Compact fusion reactors

Tomas Lindén

Helsinki Institute of Physics

26.03.2015

Fusion research is currently to a large extent focused on tokamak (ITER) and inertial confinement (NIF) research. In addition to these large international or national efforts there are private companies performing fusion research using much smaller devices than ITER or NIF. The attempt to achieve fusion energy production through relatively small and compact devices compared to tokamaks decreases the costs and building time of the reactors and this has allowed some private companies to enter the field, like EMC2, General Fusion, Helion Energy, Lockheed Martin and LPP Fusion. Some of these companies are trying to demonstrate net energy production within the next few years. If they are successful their next step is to attempt to commercialize their technology. In this presentation an overview of compact fusion reactor concepts is given.

CERN Colloquium 26th of March 2015

Contents

1 Introduction

2 Funding of fusion research

3 Basics of fusion

4 The Polywell reactor

5 Lockheed Martin CFR

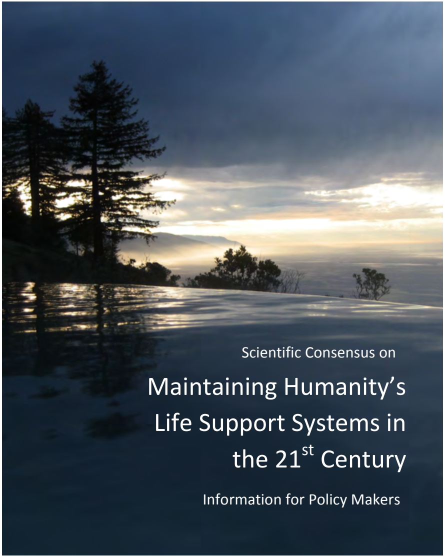
6 Dense plasma focus

7 MTF

8 Other fusion concepts or companies

9 Summary

Introduction



- Climate disruption
- Pollution
- Extinctions
- Ecosystem Transformation
- Population growth and consumption

There is no silver bullet to solve these issues, but energy production is central to many of these issues. Economically practical fusion power could contribute significantly to meet the future increased energy production demands in a sustainable way.

Funding of fusion research

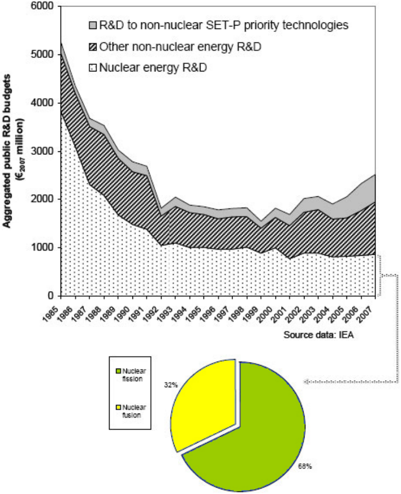
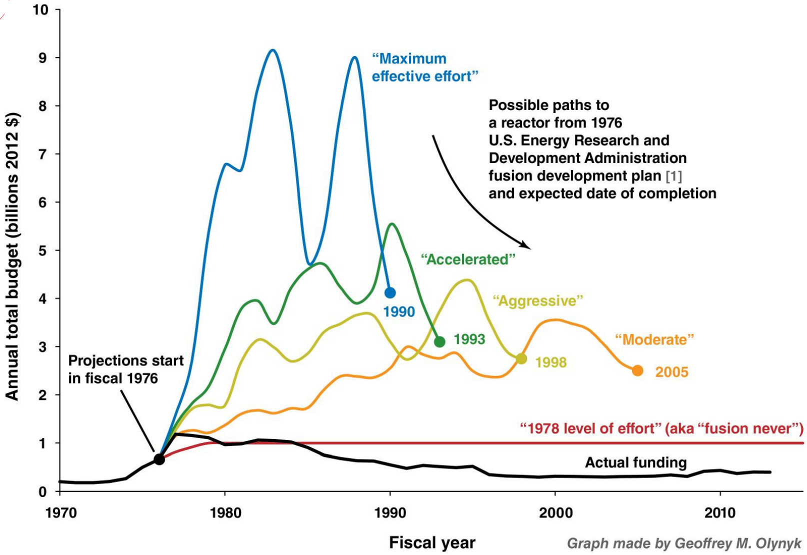


Figure: EU public energy R&D funding 1985-2007 with 2007 breakdown [1].

Weapons spending was 1350 billion EUR according to the SIPRI annual report 2013 [2]. This corresponds to 2,5 % of the worlds GDP. The funds for fusion research are small compared to this sum.

Funding of fusion research



[1] U.S. Energy Research and Development Administration, 1976. "Fusion power by magnetic confinement: Program plan" ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065

Figure: The 1976 planned and 1970-2013 realized US fusion research funding.

