1 of 1

"COAXIAL SLOW SOURCE"

FINAL TECHNICAL REPORT

DOE GRANT #DE-FG06-87ER53243

November 16, 1991 - November 15, 1993

Robert D. Brooks and Thomas R. Jarboe
Aerospace & Energetics Research Program
University of Washington
Seattle, Washington 98195

(UW/AERP #42)

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the U.S. Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe upon privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

This report describes work performed by the University of Washington Aerospace and Energetics Research Program involving the Field Reversed Configuration (FRC) approach to magnetic confinement fusion. The group's effort involved continued research on the Coaxial Slow Source annular FRC experimental device located on campus, as well as support for the Large s Experiment (LSX) operated by Spectra Technology Incorporated, Bellevue, Washington.

The primary accomplishments of the group are documented in three recent Ph.D. dissertations and publications in scientific journals. After a brief summary, this report consists of a list of the group's publications, the abstracts of the principal publications on the CSS device, and the abstracts of the three Ph.D. dissertations. Details of the research can be found in the complete publications available in the archival journals and the complete dissertations available from University Microfilms, 1490 Eisenhower Place, P. O. Box 975, Ann Arbor, MI 48106.

The Coaxial Slow Source (CSS) device, which consists of two coaxial theta pinch coils, was designed to address two issues important to FRC research. First, the initial bias field, and hence flux in a given conventional FRC device, which can be reconnected to form the configuration is limited (≤ 1 kG) by destructive axial dynamics. Second, the voltages required to produce rapid current reversal in the conventional FRC coil are very large. Clearly a low voltage formation technique without flux addition limitations is desirable. Coaxial coil geometry allows for the addition of as much magnetic flux to the annular plasma between them as can be delivered by the inner coil (25 mWb). Furthermore the device can be operated at loop voltages less than 1 kV and on

resistive diffusion ($>50 \mu\text{s}$), rather than implosive ($<5 \mu\text{s}$), time scales. The inner coil is of a novel design so as to allow it to be cantilevered from one end to permit translation of the plasma. Following formation, the Annular Field Reversed Configuration (AFRC) would be translated off the inner coil to re-form as a true compact toroid (having no material wall inside the torus).

The CSS began operation in 1985. The early experiments employed a two-turn inner coil and single turn outer coil, each energized separately by its own system of capacitors and switches. Although this configuration enabled independent control of the inner and outer coils, such flexibility resulted in imbalanced magnetic flux delivery on the inner and outer sides of the plasma. This had the effect, diagnosed most clearly through magnetic and end on visible light photographic diagnostics, of pushing the plasma against a coil, in contact with the quartz vacuum wall. In order to resolve this difficulty the parallel configuration was devised. This scheme involves connecting the four-turn inner and outer coils, in parallel, to a single capacitor bank. In this way the system is constrained to accumulate flux evenly on both sides of the plasma forcing it to remain well centered, away from the walls. The machine may be operated in tearing and programmed formation modes. Tearing formation mode relies on tearing and reconnection of reversed field lines originally linking each coil independently to produce flux linking the plasma. Programmed formation mode transfers flux originally linking both coils and the annular region, to link only the annular plasma, and does not require tearing.

The most important result of parallel configuration operation is that the parallel coil arrangement has been successful in controlling the radial position of the plasma toroid. Well-centered AFRCs have been produced in both tearing and programmed formation modes. Loop voltages ranging from 87.5 to 700 V have been used with fill pressures between 3 and 50 mTorr. Thomson scattering indicates electron temperatures between 3 and 20 eV. Radial dual chord interferometry places the density at 1 to $5 \times 10^{15} \text{ cm}^{-3}$. Axial magnetic fields range between 0.05 and 0.2 T. While configuration lifetimes of up to 200 μs are possible, confinements times are on the order of 10-30 μs . Tearing formation results in a coil-length, thin, annular plasma sheet which ohmically heats and is subject to tearing instabilities. Programmed formation produces shorter, fatter plasmas which have low energy content. While the parallel coil arrangement is clearly an improvement in the CSS concept, (better centered plasmas which can be formed at lower loop voltage are no longer believed to be radiation dominated) improvements in plasma temperature and confinement

properties over those of the previous coil configuration are marginal. This is due to the tilt instability. Although this instability is not destructive in the CSS, it results in short confinement times.

