Non-cryogenic ICF-target

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- **General problem: effect of the light impurities such as H, Li, Be, N, C on ignition and combustion of ICF-targets.**

  (Origin of the impurities: 1. non-cryogenic solid thermonuclear fuel, namely, DT-hydrides of light metals such as Be and Li; 2. mixing DT-fuel with target's ablator (H, Be, C.)

- **Non-cryogenic ICF-targets**

- **Non-cryogenic fast-ignited ICF-target gain**

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Effect of the light impurities on ignition and combustion of ICF-targets.

Impurities in DT-fuel

1. Mixing the DT-fuel with target's ablator ⇒ H-, Be-, C-impurities

2. Non-cryogenic solid thermonuclear fuel.
DT-hydrides of light metals as the solid chemical compounds of hydrogen's isotopes containing minimal atomic fraction of inert atoms:

BeDT, $Li_2BeD_2T_2$, $Li_2Be_2D_3T_3$, Li_2DT, Amine-borane NT_3BD_3.

Two applications

1. Studying the influence of DT-fuel mixing with target's ablator on ignition and gain

√ 2. Searching the possibilities to use the solid chemical compounds of hydrogen's isotopes as a non-cryogenic thermonuclear fuel, despite decreasing the caloric content of such a fuel in comparison with DT-ice.

Effect of the light impurities on ICF-targets ignition.

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S.Yu. Gus'kov, D.V. Il'in, V.E. Sherman. Plasma Physics Reports 2011, v.37, p. 1096:
The dependences of **ignition criterion**, **ignition energy** and **gain** of DT-fuel on the arbitrary concentration of light impurities for homogeneous, isobaric and isochoric plasmas.

Ignition criterion: $8.1\cdot 10^{40}\,\chi_F(\rho R)^2 <\sigma v> \left(\eta_\alpha + 4\eta_n\right) >$

$$6.4\cdot 10^{22}\,\chi_u \beta T^{3/2}(\rho R) + 2.8\cdot 10^{23}\,\chi_r T^{1/2}(\rho R)^2 + 2.6\cdot 10^{19}\,\chi_c T^{7/2}$$

β=0 - isobaric, β =0.87 - isochoric, β =2 - homogeneous plasmas

$$\chi_F = \left[\frac{1-x}{1+\left(\mu_a/2.5-1\right)x}\right]^2, \quad \chi_r = \left\{\frac{\left[1+(Z_a-1)x\right]\left[1+(Z_a^2-1)x\right]}{\left[1+\left(\mu_a/2.5-1\right)x\right]^2}\right\}; \; x\text{-impurity's concentr.}$$

BeDT is most promising material as a solid non-cryogenic fuel with a maximal ratio χ_F/χ_r:

BeDT – χ_F/χ_r=0.038 (χ_F=0.13, χ_r=3.44)

$Li_2Be_2D_3T_3$ – **χ_F/χ_r=0.031** (χ_F=0.1, χ_r=3.17); $Li_2BeD_2T_2$ – **χ_F/χ_r=0.029** (χ_F=0.09, χ_r=3.06)

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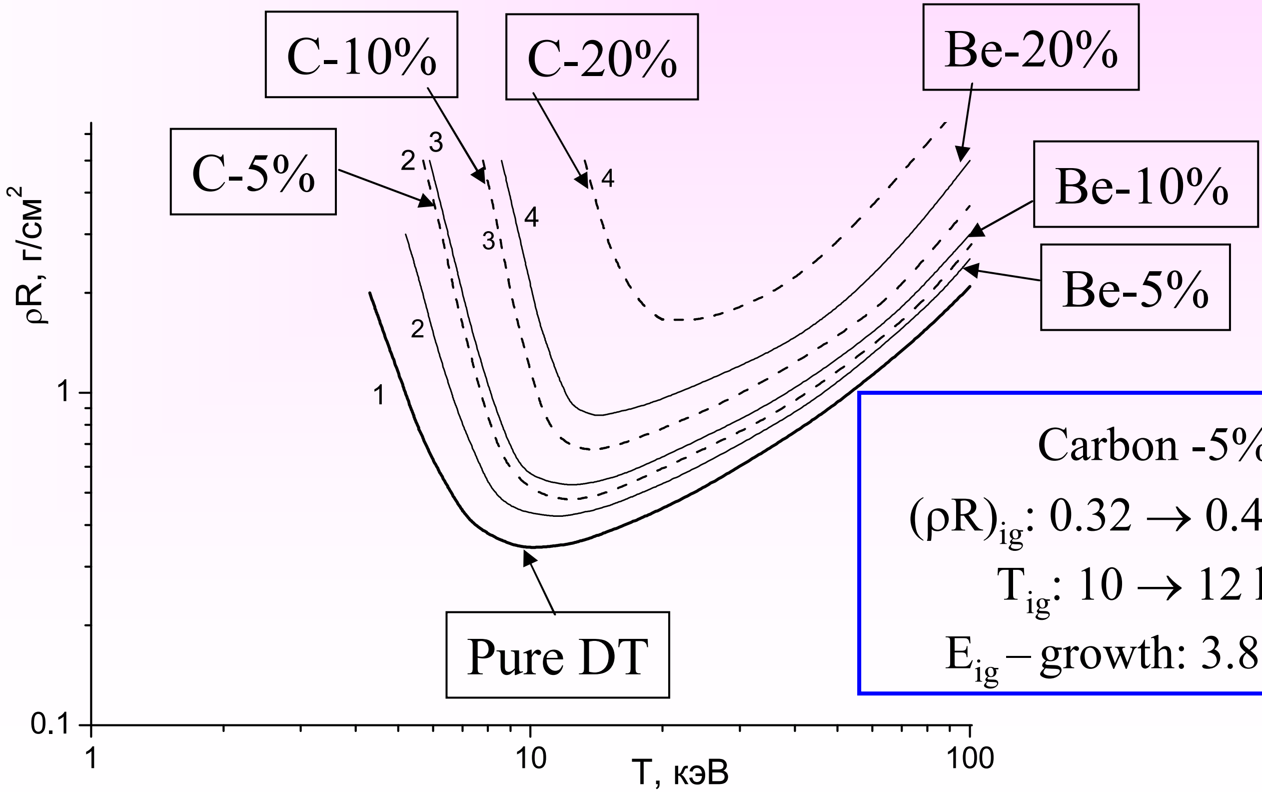
Impurities effect on ignition

