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2nd International Workshop on Proton-Boron Fusion

Parametric scan of plasma parameters for optimization of the avalanche process in p-^{11}B fusion

By:

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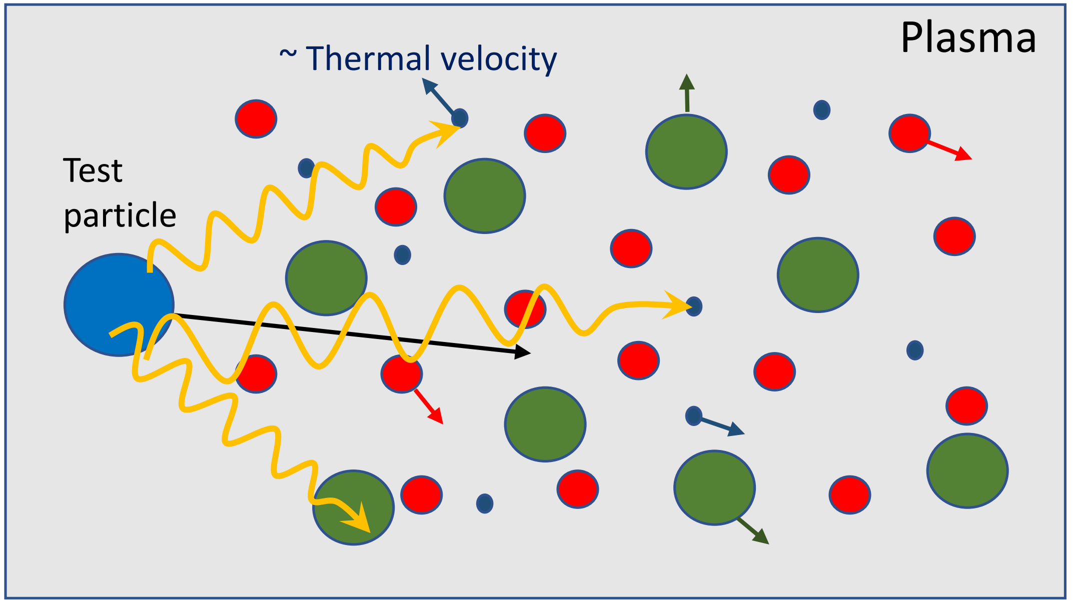
Outlook

1. Terminology
2. Introduction - Our non-LTE scenario
3. The fusion probability dependance on temperature and electron density
4. Multiplication calculations
5. Conclusion

Terminology 1 – Microscopic interactions

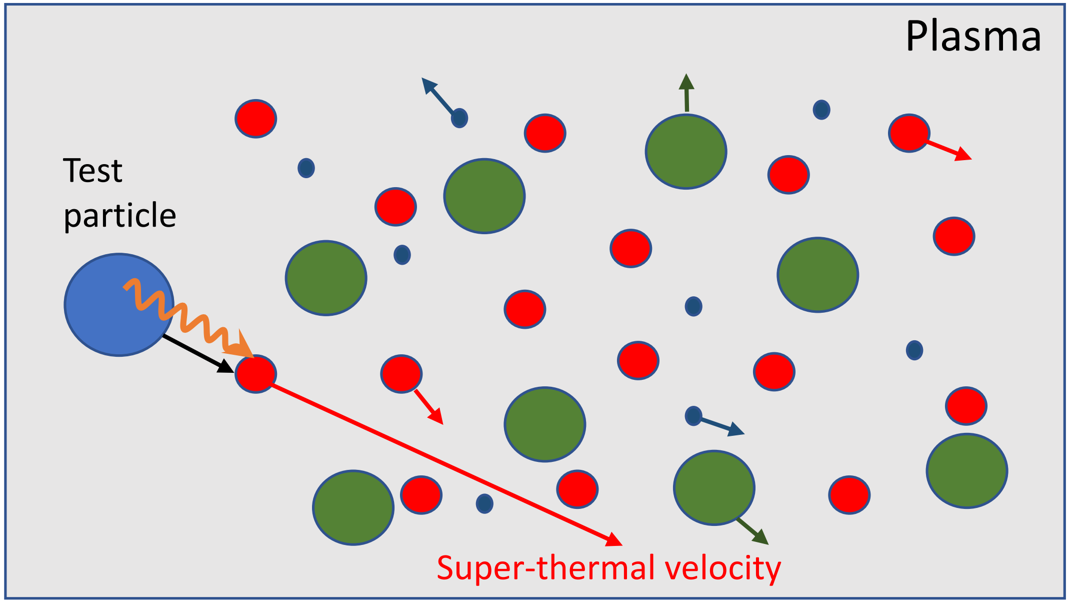
Stopping power

Averaged elastic collisions with many particles =>
After the collision, the particles energy remain close to thermal



Elastic collision

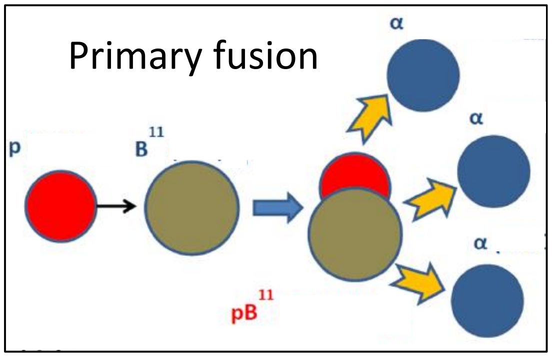
Elastic collisions with one specific particle
=>
After the collision, the particles energy is super-thermal

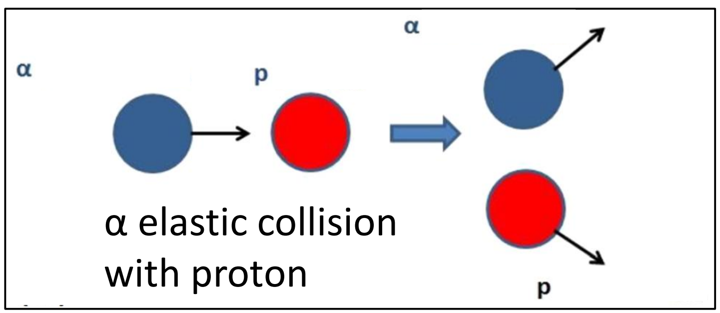


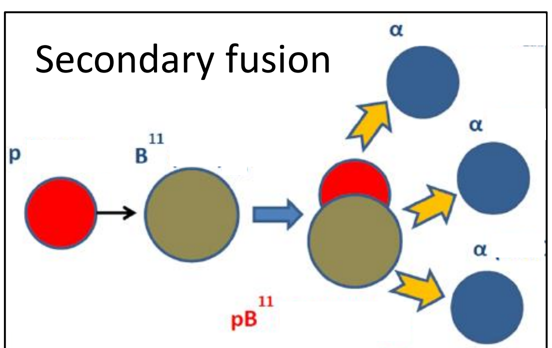
Both interactions may exist simultaneously

