ПРЕДПРИЯТИЕ ГОСКОРПОРАЦИИ "РОСАТОМ"

ФГУП "ВСЕРОССИЙСКИЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ АВТОМАТИКИ им. Н.Л.Духова"

Ion Acceleration by Intense "Slow" Light

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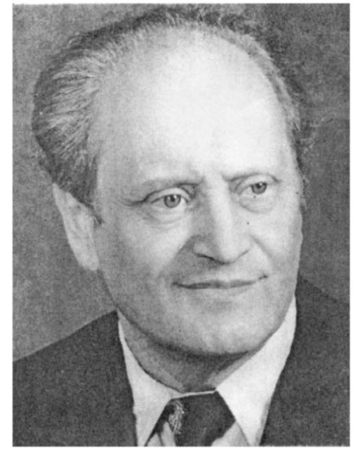
Snezhinsk, 2017

Collective ion acceleration

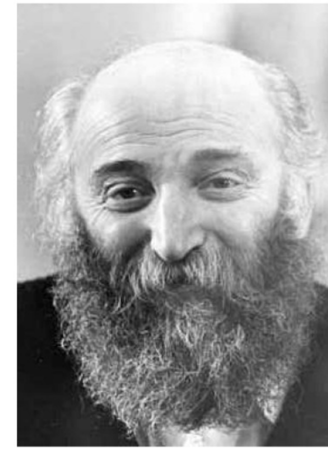
CERN Symposium on High-Energy Accelerators and Pion Physics, CERN, Geneva, Switzerland, June 11-23, 1956

