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Physics

The Fusion of Oppositely Moving Ion Bunches and the Formation of a ”Stationary“ Ion Bunch

David Garuchava*, Ketevan Sigua*

* *Elevter Andronikashvili Institute of Physics, Ivane Javakhishvili Tbilisi State University, Georgia*

(Presented by Academy Member George Chagelishvili)

Abstract. Using one-dimensional multifluid hydrodynamic simulations, we study the formation of relativistic ion bunches from overdense plasma foils irradiated by a circularly polarized pulse at 10^{24} w/cm^2 intensity. In particular, we have investigated the interaction of oppositely moving bunches. Oppositely moving bunches composed of identical ions but with different parameters pass through each other without noticeable change. The same occurs when bunches composed of different ions collide. The collision process differs when two ion bunches of the same composition and identical parameters interact. After their centers collide, the bunches themselves appear to "stop", but the ions inside continue circulating at relativistic speeds. The average rotational speed of the ions is on the same order as the velocity at which the bunch centers approached each other prior to collision. Calculations show that when two bunches with slightly different parameters (5-10%) collide, the resulting "stationary" bunch has a common center that moves at a non-relativistic velocity much lower than the initial bunch speeds. The smaller the difference between the initial parameters, the lower this residual velocity becomes. When merged bunches move at significantly lower, carefully selected optimal speeds, the interaction time is much longer, allowing the majority of ions to take part in the reaction. This significantly increases the efficiency of their use in nuclear applications.

Keywords: ion bunch, nuclear, plasma

Introduction

Currently, in some scientific centers of the world, the 10PW extra-intense lasers are being constructed. The pulse duration of these lasers is 15-100 fs, and radiation intensity in focus area is more than 10^{24}w/cm^2. The huge radiation pressure (>10^{15}atm) of such pulses causes hard compression of the target and acceleration of its particles to relativistic velocities (Esirkepov, et al., 2000; Robinson, et al., 2008; Chen, et al., 2009). The bunches developed in Radiation Pressure Dominant (RPD) regime, are characterized with high dense (10^{23}-10^{25}cm^3), small thickness (several μkm), low spread angle (4°-6°) and ultrahigh energy of particles (GeV degree). All this and electro-neutrality of plasma bunches give a certain privilege for production of driven nuclear reactions, as compared to accelerated nuclear beams in common colliders. In this respect, the discussion on the application of extra-intensive lasers has recently started and there is an expectation that this theme will attract more attention in the future as in the control fusion, as well as in production of rare isotopes (Macchi, et al., 2005; Ribeyre, et al., 2009; Atzeni, et al., 2015; Garuchava, et al., 2012).

Equations and Results of Numerical Simulations

The generation, propagation, and interaction of ion beams in the radiation-pressure-dominant (RPD) regime are described by a three-component system of Maxwell's equations. Two of these components represent different types of ions, while the third represents electrons. To simplify the solution of this highly nonlinear, multi-equation system, a one-dimensional approximation was considered (the equations are expressed in a dimensionless form):

$$\mathrm{rot}\,\vec{A}=\vec{B},\ A_z \ll A_\perp \equiv A,\ -\mathrm{grad}\varphi=\vec{E}, E_z \gg E_\perp,$$

$$\frac{\partial^2 A}{\partial \tau^2}-\frac{\partial^2 A}{\partial z^2}+\omega^2\left(\frac{n_e}{\gamma_e}+\frac{n_i}{\gamma_i}\right)A=0,$$

$$\frac{\partial p_e}{\partial t}+\frac{\partial \gamma_e}{\partial z}=-\frac{\partial \varphi}{\partial z}-\alpha n_e\frac{\partial n_e}{\partial z}-$$

$$-\beta\gamma_e p_e\left\{\left(\frac{\partial\varphi}{\partial z}\right)^2+\left(\frac{p_e}{\gamma_e}\frac{\partial\varphi}{\partial z}\right)^2\right\},$$

$$\frac{\partial p_{i1,2}}{\partial t}+\frac{\partial \gamma_{i1,2}}{\partial z}=\frac{\partial\varphi}{\partial z},$$

$$\frac{\partial n_e}{\partial t}+\frac{\partial}{\partial z}\left(\frac{n_e}{\gamma_e}p_e\right)=0,$$

