EUROfusion

Investigating differences in electron temperature measurements by ECE emission and Thomson Scattering in high performance discharges

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JET

CCFE
CULHAM CENTRE FOR FUSION ENERGY

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Outline

- Motivation and past observations
- Diagnostics employed in the study
- Database selection: campaigns and experiments
- Observations
- Conclusions

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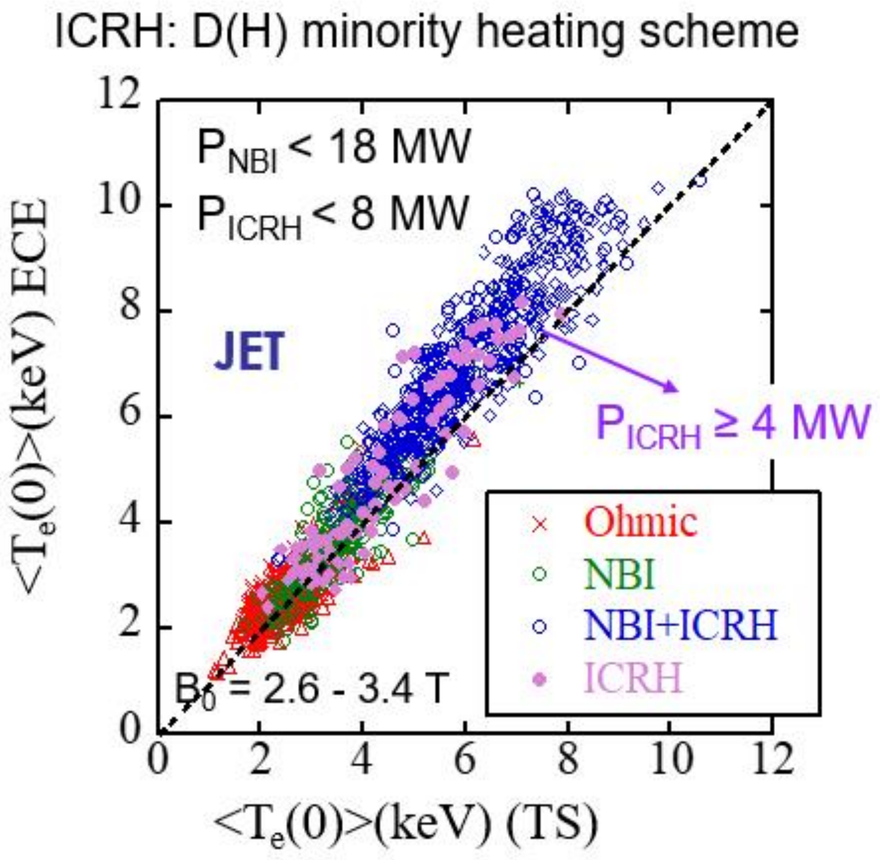
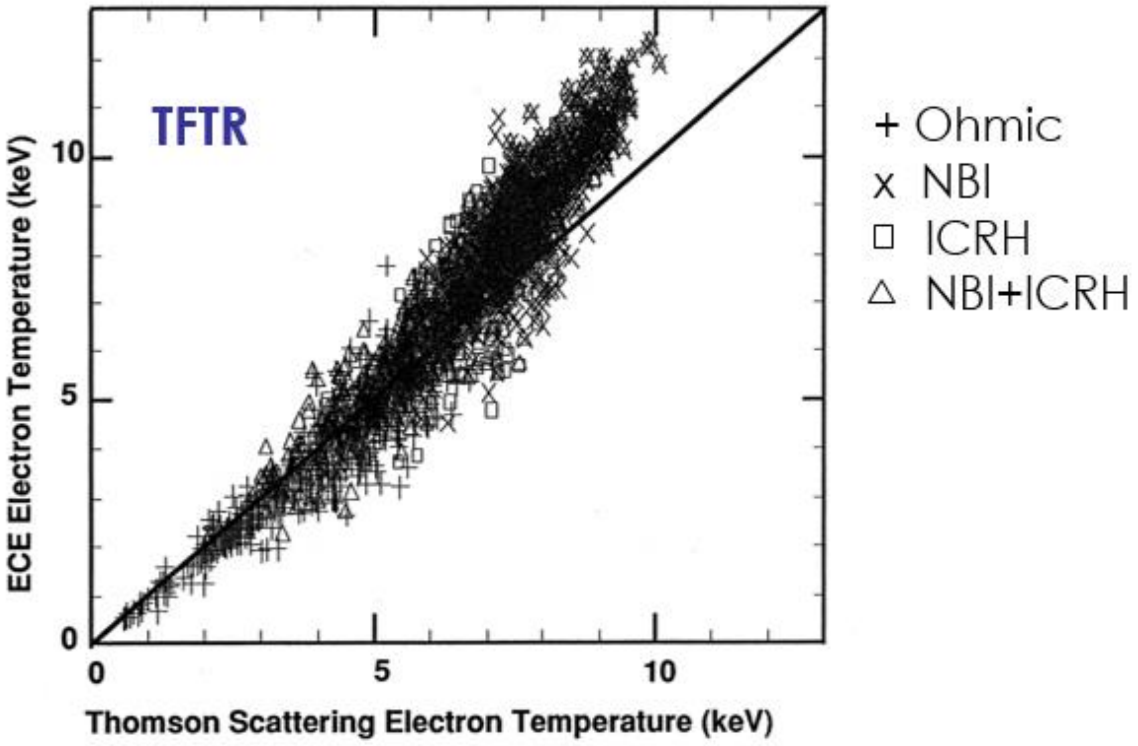
Observations of $T_{e,ECE} \neq T_{e,TS}$

E. de la Luna



E. de la Luna *et al.*, HTPD-Invited (2002)



G. Taylor et al, in Proc. 8th Joint Workshop on ECE and ECH, Borrego Springs, (1993)

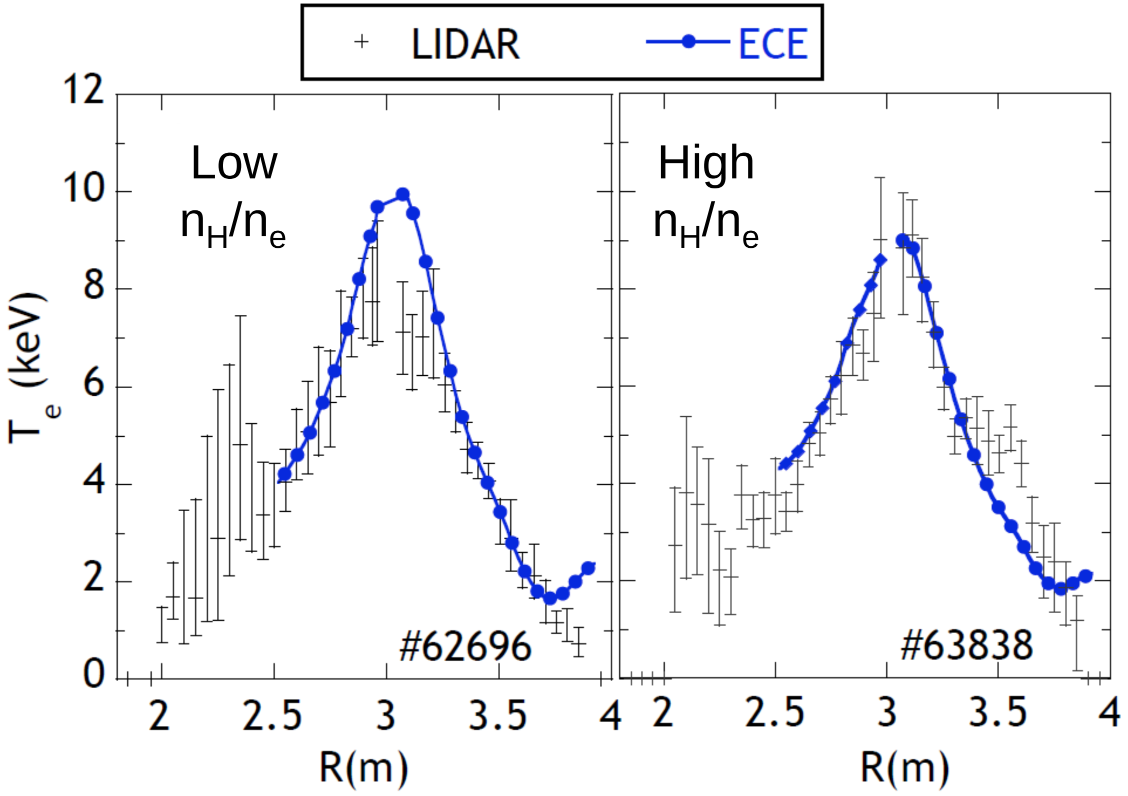
Systematic discrepancies between ECE and Thomson scattering in the central region in high T_e plasmas in JET and TFTR.

Signs of non-Maxwellian electron EDF

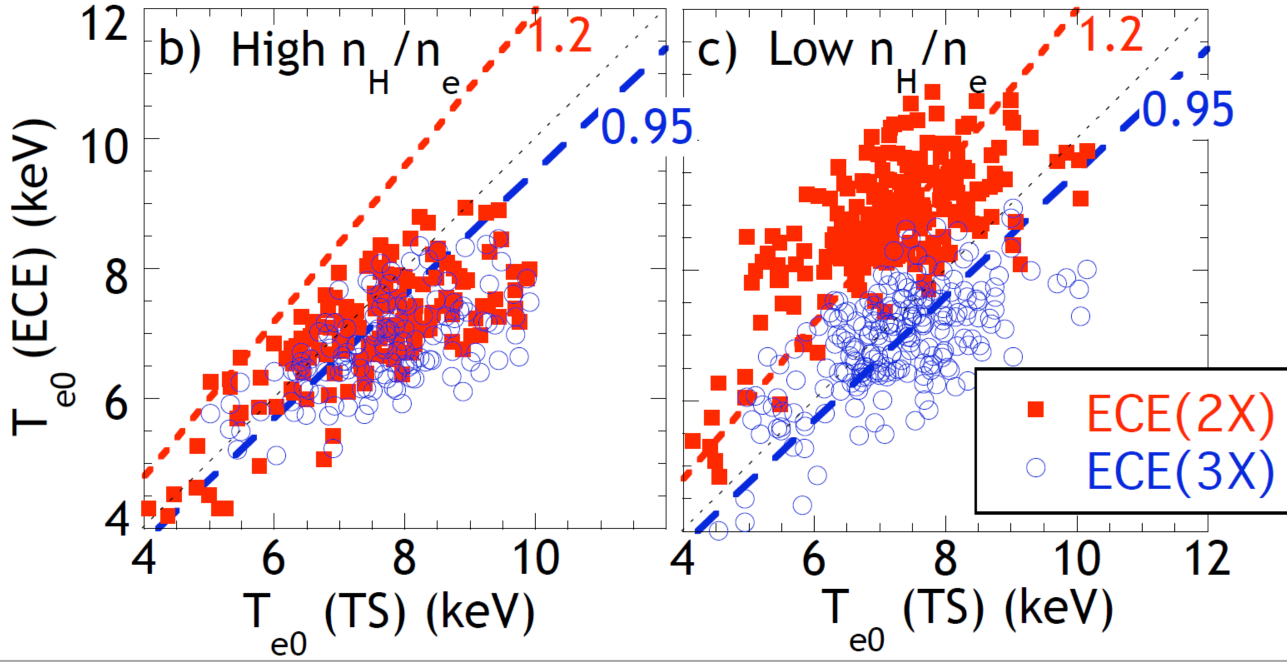
Later, discrepancy reproduced only in low H% experiments: $\mathbf{T_{X2} > T_{X3}}$ **while** $\mathbf{T_{X3} \sim T_{TS}}$.

No further low H% experiments due to machine safety concerns.

Possible effect of hot ion tail on electron distribution function (EDF) and consequence of different diagnostic principles. *[E. de la Luna EC15 proc. 2008, Krivenski FED 2001].*



E. de la Luna



Motivation

The high-performance experiments prepared and realized on JET in the last years (including the first DT pulses in 25 years and the first in a machine with ITER-like wall) constitute the best opportunity to further investigate this long-standing issue.

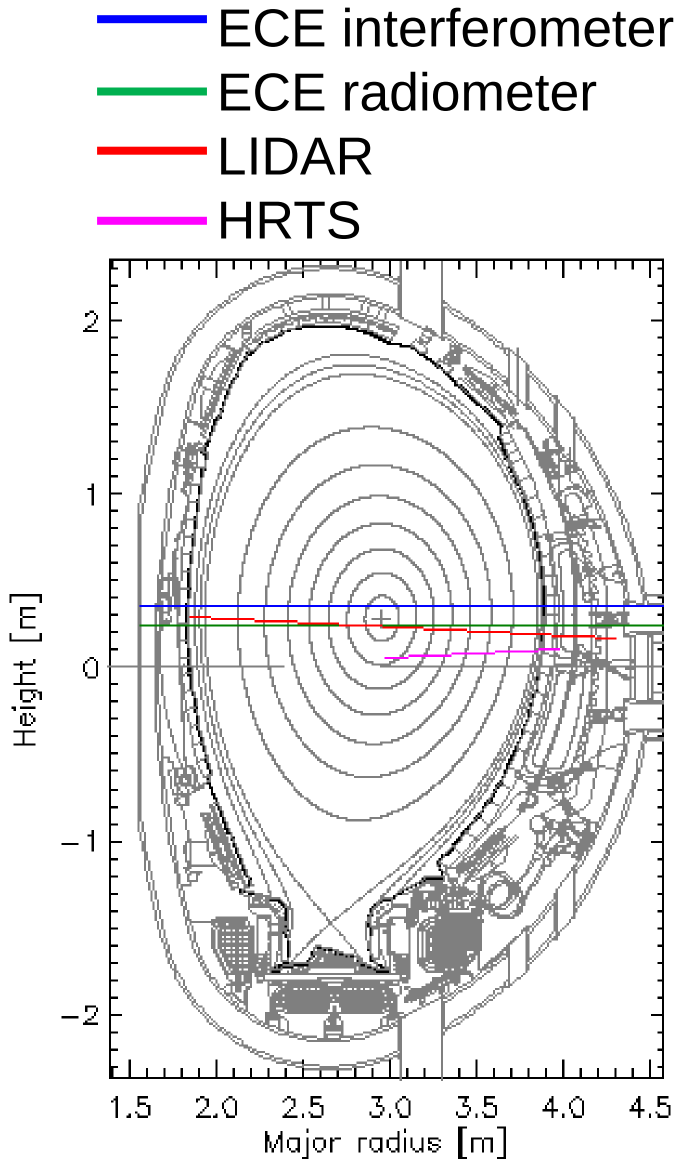
Core T_e Diagnostics

ECE

- Martin-Puplett interferometers. Absolutely calibrated with in-vessel source over 50-500 GHz (always covers 4th harmonic). Two interferometers look at X and O mode respectively. f_{acq}=60 Hz, ΔR~10 cm.
- Radiometer, 96 channels. Cross calibrated against interferometer pulse-by-pulse. f_{acq}=5 kHz, ΔR~2 cm

Thomson Scattering

- LIDAR. Independently calibrated. Covers both LFS, HFS. f_{acq}=4 Hz, ΔR~7 cm.
- HRTS. Independently calibrated. f_{acq}=20 Hz, ΔR~1.5 cm. Line of sight does not approach plasma axis in most configurations.



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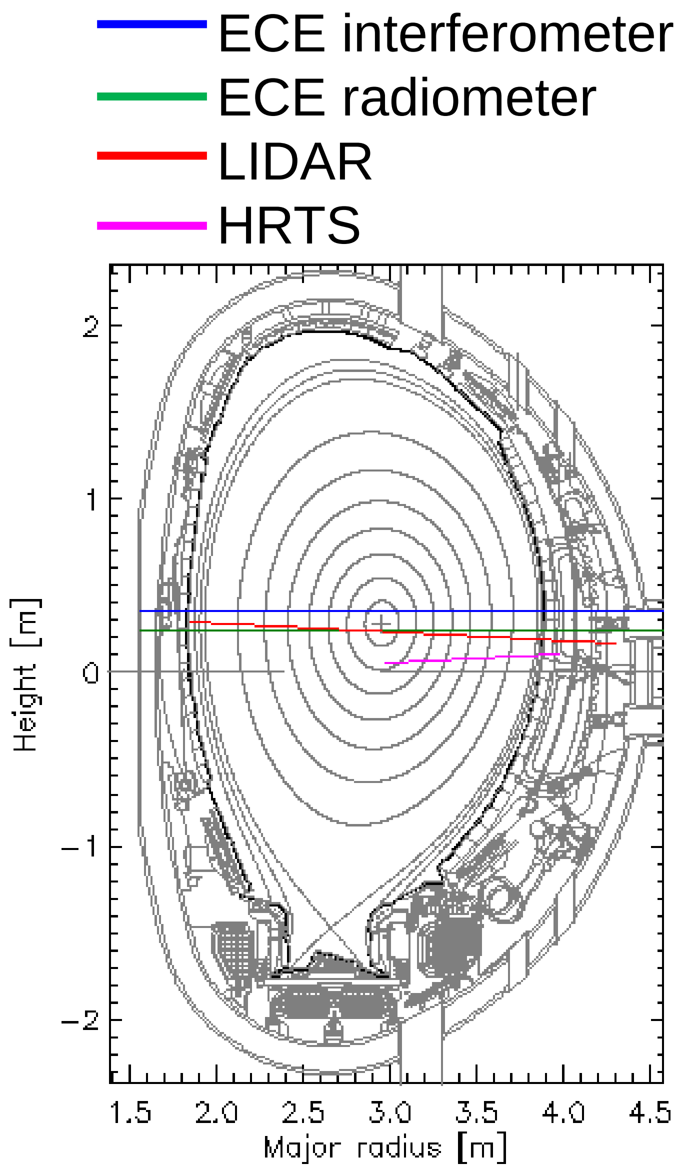
- HRTS. Independently calibrated. f_{acq}=20 Hz, ΔR~1.5 cm. Line of sight does not approach plasma axis in most configurations. *However, similar observations in ρ.*



Database selection

2018-2022: JET campaigns: **DD, TT and DT pulses.**

Database contains all points at LIDAR times at which T_e>1 keV, laser energy was good and ECE data are available +/- 10 ms around t_{LID}.

~1990 pulses, ~140000 time points.

Radial average core T_e LIDAR/ECE: [2.85, 3.15] m.

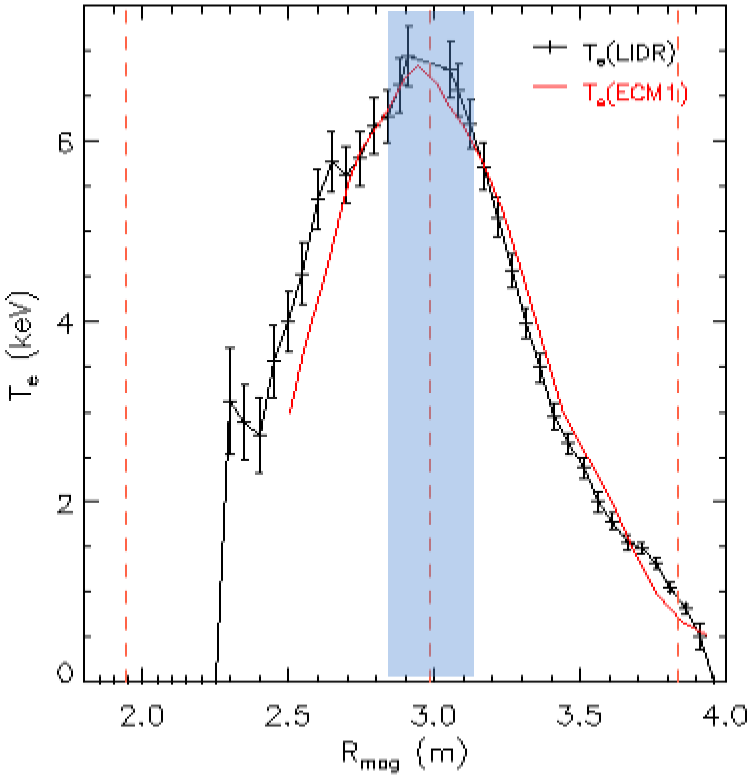
Attenuates ≠ LOS and uncertainties on eq. reconstruction.

Currently, magnetics only eq. reconstruction is used for all pulses in database.

Spectral average X2/X3: [-5%, +5%] around peak freq.

