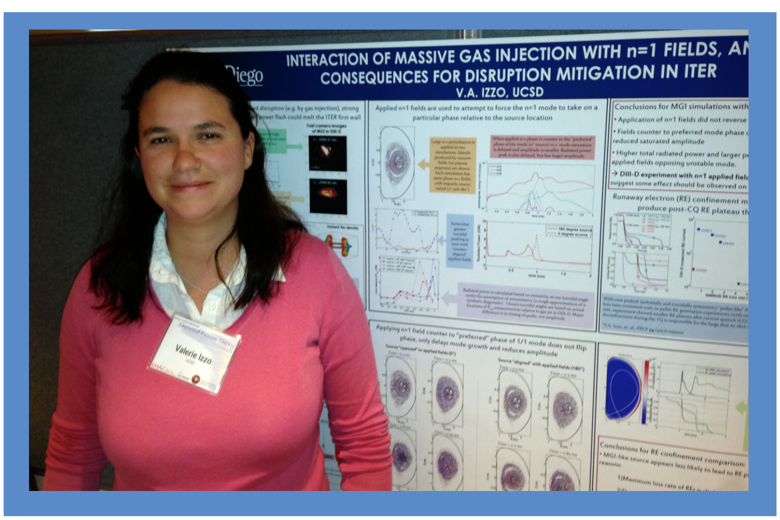
# Highlights from the 2013 International Sherwood Fusion Theory Conference, Santa Fe, NM

**The 2013 International Sherwood Fusion Theory Conference was held in Santa Fe, NM from April 15-17.**

Invited Plenary Speaker Dr. Per Helander, presenting on developments in stellerator theory

There were 15 invited talks spanning the field of fusion theory on topics such as stellerator theory, intrinsic rotation in tokamaks, transport in the plasma edge, and plasma-wall interactions. Author-provided summaries of several of the invited talks are included on pages 5 to 10 of this document. Plenary talks were given by **Per Helander** (Max-Planck-Institut fuer Plasmaphysik, Greifswald, Germany) on "**Overview of recent developments in stellerator theory**", **Amit Misra** (Los Alamos National Laboratory) on "**Stable storage of Helium at interfaces in nanocomposites**", **Sergei Krasheninnikov** (UC San Diego) on "**On the physics of the first wall in fusion devices**", and **Stuart Bale** (UC Berkeley) on "**Solar wind thermo-dynamics and turbulence: collisional – collisionless transitions**".

There was a very strong showing by graduate students, postdocs, and young scientists at the meeting. More than 25 students from around the world presented papers. A list of all participating students can be found on page 3 of this document.




Dr. Valerie Izzo, presenting a poster on the interaction of massive gas injection with n=1 field, a critical area of interest for disruption mitigation strategies on ITER.

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Photos from the Sherwood poster sessions

Dr. Anne White (MIT, Chair of Sherwood Fusion Meeting Executive committee) presented the Student Poster Awards. From left to right: Anne White;  Brendan Lyons, Princeton; Jeff Parker, PPPL; Eric Howell, Wisconsin-Madison; Matthew Beidler, West Virginia; Mordechai Rorvig, Wisconsin-Madison (not pictured: Jianhua Cheng, Colorado-Boulder). Congratulations!

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**Six "Student Poster Awards" were given to the following students for their exceptional presentations:**

**Matthew Beidler** (West Virginia University)
"Parametric Study of Incomplete Reconnection in Sawtooth Crashes"
**Jianhua Cheng** (University of Colorado, Boulder).
"The Coalescence of Magnetic Islands in a Large Aspect Ratio Current Sheet"
**Eric Howell** (University of Wisconsin-Madison)
"Two-Fluid Simulations of CHI Spheromak Formation"
**Brendan Lyons** (Princeton University)
"A new drift-kinetic equation solver for coupled neoclassical-magnetohydrodynamic simulations in axisymmetric systems"
**Jeff Parker** (Princeton Plasma Physics Laboratory)
"Zonal Flow as Pattern Formation: Merging Jets and the Ultimate Jet Length Scale"
**Mordechai Rorvig** (University of Wisconsin-Madison)
"Investigation of design principles for ITG instability optimization of general toroidal geometry"

