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on behalf of the Globus-M2 team

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in cooperation with

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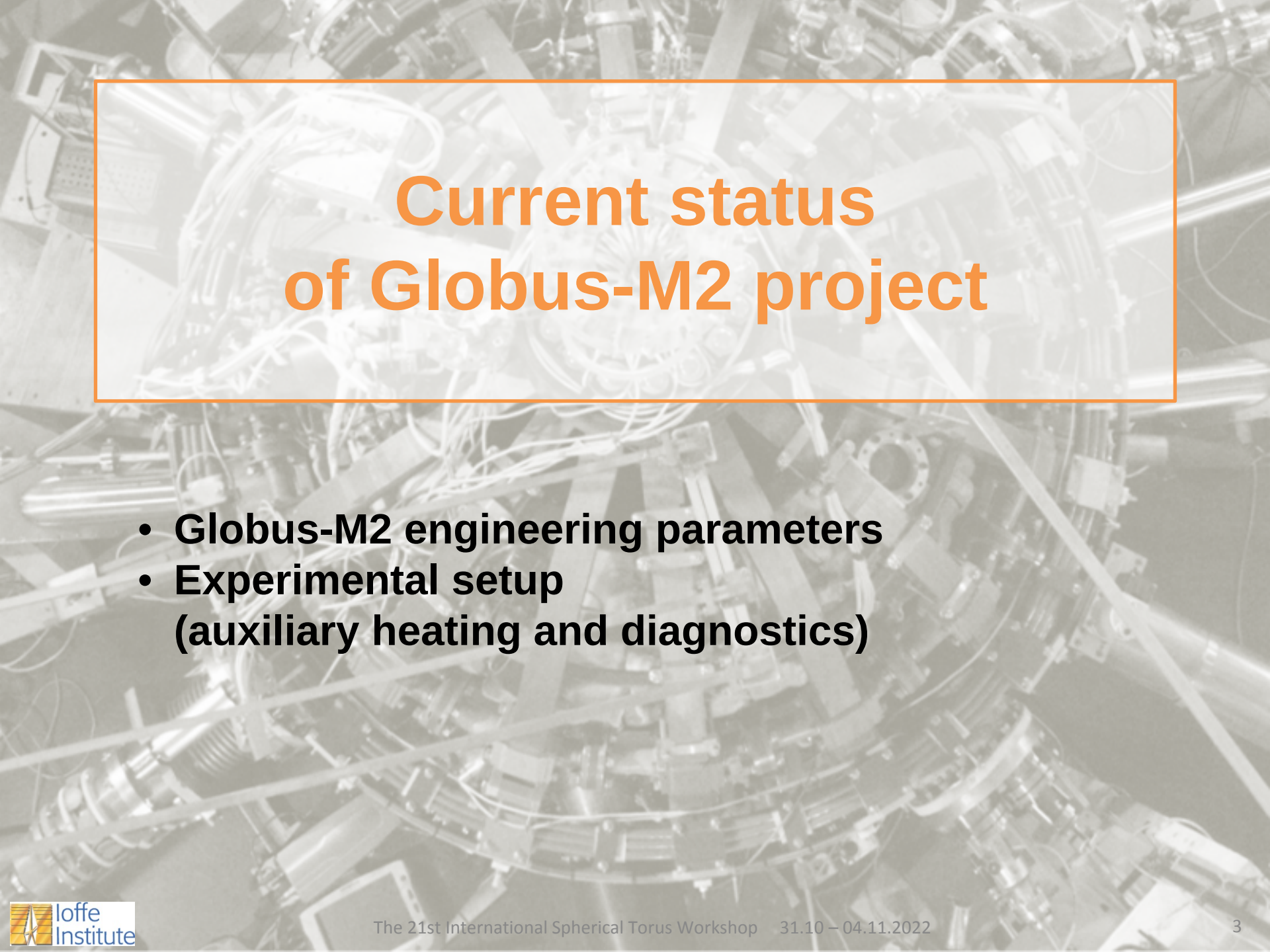
BINP SB RAS, Novosibirsk, Russia

Ioffe Fusion Technology Ltd., St. Petersburg, Russia

Overview of plasma research at the Globus-M2 spherical tokamak

Outline

- **Current status of Globus-M2 project**
- **Globus-M2 main results**
- **Upcoming experiments and future plans**

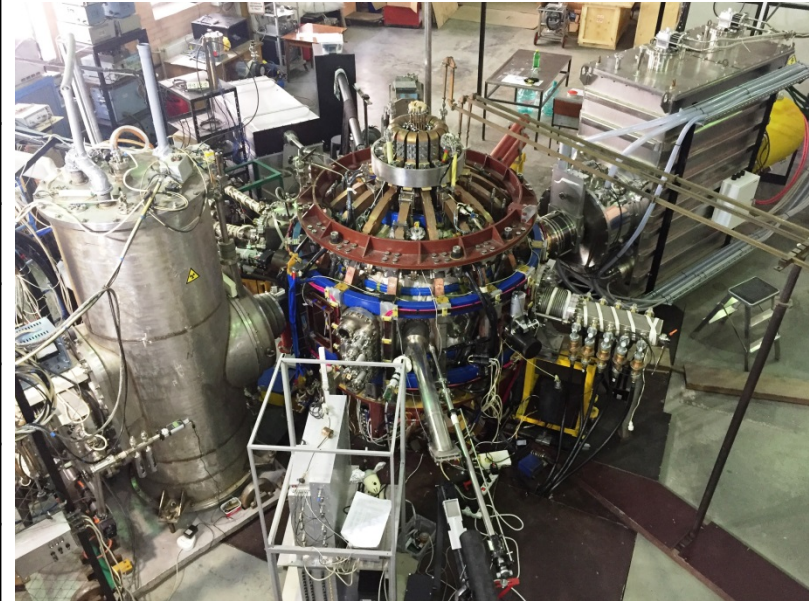


Current status of Globus-M2 project

- **Globus-M2 engineering parameters**
- **Experimental setup
(auxiliary heating and diagnostics)**

Globus-M2 engineering parameters

	Globus-M	Globus-M2 (project / achieved)
R, m	0.36	0.36
a, m	0.24	0.24
R/a	1.5	1.5
B_{tor} (on axis), T	0.4	1.0 / 0.9
I_p, MA	0.2	0.5 / 0.43
κ	≤ 2.0	≤ 2.0 / ≤ 2.0
δ	≤ 0.5	≤ 0.5 / ≤ 0.4
Ψ_{pol}, Wb	0.33	0.4
B_{tor}/R, T/m	≤ 1.1	≤ 2.7
t_{pulse}, s	0.15	0.4
NBI [E, keV \ P, MW]	30 \ 1	40 \ 1 + 50 \ 1
ICRH [f, MHz \ P, MW]	7.5 \ 0.3	6.0-15.0 \ 0.5
LHCD [f, GHz \ P, MW]	0.9 \ 0.1	2.45 \ 0.5

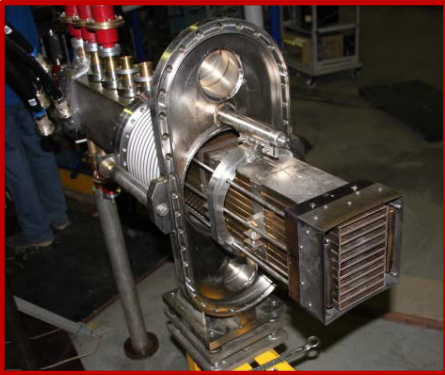
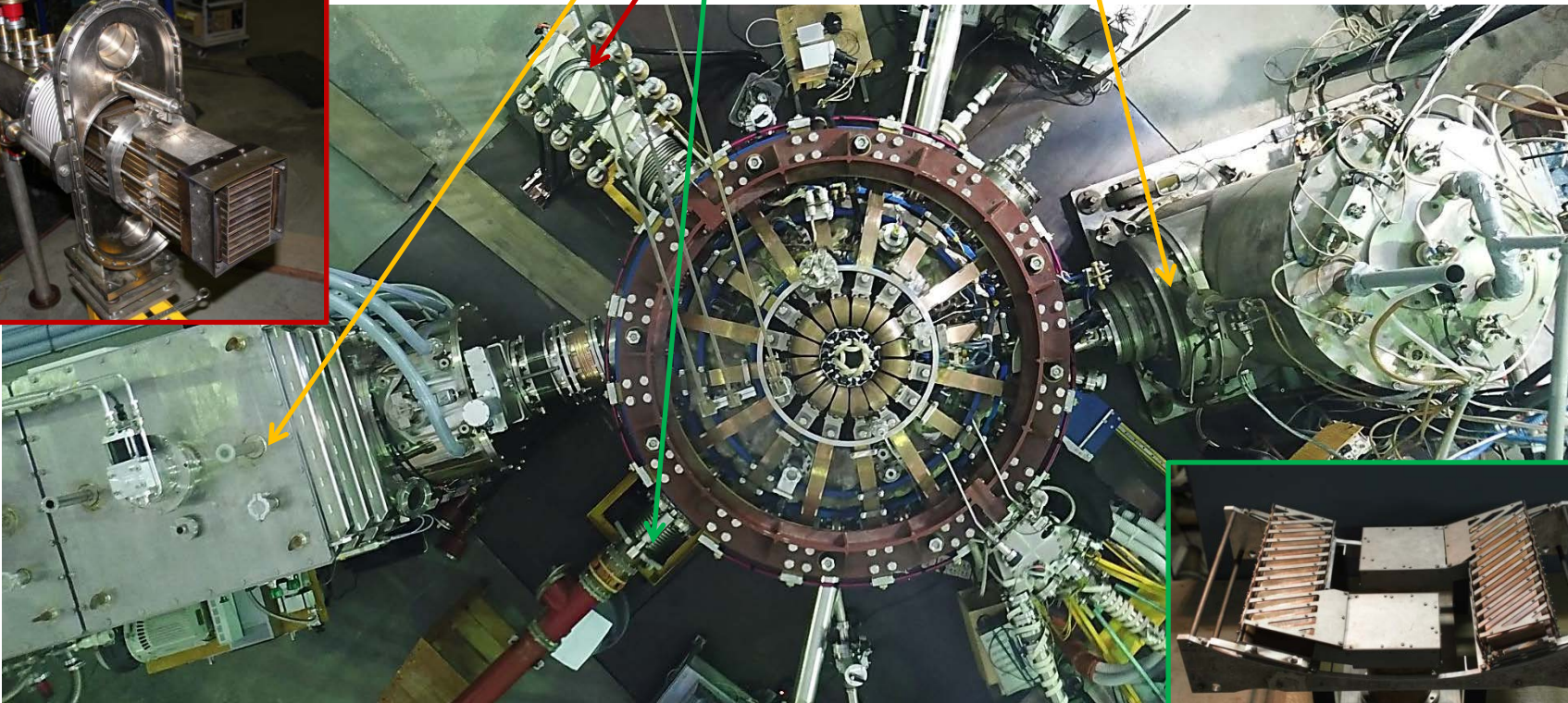


Distinctive features
of the Globus-M2 tokamak:

- New electromagnetic system and power supplies;
- Legacy vacuum vessel and in-vessel components;
- Upgraded auxiliary heating and current drive systems.

