Introduction to Plasma Physics

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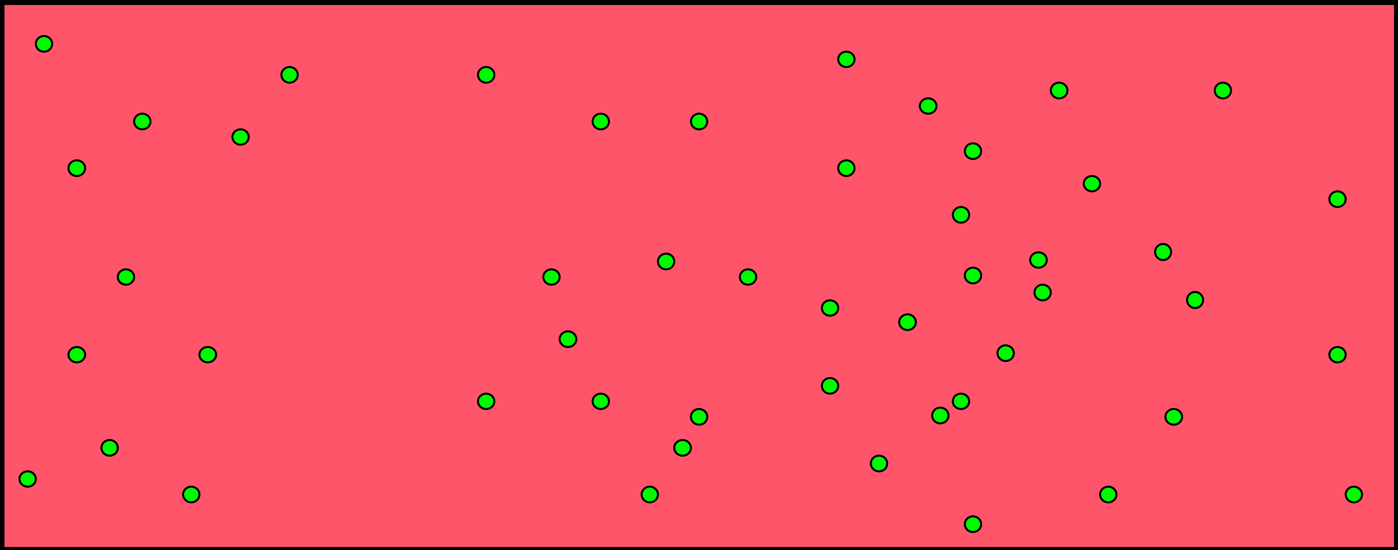
Princeton University

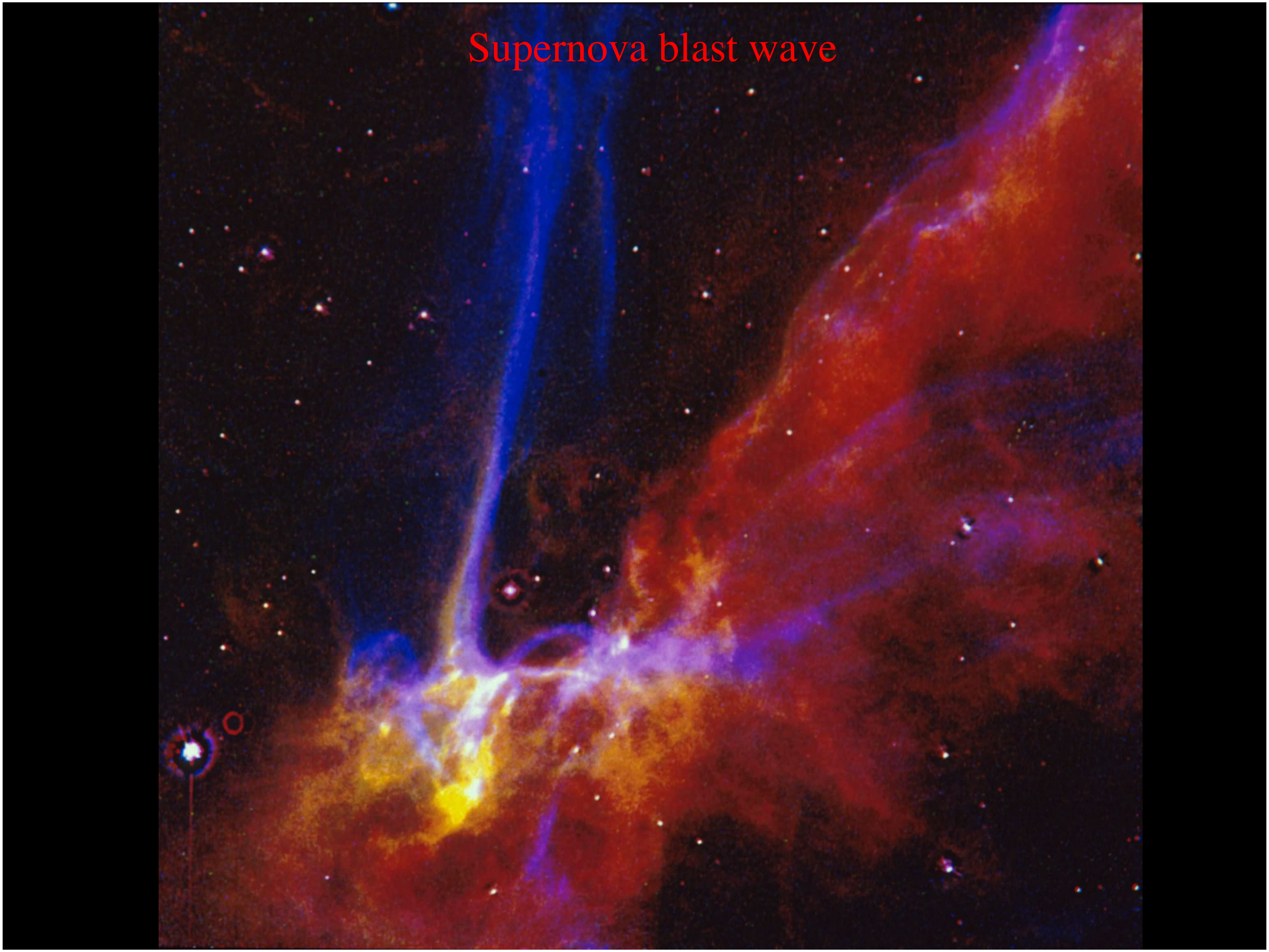
SULI Introductory Course in Plasma Physics
June 11, 2018

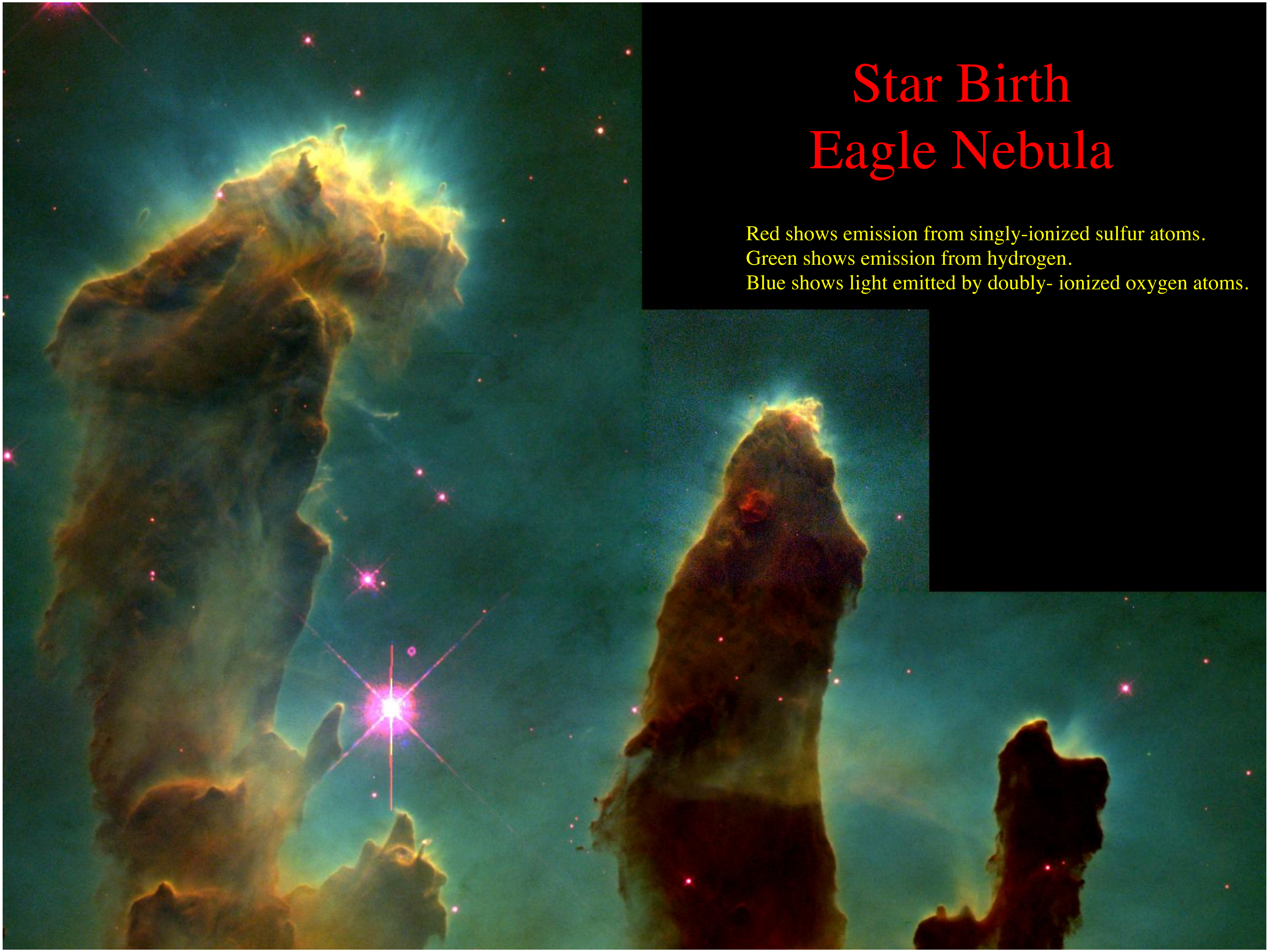
Plasma



Irving Langmuir (1881-1957); Nobel ‘32

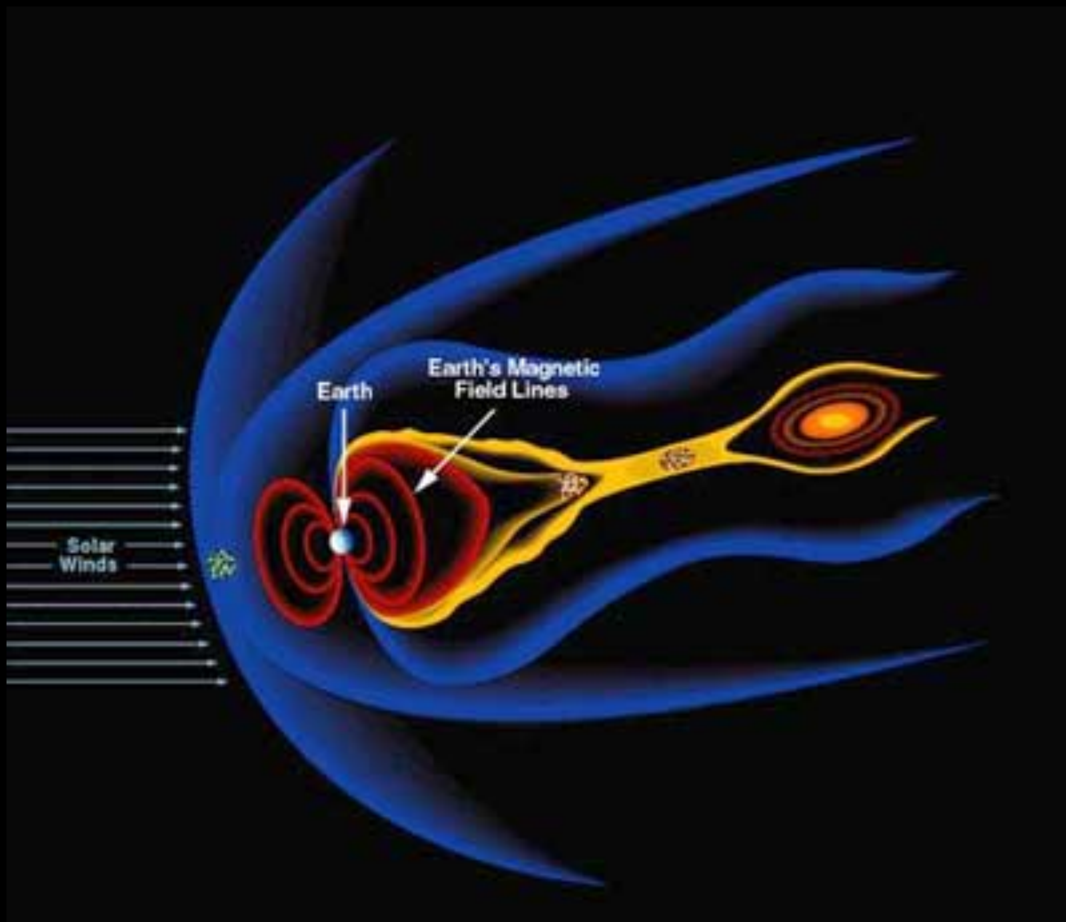
The term "plasma" for an ionized gas was coined in 1927 by Irving Langmuir, because how an electrified fluid carried ions and electrons reminded him of how blood plasma carried red and white corpuscles.


Supernova blast wave

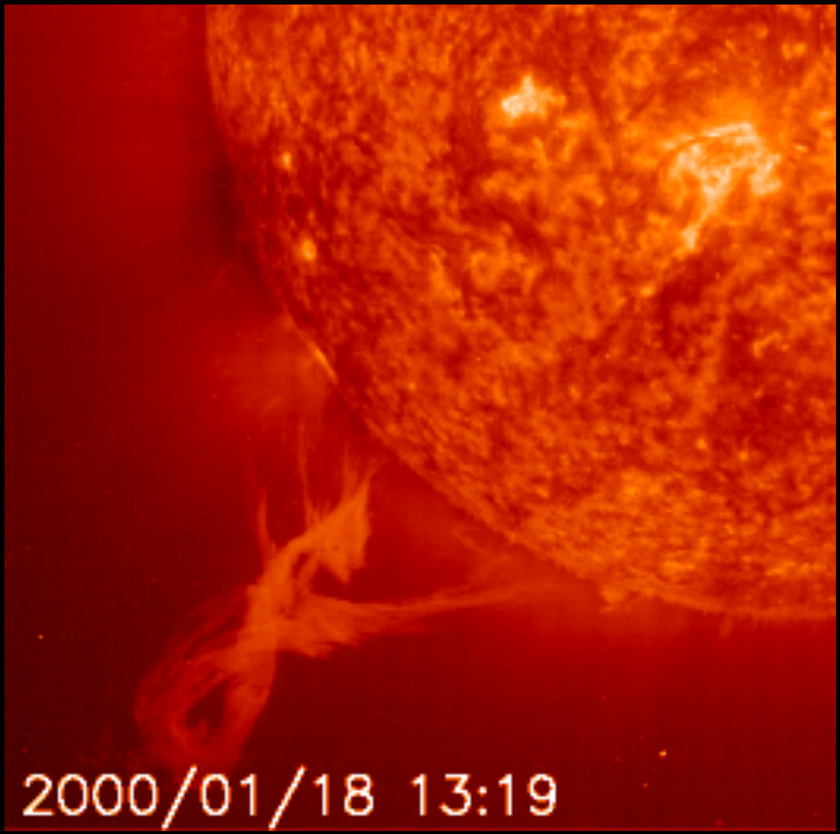


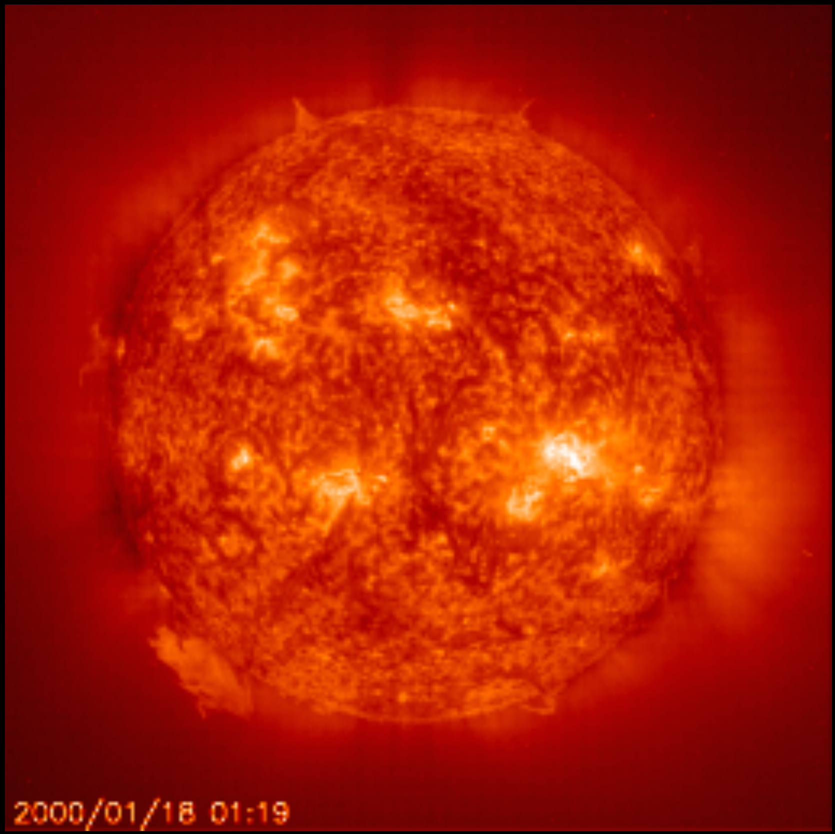
Star Birth
Eagle Nebula
Red shows emission from singly-ionized sulfur atoms.
Green shows emission from hydrogen.
Blue shows light emitted by doubly- ionized oxygen atoms.

