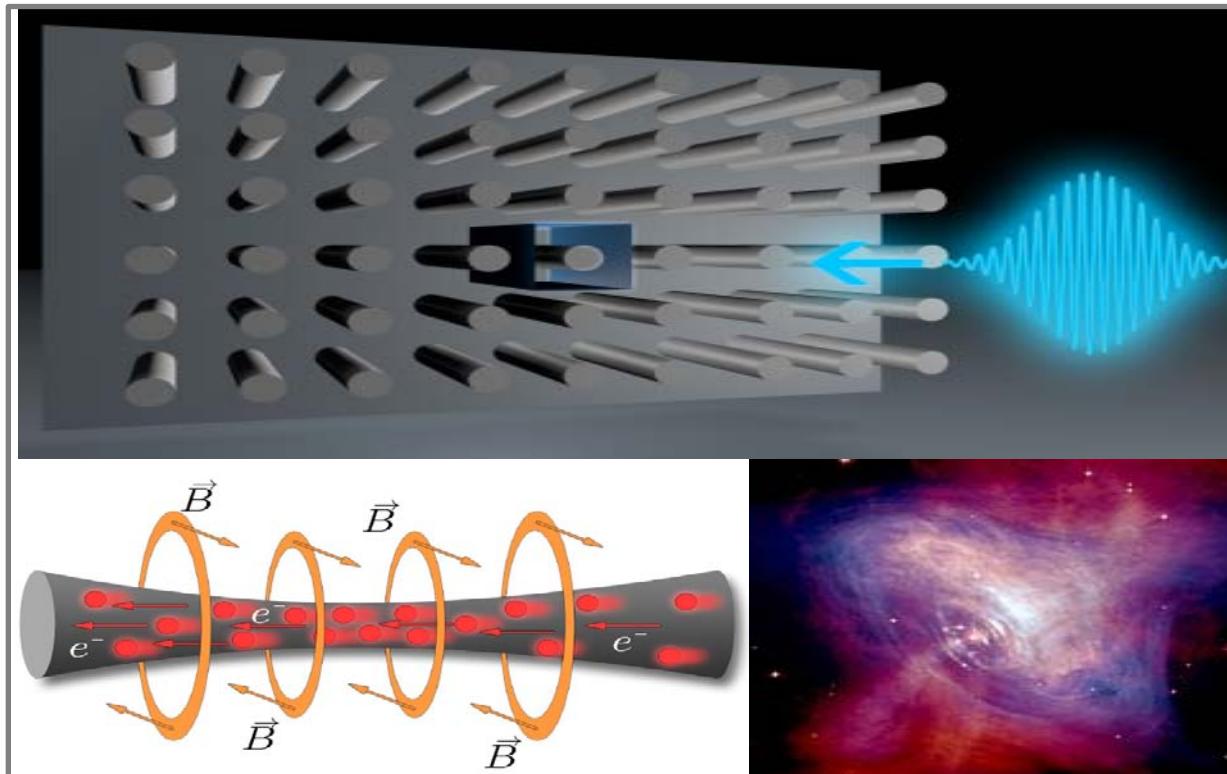


Laser absorption in nano-structured plasmas: nanopinches and UHED matter

A. Pukhov, V.Kaymak HHUD, Germany

J.Rocca, V. Shlyaptsev CSU, U.S.A.

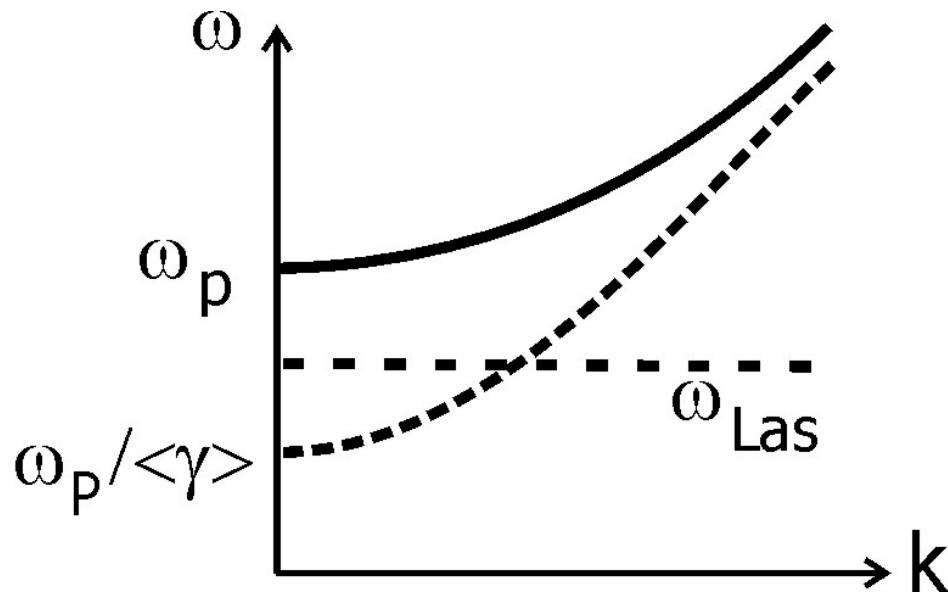


Nizhni Novgorod 2018

Outline

- **Nanostructured targets:**
 - relativistic plasma nano-photonics
 - **Relativistic nano-pinch**
 - **Ultra-High Energy Density and Terabar pressures**
 - **Fusion neutrons from nanograss targets**
-

Non-linear optics in relativistic plasmas



Dispersion of light in plasma:

$$\omega^2 = \omega_p^2 + c^2 k^2$$

Plasma frequency:

$$\omega_p^2 = 4\pi e^2 n_e / (m \langle \gamma \rangle)$$

Relativistic factor:

$$\gamma = (1 - v^2/c^2)^{-1/2}$$

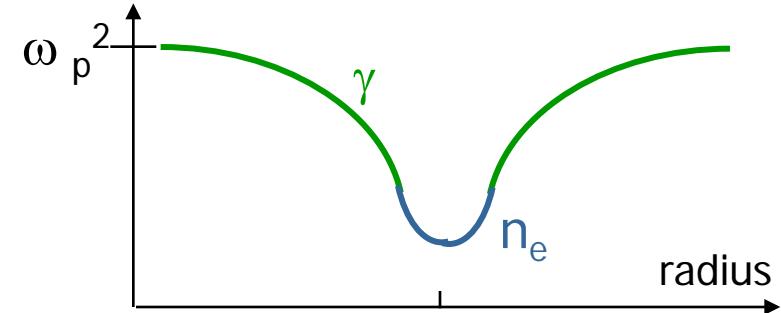
Index of refraction:

$$n_R = (1 - \omega_p^2 / \omega^2)^{1/2}$$

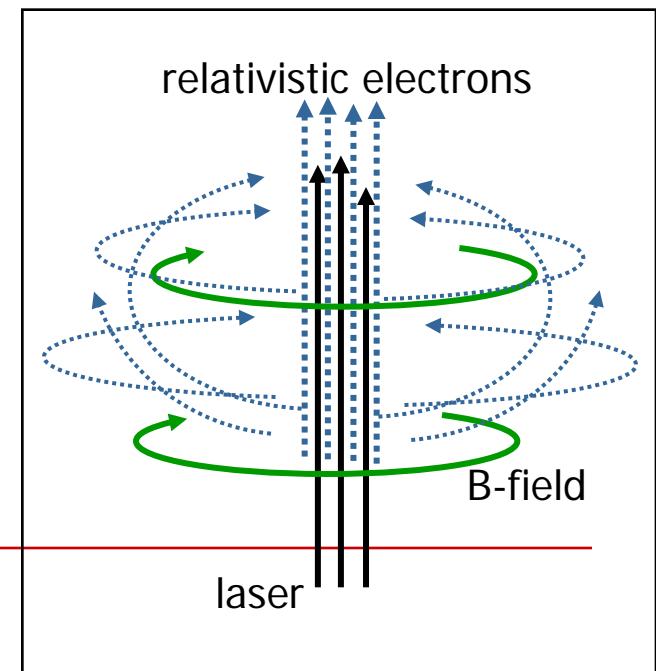
Relativistic self-focussing of laser in plasmas

$$\omega_p^2 = 4\pi e^2 n_e / m\gamma_{\text{eff}}$$

$$n = \sqrt{1 - \omega_p^2 / \omega_L^2}$$

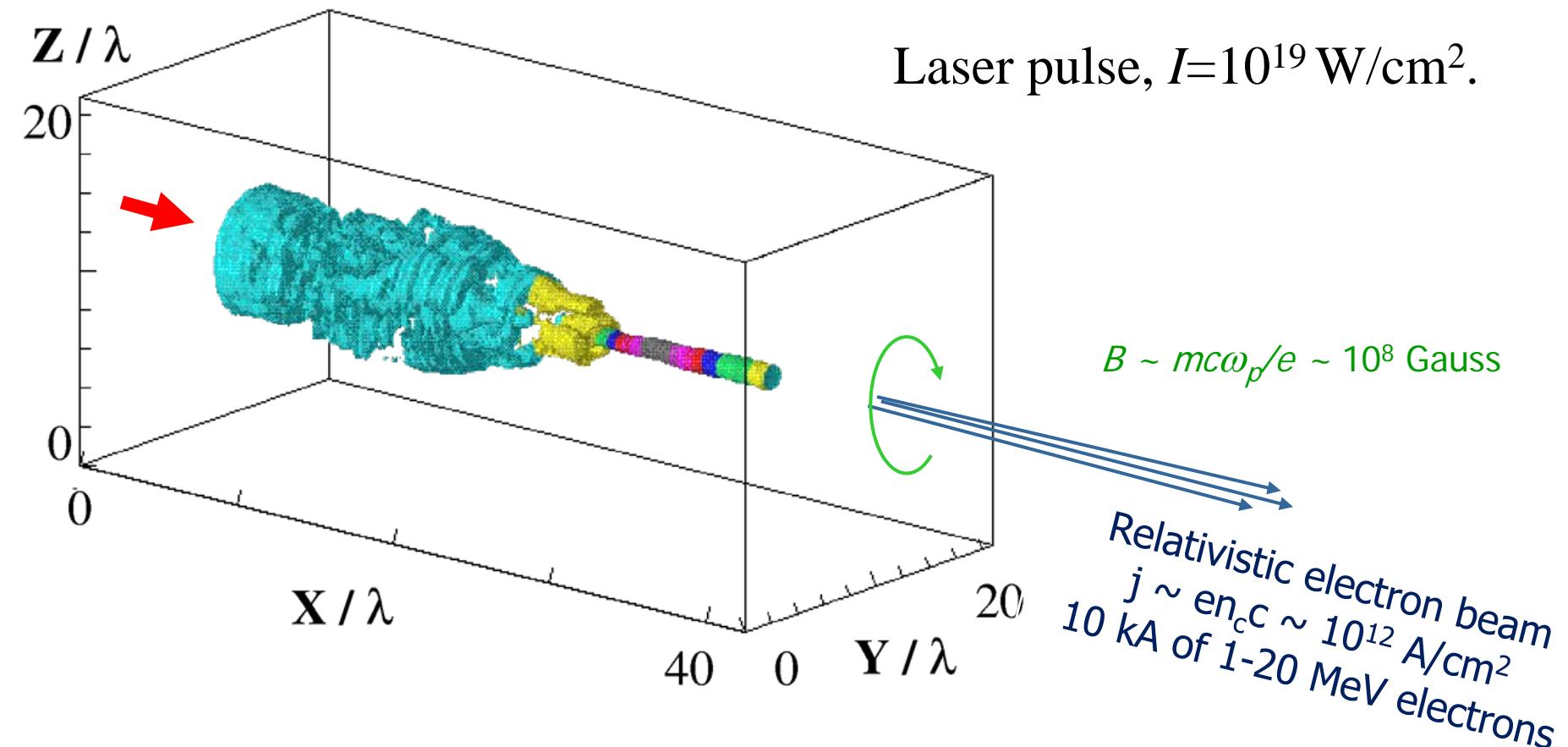


Relativistic mass increase (γ)
and electron density depletion (n_e)
enhance index of refraction in the
channel region, leading to self-
focussing



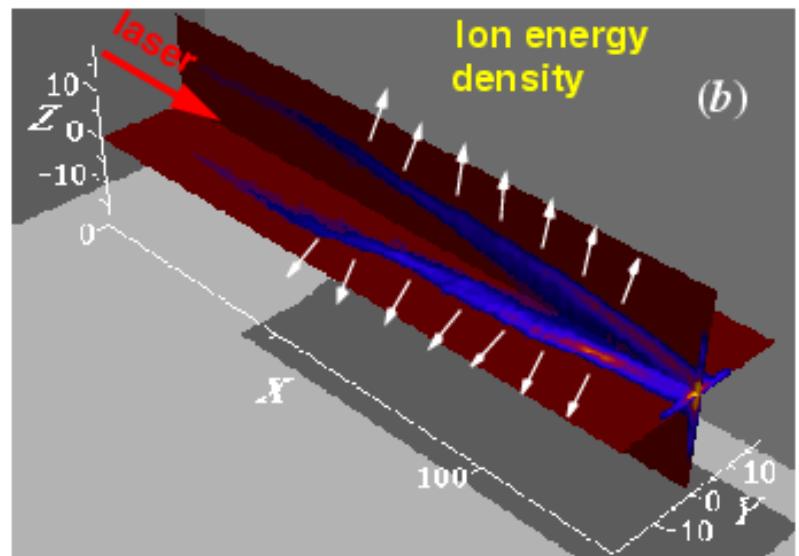
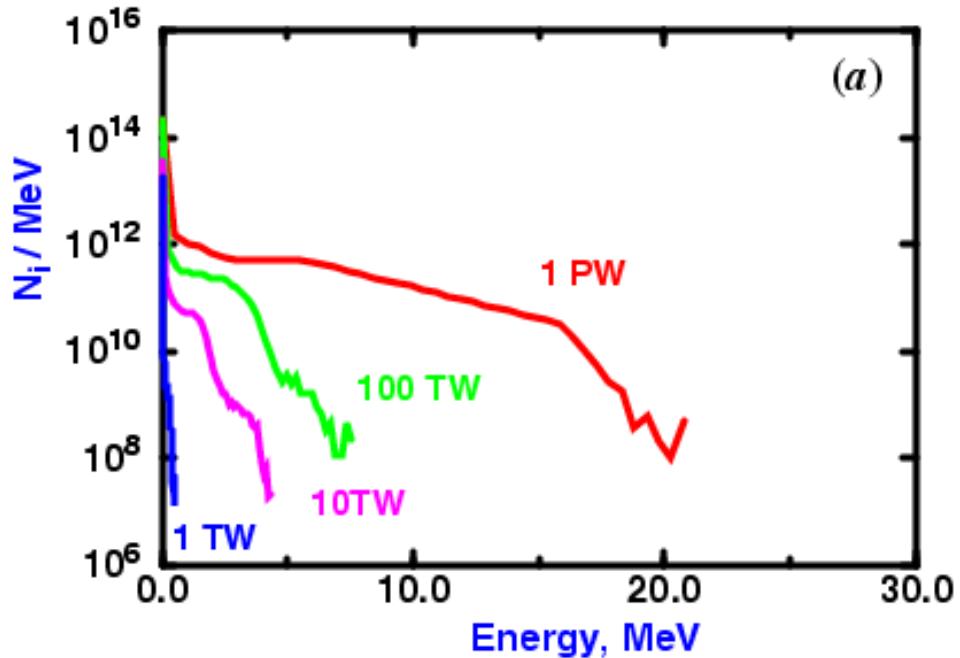
Relativistic laser self-channeling in Near Critical Density plasmas

Pukhov, Meyer-ter-Vehn, PRL 76, 3975 (1996)

