# THERMAL ENERGY CONFINEMENT AT THE GLOBUS-M SPHERICAL TOKAMAK

EX/P5-2

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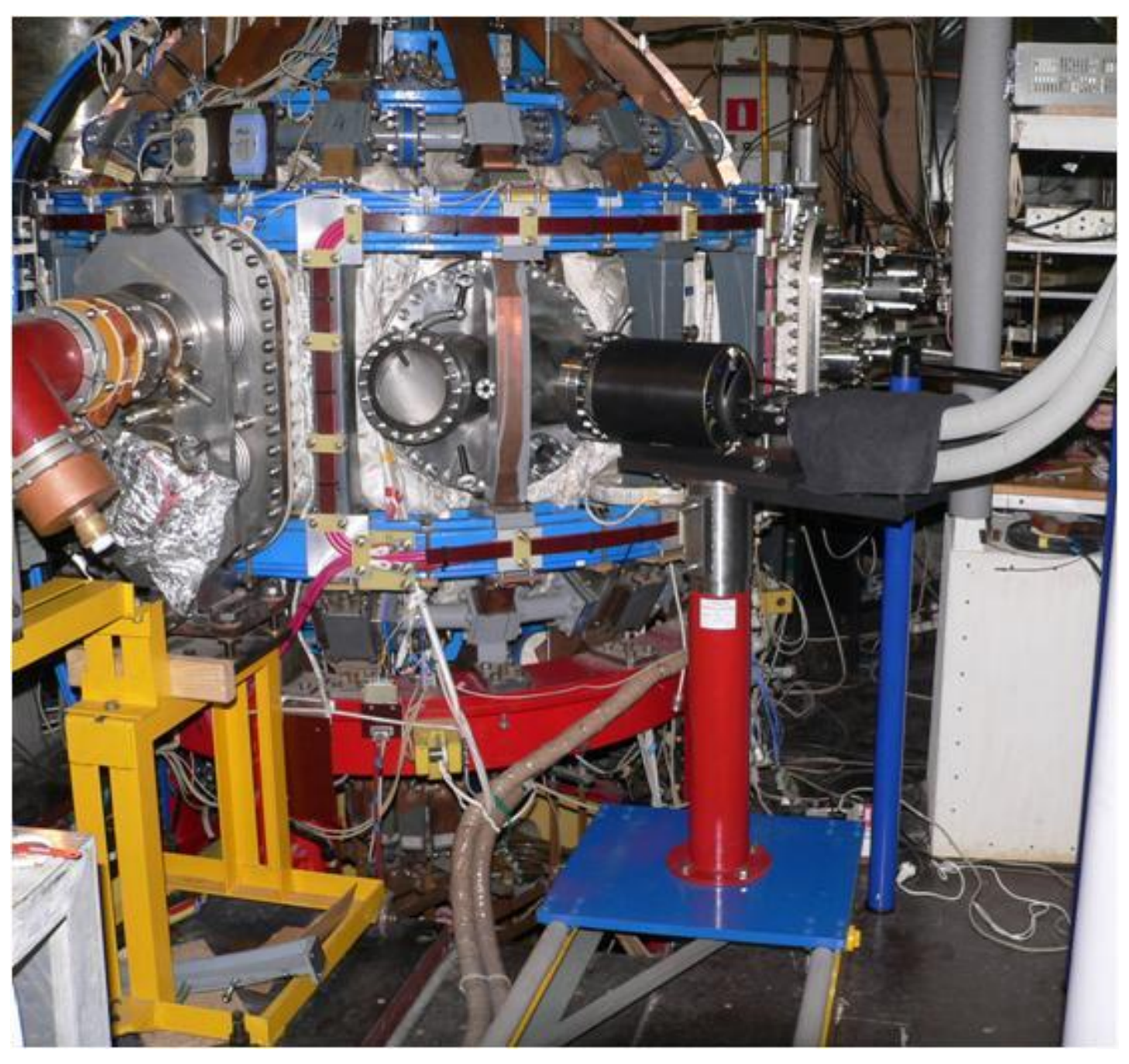
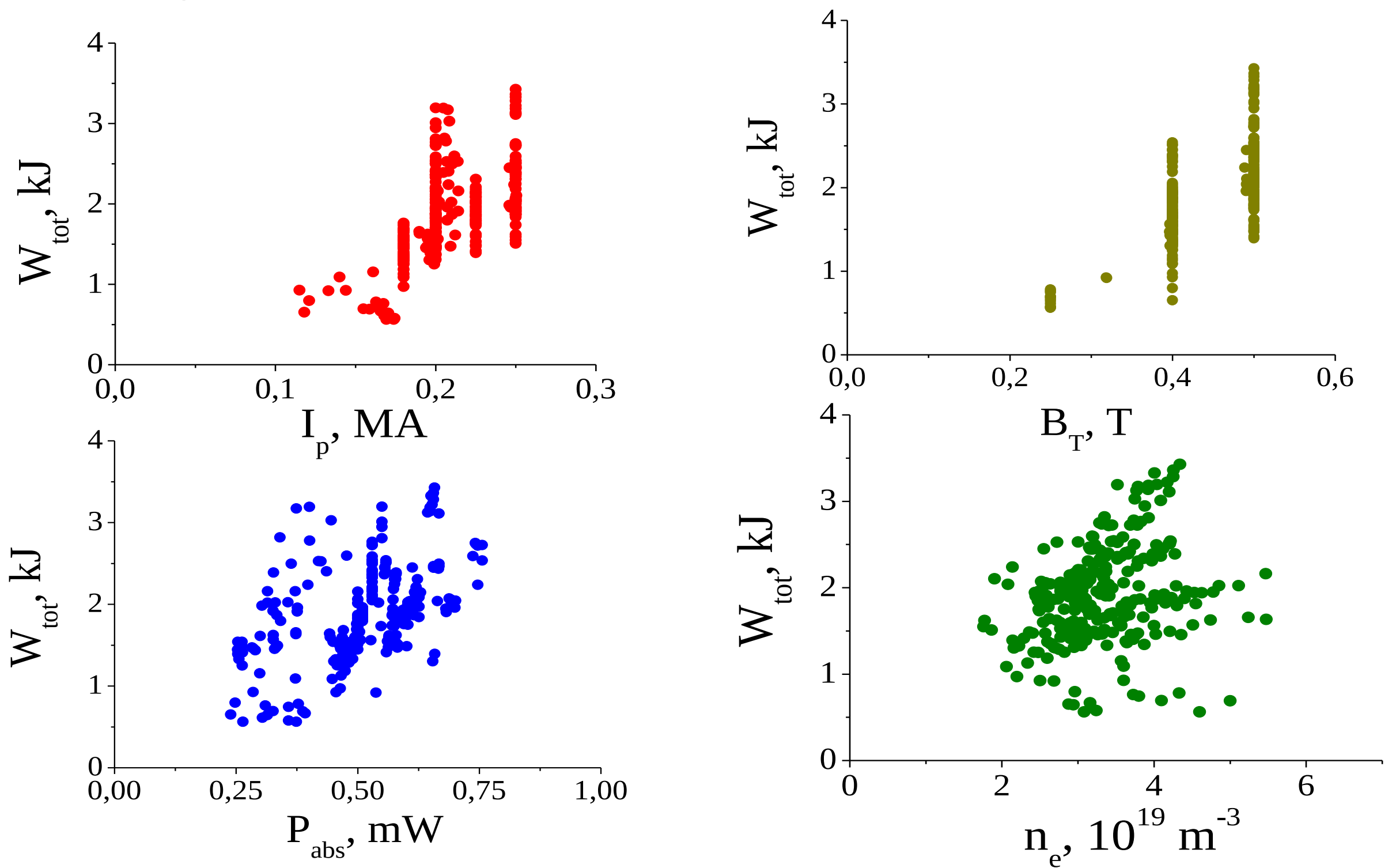
## Globus-M ST



