Overview of ECH systems in GDT

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Introduction

- GDT is an axisymmetric mirror experiment exploring high-β plasma confinement, fast-ion physics, and advanced heating methods.

- ECRH as a critical tool for raising electron temperature, validating longitudinal confinement models, and enhancing fast-ion lifetime in mirror plasmas.

- GDT successfully implemented the ECRH scheme, where the microwave beam with extraordinary wave polarization (X1) is launched towards the first harmonic resonance from the high field side (HFS).

- Main results: stable electron temperatures in keV-range, improved fast-ion confinement, ECR breakdown and electrode-based stabilization

- The review provides a technical overview of the ECH system and findings from various experimental campaigns, including recent X2 results

Outline

1. Introduction
2. Description of GDT, its ECRH system and experimental techniques
3. X1 bulk plasma heating and high T_e. ECRH-induced instability
4. Improved fast ion confinement with ECRH
5. ECR breakdown experiments
6. Recent results from X2 heating and breakdown experiments
7. Summary

The Gas Dynamic Trap

Bulk plasma:

$L \gg \lambda_{ii} \frac{lnR}{R}$, $R = \frac{B_m}{B_0}$ - *mirror ratio*

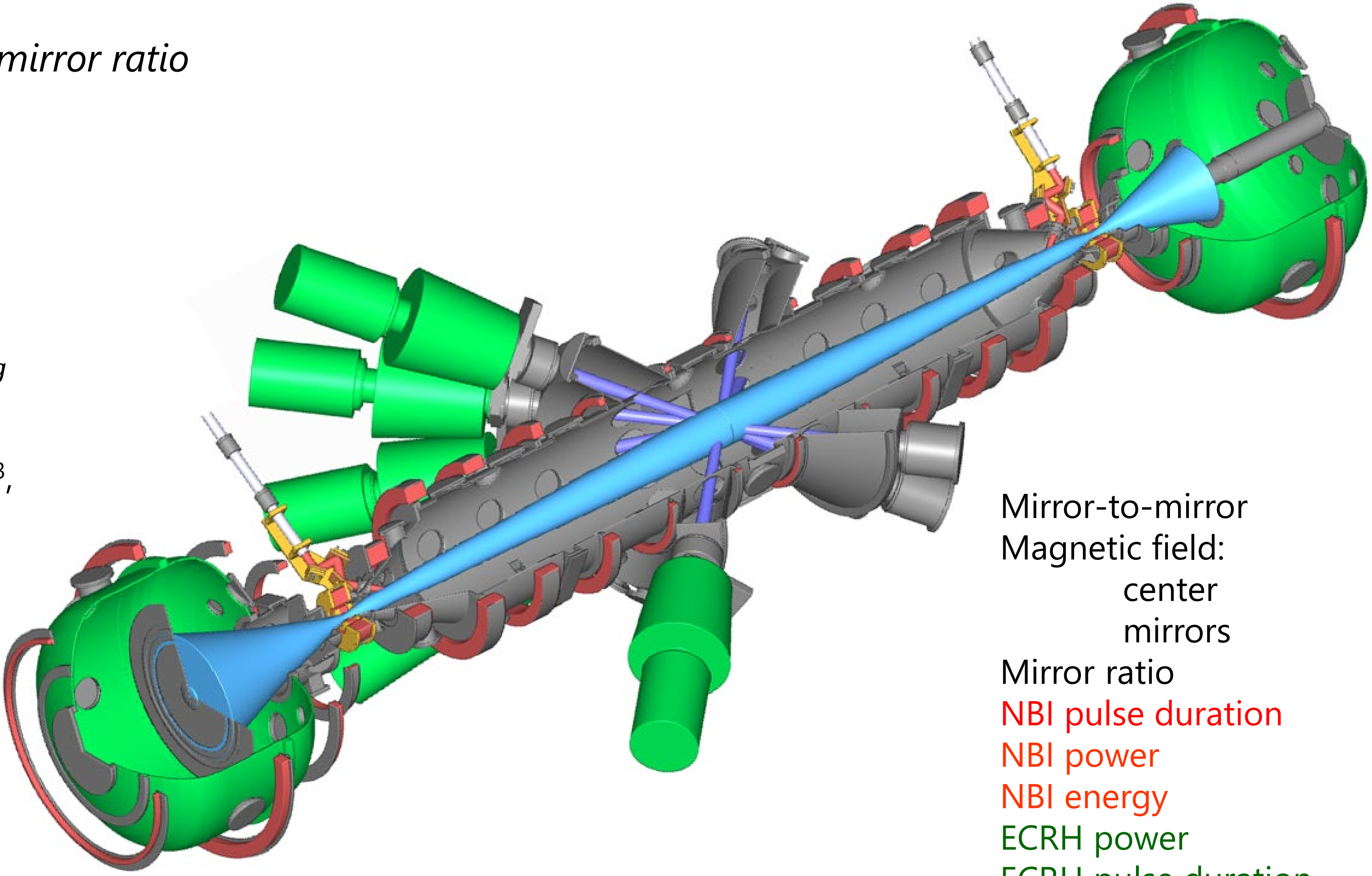
$$\tau_{GDT} \sim \frac{nLS_0}{2nv_i S_m} = \frac{LR}{2v_i}$$

Fast ions:

$\tau_{adiab} \sim \tau_{ii} lnR \gg \tau_{drag}$

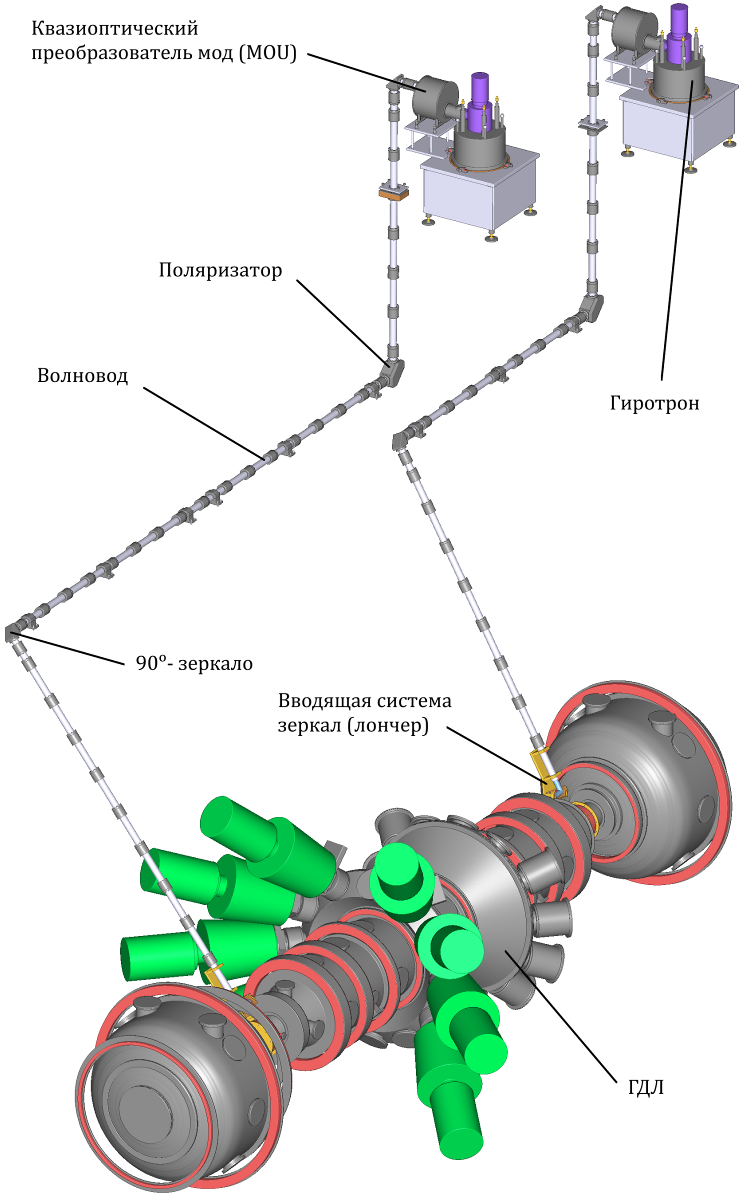
Bulk plasma:
Electrons: ≈ $2 \cdot 10^{19}$ m^{-3},
250 – 900 eV;

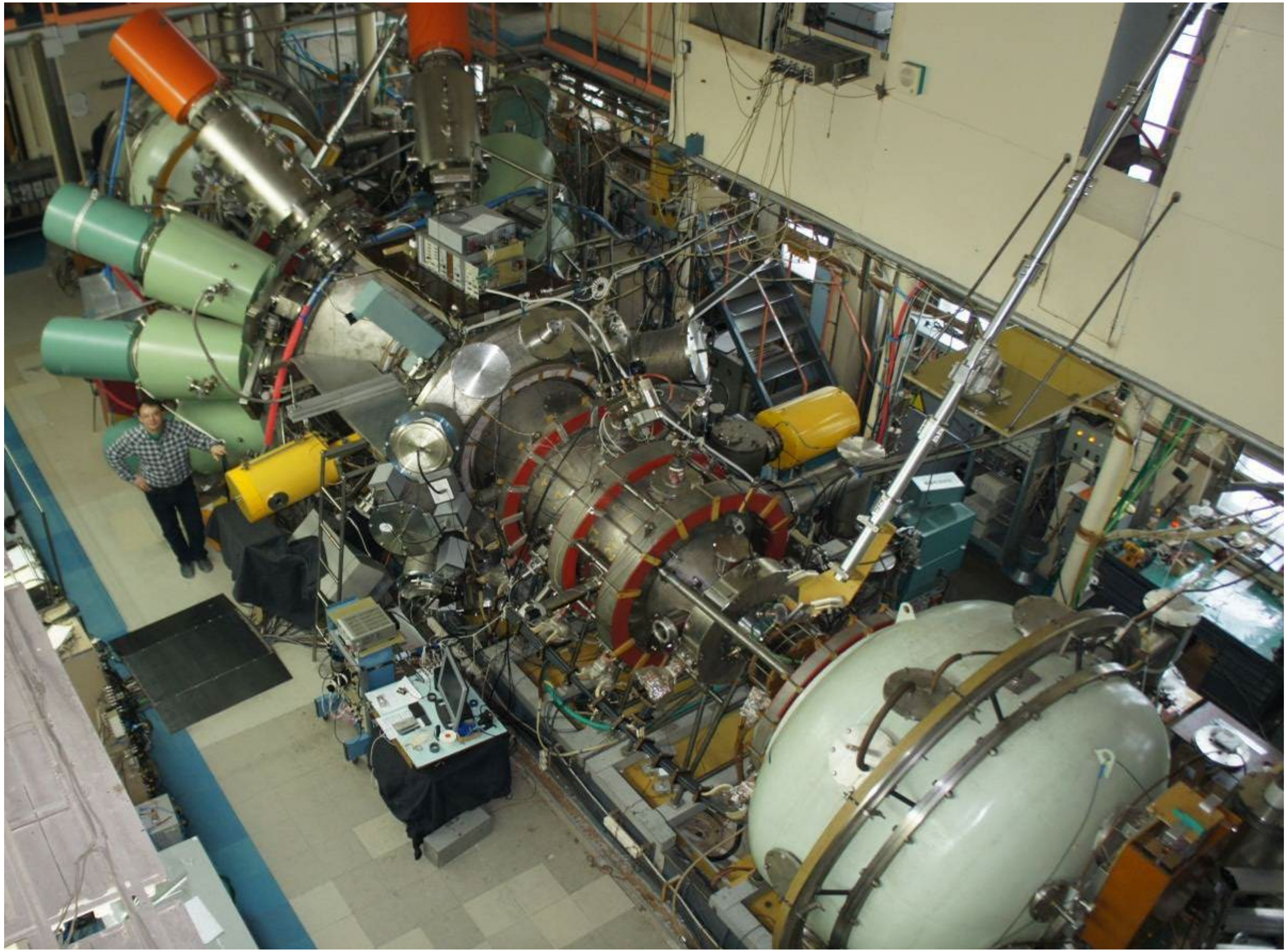
Fast ions (H^+,D^+):
Up to $5 \cdot 10^{19}$ m^{-3},
<E> ≈ 10 keV, β ≈ 0.5



