Inherent Characteristics of Fusion Power Systems: Physics, Engineering, and Economics

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Abstract

Performance scaling of fusion power sources shows that Maxwellian, magnetic, local-thermodynamic equilibrium (MM/LTE) devices require much larger sizes and *B* fields than do electron-driven, inertial electrostatic-confinement (EXL/IEC) systems for the same output. Basic economics analyses show that systems of either type must be small in size to be economically viable. This requires operation at high fusion power density and first-wall thermal fluxes; flux levels needed are well within those of practical power engineering experience. The EXL/IEC systems can satisfy these demands more readily than can MM/LTE systems. They can be operated to avoid particle thermalization, preserve ion core convergence, and yield a large power gain against losses (e.g., bremsstrahlung) for all fuels from deuterium-tritium to p-^{11}B and ^{3}He^{3}He. Direct conversion of charged-particle energy, without arcing, is inherently straightforward in the quasispherical field geometry. If losses prove to be governed by classical physics phenomena rather than turbulent transport, all research and development (R&D) from physics studies to power plants can be done at a single size (≈3-m radius) and *B* field (≈1.2 T, 12 kG); no scaling growth in size or field is required. Consequent R&D costs and time scales are estimated to be <12 years and $1 billion for development of prototype EXL/ IEC fusion power systems. Research investment seems warranted in this small-scale alternative to large-scale MM/LTE systems.

I. Introduction

More than 42 years ago, Spitzer first proposed making fusion power with magnetically confined thermal equilibrium plasmas in twisted toroidal geometries. Since that time, many of the chief practitioners of this art have overwhelmingly focused on the nature and generic features of collisionally dominated Maxwellian plasmas in magnetic (MM) confinement systems in local thermodynamic equilibrium (LTE); we call these MM/LTE systems. Today, these are characterized principally by tokamaks such as the proposed International Thermonuclear Experimental Reactor (ITER) experiment.

Based on well-developed intuition about matters pertaining to MM/LTE systems, a recent paper by Rosenbluth and Hinton[1] attempts to ascribe generic features to fusion systems. However, the basic physics, engineering, and economics assumptions of that paper are incorrect for the non-LTE systems and concepts considered. Some of the flawed conclusions thus reached by Rosenbluth and Hinton are corrected in the current paper; we use engineering and physics phenomena and technology conditions that are appropriate for each class to show the contrasting realities of economics, physics, and engineering limitations of MM/ LTE compared with non-LTE inertial-electrostatic-confinement (IEC) fusion systems.

The IEC system discussed here is a modification of Farnsworth's[2] and Hirsch's[3] earlier concepts for ion injection and was invented by one of us[4] (RWB) to avoid excessive losses by particle/grid collisions that limit the potential performance of this system. To do this, the system uses energetic electron injection to provide a spherical negative potential well that, in turn, traps ions in a recirculating spherically convergent flow. The electrons are held by a quasi-spherical magnetic confinement system of special geometry. Figure 1 shows a comparison of these approaches, here called the ion acceleration (IXL) system for the Farnsworth-Hirsch approach and the electron acceleration (EXL) system for the Bussard approach.

(Note that we limit consideration to particle kinetic/potential energy exchange driven spherical counterflow systems, as only these offer both inherent flow stability and sufficient density compaction as r → 0 to yield net fusion power.)

We note that the EXL system was specifically excluded from the Reference 1 study; consequently, the current paper is especially useful in that it fills a gap left by Reference 1. However, the main elements of our discussion apply equally to IXL systems, which Reference 1 treated by using arguments appropriate to MM/LTE systems rather than to either IXL or EXL systems.

For our comparisons, we use elementary physics and economics models that correctly and appropriately illustrate the issues. Over the past two decades, many more complex analyses of confinement physics, systems engineering, and economics have been made that support these models.[5,6,7,8,9,10,11] From this work, it is evident that the most economically attractive power generation would be provided by small-scale systems; we believe that the smallest, simplest, and least costly approach to practical fusion is found from the spherical just-mentioned IEC systems, which also offer the only reasonable hope for clean (i.e., neutron-free) power.

In this paper, first, we examine inherent characteristics of MM/LTE and EXL/IEC systems using spherically convergent flow geometries, to show the relative parameter ranges (size R, density convergence $<r_c>$, magnetic field B, and particle confinement beta β) that each must have for comparable levels of performance. This shows the generic difficulties confronting MM/LTE devices vis-a-vis the EXL/IEC approach; sizes and fields must be very much larger for MM/LTE systems than for EXL devices. This requires greater technology levels, costs, and research and development (R&D) efforts.