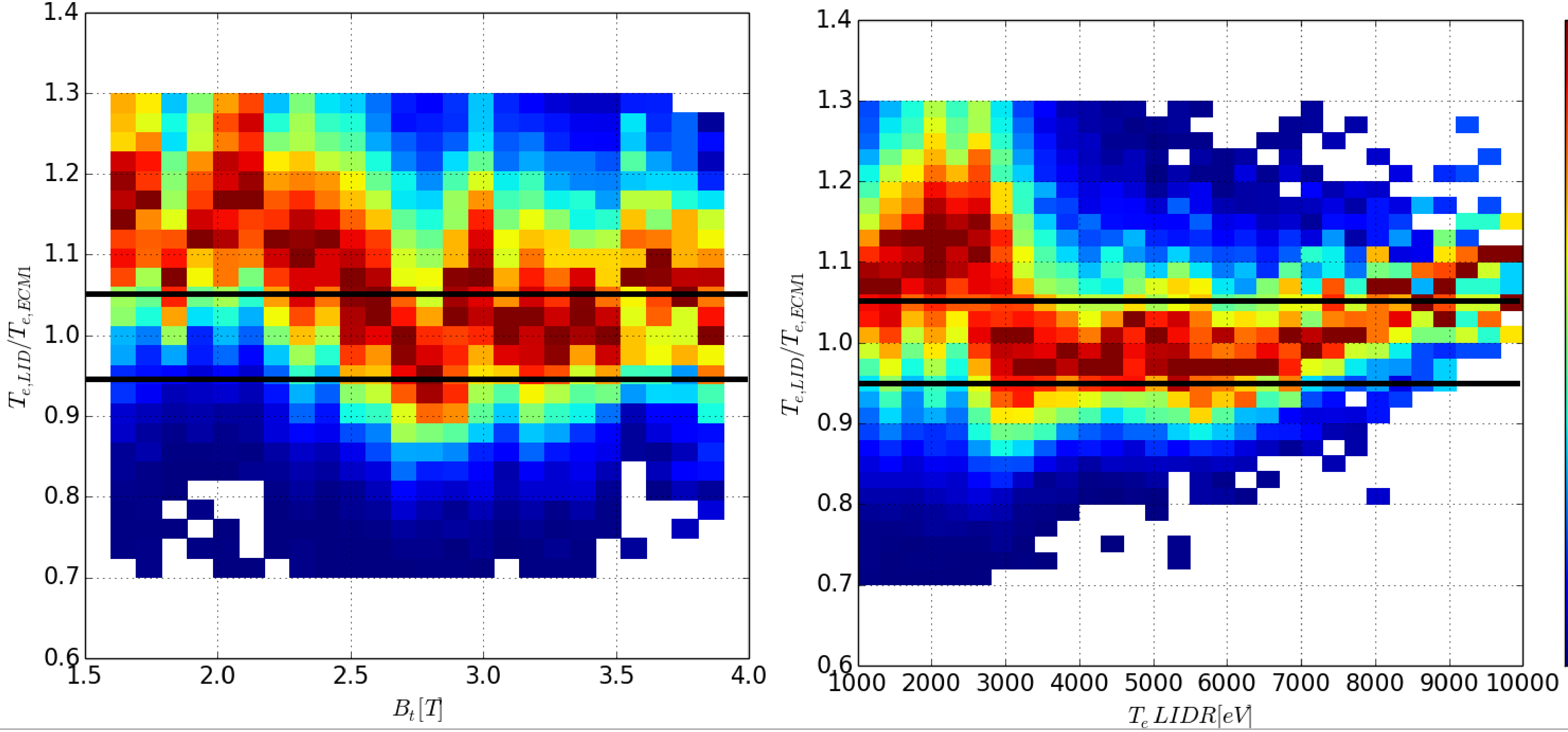
98005

LIDAR: 8.878 s, **ECE**: 8.873 s



Whole database results

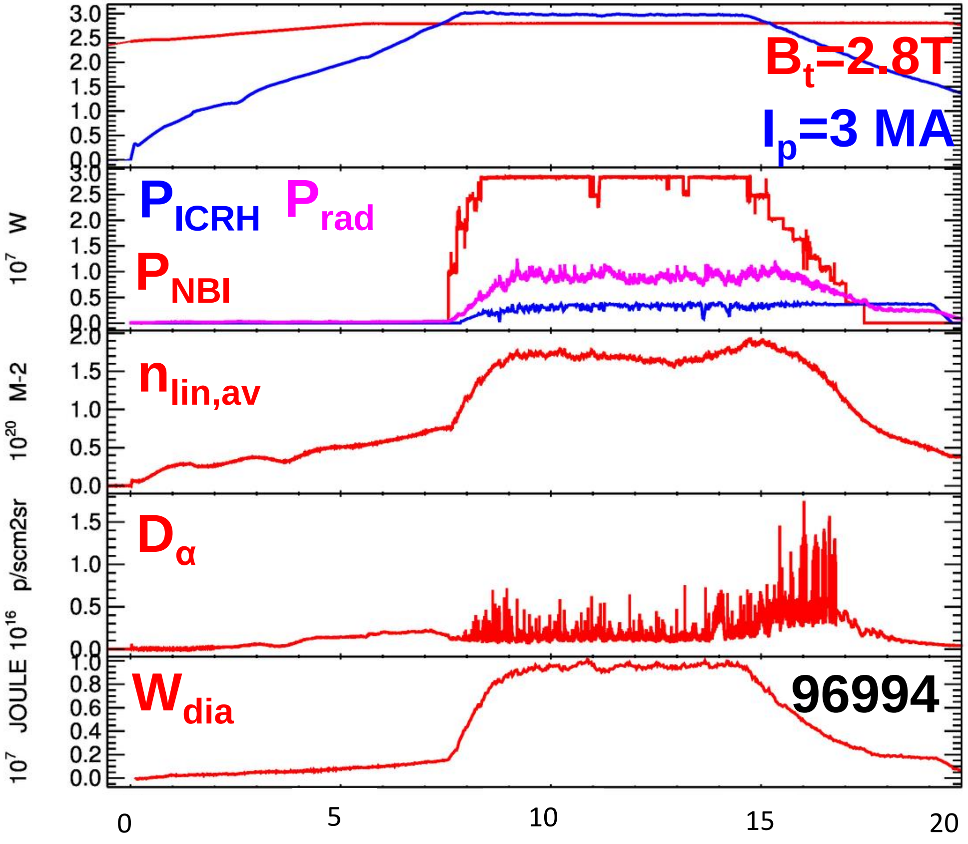
Generally good agreement TS/ECE within +/-5%. **At very high T_e, T_{LID} tends to be larger than T_{ECE}.** Low B is where the calibration uncertainties become most important.



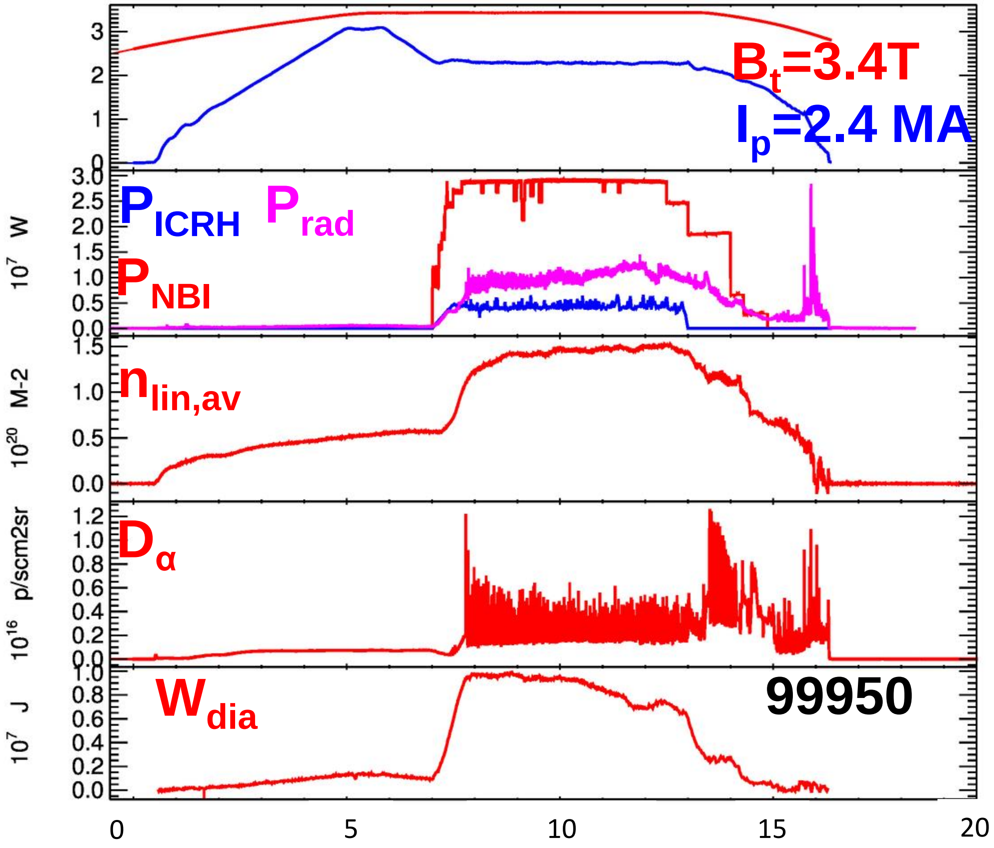
High performance database selection

Pulses which reached **T_e>5 keV** have been further selected. These mainly belonged to the high-performance JET scenarios: **~200 pulses**.

Baseline: high I_p, high n, based on ITER baseline scenario. Includes DD pulses with Ne injection.



Hybrid: high B, low I_p, high β. q_{95}~3, q_{min}>1 to avoid modes.



High performance database selection

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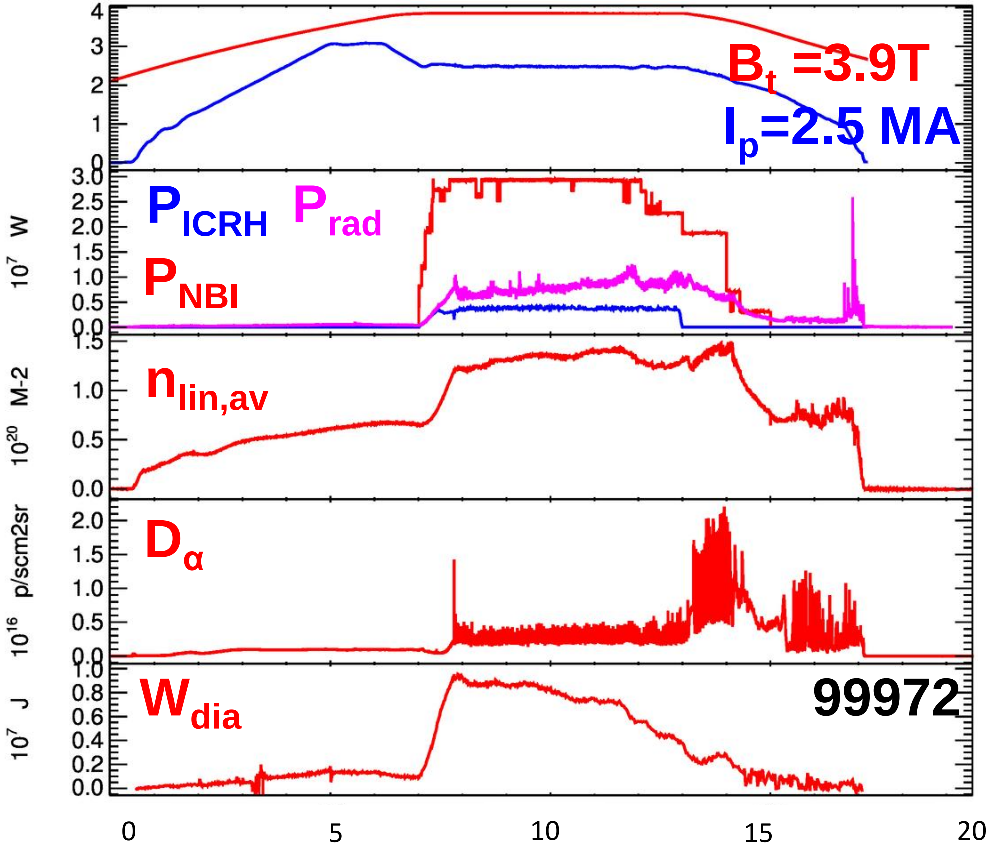
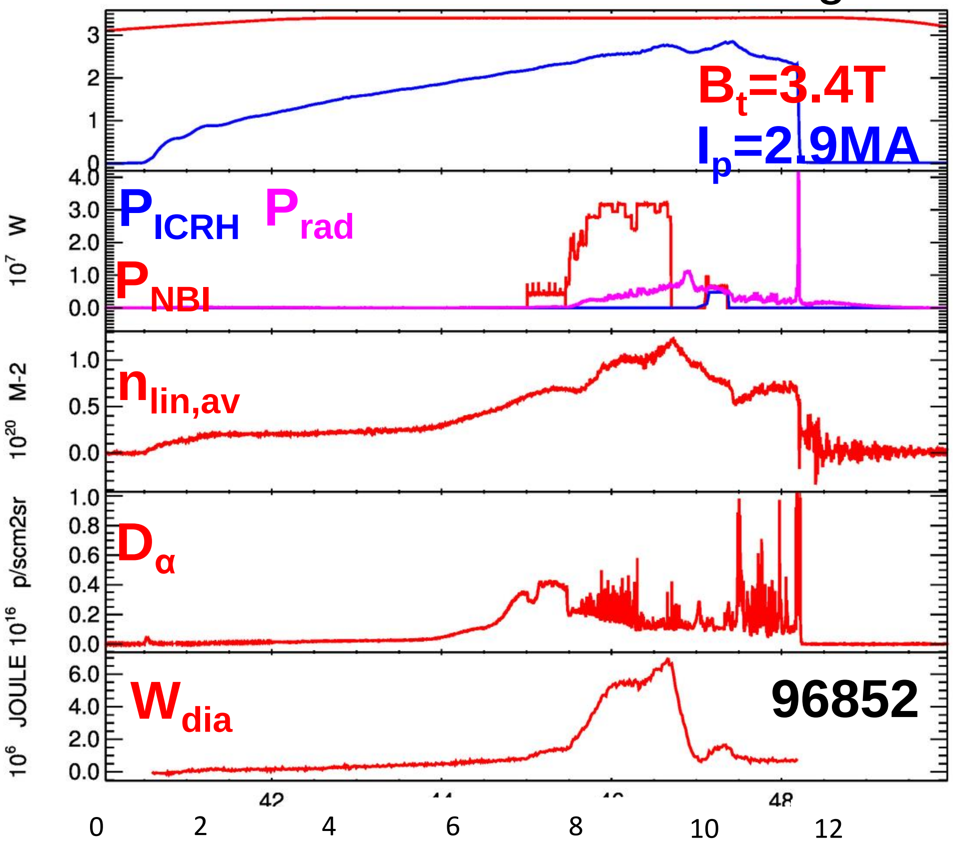
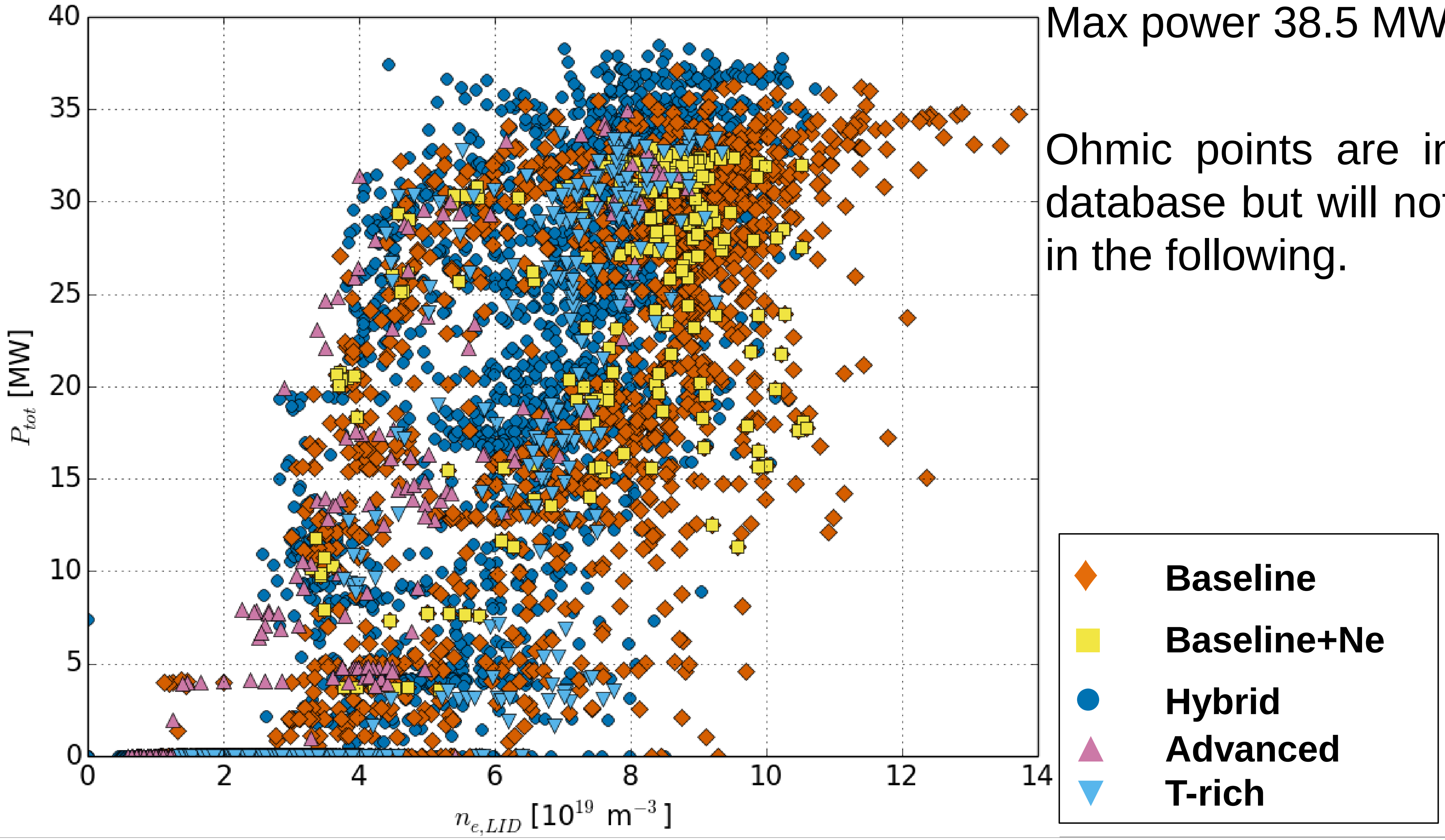
Optimized non-thermal fusion: DT hybrid-like, T-rich, D-NBI



Energetic modes and ITB studies: advanced scenario with afterglow



High-performance database : P_{tot} VS $n_{e,core}$



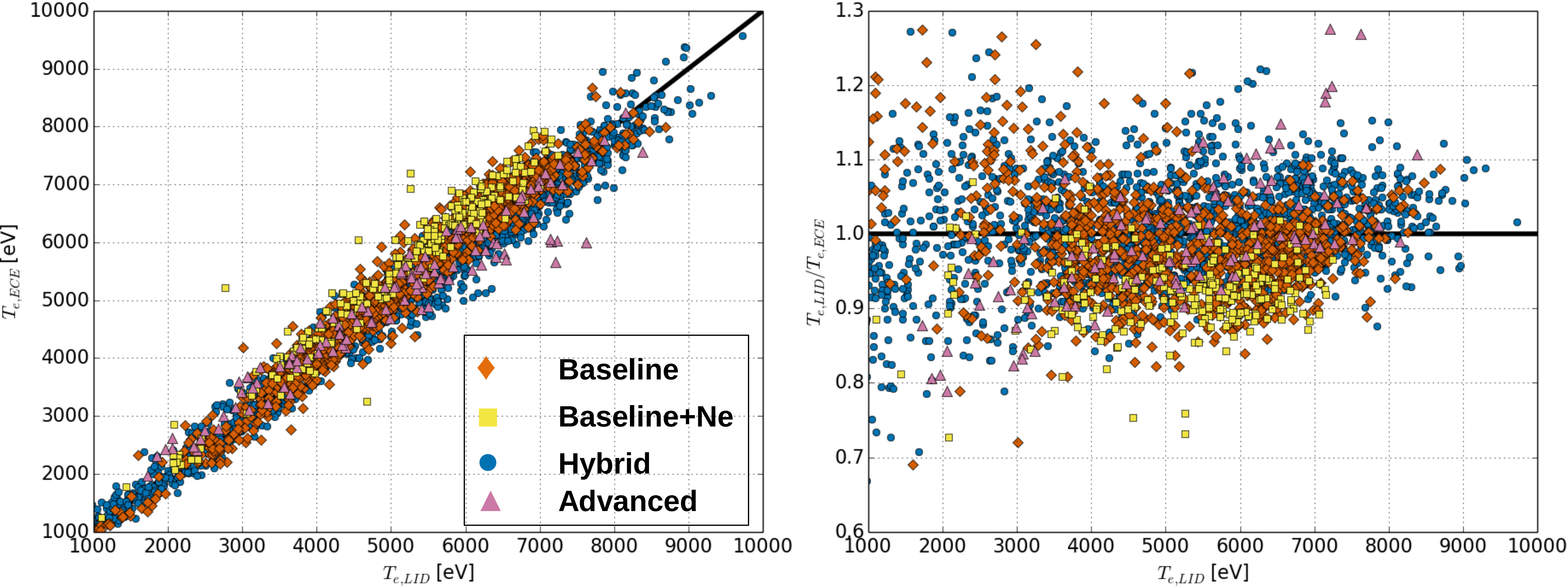
Max power 38.5 MW.

Ohmic points are included in the database but will not be discussed in the following.

All DD pulses: $T_{e,ECE}$ VS $T_{e,LID}$

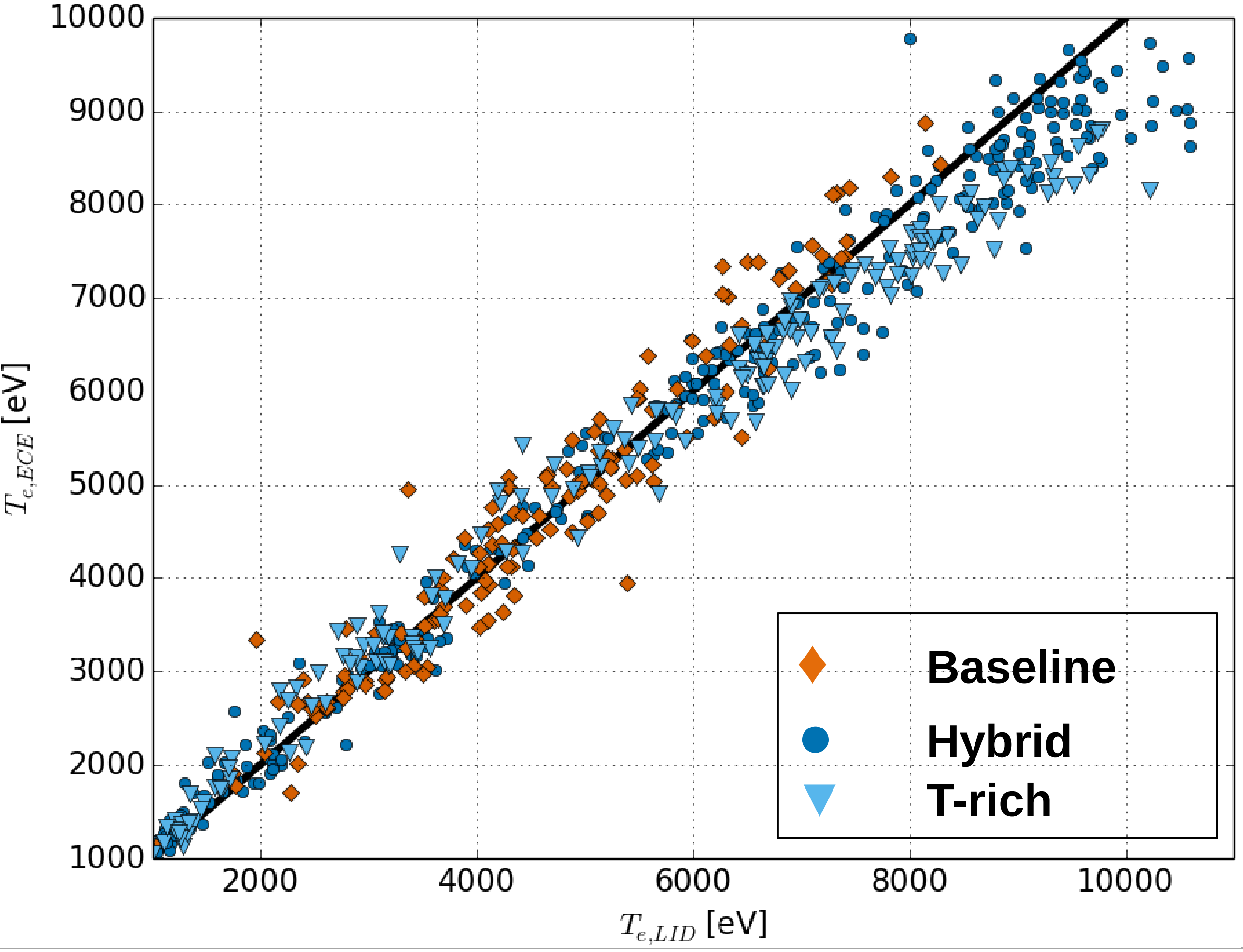
Different scenarios display well distinguished behaviour. For baseline with Ne puffing, at high T_e, **T_{LID}<T_{ECE}** is observed (similar to past observations).