Founding fathers

V.I. Veksler
1907-1966



Ya.B. Fainberg
1918-2005



G.I. Budker
1918-1977

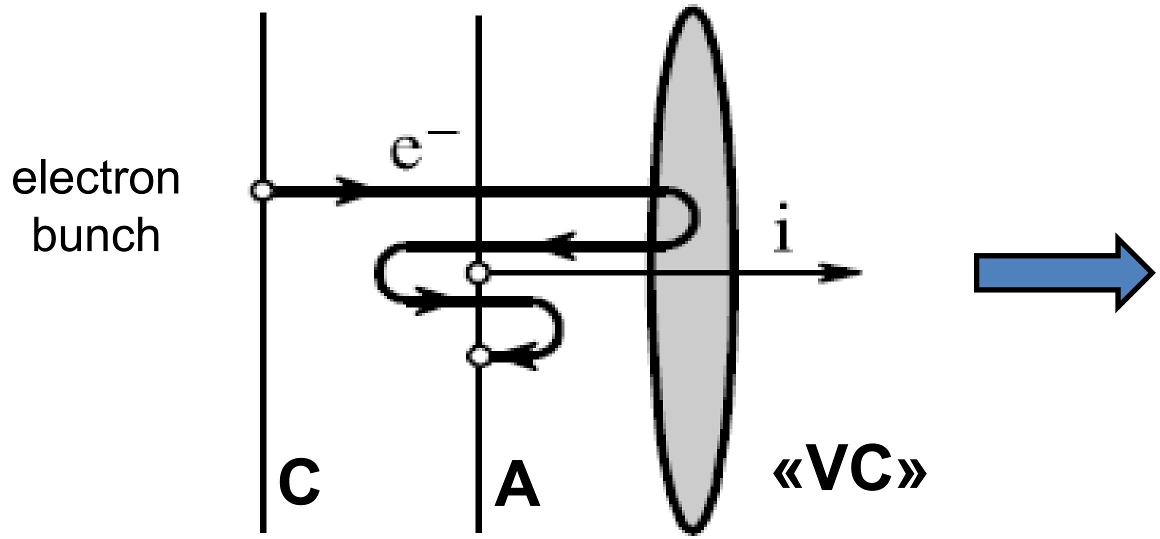
THE PRINCIPLE OF COHERENT ACCELERATION
OF CHARGED PARTICLES

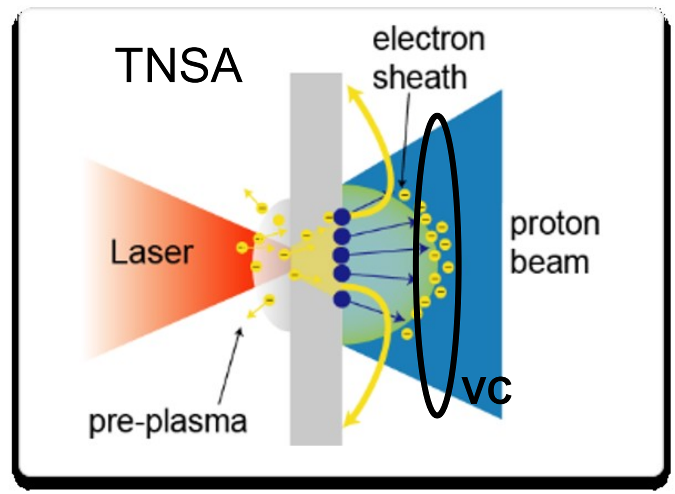
V.I. Veksler

V. I. Veksler
Sov. J. Atom. Energy **2**, 525 (1957)

Electron bunch: accelerating fields are caused by the collective effect of a large number of electrons which accelerate a smaller number of ions to energy greater than electron one

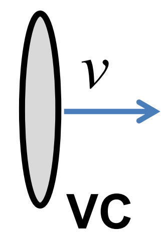
"Virtual cathode"





How to synchronize VC motion with accelerated ions?

Yu. V. Tkach et al., Zh. Tekh. Fiz. 44 658 (1974);
C. N. Boyer et al., IEEE Transactions Nucl. Sci. NS-24, 1625 (1977)

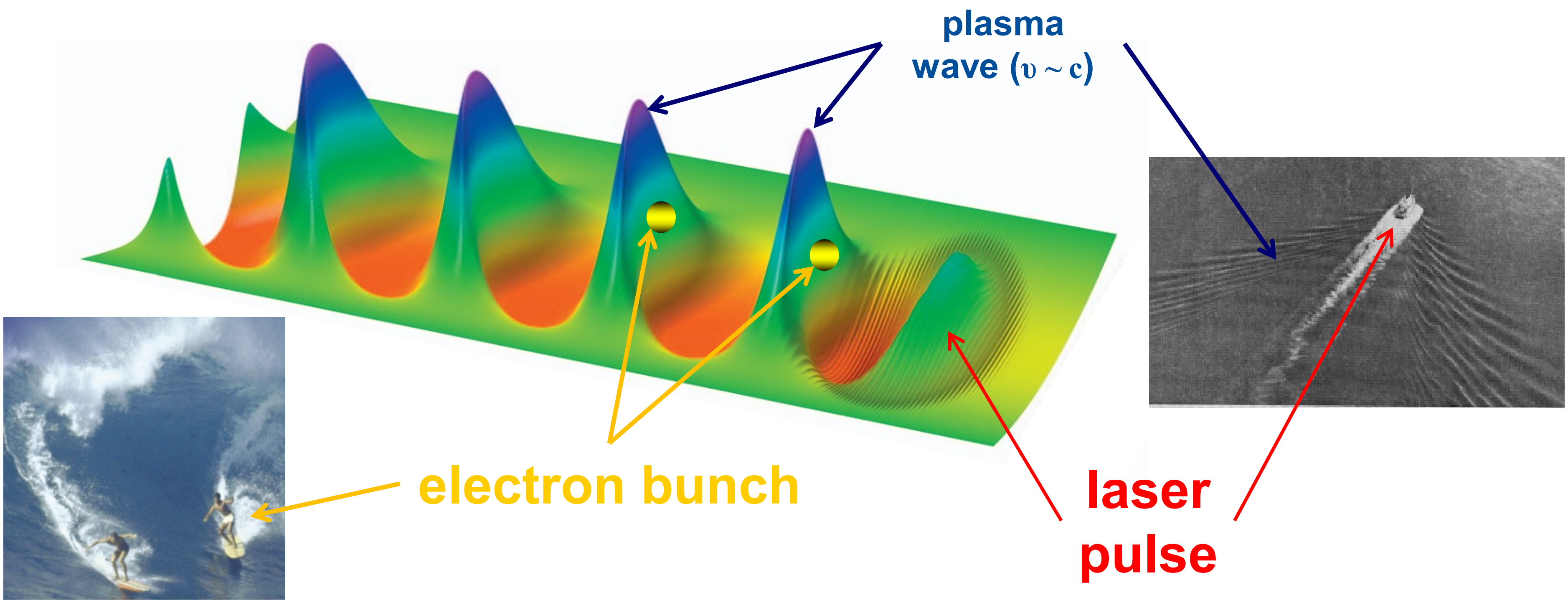


$dv/dt > 0$

formation of a virtual cathode behind the anode plane and the trapping of positive ions in the potential well of this virtual cathode. If one could control the velocity of the collective field propagation in synchronization with the positive ion velocity, the large collective fields of such a system (about 1 MV/cm, typically) would make possible the construction of an economically competitive ion accelerator.

