Nuclear Fusion

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Overview

- Introduction to Nuclear Fusion
- Analysis Tools
- Fusion Processes (Fuel Cycles)
- Considerations for Implementations
- Implementation Types
- Fusion's Status and Future

Fusion

- Nuclear fusion refers to any process of interaction of two nuclei in which they combine to form a heavier nucleus.
- For light elements, this process typically emits extra particles such as electrons and neutrinos along with a relatively large amount of energy.

Fusion as a Power Source

- The goal of fusion power production is to harness reactions of this nature to produce electrical power.
- Thermal power plants convert heat into electricity via a heat engine.
- Direct conversion involves capturing charged particles to create a current.

Net Energy

- We want net energy output from our fusion power plant.
- Later on we look at the details of the fusion energy gain factor Q, a useful quantity for describing the energy balance of a reactor.

Steady State Power

- In order to be producing useful electrical power, the reaction must be either in dynamic equilibrium or pulsed quickly.
  - JET (1982-present) (Joint European Torus)
  - ITER (~2018) (originally International Thermonuclear Experimental Reactor)
  - DEMO (~2033) (DEMOnstration Power Plant)

Energy Capture

- Emitted energy from fusion reactions is primarily in the form of high energy neutrons and various charged particles.
- Charged particles skid to a halt mainly through electromagnetic interactions
- Neutrons deposit energy primarily through nuclear interactions.
- Stopping neutrons generally requires different shielding than charged particles.

Safety Concerns

- The most popular fusion reactions produce a lot of neutron radiation.
- This fact has associated safety concerns:
  - Direct Neutron Flux
  - Activated Materials

Our Focus

- Most of the scientific work in fusion has been focused on achieving net energy gain.
- Fusion for power production requires:
  - Fusion process (fuel cycle)
  - a technique for bringing the fuel to a state in which fusion can progress. (Implementation)

Fusion Processes

- Fusion processes (or fuel cycles) are the possible fusion reactions.
- Analogous in concept and notation to chemical reactions
- An example of a fusion process, D-T:

$$^{2}H + {}^{3}H \rightarrow {}^{4}He(3.517\mathrm{MeV}) + n(14.069\mathrm{MeV})$$

Fusion Techniques

- These are the different physical methods of achieving fusion conditions.
  - Require kinetic energy to overcome the Coulomb barrier.
  - Once the nuclei are close enough to each other, the strong nuclear force becomes stronger than the electrostatic force, and the nuclei may fuse.
- Some techniques we look at later include laser implosion and the tokamak.

Analysis Tools

Ignition State

- Ignition state occurs when enough fusion energy is kept in the plasma to continue fusing other nuclei.
- The majority of energy leaves the plasma, becoming the energy that we capture to produce electricity.

Lawson Criterion

- First described by John D. Lawson in 1957, it is a measure of the conditions required for achieving ignition in a plasma.

n_e is the electron density

τ_E is the energy confinement time

For D-T the absolute minimum for the product $n_e\tau_E$ is:

$$n_e\tau_E \geq L \geq 1.5 \times 10^{20} s/m^3$$

Lawson Criterion

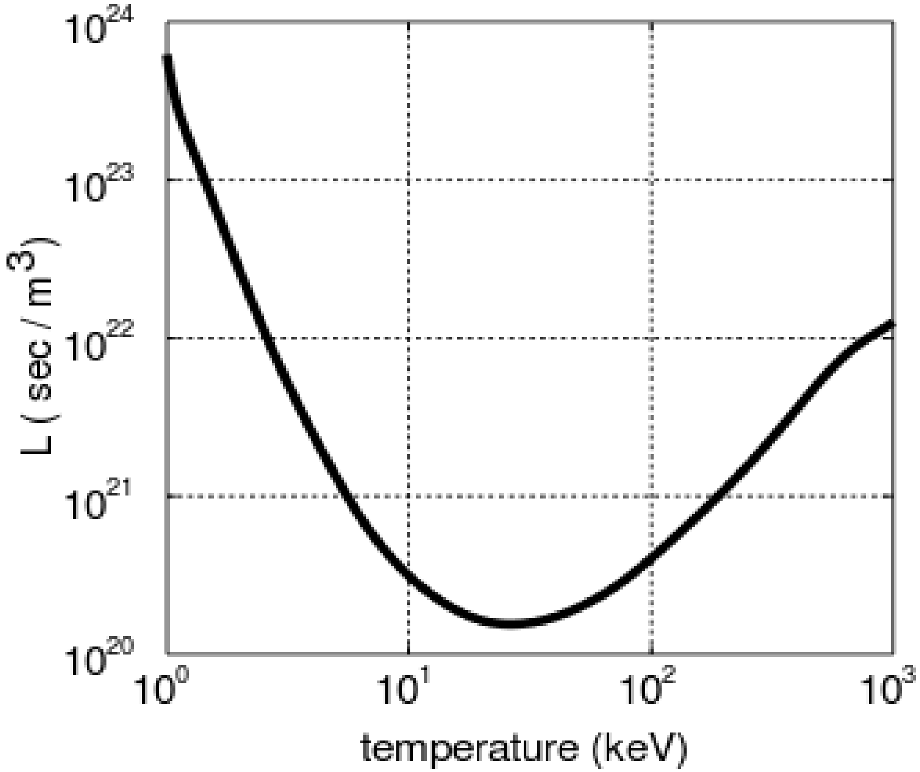
- The quantity L is defined as:

$$L = \frac{12}{E_{ch}} \frac{k_B T}{\langle \sigma v \rangle}$$

Where k_B is the Boltzmann constant.
E_{ch} is the energy of the charged products per fusion reaction
T is the temperature of the ions
σ is the fusion cross-section.
v is the relative velocity of the ions.