## Students presenting papers at Sherwood:

1. Stephen Abbott, U. of New Hampshire
2. Marco Agnese, LANL
3. Matthew Beidler, West Virginia U.
4. Francesco Boffa, LANL
5. Joshua Burby, Princeton U.
6. Jianhua Cheng, U. of Colorado-Boulder
7. Marco Chiaramello, LANL
8. Carson Cook, U. of Wisconsin-Madison
9. Brent Covele, U. of Texas at Austin
10. Ge Dong, UCI, China
11. William Farmer, LLNL
12. Maximilian Forstner, LANL
13. Jonathan Hebert, Auburn U.
14. Eric Howell, U. of Wisconsin-Madison
15. Peng Jiang, Peking U., UC Irvine
16. David Johnston, College of William & Mary
17. Jungpyo Lee, MIT
18. Brendan Lyons, Princeton U.
19. Chenhao Ma, Peking U., LLNL
20. Albert Mollen, Chalmers U. of Technology
21. John O'Bryan, U. of Wisconsin-Madison
22. Jeff Parker, PPPL
23. Mordechai Rorvig, U. of Wisconsin-Madison
24. Joshua Sauppe, U. of Wisconsin-Madison
25. Jonathan Squire, PPPL
26. Michelle Victoria, MIT
27. Zhixuan Wang, UC Irvine
28. George Wilkie, U. of Maryland-College Park
29. Pengwei Xi, Peking U., LLNL

# Highlights from the 2013 International Sherwood Fusion Theory Conference, Santa Fe, NM

**Included on the following pages are highlights from several Sherwood Invited Speakers:**

**Overview of recent developments in stellarator theory**
Per Helander, Max-Planck-Institut fuer Plasmaphysik, Greifswald, Germany

**Fully implicit, energy- and charge-conserving particle-in-cell algorithms for kinetic simulation of plasmas**
Guangye Chen, Los Alamos National Laboratory

**Neoclassical flows and transport in the tokamak plasma edge and extensions to include non-axisymmetric effects**
Emily A. Belli, General Atomics

**Intrinsic rotation due to diamagnetic flows in a tokamak**
Jungpyo Lee, Massachusetts Institute of Technology (PhD student at MIT-PSFC)

**ECCD-induced tearing mode stabilization via active control in coupled NIMROD/ GENRAY HPC simulations**
Tom Jenkins, Tech-X Corporation, Boulder, CO

**Efficient non-Fourier implementation of Landau-fluid closure operators for edge plasma simulation**
Andris M. Dimits, Lawrence Livermore National Laboratory

**Overview of recent developments in stellarator theory**

Per Helander

*Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

Stellarators have always constituted an important part of the fusion programme, but their properties are not well known everywhere in the plasma physics community. This talk will give an overview of the physics of these devices, in particular how they resemble and differ from tokamaks. The next large European fusion experiment, Wendelstein 7-X, and its goals will be presented and put in the wider context of stellarator and fusion research.

Toroidal plasma confinement requires a twisted magnetic field, and this twist can be achieved in three basic ways. One of them (a toroidal current) is used in the tokamak and the other two in stellarators (torsion of the magnetic axis and poloidal rotation of the flux-surface cross section). The latter have the advantage of not requiring a plasma current (thus avoiding current drive, kink modes, tearing modes and disruptions) and the disadvantage of producing unconfined orbits. As is well known, this problem can be overcome by endowing the magnetic field with a "hidden symmetry", i.e., by making it quasisymmetric or omnigenous, which reduces the neoclassical transport almost to the level of axisymmetric devices – which is necessary for achieving acceptable confinement even in the absence of turbulence. More recently, it has emerged that this type of magnetic-field optimisation automatically has a number of other important implications for plasma properties such as the bootstrap current and plasma rotation, as well as for microinstabilities. Indeed, it can be shown that so-called quasi-isodynamic stellarators (to which Wendelstein 7-X is a first approximation) are automatically immune to many trapped-particle instabilities (1,2). A comparison between these analytical predictions and the latest gyrokinetic simulations will be presented. It has recently become possible to simulate linear gyrokinetic instabilities globally in the entire volume of a stellarator, and to make nonlinear turbulence simulations on an entire stellarator flux surface, whilst making a local approximation in the radial direction.

