Design Considerations for Clean QED Fusion Propulsion Systems

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Abstract

The direct production of electric power appears possible from fusion reactions between fuels whose products consist solely of charged particles and thus do not present radiation hazards from energetic neutron production, as do reactions involving deuteron-bearing fuels. Among these are the fuels $p^{11}B$, ^{3}He, and ^{6}Li. All of these can be "burned" in inertial-electrostatic-fusion (IEF) devices to power QED fusion-electric rocket engines. These IEF sources provide direct-converted electrical power at high voltage (MeV) to drive e-beams for efficient propellant heating to extreme temperatures, with resulting high specific impulse performance capabilities. IEF/QED engine systems using $p^{11}B$ can outperform all other advanced concepts for controlled fusion propulsion by 2-3 orders of magnitude, while $^{6}Li^{6}Li$ fusion yields one order of magnitude less advance. Either of these fusion rocket propulsion systems can provide very rapid transit for solar system missions, with high payload fractions in single-stage vehicles. The $^{3}He^{3}He$ reaction can not be used practically for direct electric conversion because of the wide spread in energy of its fusion products. However, it may eventually prove useful for thermal/electrical power generation in central station power plants, or for direct-fusion-product (DFP) propellant heating in advanced deep-space rocket engines.

The OED Engine System and IEF Power Sources

Clean fusion fuels can be "burned" in inertial-electrostatic-fusion (IEF) devices of the type previously described[1,2] as the power source for QED rocket engines. In these, the IEF sources provide direct-converted electrical power at high voltage (MeV) to drive quasi-relativisitic e-beams (reb) for 100%-efficient propellant heating to extreme temperatures, giving high specific impulse performance from subsequent nozzle expansion. Figure 1 shows an outline of an all-regeneratively-cooled (ARC) IEF/QED engine system.

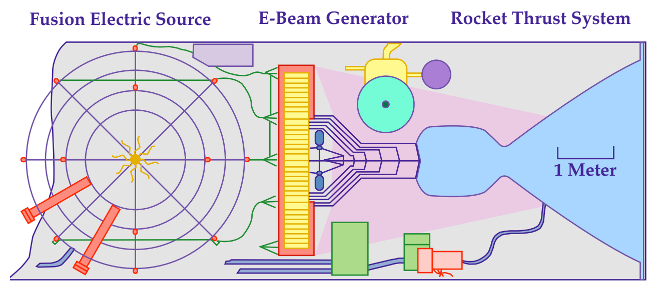

Figure 1 — Schematic Outline of ARC/QED Engine System, Showing IEF Fusion-Electric Source, Electrical Subsystem including REB e-Beam Generator, and Rocket Thrust System

The IEF fusion-electric source systems of interest here all use quasi-spherically-symmetric magnetic fields to confine electrons which are injected at high energy E_o, so as to form a negative electric potential well that can confine fusion ions in spherically-converging flow. Figure 2 shows a schematic diagram of this electron acceleration (EXL) IEF system. Fusion ions are inserted into the well near its boundary R, so that they "fall" towards the center and oscillate across the machine, with density increasing rapidly ($1/r^2$) towards the center. Their injection rate is controlled (relative to electron drive current) so that their core energy reaches the specified central virtual anode height $\eta = \delta E_o$ desired for system operation. They reach maximum density at a core radius set by the ratio of their initial transverse energy $dE_\perp$ at injection, to their energy $E_c = (1-\eta) E_o$ at the core boundary r_o, as given by $< r_c > = r_c/R = (dE_\perp/E_o)^{0.5}$. Typical ion core convergence ratios are $0.001 < < r_c > < 0.01$, which yield core ion density increases 1E4-1E6 above the minimum ion density near the edge of the polyhedral magnetic surface.

