CONF 901025--2

LA-UR 90- 2864

SEP 0 7 1990

IAEA-CN-53/C-4-4

LA-UR--90-2864

DE90 016443

TITLE: **TILT STABILITY AND COMPRESSION HEATING STUDIES OF FIELD-REVERSED CONFIGURATIONS**

AUTHORS: D.J. REJ, M. TUSZEWSKI, D.C. BARNES, R.D. MILROY, A.D. BAILEY, G.A. BARNES, M.H. BARON, R.E. CHRIEN, J.W. COBB, E.A. CRAWFORD, A. ISHIDA, R.E. SIEMON, J.T. SLOUGH, J.L. STAUDENMEIER, L.C. STEINHAUER, S. SUGIMOTO, D.P. TAGGART, T. TAKAHASHI, R.B. WEBSTER, B.L. WRIGHT

SUBMITTED TO: *13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research*

International Atomic Energy Agency

Washington, D.C.
October 1-6, 1990

Los Alamos Los Alamos National Laboratory Los Alamos, New Mexico 87545

TILT STABILITY AND COMPRESSION HEATING STUDIES OF FIELD-REVERSED CONFIGURATIONS

D.J. REJ, M. TUSZEWSKI, D.C. BARNES, R.D. MILROY[1],
A.D. BAILEY[2], G.A. BARNES, M.H. BARON[3],
R.E. CHRIEN, J.W. COBB,[4] E.A. CRAWFORD[1],
A. ISHIDA[5], R.E. SIEMON, J.T. SLOUGH[1],
J.L. STAUDENMEIER[6], L.C. STEINHAUER[1],
S. SUGIMOTO[7], D.P. TAGGART, T. TAKAHASHI[8],
R.B. WEBSTER, B.L. WRIGHT
Los Alamos National Laboratory,
Los Alamos, New Mexico,
United States of America

Abstract

TILT STABILITY AND COMPRESSION HEATING STUDIES OF FIELD-REVERSED CONFIGURATIONS.

The first observations of internal tilt instabilities in field-reversed configurations (FRCs) are reported. Detailed comparisons with theory establish that data from an array of external magnetic probes are signatures of these destructive plasma instabilities. This work reconciles theory and experiments and suggests that grossly stable FRCs are restricted to very kinetic and elongated plasmas. Self-consistent three-dimensional numerical simulations demonstrate tilt stabilization by the addition of a beam ion component. High-power compression heating experiments with stable equilibrium FRCs are also reported. Plasmas formed in a tapered theta-pinch coil have been translated along a guide magnetic field into a new single-turn compression coil where the external field is increased up to 7 times the initial value in 55 μs. Substantial heating is observed accompanied by a decrease in confinement time.

---

[1] Spectra Technology, Inc., Bellevue, Washington, United States of America
[2] California Institute of Technology, Pasadena, California, United States of America
[3] Auburn University, Auburn, Alabama, United States of America
[4] Institute for Fusion Studies, University of Texas, Austin, Texas, United States of America
[5] Niigata University, Niigata, Japan
[6] Pennsylvania State University, University Park, Pennsylvania, United States of America
[7] Osaka University, Osaka, Japan
[8] Nihon University, Tokyo, Japan

1. TILT STABILITY STUDIES

1.1 In-situ confinement studies

For the last five years, the world's largest field-reversed configurations (FRCs) have been studied in the FRX-C/LSM experiment[1]. The experimental apparatus (Fig. 1), diagnostics, and FRC formation method are described elsewhere.[1] FRCs are formed with reverse bias fields, $0.03 \leq B_b \leq 0.11$ T, and fill pressures, $2 \leq p_o \leq 12.5$ mtorr. However, FRCs with good confinement have been restricted to $B_b < 0.08 - 0.09$ T and $p_o < 5$ mtorr for unclear reasons.[1] Detailed confinement studies[2,3] have recently explored the transition from good to bad FRC confinement. Inferred field null resistivities and electron thermal diffusivities are higher than classical for the well-confined FRCs by factors 5 - 20 and 35 - 140, respectively. These factors rapidly increase to much higher values during the transition to bad confinement, suggesting non-local, non-diffusive transport mechanisms such as formation dynamics or instabilities. Many studies have attempted to explain the above limitations in terms of some formation inadequacy, but they have proved inconclusive.[4] Other studies, reported below, have then attempted to identify FRC gross instabilities.

