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Non-Maxwellian EEDF Features in JET DTE3 Plasmas via ECE and Thomson Scattering Comparison

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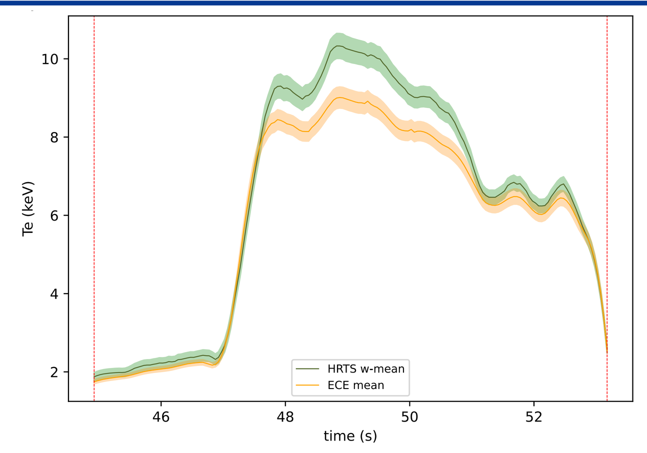
** See C. Maggi et al. Nucl. Fusion 64, 112012 (2024)
*** See N. Vianello et al. Nucl. Fusion 66 116010 (2026)

Introduction:

- Burning plasma conditions studies are of fundamental importance for future fusion reactors: next-generation tokamaks will reach very high temperatures and sustain them for long durations
- The measurement of the core electron temperatures becomes challenging when the Elector Energy Distribution Function (EEDF) is not Maxwellian
- Discrepancies arise between diagnostics such as Thomson Scattering and ECE [1] .
- Accurate temperature measurements are critical for future reactors like ITER, CFETR or DEMO, where core Te is expected to be up to 25 keV [1 - 3].
- The discrepancies highlight not only a diagnostic issue but also an opportunity to deepen the understanding of core plasma physics: Deviations from a Maxwellian distribution can significantly affect electron temperature measurements [3], which strongly depend on the shape of the EEDF [4,5].

