CUMULATIVE REPORT 1978-2014
GEORGIA INSTITUTE OF TECHNOLOGY
FUSION RESEARCH CENTER
June, 2014

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Prepared by
W. M. Stacey
Prior to the 1990s, plasma research in the GIT-FRC was in the areas of impurity transport and rotation (refs A), experimental plasma physics (refs B) and a general range of plasma physics such as MHD and burn control (refs C). In the early-1990s the plasma research activities of the GIT-FRC were focused more strongly on the plasma edge and plasma rotation, and new research projects were undertaken on impurity-seeded radiative power exhaust (refs D), neutral atom transport (refs E) and edge radiative instabilities (refs F). Independent calculations by the GIT-FRC group and by a group in Germany led to the radiative edge/radiative divertor power exhaust solution being examined and ultimately adopted for ITER. In 1998, Tom Simonen, then Director of the DIII-D Program, invited Prof. Stacey to utilize the modeling and computational resources of the FRC to support the DIII-D Program as part of the DIII-D National Team. The initial DIII-D effort was directed towards the radiative edge impurity “seeding” experiments which DIII-D was undertaking in support of the effort to develop a radiative power exhaust solution for ITER.

GIT work on DIII-D evolved in the early 2000s to encompass radiative instabilities such as MARFEs and disruptions (refs F) and neutral particle recycling (refs E) calculations in the plasma edge. Predictive models for density limits due to MARFEs, disruptions, divertor choking, etc. were developed, incorporated in a GIT plasma edge modeling code for DIII-D (an early version of GTEDGE), and validated by experimental comparison. A new interface current balance methodology for neutral atom transport in the complex edge geometry of DIII-D was developed and incorporated in the GTEDGE code and in the more geometrically comprehensive GTNEUT code (Refs E13 & 14) which is used for detailed analysis of neutral recycling in DIII-D experiments. GTNEUT was demonstrated to obtain accuracy comparable to Monte Carlo but in a few percent of the MC computing time, and was used for several DIII-D neutral recycling analyses (Ref E17).

Analysis of plasma rotation measurements in DIII-D using an extended neoclassical viscosity theory (developed in large part in the GIT-FRC) has demonstrated that, when poloidal asymmetries in flux surface geometry and plasma variables are taken into account, there is good agreement with experimental measurements, except in the plasma edge. This work established a validated predictive capability for toroidal velocity (Refs A30 & 31). A different methodology has been developed for calculating the intrinsic rotation due to ion orbit loss which predicts the intrinsic rotation measured in DIII-D quite well (Refs. A32 & 34).

For the past decade, the major focus of the GIT analysis and interpretation of DIII-D experiments has been in the area of plasma edge physics (refs G & H). A systematic development (particle, momentum and energy balance) of the equations that should be used to calculate or interpret the measurements of profiles of pressure, density, temperature, rotation, electric field, etc. in the plasma edge identified the importance of non-diffusive transport effects (electromagnetic particle pinch, ion orbit loss) which must be incorporated in the existing equations used for such analyses. A new generalized diffusion theory (Ref H14) was developed and incorporated in the GTEDGE code, which was applied to interpret the diffusive and non-diffusive transport underlying the measured parameter profiles in the DIII-D edge plasma Refs H). New insights have been obtained about the evolution of edge profiles at the L-H transition,
between ELMs, etc., and about the differences in edge transport between H-mode and RMP discharges, between L-mode and H-mode discharges, etc. New and extended techniques for data fitting have been developed in collaboration with DIII-D experimentalists.

The work of the GIT-FRC on plasma physics research and the analysis and interpretation of DIII-D experiments from 1978-2014 was performed by Profs. G. Bateman (NRE), J. Mandrekas (NRE), W. M. Stacey (NRE), C. E. Thomas (NRE) and E. W. Thomas (PHYS), and by a score or more of post-doc and graduate student researchers, working in collaboration with physicists from GA, ORNL, PPPL, LLNL, UCSD and UTEXAS. Numerous papers in leading peer-reviewed journals and presentations at APS-DPP, TTF, H-Mode, PET and other conferences. 17 PhD theses, 5 MS theses and 15 undergraduate research projects have resulted from the GIT-FRC plasma research since the 1980s, many of them associated with the analysis and interpretation of DIII-D experiments.

