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Thorium Fuel Cycle Using Electrostatic and Electrodynamic Neutron Generators

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ABSTRACT

The use of Diode and Wiffle Ball (WB) cusped magnetic field configurations is discussed in the context of their use as compact drivers in Electrostatic and Electrodynamic Inertial Confinement (EIC) Fusion, for a Fusion-Fission Hybrid using a thorium molten salt breeder.

The use of a fusion fission thorium hybrid in association with these configurations considering the catalyzed DD and the DT fusion reactions and a molten salt using Th^{232} as a U^{233} breeder is analyzed.

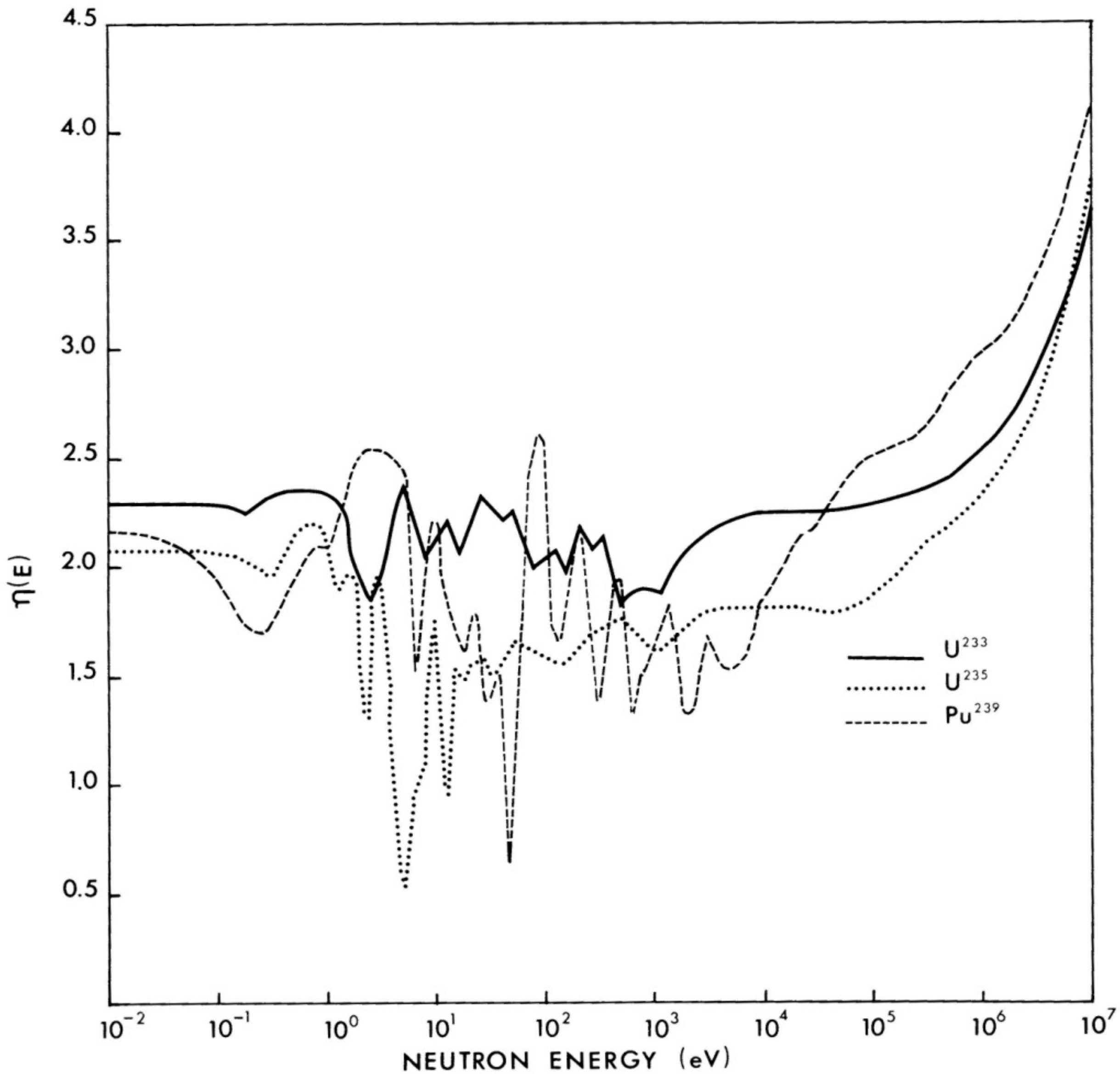
Energy and material balances in the coupled system is conducted. It shows that the energy multiplication in the coupled system approaches infinity as the conversion ratio of the fission satellites approaches unity.

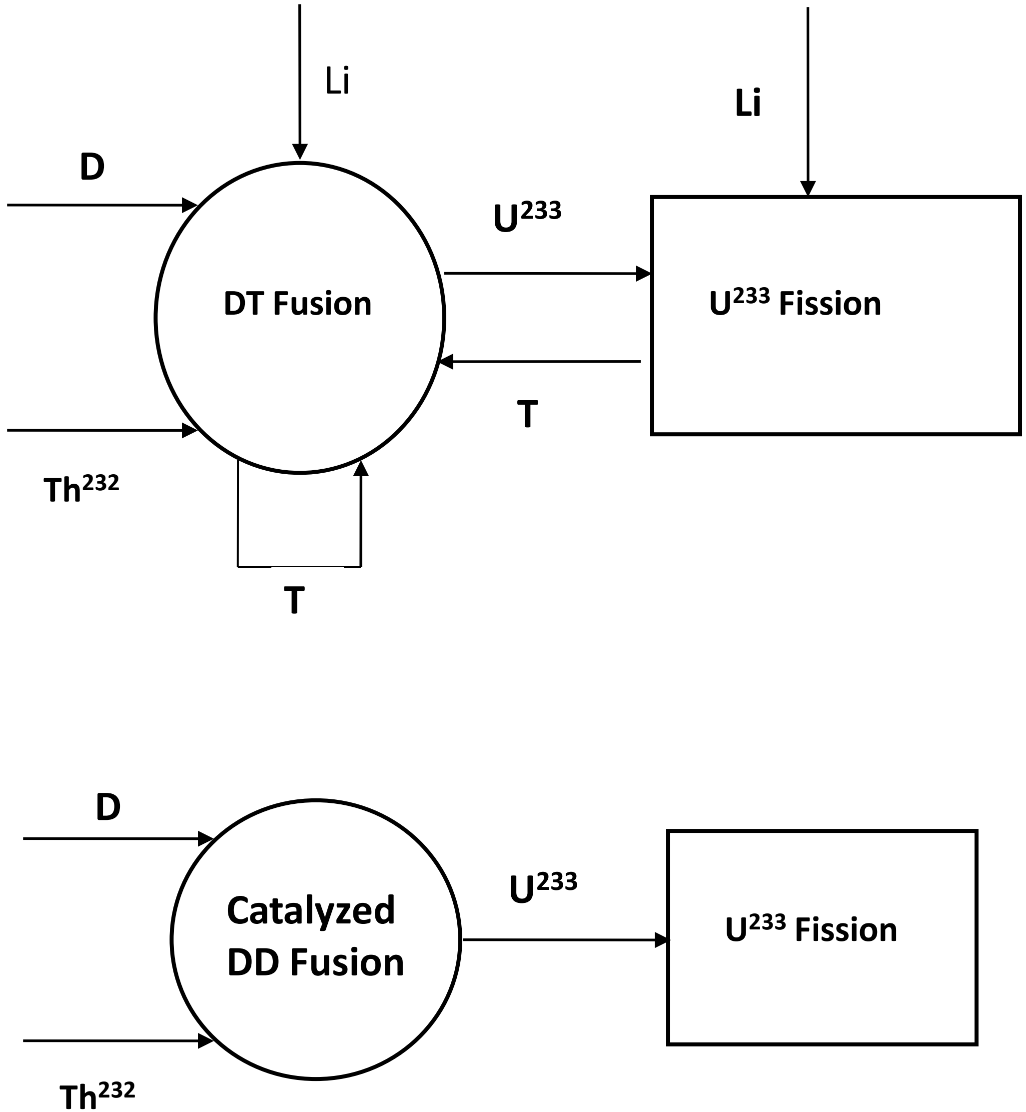
Such a configuration would allow enough energy breakeven for a sustainable long term energy system with a practically unlimited fuel supply base. Deuterium can be extracted from water in the world oceans, and thorium is four times more abundant than uranium in the Earth's crust.

