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Ioffe Institute

Electron heating during neutral beam injection at Globus-M2.

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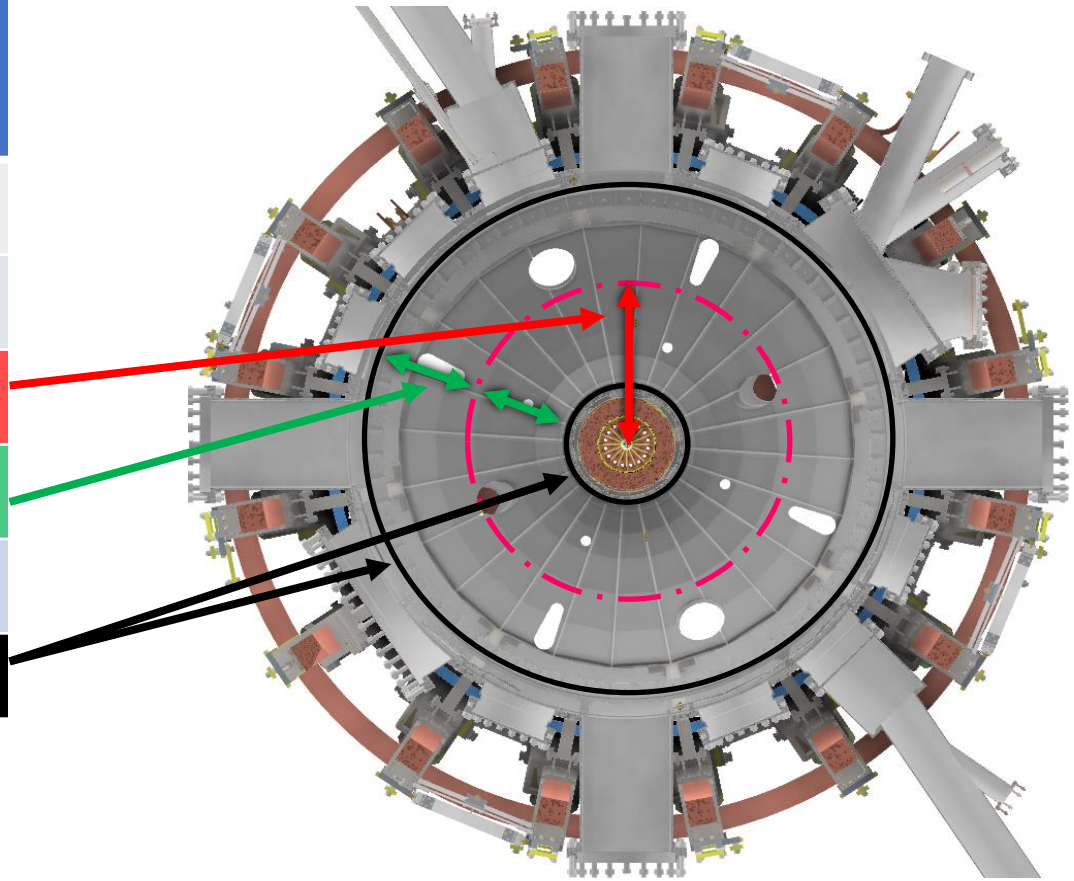
Experiment setup

Globus-M2 equatorial cross-section

Globus-M2 Spherical tokamak
B_T = 0.9 T
I_p = 0.4 MA
R = 0.36 m
a = 0.24 m
R/a = 1.5
Graphite wall



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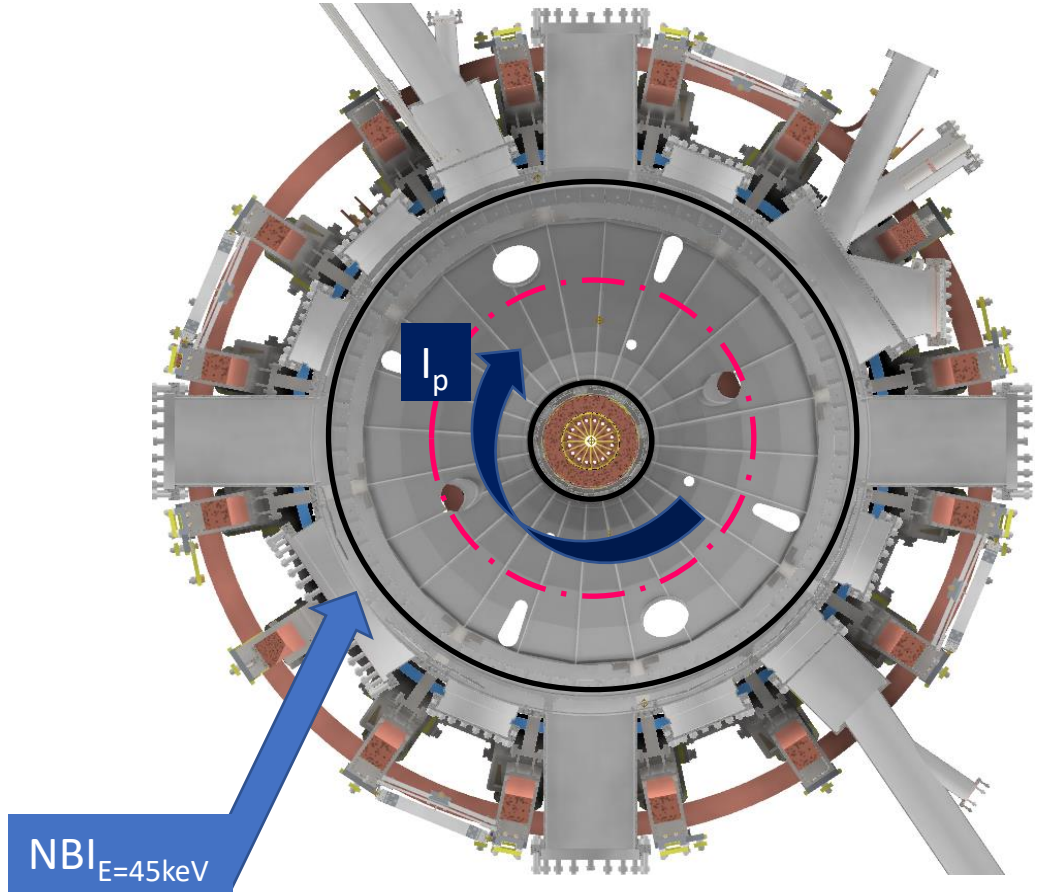
$NBI_{E=45keV}$
P = 0.75 MW
E = 45 keV

Globus-M2 equatorial cross-section



$NBI_{E=45keV}$ experiment setup

Globus-M2 equatorial cross-section

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B_T = 0.9 T
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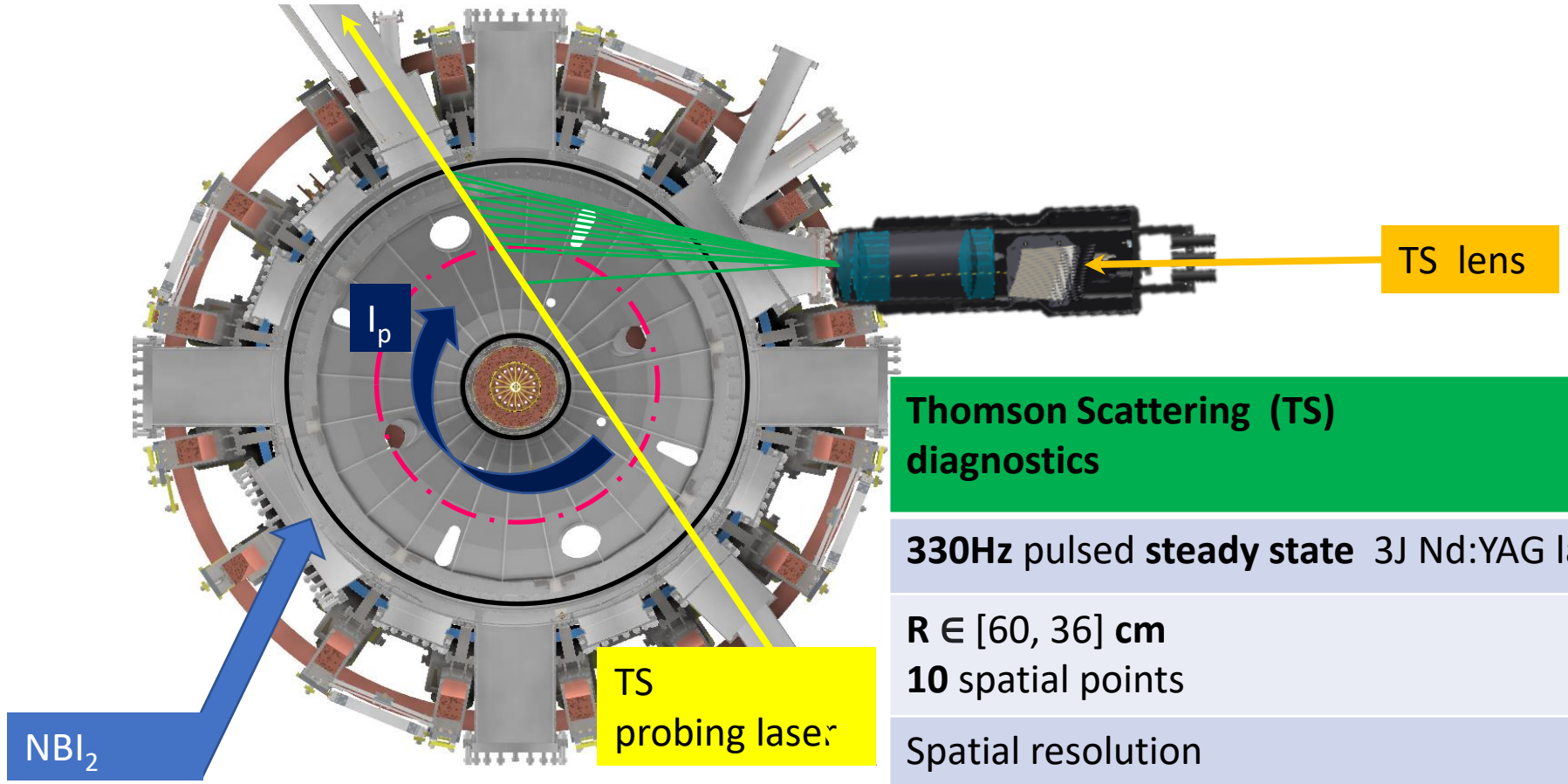
R/a = 1.5
Graphite wall

