Outline (subject to change without notice):

Part three: Twenty years away, forever

- Fusion reactor basics
- Confinement – magnetic, inertial, etc.
- Pulsed, but not Orion: Daedalus and Icarus
- VASIMR and the almost-fusion

Outline (subject to change without notice):

Part four: Speculations

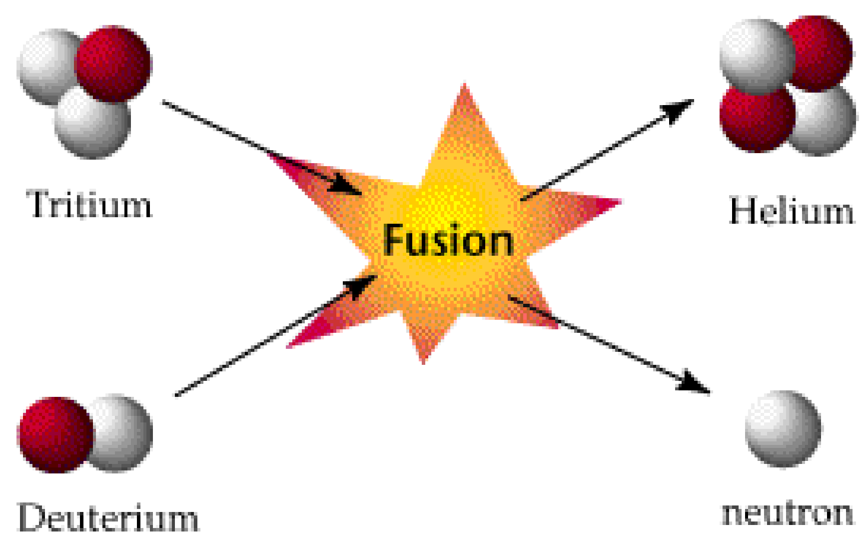
- Tokamak, spheromak, other-o-mak
- Smoke rings and disposable liners
- Pinch devices
- The Farnsworth Paradox
- The Bussard ramjet

Intro to fusion:

- Instead of splitting heavy atoms apart, we shmoosh light ones together
- Fission can happen all by itself, but fusion requires energy to start it
- Fusion can produce less radioactive waste

Energy In	Reaction	Energy Out
0	$2\ H_2 + O_2 \triangleright 2\ H_2O$	5.9 eV
0	$^{235}U + n \triangleright A + B + 2\ n$	200 MeV
3.5 keV	$^{2}H + ^{3}H \triangleright ^{4}He + n$	17.6 MeV
30 keV	$^{2}H + ^{2}H \triangleright ^{3}He + n$	3.3 MeV
30 keV	$^{2}H + ^{2}H \triangleright ^{3}H + ^{1}H$	4.0 MeV
300 keV	$^{2}H + ^{3}He \triangleright ^{4}He + ^{1}H$	18.3 MeV
123 keV	$^{1}H + ^{11}B \triangleright 3\ ^{4}He$	8.7 MeV

Some common reactions (more messy in real life)



Note on the table: first we have an "energy in" column. This is the amount of energy required to satisfy the "Lawson criterion".

For any particular reaction, the Lawson criterion is the product of the confinement time, plasma temperature, and density. If that criteria is met, then a fusion reaction will occur.

It's usually given as an average energy (read: temperature) that fulfills the product.

Energy In	Reaction	Energy Out
0	$2\,H_2 + O_2 \triangleright 2\,H_2O$	5.9 eV
0	$^{235}U + n \triangleright A + B + 2\,n$	200 MeV
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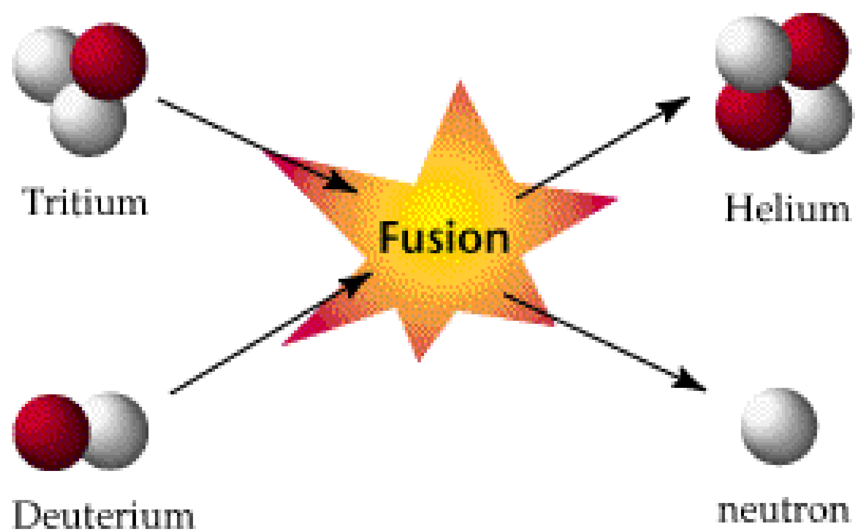

Next: energy out. Fission produces approximately 200 MeV per reaction. Fusion is more like 10-ish MeV. So what gives?

When taking into account the mass of the reactants, it turns out that fusion produces about 3 times more energy than fission on a per-unit-mass basis.

Also note: there's a lot more hydrogen in the universe than there is uranium.

Energy In	Reaction	Energy Out
0	$2 H_2 + O_2 \triangleright 2 H_2O$	5.9 eV
0	$^{235}U + n \triangleright A + B + 2 n$	200 MeV
3.5 keV	$^2H + ^3H \triangleright ^4He + n$	17.6 MeV
30 keV	$^2H + ^2H \triangleright ^3He + n$	3.3 MeV
30 keV	$^2H + ^2H \triangleright ^3H + ^1H$	4.0 MeV
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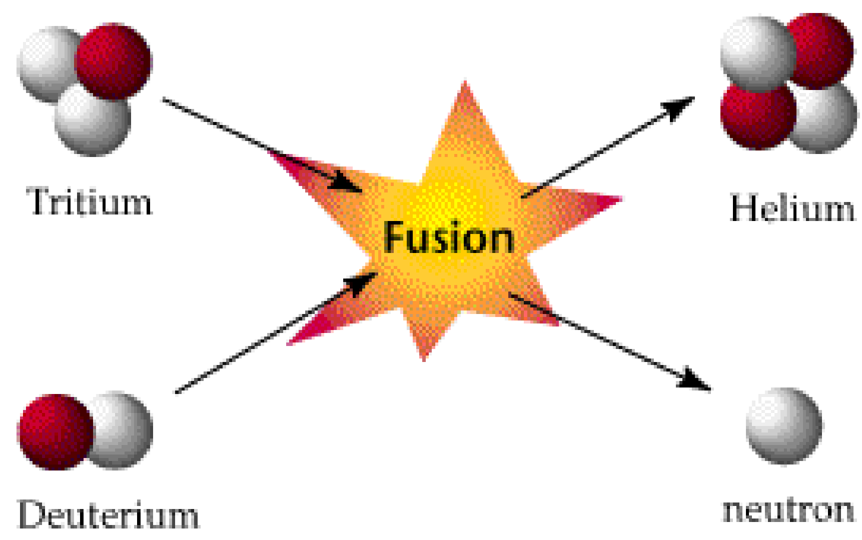
Some common reactions (more messy in real life)



Finally, just like with fission, fusion reactions can get very complicated very quickly.

Let's say you start with a deuterium-deuterium reaction. There's a roughly equal chance that you'll get tritium or helium as a product. And then those will want to enter other reactions, to produce things like lithium and nitrogen, which will then in turn want to enter other reactions…

Even an "aneutronic" reaction will not remain entirely aneutronic.

