Study of fast ion transport and losses during Alfvén type MHD instabilities at Globus-M2

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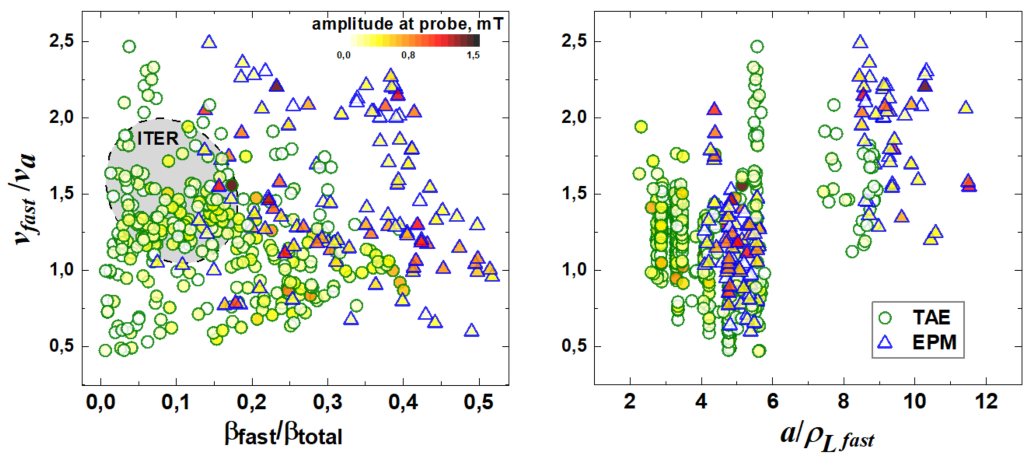
ABSTRACT

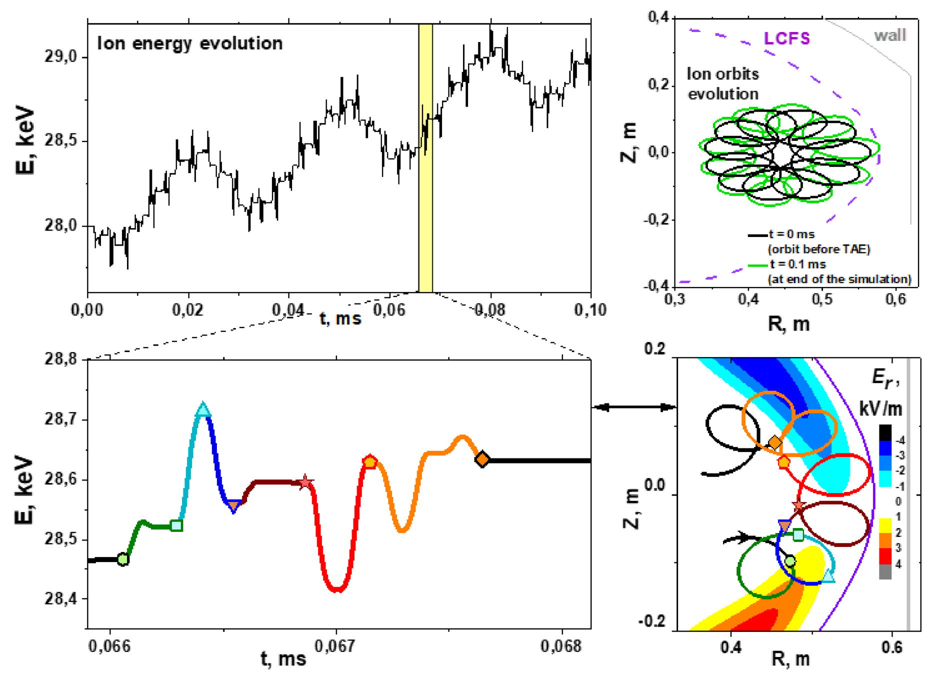
- The steady-state operation of a thermonuclear reactor requires low fast-ion losses, which are compromised by magnetohydrodynamic (MHD) instabilities that cause significant particle redistribution;
- This work investigates Alfvén instabilities [1] (TAE/EPM) to understand their driving mechanisms and impact on fast-ion transport, which is essential for developing mitigation strategies;
- The study is conducted on Globus-M/M2 spherical tokamaks in a wide range of plasma parameters: I_p = 160-450 kA, B_T = 0.4-0.9 T, $n_e = 10^{19}$-10^{20} m^{-3}, E_{NBI} = 20-50 keV, P_{NBI} = 0.3-1.5 MW. The non-dimensional parameter domain v_{fast}/v_a-$\beta_{fast}/\beta_{total}$ achieved in these experiments covers domain of the future ITER DD and DT experiments.



