CORE TRANSPORT STUDIES IN FUSION DEVICES

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Abstract

Comprehensive first principles modelling of fusion plasmas contains many numerical and theoretical challenges: a complicated magnetic geometry, long range electromagnetic interactions, collective modes, and extreme density and temperature gradients driving turbulent fluctuations, to name just a few. HPC provides the tools for tackling these challenges and is the focus of a major undertaking within the European fusion community [1].

In this work, the turbulent transport of trace impurities in a tokamak device has been studied using quasi-linear and non-linear gyrokinetic simulations from the GENE code[2, 3]. The results are quantitative and qualitative assessments of the transport properties of several impurity species, and the dependence thereof on various plasma parameters.

Gyrokinetic simulations – GENE

Kinetic descriptions of plasmas deal with the time evolution of *distribution functions* for the constituent species. The gyrokinetic approach relies on the assumption that the species' gyration around the magnetic field lines is fast and narrow compared to the time and length scales of the turbulence. This is generally valid for magnetic confinement fusion plasmas. Averaging over the gyro orbit, one velocity space coordinate is removed and the phase space reduced from 6 to 5 dimensions – 3 for *position* and 2 for *momentum*. Since the equations governing the evolution of distributions are all coupled, the resulting decrease in numerical complexity is considerable.

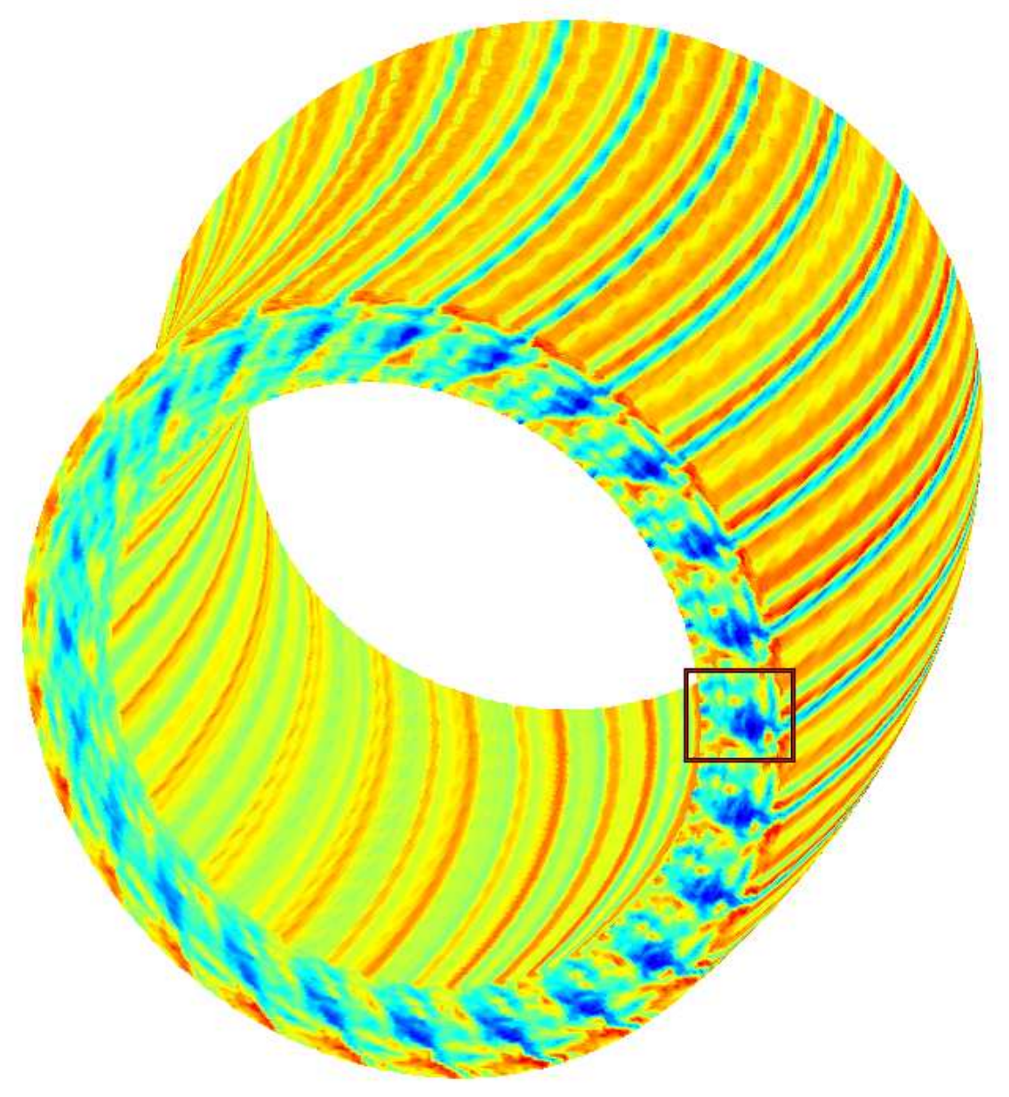

