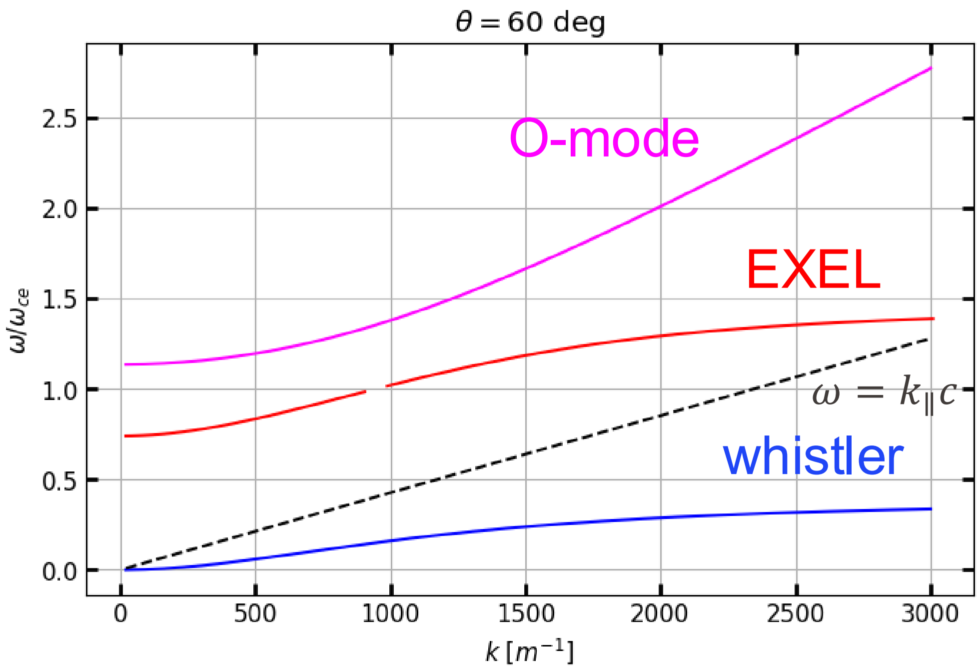
Benchmark ALPS on prescribed distributions

☞ Analytical distribution from [Fülöp 2006, Pokol 2014]

$$f_0(p_\parallel, p_\perp, t) = \frac{n_{r0}\alpha}{2\pi c_Z p_\parallel} \exp\left(\frac{(E-1)t/\tau_c - p_\parallel}{c_Z} - \frac{\alpha p_\perp^2}{2p_\parallel}\right)\left(\exp\left(\frac{p_\parallel - p_{\max}}{\sigma_p}\right) + 1\right)^{-1}$$

☞ Three modes are recovered with cold Bimaxwellians [Kómár 2013]

- $B = 2\,T$
- $n = 5.10^{19}$
- $T = 0\,eV$
- $Z_{eff} = 1$
- $n_{RE}/n = 6.10^{-3}$



Benchmark ALPS on prescribed distributions

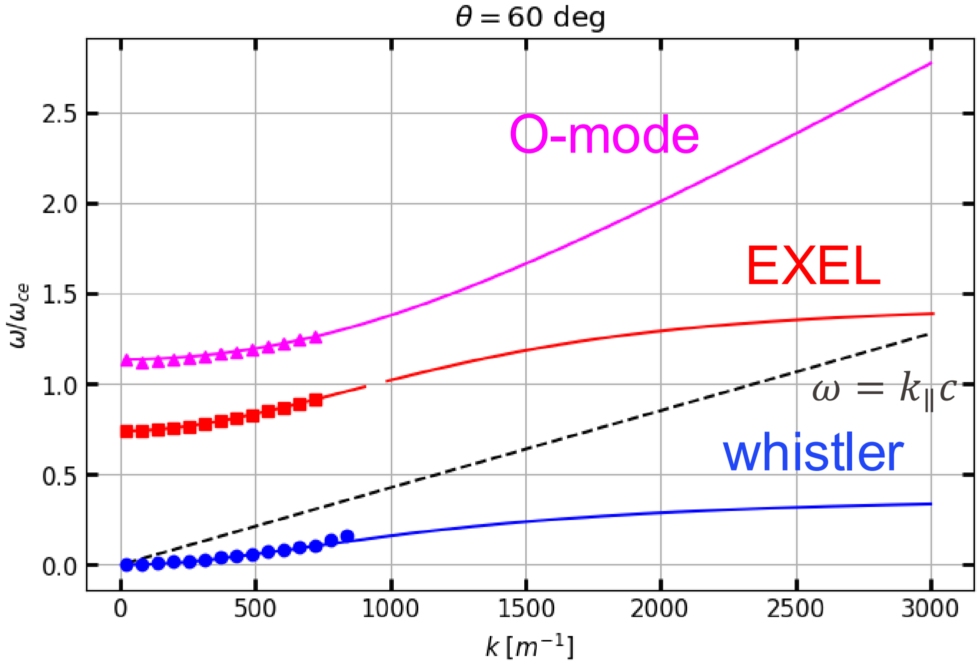
☞ Analytical distribution from [Fülöp 2006, Pokol 2014]

