Multi-angle measurement of EC emission by fast electrons: sensitivity study

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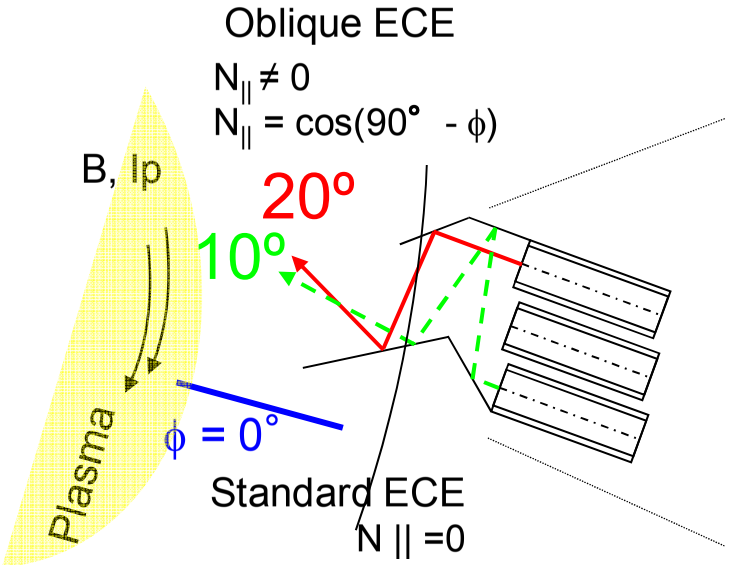
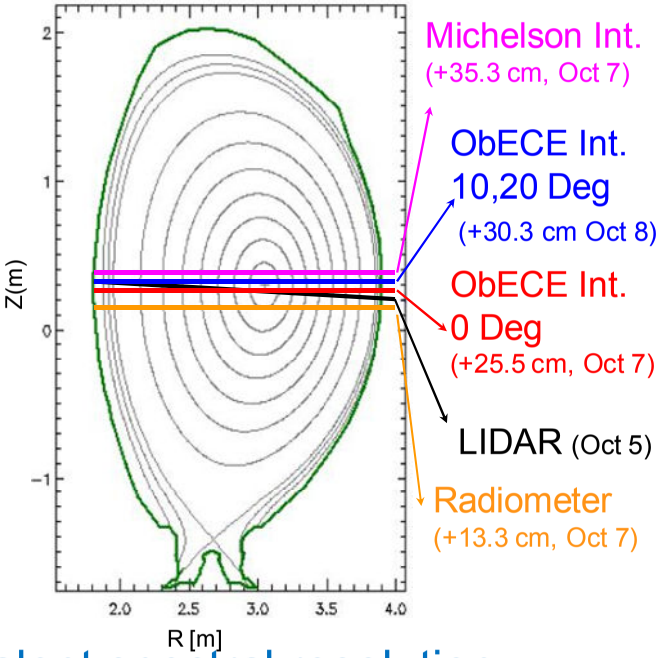
Analysis of the superthermal ECE spectrum below the 2nd harmonics in presence of Lower Hybrid power.

- Motivation and tools:
  - Multiple angle ECE observations correspond to probing the electron velocity distribution function at multiple electron energies:
  - $$\omega - k_{//}v_{//} = n\Omega/\gamma$$
  - Emission code SPECE incorporates a model for the simulation of the fast electron tail driven by Lower Hybrid waves.
  - The model has been used to fit, varying the control parameters, the experimental signals of the Oblique ECE diagnostic.
  - This gives information about the LHCD deposition region, the characteristics of the electron tail, the fraction of driven current.
  - The sensitivity of the simulated spectra to the parameters have been studied, in order to assess the level of confidence on the values obtained from the best fit.

Multiple angle ECE system at JET

- Setup:
  - 3 Lines of sight: Φ = 0º, ~10º, ~22º
  - 2 Linear polarization for each oblique line of sight
  - Perpendicular (Φ = 0º) in a different octant, redundant (ECM Michelson diag.)
- Antenna
  - compact design
  - machined in a single piece
  - single ellipsoidal mirror shared by two lines
  - ~50 mm beam radius at plasma

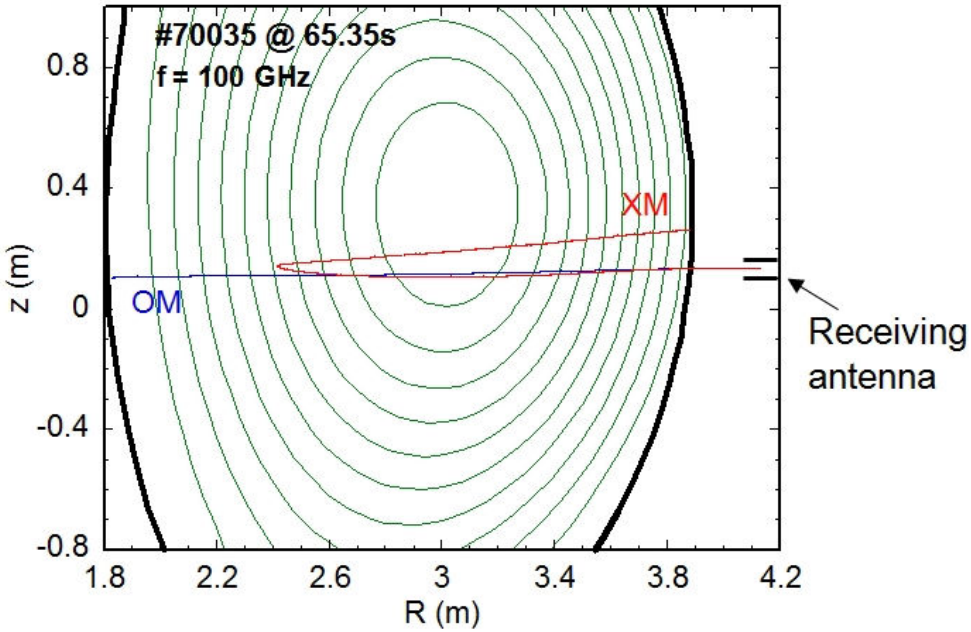




- ~5 ms/radial profile time resolution, 7-14 GHz equivalent spectral resolution
- Spectral coverage: 1st-4th harmonics (75-350 GHz)
- Relative calibration (absolute later this year)

The SPECE code: equation of radiation transfer in general tokamak equilibrium.

- Raytracing code originated by the beam-tracing code GRAY
  D. Farina, FST (2005)
- SPECE needs:
  - magnetic equilibrium
  - n_e and T_e profiles
- Computes EC emission using fully relativistic description for Maxwellian or multi-Maxwellian e.d.f.



- Initial conditions given at the antenna
- Cold trajectory integrated backwards to the plasma (with step $d\underline{s} = -\underline{v}_g dt$) for O- and X-mode

- Allows detailed description of real ECE diagnostic configuration
  - Accounts for antenna polarization, finite beamwidth, wall effects
  - Optimization with free parameters (equilibrium correction)

5 parameters to control the shape of the distribution function in momentum and in space (u=p/mc normalized momentum, ψ normalized poloidal flux coordinate):

$$f(\psi,\vec{u}) = (1-\eta(\psi))\cdot f_{M,T_b}(|\vec{u}|) + \eta(\psi)\cdot \sum_{i=1}^{N} f_{M,T_{tail}}(|\vec{u}-\vec{u}_{0,i}|)$$

Brusati et al., Nuclear Fusion vol 34, No.1, pp. 23-42 (1994)

Density fraction of suprathermal electrons **peaked at $\psi=\psi_0$**, **peak value $\eta=\eta_0$**, gaussian decrease with **width ψ_c**

$$\eta(\psi) = \eta_0 \cdot \exp\left[-\frac{(\psi-\psi_0)^2}{2\cdot\psi_c^2}\right]$$

Temperature T_{tail} determines "spread" of the tail in u_{perp}. Maxwellians **spacing** in $u_{||}$ linked to maxwellians width ($T_{tail}^{1/2}$).