Alfvén-type instabilities parameter domain of the Globus-M/M2 experiments. Shaded regions – ITER parameter domain. The color differentiation of the dots corresponds to the amplitude of the burst.

SIMULATIONS OF FAST ION TRANSPORT

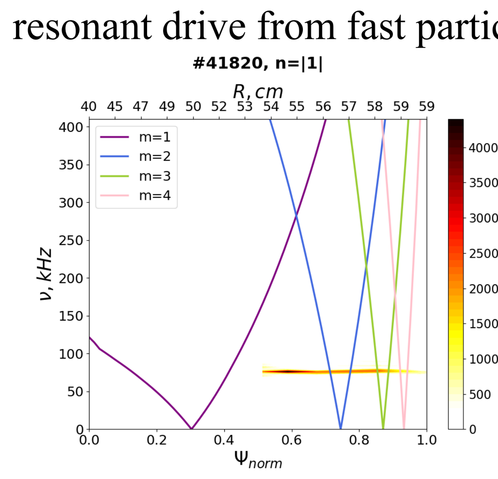
1. Was used approach introduced in [4] as a basis + 2 critical modifications:
   - Replacement of the isotropic fast ion distribution with an anisotropic distribution obtained from the NUBEAM code;
   - The full-orbit approach was employed instead of the GC-approximation.
2. An ensemble of 10^5 ions was generated (sampled from the dist. func.);
3. Each ion was tracked in time-varying 3D electromagnetic fields to identify losses:
   - A particle was flagged as lost if its orbit intersected the LCFS (CX time near the plasma edge is much shorter than the slowing-down time);
   - Mode characteristics (frequency, localization, amplitude, mode numbers) were taken from experimental measurements (DBS, magnetic probes) and the linear mode phase was calculated as $\Phi_{n,m} = -n\zeta + m\theta - \omega t$;
   - The model assumed a constant mode frequency;
   - The 3D structure of the tokamak wall was not included.



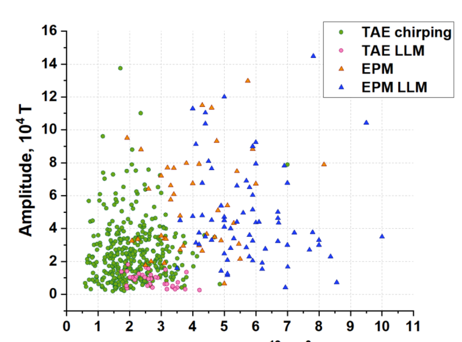
Simulation of 28 keV D⁺ orbit change during n=1, m=2,3 TAE.

INITIAL INVESTIGATION OF EPM

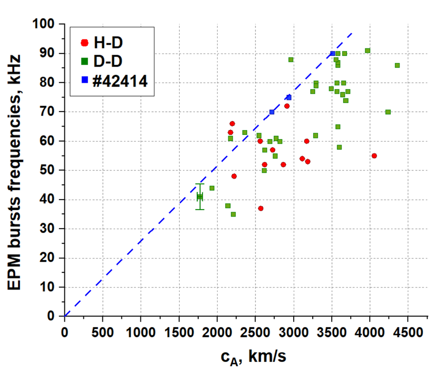
- The improved plasma parameters and fast-ion confinement at Globus-M2 gave rise to previously unobserved EPMs. These modes emerge when the resonant drive from fast particles exceeds the continuum damping threshold.



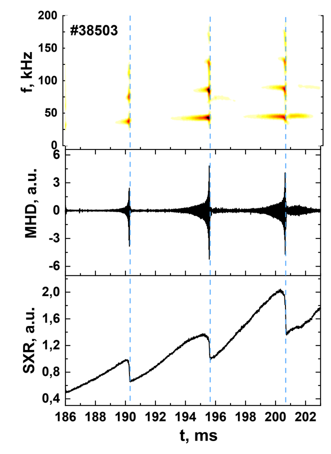
Dispersion relation in cylindrical approx. for discharge #41820 (173 ms). EPM localization from DBS (experiment) [5].



