Spherical Tokamak Globus-M2: Design, Integration, Construction

V.B. Minaev[1], V.K. Gusev[1], N.V. Sakharov[1], V.I. Varfolomeev[1], N.N. Bakharev[1], V.A. Belyakov[2], E.N. Bondarchuk[2], F.V. Chernyshev[1], V.V. Dyachenko[1], A.D. Iblyaminova[1], A.A. Kavin[2], N.A. Khromov[1], G.S. Kurskiev[1], A.N. Labusov[2], V.V. Mikov[3], A.B. Mineev[2], I.V. Miroshnikov[4], M.I. Patrov[1], Yu.V. Petrov[1], V.A. Rozhansky[4], A.N. Saveliev[1], I.Yu. Senichenkov[4], P.B. Shchegolev[1], O.N. Shcherbinin[1], I.V. Shikhovtsev[5], V.V. Solokha[1], V.N. Tanchuk[2], A.Yu. Telnova[1], V.A. Tokarev[1], S.Yu. Tolstyakov[1], E.G. Zhilin[6]

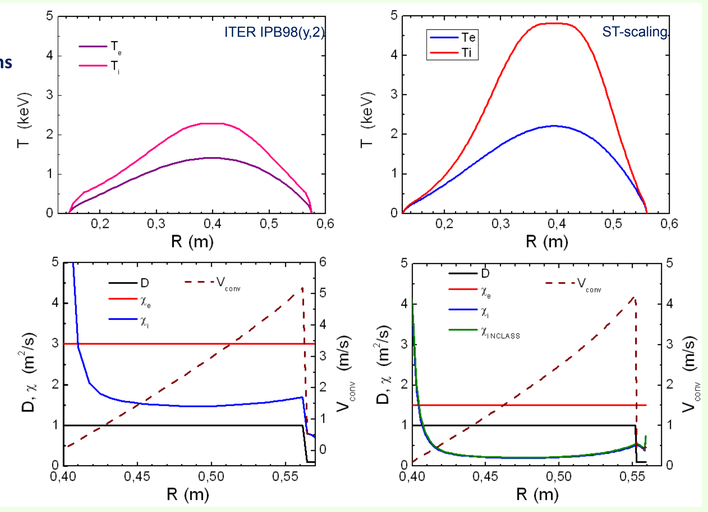
[1)] *Ioffe Physical-Technical Institute of the Russian Academy of Sciences, Saint Petersburg, Russia*
[2)] *JSC «NIIEFA», Saint Petersburg, Russia*
[3)] *JSC «INTEKHMASH», Saint Petersburg, Russia*
[4)] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia*
[5)] *BINP SB RAS, Novosibirsk, Russia*
[6)] *Ioffe Fusion Technology Ltd., Saint Petersburg, Russia*

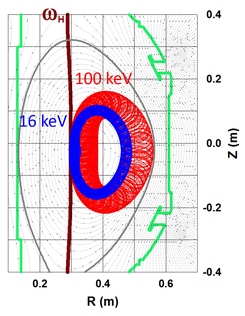
Introduction. The Globus-M spherical tokamak [1] has demonstrated practically all of the project objectives during the 15-year period of operation. The main factor limiting further enhancement of plasma parameters is a relatively low toroidal magnetic field [2-5]. The increase of the magnetic field up to 1.0 T together with the plasma current up to 0.5 MA will result in the significant enhancement of the operating parameters in the upgraded Globus-M2 machine [6,7]. The experimental program will be focused on plasma heating and non-inductive current drive [8-10] and will serve creation of physical and technological base for the compact fusion neutron source development.

Globus-M data extrapolation

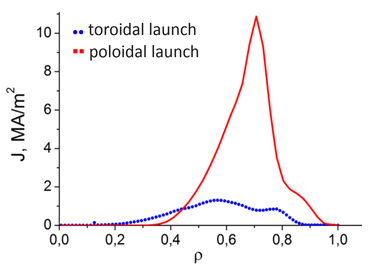
- ASTRA and NUBEAM codes were used for simulations of the Globus-M2 high density deuterium shot (B_t=1.0 T, I_p=0.5 MA, $<n_e>=0.7\times10^{20}$ m^{-3}) with D-NBI (30 keV, 1 MW).
- The electron thermal diffusivity was estimated with the help of two scalings:
  ITER IPB98(y,2) - pessimistic [11];
  ST-scaling - optimistic [12].

➢ The electron temperature exceeds 1.5 keV in the plasma core for both cases.

