The Advent of Clean Nuclear Fusion: Superperformance Space Power and Propulsion

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ABSTRACT

Success has been achieved from research and development work conducted since 1986 on a unique concept for creating and controlling nuclear fusion reactions, in an inertial-electrodynamic fusion (IEF) device of special, quasi-spherical configuration. Final design insights were proven by experiment in Oct/Nov 2005, from which full-scale designs can be determined. This allows demonstration of full-scale, clean, nuclear fusion power systems, based on use of p+B11 → 3 He4. This demonstration will require about $ 200 M (USD) over 5 years, with an IEF machine of 2.5-3 m in diameter, operated at over 100 MW. It will open the door to superformance, practical, economical spaceflight, as well as clean fusion power, and mark the end of dependence on fossil fuels. The main point of this paper is to present these results of EMC2's 20 years of study and research of this approach to clean fusion power.

This concept derives from early work (1960's) of P. T. Farnsworth and R. L. Hirsch (F/H), who used spherical screen grids biased to high potentials to energize and accelerate ions to the center, where fusion occurred. Ion collisions with grids gave unavoidable losses, limiting power gain to less than 0.001. The EMC2 device avoids these by using energetic electrons, trapped in a quasi-spherical polyhedral magnetic field, to generate a spherical electric potential well. Ions dropped into this well at its edge will accelerate towards its center increasing in density and kinetic energy, collide at high energy, and make fusion. By this unique design, the power loss problem is shifted from grid collision of ions (F/H) to that of electron transport losses across high B fields to the confining magnets. The two competing phenomena, power loss and fusion generation, are thus decoupled by the basic design approach, and each can be optimized separately.

The concept was invented by Dr. R.W. Bussard in 1983, patented in 1989 (and lastly in 2006), and studied by EMC2 since 1986. Design studies of IEF-based space propulsion (*AIAA Prop. Conf, 1993,97; IAC, Graz, 1994, Toulouse, 2001*) show that this can yield engine systems whose thrust/mass ratio is 1000x higher for any given specific impulse (Isp), over a range of 1000 < Isp < 1E6 sec, than any other advanced propulsion means, with consequent 100x reduction in costs of spaceflight.

INTRODUCTION AND SUMMARY

EMC2 has been conducting Research and Development (R&D) on its unique concept for controlled inertial-electrodynamic-fusion (IEF) power generation since its invention in 1983/84 (Ref. 4, and other patents filed in 2006), with detailed studies since 1986/87. The EMC2 concept is *electrodynamic*, rather than *electrostatic*, as initially studied by earlier workers (Ref 1,2,3) in which fixed (static) grids were used to generate confining electric fields. R&D work on the physics issues of the concept has been carried out under EMC2 and US Department of Defense sponsorship since 1987, with experimental work since 1989. Early work (1987/94) was reported at meetings of the American Physical Society's Division of Plasma Physics, and in a wide array of internal and external technical reports and journal articles (Refs. 2-16). However, by direction of its U.S.Navy sponsors, EMC2 was precluded from publishing technical papers on its R&D work and results from late 1994 through 2005.

During this eleven year period it was acceptable to publish technical papers on the potential application of this new high-performance fusion energy system to space flight systems and applications without disclosing the means to achieve such energy systems. And, of course, one very important application of this concept, if successful, has always been to provide power to drive superperformance propulsion systems for vastly improved spaceflight. To this end, a series of technical papers was written and presented at meetings and conferences in this period (Refs. 20-23).

Results of these studies showed that IEF power sources could be used for a wide variety of aerospace propulsion applications, ranging from HTOL vehicles from earth-to-orbit, to fast transit vehicles to the orbit of Saturn and throughout the solar system, along the lines first laid down by Hunter (Ref 24), and even to the fringes of interstellar space (Ref. 22). Their potential performance exceeded that of all other rational alternatives by a factor of the order of 1000x; that is the engine systems provided Isp 1000x higher at the same thrust/mass ratio, or thrust/mass ratios 1000x higher than others at the same Isp. Figures 1 and 2 show schematic outlines of the types of engine systems considered, and the general performance spectrum just described.

Since the R & D program has now concluded, for want of further funding, just as it reached final success, it is now possible to publish the results of the work of the past 12-19 years. Accordingly, this paper presents an informal short summary of these results and conclusions of the R&D work of EMC2, over the period since 1987, on the Polywell inertial-electrodynamic concept for clean (non-radioactive) nuclear fusion and fusion-electric power. This summary presumes a general knowledge of the classical basic physics phenomena that this embodies and on which its performance is based. It also summarizes the present prospects and needs

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for the major next step to clean fusion net power systems, following the groundwork and fully established knowledge from work carried out to date.

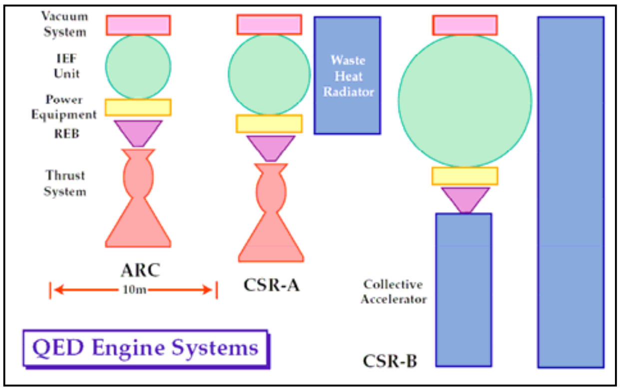

Figure 1. Schematic of different types of engine systems

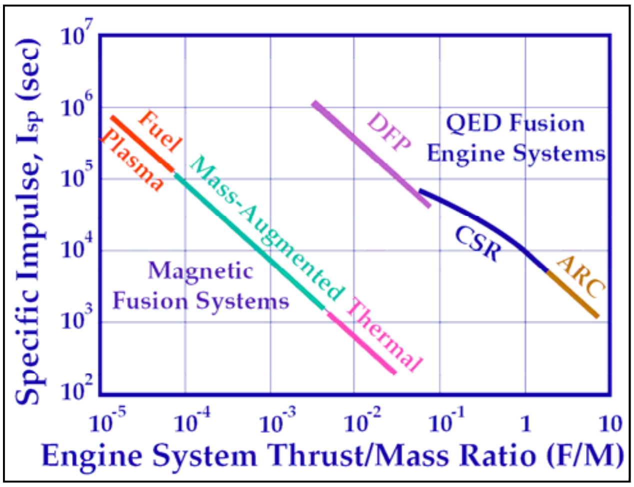

Figure 2. Mechanical characteristic of engine systems

The most important result and conclusion from this work is that it is now possible to design, build, construct and test a full-scale demonstration fusion power plant, with a high degree of confidence. If designed to run on deuterium (D) the RDT&E cost is estimated at about $ 150 M over 5 years, while a plant designed to run on the unique fusion reaction between hydrogen (p, or H) and boron-11 (B11) - which is totally neutron-free - will cost about $ 200 M.

It is important to note that this Polywell concept and device is the only fusion system that can utilize this clean pB11 reaction, which yields only charged alpha particles (Figure 3).

BACKGROUND OF PROGRAM

This work has been supported since its beginning by the DoD (SDIO/DNA, DARPA, and the U.S.Navy). It reached final success in proving the ability to control e-losses sufficiently to ensure that net power, clean fusion systems could be built at larger sizes from the EMC2 device, in a series of critical experiments conducted in November 2005. However, the lab was shut down in the ensuing 2 months due to the failure of funding in the FY 2006 budget to complete the present U.S.Navy contract under which EMC2 has been conducting this work. The EMC2 labs and offices in which it has been conducted have been closed. Ironically this shutdown was at the time of the program's final and greatest success in experimental results!. This is discussed further below.

