Globus-M Results Toward Compact Spherical Tokamak with enhanced Parameters Globus-M2

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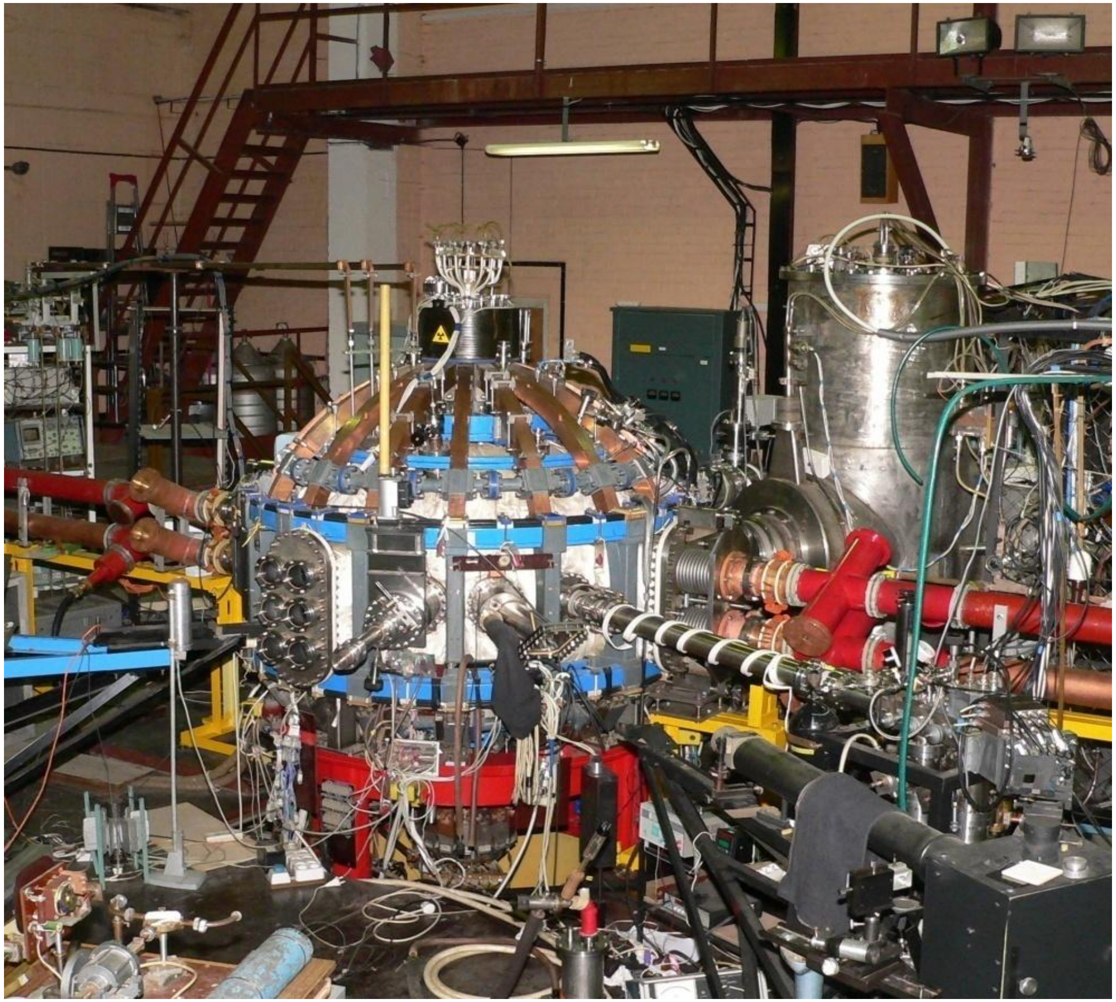
Globus-M spherical tokamak demonstrated practically all of the project objectives



R	0.36 m
a	0.24 m
R/a	1.5
B_{tor}	0.4 T
I_{pl}	< 0.36 MA
κ	< 2.0
δ	< 0.5
β_{tor}	<15 %
β_N	<6.0 %mT/MA
T_{pulse}	<130 ms
NBI [E/P]	30 keV / 1 MW
ICRH [F/P]	10 MHz / 0.3 MW
T_e [max]	~1 keV
T_i [max]	~0.8 keV
q_{95} [min]	>2
B_{tor}/R	<1.5 T/m
<n> [max]	$<1.2 \cdot 10^{20}$ m^{-3}

Maximal *T* and *n* values were obtained in different regimes

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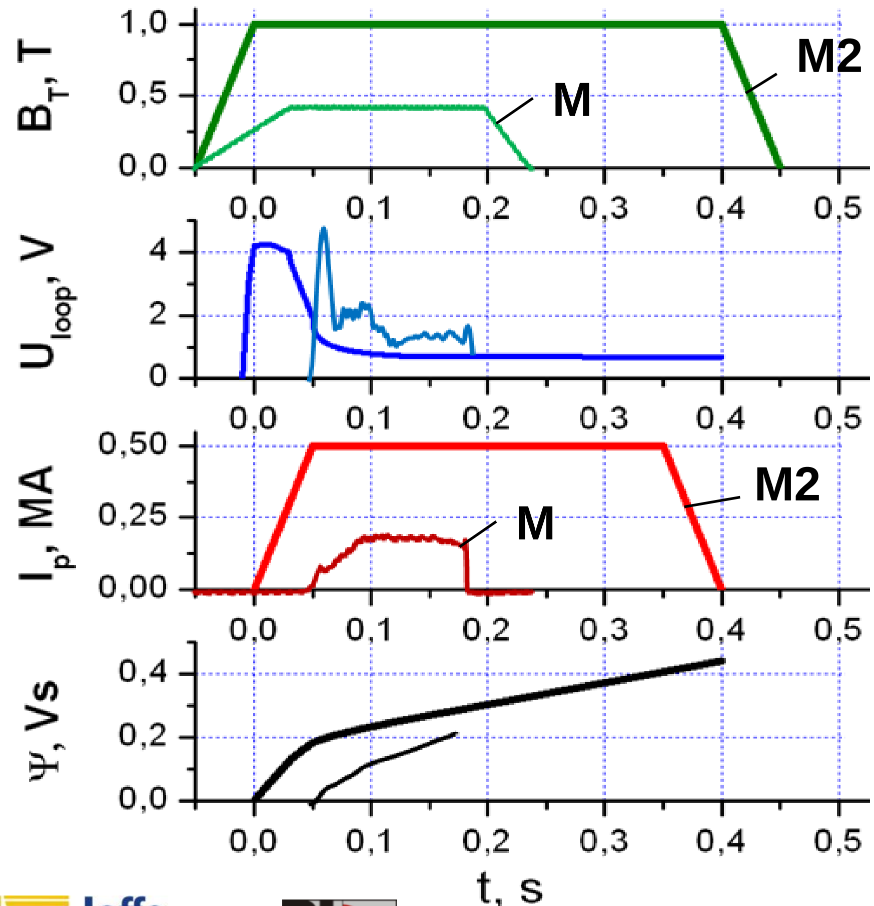
Close fitting wall; RGT tiles; Plasma gun; LH CD system

We propose the simplest way to improve plasma parameters: both magnetic field and plasma current 2.5 increase retaining other machine parts unchanged. The machine name is “Globus-M2” ST



“B-max” regime providing:

$B_T(R=0.36)$ = 1 T for Δt =0.4 sec,

I_P = 0.5 MA for 0.3 sec

“t-max” regime for noninductive current drive experiments providing:

$B_T(R=0.36)$ = 0.7 T for Δt = 0.8 sec

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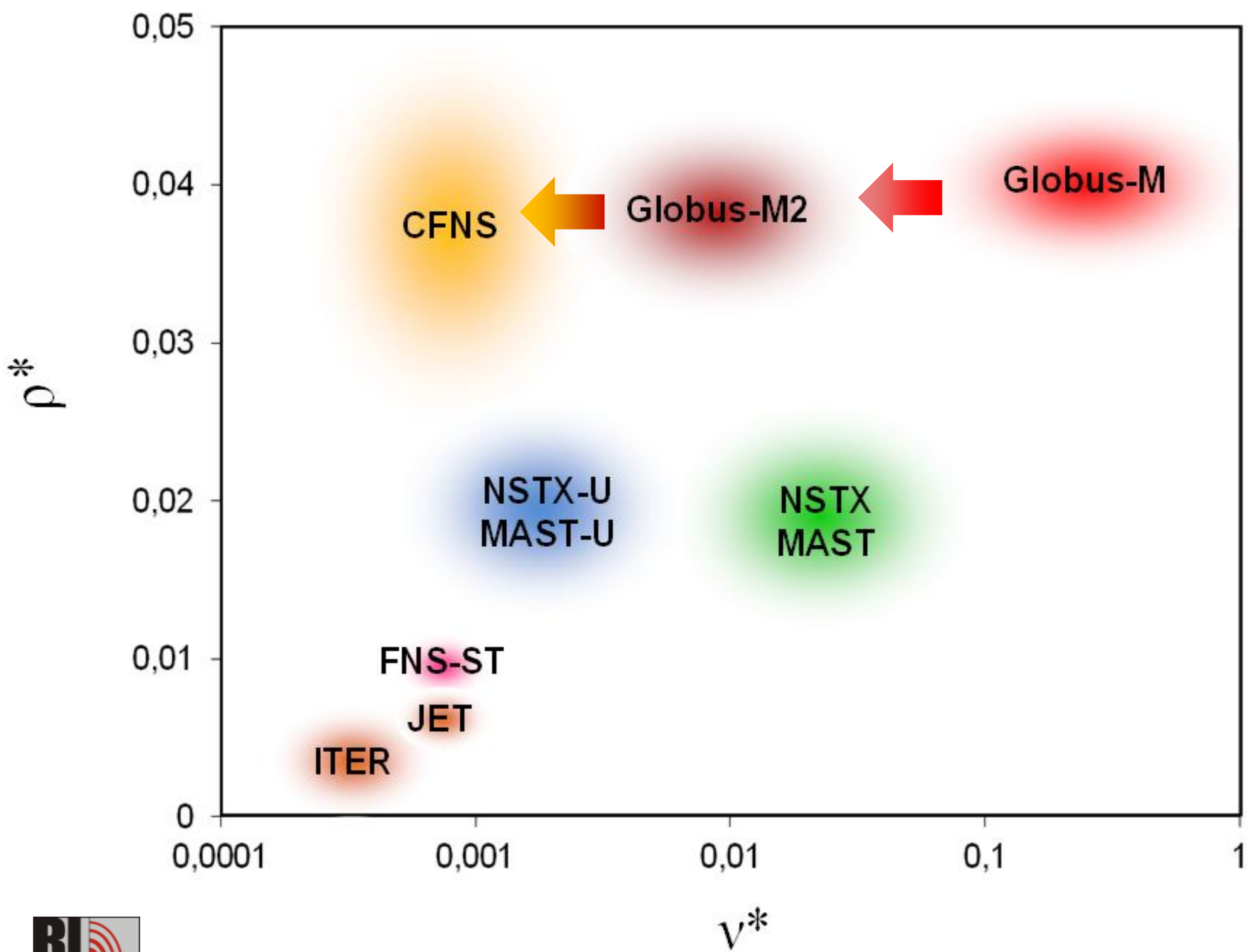
Objectives of Globus-M2 permit regime modeling for Compact Fusion Neutron Source (CNFS)



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Globus-M confinement, heating, fast particle physics and edge plasma issues

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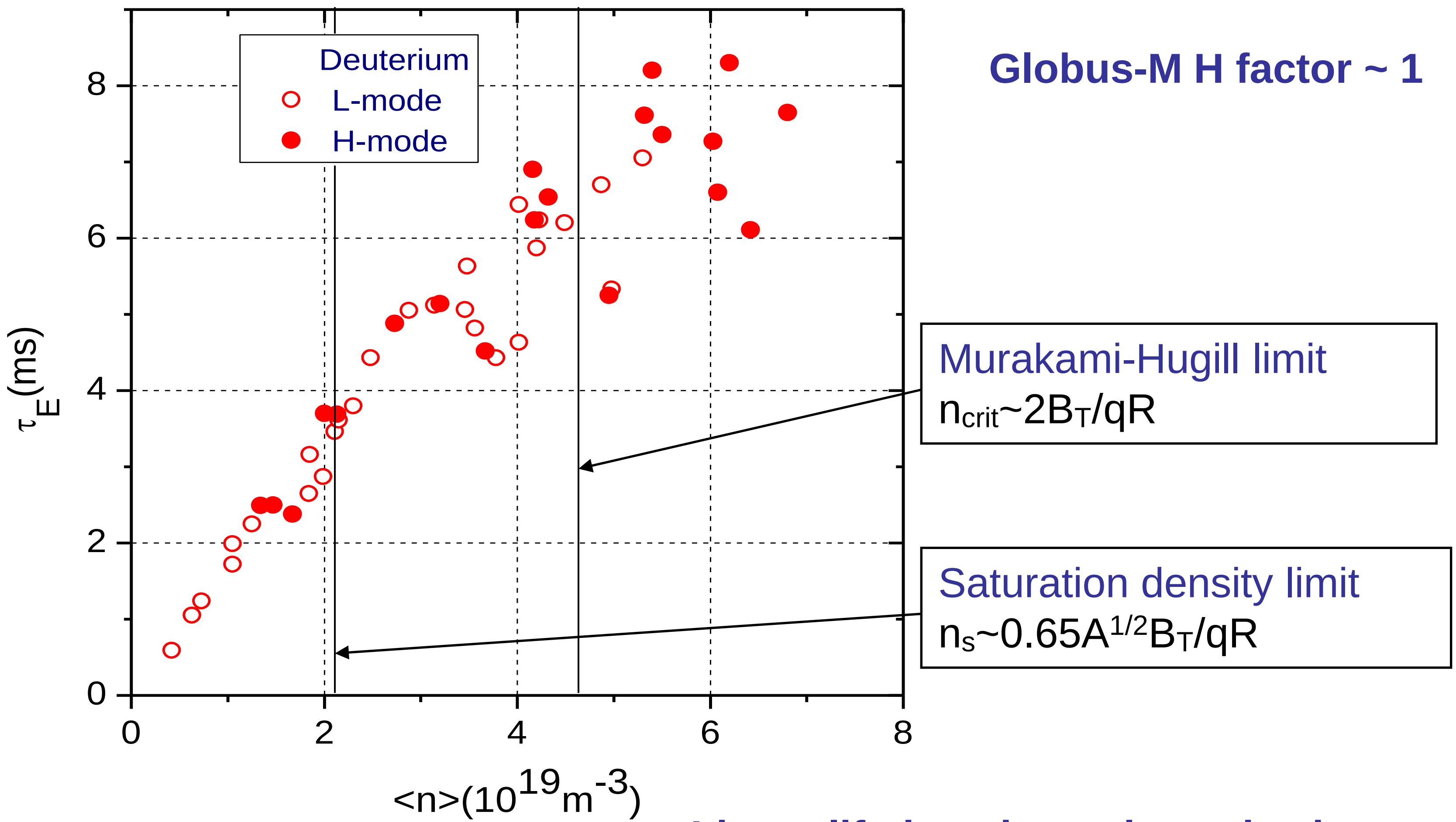
Ohmic L and H-mode confinement



Globus-M H factor ~ 1

Linear lifetime dependence is characteristic for small size machines with domination of electron heat transport, e.g. Alcator-A, ISX-B, etc