Second, we give a simple economic model for fusion power source systems (both MM/LTE and EXL/IEC) that shows the relationship between dominant engineering design parameters, technology levels, and inherent costs. Conclusions drawn from these are found to agree with those from a variety of detailed engineering and economics studies done within the main fusion program. From this, it is evident that the attainment of useful economic performance requires a small size confinement system surface and a high-power flux through this surface.

Third, we discuss the dominant physics phenomena that limit EXL/IEC systems, show their boundaries, and give examples of the performance projected for such systems using various fusion fuel combinations on the presumption that the classical physics on which they rest will be proven by experiment. This presumption allows good estimation of the research program needed for IEC power development. Of course, experiments are necessary to accomplish such proof, and these cost time and money. We believe that the economic promise of this small-scale approach suggests that some modest fraction of the U.S. fusion program budget might well be directed to the study of EXL/IEC physics.

II. Comparison of MM/LET and EXL/IEC Fusion Power Systems

Conventional large-scale tokamak systems use magnetic fields to attempt to confine collisionally dominated neutral plasmas. In consequence, they have a modest spatial variation of density across their confinement region, are Maxwellian and operate in (near) LTE throughout the system, and have ion particle (and energy) losses determined principally by surface region collisionality.

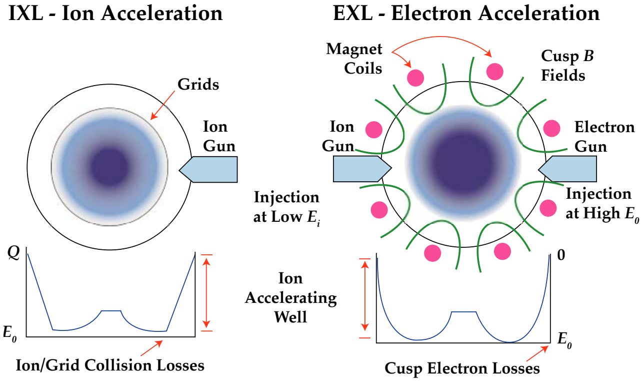


Figure 1 — Two basic approaches to IEC fusion: IXL and EXL systems

In contrast, EXL/IEC systems operate with non-neutral plasma conditions throughout the system and have a very large variation of density across the confining region, peaking at the center into a small reacting core, with losses dominated by electron escape through the surface magnetic cusps of the quasi-spherical confinement system. The ions and electrons in EXL systems are never in LTE, and the entire system acts as an energy and momentum transformer, exchanging electron surface injection energy for central potential energy and central ion kinetic energy.

These systems can attain very high total particle densities while maintaining deep potential wells with only trivial deviation from net-average neutrality. An elementary application of Poisson's equation shows that a charge density difference of only ~$10^6/cm^3$ *is sufficient for a 100-keV well depth on a 1-m sphere; thus, a system with net-average density of, e.g.,* $10^{12}/cm^3$ *(and central core density up to* $10^{18}/cm^3$*) will be only* 10^{-6} *deviant from neutrality. The fusion power is, of course, determined by the total density, not the unneutralized charge density.*

It is well known[12] that the confining mechanism that allows fusion power production in MM/LTE systems is simply that of magnetic pressure confining the LTE plasma ions. It is equally true,[13] though less well known, that this same confining mechanism limits EXL system power generation by limiting the electron surface density to the magnetic beta-limit condition. For these two approaches, the magnetic pressure balance becomes:

$$\text{MM/LTE: } \beta_i B_i^2 = n_i E_i$$

and

$$\text{EXL/IEC: } \beta_e B_e^2 = n_e E_e \quad (1)$$

where the subscripts i and e refer to ions and electrons, respectively. For power generation in both systems, the controlling ion density is that at the device center, where $n_i \approx n_c$. In the MM/LTE system, this is given directly by (1), with B, E, and n taken at the core. However, the energy-conserving spherically convergent flow of ions and electrons in the EXL system gives a peaking of ion (and electron) density toward the center, generally according to $n_c \approx n_e (R/r_c)^2 = n_e/<r_c>^2$, where r_c is the minimum radius of convergence, set by conservation of ion transverse momentum in the flow. Thus, we have:

$$\text{MM/LTE: } n_c \approx \beta_i B_i^2 / E_i$$

and

$$\text{EXL/IEC: } n_c \approx \beta_e B_e^2 \ / <r_c>^2 E_e \quad (2)$$

Figure 2 shows a comparison of typical particle and energy distributions in these two systems and some numerical values for typical densities. Note that the MM/LTE system shows a quasi-parabolic diffusive density distribution for both mean energy E_m and reactive tail energy E_o, while the EXL/IEC system exhibits geometric convergence at least as fast as $1/r^2$. Since the fusion reaction rate density is $q_f = b_{ij} n_c^2 \sigma(E) v(E)$, the total fusion power generation is given by $P_f = E_f \int q_f(E)\, d^3 r$. For systems operating on the same fuels at effective reaction energies E_o such that the reactivity $<\sigma v> = (\sigma v)$ is the same in both systems, the relative fusion power production of both systems becomes proportional only to the square of the core region ion density n_c and the active volume V_c. In the MM/LTE system, this may occupy the order of half of the radial extent of the plasma system. If a spherical system is assumed (for convenience), the MM core volume is then $V_c \propto (R/2)^3 = R^3/8$. In the EXL system, the reacting volume is small; thus, $V_c \propto r_c^3 = <r_c>^3 R^3$. With these scalings, the relative fusion power outputs become:

$$MM : P_f \propto \frac{n_c^2 R^3}{8} \propto \frac{\beta_i^2 B_i^4 R^3}{8} \quad (3a)$$

and

$$EXL : P_f \propto n_c^2 R^3 < r_c >^3 \propto \frac{\beta_e^2 B_e^4 R^3}{< r_c >} \quad (3b)$$

For operation assuming the same values of magnetic beta and system power for the two approaches, it is immediately evident that the EXL system requires much smaller B fields and/or sizes, by the factor $(B^4R^3)_e/(B^4R^3)_i = <r_c>/8$, than does the MM system.

In fact, the magnetic beta attainable for ion confinement in MM systems is generally much less than unity; typically, $\beta_i \approx 0.15$ is hoped to be achieved in large tokamak MM systems. In contrast, the confinement of electrons (not neutral plasma) at modest density (as characteristic at the EXL system edge) is readily able to reach unity beta; thus, $\beta_e \approx 1$ is typical. By using these in Eqs. (3a) and (3b) for equal fusion power, $P_f(\text{MM}) = P_f(\text{EXL})$ gives:

$$B_e^4 R^3 \big|_{EXL} = \left(\frac{\beta_i \langle r_c \rangle}{8 B_e}\right) B_i^4 R^3 \big|_{MM}$$

$$\approx \left(\frac{\langle r_c \rangle}{50}\right) B_i^4 R^3 \big|_{MM} \quad (4)$$

Early experiments achieved $<r_c> = 0.02$ in small IEC systems with limited precision of construction.[14] Convergence ratios of 0.003 to 0.01 are expected to be attained in well-constructed larger systems. By taking $<r_c> = 3.33 \times 10^{-3}$ as an example, (4) gives:

$$B_e^4 R^3 \big|_{EXL} = 6.67 x 10^{-5}\, B_i^4 R^3 \big|_{MM} \quad (5)$$

Thus, for systems of equal size, the relative magnetic field strengths would be $B_e(\text{EXL}) \approx 0.090 B_i(\text{MM})$. Since the cost of B fields varies about as B^2R^3, EXL/IEC systems might be very much less costly than MM/LTE systems, \$(EXL)/\$(MM) ≈ 0.008.

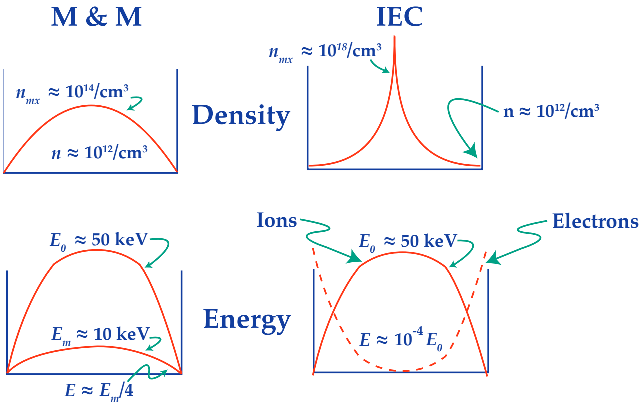
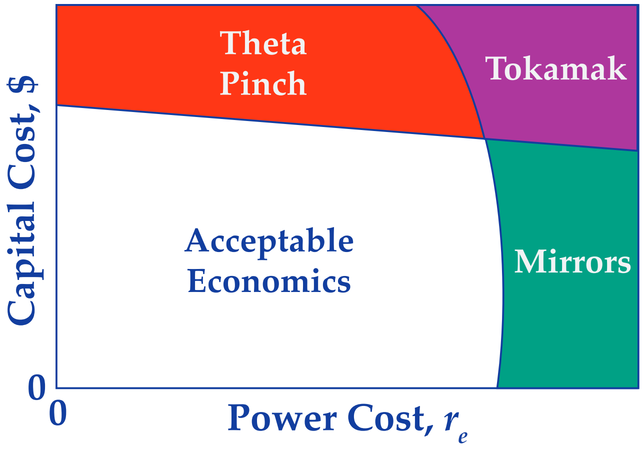