Basics of fusion

Fission development:

- 1938: Hahn, Strassmann, Frisch, Meitner uranium fission
- 1945: Fission bombs in Hiroshima and Nagasaki
- 1951: The first electricity producing fission reactor

Fusion development:

- 1920: Eddington suggests that the suns energy comes from fusion
- 1946: The first patent on a fusion reactor
- 1950: Sakharov, Tamm & Lavrentiev develop the *tokamak* concept
- 1952: The first fusion bomb
- 1969: Tokamak research declassified, big influence in the west
- **1985**: The Soviet Union suggests an international tokamak (ITER)
- 1997: JET produces 16,1 MW fusion power, $\mathbf{Q = 0.65}$, $V_p = 100$ m^3
- **2021-22**: ITER ($V_p = 840$ m^3, 13 G€) first DD-plasma
- **2027-28**: ITER DT-plasma as fuel

Basics of fusion

Some of the most important fusion reactions for energy production:

$D + T \rightarrow$
$He(3,52\ MeV) + \mathbf{n}(14,07\ MeV)$

$D + D \rightarrow$
$^3He(0,82\ MeV) + \mathbf{n}(2,45\ MeV)$, 50 %
$T(1,01\ MeV) + p(3,02\ MeV)$, 50 %

$D + {}^3He \rightarrow$
$He(3,67\ MeV) + p(14,68\ MeV)$

$p + {}^{11}B \rightarrow$
$3He(8,68\ MeV)$

$^3He + {}^3He \rightarrow$
$He(12,86\ MeV) + 2p$

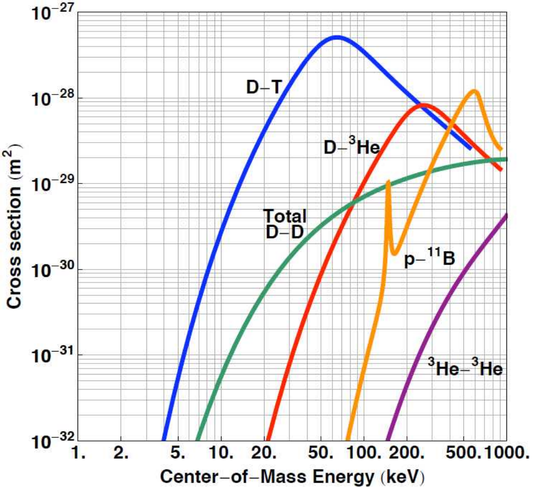


Figure: Cross sections as a function of center of mass energy for some of the most important fusion reactions [3]. (1 keV ≈ 8 MK)

Basics of fusion

Aneutronic fusion:

- The reactor will not be activated and there will not be much radiation damage if the reaction is aneutronic.
- Can enable nonthermal energy production through braking of charged particles in an electric field.
- In theory a higher efficiency can be reached compared to traditional steam turbines.
- Avoiding expensive turbine technology can give reduced costs.
- Side reactions can still produce some neutrons.

Basics of fusion

Nuclear fuels

- **Fusion fuels:**
  - Proton stable, can be extracted from (sea)water
  - Deuterium stable, can be extracted from (sea)water, 33 g D/m^3
  - Tritium decays to ^{3}He, $t_{1/2}$=12,32 year. Tritium can be produced from lithium with neutron irradiation:
    - $\mathrm{n} + {}^6\mathrm{Li} \rightarrow \mathrm{T} + \mathrm{He}$
    - $\mathrm{n} + {}^7\mathrm{Li} \rightarrow \mathrm{T} + \mathrm{He} + \mathrm{n}$
  - ^{3}He stable, $\approx$ 400 kg on earth, $\approx 10^9$ kg on the moon, $\approx 10^{23}$ kg on the giant gas planets [4], can be collected from decaying T
  - ^{11}B stable, 80,1 % of natural boron
- **Fission fuels:**
  - ^{232}Th (^{233}U): ex. Thorium molten saltreactor, or accelerator driven reactor (ADS)
  - ^{235}U, traditional reactors
  - ^{238}U (^{239}Pt), fast breeder reactors

Basics of fusion

The Q of a reaction is defined as:

$$Q = P_{out}/P_{in} \tag{1}$$

where P_{out} = fusion power and P_{in} = start- and running power.

The ratio of plasma pressure to magnetic pressure β is often limited by plasma instabilities.

$$\beta = p_{kin}/p_{mag} \tag{2}$$

where $p_{kin} = N_i k T_i + N_e k T_e$, $p_{mag} = \frac{B^2}{2\mu_0}$. N_i (T_i), N_e (T_e) = ion- respective electron particle density (temperature), k = Boltzmann constant and B = the magnetic field and μ_0 = the permeability of vacuum [5]. The ITER β design value is ≈ 0.03 [6]

Fusion power is proportional to β^2.

A *compact* fusion reactor in this context has a significantly smaller plasma volume than a traditional tokamak.

Plasma instabilities

An important part of plasma physics are the instabilities that can occur in a plasma.

Examples of some instabilities that can occur in some of the reactors discussed here:

- Filament
- Kink
- Rayleigh-Taylor
    - Richtmyer-Meshkov
- Tilt
- ...