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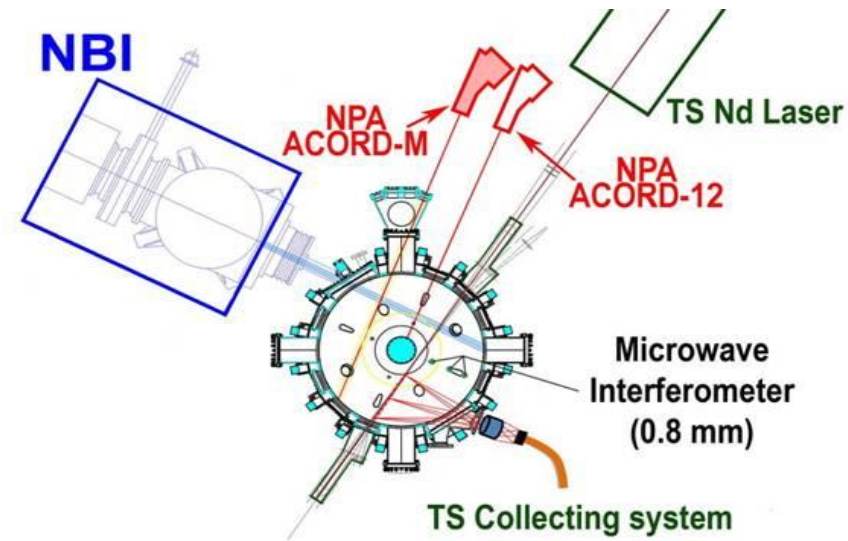
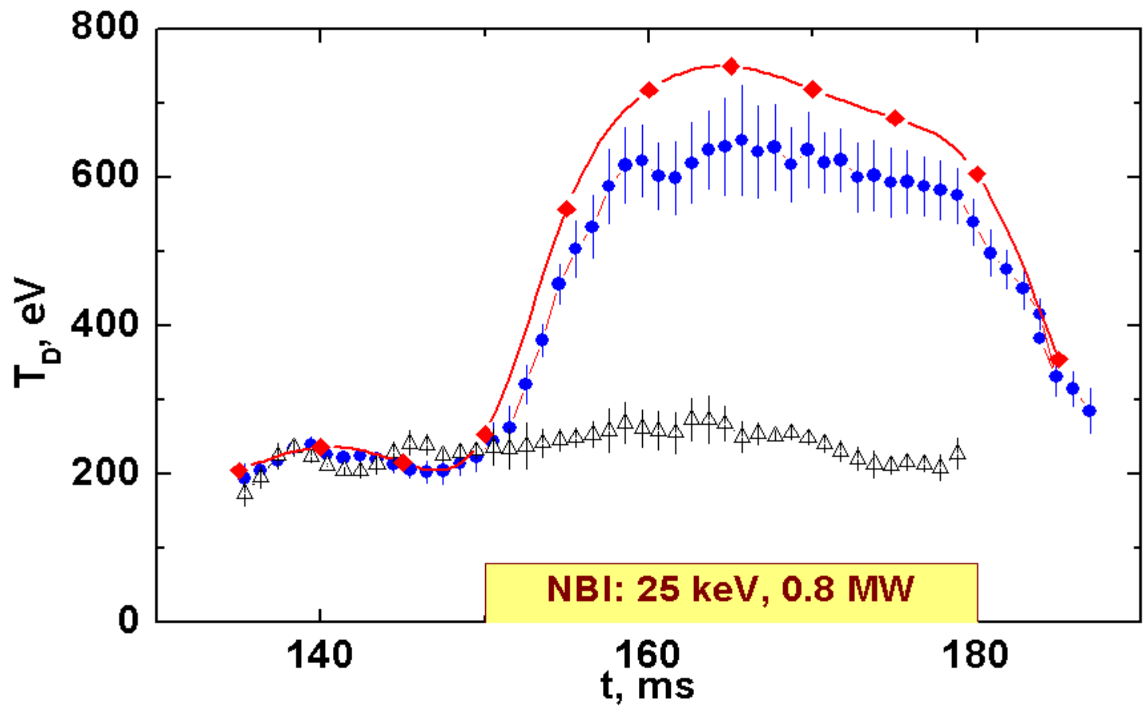
NB injection is the major instrument for plasma auxiliary heating in Globus-M



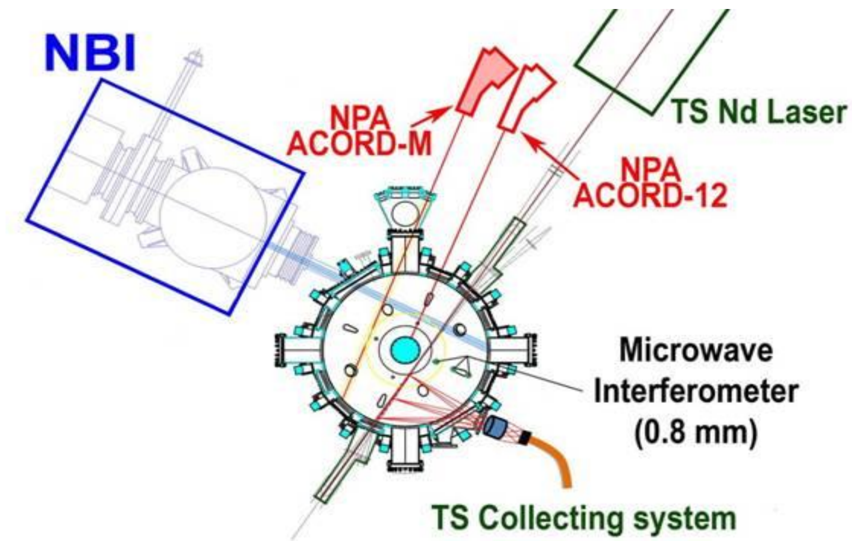


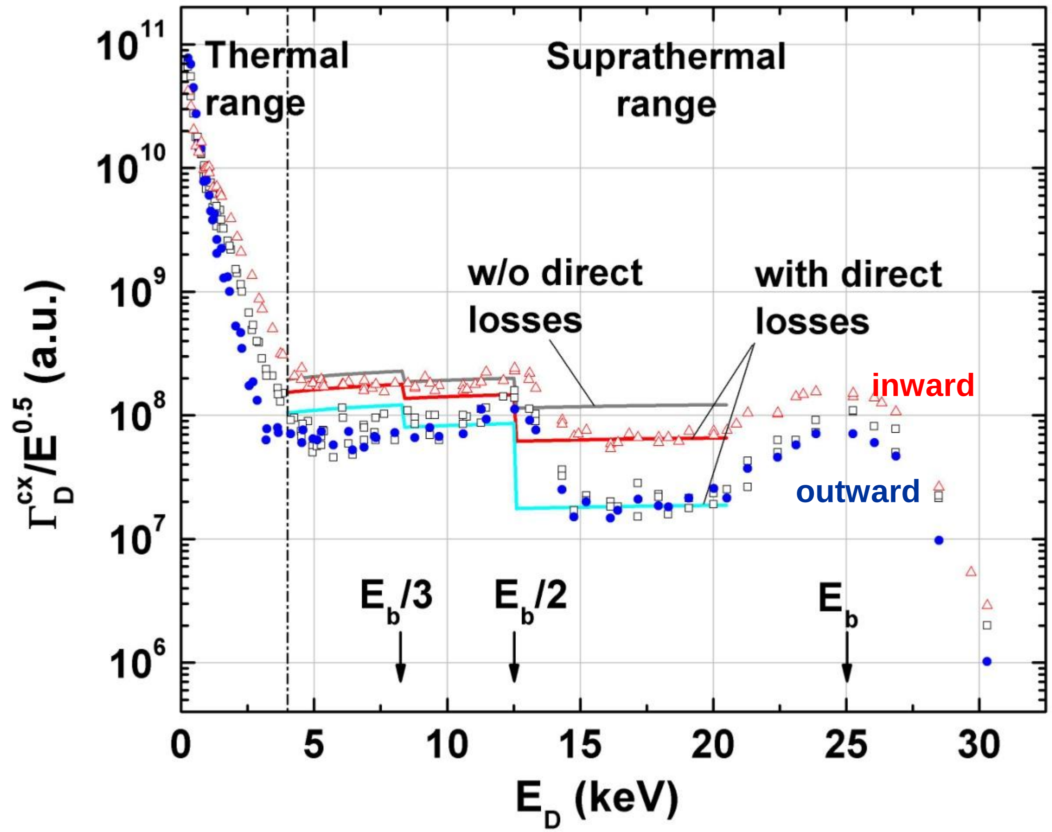
In spite of difficulties connected with a compact size of the machine good ion heating efficiency during NB injection observed at low density.