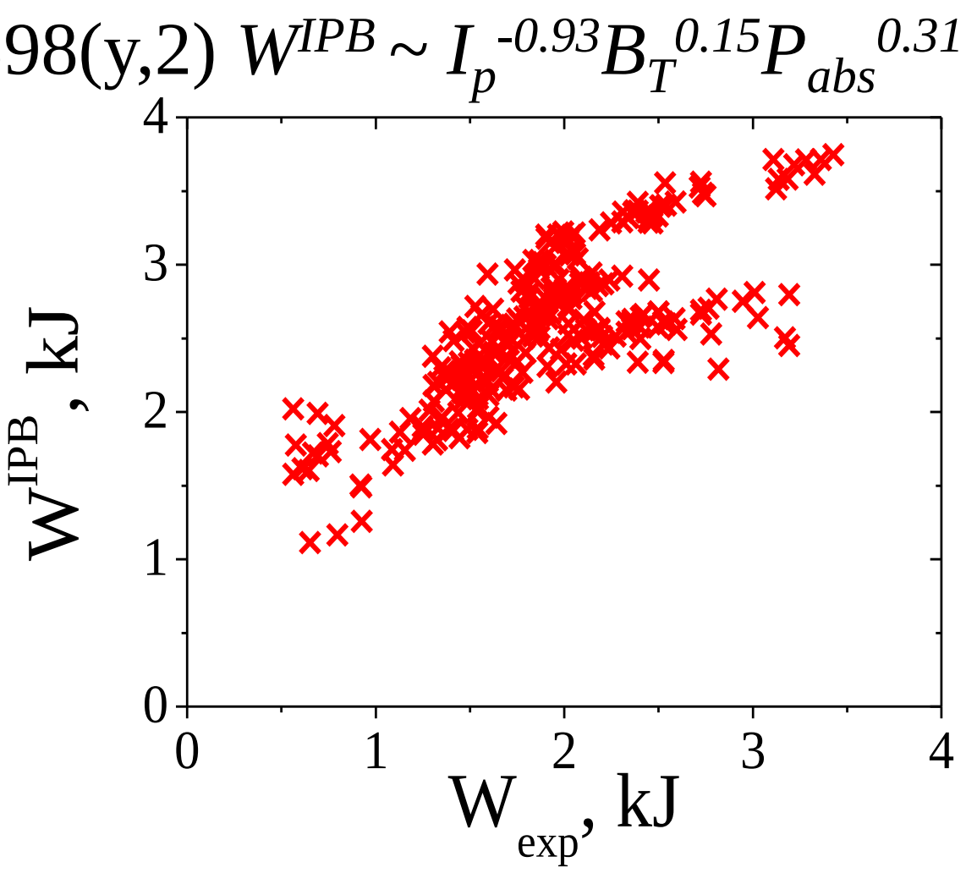
- **Ip ≤ 0.25 MA**
- **$B_{tor}$ = 0.4 T**
- **R = 0.36 m**
- **a = 0.24 m**
- **R/a = 1.5**
- **k = 1.8-1.9**
- $<n_e>_{max} \approx 1\cdot10^{20}\ m^{-3}$
- $T_{e\,max} \approx 1.4\ keV$
- $T_{i\,max} \approx 0.9\ keV$
- **$P_{NBI}$ < 1.2 MW**