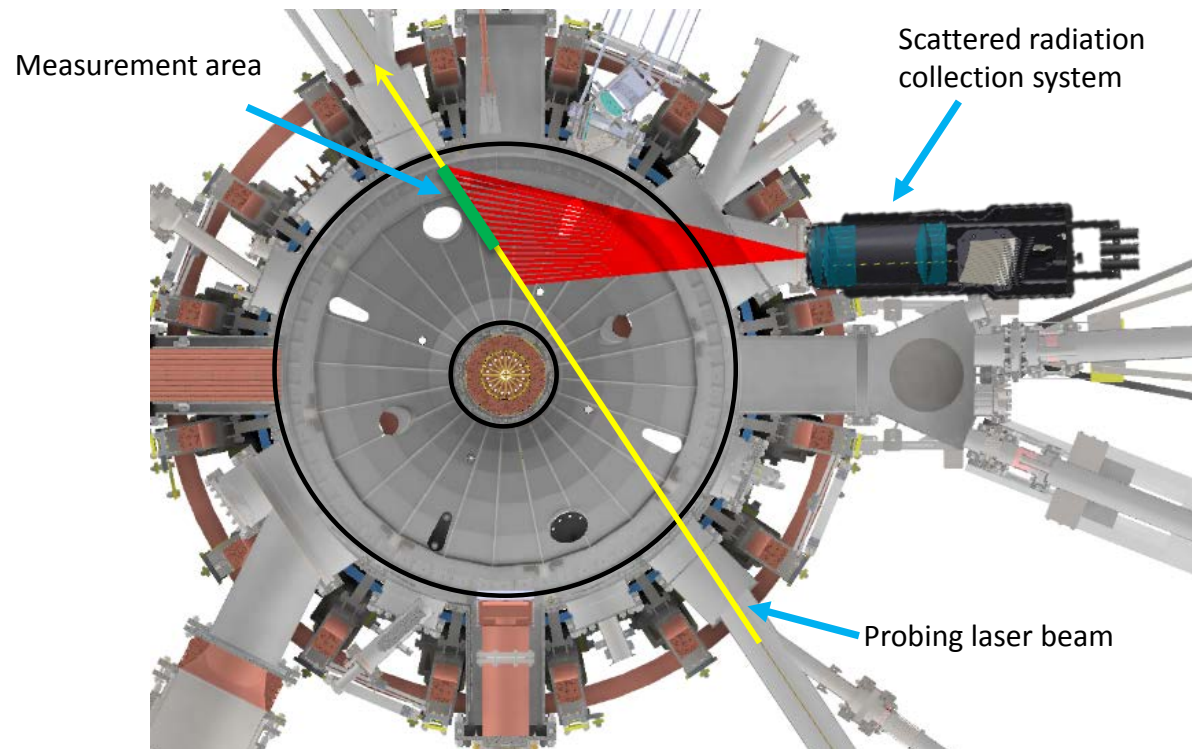
Auxiliary heating and CD systems

NBI	1 MW, 18-30 keV 1 MW, 25-50 keV	4 MW/m ³
LHCD	0.5 MW, 2.45 GHz	
ICRH	0.5 MW, 6-15 MHz	



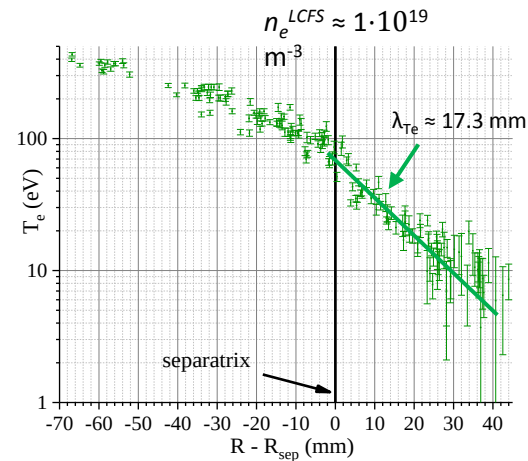
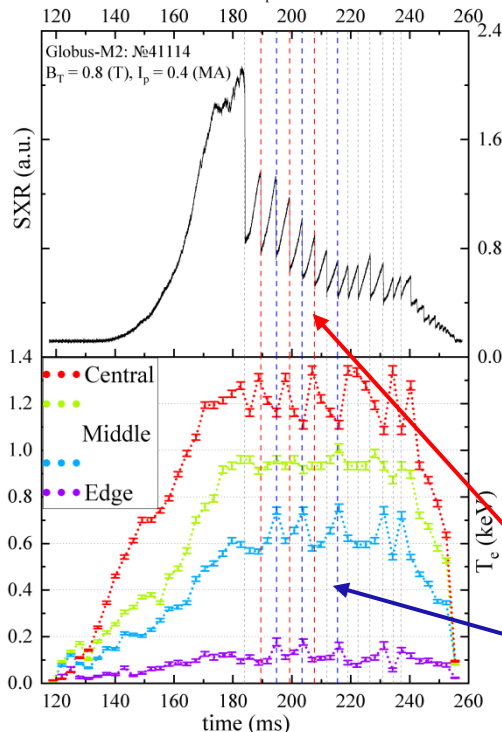
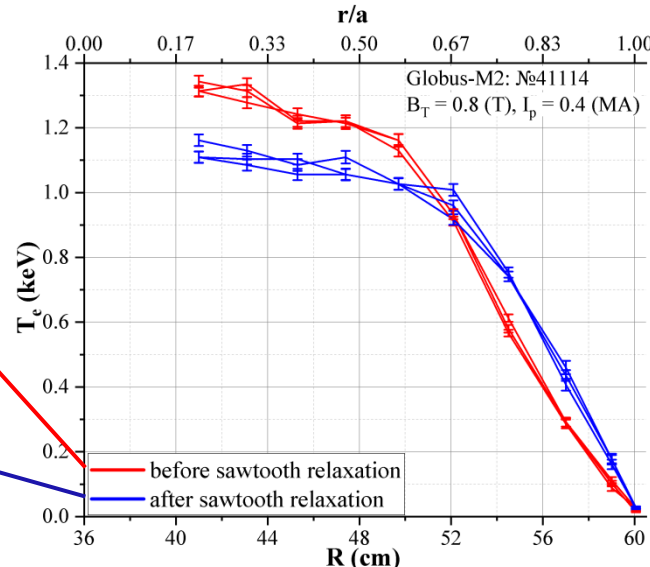
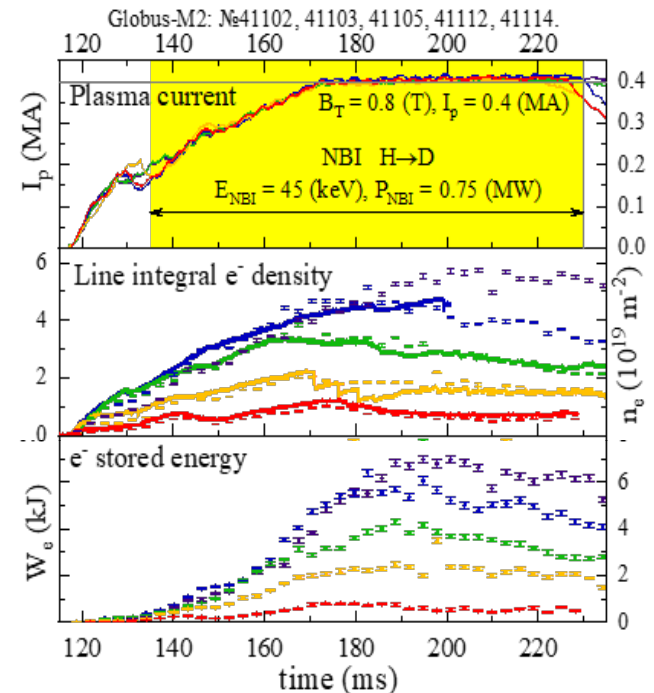
Thomson scattering diagnostics

- Probing laser DPSS Nd:YAG **1064 nm**, $E_L = 0,5-3$ J, **330 Hz**.
- Measurements of $n_e(R,t)$ and $T_e(R,t)$ in steady state mode.
- **10 spatial points** (possible increase up to 20-30) are available from the side of a low magnetic field from the separatrix to the magnetic axis with a **resolution of 10 - 20 mm**.
- Temperature measurements in the range **from 5 eV up to 5 keV**, at plasma density **from $5 \cdot 10^{17}$ up to $3 \cdot 10^{20} \text{ m}^{-3}$** .

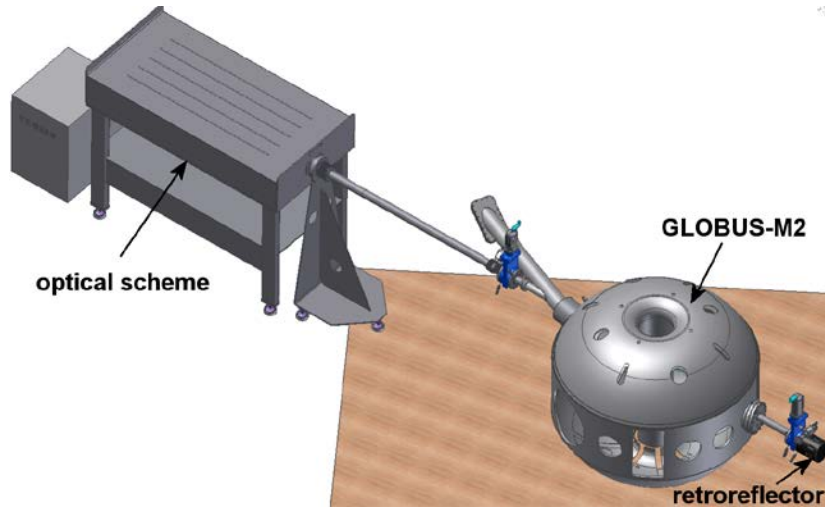


Thomson scattering diagnostics

- Possibility to measure T_e and n_e outside the separatrix and, as a result, to estimate the SOL power e-folding length.
- Determining the inversion radius for sawtooth oscillations.
- Combined analysis of TS and magnetic reconstruction data makes it possible to determine the dynamics of:
 - averaged plasma density;
 - energy stored by electrons.



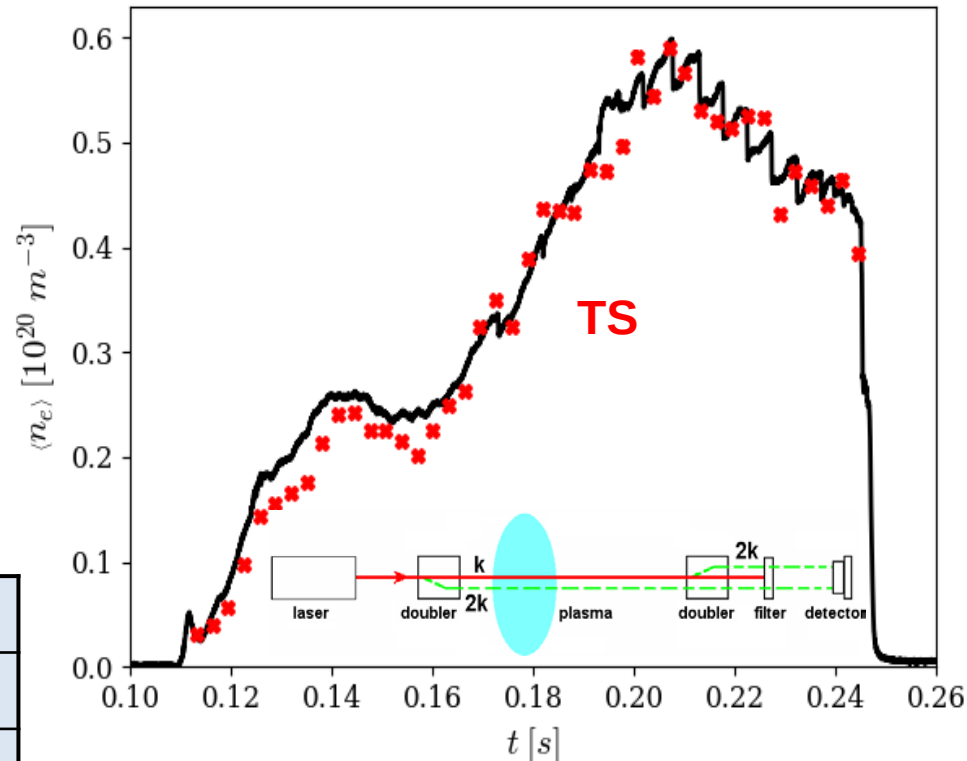
IR two-color dispersion interferometer



Linear density range	$5 \times 10^{17} - 3 \times 10^{20} \text{ m}^{-2}$
Spatial resolution	2 cm
Time resolution	20 μs
Probing wavelength	9.6 / 4.8 μm