$(2\text{-}4)\cdot 10^{19}$ m^{-3}

$\chi_i \sim \chi_{i,neo}$

Fast particle first orbit losses at various major radii





- "Horizontal" lines approximate Fokker-Planck equation solution with slowing down losses and allow for direct losses estimate
- Direct fast particle losses is the main mechanism deteriorating NB plasma heating in Globus-M
- "Bump on tail" – demonstrates additional source of losses

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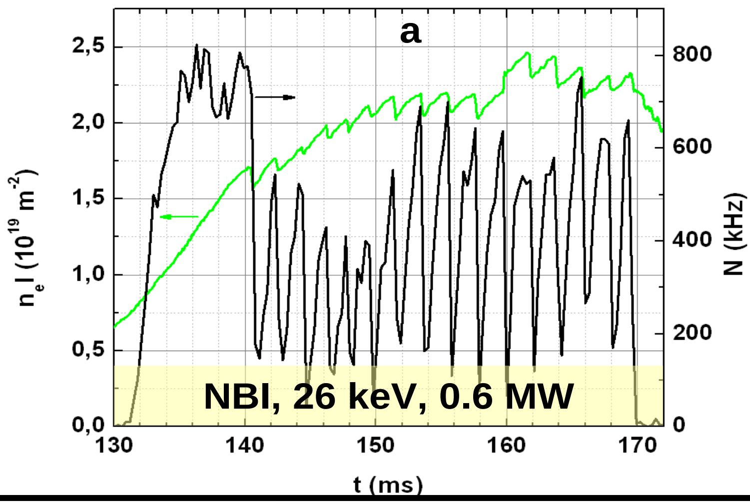
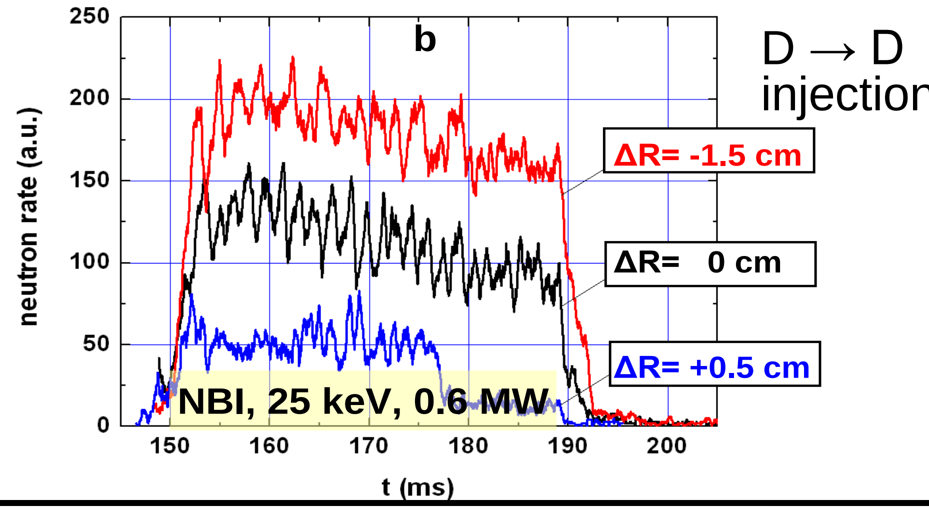
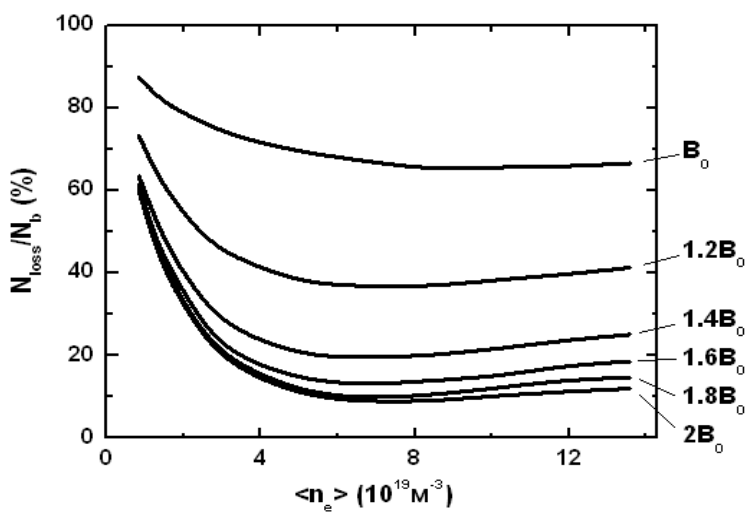
Sawteeth are responsible for additional fast particle direct losses, producing "bump on tail" distribution





Drastic decrease of fast particle losses can be achieved by total magnetic field increase



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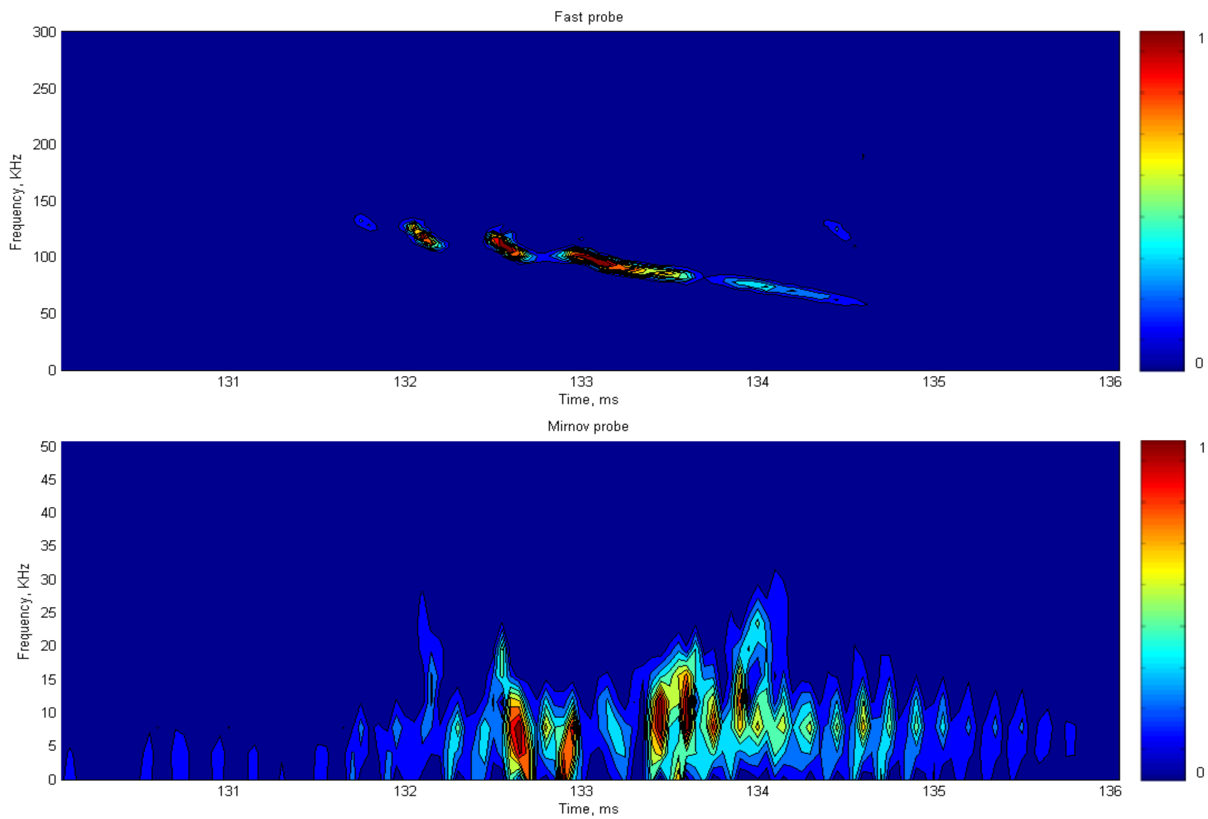
TAE single n=1 mode excitation

H-NBI into D-plasma, E= 27 keV



- **Magnetic field 2.5 fold increase make it possible 6 fold beam energy increase without TAE spectrum enrichment:**
  $V_b/V_A \approx 1$ on Globus-M
  $V_b/V_A \sim \sqrt{E_b/B}$ at n_e=const
- **Unlike TAE EPM is recorded as multimode excitation**
- **No additional Fast particle losses – evidence is neutron flux measurement**
- **Expectations for Globus-M2 are favourable**

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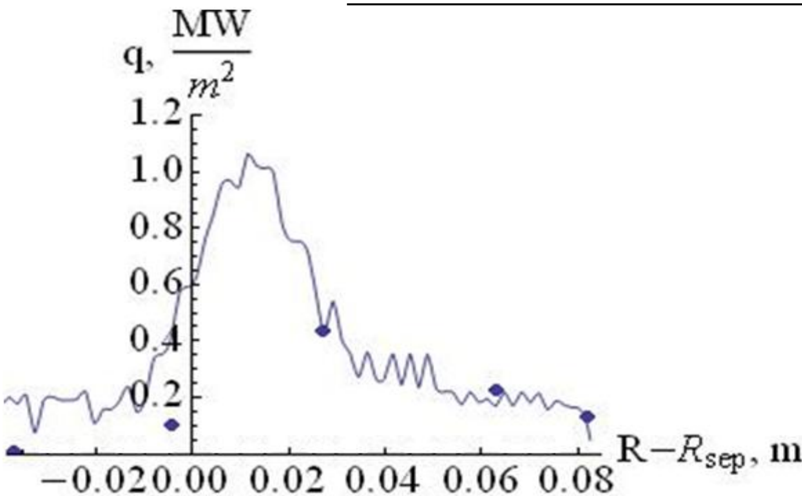
Prospects for edge plasma parameters is important issue for the upgraded machine