1.2 Observations of tilt instabilities

A Mirnov loop array consisting of 64 external B_θ pick-up loops (8 axial $\times$ 8 toroidal) has been recently installed on FRX-C/LSM.[5] This diagnostic, shown partially in Fig. 1, allows separation of axially-even and odd components and toroidal Fourier analysis for the $n < 3$ components. Several instabilities have been detected, including rotational modes[6], transient flutes[1], and tilt instabilities[7]. The latter (axially-odd, $n = 1$) are observed whenever the FRC confinement is poor. The tilt data have been compared with calculated tilt asymmetries in 3-D resistive-MHD simulations[8]. The 2-D FRC equilibrium in Fig. 1 was given a 1% tilt perturbation and the $n = 1$ tilt instability developed as shown in Fig. 2(a). Such comparisons clearly have identified many features of the data (time histories, axial dependence) with signatures of internal tilt instabilities. In particular, calculations show a rapid transition from closed to open field lines around peak tilt amplitude. The B_θ data track the global features of this transition, and other diagnostics display sudden changes consistent with field line opening.

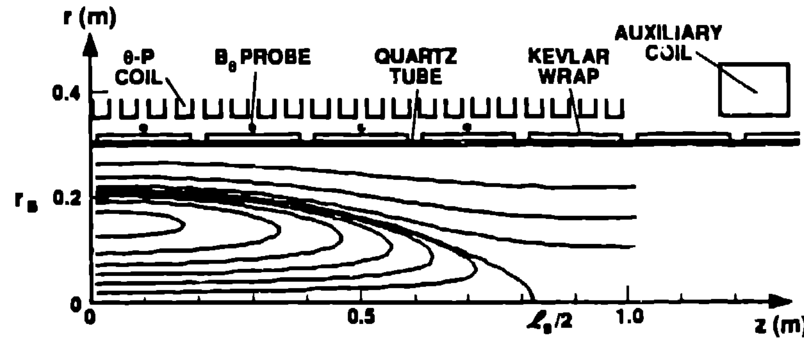

FIG. 1. The FRX-C/LSM experiment, including flux contours for a typical FRC equilibrium.

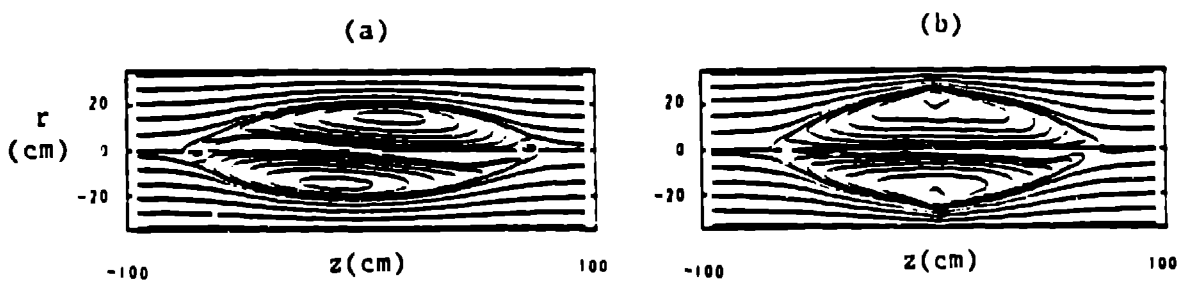

FIG. 2. Flux contours at 3 tilt growth times from 3-D simulations showing (a) tilted flux surfaces without ion beam (f_B = 0), and (b) predicted tilt stabilization with an ion beam ($f_B = 6\times10^{-3}$).