Energy In	Reaction	Energy Out
0	$2\,H_2 + O_2 \triangleright 2\,H_2O$	5.9 eV
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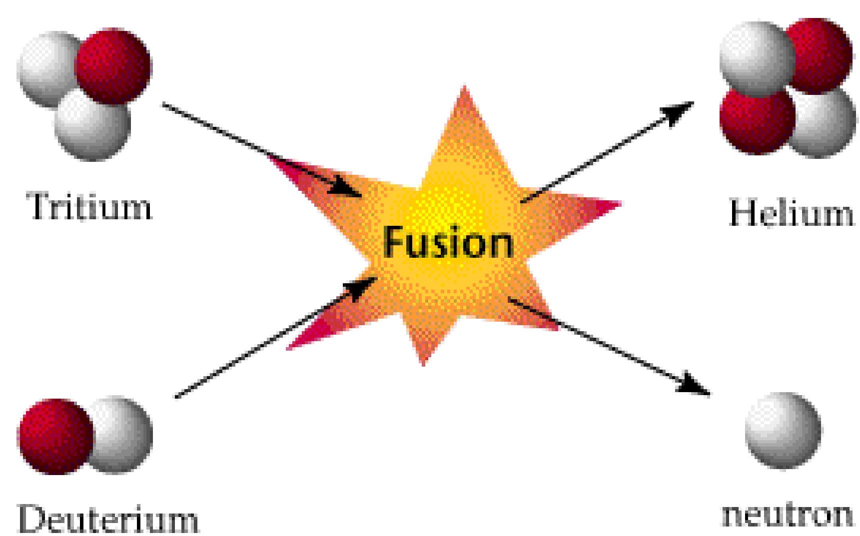
Some common reactions (more messy in real life)

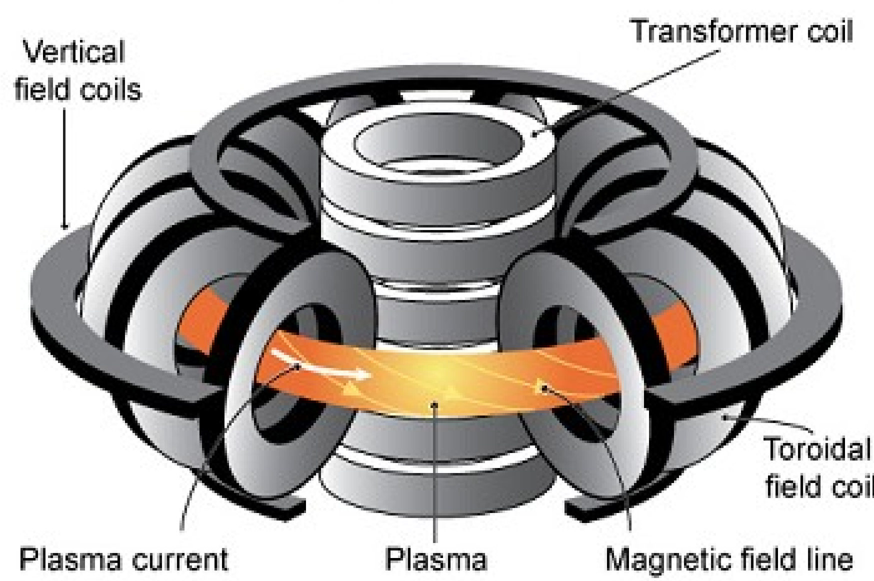


In order to meet the Lawson criteria, we need two things: heat and compression. The more we have of the one, the less we need of the other (no cold fusion jokes, please – they are no longer funny).

Heating is pretty simple: RF excitation, electric arcs, lasers, etc. Compression (and confinement) is the hard one.

The Virial theorem – a statistical-mechanical relationship between average kinetic energy and potential energy.

As applied to plasma physics, the Virial theorem states that a plasma cannot be self-confining. Way to make this hard, Virial. Thanks.



Tokamak Reactor Schematic
(image courtesy of General Fusion Inc, ©2010)

Magnetic confinement (MCF)

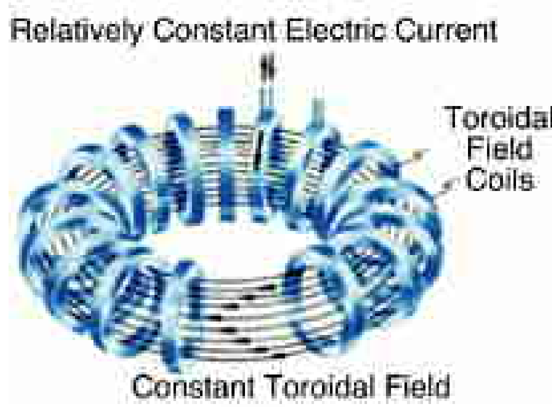
With enough rubber bands, you can hold jell-o together.

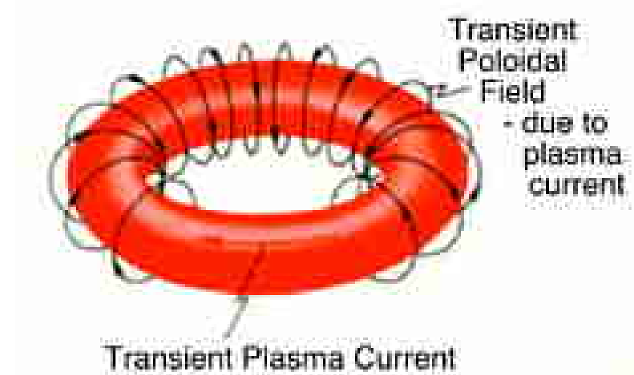
Hot plasma is given a spin

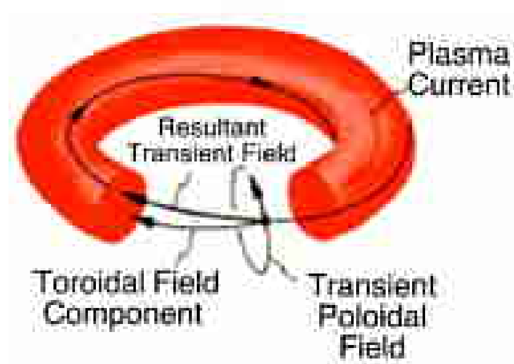
Multiple fields are applied

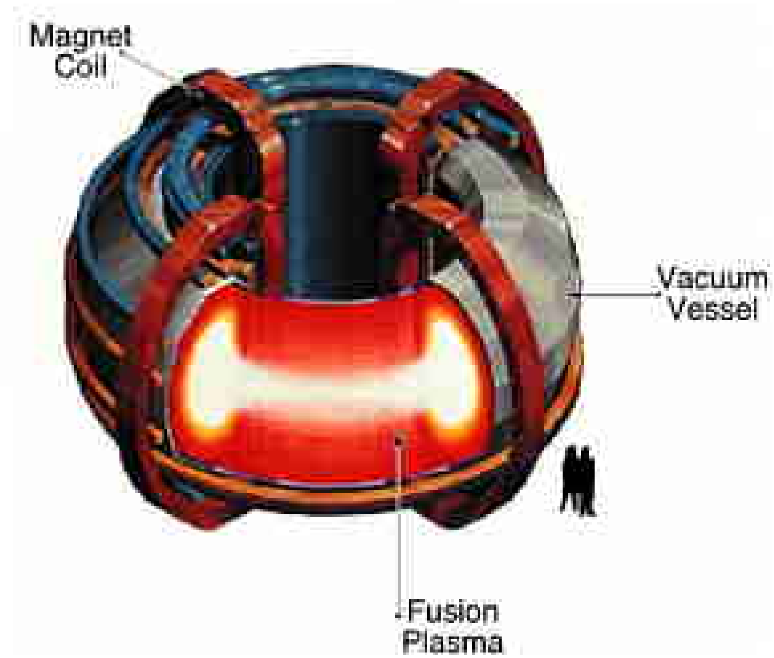
We really hope that this makes the plasma want to stay away from the chamber walls

The chamber can be toroidal (tokamak), spherical-ish (spheromak), or even linear (using mirror-magnets)









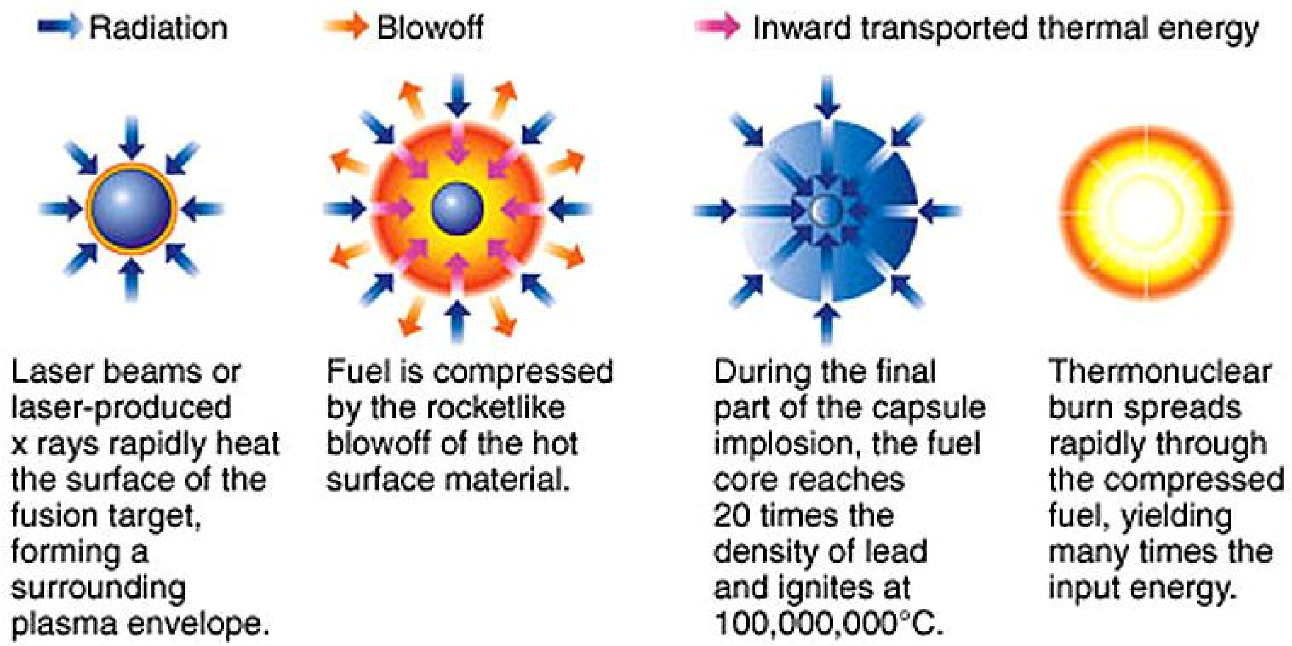
Inertial confinement (ICF)