Lawson Criterion

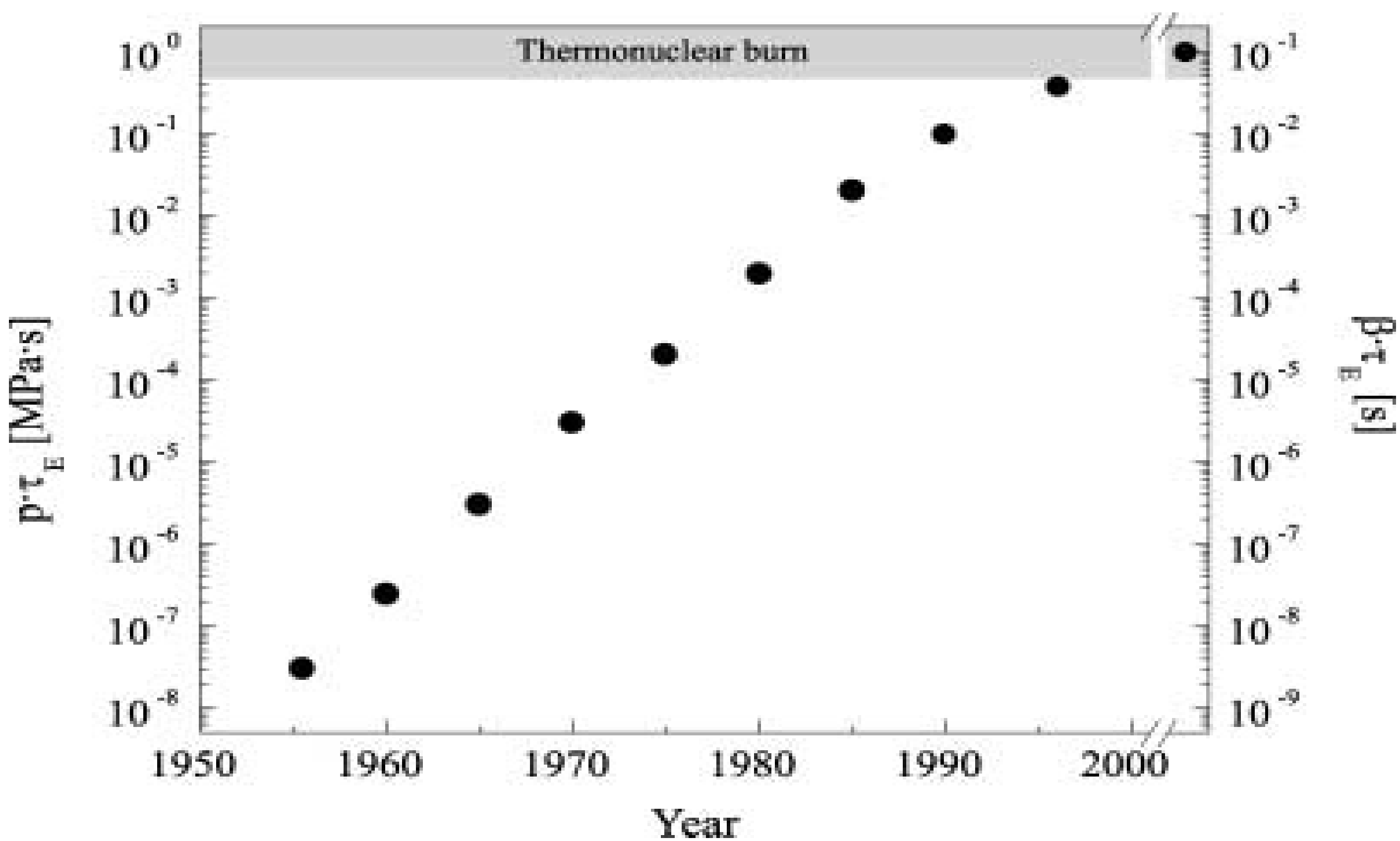
- For D-T:



Wikimedia Commons (Modified)

Fusion Performance Parameter

- Product of τ_E with plasma pressure ρ.
- For D-T this must reach about 1MPa·s at a plasma temperature of 15keV.



Schumacher (2004)

Energy Gain Factor

- Energy Gain Factor is often referred to as 'Q'
- Q is defined as: power from fusion divided by the power of external heating required to keep fusion going.

$$Q = \frac{P_{fusion}}{P_{heating}}$$

Energy Gain Factor Q

$$Q = \frac{P_{fus}}{P_{heat}} = \frac{P_{fus}}{\eta_{heat} f_{recirc} \eta_{elec} (1 - f_{ch}) P_{fus}}$$

$$Q = \frac{1}{\eta_{heat} f_{recirc} \eta_{elec} (1 - f_{ch})}$$

Where the quantities are defined as follows:
P_{fus} is the power output of the fusion reactions
P_{heat} is the heating power from external sources
f_{ch} is the fraction of the fusion energy kept in plasma (charged)
$1 - f_{ch}$ is the fraction of the fusion energy in neutrons
η_{elec} is the efficiency of converting heat to electricity
η_{heat} is the efficiency of converting electricity to heat
f_{recirc} is the fraction of electricity used to run reactor systems

