Ioffe Institute

Thermal energy confinement at the Globus-M spherical tokamak and first results from the Globus-M2 experiments

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and Globus-M2 team.

Outline

Ioffe Institute

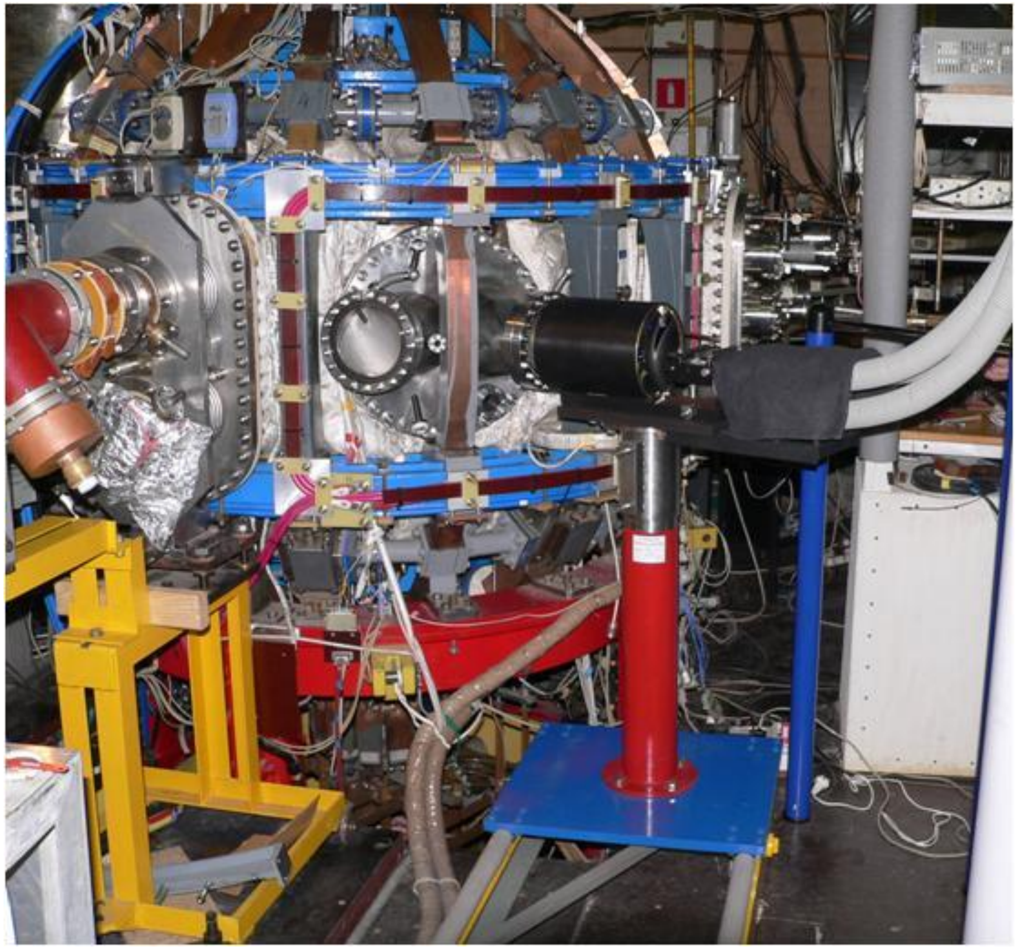
Thermal energy confinement at the Globus-M

- Energy confinement in OH regime
- NBI heating efficiency at the Globus-M
- Thermal energy confinement dependence on B_T and I_p
- The role of collisionality on electron heat transport

First results from the Globus-M2 experiments

- B_T and I_p impact on energy confinement
- Heat transport analysis

Globus-M tokamak



- $I_p \lesssim 0.3$ MA
- $B_T \lesssim 0.5$ T
- $R = 0.35$ m
- $a = 0.21$ m
- $R/a = 1.5 - 1.6$
- $k = 1.8\text{-}2.2$
- $< n_e > \lesssim 1 \cdot 10^{20}\ m^{-3}$
- $T_e \lesssim 1.5\ keV$
- $T_i \lesssim 0.9\ keV$
- $P_{NBI} \lesssim 1$ MW

H-mode

H-mode access in pure ohmic heating and in NBI regimes

OH H-mode

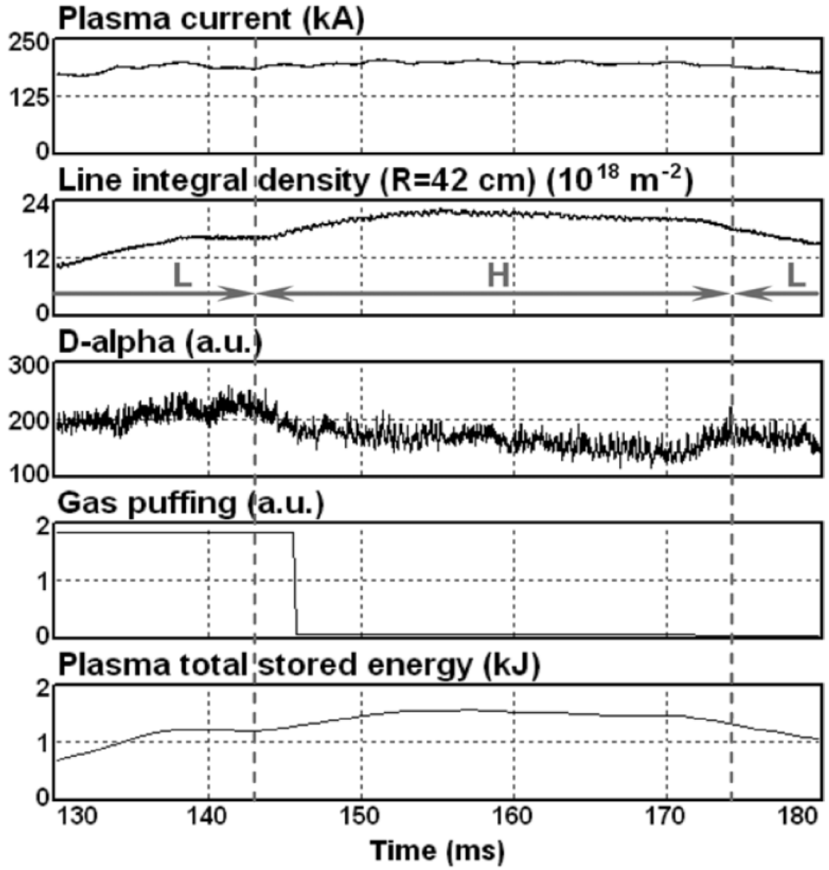


Figure 7. Time evolution of plasma parameters in OH discharge with H-mode. Shot #18083.

NBI H-mode

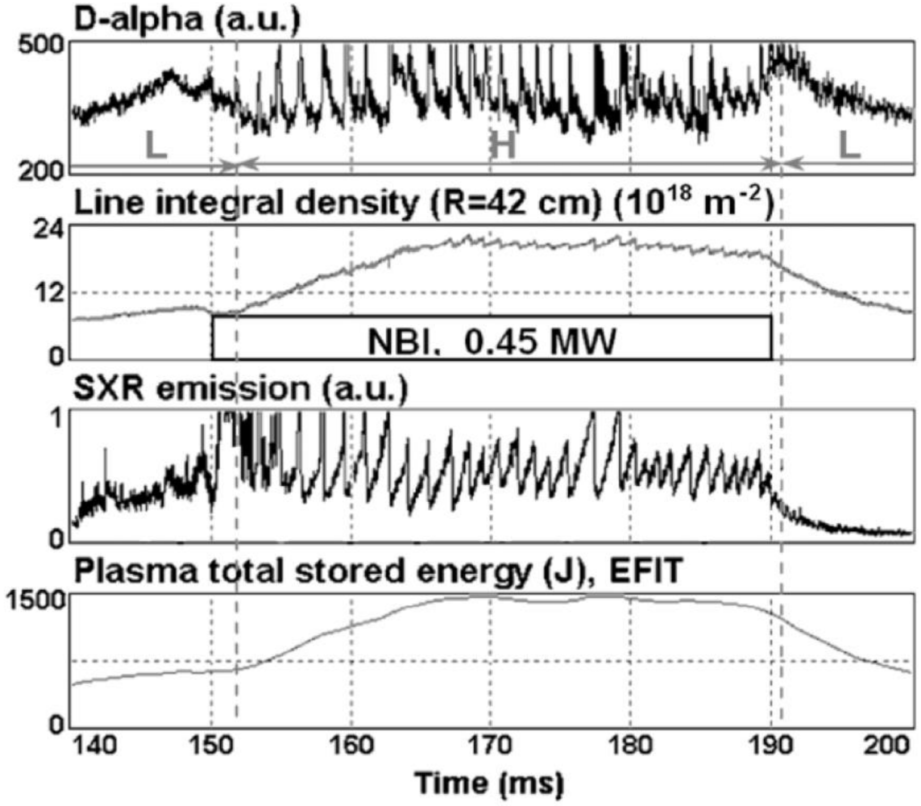
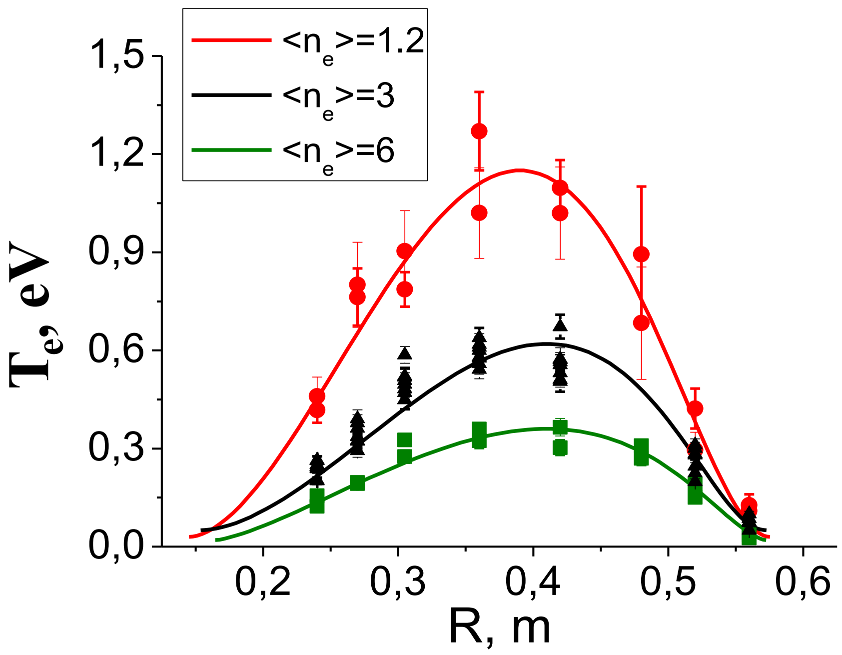
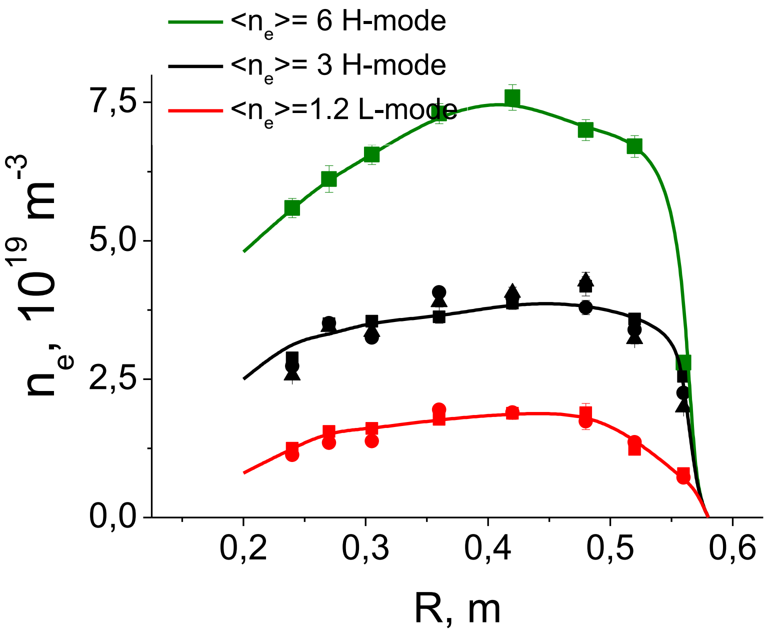


Figure 10. *L–H* transition in the NBI heated Globus-M shot #19518.

Nucl. Fusion ***49*** *(2009) 104021*

Energy confinement in <u>Ohmic heating</u> regime
I_p=0.2 MA, B_T=0.4 T

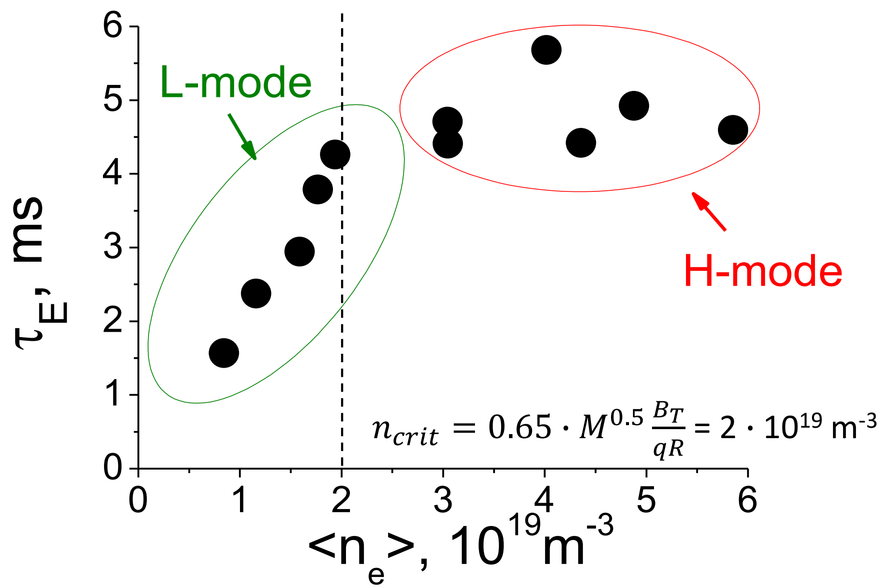


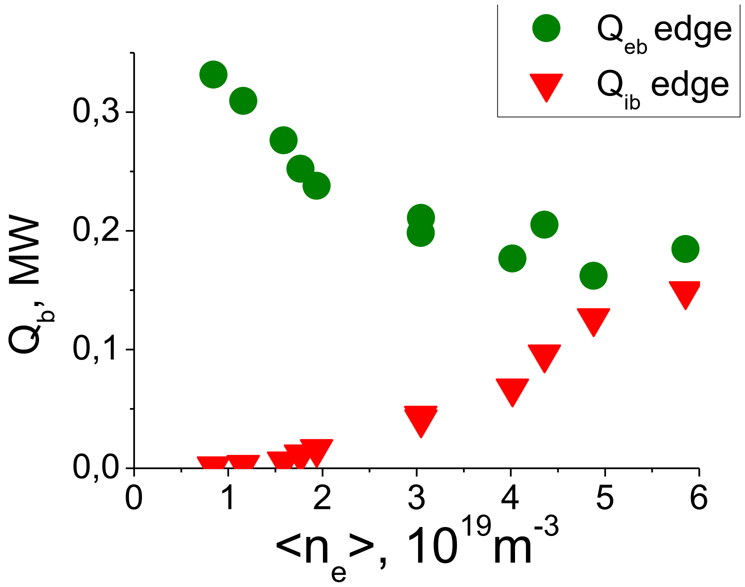


Electron density rise is accompanied by:

- *T_e decrease*
- *steep ∇n_e formation at the edge*

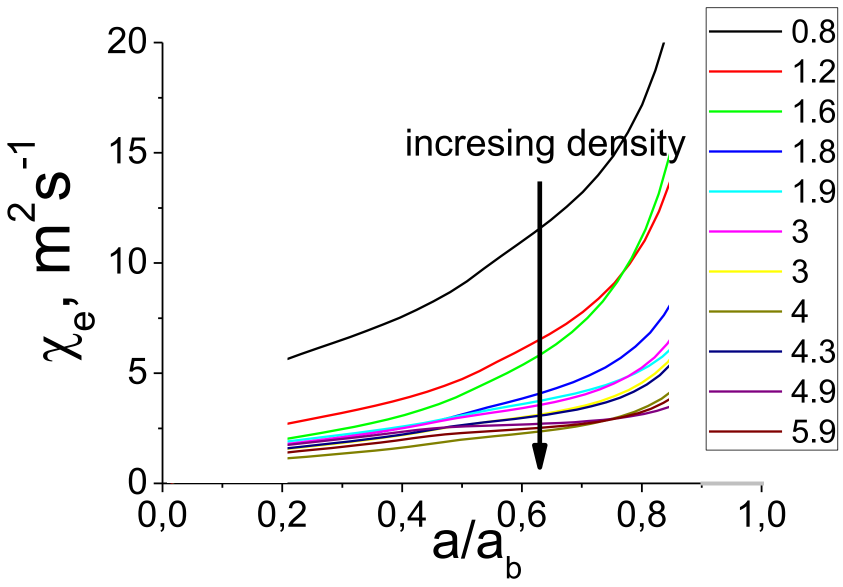
Energy confinement in ohmic heating regime
I_p=0.2 MA, B_T=0.4 T