Figure 2 — Comparative spatial distribution of particle densities and energy; note strong peaking and non-LTE distribution in IEC system and weak variation in MM system; *Em* is mean energy of Maxwellian distribution while *Eo* is effective reaction energy

These results are inherent in the difference between these two approaches. The MM system uses magnetic field pressure to confine neutral plasmas whose loss rates are governed by ion momentum, while the EXL system confines electrons in the edge region against electron radial momentum. This basic momentum balance (i.e., particle kinetic compared with magnetic field pressure) is reflected in the relative magnetic pressures required for each system. Taking $\beta \approx 0.15$ and $B \approx 20$ T as typical for reactor versions of MM tokamaks, gives $\beta B^2 \approx 60$; for EXL reactors, fields are typically $B \approx 1$ T, giving $\beta B^2 \approx 1$. The ratio of these is 60, approximately the same as the square root of the ratio of electron-to-fusion fuel ion mass; confining electrons alone is simply much easier than ions in a neutral plasma. Because of this, the EXL/IEC approach requires inherently much lower technology levels in reactor embodiments than does the MM/LTE approach. And, as a result, the costs and time scales of R&D for development to power reactor status are likewise greatly reduced relative to those for MM/LTE systems. This is discussed further in Section IV.

III. Economic Scaling of FPS Systems

For our purposes here, the cost of power can be broken into two major elements: that of the fusion power source (FPS) system and that of the balance-of-plant (BOP) systems that receive the fusion source power and convert it to output electricity on a utility grid. For fusion systems that produce hot working fluids (e.g., steam), the BOP systems are comparable in cost for nearly all FPS concepts (i.e., steam is steam whether it comes from coal, oil, or fusion-fired boilers); thus, their cost will be roughly the same for the same thermal power processed. The variability in cost among fusion power plant concepts arises from the variation in costs of differing FPS systems. Quite obviously, very large, radioactive, remotely operated fusion systems with low duty factors will cost much more (per unit power) than will small systems (of comparable power) without these negative characteristics. These evident facts can be quantified by the use of algorithms relating design and performance parameters to the economics of FPS systems.



$\$_{\mathrm{cap}} = K_{cap} R^3$, $K_{cap} = \$\mathrm{M/m^3}$, $P_e = K_p \Phi_w R^2 \eta_c$, $K_p = 8 - 12$
R = system size, m; Φ_w = wall power flux, MW/m^2
P_e = electric power output, MWe; η_c = conversion efficiency

Figure 3 — Fusion power source economic scaling: capital cost and electric power output for theta pinches, tokamaks, and mirrors, in economics phase-space

Such a simple analysis was made nearly 20 years ago under the sponsorship of the Controlled Thermonuclear Research Division of the U.S. Atomic Energy Commission.[15] This was based on the concept of an economic phase-space in which all FPS systems could be portrayed by their contribution to the rate cost of power [r_e, mill/kW(electric) • hour) and their installed capital cost ($\$_{cap}$, dollars). Clearly, a power source system is unattractive if either:

a) Its installed capital cost is too large, no matter how low its rate charge.

b) Its contribution to power cost rates is too high, no matter how low its capital cost.

These boundaries are shown in the economic phase-space of Figure 3. Also noted on Figure 3 are the relative positions of the economic failure modes of the three principal approaches studied (in 1975) for MM/LTE fusion: toroidal theta-pinch machines, mirror machines, and tokamaks. In this work, it was shown[15] that use of hybrid (fission) blankets as power multipliers around mirror and theta-pinch fusion sources could improve their system economic performance but that this would not work for low-beta tokamaks; these simply had to become smaller for acceptable economics.

The capital cost and electric power production capability of any FPS can be written as shown in the equations at the bottom of Figure 3. These parameters are dominated by the first-wall power flux Φ_w (MW/m^2) and associated fast neutron flux $\Phi_{fn} = \Phi_w f_n$, the allowable neutron dose D_{fn} (MW$_{fn}$ • year/m^2), first-wall materials lifetime $\tau(\mathrm{year}) = D_{fn}/\Phi_{fn}$, the power conversion efficiency η_c, and the system size $R(m)$. It is convenient to define an allowable first-wall fusion power fluence $D_w = D_{fn}/f_n$. Here, the coefficients depend on the choice of materials (e.g., superconductors compared with normal magnets) and on the details of the FPS system (e.g., ohmic compared with radio-frequency heating compared with neutral beam injection drives, etc). The numerical values given are crudely representative of superconducting magnet systems.