Mirror-to-mirror	7 m
Magnetic field:	
center	0.35 T
mirrors	12 T
Mirror ratio	35
NBI pulse duration	5 ms
NBI power	5 MW
NBI energy	23 keV
ECRH power	1.2 MW
ECRH pulse duration	8 ms

ECRH system (since 2014)



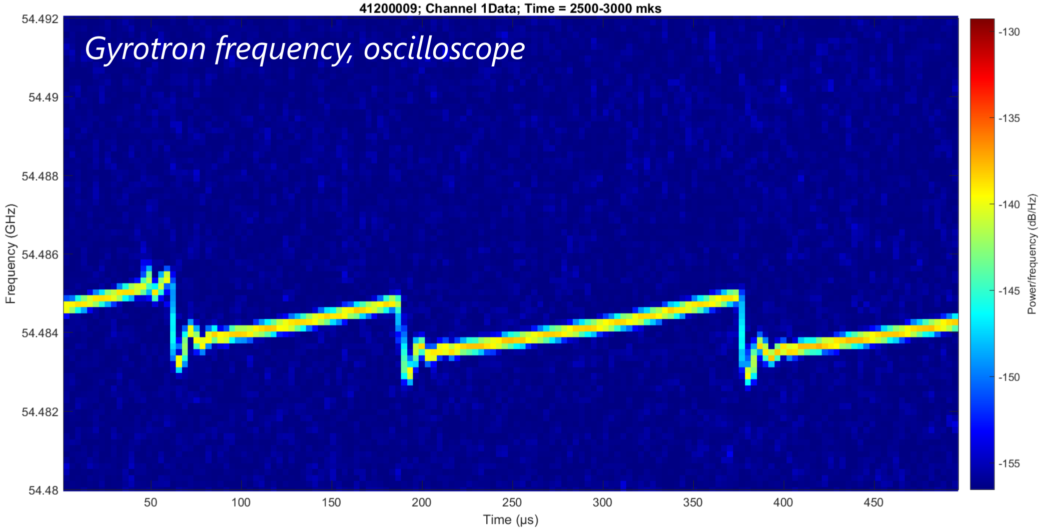


ECRH system

ECRH system uses two 54.5 GHz, 500 kW, 100 ms (nominal) gyrotrons repurposed from AMBAL project.

Power supplies are capacitor based with sawtooth stabilization and pulse duration ≤ 8 ms.

Transmission line is a 63.5 mm corrugated non-evacuated waveguide with 2 miter bends, and a 2-in-1 grating polarizer.



Around 2016 one of the gyrotrons experienced rapid cathode degradation, was repaired, but eventually was replaced with a new triode 800 kW gyrotron.

Currently the new gyrotron is still used in diode configuration without body power supply, producing ~ 300 kW.

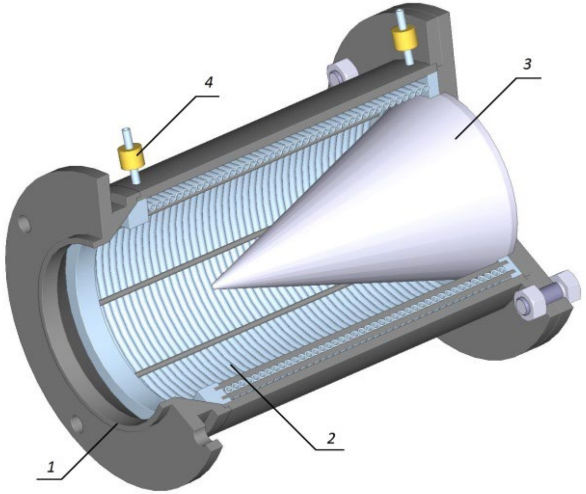
Transmission line breakdowns can happen at ~ 500 kW but can be alleviated by dry air venting of the waveguides.

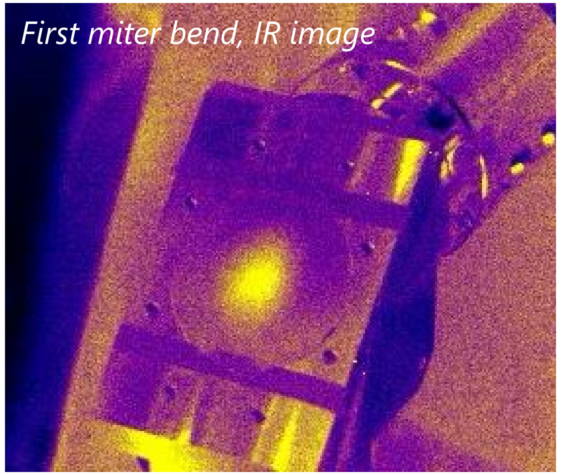
Measured power (after MOU)	450/460 kW
Cathode voltage	72 kV
Beam current	24 A
Magnetic field	2.1 T
Cryomagnet current	57.65 A
Waveguide losses	6% / 8%
MOU losses	< 13%
Measured frequency	54.484±0.002 GHz
	54.560±0.002 GHz

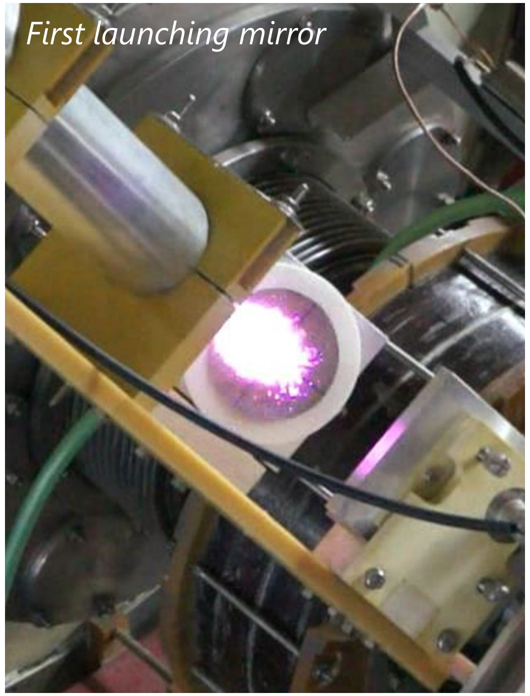
Microwave techniques

The team uses a combination of IR, surface breakdown and calorimetric techniques to tune the tubes and align the transmission lines.

The liquid-based calorimeter is good up to ~ 450 kW. New solid-state version at WHAM was tested up to 650 kW.

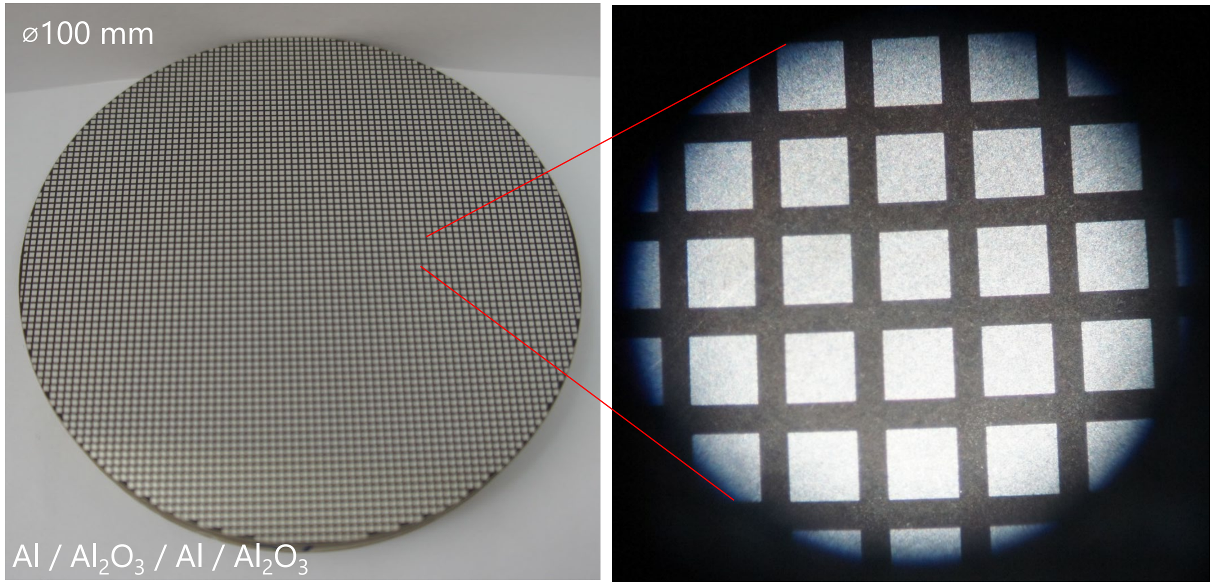






The was a short experimental test of planar resonant absorbers and the technique has a potential for time-resolved frequency-selective microwave power measurements.

Planar Holographic Metasurfaces for Terahertz Focusing. S.A. Kuznetsov et al 2015 Scientific Reports 5 7738. https://doi.org/10.1038/srep07738

