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SPRING COLLEGE ON PLASMA PHYSICS

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HYDRODYNAMICS OF THE LASER TARGET COMPRESSION - II

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HYDRODYNAMICS OF THE LASER TARGET COMPRESSION.

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PROBLEM: Low-enthropy compression of the Laser targets.

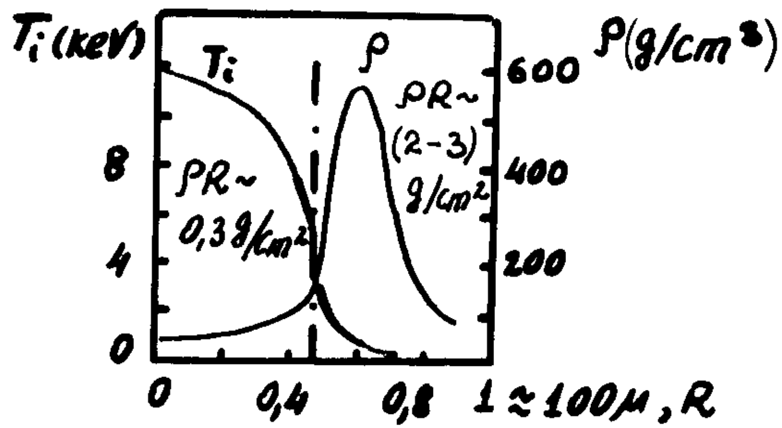
Conditions: - shock wave enthropy is minimal;
- additional enthropy sources, such as hot electrons and own x-ray radiation is not.

Compression ways:
- direct, under short wave lasers;
- direct, under long wave lasers;
- undirect, under x-ray.

Aspects:
- state of the „corona".
- ablation pressure and shell implosion,
- Heating and compression of the fuel,
- Thermonuclear efficiency.

IMPLOSION PARAMETERS FOR IGNITION.

1. Plasma parameters.



2. Implosion parameters.

- Absorption: $k_a > 60\%$,
- acceleration of the shell:
ablative pressure - (30÷50) Mbar
velocity - $v > 200$ km/s
hydrodynamics efficiency -

$$\eta = \frac{M v^2}{2 E_a} = 10-15\%,$$

- compression: $\rho \gtrsim 200\ g/cm^3$

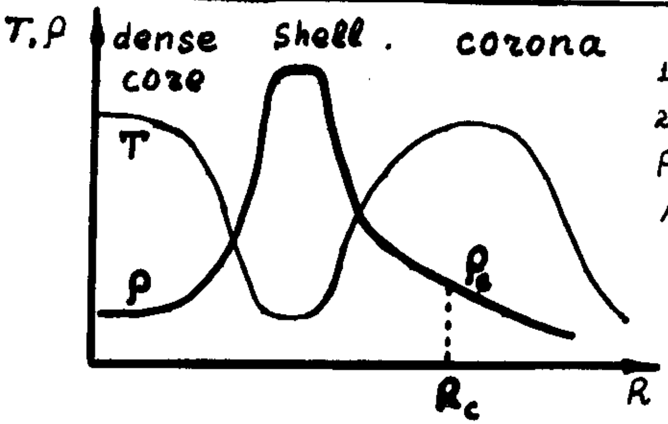
FOR TARGET MASS:

$M = (2 \div 6)\cdot 10^{-2} g$, $M_{DT} = (1 \div 3)\cdot 10^{-3} g$.

DIRECT COMPRESSION. SHORT WAVE LASER. SHELL TARGET.

HYDRODYNAMICS REGIME OF COMPRESSION.

$$q = 10^{13} - 10^{14}\ W/cm^2,\ \lambda \le 1\,\mu m.$$



1. ZhETP, 1976, v71, p594.
2. Trudy of Lebedev Phys. Inst, 1982, N 134, p. 52.

Steady-state corona.

$$q \sim \rho_c v_i^3 \sim \ae T^{7/2}/R$$

optimal state: $q \sim \rho_c v_i^3 >> \ae T^{7/2}/R.$

1. $R_c \approx R_T \approx R_s$ 2. energy equation:

$$q = \left(\varepsilon_c + \frac{p_c}{\rho_c} + \frac{u_c^2}{2}\right)\rho_c u_c^2;\ \varepsilon_c = \frac{p_c}{(\gamma-1)\rho_c},\ u_c = C.$$

corona scaling:

- sound velocity: $C = \left[\frac{2(\gamma-1)}{3\gamma-1}\cdot\frac{q}{\rho_c}\right]^{1/3} \simeq 4\cdot 10^7 q^{1/3} \lambda^{2/3},\ cm/s$

- ablative pressure:

$$P_a \simeq 2\rho_c C^2 = 2\left[\frac{2(\gamma-1)}{3\gamma-1}\cdot\frac{q}{\rho_c}\right]^{2/3}\rho_c \simeq 21 q^{2/3}\lambda^{-2/3},\ Mbar$$