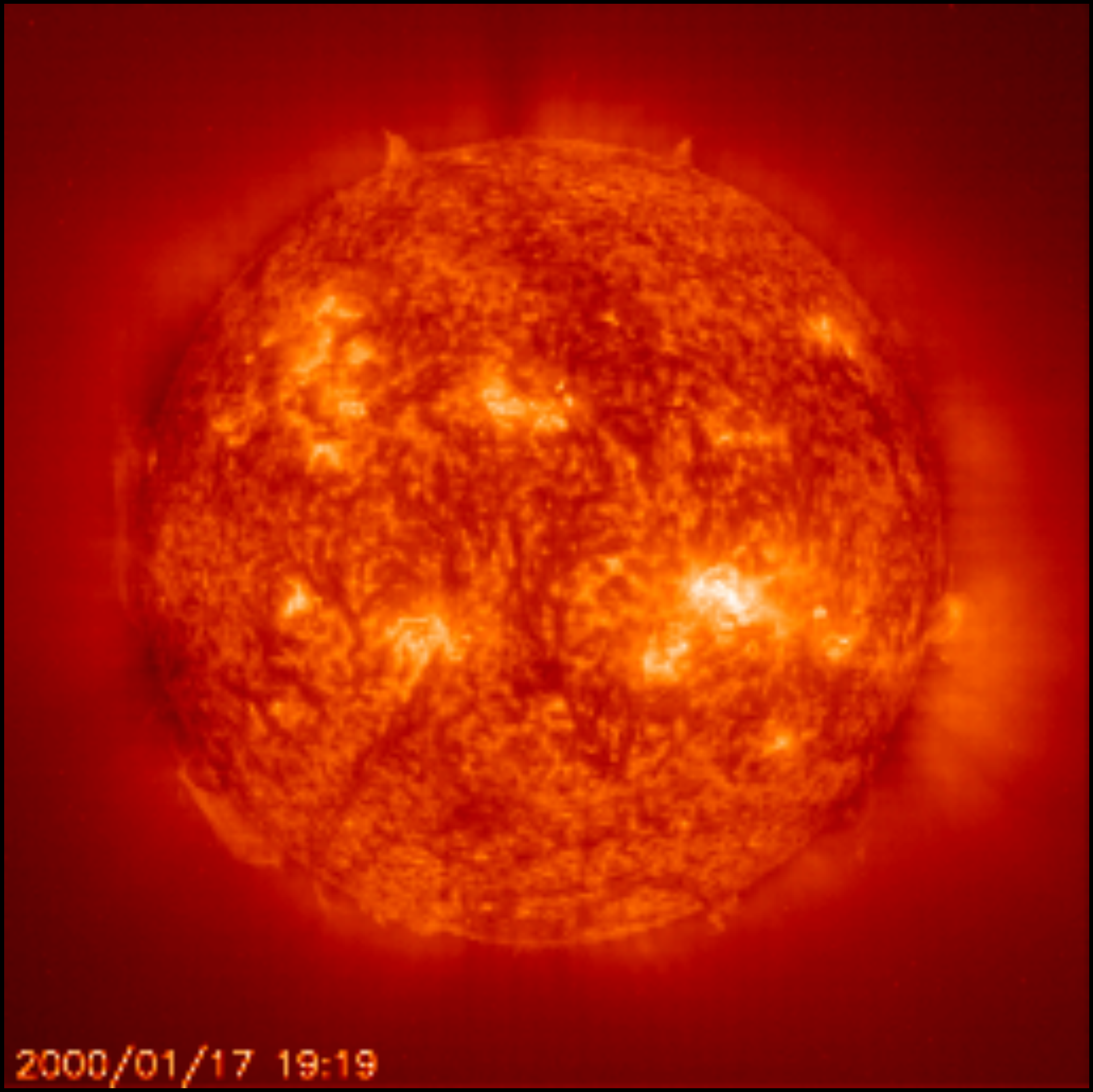
Magnetic Reconnection produces high energy electrons



Solar Prominence

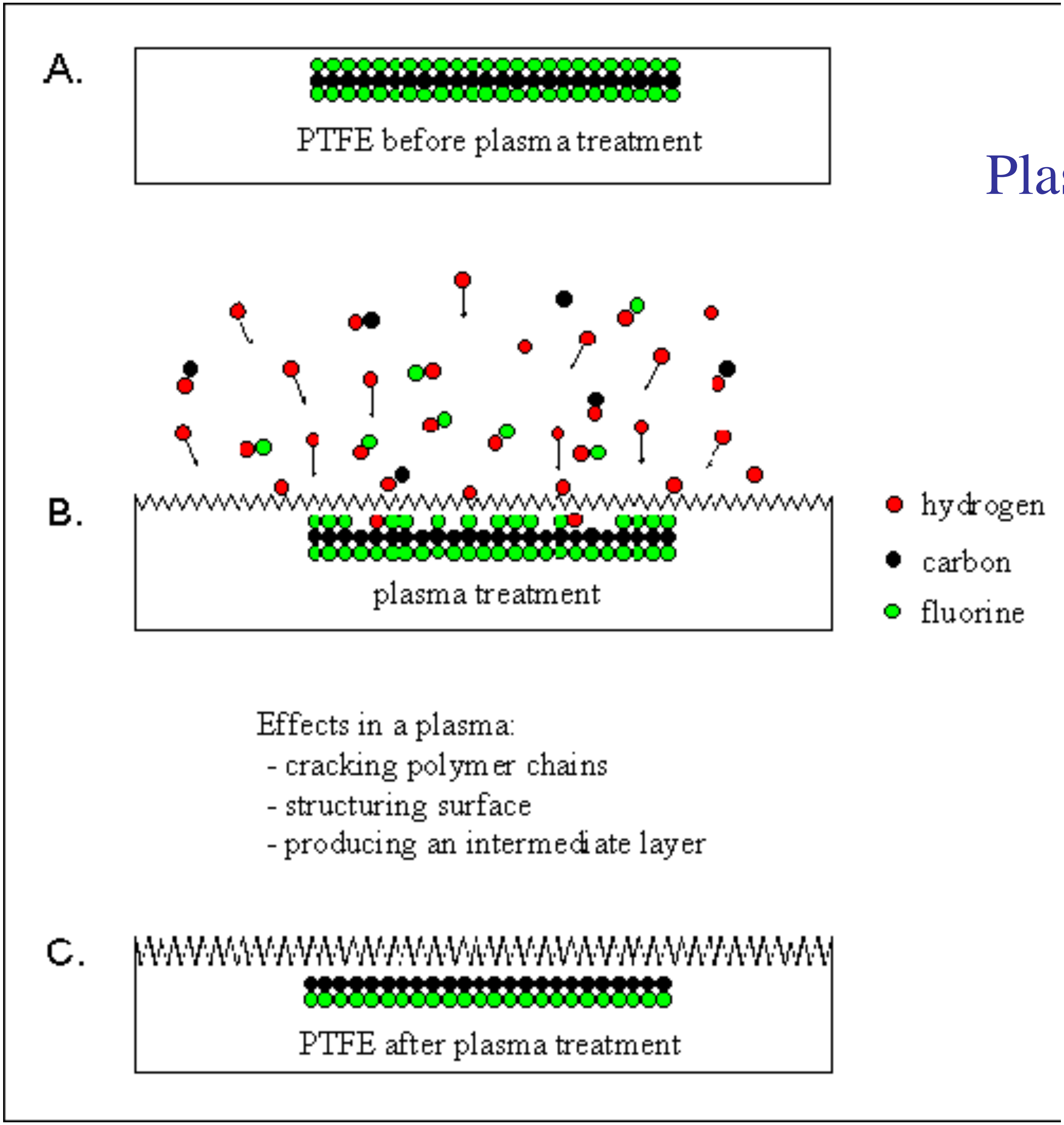




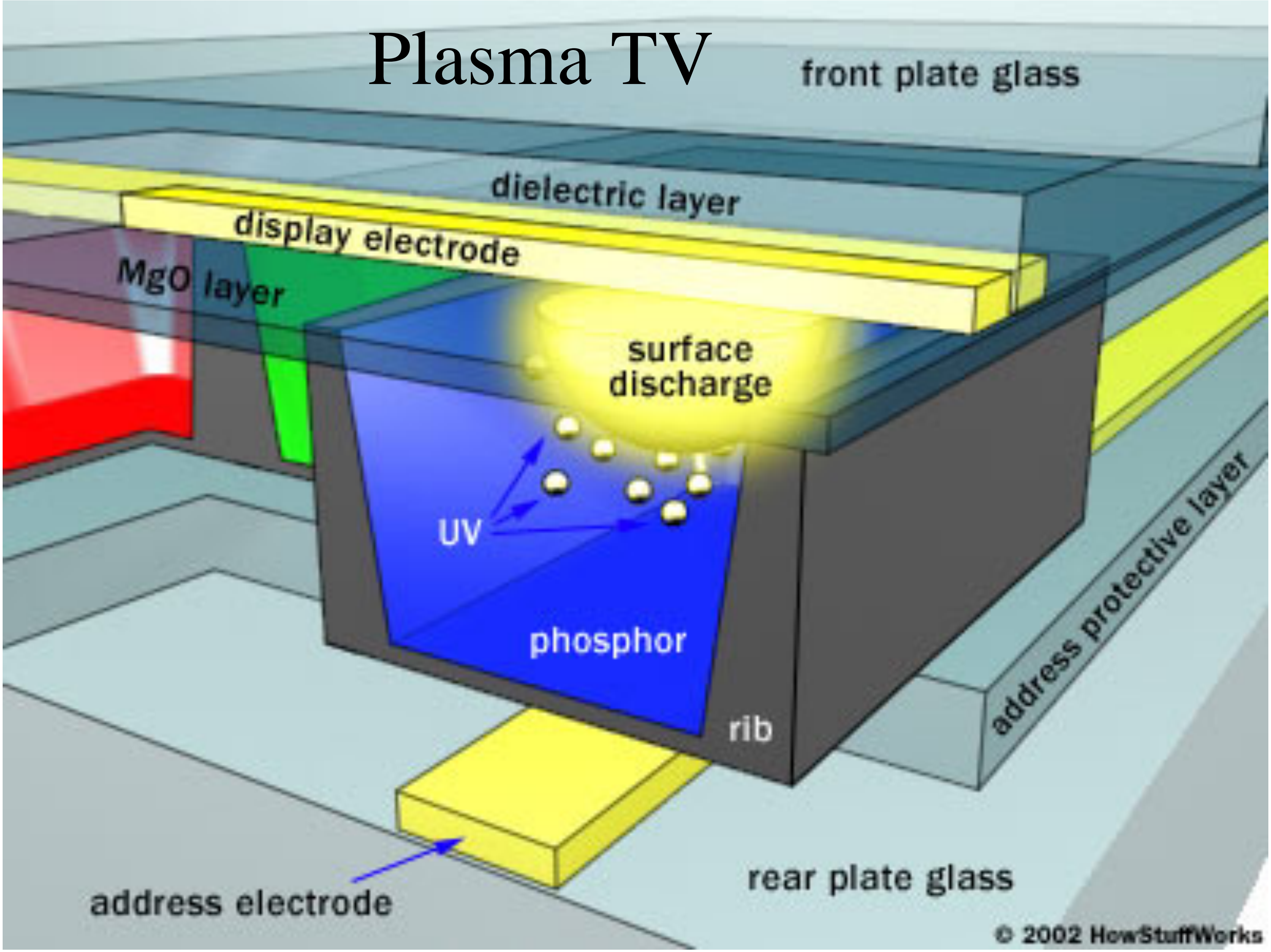


Solar Prominence

Plasma Etching

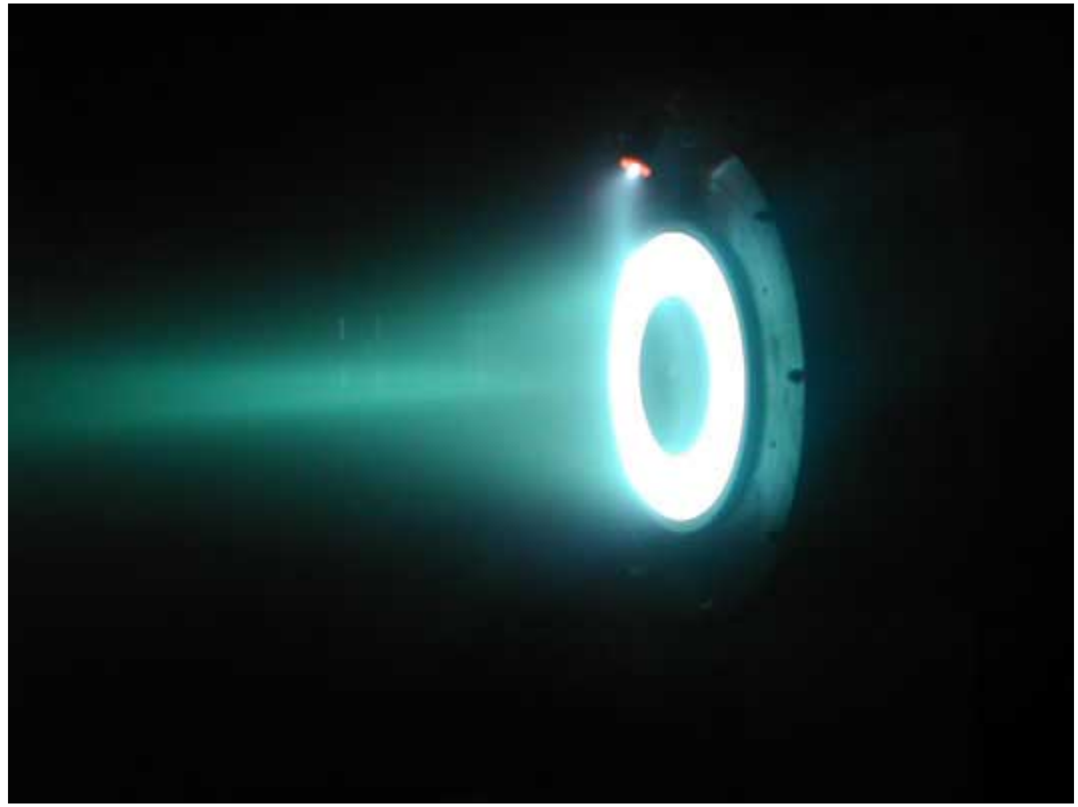


Plasma TV

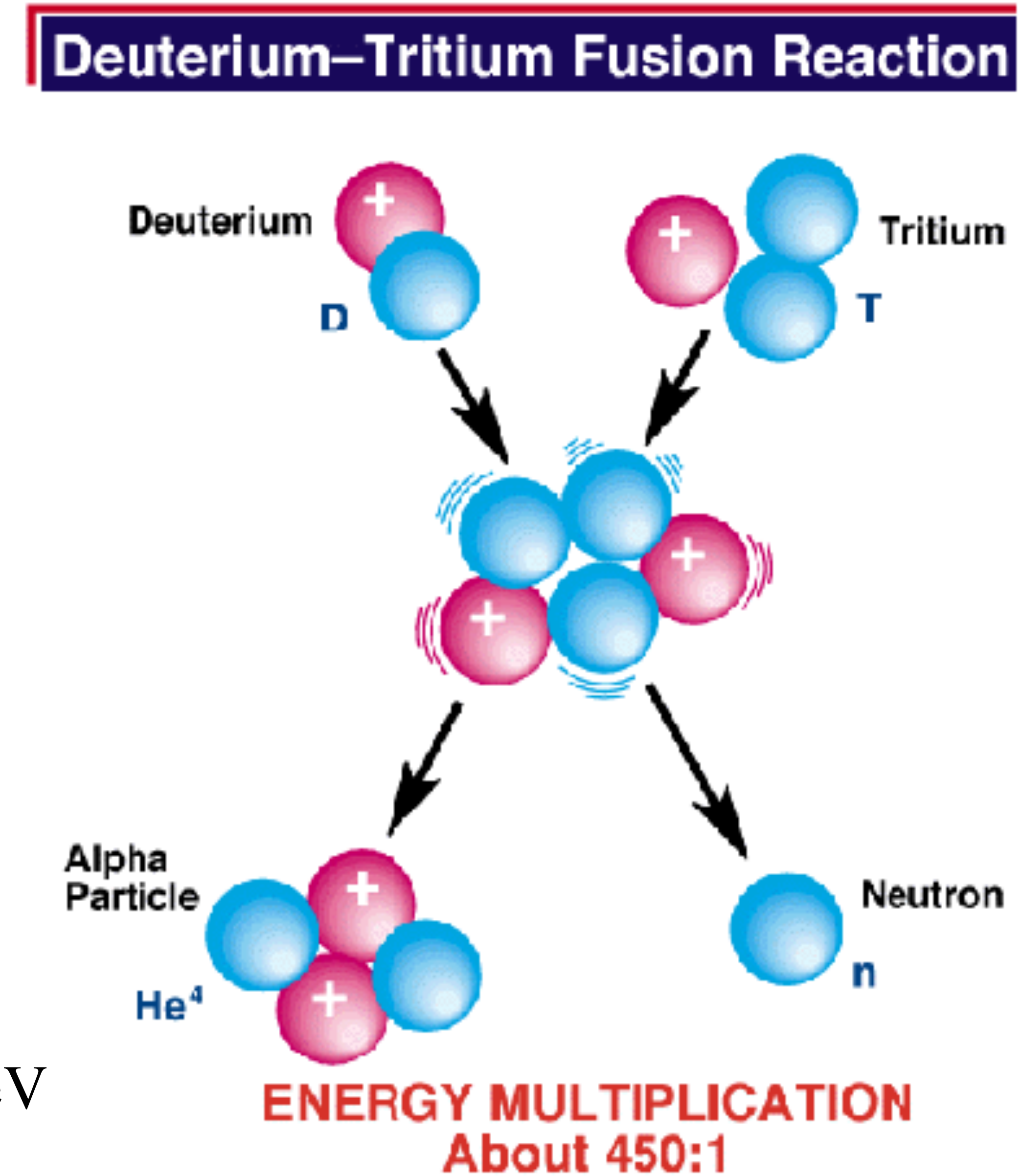

front plate glass
dielectric layer
display electrode
MgO layer
surface discharge
UV
phosphor
rib
address protective layer
rear plate glass
address electrode
© 2002 HowStuffWorks

Plasma Thrusters used on Satellites

Plasma thrusters have much higher exhaust velocity than chemical rockets: reduces amount of propellant that must be carried. Can be powered by solar panels, fission, or fusion.