NBI_2
P = 0.75 MW
E = 45 keV



Thomson Scattering (TS) diagnostics

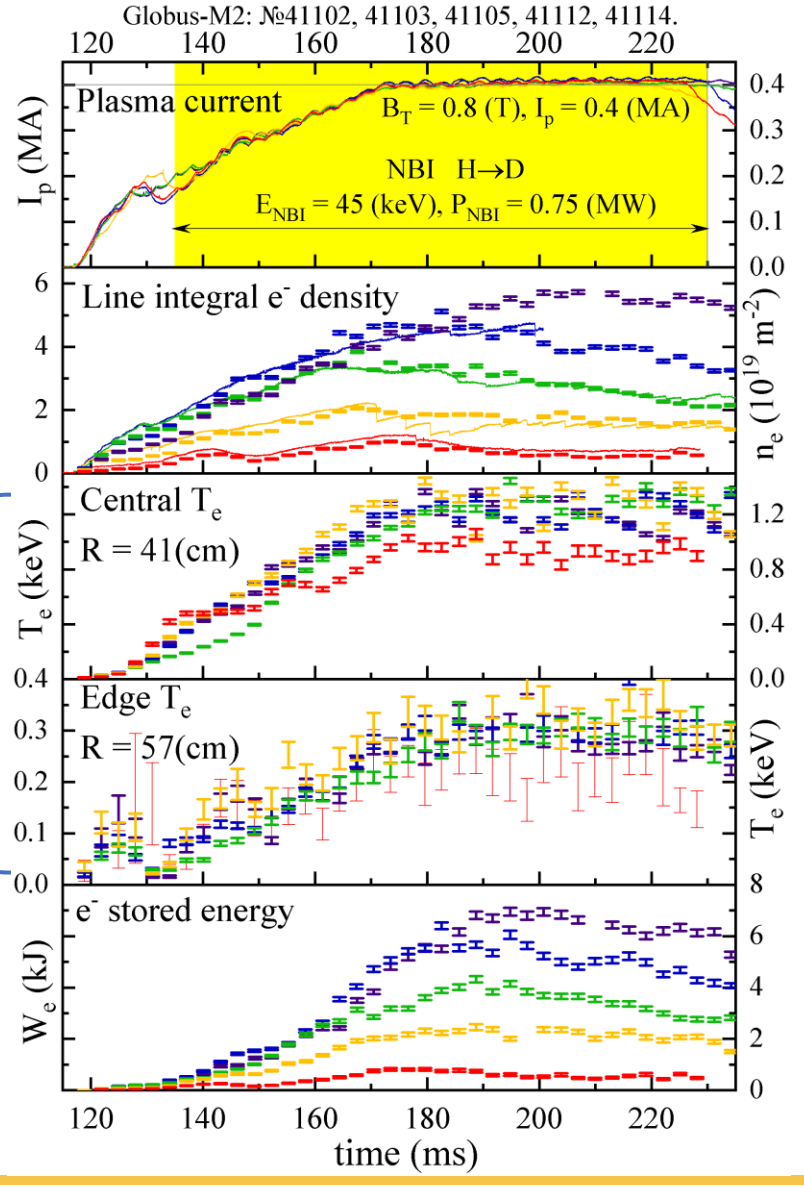
330Hz pulsed **steady state** 3J Nd:YAG laser

R ∈ [60, 36] **cm**
10 spatial points

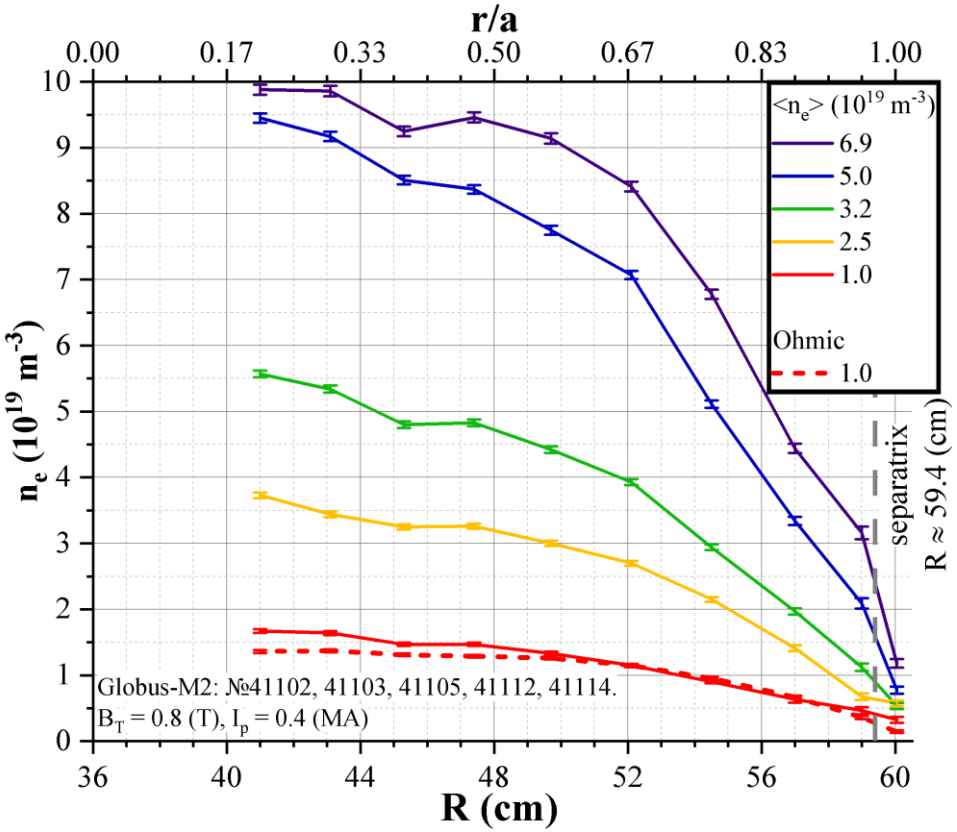
Spatial resolution
ΔR = [21 – 11] mm

$NBI_{E=45keV}$ experiments

- NBI started at I_p ramp-up
- n_e varied in range $0.7 \cdot 10^{19} – 7.5 \cdot 10^{19}$ (m^{-3})
- **T_e is independent from $<n_e>$** except for low $<n_e>$ (red).
- W_e proportional to $<n_e>$, **absence of saturation**

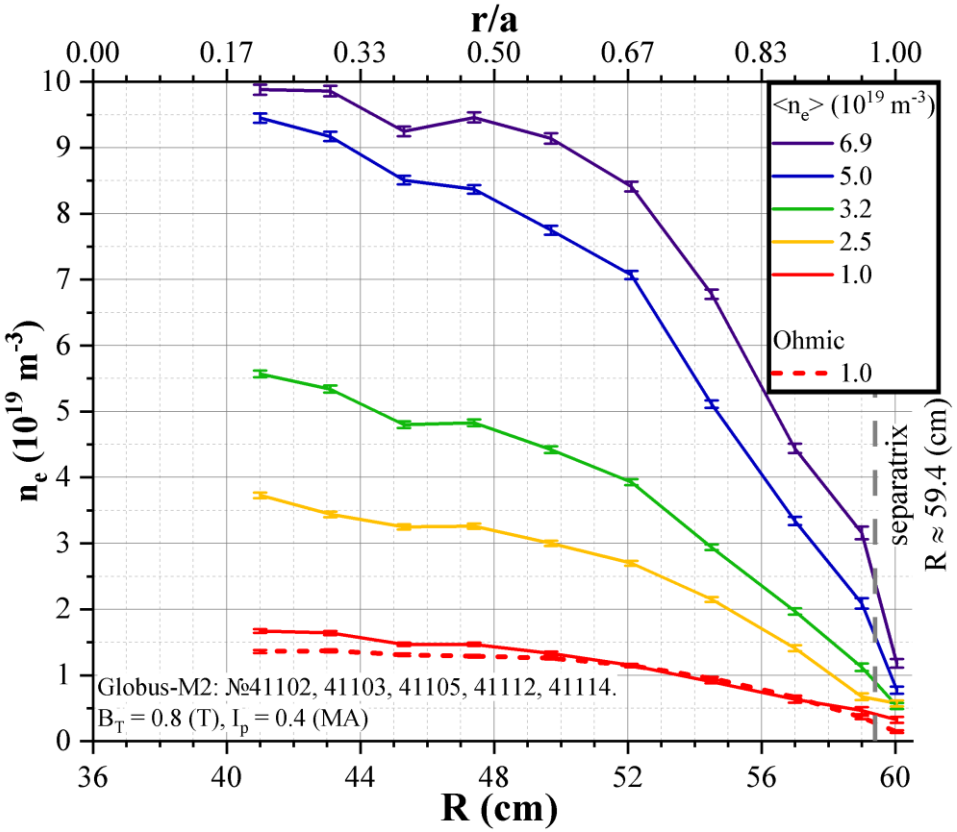


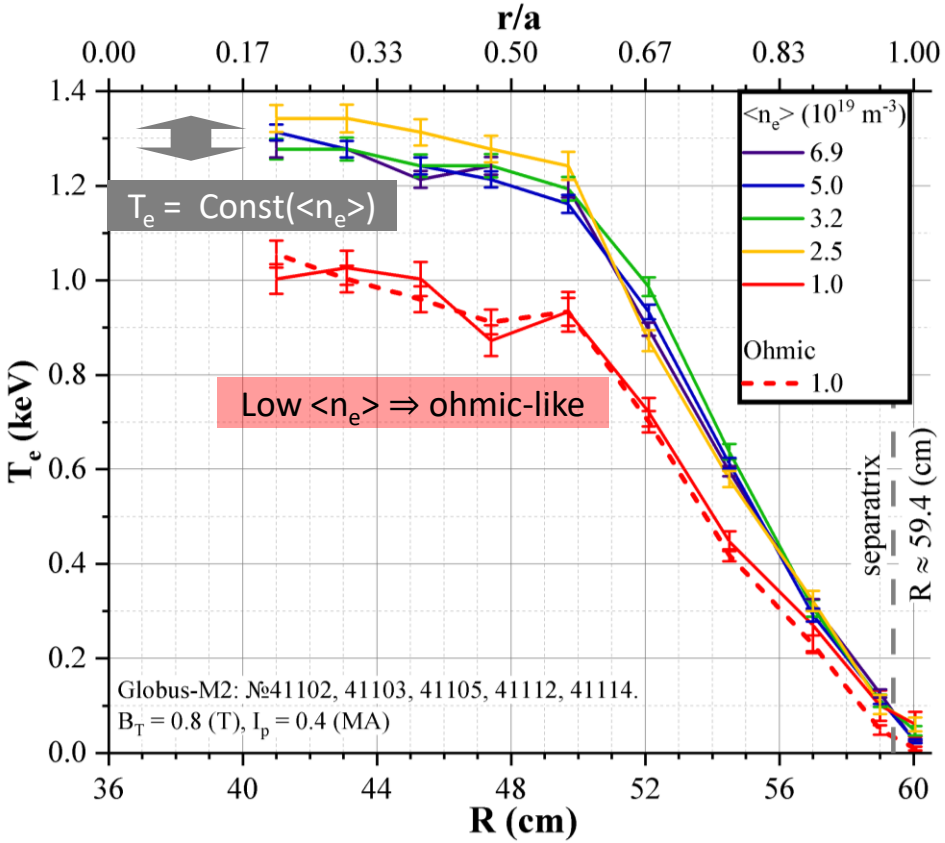
$NBI_{E=45keV}$ experiments



- peaked n_e profiles
- n_e gradient increase with <n_e> for $r/a \leq 0.9$
- n_e *edge* pedestal is rises for high <n_e>