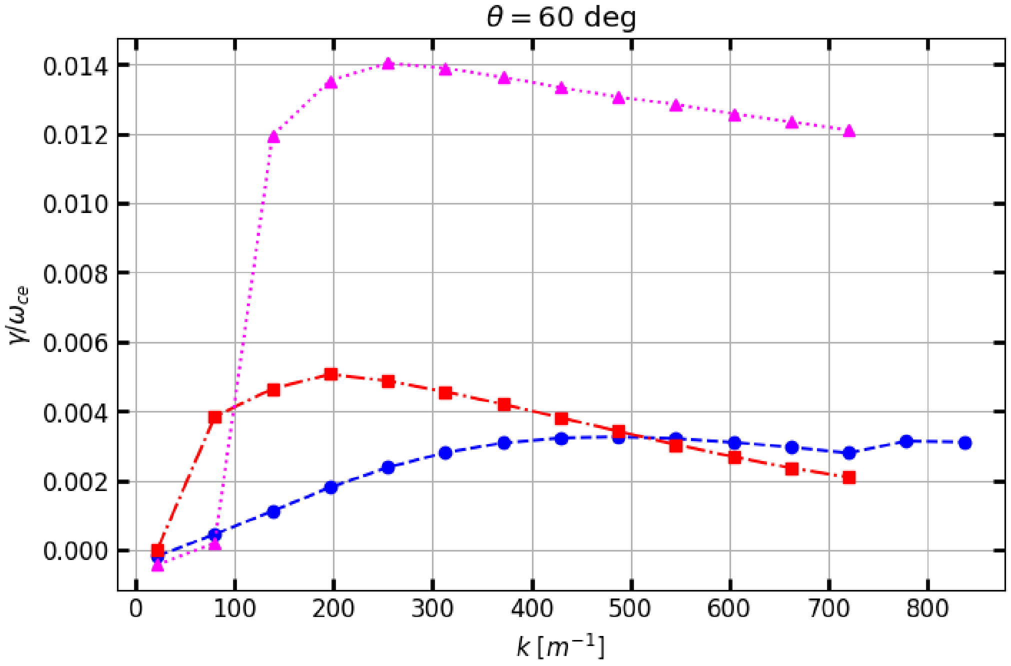
$$f_0(p_\parallel, p_\perp, t) = \frac{n_{r0}\alpha}{2\pi c_Z p_\parallel} \exp\left(\frac{(E-1)t/\tau_c - p_\parallel}{c_Z} - \frac{\alpha p_\perp^2}{2p_\parallel}\right)\left(\exp\left(\frac{p_\parallel - p_{\max}}{\sigma_p}\right) + 1\right)^{-1}$$

☞ Three modes are recovered with cold Bimaxwellians [Kómár 2013]

☞ Adding the runaway population

- $B = 2\ T$
- $n = 5.10^{19}$
- $T = 0\ eV$
- $Z_{eff} = 1$
- $n_{RE}/n = 6.10^{-3}$





Benchmark ALPS on prescribed distributions

☞ Analytical distribution from [Fülöp 2006, Pokol 2014]

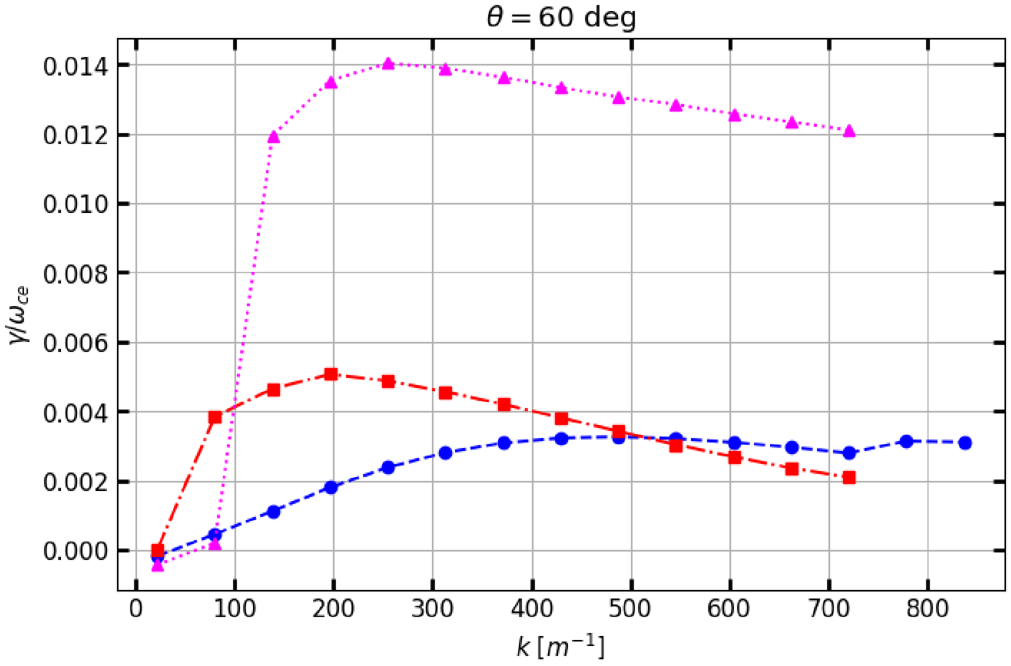
$$f_0(p_\parallel, p_\perp, t) = \frac{n_{r0}\alpha}{2\pi c_Z p_\parallel} \exp\left(\frac{(E-1)t/\tau_c - p_\parallel}{c_Z} - \frac{\alpha p_\perp^2}{2p_\parallel}\right)\left(\exp\left(\frac{p_\parallel - p_{\max}}{\sigma_p}\right) + 1\right)^{-1}$$

