ECH AND ECE APPLICATION FOR SPECTRAL ANALYSIS OF THE GLOBAL PLASMA OSCILLATIONS AT TOKAMAK. EXPERIMENTS ON T-10

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MOTIVATION

- important problem for ITER (“mode suppression”, disruptions)
- dynamic similarity of so called MHD events (*tearing, kink, lock-mode, fishbone and other)*
- observation of many impressive kinetic phenomena (strong oscillations of electron distribution function, high energy electrons, high frequency plasma noises)

GOAL

In general - creation and testing of kinetic model for global plasma oscillations

In party - **comparison of calculating and experimental spectral characteristics of eigen plasma oscillations**

METHODOLOGY

ON-AXIS ECH - 1 – 3 gyrotrons 140 GHz, power 0.2 - 1.2 MW,

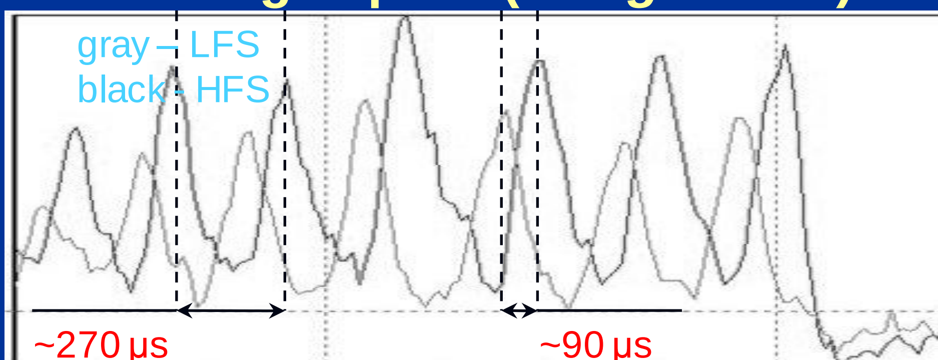
In addition OFF-AXIS ECH - 1 – 2 gyrotrons 129 GHz, up to 0.8 MW.

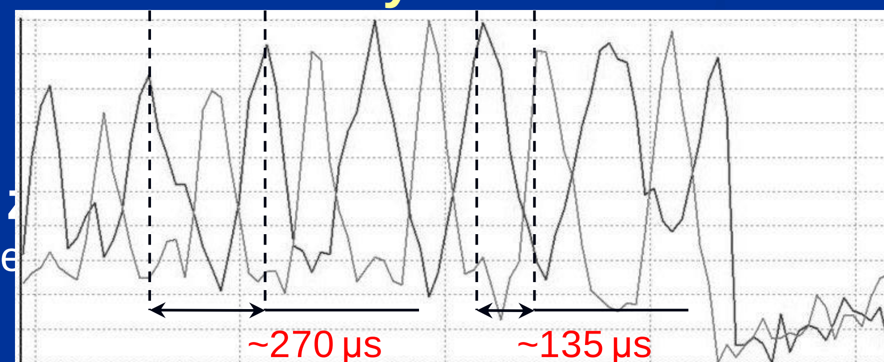
All launches – across the magnetic field. This method allows to get discharges both with single driving modes (m/n=1/1) and with family of modes (m/n=1/1, 3/2, 2/1, 3/1) by small change of current penetration to plasma center. At represented examples: B_t=25 kGs, I_p=250 kA, $\tilde{n}_e \sim 1.7 \cdot 10^{13}$cm^{-3}, $q_l \sim$ 3.1, column displacement Δ= -1cm, digitization – 15 μs

DIAGNOSTICS

ECE - 24 channels, 2nd resonance X-mode, IF band – 300 or 600 MHz

high space (*along radius*) resolution for every channel !!!



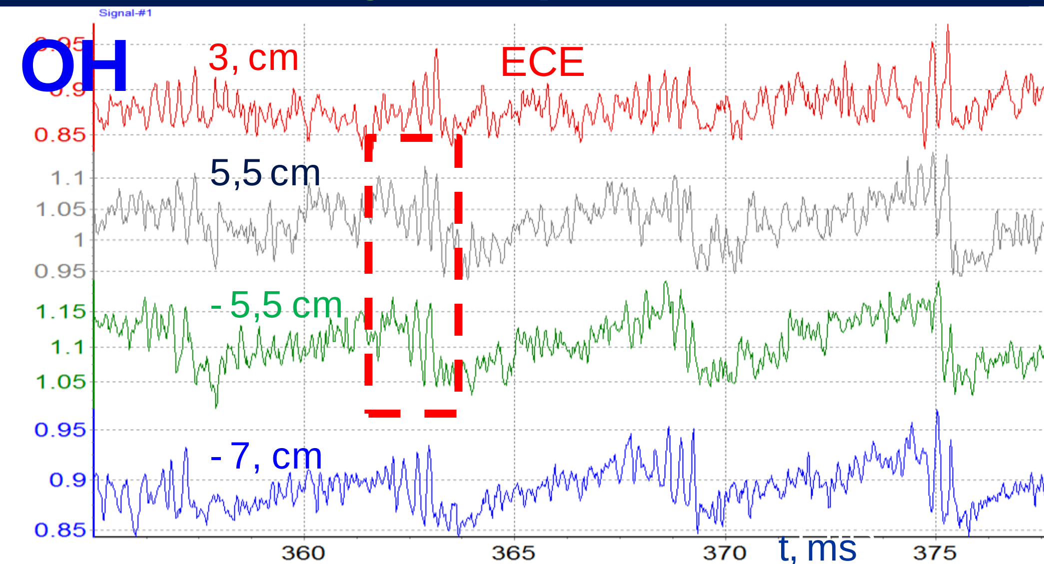


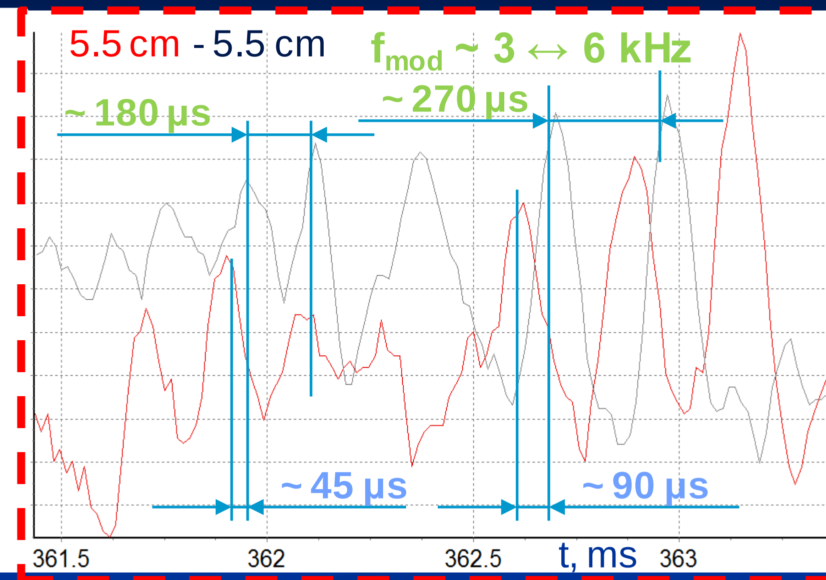
High space resolution (total angle of the antenna pattern ≤1^0, the inclination angle for compensation of the relativistic frequency shift ~1^0, the space resolution – no worse 1 cm), **disturbance motion is nonuniform**

Low resolution (angle of the antenna pattern ~2-3^0, zero angle of the inclination, the resolution – 2-2.5 cm), ECE signals are similar to the chord SXR signals, **disturbance motion looks like uniform**. Effect is hidden by averaging at real and energy space

METHODICALLY

Two kinds of disturbances of electron temperature are marked out: modulating and spiral





