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Impurity transport in mixed-collisionality stellarators

Gaining control over neoclassical impurity accumulation in stellarators has been a longstanding need. Heavy, highly charged impurities, which can radiate strongly and degrade energy confinement, are expected to be driven inward by the negative radial electric field characteristic of fusion-relevant plasmas. However, such expectations were based on calculations that applied various simplifications, such as retaining only pitch-angle scattering to describe collisions between species, or taking the limit of a trace impurity population. Therefore, there has been a strong recent interest in returning to more complete analytic calculations [1,2,3]. We focused on the behavior of the impurity flux in a mixed-collisionality plasma. A single impurity species, z, highly charged (Ze, $Z > 1$) and thus in the collisional regime, was taken to be present in a low-collisionality background plasma. The bulk ions, i, with ion temperatures $T_i = T_z$, were taken explicitly to be in the $1/\nu$ or $\sqrt{\nu}$ regimes. The treatment of the latter was enabled by the recent development of a unified analytic description of the distribution function across these two low-collisionality regimes [4].

The radial impurity flux can be decomposed into a sum of contributions, representing the effects of parallel friction against the background ions and the pressure anisotropy [5,1],

$$\Gamma_z = \frac{1}{Ze}\left\langle uBR_{zi\,\|} + (p_{z\|} - p_{z\perp})\frac{\nabla_{\|}(uB^2)}{2B}\right\rangle \quad (1)$$

Here $\langle ... \rangle$ denotes the flux surface average [6] and the equilibrium function u satisfies $\boldsymbol{b}\cdot\nabla u = -(\boldsymbol{b}\times\nabla r)\cdot\nabla(B^{-2})$. The anisotropy drive is weak when the impurities are collisional, which can be quantified by the following inequality of the collisionalities, ν_{*ab} , taken to be satisfied in the calculations,

$$\frac{1}{\nu_{*iz}} \ll \frac{n_i}{n_z}\sqrt{\frac{m_i}{m_z}}\nu_{*zz}. \quad (2)$$

(For example, this would hold for trace levels of Ar^{16+} with bulk ion parameters typical of high-performance scenarios.) The inter-species friction between the disparate mass ion populations can be captured by a model collision operator, C_{zi}, retaining pitch-angle scattering and momentum conservation,

$$R_{zi\,\|} = m_i\int \nu_D^{iz}(v)v_{\|} f_i d^3 v - \frac{m_i n_i V_{z\|}}{\tau_{iz}}, \quad (3)$$

where τ_{iz} is the bulk-impurity collision time and $V_{z\|}$ is the parallel impurity flow.

The impurity flux is thus known once the piece of the bulk ion distribution function which is odd with respect to the

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parallel velocity $v_{\|} = \sigma|v_{\|}|$, $\sigma = \pm 1$, is determined. Splitting the kinetic equation into even and odd pieces,

$$v_{\|} \nabla_{\|} f_{\rm i}^{\mp} = C_{\rm i}^{\pm}(f_i) - \boldsymbol{v}_{\rm di} \cdot \nabla f,$$

where $\boldsymbol{v}_{\rm di}$ is the bulk ion drift velocity, and the distribution is obtained by formally integrating along a field line. This is reasonably straightforward to evaluate when the bulk ions are in the 1/ν regime—collisions are sufficiently dominant that the distribution function will be close to Maxwellian, $f_{\rm Mi}$, and common expansion treatments can be used [6]. At lower collisionality, loss regions can form due to particle drifts and the plasma is not generally in a local thermodynamic equilibrium. Confinement can be restored by the radial electric field [7], or by suitable restrictions on the system geometry [8], and we assume that one of these conditions holds. The relevant expression for the drift can then be written as

$$\boldsymbol{v}_{\rm di} \cdot \nabla f_i^{+} = (\boldsymbol{v}_{\rm di} \cdot \nabla r - \overline{\boldsymbol{v}_{\rm di} \cdot \nabla r}) \frac{\partial}{\partial r}(f_{\rm Mi}) \qquad (4)$$

where the second term represents the effect of the trapped region of velocity space in the $\sqrt{\nu}$ regime, and the overbar denotes the orbit average.