PLASMA PHYSICS PAPERS BY GIT-FRC RESEARCHERS

A. PLASMA ROTATION & IMPURITY TRANSPORT
11. "Analysis of the Unbalanced NBI Rotation Experiments in the ISX-B, PLT and PDX Tokamaks", Nucl. Fusion, 26, 293 (1986); C.M. Ryu, M.A. Malik and W. M. Stacey
17. "Control of Plasma Rotation by Controlling the Content of Highly Collisional Ions in Strongly-Rotating Tokamak Plasmas with Unbalanced Neutral Beam Injection", Fusion Techn., 23, 139-156 (1993); G.W. Neeley and W. M. Stacey
B. EXPERIMENTAL PLASMA PHYSICS


C. TRANSPORT, MHD & OTHER PLASMA PHYSICS


D. IMPURITY-SEEDED PLASMA POWER EXHAUST
5. "Analysis of the Performance of the ITER Divertor and Analysis of the ITER Tokamak Edge Parameter Database", 16th IAEA Fusion Energy Conf. (Montreal, 1996); many authors.


E. NEUTRAL PARTICLE TRANSPORT


F. RADIATIVE INSTABILITIES & EDGE DENSITY LIMITS


G. PLASMA EDGE & DIVERTOR MODELING

H. EDGE PEDESTAL STRUCTURE & TRANSPORT
38. “Sensitivity of the interpretation of the experimental ion thermal diffusivity to the determination of the ion conductive heat flux”, Phys. Plasmas 21, 042508 (2014). W. M.
FUSION TECHNOLOGY AND REACTOR DESIGN RESEARCH IN THE GEORGIA INSTITUTE OF TECHNOLOGY FUSION RESEARCH CENTER 1978-2014

The initial work on fusion technology and design at Georgia Tech was associated with the US contribution to the IAEA INTOR Workshop to evaluate the readiness of fusion to move forward to the experimental power reactor stage, during the late 1970s and 1980s. (Refs I) The US effort in INTOR was organized and managed by Prof. Stacey and contributed to by Profs. M. A. Abdou, G. Bateman and C. E. Thomas from the GIT-FRC and hundreds from other organizations. When the ITER project was formed at the end of the INTOR Workshop, Prof. Stacey served as Chairman of the ITER Steering Committee US through the 1990s, and researchers in the GIT-FRC turned their attention to technology investigations of plasma-materials interactions, tritium breeding blankets and low-activation structural materials (refs J). Applications of variational methods to nuclear reactor dynamics and neutral particle transport in plasmas was also examined (Refs. L).

In the 1990s and continuing today, student design projects guided by Profs. Stacey (NRE), Mandrekas (NRE), Lackey (ME), Ghiaasiaan (ME), Tedder (ChE), Van Roojen (NRE) and Erickson (NRE) investigated several fusion-fission transmutation reactor concepts and performed supporting fuel cycle and dynamic safety analyses (refs K). The fuel cycle work led to a collaborative effort with the Karlsruhe Institute of Technology over several years on the evaluation of the GIT SABR concept (a tokamak based on ITER physics and technology surrounded by an annular metal-fueled, sodium-cooled fast reactor of the IFR type—Refs K21 & K32) for the transmutation of spent nuclear fuel.

The FRC being located in a nuclear engineering department provided many opportunities for adapting and extending fission reactor physics and engineering methodologies for application to fusion plasma and reactor analysis. Much of the work on radiative instabilities (Ref F28) was based on the stability analysis methodology of nuclear reactor physics, and the Transmission-Escape Probability method (Refs E) for neutral atom transport was adapted from the neutron transport theory of nuclear reactor physics. The nuclear fuel cycle methodology and the reactor and heat removal systems transient analysis methods of nuclear reactor physics were adapted for the SABR fuel cycle (Refs K9, K15, K24, K30) and dynamic safety (Ref K25) analyses. Variational analysis methods were developed for nuclear reactor dynamics and neutron transport analyses (Refs I1-I3)) and then applied to neutral particle reaction rate calculations (I4).

Several hundred graduate and advanced undergraduate students have been involved in this effort, which has led to 4 PhD theses and 9 MS theses, as well as numerous publications and presentations.
I. EXPERIMENTAL FUSION POWER REACTORS, INTOR & ITER
38. "Active Control of Thermonuclear Burn Conditions for the International Thermonuclear Experimental Reactor", *Fusion Techn.*, 18, 606 (1990); J. Mandrekas, W. M. Staczy, with others.


J. FUSION REACTORS & TECHNOLOGY


3. The Influence of Physics Parameters on Tokamak Reactor Design", Nucl. Techn., 43, 28 (1979); W. M. Stacey with others.