ON PHYSICAL NATURE - oscillations are the **eigen** and **forced**

$f^k_{m/n}$ **-** the **eigen** (resonant) oscillations – are initial cause of all branches, they are inherent to certain rational magnetic surface $q_{m/n}$, important property **- variations of their frequencies are small**

$f^k_{m/n} = 1/t_{delay}$ are the **eigen** always

$f^k_{m/n} = f^k_{mod}$ - in many cases - are also **eigen (**peripheral modes under OH, periodically for internal modes under ECH)

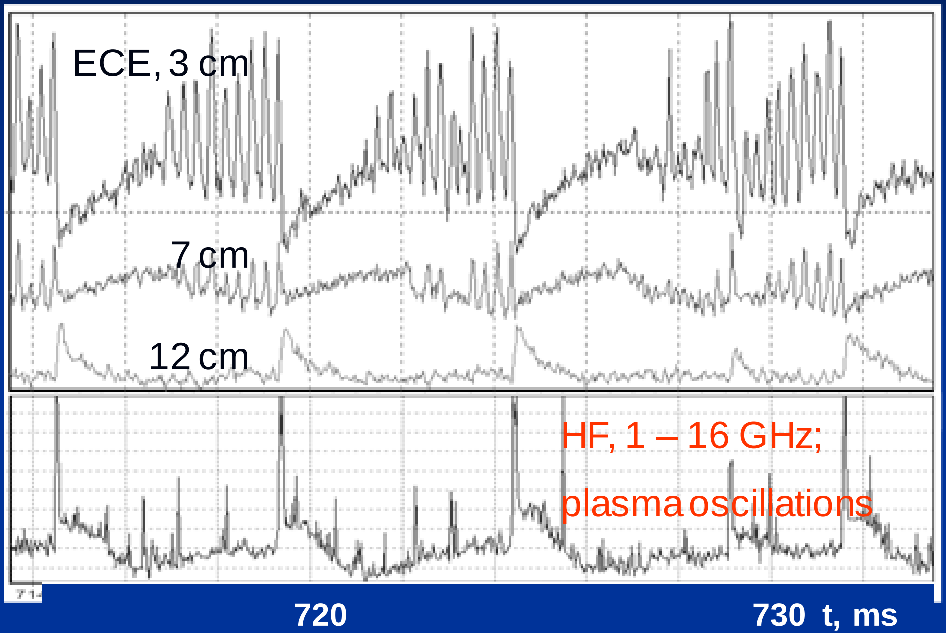
f^k_{mod} - changes of frequencies are comparable with their values

f_{forced} – is reaction of other $q_{m/n}$ zones to primary (eigen) self-excitation, they look like even harmonics f^2_{mod} or odd subharmonics $f^{1/2,\ 3/2}_{mod}$

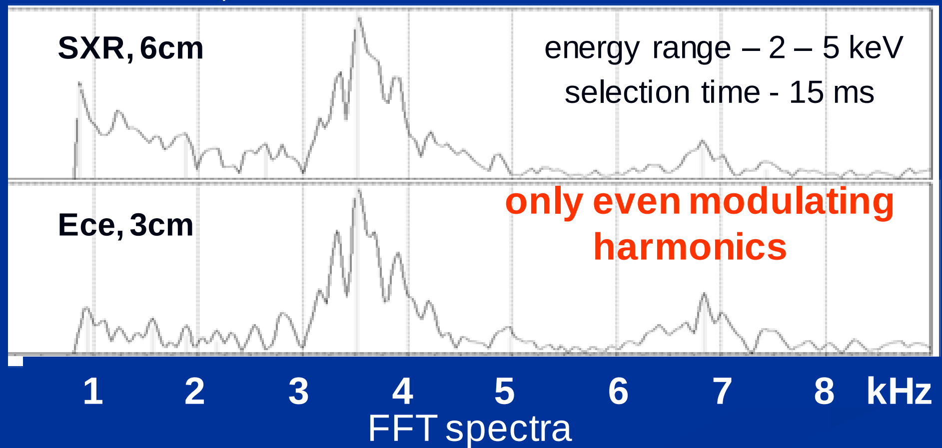
EXPERIMENT ECH

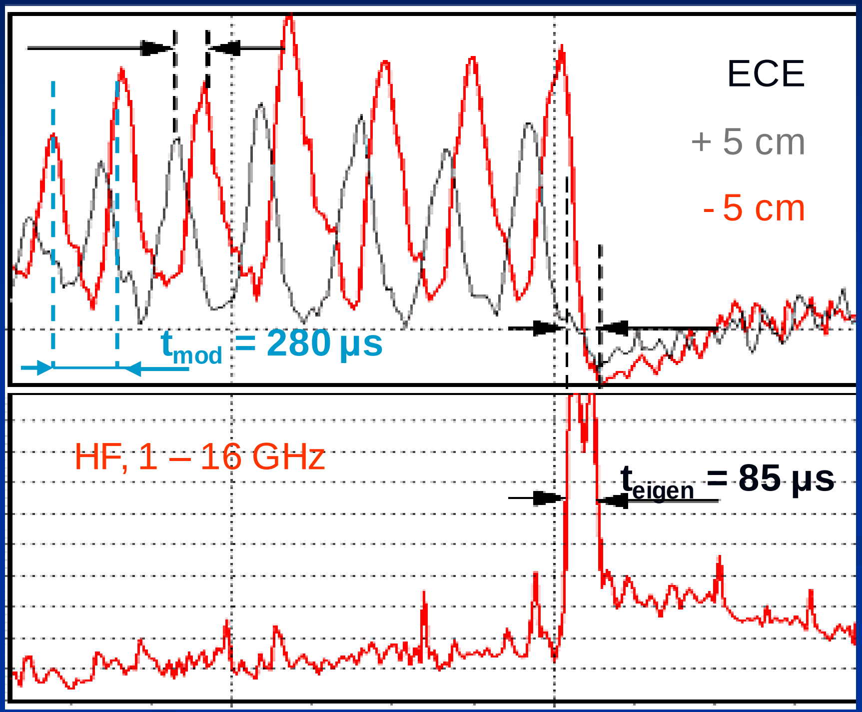
Two kinds of discharges:

only single mode m/n=1/1

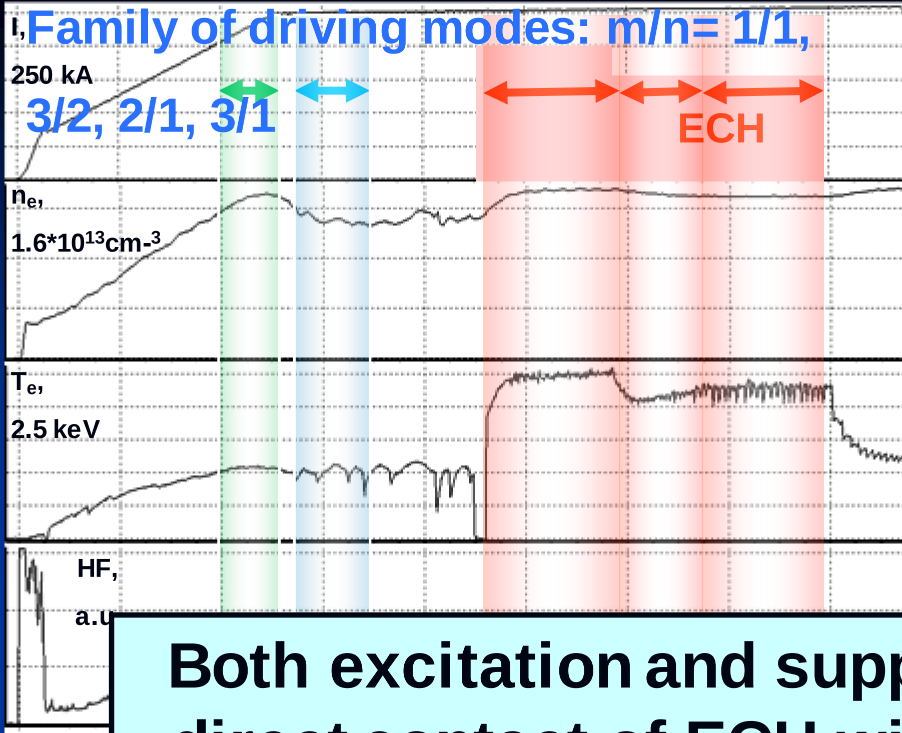


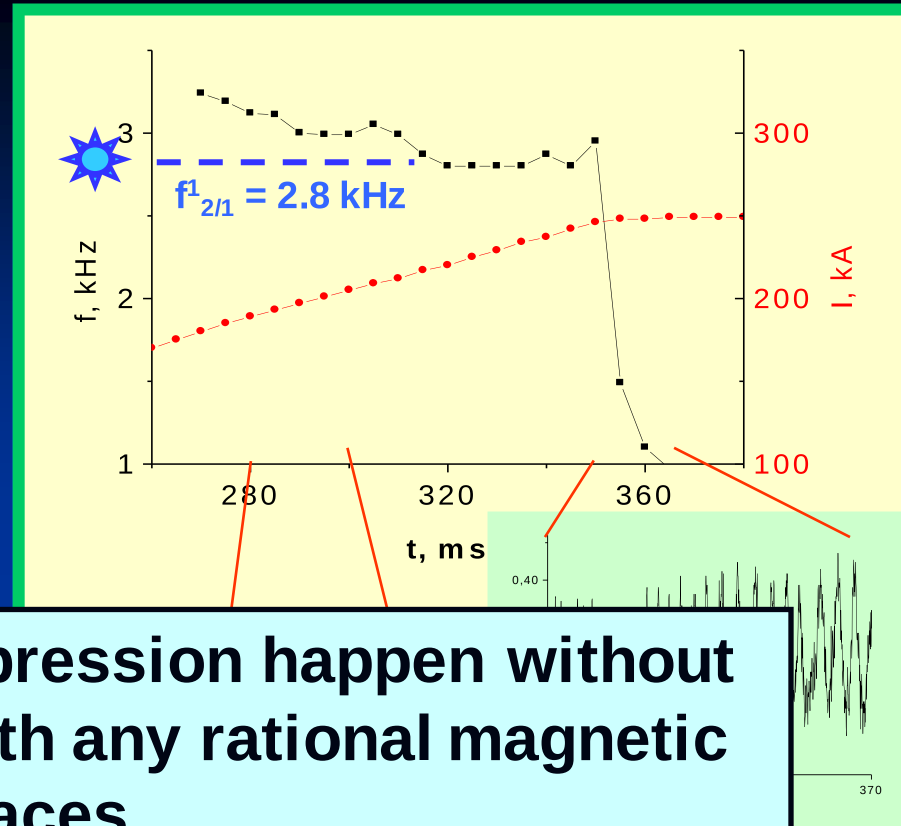
B_t = 25 kGs, I_p = 250 kA, n_e = 1.7*10^{13}cm^{-3}, **on-axis ECH**



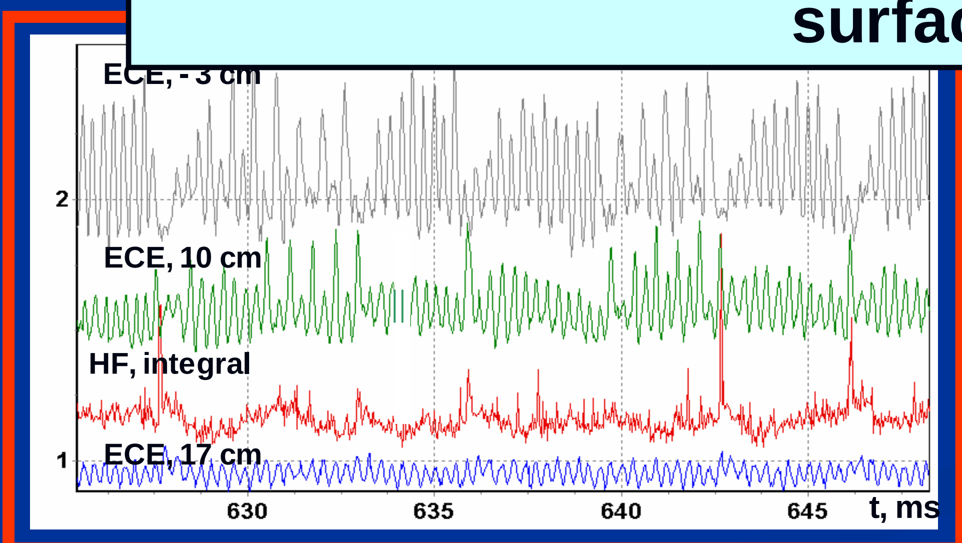


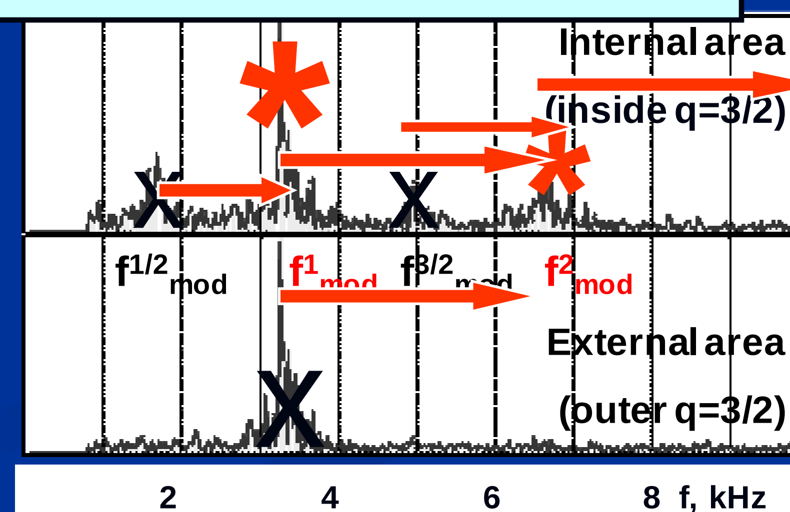
Time delay (here corresponds to eigen frequency ~ 12 kHz) does not depend on ECH power (0.2 – 2 MW), electron temperature (1 – 3.5 keV), plasma density (1 – 2.5*10^{13} cm^{-3}).



