3rd year admission exam

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Atom trapping and laser accelearation: how light accelerates matter

Low energy physics presentation.

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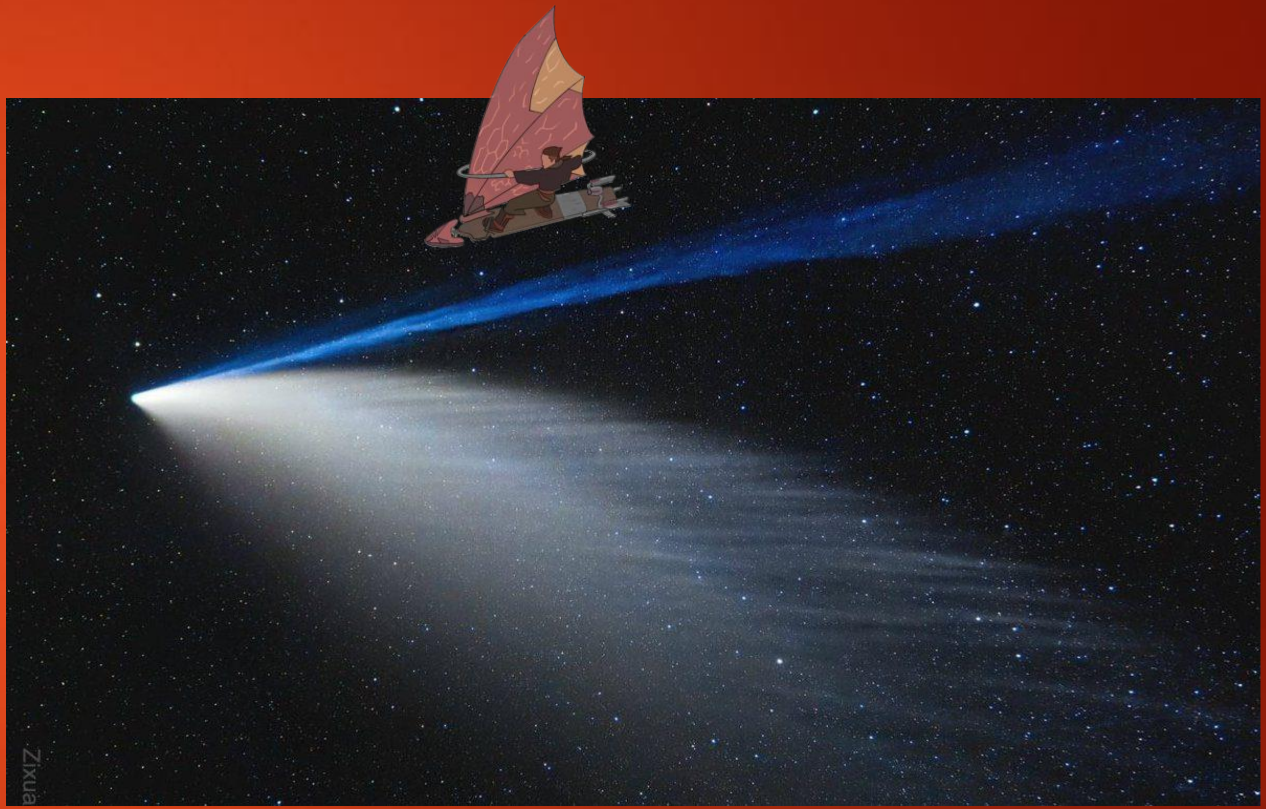
Radiation pressure

Once they said that:

1. "Provide ships or sails adapted to the heavenly breezes, and there will be some who will brave even that void"
2. Light is an electromagnetic wave;
3. Light carry energy.

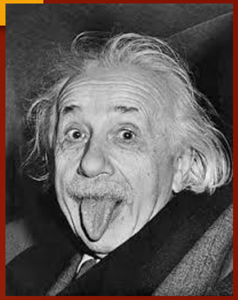
$$P_{rad} = \frac{I}{c}$$

$$F_{rad} = \frac{\sigma_{abs} \times I}{c}$$

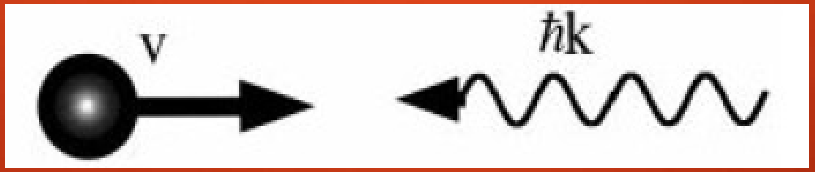


AnotherONE said that:

1. "when a light ray is emitted from a point, the energy is not distributed continuously over an increasing volume, but consists of a finite number of energy quanta localized at points in space, which move without dividing and can be absorbed or generated only as a whole."
2. “It seems to me that the observations associated with the photoelectric effect can be explained if one assumes that the energy of light is distributed in discrete packets (quanta) rather than continuously.”



Light behave like a particle and interacting they must **conserve energy and momentum .**