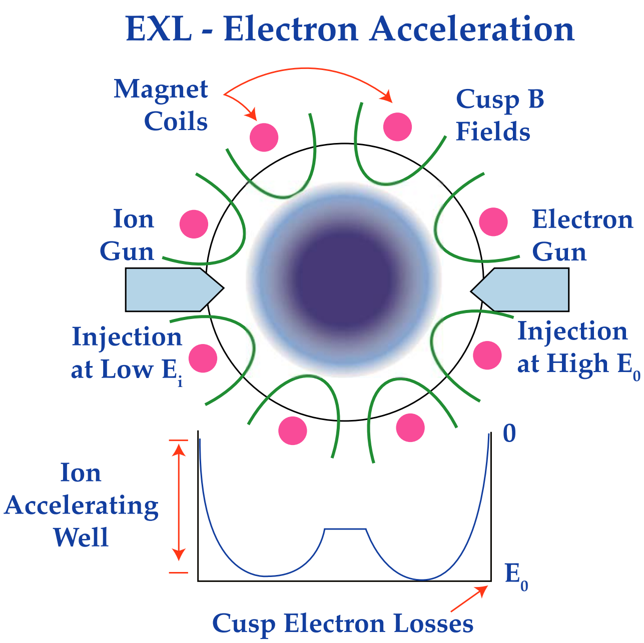

Figure 2 — EXL/IEF System: Spherically-Convergent Ion Flow by Electric Field Gradients in Electron-Driven Negative Potential Well, supported by Quasi-Spherical External Polyhedral Magnetic Fields

Clean Fusion Reaction Characteristics

The direct production of electric power at modest currents and high voltages appears possible from fusion reactions between selected types of fusionable fuels whose fusion products consist solely of charged particles. These reactions are free from the direct radiation hazards of energetic neutrons, which always characterize reactions involving deuteron-bearing mixtures. Among these clean fuels are those involving p, ^{11}B, ^{3}He, and ^{6}Li, reacting according to:

$p + 11B \rightarrow\ ^4He$	(8.68 MeV)	(1)
$^3He + {}^3He \rightarrow\ ^4He + 2p$	(12.9 MeV)	(2)
$p + {}^6Li \rightarrow\ ^4He + {}^3He$	(4.0 MeV)	(3a)
$^3He + {}^6Li \rightarrow 2\ ^4He + p$	(16.9 MeV)	(3b)
$^6Li + {}^6Li \rightarrow 3\ ^4He$	(20.9 MeV)	(3)

The three fusion reactions given above can each be used to produce electric power directly in such IEF devices, by causing the electrically-charged fusion product ions to move against an externally imposed radial electric potential as travel away from their birth point in the core region. Collection of these particles is made, as they approach zero kinetic energy, by grids or plates placed at appropriate radial positions along the particle expansion path. These collectors are connected to the electrical circuit in which current is driven through the system external load.

In this direct conversion system (DCS) the easiest fusion reaction products to direct-convert are those of 1. Here the fusion product alphas are found at relatively well-determined energies, because of the nature of the decay process of the ^{8}Be resulting from fission of the excited state ^{12}C produced in the fusion process; these energies are roughly 2.46 MeV and 3.76 MeV. Since the alphas are all charged to $Z = 2$, their deceleration by electric fields requires a retarding potential of only 1.88 MeV, plus the product energy spread, at most. This can be sustained by spherically symmetric grids located at 0.5-1m outside of the IEF ion-confining region. Thus, complete direct conversion ^{11}B IEF systems need be only about 1-2m larger in diameter than the size required for producing the controlled fusion process, itself.

The third reaction proceeds in two stages, requiring recycle of the ^{3}He produced in (3a) as a fuel for (3b). The charged particle products that go to make up this fusion chain each have relatively well-defined energies, again a result of the finite lifetime of the ^{8}Be produced as the precursor of the two alpha products of reaction (3b). The energy of these products is 1.7 MeV for the alpha particle from (3a), 1.9 MeV for the alphas from (3b), 2.3 MeV for the ^{3}He in (3a), and 15.0 MeV for the proton from (3b).

Of these, difficulties arise only in the case of the very energetic proton. This is because its energy is high and its charge is only $Z = 1$, thus a decelerating potential of 15.0 MeV must be provided. The DCS grid/collector spacing required for this level of standoff will be about 7-8 times larger than that required for the p^{11}B system. Thus, direct convertor IEF sources using this fuel will always be large in size. However, this does not mean that they must be excessively massive. because the interior of the IEF and the DCS is essentially free of structure; it is a good vacuum. The mass of such systems varies roughly as their surface area, not as their volume. This is discussed further, below. For many applications to space flight, the overall size is of much less importance than the mass of the system being considered.

