An Industry Emerges

"We're here to put a dent in the universe, otherwise why else even be here?" – Steve Jobs

ITER is expensive. Nobody knows how much. It could be 16, 21 or 50 billion dollars [9-12]. It is not going to be commercial at that price. Moreover, ITER will never make energy. That was fine, when it was the only path to fusion power. But that is not true anymore.

NIF has failed. It cannot get ignition [17]. Even if it could, would it be commercial? The machine is complex. It is expensive and inefficient. Heaps of taxpayer dollars were spent on this. The public should be furious. Someone needs to be held accountable.

These efforts have stalled. Their future looks dim. But, we cannot wait fifty years for fusion power. Climate change will not allow us. Young fusioneers realize this. They are not joining ITER or NIF. They are joining a new breed of companies. Together, they are building an entirely new fusion industry. Their collective hope, is to put a dent in the universe.

The Staff Of General Fusion:

Executive Summary:

This post examines alternative fusion as a fledgling industry. Fusion and climate news from July to November 2014 is summarized. An argument for alternatives over the laser or tokamak family of concepts is made. Alternative fusion includes: polywells, fusors, dense plasma focus, beam fusion, field reversed configurations and cusp confinement. It is estimated that this industry has ~450 million invested and engages ~330 people across ~12 organizations. These companies suffer from the classic first-mover problems: training talent, attracting capital and technical hurdles. Designs are compared using their neutron rates, shot time and energy extraction method. The implications of the energy balance on conduction loss, radiation and efficiency is mentioned. Four new principals for fusion power are presented. These are: avoiding a thermalized ion cloud, electric heating, cusp confinement and direct conversion. The post ends with a discussion of the implications and potential of these changes.

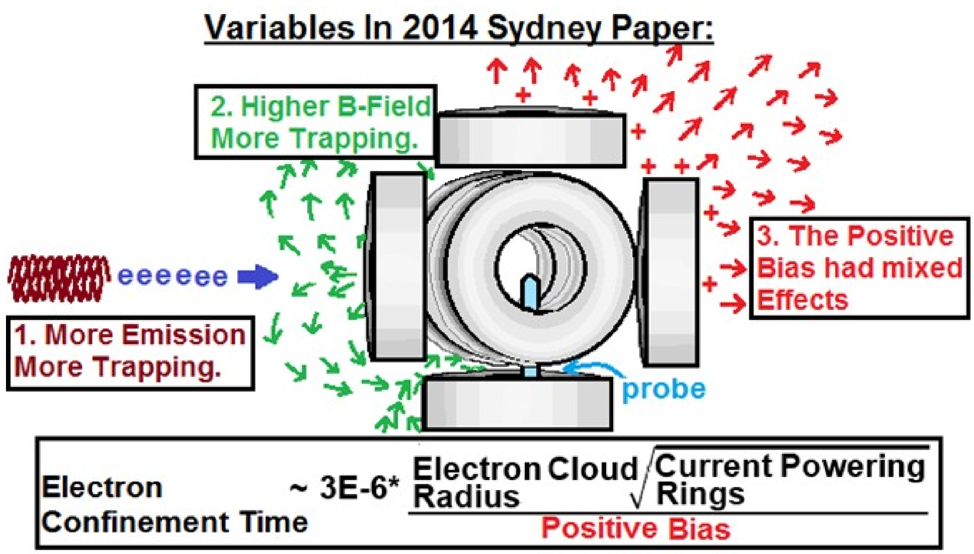
News:

In July, both Science and Nature reported on alternative fusion [31, 32]. This was a major milestone. It put a new spotlight on researchers who had been laboring away in obscurity. Natures' article was more critical - covering Tri Alpha, Helion and General Fusion. The Science work was longer and upbeat. It detailed General Fusion, focus fusion, Tri Alpha and the polywell. The author, Daniel Clery was just publishing a great new book on fusion [38].