The radiation of both wavelengths propagates along one path

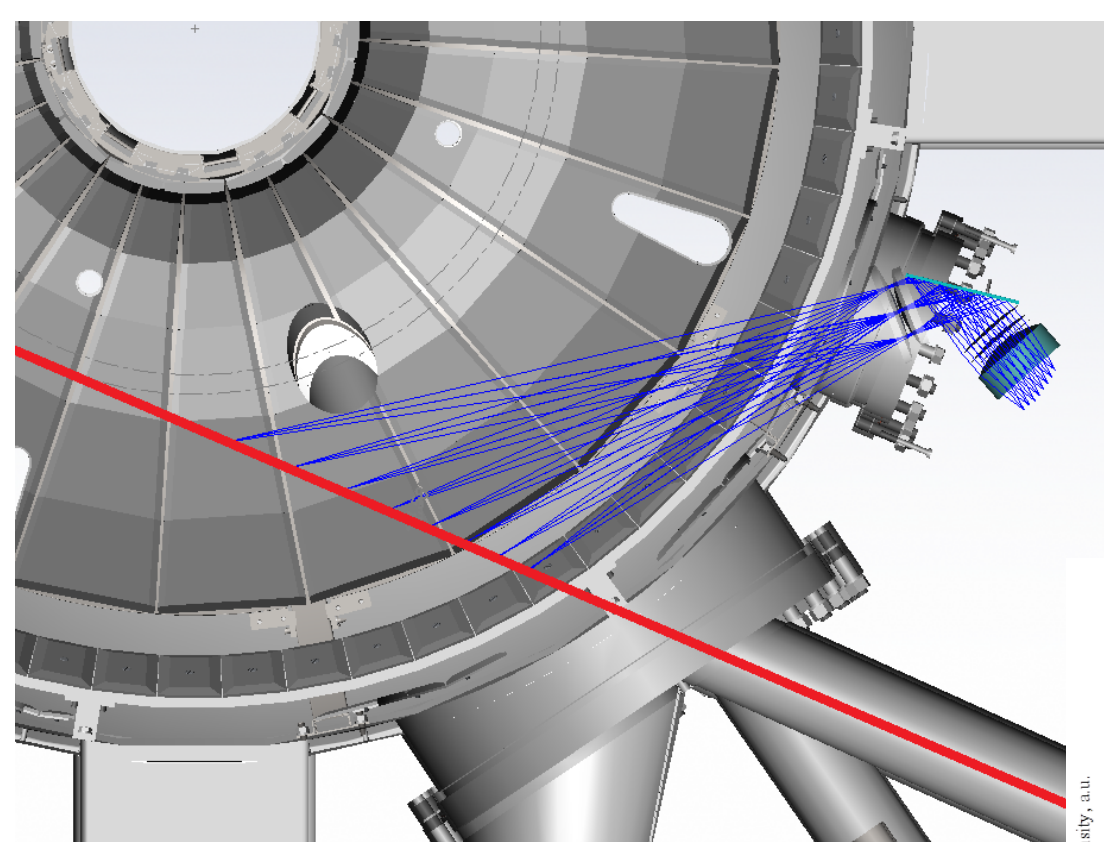
- Less sensitivity to vibrations compared to conventional IR interferometers



Wavelengths 9.6 and 4.8 μm

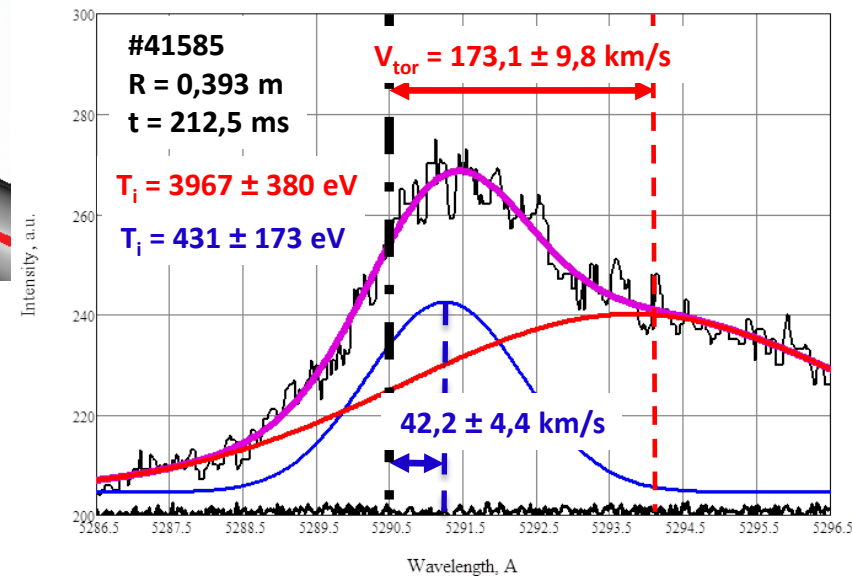
- Less sensitivity to refraction in comparison with microwave interferometers
- Robust operation is provided by usage of acousto-optical modulator and quadrature analysis method

CXRS



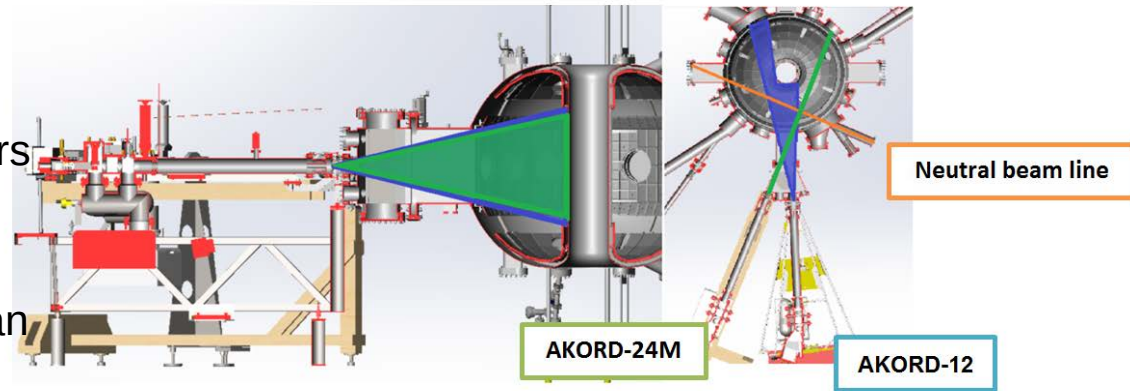
- The radiation of the C^{5+} line ($n = 8 \rightarrow 7$) is used.
 $\lambda_0 = 5290.525 \text{ \AA}$
- 8 spatial points located on the side of a low magnetic field from the separatrix to the magnetic axis.
- Measurements of the ion temperature profile $T_i(R, t)$ and the velocity of toroidal plasma rotation $V_{tor}(R, t)$.

chord #	1	2	3	4	5	6	7	8
R, m	0.36	0.39	0.42	0.45	0.48	0.51	0.53	0.56
Angle to magnetic surf., deg.	6.1	2.2	0.2	-0.5	-0.2	0.6	1.9	3.3

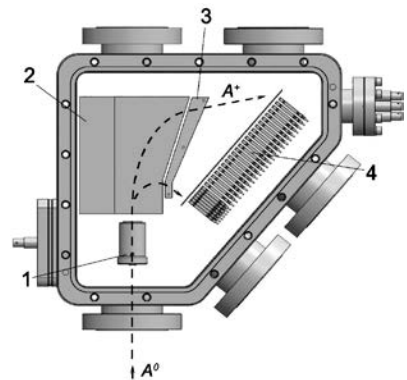


NPA

- The scanning system makes it possible to change the line of observation between tokamak shots in the vertical plane for both analyzers and in the horizontal plane for AKORD-12.
- In the case of discharges with NBI, an active scheme of diagnostics is realized. The measurements are localized in the region where the beam intersects with the analyzer's observation line, which makes it possible to reconstruct the ion temperature profile or the spatial distribution of fast ions.
- The new compact analyzer CNPA-09 has been tested in the experiment. It allows simultaneous registration of the entire energy spectrum from thermal to the energy of the injected beam and is less sensitive to stray magnetic fields.



A^0 – incoming atoms,
 A^+ - secondary ions,
 1 – stripping unit,
 2 – permanent magnet,
 3 - capacitor,
 4 - detectors.



Detecting atoms	H_0 or D_0
Energy range (H_0)	0.8 - 120 keV
Energy range (D_0)	0.8 - 60 keV
Mass suppression (H/D)	100
Number of energy channels	44
Energy resolution (for 15-50 keV)	10 %
Time resolution	100 μ s

Neutron spectrometer

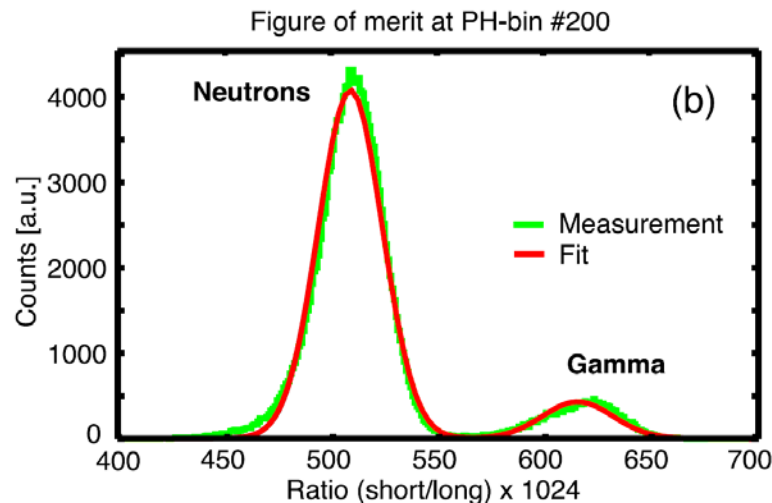
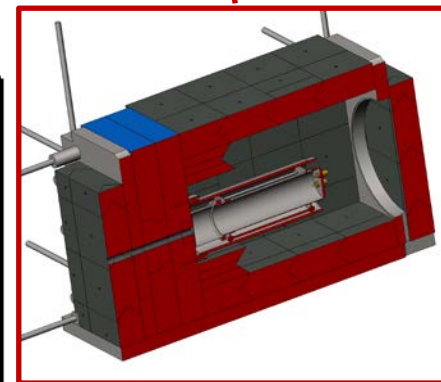
Two neutron spectrometers based on a liquid scintillator BC-501A (Saint Gobain Crystals) were installed.



- To reduce the effect of scattered neutrons and gamma radiation, the detector is protected with polyethylene and lead and equipped with collimator.
- The BC-501A scintillator provides good n/gamma separation.



