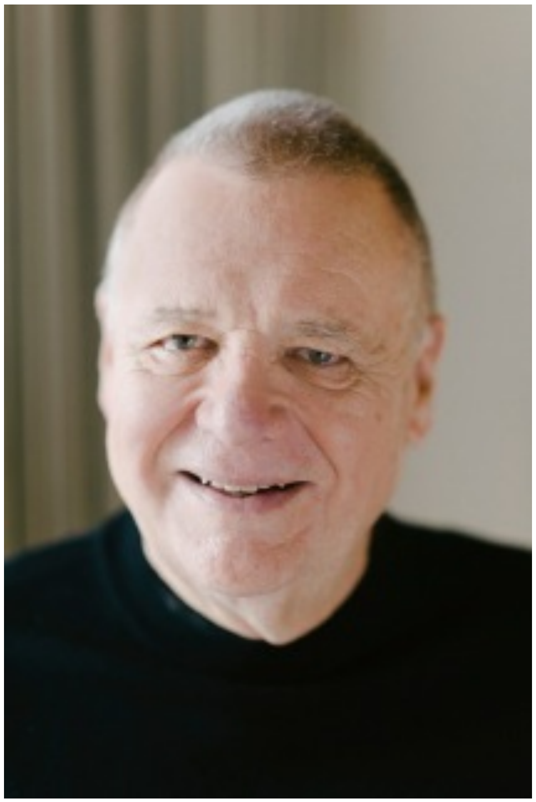
A Retrospective on Dalton Schnack's Contributions to Plasma Science



Dalton Schnack, 1943-2013

Inaugural presentation for a memorial seminar series

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Thesis: Dalton Schnack helped develop the science of nonlinear plasma MHD for multiple sub-disciplines.

OUTLINE

- Reversed-field pinch physics
  - Single-helicity evolution
  - Multi-helicity dynamics
  - Non-ideal boundary physics
- Solar physics
- Other physics collaborations
  - Tokamak contributions
  - Basic plasma studies
- Numerical development
  - Spectral methods
  - Semi-implicit time-advance for MHD
- Summary and closing thoughts

Reversed-field pinch: Early numerical studies investigated nonlinear single-helicity evolution.

- Self-reversal in pinches had been measured experimentally by 1970.
- Taylor's hypothesis [PRL 33, 1139 (1974)] provides a nonlinear explanation, but it does not describe the underlying resistive-MHD dynamics.
- Schnack's PhD study [NF 19, 977 (1979)] was one of the earliest to consider nonlinear tearing-mode evolution in pinch profiles.
  - S=100, $\beta > 0$ computations started from the Bessel-function profile with λa large enough for instability.
  - Saturation of *m*=0, 1, and 2 are computed, and *m*=1 (shown) is considered the most dangerous, due to saturation amplitude.
- Schnack's nonlinear resistive-interchange study [NF 21, 1447 (1981)] with $\beta(0)$ = 18% finds *m*=0 to be most important.

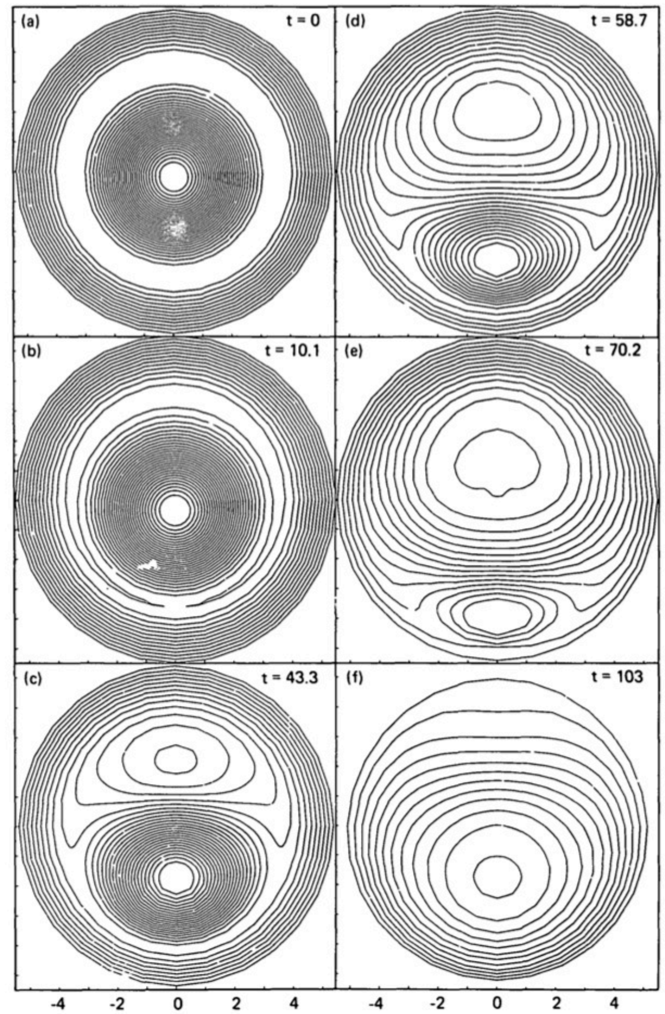

FIG.7. Magnetic flux surfaces for m = 1.