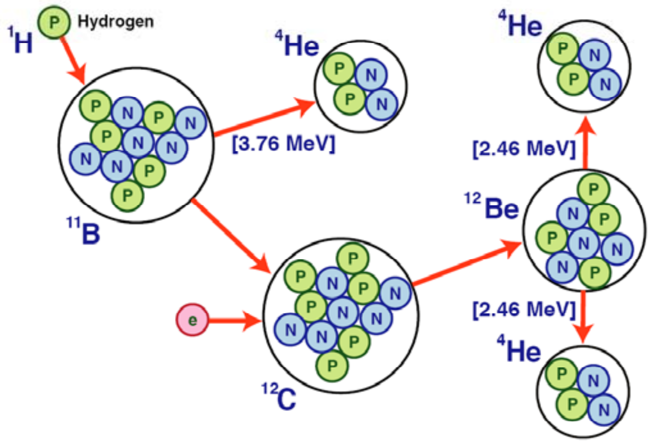

Figure 3. Aneutronic fusion: p + B11 → 3 He4

TECHNICAL HISTORY OF RESEARCH AND DEVELOPMENT (R&D) WORK

The EMC2 experimental R&D effort began in 1994 with design and test of a small machine (R = 5 cm), called WB-1, to verify polyhedral B field effects. This device utilized uncooled solid-state magnets in a truncated cube arrangement, and was simple to build and test, but inherently had circular line cusps on all its main face magnets. This resulted in large electron loses through these line cusps, but experiments showed electron trapping within these limits.

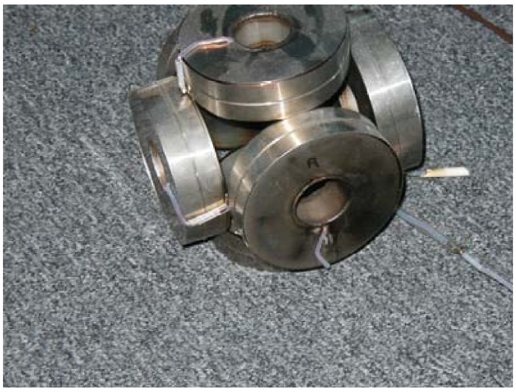

Figure 4. WB-2 reactor

This was succeeded by WB-2 (1994-95) another truncated cube configuration, with an interior half-width of R = 5 cm, but with uncooled wound coil magnets on all six main faces. Figure 4 shows WB-2. WB-2 tests proved the principal effect of internal cusp confinement of electrons under high current drive conditions, as shown in Figure 5. Subsequent tests were made on similar but larger machines, WB-3 (1998-2001) and WB-4 (2001-2003) with R = 10 cm and R = 15 cm, respectively. Figures 6 and 7 show these devices.

All of these machines were tested inside vacuum tanks and had open faces on all cusp axes (the main faces and corners) to allow full circulation of electrons out and back along the polyhedral B fields produced by the magnet coils. WB-4 produced fusions in DD under a short-pulsed-mode drive in December 2003, at about 1E6 fus/sec at 12 kV drive energy and 10 kV well depth.

Figure 5. Electron confinement obtained in WB-2 under high current conditions

In parallel with this work, a closed-box machine (PXL-1) was built and tested to study electron cyclotron resonance (ECR) ionization of internal background neutral gas, and ion focusing in negative potential wells. Even though it was driven by a single electron emitter, its tests showed good ion focusing to the potential well center of the device. Figure 8 shows this machine. It did not allow electron recirculation from the interior of the device and thus was limited (by wall collision losses of electrons) in its ability to reach high electron densities.

Figure 6. WB-3 reactor

Also in parallel, two single-turn, water-cooled, polyhedral tube/coil devices (MPG-1,2) were built and tested at low B field but high voltages (2001-2002). Both showed DD fusion reaction output with deep potential wells. And, also in parallel, a fast- pulsed adiabatic compression device (PZLx-1) was built and tested (2002-2003) to study hydromagnetic stability of the polyhedral fields under static and dynamic conditions. Figure 9 shows this device; a single-turn solid copper coil system driven by a fast capacitor bank energy system to 35 kG central fields, in ca. 2 msec. This was limited by Paschen arcing to starting energies (of electrons) of about 300 eV, but produced 1E6 fus/sec in DD at its pulse peak.

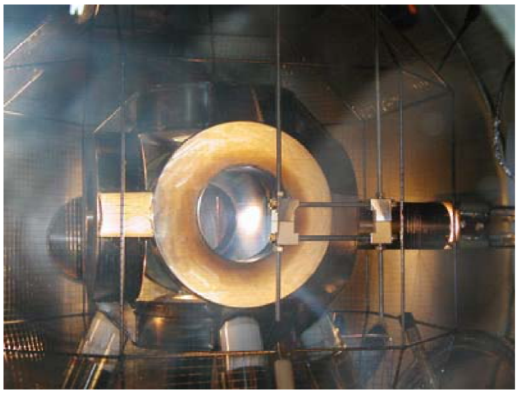

Figure 7. WB-4 reactor assembled for operation

Figure 8. PXL-1 reactor for studying the electron cyclotron resonance

Figure 9. Pulsed compression device PZLx-1 built to study hydromagnetic stability of polyhedral field

Finally, a larger version of the closed box device (PXL-1) was built as WB-5 (2004-2005), to test improvements in magnetic insulation by use of external surface and cusp coils at high fields. Figure 10 shows this system. Its test results showed 1000-fold improvement (in ability to reach deep fractional well depth at given starting pressures; early work was limited to 3E-9 torr, while WB-5 ran at 3E-6 torr) from early work (1989-91) on a larger closed-box machine (Ref. 6) but its inability to be driven beyond this increase illuminated the critical and dominating effect of unshielded surface losses of electrons, on overall system performance.

This is discussed further, below. The insights gained from test of this device led to new engineering physics design constraints, which avoided all such loss phenomena, and which were immediately and rapidly embodied in a new machine, WB-6 (2005), shown in Figures 11-13.

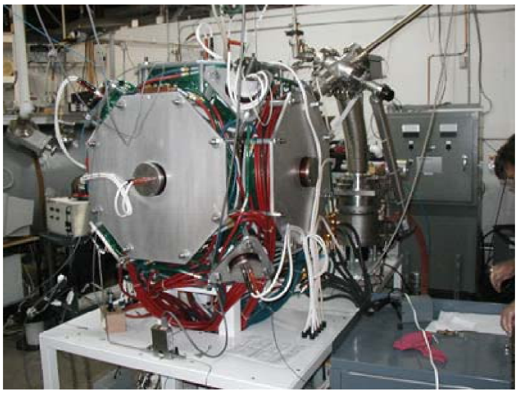

Figure 10. WB-5 reactor showed an enhancement of 1000-fold over previous results of WB-4

Figure 11. Construction detail of WB-6 coils

This was hastily built and tested (October/November 2005) with impressive and startling results, giving DD fusions at over 100,000x higher output (at 1E9 fus/sec) than all prior similar work at comparable drive conditions (Ref. 3). All testing was necessarily short-pulsed (discussed further below), but all basic engineering design conditions were proven by this machine (together with the results from its predecessors), to enable design of a full-scale power plant system.

RESULTS OF PROGRAM WORK

Thus, all of the individual physics issues and effects required to make the concept work HAVE been proven by the extensive experimental tests made since 1994 in the EMC2 R&D program. These include:

- The WB cusp trapping effect (explained further below; WB-2,3,4,5), its physics and numerical rates.

- The need for electron recirculation through all cusps of the machine, so that cusp electron flow is not a loss mechanism.

- The consequent elimination of the WB trapping factor as a measure of "losses" it is simply a measure of density ratios inside and outside the machine.

- The ECR means for neutral gas wall reflux suppression (PXL-1, WB3,4).

- The ability of machines to act as electron extractors from e-emitters located on axes (WB-2,3,4,6).

- The appropriate on-axis positioning of such emitters relative to machine dimensions (WB-4,6).

- The restrictions on machine relative dimensions due to electrostatic droop from emitters and external walls (extensive electrostatic computer simulations/codes).

- The proper positioning of external walls and choice of neutral gas pressure for suppression of arcing (every machine tested).

Figure 12. WB-6 reactor configuration

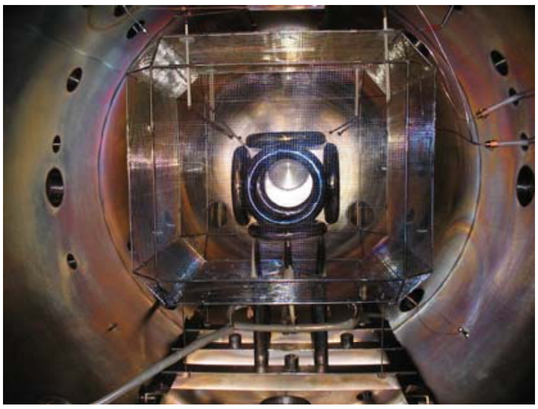

Figure 13. WB-6 assembled. WB-6 achieved a record of DD fusions (1E9 fus/sec) at a potencial well of 10 KV

- The conditions for arc faulting in machine operation (every machine tested).