The energy distribution among the reaction products in 2 is very much less well-defined, as the proton energy can range from about 10.7 MeV to nearly zero, with corresponding variation of alpha energy from 1.1 MeV to 6.4 MeV. Here, again, the energetic proton gives the most difficulty in direct conversion. And the spread in energy forces the collection of fusion products over the entire dimension of the decelerating system, thus many collection grids are required. This poses both mechanical and thermal problems considerably worse than those for the two other systems with well-defined fusion product energies. Indeed, the ^{3}He^{3}He system might best be used to drive a diluent/propellant system *directly*, rather than attempt to go through a direct-electric-conversion cycle to produce power for subsequent propellant heating. Such a diluted-fusion-propellant (DFP) system forms the basis for a quasi-interstellar clean fusion propulsion system recently analyzed for rapid flights to the Oart cloud, at 550 A.U.[3]

Vacuum System and Fuel Recycling

All of these IEF sources must be maintained at a (low) desired background pressure (typically 1E7 torr, or less) by a continuously-pumped vacuum system. This will remove both unburned fuel atoms as well as the fusion products, themselves. Since the overall IEF source must be closed to conserve fuels, the vacuum system must also be capable of separating fusion products from unburned fuels, so that unused fuel atoms can be re-injected into the fusion unit. Figure 3 shows a schematic outline of the IEF system, including its vacuum, separation, and waste heat cooling subsystems.

The only exhaust product from such system is ^4He and p (only from reaction 2; that from reactions 3b is reburned in 3a — here the proton is only a nuclear-reaction catalytic agent). Separation of ^4He and p from ^3He and ^{11}B can be accomplished most simply by electromagnetic means, in which ions are deflected through a strong magnetic field, and collected at differing cyclotron radii at 180° from their injection point. The large difference in charge/mass ratio of the four atoms of interest (^{11}B, ^4He, ^3He, and p=^1H) when singly-ionized makes this separation relatively straightforward and efficient. The mass of equipment and drive power required for this function will not dominate the engine system.

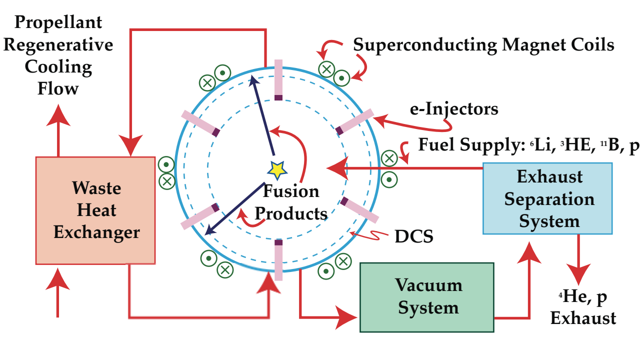

Figure 3 — Schematic Diagram of IEF Source System, showing Vacuum Pumping, Gas Separation, Exhaust and Fuel Atom Recycling, Waste Heat Regenerative Cooling. and Direct Conversion System (DCS) Components

System Thermal Loads and Waste Heat Disposal

The other requirement for IEF source operation is the removal of unavoidable waste heat from the magnet coil containers, the vacuum shell and external structures (such as electron injection guns) of the complete system, and the decelerating grids of the DCS structures. If the magnet coils are inside the vacuum shell the thermal power load on each of these will be due to two sources:

1. Bremsstrahlung from electrons in the fusion core.
2. Direct heating by collision with fusion product ions escaping from the core.

In addition, the external vacuum shell must absorb the thermal load due to collision with the (small) residual energy of fusion ions after passing through the direct convertor system. If the magnet coils are outside the vacuum wall their heat load will be only that of thermal leakage from the external environment, and this can be kept to insignificant levels.