(1) J.H.E. Proll, P. Helander, J. W. Connor and G. Plunk, Phys. Rev. Lett. **108**, 245002 (2012).
(2) P. Helander et al., Plasma, Phys. Control. Fusion **54**, 124009 (2012).

## Fully implicit, energy- and charge-conserving particle-in-cell algorithms for kinetic simulation of plasmas

G. Chen, [1] L. Chacón, [1] D. C. Barnes, [2] D. Knoll[1] and the CoCoMANS team[1]
*[1]LANL, NM 87545, [2]Coronado Consulting, Lamy, NM 87540*

In this talk we present a proof-of-principle one-dimensional fully implicit, nonlinear, electromagnetic full-$f$ particle-in-cell (PIC) algorithm for kinetic plasma simulations. The algorithm employs a Jacobian-Free-Newton-Krylov (JFNK) method to implicitly advance particles and fields at the same time self-consistently. Unlike explicit PIC schemes, implicit PIC is not subject to stringent CFL stability time-step constraints, and does not suffer from finite-grid instabilities (which in explicit schemes forces one to resolve the Debye length). Innovative nonlinear elimination (of the particle equations from the field solver) and fluid preconditioning make the implicit method practical. Moreover, emerging computing architectures such as GPUs can be effectively exploited to push the particles. As a result, the approach may enable system-scale full-$f$ kinetic simulations.

The implicit scheme has been formulated to conserve total energy and local charge exactly in a discrete manner, which is critical to the long-term accuracy of system scale kinetic simulations. Such a formulation has been extended to use mapped (curvilinear) meshes. The approach has been demonstrated both with electrostatic and non-radiative electromagnetic (Darwin) models, tested against a wide range of basic multi-scale physics problems including two-species ($e$-$i$) electrostatic ion acoustic shock wave, electron/ion Weibel instability, electromagnetic ion cyclotron instability, and kinetic Alfvén wave (KAW) with ion-ion streaming instability.

Figure 1. KAW ion-ion streaming instability

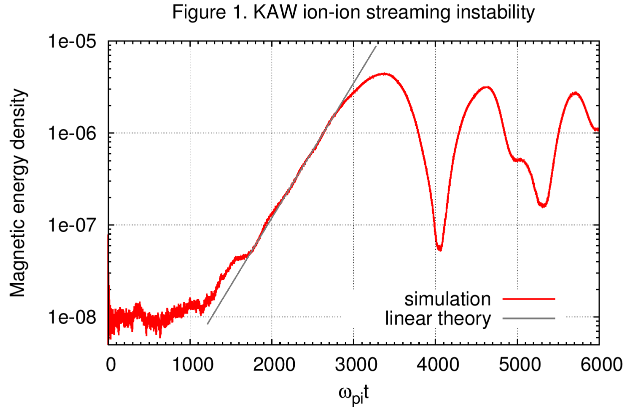



Figure 1 depicts results from a sample simulation of a KAW generated by ion-ion streaming at relatively low (2.5 Alfvén) speed and low plasma beta ($\beta_e$=0.1) with a realistic mass ratio ($m_i/m_e$=1836). The KAW propagates at a large angle (70°) with respect to the magnetic field, and interacts with both electrons and ions. The simulation is performed without resolving the Debye length or the speed of light. Excellent agreement is seen in the growth rate between the simulation and that predicted by linear Vlasov theory.

**Neoclassical Flows and Transport in the Tokamak Plasma Edge and Extensions to Include Non-Axisymmetric Effects**

Emily A. Belli

The drift-kinetic code NEO has been used to explore the neoclassical transport for parameters relevant in the plasma edge. NEO is based on a $\delta f$ expansion of the fundamental drift-kinetic-Poisson equations and provides a first-principles calculation of the neoclassical transport coefficients. The code retains complete kinetic dynamics and makes no approximations beyond the drift ordering. NEO includes multiple ion species, general geometry, full rapid toroidal rotation effects (including centrifugal effects), and the full linearized Fokker-Planck collision operator with complete cross-species collisional coupling for arbitrary mass ratio, thus strictly preserving the ambipolarity property.