For systems of equal electric power output, these reduce to the formulas shown in Figure 4, which include a plant utilization factor f_u Both forms of the Figure 4 equation show clearly that the dominant factors are system size R, return on investment (ROI), first-wall flux Φ_w, and allowable first-wall fluence D_w. If ROI is taken as near-zero (as is often conceived in government projects), the first-wall fluence limit alone sets allowable size. In a realistic economic world, the ROI/Φ_w term is dominant, and size alone is the cost determinant.

Fusion Power Core Economic Scaling - II

$$r_e = \left(\frac{K_{cap}R}{K_p\eta_c}\right)\left(\frac{10^6}{8760 f_u}\right)\left(\frac{ROI}{\phi_w}+\frac{1}{D_w}\right)$$

$$r_e = \left(\frac{R}{D_w}\right)\left(ROI\,\tau_w + 1\right)\left(\frac{10^6 (K_{cap}/K_p)}{8760 f_u \eta_c}\right)$$

r_e = mills/kw$_e$ hour, f_u = use fraction,
D_w = damage fluence,
ROI = return on investment/year
τ_w = first wall lifetime = D_w / Φ_w

Figure 4 — Fusion power source economic scaling; basic rate cost algorithms for fusion systems

Two examples serve to illustrate the problem. Consider two systems of equal power but of differing size. One with R = 8 m and one with R = 1 m. The materials dose limit is taken the same for both systems at D_w = 12 MW • year/m^2 [assumes deuterium-tritium (DT) fuel], and a return on investment of 0.25/year is assumed. The small system is assumed to have a tenfold higher first-wall flux and a somewhat larger use factor (0.9 compared with 0.7) than the large system, but it is penalized by a two times lower conversion efficiency (0.2 compared with 0.4). For these conditions, it is evident that costs of the small system are about one-eighth those of the large one, provided that it is driven at the assumed large first-wall flux. These examples are summarized in Figure 5.

Fusion Power Core Economic Scaling - III

Examples: for ROI = 0.25, D_w = 12 MW year/m^2	
R = 1.0 m	R = 8.0 m
f_u = 0.9	f_u = 0.7
η_c = 0.2	η_c = 0.4
Φ_w = 40 MW/m^2	Φ_w = 4 MW/m^2
r_e = 14.2 mills/kW$_e$ hour	r_e = 118.9 mills/kW$_e$ hour
Exclusive of Balance of Plant	

Figure 5 — Fusion power source economic scaling; examples of rate cost contribution of FPS from high-power density, small system via-a-vis low-power density, large system

These examples assume the use of DT, with only 20% of its power as thermal wall load; thus, they require only 8 MW(thermal)/m^2 for the small FPS system, which is well below acceptable heat transfer limits. In fact, studies made nearly 20 years ago[16,17] as part of the thermonuclear fusion program work at the Lawrence Livermore National Laboratory (LLNL) showed that first-wall thermal fluxes of 33 to 42 MW(thermal)/m^2 would be feasible with proper materials and design. Within these limits, the general result of these simple scalings is quite clear: Large systems are not as economically practical as small systems, on grounds of power costs alone.

These simple scaling law arguments are supported by highly detailed design studies [10,11] and related economic analyses, carried out as part of the ARIES tokamak studies. A recent survey[18] of these studies compared all of the most advanced current concepts of large tokamaks with each other and with other alternative sources of power and concludes that even though "... *physics 'miracles' and advanced technology* ..." are required, they are all still "... *marginal or far from economic competitiveness* ..." as compared with energy costs from coal, oil, gas, or nuclear plants. Indeed, Hirsch,[19,20] on behalf of the Electric Power Research Institute (EPRI), has noted that the utilities have little interest in large DT tokamak machines and would prefer systems that are smaller, cleaner, and with potentially much less cost. More recently, studies concluded by Perkins et al.[21] at LLNL show the economic problems of ITER (and other large tokamaks) compared with pressurized water reactor (PWR) fission systems and other alternatives and also focus on the need for a new fusion power approach that offers the virtues sought by the utilities (EPRI, above).

