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A QUICK HISTORY OF THE EMC2 POLYWELL IEF CONCEPT

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PATENTS

Fundamental idea conceived in January 1983
    Overcame inherent limits of Farnsworth/Hirsch work of 1960's, and concepts of Elmore, Tuck and Watson of 1950's

First patent filed in 1985; issued 1989
    On polyhedral IEF systems, with magnetic confinement of electrons, electrostatic confinement of ions

Second patent filed in 1990; issued in 1992
    On electrostatic wave trapping of electrons and ions in IEF

Third patent filed September 2006
    On optimal engineering designs and constraints for net fusion power production

PAPERS

Many physics papers published and/or given at APS Plasma Physics Division and Sherwood Theory conferences, from 1990 through 1994. Participation stopped in 1995 at USN suggestion

Systems design and applications papers for Polywell IEF use in advanced space rocket systems, given at AIAA, STAIF and other aerospace-and fission-fuel-related conferences from 1988/1993-2004

Many (hundreds) detailed internal technical papers, documents, reviews and reports developed during program work, 1988/2006.

Detailed FINAL REPORTS (lengthy technical monographs) developed and submitted for all contracted program efforts, 1986/2006

R&D WORK

First small (50 K) study, DARPA, 1985/1986
    Define concept, limitations of physics and engineering, critical problems, and potential systems and applications

SDIO/DNA major study (250 K), 1987/1988
    USN approached for joint DARPA/NRL program; NRL (Coffey) rejected

DARPA/HEPS R&D program (30 M reduced to 10 M); 1989/1992
    Program ability to reach main objective destroyed by dismissal of DARPA Director 4 months after program start; funds reduced by 3x

DoE Hq study (toroidal polyhedral IEF; 100 K); 1992/1993
    Application of polyhedral IEF to toroidal systems, and study of fuel/gas vacuum system separation means

USN SBIR Phase I (50 K); 1992/1993
    Basic concepts, physics and engineering features, propulsion applications

EPRI IEF Power Plant study (150 K), 1993
    Physics./engineering features of IEF for utility plants

USN SBIR Phase II (750 K), 1993/1995
    First small scale experimental study of Wiffle Ball behaviour; study of electron trapping and transport

LANL/UI joint study (315 K), 1992/1994
    Physics and engineering aspects of ion-driven IEC systems (e.g. Hirsch/Farnsworth devices); fusion reactions in CP frame systems

SDIO/NASA study (280 K), 1993/1994
    Physics and application of polyhedral IEF to space missions; electrostatic wave trapping enhancement of fusion

USN major R&D program (12.7 M) 1999/2004
    Main experimental effort to determine transport, trapping, ionization, ECR, fusion reactions and rates, background gas suppression, e- and i+ gun/source development, e.s. codes, potential distributions, scaling laws, etc, etc.

USN transition/followon program (5. M; funded to 3.2 M), 2003/2006
    Extension of previous USN work, to expand from knowledge attained from prior work, and focus on remaining paths for achievement of simulated breakeven polyhedral IEF devices and systems

MACHINES

PRE-USN

SDIO/DNA 1987/88, small scale recirculating-electron (open corners) Polywell, R = 3 cm, low voltage and current 800-1000 V, 10-20 mA, B = 50-60 G

DARPA/HEPS, closed cubical box, large device, R = 93 cm, 25 ms pulsed, E = 15 kV, Ie = 5-10 A, water-cooled, truncated-cube coil magnets, B = 3.5 kG

USN/EMC2

DG-1.2, 1994, double-grid Hirsch/Farnsworth devices, R = 3 cm, calibrate instruments and show DD fusion at small scale, up to 5-6 kV, 100 mA

WB-1, 1994, R = 5 cm, uncooled, fixed solid-state magnets, annular ring cusp losses, recirculating electrons, B = 800 G, Ie = 4-5 A (max), E = 1-2 kV