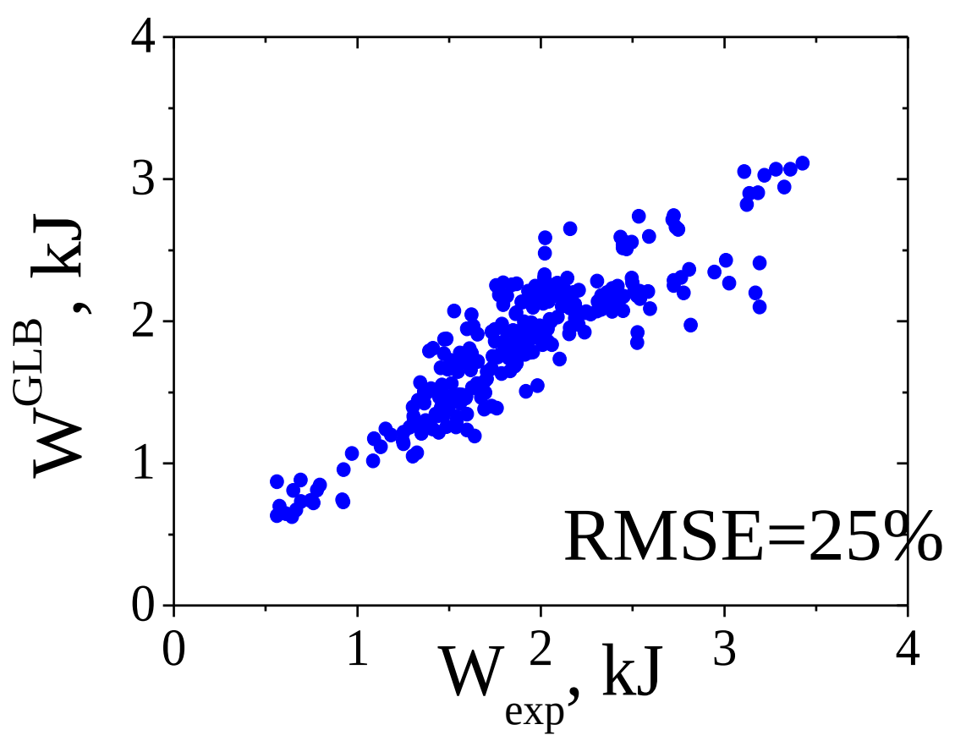
- NBI H-mode
- Deuterium plasma
- $P_{NBI}$=0,35-0,75 MW
- $E_b$=26-28 keV
- $P_{abs}$ – 3D fast ion tracking algorithm
- $W_{tot}$ – diamagnetic measurements
- $W^{th}$ = 0.9-0.95 $W^{MHD}$
- dW/dt=0, dI/dt = 0

## Dimensional analysis: $W^{GLB}=C\cdot I_p^{\alpha I}B_T^{\alpha B}P_{abs}^{\alpha P}n_e^{\alpha n}$

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



$W^{GLB} \sim I_p^{0.77} B_T^{1.3}P_{abs}^{0.2}n_e^{0.67}$



| | Value | err | Pearson | | | |
|---|---|---|---|---|---|---|
| | | | αI | αB | αP | αn |
| αI | 0,77 | 0,08 | - | -0.33 | -0,57 | -0,07 |
| αB | 1,3 | 0,06 | -0.33 | - | -0,14 | 0,18 |
| αP | 0,2 | 0,04 | -0,57 | -0,14 | - | 0,17 |
| αn | 0,67 | 0,04 | -0,07 | 0,18 | 0,17 | - |

$$\tau_E^{GLB} \sim I_p^{0.51\pm0.26}\ B_T^{1.2\pm0.1}P_{abs}^{-0.54\pm0.26}n_e^{0.67\pm0.04}$$

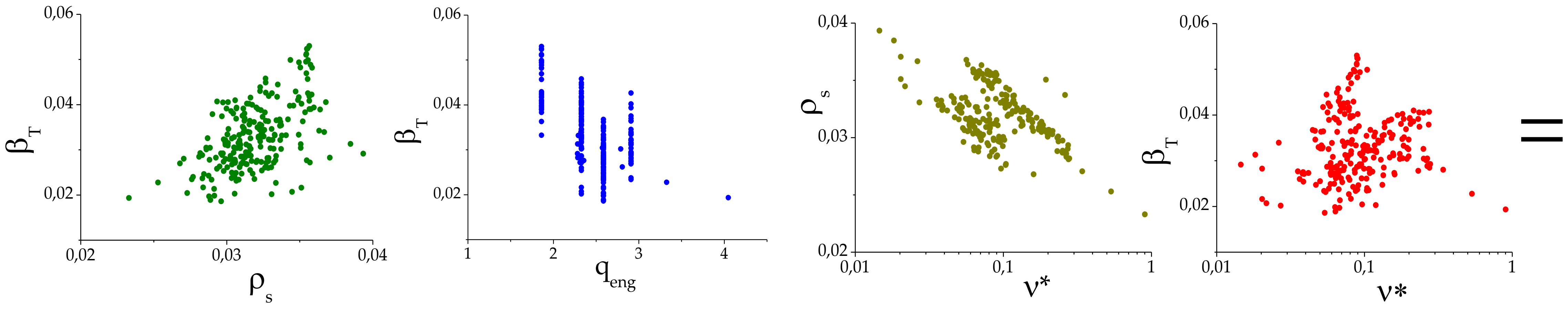
- Regression yields $W^{GLB} \sim I_p^{0.77} B_T^{1.3}P_{abs}^{0.2}n_e^{0.67}$ with RMSE=25%
- $\rho(I_p,P_{abs})$= -0.57 => higher $|\alpha P|$ solutions will satisfy for lower $|\alpha I|$ values *(fast ion losses depends mostly on plasma current in Globus-M(*))*
- $\tau_E \sim P_{abs}^{-0.28}$ (**) => fixed $\alpha P=0.72$ yields $\alpha I=0.25$ and $\alpha B=1.2$ with RMSE=30%
- $\tau_E$ dependence on $n_e$ and $B_T$ is very strong: $\tau_E \sim B_T^{1.2\text{-}1,3}$; $\tau_E \sim n_e^{0,67}$
- $\tau_E$ dependence on $I_p$ and $P_{abs}$ is unclear: $\tau_E \sim I_p^{0.25\text{-}0,77}$; $\tau_E \sim P_{abs}^{-(0,28-0,8)}$

