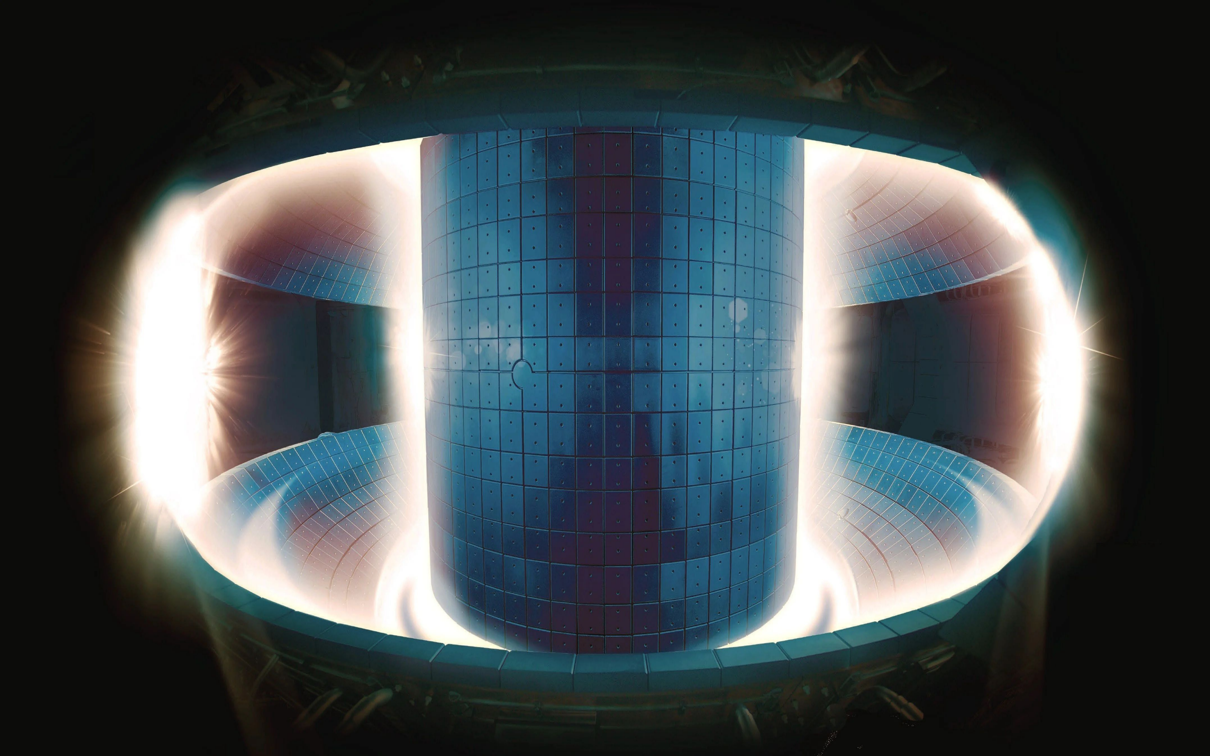


Confinement Concepts

Proseminar & Seminar Plasma Physics (WS 2023/24)

Nils Sekinger

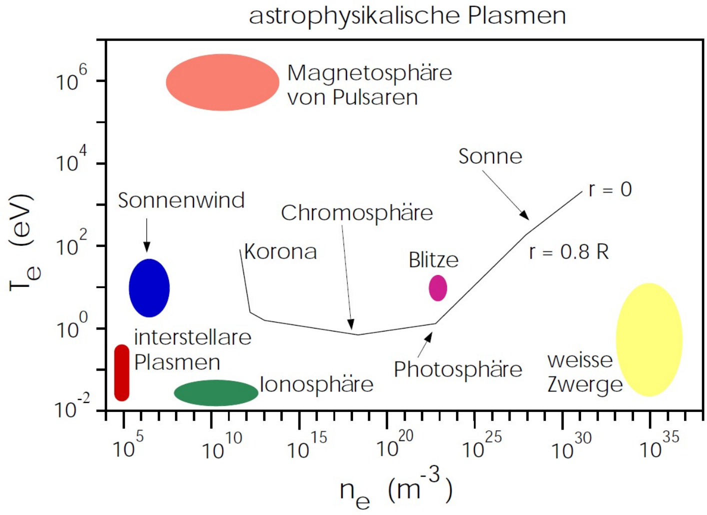
Max Planck Institute for Plasma Physics

Nov 21st 2023

Outline

Cover Picture

natural occurring plasmas



Occurrence of Astrophysical Plasmas (© SIG - Skript)