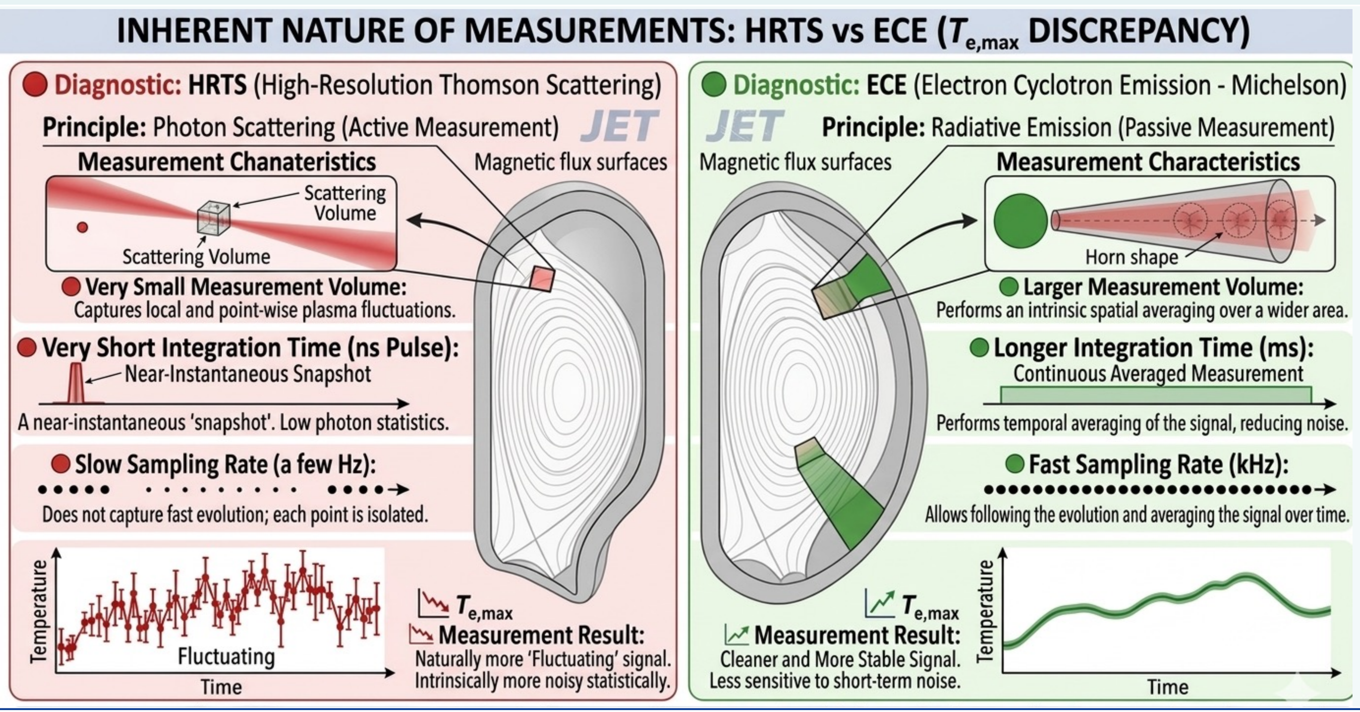


History bullets/previous studies:

- Numerous papers over the past decades have reported on discrepancy studies on different machines [8,9].
- A dependence of the discrepancy on the electron energy distribution function has been identified [5,10].
- More recently significant efforts have focused on analysing the JET DTE2 data [4,5,7] and improving the modelling [11].

Diagnostics for the comparison

ECE and Thomson Scattering (TS) are the two most widely used and reliable electron temperature diagnostics in tokamaks.
Despite fundamentally different physical mechanisms, geometrical configurations, integration times, and spatial sampling volumes, rigorous methods allow direct comparison [7,8].



EEDF Sensitivity Differs Between Diagnostics

The Thomson Scattering signal is proportional to the Velocity Distribution Function (VDF), denoted as f(v). Specifically, TS samples the projection of the VDF along the scattering vector $k = k_s - k_i$:

$$S(\mathbf{k},\omega) \propto \int f(\mathbf{v})\delta(\omega - \mathbf{k}\cdot\mathbf{v})\,d\mathbf{v}$$

$$S(\lambda) \propto \frac{n_e}{\lambda^2}\cdot\exp\left(-\frac{m_e c^2}{k_B T_e}\left[\sqrt{1+\left(\frac{\Delta\lambda}{\lambda_i}\right)^2\frac{1}{\sin^2(\theta/2)}}-1\right]\right)$$

$$T_e^{\mathrm{ECE}}(\omega) \propto \int_{R_0}^{R_0+a} j(\omega,R)\cdot\exp\left(-\int_R^{R_0+a}\alpha(\omega,R')\,dR'\right)dR$$

Local emission coefficient

$$j(\omega,R) = \int_0^\infty \alpha_{\mathrm{em}}(\omega,p,R)\cdot f(p,R)\cdot p^2\,dp$$

Local absorption coefficient

$$\alpha(\omega) \propto \int \mathcal{K}(\omega,p)\cdot\left(\frac{\partial f(p)}{\partial p_\perp}\right)d^3p$$

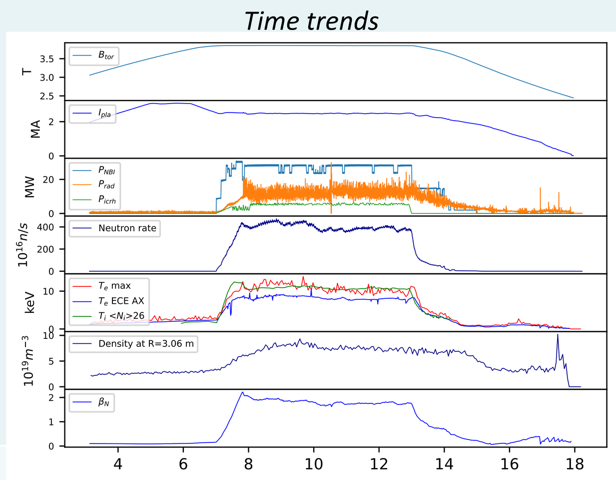
$$T_e^{\mathrm{ECE}}(\omega) \propto \int_{R_0}^{R_0+a} \exp\left(-\int_R^{R_0+a}\alpha(\omega,R')\,dR'\right)dR$$

The strong sensitivity of ECE to very small perturbations in the electron distribution is due to the fact that the absorption coefficient is proportional to the derivative of the distribution function.