$$(\rho R)_{\min} \approx 0.3 \left[\frac{\beta \left(\frac{\mu_*}{2.5} \right)^{1/2} \left(\frac{1+Z_*}{2} \right)^{3/2}}{(1-x)^2 - 0.06 \left(Z^2 \right)_* Z_*} \right]^{1/2}, \frac{g}{cm^2}$$

Isochoric (fast-ignited) plasma

T_{ig}=15-20 keV



Carbon -5%.

$(\rho R)_{ig}$: 0.32 → 0.47 g/cm²

T_{ig}: 10 → 12 kev

E_{ig} – growth: 3.8 times

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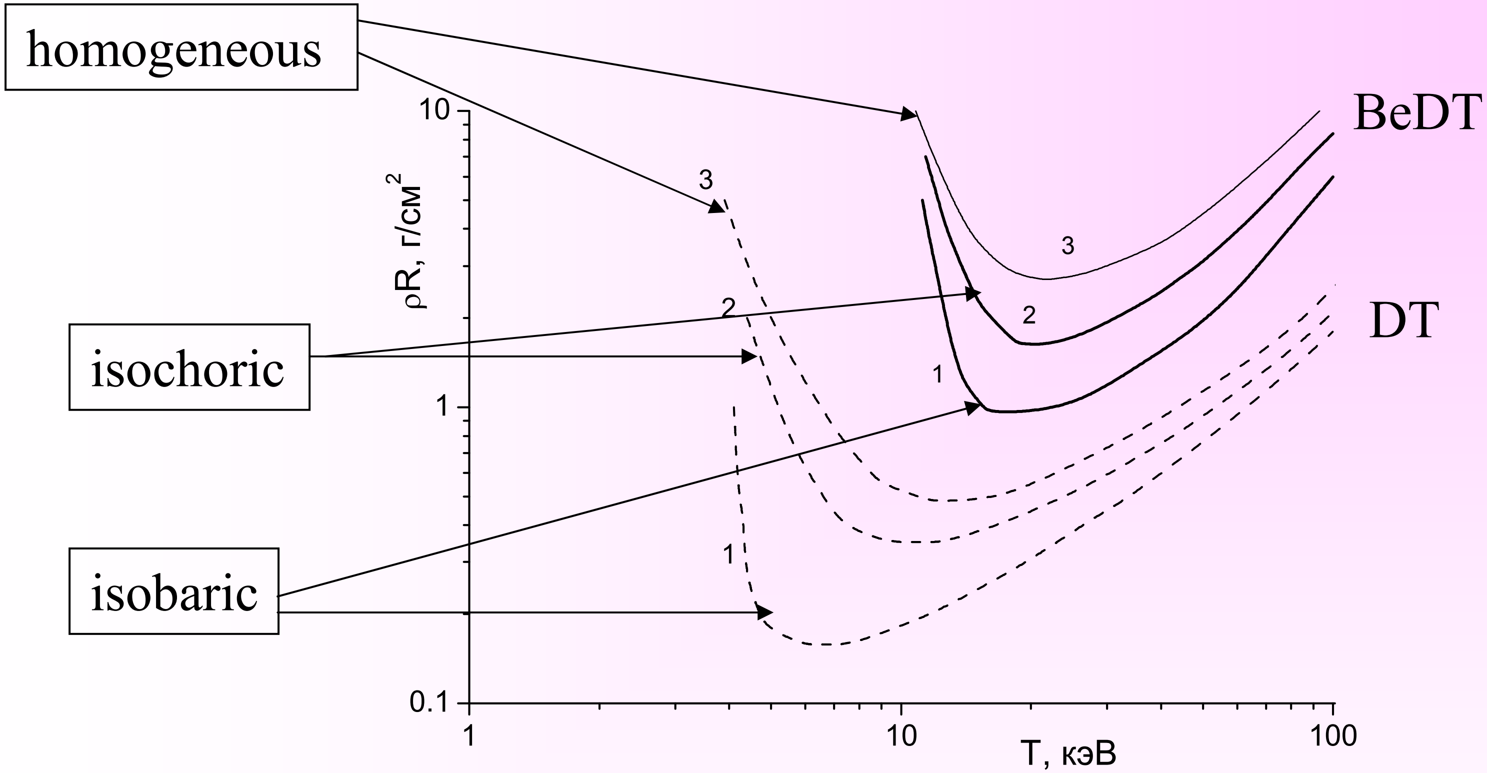
Ignition of BeDT-plasmas