The approach would provide the possibility for the eventual introduction of aneutronic fusion cycles such as the pB^{11} cycle for energy production as well as for space propulsion.

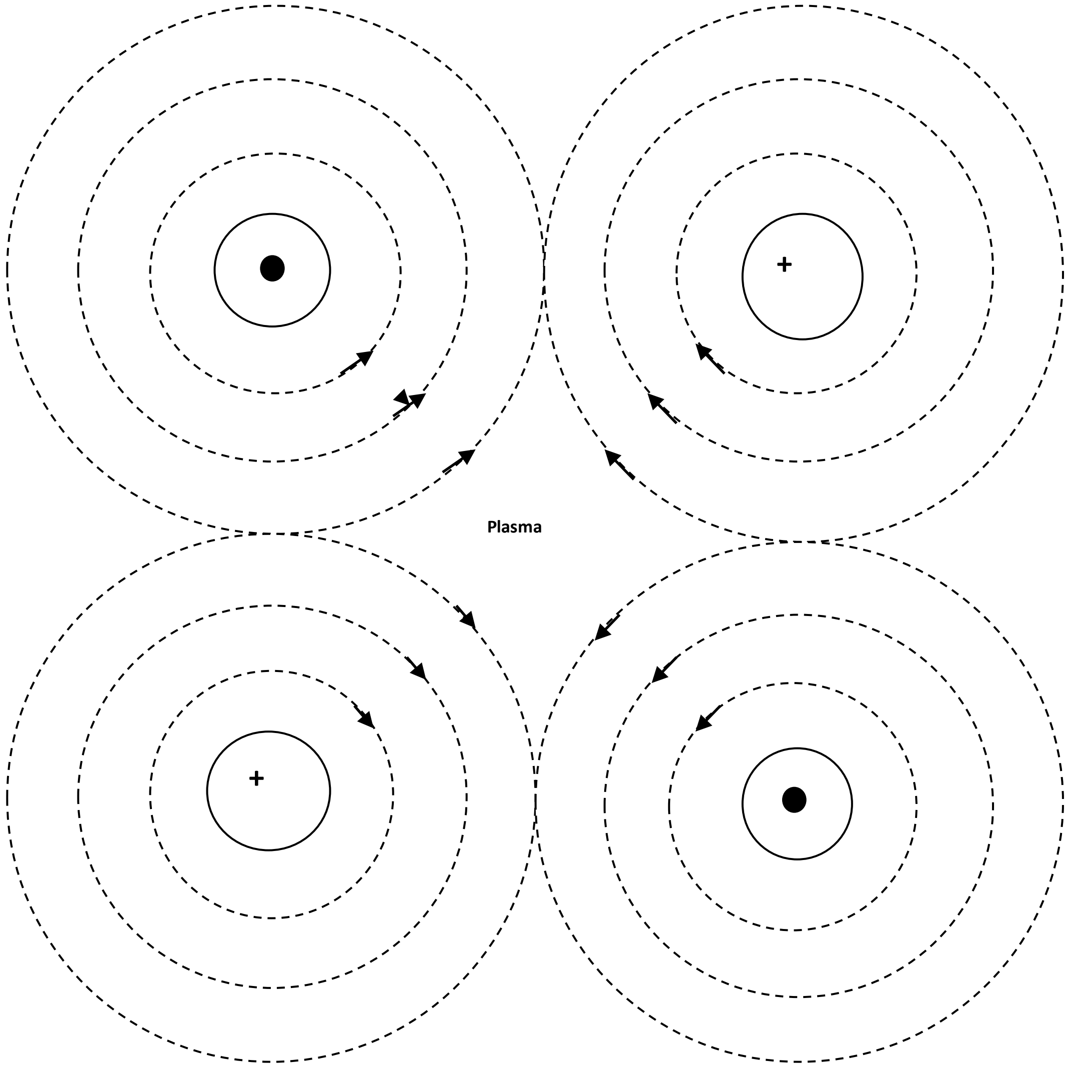
Such an alternative sustainable paradigm would provide the possibility of an optimized fusion-fission thorium hybrid for long term fuel availability with the added advantages of higher temperatures thermal efficiency for process heat production, proliferation resistance and minimized waste disposal characteristics.

Regeneration factor as a function of neutron energy for the different fissile isotopes. Breeding in the Thorium-U^{233} fuel cycle can be achieved with thermal or fast neutrons.

