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OVERVIEW OF GLOBUS-M2 SPHERICAL TOKAMAK RESULTS AT THE ENHANCED VALUES OF MAGNETIC FIELD AND PLASMA CURRENT.

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ABSTRACT

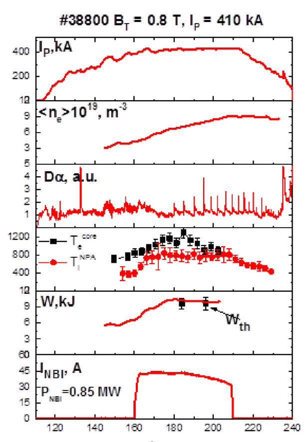
- Experiments were performed with the toroidal magnetic field up to 0.8 T and plasma current up to 0.4 MA (80 % of the design values)
- Temperature of electrons and ions above 1keV at the plasma density of $10^{20} m^{-3}$ was recorded at neutral beam injection (850 kW, 28.5 keV).
- Heat conductivity analysis was made by means of the codes ASTRA7.0, NCLASS, SPIDER, NUBEAM, 3D Fast Ion Tracking algorithm on the base of experimental data. A scaling for spherical tokamaks, which demonstrate strong τ_E dependence on magnetic field and dependence on plasma current has been confirmed for magnetic field up to 0.8T. For Globus-M/M2 it is $\tau_E^{GLB} \sim I_p^{0.43\pm0.22} B_T^{1.19\pm0.1}$.
- The dependence of the normalized energy confinement time ($B_T\tau_E$) on collisionality (ν^*) in a wide range 0.02<v*<0.2 was determined as $B_T\tau_E \sim \nu^{*-0.74}$.
- A non-inductively driven current was recorded during the launch of the electromagnetic waves of the lower hybrid frequency range (2.45 GHz) with the help of toroidally oriented grill. The fraction of noninductively driven current has exceeded 70% in the discharge with a total current of 0.2 MA. The achieved values of efficiency $\eta=(0.15\text{-}0.4)10^{19}\ Am^{-2}W^{-1}$ are comparable with the results obtained on traditional tokamaks.
- The report presents results of experiments on the study of Alfvén modes (AM). The resulting scaling for the loss of fast ions caused by toroidal Alfvén eigenmodes (TAE) demonstrates their decrease with increasing magnetic field and plasma current. Observation of Alfven cascades (ACs) made it possible to apply the method of MHD spectroscopy to determine the evolution of q_{min} in a discharge.
- Also presented are the results of comparing the experimentally measured SOL characteristics with modeling using the SOLPS-ITER code.
- Attention is also paid to the development of diagnostics.

BACKGROUND

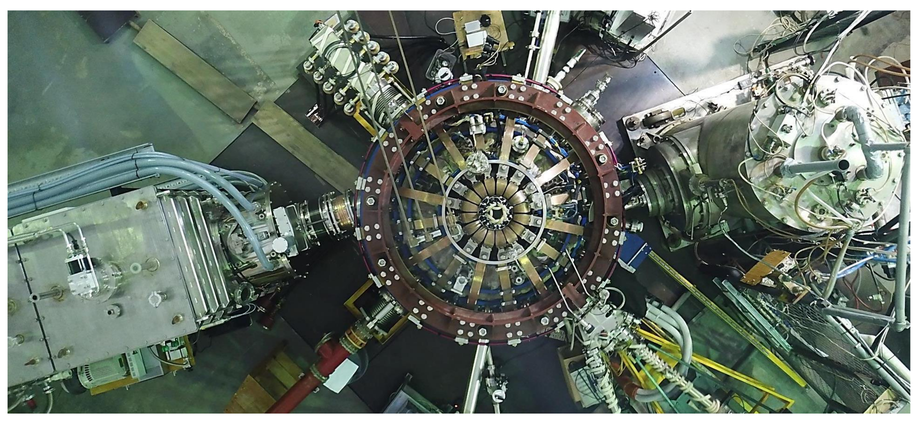
The purpose of research carried out on spherical tokamaks is to create scientific and technological basis for a compact purely thermonuclear reactor and/or a fusion neutron source (FNS) for further use as a controlled core of a fusion-fission hybrid reactor. To solve both problems, it is necessary to achieve long plasma confinement times, as well as to provide a spherical tokamak with effective methods and sources of non-inductive plasma heating and current drive to ensure a continuous operation. Along with this, it is required to solve a number of other problems, such as: a) confinement of fast ions in a compact tokamak; b) advanced tokamak high performance regimes with sub-fusion plasma parameters in compact ST; c) interaction of plasma with the first wall under conditions of high energy flux densities, etc. These problems are the subject of research carried out at the Globus-M2 spherical tokamak.

