RECENT ADVANCES AT THE GLOBUS-M2 TOKAMAK

N.N. Bakharev and Globus team

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Outline

- Introduction
- Wall conditioning
  - Inter-Shot boronization
  - In-situ wall diagnostics
- Confinement & heating
  - Hot ion mode during NBI
  - ICRH
- SOL
  - High field side high density
  - Power decay length
- Instabilities
  - Alfvén Instabilities
  - ELMs
- Globus-3
- Conclusion

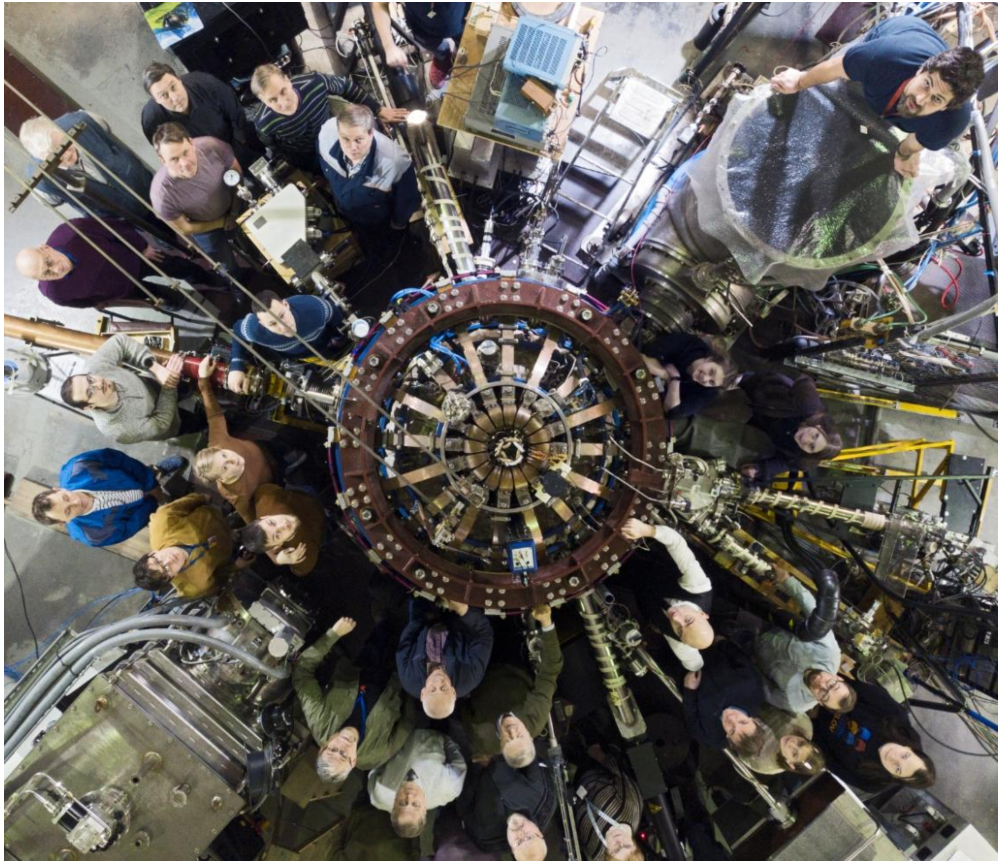
Globus-M2

Parameter	Value design/achieved
R [cm]/a [cm]	36/24 = 1.5
k	2.0/2.1
δ	0.5/0.4
B_T [T]	1/0.95
I_p [kA]	500/450
t_{pulse} [ms]	400/170
E_{NBI} [keV]	30-50
P_{NBI} [MW]	2/2
Max T_i, [keV]	4.7 at $\langle n_e \rangle_l = 5 \cdot 10^{19} m^{-3}$
Max T_e [keV]	1.8 at $\langle n_e \rangle_l = 5 \cdot 10^{19} m^{-3}$

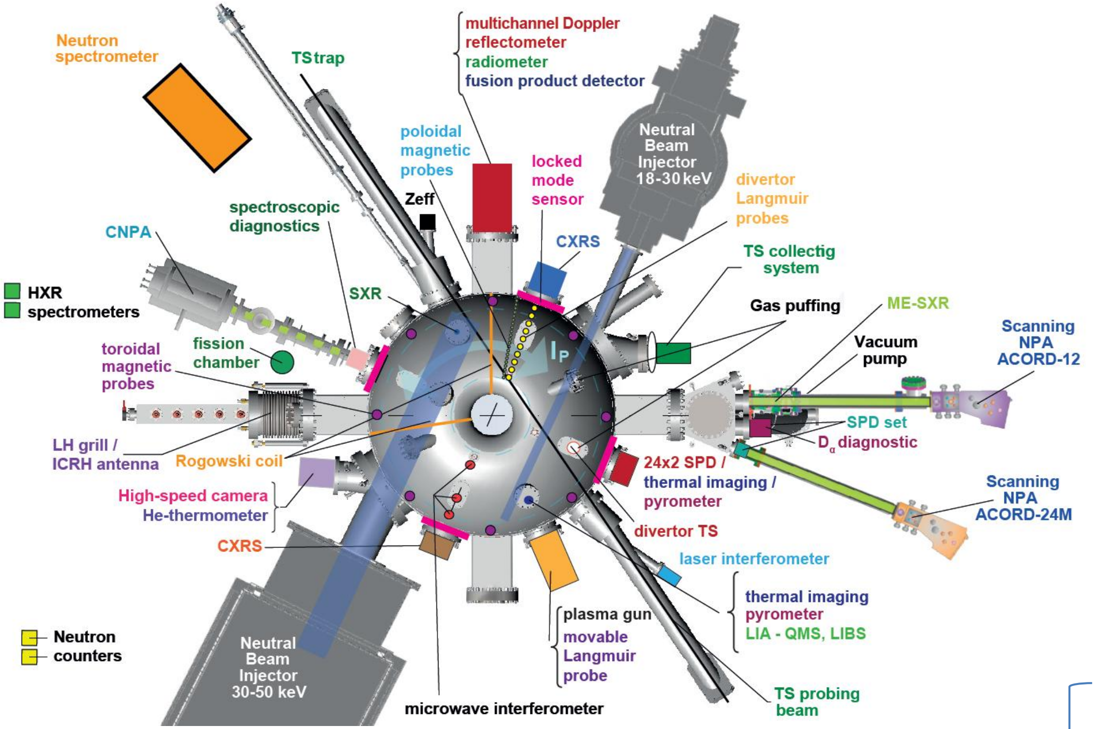
Extreme specific heating power ≈4 MW/m³

Additional systems:

2.45 GHz LHCD, 5-15 MHz ICRH



Diagnostics Development



- **dispersion interferometer**

[IVANENKO, S.V. et. al., Fus.Eng.Des. 202 (2024) 114409]

- **charged fusion product detector**

[BAKHAREV, N. N., et al. Tech. Phys. Lett. **50** 10 (2024) 24-27.]

- **two-color pyrometer**

[VORONIN, A. V., et al. Tech. Phys. 68 12 (2023) 799-805],

- **locked-mode sensor**

[PETROV, Y. V., et al., Plasma Phys. Rep.. **50** 7 (2024) 773-780.]

- **high-speed cameras** [TIMOKHIN, V., EX-E P4]
- **Silicon Precision Detector array**
- **Real time Plasma EQ and control**

(under implementation)

[KORENEV, P. S., et al. Tech, Phys, Lett. **49** 4 (2023) 372-375.]

- **LIA-QMS, LIBS**

[RAZDOBARIN, A.G. et al. Plasma Phys. Rep. **50** 6 (2024) 667–677][O.S. MEDVEDEV, et al., Nucl. Mater. and Energy. **41** (2024) 101829.]

ITER technologies

- **U^{235} neutron cameras**

[KORMILITSYN TEC-FNT, P6]

- **Divertor Thomson Scattering**

[ERMAKOV, N. V., et al., Plasma Phys. Rep. 49 12 (2023) 1480]

Inter-Shot Boronization (ISB)

New boronization technique was utilized during the 2024-2025 campaign.

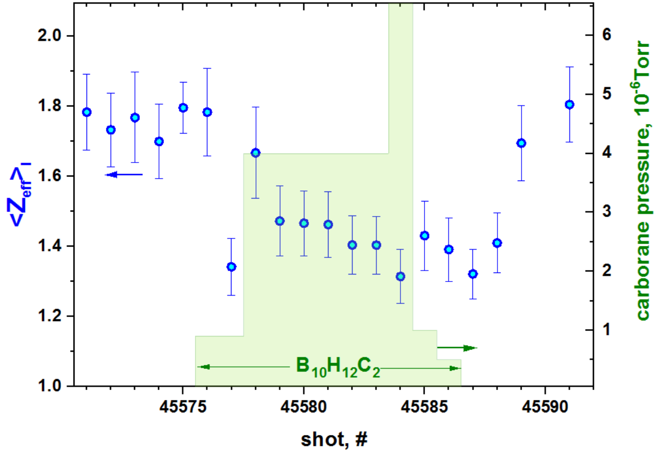
Significant advantage over conventional glow discharge boronization (GDB)

Technique:

- vessel with carborane ($B_{10}H_{12}C_2$) connected to tokamak – gas inflow between shots.
- Boronization is happening in the initial phase of the discharge->doesn't affect plateau

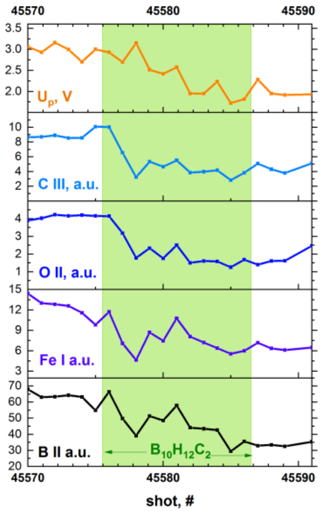
Z_{eff} decreases during ISB

$\langle n_e \rangle = 2*10^{19} m^{-3}$, before sawtooth start



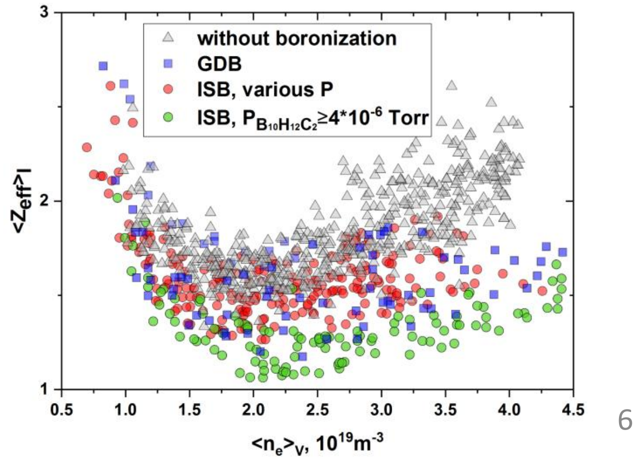
[Bakharev N.N. et al. submitted to PoP]

U_p, and impurity lines demonstrate similar behaviour.