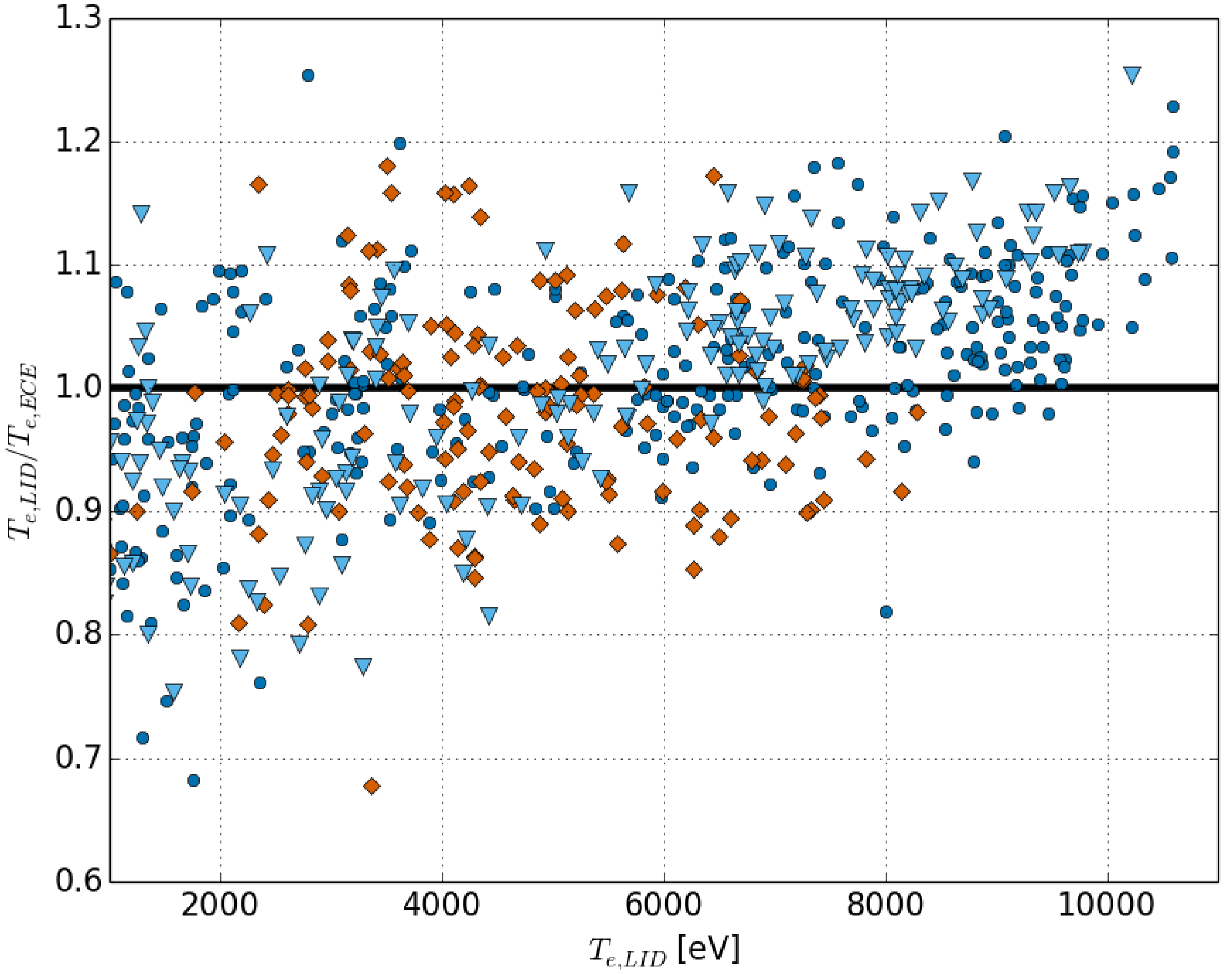
Of particular interest is the difference in baseline pulses with and without Ne puffing.



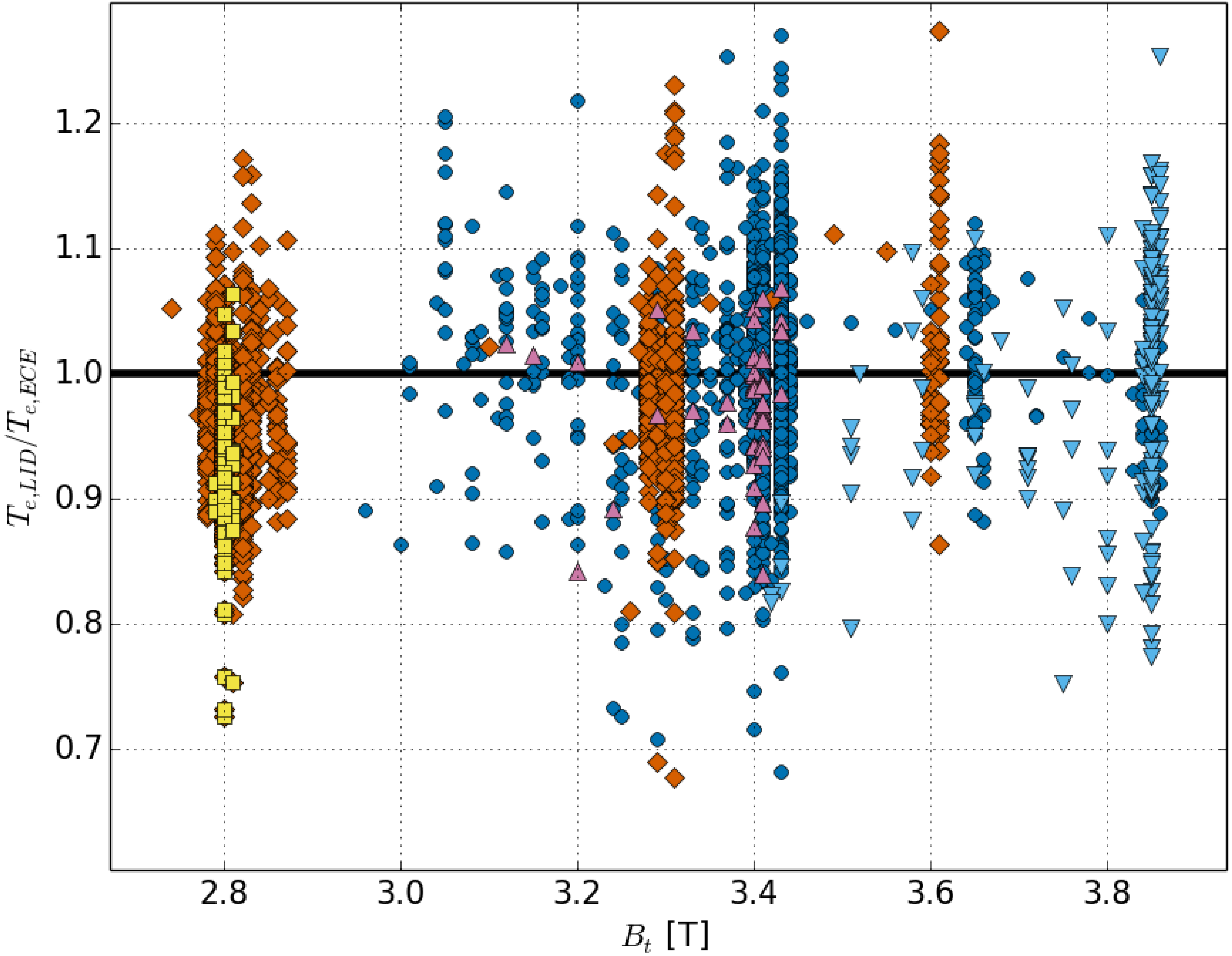
DT pulses: $T_{e,ECE}$ VS $T_{e,LID}$

In DT, hybrid-like pulses display the largest discrepancies between ECE and LIDAR: **T_{LID}>T_{ECE} for high T_e.** T-rich pulses, in particular display the largest difference.



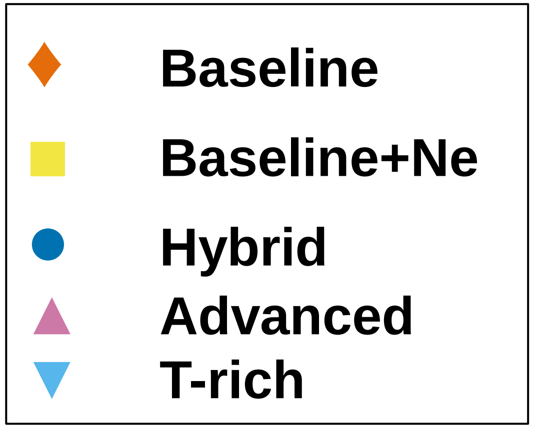


No correlation with B_t

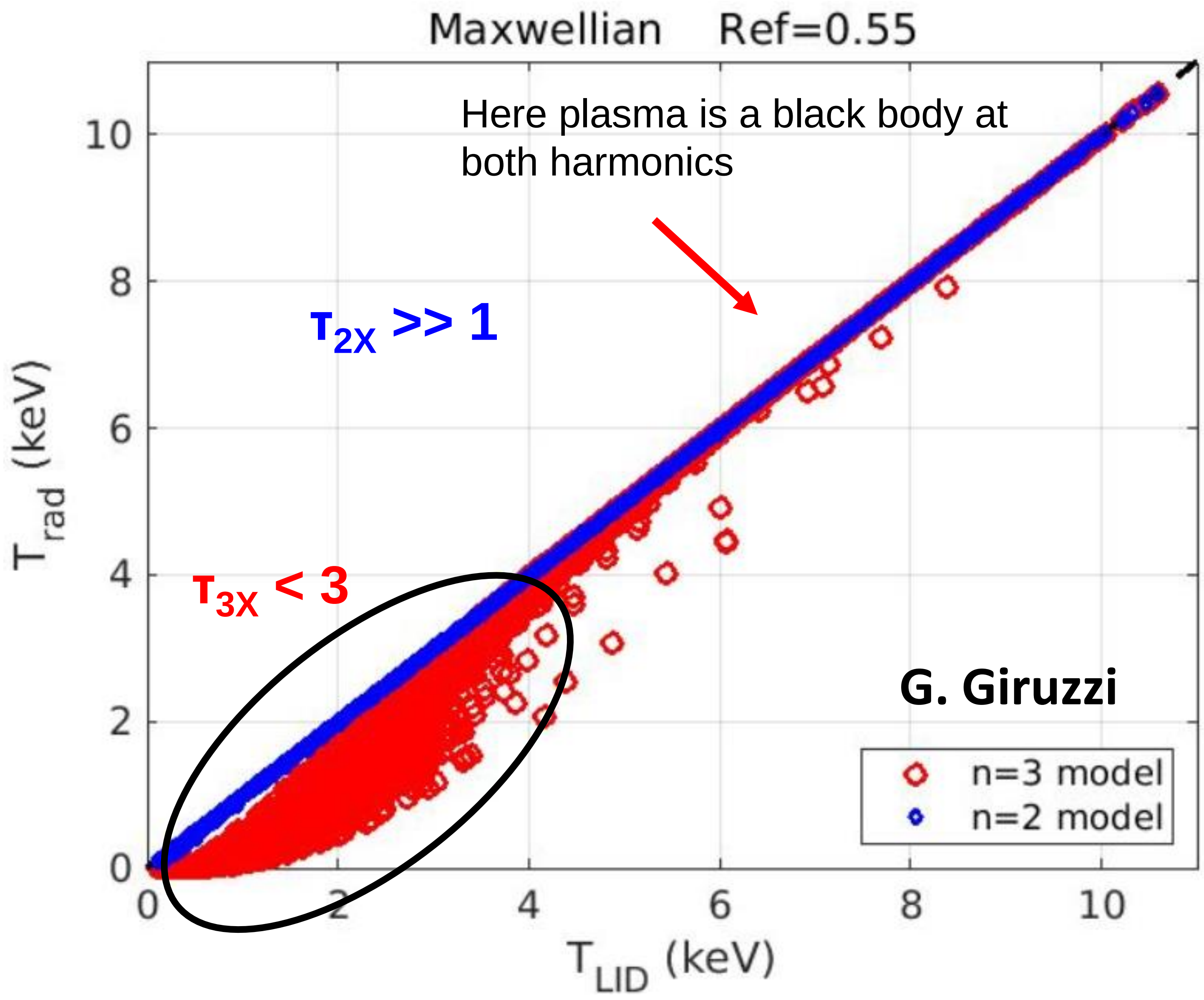


No correlation between T_{LID}/T_{ECE} and B_t.

This excludes issues with the ECE X2 calibration (frequency dependent, hence B dependent).



X2/X3 comparison prediction for Maxw. EDF



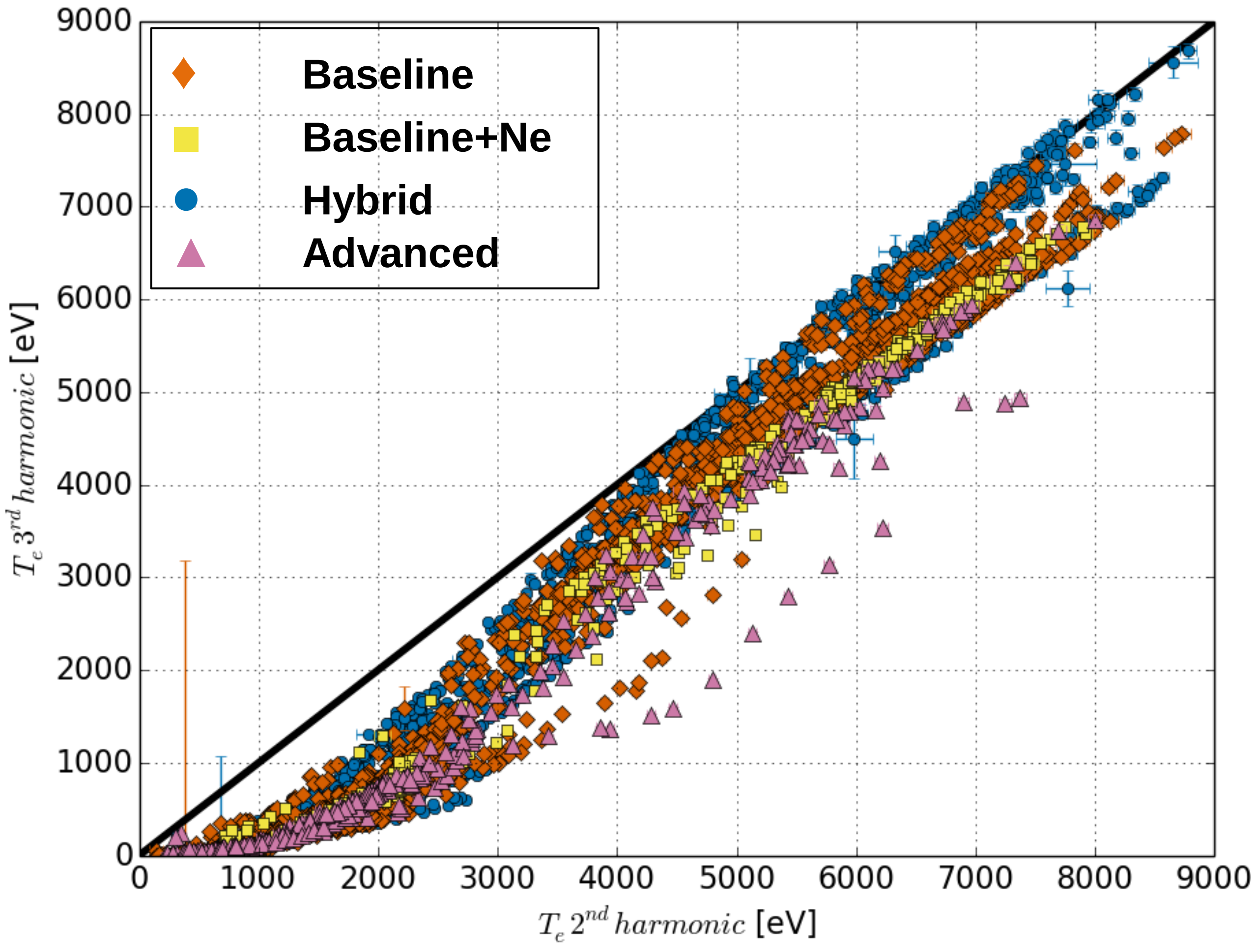
ECE emission predictions for X2/X3 starting from core T_e, n_e and B_t in database against LIDAR measurements.

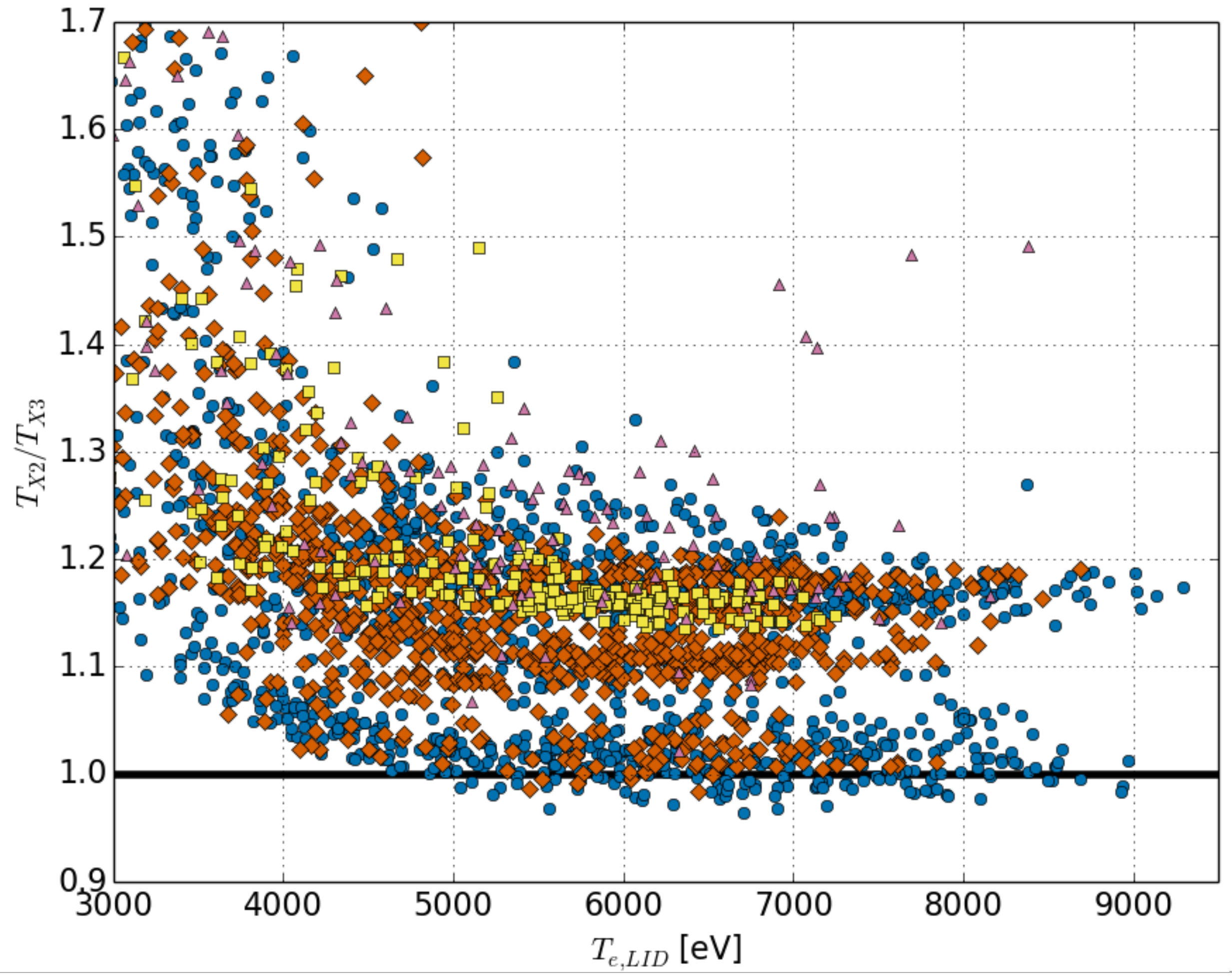
Deviations from this behaviour could be indications of non-maxwellian EDF characteristics.

All DD pulses: T_{X3} VS T_{X2}

Two branches are visible, corresponding to what would be expected for Maxwellian (T_{X3}~T_{X2}) or non-Maxwellian (T_{X3}<T_{X2}) EDF.

Notice that to confirm Maxwellian EDF (for thick X3) one should have $T_{X3}=T_{X2}=T_{LID}$

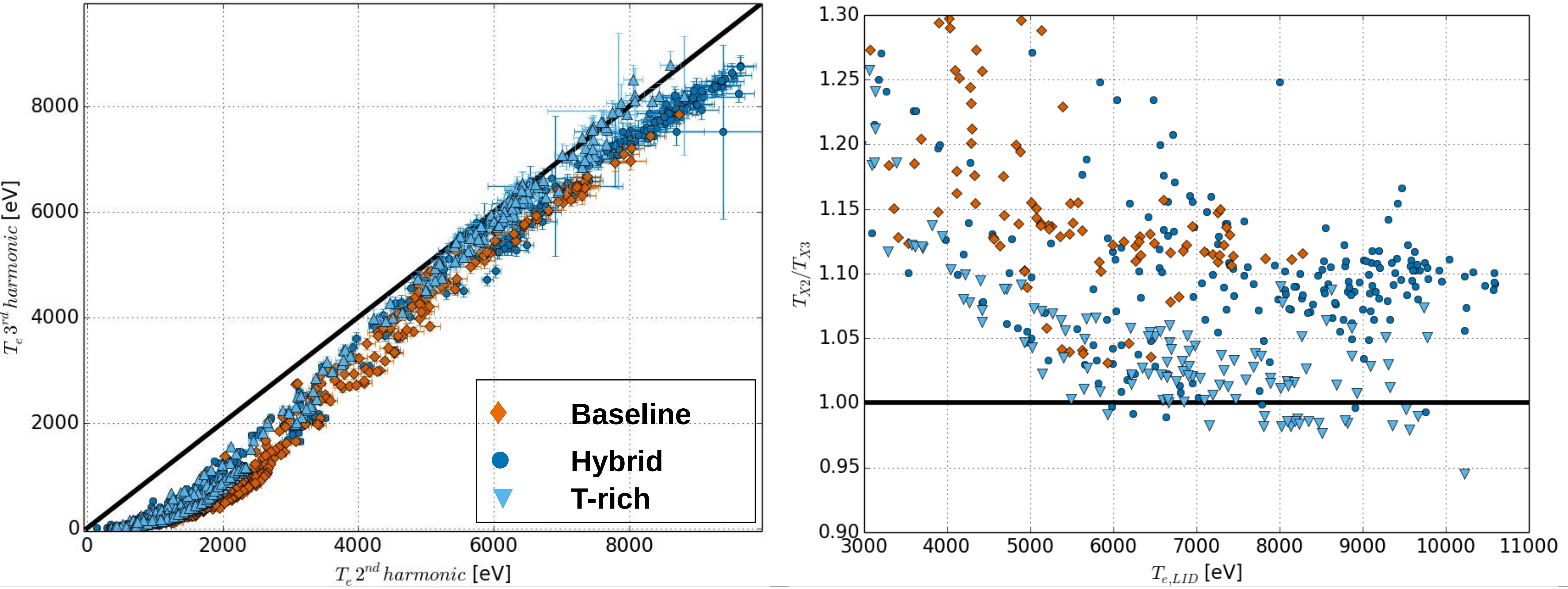




DT pulses: T_{X3} VS T_{X2}

Differences between scenarios are most evident.

T-rich plasmas display different behaviour compared to standard hybrid pulses.



Conclusions: ECE/TS discrepancies observed

Database contains a large range of plasma conditions and scenarios.

- Many pulses with high T_e where discrepancies are visible, but **no systematic reproduction of previous observations**: richer phenomenology compared with past results.
- Comparison of X2/X3 spectra suggests the presence of non-maxwellian EDF in most pulses.

No clear cause for these discrepancies yet.

Simple model of EDF perturbation can be a useful tool to understand if EDF distortions could reproduce these results → <u>See next talk by G. Giruzzi.</u>

Future work:

- Employ SPECE simulations (assume Maxwellian EDF) to compare with experimental spectra
- Analyse oblique ECE data collected during DT campaign.
- Improve eq. reconstruction adding constraints (electron and ion profiles, fast particles).

