Text books on fusion research

M. Kaufmann: Plasmaphysik und Fusionsforschung" , Springer 2013 (German only)

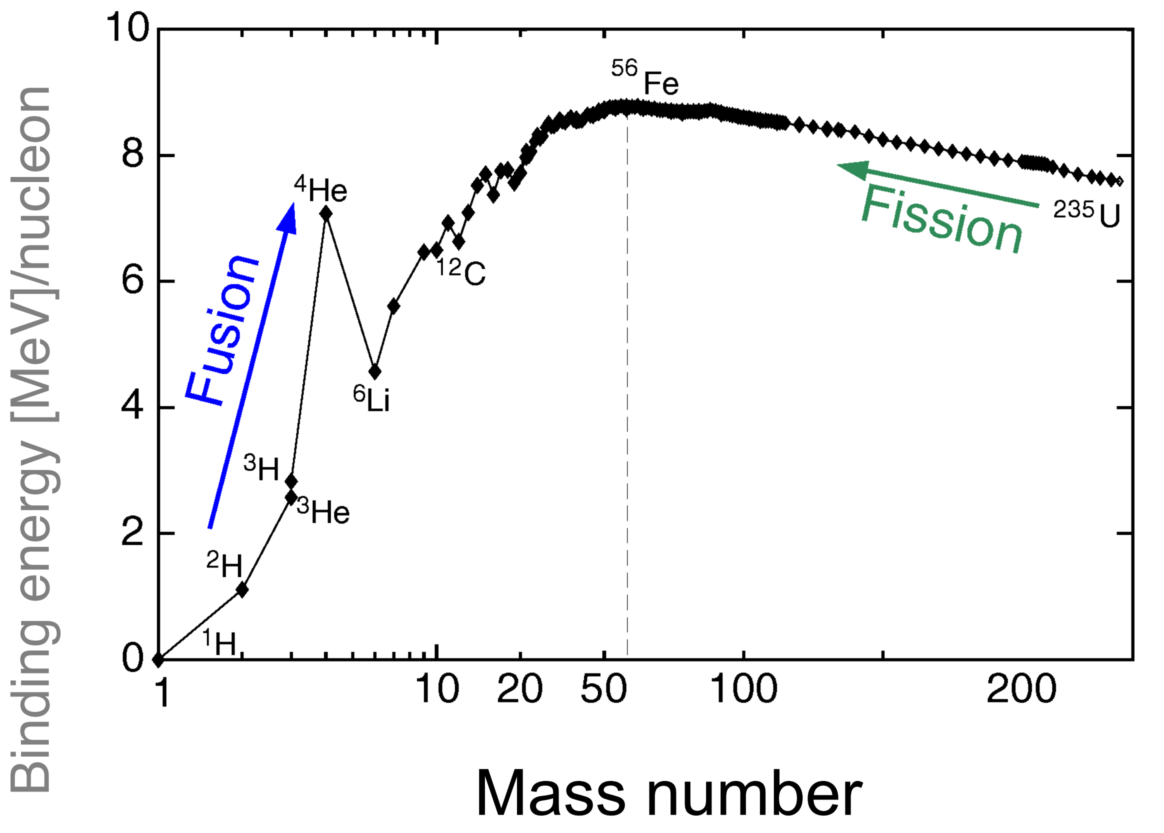
R.J.Goldston, P.H. Rutherford „Introduction to Plasma Physics"
(CRC Press English 1995, Springer German 1998)

F. Chen Introduction to Plasma Physics and Controlled Fusion (Springer 2019)

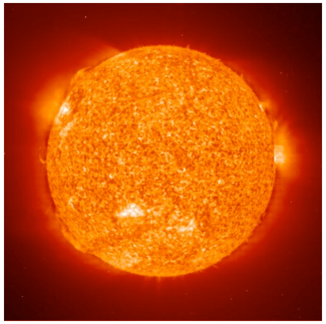
J. Freidberg. Plasma Physics and Fusion Energy (Cambridge 2008)

J. Wesson „Tokamaks" (Oxford 2011)

Gain of energy due to nuclear fusion



How does the sun produce energy?



- **18th century: sun burns coal?**

  Given the mass M_s~2 10^{30} kg, sun‘s life time would be ~4600 years (but age of the earth already known to be a few billion years)

- **19^{th} century (Helmholtz): gravitational energy?**

  Sun makes use of gravitational energy, released by slow contraction: life time ~19 Mio years, still not enough

- **20^{th} century (Rutherford 1923) fusion of 4 protons?**

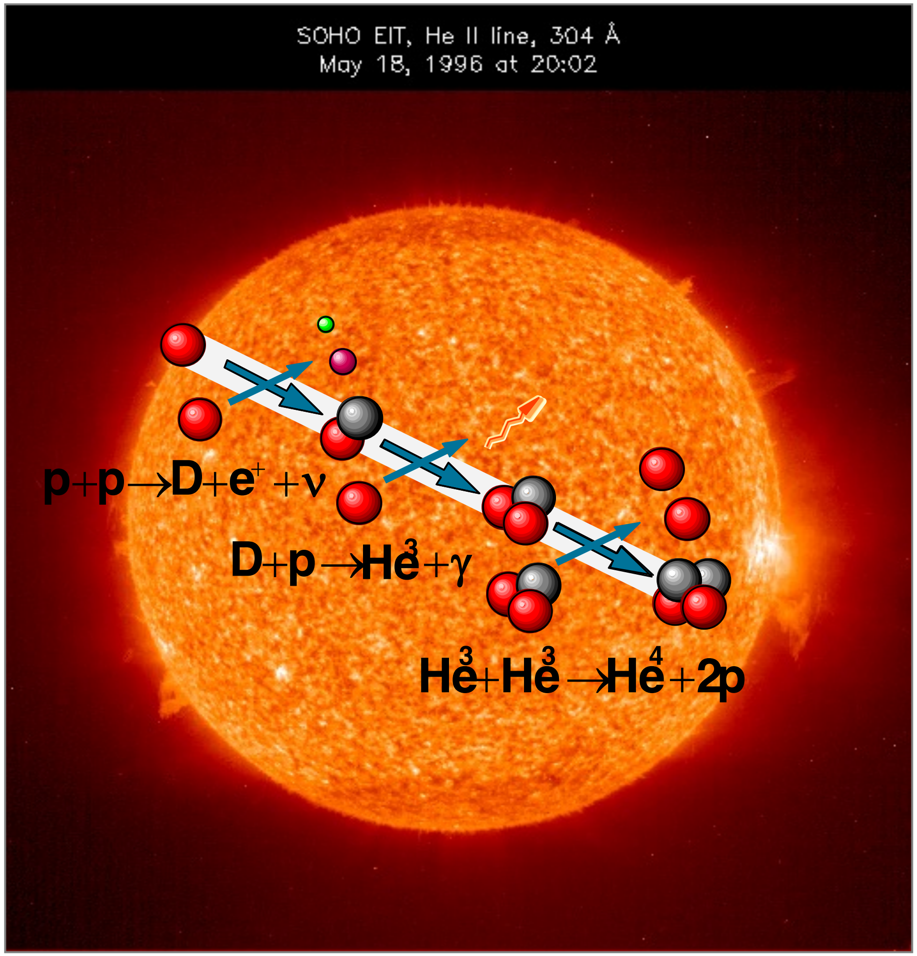
  But low probability of simultaneous collision of 4 protons

  Tunnel effect not yet know, thus temperature was too low given the large Coulomb repulsion

$$E_{pot} = \frac{Z_1 \cdot Z_2 \cdot e^2}{4\pi \cdot \varepsilon_0 \cdot r_m}$$

~400 keV for Z=1

Proton chain in the sun and in small stars (T<2keV)



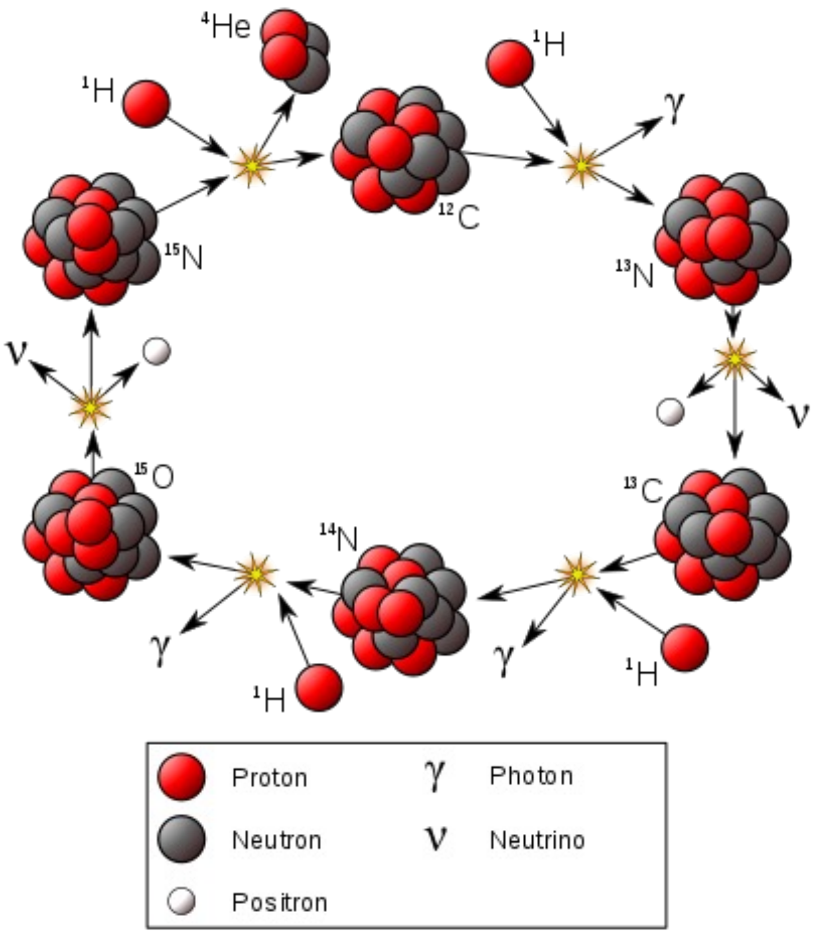
First reaction very slow, as weak interaction involved

$$4p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 2\gamma + 25.7\,\mathrm{MeV}$$