($x \approx 0.33$, $\mu^* = 4.67$, $Z_* = 2$, $(Z^2)_* = 6$)



33% impurity of beryllium increases:

$(\rho R)_{min}$ in about **5 times** and T_{ig} **in about 2 times** in **c**omparison with pure DT-fuel.

Burning out

$$BeDT: \quad g = \frac{\rho R}{\rho R + 10.8} \rightarrow \rho R \sim 5-6\ g/cm^2$$

$$DT: \quad g = \frac{\rho R}{\rho R + 6.5} \rightarrow \rho R \sim 3-4\ g/cm^2$$

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Spark ignition. Analytical consideration

Ignition requirements for isobaric BeDT-plasma : $(\rho R)_{ig(min)}$=0.9 g/cm^2 *and* T_{ig}=15 *keV*

BeDT-plasma energy of the burning target

$$\rho R > (\rho R)_{ig} \quad \text{and} \quad \rho_{cold} >> \rho_{ig}$$

$$E_{plasma}(J) \approx \frac{4.2 \cdot 10^9}{\rho_{ig}^2} \times \left[1 + 3.3 \cdot (\rho R - 0.9) \frac{\rho_{ig}}{\rho_c} \right]$$

Gain: $G_F \equiv E_{fusion} / E_{plasma}$

$$G_F \approx 86 \times \left(\frac{\rho R}{\rho R + 10.8} \right) \times \left[\frac{1 + 3.3(\rho R - 0.9)}{1 + 3.3(\rho R - 0.9) \frac{\rho_{ig}}{\rho_c}} \right]$$

	G_F	E_{ig}, MJ	E_c, MJ	E, MJ	ρ_{ig}, g/cm^3
ρR = 6 г/см^2, $g \approx 0.36$					
ρ_c=500 g/cm^3	**200**	1.6	2.8	4.4	50
ρ_c=1000 g/cm^3		0.42	0.68	1.1	100

- These gains could be enough for heavy ion fusion at the driver energy of **15-20 MJ**.
- Spark-ignited BeDT-target can be used as a source of neutrons in the hybrid fusion-fission reactor at the laser energy **5-7 MJ** .

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Fast ignition. Analytical consideration.

Ignition requirements for isochoric BeDT plasma: $(\rho R)_{ig(min)} = 1.5\ g/cm^2$ *and* $T_{ig} = 20\ keV$

BeDT-plasma energy of the burning target

$$\rho R >> (\rho R)_{ig} \text{ and } \rho = \rho_{ig}$$

$$E_{plasma}(J) \approx \frac{2.6 \cdot 10^{10}}{\rho^2} \times \left[1 + 5.8 \cdot 10^{-5} (\rho R)^3 \rho^{2/3}\right]$$

Gain: $G_F \equiv E_{fusion} / E_{plasma}$

$$G_F \approx 64 \times \left(\frac{\rho R}{\rho R + 10.8}\right) \times \left[\frac{1 + 0.3 (\rho R)^3}{1 + 5.8 \cdot 10^{-5} (\rho R)^3 \rho^{2/3}}\right]$$

	G_F	E_{ig}, kJ	E_c, kJ	E, kJ
$\rho R = 6\ g/cm^2$, $g \approx 0.36$				
$\rho = 300\ g/cm^3$	**940**	280	160	440
$\rho = 500\ g/cm^3$	**820**	100	80	180
$\rho = 700\ g/cm^3$	**740**	50	50	100
$\rho = 1000\ g/cm^3$	**650**	25	31	56

The target with BeDT-fuel can be fast ignited by laser-produced beams of electrons or ions with energy **50-100 kJ** at the fuel density of **1000-700 g/cm³** or fast ignited by heavy ion beam with energy of **100-280 kJ** at the fuel density of **500-300 g/cm³**.