$$\frac{\partial n_{i1,2}}{\partial t}+\frac{\partial}{\partial z}\left(\frac{n_{i1,2}}{\gamma_{i1,2}}p_{i1,2}\right)=0,$$

$$\frac{\partial^2\varphi}{\partial z^2}=n_e-n_1-n_2,$$

$$\gamma_e^2=1+A^2+p_e^2,\ \gamma_{i1,2}^2=\frac{m_{i1,2}}{m}+A^2+p_{i1,2}^2,$$

$$\alpha=3\frac{T_0}{mc^2},\ \beta=\left(\frac{4\pi}{3}\frac{r_e}{\lambda}\right)^2,\ r_e\equiv\frac{e^2}{mc^2},\ \lambda=2\pi/\omega_0,$$

$$n_e\equiv n_e/n_{0e}, n_{i1,2}\equiv n_{i1,2}/n_{0e},\ t\equiv\omega_0 t,\ z\equiv\frac{\omega_0 z}{c},$$

$$\varphi\equiv\frac{e^2}{mc^2}\varphi,\ A\equiv\frac{e}{mc^2}A,\ A^2\equiv|A|^2,\ p_e\equiv\frac{p_e}{mc},$$

$$p_{i1,2}\equiv\frac{p_i}{mc},\ \omega\equiv\frac{\omega_{pe}}{\omega_0},\ E\equiv\frac{e}{m\omega_0 c^2}E,$$

With initial and boundary conditions:

$$A\equiv A_0\exp\left[-0.5\left(z-z_0-t\right)^s/a_z^s\right]$$
$$\left\{\overline{x}\cos\left(z-z_0-t\right)+\overline{y}\cos\left(z-z_0-t\right)\right\},$$
$$n_e\left(t=0\right)=$$
$$\frac{1}{2}n_{e0}\left[\tanh\left(\frac{z+z_d/2}{z_\ell}\right)-\tanh\left(\frac{z-z_d/2}{z_\ell}\right)\right],$$
$$n_{i1,2}\left(t=0\right)=$$
$$=\frac{1}{2}n_{i1,2}\left[\tanh\left(\frac{z+z_d/2}{z_\ell}\right)-\tanh\left(\frac{z-z_d/2}{z_\ell}\right)\right],$$

where E denotes the longitudinal electrostatic field; A and φ are the vector and scalar potentials of the electromagnetic field, respectively; e, m, n_e, and p_e are the electron's charge, rest mass, concentration, and momentum. Similarly, m_{i1}, m_{i2}, n_{i1}, n_{i2}, p_{i1}, p_{i2} refer to the mass, concentration, and momentum of two different ion species. The last term in the electron motion equation accounts for the radiation reaction force caused by radiation emitted by relativistic electrons accelerated by ultra-intense laser fields (Tamburini, et al., 2010).

When ultra-intense, high-frequency (infrared and more frequency) electromagnetic pulses interact with dense media, the surface layer of the target is instantly and completely ionized at the initial stage. A portion of the high-frequency radiation, although lower in intensity, still remains relativistic and, for which $\omega \gg \omega_{pe}$, penetrates deeper into the medium, further ionizing it. In the case of low-frequency electromagnetic waves, ionization is primarily driven by the giant electrostatic field generated by charge separation. This field strips electrons from atoms directly and causes further ionization through collisions of these accelerated electrons with other atoms. The freed electrons, under the influence of the huge radiation pressure (~10^{15} atm), accelerate to relativistic speeds (~0.8c) in less than a wave period. Due to their large inertia, ions cannot keep up with the electrons in this short time and fail to gain significant speed. This results in the creation of a colossal relativistic electrostatic field between the accelerated electrons and the nearly stationary ions, with a field strength of approximately $\frac{eE_z}{m_e\omega c}$ ~ 100-500. In this field, and under the pressure of the radiation, ions gradually accelerate over several wave periods (depending on their mass and charge) to relativistic speeds (~0.5c). The electrostatic field intensifies at the beginning of the interaction between the electromagnetic wave and the plasma. More and more electrons are struck by the electromagnetic "hammer," causing more of them to outrun the inertial ions. These forward-running relativistic electrons then decelerate in the electrostatic field and due to the radiation reaction force. The leading electrons eventually stop, seemingly waiting for the lagging ones ("not breaking away from the collective"), and begin accelerating again – either pulled by catching-up ions or re-accelerated by another electromagnetic "hammer" (a process that can only occur in the initial stages before the pulse is reflected). Then, new electrons take the lead and repeat the cycle.

