

## **ANNUAL REPORT 2013 & SUMMARY 2010-13**

### **FUSION RESEARCH CENTER & FAST REACTOR RESEARCH GROUP**

#### **GEORGIA INSTITUTE OF TECHNOLOGY**

##### **I. COLLABORATION IN ANALYSIS & INTERPRETATION OF DIII-D TOKAMAK EXPERIMENT**

The Georgia Tech Fusion Research Center is part of the National Team for the DIII-D National Tokamak Facility. During the past few years (2010-13) the Georgia Tech effort has concentrated on modeling and interpretation of DIII-D experiments in two areas—1) edge plasma physics and 2) plasma rotation. The edge plasma physics work has resulted in significant new insights and modeling of non-diffusive transport effects ( i)particle pinch due to electromagnetic forces and ii) ion orbit losses of particles, momentum and energy) that have led to new insights of how to understand the underlying transport causing the experimentally observed changes in the plasma edge across the L-H transition, with the application of resonant magnetic perturbations and between ELMs. The rotation work has led to the development of an extended neoclassical rotation theory in an elongated flux surface representation in order to properly model the important poloidal asymmetries, implementation of this theory in the GTROTA code, and determination that the predicted poloidal and toroidal rotation velocities were within 10-20% of measured values in DIII-D, except in the edge plasma. A model for the intrinsic rotation produced in the plasma edge by ion orbit loss of thermalized ions was developed and shown to agree with both probe and charge-exchange-recombination measurements in DIII-D. An initial model has been developed which relates the structure in various edge profiles (density, temperature, rotation, electric field) which enables measured changes in these profiles to be interpreted in terms of changes in the underlying transport processes. In a related effort, a plasma dynamics simulation code being developed for ITER and SABR safety analysis is being benchmarked against DIII-D discharges. This work has resulted in 16 papers and 23 presentations over the past 3 years; the papers can be accessed on this website under the “rotation” or “pedestal” links.

##### **Fusion Papers Published**

1. “Evolution of the H-mode edge pedestal between ELMs”, *Nucl. Fusion* 51, 063024 (2011); W. M. Stacey and R. J. Groebner.
2. “Numerical Investigation of Extending Diffusion Theory Codes to Solve the Generalized Pinch-Diffusion Equations in the Edge Pedestal”, *Fusion Sci. & Technol.* 61, 227 (2011); J. P. Floyd and W. M. Stacey.
3. “X-transport of ions in diverted tokamaks, with application to DIII-D”, *Phys. Plasmas* 18, 122504 (2011); W. M. Stacey.
4. “The effect of ion orbit loss on the interpretation of ion and energy particle transport in the DIII-D edge plasma”, *Phys. Plasmas* 18, 102504 (2011); W. M. Stacey.
5. “Non-diffusive transport in the tokamak edge plasma”, *Nucl. Fusion*, 52, 114020 (2012); W. M. Stacey, R. J. Groebner and T. E. Evans.
6. “Intrinsic rotation produced by ion orbit loss and X-loss”, *Phys. Plasmas* 19, 112503

