Energy Generation through Nuclear Fusion

Nathaniel J. Fisch
Department of Astrophysical Sciences
Princeton University

Alternative Sustainable Energy Research Initiative
Weizmann Institute of Science
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This talk will explore how energy may be generated through nuclear fusion.

Princeton Plasma Physics Laboratory

- 436 FTE employees
- 20 postdocs
- 38 graduate students

~ 250 visiting scientists
(40 resident)

Founded 1951

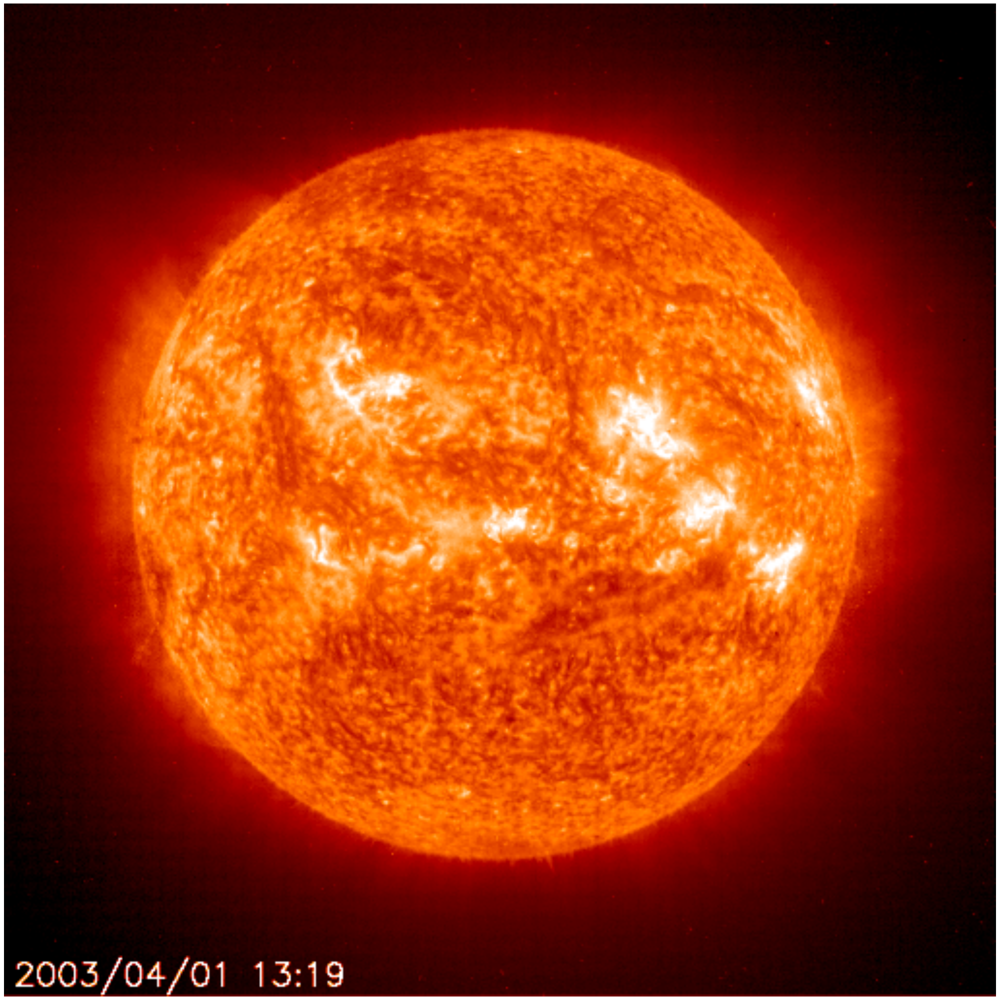
www.pppl.gov

U.S. DEPARTMENT OF ENERGY | Office of Science

PRINCETON UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Energy from Nuclear Fusion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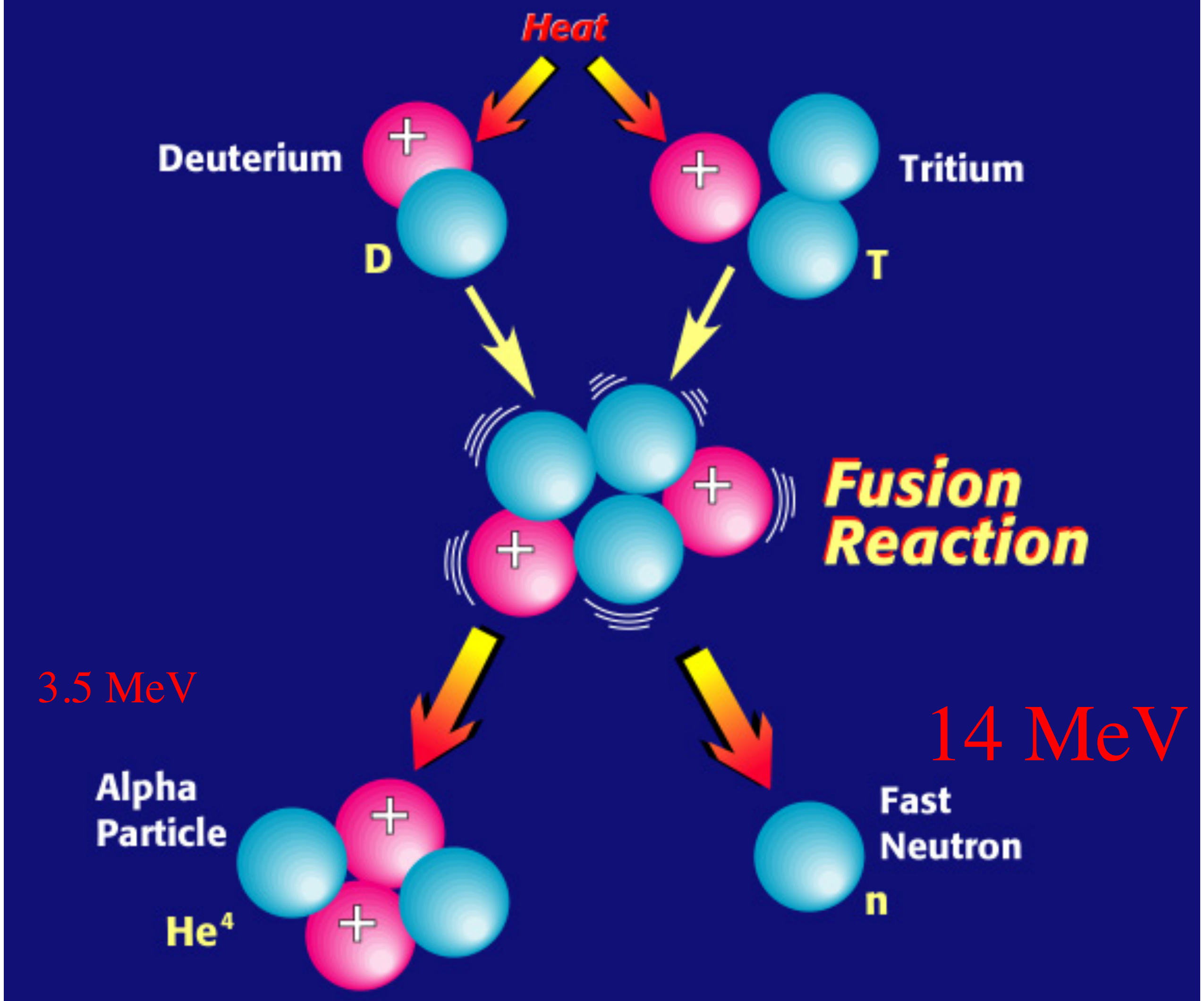
10 million
degrees

Fusion power density in sun ~ 300 W/cubic meter,

In laboratory plasma ~ 10 MW/cubic meter

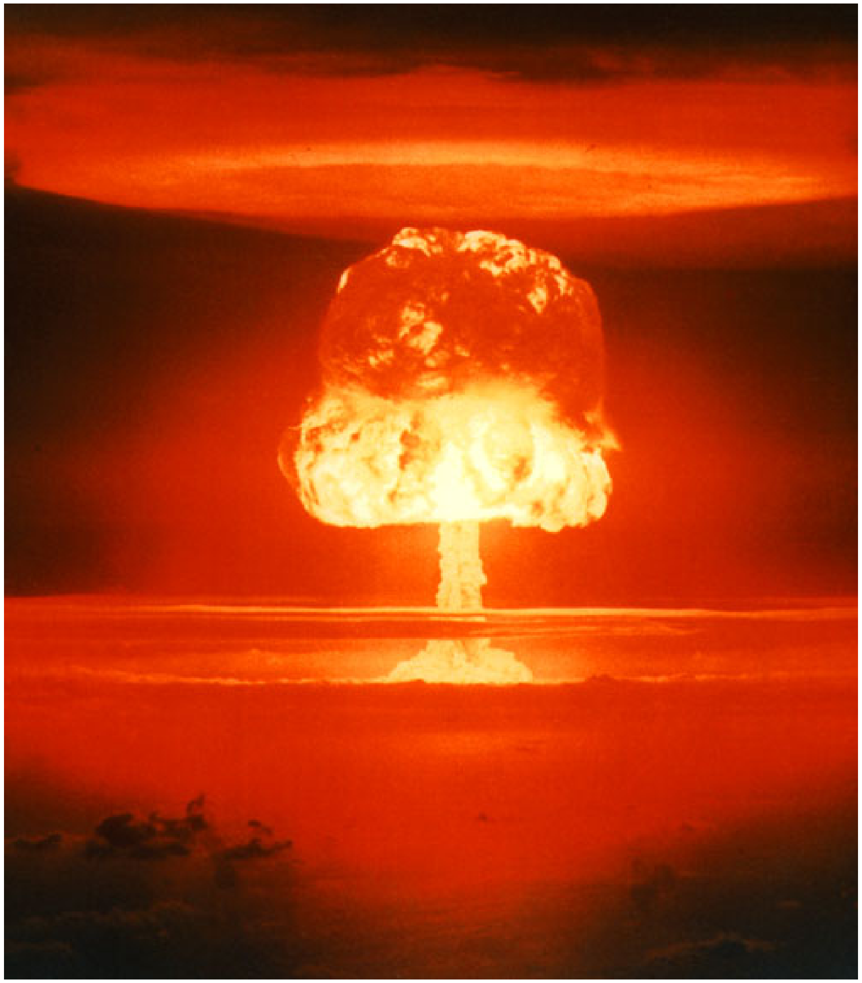
Deuterium–Tritium Fusion Reaction



Energy Multiplication
About 450:1

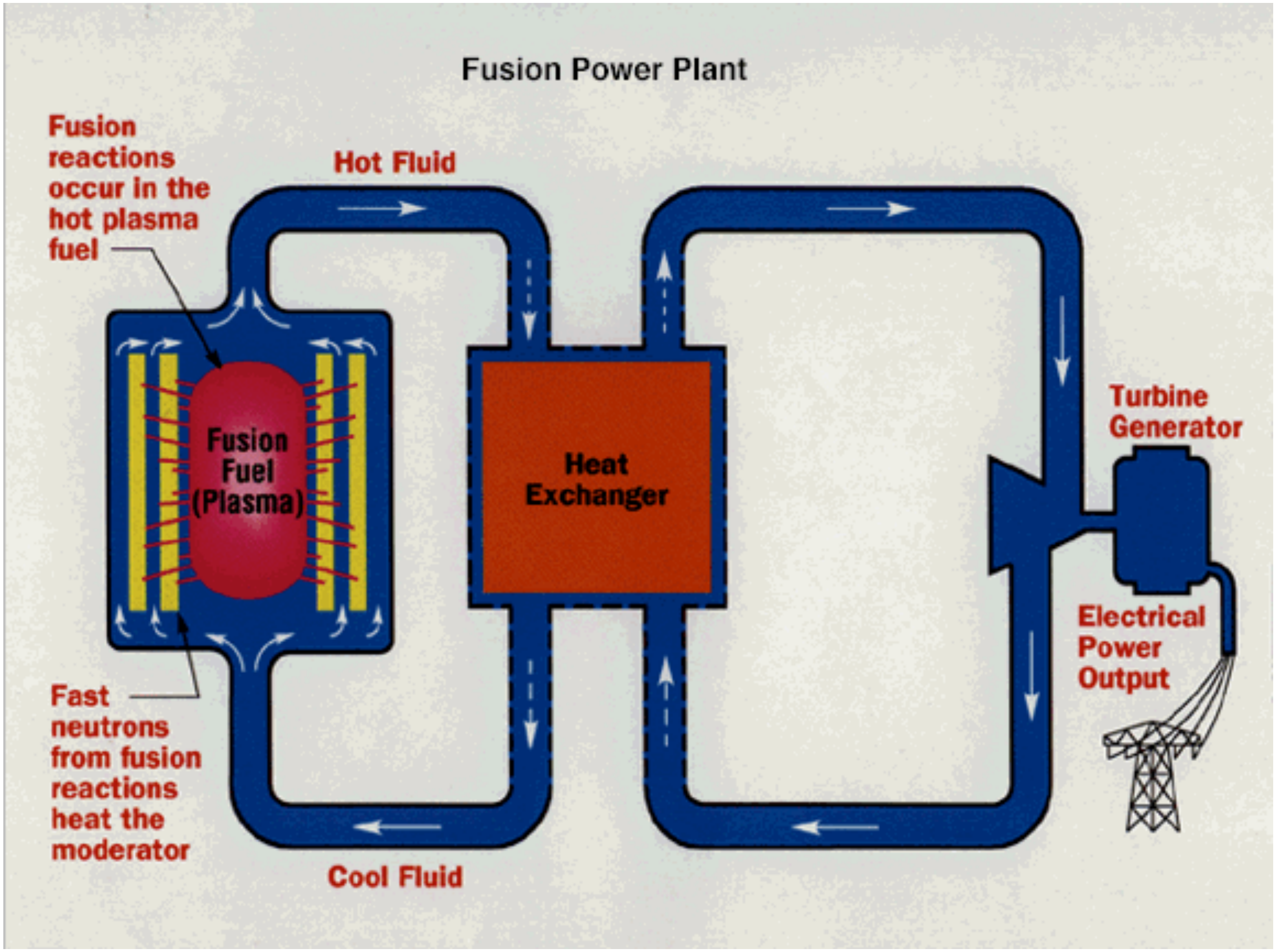
"Uncontrolled" Release of Fusion Energy Works: Operation Castle

Castle Bravo
February 28, 1954
15 Megatons



Castle Romeo
March 27, 1954
11 Megatons (500 x Nagasaki)

Goal: Magnetic Fusion Power Plant



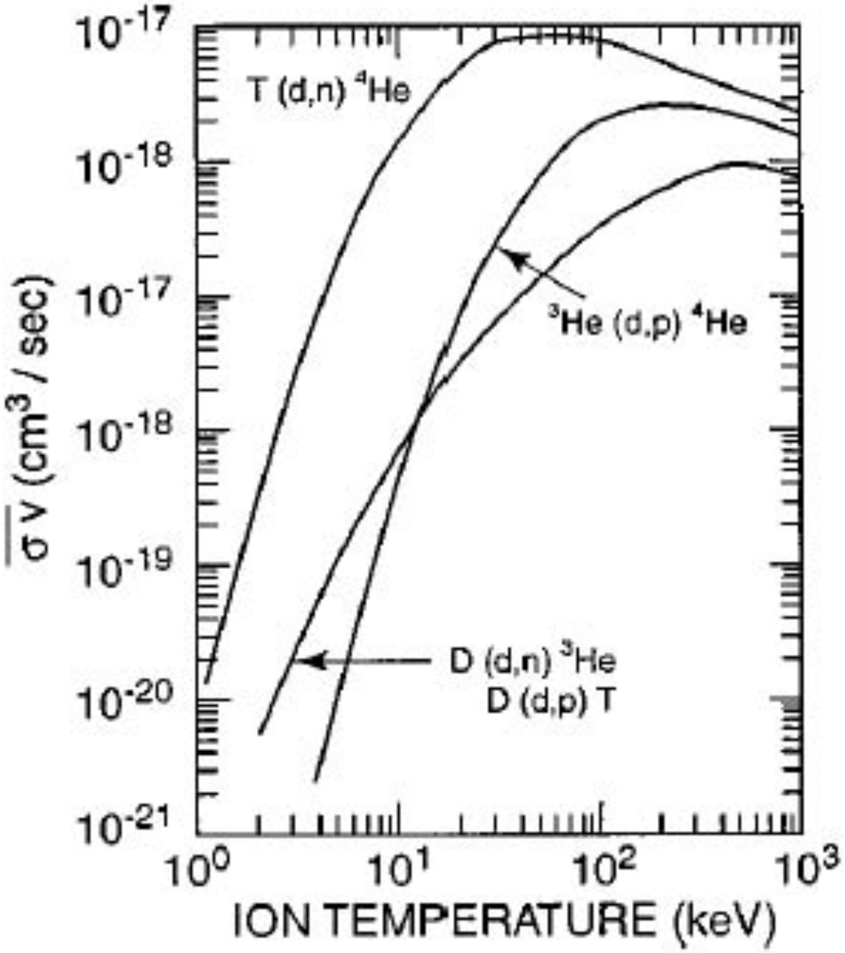
Easiest Fusion Reactions

D + T → ^{4}He (3.5 MeV)+ n
(14.1MeV)

