Fusion Research in Ioffe Institute

L.G.Askinazi

On behalf of FT-2, Globus-M, TUMAN-3M, Diagnostics and Theory Teams
Ioffe Institute, St. Petersburg, Russia

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Joint-Stock Company "INTEHMASH", St. Petersburg, Russia
KTH Royal Institute of Technology, Stokholm, Sweden
Saint Petersburg State Polytechnical University, St. Petersburg, Russia

Outline

- Fusion Research in Ioffe: Directions and Structure
- Tokamak Plasma Physics:
  - –LH Current drive (FT-2 and Globus-M)
  - –NBI, Fast particles and Alfven waves physics (Globus-M and TUMAN-3M) in support of Globus-M2 project
  - –GAM studies: turbulence, GAM and transport interplay (FT-2, Globus-M and TUMAN-3M)
- Plasma Theory
- Diagnostics for ITER

Fusion Research in Ioffe Institute: Directions and Structure

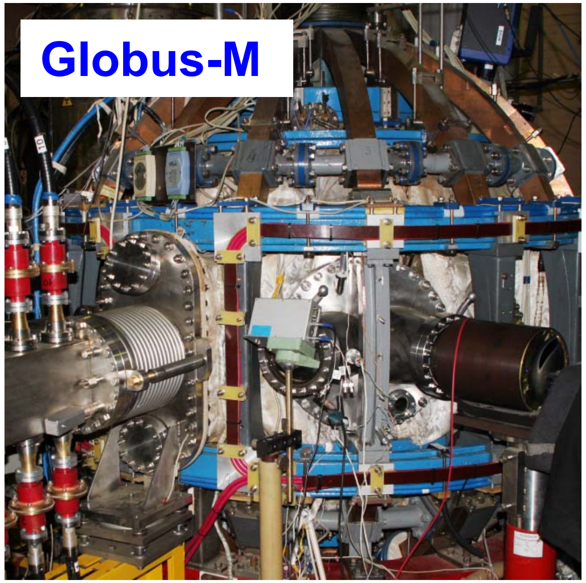
Fusion research in Ioffe Institute is being conducted in two major fields:

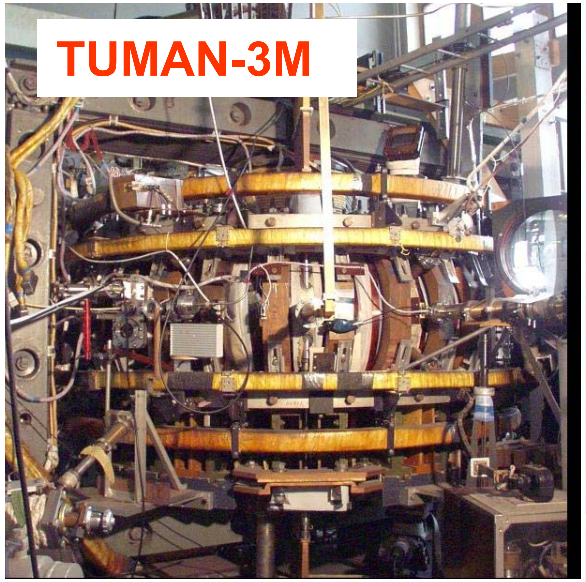
- **Basic high temperature plasma physics, both experimental and theoretical:**
  - Wave propagation in toroidal plasmas
  - Energetic ion physics
  - Plasma turbulence characterization and its interplay with confinement
- **Reactor oriented studies:**
  - Development of tokamak plasma diagnostics, including three contracts with ITER IO
  - Research in support of neutron source based on spherical tokamak concept

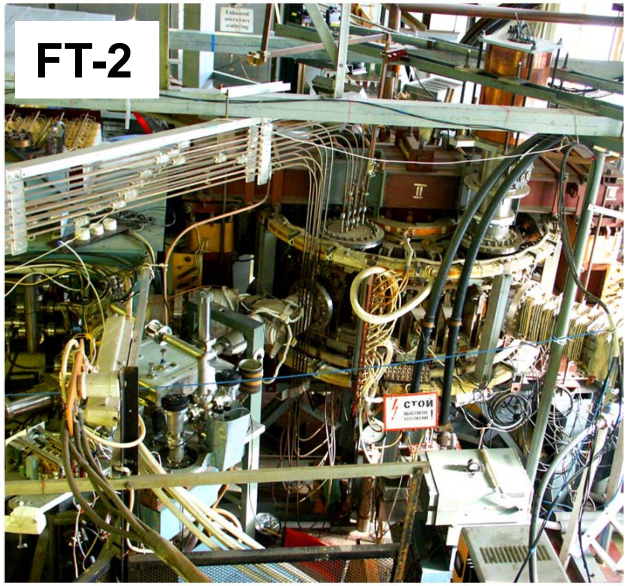
Tokamak Plasma Physics

Tokamak experiments

	A	R, m	a, m	B_t, T	I_p, kA	Shaping	Limiter or Divertor	Auxiliary Heating and CD (MW)
Globus-M	1.5	0.36	0.24	0.4	250	b/a= 2.0 $\delta \leq 0.5$	divertor	NBI (1.0), ICRH (1.0), LHCD (0.5)
TUMAN-3M	2.4	0.53	0.22	1.0	190	circular	limiter	NBI (0.6)
FT-2	7	0.55	0.08	2.3	35	circular	limiter	LHCD, LHH (0.3)



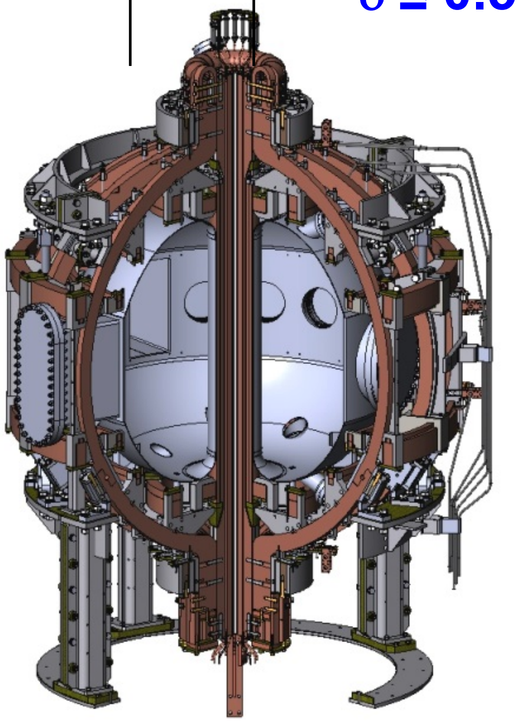




Tokamak Plasma Physics

Globus-M upgrade: Globus-M2 project

	A	R, m	a, m	B_t, T	I_p, kA	Shaping	Limiter or Divertor	Auxiliary Heating and CD
Globus-M2	1.5	0.36	0.24	1.0	500	b/a= 2.0 $\delta \le 0.5$	divertor	NBI (1.0), ICRH (1.0), LHCD (0.5)