K. FUSION-FISSION TRANSMUTATION REACTORS


L. VARIATIONAL METHODS


ONGOING THESIS RESEARCH

PhD
Student: John-Patrick Floyd
Topic Area: Evolution of Edge Profiles and Transport Between ELMs in DIII-D.
Background: Refs. H13
DIII-D Collaborator: R. J. Groebner

Student: Theresa Wilks
Topic Area: Radial Electric Field and Profile Structure in the DIII-D Edge Plasma
Background: Refs. H34, H36
DIII-D Collaborator: T. E. Evans

Student: Jonathan Rovetto
Topic Area: Interpretation of Edge Thermal Transport in DIII-D & Comparison with Theory
Background: Refs. H16, H38
DIII-D Collaborator: TBD

Student: Andrew Bopp
Topic Area: Dynamic Safety Analysis of the SABR Fusion- Fission Hybrid
Background: Refs K25

MSNRE
Student: Timothy Collart
Topic Area: Interpretation of Angular Momentum Transport in DIII-D & Comparison with Theory*
Background: Refs. A31, A34, H15
DIII-D Collaborator: B. A. Grierson

Student: Maxwell Hill
Topic Area: Benchmarking a Burning Plasma Dynamics Model to DIII-D Data*
Background: Refs. I36-I39, J17
DIII-D Collaborator: TBD

Student: Nicholas Piper
Topic Area: Interpretation of Change in Edge Toroidal Rotation Profile Across L-H Transition in DIII-D*
Background: Refs. H31
DIII-D Collaborator: R. J. Groebner

Student: Matthew Schumann
Topic Area: Poloidal Distribution of Particle, Momentum and Energy Fluxes into the SOL in DIII-D*
DIII-D Collaborator: TBD

• Intend to continue this area of research for a PhD thesis.
PEOPLE IN GIT-FRC

FACULTY

M. A. Abdou (NRE)  Fusion Nuclear Engr*  1978-79
G. Bateman (NRE)  Plasma Theory & Comp*  1980s
A. S. Erickson (NRE)  Heat Removal, Fusion-Fission*  2010s
S. M. Ghiaasiaan (ME)  Heat Removal*  1990s-2000s
N. E. Hertel (NRE)  Waste Management*  1990s
W. J. Lackey (ME)  Materials Fusion-Fission*  1990s-2000s
B. Petrovic (NRE)  Fuel Cycle, Fusion-Fission*  2010s
W. Van Rooijen (NRE)  Reactor Phys., Fusion-Fission*  2000s

*principal research interest

POST-DOCS

Z. El-Derini  Plasma Phys.  1979
A. W. Bailey  Plasma Phys.  1980s
C. M. Ryu (NFRI-Kor)  Plasma Phys.  1980s
J. Mandrekas (OFES-DOE)  Plasma Phys.  1980s
M. Kwon (NFRI-Kor)  Plasma Phys.  1990s
R. W. Johnson  Plasma Phys  2000s

