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Relativistic magneto-active laser plasmas

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Relativistic laser-produced plasma

$a \rangle 1 \qquad a = \frac{mv\gamma}{mc^2} = \frac{eA}{mc^2} = \frac{eE}{m\omega c} = 0{,}85\sqrt{\frac{J}{10^{18}}} \qquad J > 1{,}4 \times 10^{18}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$

Electron energy $\varepsilon \geq m_e c^2$

Unique medium – unique parameters

Ion temperature	T_i	**100 keV**
Pressure	P	**10^{11} bar**
Magnetic field	B	**10^9 Gs**
Electric field	E	**10^{12} V/cm**
Electron energy	ε_e	**350 MeV**
Proton energy	ε_p	**60 MeV**

Relativistic laser-produced plasma

Our base for experimental research

Laser unit

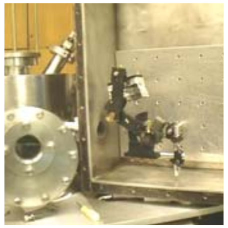
$J \geq 3\times10^{18}$ **W/cm^2**

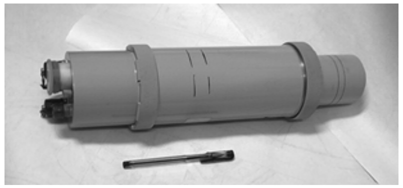
$\lambda = 1{,}06\ \mu m$

$\varepsilon_{pulse} = 10^{--}$ **J**

contrast > 10^{10}

Diagnostic complex





X-ray

- quartz crystal

Neutrons

- ^{3}He counters

- plastic scintillators

γ-radiation

- stylbene

- NaI(Tl)