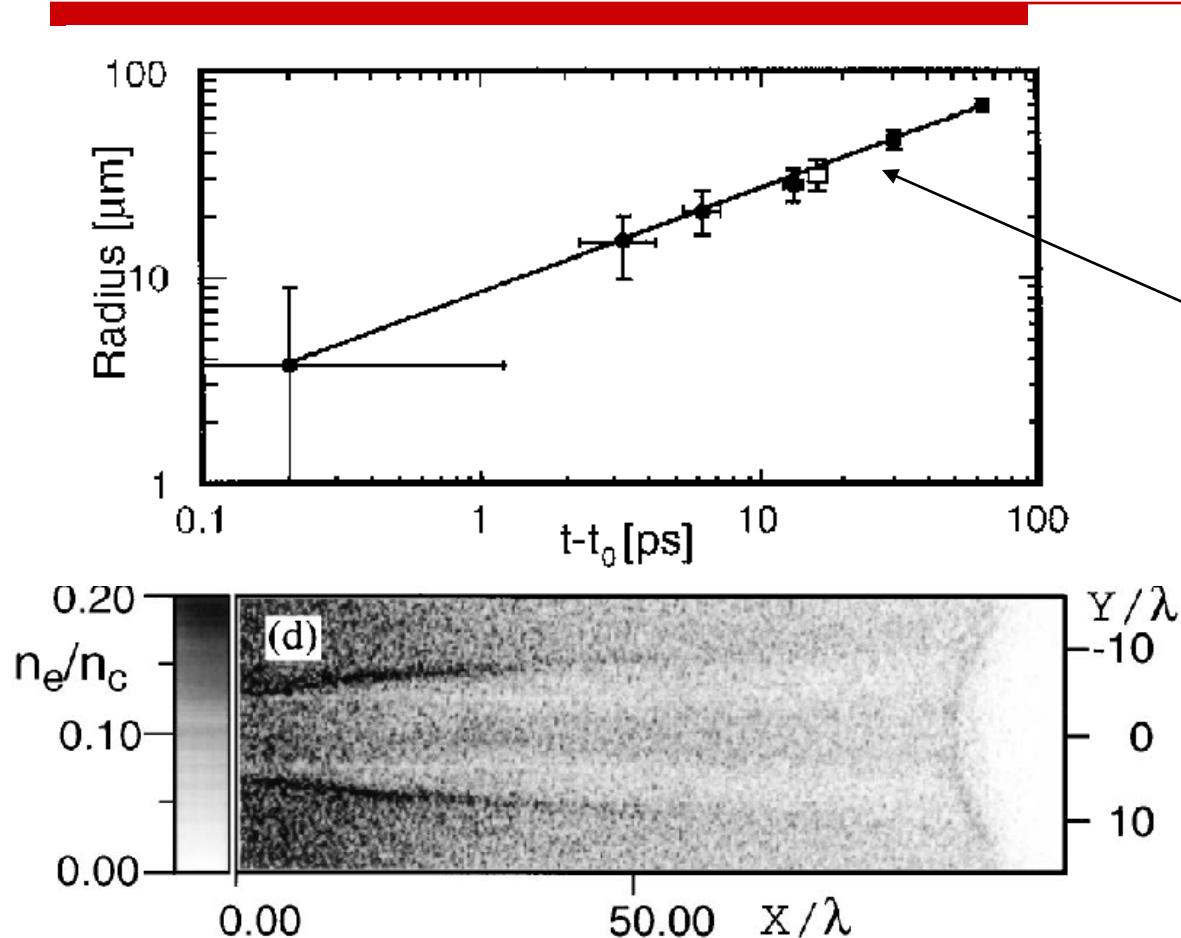


Explosion of the ion channel

A.Pukhov et al., Phys. Plasmas **6**, p.2847 (1999).



Channel expansion: Strong cylindrical blast wave



M.Borghesi et al.
PRL 80, p.5137 (1998).

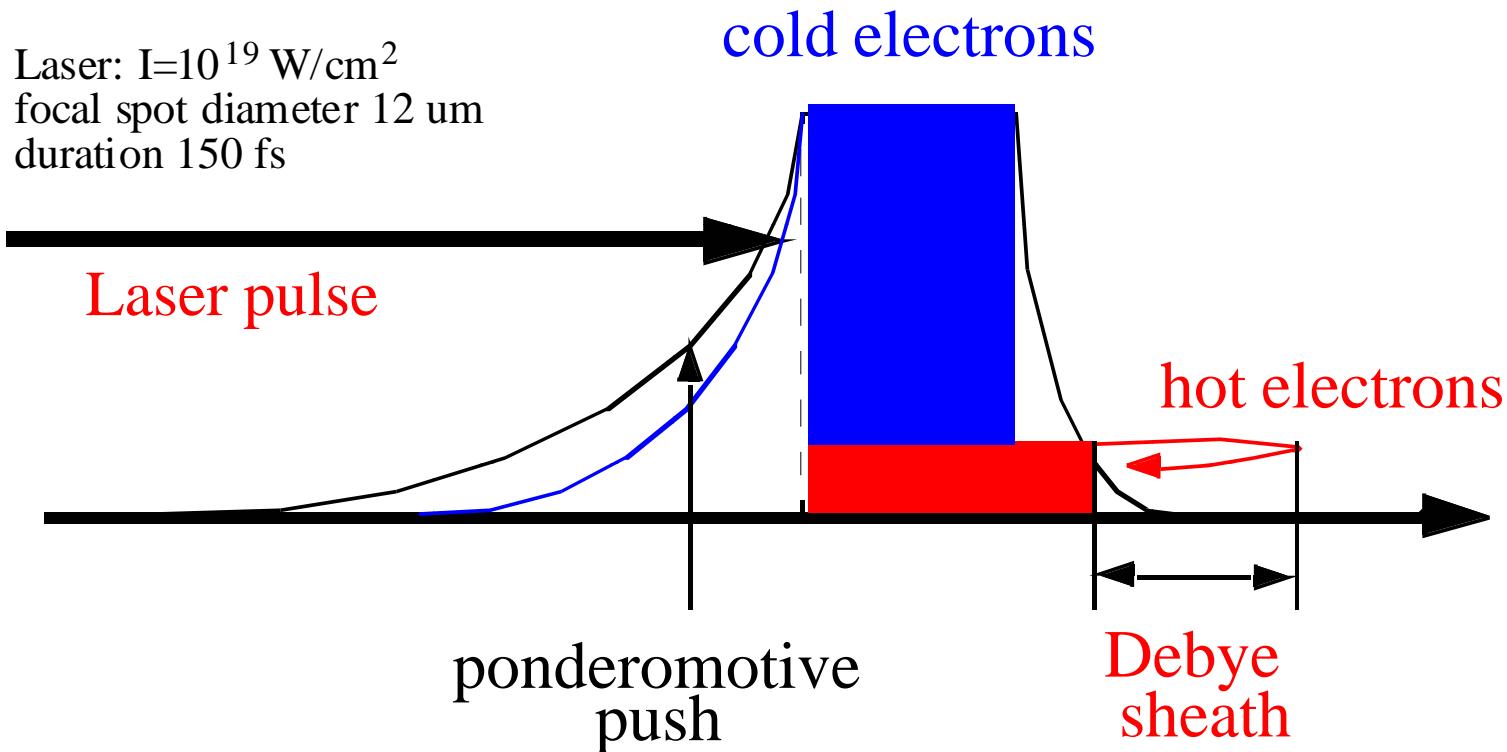
$$R \sim \sqrt{t}$$

Strong shock
scaling
cylindrical
blast wave

Ion acceleration from solid targets

A.Pukhov, Phys. Rev. Lett. **86**, p.3562 (2001).

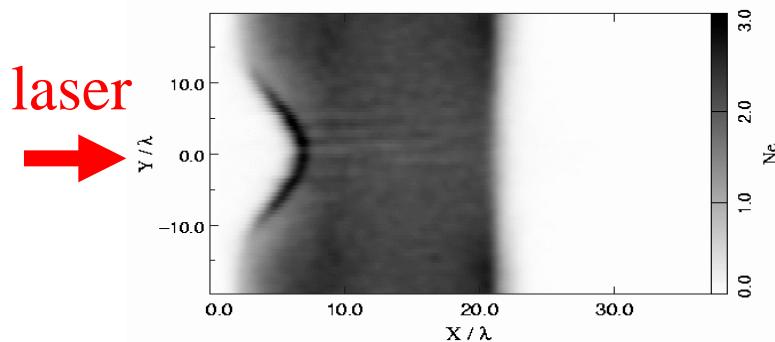
Laser: $I=10^{19} \text{ W/cm}^2$
focal spot diameter 12 μm
duration 150 fs



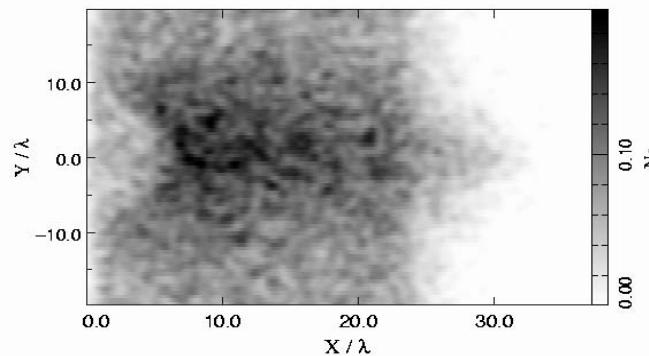
Ion acceleration from solid targets

A.Pukhov, Phys. Rev. Lett. **86**, p.3562 (2001).

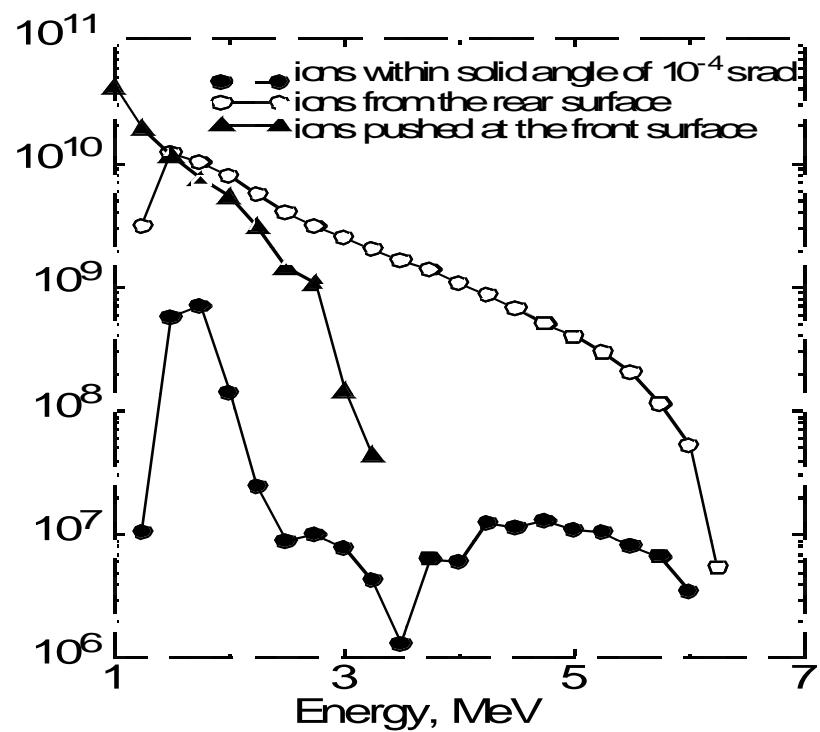
Cold electrons



Hot electrons

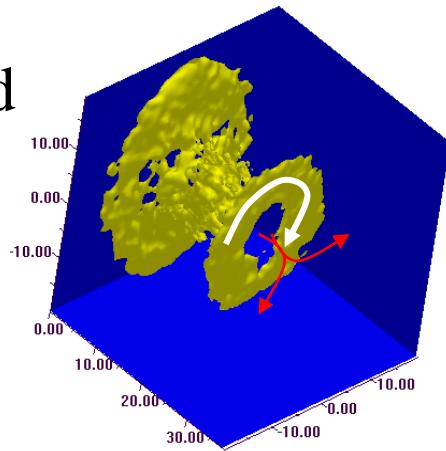


Ion energy spectrum

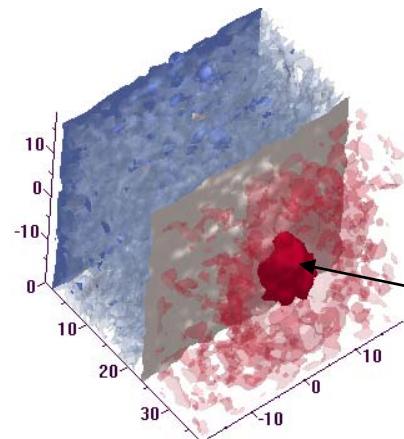


Fields in laser-solid interaction

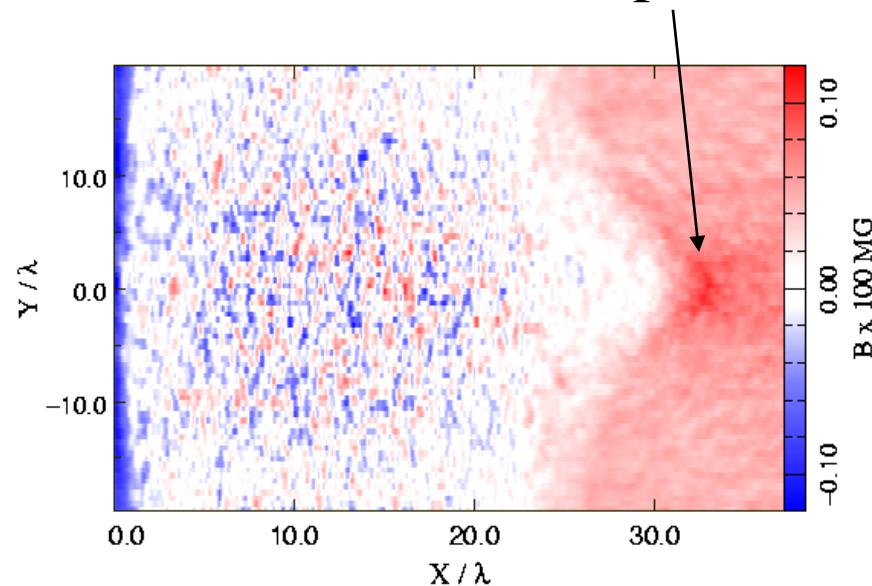
B-field



E-field



Thermal expansion



Debye sheath

Limitations of plain plasma targets

1. Laser can propagate till (relativistic) critical density only
2. Heating of higher density plasmas is indirect.
It is mediated by fast electrons/ions:
efficiency losses
3. Heated overdense region is large
because of large stopping range of relativistic particles:
the heating power is limited,
thus limited energy density

Engineering interaction: Relativistic plasma nanophotonics

Why structured plasmas?

1. Laser technology allows for clean relativistic pulses
2. Nanotechnology and 3D printing provide quite involved regular target structures at nano- and micro-scales

What we expect?

1. Higher absorption efficiencies at higher densities
2. New non-linear physics

Relativistic plasma nano-photonics

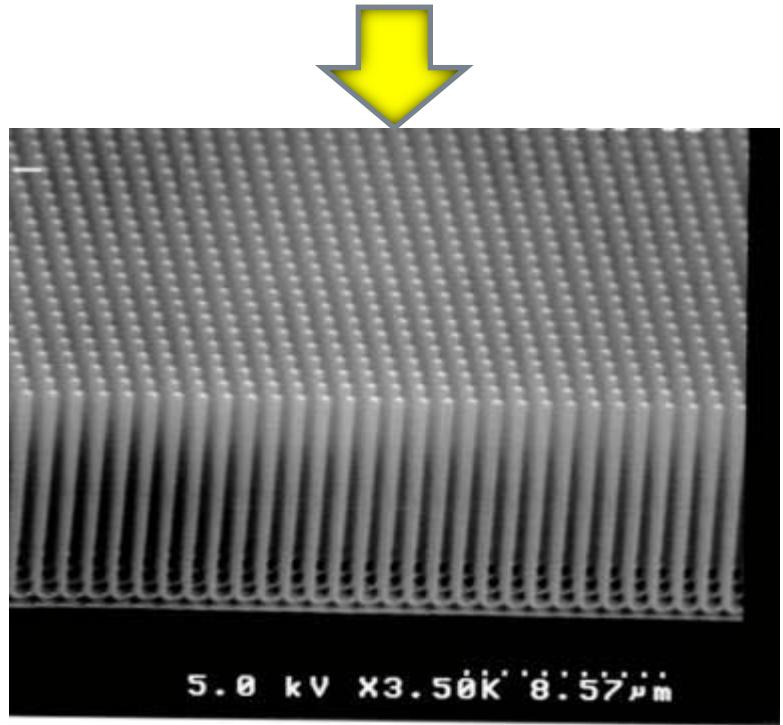
Purvis et al. *Nature Photonics* (2013)

“Nanograss”:
array of nanowires.