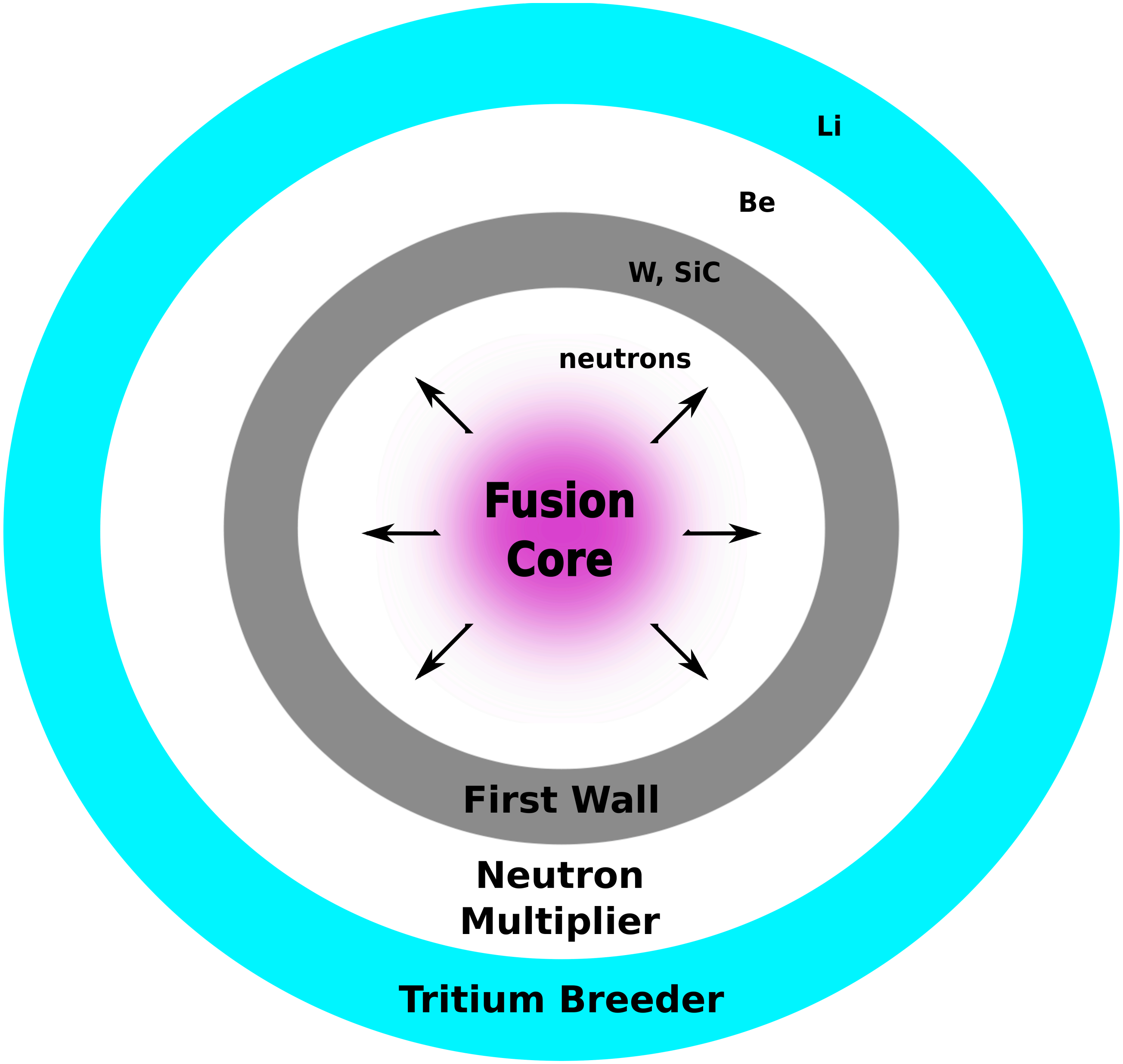
D + ^{3}He → ^{4}He (3.6 MeV)
+H(14.7MeV)

D + D → ^{3}He (0.82MeV)+ n
(2.45 MeV)

D + D → T(1.01 MeV) +
H (3.02 MeV)



Need to breed T or ^{3}He



Li

Be

W, SiC

neutrons

Fusion Core

First Wall

Neutron Multiplier

Tritium Breeder

Neutron Shield
Coolant
Heat Exchanger
Power Generator

Advantages of Fusion

- Nearly inexhaustible materials

  Deuterium from water, Tritium from lithium + neutron

- Available to all nations

  reduced conflict over resources

- Clean

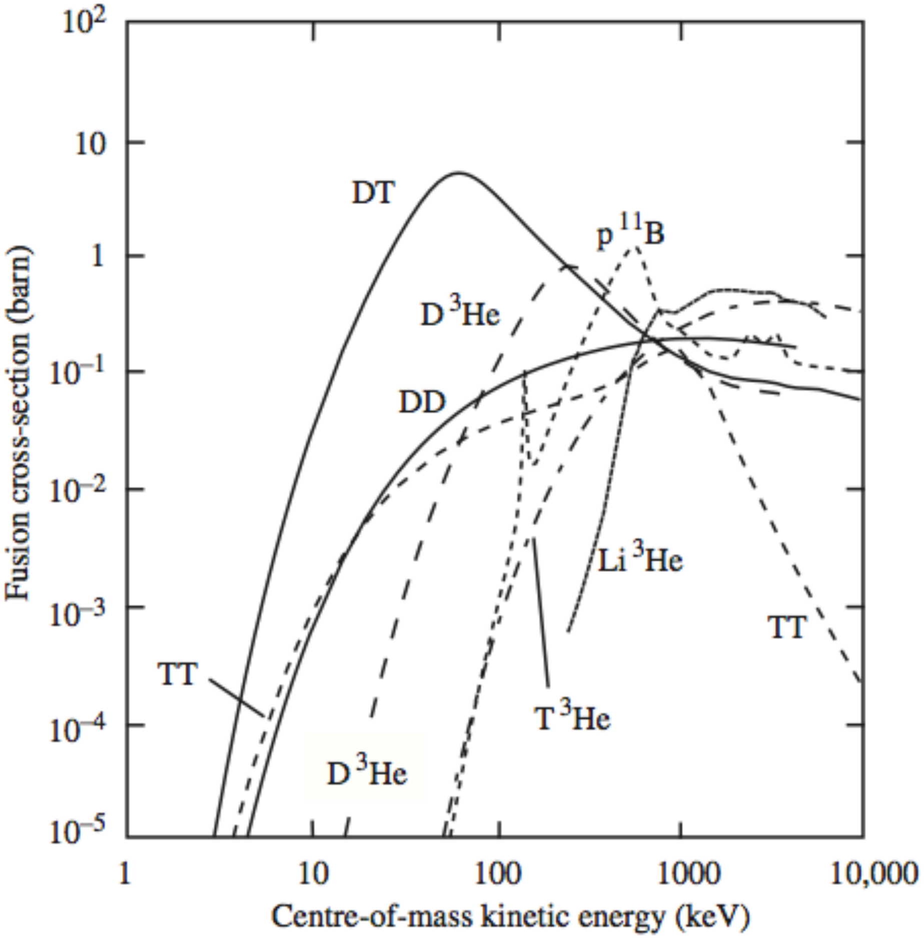
  no greenhouse gases, no acid rain

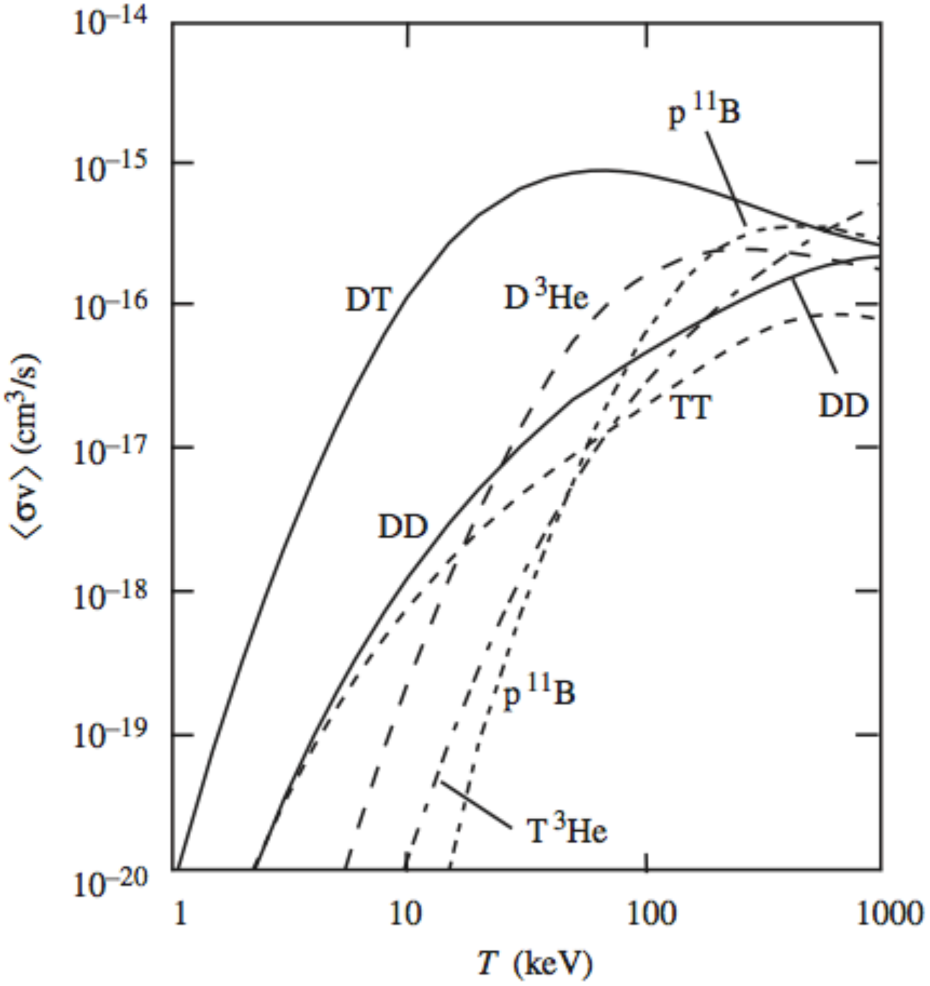
- Safe

  no runaway reactions or meltdown
  only short-lived radioactive waste
  little proliferation risk

Aneutronic Fusion Reactions

$p + {}^{11}B \rightarrow 3\ {}^{4}He\ (8.7\ MeV)$

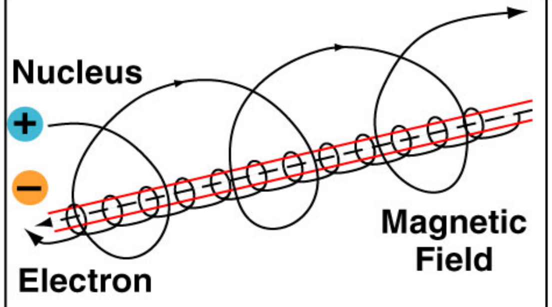


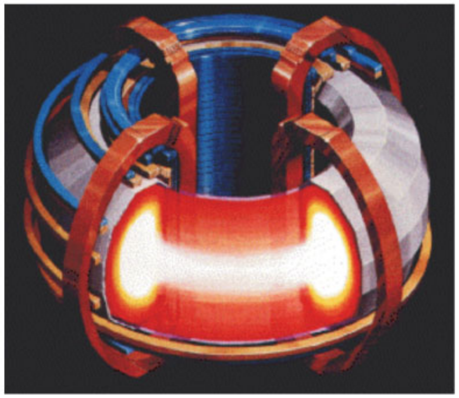


Need to reflect radiation

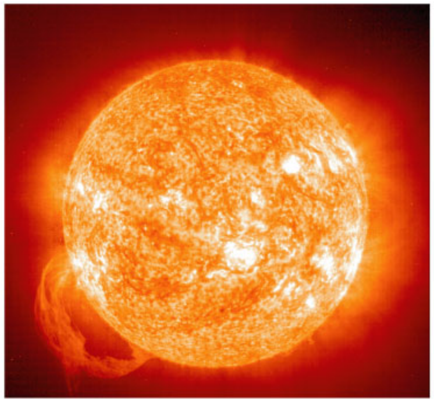
Fusion requires confinement of plasmas at high temperatures

Magnetic Confinement

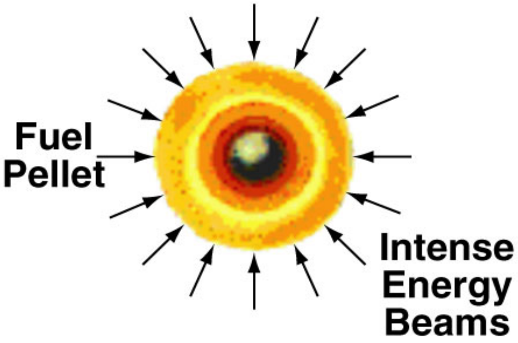


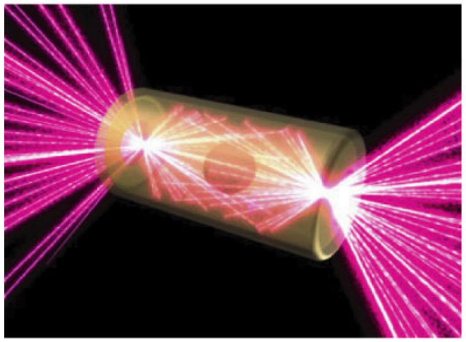


Gravitational Confinement



Inertial Confinement



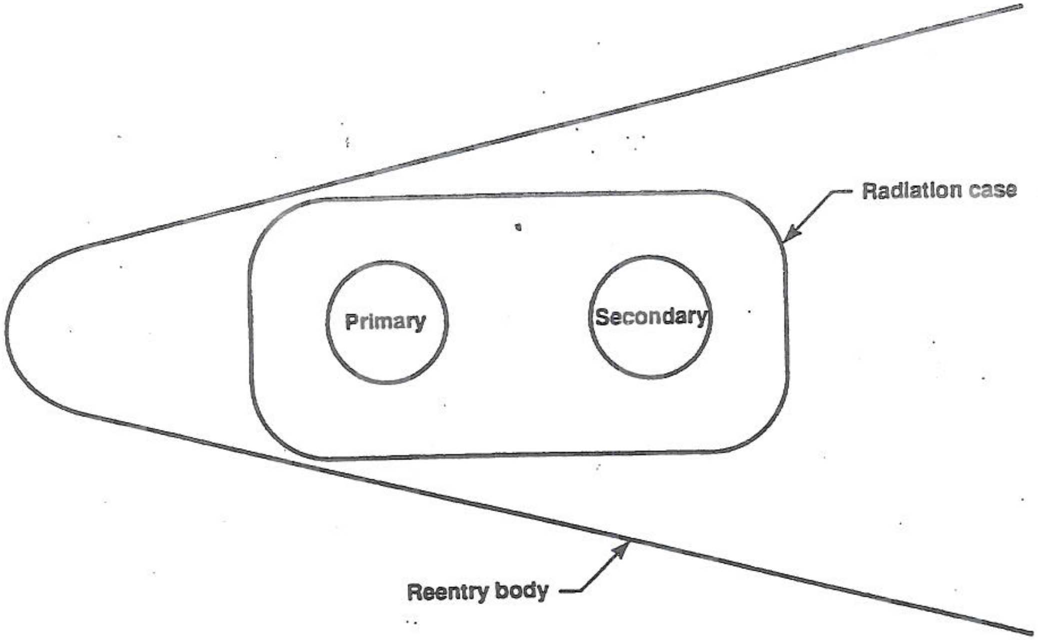


Replace primary by lasers (Nuckolls *et al*.)

Hydrogen Bomb Teller-Ulam "Design"

July 2, 1945
Letter to Leo Szilard (Published in Memoirs, p. 207)
"Our only hope is in getting the facts before the people.
This might help convince everybody that h next war will be fatal.
… This responsibility must in the end be shifted to the people as
a whole and that can be done only by making the facts known."

Teller: *Gamma and X-ray radiation produced in the primary could transfer enough energy into the secondary to create a successful implosion and fusion burn*



Mark 17 The First US TN Bomb

Ivy Mike: First TN Device Test:
10MT 10/31/52

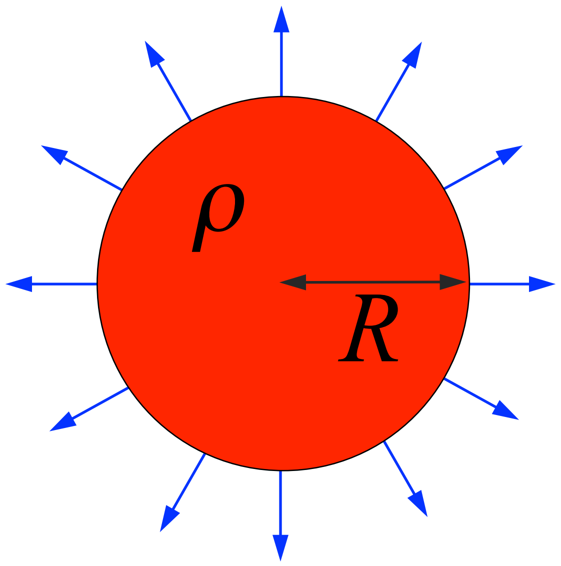
Inertial confinement

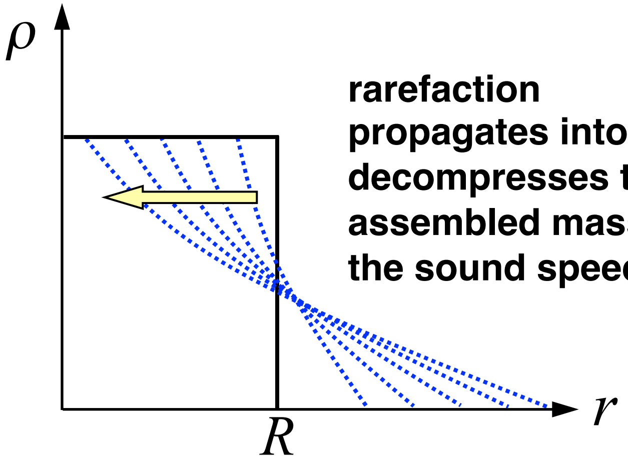
mass averaged confinement time

$$\langle \tau_c \rangle \cong \frac{1}{M}\int_0^R \rho \, \frac{R-r}{c_s} 4\pi \, r^2 dr$$

$$= \frac{4\pi \dfrac{\rho}{c_s}\left(\dfrac{R\, r^3}{3} - \dfrac{r^4}{4}\right)\Bigg|_0^R}{\dfrac{4\pi}{3}\rho \, R^3}$$

$$= \frac{R}{4c_s}$$





rarefaction propagates into and decompresses the assembled mass at the sound speed c_s

Burn fraction determined by *areal density* $\rho\, R$

fusion burn rate

$$\frac{dn_T}{dt} = n_T n_D \langle \sigma v \rangle$$

$$\Rightarrow \frac{dn}{dt} = \frac{n^2}{2}\langle \sigma v \rangle \quad , \quad n_T = n_D = \frac{n}{2}$$

➡

integrating over confinement time

$$\frac{1}{n} - \frac{1}{n_0} = \frac{1}{2}\langle \sigma v \rangle \tau_c \quad , \quad \tau_c \cong \frac{R}{4c_s}$$

burn fraction

$$f = 1 - \frac{n}{n_0} = \frac{\rho R}{\rho R + 8\, m_i\, c_s / \langle \sigma v \rangle} \cong \frac{\rho R}{\rho R + 70\ \mathrm{kg/m^2}} \quad , \quad T_i = 30\ \mathrm{keV}$$

Require $\rho\, R \geq 3\ \mathrm{g/cm^2}$ for $f \geq 1/3$

Fuel compression ~ factor of 1000

$$f \sim 1/3 \;\Rightarrow\; \rho R \cong 3.0\,\mathrm{g/cm^2} \;\Rightarrow\; M = \frac{4\pi}{3}\rho R^3 = \frac{4\pi}{3}\frac{(\rho R)^3}{\rho^2}$$