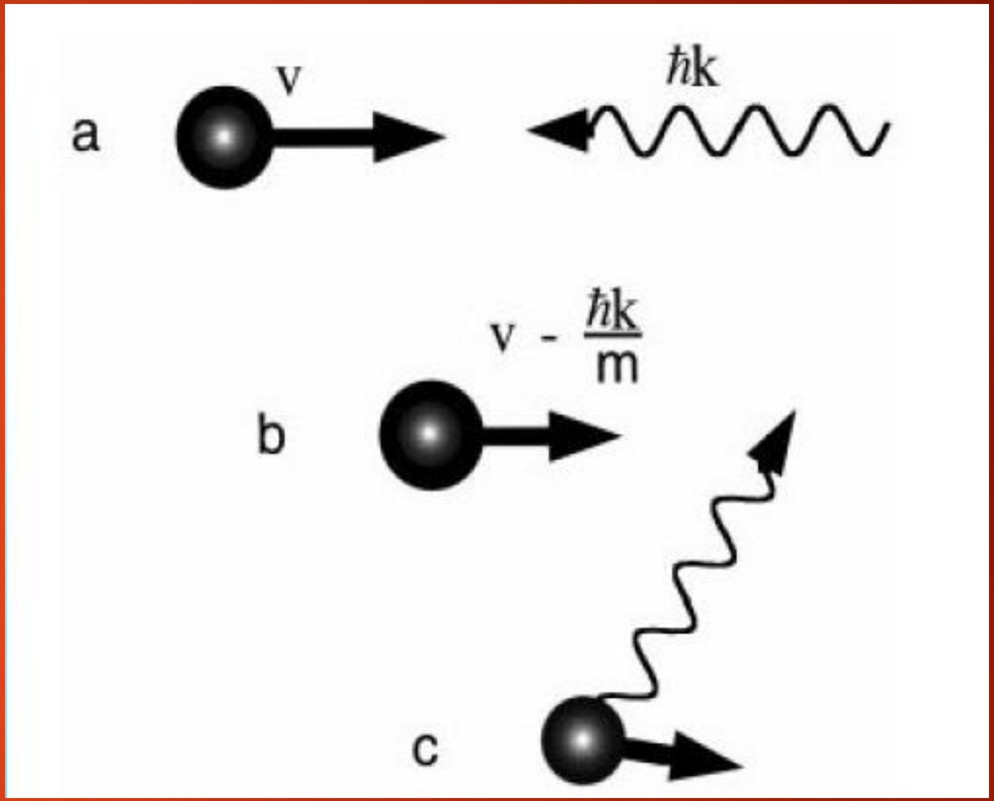
Light-atom interaction

- When a photon is absorbed by an atom, it exerts a force on the atom, increasing its energy while decreasing its momentum.
- The force applied to the atom must take into account the fact that photoabsorption is a resonant effect.

$$\vec{F} = \hbar \cdot \vec{k} \cdot \Gamma \approx (\mathrm{Li})10^{-19}N$$

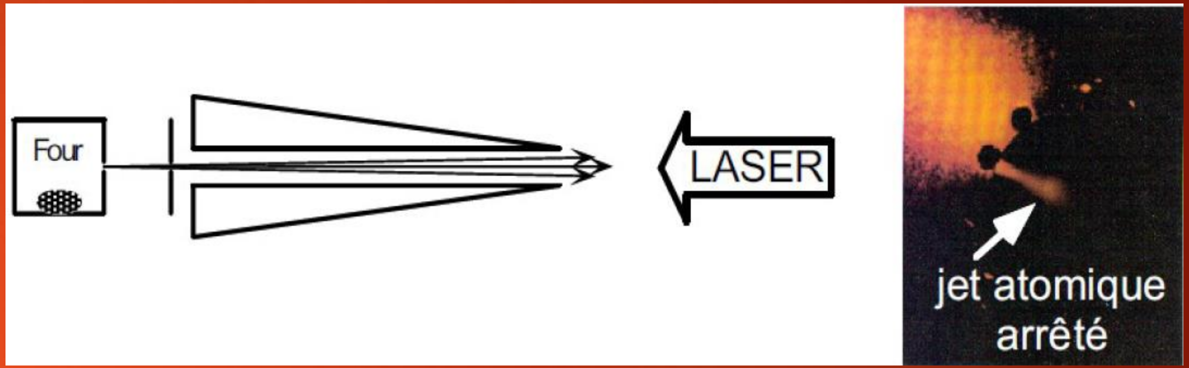
$$a = F/m \approx (\mathrm{Li})10^{5}g$$

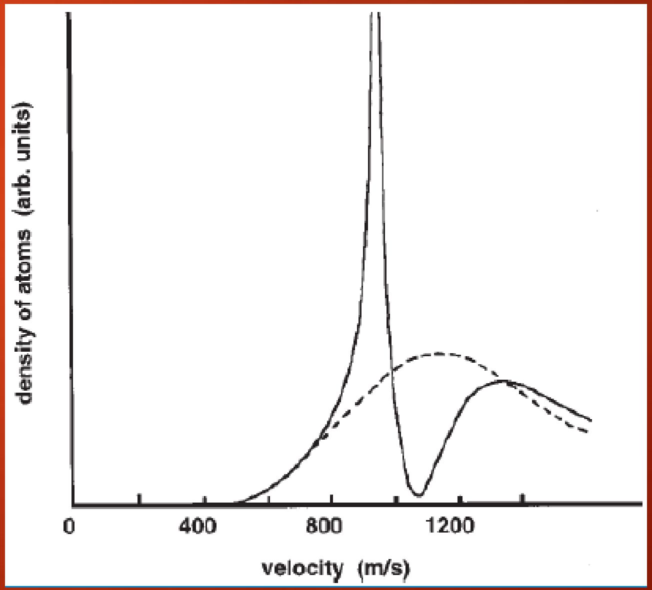
- Apparently, the spontaneous re-emission of the photon cancels out the deceleration, but using a laser, the atom receives a continuous kick that reverses its motion direction.



Laser frequency alignement

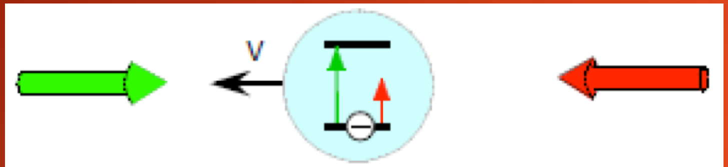
- If the frequency is not aligned to the resonant frequency the absorption efficiency is reduced
- Even if you align the laser frequency to the resonant frequency of the target atoms you must always take into account of the atom velocity distribution.
- Three ways exist to align the laser frequency to the target resonant frequency:
    - **frequency chirping**, you change the laser frequency;
    - **Zeeman slower**, you use magnetic field to change the energetic level of the target;
    - **broad band laser**, you can use all the frequency of a laser to cover a larger range to cover all the frequency possibilities.