Terminology 2 – Microscopic interactions

Elastic chain reaction

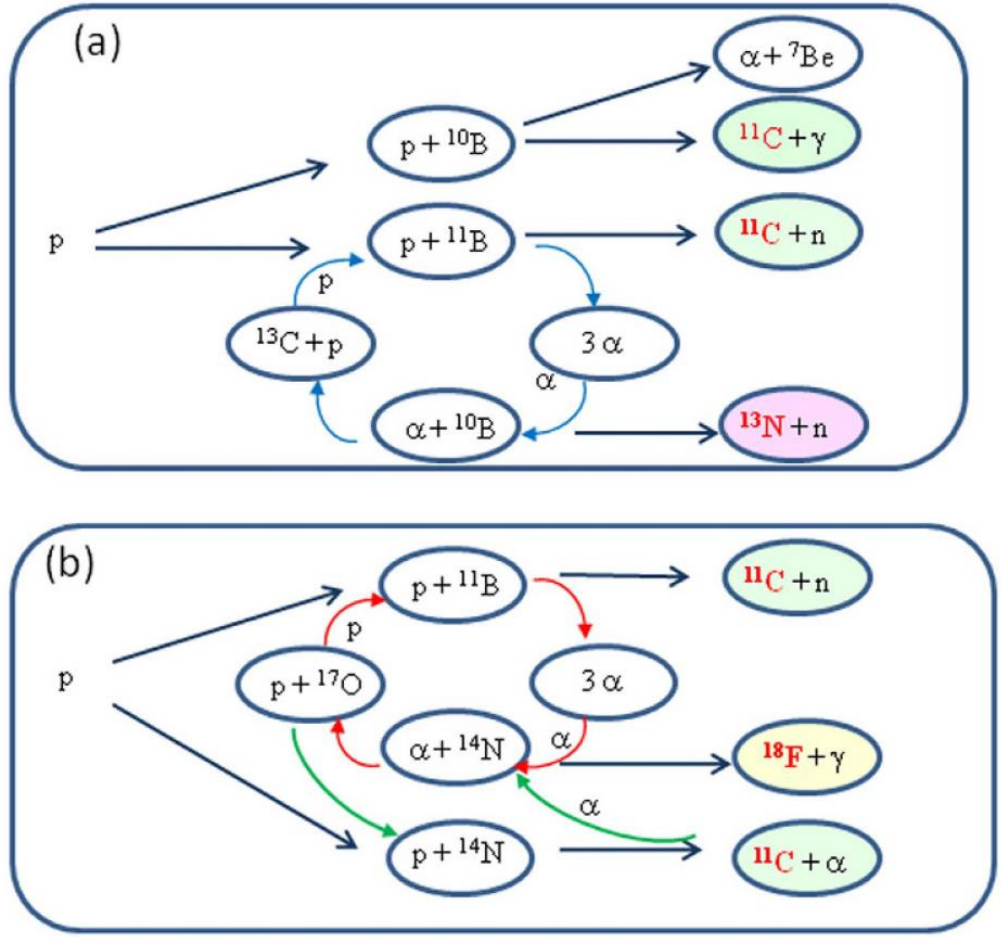






S. Eliezer et al., Phys. Plasmas, **23**, 050704, (2016)

Nuclear chain reaction



C. Labaune et al., Scientific Reports, **6**, 21202 (2016).

Terminology 3 – Avalanche effect -Macroscopic effect

Can happen in LTE or non-LTE

$$dN = N \cdot \alpha \cdot dt \Rightarrow M = \frac{N}{N_0} = e^{\int_0^{t'} \alpha\, dt}$$

M – Multiplication factor

Non-LTE p-B fusion case [an over simplified view]

The fusion probability in a time interval:

$$\Delta P_f(t, t+dt) = n_B \sigma_f(v_{p0}) v_{p0} dt$$

The number of fusion reactions in a time interval:

$$dN_f = N_p(t) \cdot \Delta P_f(t, t+dt) = N_p(t) n_B \sigma_f(v_{p0}) v_{p0} dt$$

$$dN_\alpha = 3 N_p n_B \sigma_f(v_{p0}) v_{p0} dt$$

The number alphas generated in a time interval

$$dN_p = dN_\alpha \cdot P_{\alpha p} = P_{\alpha p} 3 N_p(t) n_B \sigma_f(v_{p0}) v_{p0} dt$$

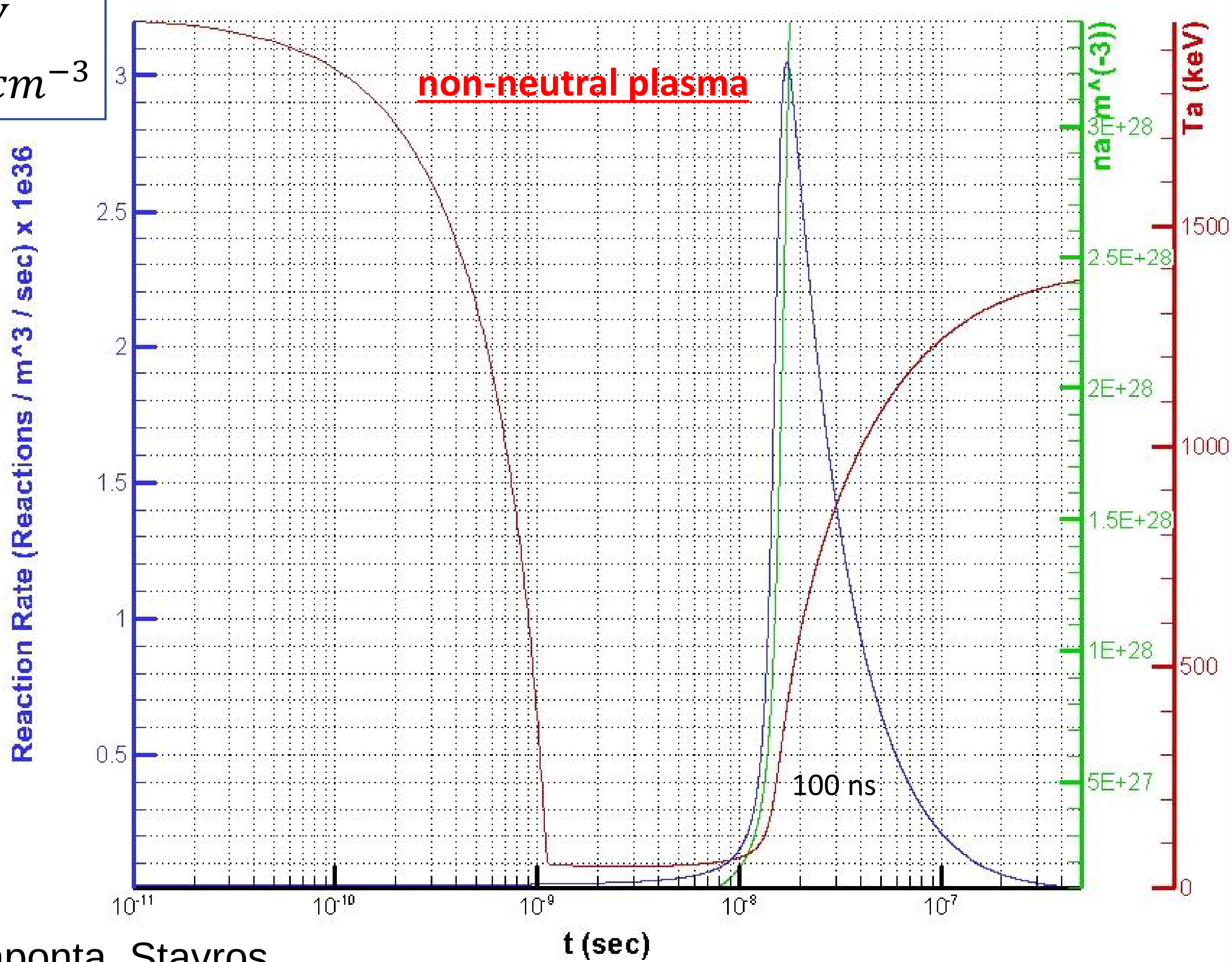
The number protons is determined by the elastic collision probability.

