# Inertial-Electrostatic-Fusion: A Promising New Power Concept

By Robert W. Bussard, EMC2-0493-04, 17 April 1993

## Introduction and Background

Inertial electrostatic confinement (IEF) systems utilize the kinetic energy of ions projected radially inward by imposition of an accelerating electric potential gradient outside the central region of a spherical system. By this means ions will converge towards the center point of such systems, increasing in density and energy as they do so. At the system center they will either undergo fusion reactions, producing fusion products that leave the system at high energy, or be scattered back up into the confining electric field. Ion recirculation will continue in this fashion until fusion occurs or other, second order effects cause their loss from the system. The accelerating electric field can be provided by either of two methods. First is to use a set of spherical grids, biased so as to accelerate positive ions inward; this is called the IXL system. The other produces a negative potential well by injection of energetic electrons into a magnetically confined quasi-spherical geometry; this is the EXL system. The general outline of both systems is shown in Figures 1, 2.

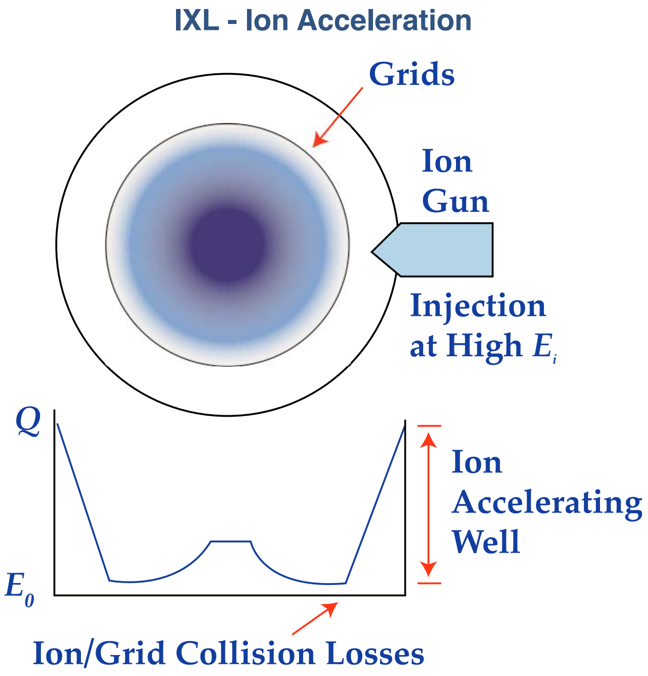


Figure 1 — Ion acceleration by grid potential; the IXL system

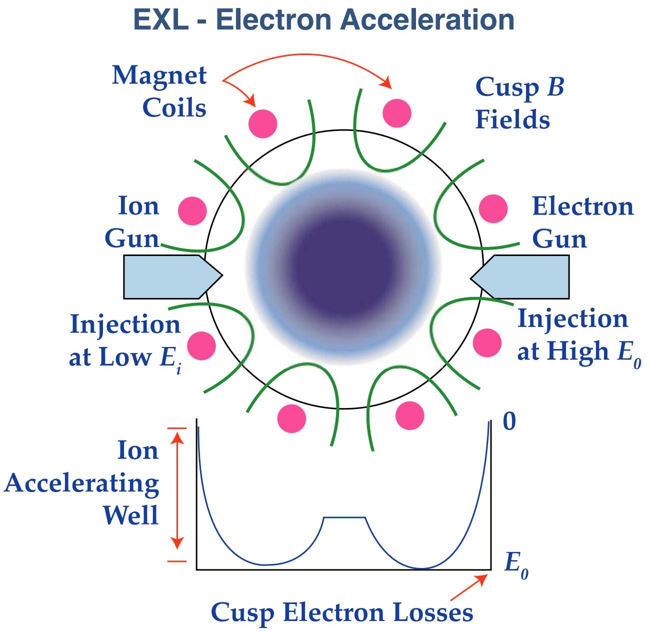


Figure 2 — Ion acceleration by electron-driven negative potential well, the EXL system

The confinement of ions by this means has advantages over conventional fusion plasma systems in local thermodynamic equilibrium (LTE), in both energy distribution (mono-energetic vs. Maxwellian) and in the absence of significant losses by collisional mechanisms. The unique energy distribution associated with spherically-convergent kinetic driven flows gives a great increase in ability to control collisional interactions governed by energy-dependent cross-sections. And the spherical flow geometry ensures that all collisions take place in or near the central core and thus can not lead to spatial losses through the system edge. These features are shown in Figure 3.

