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Energy Penetration into Arrays of Aligned Nanowires Irradiated with Relativistic Intensities: Scaling to Terabar Pressures

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Abstract

Ultra-high-energy-density (UHED) matter, characterized by energy densities > 1 x 10^8 J cm^{-3} and pressures greater than a gigabar, is encountered in the center of stars and in inertial confinement fusion capsules driven by the world's largest lasers. Similar conditions can be obtained with compact, ultra-high contrast, femtosecond lasers focused to relativistic intensities onto targets composed of aligned nanowire arrays. Here we report the measurement of the key physical process in determining the energy density deposited in high aspect ratio nanowire array plasmas: the energy penetration. By monitoring the x-ray emission from buried Co tracer segments in Ni nanowire arrays irradiated at an intensity of 4 x 10^{19} W cm^{-2}, we demonstrate energy penetration depths of several μm, leading to UHED plasmas of that size. Relativistic 3D particle-in-cell-simulations, validated by these measurements, predict that irradiation of nanostructures at intensities of > 1 x 10^{22} W cm^{-2} will lead to a virtually unexplored extreme UHED plasma regime characterized by energy densities in excess of 8 x 10^{10} J cm^{-3}, equivalent to a pressure of 0.35 Tbar.

Introduction

Laboratory creation of matter in the ultra-high-energy-density (UHED) regime is of great interest for the realization of inertial confinement fusion [1-2], to further the understanding of atomic processes in astrophysical and extreme laboratory environments [3-5], and to generate intense sources of x-rays and high energy particles [6-7]. However, the creation of matter in this regime in the laboratory has been limited to the central hot-spot of the spherically imploded capsule in inertial confinement fusion experiments conducted using the world's highest energy lasers [8-9]. The ability to create UHED matter using smaller facilities is thus of great interest in order to make this extreme plasma regime more accessible for fundamental studies and applications. One such application is the efficient conversion of optical laser light into bright flashes of x-rays, which requires the radiative lifetime of the plasma to be shorter than the hydrodynamic cooling time. This in turn demands simultaneously having a large collision rate (and therefore a large density of energetic electrons), and a large plasma size. However, heating a large UHED plasma volume is a challenge that even many of today's most powerful lasers fall short of achieving when irradiating solid slab targets. In such a conventional heating scheme, the leading edge of the laser pulse rapidly creates a plasma blow-off, which prevents the remainder of the laser pulse from directly heating the solid region of the target. Heating by hot-electrons using today's most energetic short pulse lasers have just surpassed the boundary into the UHED regime (e.g. achieving 2 Gbar). For example, temperatures of 0.6 keV at density 1.5 g/cc were recently reported for a 0.15 μm thick Al foil tamped by 10 microns of plastic on both sides, irradiated by 100 J pulses of 0.5 ps duration [10]. Simulations indicate a pressure of 0.5 Gbar and an energy density approaching 1 x 10^8 J cm^{-3} J was obtained. Similar temperatures were achieved at a density of 9 g/cc, and therefore higher pressure and energy density, using diamond tamped Al targets compressed with a pair of 200 J long laser pulses before the arrival of the short heating pulse. Several other experiments in which pulses of 0.35-2 ps duration irradiated plastic foils with buried metal layers reported similar temperatures [11-14]. Heating with 400 J pulses of 0.8 ps duration achieved a 5 keV surface temperature decreasing to 0.6 keV at 1.3 μm depth [15].

Alternatively, irradiation of high aspect-ratio vertically-aligned nanowire arrays with ultra-high contrast femtosecond laser pulses of only Joule-level energy provides a unique combination of nearly complete optical absorption and drastically enhanced light penetration into near-solid density targets, allowing the material to be volumetrically heated deep into the UHED regime. Other types of structured targets have also been successfully used to increase absorption, as evidenced by enhanced x-ray emission from "smoked" targets [16], nanospheres [17], gratings [18-19] and "velvet" nanowire targets [20-23]. However, high aspect ratio aligned nanostructures with vacant spaces surrounding them are unique in allowing for the deep penetration of ultrafast optical laser pulse energy into the material, where light is trapped and

practically totally absorbed [24]. Electrons ripped off the nanowire surface by the large laser field are accelerated to acquire high energy in the voids. Collisions of these energetic electrons with the nanowires rapidly heats the material to extreme temperatures, causing the nanostructures to explode and rapidly fill the voids. When the gaps are filled with plasma, a continuous critical electron density layer is formed that forbids further coupling of laser energy into the material. The use of sufficiently short laser pulses allows for very efficient coupling of the pulse energy deep into the nanowire array, heating a large volume of near solid-density material several microns in depth to multi-keV temperatures. This new approach to volumetric heating opens access to the UHED plasma regime using table-top, Joule-class sub-hundred-femtosecond lasers.

Considering that the aligned nanowire arrays are highly optically absorbent, the heat penetration depth into the arrays is the key unknown parameter for determining the plasma volume heated and thus the deposited energy density. Herein we report the first definitive measurement of the volume of heated material in arrays of high aspect ratio aligned nanowires irradiated by femtosecond pulses of relativistic intensity. We present the results of experiments at an intensity of 4×10^{19} W cm^{-2} that show heating of near-solid density matter to multi-keV temperatures over depths of several microns. The results serve to validate a model of the relativistic interaction that is used to study the physics of these unique plasmas and to predict the UHED conditions that will be achieved when the intensity is increased to the limit of currently available laser systems and beyond. As shown below, this approach promises to achieve unprecedented energy densities in excess of 8×10^{10} J cm^{-3}, equivalent to 0.35 Tbar pressures using existing ultrafast laser facilities.

The measurement technique consists of monitoring the He-α line emission from buried nanowire segments of a selected tracer material. This required growing arrays of ordered nanowires that have a compositional change along the length of each nanowire (Fig. 1a, 1b). We found it advantageous to choose neighboring elements on the periodic table that have similar ionization dynamics for the top and buried (tracer) segments to form an array that does not differ significantly from one of uniform composition. This selection also allows the characteristic spectral lines of both materials (e.g. the He-α lines) to be recorded simultaneously within the spectral window of a single crystal spectrometer. In this experiment, the composition of the top segment of the nanowires was nickel (Z=28), and the buried tracer element was cobalt (Z=27). The experiments were simulated using the combination of a relativistic 3-D particle-in-cell- PIC code in combination with a transient atomic kinetics and radiation transport model.

Results and Discussion

The experiments were conducted by irradiating the segmented nanowire arrays with λ= 400 nm, ultra-high intensity contrast (>10^{12}) pulses of 0.6 J of energy and 55 fs FHWM duration from a frequency doubled Titanium:Sapphire laser at Colorado State University (see Materials and Methods). The ultra-high contrast is crucial to preserve the nanowires until the arrival of the intense laser pulse. The laser pulses were focused onto the nanowire arrays using an f/2.7 parabolic mirror. The emitted x-ray radiation was analyzed with a von Hamos crystal spectrometer [25] in which a mica crystal spectrally disperses the signal onto a 2D back-thinned CCD sensor array.

Figure 1c shows a single-shot spectrum from an irradiated dual composition Ni-Co nanowire array in which the He-like lines of the Ni and Co segments were simultaneously recorded. Both materials have a high Young's modulus, which facilitates the growth of arrays of well aligned, high aspect ratio nanowires. The nanowire arrays were grown by sequential electro-deposition of the selected metals into porous anodic aluminum oxide membranes. Subsequent dissolution of the membranes results in free-standing aligned nanowire arrays (see Materials and Methods). The compositional change was thus created by first growing 3-4 μm long Co nanowires at the base of each array, followed by the growth of segments of Ni of several selected lengths on top. The change in composition along the nanowires is visible in the scanning electron microscope energy dispersive spectroscopy (EDS) measurement shown in Fig. 1b. The arrays used in the experiment consisted of nanowires 55 nm in diameter spaced such that the array had an average atomic density corresponding to 13% of solid density.

Figure 2 shows a series of measured spectra resulting from irradiating Ni-Co nanowire targets in which the top wire segment of Ni increases in length from 1.5 μm to 5 μm. The spectra show an increase in the He-like Ni line emission signal and a corresponding decrease in the Co He-like signal as the length of the top Ni nanowire segment increases. In the case of the array with a 1.5 μm-long top Ni layer, the Co lines dominate. This is a first clear indication that the heat penetrates more than 3 μm along the length of the nanowires. A decrease in intensity of the Co lines is subsequently seen as the length of the top nickel layer is increased. The emission from He-like Co ions is observed for targets with up to 4 μm of Ni on top. As the top Nickel layer reaches 5 μm in thickness, the Co lines decrease in intensity to a level near that of the continuum background signal that results from bremsstrahlung and radiative recombination. This demonstrates, in agreement with the simulations discussed below, that sufficient heat to ionize Co ions to the He-like stage penetrates at least 4 micron deep into the near-solid density material. Figure 3 plots the measured peak intensity of the Co and Ni He-α lines as a function of Ni nanowire segment length. The Ni lines become stronger as the length of the top segment of this material is increased up to 3-4 μm, length beyond which their strength

saturates. Simultaneously the strength of the Co lines decreases until they disappear into the continuum when the Ni segments reach 5 micrometers in length.

Simulations of the x-ray emission spectra of arrays with top Ni segments of different length were conducted with a transient atomic kinetics and radiation transport model that uses the electron energy distribution computed the by relativistic 3D PIC simulations (see Materials and Methods). The synthetic spectra (top row of Fig. 4) closely replicate the observed features of the experimental data. The bottom panel of Figure 4 illustrates the good agreement between the measured and simulated Co/Ni line ratios as a function of Ni wire segment length. Figure 5 shows the simulated spatial distribution of He-like Ni and Co ions for an array with a top segment of 3 μm Ni nanowires after the peak of the laser pulse. It illustrates the generation of He-like Co ions several microns under the top Ni nanowire layer. The agreement between measurement and simulations validate the model, which is used below to predict the plasma conditions that could be obtained by increasing the irradiation intensity.