$$\frac{dN_p}{N_p(t)} = P_{\alpha p} 3 n_B \sigma_f(v_{p0}) v_{p0} dt \Rightarrow M = \frac{N_{pf}}{N_{p0}} = e^{\int_0^{t'} P_{\alpha p} 3 n_B \sigma_f(v_{p0}) v_{p0} dt}$$

Terminology 4

LTE case - Simulation of p-B fusion with 4 thermal fluids (B,p,e,α)

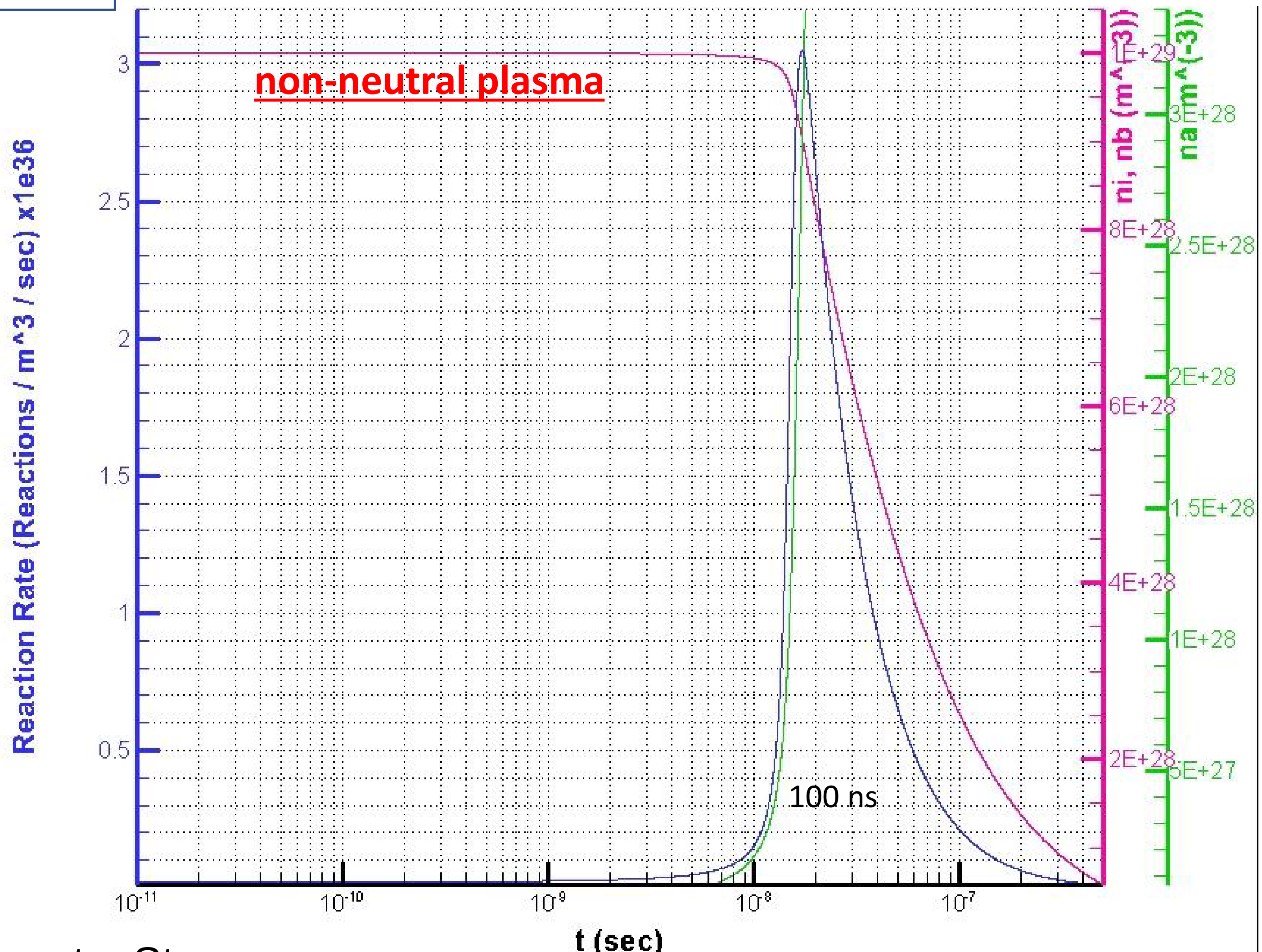
$T_p = T_B = 40\ \mathrm{keV}$
$n_B = n_P = 10^{23}\ cm^{-3}$



Simulation by:
Chrysovalanti Daponta, Stavros Moustaiz

Terminology 5

$$T_p = T_B = 40 \text{ keV}$$
$$n_B = n_P = 10^{23}\ cm^{-3}$$



Simulation by:
Chrysovalanti Daponta, Stavros Moustaiz

Introduction - Our non-LTE scenario

We do a parametric scan to try to maximize the number of elastic chain reactions and hopefully achieve even avalanche [although this may not be necessary to achieving energetic gain].

