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SPRING COLLEGE ON PLASMA PHYSICS

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KINETIC PROCESSES FOR HIGH ENERGY PARTICLES IN MAGNETIC ACTIVE LASER PRODUCED PLASMA

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KINETIC PROCESSES FOR HIGH ENERGY PARTICLES IN MAGNETIC ACTIVE LASER PRODUCED PLASMA.

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ASPECTS:

1. INFLUENCE EXTERNAL AND INSIDE (SPONTENEOUS FROM HYDRODYNAMIC INSTABILITES) MAGNETIC FIELDS ON THE TRANSPORT PROCESSES OF THERMONUCLEAR PARTICLES - INCREASING ENERGY DEPOSITED BY α-PARTICLES IN IGNITION REGION OF PLASMA.

2. INFLUENCE EXTERNAL AND INSIDE MAGNETIC FIELDS ON THE TRANSPORT PROCESSES OF HOT ELECTRONS - DECREASING ENERGY TRANSFERED BY HOT ELECTRONS TO COMPRESSED PART OF LASER TARGET.

I. ENERGY TRANSFER BY α-PARTICLES IN LASER-PRODUCED PLASMA IS PLACED IN EXTERNAL MAGNETIC FIELD.

SCALE OF REQUIRED FIELD:

$$\underline{R_L \sim R_f}$$

$$R_L = \frac{v_\alpha \cdot m_\alpha \cdot c}{e_\alpha \cdot B} \text{ - LARMOR RADIUS}$$

$R_f \sim 50-100\,\mu$ - RADIUS OF IGNITION REGION OF PLASMA.

$$\underline{B \simeq \frac{2{,}6 \cdot 10^5}{R_f(cm)}, G}$$

EFFECT OF „FREEZING" OF MAGNETIC LINES:

$$\underline{B = B_0 \left(\frac{R_0}{R_f}\right)^2}$$

$$\underline{B_0 \simeq \frac{2{,}6 \cdot 10^5}{R_0} \cdot \left(\frac{R_f}{R_0}\right), G.}$$

TARGETS FOR IGNITION:

$R_0 = 10^{-1} \div 5 \cdot 10^{-1}\, cm$, $\frac{R_0}{R_f} \simeq 20 \div 10^2$

$\underline{B_0 \simeq 5 \div 50\, kG.}$

$\underline{B \simeq 5 \div 50\, MG.}$

KINETIC EQUATION:

$$\frac{\partial f}{\partial t} + \vec{V}_\alpha \vec{\nabla}_r f = R_\alpha + \sum_k C_{k\alpha} - \frac{e_\alpha}{m_\alpha \cdot c}[\vec{V}_\alpha \times \vec{B}]\vec{\nabla}_v f$$

APPROXIMATIONS:

1. STATIONARY RROUCESS: $\frac{\partial f}{\partial t} \to 0$.

2. SPHERICAL SYMMETRY.

3. $R_\alpha = \dot{n}_\alpha \delta(v - v_0)$ - SOURCE OF α-PARTICLES

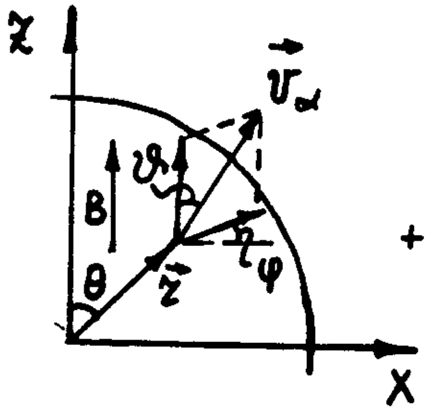
$\dot{n}_\alpha = \frac{n^2 (\overline{\sigma v})_{DT}}{4}$, ISOTROPIC

4. COULOMB COLLISIONS WITH ELECTRONS OF PLASMA:

$$C_{k\alpha} = -\frac{\partial f_\alpha a_{\alpha e}}{\partial v_\alpha}, \quad a_{\alpha e} = -\frac{8\sqrt{\pi}\,\Lambda_{\alpha e}(e_\alpha e)^2 \cdot m_e^{1/2} n_e \cdot v_\alpha}{3 T_e^{3/2} m_\alpha}$$

$a_{\alpha e} = \frac{dv_\alpha}{dt}$ - RATE OF SLOWING DOWN OF α-PARTICLES.