The radiation and collisional loads result from geometric intercept of the relevant energy streams, but the post-convertor wall load depends on the excess energy allowed to the fusion ions after passing through the electrical deceleration portion of the convertor. In design of systems with internal (to the DCS) magnet systems it has been found difficult to reduce the magnet geometric intercept fraction below about 0.05 of the "all-sky" area. If the magnet is external (to the vacuum wall) the DCS grid/collectors will intercept the radiation and particle flux. However, here it seems possible to achieve a grid intercept area fraction as small as 0.025. Thus, depending on the magnet placement, either 5% or 2.5% of the fusion product charged particle power and the core bremsstrahlung power will be incident on the convertor grids and/or coil containers. The vacuum shell must absorb the rest of the bremsstrahlung and all of the unconverted charged particle kinetic power. For those reactions with well-defined product energies (reactions 1 and 3), this latter can be kept to less than 50 keV, limited only by the energy spread introduced by the confining potential well depth, itself.

Finally, electrons must be injected to make up their losses from the EXL fusion system magnetic cusps. The injectors must supply the current needed to operate in the high-beta "wiffle-ball" (WB) electron diamagnetic mode.[4] Required injection current (and electron loss power) is reduced by an e-gun electron reflectance factor of $(1-\alpha_R)$; typically $\alpha_R = 0.9$. This loss power must be taken as waste heat, from cooling of the gun grids and any other internal-limiter structures at the ion confining radius. The *total* electron injection power must also include the bremsstrahlung power which can be supplied only by electron input; in IEF systems fusion energy can *not* drive the bremsstrahlung, as it can in large, equilibrium magnetic confinement machines. Thus, the waste heat power to be handled by the IEF source system includes all of the bremsstrahlung and the WB electron injection power and a small fraction (0.025-0.05) of the fusion product kinetic power. This ignores the power required for the superconducting magnet coil cryogenic system, but this can always be made small relative to other power losses. To estimate heat loads and output performance of such IEF sources, it is necessary to determine the gross fusion power, gross electric: gain (G_{gr}), net electric: power output (P_{net}), drive power and bremsstrahlung power for their operation. A complex power balance code (PBAL) has been developed for such parametric analyses. Figures 4, 5, and 6 show performance of EXL systems for the clean reactions, above, using superconducting magnets, with α_R = 0.9, virtual anode height fraction η = 0.001, ion core convergence ratio $\langle r_c \rangle$ = 0.0015, no thermal conversion, and DCS conversion efficiency η_{dc} = 0.94. These show (G_{gr}) and (P_{net}) as a function of (E_o) for various system radii, for the given B fields.

As an example consider a $p^{11}B$ source with an active (fusion-ion-confining) radius of R = 25 m; driven by electron injection at 200 keV, operated with ion convergence ratio $\langle r_c \rangle$ = 1.5E-3 at a virtual anode height fraction of η = 1E-3, with a B field of 25 kG (2.5T) at R provided by superconducting magnets. Assume further that the magnets are outside the DCS (this is practx:al only for the small d.c. standoff dimensions that can be used with $p^{11}B$) but that the fast alpha particles collisionally deposit 0.035 of their energy on the internal converter grids; this is equivalent to a geometric grid intercept fraction of 0.236. Finally, for a particle energy spread of ±50 keV from the fusion source and a 25 keV offset in converter voltage bias, the converter efficiency will be 0.974. Then, the complete conversion efficiency of the DCS will be 0.94. There is no thermal conversion, as the waste heat is all taken up in regenerative cooling by external propellant flow. Figure 4 shows that such an IEF device will yield net electric power P_{net} = 9800 MWe at a gross electric: gain of G_{gr} = 42. The drive power is P_{drive} = 239 MWe and the gross fusion power required is P_{gross} = 10,680 MWcp, of which 641 MW strikes the grids or the vacuum shell. The total waste heat load is thus 880 MWth (drive and waste cp power); about 9.0% of the electric power produced.

This system will be limited to a propellant specific impulse of about I_{sp} = 3770 sec for monatomic hydrogen propellant, if baseline regenerative cooling can be run at 2000°K. Higher I_{sp} can be attained only by reducing the waste heat power fraction or by use of auxiliary controlled space radiation of waste heat, to reduce the regenerative cooling power fraction. If the geometric grid intercept fraction can be reduced to 0.0675 and the grid bias to 20 keV (for same particle energy spread), the gross fusion power required becomes 10,318 MWcp and the monatomic H propellant performance limits will rise to I_{sp} = 4920 sec. And, if the grid intercept fraction can be reduced to zero (e.g. by "magnetic insulation"), the propellant performance limit becomes I_{sp} = 13,340 sec with monatomic hydrogen propellant, or I_{sp} = 6471 sec with fully-dissociated ammonia (NH_3). All of these examples avoid the use of (massive) controlled space radiators (CSR), and thus retain the ability to produce high power with very small system mass, giving large thrust/mass ratios [F] relative to other concepts for advanced high I_{sp} performance propulsion systems.

