TOKAMAK RESEARCH IN IOFFE INSTITUTE

N.N. Bakharev et al.

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Outline

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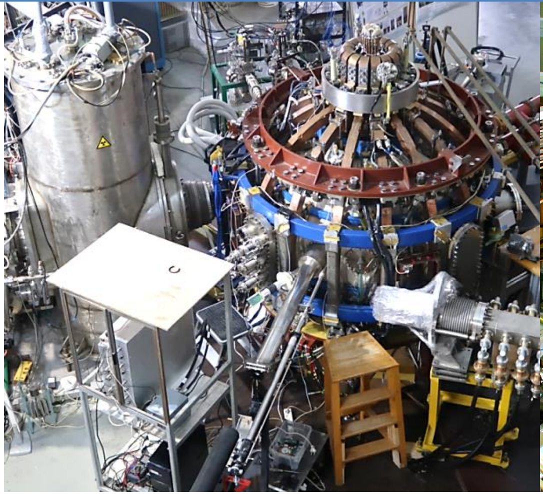
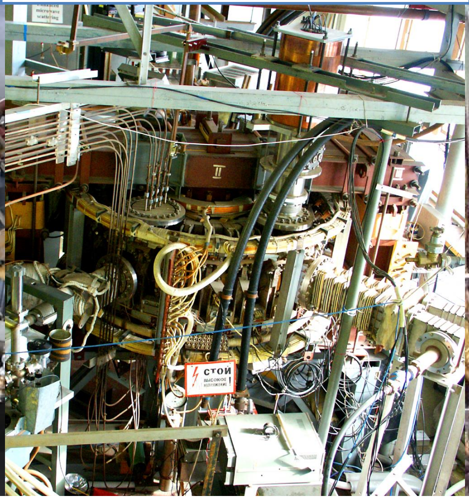
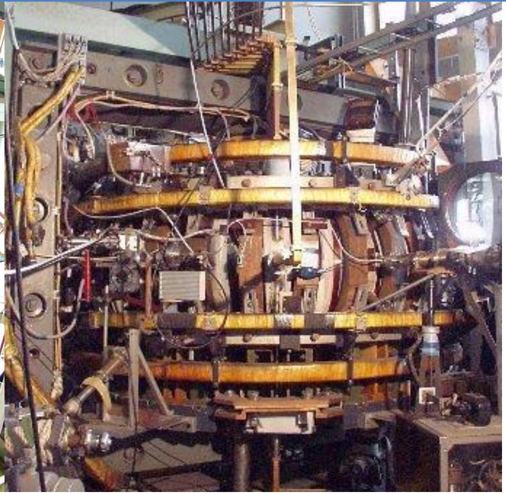
Introduction

- In 2018, Ioffe Institute celebrates its 100th anniversary.
- Fusion research in Ioffe Institute has been going on for more than 60 years.
- At present – theory group, ITER group, 3 tokamaks:

	Globus-M2	FT-2	TUMAN-3M
R [cm]/a [cm]	36/24 = 1.5	55/8 = 6.8	53/22 = 2.4
B_T [T] / I_p [kA]	1 / 500	3 / 40	1 / 180

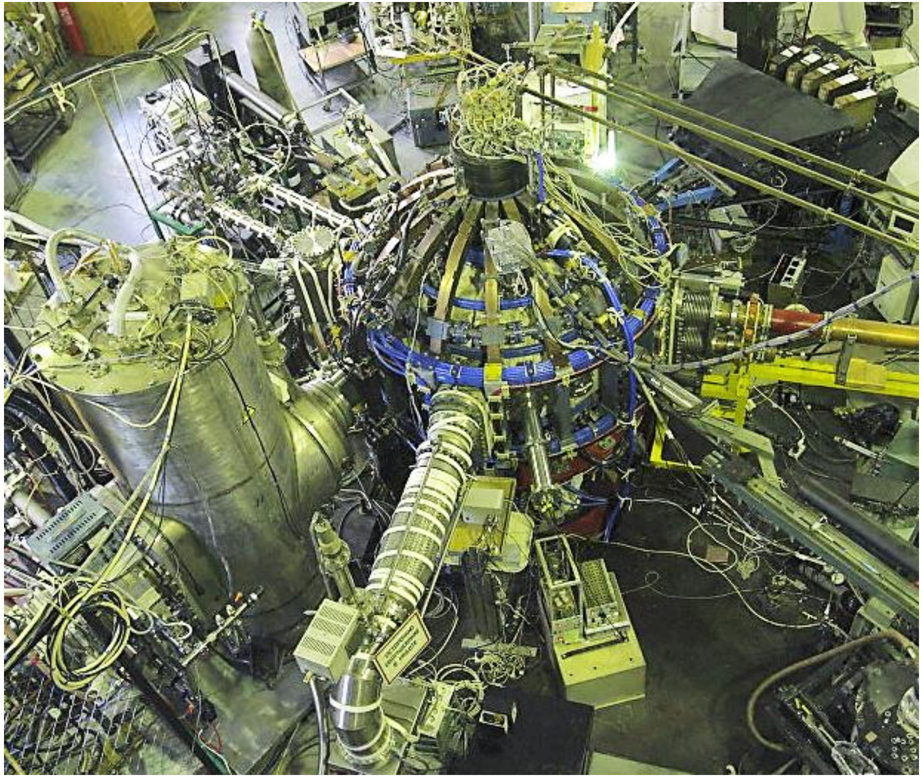






Globus-M

parameter	value
R [cm]/a [cm]	36/24 = 1.5
k	≤ 2.0
δ	≤ 0.5
B_{T}, T	0.5
I_p , kA	≤ 250
t_{pulse} , ms	≤ 130
P_{NBI} [MW]	≤ 1



1999 – 2017

Last experimental campaign:

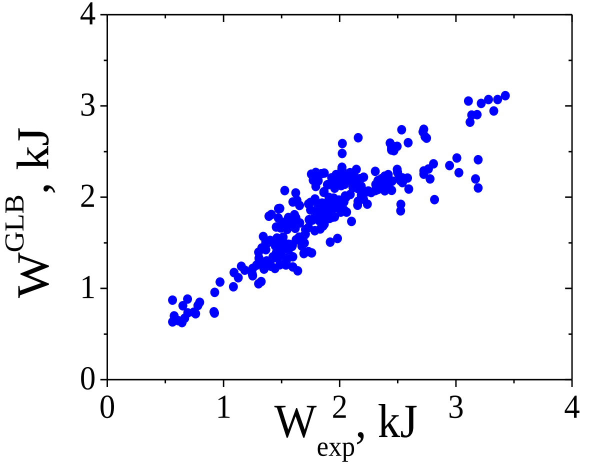
B_T: 0.4 T → 0.5 T
I_p: 200 kA → 250 kA

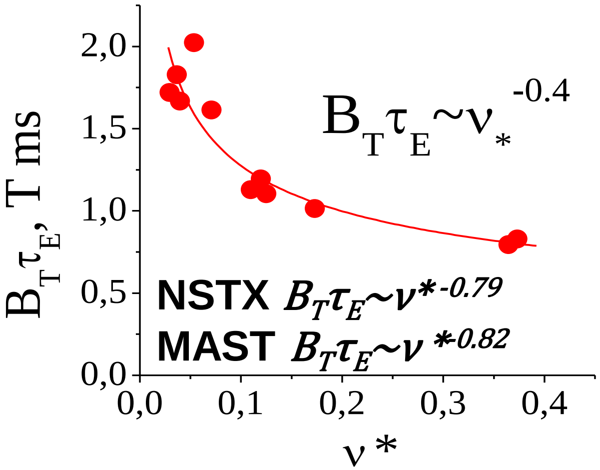
[Bakharev N.N. et al. Nucl. Fusion 2018 accepted manuscript]