*(*) Bakharev N.N. Nuclear Fusion 55 (2015 ) 043023*
*(**) Kurskiev G.S. Plasma Phys.Control. Fusion 59 (2017) 045010 (7pp)*
*(OH vs NBI, 0.2 MA, 0.4 T)*

- $H^{IPB98(y,2)}$: 0.5-1.3, median ~0.7
- IPB98(y,2) is poorly suited to describe the Globus-M database (fit $W^{IPB}=C*I_p^{-0.93}B_T^{0.15}P_{abs}^{0.31}n_e^{0.41}$ *yields* RMSE>50%)

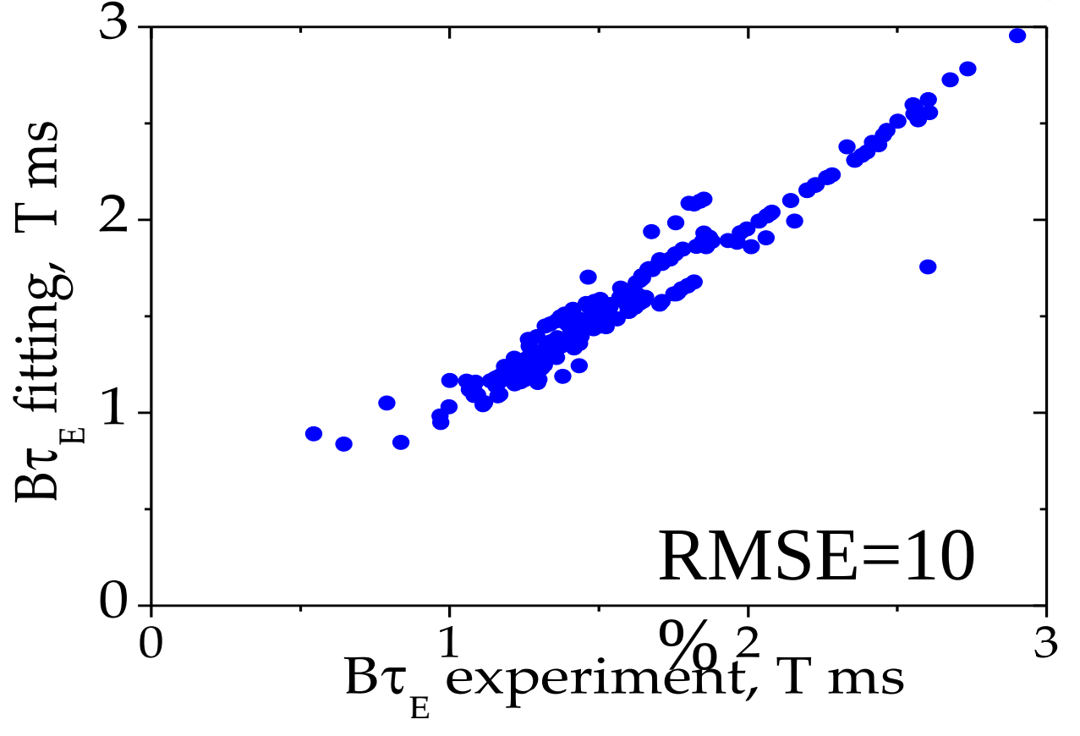
## Dimensionless analysis: $B_T\tau_E \sim \rho^{*x\rho}\beta_T^{x\beta}\nu^{*x\nu}q_{eng}^{xq}$

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



=>

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



Pearson correlation coefficients: 0.5-0.66
Moderate interdependence

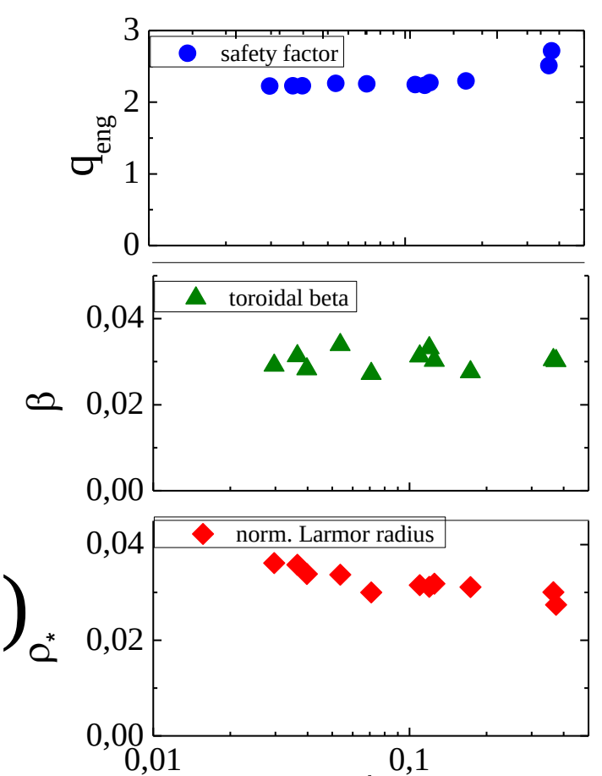
gyroBohm, RMSE=10%
$B_T\tau_E \sim \rho^{*-3}\beta_T^{1.49}\nu^{*-0.47}q_{eng}^{0.77}$
ρ(xq,xβ) = 0.51
ρ(xq,xν) = -0.01
ρ(xβ,xν) = 0.21