Hall Thruster developed at PPPL

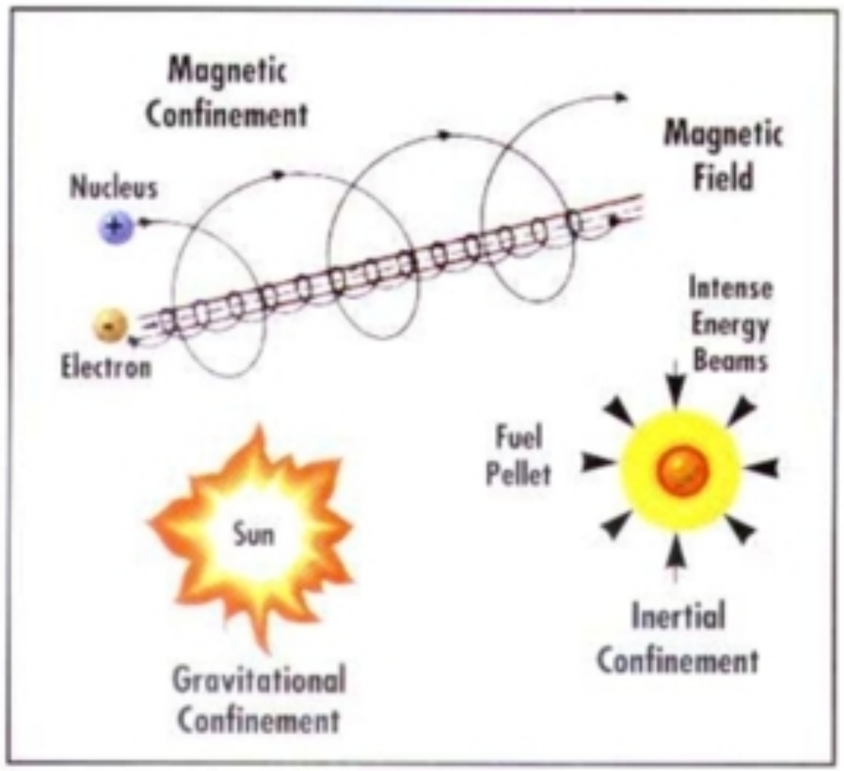

Deuterium–Tritium Fusion Reaction
Deuterium
D
Tritium
T
Alpha
Particle
He4
Neutron
n
ENERGY MULTIPLICATION
About 450:1

14 MeV

3.5 MeV

Plasma Confinement

magnetic

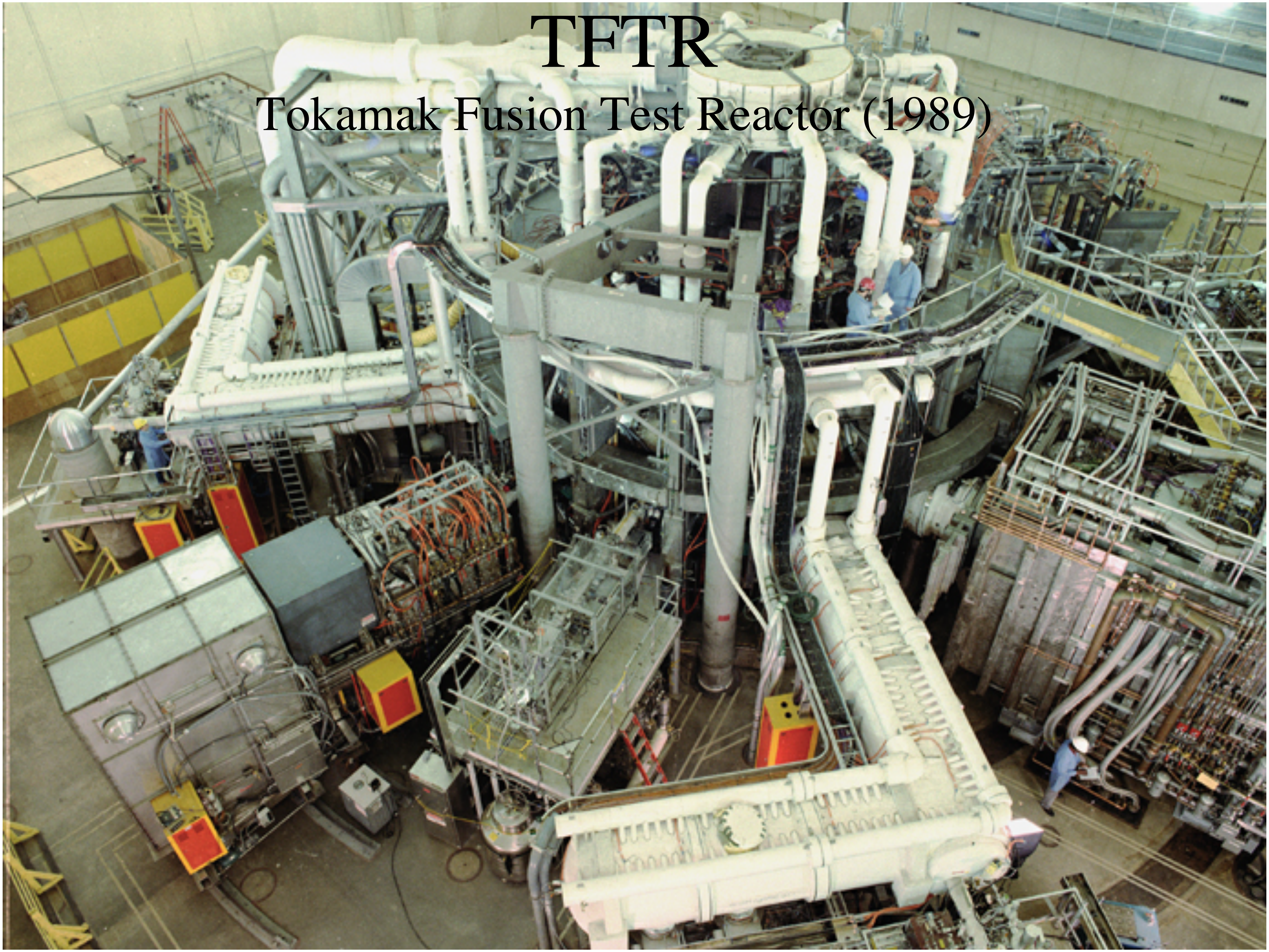


"inertia"

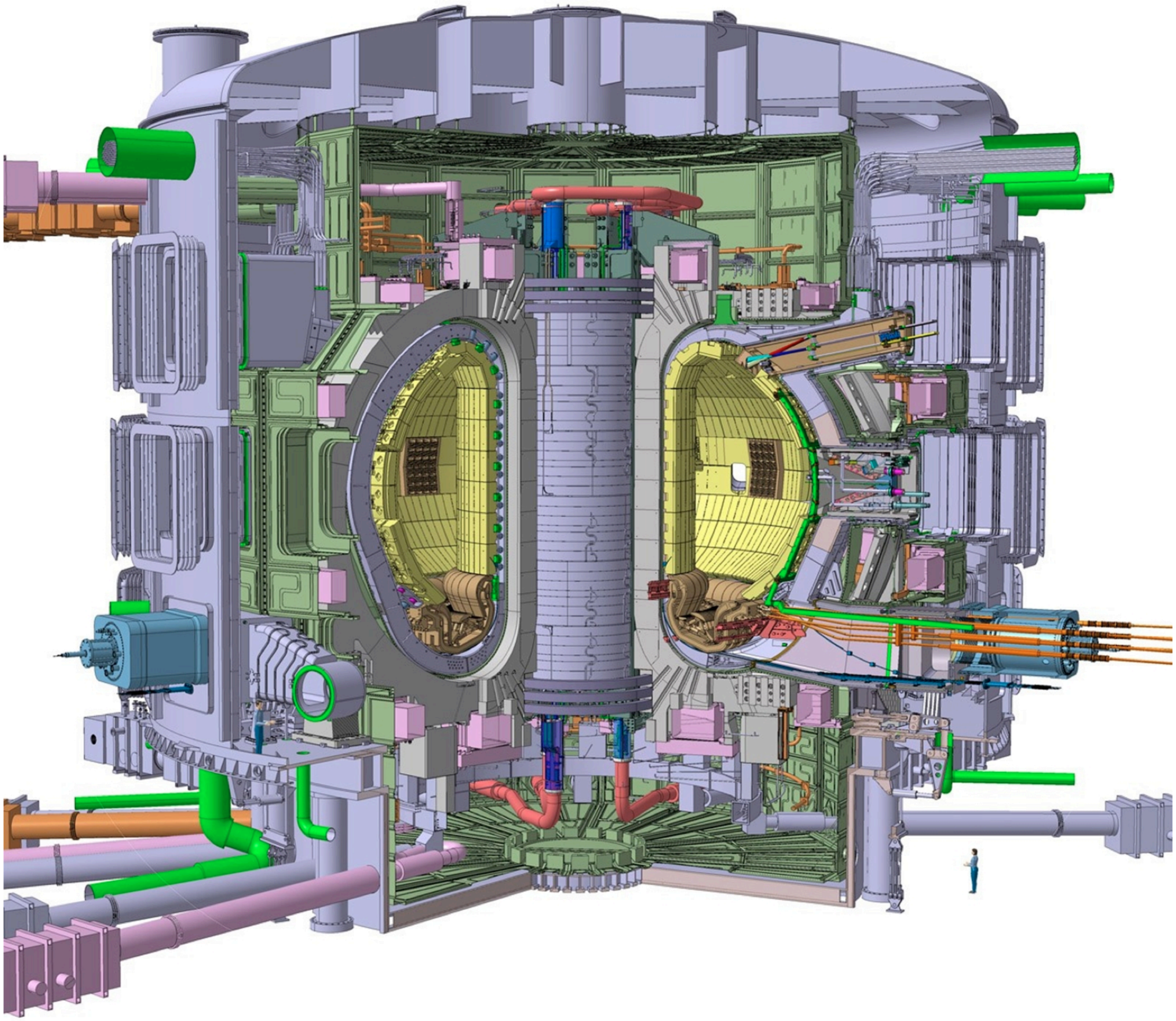
gravitational

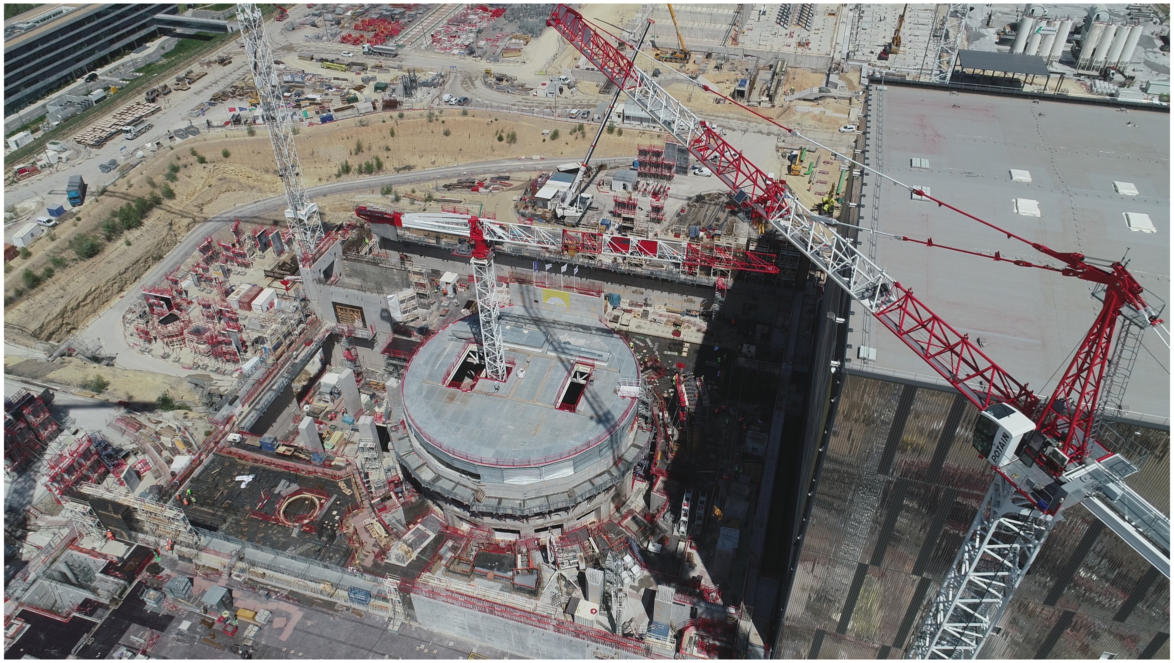
TFTR

Tokamak Fusion Test Reactor (1989)

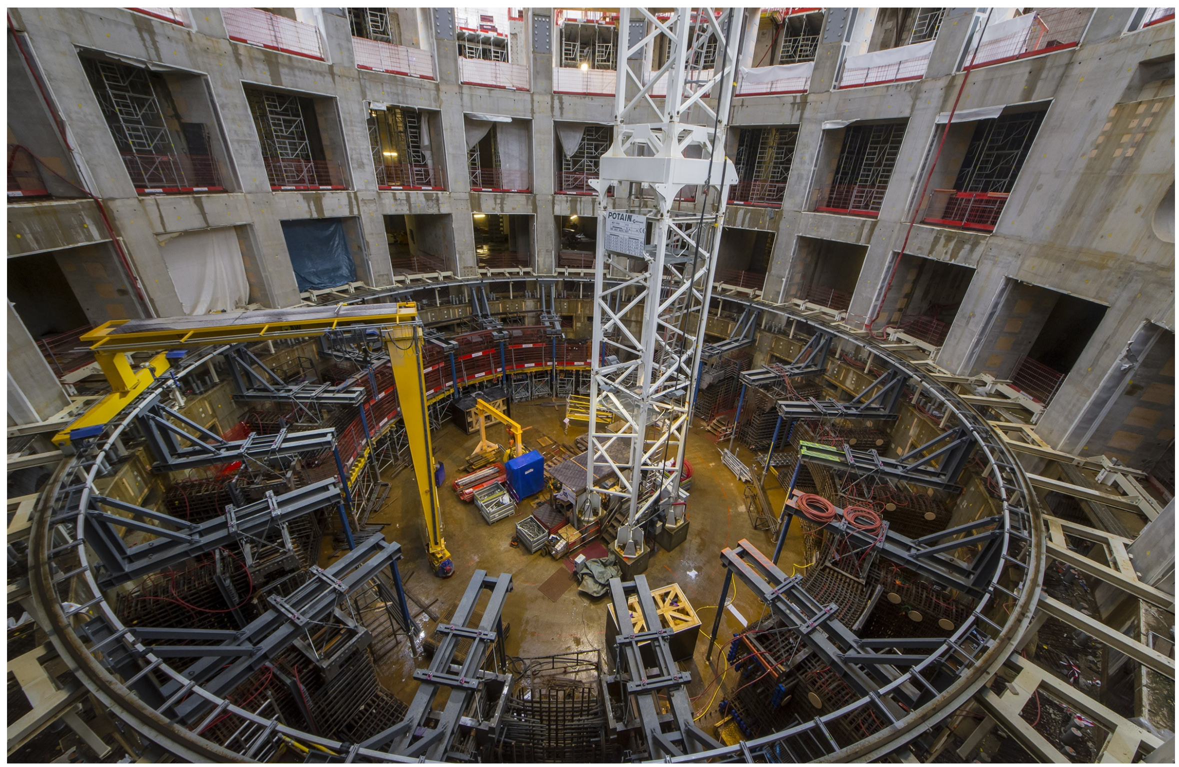


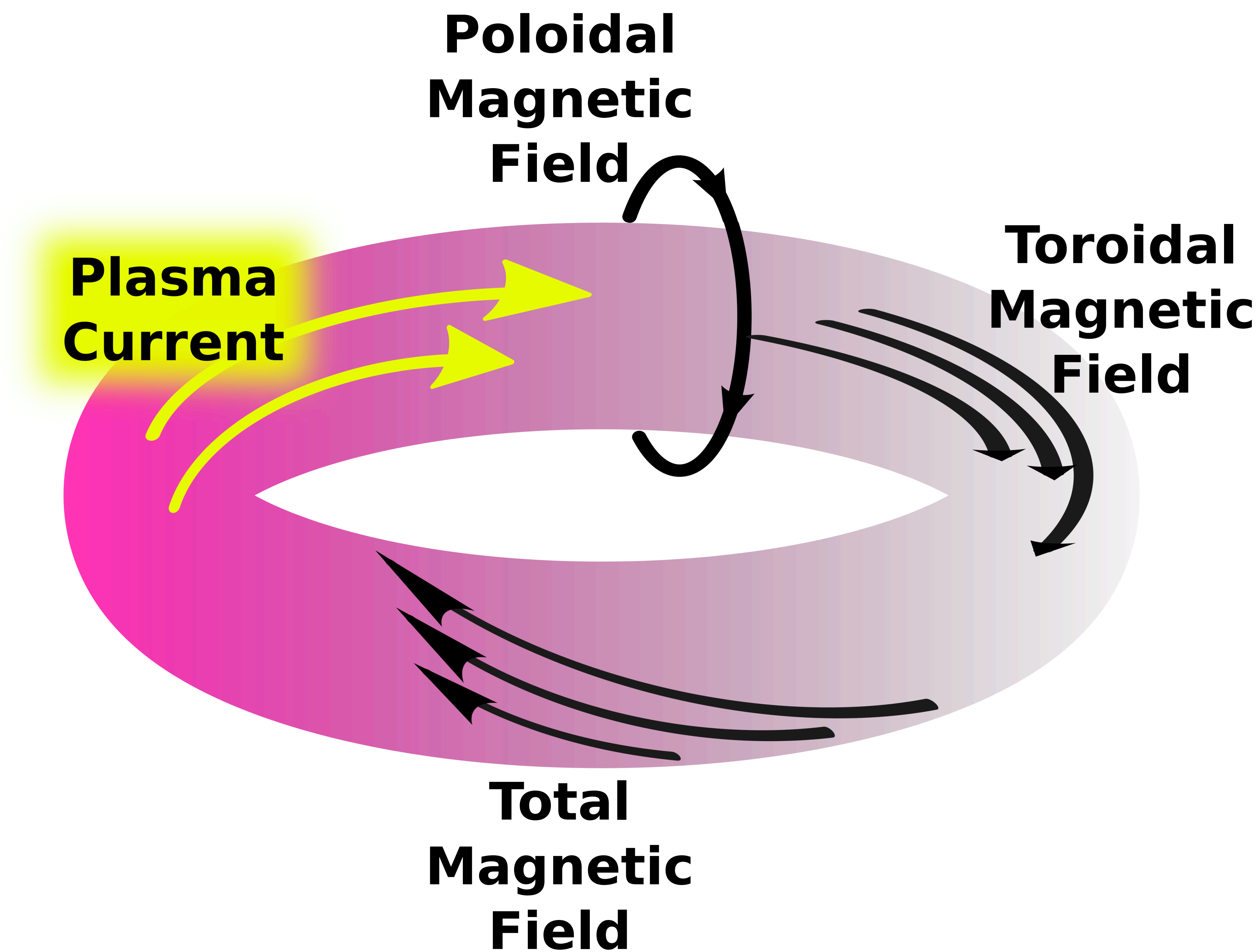
ITER





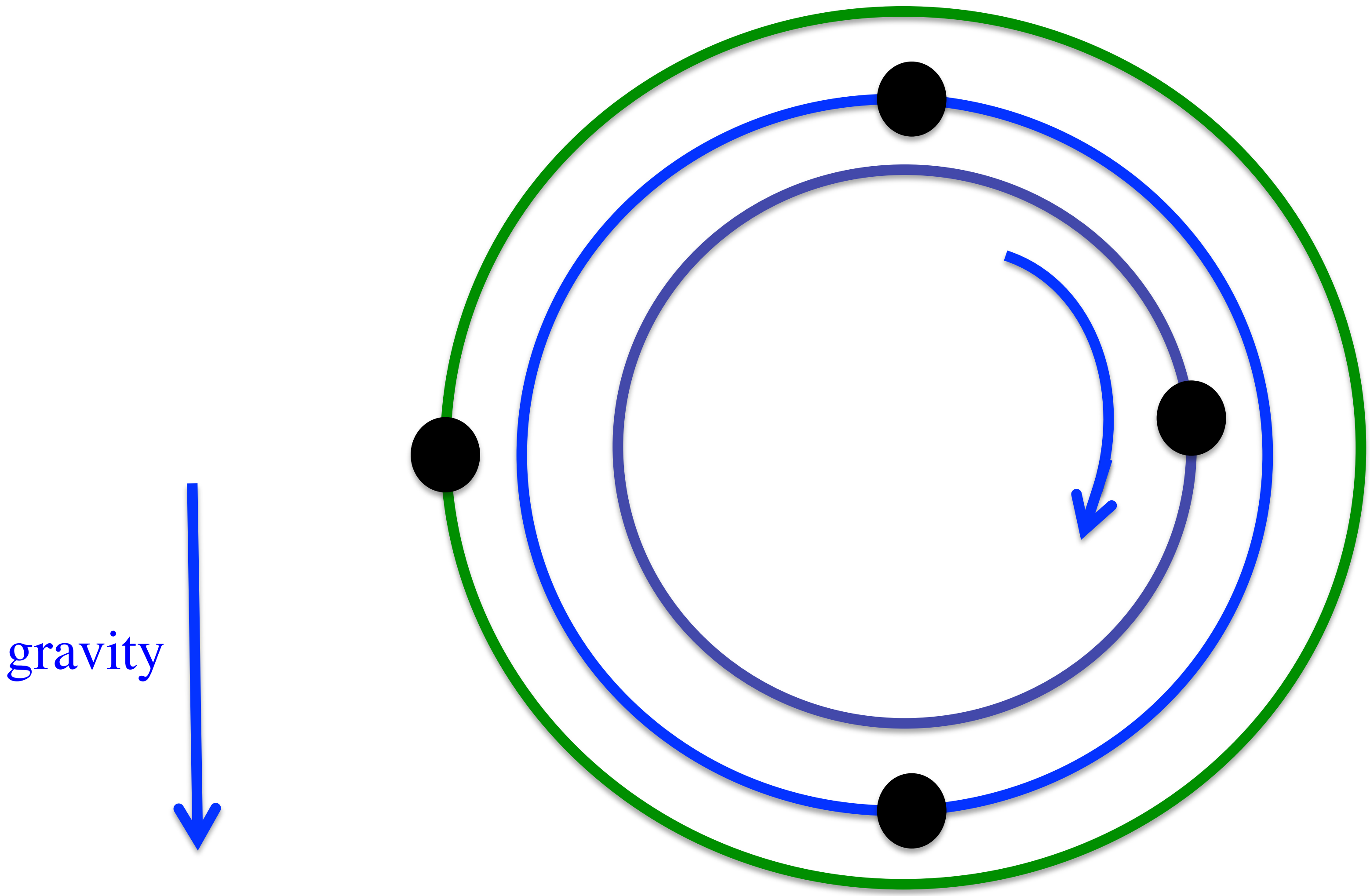
ITER in 2018



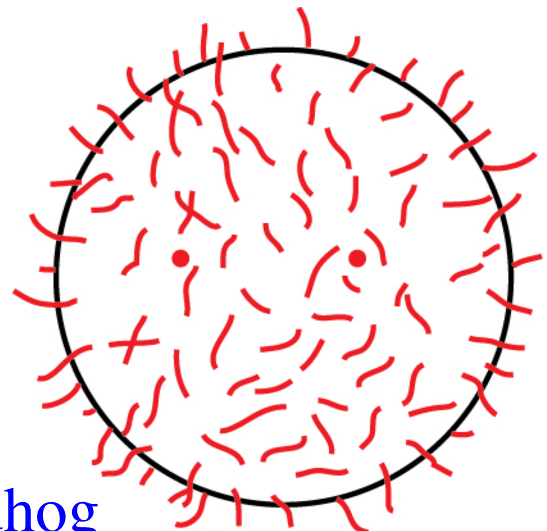

Poloidal Magnetic Field
Plasma Current
Toroidal Magnetic Field
Total Magnetic Field

Why is Poloidal Magnetic Field Needed?

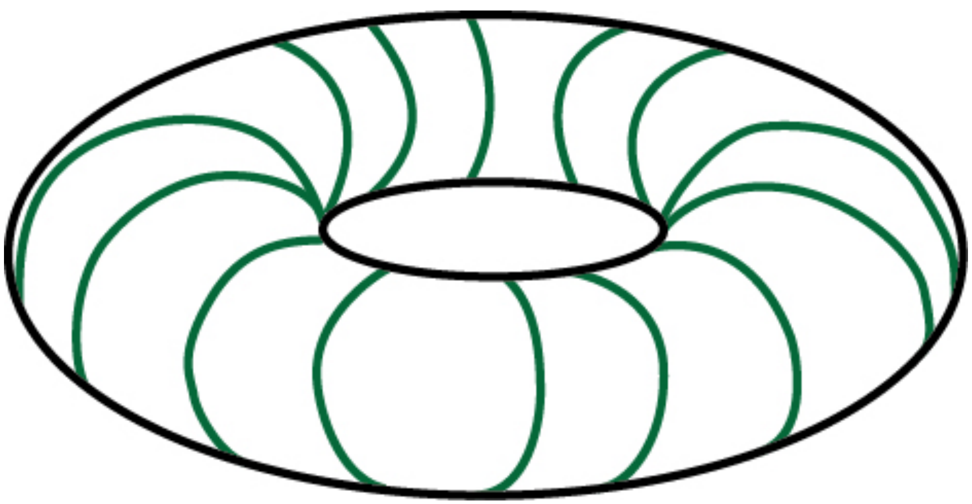
Stabilization of Sedimentation in Swirling Liquid



Why is a magnetic container donut-shaped?



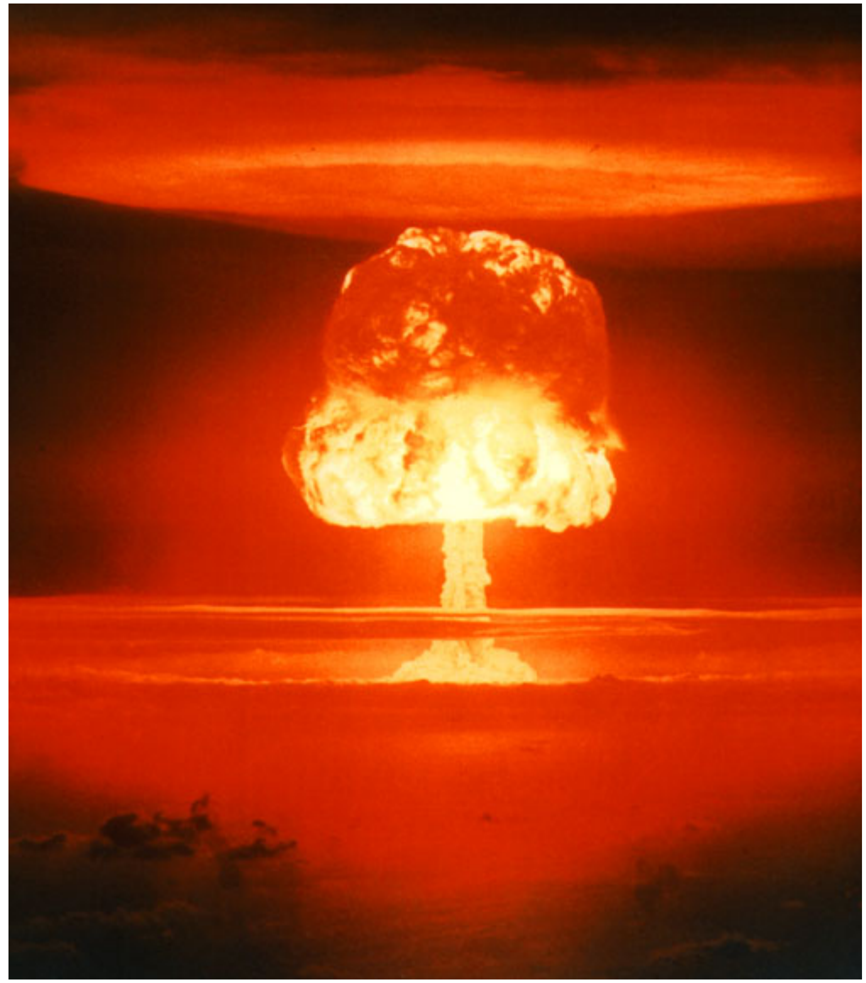
hairy groundhog



Not simply-connected

“Uncontrolled” Release of Fusion Energy Works: Operation Castle

Castle Bravo
February 28, 1954
15 Megatons

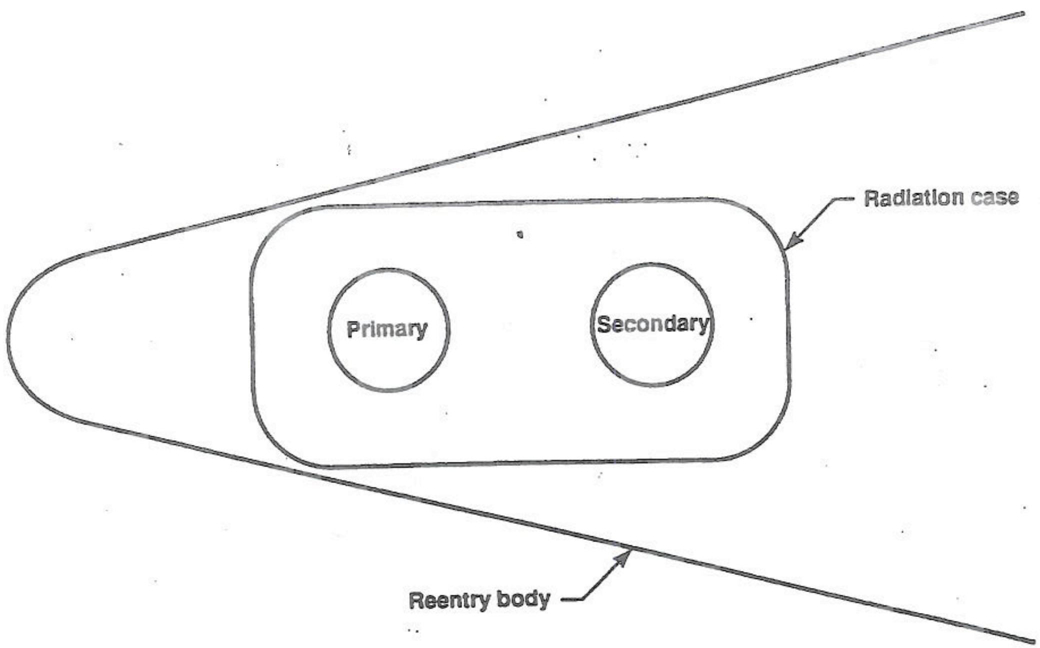


Castle Romeo
March 27, 1954
11 Megatons (500 x Nagasaki)

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 the 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 Fusion

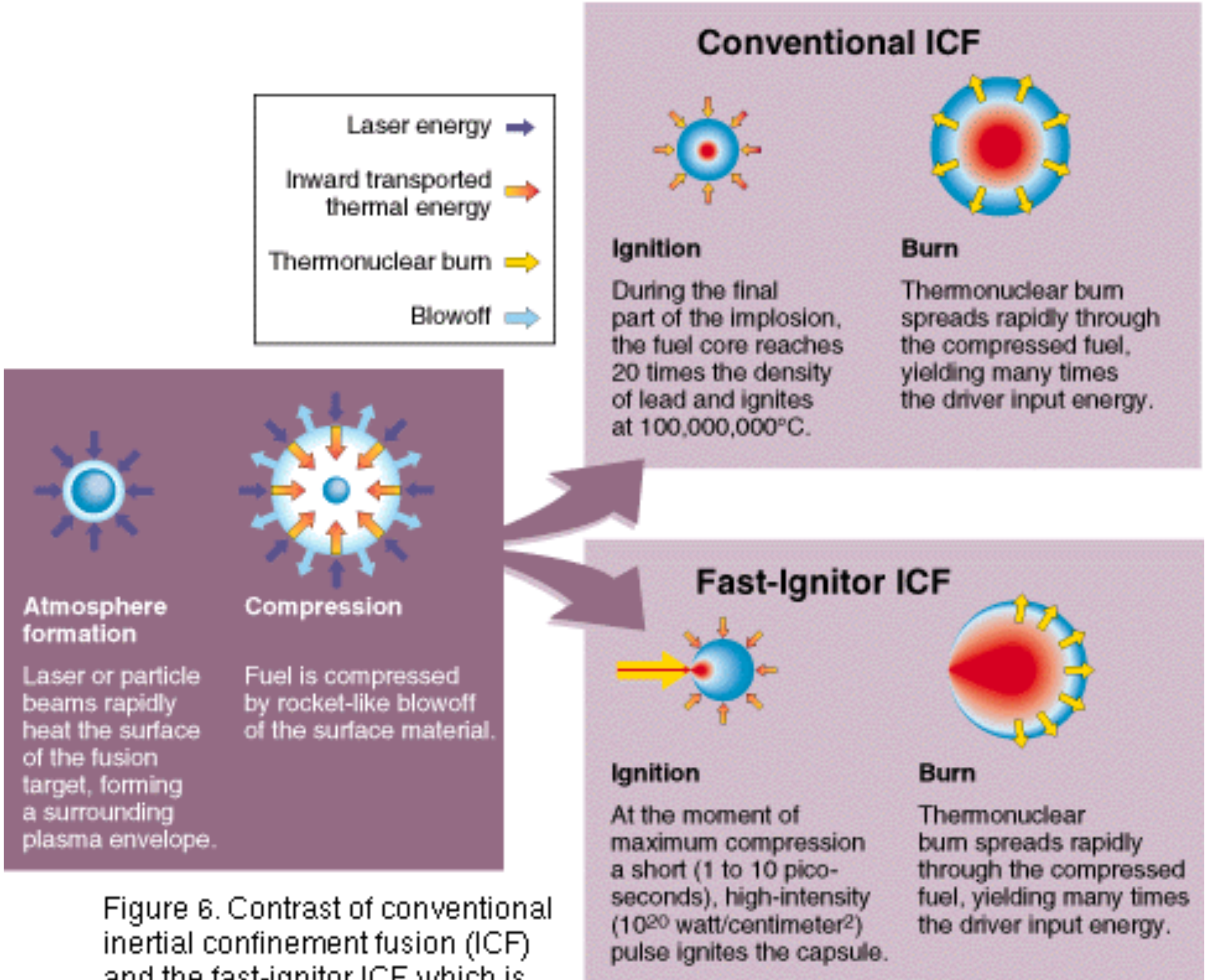
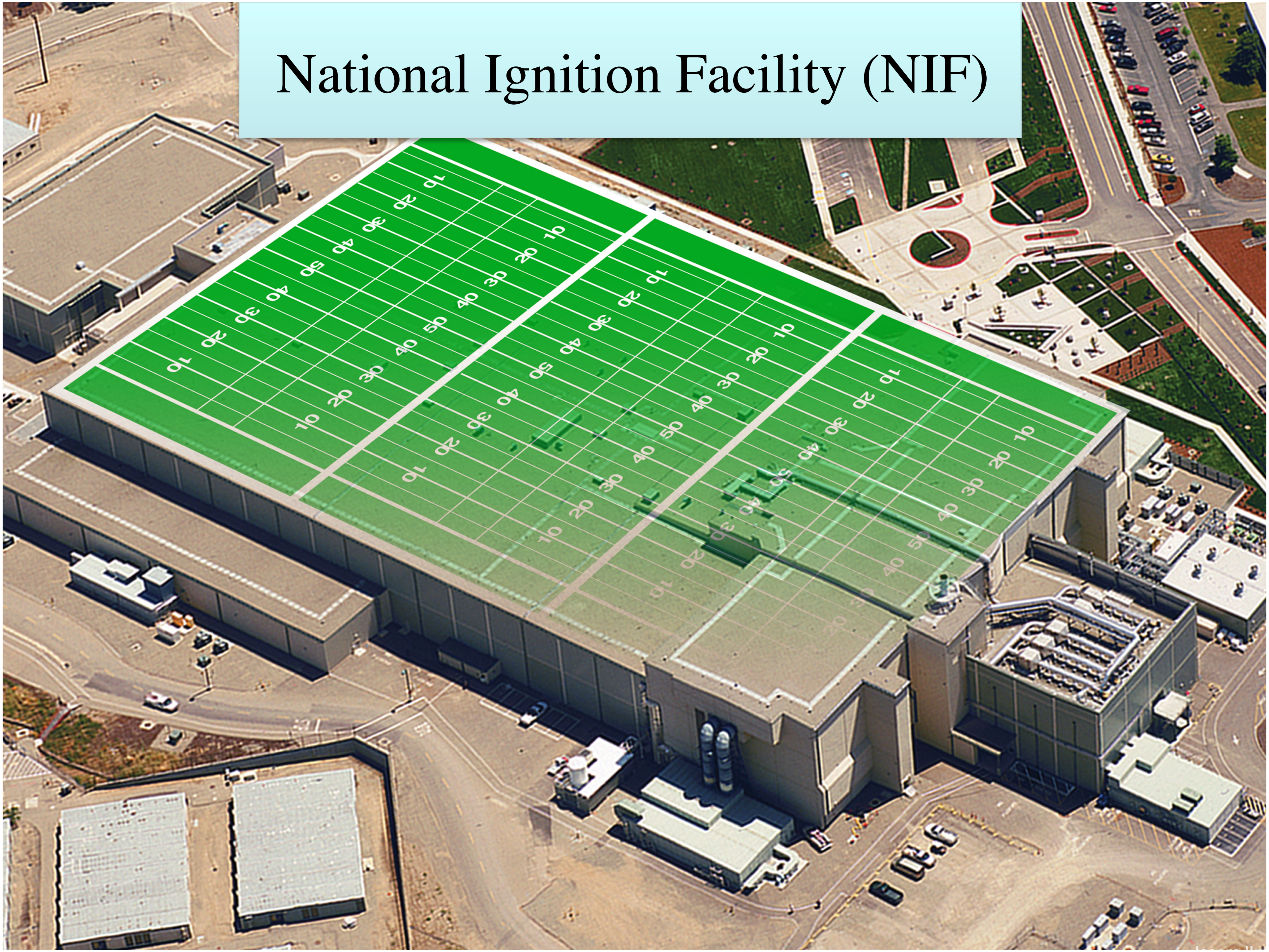
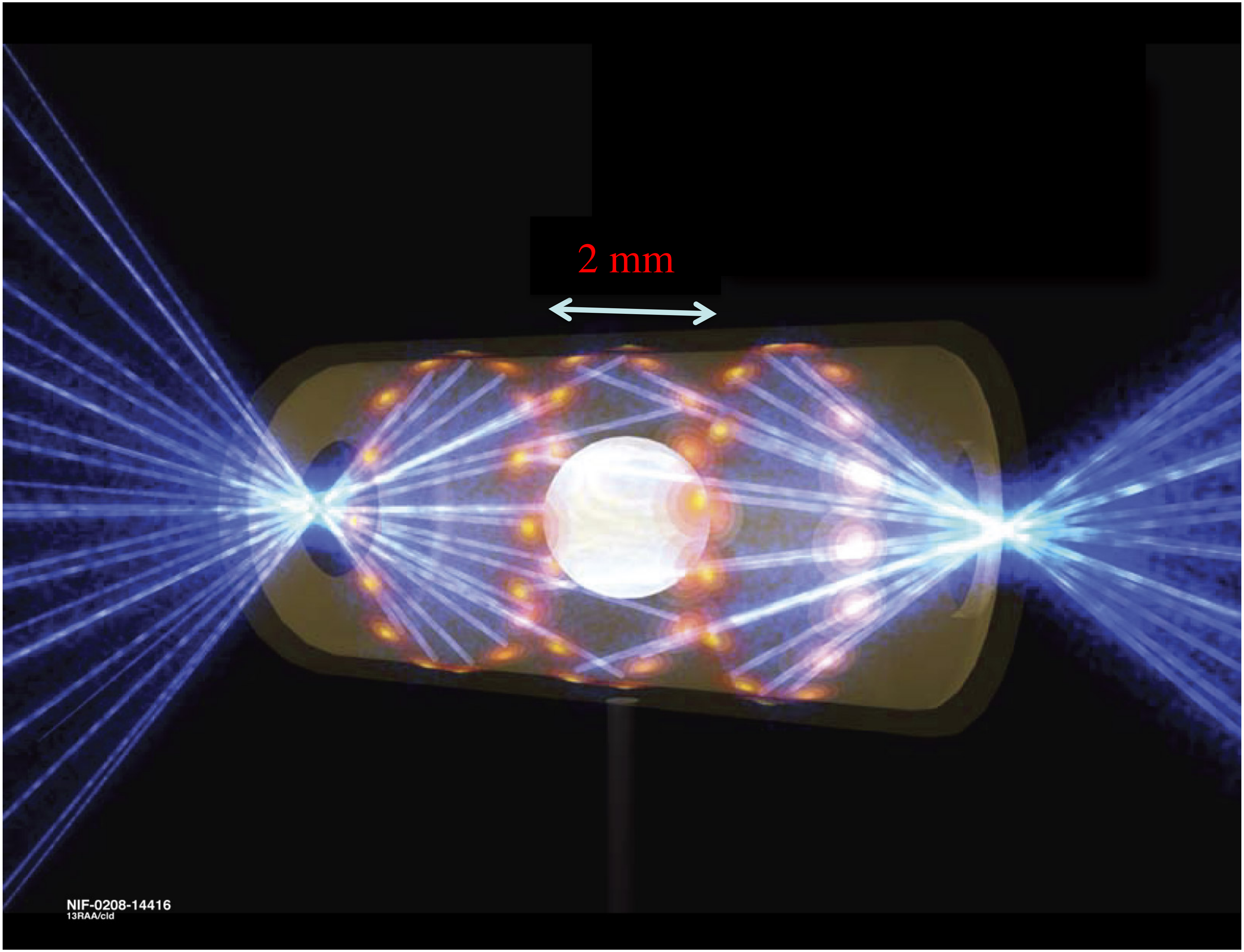


Figure 6. Contrast of conventional inertial confinement fusion (ICF) and the fast-ignitor ICF, which is used on the Petawatt laser.

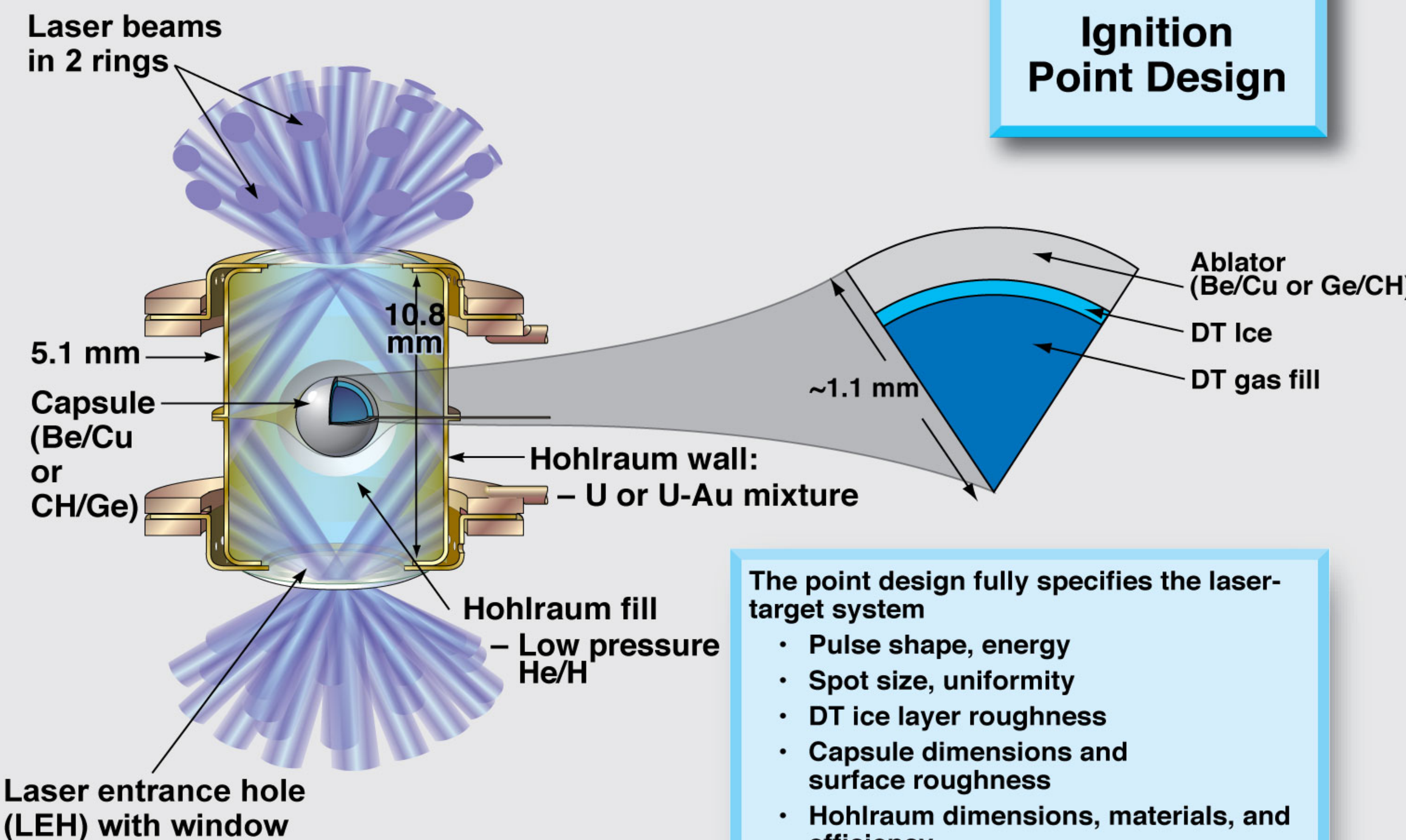
National Ignition Facility (NIF)



NIF Target Chamber


2 mm
NIF-0208-14416
13RAA/cld

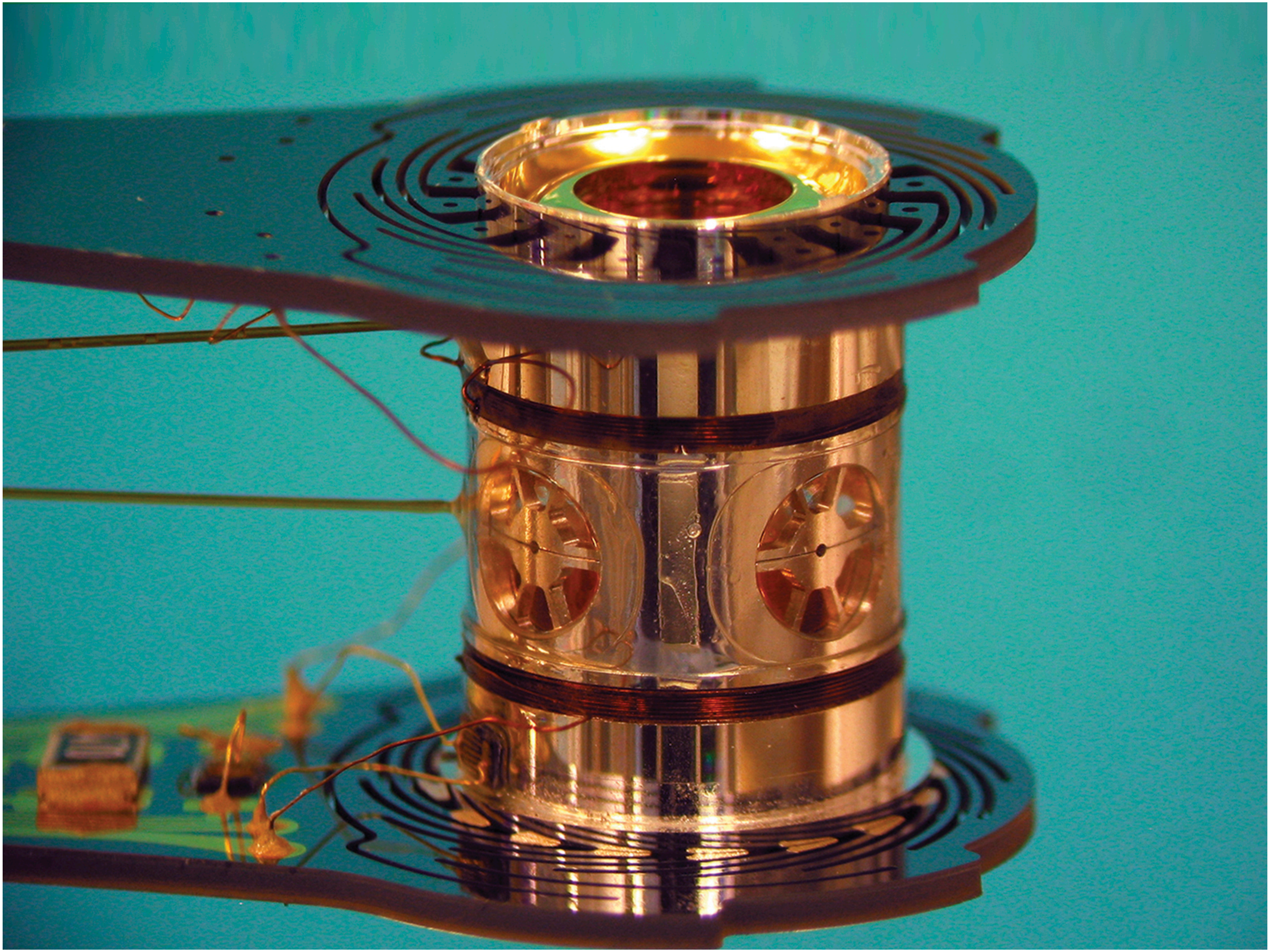
Ignition Point Design

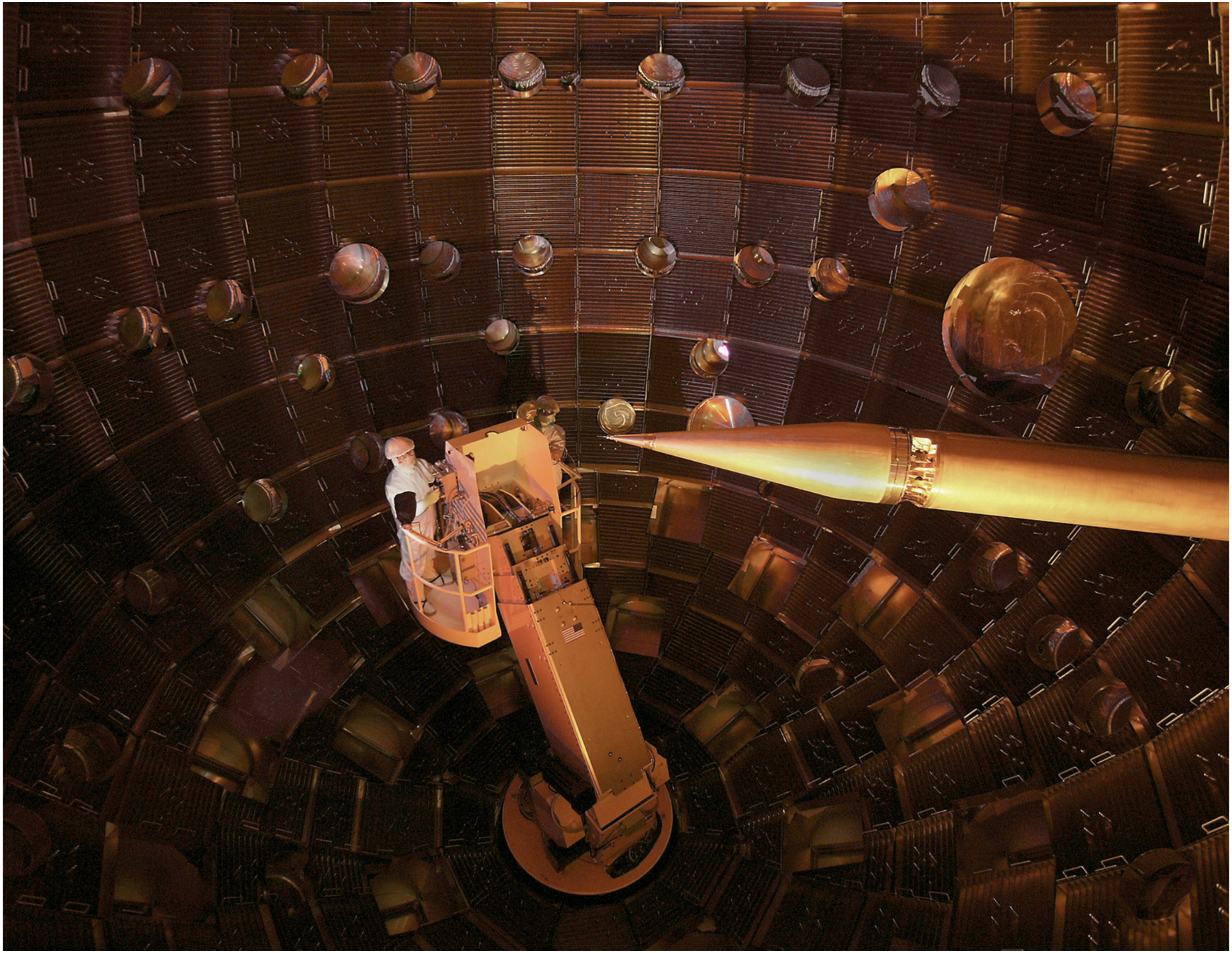


The point design fully specifies the laser-target system

- Pulse shape, energy
- Spot size, uniformity
- DT ice layer roughness
- Capsule dimensions and surface roughness
- Hohlraum dimensions, materials, and efficiency
- Target thermal and position stability
- Diagnostics

NIF-0706-12366r2
11GB/cld



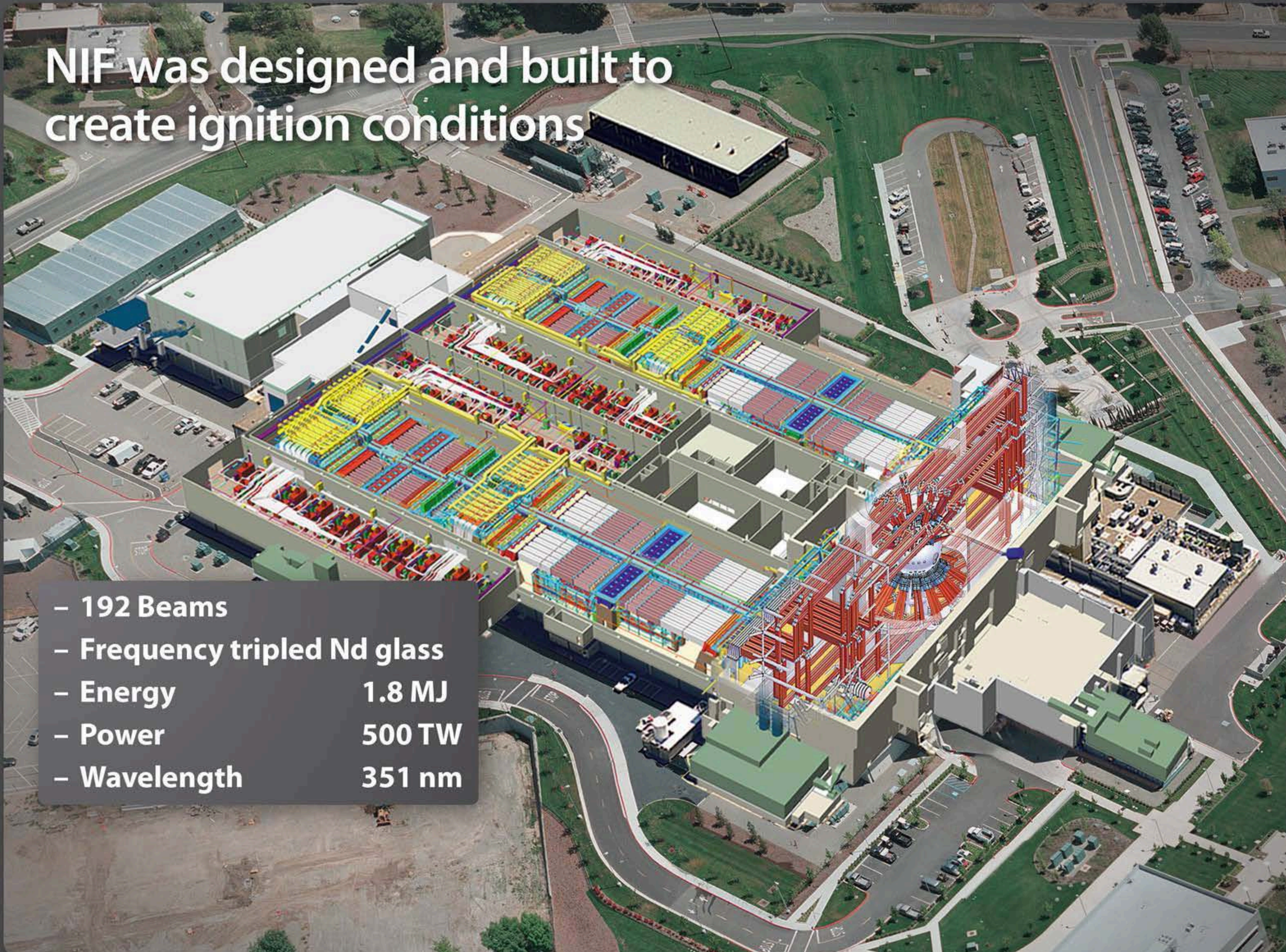



LLNL
National Ignition Facility
NIF-0605-10997-L50
27EIM/cld

Cardinal
Stanford
GOLDEN BEARS
CALIFORNIA
Cal
Bruins
UCLA


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

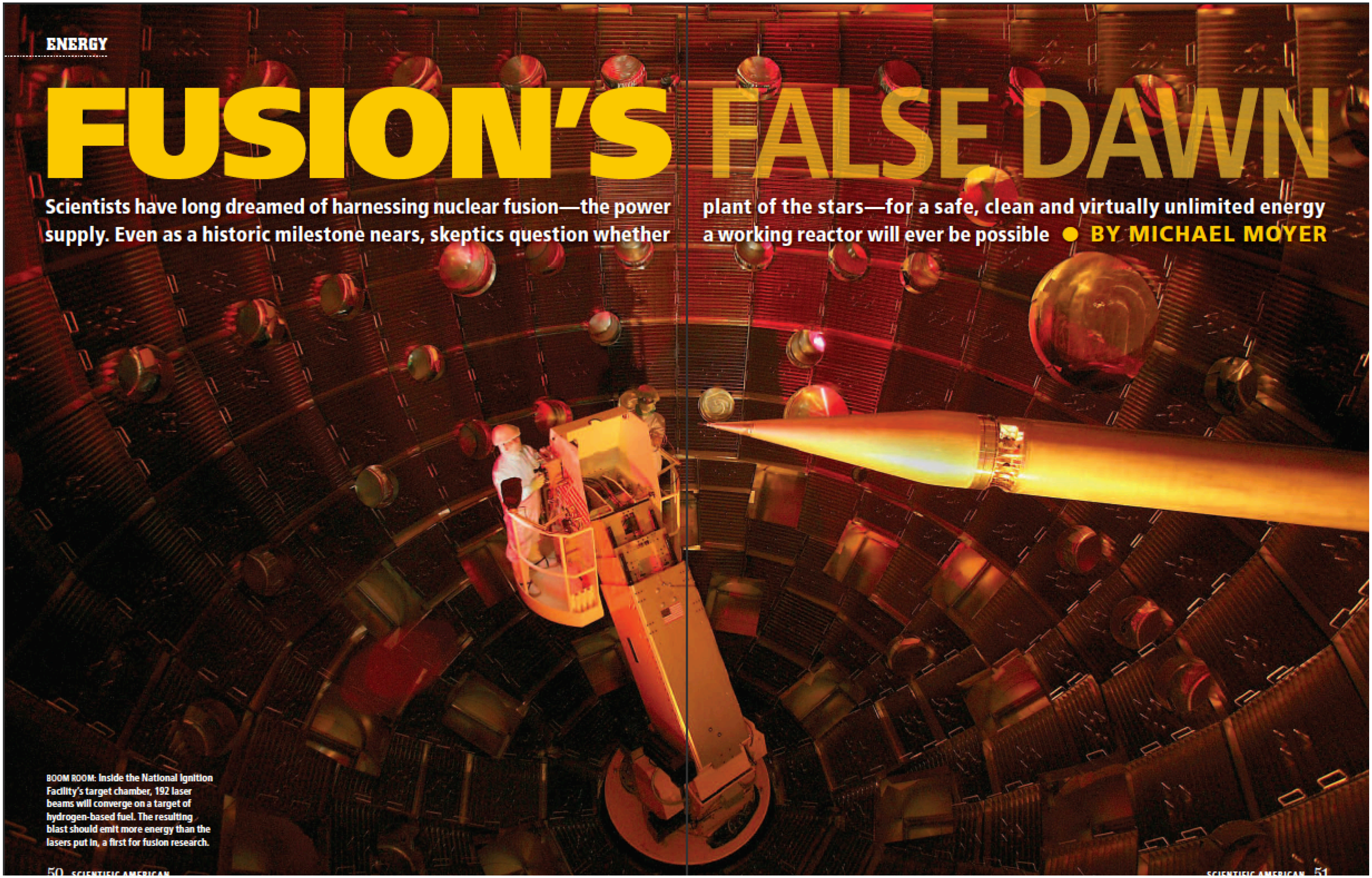

lasers.llnl.gov


Target
Chamber
NIF-0105-10124
31EIM/dj
P8136

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.

nature International weekly journal of science

NATURE | NEWS

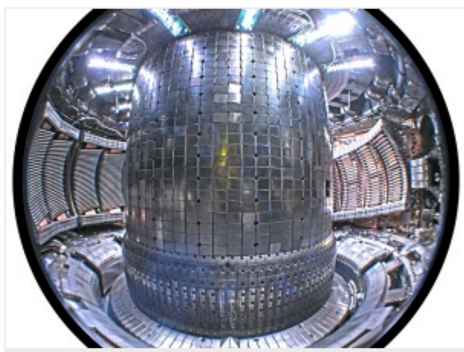
US fusion in budget vice

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

THE BIG QUESTIONS
THE FUTURE OF SCIENCE BROUGHT TO YOU BY STATOIL

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,

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.

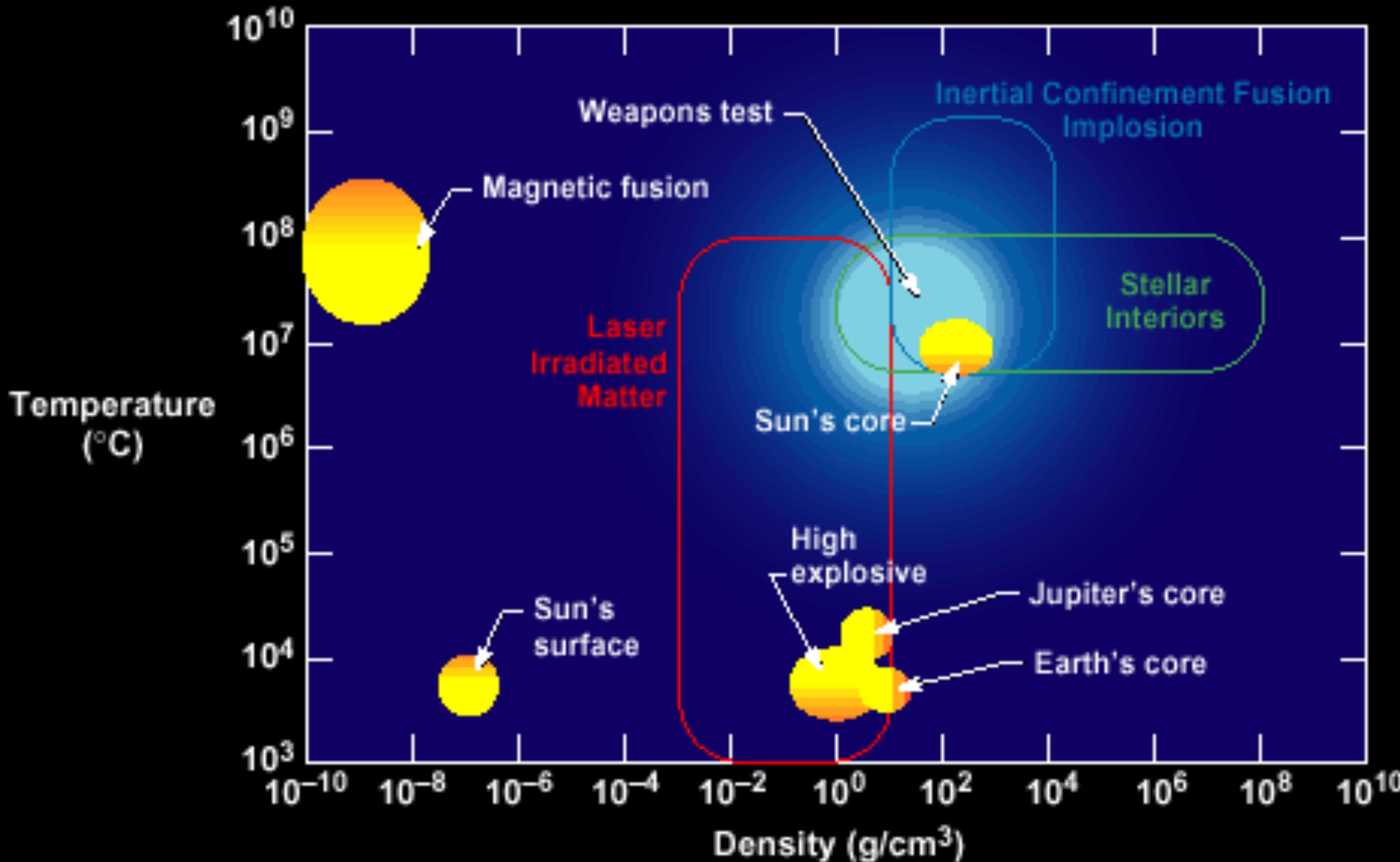
Progress in Magnetic Fusion Energy (MFE)

Plasma conditions have been produced near the regime for energy production

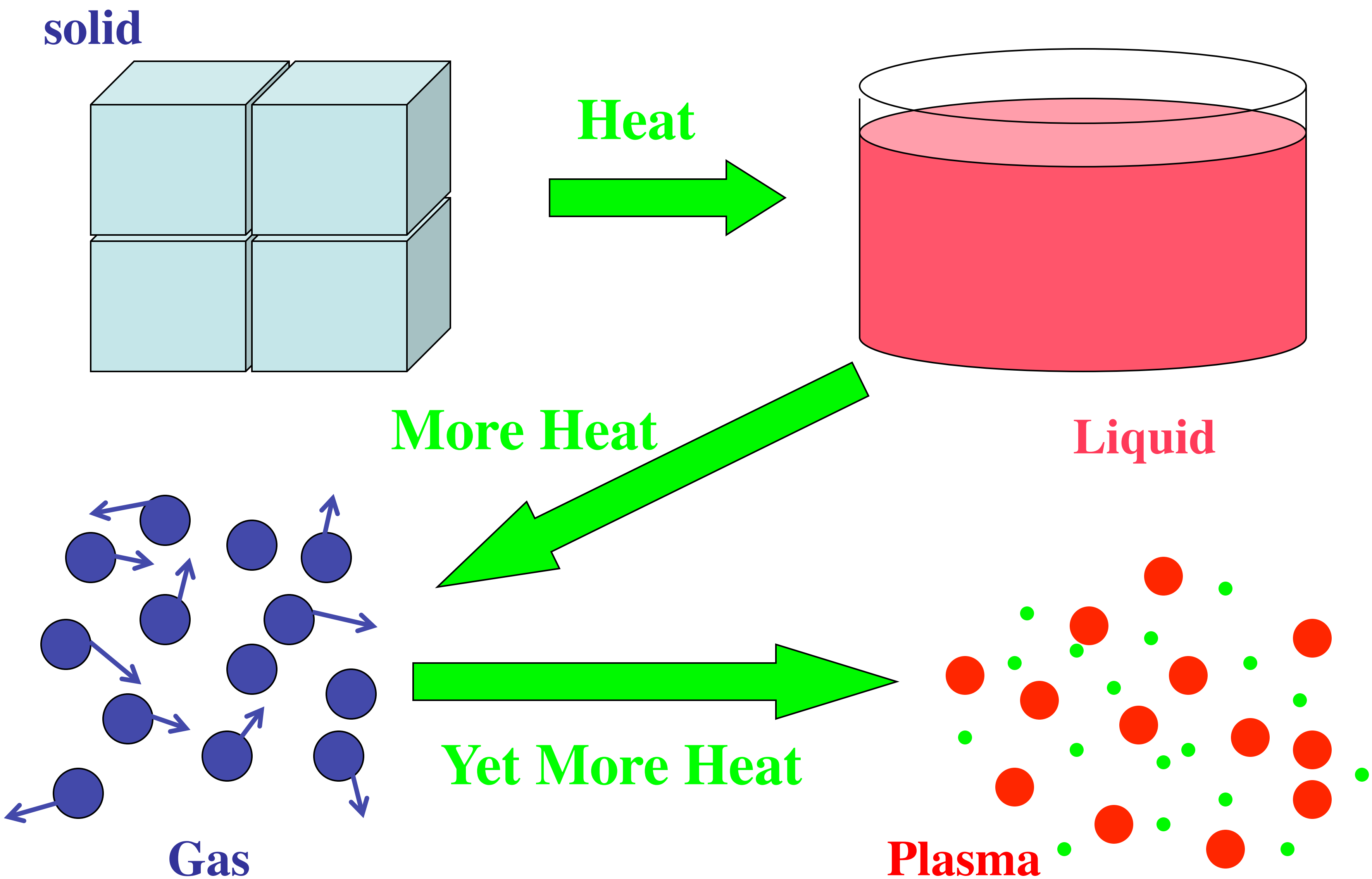
The world has joined together to produce a burning plasma (ITER)

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

Plasma Regimes for Fusion



Plasma--4th State of Matter



States of Matter

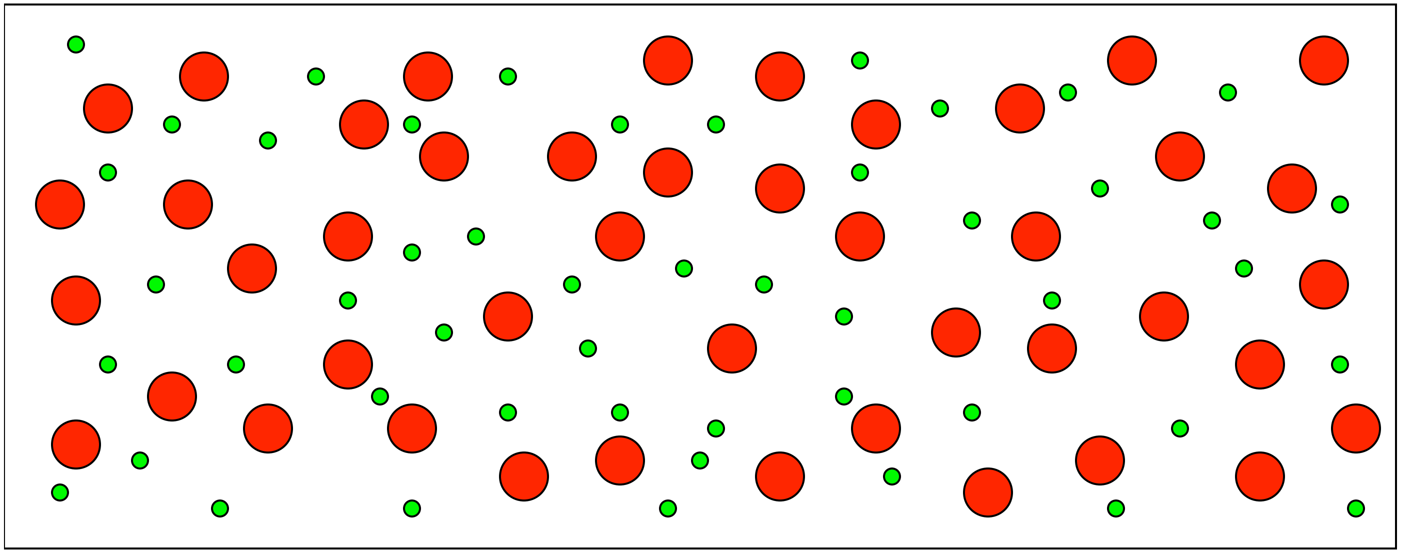
1. Just an approximation, not a material property.

2. Depends on time scales, space scales, and physics of interest

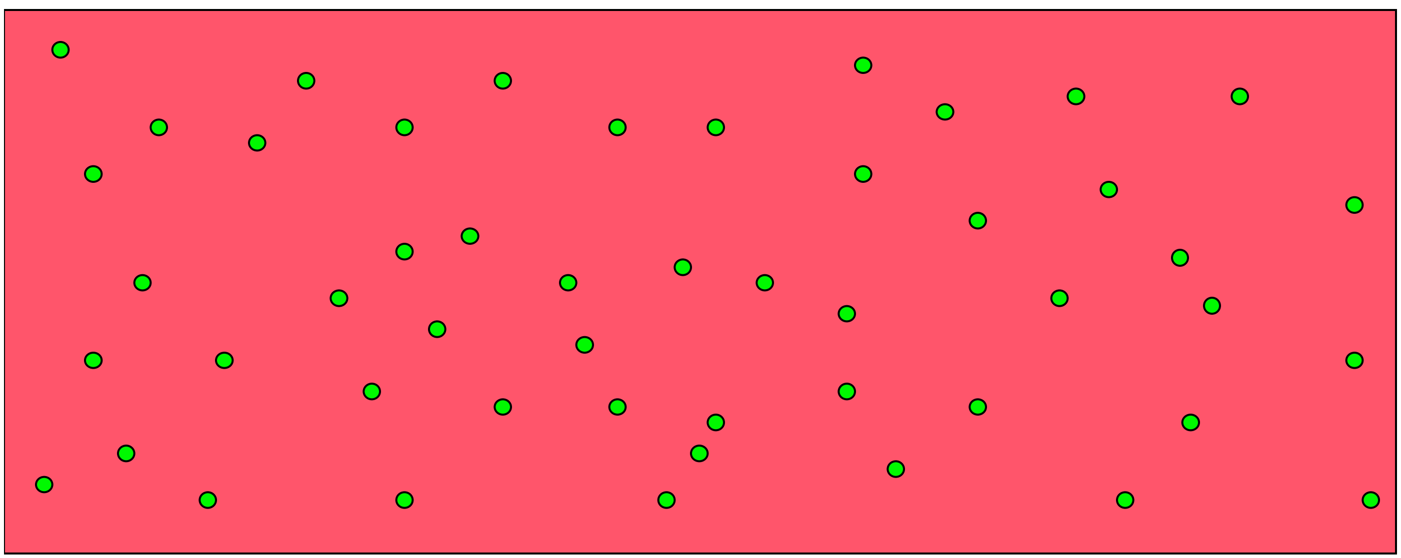
Properties of Plasma

1. Conducting medium, with many degrees of freedom
2. Shields electric fields
3. Supports many waves:
   1. vacuum waves, such as light waves
   2. Gas waves, such as sound waves
   3. A huge variety of new waves, based on electromagnetic coupling of constituent charged particles, and based on a variety of driving electric and magnetic fields