$Z_{eff} < 1.1$ during NBI in C-wall tokamak

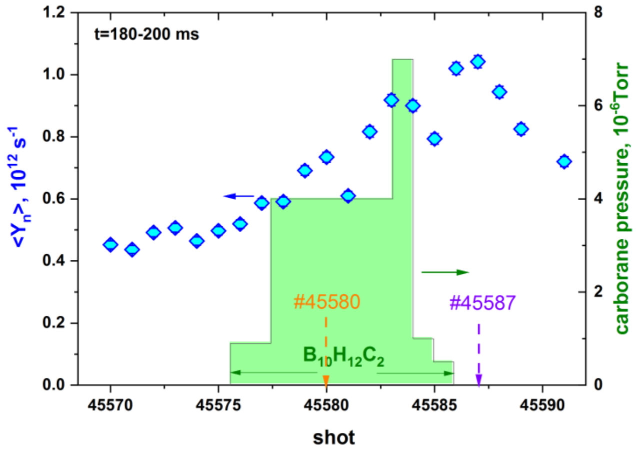
B_T = 0.7-0.8 T, I_p=300 kA, P_{NBI} = 700 kW, 40 keV D NBI



Inter-Shot Boronization (ISB)

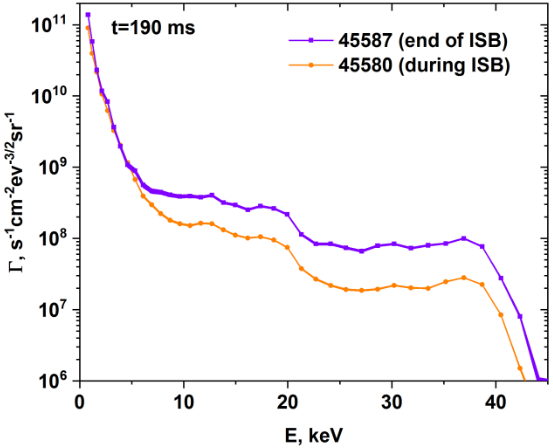
DD Neutron rate doubling

While NUBEAM modeling
predict neutron rate decrease

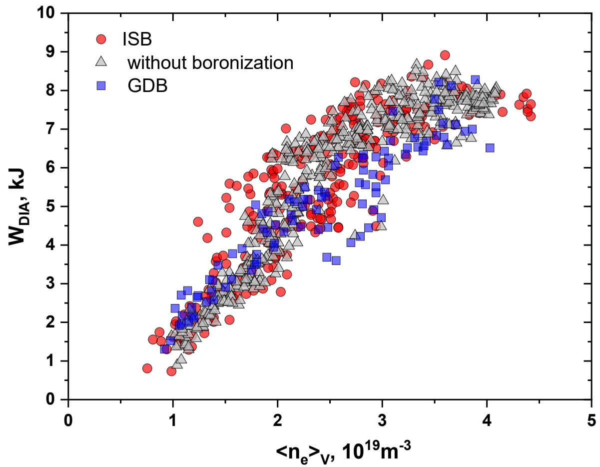


Fast ion confinement improvement

NPA energy spectra:



Same stored energy at
lower P_{OH}
But at higher P_{NBI}



For the same n_e #41570 vs #41580:

- NUBEAM simulation: 30% Y_n decrease
- Experiment: 60% Y_n increase

Most probable explanation: decrease of Charge-Exchange losses

No energy confinement change

As compared to the case without boronization
τ_E~12 ms ($\langle n_e \rangle_V \approx 3 \cdot 10^{19}$m^{-3}) is consistent with Glb-21 scaling

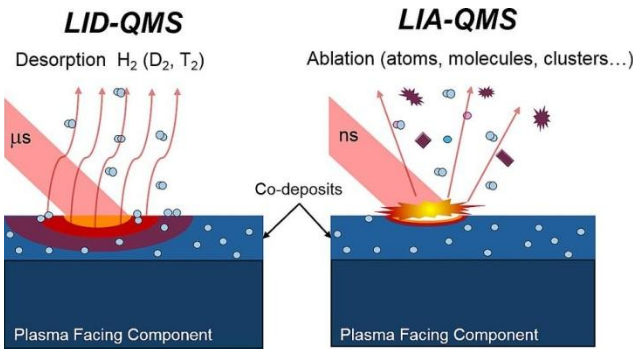
3D localized in-situ co-deposition study

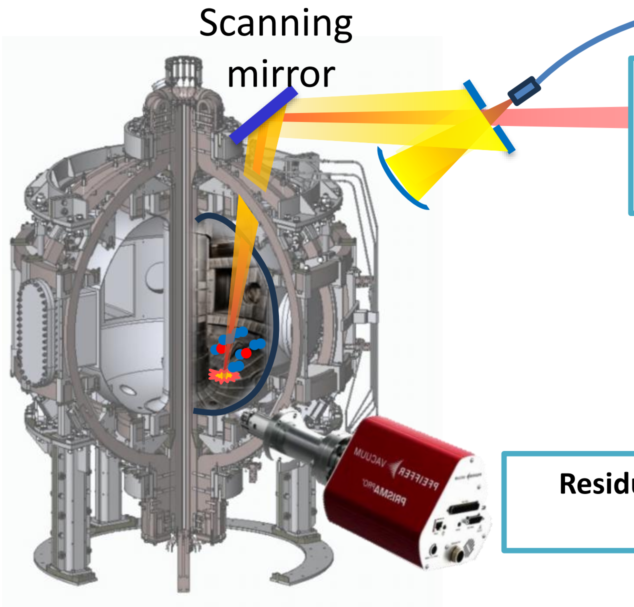
LIA-QMS (Laser-Induced Ablation + Quadrupole Mass-Spectrometry) – **in-situ** layer-by layer H/D concentration

LIBS (Laser-Induced Breakdown Spectroscopy)-Elemental composition with ~500 nm depth resolution

[RAZDOBARIN, A.G. et al. Plasma Phys. Rep. **50** 6 (2024) 667–677]

[O.S. MEDVEDEV, et al., Nucl. Mater. and Energy. **41** (2024) 101829.]





Nd:YAG laser
1064 nm, 9 ns
5-10 J/cm2

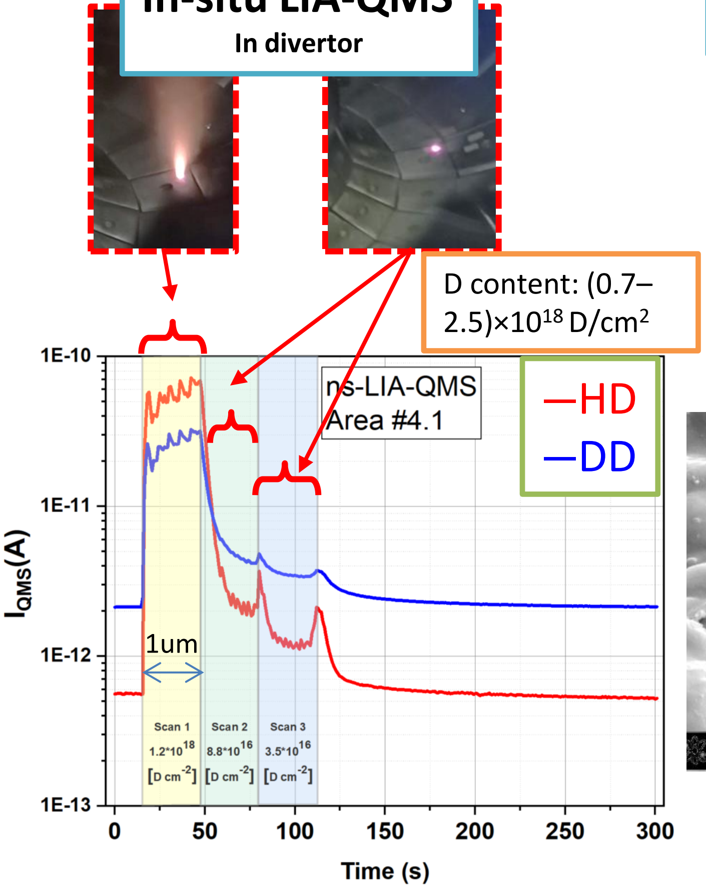
Optical spectroscopy (LIBS)

1) **Wideband spectrometer 250-750 nm for elemental analysis**
2) **High resolution spectrometer 655-657 nm for hydrogen isotopes separation**