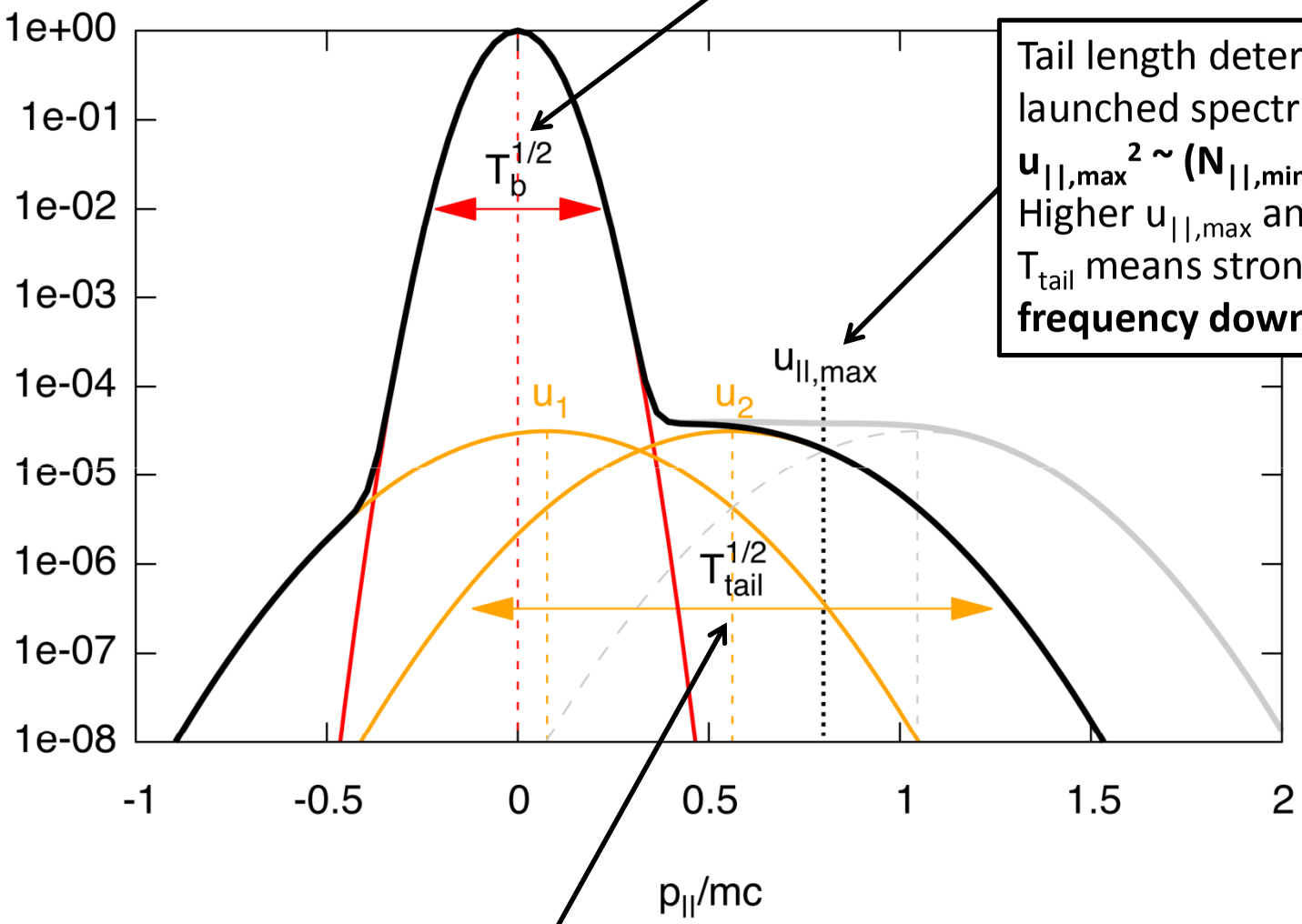
$$u_{0,1} = \sqrt{T_b/mc^2}$$

$$u_{0,i} = u_{0,i-1} + 2\sqrt{T_{tail}/mc^2}$$

Suprathermal tail extends up to normalized **parallel momentum u_{max}**. This determines the **number N** of maxwellians used to model the tail.

$$N = 1 + \mathrm{int}\left[\frac{u_{max}-u_{0,1}}{2\sqrt{T_{tail}/mc^2}}\right]$$

When cold resonance n=2 inside plasma volume: plasma optically **thick** and antenna temperature $T_a \sim T_b$



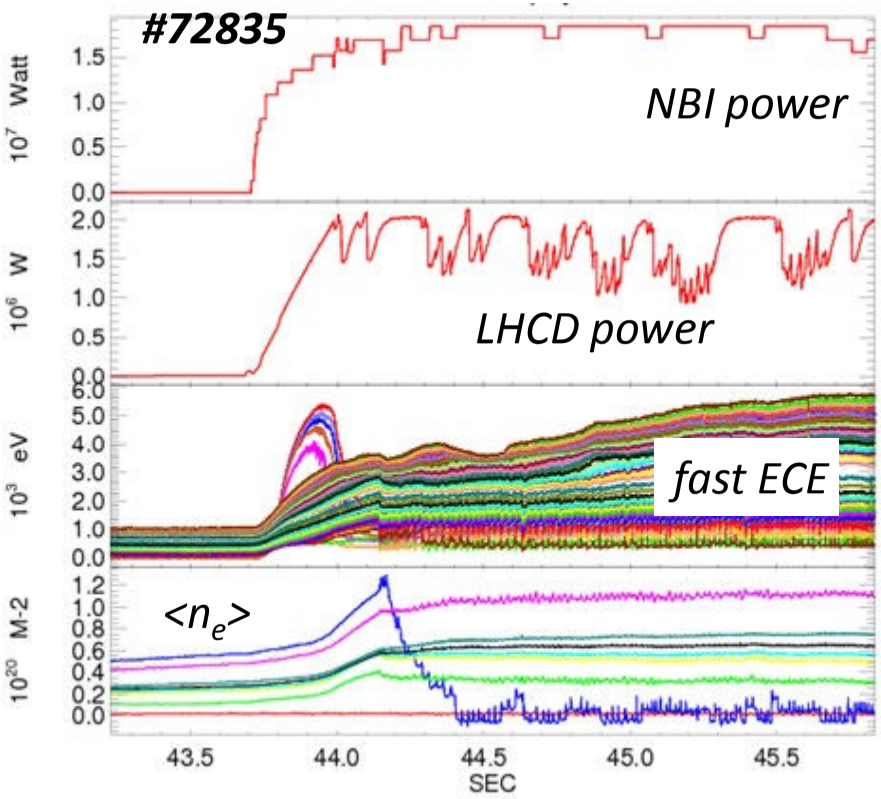
Tail length determined by launched spectrum:
$u_{||,max}^2 \sim (N_{||,min}^2-1)^{-1}$
Higher $u_{||,max}$ and higher T_{tail} means stronger **frequency downshift**

