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マイクロバブル爆縮による超高場と高エネルギープロトンの生成
Generation of Ultrahigh Field and Relativistic Protons by Bubble Implosion

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We propose a novel concept of micro-bubble implosions. A micro-bubble implosion combines micro-bubbles and ultraintense laser pulses of 10^{20} - 10^{21} W cm^{-2} at a high repetition rate to generate ultrahigh fields and relativistic protons. The bubble wall protons undergo volumetric acceleration toward the center due to the spherically symmetric Coulomb force and the innermost protons accumulate at the center with a density comparable to the interior of a white dwarf. Then an unprecedentedly high electric field is formed, which produces an energetic proton flash. We have confirmed the robustness of Coulomb-imploded bubbles in terms of three-dimensional particle simulations, which behave as nano-pulsars with repeated implosions and explosions to emit protons.

Suppose that spherical bubbles with radii of the order of $R_0 \cong 0.1$ - 10 μm are contained in a uniform solid target, which is assumed here to be pure hydrogen just for simplicity. When irradiating the target by ultraintense femtosecond laser pulse with an intensity of $I_L \cong 10^{20}$ - 10^{22} W cm^{-2}, hot electrons with temperature of $T_e \cong 10$ - 100 MeV are generated. The hot electrons run around in the target to ionize the atoms to the ionization state $Z = 1$ almost instantaneously with its initial solid density $n_{i0} = 5 \times 10^{22}$ cm^{-3} being kept constant. The hot electrons fill the bubbles in a very short period of the order of a few fsec (Fig.1(a)). It should be noted that the high mobility of hot electrons often results in unwelcome energy dissipation and entropy increase in many applications. However, in the present scheme, such features of electrons play the crucial role

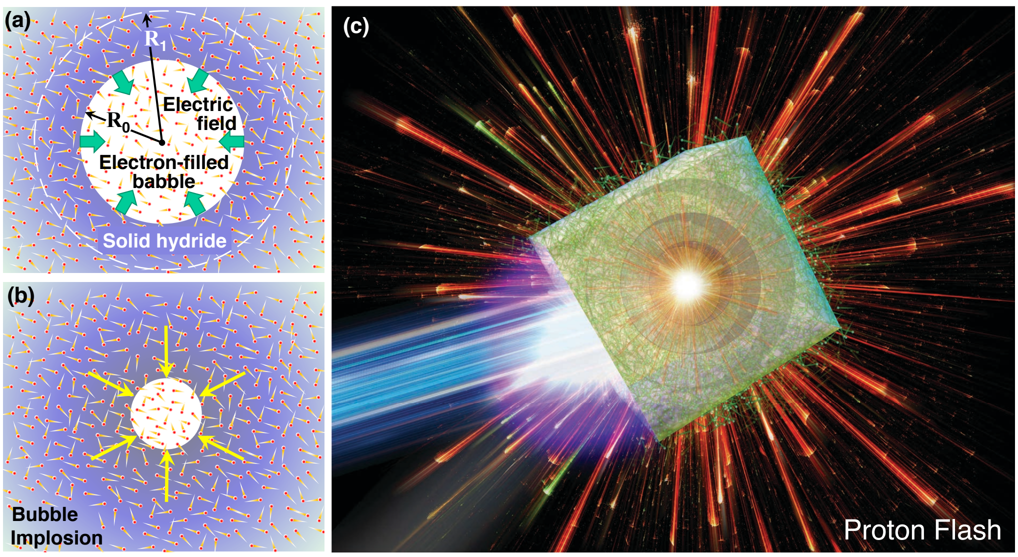

Figure 1. (**a**) Initial phase: The inner volume of a bubble surrounded by solid matter is filled with hot electrons. Bulk atoms composing the solid matter will be ionised in a very short time to "feel" the volumetric Coulomb force because of the bubble electrons. (**b**) bubble implosion phase: The ions begin to accelerate toward the bubble centre in a spherically symmetric manner, where the innermost ions are most strongly accelerated until the very final moment of the collapse at the centre. (**c**) Envisioned picture showing the whole main events integrated, i.e., laser illumination, hot electron spread, implosion, and proton flash.