The energy density and pressure for hot electron gases are given by integrals of the energy and momentum-velocity product, weighted by the distribution function. We have calculated the energy density directly from the particle data from the PIC simulation, and estimated the pressure from that, using a formula for an equilibrium relativistic gas, accurate to 1 % [26] (see Materials and Methods). Computed maps of the kinetic energy density at four different times during the plasma evolution are shown in Fig. 6. Optical field ionization is observed to begin the heating process at the nanowire surface, with the strong electric field of the laser pulse stripping electrons and creating ionization states up to Z = 18. The electrons are rapidly accelerated into the gaps. Collisional electron impact ionization produces higher ionization states as the hot electron population deposits its energy deep into the nanowire cores. The electrons stripped from the wires are accelerated towards the substrate. Charge balance demands the generation of a large laser-induced return current through the nanowires. The resulting strong quasi-static self-generated azimuthal magnetic field pinches the nanowires into a hot, extremely dense plasma [27]. A plasma density surpassing 10^{24} cm^{-3} with an energy density of 22 GJ cm^{-3} and pressure of 125 Gbar is quickly reached within the wires near their tips (+4 fs frame in Fig. 6). The laser pulse continues to propagate down the length of the wires and deep into the array as long as the inter-wire gaps remain free of dense plasma. As the wires expand, the inter-wire gaps are filled with a super-critical density plasma. Collisions homogenize the plasma, creating a uniform plasma layer several microns thick in which the atoms are ionized up to the He-like stage observed in the measurements. In the two earliest frames in Fig. 6 (+4 fs and +44 fs), the wire tips appear to be loosely connected by regions of higher energy density. This is a result of the array geometry in which the gaps are narrower in the directions directly between wires. These narrower gap regions thus fill with particles quicker and reach higher energy densities faster than the diagonal regions. Expansion of the

wires continues to progressively close the inter-wire gaps along the length of the wires (+124 fs frame in Fig. 6) until the whole target cross section is filled with material at an energy density of 1 GJ cm^{-3} and pressure of 7 Gbar (+304 fs frame in Fig. 6). A thermalized electron temperature of ~ 14 KeV is reached over the plasma volume with an average electron density greater than 3 x 10^{23} cm^{-3}. Even higher plasma densities can be obtained irradiating arrays with higher wire filling factors, arrays made of a higher Z material, or a combination of both. As an example in the supplemental material we include a spectrum of a Ni nanowire target with an average atomic density corresponding to 30% solid density irradiated at an intensity of 4 x 10^{19} W cm^{-2} (Fig. S3). The spectrum is again dominated by He-like and Li-like lines, which indicate the high degree of ionization in maintained. In this case the average electron density of the homogenized plasma increases to ~ 7 x 10^{23} cm^{-3}, nearly 100 times the critical density.

We have conducted additional PIC simulations to predict the plasma conditions that could be achieved by further increasing the laser irradiation intensity to 1 x 10^{22} W cm^{-2} (a_0= 34). The results suggest the generation of unprecedented energy densities and pressures. This is illustrated in Fig. 7 for an array of 400 nm diameter Au nanowires with an average atomic density corresponding to 12% of solid density, irradiated with a 30 fs duration pulse. The plasma density in the gold nanowires during the nano-scale pinch compression phase reaches 2 x 10^{25} cm^{-3}, which corresponds to nearly 3200 times the critical density (Fig. S4, supplemental section). Other laser-target configurations can reach 9000 times the critical densities during the nano-pinch, 6 x 10^{25} cm^{-3}. Such extreme peak densities approach those obtained in fusion hot spots using megajoule laser energies at NIF (~ 1 x 10^{26} cm^{-3}) [28], but with temperatures that are potentially orders of magnitude higher. The energy density within the nanowires is predicted to reach a peak value of 2 TJ cm^{-3}, equivalent to a pressure of 7 Tbar near the end of the laser pulse (+21 fs frame in Fig. 7). The expansion of the heated nanowires is computed to create a plasma layer in which the energy density is 80 GJ cm^{-3}, equivalent to a 0.35 Tbar pressure (+500 fs frame in Fig. 7), larger than the solar interior pressure. The electron energy can be described by a two temperature distribution, which rapidly thermalizes into a single temperature distribution defined by an electron temperature of ~ 500 KeV, 500 fs after the peak of the laser pulse (see Fig. S1 in supplemental section). Figure 8 shows that the gold atoms are predicted to reach extreme degrees of ionization. At 20 fs after the peak of the laser pulse Ni-like Au ions are dominant while ions up to Ne-like like (Au^{+69}) are also predicted to be present within the nanowires for depths up to several microns. A few hundred femtoseconds after the end of the laser pulse (e.g. 500 fs) the plasma is still hot and ionization still continues, creating charge states up to Au^{+70}. Moreover, irradiation of an array of 150 nm diameter Au nanowires with an initial average density of 30% solid is predicted to result in denser plasma in which Au atoms near the tip of the array are computed to be ionized to the Be-like stage, Au^{+75}. Irradiation of higher Z elements is expected to result in even higher charge states.

These extreme energy densities offer important advantages for the efficient generation of ultra-short pulses of x-rays and neutrons. In the case of x-ray generation, the large plasma density decreases the radiative lifetime. This results in an increase in the hydrodynamic-to-radiative lifetime ratio that leads to a large increase in conversion efficiency. Accordingly, in experiments we have conducted with aligned gold nanowires we have measured a record conversion efficiency into ultra-short pulses of > 1 keV photons of 10 % in 2π str. In the case of the generation of neutrons by deuterium-deuterium or deuterium-tritium fusion reactions the high density of energetic ions is an important advantage because the reaction rate is proportional to the square of the density. These aligned nanostructure plasmas share some similarities to the efficient volumetric heating of clusters in a supersonic gas jet [29], but with the additional advantage of having several orders of magnitude higher average density, potentially leading to record fusion neutron yields with compact lasers.

It is also of interest to gain insight on how the energy density scales with irradiation intensity. However, this scaling would have a very limited range of applicability without the simultaneous change of the nanostructure target parameters, for example the nanowire diameter. The ideal configuration for many applications such as neutron generation, efficient conversion into x-rays, and the creation of highest-z ions, requires obtaining a plasma lifetime as large as possible compared to the characteristic times of the fusion reactions, radiation cooling, and ionization time respectively. That means that the laser energy deposition depth has to be typically of the order of the laser focal spot size, which in our case is 4-6 μm. As the irradiation intensity is increased, scaling of the inter-wire distance is required to maintain such constant energy penetration depth. Otherwise not only would the laser energy penetration depth be either too short or too long, but also the efficiency of the laser energy deposition would decrease. This is because there exists a time for the closure of the inter-wire space for the laser by the expanding plasma, after which a continuous critical density layer is formed which increases the fraction of laser energy reflected. Therefore, to determine the energy density scaling we took the strategy of keeping the energy penetration depth approximately constant and comparable to focal spot size, while scaling the inter-wire spacing and nanowire diameter (the latter is required to keep the average atomic density constant). For this case of approximately constant energy deposition depth the peak value of the energy density (ED) occurring near the end of the laser pulse is computed to scale approximately linear with intensity I (ED~ I, see Fig. S5 in supplemental session). In comparison, at later times when that nanowires are completely dissolved into a homogeneous plasma, the energy density behaves as a sub-linear function of the laser intensity , $ED \alpha I^{0.5}$, due to the faster thermal spread of the hotter plasma at larger intensities.

In conclusion, these results open a path to obtaining unprecedented pressures in the laboratory with compact lasers for the study of high energy density physics, high ionization states of high-Z

atoms in high density plasmas, and effects of opacities at ultrahigh pressures, temperatures, and densities. The experimentally validated numerical model predicts that experiments at an increased intensity of 1 x 10^{22} W cm^{-2} will result in the generation of unprecedented Tbar-level pressures in laboratory plasmas, surpassing even those in spherical compression laser fusion experiments. These plasmas can lead to record conversion efficiency of optical laser light into ultrafast x-ray flashes and to the efficient production of ultrafast neutron pulses by fusion in near-solid density plasmas.

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Materials and Methods

Experimental set up

The dual-composition segmented nanowire array targets were irradiated with 400 nm wavelength, 0.6 J energy laser pulses of 55 fs FHWM duration from an ultra-high contrast frequency-doubled Titanium:Sapphire laser. The ultra-high contrast, which is necessary to prevent destruction of the nanowires prior to the arrival of the main pulse, was achieved by frequency doubling with an 800-µm thick Type 1 KDP crystal. The 400 nm second harmonic light was separated from the 800 nm fundamental beam using a series of four highly selective dichroic mirrors. These high contrast pulses were focused to a ~ 5 µm diameter spot using a 90 degree off-axis parabolic mirror to achieve intensities of (4 ± 1) x 10^{19} W cm^{-2} on target. The focal spot size was determined by imaging with a 10X objective onto a 12-bit CCD camera. The laser pulse duration was measured using a single-shot FROG. The laser pre-pulse contrast in the ps range was monitored with a third-order scanning autocorrelator, and in the ns range it was determined using a photodiode and a set of calibrated neutral density filters. The pre-pulse intensity contrast of the frequency-doubled pulse was inferred to be greater than 1 x 10^{12}. The laser pulse energy was monitored on a shot-by-shot basis by measuring the reflection from a 500 µm thick, 1% reflecting, multilayer coated beam splitter placed before the off-axis parabola.