The best-known single-helicity study compares RFP startup with Kadomtsev reconnection.

- The publication [PF 26, 1305 (1983)] is one of a series from the Caramana-Nebel-Schnack team.
- Explaining rapid penetration of current was the motivation.
- The sketch shown at right describes how helical flux (vertical axis on right sub-plots) is destroyed by reconnection while axial flux (horizontal axis) is preserved, leading to current penetration.
- Numerical computation is used to confirm this Kadomtsev-like model.
- Resistive transport between events is modeled separately.
- Double-reconnection relaxes a profile peaked by transport.
- 3D effects are anticipated.

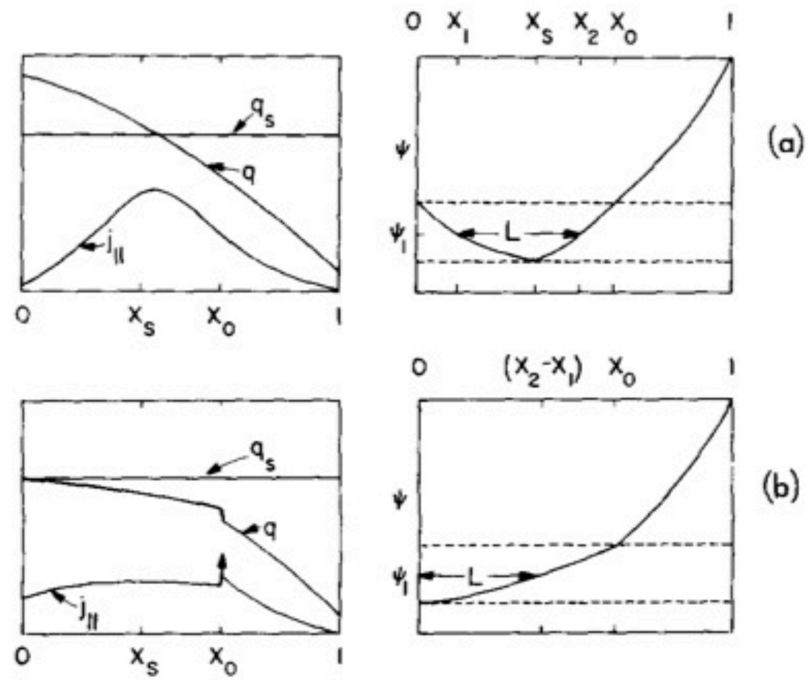

FIG. 3. Kadomtsev reconnection model for the RFP in toroidal flux representation: (a) $q, j_\parallel$, and ψ before reconnection and (b) $q, j_\parallel$, and ψ after reconnection.

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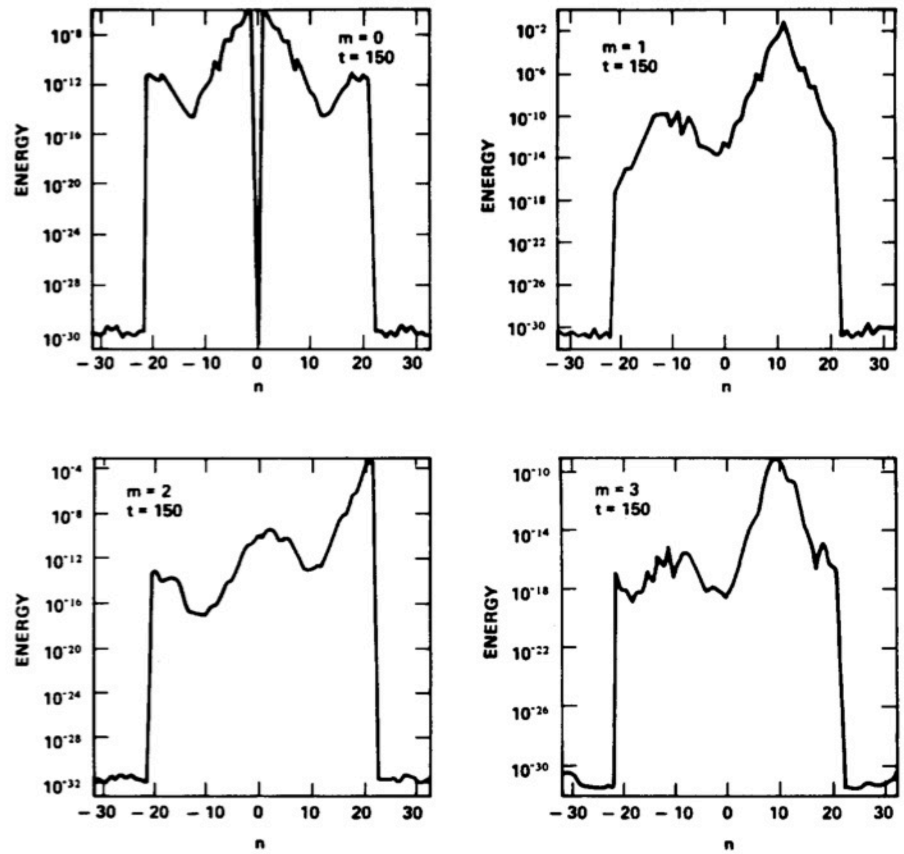
Multi-helicity computation established many of the concepts behind present-day RFP understanding.