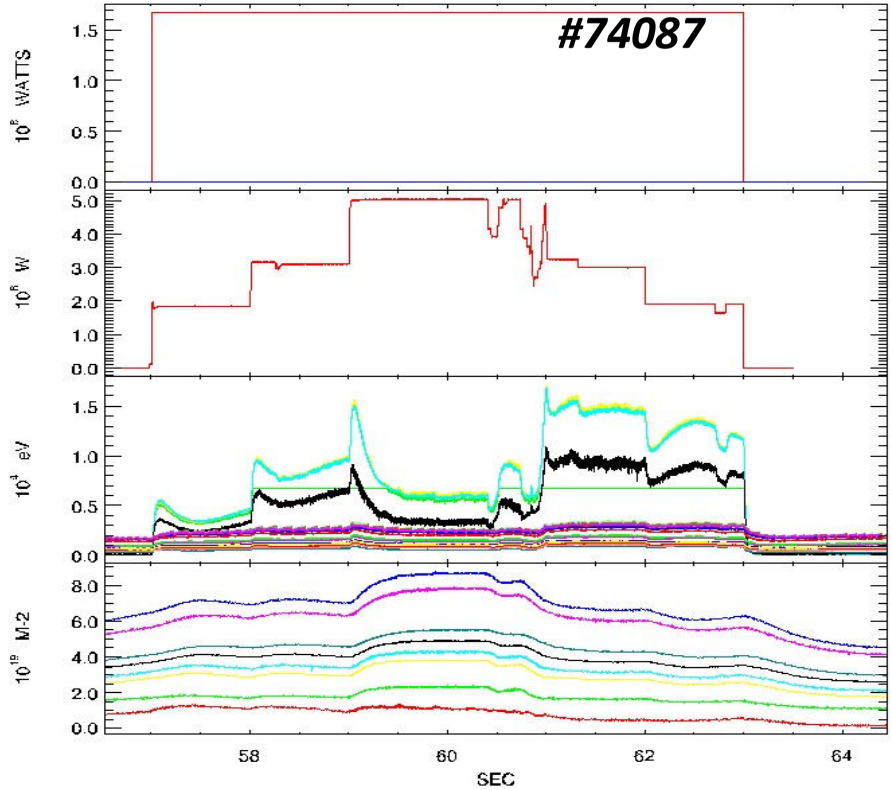
Downshifted emission visible when cold resonance n=2 is outside plasma volume: plasma optically **thin** and antenna temperature $T_a \sim \eta T_{tail}$

Database: plasma parameters range

• Magnetic field:	2.3-3.4 T
• Plasma current:	1.75-2.5 MA
• Plasma density:	4.3-11 $10^{19} m^{-2}$
• Core electron temperature:	3-8 KeV
• Superthermal peak radiative temp.:	1-8 KeV
• Additional power (total):	2-25 MW
• LH power:	1.9-5 MW
• $N_{//}$:	1.8-2.3
• Transient & steady state plasmas	

Example of different time evolution

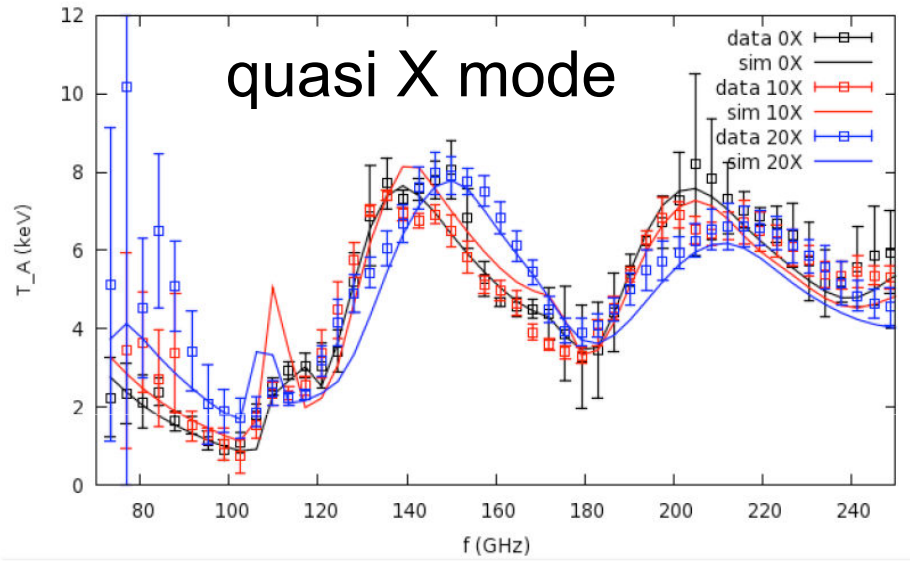


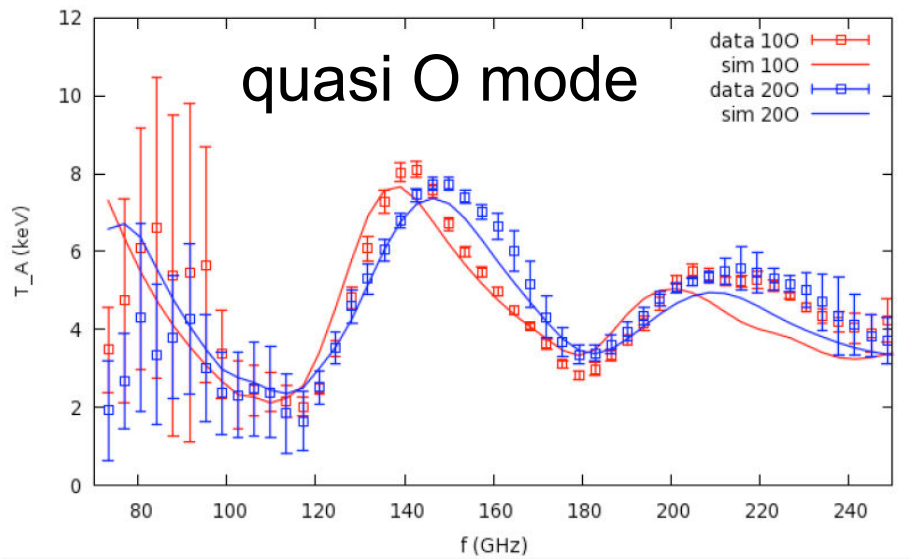


- *time traces of NBI and LHCD power, fast ECE signals (KK3) and line integrated density (KG1V).*
- *Tail formation produces an emission peak in ECE signals only around 43.9s (on left)*