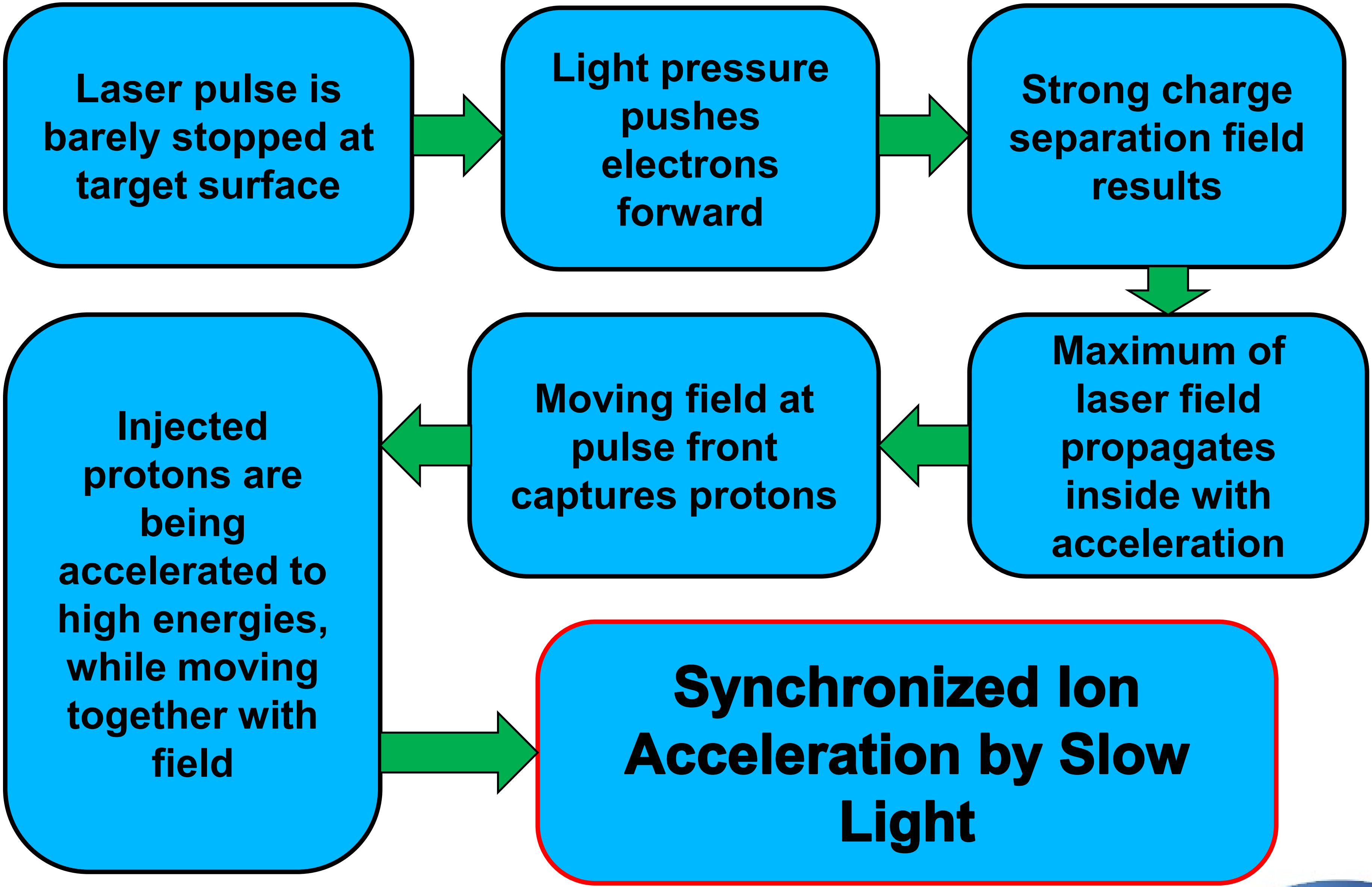
LWFA electron acceleration

LWFA (**L**aser **W**ake**F**ield **A**cceleration)



