lecture 12

Renewable Energy Sources

EE180J: Advanced

Renewable Energy Sources

EE80J: Introduction to
Proton-Proton Fusion

This is the nuclear fusion process which fuels the Sun and other stars which have core temperatures less than 15 million Kelvin. A reaction cycle yields about 25 MeV of energy.

1. Protons fuse

2. One proton is transmuted to a neutron, forming deuterium.

3. Deuterium fuses with another proton.

4. Two of the resulting helium nuclei fuse.

5. An alpha particle forms with the energetic release of two protons to complete the process.

Click on the illustration for discussion of any stage of the process.

http://hyperphysics.phy-astr.gsu.edu/hbase/astro/procyc.html
Nuclear Fusion

just opposite of nuclear fission!

why the interest?

1. potentially plentiful supply of fuel

2. Reaction easier to control -- less dangerous

3. Minimal reaction by product

BUT decades away from feasibility demo!
Nuclear Fusion.

\[ p + p \rightarrow d + e^+ + \nu_e \quad | \quad d = ^2\text{He}, \text{nucleus of He} \]
\[ \text{DIFFICULT} \]
\[ \text{energy} \quad E = Q = 2m_p - M_d - Me \quad (m_{\nu_e} = 0) \]
\[ Q = 0.42 \text{MeV} \quad \text{produced.} \]

\[ \text{generally,} \]
\[ e^+ + e^- \rightarrow 2\gamma \quad (E = 1.02 \text{MeV}) \]

\[ \text{also can get} \quad d + p \rightarrow ^3\text{He} + \gamma, \quad Q = 5.49 \text{MeV} \]
\[ d + d \rightarrow ^4\text{He} + \gamma, \quad Q = 23.8 \text{MeV} \]
\[ \text{not very likely.} \]

\[ \text{and} \quad d + d \rightarrow ^3\text{He} + n, \quad Q = 33 \text{MeV} \]
\[ \quad \rightarrow ^3\text{He} + p = 4 \text{MeV} \]

\[ \text{or} \quad d + ^3\text{He} \rightarrow ^4\text{He} + n, \quad Q = 3.76 \text{MeV} \]
\[ \text{(star nucleosynthesis)} \]

\[ \text{In SUN!} \quad ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2^1\text{H} + \gamma \quad (Q = 12.86 \text{MeV}) \]
\[ 85\% \text{ of energy from SUN!!} \]

\[ \text{NOTE!} \quad d \text{ occurs naturally on earth} \]
\[ \text{radiation half-life is 12\,yr} \]
Nuclear Fusion.

At present, most 'H nuclei in sun are unreacted.

Could we reproduce SUN in the lab?

In SUN \( 10^{57} \) \( p \rightarrow E + 3.8 \times 10^{26} \) watt \( \frac{E}{c} \geq 3.8 \times 10^{26} \) Joule/sec.

Along with \( p+p \rightarrow d+e^++\nu e \)
we have many reactions going on in sun.

Entire cycle is COMPLEX

But when one nuclei of the entire cycle
one gets a \( Q = 26.7 \) MeV release
\( = 4 \times 10^{-12} \) Joule/sec.

\[ \text{# pp reaction cycles/sec} = \frac{3.8 \times 10^{26} \text{ Joule/sec}}{4 \times 10^{-12} \text{ Joule/cycle}} \times 10^{38} \text{ pp cycles/sec} \]

Which corresponds to about
\( 4 \times 10^{38} \) proton fired/sec.
Nuclear Fusion

\[
\text{Then } \frac{10^{57}}{1 \text{ in } 4 \times 10^{38}} = 1 \text{ in } 2.5 \times 10^{18} \text{ is fraction of proton-fusing/\&c!}
\]

- If Sun produced energy at constant rate it would exist for \(2.5 \times 10^{18} \text{ yr}\) before it burnt up \(-\ 80 \text{B years!}\)
- It would take 80B years to extract all the energy

So we need to look at other reactions at last all
Feasibility of a d-d reaction

deuterium occurs naturally
atomic % = 0.0156 %  \text{ wt %} = 0.000312 \text{ some } A_d = 2A_H \text{ atomic}

mass of water in oceans is:
\[ M = (1.3 \times 10^9 \text{ km}^3) \times 10^9 \text{ m}^3 / \text{km}^3 \times 10^6 \text{ g/m}^3 \]
\[ = 1.3 \times 10^{24} \text{ gms (H}_2\text{O)} \]
\[ = \frac{2}{2H_6} x M = 1.44 \times 10^{23} \text{ gm H}_2\text{O} \]
\[ = \frac{H}{H_2O} \]
\[ = 1.44 \times 10^{23} \text{ gm} \times 0.000312 \]
\[ = 4.49 \times 10^{22} \text{ gm deuterium} \]
\[ = 1.35 \times 10^{43} \text{ atoms of deuterium in ocean} \]