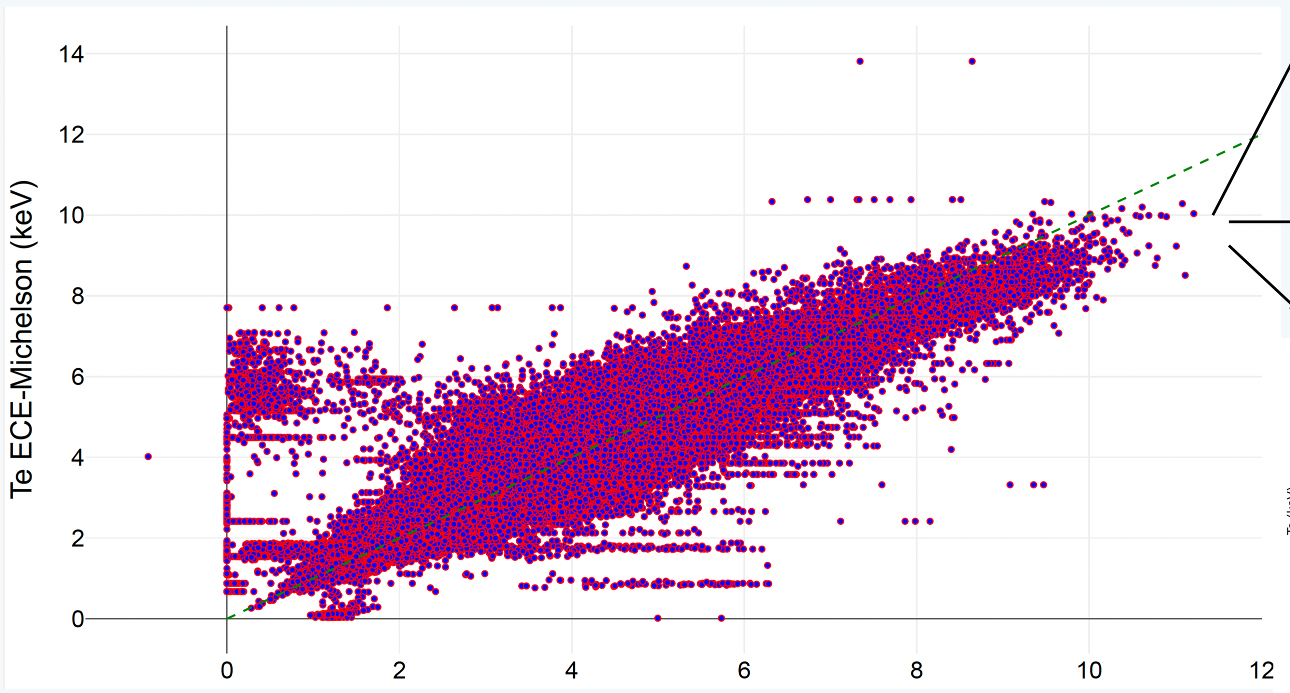
The extendend-DTE3 dataset:

Dataset & Selection Criteria
- Extended JET-DTE3 Analysis: Full dataset screened (>4000 shots).
- Data Pre-treatment: Automated detection of spikes and anomalous values
- Selection Filters: Maximizing statistical volume above a minimum electron temperature threshold (using Max Te-HRTS).
  Simultaneous availability of both ECE-Michelson and HRTS diagnostics.
- Final Database: ~1200 shots compiled,
  preserving both raw and processed data structures.
- A number of tools available for data analysis