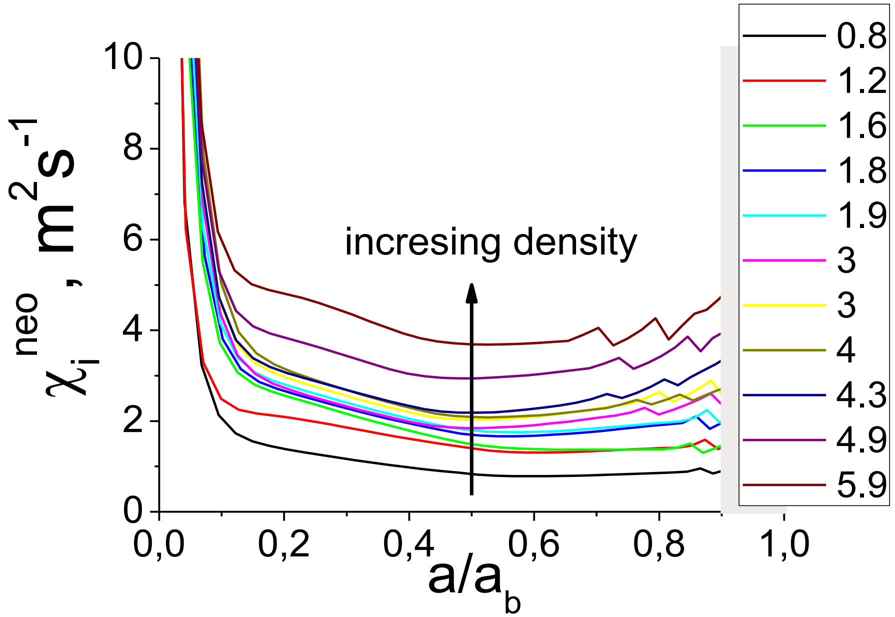


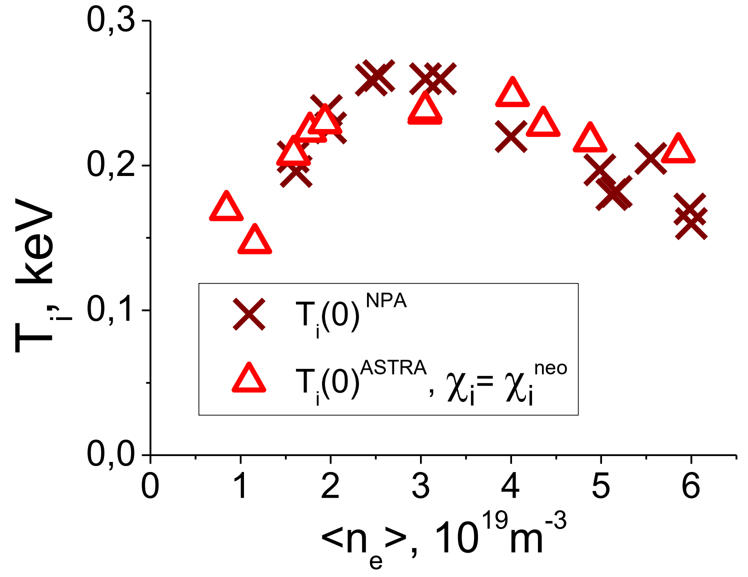


- $n_e < 2\text{-}3 \cdot 10^{19}$ m^{-3}
  - linear ohmic confinement regime (LOC)
  - $\tau_E \approx 1{,}7 \cdot \tau_E^{neoalcator}$
  - heat loss through electrons
- $n_e > 3 \cdot 10^{19}$m^{-3}
  - transition to H-mode
  - a significant part of the energy goes through the ion channel
  - $\tau_E \approx 0{,}7 \cdot \tau_E^{IPB98(y,2)}$

Energy confinement in ohmic heating regime
I_p=0.2 MA, B_T=0.4 T

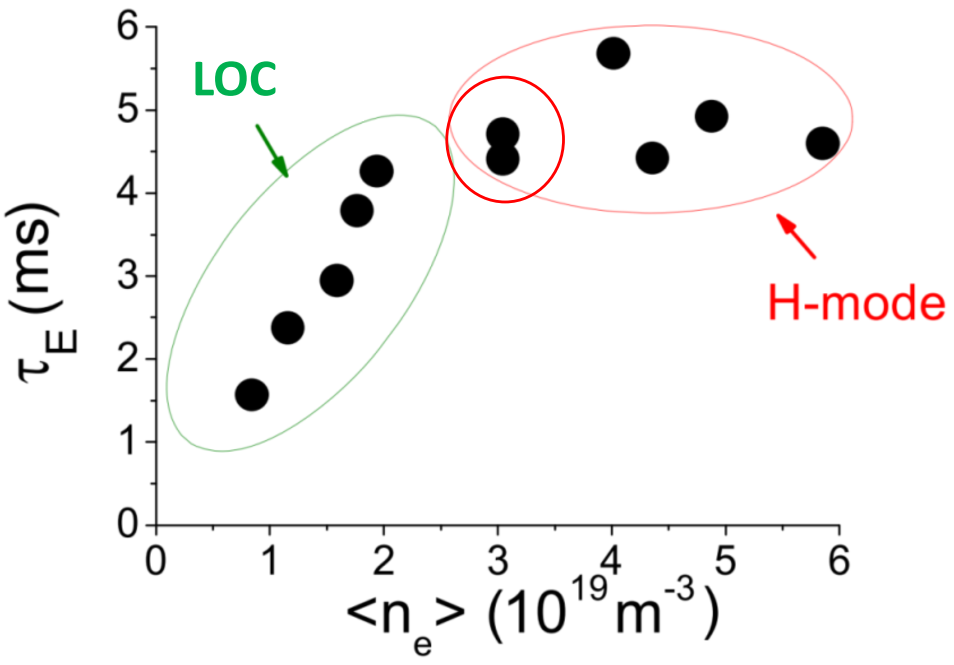






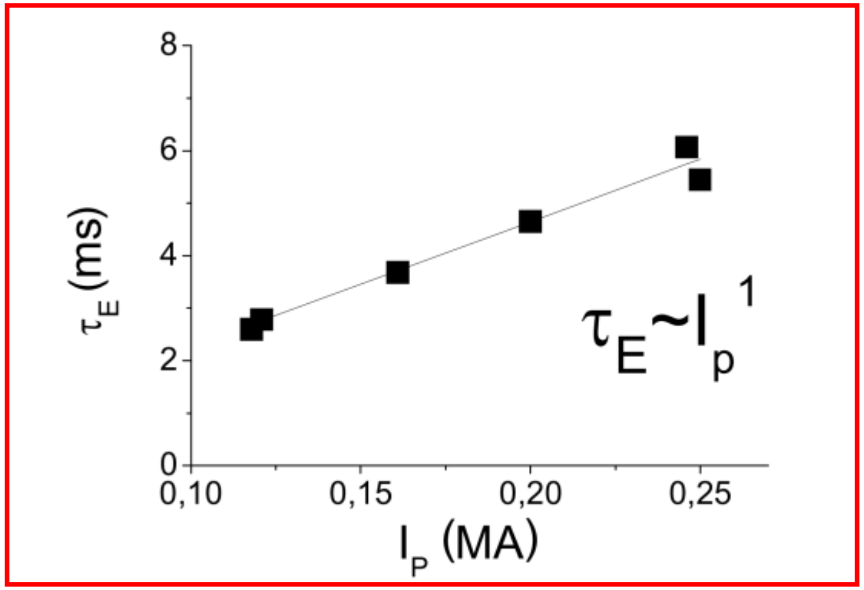
- *Electron heat diffusivity decreases with increasing density from* 15 downto 2 m^{2}s^{-1}
- *Ion heat diffusivity is neoclassical, rises from* 1 to 5 m^{2}s^{-1}

Energy confinement in OH H-mode
fixed B_T=0.4 T, I_p = 0.1-0.25 MA

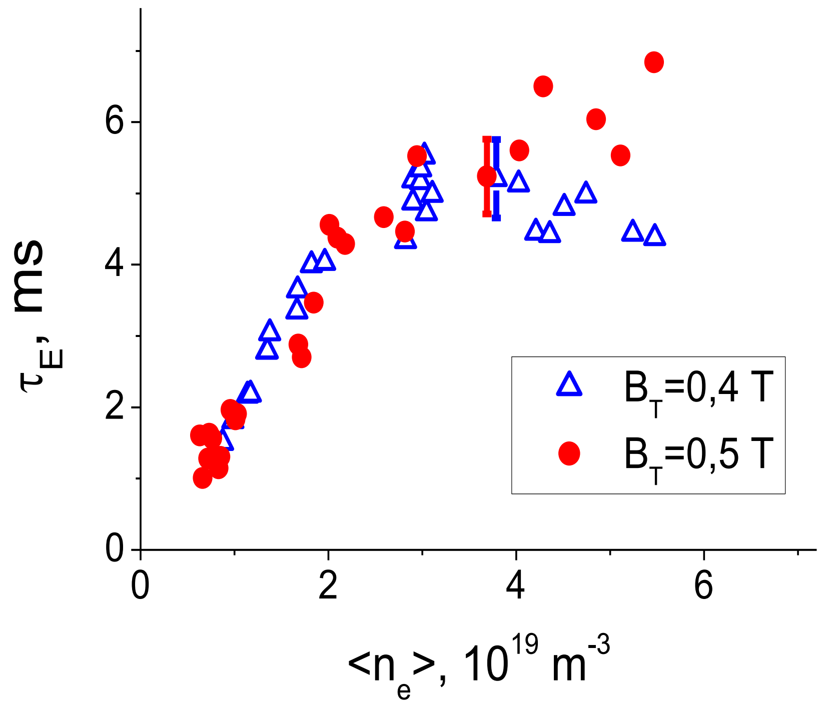


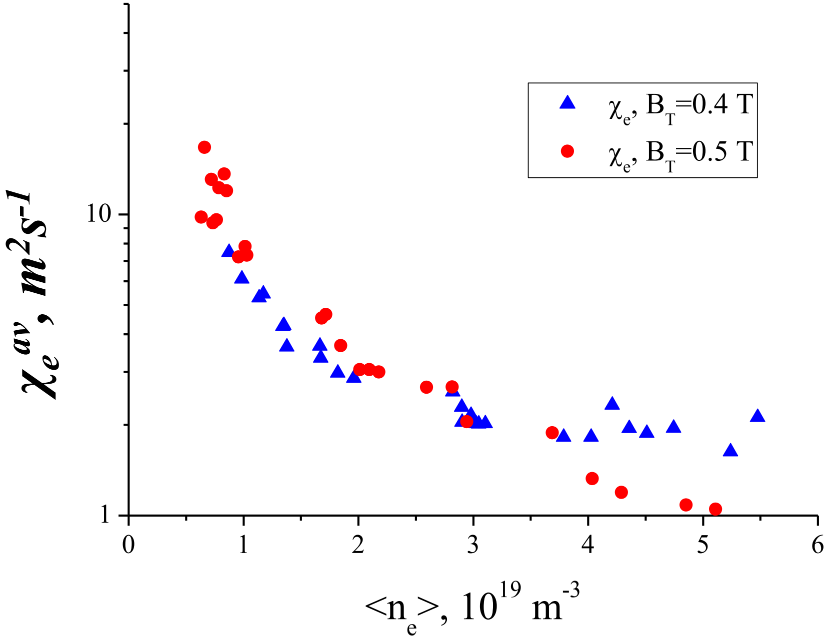
Energy confinement times depend linearly on plasma current

- H-mode:
  - $\chi_i = \chi_i^{neo}$
  - $I_p \uparrow$ -> $\chi_e \downarrow \chi_i \downarrow$
  - $\tau_E \sim I_p^{\,1}$



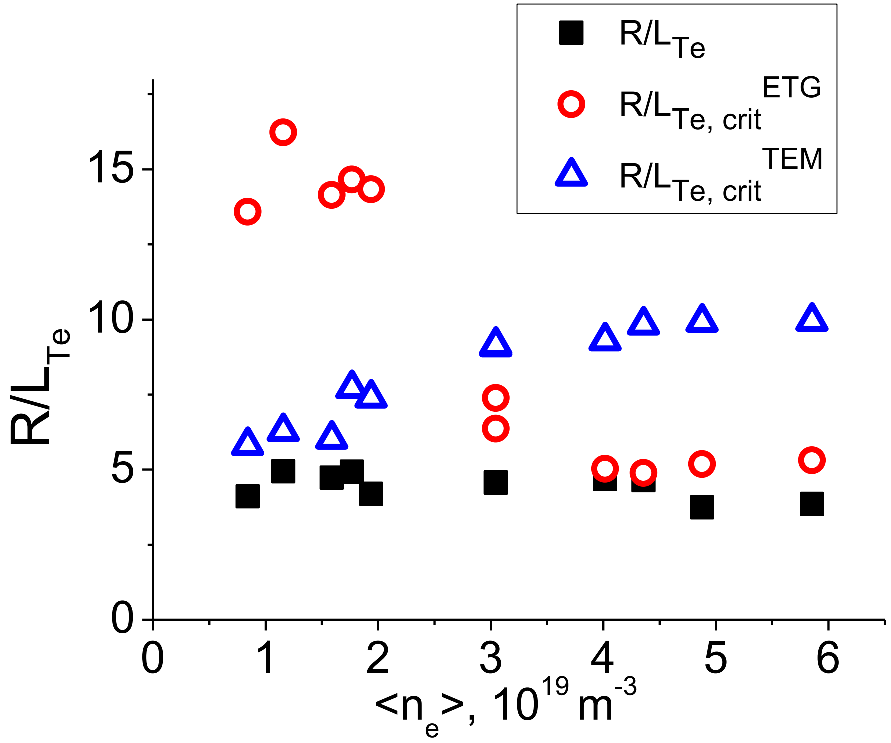
Energy confinement in OH H-mode fixed I_p=0.2 MA T, B_T = 0.5-0.5 T





- $\tau_E \sim B_T$ for moderate density 4 – 6 10^{19} m^{-3}
- electron heat transport improves – χ_e decreases in the plasma core

Analysis of microinstabilities in OH regime



$$\frac{R}{L_{Te,crit}}^{TEM} = \frac{0.357\sqrt{\varepsilon}+0.271}{\sqrt{\varepsilon}}\left[4.90-1.31\frac{R}{L_N}+2.68\hat{s}+\ln\left(1+20\nu_{eff}\right)\right]$$

TEM: Peeters A.G. et al 2005 Phys. Plasmas ***12*** *022505*

$$\nu_{eff}\approx 0.1\frac{n_e^* Z_{eff}}{T_e^2}$$

$$\frac{R}{L_{Te,crit}}^{ETG} = \left(1+Z_{eff}\frac{T_e}{T_i}\right)\left(1.33+1.91\frac{\hat{s}}{q}\right)f(\varepsilon)$$

ETG: Jenko F. and Dorland W. 2002 *Phys. Rev. Lett.* **89** 225001

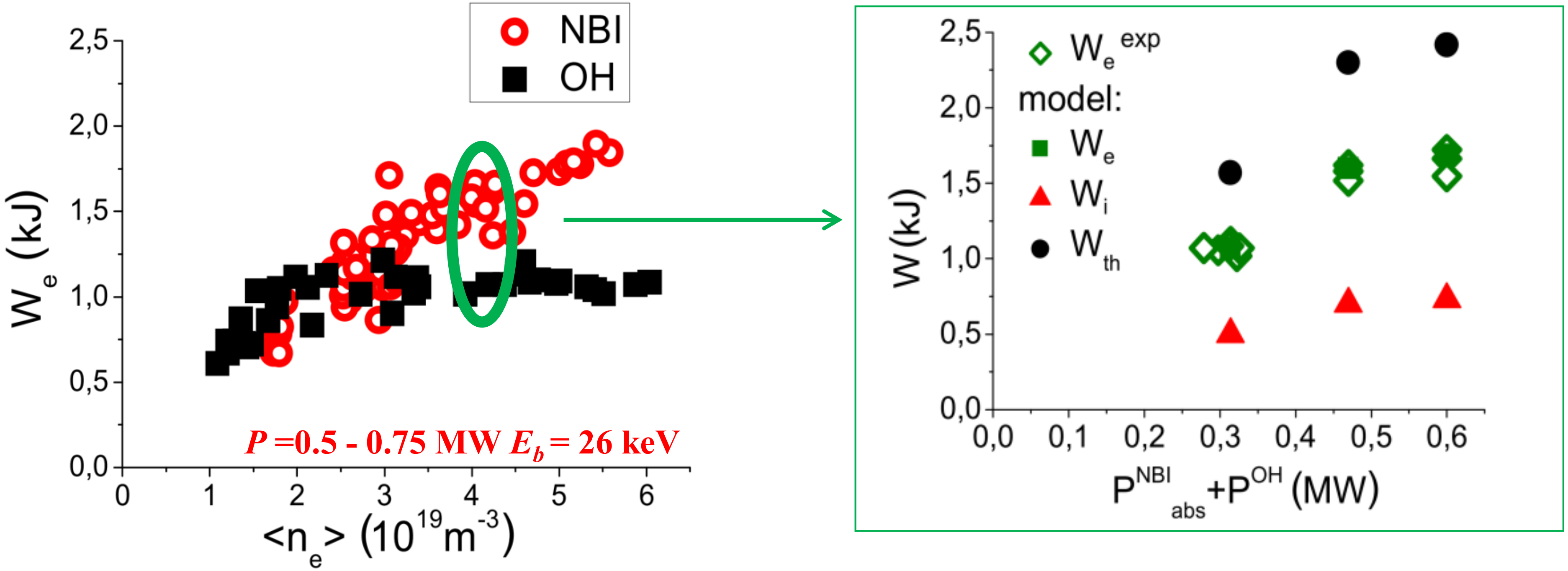
LOC: $n_e<2.5\cdot10^{19}$ m^{-3}, $\tau_E \approx 1{,}7\cdot \tau_E^{\text{neoalcator}}$

