System/Subsystem Engineering Interface Considerations and R&D Requirements for IEF/QED Engine Systems

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Abstract

Extremely advanced space propulsion systems, based on use of inertial-electrostatic-fusion (IEF) light-weight, high power fusion energy sources (FES), use $p\,^{11}B$ reactions for radiation-free production of energetic charged particles. These can be converted directly to electrical power to heat propellant by injection of sub-relativistic e-beams (REB) into propellant in magnetically-insulated thrust (BMT) chamber. This paper presents an examination of engineering interfaces and limits important in each major subsystem of a complete IEF engine system. In the FES, the principal limit is high voltage standoff and arcing; in the REB e-beam transport stability and limits on diode emission are of concern, while main BMT problems include e-beam injection, coupling to propellant plasma, and suppression of plasma-to-structure heat transfer. In the complete QED engine system the principal problem is maintenance of vehicle charge neutrality. Potential engineering solutions for each of these are defined and examined and their limits determined. An R&D program to address and resolve these (and allied) issues has been shown to require about $3-3.5B over 14-17 years, to yield a full-scale prototype QED engine system, at 5000 MWe with $I_{sp} > 2500$ sec at $F \approx 40{,}000$ kgf (400 kN).

The QED Engine System and IEF Fusion 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 fusion-electric-sources (FES) provide direct-converted electrical power at high voltage (MeV) to drive quasi-relativistic e-beams (REB) to heat a propellant working fluid to extreme temperatures. This is accomplished by injection into and expansion from a beam-heated magnetically-insulated thrust (BMT) chamber. Figure 1 shows an outline of an all regeneratively-cooled (ARC) version of such an IEF/QED engine system.

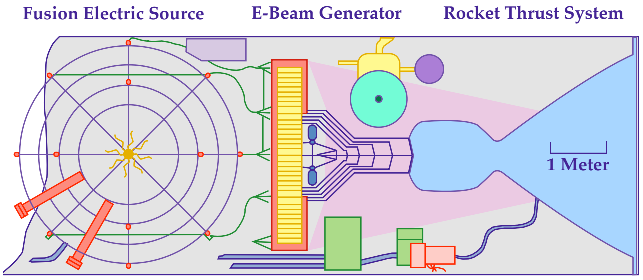

Figure 1 — Schematic Outline of ARC/QED Engine System, Showing IEF Fusion-Electric Source, Electrical Subsystem including REB e-Beam Generator, and BMT Rocket Thrust System

Engineering Interface Issues in QED Engine Systems

These three main subsystems are shown in Figure 1 as they are connected to form the complete QED engine system.

Between each subsystem there is an interface, through which various design parameters and operating phenomena must pass, from one subsystem to the next. In addition, the overall QED engine system is a subsystem within the complete aerospace vehicle that it drives, and it has interface effects with the complete vehicle and the environment through which the vehicle flies. Examination shows that there are eight main interface areas. in which technical issues must be identified and resolved, for the QED engine system to be able to function effectively with high performance. These are listed below for each subsystem/system and their potential solutions are summarized, as follows:

Sub-system	Interface Problem/Issue	Potential Solution
FES	• Internal DCS coil/grid/wall arcing • External high voltage standoff	• Existing IEF B field external to s/c coils, ca. 30-3 kG in-situ • Pressurized SF_6 gas insulation, ca. 4-8 atm. required
REB	• e-beam transport stability • Diode emission limits	• Superimposed axial B field, ca. 2-5 kG required • Superimposed axial B field, ca. 1-3 kG required
BMT	• e-beam injection/window • e-beam coupling to plasma • Plasma/wall heat transfer	• Differentially-pumped vacuum window; dynamic pressure balance • Spatial gradients, helical B fields, or unstable short pulses • Tangential radial inflow, magnetic insulation, ca. 3-7 kG required
QED System	• Positive charge buildup on engine • System from excess electron ejection	• Efficient e-beam energy coupling to BMT fluid/plasma flow • Closure of e-current to vehicle, at low electron energy

These issues/problems and their engineering solutions are examined in this paper, to define details of their features and assess adequacy of the engineering solutions seen for their resolution. From this, R&D requirements, plans and programs can be outlined to test and prove each of these solutions. This has been done and summarized as an R&D "Roadmap" plan for development of prototype full-scale QED engines for HRST/SSTO and other space applications. Results of this R&D plan are given following the analysis presented herein (below) of the eight critical interface issues defined above.