The Staff Of Phoenix Nuclear Labs:

In August, Phoenix Nuclear Labs announced it could churn out 100 billion neutrons a second, for an entire day [34, 35]. Wow. That is 24 hours of constant fusion. That is 1,400 times longer than the worlds' best tokamak [65]. This hints at what is possible when you use an electric field to heat ions to fusion conditions. Also in August, the government finally moved into alternative fusion. ARPA-E started a program named alpha. The budget of 30 million should fund about ten projects [13]. ARPA-E sees only two paths to fusion power. Laser fusion makes a high density plasma, while tokamaks makes a low density plasma. They want a third, middle range, high repetition option. By middle densities, they mean 1E18 to 1E23 ions per cubic centimeter [14]. Dr. Bussards' polywell got there (1E19) but Dr. Park's did not (1E16) [18, 3]. This request says much more about the governments' antiquated thinking. First, these new devices do not all pulse. Fusors can run continuously. Secondly, many schemes have no need for ‘drivers’ and ‘targets’. General Fusion and Tri Alpha are notable exceptions [19,20].   But, the polywell, the dynomak and Lockheeds’ designs do not work this way [21, 1, 27, 28].

In September, a fifth paper was published by the University of Sydney [29]. Their old papers have been covered on this blog [39 - 45]. Their new polywell has better electron injectors and is ten times stronger. The team also built a new capacitance probe. Validating this probe was hard. This was used to measure the voltage in the polywell, under different conditions. This work is illustrated below.



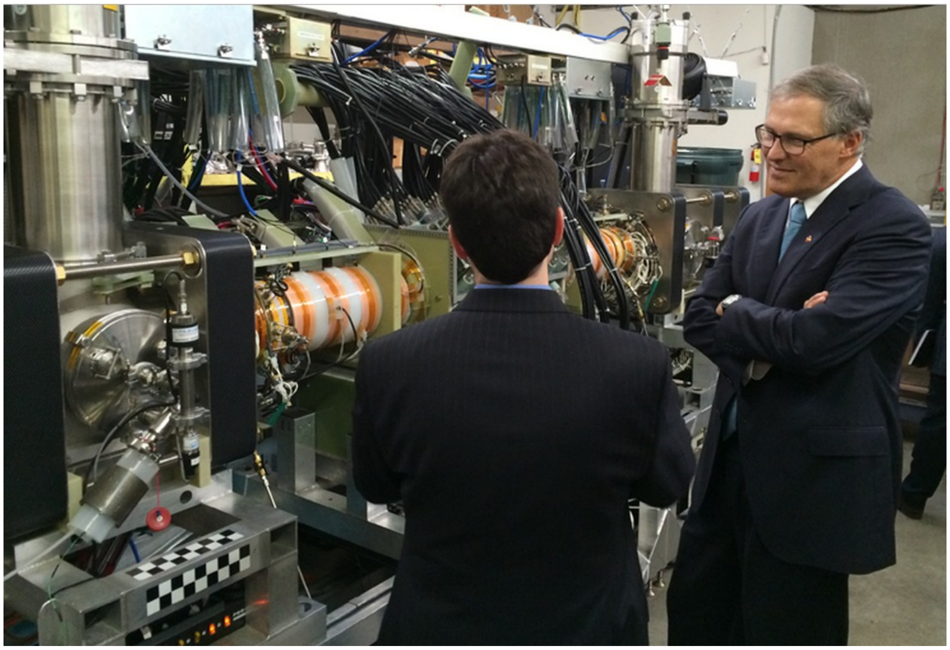
The coil made electrons that were attracted to the positive rings. As they approached the magnetic field overpowered, drawing the electros into the trap. The probe measured the amount trapped. The team found that trapping increased when more electrons were emitted. It also got stronger as the magnetic field rose. This is not surprising. Of the two variables, emission was more powerful. Trapping was connected to these variables with some rough math. You should [read the paper yourself] [39].

The Lockheed Martin Team:

In October, Lockheed Martin revealed its fusion technology. This got international press [46 - 52]. Lockheed failed to give any data. They opted for a dreamy video and three patents [27, 28, 52]. This is unacceptable. We are building the case for fusion power. This is a long term effort. It can only be sustained by a community. A community of teachers, engineers, investors, policy makers, academics and businessmen. Everyone has a role here. The community needs to hear the newest data, presented in a clear manner. When this system breaks down – bad things happen. Lockheed should have done a paper before issuing a press release. Finally, the 16th IEC conference was held at University of Wisconsin Madison. The polywell had a big impact this year. Dr. Park gave a polywell keynote and Dr. Santarius discussed his modeling efforts [53]. Devlin Baker premiered his excellent modeling code and George Miley discussed the IEC family of technologies. Dr. Hirsch predicted that ITER funding would fall and IEC research could rise in its' place [53]. It was a good conference.