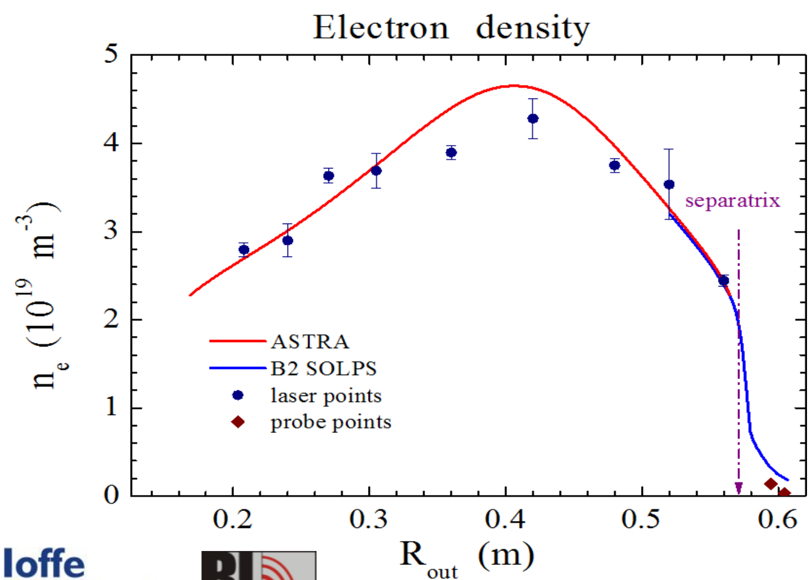


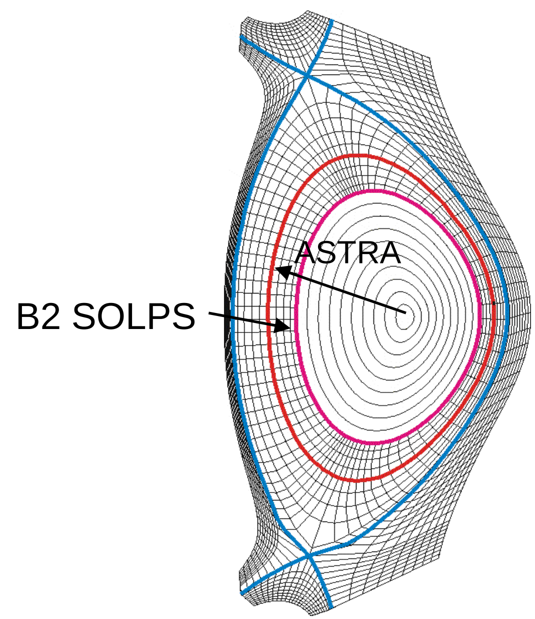
IR videocamera and Langmuir probes data:

SOL heat flux e-folding length, $\lambda_{qMP} \approx$ 3-5 mm SOL divertor plates width, $\lambda_{qD} \approx$15-20 mm

$P_{max}/S \approx 1.1\ MW/m^2$ (OH LSN discharge)

$\lambda_{qMP}(1T) = 2a\rho/R \sim 2a\sqrt{T_i} / RB_{pol} \sim \lambda_{qMP}(0.4T)$





ICRH prospects for 1 T in Globus-M2

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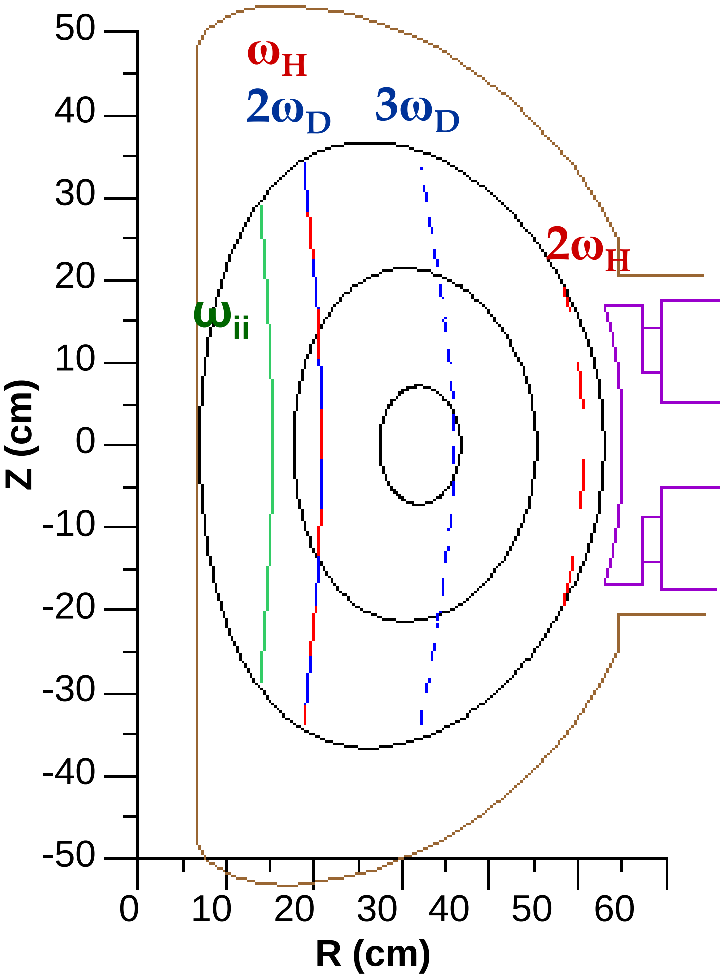
If B_T is increased from 0.4 to 1 T what will be benefits for ICRH heating by FMS waves at fundamental harmonic range?



B_T	0.4T	1 T
$1f_{ci}$ for H^+	6.1 MHz	15.2 MHz

- Single pass resonance absorption of FMS waves increasing due to λ decrease
- Ion-ion hybrid resonance absorption increasing
- High magnetic field improves fast ion confinement and heating efficiency