Energy Gain Factor Q Calculation

We assume that $f_{ch} = 0.2$ for the D-T reaction, and we estimate $\eta_{heat} = 0.7$ and $\eta_{elec} = 0.4$. We estimate $f_{recirc} = 0.2$ for an economical reactor. Plugging these in we arrive at:

$$Q = \frac{1}{(0.7)(0.2)(0.4)(1 - 0.2)}$$

$$Q = 22.32$$

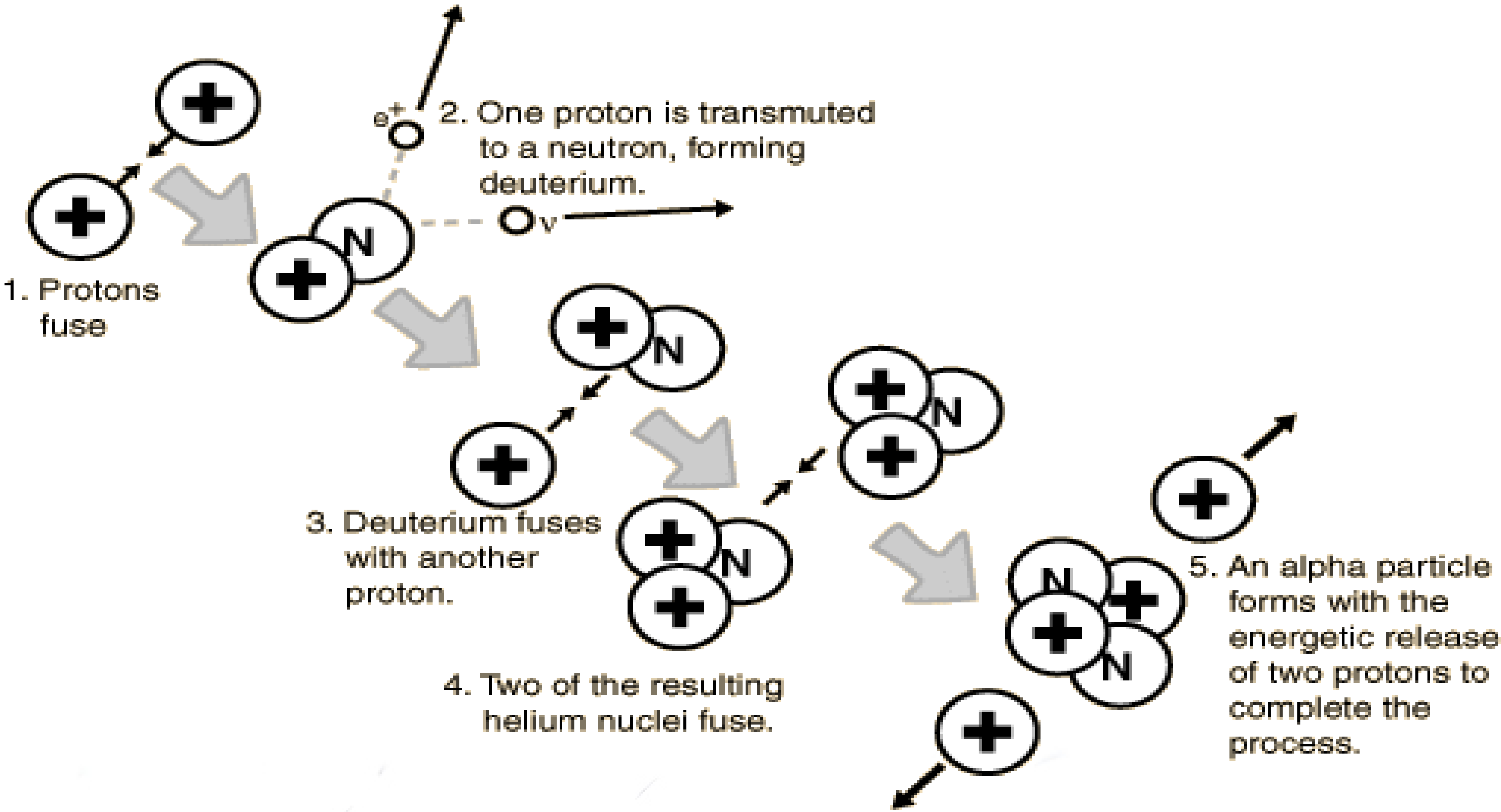
Fusion Processes

Proton-Proton Chain

- Slow process in the sun for two reasons:
  - overcoming coulomb barrier relies on quantum tunneling
  - relies on weak interactions.
- Dominant energy source in stars similar to or lighter than our sun.
- First reaction in the process:

$$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e + (0.42\mathrm{MeV})$$

Proton-Proton Chain

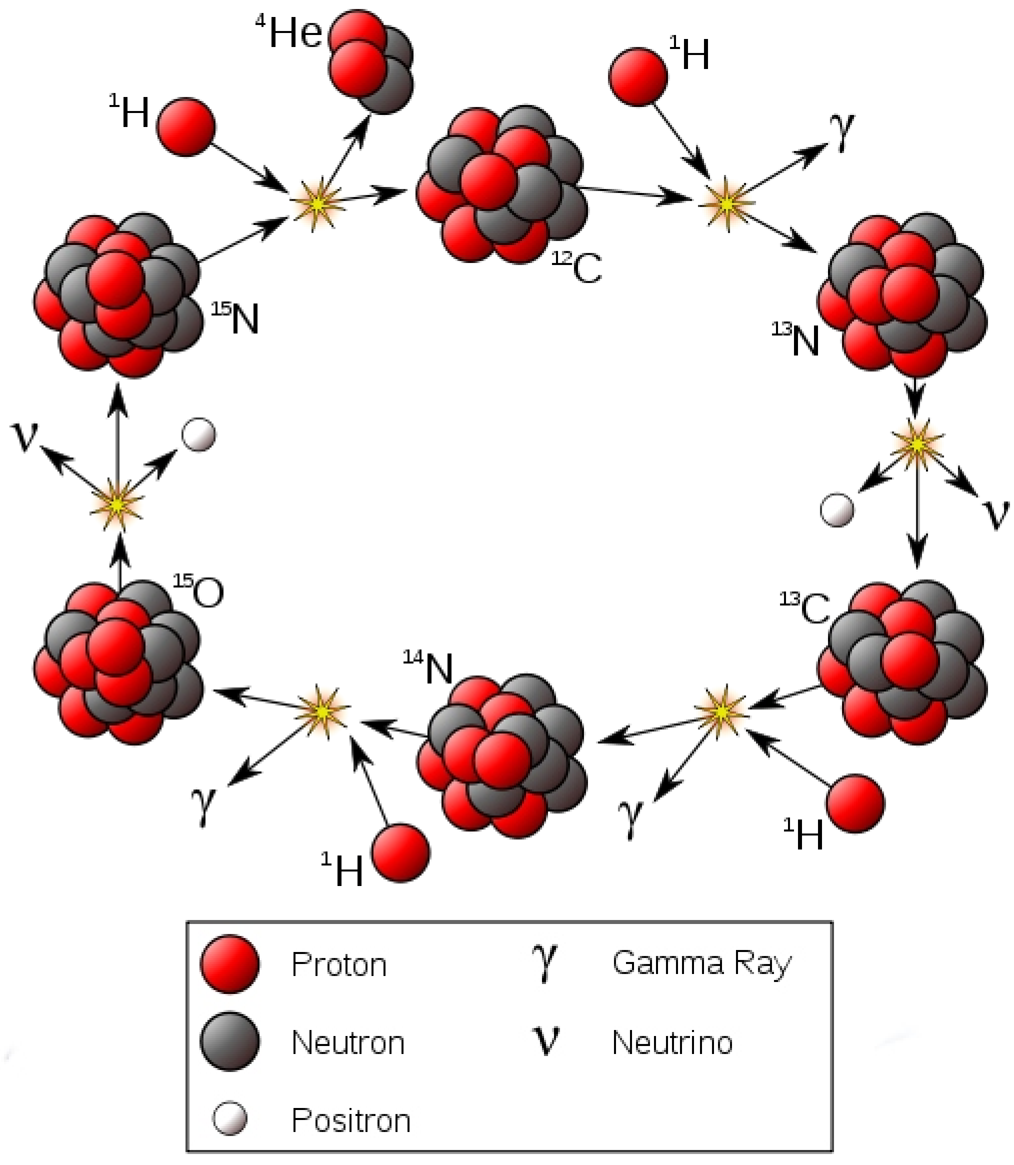


HyperPhysics Online (2010)

CNO Cycle

- CNO stands for Carbon-Nitrogen-Oxygen
- Four protons are converted into a helium-4 nucleus, two positrons, gamma rays, and neutrinos.
- A heavy nucleus acts as a catalyst.
- The heavy nucleus is transformed in a cycle, but is not consumed in the cycle.
- Dominates in stars more than 1.5 times the solar mass.

CNO Cycle



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Deuterium-Deuterium (D-D)

- Possibility for terrestrial use
- Reaction rate peak at 15 keV
- Deuterium available in the earth's oceans
- Two processes with equal probability:

$$^2H + {}^2H \rightarrow {}^3H \ (1.01\mathrm{MeV}) + p^+ \ (3.02\mathrm{MeV})$$

$$^2H + {}^2H \rightarrow {}^3\mathrm{He} \ (0.82\mathrm{MeV}) + n \ (2.45\mathrm{MeV})$$

Deuterium-Tritium (D-T)

- Properties that make it more desirable than D-D:
  - Even higher cross section than D-D
  - Reaction rate peak at 13.6 keV
- Disadvantages:
  - Blanket of Lithium required for breeding tritium
  - Neutron carries off 80% of energy

$$^{2}H + {}^{3}H \rightarrow {}^{4}He\ (3.517\mathrm{MeV}) + n\ (14.069\mathrm{MeV})$$

Deuterium-^{3}He (D-He)

- Advantages:
  - Comparably high energy yield (18.3MeV)
  - Aneutronic
  - Direct conversion is possible
- Disadvantages:
  - Helium-3 is hard to acquire currently
  - Reaction rate peaks at 58 keV

$$^2H + {}^3\text{He} \rightarrow {}^4\text{He}\ (3.6\text{MeV}) + p^+\ (14.7\text{MeV})$$

p-^{11}B

- Advantages
  - Aneutronic
  - Direct conversion possible
  - Fuel availability
- Disadvantages:
  - Reaction rate peaks at a relatively high energy of 123 keV

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

Muon Catalyzed Fusion

- Muon instead of an electron orbiting a nucleus has the effect of lowering the coulomb barrier.
- Lower temperatures.
- Problem: Alpha sticking
- Need a cheap source of a very large number of Muons.

Considerations for Implementations

Magnetic Pressure

- Temperatures are too high for material confinement.
- Charged particles tend to spiral around magnetic field lines.
- Magnetic fields exert a pressure on the plasma to keep it contained.

Power Density

- Power Density varies as:

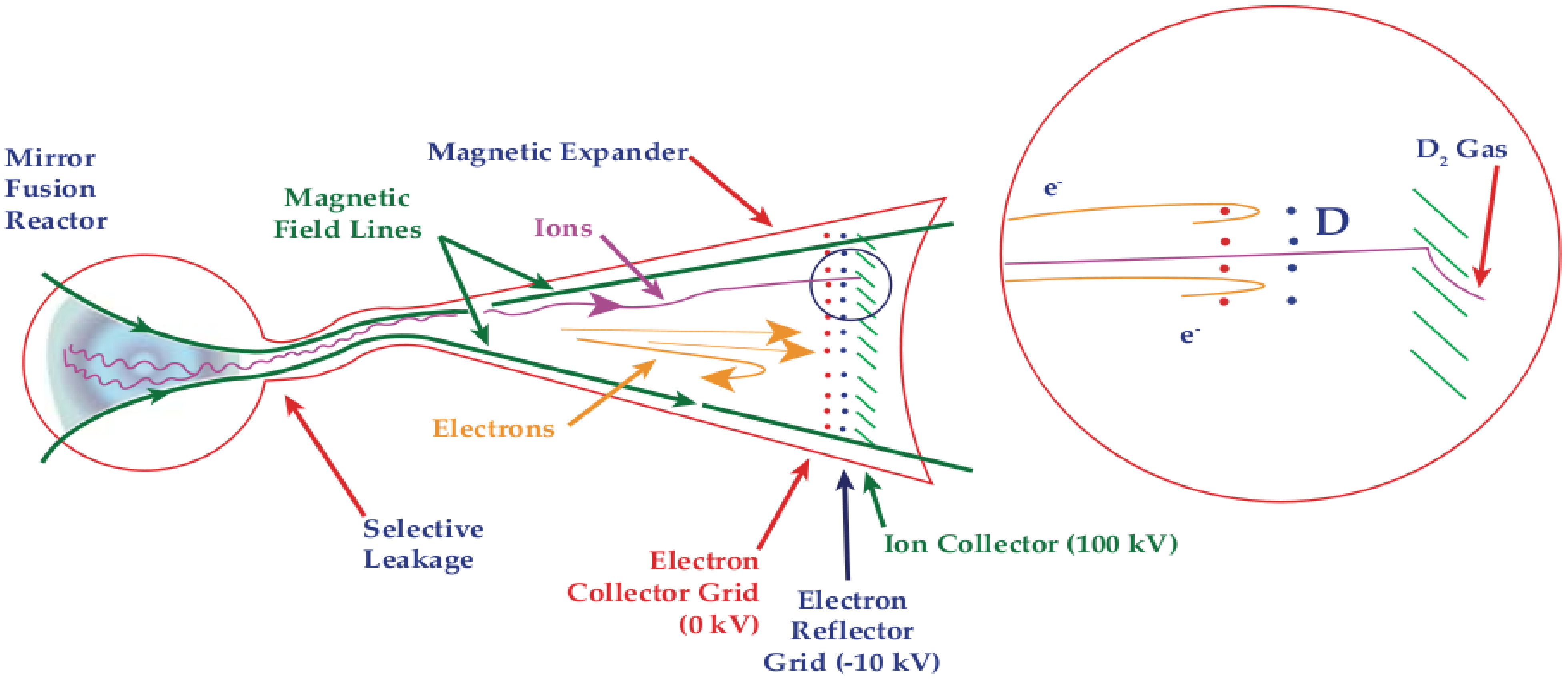
$$\frac{P}{V} = E_{fus}\frac{1}{4}n_e^2\langle\sigma v\rangle$$

P is the power
V is the volume
n_e is the electron density of plasma
σ is the fusion cross-section
v is the relative velocity of the ions
E_{fus} is the energy emitted from one fusion reaction

Direct Conversion

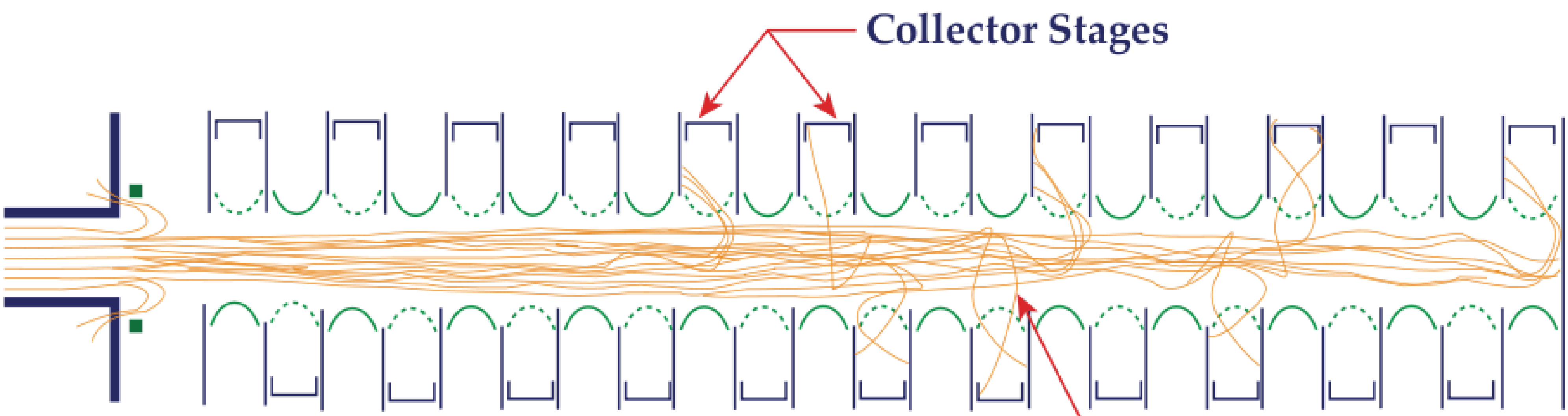
- Use graded positive potentials to slow down positively charged particles.
- Kinetic energy is transformed into potential energy as they climb potential hills.
- Ions strike the target electrode, stealing electrons, creating a further positive potential.
- Electrons are reflected to a different collection surface

Direct Conversion



Moir, R.W. (2009)

Direct Conversion



Moir, R.W. (2009)

Materials

- Very high neutron flux for popular fuel cycles
- Using a divertor system, the energy flux may be tremendous
  - As high as 100MW per square meter.
  - No known material can handle this.
  - Plan is to disperse the energy over wider area.

Implementations

Laser Implosion

- Also known as Inertial Confinement Fusion
- Pellet-based techniques have existed since the 70s
- High powered lasers are the key
  - Difficulty of even laser pressure
  - Efficiency of laser energy
- Ignition state may be possible

Laser Implosion
Laser Mégajoule

CEA – Laser Mégajoule Official Website (2010)

Laser Implosion
National Ignition Facility

Wikimedia commons (2010)

Laser Implosion
Fast Ignition Systems

- Use laser implosion for pressure, but other techniques for heating
  - Single ultra high power laser burst
  - Z-pinch
- Could dramatically lower the energy needed to achieve fusion conditions.