Plasmoids

Self contained plasmas where the magnetic fields are mostly generated by currents circulating in the plasma are called *plasmoids* or *Compact Torii* [7]:

- **Field Reversed Configuration (FRC)**
- **Spheromak**

Plasmoid	Axial-symmetry	Poloidal field B_p	Toroidal field B_t	B_t on surface
FRC	yes	yes	no	no
Spheromak	yes	yes	yes	no

The poloidal field is contained in planes through the symmetry axis.
The toroidal field circulates the symmetry axis.
FRC-plasmoids can reach $\beta \approx 1$.

Basics of fusion

Examples of fusion **confinement** methods:

- **Magnetic Confinement Fusion** (MCF)
  - Tokamak (JET, ITER, ...), stellarator (Wendelstein 7-X), ...
  - $N \approx 10^{14}/\mathrm{cm}^3$, $\tau \approx 1$ s
- **Inertial Confinement Fusion** (ICF)
  - Laser fusion (National Ignition Facility, High Power laser Energy Research facility (HiPER), ...)
  - $N \approx 10^{25}/\mathrm{cm}^3$, $\tau \approx 1$ ns
  - Heavy Ion Fusion (HIF)
- **Inertial Electrostatic Confinement** (IEC)
- **Magnetized Target Fusion** (MTF) also **Magneto Inertial Fusion** (MIF) (General Fusion, Sorlox, ...)
  - $N \approx 10^{19}/\mathrm{cm}^3$, $\tau \approx 1\ \mu$s

Magnetic confinement- and laser fusion get the majority of the funding

- The emphasis of laser fusion is on military applications

The Polywell reactor

- R. Bussard (1928–2007) begun in 1983 Polywell studies [9, 10, 11]
- The name **Polywell** comes from **poly**hedral and potential **well**
- A quasi radial *magnetic* mirror like field confines *electrons*
- The *ions* are accelerated and confined by the *electric field* created by the electrons
- The quasi neutral plasma has an electron surplus fraction of 10^{-6}
- The electron losses can be minimized by shaping the magnets conformal to the magnetic field to enable electron recirculation
- The *good curvature of the magnetic field stabilizes the plasma*
- A Polywell might use aneutronic fuels like $\mathrm{p}^{11}\mathrm{B}$
- Bussard founded the company **EMC2**, funded by the US Navy until 2006, when the project terminated and results were published
- The US Navy restarted funding EMC2 in 2007
- EMC2 has built and studied about ten Polywell devices
- Polywell research is performed in the USA at Wisconsin and Convergent Scientific Inc. as well as in Australia (Sydney) and Iran

The Polywell reactor

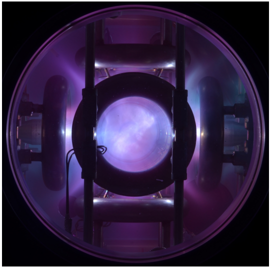


Figure: An EMC2 Polywell with a side length of 21.6 cm built for β=1 studies.

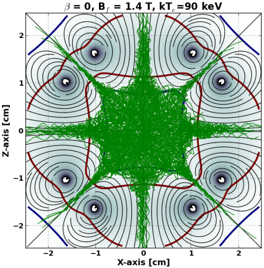


Figure: Polywell field lines for $\beta = 0$. Simulated electron trajectories are shown in green.

EMC2 has shown:

- 1995: Electrostatic fusion in a Polywell (a potential well for ions) [12]
- 2013: A high β-value in a Polywell simultaneously with significantly increased electron confinement [6]
- *To show the scientific feasibility of the Polywell for energy production, both of these have to be demonstrated at the same time*

The Polywell reactor

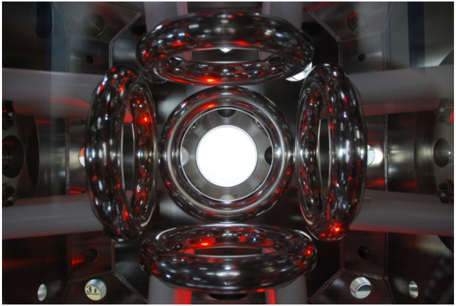


Figure: The EMC2 Polywell experiment WB-8

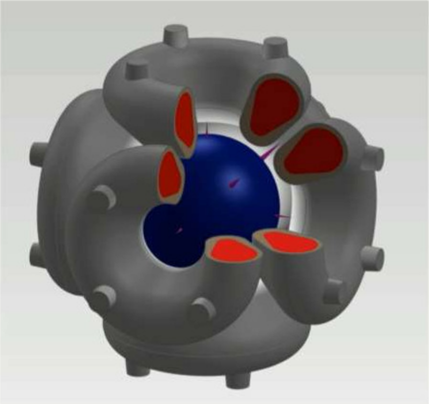
To continue Polywell research EMC2 is seeking new funding of 30 M$ for a three year programme with the following goals [13]