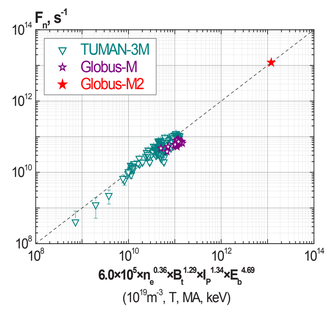




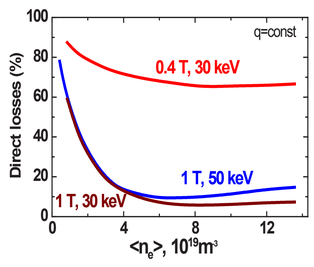
- Hydrogen ions with energy up to 100 keV, arising during IC heating, are well confined in Globus-M2.
- Absorption of input power increases due to improved antenna-plasma coupling [8].

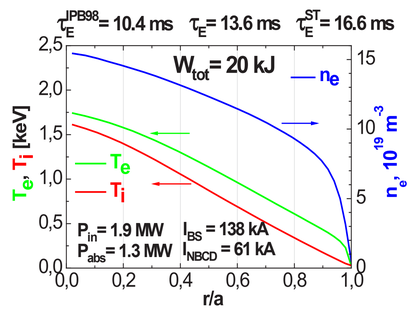


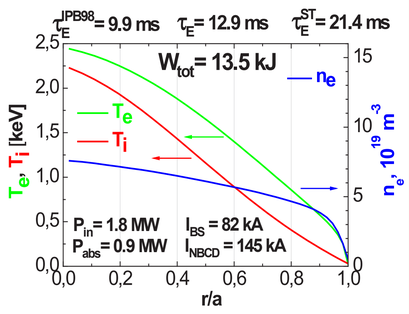
- The efficiency of low-hybrid current drive increases in Globus-M2.
- Both toroidal and poloidal launching are possible in general.
- Calculations predict that low-hybrid wave (2.45 GHz) application is able to provide fully non-inductive current regime for the 0.5 MW level of input power [13].



- It is expected at least two orders of increase in the neutron flux rate during the deuterium beam injection into deuterium plasmas as compared with Globus-M [14].
- NUBEAM simulation confirms this result [9].



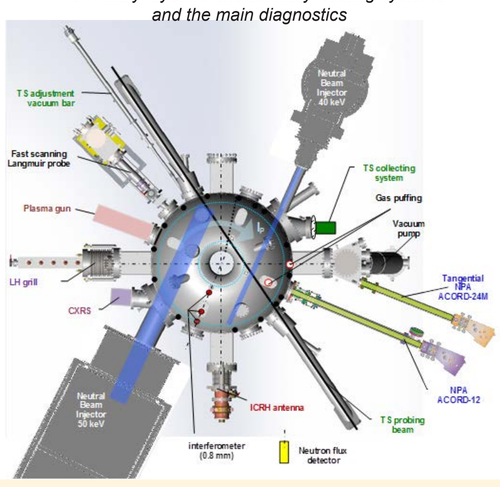




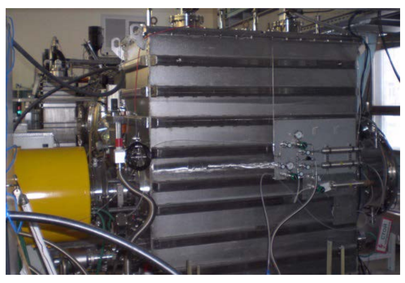
- The percentage of direct losses during NB injection drops significantly in comparison with Globus-M conditions [9].
- The direct losses of the main component of the 50 keV beam will not exceed 20% even for the moderate density regimes.
- About one third of the plasma current will be sustained non-inductively during injection of 1 MW beam with 50 keV energy.
- The fraction of the non-inductive current will attain the value of 45% in the case of application of both existing beam lines (1 MW, 50 keV and 1 MW, 40 keV) [15].

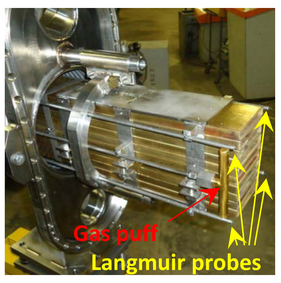
System integration

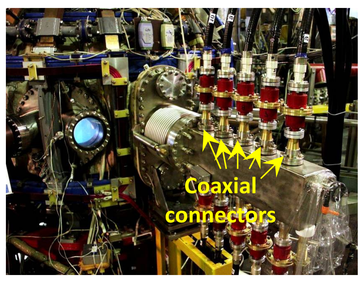
Preliminary layout of the auxiliary heating systems and the main diagnostics