The tilt instability in the CSS is an interesting example of hydromagnetic instability in a driven, dissipative system. The findings are significant for two reasons. (1) It is one of the few clear observations of a tilting mode in FRC-like geometry; and (2) It provides evidence that ideally unstable modes can be suppressed by dissipative effects if the configuration is not driven sufficiently hard to take it out of the low Lunquist number regime.

The tilting instability in the CSS could possibly be overcome by the addition of conducting end walls or additional mirror coils. Formation and heating of the $\beta=1$ configuration by ohmic dissipation would still be a formidable task. Although we found that impurity radiation was not important in the CSSP, care must be taken to avoid radiative collapse. We have shown analytically that driving the configuration harder by more rapid flux addition leads to axial contraction, higher density and a radiation barrier which prevents further temperature increase. Where slower flux addition can allow ohmic heating at a lower density until the temperature is above the barrier.

In addition to the work on the CSS device, the group participated in the LSX project. The results of that research can be found in the LSX reports and in the Ph.D. dissertation by R. Maqueda.

Recent CSS Group Publications

J. R. Sobehart and R. Farengo "Low frequency drift dissipative modes in field reversed configurations" *Phys. Fluids B* **2**, 3206 (1990).

R. D. Brooks, R. Farengo, T. R. Jarboe., G. C. Vlasses, R. J. Maqueda, R. Smith, R. Raman, R. G. Berger and W. F. Pierce, "The coaxial slow source: parallel operation and the radiation barrier" *Proceedings of the 11th US-Japan Workshop on Compact Toroids*, Los Alamos, NM, 1989 (Los Alamos National Laboratory, Los Alamos, NM, 1990), p.120.

R. Farengo and R. D. Brooks, "Current limit in Ohmically Heated high-beta plasmas: Application to field reversed configurations" *Phys Fluids B* **3**, 130 (1991).

R. Farengo and T. R. Jarboe, "Current drive by tokamak injection" *Fusion Technology* **20** (1991) 407.

G. A. Wurden, R. J. Maqueda, E. A. Crawford, A. L. Hoffman, Y. Ito, R. D. Milroy and J. T. Slough, "Initial experimental results in the LSX field reversed configuration" 1991 US-Japan CT Workshop, Tokyo.

J. T. Slough, A. L. Hoffman, R. D. Milroy, E. A. Crawford, Y. Ito and G. A. Wurden, "Formation, confinement and stability of compact toroids in LSX" *Controlled Fusion and Plasma Physics* **15C** pt II (1991) 297.

G. A. Wurden, R. J. Maqueda, C. L. Painter, E. A. Crawford, A. L. Hoffman, Y. Ito, R. D. Milroy and J. T. Slough, "Initial experimental results in the LSX field reversed configuration" *Controlled Fusion and Plasma Physics* **15C** pt II (1991) 301.

R. Farengo and R. D. Brooks, "Plasma Heating and Dynamics in the Coaxial Slow Source" *Nucl. Fusion* **32** (1992) 67.

R. Farengo, "Internal tilting instability in annular field reversed configurations" *Phys. Fluids B* **4** (1992) 280.

R. J. Maqueda, G. A. Wurden and E. A. Crawford, "Wideband 'silicon bolometers' on the LSX field reversed configuration experiment" *Rev. Sci. Instrum.* **63** (1992) 4717.

T. W. Fehr and W. F. Pierce, "A dual chord zero-crossing detection circuit for fractional fringe interferometry" *Rev. Sci. Instrum.* **63** (1992) 5475.