As 2014 came to an end, the IPCC issued its' most damning climate change report to date [138]. The atmosphere and oceans have already warmed. The snow and ice packs have already melted. The sea has already risen. Carbon dioxide has reached levels not seen in the last 800,000 years [137]. Ban Ki-moons' words were unequivocal: "Science has spoken. Time is not on our side. Leaders must act" [136]. Will leaders act? They have failed so far. Money seems to be the main obstacle. If you do not think money runs the world: ask someone with a job. Burning things for energy, is just so damn cheap. Fusion power could all change that. We are here to try for that solution. We must act, if our leaders fail to. We are running out of time.

Washington State Governor Jay Inslee Visits Fusion Startup Helion:



"If you can't fly, then run, if you can't run, then walk, if you can't walk, then crawl, but by all means keep moving" – Martin Luther King

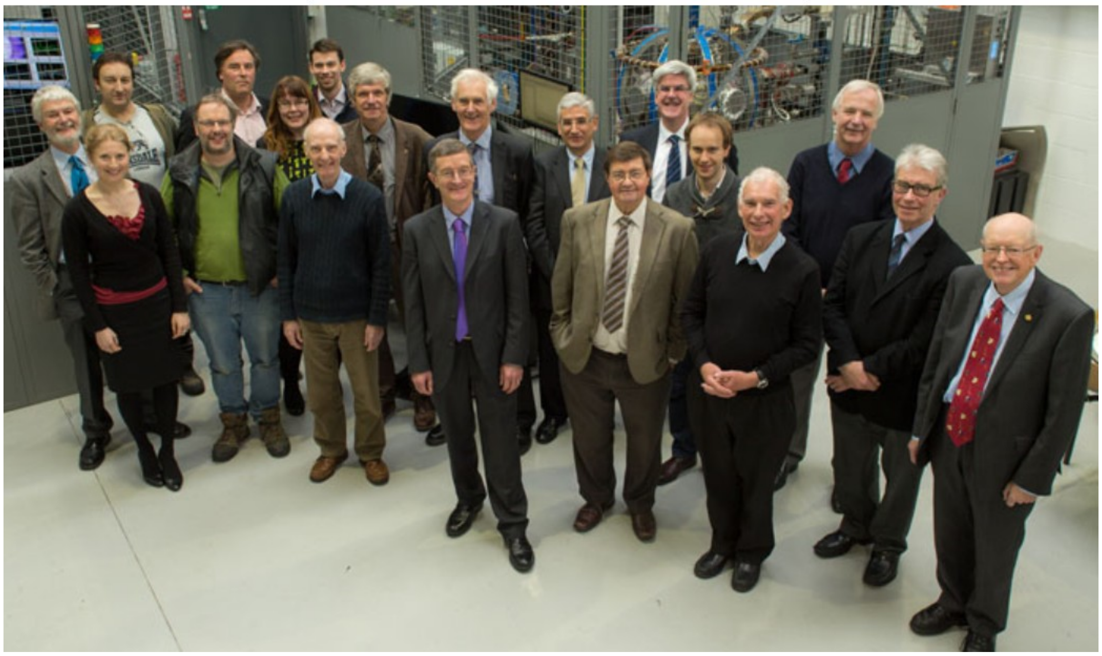
Old ideas are ending:

Traditionally, fusion has focused on any idea in the laser or tokamak family. Laser fusion means inertial confinement fusion. This includes: direct drive or indirect drive, fast ignition or magneto-inertial fusion [54]. Basically, any time you are squashing stuff with a laser. This set of ideas has received over 12 billion in US funding in its' fifty year lifespan [36]. Currently, it has a poor outlook. The flagship machine, NIF, was costly and complex. It was also a colossal failure [55]. The other family of ideas revolves around the tokamak. The tokamak family covers: spheromaks, the levitating dipole and all the stellerator designs [56, 57]. Basically anytime plasma is raced around in a loop. Over 177 tokamaks have been built, designed or operated. The newest version, ITER is very expensive, complex and behind schedule [64]. Things are not going well.

