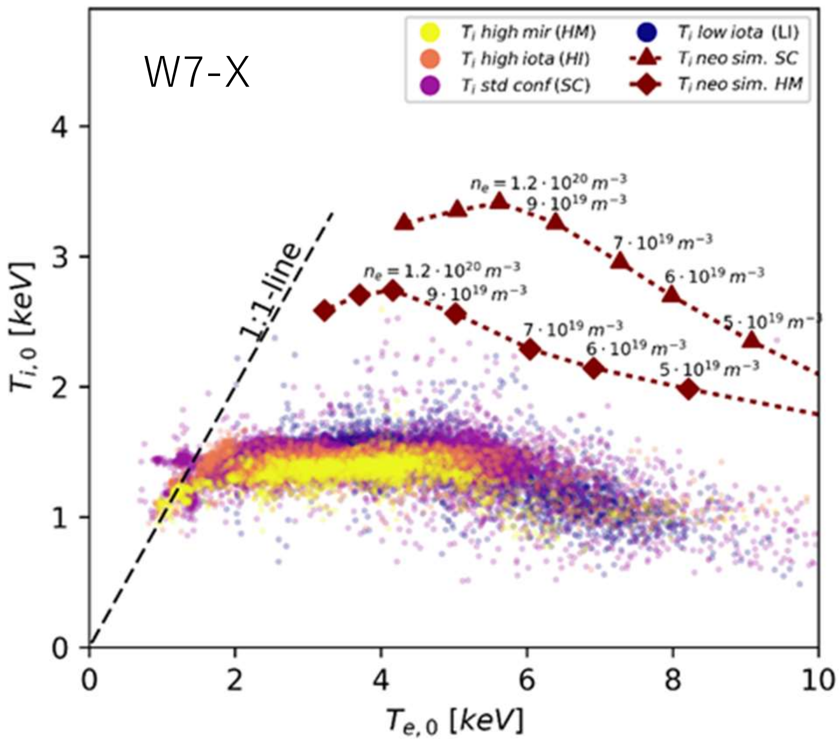
Ion transport in electron heated plasmas

Marc Beurskens, Kenji Tanaka, and Felix Warmer

Report Experiment 15 January

Ion temperature clamping generally observed in W7-X with ECRH



In ECRH plasmas with gas fuelling, generally

- Ion temperature is clamped at $T_i \sim 1.5 \pm 0.2$ keV
- It is well below neoclassical predictions
- It is virtually configuration independent

As well as lots of evidence for turbulent tranport:

- Density profiles are flat to slightly peaked (not hollow)
- Impurity transport is turbulent
- Turbulent electron heat tranport is diffusive

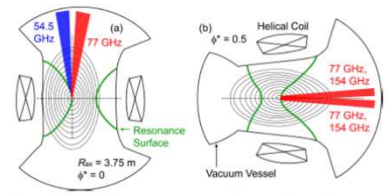
Key question to this paper:

→ what is causing T_i to be clamped at 1.5 keV?

Electron heating in W7-X and LHD

- **W7-X :**
  - ECRH heating is the main heating source with P_{ECRH} < 7MW and with steady state capability (140GHz)

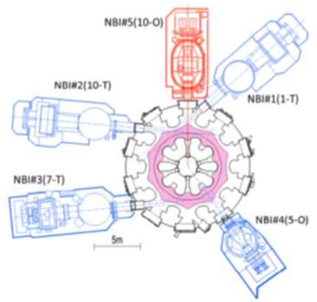
- **LHD:**
  - ECRH heating has breakdown as main purpose. Available sources P_{ECRH} ~ 3 MW for 2s
    - U port One 77GHz 1MW for 2sec 0.8MW for 3sec
    - O port: One 77GHz 1MW for 2sec 0.8MWfor 3sec
      Two 154GHz 1MW for 2sec 0.8MWfor 3sec
      one 154/116GHz dual freq 1MW for 1sec



U-port injection O-port injection

  - NNBI: negative ion beams: mainly electron heating: P_{NNBI} = 15 MW for H and 10 MW for D

	H [MW]	D [MW]
NNBI-1	5.5	3.3
NNBI-2	5	3
NNBI-3	5	3.3
PNBI-4	5 - 6	9
PNBI-5	6	9



Ion transport under electron heating (M. Beurskens (IPP), K. Tanaka, F. Warmer(IPP))

Experimental conditions:

(R_{ax}, Polarity, B_t) = (3.6 m, CW, 2.85 T) H2 gas puff

Shot #: 167117-167185 (59 + 9 shots)

Background and motivations

Increase of Ti under electron heating is essential for the fusion reactor. In W-7X, and AUG, the saturation of increase of Ti is observed. This is called “Ti clamping”. This can be interpreted as the enhancement of the Ti stiffness with higher Te/Ti. In particular, this study is important in high density with electron heating, where the ion heating is equipartition heating, since such condition is similar to the one in the reactor. We aimed density scan and power scan to obtain the dataset of this study.

Results

We try to use high power of electron heating. Thus, we planned to use two 154GHz balanced tangential ECRH, one 77GHz perpendicular ECRH, NNB and PNB. All systems worked very well without much failure and we could achieve most session goals in 59 pulses as well as conduct 9 addition density modulation experiments. This time we did not use pellets as repetitive pellet injection was not possible. With gas puffing, CXS7 worked at up to ~$5x10^{19}m^{-3}$. Perhaps data can be improved by averaging of spectra over multiple beam blips?

- In Pure ECRH we have a good density scan dataset to be compared to W7-X at 1-5e19 m^{-3}
- At 3e19 m^{-3} we have a very complete power scan from 3-12MW
- At 5e19 m^{-3} and above more useful power scans were conducted

Pre selection of shots for analysis exp 15.01.2021.