- The "team's" first multi-helicity publication [PF 28, 321 (1985)] followed Aydemir and Barnes' result on self-reversal in incompressible dynamics [PRL 52, 930 (1984)].
- The PF 28 paper compares single- and multi-helicity evolution at low (1.5) and high (1.8) values of the pinch parameter Θ. *R/a*=5 is based on ZT-40, and S=1000.
- *m*=1 instabilities saturate at lower amplitude due to nonlinear coupling to stable *m*=0 and *m*=2 (right).
- Stochastic magnetic field results from island overlap. [Also shown by Aydemir and Barnes.]
- Generation of reversed toroidal flux is explained in terms of fluctuation-induced **E**. With a sign error,

$$\langle E_\Theta(r_v)\rangle = \eta_0\langle J_\Theta(r_v)\rangle + \sum_{m=0}^{M}\epsilon_m,$$

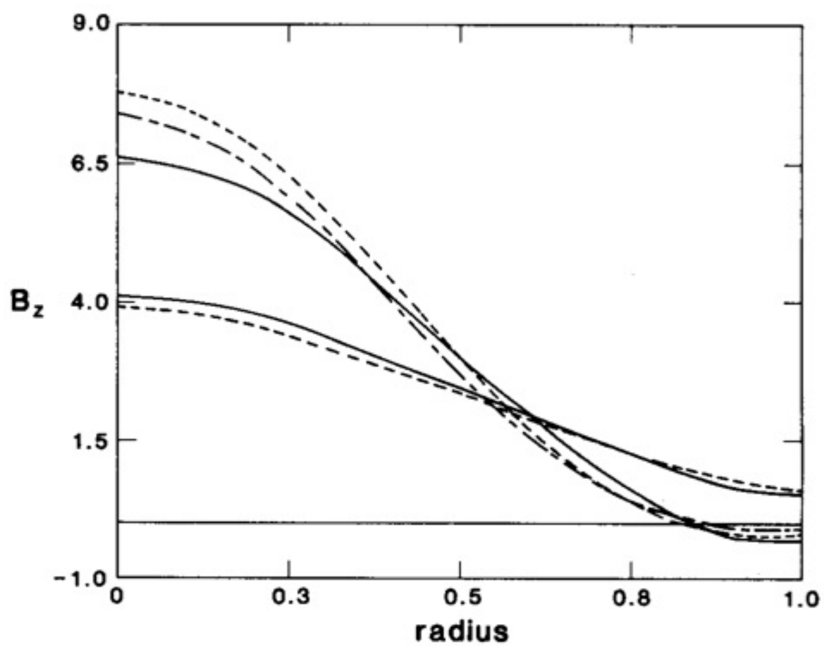
where

$$\epsilon_m = \sum_{n=0}^{N}\langle \mathbf{v}_{m,n}\times\mathbf{b}_{m,n}\rangle_\Theta .$$

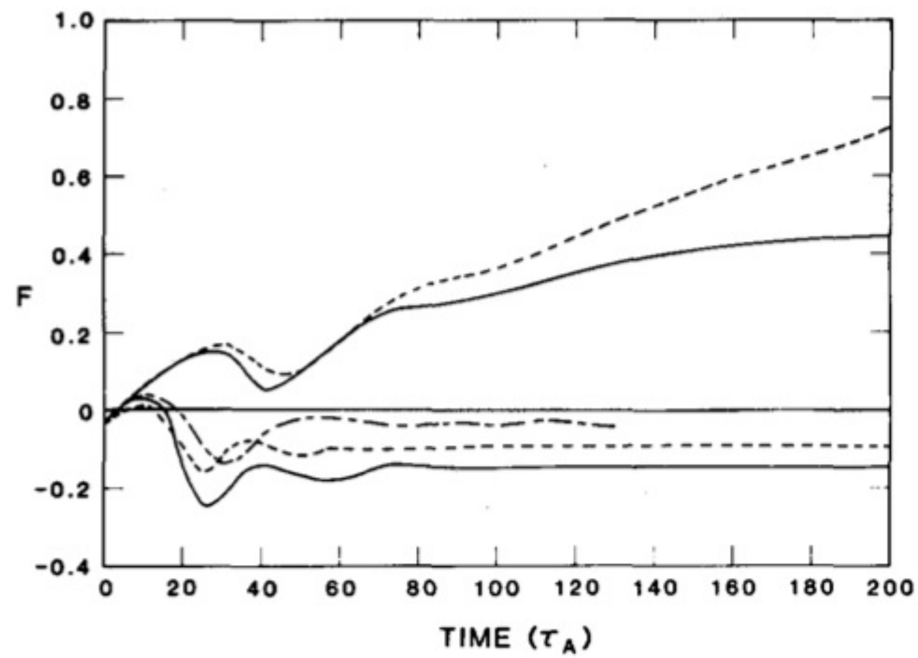


A multi-institutional group investigated the importance of compressibility for RFP sustainment.