The emitted x-ray spectrum was measured with a von Hamos crystal spectrometer [25]. The spectrometer uses the third-order reflection from a cylindrically bent mica crystal to spectrally disperse the x-ray signal onto a back-thinned 2D CCD sensor. The sensor is shielded from electromagnetic noise and visible light by an electrically and optically sealed faraday cage,

in which the diffracted x-ray signal reaches the CCD through a 12.5 μm thick Al foil filter. The thickness of the Al filter was selected to also stop lower order reflections from the mica crystal.

Vertically Aligned Nanowire Arrays

The nanowire arrays were grown by the electrodeposition of metallic ions into porous alumina templates. The density of pores determines the average density of the nanowire array. A Watts Bath [30] solution was used for the deposition of both nickel and cobalt materials. This galvanostatic electrodeposition allows for the wires to be grown to a desired length inside the template pores. As the buried tracer experiments required the wires to consist of segments of two different materials, Co was first deposited in the pores to a length of 3-4 μm, followed by subsequent deposition of Ni at variable lengths between 1 and 6 μm. High resolution transmission electron microscope dispersive x-ray spectroscopy (EDS analysis) revealed that the junction region between the Co and Ni layers is smaller than 100 nm in length. Once the deposition was complete, wires were freed from the template through a dissolving process in 4M NaOH. EDS from a scanning electron microscope was used to measure the elemental composition of the array along the length of the nanowires in each array (Fig. 1b).

Simulation tools

The relativistic 3-dimensional Virtual Laser-Plasma Laboratory (VLPL) code [31] was used for the PIC simulations. The capabilities of its standard algorithms were extended by adding packages for optical-field ionization (OFI) and binary collisions, including electron impact ionization. OFI was treated as an under-barrier tunneling phenomenon in the static electric field [32-33] with only sequential field ionization considered. The probabilities for Coulomb collisions between all particles in one mesh cell were calculated by a binary collision package. PIC simulations utilized a three-dimensional geometry and self-consistently included ionization physics for both the Ni and Co atomic species present in the target. A linearly polarized plane wave with 400 nm wavelength and Gaussian time-envelope $a(t) = a_0 \exp(-t^2/\tau^2)$ was used to simulate the laser pulse where the normalized vector potential $a_0 = eA/mc^2 = 2.16$ corresponds to a laser intensity of $I_0 = 4{\times}10^{19}\ W/cm^2$ and a 55 fs FWHM pulse duration. The laser pulse was assumed to impinge on the nanowire array at normal incidence. The PIC simulation space consisted of a cell volume encompassing the wires and inter-wire gaps, as well as space above the array to allow for expansion of the wire material as it explodes and thermalizes. The simulation describes all phases of the laser interaction with the nanowire array and subsequent explosion and thermalization. The code accounts for local field enhancements, field fluctuations, and resonance heating. Bulk resonances, however, are not considered to be present due to the average density being higher than the critical density and the spacing of the nanowires being smaller than the wavelength of the laser.

Simulations were also conducted with two post-processor atomic models based on the code Radex [34] using atomic data from the HULLAC code [35]. The first of these atomic models was used to compute the intensity ratio of Co/Ni He-line lines. It utilizes the exact particle energy distribution computed with the PIC code. The second model, used to simulate the spectra (Fig. 4, top), is a very detailed atomic code that considers a large number of excited levels from all the ionization stages present. This greatly more computational intensive model uses a two-temperature approximation to the electron energy distribution computed by the PIC code. Lines were computed taking into account natural, Doppler, collisional, and Stark broadening. The Biberman-Holstein approximation [36-37] was used for radiation transport of the He-alpha lines. For comparison with experiments instrumental broadening was added to the synthetized spectra (Fig.4). The continuum was simulated by simple approximations for bremsstrahlung and radiative recombination radiation.

Estimation of the pressure from the energy density

The relationship between energy density and pressure can be readily calculated in the equilibrium case, where the distribution function is a relativistic Maxwellian, and in the non-equilibrium ultra-relativistic case, where the particle velocities are all close to the speed of light. The result for an equilibrium relativistic gas is given by Synge [38]. We use a simple approximation, accurate to 1 %, given by Ryu, et al. [26].

Defining β as the ratio of kinetic energy density to rest mass energy density, we find the following formula for α, the ratio of kinetic energy density to pressure:

$$\alpha = \frac{6}{1 - \delta + \sqrt{\delta^2 + 6\delta + 1}} \; ; \; \delta \equiv \frac{1}{\beta} .$$

The large and small β limits give the well-known results, α=3/2 and α=3, respectively. The full dependence of $\alpha(\beta)$ is shown in Fig. S2 in the supplemental section.

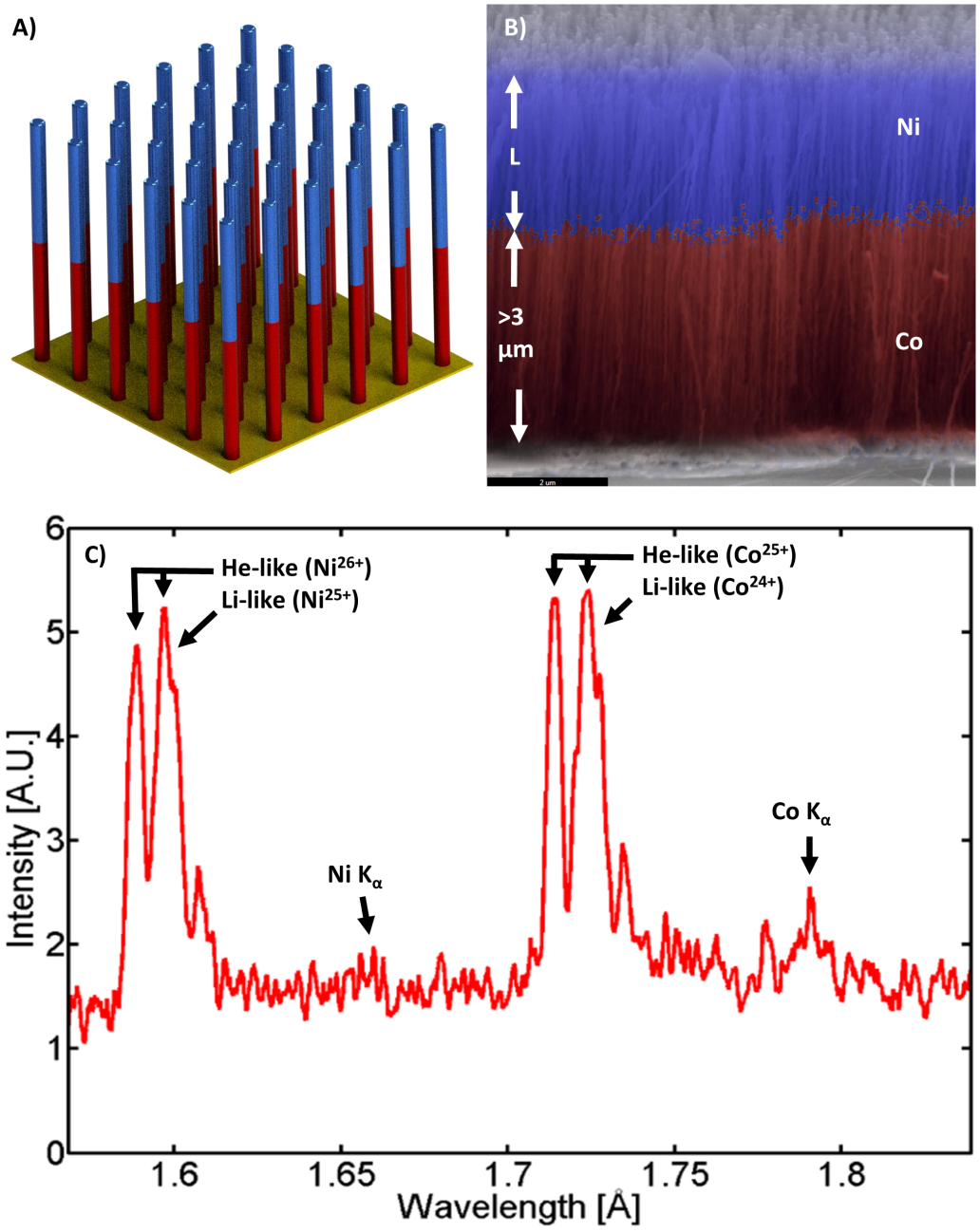

Figure 1. (A) Schematic diagram of segmented two-composition Ni-Co nanowire array. The top Ni segment ranges in length from 1 to 6 micron. The nanowires are 55 nm in diameter and form an array that is 13% of solid-density. (B) Scanning electron microscope image with energy-dispersive spectroscopic elemental composition measurement indicating the concentration of Ni (blue) and Co (red). (C) Example spectra showing the He-like lines dominance over the K_α lines for the two elements as recorded with a von Hamos spectrometer.