- ECRH power scan was not done as Power was limited to $P_{ECRH} =$ 2-2.5MW
- Negative NBI (1,2,3) excellent perfomance 3 sources: $P_{n\text{-}NBI} < 9$ MW
- Pre-selection for discussion today:

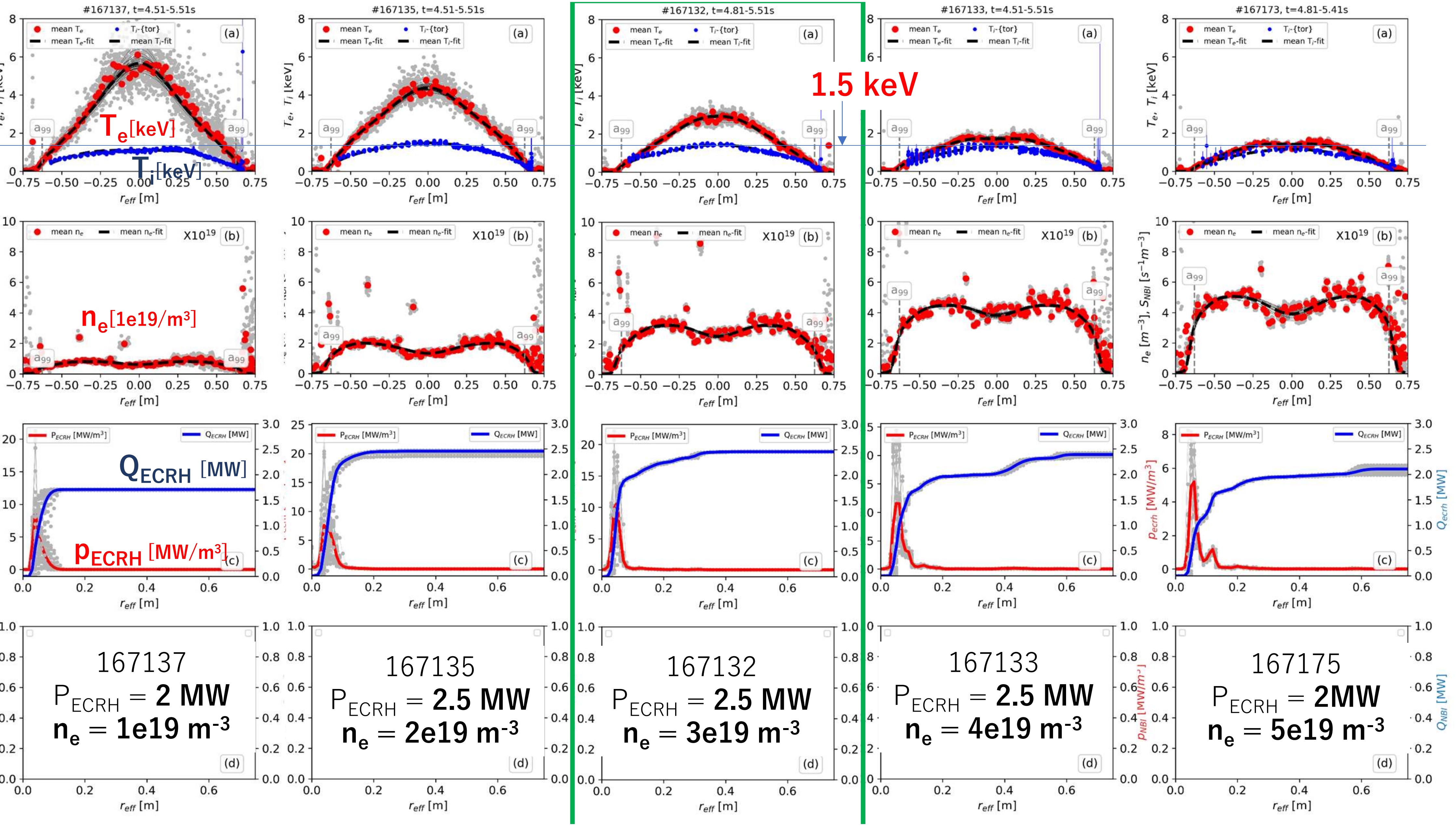
Density scans

- ECRH: $n_{e,max} = 1\text{-}6\ 10^{19}\ m^{-3}$, $P_{ECRH} = 2\text{-}2.5$ MW
- nNBI: $n_{e,max} = 2\text{-}7\ 10^{19}\ m^{-3}$, $P_{n\text{-}NBI} = 9$ MW

Power scans:

- nNBI: $n_{e,max} = 3\ 10^{19}\ m^{-3}$, $P_{n\text{-}NBI} = 3\text{-}9$ MW
- ECRH+nNBI: $n_{e,max} = 3\ 10^{19}\ m^{-3}$, $P_{ECRH} = 2.5$ MW, $P_{n\text{-}NBI} = 0\text{-}6$ MW

ECRH: Density scan from $n_{e,max} = 1\text{-}6\ 10^{19}\ m^{-3}$, $P_{ECRH} = 2\text{-}2.5$ MW