Fusion Electric Source (FES) System

The IEF fusion-electric source (FES) 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. 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 $E_e = (1-\eta)E_o$ at the core boundary r_c, 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.[3,4]

Clean Fusion Reactions and Direct Electric Conversion

The direct production of electric power at modest currents and high voltages is uniquely possible at very high efficiency from fusion reactions between hydrogen (p) and boron-11 (^{11}B). As shown in Eq. 1, this reaction produces only charged alpha particles, thus is free from the direct radiation hazards of energetic neutrons, which always characterize fusion reactions involving deuteron-bearing mixtures. Thus, electric power production by direct conversion is simple, by causing the electrically-charged fusion product ions to move against an externally-imposed radial electric potential as they travel away from their birth point in the core region. Collection of these particles is made as they approach zero kinetic energy, by grids 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.

$$P + {}^{11}B \longrightarrow {}^{12}C \longrightarrow {}^{8}Be + {}^{4}He \quad \text{(Eq. 1)}$$

and 1E-13 sec later, $^{8}Be \longrightarrow 2\ {}^{4}He$ (8.68 MeV)

In this reaction the initial fusion product alpha is emitted at a fixed energy of 3.76 MeV, while the later two follow with 2.46 MeV in the center-of-mass reference frame of their precursor ^{8}Be, moving with 1.88 MeV. Thus, a direct conversion system (DCS) here can convert 42.2% of the alpha energy with near-100% efficiency, leaving the remaining 57.8% to be converted by potential-biased grids spaced to collect the distribution of the final two alphas.

This distribution in the space (laboratory) frame is determined by their relative angle of fission with that of the 1.88 MeV motion of the ^{8}Be. The resulting distribution is spread from 74 keV to 4.846 MeV and peaks strongly at about 3.76 MeV. However, it is important to note that the forward-peaking of this distribution results in 94% of the secondary alpha energy being above 1.24 MeV, thus requiring DCS grids to span only a range of voltage from 0.62 - 2.42 MeV for the $Z = 2$ alphas.

Of course, the external shell and grids must be biased at voltages less than these values by the electrical depth of the potential well, itself, since the alphas produced at the well center must "climb" out of the well to reach the external DCS region. This well-depth climb is not "lost" energy, for the alphas actually supply their energy in this escape path to continue maintenance of the well at its specified depth. As an example, the actual grid voltages for a typical 180 kV deep well (useful for a $p^{11}B$ IEF system) might be from a lower bound at 0.44 MV to an upper potential of 2.24 MV at the outer shell, biased relative to the internal magnet coil system.

This DCS could be formed of concentric spherically-symmetric grids spaced at 150 kV potential drops, giving an average inter-grid energy loss of about 5.2% over the system. Achievable vacuum voltage gradients (ε) have been found to be in the range of $15 < \varepsilon < 50$ kV/cm. Taking 15 kV/cm as readily attainable in the coil/grid/shell system space, requires 12 internal grids spaced at 10 cm intervals over a span of 120 cm outside the IEF ion-confining region, defined by the internal polyhedral magnet coils. The external shell can be another 10 cm beyond this radius. Thus, a complete $p^{11}B$ IEF DCS need be only about 1.30 m larger in radius than the size required for the IEF system to produce the controlled fusion process.

Electron Transport Across the External *B* Field in the DCS

However, electron collisions with the grid and wall structures, driven by these imposed alpha-ion-slowing-down potentials, can create secondary emission from these structures that could lead to internal arcing - even at the conservative potential gradient assumed here. Fortunately, the IEF magnetic coil system, that confirms the potential well-producing electrons, also fills the space external to the fusion region with high *B* fields. These are found to vary about as $1/\langle r\rangle^2$ in the region $\langle r\rangle = (r/R) > 1$ outside the fusion system outer radius at $\langle r\rangle = 1$.