- (2012); W. M. Stacey, J. A. Boedo, T. E. Evans, B. A. Grierson and R. J. Groebner.
7. "Interpretation of diffusive and non-diffusive transport in tokamak edge pedestal measurements", *Fusion Sci. Techn.* 63, 34 (2013); W. M. Stacey.
  8. "Effect of ion orbit loss on distribution of particle, energy and momentum sources into the scrape-off layer", *Nucl. Fusion* 53, 063011 (2013); W. M. Stacey.
  9. "GTROTA: A code for the solution of the coupled nonlinear extended neoclassical rotation equations in tokamak plasmas using successive over-relaxation and simulated annealing", *Comp. Phys. Comm.* 184, 2571 (2013); C. Bae, W. M. Stacey and T. Morley.
  10. "Extension of neoclassical rotation theory for tokamaks to realistically account for the geometry of magnetic flux surfaces", *Nucl. Fusion* 53, 043011 (2013); C. Bae, W. M. Stacey and W. M. Solomon.
  11. "Interpretation of changes in diffusive and non-diffusive transport in the edge plasma during pedestal buildup following a Low-High transition in DIII-D", *Phys. Plasmas* 20, 012509 (2013); W. M. Stacey, M-H Sayer, J-P Floyd and R. J. Groebner.
  12. "Analysis of toroidal phasing of resonant magnetic perturbation effects on edge transport in the DIII-D tokamak", *Phys. Plasmas* 20, 052505 (2013); T. M. Wilkes, W. M. Stacey and T. E. Evans.
  13. "Effect of ion orbit loss on the structure in the H-mode tokamak edge pedestal rotation velocity, radial electric field, density and temperature profiles", *Phys. Plasmas* (accepted 2013); W. M. Stacey.
  14. "Effect of non-diffusive processes on transport and its interpretation in the tokamak plasma edge", *Phys. Plasmas* (submitted 2013); W. M. Stacey.
  15. "Interpretation of momentum transport in DIII-D edge plasmas and comparison with neoclassical theory", *Phys. Plasmas* (to be submitted 2013); W. M. Stacey and B. A. Grierson.
  16. "Structure in the Edge Plasma Profiles in Tokamaks", *Contrib. to Plasma Phys.*, (submitted 2013); W. M. Stacey.

#### **Fusion Presentations**

1. "Evolution of the H-Mode Edge Pedestal Between ELMs", DIII-D Science Mtg., San Diego, 7/23/10; W. M. Stacey.
2. "Ion orbit loss in DIII-D", DIII-D Science Mtg., San Diego, 7/29/11; W. M. Stacey.
3. "Non-Diffusive Transport in the Tokamak Edge Plasma", H-Mode Workshop 2011, Oxford, UK (October 12, 2011); W. M. Stacey, Groebner and T. Evans.
4. "Numerical Investigation of Solving the Generalized Diffusion Equations in the Edge Pedestal with Extended Diffusion Theory Codes" APS-DPP, Salt Lake, November, 2011; J.P. Floyd and W. M. Stacey.
5. "Neoclassical Theory for Toroidal and Poloidal Rotation", APS-DPP, Salt Lake, November, 2011; C. Bae, W. M. Stacey and W. Solomon.
6. "Ion Orbit Loss and X-Loss Effects on the Interpretation of Transport in the Edge Pedestal", APS-DPP, Salt Lake, November, 2011; W. M. Stacey.
7. "Role of Fusion in the Sustainable Expansion of Nuclear Power", Invited lecture, Georgia Tech Energy Club, Atlanta, November, 2011; W. M. Stacey.