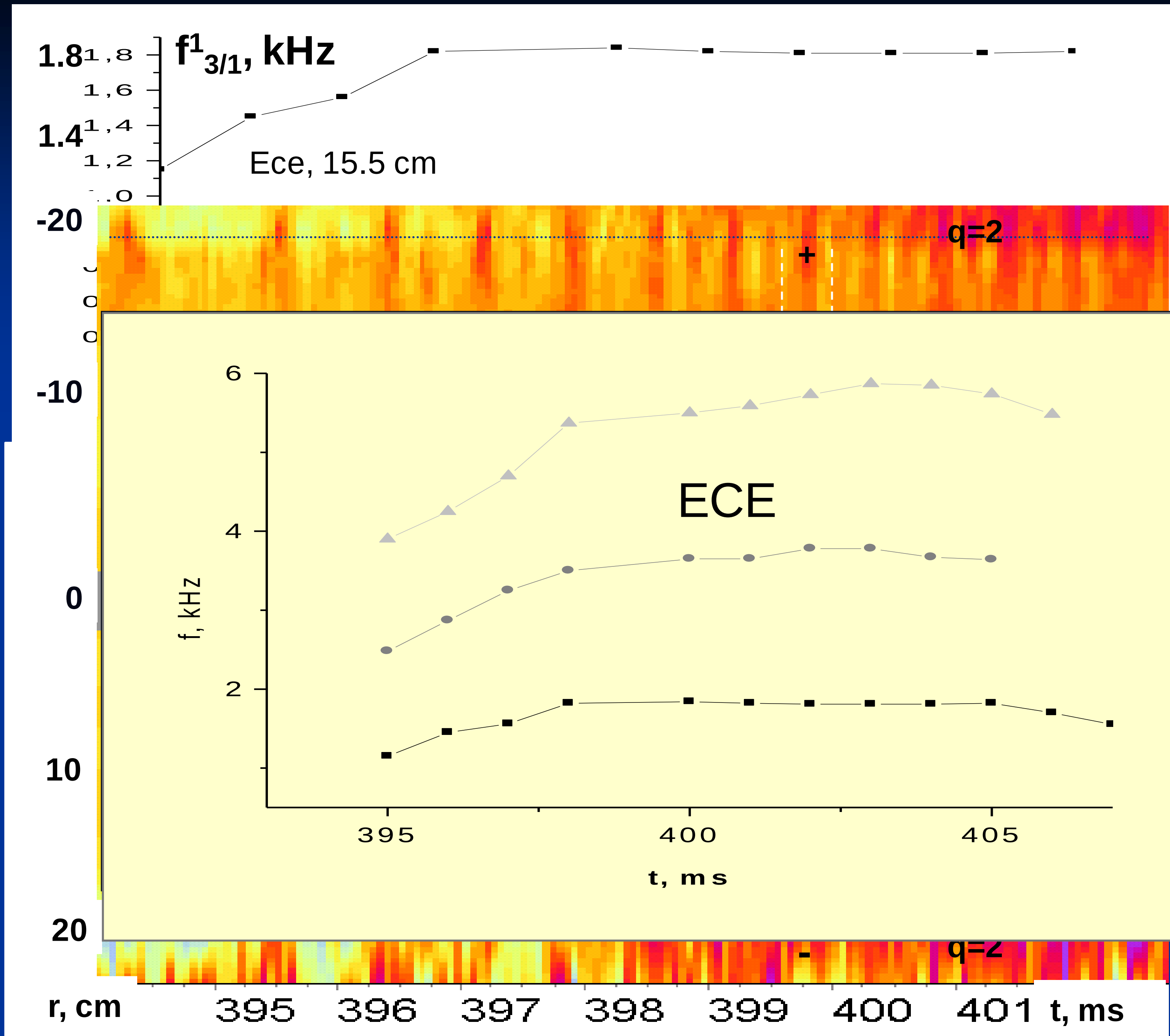


Both excitation and suppression happen without direct contact of ECH with any rational magnetic surfaces