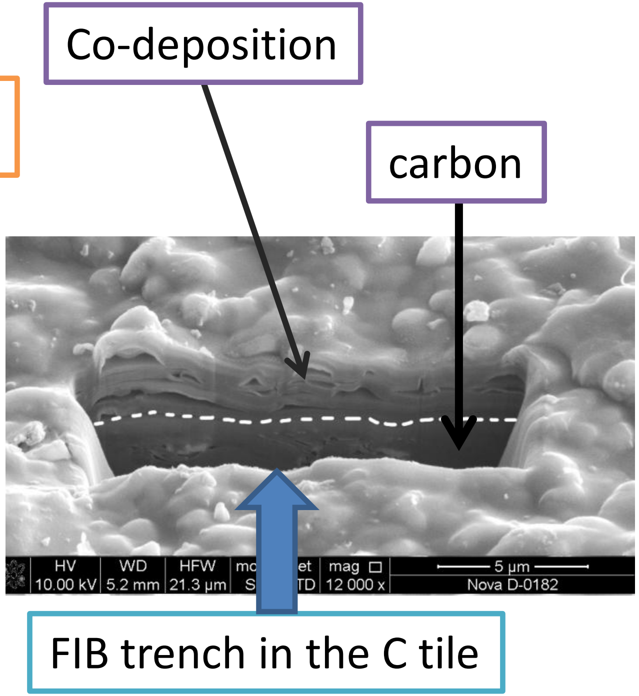
Residual gas analyzer – QMS

3D localized in-situ co-deposition study

In-situ LIA-QMS
In divertor

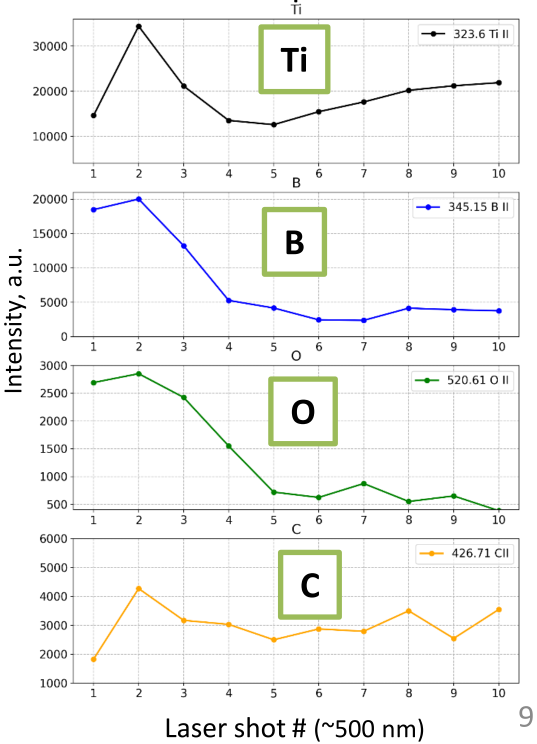


Post mortem FIB-SEM



In-situ LIBS in vacuum

Qualitative layer-by-layer elemental composition



Confinement: Hot Ion Mode

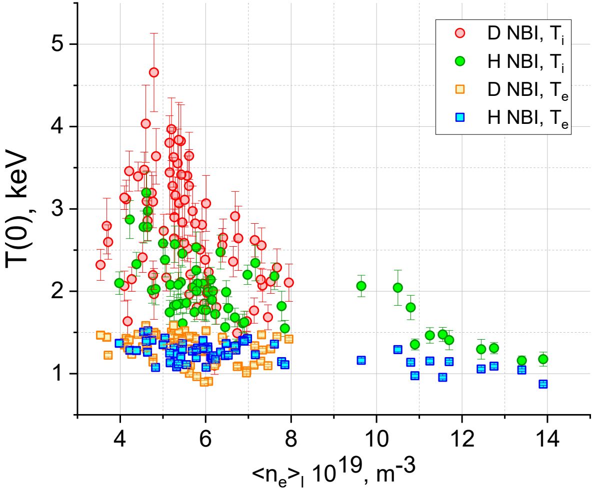
Hot-ion mode - a natural operating regime of Globus-M2
during H and D NBI in D plasma at $B_T \geq 0.7$ T

[KURSKIEV, G.S., EX-H P4]
[G. S. Kurskiev et al. Plasma Phys. Rep. 49, 403–418 (2023)]

ASTRA modeling

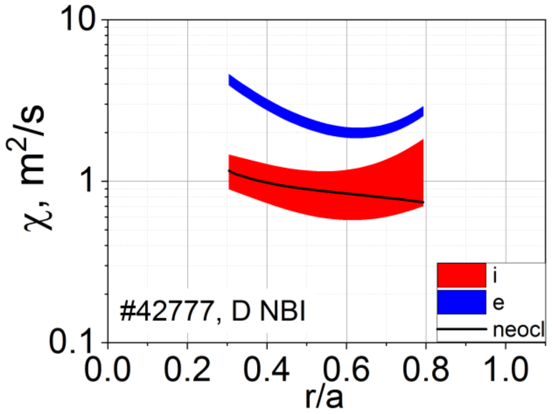
MAX $T_i(0)$
D NBI: 4.7 keV
H NBI: 2.9 keV

B_T=0.8-0.9T
I_p=300-400 kA



D NBI

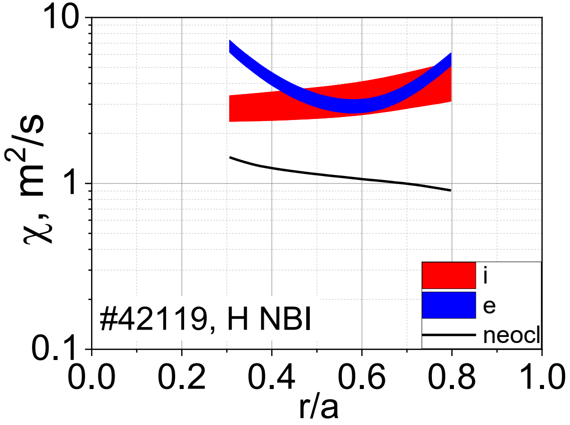
Neoclassical ion transport



τ_E = 14 ms

H NBI

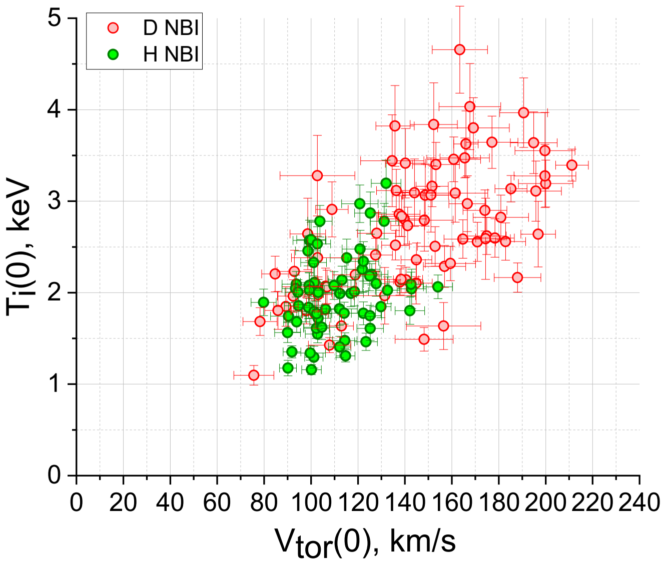
Anomalous ion transport



τ_E = 7 ms

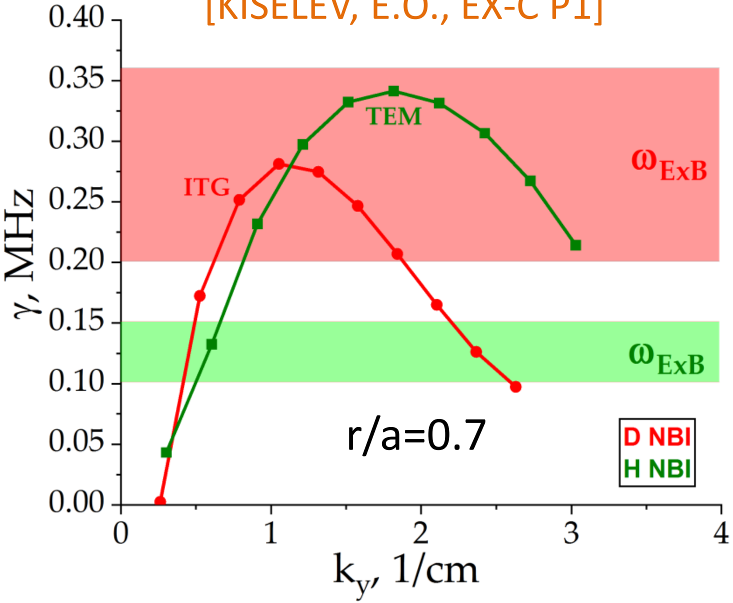
Confinement: Hot Ion Mode

Higher T_i corresponds to higher rotation velocity



Linear gyrokinetic simulation with GENE

[KISELEV, E.O., EX-C P1]

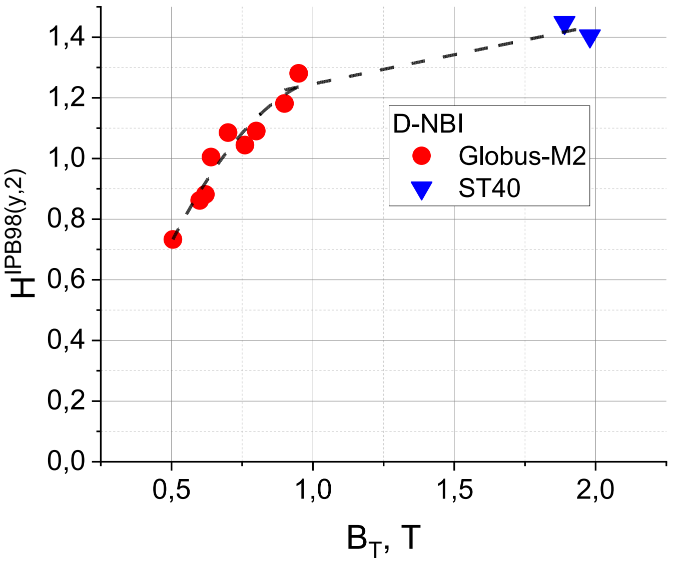


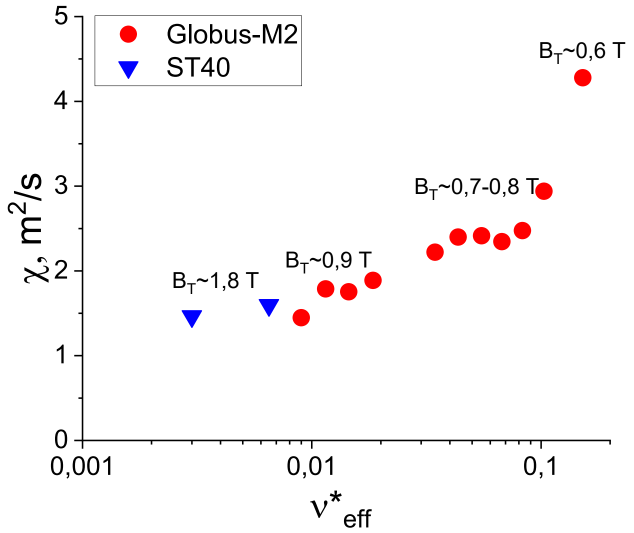
ITG is suppressed by the rotation velocity shear during D NBI
During H NBI rotation is not enough to suppress TEM

Confinement: Hot Ion Mode

Previous ST data had suggested a strong confinement improvement with B_T increase

Data from Globus-M/M2 and ST-40 data [MCNAMARA, S. A. et al. Nucl. Fusion. **63** 5 (2023) 054002][KAYE, S. M., et al. PPCF **65** 9 (2023) 095012]