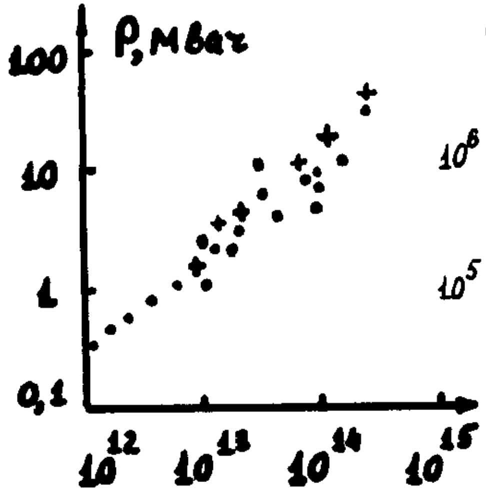
$q = 10^{14}\ W/cm^2$:

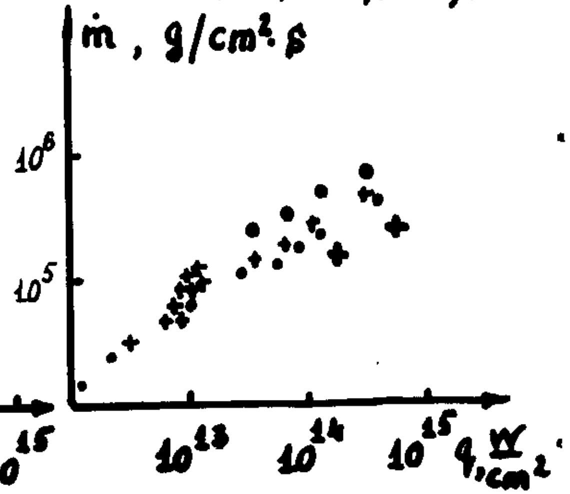
$\lambda = 1\,\mu m \rightarrow 20\ Mbar$; $\lambda = 0{,}25\,\mu m \rightarrow 50\ Mbar$

- rate of mass evaporating:

$$\dot{m} = \rho_c C \simeq 1{,}5\cdot 10^5 q^{1/3}\lambda^{-4/3},\ g/cm^2 s$$

EXPERIMENT: Plasma Phys and contr. Fusion v28, N1A, P157, 1986





- • NRL; 1,06 μm
- • ILE, OSAKA ; 1,06 μ
- + Rutherf. Lab; 0,53 μm
- + MPQ ; 1,3 μm

- • KMS ; 1,06 μ
- • NRL ; 1,06 μm
- • LLE, Rochester; 1,06 μ
- + Rutherf. Lab; 0,53 μm

SHELL ACCELARATION:

moution equation: $M\frac{du}{dt} = 4\pi R^2 P_a$

shell mass equation: $\frac{dM}{dt} = -4\pi R^2 \rho_c C$

$$\left.\begin{aligned} P_a &= 2\rho_c C^2 = 2\left[\frac{2(\gamma-1)}{3\gamma-1}\right]^{2/3} q^{2/3}\rho_c^{1/3} \\ C &= \left[\frac{2(\gamma-1)}{3\gamma-1}\right]^{1/3}\left(\frac{q}{\rho_c}\right)^{1/3}\end{aligned}\right\}\ \text{from scaling of steady-state corona.}$$

ρ_c - critical density.

Scaling lows of shell acceleration:

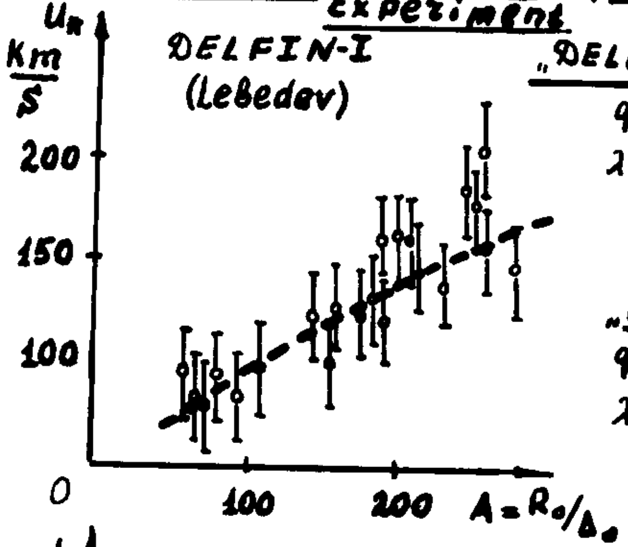
E=const:

$$u_* \simeq 2\left(\frac{2}{3}\right)^{1/3}\alpha^{1/2}c \quad , \quad \mu_* \equiv \frac{M_*}{M} \simeq \left(1-\frac{\alpha^{1/2}}{3}\right)^2$$

$$\eta \simeq \frac{4}{3}\left[\frac{2(\gamma-1)}{3\gamma-1}\right]\alpha^{1/2}\left(1-\frac{\alpha^{1/2}}{3}\right)^2, \quad \alpha = \frac{R_0}{\Delta_0}\cdot\frac{\rho_c}{\rho_{s0}} \sim A\lambda^{-2}$$

$$u_* \sim \left(\frac{R_0}{\Delta_0}\right)^{1/2} q^{1/3}\lambda^{-1/3} \qquad \eta \sim \left(\frac{R_0}{\Delta_0}\right)^{1/2}\lambda^{-1}$$