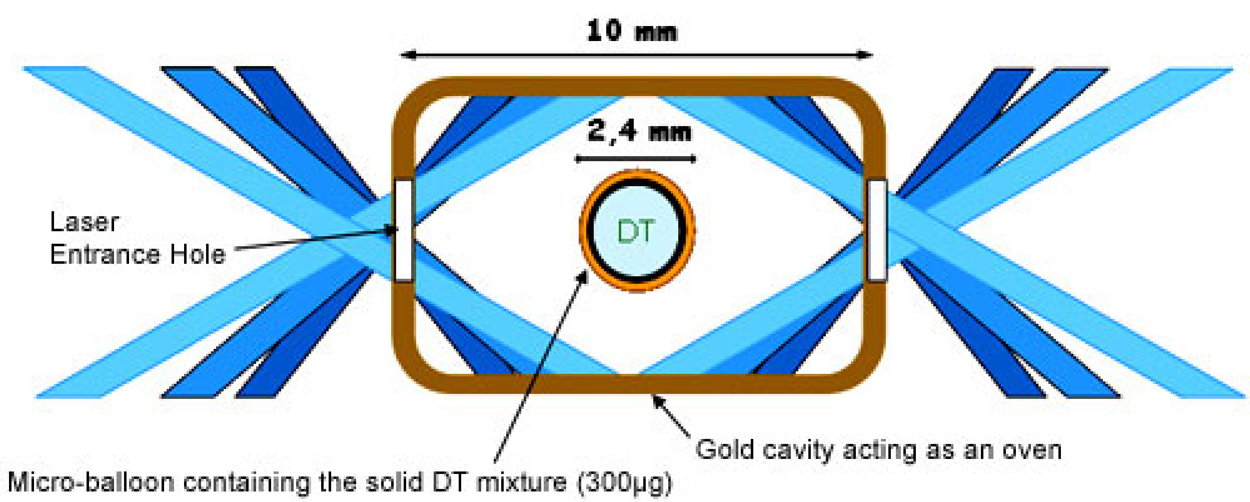
To heck with containment, we'll just whack it really hard.

It's not the lasers (or electron beams) that compress the fuel – its the x-rays that are produces when the beams hit the pellet

Apparently, the Rayleigh-Taylor instability doesn't apply to x-rays.

Pulsed, by design (so like Orion, but smaller and faster)





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Inertial Electrostatic Confinement (IEC)

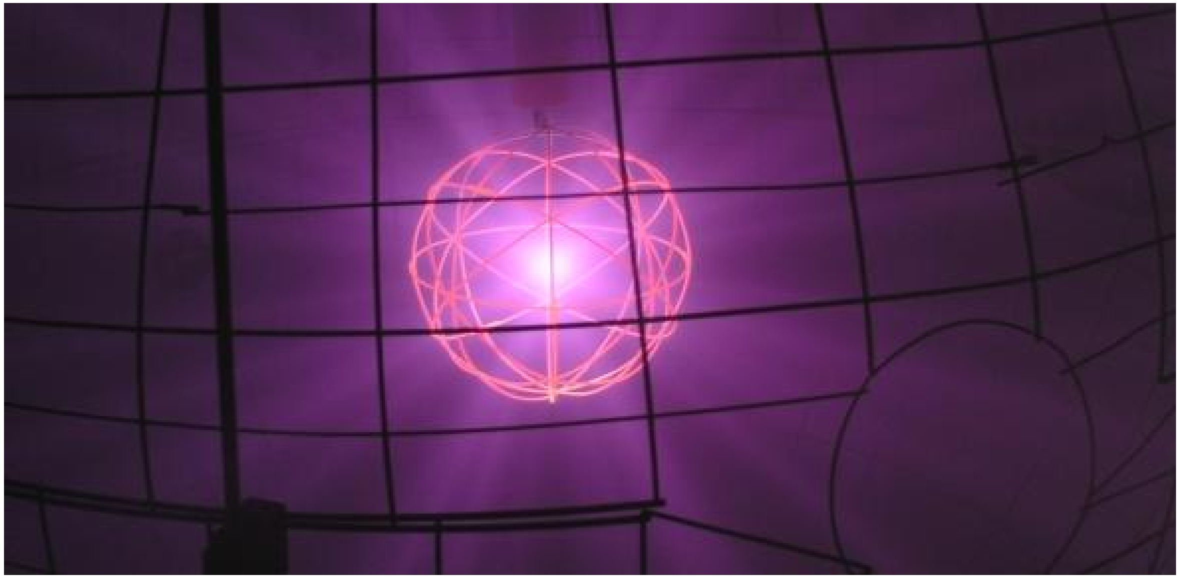
Electric fields instead of (or, even better, in addition to) magnetic

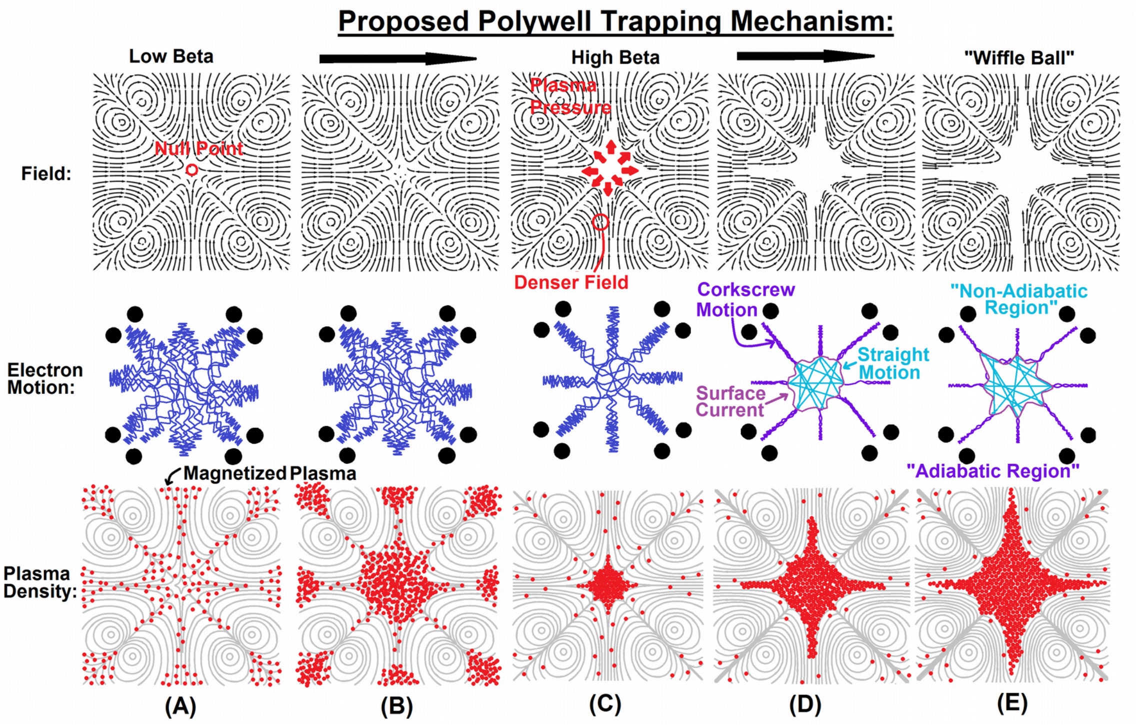
In practice, several grids, and a lot of magnets

Not very efficient (yet) and with a lot of engineering problems

On the upside, no huge magnets or frikkin' lasers

Good news everyone! Endorsed by both Robert Bussard *and* Professor Farnsworth!