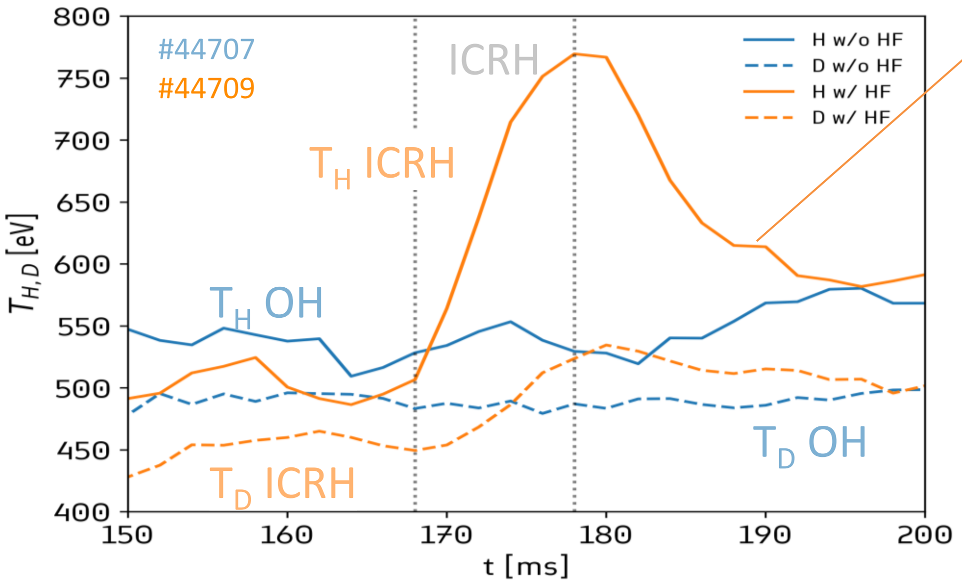


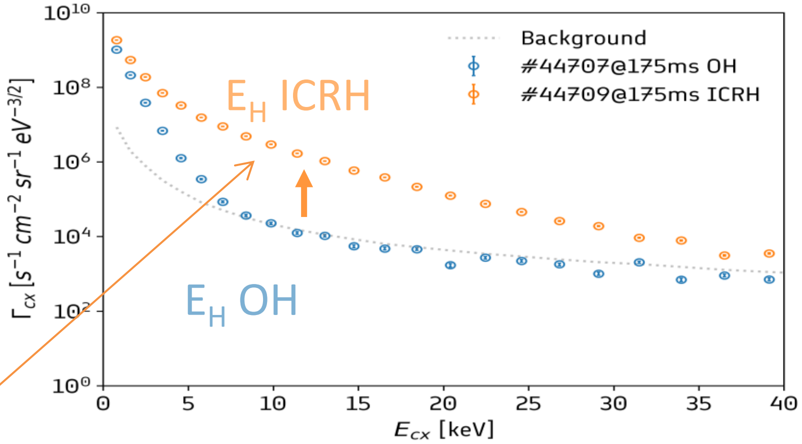


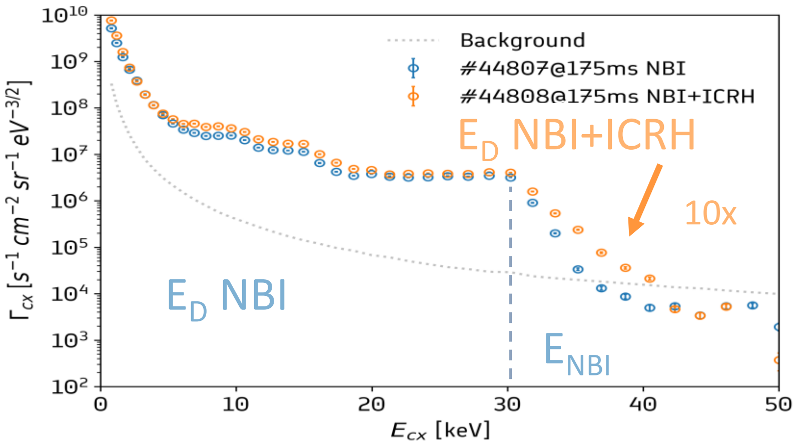
New data indicate **saturation of confinement improvement** **at B_T ~ 1 T.**

Confinement: ICRH

During Globus-M2 2024 campaign the novel experiments with ICRH in Minority Heating and 2nd harmonic regimes at B_T=0.7 T. Absorbed power ~50 kW.
MH experiments exhibited 15% increase in T_i at X_H~20%. .
2nd harm. NBI+ICRH showed 10x growth of n^D with E> E_{NBI}







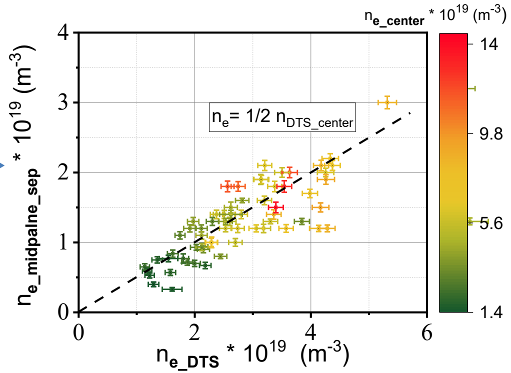
HFSHD

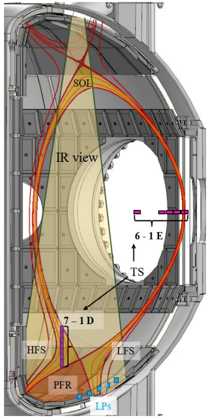
High Field Side High Density feature has been discovered in Globus-M2 using newly installed divertor Thomson scattering

[E.E. Mukhin, EX-D, P2]

Observed over a wide range of discharge parameters: $n_e(0)$: $2\cdot10^{19}$-$1.4\cdot10^{20}$ m^{-3} with and without NBI

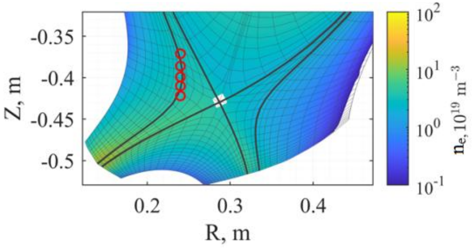
n_e at the inner divertor leg 1.5-3x higher than in midplane

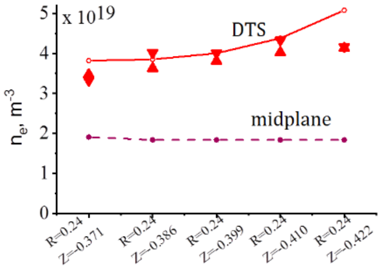


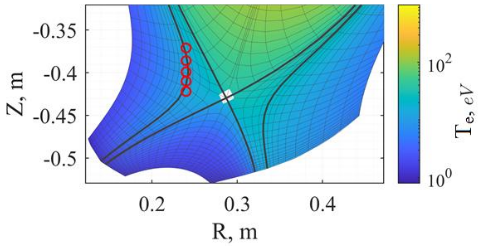


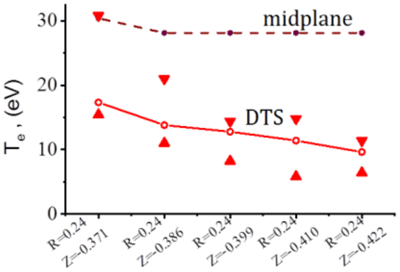
SOLPS-ITER simulation taking into account <u>drifts</u>

experiment ▲▼

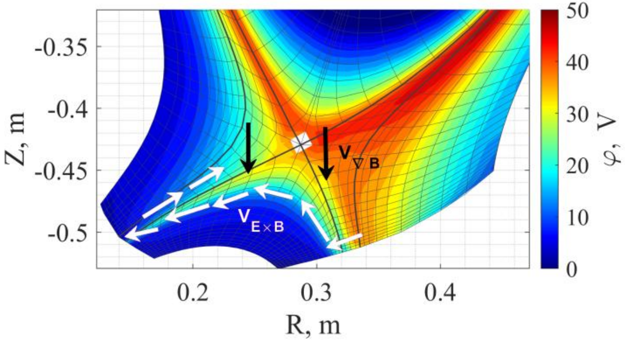








ExB drift in the HFS direction leads to the formation of a HFSHD



The total drift flux through the inner divertor separatrix equals to approximately 50% of the ion flux to the inner target

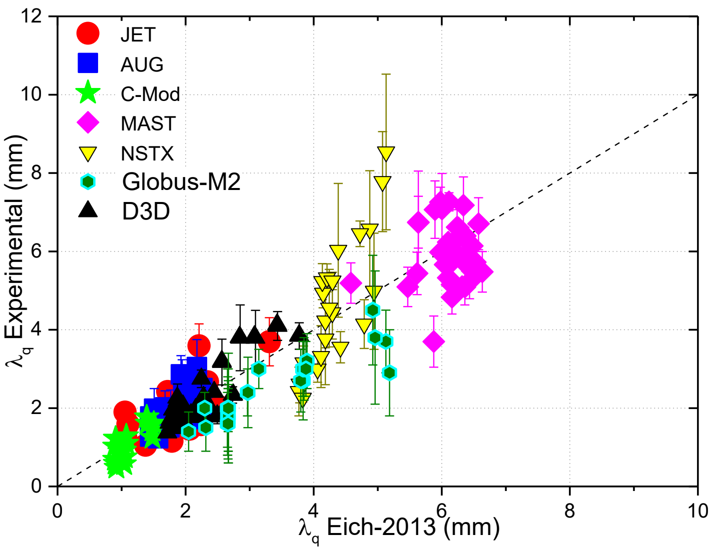
SOL power decay length

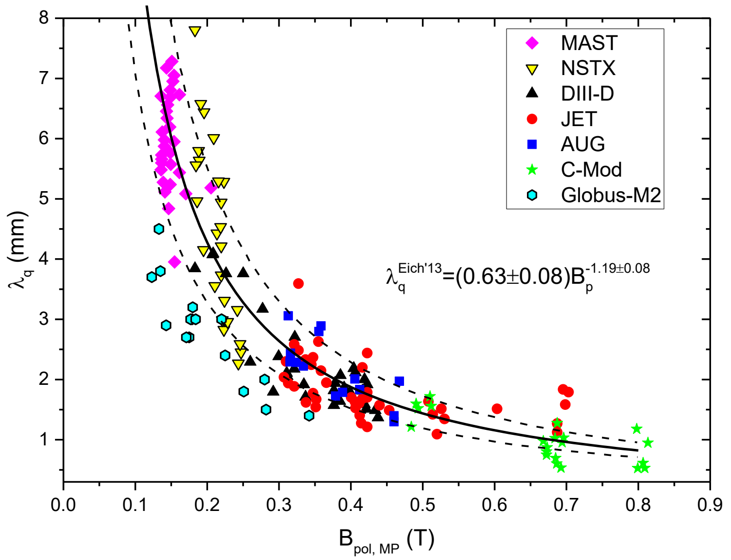
SOL power decay length λ_q was measured using IR thermography

