stellarator news

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Editor: James A. Rome Issue 142 December 2013
E-Mail: jamesrome@gmail.com Phone (865) 482-5643

Enhanced microstability in quasi-isodynamic stellarators

Optimized stellarators promise to show reduced neoclassical transport thanks to the improved confinement of trapped particles. Anomalous transport is therefore expected to play an important role, and one must study how the neoclassical optimization affects microinstabilities and the turbulence they cause. We focus on quasi-isodynamic stellarators, in which the contours of constant magnetic field are poloidally closed (see Fig. 1) and, more importantly, in which the bounce-averaged radial drift vanishes,

$$\frac{1}{\tau_b}\int_0^{\tau_b} \mathbf{v}_d \cdot \nabla\psi \, \mathrm{d}t = 0.$$

Here τ_b denotes the bounce time. This implies that the parallel adiabatic invariant

$$J = \int m v_{\parallel} \mathrm{d}l,$$

where the integral is taken between two bounce points, is a flux function, $J(\psi)$. In a maximum-J configuration [1] where J has its maximum on the magnetic axis, so that $\partial J / \partial\psi < 0$, the diamagnetic frequency ω_{*a} of species a and the bounce-averaged magnetic drift frequency $\overline{\omega}_{da}$ are in opposite directions (see Fig. 1),

$$\omega_{*a} \cdot \overline{\omega}_{da} < 0. \quad (1)$$

There is thus no resonance between these two frequencies, so that all orbits have favorable bounce-averaged curvature. Instabilities that rely on a resonance between these two frequencies should therefore be stabilized.

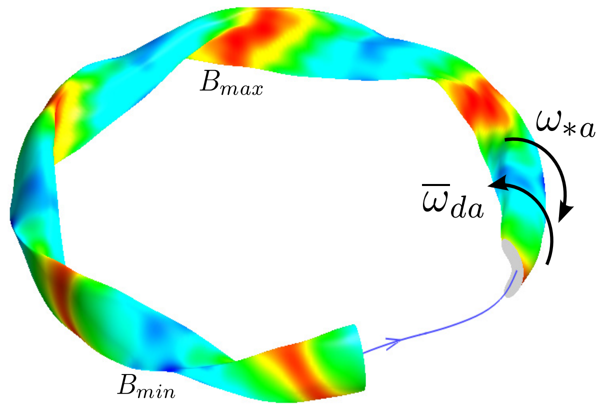

Fig. 1. Magnetic field strength |**B**| of a six-period quasi-isodynamic stellarator QIPC [2], with the directions of the diamagnetic drift frequency ω_{*a} and the bounce-averaged magnetic drift frequency $\overline{\omega}_{da}$ indicated by the arrows.

In order to analyze stability in the collisionless and electrostatic limit we define the rate of gyrokinetic energy transfer from the field to species a as

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$$P_a = -\mathrm{Re}\left\{ e_a \left(v_\parallel \hat{\mathbf{b}} + \mathbf{v_d} \right) \cdot \nabla \phi^* J_0 f_{a_1} \right\}$$

$$= e_a \mathrm{Im} \left\{ (i v_\parallel \nabla_\parallel g_a - \omega_{da} g_a) \phi^* J_0 \right\}, \qquad (2)$$

where J_0 is a zeroth-order Bessel function and ϕ is the electrostatic potential perturbation. The perturbed distribution function is given by

$$f_{a1} = g_a - \frac{e_a \phi}{T_a} f_{a0}$$

with f_{a0} being a Maxwellian at rest. Here we use the notation

$$\{\ldots\} = \int \frac{\mathrm{d}l}{B} \int \mathrm{d}^3 v (\ldots)$$

for integration over velocity space and across the entire flux surface.

The two governing frequencies of the system are defined as $\omega_{da} = \mathbf{k}_\perp \cdot \mathbf{v}_{da}$ with $\mathbf{k}_\perp = k_\psi \nabla \psi + k_\alpha \nabla \alpha$ as the perpendicular wave vector and $\omega_{*a} = T_a k_\alpha / e_a \mathrm{d} \ln n_a / \mathrm{d}\psi$ with the density n appearing in

$$\omega_{*a}^T = \omega_{*a} \left[1 + \eta_a \left(\frac{x^2}{T_a} - \frac{3}{2} \right) \right].$$

Here $x^2 = m_a v^2 / 2T_a$ denotes the normalized velocity, with the temperature T_a and particle mass m_a. The ratio between temperature gradient and density gradient is given by

$$\eta_a = \frac{\mathrm{d} \ln T_a}{\mathrm{d} \ln n_a}.$$

Note that, for a destabilizing species, the energy transfer rate must be negative, $P_a < 0$. If marginal stability is approached, so that the growth rate γ of the mode is going to zero, the contributions from all particle species should cancel,

$$\sum_a P_a = 0.$$

For modes whose frequency ω lies well below the bounce frequency ω_{ba} of the particle species a, $\omega \ll \omega_{ba}$, we find the following expression near marginal stability:

$$P_a = \frac{\pi e_a^2}{T_a} \left\{ \delta(\omega - \overline{\omega}_{da}) \overline{\omega}_{da} (\overline{\omega}_{da} - \omega_{*a}^T) \, | \overline{J_0 \phi} |^2 \; f_{a0} \right\}, \qquad (3)$$

which is always positive in maximum-J devices if the temperature gradient is not too large, $0 < \eta_a < 2/3$.