- The group applied 3 compressible and 2 incompressible codes to the same set of parameters and initial conditions (S=1000, *R/a*=1, $\lambda(0)a$=5).
- The results reported in [Aydemir, *et al.*, PF 28, 899 (1985)] consistently show sustained reversal in compressible evolution and no reversal (for these parameters) for the incompressible cases.
- The importance of pinch flow is cited as the primary distinguishing effect.



Comparison of B_z at 100 τ_A.



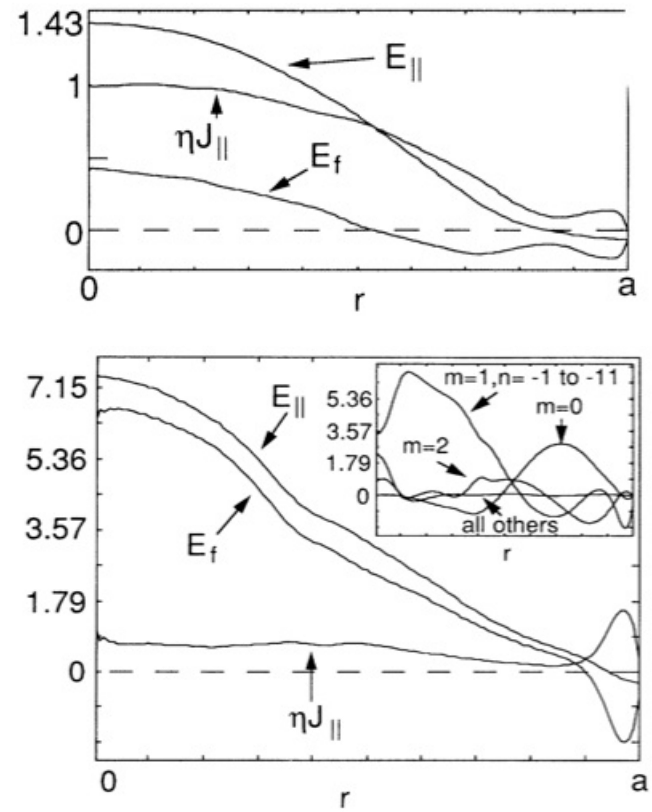
Evolution of reversal parameter.

Other studies of relaxation in RFPs consider rising-current operation, the role of *m*=0 components, and aspect-ratio scaling.

- The study on rising current [Caramana and Schnack, PF 29, 3023 (1986)] assessed which fluctuations are needed to obtain reversal at different values of the pinch parameter.
  - This publication is the first to report results from the DEBS code.
- The study of *m*=0 [Nebel, *et al.*, PFB 1, 1671 (1989)] stemmed from a conflicting description of RFP dynamo being primarily from *m*=0 [Kusano and Sato, NF 27, 821 (1987)].
  - Results in PFB 1 show *m*=1 contributions to net **E** being 10x larger than *m*=0.
  - Selectively removing *m*=0 coupling to the mean profile had little effect.
  - Prediction of fluctuation levels scaling as S^0 would later prove to be non-representative of sustainment at larger S-values.
- The aspect-ratio study [Ho, Schnack, *et al.*, PoP2, 3407 (1995)] found that the average energy per fluctuating component decreases while the number of active fluctuations increases as *R/a* is increased.

Interest on the effects of non-ideal walls grew into long-term collaborations with Wisconsin, Consorzio RFX, and KTH Royal Institute of Technology.

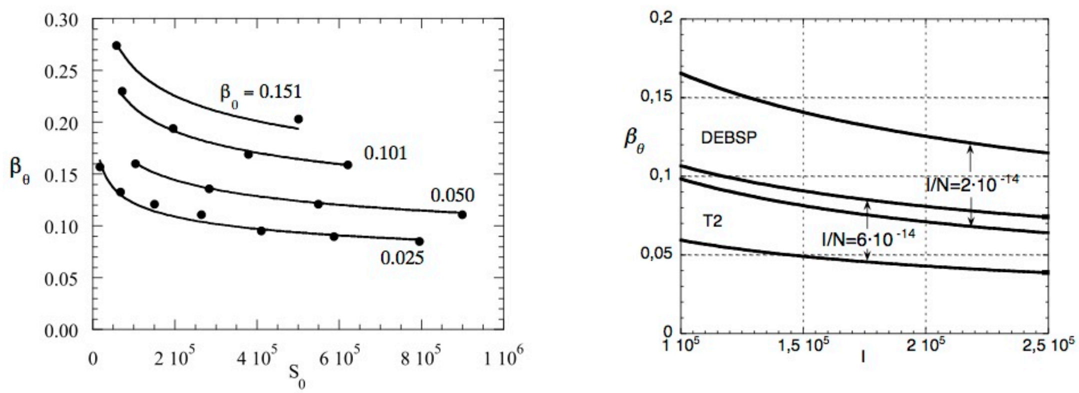
- With Schnack providing DEBS assistance, Y.-L. Ho found helicity dissipation through a resistive shell to alter the RFP dynamo and loop voltage [Ho, Prager, and Schnack, PRL 62, 1504 (1989)].
- A parameter study for RFX examined effects of the designed resistive shell while the experiment was under construction. [Schnack and Ortoloni, NF 30, 277 (1990)]
    - Large-Θ results show an external kink that is not present at lower Θ-values.
    - Results with a resistive shell show significantly larger fluctuation levels and larger loop voltage relative to ideal-wall cases.
- Sätherblom, Schnack, and Drake [PPCF 40, 1175 (1998)] show that large flow can unlock thin-wall modes and recover ideal-wall performance.