Models of Plasma

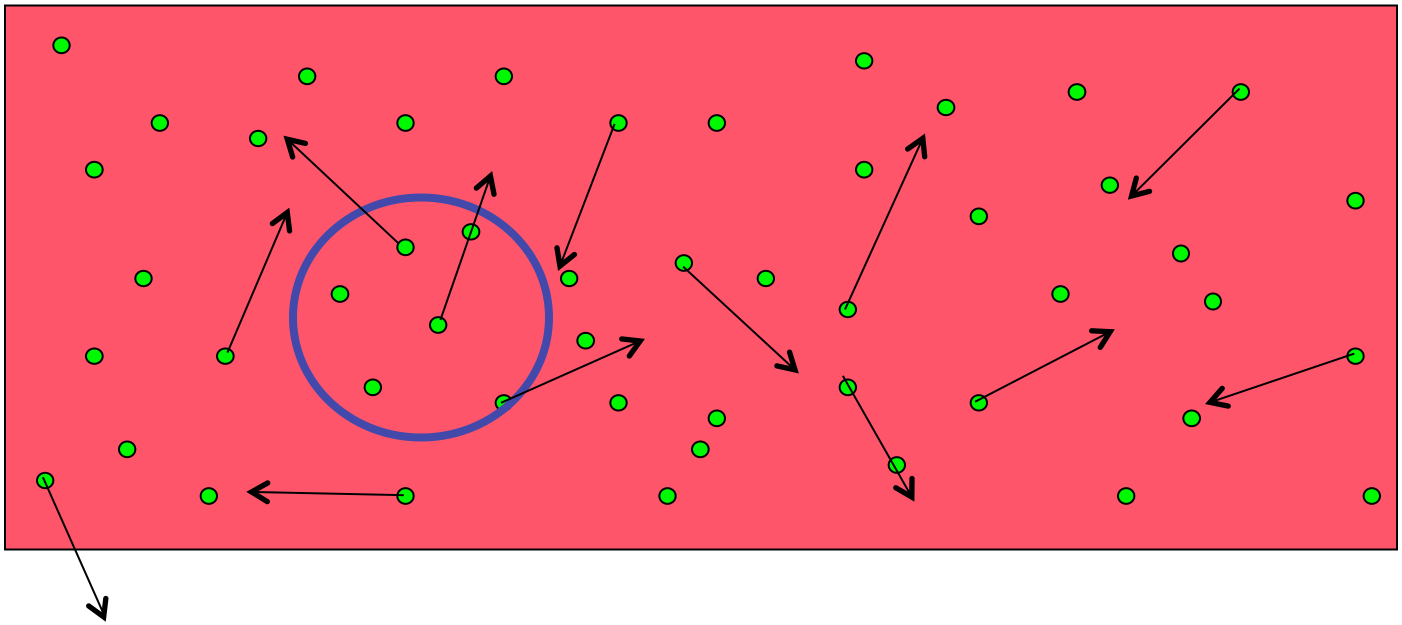


Quasi-neutral plasma



Ion neutralizing background

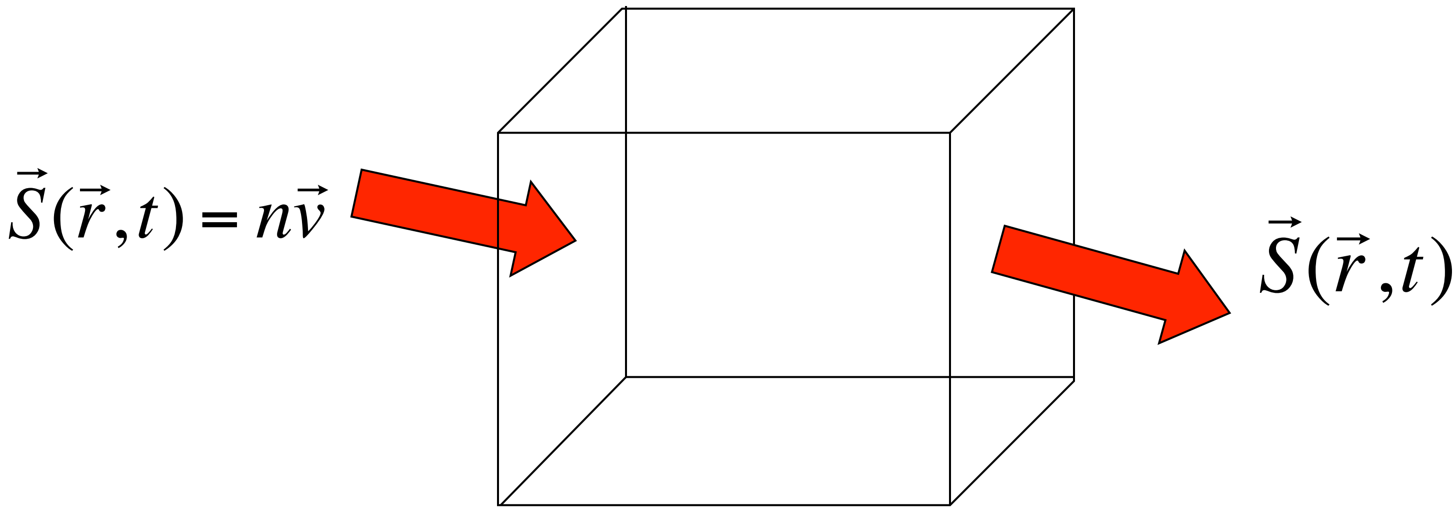
Fluid Model of Plasma



Ion neutralizing background

$$n(\vec{r},t)=\frac{\int_V f(\vec{r},\vec{v},t)\,dV}{\int_V dV} \qquad \vec{v}(\vec{r},t)=\frac{\int_V f(\vec{r},\vec{v},t)\,\vec{v}\,dV}{\int_V f(\vec{r},\vec{v},t)\,dV}$$

Fluid Equations

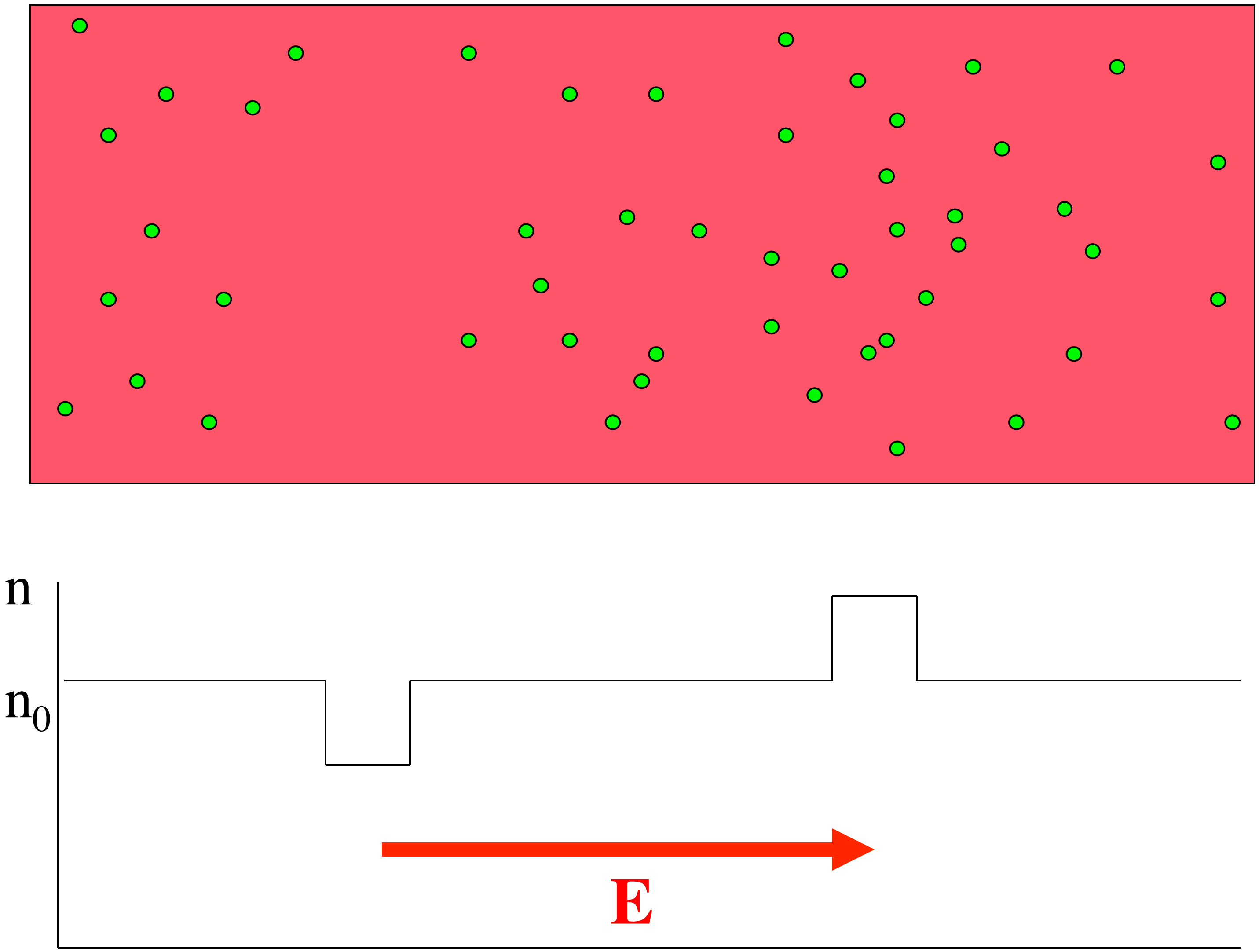


$$\frac{dN}{dt} = \int_V \vec{S} \cdot d\vec{A}$$

Continuity Equation

$$\frac{\partial}{\partial t} n + \nabla \cdot n\vec{v} = 0$$

Set up plasma oscillation



Cold Fluid Equations

$$\nabla \bullet \vec{E} = 4\pi e(n_0 - n_e)$$ Poisson's equation

$$\frac{\partial}{\partial t} n_e + \nabla \cdot n_e \vec{v} = 0$$ Particle conservation

$$\frac{\partial}{\partial t} n_e m \vec{v} + \nabla \cdot n_e m \vec{v}\vec{v} = e n_e \vec{E}$$ Momentum conservation

Plasma Oscillations (1)

$$\nabla \bullet \vec{E} = 4\pi e(n_0 - n_e)$$ Poisson's equation

$$\frac{\partial}{\partial t} n_e + \nabla \cdot n_e \vec{v} = 0$$ Particle conservation

$$\frac{\partial}{\partial t} n_e m\vec{v} + \nabla \cdot n_e m\vec{v}\vec{v} = e n_e \vec{E}$$ Momentum conservation

Linearize

$$\boxed{\begin{aligned} n_e &= n_0 + \tilde{n}(\vec{r},t) \\ \vec{v} &= \vec{v}_0 + \tilde{v}(\vec{r},t) \\ \vec{E} &= \vec{E}_0 + \tilde{E}(\vec{r},t) \end{aligned}}$$

Assume

$$\boxed{\begin{aligned} n_i &= n_0 \\ \vec{v}_0 &= 0 \\ \vec{E}_0 &= 0 \end{aligned}}$$

$$\Rightarrow \quad \nabla \bullet \left(\vec{E}_0 + \tilde{E}\right) = \nabla \bullet \tilde{E} = -4\pi e\tilde{n}$$ Linearized Poisson's equation

Plasma Oscillations (2)

Particle conservation

$$\frac{\partial}{\partial t}\left(\cancelto{0}{n_0} + \tilde{n}(\vec{r},t)\right) = -\nabla\cdot\left[\left(n_0+\tilde{n}\right)\left(v_0+\tilde{v}\right)\right]$$

$$= \cancelto{0}{-\nabla\cdot\left(n_0 v_0\right)} \cancelto{0}{-\nabla\cdot\left(\tilde{n}\tilde{v}\right)} - n_0\nabla\cdot\tilde{v} \cancelto{0}{- v_0\nabla\cdot\tilde{n}}$$

$$= -n_0\nabla\cdot\tilde{v}$$

$$\Rightarrow \qquad \frac{\partial\tilde{n}}{\partial t} = -n_0\nabla\cdot\tilde{v}$$

Linearized Particle Conservation Equation

Plasma Oscillations (3)

$$\frac{\partial}{\partial t} n_e m\vec{v} + \nabla \cdot n_e m\vec{v}\vec{v} = en_e\vec{E}$$

Momentum conservation

$$m\frac{\partial}{\partial t}\left(n_0 + \tilde{n}\right)\left(v_0 + \tilde{v}\right) + \nabla \cdot \left(n_0 + \cancelto{0}{\tilde{n}}\right) m\tilde{v}\tilde{v} = en_0\tilde{E}$$

$$\Rightarrow \quad m\frac{\partial \tilde{v}}{\partial t} = e\tilde{E}$$

Linearized momentum equation

Derivation of Cold Plasma Oscillations

$$\frac{\partial \tilde{n}}{\partial t} = -n_0 \nabla \cdot \tilde{v} \qquad \text{use} \qquad m\frac{\partial \tilde{v}}{\partial t} = e\tilde{E}$$

or

$$\frac{\partial^2 \tilde{n}}{\partial t^2} = -n_0 \nabla \cdot \frac{\partial \tilde{v}}{\partial t} \quad = -n_0 \nabla \cdot \frac{e}{m}\tilde{E}$$

use $\nabla \bullet \tilde{E} = -4\pi e\tilde{n}$

$$= -\omega_p^2 \tilde{n}$$

Plasma frequency $\qquad \omega_p^2 = \dfrac{4\pi n_0 e^2}{m}$

Plasma Oscillations

$$\nabla \bullet \vec{E} = 4\pi e(n_0 - n_e) = -4\pi e\tilde{n}$$ Poisson's equation

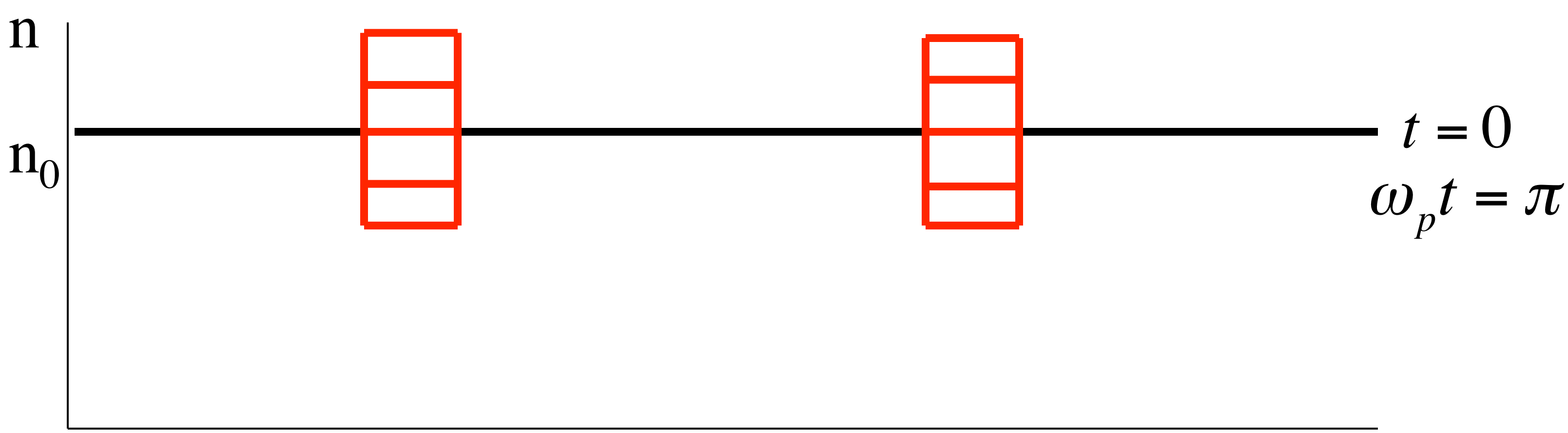
$$\frac{\partial}{\partial t} n_e + \nabla \cdot n_e v = 0$$ Particle conservation

$$\frac{\partial}{\partial t} n_e m v + \nabla \cdot n_e m v v = e n_e E$$ Momentum conservation

$$\Rightarrow \quad \boxed{\frac{\partial^2}{\partial t^2}\tilde{n} + \omega_p^2 \tilde{n} = 0}$$

$$\boxed{\tilde{n} = A(\vec{r})\cos\omega_p t + B(\vec{r})\sin\omega_p t}$$

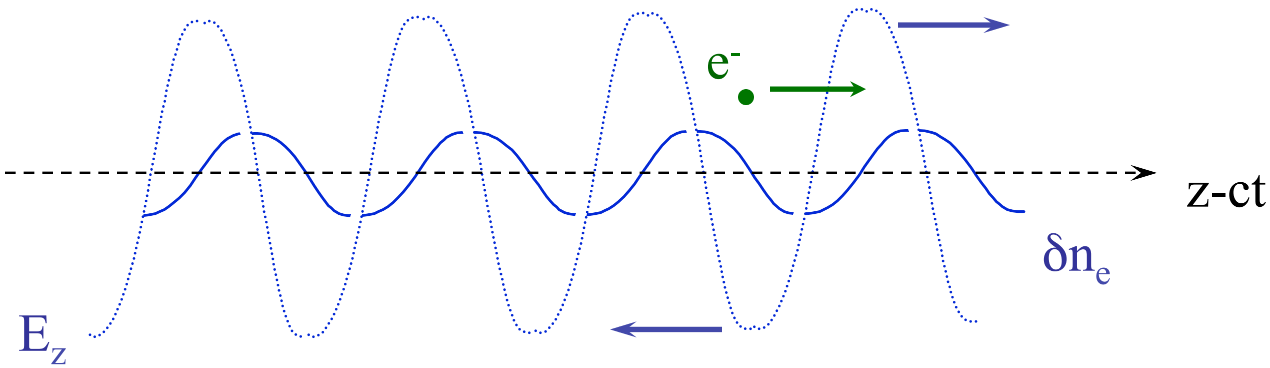
Set up plasma oscillation



Other possibilities:

$$\boxed{\Phi(x,t) = A(x)\cos[\omega_p\,(t - x/c)]}$$

Electron acceleration in a plasma wave

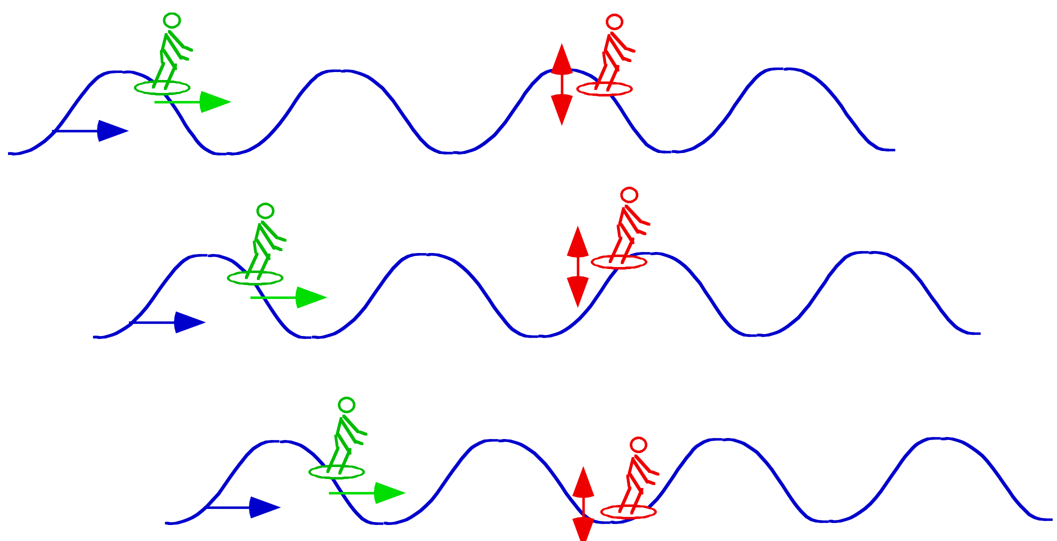


phase velocity -- arbitrary

Accelerate to TeV

Tajima and Dawson (1979)