8. "Interpretation of DIII-D Edge Pedestal Experiments", APS March Mtg, Atlanta, April, 2012; J. P. Floyd, W. M. Stacey and M-H. Sayer.
9. "Advances in Neoclassical Theory of Poloidal and Toroidal Rotation in Tokamaks", APS March Mtg, Atlanta, April, 2012; C. Bae, W. M. Stacey and W. M. Solomon."
10. "Comparison of Extended Neoclassical Rotation Theory with DIII-D Experiments", DIII-D Science Mtg, San Diego, July, 2012; W. M. Stacey, Bae and W. M. Solomon."
11. "Evolution of Edge Pedestal Profiles Between ELMs", APS-DPP Mtg., Providence, RI, October, 2012; J-P. Floyd, W. M. Stacey and R. J. Groebner.
12. "Evolution of Edge Pedestal Profiles Across the L-H Transition", APS-DPP Mtg., Providence, RI, October, 2012; M-H. Sayer, W. M. Stacey, J-P. Floyd and R. J. Groebner.
13. "Interpretive Modeling of RMP Effect on Pedestal Transport", APS-DPP Mtg., Providence, RI, October, 2012; T. M. Wilks, W. M. Stacey, J-P. Floyd and T. E. Evans.
14. "Comparison of an extended rotation theory with experiment", APS-DPP Mtg., Providence, RI, October, 2012; C. Bae, W. M. Stacey and W. M. Solomon.
15. "From ITER to Fusion Power", NE50 Georgia Tech Symposium on the Future of Nuclear Energy, Atlanta, November, 2012; W. M. Stacey.
16. "Comparison of an extended neoclassical rotation theory with experiment", Transport Task Force, Sonoma, CA, April, 2013; W. M. Stacey.
17. "Interpretation of Edge Transport", Transport Task Force, Sonoma, CA, April, 2013; W. M. Stacey.
18. "Can Ion Orbit Loss Explain the Structure in Edge Pedestal Profiles?", DIII-D Science Mtr, San Diego, June 28, 2013; W. M. Stacey.
19. "Extended Neoclassical Rotation Theory and Comparison with KSTAR Experiment", Korea-Japan Theory & Simulation Mtg, Kyoto, Aug 15, 2013; C. Bae, W. M. Stacey, S. G. Lee and L. Terzola
20. "Structure in the radial electric field, rotation velocities, density and temperature profiles in the H-mode tokamak edge pedestal", Plasma Edge Theory-14, Krakow, Poland, Sept. 2013; W. M. Stacey.
21. "Examination of the Evolution of Edge Profiles and Ion Transport between ELMs on DIII-D", APS-DPP Mtg., Denver, CO, November, 2013; J-P. Floyd, W. M. Stacey, S. Mellard and R. J. Groebner.
22. "Ion Orbit Loss Effect on Pedestal Structure", APS-DPP Mtg., Denver, CO, November, 2013; W. M. Stacey.
23. "Ion Orbit Loss Effect on Structure of the Radial Electric Field", APS-DPP Mtg., Denver, CO, November, 2013; T. M. Wilks, W. M. Stacey and T. E. Evans.

## II. DESIGN & ANALYSIS OF THE SABR FUSION-FISSION HYBRID REACTOR CONCEPT

The design and the safety and fuel cycle analyses of the Subcritical Advanced Burner Reactor (SABR) for the transmutation of the transuranics remaining in spent nuclear reactor fuel ("nuclear waste") and of the Subcritical Advanced Breeder Reactor (SABrR) for the production of fissile fuel from  $^{238}\text{U}$  are carried out jointly by members of the Fast Reactor Research Group and the Fusion Research Center at Georgia Tech. The basic concept of SABR is to combine

the fission technology of the leading S-PRISM/IFR Na-pool type fast reactors and the fusion technology that will be demonstrated in ITER tokamak to close the back end of the nuclear fuel cycle. During the past year, a major redesign of SABR was undertaken to address several issues of integration of fission and fusion technology. This work has resulted in 8 papers and 14 presentations over the past 3 years. The papers can be accessed under the “transmutation reactor” link on this website.