LH Current Drive Experiments: FT-2 and Globus-M

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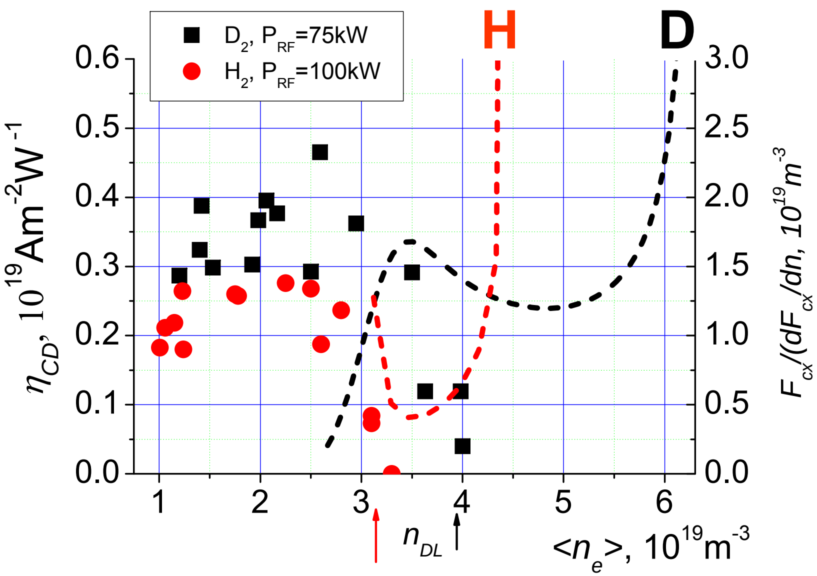
- **FT-2**: High B_t=2.3 T and moderate density → traditional toroidal grill is used (f=920MHz)
  - LHCD efficiency η_{CD} ~$0.4\cdot10^{19}AW^{-1}m^{-2}$
  - Mechanisms of LHCD offset at high density is studied (density limit)
  - LHCD density limit is just slightly higher in **D** than in **H**



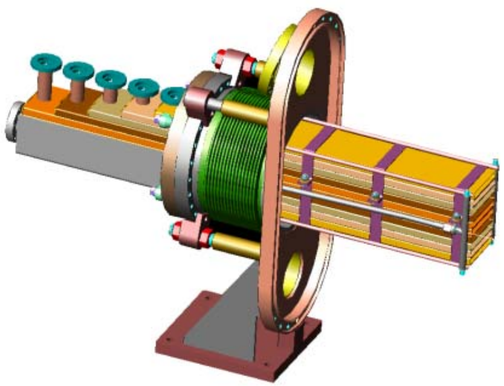
	LHCD density limit, 10^{19} m^{-3}	LH resonance density, 10^{19} m^{-3}
Hydrogen	**3.5**	**3.5**
Deuterium	**4.0**	**10**

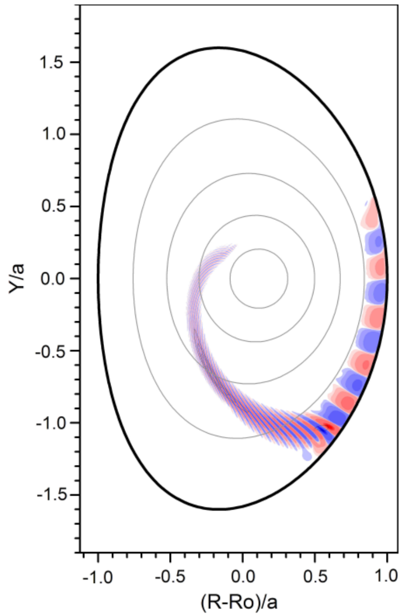
- Most probable explanation – Parametric Decay Instability of pumping wave and peripheral absorption of daughter wave

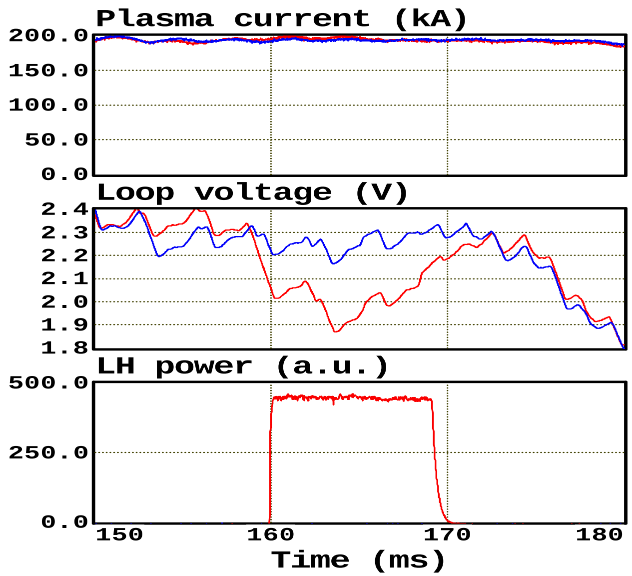
EX/P1-29, S. Lashkul

LH Current Drive Experiments: FT-2 and Globus-M

- **Globus-M**: Low B_t=0.4T and high density → high $N_{||}$ > 7-10 needed, but toroidal slowing down is inapplicable
- Alternative approach proposed and validated: LH waves (f=2.45GHz) with $N_{pol} \sim N_{||} \sim 3$ are launched in poloidal direction, gradually accumulate higher $N_{||}$ and are absorbed in a vicinity of poloidal resonance







- RF up to 30 kA (twice as high as predicted by modeling)
- LHCD efficiency $\eta_{CD} \sim 0{,}25 \cdot 10^{19} AW^{-1}m^{-2}$

TH/P1-34, V. Dyachenko

NBI, Fast particles and Alfven waves physics: Globus-M and TUMAN-3M

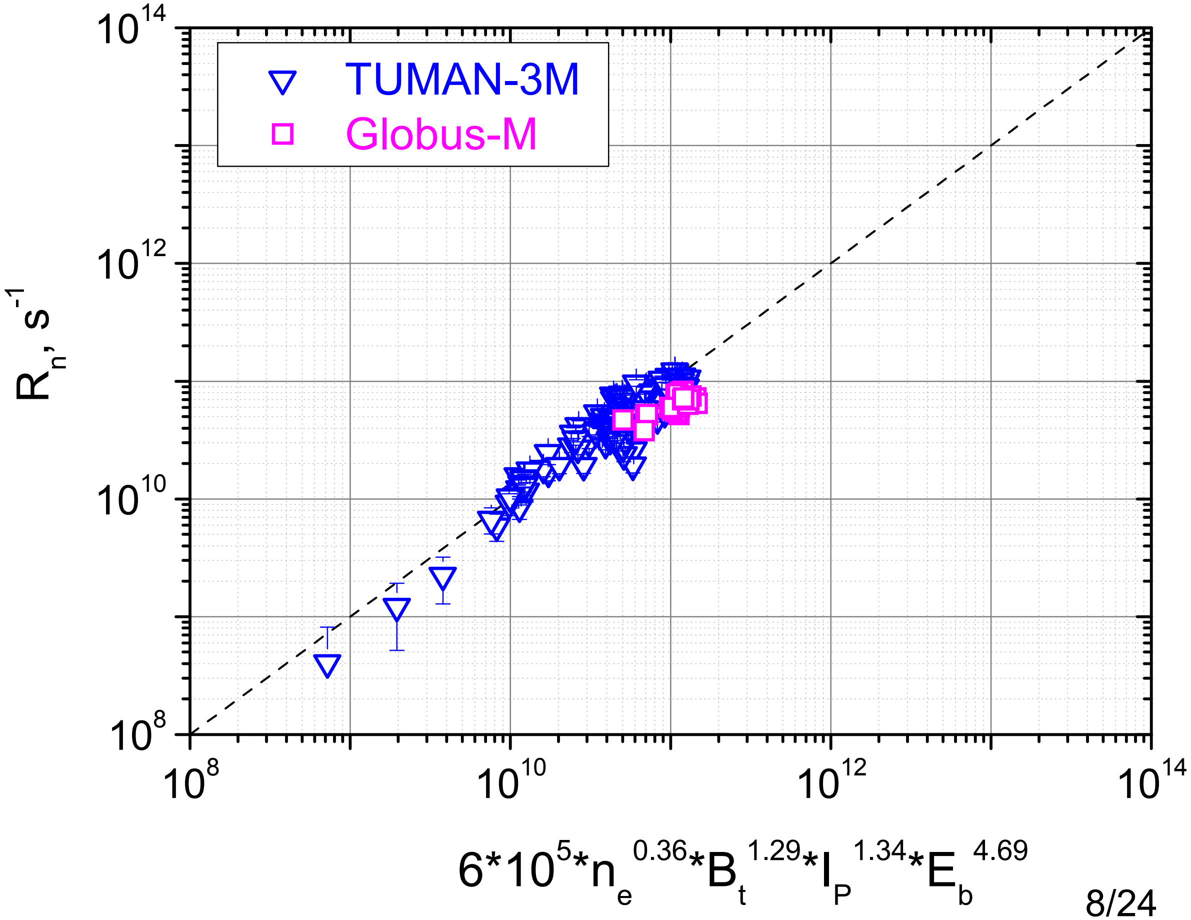
- Neutron production in beam-plasma D-D reactions

$$R_n = 6 \cdot 10^5 \cdot n_e^{0.36} \cdot B_t^{1.29} \cdot I_P^{1.34} \cdot E_b^{4.69}$$ (10^{19}m^{-3}, T, MA, keV)