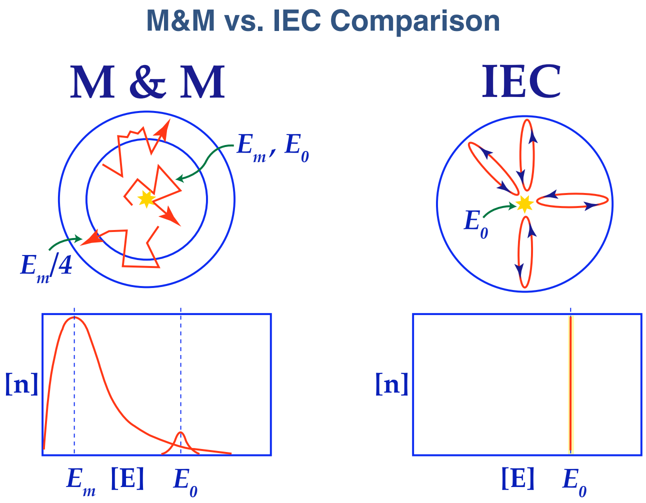


Figure 3 — Comparison of Magnetic Maxwellian (M&M) confinement with IEF systems showing particle motions and collisional energy distributions. Most fusions in M&M systems occur at energy $E_0$ well out into the Maxwellian tail where the particle density is small. But most losses result from scattering collisions near walls of the much denser low-energy ions at $E < E_{fus}$. In IEF systems, all particles are mono-energetic and collisions are near the system center. Here scattering collisions yield losses only by energy scatterings and this is a second order effect; while all collisions take place between mono-energetic particles. thus maximizing the ratio of fusion to scattering

The idea of achieving very high density plasmas by means of inertial-electrostatic convergence of charged particles in kinetically-maintained non-neutral plasma systems grew out of work by Langmuir and Blodgett[1] in the mid-1920's, to definitive concepts analyzed by Famsworth[2] in 1956-66, and Elmore, Tuck and Watson[3] in 1959. These led to studies by Hirsch[4] in the mid-1960's. Although this showed the first good performance results for IEF devices. research did not resume until the late 1980's, when Bussard[5,6,7] found a solution to a limiting problem of earlier concepts. Work continued since then has led to a good understanding of many critical aspects of the fundamental phenomena involved. This now allows definition of a clear course for significant plasma physics research, that can bring this understanding to a state of potential applications. Further, it is only from the work of recent years that the richness of these potential systems applications has been developed and understood.

## System Operation

Core recirculation ratios of $10^5$ to $10^6$ for ions (IXL) or electrons (EXL) are required to achieve net power generation from fusion in such systems. However , the mechanical grids of IXL systems limit this to no more than 10-100 re-circulations before loss of the average particle. Thus, all IXL-type schemes are doomed to failure, unless some means of great enhancement of converted core ion density can be found It is this fact that makes wave-group-trapping of such critical importance to proof-of-principle for IXL devices.

However, for EXL machines this effect is expected to be found only with large central virtual anodes. and is secondary to the trapping and confinement of electrons by electron diamagnetic confinement (the WB effect, discussed following). It may serve a useful purpose to further increase the recirculation ratio of electrons in the system as wen as enhance in-core-region trapping of ions, but is not the dominant effect for EXL devices, as the power balance is more determined by electron surface losses through the *B* fields.

A concept to overcome the grid-collision limits of IXL systems was invented by Bussard[8] and a patent issued in May 1989. Its basic feature was to replace the IXL grids by a quasi-spherical surface magnetic field around a spherical cavity, such that electrons would be confined by the magnetic field, and made to recirculate without mechanical collisional losses. By this means, a negative potential well could be created within the volume by control of the injected electron and ion currents. This negative potential well would then trap and confine the ions in recirculating motion through the system, again without collisional losses to structure. In short, to use magnetic confinement to trap energetic electrons, and the resulting negative electrostatic field to trap the recirculating ions. This electron acceleration (EXL) device has been the basis of much of the work conducted since 1985, largely under DoD sponsorship. Two basic studies of this approach published by Bussard[9] and Krall[10] outline its principles in more detail and give some idea of its range of features and operations.