Dependence of the observed Alfvén instability amplitude on the line-averaged plasma density.

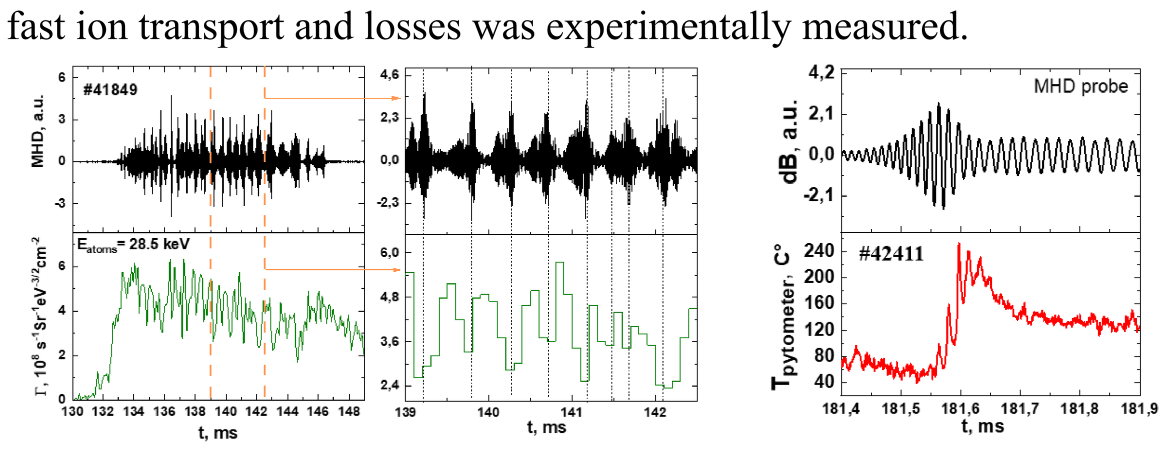


A linear dependence is observed between the EPM burst frequency and the Alfvén velocity



EPMs were observed even in discharges with strong sawtooth oscillations: MHD spectra, magnetic probe signal, SXR signal

- For the first time at Globus-M2, a direct correlation between EPM-induced fast ion transport and losses was experimentally measured.



Experimental observation of the EPMs-induced transport and losses. Transport (left): magnetic probe signal, variation of the 28.5±1.2 keV atom count rate (active NPA measurements, central ion transport study). Losses (right): magnetic probe signal, wall temperature measured by pyrometer (measurement of wall heating).

DIAGNOSTIC SYSTEM DEVELOPMENT

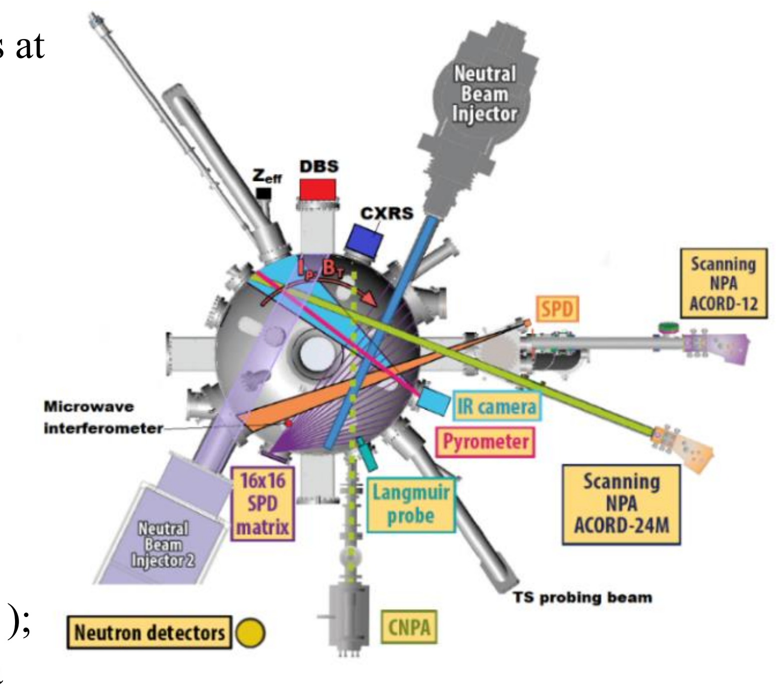
A **multi-diagnostic approach** was employed to study the influence of TAEs on fast particles at Globus-M/M2 [2]:

Alfvén Eigenmode Characterization:

- Mode Identification – toroidal (8 fast, 50–300 kHz) and poloidal (15 slow, 0–150 kHz) magnetic probes;
- Radial Localization – Doppler Backscattering (DBS) method [3].