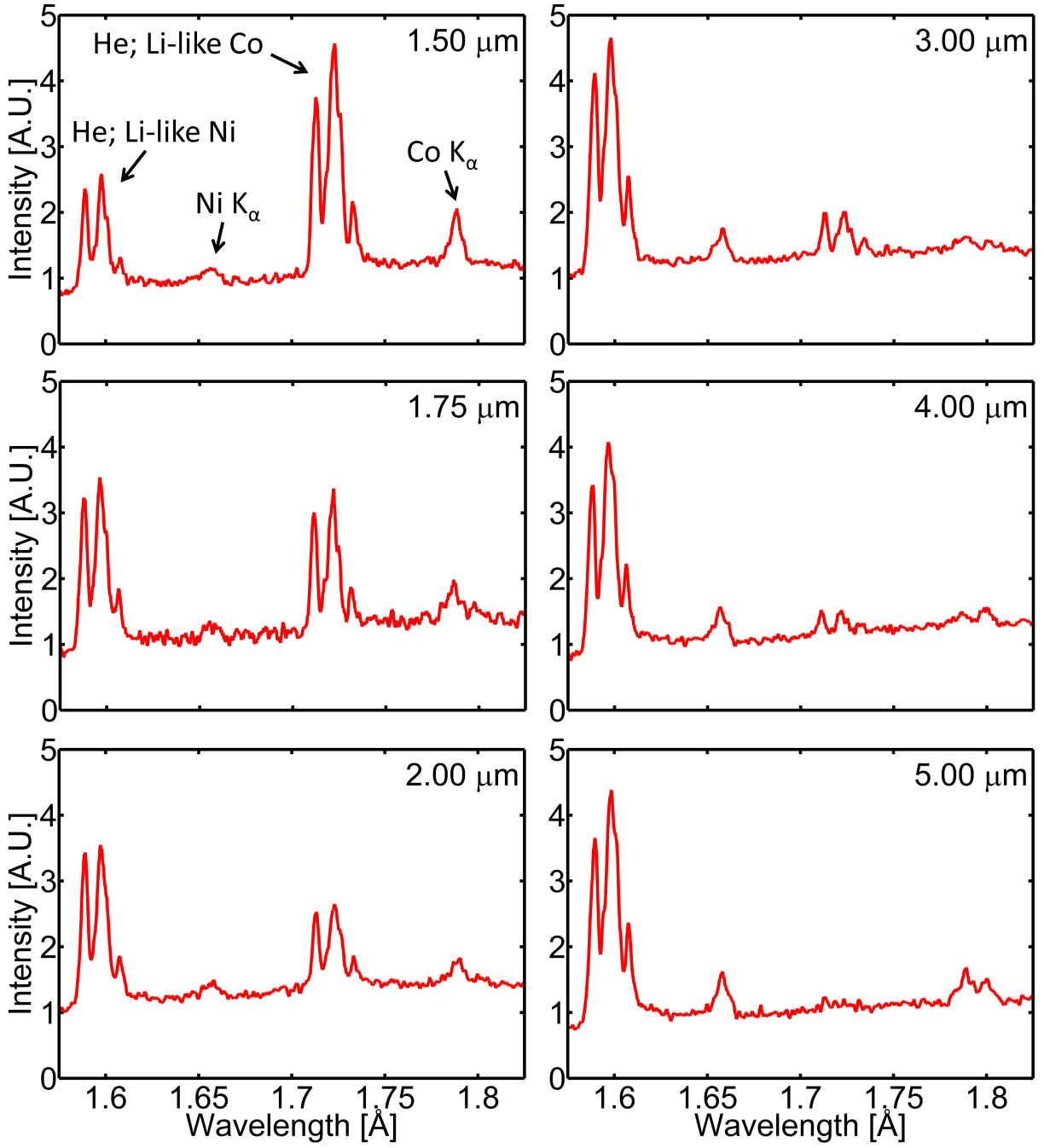

Figure 2. Measured spectra of Ni-Co segmented nanowire arrays with different lengths of Ni wires (listed in the top right corner of each plot) on top of cobalt wires, irradiated by 55 fs pulses at an intensity of ~ 4 x 10 ^{19} W cm^{-2}. The vertically aligned wires are 55 nm in diameter and form an array that has an average atomic density 13% of solid. Lines of He-like and Li-like Ni and Co are visible along with their respective K_α lines.

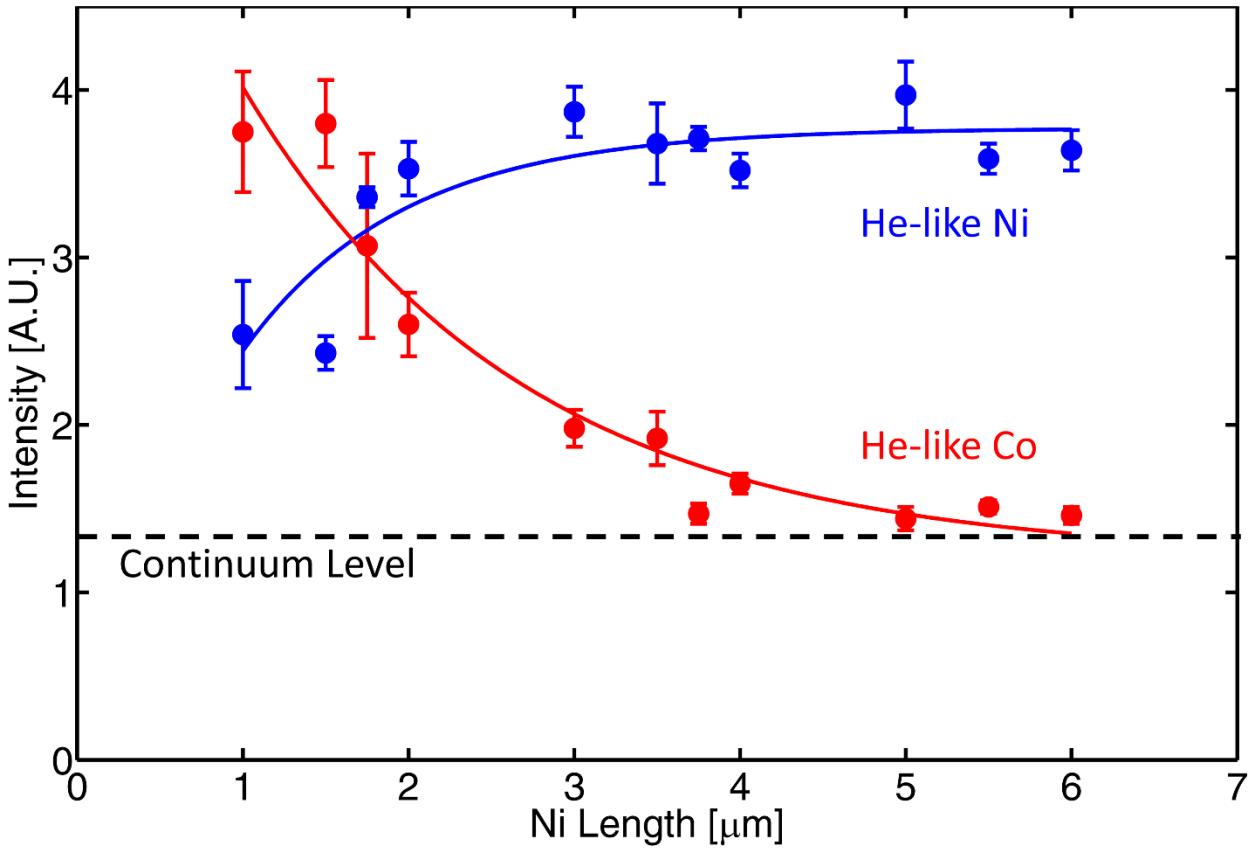

Figure 3. Measured intensities of the He-like Co and He-like Ni lines as a function of the length of the top Ni nanowire segment. The target and laser parameters are the same as for Fig. 2.