The gyro radius of 1 MeV electrons accelerated by the grid/shell potentials is only about $r_{gyro} = 2.38\ (E)^{0.5}/B \approx 0.08$ cm in the 30 kG (typical) *B* fields needed for $p^{11}B$ IEF systems. This field is reduced to about 3-4 kG at the outer edge of the DCS, thus the outer gyro radius would be $r_{gyro} \approx 1.3$ cm, *if* the electrons could be accelerated to 1.7 MeV at the edge. Since both of these gyro radii are much less than the inter-grid/shell spacings (above), and since electron transport across the *B* field can be only by electron/electron collisions, there is no possibility that such energies can ever be attained by electrons external to the IEF volume (i.e. at $r > R$). Thus the energy of electrons engaged in DCS cross-collisional transport will be limited to that at the IEF edge.

If this is $E_o = 180$ keV, for example, the electron local speed is about 1.5E10 cm/sec. These electrons will be trapped with small gyro radii in the external surface *B* field, and will make many gyro transits before being made to "jump" outward as a result of electron/electron collisions. The number of gyro turns required to reach a path length equal to the Coulomb collisional mean free path then determines the net radial speed of electron transport. This is just the basic electron speed divided by this number of turns per collision.

The electron outward flux is then this speed times the electron average density, and the net outflow current is this flux over the system surface area. Carrying out the analysis shows that net current is given by $I_{net} = 2E\text{-}18(n_e^{\,2}R^2/E^{1.5}B)$ in A/cm^2. This depends on the electron density in the DCS space. This, in turn, can not be greater than the in-situ ion density, by considerations of quasi-charge neutrality.

The ion density is only that due to the fusion product alphas, as all other (background) ions will be swept away by the imposed potentials. And this is fixed by the fusion rate so that the total fusion-driven ion current is simply $I_{ion} = 2.2E18\ P_{MWf}$, giving current in alphas per second from a system with IEF radius $R = 300$ cm operating at fusion power of $P_f = 10{,}000$ MW. With this, knowing the ion energy and system size, the average electron density can be found (as equal to the average ion density) and the net electron collisional current be determined from Eq. 2.

For the example given, this yields a current less than 1E-10 A for cross-field transport, thus internal arcing due to this effect can not be a problem. However, electrons moving outward exactly *along* cusp axes will not "see" significant *B* fields; however these cusp-axis paths can easily be disturbed by grid-produced *B* fields, with proper grid spatial design, so that electrons can not move along them without deflection, and thus can not be accelerated to very large voltages. A small *B* field here essentially will suppress any arcing tendency of the internal electrons, so that the problem of secondary electron emission and arcing cascade can be completely avoided in the DCS.

External Voltage Standoff Outside the FES

Once collected, the energetic ions will support megavoltages in the external electrical system. The external current at these voltages must be transported to the REB directly or to a dc/ac/dc down-conversion system if lower voltages are to be used in the REB. In either case, current must be transported from FES high voltage external conductors to those in the REB system, without arcing.

This can be done with vacuum transport and voltage standoffs, or with systems open to the air. Such devices have been built and are in service on several long-distance 800 kV and megavolt dc transmission lines, but these commercial units are all quite bulky and heavy. Their size and mass can be reduced drastically only if voltage gradients allowed in their internal spaces can be reduced significantly from those allowed for vacuum operation. This can be accomplished by use of SF_6 gas to pressurize the transport spaces.

Voltage breakdown in air at one atmosphere pressure requires typically about 30 kV/cm, about the same as the practical limit for vacuum breakdown in clean systems. SF_6 is a much better dielectric than air, due to its strong electro-negative molecular potentials and its larger collision cross-section for electron/molecule collisions. Use of SF_6 at pressures of 6-10 atmosphere can increase the breakdown voltage gradient by a similar factor, with great reliability, thus permitting reduction in the volume of the electrical system by the square of this factor. Thus, external voltage standoff can be ensured with equipment that is 1/30 to 1/100 the volume of conventional vacuum or air-filled devices. This results in a corresponding reduction in equipment masses. By this means, the high voltage standoff/arcing problem in external circuitry can be handled for the QED engine system.