- The need for injection of neutral gas INTO the machine interior, and for Immediate ionization of same (WB-4,5,6), or

- The requirement of ion gun injection at the interior edge of the Polywell potential well within the machine (WB-4,5),, while keeping external neutral gas density low by extensive pumping.

- The inherent hydrodynamic stability of the Polywell trapping polyhedral B field configuration (PZLx-1).

- The production of predictable fusion reaction rates within the interior of deep- well Polywell devices, at both low and high B fields (WB-4,6, MPG-1,2).

- The ability to run Polywells at current drives up several thousand amps of electron injection (WB-4,5,6).

- The determination of electron transport losses across Polywell B fields, and verification of the electron transport loss phenomena (MG transport coefficient) by extensive experimentation in all Polywell machines.

- The absolute necessity of avoiding all magnetically-unshielded surfaces in any machine design.

- The understanding of the effects of finite coil dimensions on the role of the —funny cusp" losses at corners, and the resulting need for precise construction at these points (see above), i.e. spacing at several gyro radii.

- The need for magnetic field coil containing structures to be conformal with the B fields they produce, to avoid excessive electron impact losses (as above).

- The need for independent electron guns to provide adequate drive power.

- The ability of ion-impact secondary electron emission to supply large drive current capabilities in proper Polywell machine/shell systems (WB-5).

- The requirement of large drive power, as defined in the original Polywell design and configuration concept.

SUMMARY OF TECHNICAL RESULTS

The results of all this work, and their meaning, are as follows:

1. Essentially all the research and development work that can be usefully done at the small scale available with the program-limited budgets has been done. Two small scale device tests of value remain, as does work on e-guns for full scale machines.

2. All of the basic physics effects and engineering design and construction constraints have been done, needed to make the concept work, lacking only their extension to full scale sizes (1.5 m for DD, 2 m for pB11). The next logical and practical step is to undertake a five-year program to develop and test a full-scale net-power (e.g. at 100 MW) IEF clean fusion demonstration system.

3. The results of all of the experimental studies to date have shown very stringent physics limitations that drive the engineering configurations and designs to use of fully-electron-recirculating machines, within external vacuum shells or Faraday cages, with only the internal machine at high electric potential. In this preferred arrangement, the electron emitters/sources and the external shell are all at ground potential.

4. An alternate potential arrangement could be used, in which the only elements at high negative potential are the emitters, but this can work only if it employs driven, negatively biased repellers at every cusp axis position, to prevent excessive electron loss by streaming out along each axis. Such repellers could also act as secondary electron emitters (from ion bombardment) to the degree that the primary driven emitters may be turned off - as proven in tests on WB-5.

5. In these systems electron loss phenomena are solely to (metal) surfaces of the machine system. Cross-field losses are well understood and can be controlled. However, losses to poorly shielded (by fields) or unshielded surfaces can constitute major loss channels. From WB-5 and WB-6 it has been proven that that the fractional area of unshielded surfaces must be kept below 1E-4 to 1E-5 of the total surface area, if electron losses are to be kept sufficiently small so that net power can be achieved. And, further, that no B fields can be allowed to intersect any such internal surfaces of the machine.

6. This requirement has two main consequences: (a) All coil containers/casings must be of a shape conformal to the B fields produced by their internal current conductors, and; (b) The finite size of real coils forces design so that no coils/containers can ever be allowed to touch each other, but all corners MUST be spaced at some distance from the adjacent coils, to avoid B field intercept.

7. This is the principal criterion for design and construction of any real, finite material coil and system, no matter the plan-form SHAPE of the coils, which is of no major significance (i.e. round, square, polygonal or triangular, etc). The spacing between coils should be such that the central plane B field is approximately the same as that of the B field on main face axes. Typically, this may be at minimum the order of a few (5-10) electron gyro radii at the inter-corner field strength, but not greatly larger than this (to avoid excessive degradation of the internal WiffleBall - WB - electron trapping factor in the machine main field).

8. This Wiffle Ball trapping factor (Gwb) is NOT a measure of losses in any recirculating machine, thus its value need not be as large as those potentially possible with high B fields (1E3 vs 1E6), thus greatly relaxing the need to strive for super-high Gwb factor values.

9. Wiffle Ball behavior is of value (and is essential) ONLY to establish the density ratio from the machine interior to its exterior, and this is important ONLY to assure suppression of Paschen arc breakdown outside, which destroys the electron injection drive and well potential.

10. These considerations have been driven by the long array of experiments that have been done at EMC2 since 1994, first on WB-2, then some on WB-3, then the last series of WB-4, with parallel tests of unique-feature other devices, MPG-1,2 and PXL-1, PZLx-1. Finally experiments were run in tests subsequent to these on WB-5, and lastly onWB-6, the definitive final machine, with greatly reduced losses, and record-breaking DD fusion output.

DISCUSSION OF TECHNICAL CONCEPT AND EXPERIMENTS

The basis of the EMC2 concept for inertial-electrostatic-fusion (called the "Polywell" concept) is the idea of trapping high densities of energetic electrons within a quasi-spherical magnetic field, into which a current of high energy electrons is injected to form a deep negative potential well, without use of mechanical grids. Only a very slight fractional negative deviation (1E-6) from charge neutrality (of ions vs. electrons) is required to make potential wells nearly as deep as the electron drive energy.

Ions then "dropped" into this well, at its edge, will fall to its center, with $1/r^2$ increasing density, and gaining energy sufficient to make fusion reactions among them as they collide in the central core region of this configuration. If scattering occurs, the ions simply recirculate back up the well and fall in again when they reach its edge. They are, of course, finally turned by their gyro motion in the increasing edge B field of the system, just as are the electrons. The critical element in power balance (fusion power generation vs. electron drive power losses) is the ability of the magnetic field to keep electrons inside the quasi-sphere - ions remain trapped by the electron-driven electrostatic potential well. The phenomena of fusion generation and of electron trapping and losses are essentially *decoupled* in this system.

The original patent concept, which provides the basis for the physics of this type of machine, presumed coil conductors of zero cross-sectional radius, placed exactly along vertex edges, with sharp corners where coils came together. This led to an odd point/radial-line at such corners which had zero field over zero radius. This was called a "funny cusp" by the very first reviewers of the concept (1987). It is, of course, not attainable with any realistic coil conductors of finite size, and (as discussed further below) this engineering fact has profound and dominating consequences for the design of any machine hoped to be useful and practical for net power production.

The two single-turn MPG devices (MPG-1 and MPG-2), which were invented to try to mock up the patent configuration of the coils, but with full recirculation of electrons (called MaGrid machines), did yield very deep fractional (90+%) wells, as expected. This was because the e- sources were all exactly on-axis, and were relatively distant from the main faces. This geometry yielded only a small angle subtense for the injected electrons, and thus only a small transverse spread of electron energy (relative to radial energy) at the device inner boundary (fractional well depth tends to vary as the square of the sine of the angular spread at injection). However the machines ran only at cusp-axis fields limited to 70-100 G, because of engineering limitations on drive power, cooling, and system size. These simple devices were also built with spacings at the coil corner positions, so did not suffer from the unshielded loss problem alluded to above. They did work and produced fusions in DD.

They functioned by trapping electrons in the polyhedral fields, to make deep wells - 30 kV e- drive with 27 kV well depth - with ions generated near the outer edge falling in along the well gradients, as they should. Limited drive currents (e.g. 0.3 A) gave low ion densities, such that the trapped ions could not reach ion energy much above 4.5 kV before charge exchange with the background neutral gas prevented their further heating by ion/ion collisions. The limited small drive currents completely prevented burnout of this background gas. This resulted in the generation of significant beam/background fusion reactions (at about 1E4 to 1E5/sec) due to fast ions colliding with the background neutrals. Device badly limited by limiting drive power and very limited cooling ability on the coils. These machines did prove the efficacy of Polywell trapping and produced DD fusion output.