Fast-ion transport and losses:

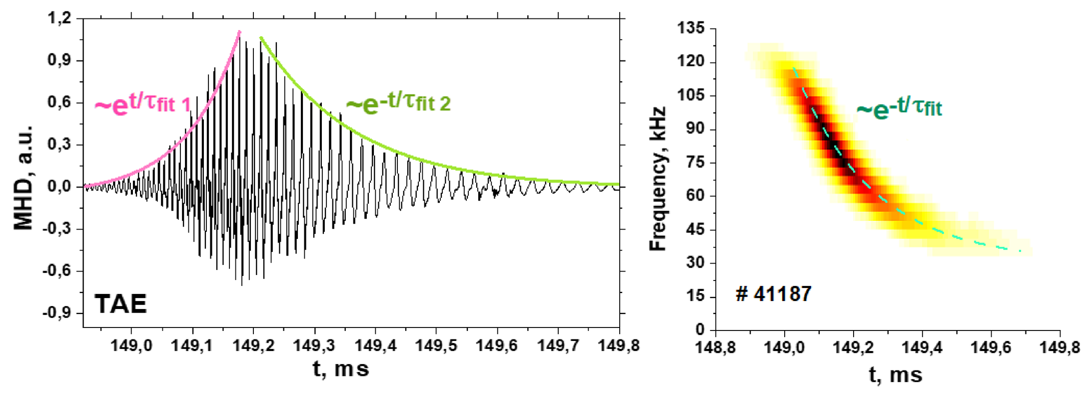
- Evolution of the fast ion spectrum – 3 NPAs, equipped with scanning systems and operating in active mode (t resol. up to 0.1 ms);
- Study co-going fast ion losses – tangential 16x16 silicon precision detector (SPD) matrix array (t resol. of 1.6 μs), study losses of trapped and counter-going ions – single-channel SPD (t resol. of ~0.2 ms);
- Study first-wall heating from Alfvén-mode-induced fast-ion losses – infrared (IR) camera (t resol. up to 0.3 ms), two-color pyrometer (t resol. up to 2 μs);
- Langmuir probe – ion saturation current (evolution of the ion flux near the separatrix);
- Neutron diagnostic system – used as a primary indicator of fast ion confinement



Globus-M2 experimental layout (top view). Marked diagnostics are used to directly study wave-induced fast ion losses and transport.

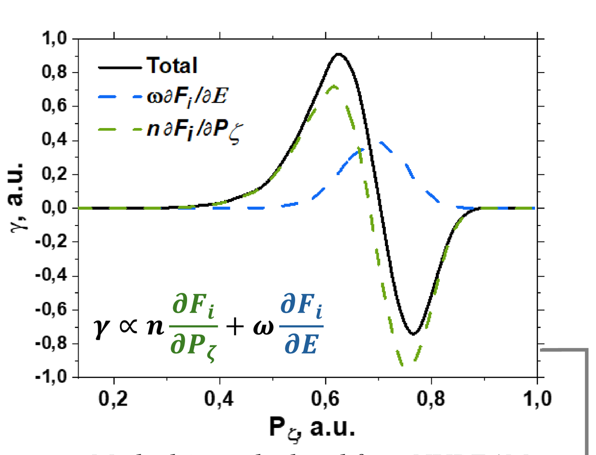
OBSERVATION OF THE FAST ION TAE-INDUCED TRANSPORT AND LOSSES

- Experiment observed a single down-chirping branch with exponential amplitude and frequency changes, consistent with the Berk-Breizman model for an anisotropic fast-ion distribution [8,9].

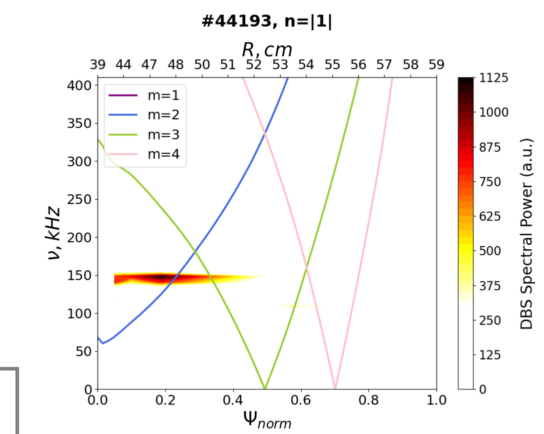


Amplitude and frequency evolution of the mode in discharge #41187.