The impurity flow required for the friction takes the well-known form $n_{\rm z}V_{\rm z\|} = (p_{\rm z}/Ze)A_{\rm 1z}uB + K_{\rm z}(r)B$. The integration constant $K_{\rm z}$ is set by the parallel force balance on the collisional impurity species, which reduces to $\langle BR_{\rm zi\|}\rangle = 0$. Using this we find that an explicit expression for $K_{\rm z}$ is not required to evaluate the impurity flux. Considering the limit of tokamak geometry, this corresponds to the well-known result that Pfirsch-Schlüter transport results from the variation of the friction around a flux surface [9].

The final expression for the impurity flux can usefully be represented in terms of the set of transport coefficients D_{ij}^{ab} and takes the form

$$\begin{aligned}\Gamma_{\rm z} &= n_{\rm z}\left(D_{11}^{\rm zi}A_{1i} + D_{11}^{\rm zz}A_{1\rm z} + D_{12}^{\rm z}A_{2\rm i}\right)\\ &= -\frac{m_{\rm i}p_{\rm i}}{Z{\rm e}^2\tau_{\rm iz}}\left[\frac{1}{Z}A_{1\rm z}\left(\langle u^2B^2\rangle - \frac{\langle uB^2\rangle^2}{\langle B^2\rangle}\right)\right.\\ &\left. -\left(A_{1\rm i} - \frac{3}{2}A_{2\rm i}\right)\left(\langle u(u+s)B^2\rangle - \langle (u+s)B^2\rangle\frac{\langle uB^2\rangle}{\langle B^2\rangle}\right)\right].\end{aligned} \qquad (5)$$

The thermodynamic forces are $A_{1a} = {\rm d}\ln p_a/{\rm d}r + Z_a e\Phi'(r)/T_a$ and $A_{2a} = {\rm d}\ln T_a/{\rm d}r$, where $\Phi(r)$ is the electrostatic potential, set to zero on the flux surface of interest. The geometric quantity $s = 0$ when the ions are in the 1/ν regime and results from the trapped particle drift in the $\sqrt{\nu}$ regime,

$$s(l) = \frac{3}{2}\int_{l_{\rm max}}^{l} {\rm d}l' \int_{1/B_{\rm max}}^{1/B(l')} \frac{d\lambda}{\xi(l')} \overline{\xi(\boldsymbol{b} \times \nabla r) \cdot \nabla\left(\frac{\xi}{B}\right)}, \qquad (6)$$

\where $\xi = \sqrt{1 - \lambda B}$, λ is the ratio of energy to magnetic moment $\lambda = \mu/\varepsilon$ and $B_{\rm max}$ is the maximum value of the magnetic field strength on the flux surface at the position $l_{\rm max}$, where the coordinate l denotes the distance along a field line.

This result contains the following interesting features. The Pfirsch-Schlüter coefficient appears and can usefully be written in terms of the parallel current with

$$\rho_{\rm i}^2 = T_{\rm i}m_{\rm i}/e^2\langle B^2\rangle,$$

$$\begin{aligned}D_{\rm PS} &= \frac{m_{\rm i}}{e^2\tau_{\rm iz}}\left(\langle u^2B^2\rangle - \frac{\langle uB^2\rangle^2}{\langle B^2\rangle}\right)\\ &= \frac{\rho_i^2}{\tau_{\rm iz}}\frac{\langle J_{\|}^2\rangle\langle B^2\rangle - \langle J_{\|}B\rangle^2}{(dp/dr)^2}.\end{aligned} \qquad (7)$$

By the Schwartz inequality, this satisfies $D_{\rm PS} \geq 0$, so the impurity density gradient drives an impurity flux in the opposite direction. When the bulk ions are in the 1/ν regime we see a cancellation among the transport coefficients, such that the electric field does not directly drive an impurity flux. This connects to the limit of tokamak geometry and is also known to hold when the bulk ions are highly collisional [1]. As $D_{12}^{\rm z} = -(3/2)D_{11}^{\rm zi}$, when the bulk ions are in the 1/ν regime we see furthermore that temperature screening will operate, just as in a tokamak. In the presence of typical inward bulk ion gradients, we can expect an outward impurity flux when $\eta_{\rm i} = \partial \ln T_{\rm i}/\partial \ln n_{\rm i} > 2$.