Even attempts to commercialize the tokamak are not succeeding. Tokamak Solutions is a British startup doing just that. It was founded in 2009 [98]. But, after spending 10 million, the company is little more than a diversion for retired scientists. The staffs' average age is over 60 [58 - 63]. They speculate about using the Tokamak as a neutron source. If this is their business model - they are going to get killed. Phoenix Nuclear Labs has already commercialized a smaller, cheaper and better neutron source. Their technology is based on fusors a much simpler path to fusion plasmas [35]. Bottom line: tokamaks and lasers are on their way out.

This is a historic. For decades, our focus has been on just "getting there". Merely getting fusion. This meant holding a hotter plasma with a higher density for longer. This is known in the field, as the triple product (density, temperature and confinement time). People ran roughshod over price, scalability, efficiency or size. No one cared: they built massive, expensive and complex machines. But today; we have arrived. We can do fusion - continuously - for thousands of hours, and for thousands of dollars [35, 22]. We are done with "getting there". The next step is commercialization.

The Staff Of Tokamak Energy:



An alternative fusion industry:

Since 2000, a dozen fusion companies have been founded [73-105]. Together, they represent a fledgling new industry. The alternative fusion industry. What does this industry look like? I estimate that as of December 2014, it has roughly 450 million in total investment [73-105]. It also engages roughly 330 people [73-105]. These people are spread across a dozen organizations. A summary of some of the relevant groups is given below [73-105].

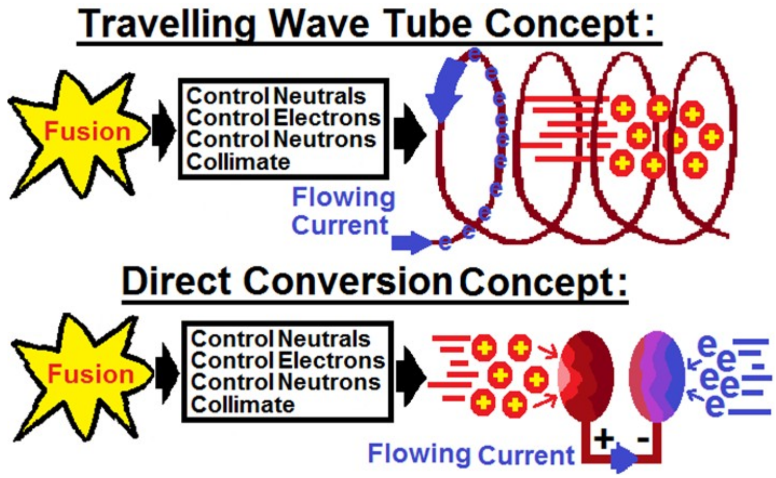
Organization:	Technology	Found/End	Participants	Est. Amount:
EMCC	Polywell-ish	1987 / -	22-30	$ 41,728,353
CSI	Polywell-ish	2010 / -	4	$ 120,000
Radiant Matter (Guess)	Polywell-ish	2010 / -	2	$ 30,000
Lockheed Martin (Guess)	Polywell-ish	2007 / -	6-8	5 to 10 Million
Iran Polywell (est)	Polywell-ish	2010 / -	8	$ 8,000,000
Pomethius Fusion Perfection	Polywell-ish	2008 / 2013	2	$ 40,000
SHINE Medical	Fusor-ish	2010 / -	15-25	$ 134,000,000
Phenoix Nuclear Labs	Fusor-ish	2005 / -	25-30	$ 34,874,182
Tri Alpha Energy (est)	Field Reverse	1998 / -	150	$ 150,000,000
MSNW	Field Reverse	1994 / -	7-11	$ 5,000,000
Helion	Field Reverse	2010 / -	4-11	$ 6,500,000
LPPX	Focus Fusion	1974 / -	7	$ 4,480,279
General Fusion	Mag. Target	2002 / -	60	$ 55,000,000
FP Generation	Beam Fusion	2009 / 2011	6	$ 3,000,000
		Total:	334	$ 450,272,814

These firms are expanding several root technologies simultaneously. These are: polywells, fusors, dense plasma focus, beam fusion, field reversed configurations and cusp confinement. There is plenty of overlap. For example: general fusion has a hybrid between a field reversed configuration and a laser fusion style implosion [33]. Because it is so new - the industry suffers the classic "first-mover" disadvantages. They have to find a way to get funding, train talent and solve incredible technical problems. The groups have plenty in common: determined founders, failures and funding issues. The collective goal is fusion energy - but there are differing views on how get there.