$NBI_{E=45keV}$ experiments

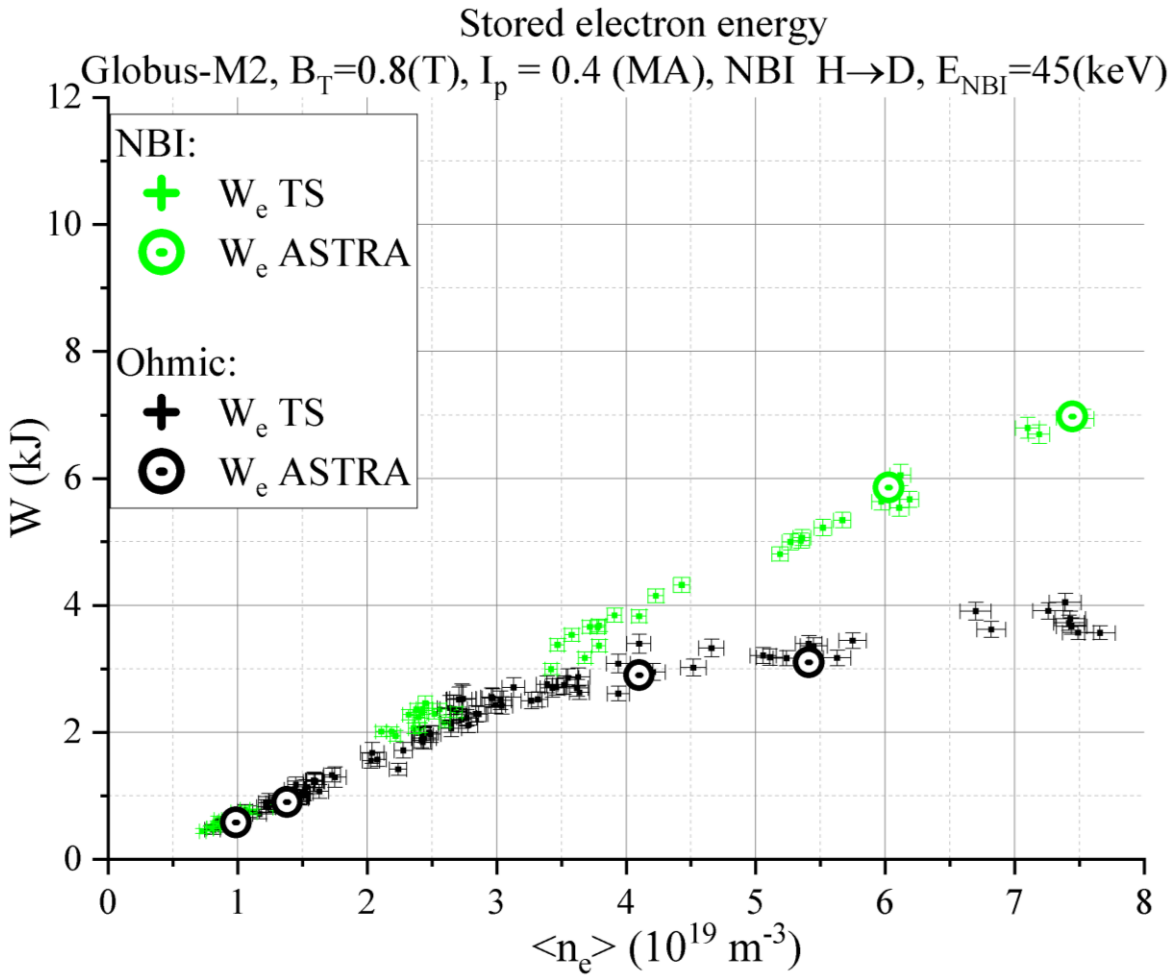




- peaked n_e profiles
- n_e gradient increase with <n_e> for $r/a \le 0.9$
- n_e *edge* pedestal is rises for high <n_e>

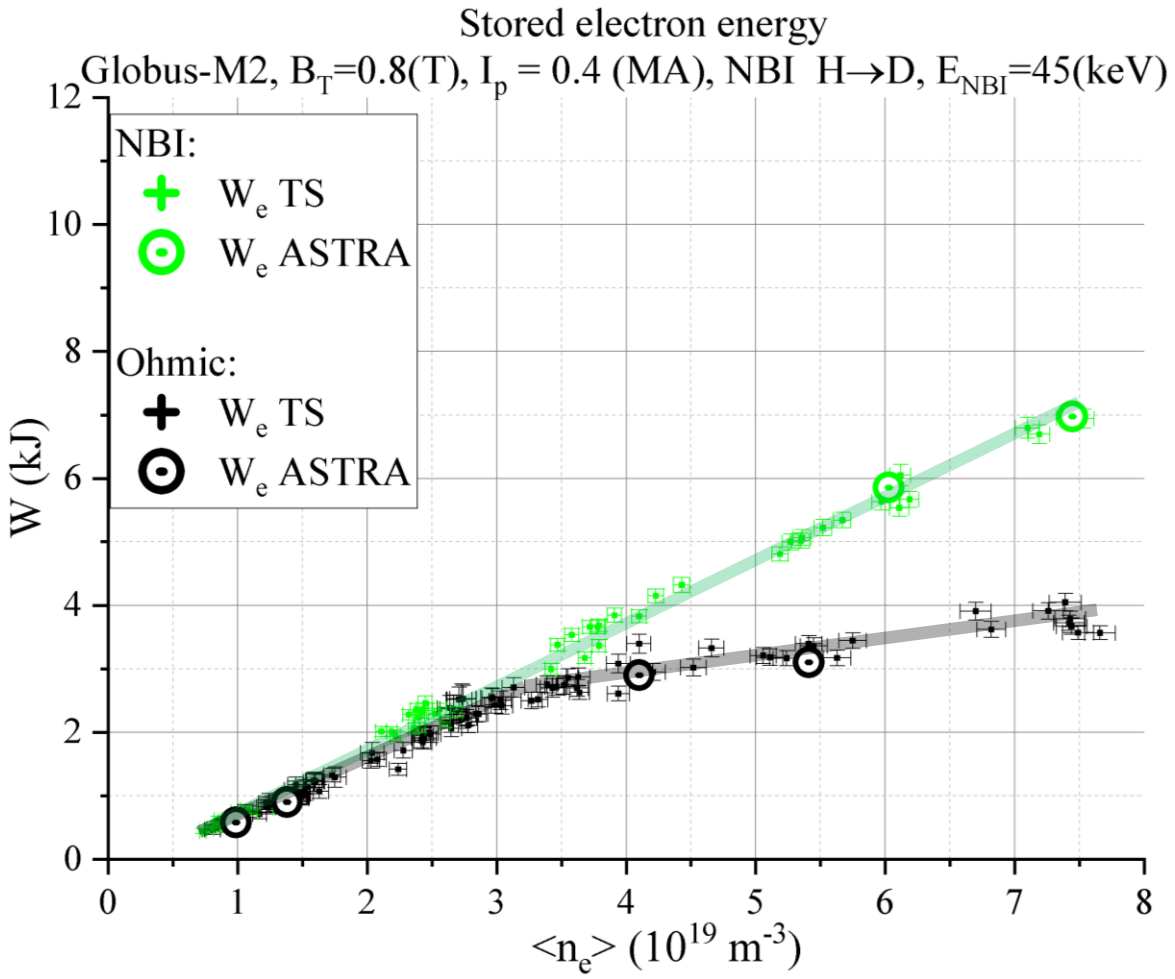
- T_e gradient is independent from <n_e>
- Central T_e=1.3 (keV) at $n_e=1\cdot10^{20}$ (m^{-3})

$NBI_{E=45keV}$ experiments



- Linear W_e ($<n_e>$) rise in $NBI_{E=45}$ regime
- $NBI_{E=45keV}$ regime has 175% of ohmic W_e at high $<n_e>$
- **Electron heating is evident for $NBI_{E=45keV}$** regime

$NBI_{E=45keV}$ experiments



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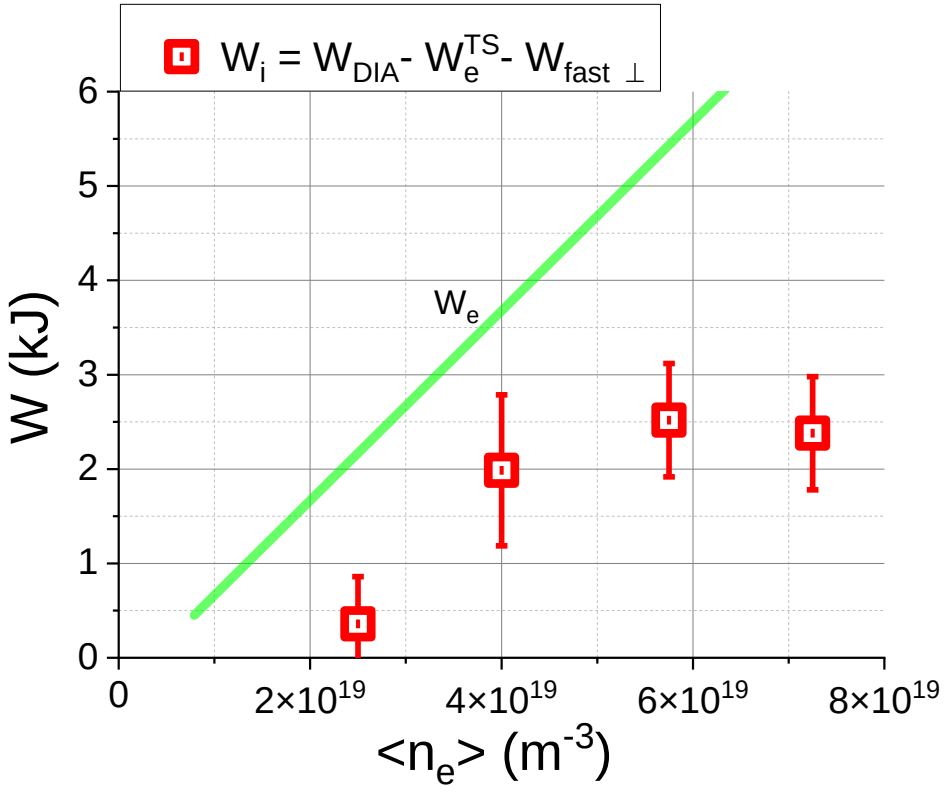
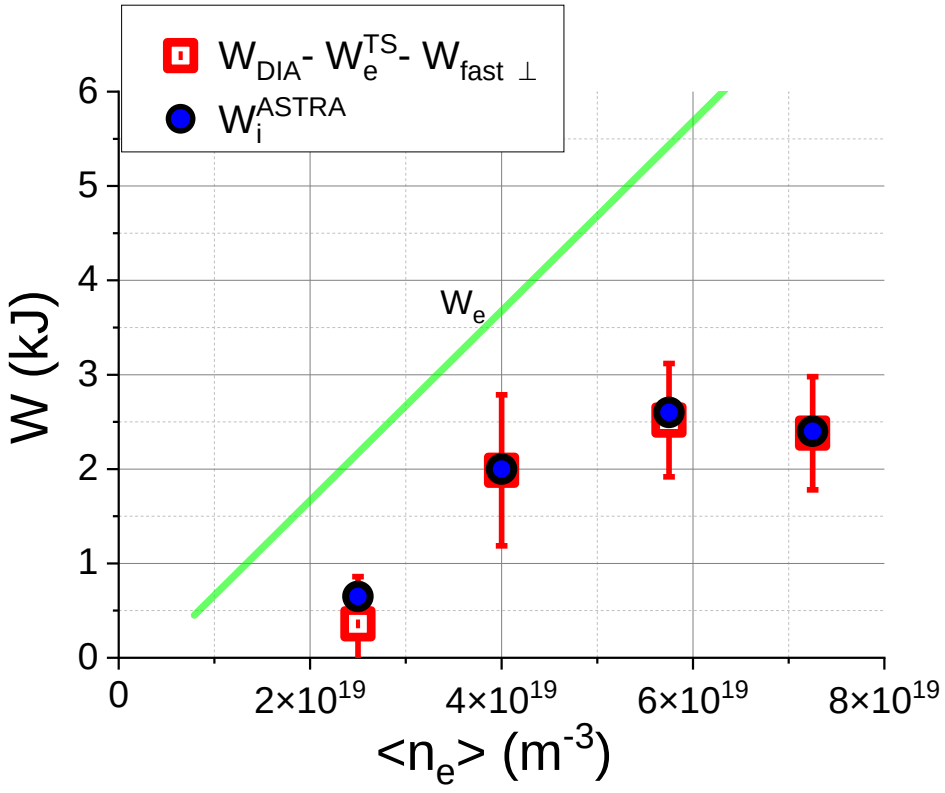
- $NBI_{E=45keV}$ regime has 175% of ohmic W_e at high <n_e>
- **Electron heating is evident for $NBI_{E=45keV}$** regime