Simulation results with an ideal wall (top) and with a resistive wall (bottom), where τ_w= 0.1 τ_r. [Ho, PRL 62]

Other RFP collaborations addressed feedback, confinement scaling, and self-similar decay.

- The first feedback study [Zita, Prager, Ho, and Schnack, NF 32, 1941 (1992)] used a perfect response (B_r=0) for selected components and compared results from HBTX1, where feedback on the external (1,2) component maintained reversal.
- Paccagnella, Schnack & Chu [PoP 9, 234 (2002)] studied the ideal-plasma case further.
- Scheffel used Schnack's finite-β version of DEBS and linear regression analysis to obtain energy confinement scaling as a function of current and S-value [NF 40, 1885 (2000)].

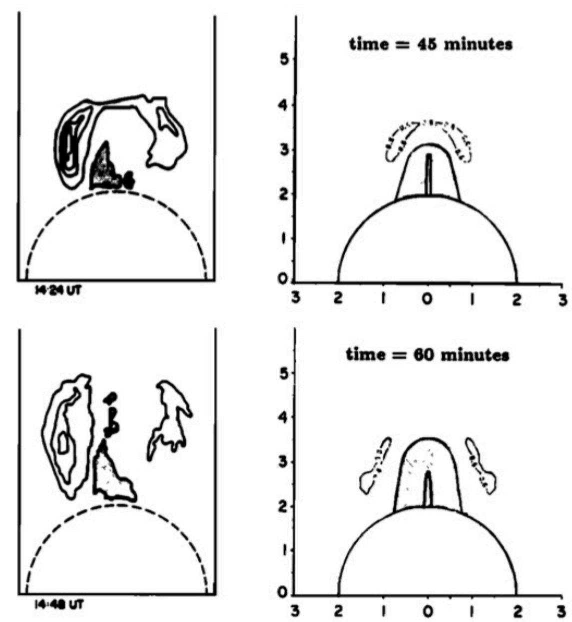


Simulation results (left) and $\beta(I)$ comparison with Extrap-T2 (right). [NF 40, 1885]

- Reusch, *et al.* [PRL 107, 155002 (2011)] compares measured T_e profiles and magnetic fluctuations from DEBS to identify trapped-particle effects on MST confinement.
- Nebel, Schnack, and Gianakon [PoP 9, 4968 (2002)] use DEBS to optimize surface fields for MHD-stable decay.

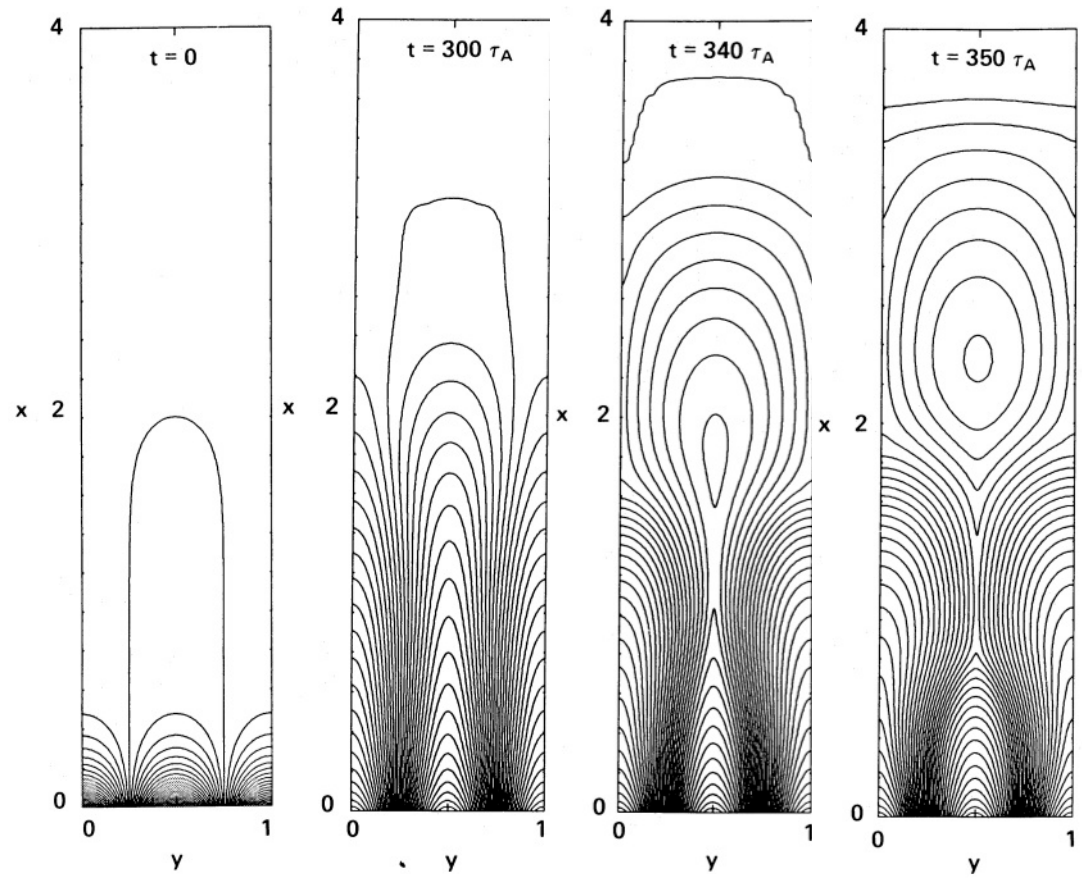
Solar physics: Numerical technology transfer and collaborations led to productive solar physics studies.

