Numerical simulations of ignition and fusion burn wave propagation in proton-boron fuel

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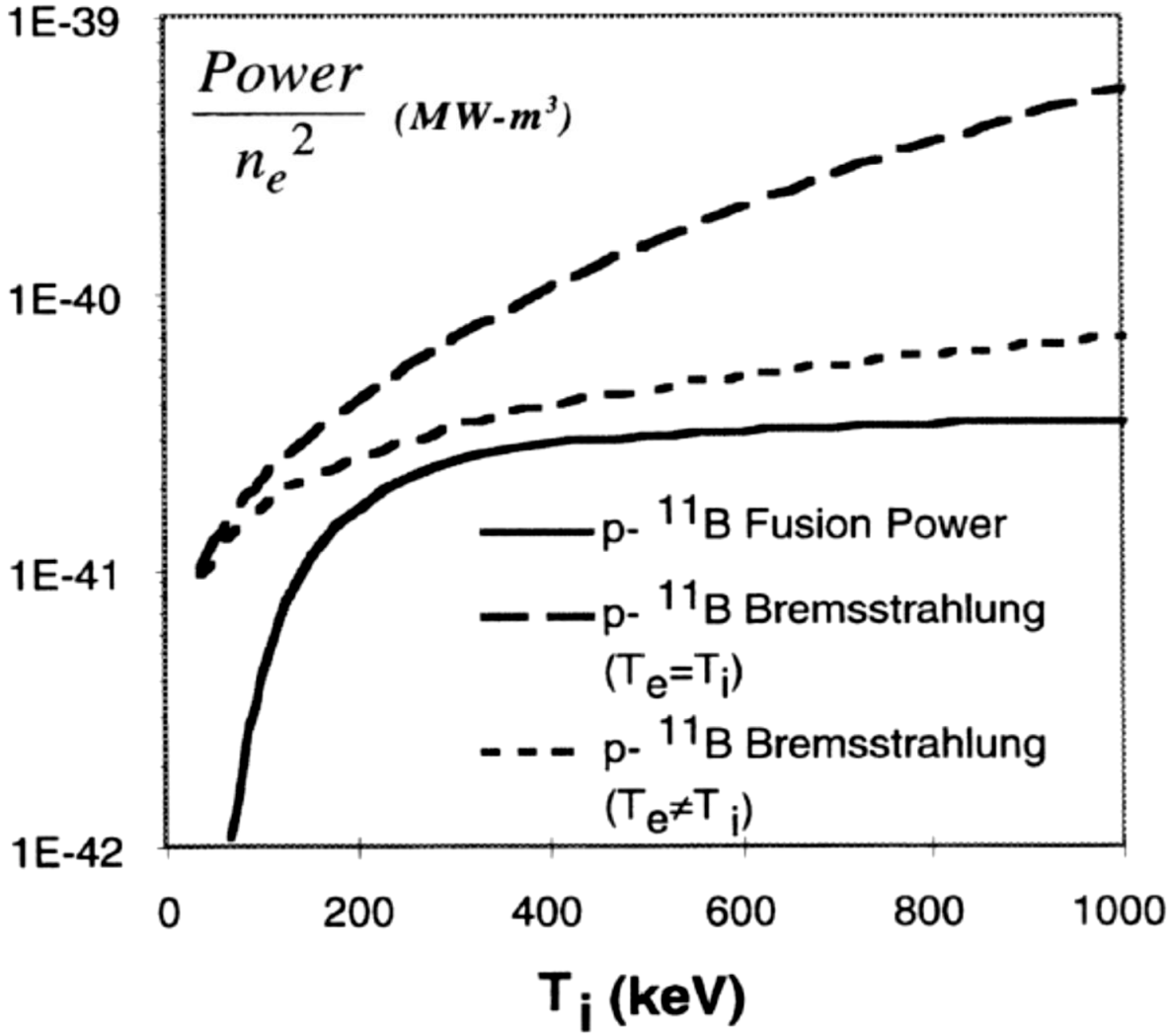
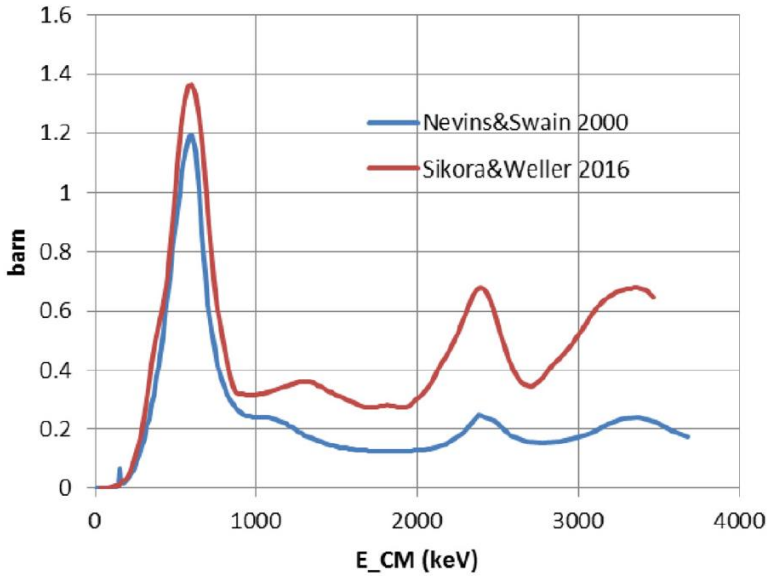
Feasibility of the proton-boron fusion

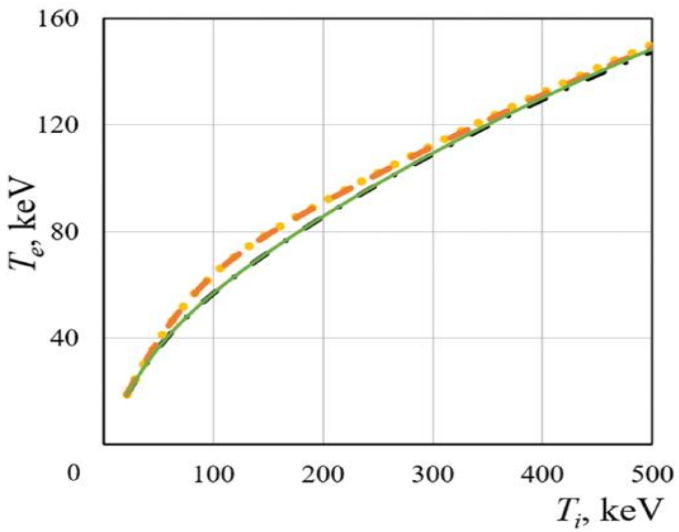


Nevins, W. M., Journal of Fusion Energy, 17(1), 25-32 (1998)

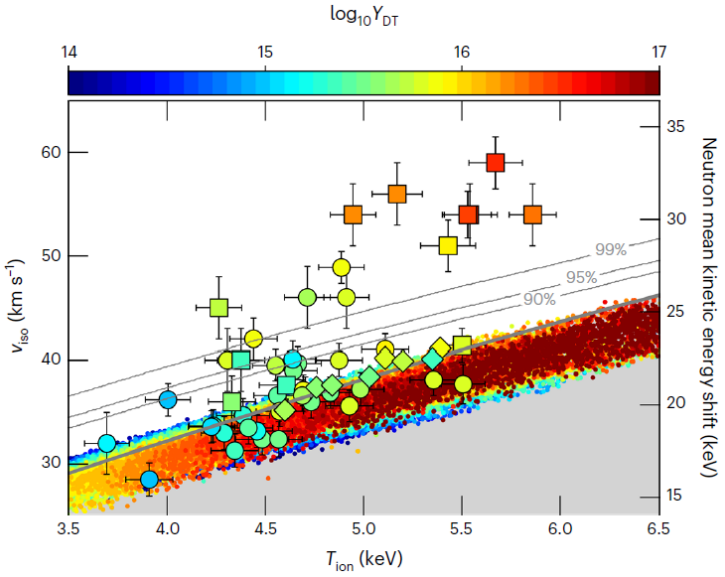
Feasibility of the proton-boron fusion



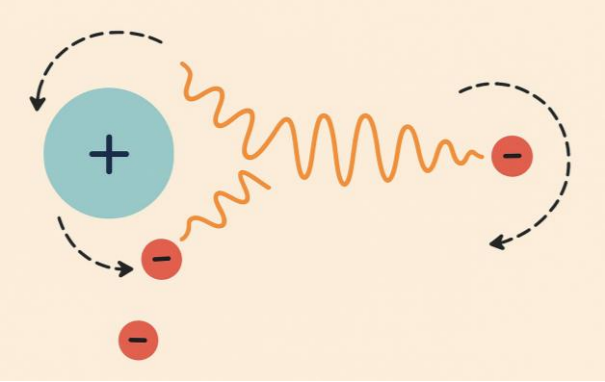
1. Updated $p^{11}B$ cross-section data



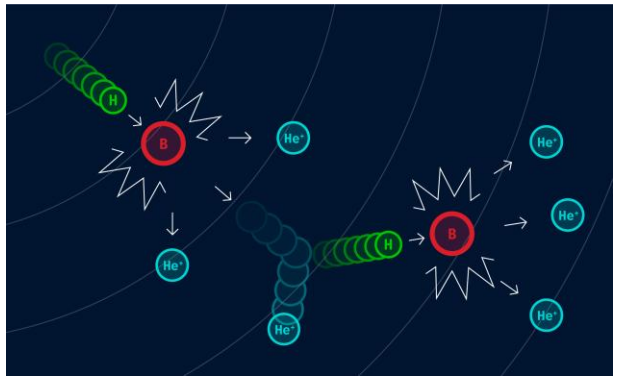
2. Non-isothermal plasma: electrons are much cooler than ions



3. Suprathermal effects (non-Maxwellian distribution due to upscattering of protons by fusion-born α-particles, in-flight reactions)

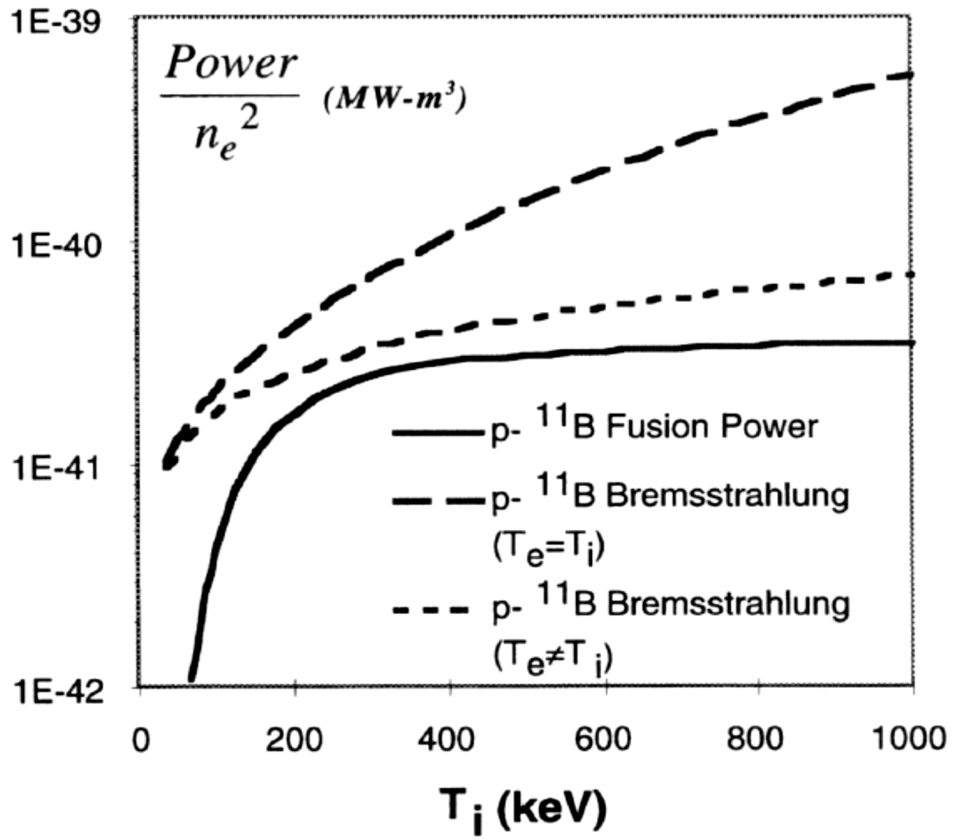


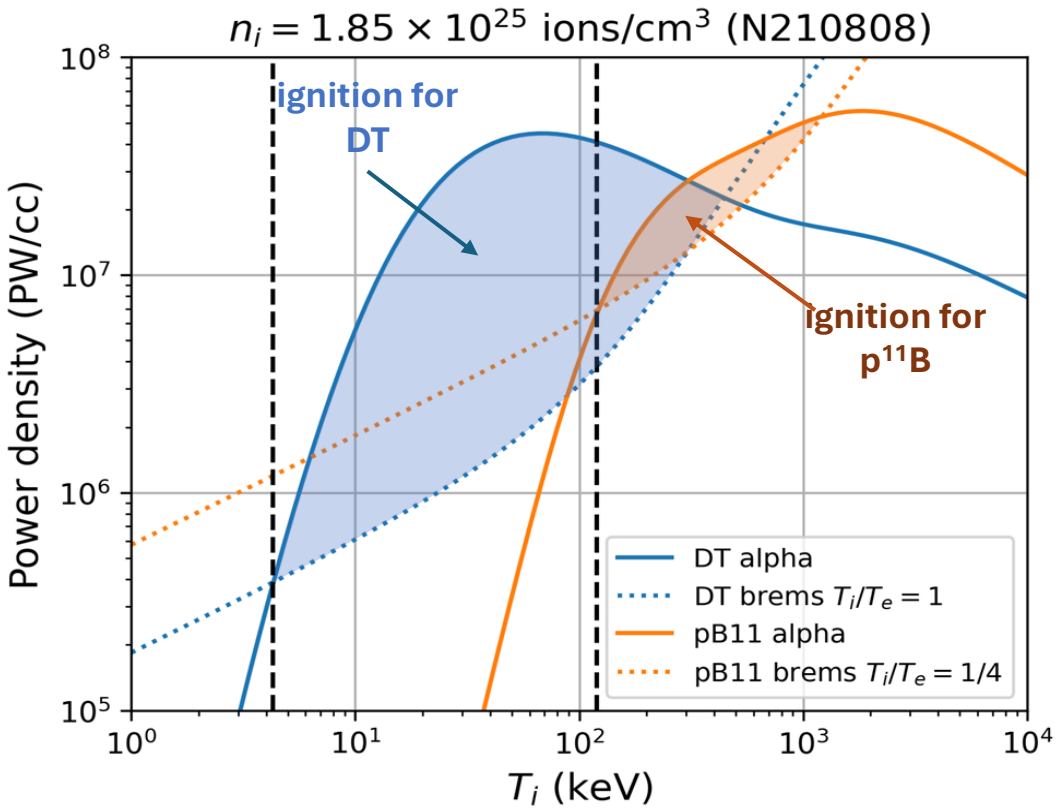
4. High bremsstrahlung reabsorption in dense plasmas



M.H. Sikora, H.R. Weller, J. Fusion Energ. 35, 538 (2016)
E.P. Hartouni, et al., Nature Physics 19.1, 72 (2023)
S. Putvinski, D. Ryutov, etc., Nucl. Fusion 59, 076018 (2019)
E.G. Vovkivsky, A.Yu. Chirkov, Fusion Sci. Technol. (2025)
E. Ghorbanpour, F. Belloni, Front. Phys. 12, 1405435 (2024)

Feasibility of the proton-boron fusion

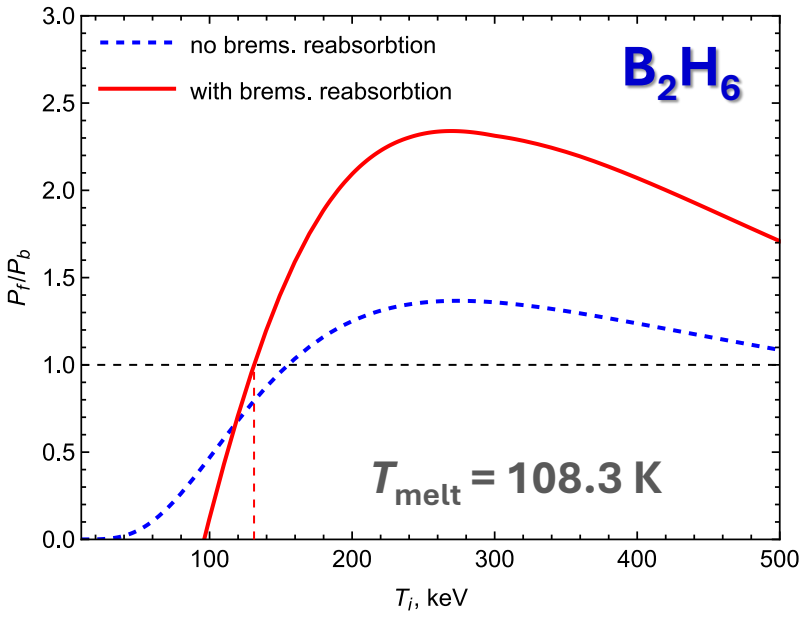


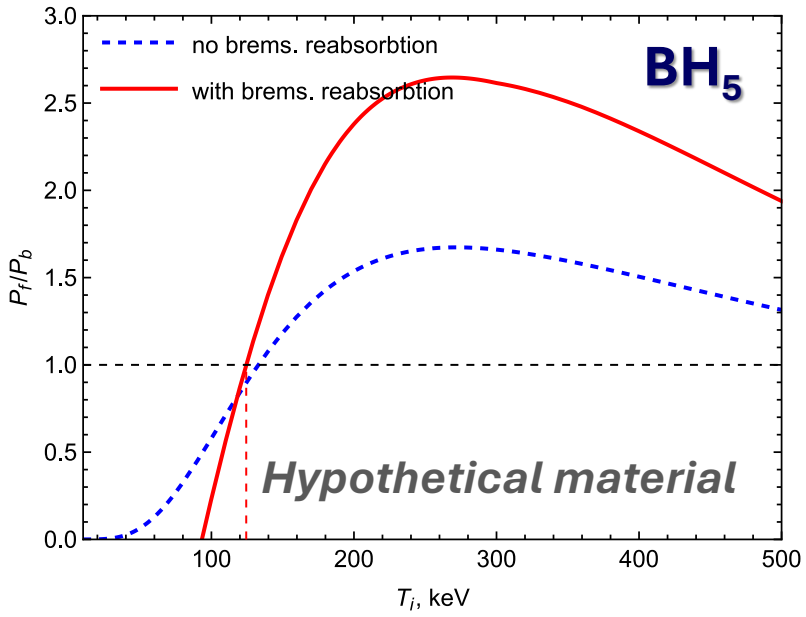


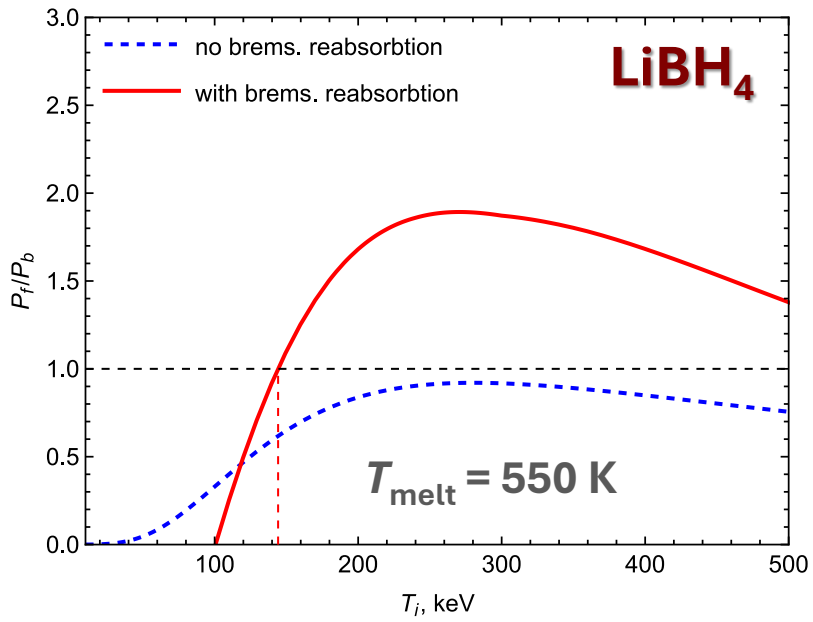
T.A. Mehlhorn, M. Tabak, M. Borscz, unpublished

- The latest cross-section data is considered
- The suprathermal effects, including large-angle α-p scattering, can provide extra 20% of fusion power
- The electron temperature is estimated to be 2-4 times smaller than the ion temperature

Ignition parameters considering bremsstrahlung reabsorption







Electron-to-ion temperature ratio: $T_e = T_i/3$

Suprathermal effects:
20% for B-H compounds,
16% for Li-B-H compounds

The bremsstrahlung reabsorption ratio is estimated using 1D HELIOS hydro code and PROPACEOS opacity tables

Ignition parameters as given by the energy balance equations[1]

- **Isochoric self-heating condition**

$$W_{\mathrm{dep}} \geq W_{\mathrm{rad}} - W_{\mathrm{heat}} - W_{\mathrm{mech}},$$

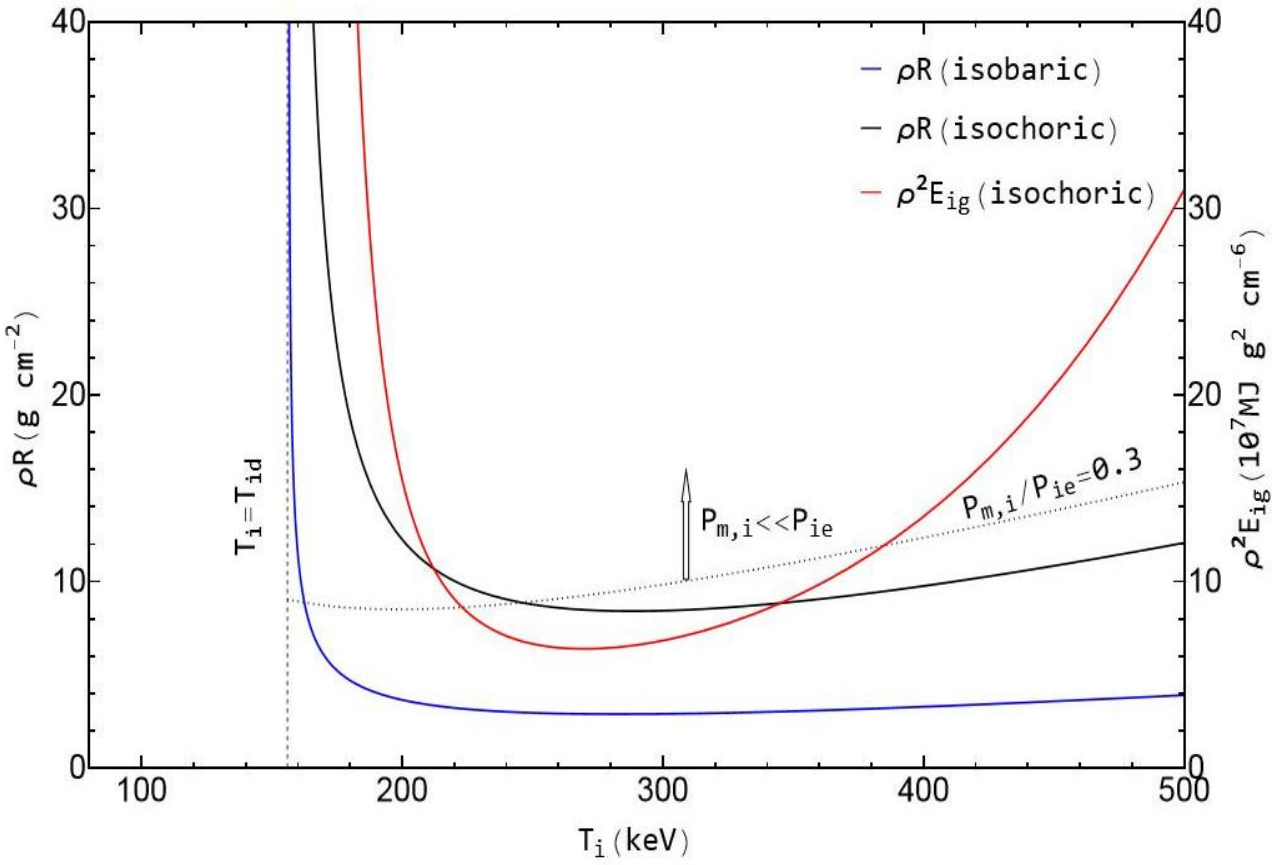
where the temperature of electrons is calculated self-consistently from the energy balance for ions:

$$\eta_i W_{dep} - W_{ie} = 0.$$

- **The ignition energy is**

$$E_{ig} = \frac{3}{2} pV = 2\pi(\Gamma_i T_i + \Gamma_e T_e)\frac{(\rho R)^3}{\rho^2}$$

For ρ = 4000 g/cm³, the minimum of E_{ig} is detected at $\rho R \simeq 8.5\ \mathrm{g/cm^2}$ and $220 \lesssim T_i \lesssim 340\ \mathrm{keV}$ ($80 \lesssim T_e \lesssim 95\ \mathrm{keV}$), where it is still considerably large (~ 1.7 MJ).

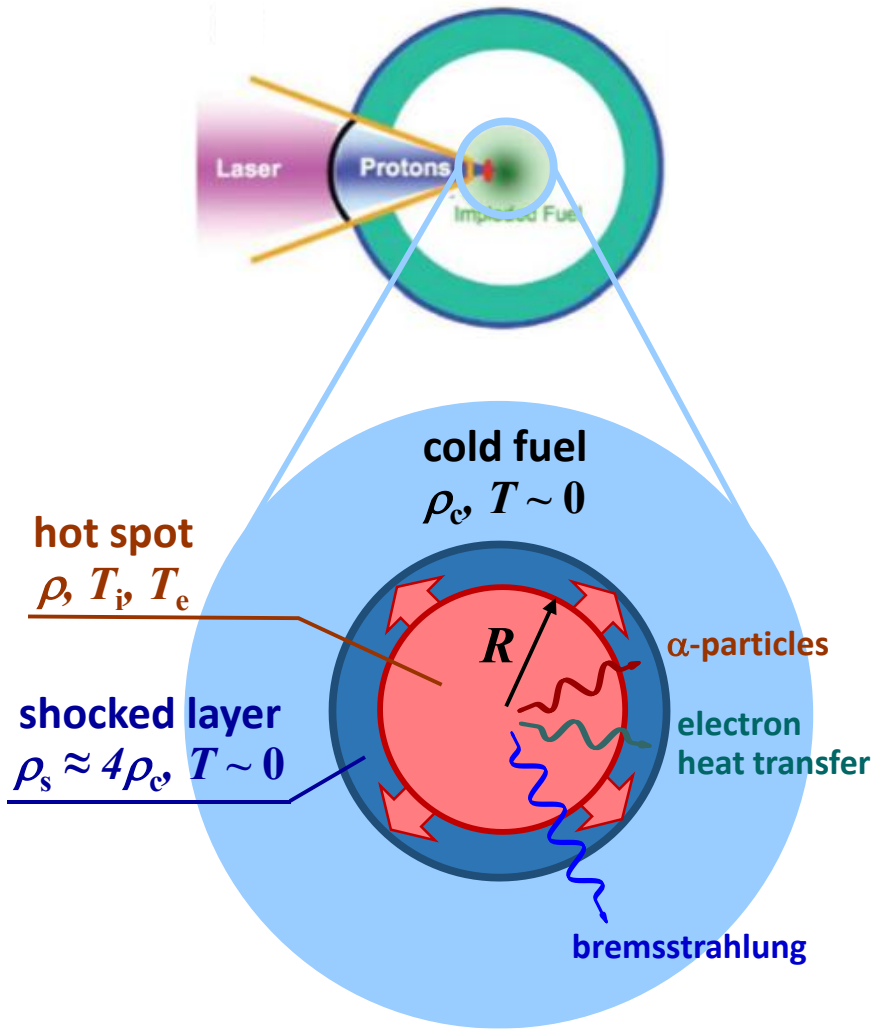


Calculations are made for $n_i = 10^{26}\mathrm{cm}^{-3}$, $n_B/n_p = 0.15$, and **20%** increase from suprathermal effects

[1] E. Ghorbanpour, F. Belloni, Front. Phys. 12, 1405435 (2024)

Simulation of the hot spot dynamics in 0D

- Extension of the model originally proposed for the D-T fuel[1]
- Dynamics of the plasma density, hot spot radius, *electron and ion temperatures* in a uniform spherical plasma
- Up-to-date p-^{11}B reaction cross section[2]
- Increase of α-particle energy deposition (roughly by 20%) due to suprathermal effects[3]
- Relativistic corrections for bremsstrahlung and ion-to-electron energy transfer



[1] S. Atzeni, A. Caruso. Nuovo Cimento, 80B, 71 (1984)
[2] A. Tentori, F. Belloni. Nucl. Fusion 63, 086001 (2023)
[3] S.V. Putvinski, D.D. Ryutov, P. N. Yushmanov, Nuclear Fusion, 59, 076018 (2019)

Simulation of the hot spot dynamics in 0D

specific energy of ions

hot spot mass

mechanical energy loss due to expansion

$$\frac{d}{dt}(\mathcal{E}_\mathrm{i} M) = (\eta_\mathrm{i} W_\mathrm{fus} - W_\mathrm{ie} - W_\mathrm{m,i})V,$$

energy balance for ions

fusion-born α-particle energy deposition

ion-to-electron energy transfer

bremsstrahlung energy loss

$$\frac{d}{dt}(\mathcal{E}_\mathrm{e} M) = (\eta_\mathrm{e} W_\mathrm{fus} + W_\mathrm{ie} - W_\mathrm{m,e} - (1-\phi)W_\mathrm{br})V$$

energy balance for electrons

specific energy of electrons

electron heat conduction

$$(\mathcal{E}_\mathrm{i} + \mathcal{E}_\mathrm{e} - \mathcal{E}_\mathrm{s})\frac{d}{dt}M = (\chi W_\mathrm{fus} + W_\mathrm{hc} + \phi W_\mathrm{br})V,$$

energy gain due to ablation (expansion of the burning area)

ablation rate

hydrodynamic expansion velocity

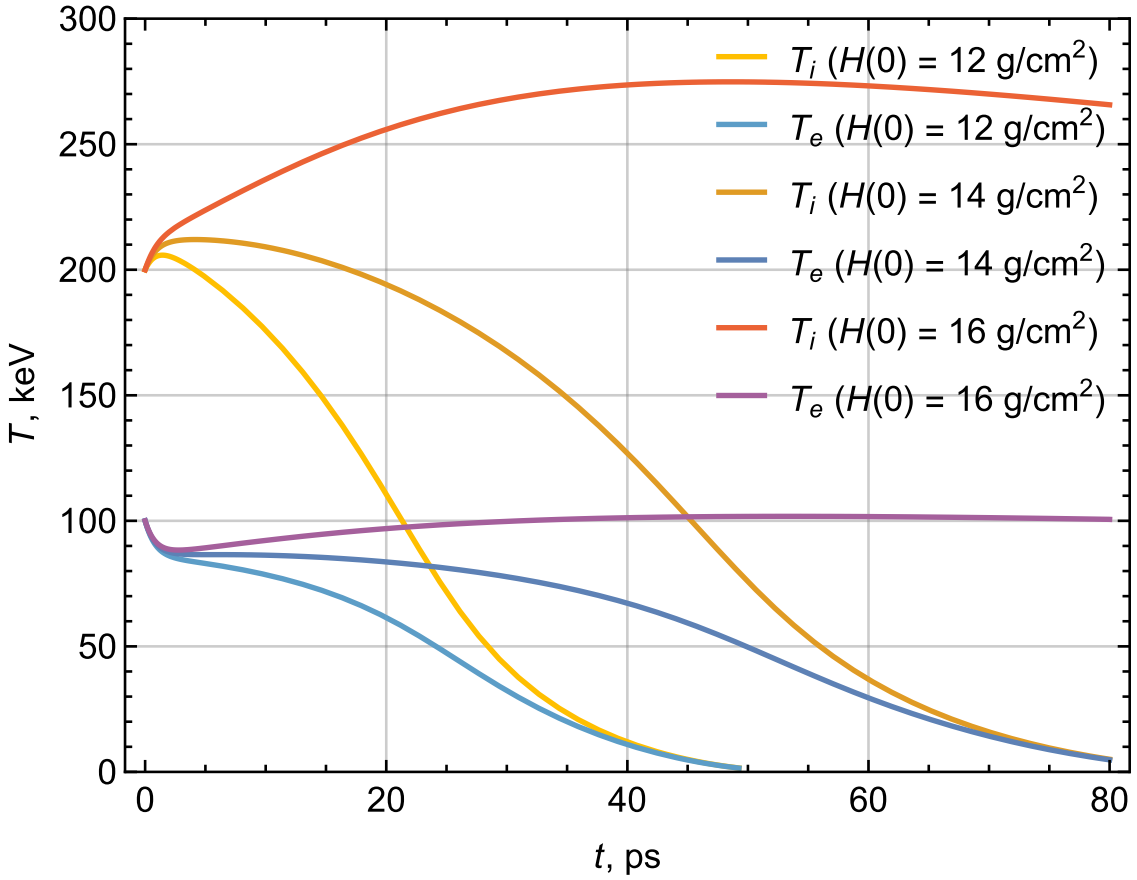
bremsstrahlung reabsorption

$$\frac{d}{dt}R = \frac{\dot{M}}{4\pi\,\rho_\mathrm{s}\,R^2} + u.$$

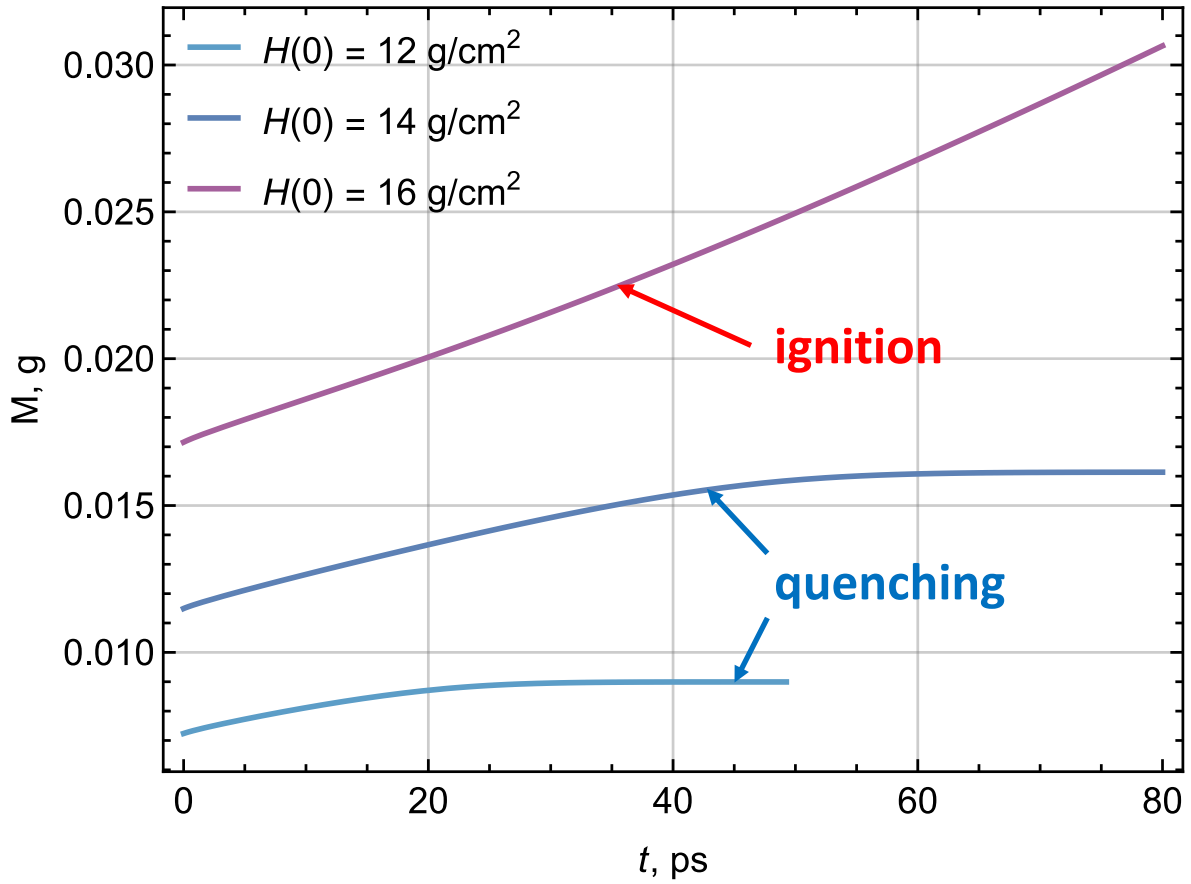
hot spot growth due to ablation and hydrodynamic expansion

0D Simulation results

Simulation parameters: $\rho(0) = \rho_c = 1000\ \mathrm{g/cc}$, $T_i(0) = 200\ \mathrm{keV}$, $T_e(0) = 100\ \mathrm{keV}$, $\epsilon = \frac{n_B}{n_p} = 0.15$



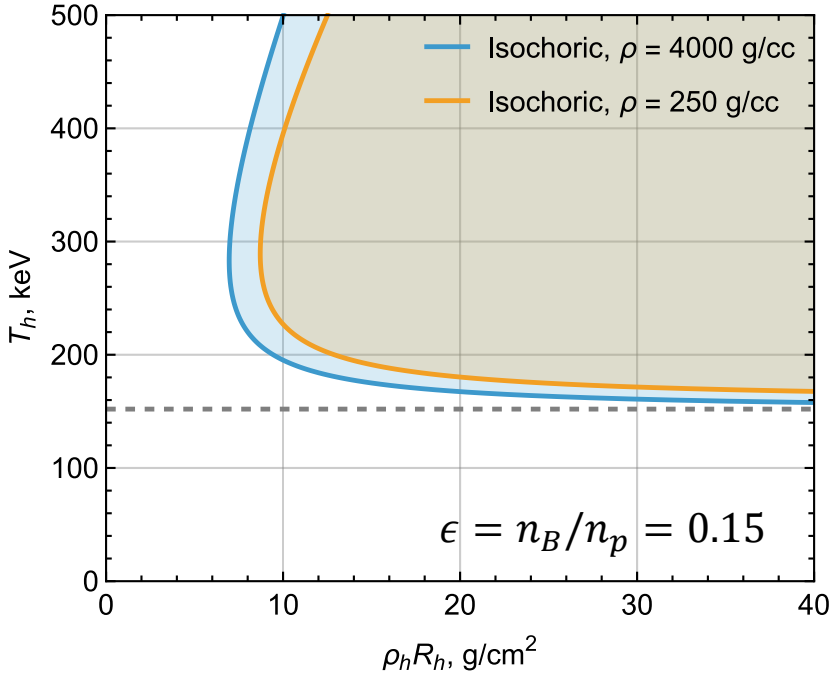
Temperature of ions and electrons



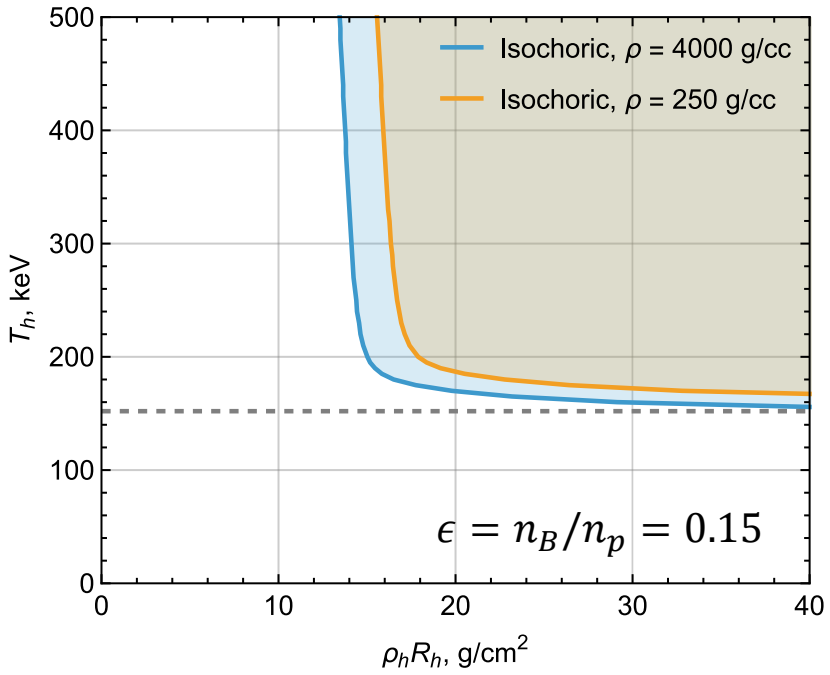
Hot spot mass

0D Simulation results

BH_5 fuel

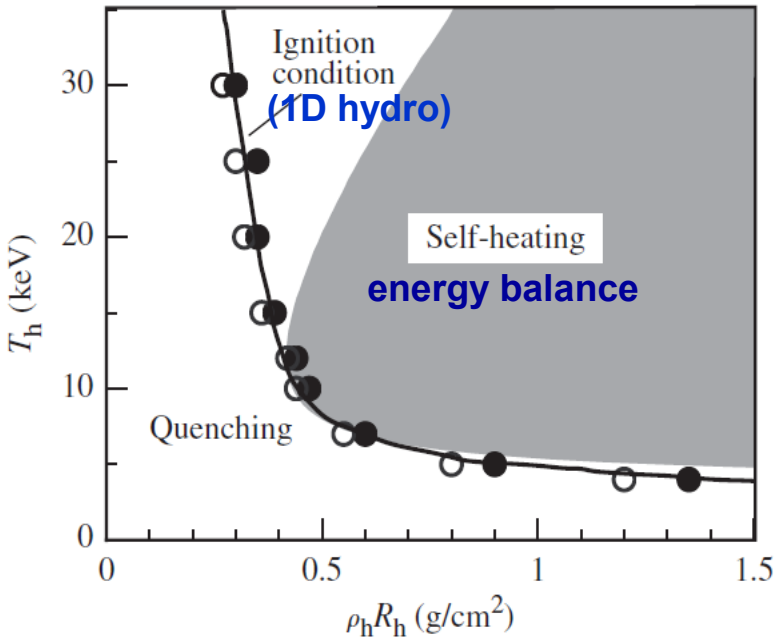


Static (energy balance)



Dynamic (0D simulations)

D-T fuel



Static + 1D hydrodynamics

T_e is calculated self-consistently either from the energy balance for ions or in the course of simulations

S. Atzeni, J. Meyer-Ter-Vehn. The physics of inertial fusion, 2004
E. Ghorbanpour, F. Belloni, Front. Phys. 12, 1405435 (2024)

1D radiation hydrodynamics simulations

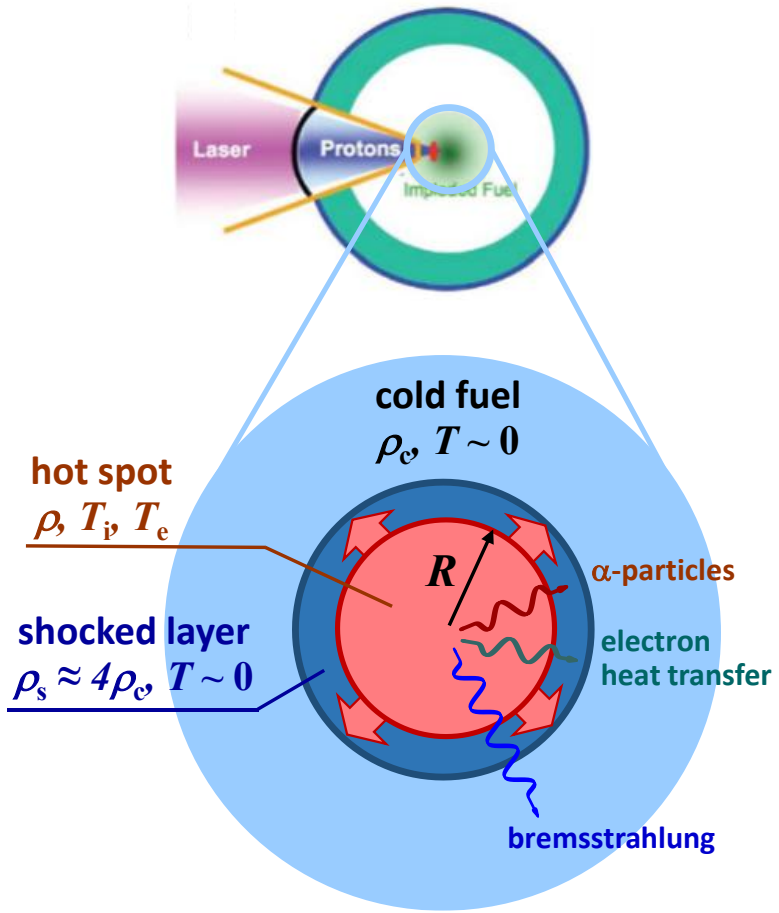
Challenges of the proton-boron fusion

1. **Finding the parameter range for the proton-boron fuel ignition** (where the self-sustaining burn wave can propagate)
2. **Obtaining sufficient target gain by optimization of boron-to-proton ratio, overall target design, etc.**
3. **Existence of solid-state chemical compounds for target that does not require low-temperature cryogenics**
4. **Implosion of the target to the required densities**
5. **Effective proton acceleration for fast ignition scheme**

1D hydrodynamics simulations

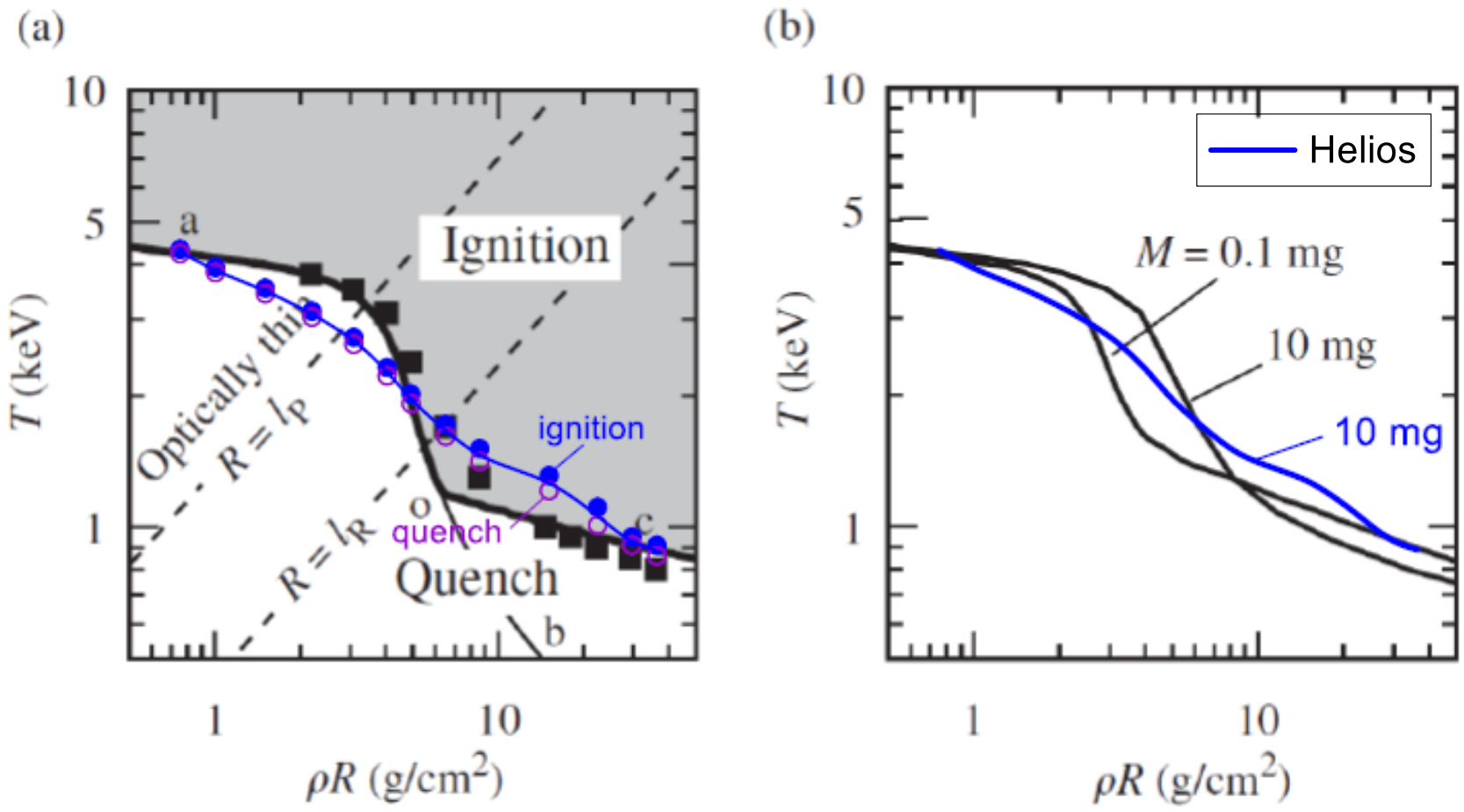
Features of the HELIOS code:

- 1-D Lagrangian hydrodynamics for planar, cylindrical, and spherical geometries
- Radiation transport for multiple photon energy groups (flux-limited radiation diffusion)
- Different temperatures of electrons and ions with ion-electron energy transfer
- Plasma thermal conduction (electrons)
- DT and $p^{11}B$ fusion, including the updated cross-sections for $p^{11}B$ and alpha-particle energy deposition
- Simple fuel deletion model



[1] https://www.prism-cs.com/Software/Helios/overview.html

Helios tests: DT volume ignition



Black points and curves are the original Atzeni's results (see description below), colored points and curves are the present results

Fig. 4.11 Volume ignition of DT fuel. (a) The thick solid curve a–o–c represents the ignition condition in the $\rho R, T$ plane for $M = 10$ mg of fuel. Curve a–o–b represents the self-heating boundary defined by eqn 4.45 and curve o–c is the confinement boundary defined by eqn 4.46 in the self-heating portion of the plane. The filled squares indicate the initial conditions leading to efficient burn, as found by 1D IMPLO-upgraded simulations. (b) Ignition conditions for two different fuel masses, obtained by numerical simulations.

S. Atzeni, A. Caruso. Nuovo Cimento, 80B, 71 (1984)

Helios tests: DT isobaric ignition

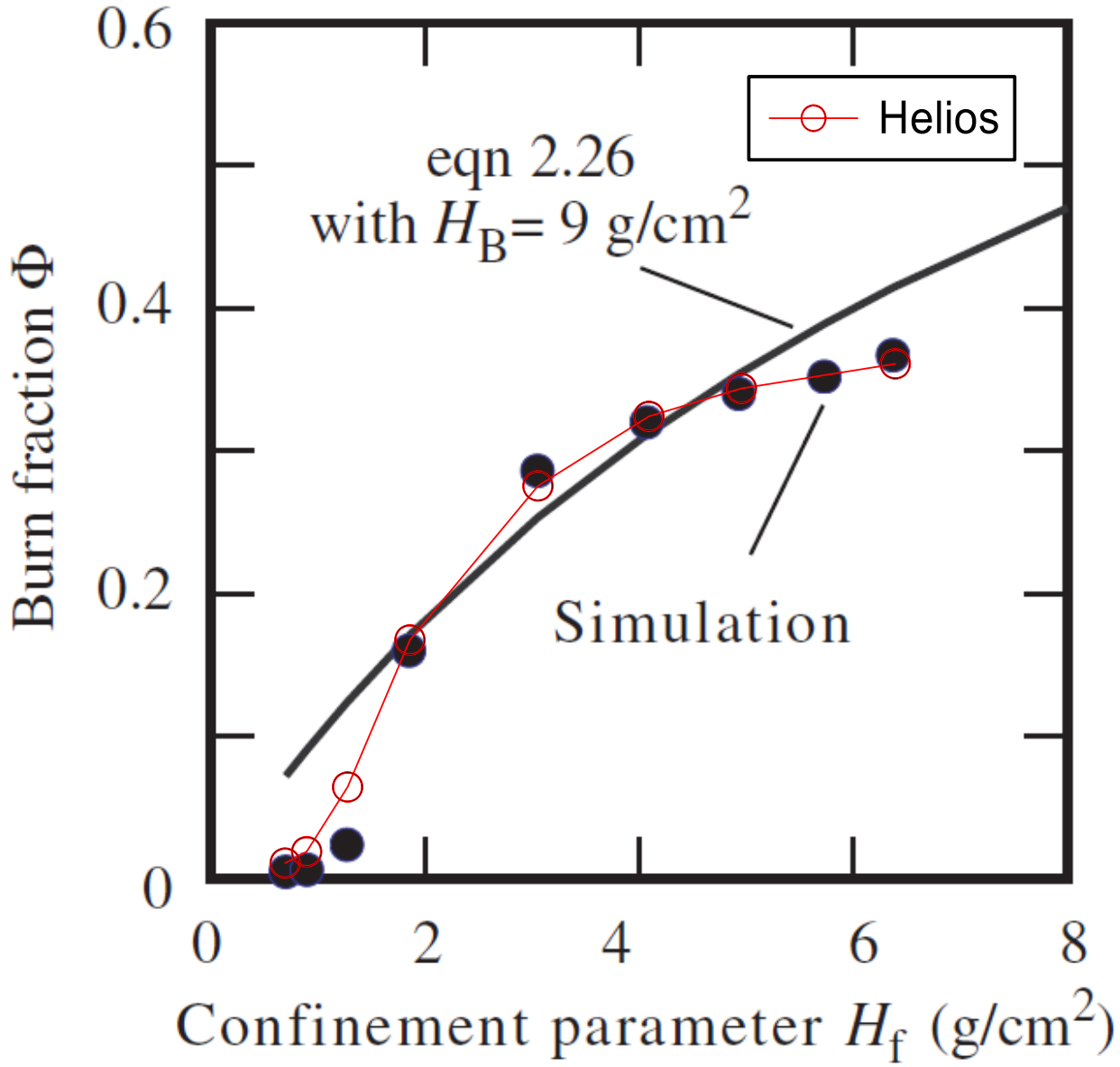


Fig. 4.13 Burn fraction versus confinement parameter $H_f = \int \rho \, dR$. The points are results of IMPLO-upgraded simulations for centrally ignited, initially isobaric DT configurations, with $M_f = 3$ mg and initial hot spot parameters $T_h = 8$ keV and $H_h = \rho_h R_h = 0.2$ g/cm^2.

S. Atzeni, A. Caruso. Nuovo Cimento, 80B, 71 (1984)

Comparison with TriForce 1D PIC-MCC simulations

Hydrodynamic expansion of DT fuel without fusion reactions

Simulation parameters:

$\rho = 250$ g/cc

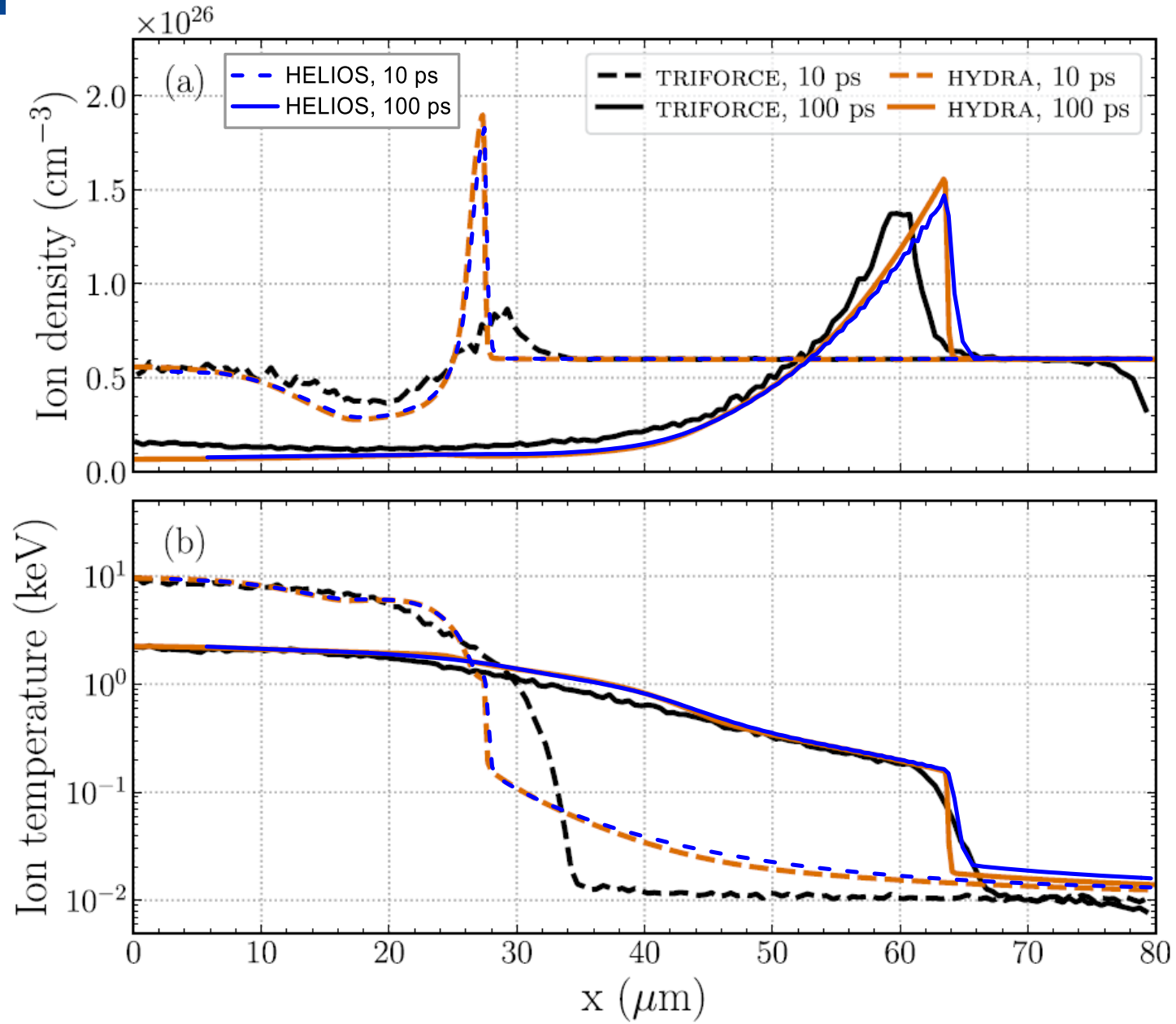
$T_{\mathrm{hs}} = 10$ keV

$H_{\mathrm{hs}} = 0.5$ g/cm^2

$H_{\mathrm{f}} = 2.5$ g/cm^2

$M_{\mathrm{DT}} = 1.05$ mg

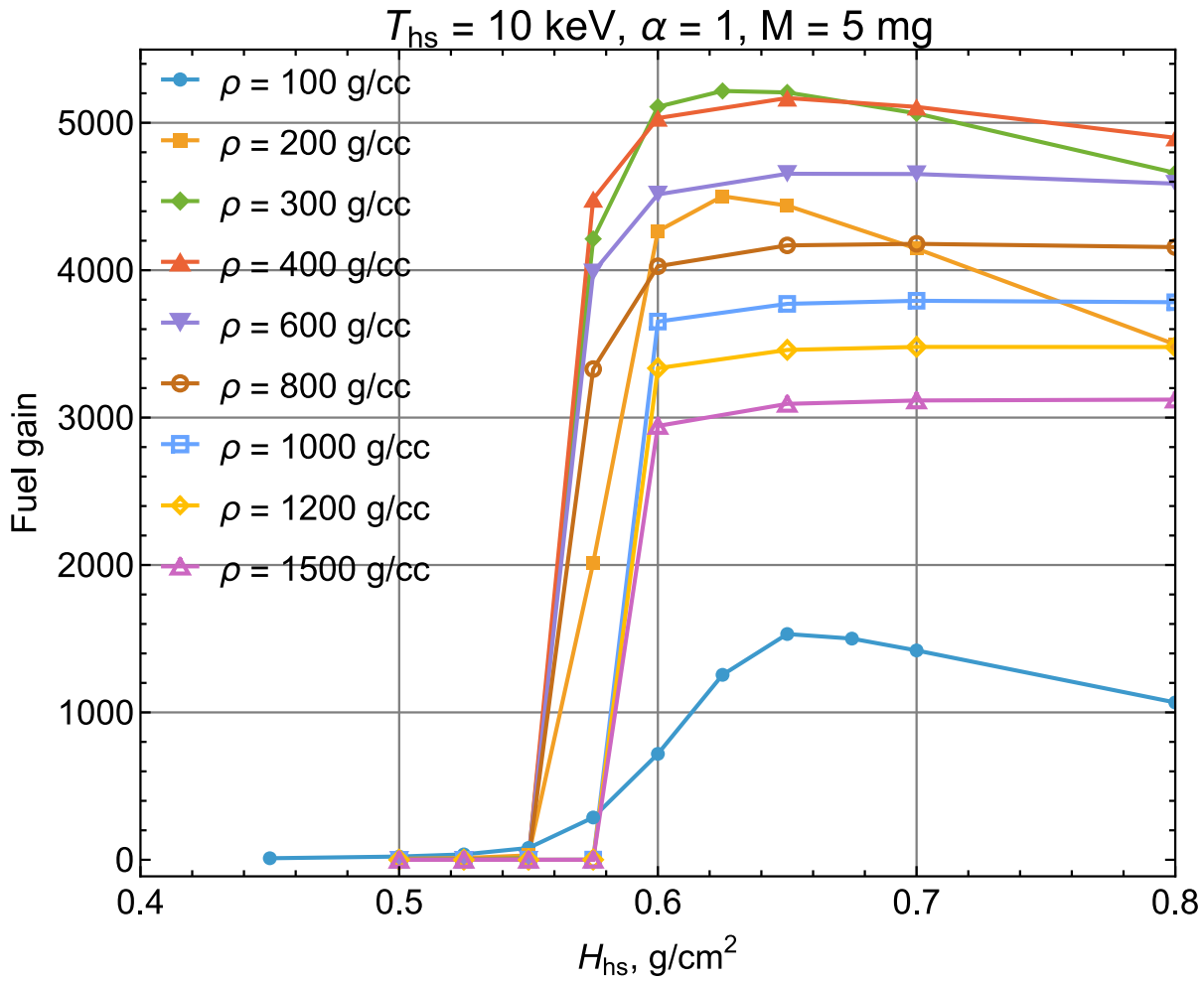
$T_{\mathrm{cold}} = 10$ eV



M. J. Lavell, A. T. Sexton, A. J. Kish, E. S. Evans, A. B. Sefkow. Phys. Plasmas 32, 053905 (2025)

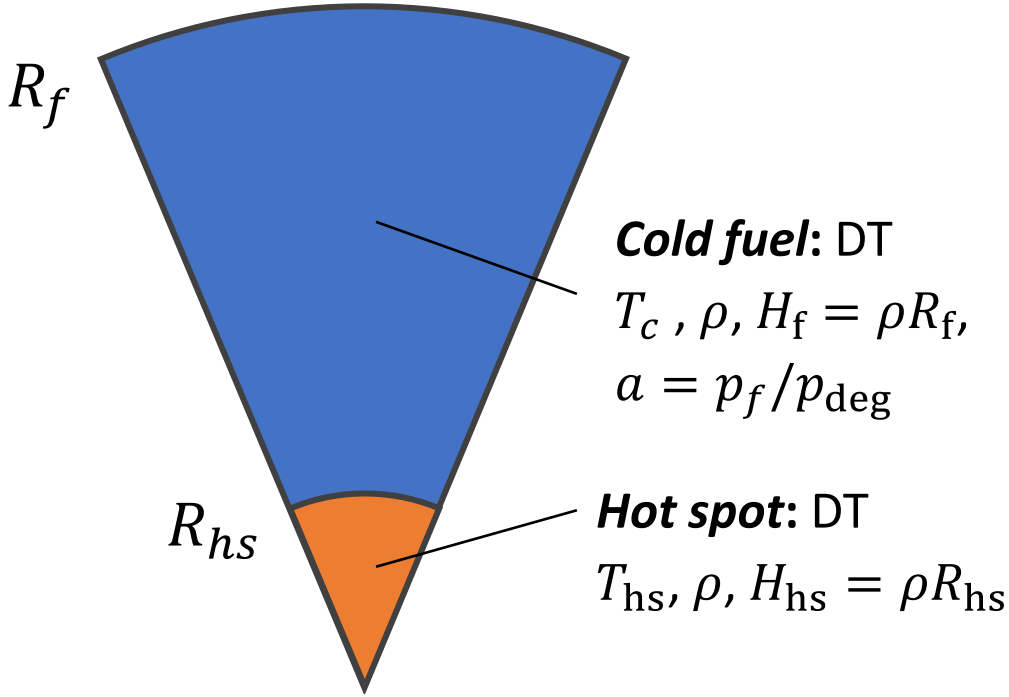
Burn propagation and gain for large DT targets

Determination of the ignition threshold using Helios



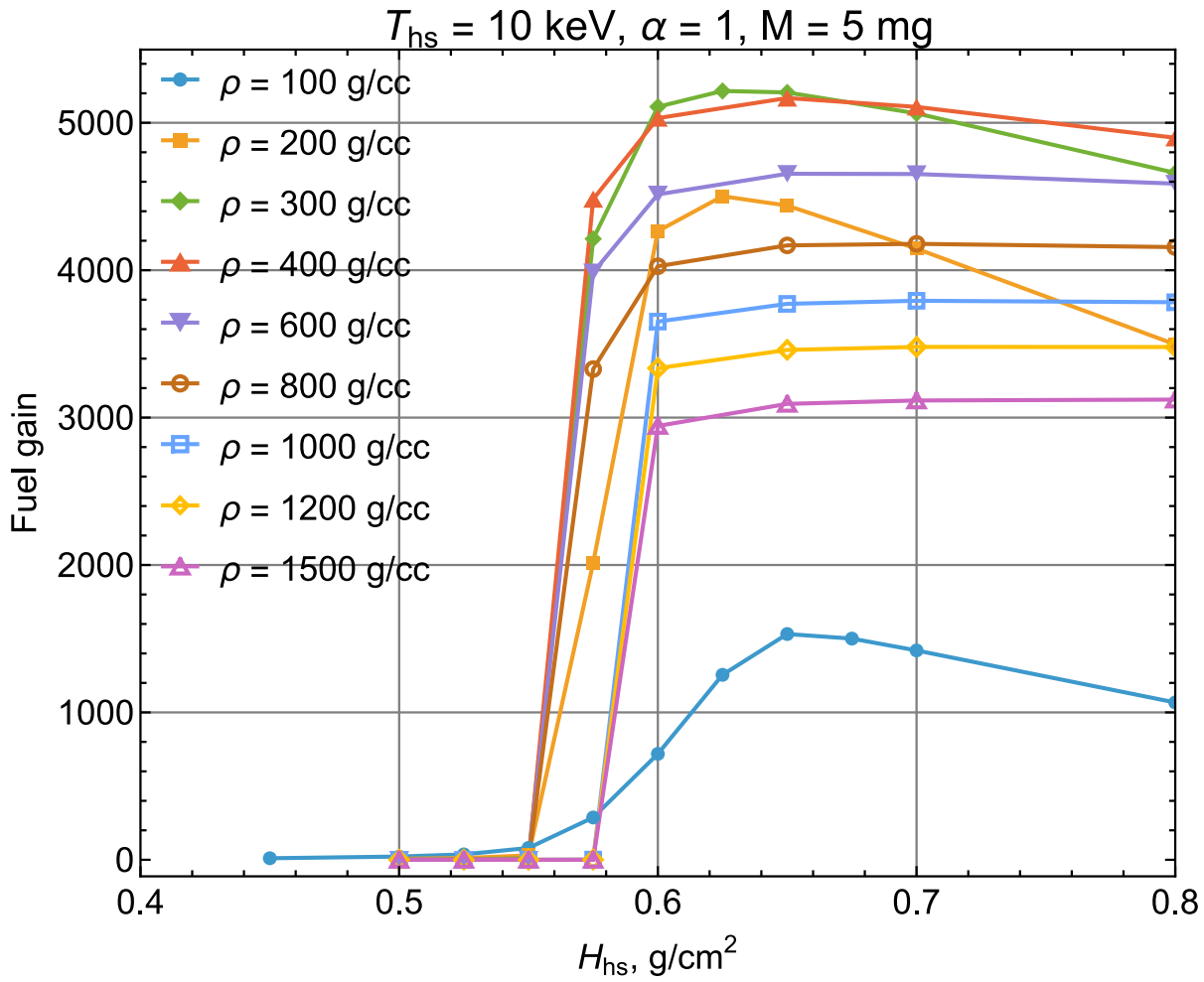
Initial isochoric configuration

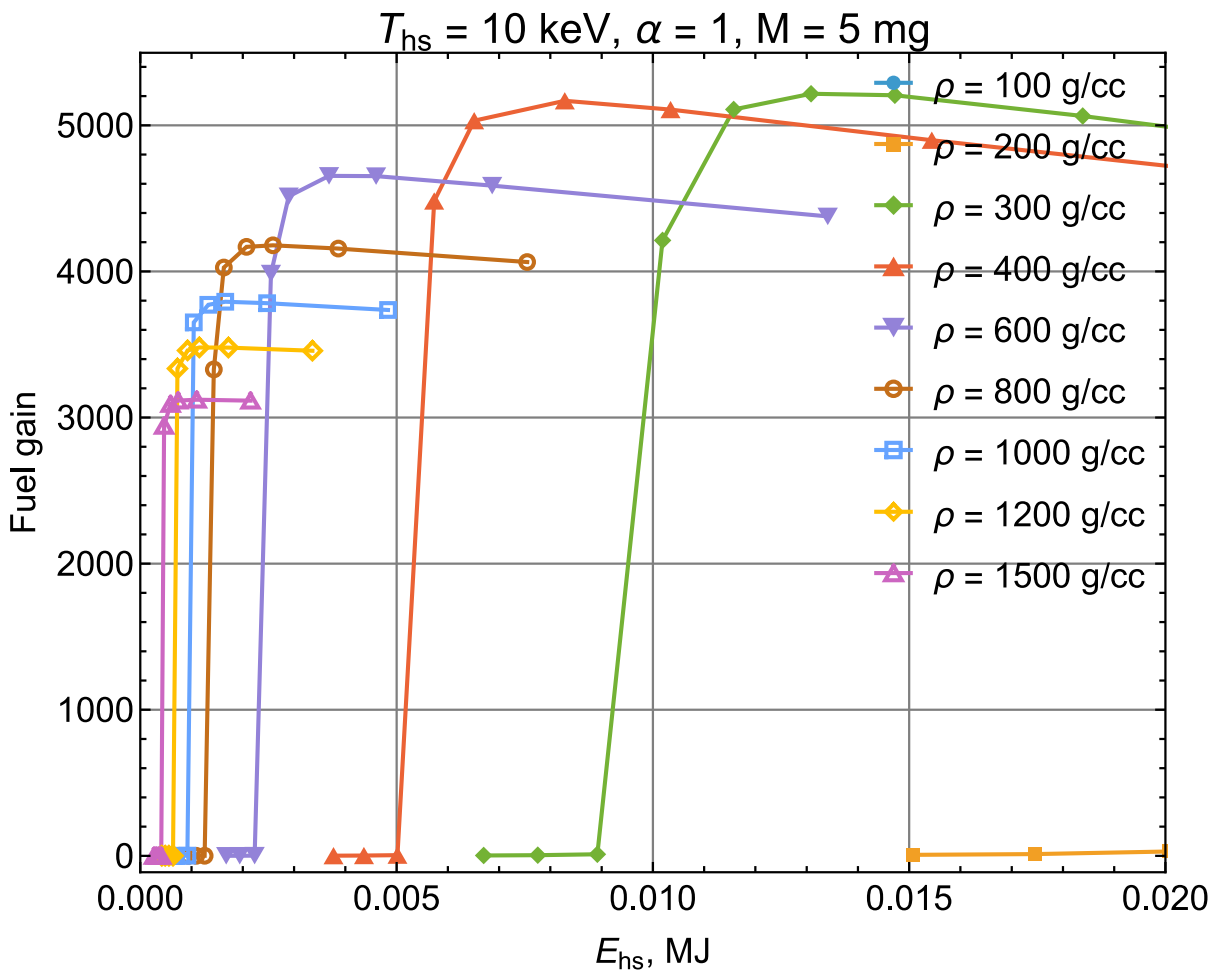
(after implosion)



$$\text{Fuel gain} = \frac{\text{Fusion yield}}{\text{Total initial energy}}$$

Determination of the ignition threshold using Helios





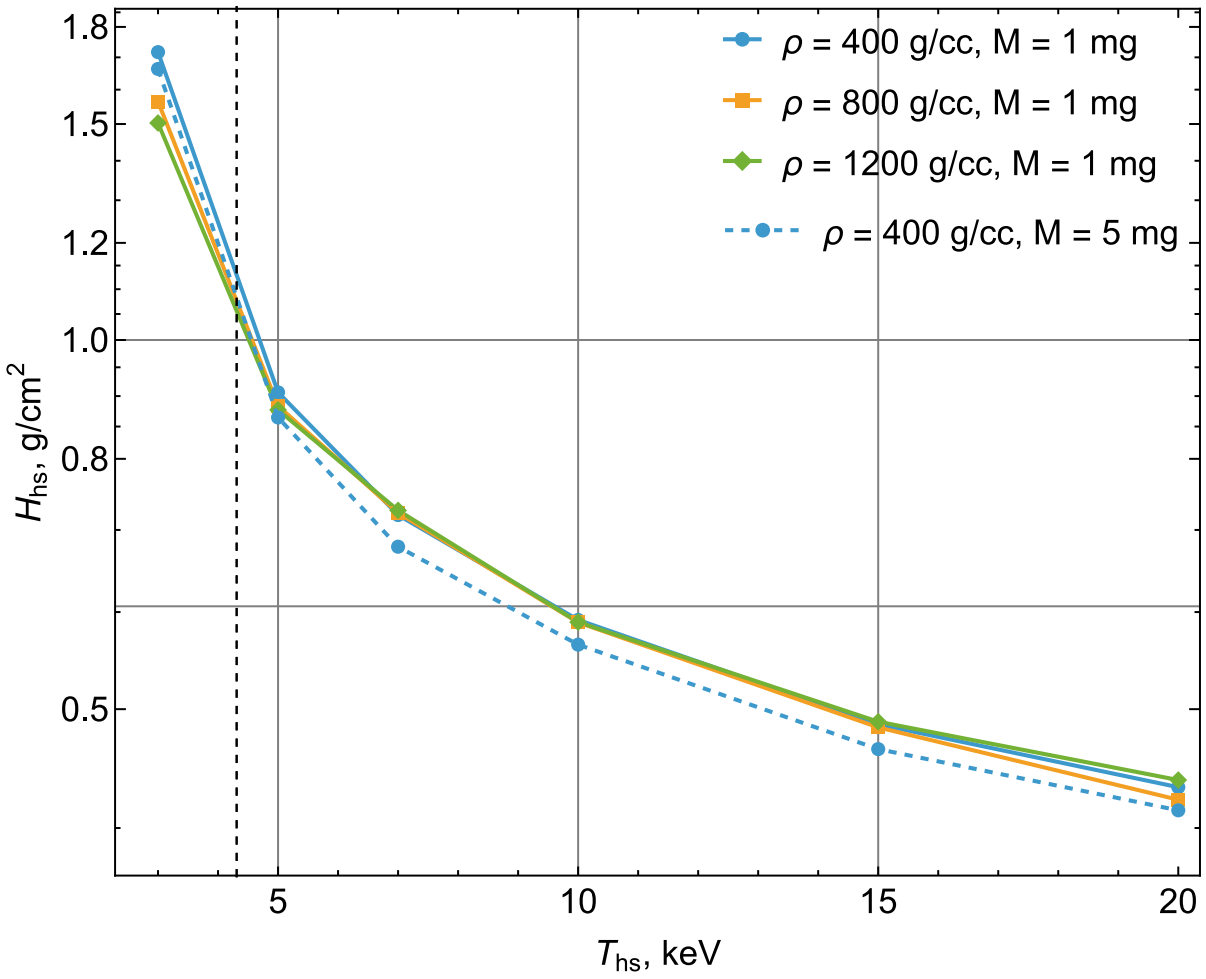
Ignition parameter for the hot spot

$$H_{\mathrm{hs}} = \rho_{\mathrm{hs}} R_{\mathrm{hs}}$$

Initial hot spot energy

$$E_{\mathrm{hs}} = \frac{3}{2} \frac{\rho_{\mathrm{hs}}}{m_{\mathrm{i,avr}}} (T_{\mathrm{i}} + Z_{\mathrm{avr}} T_{\mathrm{e}})$$

Parameter range for ignition



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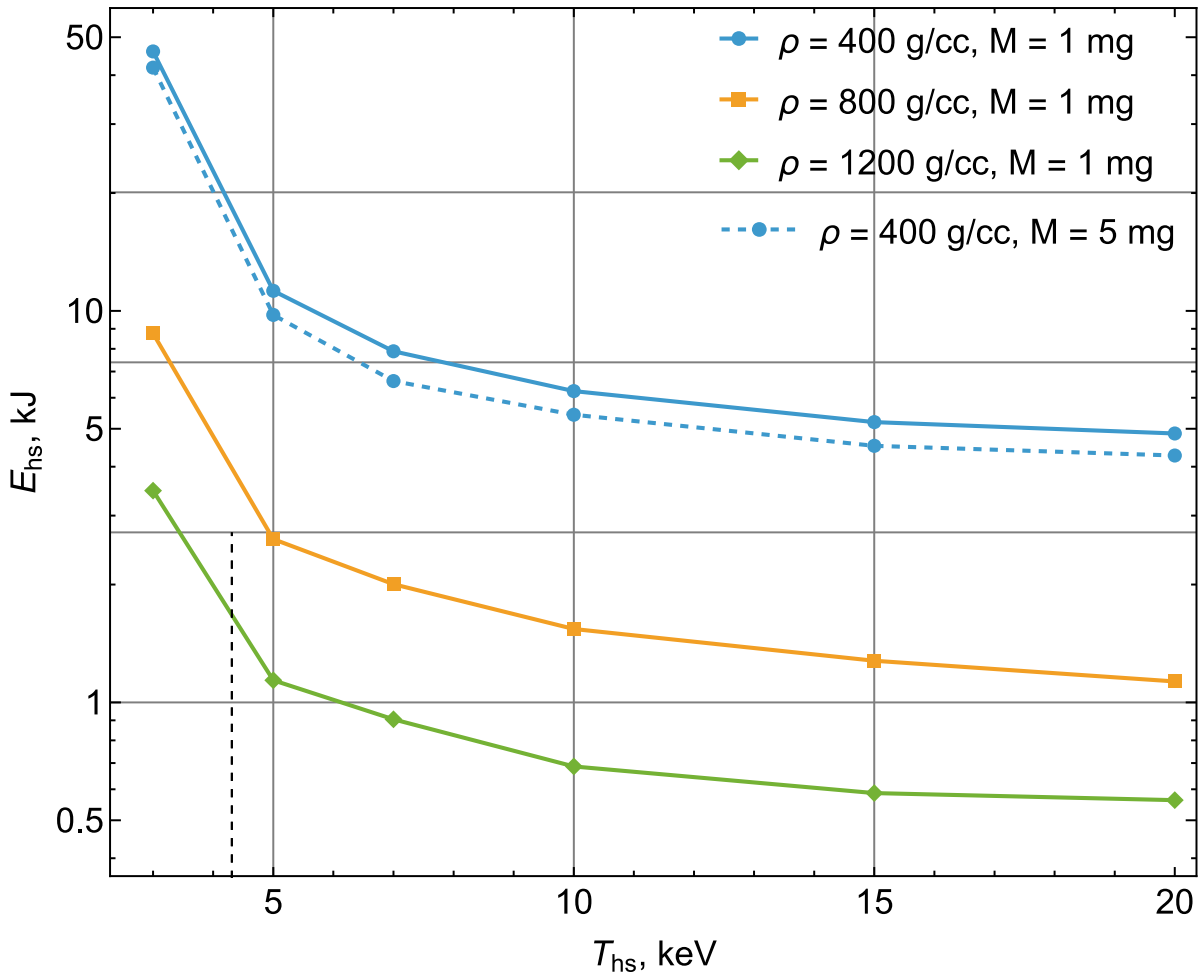
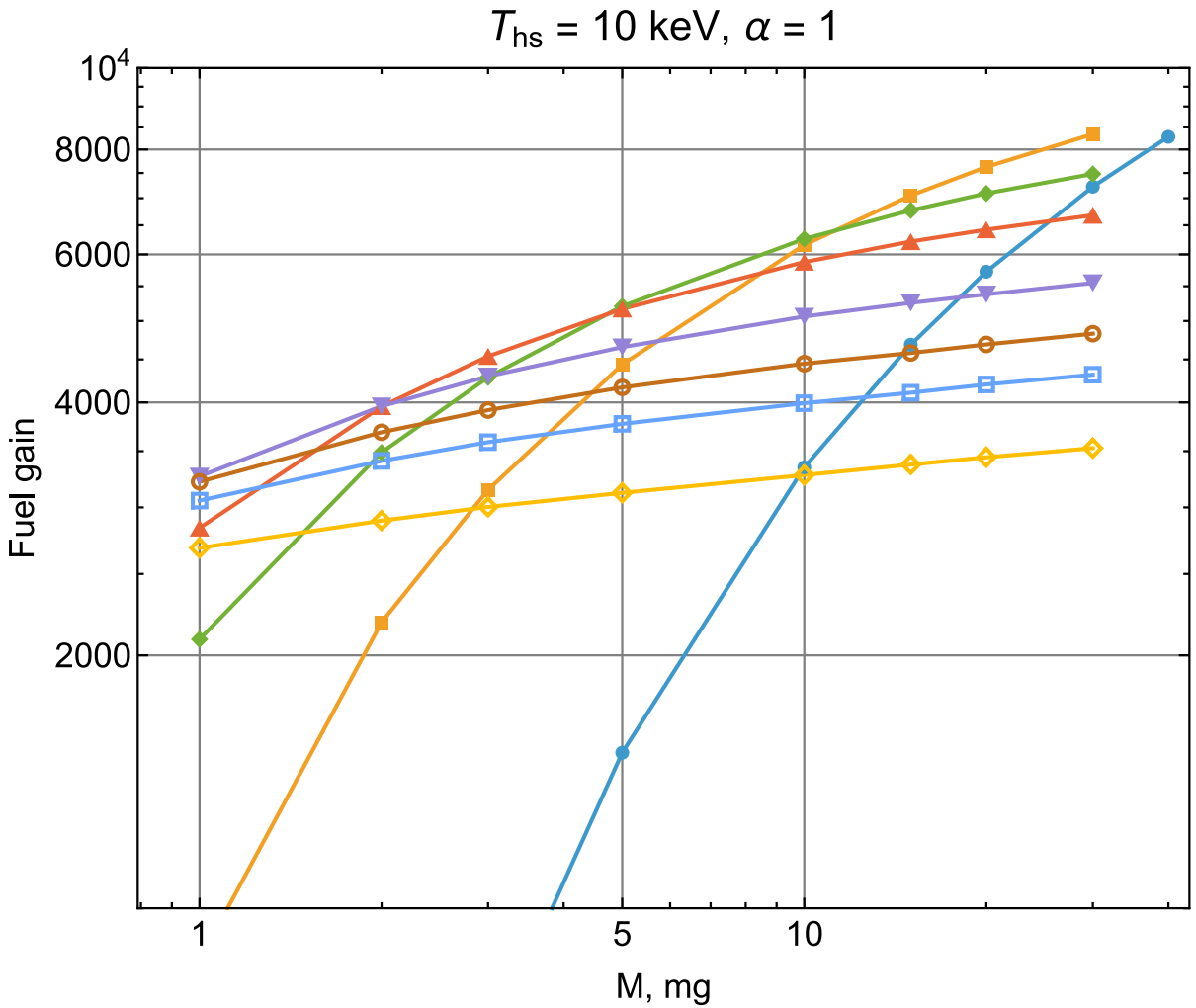


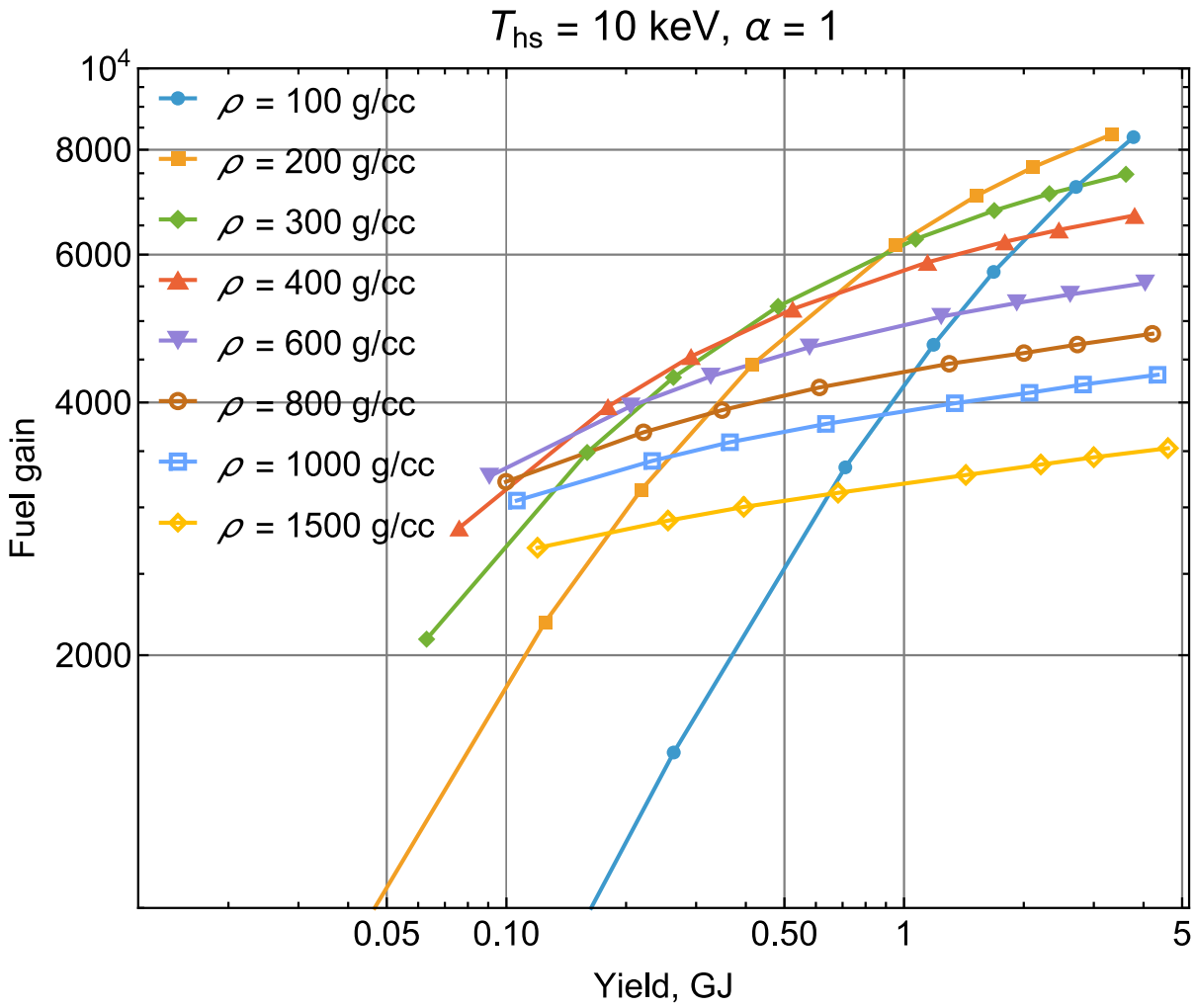
Initial hot spot energy

$$E_{\mathrm{hs}} = \frac{3}{2}\frac{\rho_{\mathrm{hs}}}{m_{\mathrm{i,avr}}}\left(T_{\mathrm{i}} + Z_{\mathrm{avr}} T_{\mathrm{e}}\right)$$

Fuel gain depending on the target size

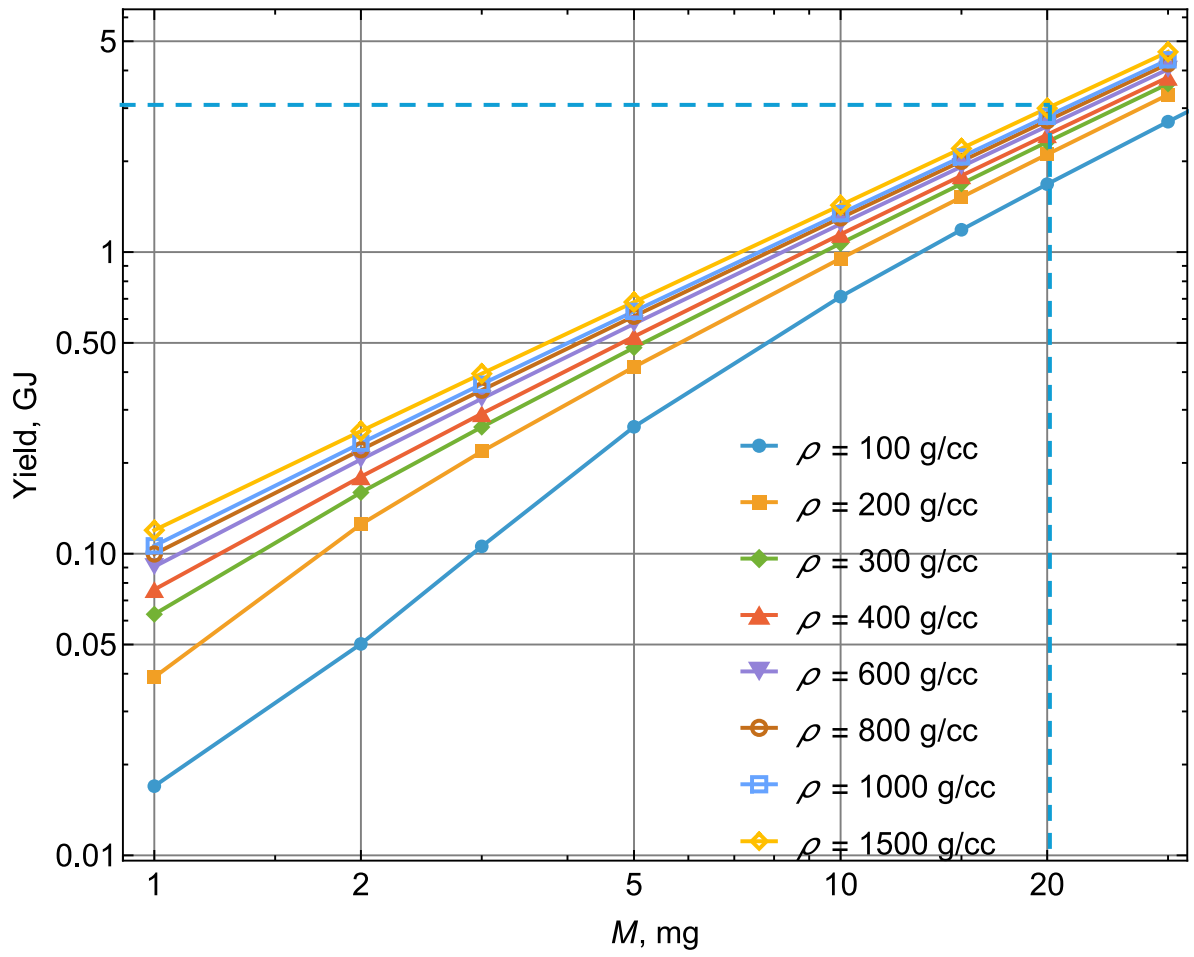


Total fuel mass

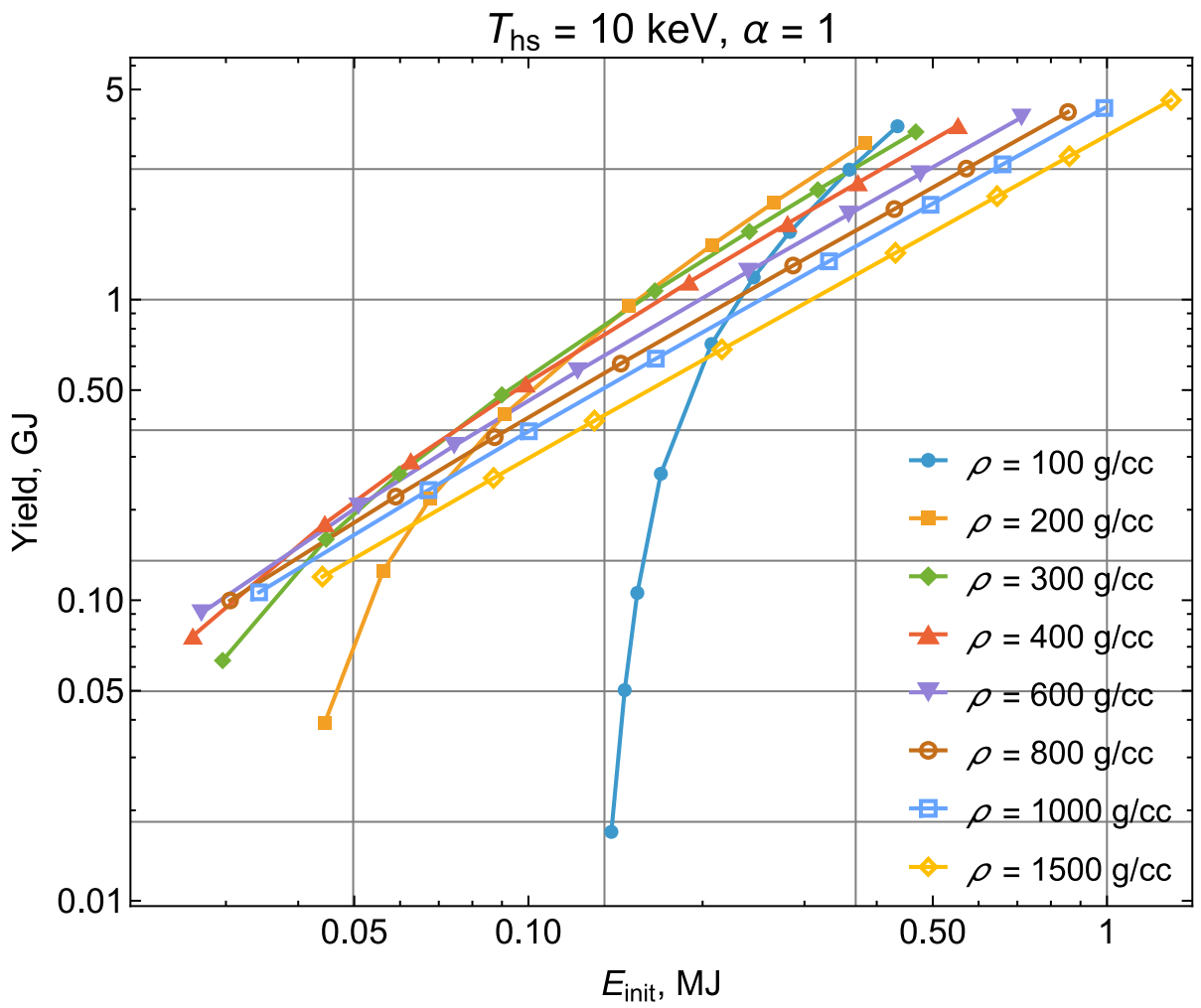


Total fusion yield

Fusion yield depending on the target size

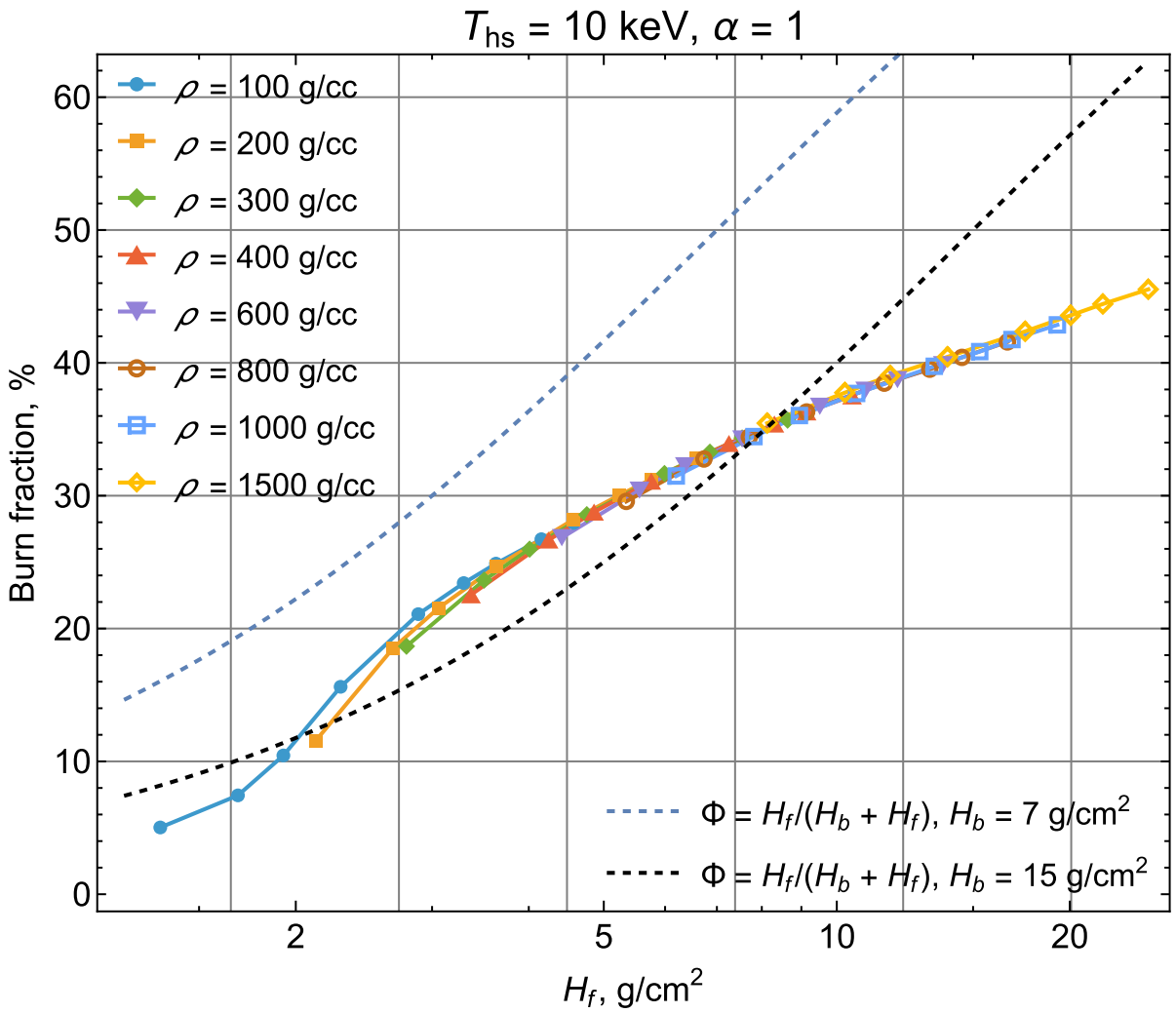


Total fuel mass



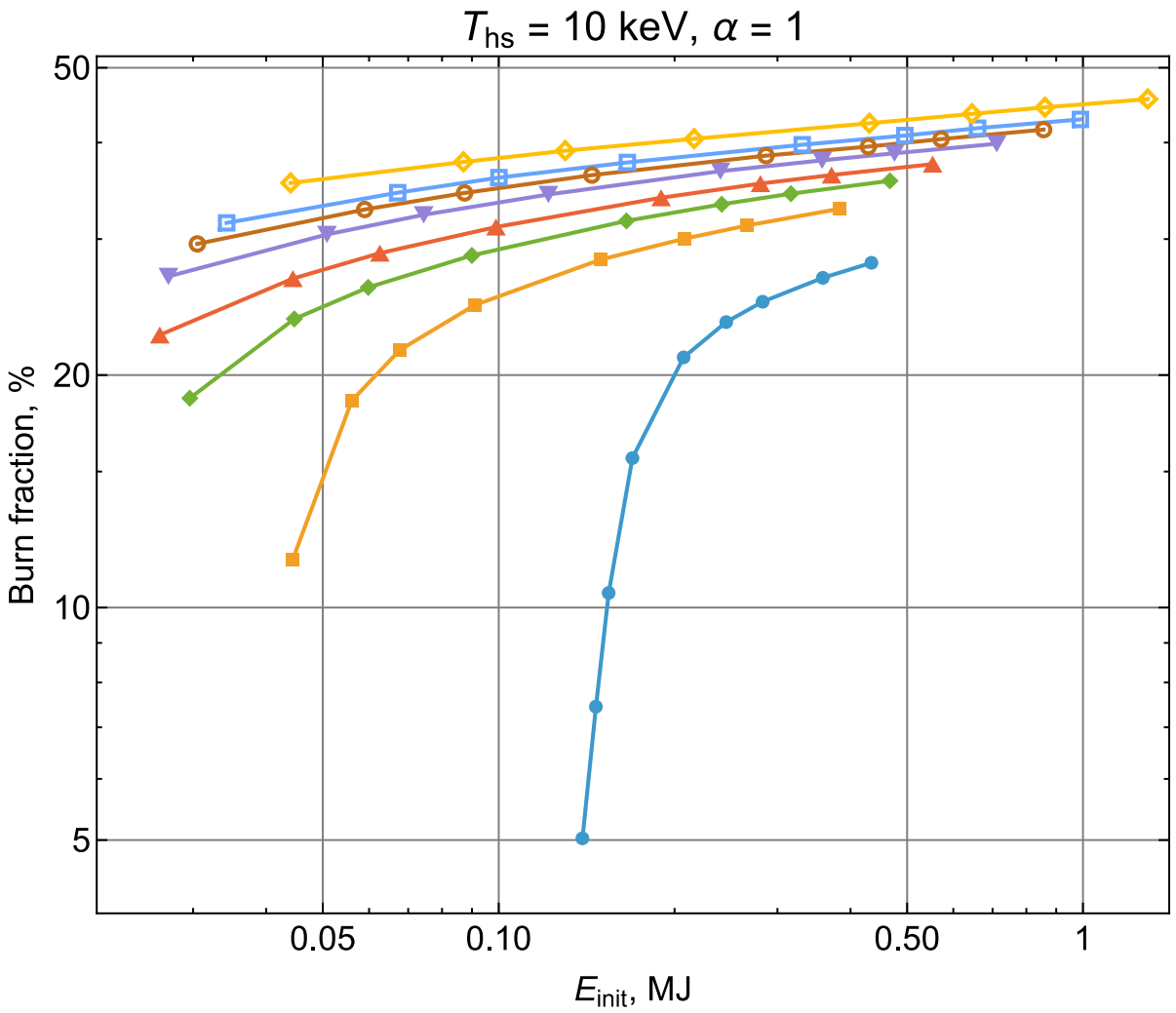
Total initial energy

Burn fraction depending on the target size



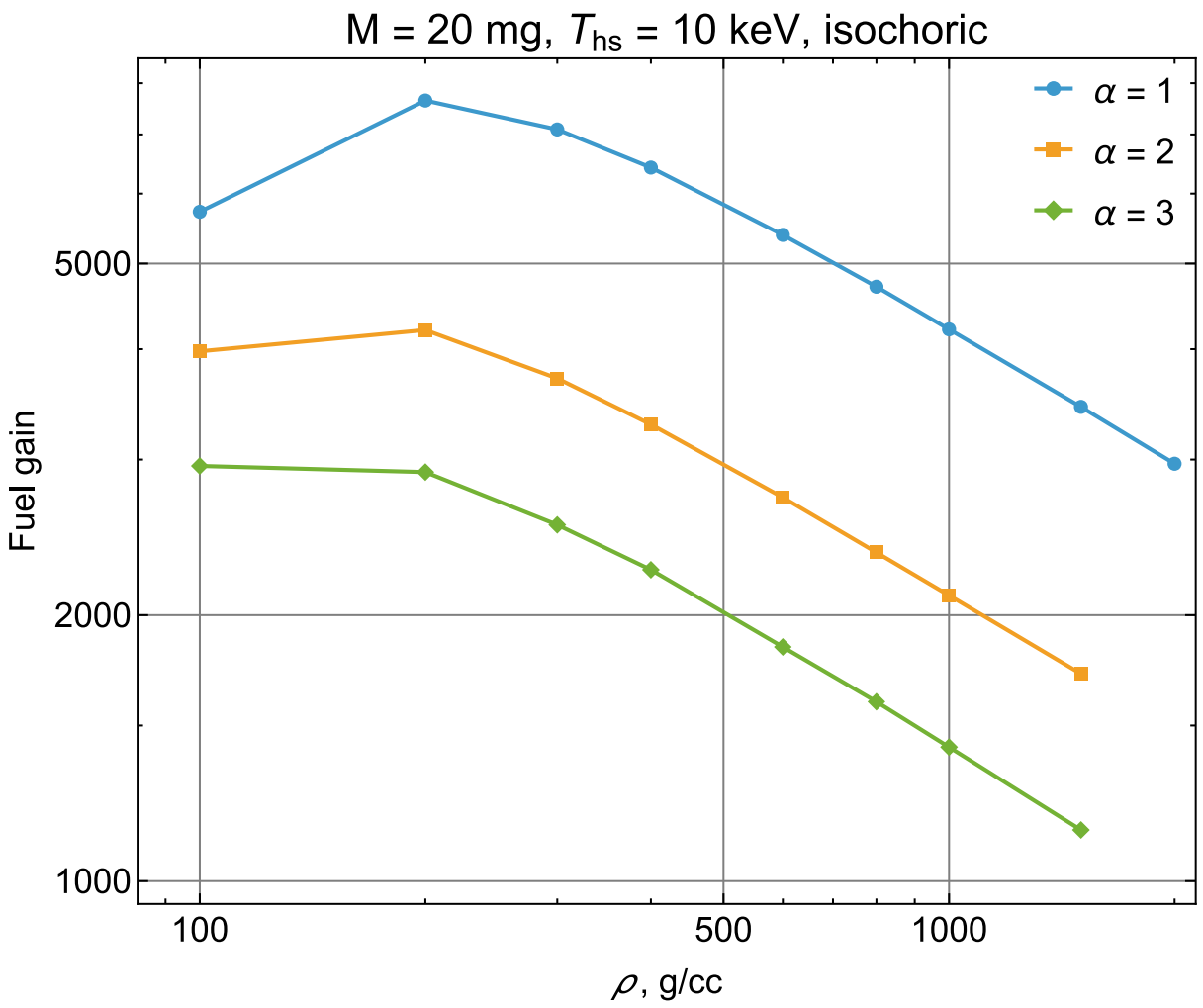
Ignition parameter for the whole target

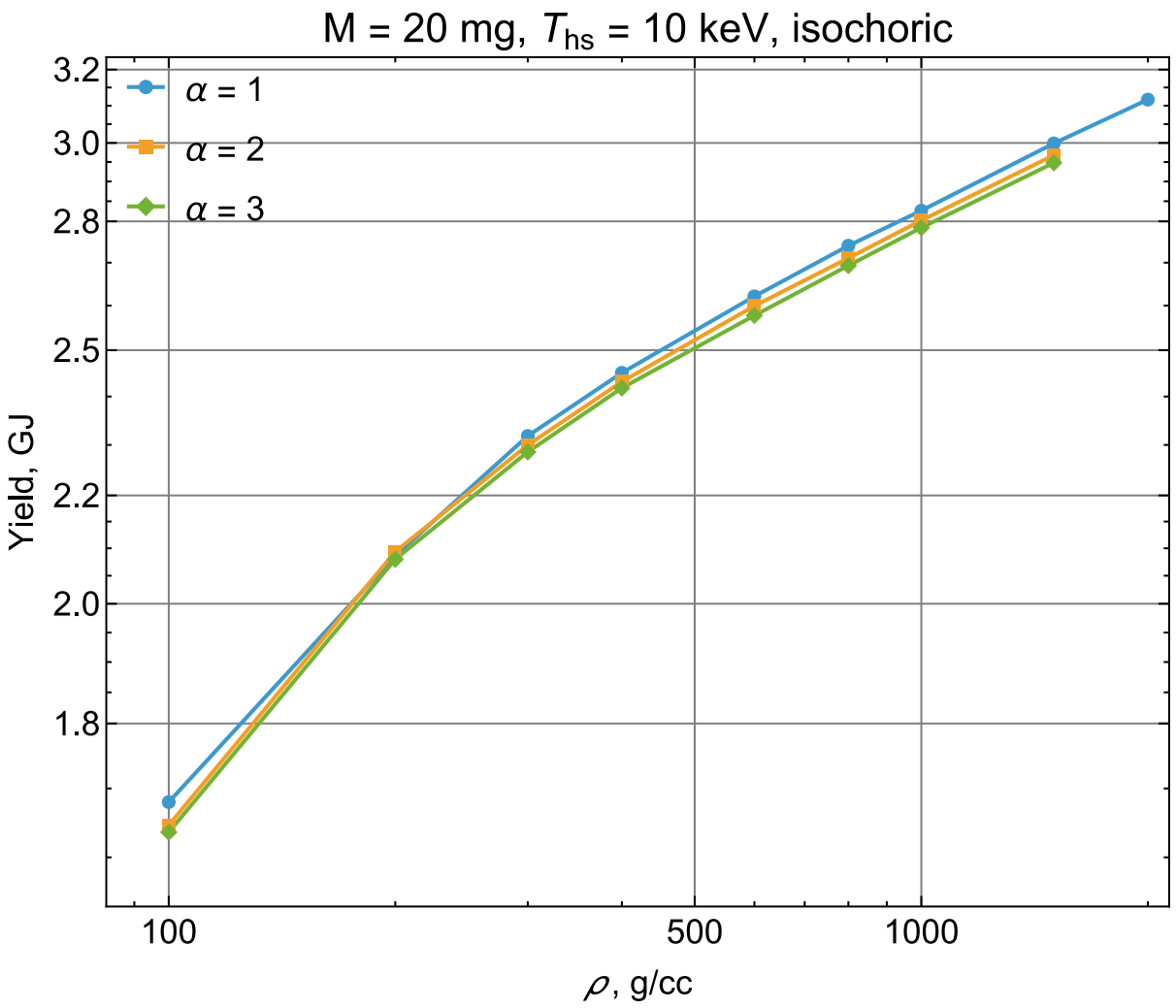
$$H_f = \rho R_f$$



Total initial energy

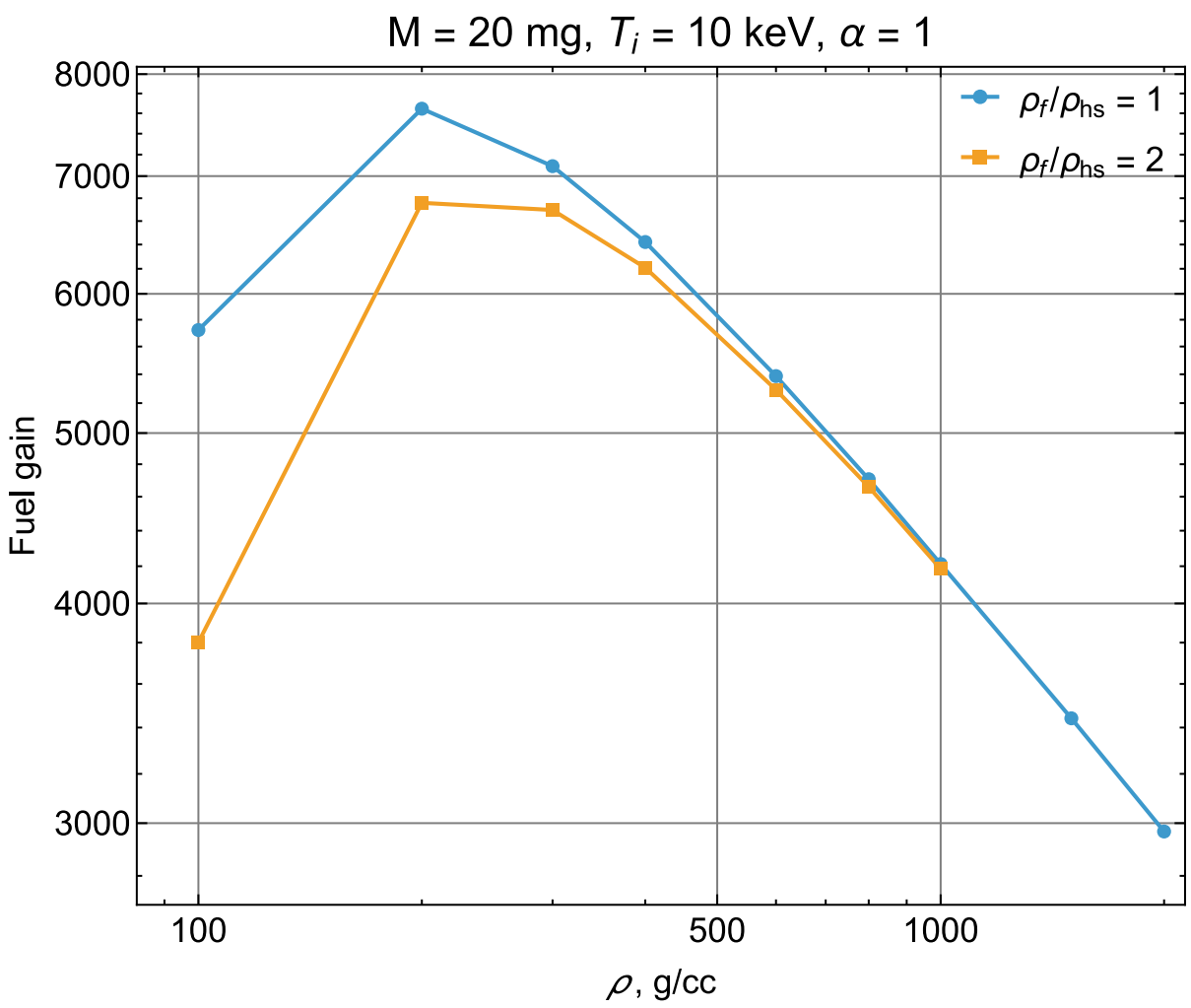
Fuel gain and yield depending on the density

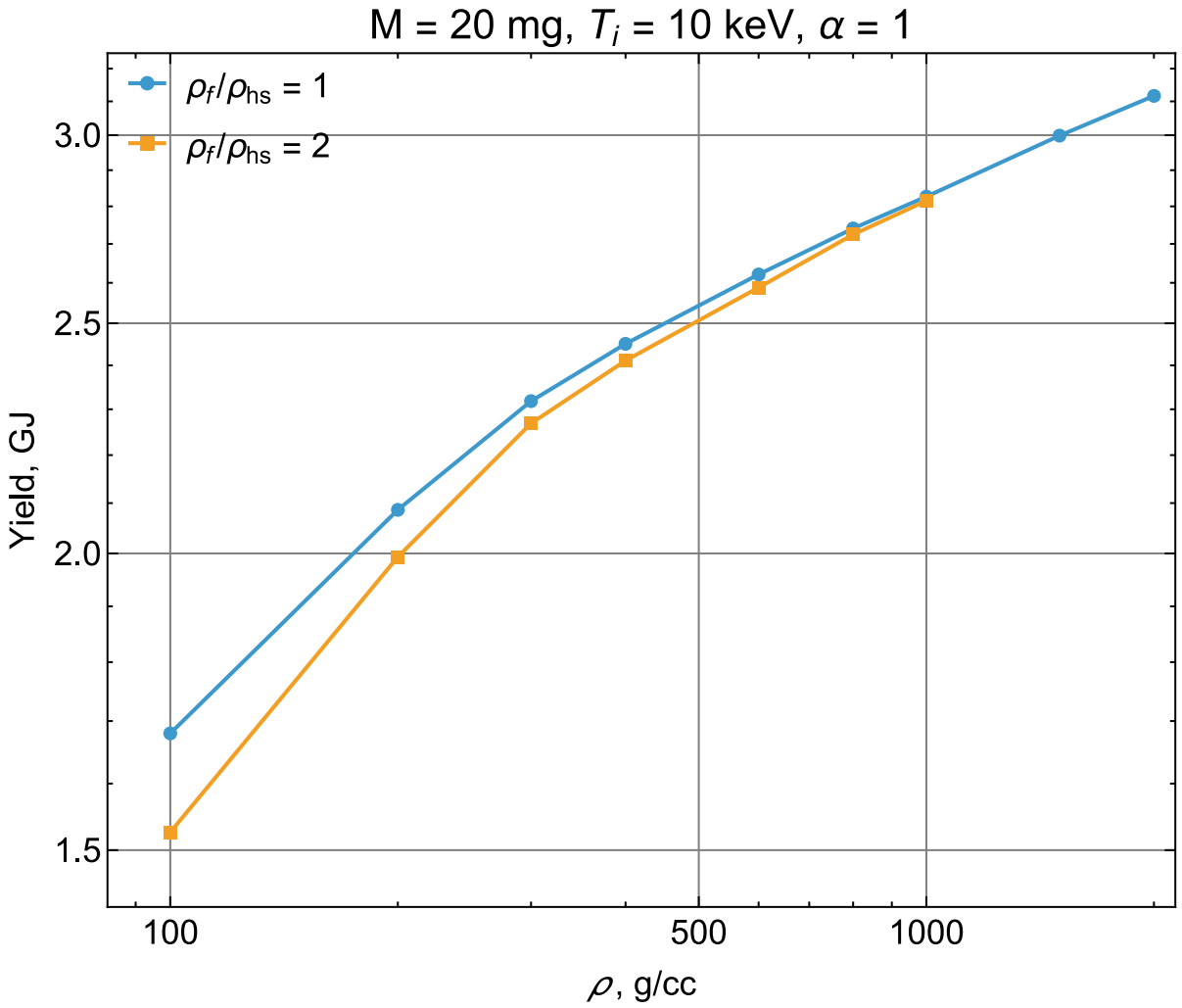




Fuel gain for different compression adiabats $a = p/p_{\mathrm{deg}}$

Fuel gain and yield depending on the density

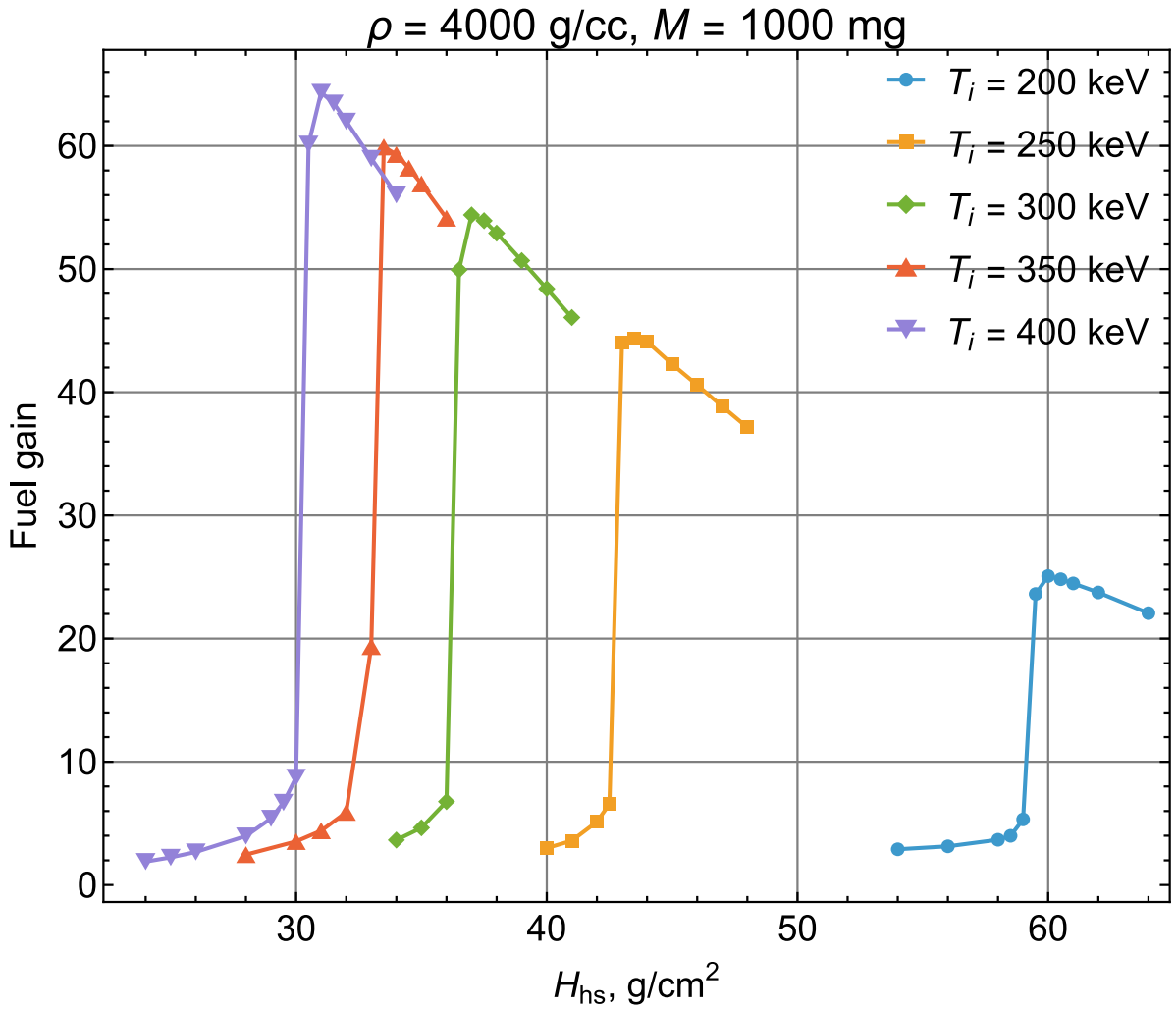


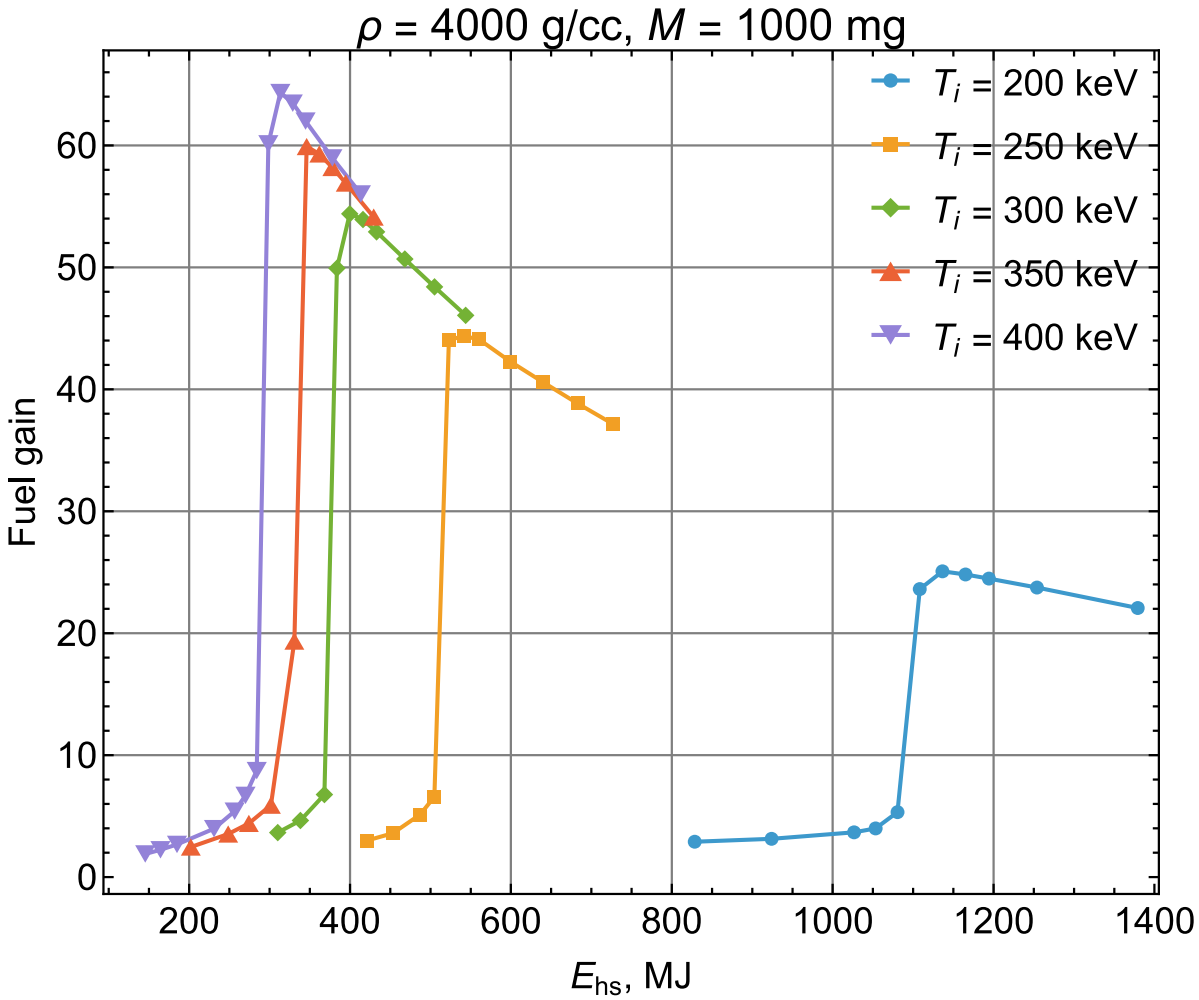


Fuel gain for different cold fuel to hot spot density ratios ρ_f/ρ_{hs}

Burn propagation in pure p-B targets

Minimal ignition parameters for BH_5





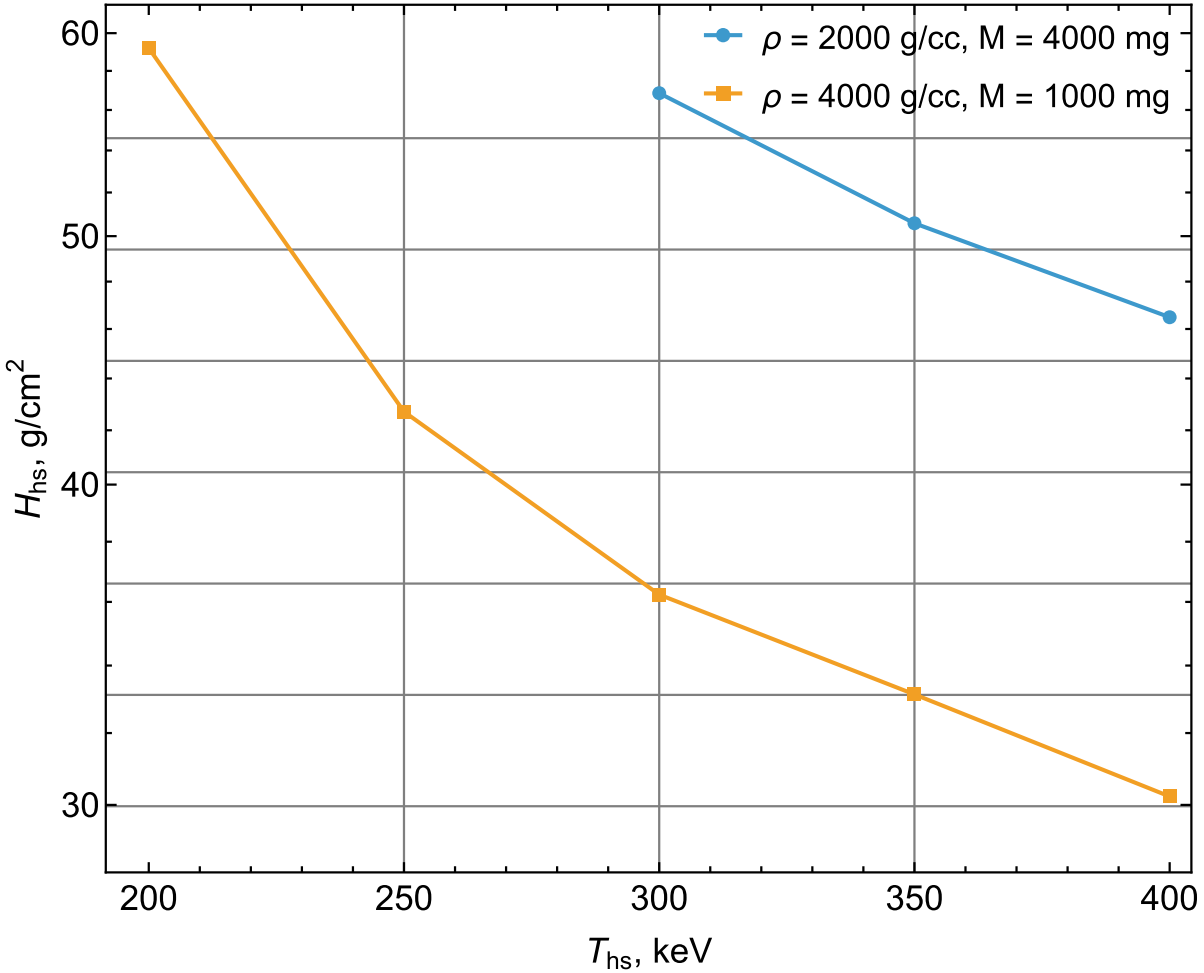
Ignition parameter for the hot spot

$$H_{\mathrm{hs}} = \rho_{\mathrm{hs}} R_{\mathrm{hs}}$$

Initial hot spot energy

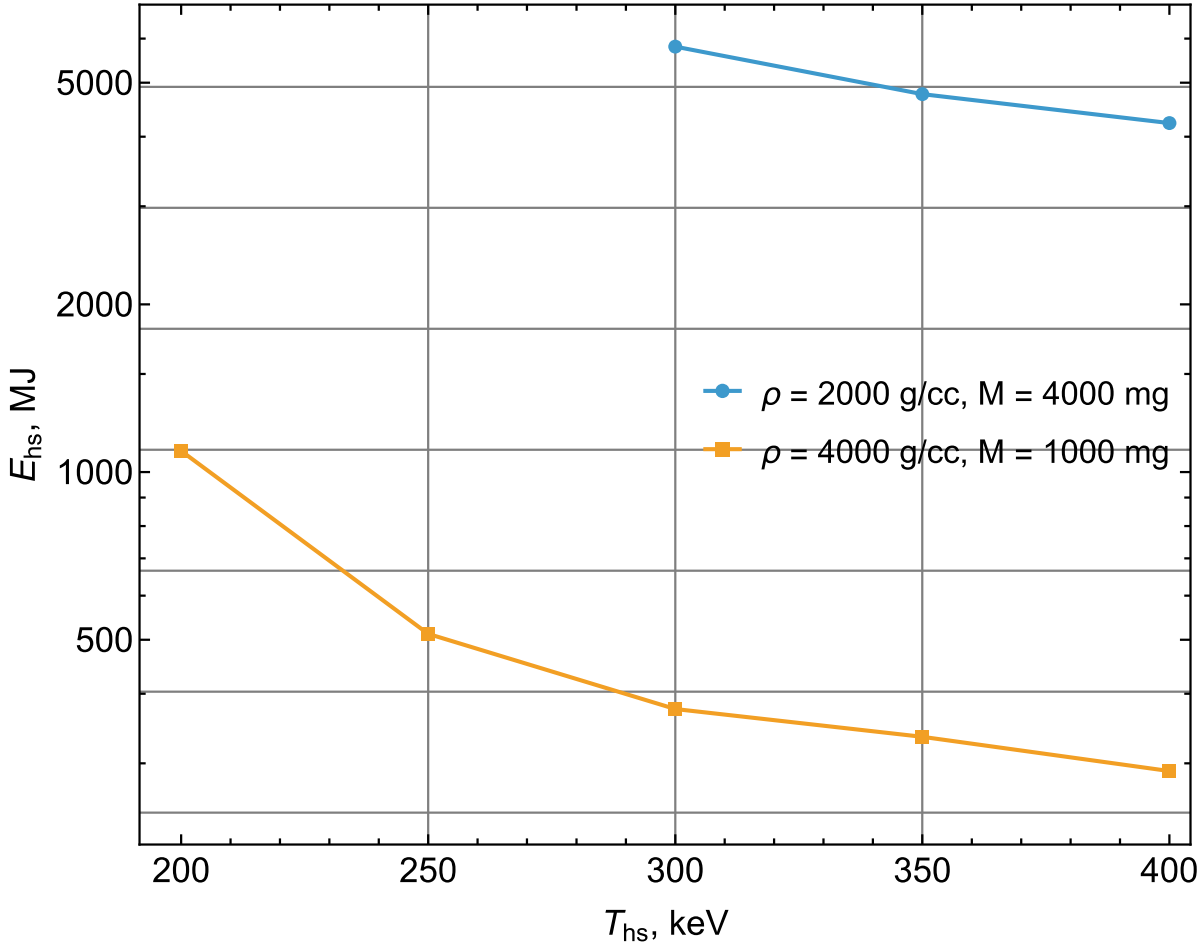
$$E_{\mathrm{hs}} = \frac{3}{2} \frac{\rho_{\mathrm{hs}}}{m_{\mathrm{i,avr}}} (T_{\mathrm{i}} + Z_{\mathrm{avr}} T_{\mathrm{e}})$$

Parameter range for ignition



Ignition parameter for the hot spot

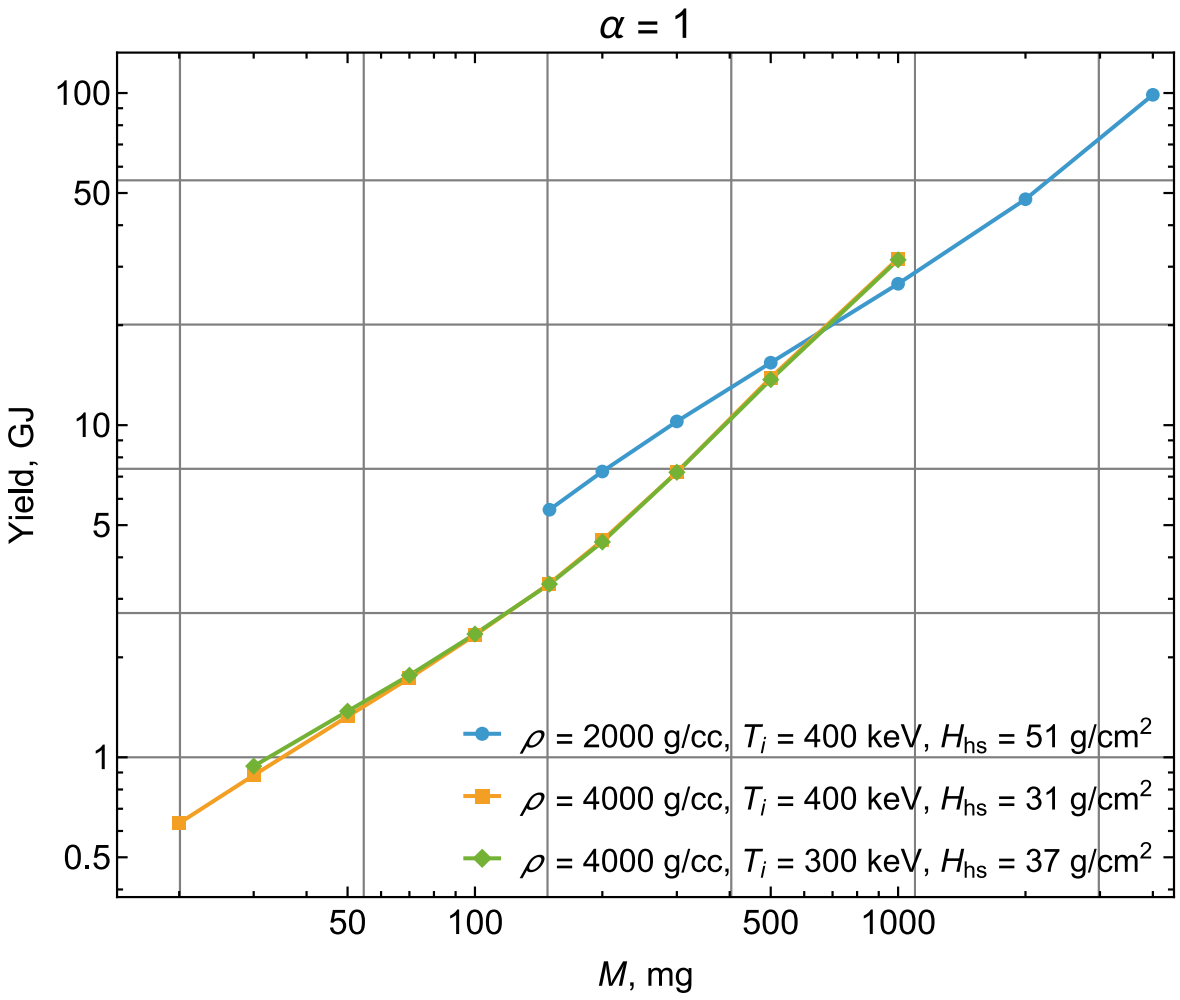
$$H_{\mathrm{hs}} = \rho_{\mathrm{hs}} R_{\mathrm{hs}}$$



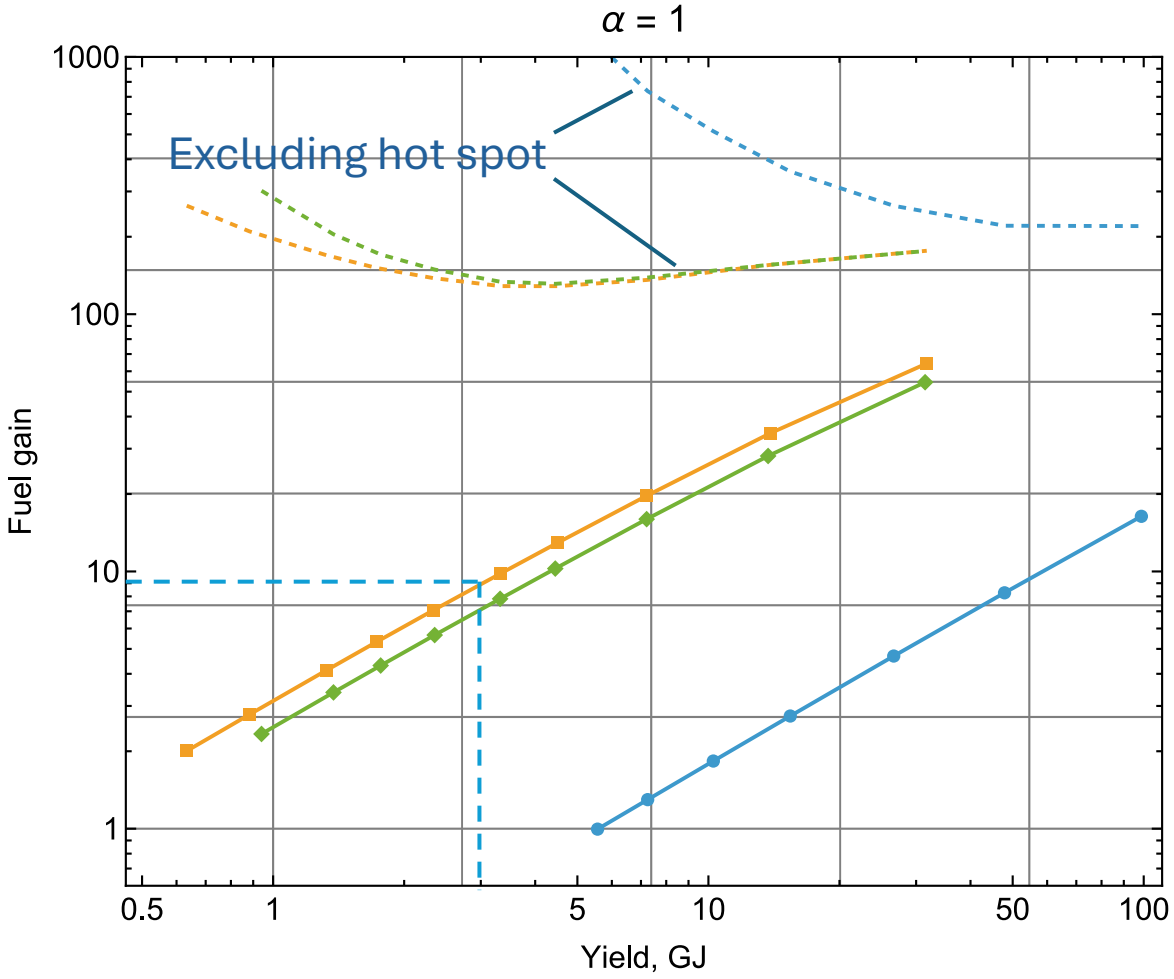
Initial hot spot energy

$$E_{\mathrm{hs}} = \frac{3}{2} \frac{\rho_{\mathrm{hs}}}{m_{\mathrm{i,avr}}} (T_{\mathrm{i}} + Z_{\mathrm{avr}} T_{\mathrm{e}})$$

Minimal ignition parameters for BH_5



Total fuel mass



Fusion yield

Burn wave propagation in D-T fuel

Simulation parameters:

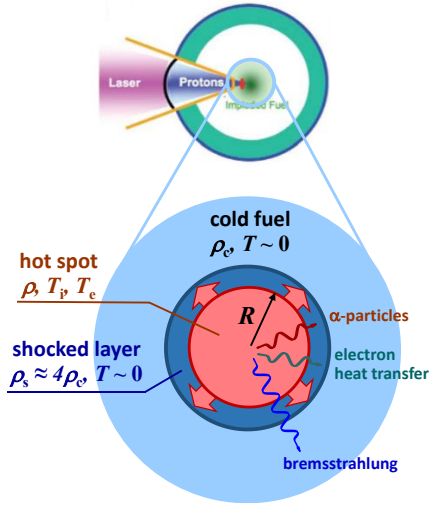
$\rho(0) = 500$ g/cc

$T_{\mathrm{i}}(0) = 10$ keV

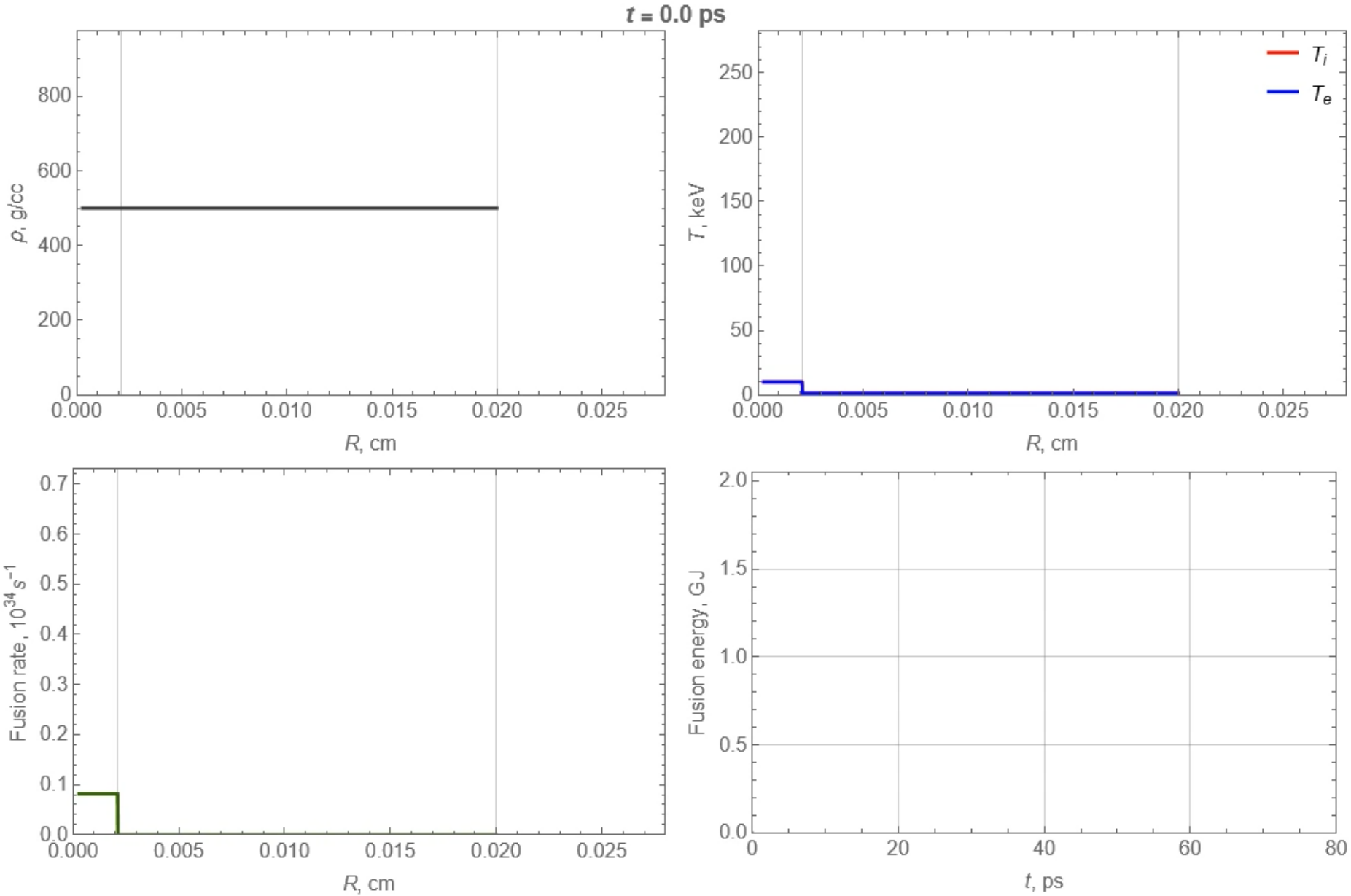
$T_{\mathrm{e}},(0) = 10$ keV

$\rho R(0) = 1.06$ g/cm^2

$n_D/n_T = 1$



1D simulations



Burn wave propagation in BH_5 fuel

Simulation parameters:

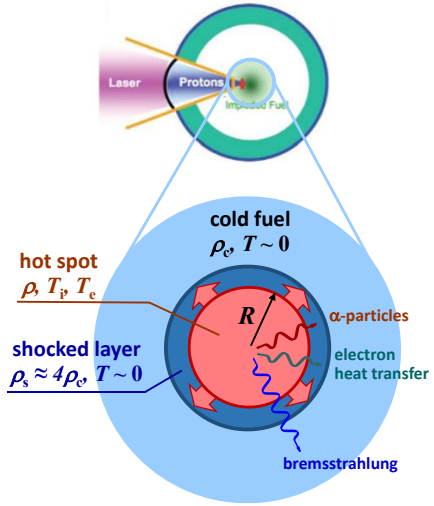
$\rho(0) = 4000$ g/cc

$T_i(0) = 300$ keV

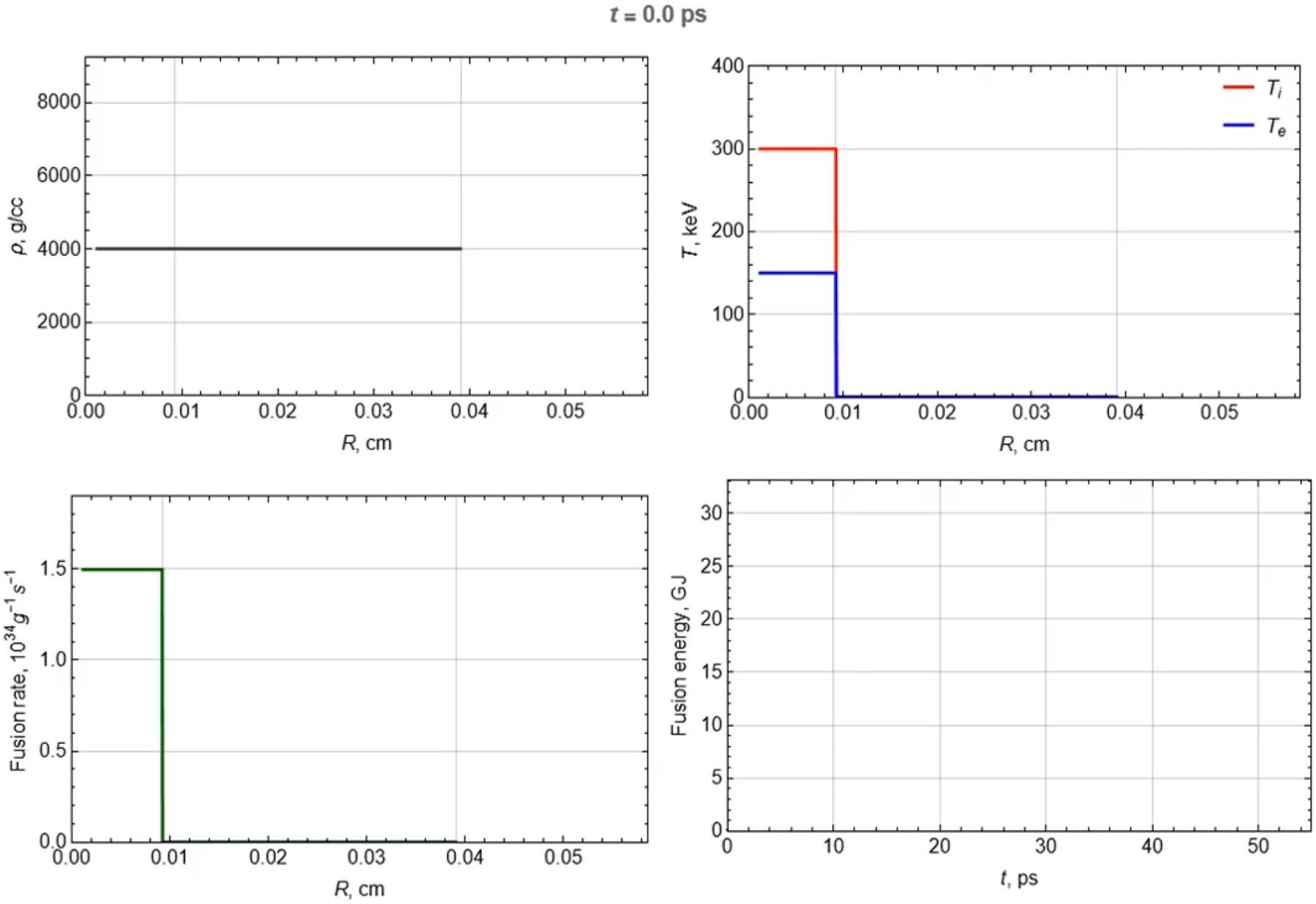
$T_e(0) = 150$ keV

$\rho R(0) = 37$ g/cm^2

$n_B/n_p = 0.2$



1D simulations



Burn wave propagation in different fuels

D-T fuel

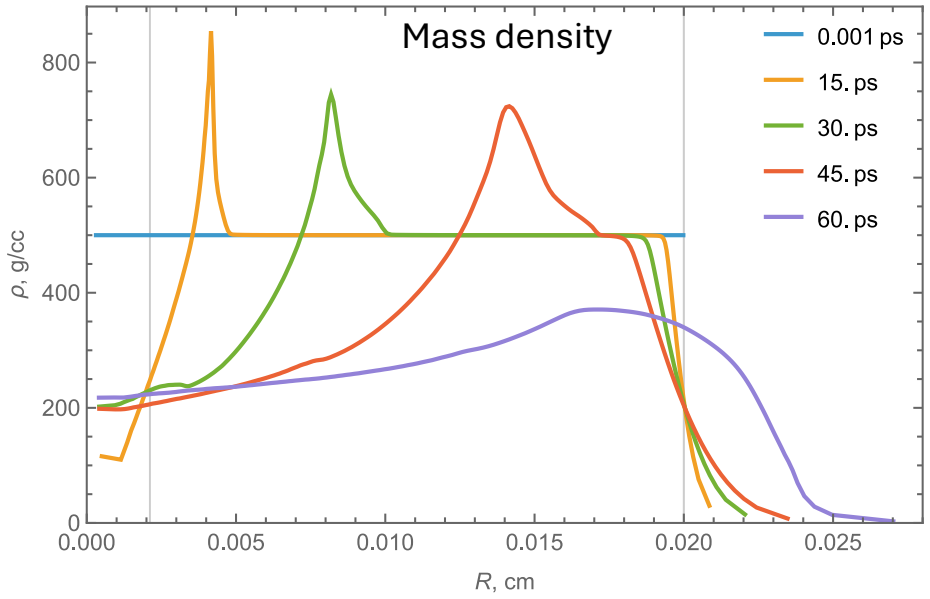
$\rho(0) = 500\ \mathrm{g/cc}$

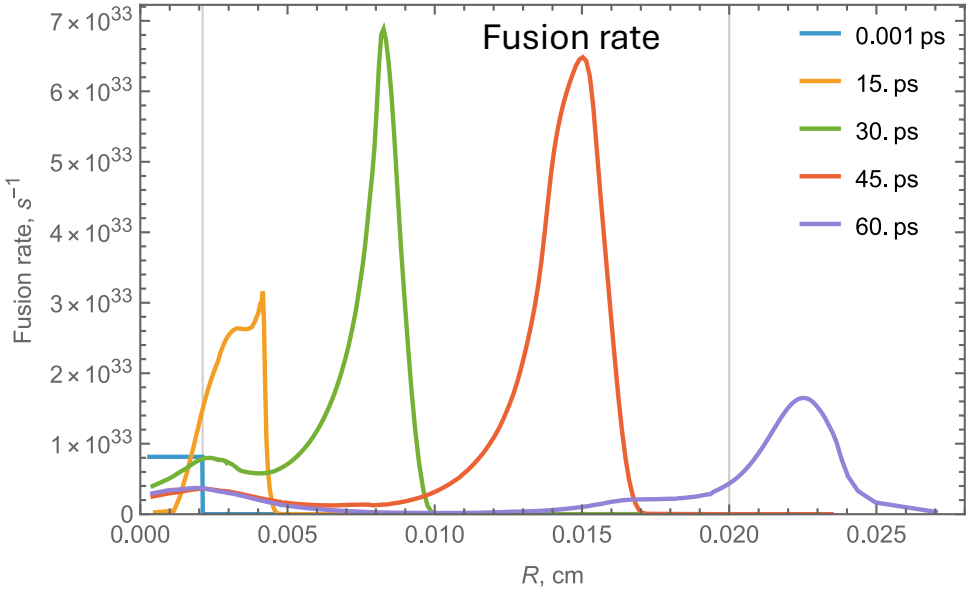
$T_\mathrm{i}(0) = 10\ \mathrm{keV}$

$T_\mathrm{e},(0) = 10\ \mathrm{keV}$

$T_\mathrm{e},(0) = 10\ \mathrm{keV}$

$\rho R(0) = 1.06\ \mathrm{g/cm^2}$





BH_5 fuel

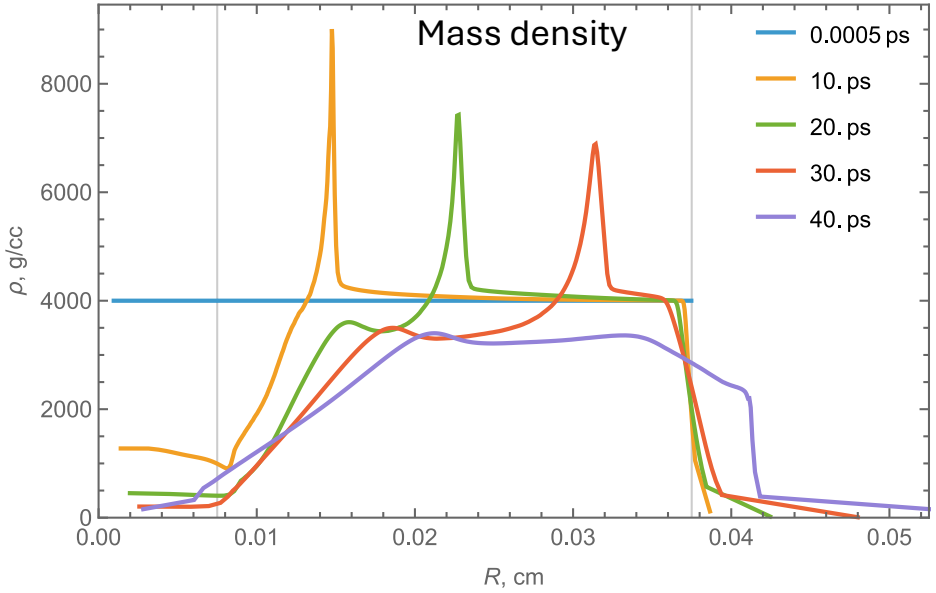
$\rho(0) = 4000\ \mathrm{g/cc}$

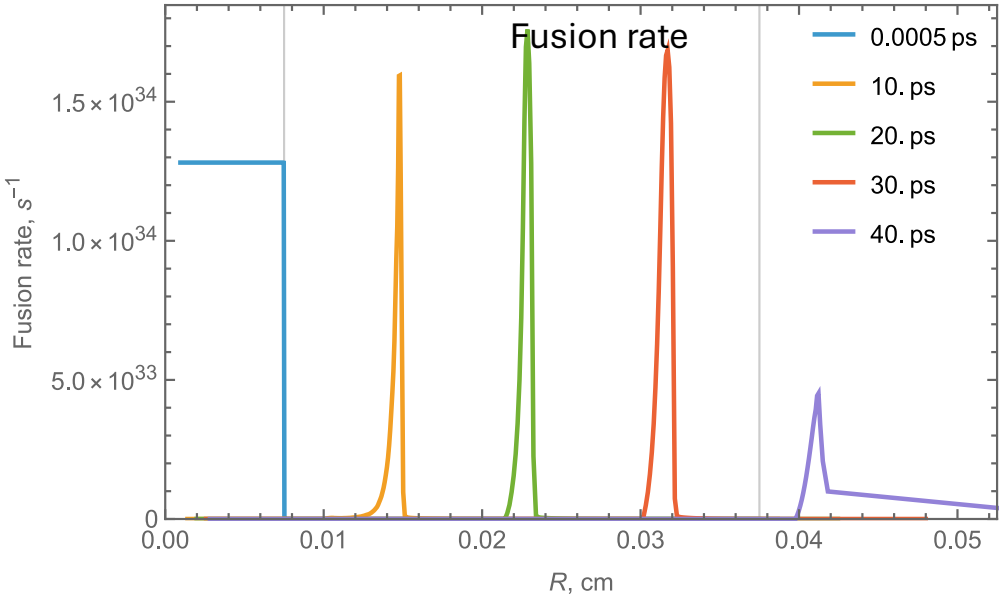
$T_\mathrm{i}(0) = 250\ \mathrm{keV}$

$T_\mathrm{e},(0) = 125\ \mathrm{keV}$

$\rho R(0) = 37\ \mathrm{g/cm^2}$

$n_B/n_p = 0.2$





Burn wave propagation in different fuels

D-T fuel

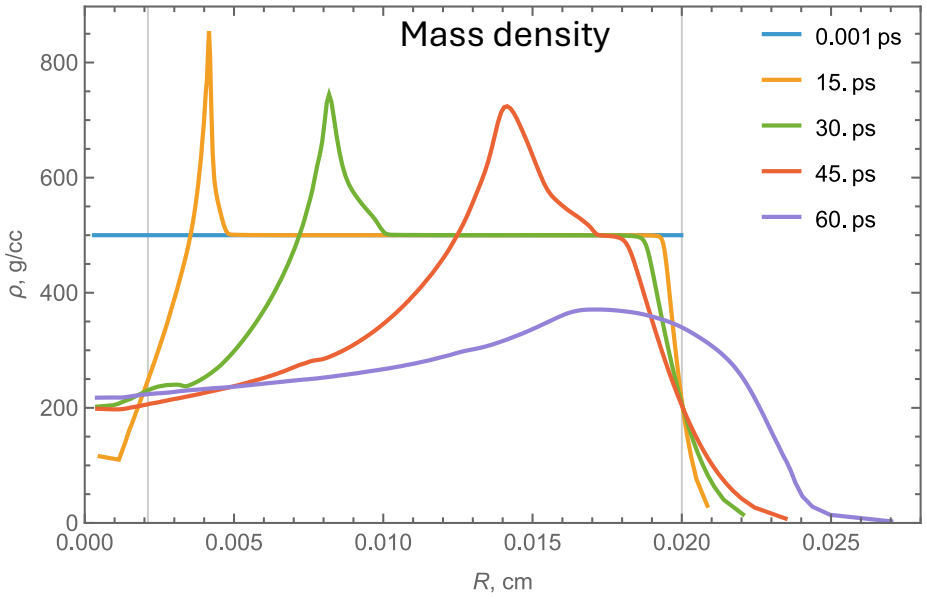
$\rho(0) = 500\ \mathrm{g/cc}$

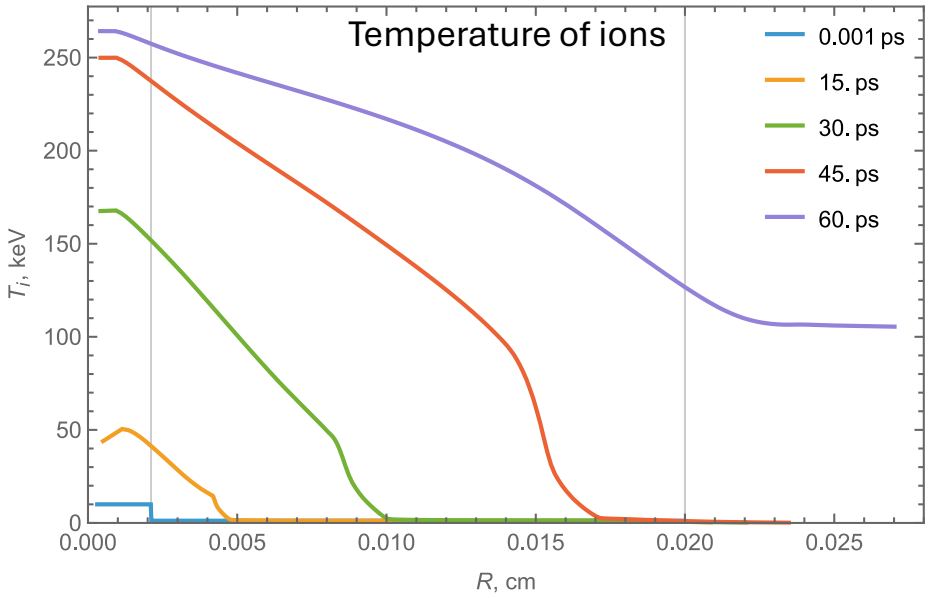
$T_\mathrm{i}(0) = 10\ \mathrm{keV}$

$T_\mathrm{e},(0) = 10\ \mathrm{keV}$

$T_\mathrm{e},(0) = 10\ \mathrm{keV}$

$\rho R(0) = 1.06\ \mathrm{g/cm^2}$





BH_5 fuel

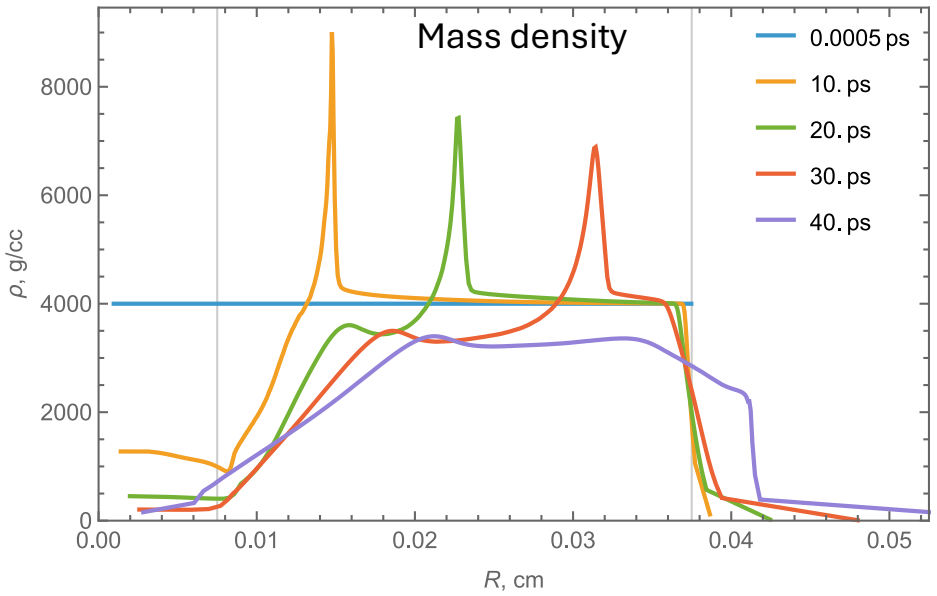
$\rho(0) = 4000\ \mathrm{g/cc}$

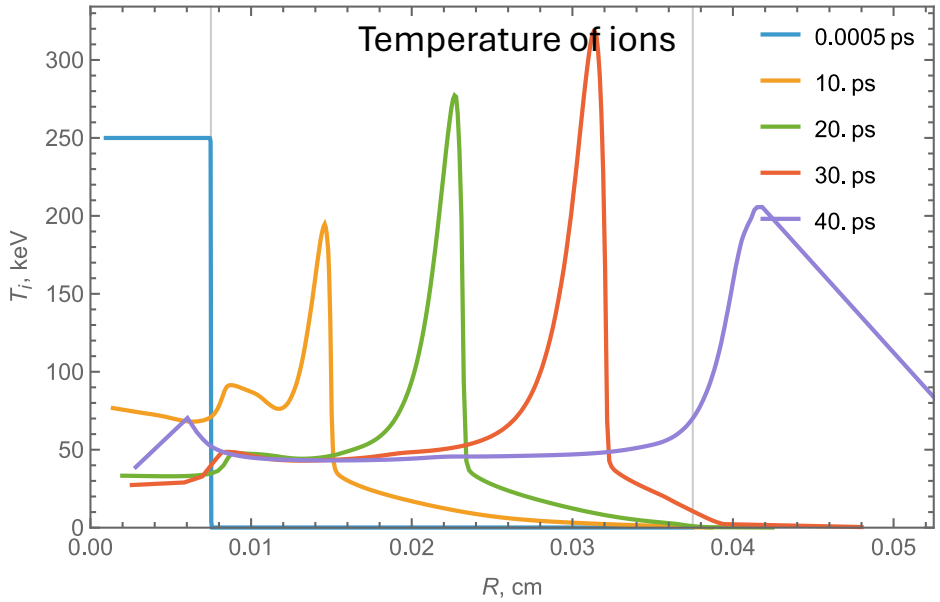
$T_\mathrm{i}(0) = 250\ \mathrm{keV}$

$T_\mathrm{e},(0) = 125\ \mathrm{keV}$

$\rho R(0) = 37\ \mathrm{g/cm^2}$

$n_B/n_p = 0.2$





Burn wave propagation in B_2H_6 fuel

Simulation parameters:

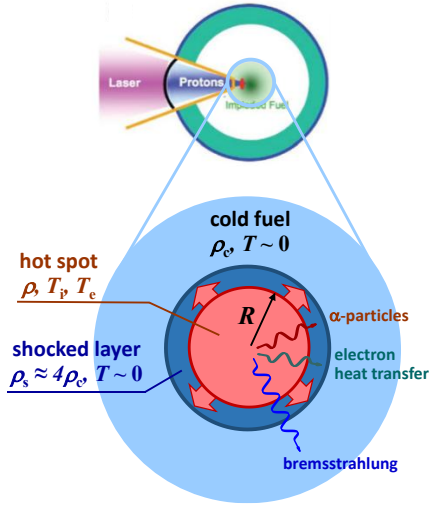
$\rho(0) = 4000$ g/cc

$T_i(0) = 300$ keV

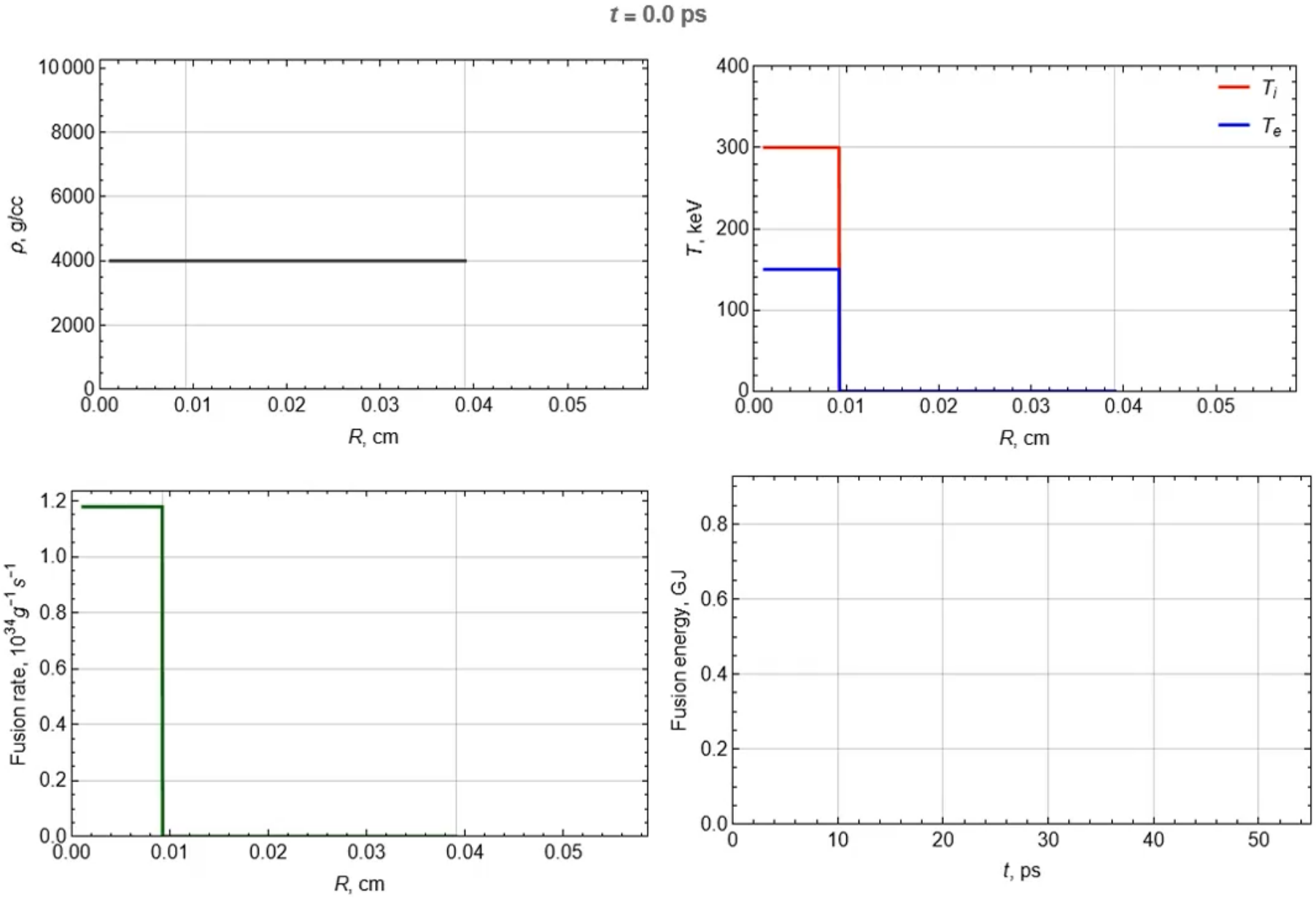
$T_e(0) = 150$ keV

$\rho R(0) = 37$ g/cm^2

$n_B/n_p = 0.333$



1D simulations



Comparison between Helios and TriForce PIC-MCC

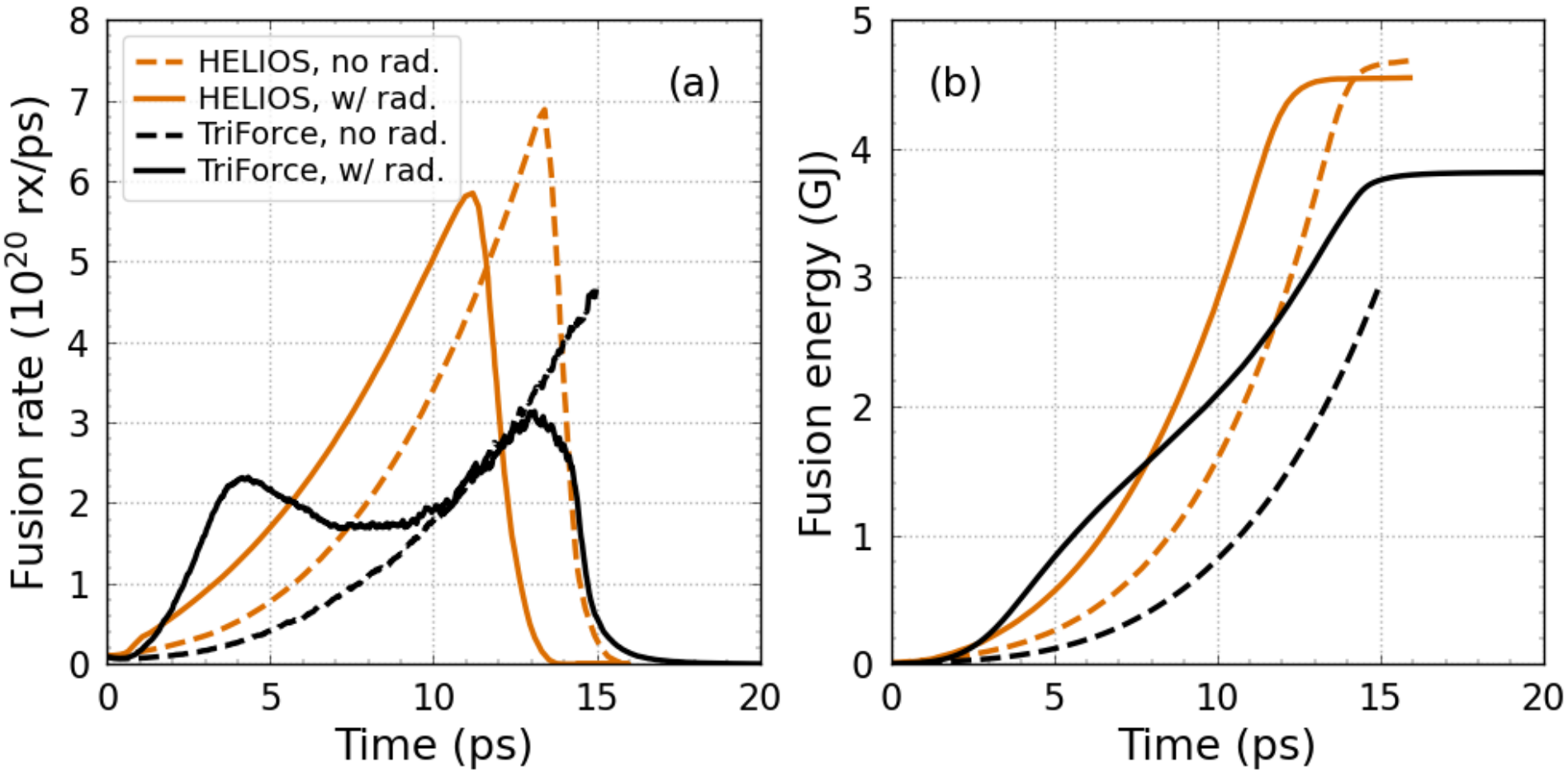
$\rho = 8000$ g/cc

$T_i = 500$ keV

$T_e = 333$ keV

$\rho R_{hs} = 16$ g/cm^2

$n_B/n_p = 0.2$



Michael Lavell, Adam Sefkow, private communication

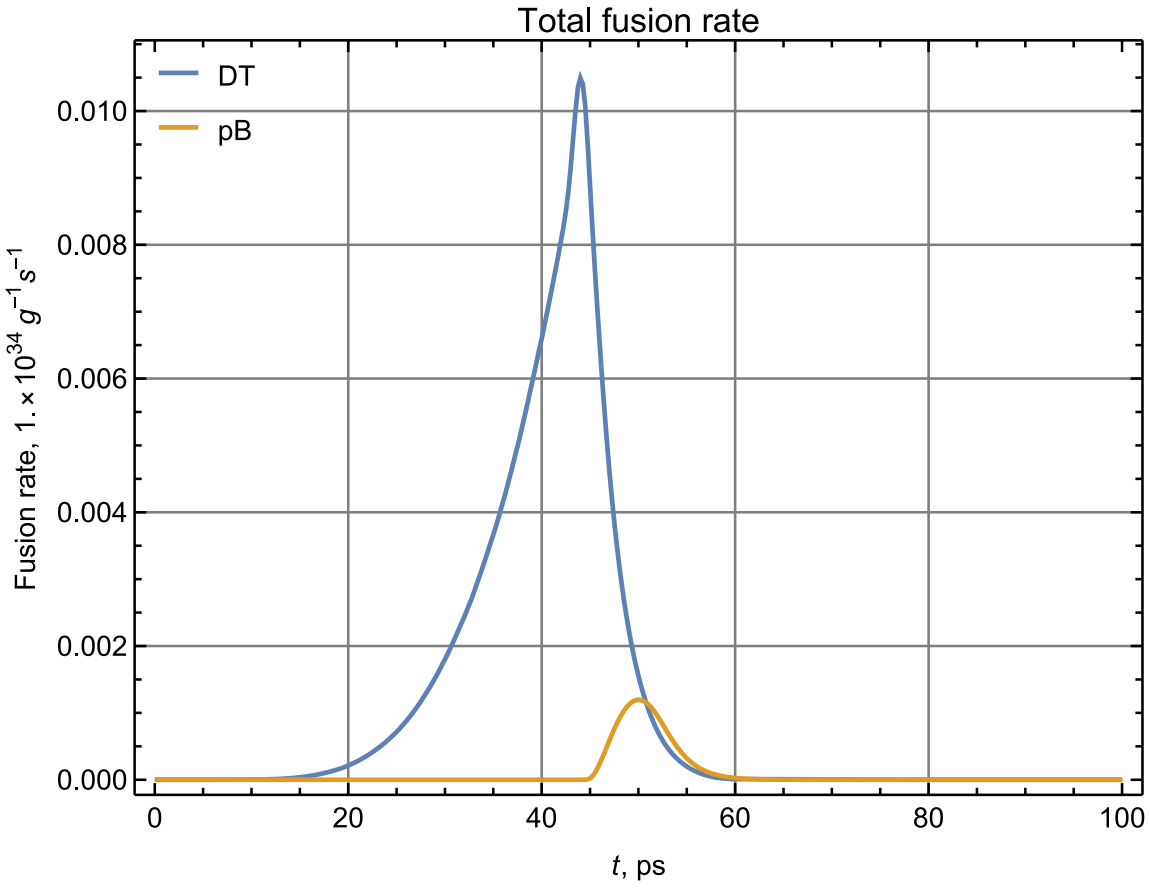
Summary on pure pB fuels

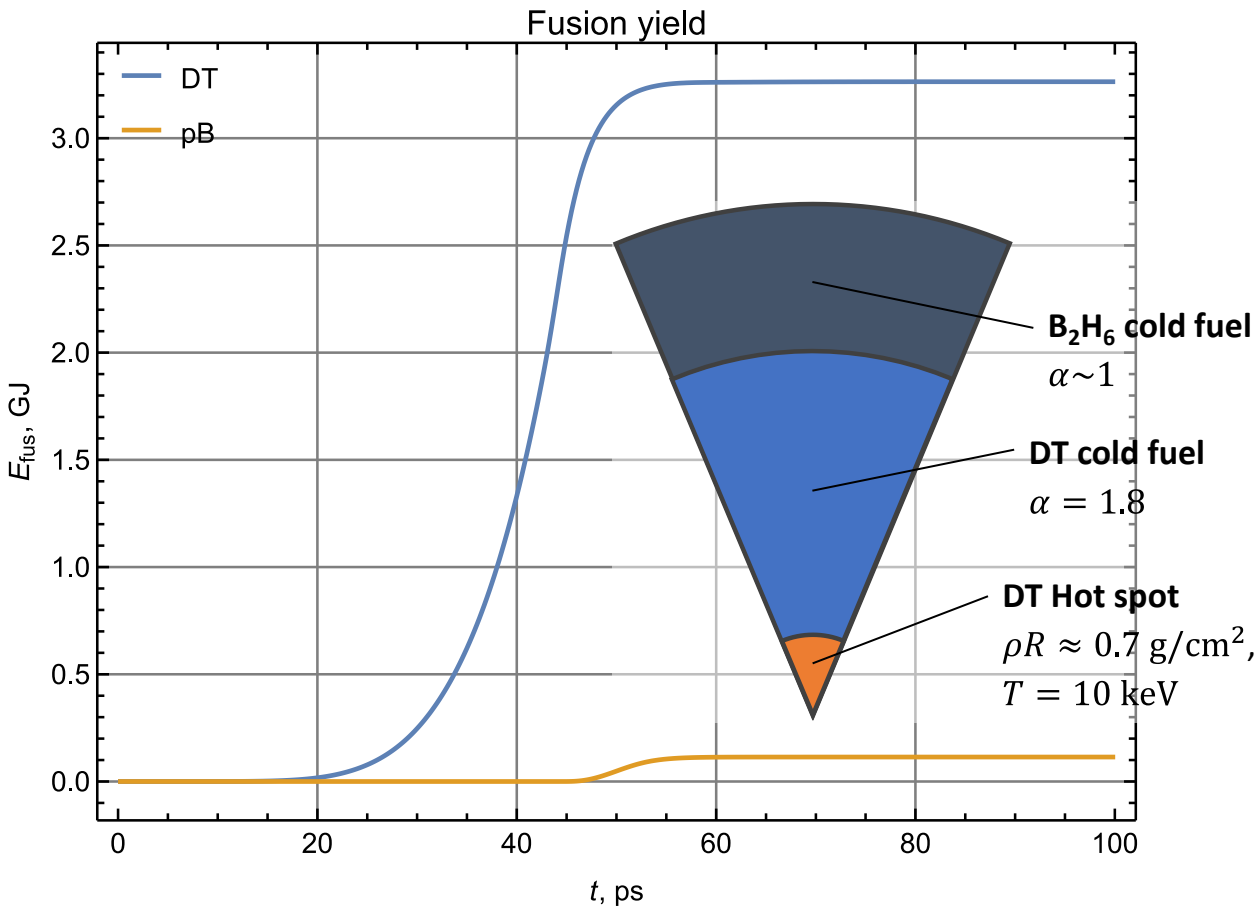
- Pure hydrogen-boron requires initial hot spot temperatures T_{hs} > 200 keV, densities ρ > 2000 g/cc, and ignition energies E_{hs} > 300 MJ (for BH_5)
- BH_3 does not allow burn wave propagation for $\rho \leq 4000$ g/cc and $\rho R \leq 60$ g/cm^2
- The fuel gain for r ≤ 4000 g/cc and Yield ≤ 3 GJ is less than 10
- Most of the initial energy is required by the hot spot (not the compressed cold fuel)

Burn parameters and gain for DT + pB targets

Fusion rate and yield for DT + B_2H_6 shell

$$\rho = 1000\ \mathrm{g/cc},\ M_{DT} = 20\ \mathrm{mg}\ ,\ M_{\mathrm{B_2H_6}} = 30\ \mathrm{mg}$$



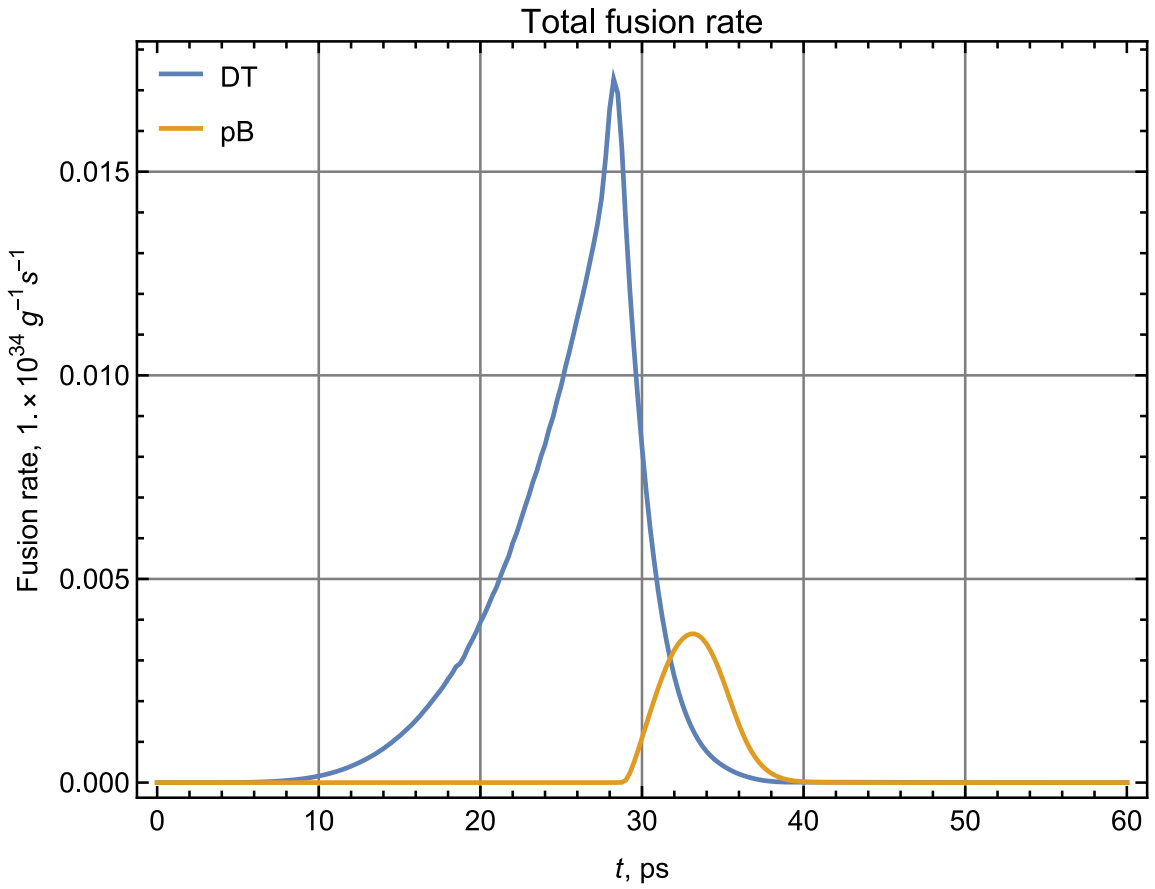


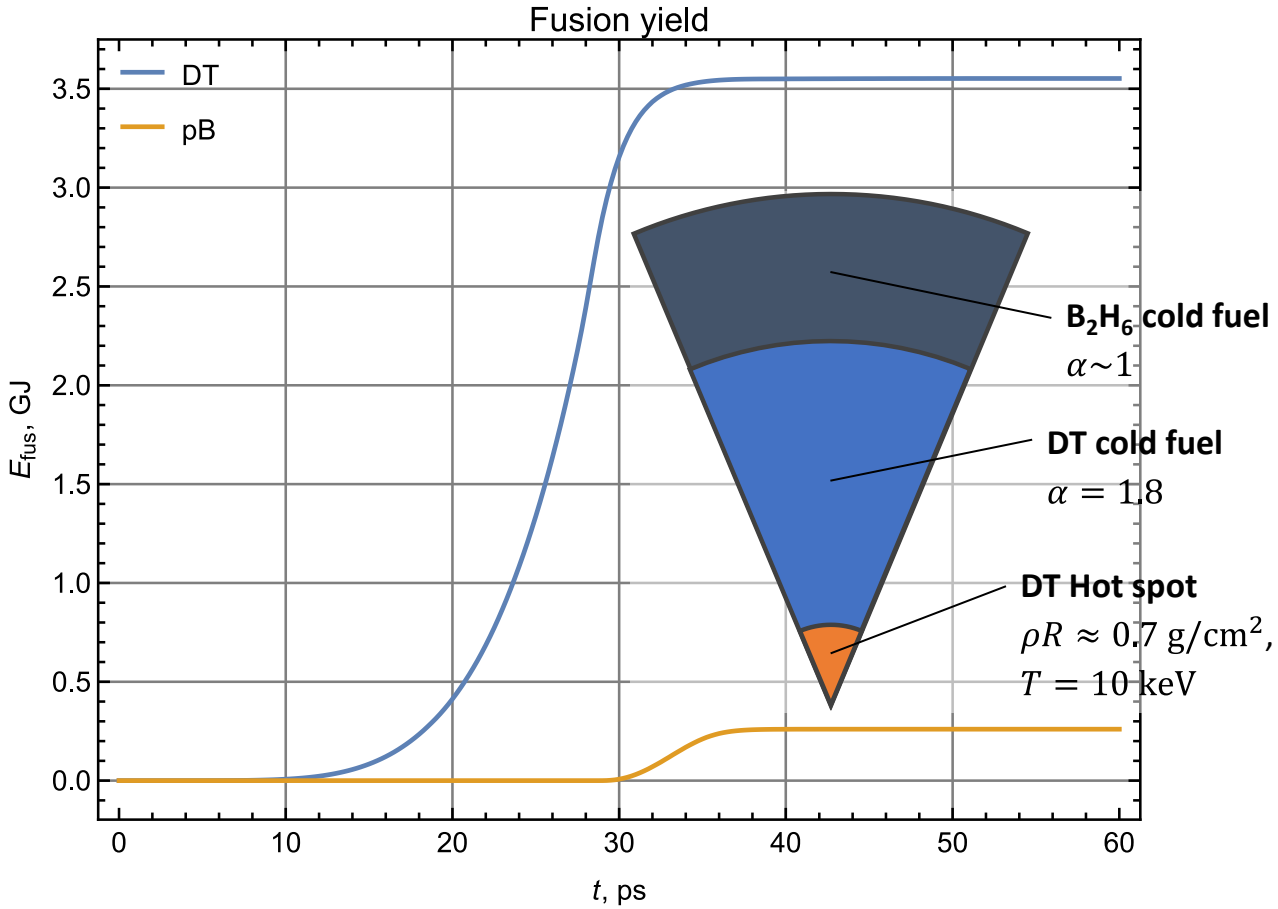
Total fusion yield: 3.37746 GJ, DT yield: 3.2634 GJ (96.6 %) , B_2H_6 yield: 0.114064 GJ (3.4 %)

Total fuel gain is 1055.8

Fusion rate and yield for DT + B_2H_6 shell

$$\rho = 2000\ \mathrm{g/cc},\ M_{DT} = 20\ \mathrm{mg}\ ,\ M_{\mathrm{B_2H_6}} = 30\ \mathrm{mg}$$





Total fusion yield: 3.8124 GJ, DT yield: 3.55216 GJ (93.2 %) , B_2H_6 yield: 0.260241 GJ (6.8 %)

Total fuel gain is 768.4

Burn wave propagation in DT + B_2H_6 shell

Simulation parameters:

$\rho(0) = 4000$ g/cc

$T_i(0) = 10$ keV

$T_e(0) = 10$ keV

$\rho R_{DT} = 1$ g/cm^2

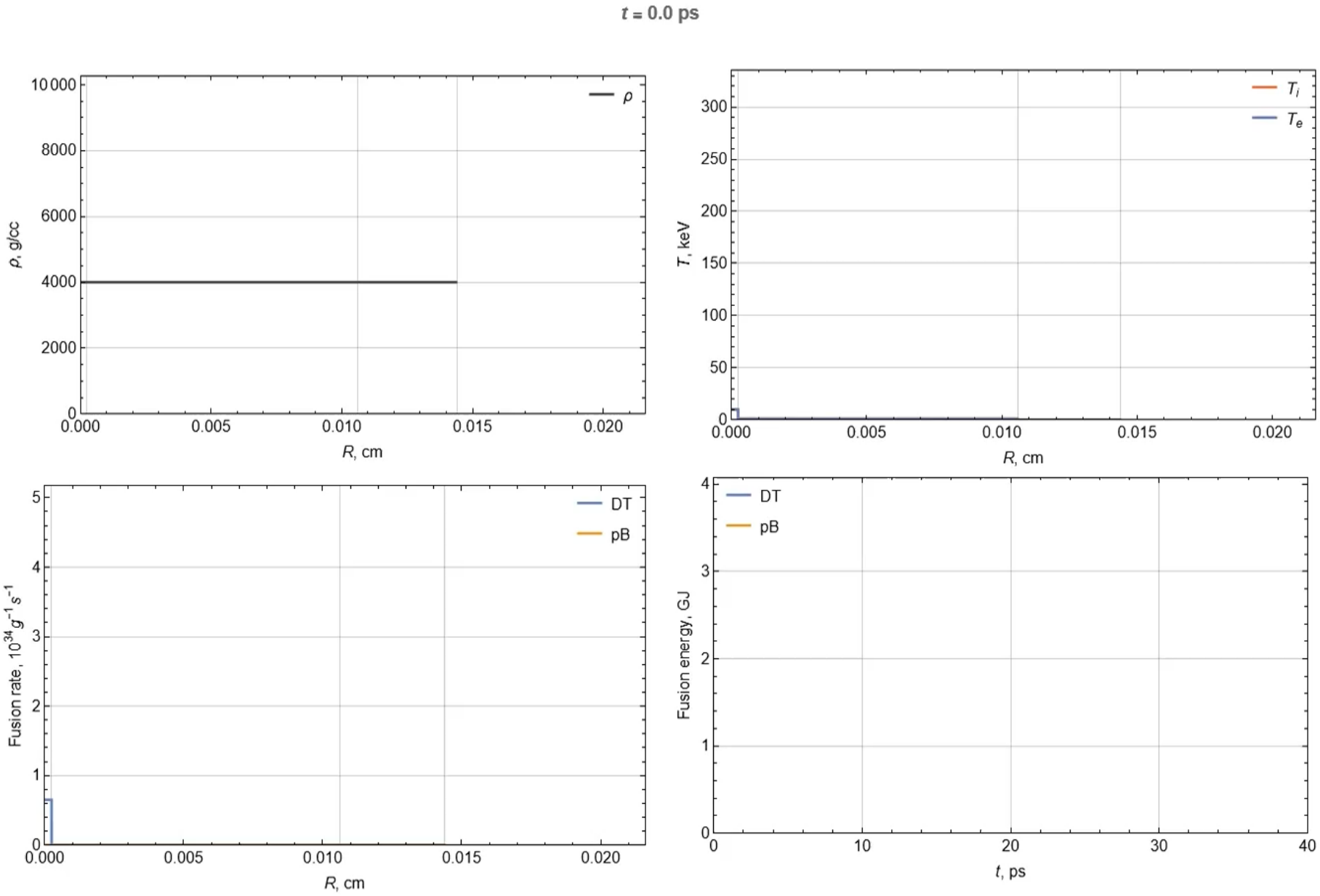
$\rho R_{pB} = 42.4$ g/cm^2

$\rho R_f = 57.6$ g/cm^2

$M_{DT} = 20$ mg

$M_{pB} = 30$ mg

$n_B/n_p = 0.333$



1D simulations

Fusion rate and yield for DT + B_2H_6

DT + B_2H_6: $M_{DT} = 20\ \mathrm{mg}$, $M_{\mathrm{B_2H_6}} = 30\ \mathrm{mg}$, $T_{\mathrm{hs}} = 10\ \mathrm{keV}$, $H_{\mathrm{hs}} = 0.6 - 0.8\ \mathrm{g/cm^2}$, $\alpha_{\mathrm{DT}} = 1.84$, $\alpha_{\mathrm{B_2H_6}} = 1.01$

ρ, g/cc	H_f, g/cm^2		E_{init}, MJ	burn-out, %		Fusion yield, GJ			Fusion yield share, %		Fuel Gain
	DT	B_2H_6		DT	B_2H_6	DT	B_2H_6	Total	DT	B_2H_6	
500	10.6	14.4	2.088	44.3	2.6	2.992	0.047	3.039	98.5	1.5	1455.4
1000	16.8	22.9	3.199	48.4	6.3	3.264	0.114	3.378	96.6	3.4	1055.8
2000	26.7	36.3	4.962	52.6	14.3	3.552	0.260	3.812	93.2	6.8	768.4
4000	42.4	57.6	7.754	57.6	32.7	3.886	0.595	4.481	86.7	13.3	577.9

DT only: $M_{DT} = 20\ \mathrm{mg}$, $T_{\mathrm{hs}} = 10\ \mathrm{keV}$, $H_{\mathrm{hs}} = 0.6 - 0.8\ \mathrm{g/cm^2}$, $\alpha_{\mathrm{DT}} = 1.84$

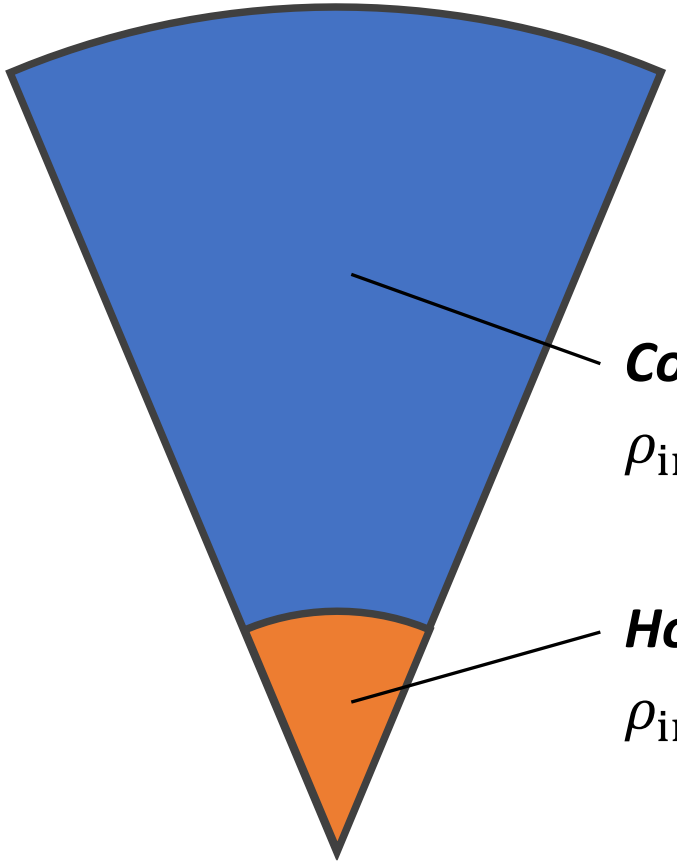
ρ, g/cc	H_f, g/cm^2	E_{init}, MJ	burn-out, %	Fusion yield, GJ	Fuel Gain
500	10.6	0.784	37.5	2.528	3223.1
1000	16.8	1.224	41.5	2.802	2288.1
2000	26.7	1.922	45.9	3.098	1612.1
4000	42.4	3.026	50.4	3.403	1124.7

Burn propagation and gain for $B_2(DT)_3$ targets

Non-cryogenic/low-neutronic target designs

Tabelle 3 Kristallographische Daten

Summenformel	B_2H_6
Molmasse	27.67 g/mol
Raumgruppe	$P2_1/n$
Z	4
Temperatur	94(1) K
a	4.400(7) Å
b	6.487(7) Å
c	5.734(7) Å
β	105.35(5)°
Dichte berechnet	0.582 gcm^{-3}
F_{000}	32
Kristallgröße	∅ 0.5 mm (Kapillare)
λ	0.71073 Å
$\sin \theta/\lambda_{max}$	1.11 $Å^{-1}$
Indexgrenzen	$-9 \geq h \geq 9; 0 \geq k \geq 14; 0 \geq l \geq 12$
Anzahl gemessener Reflexe	5354
Symmetrieunabhaengige Reflexe	1779
Anzahl der Reflexe > $3\sigma(F_o)$	797
Redundanz	2.9
R_{int}	6.17 %
R_1(multipol)	2.93 %
R_w	3.25 %
R_{all}(multipol)	8.26 %
Gof	1.28
Nref/Nvar	24.2

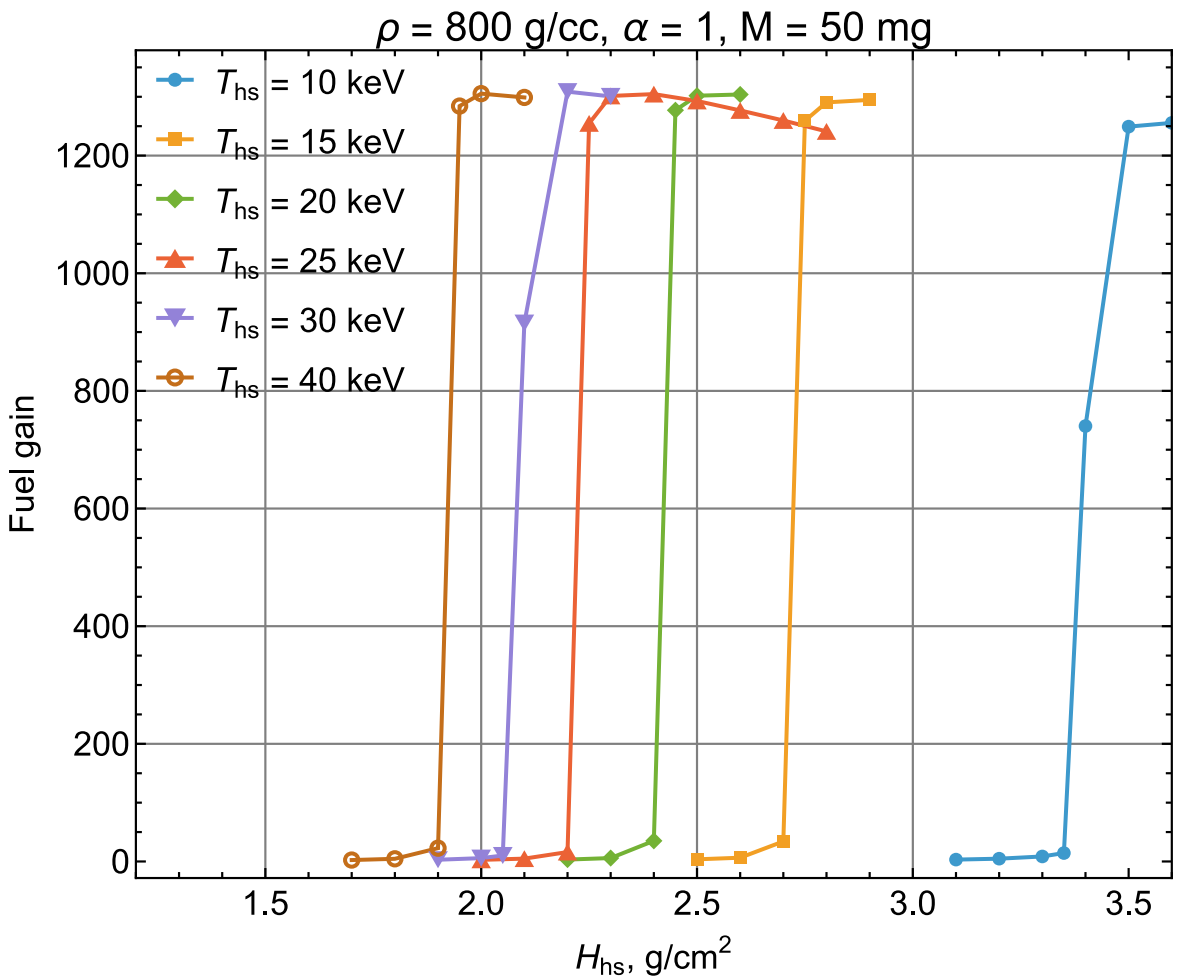


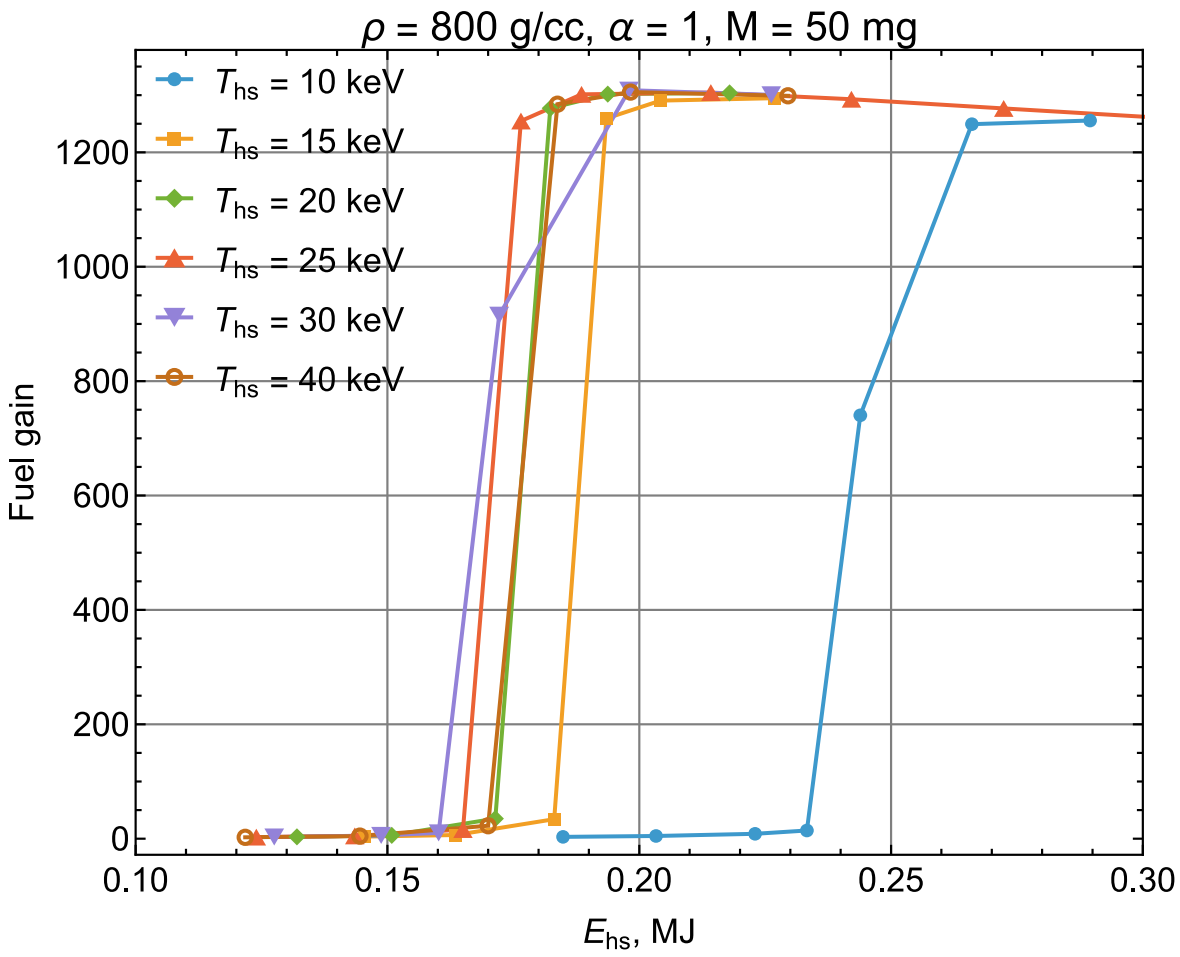
Cold fuel: solid $B_2(DT)_3$, $\rho_{\mathrm{init}} = 0.77\ \mathrm{g/cc}$

Hot spot: solid $B_2(DT)_3$, $\rho_{\mathrm{init}} = 0.77\ \mathrm{g/cc}$

C.B. Hübschle, M. Messerschmidt, D Lentz, Peter Luger,
Anorg. Allg. Chem. 2004, 630, 13131316, doi: 10.1002/zaac.200400104

Ignition threshold for pure $B_2(DT)_3$





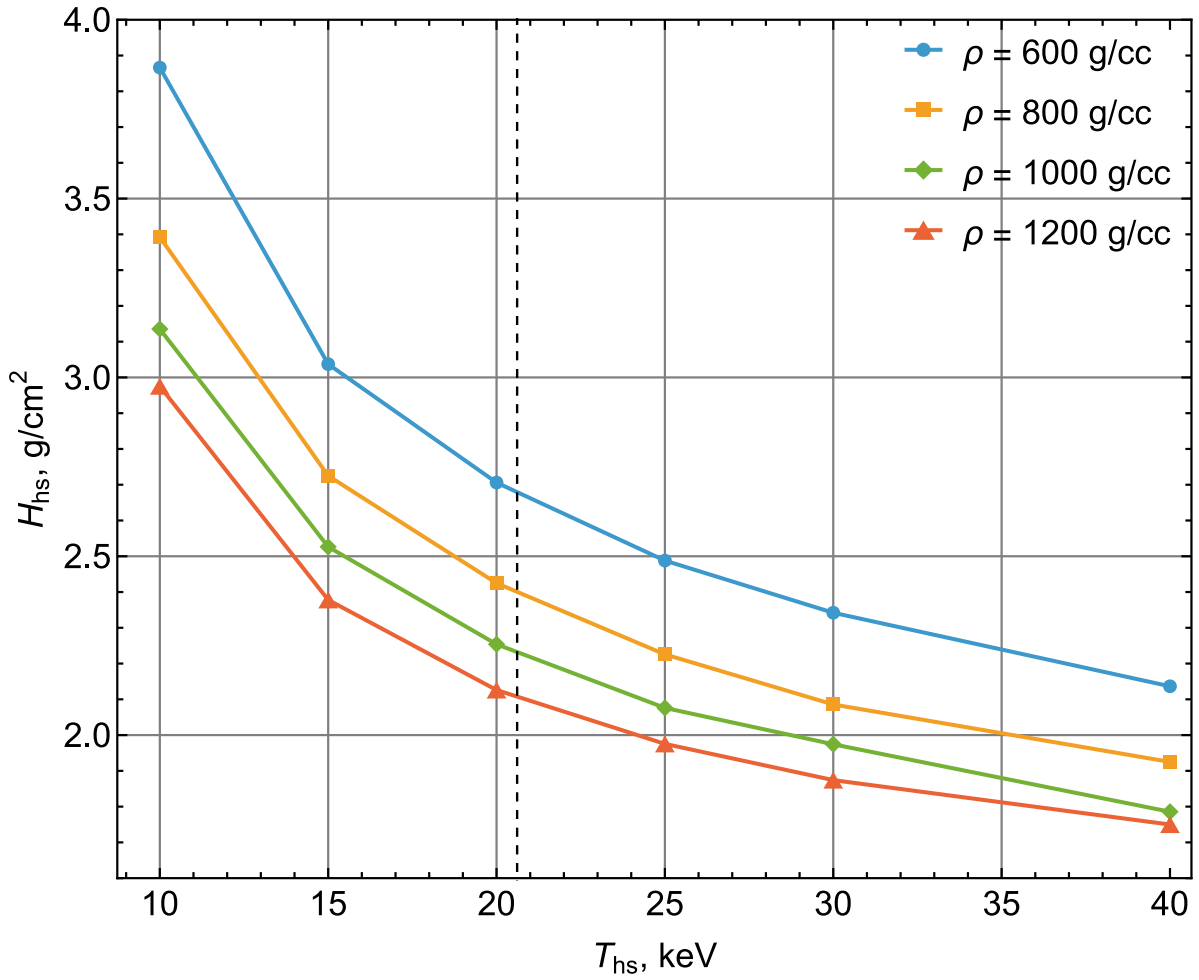
Ignition parameter for the hot spot

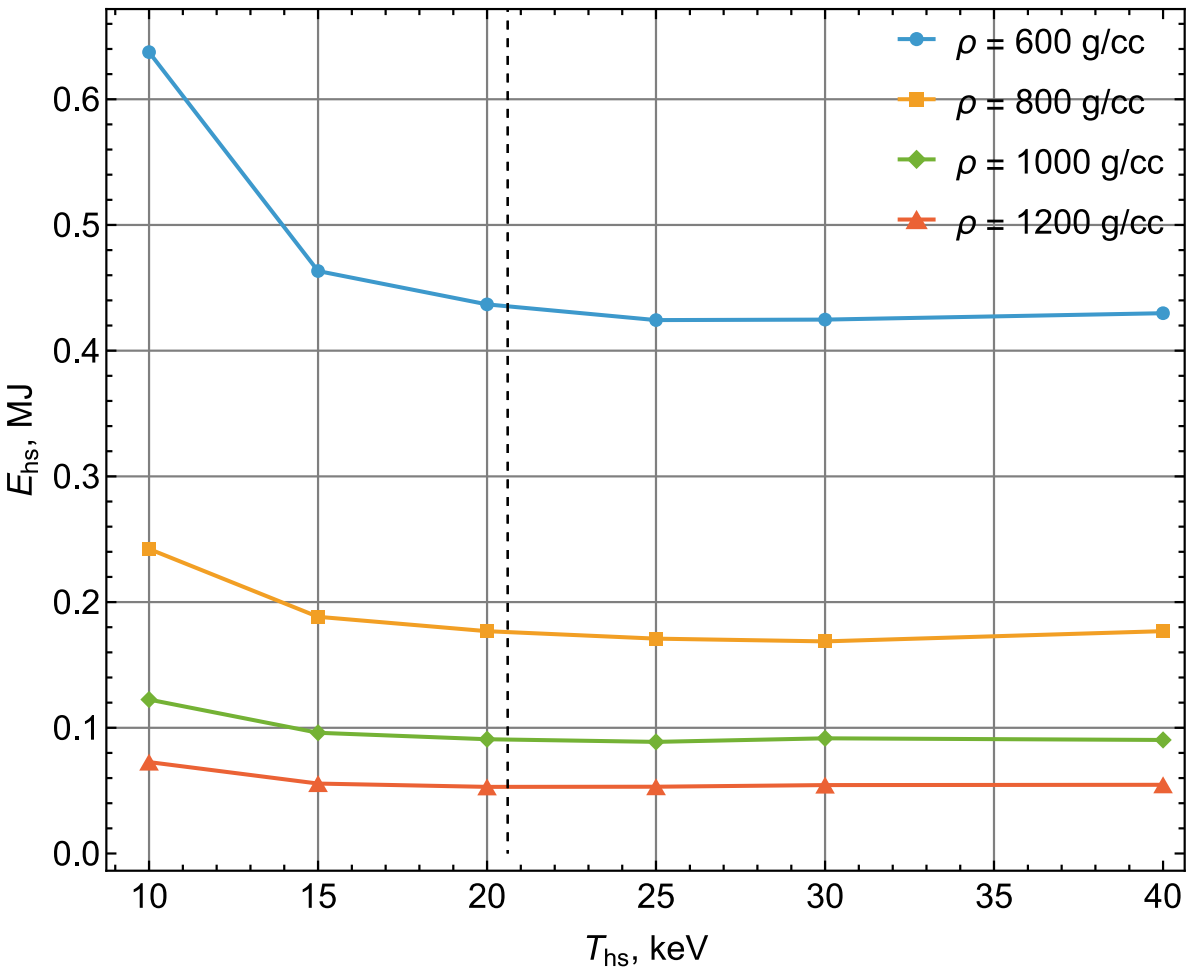
$$H_{\mathrm{hs}} = \rho_{\mathrm{hs}} R_{\mathrm{hs}}$$

Initial hot spot energy

$$E_{\mathrm{hs}} = \frac{3}{2} \frac{\rho_{\mathrm{hs}}}{m_{\mathrm{i,avr}}} (T_{\mathrm{i}} + Z_{\mathrm{avr}} T_{\mathrm{e}})$$

Ignition threshold for pure $B_2(DT)_3$





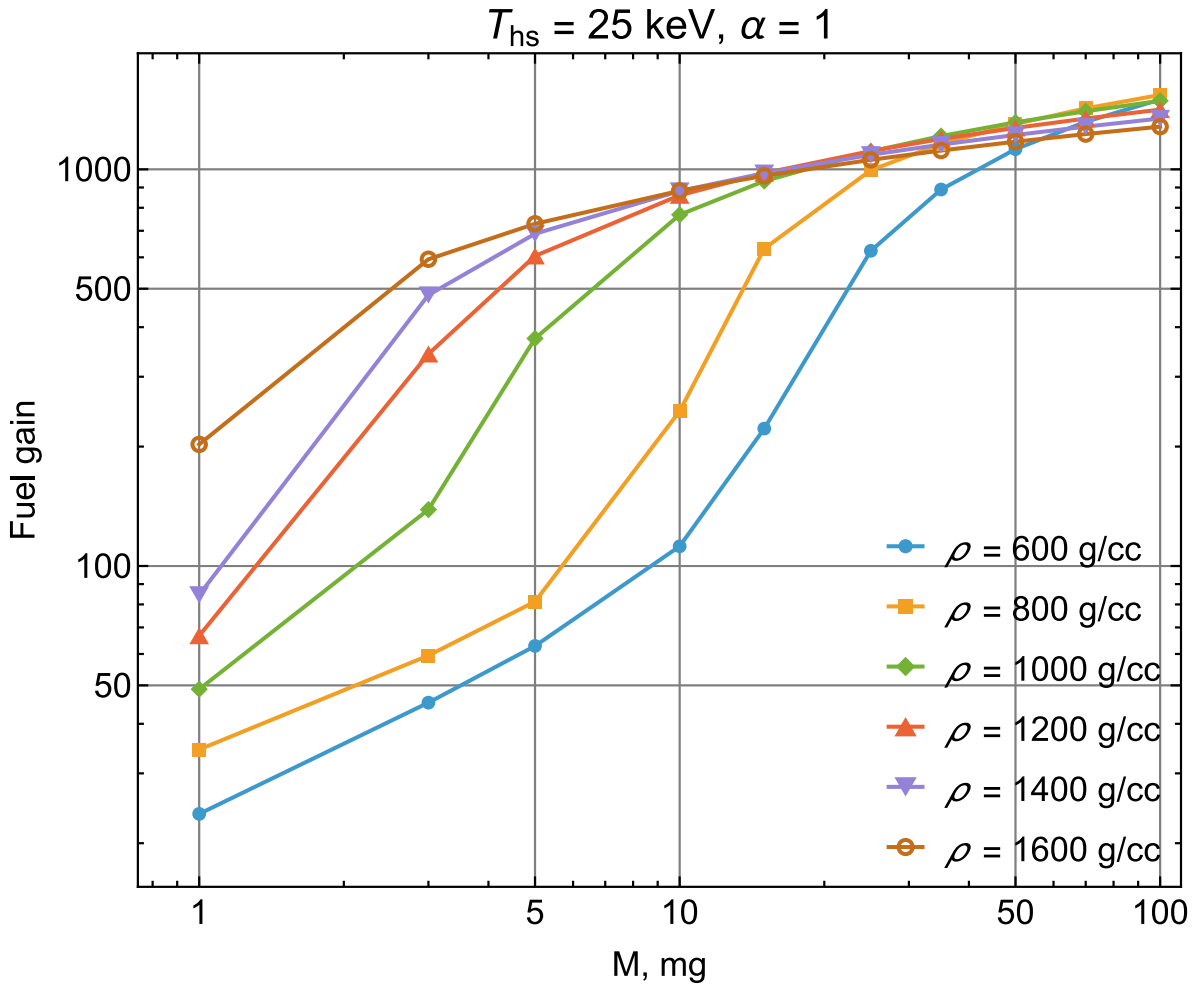
Ignition parameter for the hot spot

$$H_{\mathrm{hs}} = \rho_{\mathrm{hs}} R_{\mathrm{hs}}$$

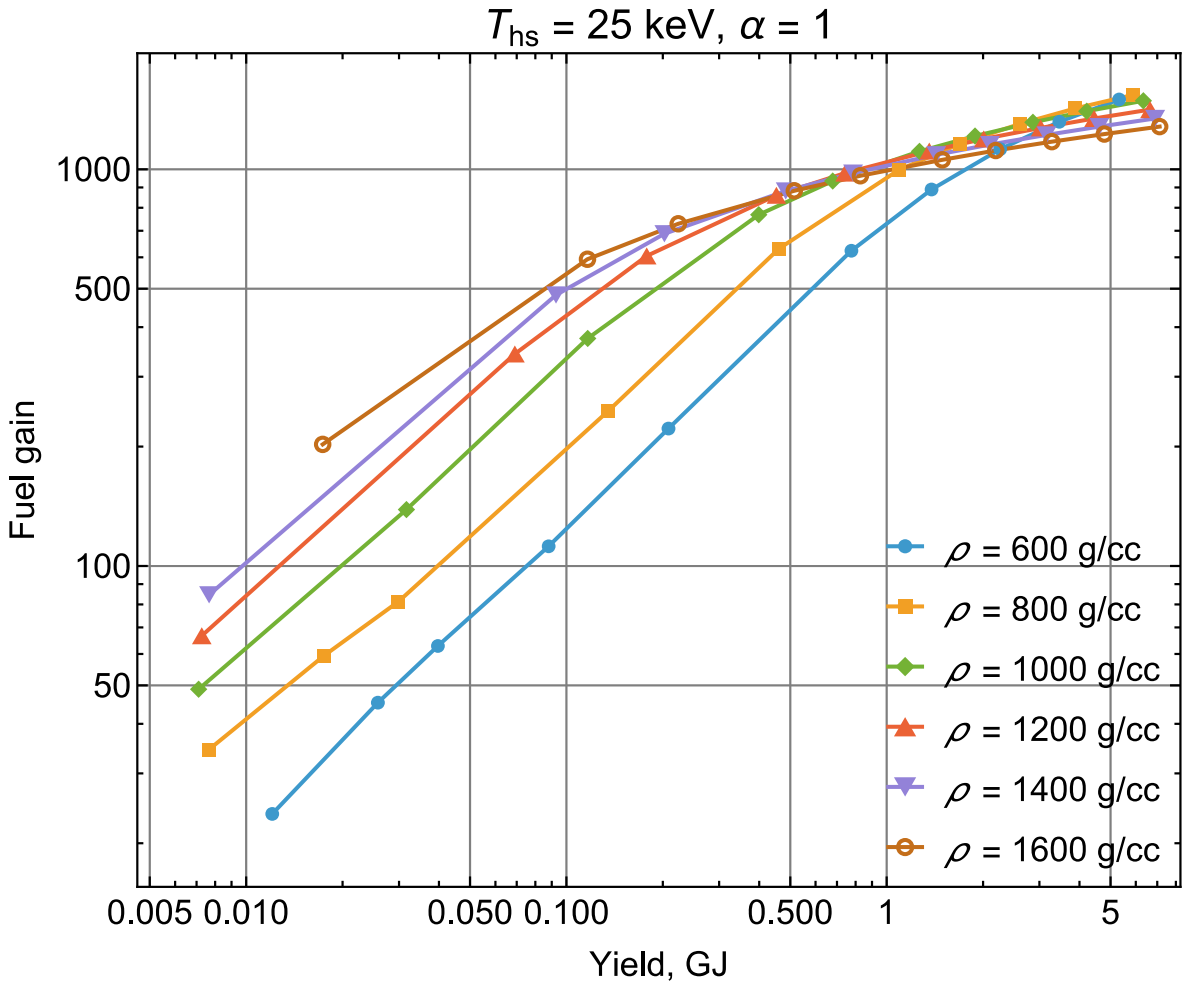
Initial hot spot energy

$$E_{\mathrm{hs}} = \frac{3}{2} \frac{\rho_{\mathrm{hs}}}{m_{\mathrm{i,avr}}} (T_{\mathrm{i}} + Z_{\mathrm{avr}} T_{\mathrm{e}})$$

Burn fraction and yield depending on the target size

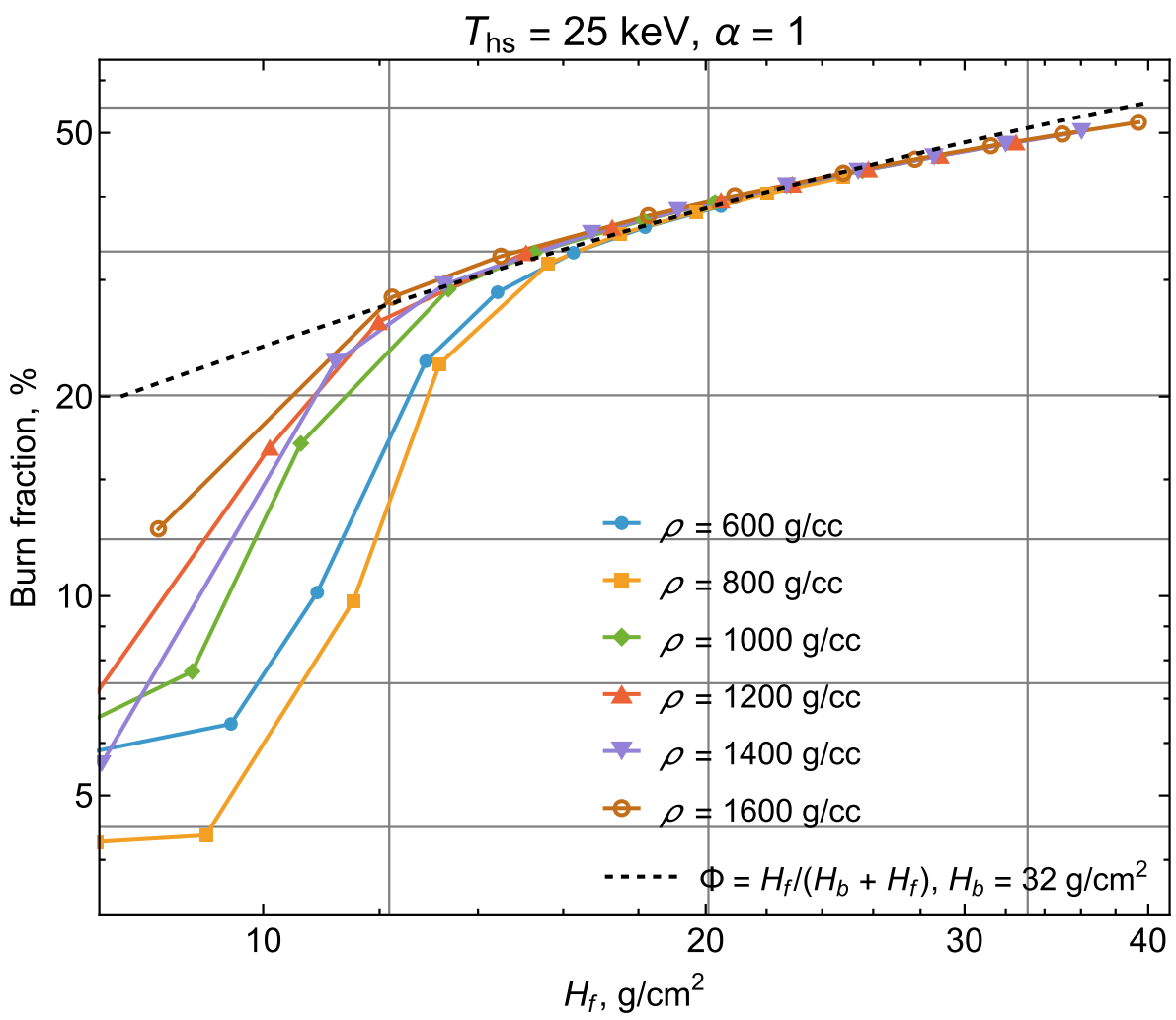


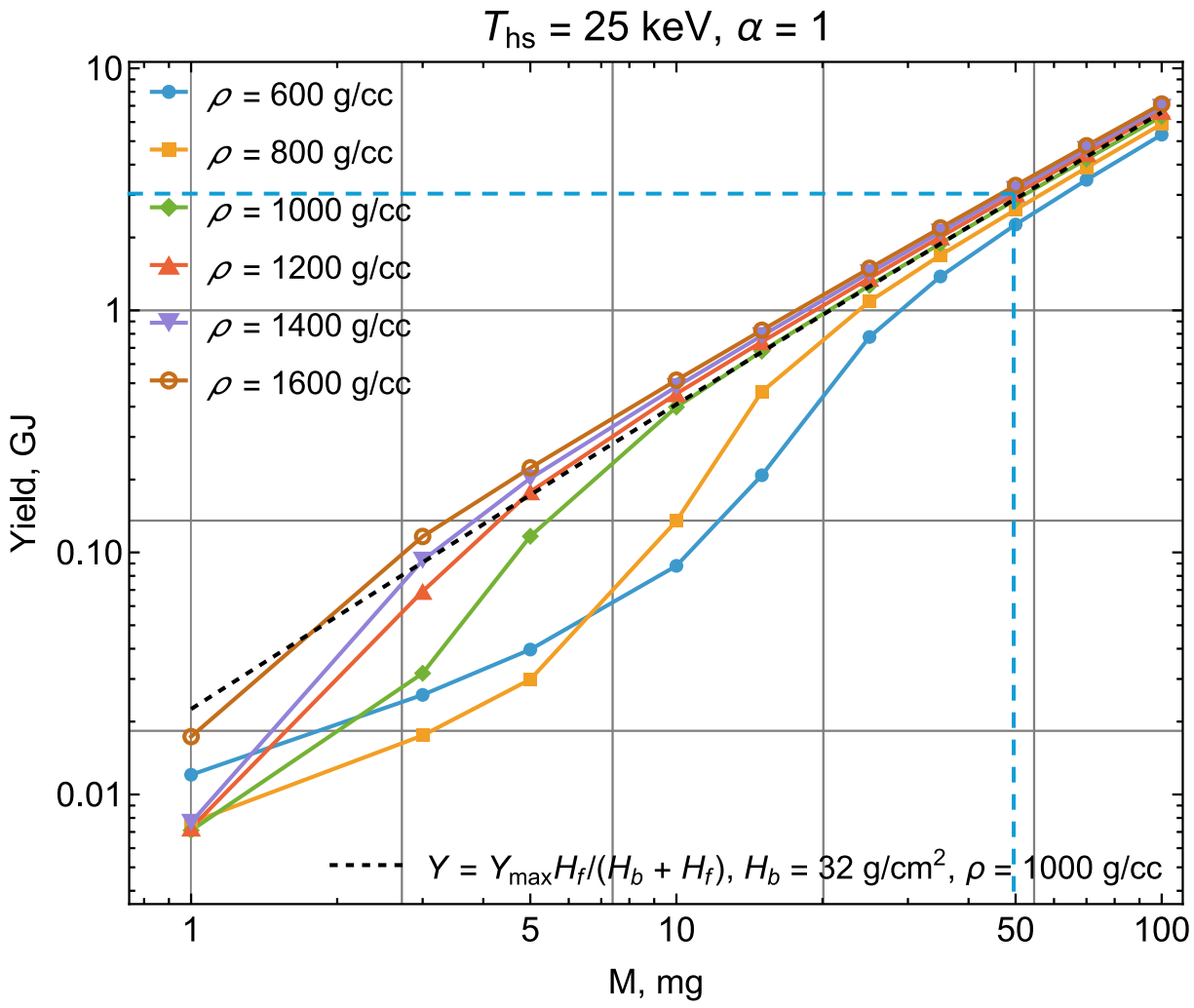
Total fuel mass



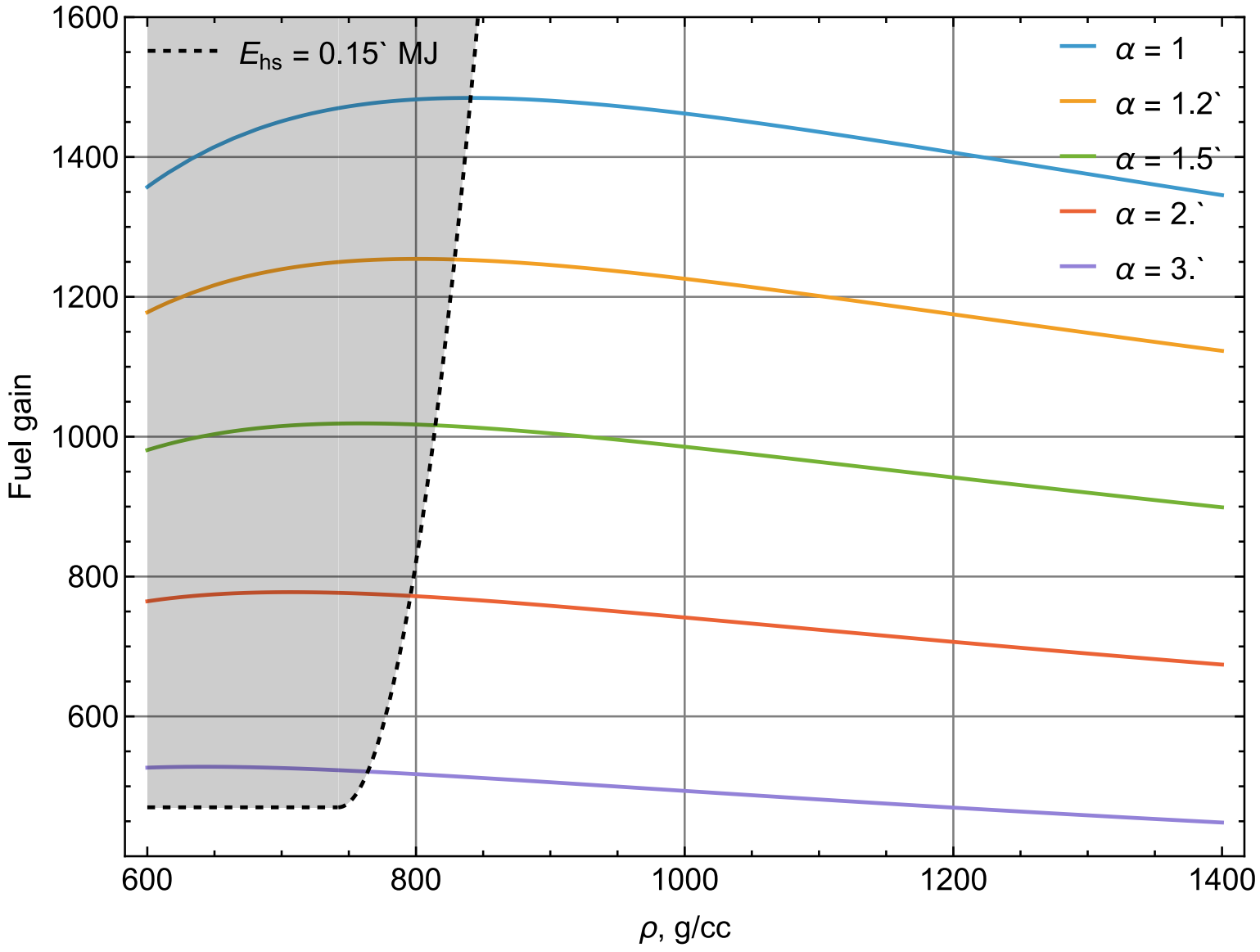
Fusion yield

Burn fraction and yield depending on the target size

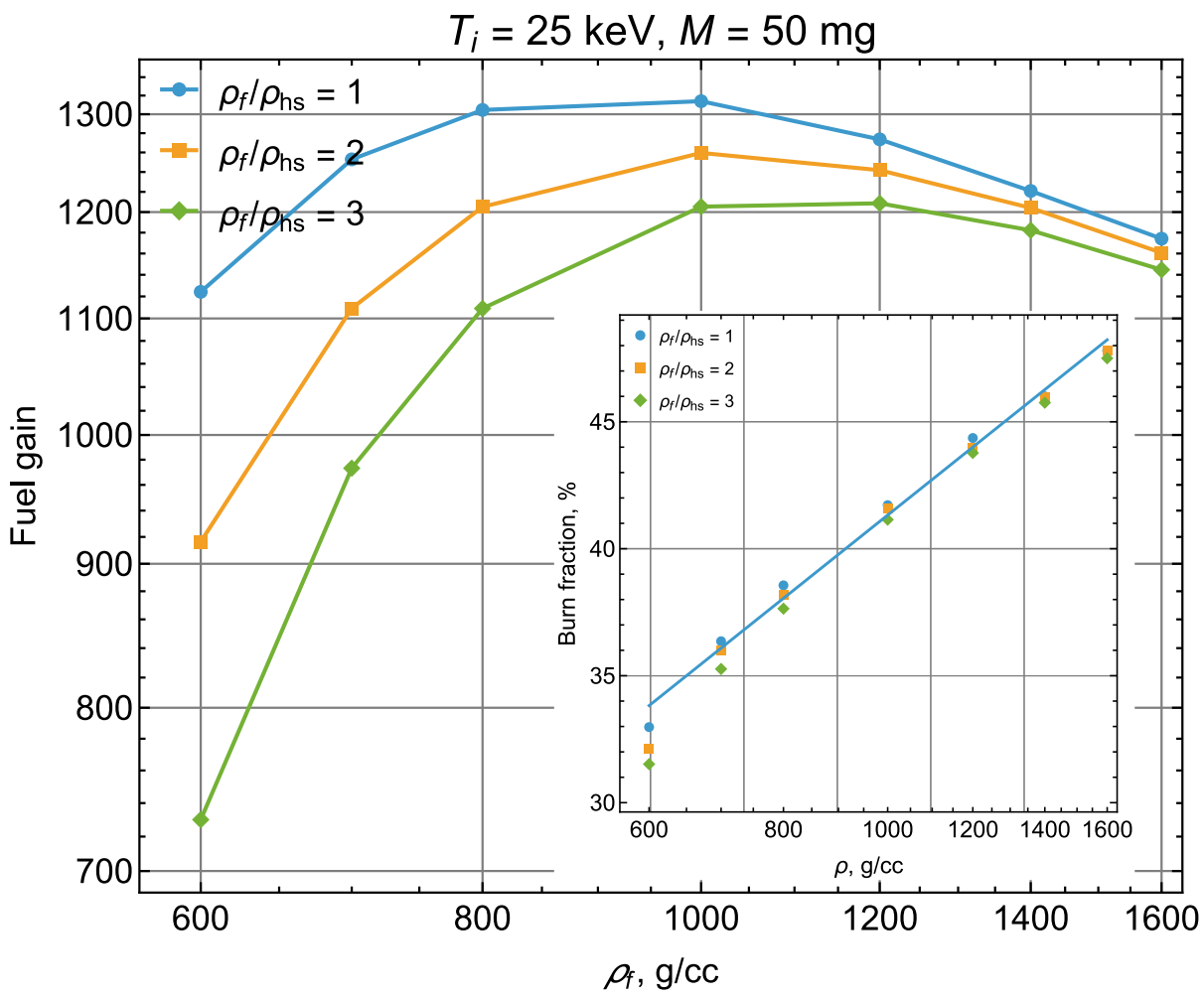


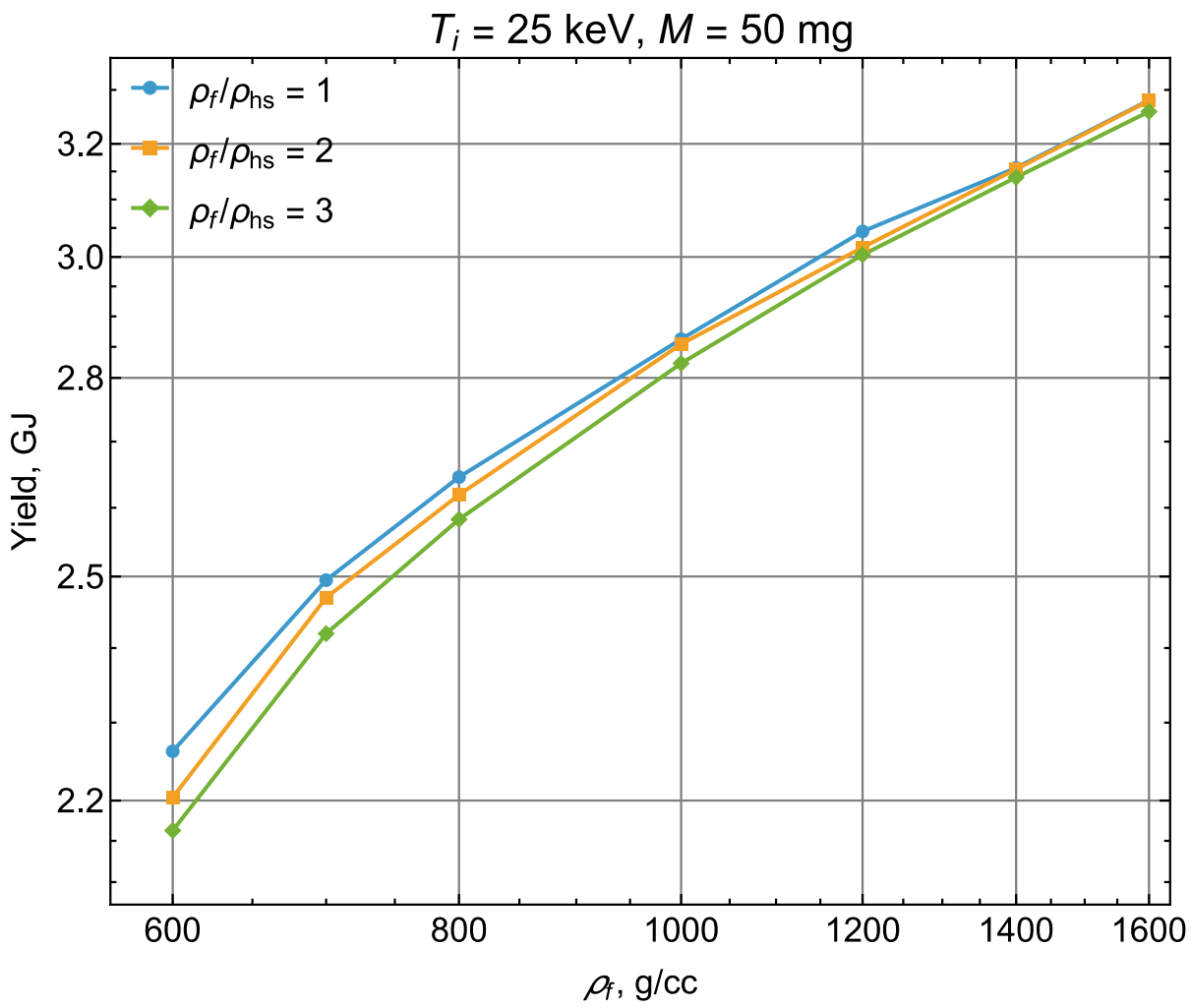


Maximal fuel gain for $B_2(DT)_3$



Non-isochoric initial configurations





Fuel gain for different cold fuel to hot spot density ratios ρ_f/ρ_{hs}

Non-cryogenic/low-neutronic target designs

Online Hydrogen Density Calculator

The calculator below can be used to estimate the density and specific weight of gaseous hydrogen at given temperature and atmospheric pressure (1 bara/14.5psia).
The output density is given as kg/m^3, lb/ft^3, lb/gal(US liq) and sl/ft^3. Specific weight is given as N/m^3 and lb$_f$/ ft^3.

77 *Temperature*

Choose the actual unit of temperature: ○ °C ○ °F ◉ K ○ °R

Calculate density of hydrogen!

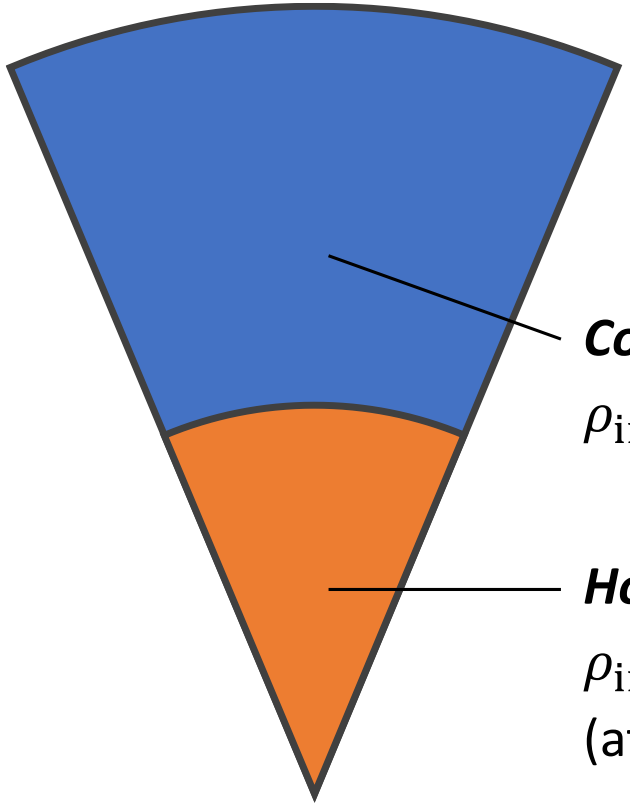
Hydrogen density at 77 K and 1 bara:

0.316 kg/m3
0.0197 lbm/ ft3
0.00263 lbm/gal(US liq)
0.612x10-3 sl/ ft3

Hydrogen specific weight at 77 K and 1 bara:

3.09 N/m3
0.0197 lbf/ ft3

Error within +/-0.1 %

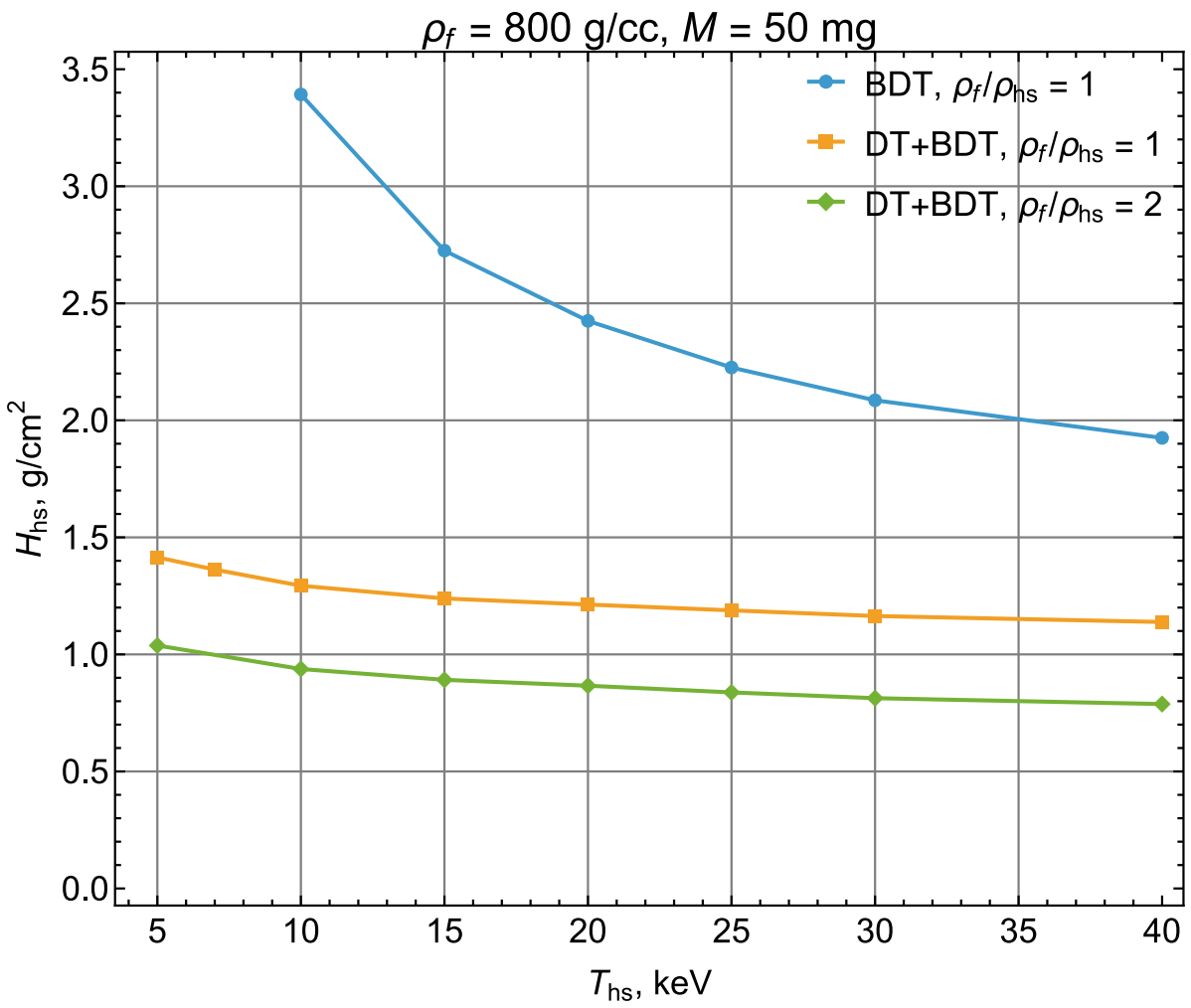


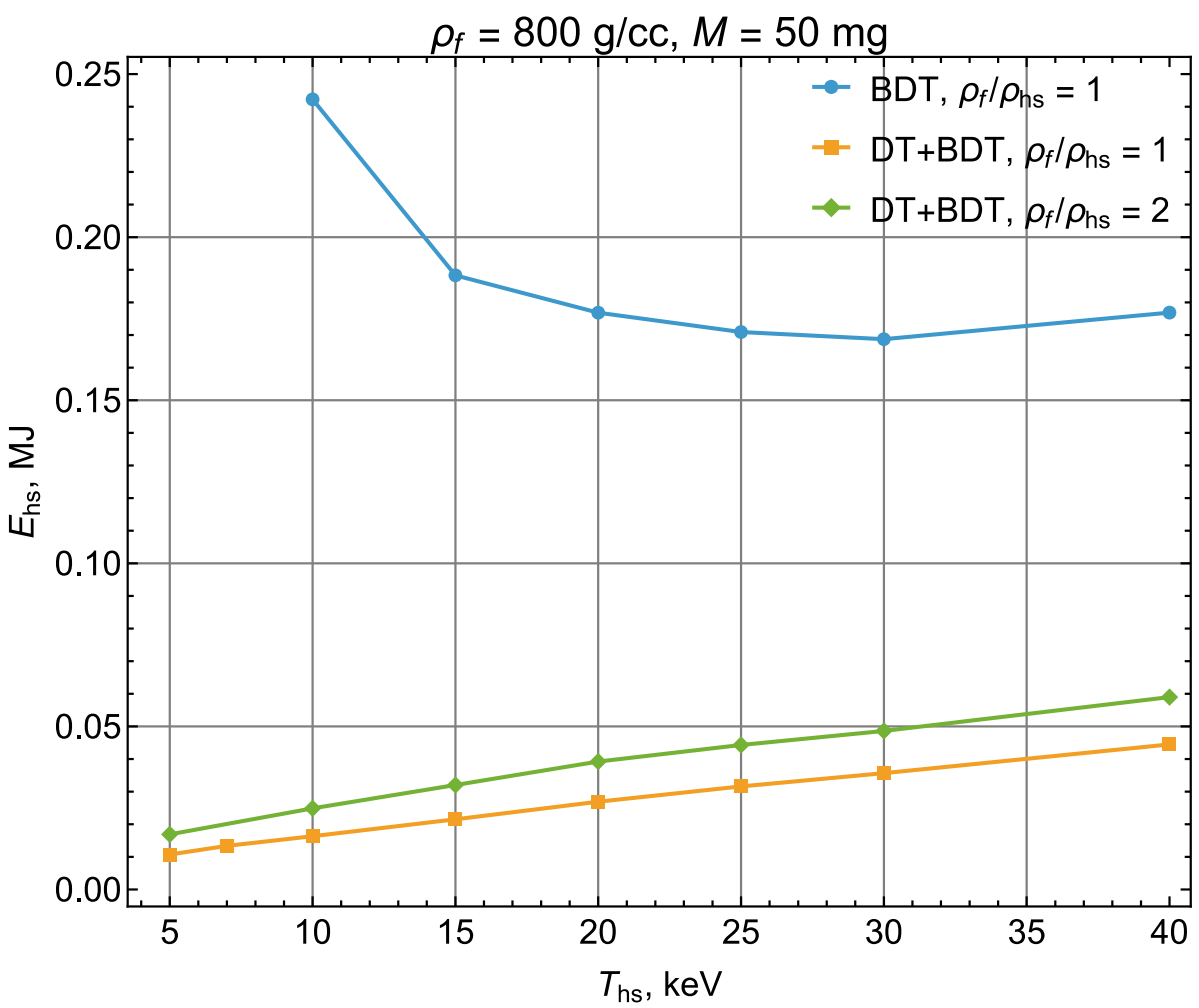
Cold fuel: solid $B_2(DT)_3$, $\rho_{\text{init}} = 0.77$ g/cc

Hot spot: DT gas, $\rho_{\text{init}} = 0.79$ mg/cc (at $T = 77$K)

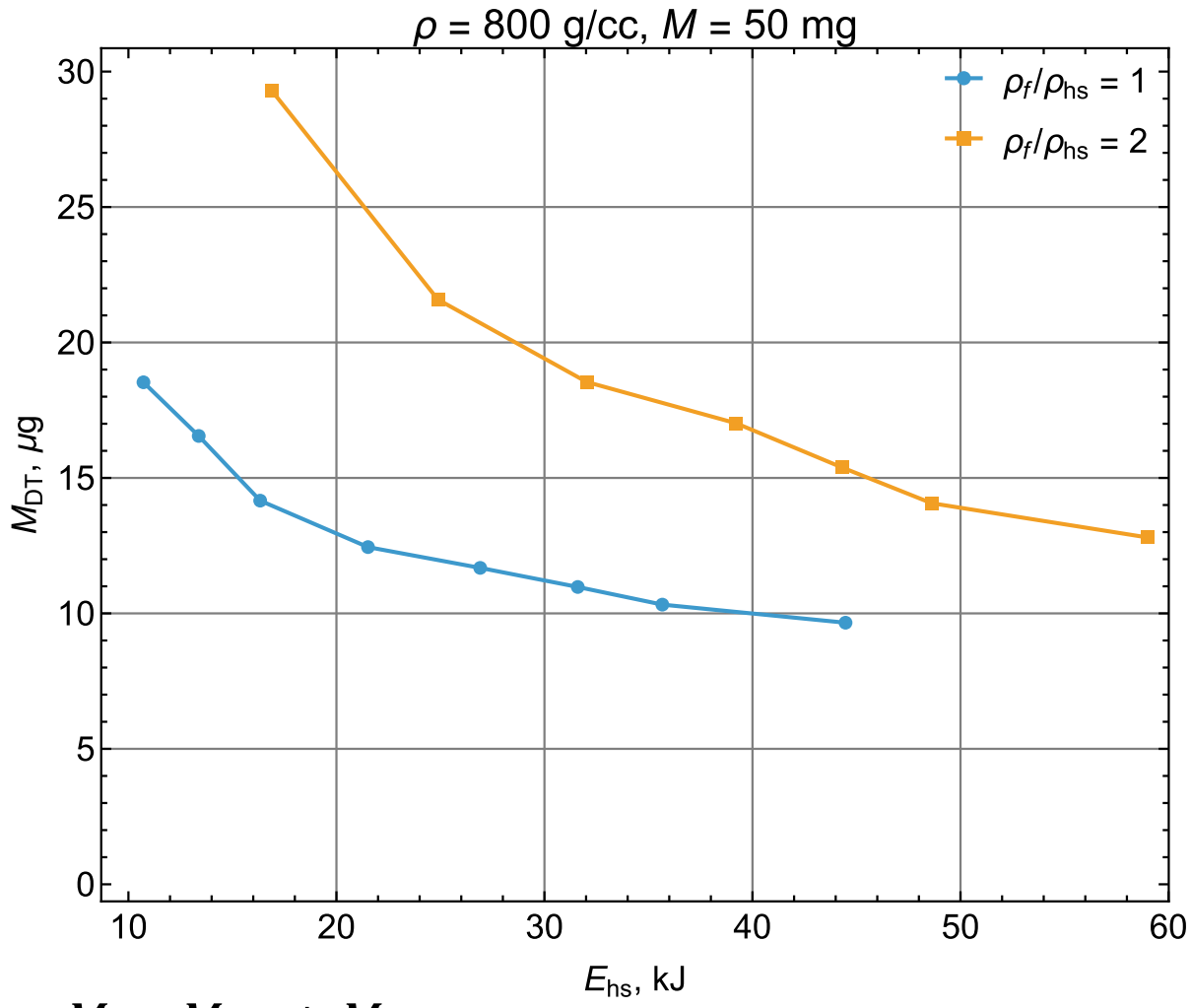
The Engineering ToolBox, https://www.engineeringtoolbox.com/hydrogen-H2-density-specific-weight-temperature-pressure-d_2044.html?vA=77&degree=K

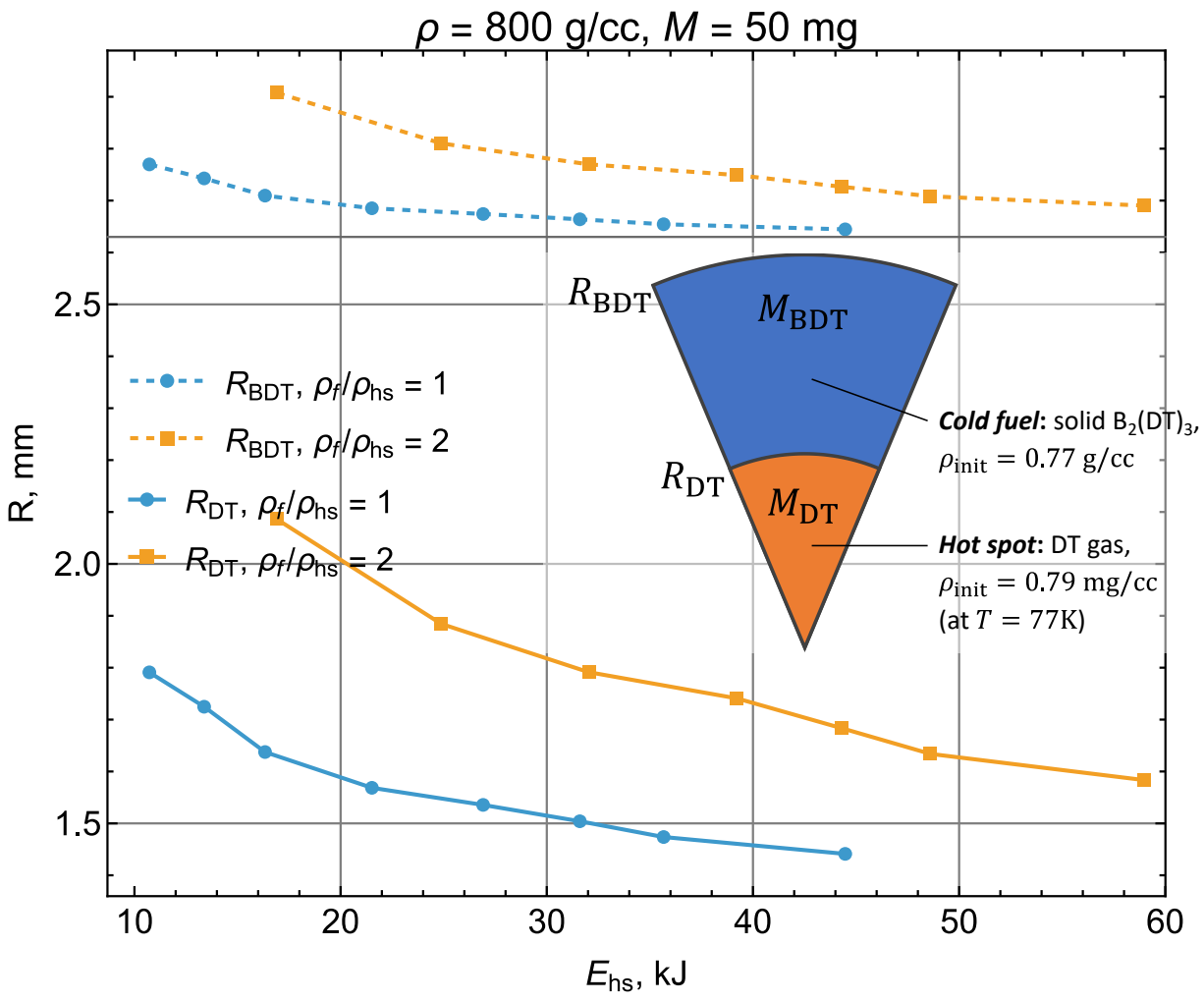
Ignition threshold for DT + $B_2(DT)_3$





Ignition threshold for DT + $B_2(DT)_3$

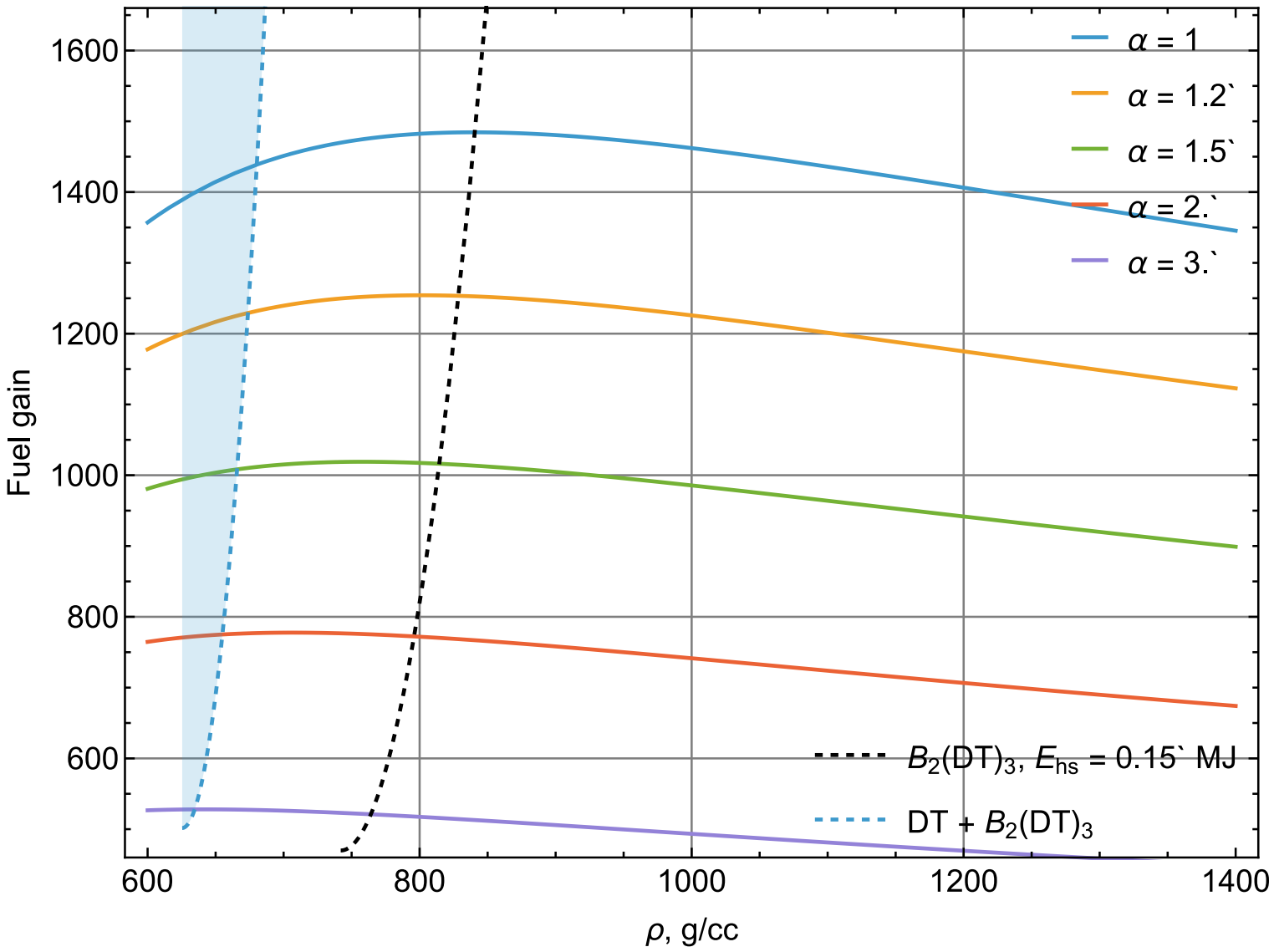




$$M = M_{\mathrm{DT}} + M_{\mathrm{BDT}}$$

$$\rho = \rho_{\mathrm{DT}} = \rho_{\mathrm{BDT}}$$

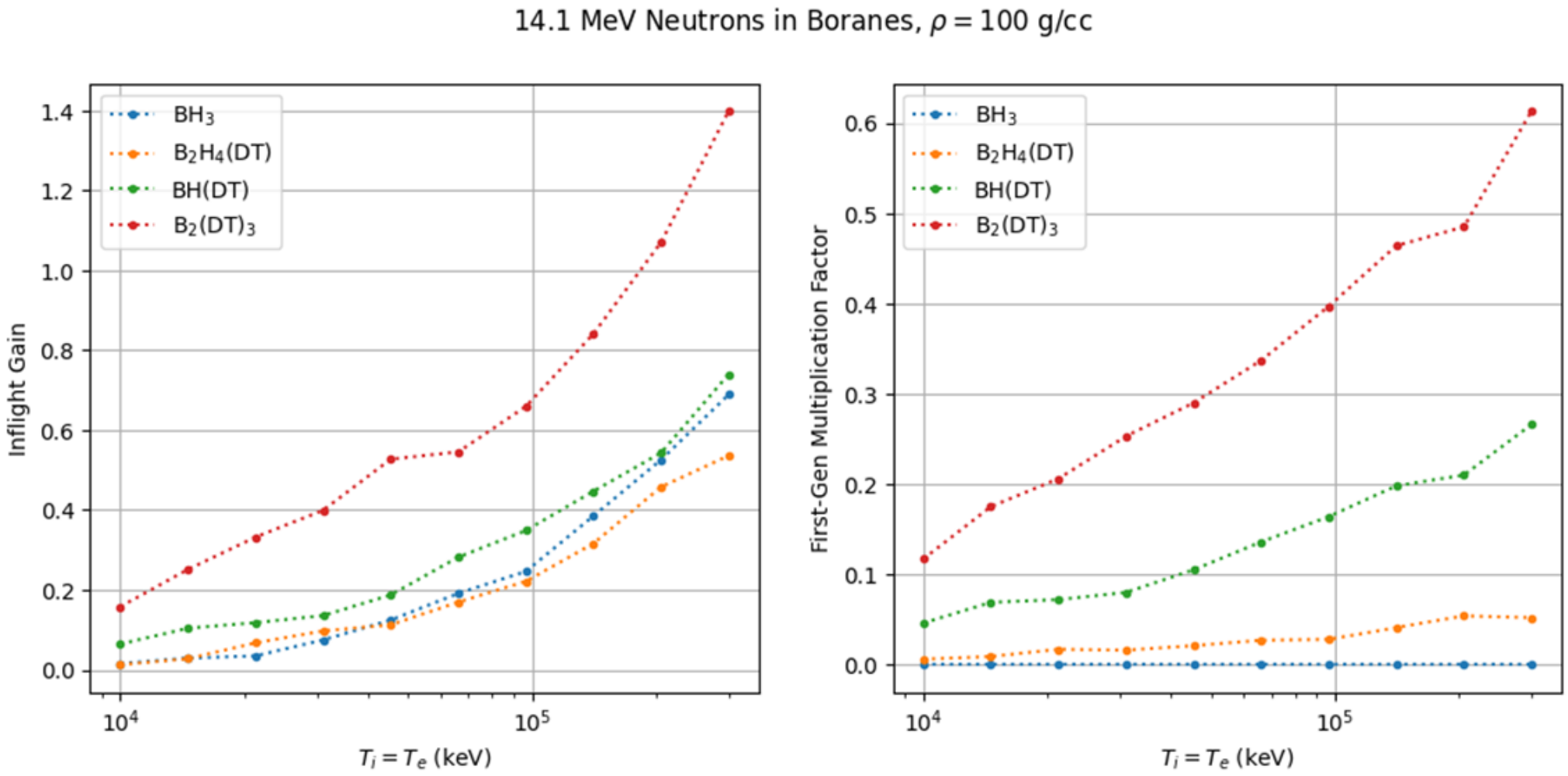
Maximal fuel gain for DT + $B_2(DT)_3$



Target designs

Materials	Melting temperature	Ignition energy	Neutron flux	Fuel gain isochoric, $\alpha = 1$	Mass density, g/cc
$LiBH_4$	550 K	> 1 GJ	Very low	< 5	> 4000
B_2H_6	108.3 K	> 1 GJ	Very low	< 5	> 4000
BH_5	?	300 – 500 MJ	Very low	< 10	4000
$B_2(DT)_3$ + pB shell	108.3 K	30 – 150 kJ	Moderate	500 – 600	800 – 1500
DT gas + $B_2(DT)_3$ + pB shell	108.3 K	10 – 50 kJ	Moderate	500 – 650	700 – 1500
Solid DT + pB shell	19.8 K	0.5 – 10 kJ	Moderate	900 – 1500	500 – 1500
$B_2(DT)_3$	108.3 K	30 – 150 kJ	High	1200 – 1300	800 – 1500
DT gas + $B_2(DT)_3$	108.3 K	10 – 50 kJ	High	1300 – 1400	700 – 1500
DT gas + Solid DT	19.8 K	0.5 – 10 kJ	High	4700 – 7100	300 – 800

Neutron energy deposition and suprathermal effects*



* Marcus Borscz et al, 5th International Workshop on Proton-Boron Fusion, Belgrade, Serbia, 8-11 September 2025

$$\text{Inflight Gain} = \frac{Q_{tot} + K_{dep}}{K_{i,0}}$$

Conclusions

Key benchmark in IFE target design:

<$5 fuelling (production and handling) cost per 1 GJ of electric output

HB11 Energy principles in target design:

- **Low rep-rate Large targets** (~ 3 GJ fusion yield, ~ 1Hz repetition rate)
- **Avoiding helium-temperature cryogenics** (advanced fuels)
- **Maximizing energy coupling** (direct drive, proton fast ignition)
- **Tolerate ~100 kJ hot spot energy, 1000 g/cc implosions, ~3 MJ initial fuel energy**
- **Attenuate neutron flux for engineering and reactor lifetime margins**
- **Reduced use of tritium for fuel cycle management**

Conclusions

1D radiation-hydrodynamics simulation results:

- Pure hydrogen-boron requires impractically high densities (~ 10 kg/cc) and/or ignition energies (~ 10 MJ) while providing not sufficient gain for a commercially viable solutions
  - "pB does not work alone as IFE fuel"
- Possible implementation of HB (BH_x or LiBH4) in IFE target design includes neutron-attenuating/confining shells deposited around DT-burning cores
- Pure solid $B_2(DT)_3$ demonstrates commercially viable 1000+ fuel gain @ 800 g/cc cold fuel density, 50 mg fuel mass, α = 1.5, and 150 kJ hot spot energy
- Further IFE target design for advanced fuels requires kinetic models and code development with comprehensive considerations of neutron transport, radiation transport, and suprathermal effects.

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- Ali Hassan, University of Catania, Italy
- Voss Scientific (C. Thoma and D. R. Welch): Chicago PIC code
- Prism Computational Sciences (I. Golovkin): HELIOS hydrocode, EOS