5. SCATTERING OF α-PARTICLES ON PLASMA IONS IS NOT ACOUNT.



$$(\sin\theta\cdot\sin\vartheta\cdot\cos\varphi+\cos\theta\cdot\cos\vartheta)\frac{\partial}{\partial y}F+$$
$$+(\cos\theta\cdot\sin\vartheta\cdot\cos\varphi-\sin\theta\cdot\cos\vartheta)\cdot\frac{1}{y}\frac{\partial}{\partial\theta}F-$$
$$-\frac{1}{\xi}\cdot\frac{\omega_B}{\omega}\cdot\frac{\partial}{\partial\varphi}F=\dot{n}_\alpha\delta(1-\xi)$$

$F(\xi,y,\theta,\vartheta,\varphi)=f\cdot\omega v_{\alpha 0}\xi$;

$\omega=\dfrac{|a_{\alpha e}|}{v_\alpha}$ - FREQUENCY OF COULOMB COLLISIONS ON PLASMA ELECTRONS;

$\xi=\dfrac{v}{v_{\alpha 0}}$, $v_{\alpha 0}\simeq 1{,}3\cdot 10^9$ cm/s ;

$y=\dfrac{r}{\lambda_0}$, $\lambda_0\simeq\dfrac{2{,}6\cdot 10^{21}\,T_e^{3/2}}{n_e}$ - LENGTH OF THE α-PARTICLES SLOWING DOWN.

$\omega_B=\dfrac{e_\alpha\cdot B}{m_\alpha\cdot c}$ - LARMOR FREQUENCY.

BOUNDARY CONDITIONS:

1. $F\Big|_{\xi=1\,(v_\alpha=v_{\alpha 0})}=\dot{n}_\alpha(r)$

2. $F\Big|_{\substack{y=\varepsilon\,(r=R)\\ \xi_r<0}}=0$; $\dfrac{\partial F}{\partial\theta}\Big|_{\substack{y=0\\(r=0)}}=0$; $\dfrac{\partial F}{\partial\varphi}\Big|_{\substack{\theta=0\\ \theta=\pi}}=0$

$$\xi_r\equiv\frac{v_r}{v_0}=\sin\theta\cdot\sin\vartheta\cdot\cos\varphi+\cos\theta\cdot\cos\vartheta$$

CHARACTERISTIC OF KINETIC EQUATION

$$S = \frac{1}{\lambda_0}\left(\lambda_\parallel^2 + \lambda_\perp^2 - 2r\lambda_\perp \sin\theta - 2r\lambda_\parallel \cos\theta + r^2\right)^{1/2}$$

$\lambda_0 = v_0/\omega$

$\lambda_\parallel = \lambda_0\left(1 - \frac{v}{v_0}\right)\cos\vartheta$ - LENGTH OF SLOWING DOWN IN DIMENTION, WHICH IS PARALLEL TO $\vec{B}$

$$\lambda_\perp = \lambda_0 \cdot \frac{\omega \sin\vartheta}{\omega_B^2 + \omega^2}\left[\omega \cos\left(\varphi - \frac{\omega_B}{\omega} \ln \frac{v}{v_0}\right) + \right.$$

$$\left. + \omega_B \cdot \sin\left(\varphi - \frac{\omega_B}{\omega} \ln \frac{v}{v_0}\right) - \left(\omega \cos\varphi + \omega_B \sin\varphi\right)\right] -$$

LENGTH OF SLOWING DOWN IN THE DIMENTION, WHICH IS PERPENDICULAR TO MAGNETIC FIELD $\vec{B}$.

EQUATION : $\frac{\partial F}{\partial S} = 0$!

SOLUTION $F\Big|_{S=const} = const$ - MAY BE USED FOR NUMERICAL METHODS, IN PARTICULAR, FOR MONTE-CARLO METHOD.