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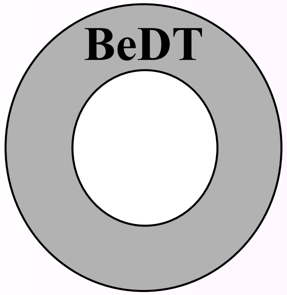
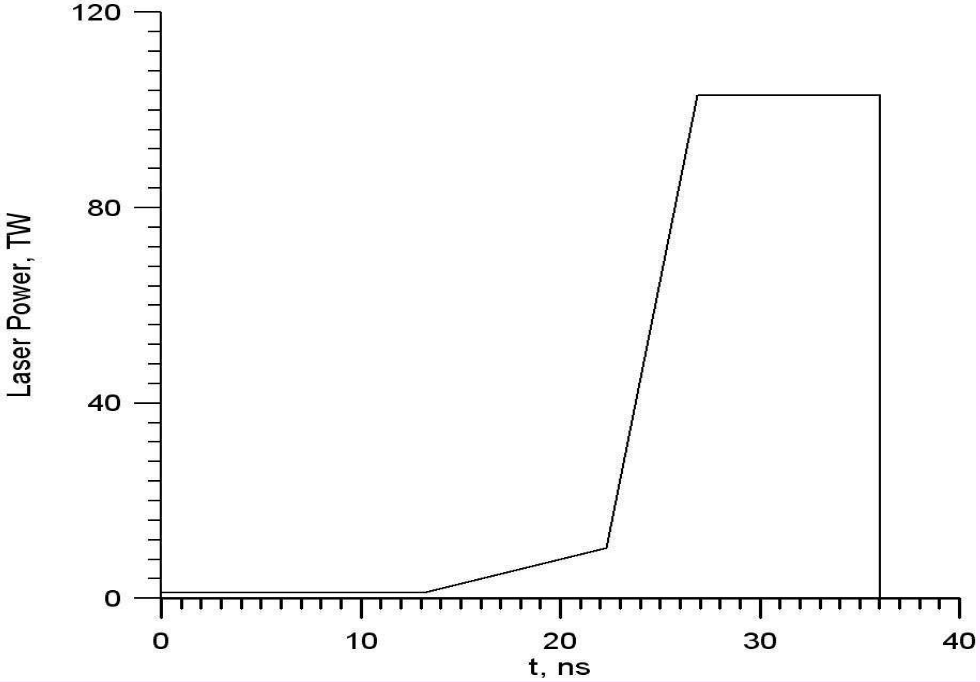
Fast-ignited BeDT-target. Numerical simulations





E_L (MJ)	Mass (mg)	Radius (cm)	Hydro efficien. (%)	τ_{LAS} (nc)	Impl. time (ns)	ρR (g/cm²)
0.57	3.5	0.19	10.2	27.5	28.5	5.25
0.85	5.3	0.22	10.0	31.5	32.8	5.86
1.27	8.0	0.25	9.9	36.0	37.8	6.65
1.91	11.0	0.28	9.9	41.2	43.4	7.48
2.86	18.0	0.33	9.8	47.2	49.9	8.30

Fast-ignited BeDT-target. Laser & target.