Comparisons of the main ion flows in the edge of DIII-D L-mode discharges have found that the NEO simulations of the deuterium parallel flow, which were done inside the separatrix, trend to agreement with Mach probe measurements outside the separatrix upon approach to the last closed flux surface. Furthermore, in both the simulations and measurements, it was found that while the deuterium and carbon parallel flows appear to be correlated in the core, they can differ significantly in the edge. These results indicate that the flows remains essentially neoclassically-driven even close to the plasma edge and that deviations between the deuterium and carbon flows in the edge can be explained by neoclassical physics.

An assessment of the accuracy of analytic models for the bootstrap current has found that NEO provides a 15% correction to the commonly-used Sauter model [1] for experimental DIII-D and NSTX plasmas. Even this small correction has the implication that NEO can significantly improve the accuracy of peeling ballooning and kinetic ballooning mode stability calculations in the edge barrier region. Analysis of the new formula by Koh et al. [2], which is a modification of the Sauter model designed to bring closer agreement between the XGC0 code and the Sauter model in the pedestal, has found that while the Koh modification is negligible for typical DIII-D plasmas, there is a large discrepancy between NEO and the Koh formula in the pedestal for NSTX plasmas. Further analysis finds that the Koh formula essentially exhibits an anomalous spike at large inverse aspect ratio and large to intermediate collision frequency ($\nu_{*e} \sim 1$) even at moderate gradients, a region of parameter space where standard neoclassical theory is rigorously valid, and thus is not accurate in regions where it differs from the Sauter model.

Extensions for non-axisymmetric effects have been included in NEO via a perturbative approach for the purpose of studying small non-axisymmetric effects, such as magnetic field ripple and resonant magnetic perturbations in tokamaks. For these studies, a new 3D local analytic equilibrium solver has been developed, based on the formalism by Hegna [3]. The method is analogous to a 3D extension of the Miller formalism for shaped axisymmetric equilibrium. Unlike a global solver, the method easily allows for systematic studies of the effects of 3D flux surface shaping parameters and ensures good flux surfaces, without any islands or stochasticity, which is essential for coupling with the NEO drift-kinetic equation solver.

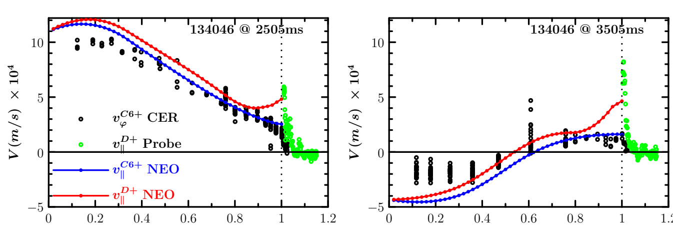



Figure 1: Velocity comparison of the CER carbon toroidal and Mach-probe deuterium parallel measurements with the NEO-computed carbon and deuterium parallel velocities for co- (2500ms) and counter- (3500ms) NBI phases.

[1] Sauter et al., Phys. Plasmas **6**, 2834 (1999); Phys. Plasmas **9**, 5140 (2002).
[2] Koh et al., Phys, Plasmas **19**, 072505 (2012).
[3] C. Hegna, Phys. Plasmas **7**, 3921 (2000).

# Intrinsic rotation due to diamagnetic flows in a tokamak

Jungpyo Lee, Felix I. Parra, and Michael Barnes

MIT PSFC

Intrinsic rotation is generated by turbulent momentum redistribution. To have non-zero momentum redistribution, one must break a lowest-order symmetry of the turbulence that makes momentum transport vanish. This requires inclusion of higher order terms in the gyrokinetic expansion. Here, we focus on the higher order corrections in rhostar poloidal due to diamagnetic particle and heat flows within the flux surface driven by radial gradients of pressure and temperature. In a non-rotating plasma, the toroidal component of diamagnetic particle flow balances the ExB flow driven by the radial electric field. We show that diamagnetic flow causes momentum transport that is different from the one generated by ExB flow of the same size. In the pedestal where the flow due to the strong pressure drop is canceled out by the negative radial electric field, the difference between the two types of momentum flux causes significant intrinsic rotation peaking, comparable in size to measurements. These diamagnetic effects may also explain the transition from co-current intrinsic rotation to counter-current intrinsic rotation when the density of the plasma is increased in experiments.