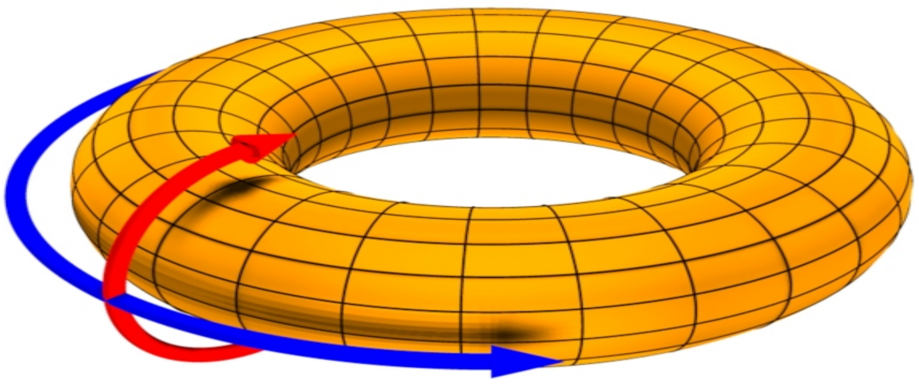
Tokamak

- The name tokamak is a transliteration of a Russian acronym standing for a phrase similar to “toroidal chamber with magnetic coils”.

Wikimedia commons (2010)

Tokamak

- Poloidal magnetic field necessary.
- Electric current through the plasma to generate poloidal component.



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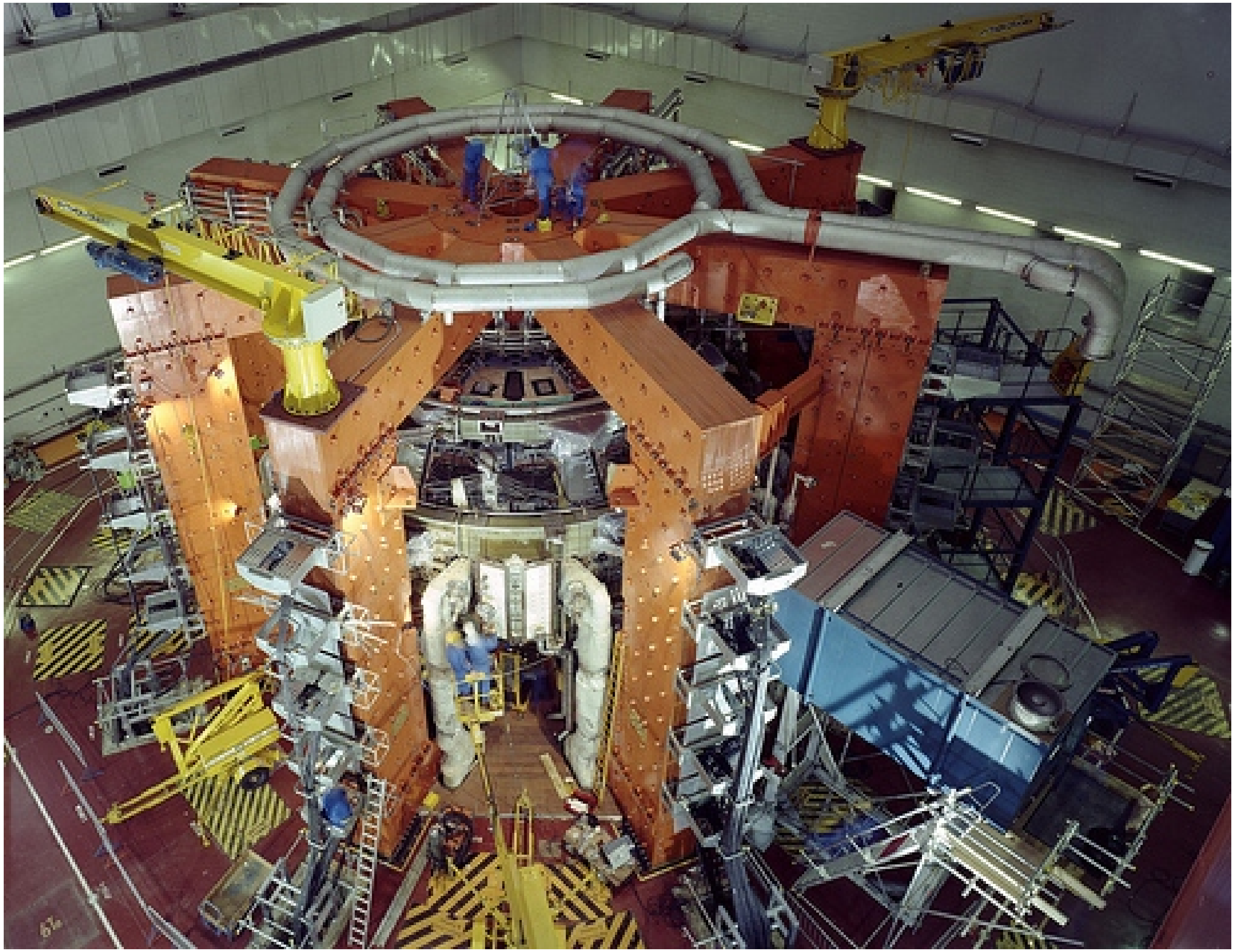
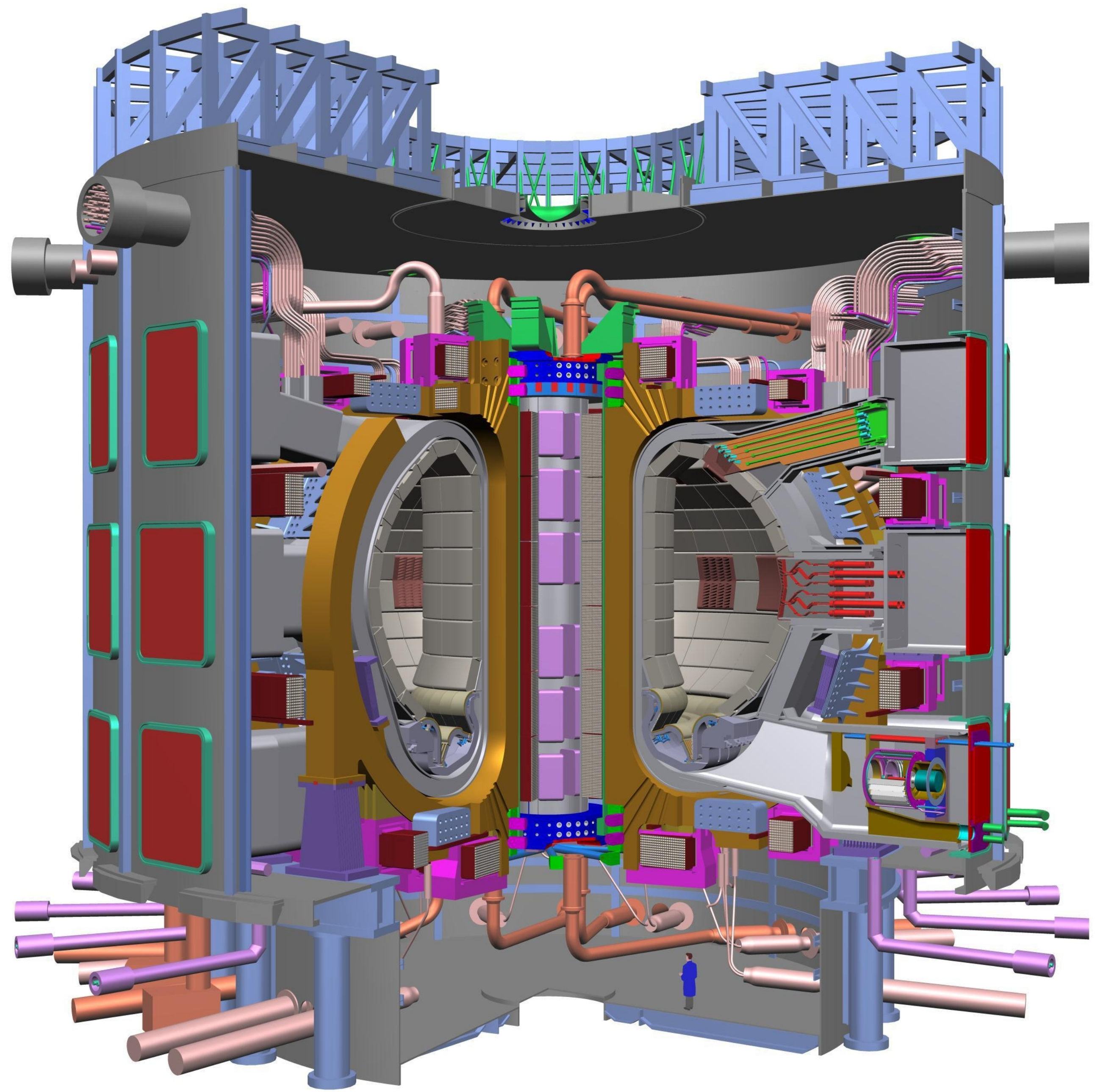
Tokamak: JET