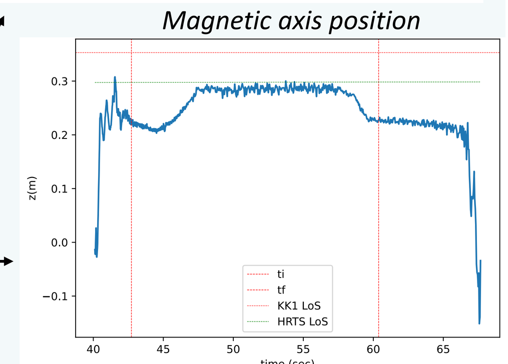
Time trends

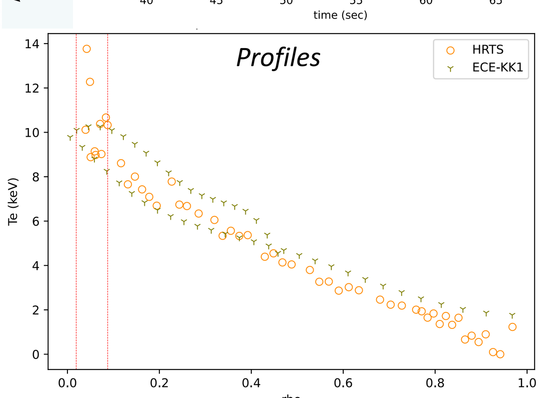


Note:
Average values inherently sit below the peak temperatures reached.

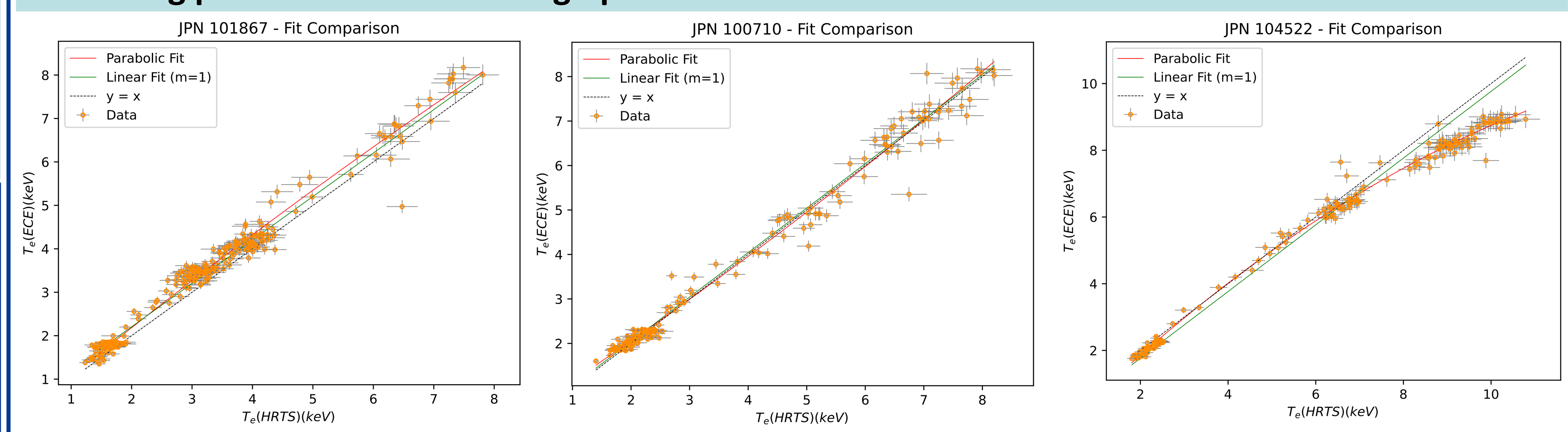


Magnetic axis position





The fitting procedure – a clustering operation



- Case A: T_e^{ECE} vs T_e^{TS} **linear** up to 8-9 keV. T_e^{ECE} higher than T_e^{TS}
- Case B: $T_e^{ECE} = T_e^{TS}$ **linear** up to 8-9 keV
- Case C: $T_e^{ECE} < T_e^{TS}$ at higher Te (>6-8keV) are best fitted with the **quadratic** poly

Combined statistical test to establish the best fit:
- χ^2 → to evaluate the goodness of the fit. - "the fit is good"
- p-value → Assesses the significance of χ^2 - "it is statistically valid"
- BIC (Bayesian Information Criterion) → Compares models penalizing complexity – "it's the best trade-off"