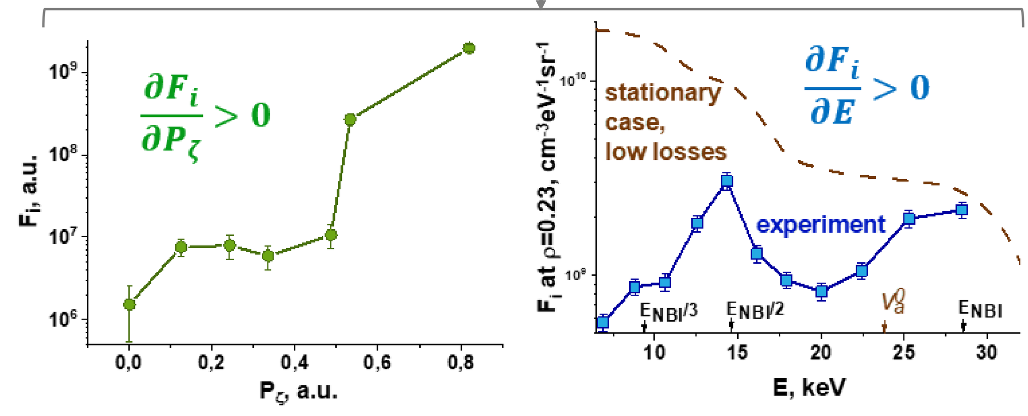
- TAE exists in the continuous frequency spectrum gap, caused by the toroidicity of plasma and being weakly damped is easily destabilized by the super-alfvenic particles [1].



Mode drive calculated from NUBEAM distribution (#37001, 141 ms).

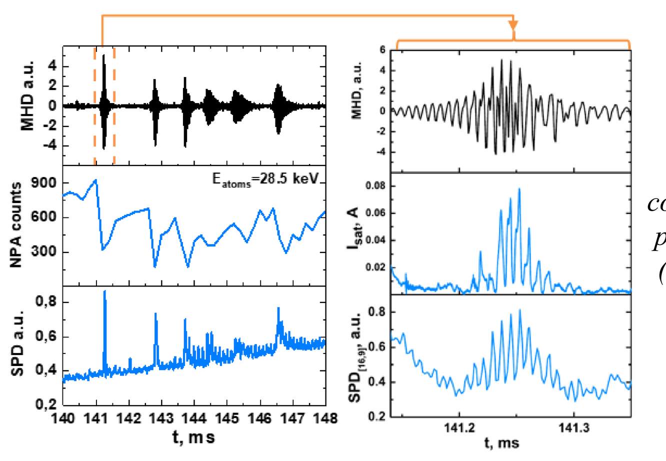


Dispersion relation in cylindrical approx. for discharge #44193 (147 ms). TAE localization from DBS (experiment) [5].

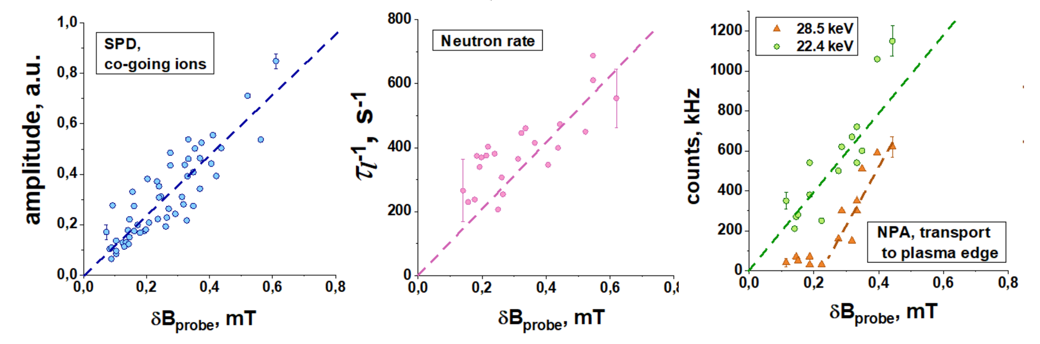


Experimental NPA measurements prior to TAE burst.