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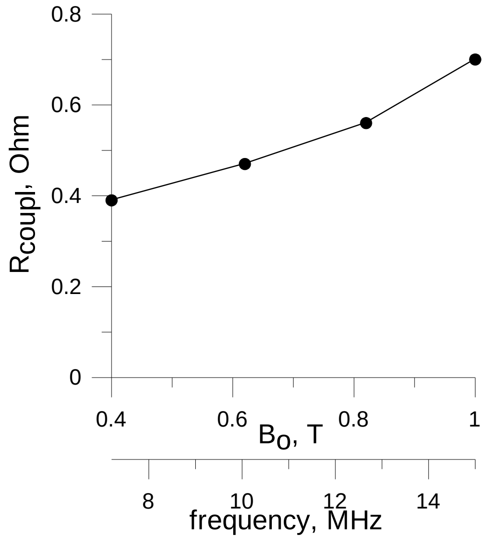
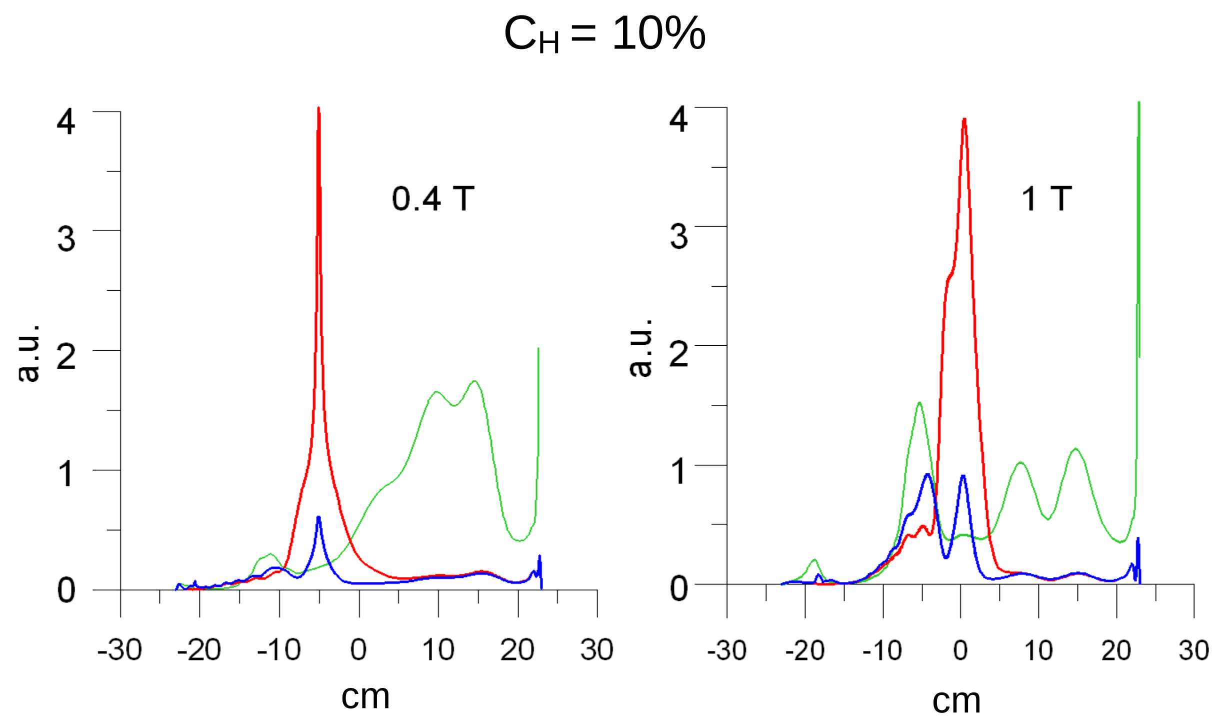
ICR heating efficiency increases with magnetic field raise from 0.4 T to 1 T



Antenna-plasma coupling resistance raise increases RF power absorption efficiency with magnetic field



Particle	Fraction of power at 0.4 T	Fraction of power at 1.0 T
e^-	0,641	0.46
p^+	0,260	0,38
d^+	0,099	0,16

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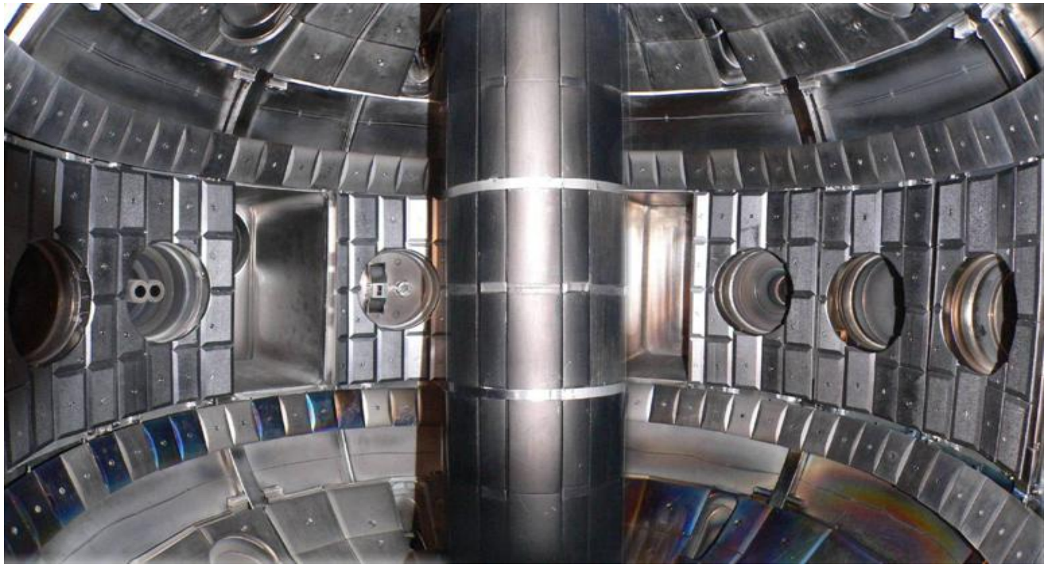
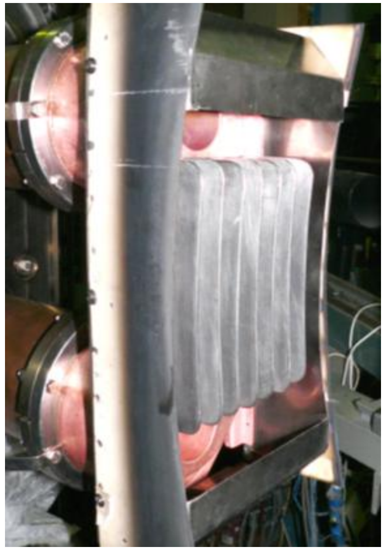
LH CD experiment in Globus-M and expectations for Globus-M2

Novel experimental arrangement was used in experiment with plasma breakdown, current ramp-up and sustainment by LH waves



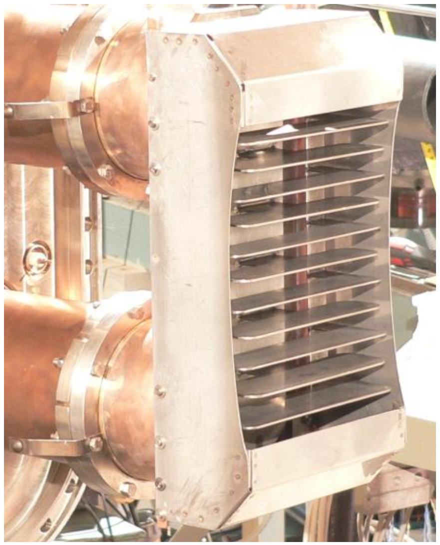


NEW antennae with "toroidal" slow down:

$N_{tor} \approx (6 - 7)$

$N_{pol} \approx 1$

Vessel walls were totally protected by graphite



OLD antennae with "poloidal" slow down:

$N_{tor} \approx (1.0 - 15)$

$N_{pol} \approx (7 - 8)$

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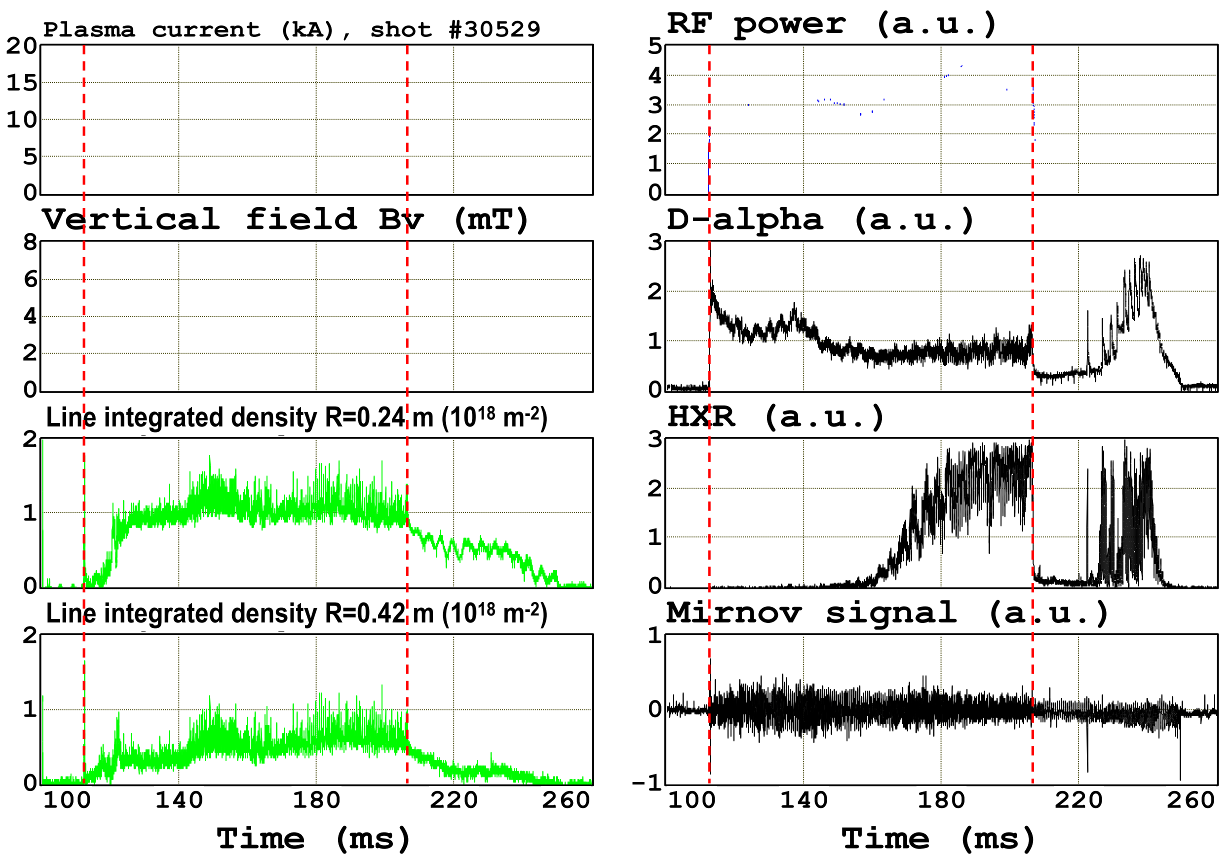
Total driven current comprises at least by 80% of noninductively driven current by LH waves at 900 MHz and 60 kW RF power launched