TUMAN-3M

Globus-M

Valid for the range:
$n_e > 2 \cdot 10^{19}$ m^{-3}
$I_P > 140$ kA
$E_b < 26$ keV(G)
$E_b < 22$ keV(T)
Single NBI box



NBI, Fast particles and Alfven waves physics: Globus-M and TUMAN-3M

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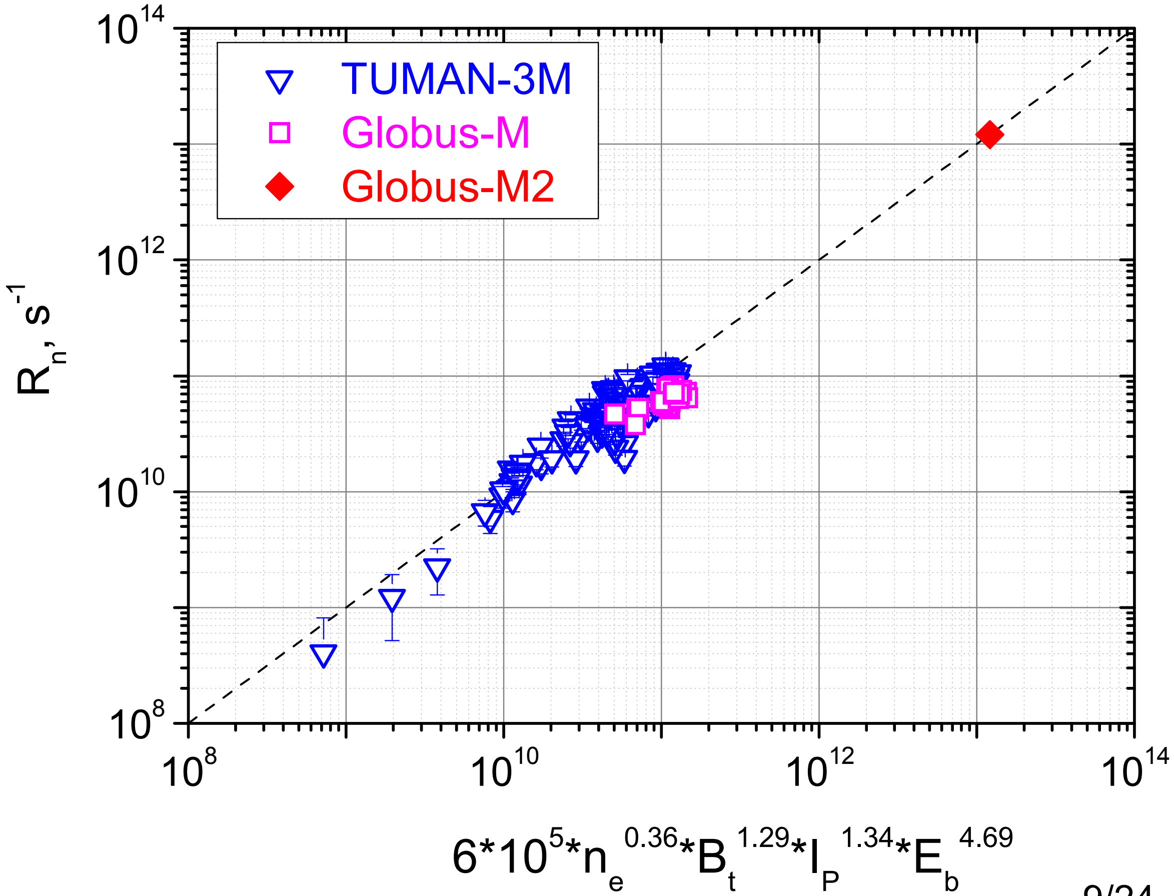
×100 increase in neutron rare is predicted for **Globus-M2**

B_t=1T

I_p=500 kA

E_b=60 keV

P_b=1 MW



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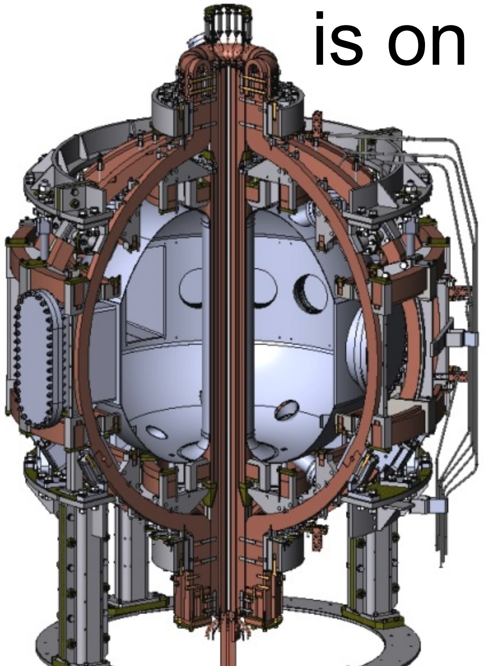
Globus-M2 status

Globus-M Upgrade (Globus-M2 Project) is on the way: first plasma is awaited in 2016



Globus-M2	"B-max" regime	"t-max" regime
Plasma major / minor radius	0.36 / 0.24 m	0.36 / 0.24 m
Toroidal Field	1.0 T	0.7 T
Plasma Current	0.5 MA	0.5 MA
TF flattop	0.4 s	0.7 s
Basic regime	Inductive / CD	Inductive / CD
TF field ripple at R = 0.6 m	$\leq$ 0.4%	$\leq$ 0.4%

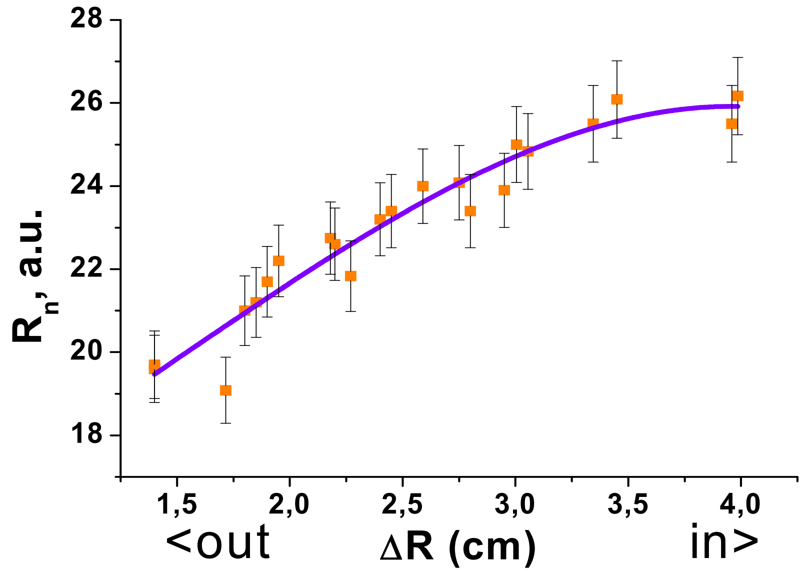
- ✓ **The manufacturing of a new magnetic system was successfully started**
- ✓ **Special conductors for the TF and PF magnets have been manufactured and delivered to the Ioffe Institute**
- ✓ **New power supplies is under development**