Gwb (The WB trapping factor) in these two devices was of order 2-8, which is a very small Wiffle Ball trapping factor. Much higher Gwb values could be attained if machines were built with much larger B fields and at larger sizes, well beyond the program budget. In the MPG series, cooling limits prevented higher currents, and multiple turns to get higher B fields were out of reach (insulation breakdown in simple, multi-turn coils, at high drive voltages) with the available effort.

Technical Design Considerations

In order to make net power in a Polywell, there must be no more than about 3E-5 fractional metal surface area unprotected by magnetic field insulation. Otherwise, direct field-free electron losses will exceed both WB and MG transport power flows, and system will not be able to yield positive gain. Corollary: No closed box configuration can be made to function as a net power Polywell, with any conceivable practical magnetic coil surface protection windings. I.e. it is not possible, in a practical, constructable system, to cover all but 1E-5 of a closed box system with protective fields. This means that the ONLY Polywell systems that can be made to work are those in which there is NO metal surface exposed - this requires open cusp, recirculating electron flow, around B field coils that are spatially conformable to the magnetic fields surfaces that they produce. And this forces the coils to be spaced at a significant interval at their corner "touching" points, to allow free electron flow through these points. This also makes the WB trapping factor simply a measure of electron density ratios (inside to outside) rather than a measure of —losses" to containing walls and structures. And, because of this, it is not necessary of achieve Gwb values greater than, at most, 1E4 - rather than the 1E6 required for non-recirculating machines.

Electron Recirculation and Thermalization

Thus, in order for a Polywell to be driven in the mode described for the basic concept, open, recirculating MaGrid (MG) machines are *essential*. This, in turn, requires that the entire machine be mounted within an external container surrounding the entire machine, and that the machine be operated at a high positive potential/voltage (to attract electrons) relative to the surrounding walls. Note that this was the electric potential configuration used in the earliest MG machines, the WB-2 device, that proved internal magnetic trapping of electrons, called the Wiffle-Ball (WB) effect. And in the first proof of Polywell fusion reactions, in MPG-1,2, and in fusion production in the later devices, WB-4, 6. Questions have always been raised concerning the ability of the device to maintain its quasi-monoenergetic energy distributions among the ion and electron populations. These are, of course, driven by the dynamic injection of fast electrons, and their subsequent loss to structures.

If electrons live sufficiently long in the machine they could become Maxwellianized (thermalized) and develop high energy loss distributions. However, this has been found not to be the case. The same arguments have been found for the ions, as well. Detailed analyses show that Maxwellianization of the electron population will not occur, during the lifetime of the electrons within the system. This is because the collisionality of the electrons varies so greatly across the system, from edge to center. At the edge the electrons are all at high energy where the Coulomb cross-sections are small, while at the center they are at high cross-section but occupy only a small volume for a short fractional time of their transit life in the system. Without giving the details, analysis shows that this variation is sufficient to prevent energy spreading in the electron population before the electrons are lost by collisions with walls and structures. Similarly, for ions, the variation of collisionality between ions across the machine, before these make fusion reactions, is so great that the fusion reaction rates dominate the tendency to energy exchange and spreading.

Ions spend less than 1/1000 of their lifetime in the dense, high energy but low cross-section core region, and the ratio of Coulomb energy exchange cross-section to fusion cross-section is much less than this, thus thermalization (Maxwellianization) can not occur during a single pass of ions through the core. While some up- and down- scattering does occur in such a single pass, this is so small that edge region collisionality (where the ions are dense and "cold") anneals this out at each pass through the system, thus avoiding buildup of energy spreading in the ion population (Ref. 14). Both populations operate in non-LTE modes throughout their lifetime in the system. This is an inherent feature of these centrally-convergent, ion-focussing, driven, dynamic systems, and one not found (or even possible) in conventional magnetic confinement fusion devices.

Tests made on a large variety of machines, over a wide range of drive and operating parameters have shown that the loss power scales as the square of the drive voltage, the square root of the surface electron density and inversely as the 3/4 power of the B fields. At the desirable beta = one condition, this reduces to power loss scaling as the 3/2 power of the drive voltage, the 1/4 power of the B field, and the square of the system size (radius). Since the fusion power scales as the cube of the size, the fourth power of the B field, and a power of the E drive energy equal to the E-dependence of the fusion cross-section (cross-section proportional to E to the s power), minus 3/2. For DD, s = 2-4, while for DT, s = 3-6 in useful ranges of drive energy. For pB11, the cross section scales about as s = 3-4 over the system-useful range.

Thus, the ratio of MG power loss to fusion power production will always decrease with increasing drive voltage, increasing B field, and increasing size. Because of this, it is always possible to reach a condition of power breakeven in these polyhedral electric- fusion machines, with any fusion fuel combination. This is *not* the case in Maxwellian, equilibrium fusion devices (e.g. the —magnetic confinement" devices of the DoE, et al) as these are severely limited by ion collisional losses to their walls, and by bremsstrahlung losses from the denser but less-reactive distributions in their equilibrium plasmas.

Design Considerations from Computer Simulation Codes

Device and system operation and performance at startup conditions, at very early times, have been modelled by complex electrostatic computer codes, that determine the coulombic interactions between all particles throughout the system and plot trajectories and densities in the system. Results of these computations show conclusively that B-field intercepts with containing structures ensures excessive losses of electrons, as previously discussed. However, these early-time computed results do not show the realistic effects of collective phenomena beyond startup (from low- to high-beta).

These have been readily modelled successfully by a major plasma phenomenological code (the EIXL code) developed by EMC2 since 1990. This is a 1.5- dimensional Vlasov-Maxwell code, in which diamagnetic expansion of B fields is included, particle collisions are estimated from density and energy distributions, fusion rates and output are calculated and bremmstrahlung losses are included, and which includes such phenomena as central core inertial-collisional-compression effects which can apply to core ion compression in Polywell devices. Figures 14 and 15 summarize this code and give a sample output for a pB11 system.

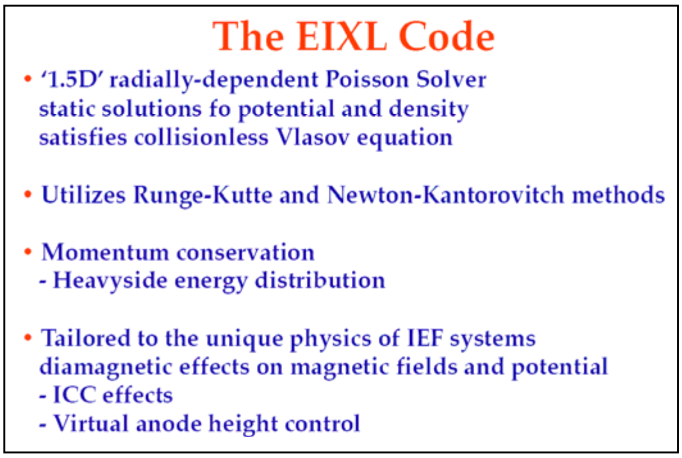

Figure 14. EIXL modeling software

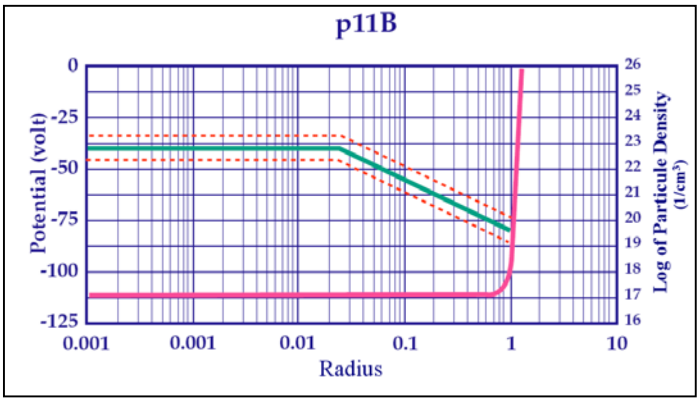

Figure 15. Graphical output from EIXL simulation

Arcing and Wiffle-Ball Trapping

As previously noted, no Polywell can operate at all if arcing occurs *outside* the machine, between the walls and the machine, because this destroys the ability of the driving power supplies to produce deep potential wells. Thus the mean free path for ionization *outside* the machine (inside the container) must be much greater than the external recirculation factor, times the machine-to-wall distance. Since the mfp for ionization is inversely proportional to the product of the local neutral density and the ionization cross-section, this condition can ALWAYS be satisfied, IF the external neutral gas pressure is made sufficiently small. In order to avoid external arcing, the densities thus required are very much too low to be of interest for fusion, thus the density *inside* the machine (at its boundary) must be very much higher than that outside. This ratio is the Gmj factor, which is the ratio of electron lifetimes within the machine *with* B fields on, to that *without* any B fields.