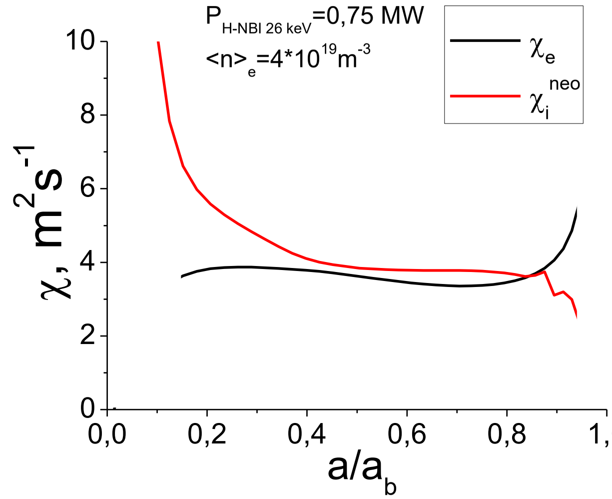
- $R/L_{Te} \approx 4{,}5$ that is close to critical value for TEM ($R/L_{Te}^{crit}(TEM) \approx 6$)

OH H-mode $n_e>2.5\cdot10^{19}$ m^{-3} $\tau_E \approx 0{,}7 \cdot \tau_E^{\text{H-mode}}$

- $R/L_{Te} \approx 4$ that is close to critical value for ETG ($R/L_{Te}^{crit}(ETG) \approx 4$)
- Ion heat transport is neoclassical

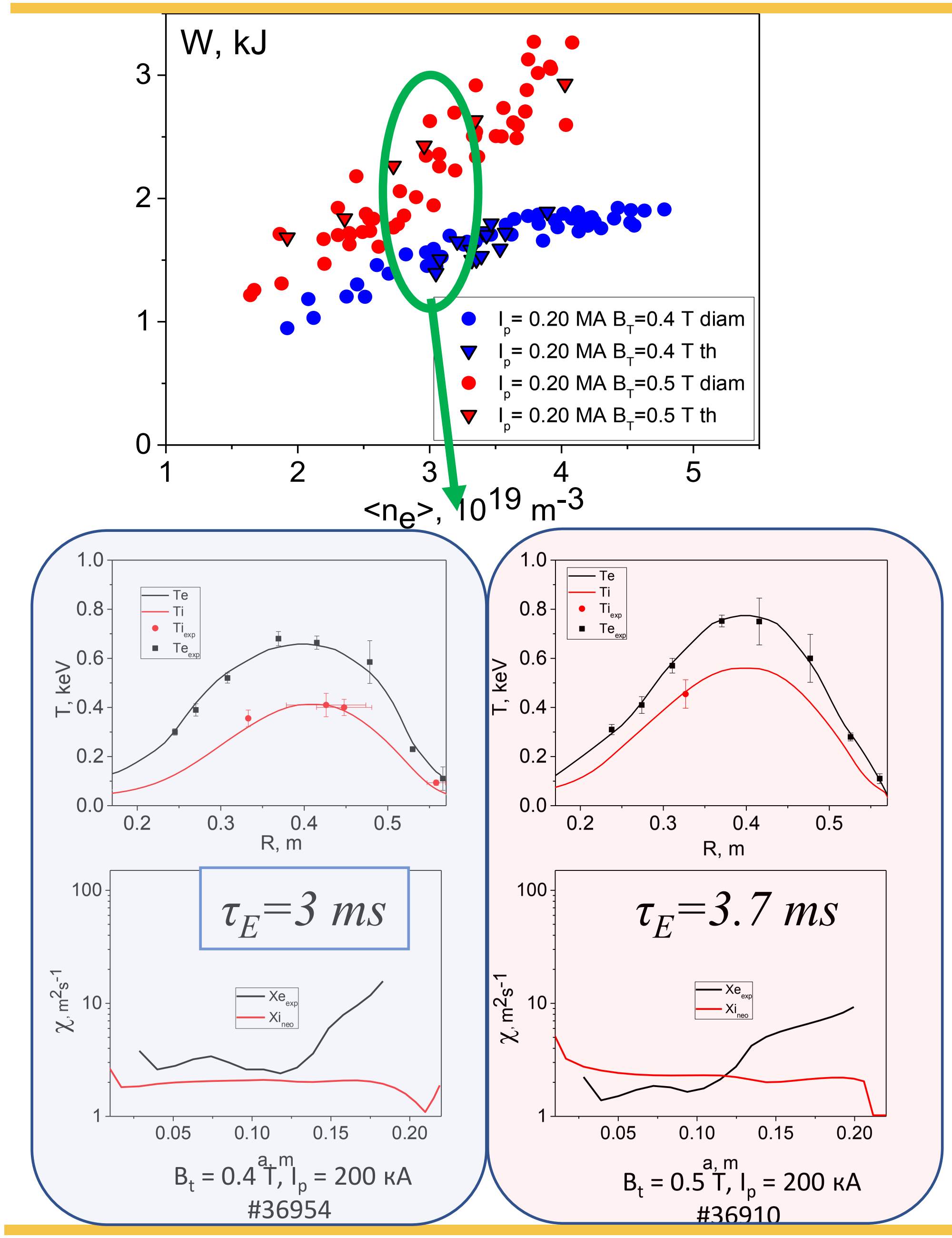
Neutral Beam Heating I_p=0.2 MA B_T=0.4 Тл

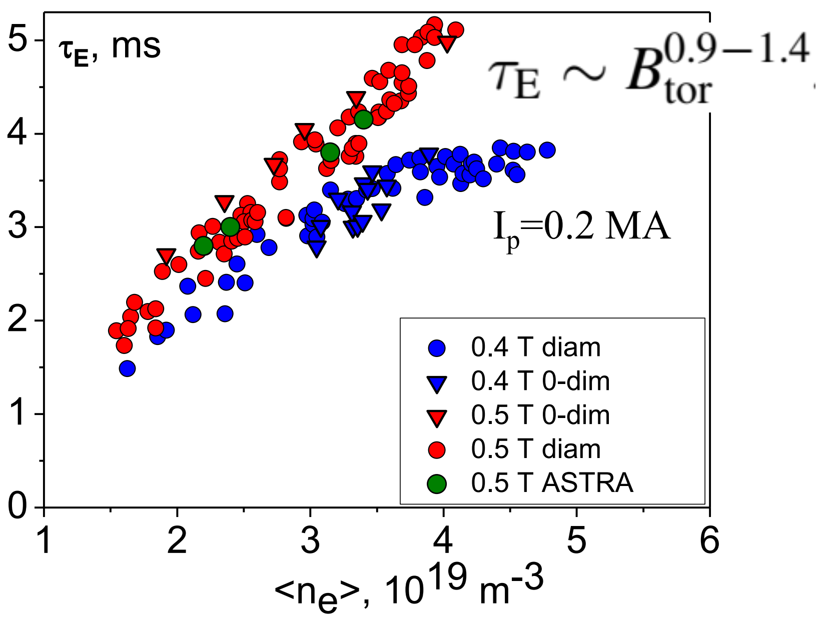




- Significant heating of the plasma electron component is observed
- $W \sim P^{0.72\pm0.17}$
- Ion heat transfer is consistent with neoclassical theory $\chi_i = \chi_i^{neo}$

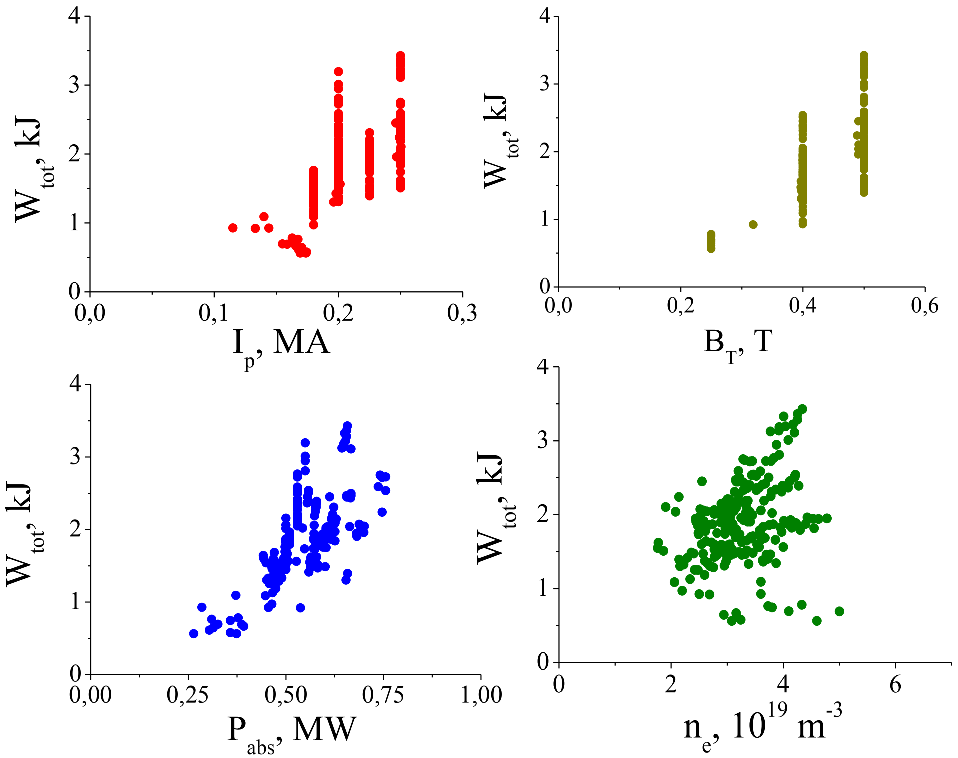
The effect of B_T on τ_E in the NBI H-mode





- W and τ_E rises with B_T
- Electron heat diffusivity decreases
- Ion heat transfer is consistent with neoclassical theory $\chi_i = \chi_i^{neo}$

Globes-M NBI H-mode database



I_p=0.12-0.25 MA,

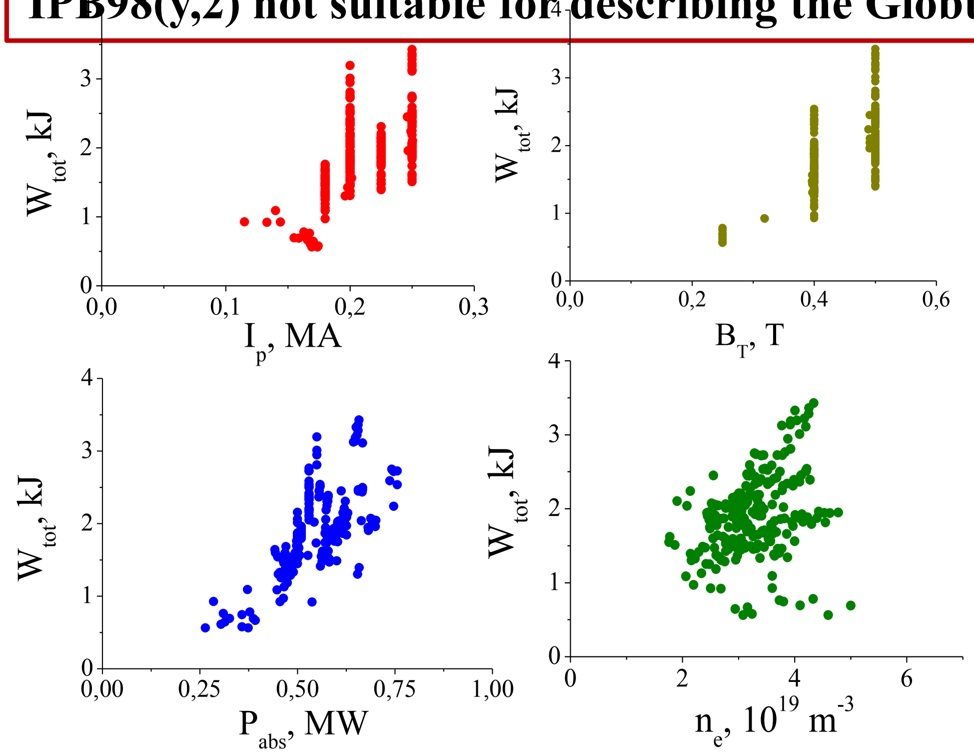
B_T=0.25-0.5 T,

P_{abs}=0.2-0.8 MW,

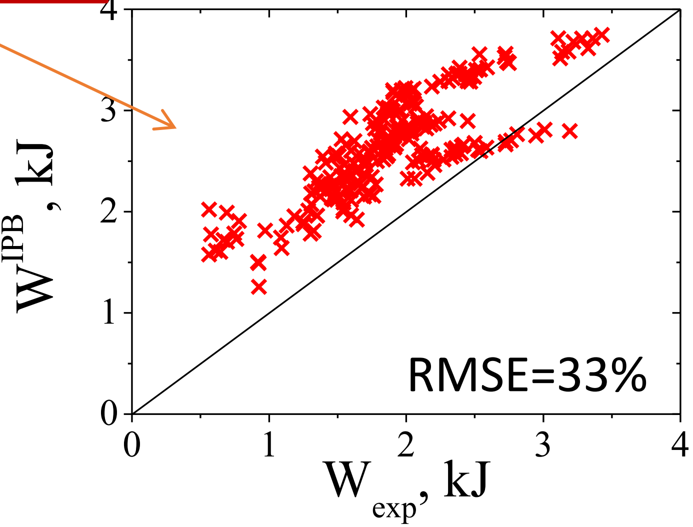
n_e=1.8-5.5 10^{19} m^{-3}

Globes-M NBI H-mode database

IPB98(y,2) not suitable for describing the Globus-M experiment



IPB98(y,2) $W^{IPB} \sim I_p^{-0.93} B_T^{0.15} P_{abs}^{0.31} n_e^{0.41}$



I_p=0.12-0.25 MA,

B_T=0.25-0.5 T,

P_{abs}=0.2-0.8 MW,

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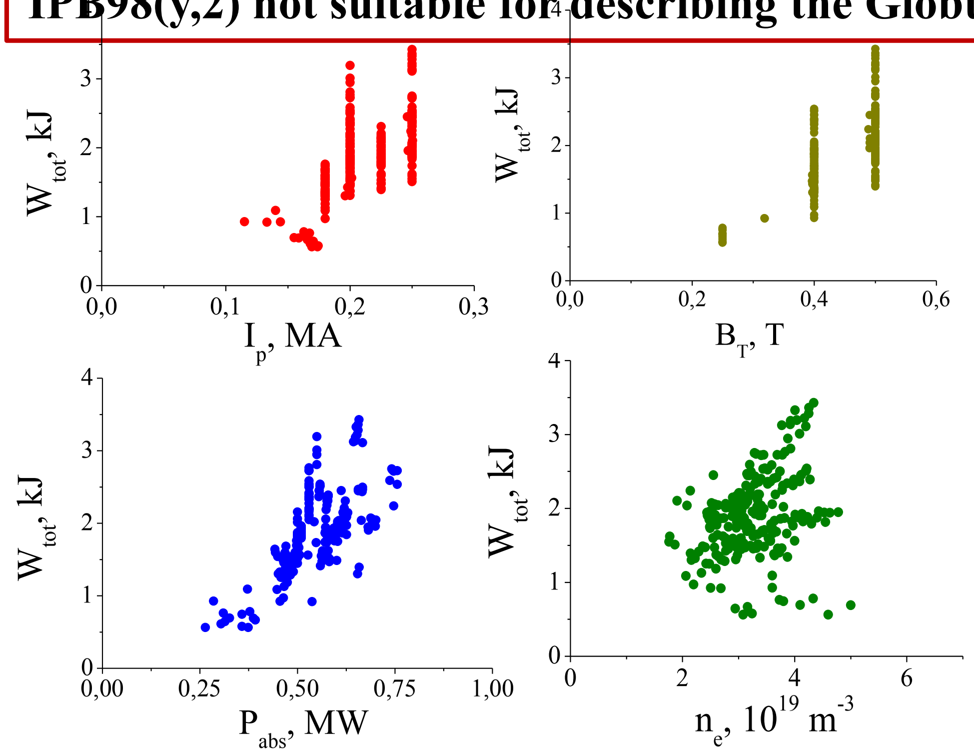