Dense Plasma Focus and Z-Pinch Devices (DPF, ZPD)

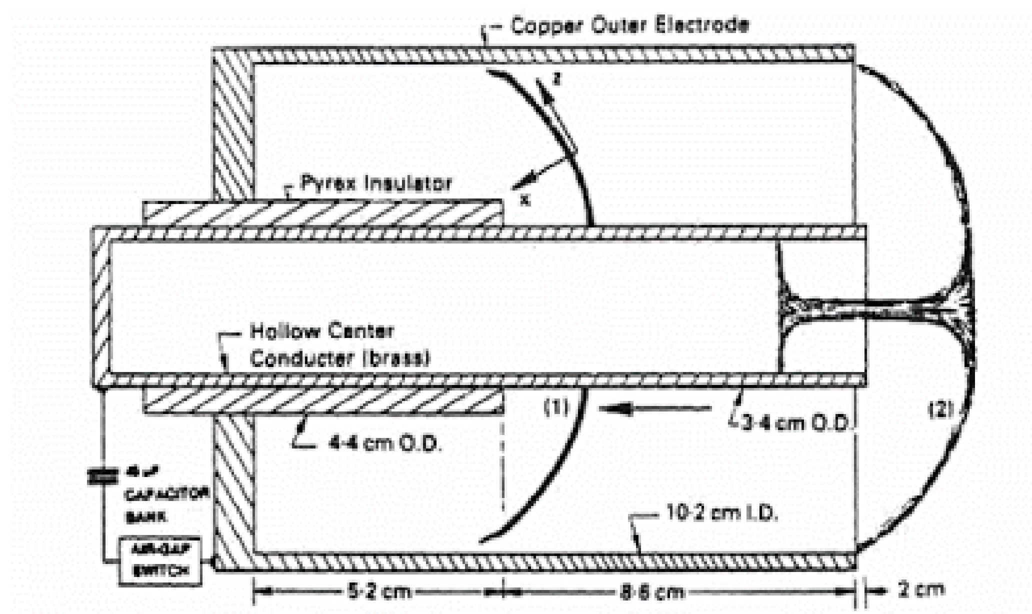
Pulsed (like inertial) but really magnetic confinement

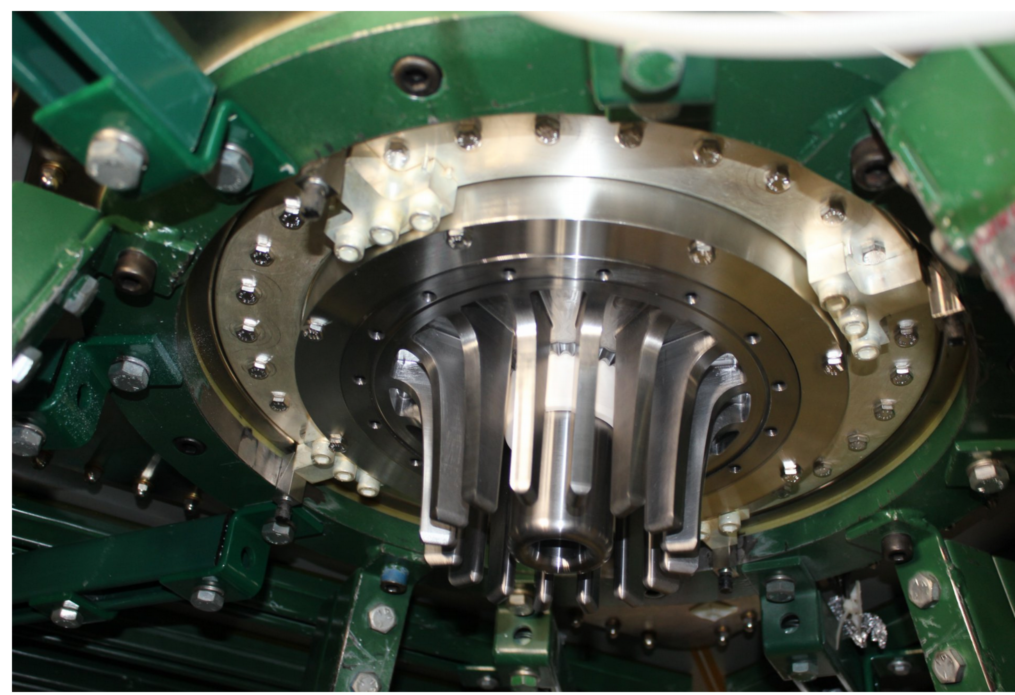
Uses a high-current pulse to create a self-field (J X B force) and accelerate the plasma toward a focal point

When the field collapses, it traps some of the plasma along with it

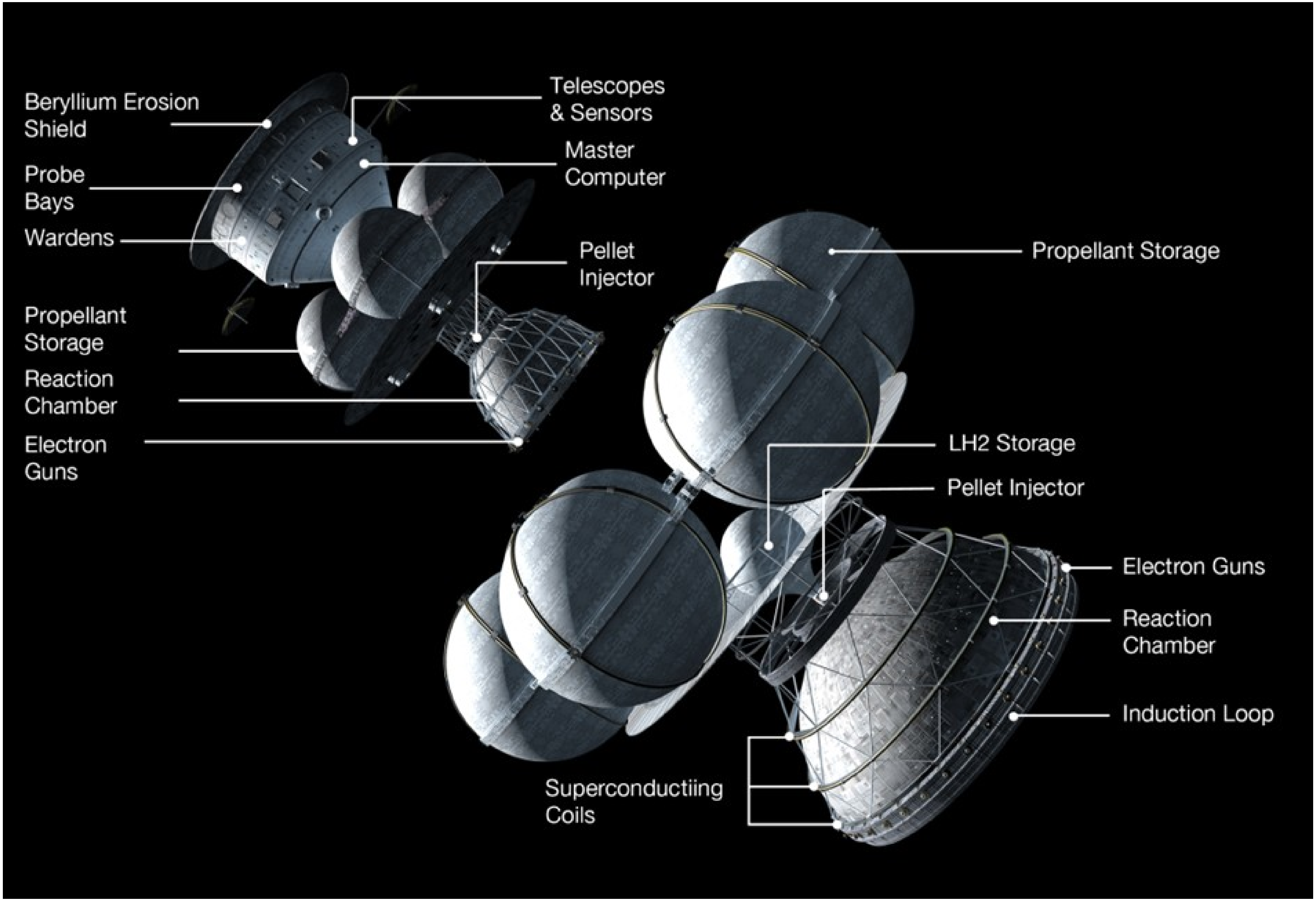
Heats and compresses in one step and nothing to align or supercool

But *very* prone to instabilities





Part 3: History – pulsed (but not Orion)