Scintillator size	Ø51× 51 mm
Light output (% Anthracene)	78
Density	0.84 g/cm ³
Ratio H:C atoms	1.212
Decay time (short component)	3.2 ns
Wavelength of maximum emission	425 nm
Signal sampling rate	> 500 MHz
Maximum counting rate (with n/gamma separation)	~10 ⁶ 1/s



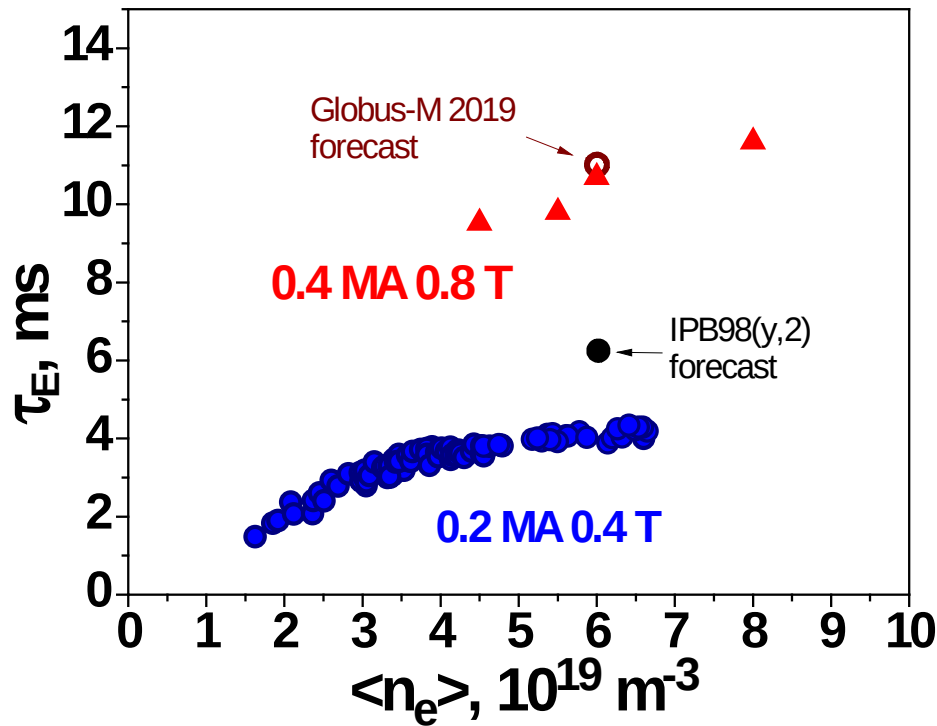
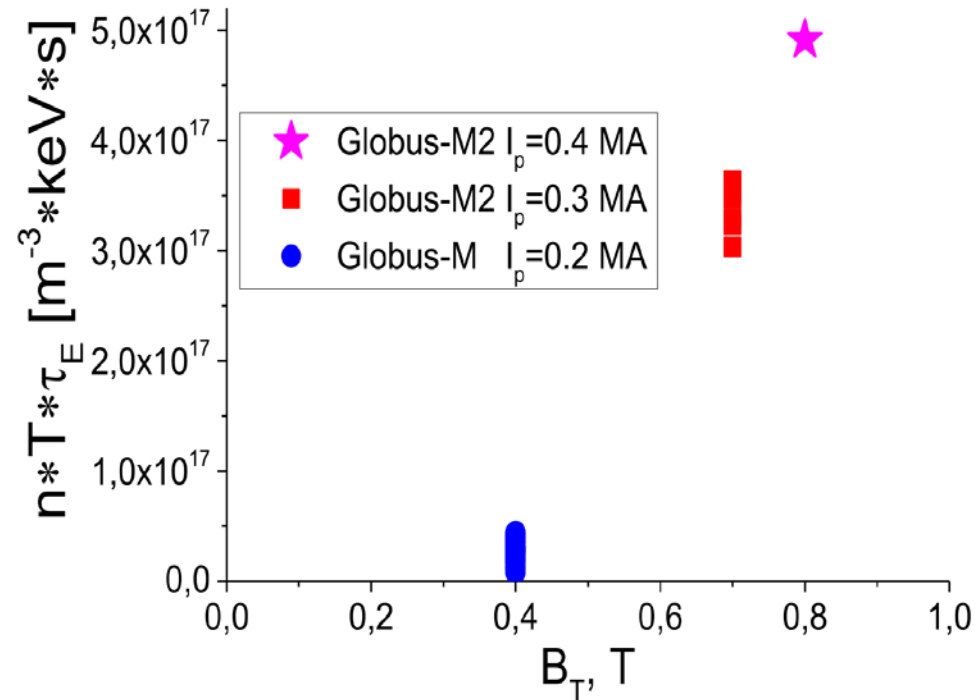
*Lead shield inside
polyethylene*



Globus-M2 main results

- **Energy confinement at an increased magnetic field**
- **Low hybrid current drive**
- **Influence of TAE on the fast ion confinement**
- **Reducing the heat load on the divertor with nitrogen puffing**
- **Observation of the hot ion mode**

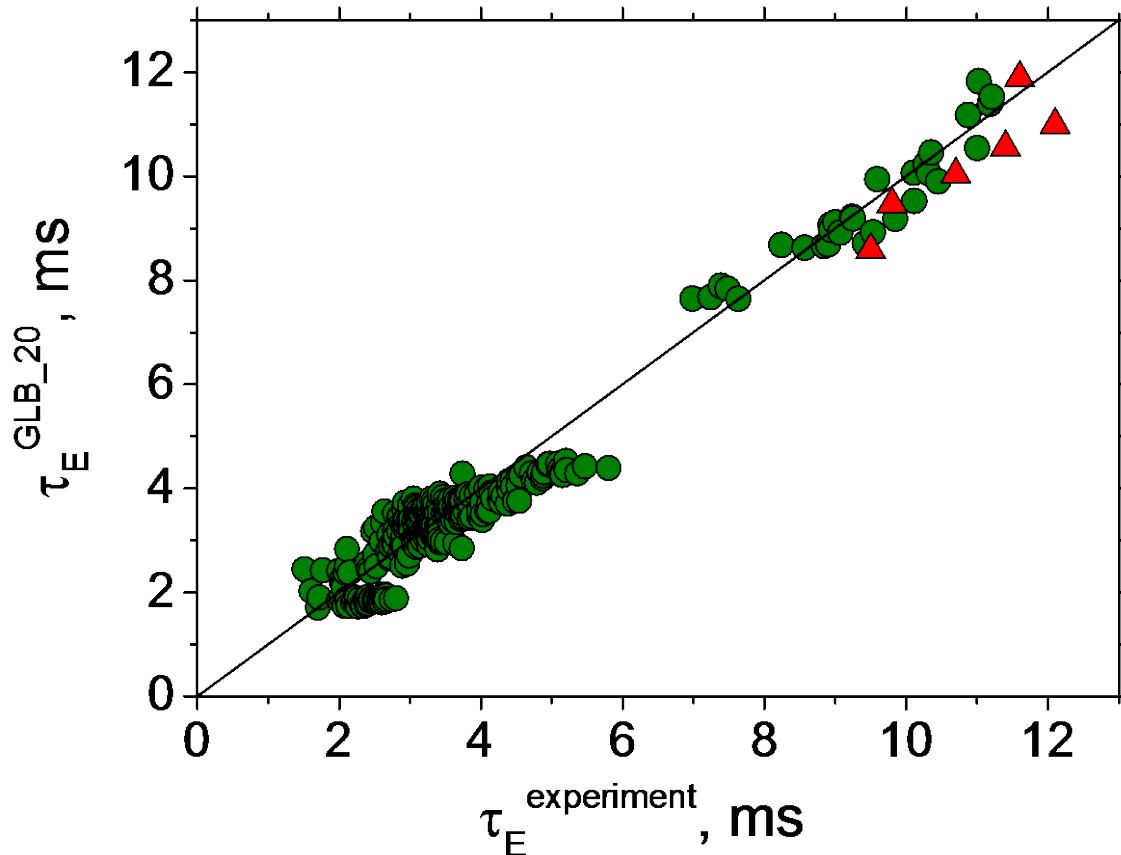
Energy confinement at an increased magnetic field



- An increase in the toroidal magnetic field from 0.4 to 0.8 T led to an increase in the value of $n \cdot T \cdot \tau_E$ by an order of magnitude due to a fourfold increase in temperature and a threefold increase in the energy confinement time.

Energy confinement at an increased magnetic field

$$\tau_E^{GLB_2020} = 0.01 \cdot I_p^{0.43 \pm 0.22} \cdot B_T^{1.19 \pm 0.1} \cdot P_{abs}^{-0.59 \pm 0.23} \cdot n_e^{0.58 \pm 0.1}$$



- For spherical tokamaks in the studied range of B_T (up to 0.8 T) and I_p (up to 0.4 MA), a strong dependence of the energy confinement time on the magnetic field was confirmed, which differs significantly from the scaling for conventional tokamaks:

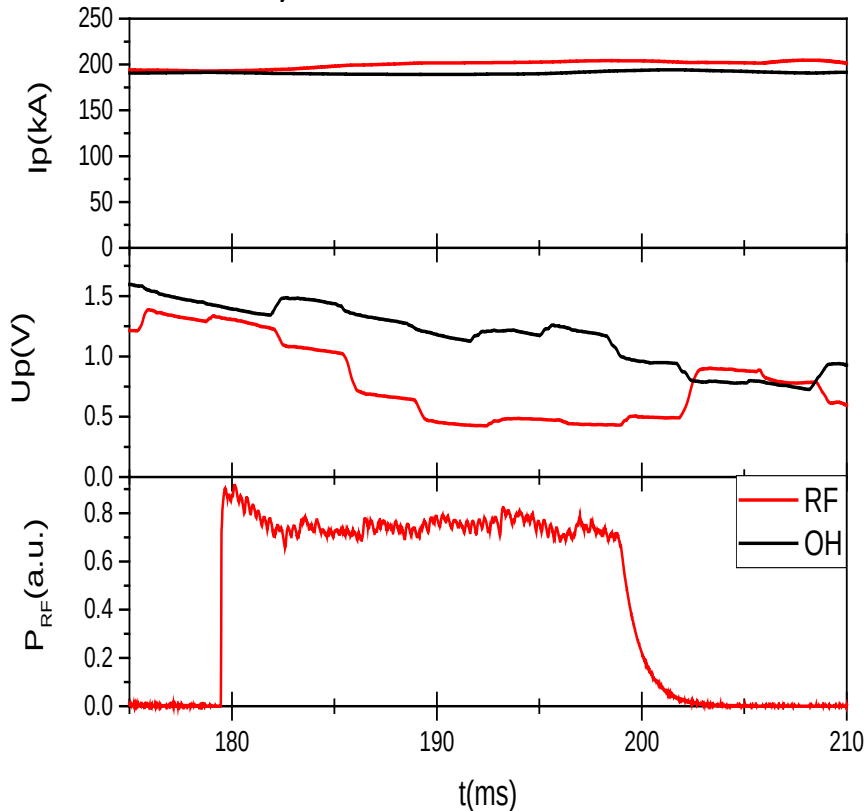
$$\tau_E^{IPB98(y,2)} \sim I_p^{0.93} \cdot B^{0.15} \cdot P_{abs}^{-0.69} \cdot n_e^{0.41}$$

- Using the data obtained from the spherical tokamaks START, MAST, NSTX, a scaling for the energy confinement time was derived, taking into account the size of the facility:

$$\tau_E^{scal} = 0.066 \cdot I_p^{0.53} \cdot B_T^{1.05} \cdot P_{abs}^{-0.58} \cdot n_e^{0.65} \cdot R^{2.66} \cdot \kappa^{0.78}$$

Low hybrid current drive

Toroidal launch of the LH waves
38686/38694

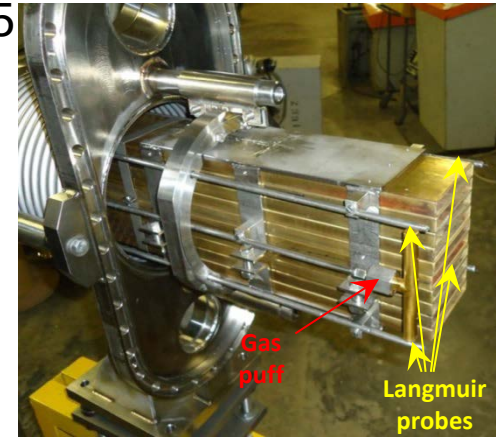
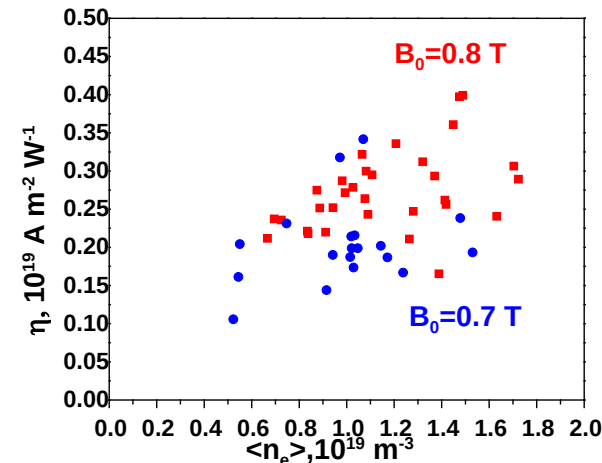