- charged particles – p, α

- ion temperature T_i

- magnetic field B

- particle velosity V_i

Relativistic laser-produced plasma

Our base for theoretical research

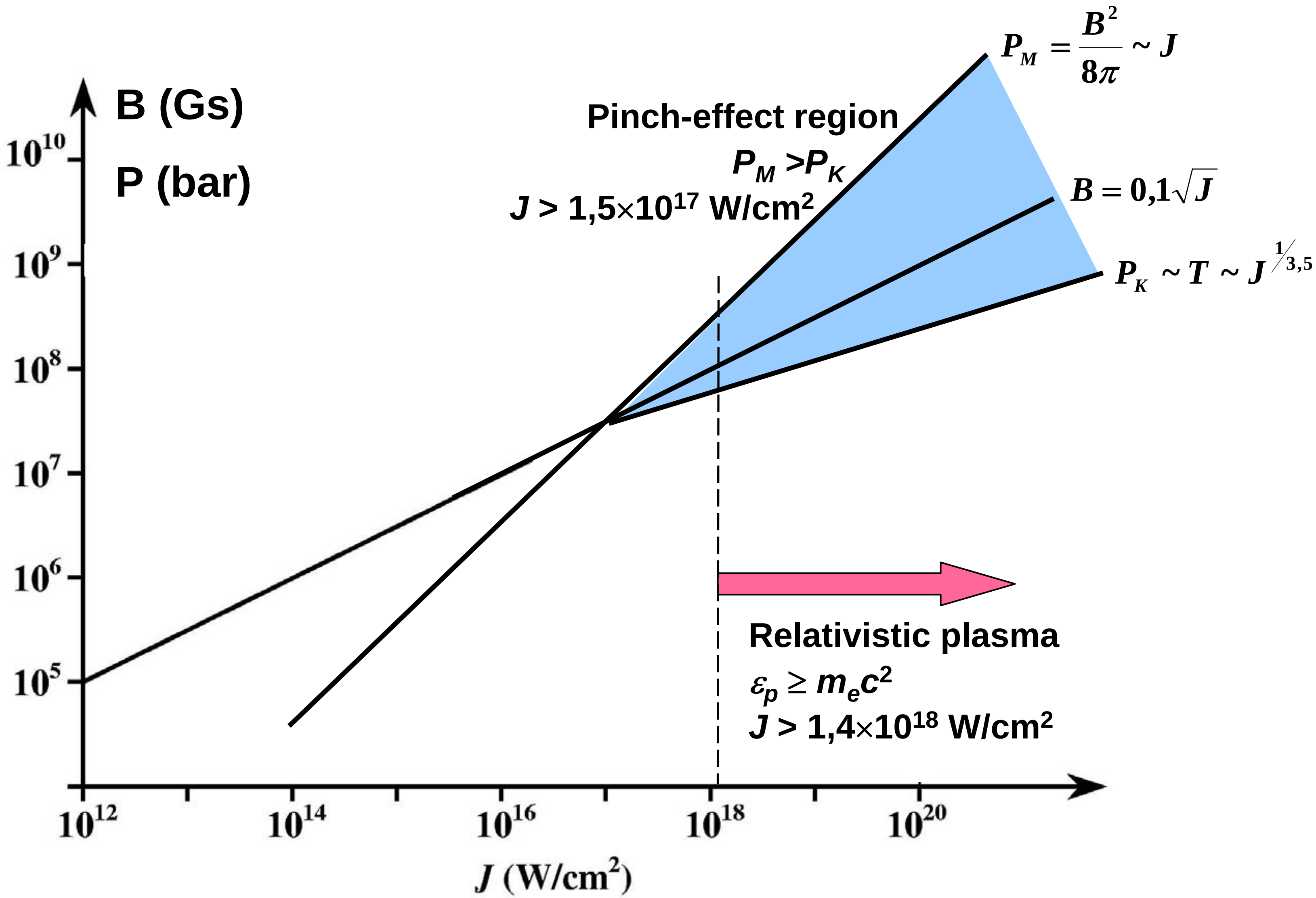
Relativistic

1. Plasma physics
2. Electrodynamics
3. Magneto-hydrodynamics
4. Quantum mechanics

Numerical simulation

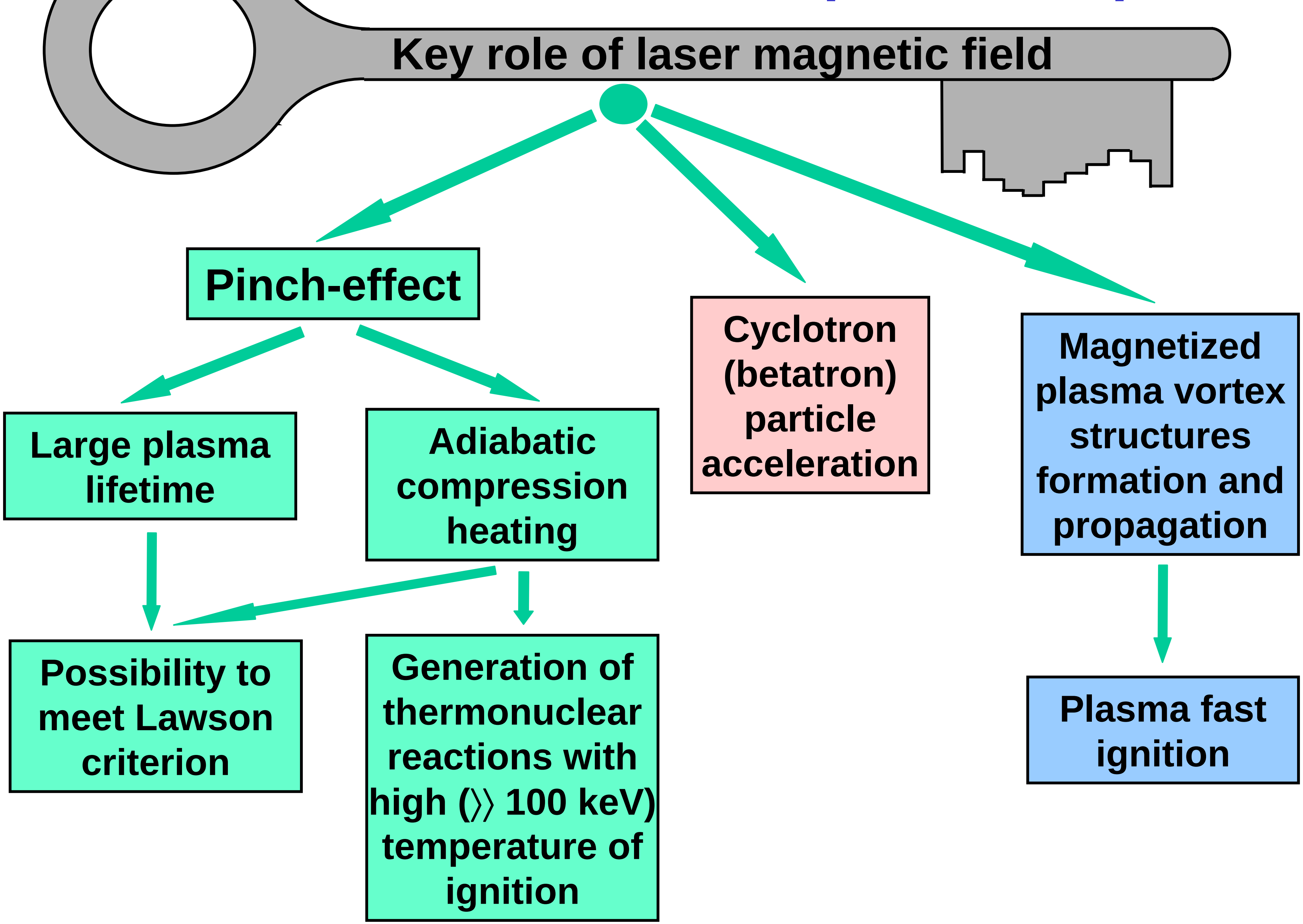
PIC-code “KARAT”