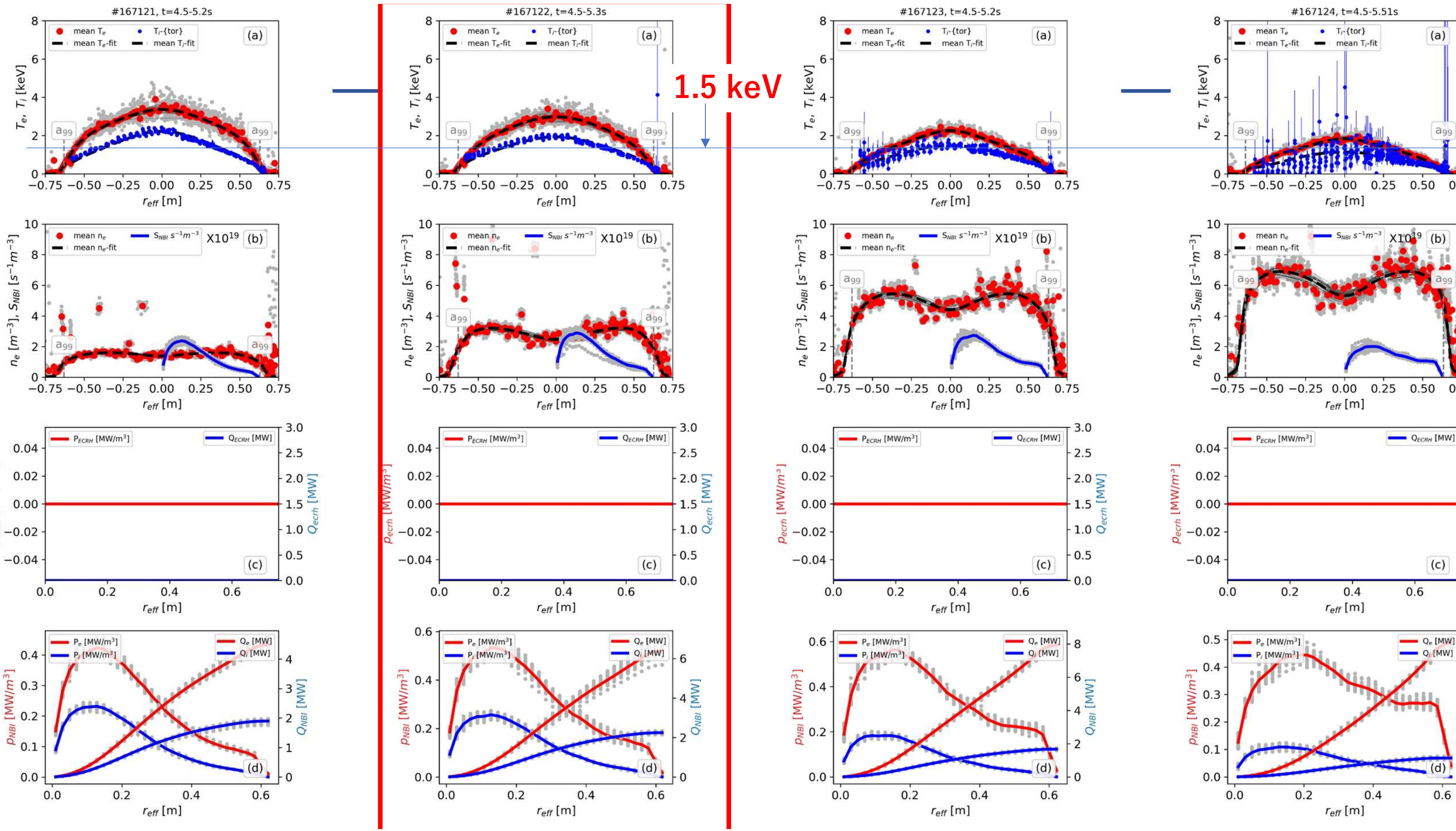


#167137, t=4.51-5.51s
#167135, t=4.51-5.51s
#167132, t=4.81-5.51s
#167133, t=4.51-5.51s
#167173, t=4.81-5.41s
1.5 keV
Te[keV]
Ti[keV]
ne[1e19/m3]
QECRH [MW]
pECRH [MW/m3]
167137
PECRH = 2 MW
ne = 1e19 m-3
167135
PECRH = 2.5 MW
ne = 2e19 m-3
167132
PECRH = 2.5 MW
ne = 3e19 m-3
167133
PECRH = 2.5 MW
ne = 4e19 m-3
167175
PECRH = 2MW
ne = 5e19 m-3

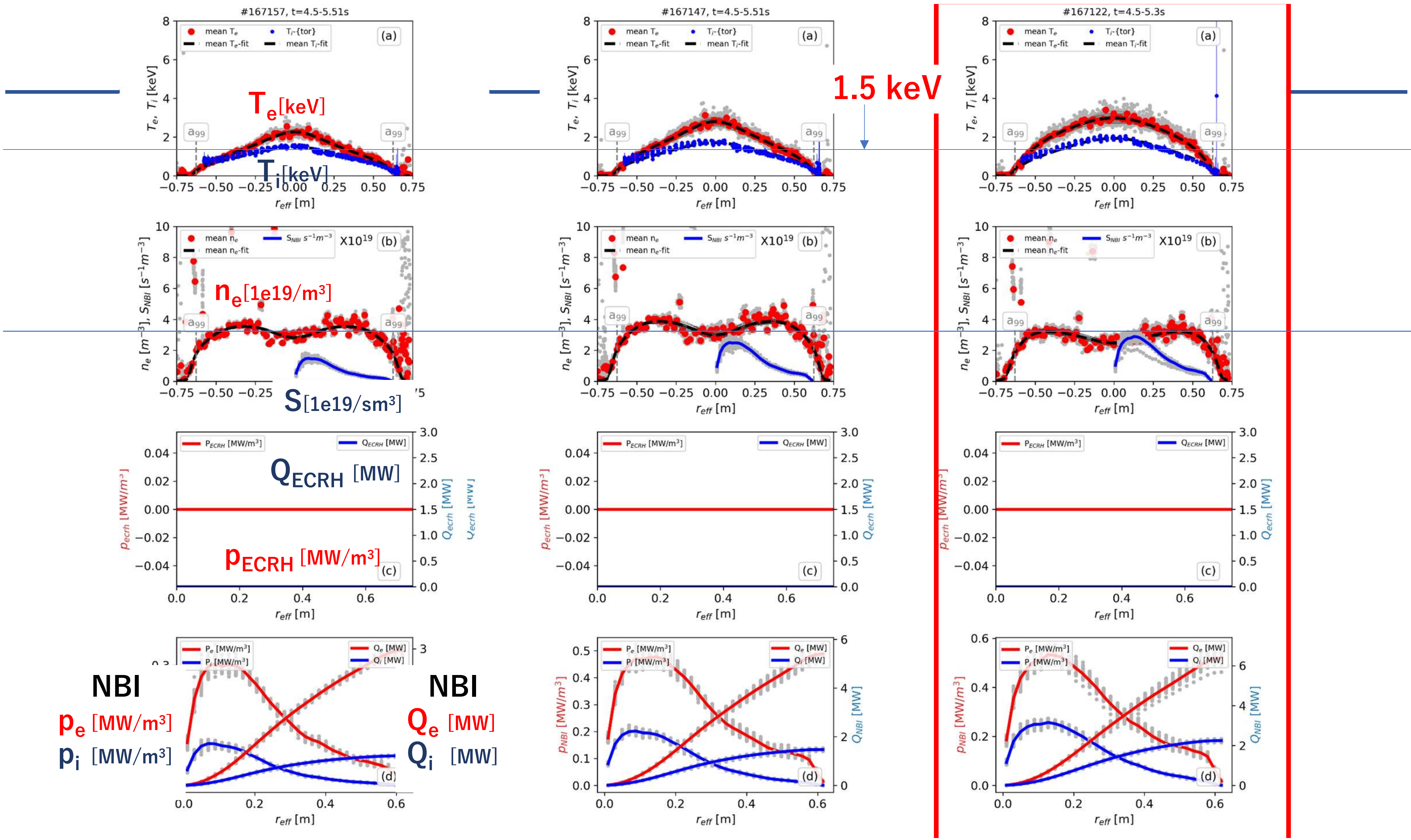
N-NBI: Density scan from $n_{e,max} = 2\text{-}7\ 10^{19}\ m^{-3}$, $P_{n\text{-}NBI} = 9$ MW (3 sources)

~ 2/3 $P_{n\text{-}NBI}$ → electron

~ 1/3 $P_{n\text{-}NBI}$ → ions (varies)


#167121, t=4.5-5.2s
#167122, t=4.5-5.3s
#167123, t=4.5-5.2s
#167124, t=4.5-5.51s
1.5 keV
mean T_e
T_i-{tor}
mean T_e-fit
mean T_i-fit
T_e, T_i [keV]
r_{eff} [m]
a_{99}
(a)
mean n_e
mean n_e-fit
S_{NBI} $s^{-1}m^{-3}$
X10^{19}
n_e [m^{-3}], S_{NBI} [$s^{-1}m^{-3}$]
(b)
P_{ECRH} [MW/m^3]
Q_{ECRH} [MW]
p_{ecrh} [MW/m^3]
Q_{ecrh} [MW]
(c)
P_e [MW/m^3]
P_i [MW/m^3]
Q_e [MW]
Q_i [MW]
p_{NBI} [MW/m^3]
Q_{NBI} [MW]
(d)