WB-2, 1994/96, in-vacuum, recirculating (MG) uncooled wound-coil magnets, B = 1300 G, E = 1-2 kV (failed at 4.5 kV), truncated cube coils, 1-4 A

PXL-1, 1996/97, closed box, R = 13 cm, uncooled pancake coils on truncated cube faces, B = 1800 G single e-gun, Ie = few A, E = 4-5 kV, 2.45 GHz ECR

WB-3, 1998/2000, larger WB-2, recirc (MG), R = 10 cm, E up to 15 kV, Ie = 3 A, multiple emitters, B = 2400 G, 2.45 GHz ECR

MPG-1,2. 1999/2001, single-turn, water-cooled, recirc (MG) copper coils, pure edge-wound, E = 30 kV, Ie = 0.4 A, B = 70-100 G, ECR on coil surface only, R = 7/10 cm

WB-4, 2001/03, R = 15 cm, B = 5 kG, E = 15-30 kV, Ie = 2-4 A, water-cooled, canned, recirc (MG) copper coil truncated cube faces, 2.45 GHz ECR, several emitters

PZLx-1, 2003/04, adiabatic compressor, pulsed, un-cooled single-turn coil, bulk copper device, R = 3 cm, B = 35 kG (max pulsed), Ee(injection) = 15 kV, Ie = 10-100 A, Ee(at compression start) = 400-500 eV

MPG-4, 2003/04, larger MPG-1, with 7 turn coils, water-cooled tubing, ECR, etc

WB-5, 2004/05, larger PXL-1, external water-cooled coils, truncated cube, closed-box, max B = 6 kG, E = 15 kV, R = 40 cm, Ie 3-5 A (up to 3kA, pulsed)

WB-6, 2005, R = 15 cm, B = 1.3 kG, E = 12.5 kV, clean recirc truncube with minimal spaced corner interconnects, multi-turn, conformal can coils, uncooled, cap pulsed drive, Ie to 2000 A, incorporated final detailed engineering design constraints.

RESULTS

WB-1 showed surface transport losses, and annular cusp losses, in accord with theory

WB-2 proved WB-trapping, low voltage, modest B fields, few A current; diamagnetic B field effects, probe measured well shape, showed deep (fractional) potential wells, developed first empirical transport scaling electron loss formulae

PXL-1 showed ECR suppression of neutral wall reflux, ion focussing at device center, WB diamagnetic current formation around cusps

MPG-1,2 showed first Polywell trapped ion fusion reactions, driven by electron injection, at up to 27 kV, supported MG transport equation scaling from WB-2 work

WB-3 showed deep potential wells, diamagnetic electron formations at low energy, ECR ionization inside and outside of machine

WB-4 showed deep potential wells, ECR neutral control both inside and outside of machine (low density), varied potential configurations, trapped ion fusion reactions under pulsed gas operation mode, agree with models/theory

PZLx-1 showed stability of polyhedral field shape under compression, fusion reactions in short pulse mode, high B fields, neutral plasma compression

WB-5 showed deep potential wells, potential well formation, fusion and oscillatory well collapse arising from limited power supply current capability, performance and design constraints of closed configuration, critical discovery of 1E-5 unshielded metal limit.

WB-6 showed 1/10 of loss coefficient of WB-4, and ran as a deep well Polywell at 10-12 keV, producing DD fusions at 2.5E9 fus/sec. This is 200,000 times higher than the early work of Hirsch/Farnsworth and a world's record for such IEF devices at same conditions.

PROVEN

High energy potential well depth, ion focussing and trapping, fusion reactions, electron trapping, electron (MG) transport loss scaling, cusp loss mechanisms, well and field macro-stability, neutral gas wall reflux suppression, limiting configurations and detailed design constraints for minimal losses, computer code design ability for machine B and E fields, fusion/electric power systems design codes, DD fusion output in five machines, **world's record DD fusion output in final experiments, determined and verified all design scaling laws for physics and engineering constraints**, definition of RDT&E for full scale net-power demonstration, prototype development plans, schedules and costs.