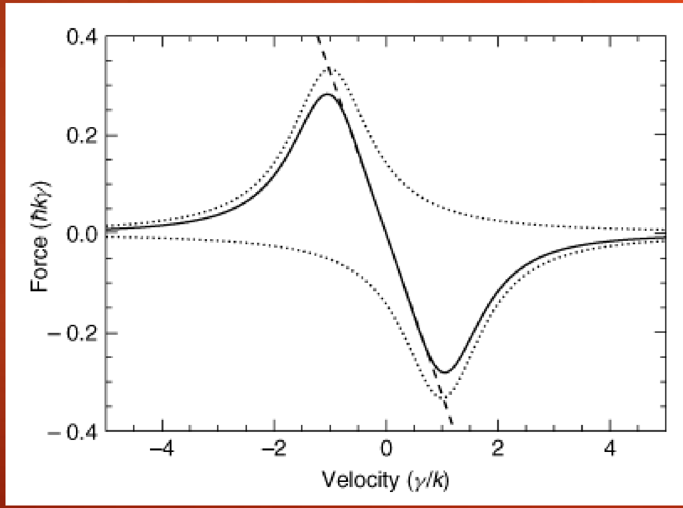


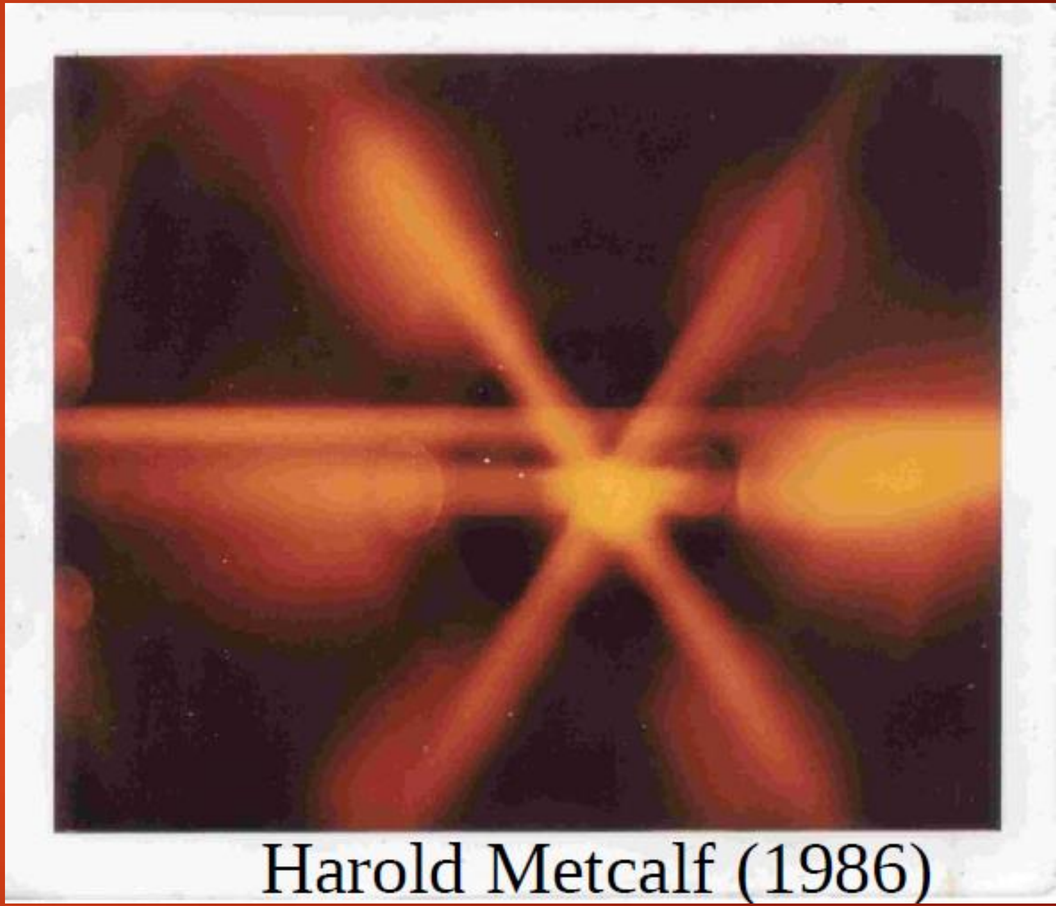
Optical mollasses

- In a vapor, a 3D system atoms can move freely.
- To erase the red(blue)-doppler effect one can use two beam opposite.



- Applying the two beams the overall force applied is like a friction force.

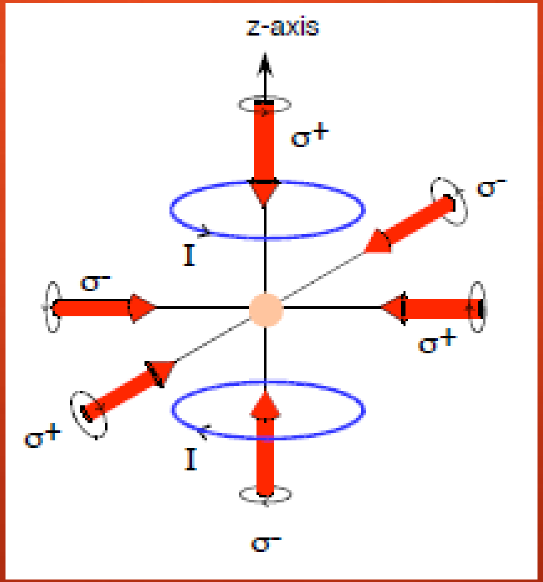




Magneto Optical Trap

- The obtained equilibrium in the laser intersection point is not stable.
- Establish a potential well with two anti-Helmotz coils to have a linear gradient magnetic field with the zero set in the center.
- Zeeman effect dependent on the atom position.
- Circular polarization beams introduce selection rules making the atoms oscillating around the zero.