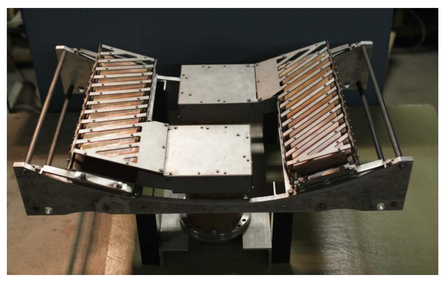
- Maximal NB energy is increased up to 40 keV for the existing 1 MW injector. In the sequel we plan to extend the beam pulse duration. Development of a new feeding system with grid power supplies is required thereto.
- A new 1 MW injector, which provides 50 keV atomic beam, will be applied in addition to the first one. Its pulse duration fits the maximal plasma shot length in Globus-M2.
- Both beams will be launched tangentially to the plasma column.







- Upgrade of 2.45 GHz LHCD system is on the way. A new waveguide line with a divider of RF power provides transmission of about 0.5 MW of RF-power from the klystron to the antenna-grill.
- A new 10-waveguide grill provides rotation around its longitudinal axis during the installation and, as a result, changing of wave launching direction from toroidal to poloidal one and vice-versa.
- A new high voltage one second duration power supply was developed and manufactured for feeding of the klystron generator.



- The IC heating experiment will be continued on the Globus-M2 tokamak.
  A new double-strip antenna for the IC heating system has been manufactured.

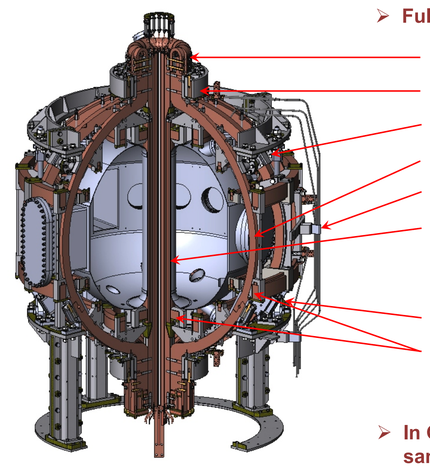
➢ Installation of new equipment requires some rearrangement of the diagnostic setup.

Design of the upgraded machine

Two basic plasma shot scenarios for the Globus-M2 tokamak

Engineering parameter	B-max regime B_T = 1.0 T (at R = 0.36 m)	t-max regime B_T = 0.7 T (at R = 0.36m)
Plasma current	0.5 MA	0.5 MA
CS magnetic flux consumption	0.4 Wb (+/- 0.2 Wb)	0.4 Wb (+/- 0.2 Wb)
Duration of TF flattop	≤ 0.4 s	≤ 0.7 s
Basic regime	Inductive	Inductive / Non-inductive CD
TF field rippling at R=0.6m	≤ 0.4%	≤ 0.4%
Number of working pulses in regime with maximal load	5000	10000
Minimal pulse repetition rate	Every 15 min	Every 15 min

- The electric current through the toroidal field coil reaches the value of 110 kA providing the magnetic field of 1.0 T. That is equal to 1.76 MA of total current in TF coil central rod.
- Current of ± 70 kA passes through the central solenoid providing magnetic flux variation of about 0.4 Wb.



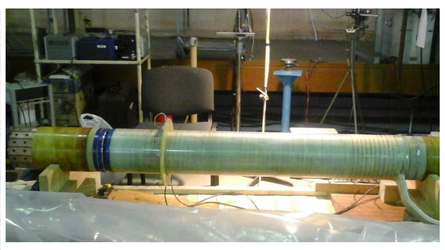
➢ Fully revised design of magnets was developed for the upgraded tokamak.

- Flexible bas bars are placed outside the maximal stresses zone.
- Bandage rings bear higher thermal and mechanical loads.
- Upper supporting ring and 4 load-bearing crosspieces are added.
- TF coil limbs are made of high grade copper (σ_{02} > 220 MPa).
- Water cooling is applied to all poloidal field coils.
- Central Column is redesigned completely.
  CS is wound in two layers in situ around the TF coil inner rod with a 1 mm gap. The temper hard copper conductor (σ_{02} > 290 MPa) of trapezoidal cross-section is used.
- Support structure is redesigned.
- PF1 and PF3 coils are redesigned.

➢ In Globus-M2 the vacuum vessel and the in-vessel components remain the same that allows reducing the project costs.