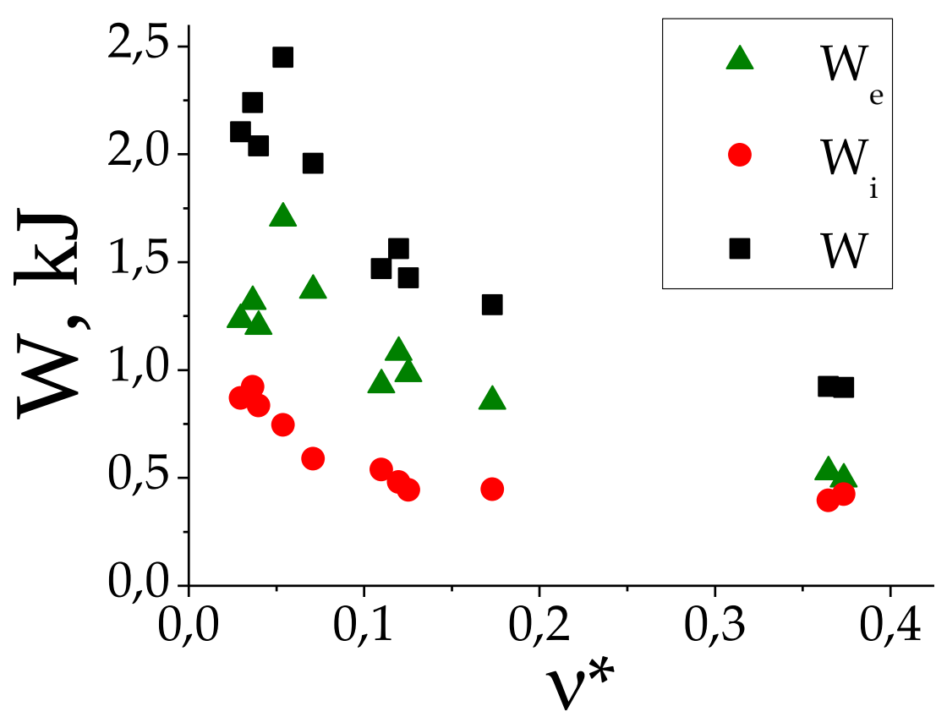
Bohm, RMSE=11%
$B_T\tau_E \sim \rho^{*-2}\beta_T^{1.37}\nu^{*-0.41}q_{eng}^{1.04}$
ρ(xq,xβ) = 0.49
ρ(xq,xν) = 0.08
ρ(xβ,xν) = 0.16

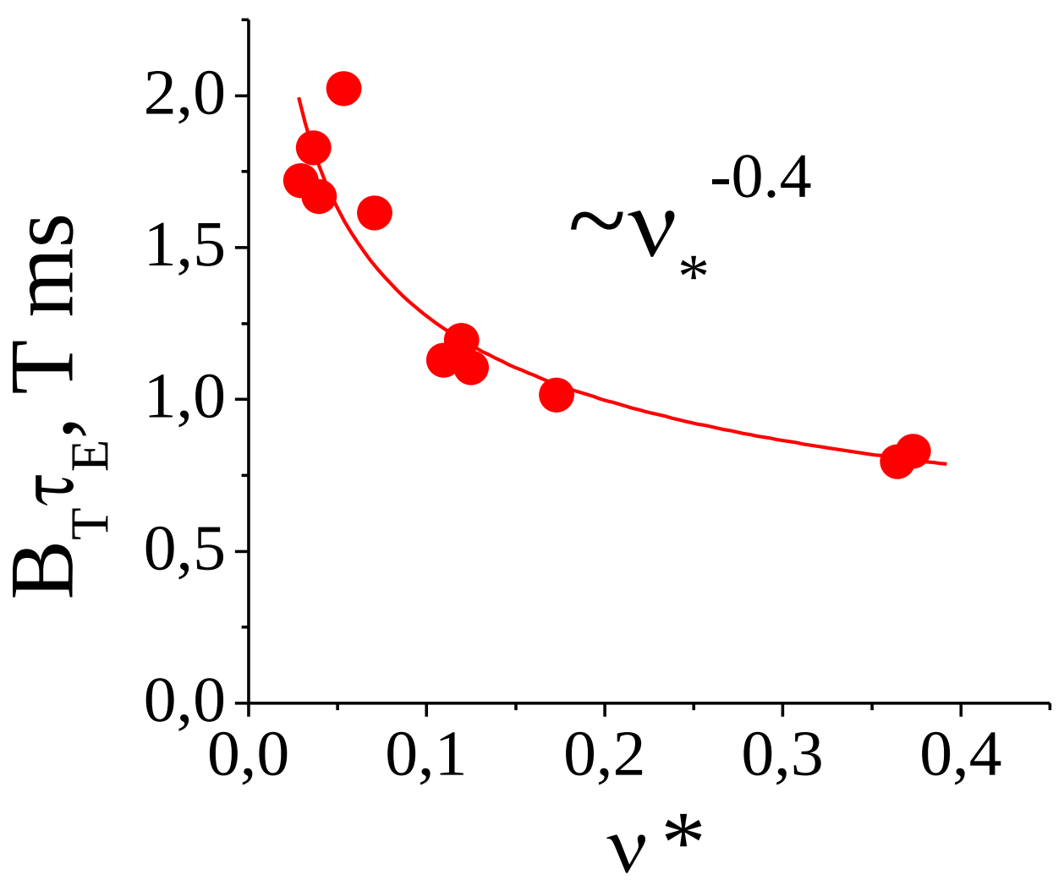
- $B_T\tau_E \sim \nu^{*-(0.47-0.41)}$
- $B\tau_E$ dependence on q an β cannot be quantified well <= high ρ(xq,xβ) values
- q an β increase have strong stabilizing effect on thermal energy confinement