Experiment



"DELFIN", "Omega" (LLE):

$q \simeq 10^{14}$ W/cm²

$\lambda = 1{,}06$ μm, $A = 200$-300

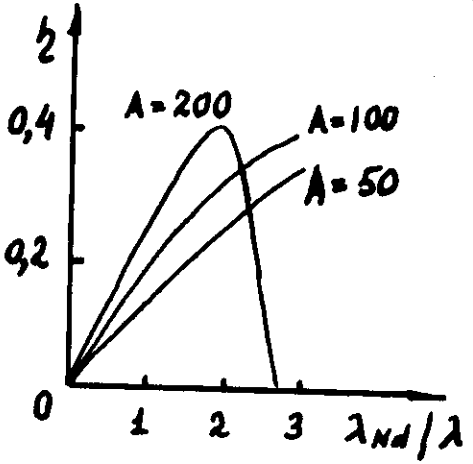
$u = 200$-300 km/s

"Gekko 12" (ILT):

$q = (4{,}6-7{,}9)\cdot 10^{14}$ W/cm²

$\lambda = 0{,}53$ μm, $A = 200$-400

$u = 500$-1000 $\frac{km}{s}$!



"DELFIN-I" (Lebedev)

$\eta \sim 10\%$!

"Gekko 12" (ILT)

$\eta \sim 6$-8%

ACCORDANCE OF THE TARGET AND LASER PULSE PARAMETERS.

Trudy of Lebedev Phys. Inst. 1985, N149, P.60

accordance low: $t_* = t_L$

$$t_* = R_0/u_* \quad , \quad u_* \simeq 2\left(\frac{2}{3}\right)^{1/3}\alpha^{1/2}c$$

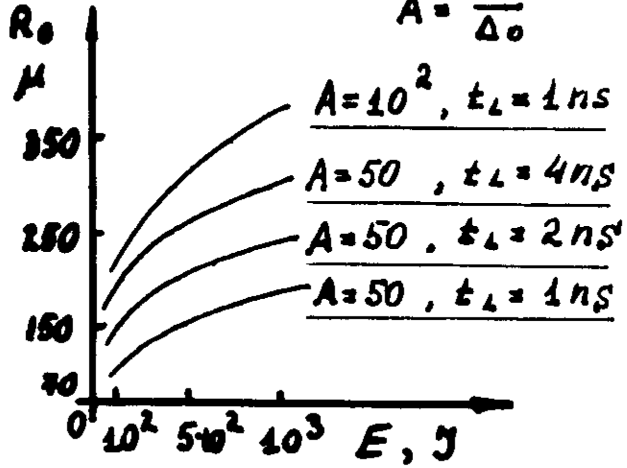
$$\alpha = \frac{R_0}{\Delta_0}\cdot\frac{\rho_c}{\rho_{s0}} \quad , \quad c = \left[\frac{2(\gamma-1)}{3\gamma-1}\right]^{1/3}\left(\frac{q}{\rho_c}\right)^{1/3}$$

relation between target and laser parameters:

$$R_0 = \left\{\left(\frac{2}{\pi_i 4}\right)^{1/3}\cdot 2\left(\frac{2}{3}\right)^{1/3}\left[\frac{2(\gamma-1)}{3\gamma-1}\right]^{1/3}\right\}^{3/5}\left(\frac{\rho_c}{\rho_{s0}}\right)^{1/10}\rho_{s0}^{-1/5}\left(\frac{R_0}{\Delta_0}\right)^{3/10} t_L^{2/5} E^{1/5}$$

$E = \dot{E} t_L$

$A = \frac{R_0}{\Delta_0}$



SHELL TARGET COMPRESSION.

$$\rho_* = \left[\frac{(\gamma-1)}{2}\cdot\frac{\eta E_a}{\sigma_v}\,\beta\,\mu_*\,\frac{M_s}{M}\right]^{1/(\gamma-1)}$$

$$\sigma_v = P_v/\rho_v^{\gamma},\quad P_v = \frac{2}{(\gamma+1)}\rho_0 D^2,\quad \rho_v = \left(\frac{\gamma+1}{\gamma-1}\right)\rho_0$$

Gas target $\rightarrow D \sim u_* \rightarrow P_v \sim u_*^2$

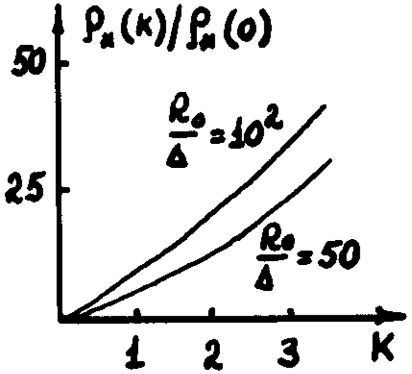
Cryogenic target $\rightarrow D \sim \left(\frac{\Delta}{R_0}\right)^{1/2} u_* \rightarrow P_v \sim \left(\frac{\Delta}{R_0}\right) u_*^2$