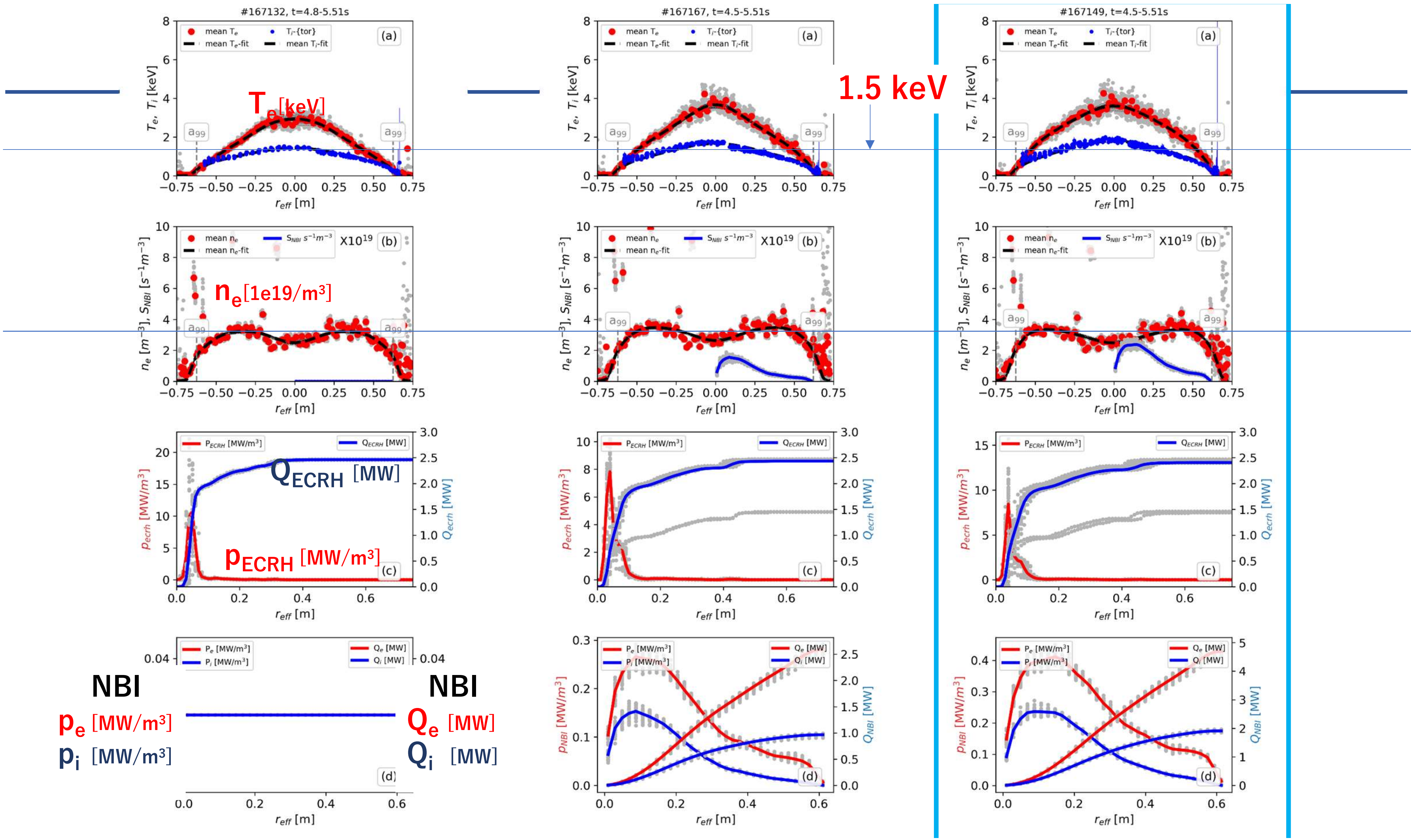
N-NBI: Power scan at $n_{e,max} = 3\ 10^{19}\ m^{-3}$, $P_{n\text{-}NBI} = 3\text{-}9$ MW (1-2-3 sources)



#167157, t=4.5-5.51s
#167147, t=4.5-5.51s
#167122, t=4.5-5.3s
mean Te
Ti-{tor}
mean Te-fit
mean Ti-fit
(a)
a99
Te, Ti [keV]
reff [m]
Te[keV]
Ti[keV]
1.5 keV
mean ne
SNBI s−1m−3
mean ne-fit
X10^19
(b)
ne [m−3], SNBI [s−1m−3]
ne[1e19/m3]
S[1e19/sm3]
PECRH [MW/m3]
QECRH [MW]
(c)
pecrh [MW/m3]
Qecrh [MW]
QECRH [MW]
pECRH [MW/m3]
Pe [MW/m3]
Pi [MW/m3]
Qe [MW]
Qi [MW]
(d)
pNBI [MW/m3]
QNBI [MW]
NBI
pe [MW/m3]
pi [MW/m3]
NBI
Qe [MW]
Qi [MW]

ECRH+nNBI: Power scan at $n_{e,max}$ = 3 10^{19} m^{-3}, P_{ECRH} = 2.5 MW,

P_{n-NBI} = 0-6 MW (0-2 sources)