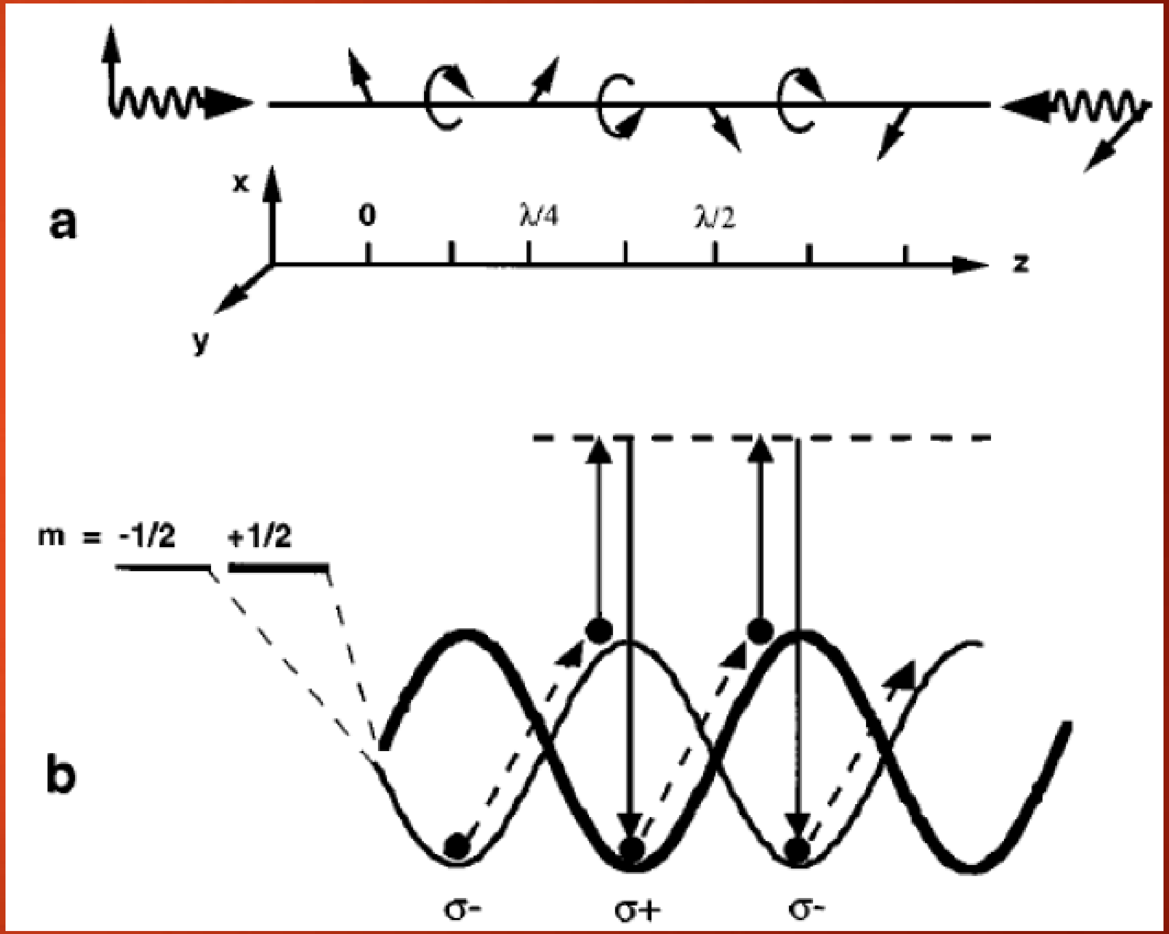
$$\frac{F}{m} = \gamma v + \omega_{vib}^{2} z + O(v^2, z^2)$$



Sodium trap in Siena laboratory

Sisyphus cooling

- Using a single laser and a mirror, we can create two counter-propagating laser beams.
- The interference of these beams forms a standing wave with a spatially varying polarization, known as a polarization grating.
- When an atom absorbs a photon from one of the beams, it is excited to a higher energy level; after spontaneous emission, it typically decays into a lower-energy ground state.
- The continuous alternation between climbing the optical potential created by the polarization gradient and being optically pumped back to a lower-energy state results, on average, in a net loss of kinetic energy.
- This mechanism allows atoms to reach temperatures on the order of μK.



Why don't we use laser to accelerate?

Collective acceleration in plasma

- Laser pulse length must be half of plasma wavelength to create coherent excitations within the target:

$$l_p = 2\pi c/w_{pe} \sim o(fs); w_{pe} = \sqrt{\frac{ne^2}{\epsilon_0 m_e}}$$

- This is the base of the "ultrafast dynamical stability".
- HIgh laser frequency to get coherence between electron acceleration and laser pulses
- Pondemorotive force, due to the EM wave fields moves the electrons laterally creating an E_{wake} cavity within the plasma.
- The E wake accelerate the plasma electrons with a force proportional to e^2.

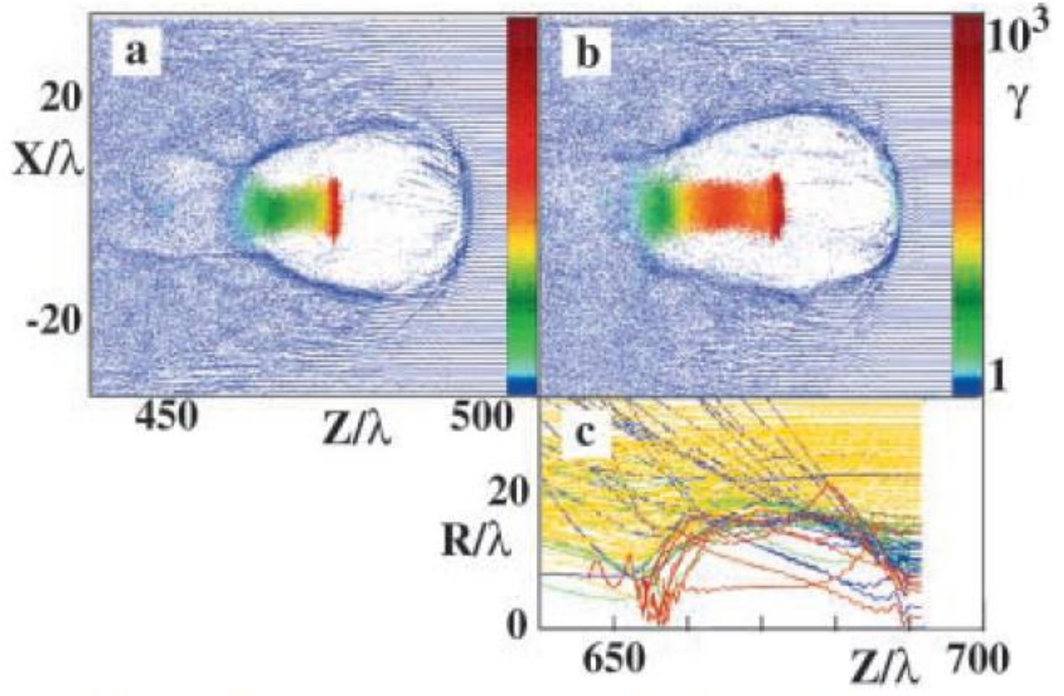


FIGURE 4 Solitary laser-plasma cavity produced by 12-J, 33-fs laser pulse. **a** $ct/\lambda = 500$, **b** $ct/\lambda = 700$, **c** electron trajectories in the frame moving together with the laser pulse; *color* distinguishes electron groups with different distances from the axis initially