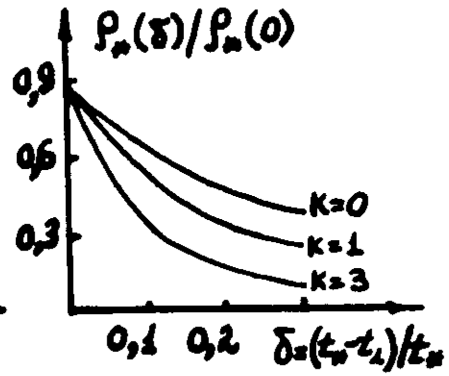
$$\frac{\delta_c}{\delta_g} \sim \frac{\Delta}{R_0} \longrightarrow \frac{\delta_c}{\delta_g} \sim \left(\frac{R_0}{\Delta}\right)^{1/(\gamma-1)}$$

Trudy of Lebedev Inst. 1985, N149, P.60.

Power profiling of laser pulse.

$$\dot{E}_L(t) \sim \left(t/t_L\right)^k \rightarrow \rho_*(k)/\rho_*(0) \sim \left(\frac{R_0}{\Delta}\right)^{\frac{2k+3}{(\gamma-1)(k+3)}}$$





$\frac{M_s}{M} = 5$: $\quad \frac{\rho_*}{\rho_0} = 4\cdot 10^3$

$k=0 \rightarrow \frac{R_0}{\Delta} = 180$

$k=2 \rightarrow \frac{R_0}{\Delta} = 40$!

$k=4 \rightarrow \frac{R_0}{\Delta} = 20$!

Kvantovaya Electronika 1985, V.12, N2, P.410.

STABILITY OF DIRECT SHELL TARGET COMPRESSION.

Saturation processes for hydrodynamic unstability:

- heat conductivity smoothing,
- convective carring out of the perturbations from hydrodynamic unstability region.

$$\gamma < \sqrt{kg}$$

Theory, numerical calculations (Lebedev, Rutherford lab., NRL (USA)):

$$\frac{\gamma}{\sqrt{kg}} \simeq \begin{cases} 0,2\div 0,3 & \text{for } \lambda = 1\,\mu m \\ 0,3\div 0,4 & \text{for } \lambda = 0,5\,\mu m \\ 0,4\div 0,5 & \text{for } \lambda = 0,25\,\mu m \end{cases}$$

Experiment (Rutherford lab):

$$\frac{\gamma}{\sqrt{kg}} \simeq 0,3\div 0,4 \quad \text{for } \lambda = 1,06\,\mu m.$$

Requirements for compression stability:

- shell unhomogenety – $a \lesssim 1\%$
- irradiation unhomogenety – $\Omega \lesssim 3\%$

$\left.\right\} \frac{R}{\Delta} = 10^2$

Better experimental results for Ω:

$\Omega \sim 1\%$ – „Omega", LLE, Rochester Univ. USA.
24 beams, $\lambda = 0,351\,\mu m$, 80 J/B.

LA[illegible]ER. RESULTS, PROGNO[illegible] LEMS.

Experimental results:

- absorption → $K_a > 50\%$
- acceleration → $v = 200-400$ km/s, $\eta \sim 10\%$
- compression → $\rho_* \sim 10-30\ g/cm^3$, $N \sim 10^{13}$, $n\tau T \sim 10^{14}$ } NOVA

Problems:

- Hydrodynamic stability of the thin shell target compression with $\frac{R_0}{\Delta_0} \geq 10^2$. Symmetry $- \Omega \leq 3\%$.
- Parametric processes for target of reactor scale ($L/\lambda >> 1$). Stimulated scattering, superthermal electrons.

Prognosis:

$E = 10\ kJ,\ M = 10^{-5}-10^{-4}\,g \rightarrow E = 1\ MJ,\ M = 10^{-3}-10^{-2}\,g$

reactor scale:

$$\left.\begin{array}{l} K_a \sim 70\% - 75\% \\ \eta \sim 12\% - 18\% \\ \rho_* \sim 200-600\ g/cm^3 \end{array}\right\} \lambda = 1{,}06 - 0{,}27\ \mu m$$

Gain: 1μ: $E_L \sim 1MJ \rightarrow 30$, $E_L \sim 10MJ \rightarrow 150$

$0{,}[illegible]\mu$: $E_L \sim 1MJ \rightarrow 100$, $E_L \sim 10MJ \rightarrow 400$