Globus-M2 is a modernized version of the Globus-M tokamak in which the vacuum chamber and the entire diagnostic complex are preserved, and a new electromagnetic system is significantly strengthened in order to withstand higher currents and, accordingly, increased mechanical loads. The tokamak was designed to reach the toroidal magnetic field as high as B_T =1 T and the plasma current I_p = 0.5 MA. The magnetic system provides operation in diverter single or double null configuration with the aspect ratio $A = R/a$ = 1.5 plasma minor radius a = 0.24 m, triangularity up to δ~0.5 and elongation up to κ~2.2. Currently 80% of highest magnetic field and plasma current value are reached, so during the reported period the experiments were performed with the toroidal magnetic field up to 0.8 T and plasma current up to 0.4 MA. The report provides an overview of the results obtained on Globus-M2 since the last IAEA conference

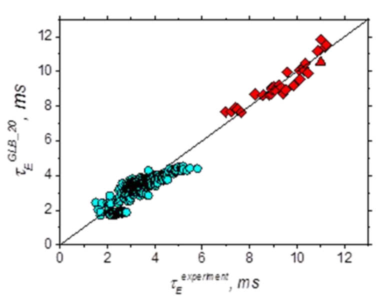
ENERGY CONFINEMENT



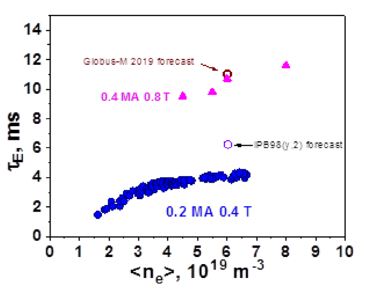
Plasma parameter waveforms



$\tau_E^{GLB} \sim I_p^{0.43} B_T^{1.19}$

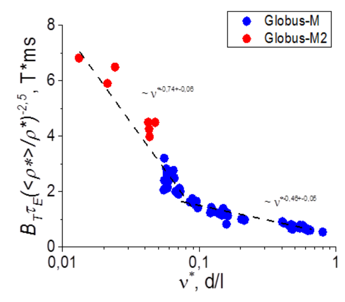


τ_E scaling in the range of 0.25 T<B_T< 0.8 T
0.1 MA< Ip < 0.4 MA



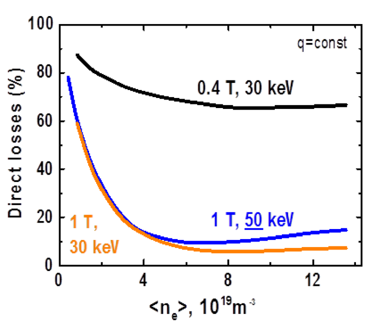
τ_E increase in Globus-M2 in comparison with Globus-M

- Globus-M2 (a=0.36 m, R=0.24) has reached B_T = 0.8 T and I_p = 400 kA (80% of the design values).
- Regimes with T_e and T_i in the keV range, <n_e> ~ 10^{20} m^{-3} and with low collisionality were obtained.
- 3 fold increase of τ_E at 2 fold increase of B_T – significantly more, than predicted by IPB98(y,2) scaling
- the ST scaling is valid for a wide parameter range $\tau_E^{GLB} \sim I_p^{0.43} B_T^{1.19}$
- Globus-M/M2 scaling for normalised confinement time shows strong dependance on collisionality $B_T\tau_E \sim \nu^{*-0.74}$ unlike the IPB98(y2) scaling: $B_T\tau_E \sim \nu^{*-0.01}$