Upon lowering the bulk ion collisionality, the coefficients of the electric field drive no longer cancel. Whilst the net contribution is proportional to a geometric factor which is not sign definite, we may expect that it will be small in a well-optimized device. The relation $D_{12}^{\rm z} = -(3/2)D_{11}^{\rm zi}$ persists, allowing either temperature screening to persist, or an additional outward flux to be driven by the density gradient, depending on the sign of the geometric factor. It is a short step to extend the above analysis to the case of two collisional impurity species, of disparate mass, present in a low collisionality bulk plasma. The total impurity current displays the same temperature screening properties as the single impurity species result.

Indications of temperature screening were already noted in numerical studies of neoclassical transport in W7-X configurations [10] with the continuum δf SFINCS code [11]. SFINCS retains the full linearized multispecies Landau collision operator. Initial successful comparisons of the predictions above to the results of SFINCS simulations were presented in Ref. [12]. An example is given in Fig. 1, which shows the variation in the net flux of Fe^{16+} driven by the ion temperature gradient with the iron self-collisionality, for a weak electric field. The predicted values at high collisionality and in the mixed-collisionality range are shown, along with the deviations expected when collisions are described only by pitch-angle scattering. Therefore we expect that the analytic results obtained can be usefully applied to guide the identification of regions of parameter space with reduced impurity transport, and a longer dedicated numerical study is under way.

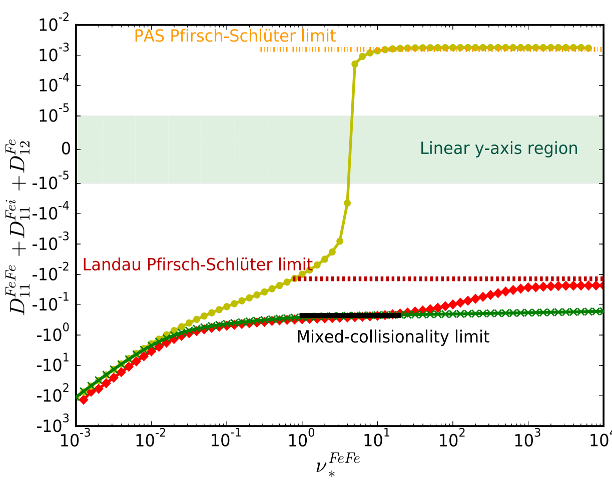

Fig. 1. Normalized transport coefficients of Fe^{16+} impurity flux, driven by the bulk ion temperature gradient in an H^+ plasma for $E_r \sim 0$, as a function of impurity self-collisionality at fixed density ratio, in the W7-X standard configuration. Red: SFINCS output with full Landau collision operator; yellow: SFINCS output retaining only pitch-angle scattering in collisions; green: output from DKES using pitch-angle scattering with momentum conservation.

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Coordinated Working Group Meeting (CWGM17) for Stellarator-Heliotron Research

The 17th Coordinated Working Group Meeting (CWGM17) was held, with about 40 participants, on 6 October 2017 in Kyoto, following the 21st International Stellarator-Heliotron Workshop (ISHW). Due to time constraints, this was just after the adjournment of the ISHW (~2 hours). The main purpose of this meeting was to follow up on the previous 16th CWGM (see *Stellarator News*, Issue 158, August 2017).

The agenda is as follows:

- Brief report from 16th CWGM (Jose-Luis Velasco)
- EUROfusion-supported activities at NIFS (Andreas Dinklage, on behalf of Arturo Alonso)
- Discussion on sessions with ongoing intensive collaborations:
    - Transport modeling (Shinsuke Satake)
    - Energetic particles/AE control (Satoshi Yamamoto)
    - Impurity transport (mainly on TESPEL injection) (Naoki Tamura)
    - Core electron-root confinement (Felix Warmer)
    - Turbulence/isotope effect (Motoki Nakata)
- Setting up milestones: joint actions, joint papers, etc.