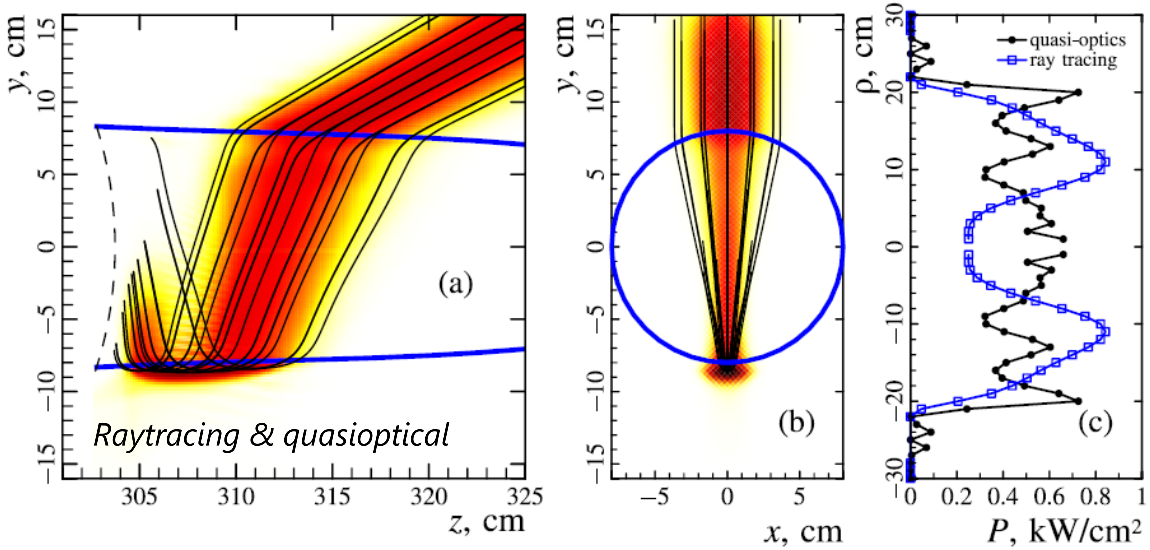


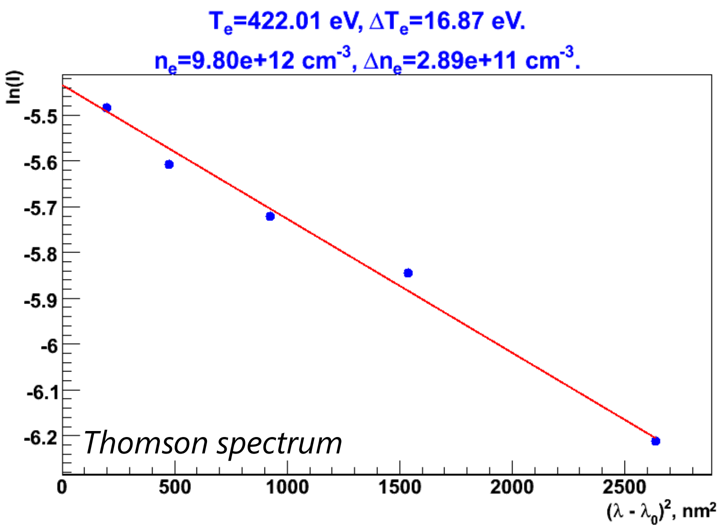
First ECH campaign

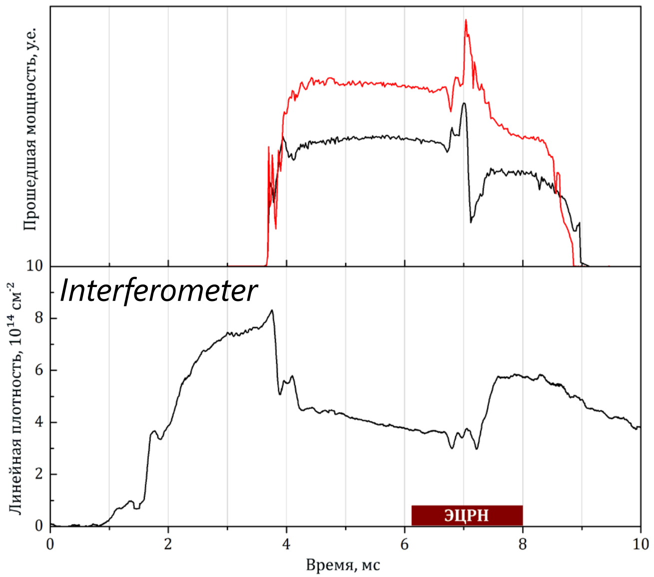
Initial idea behind the X1 heating scheme in GDT was microwave beam trapping in plasma, which would lead to broad power deposition and bulk electron heating

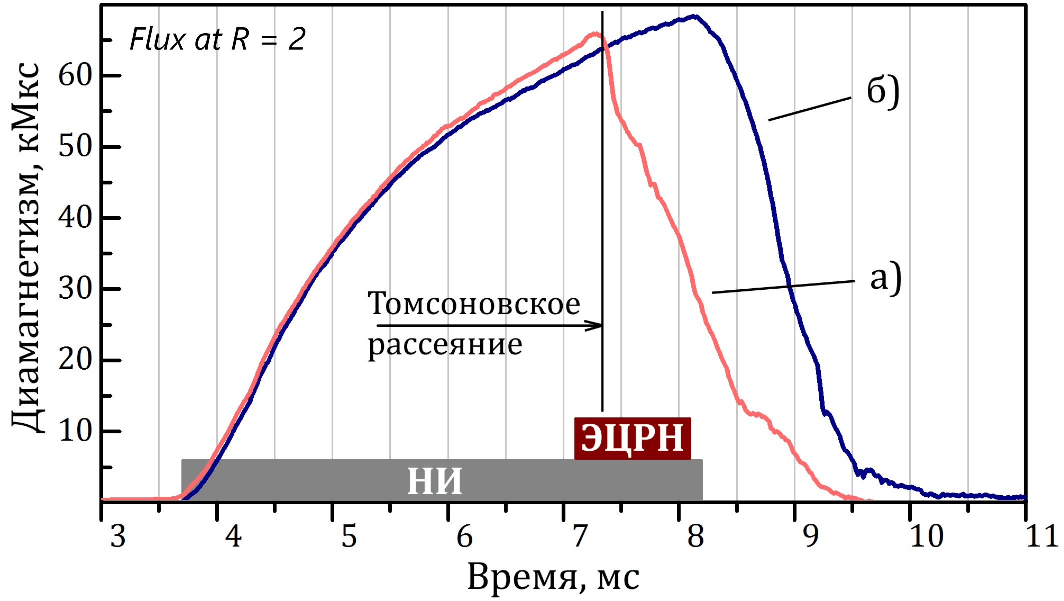
In practice, doppler-broadening of the resonance due to low field gradient led to unstable heating with unexpected effect of temperature peaking on axis

An MHD instability developed leading to complete loss of confinement







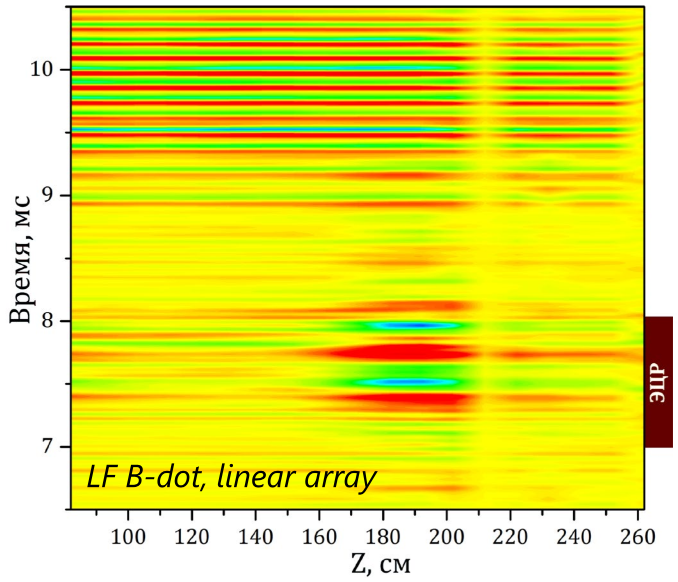


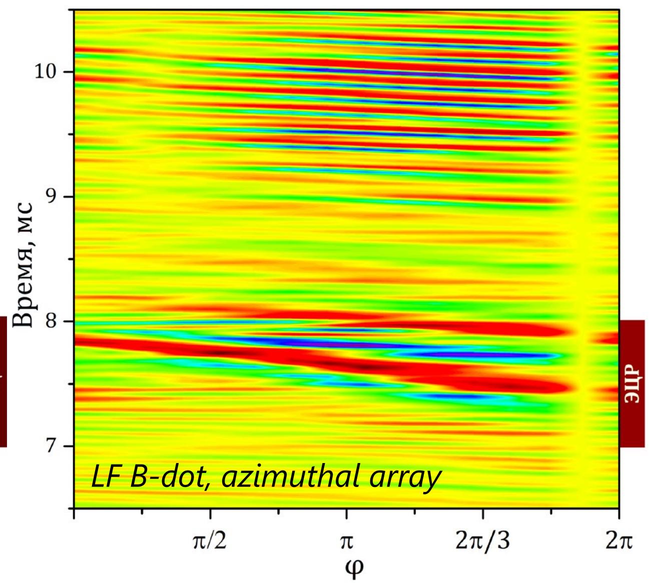
ECRH-induced instability

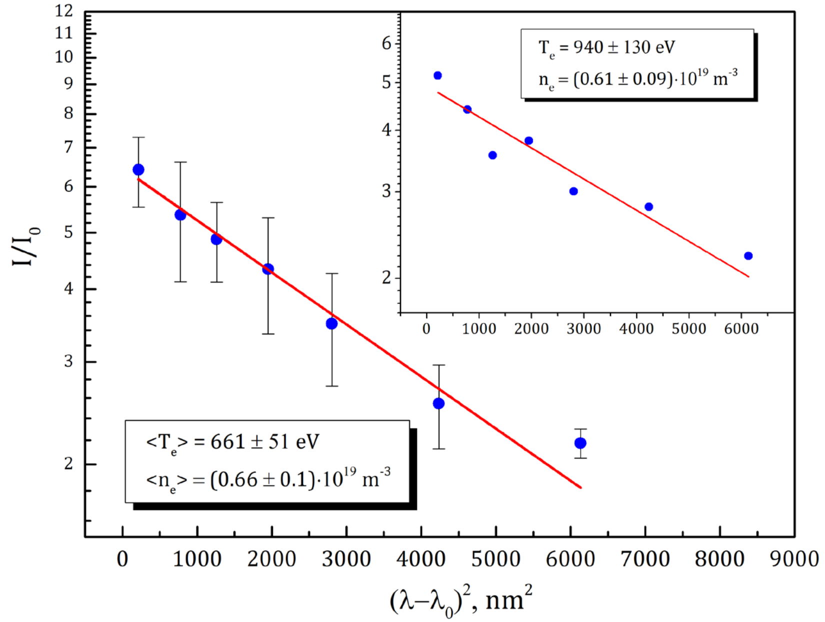
The instability appears as m = 1 flute mode shortly after peak T_e is reached.

The instability is seen by LF magnetic probes, flux loops, shinethrough detectors and interferometer.

The highest reported temperature of 900 eV was achieved in an unstable regime with negative bias applied to endrings and grounded limiter.