FIGURE 1: One eighth of the toroidal annulus made up of the flux tube as it twists around the torus following the B field, showing the variation of n_D, the density of background Deuterium ions. The area corresponding to the cross-section in figure 2 is marked. ITG mode dominated case with Mo ($Z = 42$) impurity at $t \approx 300\,c_s/R$.

The GENE code [3], is a massively parallel simulation code, solving the non-linear time evolution of the gyrokinetic distribution functions on a fixed grid in phase space, i.e. an Eulerian approach. In GENE, the *radial* (x) and *poloidal* (y) dependence is treated *spectrally*, i.e. those directions are discretised explicitly in k-space, whereas the *toroidal* (z) direction is discretised in real space. Though this means that *Fast Fourier Transforms* have to be employed in every time-step, this is more efficient than the convolutions that would otherwise have to be performed. The velocity space integrations are performed in real space for both the *parallel* ($v_{\|}$) and *perpendicular* (μ) directions. [2]

The simulation domain generally used in GENE is a so called *flux tube*. This is in essence a box that is elongated and twisted along with the B field as it traverses the tokamak. An illustration of the result as the tube wraps up on itself can be seen in the cutaway out figure 1, where an area corresponding to a cross-section of the flux tube has been marked. Such a cross-section is shown in detail in figure 2. There the size of the turbulent features can be seen, which compared to the resolution of $\sim 125 \times 125$ ion gyro radii, supports the gyrokinetic approach.