J. T. Slough, A. L. Hoffman, R. D. Milroy, E. A. Crawford, M. Cecik, R. Maqueda, G. A. Wurden, Y. Ito and A. Shiokawa, "Confinement and stability of plasmas in a field-reversed configuration" *Phys. Rev. Lett.* **69** (1992) 2212.

A. L. Hoffman, L. N. Carey, E. A. Crawford, D. G. Harding, T. E. DeHart, K. F. McDonald, J. L. McNeil, R. D. Milroy, J. T. Slough, R. Maqueda and G. A. Wurden, "The large-s field-reversed configuration experiment" *Fusion Technology* **23** (1993) 185.

W. F. Pierce, R. J. Maqueda, R. D. Brooks and R. Farengo, "Initial results from parallel coil operation of the coaxial slow source field reversed configuration device" *Nucl. Fusion* **33** (1993) 117.

R. Raman, G. C. Vlasses and T. R. Jarboe, "Energy Balance in the CSSU device" *Nucl. Fusion* **33** (1993) Nov.

**INITIAL RESULTS FROM
PARALLEL COIL OPERATION
OF THE
COAXIAL SLOW SOURCE
FIELD REVERSED CONFIGURATION
DEVICE**

W. F. PIERCE, R. J. MAQUEDA, R. D. BROOKS, R. FARENGO
(Aerospace and Energetics, University of Washington, Seattle, Washington,
U.S.A.)

ABSTRACT. The Coaxial Slow Source (CSS) is a device in which 'annular' Field Reversed Configurations (FRCs) (small aspect ratio, elongated, toroidal plasmas with poloidal field only) are formed in the space between coaxial coils carrying toroidal currents. The device is constructed so that the plasma can be translated into a simple cylindrical chamber and re-formed as a conventional FRC. Formation of FRCs on slow time-scales (50-250 μ s) at low loop voltage (87.5-700 V) has been demonstrated. In this paper we report initial results from the new parallel configuration device, CSSP, in which the inner and outer coils are connected in parallel to the capacitor banks. The parallel coil arrangement has significantly reduced plasma contact with the walls and thus impurity content. Configurations with confinement times of 10-30 μ s, densities of $3 \times 10^{21} \text{ m}^{-3}$ and temperatures of 3-20 eV are typical. Results are presented on formation, energy balance, a non-destructive tilt instability and dynamics associated with magnetic tearing.

Published in Nuclear Fusion, Vol **33**, No.1 (1993) 117.

PLASMA HEATING AND DYNAMICS IN THE COAXIAL SLOW SOURCE

Ricardo Farengo, Robert D. Brooks

Aerospace and Energetics Research Program, FL-10

University of Washington, Seattle, WA 98195 USA

ABSTRACT

Simple semi-analytical models are presented to calculate the temporal evolution of the plasma temperature and length or thickness in the Coaxial Slow Source [Nucl. Fusion **27** (1987) 1478] for both tearing and programmed formation. It is assumed that energy is delivered to the plasma via ohmic heating and compressional work and is lost through impurity line radiation. The plasma is considered to be always fully ionized and in pressure balance, the external magnetic field is taken to be a known function of time and particle losses are neglected. In tearing formation a long and thin plasma sheet is initially formed. This can be studied using a 1D model and it is shown that the higher the external field and the smaller the line integrated density the faster the temperature increases. In programmed formation an axial equilibrium is quickly established and a 2D model is required. It is shown that when the external field exceeds a critical value, that depends on the temperature, impurity fraction and effective plasma thickness, the radiated power overcomes ohmic heating and a radiative collapse occurs. Various external field time-histories are analyzed in order to determine the conditions that result in the fastest temperature increase.

Published in Nuclear Fusion, Vol **32**, No.1 (1992) 67.