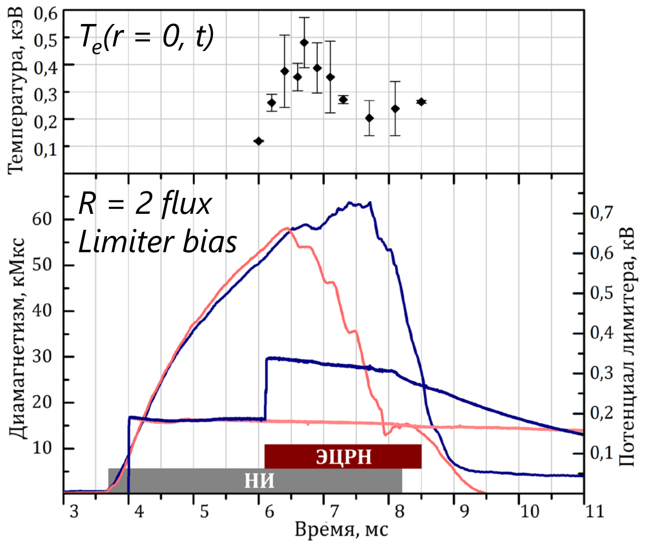


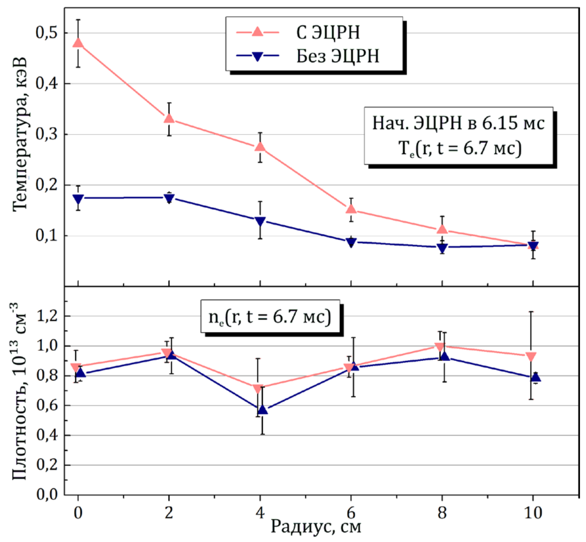




Outer plot: Thomson spectrum averaged over a series of consecutive shots

Inner plot: Spectrum in a single shot

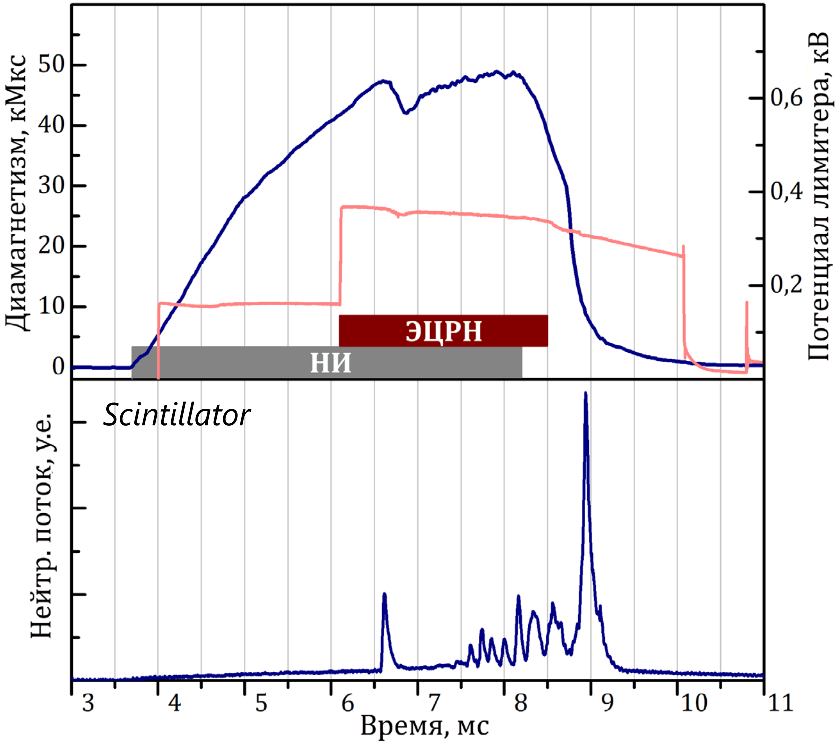


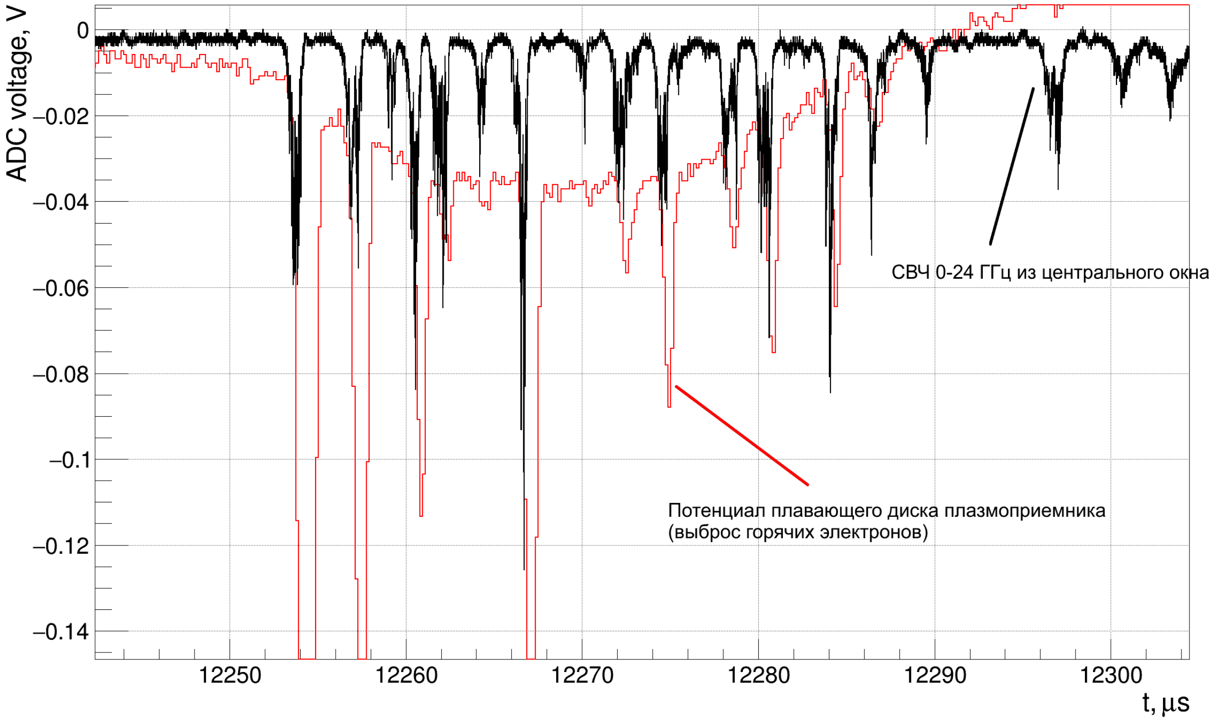


Evidence of hot electrons during ECH

In low density regimes (< $1 \cdot 10^{13}$ cm^{-3}) the plastic scintillator measures HXR bursts coinciding with instability and originating from the central cell. These bursts are likely MHD-related.

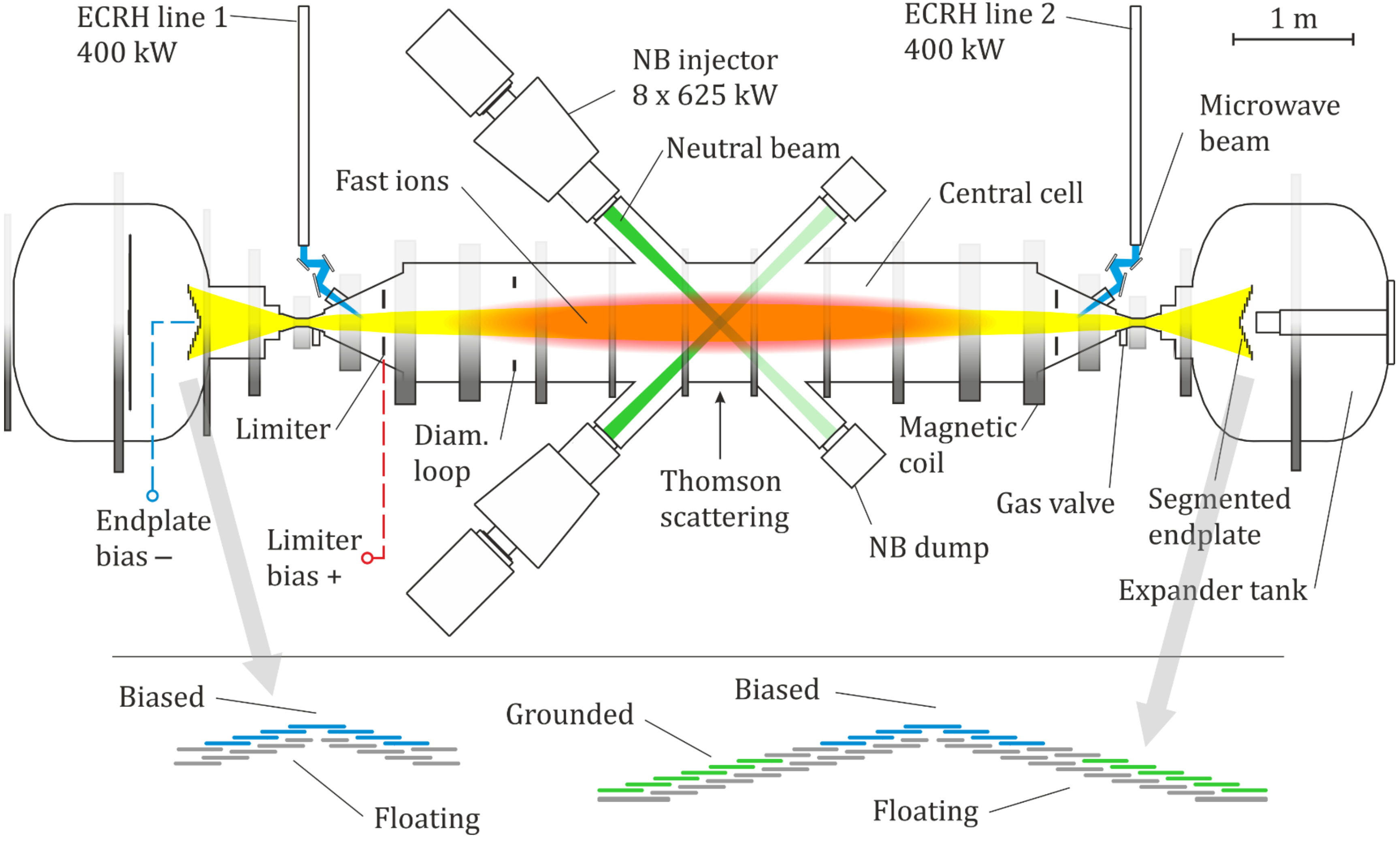
The bursts may also appear during the decay stage, also detectable on floating endrings and ECE measurements – an indication of loss-cone hot electron instabilities.





Sectioned electrodes for additional stabilization

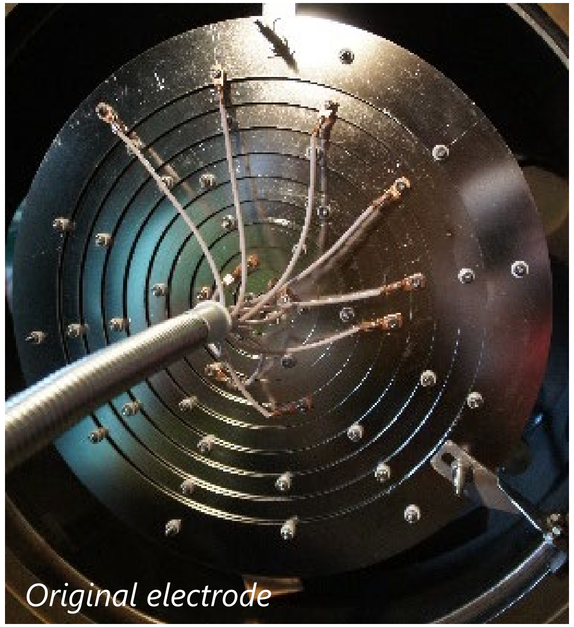
In 2017, a system of sectioned endplate electrodes has been installed to bias the unstable axial region of plasma.

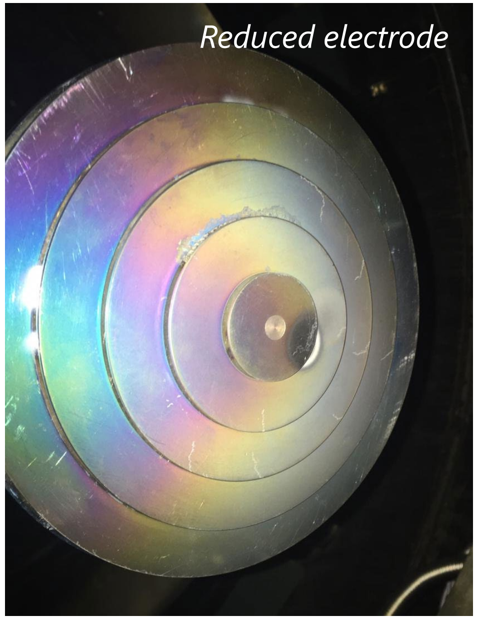


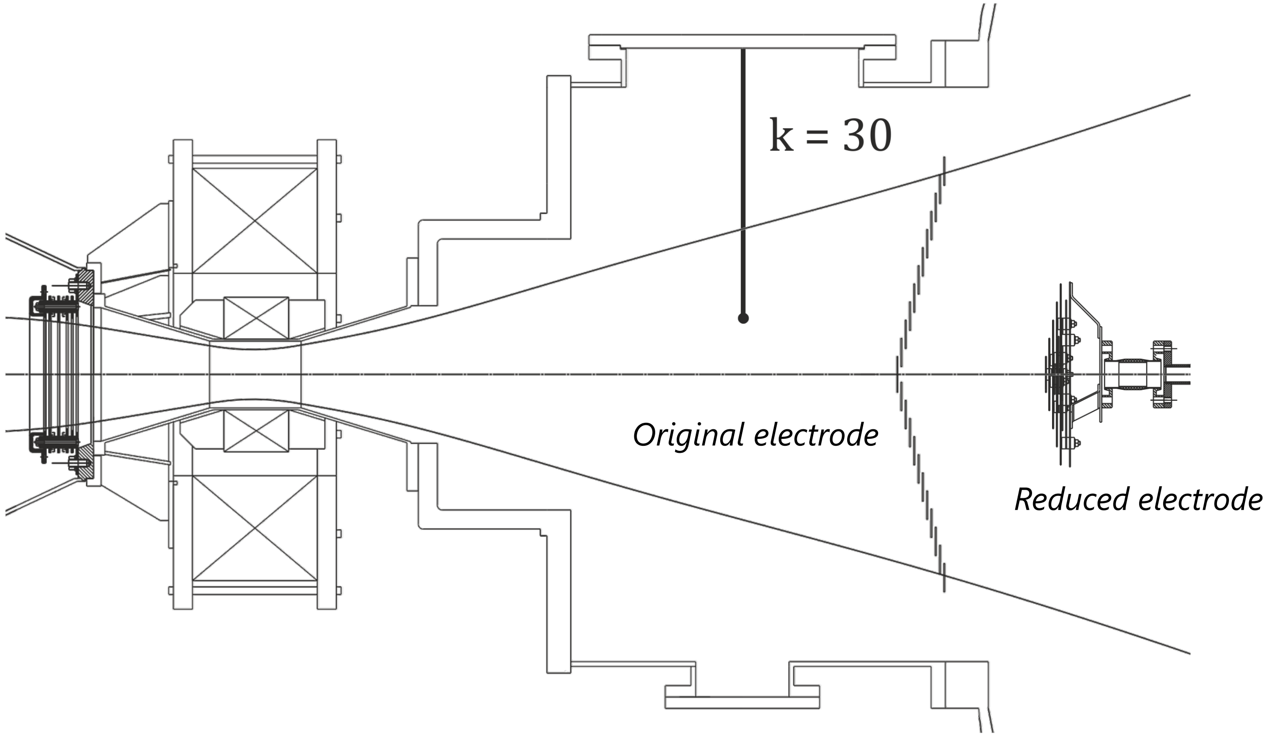
Initial attempts

Initially, electrodes installed at expansion ratio K ≈ 80 were detrimental to confinement, limiting T_e to ~100 eV even without ECH.

The likely cause was gas accumulation in a closed volume downstream of the mirror. After removing a section of the electrodes, T_e returned to ~200 eV.





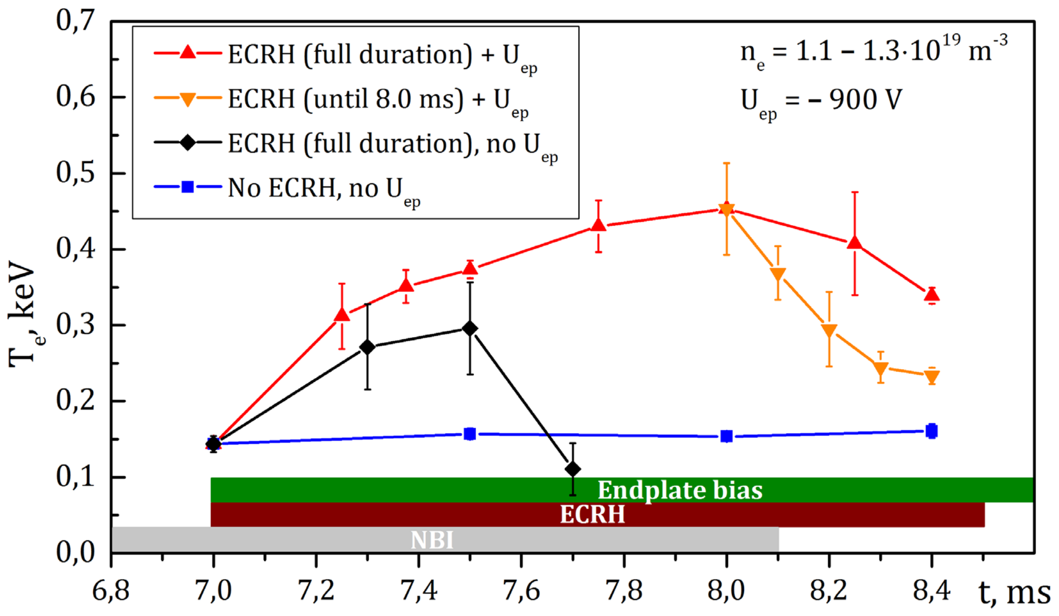


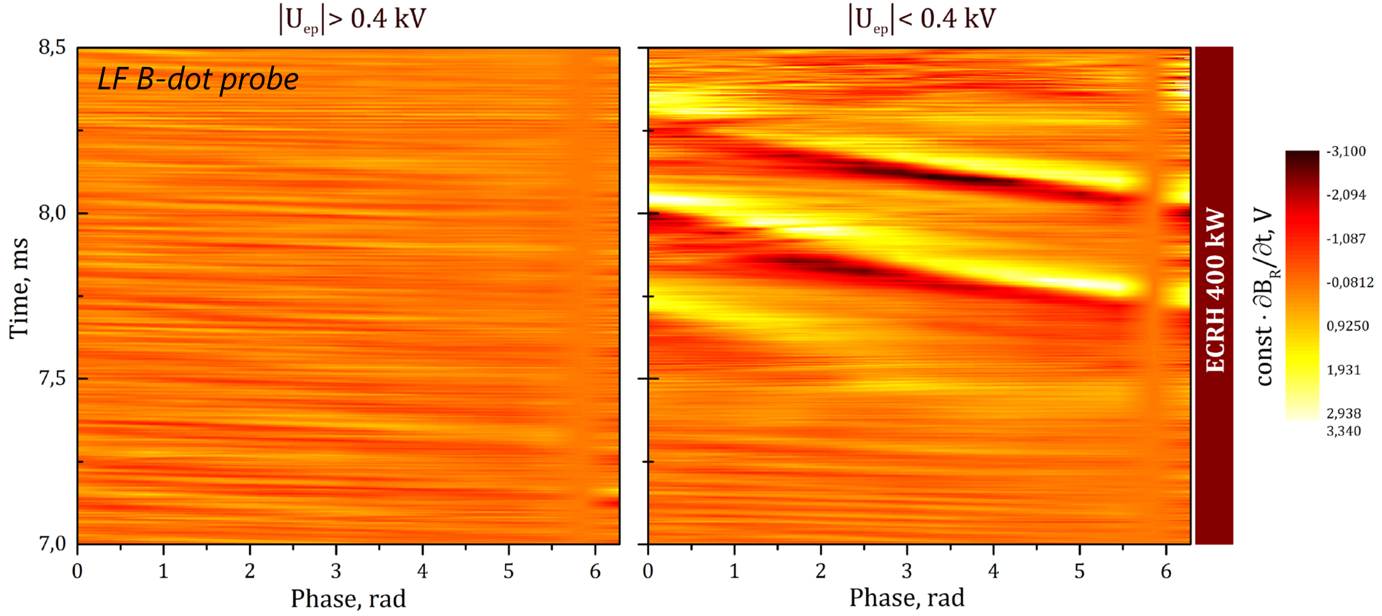
Stabilized high-T_e discharges

Application of negative bias (-400 V) to central section of the endplate leads to stabilization of ECRH-induced instability.

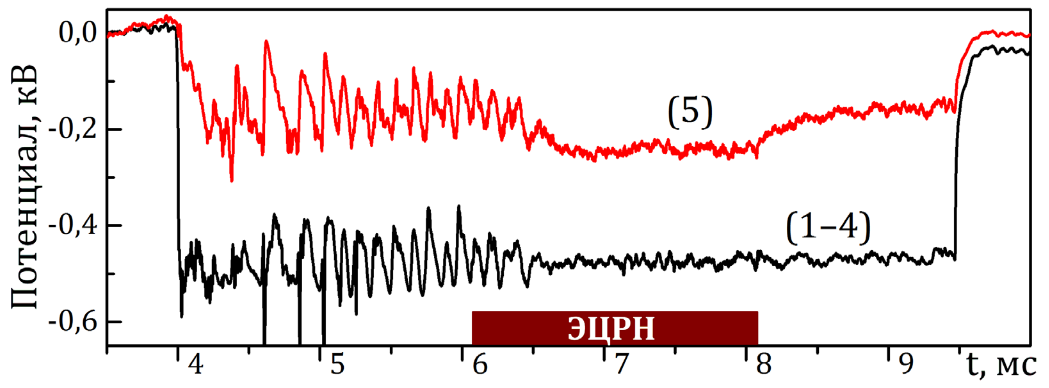
High temperature is maintained until the end of heating pulse, but peak value is not changed and determined by electron energy confinement time

Variation of electron temperature is explained by 0.1-0.2% variation of magnetic field in ECR zone.



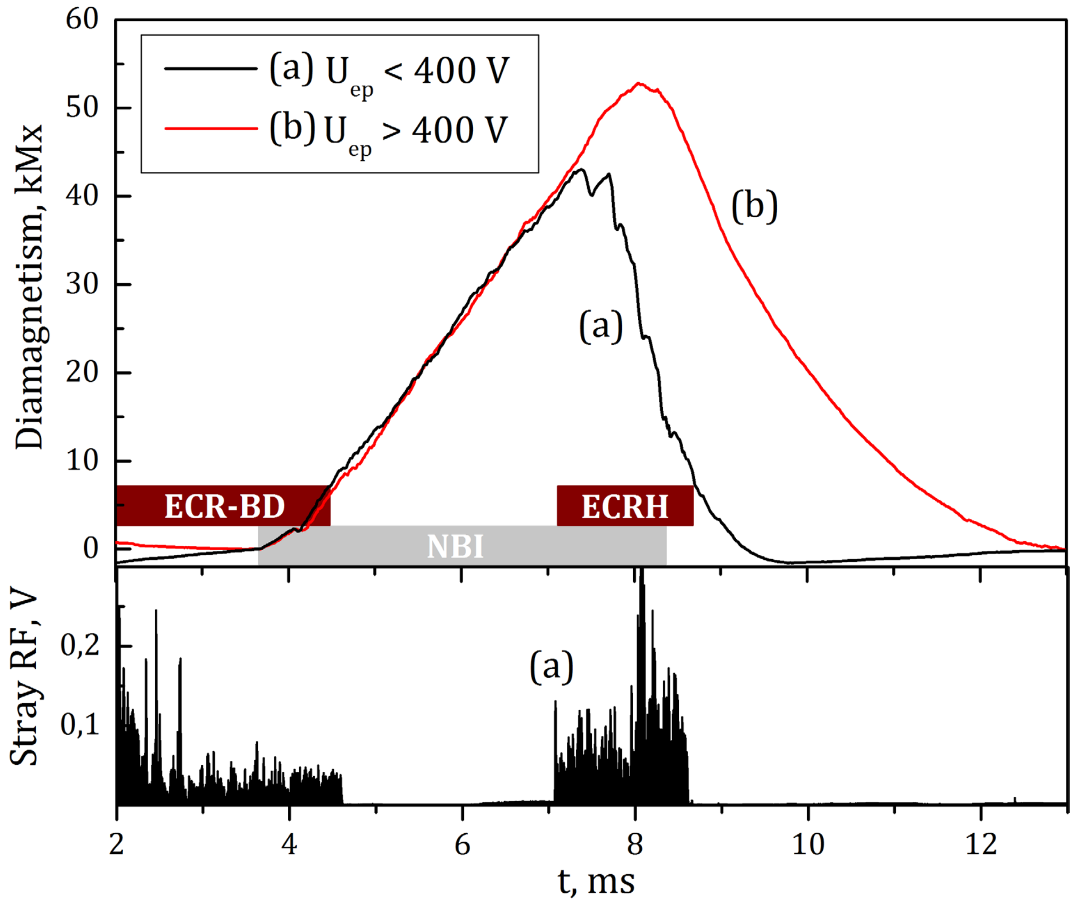


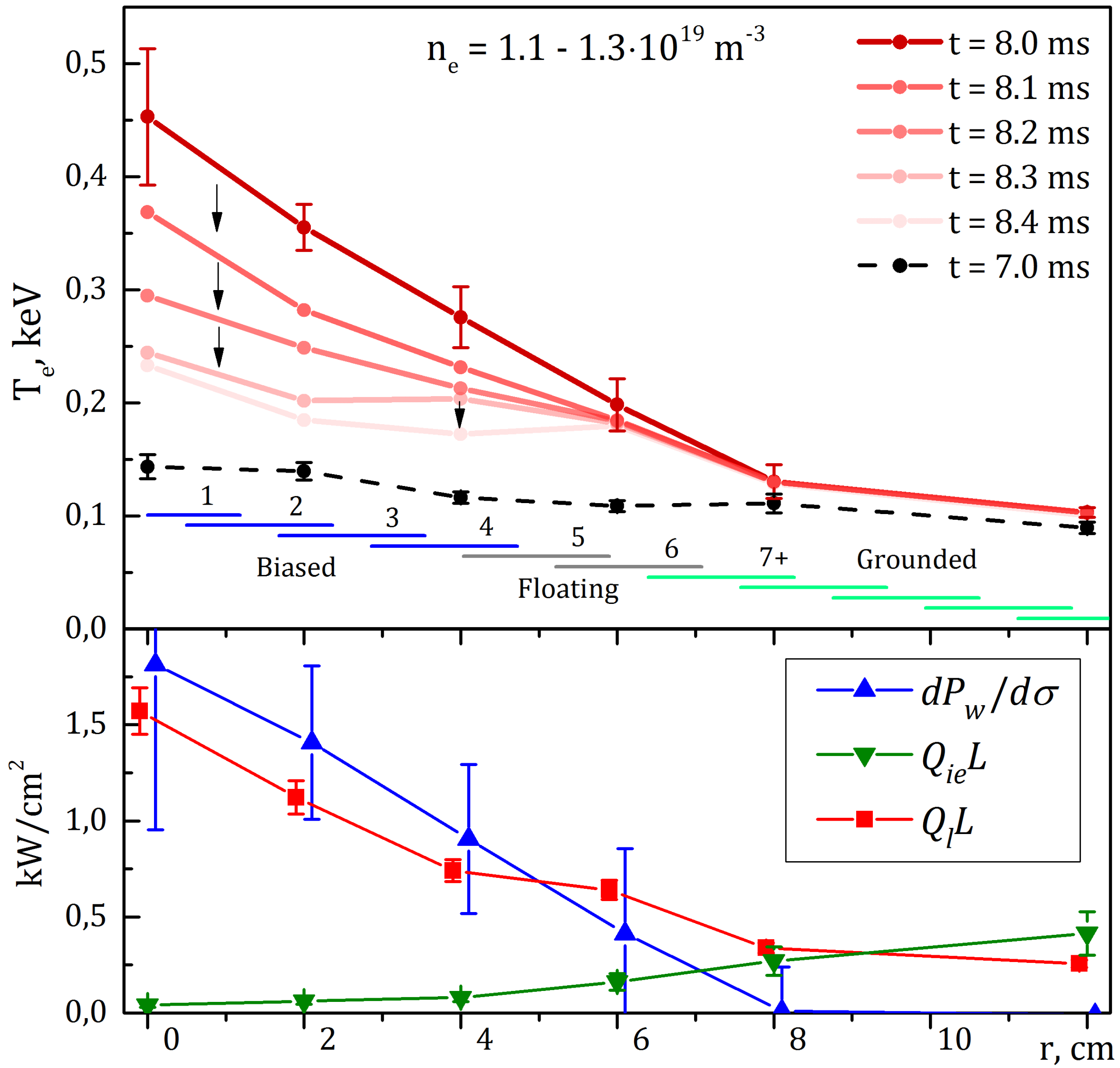
Bias voltage (black) and floating ring voltage (red)



Stabilized high-T_e discharges

Stable relaxation of T_e profile is consistent with gasdynamic losses, and the stabilization effect is consistent with pressure-gradient nature of the instability





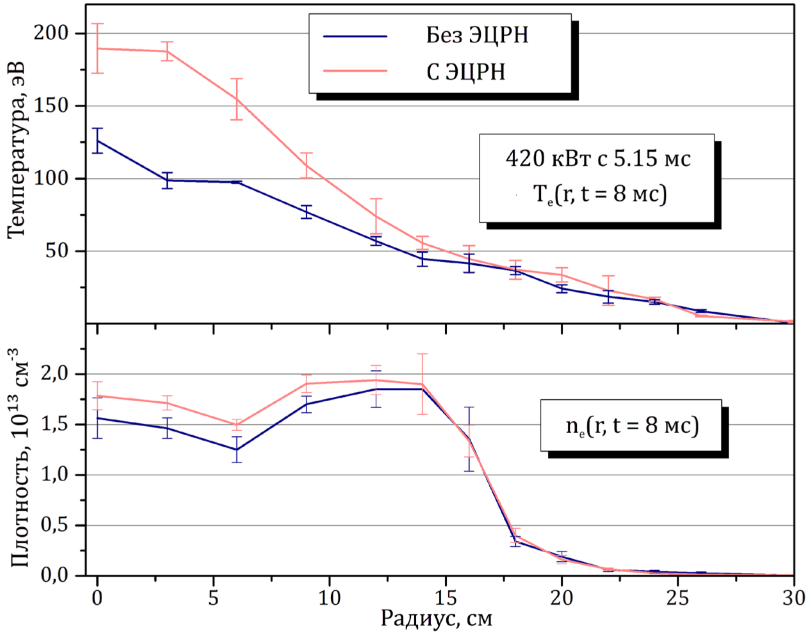
Stable ECRH regimes

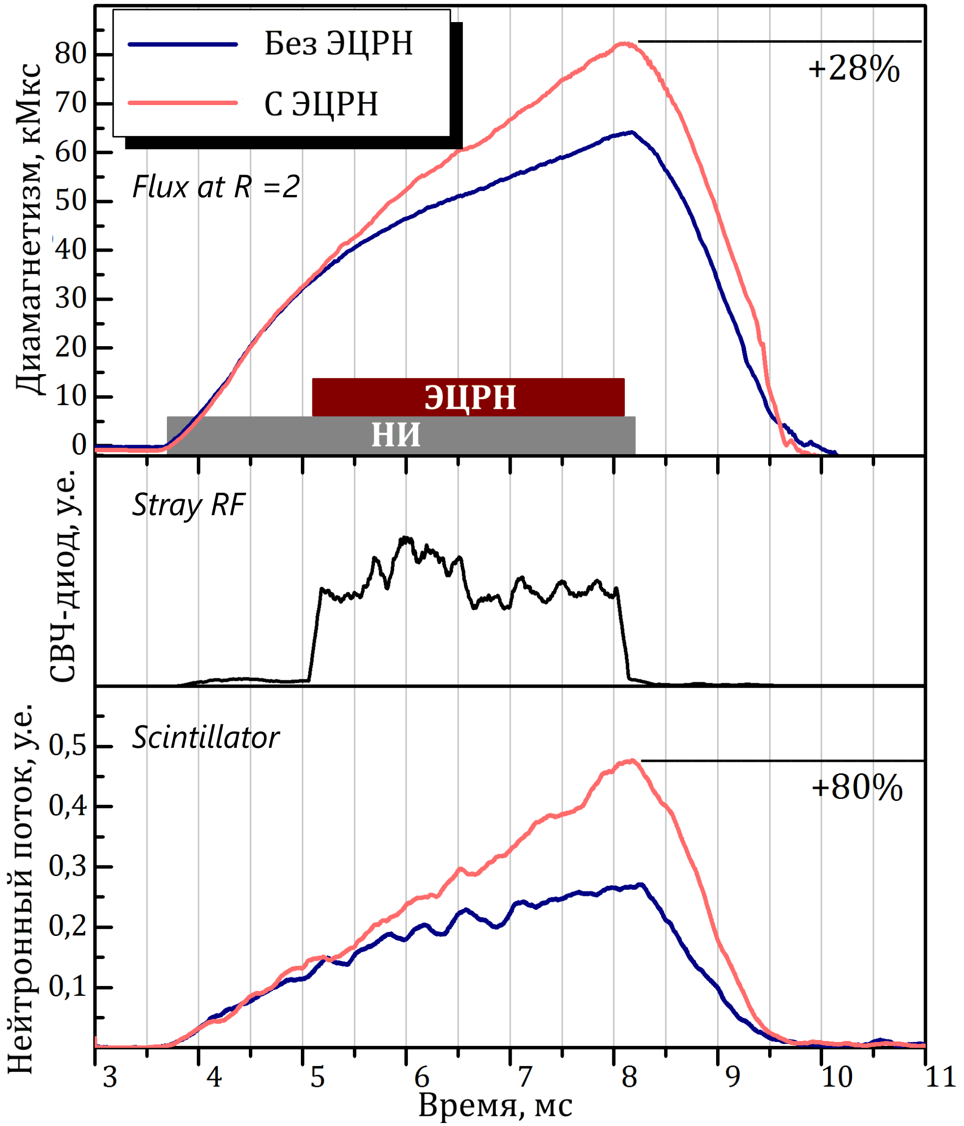
By modifying the density profile and changing the magnetic field in ECR zone, it is possible achieve wider ECRH power deposition.

In this case, no instability appears and there are no HXR bursts characteristic to high-T_e discharges.

Both plasma pressure and neutron flux increase indicating improved fast ion confinement.

T_e and n_e profiles with (red) and without (blue) ECRH



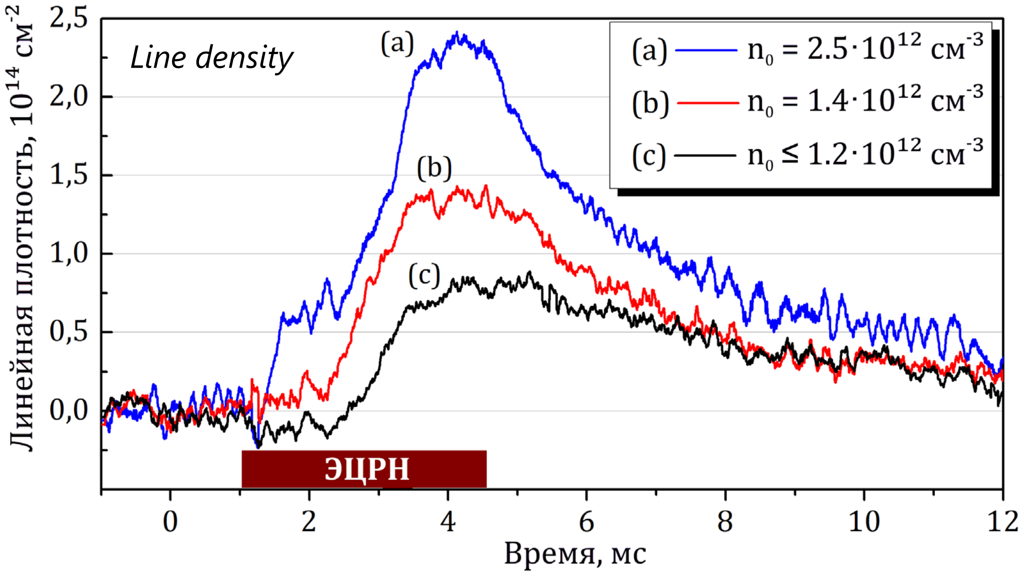


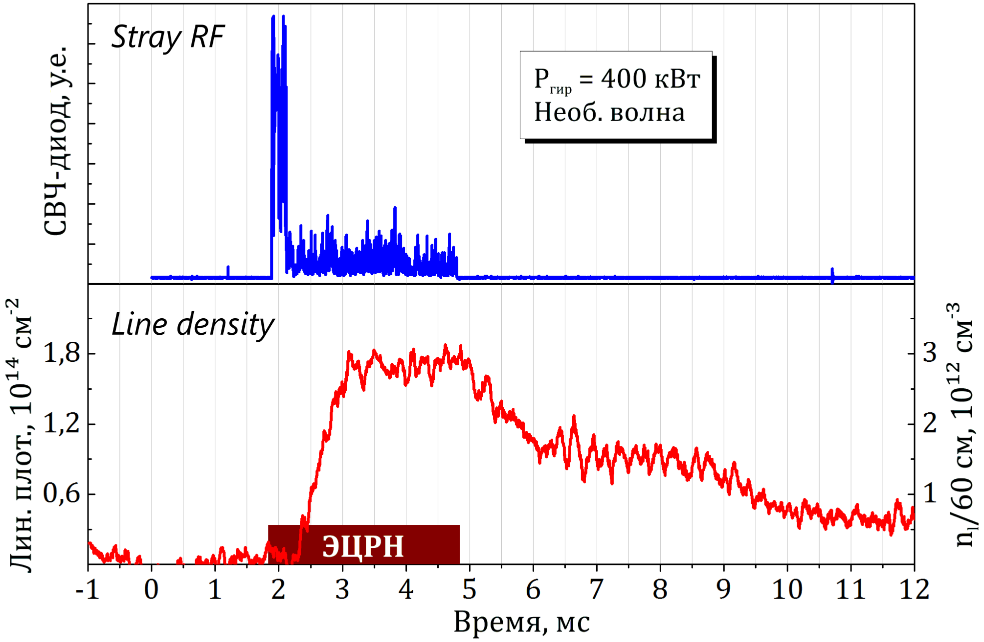
ECR breakdown experiments

In 2016 it was shown that 50 kW X-polarized microwave beam directed at fundamental resonance in magnetic field can produce sufficiently dense plasma for NBI injection