APPROXIMATE ANALITICAL SOLUTION ON BASED ASIMTOTIC ANALISSES FOR TWO CASES:

1. $B = 0$, 2. $B \Rightarrow \infty$

1. $B=0$.

$$S \to S_0 = \lambda_0^{-1}\left[\lambda^2 - 2r\lambda\cos(\vartheta-\theta) + r^2\right]^{1/2}$$

$$\frac{E}{E_0} = \begin{cases} \frac{3}{2}\tau - \frac{4}{5}\tau, & IF\ \tau = \frac{R}{\lambda_0} \leq \frac{1}{2} \\ 1 - \frac{1}{4\tau} + \frac{1}{160\tau^3}, & IF\ \tau \geq \frac{1}{2} \end{cases}$$

FRACTION O[F] α-PARTICLES ENERGY DEPOSITE[D] IN PLASMA

(Gus'kov S.Yu., Krokhin O.N., Rozanov V.B. Quantum ELECTRONICS, 1975, N2, p. 2315.)

2. $B \Rightarrow \infty$ $(\omega/\omega_B \to 0)$.

$$S \to S_\infty = \lambda_0^{-1}\left(r^2 - 2r\lambda\mu_2\cdot\mu_1 + \lambda^2\mu_2^2\right)^{1/2}$$

$\mu_1 = \cos\theta$, $\mu_2 = \cos\vartheta$

METHOD OF CHARACTERITICS:

$$f = \begin{cases} \frac{n_\alpha(S_\infty)}{|a_\alpha|}, & IF\ \lambda\mu_2 \leq R - r, -1 \leq \mu_1 \leq 1. \\ \frac{n_\alpha(S_\infty)}{|a_\alpha|}, & IF\ R - r \leq \lambda\mu_2 \leq R + r, -\mu_1^* \leq \mu_1 \leq 1 \\ 0, & IF\ R - r \leq \lambda\mu_2 \leq R + r, -1 \leq \mu_1 \leq -\mu_1^* \\ 0, & IF\ \lambda\mu_2 \geq R + r, -1 \leq \mu \leq 1 \end{cases}$$

$$\mu_1^* = \left(R^2 - r^2 - \lambda^2\mu_2^2\right)/2r\lambda\mu_2.$$

NUMBER OF α-PARTICLES, WHICH ARE TERMOLISED IN PLASMA:

$$N = \int_0^R n_\alpha(r)\, 4\pi r^2 dr - 4\pi R^2 \int_0^{v_0}\int_{-1}^{1}\int_{-1}^{1} f\Big|_{r=R} \cdot v\, dv\, \mu_1 d\mu_1\, \mu_2 d\mu_2$$

α-PARTICLES ENERGY, WHICH IS DEPOSITED IN PLASMA:

$$E = \frac{m_\alpha v_0^2}{2}\int_0^R n_\alpha(r)\cdot 4\pi r^2 dr - 4\pi R^2 \int_0^{v_0}\int_{-1}^{1}\int_{-1}^{1} f\Big|_{r=R} \cdot \frac{m_\alpha v^2}{2}\cdot v\,dv\cdot \mu_1 d\mu_1 \cdot \mu_2 d\mu_2$$

$n_\alpha = const \neq f(r)$

$$\frac{N}{N_0} = \begin{cases} \frac{3}{4}\tau, & \text{IF } \tau \le \frac{1}{2} \\ 1 - \frac{3}{8\tau} + \frac{1}{64\tau^3}, & \text{IF } \tau \ge \frac{1}{2} \end{cases}$$