#### **SABR & SABrR Papers Published**

1. “Fuel Cycle Analysis of the SABR Subcritical Transmutation Reactor Concept”, *Nucl. Technol.* 172, 48 (2010); C. M. Sommer, W. M. Stacey and B. Petrovic.
2. “Dynamic Safety Analysis of the SABR Subcritical Transmutation Reactor Concept”, *Nucl. Technol.* 171, 123 (2010); T. S. Sumner, W. M. Stacey and S. M. Ghiaasiaan.
3. “SABR Fusion-Fission Hybrid Fast Burner Reactor Based on ITER”, Proc. 11<sup>th</sup> OECD/NEA Information Exchange Meeting on Actinide Partitioning and Transmutation”, San Francisco (2010); W. M. Stacey, C. S. Sommer, T. S. Sumner, B. Petrovic, S. M. Ghiaasiaan and C. L. Stewart.
4. “Advanced Fuel Cycle Scenario Study in the European Context by Using Different Burner Reactor Concepts”, Proc. 11<sup>th</sup> OECD/NEA Information Exchange Meeting on Actinide Partitioning and Transmutation”, San Francisco (2010), ISBN 978-92-64-99174-3; V. Romanello, C. Sommer, M. Salvatores, W. M. Stacey, W. Maschek, B. Petrovic, F. Gabrelli, A. Schwenk-Ferrero, A. Rineiski and B. Vezzoni.
5. “Comparison of the Waste Transmutation Potential of Different Innovative Dedicated Systems and Impact on the Fuel Cycle”, Proc. ICENES-2011 Conf. (2011); V. Romanelli, M. Salvatores, C. M. Sommer, W. M. Stacey, et. al.
6. “Fuel Cycle Analysis of the SABR Transmutation Reactor for Transuranic and Minor Actinide Burning Fuels”, *Nucl. Technol.* 182, 274 (2013); C. M. Sommer, W. M. Stacey, B. Petrovic and C. L. Stewart.
7. “The SABrR Concept for a Fission-Fusion Hybrid  $^{238}\text{U}$ -to- $^{239}\text{Pu}$  Fissile Production Reactor”, *Nucl. Technol.* (accepted 2013); C. L. Stewart and W. M. Stacey.
8. “Resolution of Fission and Fusion Technology Integration Issues: An Upgraded Design Concept for the Subcritical Advanced Burner Reactor (SABR). *Nucl. Technol.* (submitted 2013); W. M. Stacey, C. L. Stewart, J-P. Floyd, T. M. Wilks, A. P. Moore, A. T. Bopp, M. Hill, S. Tandon, A. S. Erickson.

#### **SABR & SABrR Presentations**

1. “The Case for Fusion-Fission Hybrids: Enabling Sustainable Nuclear Power”, MIT Plasma Fusion Science Center seminar, January, 2010; W. M. Stacey
2. “The Case for Fusion-Fission Hybrids: Enabling Sustainable Nuclear Power”, Georgia Tech NRE&MP seminar, April, 2010; W. M. Stacey.
3. “The Georgia Tech SABR Studies of a Fusion-Fission Hybrid Fast Burner Reactor”, ANS annual mtg, San Diego, June, 2010; W. M. Stacey, Sommer and B. Petrovic.

4. "Advanced Fuel Cycle Scenario Study in the European Context by Using the SABR Hybrid Fusion-Fission System", NEA 11<sup>th</sup> InformationExchange Meeting on Actinide and Fission Product Partitioning and Transmutation, San Francisco, November, 2010; V. Romanelli, C. M. Sommer, M. Salvatores, W. M. Stacey, et al.
5. "SABR Fusion-Fission Hybrid Fast Burner Reactor Based on ITER", NEA 11<sup>th</sup> InformationExchange Meeting on Actinide and Fission Product Partitioning and Transmutation, San Francisco, November, 2010; W. M. Stacey, Sommer, B. Petrovic et al.
6. "Georgia Tech SABR Studies of a Fusion-Fission Hybrid Fast Burner Reactor", Seminar, Karlsruhe Institute of Technology, Karlsruhe, Germany, February 1, 2011; W. M. Stacey.
7. "The Fission-Fusion Hybrid for Closing the Nuclear Fuel Cycle on the Path to Commercialization of Fusion", Invited lecture, Electric Power Research Institute Workshop on Commercialization of Fusion, Palo Alto, CA, July 21, 2011; W. M. Stacey.
8. "Fuel Cycle Analysis of the SABR Fusion Fission Hybrid Burner Reactor", ANS annual mtg., Orlando, June, 2011; M Sommer, W. M. Stacey and B. Petrovic.
9. "Principles and Rationale of the Fusion-Fission Hybrid Burner Reactor", FUNFI-2011 Workshop on "Fusion for Neutrons and Sub-critical Nuclear Fission", Invited tutorial lecture, Varenna, Italy, September 13, 2011; W. M. Stacey.
10. "Sustainable Expansion of Nuclear Power", Invited lecture, France-Atlanta Workshop on Nuclear Energy, Atlanta, November, 2011; W. M. Stacey.
11. "Role of Fusion in the Sustainable Expansion of Nuclear Power", Invited lecture, Georgia Tech Energy Club, Atlanta, November, 2011; W. M. Stacey.
12. "Sustainable Nuclear Power", Seminar, NRE Program, Georgia Tech, March, 2012; W. M. Stacey.
13. "The Subcritical Advanced Burner Reactor (SABR)", APS March Mtg, Atlanta, April, 2012; W. M. Stacey, C. Stewart, A. Bopp and A. Moore.
14. "From ITER to Fusion Power", NE50 Georgia Tech Symposium on the Future of Nuclear Energy, Atlanta, November, 2012; W. M. Stacey.