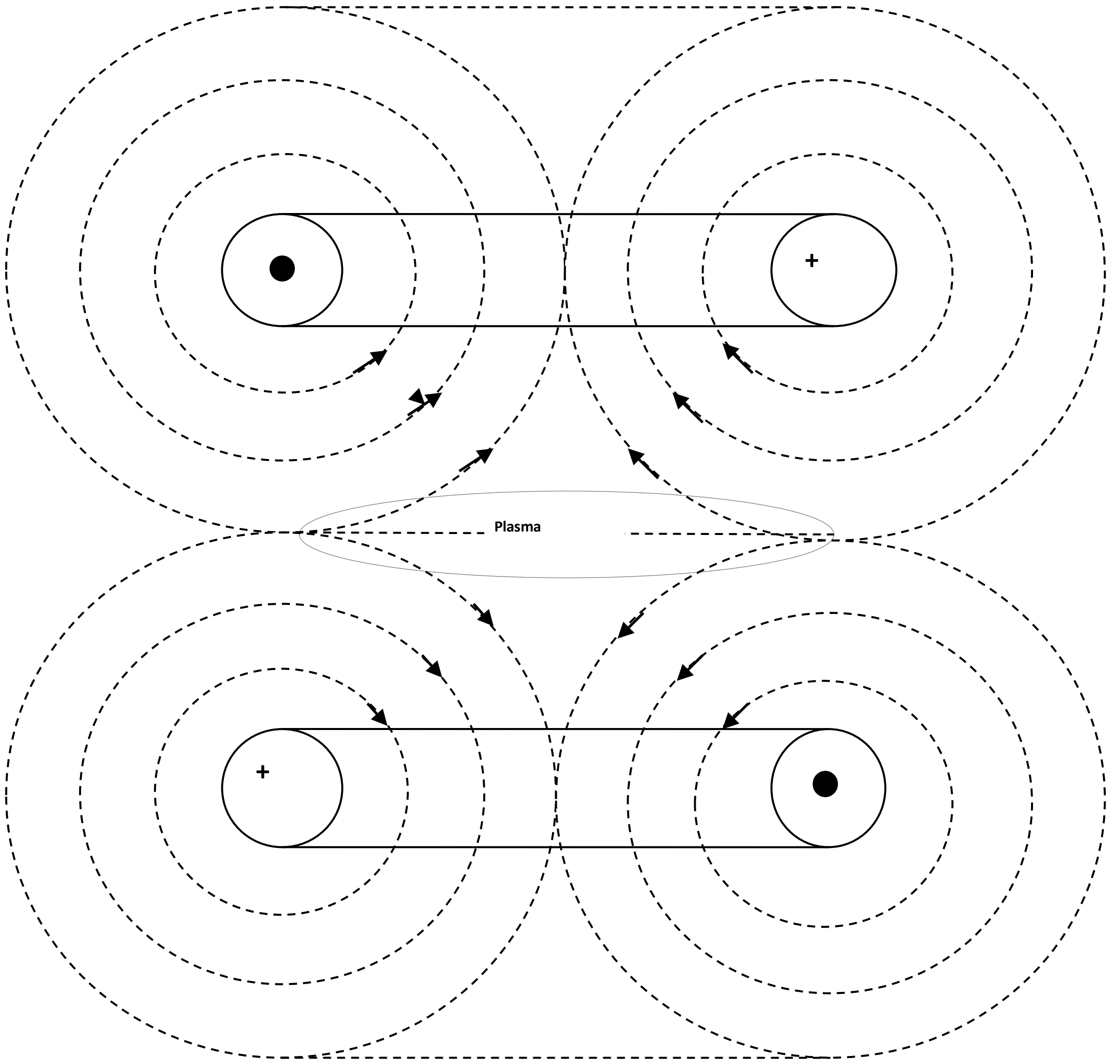




Material flows in the DT (top) and Catalyzed DD fusion-fission hybrid (bottom) Fuel Factory alternatives with U^{233} breeding from Th^{232}.

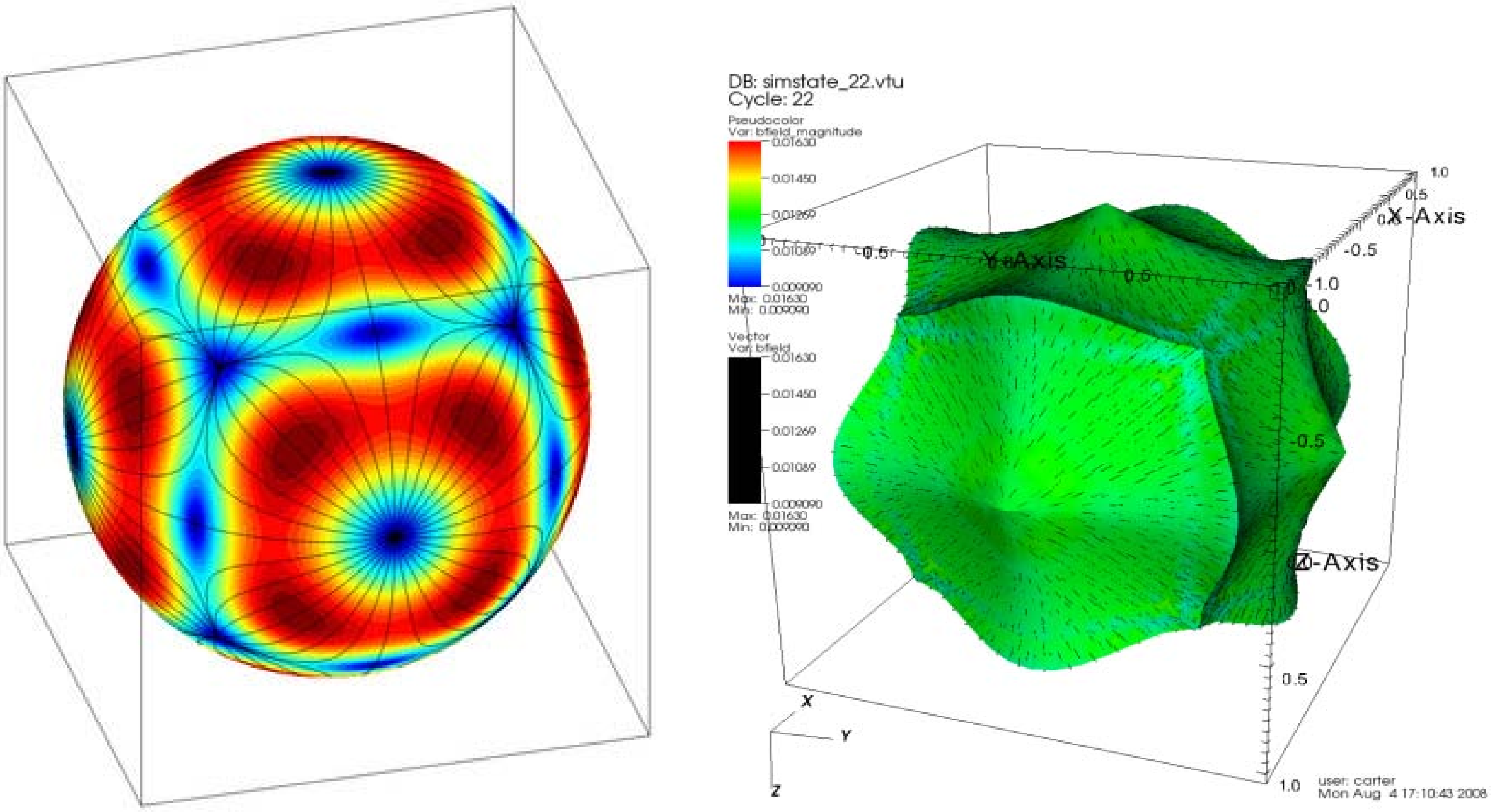


Linear cusp magnetic field configuration produced by an array of four straight line currents in wires alternating in direction (Ioffe bars).