Laser WakeField Acceleration

- The acceleration mechanism that take the name from this process is called Laser Wakefield Acceleration (LWFA).
- The energy of the accelerated electrons depends on the laser intensity: the higher the intensity, the greater the electron energy.
- When the laser intensity become too high the electrons can escape from the wake beeing accelerated on the front of the laser pulse.
- This effect is known as Breakave.
- The figure shows two examples of electron energy spectra obtained using two laser intensities, both above the breakwave threshold.
- The accelerating gradient obtained is of the order of 10-100 GeV/m

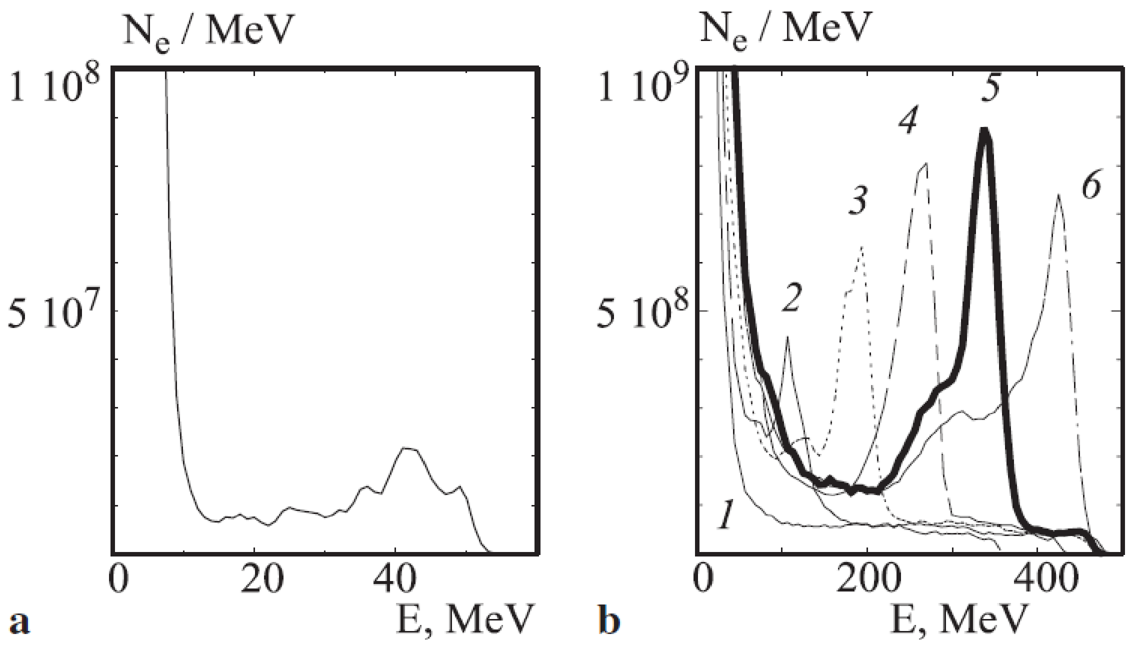
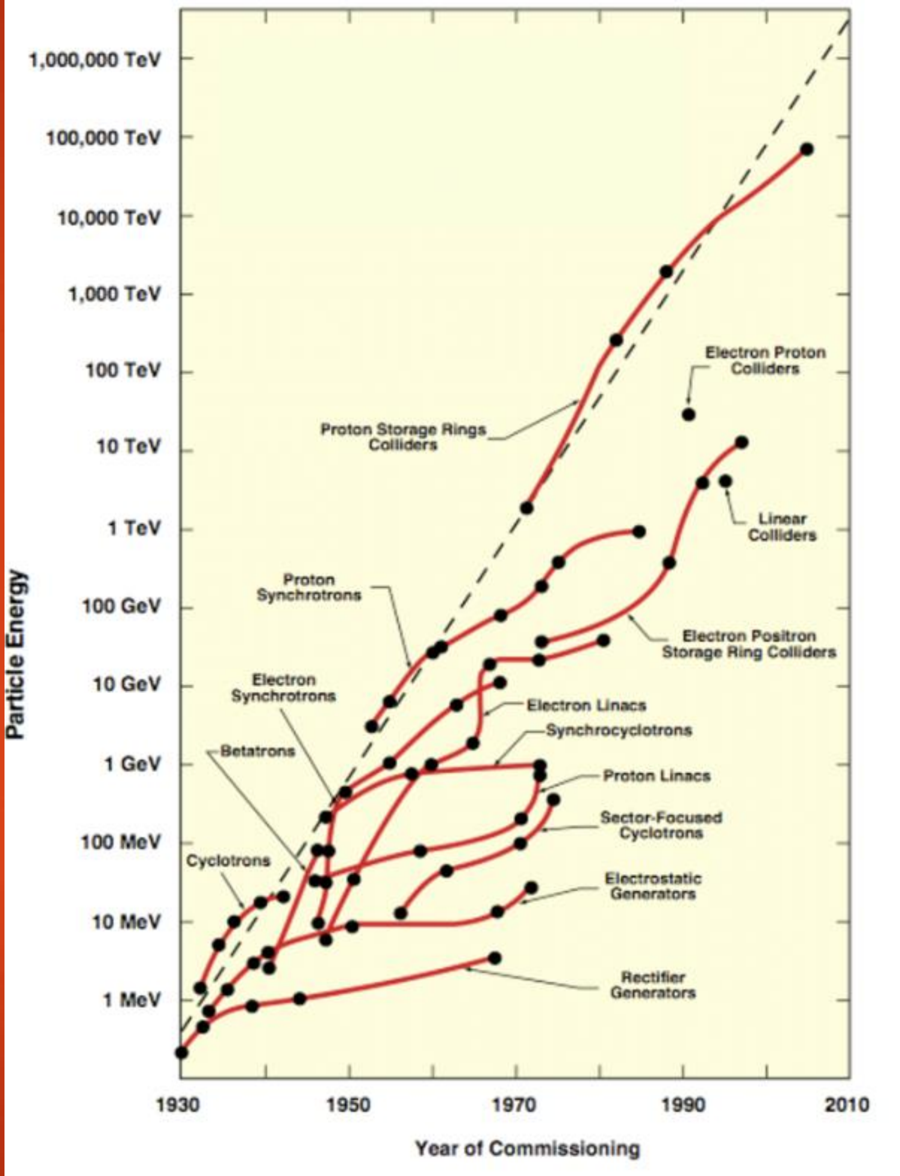