In contrast, in order to be of interest for fusion, the interior density must be above some numerical value for any given size of machine. Typically this requires electron densities at the interior boundary of order 1E13/cm3, or higher. While the exterior densities (of neutrals able to be ionized) must typically be below 1E10/cm3 or less. Thus a minimum value exists for Gmj (here, typically 1E3), below which no machine can give significant fusion or net power, independent of the unprotected wall loss problem. Both must be solved simultaneously

In any realistic device, the effective overall trapping factor is reduced from the pure WB mode by circulation through the semi-line-cusps at the spaced corners, which allow much greater throughflow per unit area than through the point cusps of the polyhedral faces. The line-cusp throughflow factor is called Glc. These two effects act as parallel loss-flow channels, and combine to produce an overall trapping factor Gmj, which is the inverse sum of each of their contributions, as weighted by their fractional areas involved. Thus the overall trapping factor for inside/outside density ratios, is given by 1/Gmj = fwb/Gwb + flc/Glc, where the fractional areas are flc + fwb = 1. Solving this algebraic identity gives the effect of corner flow paths on the entire Gmj system as Gmj/Gwb = 1/[fwb + (Gwb/Glc)flc]. If corner flow paths are not to dominate the trapping, the second term in the denominator must be kept small relative to the first (WB) term, thus flc/fwb << Glc/Gwb.

Analysis shows that line cusp corner spacing flow factors are roughly equal to the square root of the mirror reflection coefficient Gmr for point cusps at the corner field strength, thus Glc = SQRT(Gmr). Gmr values may be as high as 80-100 in suchmachines, thus Glc = 10 is a reasonable value for the corner flow. Using this, and noting that fwb must be close to unity, gives the approximate result that flc << 10/Gwb for effective operation. In a truncated cube configuration Gwb = (BR)^2/110E, for B in Gauss, E in eV and R in cm. Typically, machines may have Gwb > 1E4, thus the fractional corner cusp flow area must be flc << 1E-3 as required to maintain good density ratios from the interior to the exterior, to prevent arcing, and retain high enough density inside for useful fusion. Note that this condition does not relate directly to the problem of electron losses to unshielded structure, which is also determined by the fractional impact areas involved as well as by the degree to which local arcing may occur to focus high current density discharges in the system.

Arcing can take place inside the system whenever sufficient deviation from local B field insulation is driven by ―pinch effect" currents to the otherwise shielded metal surfaces. The arc pinch B field is given as Bp = 0.2Ip/rp, where Ip is the pinch current and rp is its radius (gaussian units), and Ip = (pi)(rp)^2(jp), where jp is the pinch current density (A/cm2), this becomes Bp = 0.2pi(jp)(rp) for B in Gauss. Now the condition for arc formation is when the pinch field significantly disturbs the shielding main B field Bo, thus when |Bo-Bp| << Bo. This yields the constraint that Bp/Bo << 1, or that Bo >> 0.2pi(jp)(rp). From MHD stability theory (and copious experiments since 1955) it has been found that pinch discharges are inherently unstable if current densities and radii are above some defined levels in any system. The condition is approximately given by rb^2 > 3E9[SQRT(Ee)]/ne; this yields rb > 0.2 cm for typical conditions of interest. Thus, it is possible to suppress such effects by avoiding all sharp corners and electric field focus points in the design and construction of the interior of the device, so as to prevent the attainment of high current densities over very small areas in arc formation.

A key issue here is how to reduce capacitor-drive currents to the levels that are actually needed for useful experiments. This is a matter of controlling the overall circuit impedance Z of the machine test system as it runs. This impedance is simply the ratio of electron drive injection energy to the electron current e-losses to the machine (not to the walls and tanks) in machine operation. This, in turn, is dominated by the three factors in e-loss phenomena:

1. Direct MG transport through the B-shielded surfaces,
2. Electron losses to poorly shielded or unshielded metal surfaces, and
3. Losses due to local arcing.

Thus Z = Ee/Iej, where Iej is the sum of these three e-loss current effects.

As discussed above, arcing can be suppressed and avoided internally, by proper design of the surfaces to avoid electric field-enhancing sharp corners and small areas. Poorly shielded areas, such as the interconnects between spaced corners of the coil systems, can be minimized by careful design to minimize area and avoid sharp corners, and by use of internal B fields produced by current carriers through the interconnects. And the main MG transport losses can be controlled by use of the well-developed transport models and equations obtained from 13 years of EMC2 experimental research. In general, the impedance can be controlled successfully, but only with proper care in design and construction of the devices.

On electron trapping: Since the ion density is nearly equal to (and thus set by) the trapped electron density, it is desired to have the highest possible electron density for the least possible drive current. This requires that the transport loss of electrons *across* the trapping B fields be small, and that their flow *along* the cusp axes of the polyhedral B fields also be kept small. Cross-field transport constitutes an unavoidable loss to coil structure, while cusp axis flow need not be a “loss“ if the device is open and the electrons can recirculate along the cusp axes to the outside of the machine, thence to return along cusp axes field lines. This type of recirculating machine with magnetically protected coil surfaces is called a MagneticGrid (or MagGrid; MG) machine. It requires that the machine, itself, be centered inside of a containing wall or shell, that is held at a potential below that of the machine proper, by the voltage used to drive the electron injectors.

Initially, when the electron density is small, internal B field trapping is by simple “mirror reflection“ and interior electron lifetimes are increased by a factor Gmr, proportional linearly to the maximum value of the cusp axial B field. This trapping factor is generally found to be in the range of 10-60 for most practical configurations. However, if the magnetic field can be “inflated“ by increasing the electron density (by further injection current), then the thus-inflated magnetic “bubble“ will trap electrons by “cusp confinement“ in which the cusp axis flow area is set by the electron gyro radius in the maximum central axis B field. Thus, cusp confinement scales as B^2. The degree of inflation is measured by the electron “beta“ which is the ratio of the electron kinetic energy density to the local magnetic energy density, thus beta = $8(\pi)nE/B^2$. Figure 16 shows two means of reaching WB beta = one conditions.

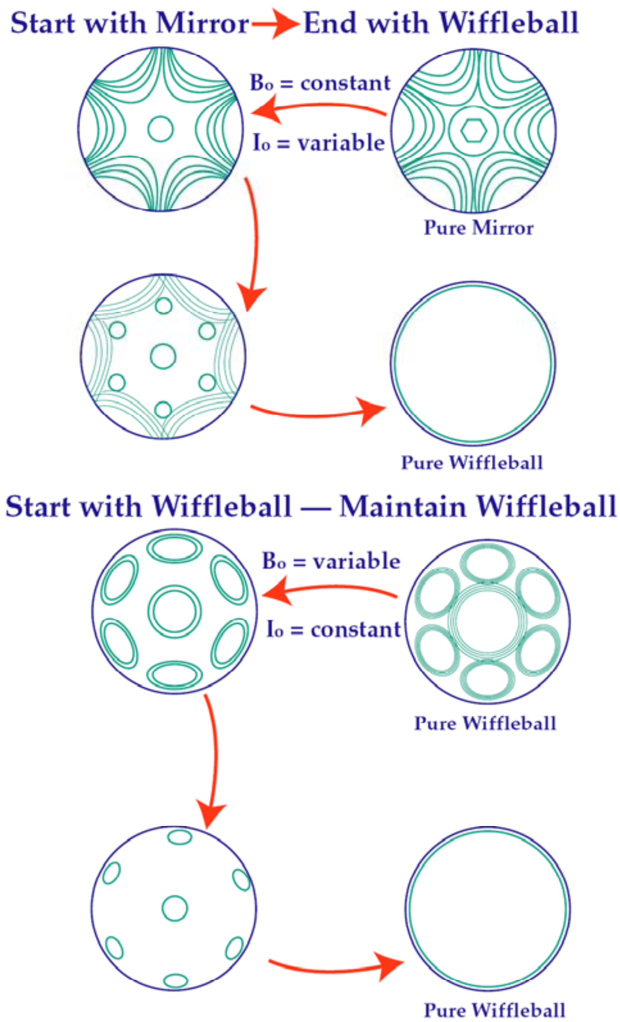

Figure 16. Two different ways of achieving wiffleball

The highest value that can be reached by electron density is when this ratio equals unity; further density increases simply “blow out“ the escape hole in each cusp. And, low values of this parameter prevent the attainment of cusp confinement, leaving only Gmr, mirror trapping. When beta = unity is achieved, it is possible to greatly increase trapped electron density by modest increase in B field strength, for given current drive. At this condition, the electrons inside the quasi-sphere “see“ small exit holes on the B cusp axes, whose size is 1.5-2 times their gyro radius at that energy and field strength. Thus they will bounce back and forth within the sphere, until such a ―hole“ is encountered on some bounce. This is like a ball bearing bouncing around within a perforated spherical shell, similar to the toy called the “Wiffle Ball“. Thus, this has been called Wiffle Ball (WB) confinement, with a trapping factor Gwb (ratio of electron lifetime with trapping to that with no trapping).