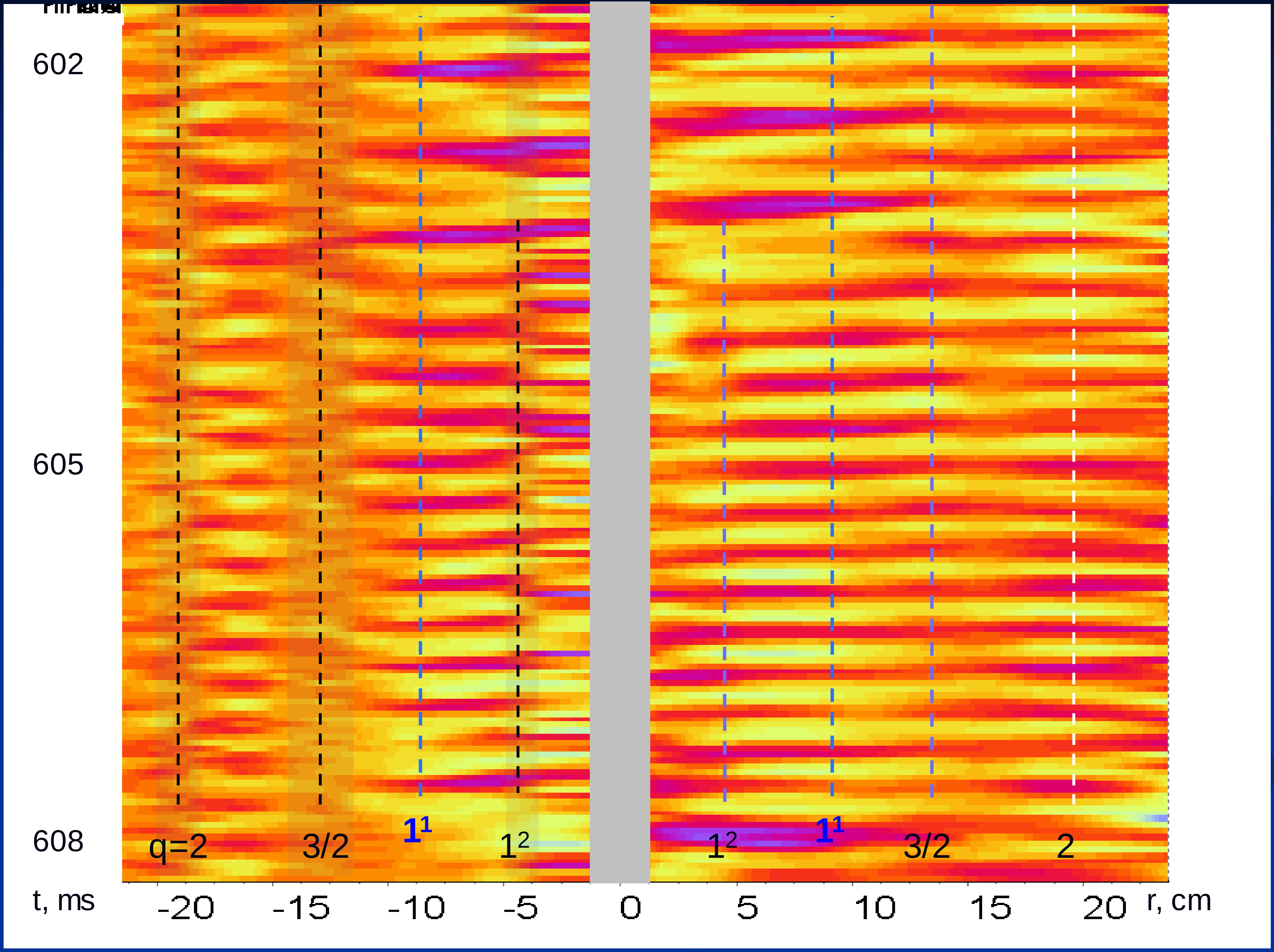


Fishbone like signals of ECH

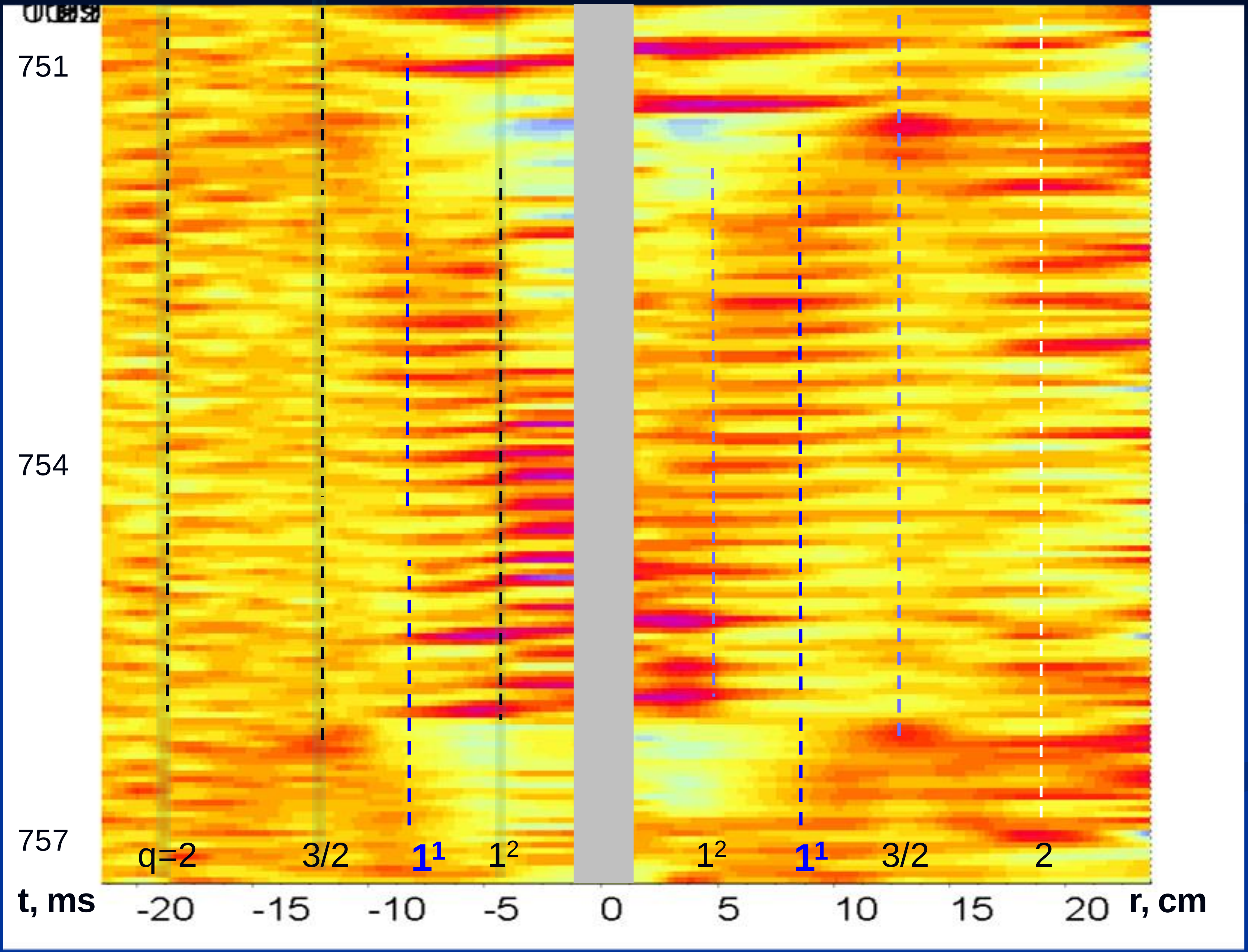


$f^1_{3/1}$, kHz
1.8
1.4
Ece, 15.5 cm
-20
-10
0
10
20
q=2
+
-
q=2
r, cm
395
396
397
398
399
400
401
t, ms
ECE
f, kHz
6
4
2
395
400
405
t, ms

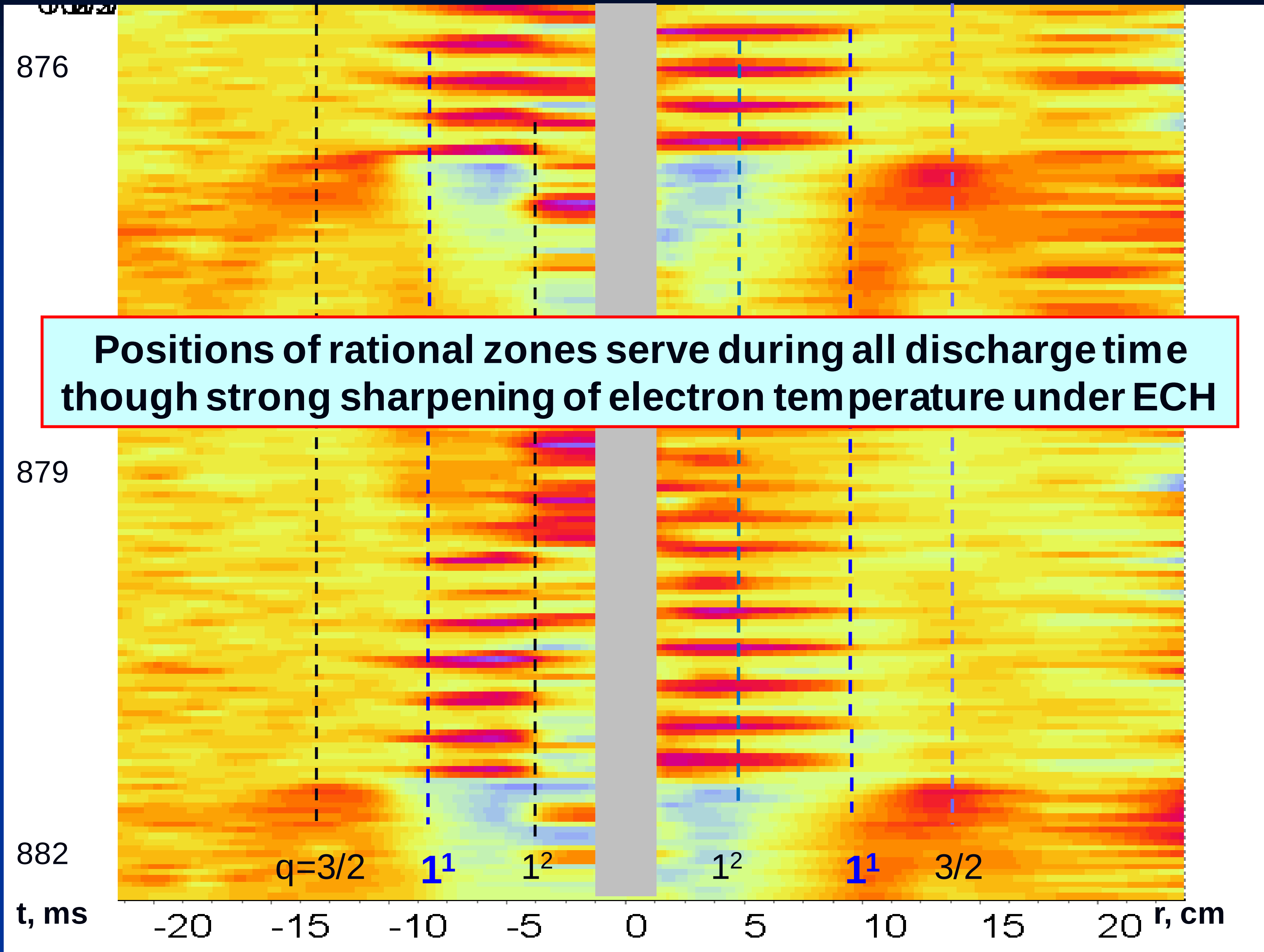
Positions of $r_{m/n}$ 1st *fishbone like* ECH stage