to provide super high uniformity of the implosion and an ultrahigh field. Because of the electrons flying in the bubble, the ions on the bubble surface “feel” strong electrostatic (Coulomb) force and begin volumetric implosion toward the bubble center as illustrated in Fig.1(b). The innermost ions continue to implode until they are unprecedentedly compressed to a nanometer scale such that their radial inward motion is stopped by the resulting outward electric field. Upon collapse of the bubble, the innermost ions “find” that their following ions just behind them have built up an extraordinary steep slope of Coulomb potential. Then they slide down the slope with resulting energies many times higher than the energy gained during the implosion. Figure 1(c) illustrates the envisioned mechanism with the main events depicted on the same image, i.e., laser illumination, hot electron spread, implosion, and proton flash.

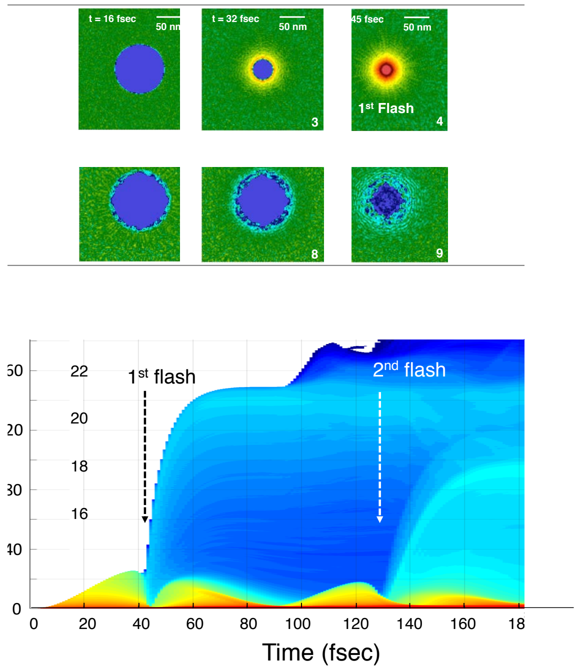

Figure 2 shows three-dimensional PIC simulation result for bubble implosion by using a proton plasma. Each side of a periodic cube box and the cell size are set to be 240 nm and 2 nm, respectively. At t = 0, the interior of the bubble with R_0 = 60 nm is perfect vacuum. An otherwise uniform plasma composed of cold ions and hot electrons characterized by T_e = 1 MeV, Z = 1, and n_{i0}= 3 × 10^{21} cm^{-3} are initiated. (a) Snapshots of the bubble collapse with the proton density distributions color-coded. The bubble is found to pulsate repeating implosion and explosion. (b) Temporal evolution of the proton energy spectrum for the same case as (a). At each collapse, proton flash is observed. The bubble thus behaves as a nano-pulsar, alternating implosions and explosions to periodically emit energetic protons. The highly robust bubble oscillation is attributed to the collective nature of the spherically symmetric Coulomb system.

In short, we propose a novel concept, bubble implosion, to generate an ultrahigh field to accelerate pro- tons to relativistic energies. A simple model and 1D, 2D, and 3D simulations comprehensively investigate the dynamics of the bubble implosion. This phenomenon is very likely to occur in reality. A stable implosion shrinks to a nanometer size and achieves an ultradense proton core, forming an unprecedentedly high electric field and producing proton flashes. The generation of an ultrahigh field is attributed to spherical convergence to the center. Moreover, Coulomb-imploded bubbles are robust and behave as nano-pulsars repeating implosion and explosion to emit energetic protons. Although the present paper assumes pure hydrogen targets, a modified scenario should be applicable to other hydrides.

Current laser technology is suitable to experimentally identify bubble implosion by observing proton emissions at relativistic energies, which will be a major breakthrough to crack the 100-MeV barrier. For such experiments, a uniform and well-activated Coulomb field must be created inside the bubbles by laser irradiation of micron-sized bubbles embedded inside a solid target. We have demonstrated in terms of the 2D simulation that a symmetric bubble implosion can be achievable even under a realistic condition of laser-matter interaction. Consequently, the present concept should provide a new platform to elucidate fundamental phenomena in the fields of high-energy-density physics and astrophysics.

Reference “Generation of ultrahigh field by micro-bubble implosion”
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