Data quality

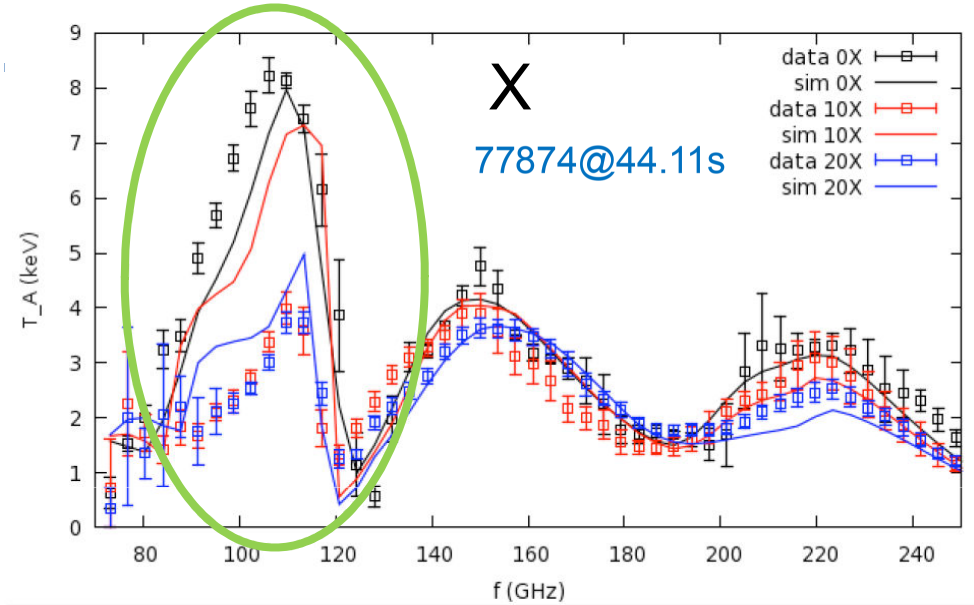
77874@45.50s

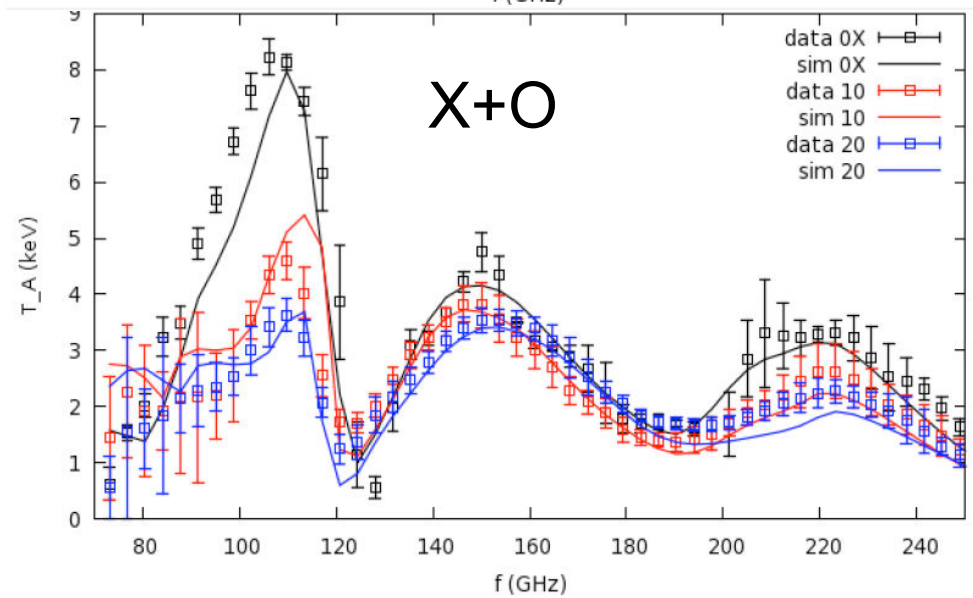




- In the case shown: thermal plasma (with heating)
- Usually good agreement between data and simulations for all the 5 channels 0X, 10X, 10O, 20X, 20O
- Error bars take into account
  - statistical errors (from time average, ~50ms) and
  - Calibration errors. Calibration obtained from comparison with simulation, benchmarked (perp. emission) with an absolutely calibrated diagnostics, averaged on many timeslices in different conditions

Polarization modes

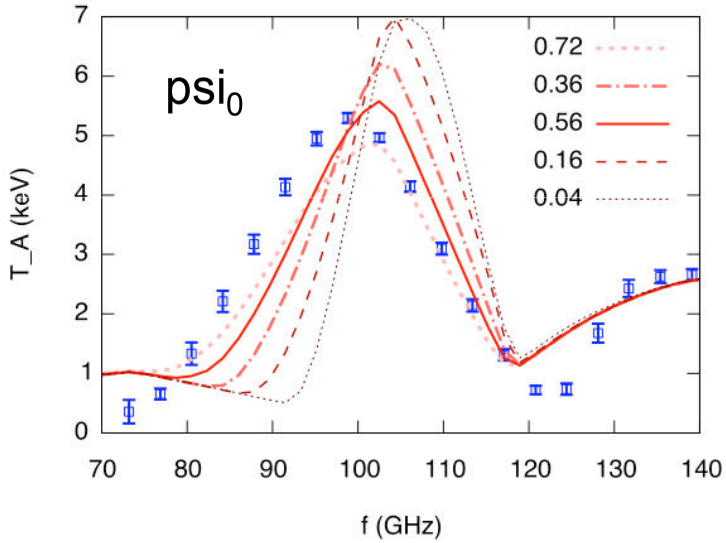




- In the case shown: plasma with LH driven tail
- The expected (simulated) Xmode/Omode ratio in not seen when
  - the ratio of the two polarization modes is >>1
  - AND/OR plasma is optically thin
- as is the case for the superthermal peak
- Agreement with data is re-established comparing TOTAL emission (X+O)

Scan in spatial localization of suprathermal electrons (ψ_0, ψ_c)

- Current kept constant at I_{LH}/I_P=430kA/2MA for all the cases
- Radial extent of the affected region ($\Delta\rho \sim \psi_c/\psi_0$) kept constant when varying ψ_0



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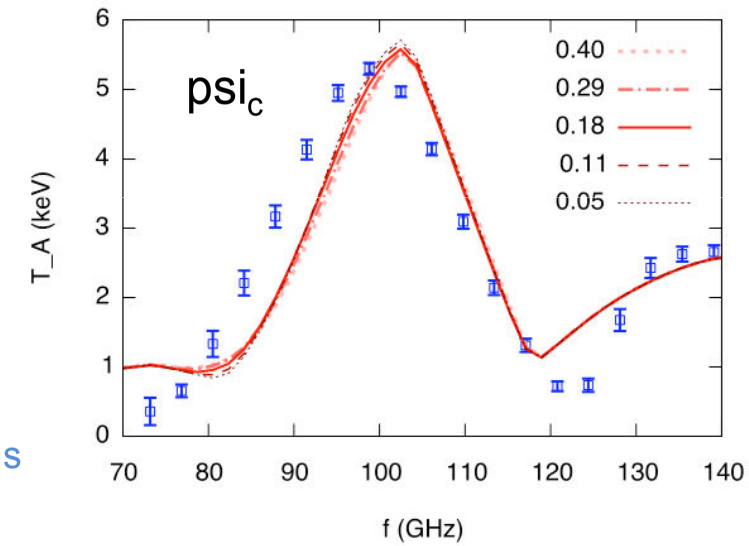
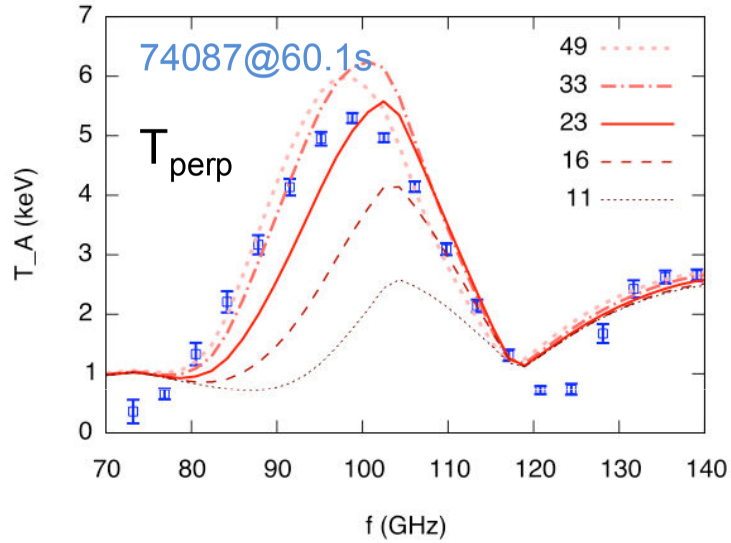
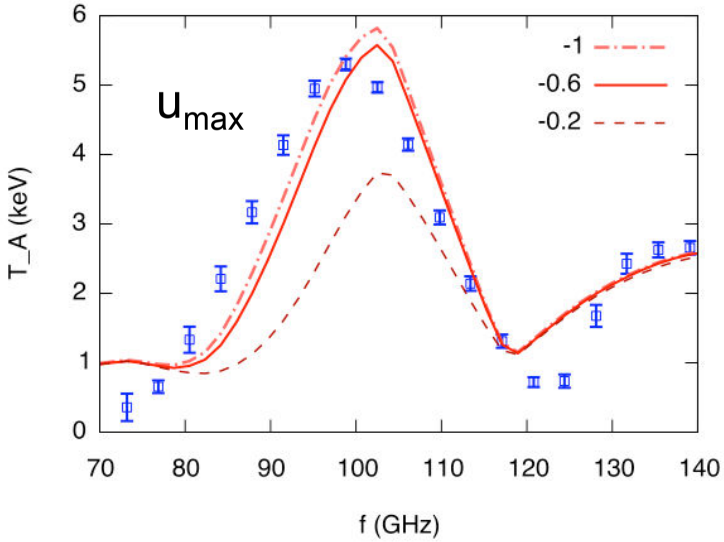
@60.1s