Ions behave similarly, though with slower initial speeds: they first accelerate to a peak speed, then decelerate, pause, and begin accelerating again. In this way, electron and ion bunches are formed. Inside these bunches, electrons and ions are constantly in motion – accelerating, decelerating, and re-accelerating – emitting electromagnetic waves throughout this process.The electromagnetic "hammer" progressively acts on deeper layers of the target. These inner-layer particles also begin similar motions and immediately become part of their own bunches. Over time, the bunches grow in thickness and concentration. There is a distinct spacing between the density peaks of the bunches, meaning very strong electrostatic fields exist between them. These fields play a crucial role by preventing bunch dispersion.Eventually, ion bun-

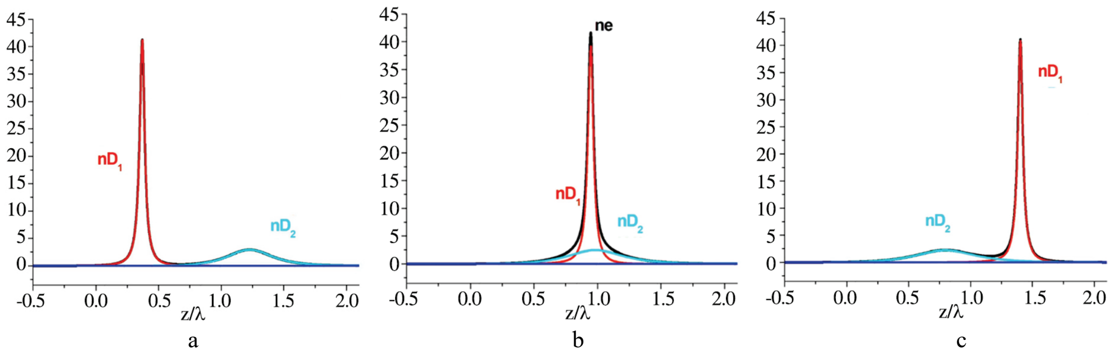

Fig. 1. The interaction dynamics of oppositely moving two deuterium bunches with different parameters: a) before the collision, b) during the collision, and c) after passing through each other.

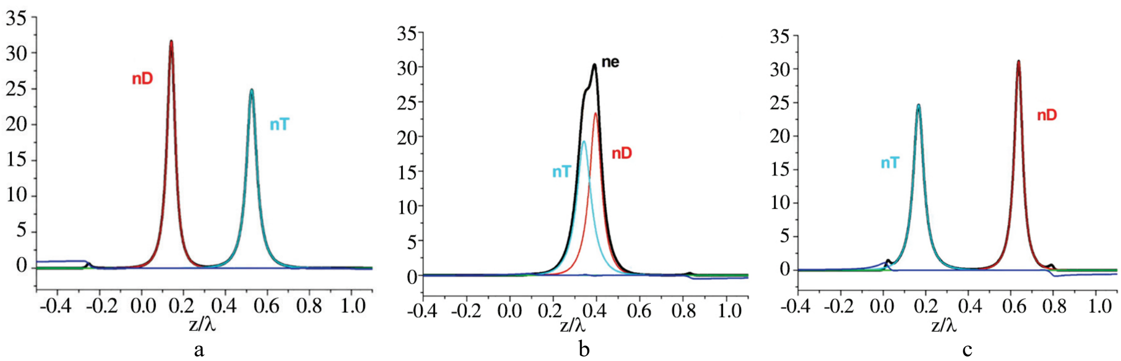

Fig. 2. The interaction dynamics of oppositely moving deuterium and tritium bunches: a) before the collision, b) during the collision, and c) after passing through each other.