Paths to fusion power:

All these concepts work with plasma. This is a soup of electrons and ions. The goal for every idea is to make the ions collide and fuse. This makes neutrons. The more neutrons, the more fusion. Amateurs can make a million a second [22, 23]. Phoenix Nuclear Labs can do 100 billion while JET can do at least 16 quadrillion (the world record) [24, 65]. Next, you must sustain fusion. This "shot time" is driven by containment. Focus fusion argues that all they need is a nanosecond for net power, while General Fusion is aiming for hundreds of microseconds and Tri Alpha Energy says it can do 5 milliseconds [30, 31, 66, 67]. But who knows? Mr. Griengers' homemade fusor can fuse for hours at room temperature [22, 23]. Could the polywell give the same behavior? Dr. Park has suggested it; especially if the plasma can be heated steadily [1].

Once you contain the hot plasma, you must extract energy. Not every team has planned this far. General Fusion wants to absorb everything in a liquid blanket, heat it and make steam [29]. Focus fusion has suggested a traveling wave tube [30]. Polywellers have pushed for a form of direct conversion. These last two ideas are shown below.



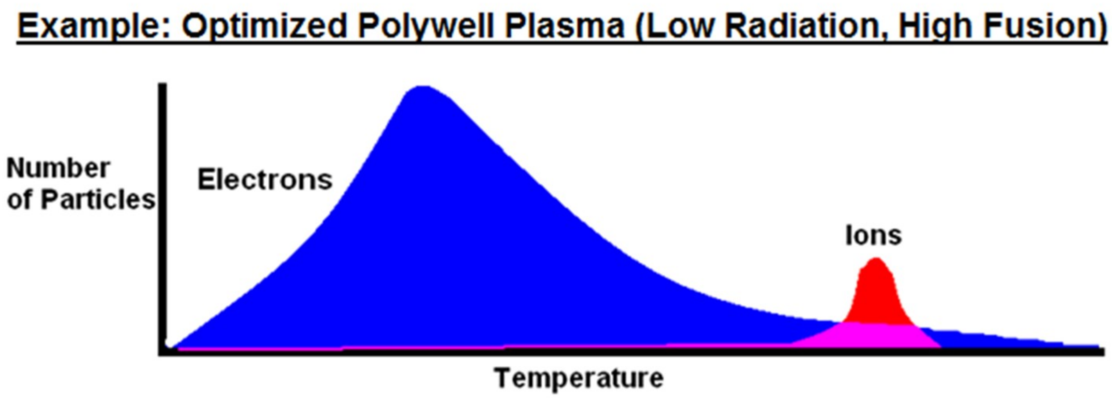
Here is how these ideas work: exhaust from fusion is a mixture of neutrals, ions, electrons and gas. It is a mess. It comes off in all directions. It comes off at many speeds. First, we must beat this stuff into submission. Ideally, we only want a beam with one kind of charge. The traveling wave tube uses a positive beam. Ions fly down the center. They pull electrons from the surrounding wire. This makes a flowing current. Direct conversion puts metal in the way of the beam [127 - 129]. Ions are absorbed – holding one side of a circuit, steadily positive. You can draw a current from this. Several teams have discussed integrating these extraction methods directly into their design [20, 122]. But, though we can do relatively cheap fusion, for hours [22, 23, 35] no commercial team can steadily draw a current from fusion. Not yet.

The Energy Balance:

What comes after energy collection? Optimization. That will revolve around the energy balance. Any hot plasma concept must grapple with this equation.

$$\text{Net Power} = (\text{Fusion Rate} - \text{Conduction} - \text{Radiation}) \times \text{Efficiency}$$

John Lawson gave us this equation in 1957 [108]. It is the energy balance for a machine fusing with a hot plasma. We have always merely tried to boost the first term: the fusion rate. But we may finally be changing focus. The next term is conduction. This is the loss of mass. Anytime a plasma touches a surface, it is lost. The newest designs (polywells, Lockheeds' machine, the dynomak, Phoenix Nuclear Labs' device) all appreciate this. They all have smooth surfaces - and some cases, no surfaces at all. Both PNL and the polywell have vast spaces in the center [1, 24]. Space without a solid wall limits conduction loss. After this comes the radiation term. If a particle ***ever*** changes speed, it loses some energy as light [109]. This happens everywhere inside the cloud, and for many reasons. Radiation is a function of cloud composition, temperature, density, size and structure. Fusioneers are ***just*** starting to tune their plasmas to beat this problem. For example: the polywell works best with tons of cold electrons, and a few hot ions [25].