Sub-Relativistic-Electron-Beam (REB) System

The REB system consists of the FES-supplied voltage/current conversion equipment, and the e-beam accelerator system, including its driving power supplies, up to the point of input of the e-beam into the BMT system. High voltage from the FES is first down-converted (if lower voltages are desired) and current fed to an electron-emitting diode. This is driven by a high voltage extractor to produce the electron stream that the REB system will accelerate to become the uni-directional e-beam to be used for propellant heating.

Two significant problems arise here. First is the ability of the diode to emit sufficient electron current to support the very large powers of the FES supply, and the second is the need to avoid beam instability in the acceleration of the resulting diode electron output.

Emission Limits

Emission of electrons from any surface is limited by the Child-Langmuir law, derived from elementary considerations of potential distributions allowed by Maxwell's equations. The simplest form of this law gives the current density (j) that can be extracted by a voltage (V) imposed on an extractor grid at a distance (d) from the emitting surface. In units of A/cm^2, volts and cm, this is $j = 3E\text{-}6(V^{1.5}/d)$. While the formula allows current densities up to very high values as possible, in practical fact the difficulty arises that the extraction voltage gradient (ε) can not be made larger than some limiting breakdown voltage (arcing, again), so that the current density output is also so limited. A constant voltage gradient of $\varepsilon = 30$ kV/cm prevents practical diode emission (without filamentary arcing that would damage the diode) above about 10 A/cm^2 for even small grid/diode spacings. But an FES producing 4000 MWe power at 400 kV will be delivering a current of 10,000 A to the REB electrical system.

If diode current densities are limited to 10 A/cm^2, the diode area must be 1000 cm^2, a wholly impractical size for the production of a compact e-beam to inject into the BMT chamber. The solution to this problem is to inhibit the filamentation proclivities of the diode emission at high currents, by the imposition of a significant magnetic field along the axis of the grid/diode/reb system. Emitted electrons are then constrained to move along the field, and are trapped in gyro radius motion around field lines so that they can not readily collapse into intense filaments which destroy the diode and starve most of its emitting surface. This can keep the emission spread out over the surface and allow attainment of much higher average and distributed current densities, as needed.

To analyze this, consider the self-pinching of emitter current as due to the B field associated with the current itself. This is just $B = 0.4(I/d)$ (Gauss, amps, cm) or, replacing the current I with the current density, $j = n_e v_e(\pi/4)d^2$, by $B = 0.1\pi(jd)$. Now, taking the internal emitted current beam transverse (i.e. random) energy density as equal to the magnetic pressure exerted on the current flow by this self-B-field- (this is a beta = unity condition for the transverse electron energy) gives another limiting relationship between j, V and d, as $B^2/8\pi = jK$ where $K = (v_\perp / v_e)$ is the ratio of average transverse electron speed to axial electron speed. This latter is a measure of the thermalization of the emitted current flow.

Now, using the voltage gradient in the Child-Langmuir formula (above) and equating this with the limiting current from the B field pressure balance just cited, allows determination of the effective electron thermal velocity spread for any given gradient. For $\varepsilon = 30$ kV/cm, as before, this is found to be $(v_\perp / v_e) = 0.05\, d^2$. Using this result in a similar B field pressure balance equation for axial B field suppression of self-pinching, with a diode/grid spacing of $d = 1$ cm, gives the minimum B field required to prevent collapse as $B_{ax} \approx 400$ G (0.04 T).

Realistic systems have effective axial-field beta values of 0.1, so that the B field needed will be larger by $1/(\beta)^{0.5} \approx 3$, or $B \approx 1200$ G (0.12 T). With this sort of field, emitter current densities can be increased to values useful for the QED system.

Accelerator Beam Stability

Beam instability in the post-emitter phase can also occur because of self-field beam distortion effects, leading to kink and sausage instabilities and beam breakup. As before, this can be inhibited and suppressed by the imposition of a sufficiently large axial B field. Here the suppression must act against spatial displacement of the e-beam, such that sidewise motion attempts to generate transverse energies/velocities equivalent to the basic axial energy/velocity of the beam itself. Thus the B field pressure balance must act against an effective internal kinetic pressure set by the beam energy, as $B^2/8\pi \geq n_b E_b$.