OV/P-04, V. Gusev
FIP/P8-25, V. Minaev

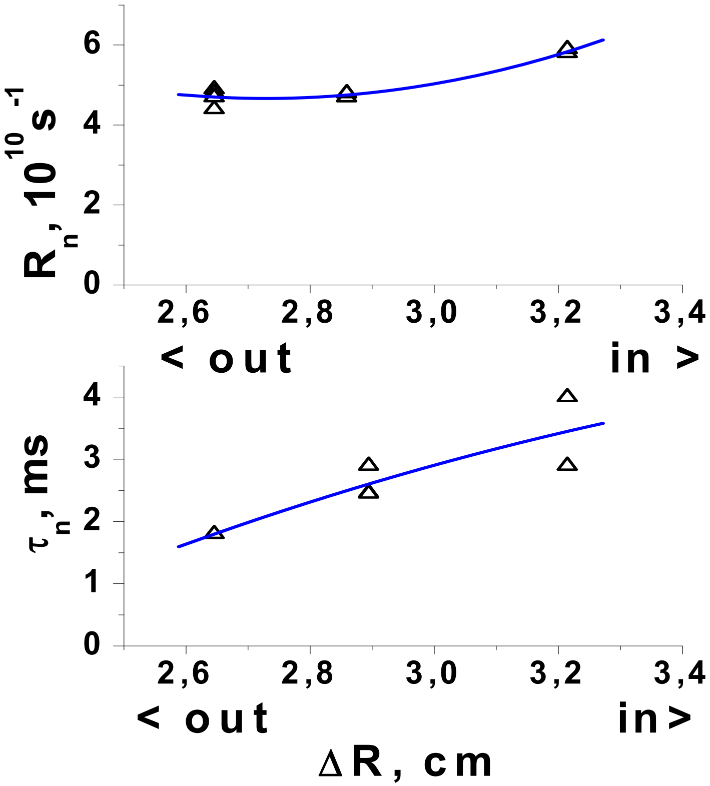
NBI, Fast Ions and Alfven waves physics: Globus-M and TUMAN-3M

- Fast Ions confinement in **Globus-M** and **TUMAN-3M**: plausible effect of inward shift ΔR of plasma column

Globus-M



TUMAN-3M

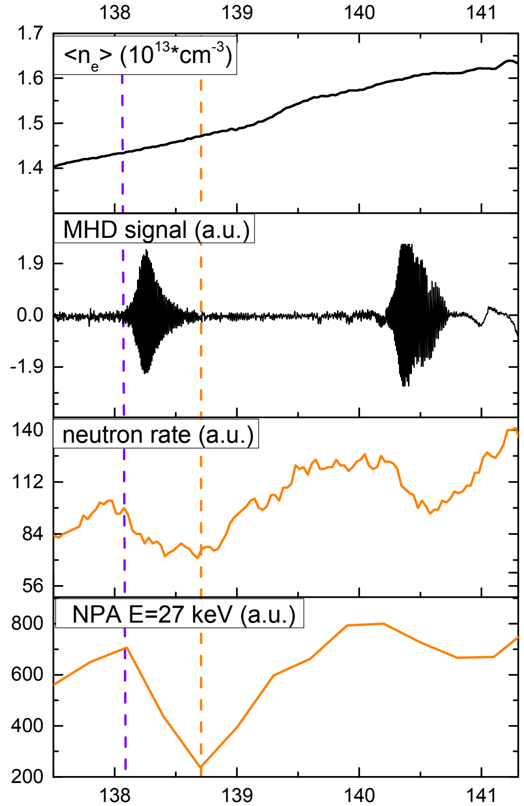


EX/P1-33, N. Bakharev

EX/P6-58, V. Kornev

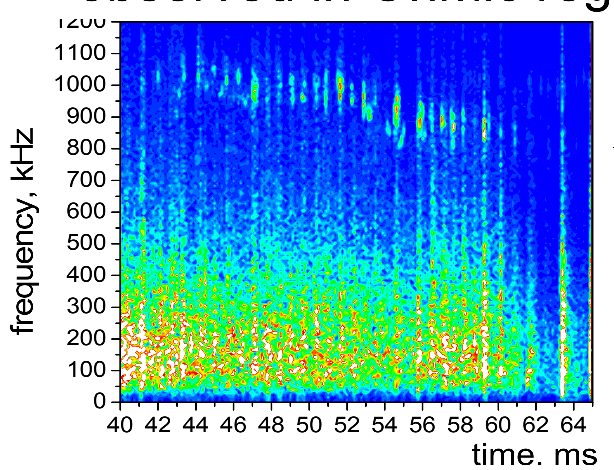
NBI, Fast Ions and Alfven waves physics: Globus-M and TUMAN-3M

