All you need to know about Magnetic Fusion Energy, from Mitchell Street to Provence in 25 minutes or less

Cornell LPS@50: an ANNIVERSARY SYMPOSIUM

Don Rej
Director, Office of Science Programs at LANL

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Has it really been 40 years?
Career Highlights

- Magnetic Fusion Energy (MFE)*
  - Electron Rings for MFE
  - Field Reversed Configurations
  - Fusion Diagnostics
  - Stellarators

- Plasma Materials Science
  - Plasma Source Ion Implantation
  - Materials Surface Modification with Intense Ion Beams

- Particle Accelerators
  - RF LINACS

- Private – Public Partnerships

- Line, Program, & Project Management

- Government Advisor

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*While my talk will focus on MFE, I want to recognize Cornell alumni who, unlike me, have devoted their entire distinguished careers in MFE:

- Paul Bonoli (MIT)
- Stan Luckhardt (MIT, UCSD)
- Stewart Zweben (PPPL)

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Also, exceptional Cornell postdoc and visiting faculty mentors during my tenure involved in MFE:

- Hal Davis (LANL)
- John Finn (NRL, LANL, Tibbar)
- Raghavan (“Jay”) Jayakumar (MIT, LLNL, GA)
- Clark Swannack (LANL)
- Dan Taggart (NRL, LANL)
- Alan Turnbull (GA)
- Michel Tuszewski (UC Berkeley, LANL, Tri Alpha Energy)
- Prof. Kiyoshi Yatsui (Nagaoaka University of Technology)
Of the plethora of Magnetic Fusion Energy (MFE) ideas over 70 years, we will focus on three very different MFE configurations:

**Field Reversed Configurations:** A fusion reactor engineer’s dream but far from physics proof-of-concept

**Stellarators:** A fusion reactor engineer’s nightmare but on the threshold for a major physics proof-of-concept

**Tokamaks:** A fusion reactor engineer’s challenge but has the most promising performance to date

Cornell Relativistic Electron Coil Experiments (RECE): Field Reversed Configuration research at the Mitchell Street High Voltage Lab

RECE-Christa magnetic trap

5 MeV Marx generator and blumlein to drive a diode electron beam injector

Topnotch engineers, technologists and machinists were “hands-on mentors”: Jim Ivers, Jim Milks, Mark Newall, Frank Redder, Cornell machine shop

FIG. 4. Schematic diagram of the RECE-Christa device and associated diagnostics.
Manipulating electron rings: trapping, stacking, and adiabatic compression

FIG. 3. Typical time dependence of ring parameters over first 360 µs sec.

FIG. 2. Magnetic-field profile at different times, and pulse driving current wave forms. Injector position is 115 cm, upstream and downstream pulse coil positions are 292 and 265 cm, respectively.

FIG. 5. Oscilloscope recordings, from a set of on-axis probes, showing ring translation and stacking to field reversal.

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Generation of Field-Reversing E Layers with Millisecond Lifetimes

H. A. Davis, R. A. Mager, and H. H. Fleischmann

Laboratory of Plasma Studies and School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

(Received 9 June 1976)

Field-reversing electron rings, exhibiting initial axial field changes \( \Delta B_A / B_A \approx 17\% \), and having overall lifetimes of greater than 100 μs, have been generated by injection of 2.5-MeV, 20-kA electron-beam pulses into the relativistic-electron-collider experiment (RECE-C) drift region field, \( B_d(0) \). These lifetimes, which are comparable with those expected from collisional diffusion of the fast electrons, constitute an improvement of more than a factor of 20 over the earlier results from RECE-Beta.

FIG. 4. Measurements of ring radius with end-on framing photography. For typical recordings \( r \approx 10 \) showing electron rings with axial detectors before, during, and at peak compression. Compression-induced fractional change in major ring radius for various compression ratios and rings.