### III. PEOPLE

The above work was performed performed by faculty and graduate students working in the Fusion Research Center ([www.frc.gatech.edu](http://www.frc.gatech.edu)) and Fast Reactor Research Group ([www.frrg.gatech.edu](http://www.frrg.gatech.edu)) i at Georgia Tech, in collaboration with members of the DIII-D Team and other collaborators from other institutions. Eight graduate students and four undergraduate students have been involved in the Fusion Research Center (FRC), and three graduate students have been involved in the Fast Reactor Research Group.. The work resulted in 3 PhD and 5 MS theses over the period 2010-2013. The principal Georgia Tech faculty members involved in the work have been: fusion W. M. Stacey; fast reactors—W. M. Stacey, B. Petrovic, S. M. Ghiaasiaan and A. S. Erickson. The principal members of the DIII-D Team with whom there has been active collaboration in fusion are R. J. Groebner (GA), T. E. Evans (GA), W. M. Solomon (PPPL), B. A. Grierson (PPPL) and J. A. Boedo (UCSD). In the fast reactor area, there has been collaboration with E. A. Hoffman (ANL).

## Students Involved in Fusion and Fast Reactor Research at Georgia Tech 2010-2013

	Undergrad Research	Spec. Prob.	M S Thesis	PhD Thesis	Present
<b>Fusion Research Center</b>					
Jonathan Roveto			2014*	2017*	GIT
Nicholas Piper			2014*	2017*	GIT
Matthew Schumann			2014*	2017*	GIT
Steven Mellard	2013				GIT
Max Hill		2013	2014*	2016*	GIT
Thomas Blanton	2012				GIT
Shubhang Tandon	2012	2013			MIT
Tim Collart	2012		2014*	2016*	GIT
Theresa Wilkes		2013	2013	2015*	GIT
Min-hee Sayer			2012		US Navy
Cheonho Bae				2012	KSTAR
John-Patrick Floyd	2006	2008&13	2011	2014*	GIT
<b>Fast Reactor Research Group</b>					
Chris Stewart		2013	2013	2016* **	GIT
Andrew Bopp		2013	2013	2016*	GIT
Alex Moore		2013	2013**	2016* **	GIT
Tyler Sumner				2010	ANL
Chris Sommer				2010	KAPL

\*anticipated, \*\*in another topic area

## Theses 2010-2013

### Fusion

C. Bae, Ph.D., 2012, "Extension of neoclassical rotation theory for tokamaks to realistically account for the geometry of magnetic flux surfaces"

T. M. Wilks, MS, 2013, "Toroidal Phasing of Resonant Magnetic Perturbation Effect on Edge Transport in the DIII-D Tokamak"

M-H. Sayer, MS, 2012, "Evolution of Radial Force Balance and Radial Transport over a L-H Transition"

J-P. Floyd, MS, 2011, "A Numerical Investigation of Extending Diffusion Theory Codes to Solve the Generalized Diffusion Equation in the Edge Pedestal"

### Fast Reactors

A. T. Bopp, MS, 2013, "The Calculation of Fuel Bowing Coefficients in a Subcritical Advanced Burner Reactor"

C. L. Stewart, MS, 2013, "The SABrR Concept for a Fission-Fusion Hybrid  $^{238}\text{U}$ -to- $^{239}\text{Pu}$  Fissile Production Reactor"