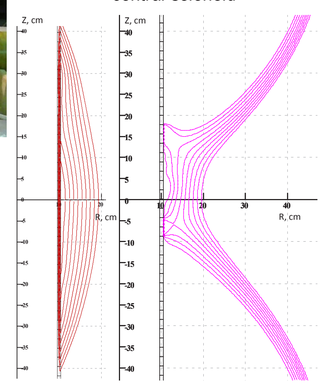
Construction, current status and plans

- Magnets for Globus-M2 have been manufactured and delivered to the Ioffe Institute.



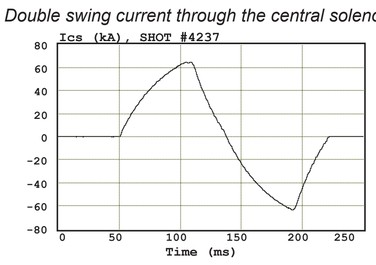
- The structure of the magnetic field generated by the solenoid was measured during a special test experiment.
- A computer model of the solenoid was developed.
- Some asymmetry of the field relative to the equatorial plane, which is rapidly abated outward solenoid surface, may be caused by some irregularity in the coil pitch.

Maps of surfaces of constant magnetic flux (left) and constant magnitude of poloidal magnetic field (right) for the Globus-M2 central solenoid

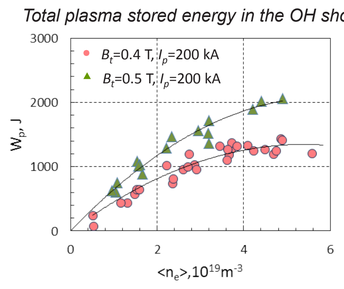


- Two novel thyristor rectifiers have been manufactured and delivered to the Ioffe Institute:
  one of them provides current swing of ± 70 kA amplitude in the central solenoid,
  another one supplies toroidal field coil with maximum current of 110 kA.
- Major repair of all electric grid transformers was made.

Double swing current through the central solenoid

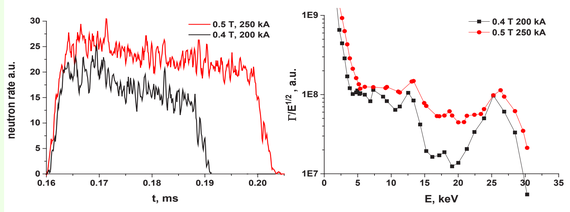


Total plasma stored energy in the OH shots



- Toroidal magnetic field and plasma current were increased by 25% from 0.4 T and 200 kA to 0.5 T and 250 kA respectively during last experimental campaign.
  One of the rectifiers was tested in the plasma experiment, feeding the current through the Globus-M central solenoid.
- In ohmically heated plasmas a significant growth of plasma stored energy was found, that indicates improvement of confinement due to toroidal magnetic field rise.
  The data were obtained from the analysis of plasma diamagnetism. Selected values of Wp were verified by kinetic measurements of electron temperature and density profiles.

Neutron flux and CX spectra during 26 keV D-NBI into D-plasma

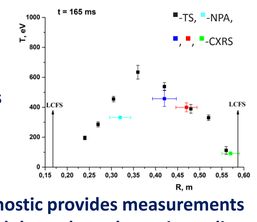


- About 30% D-D neutron rate growth was observed after the plasma current and magnetic field increase. The main reasons for this are central electron temperature rise (from 600 eV to 900 eV) and the fast ion losses decrease.
- Reduction of the first orbit and slowing down losses of the injected particles and decrease of the saw-tooth oscillations impact on the energetic ion confinement resulted in the change of the CX spectra shape.

➢ We plan one more experimental campaign with fully upgraded tokamak power supplies by the end of the year.

- Some new diagnostic systems were developed:
  - CXRS measurements of ion temperature were performed in a simple 2-chord set-up [16]. The results are in agreement with NPA data [17]. A new 8-channel fiber-optical system is on the way.

Ion and electron temperature measurements



- A fast scanning Langmuir probe diagnostic provides measurements of multiple plasma parameters in a midplane along the major radius for a 10 ms period at a depth of 6 cm.
- Two 24-channel SPD diode arrays (ΔE=1 - 40000 eV) are aimed at investigation of evolution of radiative losses spatial distribution.
- Five additional channels were added to increase spatial distribution of Thomson scattering diagnostic on plasma periphery up to 1 cm.

➢ Replacing of existing magnets with new ones and first plasma are expected in 2017.

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This report employs the results, which have been obtained with the help of the unique scientific device spherical tokamak Globus-M.

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Contacts: Vladimir.Minaev@mail.ioffe.ru