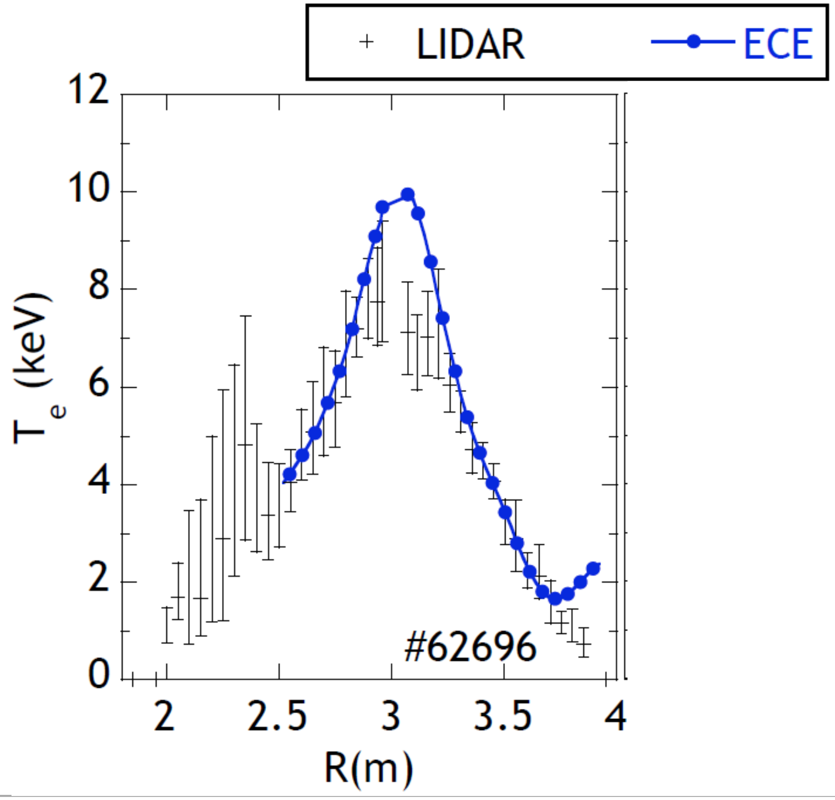
Backup slides

Signs of non-Maxwellian electron EDF

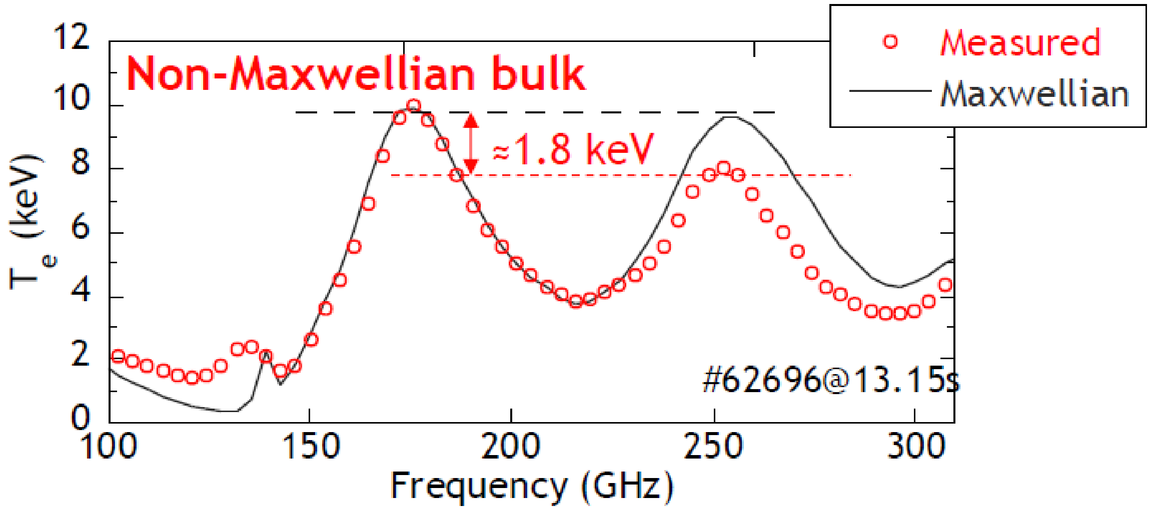
Different H concentration found to affect TS/ECE agreement. Lower H correlates with $T_{X2}>T_{X3}$ while $T_{X3}\sim T_{TS}$.

Possible effect of hot ion tail.

[E. de la Luna EC15 proc. 2008]



T_e from 3[rd] harmonic ECE emission consistent with Te (TS)



E. de la Luna

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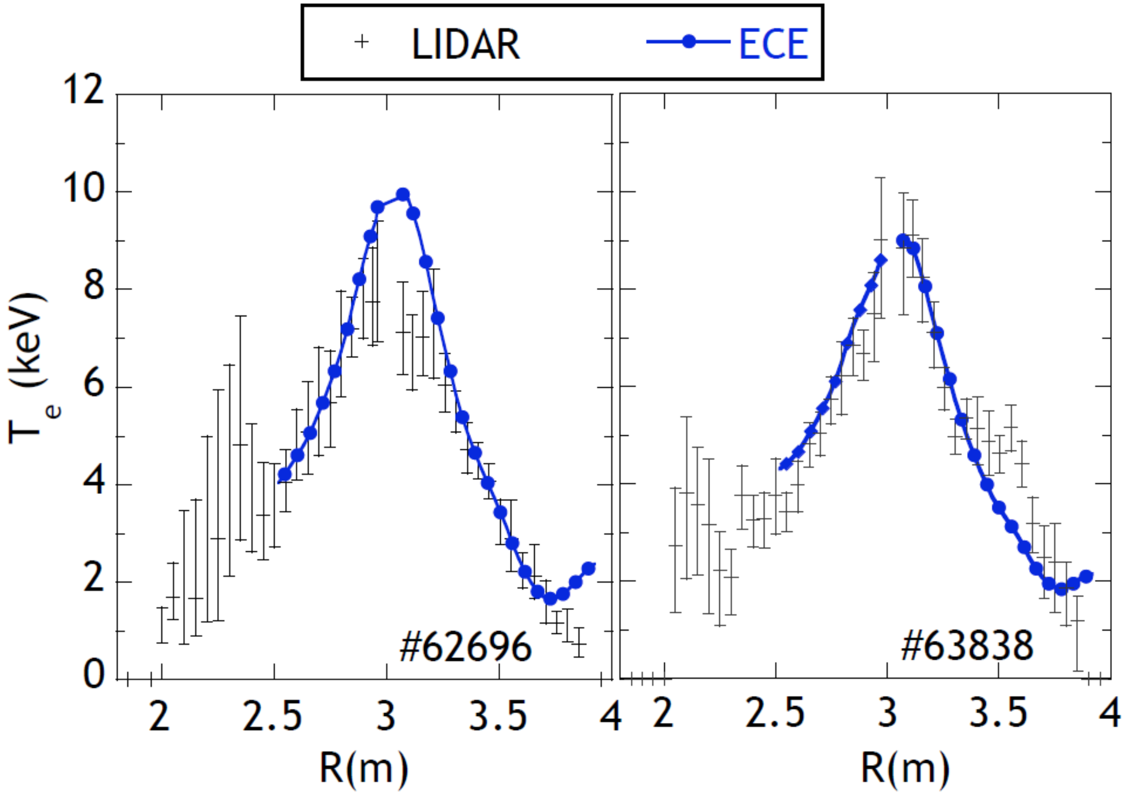

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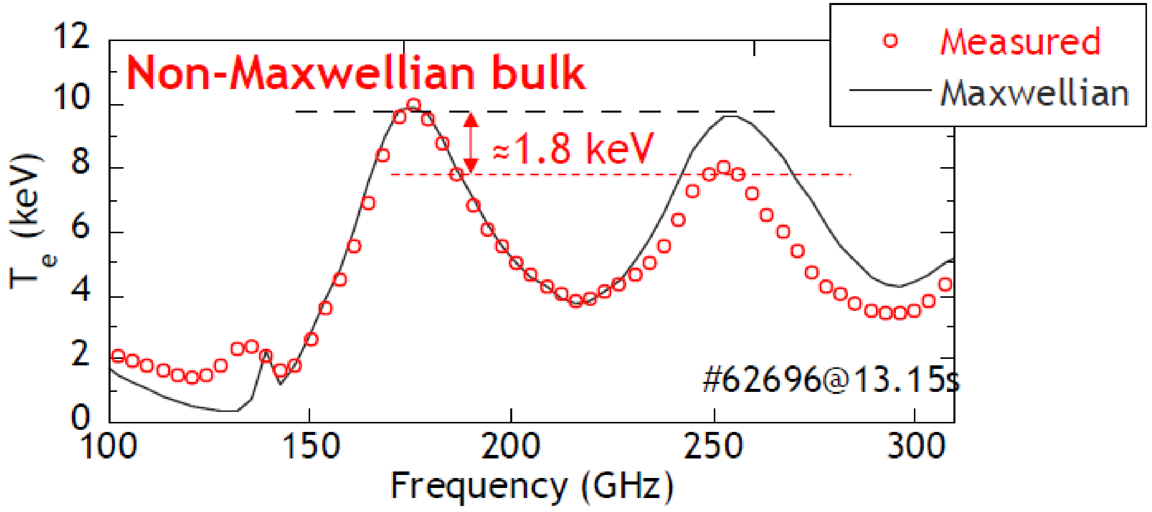

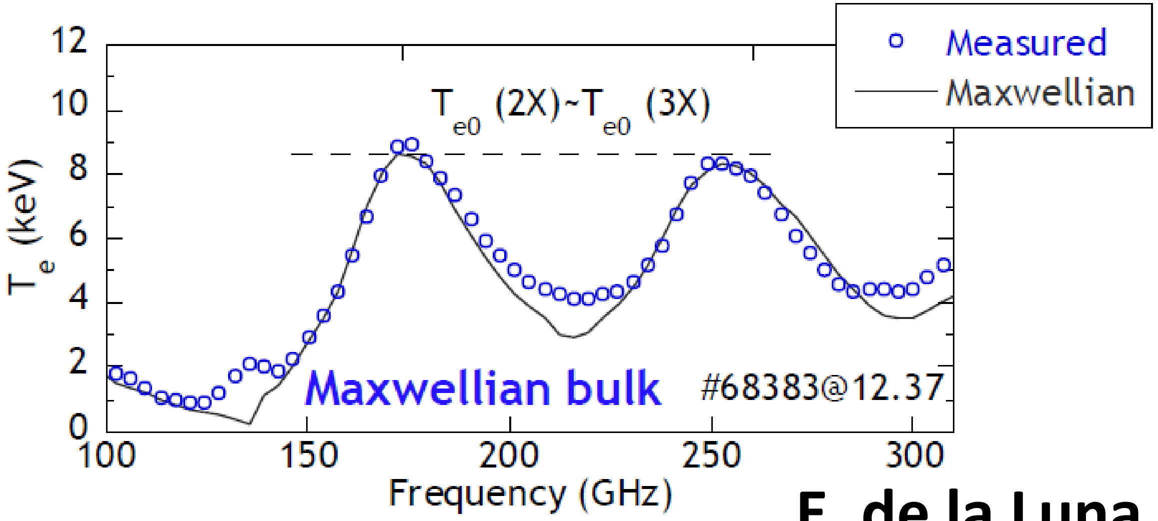

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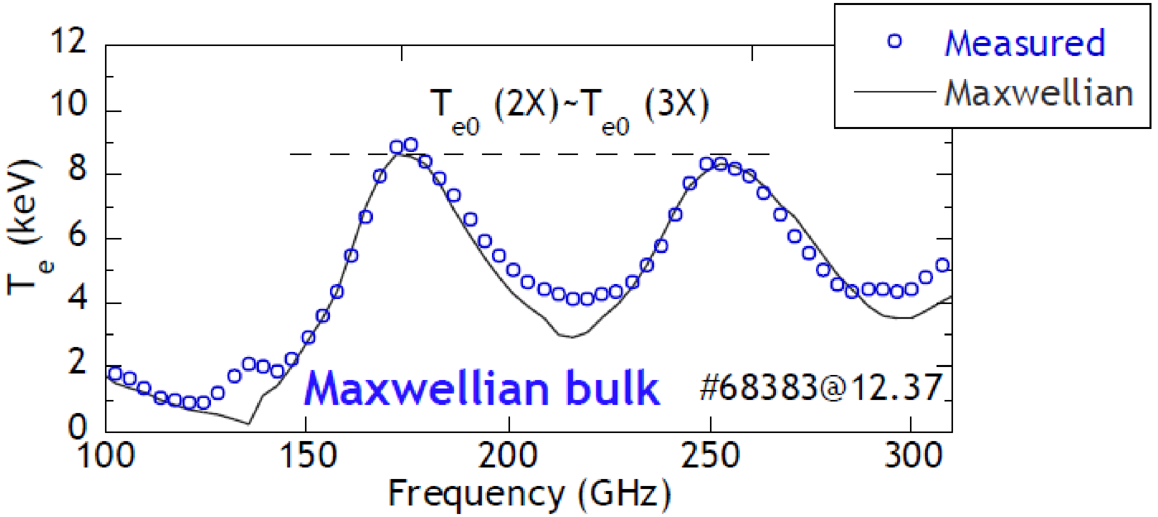
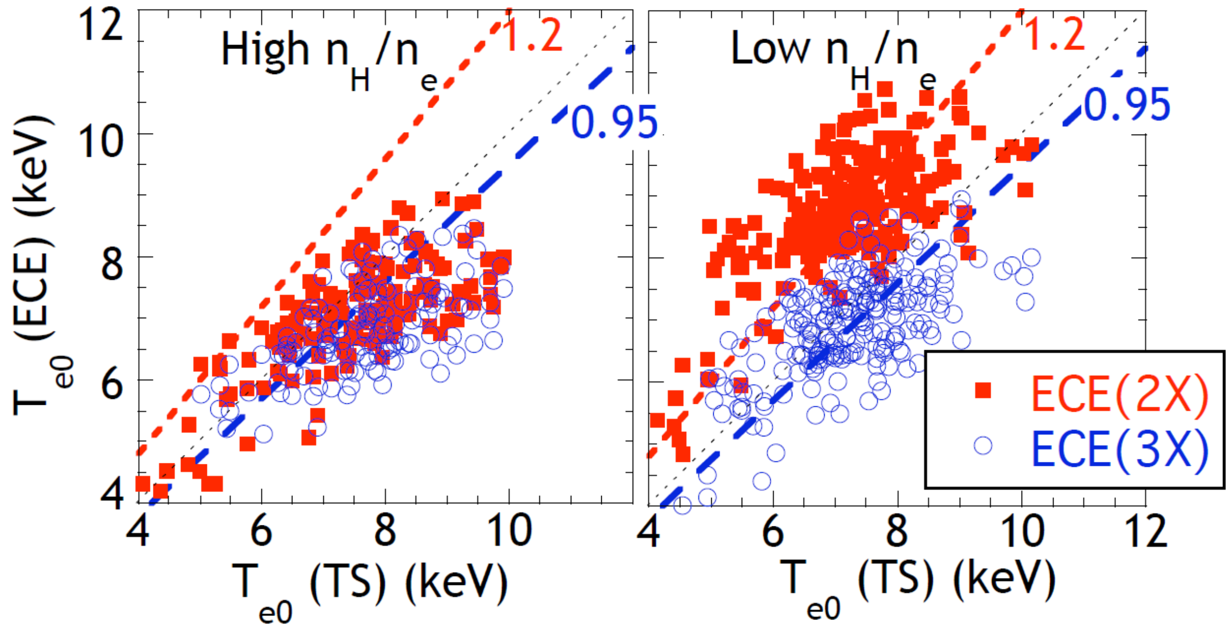
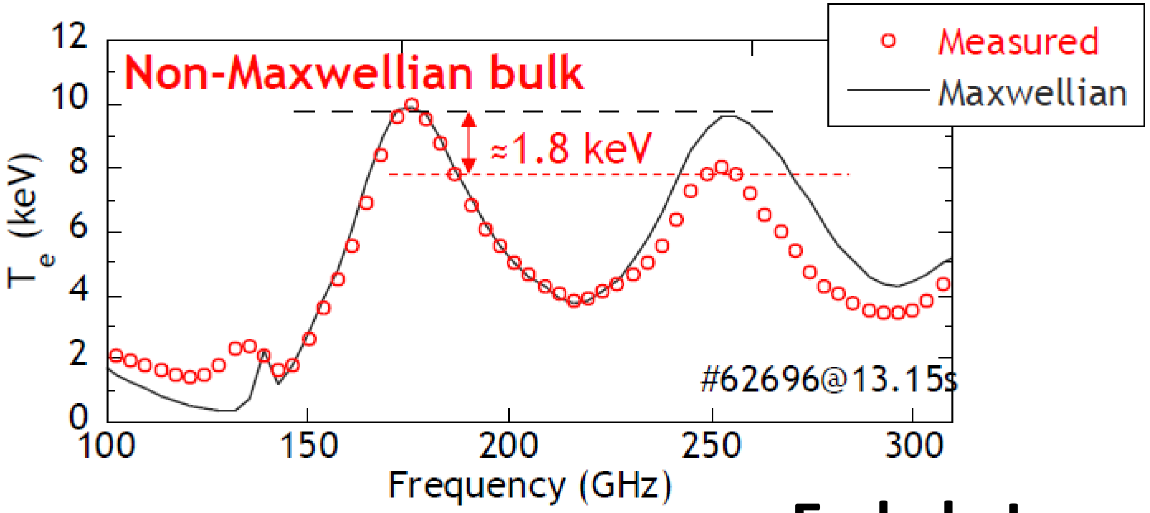
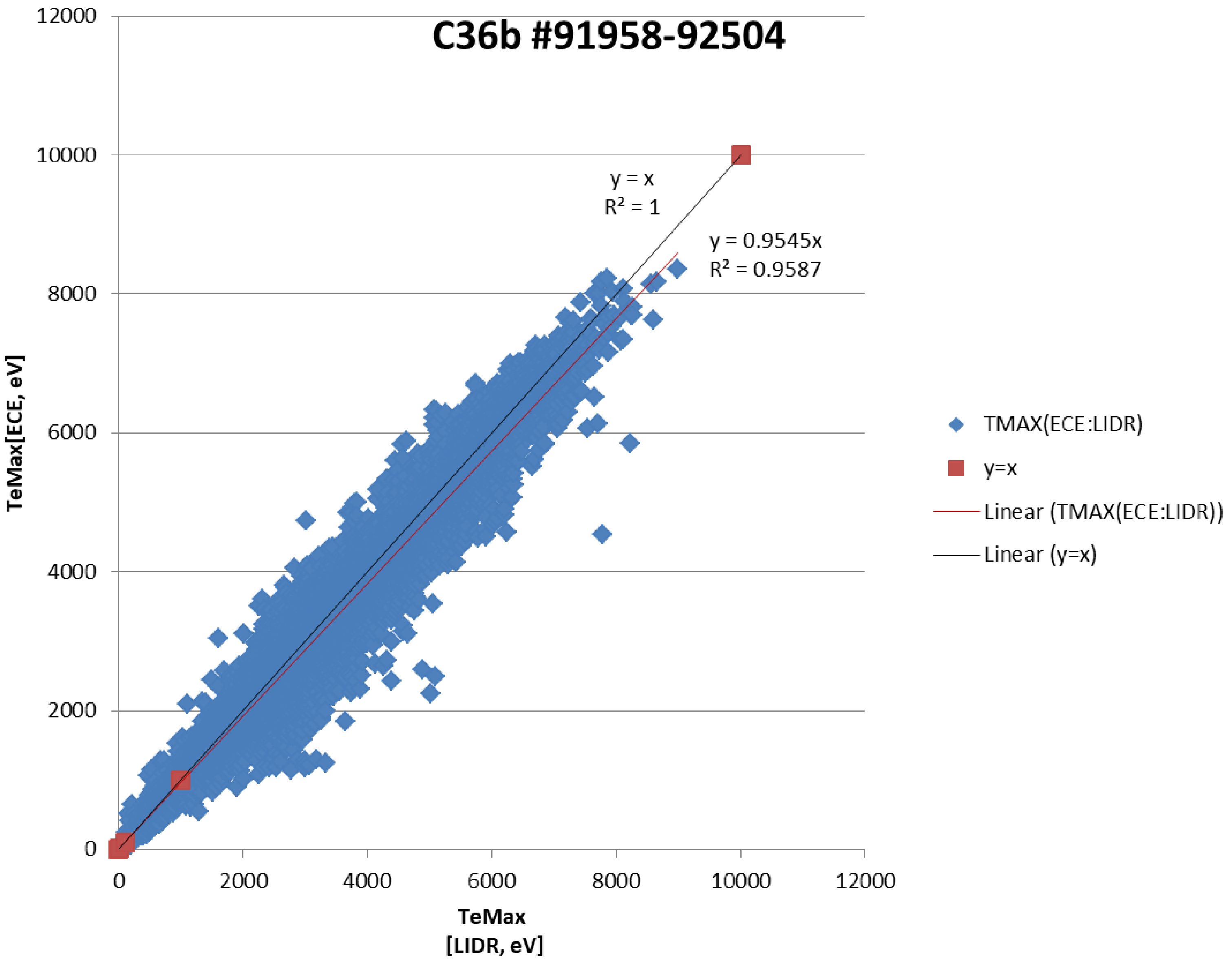






E. de la Luna

Discrepancy not observed in later plasmas



More recent pulses at JET (2010-2016) never observed the discrepancy, even though high T_e was reached.

Hints of $T_{e,ECE}<T_{e,LID}$ for the highest T_e, opposite to past observations.