If we consider low-frequency modes so that $\omega \ll \omega_{ba}$ holds for all species, then there cannot be a point of marginal stability and thus no unstable mode exists. This applies, for example, to the collisionless trapped-particle mode, which should therefore be absent in quasi-isodynamic stellarators. If only the electrons are bouncing faster than the mode in question, so that Eq. (3) applies only to the electrons, then the electrons are not contributing to destabilization and it must be the ions that drive the instability. Moreover, it can be shown that any possible mode must be travelling in the ion diamagnetic direction.

Also, classical electron-driven trapped-electron modes (TEMs) should therefore be absent in quasi-isodynamic stellarators with the maximum-J property [3, 4].

While these findings are very promising, it has been shown that perfectly quasi-isodynamic configurations cannot exist [5]. This raises the question of whether enhanced stability also prevails in only approximately quasi-isodynamic configurations such as Wendelstein 7-X (W7-X). Gyrokinetic flux-tube simulations were performed with the GENE code [6]. Collisions and electromagnetic effects were neglected. To highlight the effect of geometry on the stability of trapped-particle modes, a realistic tokamak equilibrium for DIII-D and a vacuum equilibrium for the high-mirror configuration of W7-X were compared.

Tokamaks are non-maximum-J devices, since Eq. (1) is violated for deeply trapped particles, so that significant TEM growth rates can be expected. W7-X is not perfectly quasi-isodynamic either; that is, the stability criterion is not fulfilled for *all* orbits, but the fraction of trapped particles experiencing an unfavorable curvature is much smaller than in DIII-D. As a result, TEM activity should therefore be reduced.

In simulations with adiabatic electrons, in which only the ion temperature gradient scale length L_{T_i} and the density gradient scale length L_n were varied and thus only ion temperature gradient (ITG) modes are expected, comparable growth rates are found in both devices (Fig. 2). In both machines a strong destabilization is seen with increasing temperature gradient a/L_{T_i}, where a is the minor radius of the configuration. Reduced growth rates were not expected in W7-X, because the predicted stabilization through the electrons is an effect of the nonadiabatic electrons.

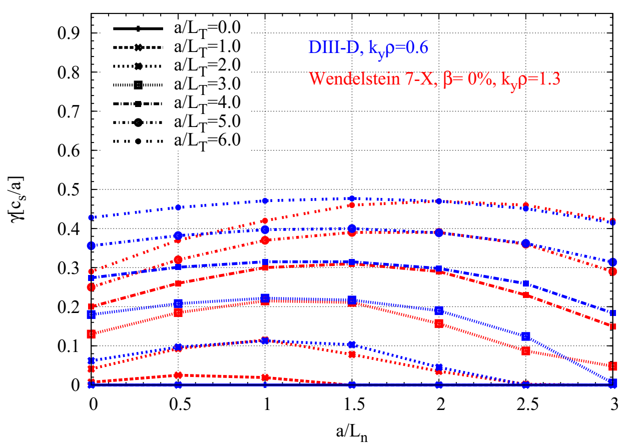

Fig. 2. Growth rates for ITG modes with adiabatic electrons in DIII-D and W7-X.

If kinetic electrons are considered in the simulations, the growth rates differ greatly, see Fig. 3. While a clear destabilization by the electrons can be observed in DIII-D, the growth rates in W7-X are reduced in large parts of parameter space. Only modes existing at low temperature gradient are somewhat destabilized. Analyzing the energy transfer in the simulations near marginal stability shows that the electrons draw energy from the mode and therefore stabilize it, just as predicted from analytical theory.

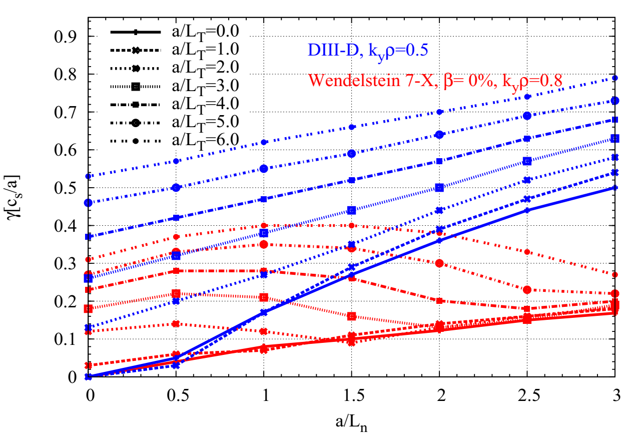

Fig. 3. Growth rates for ITG modes with kinetic electrons in DIII-D and W7-X.