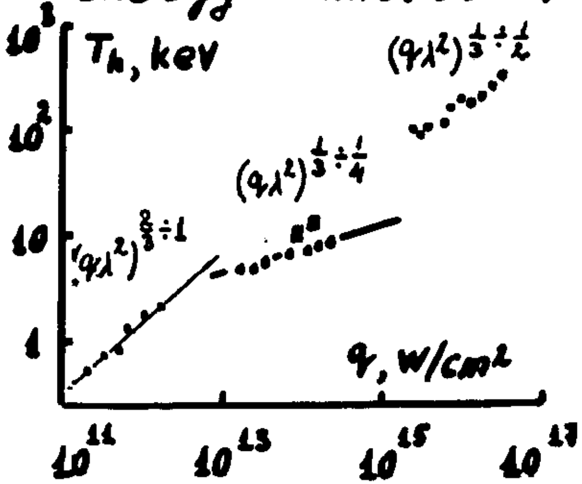
DIRECT COMPRESSION. LONG-WAVE [illegible]-LA[illegible]

1. Resonance absorption of laser energy. Absorption efficiency:

   25-30% at $q \simeq 10^{13} - 10^{14}\ W/cm^2$

2. Absorption laser energy is transformed to the hot electrons energy. Efficiency transformation ~ 90%

3. Efficiency of the accelaration and compression of the target under CO_2-laser are determined by energy transfer of hot electrons.



$q = 10^{13} - 5 \cdot 10^{13}\ W/cm^2$

$T_h = 10-12$ keV

$$\ell \simeq 2 \cdot 10^{-6} \frac{E_h^2}{(Z+3)^{1/2} \rho},\ cm$$

$E_h = (4-5)\,T_h$

$\ell = 30-70\ \mu m$

Scaling:

$$M = 4\pi R_0^2 \Delta_0 \rho_0 = 4\pi \left(\frac{R_0}{\Delta_0}\right)^2 \Delta_0^3 \rho_0 \sim E \rightarrow \Delta_0 \sim E^{1/3}$$

$1\,KJ$: $M = 10^{-6} - 10^{-5}\,g$; $A = 10^2$, $\rho_0 = 1\,g/cm^3 \rightarrow \Delta_0 \simeq (2 \div 6)\,\mu m$

$1\,MJ$: $M = 10^{-3} - 10^{-2}\,g$; $A = 10^2$, $\rho_0 = 1\,g/cm^3 \rightarrow \Delta_0 = 30-80\,\mu$

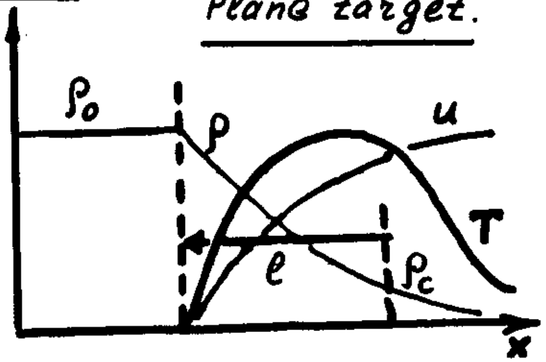
CORONA [illegible] MELL A

- $E \lesssim (3\text{-}4)T_h$ - corona transfer, $E \gtrsim (3\text{-}4)T_h$ - preheating core
- energy transfer by hot electrons leades to homogeneous distribution of the absorbed laser energy on corona mass determed by path length of the hot electrons. (scattering, spherical corona)

Trudy of Lebedev Physical Inst., 1986, N170, p.113.

ablative pressure; hydrodynamic efficiency:

Plane target.



$$l \sim \frac{T_h^2}{\rho_0}$$

$$m_c = \lambda \rho_0 \sim T_h^2$$

simple scalling:

$$T \sim \dot{E}t/m_c, \quad u \sim T^{1/2} \rightarrow \Delta x \sim T^{1/2} t$$

$$\rho \simeq m_c/\Delta x \rightarrow \rho \simeq m_c/T^{1/2}t = m_c^{3/2} \dot{E}^{-1/2} t^{-3/2}$$

$$P_a \sim T\rho \rightarrow P_a \sim \dot{E}^{1/2} m_c^{1/2} t^{-1/2}$$

accuracy solution: $P_a = \left[\frac{3(\gamma-1)}{\pi(3\gamma-1)}\right]^{1/2} \frac{\dot{E}^{1/2} m_c^{1/2}}{t^{1/2}}$

For $T_h \sim (\dot{E}\lambda^2)^{1/3}$: $P_a \sim \dot{E}^{0,83} \lambda^{0,66} t^{-0,5}$

Numerical results of ILT (OSAKA):

$$P_a \sim \dot{E}^{0,84} \lambda^{0,56} t^{-0,33}$$

$q \sim 10^{14}\ W/cm^2$, $\lambda = 10,6\mu$, $t \sim 1\,ns$:

$$P_a \sim 10\text{-}12\ \text{MBar}$$

hydrodynamic efficiency:

$$\eta \equiv \frac{mv^2}{2\dot{E}t} = \frac{6}{\pi}\left(\frac{\gamma-1}{3\gamma-1}\right) \cdot \frac{m_c}{m_0 - m_c}, \quad m_c + m = m_0$$

$$\frac{m_c}{m_0} = \frac{1}{4} \rightarrow \eta = 11\% \qquad \frac{m_c}{m_0} = \frac{1}{3} \rightarrow \eta = 14\%$$

SPHERICAL STEADY-STATE CORONA.