An EXL system is driven by injection of electrons into a polyhedral polar magnetic cusp geometry, whose field configuration has true MHD stability and is minimum-*B* in the sense that the field drops rapidly with decreasing radius towards the system center. A general description of the physics of EXL devices was given by Krall, et al.[11] Analysis of both this device and IXL systems has been carried out by a 1.5-D computer code developed to solve Poisson's equations subject to the Vlasov equation for each species recirculating through the system. This is called the EIXL code, and is described elsewhere.[12] Analysis of IEF systems by this and a related power balance code (the PBAL code) have shown[13] the nature of the operation of this device.

One- and two-dimensional numerical computations of electron losses through the polyhedral cusps have also been made with particle-in-cell (PIC) codes, using Cray computers, to assess the plasma behavior in the system. The results do exhibit the diamagnetic electron flow behavior. required for proper operation, in good agreement with the models. Of course, experiments are essential to support these results. If diamagnetic electron behavior can be proven, the device has a good probability of being able to be made to function as a fusion machine; albeit there remain other second-order problems to be tested and verified by experiment, as well. These latter include maintenance of core convergence and of relatively mono-energetic particles.

All analyses and theory to date have shown that the core will not spread, and that Maxwellianization will not occur to any significant degree over the lifetime of the particles in the system. The key to understanding this is that all of the particles will naturally leave (or can be controlled to leave) the system after a finite time, or be fusioned. They do not have to "live" in the system long enough to become Maxwellianized or to allow buildup of core spreading momenta. In fact, Rosenberg and Krall[14] have shown that transverse momentum will not build up, due to rapid isotropization at the system edge. In this respect (as wen as in many others) the device is quite different from all other, more conventional magnetic confinement systems (e.g. tokamaks).

## Electric Power Generation Plants

The promise of small-scale commercial fusion power plants using these concepts has been one of the drivers for the past several years of power systems analysis and design work on IEF systems. Detailed study of the power balance in IEF devices has been conducted for a variety of fusion fuels, using a power balance computer code (PBAL) that includes the engineering constraints of magnets (both normal and superconducting), first wall thermal transfer and stresses, plasma performance as affected by drive conditions, system unit size, losses due to bremsstrahlung, parametric thermal and direct conversion efficiencies. dimensional requirements of direct conversion, etc. It is based on operation in the fully diamagnetic WB mode, with large recirculation ratio in the electron flow. This has been run on 486DX2/50 computers over a large range of parametric design variables.

The fuels considered have been DT, pure DD, DD-1/2-catalyzed with the $^3$He produced in one branch of the DD reaction, DD-fully-catalyzed with the $^3$He just-mentioned plus that obtained from decay of the T produced in the other DD branch, D$^3$He mixtures over a wide mixture ratio (from nearly-pure D to nearly-pure $^3$He), $^3$He$^3$He, fully-catalyzed $^6$Li$^6$Li reaction (through the p$^6$Li, $^3$He$^6$Li chain), and p$^{11}$B. It has been determined that parametric engineering conditions can be found that allow all of these to be operated with net positive power gain of useful and practical magnitude, and that these engineering conditions are generally less severe than those required for most other magnetic fusion system concepts.

The models chosen for systems study of the IEF FPC unit vary, depending on the fuel chosen for study and use. In general, the DT fuel combination has not been pursued, even though it leads to very small systems with large gain, because of the extreme hazard potential associated with the 14.1 MeV neutron inherent in the DT fusion reaction. This forces the development of new materials, and leads to the generation of excessive amounts of radioactive structural waste. Instead, emphasis has been on use of the DD 1/2-cat fuel mixture and on clean p$^{11}$B. The former yields only 9% of its energy in neutrons, and these are at almost the same energy as those found in fission reactors. Thus, materials problems are minimized (or made comparable to those of conventional structures — not fuel elements — in fission reactors). Normal stainless steels can be used, with PWR-like steam power cycles; structure lifetime would be ca. 10-20x longer than for DT reactors. A DD 1/2-cat utilities FPC is shown in Figure 4, following. The core radius of this nominal 500-900 MWe (net) FPC unit is about 3.5 m.