Laser plasma magnetic fields

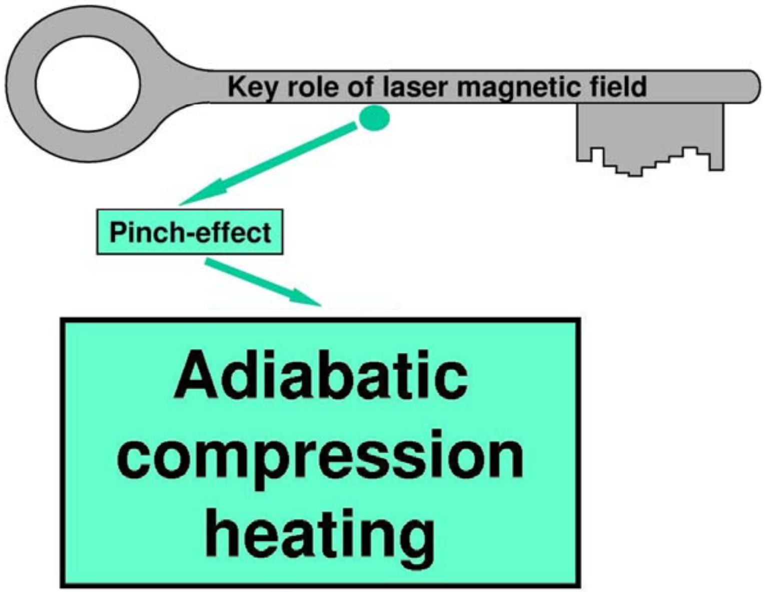


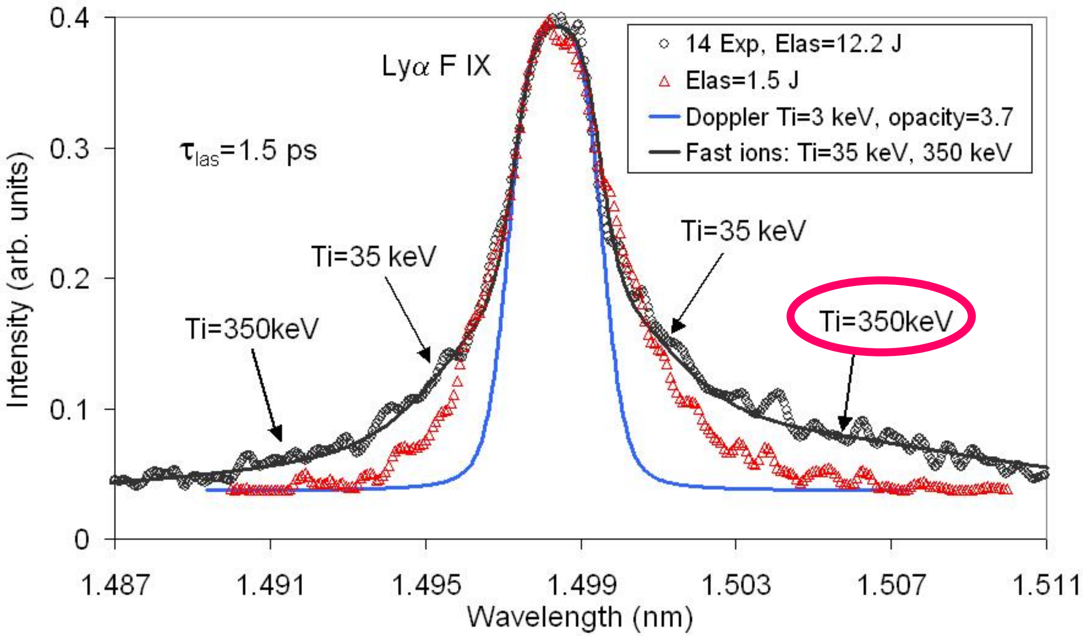
$J = 10^{18}$ W/cm^2; B = 100 MGs; $P_M = 4\times10^{-8}B^2$ = 400 Mbar; T_i = 350 keV

Relativistic laser-produced plasma



Experimental investigations I





1. Generation of fast MeV electrons

a) $\gamma_{BREMSST}$ **(Scintillation detector + Pb filters)**

b)
$$\begin{cases} {}^{9}\mathrm{Be}(\gamma,n)2\alpha \text{ with } E_{THRESH} = 1{,}67\,\mathrm{MeV} \\ {}^{181}\mathrm{Ta}(\gamma,n){}^{180}\mathrm{Ta} \text{ with } E_{THRESH} = 7{,}56\,\mathrm{MeV} \end{cases}$$