Structured material
of high average density

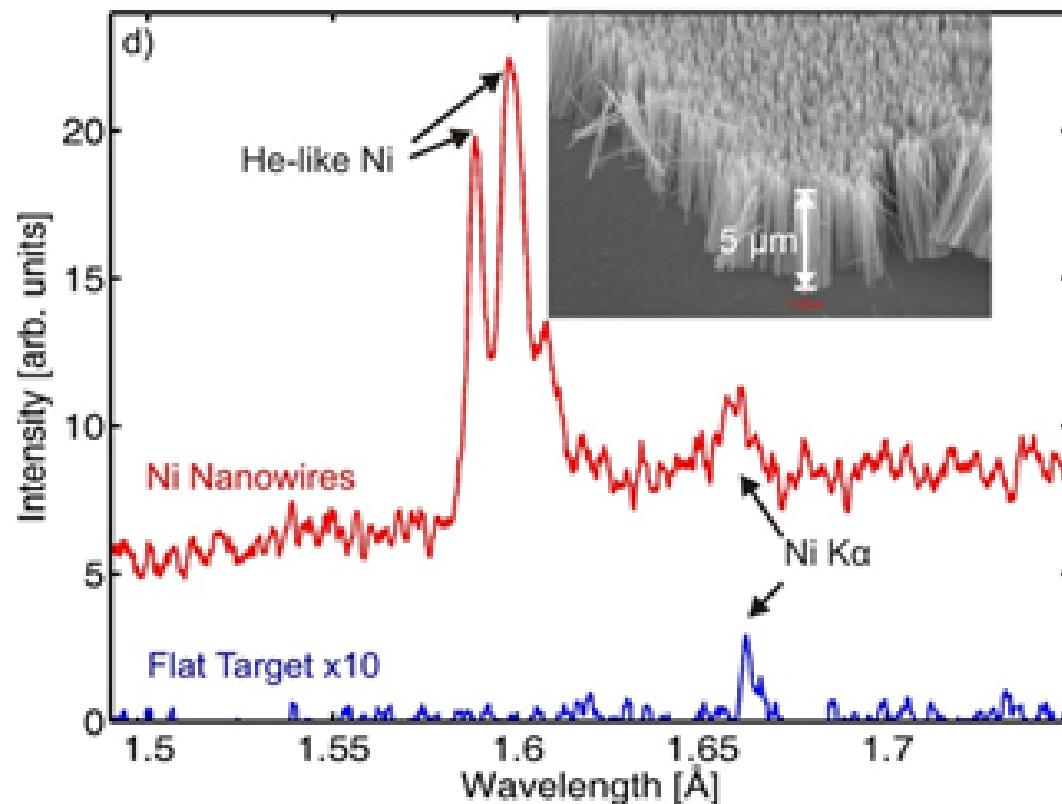
- What is the absorption mechanism?
- Is it a way to create
high density hot plasma?
- What is the optimal structure?
- New nonlinear physics

Laser, $10^{18} \dots 10^{20} \text{ W/cm}^2$



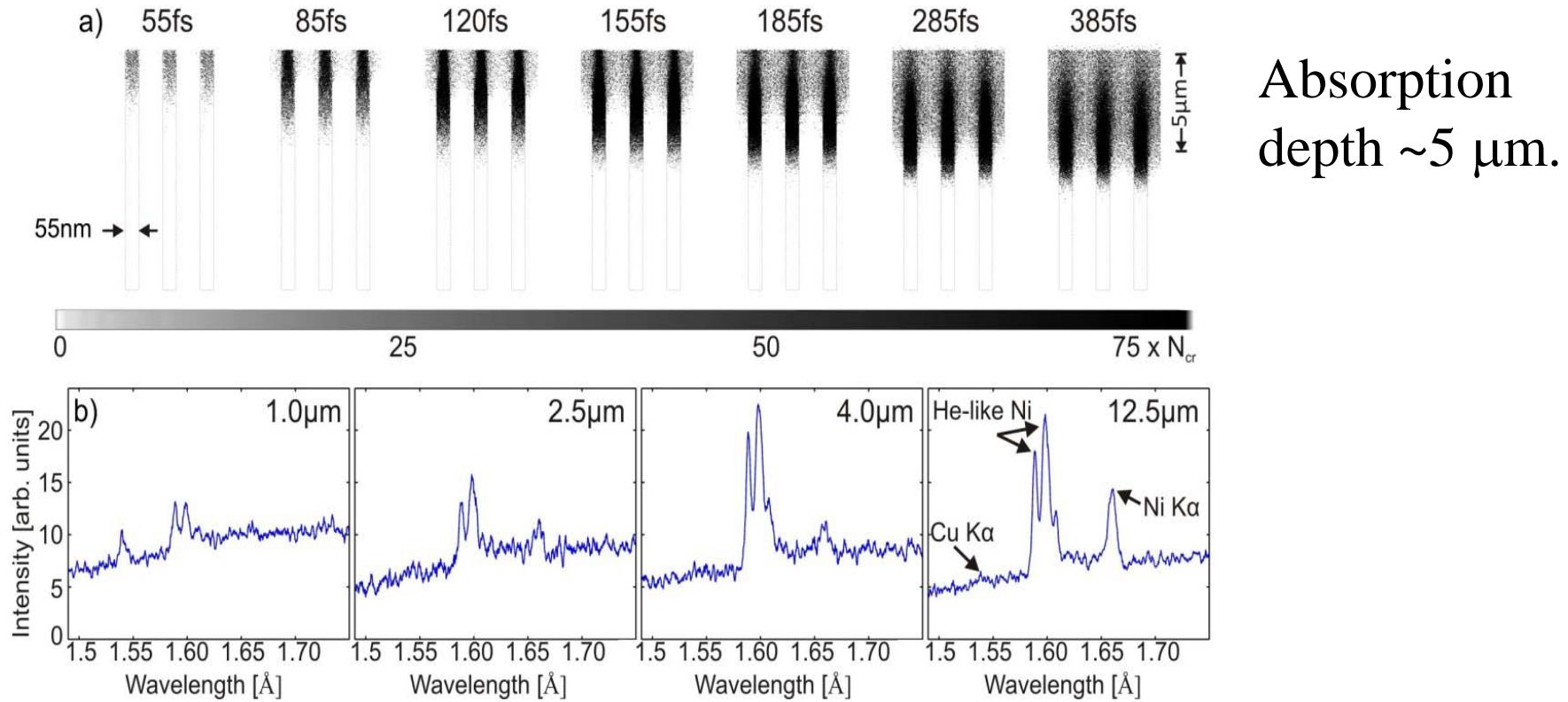
Several orders of magnitude higher x-ray yield from nanoplasmas

Purvis et al. *Nature Photonics* (2013)



He-like Ni in 3D PIC simulations

Purvis et al. *Nature Photonics* (2013)



Nanowire electron density dynamics

ne, -72.0 fs after peak

ne (ncr):

50

300

600

1000

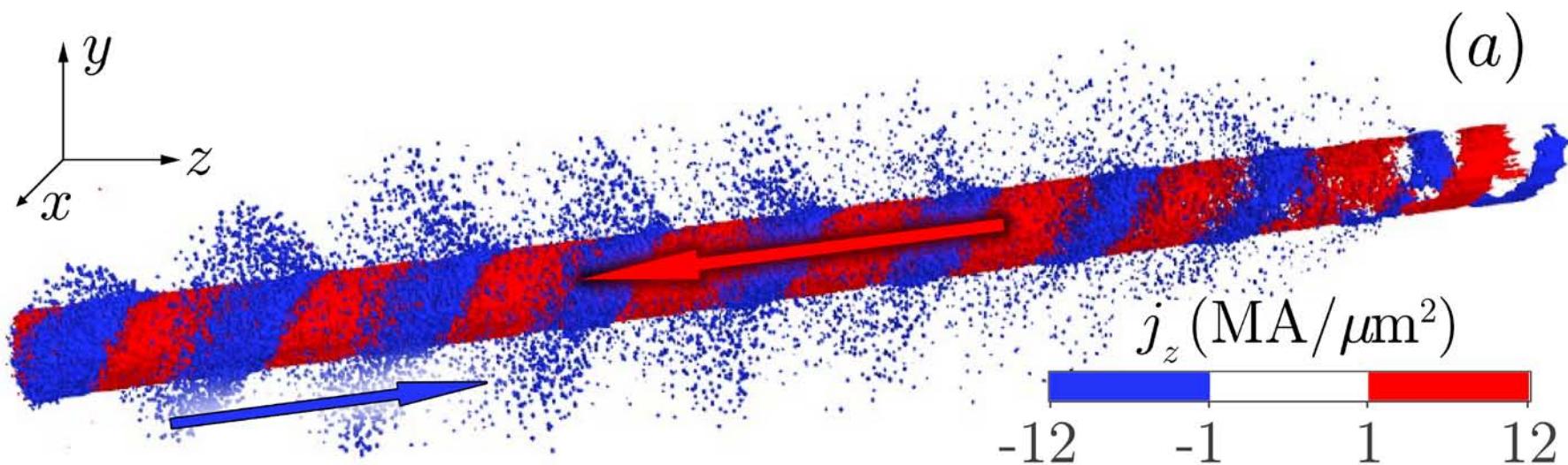
1800



frame 5
diameter = 300 nm
length = 5 μm
density = 7 % solid
material = carbon
wavelength = 400 nm
 $a_0 = 17$
pol. = circ. pol.
cells = 100x100x1080