JET Promotional Image (2010)

Tokamak: ITER

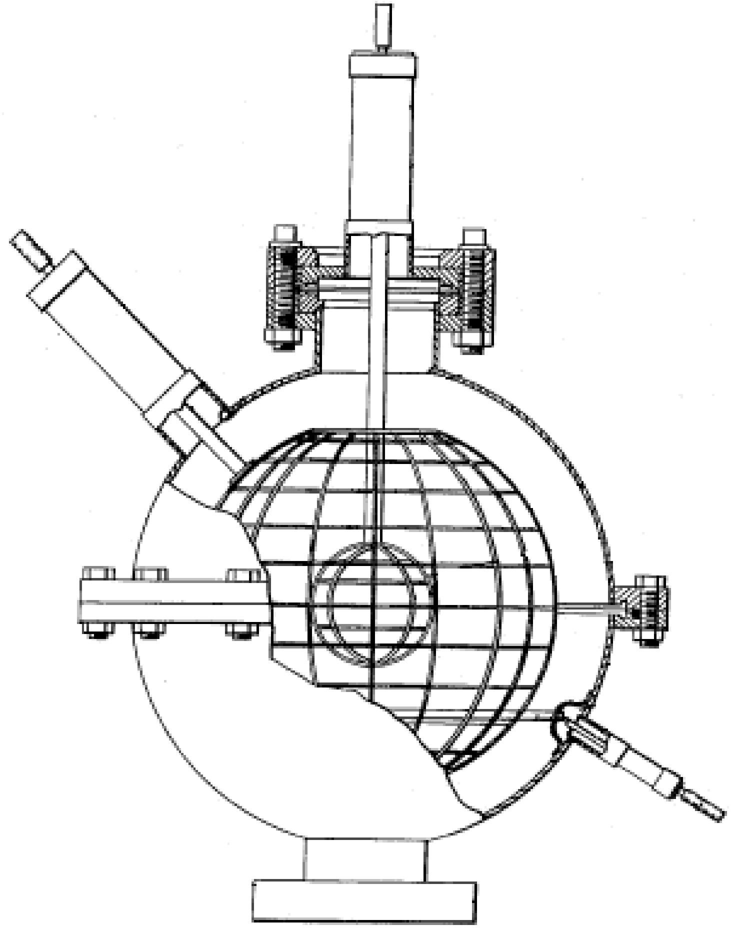


Inertial Electrostatic Confinement

- Inertial Electrostatic Confinement (IEC) uses electric confinement instead of magnetic.
- Potential well created by an electrode at negative potential.
- Ions are accelerated towards central electrode.