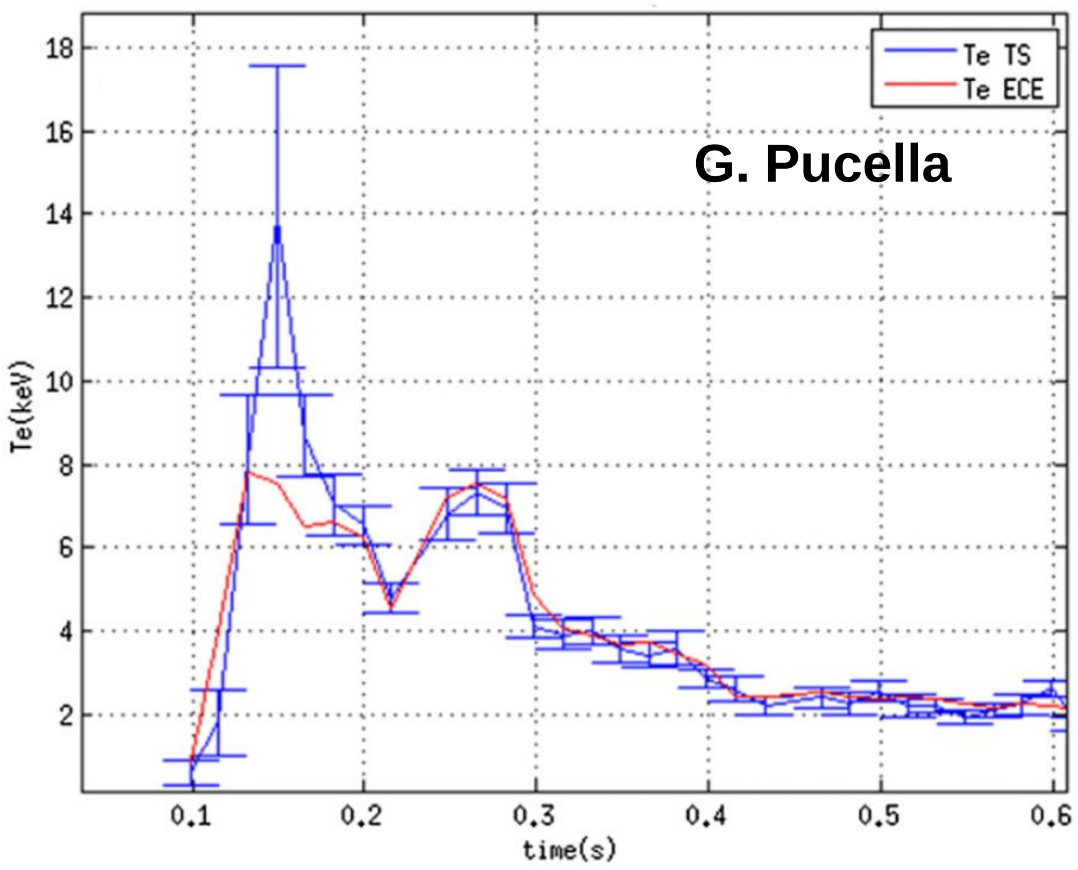
Observations in other machines

Alcator C-Mod

- Plasmas with T_e up to 8 keV, heated with different configurations of ICRH. No evidence of discrepancies between TS and ECE (grating polychromator and Michelson interferometer) were observed.
  [A. White et al., NF, 2012]

FTU

- High T_e (up to 14 keV) reached in EC heated pulses on current ramp-up. In the core, $T_{e,ECE}<T_{e,TS}$ were measured for $T_{e,TS}>8$keV using TS and Michelson interferometer.
  [G. Pucella et al, NF 2022]



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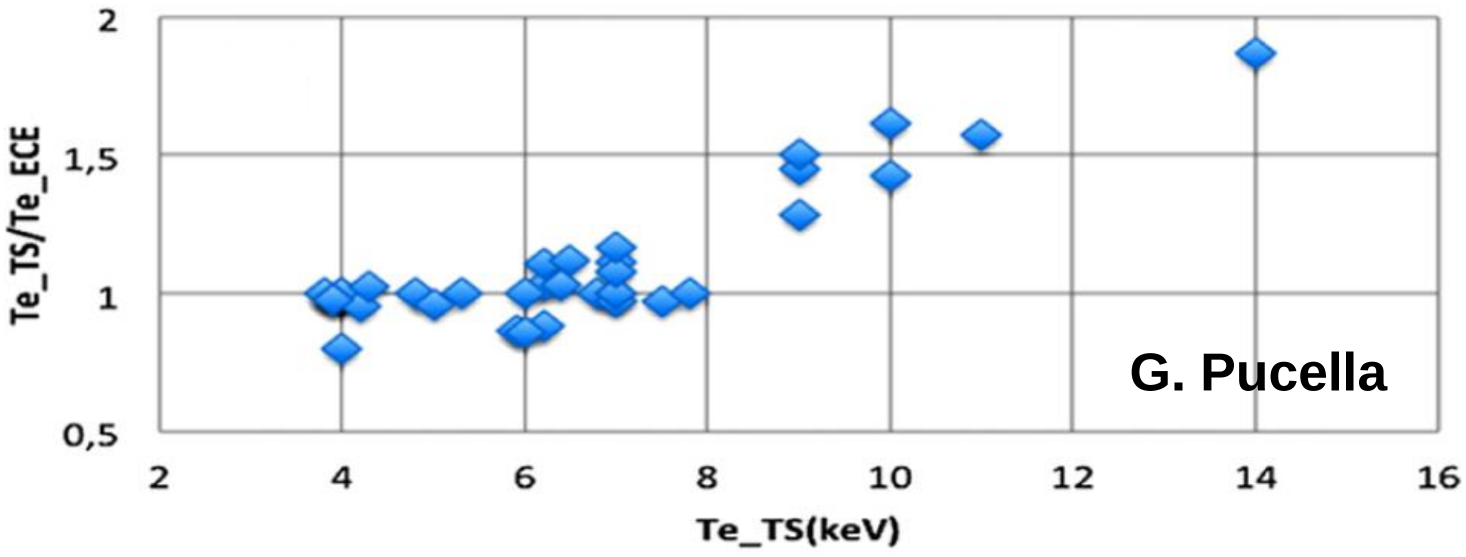
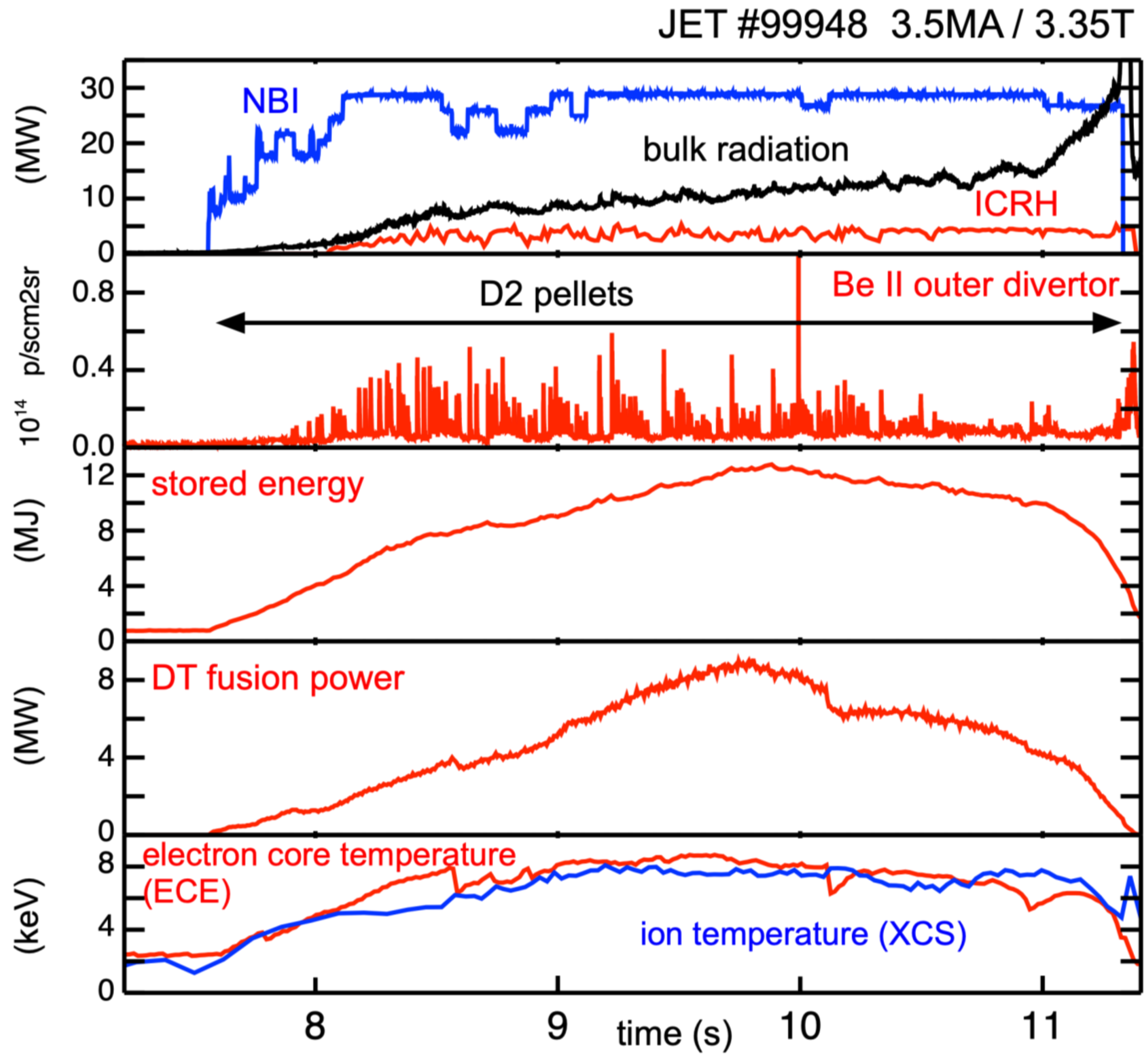


Baseline scenario

L. Garzotti et al 2019 Nucl. Fusion 59 076037



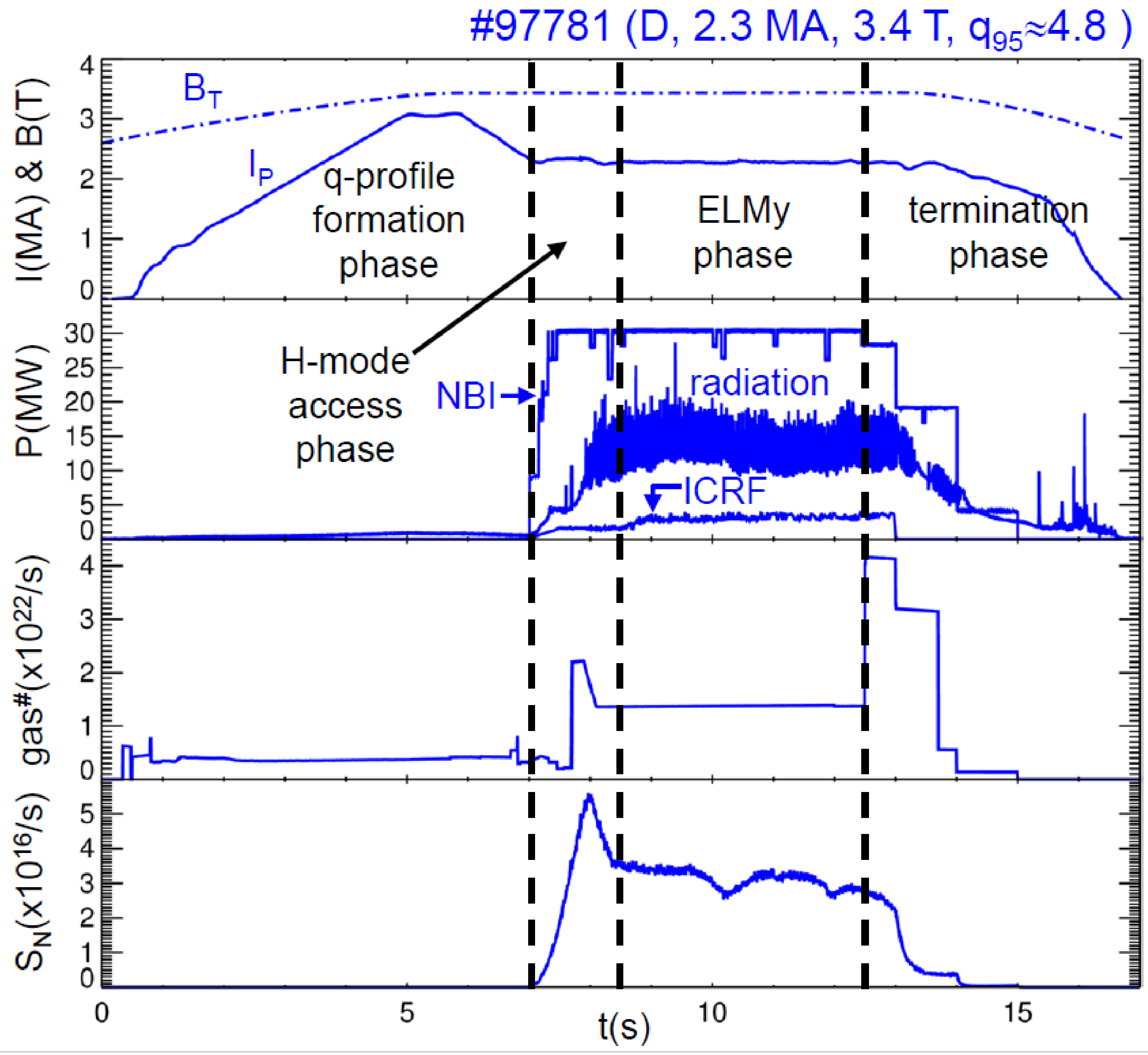
Baseline:

high I_p, high n, based on ITER baseline scenario. Includes pulses with Ne injection.

F. Rimini

Hybrid scenario

J. Hobirk et al 2012 Plasma Phys. Control. Fusion 54 095001



Hybrid:

high B, low I_p. Elevated β_p, q_{95}(>3), q_{min}>1 to avoid modes.

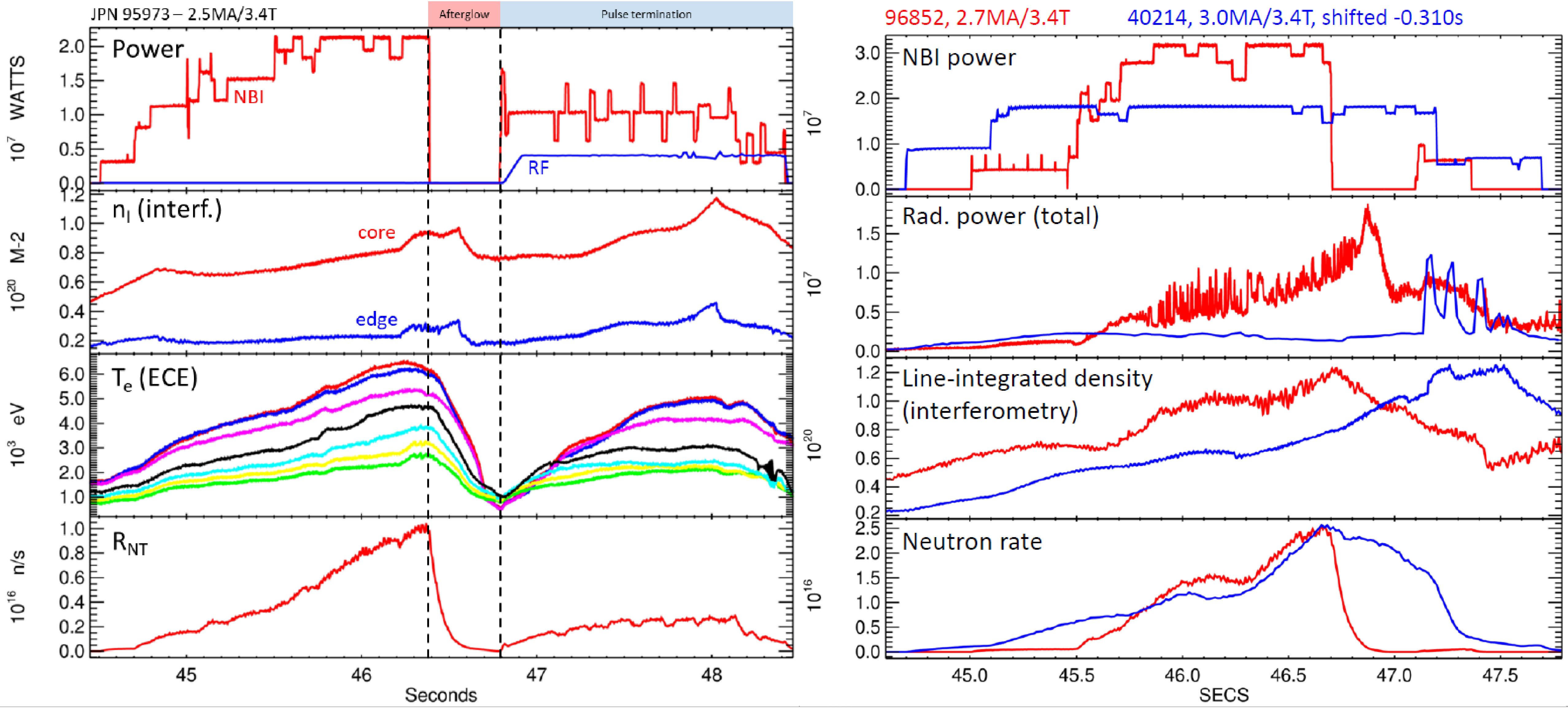
#neglects gas system response time

C. Challis

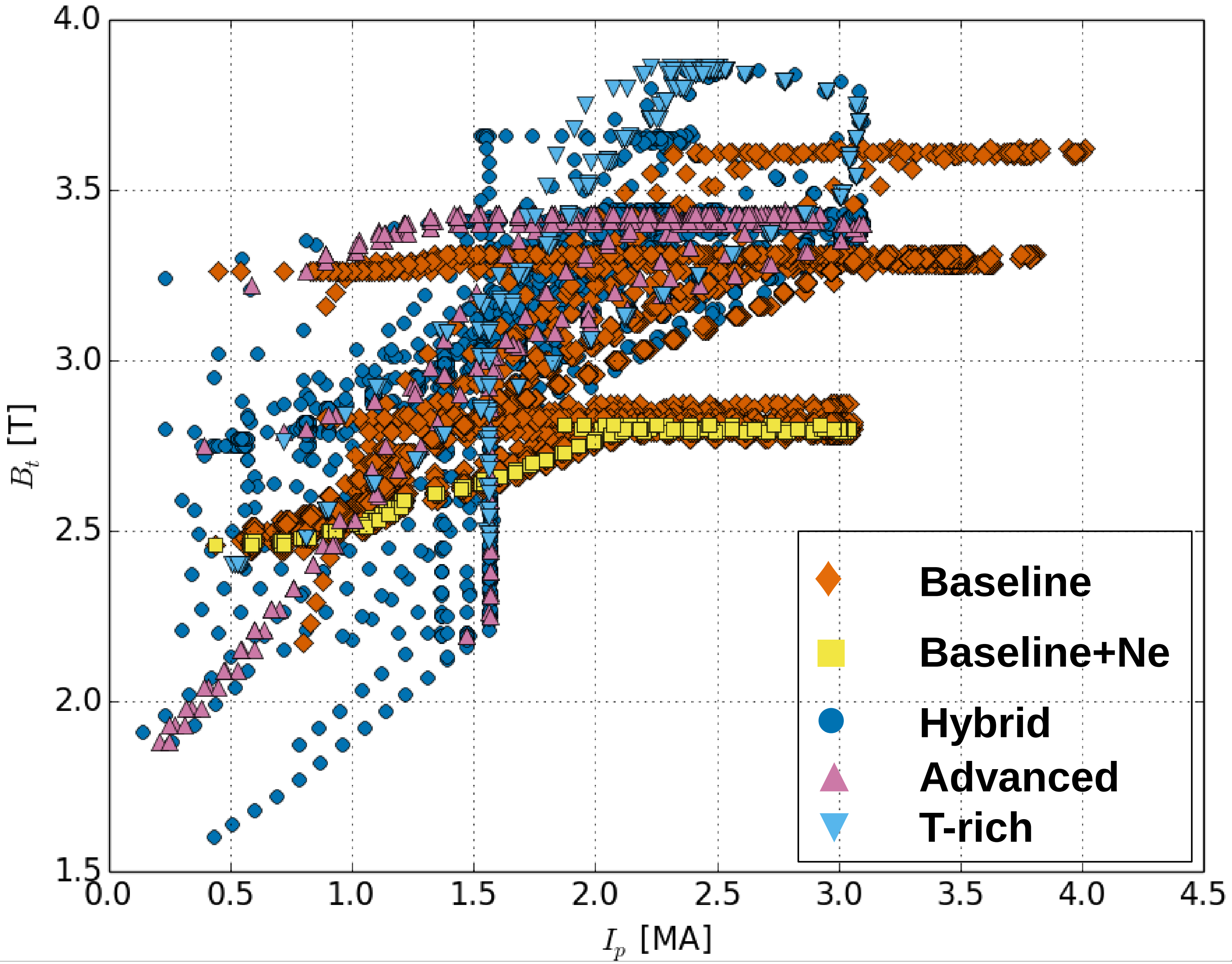
Advanced scenarios: aferglow

R. J. Dumont *et al* 2018
Nucl. Fusion **58** 082005

Energetic modes and ITB studies: advanced scenario with afterglow. **R. Dumont**



High-performance database : B_t VS I_p



Times in database cover from ramp-up to ramp-down or disruption.

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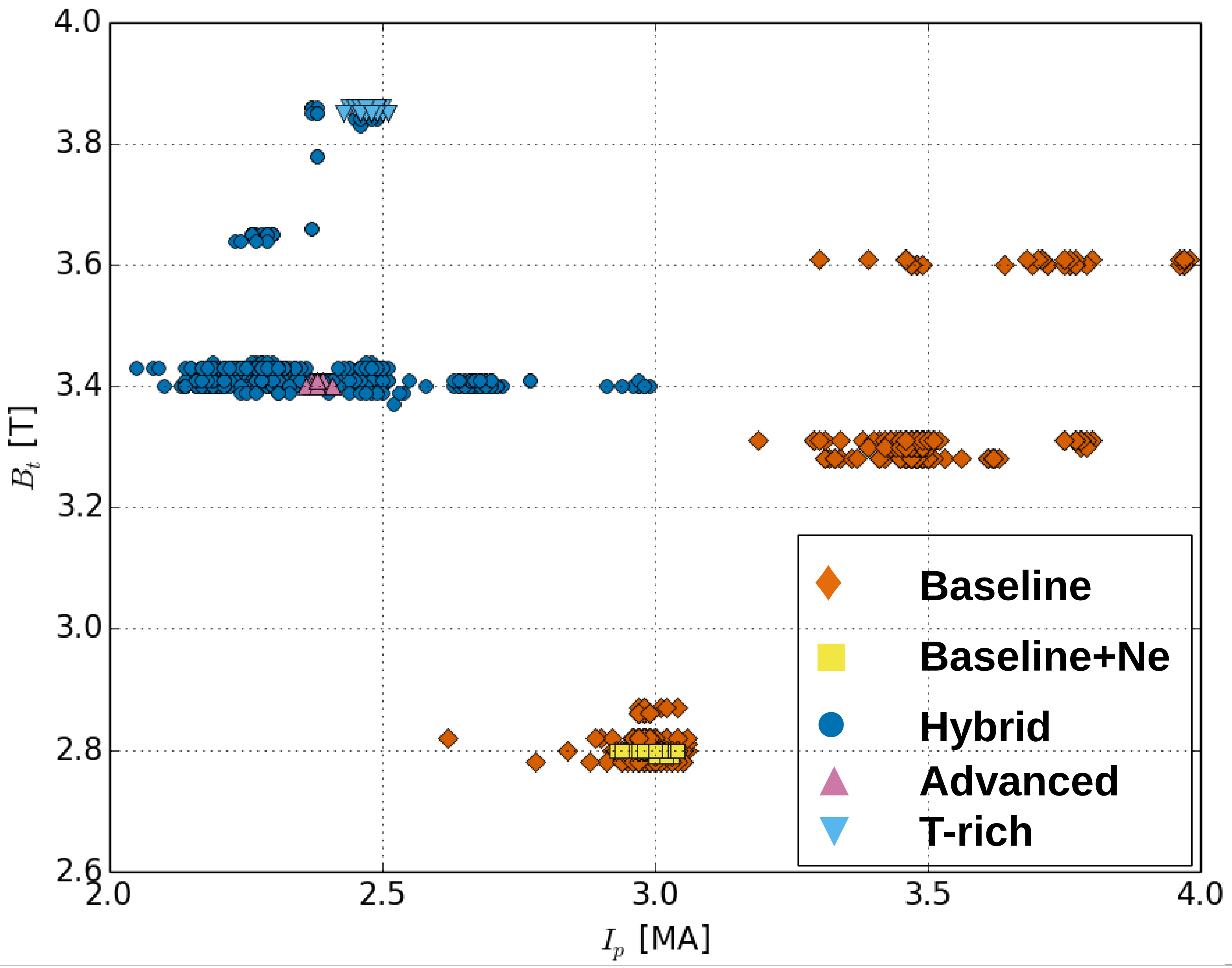


Times in database cover from ramp-up to ramp-down or disruption.

