Prospects For Fusion Energy Using Magnetic Confinement

Part I: Introduction

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Energy Gain From Nuclear Fusion

With increasing proton number, electrostatic repulsion dominates – curve has a maximum

- energy gain by fusion of light nuclei or fission of heavy nuclei
How Can You Fuse Nuclei?

Nuclei have to 'touch' in order to fuse

• need enough energy to overcome electrostatic repulsion
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Required energy for fusion of hydrogen nuclei: some 10 keV
Fusion cross section varies strongly between different fusion reactions

- D-T fusion: highest cross-section, lowest activation energy
- Cross-section for proton-chain (sun) lower by a factor of $10^{24}$ (!)
In order to gain energy from fusion reactions, one has to confine a hydrogen gas and heat it up such that the thermal energy is of the order of ~ 20 keV (equivalent to 200 Mio degrees(!))
At these temperatures, hydrogen gas becomes a Plasma (gas consisting of charged particles)

- more than 99% of visible matter in the Universe is in the plasma state
Charged particles gyrate around magnetic field lines, move freely along them

• for strong enough field, particles follow the field lines

• 'magnetic confinement' of fusion plasmas
In order to avoid end losses, confinement is achieved in toroidal geometry

- helical field lines minimise particle drifts and allow for stationary confinement
Energy Balance: the Lawson Criterion

, 'Lawson diagramm' for D-T fusion:
Plasma heating by external power

\[ Q = \frac{P_{\text{Fusion}}}{P_{\text{extern}}} \]

- \( Q = 1 \): 'Breakeven'
- \( Q \to \infty \): 'Ignition'

(self-heating by the \( \alpha \)-particles born in the fusion reaction, 'thermonuclear burn')

Energy confinement time \( \tau_E \) is a measure for the heat insulation:
- 'after \( \tau_E \) seconds, the coffee is cold'
- target parameters: \( n = 10^{20} \) particles/m\(^3\), \( \tau_E \) some seconds

\( \tau_E = 10 \) Minuten \quad \tau_E = 10 \) Stunden
Energy Balance: the Lawson Criterion

Energy confinement time $\tau_E$ is a measure for the heat insulation:

- 'after $\tau_E$ seconds, the coffee is cold'
- target parameters: $n = 10^{20}$ particles/m$^3$, $\tau_E$ some seconds

$\tau_E$ = 10 Minuten    $\tau_E$ = 10 Stunden

Note: this criterion concerns the energy/power balance of the plasma, not the whole plant (Q > 30-40 needed for net energy production)

'Lawson diagramm' for D-T fusion:
Plasma heating by external power

$Q = P_{\text{fusion}} - P_{\text{extern}} \
\Rightarrow Q \to \infty$ : 'Ignition' (self-heating by the $\alpha$-particles born in the fusion reaction, 'thermonuclear burn')
In inertial fusion, ignition and burn happen faster than expansion of the hot plasma

- same principle as the hydrogen bomb, but with manageable explosion energy (~ 1 mm pellets)
- target parameters: \( n = 10^{31} \) particles/m\(^3\), \( \tau_E \) some 10\(^{-10} \) seconds
Fusion reactions:
\[ D + T \rightarrow \text{He} + n + 17.6 \text{ MeV} \]

Primary fuels: D and Li
\[ n + ^6\text{Li} \rightarrow \text{He} + T + 4.8 \text{ MeV} \]

Primary product: high grade heat → electricity, → bio fuels...
Magnetic Confinement of Fusion Plasmas

'Stellarator': (complex) magnetic field structure generated by external coils only

Example: Wendelstein 7-X (MPI Greifswald)
'Tokamak': magnetic field partly generated by toroidal plasma current (Transformer)

Example: ASDEX Upgrade (MPI Garching), ITER (Cadarache, France)…
Magnetic Confinement of Fusion Plasmas

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Example: ASDEX Upgrade (MPI Garching), ITER (Cadarache, France)
Magnetic Confinement – Target Parameters

Needed for ignition:
- high temperature: reached 400 Mio. degrees ☺
- 'high' particle density: reached $10^{20} / m^3$ ☻
- good heat insulation: reached $\tau_E < 1$ s ☹

Temperature (Mio degrees) vs. Triple product $nT\tau_E$ graph with markers for different devices and points indicating needed parameters.
Energy Transport in Magnetically Confined Fusion Plasmas

Simple Ansatz:
• losses due to binary collisions of particle
• ignition should be achieved at $R = 0.15$ m (!)

In reality:
• ignition for $R > 6-7$ m
• energy transport dominated by turbulence

Understanding of the (nonlinear) turbulent heat transport is a central subject of fusion plasma physics!
Energy Transport in Magnetically Confined Fusion Plasmas

For diffusive process

- heat insulation improves with plasma cross section

**ASDEX Upgrade (D):**
R = 1.65 m, $\tau_E = 100$ ms

**JET (GB):**
R = 3 m, $\tau_E = 500$ ms

**ITER (F):**
R = 6.2 m, $\tau_E = 3$ s
Recent Success in Tokamaks by using D-T fuel

Late 2021: world record for fusion energy set up by JET tokamak

100 μg Tritium and 70 μg Deuterium

Using fossil fuels:
- 1.06 kg natural gas or
- 3.9 kg lignite coal
With W7-X the Stellarator is Catching Up

Complex technological problems were solved – W7-X in operation since 2016
Magnetic Field in W7-X Precisely Matches Target Configuration
In the first operational campaign, long discharges were obtained without problems

- limited by inertial cooling of wall elements (first experimental campaign until 2019)
- machine now actively cooled and resumed operation (as of October 2022)
With W7-X the Stellarator is Catching Up

2018: record values in $nT_{\tau_E}$ for a stellarator
A ‘Step Ladder’ Approach to Fusion Power

<table>
<thead>
<tr>
<th></th>
<th>ASDEX Upgrade</th>
<th>JET</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>3.3 m</td>
<td>6 m</td>
<td>12 m</td>
</tr>
<tr>
<td>Volume</td>
<td>14 m³</td>
<td>80 m³</td>
<td>800 m³</td>
</tr>
<tr>
<td>Fusion Power</td>
<td>1.5 MW (D-T equivalent)</td>
<td>~ 10 MW (D-T)</td>
<td>~ 500 MW (D-T)</td>
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ITER Partner Build Machine by ’in-kind‘ Contributions

ITER partners
- China
- Europe
- India
- Japan
- Korea
- Russia
- USA

+ partners acquire knowledge in all technologies
- very complex project management
Over the last ~ 5 years, significant private funding enabled a number of start-ups

- big chance: private companies willing to take greater risk in developing fusion technology
- big risk: scientific basis / time plans sometimes less carefully scrutinised than publicly funded ones
One optimization criterion of W7-X was to reduce collisional transport (dominates w/o optimization).

- Successful, transport now dominated by turbulence (as is the case in tokamaks).
- Starting point for further optimization studies (turbulence optimised stellarators).

The end of part I
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