FIGURE 2 Spectra of accelerated electrons: **a** final spectrum of the case of Fig. 1; **b** the case of the 33-fs, 12-J laser pulse, time evolution of the energy spectrum: (1) $ct/\lambda = 350$, (2) $ct/\lambda = 450$, (3) $ct/\lambda = 550$, (4) $ct/\lambda = 650$, (5) $ct/\lambda = 750$ corresponding to Figs. 3, 4, and 5, (6) $ct/\lambda = 850$

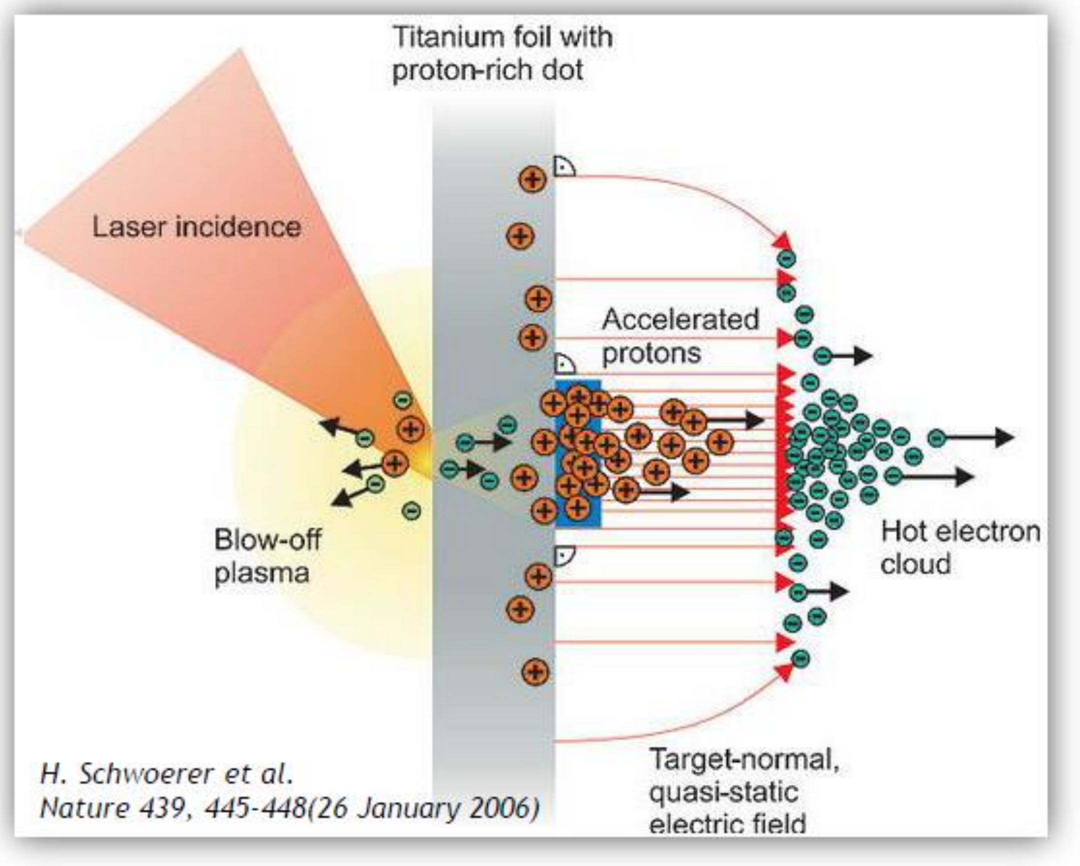
Accelerator limits

- Particle accelerators development is slowing down.
- The accelerating gradient, tipically of the order of 100 MV/m is reaching its maximum
- The extreme operating conditions in advanced accelerators are increasingly approaching the material breakdown limit.
- The infrastructure required for high-energy particle accelerators demands vast physical space.



Ion acceleration

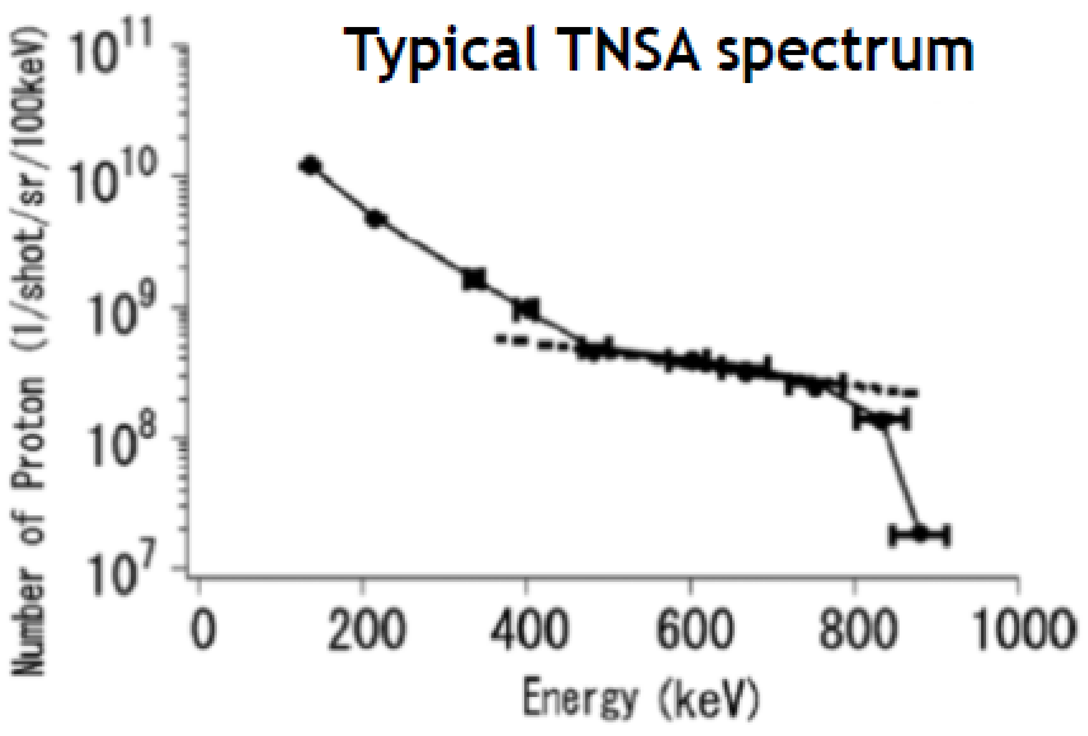
- An high-intensity laser pulse, focused onto a thin solid target, heat up the electrons that move through the material emarging from the rear side.
- The electron cloud create a charge separation and consequentially an electric field called sheath field (TV/m).
- The ions on surface could be accelerated to a speed similar to the electron which means that the kinetic energy is higher than a factor Mi/me.
- This technique is know as Target Normale Sheath Acceleration (TNSA).
- But the ions reaction time to the field is too low and the electric field is stationary to respect the foil target.