Analyses show that this factor can readily reach values of many tens of thousands, thus provides the best means of achieving high electron densities inside the machine relative to those outside the magnetic coils, with minimal injection current drive.

In a recirculating MG machine, this factor is important since it sets the *minimum* density that can be maintained *outside* the machine, for any given *interior* edge density, as required for sufficient fusion production. It is desired to keep this outside density low, in order to avoid exterior Paschen curve arcing, which can prevent machine operation. To have low exterior density of electrons, and high interior density requires large Gwb factors, thus, good Wiffle Ball confinement is essential to system operation at net power.

Thermal/Mechanical Limits On Steady-State Operation

From extensive design and experimental studies it has been found that machines able to operate in steady-state mode require internal cooling of the magnet coil windings. And this has been found impractical by any means, at the B fields required for useful fusion production, in machines below a size considerably larger than those which have been able to be studied in the EMC2/USN budget-limited program. In particular, it has been found, by detailed design studies, that superconducting (S/C) magnets can not be used practically in machines below a size of, typically 1.5-2 m radius. Below this size, water-cooled copper coils occupy less total volume (because of S/C LHe/LN2 cooling requirements) thus are more practical to build. However, water-cooled copper coils with optimal shape and configuration (for minimum electron impact losses to coil structure), able to reach conditions useful for significant fusion production, also can not be made practically below a machine size of about 1-1.5 m radius. The limitations of water-cooled copper coils made it impossible to achieve B fields above about 3 kG in the WB-4,5,6 test machines

In such Polywell® devices, the strength of the B field is determined by the total current used to create the magnetic field from its driven coils, divided by the system size/radius. This current, in turn, is fixed by the limiting current density (j+) that can be used in the coil conductors, times the cross-sectional area of these conductors. This latter is proportional to the square of the system size (for similar configurations), thus to R^2, as for the electron losses, above. Hence the maximum possible B field (for given limiting j+) is proportional directly to system size.

The engineering design configurations for normal (i.e. copper) coil conductors that can be properly cooled have been known since the beginning of this program. These require triple layer shells and internal insulation, and expensive and large scale tooling. However they can be used only in machines much larger (i.e. 1.5-2 m radius and up) than any built within the program budget and, at these larger sizes, superconductors make better coils, anyway. Machines below this size can be built with higher B fields (and thus low electron transport losses) and can be tested in Polywell mode, but *only* as pulsed, uncooled-coil machines. This limits their testing ability to, typically, a small fraction of a second (due to ohmic heating of the copper coils of the magnets).

It is thus NOT POSSIBLE to test at steady-state ALL of the physics *working in concert*, in a Polywell machine, in devices below about 1.5 m in size/radius. This fundamental fact, driven by the realities of mechanical and thermal engineering design and construction - to meet immutable constraints of the basic physics -, has made it impossible to reach the objective of a break-even fusion power machine at the sizes and scales used in the U.S.Navy IEF program conducted by EMC2 since 1991. To achieve this objective, it has now been *conclusively* proven that machines in this larger size range must be used.

Since the cost of these scales roughly as the cube of their size, the costs for proof of net power is estimated to be in the range of $ 120-180M, as compared with the approximately $ 15-18 M that has been spent over the past 13 years in this program. This estimate turns out to be completely consistent with those made originally in the earliest studies (1987-91) ever done (by EMC2) for this concept and program, which estimated a cost to proof-of-breakeven (or net power) in the range of $ 50 - $ 60 M for DD fuel, and $ 120 +M for pB11, in 1992. Scaled to today's (2005) dollars, these numbers would be very much larger.

THE FINAL MACHINE, WB-6, AND THE PATH TO FUSION POWER

Unfortunately, the ability of the program R&D work to reach full scale output conditions with steady-state operation was always limited by costs and budgets. That is why the last machine tested, WB-6, was designed as a short-pulsed machine. It was an uncooled machine, with its magnets able to run only for a few seconds at high field, and it had to be driven with (almost uncontrollable) big capacitors, to reach the e-drive currents known from basic theory to be needed (40 to a few 100 amps). These could not be supplied from the existing lab power supplies or even from the available wall power. The use of pulsed drives also forced the system to try to achieve large in/out neutral gas density ratios *without* steady-state e-driven burnout (as is essential in the basic final design) but had to make use of puff gas injected into the machine on submillisecond time scales, trying to match this with the fast discharge time of the caps; into the circuit of the machine, which was not even fully damped (RLC parameters could not be made fully stable with the equipment available).

The proper course of R&D to follow, to reach net power production has been known for a long time. WB-5 was an attempt to revisit to the first large scale closed-box experimental work (Ref. 6), to see how well electron confinement had been improved by the understanding of MaGrid insulation reached in the tests of WB-2,3,4 and MPG. It was expected that greatly increased electron trapping would result in higher electron densities at higher system starting pressures, at the same currents of e- drive. It was found that electron trapping was 1000x better than in the earlier large machine (called HEPS), with comparable electron densities at pressures over 1000x those attained in the earlier work. .However, when increased drive currents were employed to try to drive the internal densities to still higher values, the machine was unable to go significantly beyond this 1000-fold increased level, except with extreme higher currents (30 kA and up).

Extensive detailed experimental studies showed that this was due to e- losses along B-field intersect lines *into* the corners and seams (where the B fields run directly into the tank metal) of the containing tank. WB-5 was a closed box machine, like HEPS, with its coils outside - so that it could not allow e- recirculation out and back through its magnetic cusps. These losses were extensive, and attempts to reduce them by use of floating ceramic repellers placed along about 1/2 of the seam lines reduced e-losses by 2.5x but only at the price of opening up huge loss areas for trapped ions. This did show exactly how bad the unshielded metal problem was; very bad in HEPS, less so in WB-5, but actually totally intolerable in ANY machine. No matter the SHAPE of the coil/coil joint (whether sharp-corner touching or line cusp-like) what matters is that (almost) NO metal must be there at all. The coils MUST not touch and MUST be spaced apart. This is the e-loss analogue of the effect of line cusp flow paths at the spaced corners on overall trapping factors, discussed above.

Since it was always known that conformal magnet coil cans/casings were the only way to avoid B field intersect with their surfaces, but since it was difficult and costly to build such container shapes, and certainly not able to make the coils steady-state-cooled at the size/scale affordable, the design and construction of WB-6 had to use uncooled coils that could only be run in a pulsed mode. The insight derived from the experiments on WB-5 was used in the rapid design and construction of WB-6, which did use conformal coil cans and spaced coils. The last tests of WB-6 were conducted hastily during October/November 2005. These proved (by beta=one tests) to be an order of magnitude better in effective e-losses (i.e. losses greatly reduced) than WB-4. That is, the coefficient in the simplistic one-term MaGrid (MG) transport equation (for transport across the fields to the metal surfaces) normalized to experiment out at about 0.1 of that found from the WB-4 test results. This means that the effective unshielded metal surface fraction was greatly reduced in WB-6 from that of the metal structures (legs, doghouses, etc) of WB-4. The actual loss equation must have three terms for realistic modelling of the phenomena here. The first term is the simplistic one, referred to above, the second term is that concerned with e-losses to less-well-shielded or unshielded metal areas and the third term is that concerning local arcing, discussed previously.