- Reach a high β-value for $\approx$ 5 ms
- Show efficient ion heating with ($>$10 keV) electron beam injection
- Verify the Grad estimate for particle losses in a magnetic cusp

An energy producing Polywell requires that:

- Grads cusp electron loss estimate is right
- The ion heating with electron beams works efficiently

Net Power Producing Polywell Reactor



Reactor Parameters

Coil Radius: 2.0 m

B-field: 5 T

e-beam: 80 keV

Plasma pressure: 98 atm

Magnetic pressure: 98 atm

Fusion power: 1.1 GW (D-T fuel)

Heating power to plasma: 185 MW

Disclaimer: This design is for a scientific test fusion device (not for engineering demonstration)

We can build this in a few years

The Polywell reactor

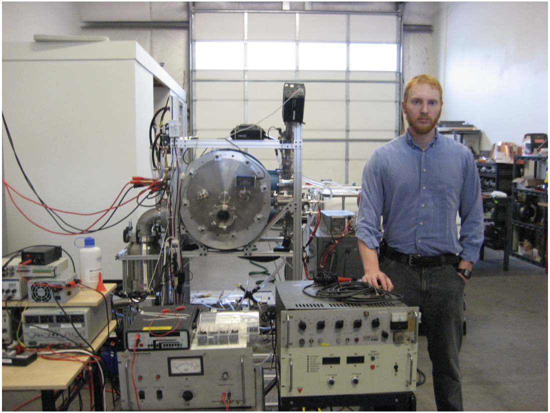
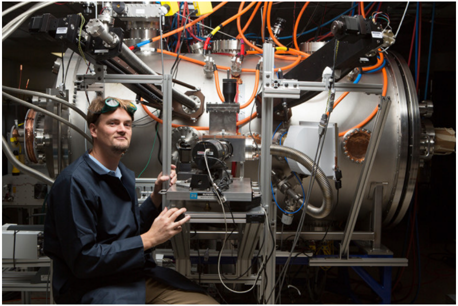
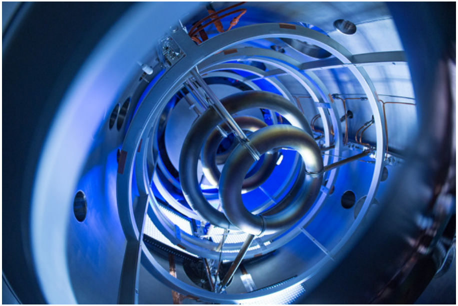


Figure: **Convergent Scientific**, Inc.

- Built and studied a R=16 cm, B=0,1 T polywell since 2012
- Works on Polywell simulations (also GPGPU)
- Seeks 1 M$ for a R = 33 cm, B=0,2 T device
- A R = 125 cm, B=3,5 T polywell needs 8-10 M$ more funding

Lockheed Martin CFR





- **Lockheed Martin** Compact Fusion Reactor project started in 2011
- T4 experiment published in February 2013 by C. Chase
- CFR patents published in 09/2014 [14, 15, 16, 17, 18, 19, 20, 21]
- T. McGuire leads the development at Skunk Works
- T4 experiment 1 m * 2 m, production reactor about 7 m * 13 m
- DT-fuel, Polywell like, axisymmetric, magnetic mirrors at ends
- Few open magnetic field lines, good field curvature, high β
- aims for a 100 MW prototype, first publication in 2015

Lockheed Martin CFR

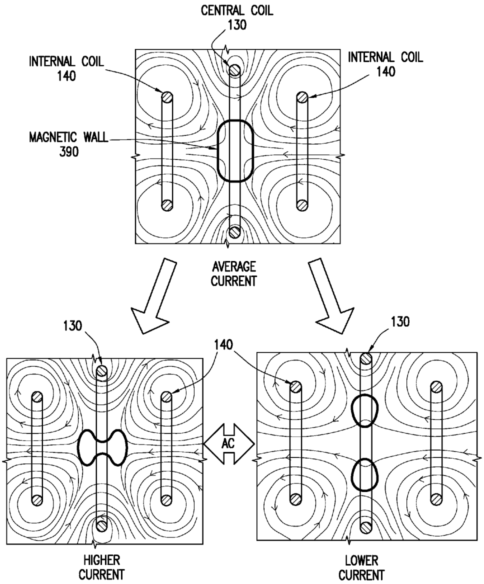


Figure: CFR central magnetic field lines [19].

Dense plasma focus

LPP Fusion (LPPF), led by E. Lerner [22]

- Dense Plasma Focus: J.W. Mather 1960s, N.V. Filippov 1954. An electric discharge creates the plasma, which develops through a series of instabilities to a plasmoid
- Goal $P = 5$ MWe, $f = 200$ Hz
- Landau quantization is expected to decrease bremsstrahlung
- For a DD-plasma E>150 keV has been measured [23], which is enough for $\mathrm{p}^{11}\mathrm{B}$
- $\tau \approx 20$ ns, surpasses 8 ns goal
- Energy transfer to the plasmoid surpasses goal with 50 %
- ρ needs to increase with 10^4 for $Q = 1$
- Worked on reducing electron induced impurities [24]
- New W electrode expected to increase ρ 50x–100x in 2015

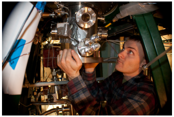


Figure: LPPF reactor [22].