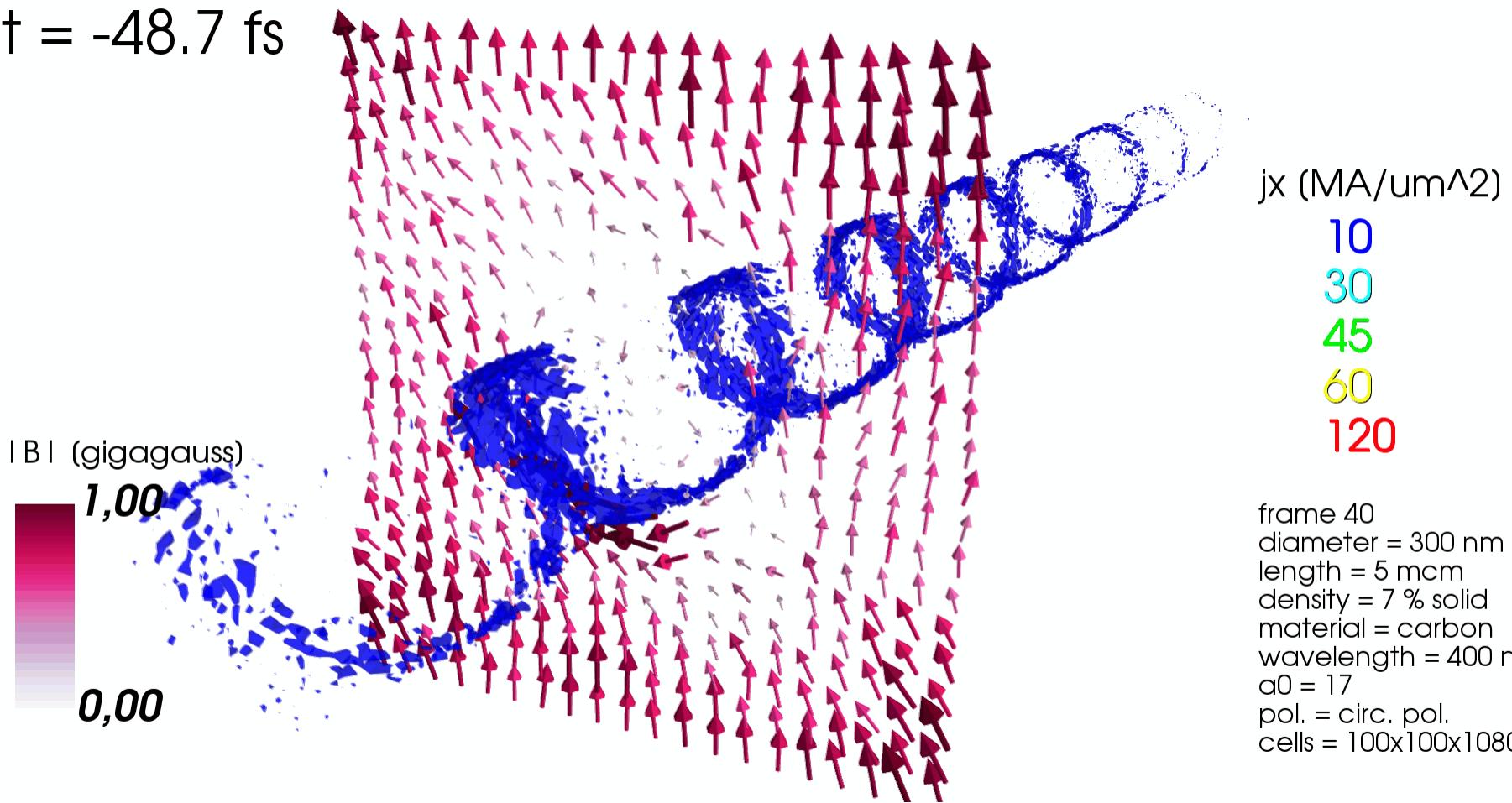
Nanoscale Ultradense Z -Pinch

Longitudinal current distribution

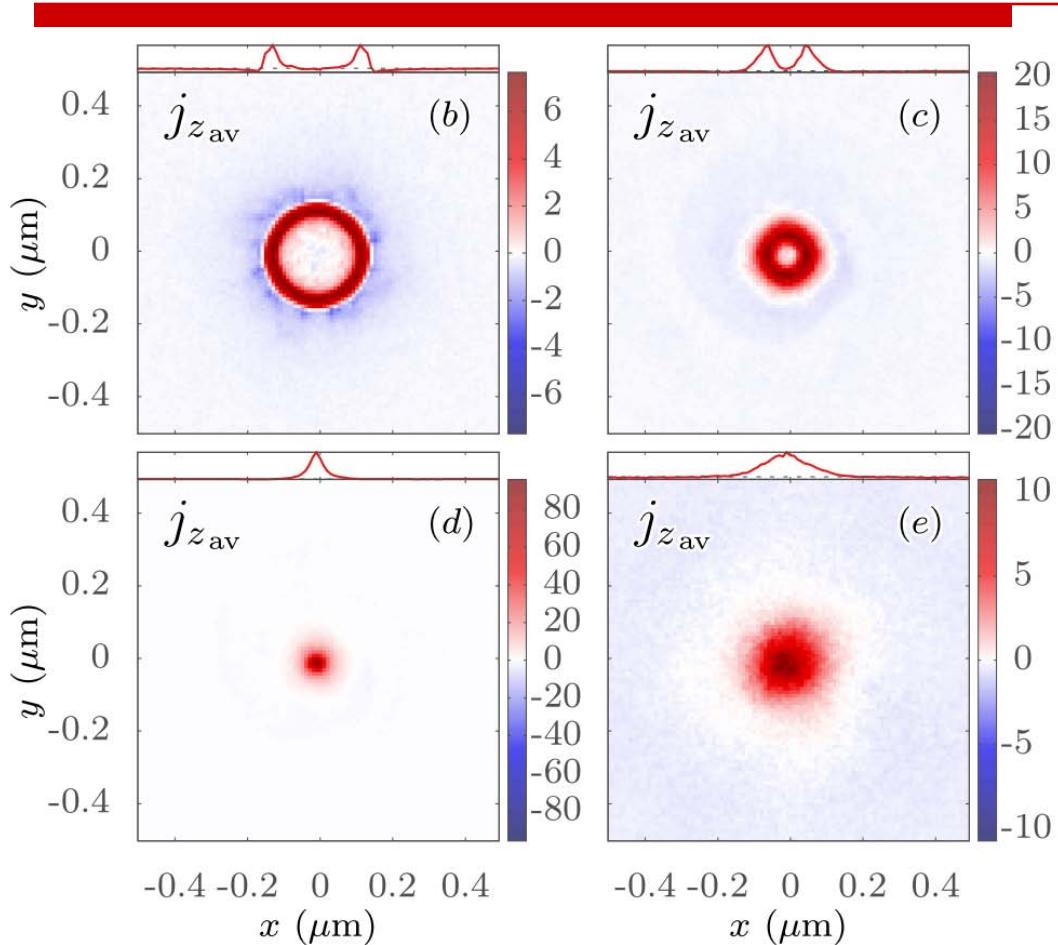


Nanoscale Ultradense Z -Pinch

$t = -48.7 \text{ fs}$



Nanoscale Ultradense Z -Pinch



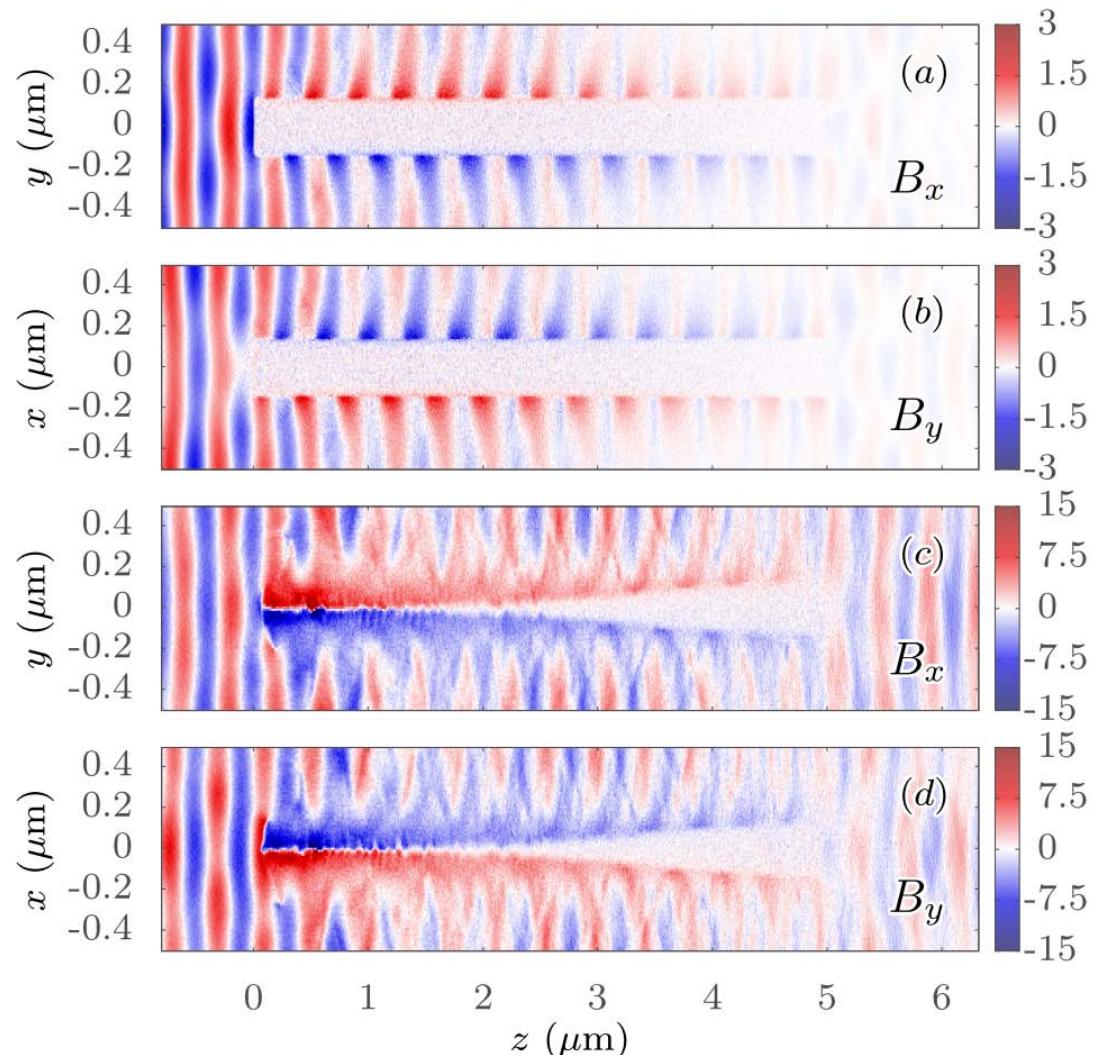
**Evolution
of longitudinal
current**

**Passage through
the pinch**

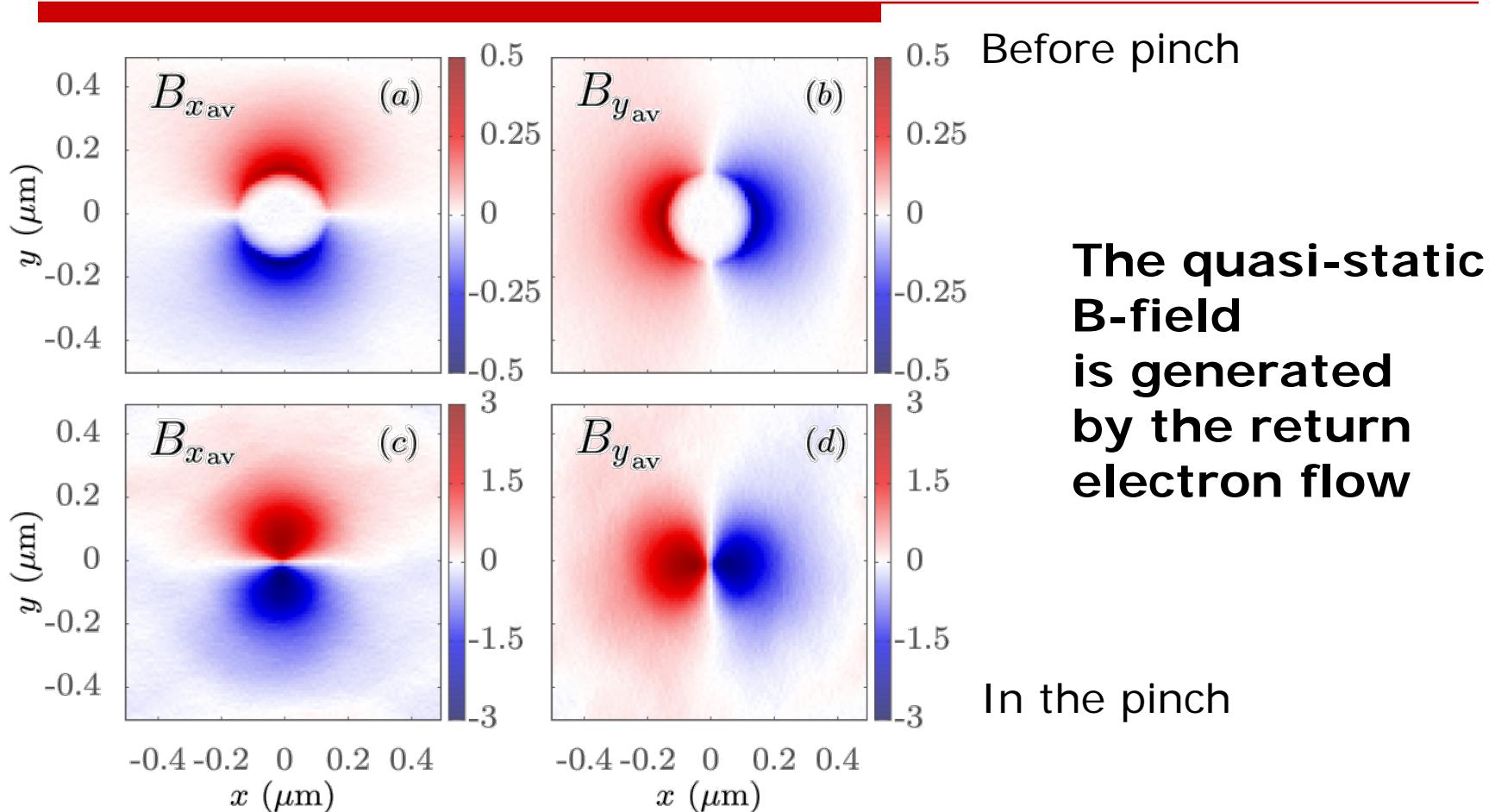
Nanoscale Ultradense Z -Pinch

**Evolution
of the B-field:**

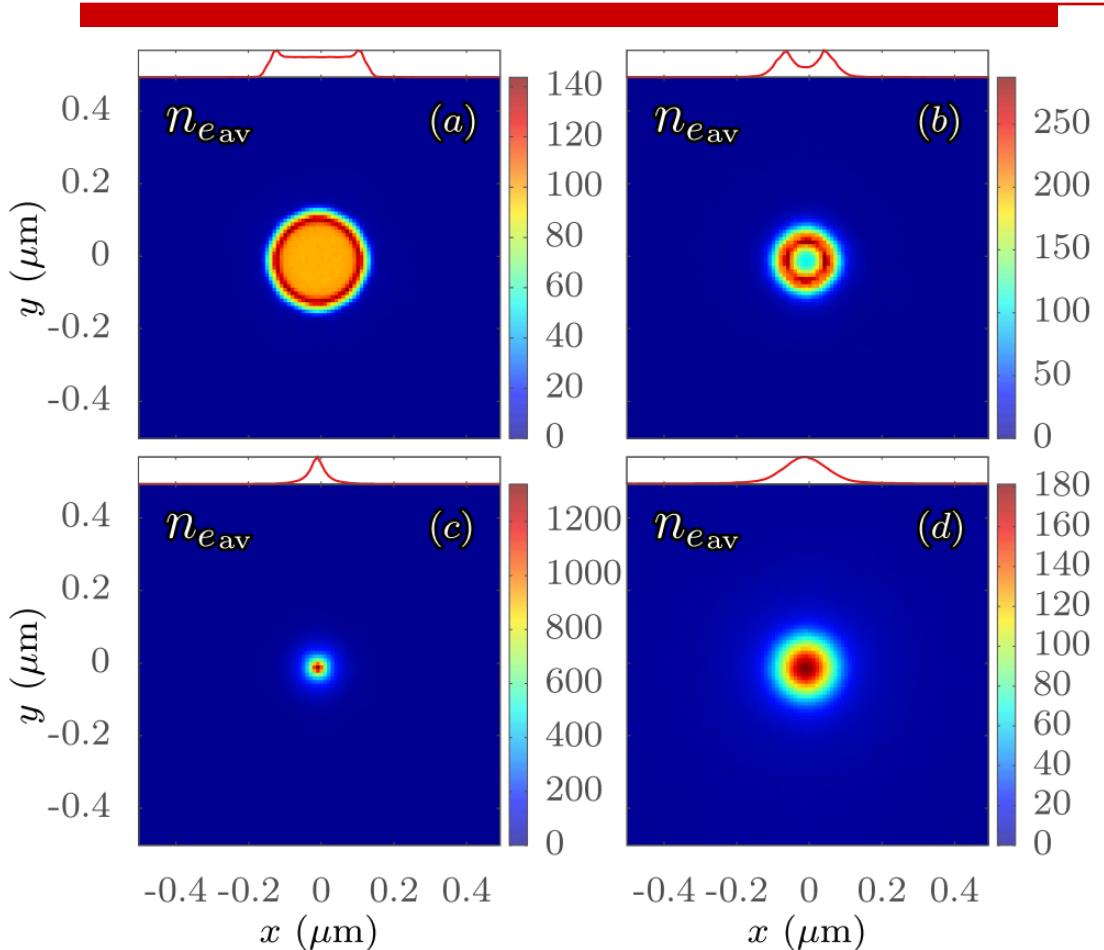
**Laser wave
in the voids
and the quasi-
static B-field
around
the nanorods**