TOC

Lawson Criterium

Energy Balance

$$\text{Net power} = \text{Efficiency} \times (\text{Fusion} - \text{Radiation loss} - \text{Conduction loss})$$

Fusion Energy

$$\text{Fusion} = \prod \text{Number density of fuels} \times \text{Cross section} \times \text{Energy per reaction}$$

Energy confinement time τ_E

$$\tau_E = \frac{W}{P_{loss}}$$

- Energy density W
- Power loss density P_{loss}

Conditions for Fusion

only 20% of total energy is available for heating
neutrons leave the plasma without interaction

Energy confinement time τ_E

$$\tau_E = \frac{W}{P}$$

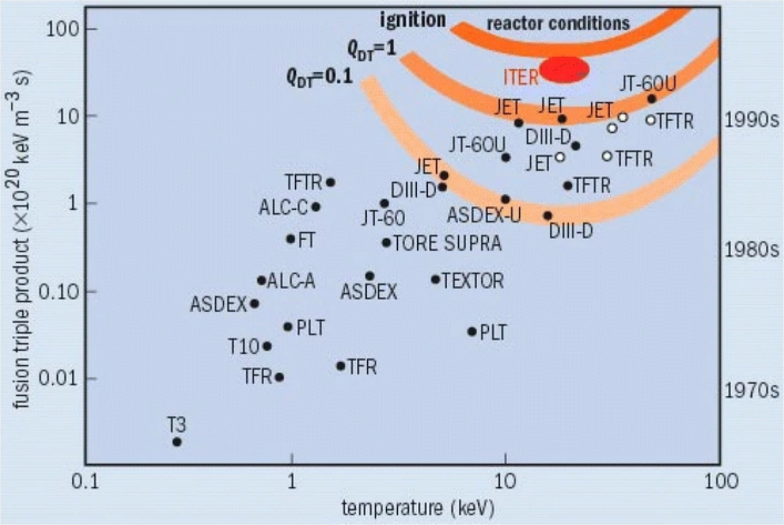
Quality Measure Q

$$Q = \frac{P_{fus,tot}}{P_{ext}}$$

W	:	energy content of plasma
P	:	power loss density
$P_{fus,tot}$	:	total fusion power
P_{ext}	:	external Power (heating, etc.)

Fusion Triple Product

Fusion Triple Product vs. temperature with Quality Measures



(© Horvath, A., Rachlew, E. Nuclear power in the 21st century: Challenges and possibilities)

Fusion Triple Product - Derivation

Approximation for Hydrogen Plasma: $W \approx 3V\bar{n}\bar{T} \quad : \quad \bar{n} \approx 2 \cdot 10^{20}\text{m}^{-3}$

Effective Charge Number

$$Z_{eff} = \frac{\sum_{Ions} n_i Z_i^2}{n_e} \qquad n_e = \sum_{Ions} n_i Z_i$$

Plasma Equation with fusion heating only

$$\left(\frac{\bar{n}}{2}\right)^2 \langle \sigma_{fus} u \rangle \epsilon_\alpha > \frac{3\bar{n}\bar{T}}{\tau_E} + c_{Br} Z_{eff} \bar{n}^2 \sqrt{\bar{T}}$$

Conditions / Variables

- $\bar{n}$: avg. particle density
- σ_{fus} : fusion cross section
- u : relative velocity
- $\epsilon_\alpha = 3.52\text{MeV}$
- $\bar{T}$: avg. temperature
- τ_E : confinement time
- $c_{Br} = 1.04 \cdot 10^{-19} \text{m}^3 \frac{\sqrt{\text{eV}}}{\text{s}}$
- $\left\langle \rho_{fus} u \right\rangle \approx T^2$

Fusion Triple Product - Formulas

Ignition Condition

$$\bar{n}\tau_E > \frac{12\bar{T}}{\langle \sigma_{fus} u \rangle \epsilon_\alpha - 4 c_{Br} Z_{eff} \sqrt{\bar{T}}}$$