- $B = 2\ T$
- $n = 5.10^{19}$
- $T = 0\ eV$
- $Z_{eff} = 1$
- $n_{RE}/n = 6.10^{-3}$

☞ Three modes are recovered with cold Bimaxwellians [Kómár 2013]

☞ Adding the runaway population

- No damping considered
  $\Rightarrow$ all mode found unstable
- EXEL more unstable than whistlers [Pokol 2014]
- O-mode more unstable for these parameters



☞ On-going work

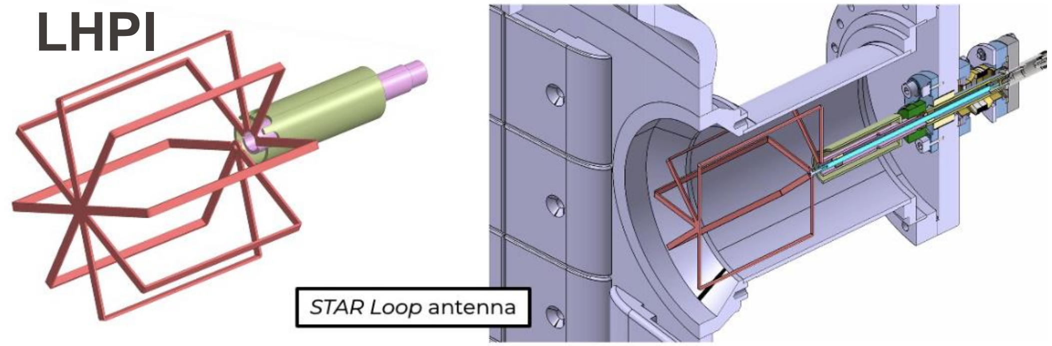
- Explore propagating angles θ
- Collisional & convective damping
- Dependence on underlying RE distribution

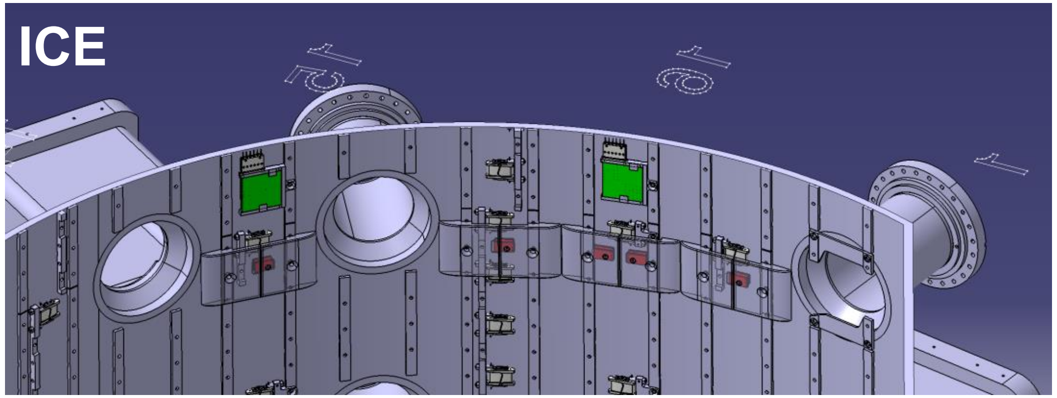
Future prospects

☞ Experimental

- Improvement of LHPI ⇒ polarisation of mode
- Improvement of ICE ⇒ wavenumber of mode

⇒ Better comparison & constraints on simulations





☞ Simulations

- Explore LUKE/DREAM distributions
- Coupling of wave solver with LUKE/DREAM for pitch angle scattering study
- JOREK simulations for Alfvén wave interaction with RE

RE distribution [Decker 2016]