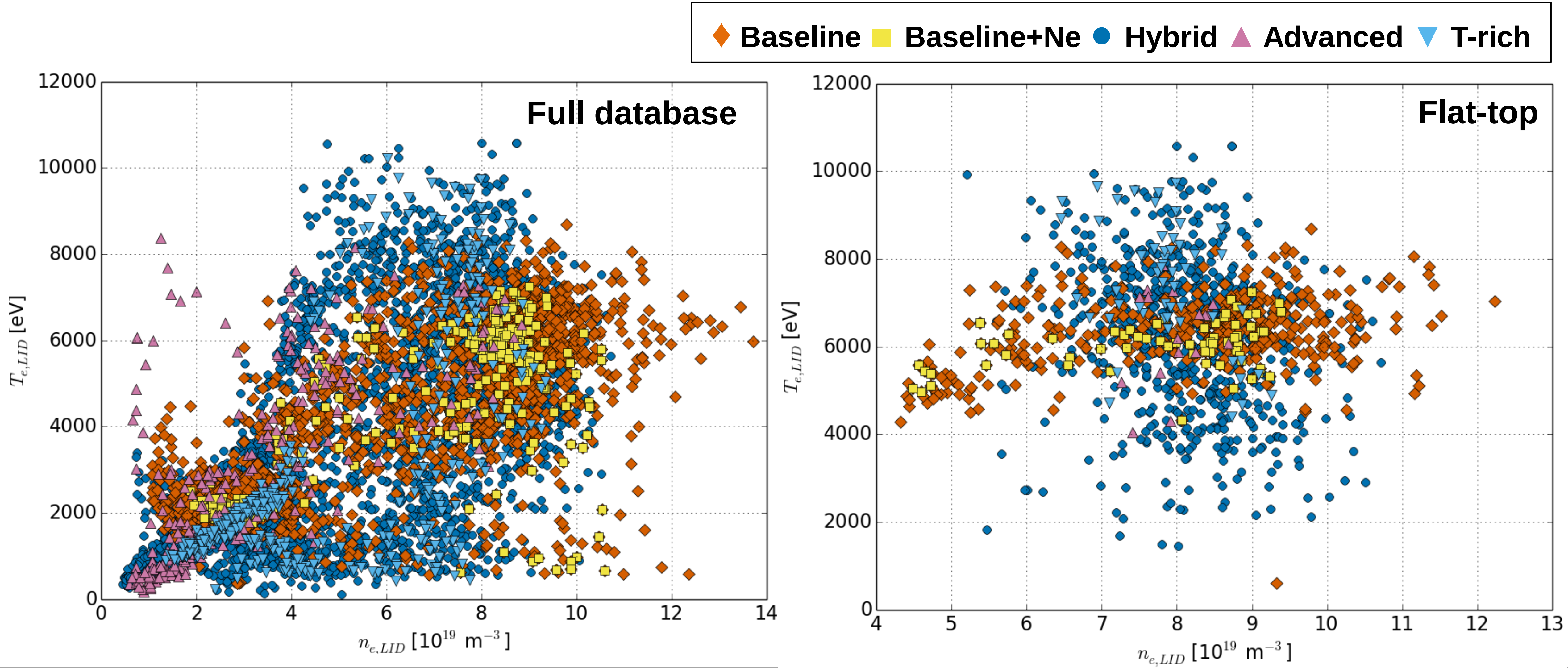
In flat-top:

$2 < I_p < 4$ MA

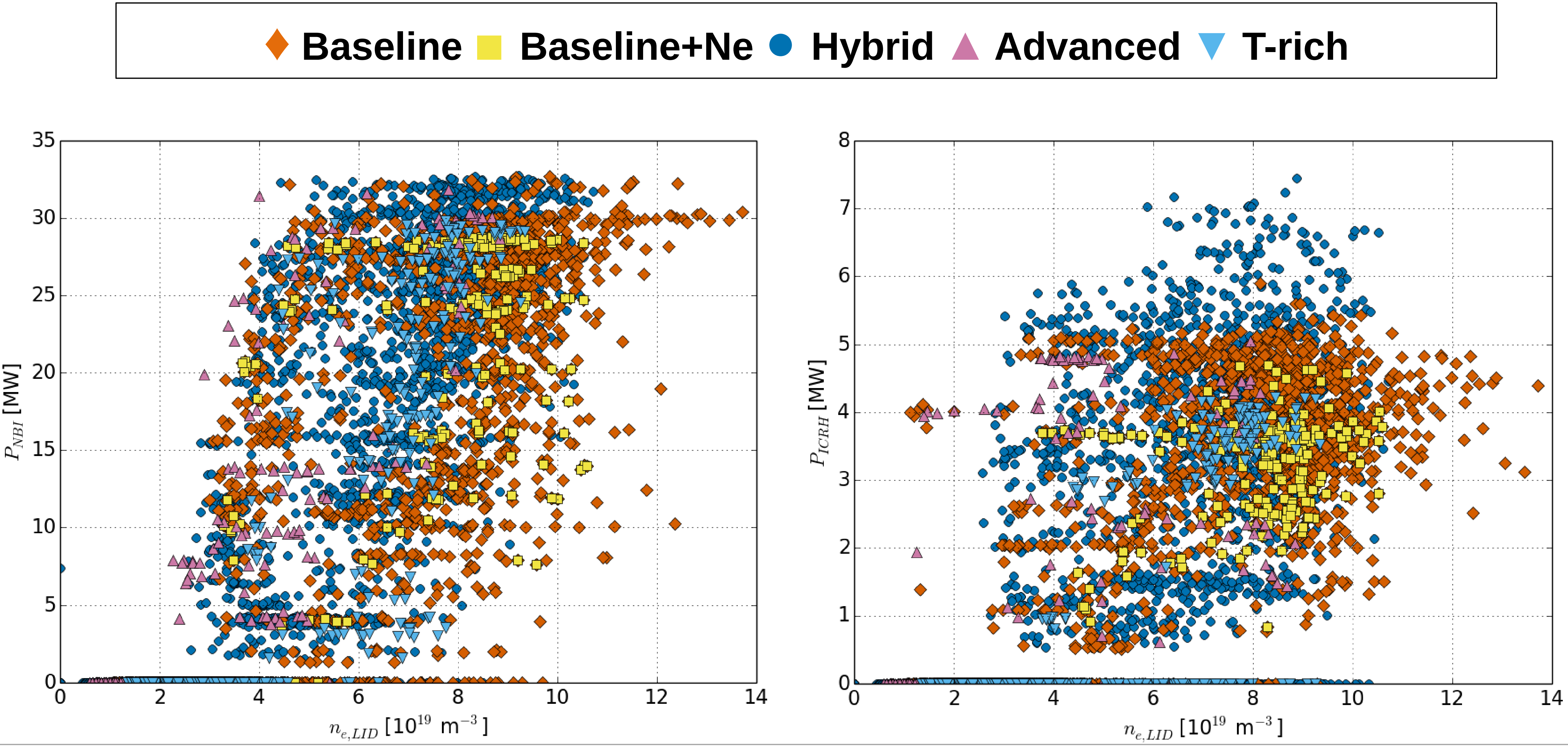
$2.8 < B_t < 3.9$ T

High-performance database : T_e VS n_e

Max T_e ~ 11 keV. Density levels are different for the various scenarios.

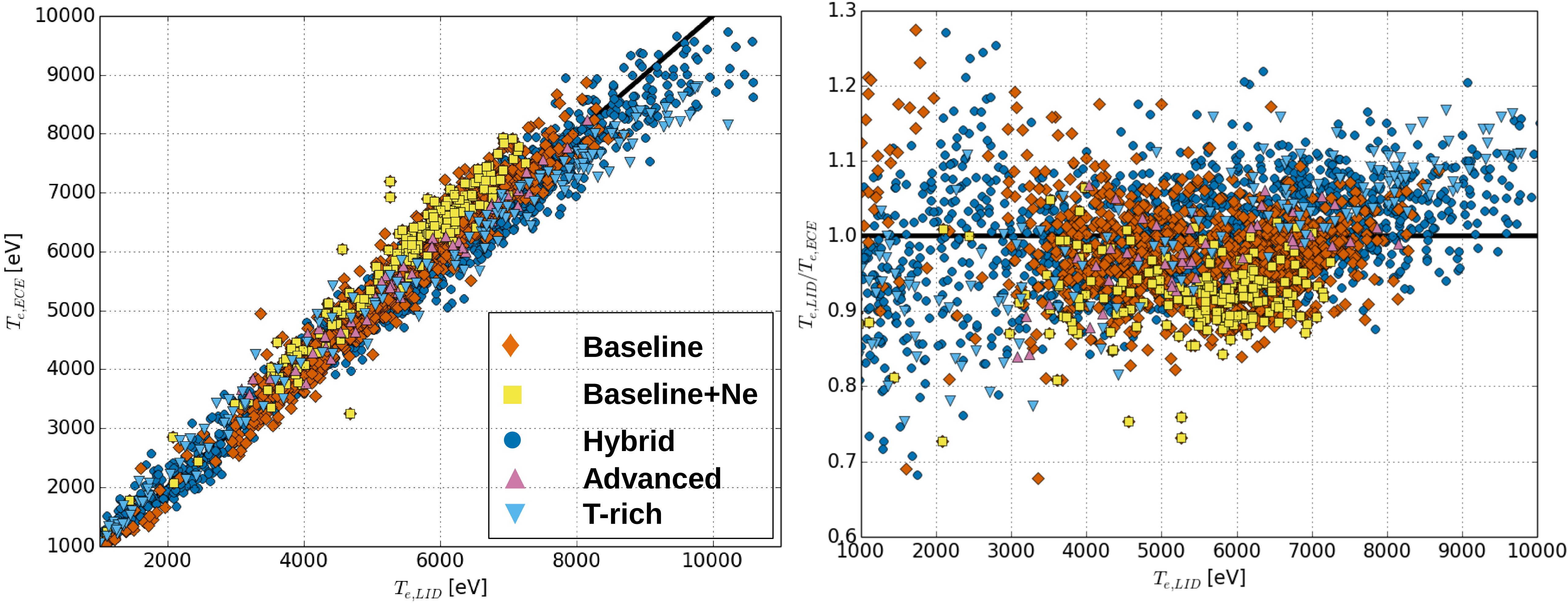


High-performance database : P_{NBI} , P_{ICRH} VS $n_{e,core}$



High-performance database: $T_{e,ECE}$ VS $T_{e,LID}$

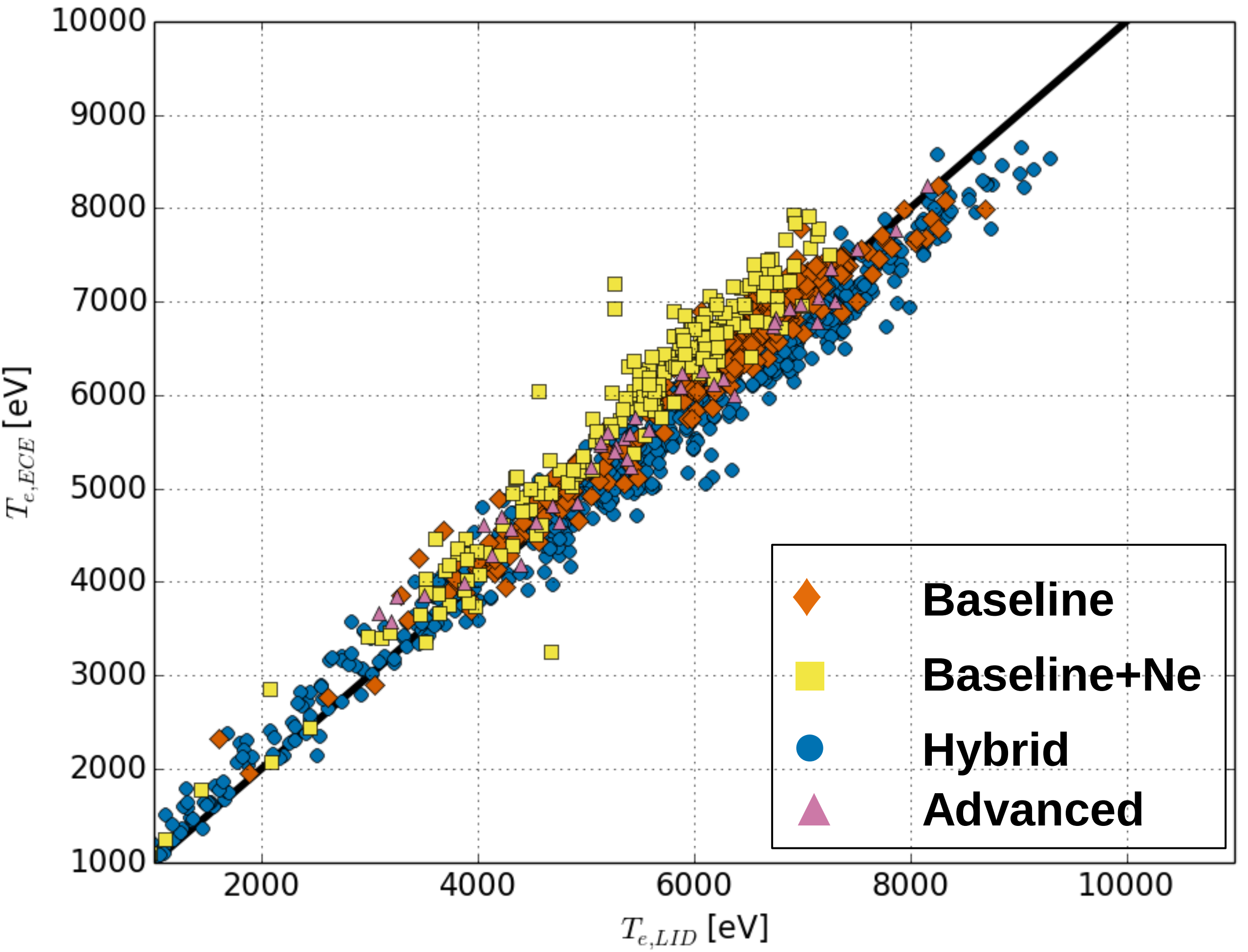
Discrepancies between LIDAR/ECE are **visible but not comparable** to past observations was found. Different scenarios, however, suggest different behaviours. At high T_e there are hints of $T_{LID}>T_{ECE}$ for hybrid pulses. **Opposite to previous observations.**

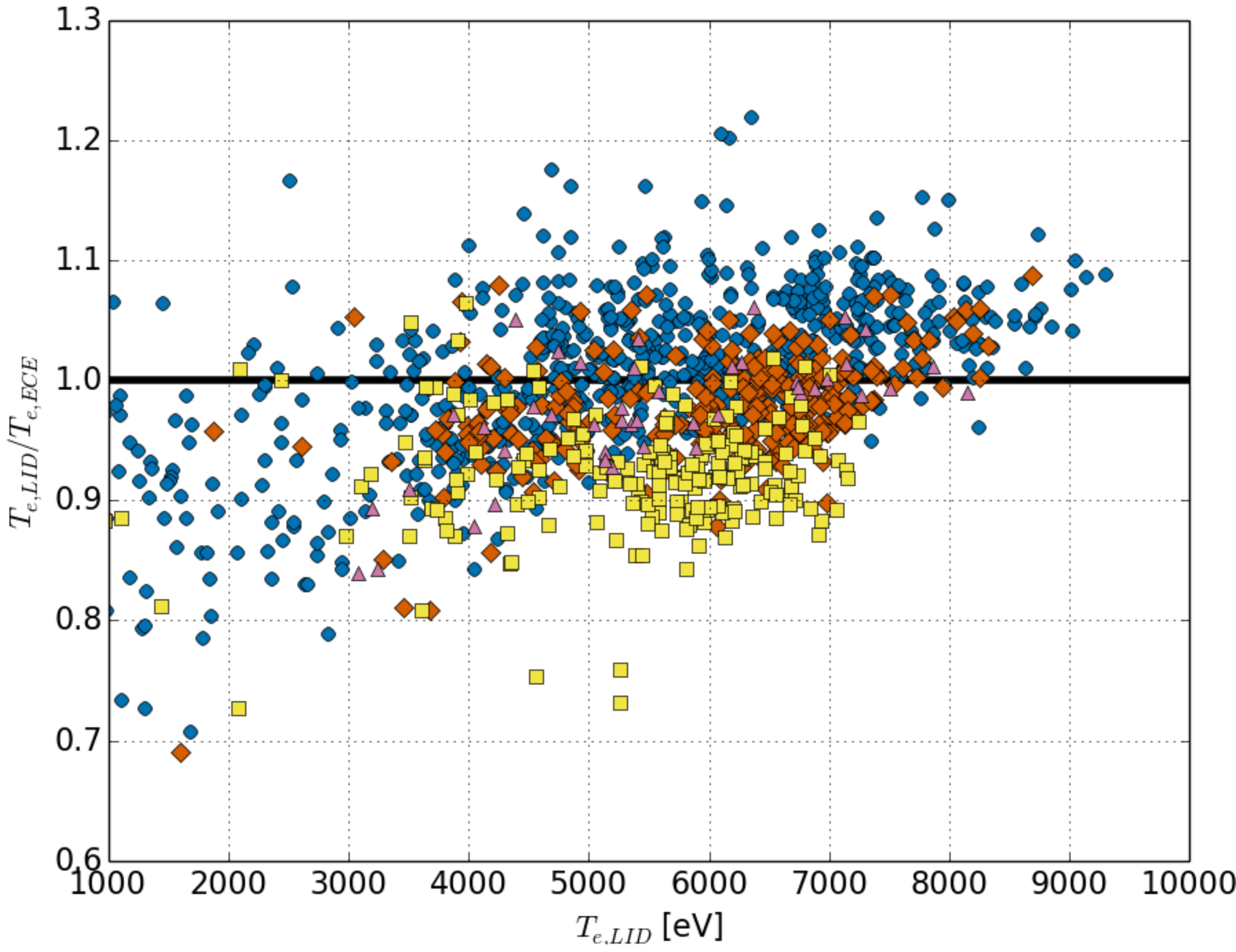


DD pulses before shutdown: $T_{e,ECE}$ VS $T_{e,LID}$

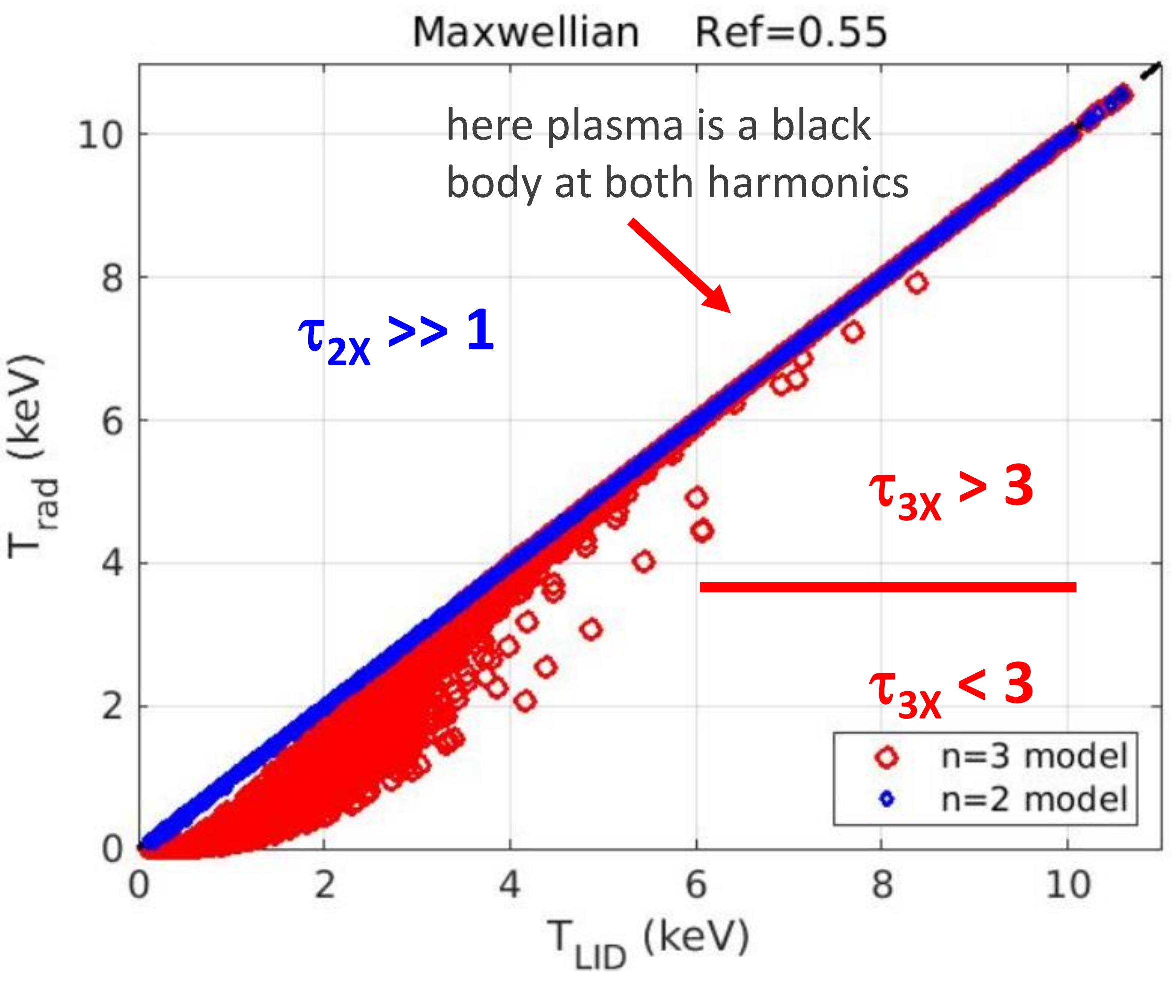
Only DD pulses from JAN-MAR 2020 (before shutdown).

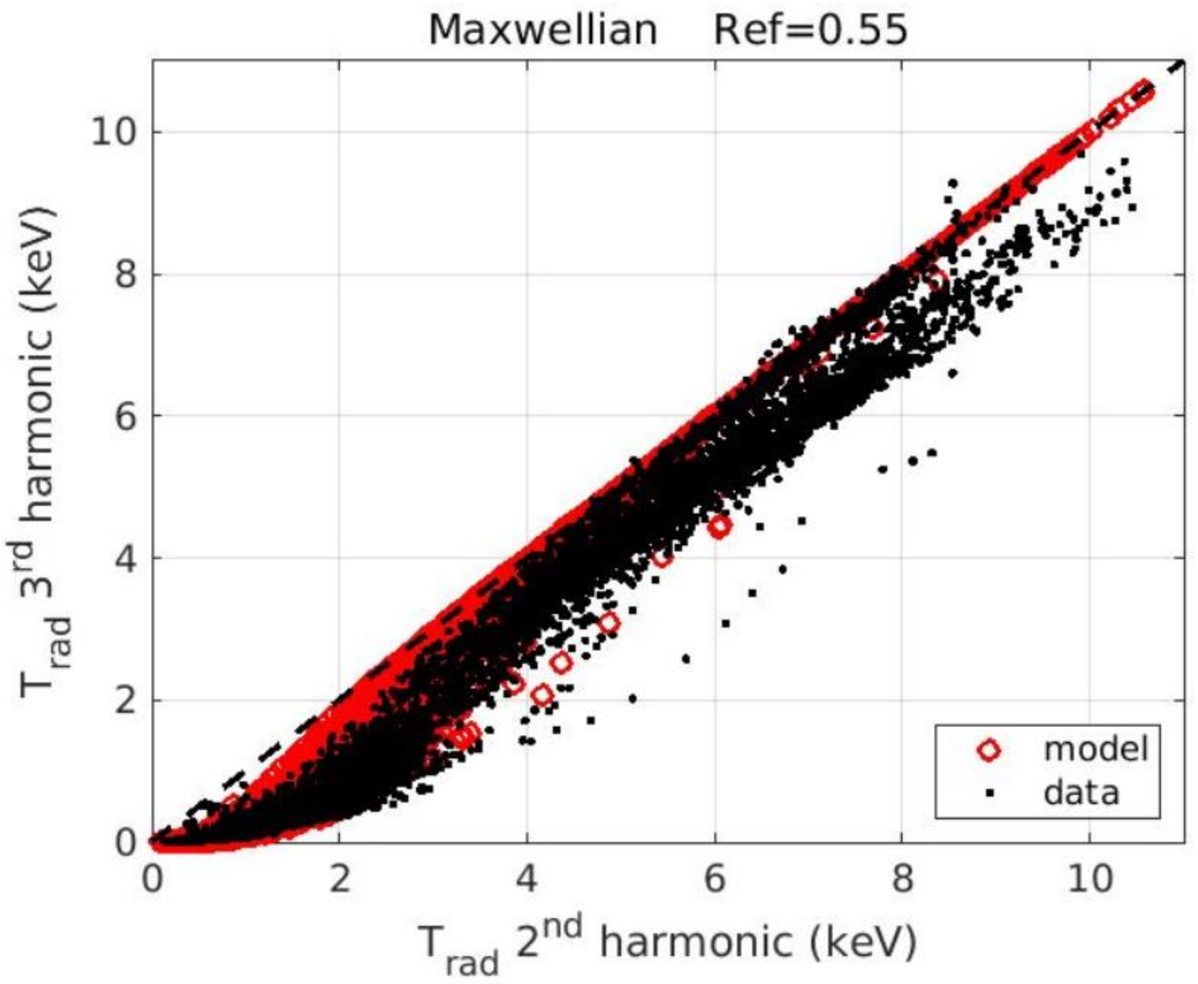
Different scenarios display well distinguished behaviour. Of particular interest is the difference in baseline pulses with and without Ne puffing.