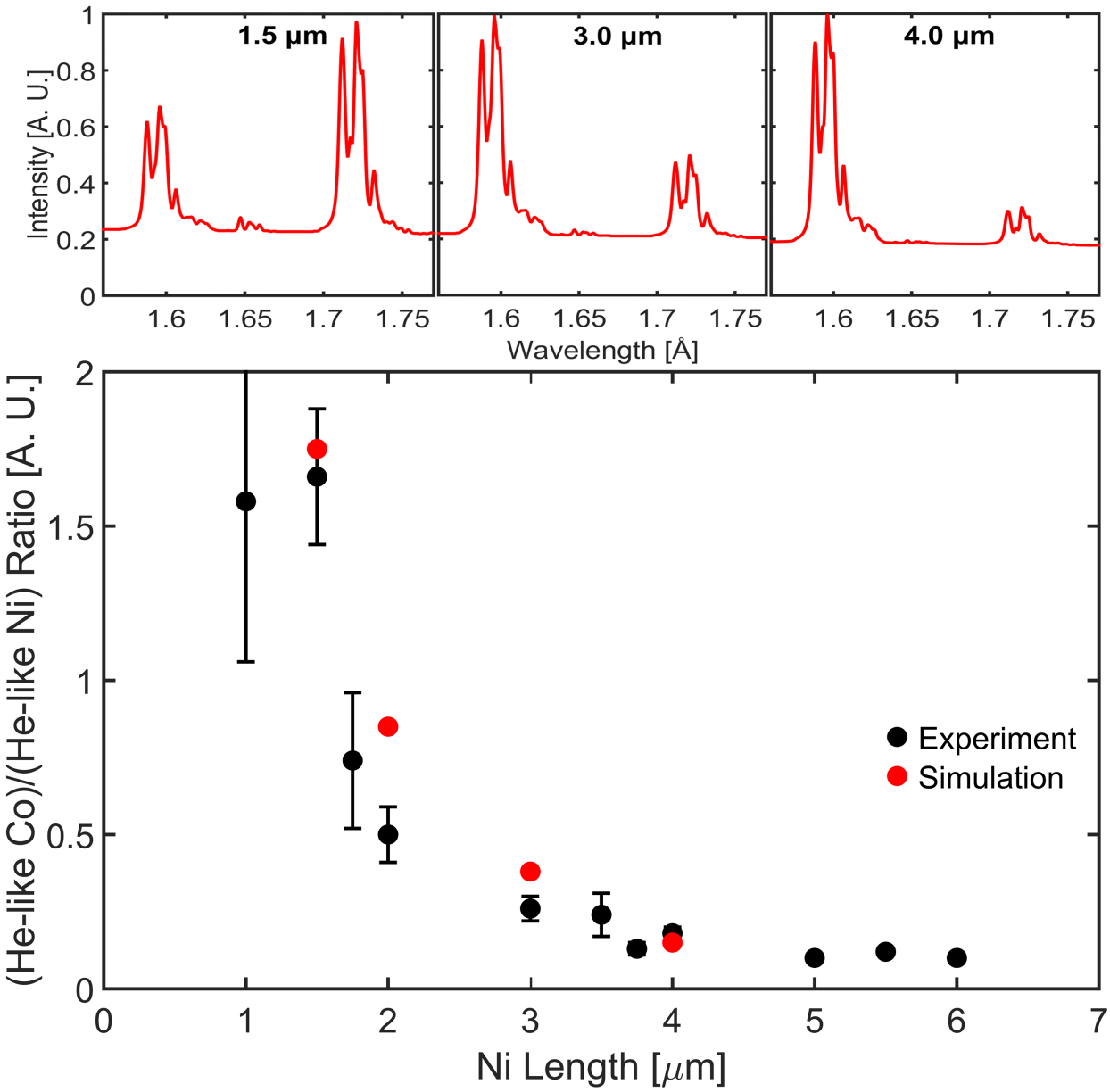

Figure 4. Simulated spectra corresponding to arrays with different wire lengths used in the experiment are shown in the top three plots. The target and laser parameters are those of Fig. 2. Measured and simulated (Co He-α)/(Ni He-α) line ratios as a function of Ni nanowire segment length are shown in the bottom plot.

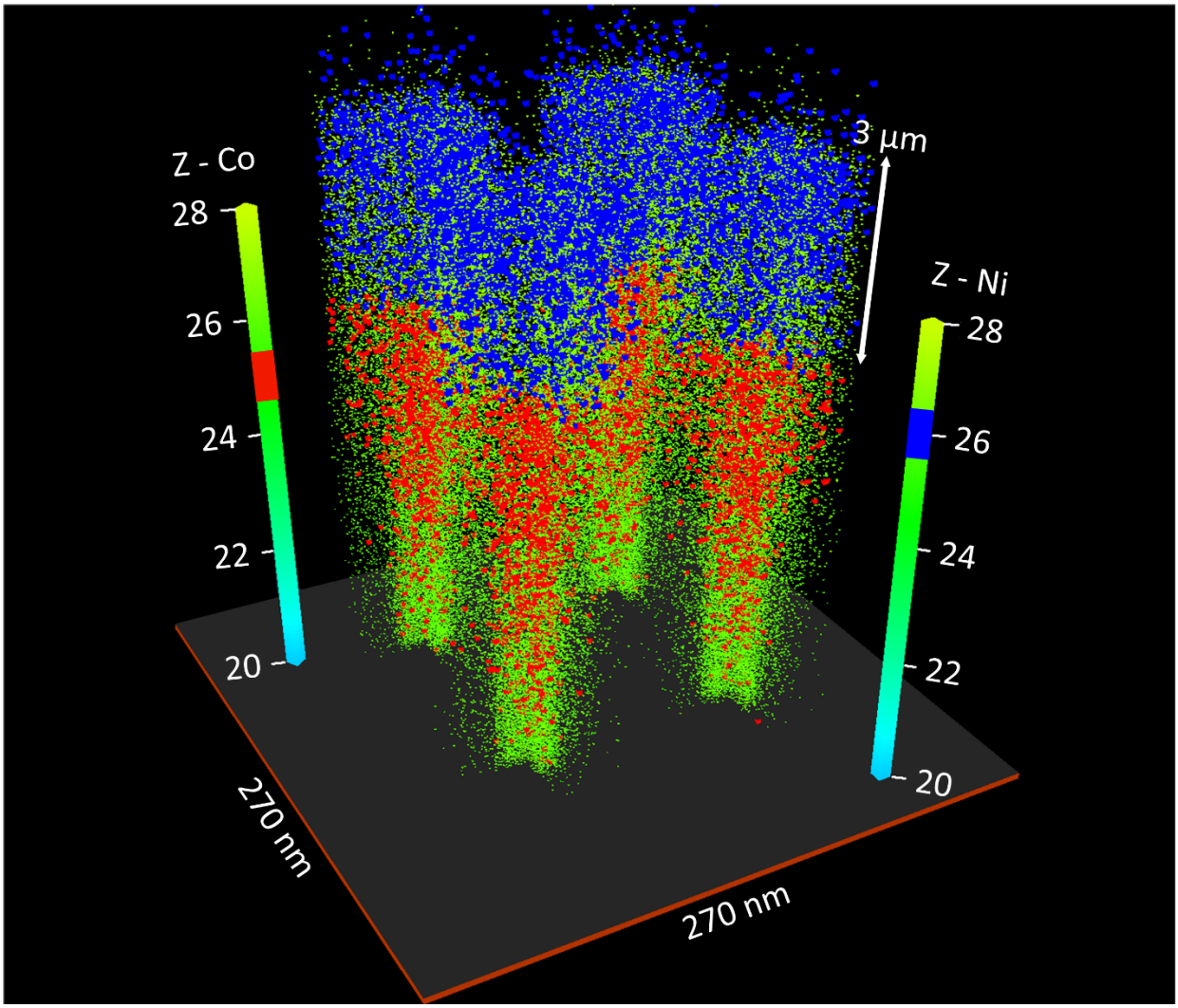

Figure 5. PIC simulation of the density of He-like ions in an array composed of segments of vertically aligned Ni and Co nanowires (blue: He-like Ni, red: He-like Co). The target and laser parameters are the same as for Fig. 2. The top Ni wires are 3.0 µm in length. The laser pulse impinges from the top at normal incidence onto the array.

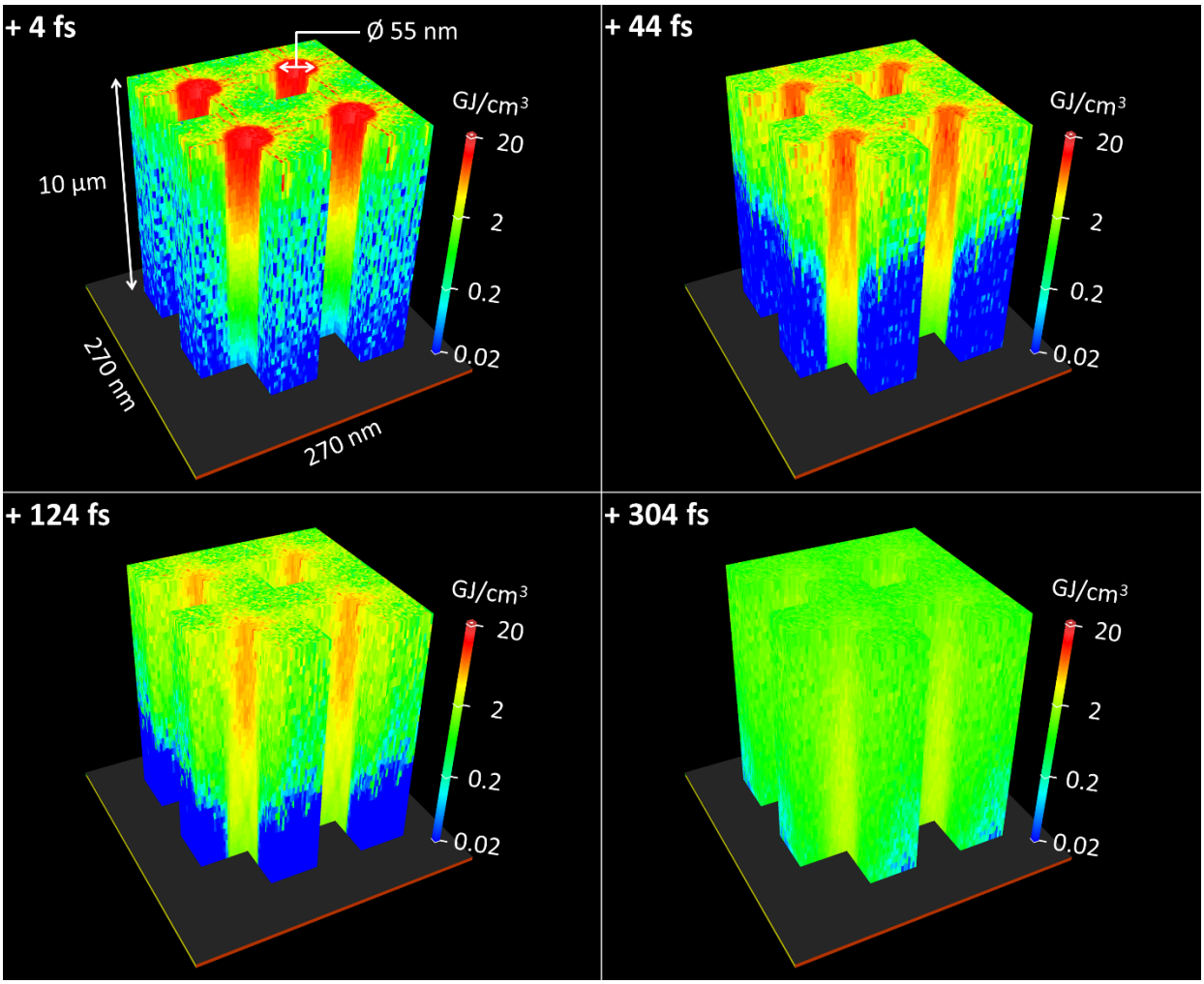

Figure 6. Energy density distribution computed by PIC simulation. The target and laser parameters are those for Figure 5. Each frame corresponds to a different time with respect to the peak of the laser pulse as indicated by the time-stamp in the top-left corner of each frame. The laser pulse impinges into the array from the top at normal incidence.