Analogy:

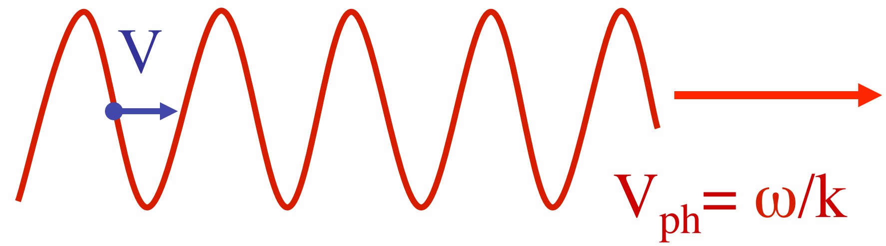


from V.Malka

Resonant Surfers

Not-resonant surfers $V \neq V_{ph}$

Accelerating Gradient in Plasma



Conventional Accelerator

Gradients ~ 20 MeV/m at 3GHz

1 TeV Collider requires 50 km

Peak gradients limited by breakdown

$$\nabla \bullet \vec{E} = -4\pi e\tilde{n}$$

Plasma Accelerator

High fields, No breakdown

(Tajima and Dawson, 1979)

$$\tilde{n}_{MAX} \approx n_0$$

$$k = \frac{\omega_p}{c}$$

$$eE_{MAX} \approx \sqrt{n_0}\, GeV/cm$$

Example

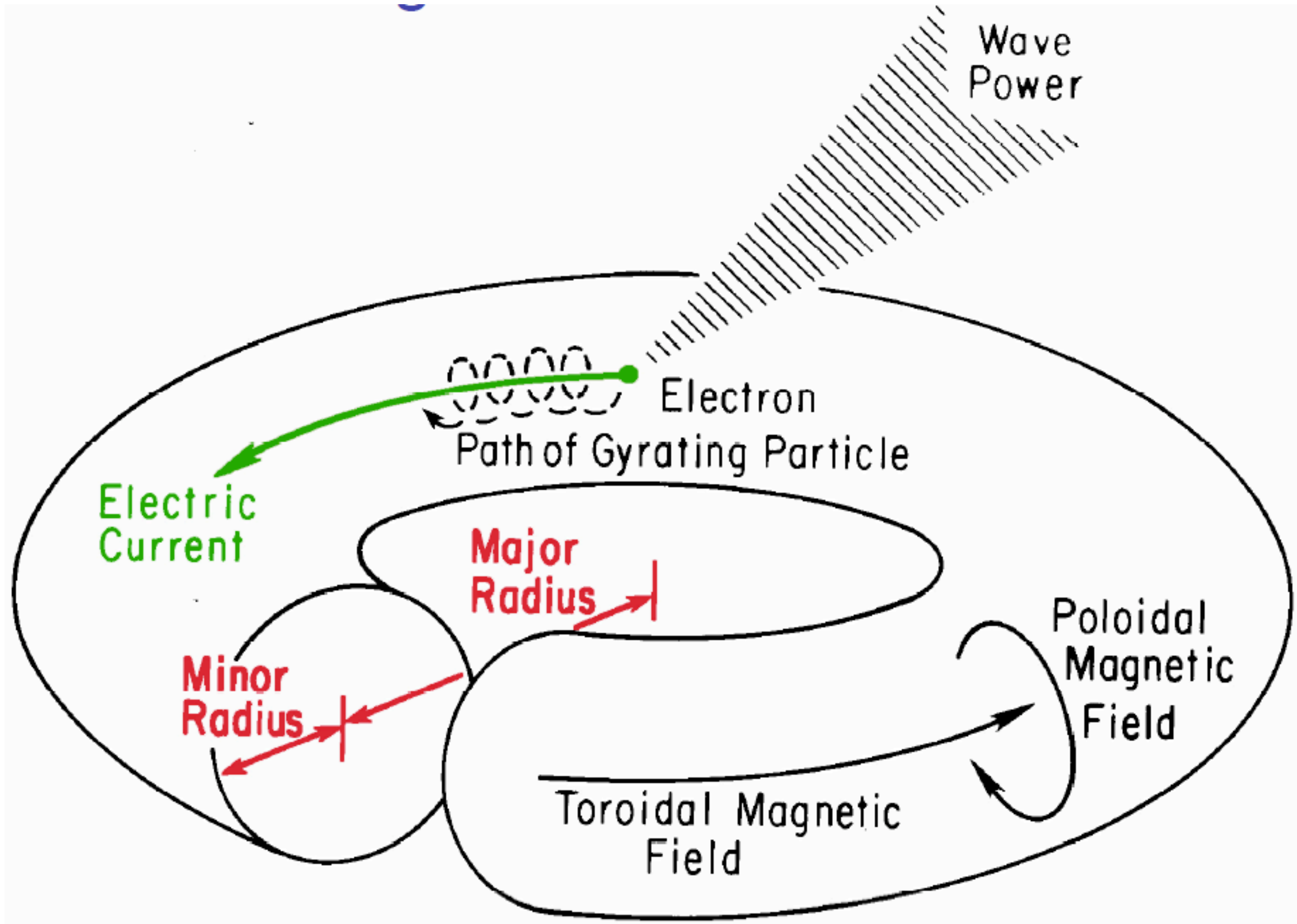
$n_0=10^{18}cm^{-3}$

eE=100 GeV/m

Note: For v << c , $\frac{v_{osc}}{c} \approx \frac{\tilde{n}}{n_0}$

Particles accelerated to relativistic energies, even as plasma motion is not

Heating a Tokamak with Waves



Tore Supra new LH coupler (2001)

Antenna fully designed for long pulse operation:

4 MW, 1000 s, 3.7 GHz

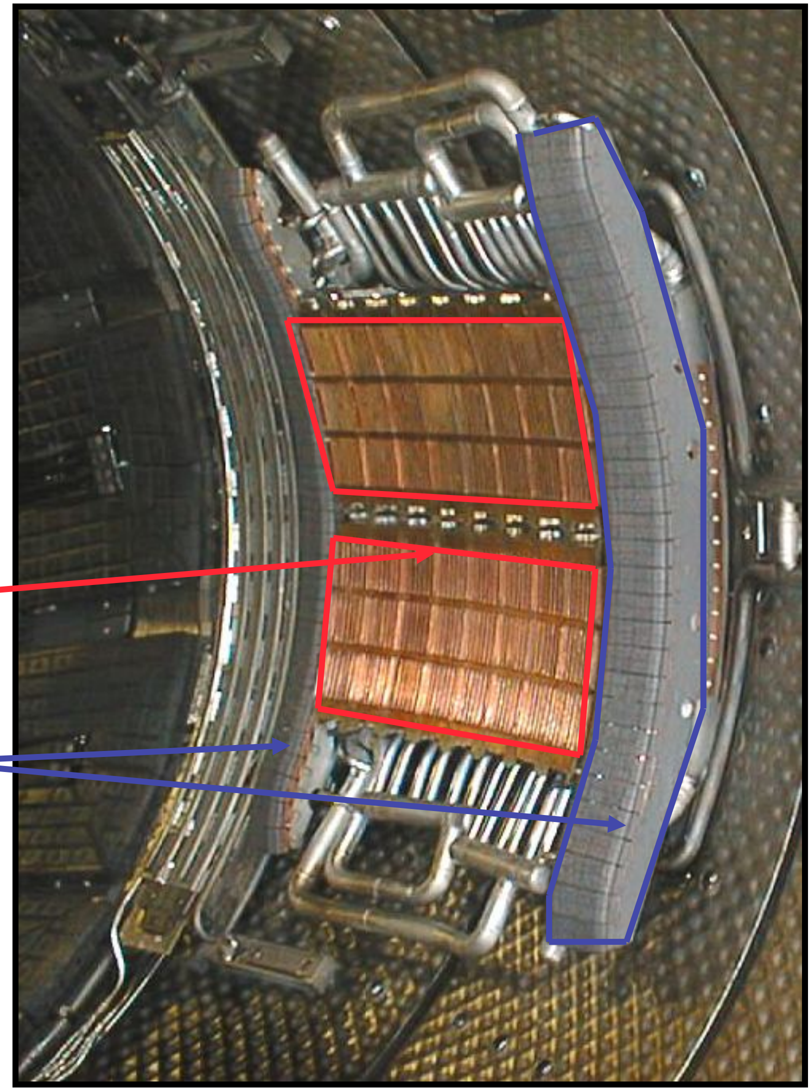
(tested up to 3 MW, 9.5 s)

Limited power density

(25 MW/m^2 at full power and $n_{//0}$ = 2)

Actively cooled side limiter

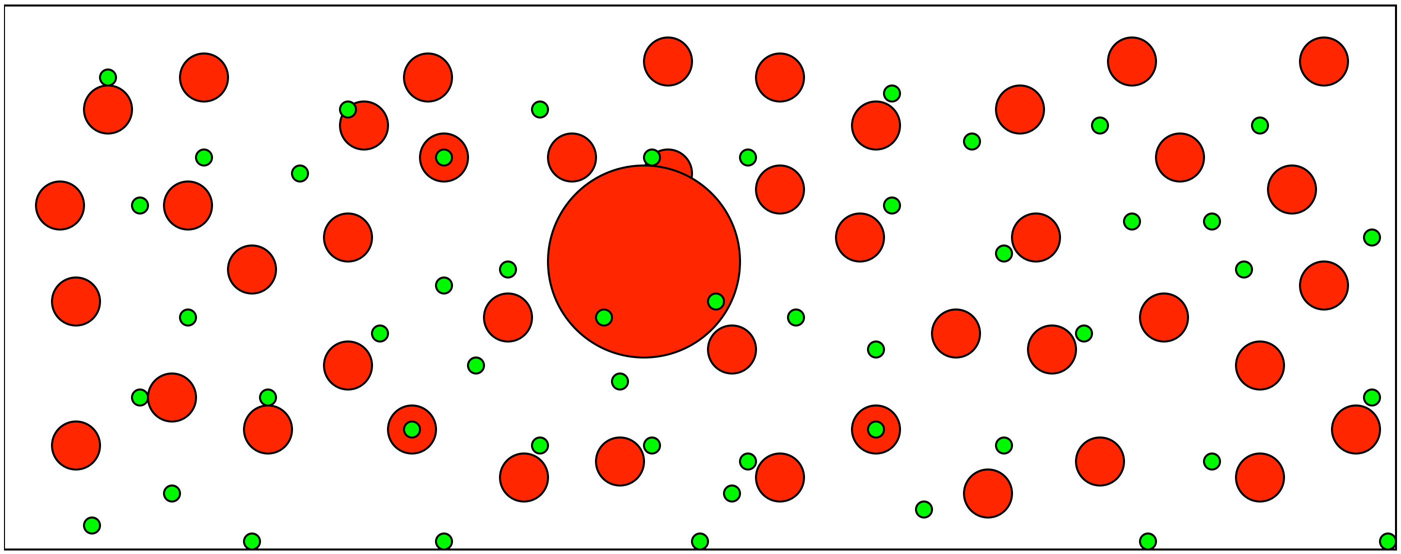
(exhaust capability:10 MW/m^2)



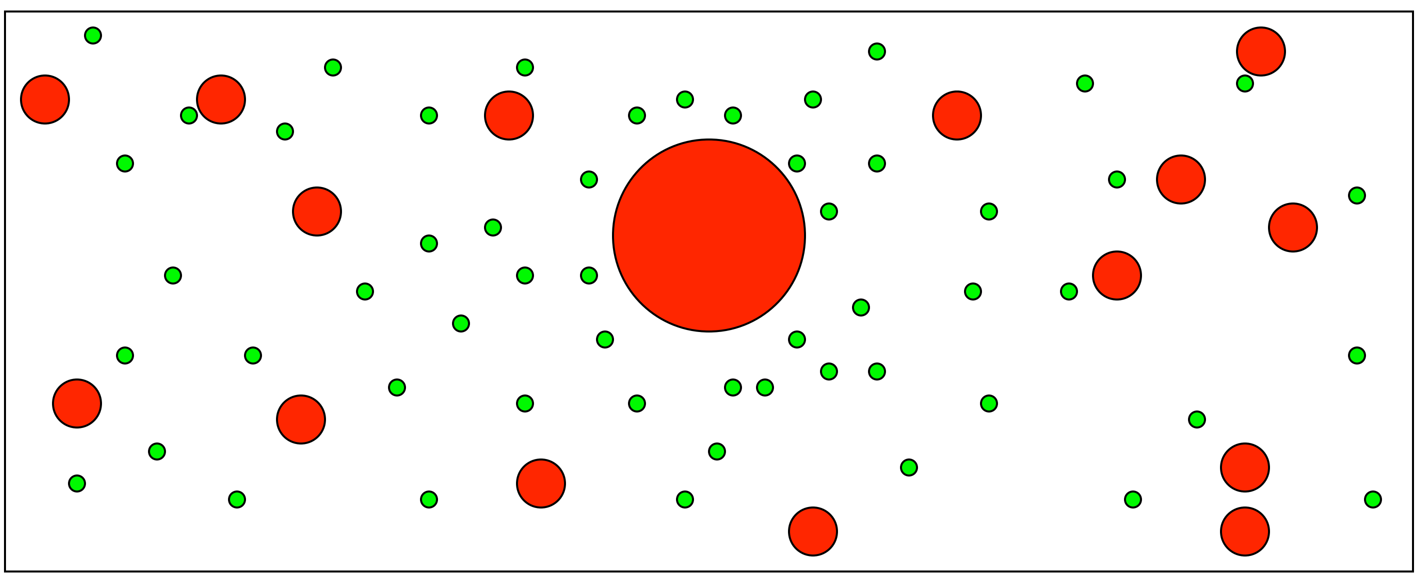
48 active / 9 passive waveguides

$1.7 \leq n_{//0} \leq 2.3$
Directivity: 70% ($n_{//0}$ = 2.0)

Plasma Shielding



Quasi-neutral plasma



Plasma Shielding

Plasma Shielding

$$\nabla \bullet \varepsilon_0 \vec{E} = \rho_T + \rho, \qquad \rho_T = Q\delta(\vec{r})$$

$$\vec{E} = -\nabla\Phi.$$

$$\rho = n_i Ze - n_e e, \qquad n_i = n_0 = const.$$

In equilibrium: $n_e = n_0 e^{e\Phi/kT}$ Gibbs

Linearize $n_e = n_0 + \tilde{n}, \qquad \Phi = \Phi_0 + \tilde{\Phi} = \tilde{\Phi}$

$$-\varepsilon_0 \nabla^2 \Phi = en_0\left(1 - e^{e\Phi/kT}\right) + Q\delta(\vec{r})$$

$$e^{e\Phi/kT} = 1 + e\Phi/kT + \ldots$$

$$-\nabla^2\Phi + \frac{1}{\lambda_D^2}\Phi = \frac{Q}{\varepsilon_0}\delta(\vec{r}), \qquad \lambda_D^{-2} \equiv \frac{n_0 \mathrm{e}^2}{\mathrm{kT}\varepsilon_0}$$

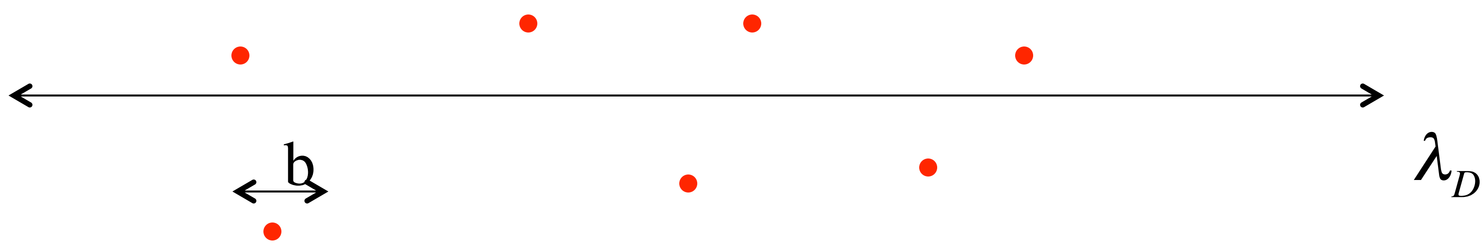
For T=10 keV
$n=10^{14}$ cm^{-3}

$$\Phi = \frac{Q}{4\pi\varepsilon_0 r} e^{-r/\lambda_D}$$

$$\lambda_D = 10^{-4}\,\mathrm{m}$$

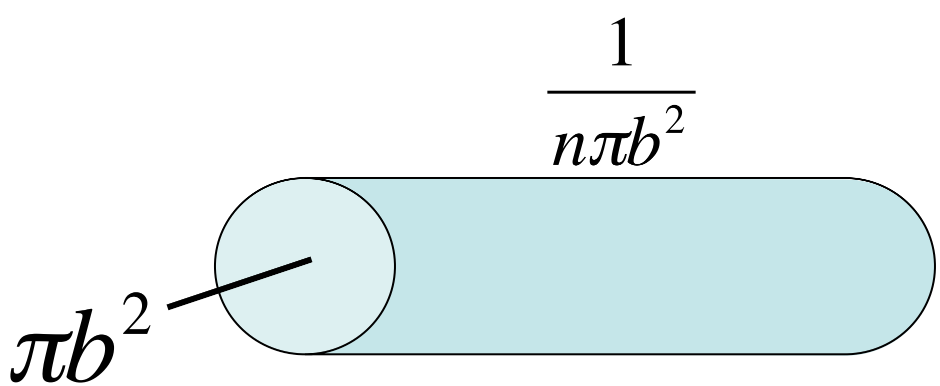
Ideal Plasma

For ideal plasma: $n\lambda_D^3 >> 1 \Rightarrow \lambda_{mfp} >> \lambda_D >> n^{-1/3} >> b$



$$b = e^2 / 4\pi\varepsilon_0 T$$

$$\lambda_{mfp} = \frac{1}{n\pi b^2}$$



Take-aways

1. Plasma phenomena appears in a variety of applications
   (astrophysics, solar physics, plasma devices, nuclear fusion)

2. Controlled fusion can be inertial or magnetic

3. Basic time scale of plasma is the plasma oscillation period ω_p^{-1}

4. Basic space scale of plasma is the plasma shielding length λ_D

5. These scales are related by electron thermal velocity $v_T = \lambda_D \omega_p$

6. Ideal plasma $n\lambda_D^3 >> 1$ is "dilute" $n^{-1/3} >> b$

7. Equivalently, plasma oscillations persist $\dfrac{\nu}{\omega_p} << 1$