$B_t = 0.8$ T; $I_p = 200$ kA ,
 $\langle n_e \rangle = (1.0 - 1.5) \cdot 10^{19} \text{ m}^{-3}$
 $T_e(0) = 500$ eV, $Z_{eff} = 2.5$

$f = 2.45$ GHz
 $P_{LH} = 150\text{-}200$ kW,
 $N_{tor} = -3.0$

$\Delta U = (0.6 - 0.8)$ V;

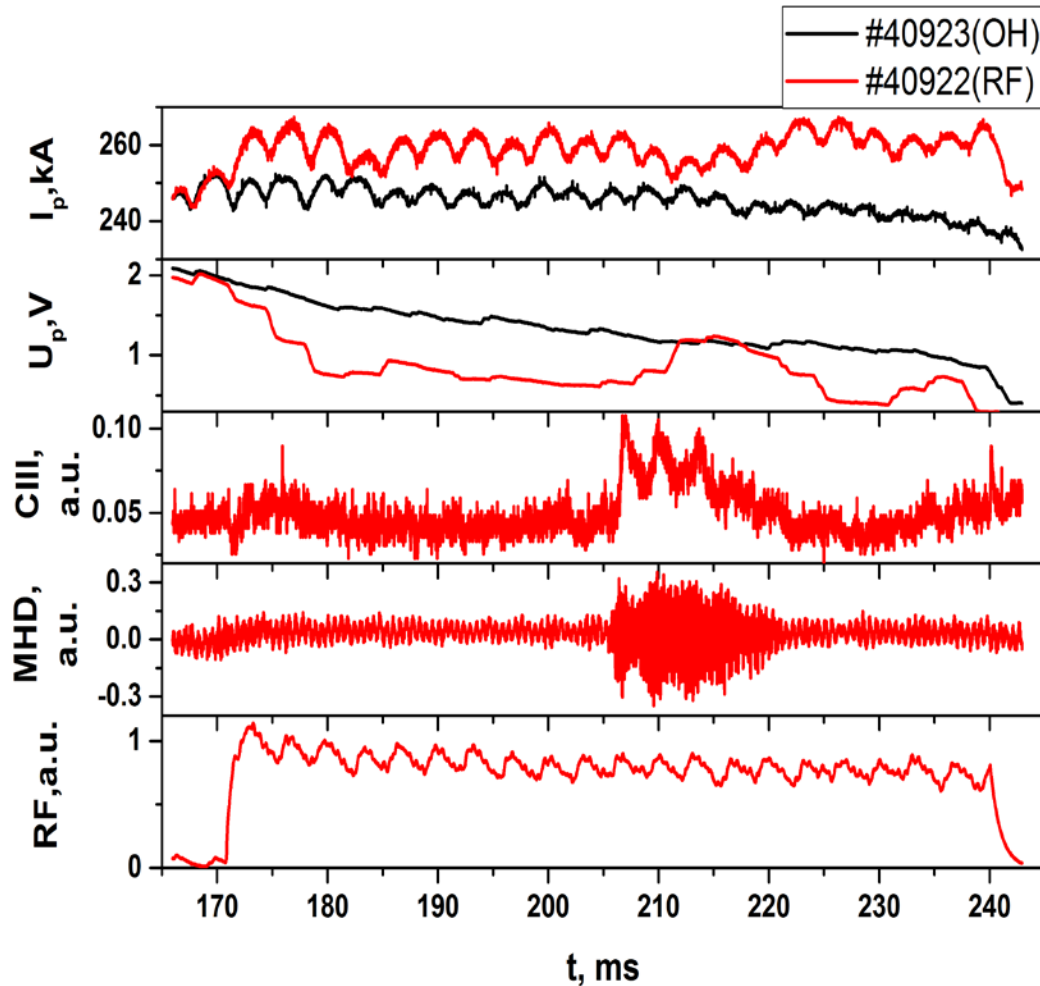
$I_{LHCD} > 50\% I_p$
 $\eta = (0.2 - 0.4) \cdot 10^{19} \text{ A} \cdot \text{m}^{-2} / \text{W}$



➤ The efficiency of non-inductive current drive at the level of conventional tokamaks was demonstrated

Low hybrid current drive

Poloidal launch for the LH waves



$B_t = 0.8$ T; $I_p = 250$ kA;
 $\langle n_e \rangle = 1.5 \cdot 10^{19} \text{ m}^{-3}$
 $T_e(0) = 550$ eV, $Z_{\text{eff}} = 2,5$

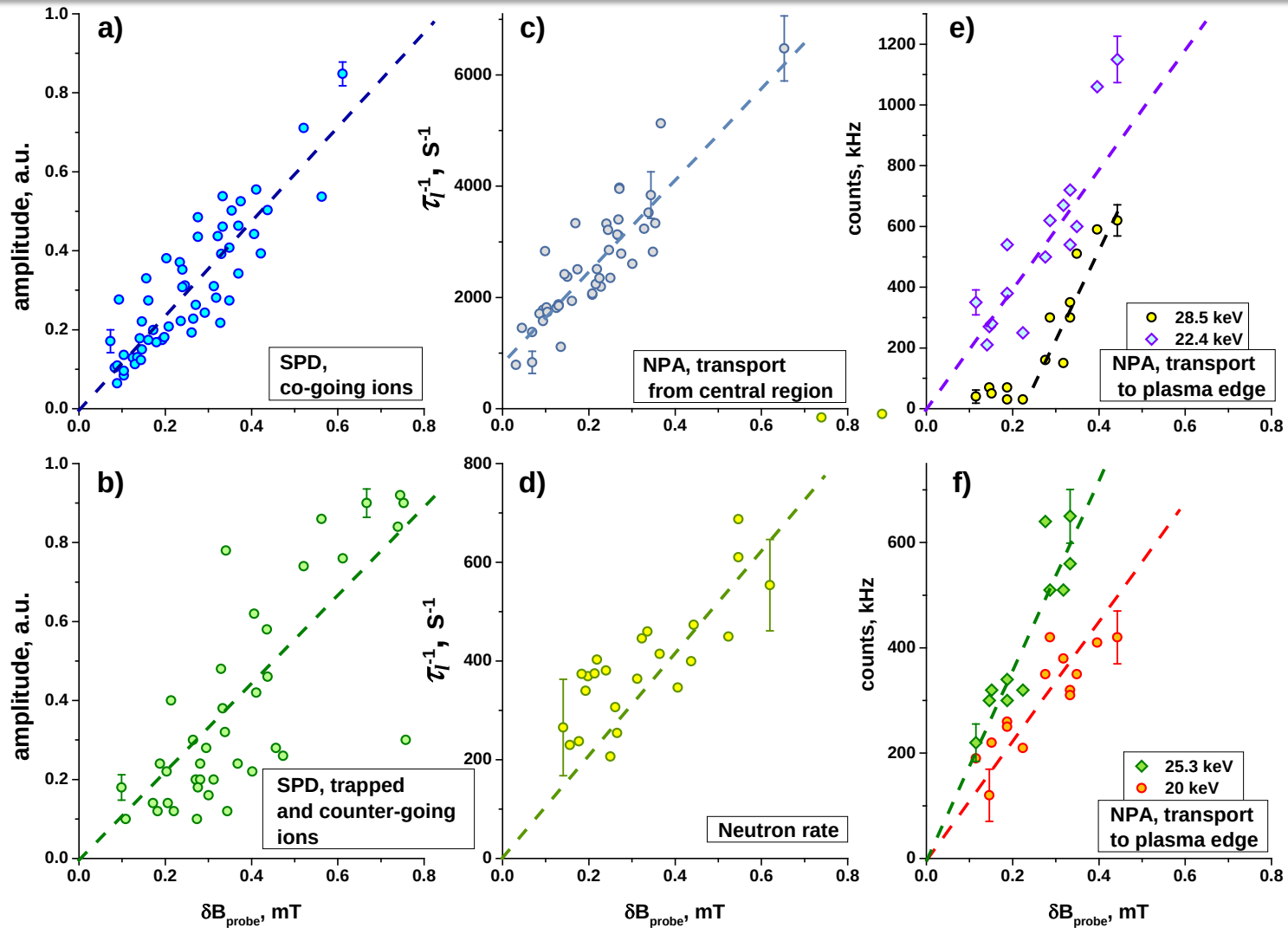
$f = 2.45$ GHz
 $P_{\text{LH}} = 200$ kW,
 $N_{\text{pol}} = -2,8$

$\Delta U = 0,8$ V; $\Delta U/U \approx 50$ %

$I_{\text{LHCD}} \approx 50\% I_p$
 $\eta \approx 0,35 \cdot 10^{19} \text{ A} \cdot \text{m}^{-2}/\text{W}$

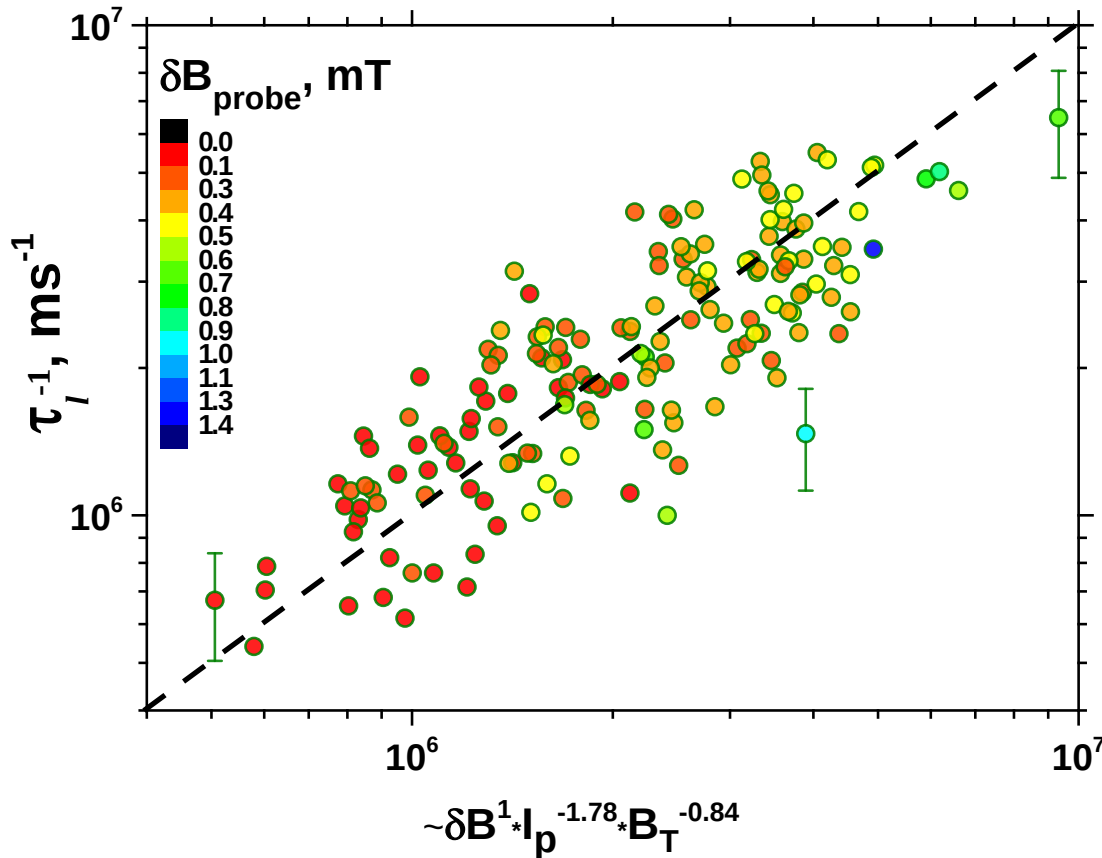
- The efficiency of current drive for poloidal and toroidal launching of pump waves is practically the same
- MHD instabilities lead to disruption of current drive

Influence of TAE on the fast ion confinement



- Various diagnostics show a linear dependence of fast ion losses on the TAE amplitude, which confirms the resonant mechanism of these losses.