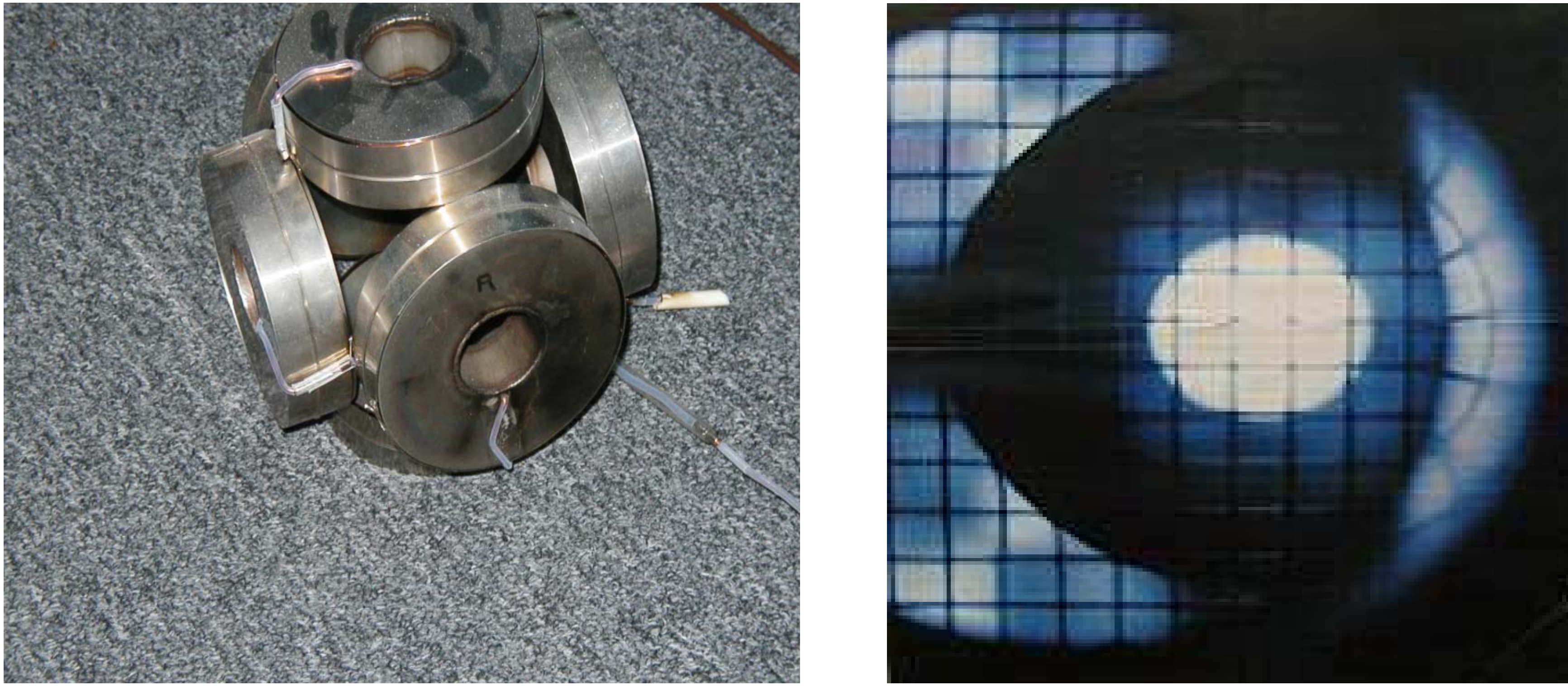


Biconal cusp magnetic field configuration produced by two parallel toroidal coils or magnets with currents flowing in opposite directions.

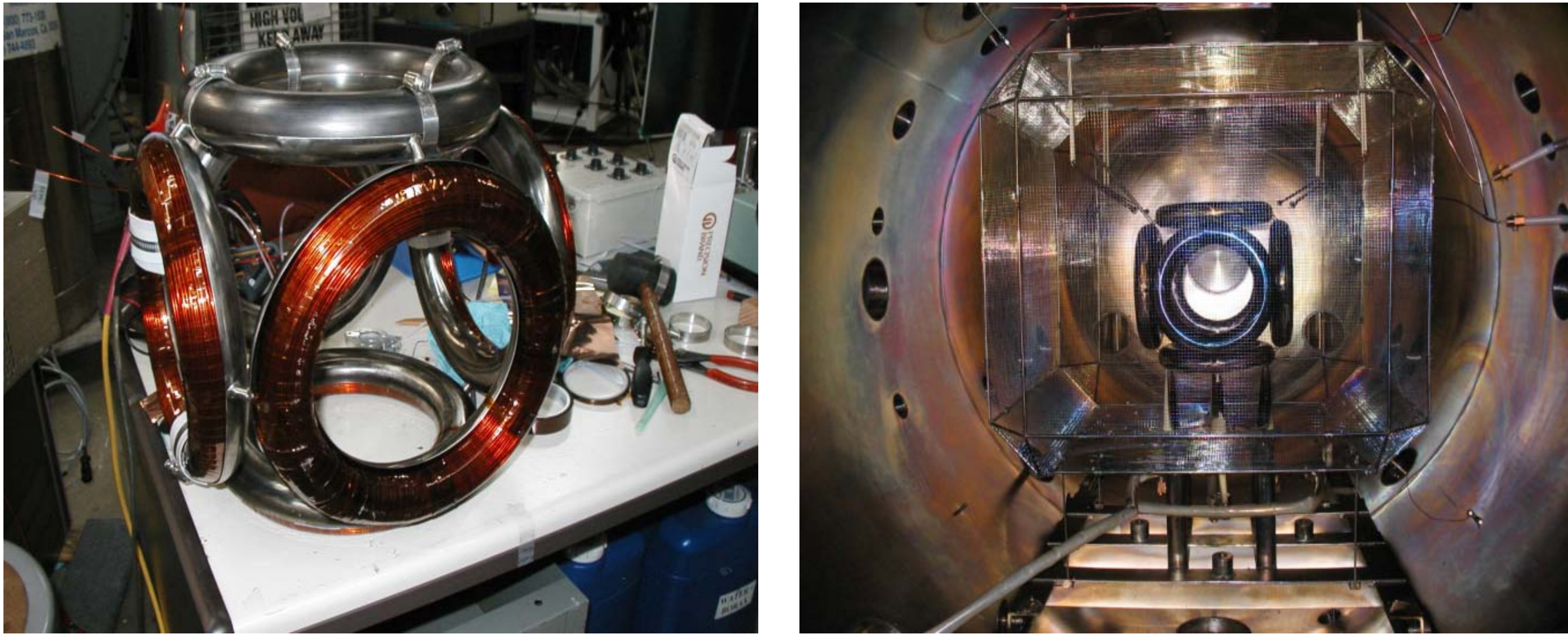
Wiffle Ball toy



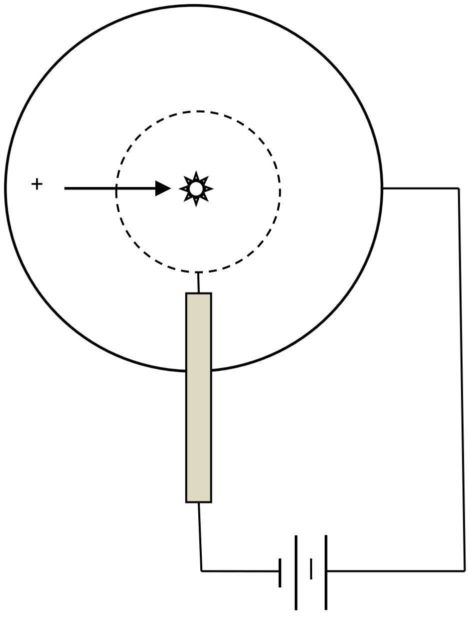
The Wiffleball cusped magnetic fields configuration