Positions of $r_{m/n}$ 2nd *ECH stage with doubling of frequencies*

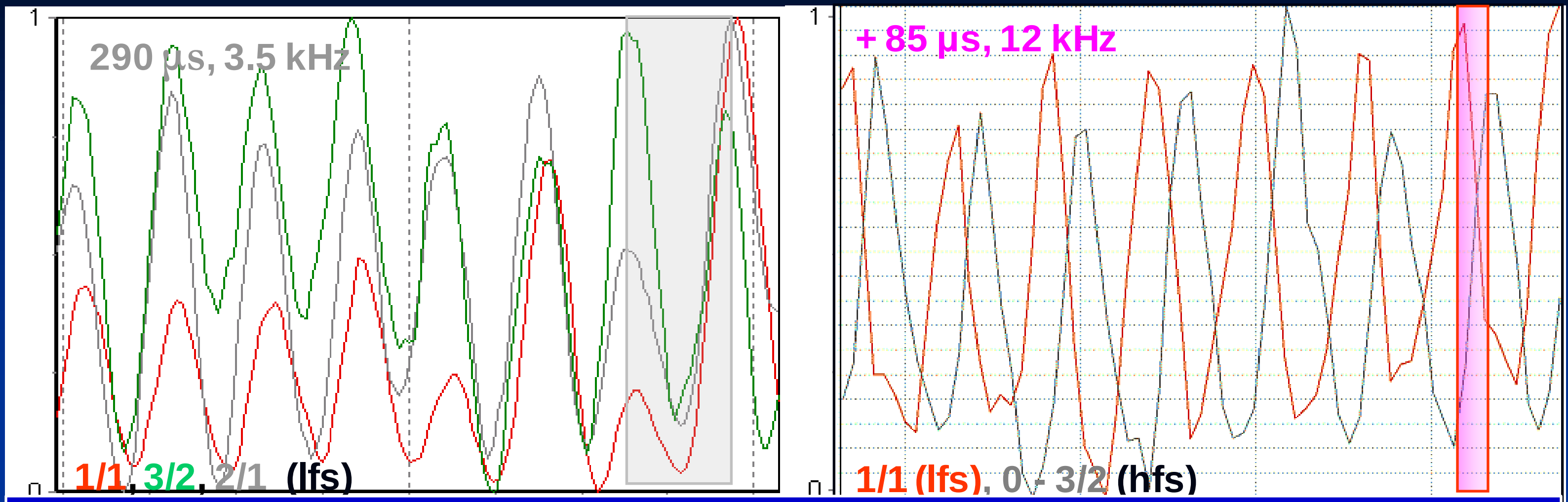


Positions of $r_{m/n}$ — 3rd *kink like ECH stage*



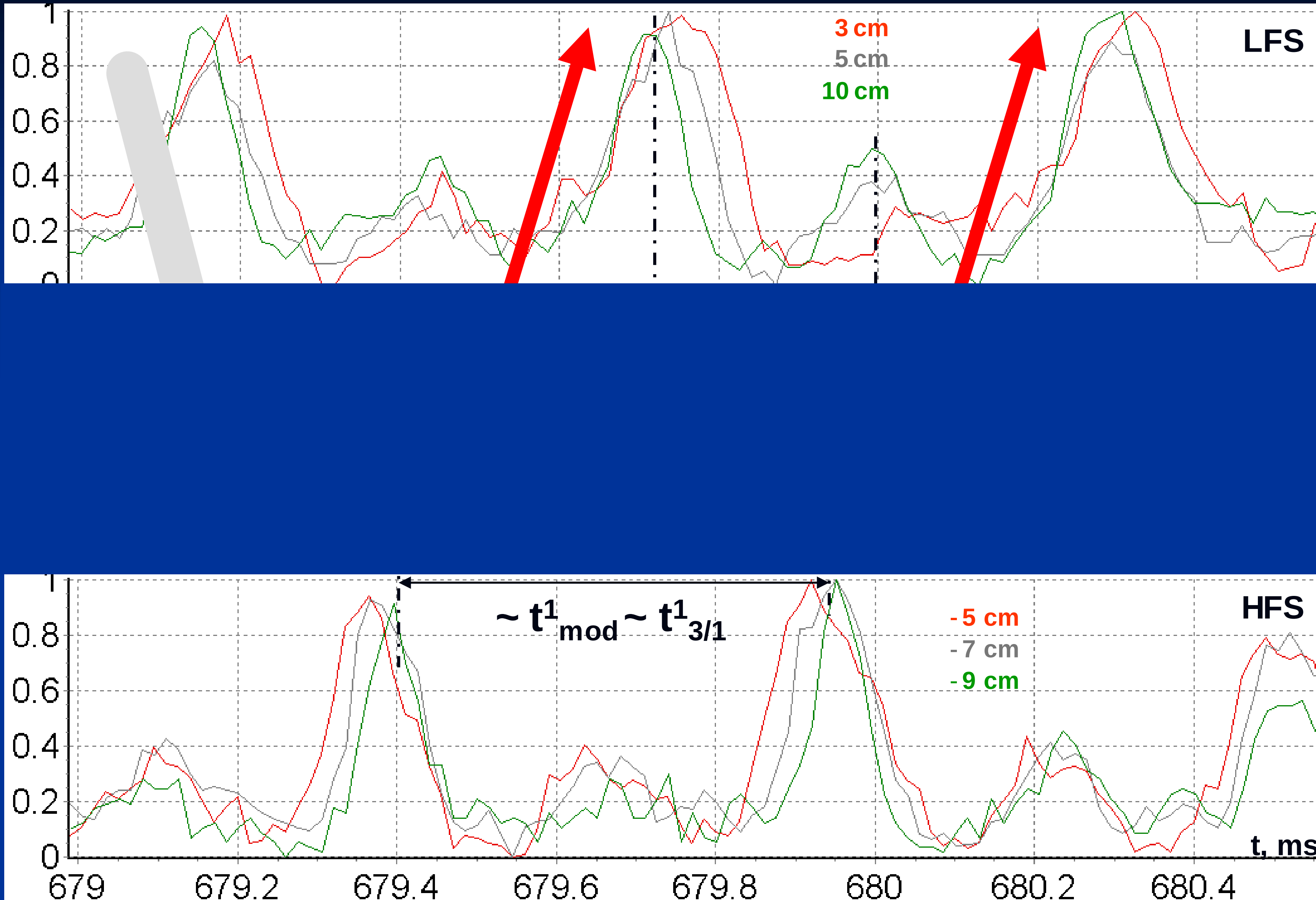
Positions of rational zones serve during all discharge time though strong sharpening of electron temperature under ECH

Phase relations (f^1_{mod} ~ 3. 5 kHz)



Delay time $t^2_{1/1}$ ~ 85 µs ($f^2_{1/1}$ ~ 12 kHz) between signals from LFS and HFS are observed **into all plasma volume**. Sign of delay depends on zone and shape of discharge.

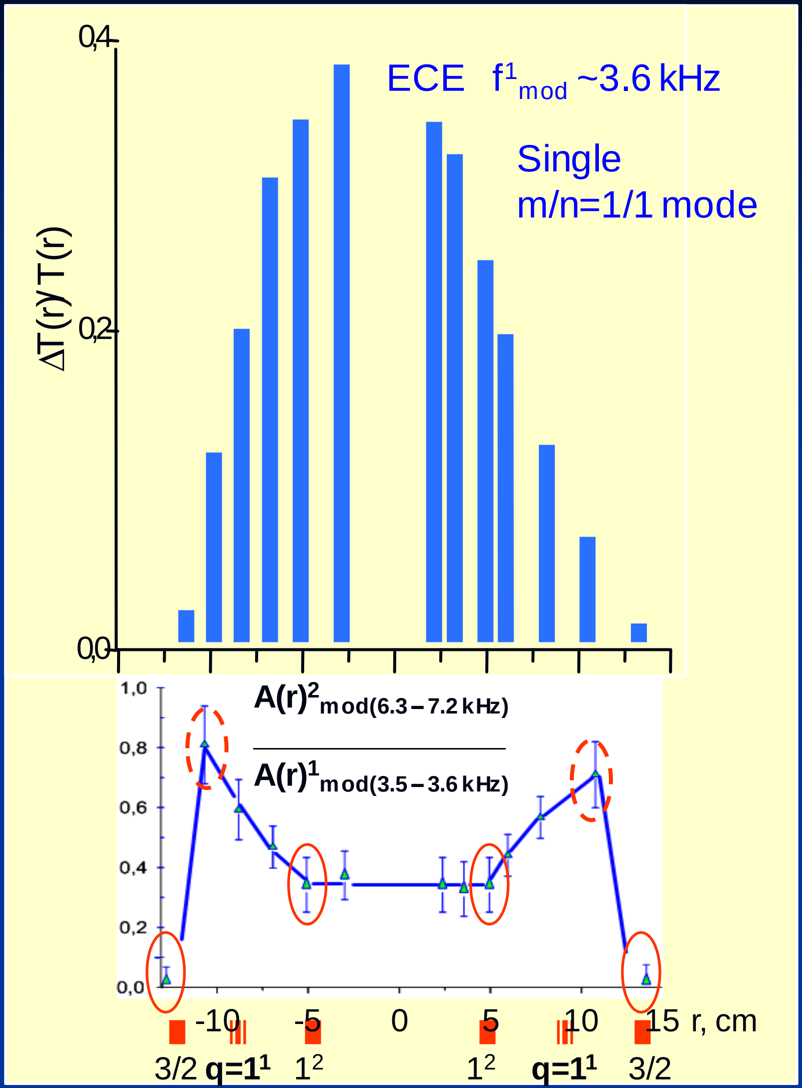
Phase relations ($f^{1/2}_{mod}$ ~ 1.75 kHz)