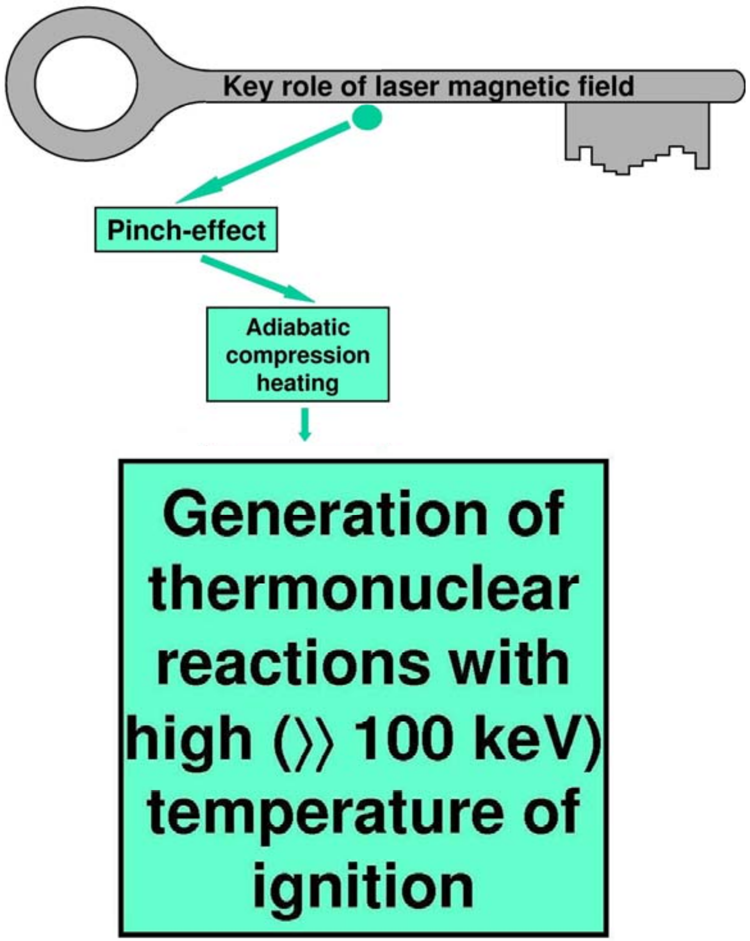
(mc^2 = 0,5 MeV)

2. Generation of fast MeV protons

a)
$$\begin{cases} {}^{7}\mathrm{Li}(p,n){}^{7}\mathrm{Be} \text{ with } E_{THRESH} = 1{,}88\,\mathrm{MeV} \\ {}^{63}\mathrm{Cu}(p,n){}^{63}\mathrm{Zn} \text{ with } E_{THRESH} = 4{,}1\,\mathrm{MeV} \\ {}^{48}\mathrm{Ti}(p,n){}^{48}\mathrm{V} \text{ with } E_{THRESH} = 5\,\mathrm{MeV} \end{cases}$$

b) CR-39 track detectors with Al filters

Experimental investigations II



1

$$D + {}^{3}He \rightarrow {}^{4}He(3{,}67\ MeV) + p(14{,}67\ MeV) + 18{,}34\ MeV$$