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Adiabatic Magnetic Compression of Field-Reversing E Layers

M. Tanoue, R. A. Mager, and H. H. Fleischmann

School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

(Received 21 January 1979)

In the RECE-Cdrift device, electron rings were adiabatically compressed in low-density hydrogen gas with axial magnetic field compression ratios \( B_f / B_d \approx 1 \), without encountering any given breakdowns or other anomalous losses. In agreement with a simplified inertial model, the field-reversal factor, \( B_f / B_d \), remains constant, and the major radius and the axial length of the rings scale with \( B_f / B_d \), while the ring current increases with \( B_f / B_d \). Furthermore, field-reversal times have been extended to 11 ms.

FIG. 6. Pull time dependence of field-reversal factors for long-lived rings.
Minimizing electron ring energy loss during translations

Axial translation of field-reversing $E$ layers

D. J. Rej, M. Tuszewski, H. A. Davis, and H. H. Fleischmann
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853
(Received 23 August 1976; accepted for publication 25 September 1978)

Experiments are described in which field-reversing $E$ layers were transported axially in RECE-Christa over a distance of up to 10 ring radii using time-varying magnetic fields. When properly executed, this process does not lead to anomalous electron losses. The translation speed appears consistent with that expected from the interaction of the rings with the axial $B_{r}$-field gradients and the resistive tank wall. No significant difference is observed between moving the rings in a homogeneous $H_{x}$ field and moving them from a transient gas cloud into a low-gas-density region.

Resistive wall interaction of axially moving field-reversed $E$ layers or plasma rings

D. J. Rej, D. A. Larrabee, and H. H. Fleischmann
School of Applied and Engineering Physics, Cornell University, Ithaca, NEW 14853
(Received 25 February 1980; accepted for publication 6 June 1980)

Calculations are performed of the interaction force between an axially moving current carrying plasma ring or $E$ layer with a resistive wall for a variety of parameters relevant to the various moving-ring-fusion schemes and experiments. Various wall configurations are considered: (i) For a thin resistive wall, the interaction force $F_{1}(v_{r})$ is found to be proportional to the axial speed $v_{r}$, or to $(1/v_{r})$ for small or large velocities, respectively, and to be strongly dependent on the ratio of the effective ring radius $R$ to wall radius $R_{w}$. In contrast, the force on the ring thickness $S$ is found small when rings with similar external field distributions are compared. For fusion-relevant ratios $R_{w}/R_{e}$, $0.7$, and $L_{e}/R_{e}$, $1-2$ ($L_{e}$ ring length), the energy losses for moving the rings in an axially uniform plasma equal to $L_{e}$ can amount to $60\%$ of the rings' magnetic self-energy. However, this energy can be strongly reduced by proper choice of parameters. (ii) The addition of a fully flux-conserving wall at a radius $R_{c}$, $R_{e}$, is also found to lead to significant reductions of $F_{1}(v)$ in the low-velocity regime, dependent in size on the ratio $a=R_{w}/R_{e}$. (iii) A finite wall thickness mainly leads to increases in $F_{1}(v)$ at large $v_{r}$, where the transit time of the rings $t_{w}=R_{e}L_{e}v_{r}^{-1}$ becomes shorter than the wall thickness. In this case, $F_{1}(v)$ remains constant.

Measurements of resistive wall and plasma drag on the axial translation of field-reversing $E$ layers

D. J. Rej, M. R. Parker, and H. H. Fleischmann
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853
(Received 28 September 1981; accepted 16 September 1982)

Results from detailed measurements and related analyses of the axial translation of strong $E$ layers in the RECE-Christa experiment testing the interaction of the rings with resistive image currents in the wall and in the ring plasma are presented. The experiments were performed under a variety of experimental conditions including cases with (i) $F_{1}$, $F_{2}$, (ii) $F_{1}$, $F_{2}$, $F_{3}$, and (iii) $F_{1}$, $F_{2}$, $F_{3}$, $F_{4}$, $F_{5}$, and $F_{6}$ denoting the retarding image forces due to interaction with wall currents and plasma currents, respectively. In the respective analyses, theoretical ring velocities are calculated from simultaneously measured ring, wall, and plasma parameters. In all cases, good qualitative and quantitative agreement [105%–120% for case (i), and 305%–50% for (ii) and (iii)] between the observed and theoretically calculated velocities is found.