H. Schwoerer et al. Nature 439, 445-448(26 January 2006)

TNSA limitations

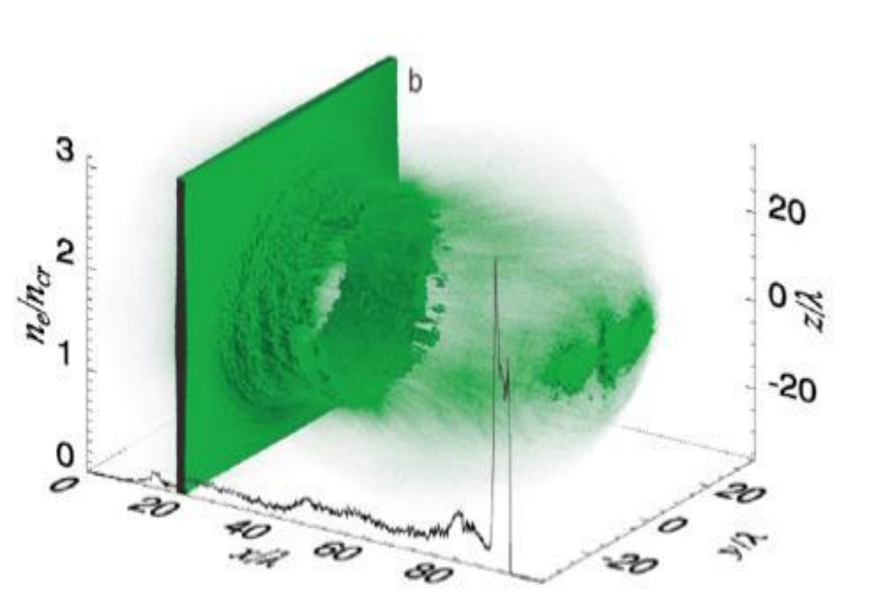
- In the year 2000 the first experiment to collectively accelerate ions by laser irradiation of a µm thick foil were reported.
- A cut off in the ion energy was observed due to different factors:
  - Ions are too slow to react to the sheath field to their mass.
  - Sheath field is stationary to the target edge and acceleration could take place only in that field.
  - Electrons slow down due to the ions attraction, resulting in a reduced sheath field

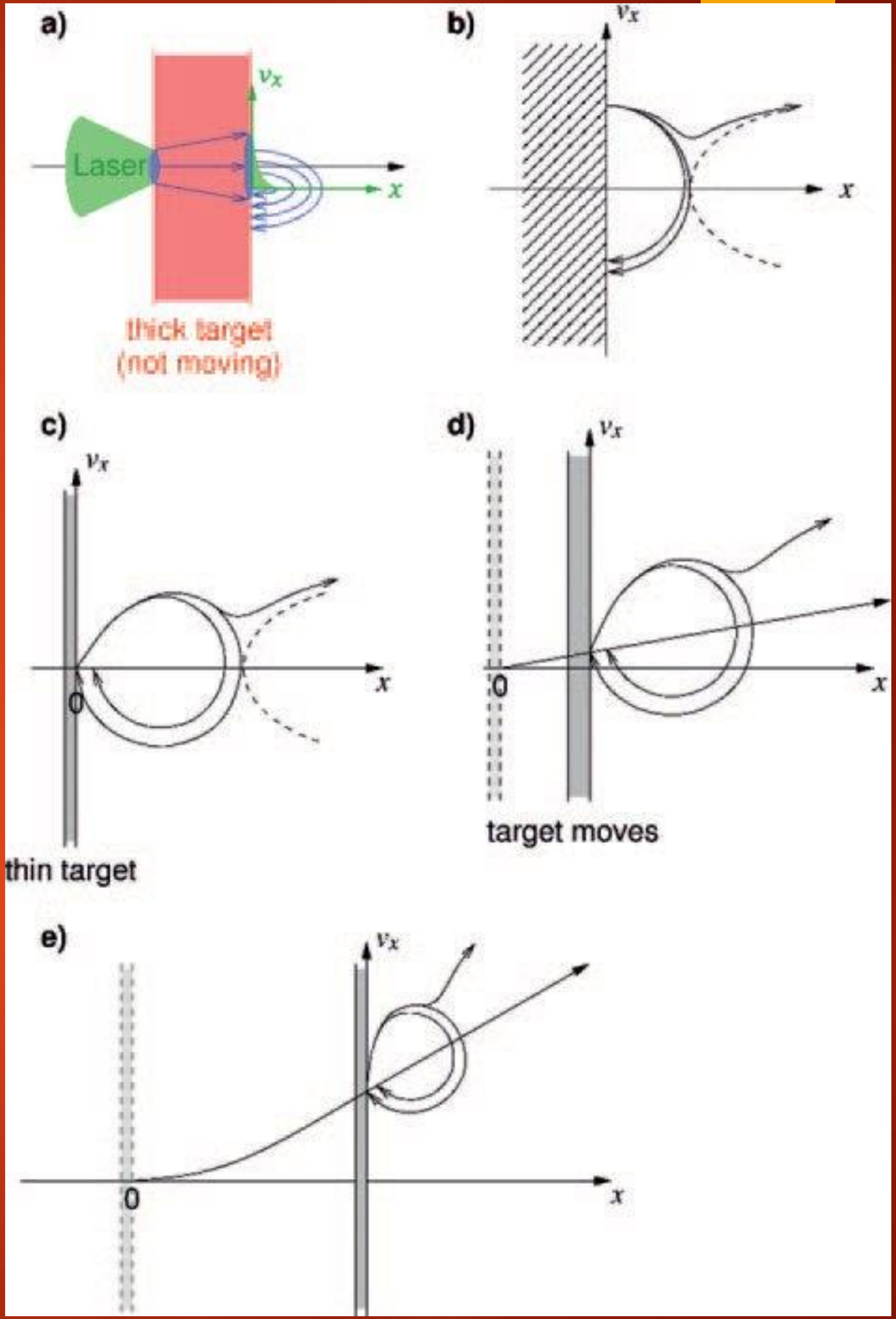


M. Nishiuchi et al.
Phys Rev Letter A - 357 339-44 (2006)

Thinner foil

- Reducing the foil thickness the electron energy is directly correlated to the laser intensity determining a narrower ion energy distribution.
- Irradiating a thinner foil a portion of the target is accelerated along the electron.
- This mechanism is called Radiation Pressure Acceleration (RPA)