Can this distribution be done? We do not know – mixing and instabilities will fight against it [130]. But, it is possible to make plasmas which do not have the common bell curve [25, 110]. Tuning plasma clouds to beat radiation loss is going to be important. Finally, there is machine efficiency. Most fusion machines are very inefficient. NIF is one example. It takes 200 units of electrical energy to make one unit of laser energy [72]. New methods for energy capture will go a long way to improve overall efficiency. Realize: if the energy balance was correct; the fusor could make net power.

New Design Principals:

Wither they know it or not, these groups are embracing a new set of design principals. I call these the new principals of fusion energy. They that have emerged in the past 10 years - outside tokamaks and laser fusion worlds.

1. The Blob is Death. In 1994, Todd Rider assessed the polywell theoretically and came to conclusion it would fail [5, 106]. This post can walk you through his work [107]. Rider did something even more profound, that few appreciate. He told us ***what not to do.*** He showed that if you merely have a hot plasma blob, you cannot expect net power. A "blob" is a hot, thermalized, uniform, unstructured cloud of ions. The blob is death. Anything you can do to get away from the blob, helps. This includes squeezing the plasma (ICF, General Fusion, Sandias' Z-machine) spinning the plasma (Tri Alpha Energy, ITER, JET, Helion), flattening the plasma (focus fusion, theta pinch) or structuring the plasma (polywell, Lockheed). The further from the blob, the better.

2. Electric heating. You can accelerate ions down a negative voltage, heating them to fusion temperatures [131]. Today, this is the ***cheapest and simplest method*** for heating to fusion. This is arguably far better than options like radiofrequency heating, neutral beam injection or magnetic oscillation. Radiofrequency heating works in the same way that a microwave heats food [21, 27, 28]. Beam injection starts by heating the gas; by temporary charging it and racing it down a voltage [132]. The beam is then neutralized and shot into the reactor. Magnetic oscillation (as I understand it) varies the field around a plasma. Lockheed is notably following this last path [21, 27, 28].

3. Cusp confinement. You can hold a plasma with a sharply bent magnetic field [1, 133-135]. This has been long predicted – but never seen until Parks' work [1]. There are many unknowns, but if it is successful - it may lead to ***the worlds' best plasma trap.*** In these systems, the plasma "pushes back" the containing field. This makes to a magnetic free region with an electric current flowing on its' skin [133-135]. Theoretically, this structure is stable; but who knows? There are a myriad of instabilities which could destroy it [130]. We may know much more when Lockheed publishes what it has learned on their system [21, 27, 28].

4. Direct conversion. Direct conversion has been discussed for decades. The trend of incorporating it directly into designs is what is exciting. This was tested on the TMX fusion device and it ***achieved a 48% efficiency*** [128].

Summary:

Certainly, fusion is changing. We need to stop seeing it as a hodge-podge of technological novelties and start seeing it as a fledgling industry. An industry where innovation is happening much faster than in "big science". An industry which must work around price. Where will all this take us? No one knows. My hope is to a cheap, scalable, clean, carbon-free energy source for all mankind. My hope is we can summon effort needed to build this tool and the wisdom to use it wisely.