## Collisionality scan $\rho^*, \beta_T, q \approx const$

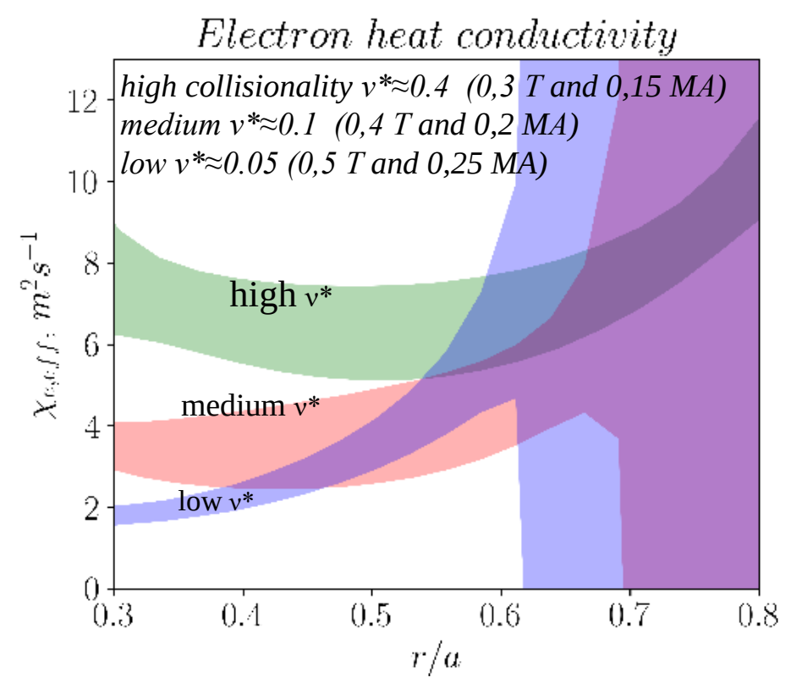
NBI H-mode
$B_T$= 0.32, 0.4, 0.5 T
$I_p$= 0.15, 0.2, 0.25 MA
$P_{abs}$ : NUBEAM
W : 0D code (TS+NPA+EFIT)

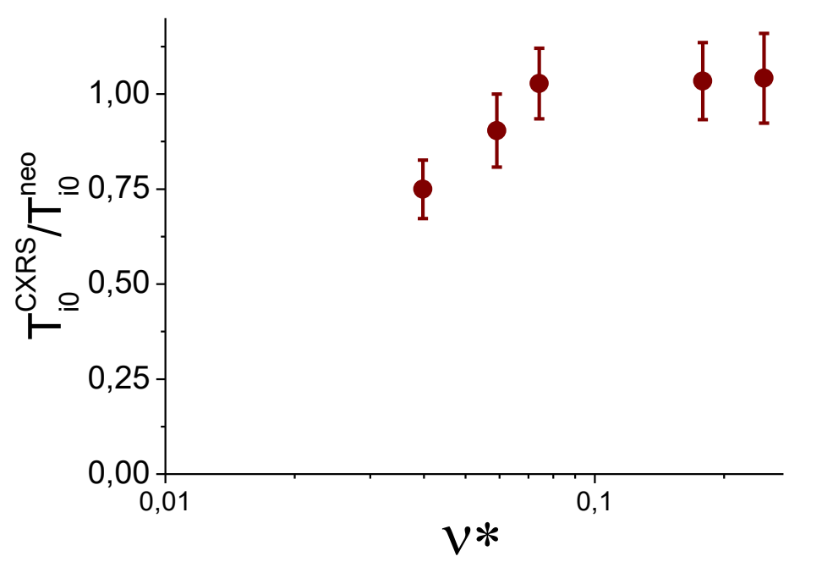






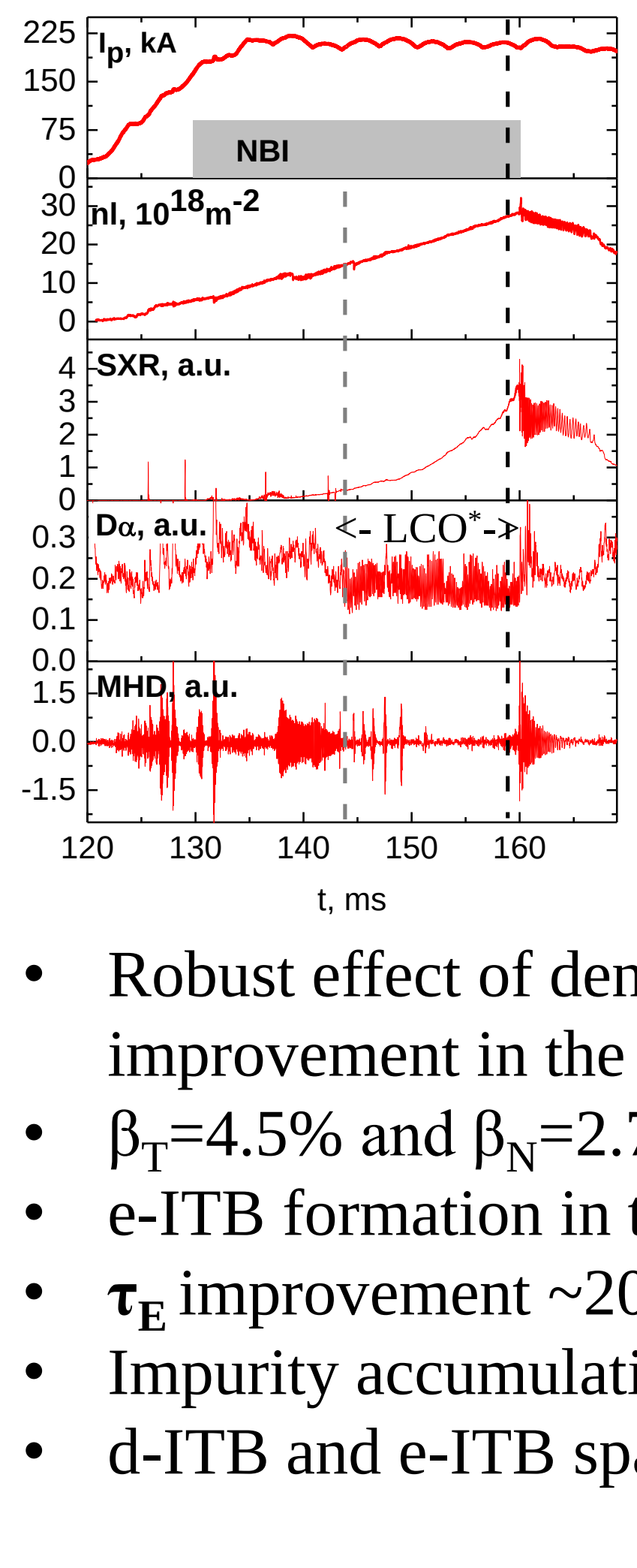
$\rho_*^2 B\tau_E \sim \nu*^{-0.45}$ and $\rho_*^3 B\tau_E \sim \nu*^{-0.52}$ => matches the regression fit result