Final tests of WB-6 were made with the fast puff-gas/cap-discharge system, starting at < 1E-7 torr tank pressure. These four definitive tests showed true Polywell potential well trapping of ions at ca. 10 kV well depth (with a 12.5 kV drive), with total DD fusion neutron output of ca. 2E5 nts over a period of about 0.4 msec; giving an average fusion rate of about 1E9 fus/sec - over 100,000 times higher than the results achieved by Farnsworth/Hirsch for DD at such low energies, and 100x higher than their best with DD even at 150 kV (Ref. 3)

This device then failed by internal coil shorting in subsequent test - the coil construction and engineering was just pushed too hard by the forced drive conditions. It is really very ironic that the program had to shut down the lab and close up - after 12 years of careful study under U.S.Navy sponsorship - just as these results have shown world record IEF output.

The only small scale machine work remaining, which can yet give further improvements in performance, is test of one or two WB-6-scale devices but with “square“ or polygonal coils aligned approximately (but slightly offset on the main faces) along the edges of the vertices of the polyhedron. If this is built around a truncated dodecahedron, near-optimum performance is expected; about 3-5 times better than WB-6. This is somewhat like a combination of MPG-1,2/WB-6, and it must also be run in the puff-gas/cap-discharge mode (as for WB-4,6) to reach useful conditions. This will also incorporate another feature found useful, that is to go to a higher order polyhedron, in order to retain good Child-Langmuir extraction by the machine itself (which is more straightforward than relying on stand-alone e-guns for the cusp-axis, very-high-B-field environment), while not giving excessive electrostatic droop in the well edges. These small scale tests are discussed further, below.

PHYSICS AND ENGINEERING ASPECTS OF PULSED OPERATION

On fusion output; the two machines that have run best, with ions trapped at near- electron-drive energies in the e-driven deep electrostatic potential wells, and ion acceleration by falling into these wells, with subsequent fusion, were WB-4 and WB-6, both in their last week of life. In both of these, neutral density in/out ratios needed to avoid Paschen arc breakdown outside the machine (for a very short time), was achieved by fast puff gas input directly into the machine interior edge.

As the neutral gas filled the machine interior, fast injected electrons created ionization in this gas. The ion and electron densities produced by this fast ionization were too low to drive the system to the electron beta=one condition. However, the low energy electrons resulting from this ionization rapidly cascaded with additional neutral atoms, being driven by electron/electron collisions with the incoming injected fast electrons, and made still more low energy electrons. The cascade time e-folds at a rate of 1/(no)(sigmaizn)(veo), where (no) is neutral density, (sigmaizn) is ionization cross-section for low energy electrons at speed (veo). Typically, for no = 1E13 /cm3 (i.e. ptorr = 3E-4 torr), veo = 1E9 cm/sec (Ee = 100 eV), and sigmaizn = 1E-16 cm2, the cascade e- folds with a time constant of about 1E-6 sec (one usec). Thus all of the neutral gas is ionized and the system is filled with low energy electrons in only a few usec. Wiffle Ball trapping works very effectively here. If all the electrons were still at ca. 100 eV, the surface beta would be about beta = 0.01, at B = 1000 G.

However, the low energy electrons are heated by fast collisions with incoming fast injected electrons. The Coulomb energy exchange time for this process is also about 1 usec. Thus the device will reach beta = one conditions when the mean electron energy is about 2.5 keV, in ca. 20 usec. Beyond this point excess electron density will be driven out beyond the beta = one limit; the field will have expanded as far as it can within MHD stability limits.

This process uses “cold“ electrons to start, with “hot“ electrons as drives, to yield a beta = one population of “hot“ electrons. Of course, while the terms —cold“ and hot“ imply Maxwellian temperature distributions, these systems do not exhibit this on the time scales of interest. This is called the “two-color“ electron startup mode, and will work for any machine which is e- driven and supplied with neutral gas input at the proper rate. This is the preferred method of startup for reactor-scale systems.

The overall result is that a deep potential well is provided in a few tens of usec, and the ions formed by ionization are trapped within this well, heated by the fast e- injection to well depth energy, and thus yielding fusion. However, the cap drive current ran away as the internal puff gas supplied leaked out into the volume around the machine and led to external arc shutdown. The arcs were from feedthrough leads into the main vacuum tank and the tank walls, and had nothing to do with the machine or its containing cage/shell. This took place over 0.5-2 msec after puff-gas actuation, so little time was available for true Polywell operation. The cap drive current to the test system then ran away to over 4000 A to this external feedthrough arcing, as the Polywell formed and fusions occurred. This destroyed the well depth (due to drop in drive voltage). However the system did run at emitter currents (to the machine) of 40 A for about 0.3-0.4 msec, proving the basic concept. Figures 17 and 18 show data from these tests.

Since the electron transit lifetime in the machine is about 0.1 microsec, even 1 msec is 10,000 lifetimes, so the process looks like “steady-state“ to the electrons (and their trapped ions). Using this pulsed puff-gas technique, DD fusion output was attained from WB-4 three times in December 2003, and (as noted above) world‘s record outputs from WB-6 in four tests during November 2005. These results show, firstly, that Polywells, driven properly, do work and, secondly, that we actually do understand how they work and thus can design and build full-scale systems with confidence.

Of course, for the steady-state operation of the basic concept, what is needed are large controllable power supplies, much larger machines (but still only to about a maximum size of 2 m radius), and controllable gas supplies and e-guns able to survive their B and E fields and gradient environments. With these the machines can be driven initially via internal neutral gas burnout, and can use the “two-color“ electron energy/density method (which has been known since 1994) to drive startup. As described above, this two-color effect (starting with “dense “cold“ electrons and transitioning very rapidly to less dense “hot“ electrons, by energy exchange

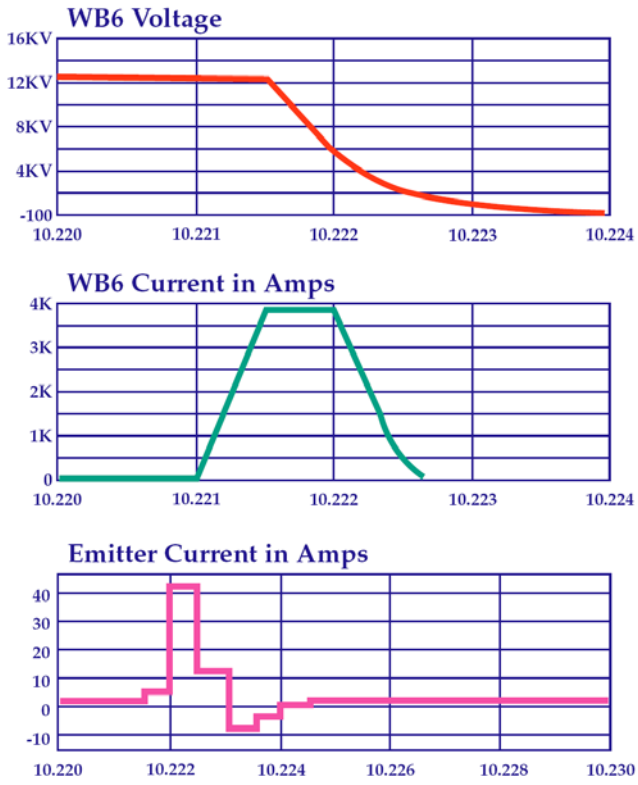

Figure 17. Input parameters in experiments with WB-6

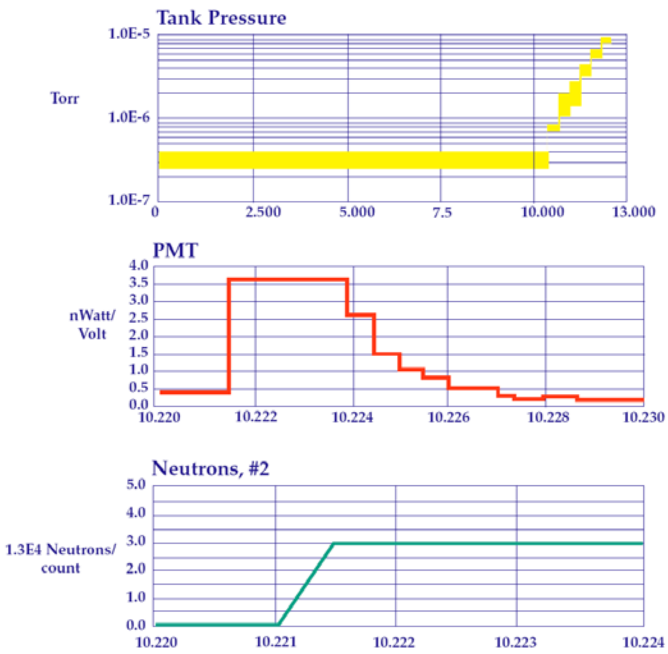

Figure 18. Neutrons obtained during WB-6 experimentation

collisions with incoming injected electrons) will occur automatically in any machine, as employed in the pulsed cap-driven tests of WB-4 and WB-6, if background neutral gas is used by fast electron injection as a source for initial ionization within the machine.