$$Y_{\alpha,p} \sim 10^{4}$$

2

$$D + {}^{6}Li \rightarrow {}^{4}He + {}^{4}He + 22{,}37\ MeV$$

$$Y_{\alpha} \sim 2\times10^{3} \quad E_{\alpha} \approx 11\ MeV$$

3

$$H + {}^{11}B \rightarrow 3\,{}^{4}He + 8{,}68\ MeV$$

$$Y_{\alpha} \sim 2\times10^{3}$$

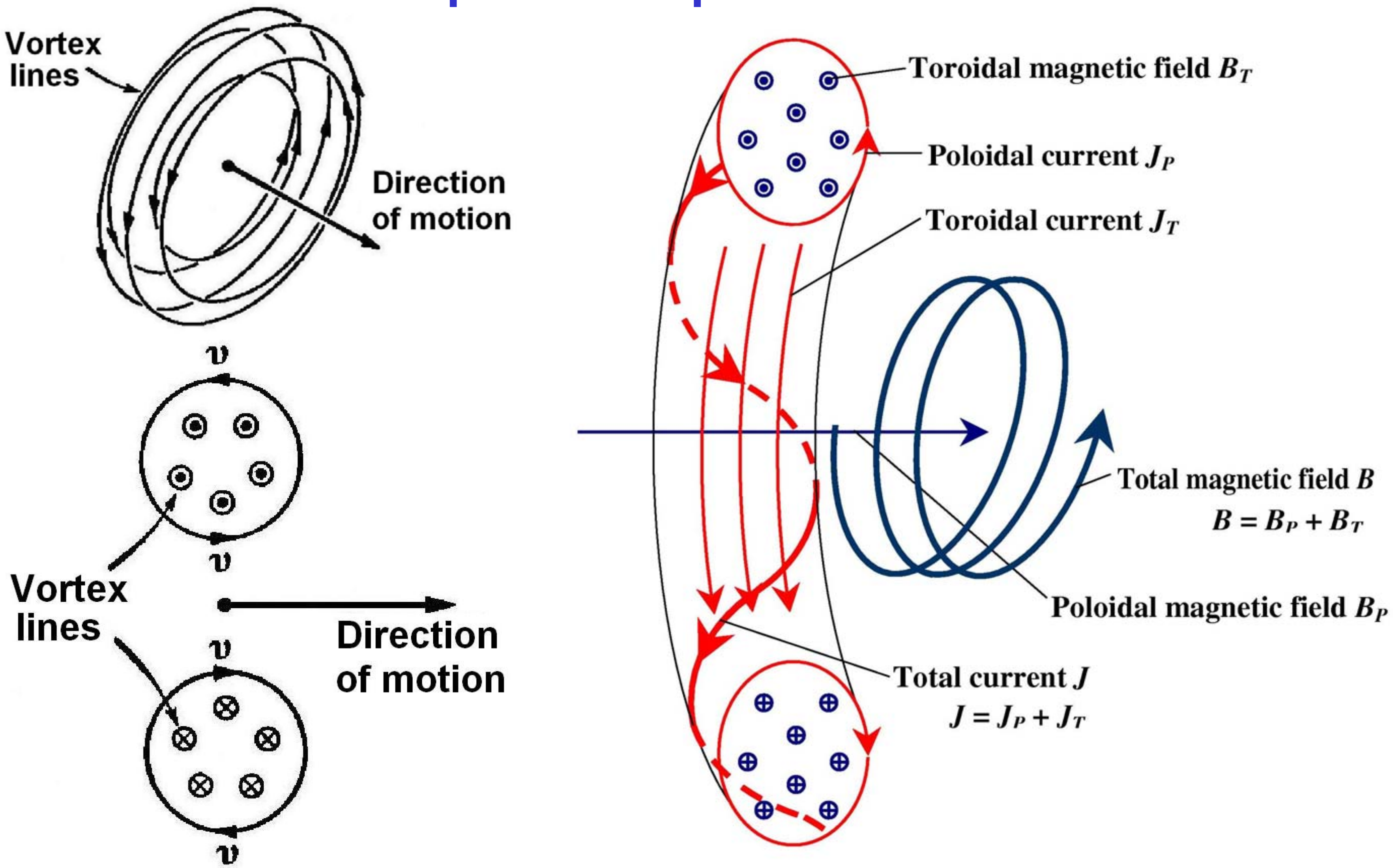
$$E_{\alpha} \approx 2{,}9\ MeV$$

4

$$p + {}^{7}Li \rightarrow {}^{4}He + {}^{4}He + 17{,}3\ MeV$$

$$Y_{\alpha} \sim 2{,}4\times10^{3} \quad E_{\alpha} \approx 9\ MeV$$

Spatial structure of magnetic fields generated in laser produced plasma



Coincidence of equations for a magnetic field in laser plasmas and for a potential vortex results in identity of their spatial structures

The transformation of rotational energy into a translation motion is a relativistic effect

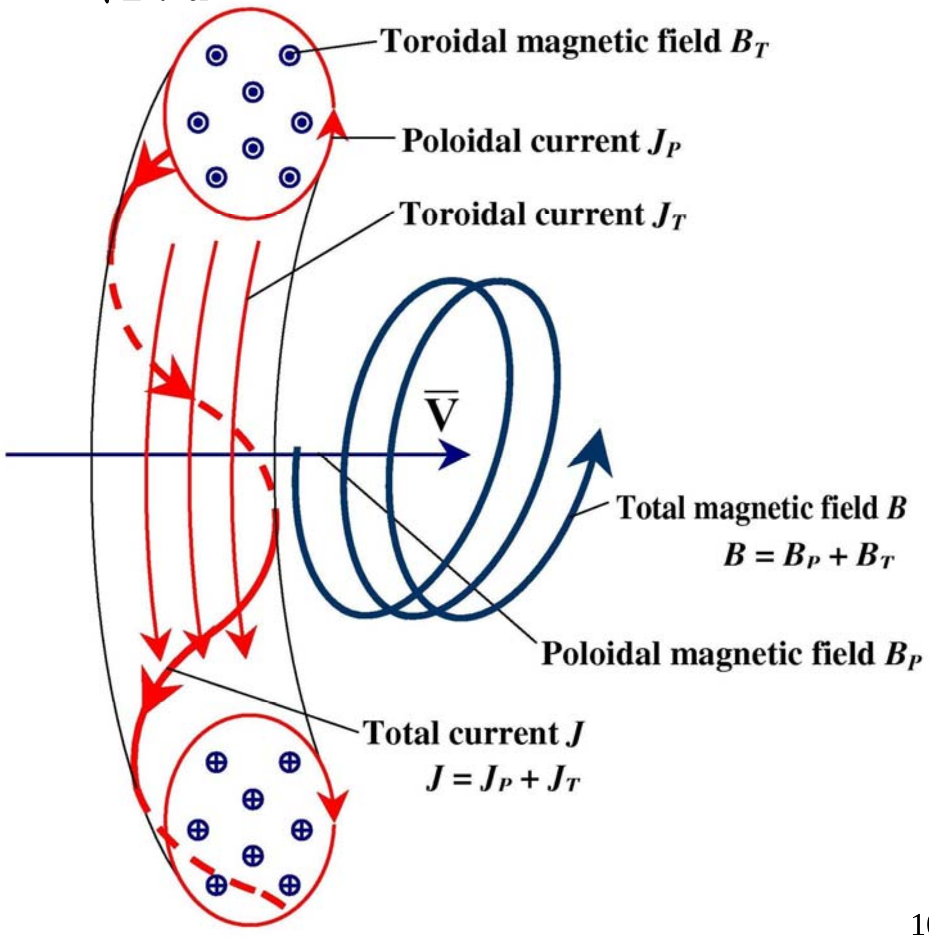
$$\frac{d}{dt}\left\{\frac{m_0\overline{\mathbf{v}}}{\sqrt{1-V^2/c^2}}\right\} = e\overline{\mathbf{E}} + \frac{e}{c}\left[\overline{\mathbf{V}}\times\overline{\mathbf{B}}\right]$$