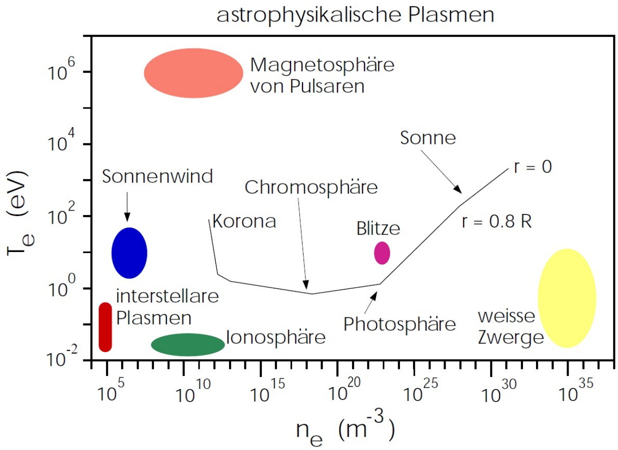
Triple Product

$$\bar{n}\bar{T}\tau_E > \frac{12\bar{T}^2}{\langle \sigma_{fus} u \rangle \epsilon_\alpha - 4 c_{Br} Z_{eff} \sqrt{\bar{T}}} \equiv F$$

Conditions / Variables

- $\bar{n}$: avg. particle density
- σ_{fus} : fusion cross section
- u : relative velocity
- $\epsilon_\alpha = 3.52\text{MeV}$
- $\bar{T}$: avg. temperature
- τ_E : confinement time
- $c_{Br} = 1.04 \cdot 10^{-19} \text{m}^3 \frac{\sqrt{\text{eV}}}{\text{s}}$
- $\langle \rho_{fus} u \rangle \approx T^2$

Gravitational Confinement



Occurrence of Astrophysical Plasmas (© SIG - Skript)

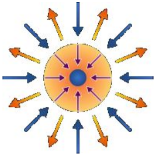
- $\bar{T}_{core} \approx 15.6 \cdot 10^6$K
- $\bar{n} \approx 150$g/cm^3
- $\tau_E \gg 1$s
- inward force: **Gravitation**
- plasma ignites under certain conditions
- outward force: **Plasma pressure**
- force equilibrium stabilises collapse

Inertial Confinement

Given Conditions

- Plasma confinement temperature $T \geq 10\text{keV}$
- Energy confinement time $\tau_E \approx 10^{-10}\text{s}$
- target repetition rate $\geq 1\text{Hz}$
- target energy output $\approx 1\text{GW} \rightarrow \leq 1\text{GJ}$ per pellet
- one D/T fusion $17\text{MeV} \approx 3 \cdot 10^{-12}\text{J}$

$\Rrightarrow$ $6 \cdot 10^{20}$ particles per pellet
$m \approx 2.4\text{mg}$
$\rho = 200\,\text{kg}/\text{m}^3$
$R = 1.3\text{mm}$



Inertial Confinement

Fusion condition

$$\frac{1}{4}\frac{n}{R_{ab}} = \frac{1}{n\langle\sigma u\rangle} = \tau_B \leq \tau_E \approx \frac{R}{c_{ion}} = \frac{R}{2}\sqrt{\frac{m_i}{k_B T}}$$

$$\implies \rho R \geq \frac{2\sqrt{m_i k_B T}}{\langle\sigma u\rangle}$$

Inserting values:

$$0.2\,\mathrm{kg}/\mathrm{m}^2 \not\geq 30\,\mathrm{kg}/\mathrm{m}^2$$

Conditions / Variables

- $T_{conf} \geq 10\text{keV}$
- $\tau_E \approx 10^{-10}\text{s}$
- $f_{rep} \geq 1\text{Hz}$
- $P_{out} \approx 1\text{GW}$
- $W_{p.Pellet} \leq 1\text{GJ}$
- $W_{D/T} \approx 3 \cdot 10^{-12}\text{J}$
- $n = 6 \cdot 10^{20}$
- $m_i = 2.5\, m_P$
- $\rho = 200\,\mathrm{kg}/\mathrm{m}^3$
- $R = 1.3\text{mm}$
- $c_{ion} \approx 10^5 - 10^6\,\mathrm{m}/\mathrm{s}$
- R_{ab} : reaction rate
- σ : fusion cross section
- u : relative velocity

Inertial Confinement - Solutions

Inequality

$$\rho \cdot R = 0.2\,\mathrm{kg/m^2} \not\geq 30\,\mathrm{kg/m^2}$$

Change the diameter of the Pellet

- $R = 1\text{mm} \rightarrow 150\text{mm}$
- $W_{p.Pellet} \rightarrow (150)^3\text{GJ} \quad \hat{=} \quad 850\text{kt TNT}$

