THE DEVELOPMENT OF ICF-TARGET DESIGHN FOR SPARK IGNITION AND FAST IGNITION. LPI ACTIVITY AND INTERNATIONAL COLLABORATION.

S.Yu. Gus'kov, N.V. Zmitrenko*, V.B. Rozanov

P.N. Lebedev Physical Institute of RAS, Moscow, Russia. guskov@sci.lebedev.ru

**Institute of Mathematical Modeling of RAS*

ELI/HiPER/PETAL ISTC WORKSHOP, November 24-25, 2008

Contents

1. Development of the design for stable compression

- "Greenhouse" target
- ICF-target for small number of laser beams
- Direct drive ICF target with thermal radiation smoothing

2. Development of the design of Fast Ignition ICF-target

- Spherical FI-targets without cone:
  Ignition by light ion beam
  Cylindrical FI-target
- Spherical FI-target with a cone - ignition by detonating hydrodynamic flow

3. International collaboration.

Direct Drive ICF with Smoothing Absorber

S.Yu.Gus'kov.
LPI RAS

1. Light foams of near and supercritical average density: $\rho_a \approx 10^{-4} \div 10^{-2}$ g/cm^3.

"Large-pore": Porous plastics ($[CH]_n$, $[CH_2]_n$); porous beryllium; agar-agar ($C_{12}H_{18}O_9$).
Small size of solids, $h_0 \sim 0.1\text{-}1$ μm. Size of cavity, $\delta_0 \sim 30 - 100$ μm

"Small-pore": Threeatsetat-cellulosa (TAC: $C_{12}H_{16}O_8$); TMPTA($C_{15}H_{20}O_6$);Polyvinylalcohol (PVA).
Small size of solids, 0.01-0.1 μm. Size of cavity 1-5 μm.

2. Light foams with clusters of heavy elements: Size of cluster - several hundred Angstrems

Laser radiation absorption and smoothing bylow-dense foam absorber

LPI&TRINITI. LPI&ENEA-Frascati. LPI&PALS-Prague.

$I \sim 10^{13} - 5\ 10^{14}$ W/cm^2, $\lambda = 0.35\text{-}1.06$ μm:

!High absorption efficiency, 80- 90 %!

!Low level, (3-5)% and narrow angle distribution of the scattering light!

!Quasi uniform deposition of laser energy on the absorption depth of 150 – 500 μm!

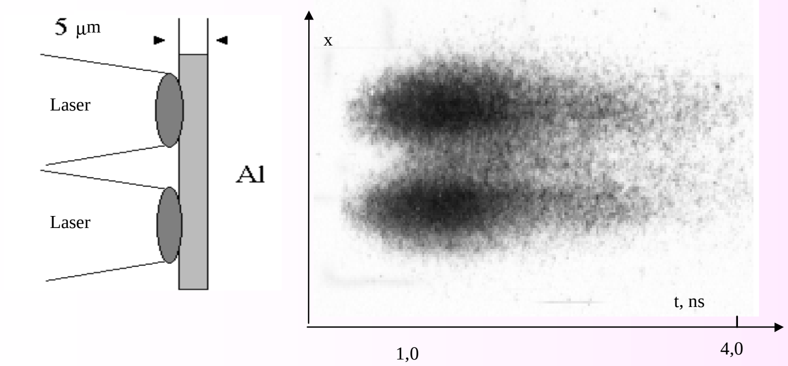
!Fast energy transfer of the velocity (1-2) 10^7 cm/c!

The beginning in the middle of 90-th: S.Yu. Gus'kov, N.V. Zmitrenko, V.B. Rozanov.
Laser Green House Target with Distributed Absorption of Laser Energy. JETP 81, p. 296, 1995.

S.Yu.Gus'kov.
LPI RAS

Absorbed Energy Smoothing

Two-beams Experiments with Jodine-laser ISKRA-4, VNIIEF-Nuclear Center, Sarov:
λ =0. 638μm, E≈100 J, I≈10^{14} W/cm^2 ,$\tau_{1/2}$ ≈0.9 ns.



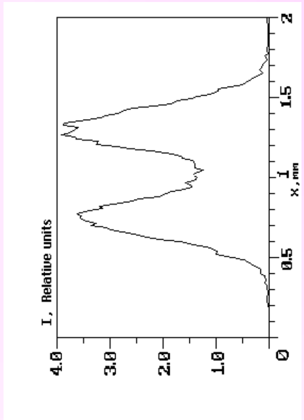
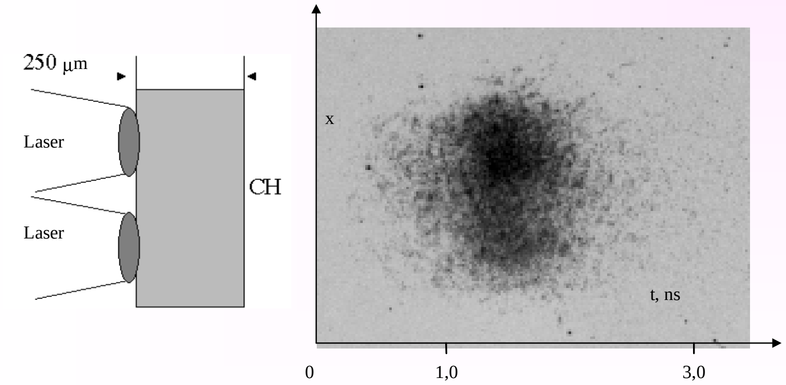


Fig. 4a.

Al foil:

Thickness, Δ=5 μm



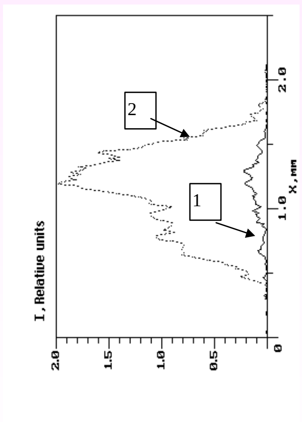


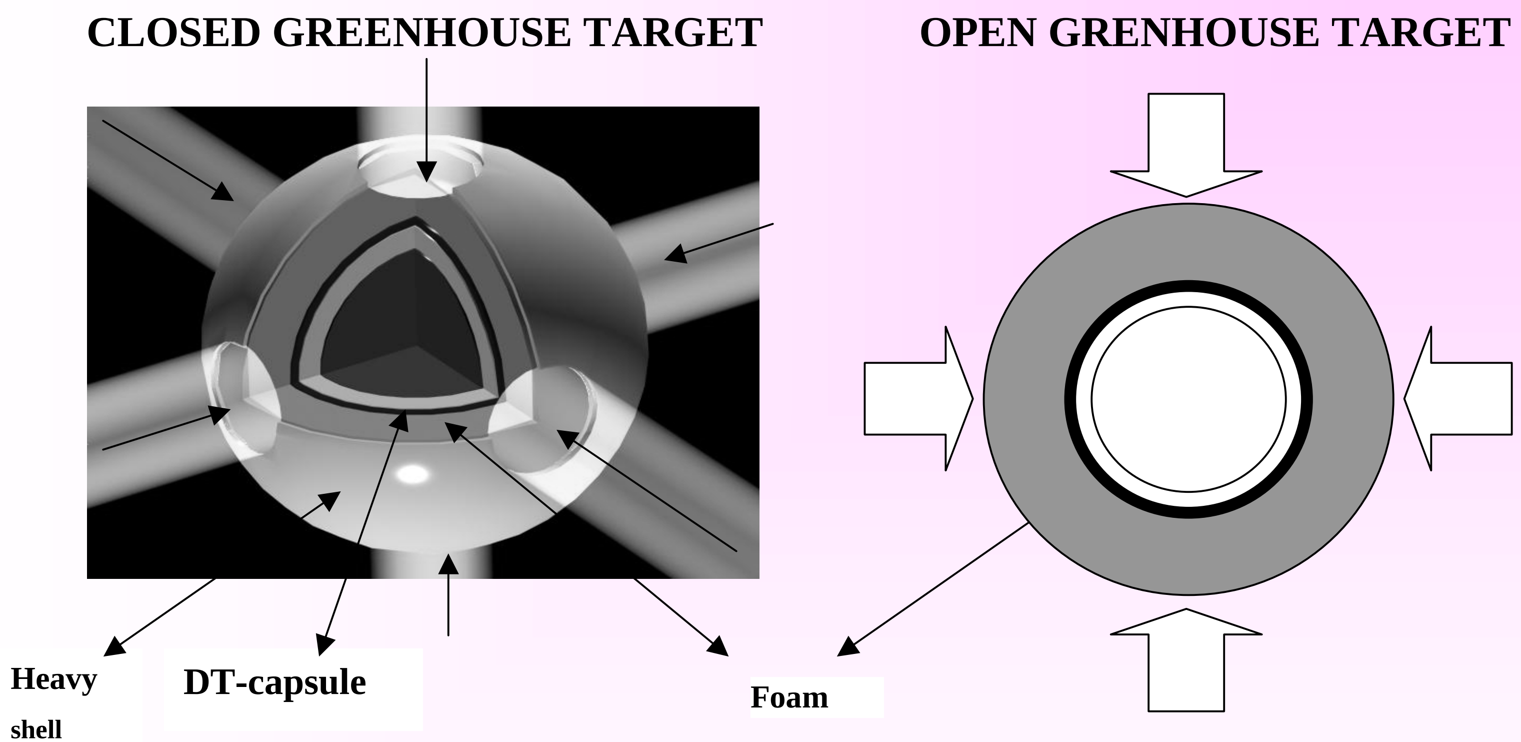
Fig. 4b.

CH-layer:

Thickness, Δ=250 μm
Density, 10 mg/cm^3

S.Yu.Gus'kov.
LPI RAS

Greenhouse Target: Direct Drive ICF-Target for Small Number Beam Irradiation



Closed GH target. λ = 1.06 μm!
E_L = 2 MJ - Gain = 50
E_L = 200kJ – Ignition

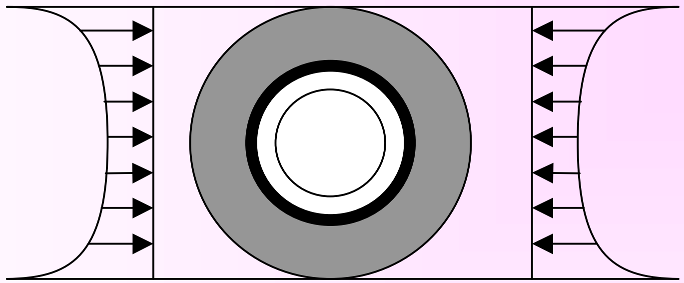
Open GH target. λ = 1.06 μm!
E_L = 2 MJ - Gain = 7–8

Basic publication: S. Yu. Gus'kov, N.N. Demchenko, V.B. Rozanov, R.V. Stepanov, N.V. Zmitrenko, A. Caruso, C. Strangio. Symmetric compression of "laser greenhouse" targets by a few laser beams. Quantum Elect. 33, 2003

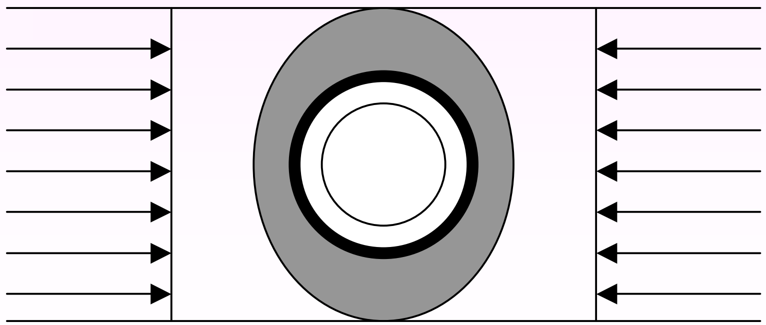
CreenhouseTargets for Two Laser Beams

S.Yu.Gus'kov.
LPI RAS

1. The irradiation of spherical target by two laser beams with special distribution of the light intensity on the beam cross section



2. The irradiation of the target with special form of foam absorber by two laser beams with uniform intensity distribution on cross section.



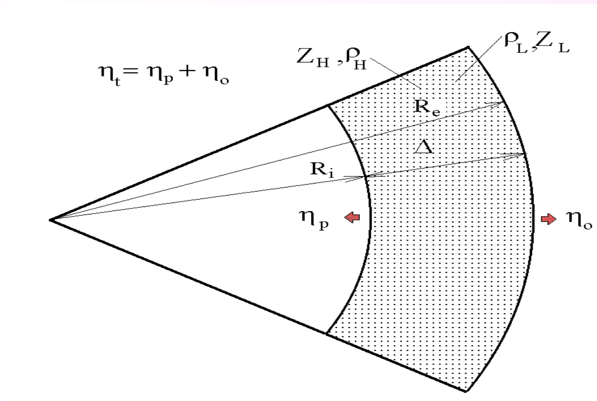
Direct Drive Target with Thermal Radiation Smoothing

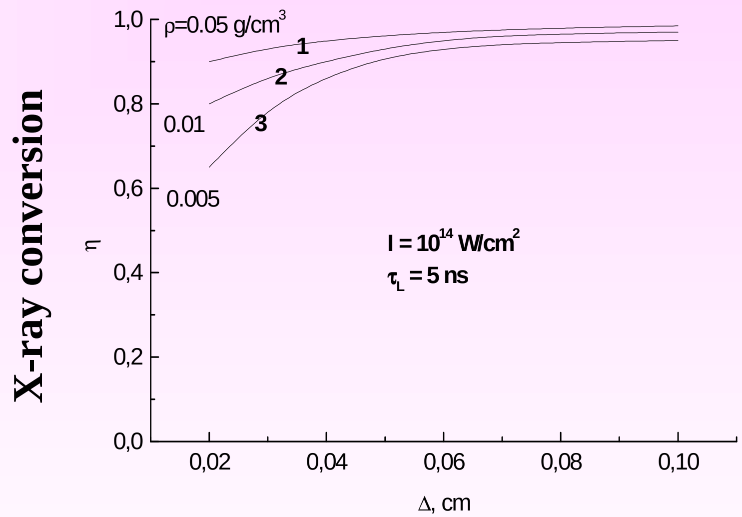
S.Yu.Gus'kov.
LPI RAS

Wide-Range Absorber-Converter:
The light foam with clusters of heavy elements, $\rho_{light} \sim \rho_{heavy}$

High X-ray conversion:
- **Thermodynamics equilibrium**
- **Small energy of hydrodynamic motion**

Porous beryllium with gold clusters at $\rho_H = \rho_L$





Be-Au. X-ray of (80-90) %: $0.01\ g/cm^2 \leq \rho_L = \rho_H \leq 0.05\ g/cm^2$ and $0.03\ cm \leq \Delta \leq 0.1\ cm$.

NIF laser ($10^{15}\ W/cm^2$, 17 ns, R= 1.1 mm):
Be-Au, Δ = 600-800 μm, $\rho = 0.01\ g/cm^3$: conversion into passing X-ray~30 %.

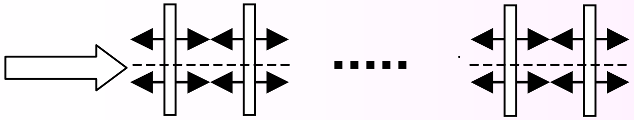
Basic publication: S. Yu. Gus'kov and Yu. A. Merculiev, Low-dense absorber-converter of laser thermonuclear target for direct irradiation by laser beams. Quantum Electronics 31, 2001

S.Yu.Gus'kov.
LPI RAS

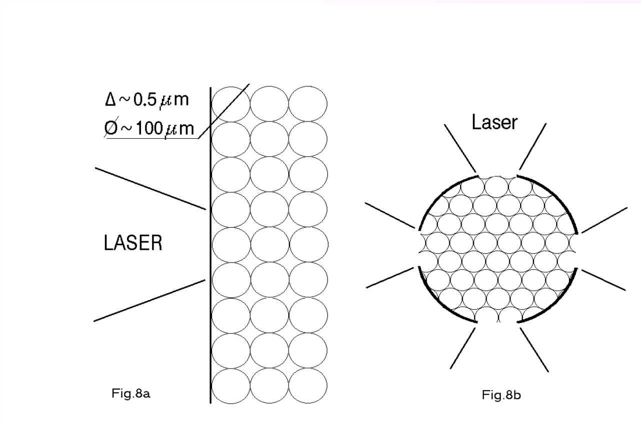
Neutron source application

Powerful Neutron Generation in Laser-Produced Plasma of Regularly Structured Matter

1. Layer-structure



2. Microshell-structure



- Wave of thermal explosions of layers or shells
- Transformation of kinetic energy to ion thermal energy
- Long time of the ion-electron energy relaxation
- Involving into the hydro-thermal dissipation process much larger mass of matter than in a single "exploding pusher" layer or shell.

$(CH)_{1/3}(DT)_{2/3}$-solids. Nd-laser: λ=0.53μm , E_L= 400 kJ, $I=5\cdot10^{14}$ W/cm^2, τ_L =1.2 ns, R_L= 450 μm.

N>10^{10} neutrons / J

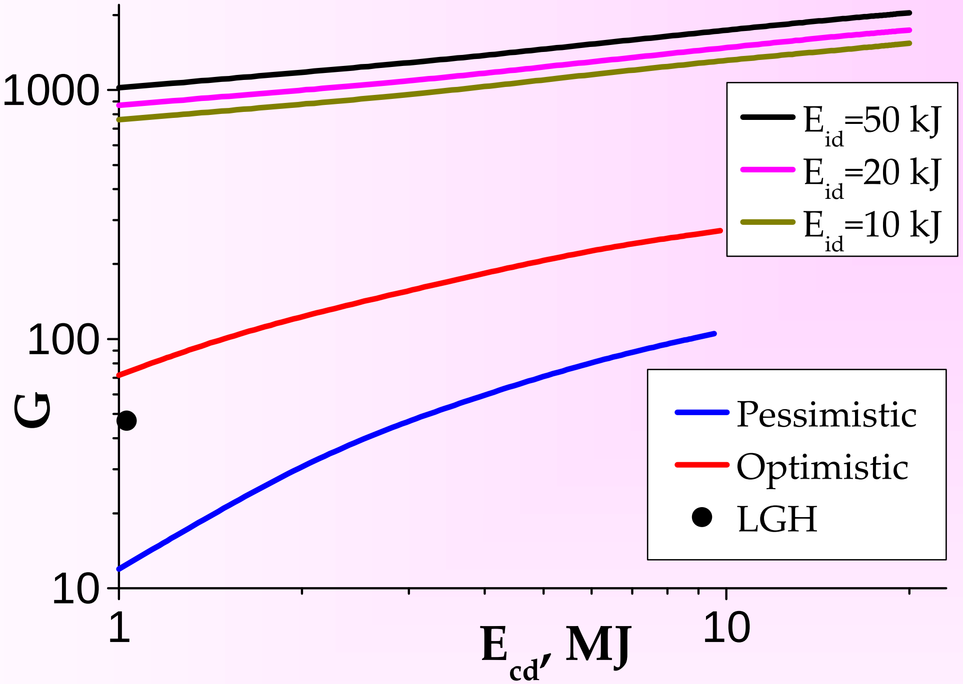
Multi layers: DT-neutron yield 10^{16} (gain G~0.1)

Multi-shells: Gain ~ 1–5

Basic publication: S. Yu. Gus'kov, N.V. Zmitrenko, V.B. Rozanov. Powerful neutron source on the base of nonequilibrium laser-produced plasma of volume-structured media. JETP Letters, 66, 555, 1997.

Spherical Fast Ignition Target Gain

S.Yu.Gus'kov.
LPI RAS



Sperical FI-targets without cone - ignition by light ion beam:

protons, deuterium, Be and others. E ~ 1 - 3 MeV per nucleon, $I_L \sim 10^{19}$ - 10^{20} W/cm^2

Spherical FI-target with a cone - ignition by detonating impactor, $I_L \sim 10^{14}$-10^{15} W/cm^2

Cylindrical FI-targets without cone - ignition by fast electrons or light ions, non-equilibrium X-ray (FEL?)

S.Yu.Gus'kov.
LPI RAS

Gain and Parameters of Fast Ignition Target and Drivers (λ=0.35 μm, Ecd = 1 - 10 MJ)

Low Aspect Ratio Target, Plastic ablator: η_{ab}=0.7. η_h = 0.2, η_t =0.64.

Spherical Target R_0/Δ_a=17. Cylindrical Target R_0/Δ_a=14

E_{cd} MJ	τ_{cd} ns	I_{cd}, 10^{13} W/cm^2	E_{id} kJ	R_0/Δ_a	R_0, cm	L/R_0	M_a, mg	M_b mg	ρ_b, g/cm^3	$\rho_b R_b$, g/cm^2	R_0/R_b	G
Spherical Target												
1	60	2	30	17	0.3	-	18	3.2	118	2.1	16.4	**650**
10	128	2	30	17	0.64	-	180	32	118	4.5	16.4	**1085**
Cylindrical target												
3	225	1.1	90	14	1.02	0.25	112	19	66	1.5	**45**	**600**
10	336	1.1	90	14	1.33	0.25	263	45	66	1.95	**45**	**784**

High Gain Spherical Target: $E_{id} \approx$ 30 kJ for $R_0/R_b \approx$ 15-20.

High Gain Cylindrical Target: $E_{id} \approx$ 100 kJ for $R_0/R_b \approx$ 45-50.

Cylindrical Target with a Spin-oriented DT - fuel:

For spin-oriented DT - fuel $\rho_{ig} \cdot R_{ig}$ decreases in factor 1.5 $\rightarrow E_{ig} \cdot \rho_b^2 \propto (\rho_{ig} \cdot R_{ig})^3$

$R_0/R_b \approx$ 20-25. $E_{id} \approx$ 150 - 200 kJ

Basic publication: S. Yu. Gus'kov. Thermonuclear gain and parameters of fast ignition ICF-targets. Laser and Particle Beams 23, 2005.

Input Channel and Edge Wall Parameters

S.Yu.Gus'kov.
LPI RAS

Requirements for the parameters:

Containment of Plasma Flows, Minimal Fuel Mass and Energy Losses

Shock wave velocity in channel wall: $D_w \approx \frac{1}{4}\left[\frac{3(\gamma_w+1)}{\gamma_a}\right]^{1/2}\left(\frac{\Delta_{a0}}{R_0}\right)^{1/2}\left(\frac{\rho_{a0}}{\rho_{w0}}\right)^{1/2} u_c$

Thickness of the wall: $\Delta_w \approx \frac{1}{2}\left[\frac{3(\gamma_w+1)}{\gamma_a}\right]^{1/2}\left(\frac{R_0}{\Delta_{a0}}\right)^{1/2}\left(\frac{\rho_{a0}}{\rho_{w0}}\right)^{1/2} \Delta_{a0}$

ρ_{w0}/ρ_{a0} = 10 - 20, R_0/Δ = 15-20: $\Delta_w \sim \Delta_{a0}$, $\Delta_w \approx$ 100 - 300 μm.

Energy Losses in the Input Channel of Spherical Target: $\chi_w \approx$ 3-5 %

Energy Losses in the Edge Wall of Cylindrical Target

Optimal length , L = $R_0/4$: Energy losses $\chi_w \approx$ **10-20 %**

Fast Ignition by Detonating Impactor

S.Yu.Gus'kov.
LPI RAS

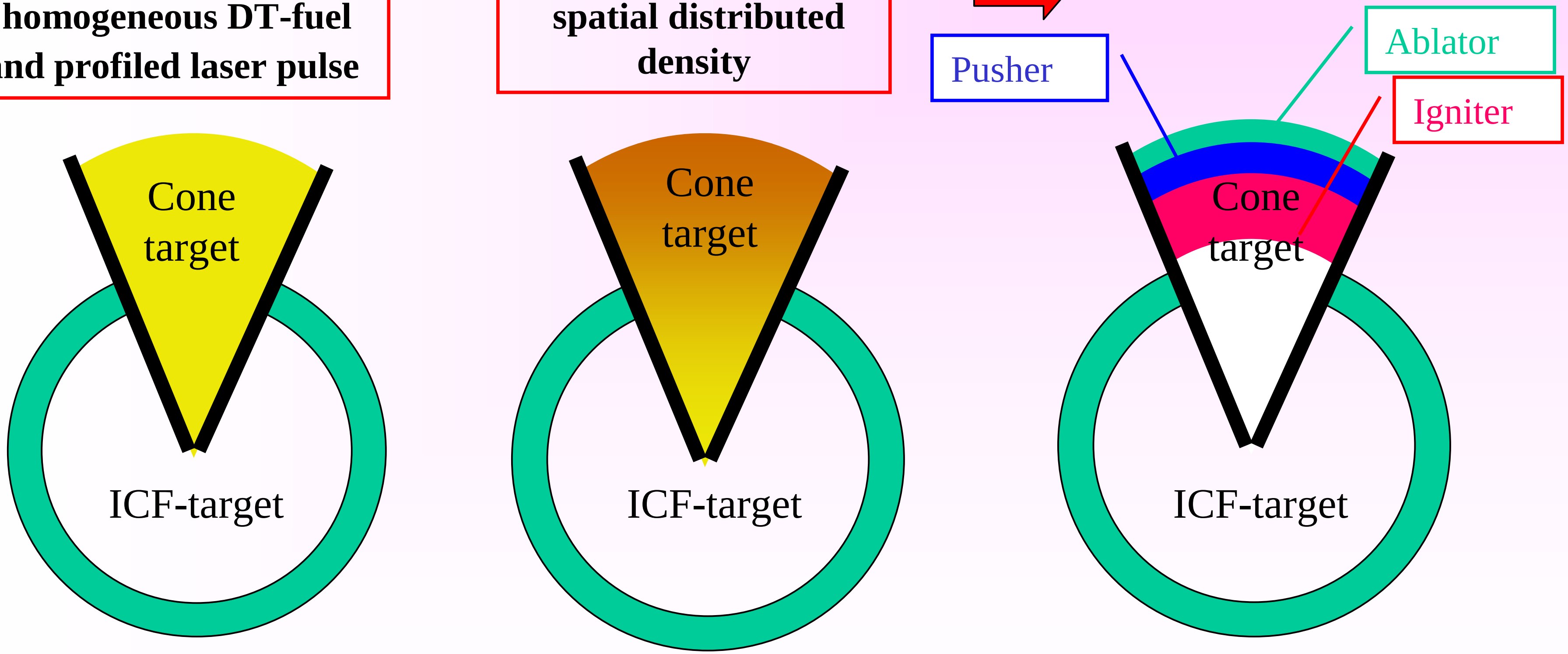
Development of "Cone-Guided Impactor" to "Target inside Target"
Ignition by Detonating Impactor - "Target From Target" Ignition

Two ICF-methods: 1. Profiled Laser Pulse, 2. Initial Density Distribution

1. Cone target with homogeneous DT-fuel and profiled laser pulse

2. Cone target with spatial distributed density

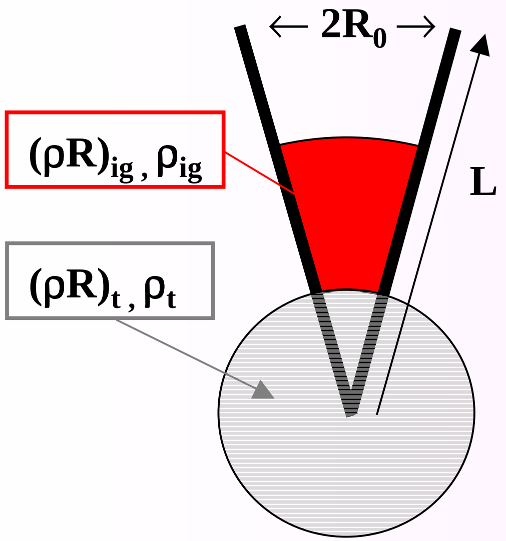
Multi-layer cone target



Basic publication: S. Yu. Gus'kov, M. Murakami. Fast ignition by the detonation wave from the impactor laser-accelerated up to velocity of 300-500 km/s. Book of Abstract of XXX ECLIM, p. 23, 2008.

S.Yu.Gus'kov.
LPI RAS

Requirements to the design



Cone opening angle

$$tg\frac{\theta}{2} = \frac{(\rho R)_{ig}}{(\rho R)_t} \times \frac{\rho_t}{\rho_{ig}}$$ ⇒ $\theta \approx 40^0\text{-}60^0$

Ignition of the igniter: $(\rho R)_{ig}$=0.4 g/cm^2
High gain of ICF-target $(\rho R)_t$=3-4 g/cm^2

$$\frac{\rho_{ig}}{\rho_t} \approx 0.5 \div 0.2$$

Shell velocity: $$u = 8{,}3\left(I\lambda^2\right)^{1/3} \ln\frac{M_0}{M_f}$$

Hydrodynamic efficiency: $$\eta = 0.64\left(\frac{M_0}{M_f} - 1\right)^{-1} \ln^2\left(\frac{M_0}{M_f}\right)$$

Evaporation - 50%, $M_0 / M_f = 2$ ⇒ Mass of ablator = a half of total mass, $\eta \approx 0.3$, $u \approx 0.57\times(I\lambda^2)^{1/3}$

$$\frac{R_0}{L} = tg\theta \ , \ \tau_L = \frac{2L}{u} \ , \ u = 0.57\left(I\lambda^2\right)^{1/3} \ , \ I = \frac{E}{\pi R_0^2 \tau} \ , \ E = \frac{E_{impactor}}{\eta}$$ ⇒ $$R_0 = 3.1 \times \frac{E_{impact}^{1/3} \lambda^{2/3} (tg\theta)^{1/3}}{\eta^{1/3} u^{2/3}} \ , \ cm$$

E_{imp}=70 kJ, u = 3.3 10^7 cm/s, η=0.3, θ=25°, λ = 0.35 μm ⇒ **$R_0 \approx$ 0.153 cm, L≈0. 32 cm, τ ≈19.5ns**

S.Yu.Gus'kov.
LPI RAS

Igniting conical target design

$R_0 \approx 0.153$ cm

DT-igniter:

$M_{igniter} \approx 4\ 10^{-5}$ g

Au-pusher:

$M_{pusher} \approx 1.5\ 10^{-4}$ g

Be-ablator:

$M_{ablator} = M_{pusher}$

$\Delta_{igniter} \approx$ 21,3 μm

$\Delta_{pusher} \approx$ 10.7 μm

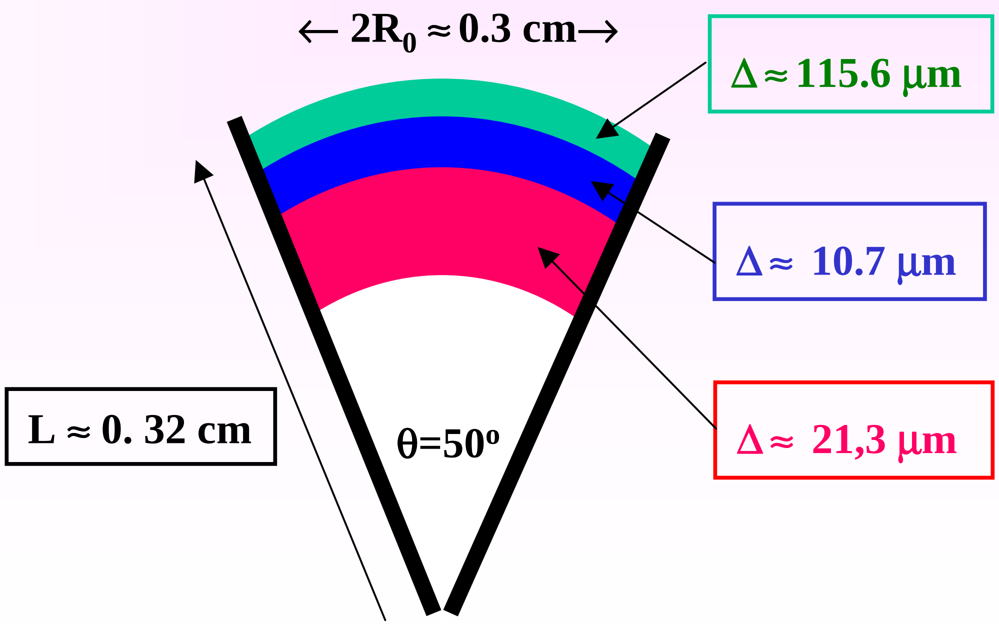
$\Delta_{ablator} \approx$ 115.6 μm

$E_{laser} = E_{impactor} / \eta K_{abs}$

$E_{impactor} \approx 70$ kJ

$\eta = 0.3$, $K_{abs} = 0.7$

$E_{laser} \approx 320$ kJ



S.Yu.Gus’kov.
LPI RAS

LPI Scientific Collaboration

In Russia:
- Institute of Mathematical Modelling of Russian Academy of Sciences
- Institute of Applied Mathematics of Russian Academy of Sciences
- Federal Nuclear Center – VNIIEF in Sarov
- Federal Nuclear Center – VNIITF in Snezhinsk
- Joint Institute of High Temperature of Russian Academy of Sciences
- Moscow Physical Technical Institute
- Moscow Physical Engineering Institute

International:
- ENEA-Frascati Research Center, Italy
- Institute of Laser Engineering, Osaka University, Japan
- Centre National de la Recherche Scientifique-CNRS, France
- Prague Technical University, Czech Republic
- Research Center PALS, Czech Republic
- Central Laser Facility RAL, UK
- DENIM, Madrid Politechnical University, Spain
- Institute of Plasma Physics and Laser Microfusion, Poland

International Projects

Previous International Projects

2 INTAS Projects and 4 ISTC Projects devoted to

- Hydrodynamic instability,
- Laser-driven compression for diamond production
- Laser plasma source of EUV
- Laser interaction with volume-structured matter

Current International Projects

Project of Russian Foundation for Basic Research and Japan Commission for Development of Science.

Title: "Design of ICF-target with low dense absorber for irradiation by small number of laser beams".

Participating Institutions.

Russia:

- P.N. Lebedev Physical Institute of the Russian Academy of Sciences
- Institute of Mathematical Modelling of Russian Academy of Sciences
- Moscow Physical Engineering Institute

Japan: Institute of Laser Engineering, Osaka University

Submitted International Projects

Submitted ISTC-Project

Title: Energy gain optimization in the fast ignition concept at the impact initiation of a fusion reaction.

Participating Institutions:

- P.N. Lebedev Physical Institute of Russian Academy of Sciences
- Russian federal nuclear center – Ye.I. Zababakhin All-Russian Scientific Research Institute for Technical Physics (Snejinsk)

Foreign collaborator: Institute of Laser Engineering, Osaka University (Japan)

Project Duration: 36 months

The scope of activity :

-Investigation of laser-driven acceleration of macroparticle up to velocities exceeding 1000 km/s and macroparticle collision with a dense target;

-Investigation of the physics of laser-driven acceleration and compression of a thermonuclear capsule and segment of a spherical along the conical channel;

-Investigation of the physics of edge initiation of thermonuclear burning wave at high-speed impact by projectile;

-investigation of fast ignition by impact of macroparticle accelerated in the conical channel of a spherical thermonuclear capsule.

S.Yu.Gus'kov.
LPI RAS

ISTC-Project

Title: "HiPER target compression including cone channel influence and real equation of state".

Participating Institutions:

• P.N. Lebedev Physical Institute of Russian Academy of Sciences

• Russian federal nuclear center – Ye.I. Zababakhin All-Russian Scientific Research Institute for Technical Physics (Snejinsk)

Partner: HiPER

Project Duration: 30 months

The scope of activity :

• Numerical modeling of hydrodynamic streams due to interaction of a thermonuclear capsule with cone wall by means of 2D-and 3D codes.

• Theoretical and numerical investigation of the development of hydrodynamic instabilities and mixing at interface between thermonuclear capsule and cone wall.

• Numerical modeling of a thermonuclear capsule compression with taking into account the perturbation of spherical motion of matter due to interaction with cone channel and real equation of state

Proposal on International Projects

S.Yu.Gus'kov.
LPI RAS

ISTC-Project

Title: "HiPER target gain at the non-central fast ignition".

Participating Institutions:

- P.N. Lebedev Physical Institute of Russian Academy of Sciences
- Russian federal nuclear center – Ye.I. Zababakhin All-Russian Scientific Research Institute for Technical Physics (Snejinsk)

Partner: HiPER

The main goal: Theoretical and numerical investigation of thermonuclear burning efficiency at the non-central ignition in the real conditions of HiPER concept

The scope of activity :

- 2D numerical modeling together with Monte-Carlo simulation of energy transfer by α-particles of thermonuclear burning wave propagation in a spherical homogeneous DT-plasma at the fast ignition in edge region of the compressed fuel heated by the different drivers: fast electrons, fast ions and shock wave.
- Theoretical and numerical investigation of HiPER's target gain dependence on the position of ignition region in the spherical-symmetry compressed fuel.
- Theoretical and numerical investigation of HiPER's target gain dependence on the form of compressed thermonuclear capsule.