In transparent plasma wakefield propagates at nearly speed of light, allowing electron acceleration to large energies. <u>Direct</u> ion injection in accelerating structure is almost **impossible** due to their larger mass → light should be **«decelerated»!**

Principal scheme



"Shutter": relativistic transparency

Dispersion law of transverse oscillations in plasma: $\omega^2 = \omega_{pe}^2 + k^2 c^2$

Similar to plasma frequency $\omega_{pe} = \sqrt{4\pi e^2 n / m_e}$

Critical density is introduces $\omega = \sqrt{4\pi e^2 n_{cr} / m_e}$

For plasma with:

$n > n_{cr}, \omega_{pe} > \omega$ radiation doesn't propagate (skinned)

$n < n_{cr}, \omega_{pe} < \omega$ radiation penetrates inside

Relativistic laser pulse results in plasma frequency change:

$$m_e \to m_e^* = \gamma_e m_e \qquad \omega_{pe} \to \omega_{pe}^* = \frac{\omega_{pe}}{\sqrt{\gamma_e}}$$

$$\gamma_e = \left[\sqrt{1+a^2} - 1\right]$$

$$a = 0.85\sqrt{\lambda[\text{мкм}]^2\, I[\text{Вт/см}^2]\, 10^{-18}}$$

For plasma with:

$\omega_{pe}^* < \omega < \omega_{pe}$

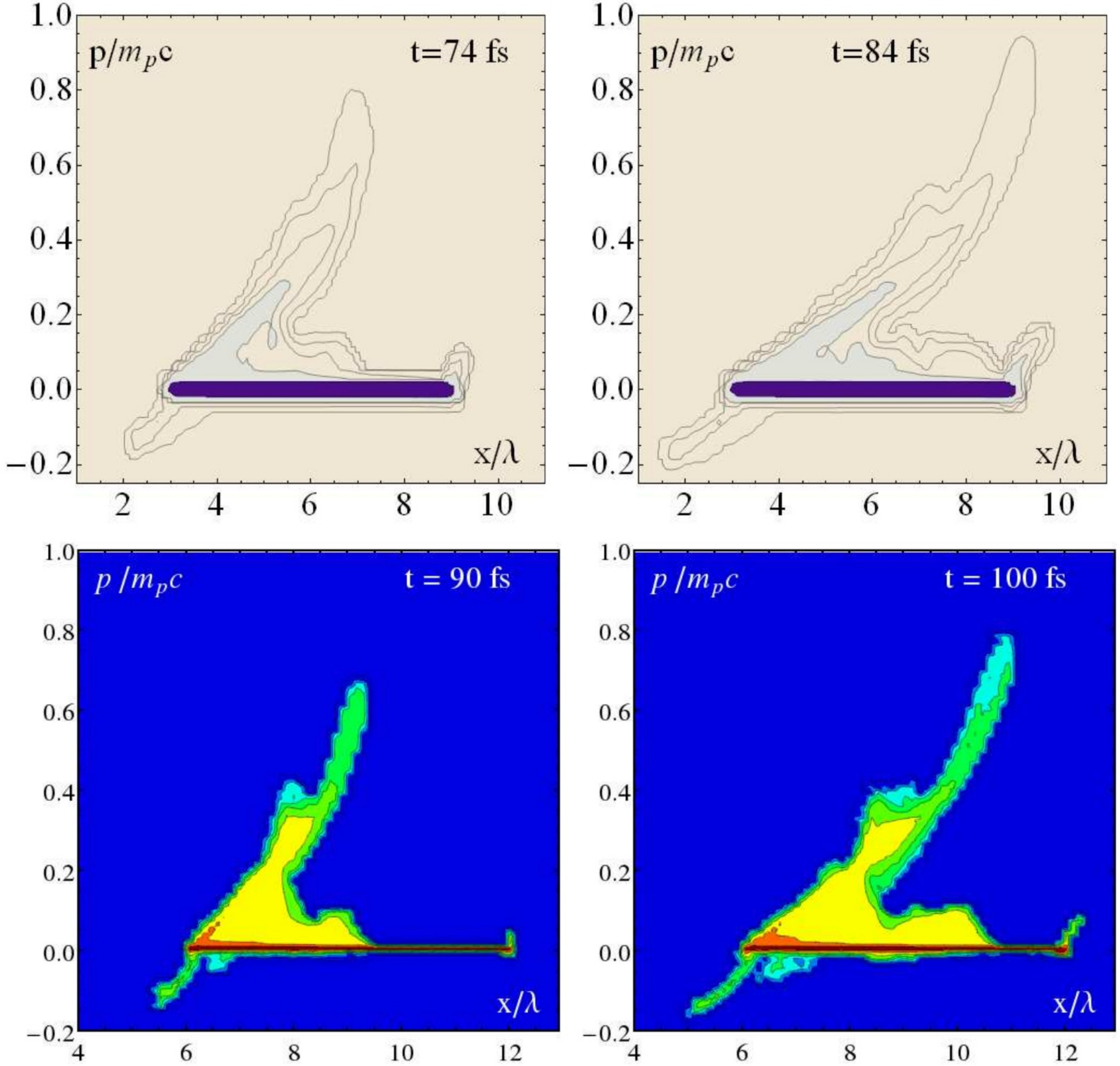
$n_{cr} < n < \gamma_e n_{cr}$

relativistically induced transparency (RITA) occurs

Group velocity in RITA-plasma: $v_g = c\sqrt{1 - \dfrac{n}{\gamma_e n_{cr}}}$

RITA-effect can be a "shutter", controlling the laser light penetration into plasma: slowing down low amplitude part ($v_g \equiv 0$) and passing high-intensity part.

3D3V PIC simulation



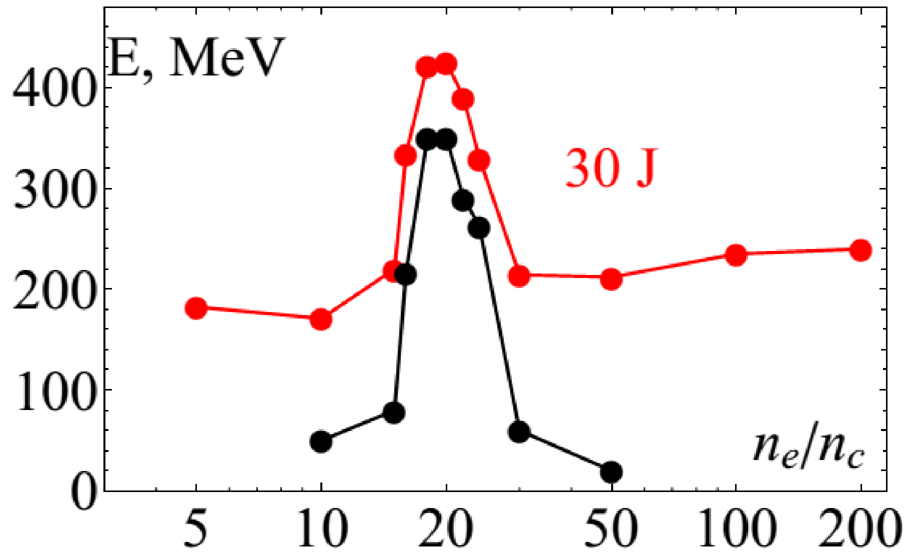
Mandor

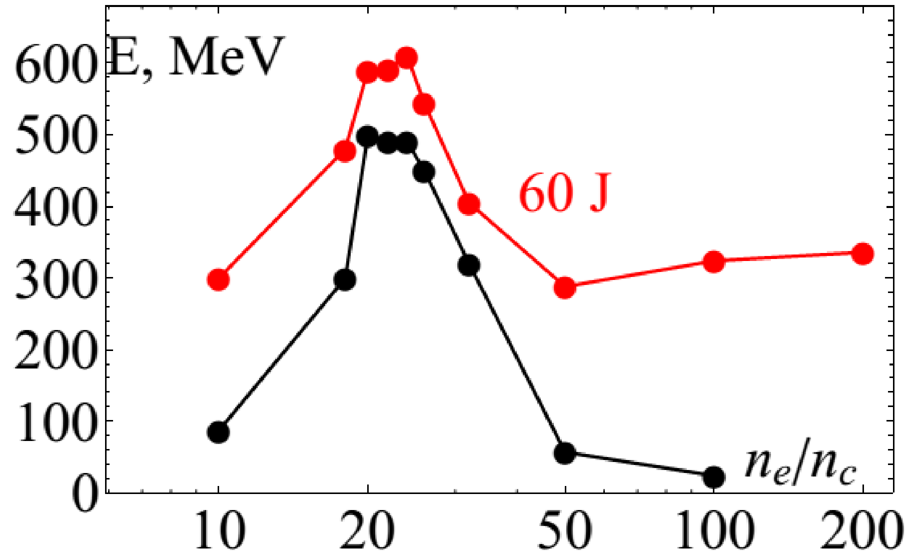
VSim (Vorpal)