$B_T\tau_E$ increases with collisionality decrease

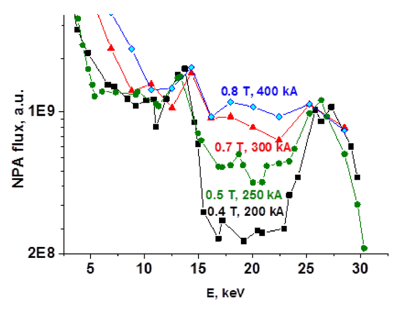
FAST PARTICLE CONFINEMENT



Full orbit modeling of fast particle direct losses in Globus-M2

Experiments prove modeling predictions

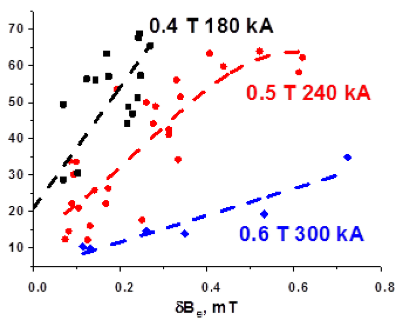
- Poor fast particle confinement in Globus-M at 0.4 T, 200 kA, strong drop of the NPA fluxes
- I_p and B_T rise improve fast ion confinement
- The drop practically disappears in Globus-M2 at 0.8 T, 400 kA
- Ions with an energy of 50 keV must be confined in Globus-M2 at B_T =1 T and I_p = 500 kA



CX particle spectra, measured with a tangentially directed NPA at 28 keV 0.8 MW NBI

ALFVÉN EIGENMODES

Toroidal Alfvén eigenmodes and fast ion losses

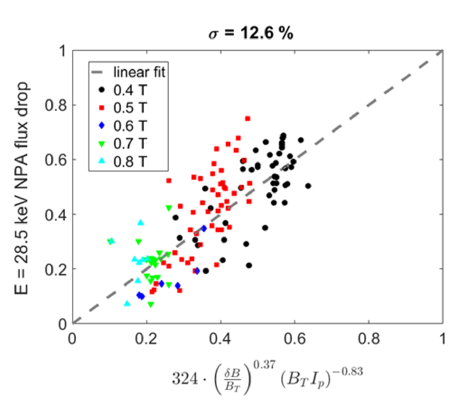


28.5 keV CX flux drop (%)

- TAE bursts result in fast particle losses and redistribution
- Neutron rate and CX flux drops are the measure of the relative losses
- Fast ion losses grow with an increase in the TAE amplitude but decrease with an increase in B_T and I_p
- Regression fit of the Globus-M/M2 data yields the scaling for relative fast ion losses:

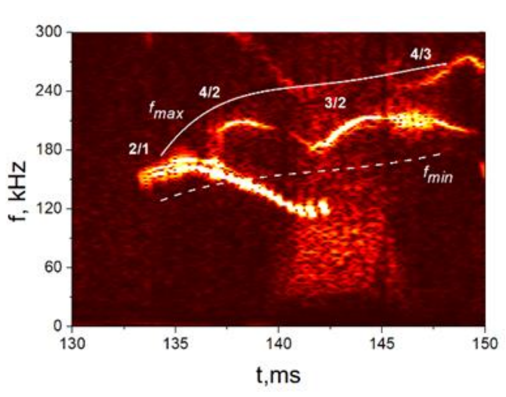
$$N/N \sim \left(\frac{\delta B}{B_T}\right)^{0.37} (B_T * I_p)^{-0.83}$$

- The scaling gives optimistic forecast for future STs.