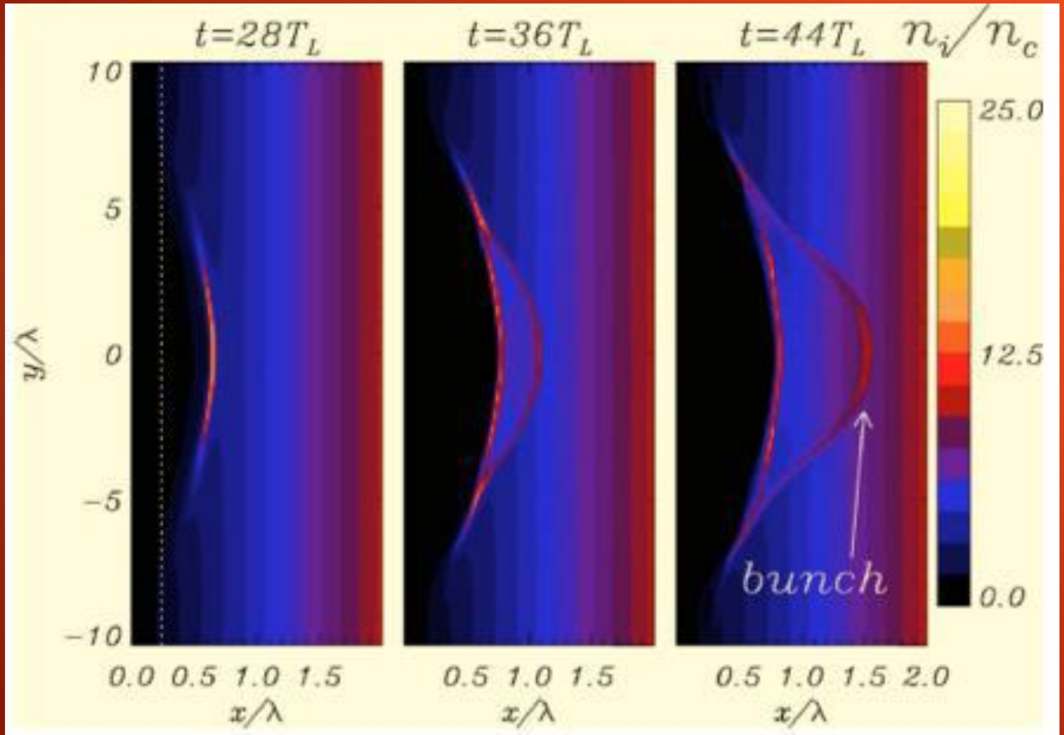


Radiation Pressure Acceleration

- There are two techniques to apply the RPA mechanism.
- Acceleration of all the ions with an energy that scales with the instensity I^2

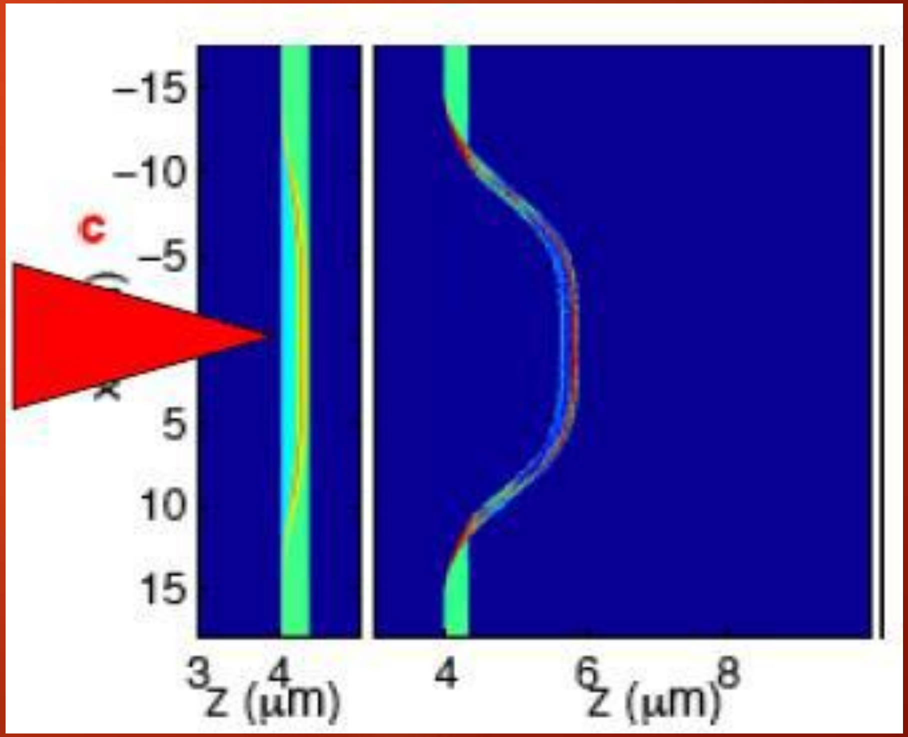
- Hole-Boring

  (thick, µm targets)



- Light-sailing

  (thin, nm targets)



Conclusion

- Radiation pressure effects was theoritized centuries ago but we waited only the last century to understand how use the light to manage the matter cynematic.
- Lasers occupy the central role for these studies.
- Atom trapping in a Magnetic Optic Trap is possible combining the Molasses optical effect, a magentic field gradient and the selection rules induced by counter propagating laser system.
- In many cases the "Sysiphus cooling" can be applied to reach μK temperature.
- Collective motion induced by laser interaction with plasma can accelerate electrons with acceleration gradient > 10GeV/m.
- The Target Normal Sheath Acceleration and Radiation Pressure Acceleratoin techniques featuring the laser interaction with low thickness material can accelerate ions.
- The studies on such accelerators are still on going to tune foil thickness and laser intensity to get monochromatic and collimated ion beams.