$NBI_{E=45keV}$ modelling



- Diamagnetic measurements allow to estimate W_i as $W_{DIA} = W_e + W_i + W_{fast\perp}$

$NBI_{E=45keV}$ modelling



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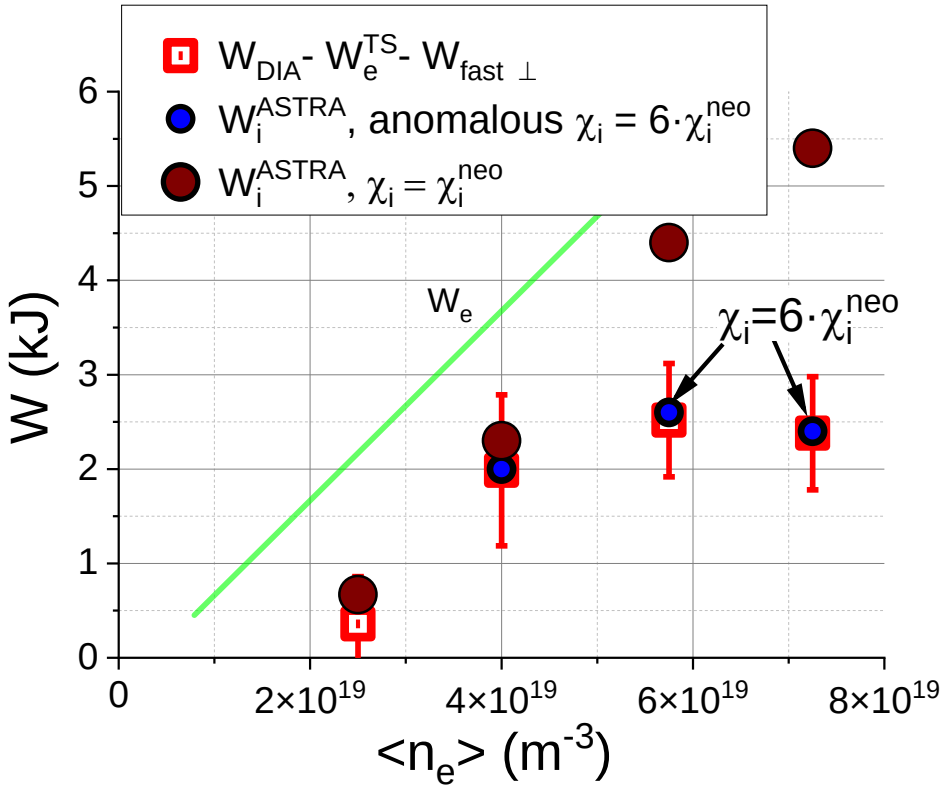

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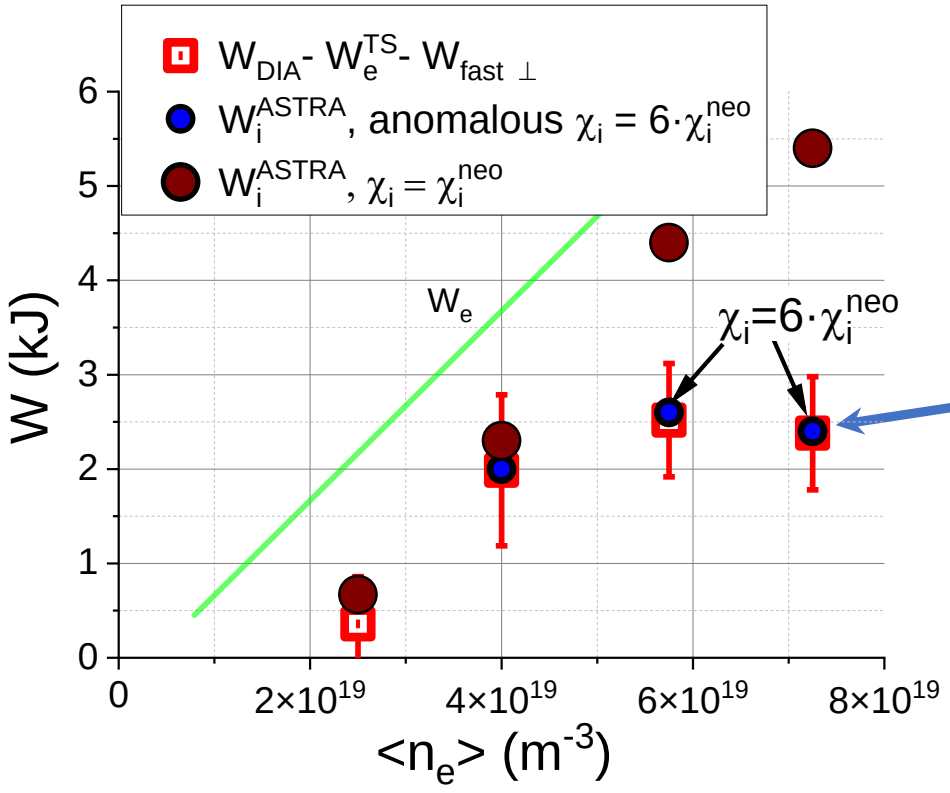
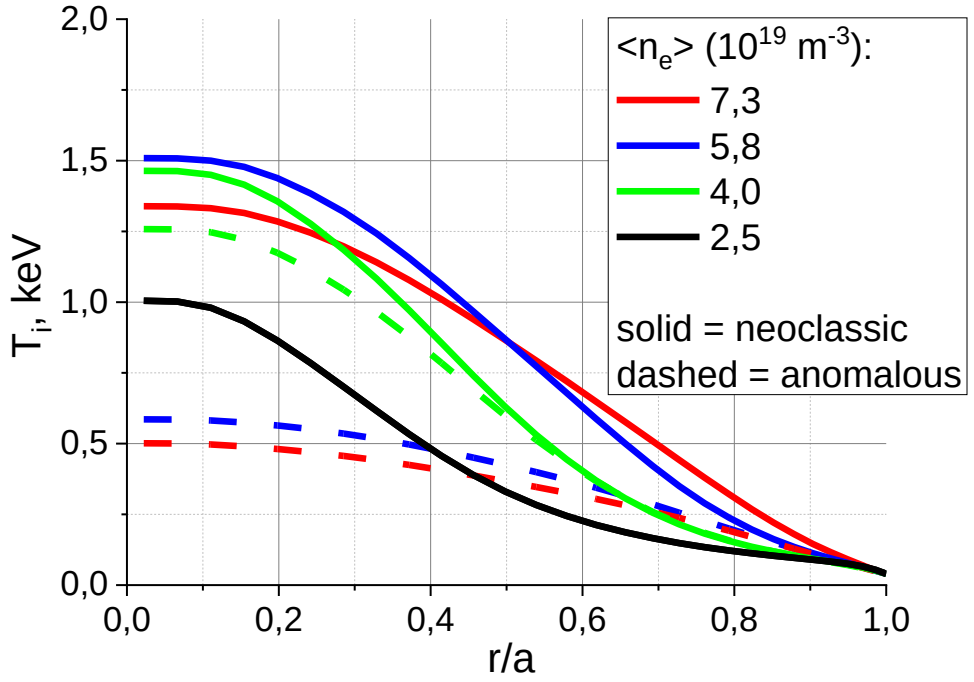
- anomalous χ_i

$NBI_{E=45keV}$ modelling

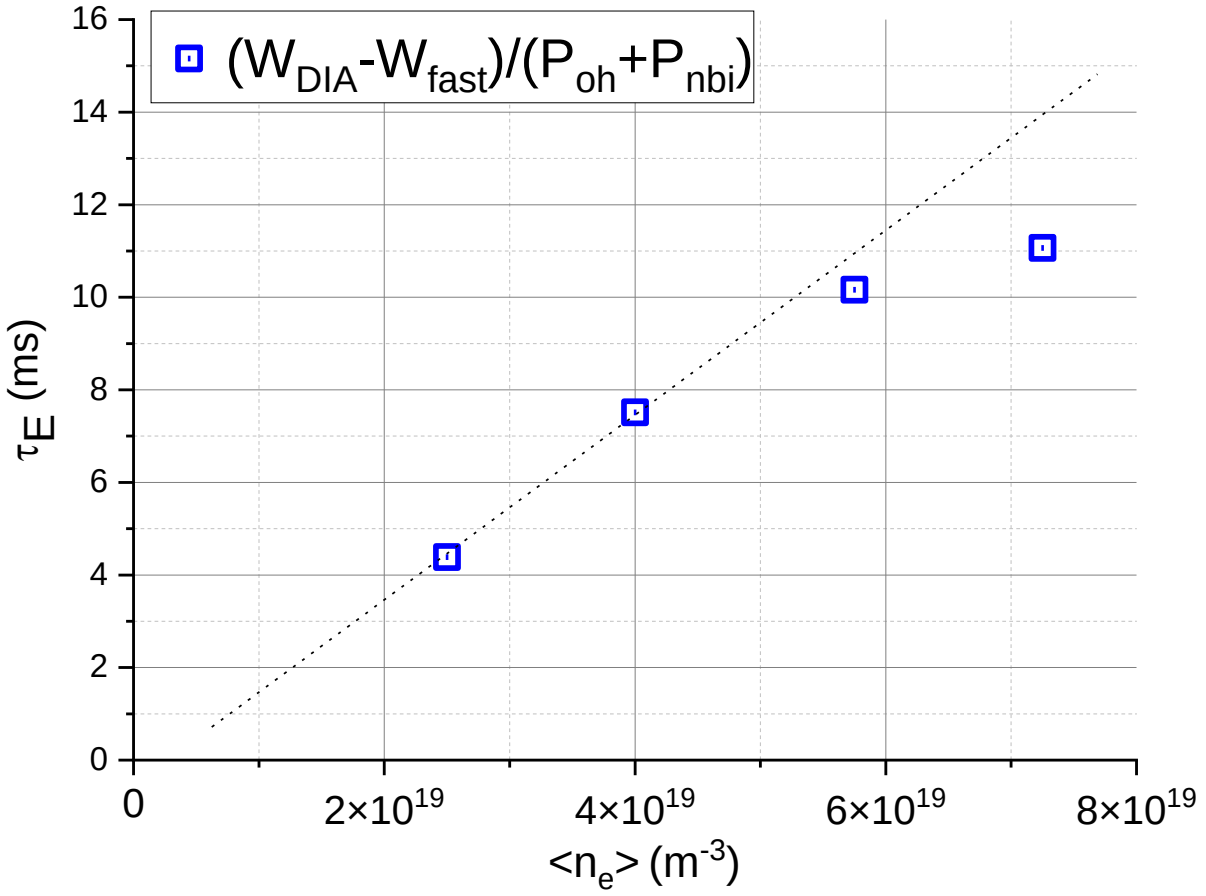


T_e = 1.3 (keV)
T_i^{neo} = 1.3 (keV)
$T_i^{anomalous}$ = 0.5 (keV)



- Diamagnetic measurements allow to estimate W_i as $W_{DIA} = W_e + W_i + W_{fast\ \perp}$
- anomalous χ_i
- $NBI_{E=45keV}$ experiments point at low T_i values