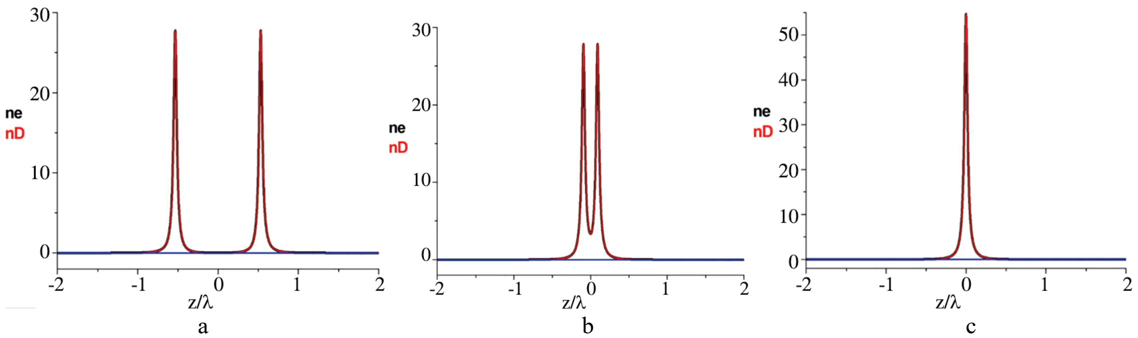

Fig. 3. The collision process of two identical, oppositely moving deuterium bunches: a) prior to the collision, after τ = 12 wave periods after the formation of the bunches; b) the beginning of the collision, at τ = 18; c) bunches merging at τ = 21. This last figure remains virtually unchanged after 100 periods.

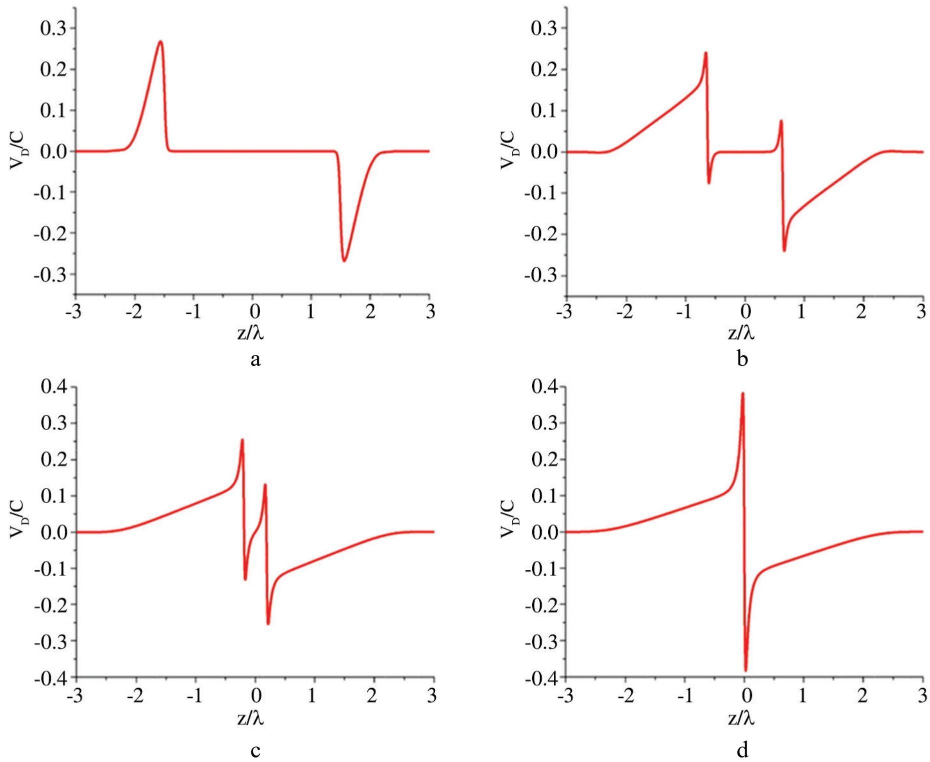

Fig. 4. Distribution of relative ion velocities within the ion bunches: a) at τ = 6, when ions of each bunch begin to influence those of the opposing bunch (onset of front compression); b) at τ = 12, when the leading fronts become more pronounced; c) at τ = 18, at the beginning of the collision, and d) at τ = 21, after the merging.

ches catch up with the electron ones. The electrostatic field weakens but remains significant. As the two bunch types overlap, ions effectively "enclose" the electron cloud. Due to their greater mass and energy, ions become dominant after the pulse is reflected. Even though the electrostatic field becomes smaller compared to its initial value, it still remains substantial. The center of the electron bunch (where concentration peaks) oscillates relative to the center of the ion bunch at a frequency of approximately ω_{pe}/γ_e. The average kinetic energy of ions in such bunches can reach GeV levels (Chen, et al., 2009).