PhD.s

R. B. Bennett (Gen Pub Util)  Plasma Impurity Transport  1984
A. B. DeWald (SRL)  Plasma-Material Interaction  1984
R. N. Norris (ORNL)  Plasma MHD Instabilities  1984
G. W. Neeley (B&W)  Plasma Impurity Transport  1987
M. A. Malik (Pak AEA)  Plasma Impurity Transport  1988
M. Kwon (KSTAR)  Exp. Plasma Phys, ICRH  1990
G. R. Hanson (ORNL)  Exp. Plasma Phys, Reflectometry  1991
G. Pautasso (ASDEX-U)  Plasma Rotation  1991
K. Indireshkumar  Plasma Phys.—Transport  1993
R. Logan  Exp. Plasma Phys, Pulsed Electrodes  1994
J. A. Favorite (LANL)  Variational Transport Theory  1997
F. W. Kelly  Plasma Radiative Instabilities  2000
R. Rubilar (KAPL)  Neutral Atom Transport  2000
E. A. Hoffman (ANL)  Fusion-Fission Fuel Cycle  2002
D.-K. Zhang (GIT)  Neutral Atom Transport  2005
Z. W. Friis (West Consult)  Neutral Atom Transport  2010
<table>
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<th>Name</th>
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<th>Topic</th>
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<tr>
<td>C. S. Sommer</td>
<td>KAPL</td>
<td>Fusion-Fission Fuel Cycle</td>
<td>2011</td>
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<td>C. Bae</td>
<td>KSTAR</td>
<td>Plasma Rotation</td>
<td>2012</td>
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<td>J-P. Floyd</td>
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<td>Edge Plasma Transport Inter-ELM</td>
<td>2014*</td>
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<td>T. M. Wilks</td>
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<td>Interp DIII-D Edge Plasma Structure</td>
<td>2015*</td>
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<td>J. J. Rovetto</td>
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<td>Interp DIII-D Edge Transport</td>
<td>2016*</td>
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<td>M. D. Hill</td>
<td></td>
<td>Fusion-Fission Plasma Dynamics</td>
<td>2016*</td>
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<td>A. T. Bopp</td>
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<td>Fusion-Fission Reactor Dynamics</td>
<td>2016*</td>
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<td>D.R. Jackson</td>
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<td>Plasma Rotation</td>
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<td>J. A. Favorite</td>
<td>LANL</td>
<td>Variational Reactor Dynamics</td>
<td>1995</td>
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<td>E. A. Hoffman</td>
<td>ANL</td>
<td>Low Activation Fusion Materials</td>
<td>1995</td>
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<td>D. C. Norris</td>
<td>SAIC</td>
<td>Plasma Facing Components</td>
<td>1997</td>
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<tr>
<td>A. N. Mauer</td>
<td>NRC</td>
<td>Transmutation Reactor</td>
<td>2002</td>
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<td>Z. W. Friis</td>
<td>West Consult</td>
<td>MARFEs &amp; H-L Transition</td>
<td>2005</td>
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<td>J. W. Maddox</td>
<td>AREVA</td>
<td>Fusion-Fission Fuel Cycle</td>
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<td>C. M. Sommer</td>
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<td>T. S. Sumner</td>
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<td>Fusion-Fission Dynamics &amp; Safety</td>
<td>2008</td>
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<td>J-P. Floyd</td>
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<td>Numerics of Generalized Diffusion</td>
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<td>Interp. RMP Phasing Exps.</td>
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<td>C. S. Stewart</td>
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<td>A.T. Bopp</td>
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<td>Fusion-Fission Bowing Coefficient</td>
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<td>M. D. Hill</td>
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<td>Modeling Diii-D Plasma</td>
<td>2014*</td>
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<td>T. G. Collart</td>
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<td>Interp DIII-D Rotation Exps.</td>
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<td>M. Schumann</td>
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<td>Interp DIII-D Divertor Exps.</td>
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<td>N. A. Piper</td>
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<td>Interp DIII-D L-H Trans Exps</td>
<td>2015*</td>
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**MSNREs**

**UNDERGRAD RESEARCH STUDENTS**

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<tr>
<td>C. Hammond(NRE)</td>
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<td>M. Carroll(NRE)</td>
<td>1998</td>
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<td>Z. Friis(NRE)</td>
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<td>S. Jones(NRE)</td>
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<td>J-P. Floyd(NRE)</td>
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<td>A. Seltzman(PHYS)</td>
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<td>S. Pinkerton(PHYS)</td>
<td>2008</td>
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<td>L. Zhou(PHYS)</td>
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<td>R. Lober(ME)</td>
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<td>T. Collart(NRE)</td>
<td>2012-13</td>
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<td>S. Tandon(ME)</td>
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<td>T. Blanton(NRE)</td>
<td>2012</td>
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<tr>
<td>S. Mellard(ME)</td>
<td>2012-14</td>
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COLLABORATORS FROM NON-GIT ORGANIZATIONS*

C. Bae KSTAR
J. A. Boedo UCSD
N. Bretz PPPL
J. D. Callen U WISC
R. J. Colchin ORNL
J. Dunlap ORNL
D. A. Ehst ANL
P. Edmonds U. TEXAS
T. E. Evans GA
J. Galambos ORNL
R. Gandy AUBURN
R. Goulding ORNL
B. A. Grierson PPPL
R. J. Groebner GA
J. J. Grudzinksi ANL
J. Harris ORNL
E. A. Hoffman ANL
G. L. Jackson GA
A. Kritz LEHIGH U
A. W. Leonard GA
A. Mahdavi GA
T. K. Mau UCSD
D. Meade PPPL
S. Medley PPPL
M. Murakami ORNL
T. H. Osborne GA
L. W. Owen ORNL
L. J. Perkins LLNL
C. C. Petty GA
T. W. Petrie GA
D. Post PPPL
J. Rapp TEXTOR
M. E. Rensink LLNL
L. Roquemore PPPL
T. D. Rognlien LLNL
V. Romanelli KFK
M. Salvatores CEA
T. Shepardt ORNL
D. J. Sigmar ORNL/MIT
W. M. Solomon PPPL
*There was a major collaboration with hundreds of physicists and engineers in the US fusion program during the course of the INTOR and ISCUS work in the 1979-2000 period which is documented elsewhere.

ACKNOWLEDGEMENT  Most of this work of the GIT-FRC has been supported, in part or in toto, by the DoE Office of Fusion Energy Science under a series of grants.