Hot electrons energy transfer.

1. $R_J \simeq R_h \simeq R_s$
2. energy equation: $q \cdot \chi(\lambda, \rho_J) = \left(\varepsilon_J + \frac{P_J}{\rho_J} + \frac{u_J^2}{2}\right)\rho_J u_J^2$

χ - energy flux tranfered to Jouguet point by hot electrons.

$\chi \simeq 0,3 - 0,6.$

corona scaling:

- sound velocity: $c = \left[\frac{2(\gamma-1)}{3\gamma-1} \frac{q\chi}{\rho_J}\right]^{1/3}$
- density in Jouguet point: $\rho_J \simeq \rho_c + \rho_0 \frac{l(\rho_0)}{R_0}$

$$l \simeq 2 \cdot 10^{-6} E_h^2/(z+3)^{1/2}\rho_0, \ cm.$$

for $\frac{R_0}{\Delta_0} = 10^2$, $\frac{l}{\Delta_0} = \frac{1}{2}$, $\rho_0 = 1\ g/cm^3$

CO_2-laser, $\rho_c \simeq 3,3 \cdot 10^{-5}\ g/cm^3$

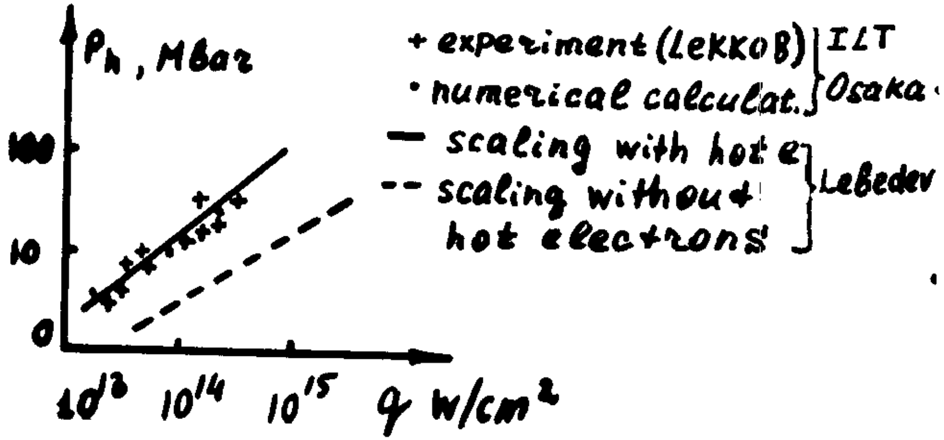
$\rho_J \simeq 5 \cdot 10^{-3}\ g/cm^3 \sim \rho_c$ (Nd-laser)

-ablative pressure: $P_h \simeq 2\rho_J u_J$

$$P_h \simeq \chi^{2/3}\left(\frac{\rho_J}{\rho_c}\right)^{1/3} P_a$$

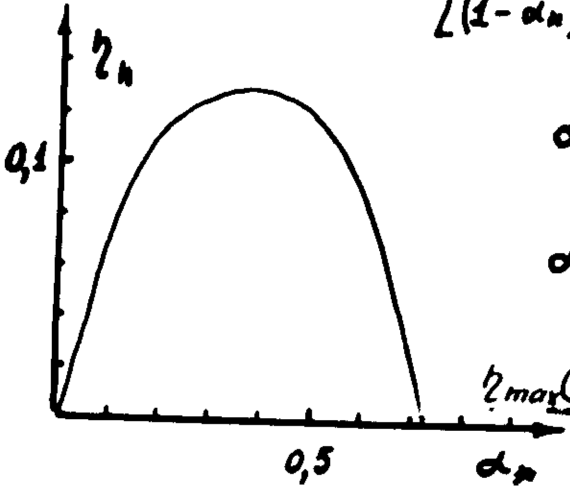
$$P_a \simeq 2\left[\frac{2(\gamma-1)}{3\gamma-1}\right]^{2/3} q^{2/3}\rho_c^{1/3}, \text{ for } CO_2\text{-laser:}$$

$$P_a \simeq 4{,}5 \cdot q^{2/3}, \text{ MBar}$$



-hydrodynamic efficiency: $\eta = \dfrac{M v^2}{2 \cdot E}$

$$\eta_h = \sqrt{6}\cdot\chi\left[\frac{2(\gamma-1)}{3\gamma-1}\right]\frac{\alpha_*^{1/2}\left[(1-\alpha_*)^{1/2}-\left(\frac{3}{8}\alpha_*\right)^{1/2}\right]^2}{\left[(1-\alpha_*)^{1/2}-\left(\frac{3}{32}\alpha_*\right)^{1/2}\right]^3}$$



$$\alpha_* = \frac{\rho_J}{\rho_0}\cdot\frac{R_0}{\Delta_0}$$

$$\alpha_* = \frac{\ell}{\Delta_0}$$

$\eta_{max}(CO_2) \simeq 12\%$, $\alpha_* = 0{,}4$

COMPRESSION UNDER LONGWAVE RADIATION: HOT ELECTRONS PREHEATING.