C. M. Sommer, PhD, 2011, "Subcritical Transmutation of Spent Nuclear Fuel"



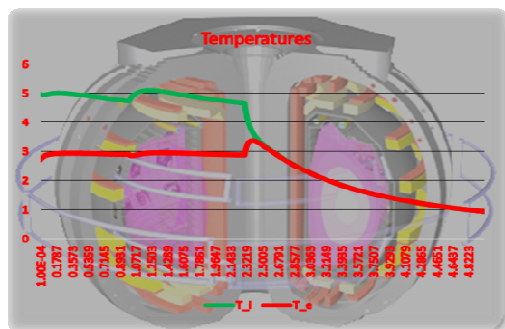
# FUSION RESEARCH CENTER

Effects on the Safety Characteristics of a Sodium-Cooled Reactor

Factor

## WHAT IS THE FRC?

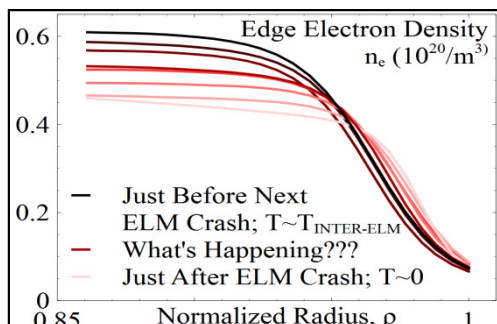
Here in the Fusion Research Center (FRC) under Dr. Weston Stacey, we research the underlying plasma physics of tokamak operation in order to further fusion technology and aid in meeting the design constraints of the ITER initiative. We focus mainly on the physics of the edge pedestal, which is the outer most region of the plasma before the vessel wall. Plasma dynamics and safety is also of key concern and we are developing a code to better describe the time dependence of experiments. Our chief collaborators are the research scientists at General Atomics who work at the DIII-D tokamak in San Diego, CA. The analytical background of Dr. Stacey and the experimental expertise of our collaborators allow us to confront problems with a holistic viewpoint.



## PLASMA ROTATION:

Cheonho Bae, Tim Collart

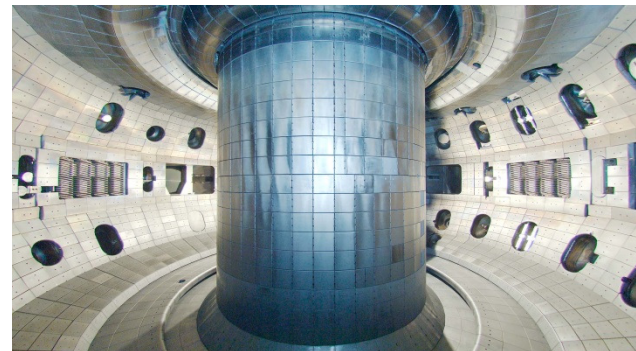
Studies on the central tokamak plasma have focused on predicting the toroidal and poloidal deuterium and carbon velocities by solving a coupled set of equations derived from the first two fluid moment equations. Recent work has accounted for the asymmetries in the actual DIII-D tokamak geometry by utilizing the Miller flux surface representation; this change from the neoclassical circularly symmetric model significantly increases the gyroviscous contribution to viscous transport. The agreement between the velocities predicted by these calculations and the experimentally measured carbon toroidal and poloidal velocities for a co-injected DIII-D shot was within 10 percent for over 90 percent of the plasma minor radius. This is a significant improvement over circular model predictions, which, although demonstrating that this approach returns answers of the same order of magnitude as experiment, varied by as much as 200 percent from the actual values.