Partial list of commercial funding into fusor based technology

Entity	Amount	Founder	Source	Award Date	Founded
FPGeneration	$ 3,000,000	Alex Klien	Unknown	2009 to 2011	2005
Phoenix Nuclear Labs	$ 500,000	Greg Piefer	NNSA Grant for Moly-99 Production	10/4/2010	2005
Phoenix Nuclear Labs	$ 20,600,000	Greg Piefer	NNSA Agreement, WIFD, moly-99 production	5/26/2012	2005
Phoenix Nuclear Labs	$ 879,000	Greg Piefer	US Army SBIR Phase II IED Dectect	10/22/2012	2005
Phoenix Nuclear Labs	$ 100,000	Greg Piefer	Army SBIR I Nuetrons For White Sands	10/22/2012	2005
Phoenix Nuclear Labs	$ 3,000,000	Greg Piefer	Army Contract -neutron radio	October 2014	2005
Phoenix Nuclear Labs	$ 590,500	Greg Piefer	angel investors	5/26/2012	2005
Phoenix Nuclear Labs	multimillion	Greg Piefer	First Sale - UE Nuclear Control	Feb 25,2014	2005
Phoenix Nuclear Labs	$ 1,150,000	Greg Piefer	private equity funding	Feb 25, 2014	2005
Phoenix Nuclear Labs	$ 250,000	Greg Piefer	Wisconsin Economic Development	Feb 25, 2014	2005
Phoenix Nuclear Labs	$ 998,134	Greg Piefer	DOE SBIR Phase II H-Ion Source	2014	2005
Phoenix Nuclear Labs	$ 149,182	Greg Piefer	DOD, SBIR I, Neutrons for Measuring Stress	2013	2005
Phoenix Nuclear Labs	$ 99,857	Greg Piefer	USAF, SBIR I, Alternative Neutron Source	2013	2005
Phoenix Nuclear Labs	$ 149,509	Greg Piefer	SBIR I, H- Ion Source	2013	2005
Phoenix Nuclear Labs	$ 174,928	Greg Piefer	SBIR I, PET Isotopes Production	2010	2005
Phoenix Nuclear Labs	$ 2,333,084	Greg Piefer	SBIR II, Army, neutrons for radiography	2009	2005
Phoenix Nuclear Labs	$ 729,988	Greg Piefer	SBIR II Army, neutrons for radiography	2009	2005
Phoenix Nuclear Labs	$ 70,000	Greg Piefer	SBIR I, Army - Neutrons for radiography	2007	2005
Phoenix Nuclear Labs	$ 100,000	Greg Piefer	STTR I, NASA - Non-ambipolar Electron Source	2006	2005
Shine Medical	$ 2,400,000	Greg Piefer	State of Wisconsin	9/3/2014	2010
Shine Medical	$ 125,000,000	Greg Piefer	Deerfield Equity	10/9/2014	2010
Shine Medical	$ 6,600,000	Greg Piefer	DOE/NNSA - Agreement	11/17/2014	2010

Partial list of commercial funding into polywells

Entity	Amount	Founder	Source	Award Date	Founded
Iran Polywell Effort	$ 8,000,000	Unknown	Iran Government	2010	2010
Convergent Scientific	$ 120,000	Devlin Baker	Unknown	2010 to Present	2010
Radiant Matter Research	Unknown	Rambonnet & de Lang	TU Delft, Octavio project	Unknown	2010
Lockheed Martin	Unknown	Tom McGuire	Unknown	Unknown	
EMCC	$ 99,123	Bussard	NAVY	11/5/2008	1987
EMCC	$ 99,355	Bussard	NAVY	12/8/2008	1987
EMCC	$ 99,355	Bussard	NAVY	12/17/2008	1987
EMCC	$ 299,843	Bussard	NAVY	3/3/2009	1987
EMCC	$ 331,174	Bussard	NAVY	5/20/2009	1987
EMCC	$ 3,216,825	Bussard	NAVY	9/11/2009	1987
EMCC	$ 1,350,000	Bussard	NAVY	9/10/2010	1987
EMCC	$ 100,000	Bussard	NAVY	5/8/2011	1987
EMCC	$ 2,022,678	Bussard	NAVY	6/22/2011	1987
EMCC	$ 1,200,000	Bussard	NAVY	5/3/2012	1987
EMCC	$ 1,120,000	Bussard	NAVY	8/23/2012	1987
EMCC	$ 1,660,000	Bussard	NAVY	9/10/2012	1987
EMCC	$ 600,000	Bussard	NAVY	2/25/2013	1987
EMCC	$ 300,000	Bussard	NAVY	4/29/2013	1987
EMCC	$ 780,000	Bussard	NAVY	5/21/2013	1987
EMCC	$ 400,000	Bussard	NAVY	5/16/2014	1987
EMCC	$ 250,000	Bussard	NAVY	7/7/2014	1987
EMCC	$ 25,100,000	Bussard	Various (HEPS, ECT..)	Found to 10/2008	1987
EMCC	$ 1,800,000	Bussard	NAVY	8/23/2007	1987
EMCC	$ 900,000	Bussard	Office of Naval Research	11/1/2005	1987