Figure: Electrode length ≈ 15 cm.

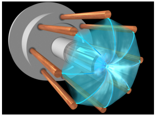
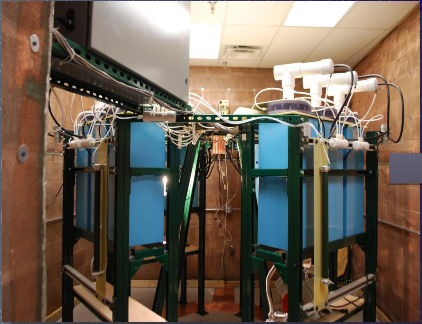


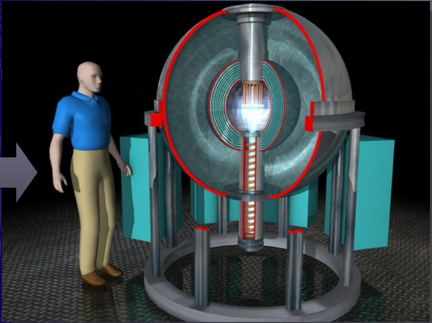
Figure: Schematic plasma discharge.

From NJ To Your Neighborhood

FF-1, 2016



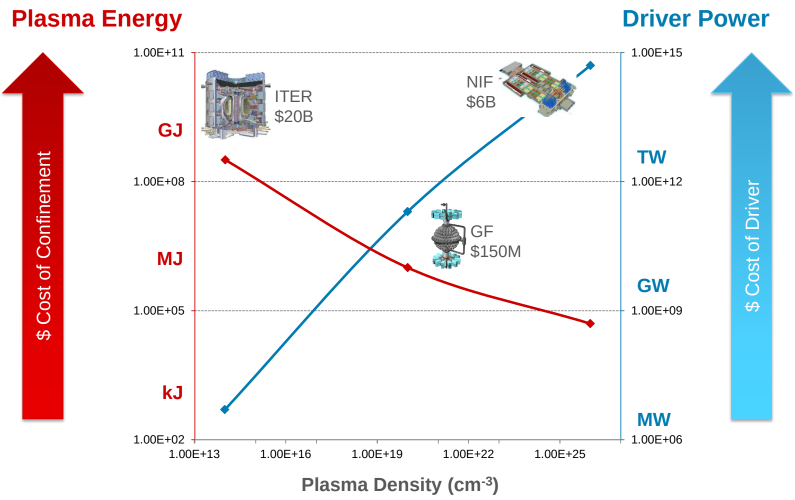
FF-X, 2019



1 Year – conclude scientific feasibility

4 Years – for commercial generator

Fusion Technologies



MTF

General Fusion - acoustically heated MTF [25, 26, 27, 28, 29, 30, 31]

- Based on LINUS concept from the 1970s
- Chief scientist and founder M. Laberge
- The planned reactor is a sphere with $r = 1{,}5$ m with a rotating molten PbLi mixture, $P = 100$ MWe, $f = 1$ Hz, $Q = 6$
- Two plasma injectors create, accelerate and compress spheromaks
- The spheromaks injected through the vortex in the middle collide
- The FRC DT-plasma is heated to fusion conditions acoustically with hundreds of computer controlled pneumatic pistons
- The GF concept has several advantages compared to a tokamak:
  - No ”inner wall” problem, no divertor needed
  - PbLi is a coolant and neutron multiplicator for T-generation
  - Can be retrofitted to turbines of existing power plants
- Potential problems
  - Compression and stability of the injected spheromaks
  - Richtmyer-Meshkov instability
  - Pb,Li-impurities can cool the plasma

MTF

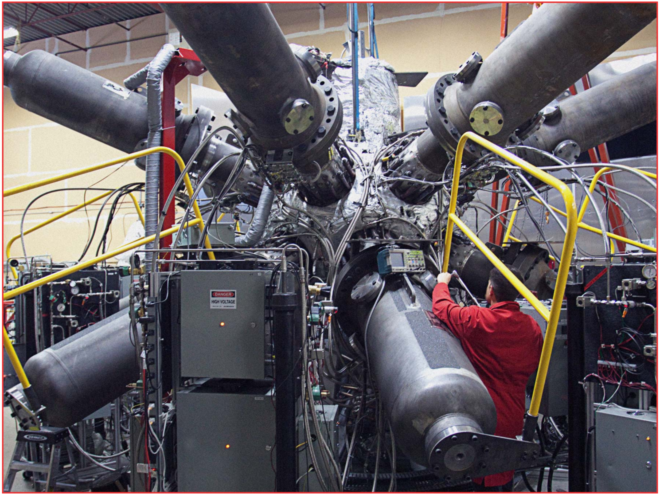
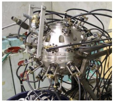


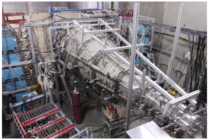
Figure: General Fusions 14 piston test reactor *"Mini-Sphere"*, with a diameter of one meter, is used for validating compression simulations.