600 Mio tons per second protons fused to 596 Mio tons ^{4}He

$$4\ {}^{1}H^{+} + 2e^{-} \rightarrow {}^{4}He^{2+} + 2\nu_e \quad +26.7\ \mathrm{MeV}$$

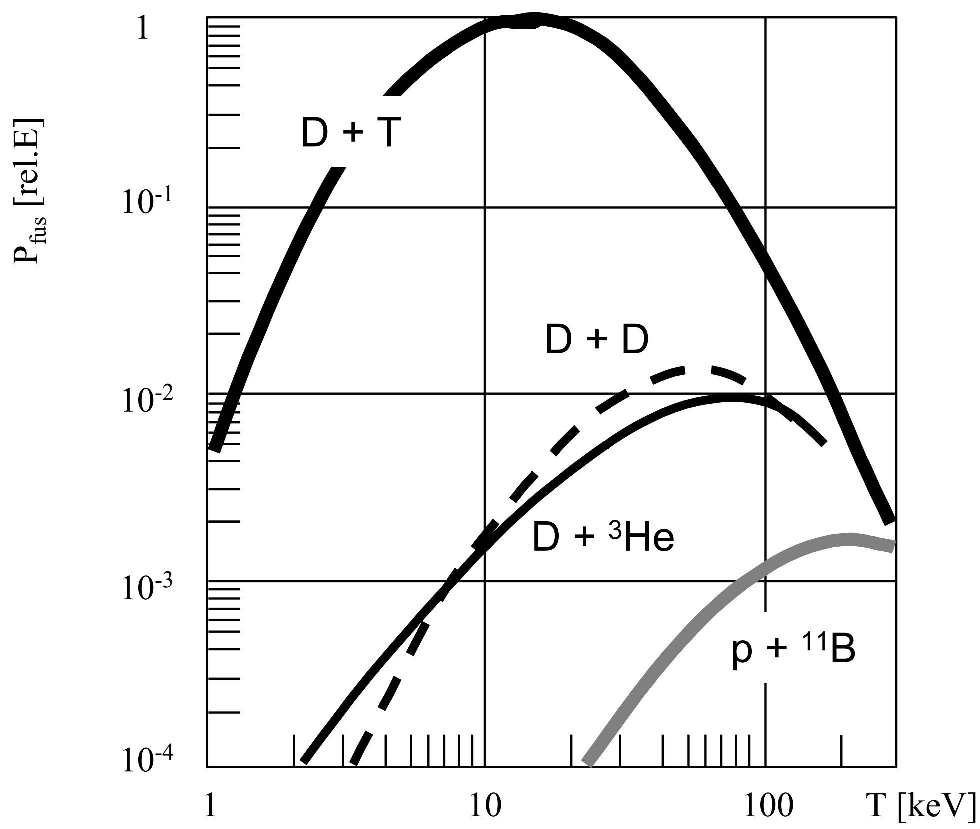
At higher temperatures fusion to heavier elements



Energy ~T^{20}
(pp chain ~T^4)

Bethe-Weizsäcker-cycle for hot stars (T > 30 Mio K), above 1.5 times the mass of the sun

Possible fusion reactions: fusion power density

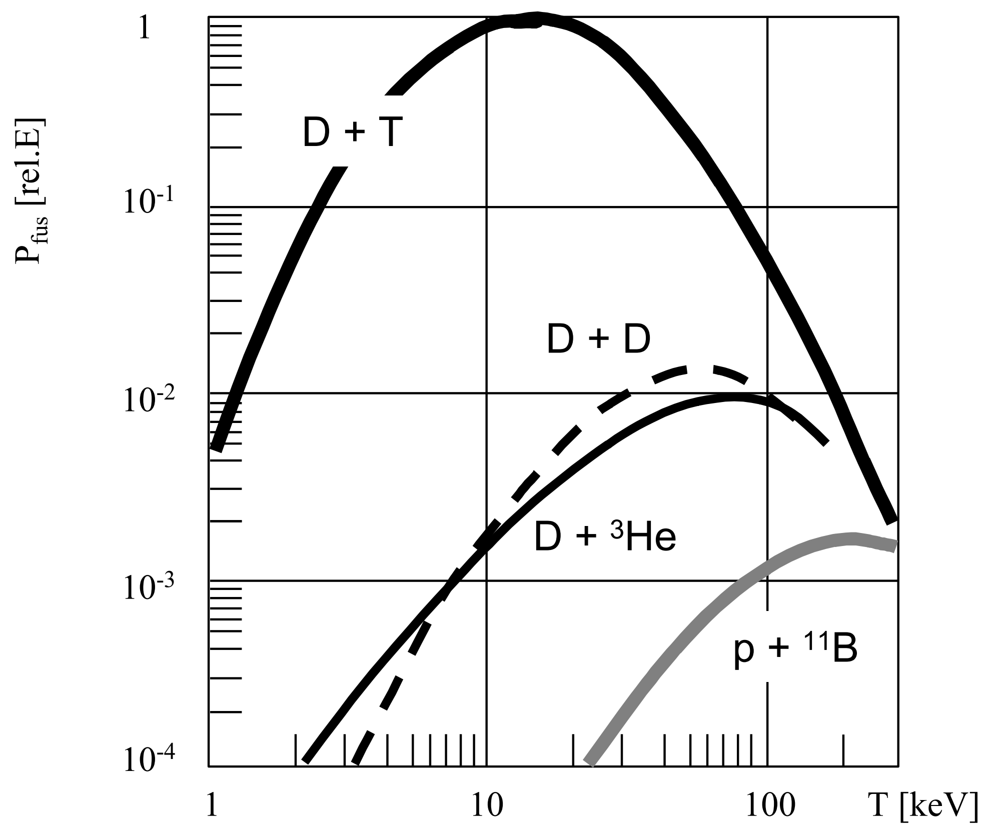


Cross section for D-T reaction about 25 orders of magnitude larger than that of proton chain

(1)	D + D	=> ^{3}He (0,8) + n (2,5)
		=> T (1) + p (3)
(2)	D + ^{3}He	=> ^{4}He (3,7) + p (14,7)
(3)	D + T	=> ^{4}He (3,5) + n (14)
(4)	p + ^{11}B	=> 3 × ^{4}He (3 × 2,9)

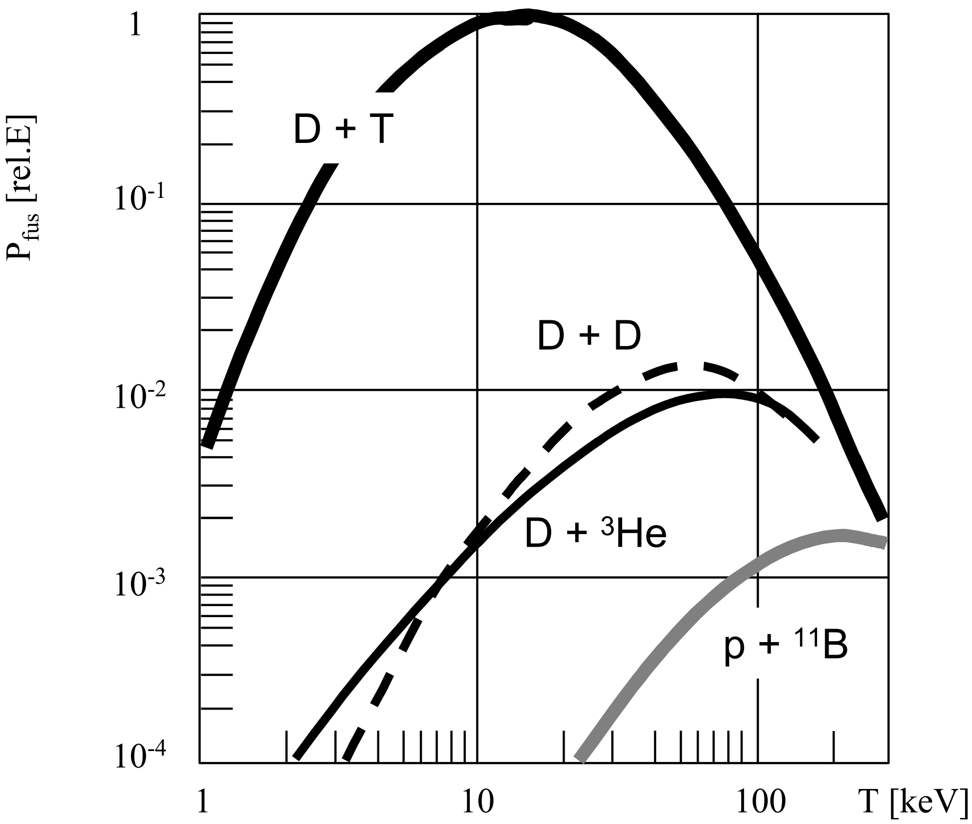
in parentheses amount of energy released (in MeV)

Possible fusion reactions: fusion power density



(1) D + D	=> ^{3}He (0,8) + n (2,5)	
	=> T (1) + p (3)	
(2) D + ^{3}He	=> ^{4}He (3,7) + p (14,7)	
(3) D + T	=> ^{4}He (3,5) + n (14)	most promising
(4) p + ^{11}B	=> 3 × ^{4}He (3 × 2,9)	Recently more often promised, but very unlikely