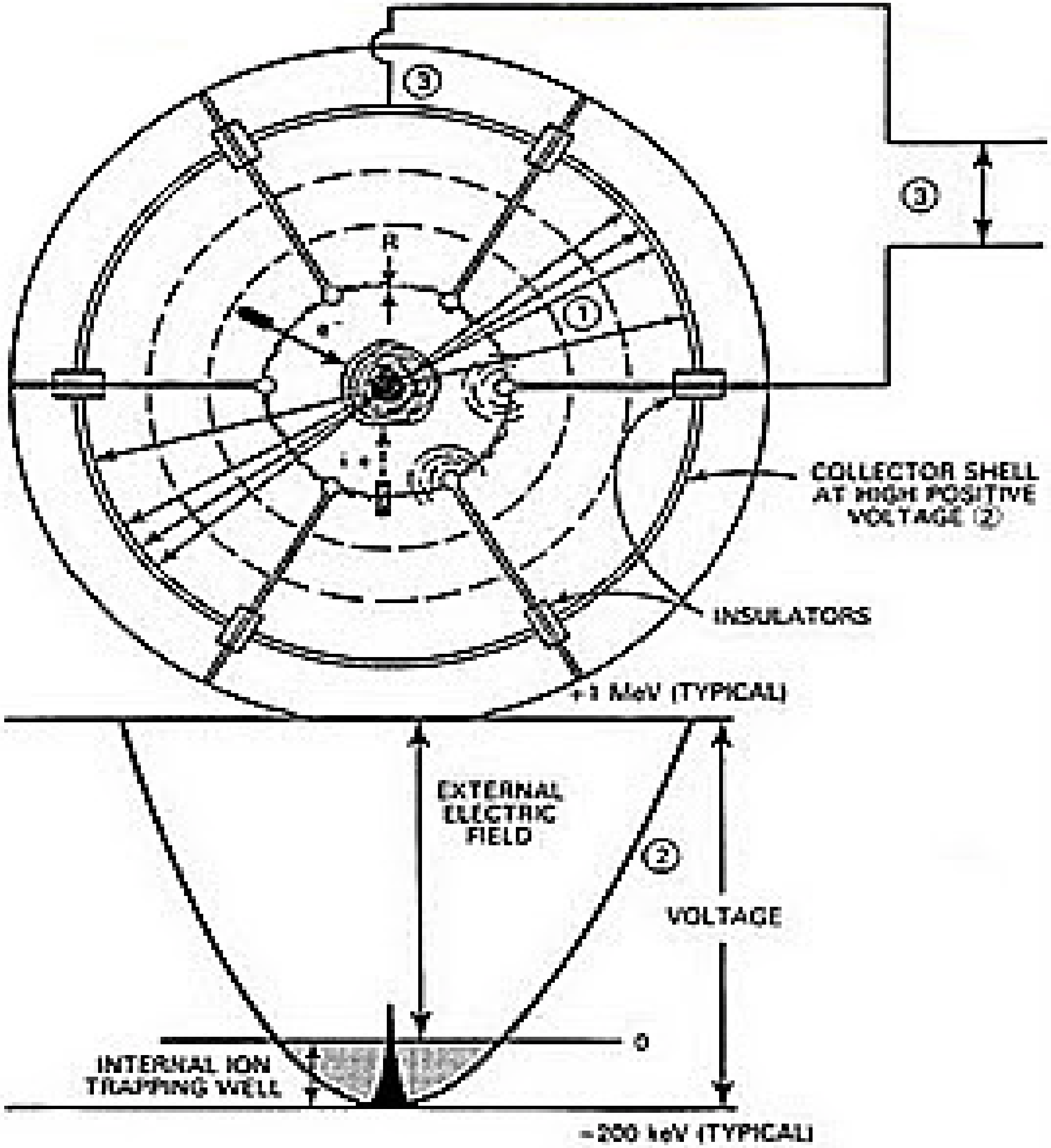
Cusped configuration Wiffle Ball WB2, 1994. Source: EMC2 Corporation



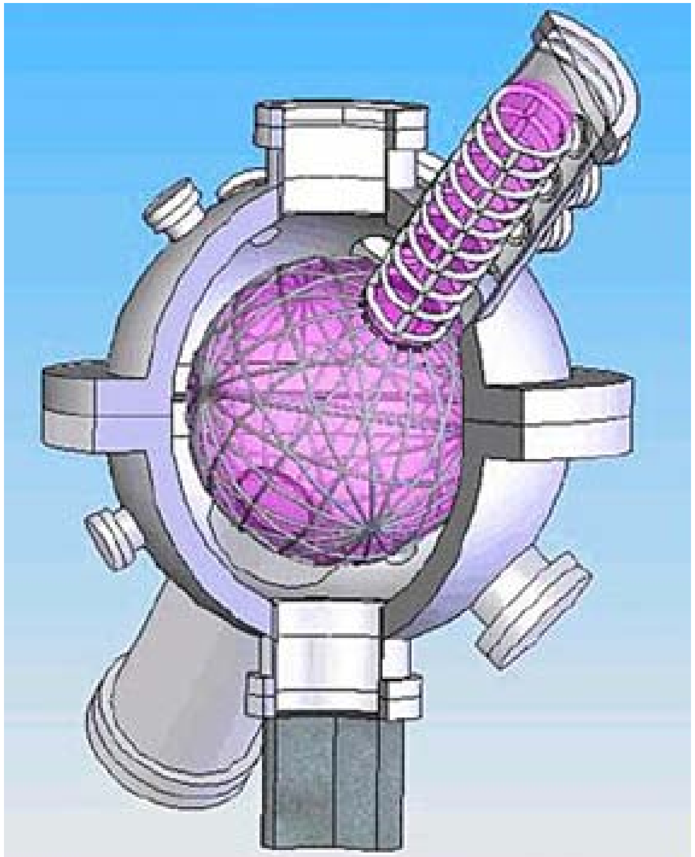
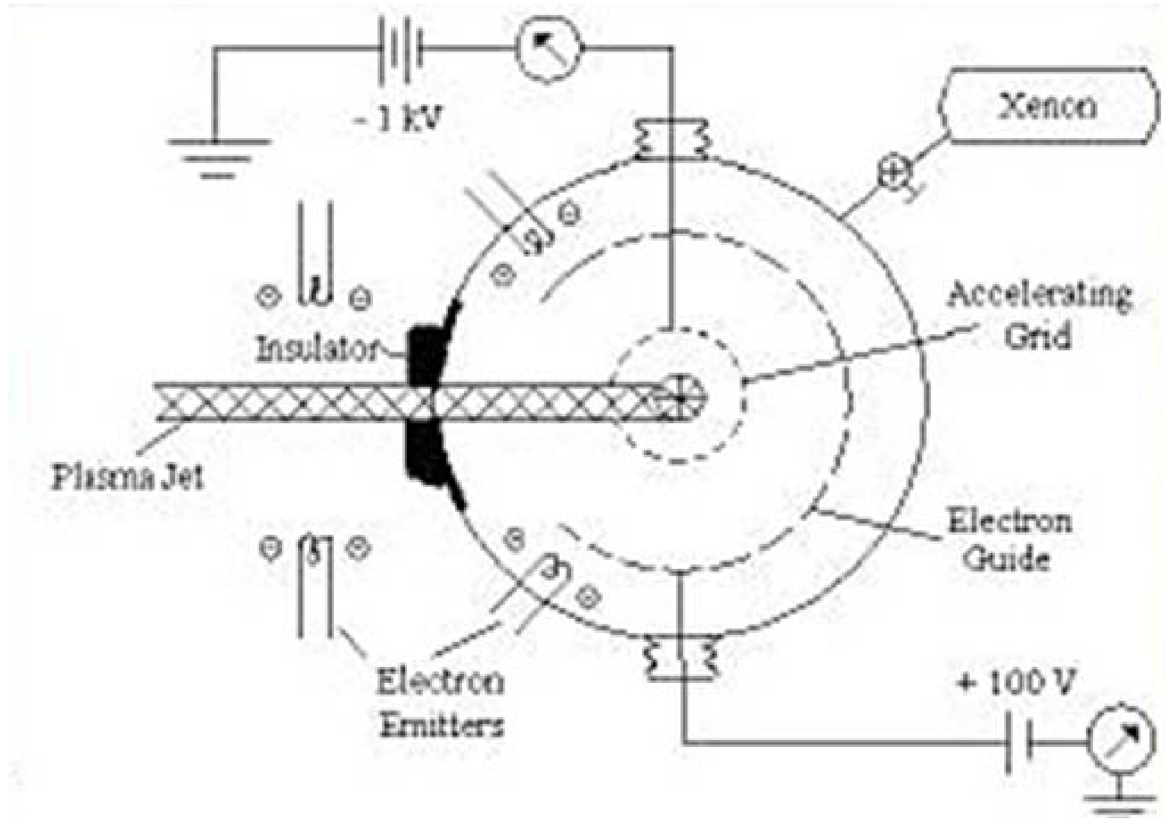
Wiffle Ball WB6 device achieved control of electron losses, 2005. Source: EMC2 Corporation