University of Washington

1993

Ph. D. Abstract

Analysis of Slow Formation of Plasmas in a Coaxial Double Theta Pinch

by Russell Berger

Chairperson of Supervisory Committee:

*Professor Thomas R. Jarboe
Department of Aeronautics
and Astronautics*

Plasma formation in a coaxial double theta pinch device is analyzed. This device, called the Coaxial Slow Source (CSS), has demonstrated the formation of annular field reversed configurations on diffusive timescales. Three analytical models are developed and used to: characterize the coupling between the magnetic configuration and the driving circuit, predict a temperature limit due to impurity radiation, and reveal an instability due to localized cooling. A comprehensive model incorporating the interactions of neutral and ionized particles is used to simulate the CSS experiment on a computer. This two-dimensional MHD two-fluid code called COAX is adapted from an earlier version. Simulations are compared to experimental data from the CSS to test the models, and quantify the physical processes involved.

The slow forming plasma is strongly influenced by the surrounding neutral fill gas due to: the energy lost by ionization of these neutrals, and enhanced heat conduction from charge exchange collisions between neutrals and ions. The friction between the neutrals and ionized fluids is important in modeling the formation dynamics. Impurities also play a role in the power balance of such plasmas by strongly emitting line radiation. Radiation from impurities appears unimportant unless the plasma contacts the vacuum chamber walls.

University of Washington

1993

Ph. D. Abstract**Hydromagnetic Stability of a Driven, Dissipative
Annular Field Reversed Configuration**

by Wilbur F. Pierce IV

Chairperson of Supervisory Committee:

Professor Thomas R. Jarboe
Department of Physics

The Coaxial Slow Source is a device which was designed as a means of forming Annular Field Reversed Configurations for magnetic fusion on relatively slow (50-100 μ s) time scales. Such configurations are predicted to be ideally unstable to magnetohydrodynamic tilting modes in which one half of torus shifts in the positive axial direction and the other half in the negative direction. These instabilities have been observed to grow and saturate at finite amplitude in our device as formation progresses. Apparently stable operating regimes of fill pressure/loop voltage have also been found. The relatively cold temperature (~ 2 eV) of the plasma gives rise to a high classical resistivity placing the Lundquist number (ratio of resistive to Alfvén time scales) between 0.5 and 10. It is proposed that resistivity, along with other dissipation mechanisms such as viscosity and ion-neutral friction, are responsible for the observed stability. Experiments were performed which explore these stability issues. A nonlinear, dynamical systems stability model, which accounts for the effects of inductive driving and dissipation, was also developed and shows some agreement with the experimental results. The findings of this study are significant for two reasons: (1) It is one of the few clear observations of tilting modes in an FRC-like geometry; and (2) It provides experimental evidence that ideally unstable modes can be suppressed by dissipative effects if the configuration is not driven sufficiently hard to take it out of the low ($O_s(1)$) Lundquist number regime.

University of Washington
1993

Ph. D. Abstract

Impurity Radiation and Energy Balance in Field Reversed Configurations

by Ricardo José Maqueda

Chairperson of the Supervisory Committee: Professor Alan L. Hoffman

Department of Aeronautics
and Astronautics

The impurity radiation and energy balance for Field Reversed Configurations (FRCs) formed in the Large s Experiment (LSX) are studied. A newly developed silicon bolometer is used to measure the radiative energy losses. A first burnthrough peak and a subsequent lower radiation stage (typically 20-100 MW), present during the equilibrium/decay phase of the FRC, are observed. The total radiation is then related to the D₂ fill pressure and compared with spectroscopic measurements and existing radiation models. The radiative energy losses can be explained by a fixed amount of impurities present in the plasma.

A new 1-D numerical model is used to study the energy balance for the FRCs. This 1-D model incorporates most of the confinement properties directly from the experiment. This allows the effects of the electron thermal conduction and the influence of the edge layer confinement to be studied. Results are presented showing that with theoretically reasonable edge confinement properties the electron collisionality governing electron thermal conduction is not far (within an order of magnitude) from that governing particle diffusion. While the electron energy losses are partitioned between conduction and convection, the ion losses are dominated by particle convection. The radiative losses become increasingly important as the overall confinement of the FRC improves.

DATE

FILMED

44 / 7 / 94

END