Clearly, the successful attainment of useful and practical fusion power will be greatly aided by the development of a concept that can, if successful, be brought to fruition at a small size, at modest cost, and in a short time with the potential for operation on clean fuels such as the ^{3}He-catalyzed deuterium-deuterium (DD) cycles or on p-^{11}B, and that, by its nature, can be developed along a rational R&D path to prototype power systems, without vast scalings in experimental system size. The very nature of the IEC approach offers just such promise for EXL/IEC systems.

IV. EXL/IEC: Physics Limits, Power Generation, and System Development

The general nature of the EXL/IEC system has been studied since 1986 by phenomenological modeling, theoretical analysis, numerical simulations, and small-scale experiments. Work to date has shown ever greater promise for success, no physics roadblocks have yet been found, critical issues have been defined, and some key phenomena have been verified to the limits of the studies. From this work, three main first-order physics questions have been identified that must be answered for proof-of-concept feasibility:

1. Can ion core convergence be preserved?
2. Can collisional thermalization be avoided while still achieving net power output?
3. Can electron losses be kept to those through surface cusps, by induced diamagnetic electron currents?

When these issues are considered, one must remember that the ion-electron population is everywhere quite different from the conventional conception of a fusion plasma. Ions are injected inside the machine radius, with a spatially isotropic energy of only one to a few electron volts. They fall down into an electrostatic potential well maintained by continuous injection of electrons at high energy. The net-average electron-ion density difference sets the well depth (not the density of electrons alone, as assumed in Reference 1). Electrons are injected with modest transverse energy through the cusp axes of the confining magnetic surface fields. These are arranged so that there are no line cusps in the system; all are single polar cusps. The electrons lose energy rapidly to the buildup of internal potential structure and quickly isotropize spatially (e.g., by electron/electrostatic wave collisions).

The ions accelerate in the well until they gain most of the well energy. From this point on (to the center), they drag electrons from the low-energy internal population into a slightly positive central core region. The height of this virtual central anode is controllable by adjustment of the relative ion and electron currents into the machine. The ions recirculate through the well until they make a fusion event or until they are upscattered to such a degree that they are captured by low-energy ion-limiters placed outside the ion injection region. These limiters are magnetically insulated against electron impact. The electrons recirculate until they are lost by escape to the external walls past the cusps or until they are significantly upscattered by collisions in the dense core regions. Collisional upscattering of either specie is greatly inhibited by the small fractional dwell time each spends in the dense collisional core region.

Collisional scattering is a distributed effect while fusion is a single-event process; thus, the ratio of fusion to upscattering (for a given ion) is larger than in LTE systems by the inverse of the fractional dwell time. It is this factor, of order 100 to 1000, that makes the EXL system possible; fusion can occur before thermalization.

The electron current flow and ion current flow are not correlated by any confinement physics. The power loss of the system is set by the electron loss, while the power generation is determined by the central ion density. This must be approximately equal to (slightly greater than) the central electron density. The electron loss rate is determined by the area of the cusp loss holes and the density of electrons in the edge region, as fixed by Poisson's equation in the diamagnetically compressed surface B field that provides the cusp confinement. Electron losses due to cross-field diffusion are negligible compared with the cusp loss rate, at the density, field, and size conditions of interest for power generation, although this process can have an influence on the size of the cusp loss hole.

Nearly all fusions take place within one or two core radii of the central core. The mean free path for fusion product interaction with the core region ions is very much larger than the core size, so much so that the interaction probability is $< 10^{-9}$. Thus, the fusion products cannot deposit their energy in the core or in the confined volume. They will escape directly, radially through or to the boundary of the confinement region, and they escape with the energy of their formation and do not thermalize as in LTE machines. This has the disadvantage that all bremsstrahlung losses must be made up by electron injection energy, not by fusion product energy. But, it has the advantage that the charged particle fusion products can be readily direct-converted outside the confinement region by the imposition of externally biased grids or collector surfaces.

The external magnetic fields inherent in the use of the confining surface polyhedral field system are sufficient to suppress electron arcing across such an external direct convertor region. Direct conversion of charged fusion products that have relatively fixed energy is possible, in principle, at very high efficiency — up to 95+%. The inefficiency arises from direct collision losses with structure and from the energy spread associated with the potential well depth. For DT (an undesirable fuel), the well depth need be only 5 to 25 keV, while the charged-particle energy is 3.5 MeV; for other fuels, the optimal well depth will be larger, but even p-^{11}B needs only 60 to 65 keV to operate at low gain near its unique fusion cross-section resonance at 58 keV, or at 180 to 220 keV for very high output and gain.