$NBI_{E=45keV}$ modelling

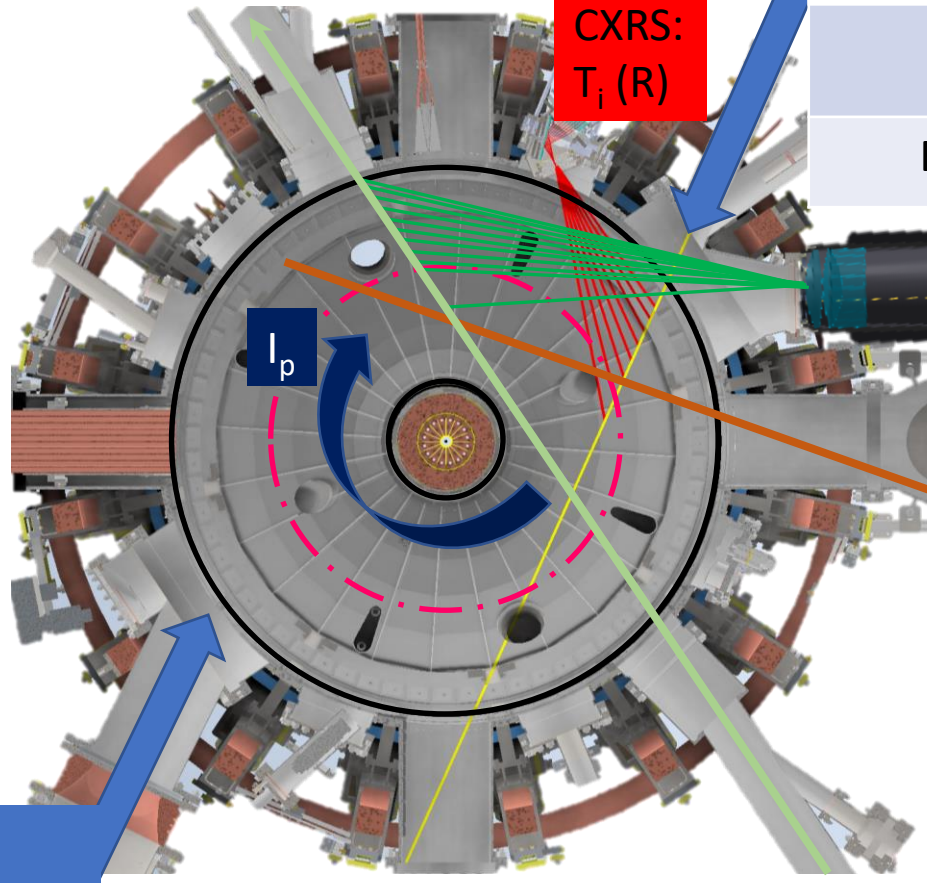


τ_E = 11(ms) for $\langle n_e \rangle \sim 7 \cdot 10^{19}$ (m^{-3}) and $NBI_{E=45keV}$ fits previous results for $NBI_{E=28keV}$

Anomalous χ_i leads to saturation of τ_E

NBI_1 + NBI_2 experiment setup

Globus-M2 equatorial cross-section



NBI_1

P ≤ 0.45 MW

E = 25-28 keV

Thomson scattering :
T_e (R), n_e (R)

NPA: T_i

NBI_2

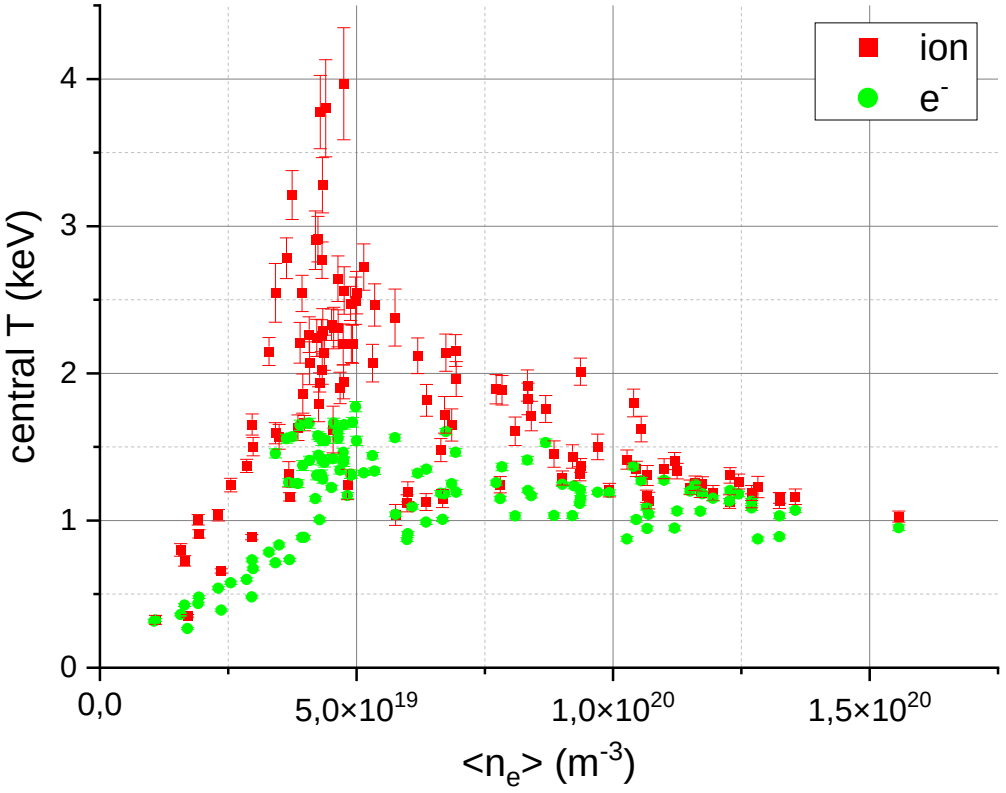
P ≤ 0.75 MW

E = 30-45 keV

NBI_2

$NBI_1 + NBI_2$ experiments

Globus-M2 B_T = 0.9 T, I_p = 0.35-0.4 MA, $NBI_1 + NBI_2$

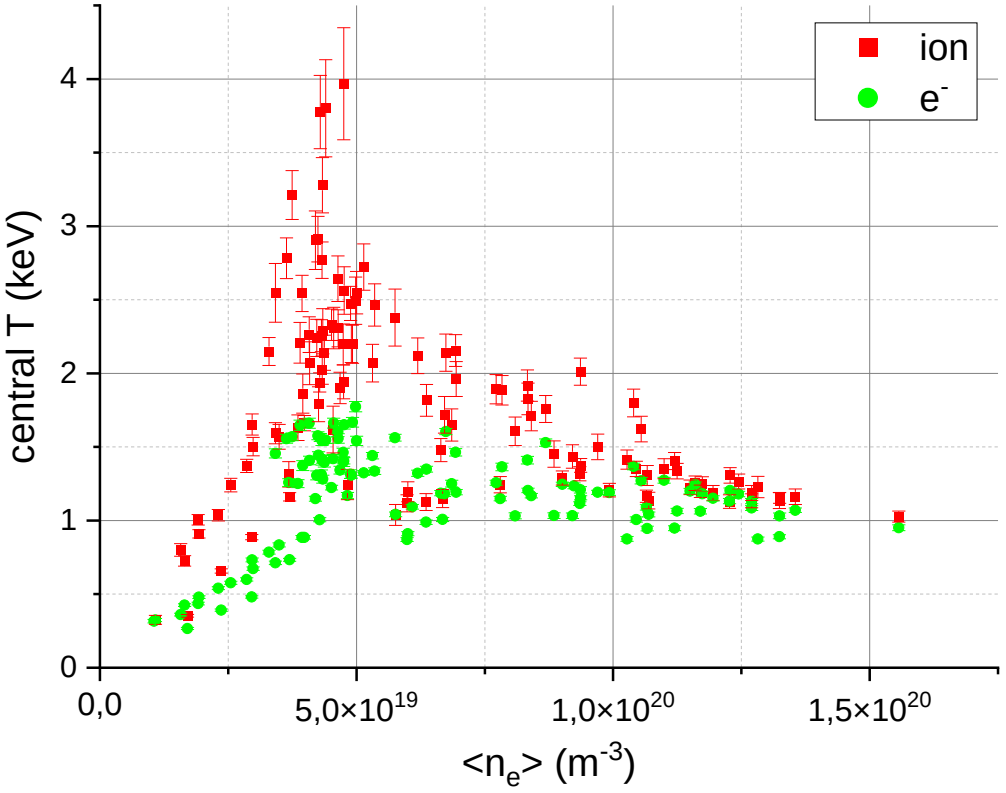


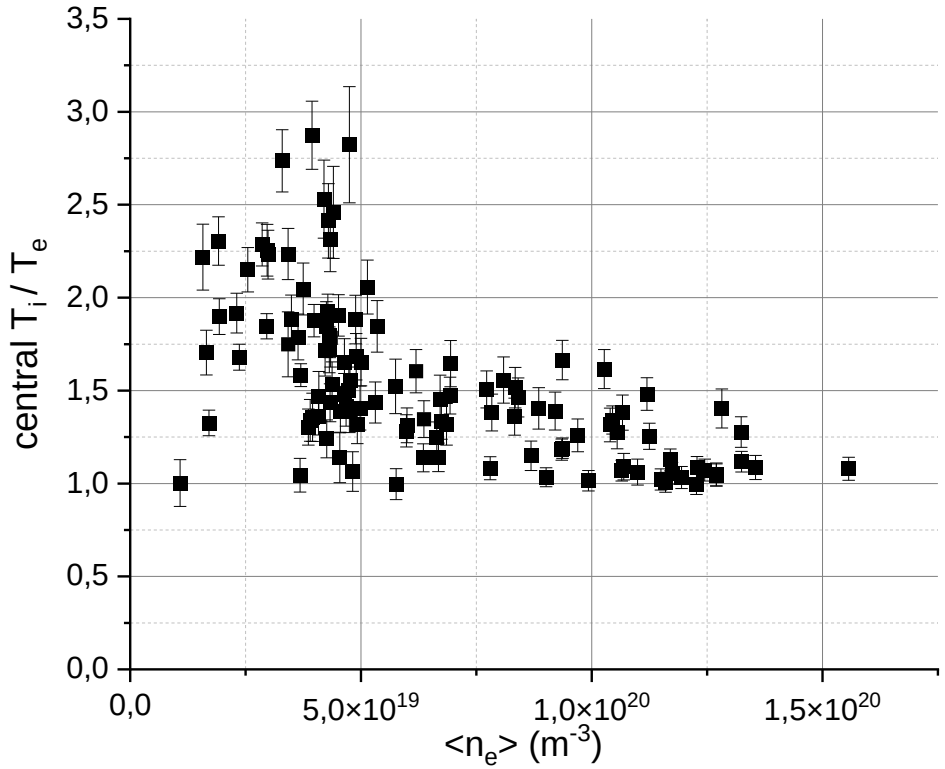
Hot ion mode achieved in wide $\langle n_e \rangle$ range 0.15 - **1.6** (**10^{20}** · m^{-3})

T_i = 4 (keV) at $\langle n_e \rangle$ = 4.9·10^{19} (m^{-3})