$$\frac{d}{dt}\left\{\frac{m_0 c^2}{\sqrt{1-V^2/c^2}}\right\} = e\left(\overline{\mathbf{E}}\cdot\overline{\mathbf{V}}\right)$$

$$\overline{\mathbf{B}} = \frac{1}{c}\left[\overline{\mathbf{n}}\times\overline{\mathbf{E}}\right]$$

$$\frac{1-\overline{\mathbf{n}}\cdot\overline{\mathbf{v}}/c}{\sqrt{1-V^2/c^2}} = Const$$

$$\frac{V}{c} = \frac{\gamma-1}{\gamma} = \frac{\sqrt{1+a^2}-1}{\sqrt{1+a^2}}$$



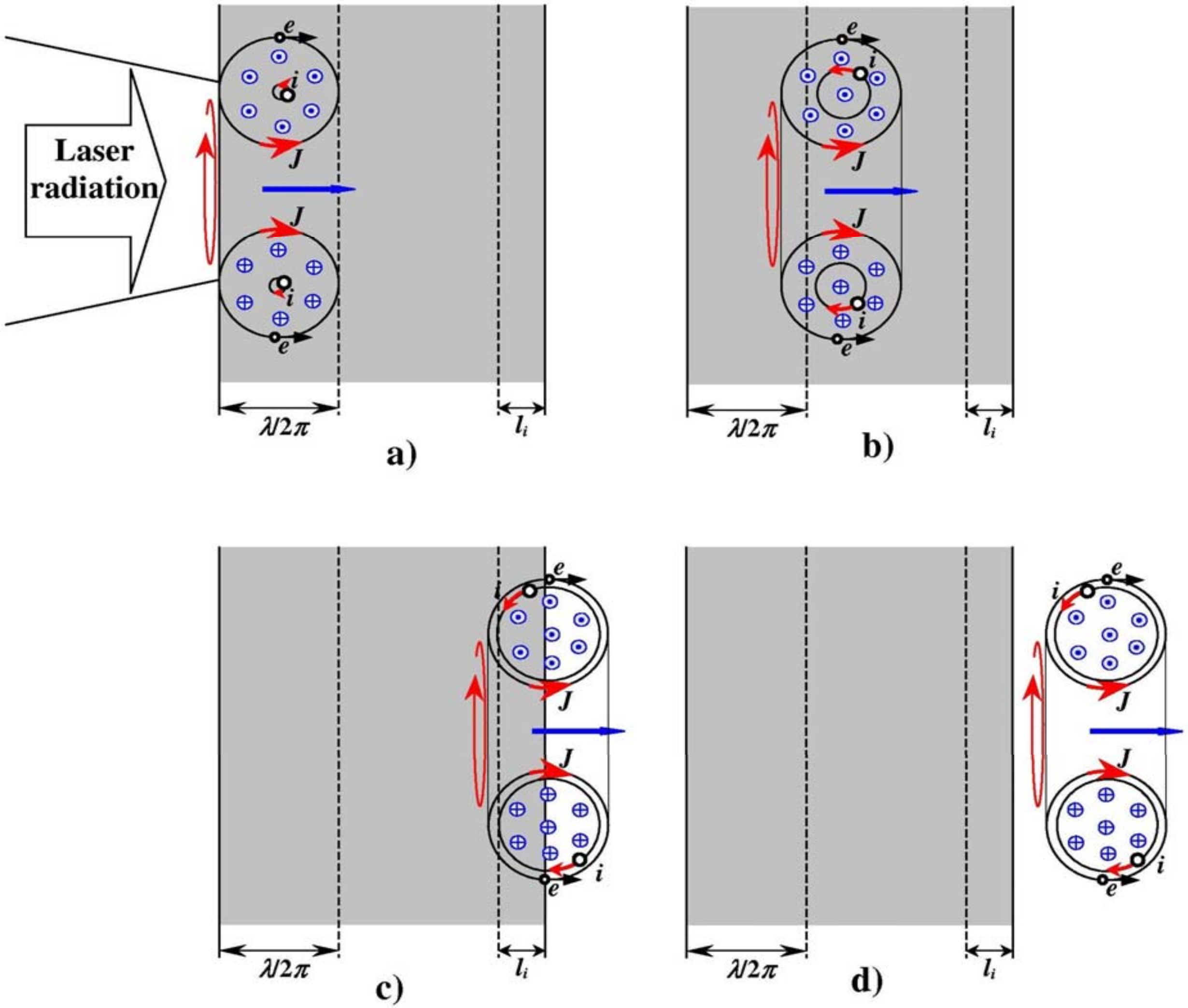
An electron vortex producing a quasi-stationary magnetic field and their analogous classical potential vortex can exist only in motion.