- Numerical methods for fusion simulation are also relevant for the stiff conditions of the solar corona, and collaborations with van Hoven's group at UC-Irvine addressed the formation of filaments.
  - The group studied radiative condensation in the presence of sheared magnetic field [van Hoven, *et al.*, APJ 317, L92 (1987)].
  - The different scalings of temperature and density dynamics with respect to $k_{||}$ is central in the condensation process [Sparks, *et al.*, APJ 353, 297 (1990)].
- Linker, van Hoven, and Schnack [JGR 95, 4229 (1990)] used MHD computation to investigate coronal mass ejection (CME) driven by solar flare dynamics.
  - Results shown at right compare relative density changes from observations (left column) with simulation results (right column).
  - Other studies had focused on thermal drives as the launch mechanism for CMEs.



Concurrent in-house efforts at SAIC grew into an internationally recognized solar physics group.

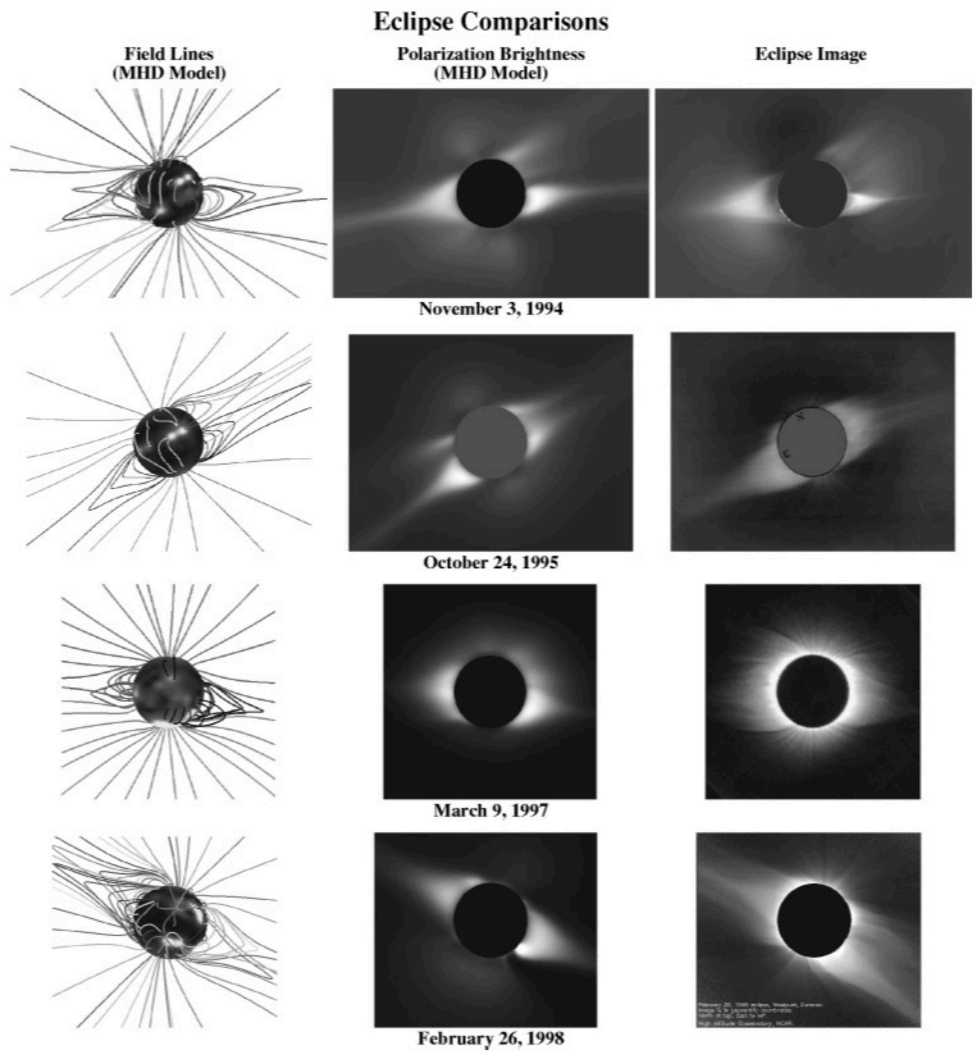
- Mikić, Barnes, and Schnack were the first to consider nonlinear resistive evolution over long time-scales while allowing 3D dynamics [APJ 328, 830 (1988)].
    - The computations prescribe tangential footpoint motion along the neutral line (into and out of page, as shown).
    - Induced magnetic tension excites ballooning.
    - Transverse forcing leads to current sheets and magnetic reconnection.
- Mikić, Schnack, and van Hoven investigate the random footpoint-motion model pertaining to current-filament formation [APJ 338, 1148 (1989)].