- In Globus-M Alfven eigenmodes cause additional losses of FI



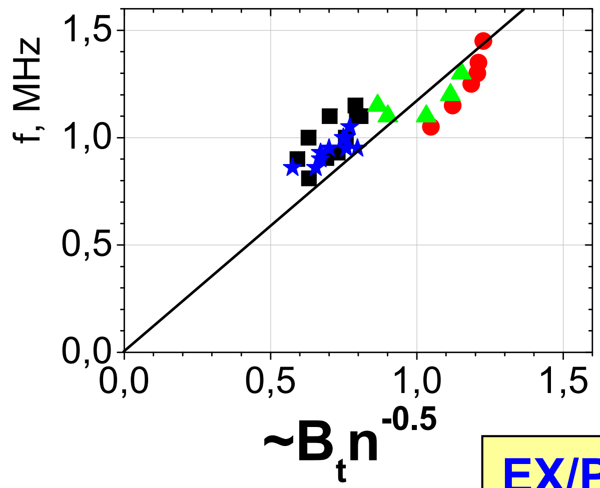
EX/P1-33, N. Bakharev

- In TUMAN-3M Alfven eigenmodes observed in Ohmic regime without FI



f ~ 0.9-1MHz

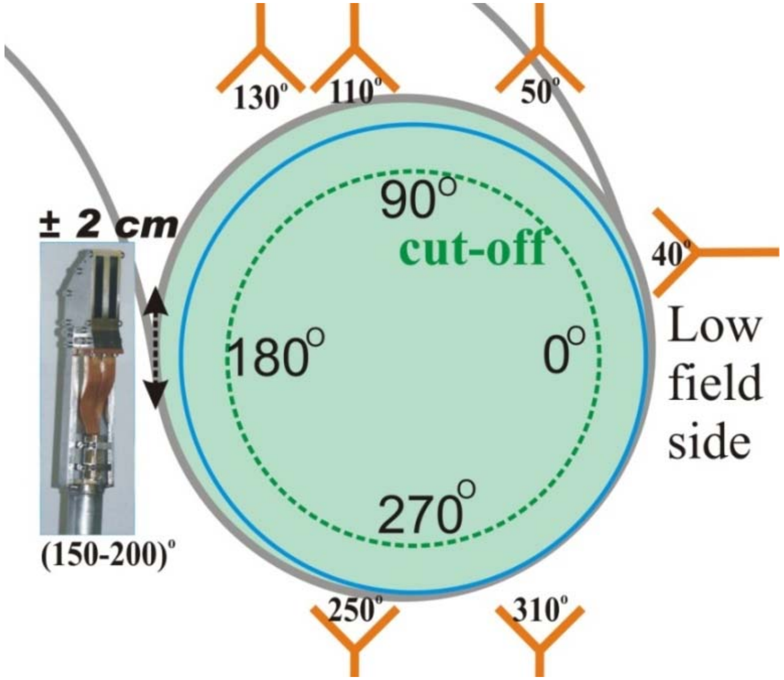
$V_A=B_t(\mu_0 n_i m_i)^{-0.5}$

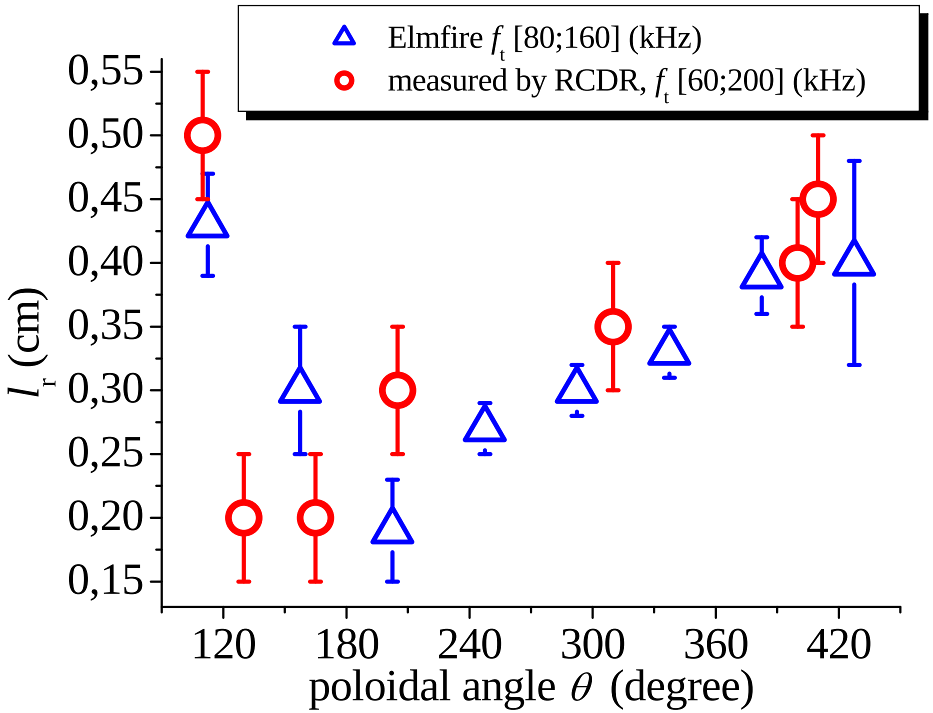


EX/P6-57, M. Vildjunas

GAM studies: turbulence, GAM and transport interplay (FT-2, Globus-M and TUMAN-3M)

- Poloidal inhomogeneity of turbulence measured for the first time in the FT-2 tokamak by Radial Correlation Doppler Reflectometry and calculated by full-f gyrokinetic code ELMFIRE (Aalto University, Espoo, Finland)





EX/P1-30, A. Altukhov

GAM studies: turbulence, GAM and transport interplay (FT-2, Globus-M and TUMAN-3M)

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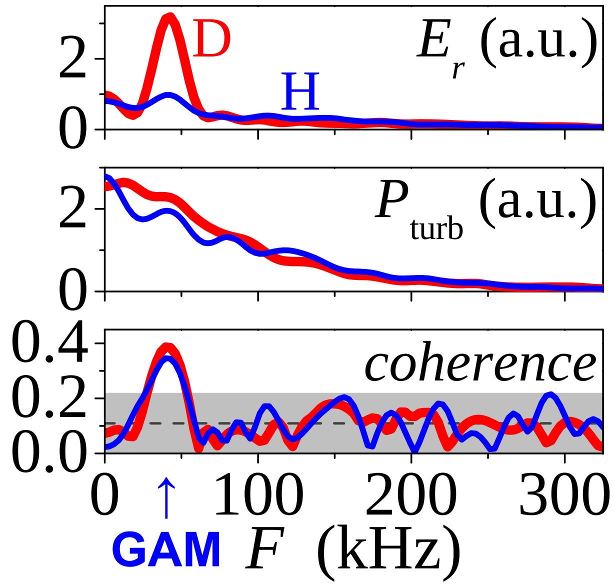
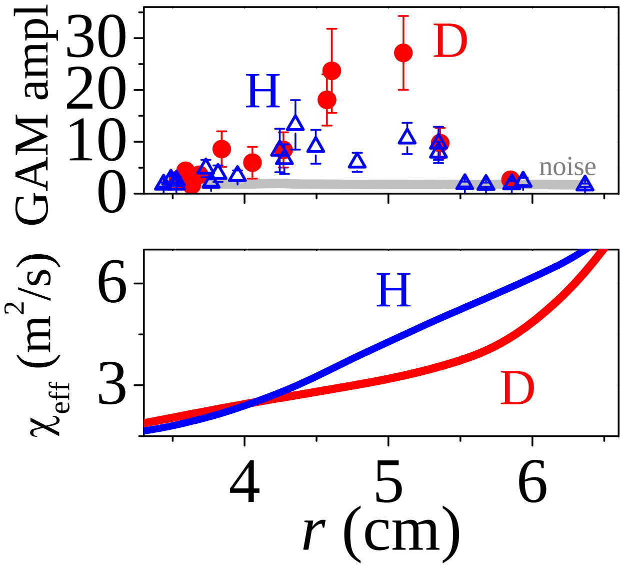
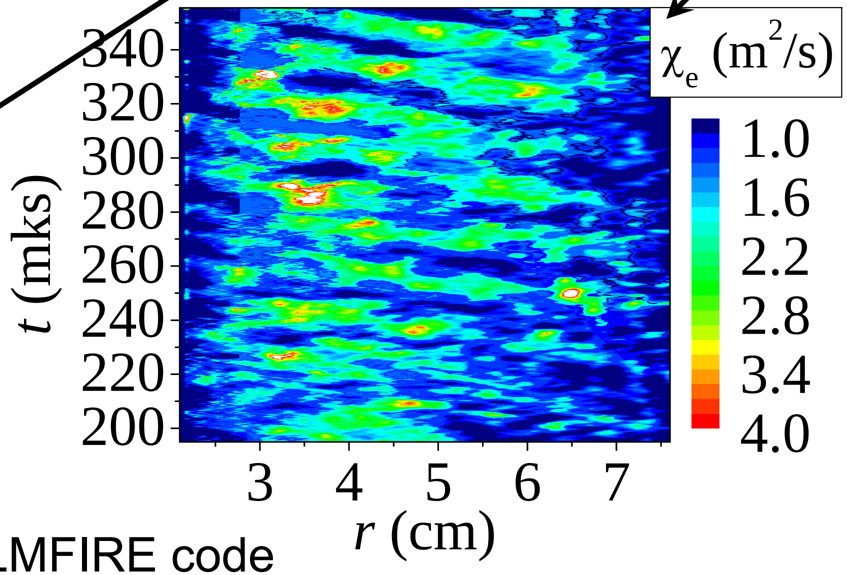




- On FT-2, turbulence level modulation at GAM frequency observed experimentally for the first time, using Doppler ES and reflectometry
- Anti-correlation of the GAM amplitude and the effective electron thermal diffusivity observed on the on FT-2 experimentally and in modeling



ELMFIRE code
(Aalto University, Espoo, Finland)

EX/11-2Ra, A. Gurchenko

GAM studies: turbulence, GAM and transport interplay (FT-2, Globus-M and TUMAN-3M)