Comparison with optimized foils

Use of **lowdensity targets** with densities near relativistic critical one can increase ion energy and reduces requirements for laser pulse quality:

Laser: 30 J, $\tau = 30$ fs, $D_f = 4$ μm, $I = 5\times10^{21}$ W/cm^2 Target: CH_2



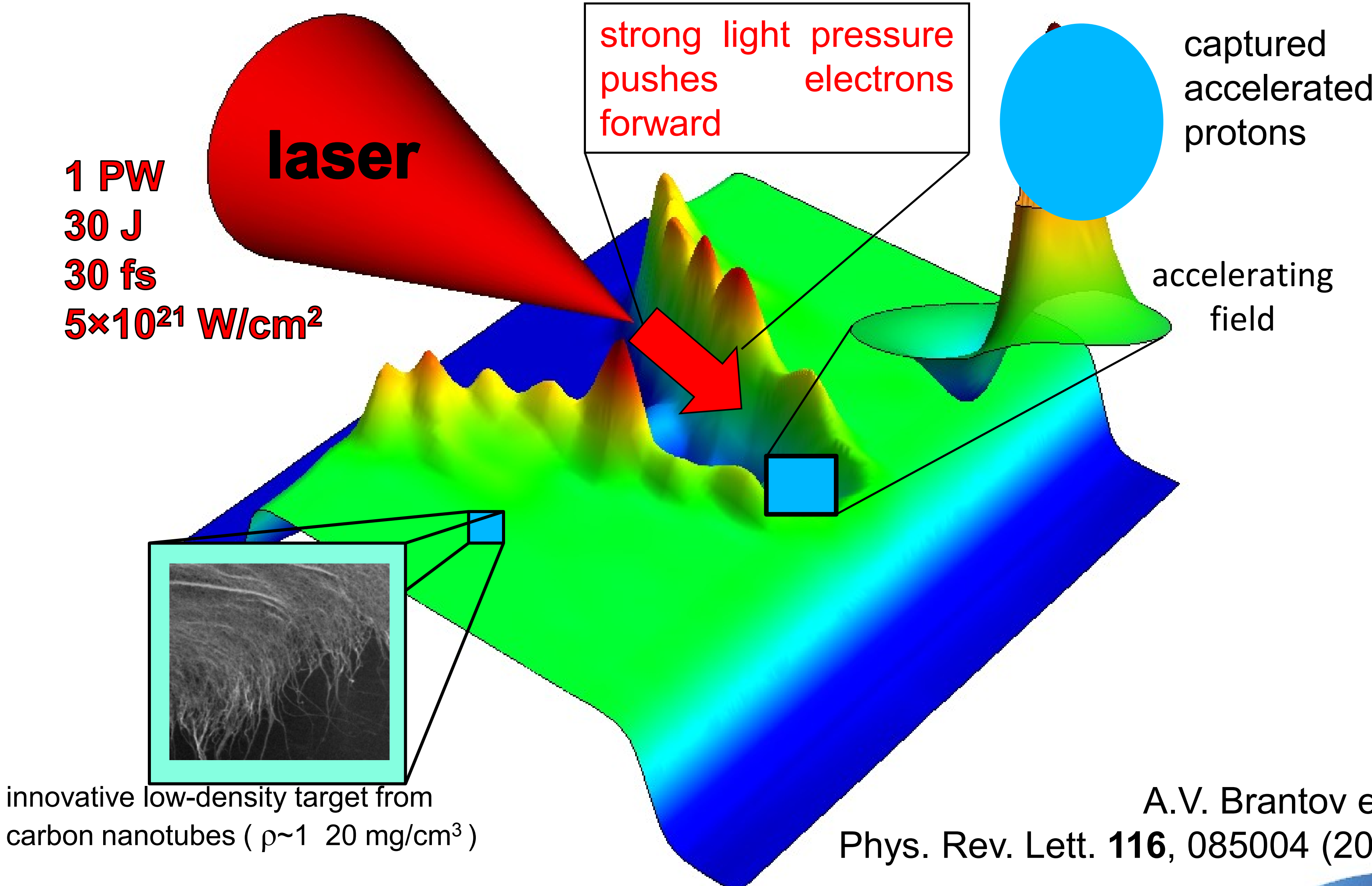


Energy gained **inside** target (**black**) and **total** energy (**red**) for targets of optimal thickness. Outside or resonance energy on the order of tens of MeVs!