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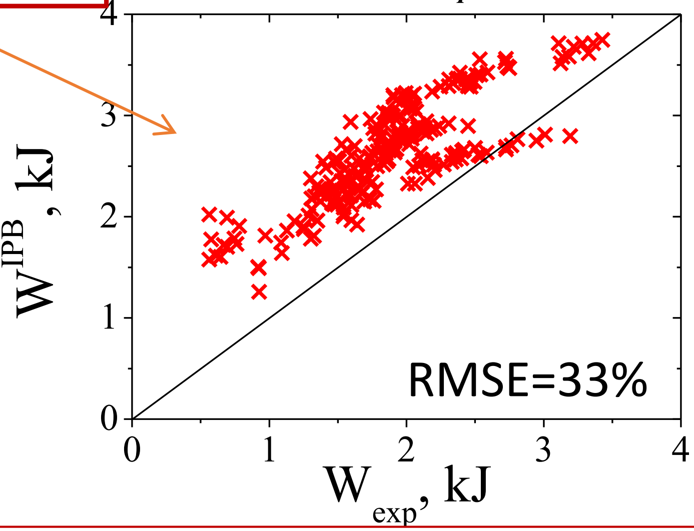
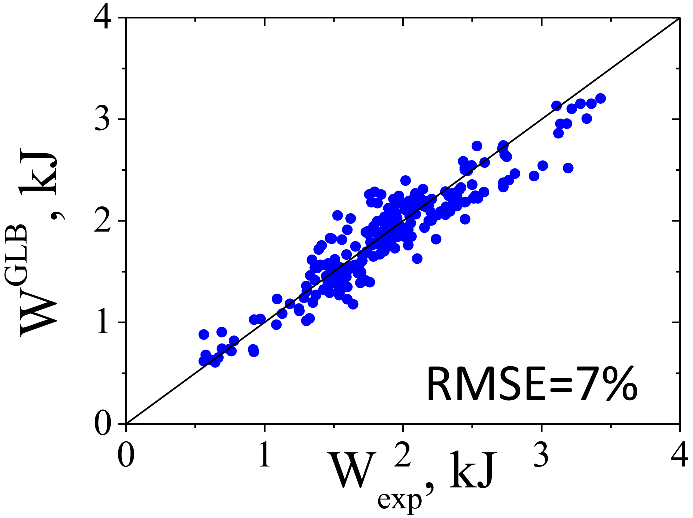


$W^{Globus\text{-}M} \sim I_p^{0.48\pm0.21}\ B_T^{1.28\pm0.12} P_{abs}^{0.46\pm0.26} n_e^{0.77\pm0.04}$



I_p=0.12-0.25 MA,

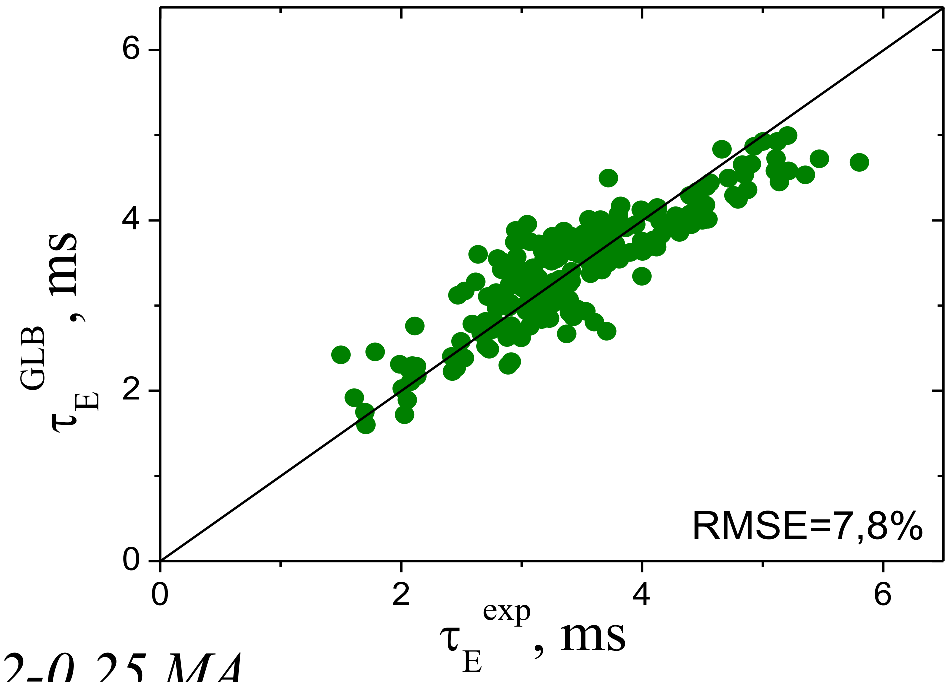
B_T=0.25-0.5 T,

P_{abs}=0.2-0.8 MW,

n_e=1.8-5.5 10^{19} m^{-3}

τ_E scaling for Globus-M

$$\tau_E^{GLB} = 6.08\, I_p^{0.48\pm0.21}\, B_T^{1.28\pm0.12} P_{abs}^{-0.54\pm0.26} n_e^{0.77\pm0.04},\ ms$$



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

ST:

$\tau_E \sim I_p^{0.59} B_T^{1.4}$ (MAST)

$\tau_E \sim I_p^{0.57} B_T^{1.08}$ (NSTX)

$\tau_E \sim I_p^{0.48} B_T^{1.28}$ **(Globus-M)**

I_p=0.12-0.25 MA,

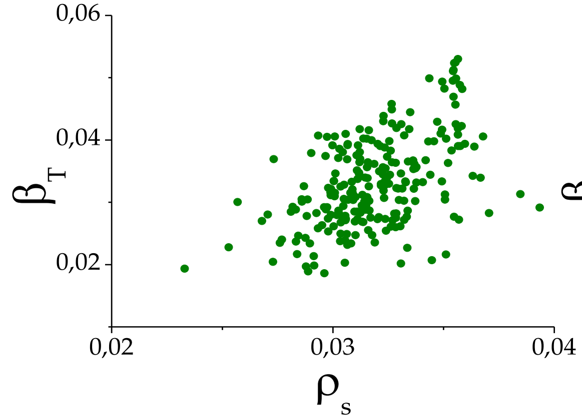
B_T=0.25-0.5 T,

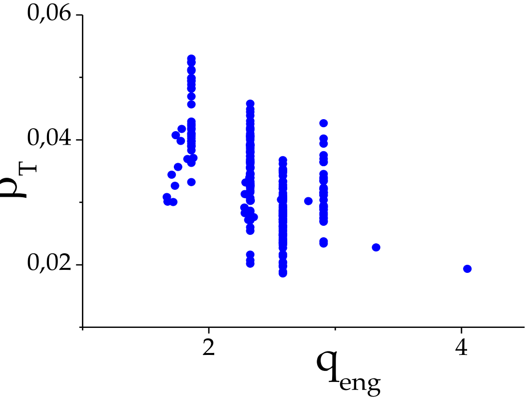
P_{abs}=0.2-0.8 MW,

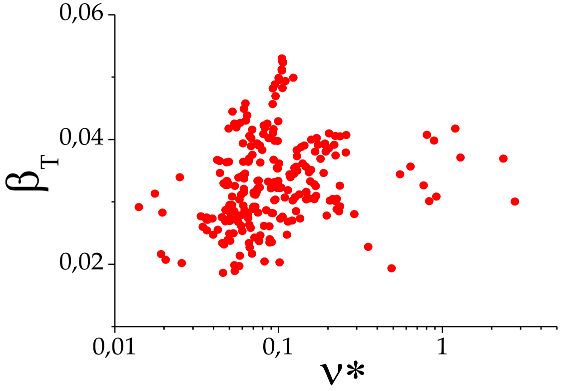
n_e=1.8-5.5 $10^{19}\ m^{-3}$

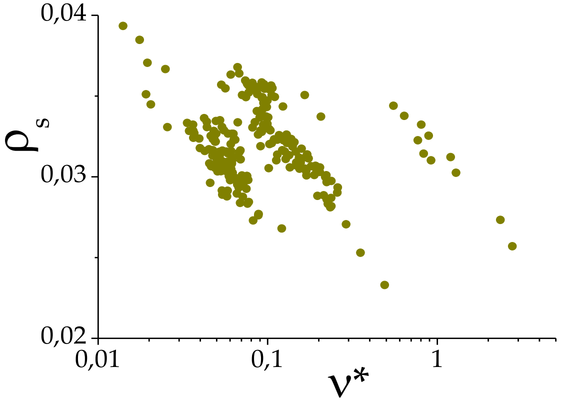
energy confinement time has strong dependence on the toroidal magnetic field at the Globus-M tokamak in NBI regime

Dimensionless analysis









$q_{eng} \sim B_T/I_p$

$\nu^* \sim n_e/T^2$

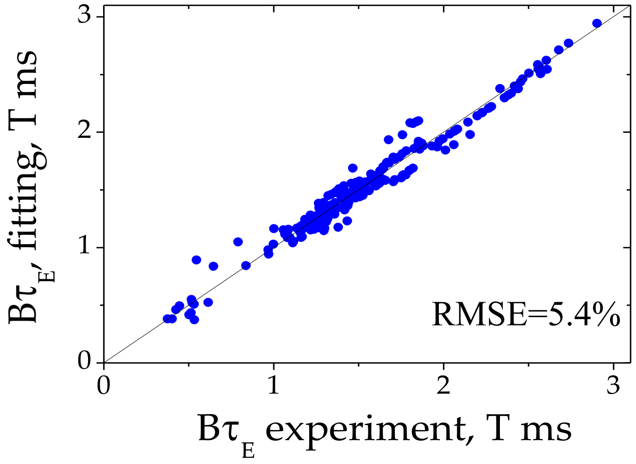
$\rho^* \sim T^{0.5}/B_T$

$\beta_T \sim W/B_T^2$

Dimensionless analysis

$B_T\tau_E \sim \rho^{*-2.7} \cdot \beta_T^{1.45} \cdot \nu^{*-0.45} \cdot q_{eng}^{0.85}$

Regression shows strong dependence of the normalized energy confinement time on the plasma collisionality



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$\nu^* \sim n_e/T^2$

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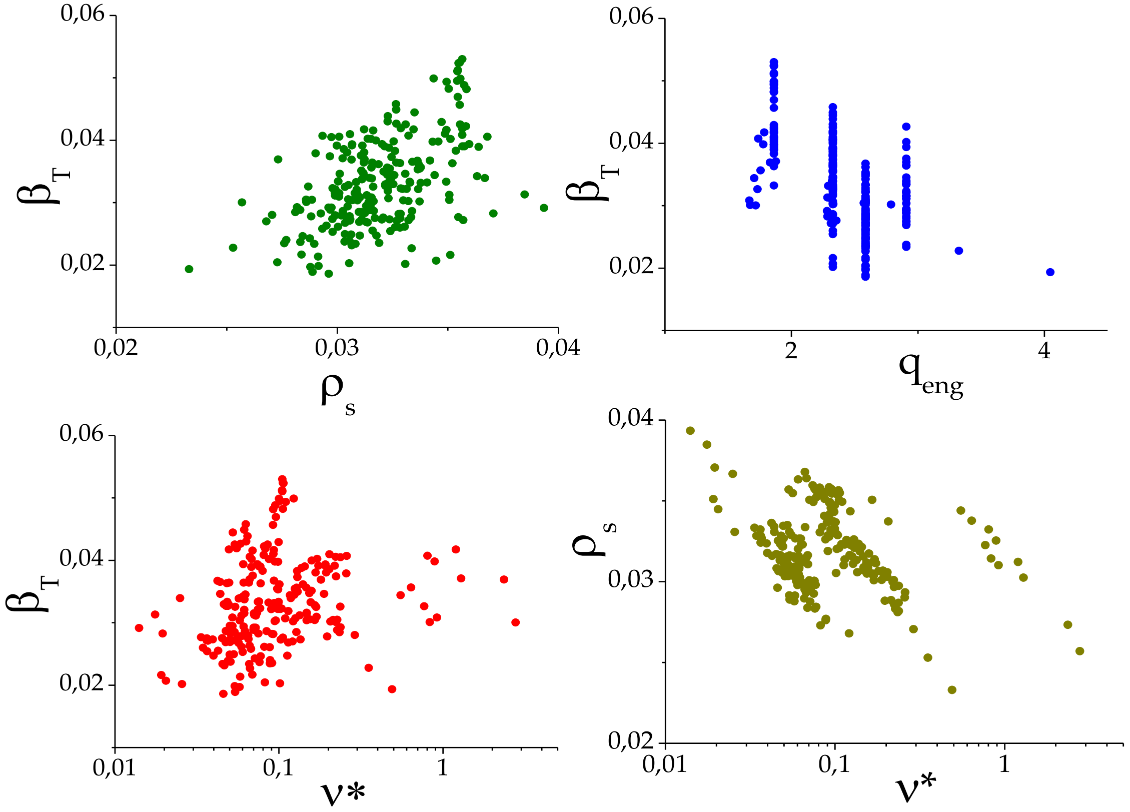
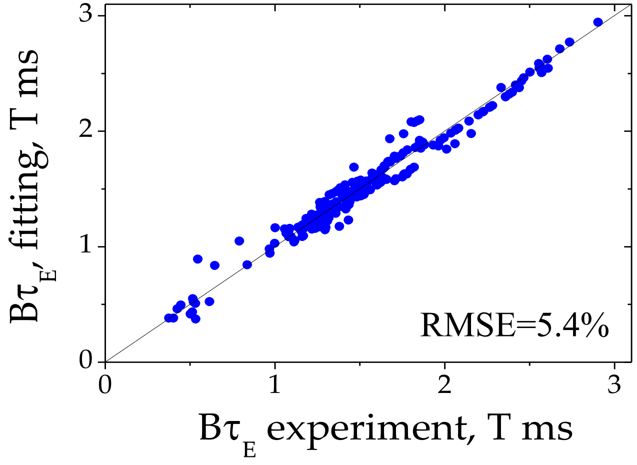


$q_{eng} = 2\pi a^2 \kappa B_T/(R\mu_0 I_p)$

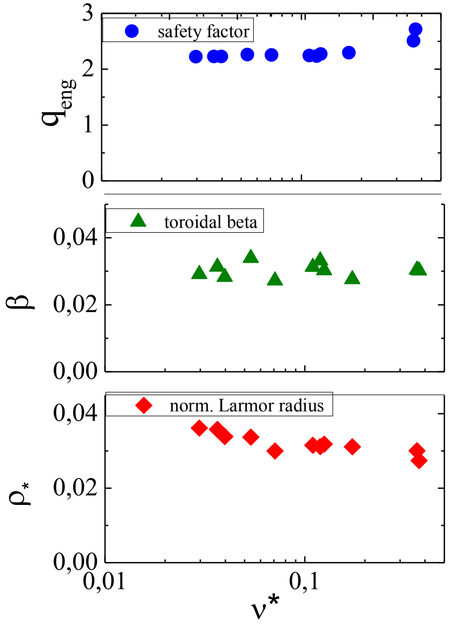
Dimensionless analysis

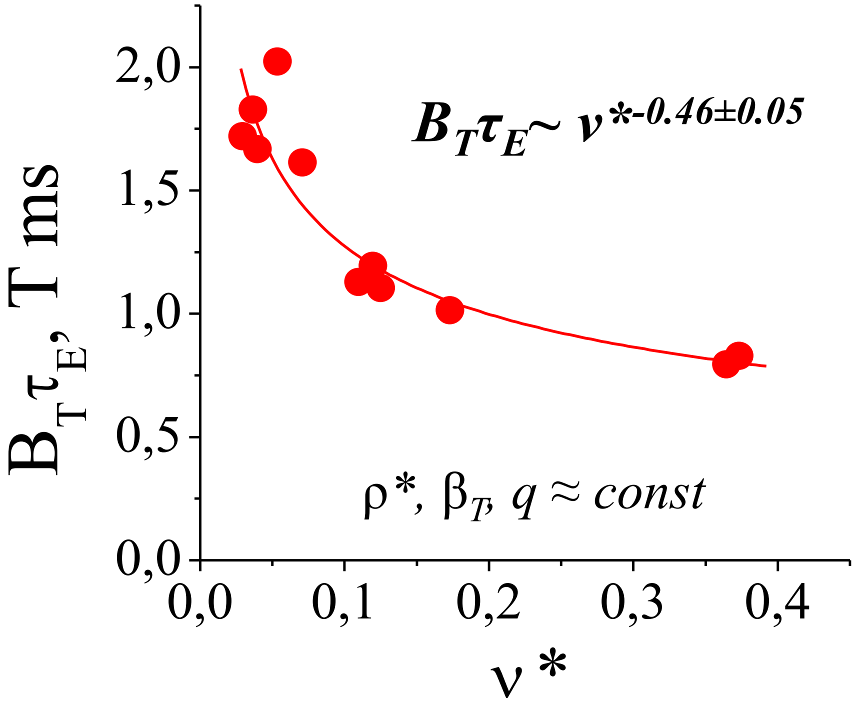
$B_T\tau_E \sim \rho^{*-2.7} \cdot \beta_T^{1.45} \cdot \nu^{*-0.45} \cdot q_{eng}^{0.85}$

$(q_{eng} \sim B_T/I_p;\ \nu^* \sim n_e/T^2;\ \rho^* \sim T^{0.5}/B_T;\ \beta_T \sim W/B_T^2;)$



- Regression shows strong dependence of the energy confinement time on the plasma collisionality
- The result is confirmed by the dedicated scan with fixed ρ^*, β_T, q

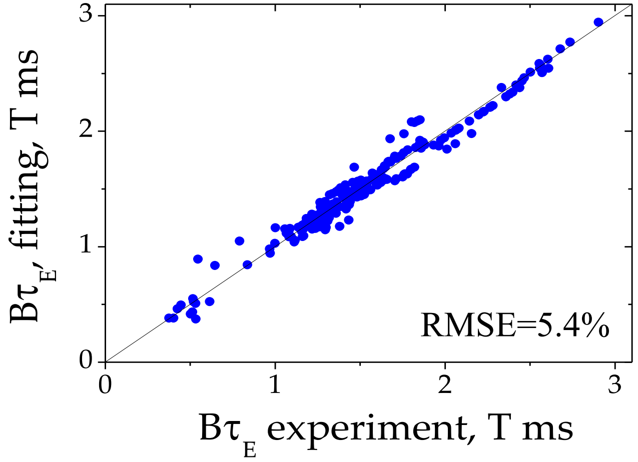




Dimensionless analysis

$B_T\tau_E \sim \rho^{*-2.7} \cdot \beta_T^{1.45} \cdot \nu^{*-0.45} \cdot q_{eng}^{0.85}$