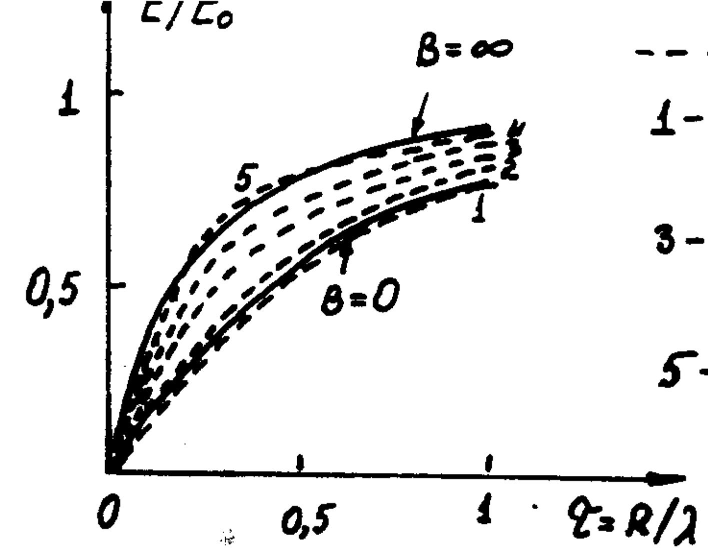
$$\frac{E}{E_0} = \begin{cases} \frac{9}{8}\tau + \frac{3}{2}\tau \cdot \ln\left(\frac{1}{2\tau}\right) + \frac{4}{5}\tau^2, & \tau \le \frac{1}{2} \\ 1 - \frac{1}{8\tau} + \frac{1}{640\tau^3}, & \tau \ge \frac{1}{2} \end{cases}$$

$$N_0 = \frac{4}{3}\pi R^3 n_\alpha, \quad E_0 = N_0 \cdot \frac{m_\alpha v_0^2}{2}.$$

$B=0$: $\tau < \frac{1}{2}\ (\lambda_0 > 2R) \rightarrow \frac{N}{N_0} = 0$

$B=\infty$: $\tau < \frac{1}{2}\ (\lambda_0 > 2R)$: $\frac{N}{N} > 0$

$B=\infty$: $\begin{cases} \frac{N}{N_0} \neq 1, \ \frac{N}{N_0} = f(\tau) < 1 \\ \frac{E}{E_0} \neq 1, \ \frac{E}{E_0} = f(\tau) < 1 \end{cases}$ | DRIFT OF α-PARTICLES TO THE DIMENTION OF THE MAGNETIC FIELD.



---- APPROXIMATION:

$1-\ \frac{\omega}{\omega_B}=0$, $2-\ \frac{\omega}{\omega_B}=\frac{1}{3}$,

$3-\ \frac{\omega}{\omega_B}=1$, $4-\ \frac{\omega}{\omega_B}=5$

$5-\ \frac{\omega}{\omega_B}=\infty$.

APPROXIMATION RESULT:

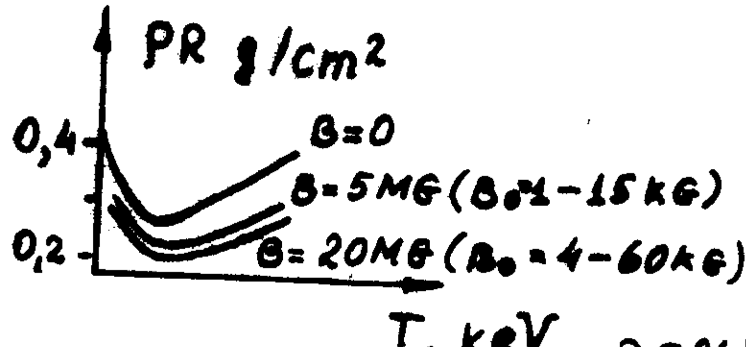
$$\frac{E}{E_0}=\begin{cases}\left[\frac{3}{2}+\frac{71}{40}\left(1+\frac{\omega}{\omega_B}\right)^{-1}\right]\tau-\left[\frac{4}{5}+\frac{27}{10}\left(1+\frac{\omega}{\omega_B}\right)^{-1}\right]\tau^2, & \tau\le\frac{1}{2}\\ 1-\left[\frac{9}{40}-\frac{17}{160}\left(1+\frac{\omega}{\omega_B}\right)^{-1}\right]\frac{1}{\tau}, & \tau\ge\frac{1}{2}.\end{cases}$$

INCREASING OF DEPOSETED ENERGY:

$B \doteq 5\,MG$ ($B_0 = 1\div 15\,kG$) $\frac{E}{E_0}\uparrow$ TO FACTOR 1,2

$B = 20\,MG$ ($B_0 = 4\div 60\,kG$) $\frac{E}{E_0}\uparrow$ TO FACTOR 1,4.