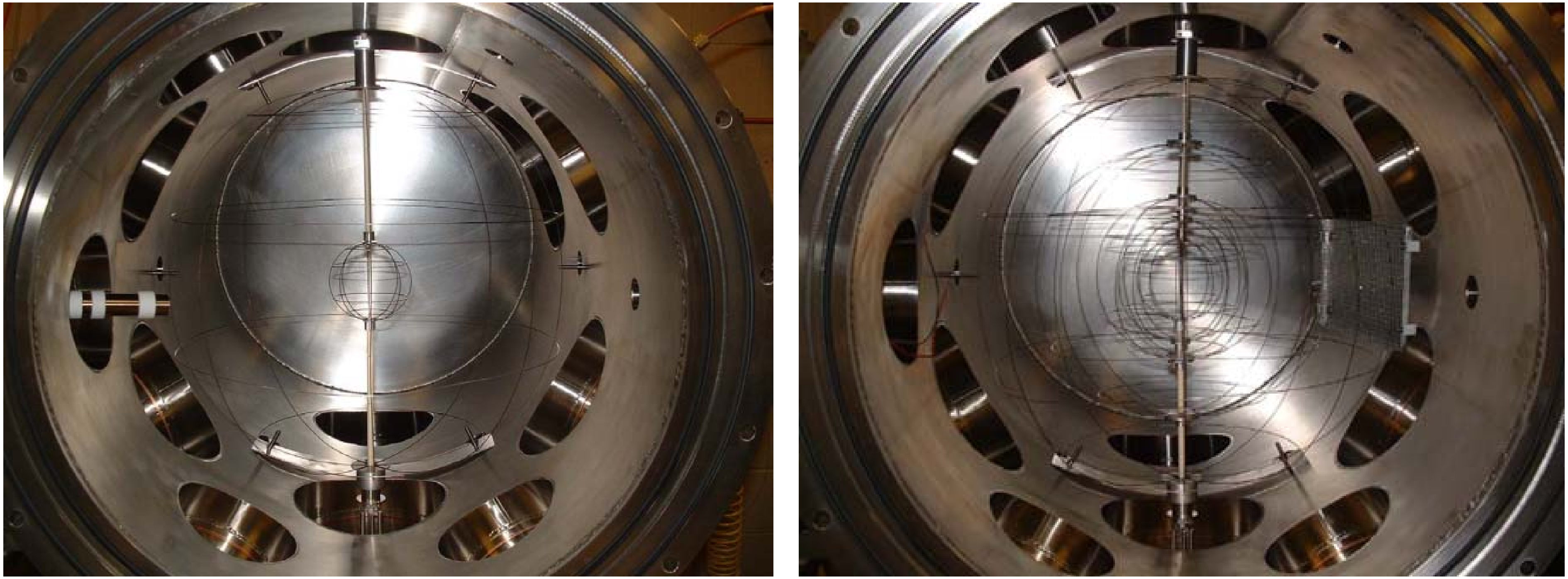
Simple two-grid diode IEC device configuration as a single diode.



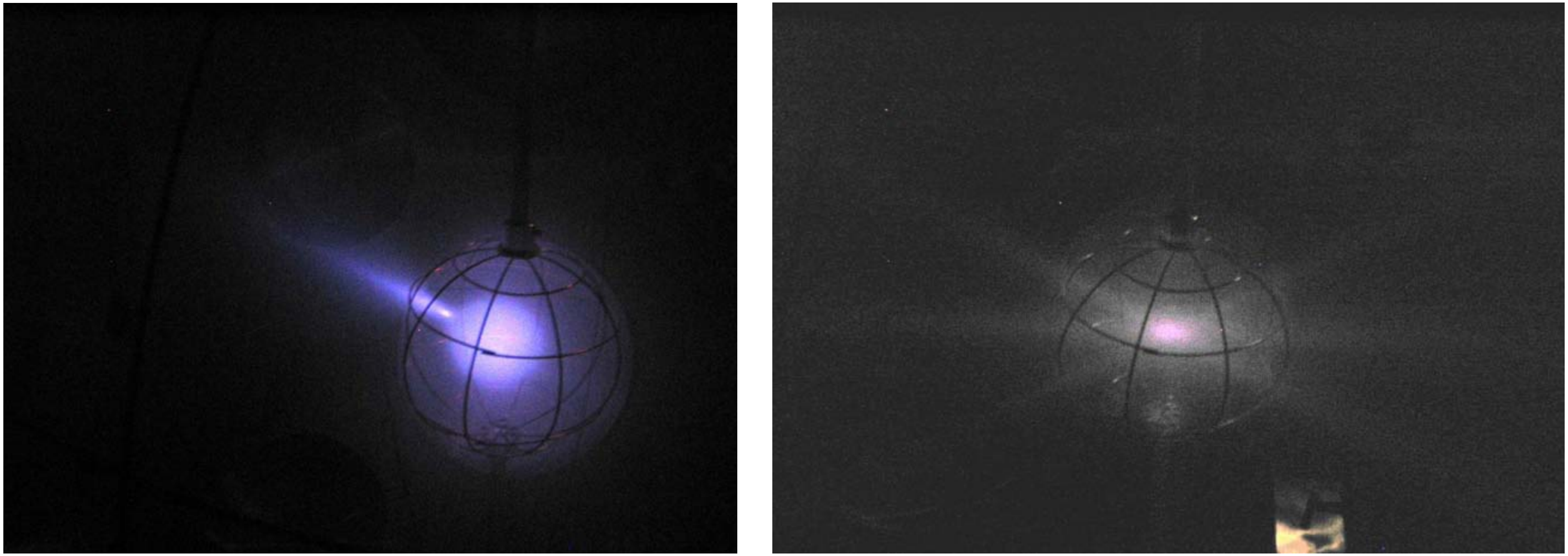
Direct energy conversion can be achieved with grid collection of the charged particles

Inertial Electrostatic Confinement IEC device operating in the jet mode. The Specific Impulse Isp = 3,000 sec, Input power = 750-800 Watt, Thrust T = 34 mN, Accelerating potential = 600 V, Jet power: Pjet = 500 Watts, Efficiency: ht = 62-68 percent



Two-grid and Multigrid systems shown in their vacuum chambers



Two grid system jet and star plasma modes

Multigrid system star mode of operation

Table 1: Catalyzed DD and DT Fusion Reaction Energetics.