Contribution of the inductive PF coil flux doesn't exceed 20%

- Inductive flux conserved in the plasma current

  $\Psi_{surf} = I_p L_{ext} = 7{,}1$ mWb

- Vertical field ramp-up flux

  $\Psi_{PF} = \Delta t_{ramp\text{-}up}\, U_{surf} = 1{,}5$ mWb

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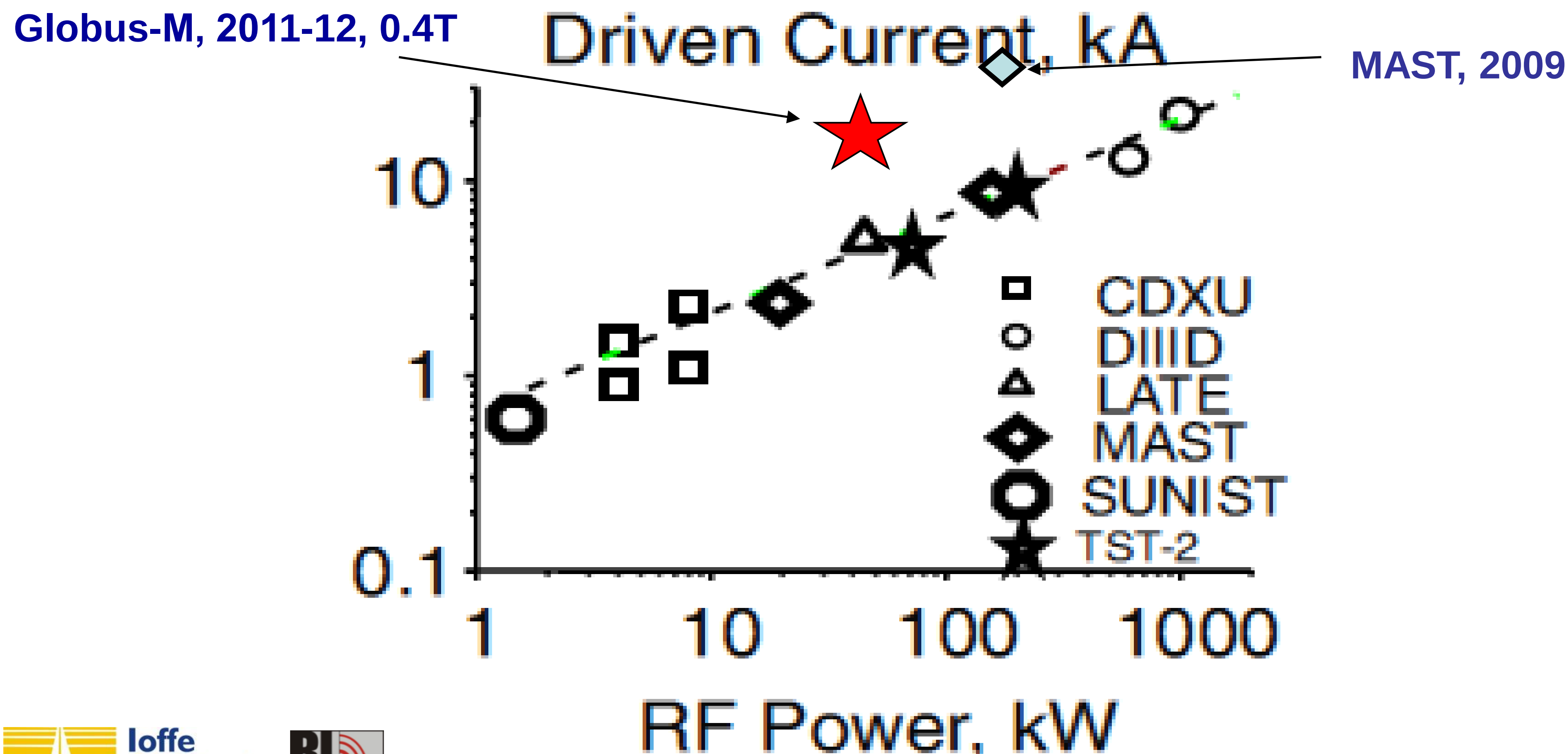
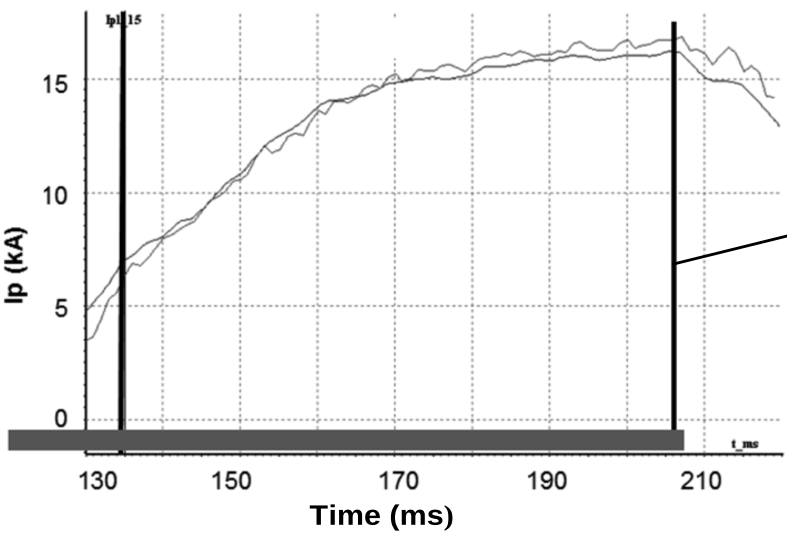
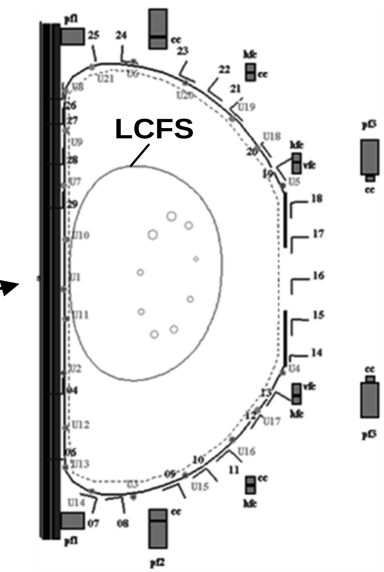
Comparison with other experiments…



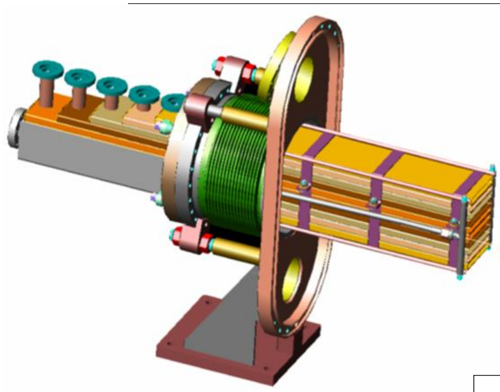
Noninductively driven current forms plasma column with closed magnetic surfaces