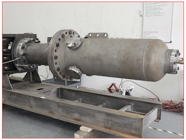
MTF

The General Fusion development plan:

- **Phase I - Proof of principle**
  - 2002 - 2008, < 1 M$
  - Research and development
- **Phase II - Show net gain**
  - 2010 - 2015, ≈ 50 M$
    - System development
    - Current status
    - Physics validation
  - Full scale prototype
    - ≈ 150 M$
- **Phase III - Commercialization**
  - Alpha and Beta power plants
  - ≈ 2 G$
  - Then power production







MTF

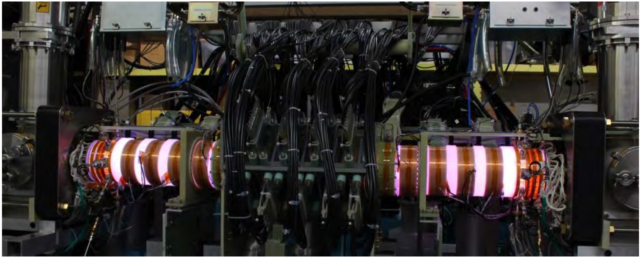


Figure: **Helion Energy, MSNW LLC** [32, 33].

- Two colliding FRCs merge to a stationary FRC
- The FRC is compressed magnetically in the burn chamber
- $T_i \approx$ 2,3 keV obtained for D-ions
- A plasmoid speed of 300 km/s has been achieved
- Plans to use D+D (^{3}He) fuel
- Targets 50 MWe prototype in 2019 and commercialization in 2022
- MSNW develops a fusion driven rocket (FDR) with NIAC funding
  - Lithium compresses the plasma, absorbs neutrons and generates T

MTF

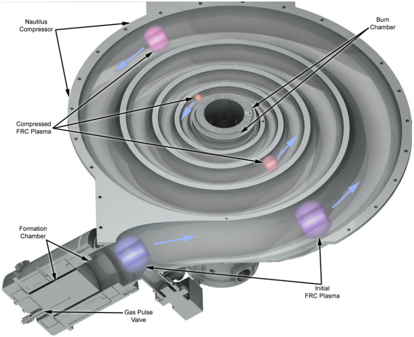


Figure: **Sorlox** Nautilus FRC compressor.

- Sorlox develops a spiral shaped FRC plasma compressor [34]
- Based on LLNL *Compact Torus Accelerator*
- Funded by DARPA with 1.15 M$
- The aim is to shoot a magnetized $5 \cdot 10^{15}$ions/cm^3 DD plasma into a spiral shaped cone with $v \approx 4800$ km/s to be heated up and compressed to 10^{18}ions/cm^3
- The plasma circulates and fuses in the center of the reactor for some 20 ms
- The target for the reactor is $P = 2$ kW - 1 MW, maybe later 1 - 10 MW
- A commercial reactor for isotope production and research is available

Other fusion concepts or companies

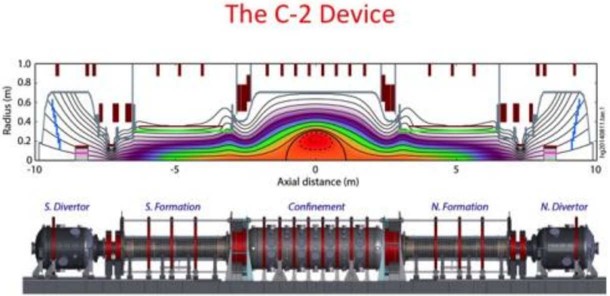


Figure: **Tri Alpha Energy** (TAE) experiment **C-2** [35, 36].

- A FRC is produced by two colliding plasmoids in the C-2 experiment
- The plasmoid injection speed is 250 km/s
- The FRC lifetime is 4 ms, $T_i \approx 0{,}5$ keV
- The goal is to support the FRC-state with neutral beam injection and possibly with current induction and heating with rotating magnetic fields
- TAE plans to use D^3He or $p^{11}B$

Other fusion concepts or companies

- Dynomak (Univ. Washington), spheromak fusion reactor
- Fusion Power Corporation, heavy ion fusion
- Spherical tokamaks
  - Running experiments
    - Mega Ampere Spherical Tokamak (MAST)
    - National Spherical Torus Experiment (NSTX)
  - Proposed experiments
    - Tokamak Energy, Inc. spherical tokamak
    - ARC, high field compact tokamak
- Farnsworth-Hirsch fusor [37, 38, 39, 40, 41] - likely the simplest fusion reactor, cannot probably be scaled up for energy production
- Phoenix Nuclear Labs, accelerator based neutron generator $3 \cdot 10^{11}$ n/s from DD-fusion [42]
- ...