***B_T*=0.5-0.95 T,** *I_p*=155-400 kA, up to 0.8 MW NBI

Comparison with multi-machine scaling

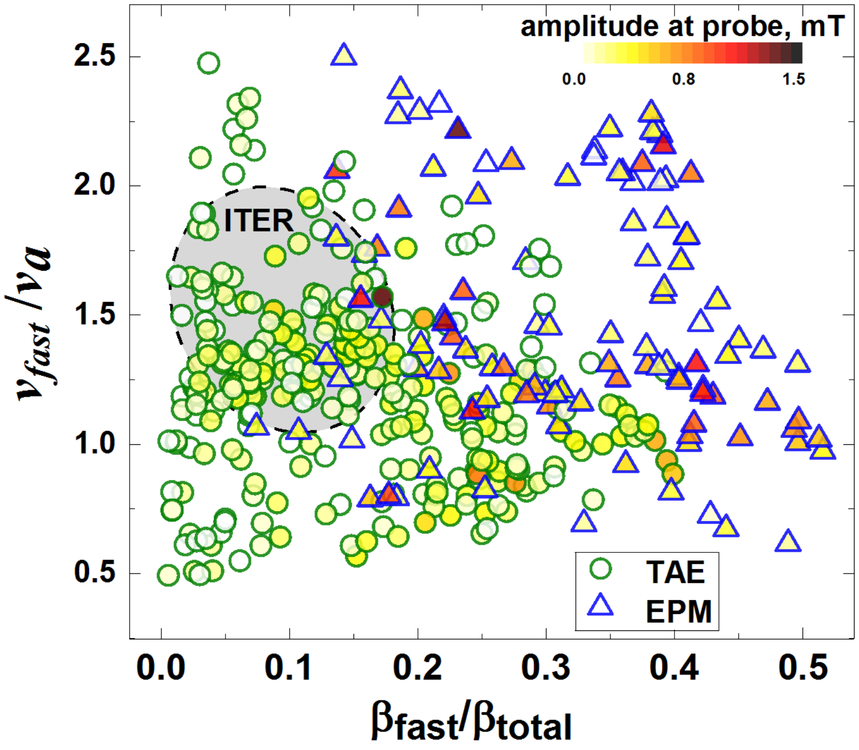
[Eich T. *et al* 2013 *Nucl. Fusion* **53** 093031]



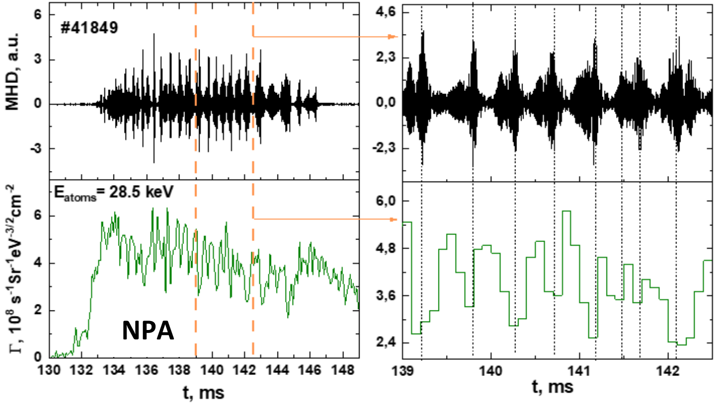


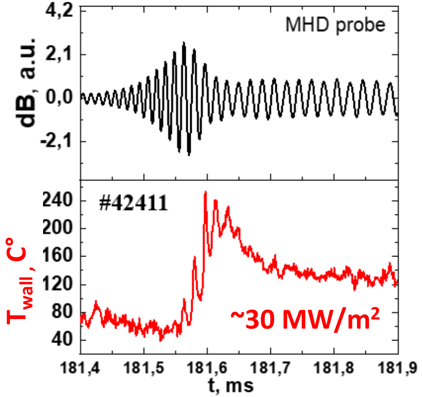
$\lambda_q^{\text{Globus-M2}} \sim B_p^{-1}$ in ST with B_T up to 0.95 T and λ_q~2mm, confirming data from conventional devices ($\lambda_q \sim B_p^{-1.19}$)

Alfvén-type instabilities exists in a wide range of experimental parameters



Improved plasma parameters and fast-ion confinement ⇒ previously unobserved **EPM**s

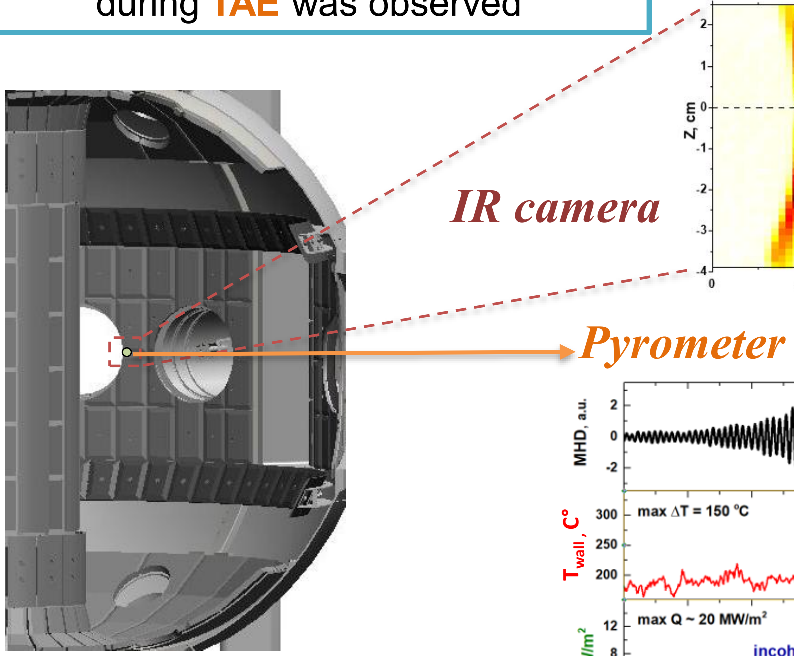


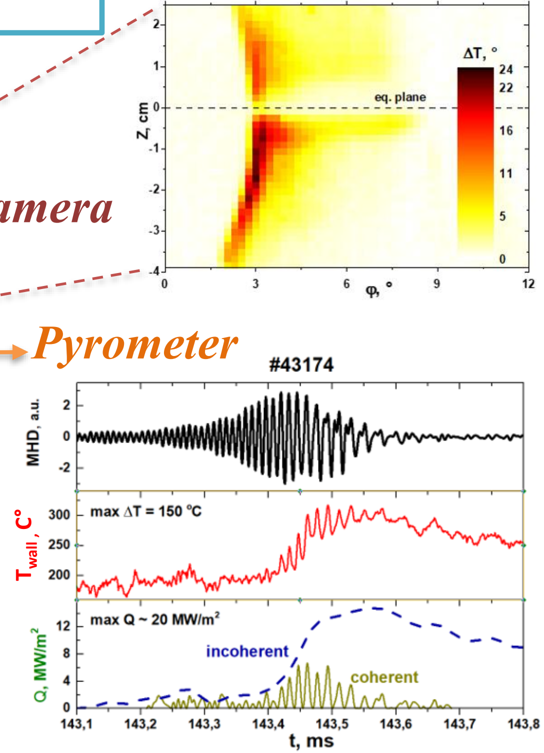


EPM-induced
fast ion transport
and losses
were observed:
up to ~30 MW/m²
local wall load

Alfvén Instabilities: TAE

Up to **20 MW/m²** local fast ion wall load during **TAE** was observed

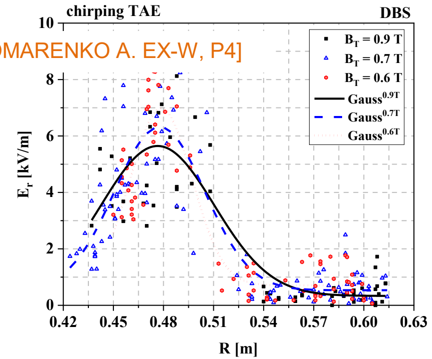


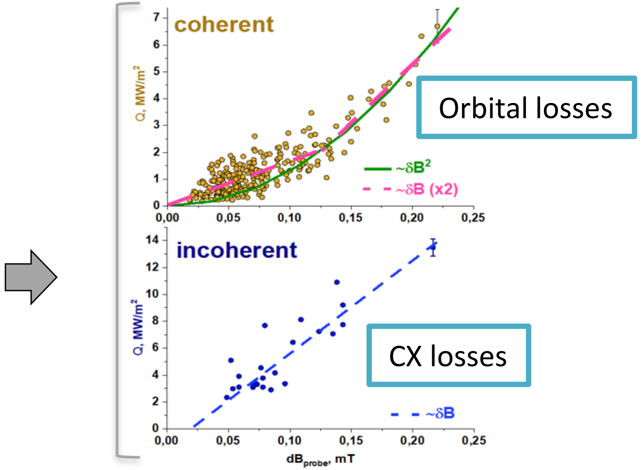


[SKREKEL O.M. EX-W, P4]

Multi-frequency Doppler backscattering method demonstrated central localization

[PONOMARENKO A. EX-W, P4]