## EDGE TRANSPORT PHYSICS AND ELMS:

John P. Floyd, Steven Mellard

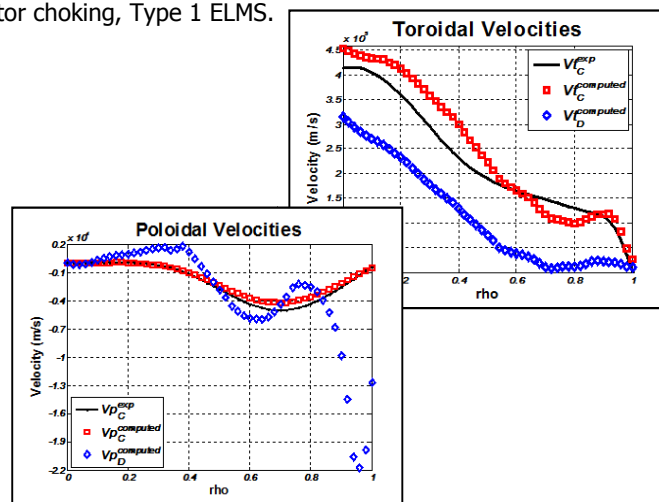
Particle transport and other processes in the far edge of the plasma are poorly understood, despite being extremely important in determining plasma performance. The cyclical formation and destabilization of Edge-Localized Mode instabilities is being closely analyzed to shed light on how the forces in the edge work, and to learn how to manipulate them for our benefit!



## PLASMA BURN DYNAMICS SIMULATION:

Max Hill

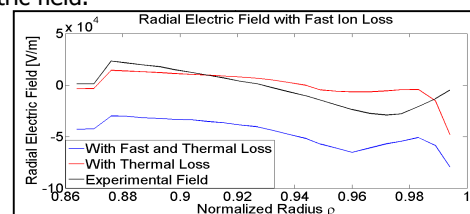
Burn control and passive safety in accident scenarios will be an important design consideration in future tokamaks, especially those used as a neutron source for fusion-fission hybrid reactors, such as the Subcritical Advanced Burner Reactor (SABR) concept. At Georgia Tech, we are developing a new burning plasma dynamics code to investigate passive safety mechanisms that could prevent power excursions in tokamak reactors. This code solves the coupled set of balance equations governing burning plasmas and models various relevant physical phenomena. Predictions are benchmarked against data from the DIII-D tokamak in San Diego, CA. We are attempting to model and examine several mechanisms to limit power excursions including: Ion-orbit loss, Thermal instabilities, Degradation of alpha-particle confinement resulting from ripples in the toroidal field, Modifications to the radial current profile, Divertor choking, Type 1 ELMS.



## ION ORBIT LOSS AND RADIAL ELECTRIC FIELD:

Theresa Wilks

The radial electric field is an important factor in dictating transport in tokamak plasmas. It proves to significantly affect the L-H transition as well as the onset of ELMS. At Georgia Tech, we are constructing theoretical models for the physical basis of the structure of the radial electric field profile using the concept of ion orbit loss and corresponding return current. Ion orbit loss is a mechanism that allows the loss of both thermal and fast ions under certain plasma conditions such as the electrostatic potential and the angle of particle trajectory. Particle losses affect the toroidal and poloidal rotation velocities, which are closely intertwined with the radial electric field.



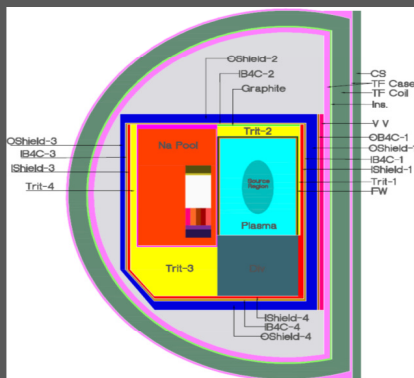


# Fission/Fusion Joint Research: Subcritical Advanced Burner Reactor



Both the Fusion and Fast Reactor Research Groups feel that better solutions to the problem of disposing of nuclear waste should be formulated, explored, and implemented, and the Subcritical Advanced Burner Reactor is our contribution to this end.