Summary

Company	Year	Funding $	Size m	Type	Method	Reaction	P target MW
General Fusion	2002	57 M	3	p	MTF	D+T(Li)	100 e
EMC2	1985	42 M	4	c	IEC	D+T	255
LM Skunk Works	2011	4 M	13		MCF	D+T	100
Helion Energy	2009	6,5 M	16	p	MTF	D+D(^{3}He)	50 e
Sorlox	2010	1,15M	< 1	p	MTF	D+D	0,002-1
LPPF	1974	4,5 M	0,15	p	DPF	$p + {}^{11}B$	5 e
Tri Alpha Energy	1998	150 M	18	p	MTF	$p + {}^{11}B$	100
Convergent Scientific	2010	120 k	7–12	c	IEC	$p + {}^{11}B$	225 e

p = pulsed, c = continuous, e = electric

Summary

- **All possibilities of achieving fusion should be researched thoroughly by increasing funding, becuse the potential benefits are enormous**
- **Fusion break even is a very hard problem**
- *Inadequate funding has affected the rate of developement*
- *Compact fusion reactors have several advantages in terms of development time, cost, placement, applications (mobile, space, medical, material physics)*
- Fusion reactions have been commercialized as neutron generators
- Small fusion reactors can be developed for medical isotope generation
- Pulsed fusion reactors could be simpler than continuous reactors
- MTF/MIF could provide a promising path to practical fusion
- *The development of plasma physics, instrumenting, software and computers has enabled some ten (privately funded) companies to do fusion research*
- CSI, LPPF and Tri Alpha Energy try to develop aneutronic $\mathrm{p}^{11}\mathrm{B}$ fusion
- **GF, HE, LM, & LPPF try to reach $Q \geq 1$ within the next few years**
- **If $Q \gg 1$ is reached, then power production might start after 2020**

Additional reading

Articles on the same topic:

- T. Lindén, *Kompakta fusionsreaktorer*, Arkhimedes 5-6, 2014, p. 16-23
- D. Clery, *Fusion's restless pioneers*, Science 345 6195, 25.7.2014 p. 370-375
- M. M. Waldrop, *The Fusion Upstarts*, Nature 511, 24.7.2014 p. 398-400

[1] EU Research & Innovation, Energy Facts and Figures, Figure: EU R&D funding 1985-2007

[2] SIPRI YEARBOOK 2013

[3] J. Santarius, Fusion cross sections plot, Fusion Technology Institute, University of Wisconsin-Madison

[4] John F. Santaurius, *Role of Advanced-Fuel and Innovative Concept Fusion in the Nuclear Renaissance*, APS Division of Plasma Physics Meeting Meeting, Philadelphia, October 31, 2006

[5] A. A. Harms, K. F. Schoepf, G. H. Miley, D. R. Kingdon, *Principles of Fusion Energy: An Introduction to Fusion Energy for Students of Science and Engineering*

[6] J. Park et al., *High Energy Electron Confinement in a Magnetic Cusp Configuration*, arXiv:1406.0133 [physics.plasm-ph]

[7] P. M. Bellan, *Spheromaks : a practical application of magnetohydrodynamic dynamos and plasma self-organization*, London : Imperial College Press, 2000

[8] I. R. Lindemuth, R. E. Siemon, *The fundamental parameter space of controlled thermonuclear fusion*, Am. J. Phys. 77, pp. 407-416, May 2009

[9] Robert W. Bussard, March 1991, Fusion Technology, Volume 19, *Some Physics Considerations of Magnetic Inertial Electrostatic Confinement: A New Concept for Spherical Converging Flow Fusion*

[10] Nicholas Krall, Fusion Technology, Volume 22, August 1992, *The Polywell: A Spherically Convergent Ion Focus Concept*

[11] Robert W. Bussard, November 9, 2006, *Should Google Go Nuclear?*

[12] Robert W. Bussard, *The Advent of Clean Nuclear Fusion: Superperformance for Space Power and Propulsion*, Proc. 57th International Astronautical Congress, Valencia, Spain October 2-6 2006

[13] J. Park, *POLYWELL - Electric Fusion in a Magnetic Cusp*, talk at Microsoft January 22, 2015

[14] T. McGuire, *ACTIVE COOLING OF STRUCTURES IMMERSED IN PLASMA*, Patent publication WO/2014/204553A3

[15] T. McGuire, *SYSTEM FOR SUPPORTING STRUCTURES IMMERSED IN PLASMA*, Patent publication WO/2014/204554A3

[16] T. McGuire, *MAGNETIC FIELD PLASMA CONFINEMENT FOR COMPACT FUSION REACTOR*, Patent publication WO/2014/204555A8