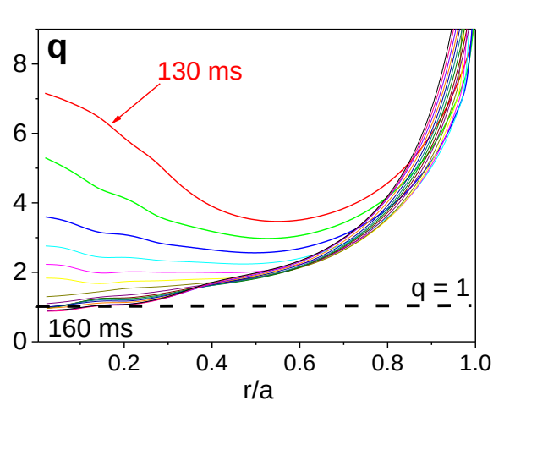


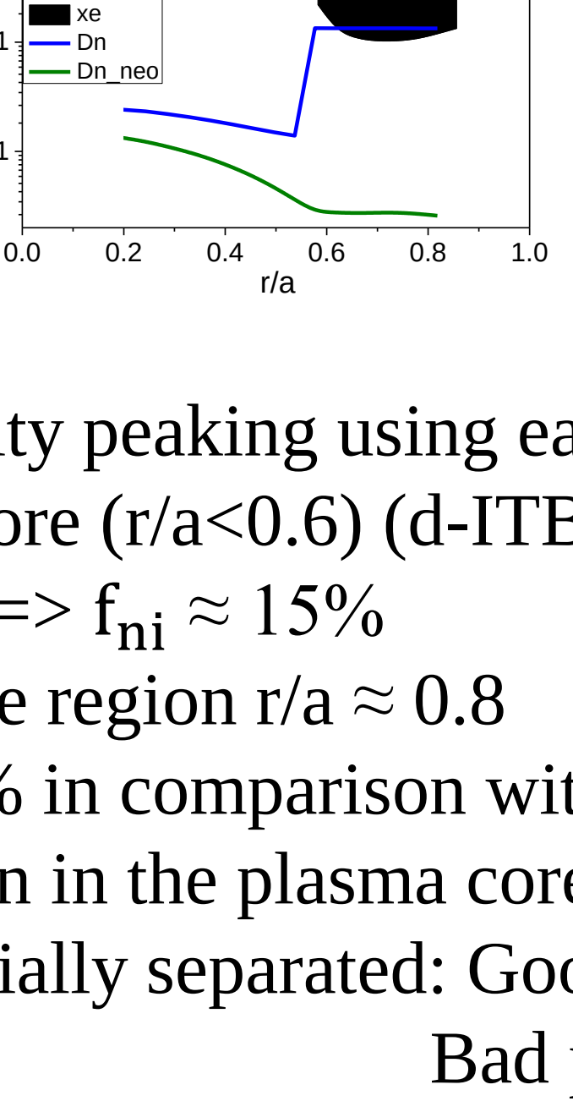


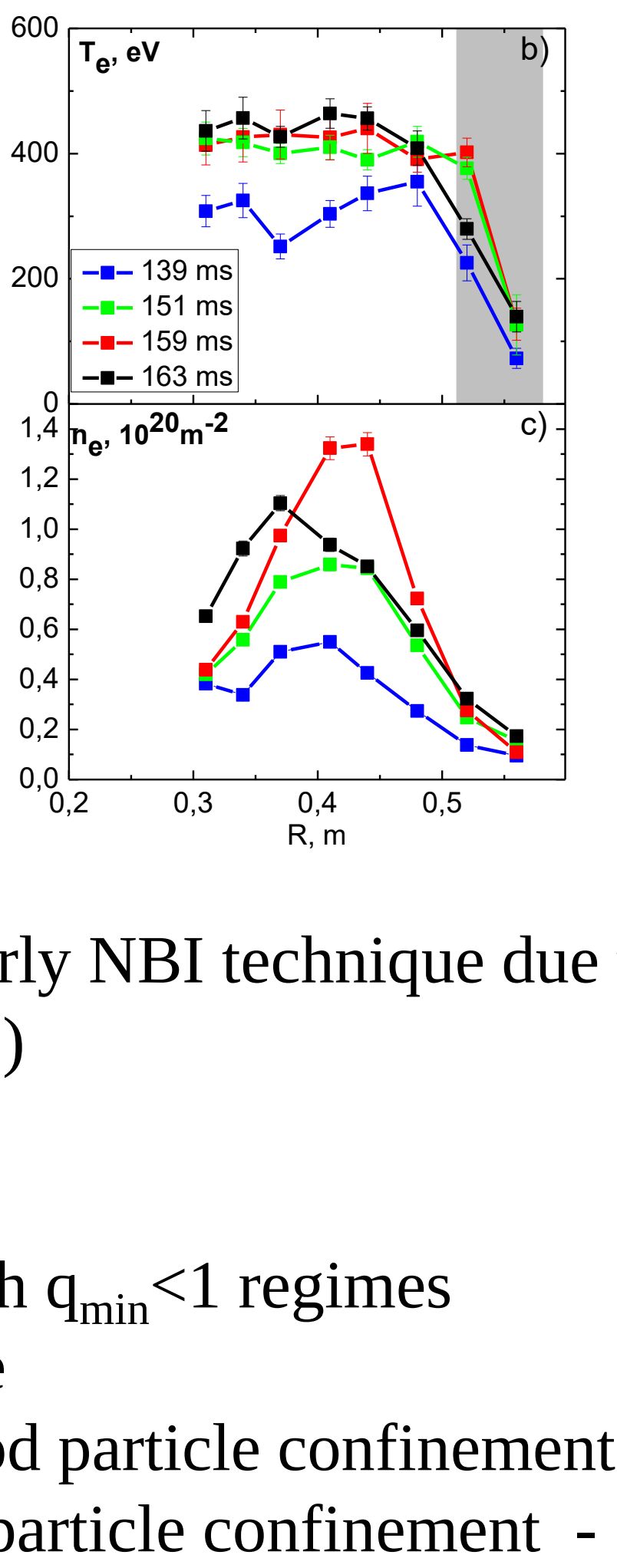
- Electron heat diffusivity decreases with collisionslity: from $B_T/\chi_e \sim \nu^{*-0.2}$ to $B_T/\chi_e \sim \nu^{*-0.6}$
- Ion heat diffusivity is close to neoclassical level for high and medium ν*
- Anomalous $\chi_i$ contribution is overseen for low collisionality

## Energy confinement in AT-like regimes









| | $B_T$=0.5 T | $B_T$=0.4 T |
|---|---|---|
| d-ITB | r/a<0.6 | 0.2<r/a<0.5 |
| e-ITB | 0.75<r/a<0.85 | 0.6<r/a<0.8 |
| ITB disruption | 160 ms | 150 ms |
| ETB | no | yes |
| H-mode | LCO | H-mode |

Similar to DIII-D: strong ITB – weak ETB
*Phys. Plasmas 25, 056113 (2018)*

- Robust effect of density peaking using early NBI technique due to particle confinement improvement in the core (r/a<0.6) (d-ITB)
- $\beta_T$=4.5% and $\beta_N$=2.7 => $f_{ni}$ ≈ 15%
- e-ITB formation in the region r/a ≈ 0.8
- **$\tau_E$** improvement ~20% in comparison with $q_{min}$<1 regimes
- Impurity accumulation in the plasma core
- d-ITB and e-ITB spatially separated: Good particle confinement - Bad thermal confinement
  Bad particle confinement - Good thermal confinement
- Different transport origin → different turbulence suppression mechanisms
- ITB disruption is concerned with q=1 surface and m=1/n=1 instability ($\beta_N$ limit is not reached, looking forward to Globus-M2 with $P_{NBI}$=2 MW)

* A.Yu. Yashin et. al. 2018 Nucl. Fusion 58 112009

## Conclusions

- Energy confinemnt time depends strong on toroidal magnetic field and density: $\boldsymbol{\tau_E \sim B_T^{1.2}n_e^{0.67}}$