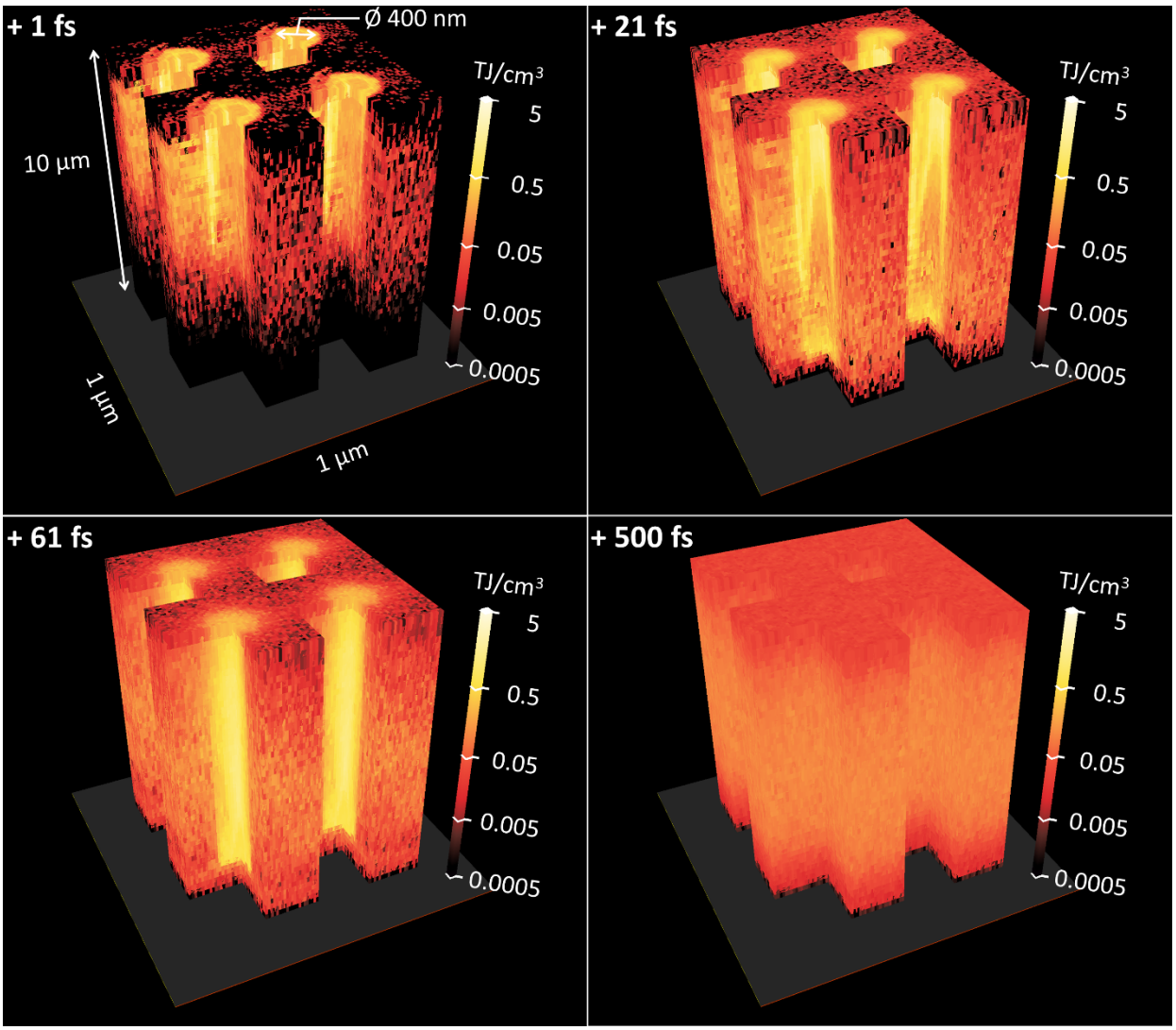

Figure 7. PIC simulated energy density distribution in an array of vertically aligned Au nanowires of 400 nm diameter irradiated with an intensity of 1 x 10^{22} W cm^{-2} (a_0= 34) using a 400 nm wavelength pulse of 30 fs duration. The average atomic density is 12% of solid density,. Each frame corresponds to a different time with respect to the peak of the laser pulse. The laser pulse impinges into the array from the top at normal incidence.

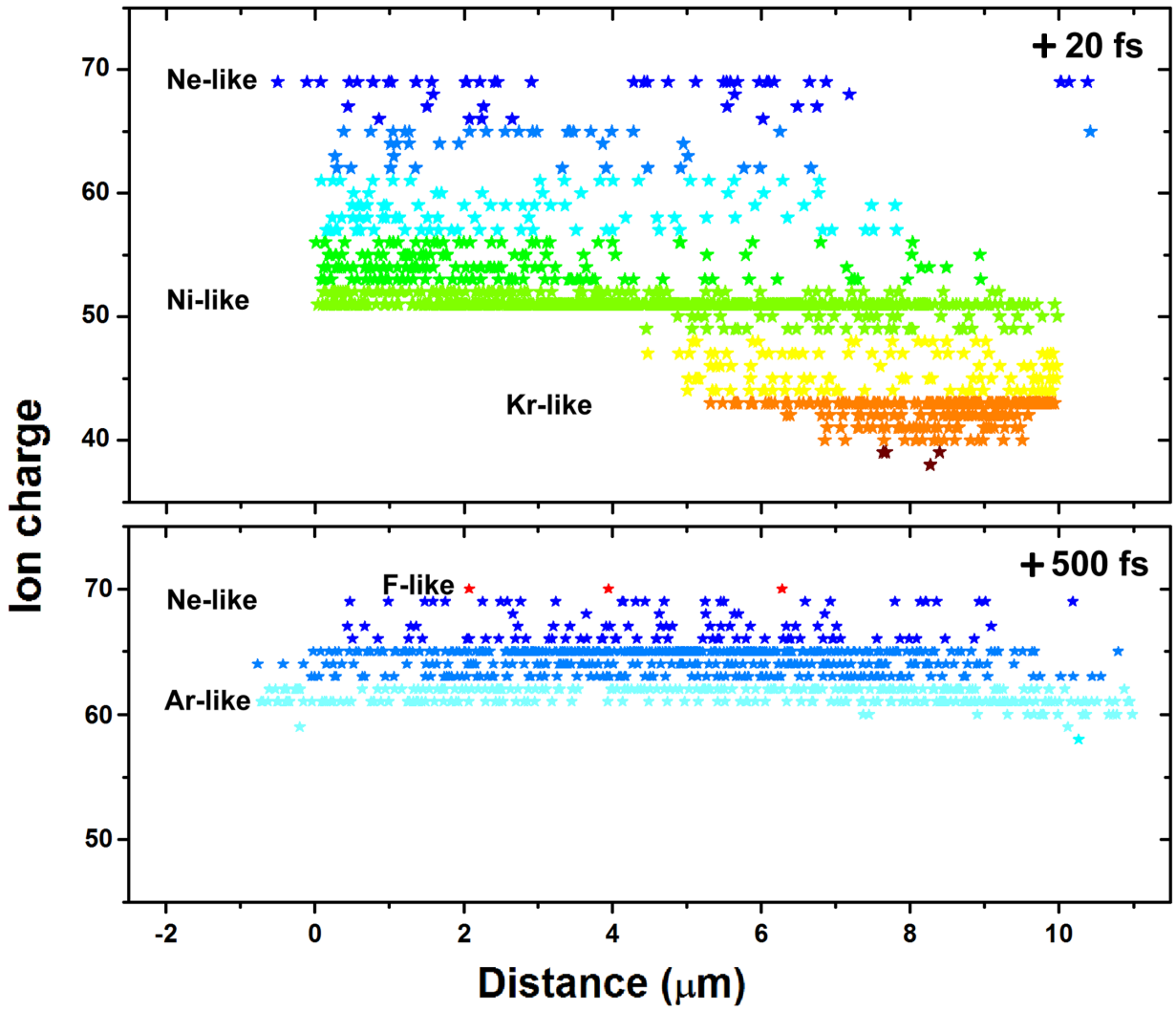

Figure 8. Ion charge distribution as a function of depth for an array of 400 nm diameter Au nanowires with 12% of solid density, irradiated at an intensity of 1 x 10^{22} W cm^{-2} as for Fig. 7. This plot was obtained by randomly choosing a fraction of the ions and placing a star at each charge and position. Groups of ionization stages are assigned different colors (e.g. Z=66 to 70 is blue) to accentuate the ion distribution and to identify rare ions, such as the F-like ions in the lower panel.

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Supplemental Section

Electron energy distribution. Shortly after the laser pulse, the electron energy distribution in the nanowire array is well described by a two-temperature distribution as shown in Fig. S1. The high energy electrons, often called hot electrons, rapidly thermalize in about 500 fs to be described by a single Maxwellian distribution. This is shown in Fig. S1 for an array of nanowires of 400 nm wire diameter with an average density of 12% solid density irradiated at an intensity of 1 x 10^{22} W cm^{-2} with a 30 fs duration laser pulse. The rapid thermalization of the MeV electrons is much faster than the collisional hot electron themalization time, and is caused by collisionless process. Anomalously rapid stopping of MeV electrons in overdense plasma has been reported to be up to 3 orders of magnitude stronger than through classical collisions [37].