For a quasi-relativistic beam (e.g. for $E_b > 300$ keV or so) the beam density is given approximately by $n_b \approx 2\text{E}8(j)$ /cm^3, for j in A/cm^2. Since $jE_b = P_e/A_b$, the beam power flux, the B field required for beam stability can be determined from combination of these two relationships, as $B^2 \geq 1.6\text{E}9(\pi)(P_e/A_b)k_e$, where k_e is Boltzmann's constant 1.6E-12 ergs/eV. For a 10,000 MWe FES with a beam area of 100 cm^2, this gives the stabilizing field as $B \geq 900$ G. In practical fact, the beta limit is much less than unity in such systems, because of ambipolar distortion effects due to background plasma, so that a B field above 2700 G is needed for these conditions. Such a field is not difficult to produce with modest solenoidal drive coils, using superconductor magnets to eliminate drive power losses. Thus REB beam stability can be achieved with reasonable engineering design and operating conditions_

Beam-Heated, Magnetically-Insulated, Thrust (BMT) System

E-Beam Injection "Window"

The e-beam supplied by the REB must be introduced into the BMT with minimal losses if it is to be effective in heating the propellant in the BMT chamber. The critical problem here is that of the "window" or opening through which the e-beam must be injected. Electrons lose energy in passage through matter according to a simple range/energy formula which shows a constant energy loss per unit distance, depending on the density of the material.

This is usually expressed as a constant energy loss per unit mass area-density, $dE/dm = 2$ MeV/(gm/cm^2) so that the loss rate through a material of density p is $dE/dz = 2p$ MeV/cm. If electrons have ca. 1 MeV of energy, it is apparent that even thin films of material (thickness t) will absorb significant fractions of the beam energy. Any energy so deposited in solid window foils must, of course, be removed by active cooling - else the foil will be vaporized.

A practical upper limit on heat transfer by fluid cooling is about $\phi = 15$ kW/cm^2. To limit power deposition to this level the window foil must satisfy the condition set by balance of fractional energy absorption to fractional power removal. This is just $2pt/E_b = \phi/(P_b/A_b)$. If the beam/injection area is 100 cm^2 (as assumed above), the power flux will be 50 MW/cm^2 for a 5000 MWe FES system. This example then shows that the foil thickness must be less than $t = 5.5\text{E-}5$ cm, if made of aluminum, for beam electrons at 1 MeV. This is quite impractical; no other reasonable set of design assumptions will yield a greatly different result. Accordingly, it appears that material foils can not be used as the interface between the REB and BMT systems.

Rather, it is possible to inject the e-beam through an open window into the BMT central core, but at the price of providing significant differential pumping to a series of injection port chambers at the inlet. Here the problem can be eased if some means can be found to couple the dynamic pressure capability of the beam into the kinetic pressure of the BMT core plasma, to act as a coupling barrier to plasma outflow into the REB vacuum system.

The beam dynamic pressure is $p_b = (n_b m_e v_e^2/2) = (n_b E_b)$. Using the beam density formula given above, $n_b \approx 2\text{E}8(j)$ /cm^3 with j in A/cm^2, and taking the power density to be $jE_b = P_b/A_b = 5\text{E}9/10 = 5\text{E}8$ w/cm^2, the dynamic pressure is $p_b \approx 1.6\text{E}5$ dynes/cm^2 = 0.16 atmosphere. This could be used to inhibit BMT core ion outflow into the REB if the BMT were operated at the same core pressure. Doing so with a core particle energy of 8 keV (85,000 °K), for example, gives the BMT core density as only $n_c = 1.25\text{E}16$ /cm^3.

This is large enough for high thrust operation with nozzle expansion through a nozzle of reasonable dimensions (e.g. 0.5 m throat diameter), but is too small to allow good energy deposition from the driving e-beam by classical range/energy collisions. Thus, while the "window" injection problem can be solved by use of an open port, this requires operation at pressures below those for efficient beam coupling by classical mechanisms.