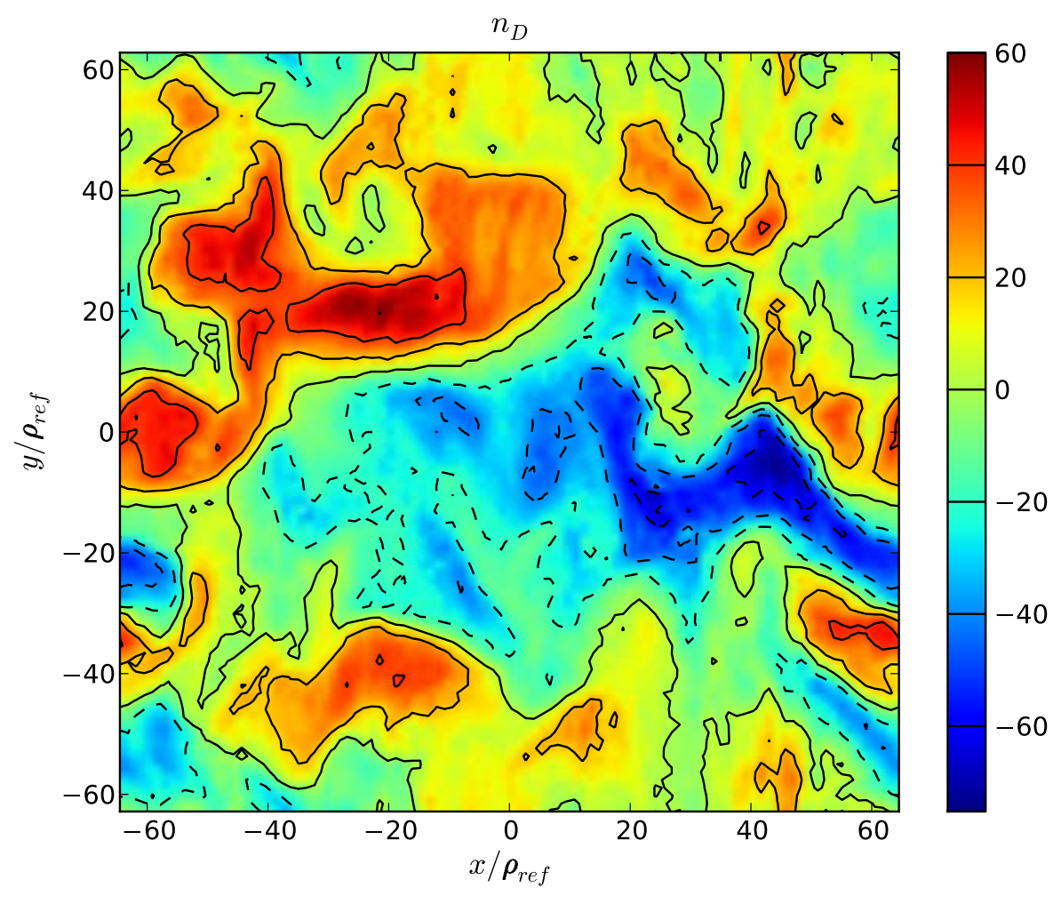

FIGURE 2: Cross-section of the flux tube showing the scale of the turbulent features in n_D, the density of background Deuterium ions. Note the periodical boundary conditions. The area corresponds to the marked area in figure 1. ITG mode dominated case with Mo ($Z = 42$) impurity at $t \approx 300\,c_s/R$.

The data presented in figures 1 and 2 are computed from the raw data. The instantaneous data size is of the order of $1\,\mathrm{GB}$ for a typical non-linear tokamak simulation, even conservatively saving time-lapse data the storage required for a single run quickly increases to tens of GB. By integrating further, however, scalar quantities can be obtained. Those quantities are often the most interesting from a physics perspective, since they are easier to compare both to theoretical, experimental and other numerical results. Examples of scalar quantities are presented in figure 3. Computing such a time series requires $\sim 40\,\mathrm{k\,CPUh}$, using 768 cores, on the *Akka* super computer [4]. The project has so far consumed $\sim 1\,\mathrm{M\,CPUh}$.