Tritium breeding



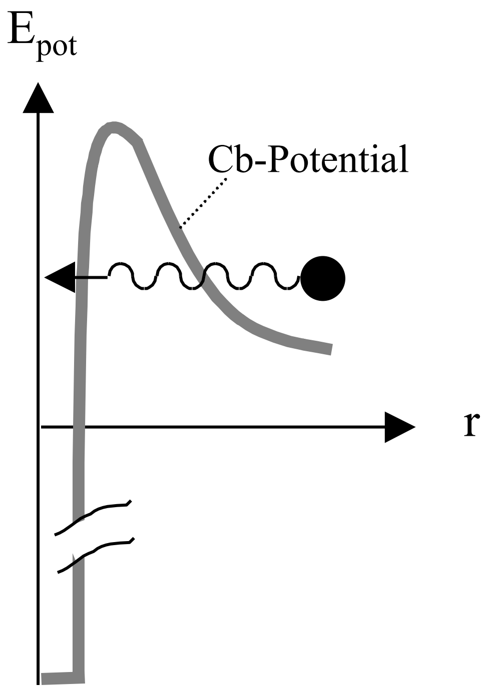
$^7Li + n \Rightarrow {}^4He + T + n$ (-2,5)

$^6Li + n \Rightarrow {}^4He + T$ (+ 4,8)

Lithium isotopes:
- 93% ^7Li
- 7% ^6Li

Neutron multiplier: Pb or Be

Miminal energy needed to overcome Coulomb repulsion



$$E_{pot} = \frac{Z_1 \cdot Z_2 \cdot e^2}{4\pi \cdot \varepsilon_0 \cdot r_m}$$

$r_m \sim 4 \cdot 10^{-15}$ m
$E_{DT} \sim 0{,}4$ MeV
(for DT)

Only after discovery of the tunnel effect fusion well processes understood:

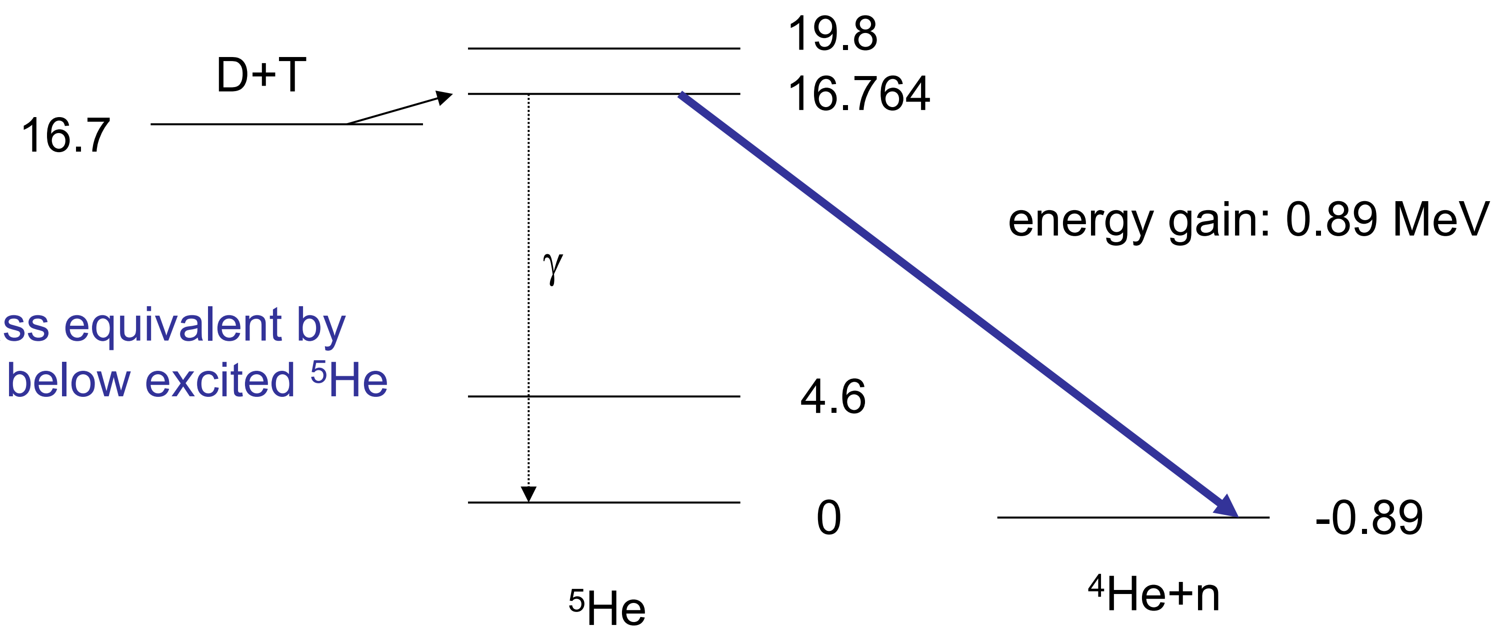
$$w_{tunnel} = const \cdot e^{-\frac{Z_1 \cdot Z_2}{v_{rel}}}$$

already significant reaction rates at 10…20 keV

Why has the reaction D-T a large cross section at relatively low tempertures?

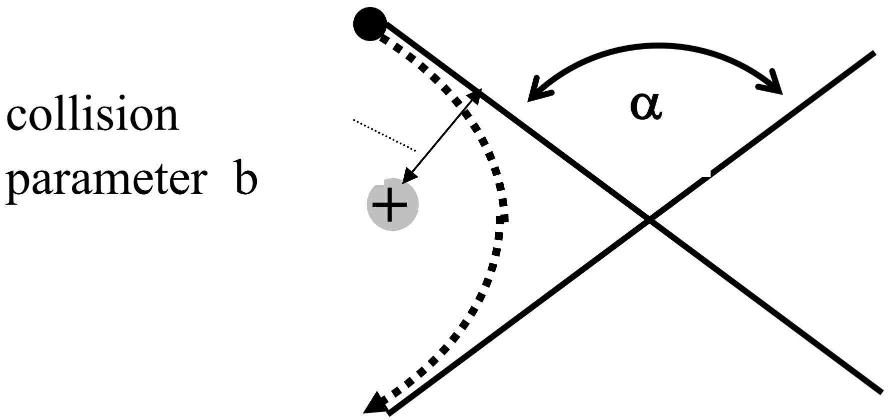
resonant mechanism!

energy level diagram of unstable $^{5}_{2}He$



D-T mass equivalent by 64 keV below excited ^{5}He state

Fusion vs. Coulomb Collisions
(or why we need a thermal plasma)



example:
e-collision with ion (charge Z)

Rutherford's formula with $m_e << m_i$:

$$\tan(\alpha/2) = \frac{W_{pot}}{2W_{kin}} = \frac{e \cdot Z \cdot e}{(4\pi\varepsilon_0) \cdot m_e \mathrm{v}^2 \cdot b}$$

cross section for scattering by 90º:

$$\sigma_{90} = \pi . b_{90}^2 = \frac{\pi \cdot Z^2 \cdot e^4}{(4\pi\varepsilon_0)^2 \cdot 4 \cdot (W_{kin})^2}$$

⇒ Coulomb cross section depends strongly on particle energy : ~ $1/W_{kin}^2$

T beam on target of deuterium ?

Assume T energy: 100 keV

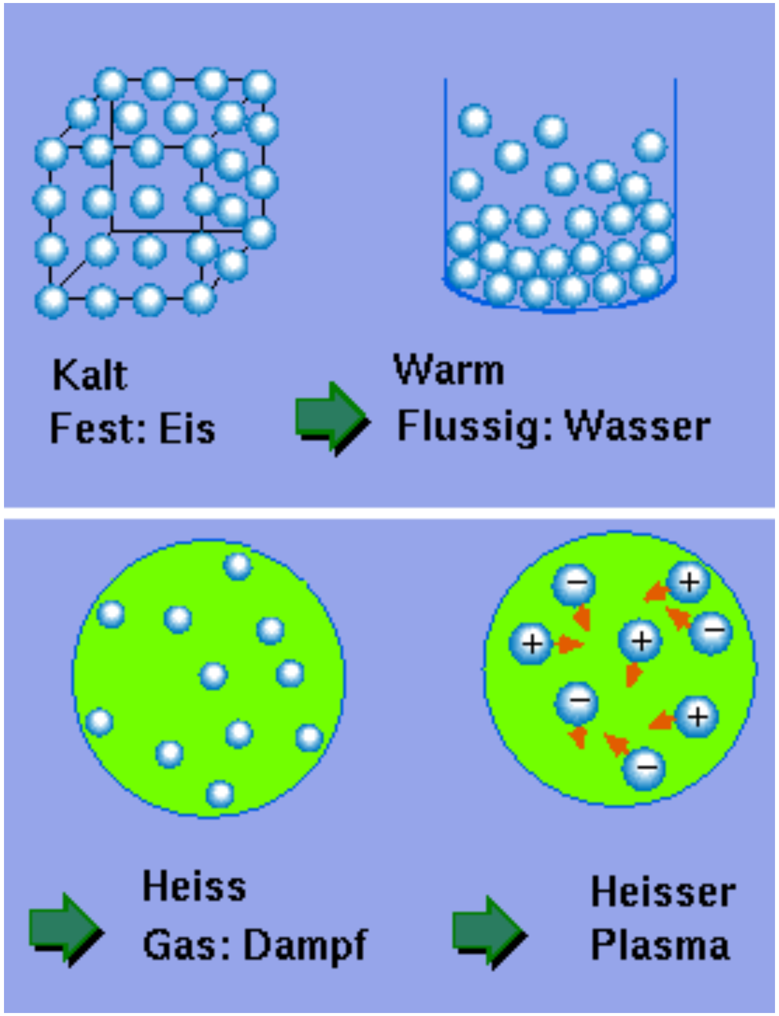
Mean free path for fusion reactions: 2.9 10^{27} m/n[m^{-3}]

Mean free path for Coulomb collision: 1.9 10^{22} m/n[m^{-3}]