ρ (g/cm^3)	R (cm)	M (g)	Y (MJ)
0.25	12.0	2.6×10^3	2.9×10^8 ~ 70 kilotons TNT
200	0.015	5.0×10^{-3}	550 ~ 1/8 ton

550 MJ x 5/sec ~ 3GJ/sec ~ 1 GJ/sec (electric)

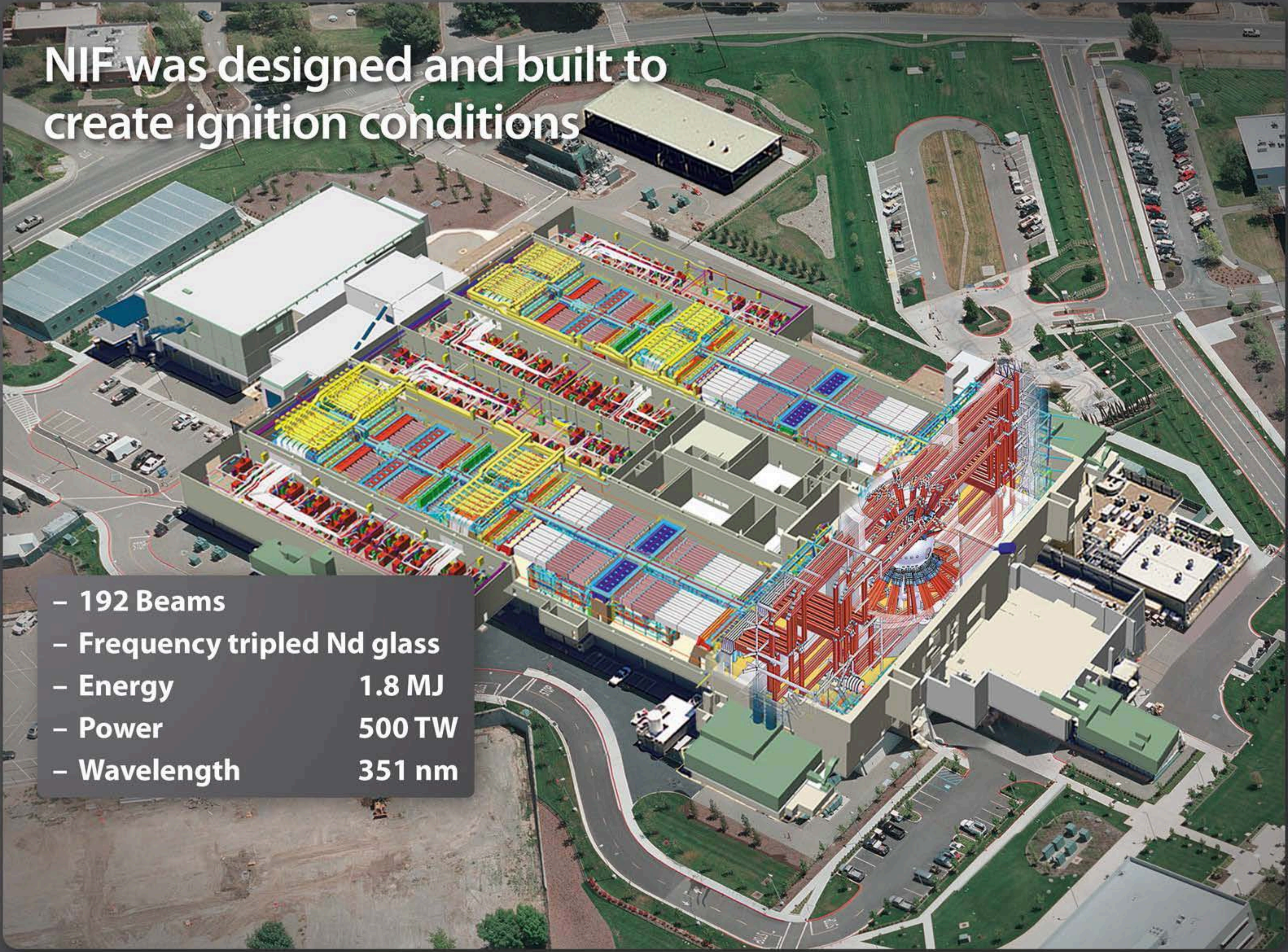

LLNL
National Ignition Facility
NIF-0605-10997-L50
27EIM/cld


Cardinal
Stanford
GOLDEN BEARS
Cal
CALIFORNIA
Bruins
UCLA
UCLA BRUINS

NIF is now operational and ignition campaigns are underway

NIF is the first laser capable of achieving fusion gain

NIF was designed and built to create ignition conditions



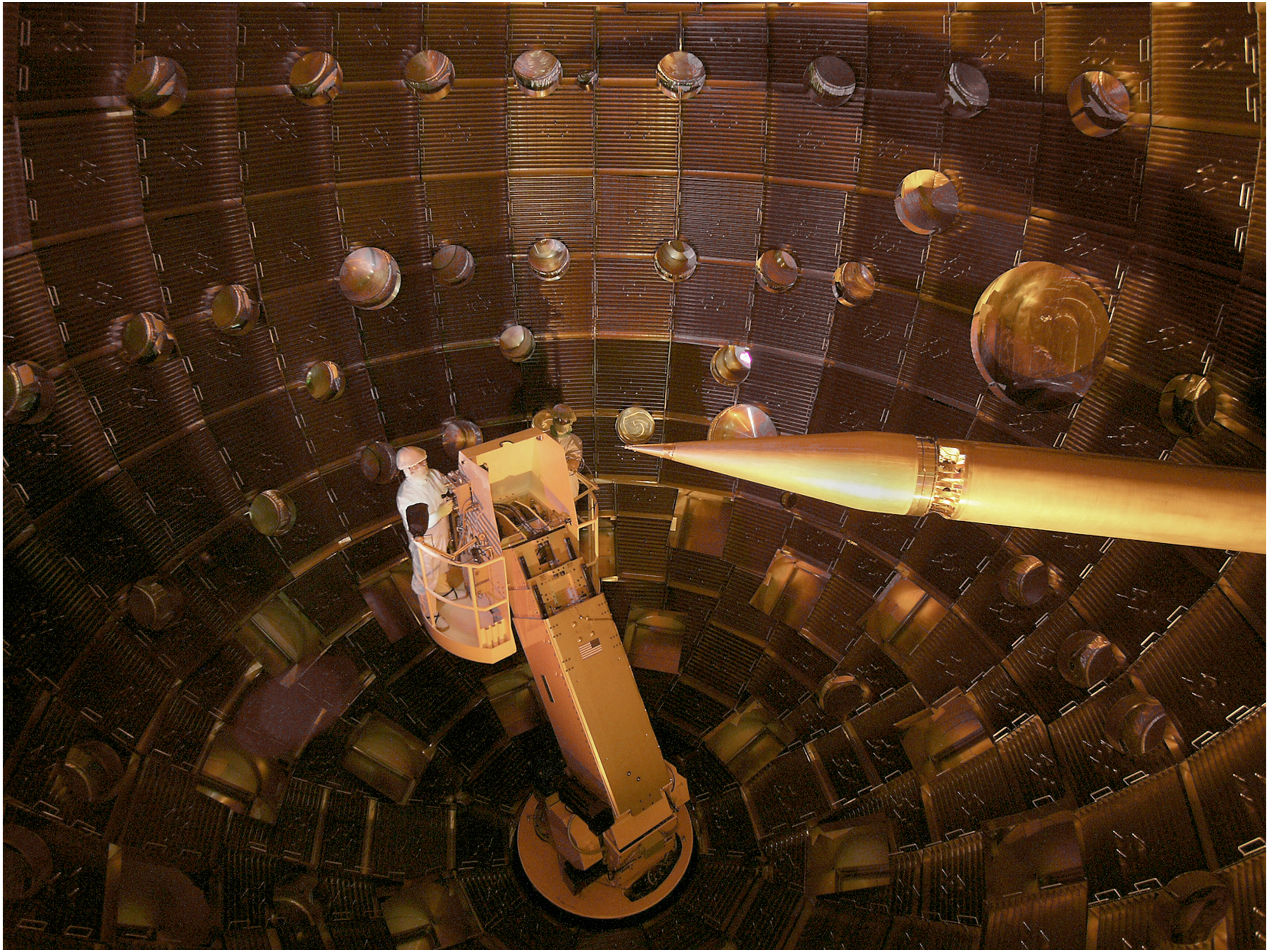
- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm

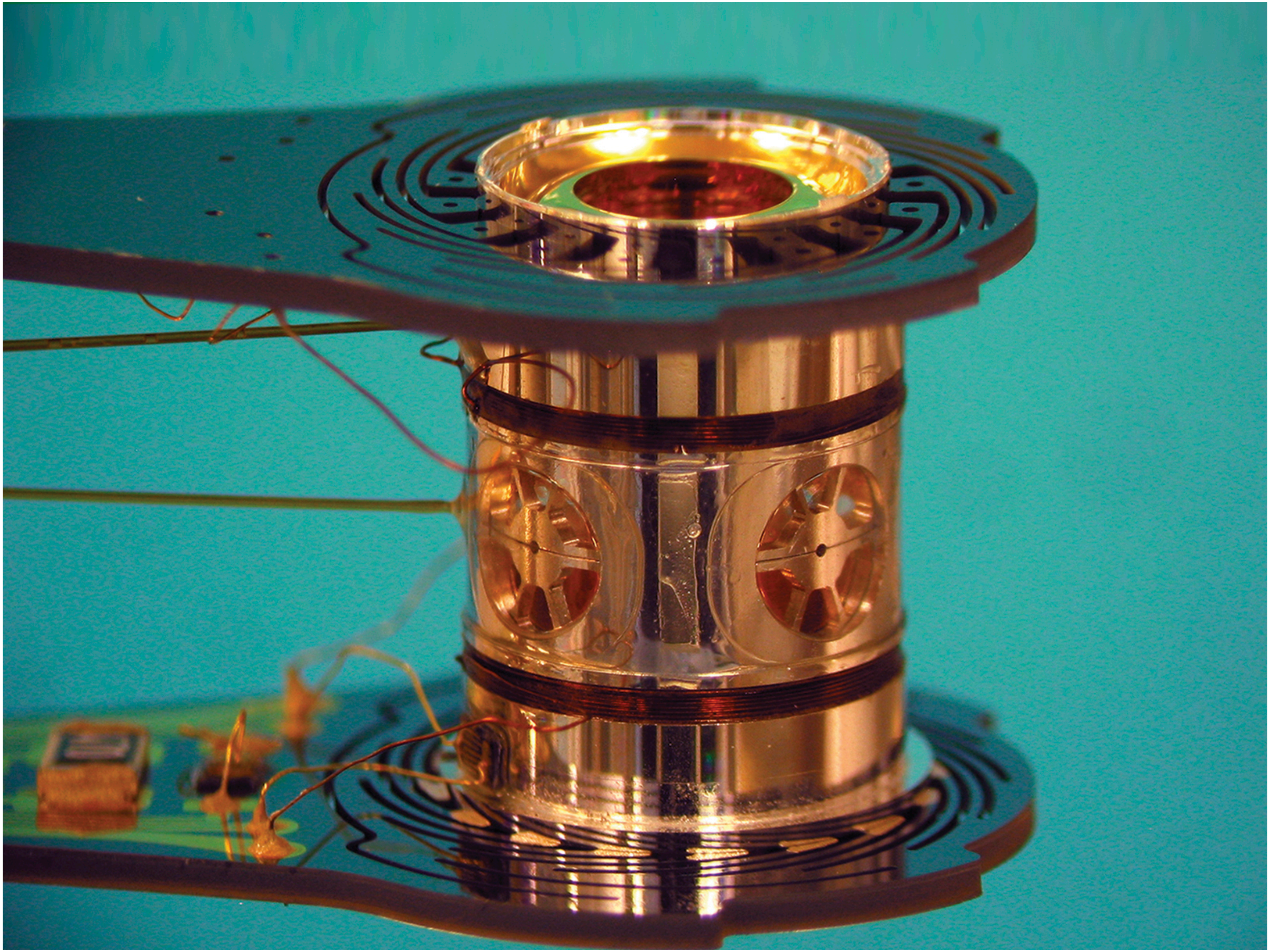

lasers.llnl.gov

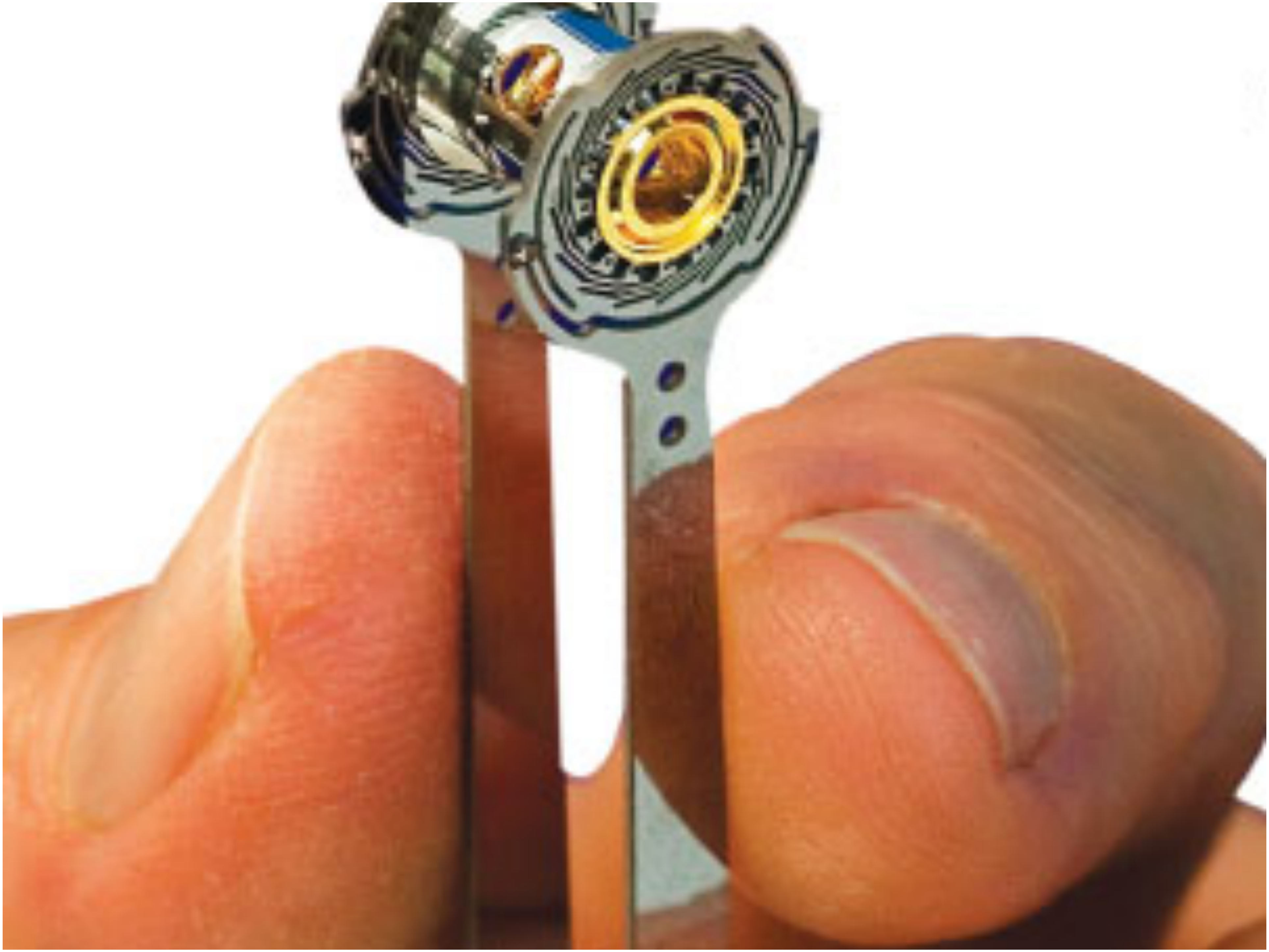
Target Chamber

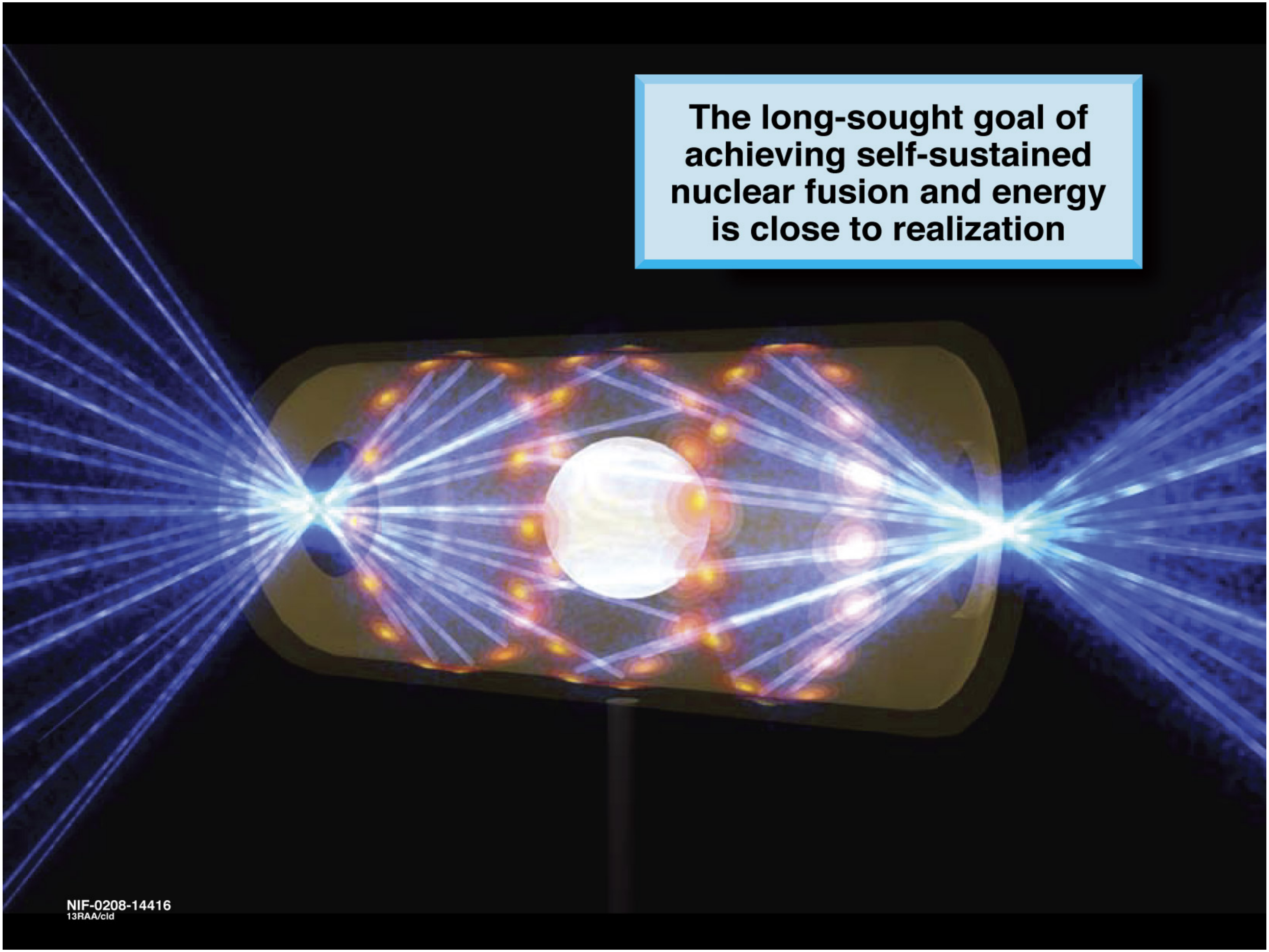
NIF-0105-10124
31EIM/dj

P8136



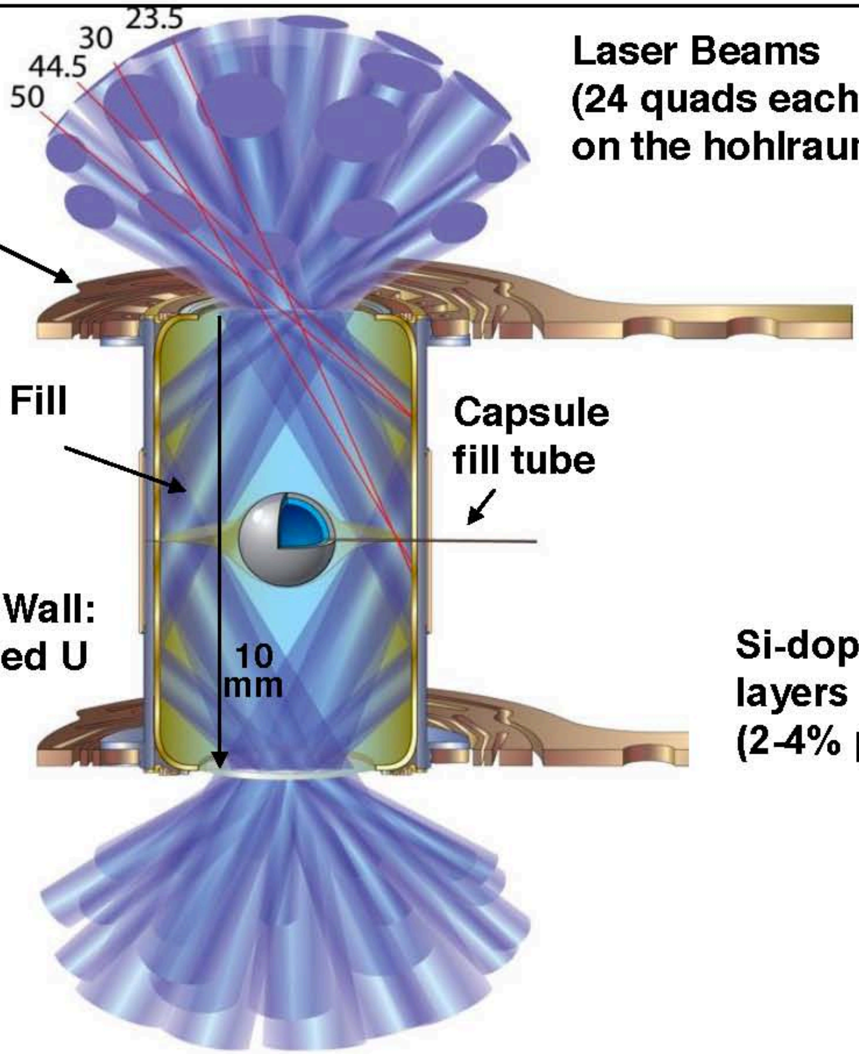






The long-sought goal of achieving self-sustained nuclear fusion and energy is close to realization

The ignition point design has a graded doped CH capsule in a Au/DU hohlraum



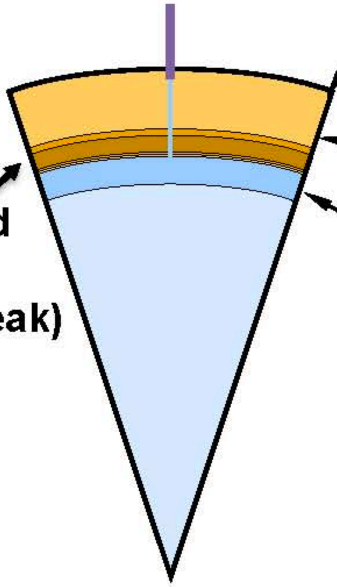
Laser Beams (24 quads each end, 2 rings on the hohlraum wall)

Cryo-cooling Ring

Hohlraum Fill He at 0.7 mg/cm^3

Hohlraum Wall: Au / Au-lined U

Capsule fill tube



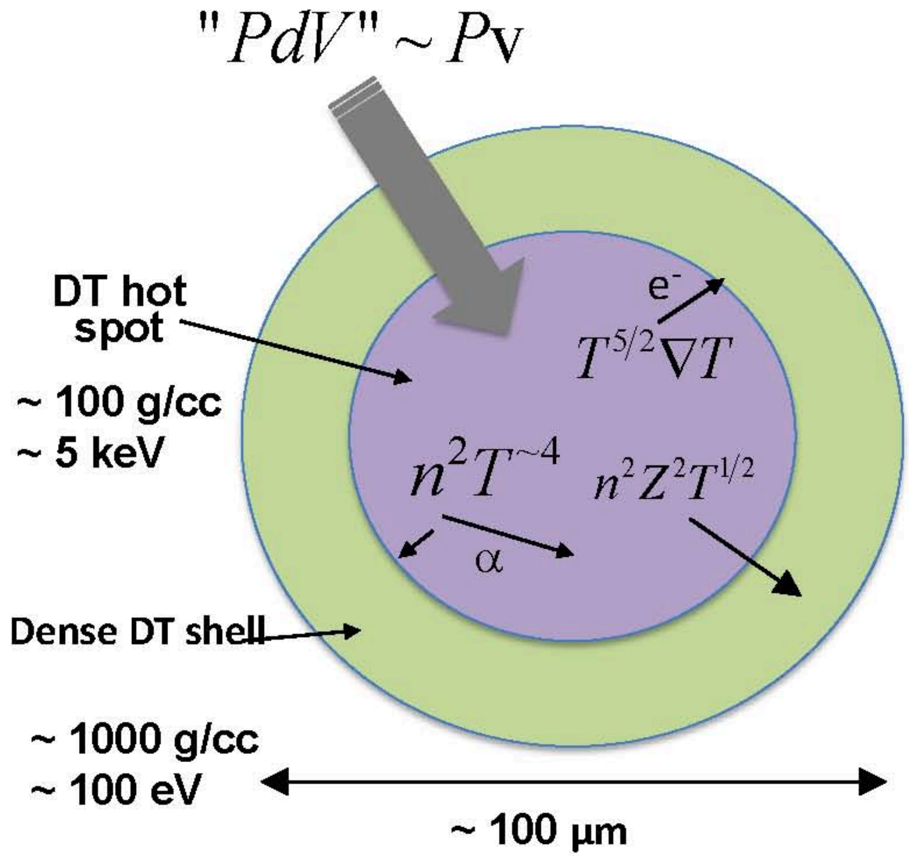
~1110 µm

~195 µm

~70 µm

Si-doped layers (2-4% peak)

To achieve ignition we have to assemble a hot spot surrounded by cold fuel



$"PdV" \sim P\mathrm{v}$

DT hot spot

~ 100 g/cc
~ 5 keV

e^-

$T^{5/2}\nabla T$

$n^2 T^{\sim 4}$

$n^2 Z^2 T^{1/2}$

α

Dense DT shell

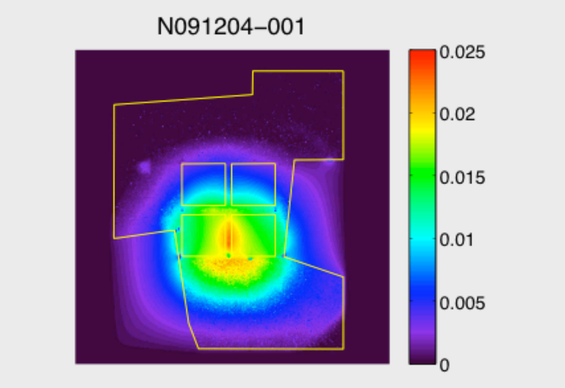
~ 1000 g/cc
~ 100 eV

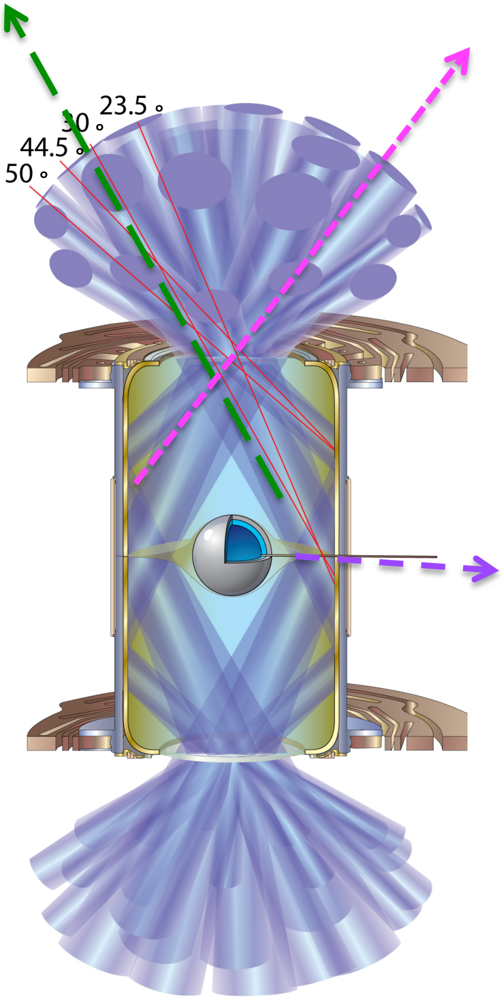
~ 100 µm

Pressure ~350 Gbr

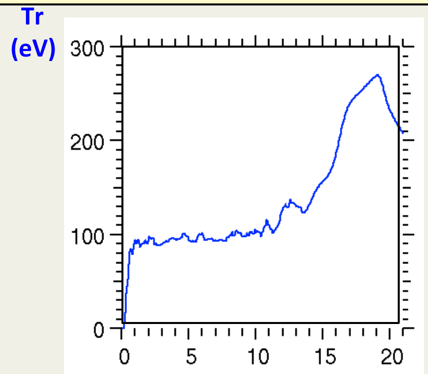
An ignition-scale hohlraum must provide good Coupling, Drive, & Symmetry

Coupling: LPI must be low enough, so that enough energy is available for drive

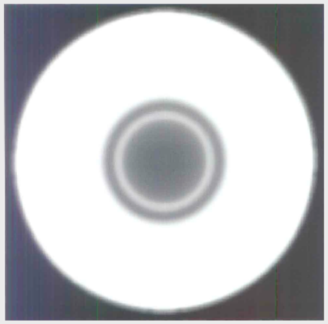




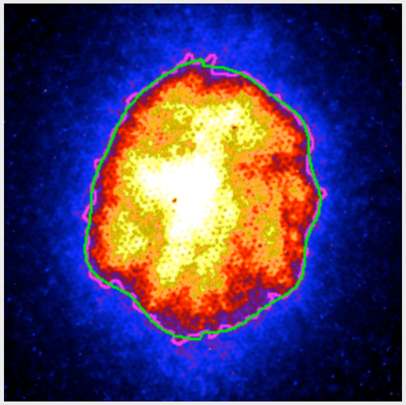
Drive: Must be high enough to implode a stable shell fast enough to get hot & ignite



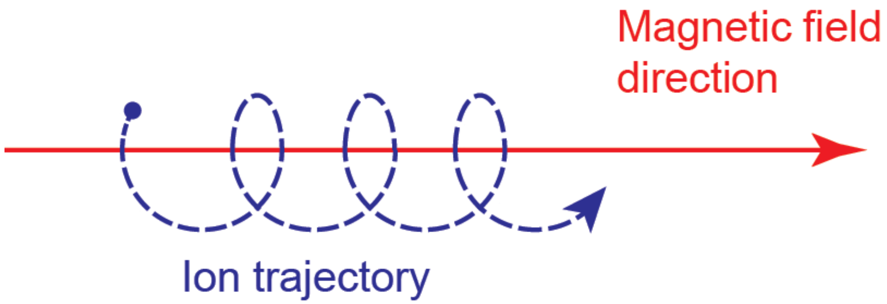
Coupling: LPI must be low enough, so hot electrons do not pre-heat the target



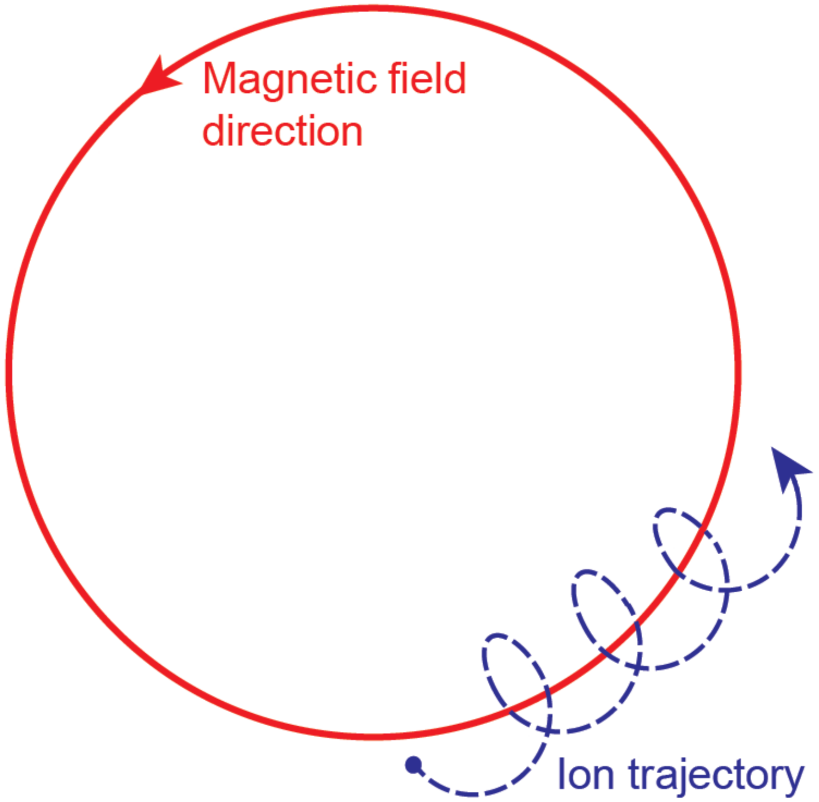
Symmetry: Must be round enough at high convergence to get dense & ignite