Nanoscale Ultradense Z -Pinch



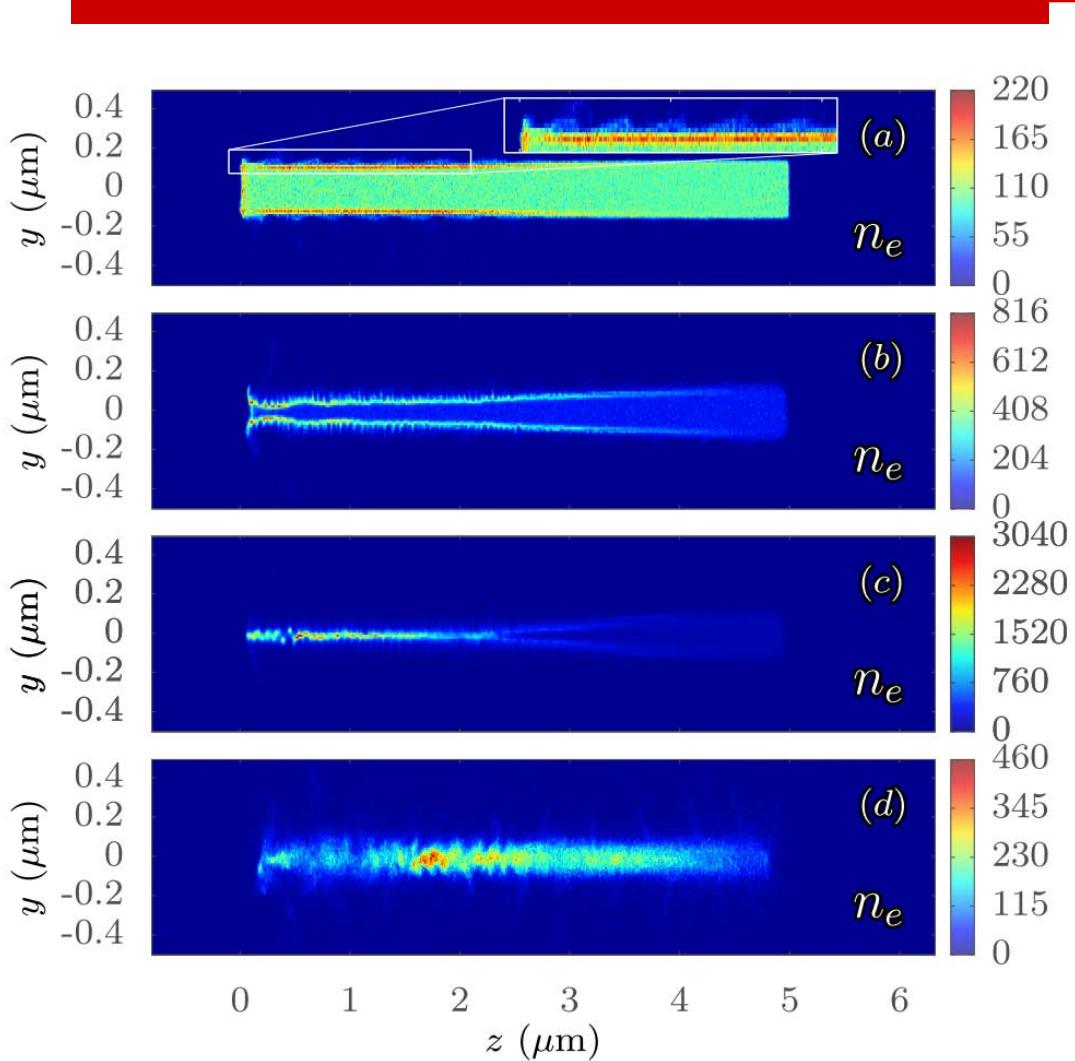
Nanoscale Ultradense Z -Pinch



**Evolution
of electron
density**

**Passage through
the pinch**

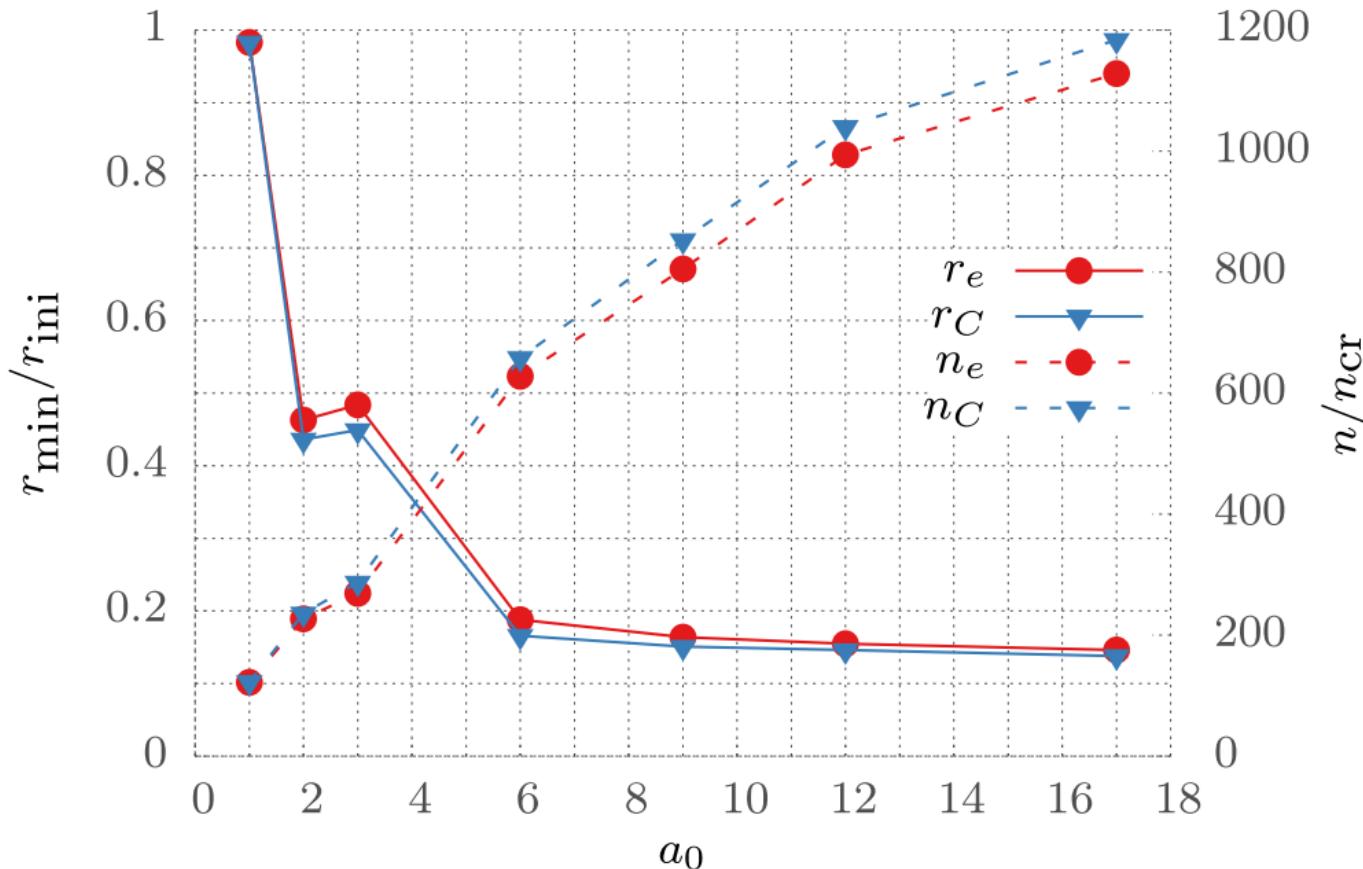
Nanoscale Ultradense Z -Pinch



**Evolution
of electron
density**

**Passage through
the pinch**

Nanoscale Ultradense Z -Pinch



Nanopinch
is clearly
a relativistic
effect

sets in when
 $a_0 > 1$

Ultra-High Energy Density Plasmas

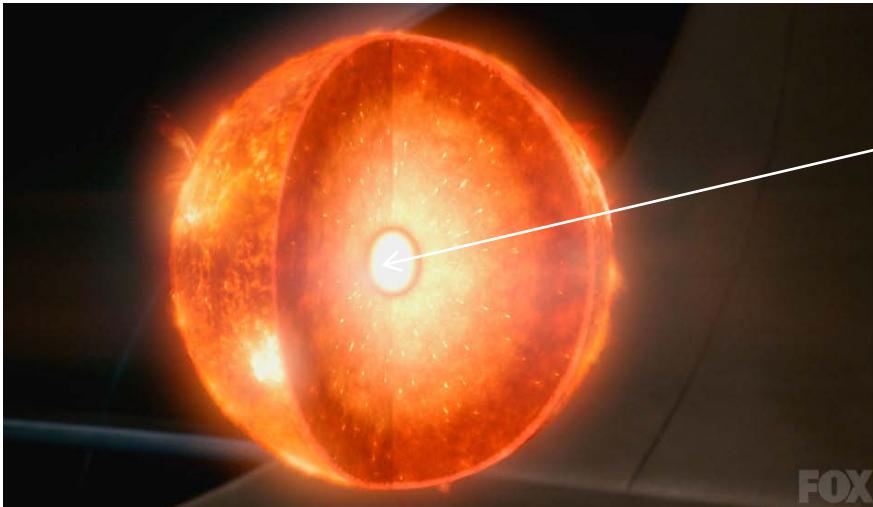
**Arrays of nanowires allow for
high density high temperature plasmas**

**Can we scale it to Terabar Pressures
near thermal equilibrium?**

What is the possible energy density?

Path to Extreme pressures by irradiation of aligned nanowire arrays

Rocca et al. LASER FOCUS WORLD 53 (5), 21-26 (2017)

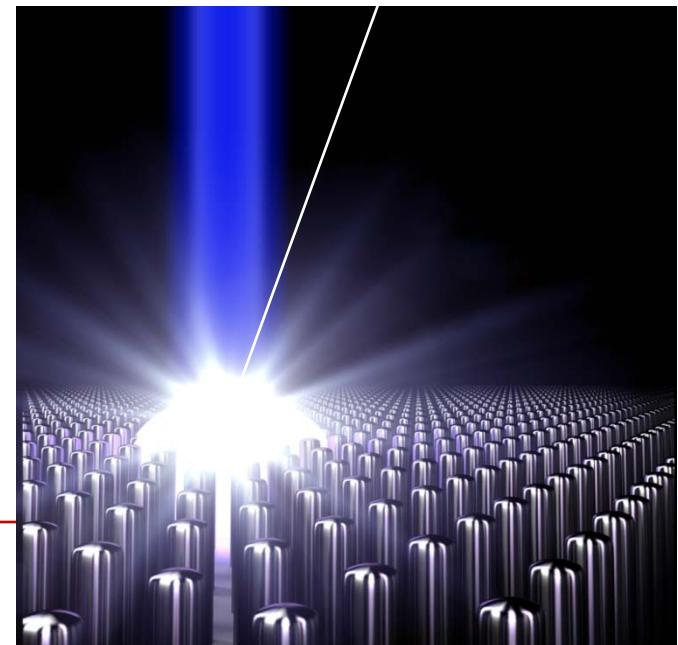
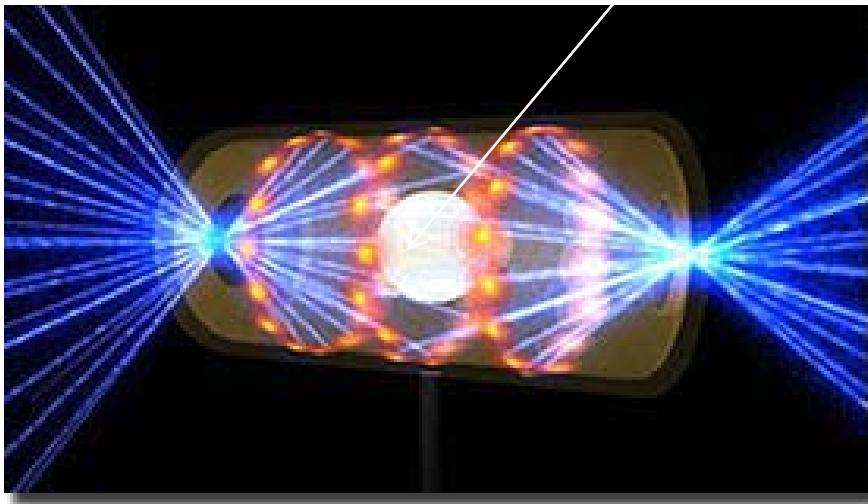


**Sun Core
240 Gbar**

Nanowire array plasma

$$I = 1 \times 10^{22} \text{ W cm}^{-2}$$

**NIF Implosion
150 Gbar**



Ultra-High Energy Density Plasmas for efficient picosecond X ray sources

Required conditions:

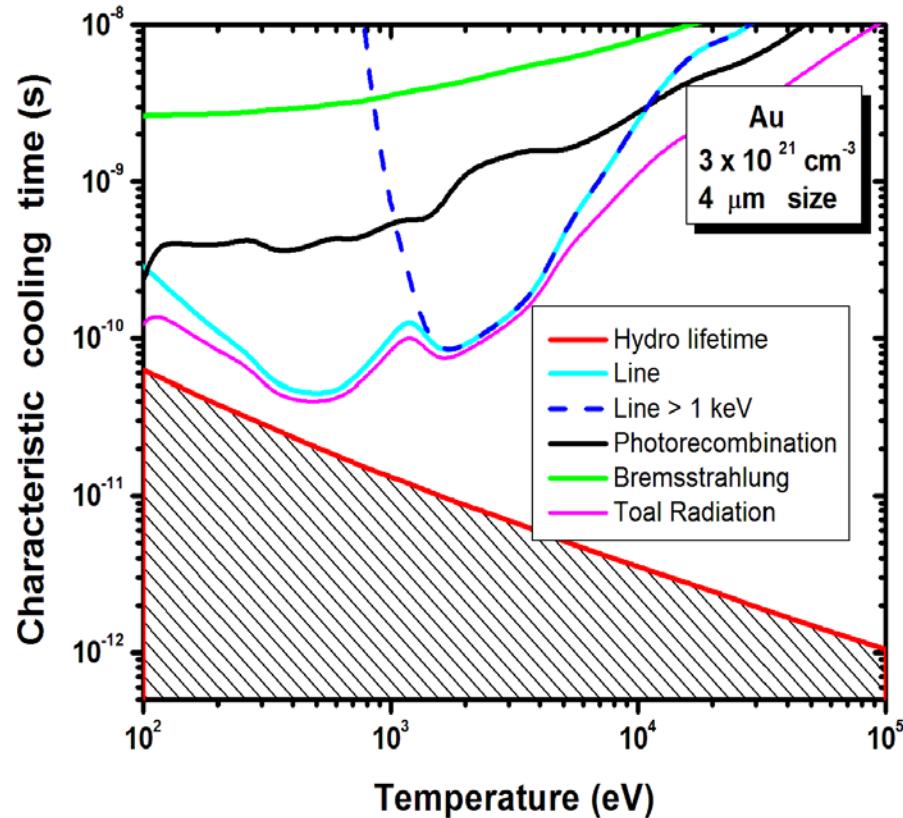
**Hydrodynamic confinement time
longer than radiative cooling time:**

$$T_{\text{conf}} > T_{\text{cool}}$$

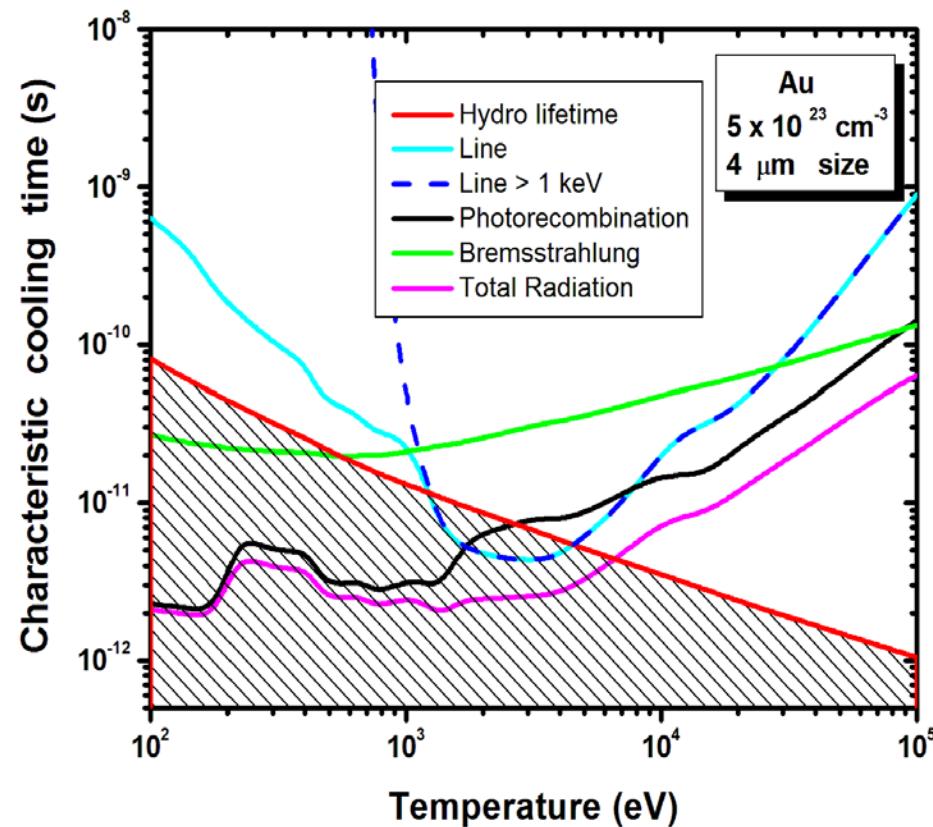
Fast thermal equilibration:

$$T_{\text{conf}} > T_{\text{equil}}$$

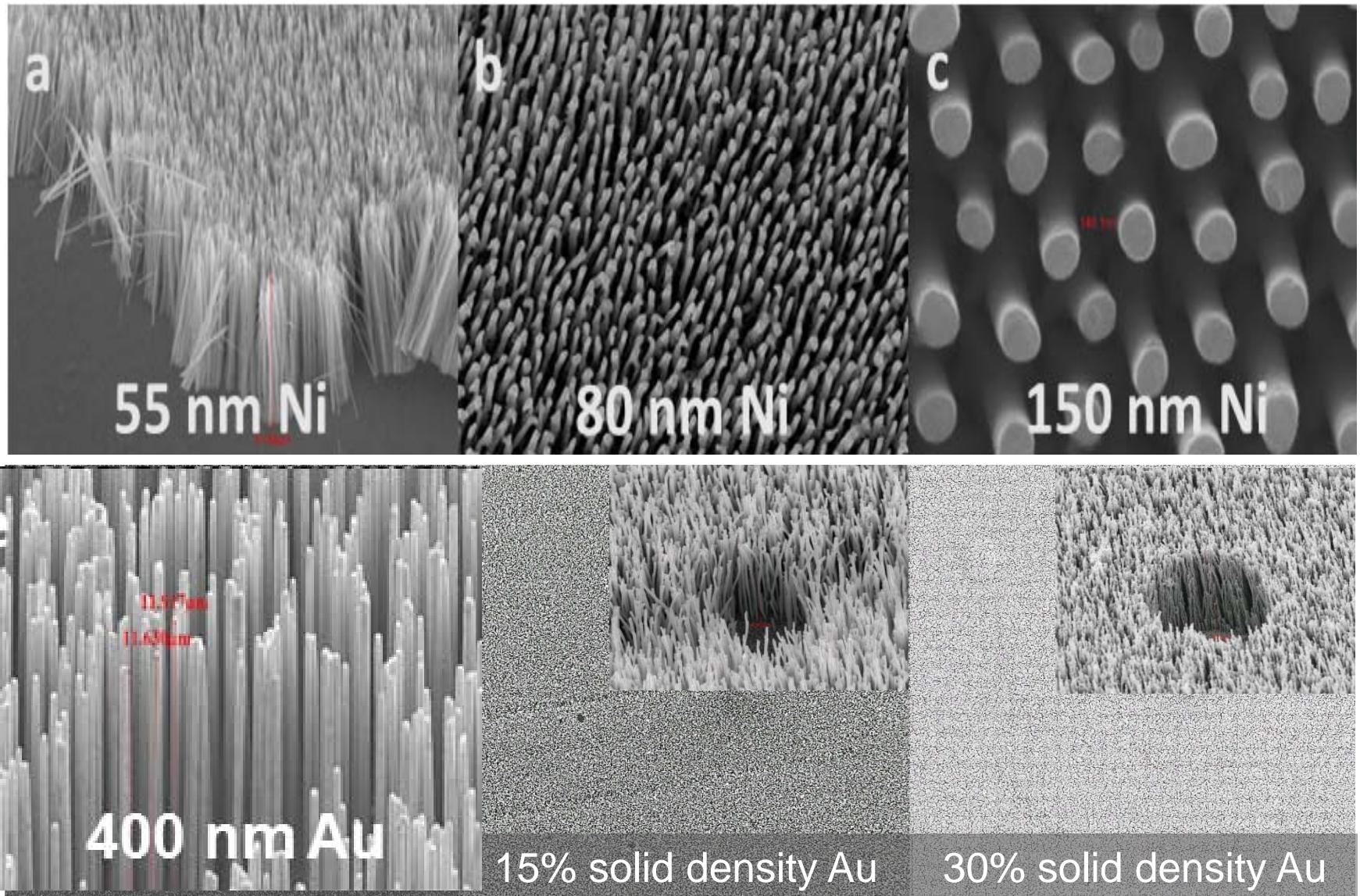
Lifetimes of plasma at the critical density for 400nm light



Lifetimes of plasma at 100x n_c for 400nm light

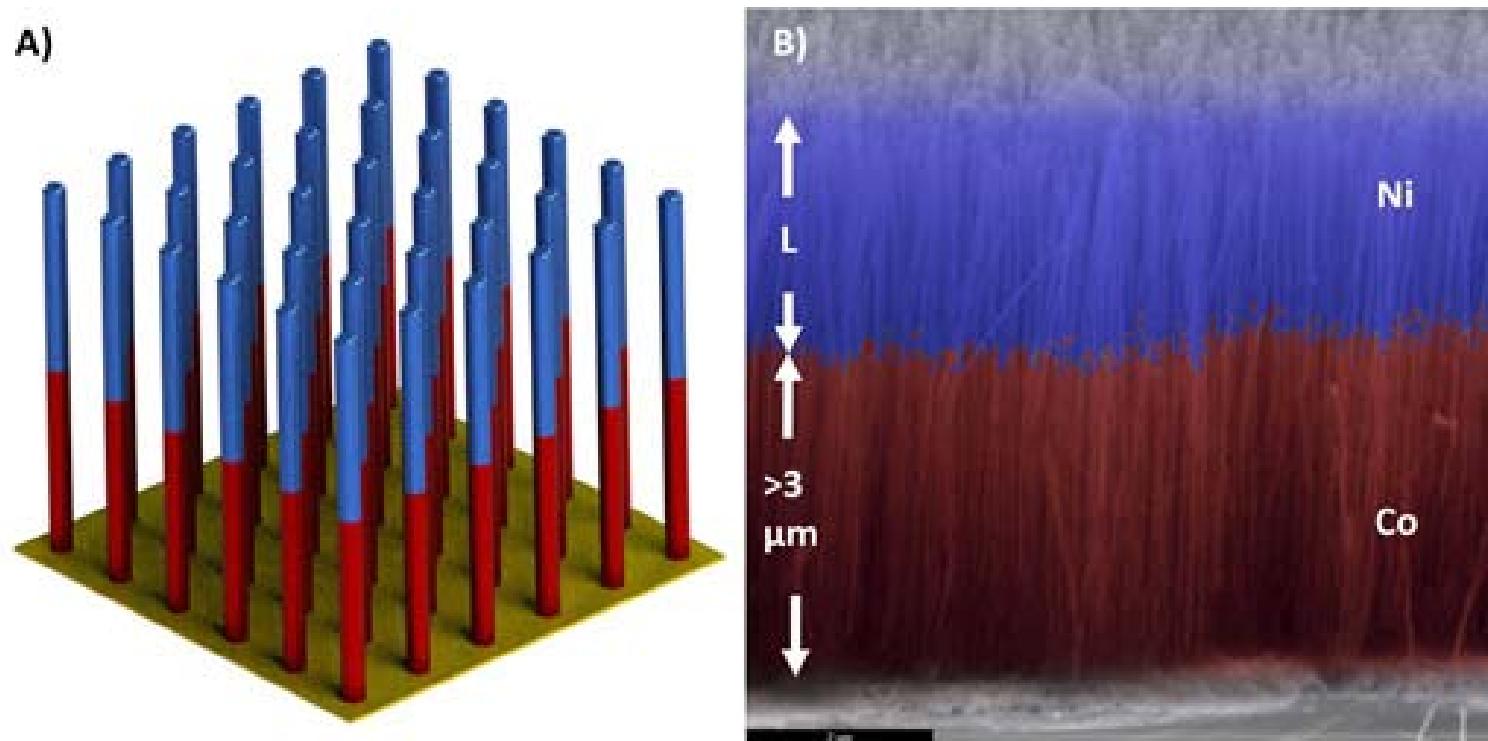


Nanowire array SEM Images

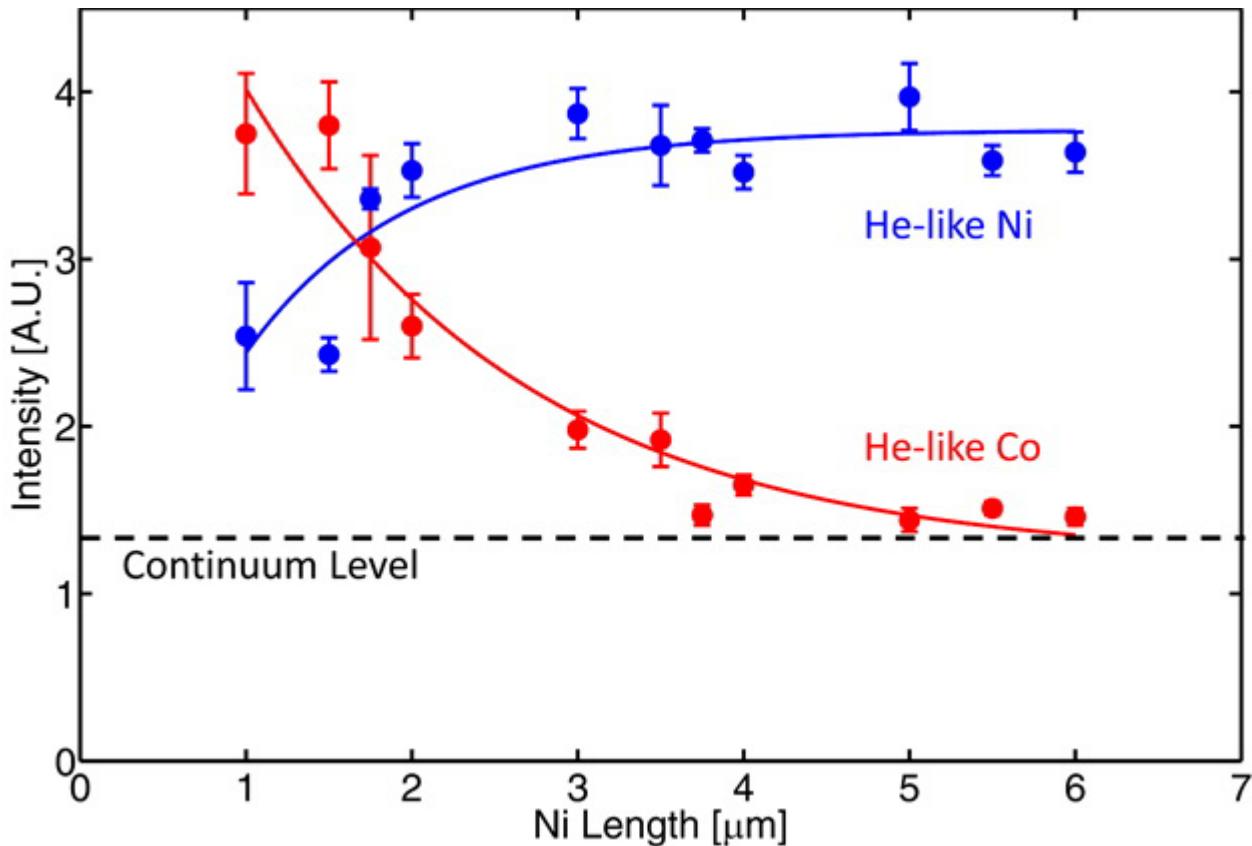


Ultra-High Energy Density Plasmas

Experiment at Colorado State University with composite nanowire arrays

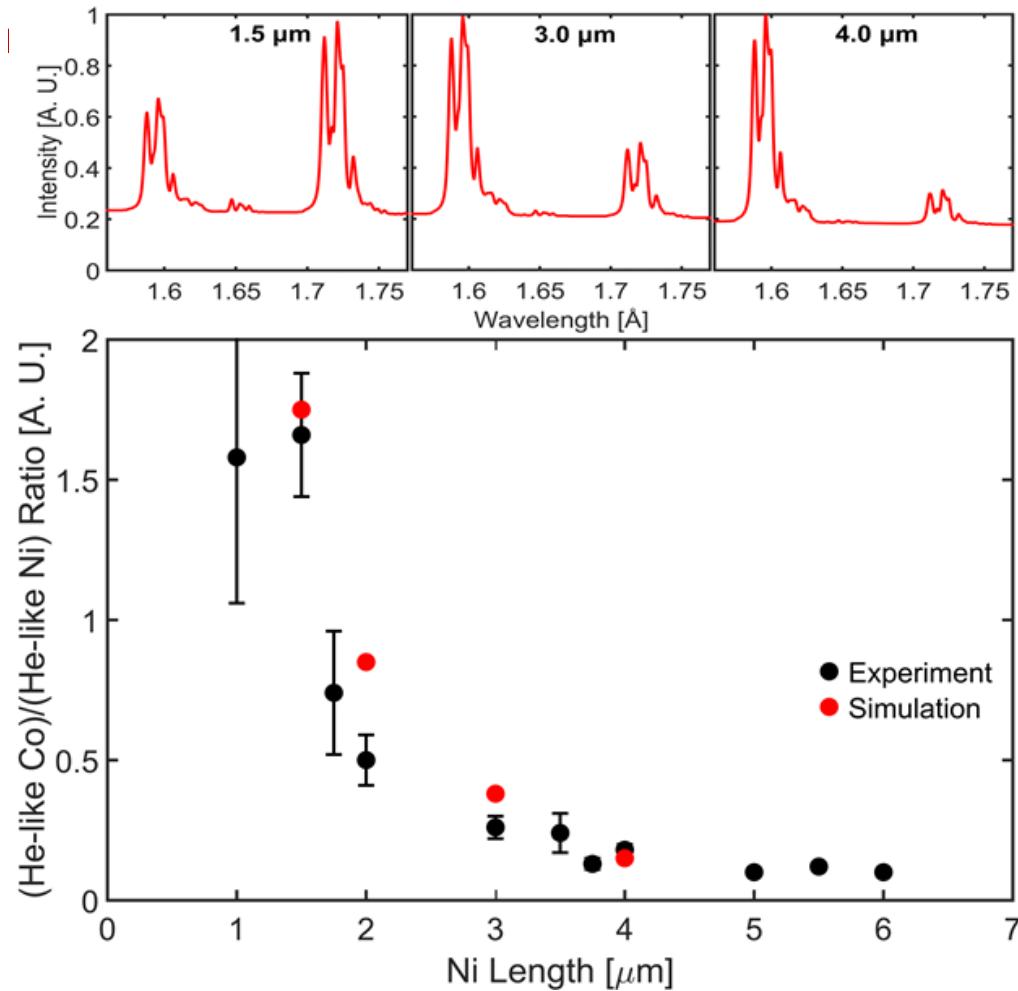


Ultra-High Energy Density Plasmas



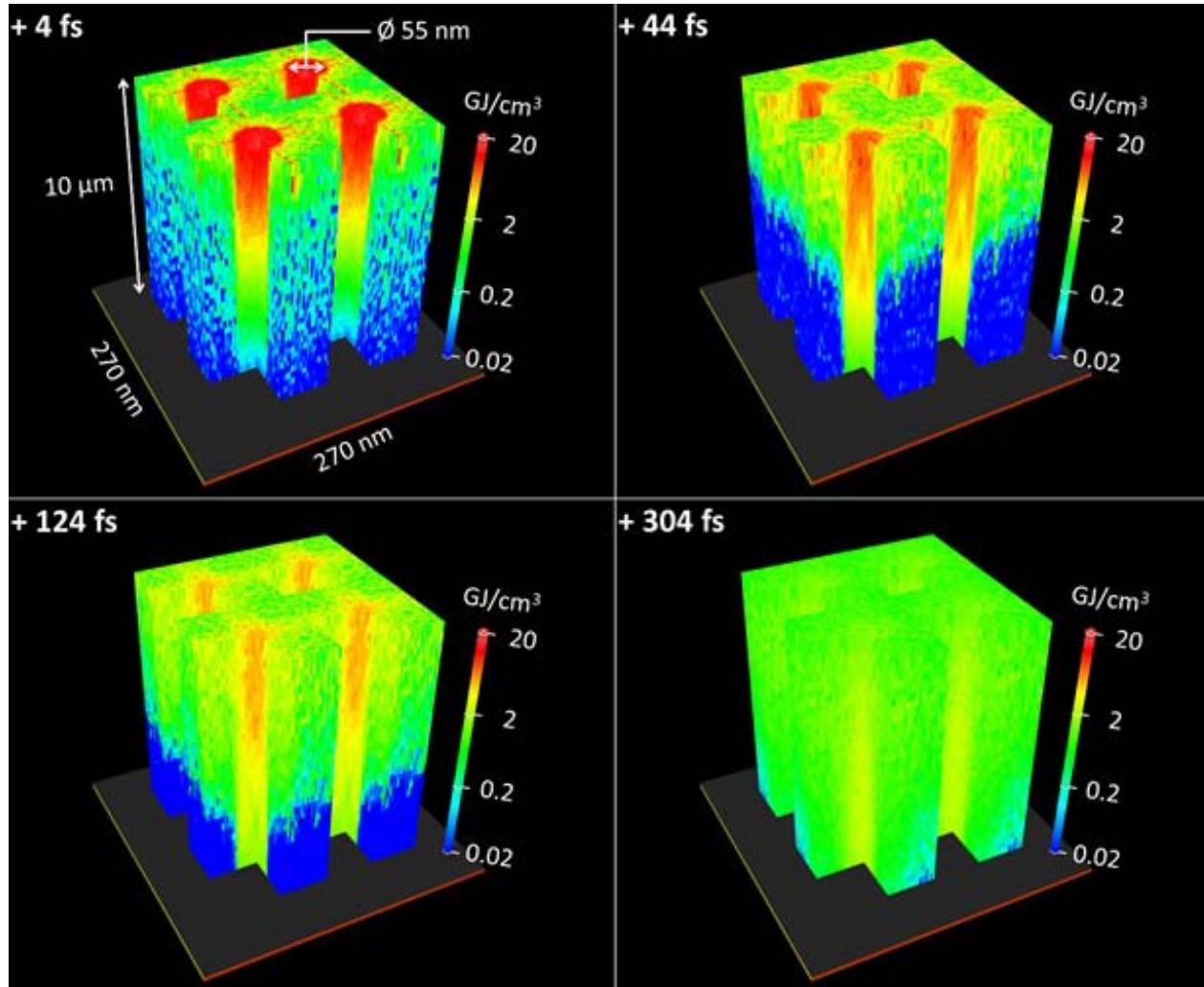
Measured intensities of the He-like Co and He-like Ni lines as a function of the Ni length