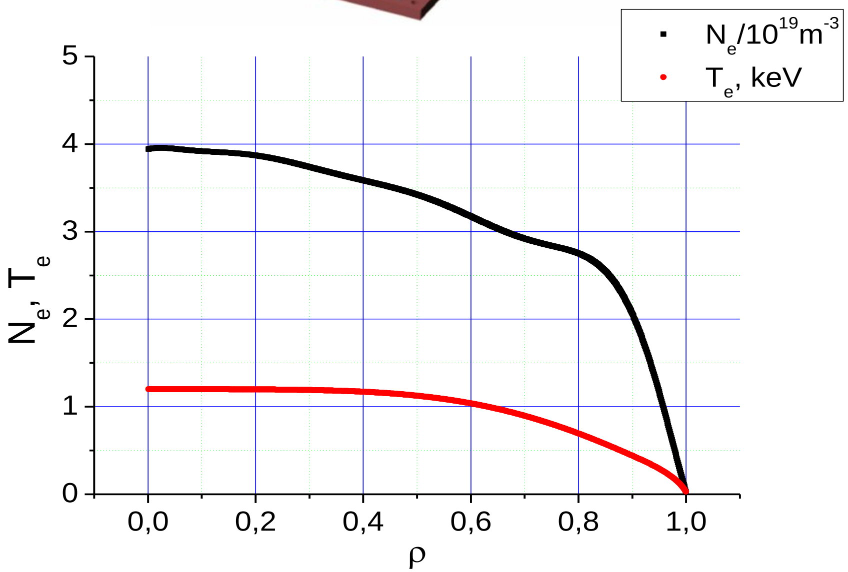


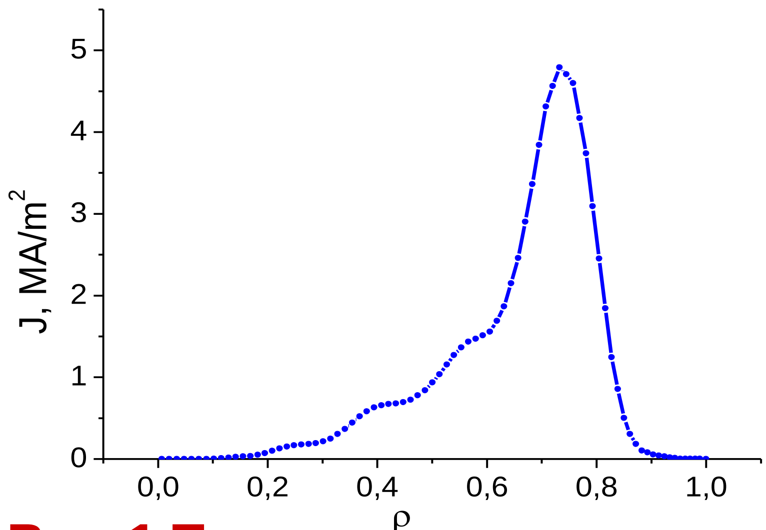
Magnetic reconstruction by current filament method was used

Preliminary ray tracing simulations of noninductive CD drive by LH waves in Globus-M2



10-waveguides Grill may be oriented both in poloidal and toroidal directions





B_T = 1 T

I_P(total) = 0.5 MA; I_P(LHCD) = 0.32 MA.

F=2.45 GHz; P_{LH} = 0.5 MW

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Globus-M2
parameter modeling

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Globus-M regimes provides basis for ASTRA code modeling of Globus-M2 parameters

Instruments: ASTRA, NCLASS, NUBEAM codes

Reference case: Globus-M high density regime with $\chi_e \approx 8\ m^2/s$

Electrons heat transport

$$\tau_E^{IPB98(y,2)} \sim I_p^{0.93} \cdot B^{0.15}$$

$$\chi_e^{(Gl-M2)} \approx \frac{1}{2.7}\chi_e^{(Gl-M)} \approx 3\,m^2/s$$

Spherical tokamak scaling (M.Valovic et al, Nucl. Fusion, 2009, V49, p075016)

$$\tau_E^{Valovic} \sim I_p^{0.59} \cdot B^{1.4}$$

$$\chi_e^{(Gl-M2)} \approx \frac{1}{6.2}\chi_e^{(Gl-M)} \approx 1.3\,m^2/s$$

Ions heat transport

$$\chi_i = \chi_i^{NEOCL} + \chi_i^{AN}$$

$$\chi_i^{AN} \approx D$$

Particle transport – unchanged

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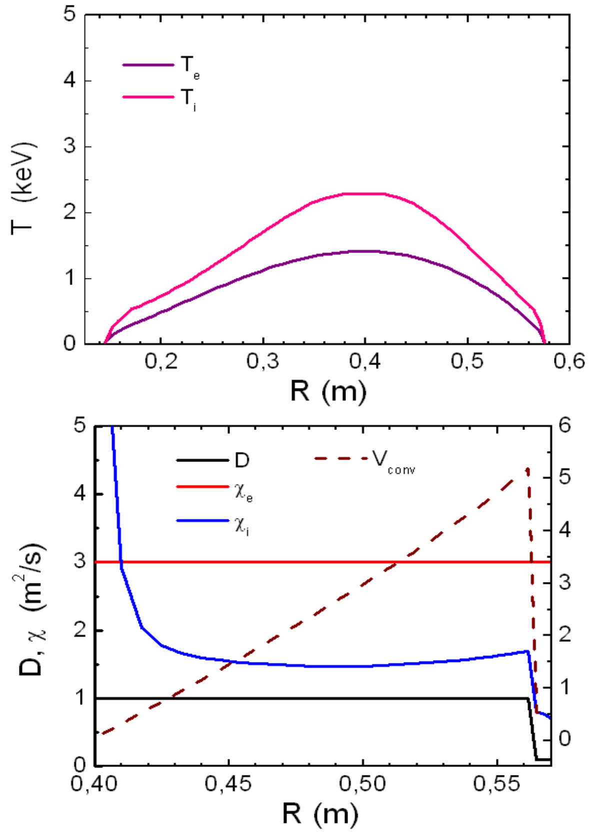
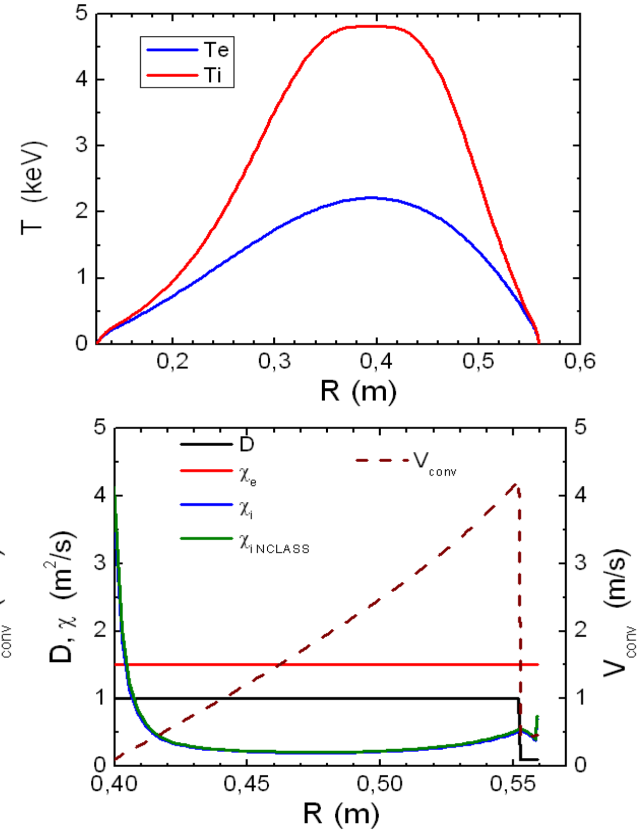
ASTRA simulation of E_D = 30 keV, P_{NB} = 1 MW NB injection into Globus-M2 discharge demonstrates high value of temperature at density ~ 0.7 $10^{20}m^{-3}$



IPB98(y,2)



Valovic scaling

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Conclusions

The analysis of Globus-M results on thermal and fast particle confinement, RF heating and CD led to the conclusion on magnetic field increase in Globus-M2

Upgrade allows for retaining the vacuum vessel and most part of the diagnostics and heating systems.

Substantial improvement in parameters can be expected for Globus-M2: density up to 10^{20} m^{-3} and temperatures in keV range could be attained with high confidence.

The dimensionless parameter range for Globus-M2 allow conditions characteristic for a compact fusion neutron source experimental support.

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