If a charged particle (for example, an electron) rotates with the velocity *V* in field of an electromagnetic wave, then this particle acquires obligatory some velocity along the direction *n* of the wave propagation.

Electrons and ions in relativistic laser plasmas form the one vortex structure – a potential vortex. This structure moves together with produced electromagnetic fields having the velocity of an electric drift (at $\overline{\mathbf{E}} < \overline{\mathbf{B}}$):

$$\overline{\mathbf{v}} = c\frac{[\overline{\mathbf{E}}\overline{\mathbf{B}}]}{\overline{\mathbf{B}}^2}$$

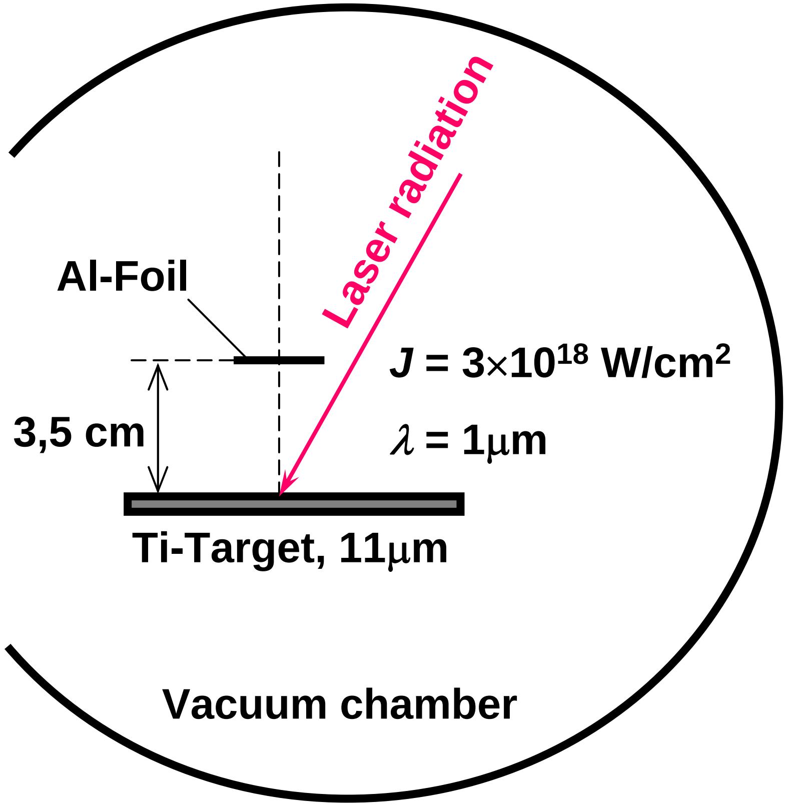
The requirement of quasi-neutrality results in motion of positively charged atomic ions.



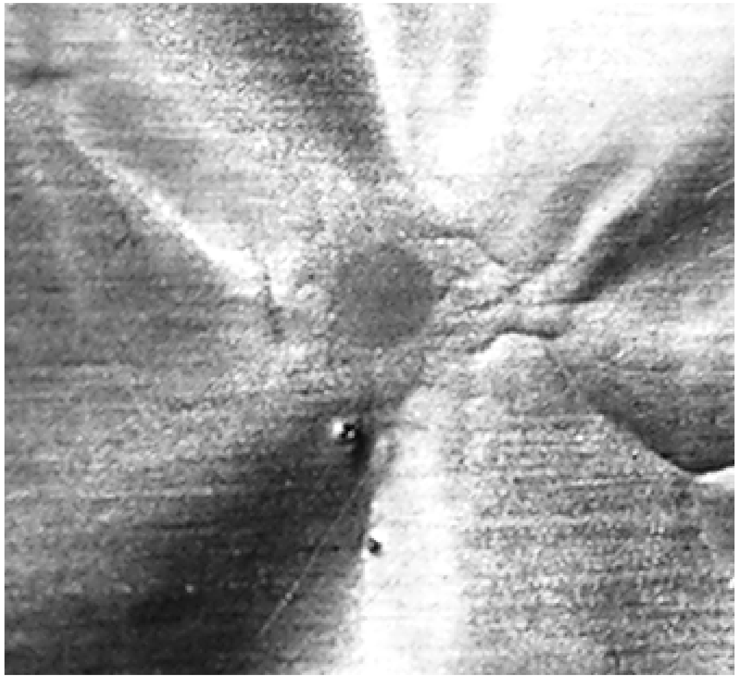
Stages of evolution of laser plasma

a) I-st stage – vortex electron structure is produced in anomaly skin-layer in order to carry magnetic field;
b) II-nd stage – ions are involved in vortex motion, they are decelerated in target with loss and acquire of new ions by vortex structure;
c) ions are not disappeared due to their deceleration in a layer which is less than absorption length in a matter;
d) propagation of quasi-neutral potential plasma vortex in a space.