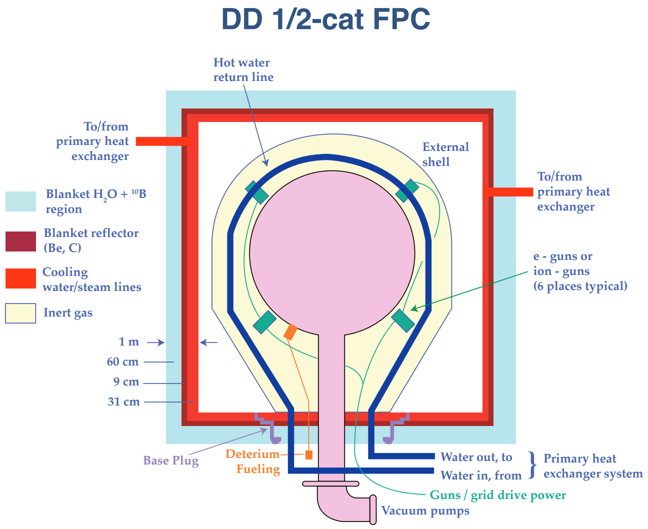
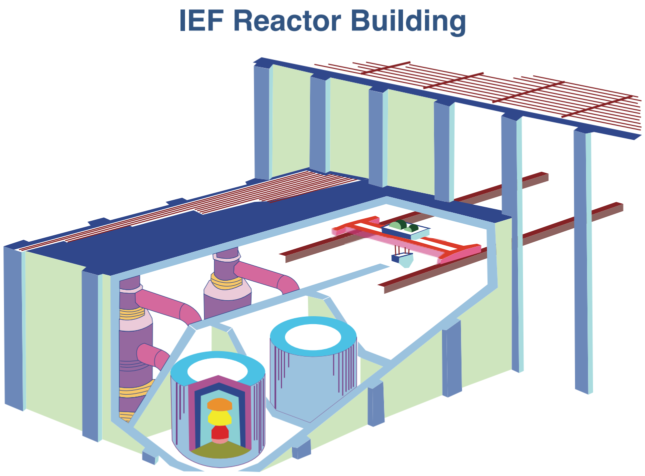


Figure 4 — DD 1/2-cat FPC in $^{11}$B n-capture blanket, showing cooling. vacuum and electrical supplies in shielded tunnel below power bay

A complete power plant might be formed of several of such units, arranged in a modular fashion, each in its own long-lived blanket environment, as suggested in Figure 5, following.



IEF Reactor Building

Figure 5 — IEF reactor building; three removable/replaceable FPC modules (no in-situ maintenance) at end-of-life (ca. 10-30 years)

This is the relatively small reactor building for the DD 1/2-cat plant. The balance-of-plant will look very much the same as any other steam-conversion-electric plant of comparable power. since the FPC units and blanket system simply produce conventional boiler-grade steam. The plant system gross gain (gross electric power divided by electric drive) for this DD 1/2-cat system is found from PBAL code runs to be about 11.0 for a 3.5 m unit operated at $B$ = 13 kG (1.3 Tesla) with superconducting magnets, ion flow core convergence ratio $<r_c>$ = 0.0033 and ion core energy of $E_o$ = 80-85 keV. At these conditions net electric power produced is 800-900 MWe. Reducing the field to 1.15 T lowers the net power to 500-600 MWe. The use of water-cooled copper magnets is also possible with the DD 1/2-eat cycle; but the gross gain for the same size/power -stem is reduced to about $G_{gr} \approx 6.6$. thus the recirculating power fraction is about 16% as compared with 9% for the superconducting example cited above. Neither of these examples has been optimized, so some margin for improvement is probable. In connection with the use of superconducting magnets, note that all the fields are quite low compared with conventional magnetic confinement devices (e.g. large tokamaks). and that the magnets are outside the vacuum system and system plasma boundary. Thus, it is relatively simple to shield these from the small neutron flux, and obtain long magnet life. Of course, copper coil magnets will not be damaged in any significant way by the external neutron flux from such DD 1/2-cat systems.

In addition to these power balance and plant considerations, detailed study has been made of a. variety of other engineering issues. These include:

(1) System startup/control; potential wells found stable over ion/electron current ratios of 4-6x;

(2) First wall neutron damage and thermal stresses; stainless steel tubing ca. 1 em diameter can be used to extract all thermal particle input at power levels cited above. within stress limits;

(3) Sputtering and high-Z impurities; the potential well does not allow accumulation of impurities in core center, and recirculation ensures that they will be swept out of system at low concentration;

(4) Hazard potentials due to T concentration, neutron activation, and $B$ field energy; all are of little note — T inventory is < 10 nanograms in device — mass activated is comparable to that in PWR < 0.1 that in DT machines - $B$ field energy is ca. 100 MJ, < 0.001 of large DT tokamak $B$ field;