Rocket Engine System Considerations

The [F] actually attainable with use of any of these IEF sources will be determined by the total mass of the complete engine system. Aside from the IEF unit, itself, these are the electrical subsystem including power conditioning and the reb accelerator, and the thrust subsystem including propellant turbopumps, gas supply lines, reb injector, heating chamber, and magnetic insulation and guide coils. These latter may include a dipole magnet acting as an expansion nozzle at the chamber exit. These subsystems will be essentially the same for all IEF fuel choices, and their mass will be relatively independent of the IEF units.

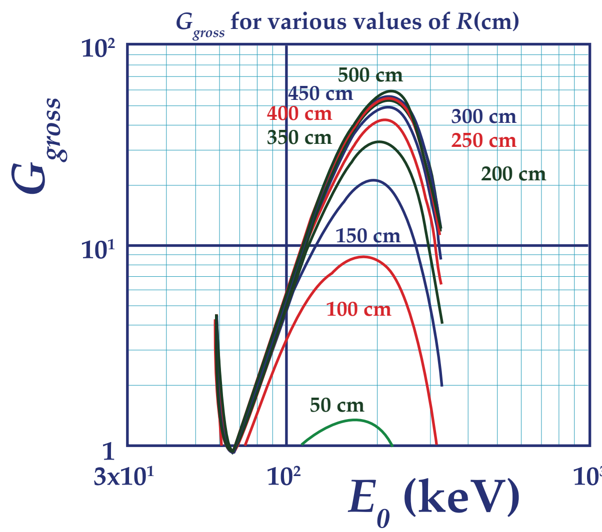

Figure 4a — G_{gross} for IEF System using $p^{11}B$ Fuel at B Field of 25 kG (2.5T)

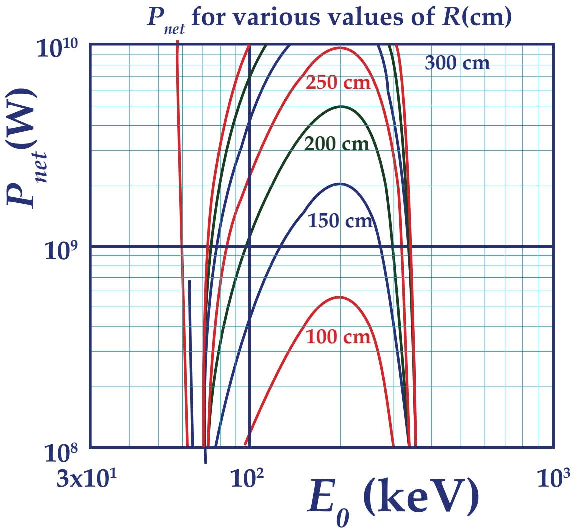

Figure 4b — P_{net}(W) for IEF System using p[11]B Fuel at *B* Field of 25 kG (2.5T)

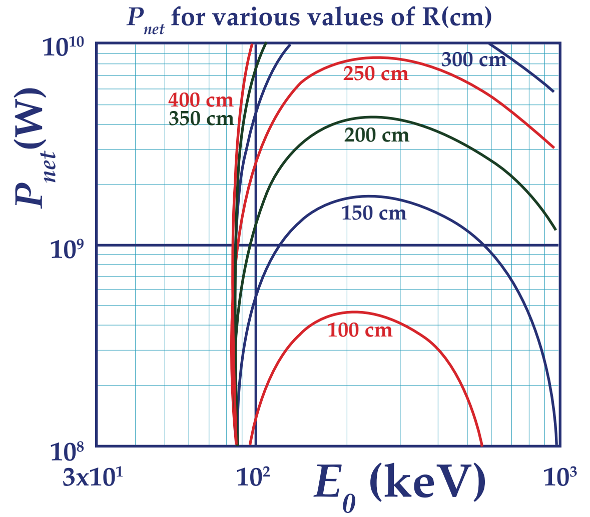

Figure 5b — P_{net}(W) for IEF System using [3]He [3]He Fuel at *B* Field of 45 kG (4.5T)