Regression fit for relative fast particle losses

Alfvén cascades

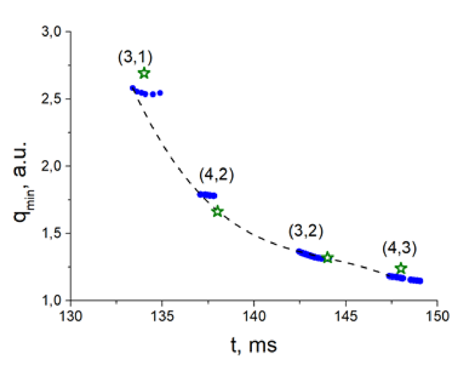


Spectrogram of the Mirnov probe signal for shot #38035 with AC

- Observation of ACs made it possible to apply the method of MHD spectroscopy to determine the evolution of q_{min}
- The AC frequency in linear approach is determined by:

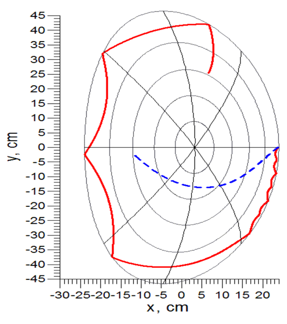
$$\omega_{AC} = \left[\left(\frac{m}{q_{min}} - n\right)^2 \frac{V_A^2}{R_0^2} + \frac{2T_e}{M_i R_0^2}\left(1 + \frac{7}{4}\frac{T_i}{T_e}\right)\right]^{1/2}$$

- The mode wave numbers were determined with magnetic probes.
- Localization of the modes was established by means of the Doppler back scattering
- Temperature and density profiles were measured with Thomson scattering and NPA



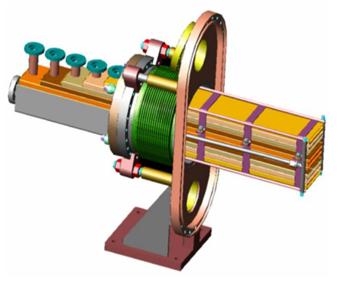
q_{min} evolution in shot #38035 (triangles – MHD spectroscopy data, asterisks – ASTRA computation result)

LOW HYBRID CURRENT DRIVE

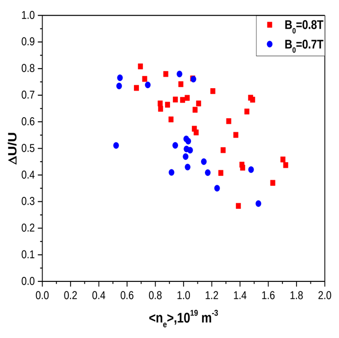


Ray tracing at toroidal launch, $N_\parallel$ = - 3.0
B_T = 0.6 T and B_T = 1.0 T

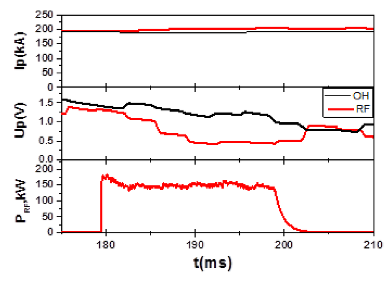
Globus-M2 is the only ST with LHCD system



- Rotatable 10-waveguide grill antennae
- Phase shift between neighbor waveguides 120º
- Toroidal and poloidal wave slowing down is possible

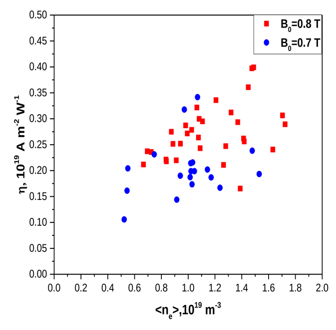


Relative loop voltage drop at LHCD 2.45 GHz, 150 kW



Toroidal grill orientation
2.45 GHz, 150 kW, $N_\parallel$ = - 3, B_T=0.8 T, <n_e>= 1×$10^{19}$$m^{-3}$, $T_e(0)$ = 500 eV