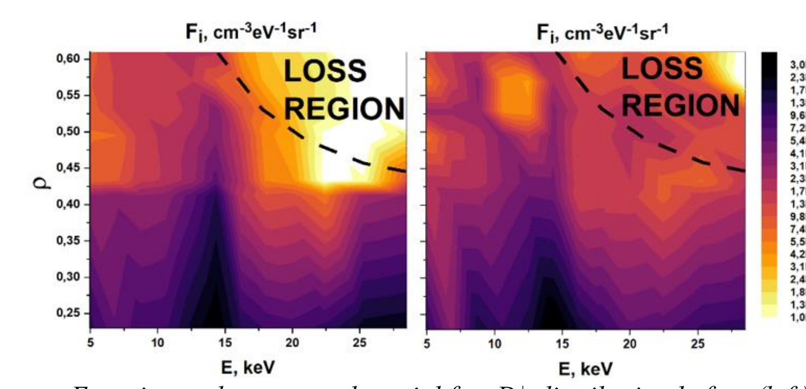
- TAE-related transport and losses were observed by multiple diagnostics. Fast ion transport from the plasma center to the periphery was observed across a wide range of energies [2].



TAE-induced transport and losses (#37001). Left (slow diagnostics): magnetic probe; 28.5±1.5 keV atom count rate (active NPA measurements in plasma center); single-channeled SPD (lost trapped and counter-going ions). Right (fast diagnostics): Langmuir probe ion saturation current; SPD matrix (column 16 row 9 cell).

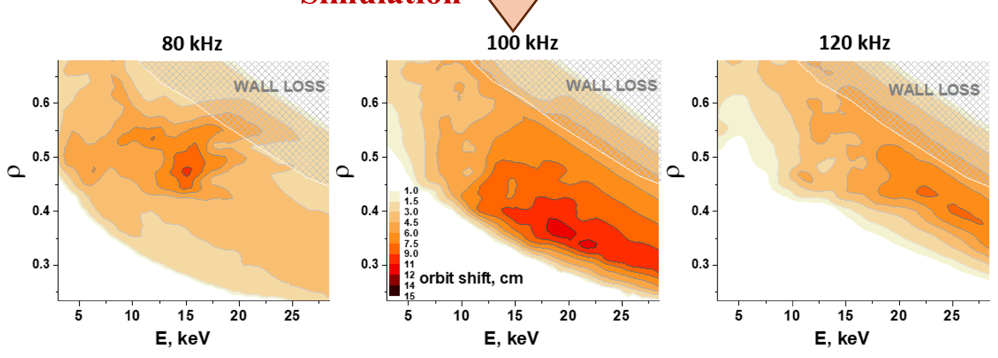


Dependence of fast ion transport and losses on TAE amplitude



Experimental energy and spatial fast D⁺ distribution before (left) and during (right) TAE (based on the active NPA measurements).

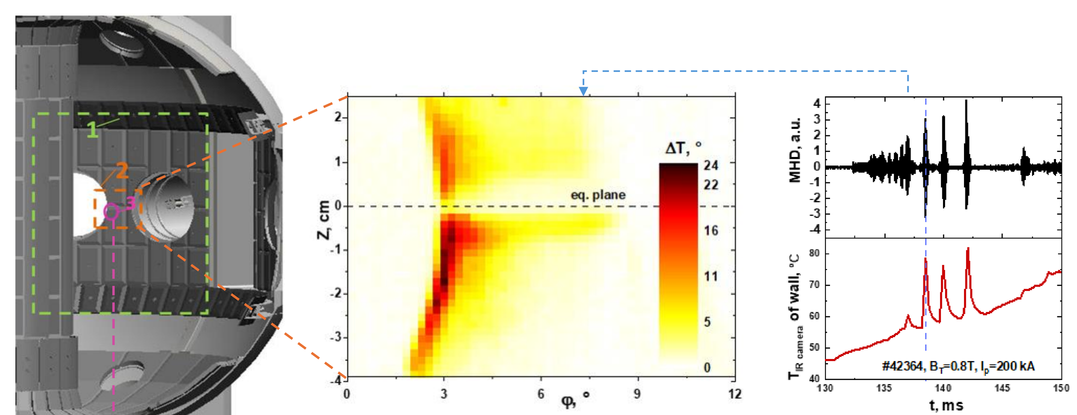
Simulation



Estimated dependence of the maximum ion orbit shift on energy and normalized effective radius during 0.1 ms TAE bursts at different frequencies at vertical NPA scan.