Influence of TAE on the fast ion confinement



Fast ion transport from the central plasma region was investigated using NPA with equatorial LOS.

Experiment:

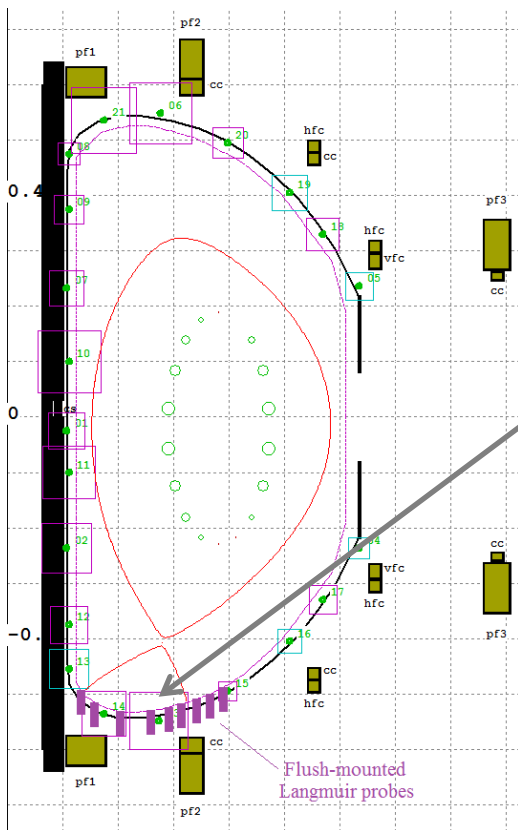
$$\tau_l^{-1} \sim I_p^{-1.78 \pm 0.06} B_T^{-0.84 \pm 0.04}$$

Modeling (ions interact with the wave at different I_p, B_T):

$$\tau_l^{-1} \sim I_p^{-1.9 \pm 0.08} B_T^{-1.18 \pm 0.37}$$

- The observed dependence of fast ion transport on plasma current and toroidal magnetic field is promising for the next generation of compact spherical tokamaks.

Reducing the heat load on the divertor with nitrogen puffing



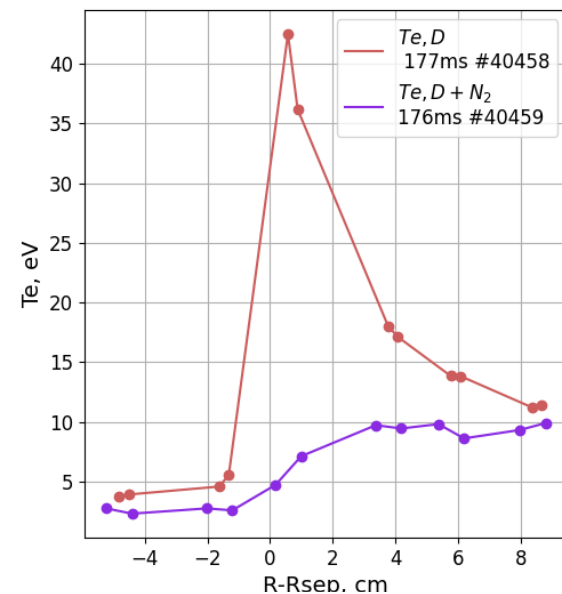
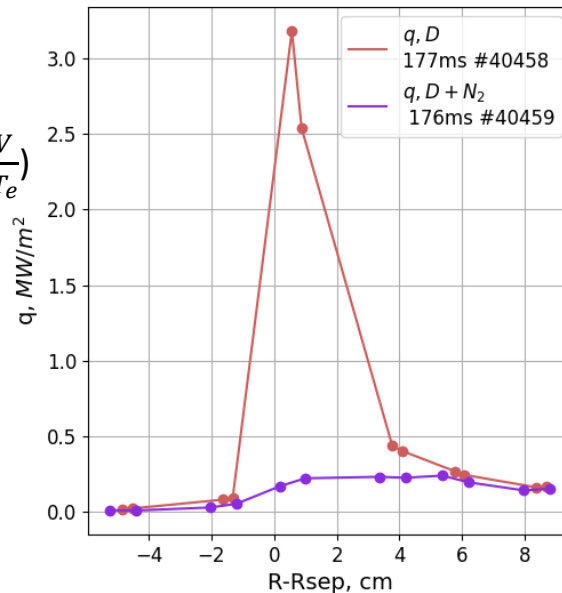
Array of 10 Langmuir probes in the divertor area



Heat flux density on the plates:

$$q = \gamma k T_e I_{\text{isat}} / (e S_{\text{pr}}),$$

$$\gamma(V) = 2.5 \frac{T_i}{T_e} - \frac{eV}{kT_e} + 2 \left[\left(2\pi \frac{m_e}{m_i} \right) \left(1 + \frac{T_i}{T_e} \right) \right]^{-1/2} \exp\left(\frac{eV}{kT_e}\right)$$

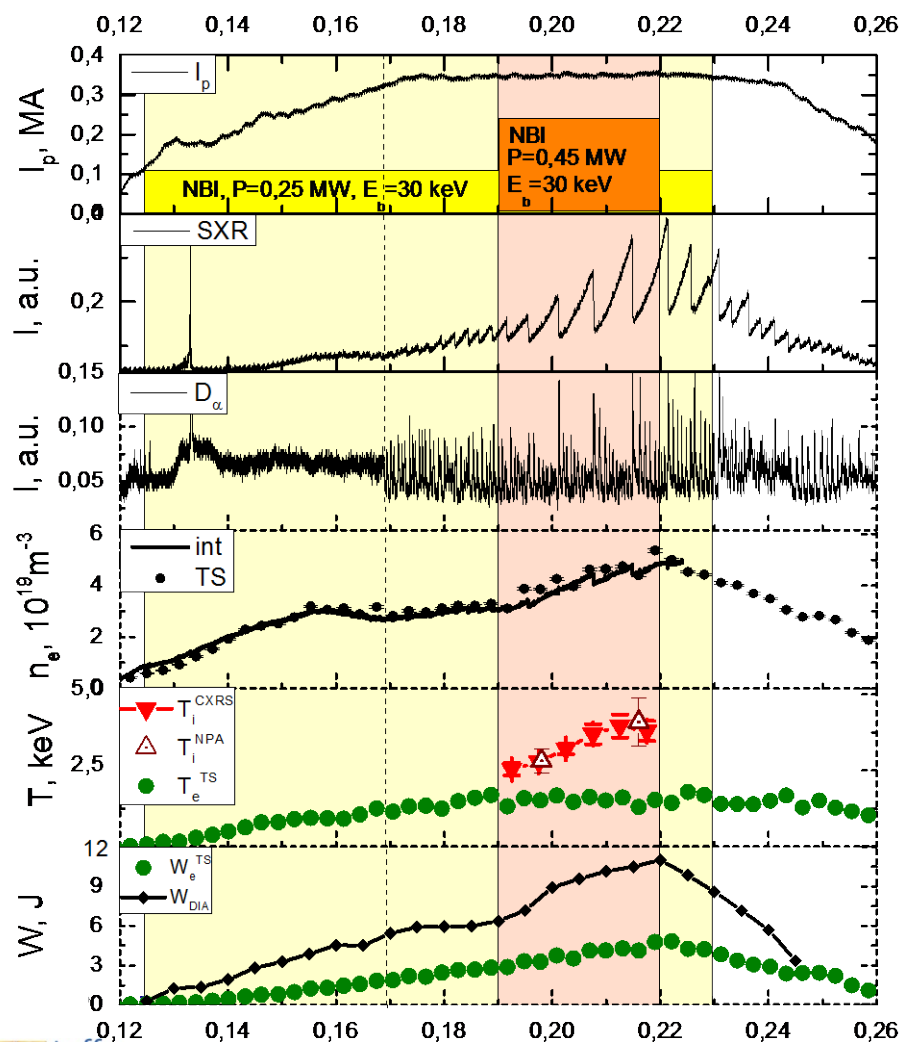


➤ The nitrogen puffing leads to a decrease in the heat flux density into the divertor by more than an order of magnitude without a significant deterioration in plasma performance inside the separatrix.

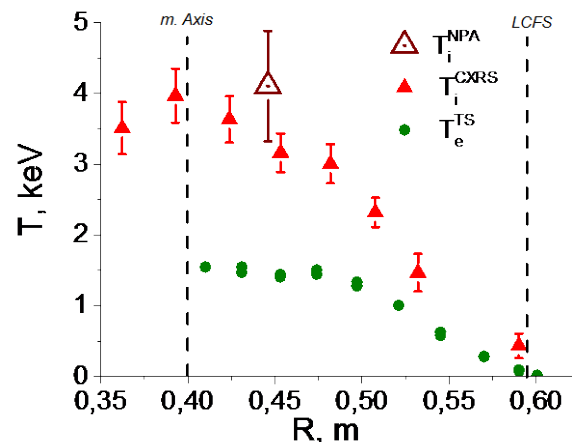
Observation of the hot ion mode

The hot ion mode ($T_i = 4$ keV) was achieved with a total injection power of 0.7 MW

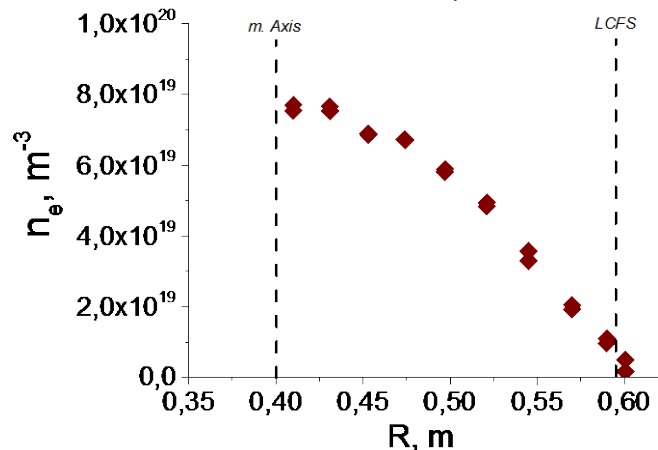
Globus-M2 #41585, $B_T = 0,9$ T, $I_p = 0.35$ MA, $\langle n_e \rangle = (4-5) \cdot 10^{19} \text{ m}^{-3}$, $\tau_E \approx 14$ ms, $V_T \approx 150$ km/h