INFLUENCE ON BREAKEVEN' CONDITIONS



$$\frac{\dot W_\alpha\cdot\frac{E}{E_0}\cdot\frac{R}{v_S}}{C\cdot T}\equiv\frac{8{,}06\cdot10^4\langle\sigma v\rangle\rho R}{\left[3(\gamma-1)U_S^3T^3\right]^{1/2}}\cdot\frac{E}{E_0}>1$$

T=15 keV:

$\sim 25\%\begin{cases}B=5\,MG\ (B_0=1\div15\,kG):\ \rho R\gtrsim0{,}2\ldots\\ B=0:\ \rho R\gtrsim0{,}3\ g/cm^2\end{cases}$

$\sim 40\%\begin{cases}B=20\,MG\ (B_0=4\div60\,kG),\ \rho R\ge0{,}1\ldots\\ B=0:\ \rho R\ge0{,}3\ g/cm^2\end{cases}$

II. α-PARTICLES. SPONTENEOUS FIELD.

DECREASING BREAKEVEN' ρR-PARAMETER:

$$B=0,\ \rho R \simeq 0{,}3\,g/cm^2: \begin{cases} B \simeq 20\,MG,\ \rho R \simeq 0{,}2\,g/cm^2 \\ B \simeq 50\,MG,\ \rho R \simeq 0{,}16\,g/cm^2 \end{cases}$$

III. HOT ELECTRONS.

CONDITION OF LOW ENTROPY, EFFICIENT TARGET' COMPRESSION: PREHEATING TARGET BY HOT ELECTRONS MUST BE LESSER THEN PREHEATING BY SHOCK WAVE.

FOR TARGET COMPRESSION UNDER ACTION CO_2-LASER WITH INTENSITY 10^{13}-10^{14} W/cm^2 THIS CONDITION IS CARRIED OUT WHEN:

EXTERNAL MAGNETIC FIELD - $B = 1$-$10\,kG$

SPONTENEOUS MAGNTIC FIELD - $B = 10^2$-$10^3\,kG$.

CONCLUSION.

MAGNETIC FIELDS: EXTERNAL - 1-50 kG AND INSIDE, SPONTENEOUS - 1-20 MG, MAY BE ADDITIONAL STRONG FACTORS OF THE INCREASING OF EFFICIENCY OF THE LASER TARGET' COMPRESSION AND BURNING.

compression in ICF.

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1. Shell target's compression
2. Shell target's acceleration
3. Using laser pulse's profiling.

Shell target's acceleration.

Final shell's velocity:

$$u_c \simeq \left(\frac{R}{\Delta_s}\right)^{1/2}\left(\frac{\rho_{cr}}{\rho_s}\right)^{1/2}\left[\frac{2(\gamma-1)}{3\gamma-1}\cdot\frac{\dot{E}_{ab}}{4\pi R^2\rho_{cr}}\right]^{1/3}$$

$$u_c \simeq \left(\frac{R}{\Delta_s}\right)^{1/2}\cdot\rho_{cr}^{1/6}\cdot q_L^{1/3}$$

„DELFIN I" experiments:

$u_c = 100 \div 200$ Km/s, at $\frac{R}{\Delta_s} = 50 \div 200$, $\lambda \simeq 1\mu$

„OMEGA" experimets:

$u_c \simeq 300$ km/s, at $\frac{R}{\Delta_s} \simeq 200$, $q_L \simeq 10^{14}$ W/cm², $\lambda \simeq 0{,}35\mu$

„Gekko XII" experiments:

Record velocity – $u_c \simeq 500$ km/s

$\frac{R}{\Delta_s} \simeq 400$, $q \simeq 3\cdot10^{14}$ W/cm², $\lambda \simeq 0{,}52\mu$

A good agreement with a theoretical predictions.

2. Shell target compression.

$$\rho = \left[\frac{\gamma-1}{2} \cdot \frac{u_c^2}{\sigma} \left(1 + \mu_{ev} \cdot \frac{M_s}{M_f}\right) \beta \right]^{1/\gamma-1}$$

$\sigma = P_w / \rho_w^{\gamma}$ - entropy characteristic.

μ_{ev} - fracton of nonevaporated mass of the shell.