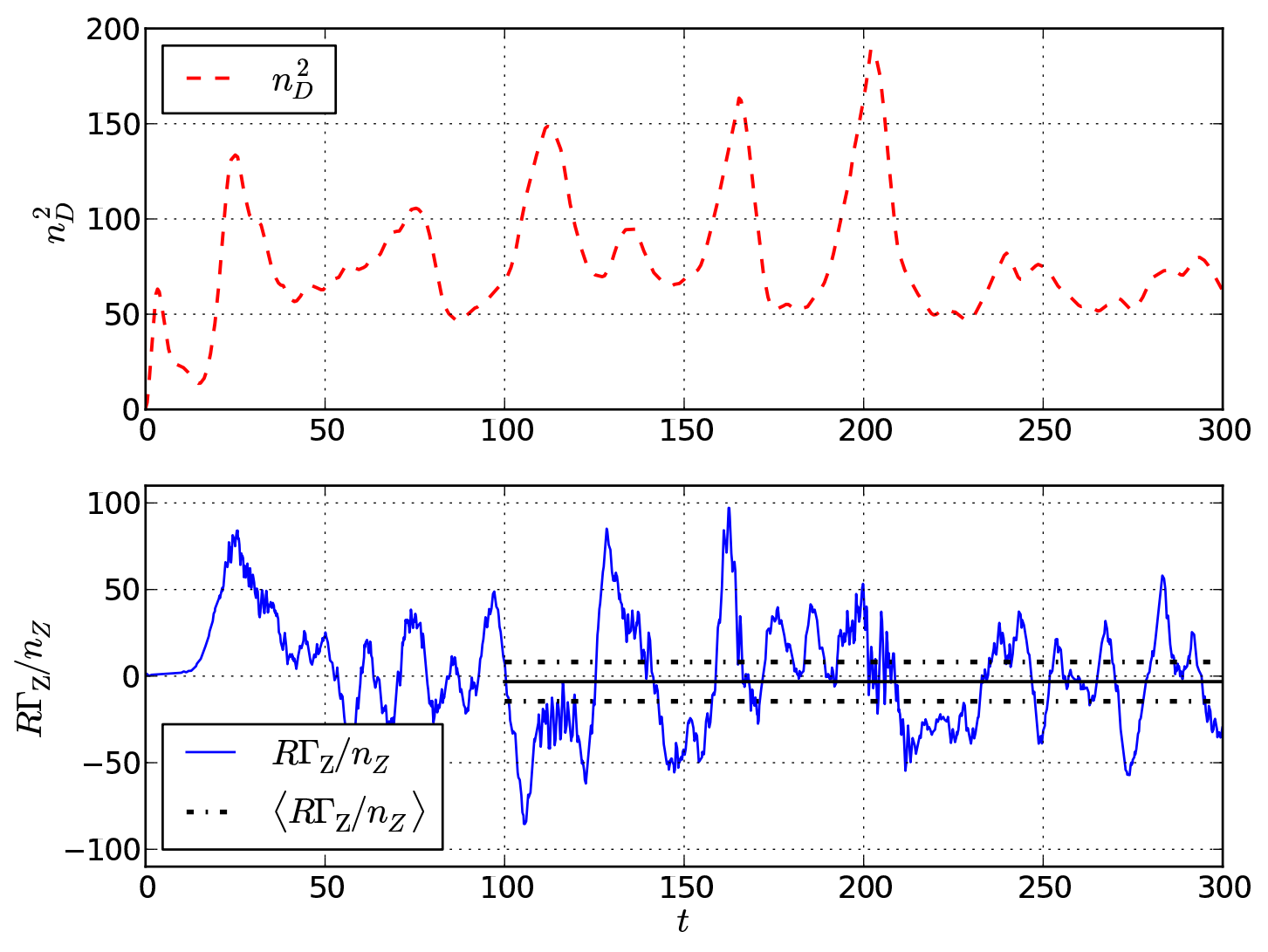

FIGURE 3: Integrating over the simulation domain illustrated in figures 1 and 2 yields time-series of scalar quantities such as the particle flux Γ for the different included species. Main ion (D) density (– –) and impurity ($Z = 42$; Mo) flux (—) fluctuations are shown, along with average impurity flux with estimated 2σ error (– · –), corresponding to the third data point in figure 4.

GENE can also be run in *quasilinear* (QL) mode. This is much more efficient, since the non-linear coupling between length scales is ignored. This method only captures the most unstable mode for the particular length scale of choice, but is useful for getting a qualitative understanding of the physical processes. A comparison of non-linear, quasilinear and fluid results is shown in figure 5 below.

Transport in tokamaks

One important application of HPC for fusion is the transport of contaminants from plasma facing surfaces: even small fractions of heavy impurities can severely harm the energy confinement in the tokamak. The stability and efficiency of future devices, such as ITER, relies on understanding and control of particle transport.

From the fluid description of plasmas [5], going to the trace impurity limit, the impurity transport equation (1) can be derived as an average over all unstable modes for a fixed length scale $k\rho_\theta$ of the turbulence [6, 7]. Here Γ_Z is the flux, D_Z the diffusion coefficient, V_Z the convective velocity ("pinch") and n_Z the particle density of the impurity Z, and R is major radius of the tokamak.

$$\Gamma_Z = -D_Z \nabla n_Z + n_Z V_Z \Leftrightarrow \frac{R\Gamma}{n_Z} = D_Z \frac{R}{L_{n_Z}} + RV_Z \qquad (1)$$