Problems of Atomic Science and Engineering, ser. „Thermonuclear fusion", 1986, v.1, p.25

Preheating by only part of the hot electrons spectrum:

$$(3-4)\,T_h \leq E_h \leq E_* \sim (6-8)\,T_h$$

$E_h \leq (3-4)\,T_h$ - absorption in the corona.

$E_h \geq (6-8)\,T_h$ - Low efficiency of the.

Hot electrons transfer is absent if transfer time > collapse time - $t_d > t_c$

Coulomb transfer time:

$$t_d = \frac{4}{3}\frac{\ell}{v_h} \simeq 1{,}4\cdot 10^{-16}\cdot\frac{E_h^{3/2}}{(z+3)^{1/2}\rho}, \text{ s}$$

$$\rho_{eff} \sim \frac{\rho_0\Delta_0}{R_p}, \quad R_p \simeq \frac{2}{(\gamma-1)}\cdot c\cdot t_c$$

Condition of low efficiency transfer:

$$t_d \simeq \frac{4{,}2\cdot 10^{-15}E_h^{3/2}c}{\rho_0\Delta_0(z+3)^{1/2}}\,t_c > t_c$$

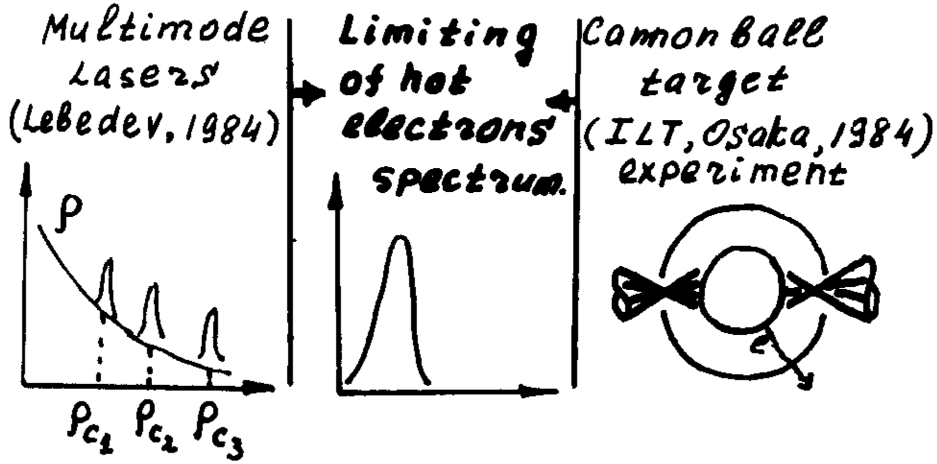
$$E_* \simeq 4\cdot 10^{9}\left[(z+3)^{1/2}\rho_0\Delta_0/c\right]^{2/3}$$

FOR $q \simeq 10^{13}-10^{14}$ W/cm², $\lambda = 10{,}6\,\mu$:

$T_h \simeq 10-15$ keV, $E_* \simeq 100-120$ keV

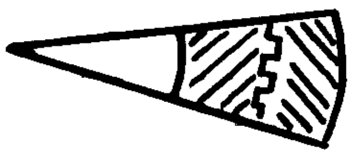
ISOLATION OF TARGET CORE FROM HOT ELECTRONS PREHEATING.

- controlling of the hot electrons spectrum.



- magnetic isolation (Lebedev, 1983-1984)

1. Spontenuos magnetic fields.



T_h = 50 - 100 keV

B = 0,1 - 1 MGs.

2. External magnetic fields.

$B \sim 10^4 - 10^5$ Gs.

DIRECT COMPRESSION. CO_2-LASER. Experimental results, problems, prognosis.

Experiments, CO_2-laser.

- Helios, LANL (USA), 1983:
  $E_L \simeq 3$ kJ, $t_L \simeq 1$ ns, 8 beams: $K_a \sim 20\%$
  $\rho \sim 0{,}4 - 2$ g/cm^3, $\eta \sim 3\%$, $N \sim 10^{10} - 10^{11}$.
- Lekko 8, ILT, OSAKA, 1984:
  $\eta \sim 6\%$, spectrum limiting, $K_a \sim 40\%$

Problems.

- Hot electrons preheating
- absorbed energy transformation into energy of fast ions.

Prognosis.

$E_L \gtrsim 1$ MJ: $K_a \sim 25-30\%$, $\eta \sim 10\%$,
$\rho \sim 100-200$ g/cm^3

Breakeven - 0,5-1 MJ (Lebedev, ILT- 1982-1984)

$K_{th} \sim 50-70$ - 10 MJ (Lebedev, 1984)

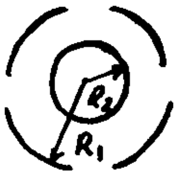
Proc. of 10-th Intern. conf. on plasma physics and controlled fusion research, London, 1984

UNDIRECT, RADIATIVE COMPRESSION.