$\Rightarrow$ not practicable

Inertial Confinement - Solutions

Inequality

$$\rho \cdot R = 0.2^{\mathrm{kg}}/_{\mathrm{m}^2} \not\geq 30^{\mathrm{kg}}/_{\mathrm{m}^2}$$

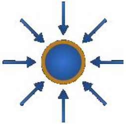
Change the diameter of the Pellet

$\Rrightarrow$ not practicable

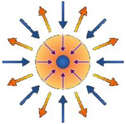
Change the density of the Pellet

- $\rho \rightarrow 1500\rho \quad \Longleftrightarrow \quad$ compression of R by factor ≥ 10
- Goal: $R = 1\text{mm} \rightarrow R = 100\mu\text{m}$ in under 10^{-10}s
- Side effect: T rises to approx. 10keV
- How?

Direct Drive



Heating process
- with LASER or heavy-ion beam(s)
- plasma forms on surface



Blow-off of surface Plasma
- pellet gets compressed by back pressure

Compressed Pellet
- $T \rightarrow$ ca.10keV
- pressure comparable to core of the sun

Self Ignition
- thermonuclear burn starts in the middle
- α-particles ignite the rest on their way out

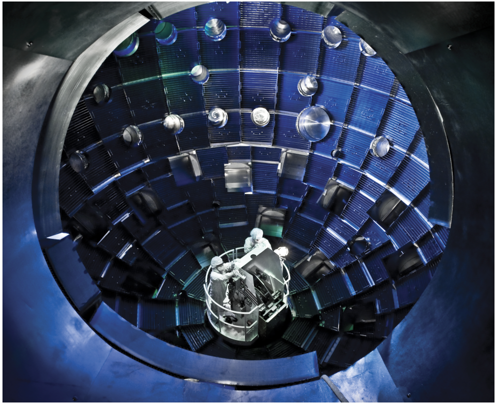
$\Longrightarrow$ Rayleigh-Taylor-Instability

Indirect Drive

- min. 2 beams
- fuel inside hohlraum
- heating via cavity radiation
- further steps as with direct drive

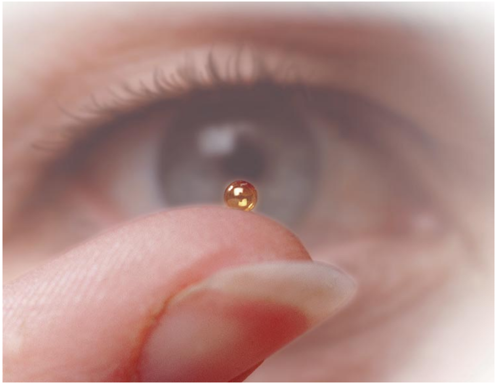
- prerequisite:
  Laser-Pulse with 1MJ in 10^{-10}s
  $\Longrightarrow 10^{16}$W

- currently: NOVA-Laser 10^{14}W

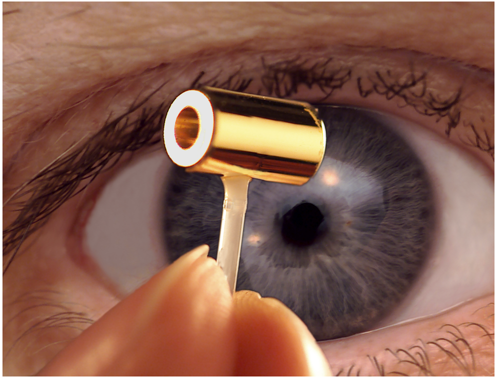


192-Beam design of National Ignition Facility target chamber (© U.S. Department of Energy)

Indirect Drive Pictures



Fusion Microcapsule (© U.S. Department of Energy)

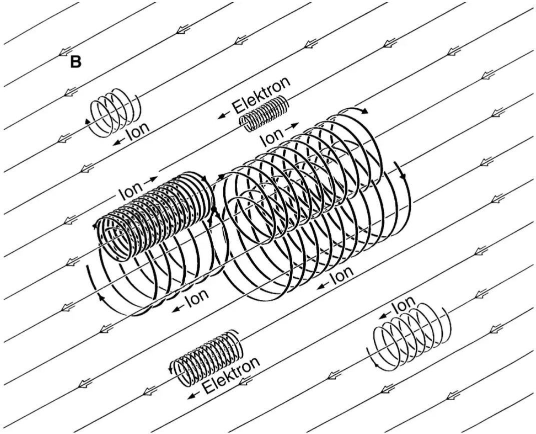


Hohlraum (© U.S. Department of Energy)