Reaction	Total Energy from fusion, E_f (MeV)	Charged Particle Energy (MeV)	Neutron Energy (MeV)	Fraction of energy to neutrons, f_n (%)	Number of Neutrons
DT reaction					
${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4(3.52) + {}_0n^1(14.06)$	17.57	3.52	14.06	80.02	1
Catalyzed DD reaction*					
(a) $\frac{1}{2}{}_1D^2 + \frac{1}{2}{}_1D^2 \rightarrow \frac{1}{2}{}_1T^3(1.01) + \frac{1}{2}{}_1H^1(3.03)$	4.04	4.04	0.00	0.00	0
(b) $\frac{1}{2}{}_1D^2 + \frac{1}{2}{}_1D^2 \rightarrow \frac{1}{2}{}_2He^3(0.82) + \frac{1}{2}{}_0n^1(2.45)$	3.66	2.43	1.23	33.61	1/2
(c) $\frac{1}{2}{}_1D^2 + \frac{1}{2}{}_1T^3 \rightarrow \frac{1}{2}{}_2He^4(3.52) + \frac{1}{2}{}_0n^1(14.06)$	8.79	1.76	7.03	80.02	1/2
(d) $\frac{1}{2}{}_1D^2 + \frac{1}{2}{}_2He^3 \rightarrow \frac{1}{2}{}_2He^4(3.67) + \frac{1}{2}{}_1H^1(14.67)$	9.17	9.17	0.00	0.00	0
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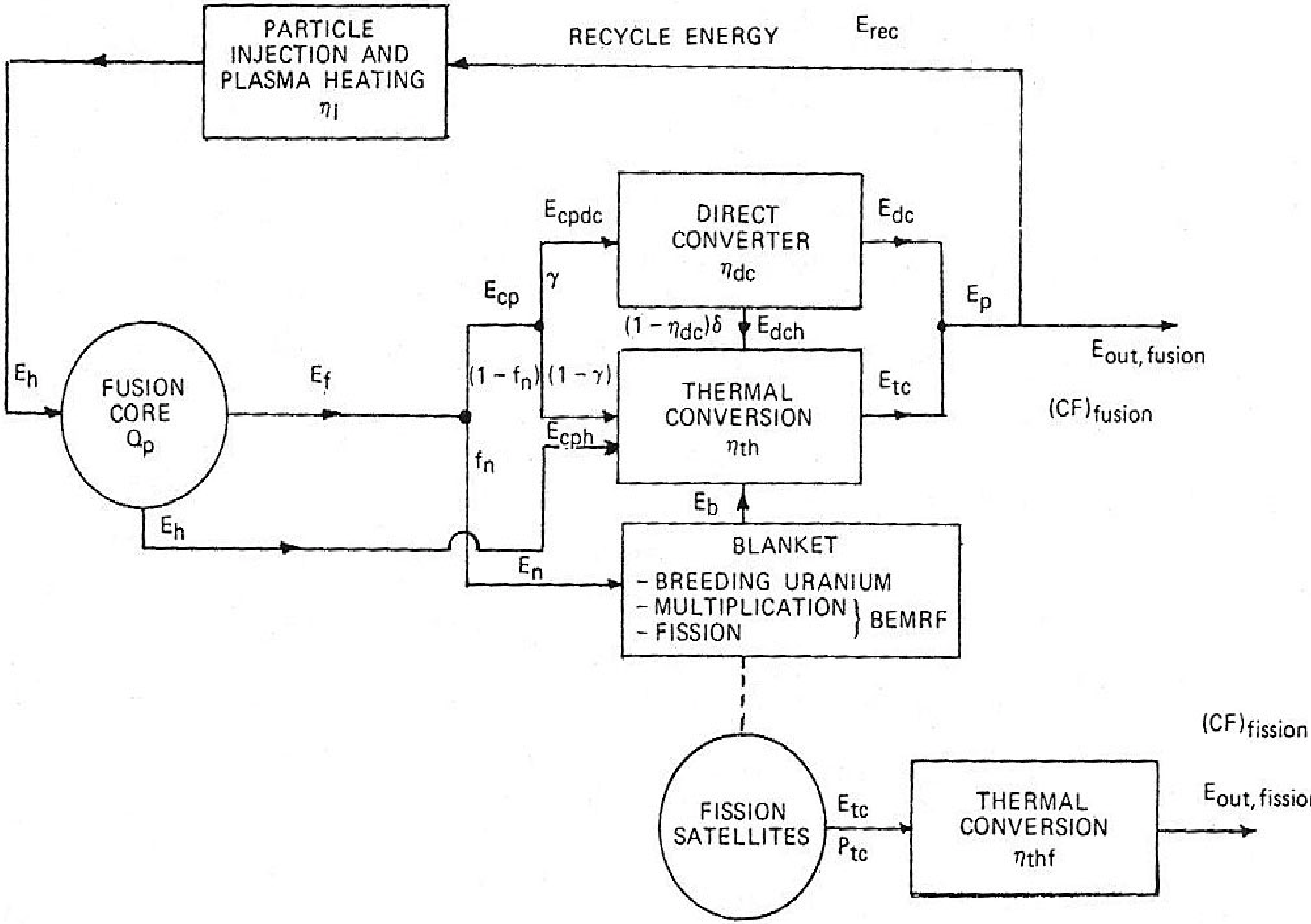
$3{}_1D^2 \rightarrow {}_2He^4 + {}_1H^1 + {}_0n^1$	21.62	13.36	8.26	38.21	1

DT and DHe³ reactions (c) and (d) proceed at the same rate as the two DD reactions. $R_1 = R_2 = \frac{R_{DD}}{2}$

***DD reactions (a) and (b) are assumed to have a branching ration of ½ and proceed at an equal rate:**



SYMBIOTIC COUPLING OF FUSION BREEDERS AND FISSION SATELLITES, ENERGY AND MATERIAL BALANCES

Comparison of the Energy Deposition Rates and Blanket Multiplication Ratios in a molten salt thorium blanket for different neutron sources

Neutron Source	Neutron Heating Rate (W per n/s)	Gamma Ray Heating Rate (W per n/s)	Total Heating Rate (W per n/s)	Th(n, f) reactions (n/s)	BEMR	BEMRF	Total Energy Deposition (MeV/source neutron)
(Na-Th-F-Be) Molten Salt							
2.45 MeV	1.82 10^{-13}	5.42 10^{-13}	7.24 10^{-13}	7.60 10^{-3}	1.84	2.41	5.90
DT	6.20 10^{-13}	1.12 10^{-13}	1.74 10^{-13}	3.28 10^{-3}	0.77	1.20	16.90
Catalyzed DD	4.01 10^{-13}	8.31 10^{-13}	1.23 10^{-13}	2.02 10^{-3}	0.93	1.38	11.40
(Li-Th-F-Be) Molten Salt							
2.45 MeV	4.42 10^{-13}	4.12 10^{-13}	8.54 10^{-13}	9.80 10^{-3}	2.18	2.92	7.15
DT	9.70 10^{-13}	9.00 10^{-13}	1.87 10^{-13}	3.52 10^{-3}	0.83	1.29	18.14
Catalyzed DD	7.06 10^{-13}	6.56 10^{-13}	1.36 10^{-13}	2.25 10^{-3}	1.03	1.53	12.64

Table 2: Comparison of the Energy Deposition Rates and Blanket Multiplication Ratios in a molten salt thorium blanket for different neutron sources .