Daedalus

2-stage ICF propulsion using
electron beams for ignition

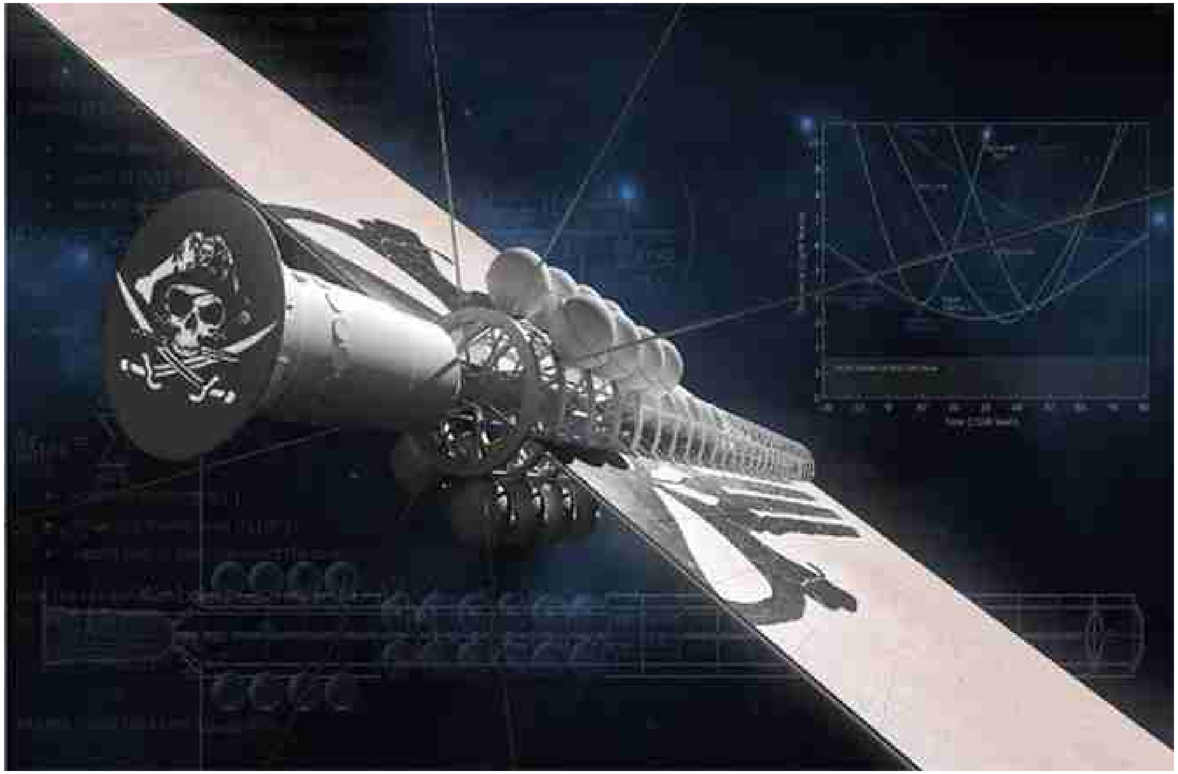
Thrust ≈ 7.5 MN (650 kN)
I_{sp} ≈ 1,000,000 sec.

Fuel Mass = 46,000 t (4000 t)
Burn Duration ≈ 2 yrs (1.5 yrs)
Stage Mass = 1700 t (900 t)

Final speed = 0.12c

Problems

No means of stopping at the target
E-beam ignition is untested
Unrealistic specific impulse



Icarus (ghost variant)

Single stage ICF propulsion
with antimatter catalysation

Thrust ≈ 1,500,000 N
I_{sp} ≈ 540,000 sec.

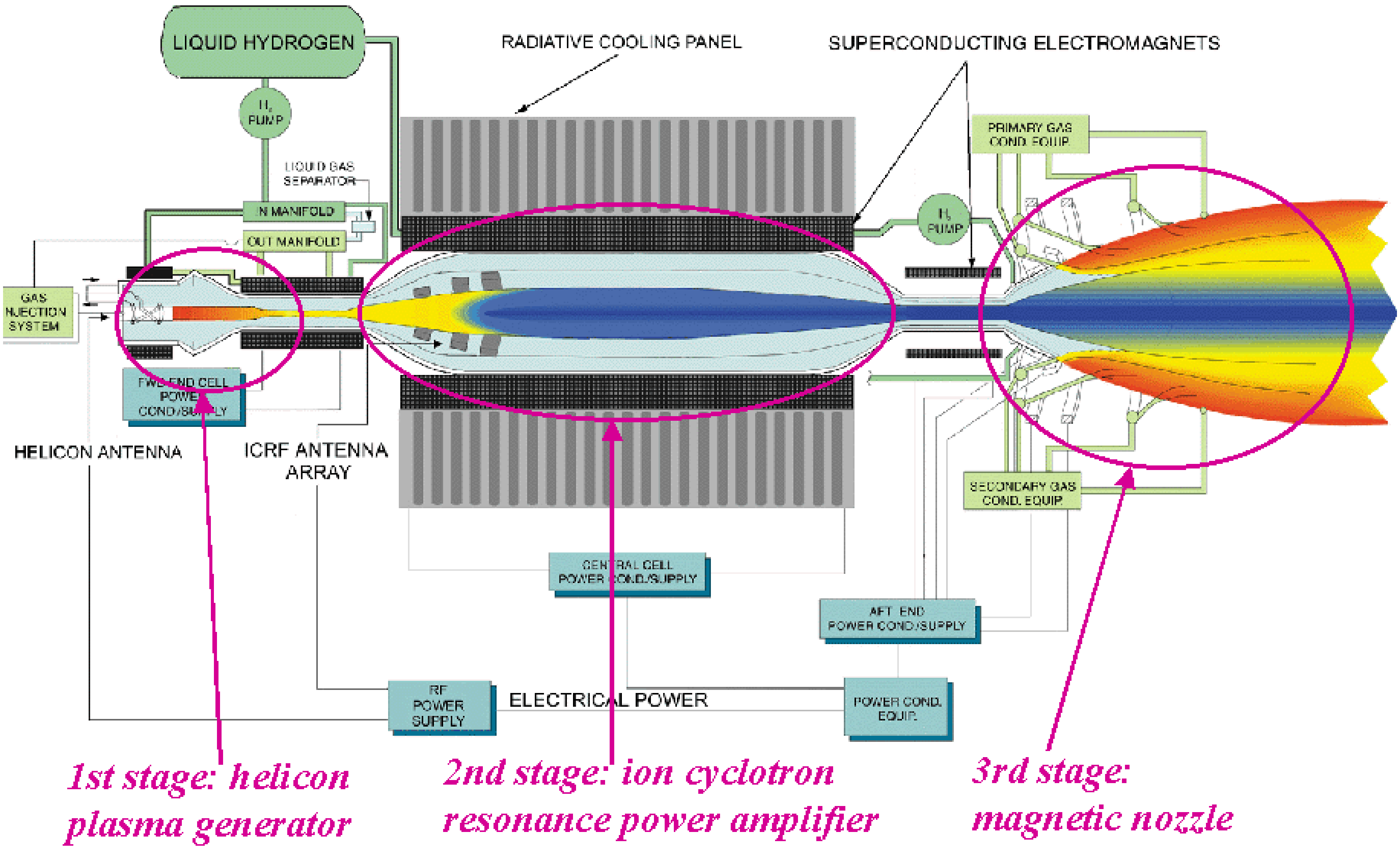
Fuel Mass = 150,000 t
Burn Duration ≈ 15 years
Stage Mass = 1150 t
Final speed = 0.06c

Magnetic sails for deceleration at the target system for proper exploration

Problem: antimatter catalysation is completely untested

Both Daedalus and Icarus are designed for interstellar exploration

What's being done right now - VASIMR



What's being done right now – VASIMR

Projected stats based on the current test article:

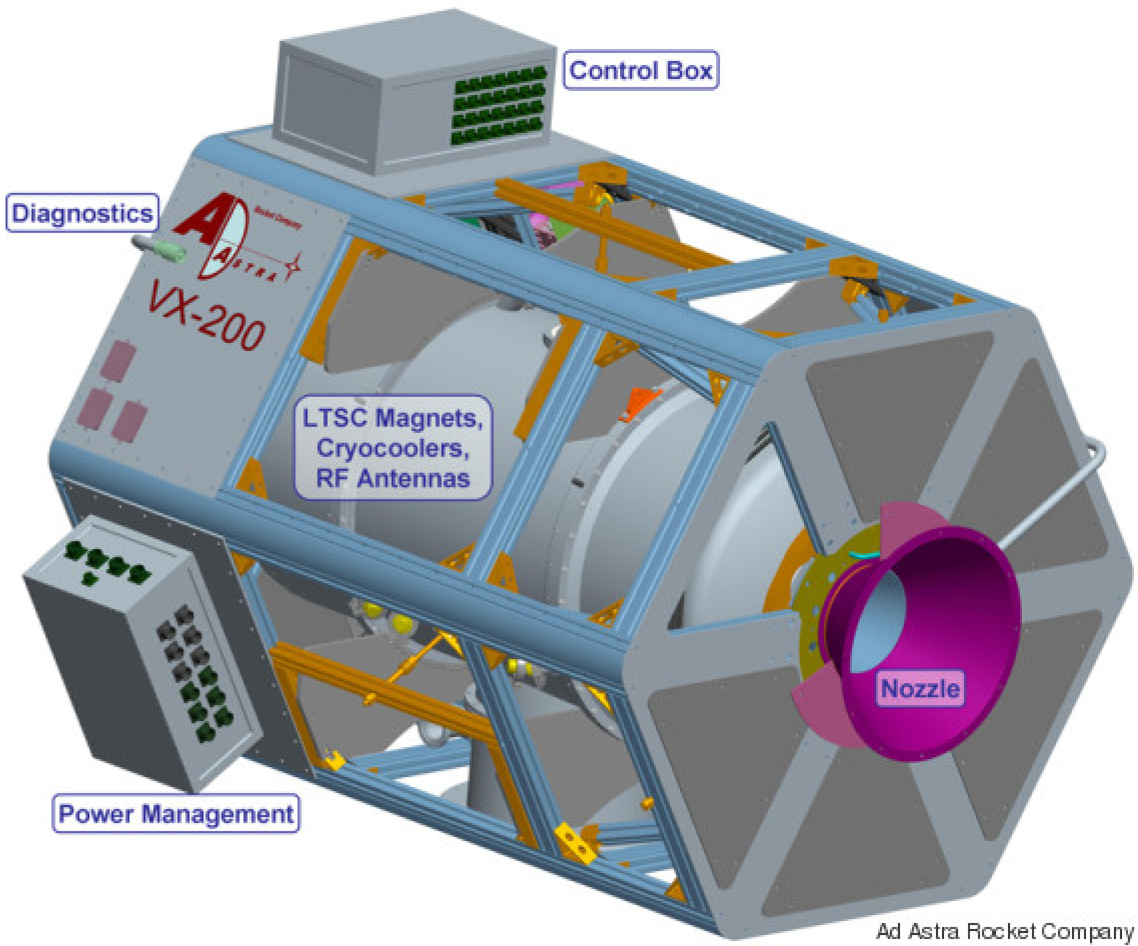
Engine mass = 10 t

Thrust = 40 N (400 N)

I_{sp} = 30,000 sec (3000 sec)

The VASIMR drive can vary its specific impulse, trading it for thrust, by changing confinement time and mass flow rate

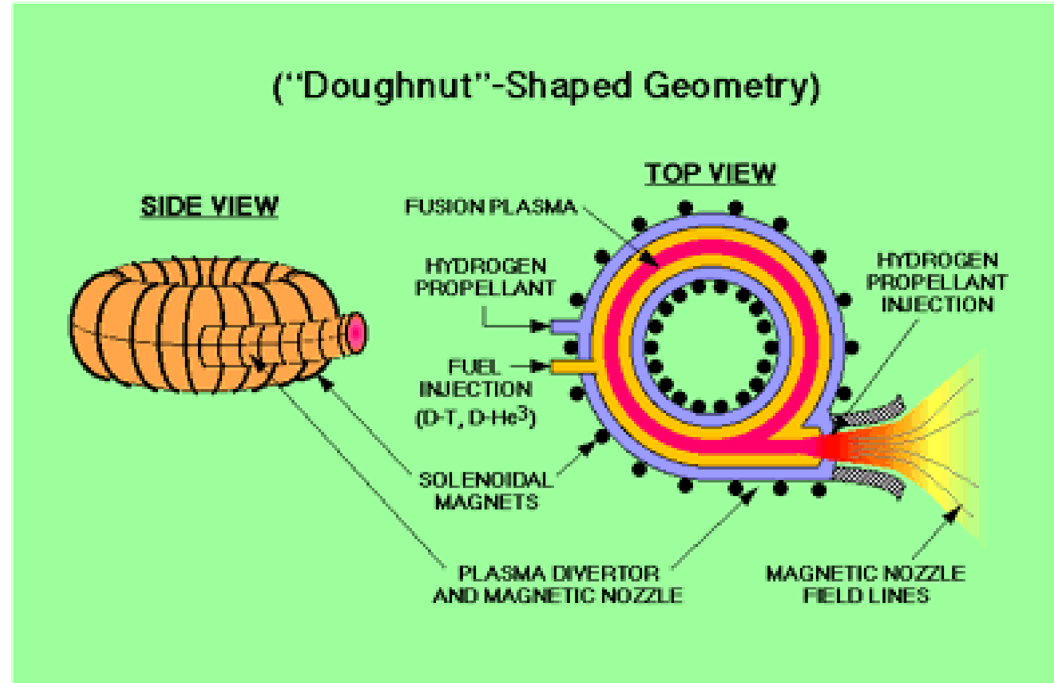
Not actually fusion!

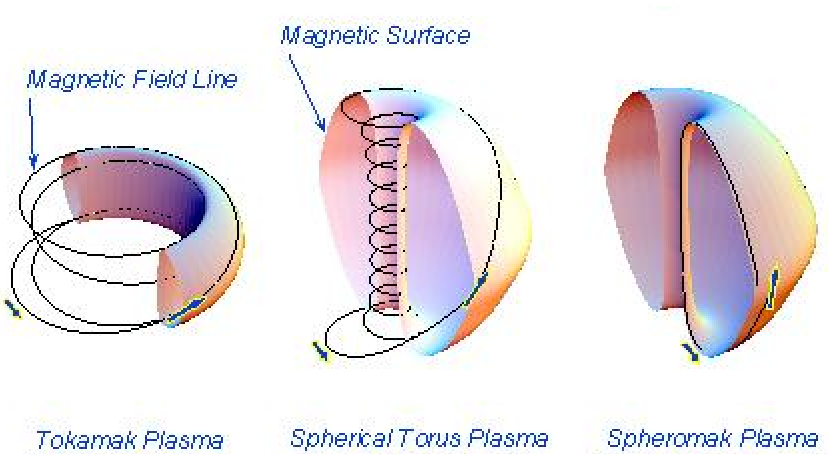


Tokamak and spheromak

Generally lousy as engines due to the mass of the magnets and their cooling systems

A spheromak tries to simplify the geometry by getting rid of some of the magnets and spinning the plasma in to a “smoke ring”





But remember the Virial theorem: a plasma cannot be self-containing

(except sometimes, almost)

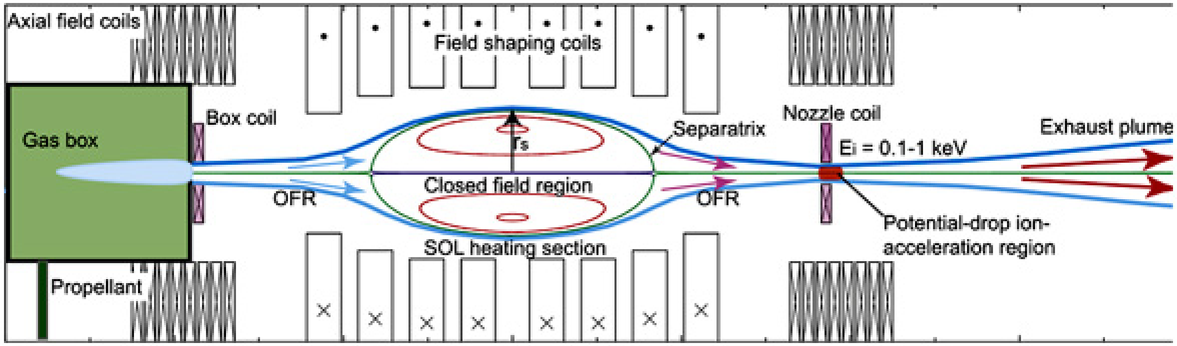
Direct fusion drive

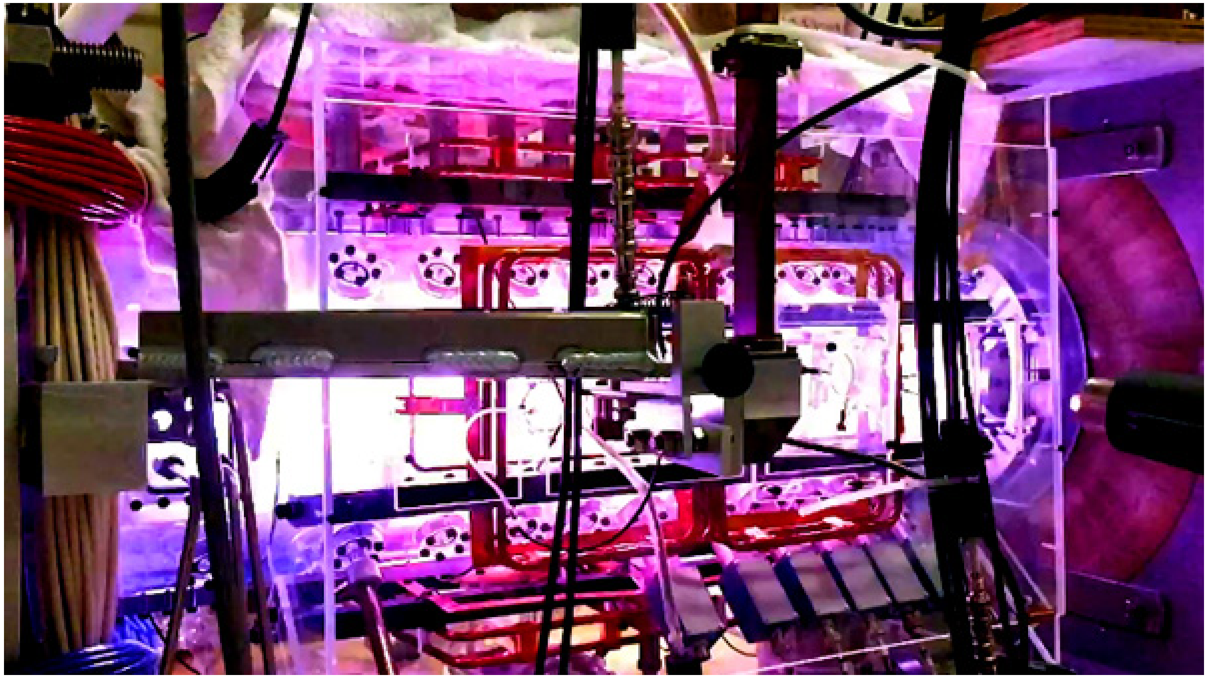
Like VASIMR, but bigger

Currently under development at Princeton Plasma Physics Lab

Essentially an "unrolled" tokamak with mirror magnets at the ends

Probably the first practical development of a fusion rocket as well as a great test bed for other concepts (FRC, MTF)