Finite Larmor Radius (FLR) theory[9] applied qualitatively to the FRC tilt mode suggests stability for s/e < 1/4, where s is the ratio of FRC minor radius to average ion gyroradius and e is the FRC separatrix elongation. Recent Hall-fluid[10] and FLR[11] calculations with a variational formalism support quantitatively the above estimate. In FRX-C/LSM, values of $s \simeq 1 - 5$, $e \simeq 3 - 8$, and $s/e \simeq 0.1 - 1.5$ have been achieved. Analysis of the entire data base reveals a gradual increase in tilt amplitudes (the best correlation found so far) and a degradation in FRC confinement as s/e increases.[7] Consistently large tilt amplitudes and poor confinement are observed for s/e > 0.5.

1.3 Theoretical FRC tilt stabilization with ion beams

If tilt stability requires s/e < 0.5 while ignition may require $s \simeq 20 - 40$, FRC fusion reactors would be unattractively long. This illustrates the need for additional stabilizing techniques. Tilt stabilization is difficult[8] but it has been recently demonstrated[12] by adding an ion beam component as a collisionless Vlasov species in the 3-D simulation of Fig. 2(a). Tilt stability of the resulting self-consistent equilibria has been studied for several values of f_B (beam/total particle inventory ratio). The tilt growth rate is reduced by about a factor of two for $f_B = 3 \times 10^{-3}$ and no growth is observed (Fig. 2b) for $f_B = 6 \times 10^{-3}$. The latter corresponds to fractions (beam/total) of 0.5 for energy and 0.25 for current. Further calculations will explore ways of reducing these fractions by optimizing the beam ion energy and its spatial distribution.

The above results suggest the feasibility of FRC tilt stabilization studies in FRX-C/LSM. Available technologies are now being considered to assess whether an ion beam can be introduced during FRC formation. In particular, the required ion beam could perhaps be obtained by plasma capture of a neutral hydrogen pulse from an intense ion diode.[13] Studies are also underway to find practical techniques in future large-size FRC devices. Partial loss of fusion products may naturally produce some beam ion component in ignited FRCs.[14]

2. COMPRESSION HEATING STUDIES

2.1 FRC translation

Preparatory translation experiments were performed on FRX-C/LSM prior to the installation of the magnetic compression hardware. FRCs were moved axially through a sharp transition and trapped inside a flux-conserving chamber (6.7-m length, 0.40-m i.d.). The confinement properties of translated FRCs are not very different from their *in situ*, non-translated, counterparts. An applied helical quadrupole field of 3% of the external field B stabilizes the destructive n = 2 mode and FRC lifetimes of up to 400 μs have been observed.[15] Internal magnetic field measurements in these translating plasmas reveal a largely force-free structure (**J** ∥ **B**) with a significant toroidal field component.[16]

2.2 High-power compression heating

The FRX-C/LSM device has recently been modified (Fig. 3) to allow high-power magnetic compression heating experiments. Kinetically-stabilized FRCs ($s \simeq 1.2$, $e \simeq 5$) formed in a deuterium puff inside a tapered θ-pinch coil are translated along a guide field into a new single-turn magnetic compression coil.