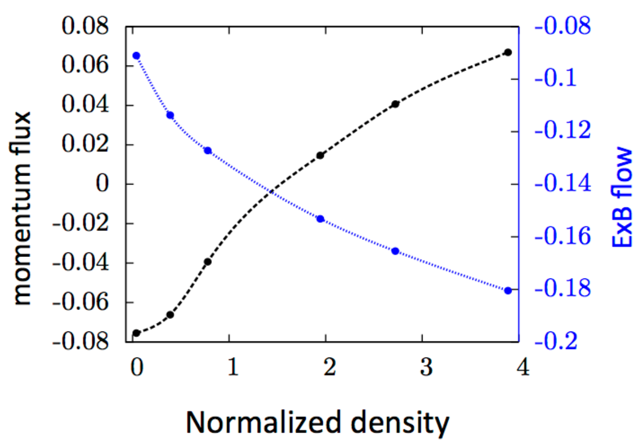



Fig. 1 Normalized intrinsic momentum flux (black) and normalized ExB flow required to cancel diamagnetic flow (blue) vs. normalized density

# ECCD-induced tearing mode stabilization via active control in coupled NIMROD/GENRAY HPC simulations

T. G. Jenkins
(in collaboration with S. E. Kruger, E. D. Held, and other members of the former SWIM project)

We have developed an advanced computational tool for modeling the mitigation and control of tearing modes in tokamaks by actively controlled radiofrequency (RF) waves. Using the formalism of Hegna and Callen [Phys. Plasmas 16, 112501 (2009)] and Ramos [Phys. Plasmas 17, 082502 (2010); 18, 102506 (2011)], we have exploited the spatiotemporal scale separation between RF and extended MHD physics to derive new terms in the extended MHD equations; these new terms arise from quasilinear velocity-space diffusion induced by the RF. These terms have been numerically implemented in a coupled model in which actively controlled RF (modeled by the GENRAY code), in response to signals from synthetic diagnostics embedded in the extended MHD code (NIMROD), is dynamically adjusted to counteract mode growth as the simulation proceeds. The coupled model can be run on high-performance computing platforms (hopper at NERSC, titan at OLCF) using thousands of processors, and has already shed light on physics effects which are difficult to study analytically (e.g. mode stabilization via misaligned RF, RF-induced stochasticity, etc.).

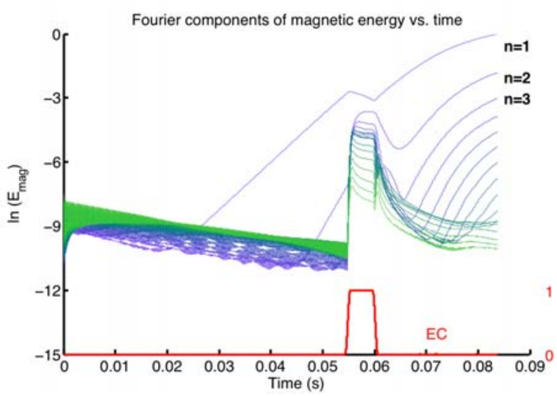



**Figure 1**: Growth of a (2,1) resistive tearing mode is temporarily arrested by the localized application of electron cyclotron current drive within the magnetic island generated by the mode. When the RF-induced current is removed, mode growth resumes.