- transformation of absorbed energy to x-ray: LLNL, UCRL-94382, PREPRINT, oct. 1986.

$q\sim10^{14}\to K_x = 85-50\%$ for $\lambda=0{,}27-1\,\mu m$ (LLNL)

- x-ray absorption:



$K_2+K_1\approx 1$, $\frac{K_2}{K_1}\sim\left(\frac{R_2}{R_1}\right)^2$

$K_2\sim\left(1+\frac{R_1}{R_2}\right)^{-1}$

for $\frac{R_1}{R_2}\sim2$, $K_2\sim0{,}2$; $\frac{R_1}{R_2}\sim3$, $K_2\sim0{,}1\to K_x=0{,}1-0{,}2$

- hydrodynamic efficiency: $\eta_x\sim\eta_{\lambda<1\mu m}$

$\eta_x\sim 20\%$.

Results: $R_0/R_f\approx30$, $V_0/V_f\approx3\cdot10^4$, corresponds 1-D calculations „NOVA" (LLNL, USA). Report on the 19-th ECLIM conf, Prague, May 1987.

ENERGY BALANCE FOR DIFFERENT WAYS

DIRECT: $\beta\equiv\frac{E_p}{E_L}=K_a\cdot\eta$ $\begin{cases}\lambda=0{,}25\,\mu m\to\beta=0{,}8\cdot0{,}12=0{,}1\\ \lambda=10{,}6\,\mu m\to\beta=0{,}25\cdot0{,}08=0{,}02\end{cases}$

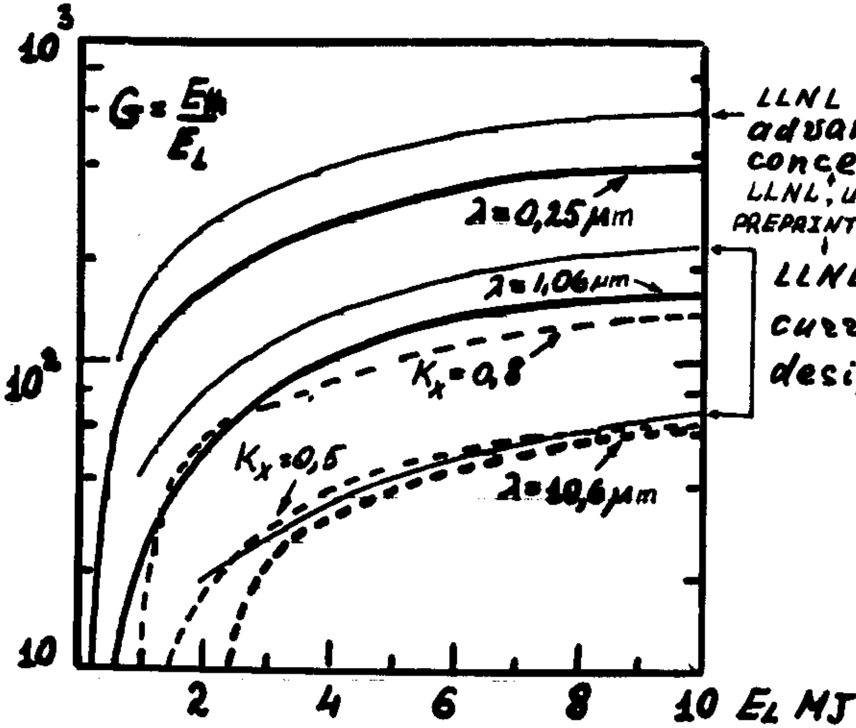
UNDIRECT: $\beta\equiv K_a\cdot K_x K_t\cdot\eta\to\beta=0{,}8\cdot\underline{0{,}8}\cdot0{,}3\cdot0{,}2\approx0{,}04$

$\beta=0{,}8\cdot\underline{0{,}5}\cdot0{,}3\cdot0{,}2\approx0{,}02$

comparision of thermonuclear gains

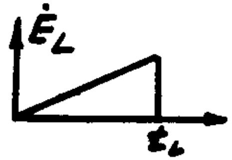
$G\equiv\frac{E_{th}}{E_L}\sim\beta\to\frac{G_{0,25}}{G_x}\sim2\div5$, $\frac{G_{0,25}}{G_{10,6}}\sim5\div6$, $\frac{K_x}{K_{10,6}}\sim1\div3$

THERMONUCLEAR GAIN.



——— Lebedev-IAM, direct compression, shortwave lasers, $\lambda\leq1\,\mu m$.

- - - - Lebedev-IAM, direct compression, Isolation from hot electrons with energy $E>4T_h$. CO_2-laser.



Kvantovaya Electronika, 1985 V.12, N6, P.1289.

- - - - LLNL; undirect, x-ray compression

LLNL, UCRL-94382 PREPRINT, oct. 1986. → $K_x=E_x/E_a$ - efficiency of transformation of absorbed laser energy to the x-ray energy.