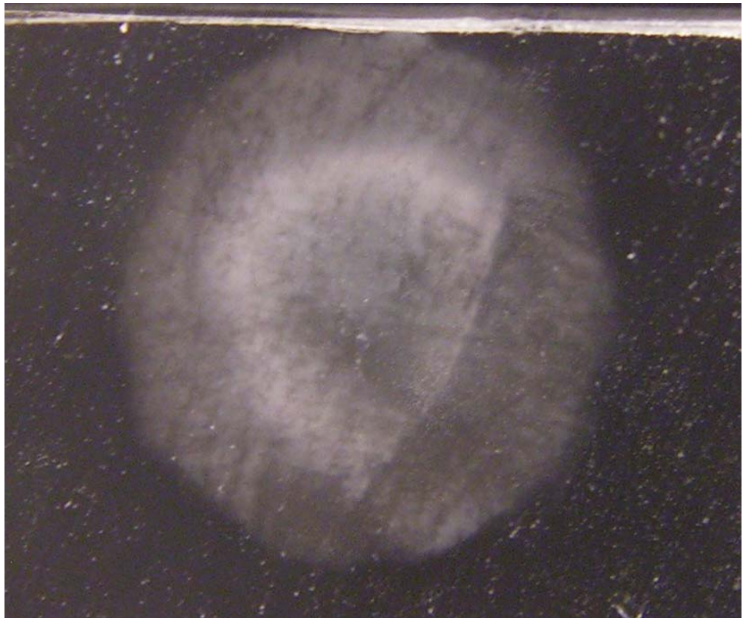
Interaction of Al-foil with ring-shape ion structure



Scheme of experiment

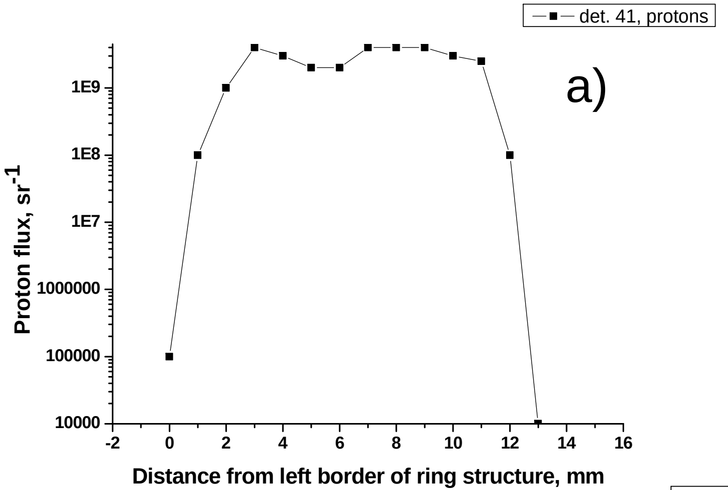


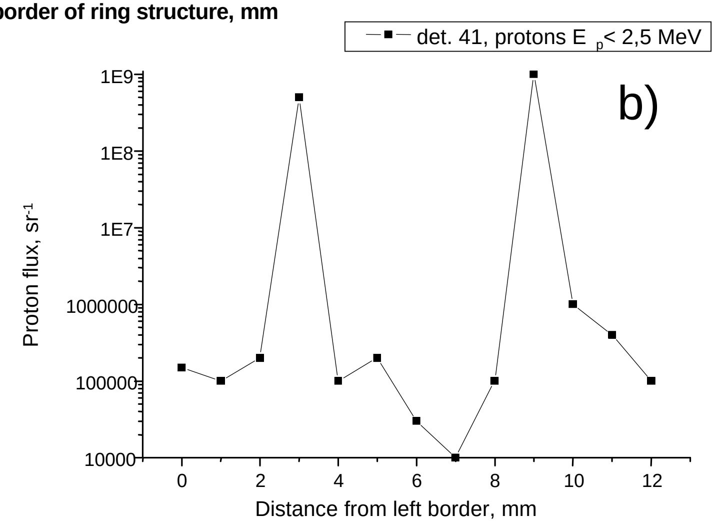
Ring structure of proton beam, moving from rear surface of the Cu foil



The photo of the track detector CR-39 covered by 11 μm Al filter. Detector CR-39 shows the tracks of protons with energies E_p > 0.8 MeV

$\varphi_{1/2} \approx 14°$ (cone half angle)





The proton distribution inside the spot for detector with 11 μm Al (E_p > 0.8 MeV). Target Cu 25 μm.

a) all protons with energy $E = 0{,}8 \div 5$ MeV

b) protons with energy $E < 2{,}5$ MeV

Conclusions

Super-strong quasi-stationary magnetic fields generated in laser-produced plasma open new possibilities for realization nuclear fusion of various perspective nuclear fuels.

The magnetic fields generated in laser plasma showed its key role in

- **Heating (> 100 keV) of plasma**
- **Large plasma lifetime**
- **Possibility of plasma fast ignition using magnetized plasma vortex structures**