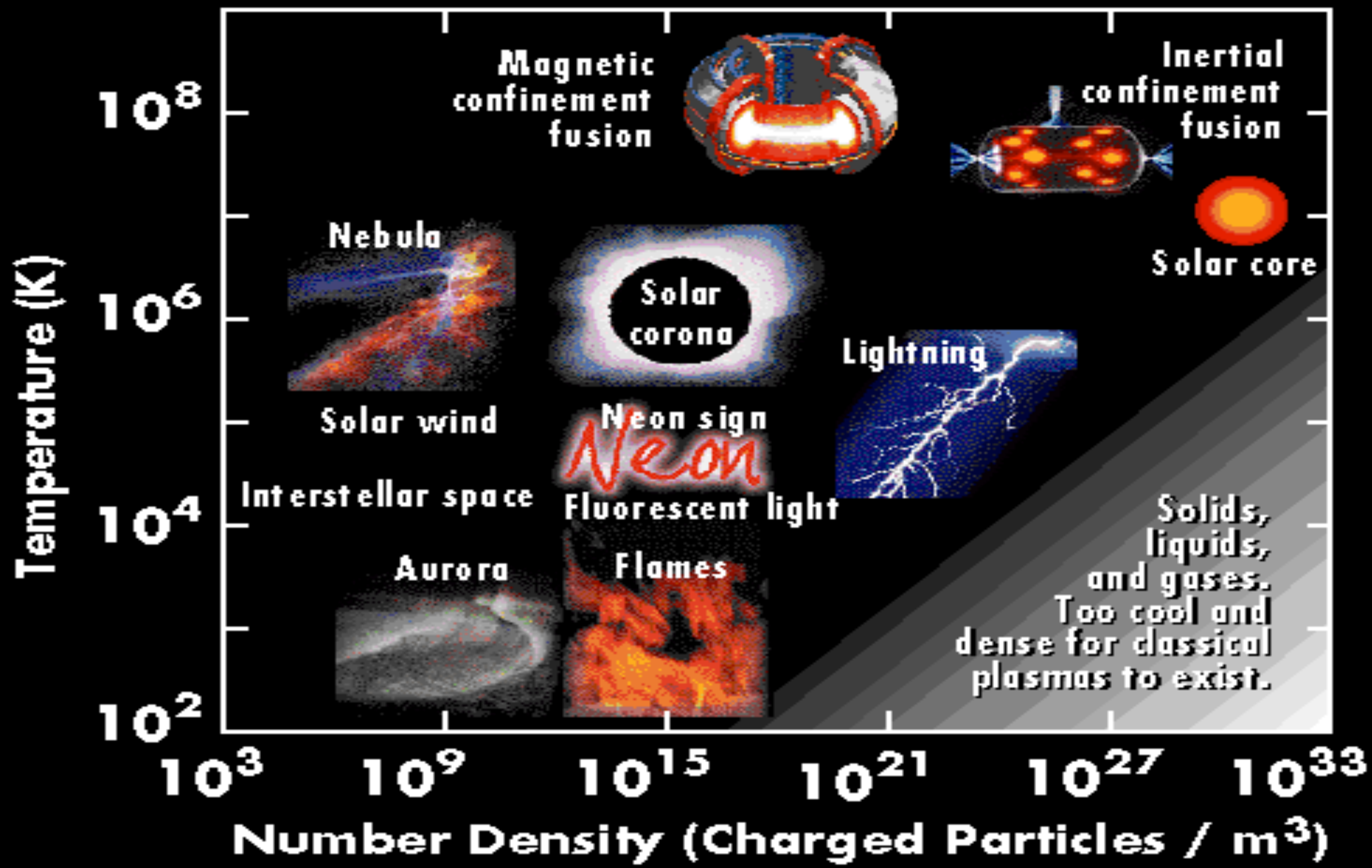
Orders of magnitude more Coulomb collisions than fusion reaction

Need to confine "thermal" plasma

Plasma, the fourth state of matter

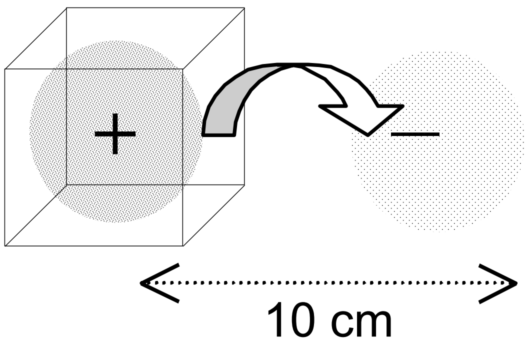


- free electrons and ions
- good electrical conductivity
- long range forces
- high thermal conductivity
- forces due to magnetic fields



Magnetic confinement fusion
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)

Quasi neutrality



Poisson equation

$$\Delta U = -\frac{1}{\varepsilon_0}\rho(r) = -\frac{e}{\varepsilon_0}\left(Zn_i(r) - n_e(r)\right)$$

For particle densities of about 10^{16} m^{-3} a shift of all electrons by about 10 cm corresponds to a voltage of about 2 Mio V

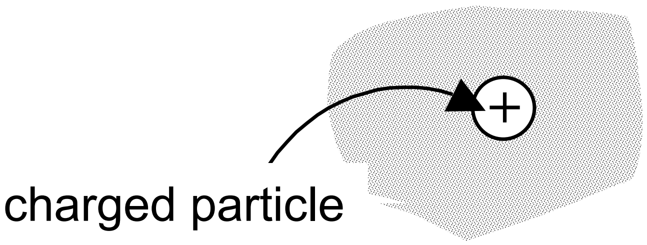
Macroscopic (> mm ... cm) charge separation in plasmas impossible!

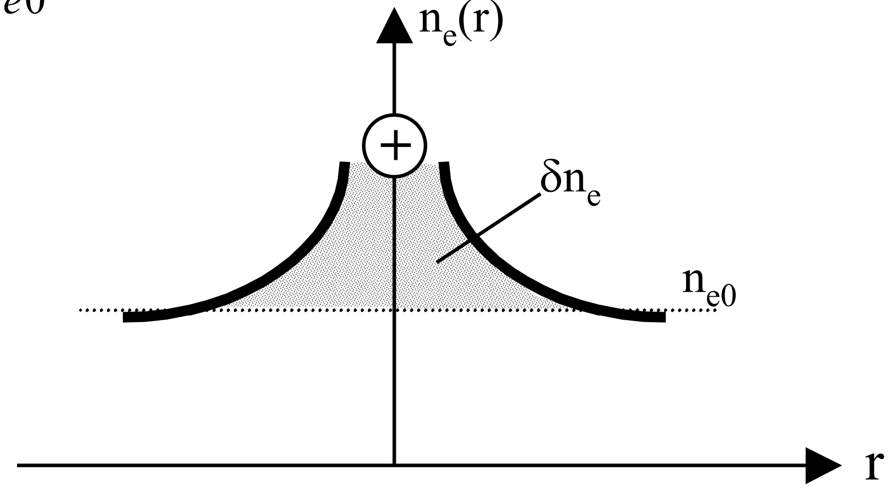
$$n_i - n_e \approx 0$$

Screening

Local deviations from quasi neutrality (microscopic scales) -> re-ordering of charged particles such that electric fields are screened on macroscopic scales

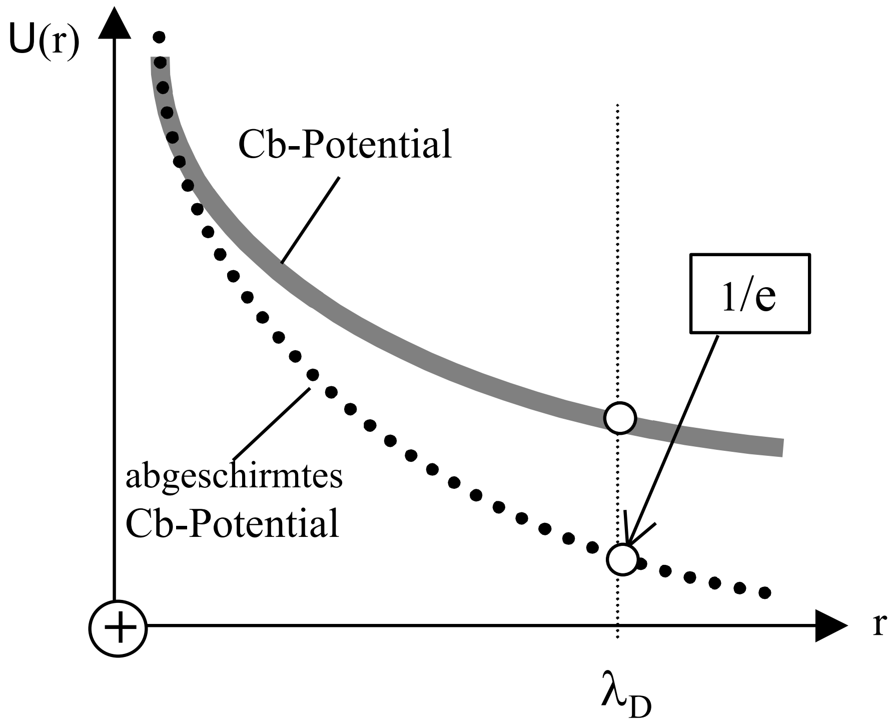
$$n_e(r) = n_{e0} \cdot e^{|E_{pot} / E_{kin}|} = n_{e0} \cdot e^{\frac{e \cdot U(r)}{kT_e}}$$





Also external fields are screened

Debye Screening



r << λ_D: Coulomb-Potential

r >> λ_D: outside Debye length only very small electrical

Inside Debye length charge separation possible
-> Plasma extensions has to be large compared to Debye length

$$N_e = n_e \cdot \frac{4\pi}{3} \cdot \lambda_D^3 = \left(\frac{\varepsilon_0}{e^2}\right)^{3/2} \cdot \frac{kT_e^{3/2}}{\sqrt{n_e}}$$

	λ_D	N_D
fusion plasma (10 keV, $10^{20}m^{-3}$)	**75 µm**	**$2\cdot10^8$**
technical plasma (5 eV, $10^{17}m^{-3}$)	**50 µm**	**$6\cdot10^4$**
astrophysical Plasma (1 eV, 10 m^{-3})	**75 km**	**$5\cdot10^{11}$**
dense plasma (1,5 eV, $10^{24}m^{-3}$)	**0,01 µm**	**3** ***=limit to non-ideal plasmas***

1 eV = 11600 K bzw. 10 keV~100 Mio K

Plasma properties

$n_e = Z\, n_i$ = strict quasi neutrality

$L >> \lambda_D$ = system size large compared to Debye length

$N_{tot} >> N_D$ = sufficient number of particles in the system

To overcome the Coulomb barrier, we need a thermal plasma as the cross section for Coulomb collisions is larger than the fusion cross section (>100 times)!