Inertial Electrostatic Confinement

Fusor



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Inertial Electrostatic Confinement
Polywell

- Robert Bussard conducted extensive work on his own specialized version of IEC.
- Instead of a physical electrode, they used a cloud of electrons contained by magnetic fields.
- Very high energies attainable.
  - Possibilities for aneutronic processes.

Inertial Electrostatic Confinement

Polywell

- Ion Density varies as $1/R^2$
- Power Density varies as $1/R^4$
- Well-deepening effect.
- New developments in 2009-2010:
  - Funding has been approved for new prototypes. (2010-2011)
  - Provisional funding for later prototypes. (~2012)

Fusion's Status and Future

Nuclear Fusion: Status and Future

- There has been demonstrable, though difficult progress made in the last several decades.
- Our understanding of the difficulties has grown, making all previous estimations of fusion's possible timeline overly optimistic.
- Current projections are more humble, but there may still be things we do not know.
- Many exciting things happening in current experiments.

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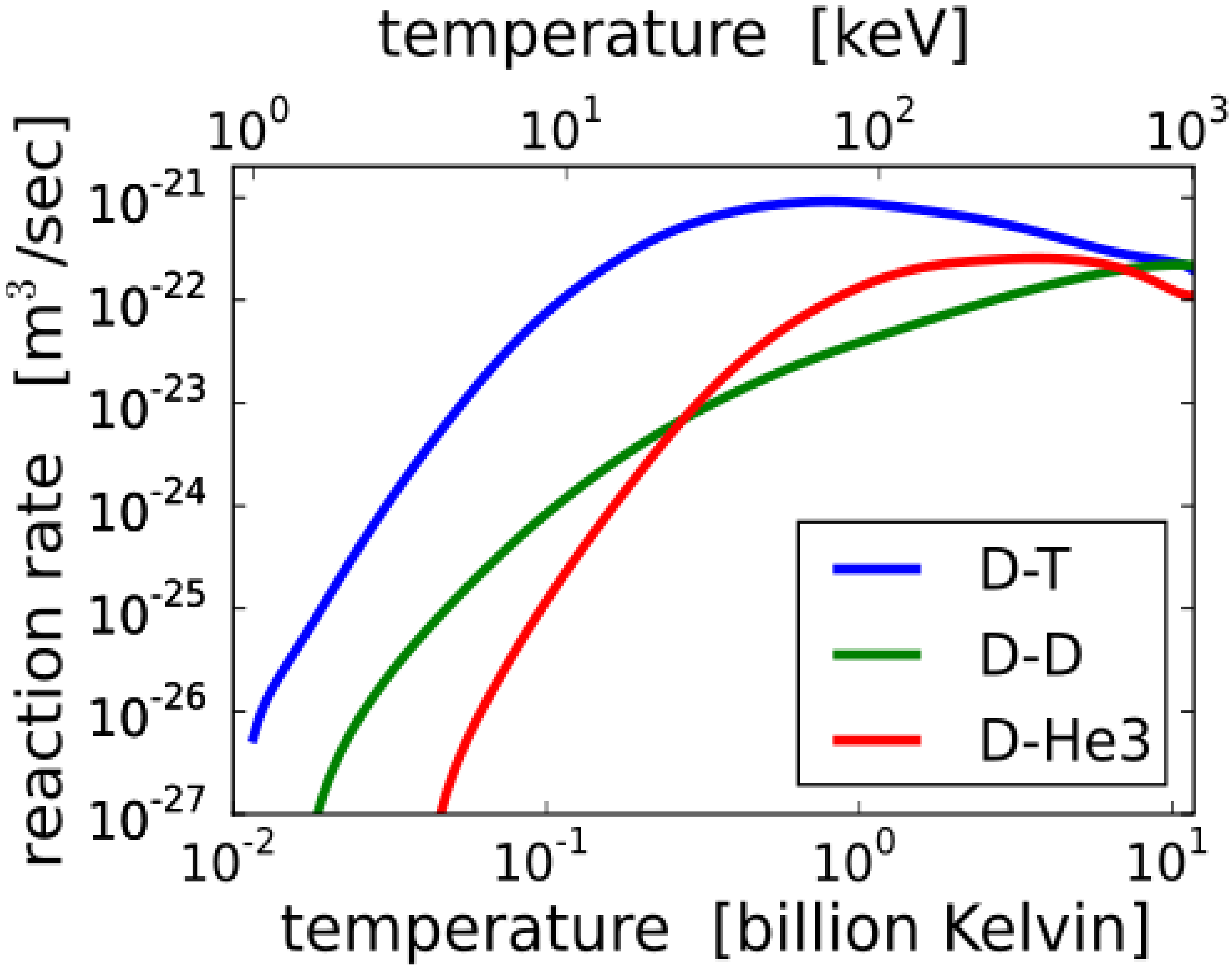
ITER and DEMO Projects Homepage: http://www.iter.org

D-D, D-T, and D-He



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Plasma Beta

- Beta is the ratio of plasma pressure and magnetic pressure.

$$\beta = \frac{\rho}{\rho_{mag}} = \frac{nk_B T}{B^2/2\mu_0}$$

ρ is the plasma pressure
ρ_{mag} is the magnetic pressure
n is the number density of the plasma
k_B is Boltzmann's constant
T is the temperature
B is the magnetic field strength
μ_0 is the magnetic permeability constant