By adjusting the ion and laser pulse parameters for specific nuclear reactions, it is possible to produce optimal energy ion bunches ranging from tens of keV up to several GeV. Moreover, ion bunch concentrations can exceed 10^{25} cm^{-3}, which is critically important for nuclear reactor efficiency. The efficiency of nuclear reactors can be significantly improved if, instead of using relativistic ion bunches, so-called “stationary” ion bunches (moving at speeds much lower than the speed of light) are used. In such bunches, relativistic rotational motion of ions around the bunch center must be maintained. Typically, ion bunches composed of identical ions but with different parameters (e.g., energy, concentration, size) interact similarly to solitons, passing through each other without noticeable change (Fig. 1). The same occurs when bunches composed of different ions (e.g., deuterium and tritium) collide (see Fig. 2).

The collision process differs when two ion bunches of the same composition and identical parameters interact (Fig. 3). As the bunches approach each other, their longitudinal dimensions begin to shrink. In addition to the electrostatic field generated by its own ions, each beam is influenced by the field of the oppositely moving bunch. This effect is stronger at the leading edge of the bunch than at the trailing edge. As a result, ions at the front of the bunch experience sharper deceleration compared to those at the rear, breaking the symmetry of the bunch fronts (Fig. 4a). The closer the bunches get, the more pronounced the deceleration, especially in the velocity distribution at the leading edge. The ions at the front begin returning more rapidly toward the bunch center – where the particle concentration is the highest – than those at the rear (Fig. 4b). After the centers of the bunches collide, the bunches themselves appear to "stop," but the ions inside continue circulating at relativistic speeds (Fig. 4c). The average rotational speed of the ions is on the same order as the velocity at which the bunch centers approached each other prior to collision. This speed can be controlled by adjusting the parameters of the laser pulse and the ultra-dense ion layer. For different types of ion bunches, the rotational energy can be tuned within a fairly wide range – from 10^4 to 10^8 eV.

Conclusion

For each desired nuclear reaction, “stationary“ ion bunches should be used with an average kinetic energy equal to the optimal collision energy established for that specific reaction. The motion of ions within the bunches is ordered, so measuring their energy through temperature (i.e., average kinetic energy of chaotic motion) is not accurate. However, by analogy, the average kinetic energy of the ions in the bunch can be referred to as an „effective temperature“. In relativistic bunches, this effective temperature can reach hundreds of billions of degrees within very small volumes (~100 μm^3) and very short timescales (~10 picoseconds). In practice, producing perfectly identical bunches is impossible. Calculations show that when two bunches with slightly different parameters (5-10%) collide, the resulting "stationary" beam has a common center that moves at a non-relativistic velocity much lower than the initial bunch speeds. The smaller the difference between the initial parameters, the lower this residual velocity becomes. In contrast, when bunches with significantly different parameters interact, their electrostatic fields, particle energies, and rotation frequencies (in the bunch-centered reference frame) differ markedly in both magnitude and frequency. The electrostatic field of one bunch acts on the particles of the other in a non-resonant and ineffective manner. As the buncges pass through each other, the ions remain under the influence of their own bunch’s electrostatic field and do not mix with ions from the interacting bunch.Using bunches formed through “stationary fusion“ for nuclear reactions offers key advantages over relativistic bunches. In relativistic bunches, the high velocities and small longitudinal dimensions result in very short interaction times during bunch-to-bunch collisions. Therefore, despite the extremely high ion densities and optimal collision velocities for nuclear reactions, only a small fraction of the ions has time to participate in these reactions.In contrast, when merged bunches move at significantly lower, carefully selected optimal speeds, the interaction time is much longer, allowing the majority of ions to take part in the reaction. This significantly increases the efficiency of their use in nuclear applications.