Magnetic Confinement

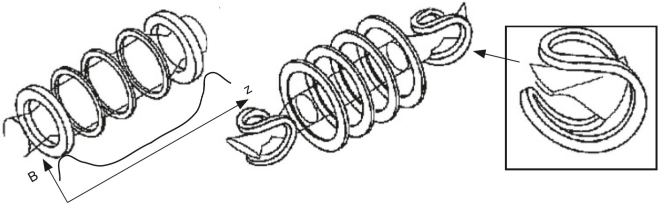
> "The mobility of electrons and ions is very high parallel to field lines and heavily reduced perpendicular to them."

- ions move along field lines
- ions gyrate around field lines
- $\bar{n} \approx 10^{20} \frac{1}{\text{m}^3}$
- $\tau_E \approx 3\text{s}$



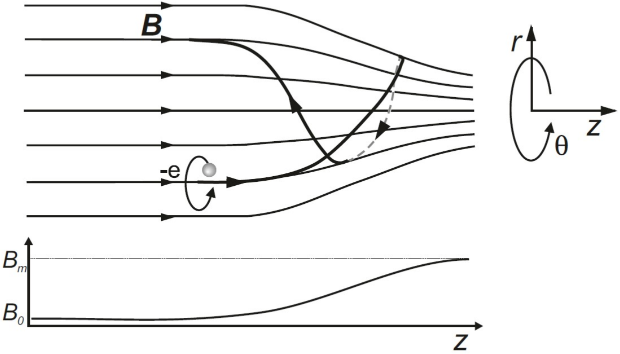
Charged particles in a magnetic field (© IPP)

Mirror Machine



Different Mirror Machine Setups
(© Stroth - Plasmaphysik)

Path of a trapped electron in a mirror machine
(© Stroth - Plasmaphysik)



Unavoidable leak due to geometric configuration

Toroidal Machines

Idea:

- bend the straight coil into a circle, connecting the ends

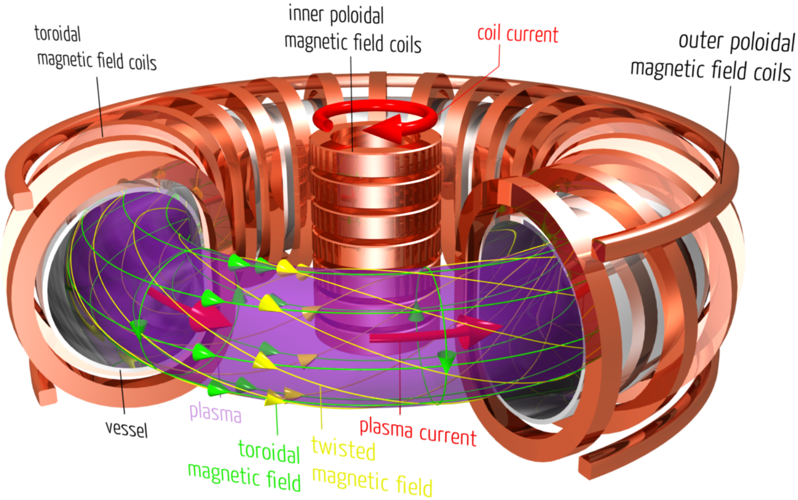
Problem:

- inhomogeneous magnetic field
- particles drift depending on the charge of the particle
- electric field by charge separation
- plasma is pushed outwards, breaking the confinement

Better Idea:

- add poloidal component to magnetic field
- magnetic field lines wind helically around torus
- alternating plasma drift $\longrightarrow$ plasma stays confined

Tokamaks



Tokamak Section View with induced Plasma current (© Princeton University)