Attendees at CWGM17.

The materials presented at the meeting are available at http://ishcdb.nifs.ac.jp/ and http://fusionwiki.ciemat.es/wiki/Coordinated_Working_Group_Meeting for those wanting more details. Below, you will find a very brief summary of the meeting.

The CWGMs have been held under the auspices of the International Energy Agency Technology Collaboration Programme for Cooperation in Development of the Stellarator-Heliotron Concept (IEA TCP-SH). For details see- http://www.iea.org/tcp/fusionpower/sh/.

EUROfusion-supported activities in NIFS (A. Dinklage, on behalf of A. Alonso)

In recent years, a wide-ranging collaboration between EUROfusion and NIFS (LHD experiment, theory/simulation) has been programmatically developed. A. Alonso (as the leader of Task Force III of Wendelstein 7-X (W7-X) experiment), and A. Dinklage (as the leader of Workpackage S1 of EUROfusion) summarized the status of these collaborations, and how they have benefited and will continue to contribute to international stellarator-heliotron programs.

Transport modeling (S. Satake)

Reported highlights of ongoing international collaboration on transport modeling (mainly on neoclassical transport) were: the impact of the electrostatic potential variation on flux surface (so-called, "Φ_1 effect," where Φ_1 denotes the electrostatic potential variation on flux surface), comparison among local drift-kinetic models, and a verification and validation study of bootstrap current. In particular, regarding the "Φ_1 effect," three relevant presentations were made at the 21st ISHW, and comparisons with experimental observations are ongoing. As future steps, comparison with gyrokinetic turbulent transport and implementation into the global calculations are anticipated.

A recently developed neoclassical code, KNOSOS (by Jose-Luis Velasco) will also be implemented in joint verification and validation activities in many of the efforts in this session.

Energetic particles (EPs), Alfvén eigenmodes (AEs) (S. Yamamoto)

Reporting on joint experiments among Heliotron J, TJ-II, and LHD on the effect of electron cyclotron heating and current drive (ECH/ECCD) on AEs (for controlling AEs), S. Yamamoto gave an invited talk at the 21st ISHW. Joint papers based on this invited talk will be submitted to *Plasma Physics and Controlled Fusion* (due Dec. 20, 2017). This activity also has a link to the International Transport Physics Activity (ITPA) via its joint activity EP-12 (Identification of AE Control Actuators and Preliminary Assessment for ITER, led by Álvaro Cappa). Recent operation/planning of lost ion probes (LIPs) in several devices will provide joint collaboration opportunities on anomalous transport of energetic particles by MHD instabilities. Pioneering work in LHD (now that neutron measurement is also available in deuterium plasmas), additional LIPs being planned in TJ-II, and an operating LIP in Heliotron J will be the basis for this collaboration.

Impurity transport (mainly on TESPEL injection) (N. Tamura)

Ongoing comparison study on general characteristics of impurity transport in helical plasmas was introduced, based on the knowledge obtained in LHD [see, e.g., Y. Nakamura, *Plasma Phys. Control. Fusion* **56** (2014) 075014]. Search for impurity accumulation in Wendelstein 7-X is based on such collaborations. Heliotron J, HSX, and TJ-II have also joined this collaboration in terms of conducting collisionality scans with measurement of radial electric field.

As for the study on the impact of the impurity source location, and on the impurity transport behaviors, a TESPEL injection unit has been installed in TJ-II by piggybacking on the pellet injector. TESPEL injection experiments in TJ-II have been conducted in 2015 and 2016 (with Al and S being used as tracers). Now a dedicated TESPEL injection system will be installed on W7-X in January 2018 as a joint project by NIFS and IPP-Greifswald.

A submission from N. Pablant (the impurity session leader for the 16th CWGM) highlighted progress for the topics identified at the 16th CWGM. This is also a good document for facilitating further progress, and thus it has been uploaded to the meeting websites.