- Increasing ψ_0 fast electrons are localized at more external radii
  - lower peak (lower density) at lower frequency (fast electrons are in a lower B region)
- ECE spectrum almost insensitive to ψ_c

eta, Tperp, umax scan





- Downshifted emission at n=2 due to suprathermal tail peaked around f ≈ 100GHz for B ≈ 2.7T
- Plasma is optically thin: emission increases with perp. energy (T_{perp}) <u>and</u> fraction of fast electrons (η_0)

T_{perp} scan:

- Scaling at $\eta_0 T_{perp}$=const
- Downshift increases with T_{perp}
- Model limitation: extent in $u_{//} = p_{//}/mc$ depends on T_{perp} → "short" tail at low T_{perp}

$u_{//max}$ scan (tail composed by 1, 2, 3 maxw.):

- Step size in scan depends on T_{perp} (=$T_{//tail}$)
- Large difference between 1 and 2 maxwellians ($|u_{//max}| \approx 0.2, 0.6$), smaller variations for larger values
- From $N_{//,LH}$=1.8, expected $u_{//max} \approx (N_{//min}^2-1)^{-1/2} \approx 0.67$

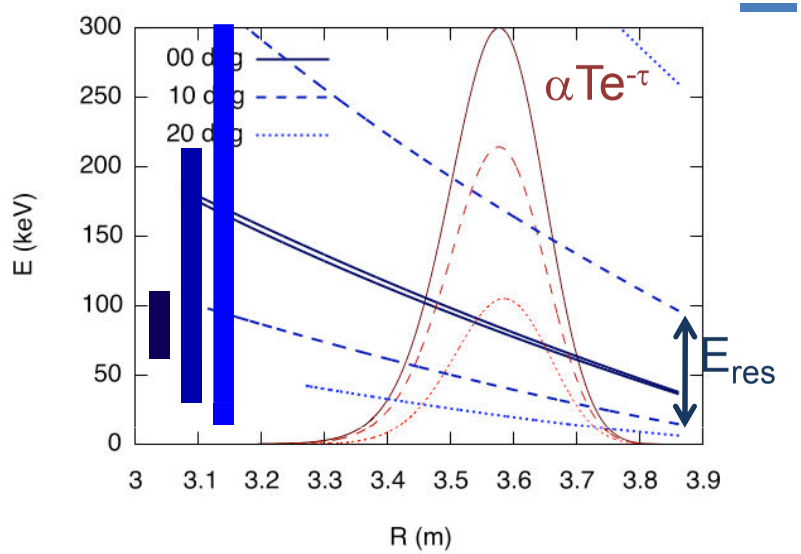
u_{max} scan for oblique lines

- f=102 GHz: cold resonance is outside the plasma
- With this configuration, oblique views sensitive to lower (and much higher) energies
- Oblique spectra less affected by changes in the energetic part of the tail
- $E = mc^2 (\gamma - 1) = mc^2 [(1 + u^2)^{1/2} - 1]$

  1 maxw., $|u| = 0.2 \rightarrow E = 10$ keV

  2 maxw., $|u| = 0.6 \rightarrow E = 85$ keV

  3 maxw., $|u| = 1.0 \rightarrow E = 210$ keV



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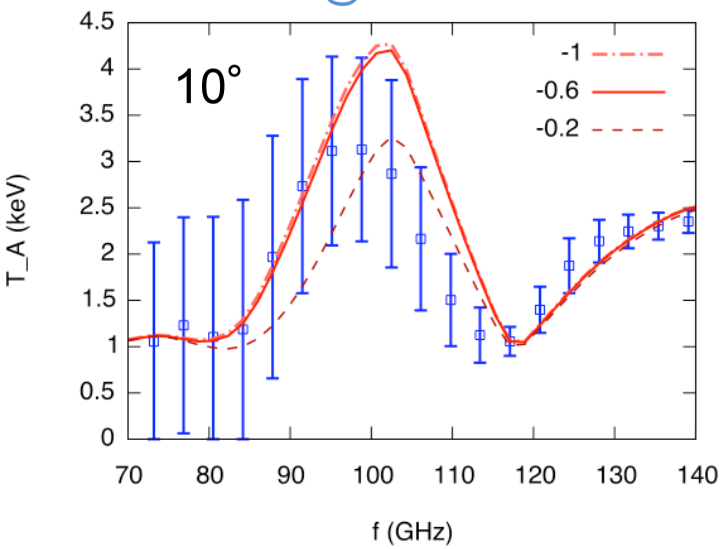
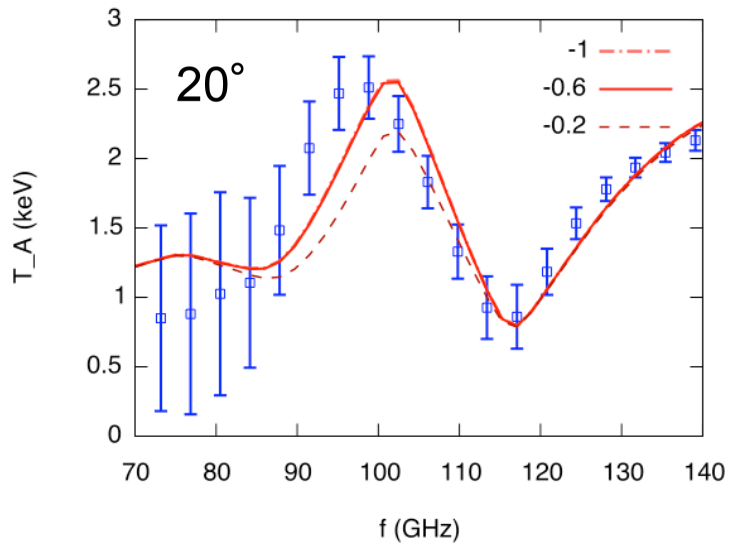
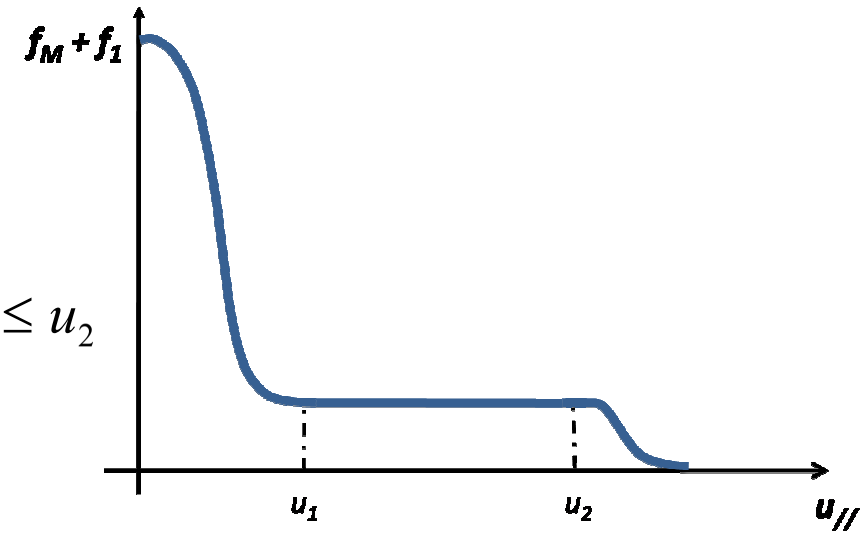