The conceptualization and preliminary design of a hybrid fusion-fission reactor has been a major project of this lab, and the schematic shown below represents the result of the latest research towards this goal. SABR is a reactor designed to use a fusion neutron source to efficiently transmute long-lived transuranics into much more active elements, facilitating their elimination. This "burning" would be done in a subcritical annular core surrounding the plasma, greatly decreasing risk while still achieving excellent power production (~3 GW) and transmutation results (reducing the need for high level waste repositories by around 10x). The fusion neutron source is based on well-known physics that are being utilized in the ITER tokamak, and the fast reactor is based on the S-PRISM/IFR designs.



## SHIELDING DESIGN & ANALYSIS

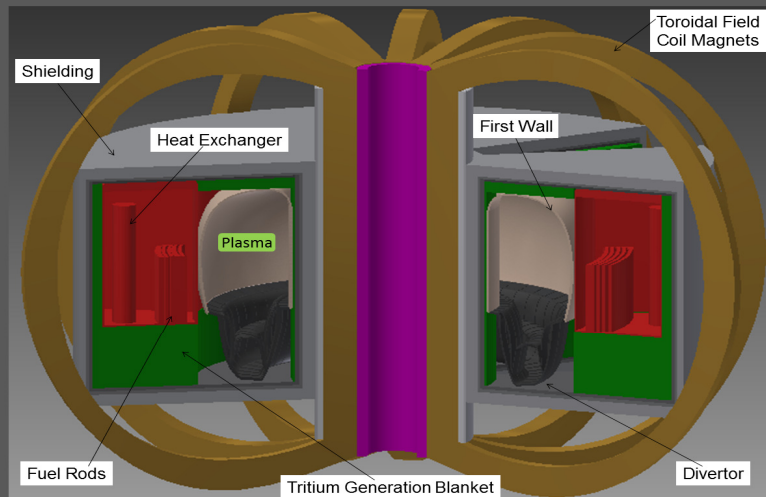
Shielding is required to protect sensitive equipment, ensure the SABR design lifetime and maintain safety barriers. In particular, the superconducting (SC) magnets need to be extensively shielded to limit radiation damage to the superconducting material and to the electrical insulating material.

We designed the shielding for SABR to allow for 40 years of operation at 75% availability, or 30 effective full-power years (full-power meaning 500MW fusion power plus approximately 3000MW fission power), without reaching radiation damage limits on the superconductor or the insulator.

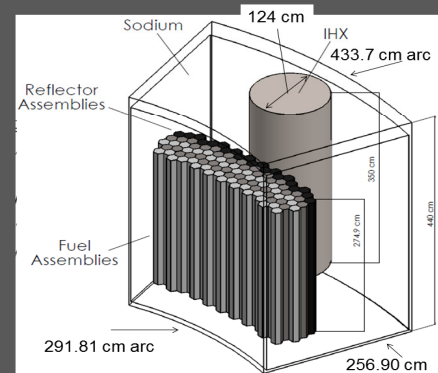
## FAST REACTOR ANNULAR CORE DESIGN

SABR's sodium-cooled annular fast reactor is broken up into 10 modular Na pools and cores which encircle the plasma chamber. Each core occupies its own pool module along with its dedicated heat exchanger and pumps. The modules are sized such that they are able to be inserted and removed between the toroidal and poloidal field coils at two locations on the annulus for refueling and shuffling purposes.

The fuel of SABR's fast reactor is a 60TRU-40Zr alloy; subcritical operation increases the margin to prompt critical by over an order of magnitude, allowing for the exclusion of  $^{238}\text{U}$  from the fuel. Removing the criticality constraint also allows for a large burnup reactivity swing without causing safety issues due to large control rod reactivity worth.



Radiation Limit	Value	Units
Insulation Dosage	$1 \times 10^9$	rads
Nuclear Heating Rate	1.0 – 5.0	mW/cc
Neutron fluence (>0.1MeV)	$1.0 \times 10^{19}$	n/cm <sup>2</sup>
Copper Stabilizer Resistivity	1.2	nΩm





# Fast Reactor Technology

## Fast Reactor Research Group

Dr. Weston Stacey, Andrew Bopp, Alex Moore, and Chris Stewart