FUSION POWER RDT&E FOR NET POWER PLANTS

While all the basic features and engineering physics constraints have been determined from the R&D work to date, there are several additional tests of small-scale machines that could yet provide valuable information for further definitive design of the next step to full-scale machines. These would be modified versions of WB-6, with emphasis on exact matching to the basic patent descriptions, to best fit the physics requirements of electron confinement and loss suppression. In addition, some effort could usefully be put into development of final configurations of cusp-axis electron emitters, and of cusp-axis repellers able to operate as secondary electron emitters under ion bombardment, to allow easy supply of electrons to these machines. Unfortunately, all such remaining small-scale tests must yet be conducted in short-pulsed mode, as previously described.

Remaining Small-Scale Experiments

- **1)** Design, building and parametric testing of WB-7 and WB-8, the final two true polyhedral coil systems, with spaced angular corners, to reduce "funny cusp" losses at the not-quite-touching points, and yet provide very high B fields with conformal coil surfaces. These would be topologically similar to the original WB-2 and PZLx-1, but without their excessive unshielded surface losses, and with pure conformal coils and small intercept fractions. These latter can be achieved by appropriate spacing between the corner junctions (typically several gyro radii at the central field strength between adjacent coils) to allow free circulation of electrons and B fields through the "funny cusp" regions, without direct B field line impact on or intersection with the coils themselves.

These should be tested best in an external vacuum system, with capacitor-driven power supply for the electron injection drive, and be driven to fusion conditions for a period of several tens of milliseconds. If these achieve true minimal losses (as derived from WB-6 results), electron trapping factors of Gmj > 5,000 will be achieved and thus yield significant fusion output, because of the very low loss design configuration of these machines. To achieve this will require both high e- drive currents (see above re secondary ion-driven sources), and controllable, pulsed, neutral gas input to the machine interior.

Tests should be run in both of two possible electrostatic potential configurations. First, with the machine as the only object at high potential, being placed at high positive potential, with the emitters and surrounding cage or shell at ground. This ensures that the only attractor for electrons will be the machine itself, so that electron losses to external structure will be kept to small levels.

Second, with all of the system components except the emitters (and associated repeller plates on axes of the cusp systems) held at ground potential, and only the emitters and repellers at high negative potential. This has the feature that the electrons recirculating through the cusps must return via magnetic field capture, else they will "see" the attractor potential of the surrounding shell and be lost. WB-4 was run in this manner and found to lose 95% of its injected electrons to attractive ground potential structures outside the machine, through a tight beam along the cusp axes. Figure 7 shows this effect in operation. Repellers/emitters on all cusp axes may be used to suppress such losses, but their diameter must be kept small relative to the cusp "hole" size/diameter.

This loss mechanism may also be mitigated by operating the external surrounding shell or cage at slightly negative potential relative to the machine, thus providing a degree of electrostatic trapping for the emitter/repeller electrons. Either system is expected to operate successfully, from prior results on WB-4 et al.

- **2)** Building and test of both ion sources and high-output electron guns and secondary electron emitters, for eventual use in large, full-scale machine drives. These may use hollow cathode techniques and (possibly) magnetron gun design concepts. Rugged and survivable e- and/or i+ guns, adequate for the needs of large machines, can be built based on present knowledge from past work. These may also invoke the use of neutral gas input through the ion/electron guns themselves, thus enhancing the ionization of neutrals as they stream into the machine interior. And, in large-scale machines, experiments to date and design models suggest that ion supply may be best accomplished by use of the "two-color" electron/neutral in-situ ionization process previously described as the main source of ions in the fast pulsed experiments. This effect will occur over only a few cm of outer radial position in any system that is designed to operate at reactor power conditions.

Longer-Term Program Needs

To proceed to realistic clean fusion power, what is needed is a long-term commitment to support this effort at the level cited above (and since 1991). On the main Polywell development, all the work done to date has been successful in illuminating the physics and engineering requirements for these systems. However, as previously remarked, it was not possible to make power breakeven fusion at the much-too-small machines, equipment, funding and staff available. It was clear from the beginning of this work (and has been so told to the DoD since 1987) that 10x more funds and people were needed, and the estimates of program size, scope and scale required for net power fusion systems have hardly varied over the past 13 years. The achievement of fully reliable e- guns required a team of 3 people working for 4 years to develop them, same for i-guns, same for diagnostics, same for microwaves, same for magnet design, same for machine design, same for theory/codes, etc, and these were needed at a machine scale of at least 1.5-2 m radius.

The work done did study, analyze, and experimentally prove all of the critical physics and engineering issues at small scale, in a way that allows scaleup to the full machine size, and it is now possible to build the e- guns and ion sources needed. Fortunately, scaleup is possible with this approach, because the dominant physics is classical, and thus readily predictable given the known and proven MG transport loss models and equations.

The only next useful step is to conclude small scale work (as described previously) and then undertake a full-scale net-power demonstration IEF system, to show total plant feasibility.

It is important to emphasize that there is nothing significantly new to be gained by further tests at sub-scale sizes (i.e. less than that needed for net power). This is an inherent consequence of the way in which the fusion power output (Pf) and system gain (Qf. ratio of fusion power to drive power) scale with the machine size (R) and electron-confining magnetic field (B). Fusion power scales as the fourth power of the B field and the cube of the size, thus $Pf = (k1)B^4R^3$, while the unavoidable electron injection drive power loss scales as the surface area of the machine, thus is proportional to R^2. Assuming the use of super-conductors for the magnetic field drive coils, the electron losses are the only major system losses. Then, the ratio of these two power parameters is the gain (Qf), which is thus seen to scale as $Qf = (k2)\ B^4R^3/R^2 = (k2)\ B^4R$.

Because of this B^4R^3 scaling of fusion output, which makes fusion power scale as the 7th power of size, and the corollary 5th power scaling of system gain, it is obvious that little can be gained short of building the next system at full-scale. Further tests at the present small scale (1/10 of that needed) will not tell much more than is already known - and R&D at 2 or 3 times the present level still does not come remotely close to reaching the conditions to prove net power.

To demonstrate net power requires a full-scale system, that can be run steady-state, cooled and with controllable timing and power supplies. And this can be done only with a funding level of $ 150 M (DD) to $ 200M (pB11), over a program duration of about five-years of carefully directed and guided effort. Given this level of funding and the DT&E it will pay for to achieve pB11 net power from a full scale demonstration system, a full scale demo plant could signal the eventual end of dependence on oil and all other fossil fuels by CY 2013. Subsequent full scale synthetic fuels and direct electric power plants could then be built over following decades by ca. CY 2030-2040. And work could begin on the application of such systems to superperformance space power and space propulsion systems, as well. The cost of this program is less than 1/8 that of the present magnetic fusion program of the US DoE.

It is sufficiently small that such a program could be undertaken by a wide variety of organizations and countries interested in solving the problem of world energy politics and economics. Countries which could logically develop interest in such an effort include China, India, Russia, Brazil, Argentina, Venezuela, Spain, Italy, and others - but none beholden to the large scale on-going expenditures in the so-called "magnetic confinement" programs of the Western technological nations.

EMC2's interest in this effort is simply to see it reach conclusion, and thus to solve the problems posed by excessive dependence on controlled fossil fuel resources - most notably oil. The achievement of full scale IEF clean fusion power systems would allow easy access to energy, both thermal and electrical, for all nations, and all peoples, everywhere - free from cartels and controlled production and pricing. This is a goal worthy of pursuit, and EMC2 will be happy to work with any organization interested in undertaking such a venture.

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