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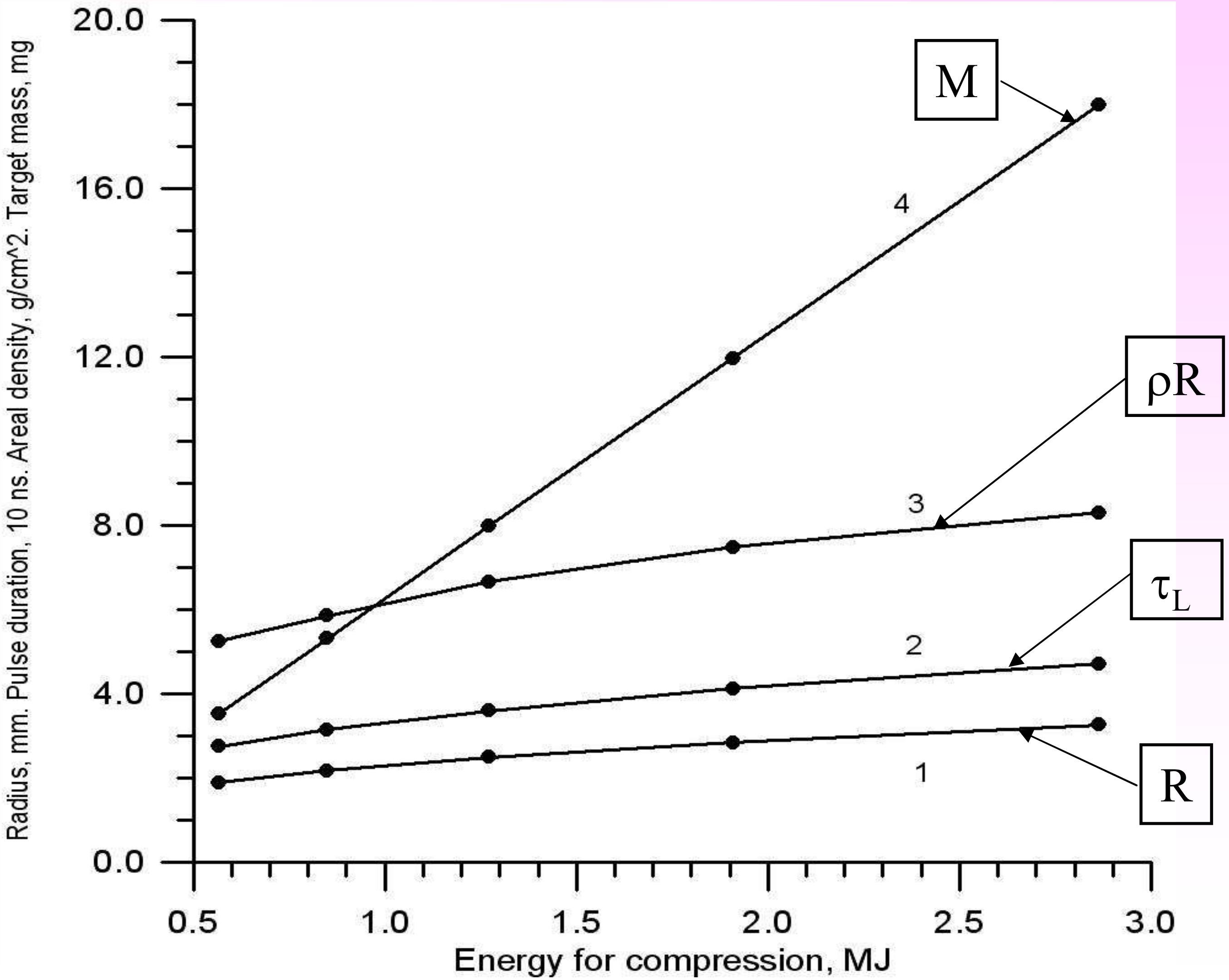

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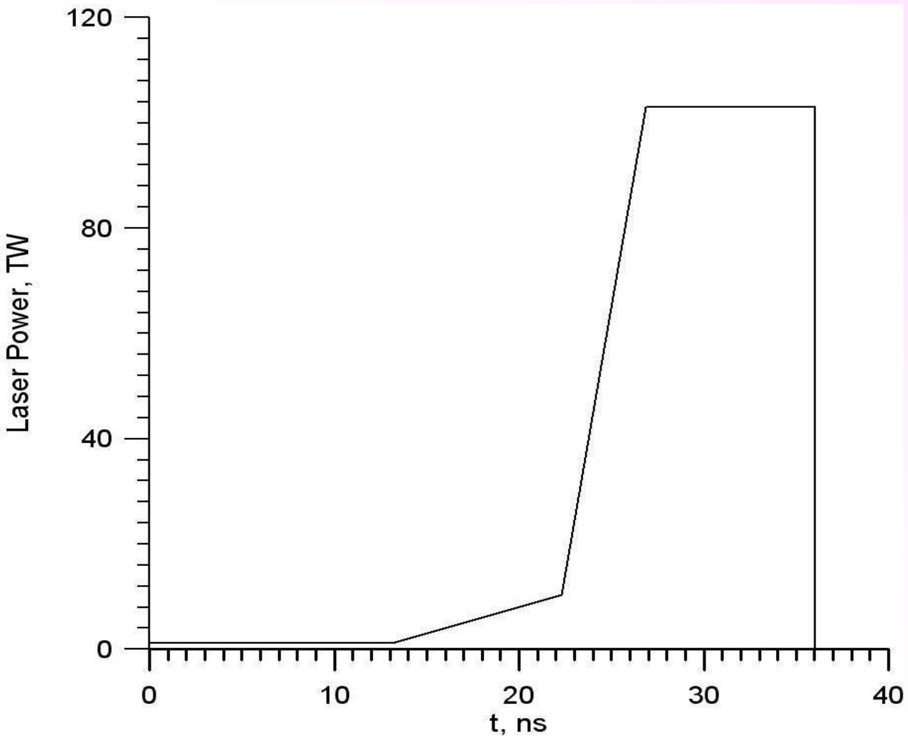
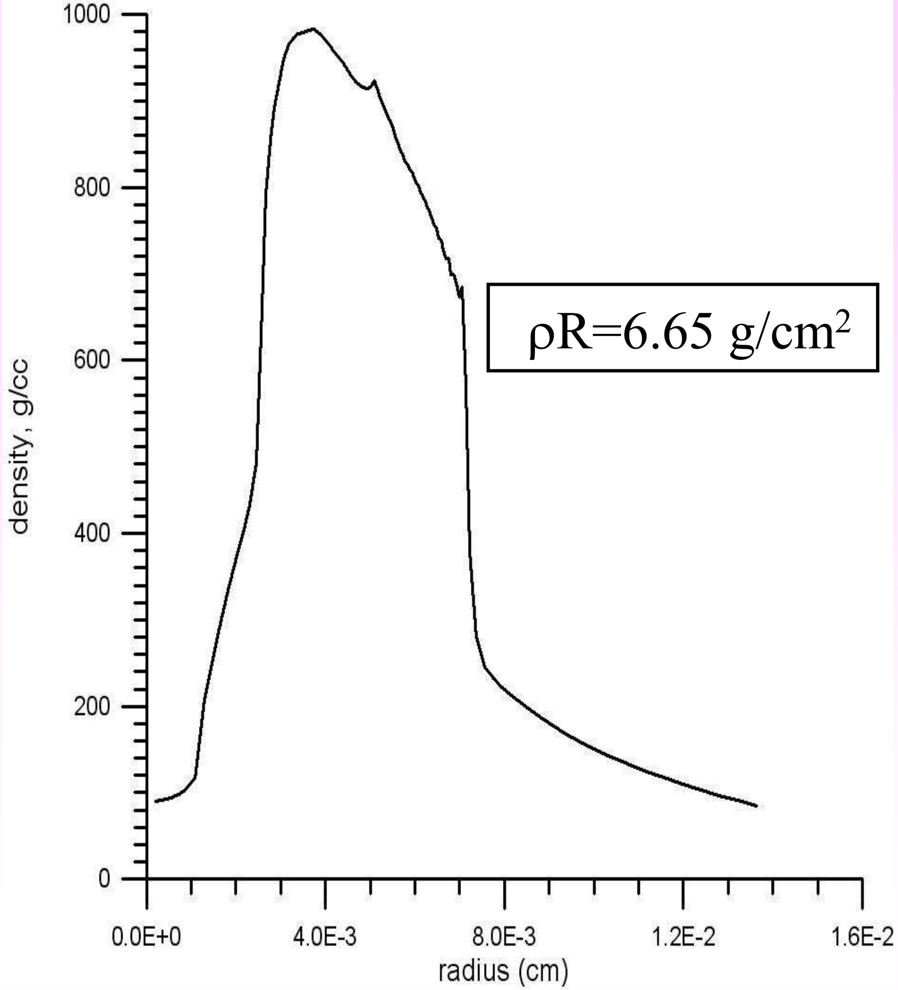
Fast-ignited BeDT-target. Compression.

R=0.25 cm, M=8.0 mg

E_L=1.27 MJ. τ_L= 36





ρR=6.65 g/cm^2

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Fast-ignited BeDT-target. Gain vs ignition energy.

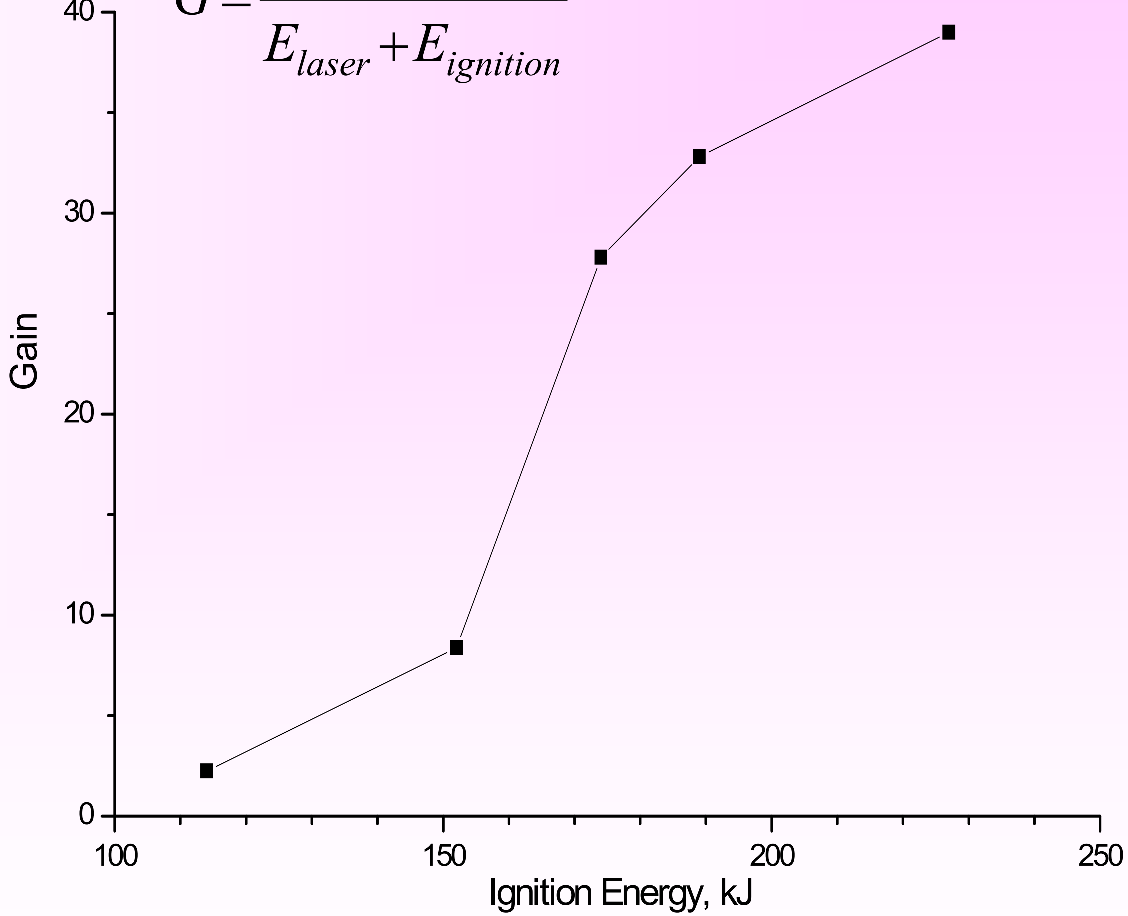
E_L=1.27 MJ. τ_L= 36 ns

R=0.5 cm, M=8.0 mg

$\rho R \approx 6.65\ g/cm^2$

$\rho_{max} \approx 960\ g/cm^3$

$$G = \frac{E_{fusion}}{E_{laser} + E_{ignition}}$$



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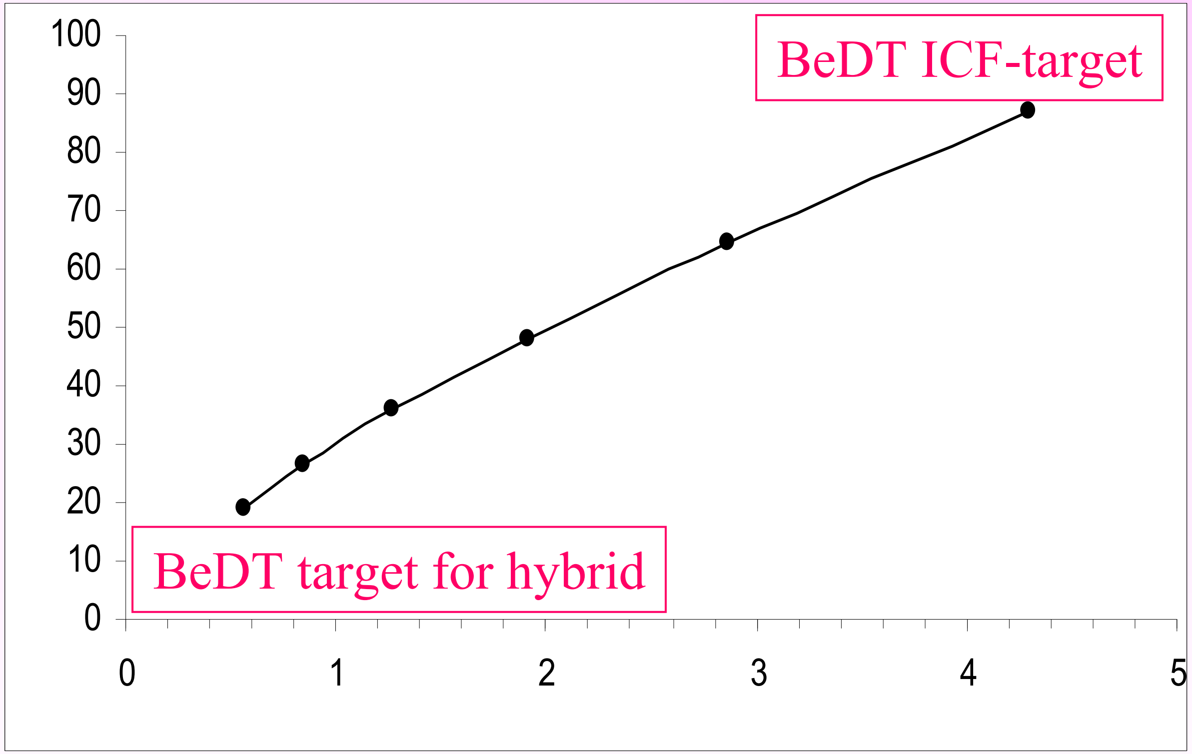
Fast-ignited BeDT-target. Gain vs total energy.

E_L (MJ)	Mass (mg)	ρR (g/cm²)
0.57	3.5	5.25
0.85	5.3	5.86
1.27	8.0	6.65
1.91	11.0	7.48
2.86	18.0	8.32
4.32	26.9	8.86

$$G=\frac{E_{fusion}}{E_{laser}+E_{ignition}}$$



$E_{laser}+E_{ig}$, J

•Fast-ignited BeDT ICF target: Laser Energy - 4.5 MJ, Ignition Energy - 180 kJ

•Fast-ignited BeDT target for hybrid: Laser Energy < 0.5 MJ

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Fast-ignited BeDT-target for hybrid.

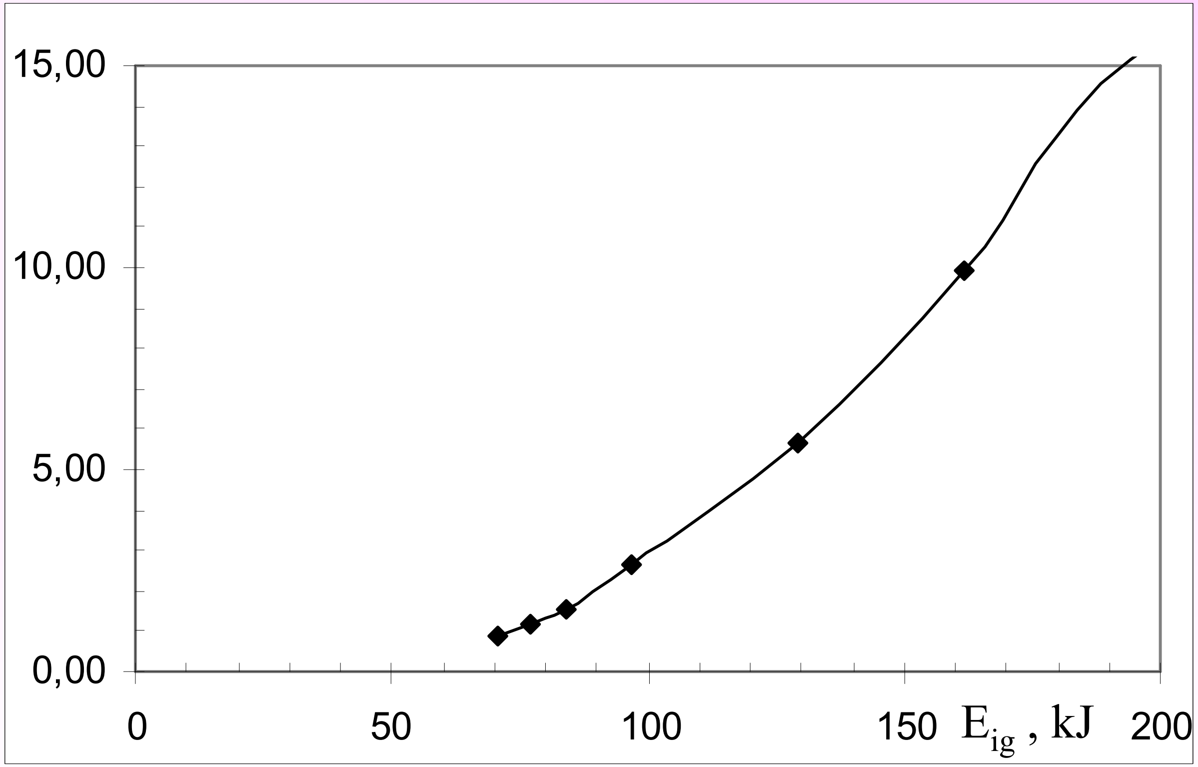
$$G = \frac{E_{fusion}}{E_{laser} + E_{ignition}}$$

E_L=0.57 MJ. τ_L= 27.5 ns

R=0.19 cm, M=3.5 mg

$\rho R \approx 5.25$ g/cm^2

$\rho_{max} \approx 920$ g/cm^3



Fast-ignited BeDT target for hybrid.

Laser Energy: 0.3-0.5 MJ. Ignition Energy: 50 -70 kJ

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Conclusions

It is suggested to apply the targets with solid non-cryogenic BeDT-fuel as:

(1) Fast-ignited ICF-target at the ignition energy of 150-200 kJ and compressing driver energy of 4-5 MJ ;

(2) Fast-ignited target for hybrid at the ignition energy of 50-70 kJ and compressing driver energy of 0.3-0.5 MJ;

(3) Spark-ignited target for heavy ion fusion at the driver energy of 15-20 MJ;

(4) Spark-ignited target for hybrid at the laser energy 5-7 MJ .