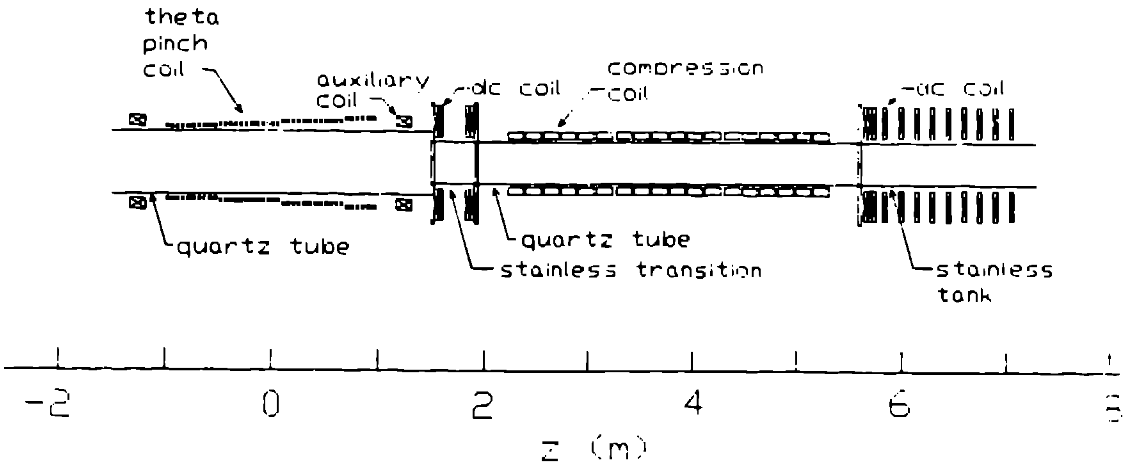

FIG. 3 Schematic diagram of the FRX-C/LSM device modified for high-power FRC compression heating experiments.

The plasma enters the compressor approximately 30 μs after formation, reflects from a downstream mirror, and becomes trapped near the center of the compression coil at 100 μs. At that time B is raised from 0.2 T up to 1.8 T in 55 μs. Significant heating, consistent with the $B^{4/5}$ adiabatic scaling, is measured (see Table I) even though a sizeable fraction of the particle inventory is lost. These observations are consistent with an energy confinement that is dominated by particle diffusion, as found in *in-situ* experiments[3]. The significant electron heating suggests that there is no fundamental thermal conductivity limit, although it may simply be a consequence of open field line confinement. The inferred poloidal flux and particle confinement times, τ_ϕ and τ_N, remain approximately equal during compression, scaling roughly with the square of the separatrix radius r_s. The confinement times for the compressed FRCs are similar to those obtained on smaller devices with comparable plasma parameters.[17]

Higher energy densities are achieved with hotter initial conditions in the θ-pinch and earlier compression during the first FRC transit through the compression coil. For this case, the total FRC plasma energy is tripled (5 - 15 kJ) with total neutron yields up to 1×10^9, $T_e = 0.4$ keV, $T_i = 1.5 - 2.0$ keV, $n_e = 3 \times 10^{21} m^{-3}$, $E_p/V = 1 \times 10^6$ Jm^{-3}, and $n\tau_E \lesssim 10^{17} m^{-3}s$. However, in contrast to the colder initial conditions, the quadrupole stabilization field (of up to 4% B) is insufficient to control the n=2 rotational mode which often terminates the FRC before peak compression. Volume-averaged measurements

TABLE I. FRX-C/LSM DATA

Parameters	Units	θ-pinch source †	Before compression	Near peak compression
time	μs	30	100	150
B	T	0.41 ± 0.02	0.23 ± 0.01	1.56 ± 0.04
r_s	mm	152 ± 11	145 ± 5	54 ± 6
<n>	$10^{21}m^{-3}$	0.6 ± 0.0	0.6 ± 0.1	6.4 ± 1.5
$T_e + T_i$	eV	516 ± 34	189 ± 49	970 ± 23
$T_e(r=0)$	eV	132 ± 26	80 ± 15	340 ± 40
poloidal flux	mWb	3.4 + 0.8	2.7 + 0.3	0.7 ± 0.3
s		1.2 ± 0.2	1.9 ± 0.3	0.7 ± 0.2
e		4.7 ± 0.4	5.7 ± 0.5	4.3 ± 0.8
τ_ϕ	μs	210 ± 67	147 ± 46	33 ± 16
τ_N	μs	175 ± 48	129 ± 66	33 ± 21
τ_E	μs	79 ± 15	51 ± 20	21 ± 7

† Data from source are for non-translated FRCs from *in-situ* experiments.[3]