(5) Ion loss by core collisional upscattering; found to be small at densities of interest, and not to cause a loss anyway - it simply puts a pumping load on the vacuum pumps;

(6) Ion injection through $B$ fields: injection can be either from high density guns (PIG-type) on cusp/vertex axes, or by neutral gas injection with internal e-ionization near edge:

(7) Bremsstrahlung losses; found not to be dominant if central anode height is kept small and device operated so that ion and electron lifetimes are below ca. 5x Maxwellianization time limits;

(8) X-rays and neutrons into coils and structures, etc.; superconducting magnets are all low field, outside the system, and easy to shield against low energy neutrons — X-rays can't get there — there is no high voltage structure inside the system to break down. etc.

While many other issues of lesser importance remain to be studied, the successful resolution of those examined to date suggests that this approach to relatively clean fusion power merits considerably more experimental analytical and design work to determine its realistic prospects. If the models and results to date are correct, this approach seems able to be brought to fruition through R&D at very much lower cost and with much less time than is projected for the big tokamaks that characterize the current US national fusion program. In fact, the IEF approach could even produce commercial power plants that would be exciting to utilities for future use.

## References

[1] Irving Langmuir and Katharine Blodgett; Physics Review, volume 24, 49-59 (1924)

[2] Philo T. Farnsworth; "Electric Discharge Device for Producing Interaction Between Nucleii." U.S. Patent No. 3,258,402, initially filed November 5, 1956; revised October 18, 1960; refiled January 11. 1962; issued June 28, 1966

[3] William Elmore, James Tuck and Kenneth Watson; Physics Fluids, volume 2, 239 (1959)

[4] Robert L Hirsch; Journal Applied Physics, volume 38. 4522 (1967)

[5] Robert W. Bussard; "A New Physical Process, Method and Apparatus for Creating and Controlling Nuclear Fusion Reactions," U.S. Patent No. 5,160,695, issued November 3, 1992, filed February 8, 1990, assigned to QED Inc., licensed to EMC2

[6] Robert W. Bussard; "Potential and Density Distributions in Inertial-Electrostatic Confinement Systems," paper 1D12, International Sherwood Theory Conference, Santa Fe, NM, April 6-8, 1992

[7] Robert W. Bussard; "Ion-Acoustic Waves and Wave-Group- Trapping in IEC Systems," Paper 8S32 and with Katherine E. King and L. W. Jameson, "Particle Trapping and Electron Two-Stream Instability in IEC Systems," Paper 8S31, Annual Meeting on Plasma Physics, APS, Seattle, WA, November 16-19,1992. Bulletin American Physics Society, volume 37, 1581, November 1992

[8] Robert W. Bussard; "Method and Apparatus for Controlling Charged Particles." U.S. Patent 4,826,626; issued May 2.1989, filed October 29, 1985

[9] Robert W. Bussard; Fusion Technology, volume 19, 273 (1991)

[10] Nicholas A. Krall; Fusion Technology, volume 22, 42 (1992)

[11] Nicholas A. Krall, K. Wong, and V. Stefan (KA), M. Rosenberg and Robert W. Bussard (EMC2), and J. Watrous (MRC); "Theory of Plasma Physics Phenomena in the Pollywell Plasma Confinement Geometry," Paper 2T9, Annual Meeting Plasma Physics Division, APS, Tampa, FL. November 4-6, 1991, Bulletin American Physics Society., volume 36, 2319 (1991)

[12] Katherine E. King and Robert W. Bussard; "EKXL: A Dynamic Poisson-Solver for Spherically-Convergent Inertial-Electrostatic Confinement Systems" Paper 2T11, Annual Meeting Plasma Physics Division, APS, Tampa FL, November 4-8, 1991, Bulletin American Physics Society, volume 36, 2319 (1991)

[13] Robert W. Bussard and Katherine E. King. "Phenomenological Modeling of Polywell/SCIF Multi·Cusp Inertial-Electrostatic Confinement Systems," Paper 2T10, Annual Meeting Plasma Physics Division, APS, Tampa FL, Nov. 4-8,1991, Bulletin American Physics Society, volume 36, 2319 (1991)

[14] M. Rosenberg and Nicholas A. Krall, Physics Fluids B, volume 4, 1788 (1992)