Partial list of commercial funding for MTF, tokamaks and dense focus

Root Technology:	Entity	Amount	Founder	Source	Award Date	Founded
Dense Focus	Lawrenceville PP	$ 300,000	Eric Lerner	NASA's JPL	1994 to 2001	1974
Dense Focus	Lawrenceville PP	$ 1,200,000	Eric Lerner	Abell Foundation	10/18/2009	1974
Dense Focus	Lawrenceville PP	$ 2,800,000	Eric Lerner	70 People	2001 to 2009	1974
Dense Focus	Lawrenceville PP	$ 180,279	Eric Lerner	Indegogo - 2,211 People	5-Jul-14	1974
Magnetized Target	General Fusion	$ 300,000	Michel Laberge	Himself	2002	2002
Magnetized Target	General Fusion	$ 1,200,000	Michel Laberge	Chrysalix	2007	2002
Magnetized Target	General Fusion	$ 13,750,000	Michel Laberge	Series A SDT Canada, Chrysalix, GrowthWorks,Braemer	8/4/2009	2002
Magnetized Target	General Fusion	$ 19,500,000	Michel Laberge	Series B	5/5/2011	2002
Magnetized Target	General Fusion	Unknown	Michel Laberge	Series C	7/31/2013	2002
Magnetized Target	General Fusion	$ 2,100,000	Michel Laberge	Series E	2/26/2014	2002
Magnetized Target	General Fusion	$ 25,000	Michel Laberge	NSE Canada	6/10/2013	2002
Magnetized Target	General Fusion	18125000 - Unknown	Michel Laberge	Unknown	2002 to 1/2/2014	2002
Tokamak	Tokamak Solutions	$ 237,136	Alan Sykes	Midven Ltd, Rainbow Seed Fund	2010	2009
Tokamak	Tokamak Solutions	$ 273,190	Alan Sykes	The Woods, Rainbow Fund, Oxford Ins & invest network	2/14/2011	2009
Tokamak	Tokamak Solutions	$ 149,589	Alan Sykes	ITER diagnostics for neutrons & power Contract	Pre 2/14/2011	2009
Tokamak	Tokamak Solutions	$ 307,975	Alan Sykes	UK SMART award #720161	8/2012 to 3/2014	2009
Tokamak	Tokamak Solutions	$ 130,503	Alan Sykes	University of York - KTP #9004	10/5/2012 to 10/16/2014	2009
Tokamak	Tokamak Solutions	$ 669,497	Alan Sykes	Two Other Knowledge transfer projects	Unkown	2009
Tokamak	Tokamak Solutions	$ 62,313	Alan Sykes	SBRI - Technology Strategy Board	4/17/2014	2009
Tokamak	Tokamak Solutions	$ 8,169,796	Alan Sykes	Unknown	Unknown	2009

Partial record of commercial funding in field reversed configuration

Organization	Founder	Amount	Award	Awarded	Founded
MSNW	John Slough	$124,999	SBIR - LaRC - ISS Launch Cubesat	2014	1994
MSNW	John Slough	$125,000	SBIR - JPL - Propulsion for ISRU	2014	1994
MSNW	John Slough	$99,999	SBIR - Propulsion with Scaling	2010	1994
MSNW	John Slough	$100,000	SBIR - JPL - Plasmoid Thruster	2009	1994
MSNW	John Slough	$599,987	SBIR - JPL - Plasmoid Thruster	2009	1994
MSNW	John Slough	$100,000	NIAC - Phase I - Dave Kirtley	8/1/2012	1994
MSNW	John Slough	$500,000	NIAC - Phase II - John Slough	8/1/2012	1994
MSNW	John Slough	$3,350,015	DOE Investment	Unknown to 9/25/13	1994
Helion	John Slough	$5,000,000	U.S. DOE	Found to 10/22/2013	2010
Helion	John Slough	$1,500,000	Y Combinator, Mithril	9/21/2014	2010
Tri Alpha Energy	Norman Rostoker	$646,710	Unknown	Pre 2/23/2001	Apr-98
Tri Alpha Energy	Norman Rostoker	$40,000,000		5/21/2007	Apr-98
Tri Alpha Energy	Norman Rostoker	$9,353,290	Undisclosed, Venrock	5/21/2007 to 6/16/2010	Apr-98
Tri Alpha Energy	Norman Rostoker	$90,000,000	Unknown	Unknown	Apr-98
Tri Alpha Energy	Norman Rostoker	Unknown	RUSNANO	3/11/2013	Apr-98

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