Stellerators

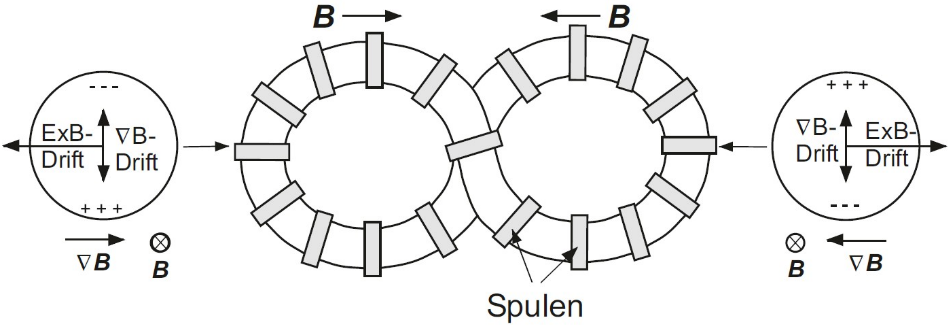
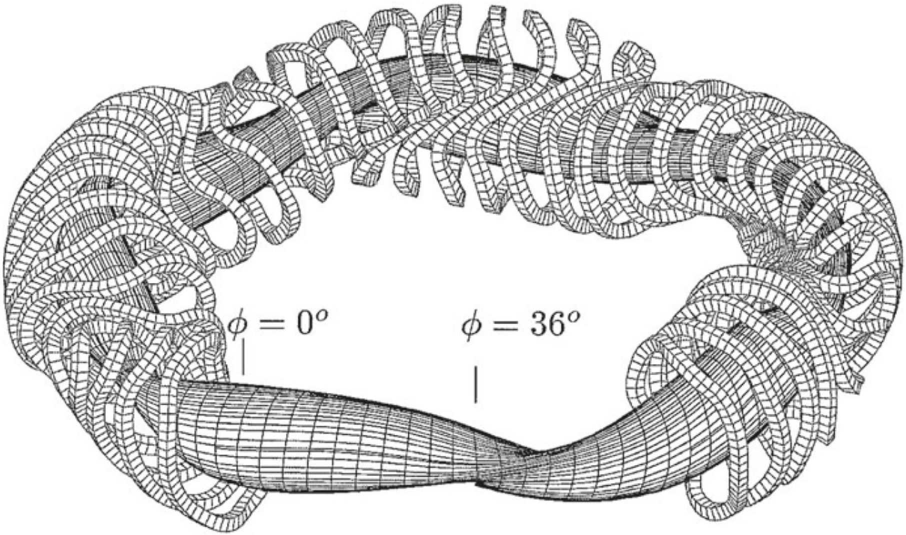


Figure 8 stellarator with some field coils and the indicated plasma. The liquid drifts occurring for two plasma cross-sections are shown qualitatively on the basis of the gradient drift. (© Stroth - Plasmaphysik)

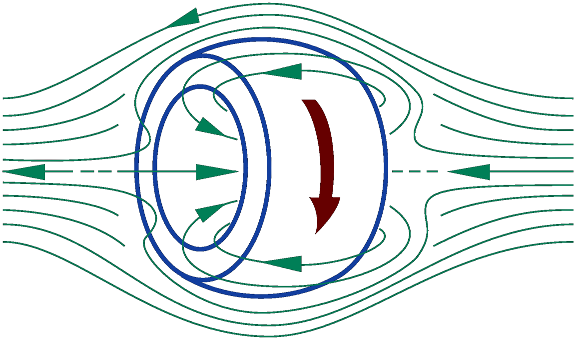
Wendelstein 7-x



Arrangement of the magnetic coils and field lines of the Welndelstein 7-x (© Stroth - Plasmaphysik)

Alternative Reactor Concepts

- compact toroids (Spheromak, Field-Reversed Configuration)
- magnetic confinement without central core



Spheromak (© Wikipedia Creative Commons CC0 License)

Inertial Electrostatic Confinement

Approach

- ions trapped with electric field creating high density plasma
- bombardment with highly energetic ions
- collision energy dependent on ion speed, not on plasma temperature
- coulomb barrier is easier to overcome, higher cross section

Problem

- necessary frequency of fusion reactions for net energy production can't be achieved

Muon Catalysed Fusion / Cold Fusion

- fusion at $900\mathrm{K}$
- reduction of coulomb barrier by replacing electrons with muons
- created particle decays in $2.2 \cdot 10^{-6}$s
- theoretically 2000 catalysed fusion reactions
- in reality 170 catalysed fusion reactions due to neutralisation possibility
- not enough for positive energy balance

Summary

FoPra Plasmaspectroscopy (© Nils Sekinger)

(I) Lawson Criterium

(II) Fusion Triple Product

- $\bar{n}\bar{T}\tau_E \geq const.$

(III) Gravitational Confinement

- high confinement time, high density, high temperature

(IV) Inertial Confinement

- $\tau_B < \tau_E$
- short confinement time, high density, high temperature

(V) Magnetic Confinement

- preferred movement of ions along (closed) magnetic field lines
- medium confinement time, medium density, high temperature