- **$\tau_E$** dependence on **$I_p$** and **$P_{abs}$** is unclear, however *(0.25<**αI**<0.77; -0,28>**αP**>-0,8)*
- Engineering scaling $\boldsymbol{\tau_E^{GLB} \sim I_p^{0.51\pm0.26}\ B_T^{1.2\pm0.1}P_{abs}^{-0.54\pm0.26}n_e^{0.67\pm0.04}}$:
  - consistent with MAST($\boldsymbol{\tau_E \sim I_p^{0.59}B_T^{1.4}}$) and NSTX($\boldsymbol{\tau_E \sim I_p^{0.57}B_T^{1.08}}$) results with conventional wall conditioning technique [*Valovic M. et. al. 2009 Nuclear Fusion 49 075016, Kay S.M. et.al. 2006 Nuclear Fusion 46 848-857*]
  - contradicts NSTX Li experiments ($\boldsymbol{\tau_E \sim I_p^{0.79}B_T^{-0.15}}$) *[Kay S.M. et.al. 2013 Nuclear Fusion 53 063005]*
  - contradicts IPB98(y,2) ($\boldsymbol{\tau_E \sim I_p^{0.93}B_T^{0.15}n^{0.41}}$)
- Normalized energy confinemnt time:
  - moderate dependence on collisionality: $\boldsymbol{B_T\tau_E \sim \nu^{*-0.46\pm0.05}}$
  - database regression results are consistent with dedicated scan results with fixed ρ*, $\beta_T$, *q*
  - collisionality dependence weaker than on MAST($\sim\nu^{*-0.85}$) and NSTX($\sim\nu^{*-0.79}$), stronger than IPB ($\sim\nu^{*-0.01}$)
  - *q* an *β* increase have stabilizing effect on thermal energy confinement
- Electron heat transport improves as *ν** decreases
- Ion heat transport is neoclassical for moderate and high *ν**, anomalous contribution for low *ν** - consistent with NSTX experiments [*Kay S.M. et.al. 2013 Nuclear Fusion 53 063005*].
- Energy confinement in Globus-M follows the ST trend, however a set of distinctive features exists

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