Maxwellian predictions and data

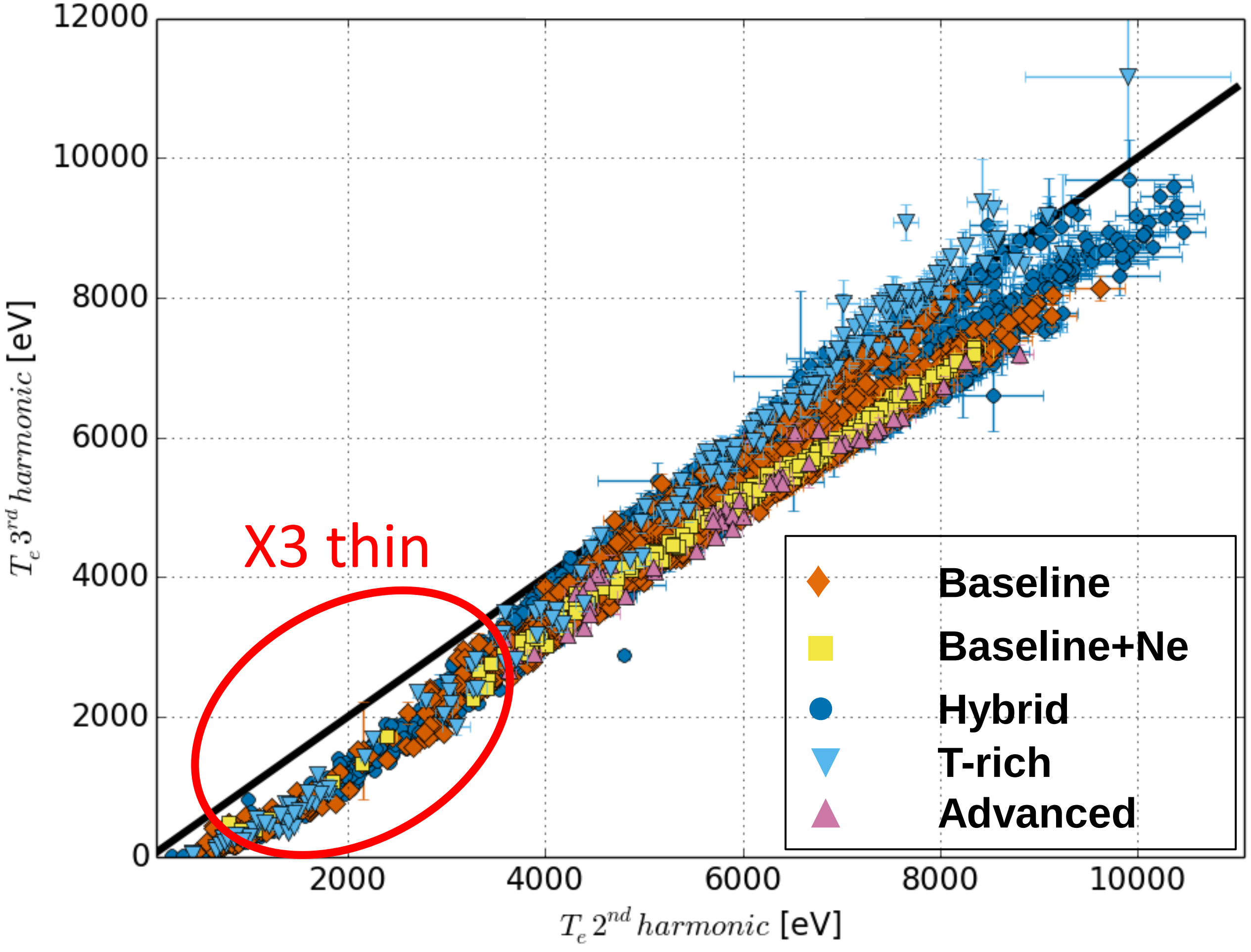


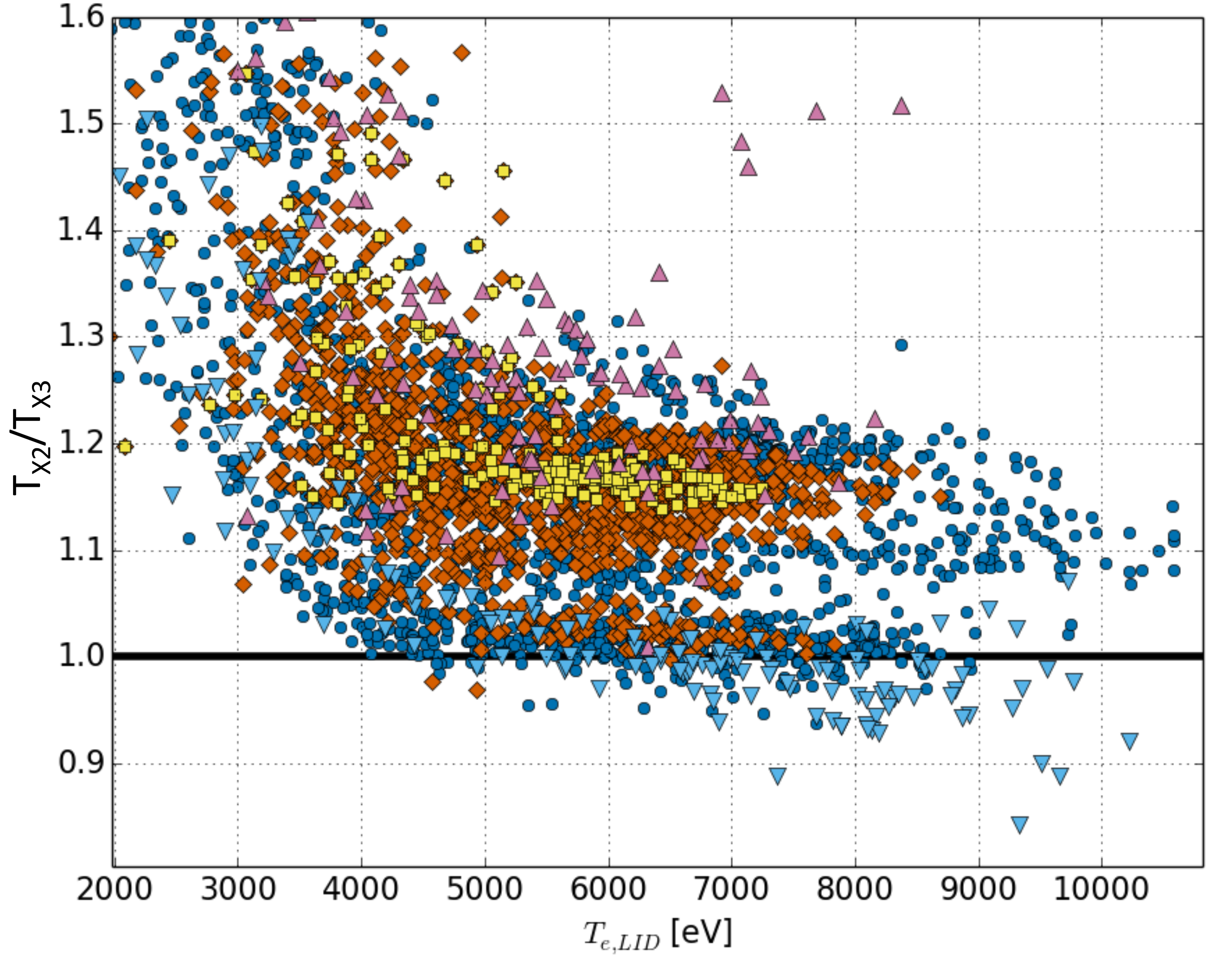


High-performance database: T_{X3} VS T_{X2}

Different trends appear looking at X2/X3: hints of non-Maxwellian behaviour.

Inside the same scenario, different behaviours can be observed.

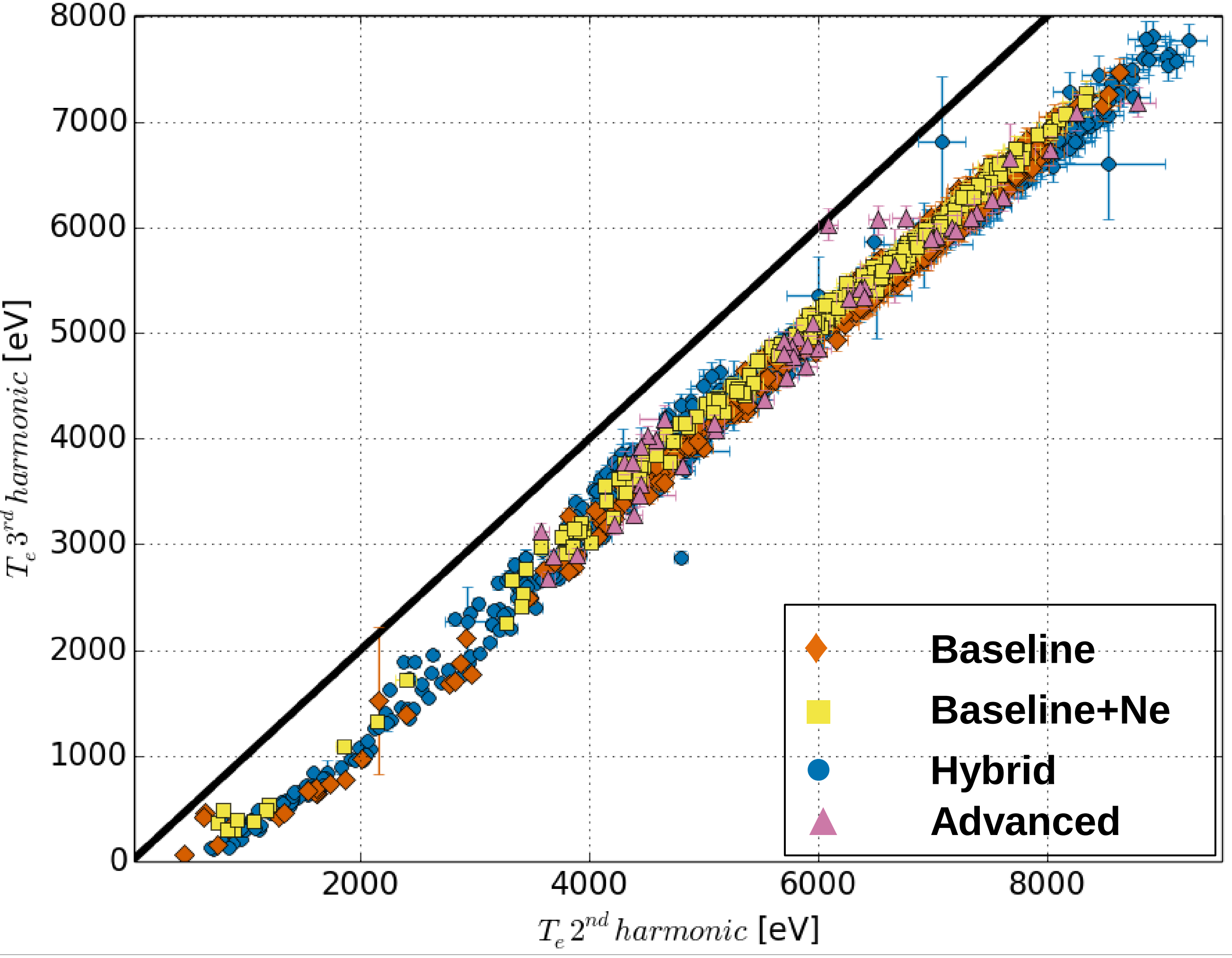


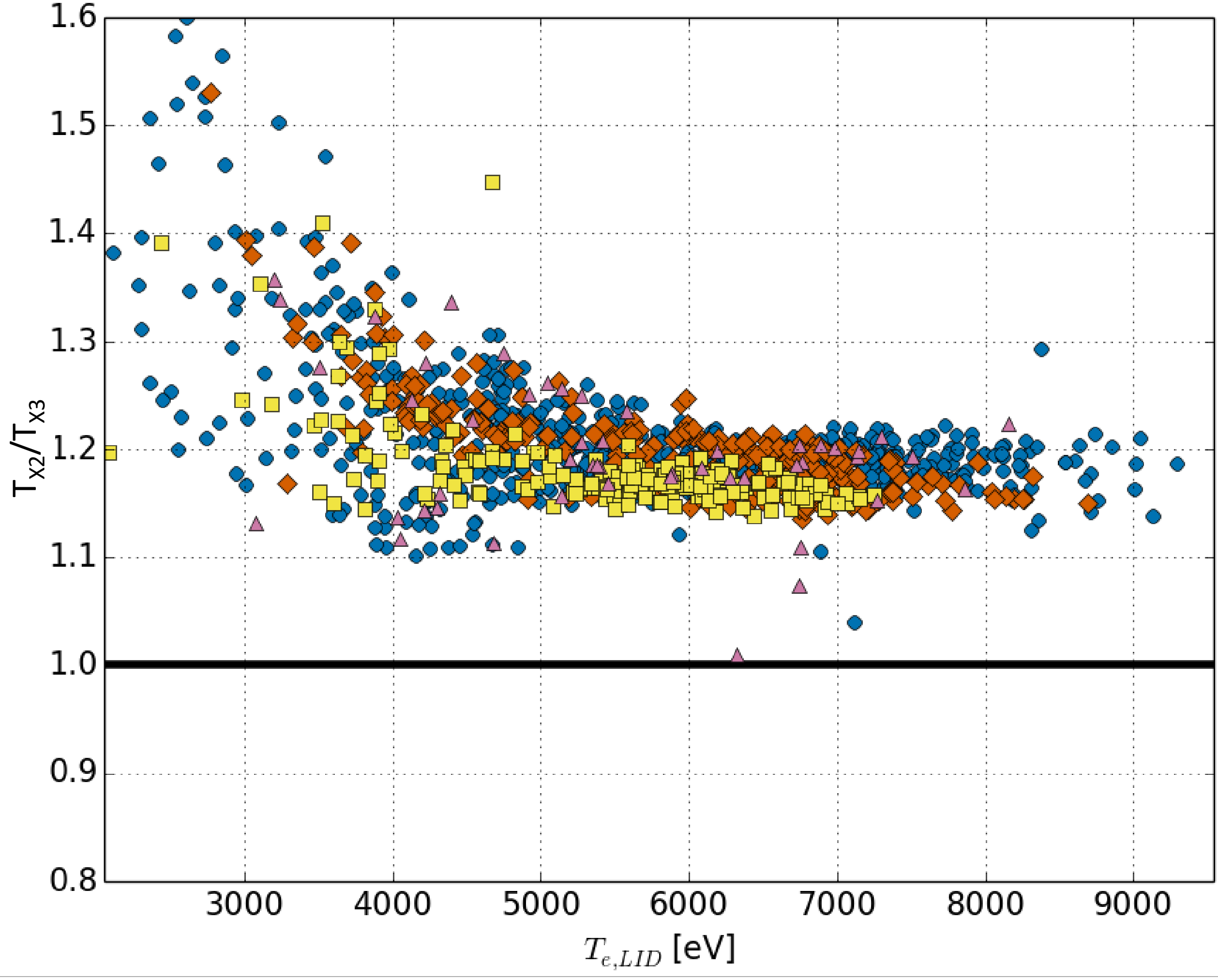


DD pulses before shutdown: T_{X3} VS T_{X2}

Only DD pulses from JAN-MAR 2020 (before shutdown).

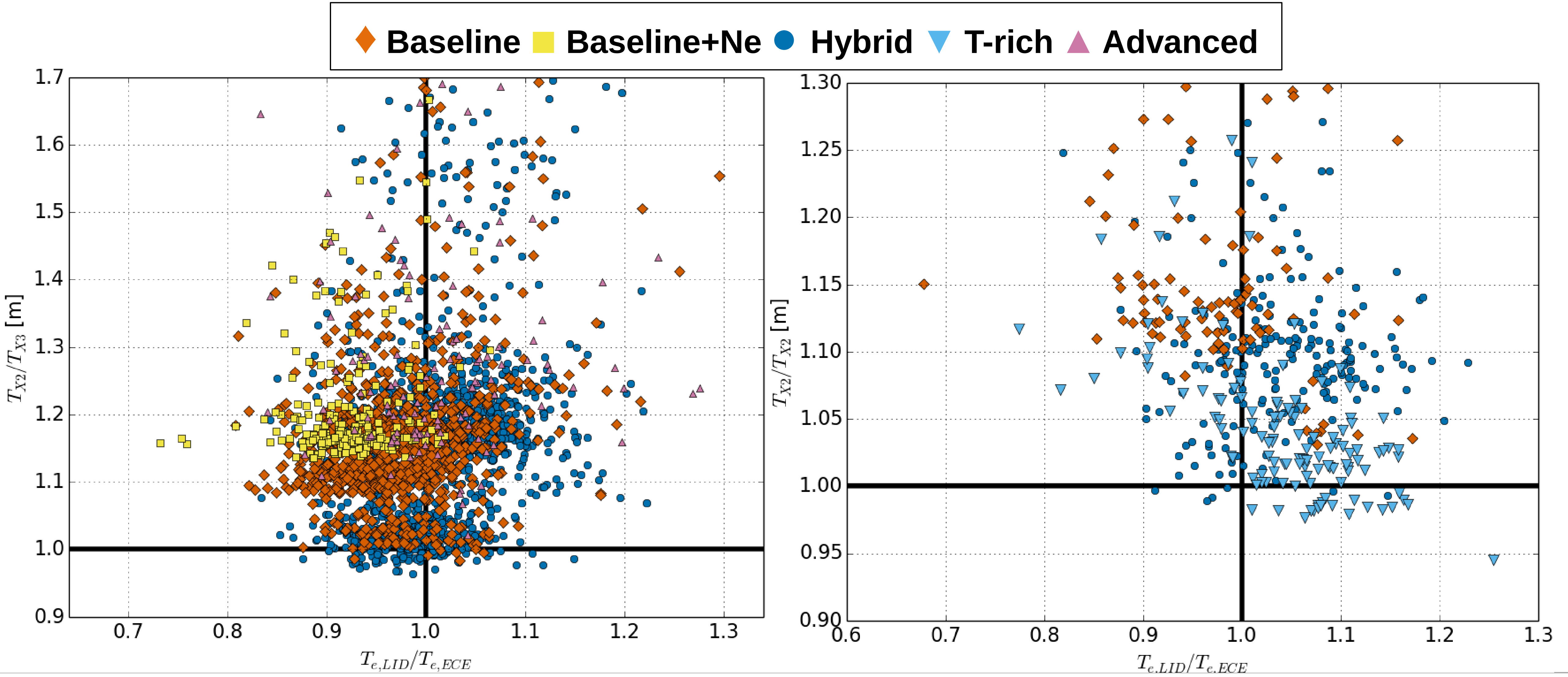
X2, X3 peaks similar for all pulses.



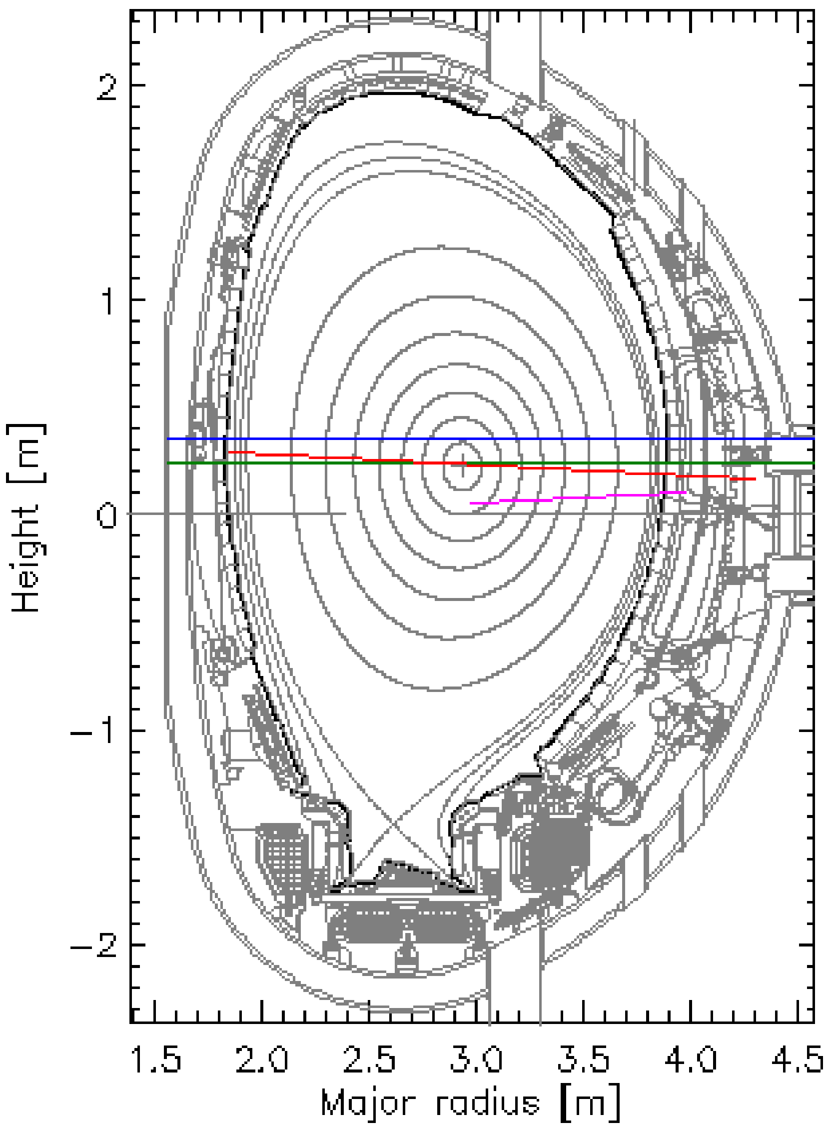


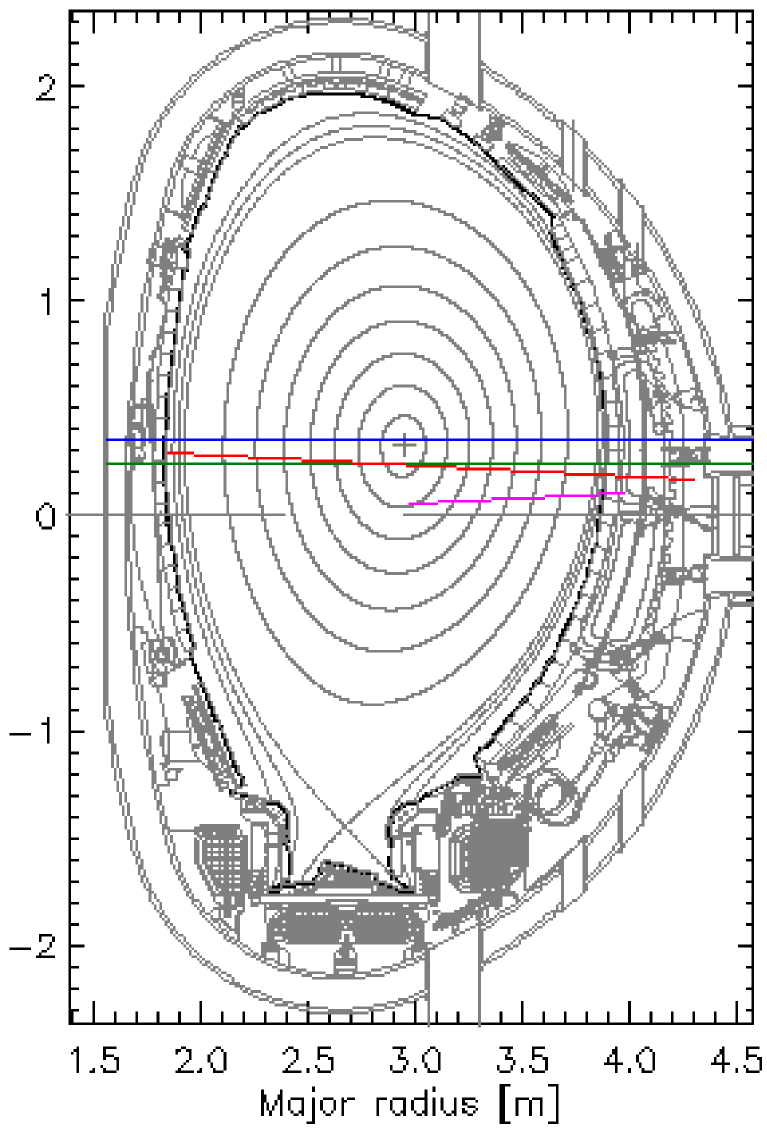
Harmonic ratio VS T_{LID}/T_{ECE}

Points distant from [1,1] should be the ones displaying non-Maxwellian features.