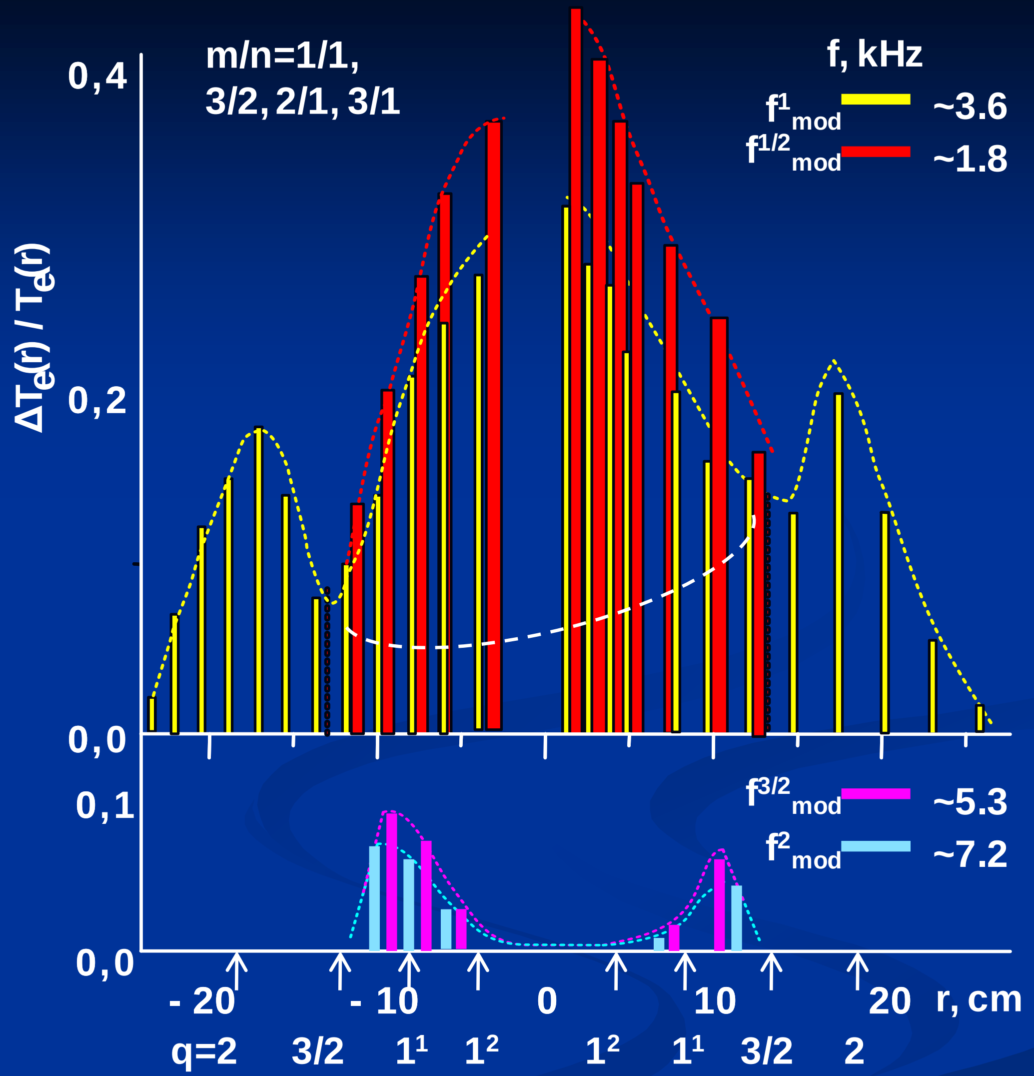


Relaxation process at HFS synchronizes motion of disturbance

Odd subharmonic $f^{1/2}_{mod}$ is product of life two eigen modes in common space

Radial distribution of oscilating amplitude





Excitation area of f^1_{mod} mode fills total volume inside the q=3/2 magnetic surface.

Even forced harmonic excites into areas bounded by adjacent rational surfaces – inside q=3/2 surface and q=1² surface

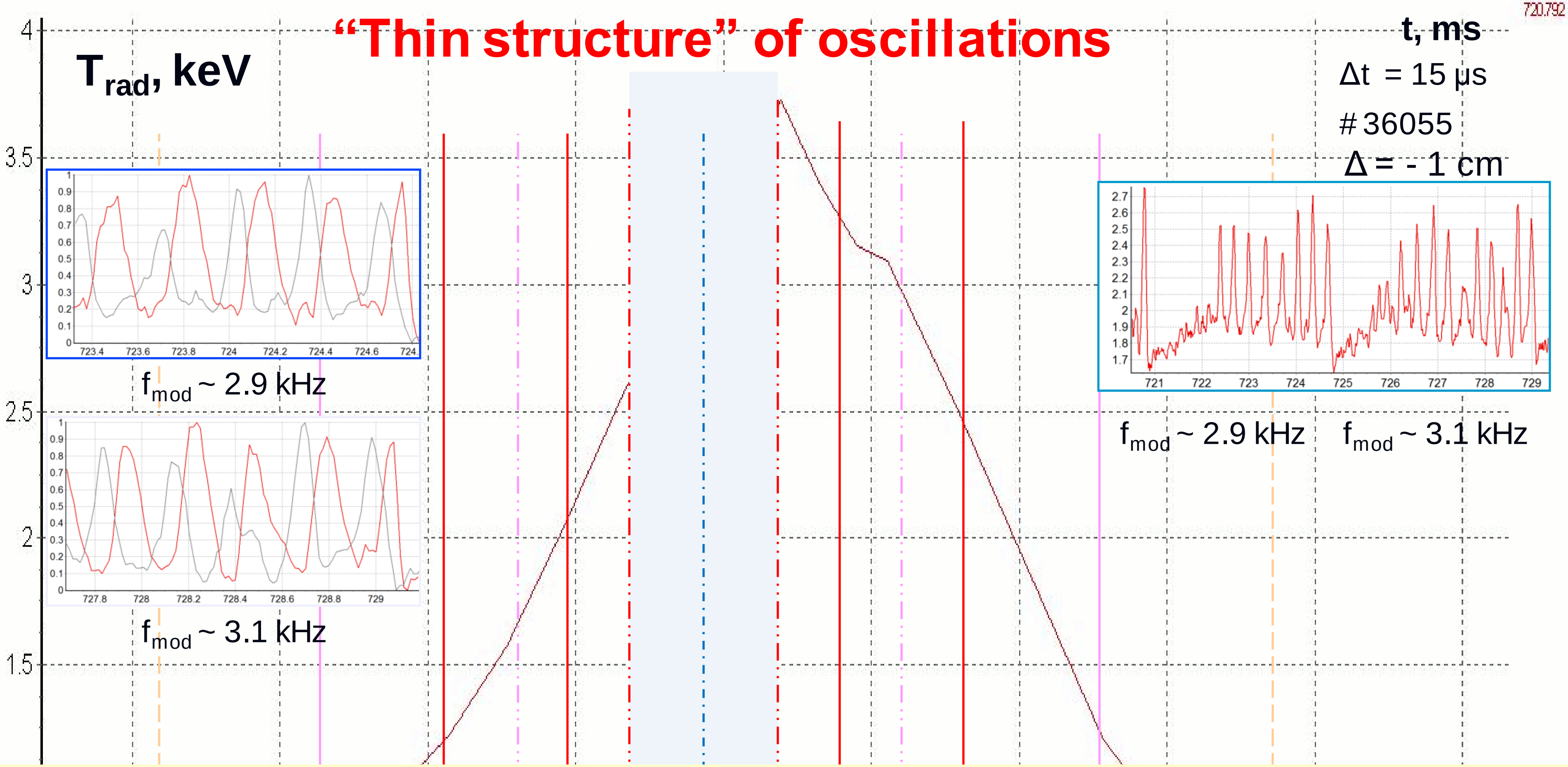
Excitation area of f^1_{mod} fills total plasma volume.