Exceptional classmates: David Larrabee and Mark Parker, and undergraduate interns Karl Bromer and Von Walters

Ethane condensation with a LN2 cryopump

FIG. 3. Typical ring propagation in the pulsed-gas shot. (a) Recordings from various probes positioned along the tank axis; (b) corresponding magnetic ring profiles at various times.

FIG. 4. Measurements of ring velocity in approximately uniform field gradient. (a) Probe recordings for $db_{r}/dz = 0.5 \, G/cm$; (b) observed velocities with $db_{r}/dz = 0.5$ and $0.35 \, G/cm$ for curves (a) and (b), respectively.
Field Reversed Theta Pinches at Los Alamos

Phases of FRC formation in a field-reversed theta pinch

LANL FRX-C/T theta pinch (left) and dc magnet coils surrounding the translation chamber (right)

LANL FRX-C/T theta pinch (left) and dc magnet coils surrounding the translation chamber (right)

MHD simulation of poloidal flux for FRC translation

Experimental measurements of excluded magnetic flux for FRC translation

FIG. 11. Time evolution of the poloidal flux contours as predicted from 2-D MHD simulations of FRC translation in FRX-C/T for the low-compression, 5 mTorr puff mode with $B_0 = 2.5$ kG and $R_w = 2.5$.

FIG. 12. Time evolution of the FRC separatrix radial profile $r_s(z)$, as inferred from excluded magnetic flux measurements. These data are from a single FRX-C/T discharge at the low-compression, 5 mTorr puff mode with $B_0 = 2.5$ kG and $R_w = 2.5$. 

Phases of FRC formation in a field-reversed theta pinch

Phases of FRC formation in a field-reversed theta pinch

LANL FRX-C/T theta pinch (left) and dc magnet coils surrounding the translation chamber (right)
1 GW magnetic-compression heating of translated FRCs

Significant electron and ion heating consistent with the expected $B^{4/3}$ adiabatic scaling was observed, despite significant particle diffusion, which is enhanced during compression.

High-power magnetic-compression heating of field-reversed configurations

D. J. Rej, D. P. Teegard, M. H. Baron, R. E. Ohlen, R. J. Gribble, M. Tusnadvári, W. J. Wagaman, and B. L. Wright
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 21 January 1992; accepted 27 February 1992)

Magnetic compression heating experiments at the 1 GW level on field-reversed configuration (FRC) compact toroidal plasmas are reported. FRCs formed in a tapered theta-pinch coil have been translated into a single-turn compression coil, where the external magnetic field is slowly raised to seven times its initial value. Significant electron and ion heating consistent with the expected $B^{4/3}$ adiabatic scaling is observed, despite significant particle diffusion, which is enhanced during compression. The $\theta$ rotational instability is enhanced during compression, but has been controlled to an extent by the application of an external quadrupole field. The particle and flux confinement times, $\tau_p$ and $\tau_\Phi$, remain approximately equal and decrease roughly with the square of the plasma radius $R$ during compression, implying a constant nonclassical field-null resistivity. The observed $\tau_p$ and $\tau_\Phi$ magnitudes and scalings are compared with classical and anomalous transport theories, and existing empirical models. Particle diffusion dominates the energy confinement, accounting for three-fourths of the total losses. Upper bounds on the electron thermal diffusivities are estimated.

Fast forward to 21st Century: Resurgence of FRCs through private investments

Tri-Alpha Energy, Inc
Foothill Ranch, CA

Helion Energy
Redman, WA

General Fusion
Burnaby, BC
The FES program mission is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source. This is accomplished by studying plasma and its interactions with its surroundings across wide ranges of temperature and density, developing advanced diagnostics to make detailed measurements of its properties and dynamics, and creating theoretical and computational models to resolve essential physics principles.

Strategies influenced by community workshops on priority research areas
For over the last 25 years, Tokamak configurations have dominated the world MFE research, including the U.S.

DIII-D  
General Atomics

C-Mod  
MIT

NSTX-U  
Princeton
U.S. is a major partner with international tokamak programs.
Stellarators

Spitzer Princeton 1951

Large Helical Device Toki 1998

National Compact Stellarator Experiment Princeton 2008

W7-X Stellarator Max Planck Inst., Greifswald, 2015
Fusion power from Tokamaks were demonstrated as a scientific proof-of-principle over 20 years ago.
Then there is ITER
While creating the first burning MFE plasma, ITER could be the most complex and expensive civilian scientific facility in history.

ITER is being built through the in-kind contributions of the seven members of the ITER Organization:

- China
- India
- Japan
- Korea
- Russia
- United States
- United Kingdom

China, India, Japan, Korea, Russia and the United States each have responsibility for ~ 9% of procurement packages.

Europe’s share, as Host Member, is ~ 45% (construction and manufacturing).
ITER is supported by the governments of more than one-half of the World's population.

Who manufactures what?
The ITER Members share all intellectual property

- Feeders (31)
- Toroidal Field coils (18)
- Poloidal field coils (6)
- Correction coils (18)
- Central solenoid (6)
- Divertor
- Cryostat
- Thermal shield
- Vacuum vessel
- Blanket modules
US ITER Project
ITER Time Line

1985: At the Geneva Summit Gorbachev suggested to Reagan that the two countries jointly undertake construction of a tokamak
1988: Conceptual design
1992: Engineering design begins
1998: 1st final engineering design
1999: USA pulls out
2001: “Cost-cutting” design was agreed
2003: U.S. rejoins; China and South Korea join
2005: Southern France announced as ITER site; special compromise between EU & Japan.
2005: India joins
2006: Project agrees to and funded with a cost estimate of €10 billion ($12.8 billion) projecting the start of construction in 2008 and completion a decade later
2007: 14 major design changes
2013: Project had run into many delays and budget overruns. The facility is not expected to begin operations at the schedule initially anticipated
2014: Scathing project review by the “Madia” committee leaks to the press
2015: Project review concludes that the schedule may need extending by at least six years; (first plasma in 2026, first D-T in 2035)
2016: Secretary of Energy report to Congress that U.S. remain a partner in the ITER project through FY 2018 and focus on efforts related to First Plasma
Management crises, change, & encouragement

Independent schedule review by experts appointed by the seven domestic agencies 2014 – 2015

Second external independent expert review of cost & schedule 2016

2015: managing the need for change

Action Plan 2015

- Set clear priorities and timeline for reform
  - Reorganized, integrated ITER Central Team with Domestic Agencies
  - Clear decision processes and accountability
  - Executive Project Board, Reserve Fund, Project Teams
  - Finalized and stabilized ITER critical component design
  - Comprehensive integrated bottom-up review of all activities, systems, structures, and components to build the ITER machine
  - Developed an optimized resource-loaded schedule for timely, cost-effective construction and operation through D-T plasma. Updated the 2010 Baseline.
  - Developed and promoted a strong, organization-wide nuclear project culture

Revised resource loaded schedule to first plasma in 2015
Staged approach from ITER first plasma to DT

Extensive interactions among IO and Das to finalize revised baseline schedule proposal

✓ Schedule and resource estimates through First Plasma (2025) consistent with Members’ budget constraints
✓ Proposed use of 4-stage approach through Deuterium-Tritium (2035) consistent with Members’ financial and technical constraints
So what’s in the future for MFE?

From the “Executive Summary”:

“...A burning plasma...is an essential step to reach the goal of fusion power generation....The committee concluded that there is high confidence in the readiness to proceed with the burning plasma step. The International Thermonuclear Experimental Reactor (ITER), with the United States as a significant partner, was the best choice. Once a commitment to ITER is made, fulfilling it should become the highest priority of the U.S. fusion research program.”

The Secretary’s report to Congress also states that DOE will seek an NAS study

From the body of the report:

• The DOE will request that the National Academies perform a study of how to best advance the fusion energy sciences in the U.S., given the developments in the field since the last Academy studies in 2004, the specific international investments in fusion science and technology, and the priorities for the next ten years developed by the community and FES that were recently reported to Congress.

• This study will address the scientific justification and needs for strengthening the foundations for realizing fusion energy given a potential choice of U.S. participation or not in the ITER project, and will develop future scenarios in either case.
Thank you again for the opportunity to return to LPS after all these years and evoking many fond memories.