ფიზიკა

ურთიერთსაწინააღმდეგოდ მოძრავი იონური გუნდების შერწყმა და „უძრავი“ იონური გუნდის ფორმირება

დ. გარუჩავა*, ქ. სიგუა*

** ივანე ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი, ელეფთერ ანდრონიკაშვილის ფიზიკის ინსტიტუტი, საქართველო*

(წარმოდგენილია აკადემიის წევრის გ. ჩაგელიშვილის მიერ)

ერთგანზომილებიანი მრავალსითხიანი ჰიდროდინამიკური სიმულაციების გამოყენებით ვსწავლობთ ზემკვრივ პლაზმურ შრეებზე წრიულად პოლარიზებული 10^{24} ვ/სმ^2 ინტენსივობის იმპულსებით დასხივებისას რელატივისტური იონური გუნდების ფორმირებას. კერძოდ, ჩვენ ვიკვლევთ ურთიერთსაწინააღმდეგოდ მოძრავი გუნდების ურთიერთქმედებას. ერთნაირი იონებისგან შემდგარი ურთიერთსაწინააღმდეგოდ მოძრავი განსხვავებული პარამეტრების გუნდები გადიან ერთმანეთში შესამჩნევი ცვლილებების გარეშე. იგივე ხდება სხვადასხვა იონებისგან შემდგარი გუნდების შეჯახებისას. დაჯახების პროცესი განსხვავდება, როდესაც ერთი და იმავე შემადგენლობისა და იდენტური პარამეტრების მქონე ორი იონური კონა ურთიერთქმედებს. კონების ცენტრების შეჯახების შემდეგ, სხივები თითქოს „ჩერდებიან“, მაგრამ შიგნით არსებული იონები აგრძელებს ცირკულაციას რელატივისტური სიჩქარით. იონების საშუალო ბრუნვის სიჩქარე იმავე რიგისაა, როგორი სიჩქარითაც სხივის ცენტრები ერთმანეთს მიუახლოვდა შეჯახებამდე. გამოთვლები აჩვენებს, რომ როდესაც ორი კონა ოდნავ განსხვავებული პარამეტრებით (5-10%) ეჯახება ერთმანეთს, შედეგად მიღებულ „სტაციონალურ“ სხივს აქვს საერთო ცენტრი, რომელიც მოძრაობს არარელატივისტური სიჩქარით, რაც გაცილებით დაბალია, ვიდრე საწყისი კონების სიჩქარეები. რაც უფრო მცირეა სხვაობა საწყის პარამეტრებს შორის, მით უფრო დაბალია ეს სიჩქარე. როდესაც გაერთიანებული კონები მოძრაობს მნიშვნელოვნად დაბალი, წინასწარ შერჩეული ოპტიმალური სიჩქარით, ურთიერთქმედების დრო გაცილებით გრძელია, რაც საშუალებას აძლევს იონების უმეტესობას მიიღოს მონაწილეობა რეაქციაში. ეს მნიშვნელოვნად ზრდის მათი გამოყენების ეფექტურობას ბირთვულ რეაქტორებში.

REFERENCES

Atzeni, S. et al. (2015). High gain target performance for inertial fusion energy. *Plasma Phys. Control. Fusion, 57,* 014022-11.

Chen, M. et al. (2009). Enhanced collimated GeV monoenergetic ion acceleration from a shaped foil target irradiated by a circularly polarized laser pulse. *Phys. Rev. Lett*., *103,* 024801-4.

Esirkepov, T. et al. (2004). Highly efficient relativistic-ion generation in the laser-piston regime. *Phys. Rev. Lett., 92*, 175003-4.

Garuchava, D. et al. (2012). Fusion and fision of rare radioactive isotops by laser driven ions. *Bull. Georg. Natl. Acad. Sci., 6*(1), 74-77.

Macchi, A. et al. (2005). Laser acceleration of ion bunches at front surface of overdense plasmas. *Phys. Rev. Lett*., *94*, 165003-4.

Ribeyre, X. et al. (2009). Studies on shock ignitions targets for inertial fusion energy. *Plasma Phys. Control. Fusion, 51,* 015013-7.

Robinson, A.P. et al. (2008). Radiation pressure acceleration of thin foils with circularly polarized laser pulses. *New J. Phys.*, *10,* 013021-12.

Tamburini, M. et al. (2010). Radiation reaction effects on radiation pressure acceleration. *New J. Phys. 12,* 123005-15.

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