Ultra-High Energy Density Plasmas



Simulated spectra
corresponding to
arrays with different
wire lengths used in
the experiment

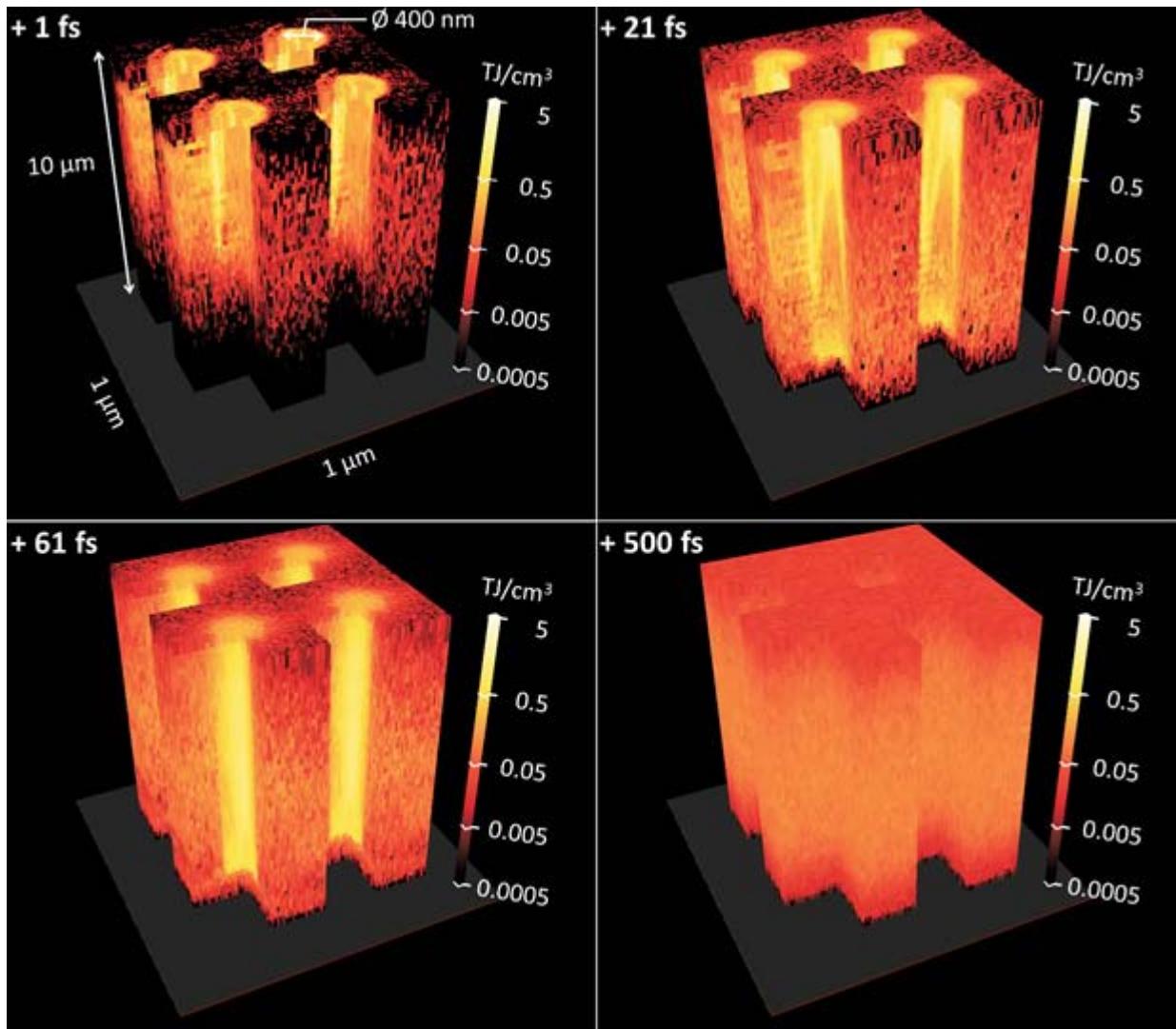
Ultra-High Energy Density Plasmas



Energy density distribution computed by PIC simulation

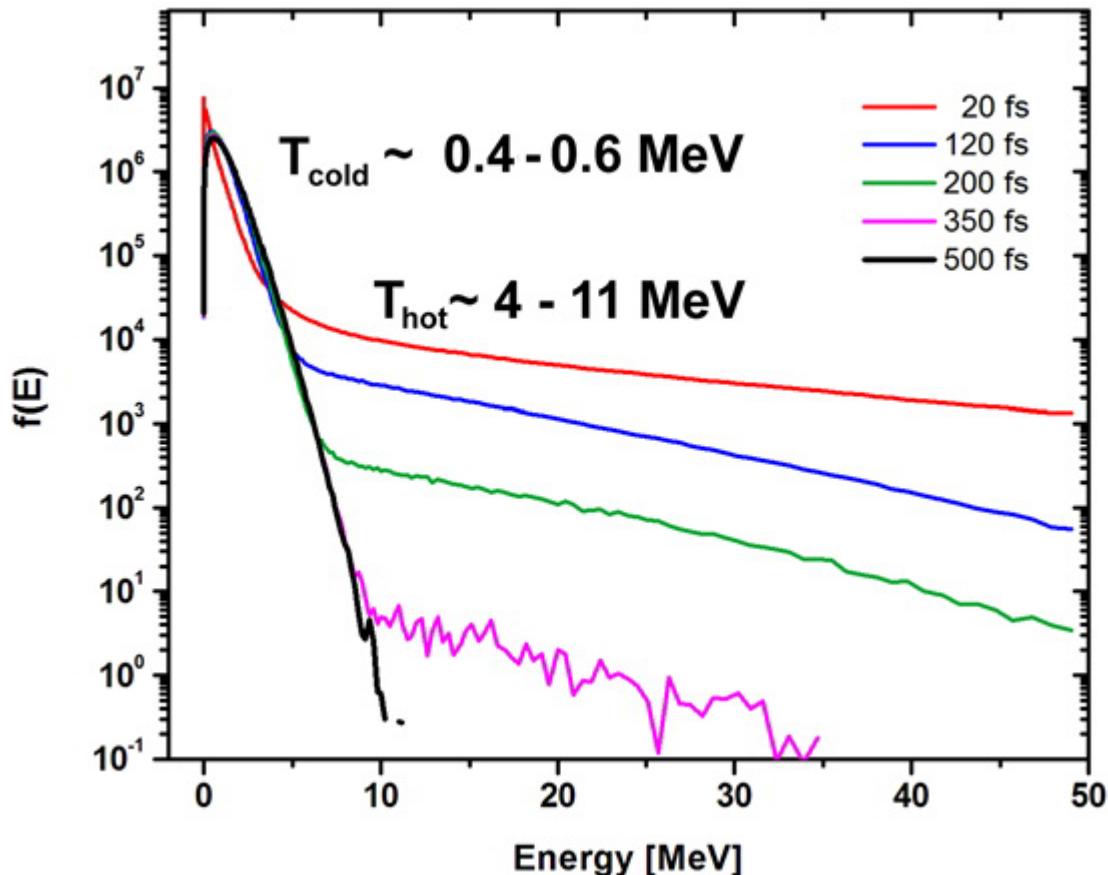
Fast homogenisation

Ultra-High Energy Density Plasmas



PIC simulated energy density distribution in an array of vertically aligned **Au nanowires** of **400 nm diameter** irradiated with an intensity of $1 \times 10^{22} \text{ W cm}^{-2}$ ($a_0 = 34$) using a 400 nm wavelength pulse of 30 fs duration.

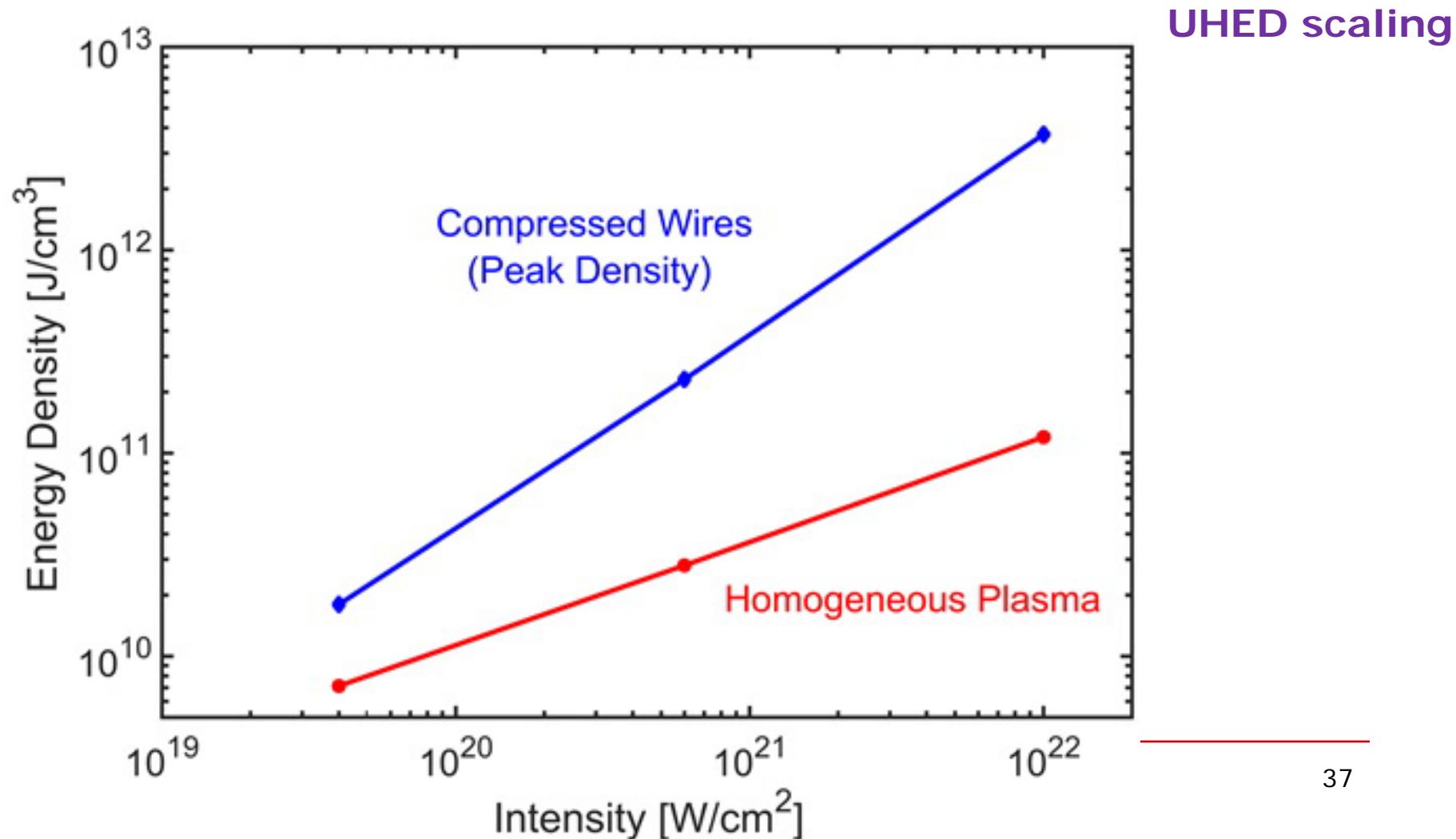
Ultra-High Energy Density Plasmas



Rapid thermalization
seen in electron
distribution function

PIC simulated
array of vertically
aligned **Au nanowires**
of **400 nm diameter**
irradiated with an
intensity of
 $1 \times 10^{22} \text{ W cm}^{-2}$
($a_0 = 34$) using a 400
nm wavelength pulse of
30 fs duration.

Ultra-High Energy Density Plasmas



Ultra-High Energy Density Plasmas

Aligned arrays of nanorods 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 **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.

Nuclear fusion in dense nanowire array plasmas

Aligned arrays of nanorods deliver up to 2×10^6 fusion neutrons/Joule, a 500 times increase respect to flat solid targets and a record yield for Joule-level lasers.

Moreover, in agreement with simulations we observe a rapid super-linear increase in the number of neutrons with laser pulse energy.

The results can impact nuclear and high energy density science and lead to bright ultrafast quasimonoenergetic neutron sources for imaging and materials studies.

Average particle energy in nanowire array plasmas

Assuming total laser energy absorption and volumetric heating of the target, the average energy per particle can be estimated to be:

$$E_{av} \approx \frac{a_0^2}{2} mc^2 \frac{n_c}{n_{av}} \frac{Z}{(Z+1)} \frac{c\tau}{L}$$

where $n_c = m\omega_0^2/4\pi e^2$ is the critical electron density, τ is the laser pulse duration and L is the absorption depth in the target with the average particle density n_{av} , Z is the ionization charge state.

For the conditions of the experiments

$a_0 \sim 3.3$, $\lambda = 400$ nm, $n_{av} = 0.2 n_{solid}$, $T = 55$ fs, and $L \sim 5$ μm

E_{av} can be calculated to be ~ 0.6 MeV.

Nuclear fusion in dense relativistic nanowire array plasmas

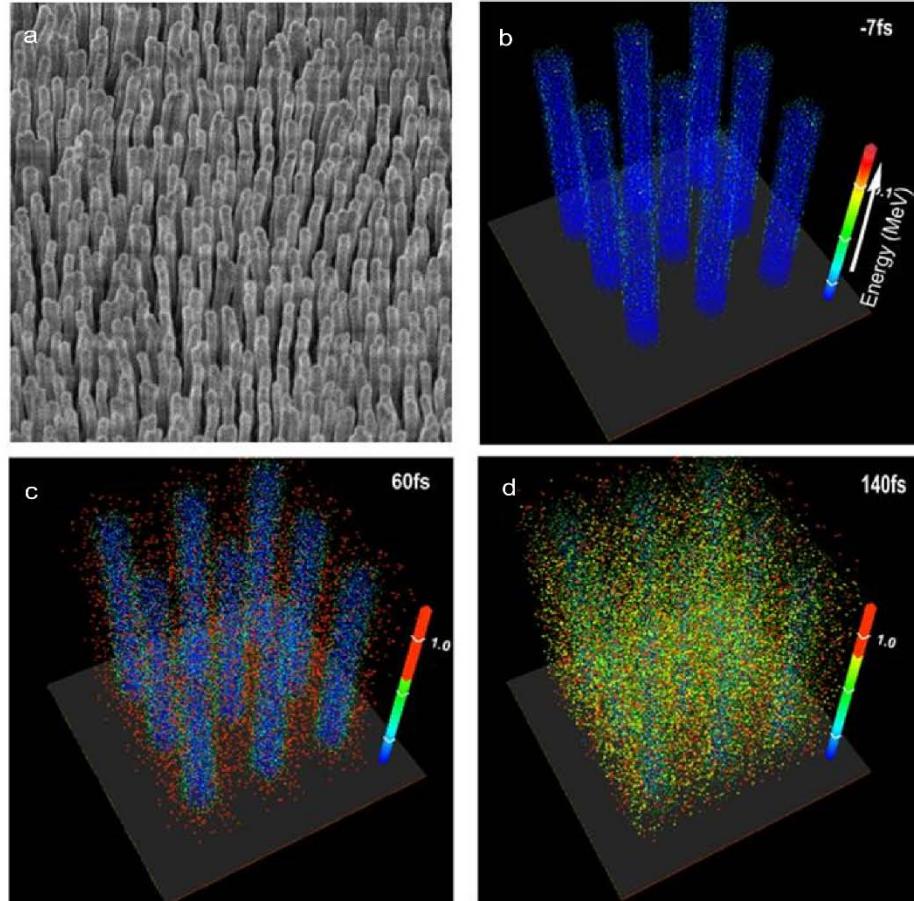


Fig. 1: (a). Scanning electron microscope image of array of 400 nm diameter CD_2 nanowires.