Z_{axis} influence on profiles



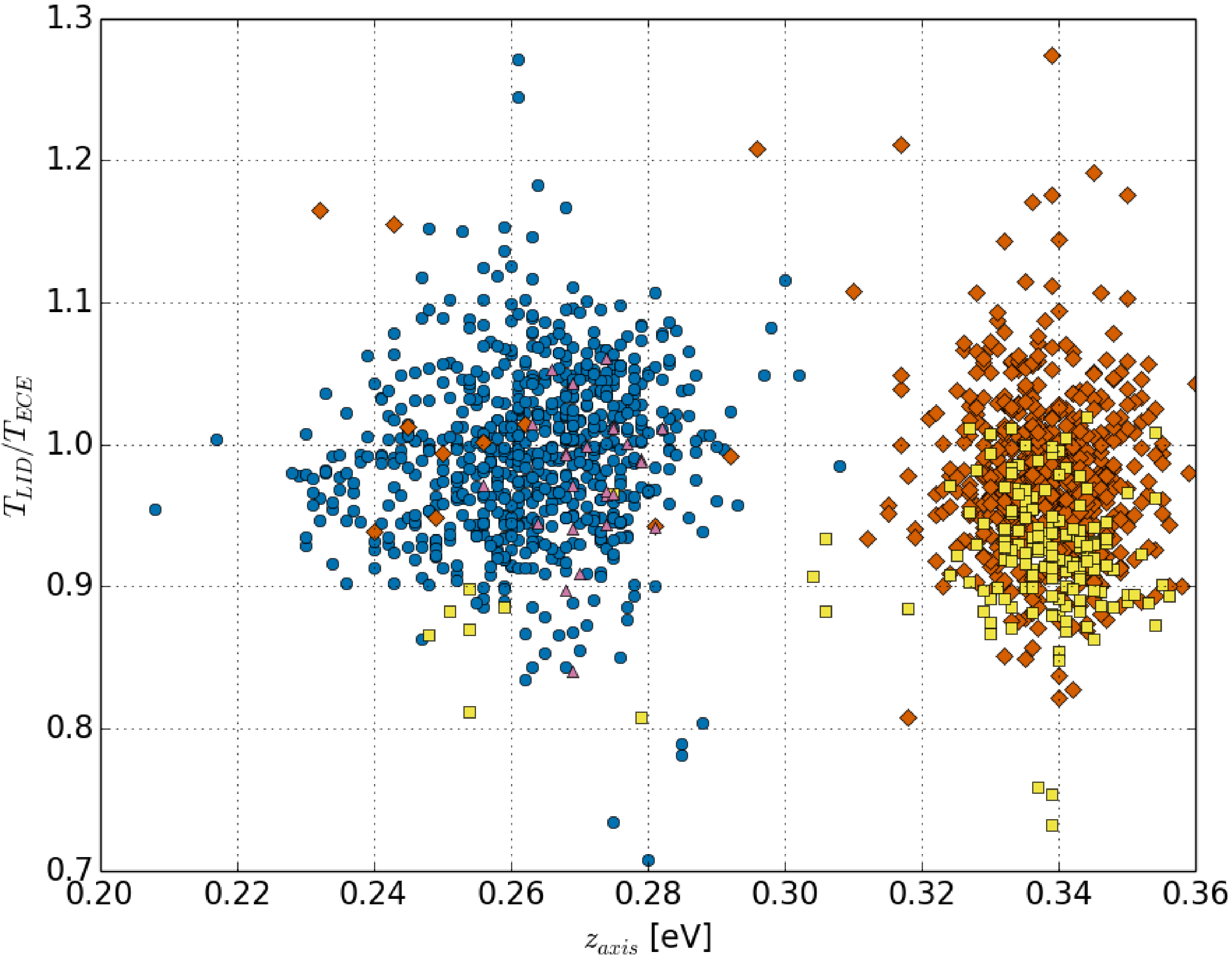


Different scenarios have different preferential plasma positions.
Hybrid: z_{axis}~0.25 m, Baseline: z_{axis}~0.35 m.
LIDAR/ECE probe the plasma core differently.

Could this alone explain some of our observations?

- ECE interferometer
- ECE radiometer
- LIDAR
- HRTS

Z_{axis} influence on profiles DD



While a difference in T_{LID}/T_{ECE} between hybrid and baseline can be seen, baseline points with and without Ne at very similar z_{axis} are still visibly different.

$7.5<n_{e0}<10.5\ 10^{19}\ m^{-3}$

- **Baseline**
- **Baseline+Ne**
- **Hybrid**
- **Advanced**

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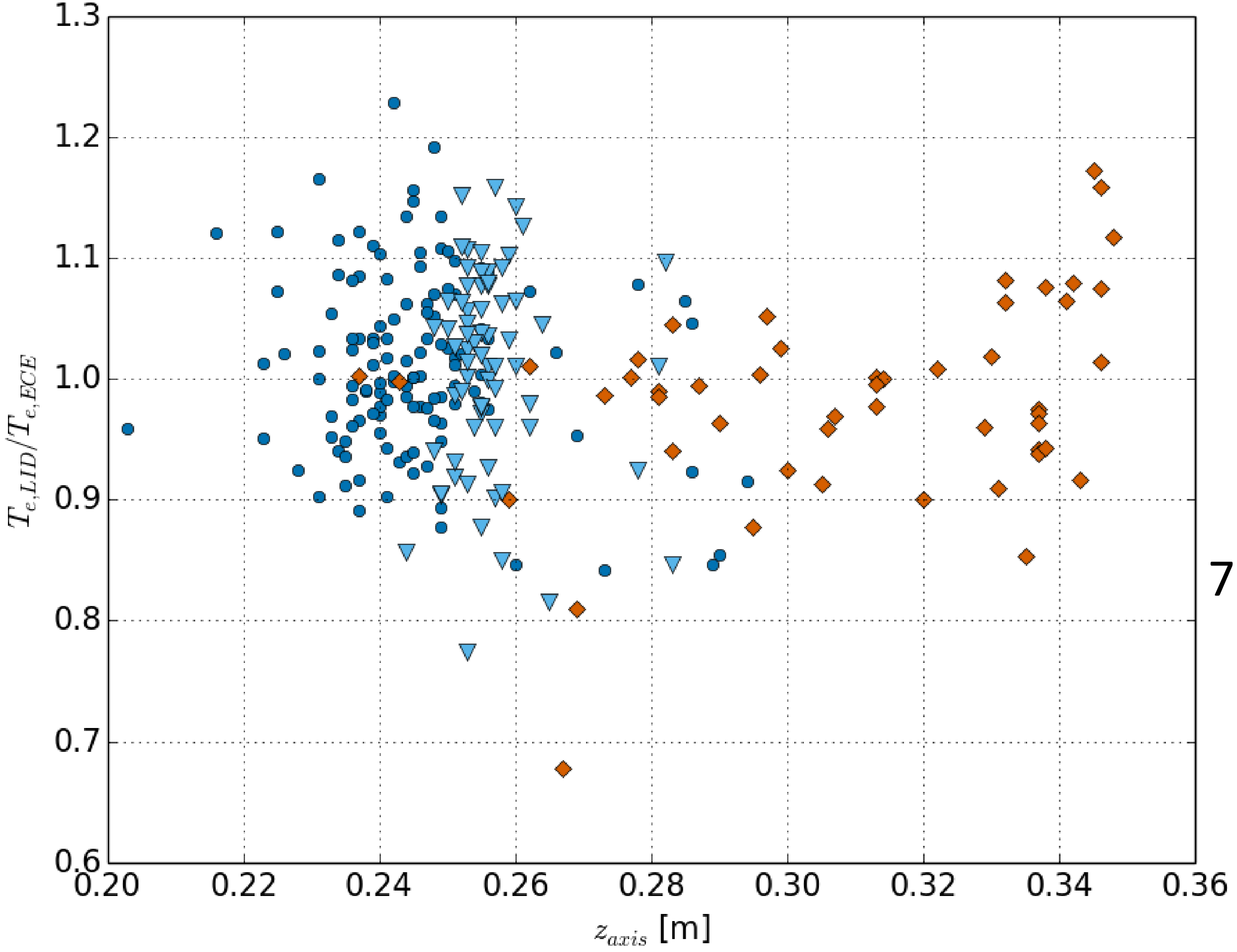
Z_{axis} influence on profiles DT



In DT the situation is less clear, but T_{LID}/T_{ECE} does not seem to correlate with z_{axis}.

$7.5<n_{e0}<10.5\ 10^{19}\ m^{-3}$

Baseline

Hybrid

T-rich

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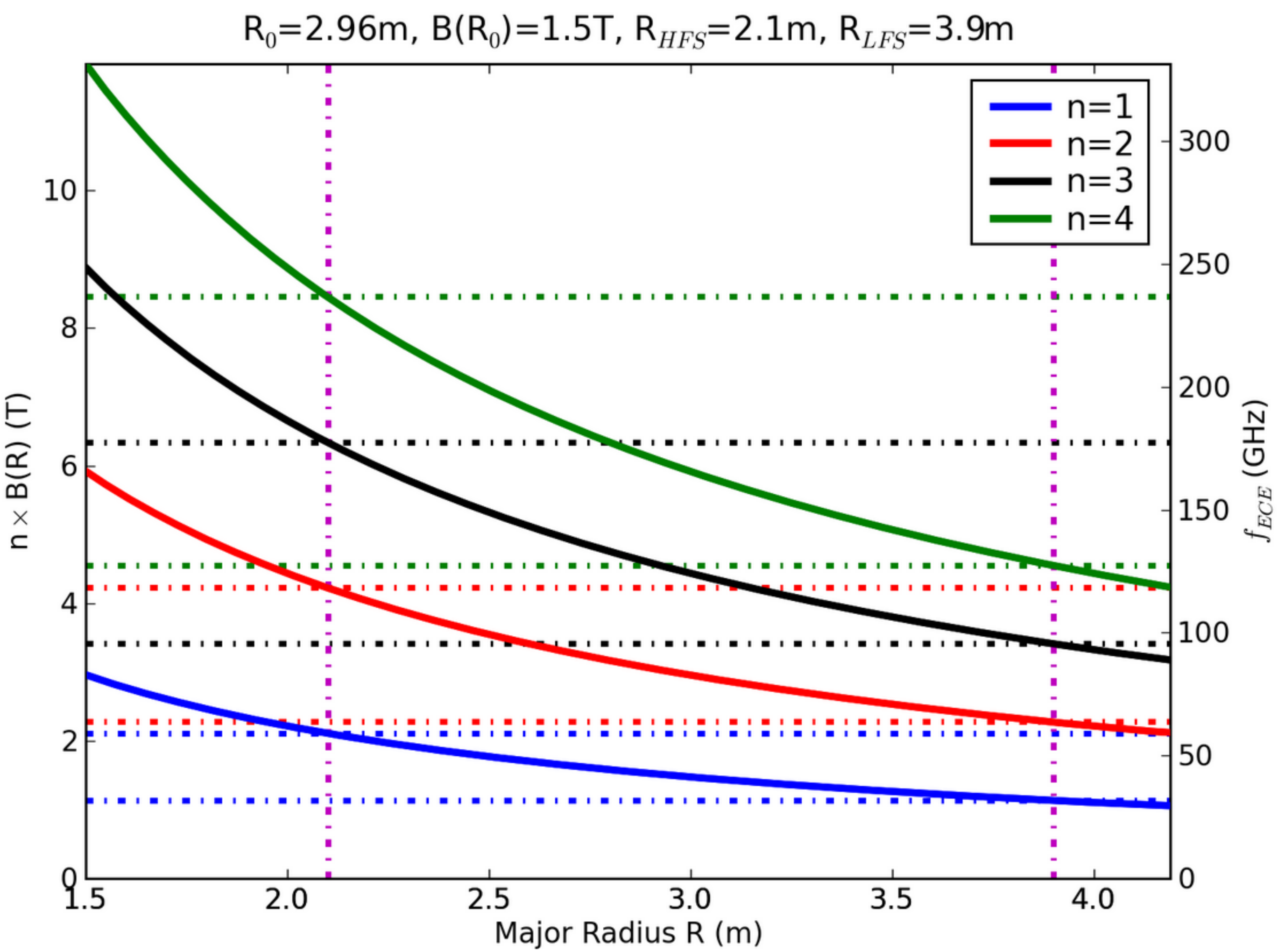
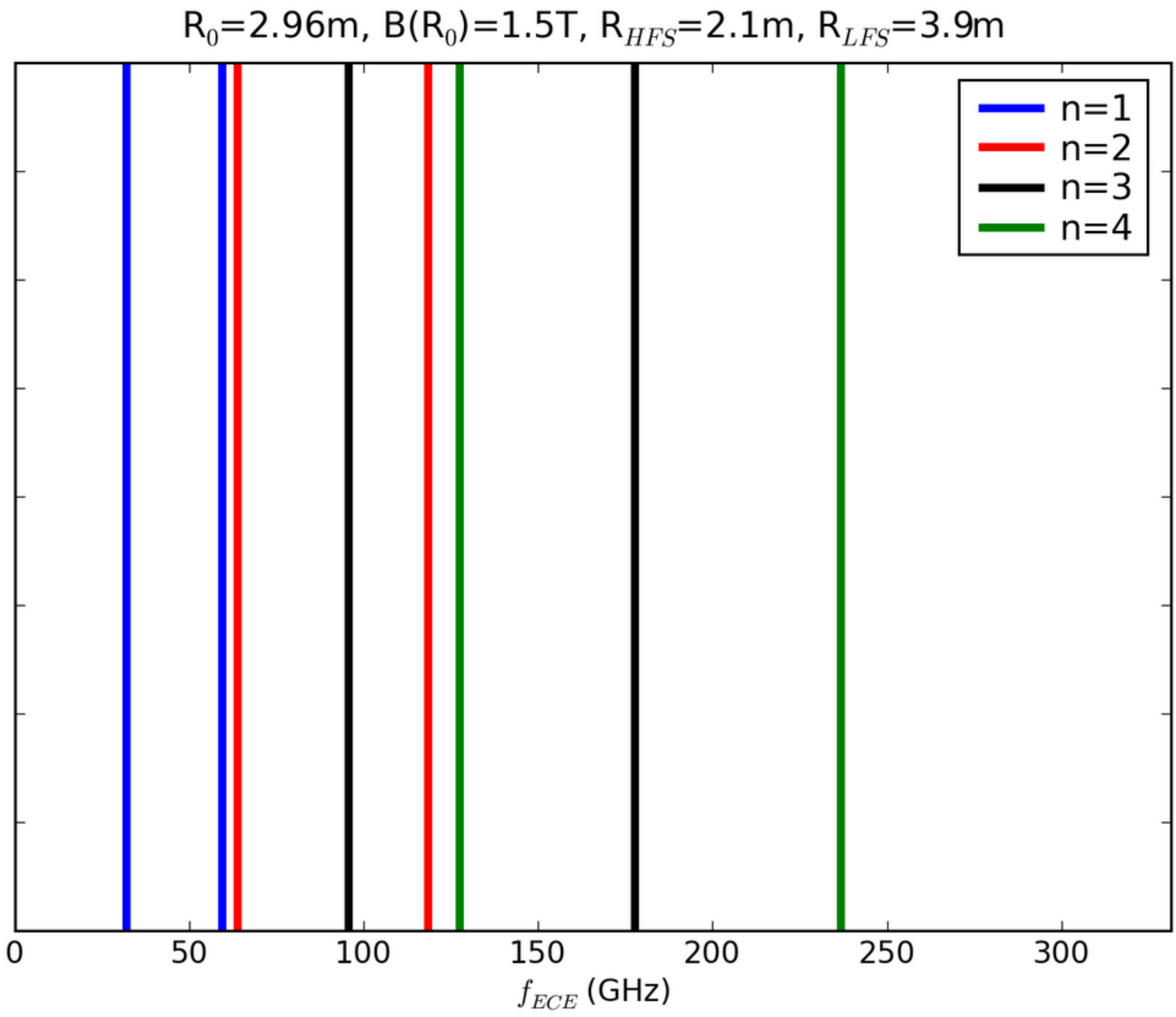
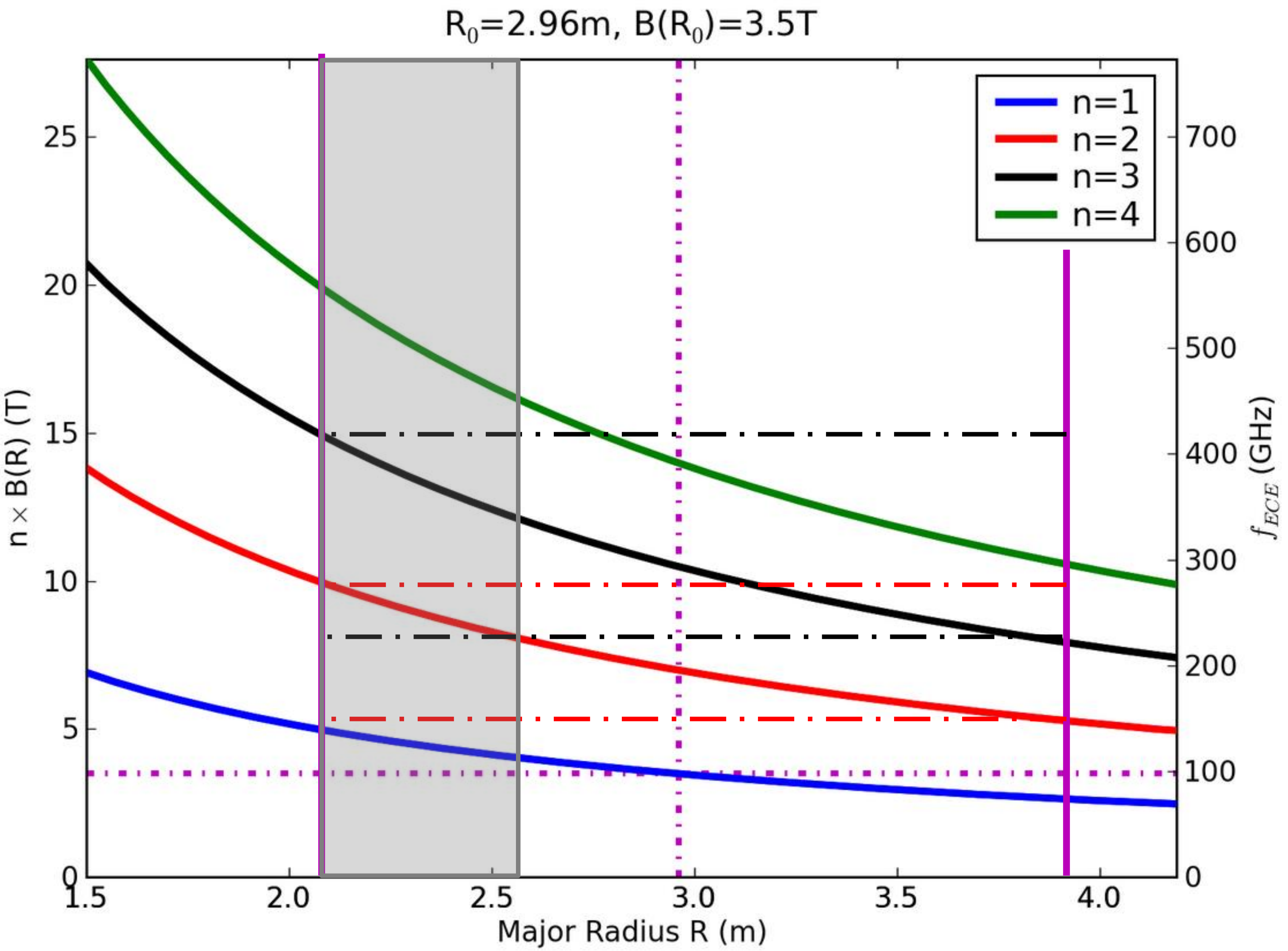
Harmonic overlap at JET





Harmonic overlap in JET



Conclusions: ECE/TS discrepancies observed

Experimental uncertainties

- ECE: long period without in-vessel calibration, compensated with frequent in-lab measurements
- LIDAR: low signal for high-energy channels at low T_e. Lack of data in TT campaign.
- Diagnostics Z_{axis}: for plasmas in database, plasma position does not affect comparison.
- Equilibrium reconstruction: despite averaging procedure, it can affect the final result. Manual effort to use pressure constrained equilibria in selected cases.

Database contains a large range of plasma conditions and scenarios.

- Many pulses with high T_e where discrepancies are visible, but **no systematic reproduction of previous observations: r**icher phenomenology compared with past results.
- Comparisons of X2/X3 spectra suggest presence of non-maxwellian EDF in some pulses.

Simple model of EDF perturbation can be a useful tool to understand if EDF distortions could reproduce these results → See next talk by G. Giruzzi.