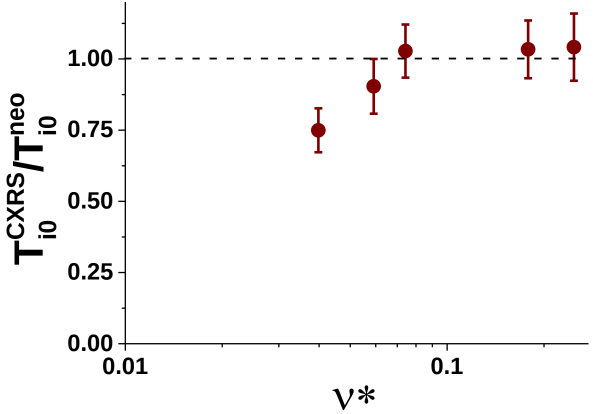
Globus-M: Energy confinement

$\tau_E^{GLB} \sim I_p^{0.51\pm0.26} B_T^{1.2\pm0.1} P_{abs}^{-0.54\pm0.26} n_e^{0.67\pm0.04}$

IPB98(y,2): $\tau_E \sim I_p^{0.93} B_T^{0.15} P_{abs}^{-0.69} n_e^{0.4}$ MAST: $\tau_E \sim I_p^{0.59} B_T^{1.4}$ NSTX: $\tau_E \sim I_p^{0.57} B_T^{1.08}$







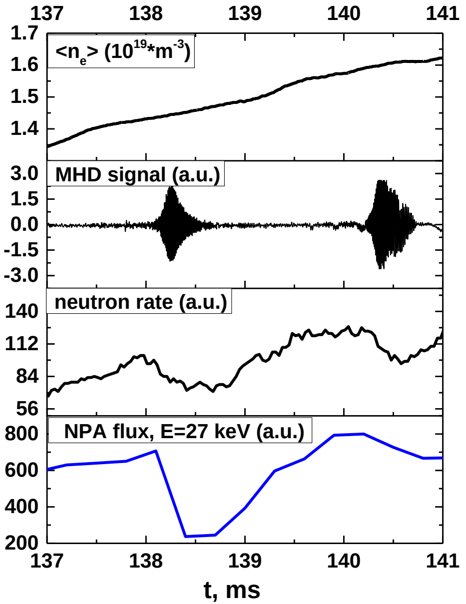
- Energy confinement time strongly depends on toroidal magnetic field.
- Normalized energy confinement time exhibits moderate dependence on collisionality.
- Ion heat transport is close to neoclassical level. Anomalous contribution is observed at low collisionality.

EX/P5-2 (Thursday), Kurskiev G.S. et al

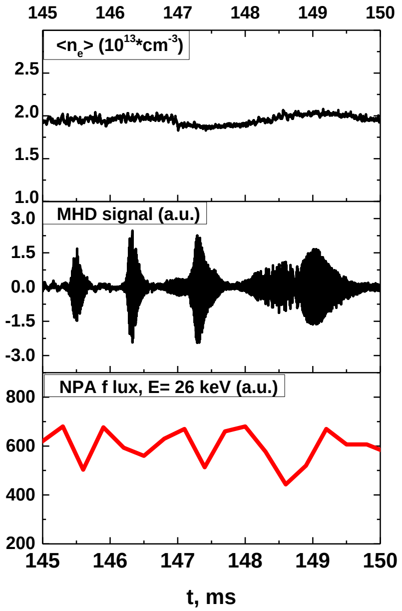
[G.S. Kurskiev et al. PPCF 59 (2017)]

Globus-M: TAE

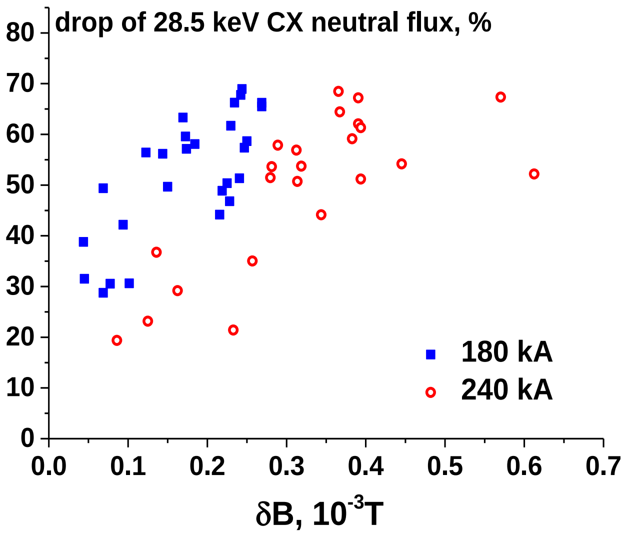
180 kA, 0.4T



240 kA, 0.5 T



TAE-induced Fast Ion losses

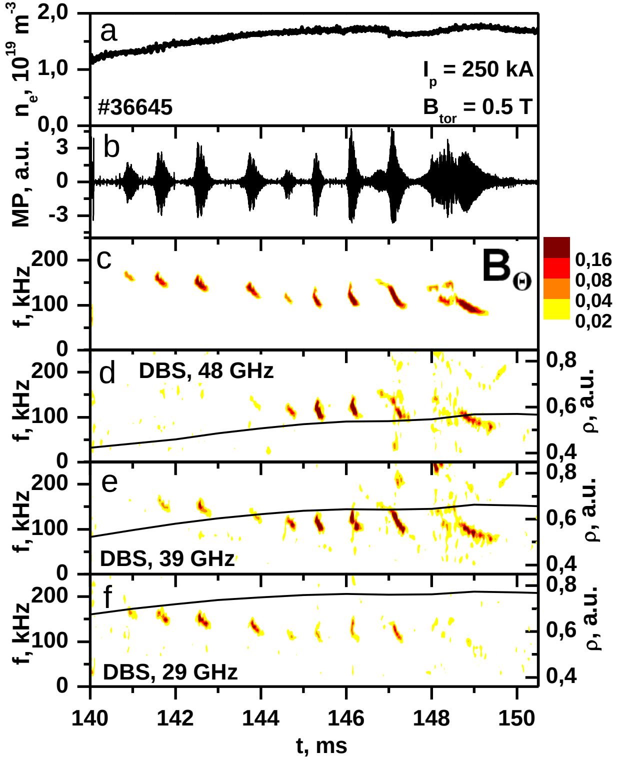


- Modes became more frequent due to better fast ion (FI) accumulation because of the better classical FI confinement and lower TAE-induced losses.
- B_T increase also resulted in FI losses decrease, but this effect was much weaker

[BULANIN V., et al. Tech. Phys. Lett. 43 12 (2017) 1067]
[GUSEV V. et al. Tech. Phys. Lett. 44 1 (2018) 67]

Globus-M: TAE

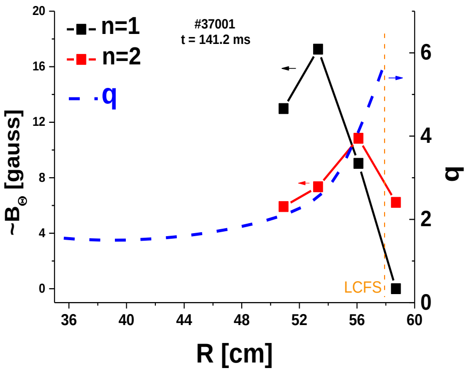
TAE localization by DBS :



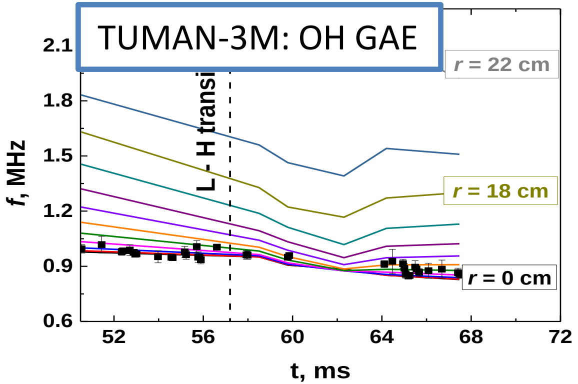
[BULANIN V., et al. Tech. Phys. Lett. 43 12 (2017) 1067]
[GUSEV V. et al. Tech. Phys. Lett. 44 1 (2018) 67]

Comparison of the experimental and calculated TAE localization

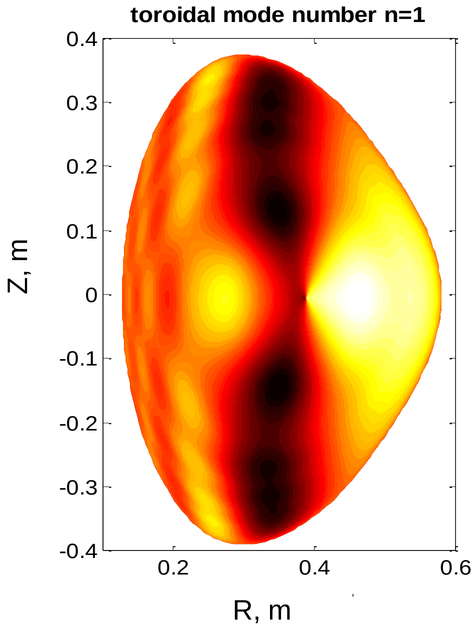
Experiment:
$\rho = 0.45 - 0.85$



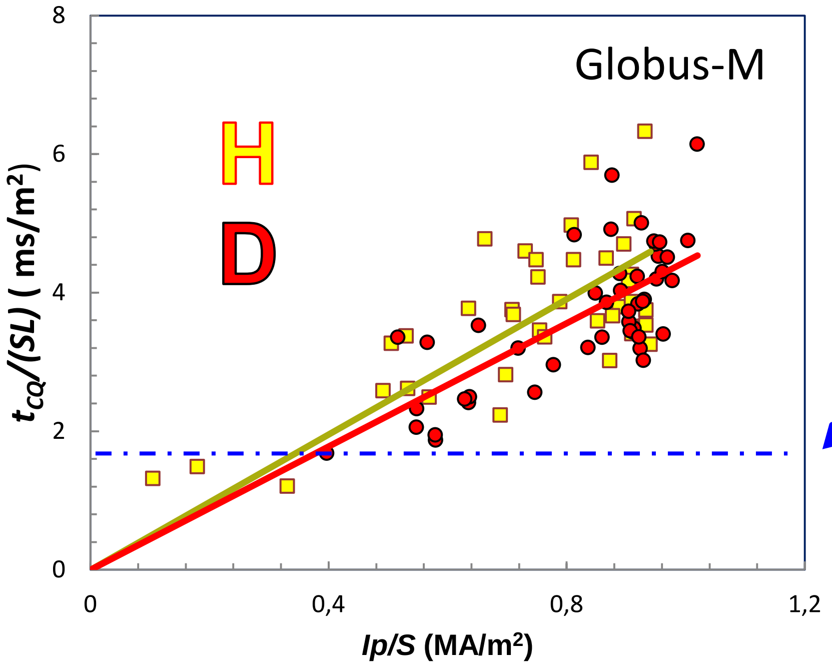
TUMAN-3M: OH GAE



KINX + KAXE modeling:
$\rho = 0.4 - 0.9$



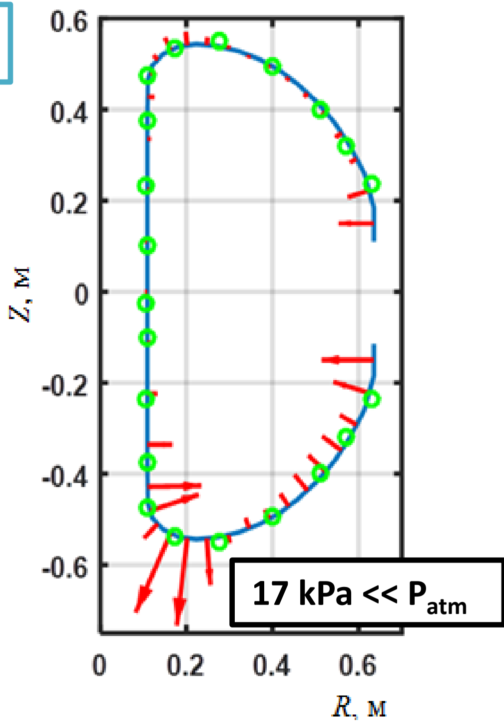
Globus-M: disruption study



IDDB: $t_{CQ} = (t_{20}-t_{80})/0.6$

IDDB:
t_{CQ}/SL : 1,7-10 ms/m²

ITER$_{min}$:
$t_{CQ}/SL \geq 1.67$ ms/m²



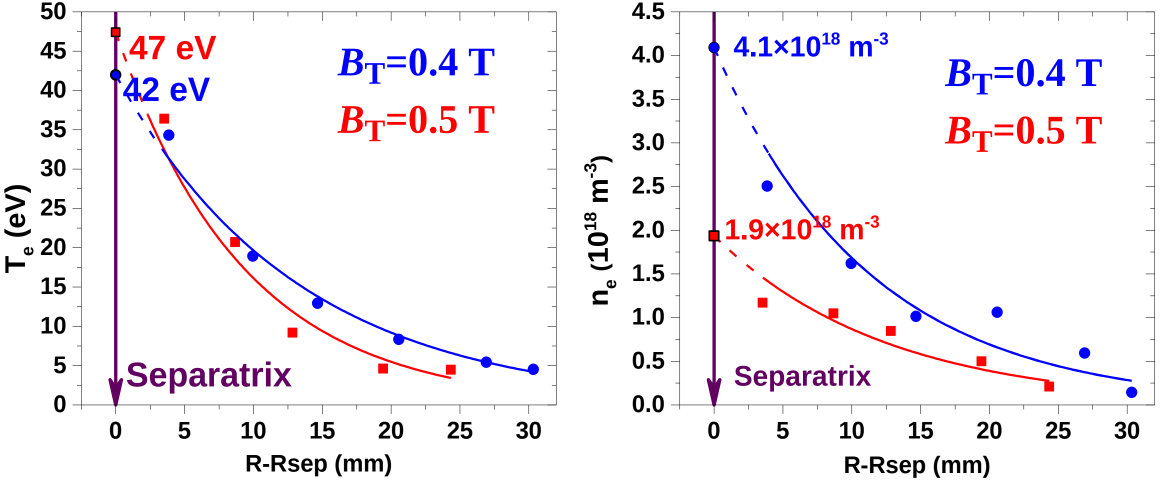
- **$t_{CQ} \sim I_p$ like in NSTX, but not in IDDB**
- **Linear dependence, almost no difference for H and D**

[SAKHAROV, N. et al, Plasma Phys. Rep. 43 (2017) 422]
[SAKHAROV, N., GUSEV V., KAVIN A. et al, Plasma Phys. Rep., 44 (2018) 335]

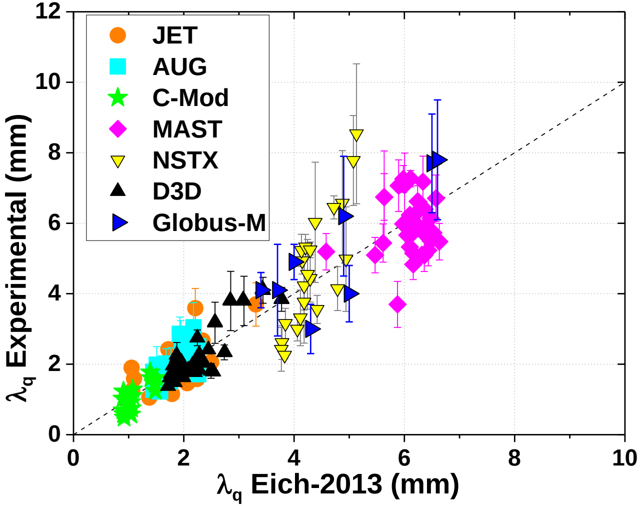
Globus-M: SOL width

New adjustable 9-pin probe was installed at LFS midplane.

Typical Globus-M T_e and n_e profiles



λ_q scaling fitting



Good agreement with both EICH scalings is observed:

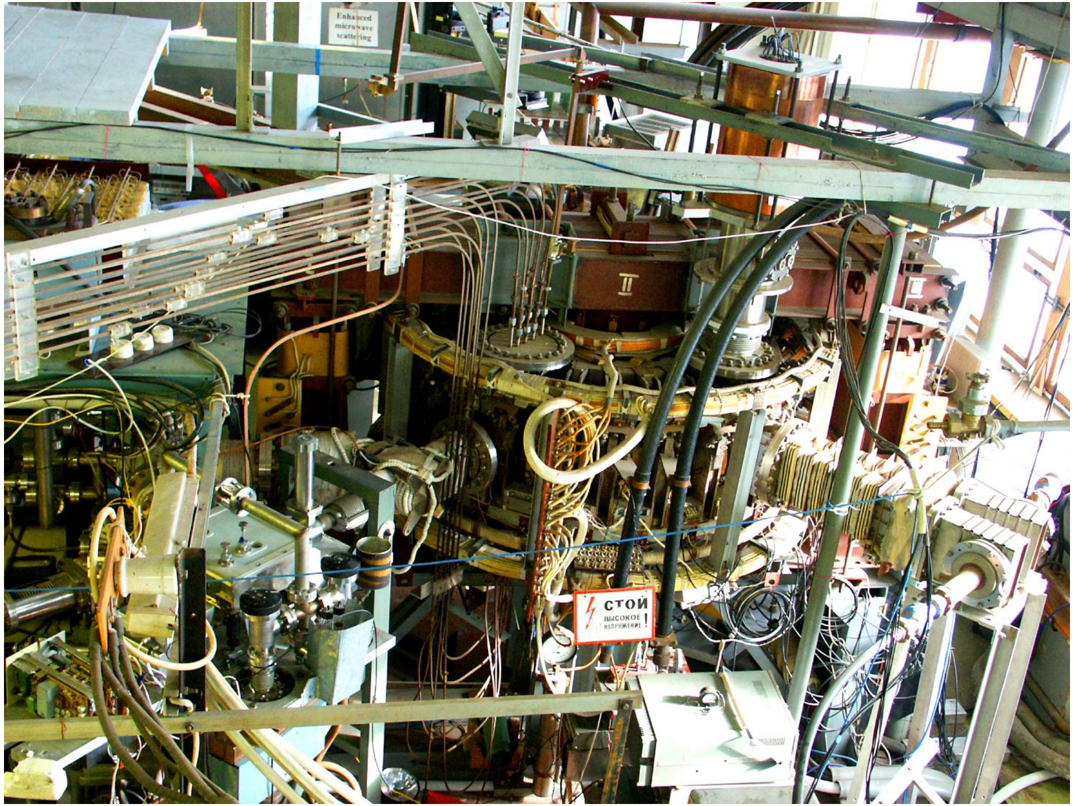
Globus-M database fitting: $\lambda_q \sim I_p^{-1.2} B_T^{0.6}$

[Eich 2011] scaling: $\lambda_q \sim I_p^{-1.1} B_T^{0.42}$

[Eich 2013] scaling: $\lambda_q \sim I_p^{-0.9}$

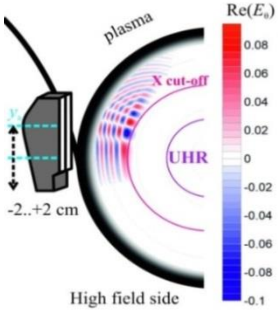
FT-2 tokamak

High field high aspect ratio tokamak.



parameter	value
R [cm]/a [cm]	55/8= 6.8
B_T, T	3
I_p , kA	≤ 40
q_a	3 - 6
P_{LHH} [kW]	≤ 180

COMPREHENSIVE BENCHMARKING OF FULL-F GLOBAL GK MODELING AGAINST THE FT-2 TOKAMAK DOPPLER REFLECTOMETRY DATA

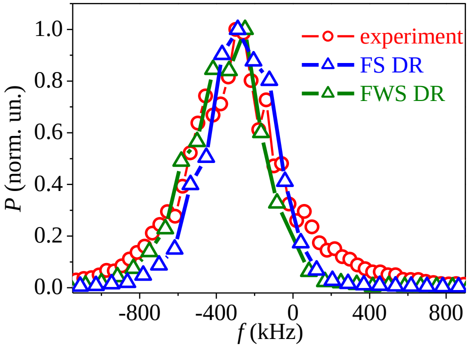


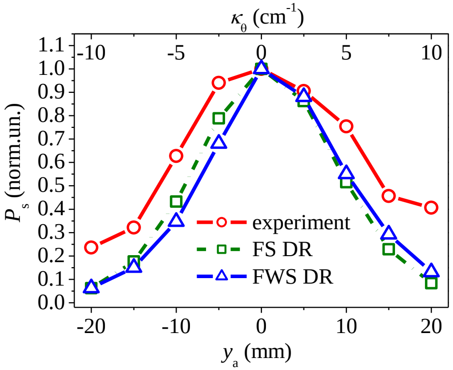
HFS X-mode DR experimental data VS ELMFIRE code modeling via

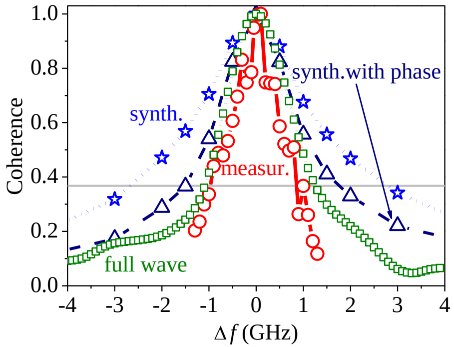
- fast linear synthetic diagnostic version based on the reciprocity theorem
- full-wave synthetic diagnostic version utilizing the IPF-FD3D code

- **Good agreement between the measured and computed DR frequency spectra (the spectra frequency shift, width and form for all incidence angles). The mean fluctuation velocity and GAM characteristics were close thus indicating correct description of the global electric field dynamics by the code.**

- **The variation of the DR signal at growing incidence angles in experiment is slower than predicted by both synthetic diagnostics because of the overestimation of the turbulence poloidal wavenumber spectrum decay rate with growing wavenumber due to incorrect modelling in the small-scale (ETG-mode) domain.**
- **The experimental radial correlation DR data is in agreement with full-wave synthetic diagnostic prediction thus indicating correct description of the turbulence radial wavenumber spectra. Substantial difference found for the fast synthetic diagnostic is related to the large contribution of long scale fluctuation, which is suppressed in experiment by the probing wave phase modulation (transition to the nonlinear regime of DR operation).**

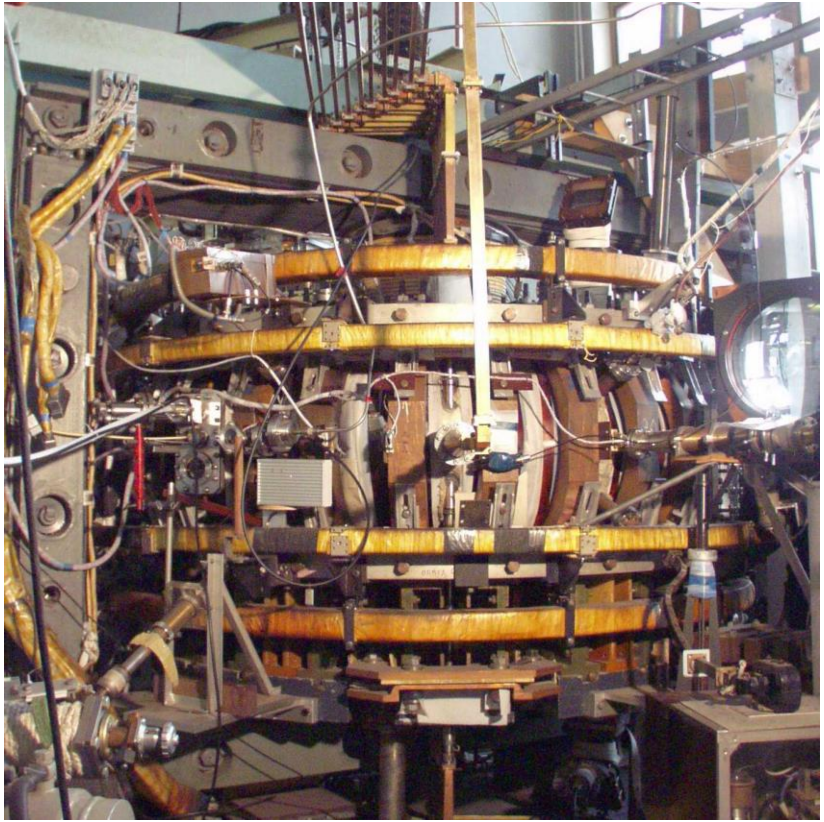






Compact tokamak TUMAN-3M

Compact conventional tokamak.



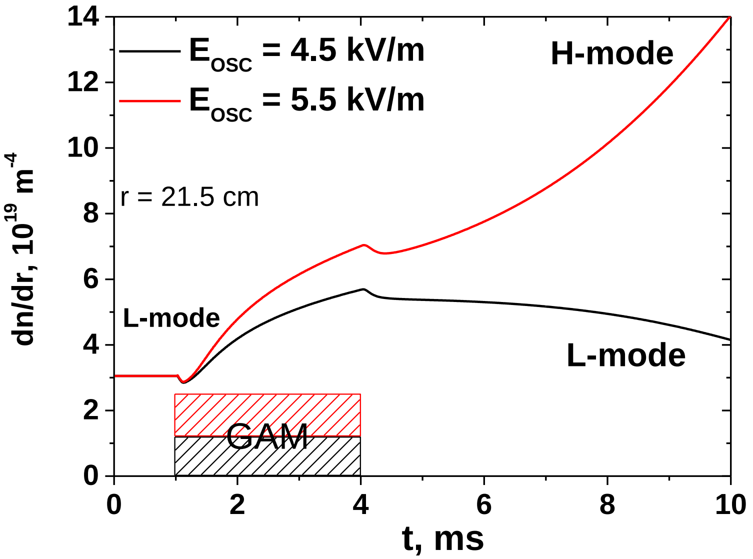
parameter	value
R [cm]/a [cm]	53/22 = 2.4
B_T, T	1
I_p , kA	≤ 180
t_{pulse} , ms	≤ 80
P_{NBI} [MW]	≤ 1

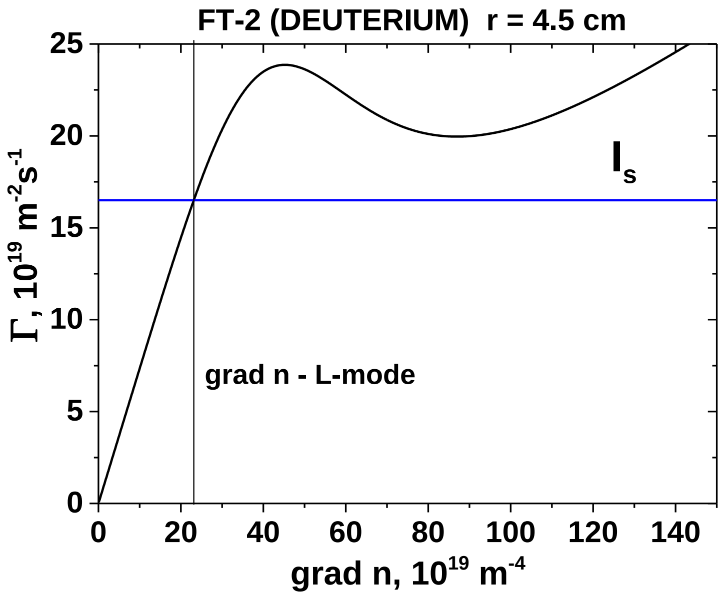
TUMAN-3M and FT-2: modeling of the GAM-triggered L-H transition

GAM-initiated LH-transition

$$\Gamma\left(\frac{\partial n(r)}{\partial r}\right) = -D_{\text{eff}}\left(\frac{\partial n(r)}{\partial r}\right)\cdot\frac{\partial n(r)}{\partial r}$$

- Observed at TUMAN-3M.
- Not observed at FT-2 for similar conditions.





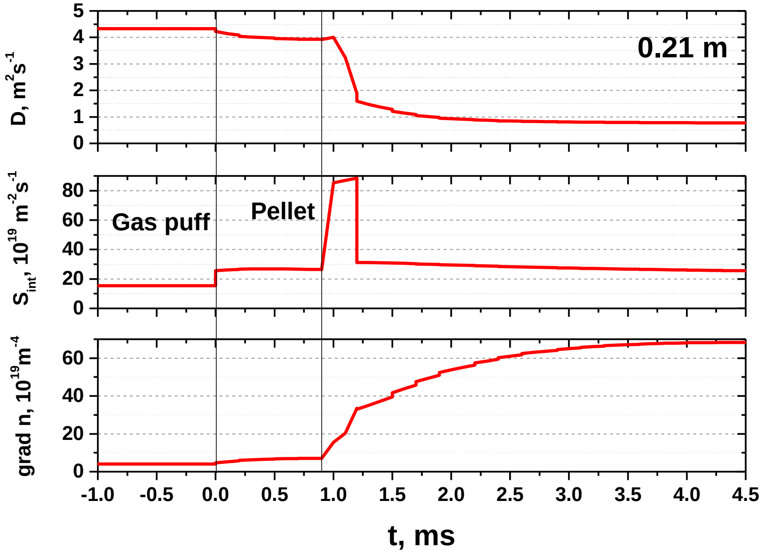
[L.G. Askinazi *et al* 2017 *Plasma Phys. Control. Fusion* **59** 014037]

Thresholds on GAM amplitude and duration exist.

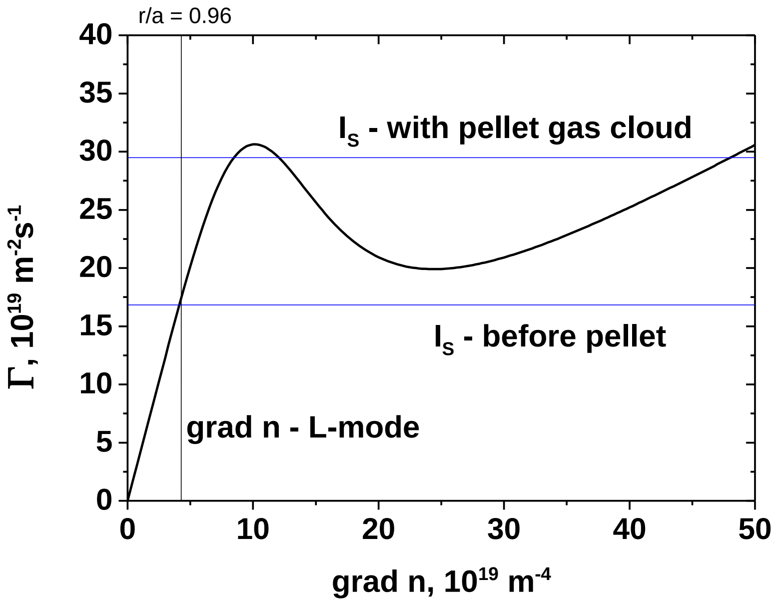
TUMAN-3M: modeling of pellet-triggered L-H transition

Pellet injection

The LH-transition occurred if the pellet evaporation was peripheral.



$$\Gamma\left(\frac{\partial n(r)}{\partial r}\right) = -D_{\mathrm{eff}}\left(\frac{\partial n(r)}{\partial r}\right)\cdot\frac{\partial n(r)}{\partial r}$$



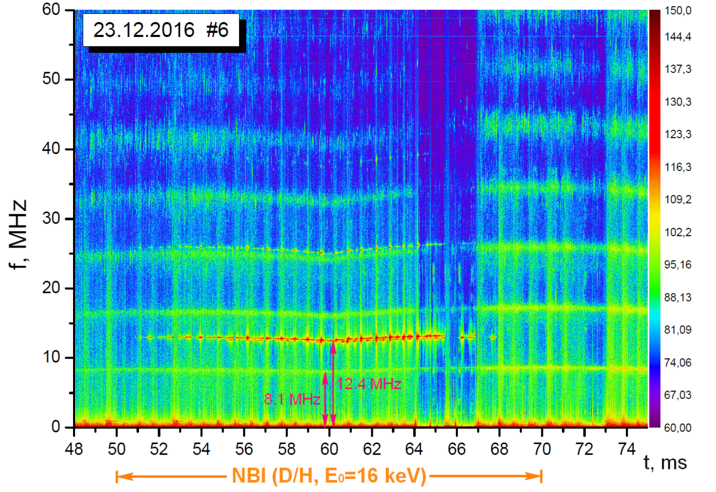
- Sufficient E_r-shear and **high particle source** is needed for GAM- and pellet- H-mode triggering.
- If particle source is too low, self-sustaining H-mode is not possible for certain scenario.

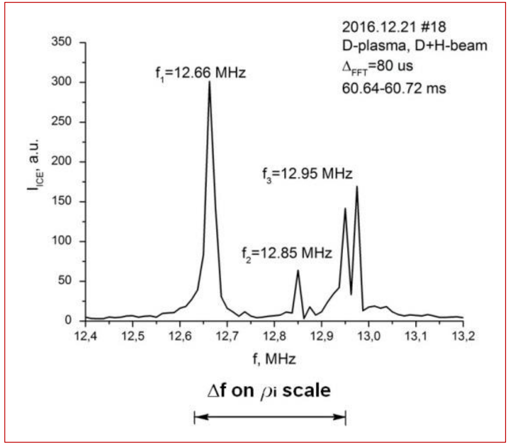
[T.P. Kiviniemi *et al* 2018 *Plasma Phys. Control. Fusion* **60** 085010]   [A.A. Belokurov *et al* 2018 *Nucl. Fusion* **58** 112007]

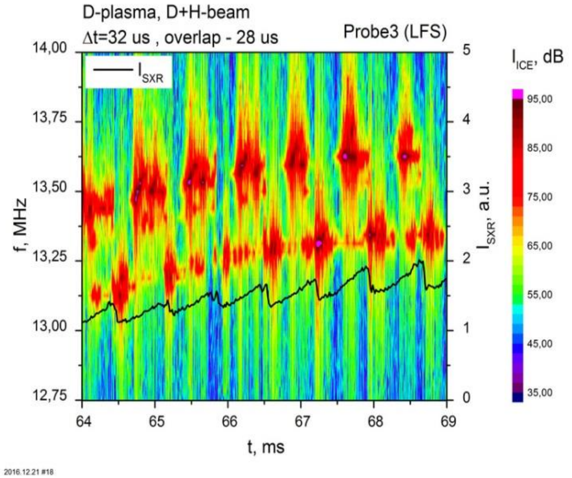
TUMAN-3M: Ion Cyclotron Emission during NBI heating

- **NBI Ion Cyclotron Emission (ICE) frequency corresponds to the central IC resonance for minority ions.**
- **Comes from core plasma region.**
- **ICE frequency depends on B_{tor} but not on n_e.**
- **Fine structure, oscillating with sawtooth.**

- CAE instability excited by stagnating fast ions:
- $w = lw_{ci} + k_{||}v_b$
- Beam with E_0, $E_0/2$, $E_0/3$, $2E_0/3$ -> fine structure
- Sawtooth may induce redistribution of fast ions



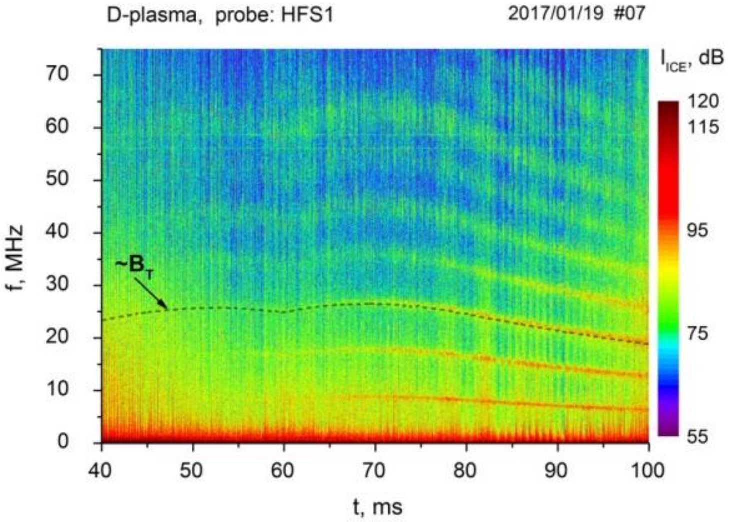


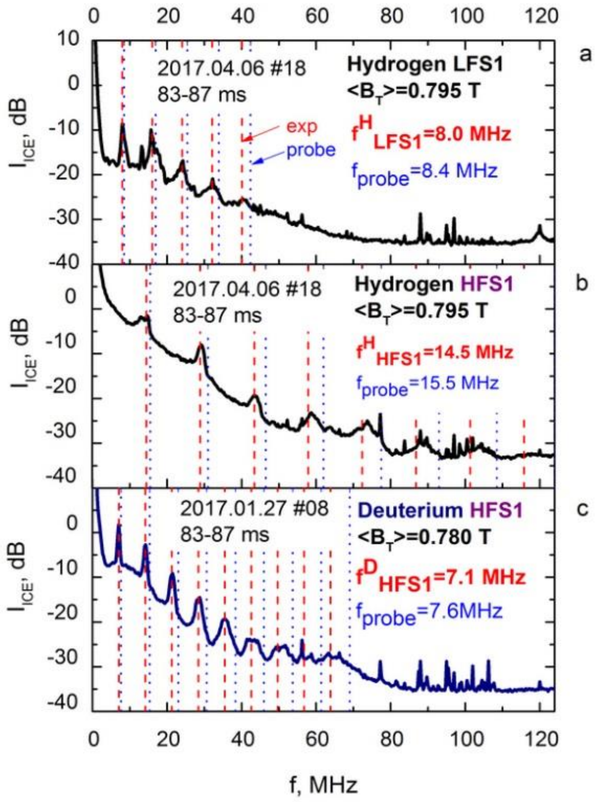


[ASKINAZI, L. et al, Nucl. Fus. 58 (2018) 082003]

TUMAN-3M: Ohmic Ion Cyclotron Emission

- **Not caused by suprathermal ions.**
- **Spectrum typically consisted of 8-9 harmonics with frequencies evolving with B_T.**
- **Detected in H and D plasmas both in LFS and HFS.**
- **OICE fundamental depends on the probe position; it corresponds to the ion-cyclotron resonance frequency of the main plasma ions in the close vicinity of the corresponding magnetic probe.**
- **Could be understood in frames of the Ion Cyclotron Drift Instability proposed by Mikhailovsky & Timofeev and based on ICE excitation in inhomogeneous plasma:** $\rho_i/a \geq 2(m_e/m_i)^{1/2}$, $a = \left(\frac{1}{n}\frac{dn}{dr}\right)^{-1}$





Spectra of OH ICE, measured by the two magnetic probes: LFS and HFS in H and D plasmas.

ANOMALOUS ABSORPTION AND EMISSION IN ECRH EXPERIMENTS
DUE TO PARAMETRIC EXCITATION OF LOCALIZED UH WAVES

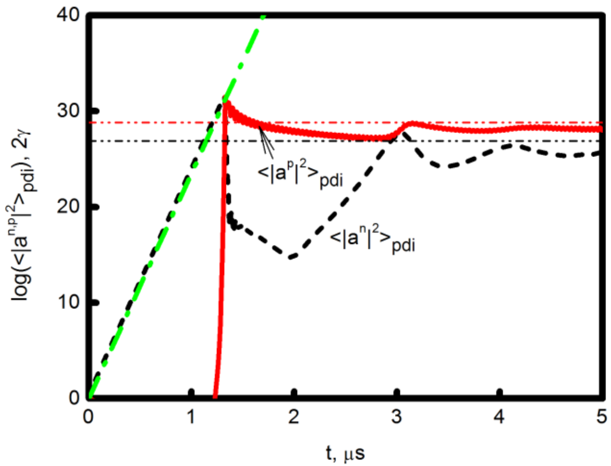
A possibility of two-UH-plasmon parametric decay instability excitation in X2 ECRH experiments in fusion devices with non-monotonous density profile is demonstrated in a wide plasma density range .

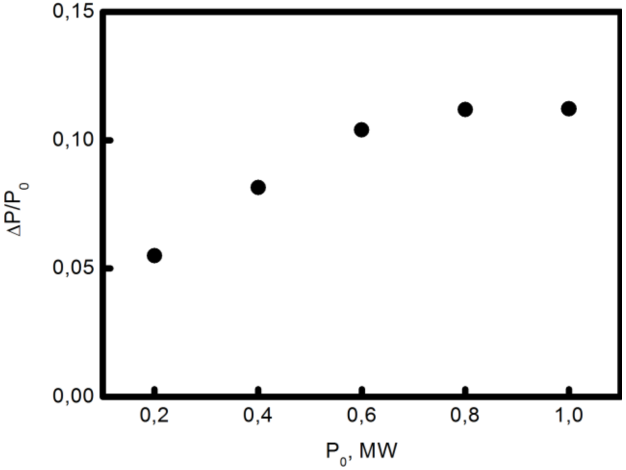
The instability leading to generation of the trapped UH wave is excited at the pump power of about 100 kW.

Well above the threshold it is leading to anomalous absorption rate of more than 10%.

The plasma microwave emission at the pump half frequency $\omega_0/2$ and at the frequency $3\omega_0/2$ is predicted at the level of 50 W.

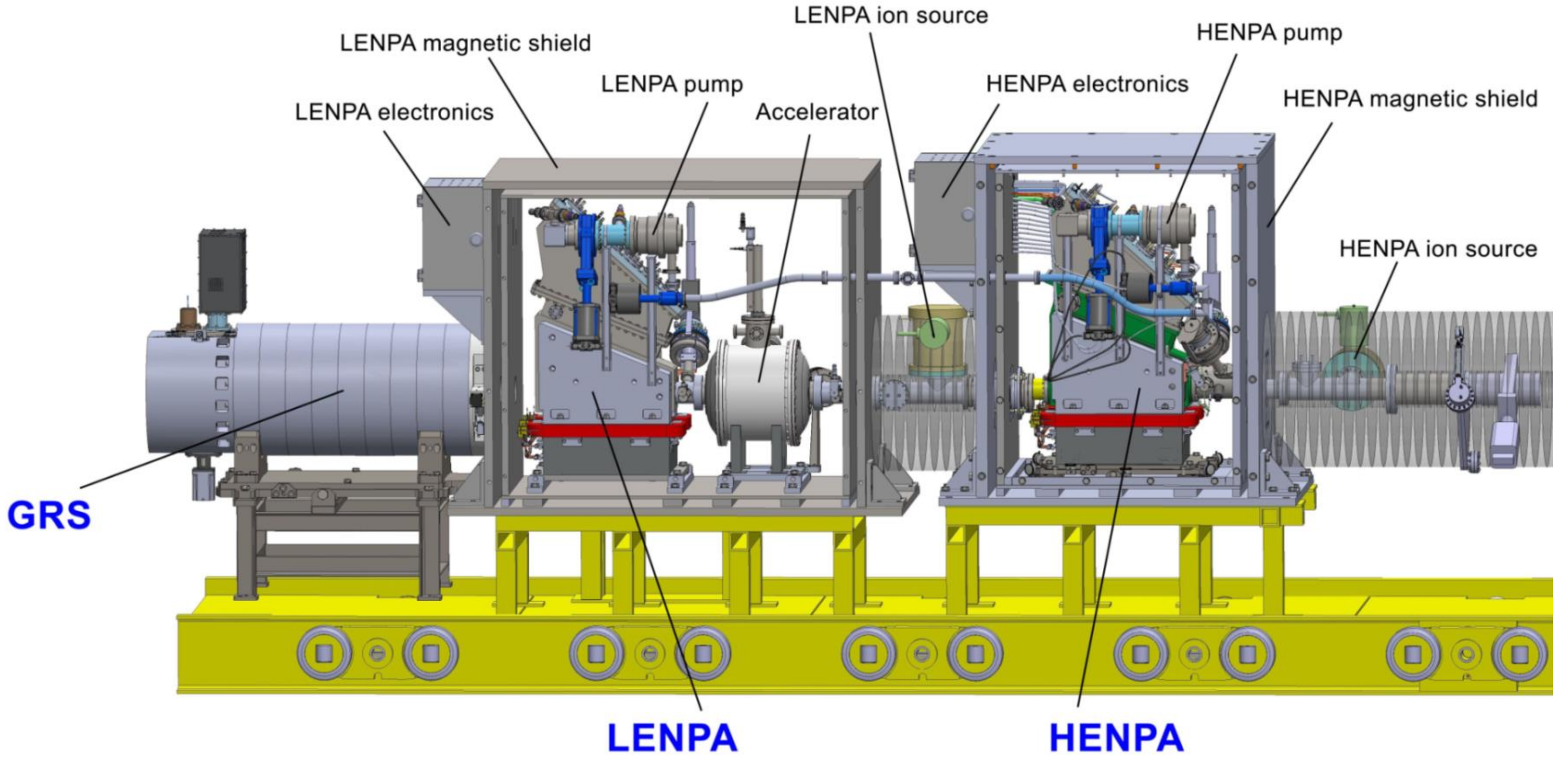
TH/P4-10 (Wednesday) E. Z. Gusakov et al.





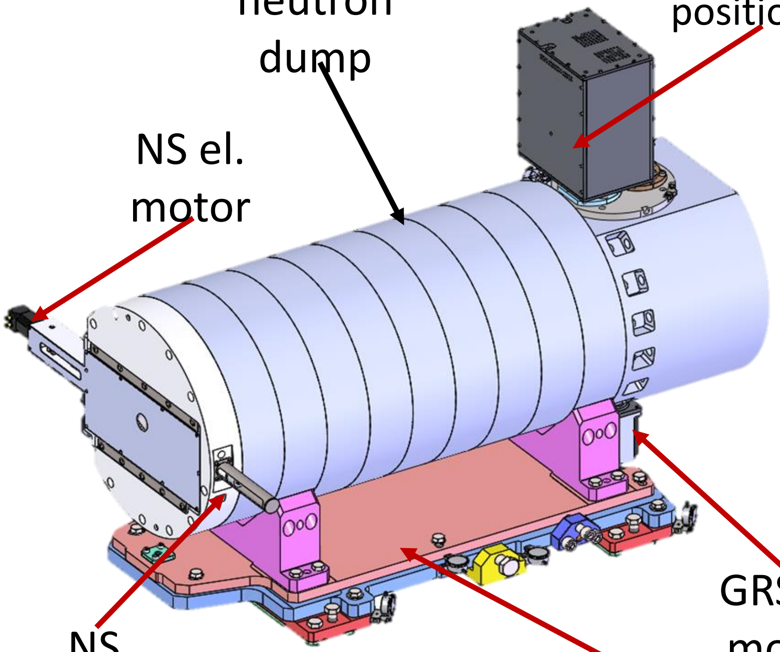
Neutral Particle Analyzer for ITER

Recent progress in the NPA developing. 3D design.



[Mironov M. et al., Nucl. Fusion 58 (2018) 082030]

ITER Gamma Ray Spectrometer



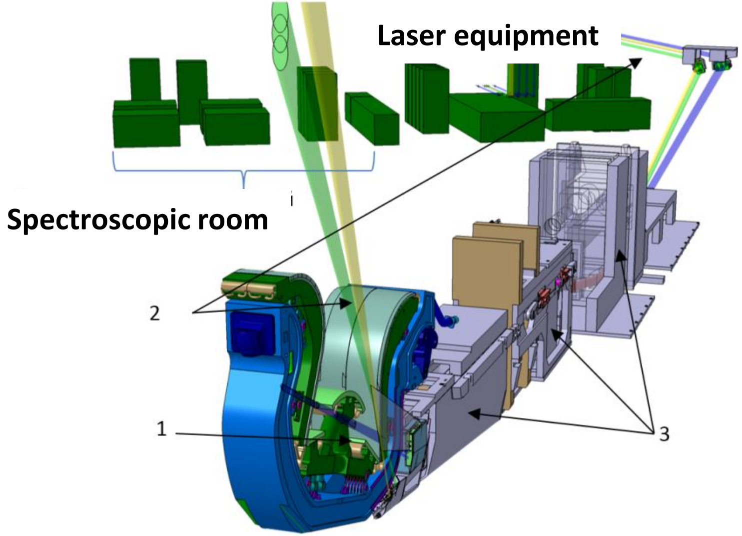
- Detectors of the GRS and NS are located in the Neutron Dump of the NPA.
- 3D-model of the ND support and alignment system has been developed.
- Electromotors, solenoids and position switches of the GRS and NS positioners have been successfully tested under the integral neutron flux of 10^{13} n/cm^2.

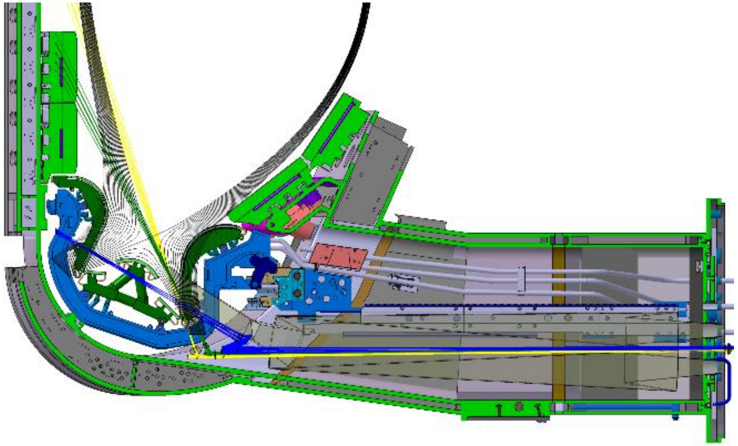
ITER Divertor Thomson scattering/Laser-induced Fluorescence

Hardware design development:

- Special lasers: Nd:YAG(1064 nm) – main diagnostic laser for ITER DTS
- Prototype of Nd:YAG(946 nm) – for double-wavelengths TS calibration ITER DTS
- Digital Filter Polychromator

[GORBUNOV A., Fus. Eng. and Design 123 (2017) 695]
[MUKHIN E.et al., Fus. Eng. and Design 123 (2017) 686]
[A.Kornev et al SOFT 2018]
[E.Mukhin et al FED 2017]





DTS/LIF equipment situated in ITER Lower Port #8. 1 — Strike point on the outer divertor target; 2 — Laser beams; 3 — Front and back racks used for arrangement of DTS/LIF in vessel equipment and neutron shield components

FIP/P1-5 (Tuesday) A. G. Razdobarin et al.

ITER Divertor Thomson scattering/Laser-induced Fluorescence

A new kind of LIF spectroscopic scheme based on laser induced quenching of the most intensive hydrogen line H_α = 656.1 nm is proposed.

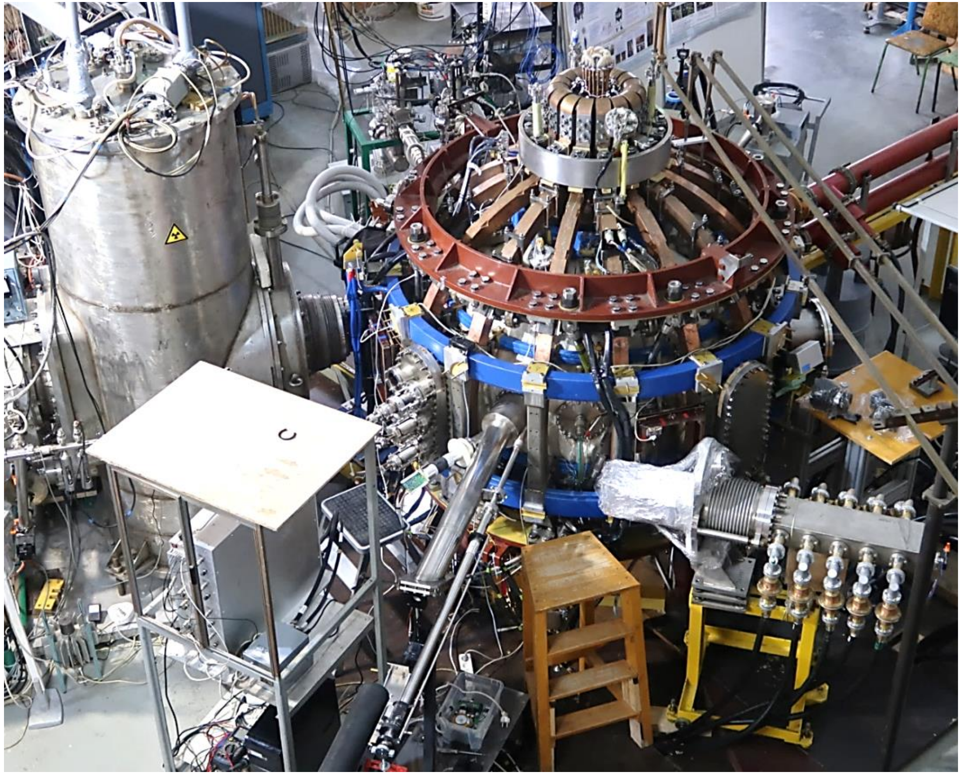
Meeting the requirements in input parameters for divertor plasma modelling DTS/LIF provides simultaneous measurements of T_e, n_e, T_i, n_i $n_{He/H/D/T}$ distribution in ITER divertor SOL providing simulation of

- **Ionization balance: Rates of ionization and recombination (T_e, n_e);**
- **Emission intensity (T_e n_e n_i $n_{He/H/D/T}$);**
- **Frictional force of the plasma flow due to collisions with neutrals (T_i n_i $n_{He/H/D/T}$);**
- **Pressure of the incoming plasma flow (T_e n_e T_i n_i).**

[A. Gorbunov et al Plasma Fus. Eng. and Design 123 2017 695]
[A. Gorbunov et al, SOFT 2018]

FIP/1-5 (Monday) E. E. Mukhin et al.

Globus-M2



First plasma: April 23rd
Experimental campaign: end of 2018

- R [cm]/a [cm]= 36/24 = 1.5
- B_T = 1T, I_p = 500 kA
- Diverse diagnostics, heating and CD systems, including 2xNBI, ICRH, LHCD, plasma gun
- Extreme P_{heat} /V = 6 MW/m³

FIP/P7-34 (Friday) V. B. Minaev et al.

Conclusion

- Experiments with increased B_T and I_p in Globus-M demonstrated discharge improvement.
- Strong dependence of τ_E on B_T was observed.
- For the first time TAE localization using DBS was measured. It is in a good agreement with modeling.
- t_{CQ} was in a good agreement with IDDB. Almost no dependence on m_i and linear dependence on I_p was observed.
- λ_q midplane dependence was estimated as ~ $I_p^{-1.2}$.
- Global full-f GK code benchmarking against DR data demonstrated good agreement in radial electric field dynamics and turbulence radial correlation properties, but not in poloidal wavenumber spectrum thus appealing to the multi-scale GK modeling
- The importance of particle source and E_r-shear was demonstrated for GAM- and pellet- induced L-H transition.
- ICE was observed in NBI-heated discharges in TUMAN-3M. The possible explanation is CAE instability, excited by stagnating fast ions. ICE was also observed in OH plasma.
- More than 10% anomalous absorption of the ECRH power is predicted due to parametric excitation of a localized UH wave. A measurable level of the plasma microwave emission at harmonics of the pump wave half-frequency is predicted .
- Considerable progress in ITER NPA, GRS, DTS\LIF development has been made.
- **New Globus-M2 spherical tokamak is online.**

Thank you
for your attention!