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{\sigma_i^2}$$

- O_i = observed data
- E_i = expected data from the model
- σ_i = uncertainty on each data point

$$p = 1 - \mathrm{CDF}_{\chi^2}(\chi^2, \mathrm{dof})$$

$$\mathrm{dof} = N - k$$

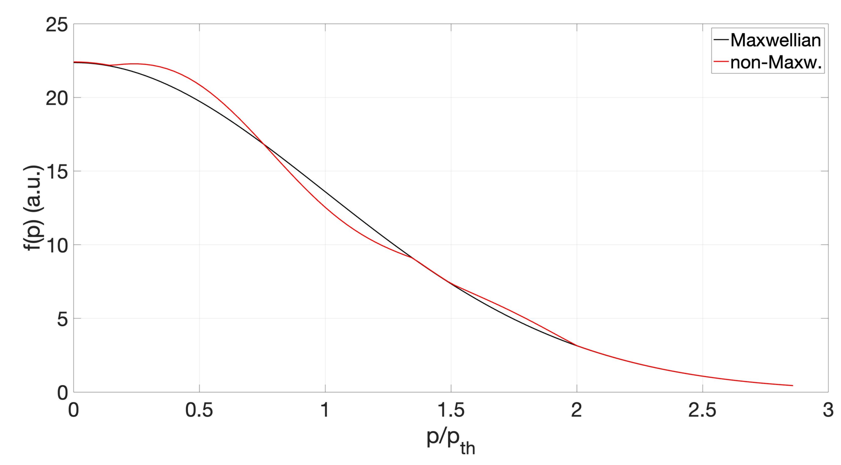
- N = number of data points
- k = number of free parameters in the model

$$\mathrm{BIC} = -2\cdot\ln(L) + k\cdot\ln(n)$$

- L = the **maximum likelihood** of the model
- k = the number of **free parameters** in the model
- n = the number of **data points**

Electron Energy distribution function shapes:

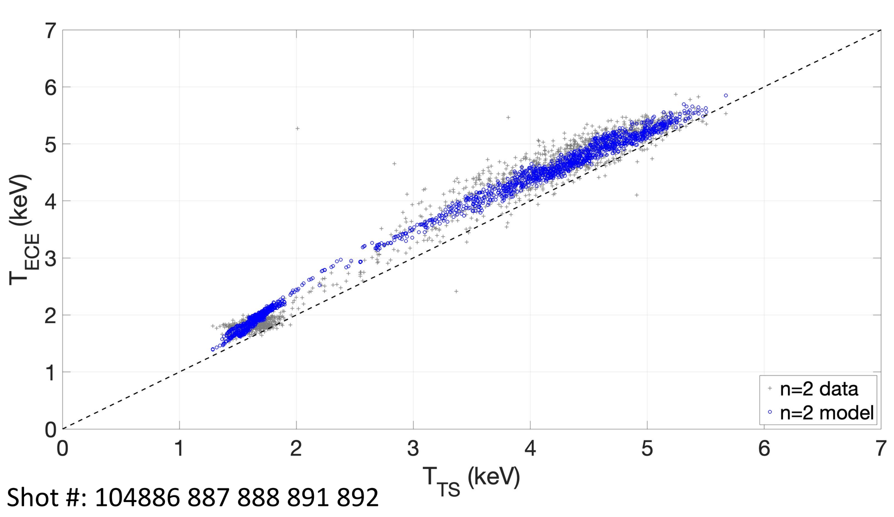
Case A:
EEDF in the second-harmonic ECE sensitivity range
→ $T_e^{ECE} > T_e^{TS}$



Two perturbations with constant intensity

$\frac{p}{p_{th}} = 0.75.$ $\frac{\delta_{0L}}{p_{th}} = 0.6.$ $f_{0L} = -0.05$ $\frac{\delta_{0R}}{p_{th}} = 0.6$ $f_{0R} = -0.05$

$\frac{p}{p_{th}} = 2.0.$ $\frac{\delta_{0L}}{p_{th}} = 0.6.$ $f_{0L} = 0.00.$ $\frac{\delta_{0R}}{p_{th}} = 0.5$ $f_{0R} = -0.02$