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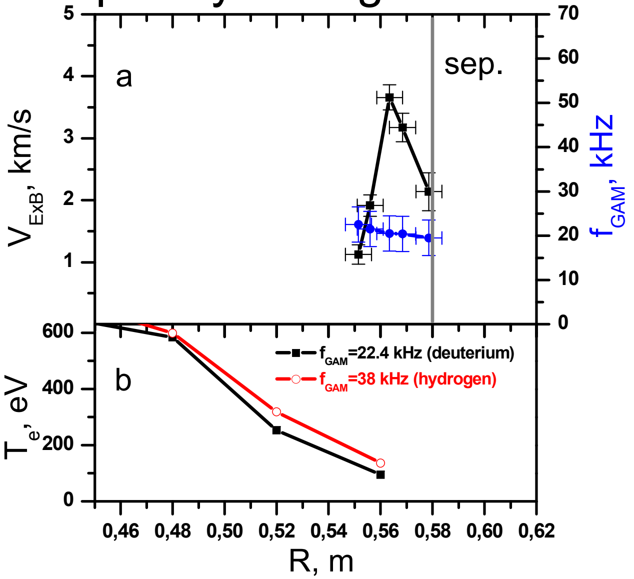
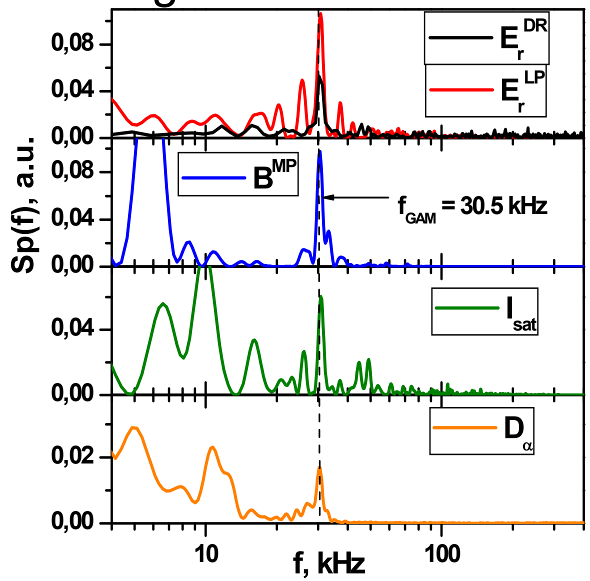
- GAM radial profile was studied using Doppler reflectometry (DR) on Globus-M and TUMAN-3M in cooperation with SPbSTU
  - by shot-to-shot spatial scan with single tunable frequency on Globus-M
  - by two-frequency DR on TUMAN-3M
- In both cases, GAM location1-2cm inside LCFS is concluded, with approx. constant frequency throughout the localization region





- On Globus-M, the evident correlation between the GAM oscillations of rotational velocity, D_α emission, peripheral plasma density and polidal magnetic field oscillations was observed

EX/P1-32, V. Bulanin

GAM studies: turbulence, GAM and transport interplay (FT-2, Globus-M and TUMAN-3M)

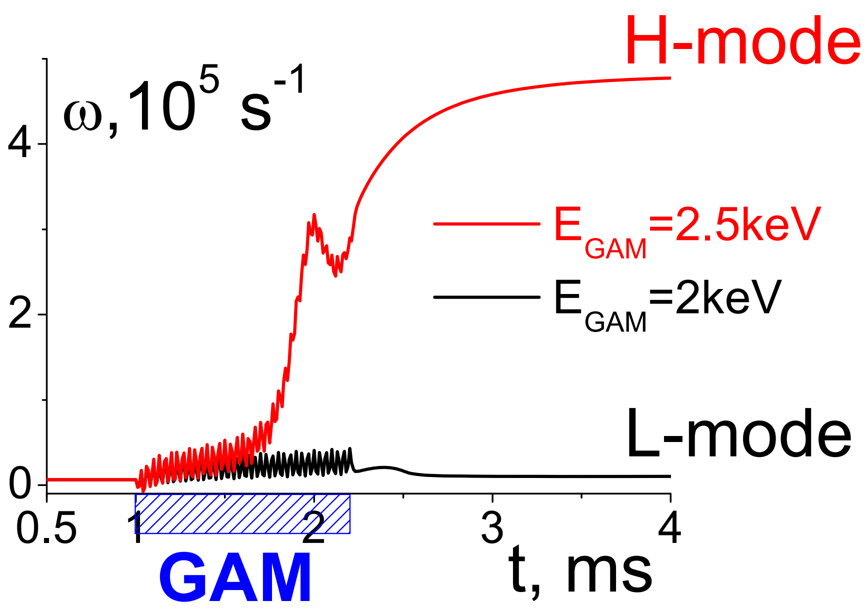
- It is seen from experiment and modeling on FT-2 that GAM modulates turbulence and anomalous transport
- In the TUMAN-3M, GAM observed with HIBP was found to precede LH transition

$$\frac{\partial n(r,t)}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r} r \cdot \left(D(r,t) \cdot \frac{\partial n(r,t)}{\partial r} - v(r) \cdot n(r,t) \right) = S(r)$$

$$E_r = E_{NEO} + E_{GAM}$$

$$D(r,t) = K_s(\omega) D_0(r)$$

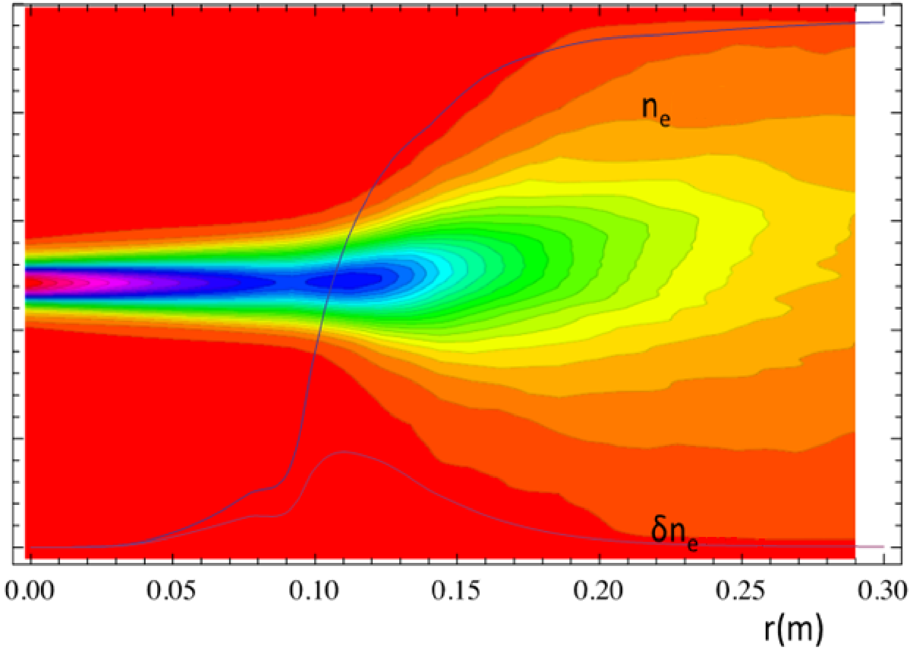
$$K_s(\omega) = 1/(1+(\omega/\gamma)^2) + K_{NEO}$$



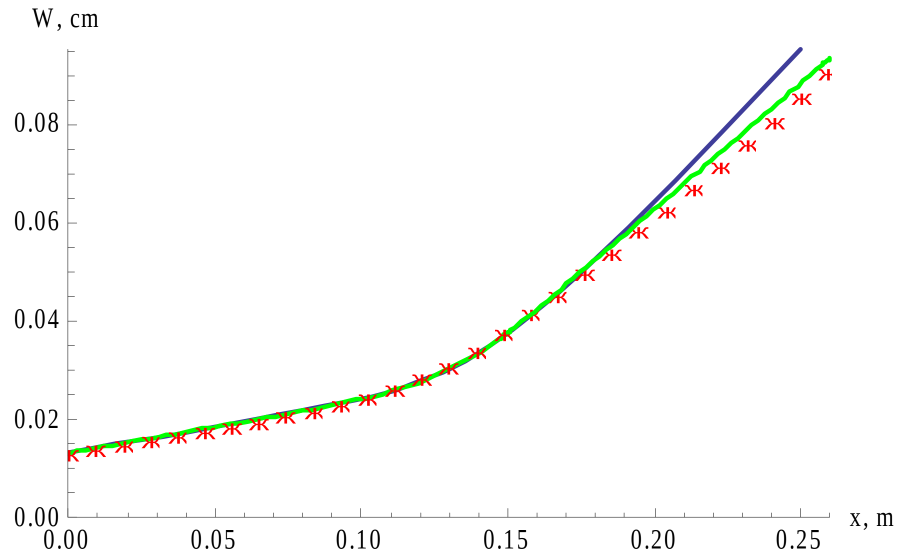
Numerical modeling of density evolution in TUMAN-3M with E_r shear-dependent diffusion shows that a GAM-like burst can be a trigger for the LH-transition, if GAM amplitude overcomes some threshold