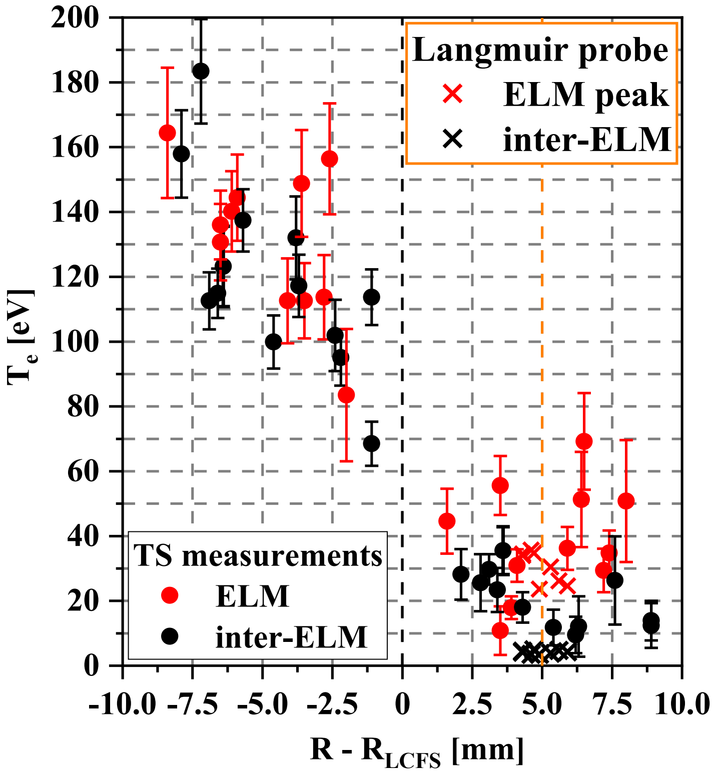




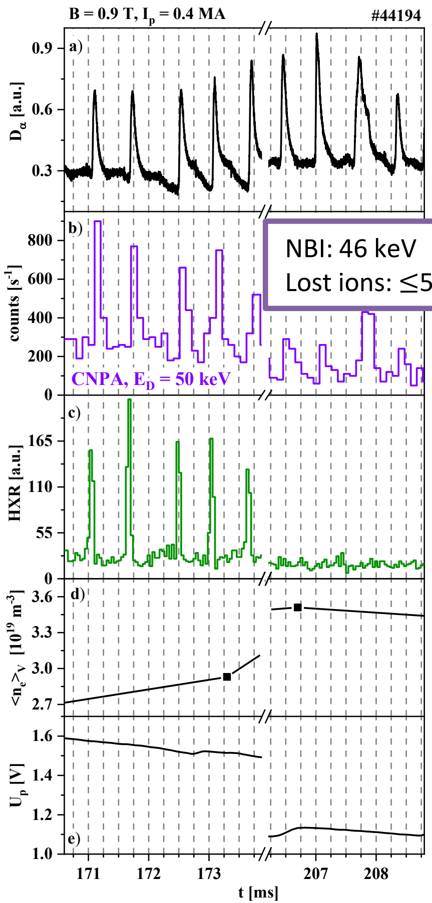
Both coherent and incoherent components are associated with the convective transport but different type of losses: orbital and CX respectively.

ELMS

During small ELMs significant T_e changes inside the separatrix were not observed



Fast particle losses associated with ELMs were found



NBI: 46 keV
Lost ions: ≤52 keV

[A. Ponomarenko et al 2024 Nucl. Fusion 64 022001]
[A.Y. Tokarev et al Plasma Phys. Rep. ***50****, 541–551 (2024)]*
[A. Yashin et al submitted to Physics of Plasmas].

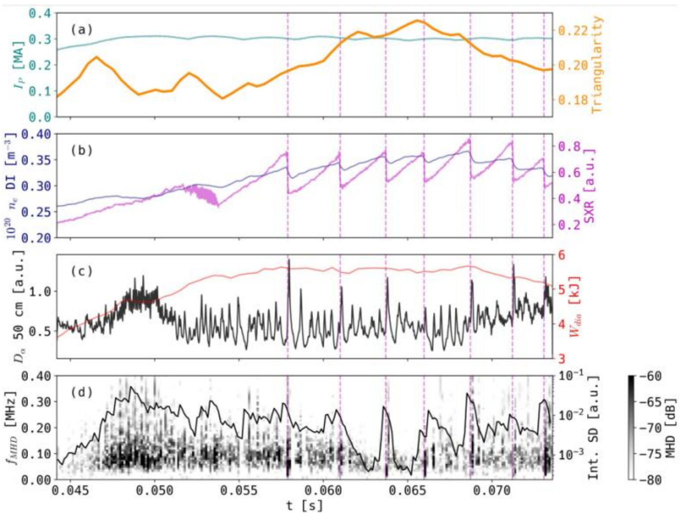
Low triangularity

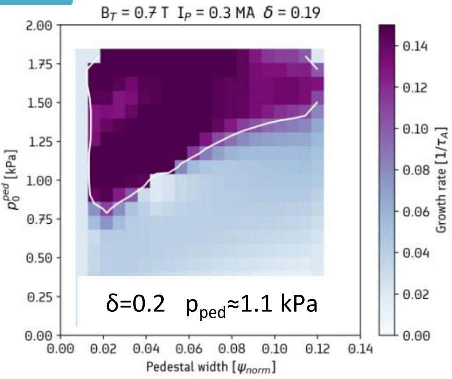
Triangularity was varied from 0.4 to 0.2

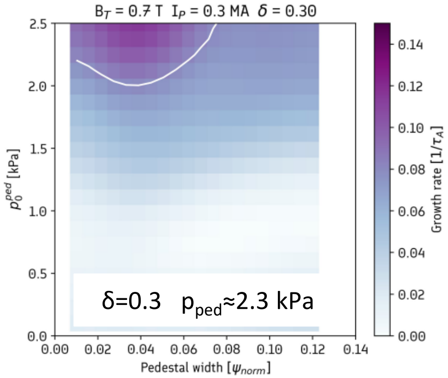
[Solokha V.V. TH-S, P7]

Low triangularity pulses (δ=0.2) exhibited small ELMs at pedestal pressure around 1 kPa

#44330

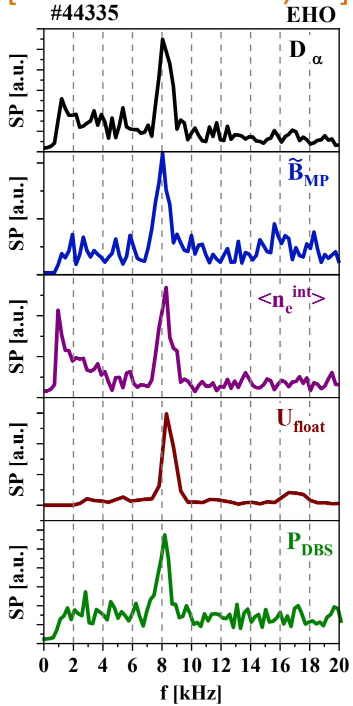






ELM-free regime with EHO

[Yashin A. Yu. EX-E, P4]

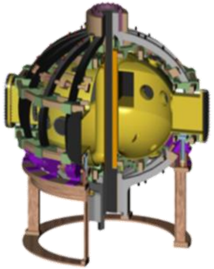


The 3-field linear MHD simulations using BOUT++ showed low-δ PB to have peeling traits and mode structure located near separatrix, while mid-δ PB have more ballooning properties and wider structure.

Globus-3

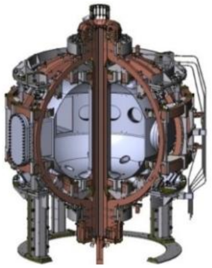
Globus-3 is the next step ST in Ioffe institute. [Minaev V.B. PWF-P2]

1999
B_T = 0.5 T
T = 1 keV



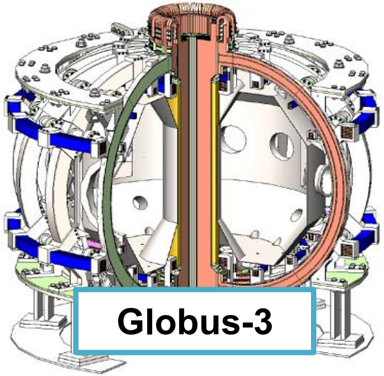
Globus-M

2018
B_T = 1 T
T = 5 keV



Globus-M2

2030
B_T = 2 T
T = 25 keV



Globus-3

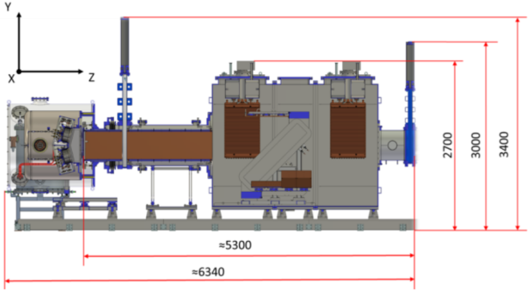
Parameter	Globus-M	Globus-M2	Globus-3
R/a	0.36/0.24=1.5		**0.775/0.44=1.76**
B_T, T	0.5	1	**2**
I_p, MA	0.2	0.5	**2**
t pulse, s	0.1	0.4	**3**
NBI, MW	1	2	**11.5 (14)**

- **Design implements Globus-M and Globus-M2 solutions, while correcting their design flaws**
- **The project is aiming to achieve thermonuclear plasma (simultaneous T_{i0}~25 keV, <n_e>~$10^{20}m^{-3}$) in H plasma**
- **Globus-3 will be a tokamak with the highest P_{aux}/V = 3-4 MW/m^3 in the world.**

Application of ICRH, LHCD and ECRH Is under consideration.

Globus-3

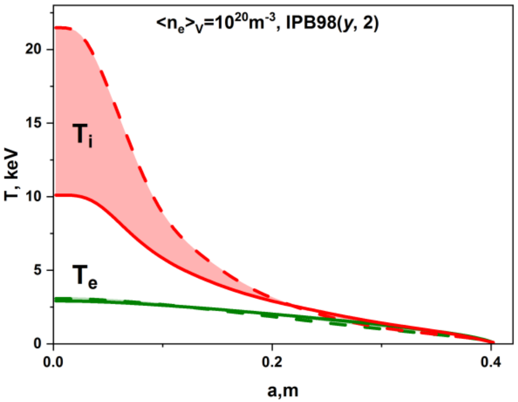
Continuous delivery of 2-3xNBI from Budker institute

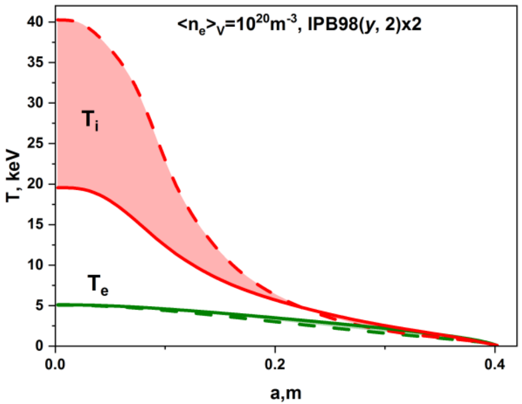


E_{NBI} =50-60 keV
P_{NBI} =5 MW

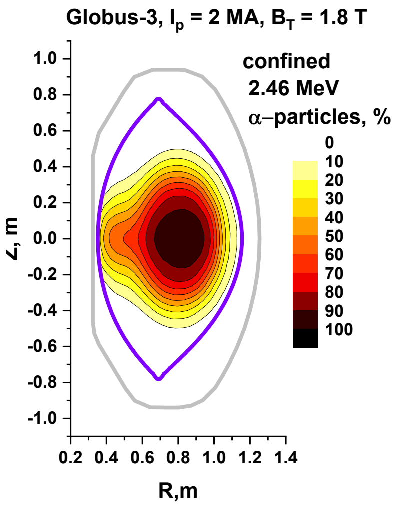
$\langle n_e \rangle_V$=10^{20}m^{-3}, 11.5 MW 60 keV NBI, Hot-ion mode, neoclassical ions