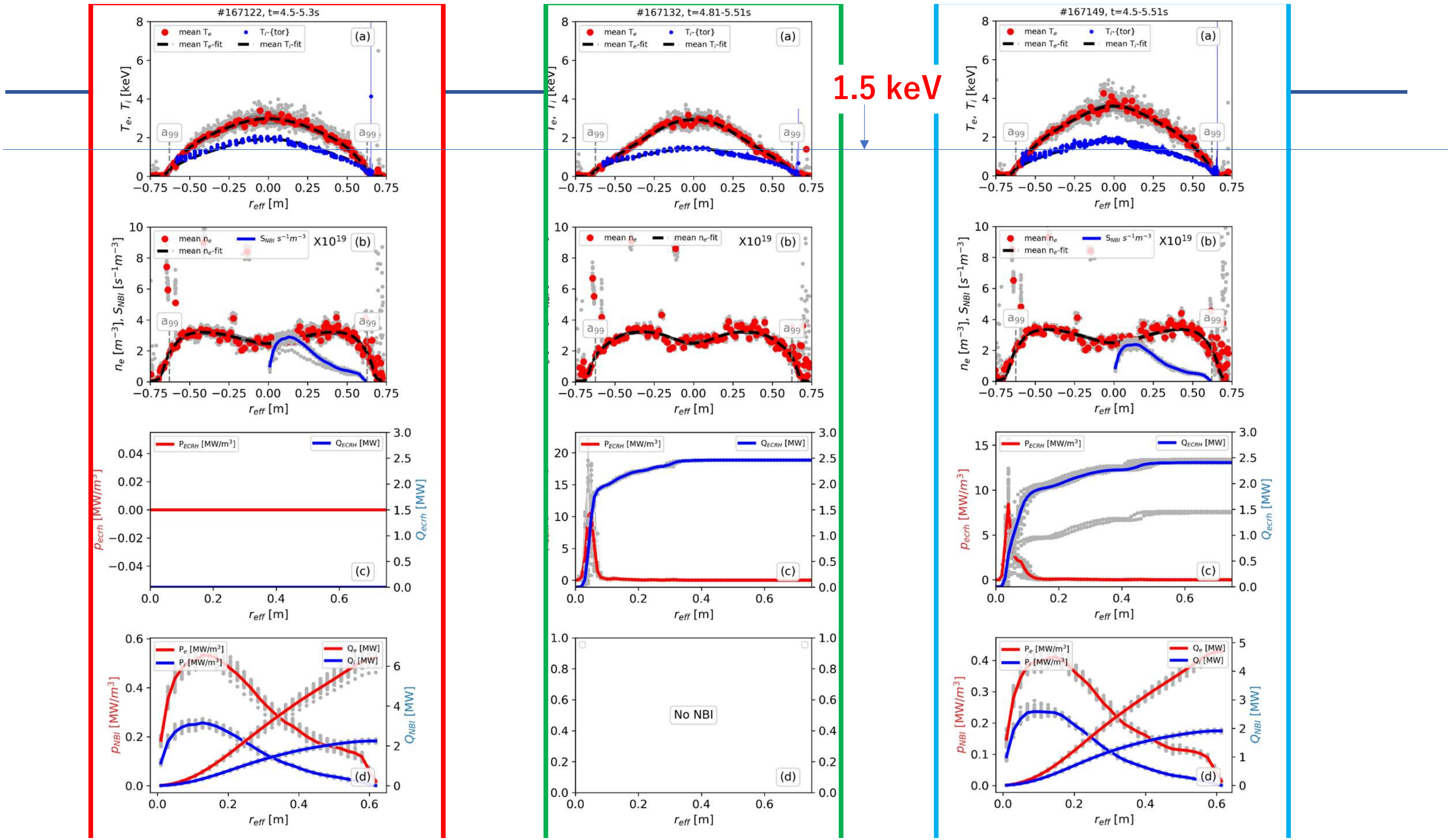

#167132, t=4.8-5.51s
#167167, t=4.5-5.51s
#167149, t=4.5-5.51s
1.5 keV
Te[keV]
ne[1e19/m3]
QECRH [MW]
pECRH [MW/m3]
NBI
pe [MW/m3]
pi [MW/m3]
NBI
Qe [MW]
Qi [MW]
mean Te
mean Te-fit
Ti-{tor}
mean Ti-fit
mean ne
mean ne-fit
SNBI s−1m−3
X10^19
PECRH [MW/m3]
QECRH [MW]
Pe [MW/m3]
Pi [MW/m3]
Qe [MW]
Qi [MW]
Te, Ti [keV]
ne [m−3], SNBI [s−1m−3]
pecrh [MW/m3]
Qecrh [MW]
pNBI [MW/m3]
QNBI [MW]
reff [m]
a99
(a)
(b)
(c)
(d)

Do we see evidence for ion temperature clamping?

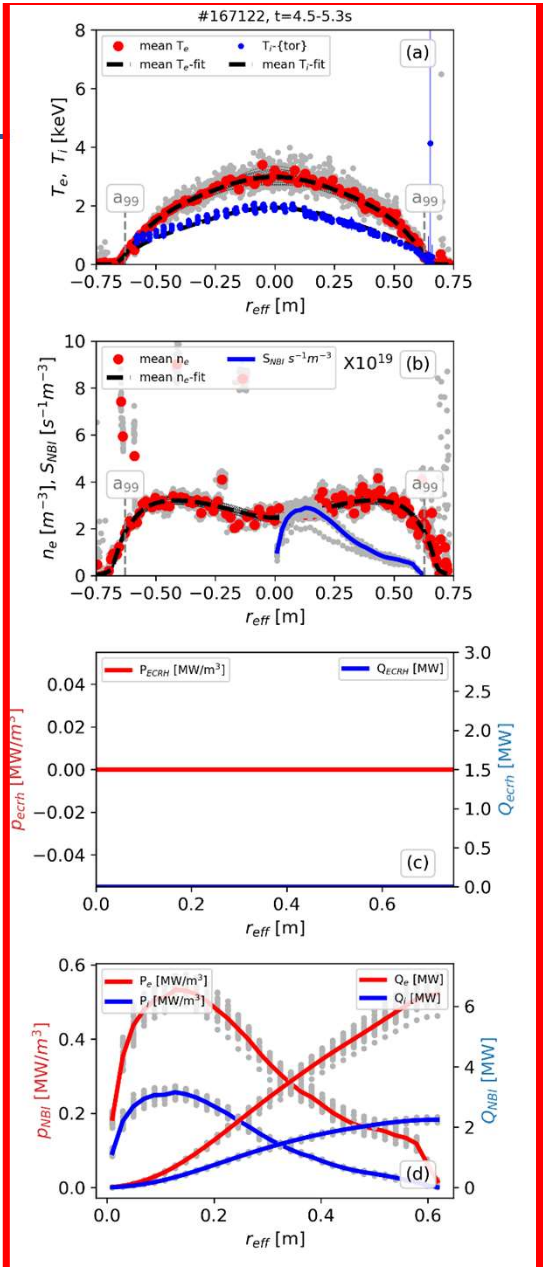
- In ECRH heated plasmas Ti ~ 1.5keV Te > Ti
- In n-NBI heated plasmas T 1.5 → 2 keV $T_e \sim T_i$ or closer at least
  (be-it with additional ion heating compomenent)