Maximum energy dependence on density is **resonanse-like**.

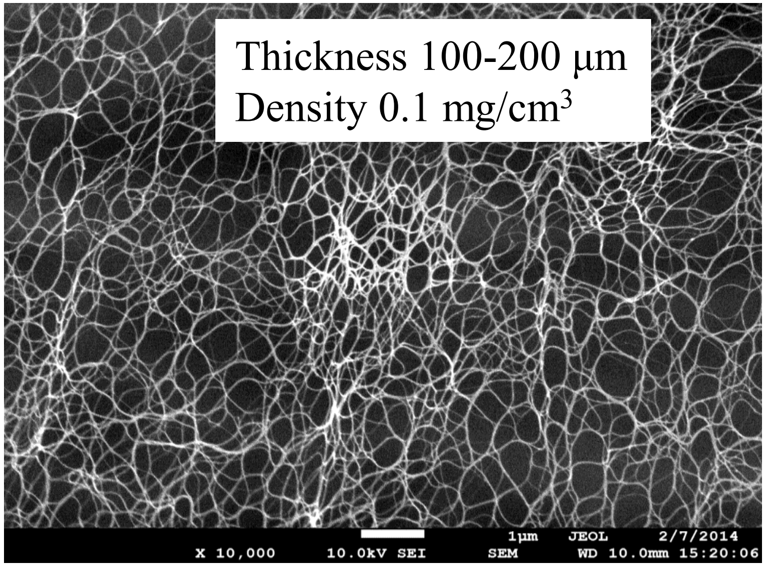
Always better than optimal solid foil!

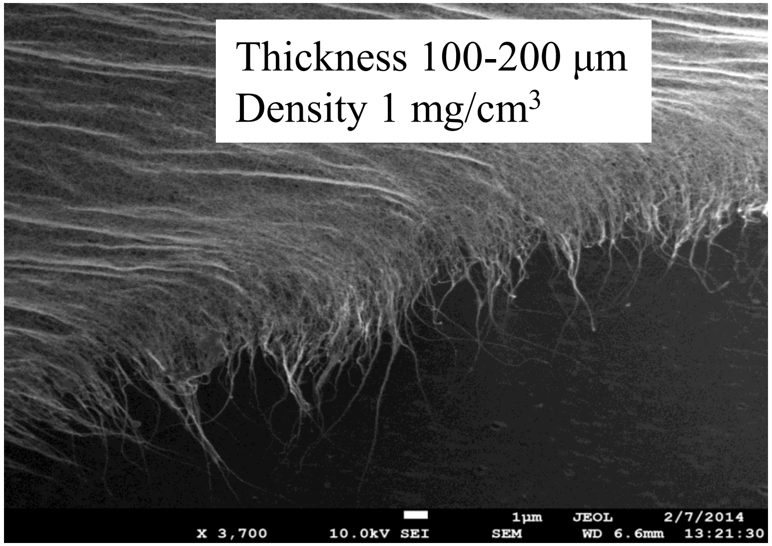
Principal scheme

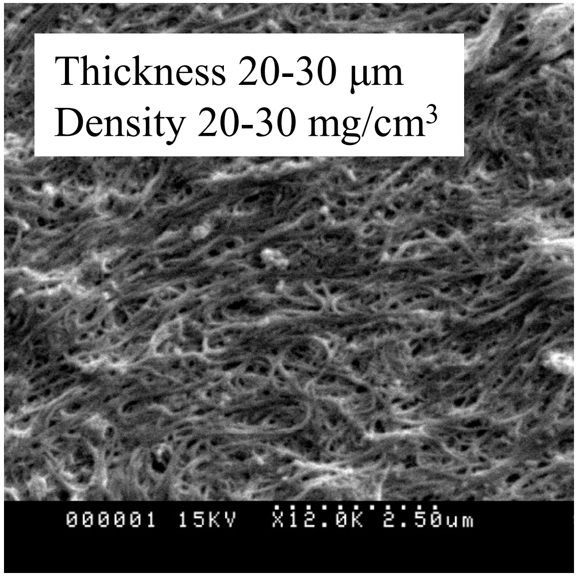


A.V. Brantov et al.
Phys. Rev. Lett. **116**, 085004 (2016).