each fission gives 3.3 \times 1.0 \text{ MEV } \text{H}_2 \text{ energy}
\[ = 3.3 \text{ MEV} \text{ fission} \]

each fission takes 2 deuterium atoms
\[ = 1.35 \times 10^{43} \]
\[ = 6.76 \times 10^{42} \text{ fissions available} \]
\[ = 6.76 \times 10^{42} \times 3.4 \text{ MEV } \times 1.6 \times 10^{-12} \text{ J/MEV} \]
\[ = 3.9 \times 10^{30} \text{ J available from ocean!} \]

current energy use = 5.7 \times 10^{20} \text{ J/yr} \implies
\[ \text{energy needed will last} \text{ 6.8 \times 10^3 \text{ yrs!}} \]
**Figure 7.1:** Fusion cross sections as a function of energy for d-d and d-t reaction
(b = barns; 1 b = $10^{-28}$ m$^2$)
Nuclear Fusion 4.

dt reaction \sim 10^3 \text{ more probable than dd} --

* Look at small reactions as candidates for a lab fusion reactor

NOTE: as times, 10 decreases the KE of the particles AND probability of reaction (think of cold vs hot water)

to get appreciable probability of fusion need energy of about 10\text{keV}

this corresponds to \( T \approx 10^{8} \text{ K} \)

how to achieve this?

- magnetic or inertial confinement

DECADES for construction

MUST get \( E_{\text{out}} > E_{\text{in}} \)

ITER goals 500MW\text{out}/50MW\text{in}
Nuclear Fusion 4.

$dt$ reaction $\sim 10^7$ more probable than $dd$ —

* Look at $\alpha$ reaction as candidate for a lab fusion reactor

NOTE: as $T$ rises, 10x the KE of the particles AND probability of reaction

(think of cold vs hot water)

to get a reasonable probability of fusion need energy of about 100 keV

this corresponds to $T \approx 10^8$ K

how to achieve this?

- magnetic / inertial confinement

DECADAS for construction —
MUST get $E_{out} > E_{in}$

ITER goal: 500 MW net/50 MW in
Nuclear Fusion 4.

d + d reaction ~ 10x more probable than dd —

talk at 1MeV reactions as candidates
for a lab fusion reactor

NOTE as times, 10x over the KE
of the particles AND
probability of reaction
(think of cold vs hot walls)

to get appensible probability of fusion
need energy of about 10^6 keV

this corresponds to T ~ 10^8 K

how to achieve this?

- magnetic 012 inertial confinement

DECADES for construction —
MUST get Eout > Ein

ITER goals: 500 MW @ 50 MW in
Proton-Proton Fusion

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Click on the illustration for discussion of any stage of the process.
Fuel ignited by inertial force.

Figure 7.11: Proposed inertial confinement fusion reactor for the production of electricity.

\[ \text{D} + \text{He} \rightarrow \text{T} + \text{He} \]

Mass: 1.14, 93.7

Water: 4.7

\( n \rightarrow 11.7 \text{MeV} \)
Ignition \( nt > 10^{20} \text{ sec/m}^3 \)

\[ n_t (s \cdot m^{-3}) \]

\[ 10^{16} \quad 10^{17} \quad 10^{18} \quad 10^{19} \quad 10^{20} \]

Temperature (K)

\[ 10^6 \quad 10^7 \quad 10^8 \quad 10^9 \]

Magnetic confinement reactors
\[ n_t > 10^{20} \text{ sec/m}^3 \]

To sustain a fusion reaction.

- Toroidal reactors
- Inertial containment

\[ t(\text{sec}) \]

\[ n(\#/\text{m}^3) \]

- Quasi steady state
- Extreme pulsed
FIGURE 7.6: Steps in the heating and compression of a fuel pellet in an inertial confinement fusion reactor. The various stages of fusion are described in the text.

(a) Initial fuel pellet

(b) Heating and compression

(c)detonation

(2) Abolition

(3) Shock wave

(4) Lateral irradiation

(5) Fusion

(6) Release of nuclear energy
Figure 7.7: Photograph of the laser fusion inertial confinement fusion system at Lawrence Livermore National Laboratory, California. Note workers in lower part of module. Power: 15 T Watts / pulse = 2.4 sec, peak power = 150 T Watts / pulse = 2.4 sec/cm.

1.8 m i.d. / channel, 15 T Watts / pulse = 2.4 sec/cm.