E-Beam/Plasma Energy Coupling

This latter problem can best be solved by use of methods to ensure beam instability and breakup, once it has entered the BMT chamber. Since most of the research over the past 40 years has gone into study of means to stabilize beams in their propagation through matter, it is not difficult to find ways to achieve the opposite (almost natural) result.

Among these are the imposition of spatially-varying B fields whose field vectors change sign with short spatial frequency. This will cause beam diameter oscillations that quickly become drivers for beam self-chopping and breakup. Another method is to use a twisted B field to promote helicity in the injection process, and thus enhance collisional effects with the radially-inflowing propellant fluid. Finally, studies made recently of this problem suggest that pulsing the beam at high frequency, so as to produce a series of short beam segments, can lead to coupling lengths as short as 10 cm at densities in the range described above. In the early 1970's a large body of work was done to promote e-beam propagation through the atmosphere.

This almost universally showed that high current density beams would naturally break into short segments within a very short distance from their injection point. Subsequent chaotic collisions of these beam segments with ambient air then took place over a longer period of time, leading to significant local air heating. In the BMT system such breakup and heating will be completely constrained by the tangential flow of the radially inflowing propellant, which is injected tangentially at high speed at the chamber boundary.

Conservation of angular momentum in this inflow ensures that this will remain stable far into the center, where the chaotic mixing and heating due to beam breakup can overpower this effect within some small radius. This critical radius can be found by solving for the rotational energy as a function of radial position in the angular-momentum-conserving inflow and setting this equal to the electron particle energy in the e-beam.

This can be expressed in an approximate form by the formula $\langle r \rangle_{crit.} \approx 8(E_o/E_b)^{0.5}$ where E_o is the propellant particle energy at its tangential injection at the BMT chamber boundary at $r = R_B$, E_b is the (local) beam electron energy, and the critical radius is given as $\langle r \rangle_{crit.} = (r_{crit.}/R_B)$. If the tangentially injected propellant has particle energy of 0.2 eV (as would be the case for heating to ca. 2100 °K by regenerative cooling requirements, for example) and the e-beam electrons are at 500 keV, the critical radius so estimated would be $\langle r \rangle_{crit.} \approx 0.005$.

In practice this would be larger because mixing instabilities would "smear out" the beam/propellant interface, and in no event could this radius be less than that of the injected beam itself. As the e-beam progresses along the BMT chamber axis, it will lose energy, and the critical interface radius will grow. By the end of the chamber, the e-beam should have lost most of its energy (if the system is to be an efficient thrust device) and the critical radius will have expanded towards the chamber outer wall. For a residual e-beam electron energy of 20 keV, this simple formula gives $\langle r \rangle_{crit.} \approx 0.8$ at the end of the chamber, as the propellant starts its nozzle contraction/expansion flow phase.

Wall Heat Transfer Inhibition

As the propellant is heated and the central core expands in its flow through the BMT chamber (as described above), it will radiate from recombination reactions and bremsstrahlung in the very hot central core axis region. Heat transfer to the walls from this source can be essentially eliminated by the tangential radial inflow geometry, which ensures that the entire temperature from injection temperature to maximum central core temperature is taken up radially.

Radiation transfer radially becomes impossible to any significant degree because the propellant density at the outer radii is so large. In addition, if necessary, the propellant can be doped (e.g. with Cs or graphite) to enhance its absorptivity, so that radiant energy never reaches the walls. The same is true in this radial inflow geometry for suppression of convection energy transport to the walls. However, as the flow moves axially downstream towards the nozzle region, and the critical radius (above) moves outward towards the boundary, convective mixing can begin at the nozzle entrance and convective heat transfer to the nozzle walls could become excessive. This can be greatly reduced by the use of magnetic insulation to prevent particle transport to the walls by trapping them on magnetic field lines generated by super-conducting coils external to the BMT system.