The same is true for simulations in which the ion temperature gradient was set to zero and only density and electron temperature gradients were varied. This combination of gradients should lead to classical TEMs. However, in W7-X the modes are clearly driven by the ions and not the electrons, so that the modes, even though they are located in the magnetic wells and therefore count as trapped-particle modes, cannot be called classical TEMs. Again, the growth rates are significantly lower in W7-X than in DIII-D.

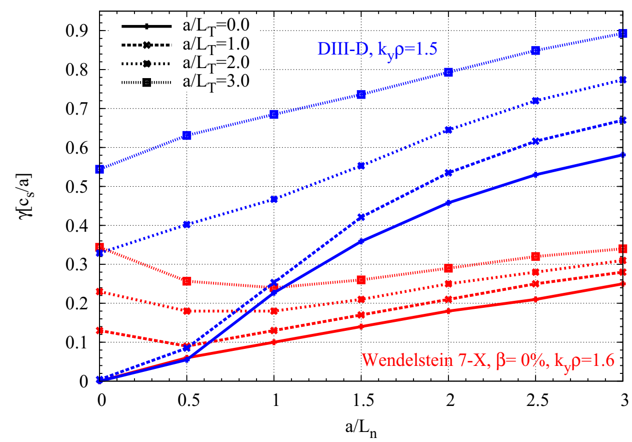

Fig. 4. Growth rates for TEMs in DIII-D and W7-X.

Therefore, it can be concluded that the enhanced stability against TEMs and other trapped-particle modes also holds in approximately quasi-isodynamic configurations. Some of the next steps will be to investigate whether this resilience still prevails in nonlinear simulations and in simulations covering the entire flux surface rather than just flux tubes.

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J.H.E. Proll,[1] P. Helander,[1] P. Xanthopoulos,[1]G.G. Plunk,[1,2] and J.W. Connor[3,4]

[1]Max Planck Institute for Plasma Physics, EURATOM Association, Wendelsteinstr.1, 17491 Greifswald, Germany

[2]Max-Planck-Princeton Research Center for Plasma Physics

[3]Culham Centre for Fusion Energy, Abingdon OX143DB, United Kingdom

[4]Imperial College of Science, Technology and Medicine, London SW72BZ, United Kingdom

The 12th Coordinated Working Group Meeting

The 12th Coordinated Working Group Meeting (CWGM12) was held on 20 September 2013 following the Joint 19th International Stellarator-Heliotron Workshop/ 16th IEA-RFP workshop in Padova, Italy. This was a very brief meeting (1.5 hour) after the adjournment of the workshops. Nevertheless, more than 25 participants from 6 nations attended. In this very short meeting, we focused on progress since CWGM11 (March 2013 at CIEMAT) and future joint activities on some topics. A report of CWGM11 is available in *Stellarator News*, June 2013.

The materials presented at the 12th CWGM are available at http://ishcdb.nifs.ac.jp/ and http://fusionwiki.ciemat.es/wiki/Coordinated_Working_Group (search for CWGM12) for those of you having further interest. Below, you will find a brief summary of the meeting.

The **Inter-Machine Validation Study** on transport models progressed enough for the contents of the joint presentation (IAEA-FEC 2012 by A. Dinklage, IPP) published in *Nuclear Fusion* (2013). Joint activities have been performed on LHD, TJ-II, and W7-AS (using materials from published literature). Discharges with comparable ion and electron temperature in medium to high density (say, $\sim 5 \times 10^{19}$ m^{-3}) have been gathered to form "step-ladder" data sets approaching the reactor-relevant collisionality regime. Complete sets of equilibrium (VMEC) and measured profiles (density, temperatures, and radial electric field) have been prepared to calculate, as the first phase, neoclassical energy diffusion properties using benchmarked (verified) numerical codes. This has been summarized in the *Nuclear Fusion* paper. As an extension of this joint activity, a systematic study has been performed to investigate nonlocal features of neoclassical transport using codes such as FORTEC-3D (see the ISHW2013 poster by S. Satake, NIFS) to analyze this data set (in relation to flows and viscosity). Gyrokinetic simulations are also anticipated by systematically utilizing this data set to simulate validation activity. This data set will be registered in the International Stellarator-Heliotron Profile Database to facilitate common use. Further joint experiments in LHD using increased electron cyclotron heating (ECH) power are being planned. It was pointed out by D. Lopez Bruna (CIEMAT) that we should facilitate study of particle transport issues in addition to ongoing energy transport issues.