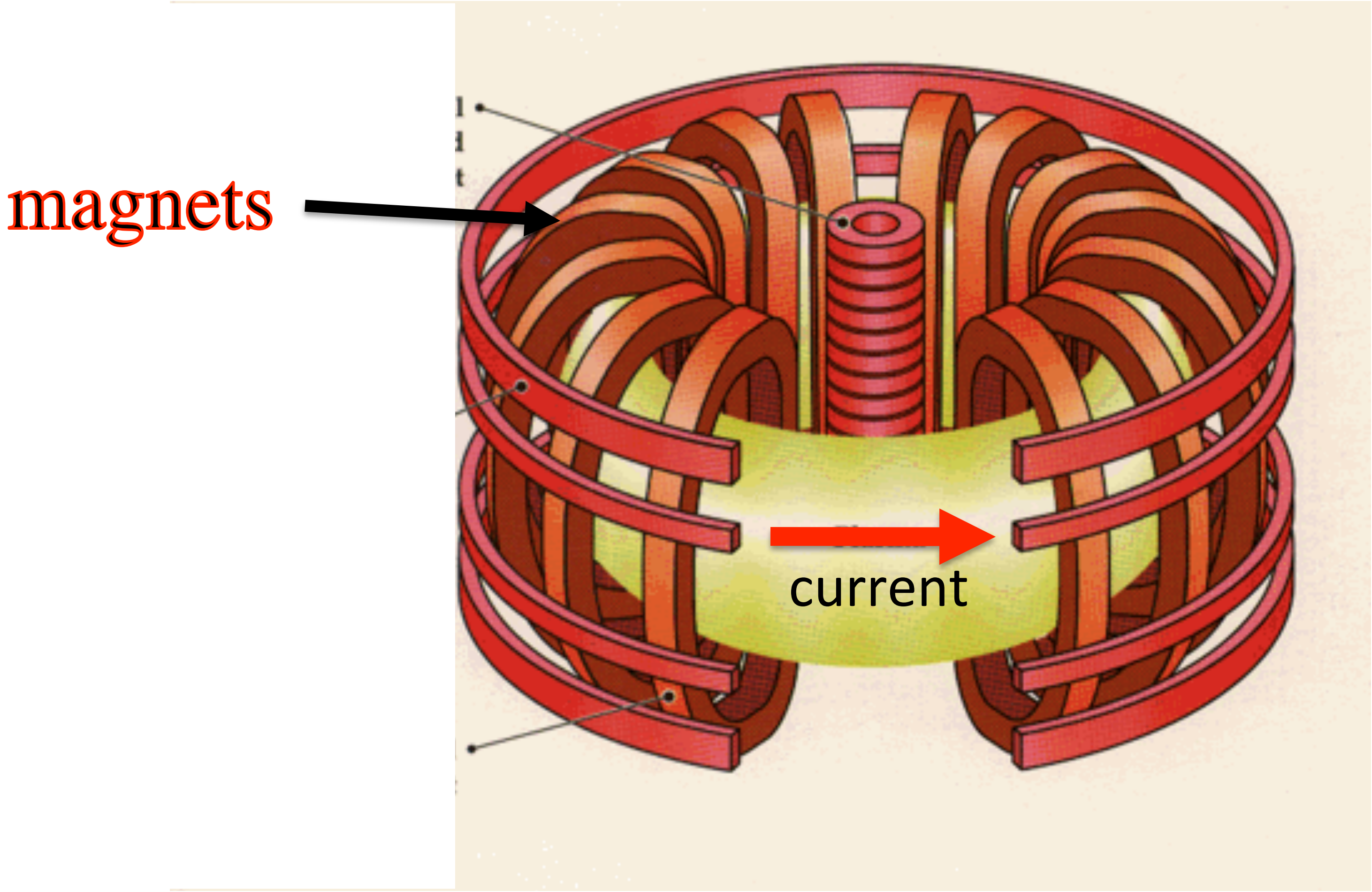
Magnetic Confinement



3D → 1D



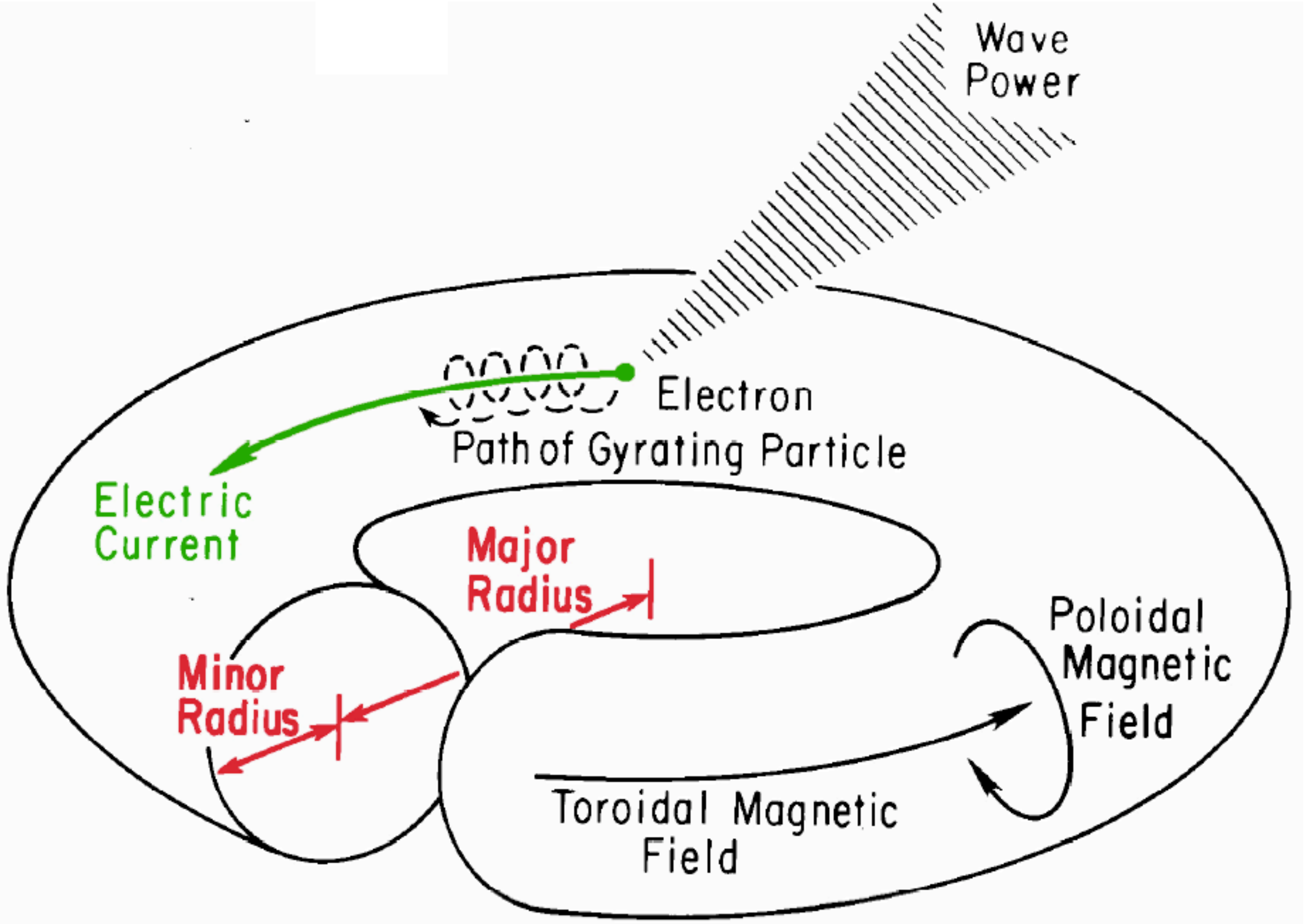
Toroidal Confinement

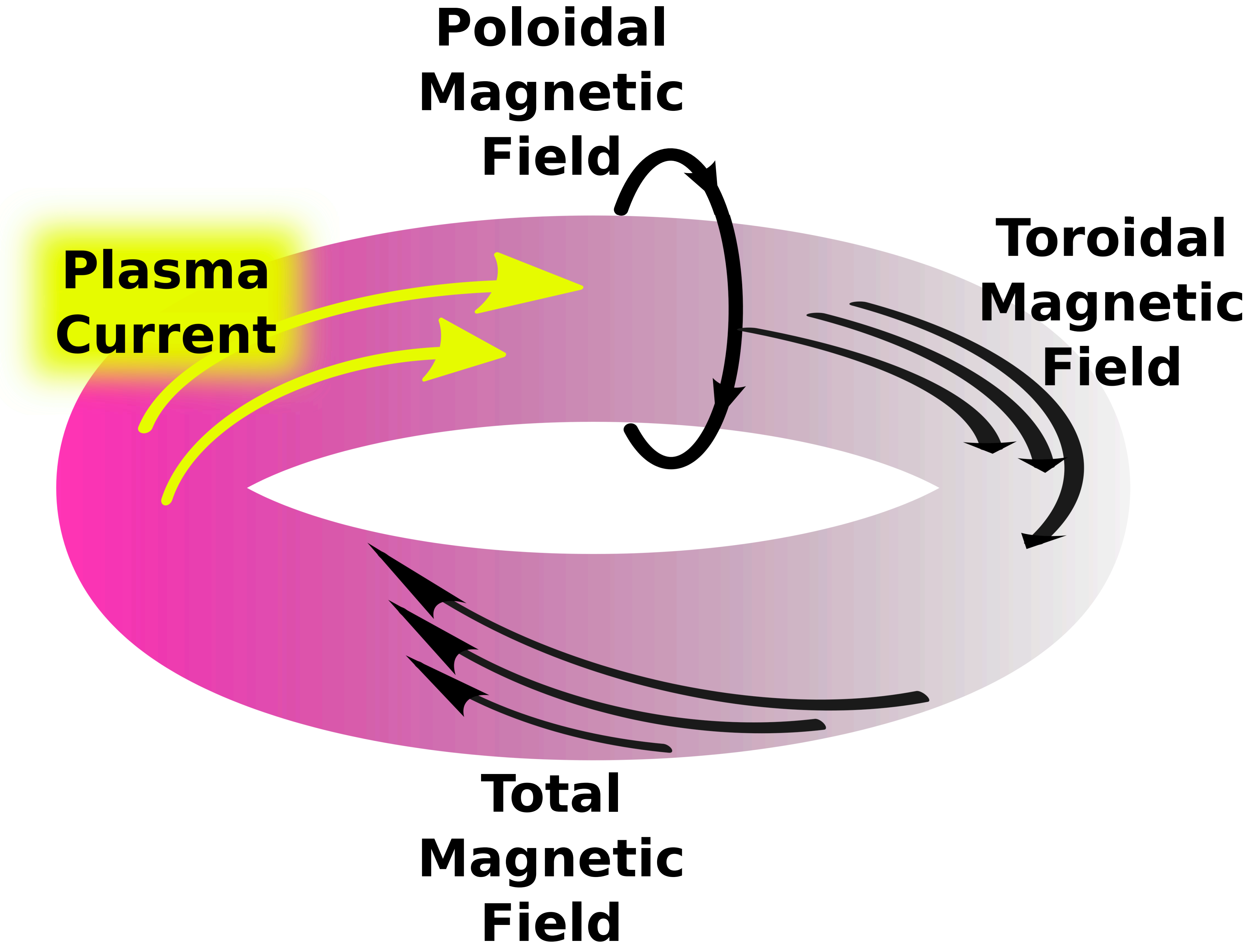


Magnetic field produced by magnets and large current in plasma

“tokamak” -- toroidalnaya kamera i magnitnaya katushka

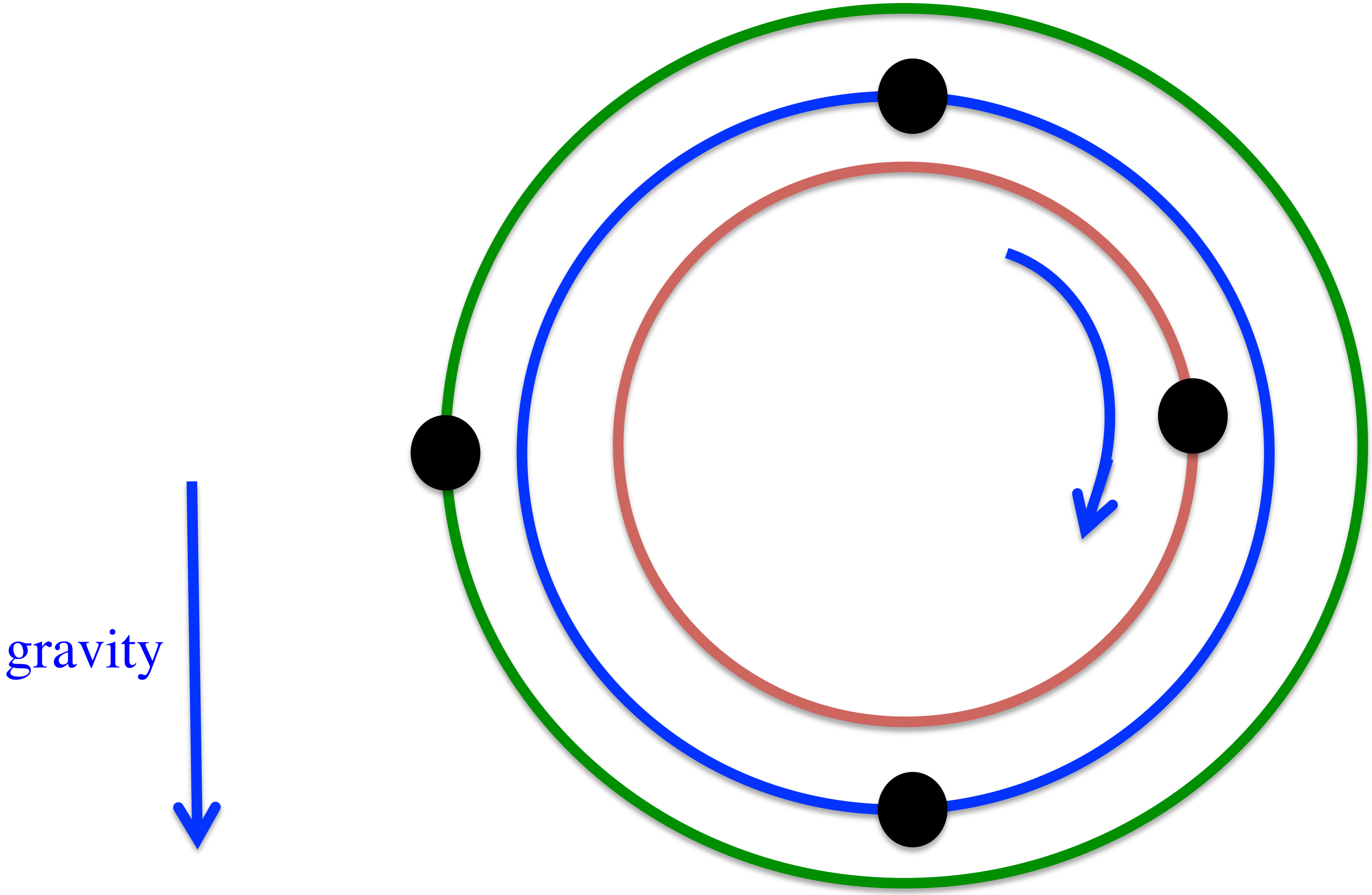
Heating a Tokamak with Waves (or Particle Beams)



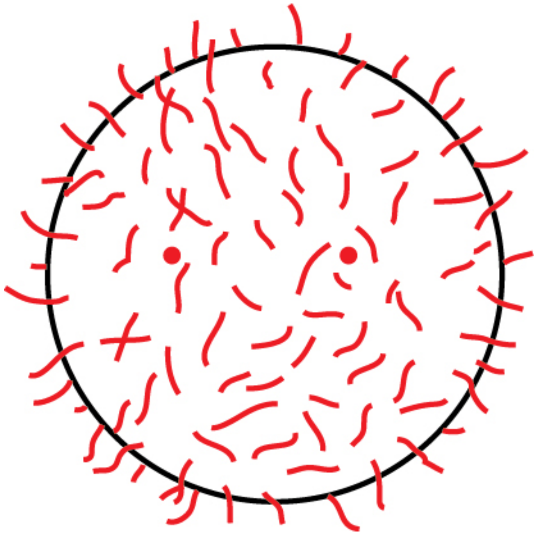

Poloidal Magnetic Field
Plasma Current
Toroidal Magnetic Field
Total Magnetic Field

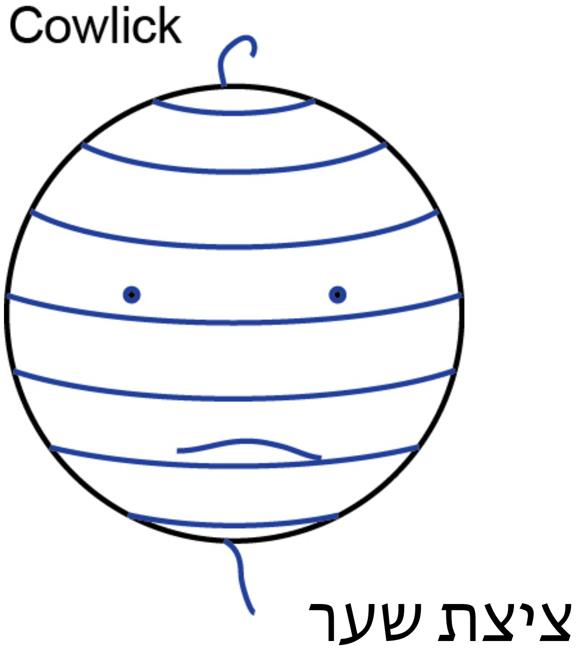
Why is Poloidal Field Needed?

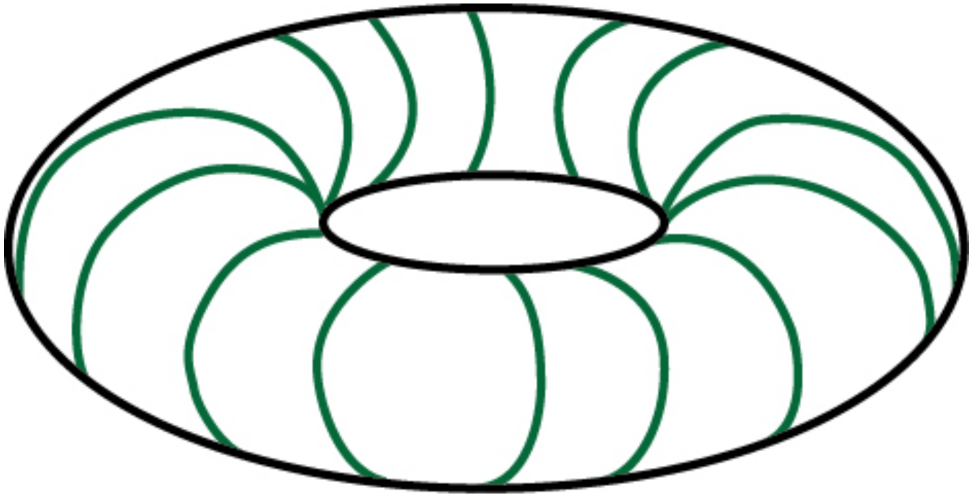
Stabilization of Sedimentation in Swirling Liquid



Hairy Groundhogs and Donuts



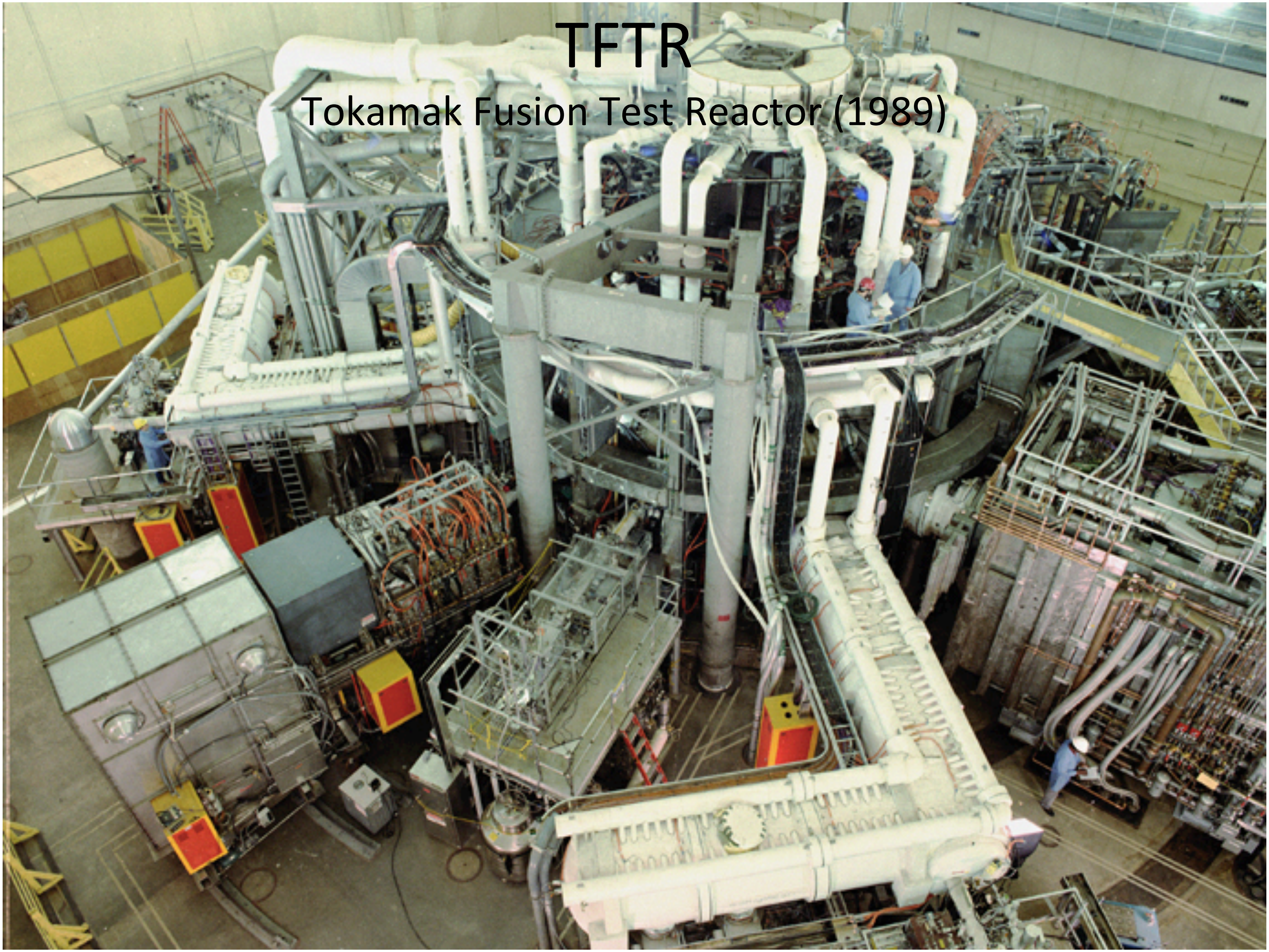




Not simply-connected

TFTR

Tokamak Fusion Test Reactor (1989)

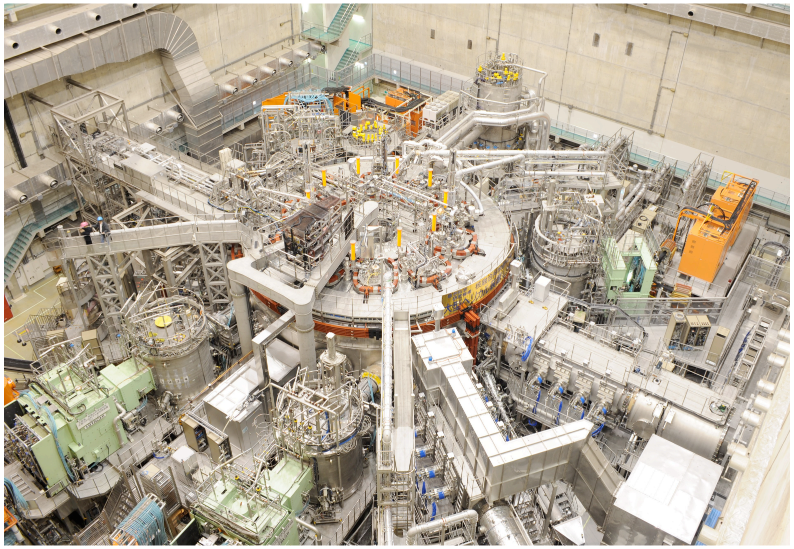


Some Current Large Magnetic Fusion Devices

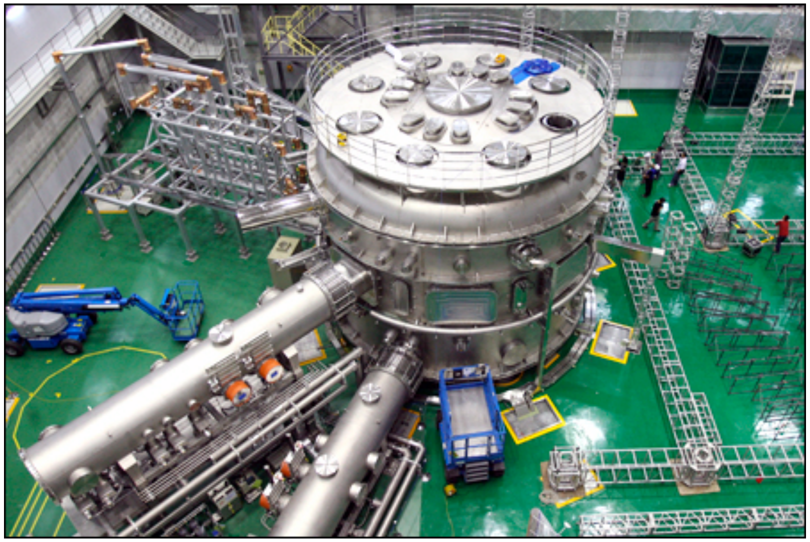
England: JET tokamak

China: superconducting tokamak EAST

Japan: superconducting stellarator



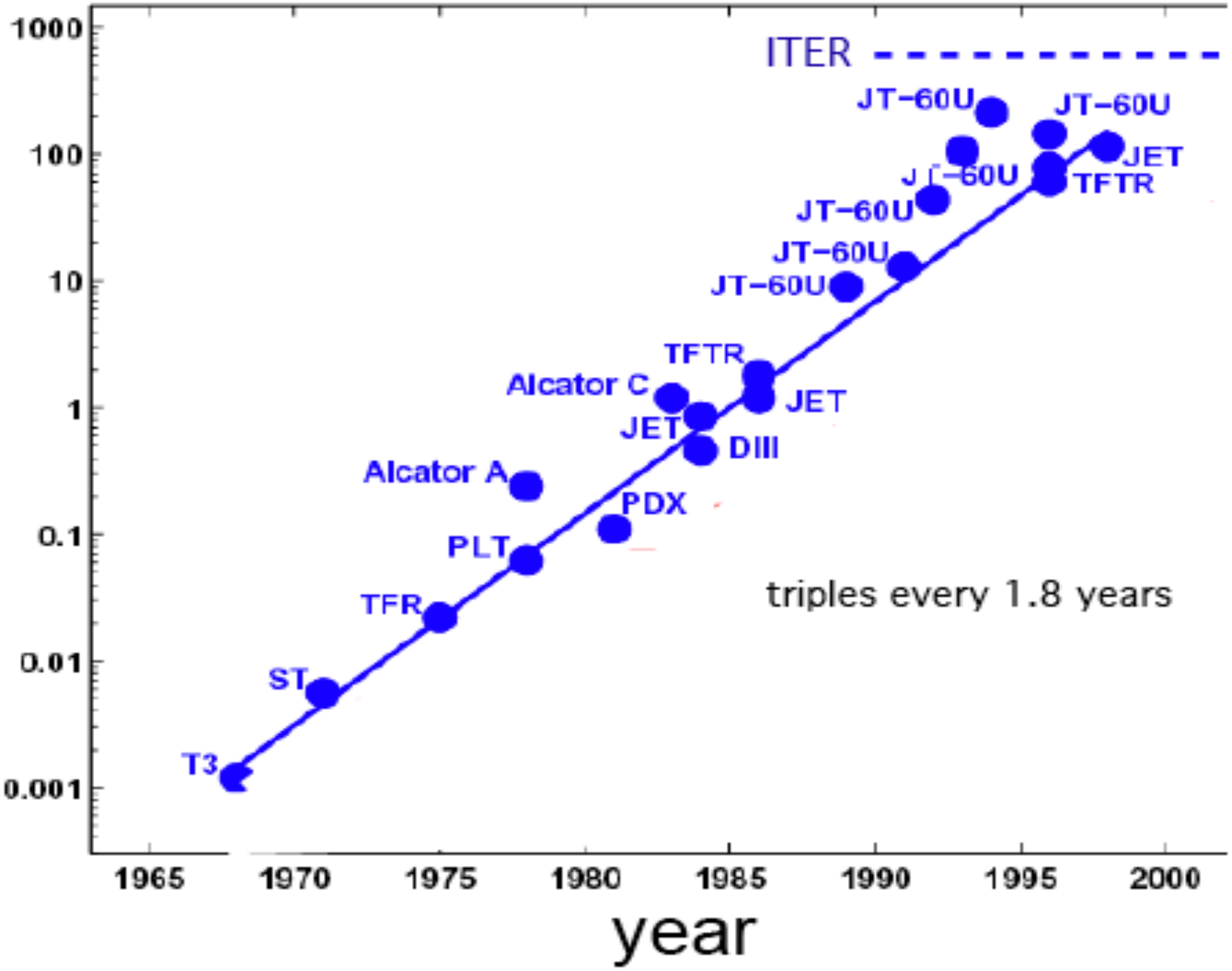
Korea: superconducting tokamak KSTAR



Progress in Magnetic Confinement

fusion triple product

$n\,T\,\tau_E$



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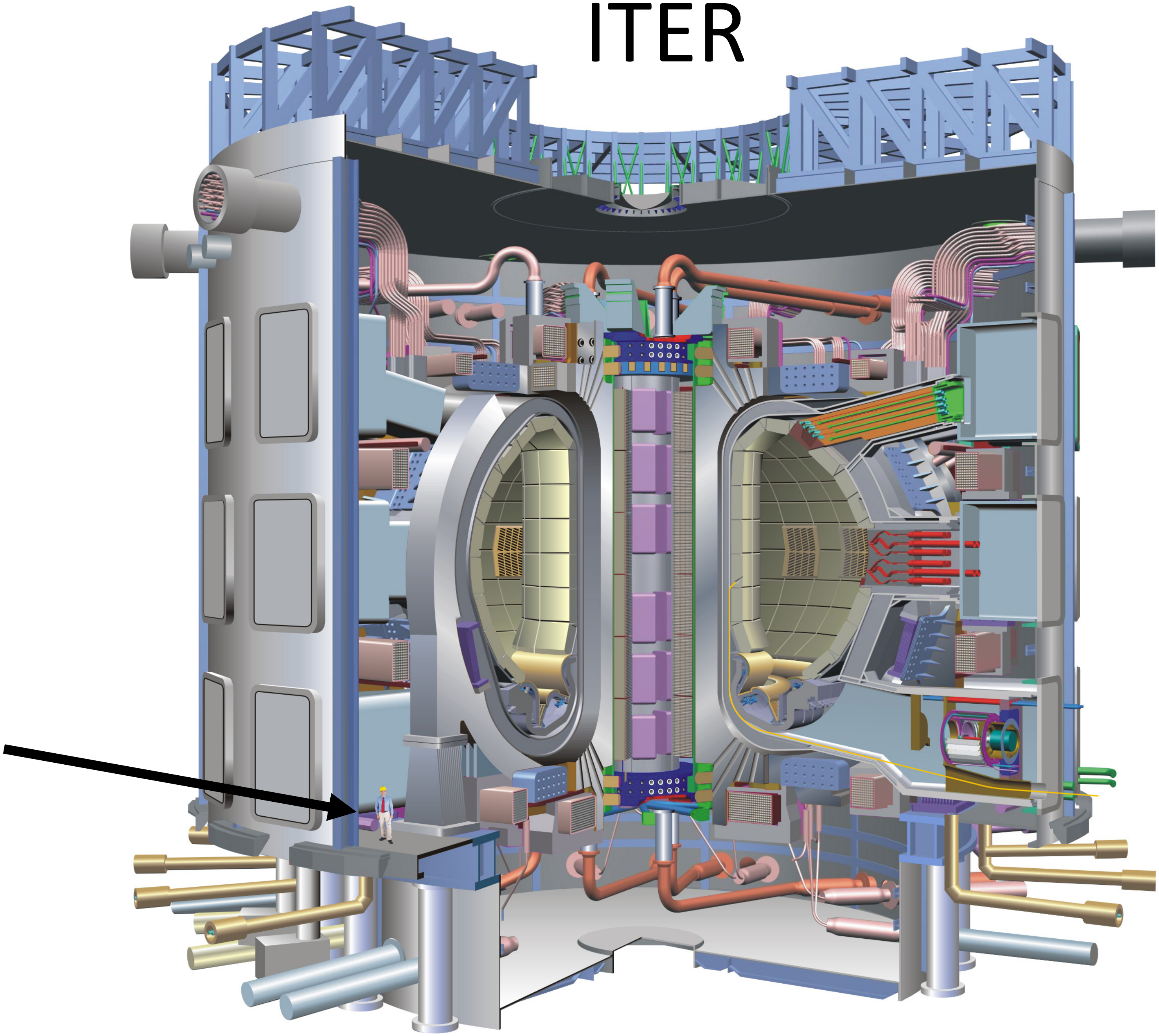
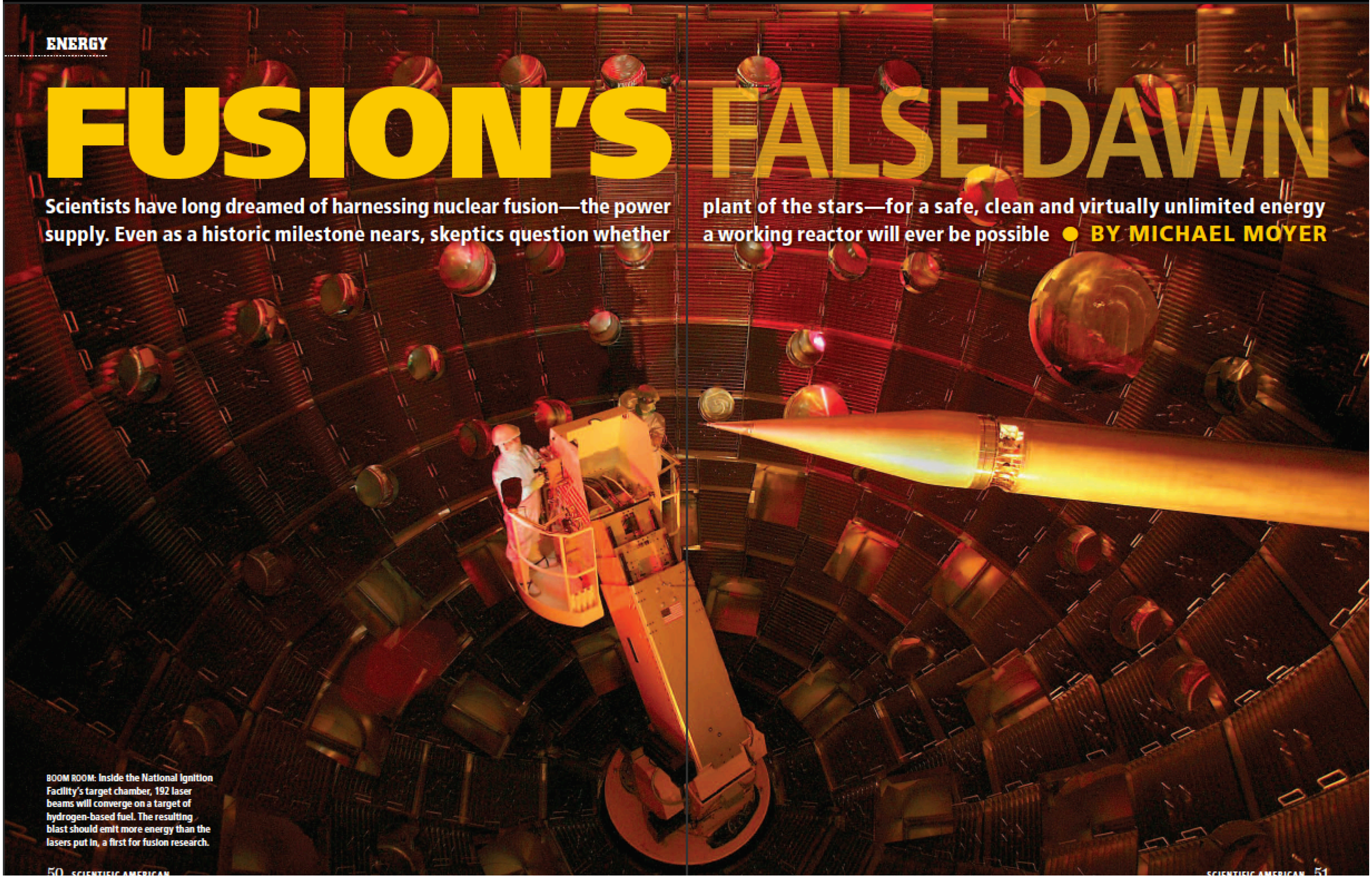


site preparation
in France

Design for 2020

SCIENTIFIC AMERICAN March 2010



ENERGY

FUSION'S FALSE DAWN

Scientists have long dreamed of harnessing nuclear fusion—the power plant of the stars—for a safe, clean and virtually unlimited energy supply. Even as a historic milestone nears, skeptics question whether a working reactor will ever be possible ● **BY MICHAEL MOYER**

BOOM ROOM: Inside the National Ignition Facility's target chamber, 192 laser beams will converge on a target of hydrogen-based fuel. The resulting blast should emit more energy than the lasers put in, a first for fusion research.

SCIENTIFIC AMERICAN™

Permanent Address: **http://www.scientificamerican.com/article.cfm?id=nuclear-fusion-project-struggles-to-put-the-pieces-together**

Nuclear Fusion Project Struggles to Put the Pieces Together

Contracting woes may cause further delays for $19.4-billion ITER, a project designed to show the feasibility of nuclear fusion as a power source

By Geoff Brumfiel and Nature magazine | Friday, October 26, 2012 | 31 comments

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nature International weekly journa

The price isn't right

ITER will cost more to build than previously thought. Now is the time to be honest about how much.

Quoting a price for a major new scientific instrument is notoriously tricky. Researchers have to estimate costs for equipment that has never been built, forecast expenditures years in advance, allow for unknown contingencies, and win approval from sceptical politicians who always want the project to cost less.

So it is not a complete surprise that a recently finished design review of ITER, a major fusion experiment to be built in Cadarache, France, is forecasting a delay of 1–3 years in its completion date and a roughly 25–30% increase in its €5-billion (US$7.8-billion) construction cost (see page 829).

The seven international partners in ITER (the United States, the European Union, Russia, China, Japan, India and South Korea) will no doubt be displeased by the news. They reached a final agreement to go ahead with ITER in 2006 based on a partially incomplete 2001 design, and may well suspect that the scientists were deliberately quoting an over-optimistic price in order to sell the project.

Whatever truth there might be in that allegation, the fusion community was making its estimate under less than ideal circumstances. ITER had been something of a political football since 1985, when it began life as part of the cold war détente. The collapse of the Soviet Union began a decade of political limbo for the project. Scientists had to radically downsize it at the end of the 1990s to appease the budget concerns of skittish member states.

As international partners came and went (and, in the case of the United States, came again), ITER subsisted on a shoestring. Meanwhile, politicians fought over the project's location. Until that debate was settled in mid-2005, only limited revisions to the design could be done. The redesign has been a top priority for the new ITER team ever since, and the group should be commended for coming forward with a higher estimate of costs after the full review.

What is worrying is that even this new price tag might not reflect the true cost of the machine. Crucially, it does not include the soaring price of commodities such as steel and copper, which are used in large quantities in the giant reactor. The ITER team claims that these costs can be excluded because individual member states will contribute finished components rather than raw materials, but this seems disingenuous. Already, the US government has doubled its estimated maximum contribution to the project, and other countries will probably have to follow suit.