These features are also a direct result of the low bulk collisionality in EXL/IEC systems that ensures the non-equilibrium and monoenergeticity of the ion and electron particle distributions. Because of this, such systems possess yet another advantage: They can be designed to operate with all of the reacting particles at the energy desired for maximum power gain. The kinetic energy distribution function of ions in EXL/IEC systems is single-valued at any given radial position; electrons are similarly single-valued in energy but are essentially spatially isotropic at all radii. The ions are spatially isotropic only in the core region and at the radius of their injection into the system. This ion edge region must, of course, be sufficiently within the physical edge of the electron-confining B field that local $\boldsymbol{V} \boldsymbol{x} \boldsymbol{B}$ deflection of the ions does not spread the core convergence beyond its natural limit due to transverse momentum inherent in the injection process.

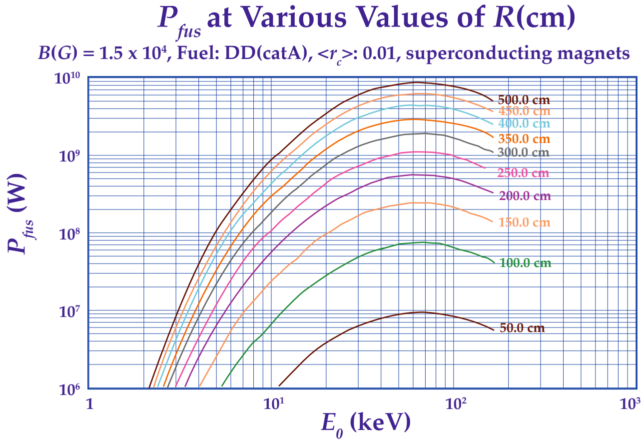


Figure 6a — Gross Fusion Power Output (fusion-drive power ratio) for DD-catA system

Transverse momentum will be added to the ions by ion-ion collisions in their radial counterflow in the mantle region (i.e., between core and edge) in every pass through the mantle. However, analysis[8] shows that this is not a problem because edge region collisionality anneals out all anisotropy (from this or any other source) in each pass. Edge region ion energy is so low (a few electron volts) that the ion-ion Coulomb cross section is sufficiently large to ensure such isotropization in each edge reflection in the combined electric potential gradient and surface magnetic field. This prevents growth of the momentum-limited converged core and preserves the system power output and gain.

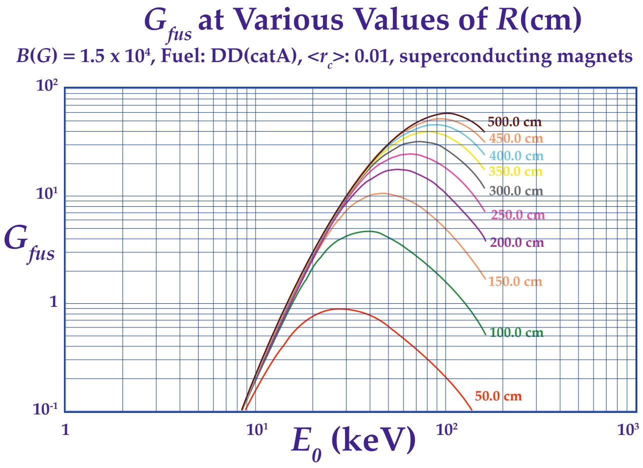
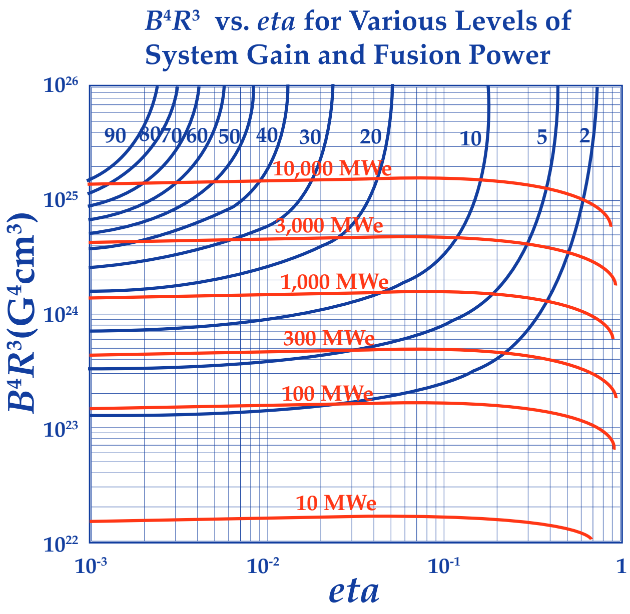


Figure 6b — Gross Fusion Power Gain (fusion-drive power ratio) for DD-catA system