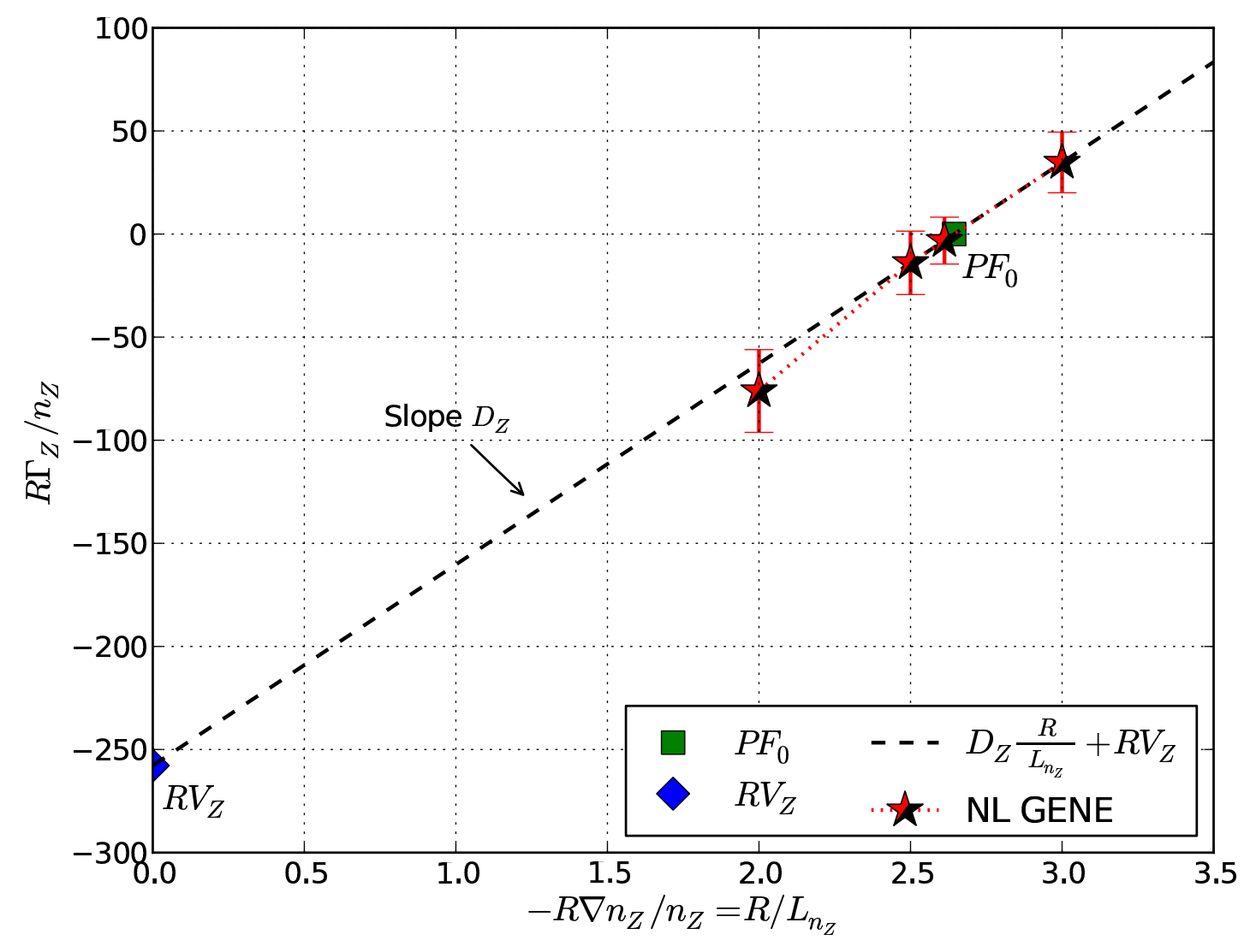

FIGURE 4: Illustration of PF_0 and the validity of the linearity assumption of $\Gamma_Z\,(\nabla n_Z \approx 0)$ for trace impurities; ITG dominated non-linear GENE result for Mo (Z=42). The parameters of equation (1) are estimated from the three data points closest to $\Gamma_Z = 0$; errorbars mark two estimated standard deviations.

The *zero flux peaking factor*, $PF_0 = \frac{-RV_Z}{D_Z}\big|_{\Gamma=0}$, is important for fusion plasmas as it quantifies the balance of convective and diffusive transport. This can be seen from equation (1) tokamak [6]. For the domain studied ∇n_Z is constant: $-\nabla n_Z/n_Z = 1/L_{n_Z}$. Setting $\Gamma_Z = 0$ in equation (1), one can interpret PF_0 as the *gradient of zero flux*. This is illustrated in figure 4. Results for the dependence of PF_0 on atomic number Z are presented in figure 5.