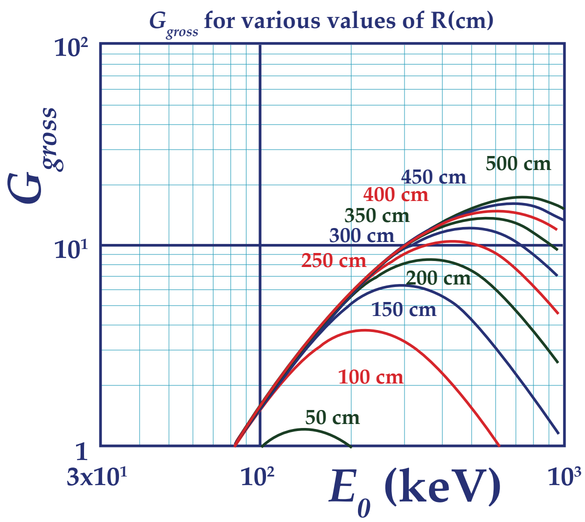

Figure 5a — G_{gross} for IEF System using [3]He [3]He Fuel at *B* Field of 45 kG (4.5T)

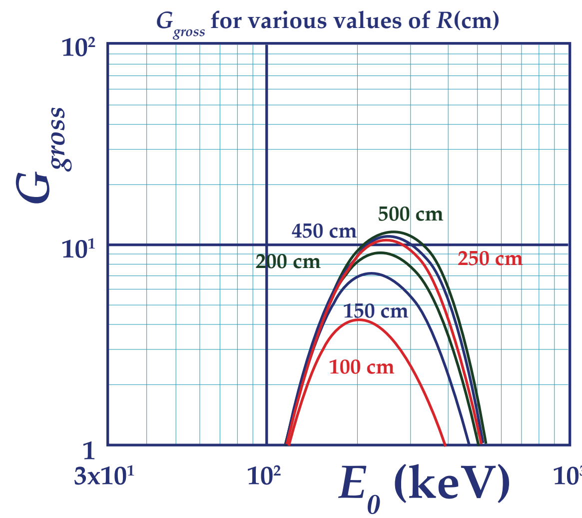

Figure 6a — G_{gross} for IEF System using [6]Li [6]Li Fuel at *B* Field of 35 kG (3.5T)

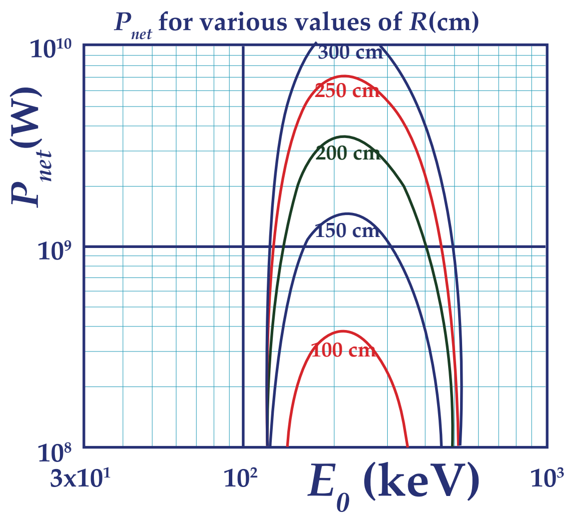

Figure 6b — P_{net}(W) for IEF System using ^6Li ^6Li Fuel at B Field of 35 kG (3.5T)

Estimates have been made previously[1] for the mass of these subsystems as a function of their power-handling capacity for given I_{sp}. These show that their specific mass is roughly in the range of $\alpha \approx$ 1-2 kg/MWe for each subsystem over the parametric range of system power (1000-20,000 MWe) and propellant performance (2000-10.000 sec) of interest. In contrast, the specific mass of an EXL fusion, source unit running on $p^{11}B$ was found to scale approximately as $(\alpha_{fs})_{p11B} = m_{fs}/P_{net} = 3/(P_{net}/2000)^{0.5}$ kg/MWe for net electric power in MWe. Since all clean fuels other than $p^{11}B$ require much larger devices than for $p^{11}B$ (because of voltage standoff dimensional requirements for their much higher charged particle energies) the IEF source unit will tend to dominate the total QED engine system mass for *all* clean fuels.The mass of an IEF unit with its DCS will be determined principally by its outer surface area. This varies as the square of the system radius, $R_s = R_o + (E_{cp}/KZ)$. Here R_o is the ion-confinement radius of the IEF fusion device, E_{cp} is the charged particle kinetic energy that must be converted into electrical energy, Z is the charge of this fusion product, and K is the allowable voltage gradient in the DCS. By analogy with the $p^{11}B$ scaling, above, the IEP fusion source specific mass α_{fs} will then scale crudely as:

$$\alpha_{fs} = \left[\frac{3}{\sqrt{\frac{P_{net}}{2000}}}\right] \frac{\left[R_0 + \frac{E_{cp}}{KZ}\right]^2}{[R_s|_{p^{11}B}]^2} \qquad kg/MW_e \quad (4)$$

Practical experience with high voltage equipment suggests that the maximum practical voltage gradient is limited to about K = 1.5 MeV/m. With this value a system using 15 MeV protons will be 9 times larger in mass than a $p^{11}B$ system of the same total power, if both have an IEF radius of R_o = 3.0 m. Thus, the complete QED engine system for such a fuel choice will be 5-7 times as massive, for the same thrust and propellant specific impulse, as that for $p^{11}B$, and its thrust acceleration capability [F] will be correspondingly less. Such an engine would still operate 1-2 orders of magnitude above performance levels estimated for more conventional fusion power and propulsion systems. For comparison, Figure 7 shows the range of I_{sp} and [F] for various classes of QED engines[3] using $p^{11}B$ IEF sources[5]. The performance of these IEF/QED engines is well within the "high-thrust" regime for interplanetary flights.

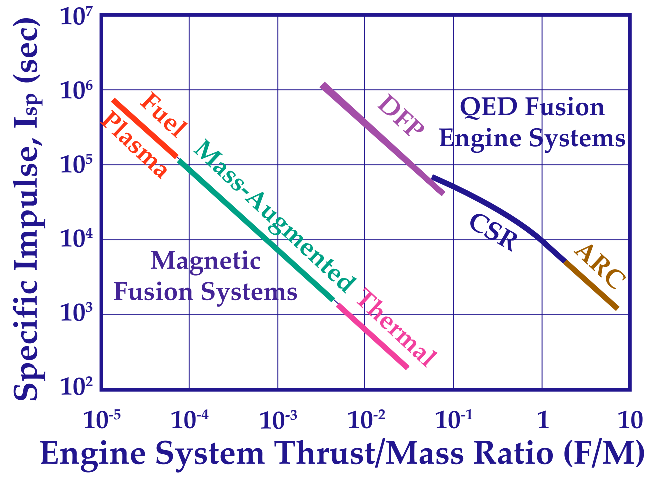

Figure 7 — Comparative Performance of IEF-QED Fusion Engine Systems vs. Magnetic Fusion Propulsion Concepts and Conventional Thermal Exhaust Systems

Conclusions

In conclusion, it is evident that $p^{11}B$ IEF QED engine systems can outperform all other advanced concepts for controlled fusion propulsion by about 2-3 orders of magnitude, while the p-catalyzed $^6Li^6Li$ fusion chain can yield only 1-2 orders of magnitude improvement. Either of these advanced, innovative rocket propulsion systems can provide very rapid transit for solar system missions, with high payload fractions in single-stage vehicles. The $^3He^3He$ reaction seems not practically able to be used for direct electric conversion required by the QED engine concept, because of the very wide and continuous spread in the energy of its charged particle fusion products. However, in a future space economy where space-based ^3He resources may be cheaply available from the Moon or the atmosphere of Jupiter, for example, its use could become practical for electrical power generation with thermal conversion cycles in central station power plants. Alternatively, it might well be employed for direct propellant heating by the energy-distributed fusion products for rocket propulsion in deep space IEF/DFP engines[3].

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