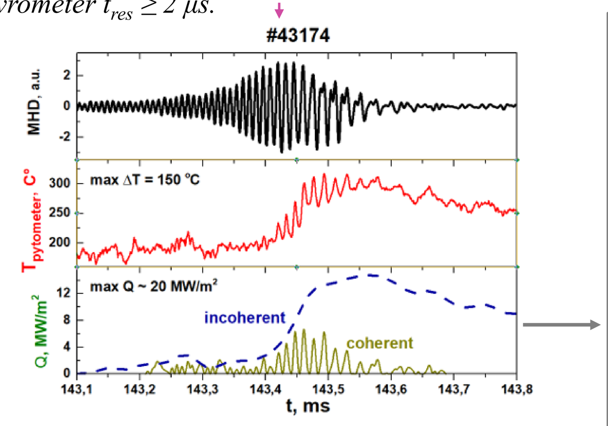
Analysis reveals that the coherent heat flux component originates from fast-ion orbital losses, while the incoherent component results from wave-induced radial transport. This transport moves ions to the plasma boundary, where high neutral density enhances charge-exchange losses. Both fast-ion loss mechanisms - orbital and CX - are caused by the **convective resonance mechanism** [4] of fast ion transport from the plasma center to the periphery.

- Orbital losses from collisions with the tokamak wall during TAE instabilities were monitored via measurements of localized heating on the outer midplane carbon tiles and the corresponding heat flux calculations [6, 7].

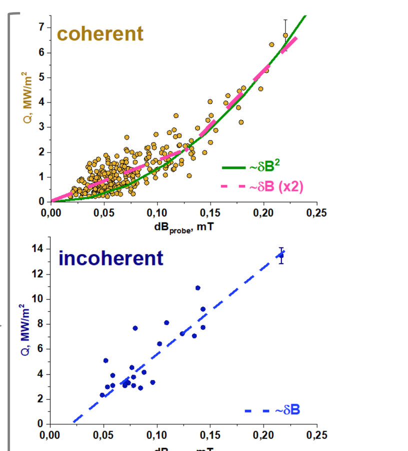


1 - IR camera t_{res} = 4.5 ms, 2 - IR camera t_{res} = 0.3 ms, 3 - Pyrometer $t_{res} \geq 2$ μs.

2D distribution of changes in carbon tiles temperature during TAE burst. Time evolution of magnetic probe signal and carbon tile local temperature measured by IR camera.

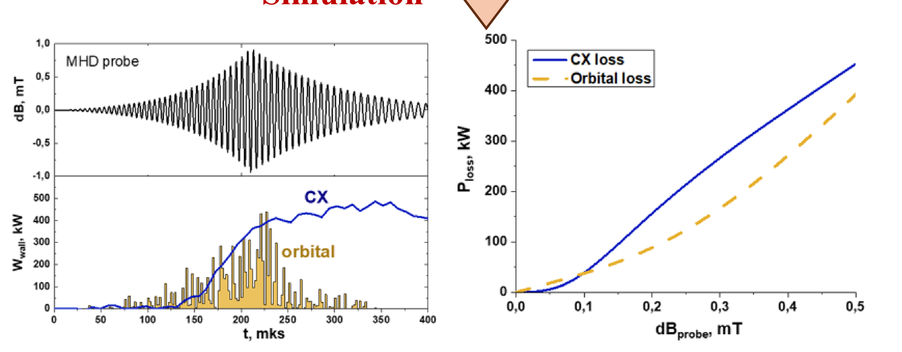


Measurement of wall heating during TAE burst: MHD probe; wall temperature (pyrometer); coherent and incoherent component of heat flux.



Dependence of wall heat flux evolution on TAE amplitude.

Simulation



Simulation of fast-ion losses induced by TAE, showing the dependence of loss power (from wall collisions and charge exchange) on the mode amplitude.

ACKNOWLEDGEMENTS / REFERENCES

- The experimental studies of fast ions were supported by the Russian Science Foundation (project no. 21-72-20007-P).

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