Fusion cross section in a thermal plasma:

$$\langle \sigma(u)\, u \rangle = \frac{(m_a m_b)^{3/2}}{(2\pi kT)^3} \int d^3 v_a \int d^3 v_b\, \sigma(|\mathbf{v}_a - \mathbf{v}_b|) \exp\left[-\frac{m_a v_a^2}{2kT}\right] \exp\left[-\frac{m_b v_b^2}{2kT}\right]$$

Centre of mass-system: $$E_{kin} = \frac{1}{2} m_a v_a^2 + \frac{1}{2} m_b v_b^2 = \frac{1}{2}(m_a + m_b) V^2 + \frac{1}{2} m_r u^2$$

$$\langle \sigma(u)\, u \rangle = \frac{(m_a m_b)^{3/2} (4\pi)^2}{(2\pi kT)^3} \int_0^\infty dV\, V^2 \exp\left[-\frac{(m_a + m_b) V^2}{2kT}\right] \int_0^\infty du\, \sigma(u)\, u^3 \exp\left[-\frac{m_r u^2}{2kT}\right]$$

$$\int x^2\, e^{-a^2 x^2}\, dx = \frac{\sqrt{\pi}}{4a^3}$$

$E_r = 1/2\; m_r u^2$

Fusion cross section in a thermal plasma:

$$\langle \sigma(u)\, u \rangle = \frac{(m_a m_b)^{3/2} (4\pi)^2}{(2\pi kT)^3} \int_0^\infty dV\, V^2 \exp\left[-\frac{(m_a + m_b) V^2}{2kT}\right] \int_0^\infty du\, \sigma(u)\, u^3 \exp\left[-\frac{m_r u^2}{2kT}\right]$$

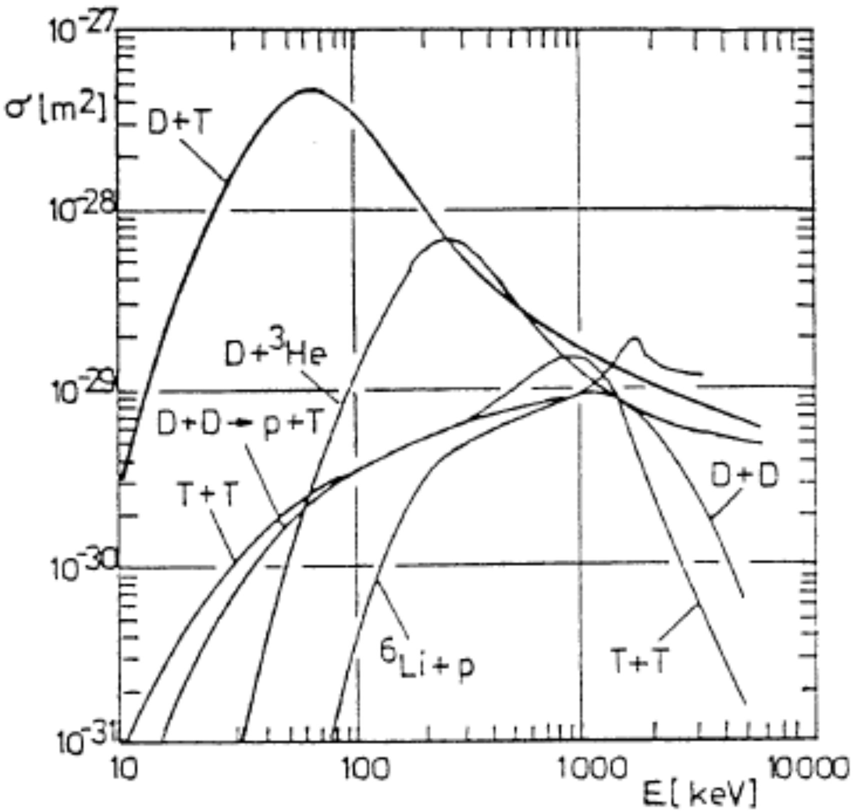
$$\int x^2\, e^{-a^2 x^2}\, dx = \frac{\sqrt{\pi}}{4a^3}$$

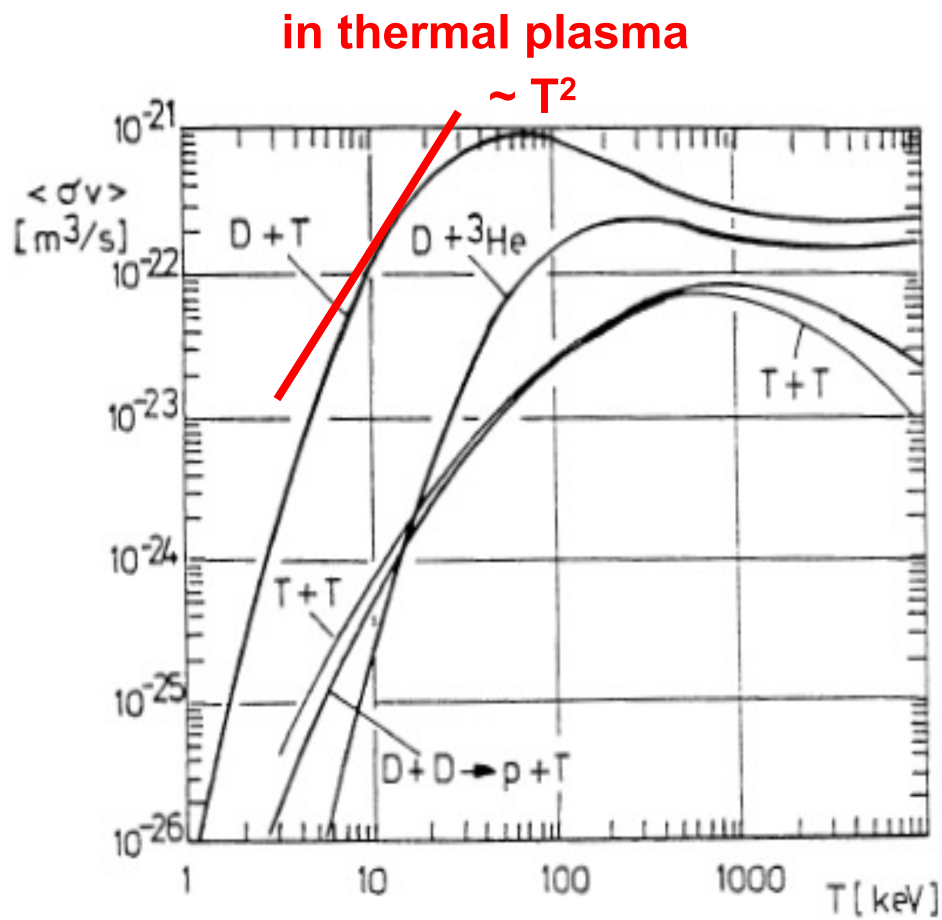
$E_r = 1/2\ m_r u^2$

$$\langle \sigma(u)\, u \rangle = \frac{4}{(2 m_r \pi)^{1/2} (kT)^{3/2}} \int_0^\infty dE_r\, \sigma(E_r)\, E_r \exp\left(-\frac{E_r}{kT}\right)$$

Thermal plasma with 10 …. 20 keV needed for gaining energy from fusion reactions

Cross section:





Deuterium-Tritium-Fusion

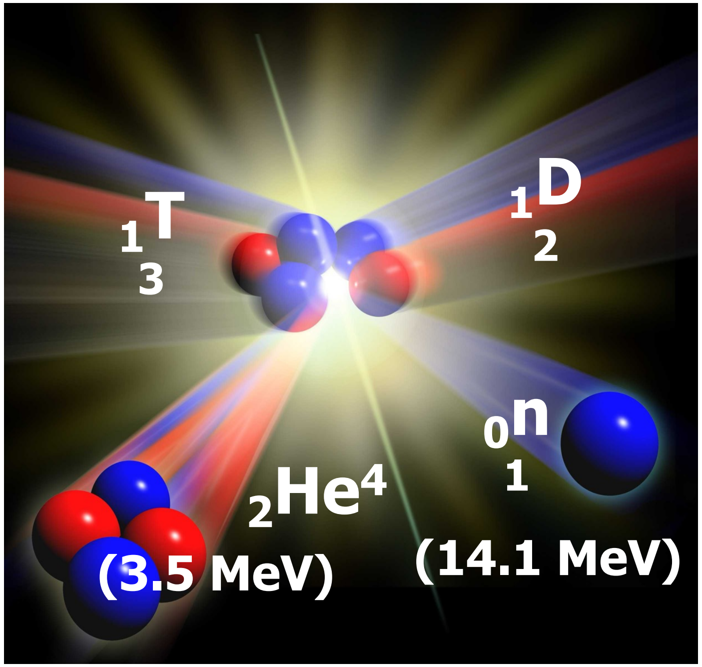
Fusion power $$P_{fus} = \frac{n_1 n_2}{2} \langle \sigma v \rangle \, Q$$

D-T fusion:

highest fusion power for $n_D : n_T = 1 : 1$

$$n_{DT} = n_D + n_T$$

$$P_{fus,DT} = \frac{n_{DT}^2}{4} \cdot \langle \sigma \, \mathrm{v} \rangle_{DT} \cdot Q_{DT}$$



How is energy gain Q_{DT} distributed to fusion products?

Deuterium-Tritium-Fusion

How is energy gain Q_{DT} distributed to fusion products?