It is believed that an MHD instability is responsible for wide density profile and ionization up to the limiter flux surface.

However, it is observed that overlapping of breakdown ECH pulse with NBI pulse leads to degraded confinement.

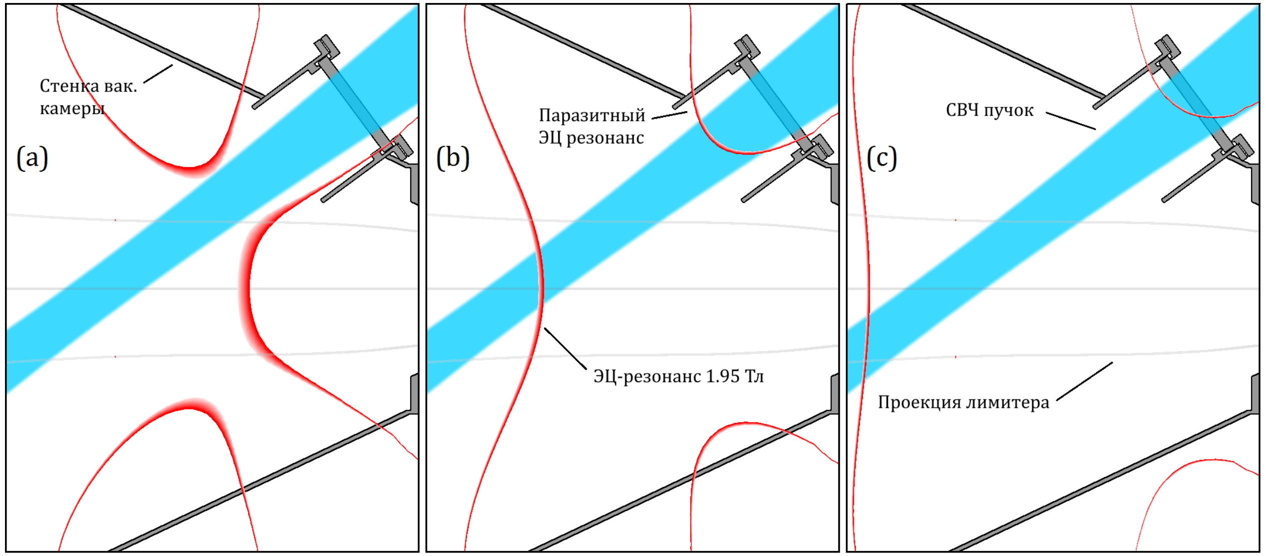


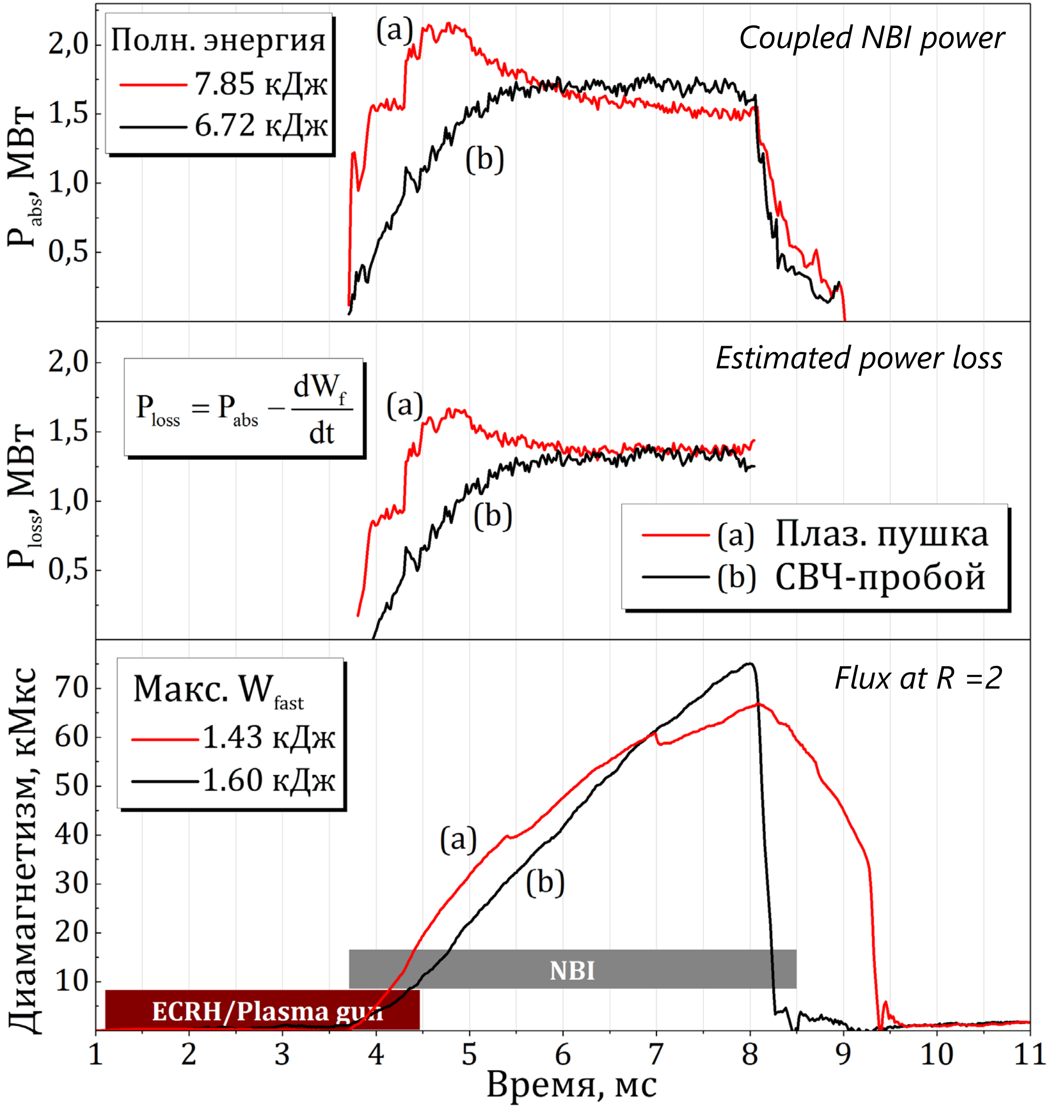


ECR breakdown experiments

The overall physical picture of breakdown is much simpler than in WHAM:

- There is no dependency of density on ECRH power after a certain threshold value
- Density dependence on gas puff is linear
- As long as there is direct intersection of the beam with the ECR layer, the breakdown develops normally



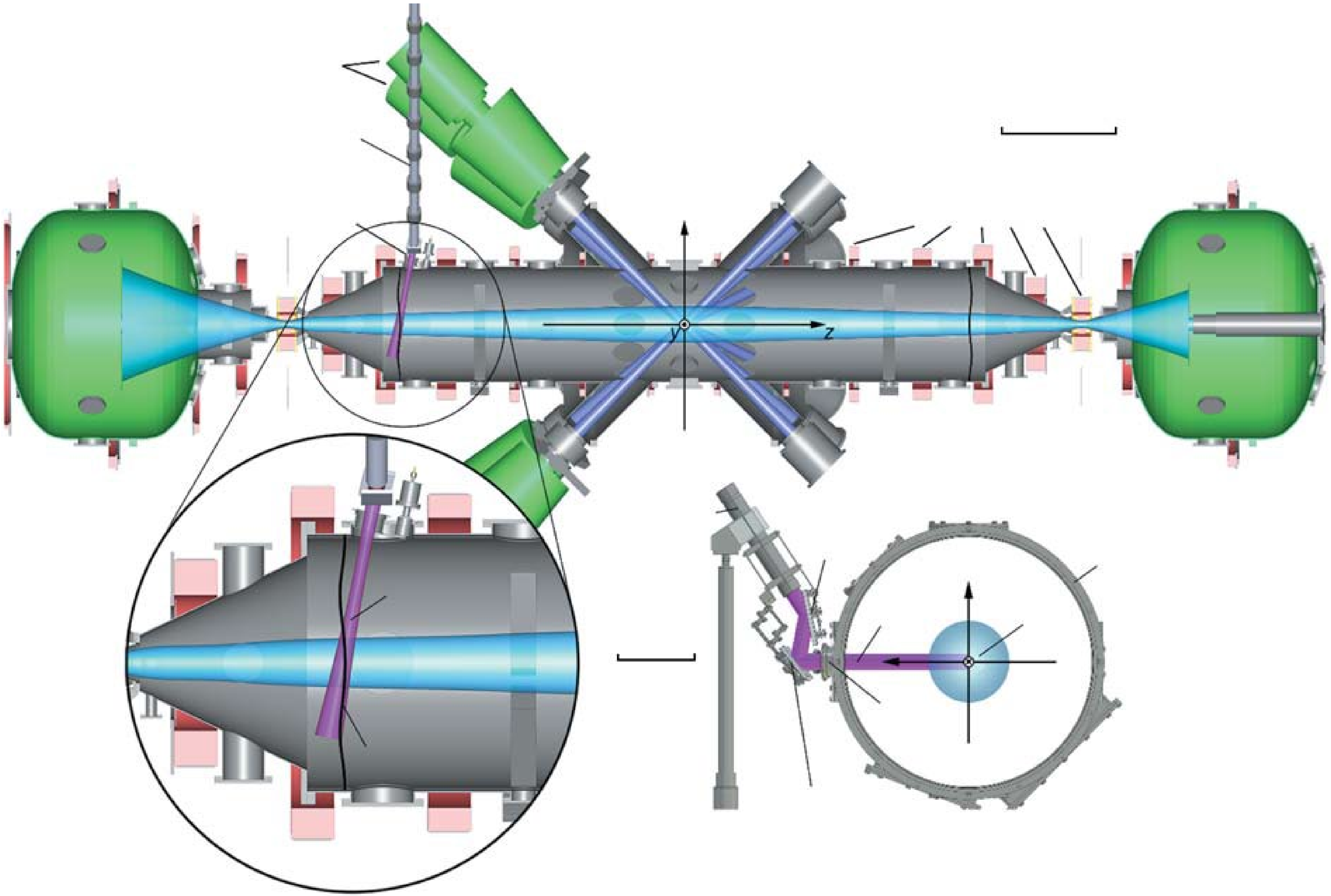


X2 heating scheme (2023 -)

Second harmonic resonance in GDT (0.975 T) is accessible through reconfiguration of the waveguide and new launching system

The beam is making a glancing trajectory with the resonance, which maximizes the resonant interaction volume

The experiments have shown that both X2 breakdown and heating are possible.