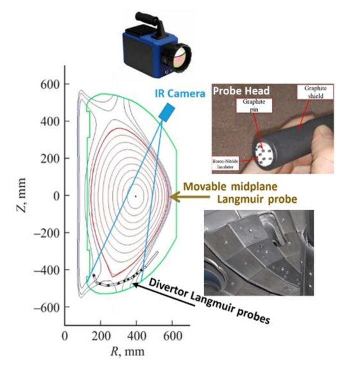
- Increase of the toroidal field improves accessibility of the plasma center region
- Toroidal grill orientation, f_0 = 2.45 GHz, P = 150 kW, $N_{||}$= -3.0 were implemented
- The value of the relative voltage drop during the RF pulse varied within the range ΔU/U ≈ (30 – 80)%, depending on density
- Achieved on Globus-M2 efficiency $\eta = (0.15 - 0.4)\cdot 10^{19} Am^{-2}W^{-1}$ Is comparable with the results obtained on conventional tokamaks



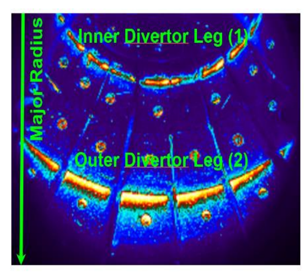
LHCD efficiency on Globus-M2

SOL STUDY

EXPERIMENT

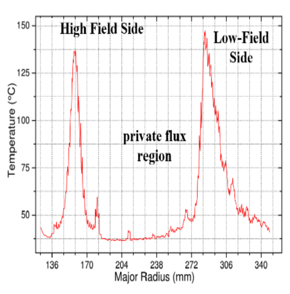


Experimental setup at Globus-M2



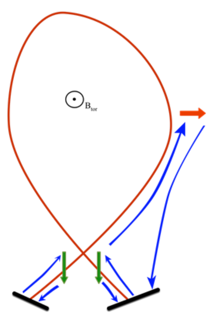
IR camera frame
LSN shot #39816
B_T = 0.7 T, I_p = 200 kA

- Globus-M2 has open divertor which is equipped with Langmuir probes imbedded into divertor plates, movable 9-pin Langmuir probe and IR-camera
- SOL width (λ_q) was obtained by analyzing the heat flux density profile
- Estimated SOL width does not contradict expectations from Eich scaling



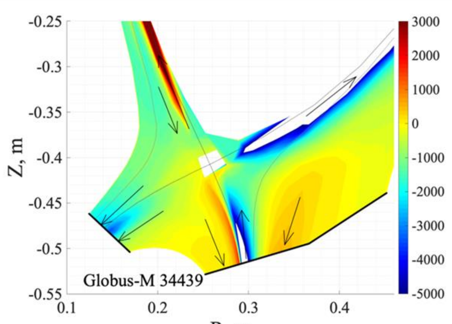
Temperature of the divertor

MODELING



The scheme of PCC (blue arrows) in the edge plasma. Red arrow - radial current with neoclassical nature, green arrows – diamagnetic current through the separatrix

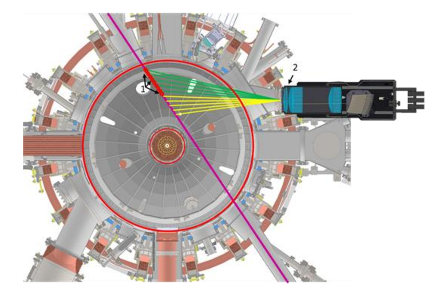
- Besides the known Pfirsch-Schlüter currents and thermoelectric current, so-called plate closing currents (PCC) flowing to and from the divertor targets were analyzed
- Globus-M discharge #34439 (I_p=114 kA, Ohmic H-mode) was modeled with two-dimensional SOLPS-ITER code
- It could be seen that the scheme in the left figure shows the same pattern of the current as the result of modeling except the HFS Strike Point region where thermoelectric current plays significant role
- The current through the magnetic sheath near the target requires the deviation of the potential from the floating value
- Measured with the divertor probes and modeled profiles of electric current density to the target and the ratio of plasma potential to the electron temperature agree reasonably well