Follows from momentum and energy conservation

momentum conservation:

$$m_{He} \cdot \mathrm{v}_{\mathrm{He}} \approx -m_n \cdot \mathrm{v}_n$$

As momentum of the particles prior to fusion reaction is negligible

Energy conservation:

$$\frac{m_{He}}{2}\mathrm{v}_{He}^2 + \frac{m_n}{2}\mathrm{v}_n^2 \approx Q_{DT} = 17{,}5 MeV$$

Deuterium-Tritium-Fusion: energy of fusion products

momentum conservation:

$$m_{He} \cdot \mathrm{v}_{\mathrm{He}} \approx -m_n \cdot \mathrm{v}_n$$

$$m_{He}^2\, v_{He}^2 = m_n^2\, v_n^2$$

$$\frac{m_{He} v_{He}^2}{2} = \frac{m_n^2\, v_n^2}{2\, m_{He}}$$

Energy conservation:

$$\frac{m_{He}}{2}\mathrm{v}_{He}^2 + \frac{m_n}{2}\mathrm{v}_n^2 \approx Q_{DT} = 17{,}5 MeV$$

$$\frac{m_n^2\, v_n^2}{2\, m_{He}} + \frac{m_n\, v_n^2}{2} = Q_{DT} = 17{,}5\ MeV$$

$$\left(1 + \frac{m_n}{m_{He}}\right) E_n = \left(1 + \frac{1}{4}\right) E_n = 17{,}5\ MeV$$

E_n=4/5 x 17,5 MeV=14.1 MeV

E_{He}= 1/5 x 17,5 MeV=3.5 MeV

Energy gain is distributed to fusion products according to: $\frac{E_{He}}{E_n} = \frac{m_n}{m_{He}} = 1:4$

Power balance – Lawson criterion

power gain (of the plasma):

$$P_{fus,charged} = \frac{n_{DT}^2}{4} \langle \sigma v \rangle_{DT} \, 0.2 \, Q_{DT}$$

Only the energy carried by the alpha particles heat the plasma
(the neutrons don‘t interact with the plasma)

total thermal energy of the plasma

power loss :

$$P_{loss} \equiv \frac{3/2 \cdot (n_e + n_{DT}) \cdot kT}{\tau_E}.$$

τ_E : Energy confinement time (characteristic cooling down time)

Power balance – Lawson criterion

$$P_{fus,charged} = \frac{n_{DT}^2}{4} \langle \sigma v \rangle_{DT} \, 0.2 \, Q_{DT}$$

$$P_{loss} \equiv \frac{3/2 \cdot (n_e + n_{DT}) \cdot kT}{\tau_E}.$$

Fusion cross section: $\langle \sigma \mathrm{v} \rangle_{DT} \sim T^2$ (at T ~ 10 … 20 keV)

Quasi neutrality: $n_e = n_{DT}$

$$P_{fus,charged} \sim \frac{n_e^2}{4} T^2 \, Q_{DT}/5$$

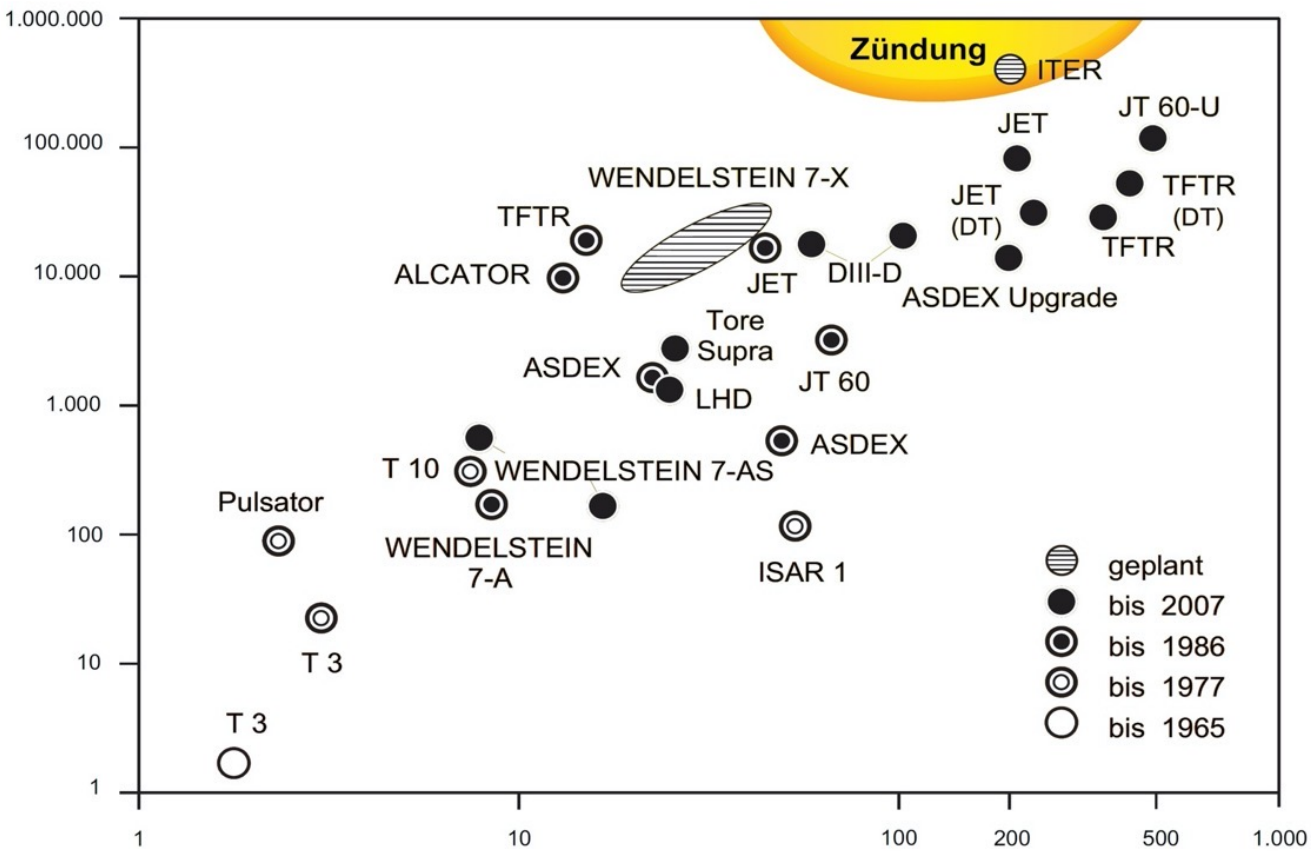
$$P_{loss} \sim \frac{3n_e}{\tau_E} kT$$

power balance : $P_{fus,charged} = P_{loss}$

Lawson criterion: $n_e \cdot T \cdot \tau_E = const$ $\langle n_e \rangle \cdot T_i(0) \cdot \tau_E = const$

Figure of merit in fusion research

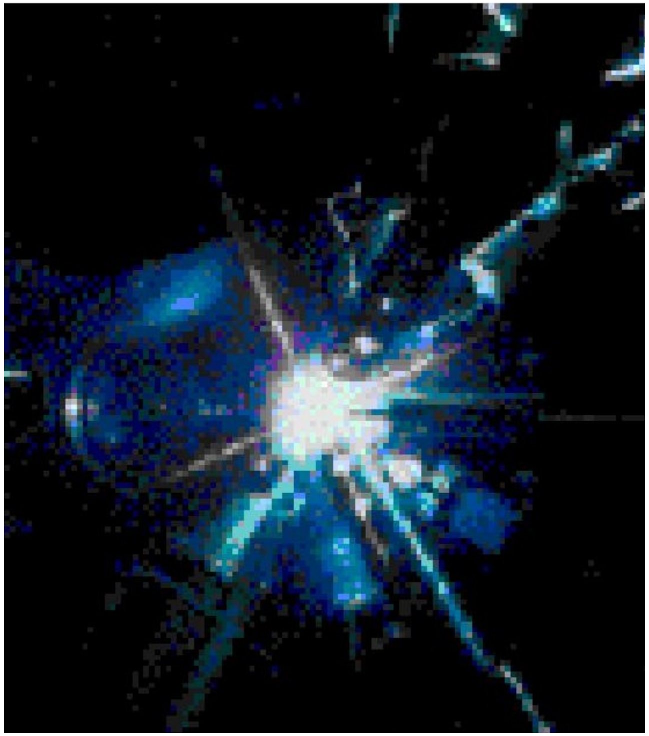
$n_e \, T \, \tau_E$



T

Inertial fusion

$n\tau_E$ and T are fixed, but pressure *p=nT is free to choose*



Inertial fusion:

- Fast heating with laser or Heavy ion beam
- confinement due to inertia (ion sound wave time scale)
- Miniature explosion

n large (10^{31} m^{-3}), τ_E small (10^{-10} s)

$\Rightarrow$ pressure comparable to the solar core (!)