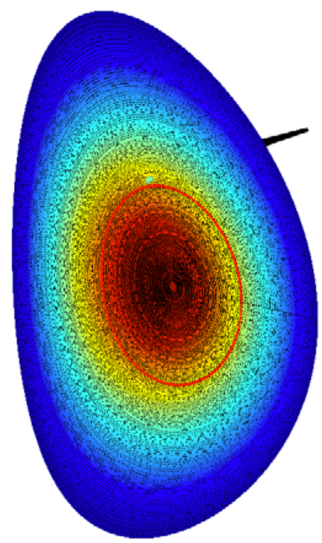


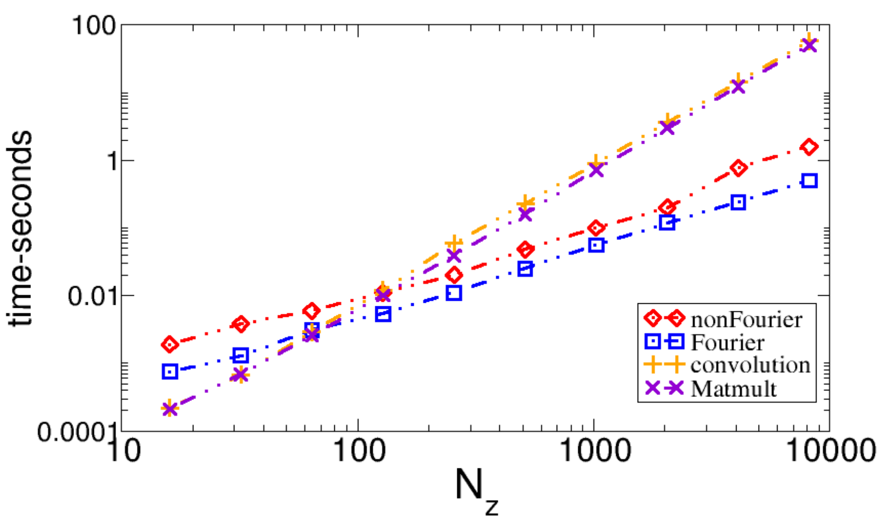
**Figure 2:** Various physics aspects of the coupled model developed by the SWIM project. Atop a cross-section of the toroidal current profile in a poloidal plane, the Poincare mapping corresponding to the magnetic field (black dots) has been superposed; the rational surface (red line) from which the (2,1) tearing mode grows is also shown. As the simulation evolves in time and this mode begins to grow, RF is injected and follows the path indicated by the (three-dimensional) black trajectories in the upper right of the plot. Quasilinear velocity-space diffusion (light green spot near the plot center) arising from the RF serves as a source of heat, momentum, and current on flux surfaces near the growing mode. These sources can be repositioned via an active control system in response to mode growth, and enable the suppression of the mode for appropriately chosen RF parameters.

# EFFICIENT NON-FOURIER IMPLEMENTATION OF LANDAU-FLUID CLOSURE OPERATORS FOR EDGE PLASMA SIMULATION*

A. M. Dimits,[1] I. Joseph,[1] S. S. Kim,[2] M. V. Umansky,[1] P. W. Xi[1,3] and X. Q. Xu[1]
[1]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[2]WCI Center for Fusion Theory, NFRI, Korea
[3]Fusion Simulation Center, School of Physics, Peking University, Beijing, China

Researchers, based at LLNL, Peking University, and NFRI, Korea, have developed highly efficient and accurate non-Fourier, configuration-space-based algorithms for the computation of nonlocal Landau-fluid (LF) closure operators. The most versatile of these methods is based on a and accurate and tunable approximation by a sum of Lorentzians in wavenumber space that allows for the use of optimized sparse linear solvers as a very efficient way to implement the nonlocality inherent in the LF operators, and results Fourier-like computational scaling.

Such non-Fourier algorithms are an essential component in implementations, which have been undertaken, of gyro-Landau-fluid (GLF) models for tokamak edge and scrapeoff layer simulation in the BOUT++ code. The GLF models provide BOUT++ with greatly increased fidelity for simulations of the edge region of the plasma, where the strongly collisional (Braginskii) approximation that underlies many fluid plasma models is often not valid. The resulting model in BOUT++ has been successfully benchmarked against previous published GLF computations.




Computational time for 1000 applications of a LF closure operator via the Fourier method and non-Fourier (sum-of-Lorentzians and two direct) methods, versus the number of grid cells in a periodic domain. The timings are for a single core of a 2.6GHz Intel Core i7 CPU.

*Work performed for US DOE by LLNL under Contract DE-AC52-07NA27344 and LLNL LDRD project 12-ERD-022.