$NBI_1 + NBI_2$ experiments

Globus-M2 B_T = 0.9 T, I_p = 0.35-0.4 MA, $NBI_1 + NBI_2$



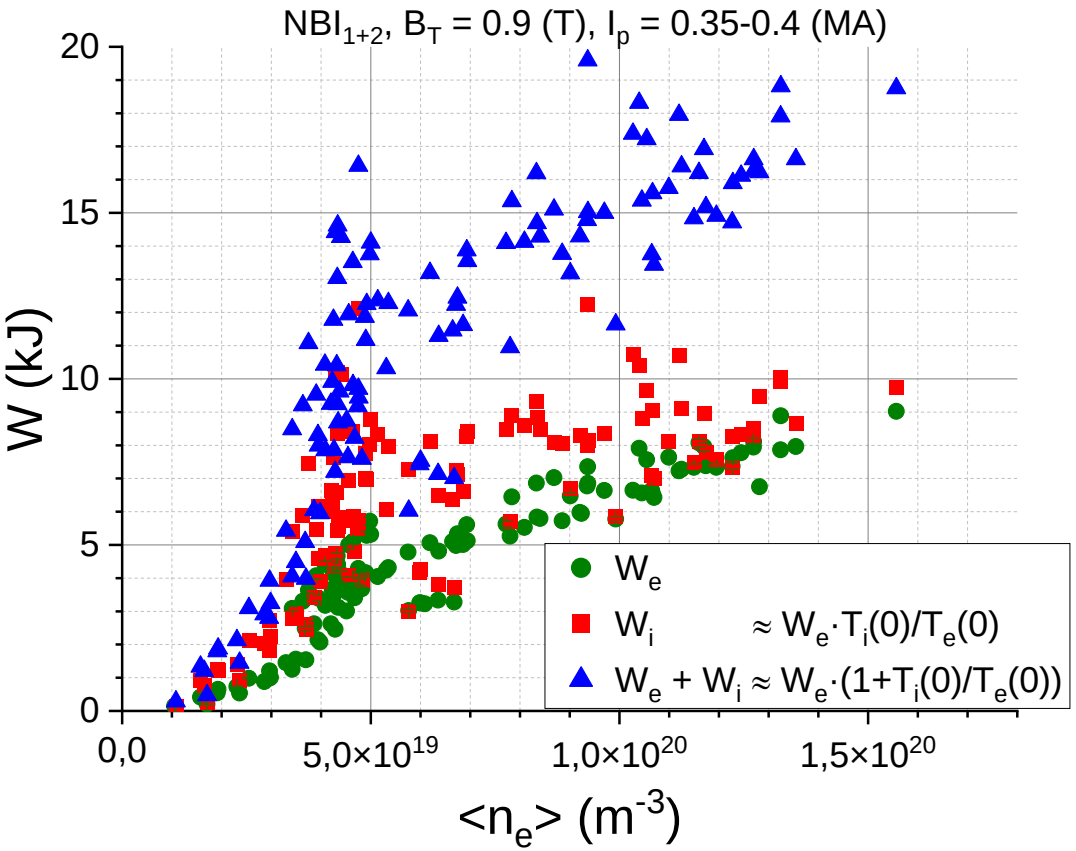


Hot ion mode achieved in wide $\langle n_e \rangle$ range $1.5 \cdot 10^{19}$ - **$1.6 \cdot 10^{20}$** (m^{-3})

T_i = 4 (keV) at $\langle n_e \rangle = 4.9 \cdot 10^{19}$ (m^{-3})

T_i / T_e up to 3

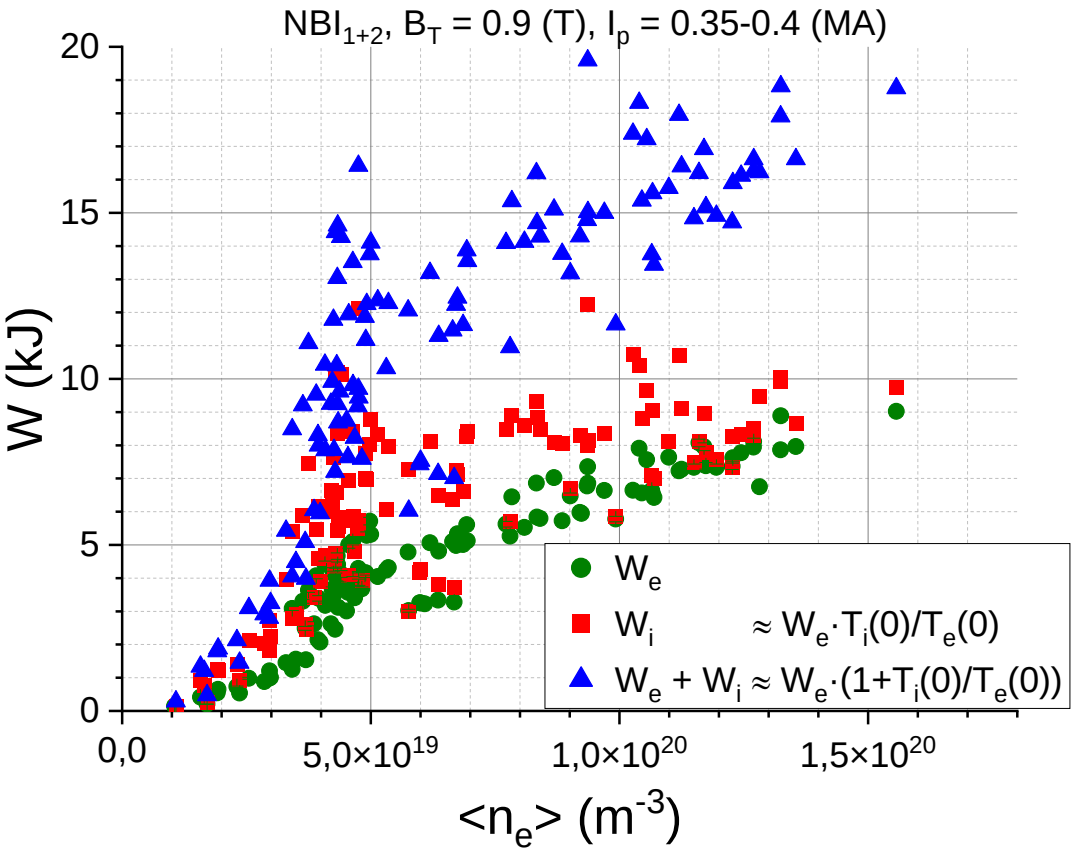
$NBI_1 + NBI_2$ experiments

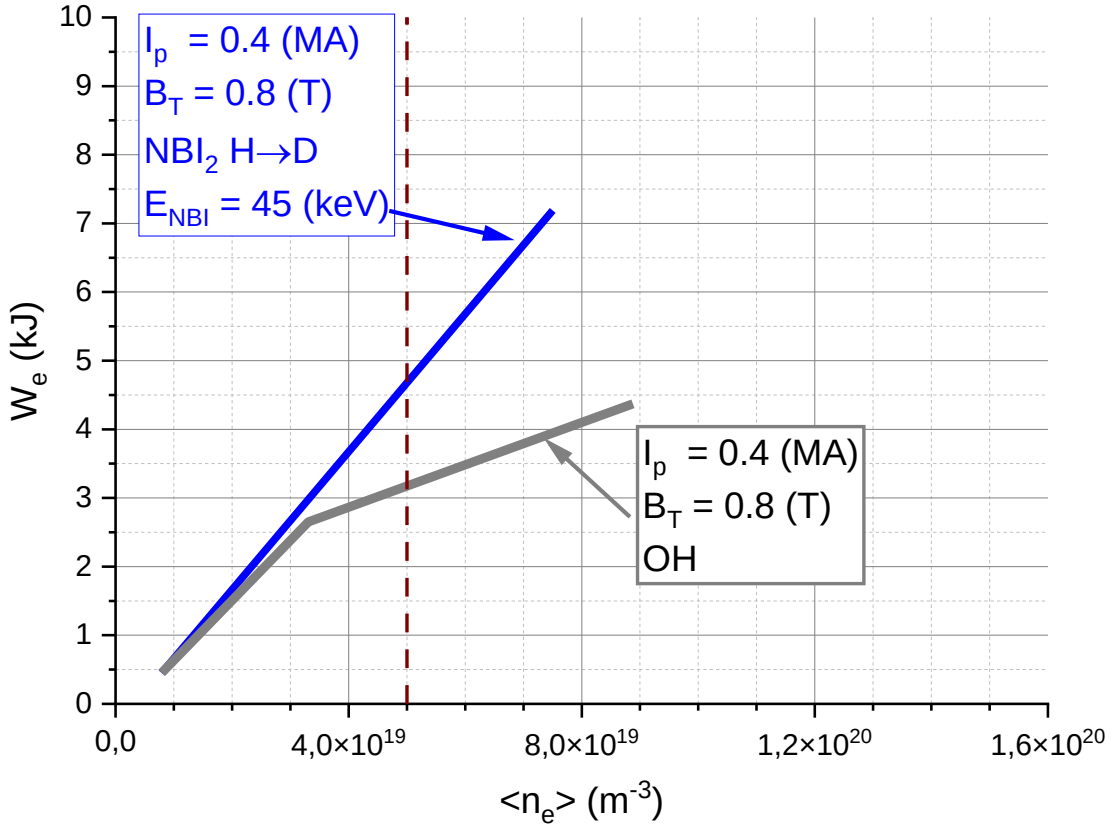


If we roughly top estimate W_i as $W_e \cdot T_i / T_e$, then:

- W_i saturates for $\langle n_e \rangle \geq 0.5 \cdot 10^{20}$ (m^{-3})
- Further W_p rise is due to W_e

$NBI_1 + NBI_2$ experiments





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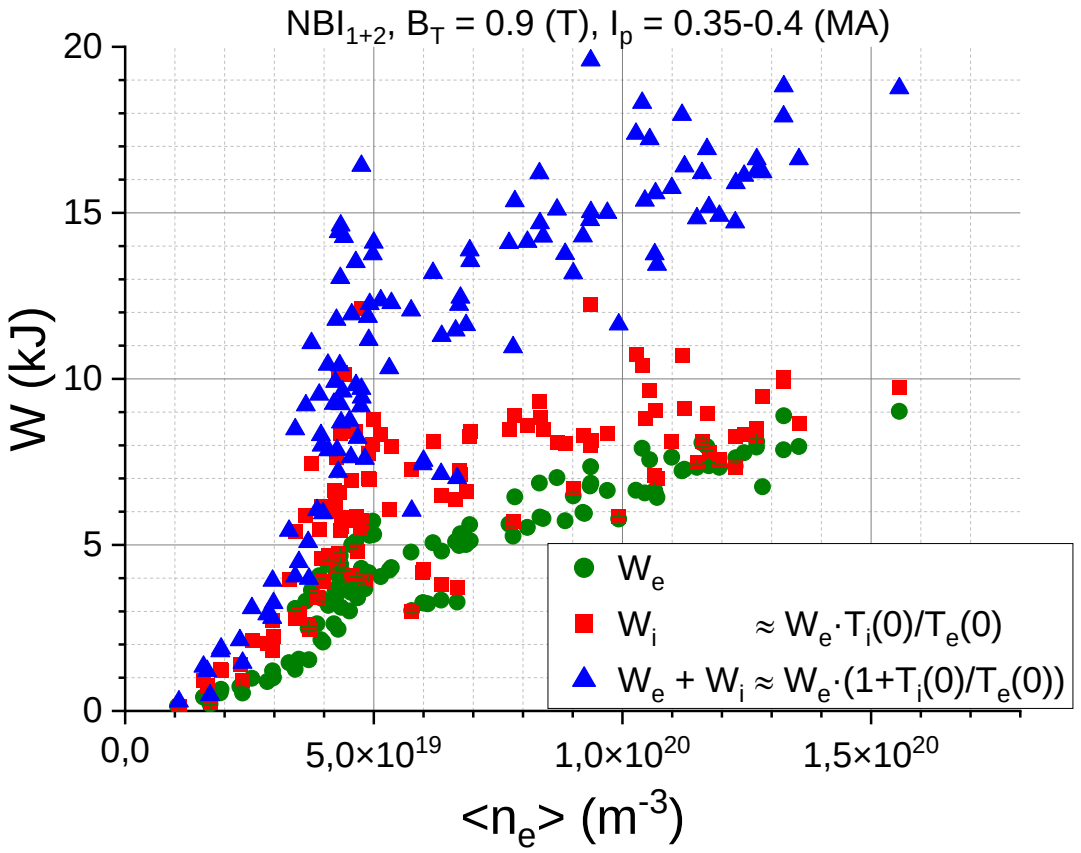
$NBI_1 + NBI_2$ experiments