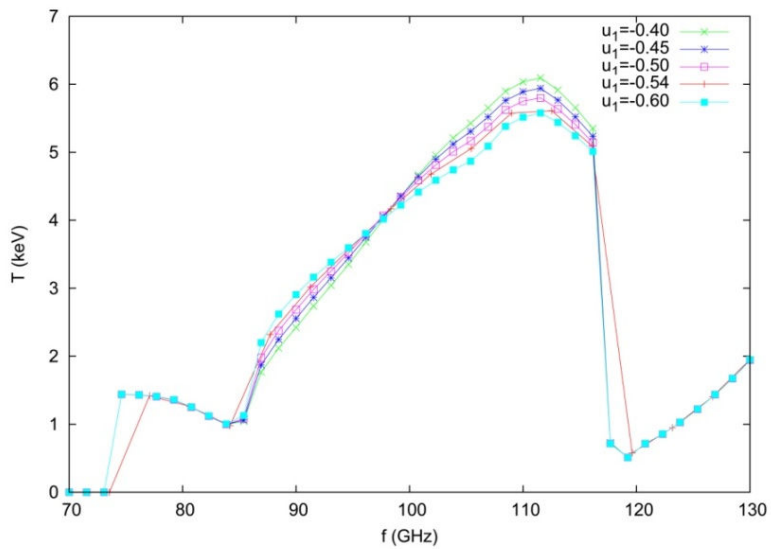


New Model for superthermal tail

$$f(\dot{p}) = (1-\eta(\Psi))f_M(\dot{p}) + \eta(\Psi)f_1(\dot{p})$$

$$f_1 = c_{\mu_{//},\mu_\perp,u_2-u_1} \cdot e^{-\frac{\mu_\perp}{2}u_\perp^2} \cdot \begin{cases} e^{-\frac{\mu_{//}}{2}(u_{//}-u_1)^2} & u_{//} < u_1 \\ 1 & u_1 \le u_{//} \le u_2 \\ e^{-\frac{\mu_{//}}{2}(u_{//}-u_2)^2} & u_{//} > u_2 \end{cases}$$





- flat in $u_{//}$ for $u_1 \le u_{//} \le u_2$
- u_1, u_2 can be varied with continuity
- Independent $T_{//}$, T_{perp}
- Same spatial dependence of superthermal fraction (η_0, ψ_0, ψ_c) (with $u = p/mc$, $\mu = mc^2/T$)
- Finer changes in superthermal tail length ($u_{//max}$) will be possible
- $u_{//max}$ and T_{perp} can be varied independently
- Benchmarking of the new model in progress

Sensitivity study

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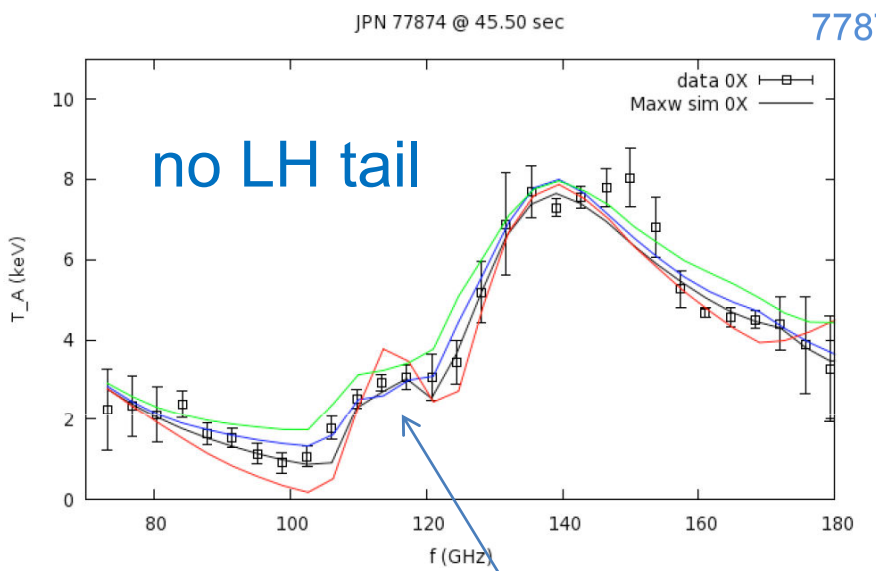
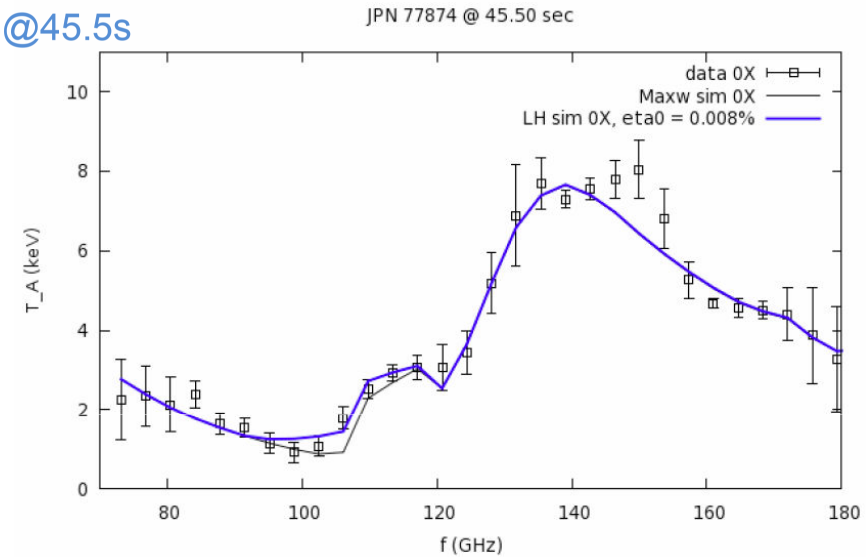
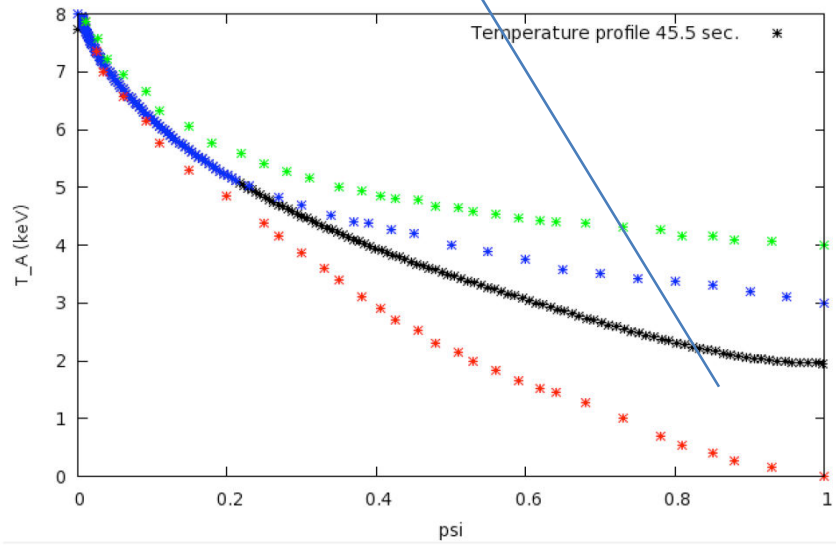