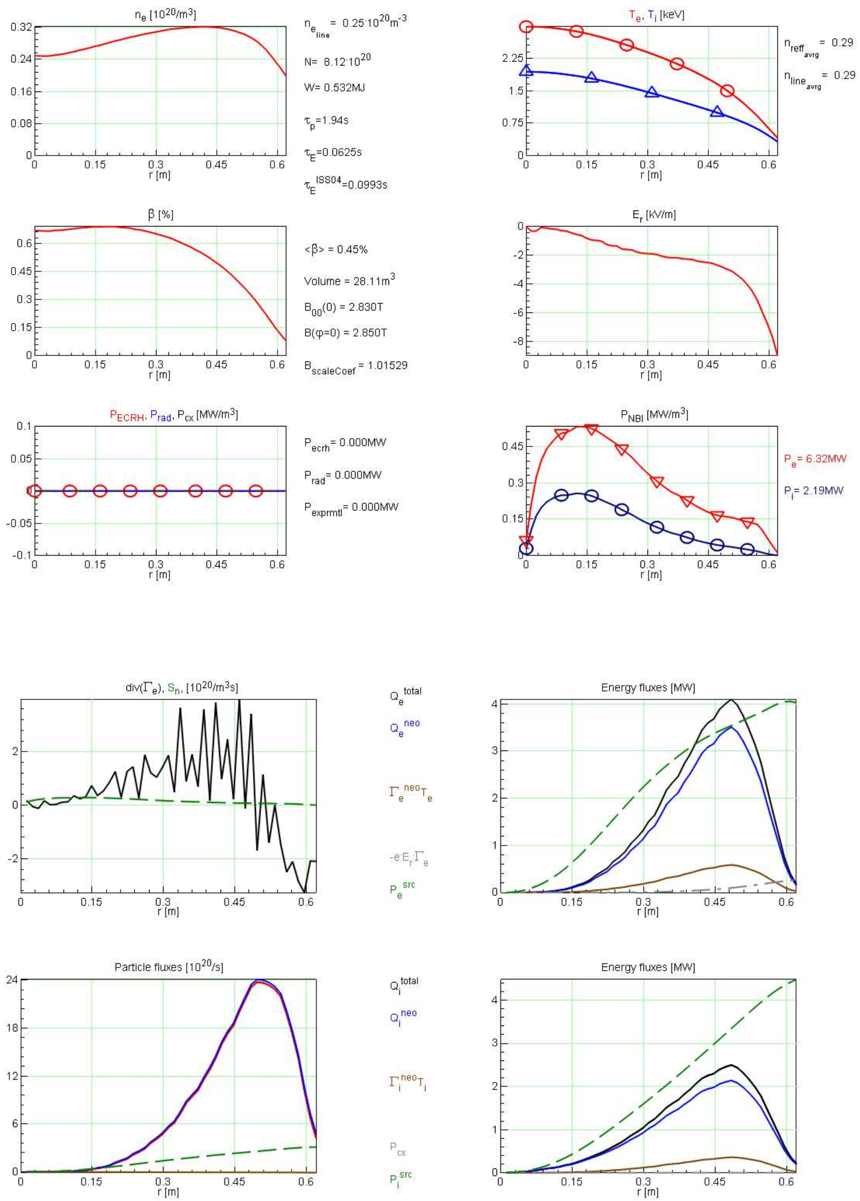
Combined ECRH and N-NBI Ti > 1.5 keV

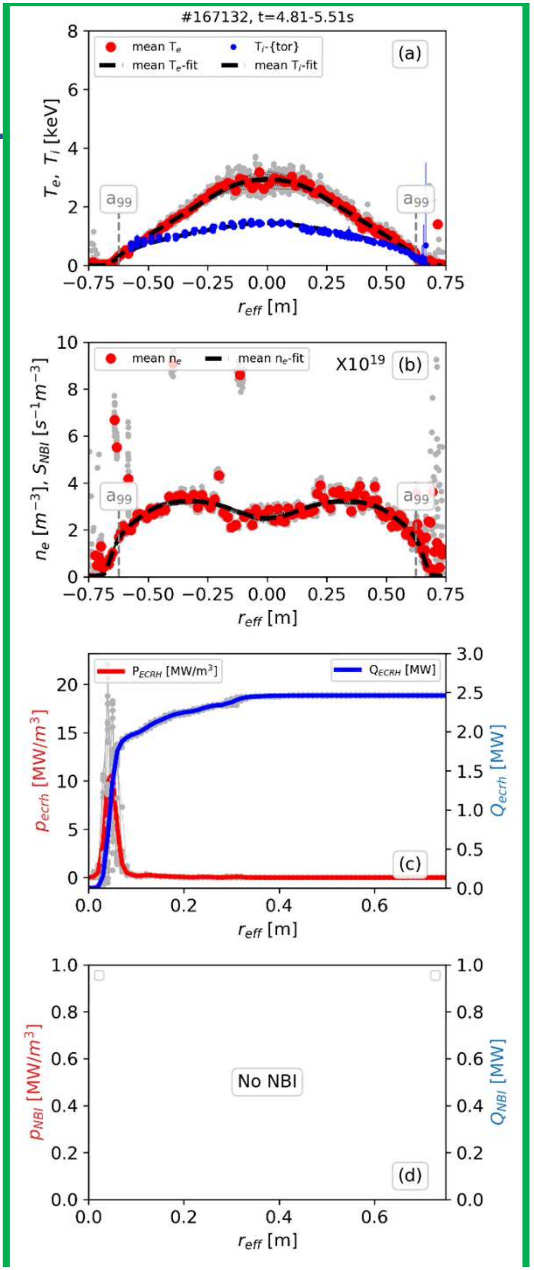
Look at power valance for three selected cases:

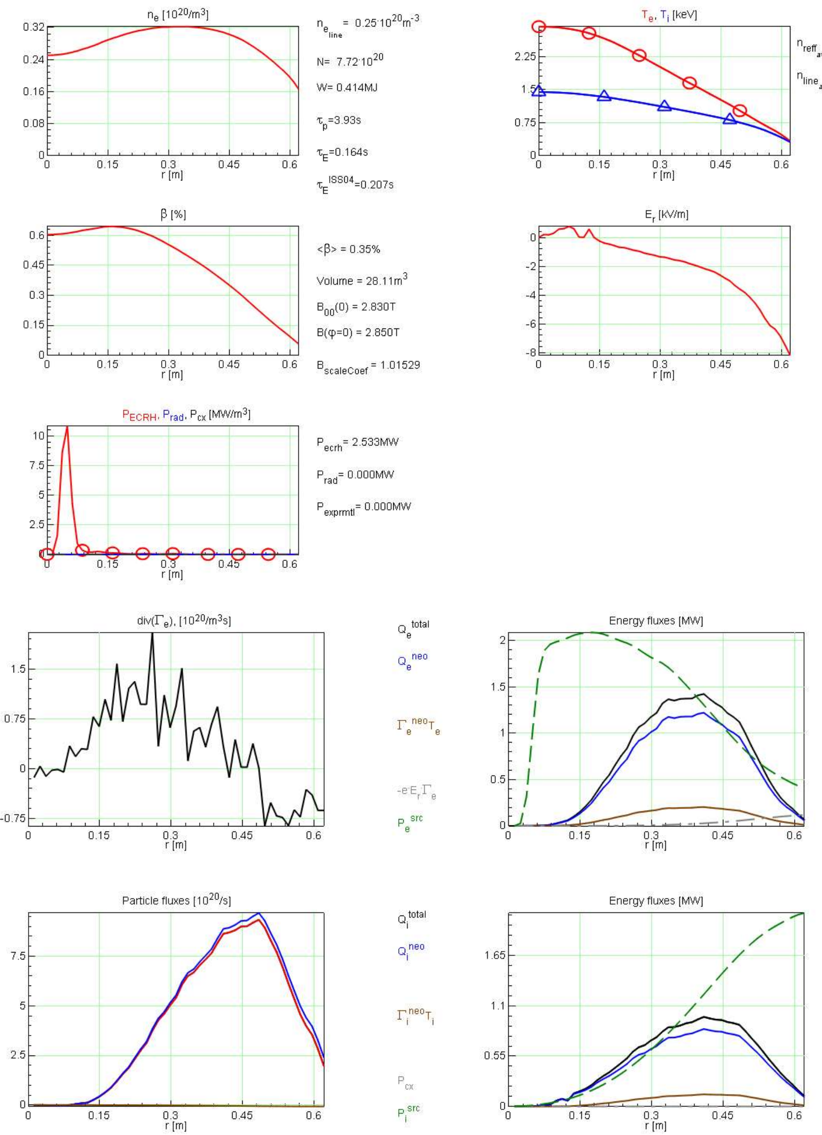


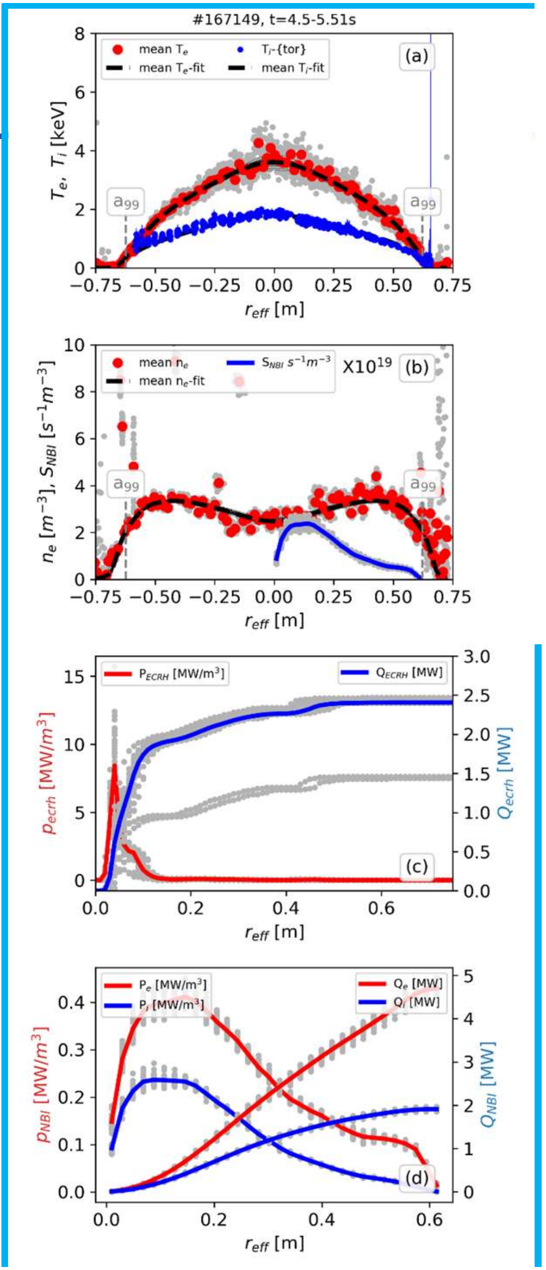
#167122, t=4.5-5.3s
#167132, t=4.81-5.51s
#167149, t=4.5-5.51s
1.5 keV
mean T_e
T_i-{tor}
mean T_e-fit
mean T_i-fit
(a)
a_{99}
T_e, T_i [keV]
r_{eff} [m]
mean n_e
mean n_e-fit
S_{NBI} $s^{-1}m^{-3}$
X10^{19}
(b)
n_e [m^{-3}], S_{NBI} [$s^{-1}m^{-3}$]
P_{ECRH} [MW/m^3]
Q_{ECRH} [MW]
(c)
p_{ecrh} [MW/m^3]
Q_{ecrh} [MW]
P_e [MW/m^3]
P_i [MW/m^3]
Q_e [MW]
Q_i [MW]
(d)
p_{NBI} [MW/m^3]
Q_{NBI} [MW]
No NBI


#167122, t=4.5-5.3s
mean Te
mean Te-fit
Ti-{tor}
mean Ti-fit
(a)
a99
Te, Ti [keV]
reff [m]
mean ne
mean ne-fit
SNBI s−1m−3
X10^19
(b)
ne [m−3], SNBI [s−1m−3]
PECRH [MW/m3]
QECRH [MW]
(c)
pecrh [MW/m3]
Qecrh [MW]
Pe [MW/m3]
Pi [MW/m3]
Qe [MW]
Qi [MW]
(d)
pNBI [MW/m3]
QNBI [MW]