All of these features and characteristics have been used as the basis for a power balance computer code for EXL system studies. This PBAL code[22] also includes bremsstrahlung losses, ohmic power for normal conductor magnets, neutron heating of superconductor magnets and power losses for cryogenic cooling systems, thermal and direct conversion efficiencies, and a variety of features associated with the diamagnetic behavior of the electrons in the cusp *B* fields. Power balance runs have been made over a wide range of machine parameters for a variety of fusion fuels, DT, DD, ^{3}He catalyzed-D, D^{3}He, ^{3}He^{3}He, ^{6}Li^{6}Li (catalyzed by p, ^{3}He), and p-^{11}B. All can be made to give net electrical power with thermal conversion systems, with reasonable sizes and B fields; direct conversion gives still higher performance for all systems.



Conditions — Fuel: DD(catA), <r_c> = 0.01, *m* = 9.94, *kl* = 2, *f2* = = 0.084, *alphar* = 0, *alphag* = 0.9, *GMG* = 1, *GICC* = 1, f_{perp} = 0.3, E_o = 100, *etac* = 1, *etadc* = 0, *N* = 8, *Ng* = 8

Figure 7 — Magnetic energy parameter MEP = 84 R3, for DD-catA cycle, for conditions given

Some of the most promising fuel cycles for central station power production appear to be the catalyzed DD cycles, which use the ^{3}He generated to react with another deuterium and the tritium generated to decay to ^{3}He for still another D^{3}He reaction. Study of these cycles,[23,24] called the DD-catA and DD-catB cycles, has shown that it is possible to conduct power system development by using hydrogen, hydrogen-diluted deuterium, and (later) externally supplied ^{3}He with deuterium, to reach the catA or catB power system regime, all with the same size, *B* field, and drive power for the experimental development machine. An example of the fusion power generation and fusion power gain (fusion-drive power ratio) from a system using the DD-catA cycle is given in Figure 6, while parametric studies shown in Figure 7 give the range of magnetic energy parameter MEP = B^4R^3 required as a function of the central virtual anode height, for various fusion power and gain values in this system. From this and related studies, the device size and field to test the full range of fuel mixtures is found to be $R \approx 2.5$ to 3.0 m, $B \approx 12$ to 15 kG (1.2 to 1.5 T), with steady-state drive power in the range of 100 to 200 MW(electric).

Since these devices are all steady state, not pulsed, the conduct of research and development is straightforward; operation is made under operator control, with full adjustment of drive power, voltage, ion and electron current inputs, and *B* field strength, to map out the performance parameter space in a continuous fashion — just as in any other normal power system development. Because of these features, the cost and time scale for development, assuming success of the basic classical physics, can be estimated with reasonable accuracy once the size, field, and drive conditions of the system are known. Such estimates have been made for time and cost schedules for a program to develop the cat A-cycle EXL system to a full-scale power plant prototype, by using the sizes and fields (above) found in these studies. Figure 8 summarizes this approach and shows this program.

- The first task is to start with DD, prove the fusion physics, stability under burn, and develop device/system controls.
- The second task is to switch to D + Variable ^{3}He and simulate catA, catB cycles. Use ^{3}He from stockpile source and the same machine used in DD task one.
- The machine would have $R \sim 2.5$-3.0 m, $B_o \sim 12$-15 kG, $E_o \sim 100$ keV, $P_{drive} \sim 200$ MWe @ I 2000 A

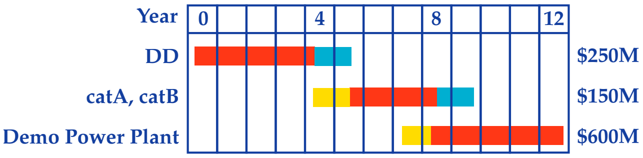


Figure 8 — Practical fusion power development; DD-catA cycle to power plant status in < 12 years at < $1B

At its conclusion, the next step would be commercial plant deployment: the use of EXL/catA to drive a conventional steam turbine-generator power system for electricity production. Because of the small size and cost of the basic EXL/IEC FPS system, this plant could make power at less cost than from any other energy source. Such a system would have only ~0.05 of the specific neutron energy output of a DT device and would be comparable to that of a PWR but without any residual fission products.

Following this path of development, practical and safe commercial fusion power could be achieved by 2006-2010 if the basic physics proves successful. It is important to note that the proof-of-feasibility point will be reached at the early DD level of testing, long before the bulk of the program funds are expended. The promise of this approach would seem to warrant attention to and support of research into its defining basic physics to see if its potential advantages can be realized. If so, IEC systems could provide an early useful fusion power option against the eventual lack of an economic supply of conventional fuels.

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