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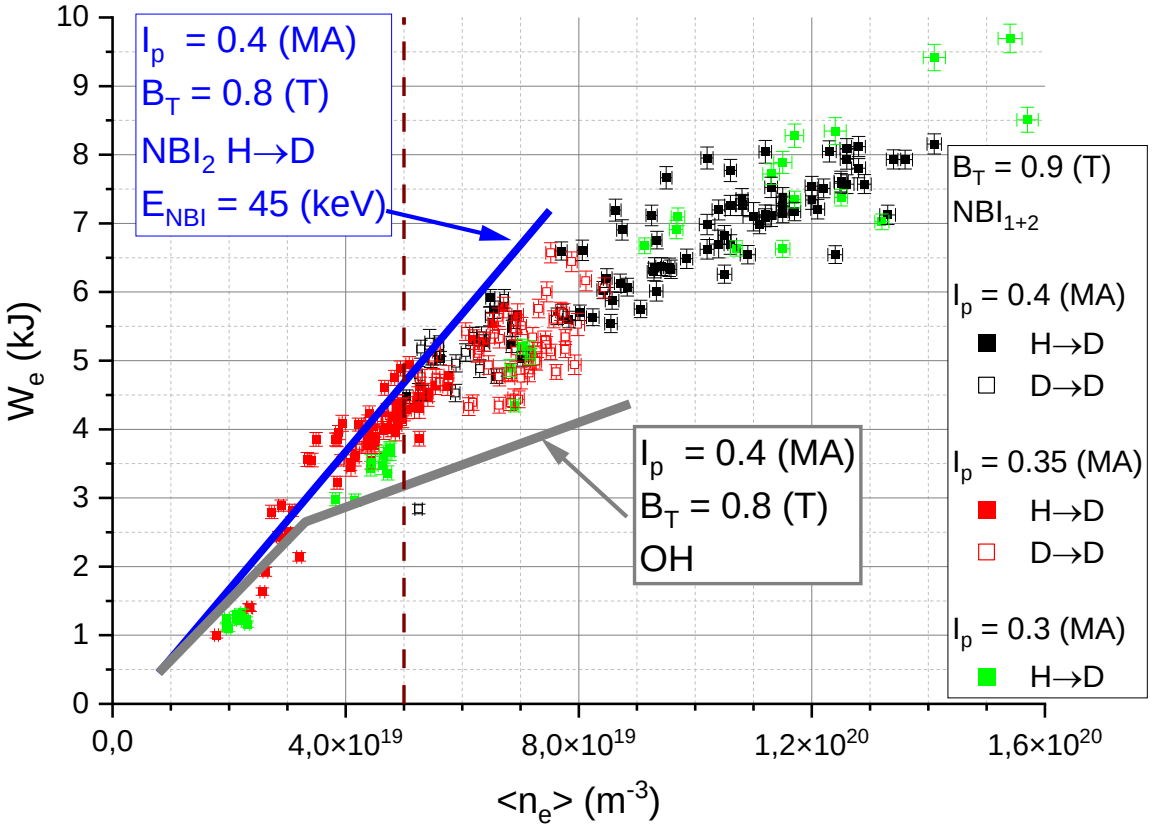
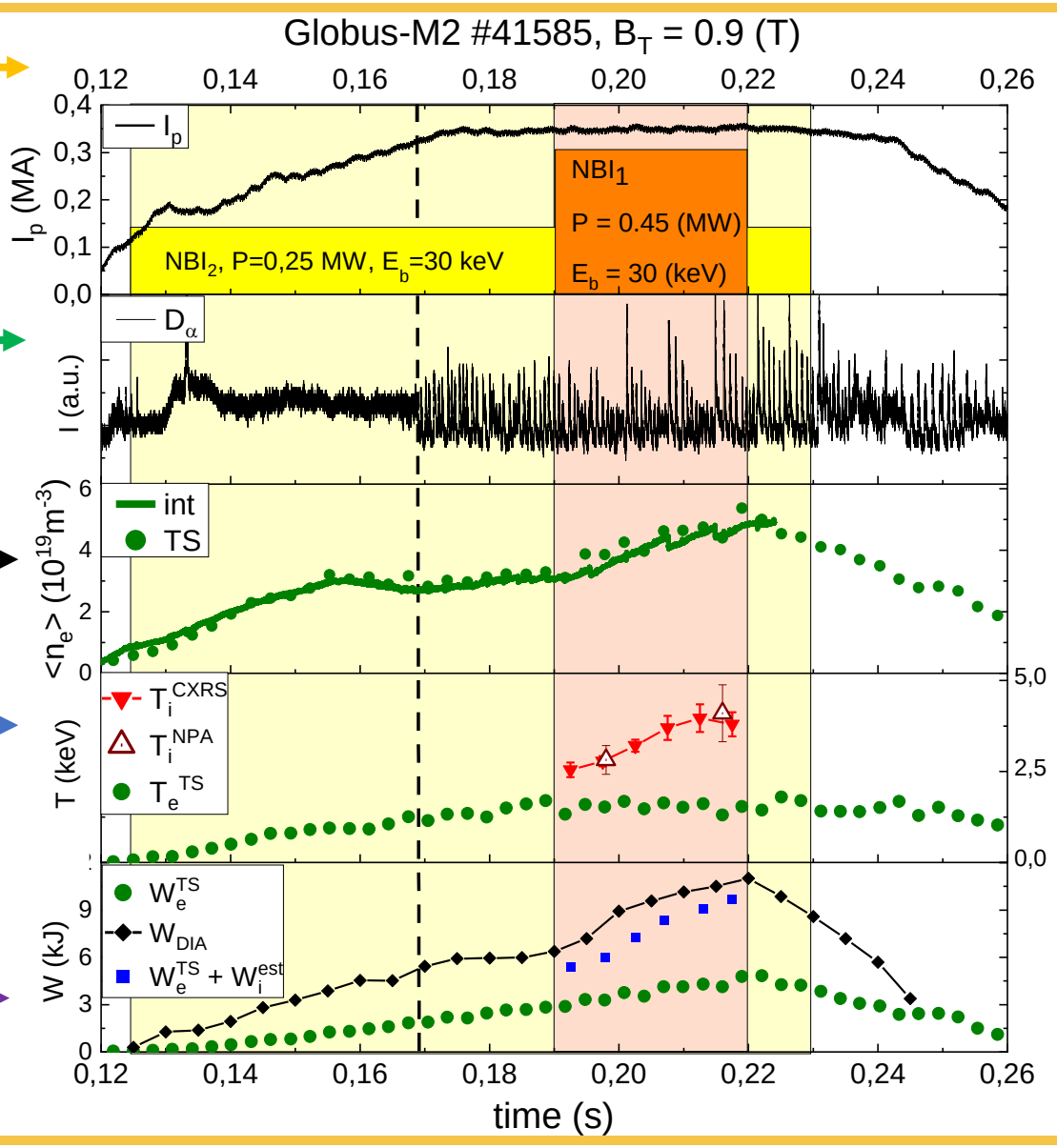


- Same linear dependency as for $NBI_{E=45keV}$ mode at low $\langle n_e \rangle$
- $\langle n_e \rangle = 5 \cdot 10^{19}$ (m^{-3}) ⇒ slope changes

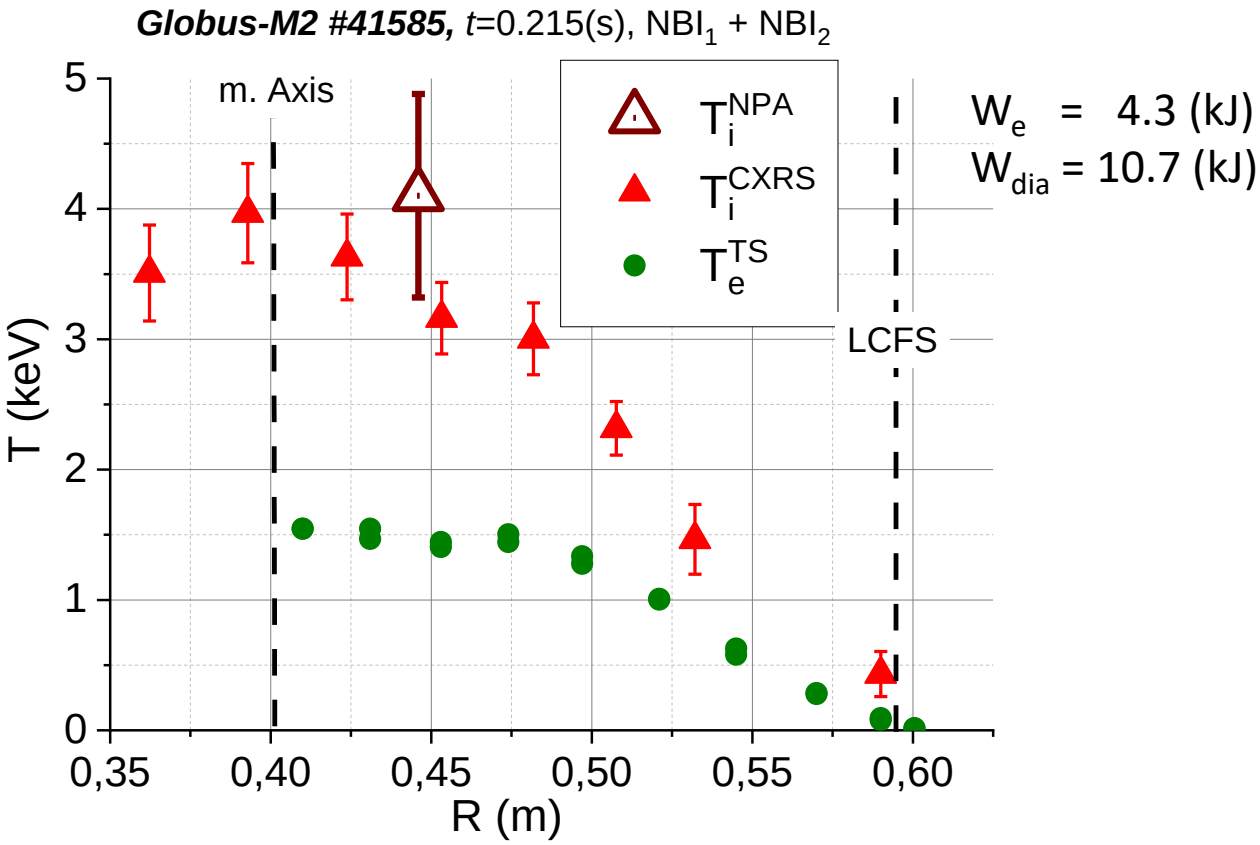
- **T_e > 1.3 (keV) for $\langle n_e \rangle = 1.7 \cdot 10^{20}$ (m^{-3})**
- **W_e is independent from I_p high $\langle n_e \rangle$**