Two maxima correspond to two sources of energy

Forced subharmonic $f^{1/2}_{mod}$ – lives into common area for $f^1_{2/1}$ and $f^1_{3/2}$ modes.

Even f^2_{mod} and **odd** $f^{3/2}_{mod}$ **– are the forced**

“Thin structure” of oscillations



Discharge possesses simultaneously by attributes of different MHD modes:

tearing – steps on T_{rad} profile;
kink – swinging of profile around magnetic axis; } They do not live in common family (!?)

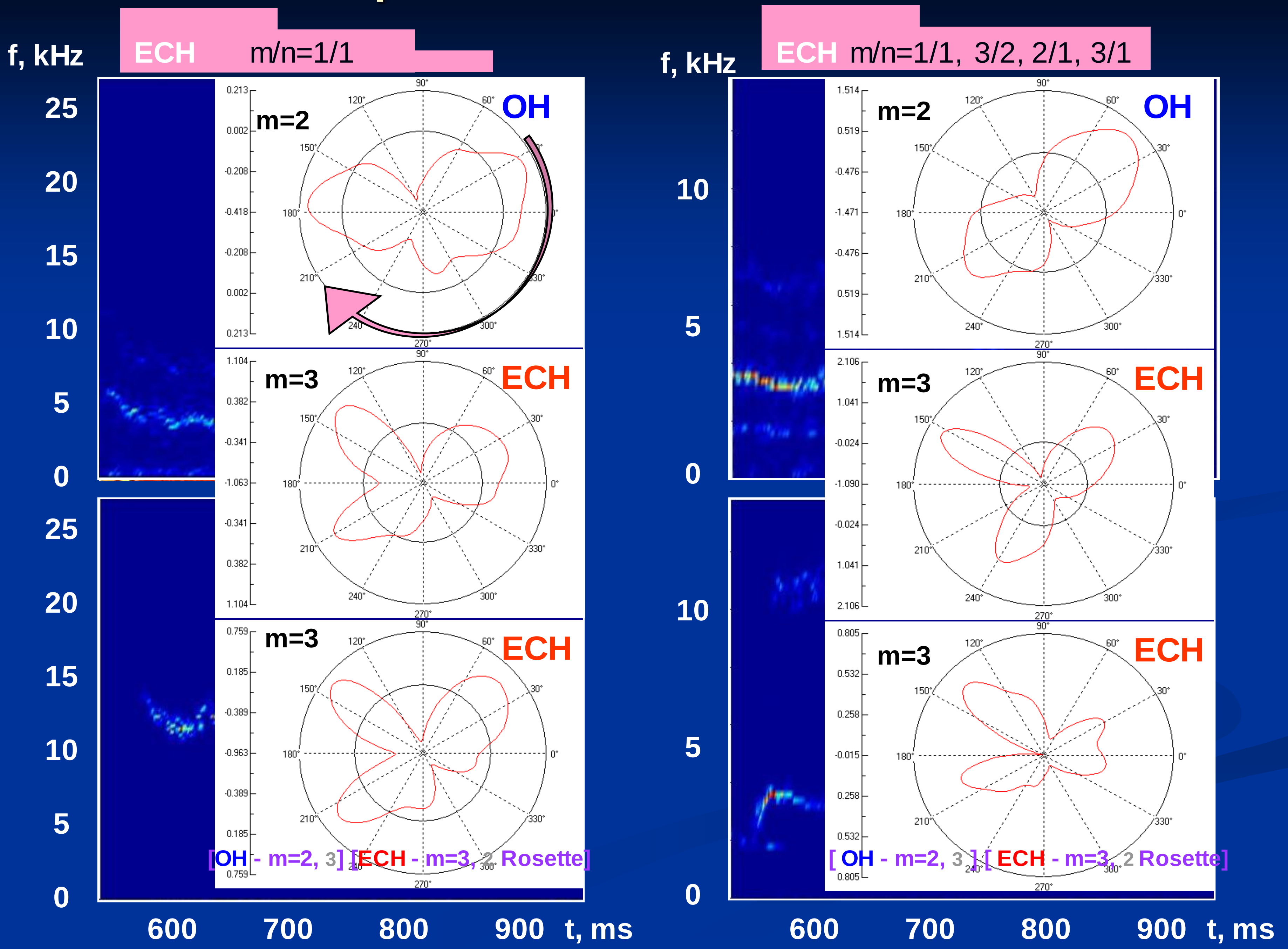
fishbone – “skeletal“ signals of ECE and magnetic probes; No NBI and high energy ions (!?)

lock mode – slowing down of disturbance motion - fast in every acts and of oscillations and slowly after start of ECH; Conducting wall is too far from central zone to excite mirror currents (!?)

flute – long tongues of plasma up to q=3/2 zone; On MHD theory it is absent at tokamak (!?)

filamentation – appearance of structures less then $r^1_{q=1}$. How it happen? (!?)

Spectra of oscillations



SUMMARY

$$f^k_{m/n} = \min < [(v_i, v_e)_{\nabla B\ drift}] > / 2\, r_{q\ m/n}$$

$$k = 2^{(s-1)} \qquad s = 1, 2, 3\ldots$$

m/n	1/1	3/2	2/1	3/1
$r^1_{m/n}$ (cm) (± 5%)	8.5	13	19	29
$<T_i>$ (eV), inside q=3/2 zone (±10%)	500			
$f^1_{m/n}$ (kHz), experiment (± 5%)	6.3	4.3	2.8	1.85
$f^1_{m/n}$ (kHz), calculation	6.5	4.2	2.9	1.9

Main parameter for all modes is ion temperature at central zone

Self-consistency between oscillation frequencies (zonal velocities) and radii of rational zones

$f^1_{1/1} : f^1_{3/2} : f^1_{2/1} : f^1_{3/1} = \mathbf{3/2}$ $\qquad$ $r^1_{3/1} : r^1_{2/1} : r^1_{3/2} : r^1_{1/1} = \mathbf{3/2}$

CONCLUSION

1. Mode excitation occurs into all area inside corresponding rational zone
2. Mode m/n=1/1 is master mode. Current oscillations on its eigen frequencies fill total plasma volume
3. Measured and calculated by **kinetic model** eigen frequencies of modes m/n=1/1, 3/2, 2/1 and 3/1 coincide with accuracy no worse $\pm$ 10%
4. Key parameter for volume resonances of all modes is evidently central ion temperature
5. Only even upper eigen harmonics and odd subharmonics excite. Deviation of eigen frequencies is not exceed 5% for basic harmonics and 20% for the upper
6. Positions of resonance rational zones do not change during current plateau stage though strong sharpening of electron temperature profile under ECH (inside q=3/2 $k_{\text{profile sharpening}} \sim 1.5$)
7. Relations of measured eigen frequencies and radii of rational zones can be represent into 5% accuracy as relation of simple numbers

$\mathbf{f^1_{1/1} : f^1_{3/2} : f^1_{2/1} : f^1_{3/1} = 3/2}$ $\mathbf{r^1_{3/1} : r^1_{2/1} : r^1_{3/2} : r^1_{1/1} = 3/2}$

$f^4_{m/n} : f^2_{m/n} : f^1_{m/n} = 2/1$ $r^4_{m/n} : r^2_{m/n} : r^1_{m/n} = 1/2$

Positions of rational zones do not depend on amplitudes of oscillations

Where they are when global oscillations are absent?