- The superthermal peak can be "confused" with the effect of a large temperature gradient/low edge temperature in a maxwellian plasma (sim & data)
- The minimal fraction of suprathermal electrons η_0 "visible" by the diagnostic has been estimated using exp. data uncertainty
- $n_{sth} \sim 4\ 10^{15}\ m^{-3}$ ($\eta_0 \sim 0.01\%$)

Summary of parameters (preliminary)

Pulse	P_{LH}(MW)	$u_{//}$	$N_{//}^{launch}$	T_{tail} (keV)	η(%)	Ψ_0	Ψ_C	I_{st}/I_{pl}(%)
73417	2.9	-0.45	1.8	38	0.08	0.4	0.2	15
73422	2.9	-0.45	1.8	28	0.08	0.4	0.2	12
73646	1.9	-0.35	1.8	45	0.1	0.5	0.3	13
73471	3.1	-	-	-	-	-	-	-
75401	2.5	-0.2	1.8	35	0.9	0.9	0.3	13
72835@43.9	2	-0.6	2.3	20	0.2	0.4	0.2	47
72835@44.1	2	-0.6	2.3	20	0.02	0.4	0.2	14
74087@57.74	2	-0.51	1.8	25	0.08	0.45	0.2	20
74087@58.5	3	-0.56	1.8	30	0.12	0.3	0.17	20
74087@60.1	5	-0.6	1.8	23	0.12	0.56	0.18	20
77874@44.1	2.5	-0.8	1.8	35	0.2	0.25	0.1	29

Conclusions

- An analysis of non thermal JET plasmas is been performed, using multi-angle ECE data and SPECE simulations
- The sensitivity to each parameters has been assessed with a scan of the parameter space using a simplified model of the LH driven edf
- The sensitivity of the technique to low superthermal electron density has been evaluated
- A more flexible model is under test…

- …to be continued
- Explanation/solution for “mixed” polarization needed

Thank you for your attention

Database ???

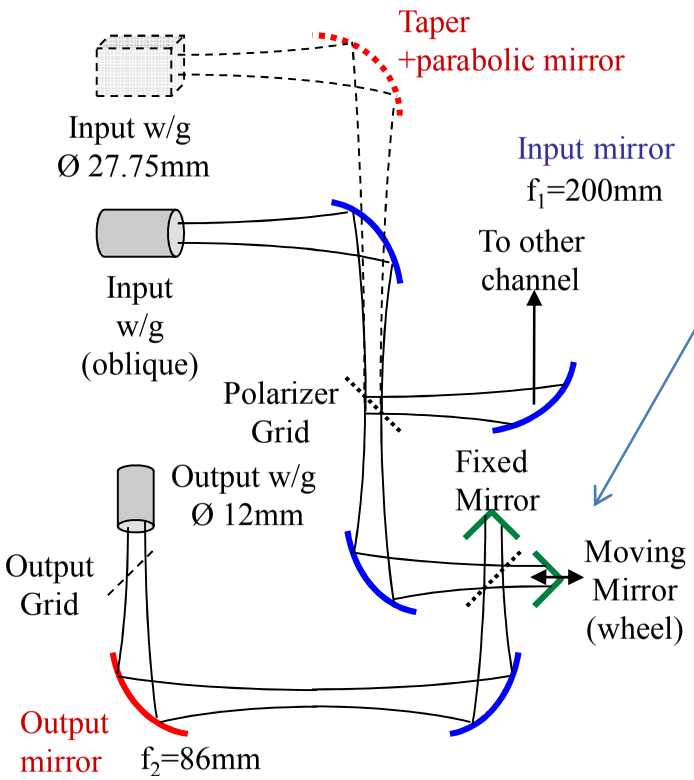
TABLE 1 . JET plasma pulses with relevant LH power injection in which the analysis of the Oblique ECE measurements has been performed

Pulse	t(sec)	B(T)	I_{pl}(MA)	$n_e(10^{19}m^{-2})$	T_e(KeV)	P_{LH}(MW)	P_{NBI}(MW)	N//	Conf.
73417	65.4	2.7	1.75	6.2	5	2.9	6	1.8	L
73422	65.2	2.7	1.75	6.3	4.8	2.9	4.3	1.8	L
73646	64.15	2.3	2	4.3	3.4	1.9	-	1.8	L
73471	64.03	2.7	1.75	11.5	5.2	3.1	13.8	1.8	H
75401	55.95	3.4	2.5	5.2	3	2.5	-	1.8	L
72835		2.7	1.8	1.1	6	2	18	2.3	H
74087	59.8	2.4	2	8	4	5	1.6	1.8	L
77895	45.5	2.7	1.8	11.1	8	2.3	23	1.8	H