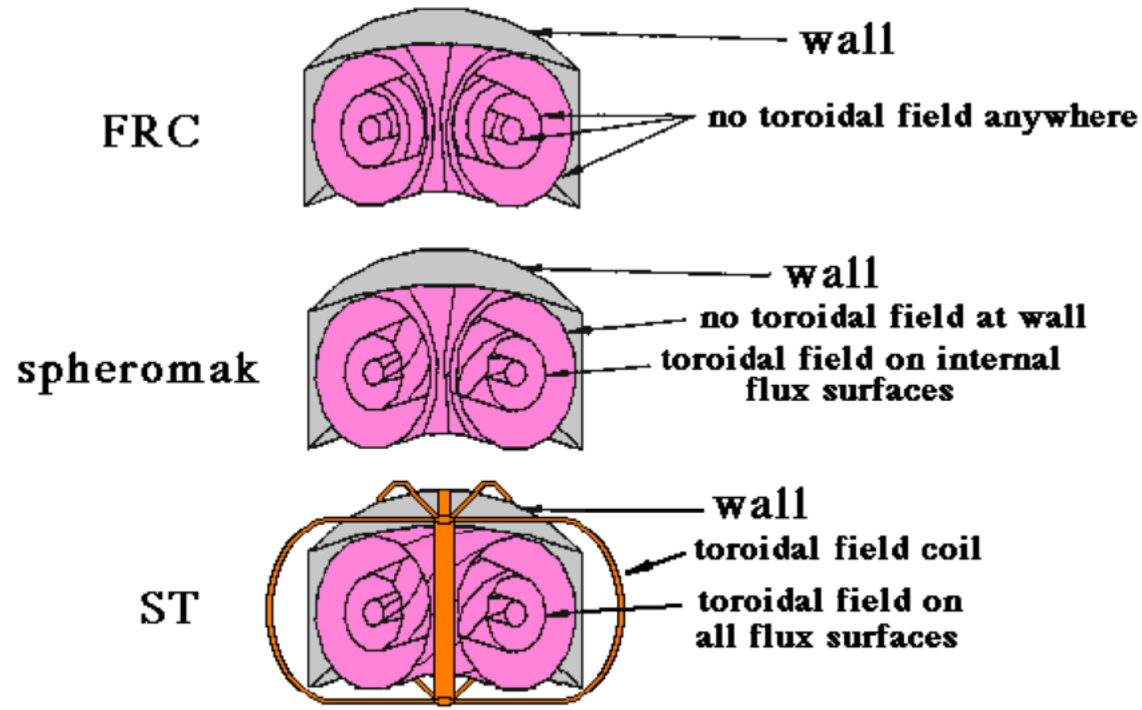


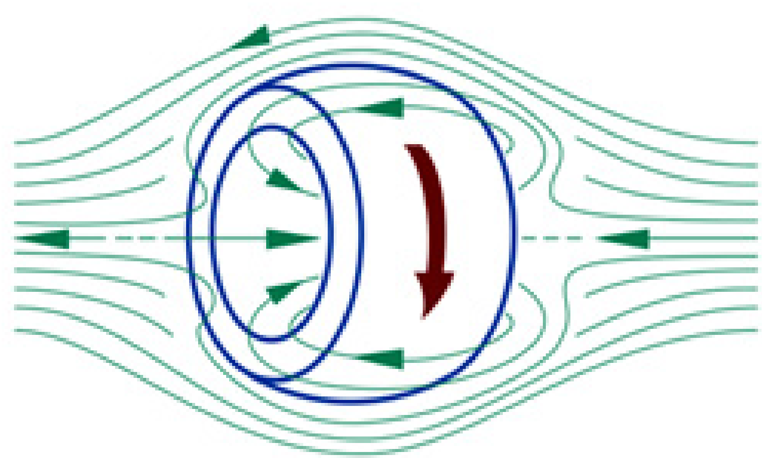
Field-reversed configuration

Plasma is “blown” in to a soliton shape (like a smoke ring)

Technically, it still doesn’t contain itself – there are still external fields needed to stabilize it and to keep it moving

In an FRC engine, the plasma is injected at one end and travels to the exhaust – the axial motion stabilizes it





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Magnetized target fusion

Start with a FRC smoke ring

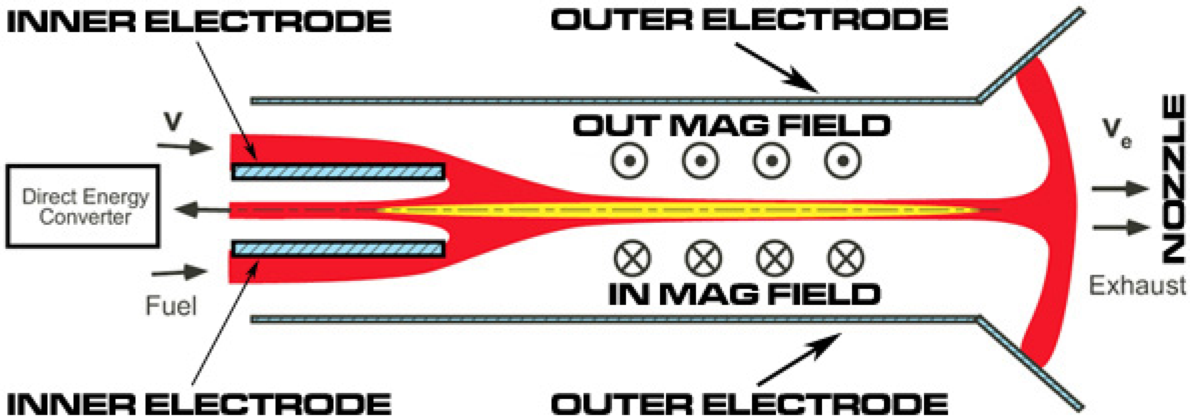
When it gets to the nozzle, use a pulsed field to collapse a liner around it

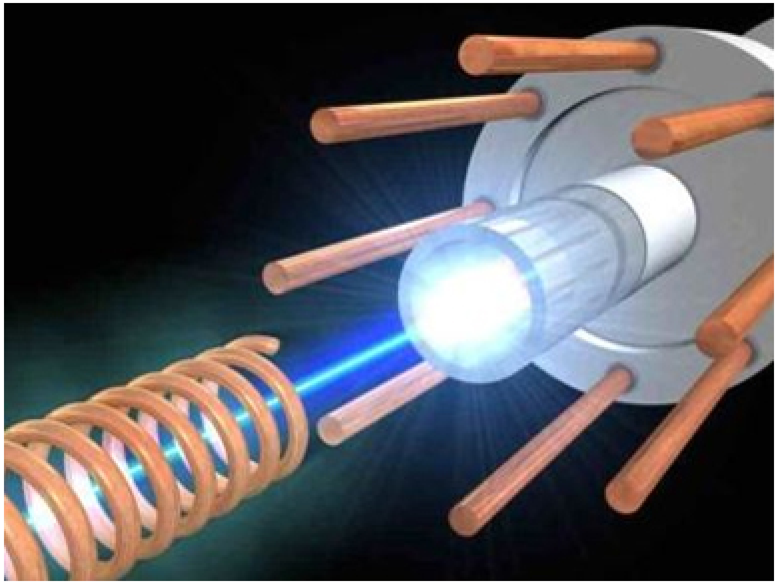
This liner can be fusion fuel (lithium, boron, whatever); a metal "wrapper"; or more hydrogen

MCF requires monstrous fields. ICF requires huge capacitor banks. By combining the best features of both, one can greatly reduce the engine mass and still get reasonable performance.