"ITER may yet follow the path of other projects whose costs spiralled out of control"

This suggests that ITER may yet follow the path of other projects whose costs spiralled out of control once they were given a political imprimatur. The danger to the project itself may seem to be limited because of its international nature, but strictly speaking there is nothing to prevent a cancellation of the sort that ended the US Superconducting Supercollider. Congress halted that experiment 15 years ago, even as the tunnels were being dug in Waxahachie, Texas.

The more likely outcome is that overruns will further undermine the credibility of science at a time when it is increasingly dependent on multinational collaborations to build instruments and data networks. Future projects such as the International Linear Collider, a next-generation particle accelerator for high-energy physics, may well face more sceptical funders if ITER's costs aren't contained.

The independent scientific and management advisory committees overseeing ITER should take a hard look at whether the latest estimates are truly realistic. If they are not, then the committees should demand that the budget include adequate contingencies for factors such as increased energy and commodity costs, as well as scenarios for construction with less than full funding. Even if it means more pain in the short run, this kind of discipline will ultimately lead to a better machine and a better future for all international collaborations. ■

News

Fusion reactor set to raid Europe's research funds

€1.4-billion gap in ITER project could be plugged with Framework cash.

Geoff Brumfiel

European nations hope to divert more than a billion euros that were earmarked for research grants to make up a budget shortfall at the experimental ITER fusion reactor, *Nature* has learned.

The proposal has alarmed scientists, who say that it will rob researchers of vital funds at a time when

This artist's impression shows what the ITER reactor site will look like - if it can

NATURE | NEWS

US fusion in budget vice

Domestic facilities struggle for survival as funding is directed to international reactor.

Eric Hand

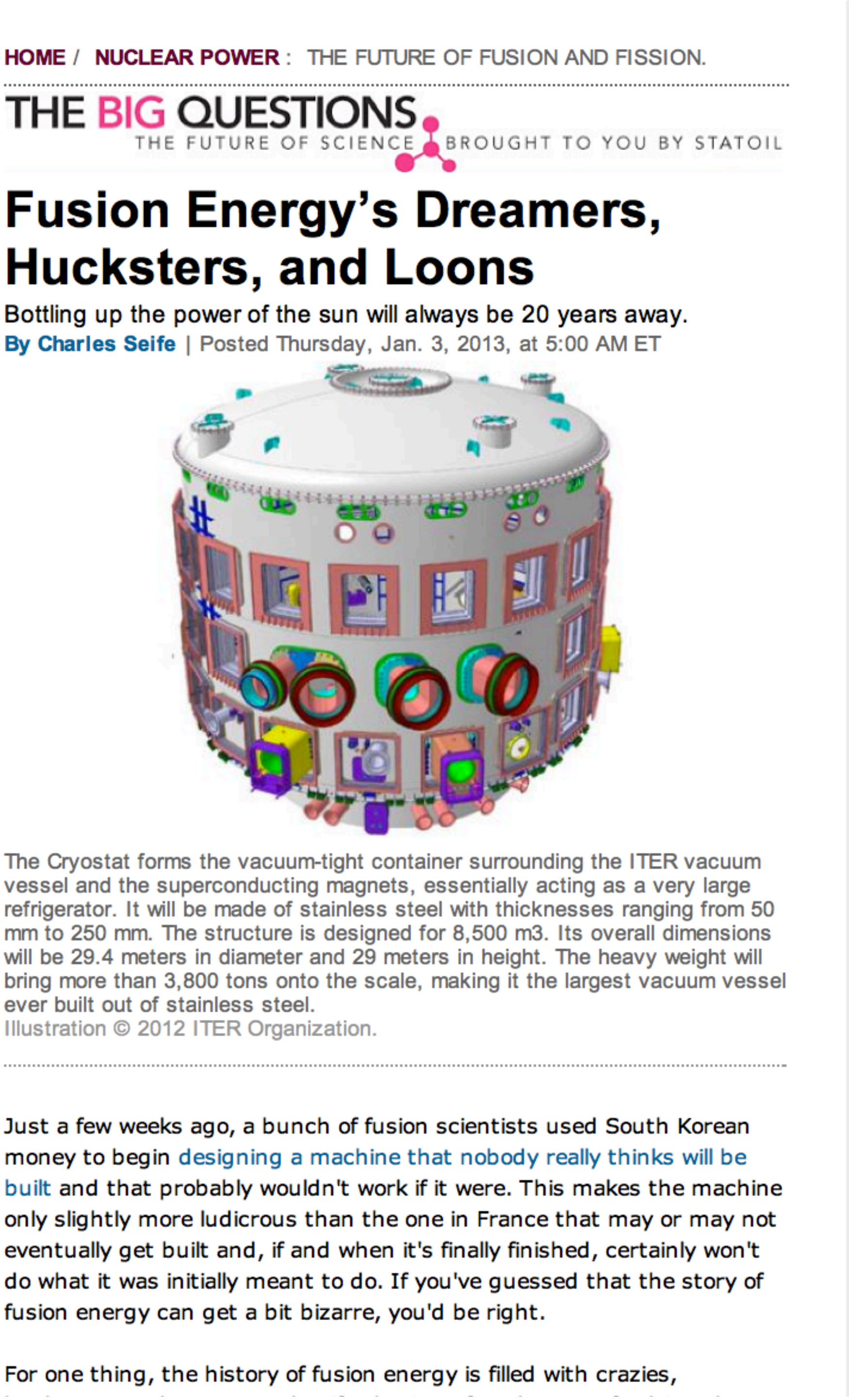
24 July 2012

For years, US researchers have been steadfast in their support of ITER, the world's largest fusion-energy experiment, which is under construction near Cadarache, France. But with funding commitments to ITER now putting the squeeze on three existing facilities in the United States, enthusiasm for the international project is becoming as difficult to sustain as a fusion reaction.

The Alcator-C-Mod fusion experiment is facing closure.

M. GARRETT

"I think we should ask whether this is the right path," Earl Marmar, head of the Alcator C-Mod fusion experiment run by the Massachusetts



Fusion Energy's Dreamers, Hucksters, and Loons

Bottling up the power of the sun will always be 20 years away.

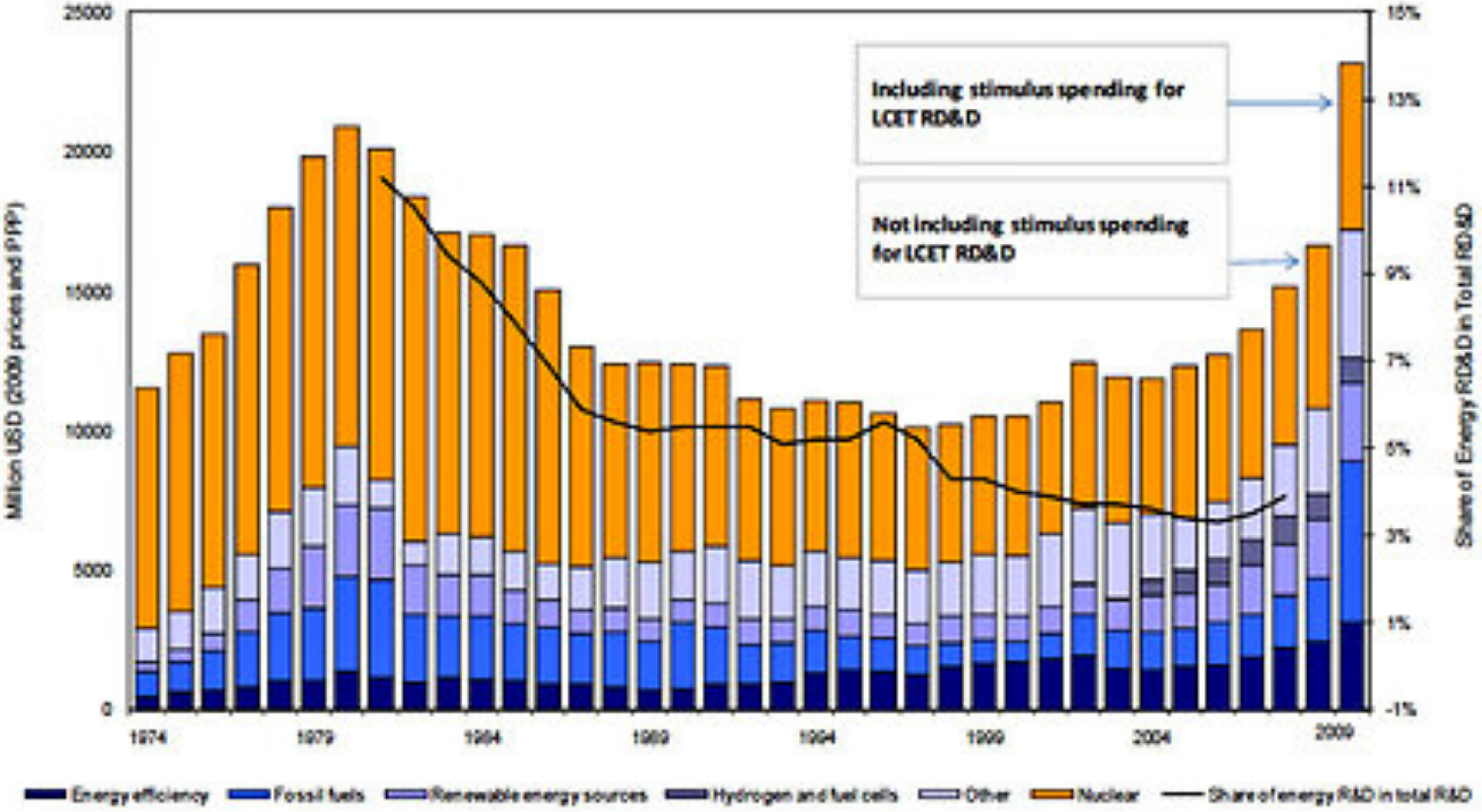
By Charles Seife | Posted Thursday, Jan. 3, 2013, at 5:00 AM ET

The Cryostat forms the vacuum-tight container surrounding the ITER vacuum vessel and the superconducting magnets, essentially acting as a very large refrigerator. It will be made of stainless steel with thicknesses ranging from 50 mm to 250 mm. The structure is designed for 8,500 m3. Its overall dimensions will be 29.4 meters in diameter and 29 meters in height. The heavy weight will bring more than 3,800 tons onto the scale, making it the largest vacuum vessel ever built out of stainless steel.
Illustration © 2012 ITER Organization.

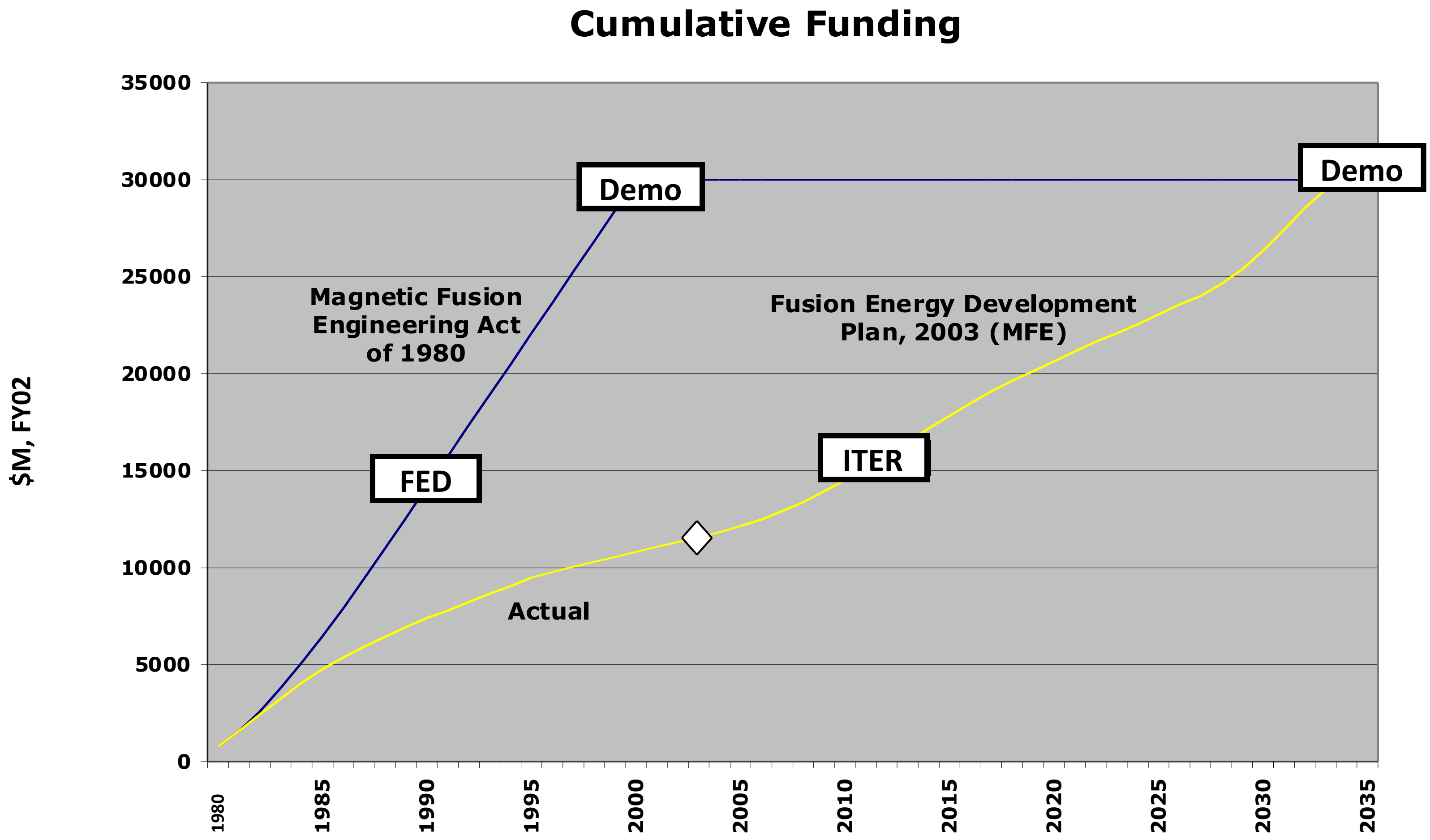
Just a few weeks ago, a bunch of fusion scientists used South Korean money to begin designing a machine that nobody really thinks will be built and that probably wouldn't work if it were. This makes the machine only slightly more ludicrous than the one in France that may or may not eventually get built and, if and when it's finally finished, certainly won't do what it was initially meant to do. If you've guessed that the story of fusion energy can get a bit bizarre, you'd be right.

For one thing, the history of fusion energy is filled with crazies,

Figure 1: Government RD&D expenditure in IEA member countries, 1974-2009



Response: Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



Fusion Development is on Budget if not on Time.

Fusion is expensive (2-3 COE)

Alternative Energy Sources: Extranalities Argument

Oil

Not Renewable.

Cost of Climate Change.

Cost of Persian Gulf wars every decade or so.

Alternative Energy Sources: Extranalities Argument

Fission

Nuclear power plants provide about 5.7% of the world’s energy and 13% of the world's electricity. In 2007, there were 439 nuclear power reactor, operating in 31 countries.

Nuclear power plant accidents include Chernobyl (1986), Fukushima Daiichi (2011), and Three Mile Island (1979).

Current estimates of a major accident are about 10^{-6}

A better estimate of a $\$10^9$ accident might be about 10^{-2} (450/3), adding about $\$10^7$ to the reactor cost.

Progress in Magnetic Fusion Energy (MFE)

Plasma conditions have been produced near the regime for energy production

The world has joined together to produce a burning plasma (ITER)

Countries are starting design of the steps after ITER, preparing for fusion power production

Future Research Directions

Methods of improving basic design

power steering before the car – but maybe important

Alternative Uses

NIF – basic science
stockpile stewardship

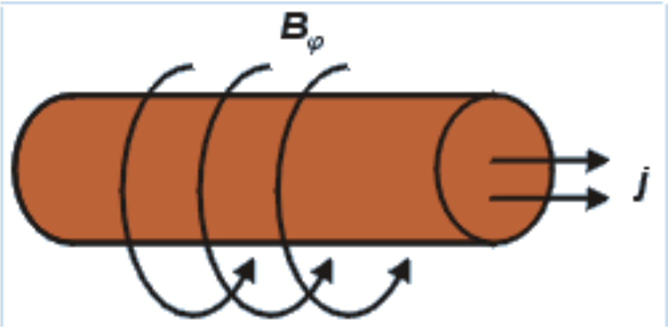
Magnetic – waste remediation

New Designs

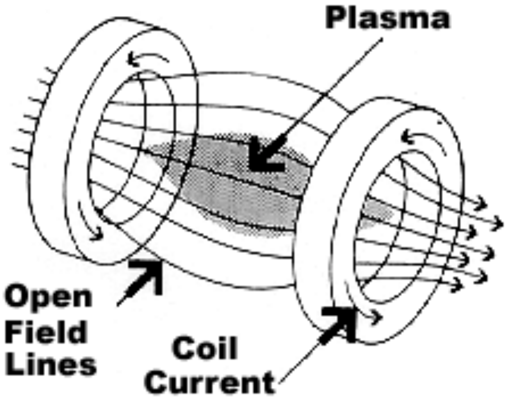
1. *limited upside unless radically new*
2. *possible game changers*
    - *energy delivery → large reactors*
    - *radiation management*
    - *new physics: muon-catalyzed, polarized nuclei*

Some Types of Magnetic Confinement

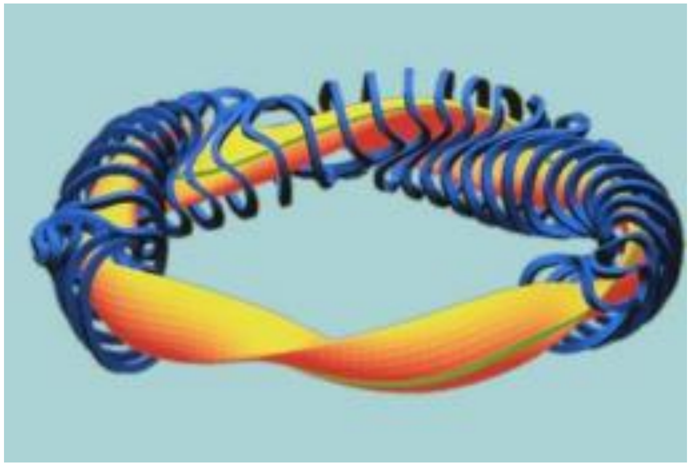
magnetic pinch



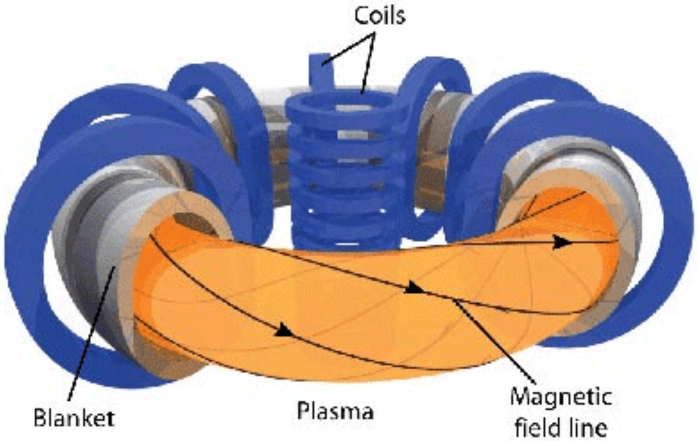
magnetic mirror



stellarator



tokamak



Future Research Directions

Double analogy:

MFE: Mirror Fusion to Toroidal Fusion

IFE: Z-pinch fusion to Laser Fusion

Physics solution:

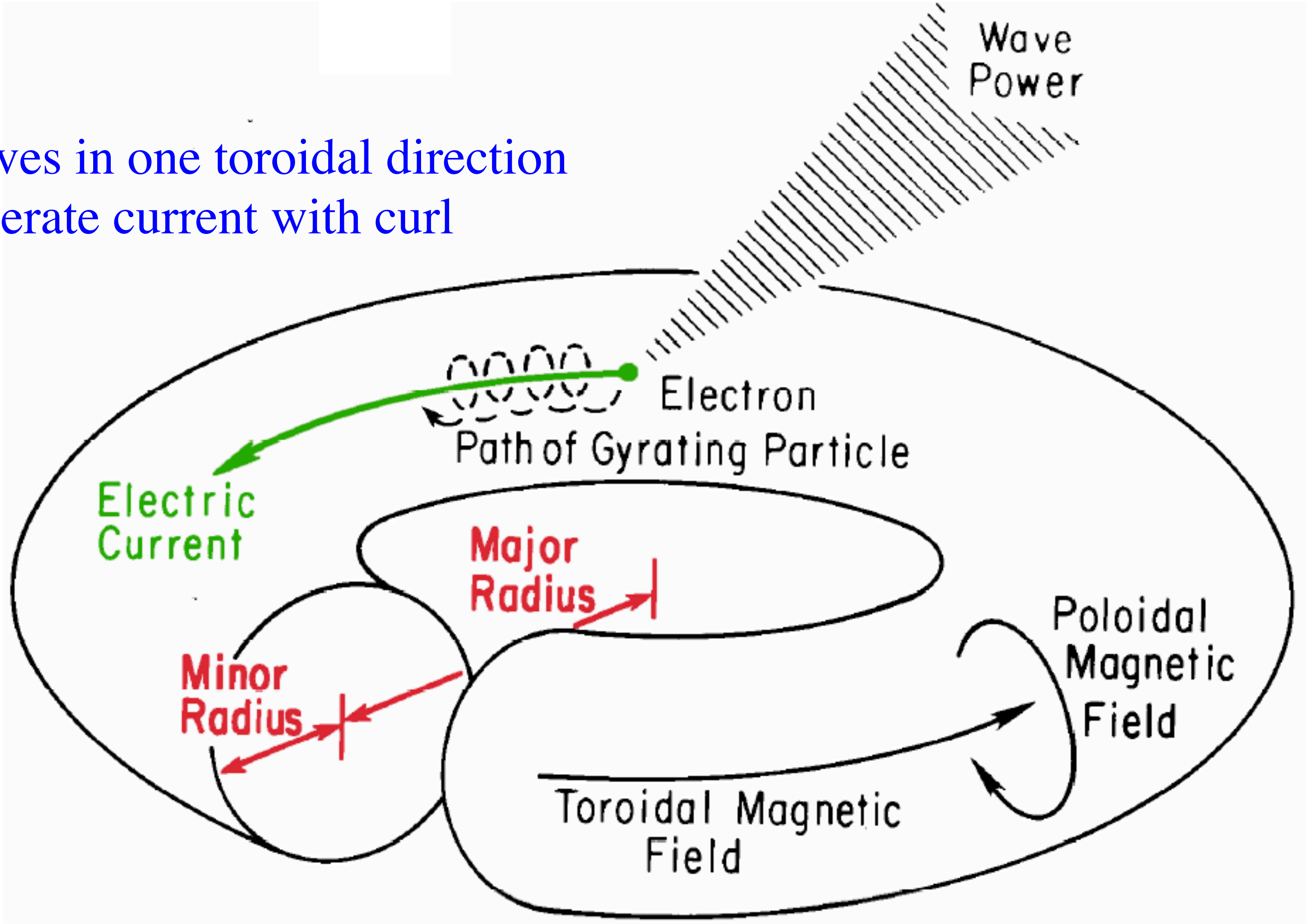
Tokamaks: good confinement (too good?)
Laser-implosion: high-compression

Engineering-compatible solution:

Mirrors: simply-connected (easy magnets)
Z-pinch: capacitor-bank-driven (rather that lasers)

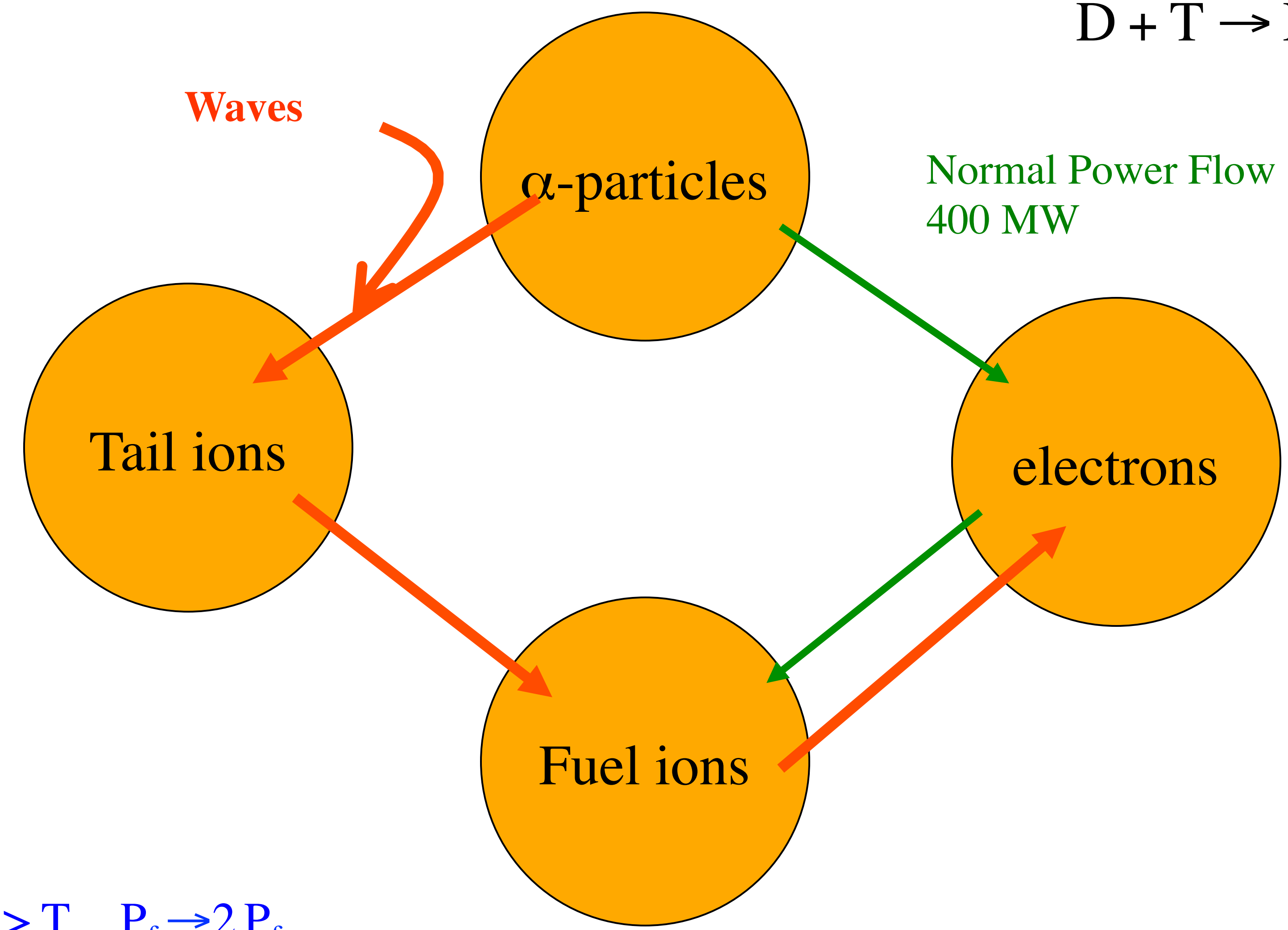
Producing Tokamak Confinement with Waves

Waves in one toroidal direction
generate current with curl



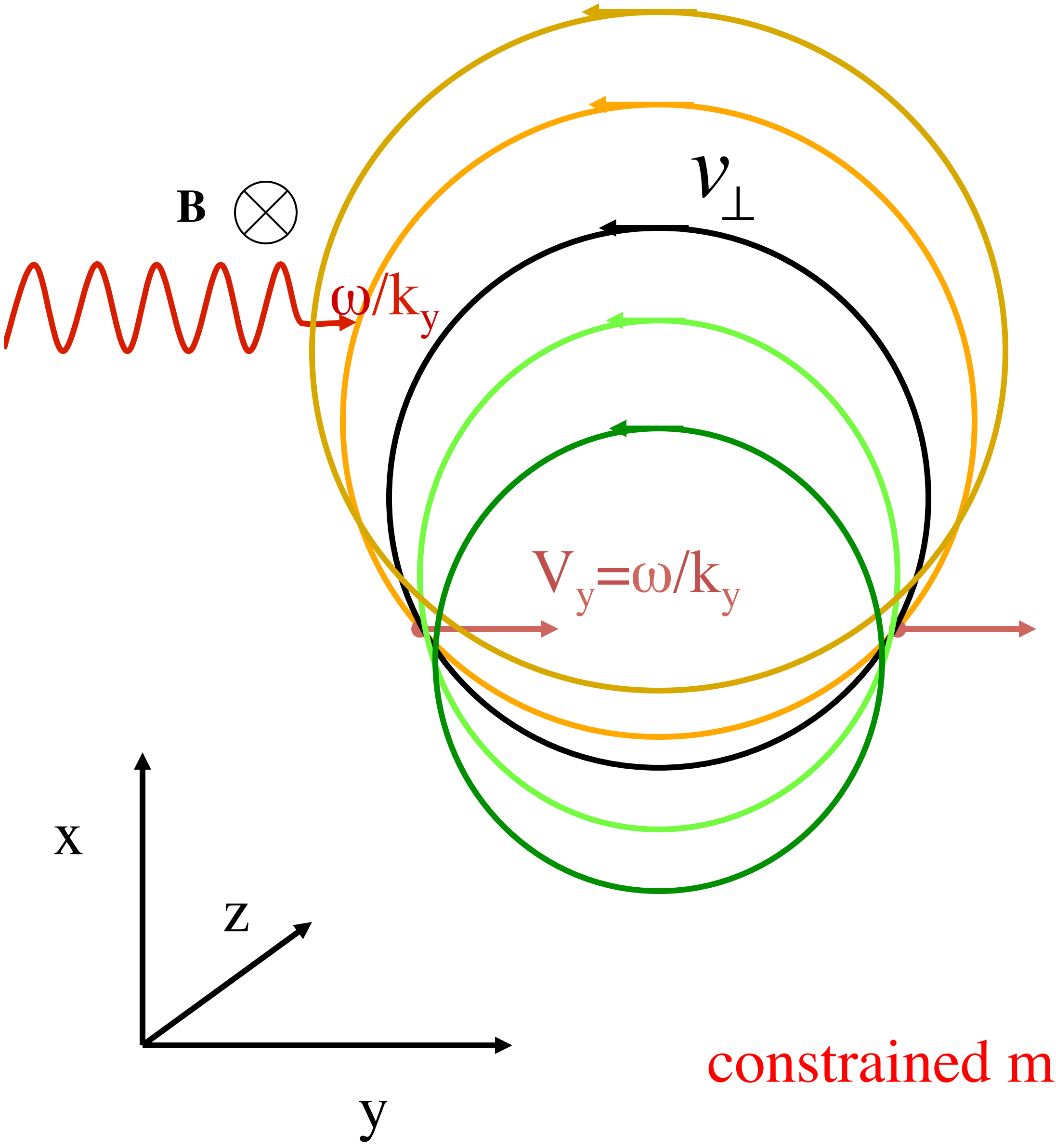
Power Flow in a Fusion Reactor

$$D + T \rightarrow He^4 + n$$



Get $T_i > T_e$, $P_f \rightarrow 2\,P_f$

Diffusion Paths

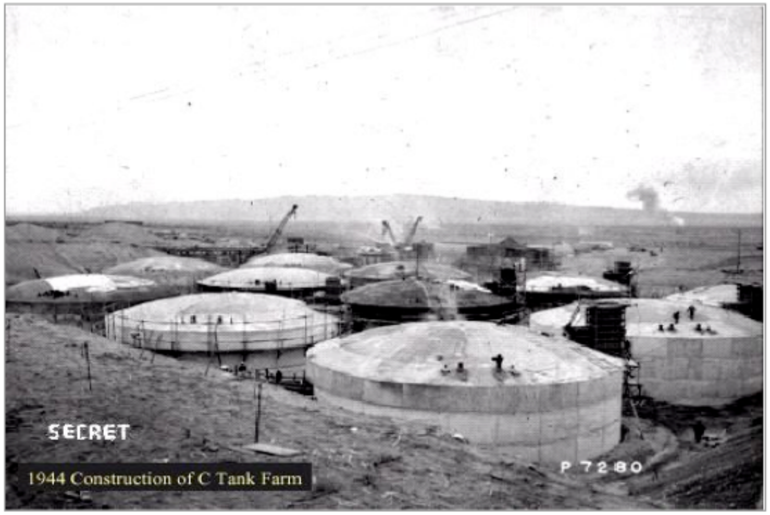


$$v_y \rightarrow v_y + \Delta v_y$$

$$\boxed{x_{gc} \rightarrow x_{gc} + \frac{\Delta E}{m\Omega \, {}^{\omega}\!/_{k_y}}}$$

constrained motion in *energy-distance* space

Waste at Hanford originates from US nuclear weapons program



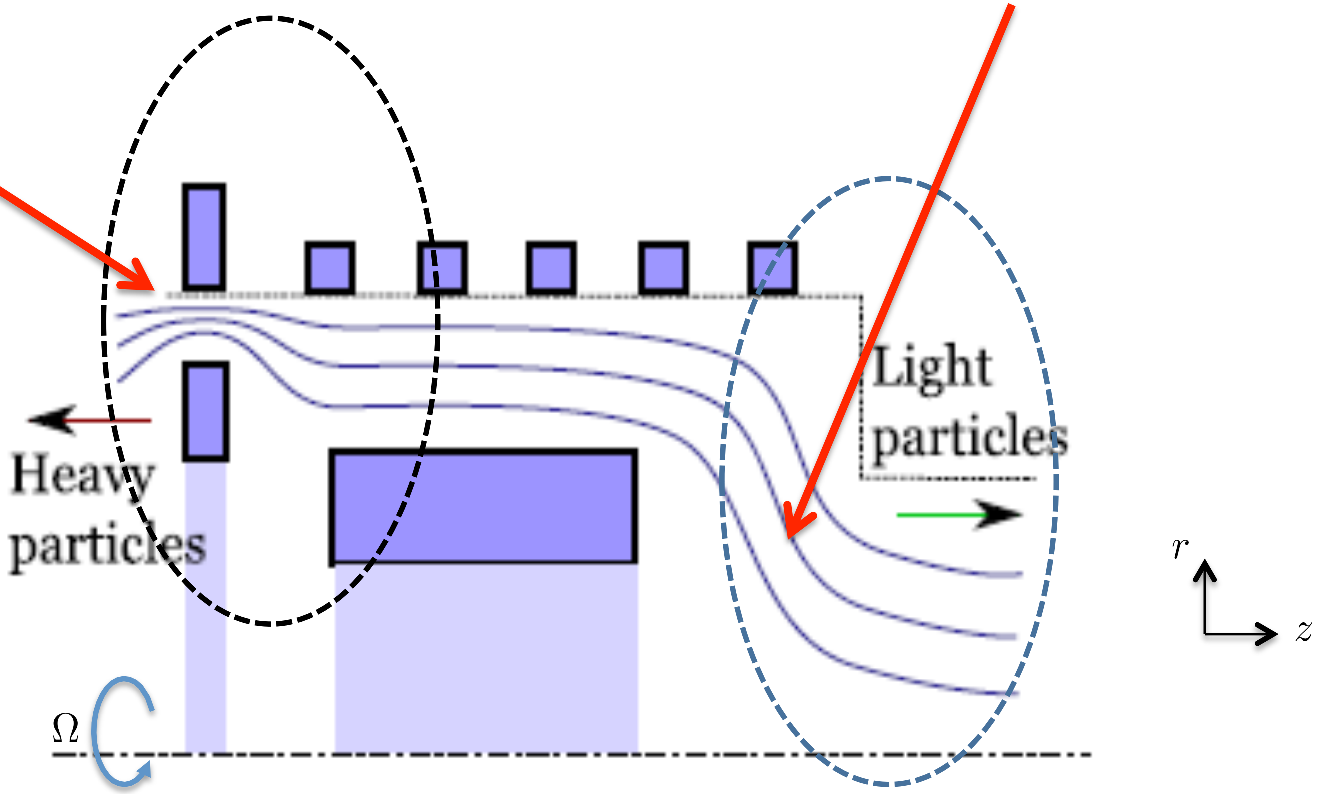
Single shell tanks constructed in 1944

Waste treatment plant in 2005

- 177 tanks contain 54 million gallons of high level waste with 194 MCi total radioactivity
- Tanks are decades past planned lifetime. Decades remain until they are fully processed.

River Protection Project System Plan, Revision 5 (2010)

Magnetic Centrifugal Mass Filter



Centrifugal force on heavy ions overcomes the magnetic mirror force.

Centrifugal force is not sufficient to confine energetic light ions.

Summary

1. Methods of Generating Fusion Energy
   - Inertial – laser-fusion (NIF)
   - Magnetic – tokamak (ITER)

2. Energy Goal is Distant – but approachable and not discountable

3. Some Intermediate goals:
   - *NIF* – *basic science*
     - *stockpile stewardship*
   - *Magnetic* – *high-throughput mass separation (waste remediation)*

4. New Designs
   - *limited upside unless radically new*
   - *possible game changers*
     - *energy delivery → large reactors*
     - *radiation management*
     - *new physics: muon-catalyzed, polarized nuclei*