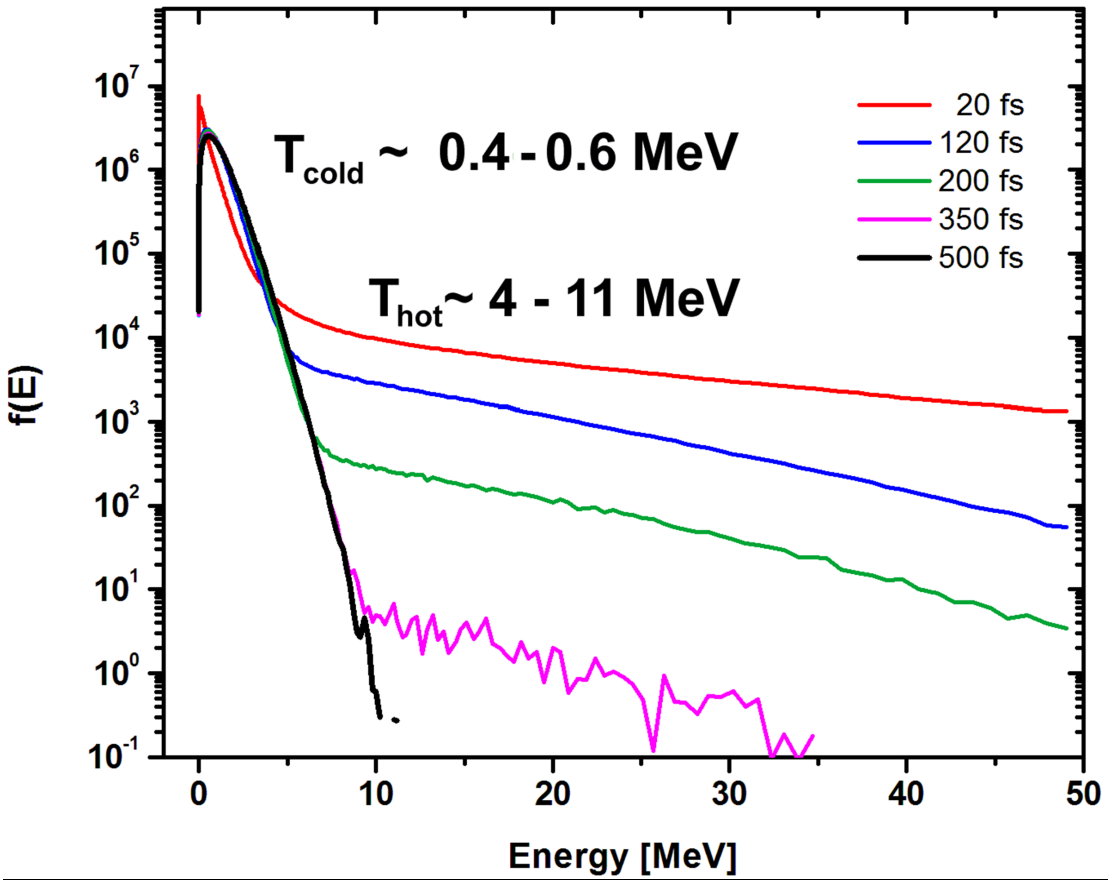

Figure S1. Electron energy distribution at different times with respect to the peak of the laser pulse averaged in space. Rapid thermalization takes place.

Pressure calculation. The pressure was calculated from the kinetic energy density computed by the PIC simulations using the approximation by Ryu et al. [26] is illustrated in Figure S2. Table S1 gives results for four particular cases discussed in the paper. The contribution of ions , amounting to about 10% at the lower intensities and about 30% at the highest intensities, is not included.

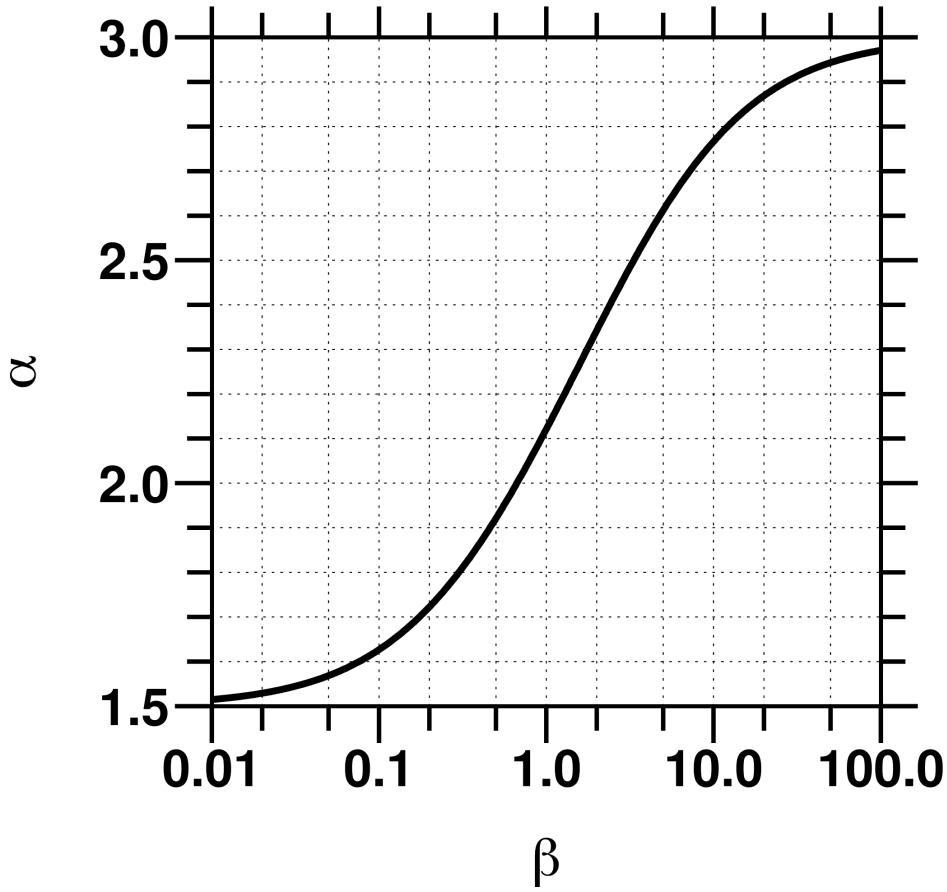

Figure S2: Ratio of kinetic energy density to pressure (α) as a function of the ratio of kinetic energy density to rest mass energy density (β).

Table S1: Pressures calculated from calculated from the kinetic energy density computed by the PIC simulations using the approximation by Ryu et al. [26].

case	I (W/cm^2)	t (fs)	n_e (/cc)	k (GJ/cc)	p (Gbar)	β	α
1	4e19	4	1.e24	22.4	125	0.27	1.78
2	4e19	304	3.e23	1.1	7.0	0.045	1.56
3	1.e22	21	3.5e24	2.e3	7.4e3	7.0	2.69
4	1.e22	500	4.85e23	82	350	2.1	2.35

Energy density scaling . The following figures are referred to in the text in relation to experiments with nanowire arrays with higher average atomic density and with the scaling of the energy density as a function of the irradiation intensity.

Fig. S3 is spectrum of a Ni nanowire target with an average atomic density corresponding to 30% solid density irradiated at an intensity of 4 x 10 ^{19} W cm^{-}. The spectrum is again dominated by He-like and Li-like lines, which indicate the high degree of ionization in maintained. Fig. S4 illustrates the plasma density during the nano-scale pinch compression phase in a gold nanowire 400 nm in diameter irradiated at an intensity of 1 x 10 ^{22} W cm^{-2} with a 30 fs laser pulse. The electron density reaches 2 x 10^{25} cm^{-3}, which corresponds to nearly 3200 times the critical density. Fig. S5. Shows the computed scaling of the energy density (ED) deposited into Au nanowire arrays as a function of the irradiation intensity for two different times during the plasma evolution. The nanowire diameter for each intensity was selected to maintain the penetration depth approximately constant