#41585, NBI 30 keV 0,45+0,25 MW, $B_T = 0,9$ T, $t = 0,215$ s



#41585, NBI 30 keV 0,45+0,25 MW, $B_T = 0,9$ T, $t = 0,215$ s

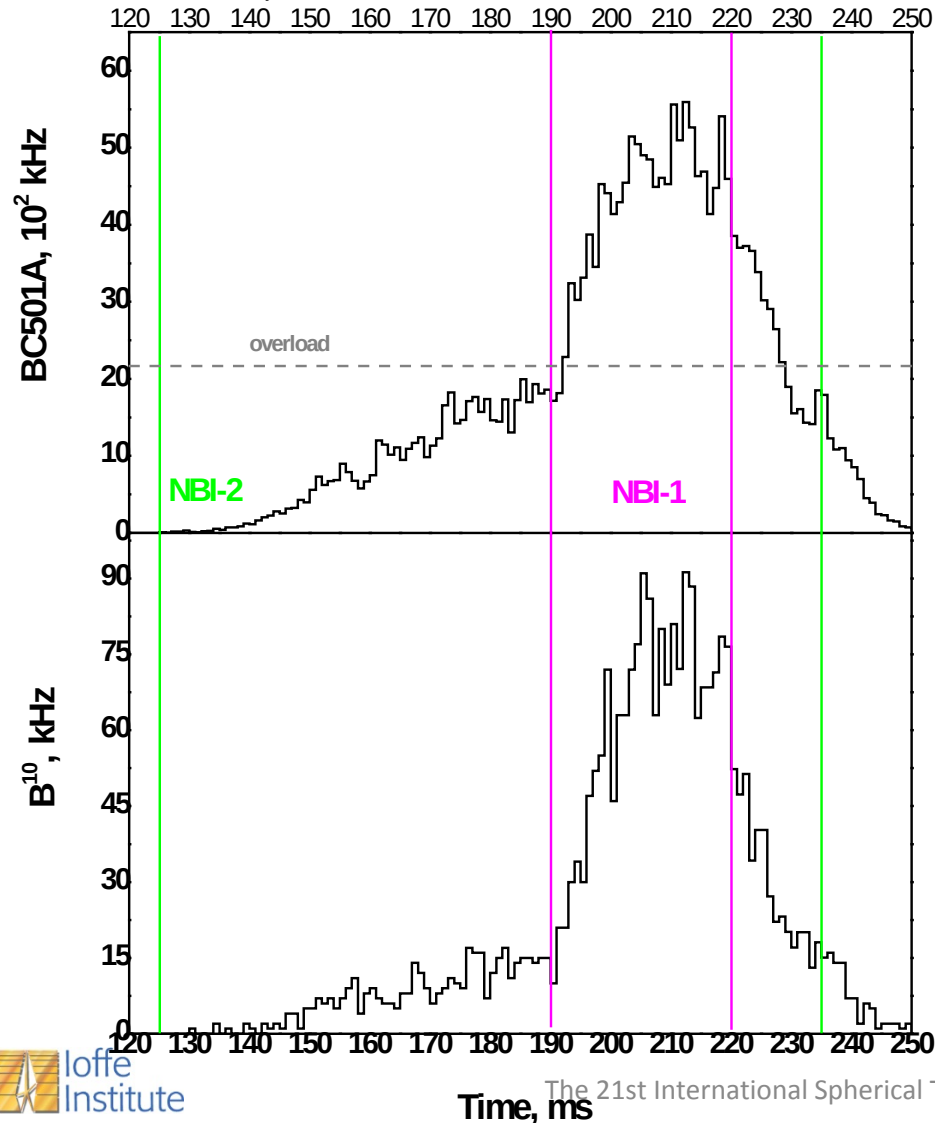


➤ $n_{i0} T_{i0} \tau_E \approx 4.5 \times 10^{18} \text{ m}^{-3} \text{ keVs}$

Observation of the hot ion mode

#41585: $B_T=0.9$ T, $I_p=0.35$ MA, $\langle n_e \rangle=(4-5)\cdot 10^{19}$ m $^{-3}$,

D-NBI: 30 keV, 0.25+0.45 MW



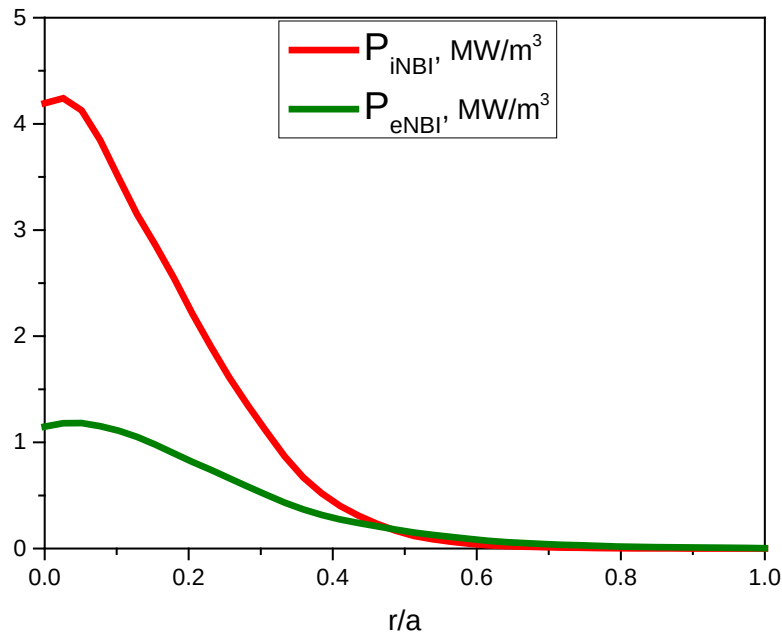
➤ The total yield of DD neutrons exceeded 10^{12} s $^{-1}$.
In terms of the DT reaction, this is more than 10^{14} s $^{-1}$.

- A collimator for a neutron spectrometer has been developed and installed.
- The diagnostic has been calibrated using a reference source Am ^{241} .

Observation of the hot ion mode

The NUBEAM code was used to determine the deposition of the neutral beam power to plasma electrons and ions.

Profiles of the absorbed beam power for the electron and ion plasma components



Input power and beam energy composition

P_{NBI} , kW	$450 (_{NBI-1}) + 250 (_{NBI-2})$
NBI-1 (E, E/2, E/3), %	82/13/5
NBI-2 (E, E/2, E/3), %	39/35/26

Balance of injected beam power

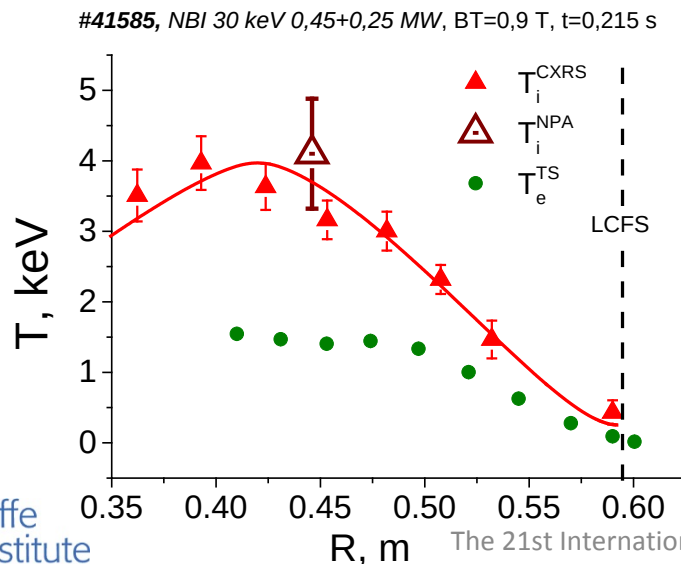
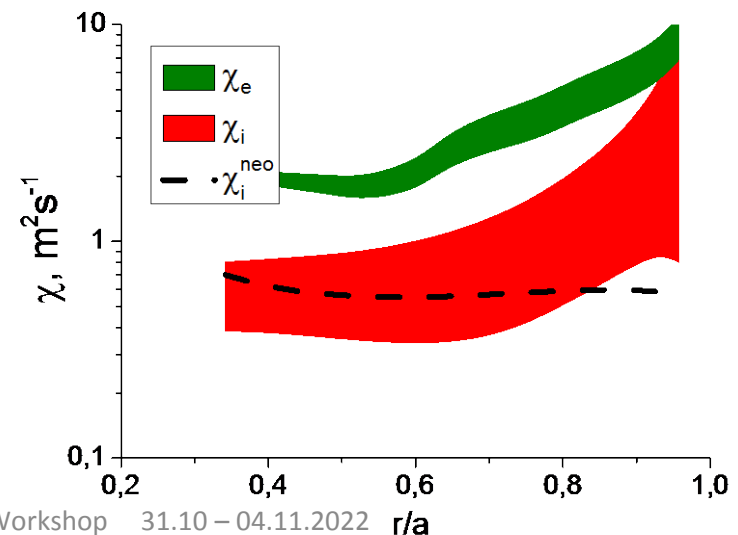
P_{iNBI} , kW	300
P_{eNBI} , kW	140
CX losses, kW	200
Bad orbit losses, kW	50
Shine-through losses, kW	10

- The obtained profiles of the absorbed beam power were utilized by the ASTRA code

Observation of the hot ion mode

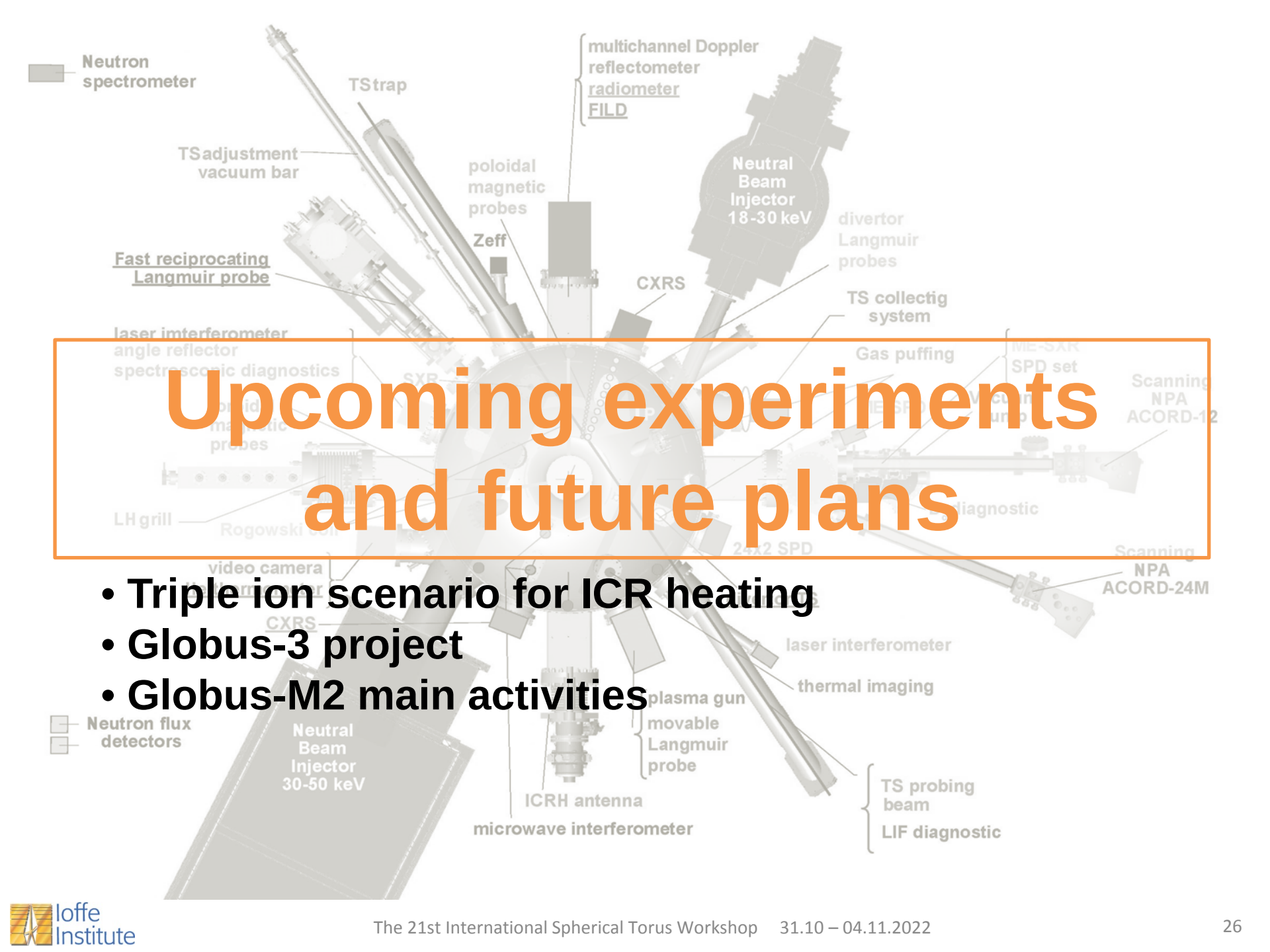
- The ASTRA code solved the poloidal magnetic flux diffusion equation together with the Grad-Shafranov force balance equation. The shape of the last closed magnetic surface, obtained using the method of moving current filaments, was used as the boundary condition.
- The value of the effective charge was used to calculate the concentration of hydrogen ions and plasma conductivity. Carbon was specified as the main impurity.
- The plasma conductivity and bootstrap current were assumed to be neoclassical and calculated using the NCLASS code. Neoclassical thermal diffusivity was also calculated using the NCLASS code.
- To determine the coefficients of electron and ion thermal diffusivity, the inverse problem was solved: the coefficients of thermal diffusivity were calculated based on the measured profiles. Measurement errors and radiation losses were taken into account.

➤ **The ion thermal diffusivity is well described by the neoclassical theory**



Achieved plasma parameters

Parameter	Achieved
Magnetic field	0.9 T
Plasma current	0.43 MA
Ion temperature	4 keV
Electron temperature	1.6 keV
Density (averaged)	$2.5 (1.5) \cdot 10^{20} \text{ m}^{-3}$
Stored energy	16 kJ
Triple product	$4.5 \cdot 10^{18} \text{ m}^{-3} \cdot \text{keV} \cdot \text{s}$
Neutron yield DD (DT equivalent)	$> 10^{12} (10^{14}) \text{ s}^{-1}$
Fraction of non-inductive current (LHCD)	$> 60 \%$



Upcoming experiments and future plans

- Triple ion scenario for ICR heating
- Globus-3 project
- Globus-M2 main activities

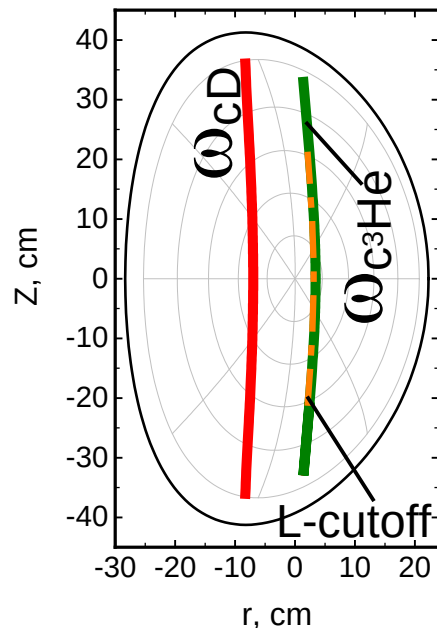
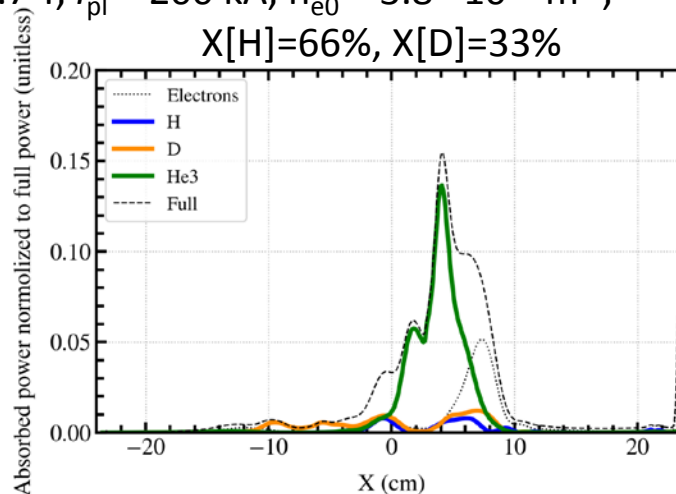
Triple ion H-D-(^3He) scenario for ICR heating

➤ Simulations of the scenario of ion cyclotron heating in plasma with three types of ions has been carried out for the Globus-M2 conditions.

- To implement the 3-ion scenario, it is necessary to choose the ratio of the H and D concentrations in such a way as to match the cutoff position of the FMS wave for a two-component H–D plasma with the position of the ^3He cyclotron resonance.

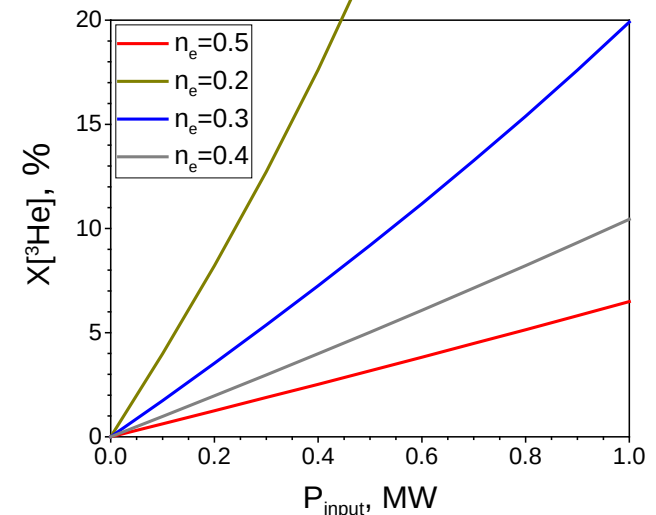
Location of cyclotron harmonics and power distribution of the absorbed wave in the tokamak cross section.

$f = 7 \text{ MHz}$, $B_{\text{tor0}} = 0.7 \text{ T}$, $I_{\text{pl}} = 200 \text{ kA}$, $n_{e0} = 3.8 \cdot 10^{19} \text{ m}^{-3}$,
 $X[\text{H}] = 66\%$, $X[\text{D}] = 33\%$



e^-	Ions	He^3	H	D
40%	60%	41%	6%	13%

Dependence of the partial concentration of ^3He on the pump power required for the fraction of accelerated ions with $E < 80 \text{ keV}$ to be more than 70%.



- Approbation of the method on the Globus-M2 tokamak

Globus-3 project

- **The development of the concept of a compact spherical tokamak of the next generation, the Globus-3 project, has begun.**

The main features of the facility:

- long pulse (plasma current plateau exceeds 2-3 seconds);
- high toroidal magnetic field B_{t0} (not less than 1.5 T);
- aspect ratio is not more than 1.8;
- powerful auxiliary heating (5-8 MW).

Restrictions on the parameters due to the existing infrastructure of the Ioffe Institute:

- total capacity of the power supplies is not more than 125 MVA;
- major radius R is not more than 1 m;
- .

Several options of the electromagnetic system (EMS) are analyzed:

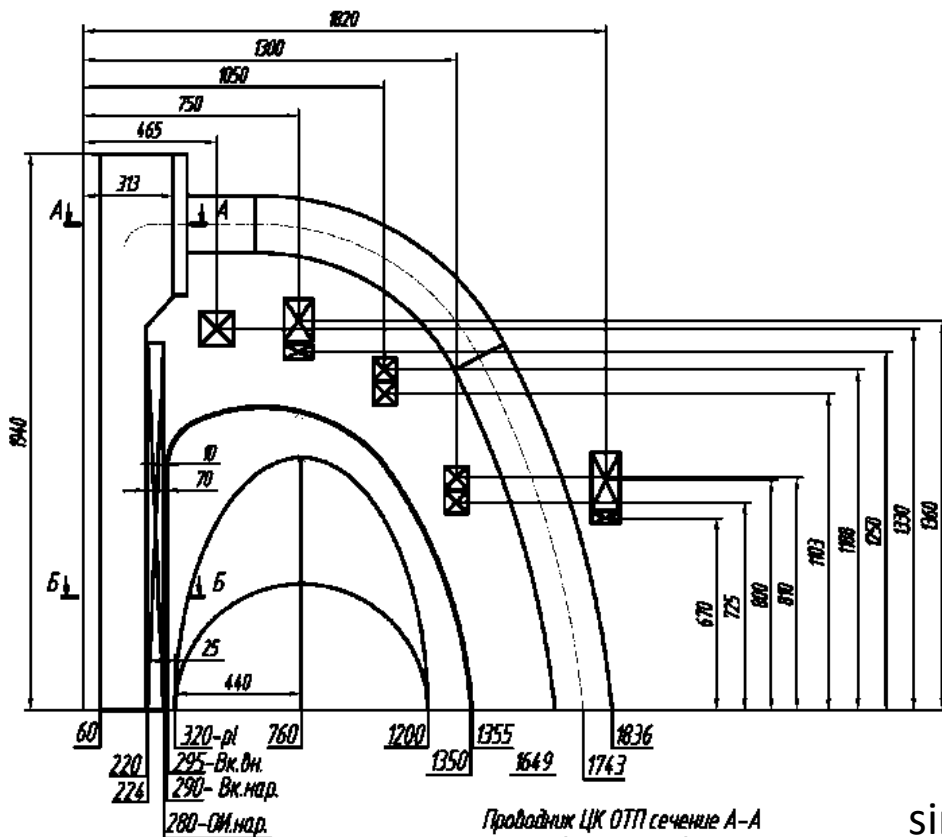
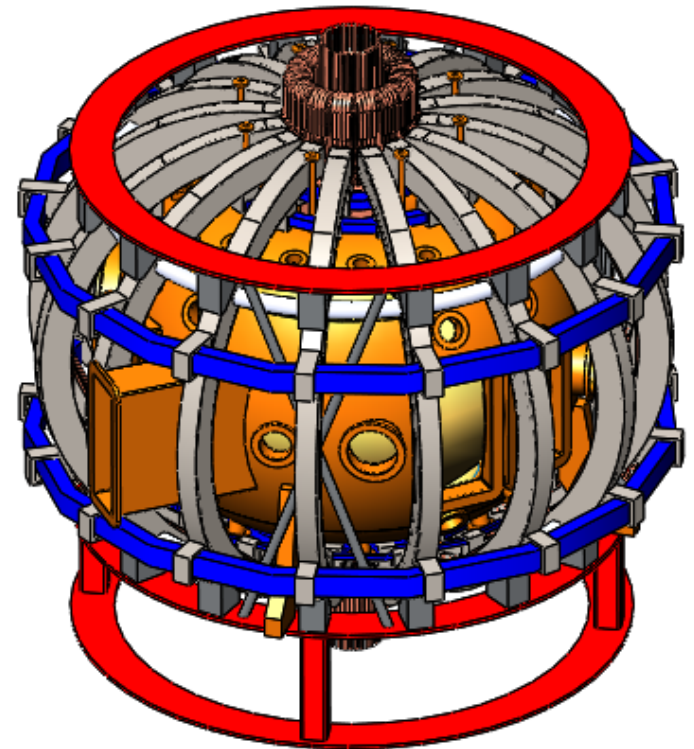
- warm copper EMS;
- copper EMS pre-cooled to nitrogen temperatures;
- superconducting EMS using LTSC and HTSC.

Globus-3 project

➤ Pre-conceptual design of a tokamak with warm copper coils was done

Main engineering parameters

$R = 0.76 \text{ m}$; $a = 0.44 \text{ m}$; $A = 1.73$; $k_{95} = 1.8$; $B_{t0} = 1.5 \text{ T}$; $I_p = 0.8 \text{ MA}$;
 $\Delta t_{I\text{-plateau}} = 2 \div 3 \text{ s}$; pulse repetition time $\leq 30 \text{ min}$; overheating of coils per impulse $\leq 40^\circ\text{C}$;
 gap between the plasma and the vessel on the HFS 25 mm ; $N_{TF} = 16$; $\Delta_{T\text{-ripple}} \leq 0.4\%$.



single-layer all-welded vacuum vessel (AISI 316L)

Globus-M2 main activities

- Achievement of a regime with maximum values of the magnetic field (1 T) and plasma current (0.5 MA)
- Investigation of plasma heating and non-inductive current drive by means of neutral beam injection
- Carrying out experiments on plasma heating using waves of the ion-cyclotron frequency range
- Discharge startup and current maintenance using waves of the lower hybrid frequency range
- Development of the next generation compact spherical tokamak



THANK YOU FOR YOUR ATTENTION !

Wednesday, Nov. 2

Ekaterina Tkachenko – “Analysis of Globus-M2 tokamak plasma heating experiments using diamagnetic measurements”.

Wednesday, Nov. 2

Anna Kudriavtseva – “Verification of toroidal field coil stress analysis based on the measurements in experiments on tokamak Globus-M2”.

Friday, Nov. 4

Nikita Zhiltsov – “Electron heating during neutral beam injection at Globus-M2”.