[17] T. McGuire, *ENCAPSULATING MAGNETIC FIELDS FOR PLASMA CONFINEMENT*, Patent publication WO/2014/204556A3

[18] T. McGuire, *HEATING PLASMA FOR FUSION POWER USING NEUTRAL BEAM INJECTION*, Patent publication WO/2014/204557A2

[19] T. McGuire, *HEATING PLASMA FOR FUSION POWER USING MAGNETIC FIELD OSCILLATION*, Patent publication WO/2014/204558A2

[20] T. McGuire, *HEATING PLASMA FOR FUSION POWER USING ELECTROMAGNETIC WAVES*, Patent publication WO/2014/204559A2

[21] T. McGuire, *MAGNETIC FIELD PLASMA CONFINEMENT FOR COMPACT FUSION POWER REACTOR*, Patent publication WO/2014/165641A1

[22] Eric J. Lerner, S. Krupakar Murali, A. Haboub, *Theory and Experimental Program for* $\mathrm{p} + {}^{11}\mathrm{B}$ *Fusion with the Dense Plasma Focus* J Fusion Energy (2011) 30:367-376

[23] Eric J. Lerner et al., *Fusion reactions from >150 keV ions in a dense plasma focus plasmoid*, Phys. Plasmas 19, 033704 (2012)

[24] Eric J. Lerner and Hamid R. Yousefi, *Runaway electrons as a source of impurity and reduced fusion yield in the dense plasma focus*, Phys. Plasmas 21, 102706 (2014)

[25] M. Laberge, *An Acoustically Driven Magnetized Target Fusion Reactor*, J Fusion Energ (2008) 27:65-68

[26] S. Howard, M. Laberge, L. McIlwraith, D. Richardson, J. Gregson, *Development of Merged Compact Toroids for Use as a Magnetized Target Fusion Plasma*, J Fusion Energ (2009) 28:156-161

[27] M. Laberge, *Experimental Results for an Acoustic Driver for MTF* J Fusion Energ (2009) 28:179-182

[28] P. J.F. Carle, S. Howard, J. Morelli, *High-bandwidth polarimeter for a high density, accelerated spheromak*, Rev Sci Instrum 84, 083509 (2013)

[29] V. Suponitsky, A. Froese, S. Barsky, *Richtmyer-Meshkov instability of a liquid-gas interface driven by a cylindrical imploding pressure wave*, Computers & Fluids 89 (2014) 1-19

[30] M. Laberge, S. Howard, D. Richardson, A. Froese, V. Suponitsky, M. Reynolds, D. Plant, *Acoustically driven Magnetized Target Fusion*, Proc. Fusion Engineering (SOFE), 2013 IEEE 25th Symposium on Fusion Engineering, June 10-14, 2013, San Francisco, California, USA, http://dx.doi.org/10.1109/SOFE.2013.6635495

[31] M. Lindstrom, S. Barsky, B. Wetton, *Investigation into Fusion Feasibility of a Magnetized Target Fusion Reactor: A Preliminary Numerical Framework*, J Fusion Energ (2015) 34:76-83

[32] J. Slough, G. Votroubek and C. Pihl, Creation of a high-temperature plasma through merging and compression of supersonic field reversed configuration plasmoids, Nucl. Fusion 51 (2011) 053008

[33] A. Pencotti, *Electromagnetically Driven Fusion Propulsion*, NASA's Innovative Advanced Concepts symposium 4-6.2.2014

[34] B. Freeze, *Method and apparatus for compressing plasma to a high energy state*, Patent publication WO 2013/070179 A1

[35] M. Tuszewski et al., *Field Reversed Configuration Confinement Enhancement through Edge Biasing and Neutral Beam Injection*, Phys Rev Lett 108, 255008 (2012)

[36] M. W. Binderbauer et al., *Dynamic Formation of a Hot Field Reversed Configuration with Improved Confinement by Supersonic Merging of Two Colliding High-Beta Compact Toroids*, Phys Rev Lett 105, 045003 (2010)

[37] Tom Ligon, *The World's Simplest Fusion Reactor, And How to Make It Work*

[38] Philo T. Farnsworth, *Electric Discharge Device for Producing Interactions Between Nuclei*, U.S. Patent Number 3,258,402 June 28, 1966

[39] Robert L. Hirsch, *Inertial-Electrostatic Confinement of Ionized Fusion Gases*, J Appl Phys **38** (1967) 4522-4534

[40] Robert L. Hirsch; *Erratum: Inertial-Electrostatic Confinement of Ionized Fusion Gases, J Appl Phys* **39**, (1968) 4047

[41] Robert L. Hirsch; *Experimental studies of a deep, negative, electrostatic potential well in spherical geometry*, 1968, Physics Fluids, 11, 2486-90

[42] G.L.Kulcinski, *Recent Progress at Phoenix Nuclear Labs and SHINE Medical Technologies*, 15th Workshop on Inertial Electrostatic Confinement Fusion, October 6-9 Uji, Kyoto, Japan