Ignition condition changes in the presence of impurities

Lawson criterion $n_e \cdot T \cdot \tau_E = const$ achieved for "pure" plasmas: $n_e = n_{DT}$

- Actually what counts for fusion reaction is n_{DT}
- In reality, not only D,T ions, but at least also He, and in addition impurities due to interaction with wall materials

With impurity ions Lawson criterion will be modified by impurity ions for two reasons:

Dilution:
at same plasma pressure
p~$n_e T$ less D-T ions

Radiation:
mainly bremsstrahlung
(but also line radiation)

Ignition condition: Effect of dilution

Quasi neutrality, more generally: $n_e = \sum_z Z n_{z,i} \quad \rightarrow \quad 1 = \sum_z Z\, n_{z,i}/n_e$

If only *D* and *T* ions: $1 = f_{DT}$ $\qquad f_{DT} \equiv \frac{n_D + n_T}{n_e}$

„dilution“ due to impurity ions:

$$1 = f_{DT} + 2f_{He} + \ldots + 6f_C = f_{DT} + 2f_{He} + \sum_{i\geq 3} Z_i f_i$$

$$f_{DT} \equiv \frac{n_D + n_T}{n_e}; \qquad f_{He} \equiv \frac{n_{He}}{n_e}; \qquad f_C \equiv \frac{n_C}{n_e}$$

Example:

10% He, 2% C

$1 = f_{DT} + 0.2 + 0.12$

$f_{DT} = 0.68$

Ignition condition: Effect of dilution

at the same pressure less D-T-ions with significant influence on fusion power:

$$P_{fus,charged} = \frac{n_{DT}^2}{4}\langle\sigma v\rangle_{DT}\ Q_\alpha = \frac{f_{DT}^2 n_e^2}{4}\langle\sigma v\rangle_{DT}\ Q_\alpha$$

Example:

10% He, 2% C

$f_{DT} = 0.68$

→ Fusion power reduced by factor of 2

Energy balance, incl.radiation losses:

$$\frac{f_{DT}^2}{4}\cdot n_e^2\cdot\langle\sigma v\rangle_{DT}\cdot Q_\alpha = \frac{3/2\cdot n_e\cdot(1+f_{DT}+f_{He}+\sum_{i\geq 3} f_i)\cdot kT}{\tau_E^*} + P_{rad}$$

τ_E^* : energy confinement time, corrected for radiation losses

He content

Energy balance:

$$\frac{f_{DT}^2}{4} \cdot n_e^2 \cdot \langle \sigma v \rangle_{DT} \cdot Q_\alpha = \frac{3/2 \cdot n_e \cdot (1 + f_{DT} + f_{He} + \sum_{i \geq 3} f_i) \cdot kT}{\tau_E^*} + P_{rad}$$

Particle balance (He):

$$\frac{f_{DT}^2}{4} \cdot n_e^2 \cdot \langle \sigma \, \mathrm{v} \rangle_{DT} = \frac{n_e \cdot f_{He}}{\tau_{p(He)}}$$

„production rate " of He

„loss rate " of He (transport)

He content

Combine energy and particle balance and solve for f_{He}:

$$\frac{f_{DT}^2}{4} \cdot n_e^2 \cdot \langle \sigma v \rangle_{DT} \cdot Q_\alpha = \frac{3/2 \cdot n_e \cdot (1 + f_{DT} + f_{He} + \sum_{i \geq 3} f_i) \cdot kT}{\tau_E^*} + P_{rad} \qquad (1)$$

$$\frac{f_{DT}^2}{4} \cdot n_e^2 \cdot \langle \sigma \mathrm{v} \rangle_{DT} = \frac{n_e \cdot f_{He}}{\tau_{p(He)}} \qquad (2)$$

(1)/(2):

$$Q_\alpha = \frac{3}{2} \frac{(1 + f_{DT} + f_{He} \ldots)kT}{\tau_E^*} \frac{\tau_p}{f_{He}} + \frac{P_{rad}\tau_p}{n_e f_{He}}$$

He content

$$Q_\alpha = \frac{3}{2}\frac{(1+f_{DT}+f_{He}\ldots)kT}{\tau_E^*}\frac{\tau_p}{f_{He}} + \frac{P_{rad}\tau_p}{n_e f_{He}}$$

Solve for f_{He}:

$$= \frac{P_{rad}}{P-P_{rad}}$$

$$f_{He} = \frac{3}{2}\frac{\tau_p}{\tau_E^*}\frac{kT}{Q_\alpha}(1+f_{DT}+f_{He}\ldots)\left[1+\frac{P_{rad}}{n_e}\frac{2\tau_E^*}{3kT(1+f_{DT}+f_{He}\ldots)}\right]$$

With $P-P_{rad}=$ $$\frac{3/2\cdot n_e\cdot(1+f_{DT}+f_{He}+\sum_{i\geq 3} f_i)\cdot kT}{\tau_E^*}$$

$$f_{He} = \frac{\tau_p}{\tau_E^*}\cdot\frac{3kT}{Q}\cdot\frac{1}{\left(1-P_{rad}/P\right)}\cdot\left(\frac{1+f_{DT}+f_{He}+\sum_{i\geq 3} f_i}{2}\right)$$

He content

$$f_{He} = \frac{\tau_p}{\tau_E^*} \cdot \frac{3kT}{Q} \cdot \frac{1}{\left(1 - {P_{rad}}/{P}\right)} \cdot \left(\frac{1 + f_{DT} + f_{He} + \sum_{i \geq 3} f_i}{2} \right)$$

simplify ($f_{He} << f_{DT}$):

$$f_{He} \approx \frac{\tau_p}{\tau_E^*} \cdot \frac{3kT}{Q} \cdot \frac{1}{\left(1 - {P_{rad}}/{P}\right)}$$

Important: particle confinement time needs to be sufficiently short

Experience: $$\frac{\tau_p}{\tau_E^*} \geq \frac{\chi_\perp}{D_\perp}; \quad \frac{\tau_p}{\tau_E^*} \approx 3$$

Now include radiation losses:

Main contributions: Bremsstrahlung and line radiation

Bremsstrahlung:

$$P_{rad,brems} = c_{brems} \cdot n_e \cdot \sum_{i \geq 1} Z_i^2 \cdot n_i \cdot \sqrt{T}$$

$$= c_{brems} \cdot n_e^2 \cdot Z_{eff} \cdot \sqrt{T}$$

Effective charge number:

$$Z_{eff} \equiv \frac{\sum_i Z_i^2 \cdot n_i}{\sum_i Z_i \cdot n_i} = \sum_{i \geq 1} Z_i^2 f_i$$

$=n_e$

Now include radiation losses:

Bremsstrahlung:

$$P_{rad,brems} = c_{brems} \cdot n_e \cdot \sum_{i \geq 1} Z_i^2 \cdot n_i \cdot \sqrt{T}$$

$$= c_{brems} \cdot n_e^2 \cdot Z_{eff} \cdot \sqrt{T}$$

$$Z_{eff} \equiv \frac{\sum_i Z_i^2 \cdot n_i}{\sum_i Z_i \cdot n_i} = \sum_{i \geq 1} Z_i^2 f_i$$

Power balance (incl. radiation losses):

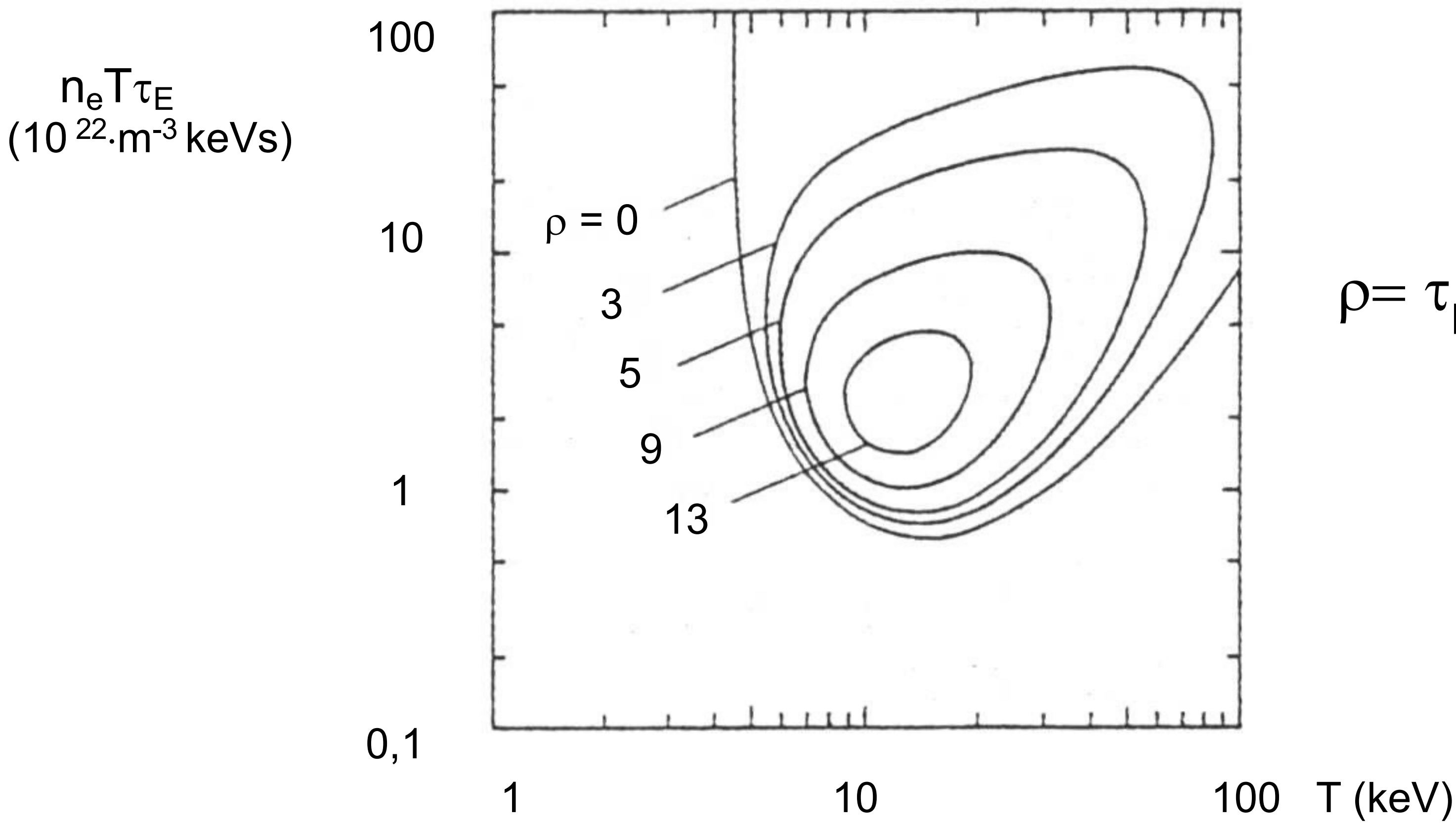
$\sim T^2$

$$n_e^2 \cdot \left\{ \frac{f_{DT}^2}{4} \cdot \langle \sigma v \rangle_{DT} \cdot Q_{DT} - c_{brems} \cdot \left(f_{DT} + 4 f_{He} + \sum_{i \geq 3} Z_i^2 f_i \right) \cdot \sqrt{T} \right\}$$

$$= \frac{3/2 \cdot n_e \cdot (1 + f_{DT} + 2 f_{He} + \sum_i Z_i f_i) \cdot kT}{\tau_E^*}$$