($q_{eng} \sim B_T/I_p$; $\nu^* \sim n_e/T^2$; $\rho^* \sim T^{0.5}/B_T$; $\beta_T \sim W/B_T^2$;)



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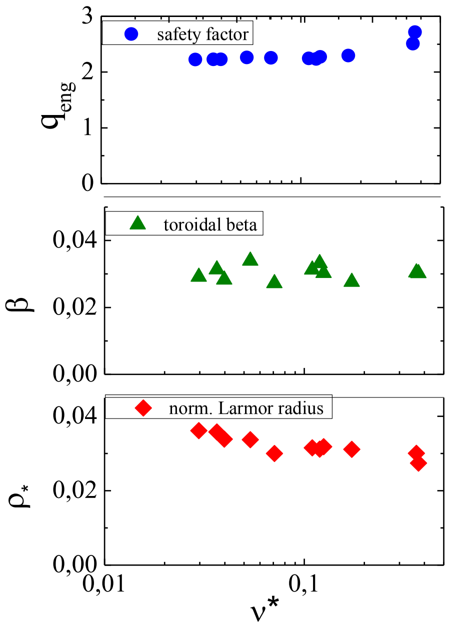
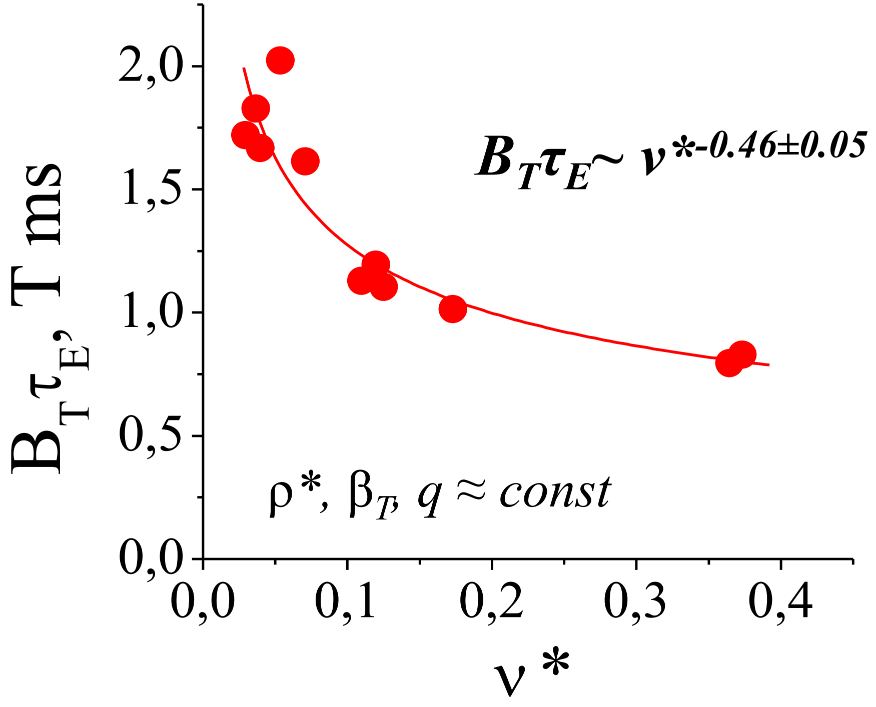




ITER: $B_T\tau_E \sim \nu^{*-0.01}$

ST:

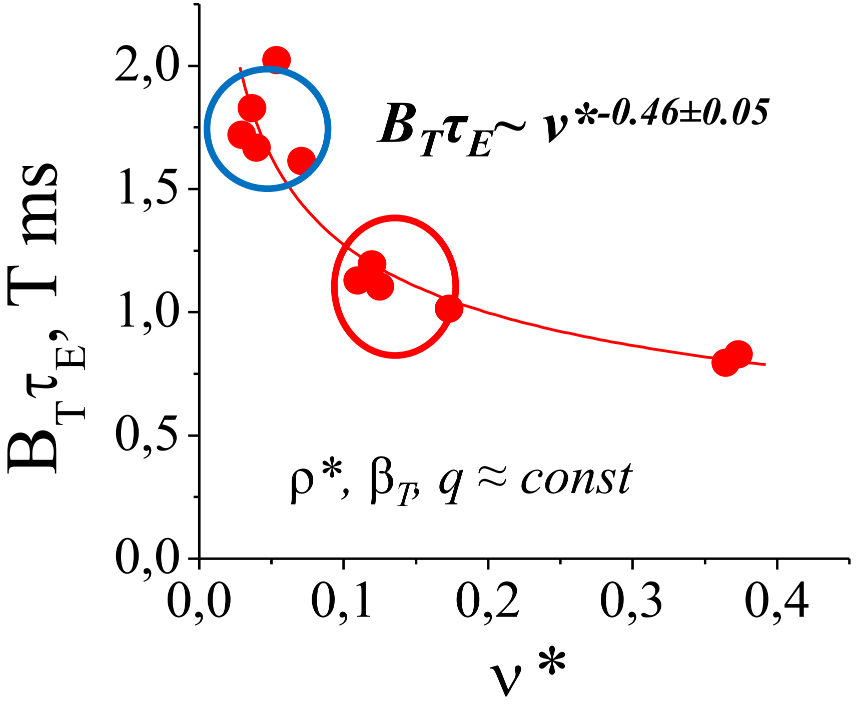
$B\tau_E \sim \nu^{*-0.85}$ *(MAST)*

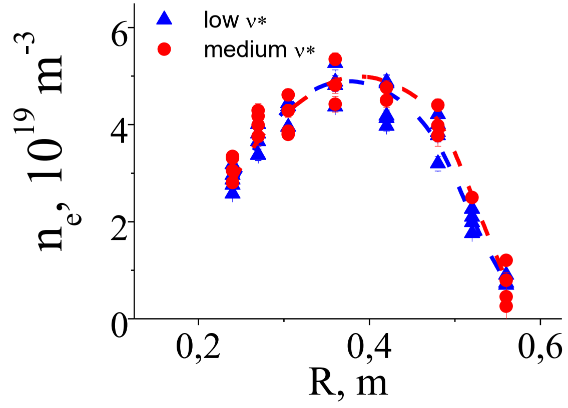
$B\tau_E \sim \nu^{*-0.79}$ *(NSTX)*

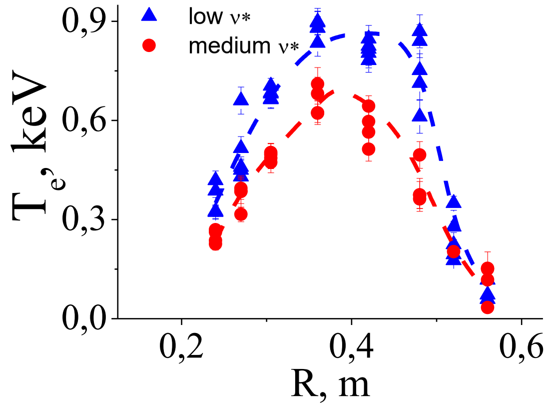
$B\tau_E \sim \nu^{*-0.46}$ ***(Globus-M)***

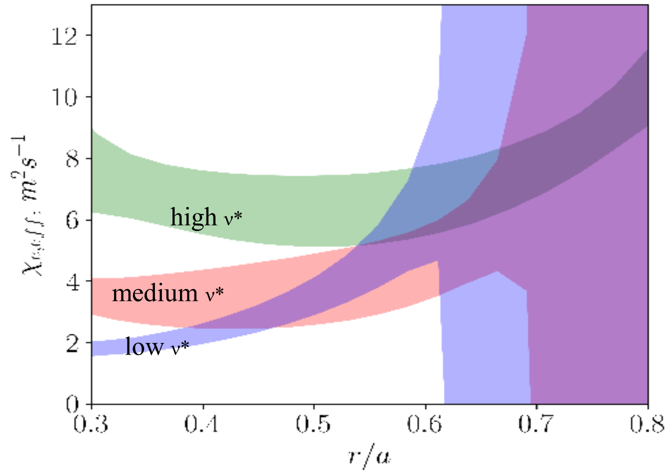
Dimensionless analysis

($q_{eng} \sim B_T/I_p$; $\nu^* \sim n_e/T^2$; $\rho^* \sim T^{0.5}/B_T$; $\beta_T \sim W/B_T^2$;)



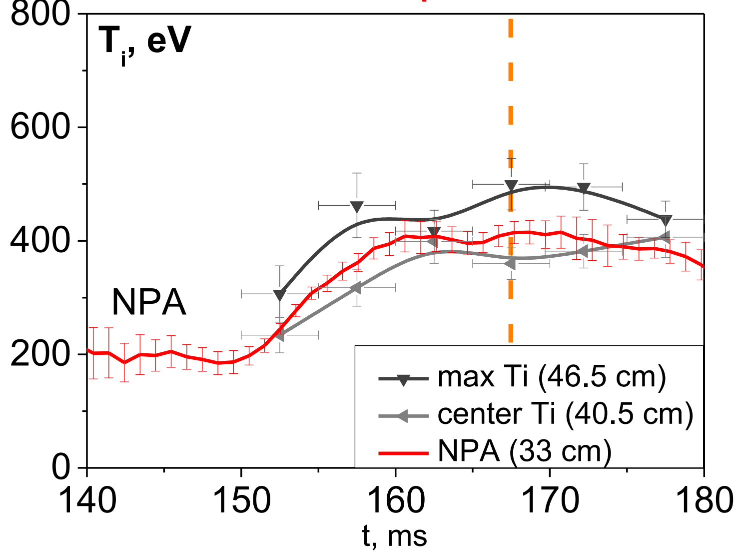


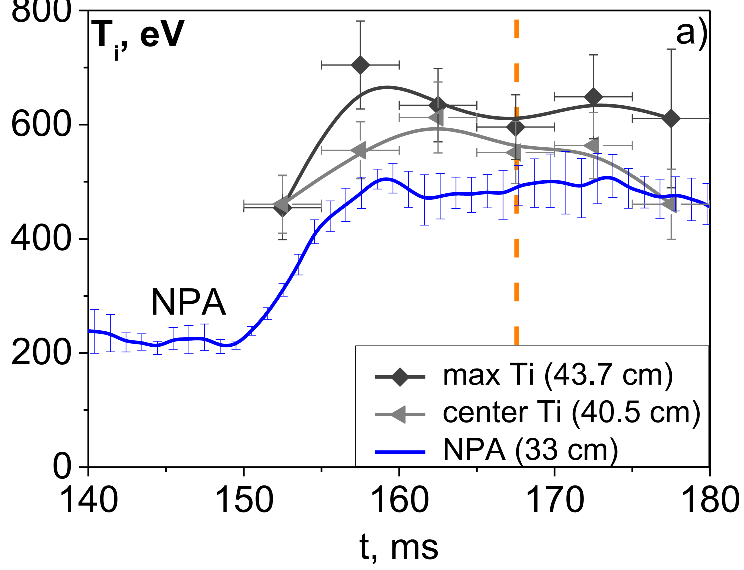




- Electron temperature gradient increases in the central region of the plasma.
- Improvement of the electron heat transport is observed in the plasma core.

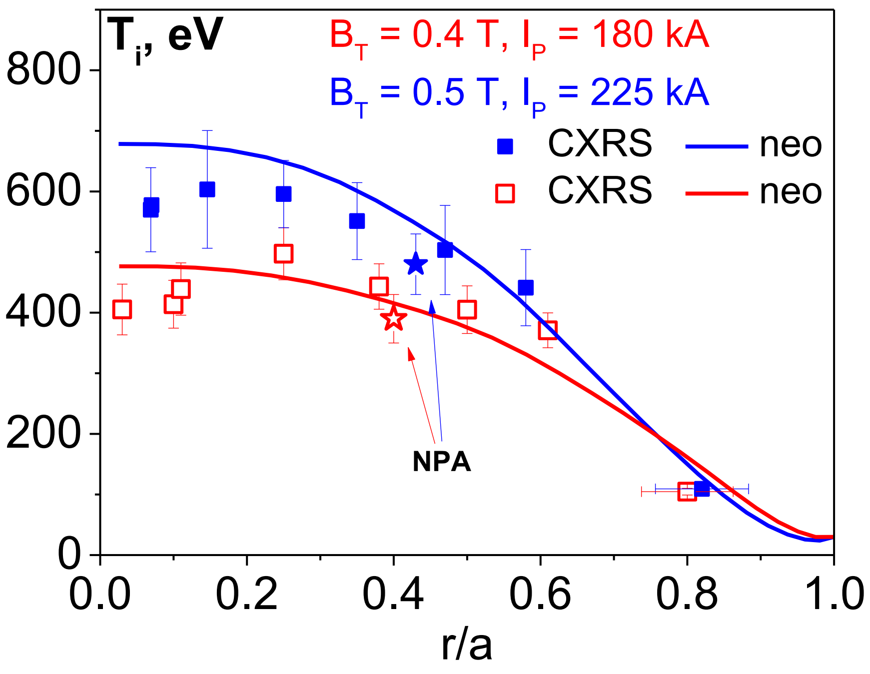
Ion heat transport in the NBI H-mode

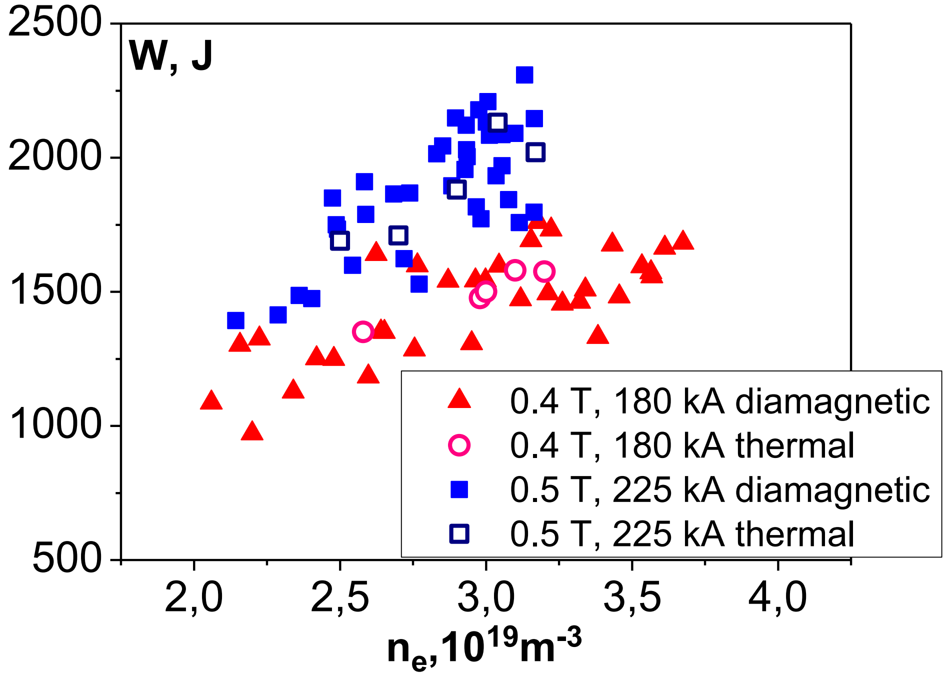

Bt=0.4 T, Ip=180 kA


Bt=0.5 T, Ip=225 kA

- Ion heat transport study was carried out using deuterium NBI E_b=26 keV P=0.65 MW
- $<n_e> = (2.5\text{-}3.5)\cdot 10^{19} m^{-3}$
- Fixed q $(\sim B_T/I_P)$:
  - Bt=0.4 T, Ip=180 kA
  - Bt=0.5 T, Ip=225 kA
- Ion heating by NBI is quite pronounced
- I_p and B_T rise lead to W and T_i increse

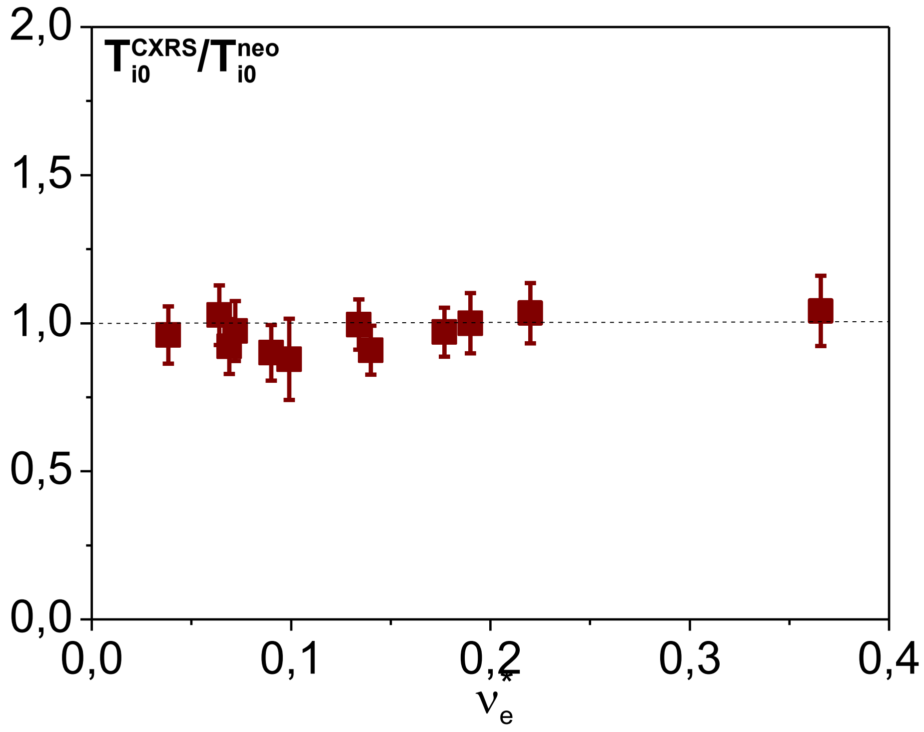
Ion heat transport in the NBI H-mode





- T_i calculated using $\chi_i = \chi_i^{neo}$ assumption is consistent with CXRS measurements
- W^{MHD} is consistent with calculated $W^{thermal}$

Ion heat transport in NBI H-mode

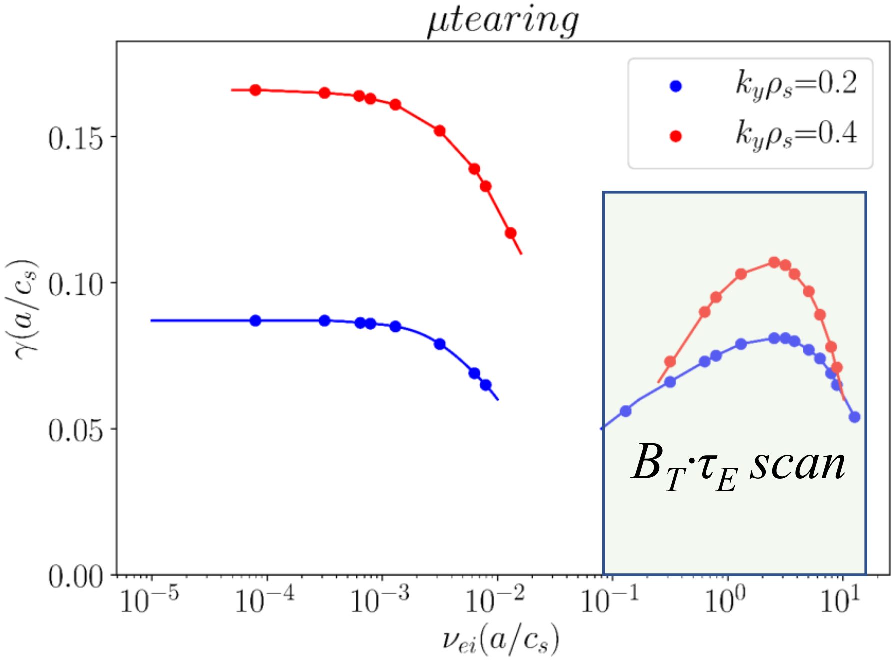


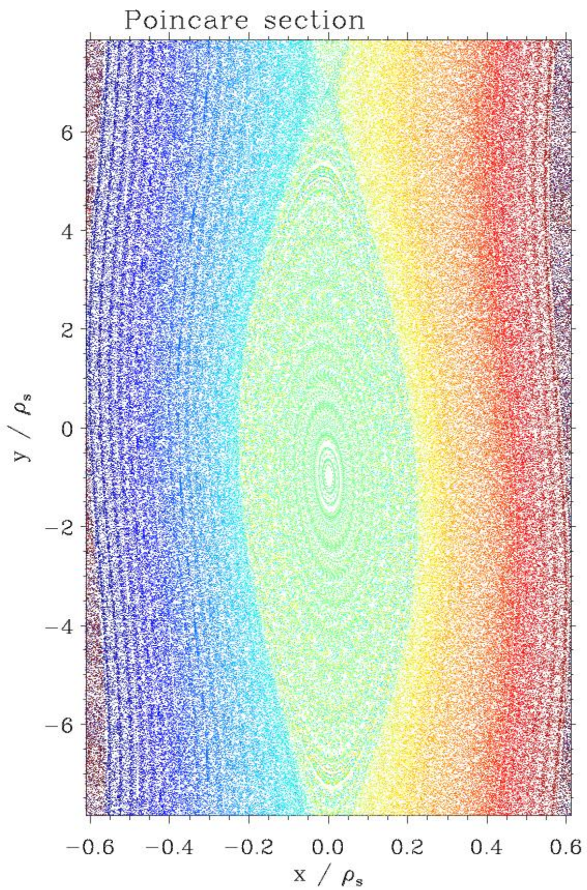
- no evidence of anomalous ion heat transport was observed in NBI H-mode *for* I_p*=0.1 – 0.25 MA,* B_T*=0.4 - 0.5 T*

Linear gyrokinetic results for NBI H-mode plasmas

- R/L_{Te} decreases down to 3.6 - 3 ($< R/L_{Te}^{crit}$(ETG)=5.6
  $< R/L_{Te}^{crit}$(TEM)=9.6)

- Linear gyrokinetic simulation using GENE for r/a=0.5:
  - *Negative increment for ETG, ITG*
  - *Microtearing mode is unstable*





Magnetic line
Poincare plot,
outboard plane

R/L_T	R/L_n	$\rho *$	βe	$\hat{s}$	q
4.2	1.5	0.03	4 %	1.23	1.38

MTM simulation: Kiselev E.O. et al 2019 to be published

Summary I: Globus-M results

Ioffe Institute

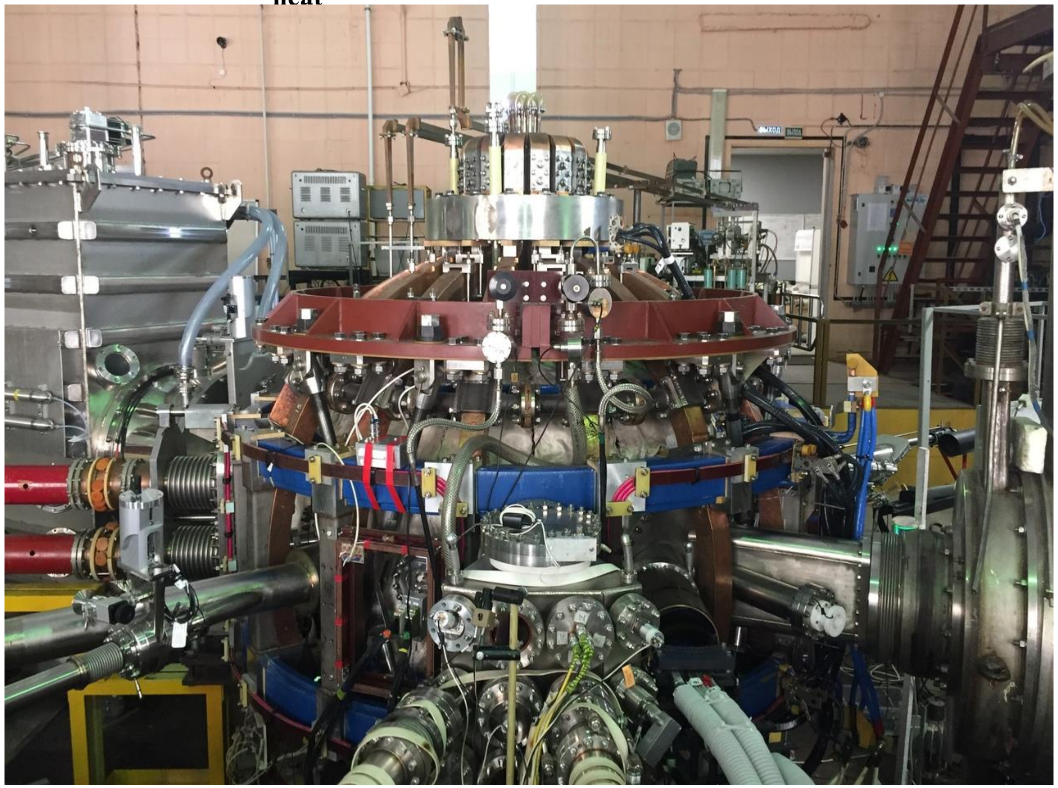
- **Toroidal magnetic field plays a crucial role in the thermal insulation efficiency in ST with R/a=1.6 - 1.7**
- **“Engineering” τ_E scaling for the Globus-M NBI H-mode:**

$$\tau_E^{GLB} = 6.08\, I_p^{0.48\pm0.21}\, B_T^{1.28\pm0.12} P_{abs}^{-0.54\pm0.26} n_e^{0.77\pm0.04}, \text{ ms}$$

- **Both electron and ion heat transport decreases with collisionality yielding $B_T\tau_E \sim \nu^{*-0.46\pm0.05}$**
- **Ion heat diffusivity doesn’t contradict with neoclassical theory predictions**
- **Microtearing mode is likely the cause of electron heat transport in Globus-M NBI H-mode plasma.**

Globus-M2

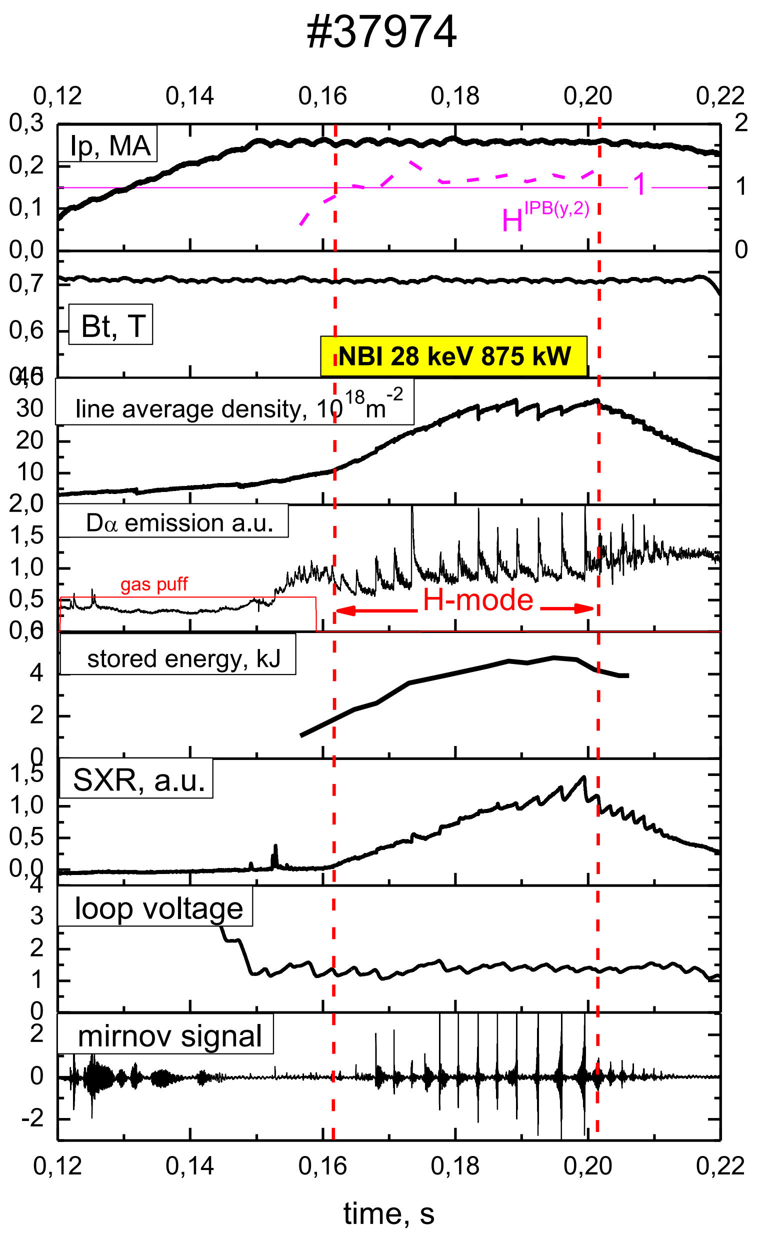
- R [cm]/a [cm]= 36/24 = 1.5
- B_T = 1T, I_p = 500 kA
- Diverse diagnostics, heating and CD systems, including 2xNBI, ICRH, LHCD, plasma gun
- Extreme P_{heat}/V = 6 MW/m^3



First plasma: April 23rd 2018

Parameter	Globus-M	Globus-M2
Btor/Ip, T/kA	0.4 / 250	**1 / 500**
NBI	1 MW 18-30 keV	**1 MW 18-40 keV + 1 MW 40-50 keV**
ICRH, kW	120	500
LHCD, kW	100	500
$\langle T_i \rangle$, keV	0.4	**1.5(3)**
$\langle T_e \rangle$, keV	0.5	**1(2)**
$\langle n_e \rangle$[max], 10^{20}m^{-3}	1	2
$\tau_{E,}$ ms	5-10	12-25

H-mode at Globus-M2



$B_T = 0.7$ T $I_p = 0.25 – 0.3$ MA

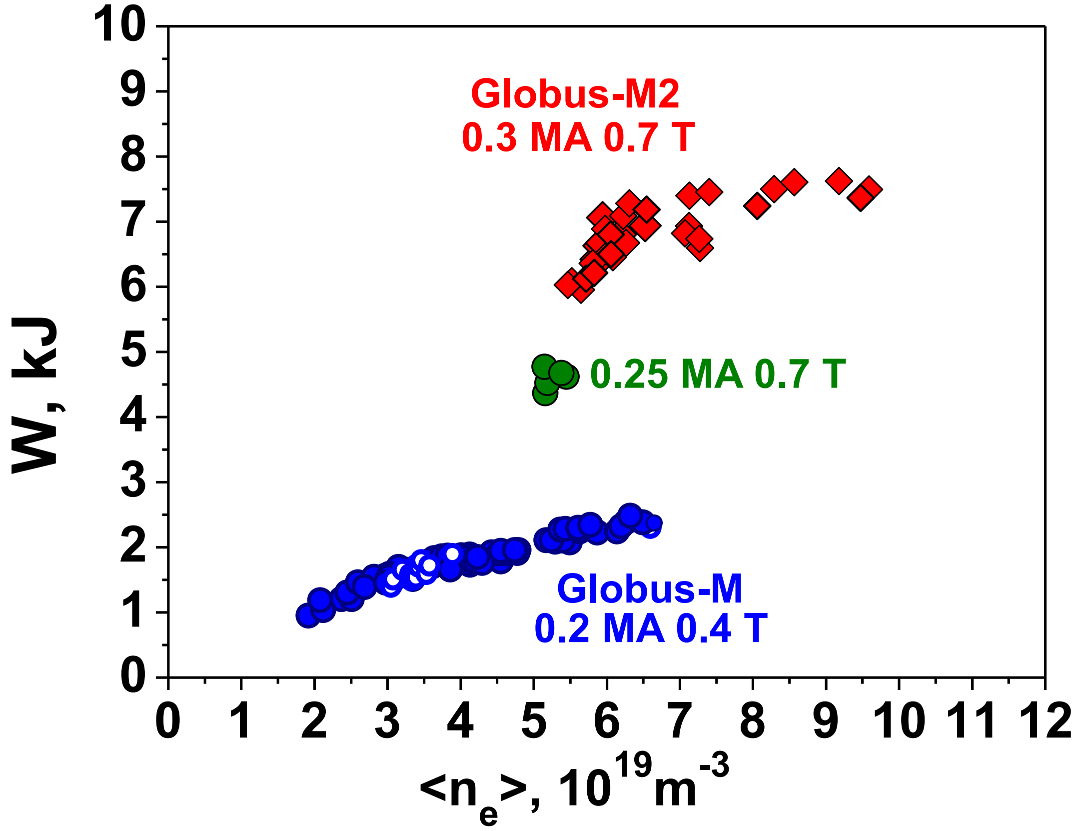
Beam absorbed power – 0.4 MW

Stable transition to H-mode under NBI

$\tau_E = 8$ ms corresponds to $H^{IPB98(y,2)} = 1.2\text{-}1.3$

Analysis of the energy confinement was carried out for the quasi-steady discharge stage $dW/dt \approx 0$

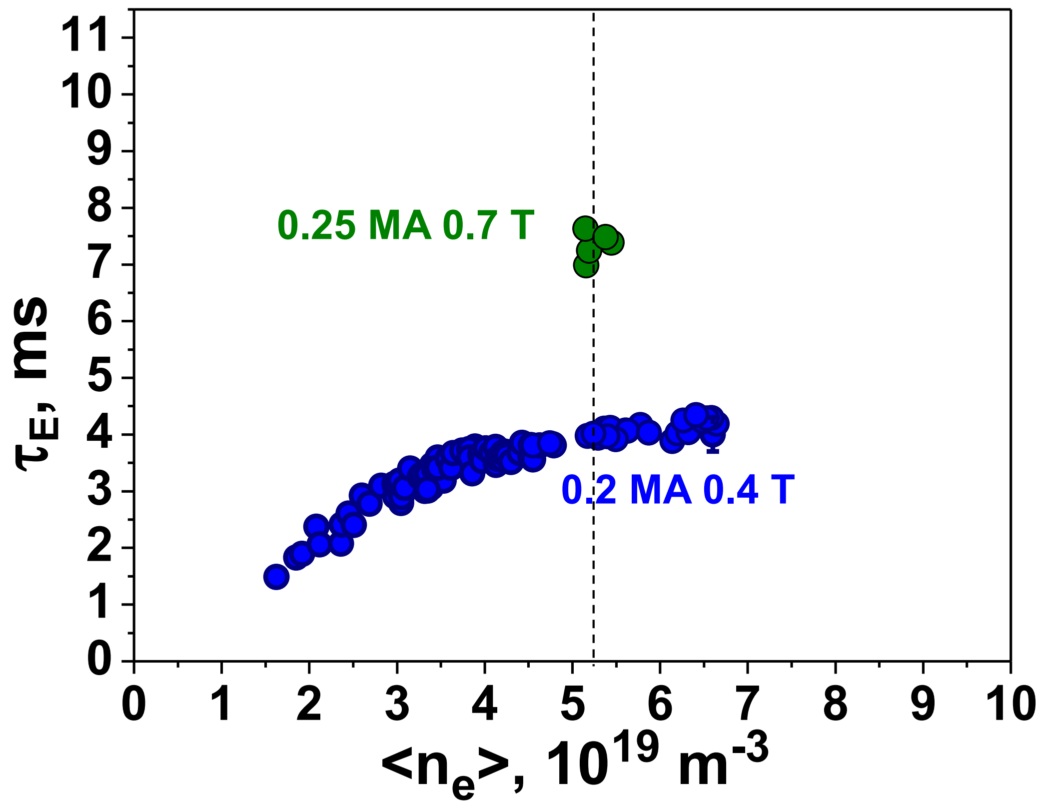
Total stored energy enhancement



Plasma total stored energy rises more then 3 times!!!

Fast ion contribution to measured total stored energy $W_{\perp}^{fast}/W \approx 0.1$ according to NUBEAM and "3D fast ion tracking" modelling

I_P and B_T impact on energy confinement

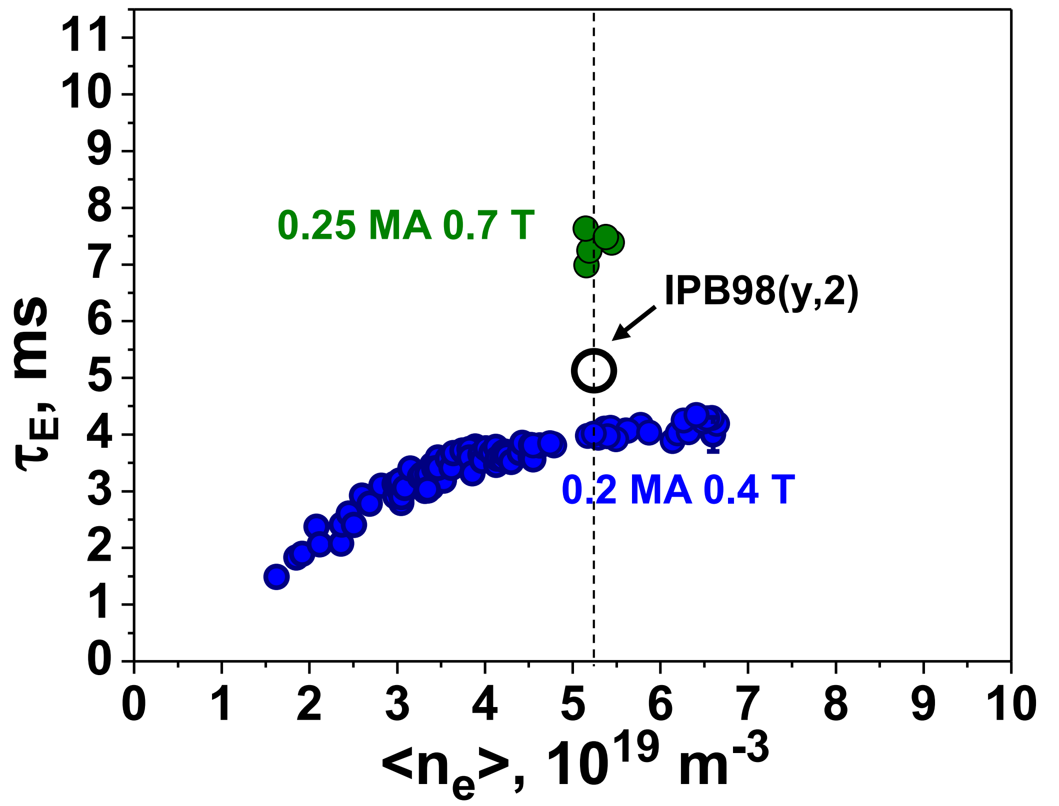


$$\tau_E^{\text{IPB98(y,2)}} \sim I_p^{0.93} B_T^{0.15}$$
$$\tau_E^{Globus-M} \sim I_p^{0.48} B_T^{1.28}$$

τ_E enchantment for scalings:

- I_p increased **1.25** times (from **0.2 MA** to **0.25 MA**)
- B_T increased **1.75** times (from **0.4 T** to **0.7 T**)
- τ_E raised ***1.9*** times (from **4** to **7.5 ms**)

I_P and B_T impact on energy confinement



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IPB98(y, 2)	
1.3	

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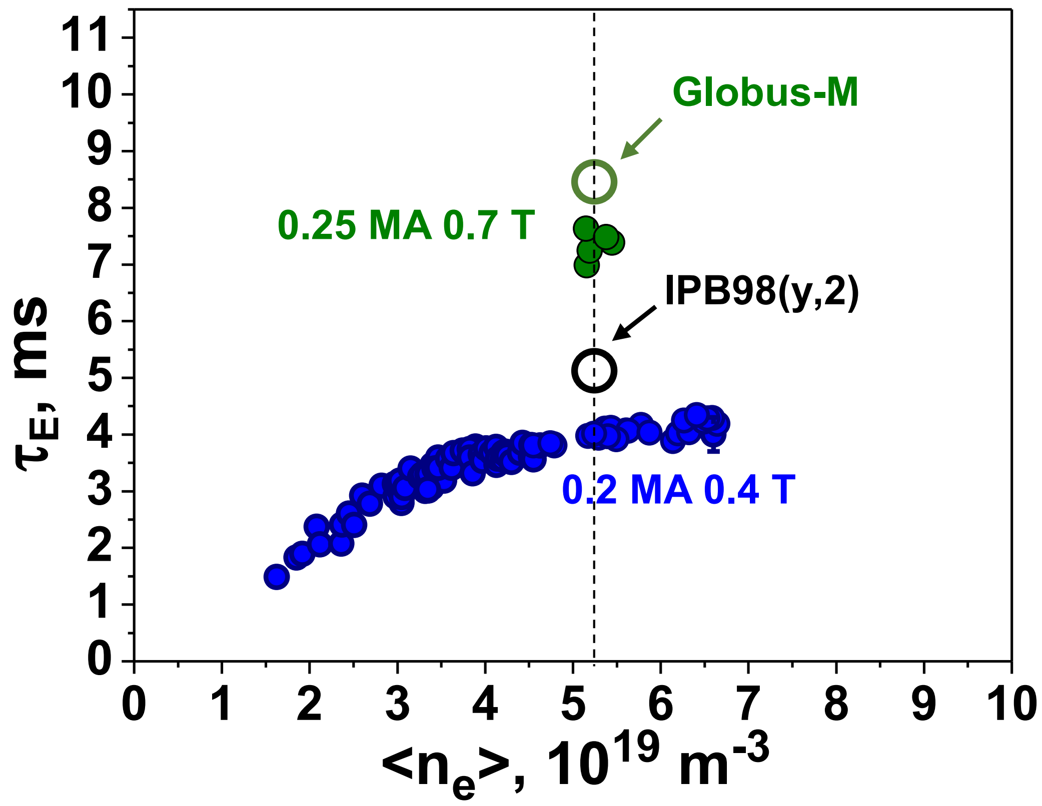

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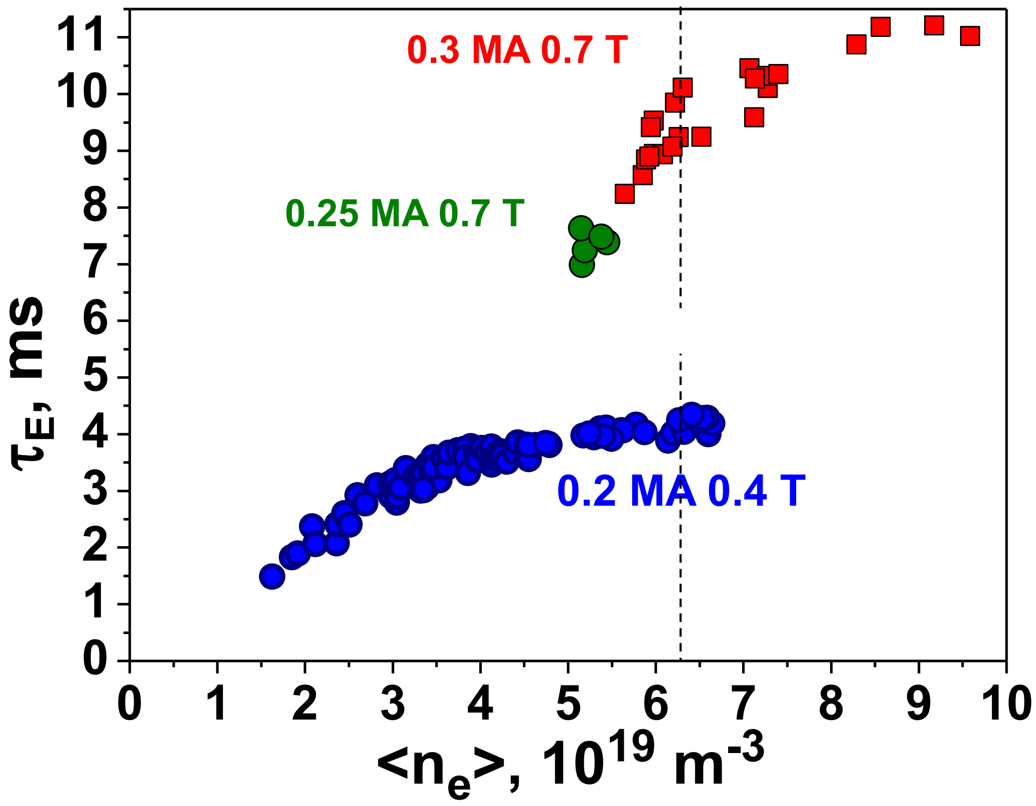
τ_E enchantment for scalings:

IPB98(y, 2)	Globus-M
1.3	2.1

- I_p increased 1.25 times (from 0.2 MA to 0.25 MA)
- B_T increased 1.75 times (from 0.4 T to 0.7 T)
- τ_E raised *1.9* times (from 4 to 7.5 ms)

I_P and B_T impact on energy confinement



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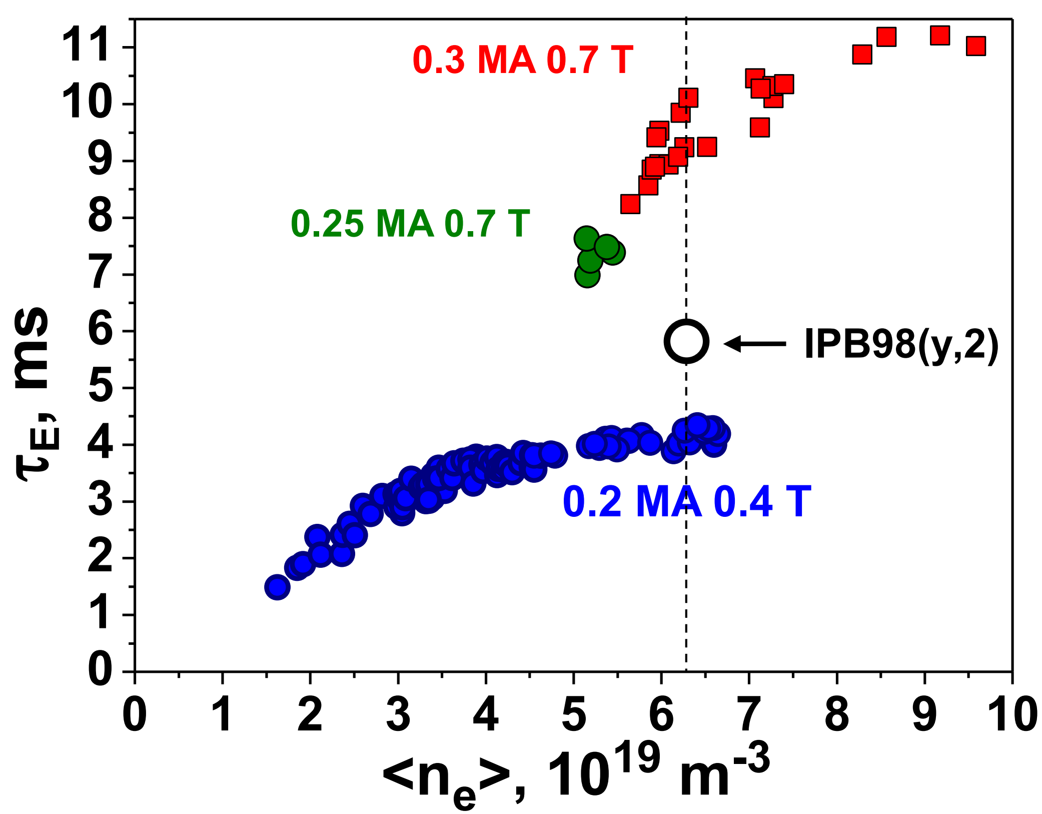
I_P and B_T impact on energy confinement



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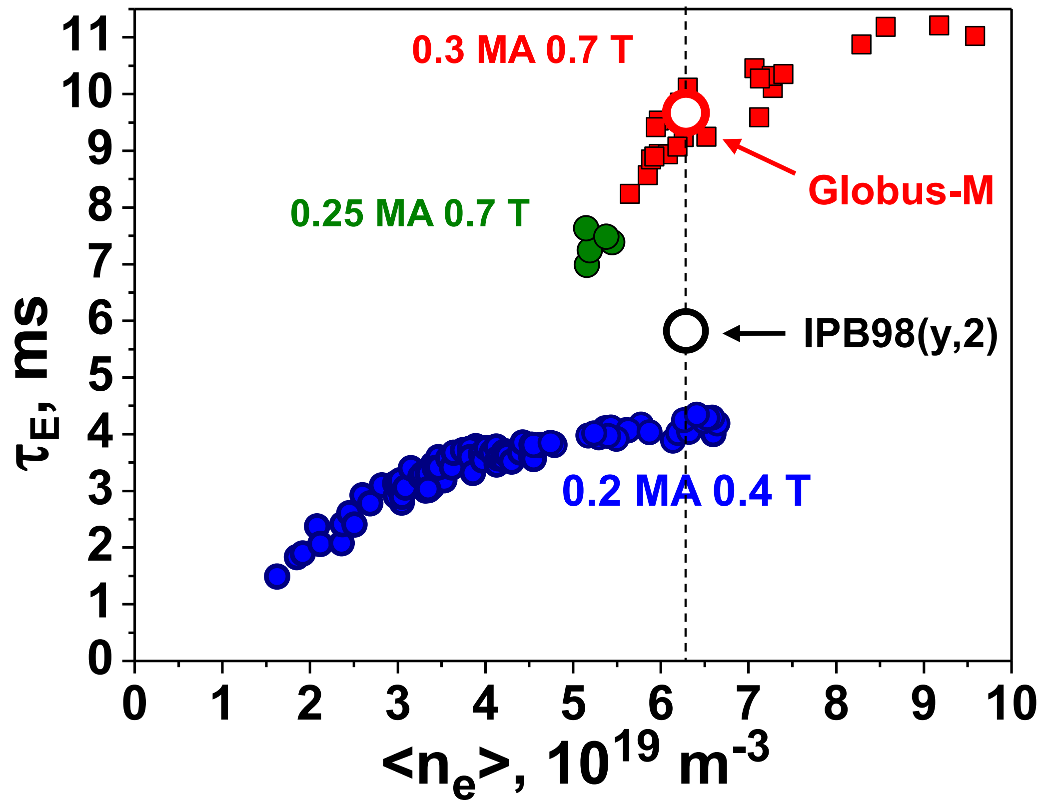

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τ_E enchantment for scalings:

IPB98(y, 2)	Globus-M
1.4	2.4

- I_p increased by **1.5** times (from **0.2 MA** to **0.3** **MA**)
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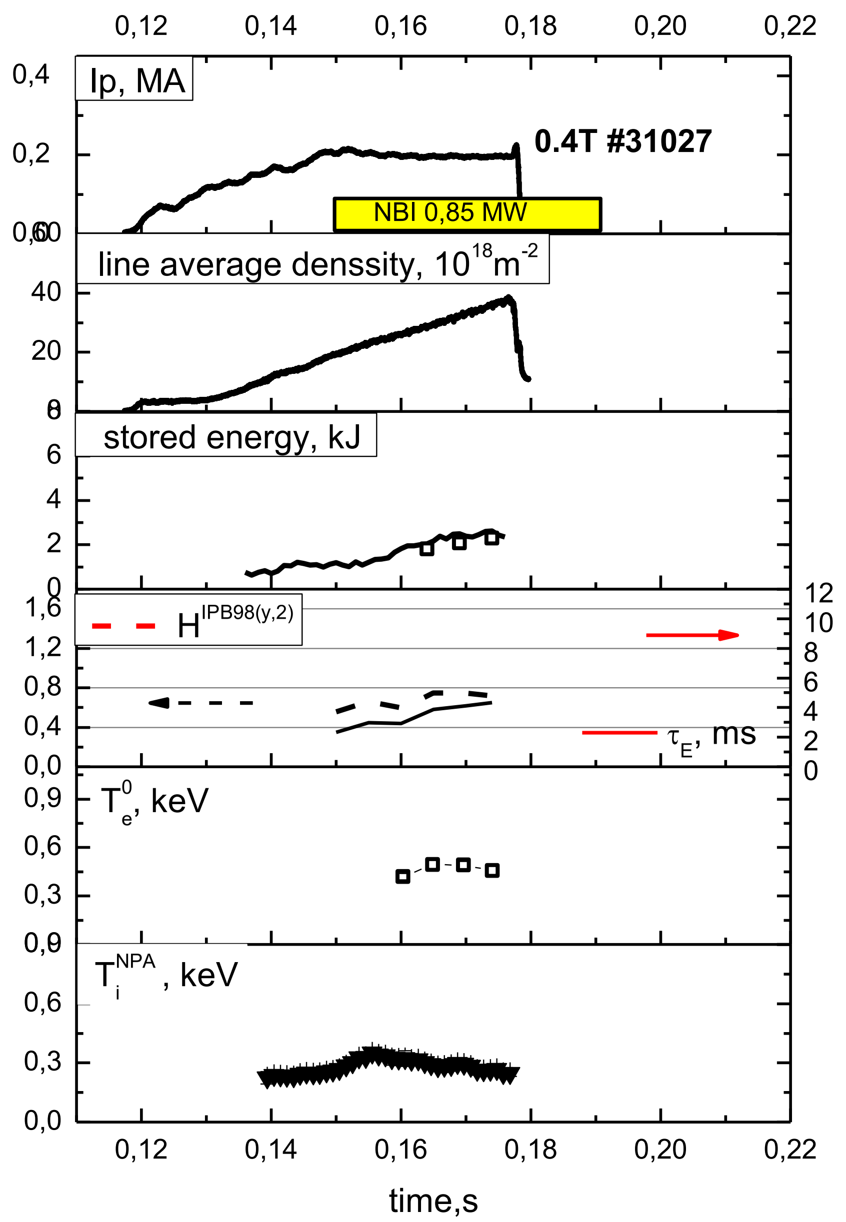
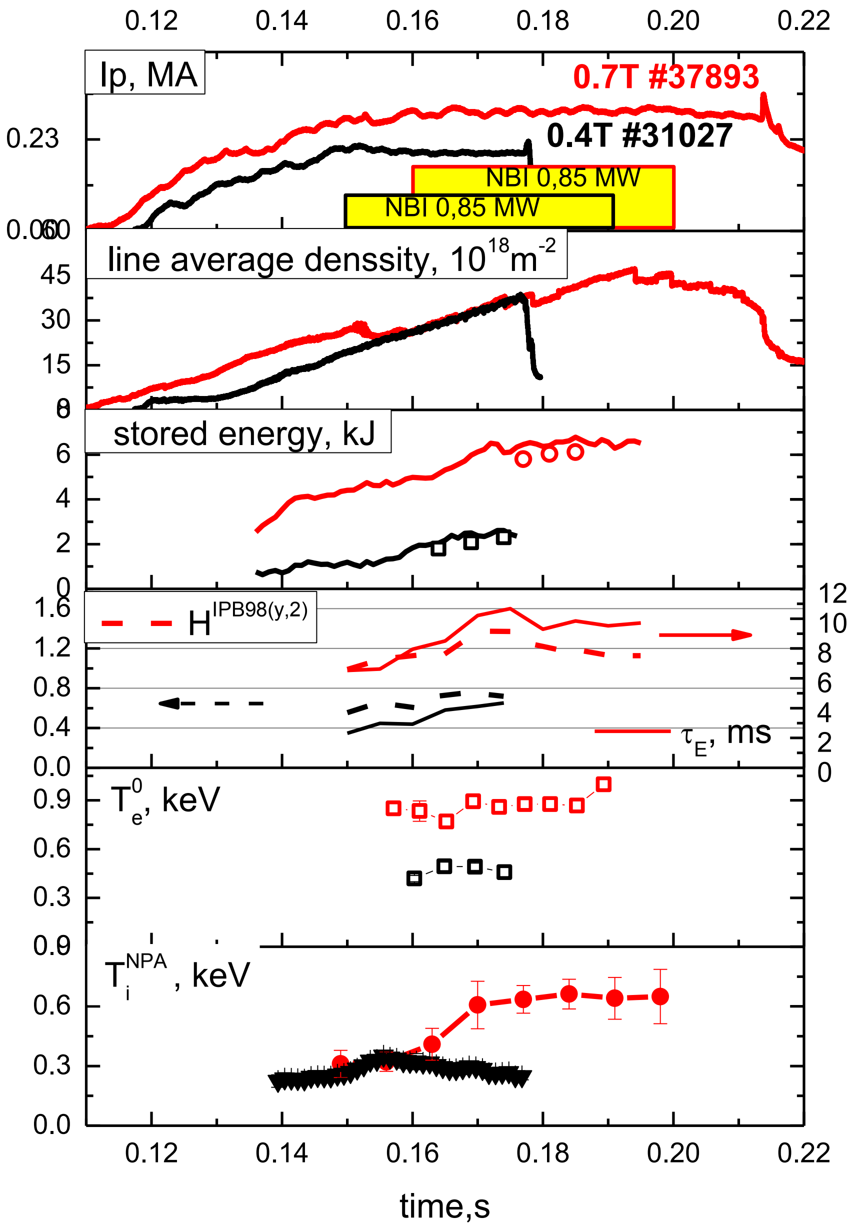
Plasma performance in high density discharge

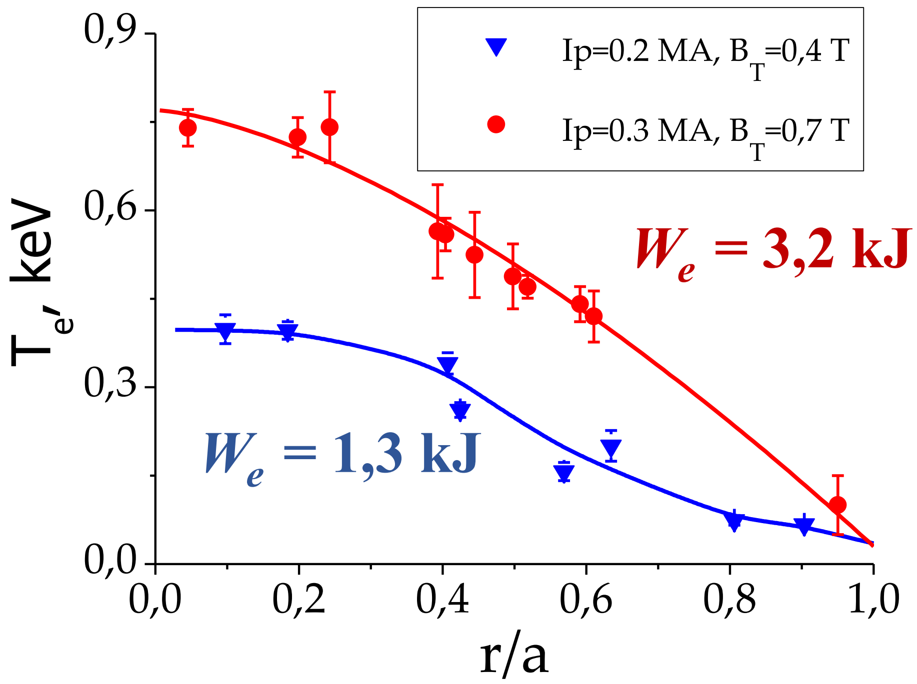


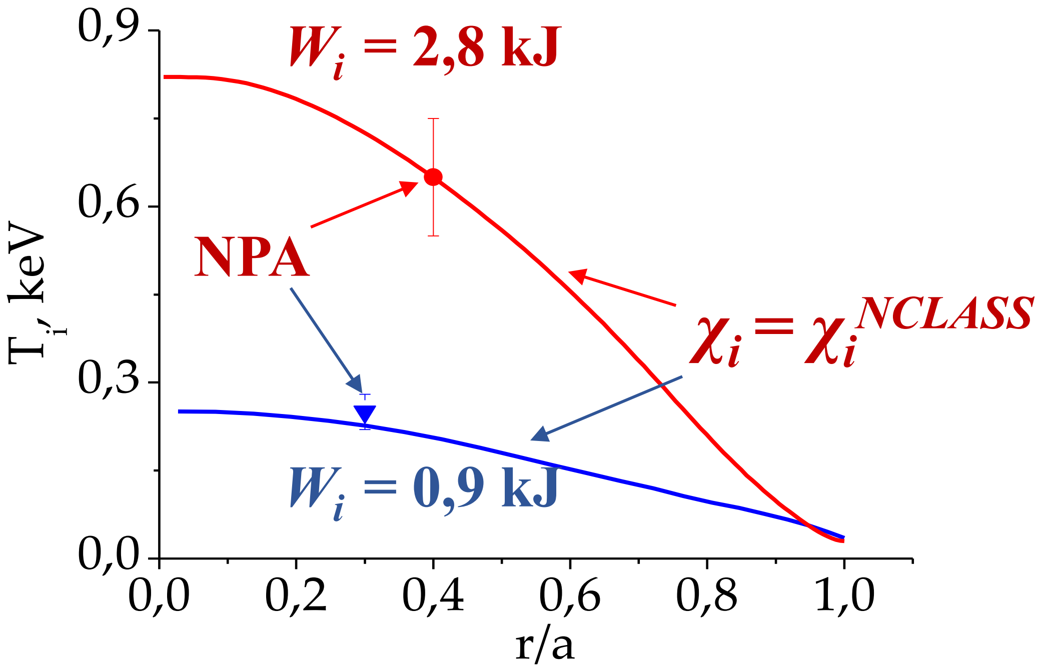
Plasma performance in high density discharge

- growth of T_e, T_i, W^{MHD} and τ_E
- W^{MHD} confirmed by kinetic measurements
- loop voltage decrease
- pulse duration increase



Transport analysis for NBI H-mode (n_e=6.5 $10^{19}m^{-3}$)

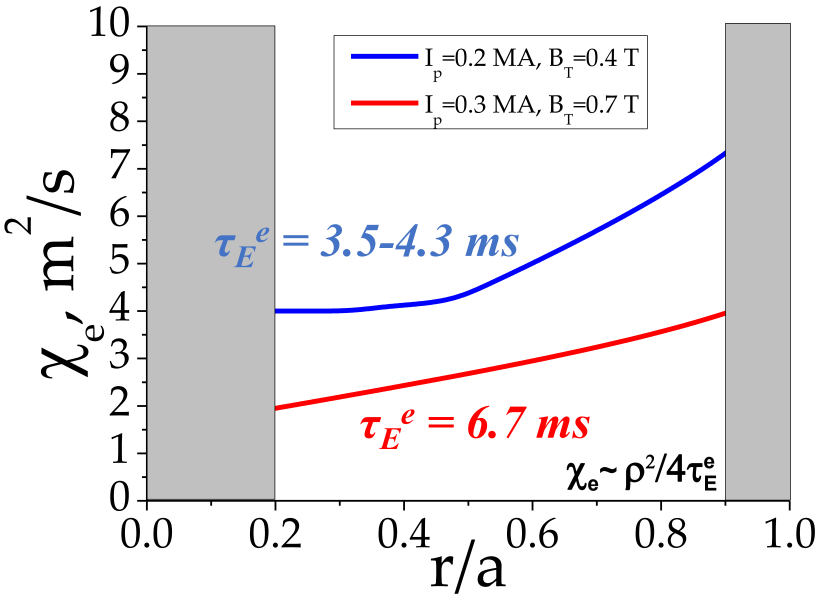


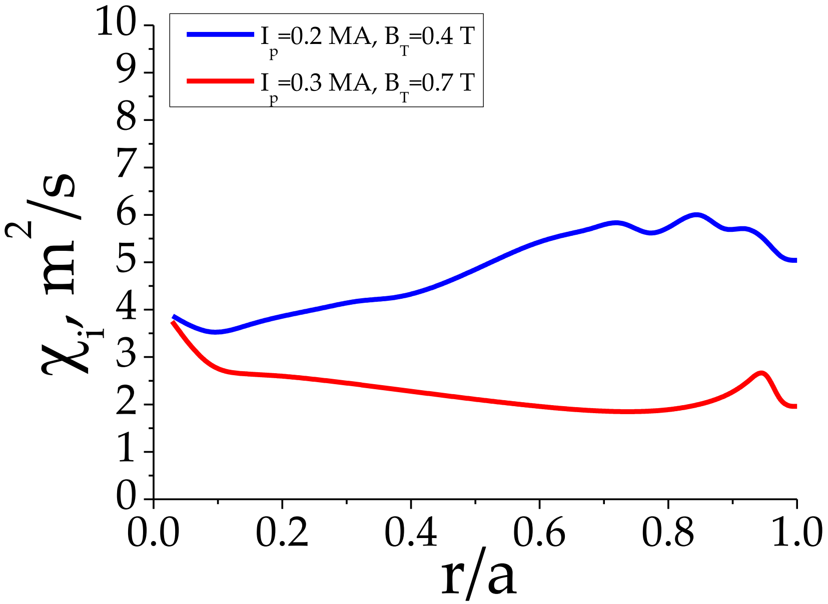


- ASTRA modelling:
  - equation for ion temperature assuming neoclassical ion heat diffusivity
  - fixed electron temperature and density profiles from Thomson scattering

- significant increase in T_i is consistent with NPA and diamagnetic measurements

Transport analysis for the NBI H-mode (n_e=6.5 10^{19}m



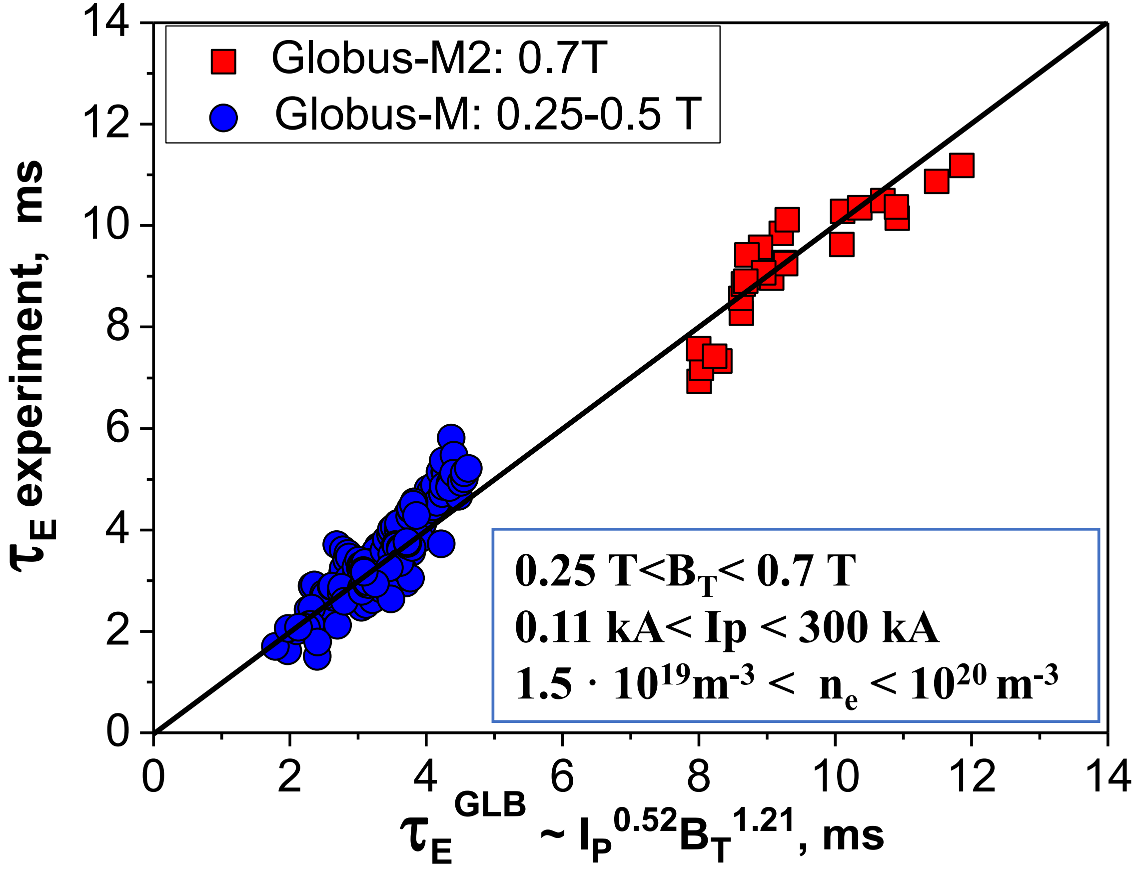


I_p and B_T rise leads to:

- χ_e drops in the plasma core by a factor of 2
- ion heat transport improves - neoclassical χ_i decreases by 2-3 times

Summary II: Globus-M2 first results

ST scaling works !



$0.25\ T < B_T < 0.7\ T$
$0.11\ kA < Ip < 300\ kA$
$1.5 \cdot 10^{19} m^{-3} < n_e < 10^{20}\ m^{-3}$

- Energy confinement enhancement is in line with ST scaling predictions
- An improvement in the thermal insulation of electrons and ions is observed
- Neoclassical effects plays a major role in Globus-M/M2 ion heat transport

$H_{IPB98(y,2)} = \tau_E^{exp} / \tau_E^{IPB98(y,2)}$: 0.8 -> 1.3