- Schnack, Mikić, and Barnes summarize applications and methods [CPC 59, 21 (1990)].

The group addressed questions of basic plasma science and developed predictive capability.

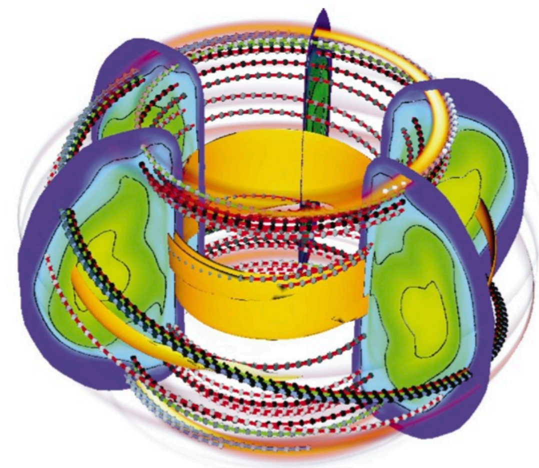
- Lionello, Schnack, Einaudi, and Velli study current-sheet formation due to ideal instability in net-current-free and current-carrying flux tubes [PoP 5, 3722 (1998)].
  - The group compared axially periodic and line-tied dynamics.
  - Results show current-sheet formation in both; axial localization occurs with tying.
- Direct comparison of predicted magnetic-field structures with eclipse images (shown) and other observations was a major accomplishment for computational science. [Mikić,*et al.*, PoP 6, 2217 (1999)]



All but Nov. 3, ’94 (top row) are predictions.

Other physics collaborations: Contributions over the last decade include tokamak and basic plasma physics.

- Kruger, Schnack, and Sovinec modeled disruption of a DIII-D discharge as a result of heating above a tearing-mode threshold [PoP 12, 056113 (2005)].
    - Localized heat deposition results from anisotropic conduction along perturbed **B**.
- The late evolution of edge-localized modes (ELMs) displays strong nonlinear coupling that is similar to RFP relaxation. [For example, Brennan, *et al.*, JPCS 46, 63 (2006) and Pankin, *et al.*, NF 46, 403 (2006)].

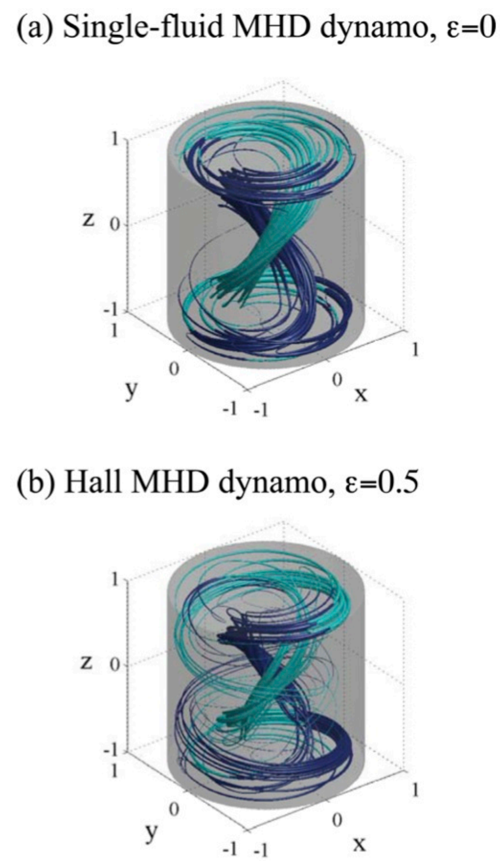


Perpendicular heat flux and field line trajectories from simulated disruption.

- Schnack collaborated on a categorization of onset conditions for tokamak tearing-modes [Brennan, *et al.*, NF 45, 1178 (2005)].
- He mentored another study of the effects of RF-driven current for stabilizing tokamak tearing modes [Jenkins, *et al.*, PoP 17, 012502 (2010)].
- His interest in drift models for tokamaks led to an APS tutorial and companion paper [Schnack, *et al.*, PoP 13 058103 (2006)].

Basic-plasma collaborations stemmed from the drift-model study and Center for Magnetic Self-Organization topics.

- Schnack had a keen interest in the so-called "gyro-viscous cancellation."
    - Ping Zhu's revision [Zhu, *et al.*, PRL 101, 085005 (2008)] of the Robert-Taylor result on drift-stabilization of the g-mode was inspired by discussions with Schnack.
- Schnack led a study of ion temperature gradient (ITG) instability in the extended-MHD model and made comparisons with kinetic simulations and analytics. [Schnack, Cheng, Barnes, and Parker, PoP 20, 062106 (2013)].
- Schnack worked with Ebrahimi and Prager on modeling the nonlinear evolution of the magneto-rotational instability (MRI) [APJ 698, 233 (2009)].
- He also work with Ivan Khalzov and colleagues on modeling MHD dynamics relevant to the Madison Plasma Couette Experiment (shown) [PoP 18, 032110 (2011)] and on relaxation theory in MHD and Hall-MHD systems [PoP 19, 012111 (2012)].