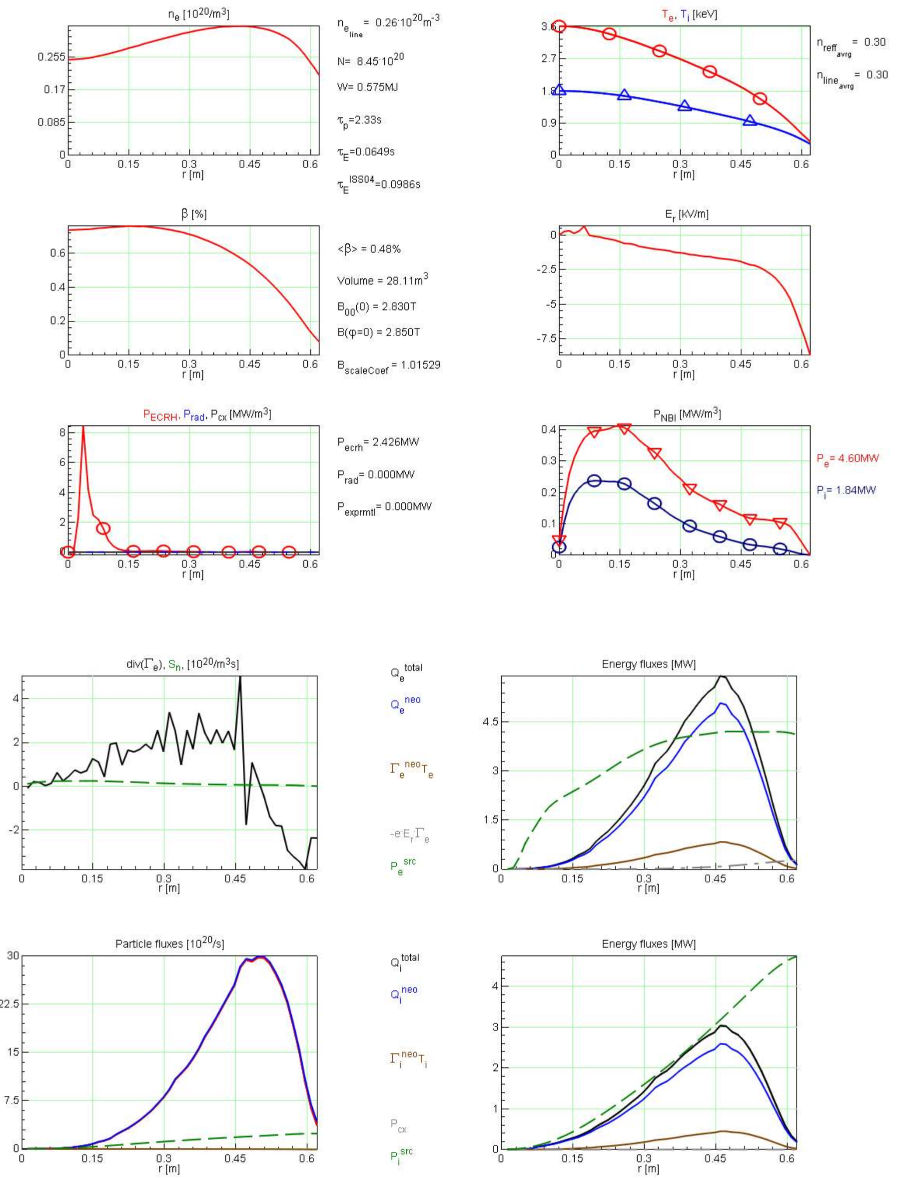

ne [10^20/m3]
ne_line = 0.25·10^20 m^-3
N= 8.12·10^20
W= 0.532MJ
τp=1.94s
τE=0.0625s
τE^ISS04=0.0993s
Te, Ti [keV]
n_reff_avrg = 0.29
n_line_avrg = 0.29
β [%]
<β> = 0.45%
Volume = 28.11m3
B00(0) = 2.830T
B(φ=0) = 2.850T
B_scaleCoef = 1.01529
Er [kV/m]
PECRH, Prad, Pcx [MW/m3]
Pecrh= 0.000MW
Prad= 0.000MW
Pexprmtl= 0.000MW
PNBI [MW/m3]
Pe= 6.32MW
Pi= 2.19MW
div(Γe), Sn, [10^20/m3s]
Qe total
Qe neo
Γe neo Te
-eErΓe
Pe src
Energy fluxes [MW]
Particle fluxes [10^20/s]
Qi total
Qi neo
Γi neo Ti
Pcx
Pi src
Energy fluxes [MW]
r [m]


#167132, t=4.81-5.51s
mean T_e
T_i-{tor}
mean T_e-fit
mean T_i-fit
(a)
a99
T_e, T_i [keV]
r_eff [m]
mean n_e
mean n_e-fit
X10^19
(b)
n_e [m^-3], S_NBI [s^-1m^-3]
P_ECRH [MW/m^3]
Q_ECRH [MW]
(c)
p_ecrh [MW/m^3]
Q_ecrh [MW]
No NBI
(d)
p_NBI [MW/m^3]
Q_NBI [MW]


n_e [10^20/m^3]
n_e_line = 0.25·10^20 m^-3
N= 7.72·10^20
W= 0.414MJ
τ_p=3.93s
τ_E=0.164s
τ_E^ISS04=0.207s
T_e, T_i [keV]
n_reff_avrg = 0.28
n_line_avrg = 0.29
β [%]
<β> = 0.35%
Volume = 28.11m^3
B_00(0) = 2.830T
B(φ=0) = 2.850T
B_scaleCoef = 1.01529
E_r [kV/m]
P_ECRH, P_rad, P_cx [MW/m^3]
P_ecrh = 2.533MW
P_rad = 0.000MW
P_exprmtl = 0.000MW
div(Γ_e), [10^20/m^3s]
Q_e^total
Q_e^neo
Γ_e^neo T_e
-e·E_r·Γ_e
P_e^src
Energy fluxes [MW]
Particle fluxes [10^20/s]
Q_i^total
Q_i^neo
Γ_i^neo T_i
P_cx
P_i^src
r [m]



#167149, t=4.5-5.51s
mean T_e
mean T_e-fit
T_i-{tor}
mean T_i-fit
(a)
a99
T_e, T_i [keV]
r_eff [m]
mean n_e
mean n_e-fit
S_NBI s^-1 m^-3
X10^19
(b)
n_e [m^-3], S_NBI [s^-1 m^-3]
P_ECRH [MW/m^3]
Q_ECRH [MW]
(c)
p_ecrh [MW/m^3]
Q_ecrh [MW]
P_e [MW/m^3]
P_i [MW/m^3]
Q_e [MW]
Q_i [MW]
(d)
p_NBI [MW/m^3]
Q_NBI [MW]



n_e [10^20/m^3]
n_e_line = 0.26·10^20 m^-3
N= 8.45·10^20
W= 0.575MJ
τ_p=2.33s
τ_E=0.0649s
τ_E^ISS04=0.0986s
T_e, T_i [keV]
n_reff_avrg = 0.30
n_line_avrg = 0.30
β [%]
<β> = 0.48%
Volume = 28.11m^3
B_00(0) = 2.830T
B(φ=0) = 2.850T
B_scaleCoef = 1.01529
E_r [kV/m]
P_ECRH, P_rad, P_cx [MW/m^3]
P_ecrh= 2.426MW
P_rad= 0.000MW
P_exprmtl= 0.000MW
P_NBI [MW/m^3]
P_e= 4.60MW
P_i= 1.84MW
div(Γ_e), S_n, [10^20/m^3s]
Q_e^total
Q_e^neo
Γ_e^neo T_e
-e·E_r·Γ_e
P_e^src
Energy fluxes [MW]
Particle fluxes [10^20/s]
Q_i^total
Q_i^neo
Γ_i^neo T_i
P_cx
P_i^src
r [m]

Strong contribution by neoclassical transport

- Consistent with the draft PRL of Felix Warmer NC plays a bigger role in LHD than we usually see in W7-X

- Whether ITG plays a role at all in clamping Ti in these plasmas remains to be seen

- Work in progress