Poloidal projection of current density (modeling results)

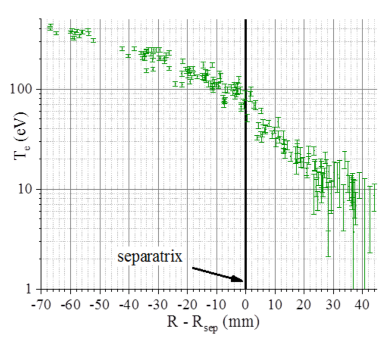
DIAGNOSTICS DEVELOPMENT

THOMSON SCATTERING NEW SYSTEM



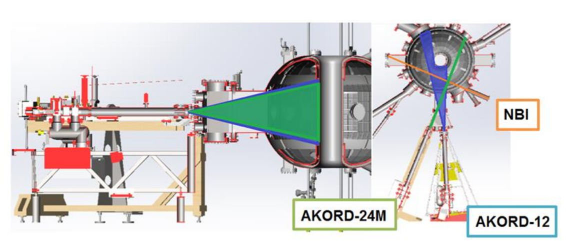
Scheme of the TS measurements on Globus-M2 (1 – spatial points, 2 – the collecting objective).

- The system includes 1064 nm Nd:YAG pulsed laser with 330 Hz repetition rate, each pulse has 10 ns duration at FWHM and carries up to 3 J of energy
- 10 spatial points on the radial profile
- Spatial resolution 20 mm in the plasma core and 10 mm at the last closed field surface from the low field side
- The new TS system provides reliable measurements of T_e < 10 (eV) with moderate electron density up to 4 cm beyond the separatrix



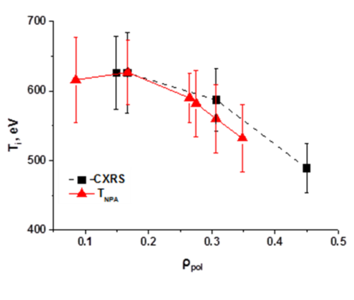
Electron temperature profile near separatrix, measured by a new TS system

NPA COMPLEX MODERNIZATION



Scanning system for two NPAs

- A scanning system for two NPAs It allows us to perform shot-to-shot spatial scanning vertically for both analyzers, and also horizontally for one of them.
- When operating in the NBI mode, the measurements are localized at the point of intersection of the analyzer line of sight and the injection line
- This makes it possible to reconstruct the ion temperature profile or fast ion distribution



Ion temperature profile. Red triangles are NPA data, black squares are CXR measurements.

CONCLUSION AND PLANS

- In the modernized Globus-M2 tokamak, discharges were carried out with a magnetic field of up to 0.8 T and plasma current of up to 400 kA, which is 80% of the design values. As a result, regimes with a temperature in the keV temperature range and with low collisionality were obtained.
- The scaling of the energy confinement time is confirmed for spherical tokamaks with a strong dependence on the toroidal magnetic field in a wider range of parameters. An increase in the energy confinement time is demonstrated with a decrease in the normalized collision frequency is demonstrated.
- In experiments on current generation by waves of the lower hybrid frequency range, a high efficiency was obtained, comparable to the results for traditional tokamaks.
- The scaling of fast ion losses caused by TAE is obtained, which demonstrates their decrease with increasing magnetic field and current, which is favorable for spherical tokamaks with higher parameters.
- A number of diagnostics have been commissioned and modernized, providing the most complete set of plasma data.
- In the near future, it is planned to bring the tokamak to its design parameters, conduct experiments on plasma heating and current generation using a new injector (50 keV energy, 1 MW power), carry out experiments on ion cyclotron heating and also continue research in all areas covered in this report.

ACKNOWLEDGEMENTS

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