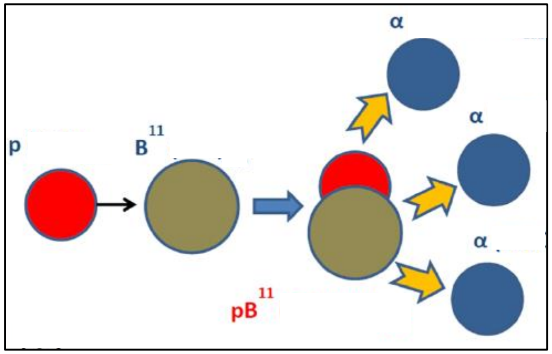
Conditions:

- Thermal plasma background (B+p)
- Super-thermal (external beam) initial protons

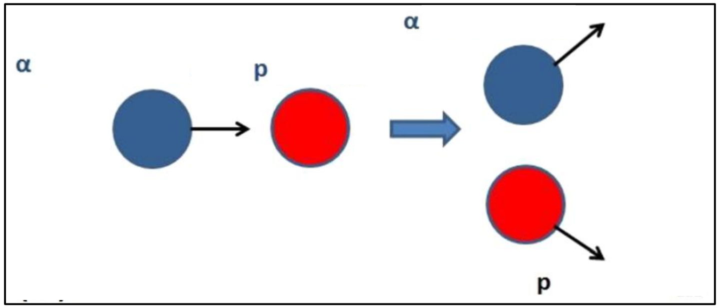
The Main challenges:

- **Stopping power (SP) –** loss of super-thermal velocities – we discuss
- **Radiation losses** – energy loss in a confinement scenario – we do not discuss

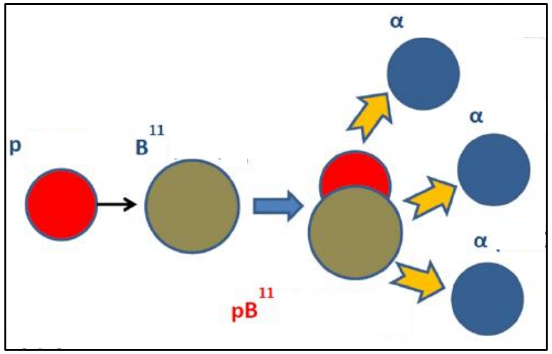
Primary fusion



α elastic collision



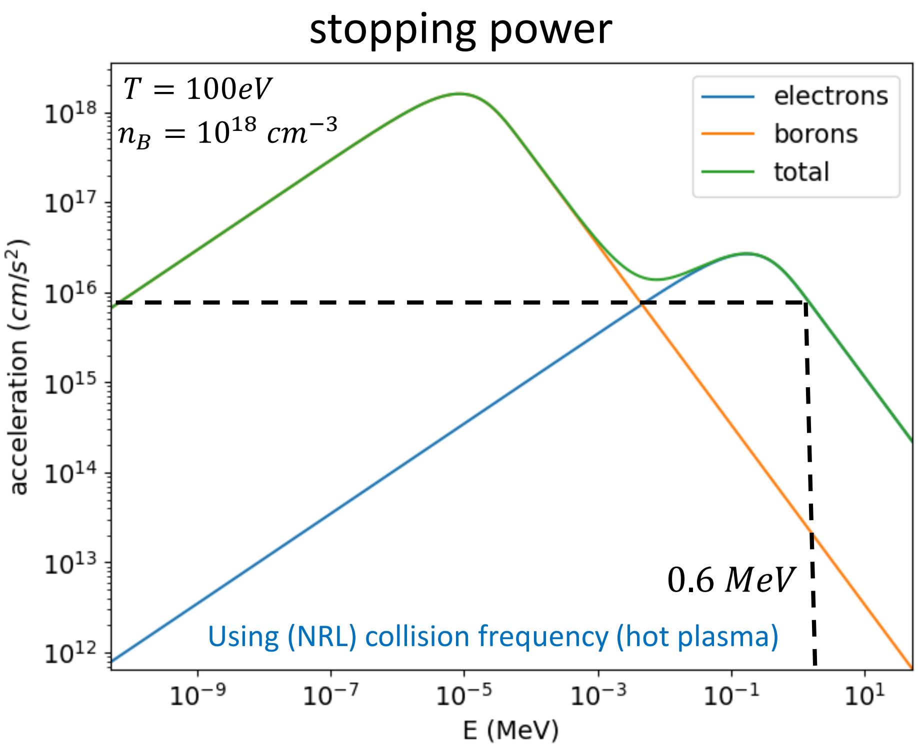
Secondary fusion

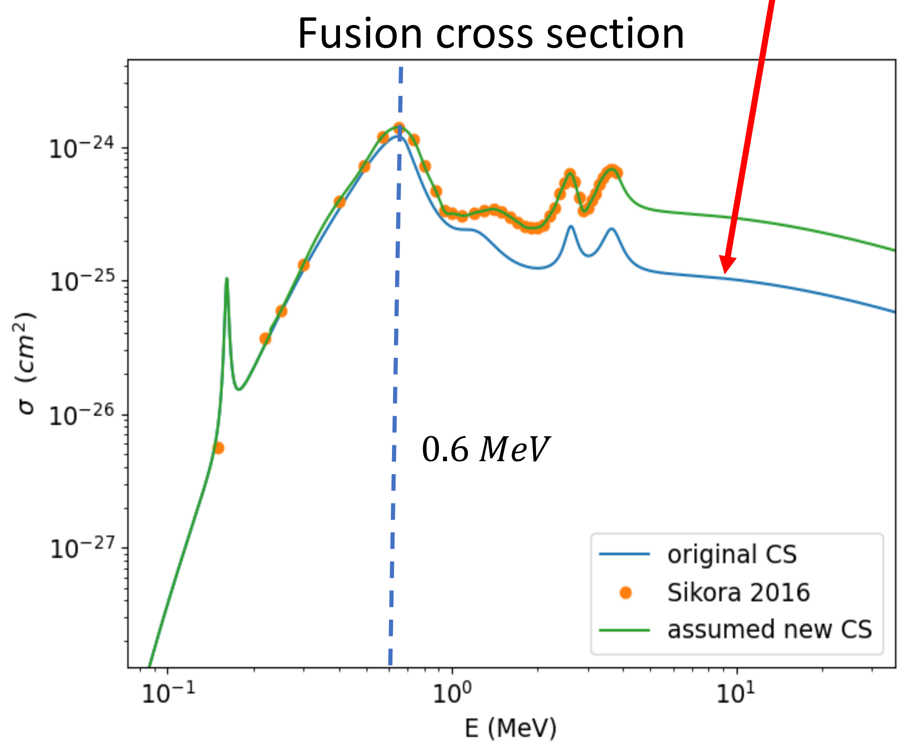


S. Eliezer et al., Phys. Plasmas, **23**, 050704, (2016).

Fusion cross section and SP

The data above ~ 4 MeV is extrapolated





$$P_f \approx \frac{stoppind\ distance}{mean\ free\ path\ for\ fusion}$$

$$\Delta X = \frac{1}{2}\frac{v_0^2}{SP(n_B)}$$ Stopping distance (constant acceleration)

$$l \approx \frac{1}{n_B \sigma_f(v_{p0})}$$ Mean free path for fusion

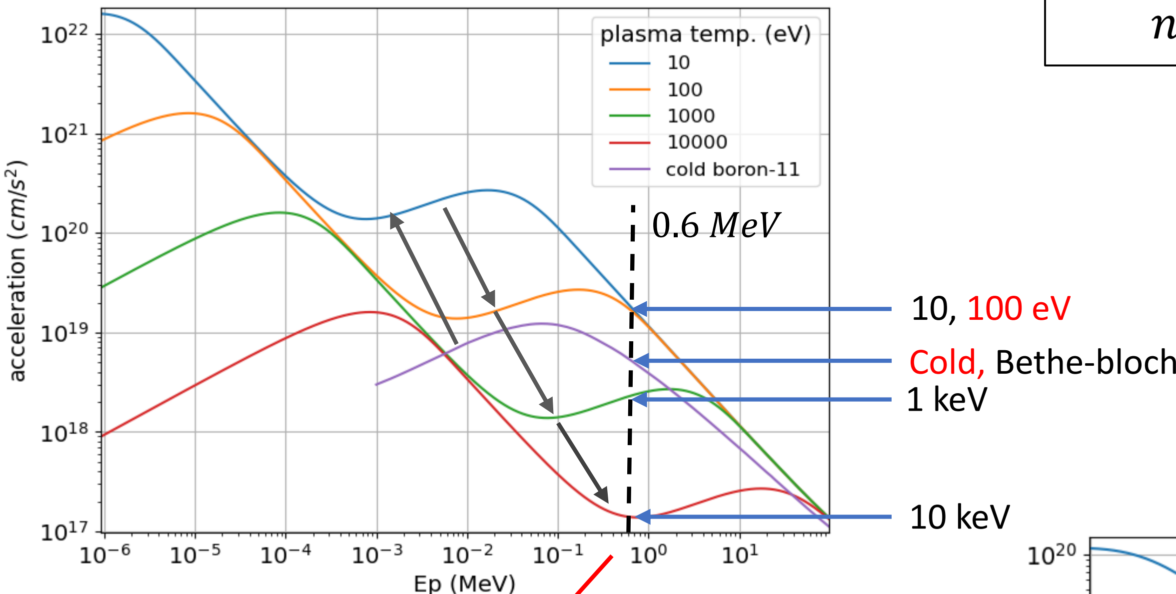
P_f (total fusion probability) is insensitive to the

Total = infinite plasma

The temperature dependence of the stopping power

From (NRL) collision frequency (hot plasma)

$$n_B = n_p = 10^{21}\ cm^{-3}$$



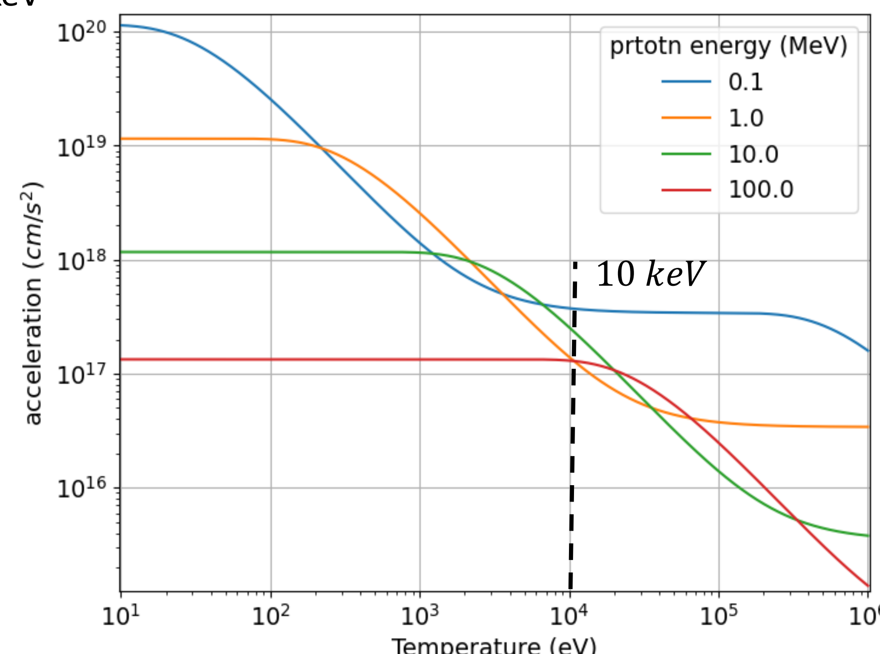
$$T = 10\ keV$$

$$S.P(v_0 = 10^9\ cm/s) \approx 10^{17}\ \ cm/s^2$$

$$\Delta X = \frac{1}{2}\frac{v_0^2}{S.P} \approx 5\ cm$$

$$l \approx \frac{1}{n_B \sigma_f(v_{p0})} = 10^3\ cm$$

$$P_f \approx \frac{stoppind\ distance}{mean\ free\ path\ for\ fusion} = \frac{5}{10^3} = \mathbf{5 \times 10^{-3}}$$



We need $S.P \approx 10^{15}$ *to get* $P_f \approx 1$

5 fusions in 1,000 protons

A more accurate calculation of the total fusion probability

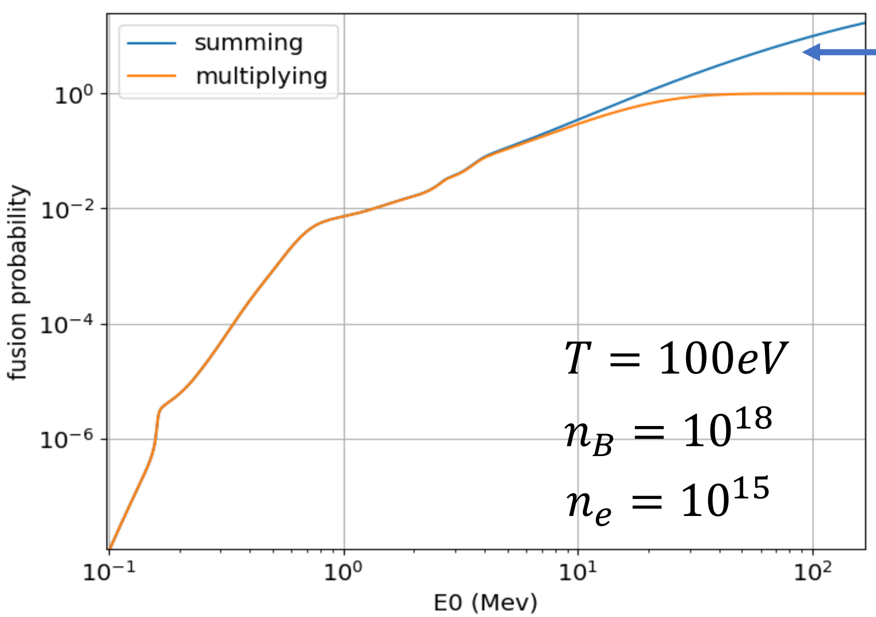
Fusion probability in a small interval along the proton track $n_B \sigma_f(v_{p0}) v_{p0} dt$

Not - the fusion probability

Not the total probability $P_f(v_0) = \int_0^{t(v_{p0}=0)} n_B \sigma_f(v_{p0}) v_{p0} dt = -\int_{v_{p0}}^{0} n_B \sigma_f(v_{p0}) \frac{v_{po}}{S.P} dv$

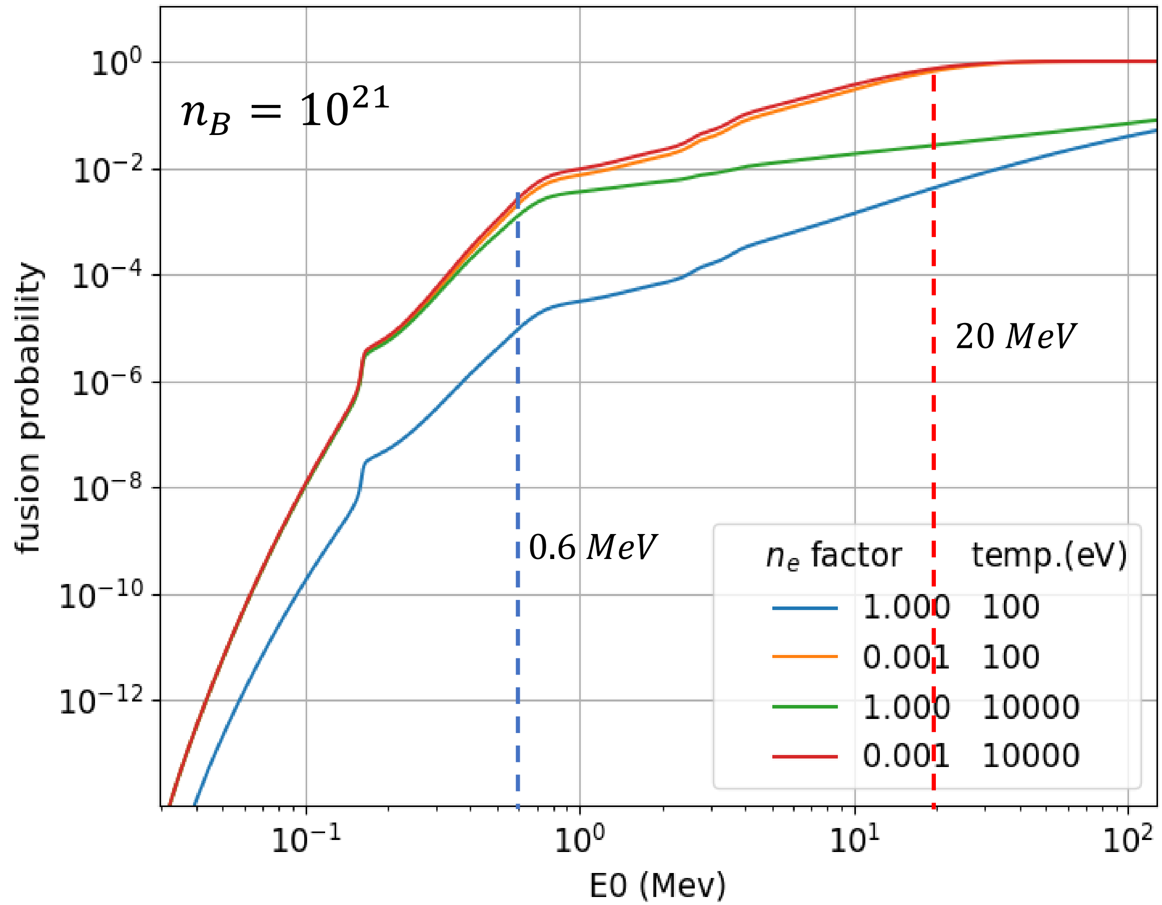
The fusion probability

$$P_f(v_0) = \left(1 - \prod_{v_p} \left(1 - n_B \sigma_f \frac{v_p}{S.P} \Delta v_p\right)\right)$$

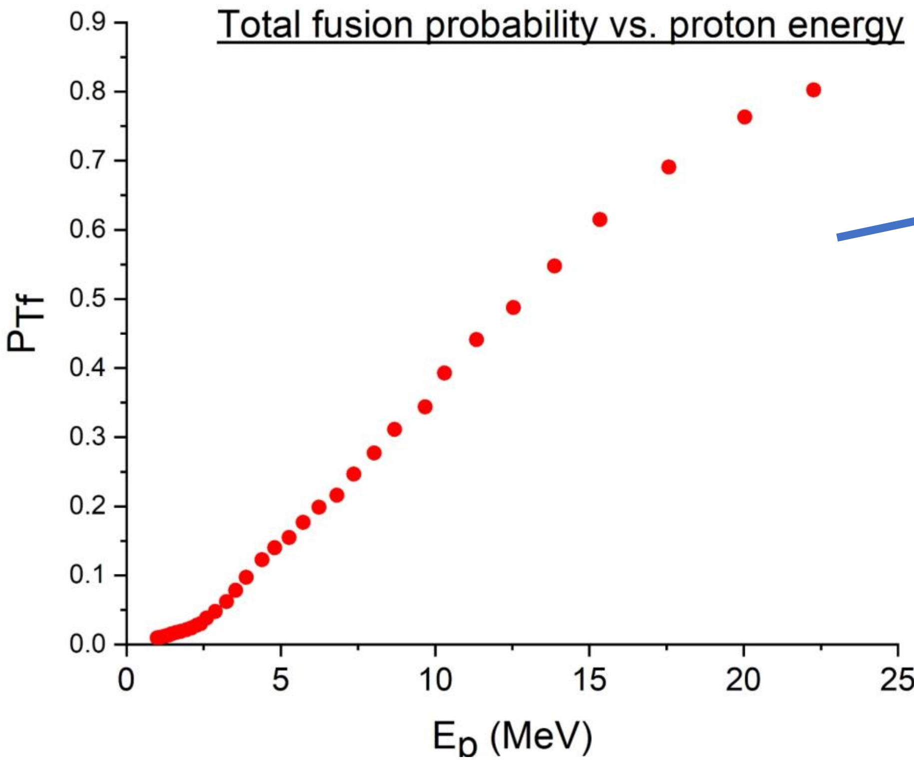


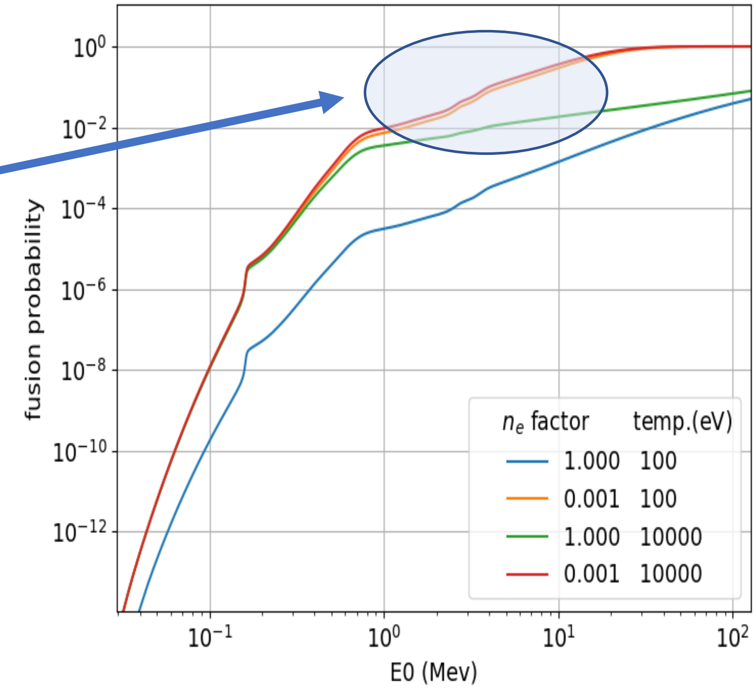
$P_f > 1$

Manipulating the electron density



By reducing the electron density by 3 order of magnitudes we get $P_f \approx$ 0.8 for 20 MeV protons already at 100 eV plasma





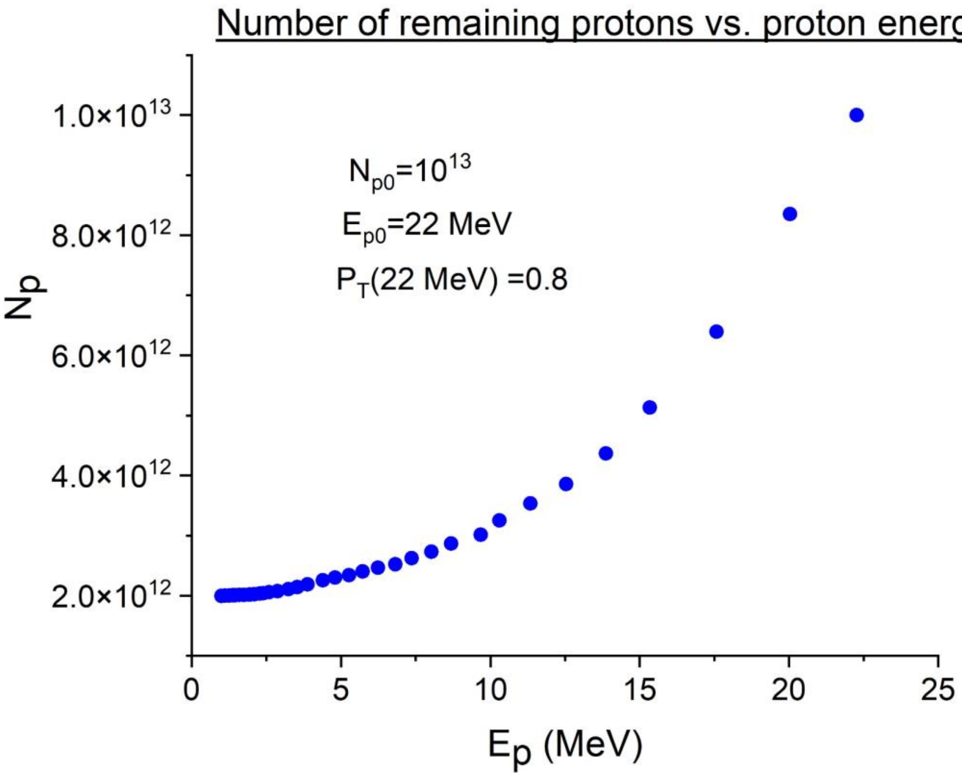
$$\Delta P_f(v, v-dv) = n_B \sigma_f \frac{v}{S.P} dv$$

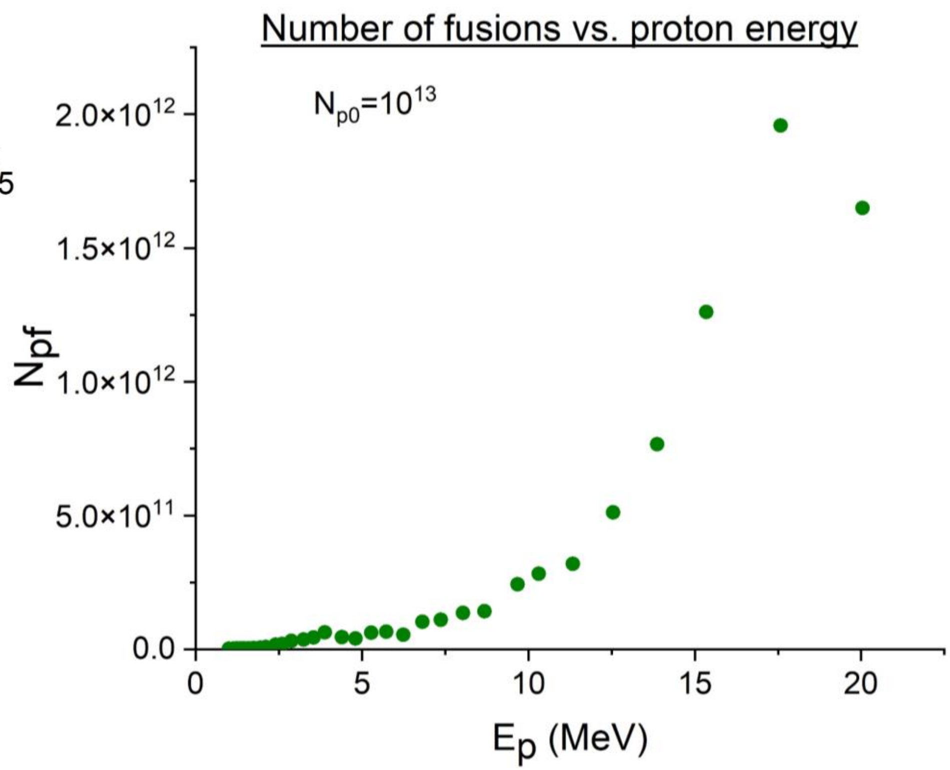
Starting with $N_{p0}(v_{max})$

$$N_f(v, v-dv) = N_p(v) \cdot \Delta P_f(v, v-dv)$$

$$N_p(v-dv) = N_p(v) - N_f(v, v-dv)$$

From v_{max} to 0

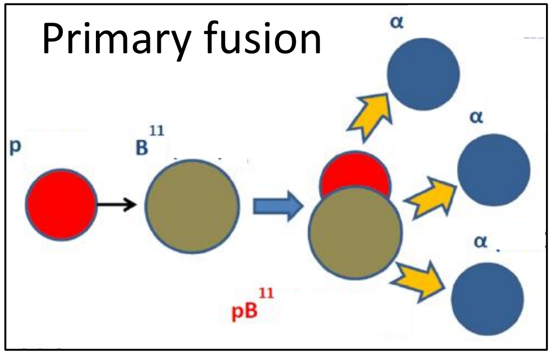




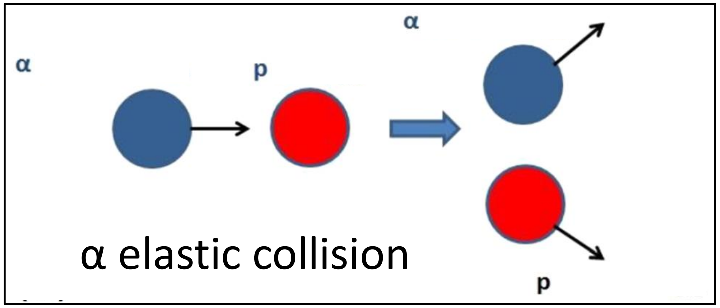
Most of the protons make fusion at high energies

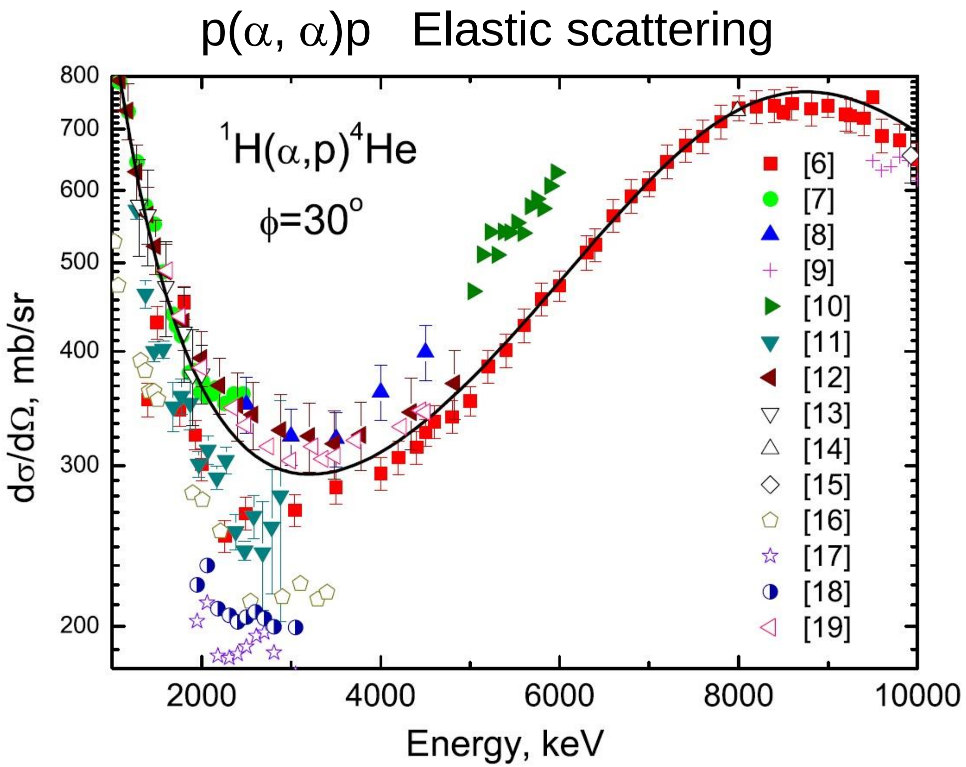
$$\bar{E} = \frac{\sum E \cdot N_{pf}(E)}{\sum N_{pf}(E)} = 17 \text{ MeV}$$

If the protons have high energy in the fusion reaction, then, this energy is transmitted to the alphas which have then higher cross section for elastic collations.



The high energy of the protons is transmitted to the alpha products





The elastic cross section is σ ~ 3 – 10 b

A.F. Gurbich, Nuclear Instruments and Methods in Physics Research B, **268, 1703** (2010).

Multiplication factor 1 (non-neutral plasma)

Simple estimation

Starting with initial number of protons ($N_{p0}(E_{p0}$=20MeV)=1x10^{13})

Calculate the total number of fusions (fusion probability=0.8)

Calculate the number of alphas from each energy (3*N_f , 2*4MeV +1*1MeV)

Split the average proton in fusion (17 MeV) energy evenly between alphas

Calculate the number of elastically scattered protons (we used elastic CS = fusion CS)

Calculate the energy of scattered protons (16/25 E_{α})

After 2 generations we got 5% (secondary reactions)more than the 0 generation fusions

Multiplication factor 2 (non-neutral plasma)

k= Percentage of secondary reactions

Numerical calculations following the paper by Fabio with:

F. Belloni, Plasma Phys. Control. Fusion, **63,** 055020, (2021)

$T_e = 10\ keV$, $T_i = 1\ keV$

$n_p = 10^{23}\ cm^{-3}$

$n_B = 0.2x10^{23}\ cm^{-3}$

$n_e = (n_p + 5n_B)\eta_e$

$\eta_e = 10^{-3}$

E_{p0} (MeV)	P_f	$\varepsilon_p = \frac{8.9[MeV]}{E_{p0}}$	k (multiplication factor)	G_B
10	0.37	0.89	0.0388	0.34
20	0.8	0.44	0.14	0.4
30	1	0.3	0.26	0.37

$E_i = E_{p0} N_0$ Initial beam energy

$N_i = P_f N_0$ Number of initial reactions

$N_s = kN_i = kP_f N_0$ Number of secondary reactions

$N_T = N_i + N_s = P_f N_0 (1 + k)$ Total number of reactions

$E_f = 8.9[MeV] * N_T = 8.9[MeV] * P_f N_0 (1 + k)$ Total produced fusion energy

$$G_B = \frac{E_f}{E_i} = \frac{8.9[MeV] * P_f N_0 (1+k)}{E_{p0} N_0} = \frac{8.9[MeV]}{E_{p0}} P_f (1 + k) = \varepsilon_p\ P_f (1 + k)$$

The cross section for elastic collations was calculated using Rutherford Eq.

We need to correct for the much higher experimental cross section

Conclusion

- We discussed p-B fusion terminology
- We discussed the temperature and electron density effects on the fusion total probability
- Decreasing the electron density has the advantages of 1) reducing the bremsstrahlung and cyclotron radiation 2) reducing the stopping power (increasing the fusion probability) 3) allows working with low temperature plasmas.
- However, the energy required to produce a non-neutral plasma must be considered.

Thank You