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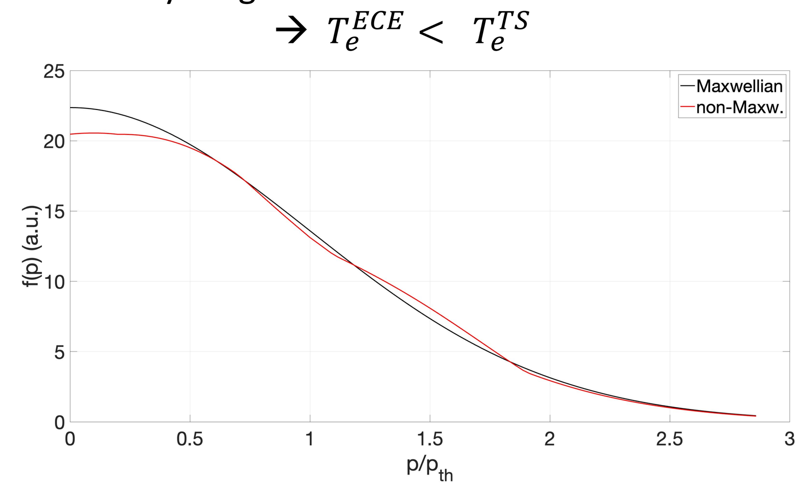
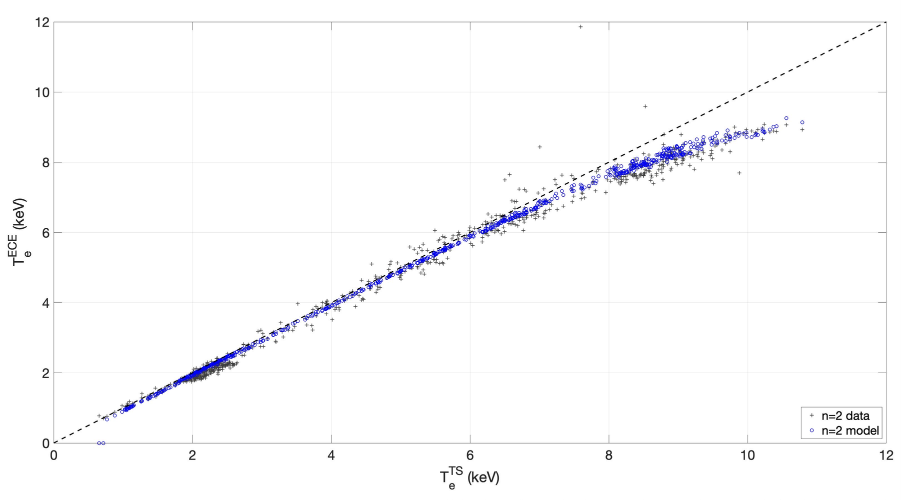
Case C:
Increased slope in the second-harmonic ECE sensitivity range
→ $T_e^{ECE} < T_e^{TS}$



Two perturbations with intensity increasing as T_e^2

$\frac{p}{p_{th}} = 0.2.$ $\frac{\delta_{0L}}{p_{th}} = 0.9.$ $f_{0L} = 0.06.$ $\frac{\delta_{0R}}{p_{th}} = 0.9$ $f_{0R} = 0.03$

$\frac{p}{p_{th}} = 1.0.$ $\frac{\delta_{0L}}{p_{th}} = 0.9.$ $f_{0L} = 0.06.$ $\frac{\delta_{0R}}{p_{th}} = 0.9$ $f_{0R} = 0.01$



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Perspectives:

Dedicated experiments (EAST, + DIII-D, W7X) will be performed next year in the framework of the JEX#17
The INDACO code as the tool for uniform analysis [7,8]
Development of a cross-machine database
Fokker –Planck solver code: Auxiliary heating and particle interactions

This contribution presents preliminary results obtained from the analysis of the 'expanded' database of JET, as part of the work carried out within the framework of the **ITPA activity (ITPA JEX#17 on 'High-Te Measurements')** currently involving JET, DIII-D, EAST, W7-X. The goal is to compare data collected across different machines worldwide to fully understand the origin of the observed discrepancy.

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