There have been studies[5] shown to be effective at particle energies up to 12 eV (temperatures up to 120,000 °K) in hydrogen plasmas, at pressures of 0.1-3 atmosphere. Operation at ca. 8 eV and 0.2 atmosphere seems possible with virtually no convective transfer to the walls if appropriate B fields are used to constrain the nozzle flow. Here, as before, the simplest criterion is that of pressure balance against the internal BMT pressure. The situation is somewhat more complex here, because the B fields must constrain the neutral plasma, not just the electrons - as in the e-beam systems. But, neutral plasma confinement by B fields suffers from ambipolar diffusion cross-field collisional transport of both species, reducing the practically attainable plasma beta to 0.1-0.15.

Taking $\beta \approx 0.15$ gives the B field required for nozzle insulation of a 0.2 atmosphere BMT system as $B \approx 5.5$ kG, larger than required for the rest of the QED system. Still, this is tractable with superconductor coils on BMT radii of 0.5-1.0 m, as contemplated.

QED Engine System Vehicle / Space Interface

As a last technical topic, consider the main requirement in the overall QED/vehicle/space interface area. This is simply that the entire flight system remain at a constant electric potential throughout flight; i.e. that it not continue to charge up electrically as electrons are ejected from the QED engine into the environment around the vehicle. This problem will be greatly eased by design of the REB/BMT system so that very little residual electron energy leaves the thrust chamber. This is desirable for efficient engine operation,in any event. Suppose that the e-beam deposits all but 20 keV of an assumed 500 keV injection into the propellant in the BMT. While this is a heating efficiency of 96%, it does not mean that 4% of the e-beam power has gone into the system walls to require regenerative cooling. Rather, it means that a current of electrons will leave the BMT nozzle carrying 20 keV energy per particle, thus 4% of the drive energy will be wasted in subsequent interactions with and heating of plasma surrounding the vehicle. Given sufficient in-situ ion/electron density in the flight space environment, these ejected electrons will eventually return to the vehicle as it charges up to a positive potential. The potential it can sustain will depend on the local in-situ density of electrons that are carrying the return current from the BMT system to the vehicle. Analysis of this requires knowledge of the space ion/electron density; studies have shown that densities comparable to the beam density at nozzle exit will result in vehicle potentials that are reduced from the residual energy of the e-beam by the ratio of the nozzle exit area to the vehicle external surface area. For a 2 m radius nozzle and a "typical" HRST vehicle this ratio is in the range of 2-5E-3, so that a 20 keV residual energy becomes a vehicle potential of about 4-10 V. The power that must be dissipated in the vehicle in this return current flow from external electron ejection is then only about 20-50 kW. Of course, all of the e-beam electrons that have impacted on the BMT structure will be returned to the FES by a hard conductor path directly from the structure. This can be a large area aluminum or copper conductor with minimal ohmic losses. In short, the return current problem seems tractable, if the e-beams can be made to heat the BMT propellant efficiently.

QED Engine System Development

All of the above interface issues need considerable R&D to determine their exact nature and to define and demonstrate the technical solutions to the problems they pose. This has been examined in detail[6] as part of the recently-concluded NASA HRST study effort over the past three years. This study and examination has resulted in the development of a "roadmap" for R&D on these and related issues, leading to the development and test of a full-scale prototype QED engine system. This system is aimed at a thrust level of 40,000 kgf (400 kN), at a power level of 5000 MWe, with a specific impulse of 2500 sec. The R&D plan developed shows achievement of this system within 14-17 years at a total cost of about $3.0-3.5B. With such an engine system, practical space flight would be here, at last.

Conclusions

Examination of eight of the main system and subsystem interface problem areas of the QED engine system concept shows that tractable engineering solutions are available for each of them, that allow attainment of very high performance rocket engine systems - if the basic FES subsystem can be developed. Analysis of the solutions available for each of these problem areas shows that they are all tractable with reasonable engineering approaches; new and novel advances are not required in magnetic field strength, fluid pumping, high voltage operation, et al. Good mechanical and electrical engineering design and development is needed, and intelligent choices must be made for optimal solutions in each area. The BMT exhibits the most difficult of these engineering problems; here clever physics design of the e-beam drive can help to ease the engineering. No intractable issues appear; what is needed is serious development of the subsystems and system. And this is seen to require about $3B over 15 years, to yield working full- scale QED engine systems.

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