Base scenario, H-factor=1	**Upside scenario, H-factor=2**





α-particle from $^{11}B(p, \alpha)2\alpha$:
10^{11} s^{-1}-10^{14} s^{-1}
Acceptable for experimental studies



Timeline:

Conceptual design – 2025 – 2026
Detailed design – 2026 – 2027
Manufacturing of EMS and VV – 2027-2029
Modernization of the power supply system – 2029 – 2031
Assembling the Globus-3 – 2030
Start-up of the tokamak with the existing heating and diagnostics systems - 2031

Conclusion

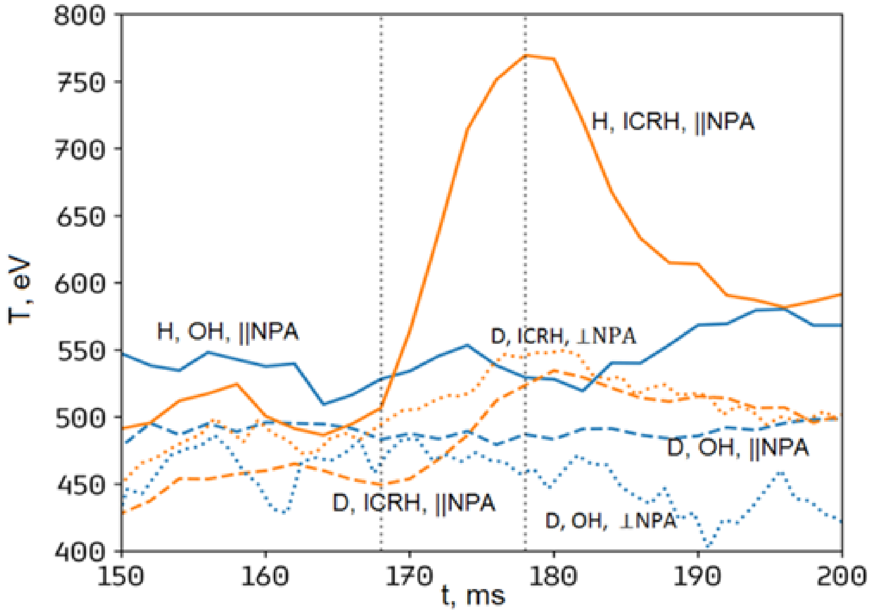
- Advanced diagnostics and control were successfully implemented
- A novel Inter-Shot Boronization technique was demonstrated $Z_{eff} < 1.1$ the neutron yield doubling.
- A hot-ion mode was established as a natural regime for Globus-M2. D NBI provides superior ion thermal insulation through toroidal rotation gradient stabilization of ITG turbulence.
- ICRH experiments demonstrated 15% T_i increase and beam ion acceleration.
- The High-Field-Side High-Density phenomenon was identified for the first time in ST.
- Alfvén eigenmodes cause up to ~30 MW/m^2 wall load.
- ELMs were shown to perturb plasma parameters only outside the LCFS but cause fast particle losses.
- The next-generation Globus-3 ST is under preliminary design. With significantly increased parameters (B_T=2 T, I_p=2 MA, R=0.775 m) it is projected to achieve fusion-relevant plasma parameters.

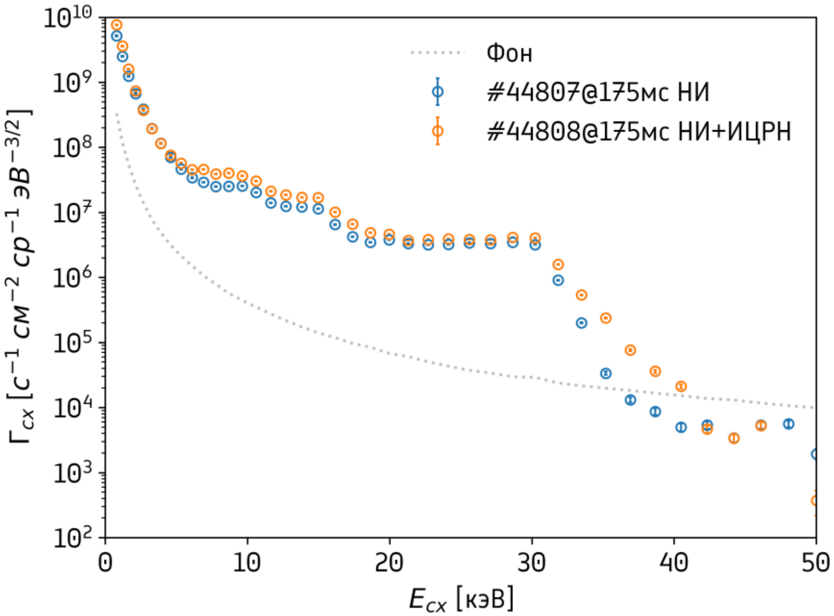
Thank you
for your attention!

Confinement: ICRH

Globus-M/M2 is the only ST successfully implementing Ion Cyclotron Resonance Heating

~100 kW ICRH

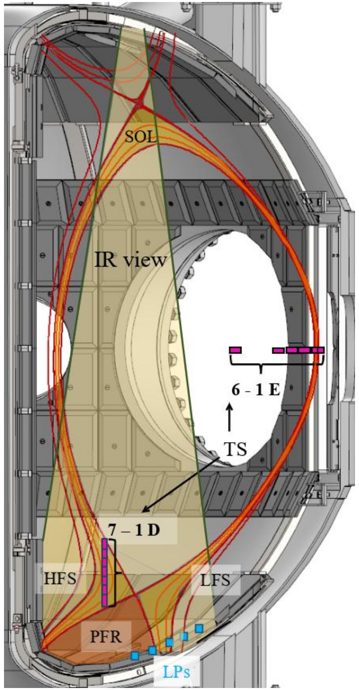




Divertor Thomson Scattering – prototyping ITER equipment

Diagnostics: [ERMAKOV, N. V., et al., Plasma Phys. Rep. 49 12 (2023) 1480]

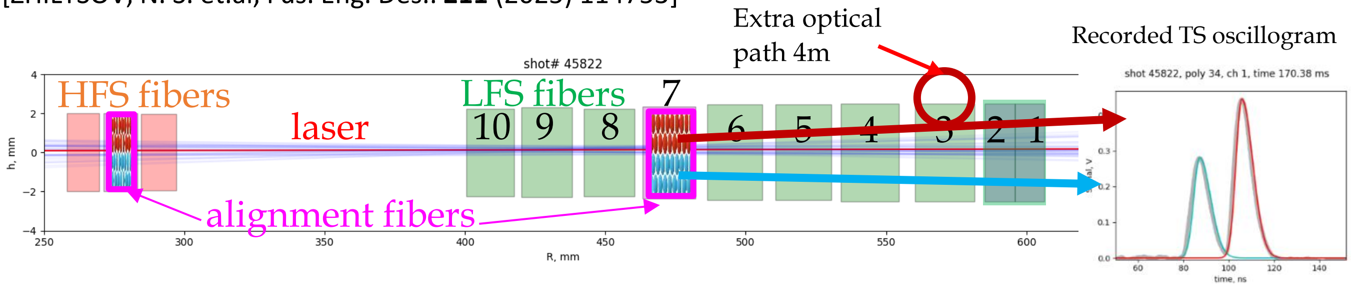
Application: [MUKHIN E.E. EX-D, P2]



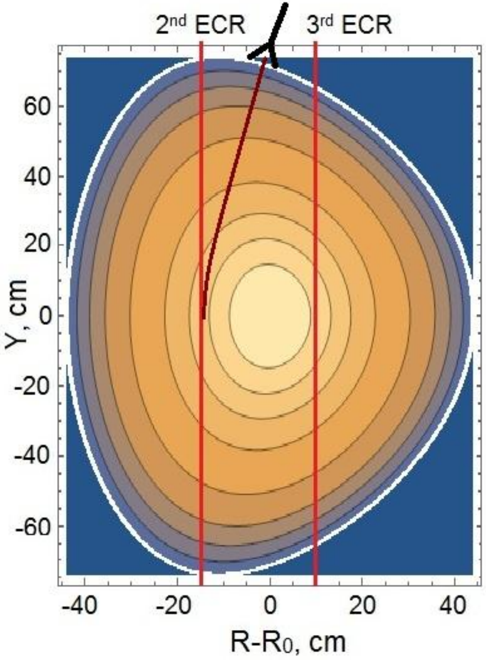
T_e : 1–100 eV
n_e: 10^{17}-10^{20} m^{-3}
9 spatial points
resolution ~1 cm,

Applicability of the TS hardware in the tokamak control system was demonstrated: $\Delta\tau < 1$ ms.
[ZHILTSOV, N. S. et al. Tech. Phys. Lett., **49** 8 (2023) 350-354.]

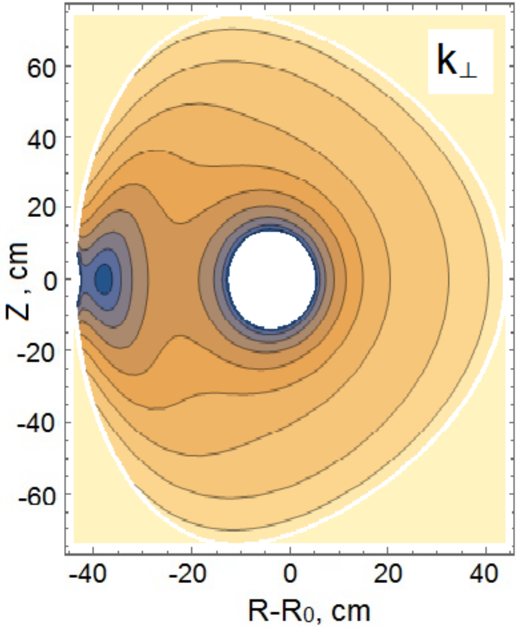
Precise (~0.1mm) online alignment of the TS diagnostics was implemented in the equatorial TS.
[ZHILTSOV, N. S. et.al, Fus. Eng. Des.. **211** (2025) 114753]



Globus-3



X2-mode



The ray-traced trajectory of the extraordinary wave is shown by the brown curve in the poloidal cross-section of Globus-3 ($n_0 = 1\times10^{20}$ m^{-3}, T_e = 3 keV, B_0 = 1.5 T) and (b) the contour diagram of the perpendicular component of the wave number of an extraordinary wave in the poloidal cross-section of Globus-3. The white region is the evanescence region due to the L-cutoff for the X-mode.