A pinch device (dense plasma focus, z-pinch, theta-pinch) traps the plasma in a collapsing field

Dead-simple in design, no alignment issues, no huge magnets (but still monstrous capacitors)





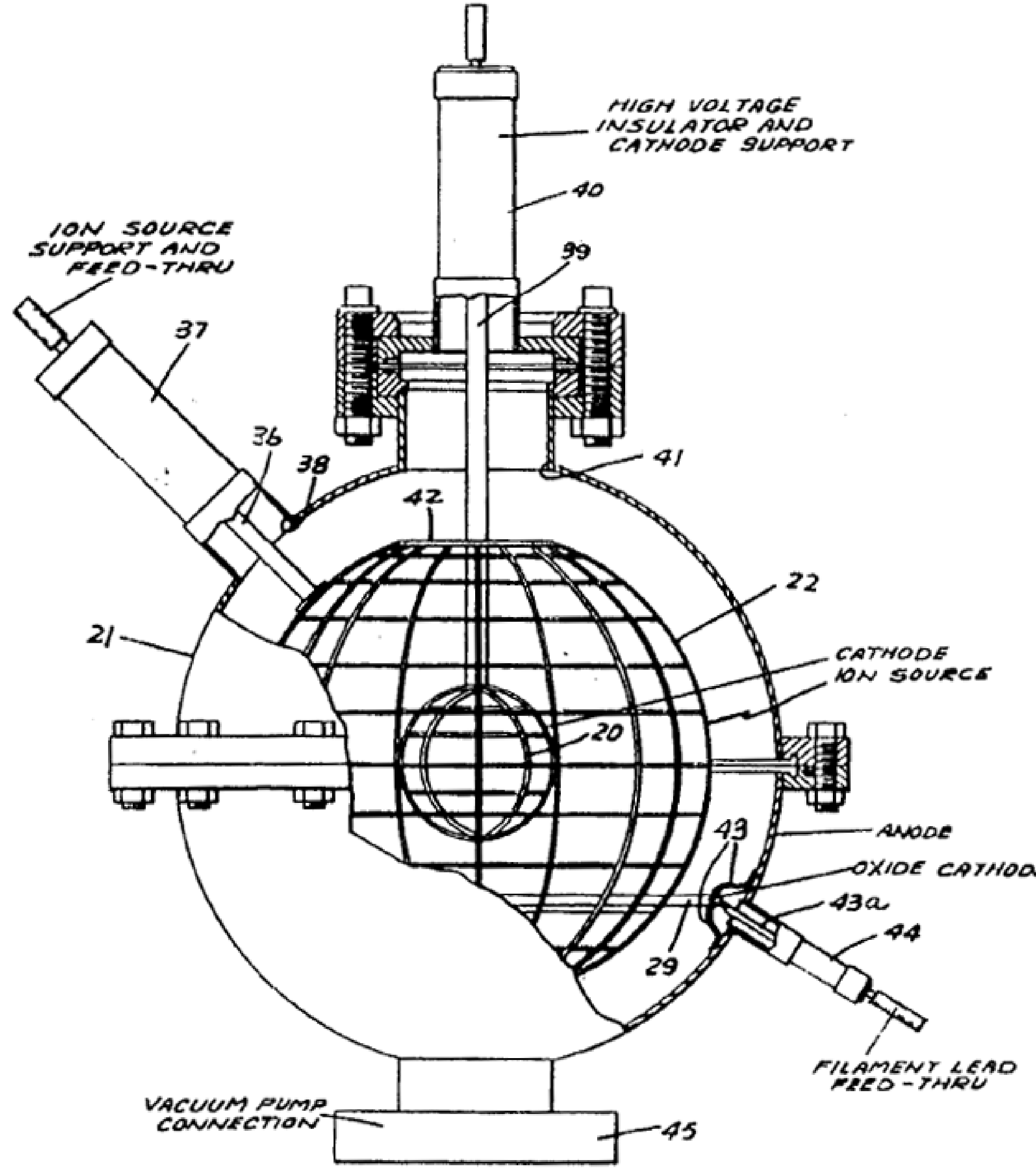
An important advantage that pinch devices have: you can build one in your garage.

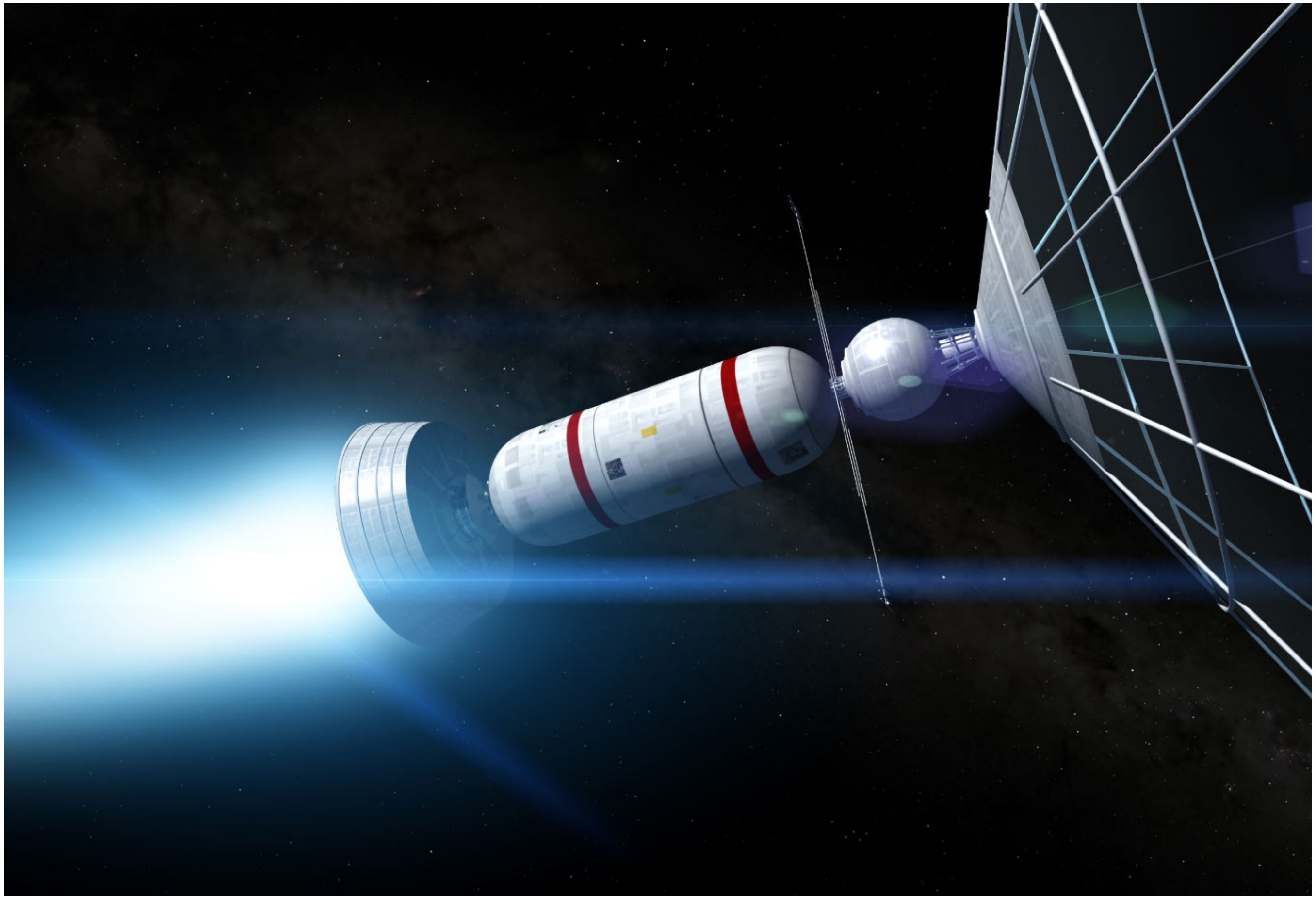
Oh, and breaking news: plasma instabilities could be overcome by introducing shear flows!

IEC has a “jet mode” that makes it useful for fusion propulsion

Still plagued by low yields, though

Good news: You can build one of these in your garage, too!





Why carry fuel?

The idea: there's free-range hydrogen in space, so we should be able to scoop it up and power whatever fusion drive we have

It sounds nice but...

Atoms per cubic meter isn't much to work with

Such a low density means that the scoop must be extraordinarily large

And these are *neutral* atoms and largely unaffected by magnetic fields

And there's a lot of un-fusable crap mixed in

Fusion drive stats (an apples to marmosets comparison)

Type	Isp (sec)	Thrust (N)	Mass (t)	Source
Tokamak / Spheromak	6800	66,000	200	Borowski et al, "A Spherical Torus Nuclear Fusion Reactor"
Direct drive	10,000	50	???	Cramer et al, "The Direct Fusion Drive Rocket"
FRC / MTF	70,000	5800	121	Adams et al, "Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets"
Pinch devices	350,000	330,000	???	Shumlak et al, "Advanced Space Propulsion Based on the Flow-Stabilized Z-Pinch Fusion Concept"
IEC	2000	67,000	54	Bussard et al, "Inertia-Electrostatic-Fusion Propulsion Spectrum"

Questions?