Neutron Source	Neutron Heating Rate (W per n/s)	Gamma Ray Heating Rate (W per n/s)	Total Heating Rate (W per n/s)	Th(n, f) reactions (n/s)	BEMR	BEMRF	Total Energy Deposition (MeV/source neutron)
(Na-Th-F-Be) Molten Salt							
2.45 MeV	1.82×10^{-13}	5.42×10^{-13}	7.24×10^{-13}	7.60×10^{-3}	1.84	2.41	5.90
DT	6.20×10^{-13}	1.12×10^{-13}	1.74×10^{-13}	3.28×10^{-3}	0.77	1.20	16.90
Catalyzed DD	4.01×10^{-13}	8.31×10^{-13}	1.23×10^{-13}	2.02×10^{-3}	0.93	1.38	11.40
(Li-Th-F-Be) Molten Salt							
2.45 MeV	4.42×10^{-13}	4.12×10^{-13}	8.54×10^{-13}	9.80×10^{-3}	2.18	2.92	7.15
DT	9.70×10^{-13}	9.00×10^{-13}	1.87×10^{-13}	3.52×10^{-3}	0.83	1.29	18.14
Catalyzed DD	7.06×10^{-13}	6.56×10^{-13}	1.36×10^{-13}	2.25×10^{-3}	1.03	1.53	12.64

ENERGY AMPLIFICATION FACTOR AND SUPPORT RATIOS

The energy amplification factor or fission to fusion energy multiplication ℓ, is then given by

$$\ell = \frac{P_{tc}}{P_f} = \frac{E_{fission}}{E_f} . \frac{U}{(1-C)(1+\alpha)} . \frac{CF_{fusion}}{CF_{fission}} \qquad (21)$$

ENERGY AND ELECTRICAL SUPPORT RATIOS

Three figures of merit can be suggested for the assessment of the symbiotic fusion and fission combination.

1. The fission to fusion energy amplification factor ℓ defined by Eq. 18. It measures the multiplication of the energy external to the fusion generators in the fission reactors satellites when the bred fissile fuel releases its energy content.

$$\ell = \frac{E_{fission}}{E_f} \cdot \frac{U}{(1-C)(1+\alpha)} \cdot \frac{CF_{fusion}}{CF_{fission}} \qquad (21)'$$

The energy amplification is increased at a first level by the factor

$$\frac{E_{fission}}{E_f} = \frac{190}{17.57} = 10.8, \text{for DT fusion}$$

$$\frac{E_{fission}}{E_f} = \frac{190}{21.62} = 8.8, \text{for Catalyzed DD fusion}$$

A much more drastic contribution can be noticed by the factor: $\frac{1}{1-C}$, where the conversion factor C is defined as

$$C = \frac{\text{average number of fissile nuclides produced}}{\text{average number of fissile nuclides consumed}}$$

As the value of the conversion factor C approaches unity, an infinite energy multiplication factor ensues:

$$\lim_{C\to 1} \ell = \lim_{C\to 1}\left[\frac{E_{fission}}{E_f} \cdot \frac{U}{(1-C)(1+\alpha)} \cdot \frac{CF_{fusion}}{CF_{fission}}\right] = \infty$$

In detail, when N nuclei of fissile fuel are consumed, NC nuclei of fertile fuel are converted into fissile nuclei. If the process is repeated, the consumption of N fuel nuclei results in the conversion of a total number of fissile nuclei as:

$$
\begin{aligned}
N_{total} &= N + NC + NC^2 + NC^3 + NC^4 + \dots \\
&= N(1 + C + C^2 + C^3 + C^4 + \dots) \\
&= N\frac{1}{1-C}, \forall\ 0 < C < 1.
\end{aligned}
\tag{24}
$$

When C = 1, an infinite amount of fissile fuel can be converted from a starting amount of fertile fuel. When C > 1 the sequence diverges since more than a fissile nucleus is created from a fertile nucleus and cannot be summed mathematically. In this case C is designated as B, the breeding ratio.

If only n recycles are involved, due to the accumulation of undesirable isotopes affecting the recycling process, Eq. 24 reduces to:

$$
\begin{aligned}
N_{total} &= N + NC + NC^2 + NC^3 + \ldots + NC^n \\
&= N(1 + C + C^2 + C^3 + \ldots + C^n) \\
&= N\frac{1 - C^{n+1}}{1 - C}, \forall\, 0 < C < 1.
\end{aligned}
$$

Fissile and fusile breeding for sodium and lithium salts in DT and DD symbiotic fusion-fission fuel factories. Blanket thickness = 42 cm, reflector thickness = 40 cm; no structure in the salt region.

Source	**Li-Be-Th-F Salt**						**Na-Be-Th-F Salt**			
	$Li^6(n,\alpha)T$	**$Li^7(n,n'\alpha)T$**	**$Be^9(n,T)$**	**F(n,T)**	**Total T**	**$Th(n,\gamma)$**	**$Be^9(n,T)$**	**F(n,T)**	**Total T**	**$Th(n,\gamma)$**
	(Nuclei / fusion source neutron)									
DD 100% 2.45 MeV	0.311	0.001	4.03×10^{-10}	1.01×10^{-7}	0.312	0.579	4.18×10^{-10}	1.04×10^{-7}	1.04×10^{-7}	0.794
DT 100% 14.06 MeV	0.391	0.073	1.08×10^{-4}	3.33×10^{-3}	0.467	0.737	1.04×10^{-4}	3.08×10^{-3}	3.18×10^{-3}	0.966
Catalyzed DD 50% 2.45 MeV 50% 14.06 MeV	0.351	0.037	5.40×10^{-5}	1.67×10^{-3}	0.390	0.658	5.20×10^{-5}	1.54×10^{-3}	1.59×10^{-3}	0.880

Parameter values for the symbiotic fusion and fission coupling

Parameter	Symbol	Catalyzed DD	DT
Beam injection and plasma heating efficiency	η_I	0.80	0.80
Fraction of fusion energy carried by neutrons	f_n	0.38	0.80
Fusion energy output per fusion reaction (MeV/fusion)	E_f	21.62	17.57
Total blanket energy multiplication	BEMRF	1.38	1.29
Fraction of fusion charged particles energy flowing to direct converter	γ	0.42	0.00
Direct conversion efficiency	η_{dc}	0.80	0.00
Fraction of energy rejected by the direct converter recoverable through thermal conversion	δ	1.00	0.00
Fusion thermal conversion cycle efficiency	η_{th}	0.40	0.40
Fission thermal conversion cycle efficiency	$\eta_{th,fs}$	0.30	0.30
Fusion plant capacity factor	CF_{fusion}	0.60	0.60
Fission plant capacity factor	CF_{fision}	0.70	0.70
Energy release per fission event (MeV/fission)	$E_{fission}$	190	190
Capture to fission ratio	α	0.10	0.10
Conversion ratio of converter reactors	C	0.60	0.60
Fissile nuclei yield per source neutron	U	0.880	0.737
Plasma power amplification factor	Q_p	0.01	0.01

Costs

Large machines cost a great deal more than smaller devices.

Costs tend to scale as the cube of the system size and the square of the B magnetic field.

Thus, full-scale machines and their development will cost in the range of $180 – 200 million, depending on the fuel combination selected.

These cost estimates closely reproduce those made throughout the USN program life, from its earliest work in 1991 to its conclusion in mid 2006 including those made at interim reviews in 1995 and 1999.

USA Navy costs expended in the electrodynamic fusion program have been approximately $18 million over about 10 years or about $1.8 million/year.

DISCUSSION

The use of Diode and Wiffle Ball (WB) cusped magnetic field configurations is discussed in the context of their use as compact drivers in Electrostatic and Electrodynamic Inertial Confinement (EIC) Fusion, for a Fusion-Fission Hybrid using a thorium molten salt breeder.

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Such a configuration would allow enough energy breakeven for a sustainable long term energy system with a practically unlimited fuel supply base. Deuterium can be extracted from water in the world oceans, and thorium is four times more abundant than uranium in the Earth's crust.

The approach would provide the possibility for the eventual introduction of aneutronic fusion cycles such as the pB^{11} cycle for energy production as well as for space propulsion.

Such an alternative sustainable paradigm would provide the possibility of an optimized fusion-fission thorium hybrid for long term fuel availability with the added advantages of higher temperatures thermal efficiency for process heat production, proliferation resistance and minimized waste disposal characteristics.

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