Conclusion

Advanced diagnostics and control were successfully implemented, including an Divertor Thomson Scattering system and fission chambers using ITER technologies and Laser Induced Ablation–Quadrupole Mass Spectrometer / Breakdown Spectroscopy.

A novel Inter-Shot Boronization technique was successfully developed and deployed, demonstrating advantage over standard GDB, leading to a significant reduction in plasma impurities ($Z_{eff} < 1.1$) and doubling of the neutron yield.

A hot-ion mode was established as a natural regime for Globus-M2. Deuterium NBI provides superior ion thermal insulation (close to neoclassical) compared to Hydrogen NBI, achieved through toroidal rotation gradient stabilization of ITG turbulence, resulting in higher ion temperatures (up to 4.7 keV) and energy confinement times.

ICRH experiments demonstrated 15% T_i increase and beam ions acceleration.

The High-Field-Side High-Density phenomenon was identified for the first time in a spherical tokamak.

Alfvén eigenmodes cause up to ~30 MW/m² wall load, with losses explained by resonant convective transport of fast ions from the plasma core. For the first time fast ion transport and losses induced by EPM were observed.

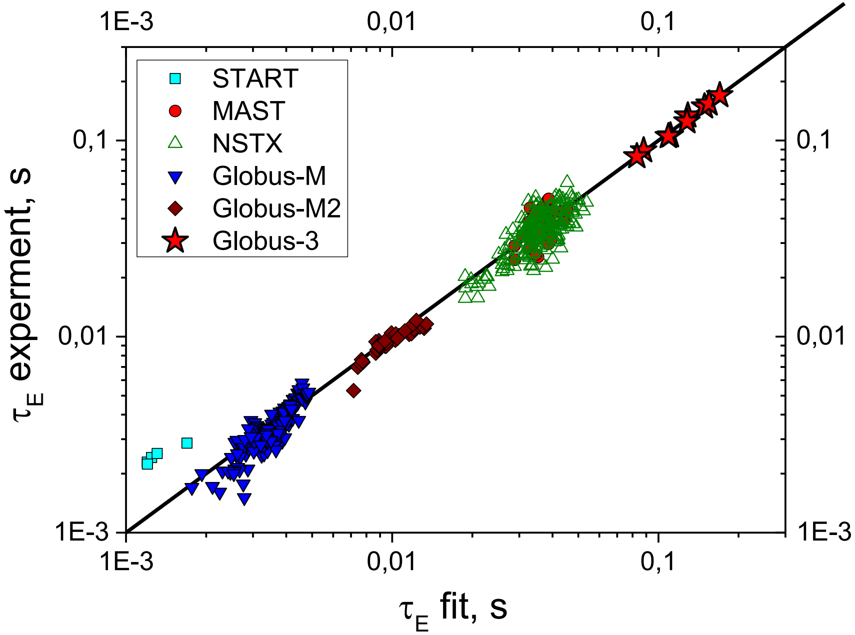
A comprehensive study of edge instabilities was performed:

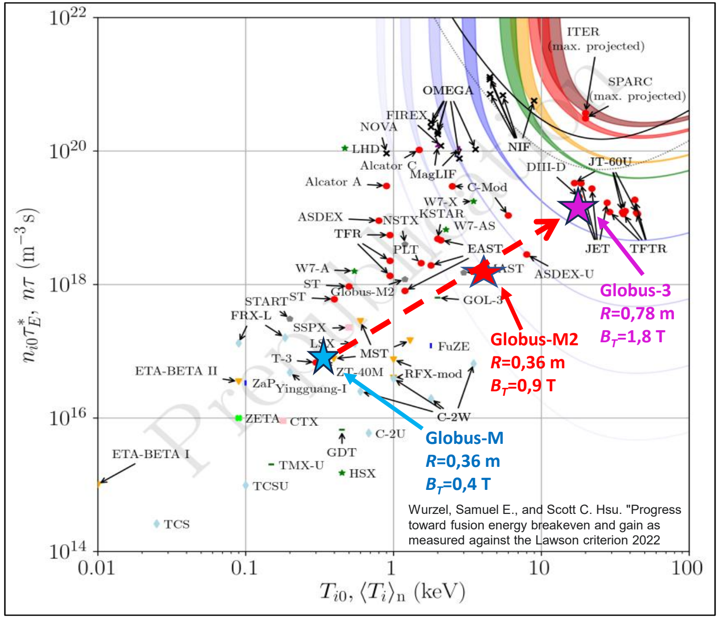
- **Small ELMs** were shown to perturb plasma parameters outside the LCFS and cause fast particle losses.
- **Low triangularity** destabilizes peeling-ballooning modes, leading to ELMs at lower pedestal pressures.
- **EHO** were observed in ELM-free regimes.

The next-generation Globus-3 ST is under preliminary design. With significantly increased magnetic field (2 T), major radius (0.775 m), and plasma current (up to 2 MA), it is projected to achieve fusion-relevant ion temperatures and study alpha-particle physics from the p + ^{11}B reaction.

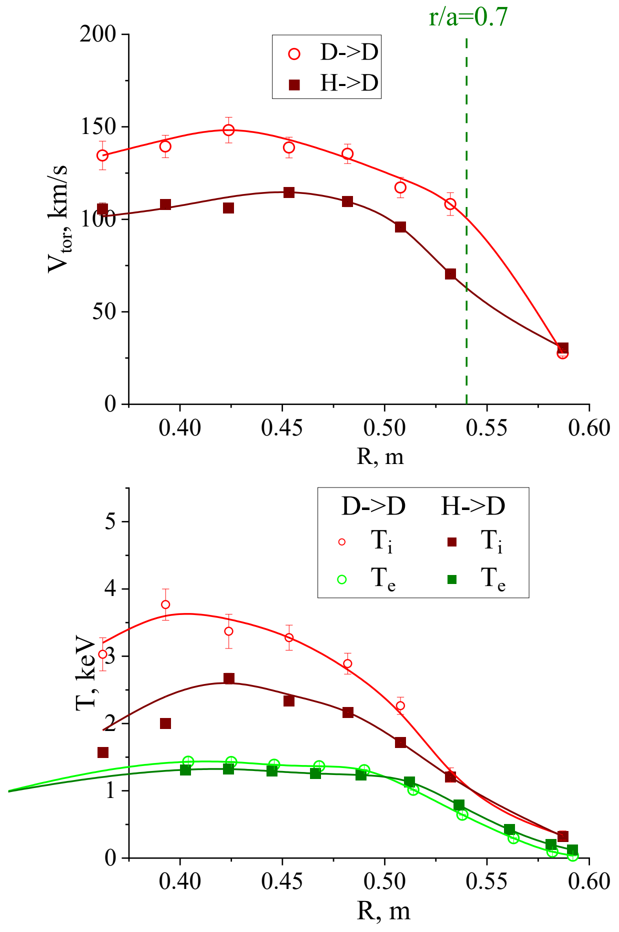
Globus-3

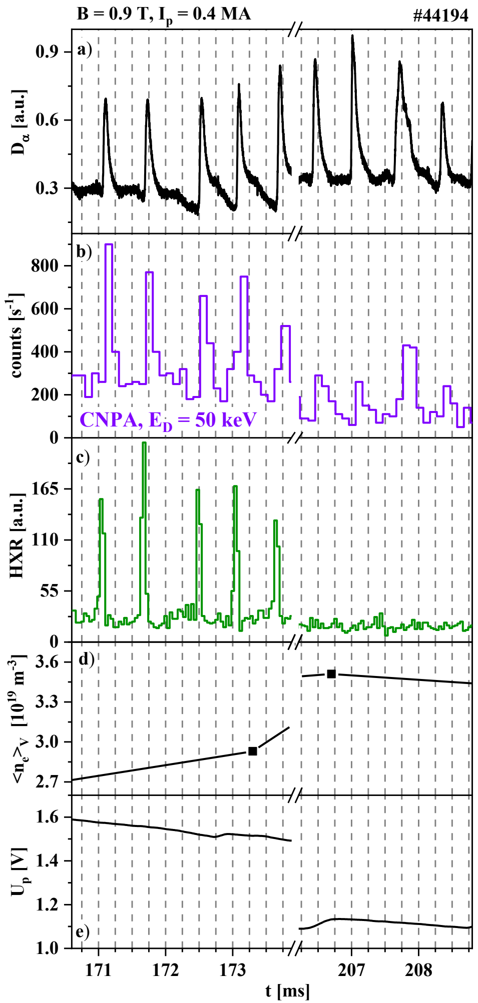
$$\tau_E^{Globus-21} = 0{,}066 \cdot I_p^{0.53} \cdot B_T^{1.05} \cdot P_{abs}^{-0.58} \cdot n_e^{0.65} \cdot R^{2.66} \cdot \kappa^{0.78}$$



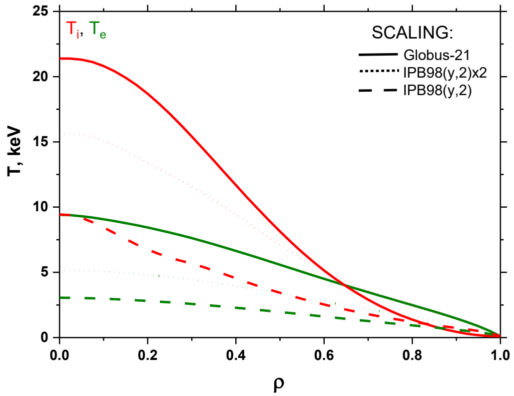


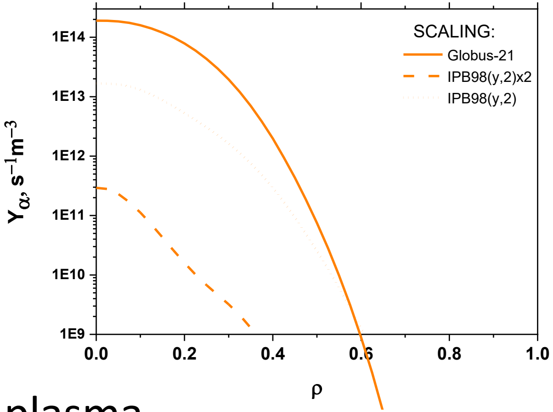
Scaling suggests the importance of B_T increase. Will be tested at Globus-3.


r/a=0.7
D->D
H->D
V_tor, km/s
R, m
D->D
H->D
T_i
T_e
T, keV
R, m


B = 0.9 T, I_p = 0.4 MA
#44194
a)
D_α [a.u.]
b)
counts [s^-1]
CNPA, E_D = 50 keV
c)
HXR [a.u.]
d)
<n_e>_V [10^19 m^-3]
e)
U_p [V]
t [ms]

Thermoneclear reaction





Beam-plasma