NBI_1 + NBI_2 experiments

- Double NBI scenario:
  - NBI_2 from 0.125 (s) to 0.23 (s)
  - I_p flattop from 0.175 (s) to 0.24 (s)
  - NBI_1 from 0.19 (s) to 0.22 (s)
- L-H transition at 0.17 (s)
  - D_α intensity drop
  - type 5 ELMs
- $\langle n_e \rangle$ from $3 \cdot 10^{19}$ (m^{-3}) to $5.5 \cdot 10^{19}$ (m^{-3}) on I_p flattop
- T_i measurements on *NBI_1* beam by CXRS and NPA matches
  - *$T_i(0)$* rises up to 4 (keV)
  - *$T_e(0)$* = 1.6 (keV)
- *W_{dia}* matches *$W_e^{TS} + W_i^{CXRS} + W_{fast\perp}$*



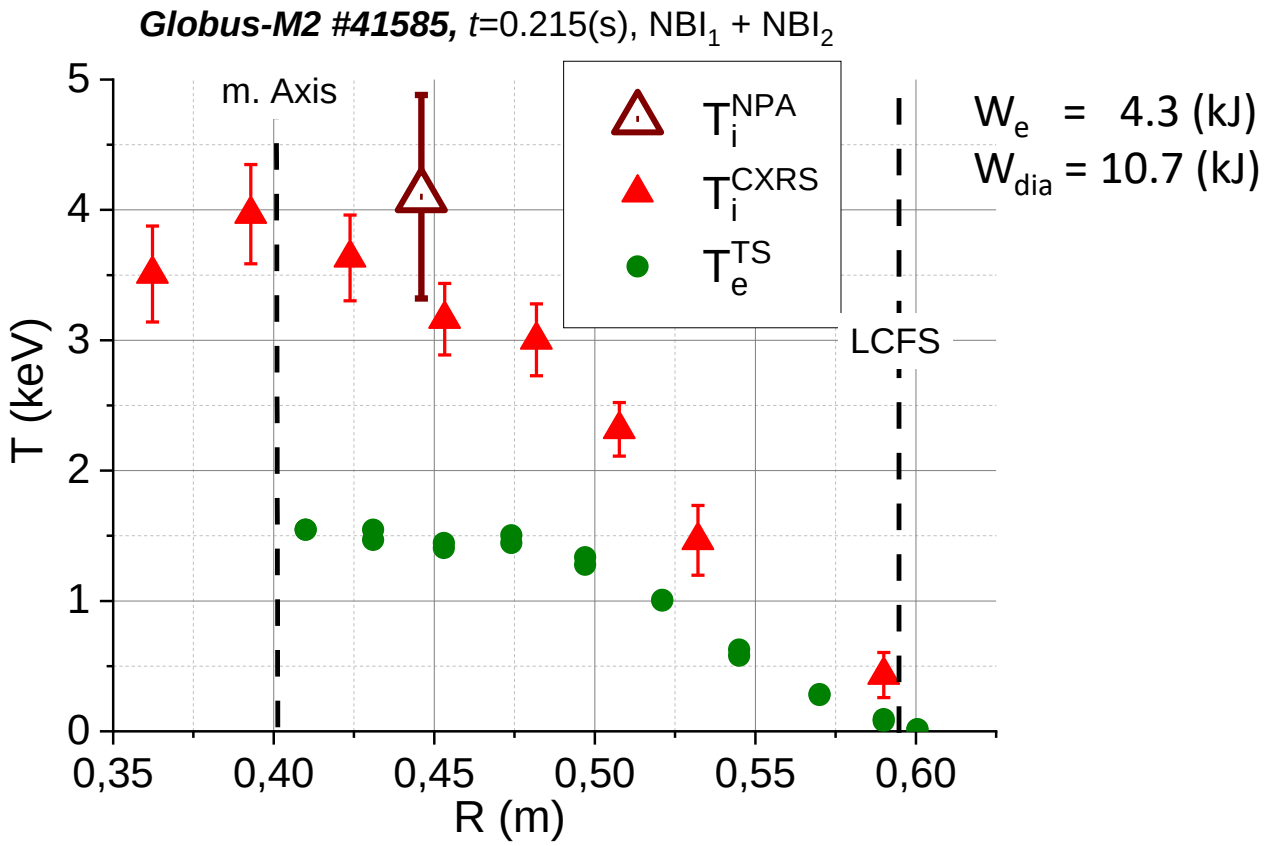
NBI_1 + NBI_2 experiments



W_e = 4.3 (kJ)
W_{dia} = 10.7 (kJ)

- $T_i(0)$ = 4 (keV)
- $T_i(0) / T_e(0)$ = 2.7
- Hot ion mode achieved with: B_T = 0.9 (T)
  I_p = 0.35 (MA)
  $P_{NBI\ 1+2}$ = 0.7 (MW)

$NBI_1 + NBI_2$ experiments



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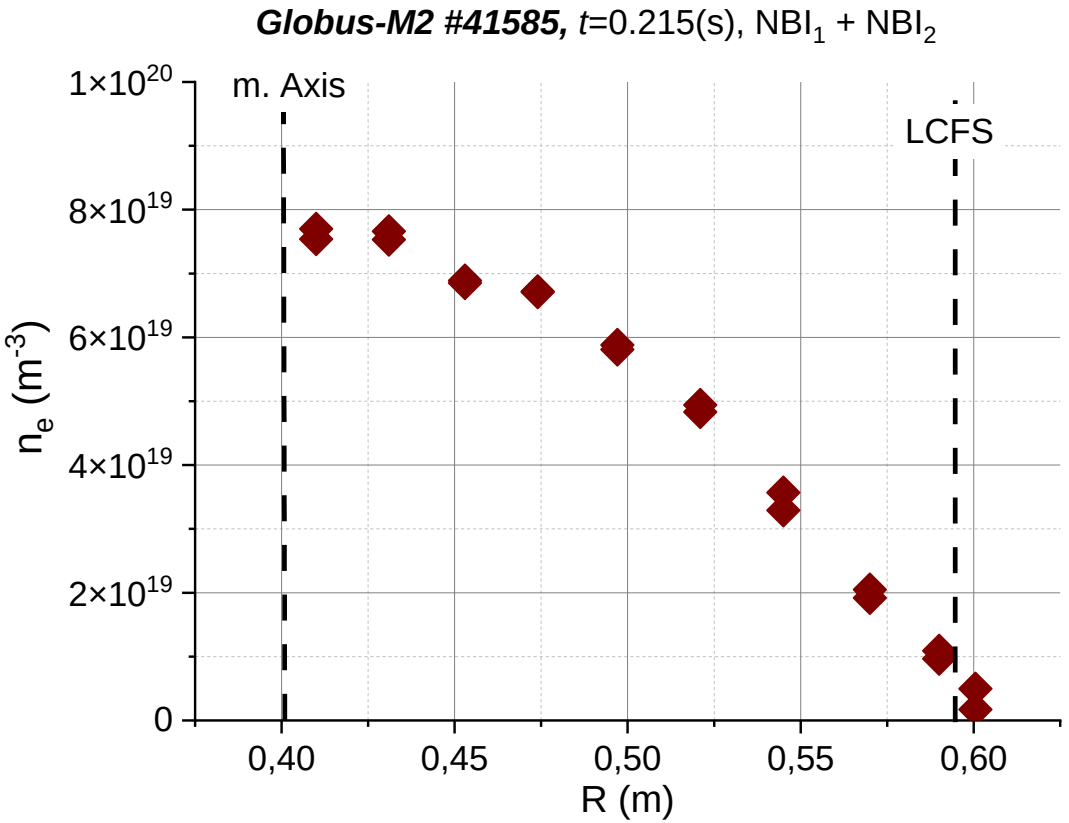

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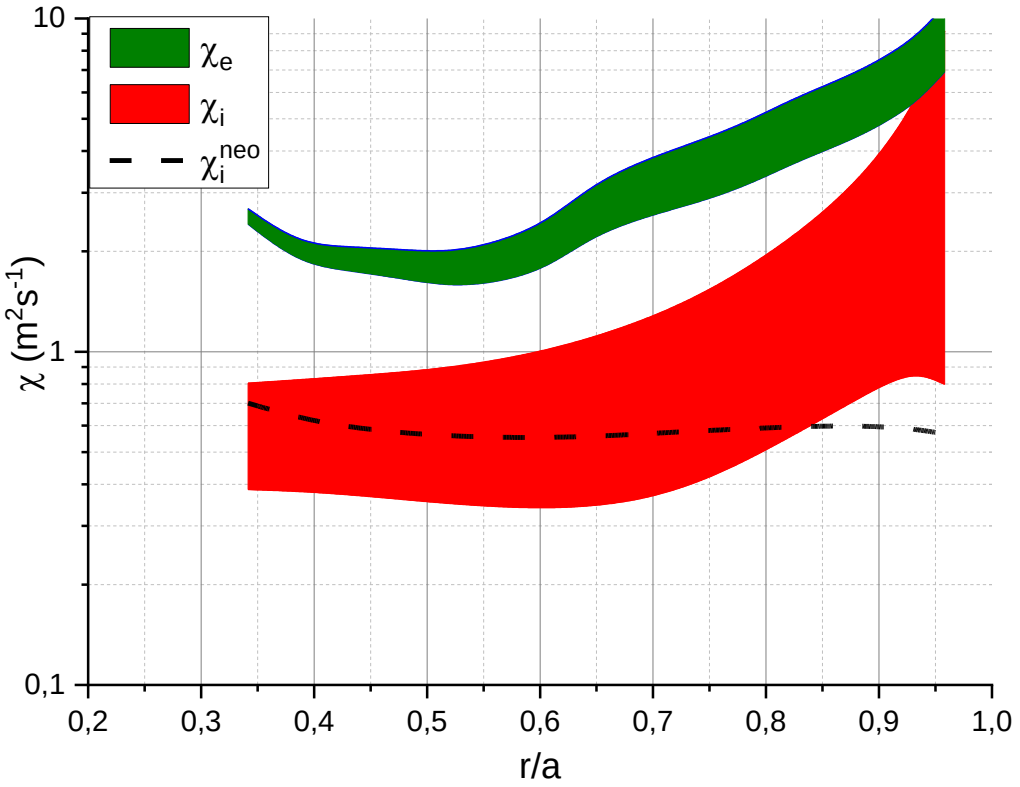
- $T_i(0) / T_e(0)$ = 2.7
- Hot ion mode achieved with: B_T = 0.9 (T)
  I_p = 0.35 (MA)
  $P_{NBI\ 1+2}$ = 0.7 (MW)

- $n_e(0) = 7.8 \cdot 10^{19}$ (m^{-3})
- Peaked n_e profile
  - NBI particle source
  - Improved central confinement

$NBI_1 + NBI_2$ experiments



- Suppressed anomalous χ_i.

  $\chi_i \leq 1$ (m^2 s^{-1}) is close to neoclassical

- Typical for Globus-M2 χ_e ~ 2 value

- τ_E = **14.3** (ms)

- $n_e(0) \cdot T_i(0) \cdot \tau_E$ = **4.3 · 10^{18}** (m^{-3} keV s)

Conclusions

Globus-M2, NBI_2 experiment:

- $NBI_{E=45keV}$ is heating electrons well

  T_e = 1.3 (keV) in $NBI_{E=45keV}$ regime is twice as in ohmic regime for $\langle n_e \rangle = 7.3 \cdot 10^{20}$ (m^{-3})

- Cold ions indicated by joint analysis of diamagnetic and TS data

Globus-M2, NBI_1+ NBI_2 experiment:

Achieved:

- Hot ion mode for $\langle n_e \rangle$ = [0.15 - 1.6] ($10^{20} \cdot m^{-3}$)
- $\boldsymbol{T_i = 4}$ (keV)
- $\boldsymbol{T_i / T_e}$ up to **3**
- $\boldsymbol{n_e(0) \cdot \tau_E = 1.1 \cdot 10^{18}}$ (m^{-3} s)