Core Electron-Root Confinement (Felix Warmer)

The CERC (Core Electron-Root Confinement) collaboration has been revived following the start of the W7-X experiment. The deuterium experiment in LHD has broadened research interest in CERC, because of isotope effects. The Heliotron J team has also published the characteristics of its CERC (or electron ITB) plasma. Based on these circumstances, comparison of CERC features (including particle transport characteristics) between LHD (hydrogen and deuterium) and W7-X (currently only hydrogen, but deuterium as well in the future), configuration effects on CERC in W7-X, expansion of CERC data on the International Stellarator-Heliotron Profile Database (ISHPDB), and neoclassical and gyrokinetic simulations for understanding CERC features. Small to medium-size devices (Heliotron J, HSX, and TJ-II) are conducting CERC experiments focusing on factors such as the impact of the magnetic island on CERC transition, and zonal flow or long-range correlation. Joint collaborations on CERC issues can be formulated by further discussions.

Turbulence/isotope effect (M. Nakata)

It was agreed at the 16th CWGM that the session Chair would be M. Nakata, succeeding C. Hidalgo and T. Estrada. Systematically summarized lists on the actions to be taken for this collaboration topic and related progress reported in the ISHW were introduced. Based on such overview of ongoing joint activities in this session, the following joint actions were proposed as short or mid-term future directions: ITG (ion-temperature gradient mode)/TEM (trapped electron mode) fluctuation (including collisional effects), isotope effect on TEM with collisions for investigating dependence on magnetic geometry and detailed mode saturation mechanisms, isotope effect on zonal flows (amplitude and width) and the role of the mean radial electric field, and turbulent impurity transport, including heating and isotopic effects (in collaboration with the transport modeling and impurity sessions). Joint efforts among simulation/theory and experiments were highly appreciated by the participants.

Milestones

Milestones for joint activities would be the 18th CWGM, synopsis compilation for the IAEA Fusion Energy Conference (2018), and major international conferences in 2018. Joint presentations and publications are encouraged among collaborators. The LHD 20th campaign will be from October 2018 to February 2019, and experiment proposals are due on 1 July 2018, according to T. Morisaki [Executive Director of Large Helical Device Project (on Science)]. Wendelstein 7-X OP1.2a and OP1.2b will be conducted in the period of 2017 and 2018.

Miscellaneous

Strengthening links to ITPA and then to ITER was raised in the discussion. Since there were several ITPA members among the participants in this CWGM, recent activities and updates in each ITPA topical group (energetic particles, transport and confinement, edge and pedestal, and integrated operation scenario) were briefly introduced. Also, replacement of the "Stellarator Representative" to be ITPA topical group was negotiated in the Executive Committee Meeting of IEA TCP-SH. Once it is authorized, it would be a good idea to publish the list of Stellarator Representatives in *Stellarator News*, for facilitating strategic discussions between CWGM and ITPA.

New data on CERC plasmas in Heliotron-J, [N. Kenmochi et al., *Plasma Phys. Control. Fusion* **59**, 055013 (2017)] were uploaded to the ISHPDB. The importance of keeping database updated for documentation and validation purposes was emphasized.

The next CWGM has already been scheduled (at the 16th CWGM); it will be held at Princeton in 2018.

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Jose-Luis Velasco (CIEMAT), A. Dinklage (IPP-Greifswald), S. Satake (NIFS), S. Yamamoto (Kyoto U.), N. Tamura (NIFS), F. Warmer (IPP-Greifswald), M. Nakata (NIFS), and M. Yokoyama (NIFS) on behalf of all the participants in the 17th CWGM.

Second LHD Deuterium Workshop Announcement

The first campaign of the LHD deuterium experiment (19th campaign) has ended. The second LHD Deuterium Workshop will be held on Feb. 7 and 8 at National Institute for Fusion Science, to discuss obtained results, relevant research around the world, and research direction of the LHD deuterium experiment, and so forth.

Your active participation is highly anticipated.

For details, please contact M. Yokoyama (yokoyama.masayuki @ nifs.ac.jp).

Tomohiro Morisaki and Masaki Osakabe for LHD Experiment Group