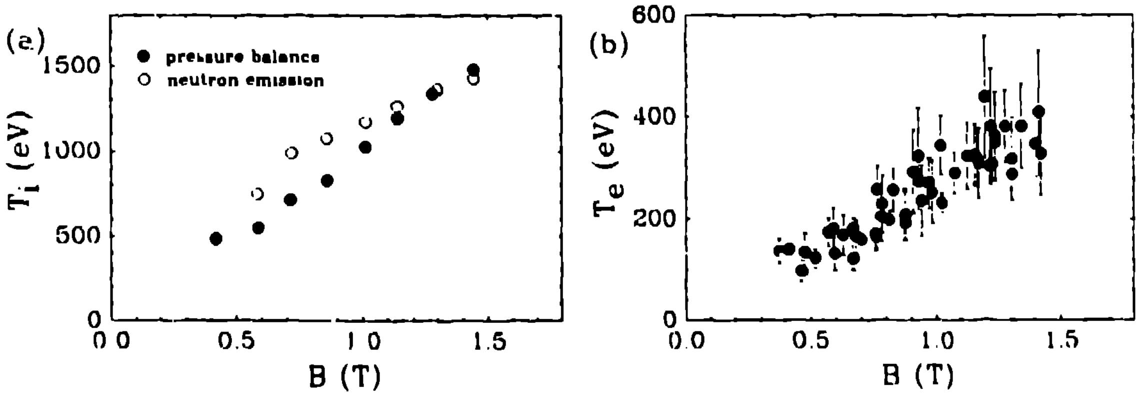

FIG. 4 (a) Ion and (b) electron temperatures vs compression field. The T_i data are averages from pressure balance, and from the neutron flux, while the T_e data represent single-point Thomson scattering measurements at r = 0 for 64 separate discharges.

of neutron emission with absolutely calibrated instruments support the peak compression ion temperatures determined from pressure balance (Fig. 4a), while Thomson scattering measurements near the geometric axis reveal substantial electron heating (Fig. 4b).

ACKNOWLEDGEMENT

FRC research at Los Alamos is funded by the United States Department of Energy.

REFERENCES

[1] SIEMON, R.E., et al., in Plasma Physics and Controlled Nuclear Fusion Research 1988 (Proc. 12 Int. Conf. Nice, 1988), Vol 2, IAEA, Vienna (1989) 517.
[2] REJ, D.J., et al., Phys. Fluids B 2 (1990) 1706.
[3] REJ, D.J., et al., Nucl. Fusion 30 (1990) 1097.
[4] TUSZEWSKI, M,. et al., to be submitted to Phys. Fluids B (1990).
[5] TUSZEWSKI, M, Rev. Sci. Instr. 61, in press (1990).
[6] TUSZEWSKI, M,. et al., Phys. Fluids B 2 (1990) in press.
[7] TUSZEWSKI, M, et al., submitted to Phys. Rev. Lett. (1990).
[8] MILROY, R.D., et al., Phys. Fluids B 1 (1989) 1225.
[9] ROSENBLUTH, M.N., et al., Nucl. Fusion Suppl., Part 1 (1962) 143.
[10] ISHIDA, A., MOMOTA, H., STEINHAUER, L.C., Phys. Fluids 31 (1988) 3024.
[11] STEINHAUER, L.C., ISHIDA, A., Phys. Fluids B 2 (1990) in press.
[12] BARNES, D.C., MILROY, R.D., submitted to Phys. Fluids B (1990).
[13] GREENLY, J., et al., J. Appl. Phys. 63 (1988) 1872.
[14] BERK, H.L., MOMOTA, H., TAJIMA, T., Phys. Fluids 30 (1987) 3548.
[15] REJ, D.J., et al., in Proc. of the 9th U.S. Compact Toroid Symp, Spectra Technology, Inc., Bellevue, Washington, USA (1989) 8.
[16] TUSZEWSKI, M, WRIGHT, B.L., Phys. Rev. Lett. 63 (1989) 2236.
[17] SLOUGH, J.T., HOFFMAN, A.L., Nucl. Fusion 26 (1986) 1693.