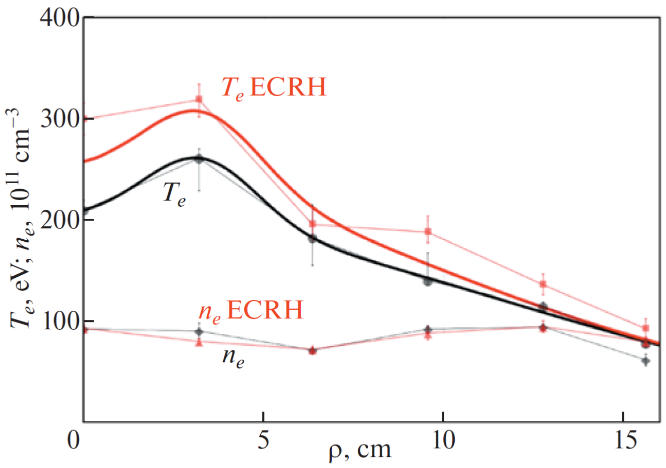
Quasi-Optical Simulations of Scenarios with the Second Harmonic Electron Cyclotron Plasma Heating at the GDT Facility. T. Khusainov et al 2024 Plasma Physics Reports 50 11 1337–1352. DOI: 10.1134/S1063780X24601585

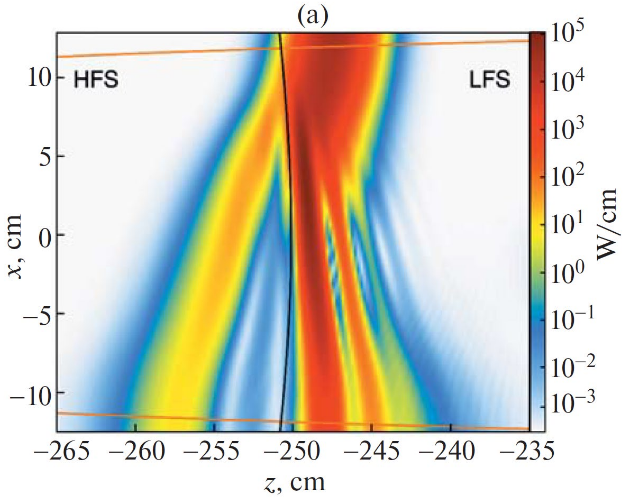
X2 heating

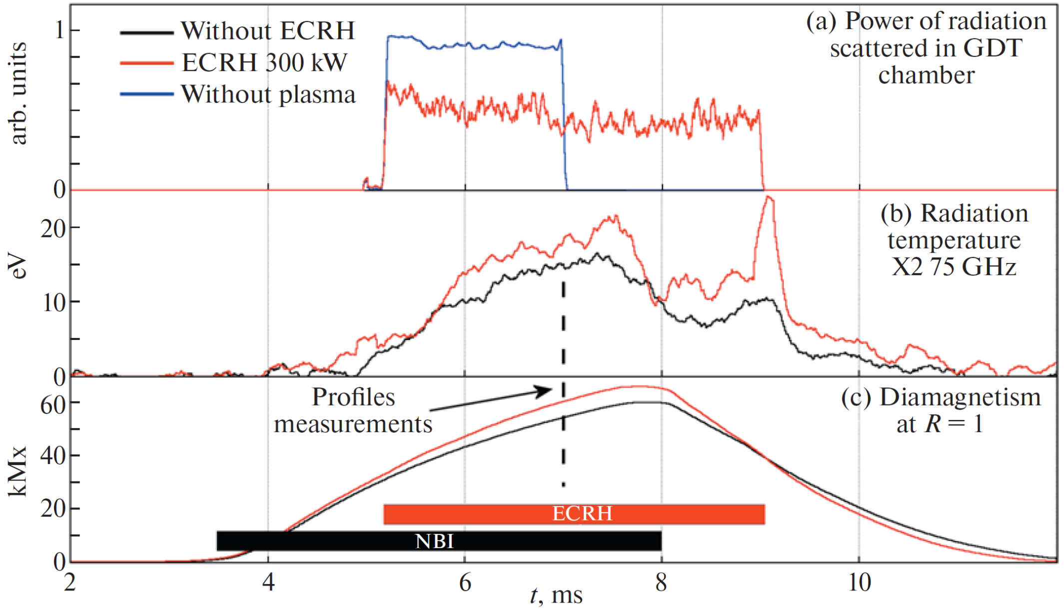
The effect on plasma pressure is modest, but the simulation demonstrate good agreement with measured temperature profiles.

The absorption is not complete: the quasioptical simulations revealed that the beam can be partially reflected from the harmonic resonance

Radiation temperature does not indicate presence of hot electrons, while the signal itself indicates optically thin plasma at X2 75 GHz resonance location.







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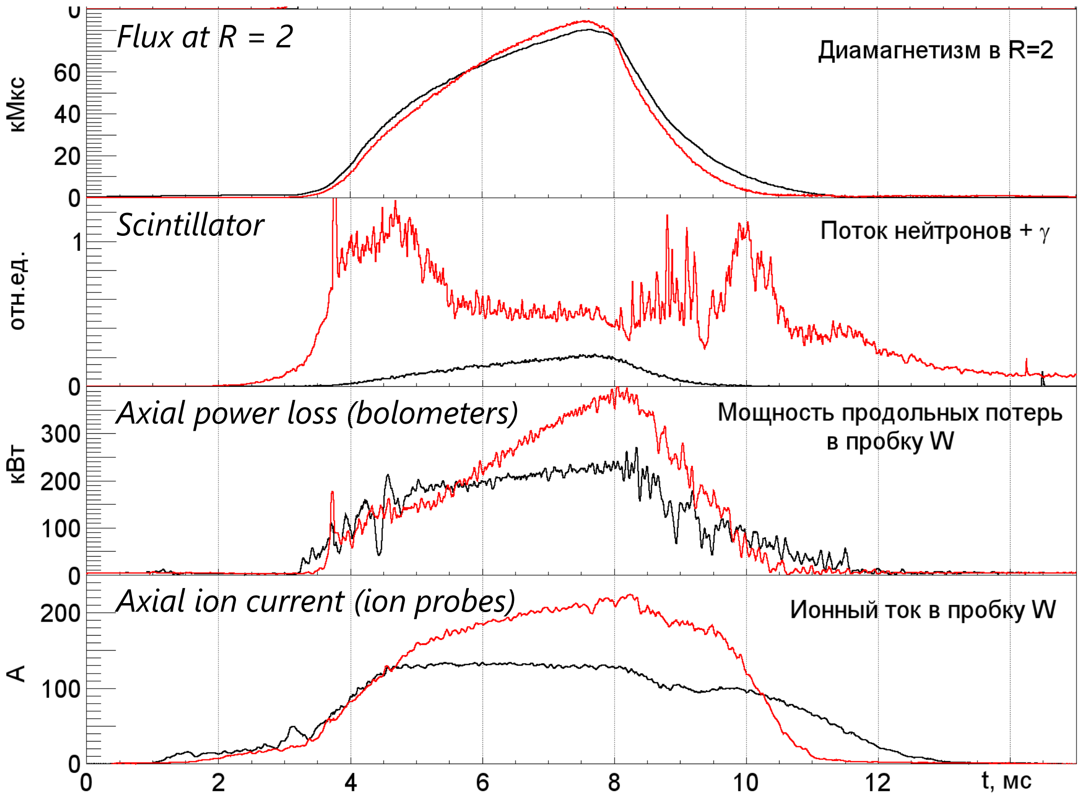
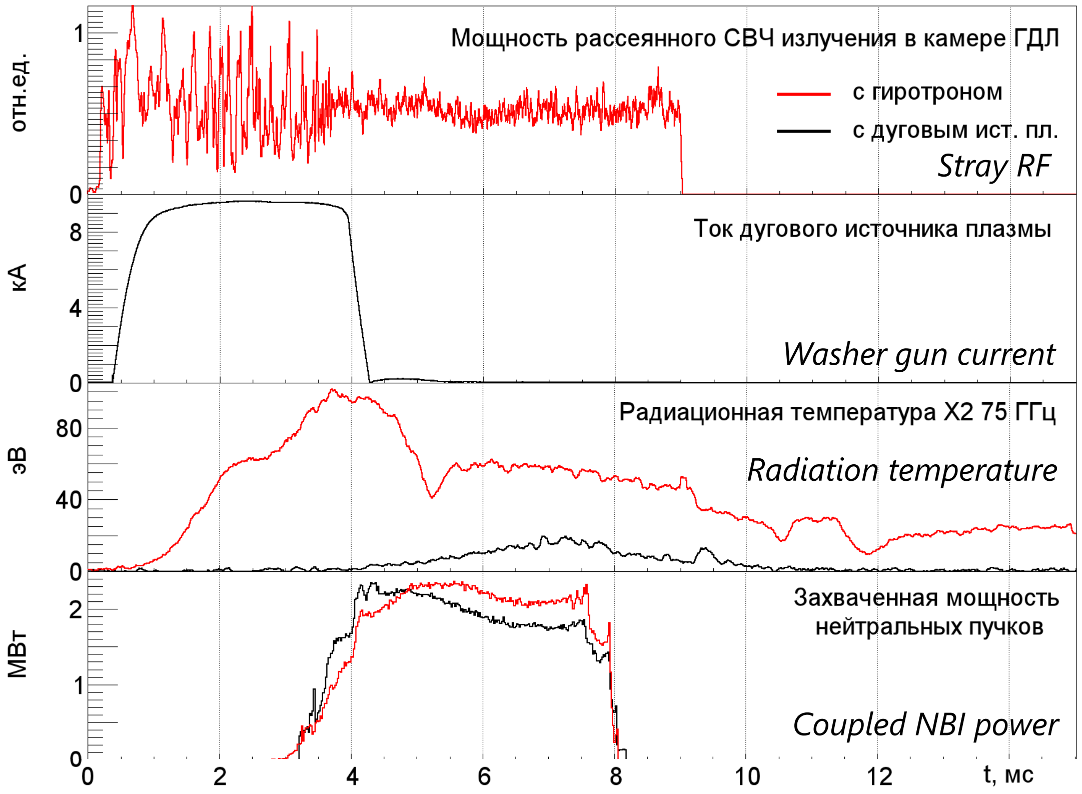
X2 breakdown

X2 breakdown requires higher prefill and develops more slowly than X1, but the resulting NBI-sustained discharge parameters are similar.

Unlike X2 heating, X2 breakdown produces hot electrons visible in radiation temperature and HXR signals.





Summary

X1 ECRH in GDT demonstrated strong electron heating, including near-keV temperatures with power deposition profiles and temperature increase consistent with ray tracing and gasdynamic confinement

Localized X1 heating triggers an m=1 instability resulting from temperature peaking, which can be mitigated by endplate biasing and control over plasma potential. Low density (< 10^{13} cm^{-3}) discharges demonstrate the highest temperatures, accompanied by bursts of hard X-ray, indicating presence of hot (> 100 keV) electrons.

Broad-profile X1 operation eliminates instability, suppresses HXR bursts, and improves fast-ion confinement, as shown by increased diamagnetism and neutron flux.

ECR breakdown at X1 enables target-plasma formation, with simple, threshold-like behavior and predictable density scaling, consistent with a simple 0D analytical breakdown model

X2 experiments confirm both heating and breakdown, with modeling–experiment agreement for temperature profiles; heating efficiency is modest due to partial beam reflection, while X2 breakdown again produces a hot-electron component.

Backup