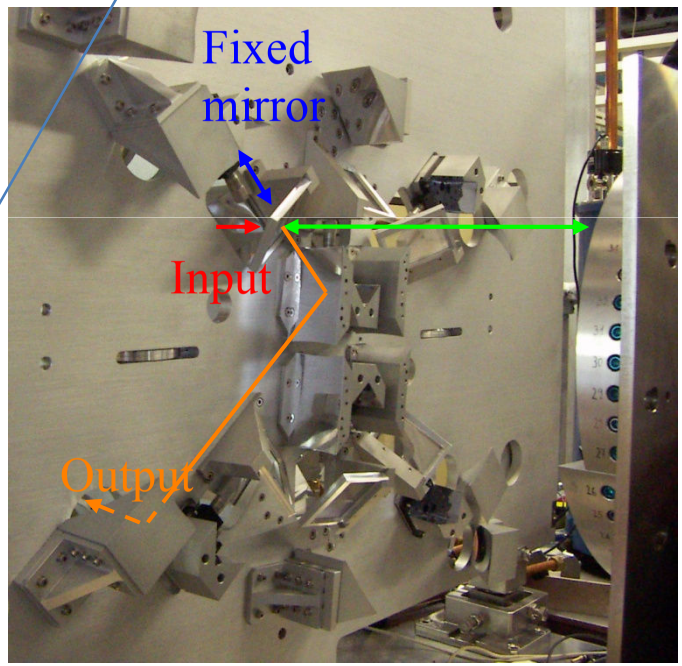
Detection system

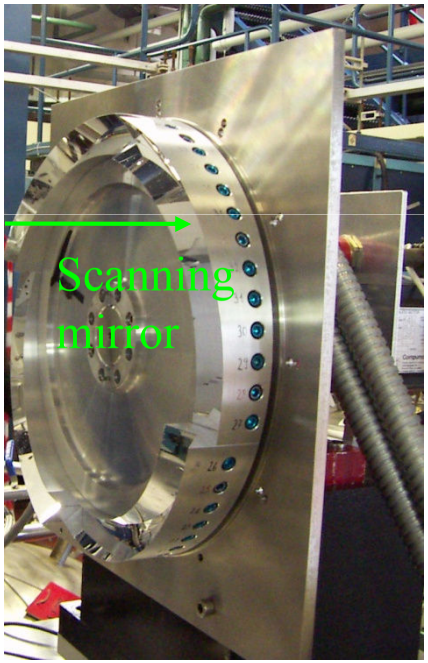
Confocal system:
Performance nearly frequency-independent

Garavaglia, Simonetto, Sozzi, FED 2007



- 5 + 1 Martin-Puplett interferometers, all sharing a common rotating mirror
- 4 helicoidal sectors roof top mirror
- Slope 4.85 deg *Buratti, Zerbini, RSI 1995*





- ~5 ms/radial profile time resolution, 7-14 GHz equivalent spectral resolution
- Spectral coverage: 1st-4th harmonics (75-350 GHz) (75-800 GHz instrumental band)
- Relative calibration (absolute later this year)

Model electron distribution function used in SPECE:

- Maxwellian bulk $f_{M,Tb}$, with temperature T_b
- Suprathermal electron tail, obtained as sum of Maxwellian distributions $f_{M,Ttail}$, with temperature T_{tail} and drift $p_{0,i}$ parallel to the magnetic field
- The suprathermal electrons are a fraction η of the total number

$$f(\vec{p}) = (1-\eta)\cdot f_{M,T_b}\left(\left|\vec{p}\right|\right) + \eta \cdot \sum_i f_{M,T_{tail}}\left(\left|\vec{p} - \vec{p}_{0,i}\right|\right)$$

The model is taken from:
Brusati et al., Nuclear Fusion vol 34, No.1, pp. 23-42 (1994)

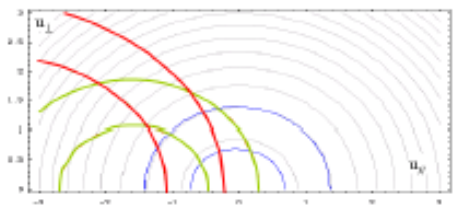
Oblique ECE

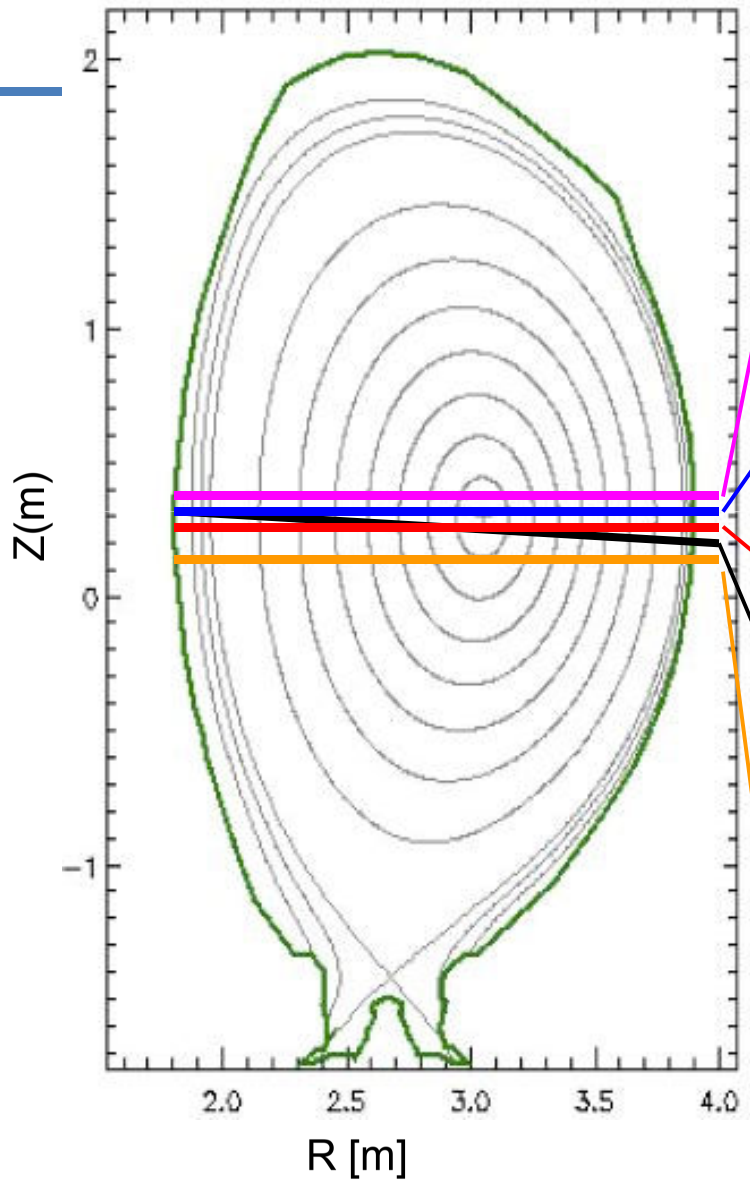
Electron Cyclotron Emission collected through antennae oriented in radial direction in the tokamak geometry is usually a reliable tool for electron temperature measurements. However a wider exploitation of the physics information brought by the EC waves is possible if the radiation is observed at multiple angles and over a wide spectral extension. In fact the resonance condition at a given frequency ω for a given propagation angle is matched by emitting electrons of energy specified through the Eq 1:

- $$\omega - k_{//} v_{//} = n\Omega / \gamma \qquad (1)$$
- where $\Omega = eB(R)/m_e$ is the cyclotron frequency corresponding to the local magnetic field $B(R)$, $v_{//}$ and $k_{//}$ are respectively the components of the electron velocity and of the wave vector parallel to $B(R)$, $\gamma = (1 - v^2/c^2)^{-1/2}$ is the relativistic factor and *n* the harmonics number.

Multiple angle observations then correspond to probing the electron velocity distribution function at multiple electron energies. This paper deals with the interpretation of the well known spectral feature arising in the region below the ECE 2nd harmonics peak when a substantial amount of RF power at Lower Hybrid frequency is injected in the plasma.

Fig 1: Resonance curves in momentum space





Michelson Int.
(+35.3 cm, Oct 7)

ObECE Int.
10,20 Deg
(+30.3 cm Oct 8)

ObECE Int.
0 Deg
(+25.5 cm, Oct 7)

LIDAR (Oct 5)

Radiometer
(+13.3 cm, Oct 7)

New ObECE
Antenna