Comparison of dynamo-driven **B** from von Karman flow in MHD and Hall regimes.

Numerical development: An emphasis on practical implicit methods began with early applications.

- The algorithm applied in single-helicity computations used the alternating-direction implicit method (ADI) with operator splitting to extend the range of stability relative to explicit MHD. [Schnack and Killeen, JCP 35, 110 (1980)]
  - Spatial differencing is conservative an on a 2D mesh over orthogonal curvilinear coordinates.
  - Verification testing includes tearing in a sheared slab.
- The development that allowed 3D RFP computations was application of spectral methods with collocation for integrating nonlinear products. [Schnack, Baxter, and Caramana, JCP 55, 485 (1984)]
  - Fast Fourier Transforms are critical for computational performance.
  - Diffusive terms were implemented with implicit solves, but the ideal part of the MHD system was solved explicitly.

Application of the semi-implicit method proved quite successful for magnetic-confinement MHD.

- Harned and Kerner [JCP 60, 62 (1985)] were the first to adapt a stabilization scheme, based on numerical dispersion, from numerical weather prediction [A. J. Robert (1969)] to fast MHD waves.
- Harned and Schnack [JCP 65, 57 (1986)] developed an anisotropic semi-implicit operator to stabilize fast and shear waves.
  - RFP computation provided the primary motivation; parallel wavenumbers in dynamics of interest are larger than in tokamak MHD.
- The DEBS algorithm [Schnack, *et al.*, JCP 70, 330 (1987)] is a leapfrog-based version.

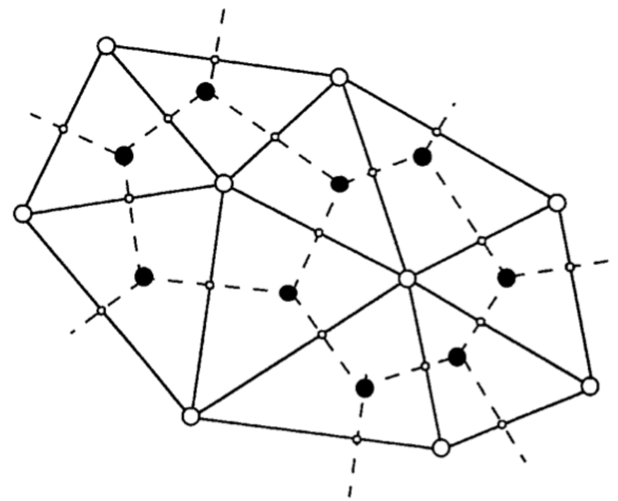
$$\frac{\partial}{\partial t}u = -c\frac{\partial}{\partial x}v \qquad \longrightarrow \qquad \frac{u^{n+1/2}-u^{n-1/2}}{\Delta t} = -c\frac{\partial}{\partial x}v^n$$

$$\frac{\partial}{\partial t}v = -c\frac{\partial}{\partial x}u \qquad\qquad \left[1+c^2\Delta t^2 L_{si}\right]\frac{v^{n+1}-v^n}{\Delta t} = -c\frac{\partial}{\partial x}u^{n+1/2}$$

where L_{si} is a self-adjoint differential operator with respect to x, and the equation is easier to solve numerically than the fully implicit system.

- This paper provides greater analysis and testing than previous MHD SI papers.

Other numerical projects include MHD on unstructured, adaptive triangular meshing and NIMROD.



- The triangular-mesh algorithm was an effort to provide efficient numerical resolution as regions of interest move due to nonlinear evolution [Schnack, *et al.*, JCP 140, 71 (1998)].
  - The finite-volume computations use a primary triangular mesh and a polygon dual mesh (shown in sketch).
  - The algorithm conserved mass, momentum, energy and preserved solenoidal properties.
- Schnack provided the essential leadership for the Non-Ideal MHD with Rotation, Open Discussion project [https://nimrodteam.org; Sovinec, *et al.*, PoP 10, 1727 (2003)].
  - A significant aspect of the study, initially, was whether management and software-development techniques like total quality management (TQM) and quality function deployment (QFD) could speed scientific code development.
  - Aspects of Schnack's semi-implicit and spectral methods have been used and extended in the algorithm [Sovinec, *et al.*, JCP 195, 335 (2004)].

Summary

- Dalton Schnack's enthusiasm for plasma science, numerical computation, and teamwork is evident in many areas.
- His nonlinear RFP studies underpin our current understanding of RFP relaxation.
- Initiative in applying fusion MHD computation to solar physics helped launch a successful group.
- Interest in learning the diversity of plasma dynamics continued throughout his career.
- Excellence in numerical computation facilitated many plasma studies.

A quote from Schnack's 1990 Computer Physics Communications paper is an appropriate closing remark:

"With continued application of the computational resources available to the community, and with good computational physics, progress can be made. It is time to put away cartoons, to stop speculating about dynamics, and to start computing."