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Analysis of the inter-species power balance in JET plasmas

(poster material … adapted to circumstances)

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AND JET CONTRIBUTORS*

view on youtube: https://www.youtube.com/watch?v=He1E_Dgz6_Q

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*See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux *et al* to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

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Overview

Motivation for this study of power balance:

- T_i from CXRS in JET-ILW (most often) difficult to analyse, long delays, often unavailable and sometimes inconsistencies (W nuisance lines)
  ⇒ need consistency checks
- $T_i < T_e$ at low power, $T_i > T_e$ in high power ‘DT scenarios’
  Neutron rates depend strongly on T_i
  ⇒ need better surrogates than simply assuming $T_i = T_e$
- Power balance is an essential part of any transport study, e.g. for comparison with GK modelling

Contents :

- Ion-electron power balance in JET
- “Equipartition temperatures”
- Fraction of ion heating source going to electrons by equipartition
- Main ion - impurity power balance
- Comparison with TRANSP
- Application of power balance for T_i profile reconstruction

ION-ELECTRON POWER BALANCE

Stationary heat balance of a main (i) and an impurity (z) species:

$$Q_i = Q_{is} - Q_{ie} - Q_{iz} \qquad Q_z = Q_{zs} - Q_{ze} + Q_{iz}$$

net source i-e and i-z equipartition

The 'Q's are volume integrals from 0 to V(r) of the local power densities, 'p's

$$Q_{is} = \int p_{is}\, dV \qquad Q_{iz} = \int p_{iz}\, dV$$

$$Q_{zs} = \int p_{zs}\, dV \qquad Q_{ie} = \int p_{ie}\, dV$$

Equipartition power density in W/m^3 for any two species i & j:

$$p_{ij} = c_{eq} \Lambda_{ij} \frac{(A_i A_j)^{1/2}}{(T_j A_i + T_i A_j)^{3/2}} \cdot Z_i^2 Z_j^2 n_i n_j (T_j - T_i)$$

$$c_{eq} = 3.2542 \times 10^{-32}\ W\, eV^{1/2}\, m^3$$

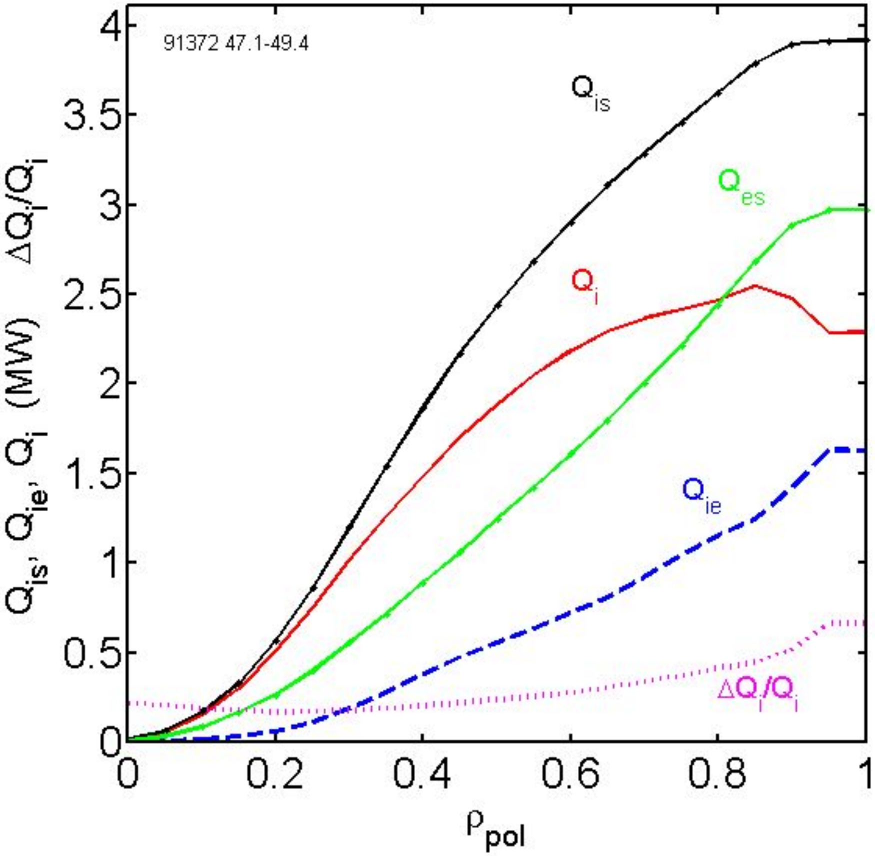
(from Wesson, also NRL formulary)

Example:

Electron-ion PB based on measurements of Te, Ti and heat deposition from PENCIL (no distinction between impurities and main ions here)

$\Delta Q_i/Q_i$ was evaluated assuming $\Delta T_i/T_i$=15%

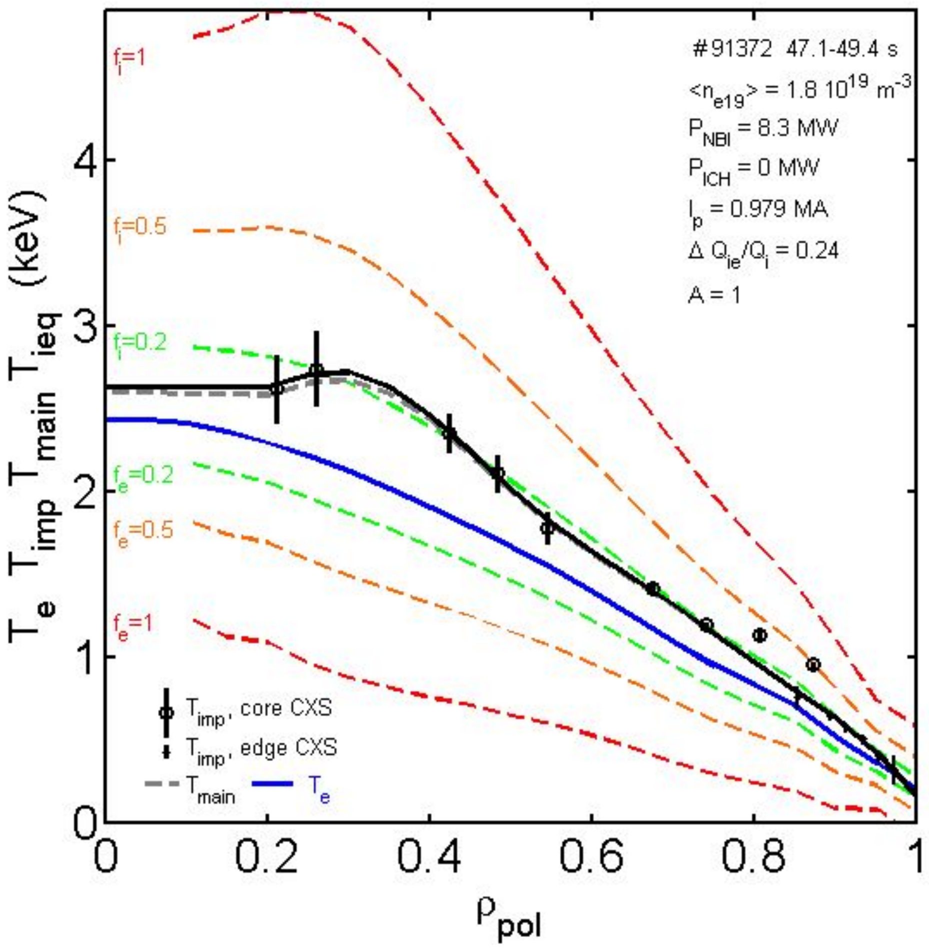
ref: H. Weisen, NF 2020



ION-ELECTRON POWER BALANCE (2)

“Equipartition temperature”

- In JET $T_e(\rho)$ and $n_e(\rho)$ are reliably measured using two Thomson scattering systems.
- The evaluation of $T_i(\rho)$ from CXRS in JET-ILW remains slow and error-prone because of the presence of W nuisance lines.
- Alternative way at looking at the electron-ion power balance: ***“What would be $T_i(\rho)$ be if a given fraction of the ion/electron deposited power was transferred to/from the electrons by thermal equipartition?”***
- Answer defines two families of ‘equipartition temperatures’ with examples shown for different $f_i(\rho)=Q_{ie}(\rho)/Q_{is}(\rho)$ and $f_e(\rho)=Q_{ei}(\rho)/Q_{es}(\rho)$

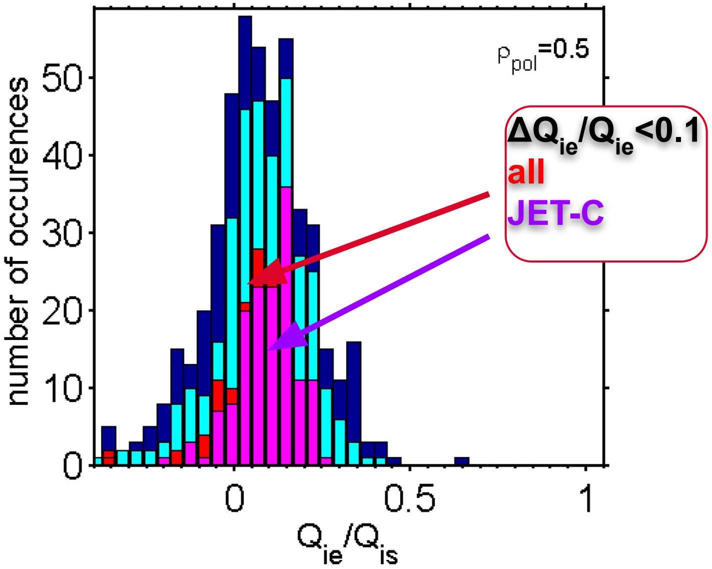


JET overview: typical ITG situation

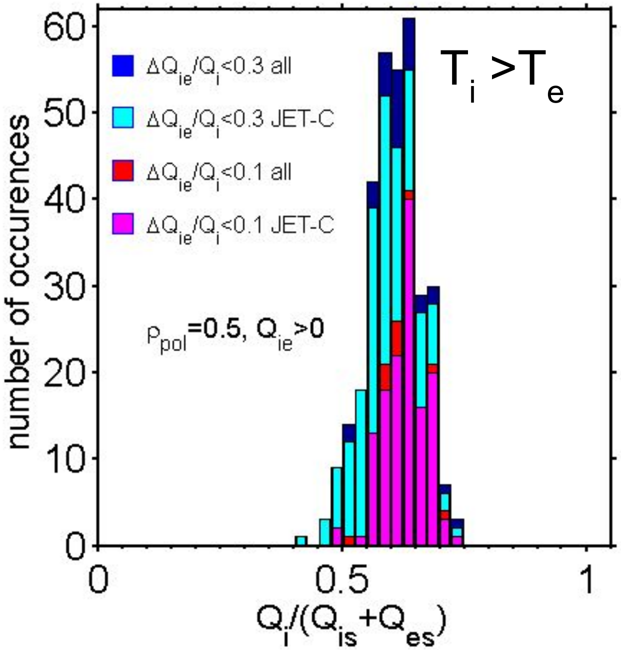
- Very wide range of conditions from JETPEAK
- For medium to high power NBI: $1<Q_{ie}/Q_{is}<0.4$
  cases with **most accurate PB**: $1<Q_{ie}/Q_{is}<0.25$

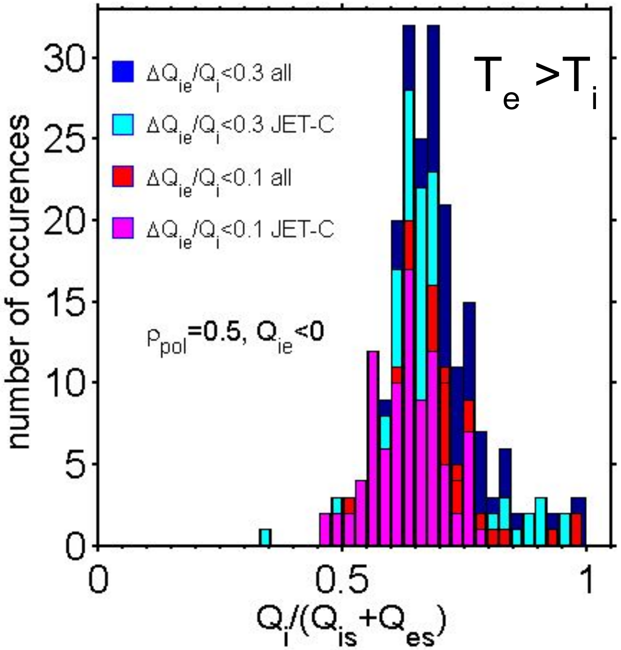
- $Q_i/(Q_i+Q_e)$ in range 0.5-0.7 for $T_i > T_e$
- $Q_i/(Q_i+Q_e)$ mostly in range 0.5-0.8 for $T_e > T_i$

⇒ Typical for ITG dominated discharges



$\Delta Q_{ie}/Q_{ie}<0.1$
all
JET-C





Ion-impurity power balance

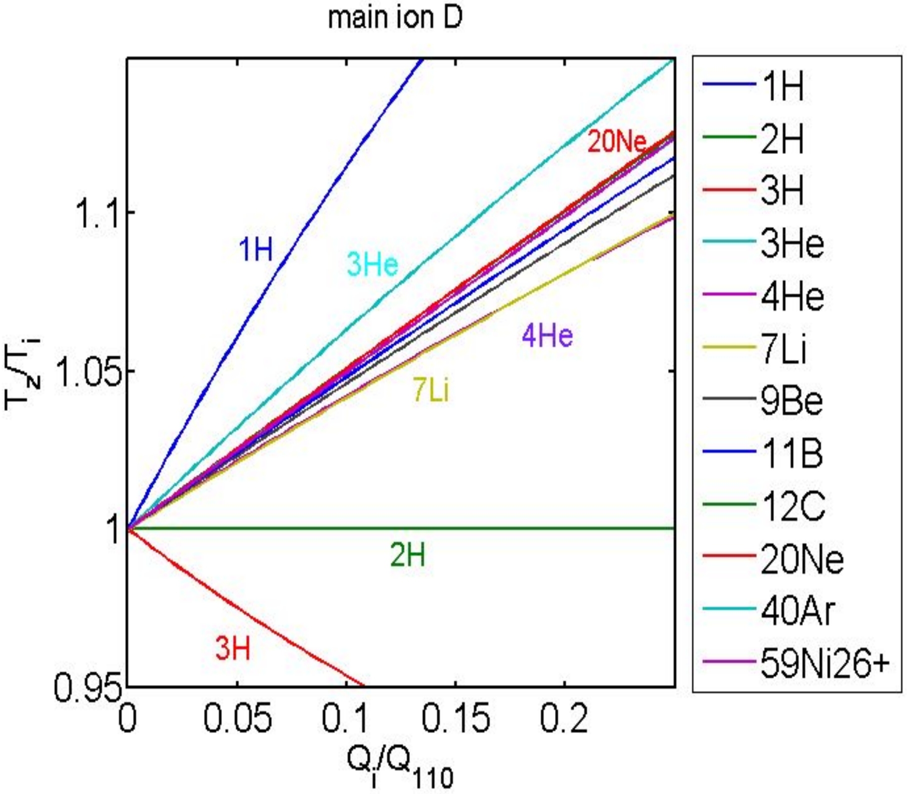
- The usual assumption $T_{main} = T_{imp}$ is not warranted at high power/low density!
- The energy exchange by collisional heating (NBI, ICRH, even ECH) scales as Z^2/A and is hence 10 larger for Neon ions (used for CXRS in JET-ILW) than for D ions!
- The stronger heating for higher Z is strongly counteracted by thermal exchange between impurities and main ions
- Additionally, main ions and impurities undergo transport
- Solution for T_z/T_i with explicit species dependence in H. Weisen, NF 2020

$$T_z/T_i \approx \frac{1+\dfrac{Q_i}{Q_{110}}\dfrac{A_i}{2^{3/2} Z_i^4 A_z \hat{A}}}{1+\alpha\dfrac{Q_i}{Q_{110}}\dfrac{1}{2^{3/2} Z_i^2 Z_z^2 \hat{A}}\dfrac{\Lambda_{11}}{\Lambda_{iz}}}$$

$$\text{where } \hat{A} = \frac{(A_i A_z)^{1/2}}{(A_i + A_z)^{3/2}}$$

$$Q_{110} = c_{eq} \Lambda_{11} 2^{-3/2} \int \frac{n_i^2}{T_i^{1/2}} dV$$

$\alpha = \chi_z/\chi_i = 1$

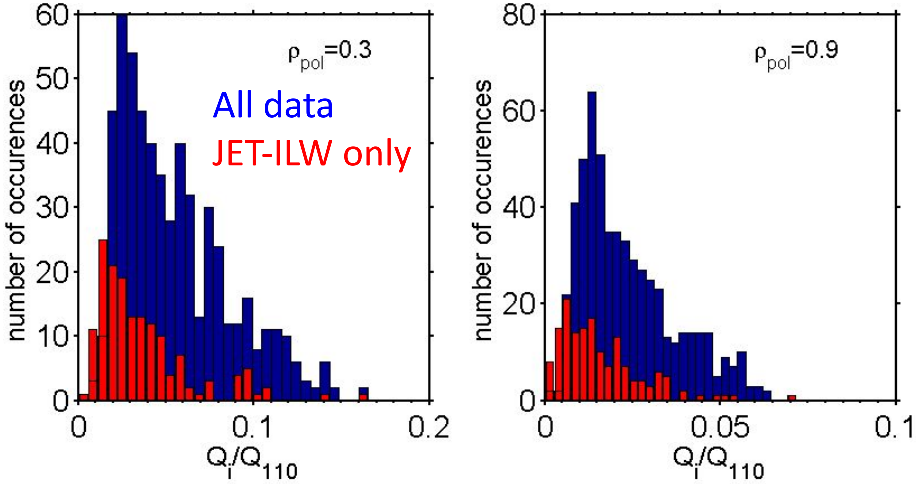


- Q_{110} is a reference ‘equipartitionality’
- T_z/T_i scales nearly linearly with Q_i/Q_{110}
- No significant species dependence for Z>3 ⇒ simplifies composite T_z profiles from several impurities. Mostly $Q_i/Q_{110}<0.1$

Species dependencies for Q_i/Q_{110}=0.1

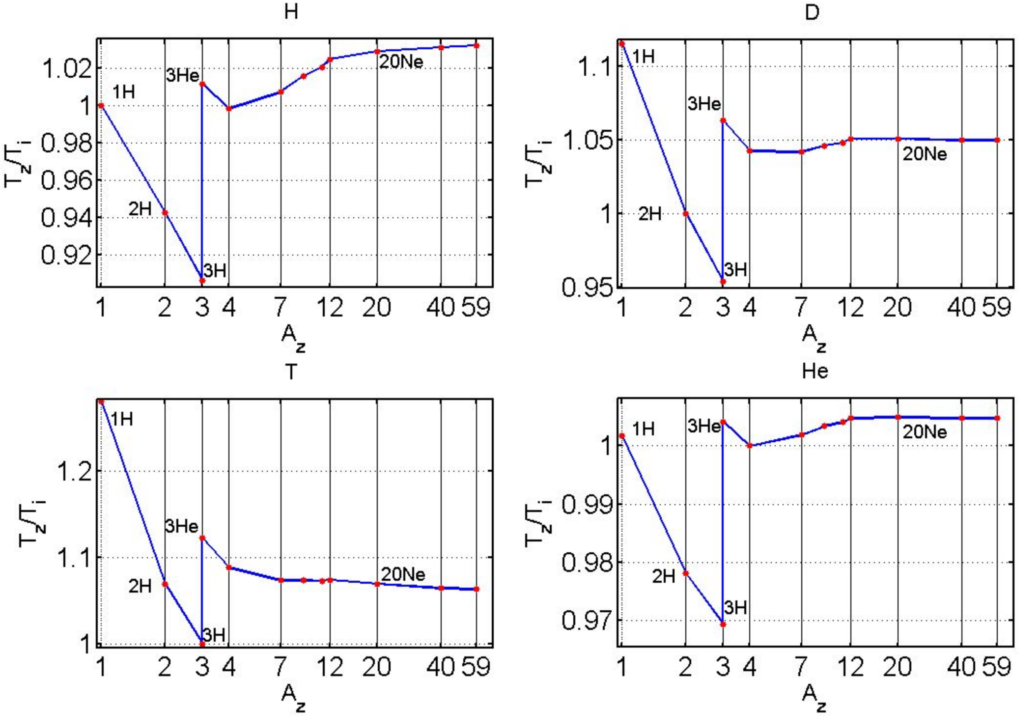
Histograms for Q_i/Q_{110}

- Q_i/Q_{110}<0.1 for majority of cases
- Q_i/Q_{110}~0.1 is obtained at high P_{NBI}, low density, e.g. AT, hybrid



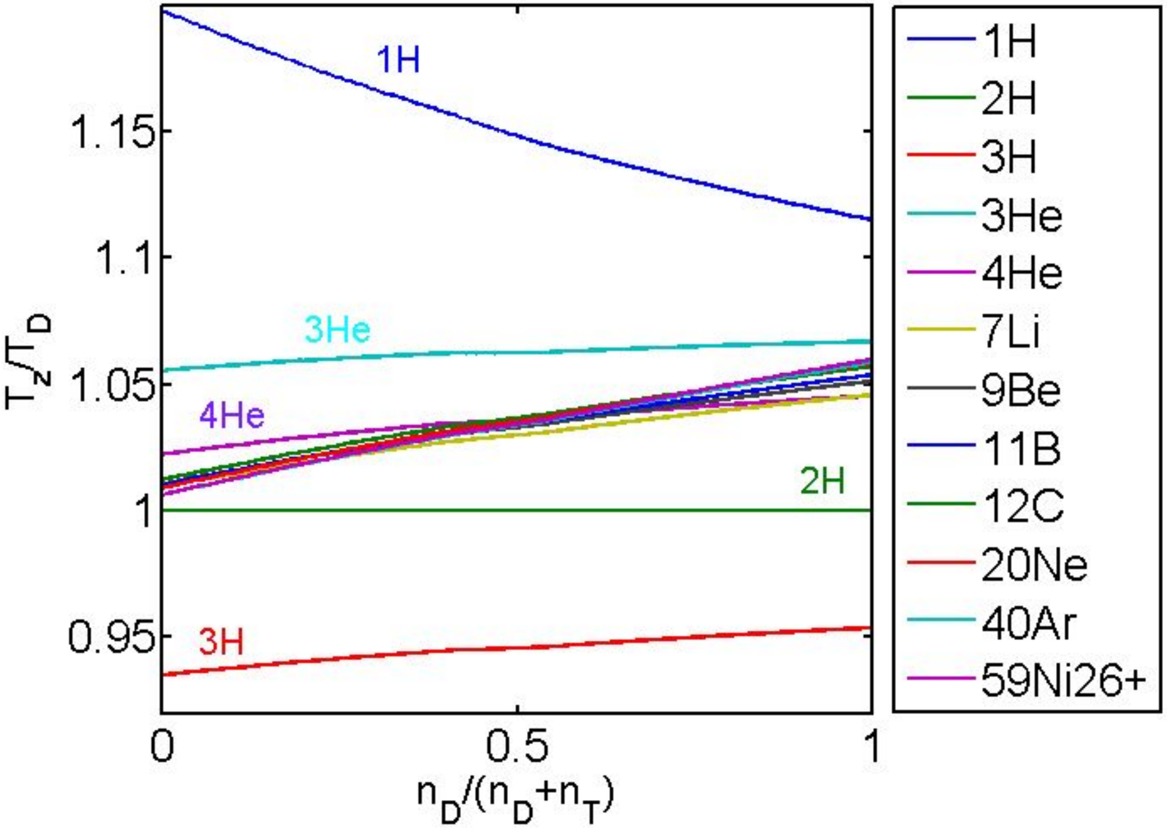
Species-resolved for Q_i/Q_{110}=0.1 and 4 main species, $\alpha=\chi_Z/\chi_i$=1

- All commonly used impurities for diagnostics have T_z within 1% B,N,C, Ne, Ar, Ni are especially close to each other
- Convenient, as no need to distinguish between T_{imp} from different species
- Highest T_H/T_T for hydrogen impurity in tritium plasma (~1.28!)



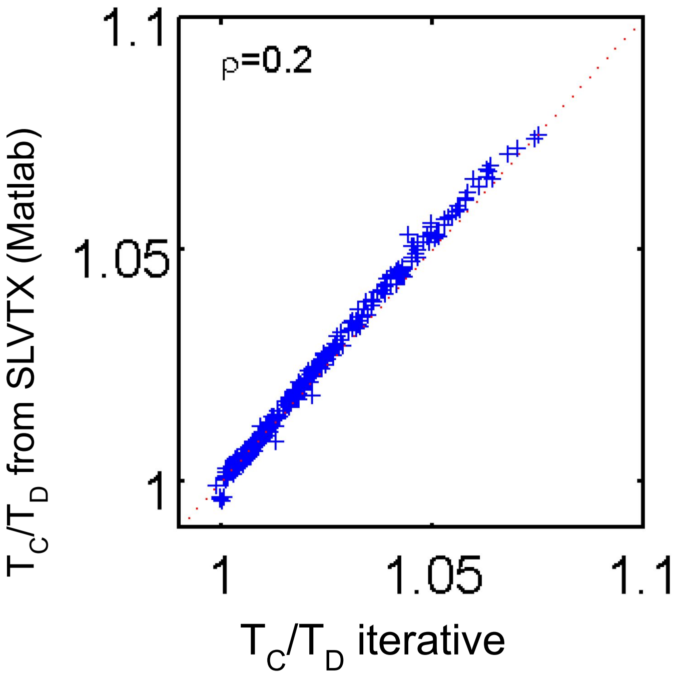
T_Z/T_D for Q_i/Q_{110}=0.1 in D/T mixture

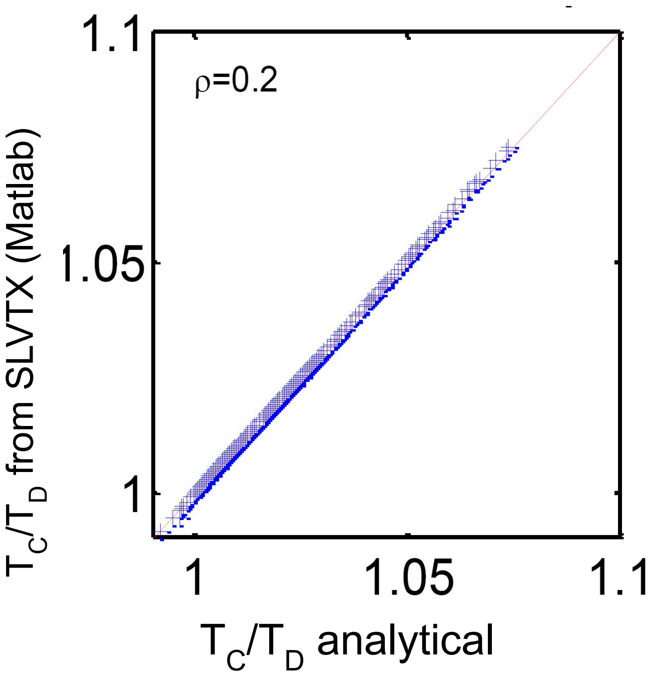
- Calculation for mixed main species technically similar to single main species, see H. Weisen, NF 2020
- Unsurprisingly, T_z/T_m in mixed isotope plasmas assumes values intermediate between those of single isotope plasmas.
- T_T/T_D ≈0.95 for Q_i/Q_{110}=0.1 (hybrids, AT)
- Inconsequential for DT operation



Comparison with TRANSP-SLVTX

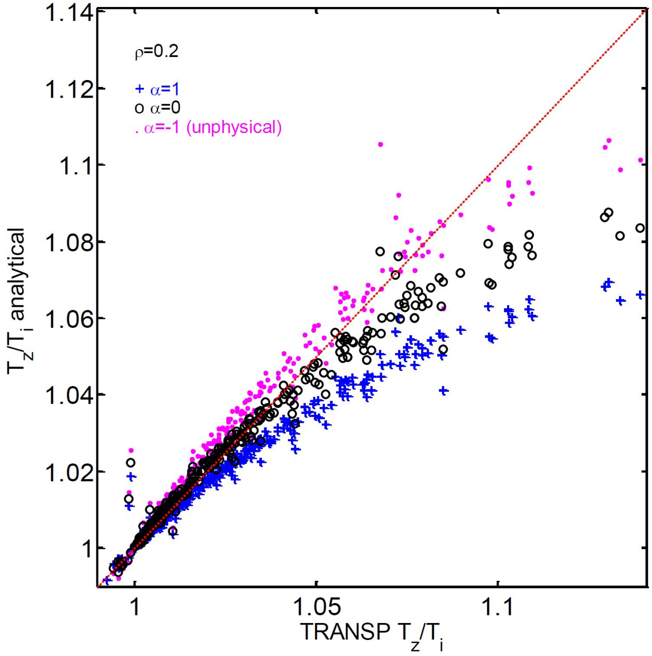
- Dataset of over 300 TRANSP JET-C runs “Neutron deficit” H. Weisen NF 2018]
- Implemented a stationary state Matlab version ($\partial/\partial t=0$) of the procedure intended for TRANSP routine SLVTX (S.D. Scott, PPPL document, 4.2.2003)
- SLVTX is based on the idea of a local confinement time and applied it to the same input data as in our own calculations (analytical and iterative).
- The SLVTX (matlab) and analytical methods are virtually indistinguishable. Both calculate a slightly larger than the fully iterative solution presented H. Weisen NF 2020. In all cases **$\alpha=\chi_Z/\chi_i=1$** is assumed.

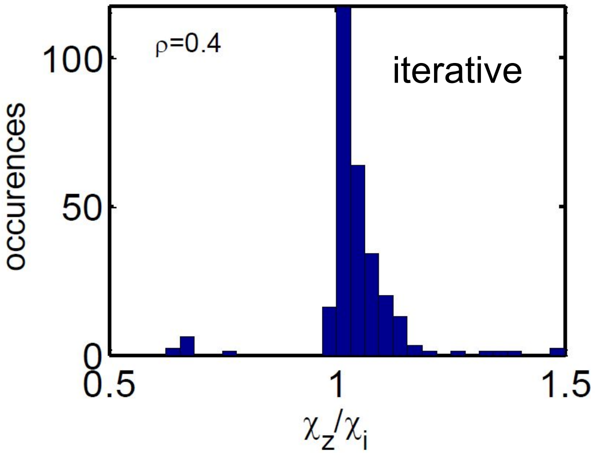


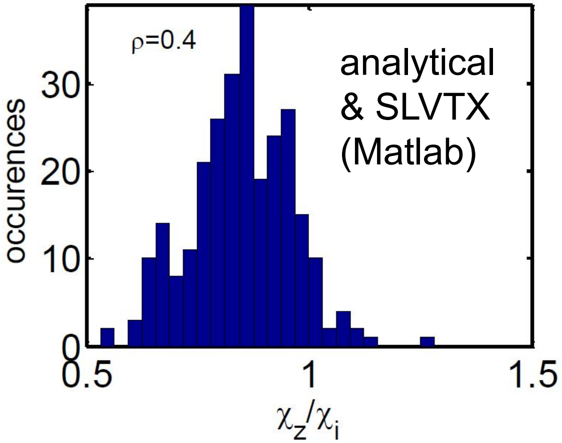


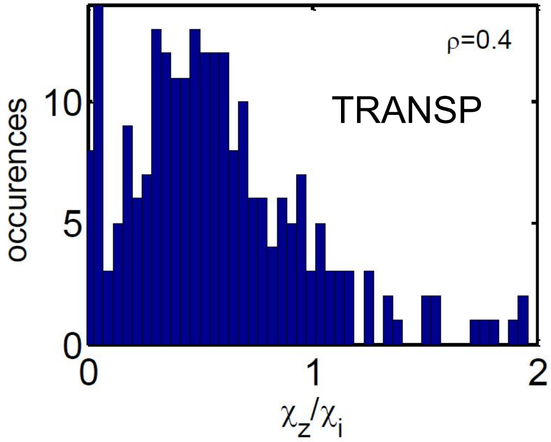
Likely error of sign in TRANSP-SLVTX

- While the intended algorithm behind the SLVTX routine in TRANSP is correct, the code implementation is not.
- At high Q_i/Q_{110} it predicts T_T/T_D twice as high as the Matlab implementation and as the analytical and iterative methods
- The difference is not a different assumption for $\alpha=\chi_Z/\chi_i$. However, setting $\alpha=\chi_Z/\chi_i$ =-1 brings “agreement” suggesting a sign error SLVTX for a term designating $\alpha=\chi_Z/\chi_i$ or Q_Z.
- Despite simplifications ($T_Z/T_i=\nabla T_Z/T_i$) the iterative solution mostly provides T_i profiles close to satisfying χ_Z/χ_i =1, the analytical solution falls short (although T_Z is very similar).
- TRANSP is far from satisfying χ_Z/χ_i =1.
- TRANSP also produces many cases where Q_{CD}/Q_{Cs}>1, i.e. the impurity power balance is crassly unphysical. (For the iterative method Q_{CD}/Q_{Cs}≃0.77)







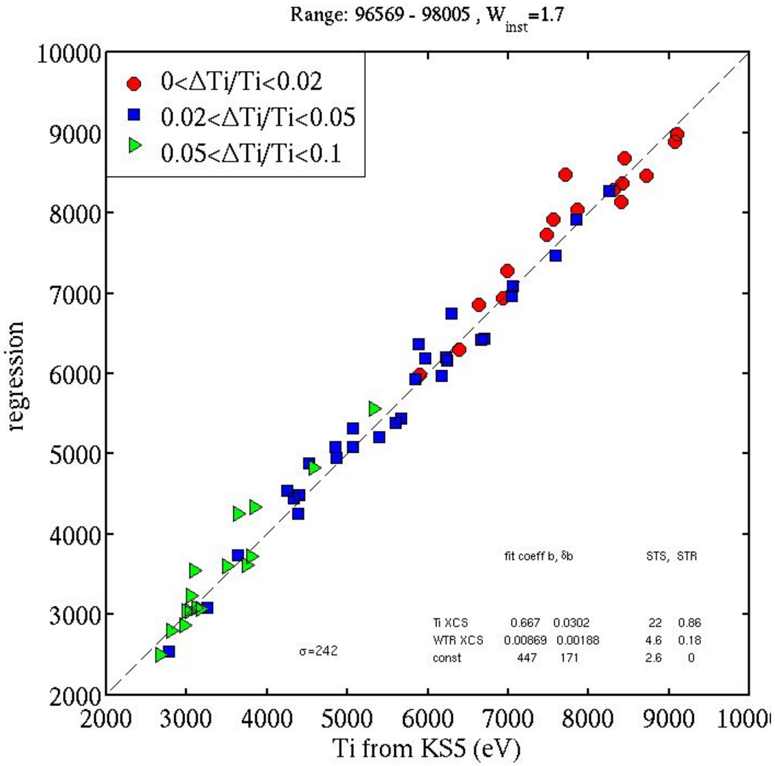


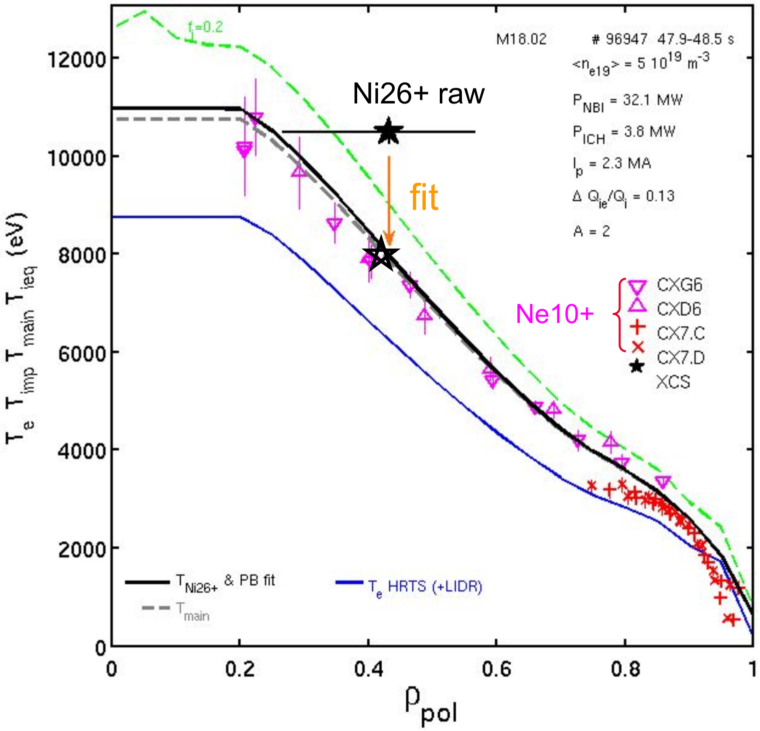
Being creative

1. You are desperate for T_D profiles (e.g. P. Sirén et al, IAEA FEC 2020) & no T_Z from CXRS
2. $<T_{Ni26+}>$ from X-ray crystal spectroscopy always available, but line averaged, rotationally shear-smeared and systematically above available and believable T_z from CXRS

ANSWER

1. Regress T_Z CXRS with $<T_{Ni26+}>$ and $<\Omega_{Ni26+}>$ to std=250eV (left figure)
2. Infer equivalent T_Z CXRS ☆ for any plasma with good Ni26+ data at that point (right figure)
3. Extrapolate T_Z to whole profile vie equipartition temperature (black —)
4. Get T_{main} from ion-impurity power balance calculations (grey--). Note: doesn't work for ion-ITBs!





one of the few high R_{DD} hybrids that has Ti from CXRS

Summary

- Equipartition limits show far the temperatures of plasmas species can go apart
- In most chiefly ion heated plasmas in JET ($T_i > T_e$, e.g. NBI) the ions lose up to ~30% of their input power to the electrons by thermal transfer
- The fraction of power lost to electrons is found to be close to constant for most of the plasma cross section
- In a wide range of JET plasmas, whether $T_i > T_e$ or $T_i < T_e$, we find $Q_i/(Q_i+Q_e) \geq 0.5$, which is a hallmark of ITG-dominated micro-turbulent transport
- Main hydrogenic ion temperatures near the magnetic axis are typically a few % lower than impurities, exceptionally up to 10% at high power and low density. The tritium temperature is predicted to be a few % below the deuterium temperature.
- For Z>3 impurity temperatures are virtually species-independent.
- The analytical method and a Matlab implementation of SLVTX produce virtually indistinguishable results. Both predict slightly larger T_C/T_D than the iterative method.
- Someone should shoulder the ungrateful task of revising the SLVTX routine’s vintage Fortran code in TRANSP.
- The power balance calculation is made good use of at JET by allowing to infer an entire ion temperature profile from a single local or line-integrated measurement, e.g. from Ni^{26+} emission, when charge exchange profile measurements are unavailable.