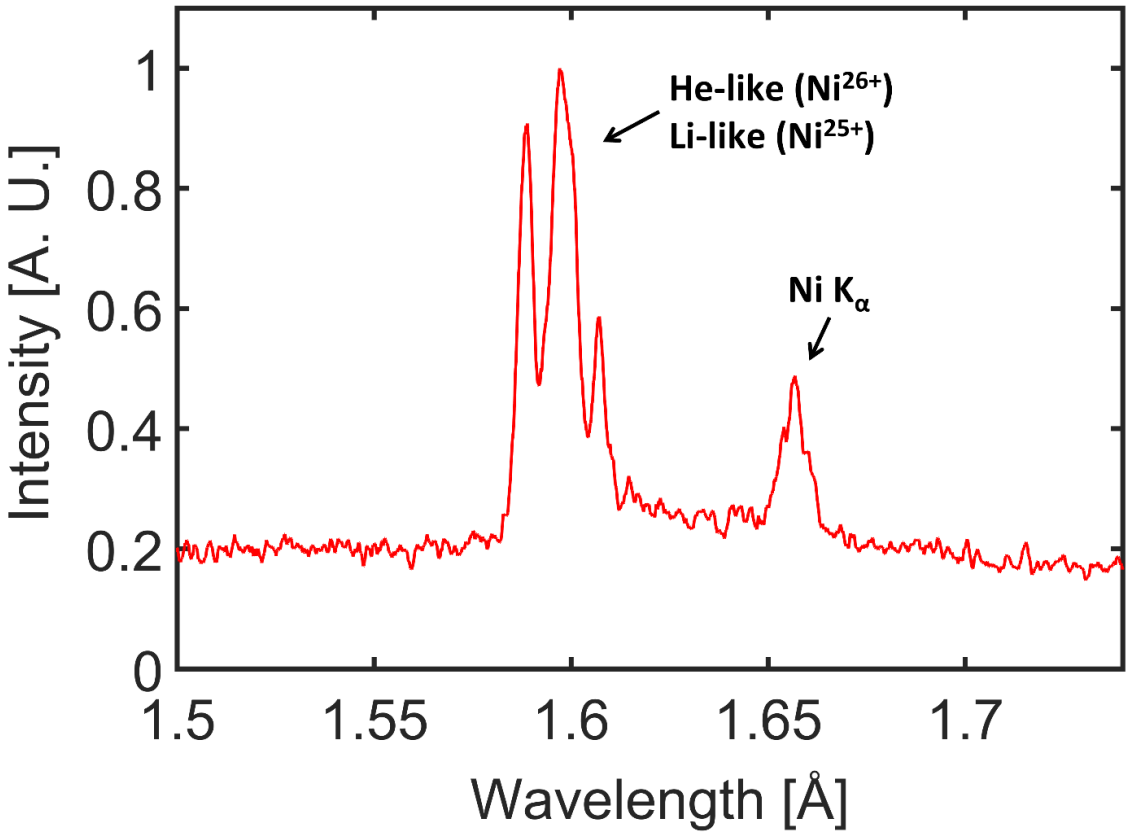

Fig. S3. Spectrum of an array of 55 nm diameter Ni nanowires with an average atomic density corresponding to 30% of solid density irradiated at 4 x 10 ^{19} W cm^{-2}. with an ultra-high contrast λ = 400 nm laser pulse of 55 fs duration. Strong He-like, Li-like Ni lines are observed.

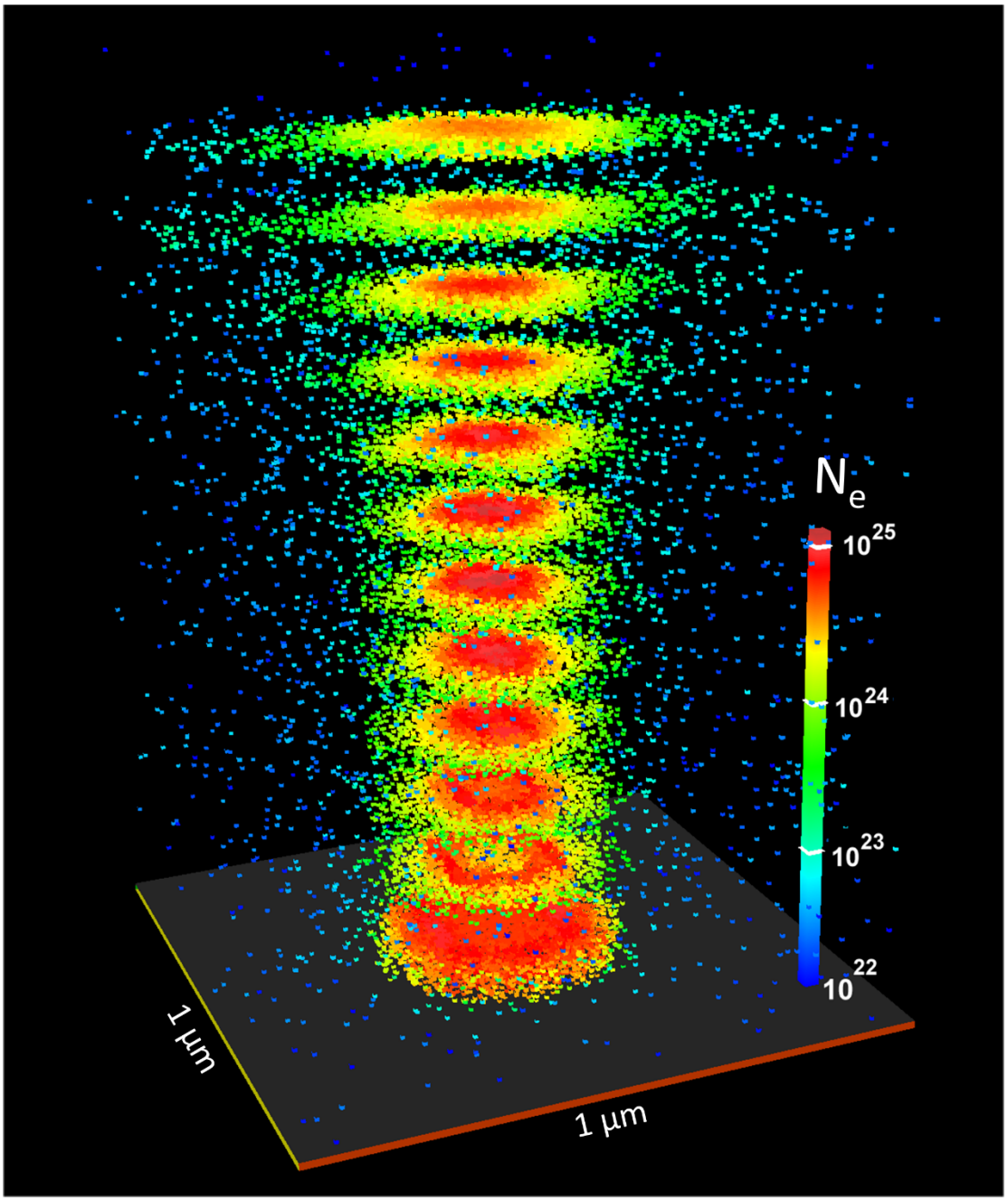

Fig. S4: Computed electron density distribution in gold nanowire 400 nm in diameter irradiated at an intensity of 1 x 10^{22} W cm^{-2} with a 30 fs laser pulse, corresponding to the conditions of Fig. 7. The plasma column has been sliced to facilitate viewing. The time corresponds to 40 fs after the peak of the laser pulse. During the nano-pinch compression phase the electron density reaches 2 x 10^{25} cm^{-3}. The electron density values are identified in the logarithmic color scale.

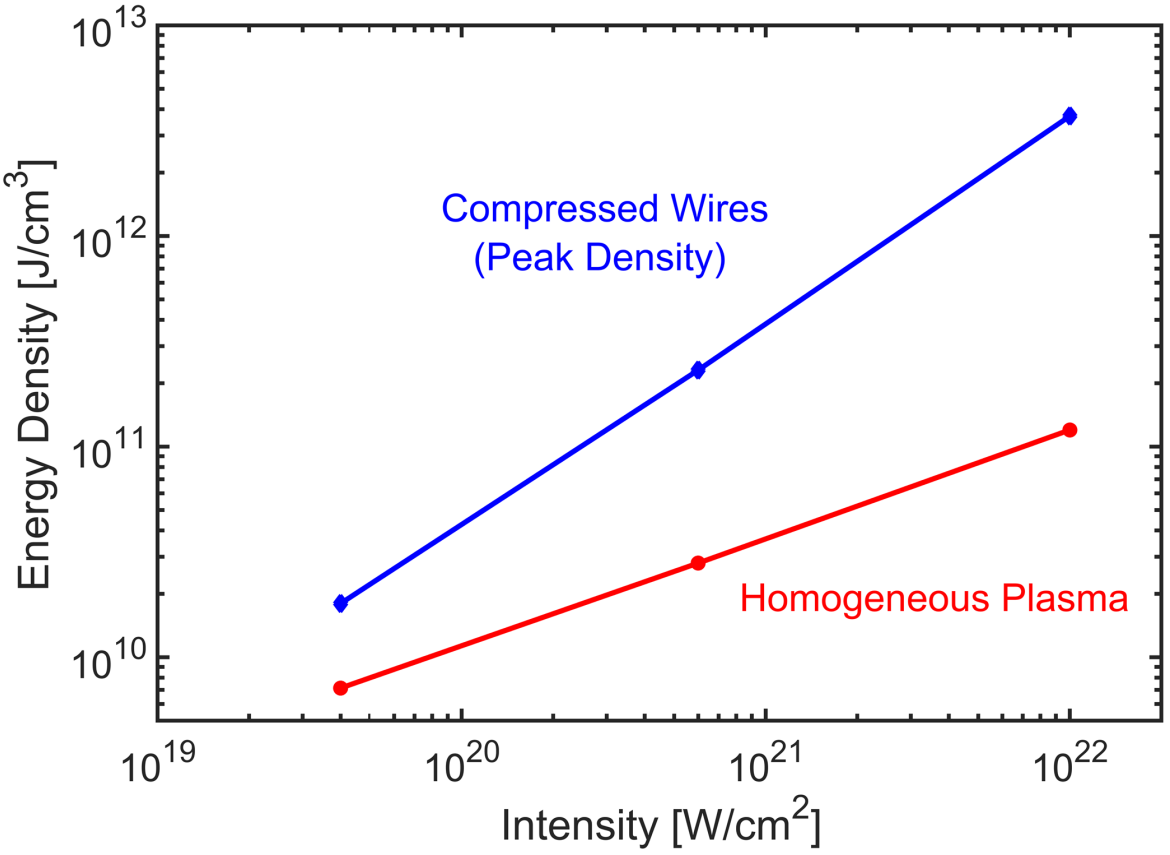

Fig. S5. Computed scaling of the energy density (ED) deposited into Au nanowire arrays as a function of the irradiation intensity for two different times during the plasma evolution : a) near the end of the laser pulse (blue trace, energy density scaling as ED ~ I) , and b) when the nanostructure is completely dissolved and the plasma becomes nearly homogeneous, but before the plasma expands as a whole (red trace, energy density scaling as ED ~ $I^{0.5}$) . The average atomic density of the array is 12% of solid density. The nanowire diameter for each intensity was scaled to maintain the penetration depth approximately constant (55 nm, 150 nm, and 400 nm respectively for the three intensities in increasing order). The laser pulse duration is 30 fs.