Collaborations on **flows and viscosity** have been promoted in terms of neoclassical viscosity analysis using numerical codes (mainly FORTEC-3D). The biasing experiment in LHD has been numerically investigated and has successfully predicted a relevant biasing voltage for transition. In such a way, experimental validation of the numerical codes has progressed. FORTEC-3D is now in preparation to be transitioned to "open source." It has already been transferred to CIEMAT (V.L.Velasco) and used for direct comparison with DKES results (nonlocal–local). It will be also transferred to HSX (October 2013) to investigate neoclassical viscosity in plasmas with a high poloidal Mach number. Other possible collaborations in progress or under consideration are:

- ⇨ IPP (potential asymmetry on a flux surface, high-Z impurity transport by EUTERP, J. M. Garcia-Regana),
- ⇨ PPPL (J.K. Park), Heliotron J (H-J)/TU-Heliac (biasing experiment), and
- ⇨ JAEA (RMP effects on JT-60/JT-60SA, M. Honda).

As you can see, various viscosity verification and validation activities are proceeding.

Collaborations have been successfully developed among TJ-II, LHD, and H-J on **Alfvèn eigen (AE) modes/energetic particles**. Contents of the joint presentation (AE modes in low-shear helical plasmas, IAEA-FEC 2012, S. Yamamoto, Kyoto U.) are anticipated to be published. Recent highlight topics are the observed effect of ECH/ECCD on AE control in TJ-II (*Nuclear Fusion* paper, K. Nagaoka, NIFS) and H-J. Mechanisms have not yet been clarified, and theoretical explanations will be explored by analyzing information from experiments (D.A. Spong, ORNL). An experiment in this regard will be also performed in the coming LHD experimental campaign with participation of E. Ascasibar (CIEMAT). There were also discussions on the strong interaction of this topic with the ITPA Energetic Particle (EP) Topical Group (especially on EP-7: ECH effect on AEs). The next ITPA-EP meeting will be held at CIEMAT in April, and contributions from CWGM are anticipated. Anomalous transport of energetic particles by MHD instabilities is also of common concern among LHD, H-J and TJ-II.

Linking to ITPA is also a major area of CWGM outreach to the wider fusion community. As introduced at CWGM11, the organizational process of the Steady State Operations Coordination Group (SSOCG), co-chaired by T. Mutoh (NIFS) and G. Sips (chair of ITPA Integrated Operation Scenario Topical Group), has progressed by creation of related International Energy Agency (IEA) Implementing Agreements with national laboratories. It has formulated seven work packages for coordinated actions; one of which (#7) is "A draft roadmap for developing steady state operation," to which stellarator-heliotrons certainly should contribute. Proposals for this issue are anticipated from the S-H community. It was also pointed out that it is odd not to have topics such as divertor operation included in the seven packages. This comment was to be transmitted to the next SSOCG meeting (to be held in Fukuoka, October, 2013).

Miscellaneous
It was pointed out by K. Ida (NIFS) that, during the joint ISH-RFP workshop, it was recognized that magnetic topology (e.g., stochasticity, magnetic islands) affects impurity transport, and systematic understanding of this should be an urgent issue. M. Kobayashi (NIFS) proposed to lead an international collaboration on this issue via the EMC3/EIRENE code, based on discussions with groups such as DIII-D (E.A. Unterberg) and TEXTOR (O. Schmitz) during the week. S. Satake (NIFS) also proposed to facilitate studies of the impurity transport issue in core plasmas with the FORTEC-3D code, by utilizing collaboration with EUTERP. Progress on impurity transport issues resulting from these joint activities is foreseen in coming CWGMs.

Finally, a data viewer named "Myview" is under development at NIFS. It was introduced and demonstrated by K. Ida as a tool to facilitate joint experiments on LHD. Details will be available soon. Visitors coming for LHD experiments are cordially invited to test Myview and submit comments for improvement. Also, Sam Lazerson (PPPL) mentioned that he has developed a utility to convert VMEC output files to the old v.6.90 format. Once compiled, it will accept any VMEC output supported by the LIBSTELL package it was compiled with. These kinds of data handling/numerical tools should facilitate our joint activities.

Next Meeting
The 13th CWGM will be held at the Uji Campus (Heliotron J site) of Kyoto University on 26 (Wed)–28 (Fri), February 2014. Those who are interested in participating, please contact K. Nagasaki: nagasaki@ iae.kyoto-u.ac.jp or M. Yokoyama: yokoyama@ LHD.nifs.ac.jp.

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M. Yokoyama (NIFS) on behalf of all participants in the 12th CWGM