EX/P6-59, A. Belokurov

Plasma Theory: Microwave beam broadening in the edge turbulent plasma



Beam expansion in the ITER-like case



Comparison of analytical predictions and numerical results

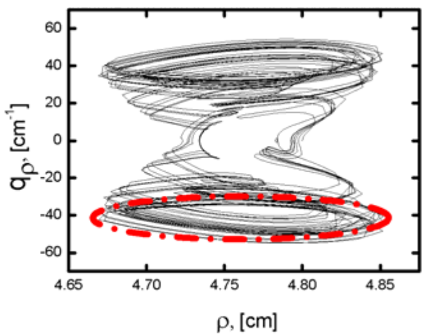
$$w^2 = \frac{\delta^2}{2} + 2\frac{x^2c^2}{\delta^2\omega^2} + \frac{1}{12\pi}\frac{\delta n^2}{n_c^{\,2}}\left(\int_{-\infty}^{\infty} \left|\delta n\right|^2_{0,\kappa_y} \kappa_y^{\,2} d\kappa_y\right) x^3$$

Expression for the beam width in the statistically homogeneous turbulence case

Plasma Theory: The low threshold parametric decay instabilities leading to anomalous absorption at ECRH in toroidal devices

Parametric excitation of the electron Bernstein wave (EBW) trapped in the drift-wave eddy

The power threshold - about 50 kW

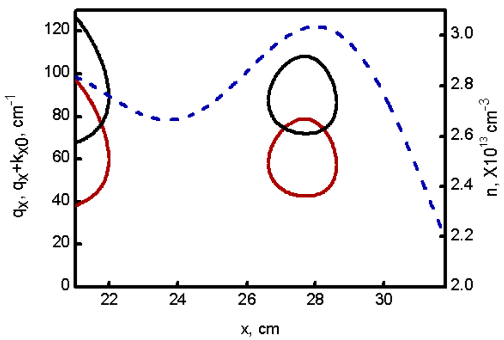


The phase portrait along the EBW ray trajectory

Able to explain fast ion tail production in TCV and TJ-II X-mode 2nd harmonic ECRH experiments

Parametric excitation of two upper hybrid (UH) plasmons trapped in the magnetic island

The power threshold is less than 100 kW



The UH waves dispersion curves and density profile in magnetic island

This decay is responsible for the anomalous backscattering observed in 2nd harmonic ECRH experiments at TEXTOR and ASDEX-UG

TH/4-2, A. Popov

Diagnostics for ITER

- Three diagnostic tools for ITER are being developed in Ioffe Institute
  - **Neutral Particle Analysis (NPA)** for measurement and control of fuel isotope composition of burning plasma
  - **Gamma Spectroscopy (GS)** intended to follow MeV-range ions born in nuclear reactions and to provide information on location of the runaway electron beams by measuring their bremsstrahlung radiation
  - **Divertor Thomson Scattering (DTS)** for detailed measurements of electron component parameters

Diagnostics for ITER: Tandem of Neutral Particle Analyzers

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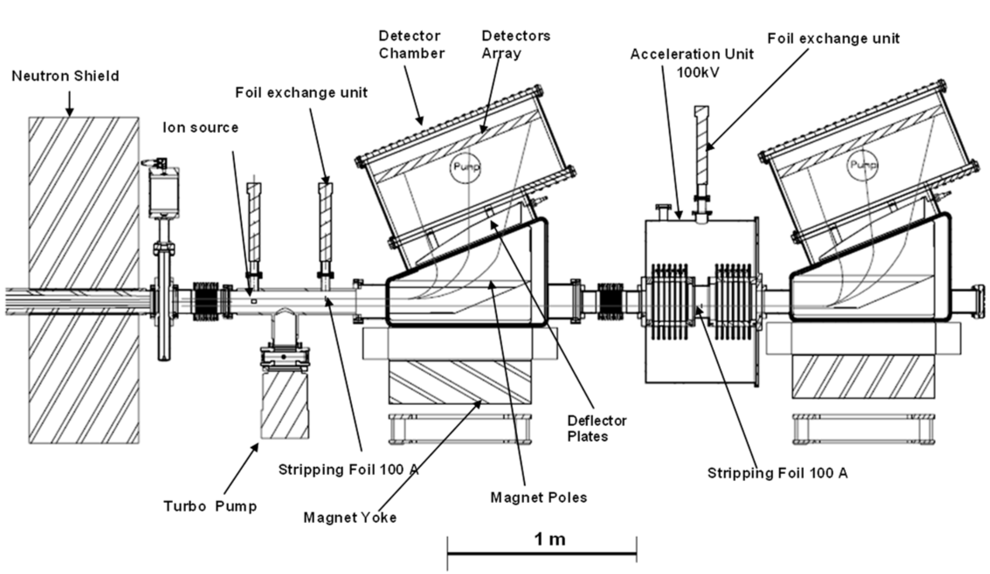
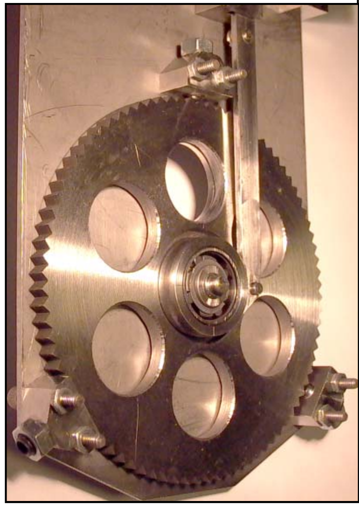
Fast D, T, He-ions Distribution Function Measurement

HENPA (0.1 – 4 MeV)

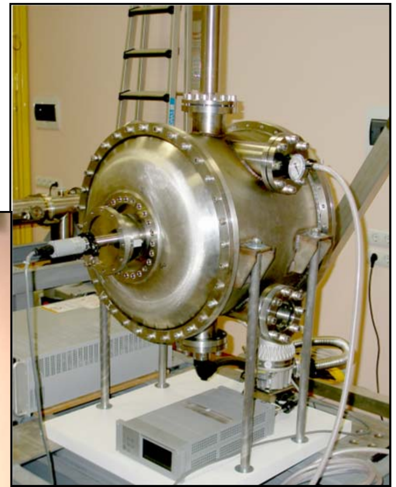
n_D/n_T Isotope Ratio Measurement

LENPA (10 – 200 keV)





stripping foil exchange unit mock-up



accelerator unit mock-up

- Compact version of the Tandem (250 x 150 x 150 cm) has been developed
- Both analyzers can operate in parallel because observation line of LENPA is shifted to ensure independence
- Time resolution 0.1 s or better, accuracy 10%

TH/P3-37, V. NESENEVICH

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Diagnostics for ITER: Gamma-ray Spectrometry

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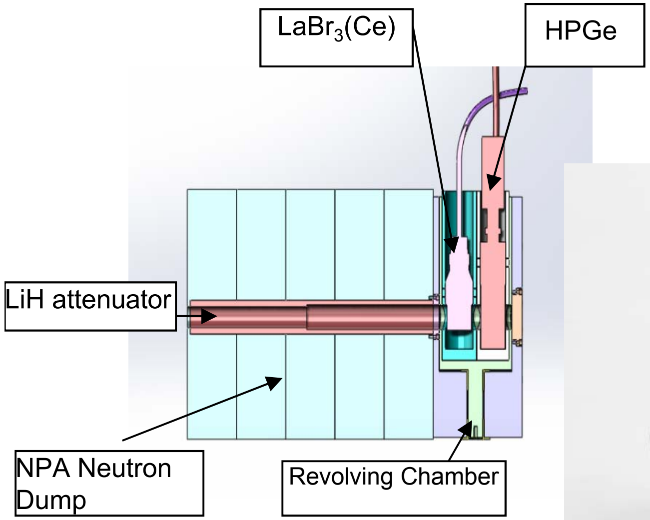
china eu india japan korea russia usa