(b-d) 3-D PIC simulation of the evolution of the energy distribution of deuterons

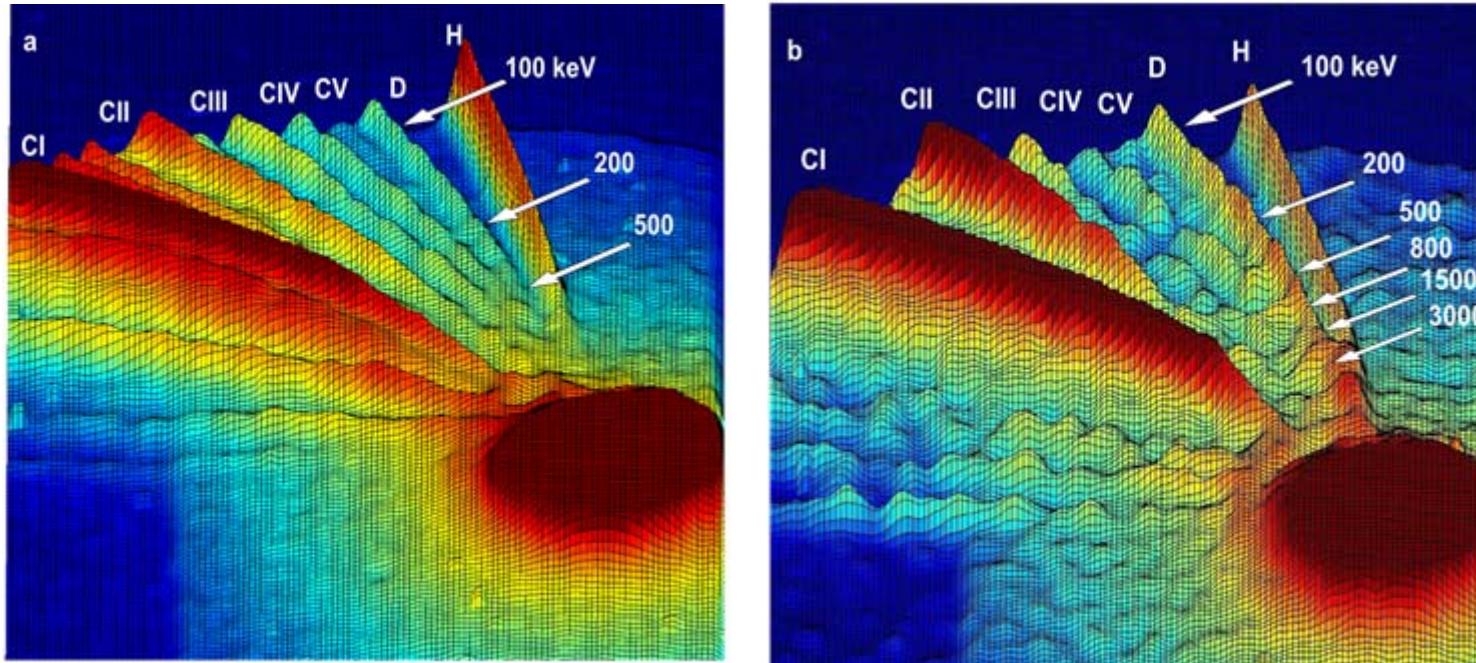
in an array of 400 nm diameter CD_2 nanowires irradiated by an ultra-high contrast $\lambda = 400$ nm laser pulses of 55 fs FWHM duration irradiated at an intensity of $8 \times 10^{19} \text{ W cm}^{-2}$.

The laser pulses penetrate deep into the array where they rapidly heats the nanowires to extreme temperatures, causing the nanowires to explode [Fig 1c,d].

Deuterons are rapidly accelerated into the voids up to MeV energies, producing D-D fusion reactions and characteristic 2.45 MeV neutrons.

Times are measured respect to the peak of the laser pulse. The average density of the nanowire array corresponds to 20% solid density.

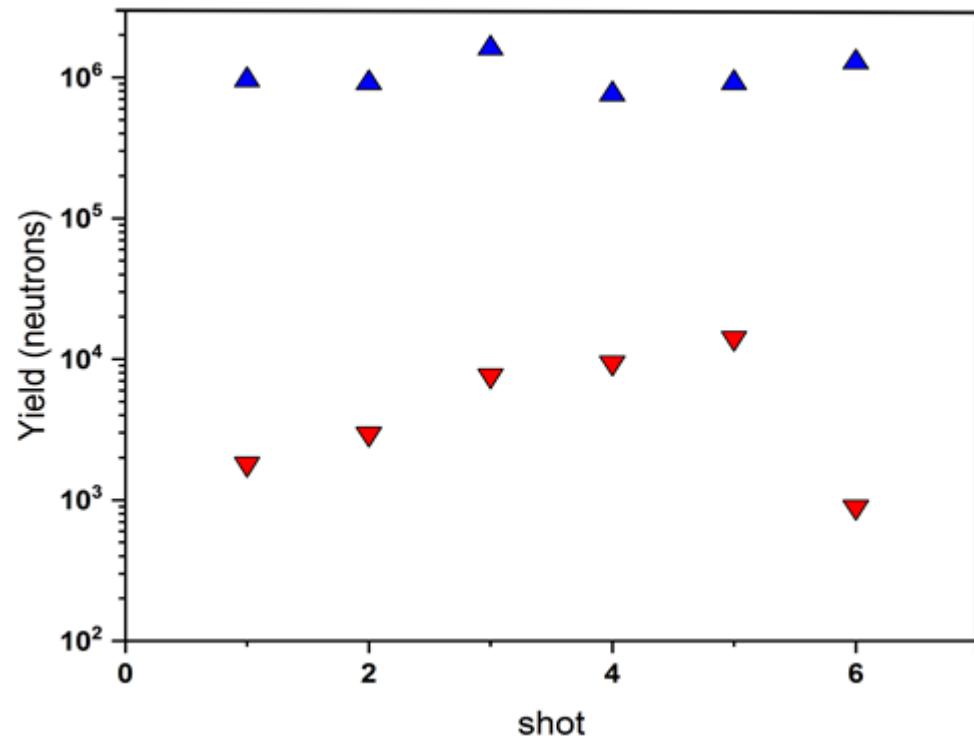
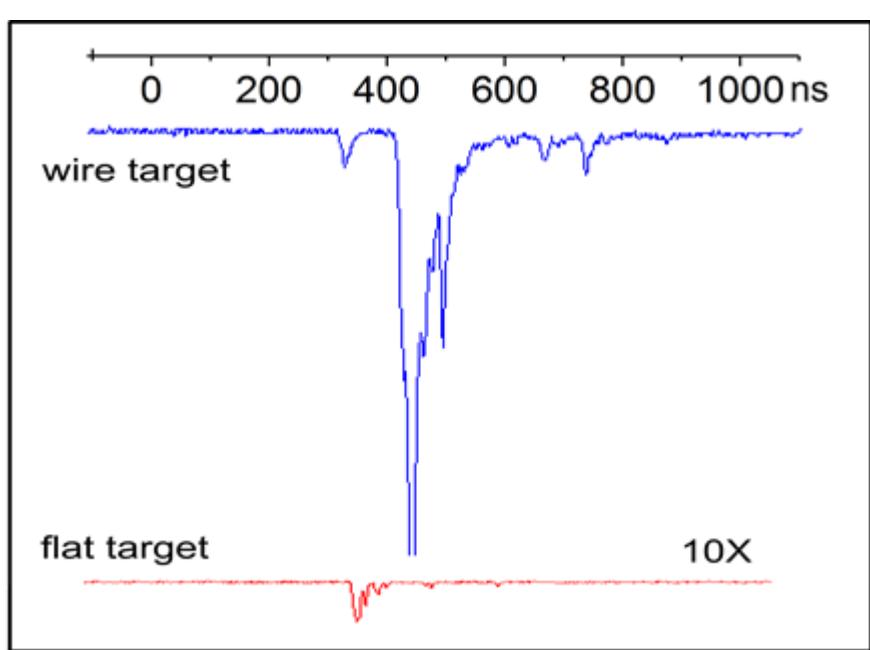
Nuclear fusion in dense relativistic nanowire array plasmas



Measured single-shot Thomson parabola energy spectra for:

- a) flat solid CD_2 target irradiated at an intensity of $\sim 8 \times 10^{19} \text{ W cm}^{-2}$. The tail of the deuteron energy spectrum reaches 0.5 MeV;
- b) array of 400 nm diameter, 5 micron long, CD_2 nanowires.

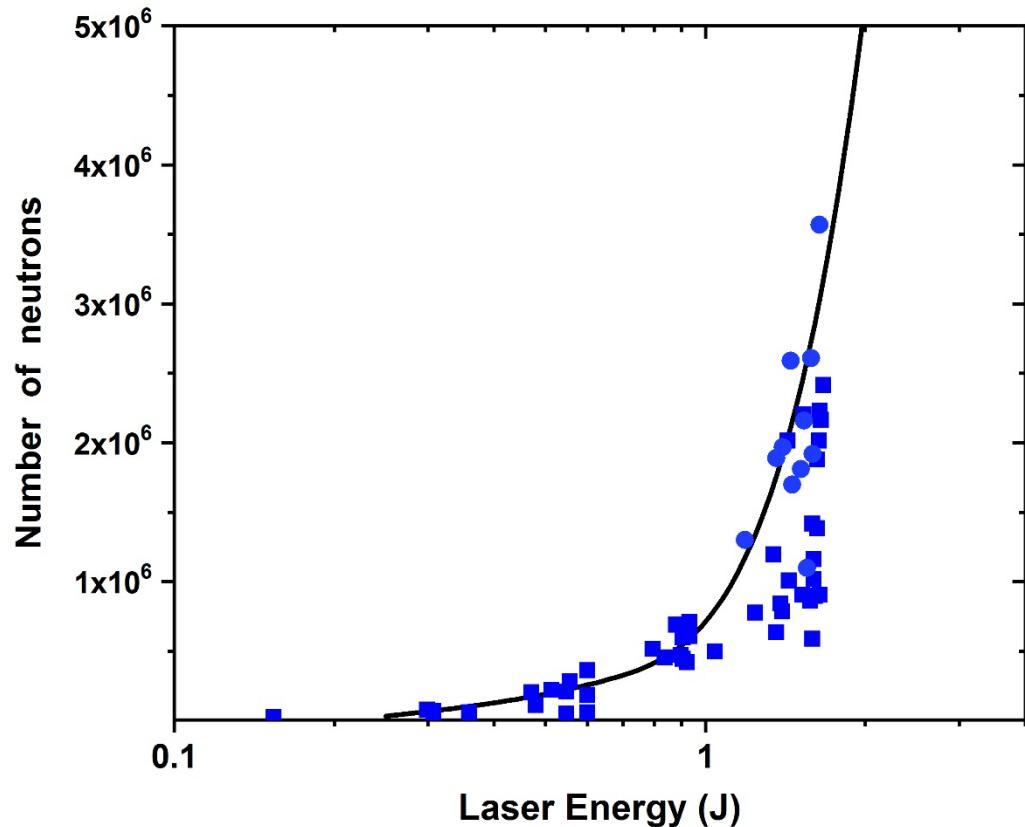
Nuclear fusion in dense relativistic nanowire array plasmas



TOF neutron signals for nanowire targets (blue trace) and flat (red) targets.

Integrated neutron signal for nanowire (blue triangles) and flat pressed (red triangles squares) CD_2 targets.

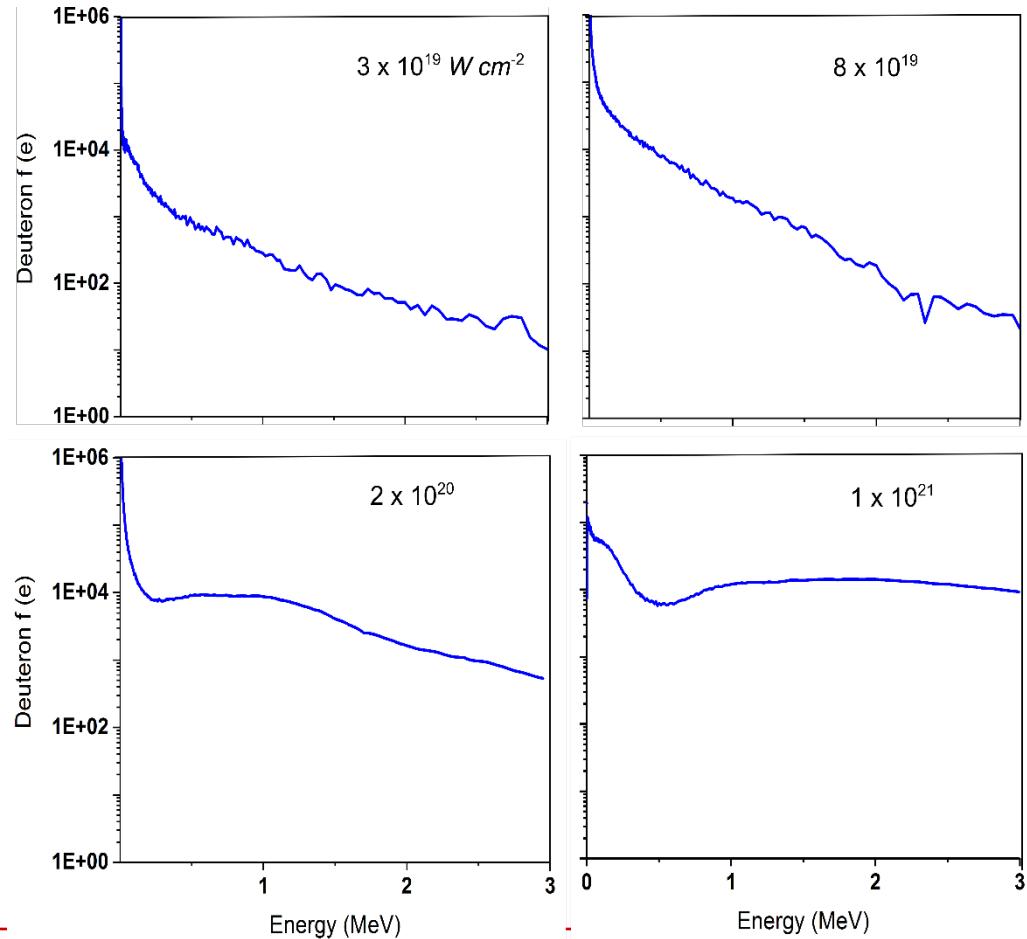
Nuclear fusion in dense relativistic nanowire array plasmas



Neutron yield as a function of laser pulse energy on target. The squares correspond to a target with 200 nm diameter wires. All the other targets consisted of 400 nm diameter wire arrays. The line shows the simulated energy dependence of the neutron yield computed using deuteron energy distributions computed by the PIC model and nuclear kinetics.

Nuclear fusion in dense relativistic nanowire array plasmas

Computed deuteron energy spectra for 400 nm diameter CD nanowires for the different irradiation intensities shown. The target average density corresponds to 20 % of solid density.



Summary

- Novel interaction physics in engineered targets
 - relativistic nanophotonics
 - relativistic nano-pinch
 - path to Ultra-High Energy Density
- Volumetric heating of nanowire targets creates very efficient source of x rays
- Great enhancement of neutron generation in deuterated nanowire targets