$\beta \approx 0{,}5 - 0{,}7$ - efficiency of the transformation of the shell kinetic energy to the internal plasma energy.

$$\sigma = \frac{\frac{2}{\gamma+1} \cdot \rho_0 u_w^2}{\left[\left(\frac{\gamma+1}{\gamma-1}\right)\rho_0\right]^{\gamma}}$$

$$\rho = \left(\frac{\gamma+1}{\gamma-1}\right)\rho_0 \left[\beta \cdot \mu_f \cdot \frac{M_s}{M_f}\right]^{3/2} \underline{\left(\frac{u_c}{u_w}\right)^3}$$

1. Gas-filled target: $u_c \simeq u_w$

$$\rho = \left(\frac{\gamma+1}{\gamma-1}\right)\rho_0 \left[\beta \cdot \mu_f \frac{M_s}{M_f}\right]^{3/2}$$

2. Criogenic target:

$\dot{E} = const$: $u \simeq u_c \left(1 - \frac{R}{R_0}\right)^{1/2}$ $u_w = u \Big|_{R = R_0 - \Delta_f} \rightarrow \underline{u_w \simeq u_c \left(\frac{\Delta_f}{R_0}\right)^{1/2}}$

$$\rho = \left(\frac{\gamma+1}{\gamma-1}\right)\rho_0 \left[\beta \cdot \mu_f \cdot \frac{M_s}{M_f}\right]^{3/2} \cdot \underline{\left(\frac{R}{\Delta_f}\right)^{3/2}}.$$

24-beams, $\lambda \simeq 0{,}35\mu$, $E_{Inc} \sim 10^3 J$, $E_{ab} \sim 800 J$.

targets:

$R_0 = 100 - 200\,\mu$, $\Delta_{SiO_2} = 5-7\mu$.

$\rho_{0DT} \sim 2\cdot 10^{-2}\, g/cm^3$ then colding into the criogenic layer with thikness:

$\Delta_f \simeq 3{,}3\cdot 10^{-2} R$

if gas-filled target: $\rho \approx 0{,}6\, g/cm^3$

Calculation for criogenic target

$\underline{\rho = 80\, g/cm^3}$

Experimental results: $\underline{\rho \approx 20 - 40\, g/cm^3}$

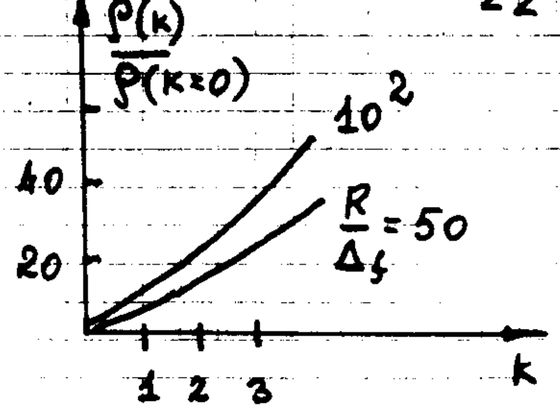
3. Profiling of laser pulse.

$$\dot{E}_L \sim \left(\frac{E_L}{t_L}\right)\cdot\left(\frac{t}{t_L}\right)^k$$

Solution of the shell motion equation

$$u \simeq u_c\left(\frac{t}{t_L}\right)^{\frac{2k+3}{3}}, \quad t_L = t_c$$

$$u_w \sim u_c\left(\frac{t}{t_L}\right)^{\frac{2k+3}{3}} \rightarrow \underline{\rho \sim \left(\frac{R_0}{\Delta_f}\right)^{\frac{2k+3}{(\gamma-1)(k+3)}}}$$



$$\left.\begin{array}{l}\frac{M_s}{M_f} = 5 \\ \delta \equiv \frac{\rho_f}{\rho_0} = 10^4\end{array}\right\} \begin{array}{l} \rightarrow \frac{R_0}{\Delta_s} \approx 180,\ k=0 \\ \rightarrow \underline{\frac{R_0}{\Delta_s} = 40,\ k=2} \\ \rightarrow \underline{\frac{R_0}{\Delta_s} = 20,\ k=4\,!} \end{array}$$