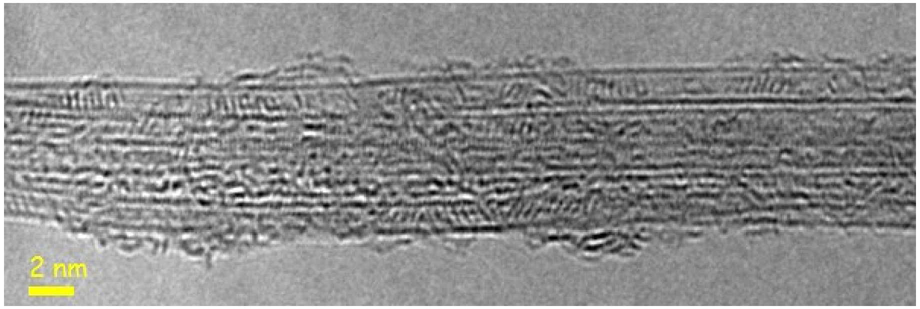
Low-density targets







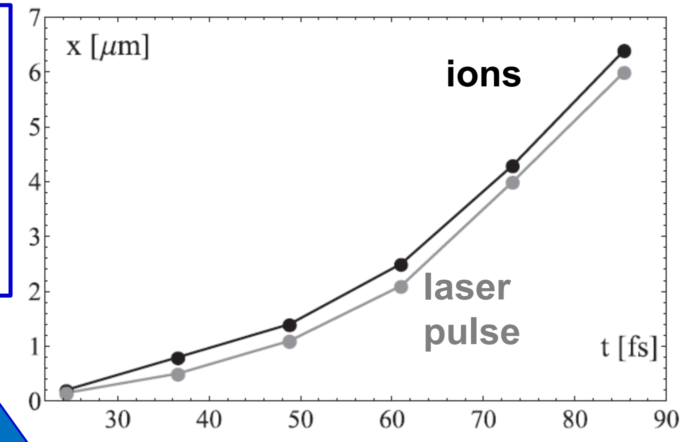
Up to 2 % of mass can be filled with hydrogen ($C_{24}H_{12}$)



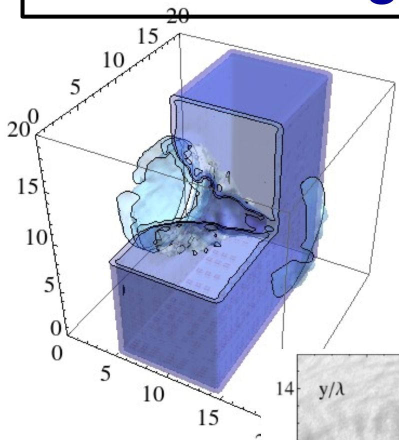
low-density targets from carbon nanotubes: density greater than gas one and lower than solid-state one

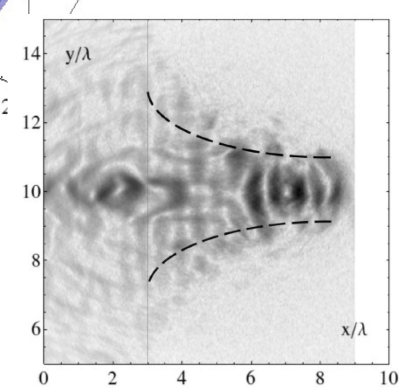
What next?

How to make laser pulse to propagate **far enough** and **with acceleration**?



Relativistic self-focusing





?

Target density profiling

$$n_e(x) = \frac{n_c}{(1 + w\,x)^2}$$

$$v_g = \frac{w_0\,t}{\sqrt{1 + (w_0\,t)^2}}$$

V.Yu. Bychenkov et al.
JETP Lett. **104**, 618(2016)

Conslusions

- New mechanism of syncronized ion acceleration by ultra-intense slow light (SASL) from low-density targets is proposed.

- Major part of energy is gained inside target, being always greater than one from optimized solid-state foils

- Low-density targets from carbon nanotubes have wide range of densities, thickness and hydrogenization and available for experiments

- Further study of laser pulse propagation in such targets is of great need

Thank you for your attention!