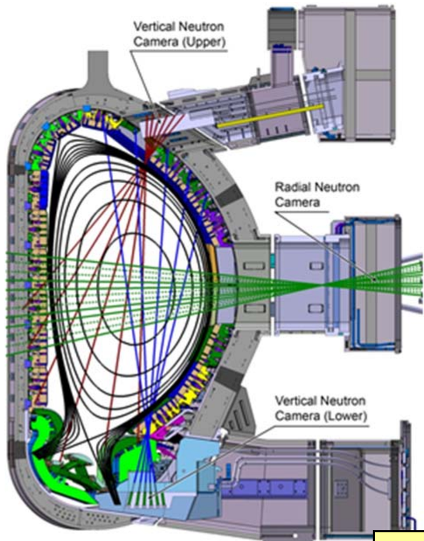
Gamma-ray Spectrometer in the NPA system will support NPA measurements of:

- Fuel ratio n_T/n_D,
- Ion temperature T_i
- Energy spectrum of confined alpha-particles



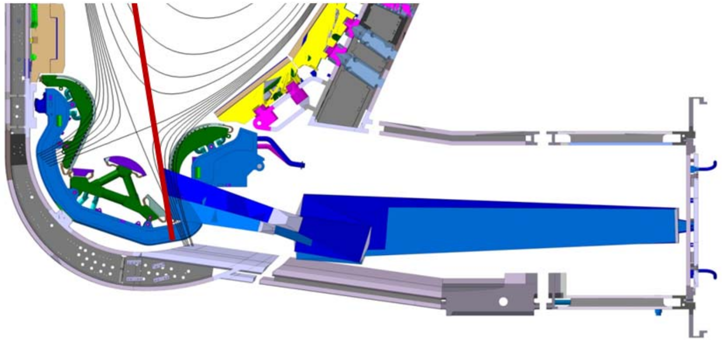
Vertical Gamma-Ray Spectrometers for H and He phases of ITER operation will be used for:

- Runaway electrons diagnostics
- Obtaining of fast-ion distribution functions
- ICRF heating optimization



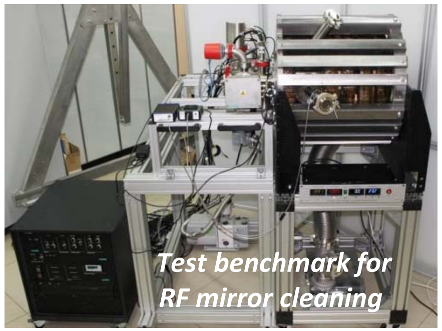
FIP/P4-4, D. Gin

Diagnostics for ITER: Divertor Thomson Scattering



Parameter	Range	Time res./ Frequency	Accuracy
n_e	10^{19}-10^{20} m^{-3}	20ms/50Hz	20%
T_e	1-200 eV 0.1-1 eV	20ms/50Hz	20% 0.2 eV

- Resolution high enough to measure steep temperature and density gradients proved by simulation
- DTS can be used as a sensor for real time control of power flux to the divertor targets
- Approbation of equipment and technique: prototyping on Globus-M
First mirror design and protection. Several protection techniques under development


Test benchmark for RF mirror cleaning


Mock-up of Diagnostic Racks


Probing laser mock-up

MPT/P4-8, A. Razdobarin
EX/P5-28, G. Kurskiev

22 Presentations at FEC 2014 from Ioffe Institute: 3 Orals and 19 Posters

OV/1-1	L.ASKINAZI	Fusion Research in Ioffe Institute
EX/11-2Ra	A. GURCHENKO	The Isotope Effect in GAM – Turbulence Interplay and Anomalous Transport in Tokamak
TH/4-2	A. POPOV	The Low Threshold Parametric Decay Instabilities Leading to Anomalous Absorption at ECRH in Toroidal Devices
OV/P-04	V. GUSEV	Review of Globus-M Spherical Tokamak Results
EX/P1-33	N. BAKHAREV	Fast Particle Behavior in Globus-M
FIP/P8-25	V. MINAEV	Globus-M2 Design Peculiarities and Status of the Tokamak Upgrade
MPT/P8-15	A. NOVOKHATSKY	Testing of Mock-ups for a Full Tungsten Divertor on Globus-M Tokamak
TH/P1-35	I. SENICHENKOV	Integrated Modeling of the Globus-M Tokamak Plasma
TH/P1-34	V. DYACHENKO	The First Lower Hybrid Current Drive Experiments in the Spherical Tokamak Globus-M
EX/P1-32	V. BULANIN	Geodesic Acoustic Mode Investigation in the Spherical Globus-M Tokamak
EX/P6-59	A. BELOKUROV	GAM Evolution and LH-Transition in the TUMAN-3M Tokamak
EX/P6-58	V. KORNEV	Effect of Horizontal Displacement on Fast Ion Confinement in TUMAN-3M
EX/P6-57	M. VILDJUNAS	Alfven Oscillations in the TUMAN-3M Tokamak Ohmic Regime
EX/P1-29	S. LASHKUL	Impact of Isotopic Effect on Density Limit and LHCD Efficiency in the FT-2 Experiments
EX/P1-28	V. ROZHDESTVENSKY	Nonthermal Microwave Emission Features under the Plasma Ohmic Heating and Lower Hybrid Current Drive in the FT- 2 Tokamak
EX/P1-30	A. ALTUKHOV	Poloidal Inhomogeneity of Turbulence in the FT-2 Tokamak by Radial Correlation Doppler Reflectometry and Full-f Gyrokinetic Modeling
FIP/P4-4	D. GIN	Gamma-Ray Spectrometer in the ITER NPA System
MPT/P4-8	A. RAZDOBARIN	RF Discharge for In-Situ Mirror Surface Recovery in ITER
SEE/P5-8	E. MUKHIN	In-Situ Monitoring Hydrogen Isotope Retention in ITER First Wall
EX/P5-28	G. KURSKIEV	A Study of Core Thomson Scattering Measurements in ITER Using a Multi-Laser Approach
TH/P3-37	V. NESENEVICH	On the Possibility of Alpha-Particle Confinement Study in ITER by NPA Measurements of Knock-on Ion Tails
IFE/P6-16	M. SHMATOV	The Perspectives of the Use of the Advanced Fuels for Power Production

Highlights

Ioffe Institute

Basic high temperature plasma physics, both experimental and theoretical:

- **LHCD studies:**
  - On FT-2, LHCD density limit was investigated and found to be governed by PDI
  - On Globus-M, LHCD scheme with poloidal slowing down was proposed and validated
- **Fast particles physics:**
  - Mechanisms responsible for fast ions losses were studied on Globus-M and TUMAN-3M in experiments with horizontal shift of plasma column
  - Alfven waves were shown to play a role in FI losses in Gobus-M
  - On TUMAN-3M, Alfven waves excitation was observed in OH regime
- **Plasma turbulence characterization and its interplay with confinement:**
  - On FT-2, strong poloidal inhomogeneity of turbulence was observed for the first time both experimentally and in full-f gyrokinetic modeling
  - GAM radial localization in vicinity of LCFS was measured both on Globus-M and TUMAN-3M
  - On FT-2, turbulence level modulation at GAM frequency was observed for the first time; strong correlation between GAM, background turbulence level and electron thermal diffusivity was observed experimentally and in modeling
  - Numerical model showing GAM ability to trigger LH transition is proposed
- **From Globus-M to Globus-M2:**
  - Increase in toroidal field, plasma current, pulse duration will result in better performance
- **Plasma theory:**
  - Importance of microwave beam broadening in the edge turbulent plasma for ITER-like case was proved analytically and numerically
  - Role of low threshold PDI in anomalous absorption of EC waves in toroidal devices is cleared up

Development of three diagnostics for ITER

- Tandem NPA
- Divertor TS
- Gamma ray spectroscopy