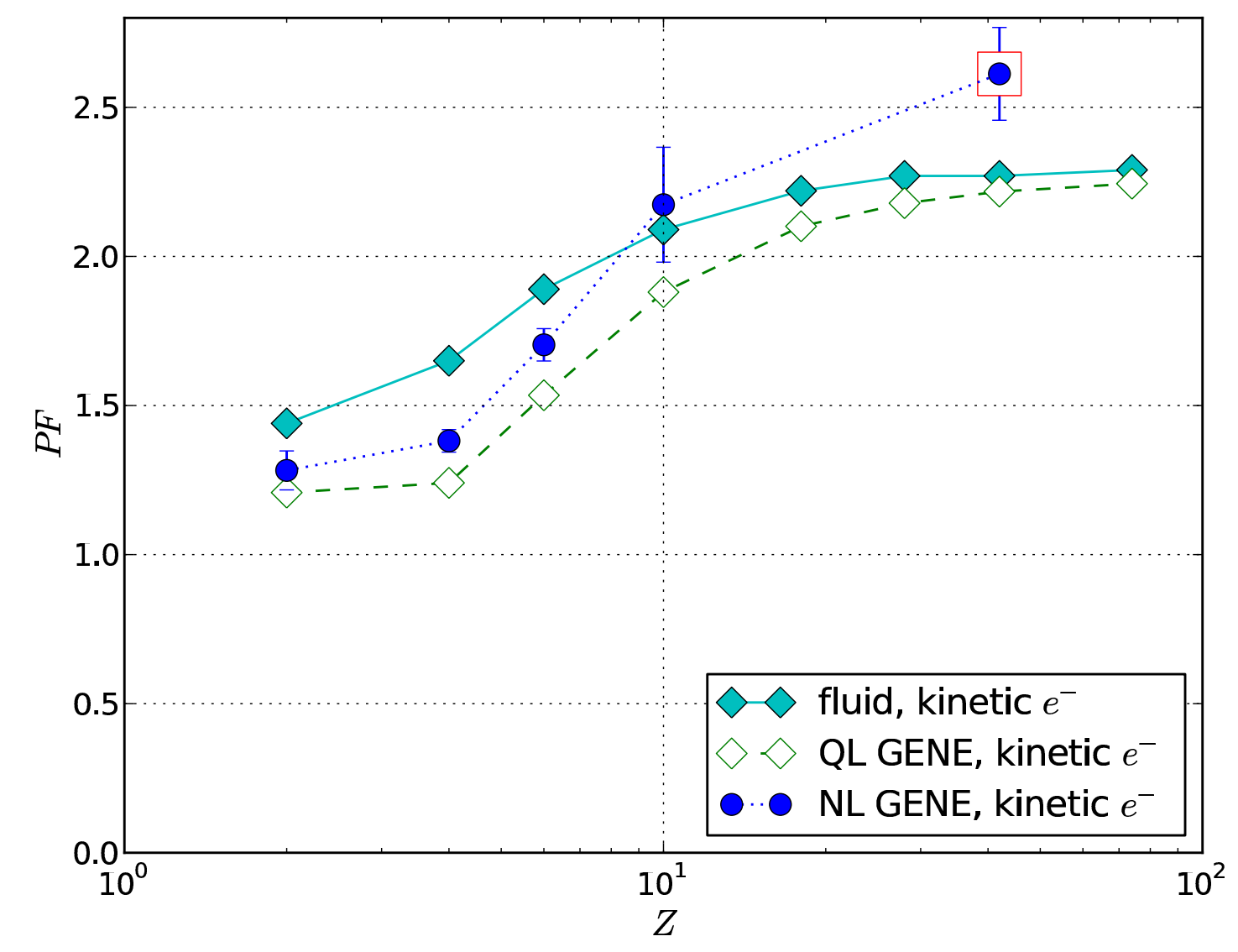

FIGURE 5: Scaling of PF_0 with impurity charge Z for ITG mode case; comparison of NL GENE, QL GENE and fluid results. Errorbars for non-linear results mark two estimated standard deviations. The data-point for the Molybdenum impurity, acquired from the data illustrated in figures 1–4, is highlighted (□).

Future outlook

The near term activities will focus on direct comparisons with experiments. For this, more details in the physics description and magnetic geometry is needed. The GENE code is in the process of being ported to the new *Lindgren* computer to support more stringent resource requirements set by a planned numerical modeling campaign of discharges from the JET tokamak.

References

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