τ_E^* : energy confinement time, corrected for radiation losses

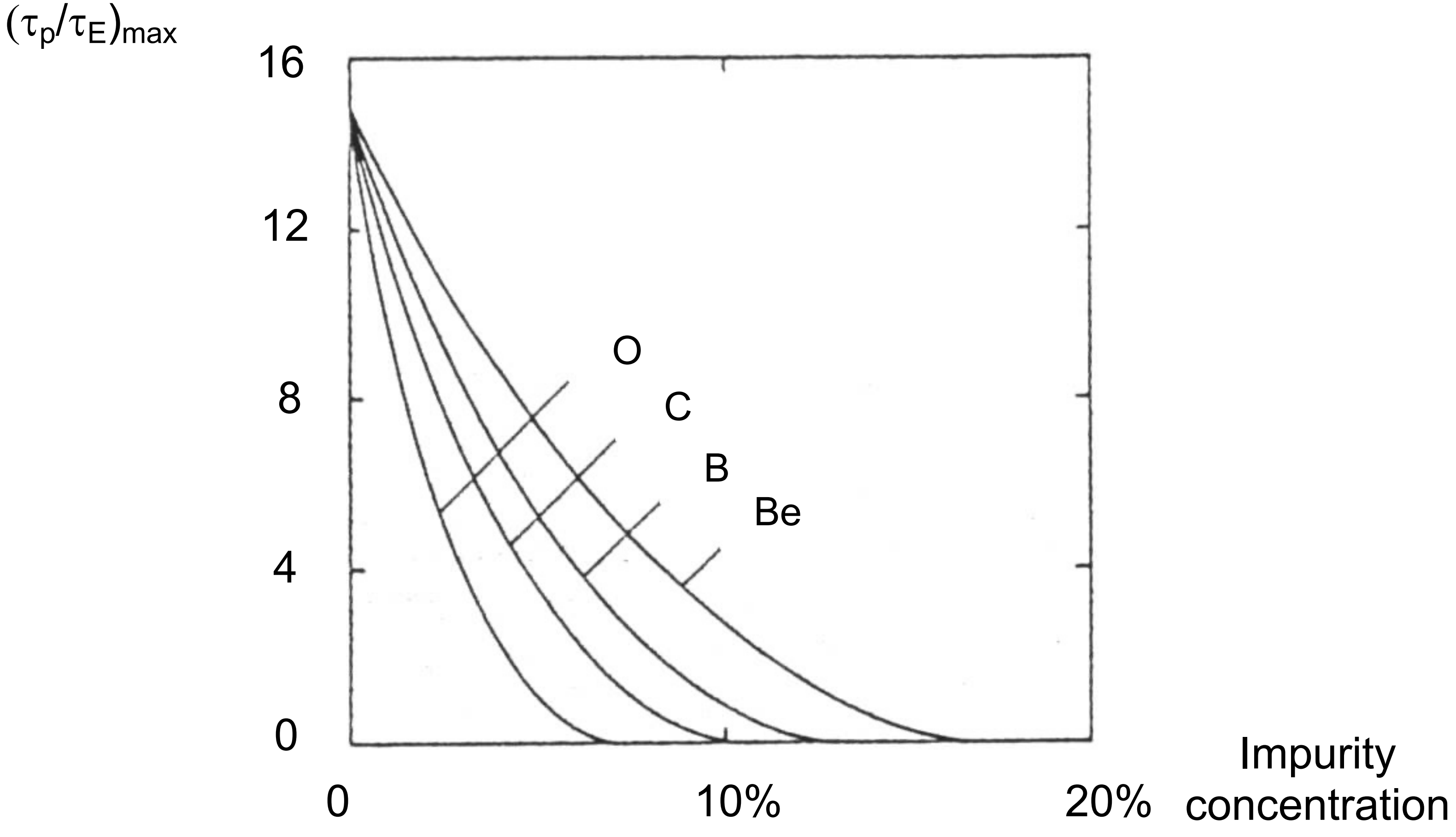
Ignition condition with helium ash:



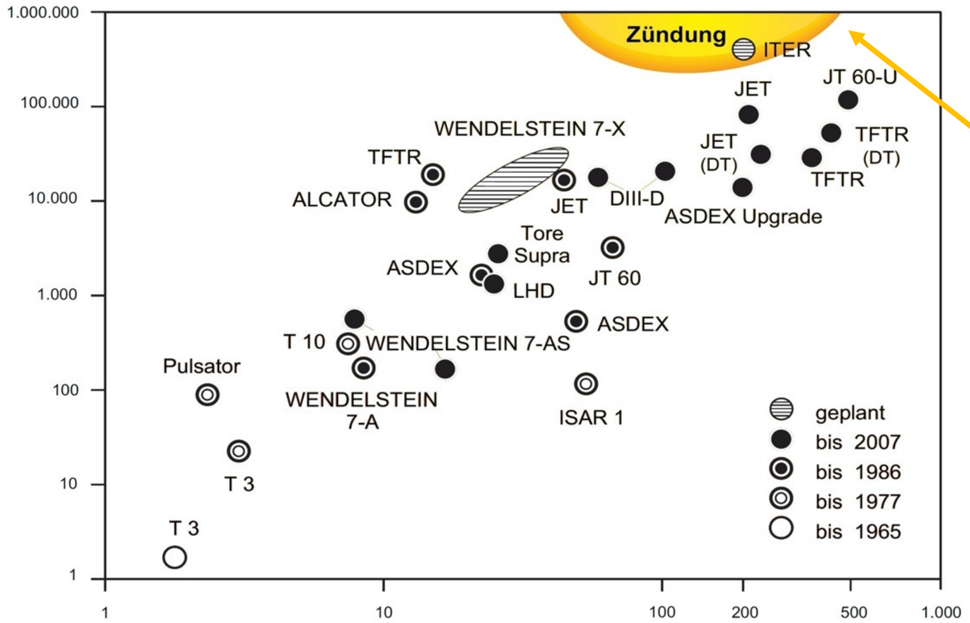
$\rho = \tau_p / \tau_E$

$$\frac{\tau_p}{\tau_E^*} \geq \frac{\chi_\perp}{D_\perp}; \quad \frac{\tau_p}{\tau_E^*} \approx 3$$

Other impurities:



Requirements for a reactor



$$Q \equiv \frac{P_{fus,tot}}{P_{extern}}$$

Q = 1 break even (definition)

Q ≥ 30..40 minimal value for economical reactor

Q = ∞ fully ignited plasma

Cold fusion ?

1989 Pons and Fleischmann claimed:

- fusion of hydrogen (protium, deuterium, tritium) nuclei in palladium during electrolysis
- their explaination: lower Coulomb barrier if hydrogen in solid state
- However: not reproducible, explaination wrong

Myon-catalysed fusion

Myonic hydrogen:

Binding length: $$a = a_0 \frac{m_e}{m_\mu} = 5.3 \cdot 10^{-11} m / 207 \approx 2.5 \cdot 10^{-13} m$$

Add myons to D_2T_2-gas mix:

- Myons slowed down by collisions with molecules
- Formation of D_2, T_2 and D-T molecules

Probability for tunneling is increased: reaction time 10^{-10}s

$$(D\mu T)^+ \rightarrow {}^4_2He + n + \mu^- + 17.6\,\mathrm{MeV}$$

Myons: catalyst

Myon catalysed fusion

- generate myons in accelerator (3 GeV)
- Myons decay with ~2 10^{-6} s $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
- Slow down in D_2T_2 gas mix , time for building DμT: 10^{-9} s
- Myon could catalyse about 2000 fusion reactions

problem: competing reaction (probability: 0.6%)

$$(D\mu T)^+ \rightarrow {}^4_2He\mu^- + n + 17.6\,\mathrm{MeV}$$

Probability that myon „survives“ N reactions: $(1 - 0.006)^N \sim 1 - 0.006\,N$

One myon can theoretically catalyse only N = 1/0.006 = 170 fusion reactions

(in experiment: about 100)

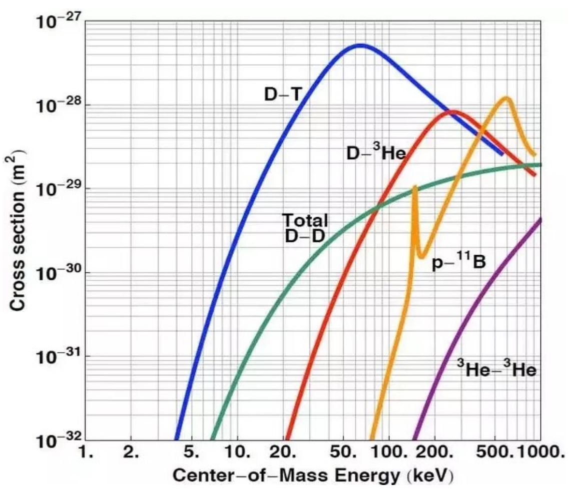
no positive energy balance

Neutron-free fusion reactions

$^{2}D + ^{3}T \rightarrow ^{4}He$ (3.5MeV) + n (14.1MeV) + 17.6MeV

$^{2}D + ^{3}He \rightarrow ^{4}He$ (3.7MeV) + p (14.6MeV) + 18.3MeV (but: D-D reaction and ^{3}He availability)

$p + ^{11}B \rightarrow 3^{4}He$ + 8.7MeV



Parameter\Reaction	D-T	D-He^{3}	D-D	H-B^{11}
optimum composition for maximum fusion power at given pressure (Te=Ti)	1:1	3:2	1:1	3:1
maximum fusion power density at constant pressure (rel.units)	1,00	0,02	0,04	0,0013
maximum ratio $<\sigma v>/T^2$	1,00	0.022	0.013	0,008
burn temperature[keV] optimized for power density at given pressure	15,00	50,00	20,00	140,00
minimum required nTτ for ignition (rel.units)	1	11	16	100

also the impurity profiles play a role: