

Relativistic nanophotonics: creating extreme plasma conditions and fields with ultrafast laser pulses

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Colorado State University





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Science



High Power Laser and ultra-Intense Laser-Matter Interaction at CSU's Advanced Beam Laboratory

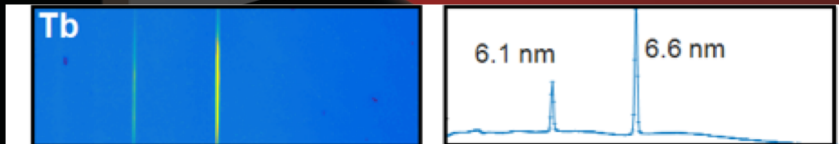
High Power Ultrashort Pulse Laser Development

Diode-Pumped: 1 J, < 5 ps, 1 kHz, 1 kW average power laser

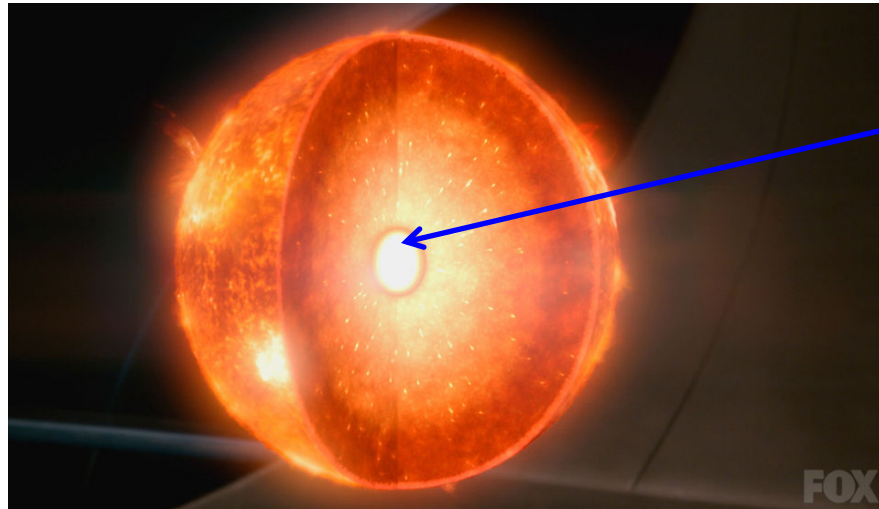
0.85 PW, 3.3 Hz laser

Soft x-ray lasers

Relativistic Laser-Matter Interactions

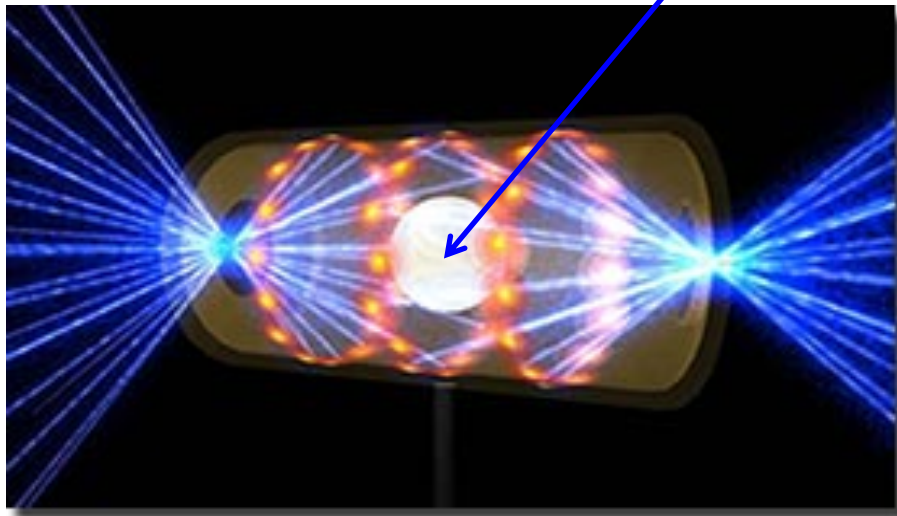


Path to extreme plasma conditions by irradiation of aligned nanowire arrays



Sun Core
240 Gbar

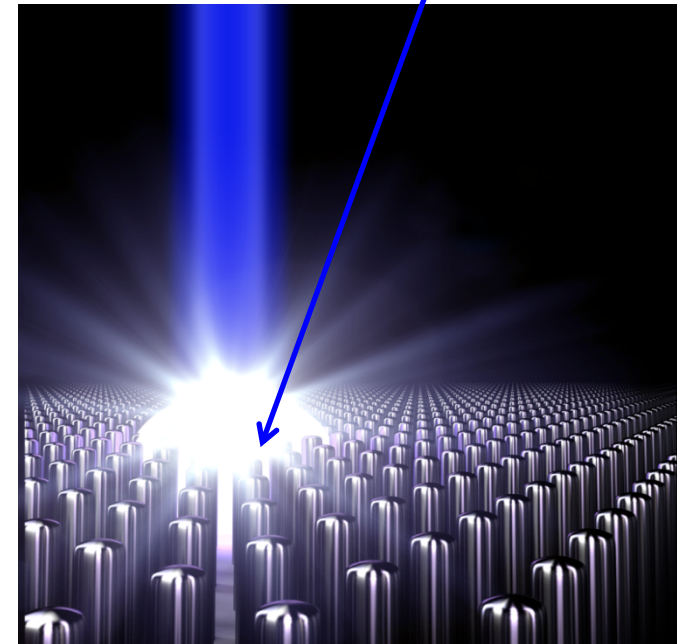
NIF Implosion
>150 Gbar



Nanowire array plasma

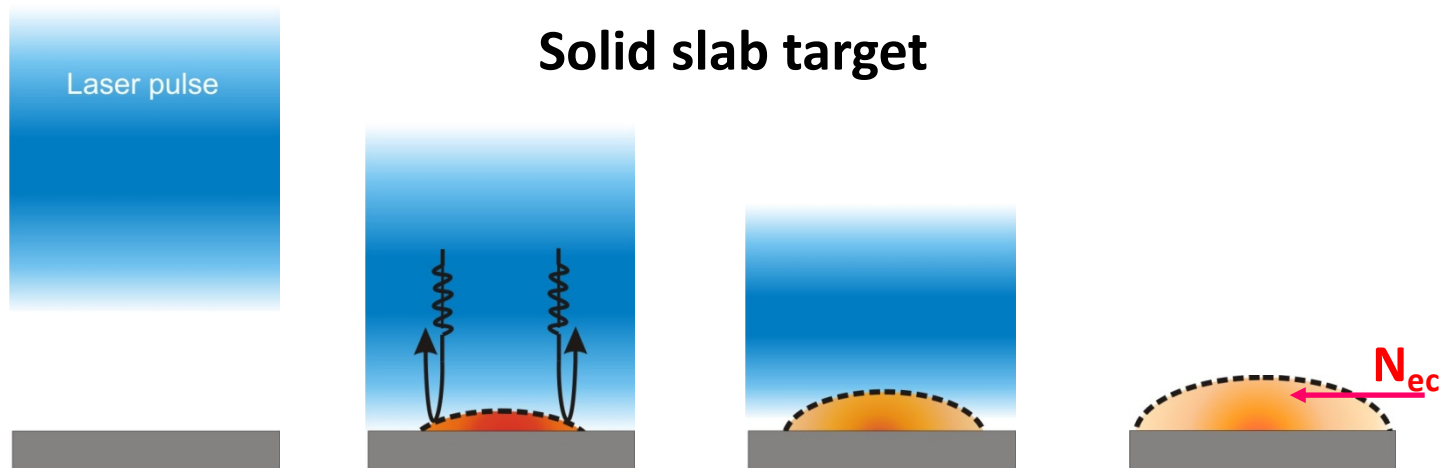
$$I = 1 \times 10^{22} \text{ W cm}^{-2}$$

> 300 Gbar (predicted)

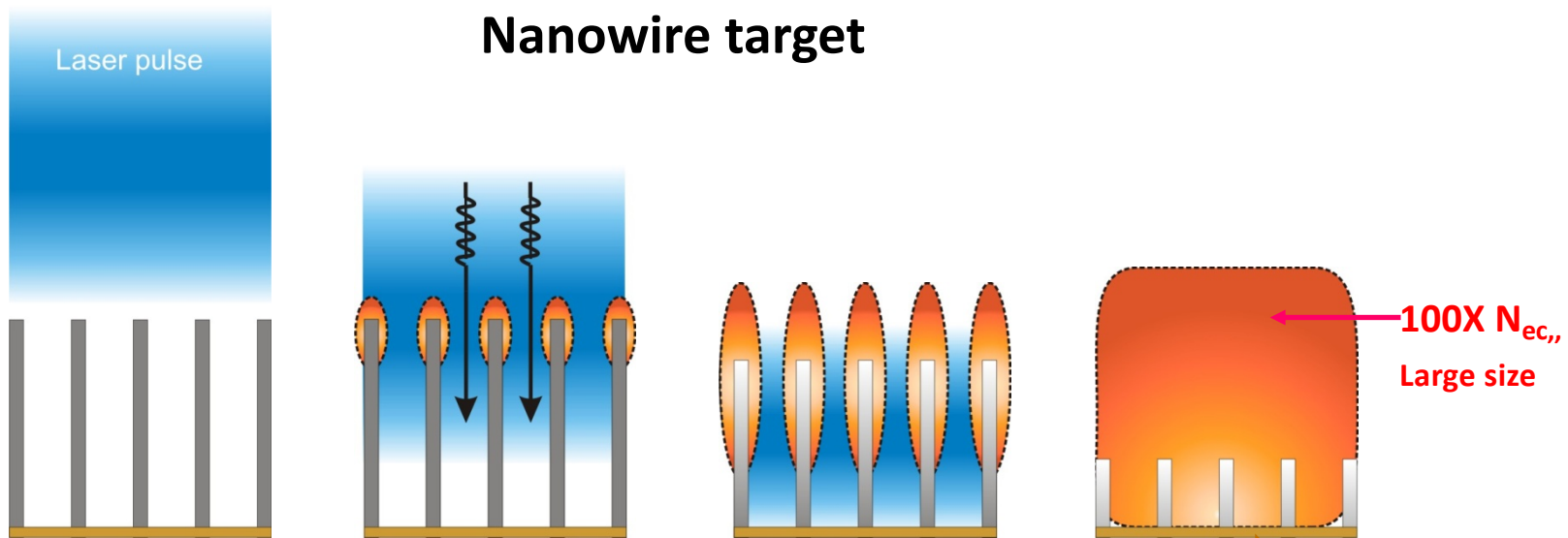


Volumetric heating of UHED plasmas by Irradiation of aligned nanowire arrays with ultrashort laser pulses of relativistic intensity

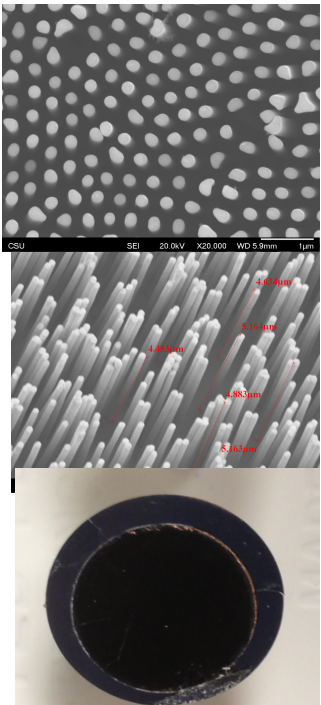
Solid slab target



Nanowire target

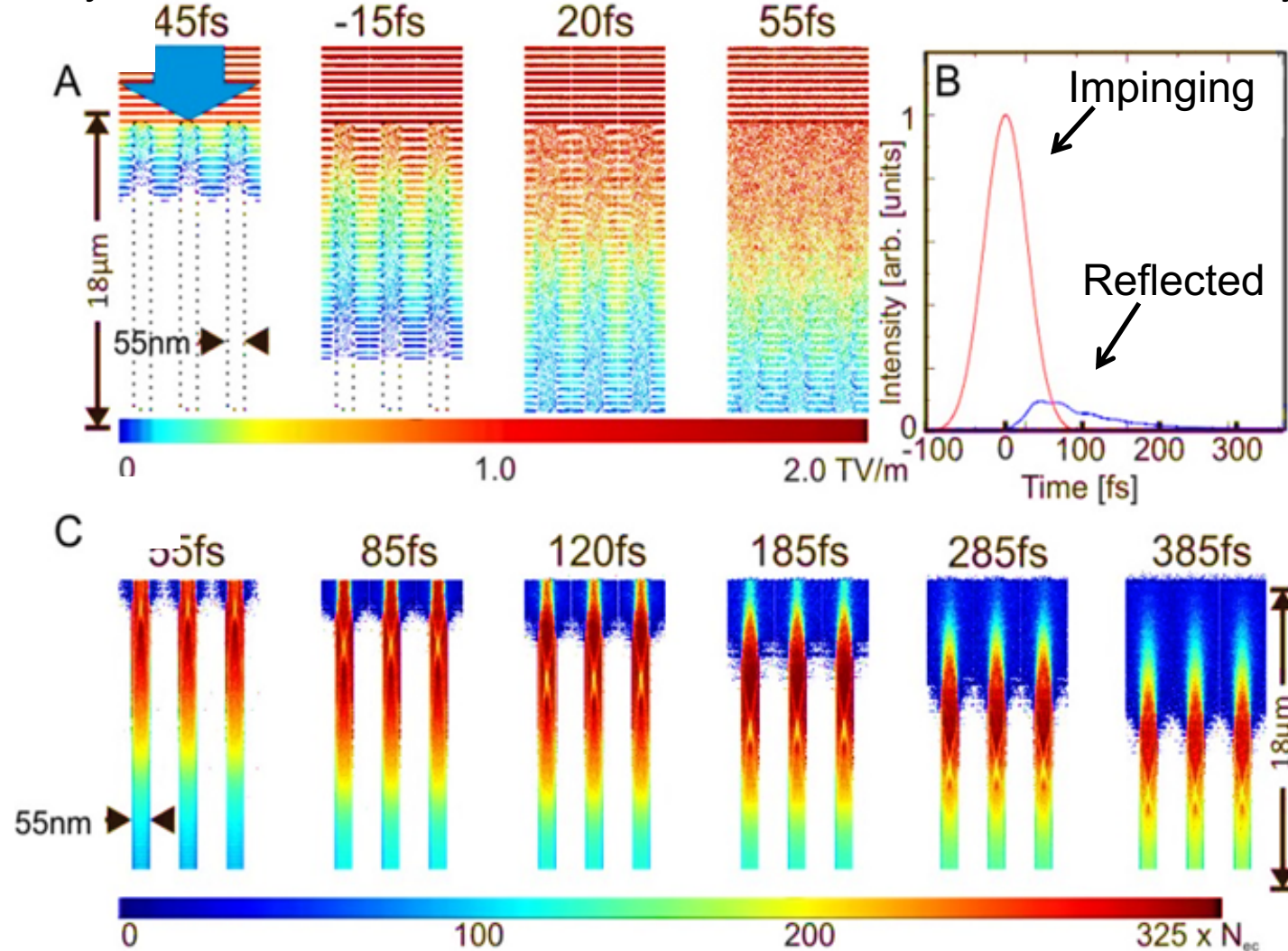
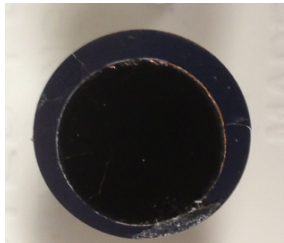


Increasing time

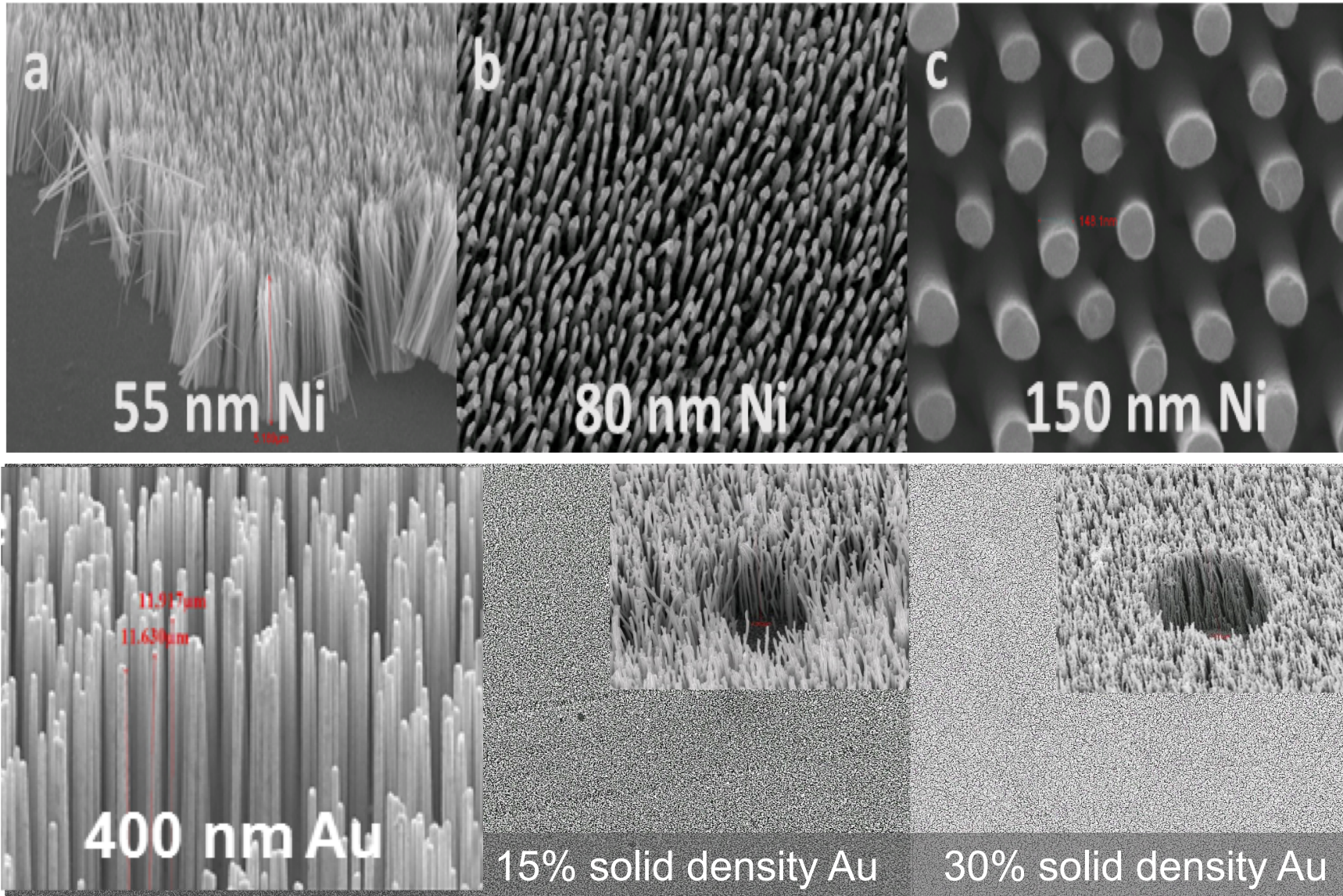


Laser irradiation of aligned nanowire arrays at $I = 5 \times 10^{18} \text{ W cm}^{-2}$ creates multi-KeV temperature plasmas with densities up to 100X critical

Intensity: $5 \times 10^{18} \text{ W cm}^{-2}$, 55 nm diameter Ni wires, 0.12 solid density target

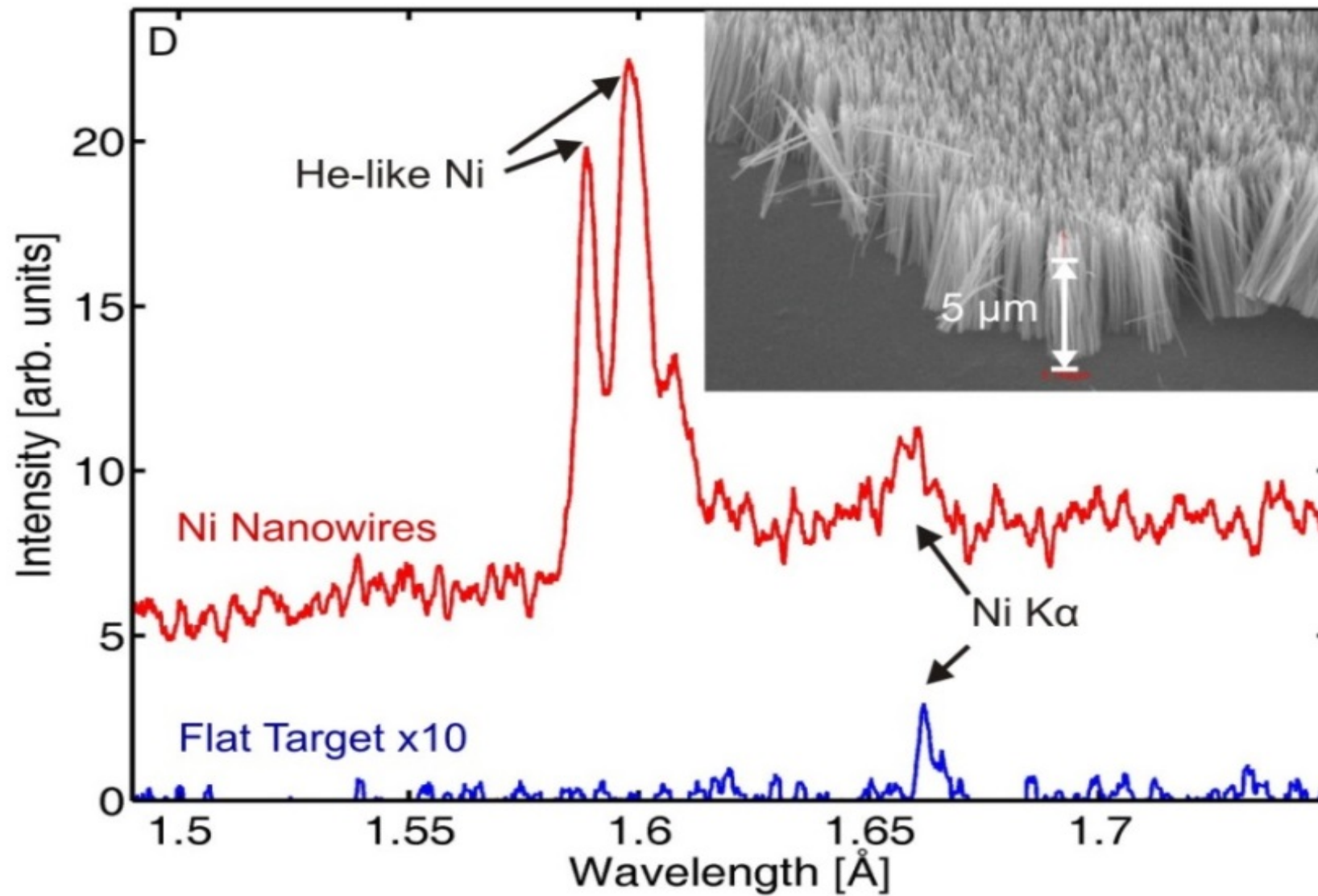


Nanowire arrays SEM Images



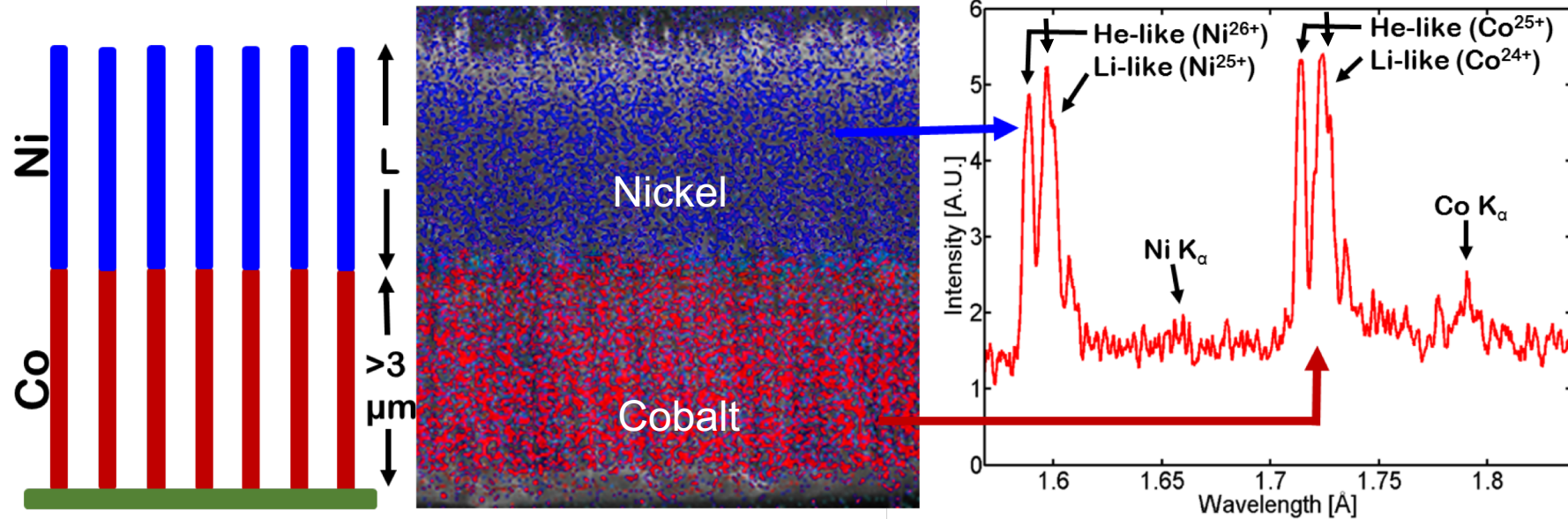
At $5 \times 10^{18} \text{ W cm}^{-2}$ Nickel He- α emission exceeds K- α

0.5 J pulse , 55 fs duration

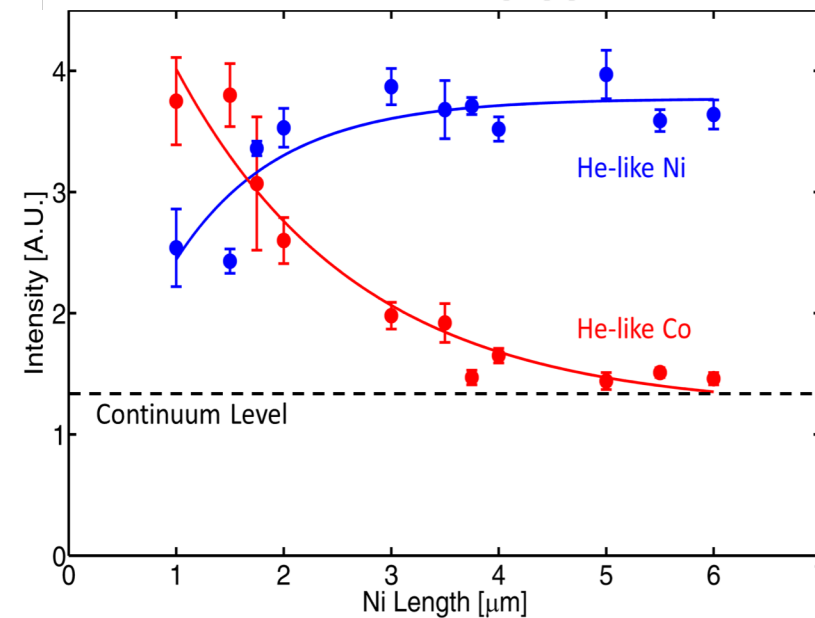
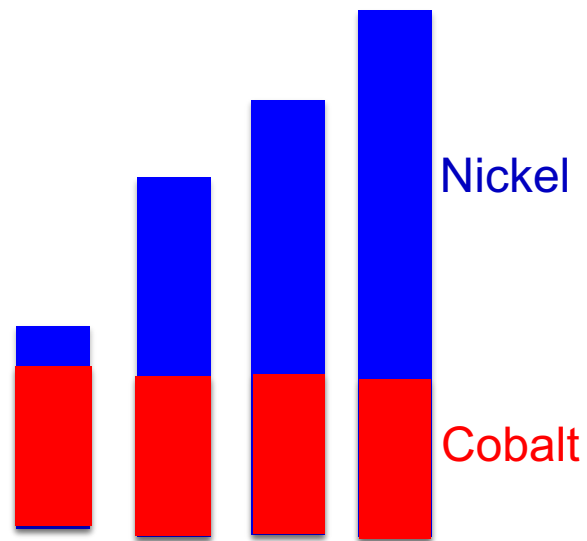


Measurement of heat penetration depth monitoring emission from buried tracer element shows volumetric heating

55 nm diameter, Ni wires, 13% solid density; $I = 4 \times 10^{19} \text{ W cm}^{-2}$, 55 fs



C. Bargsten et al.
Science Advances, 3,(2017),

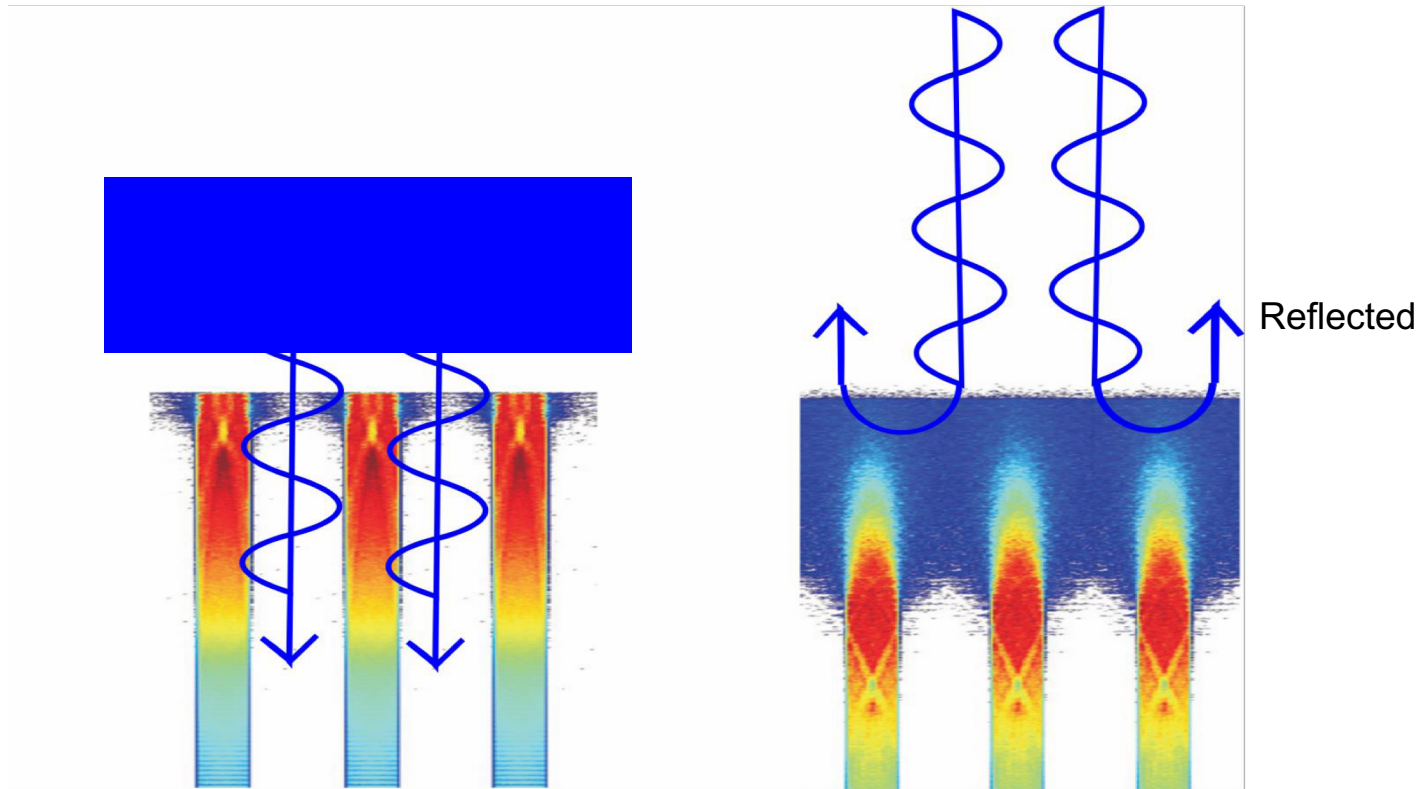


Absorption of intense ultrashort laser pulses in nanowire arrays

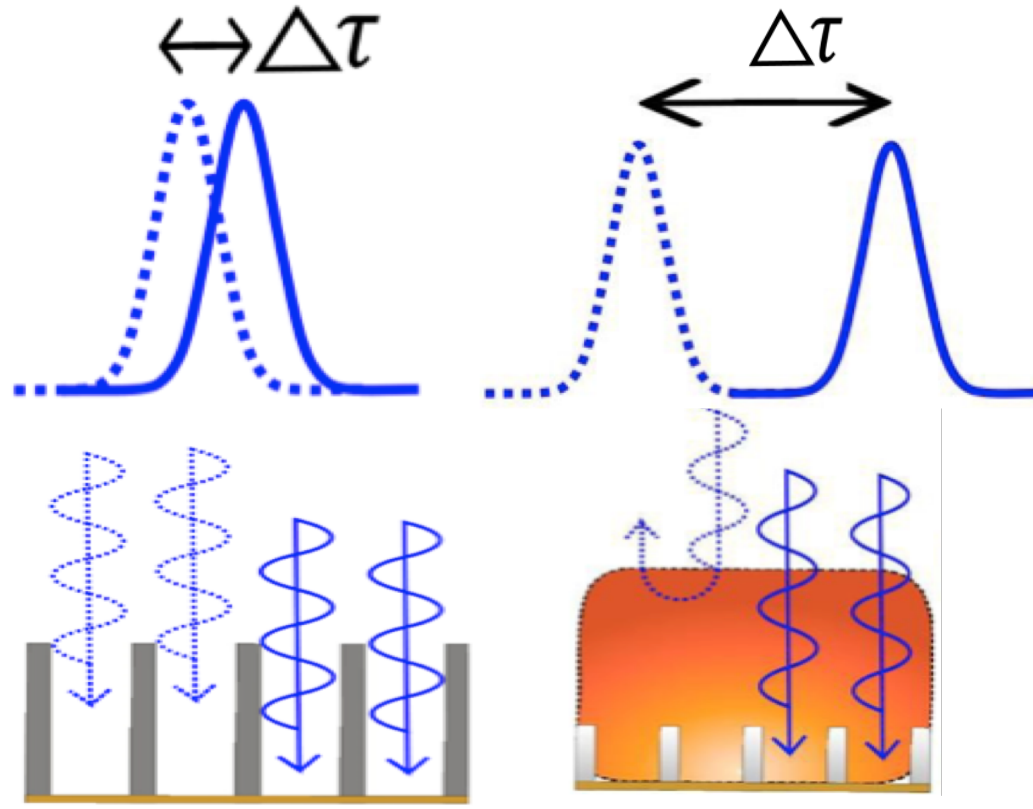
Two regimes

Short Pulse

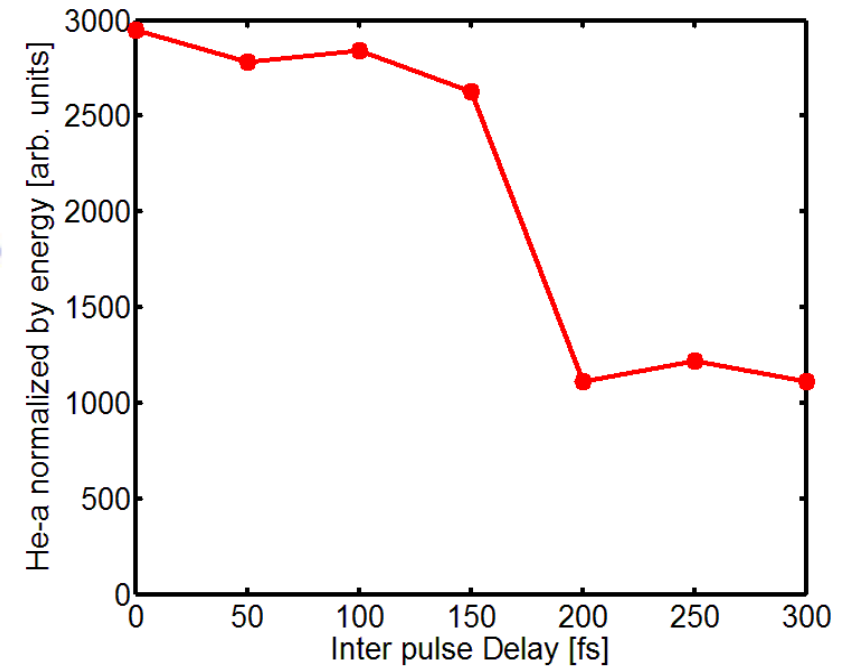
Long Pulse



Irradiation with two delayed ultrashort pulse determines the time available for efficient energy coupling



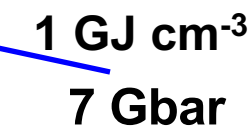
He- α line intensity drops past 150fs



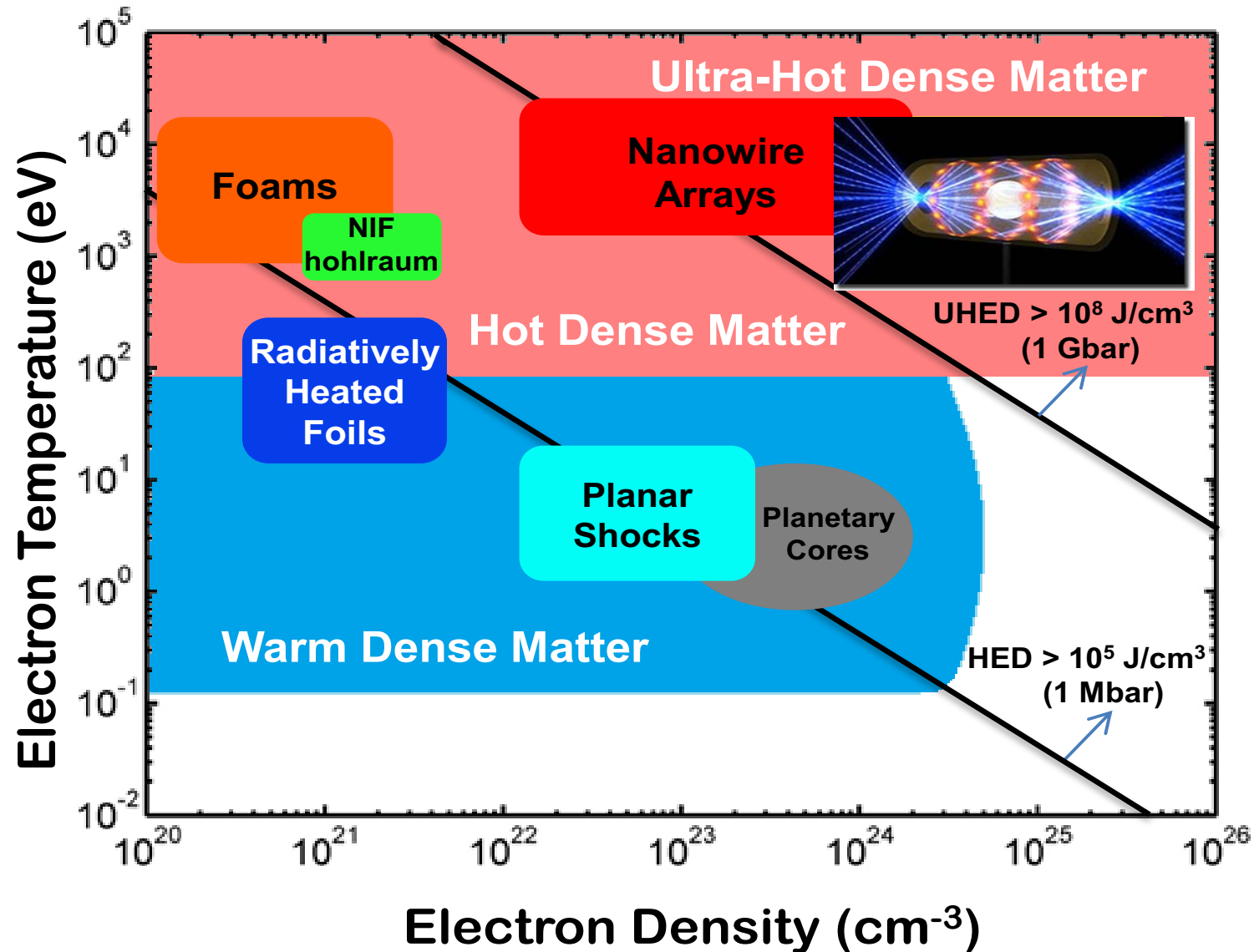
- 80nm Ni wires 12% solid density
- Pulse intensities 4×10^{19} - 1×10^{20} Wcm $^{-2}$

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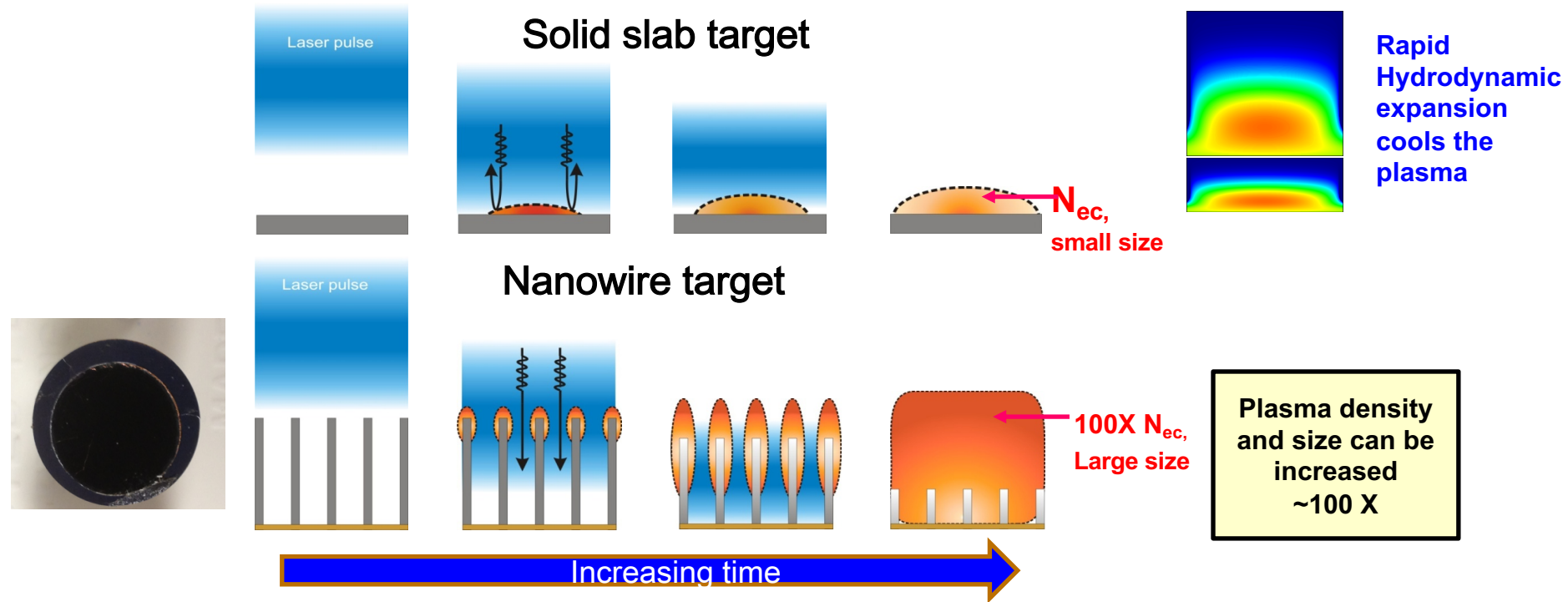
22 GJ cm⁻³
125 Gbar



Matter in the ultra high-energy density regime ($> 1 \times 10^8 \text{ J cm}^{-3}$, pressures $> 1 \text{ Gbar}$)



In volumetrically heated nanoarray plasmas radiation cooling can dominate over hydrodynamic cooling



Radiative lifetime < Hydrodynamic time

$$\tau_{rad} \propto \frac{1}{\langle \sigma v \rangle n_e} < \frac{\Delta L}{C_s} \propto \tau_{hydro}$$

Large Plasma Density

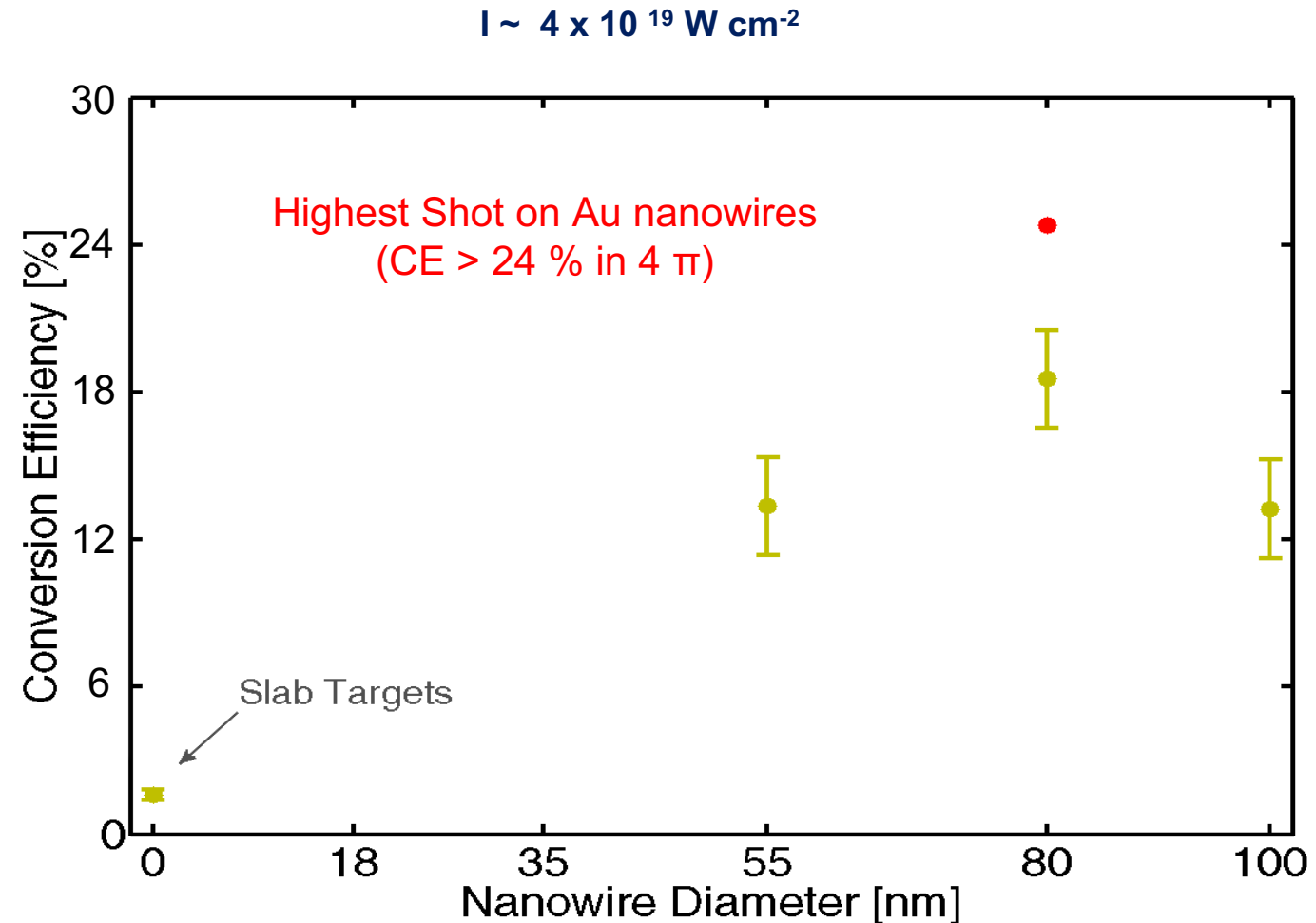
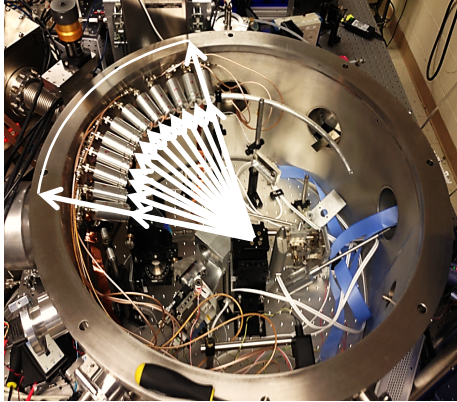
Large Plasma Size

R. Hollinger et al., Optica, 4, 1344, (2017)

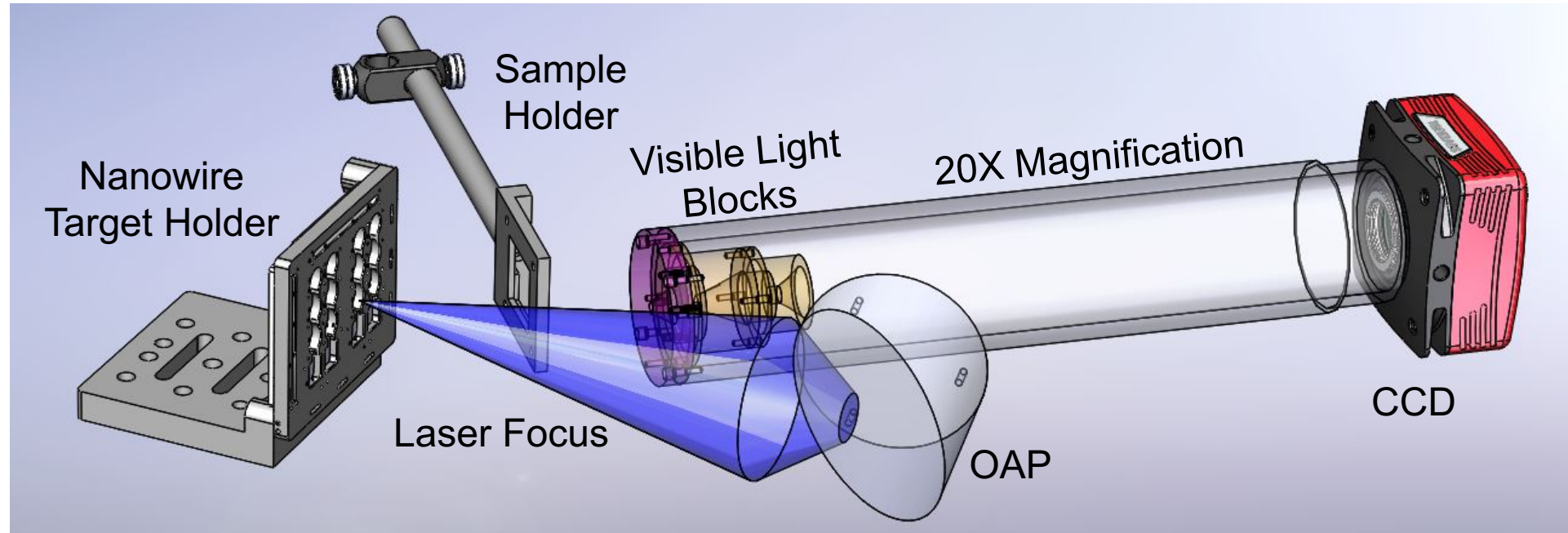
Increased X-ray CE from nanowires (< 1 % efficiency): G Kultzar et al. (PRL, 2000); T. Nishikawa et al (Appl. Phys.B, 2004); S. Modal et al (Phys. Rev.B, 2011)

Record Conversion Efficiency into > 1 KeV X-rays

CE $\sim$ 20 percent, with individual shots up to 24% CE into 4π

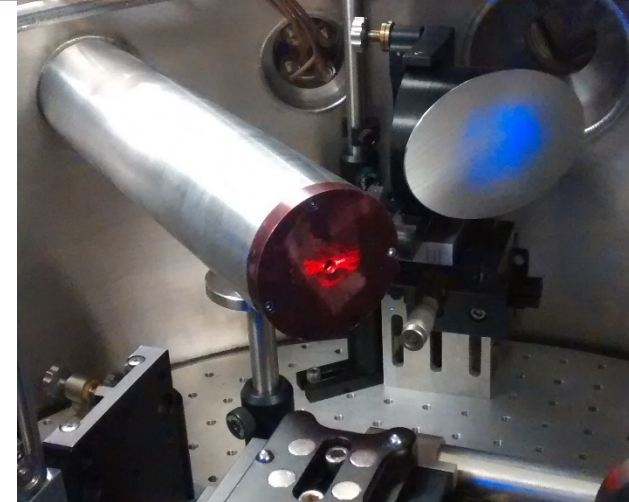
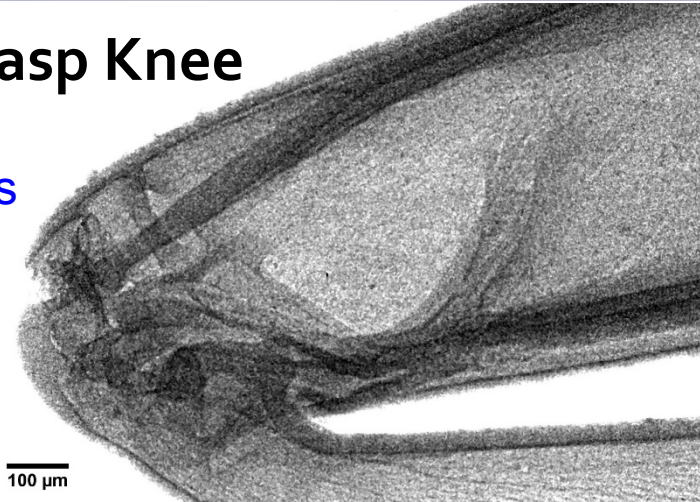


Single Shot X-ray Imaging ($3\text{ }\mu\text{m}$ Spatial Resolution)

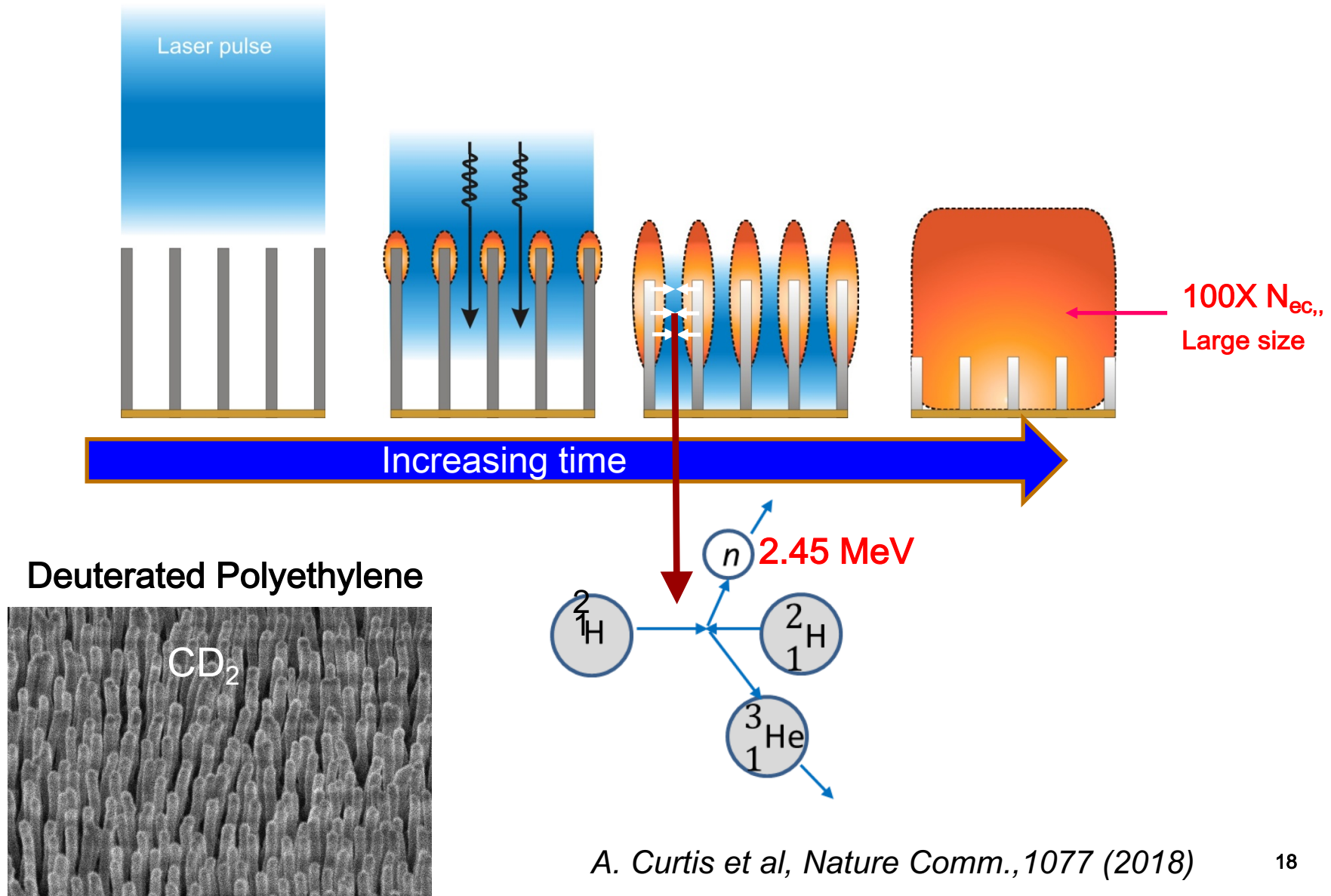


Wasp Knee

Nanowires
30 mJ on
target



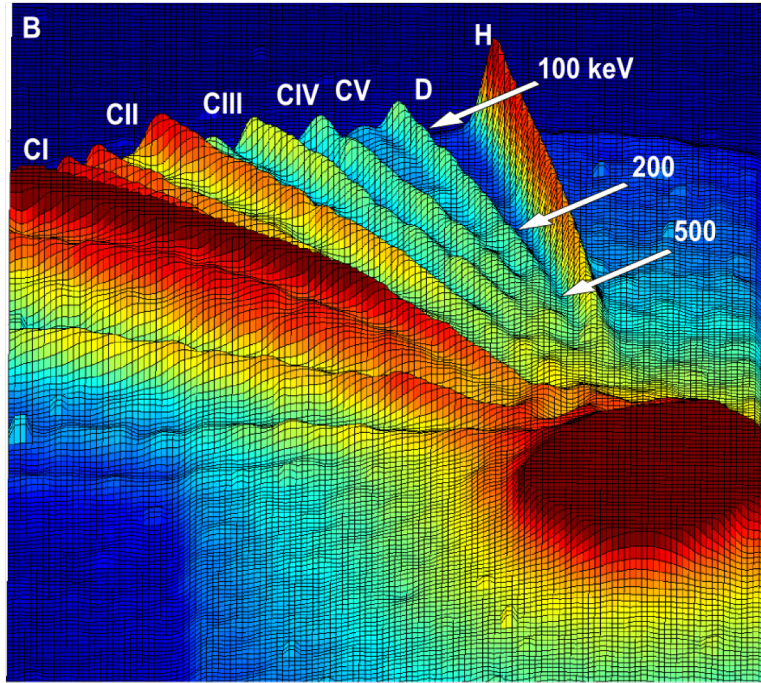
Deuterium ion acceleration and neutron production in deuterated nanowires



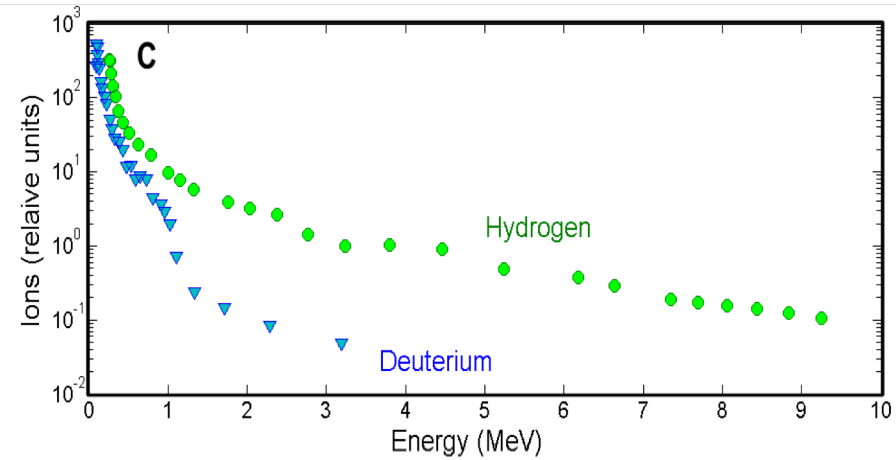
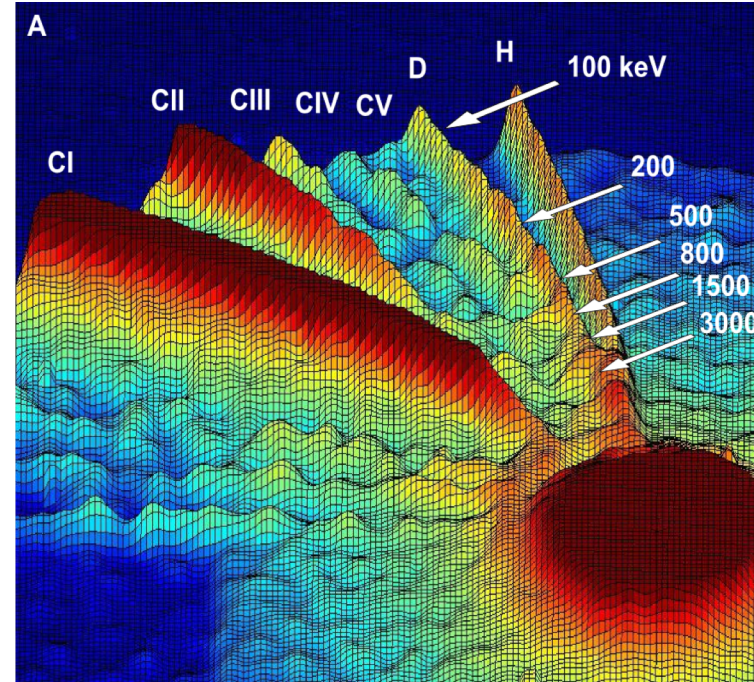
Deuteron energies up to 3 MeV measured

Intensity $8 \times 10^{19} \text{ W cm}^{-2}$

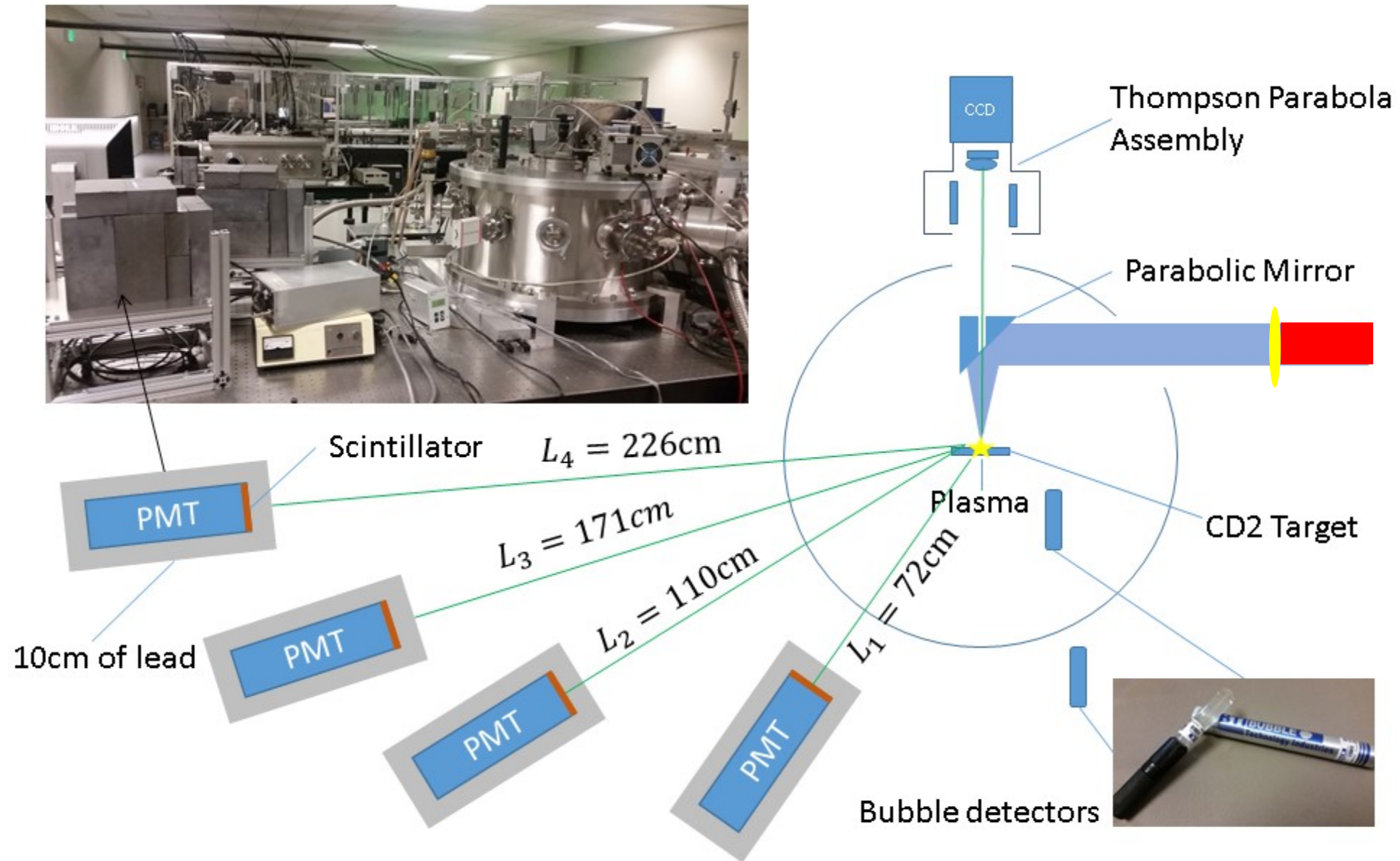
Flat Target



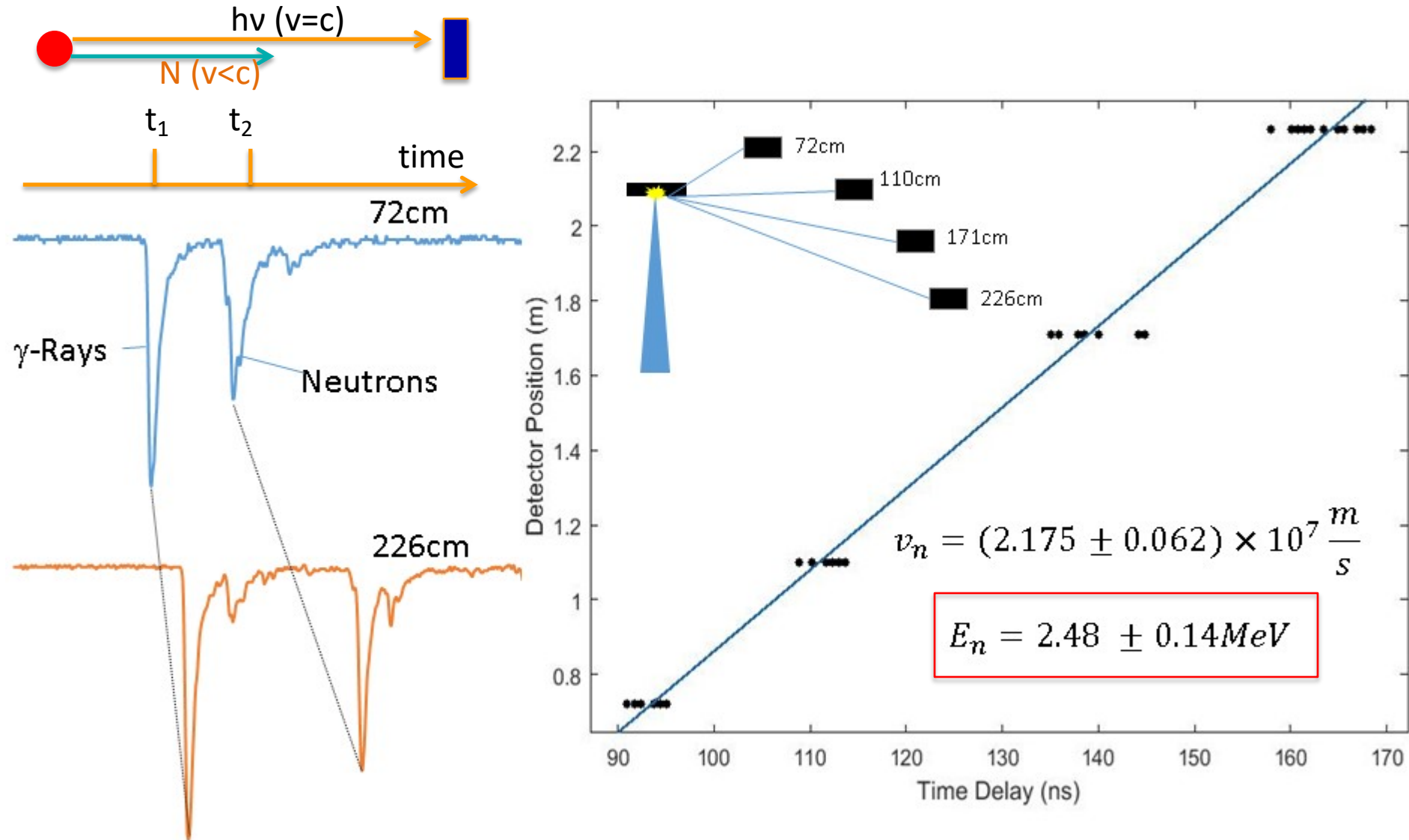
Nanowire



Deuteron and Neutron Detection Setup

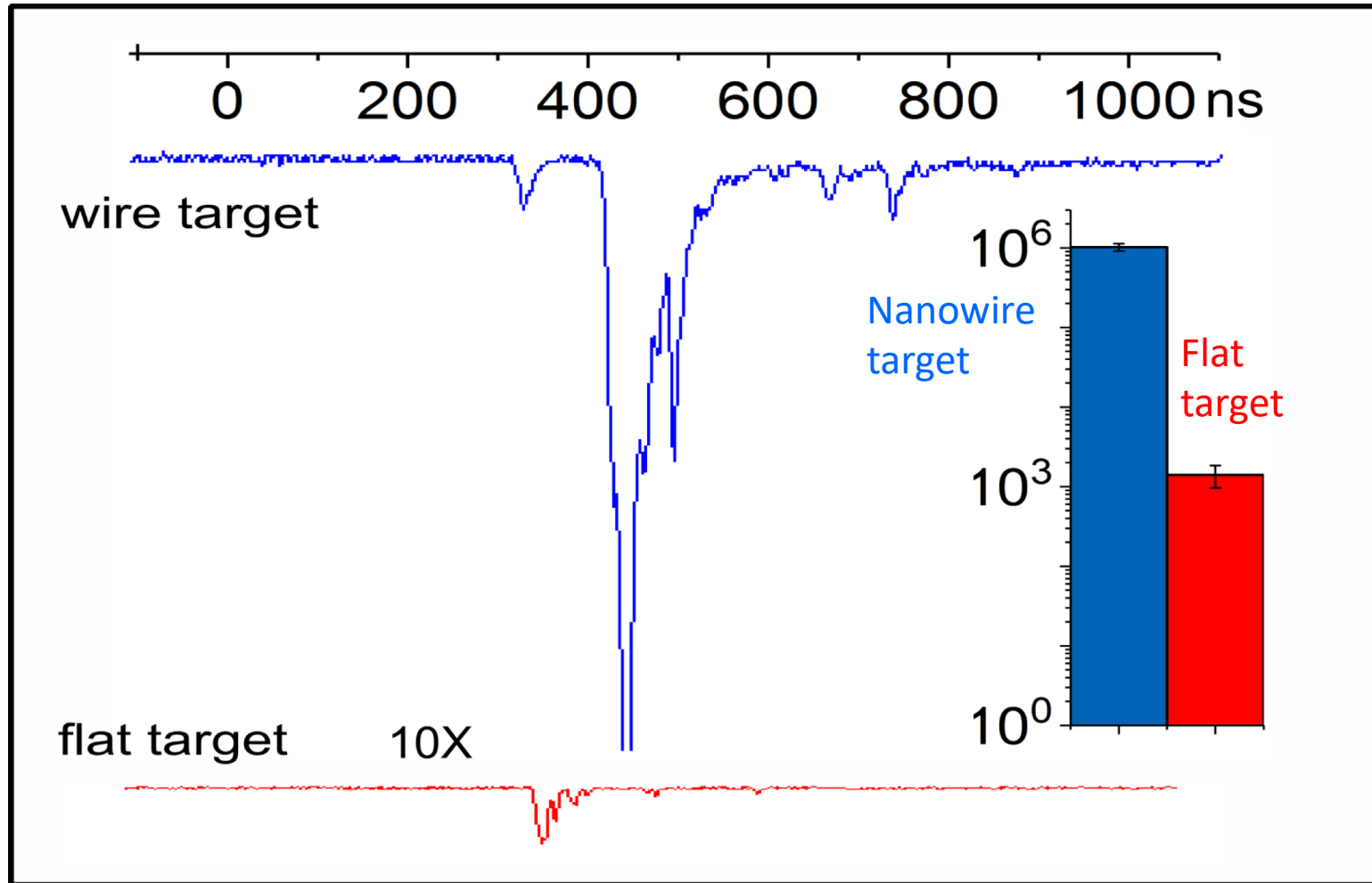


Neutron Time of Flight: D-D Fusion Neutrons



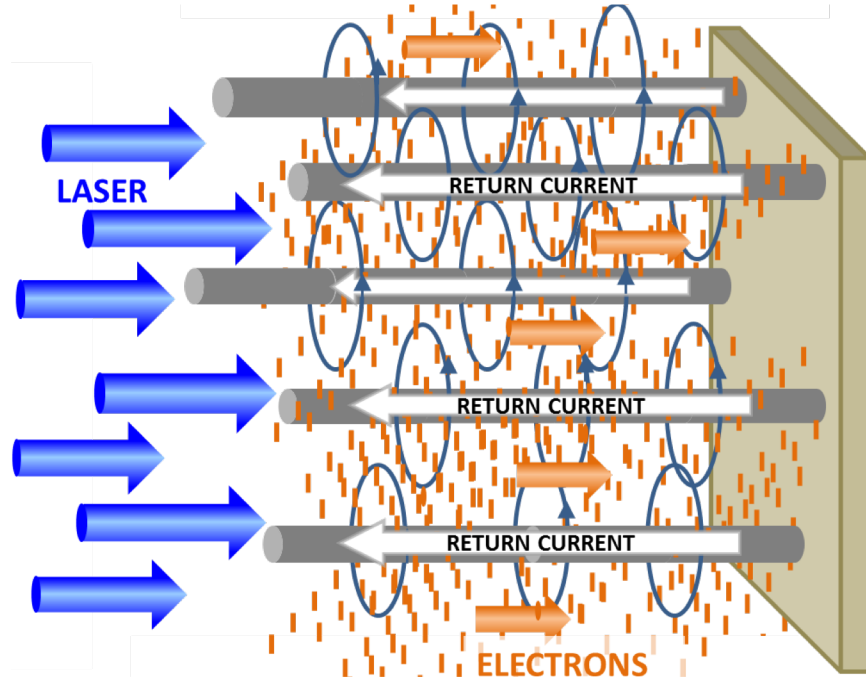
A. Curtis et al, Nature Comm.,1077 (2018)

Nanowire arrays display 500 X increased neutron yield as compared with CD₂ flat targets



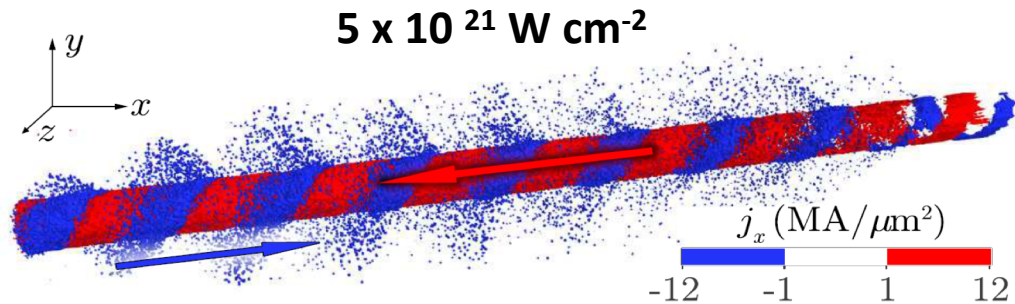
Maximum measured neutrons/shot: ($>2.5 \times 10^6$ neutrons/Joule)

Predicted Formation of Relativistic Nano-pinch



Nanowire pinch

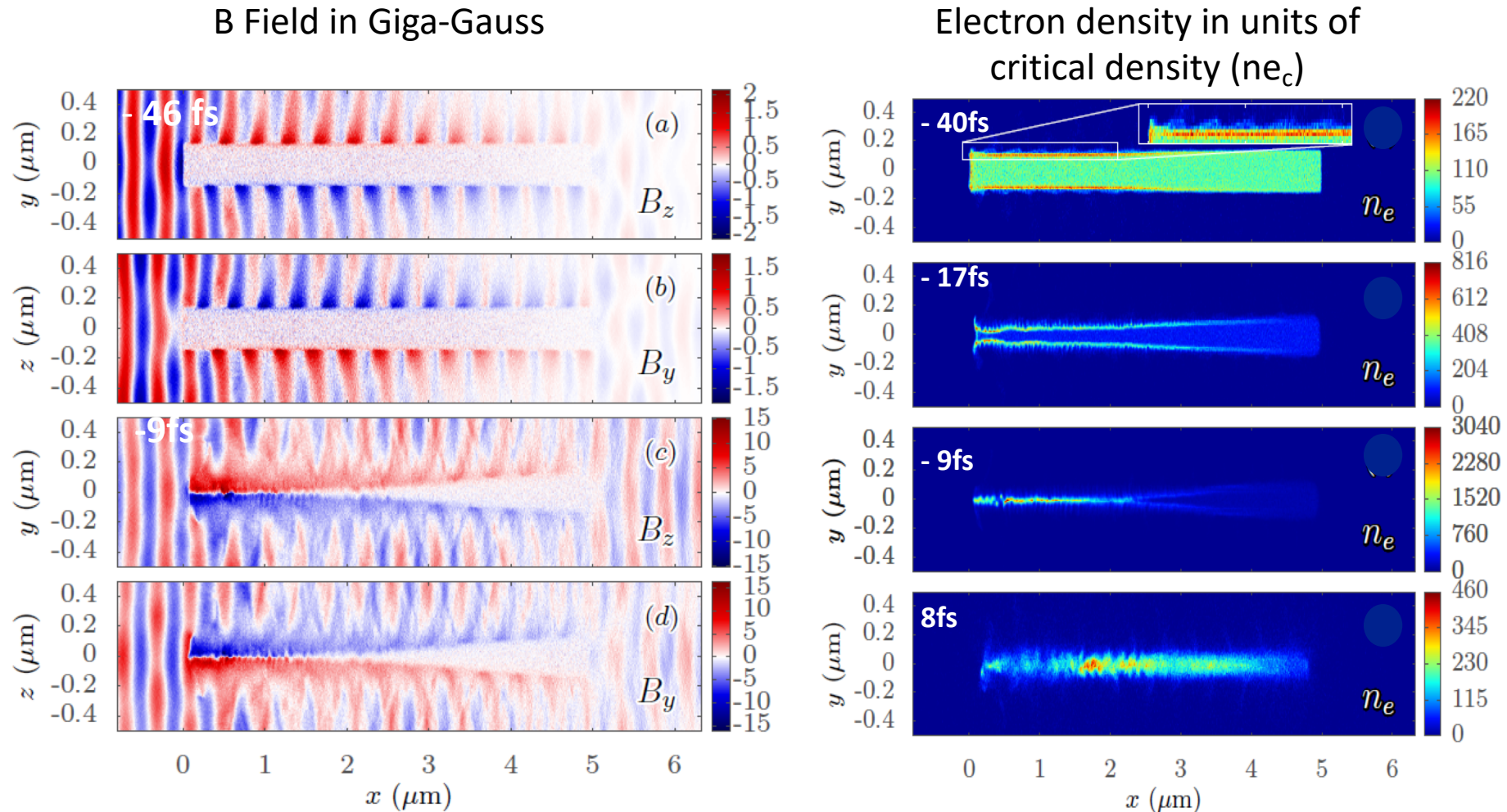
Laser-induced return current densities of ~ 0.1 Giga-Amperes per μm^2 through the wires



V. Kaymak et al, Phys. Rev. Lett., **117**, 035004 (2016)

The large return current generates a Giga-Gauss azimuthal magnetic field and nano-scale Z-pinch with > 1000 times n_{ec}

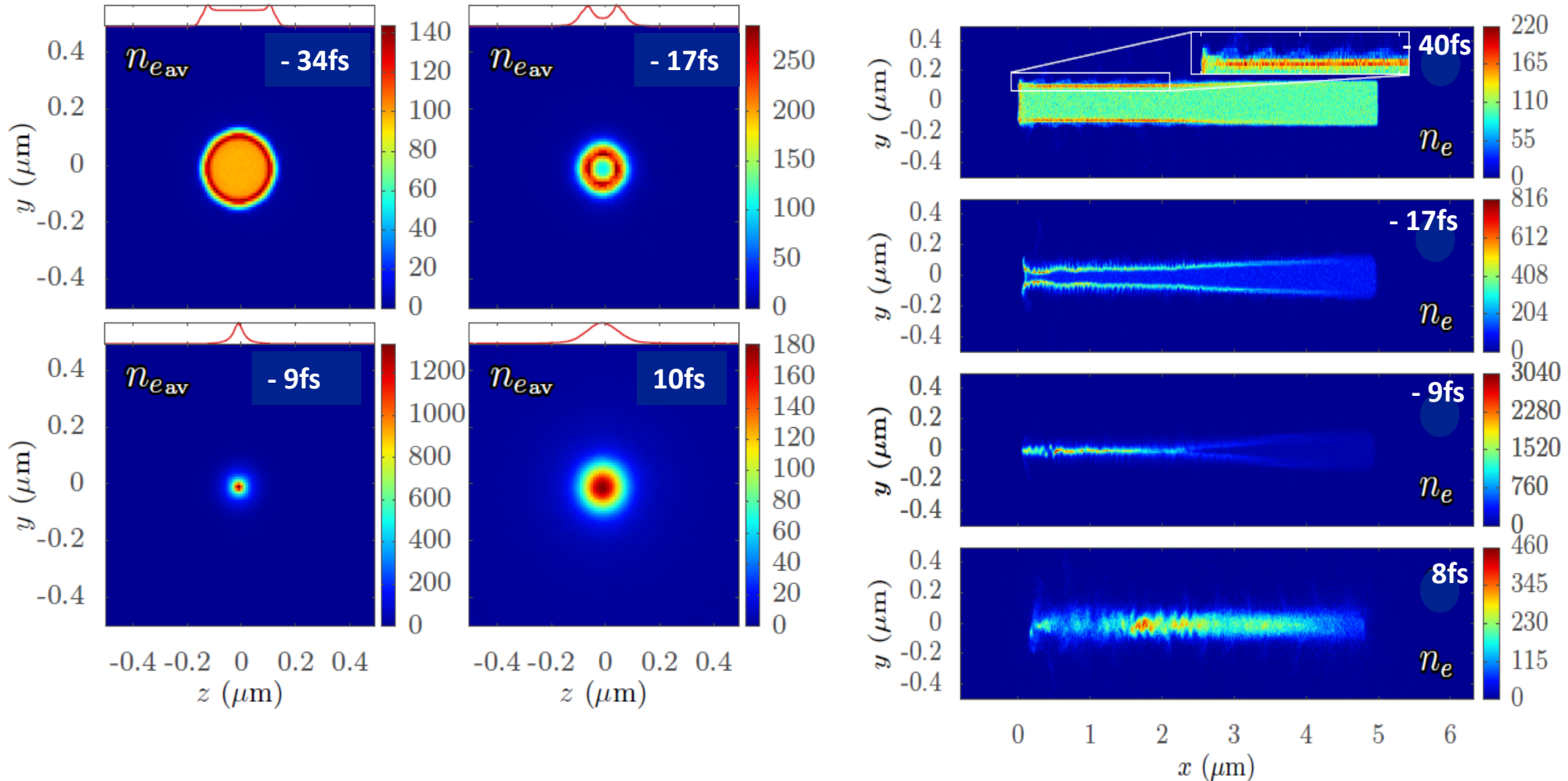
Carbon nanowires 300 nm diameter, $I=5 \times 10^{21}$ Wcm⁻²



V. Kaymak et al, *Phys. Rev. Letters* **117**, 035004 (2016).

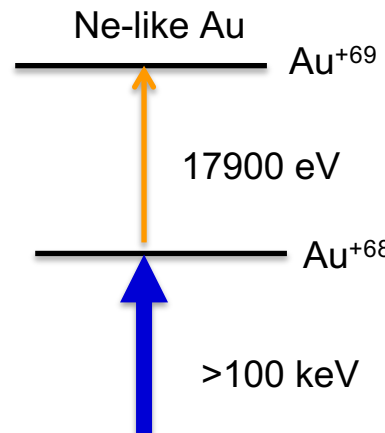
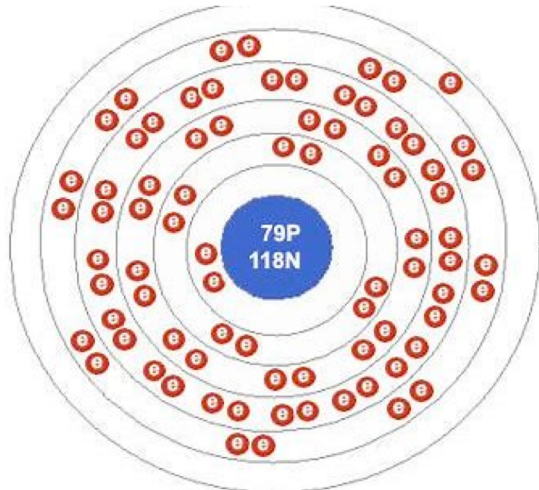
Self-generated quasi-static azimuthal magnetic field pinches nanowires into hot plasmas with $n_e > 9 \times 10^{24} \text{ cm}^{-3}$, > 1000 times the critical density

Electron density maps 300 nm C nanowires, $I = 5 \times 10^{21} \text{ W cm}^{-2}$

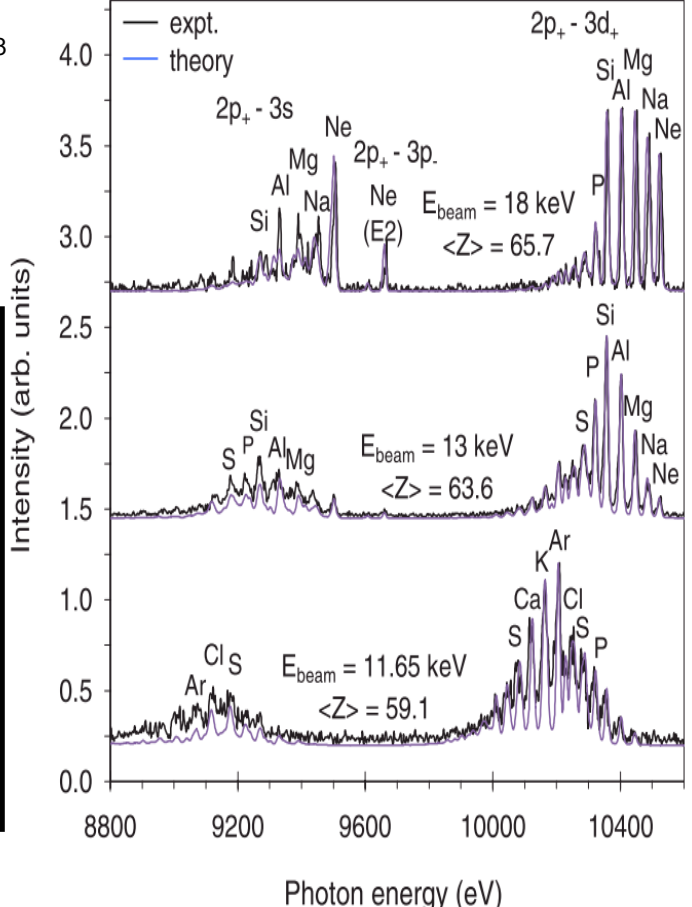
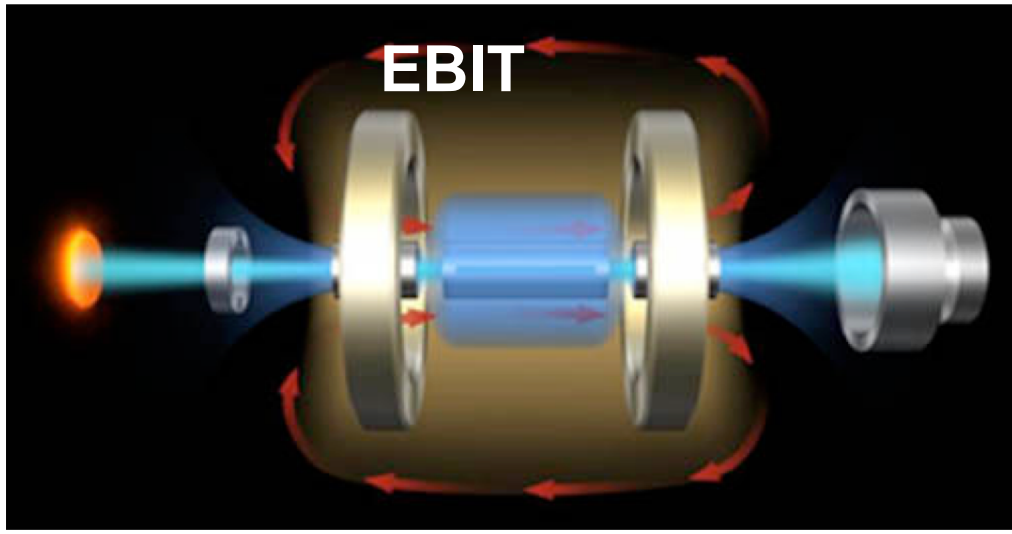


V. Kaymak et al, *Phys. Rev. Letters* **117**, 035004 (2016).

Au atoms ionized 69 times in an electron beam ion trap (EBIT)



LLNL Super EBIT
Ne = 10^{12} cm^{-3}



Densities > 10 orders of magnitude below solid density

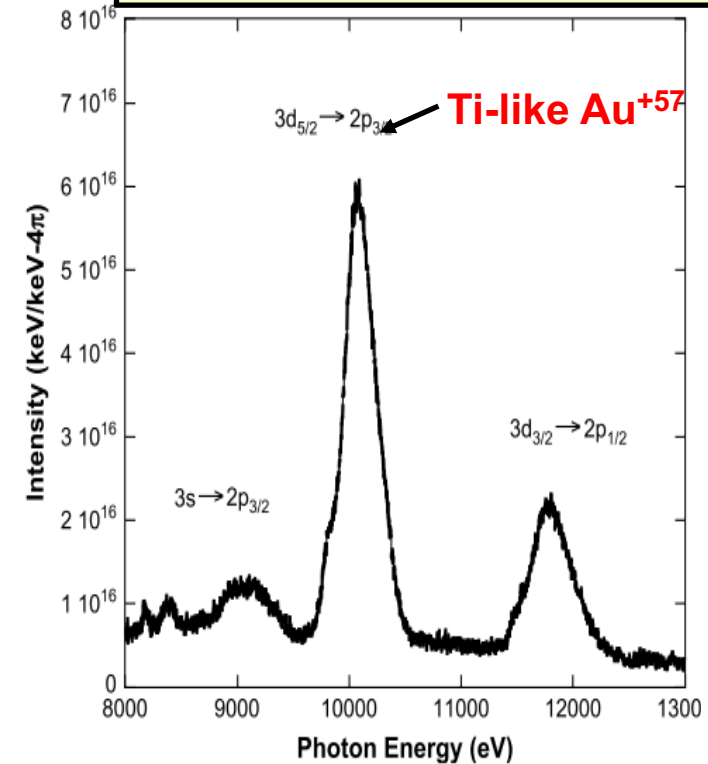
G.V. Brown et al Physical Review E 77, 066406 (2008)

High energy lasers ionizes gold to Au^{+57}

OMEGA LASER (U. Rochester)

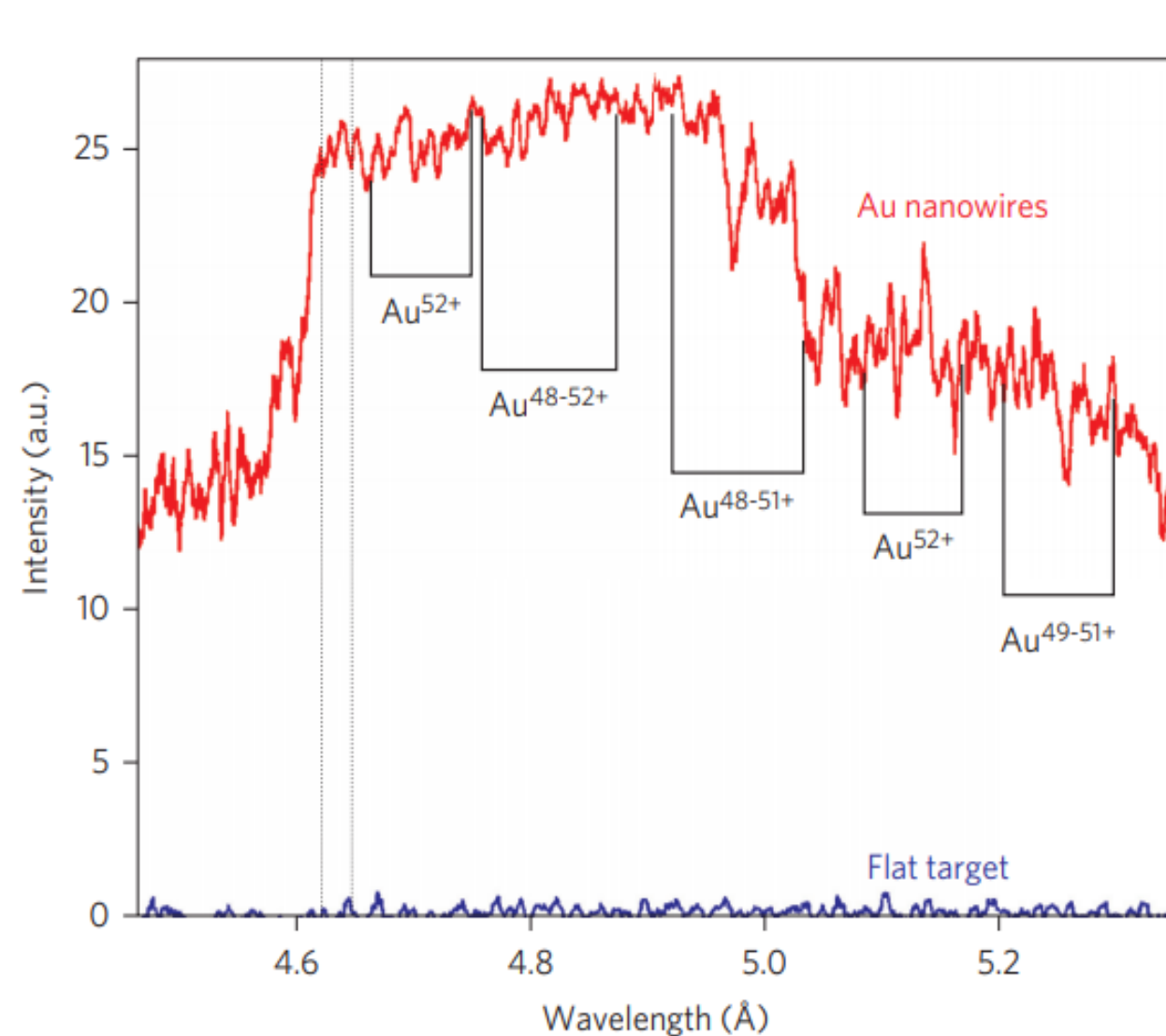


'Hot' hohlraum OMEGA
 $\text{Ne} = 10^{21} \text{ cm}^{-3}$



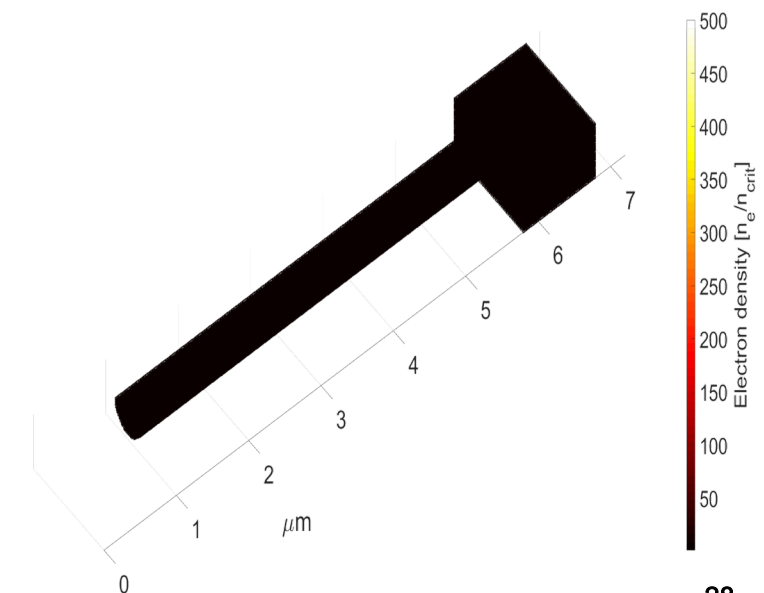
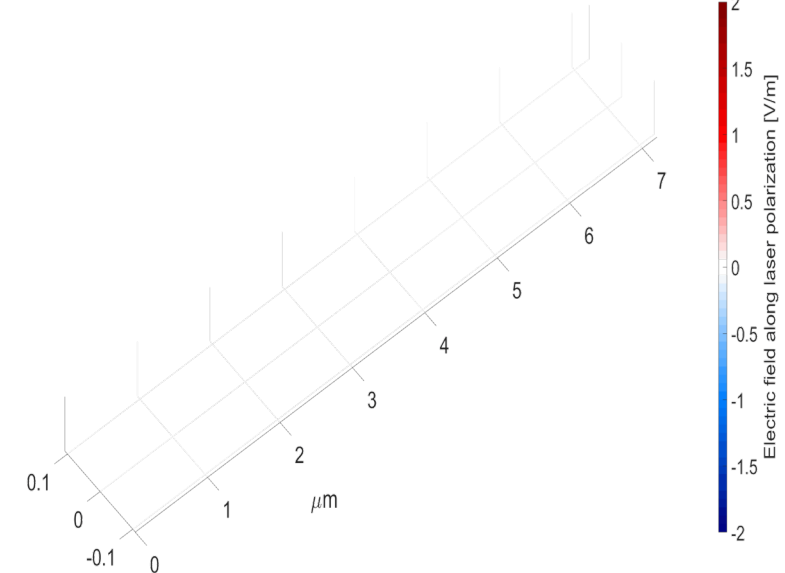
$E_L = 9 \text{ kJ}$; $T_e = 6.5 \text{ keV}$

Previous experiments at $5 \times 10^{18} \text{ W cm}^{-3}$ show emission from up to Ni-like Au^{52+} and optical volumetric heating



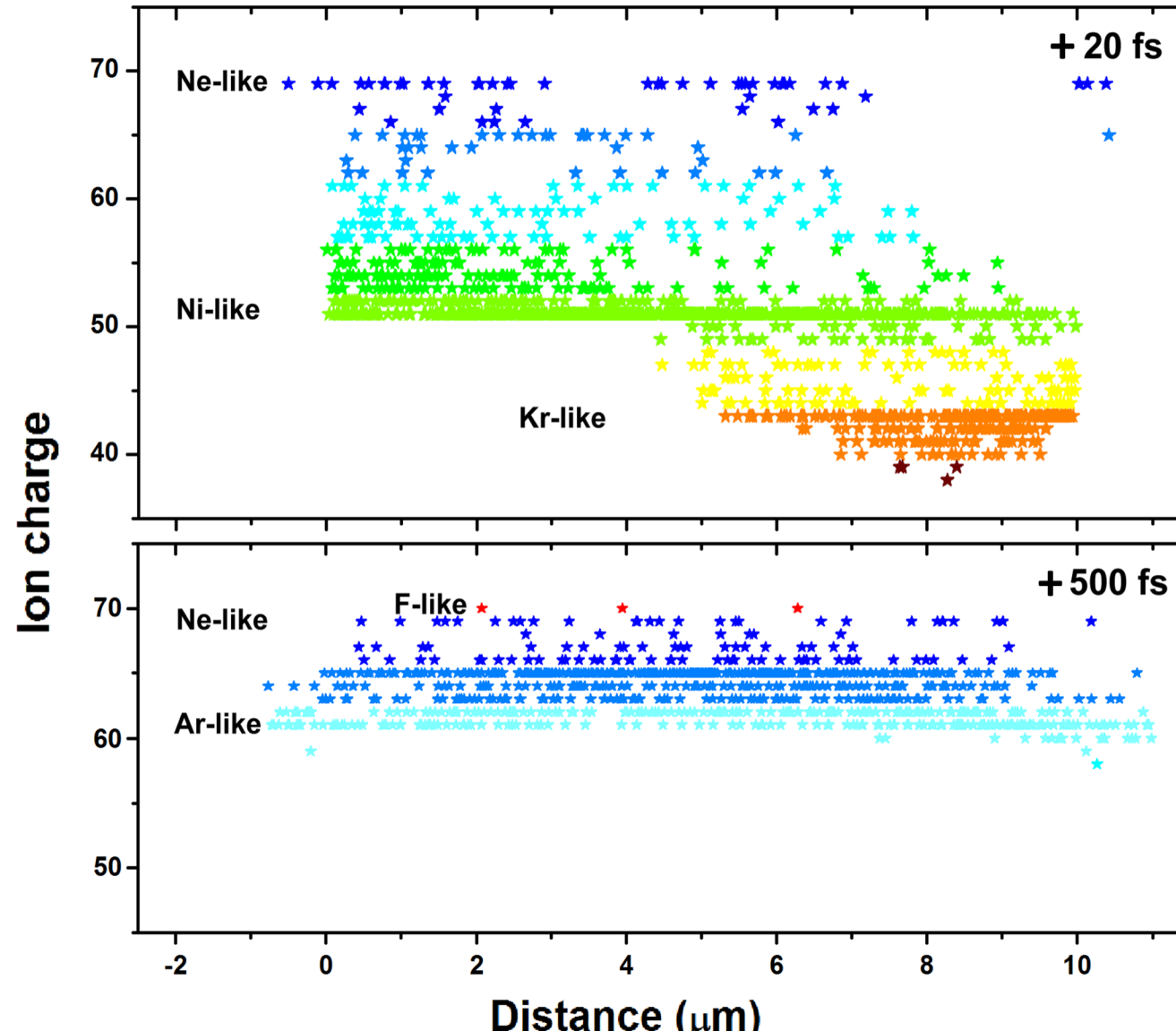
M. Purvis et al Nature Photonics 7, 796- (2013)

Electric field along laser polarization at time: -74 fs with respect to peak of pulse $\times 10^{13}$



Irradiation intensity of $1 \times 10^{22} \text{ W cm}^{-3}$ predicted to create extreme ionization states in Au (eg. F-like Au)

Ion charge distribution as a function of depth:



3.3 Hz, 0.85 PW- Ti:Sapphire Laser System



3828 Vol. 42, No. 19 / October 1 2017 / Optics Letters

Letter

Optics Letters

0.85 PW laser operation at 3.3 Hz and high-contrast ultrahigh-intensity $\lambda = 400$ nm second-harmonic beamline

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¹Electrical and Computer Engineering Department, Colorado State University, Fort Collins, Colorado 80523, USA

²Physics Department, Colorado State University, Fort Collins, Colorado 80523, USA

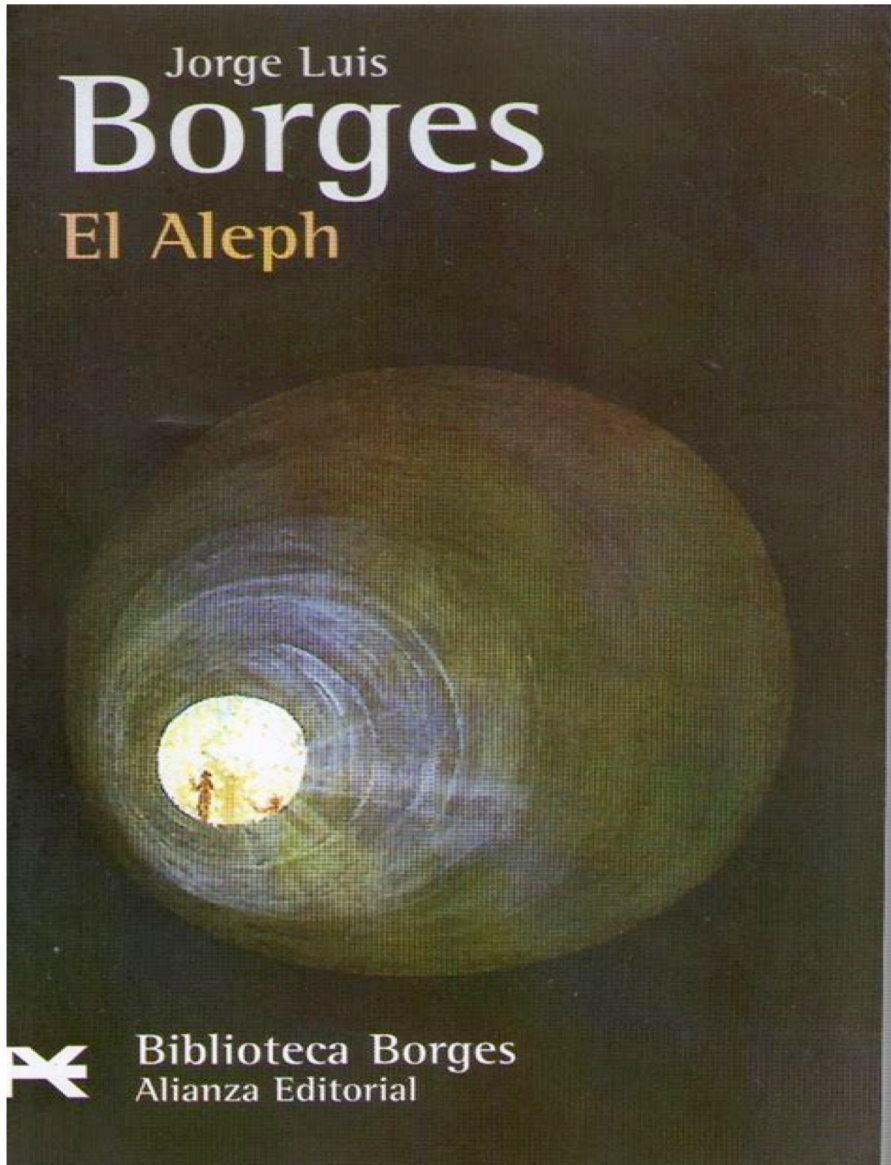
³Chemistry Department, Colorado State University, Fort Collins, Colorado 80523, USA

*Corresponding author: yongw@colostate.edu



Facility constructed with support from DOE, NSF, AFOSR, and the W.Keck Foundation

ALEPH: Advanced Laser for Extreme Photonics

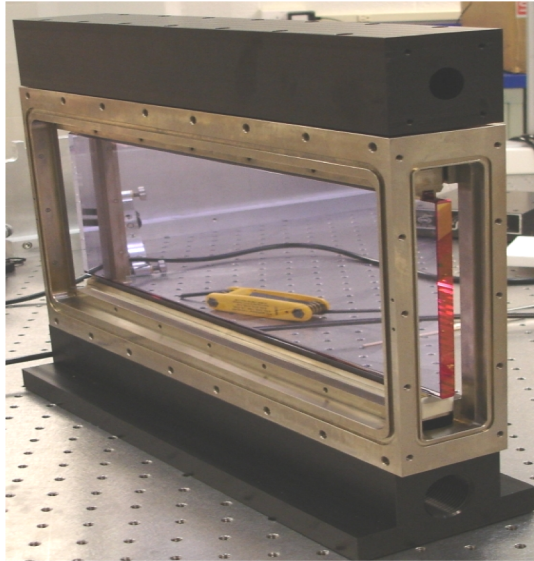
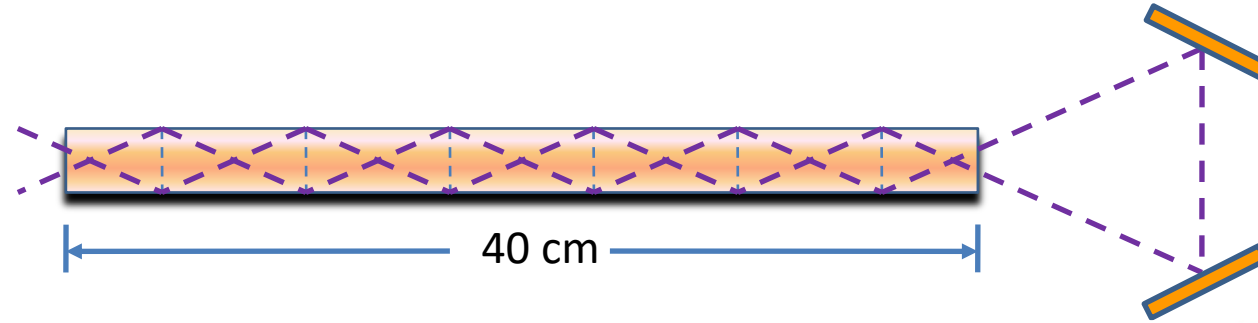


*"I saw a small iridescent sphere
of almost unbearable brilliance."*

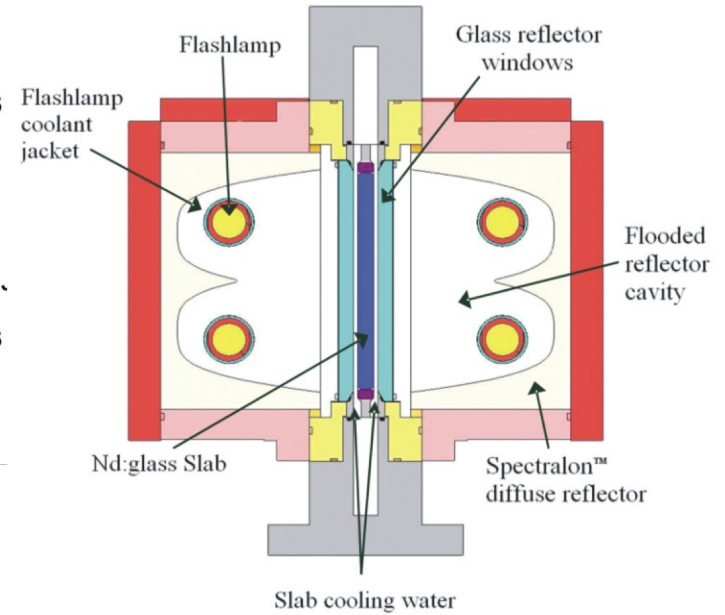
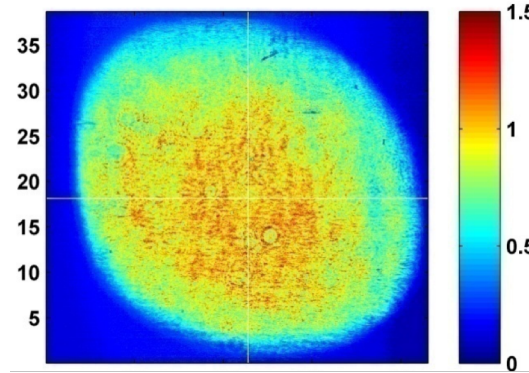
JLB

Slab amplifier on double-pass configuration

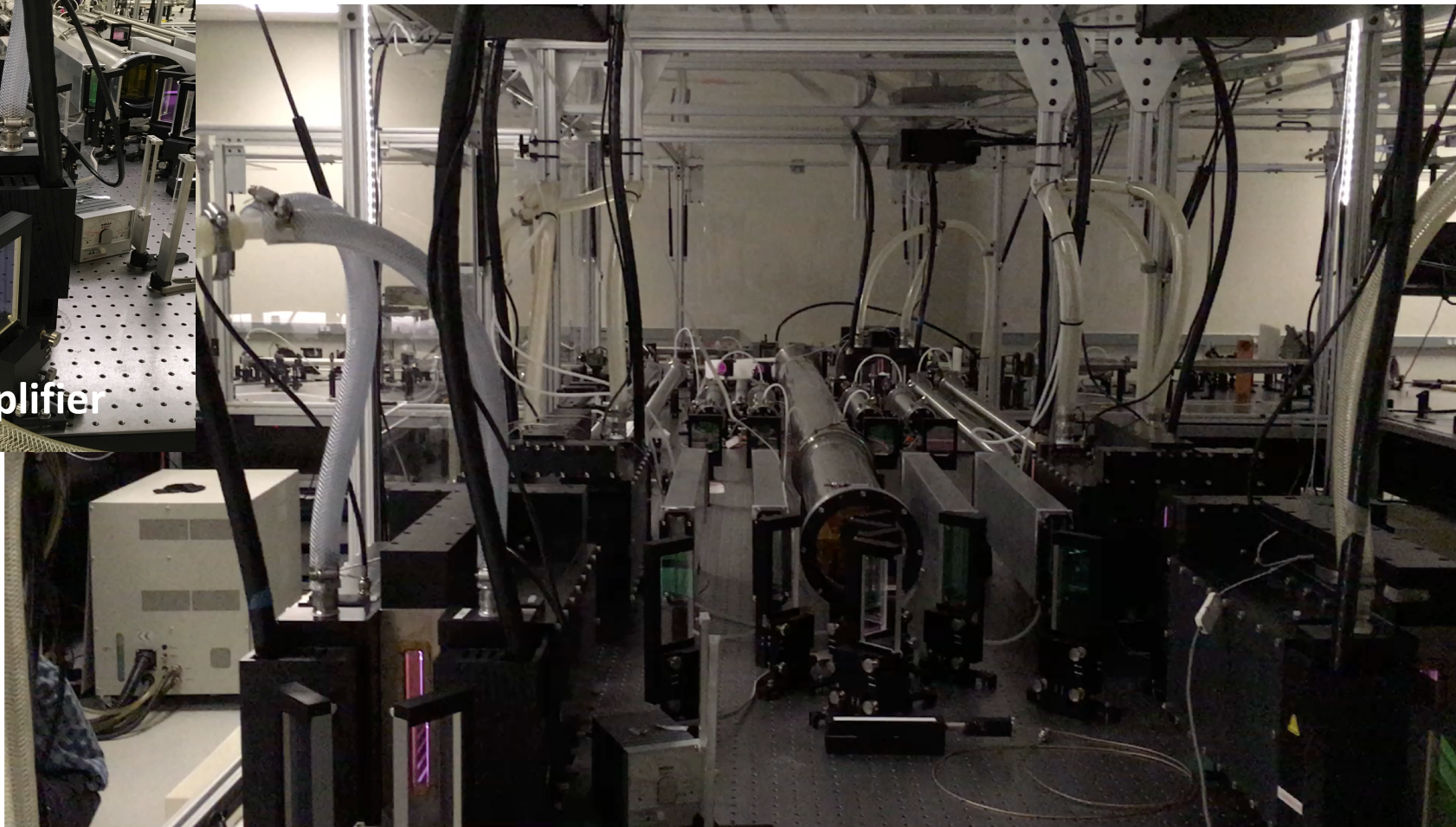
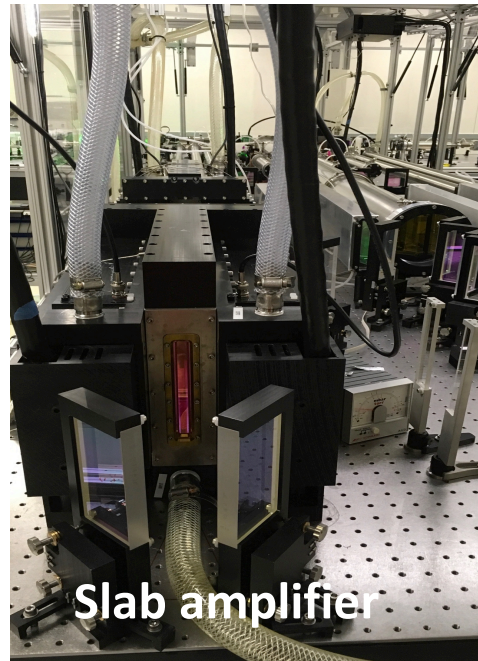
18 J at 3.3 Hz

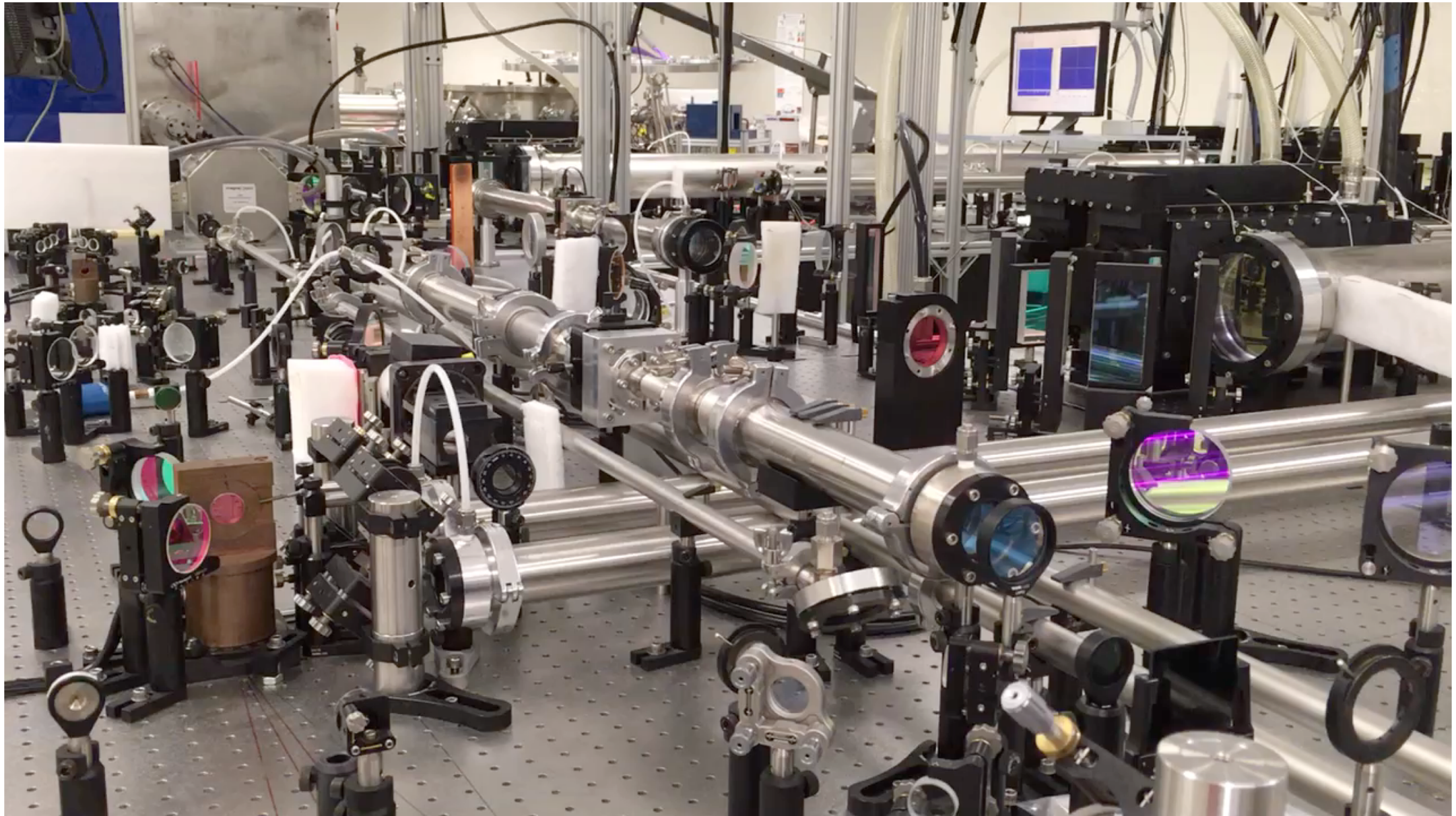


Good beam uniformity

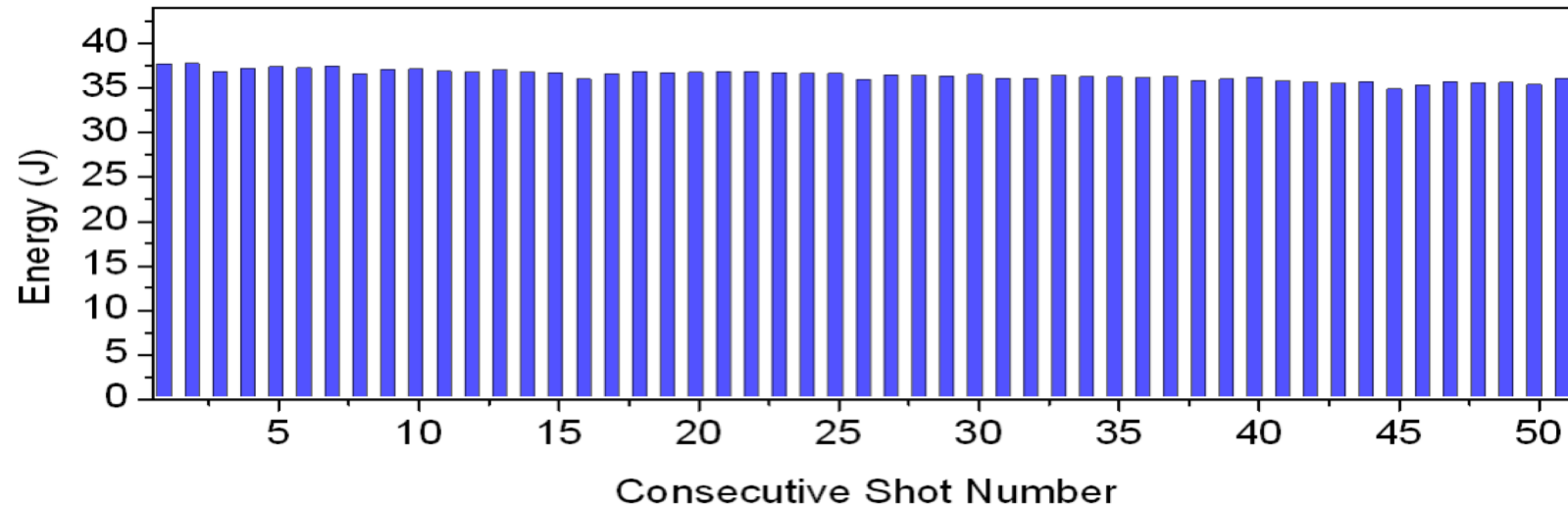


Pump laser slab amplifiers for 36 J Ti:Sapphire amplifier operating at 3.3 Hz repetition rate

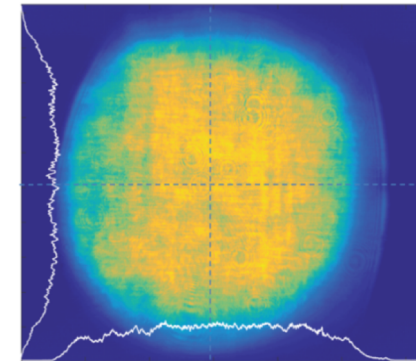




3.3 Hz laser run, 36.3 J average energy before compressor



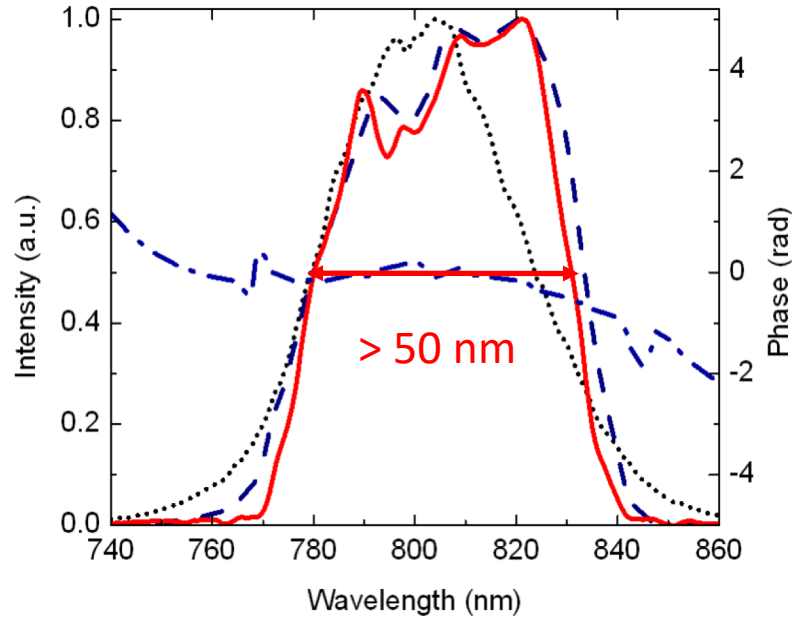
- ❑ Average pulse energy 36.3 J
- ❑ Shot-to-shot variation ~1.7% rms



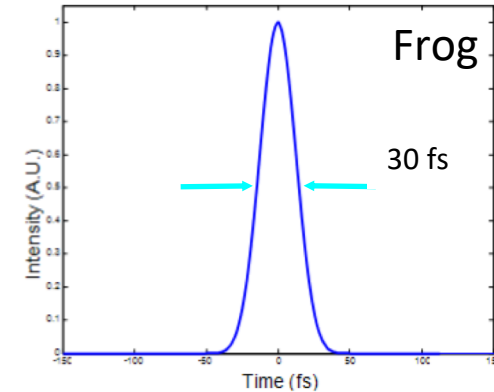
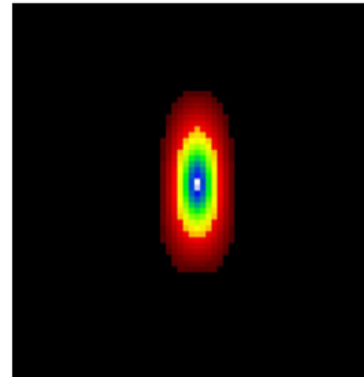
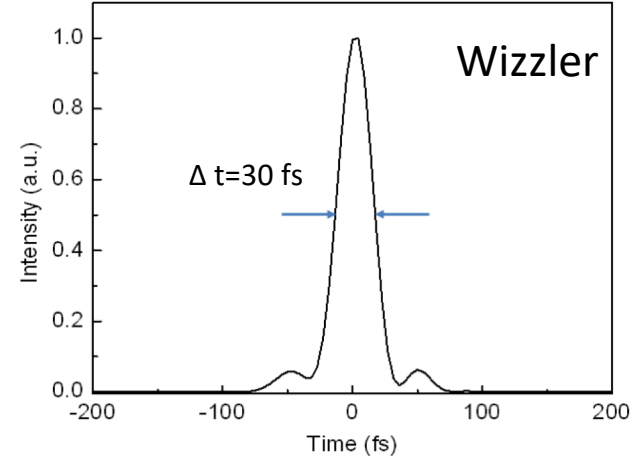
Spatial beam profile

Laser spectra, 30 fs pulse duration

laser spectra through the system



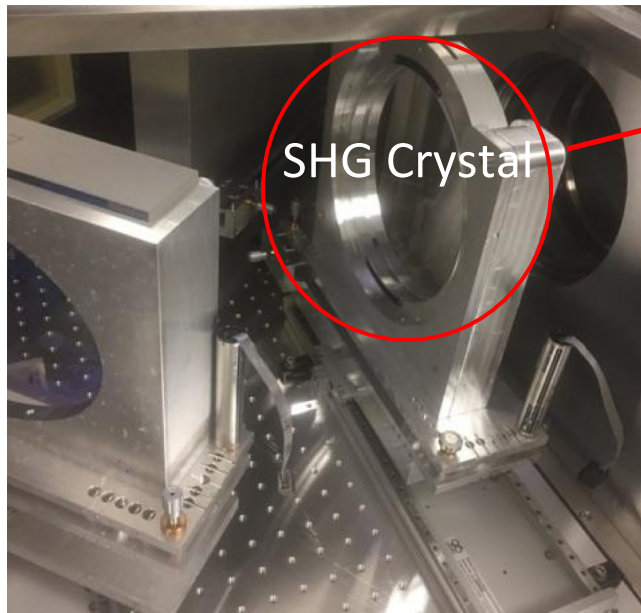
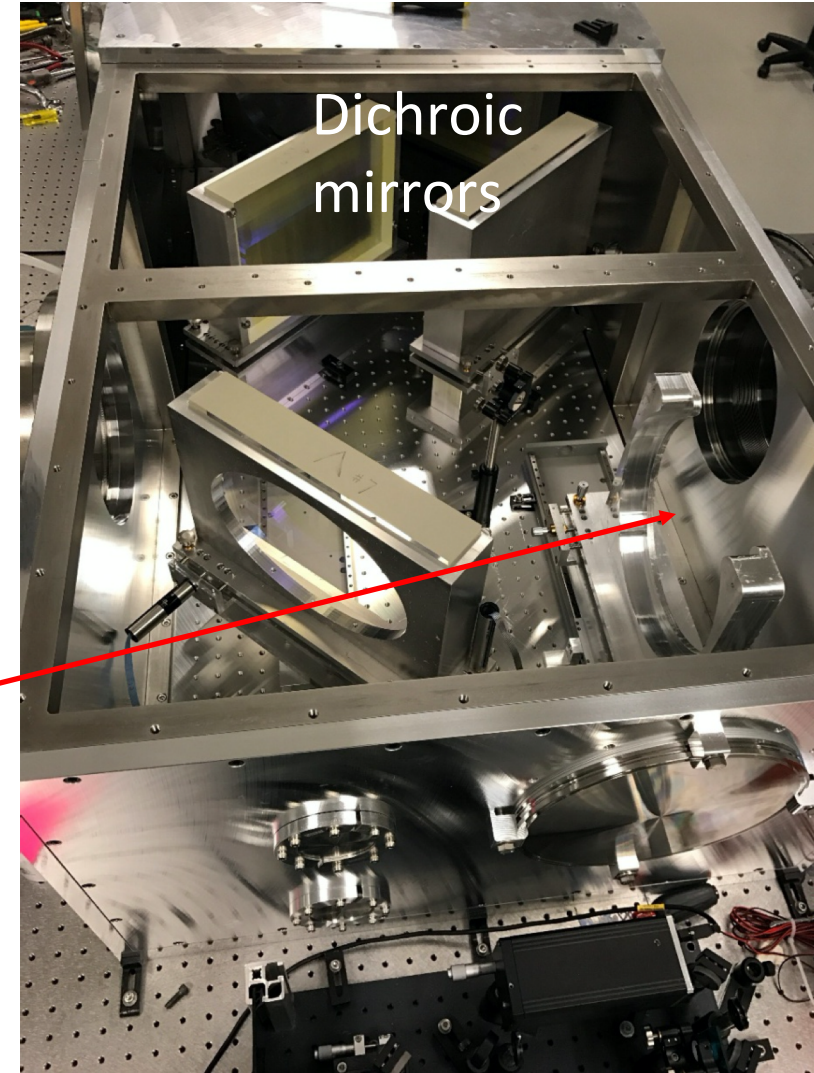
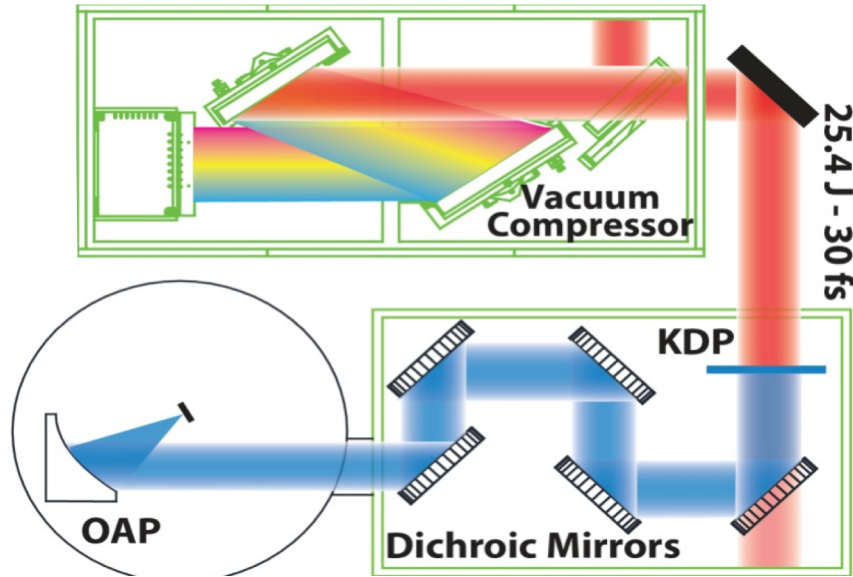
..... Stretcher
 ---- 1st stage amplifier
 — Final stage amplifier



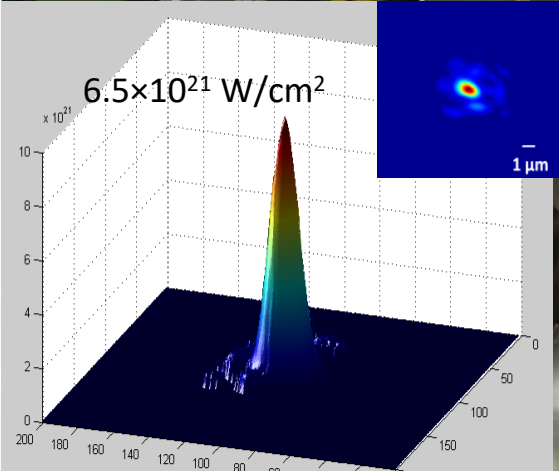
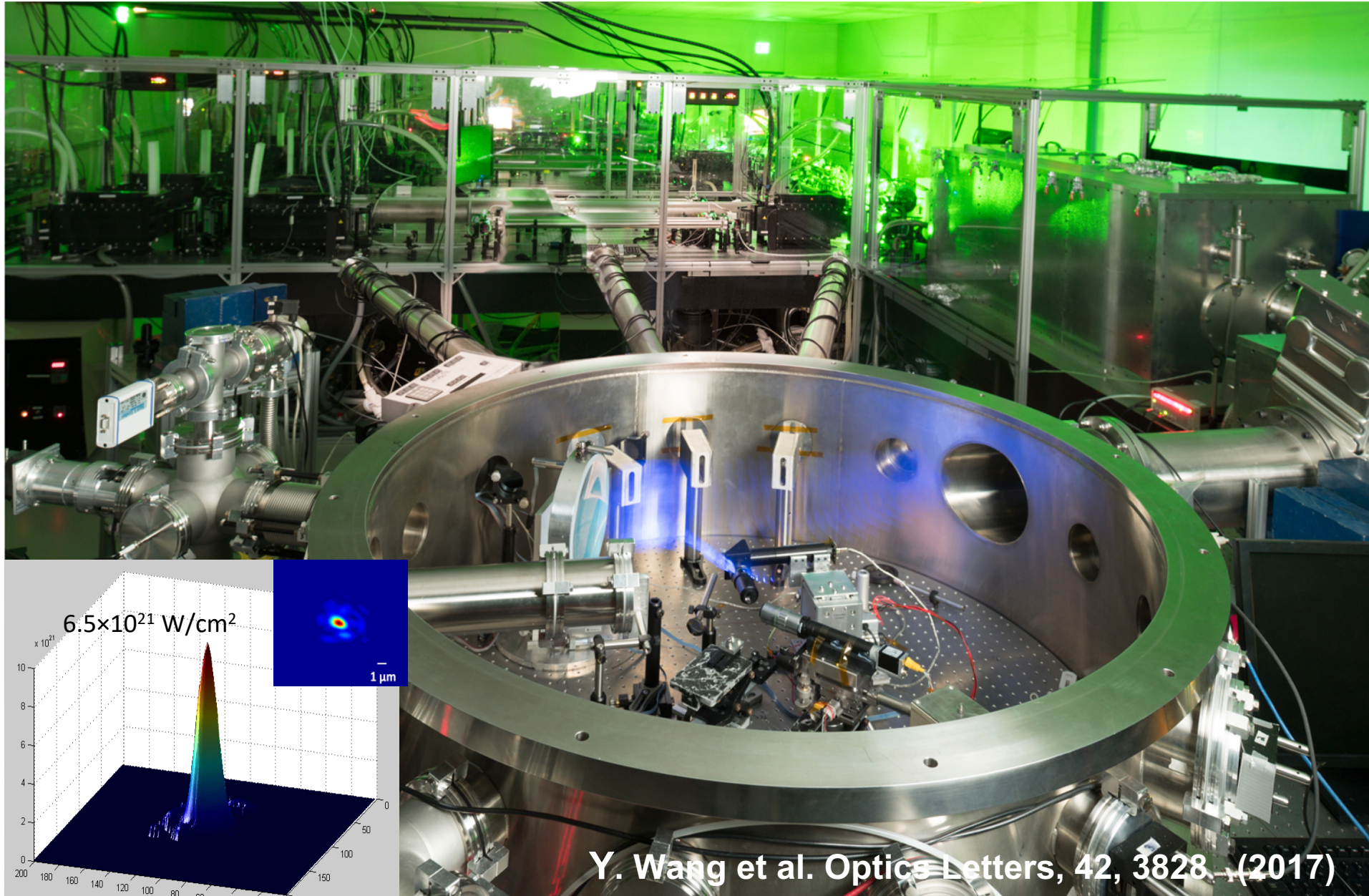
Autocorrelation trace of the compressed pulses obtained from a single shot real-time spectral phase measurement.

Ultra-high contrast pulses: $> 1 \times 10^{12}$

Frequency Doubling and filtering of fundamental beam



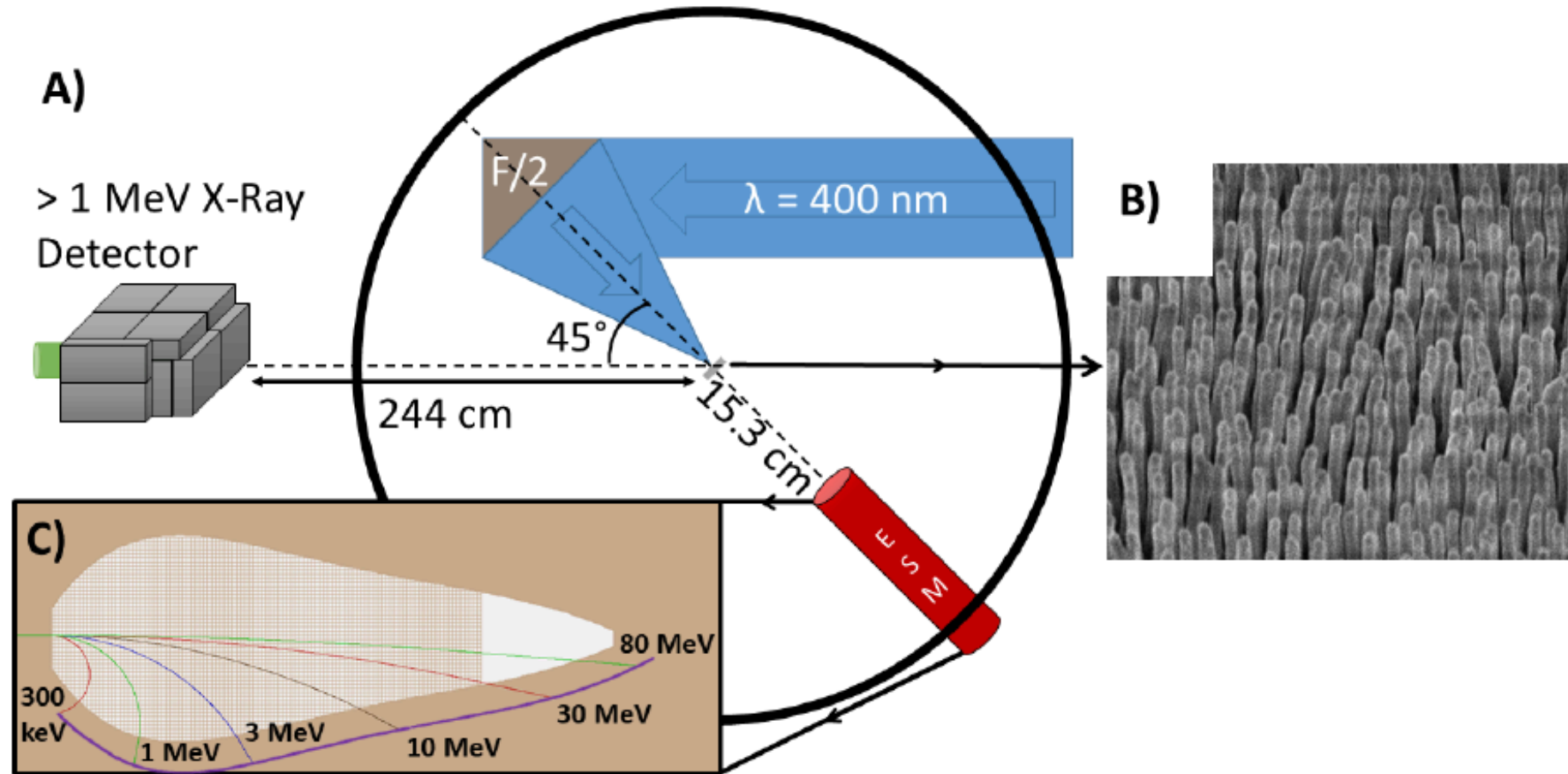
f/2 parabola achieves $6.5 \times 10^{21} \text{ W/cm}^2$



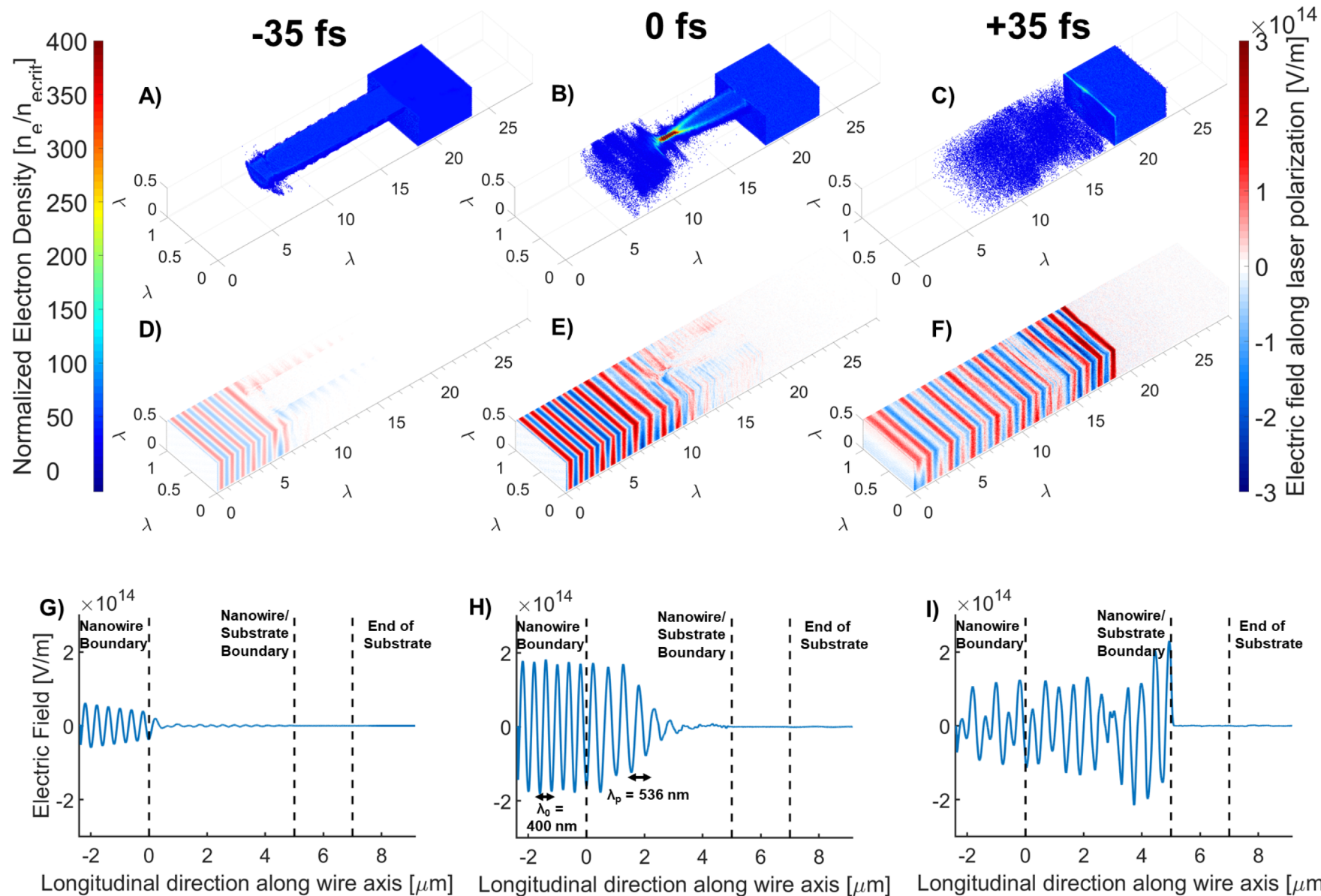
Y. Wang et al. Optics Letters, 42, 3828, (2017)

Relativistic Induced Transparency and Electron Acceleration in Dense CD_2 Nanowire array

Irradiation intensity $I = 2.7 \times 10^{21} \text{ W cm}^{-2}$

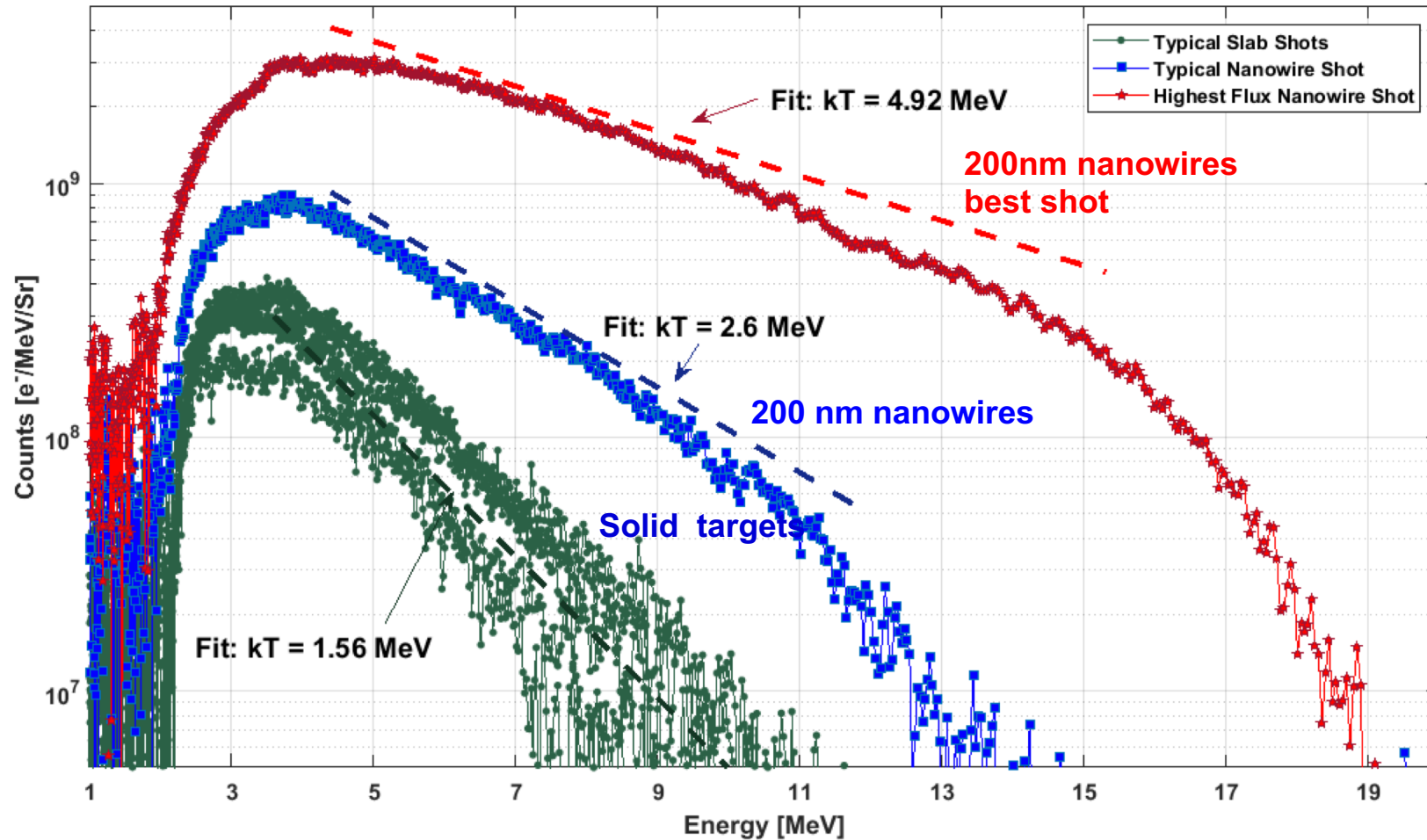


Relativistically induced transparency allows for deep laser pulse propagation into overdense CD₂ plasma



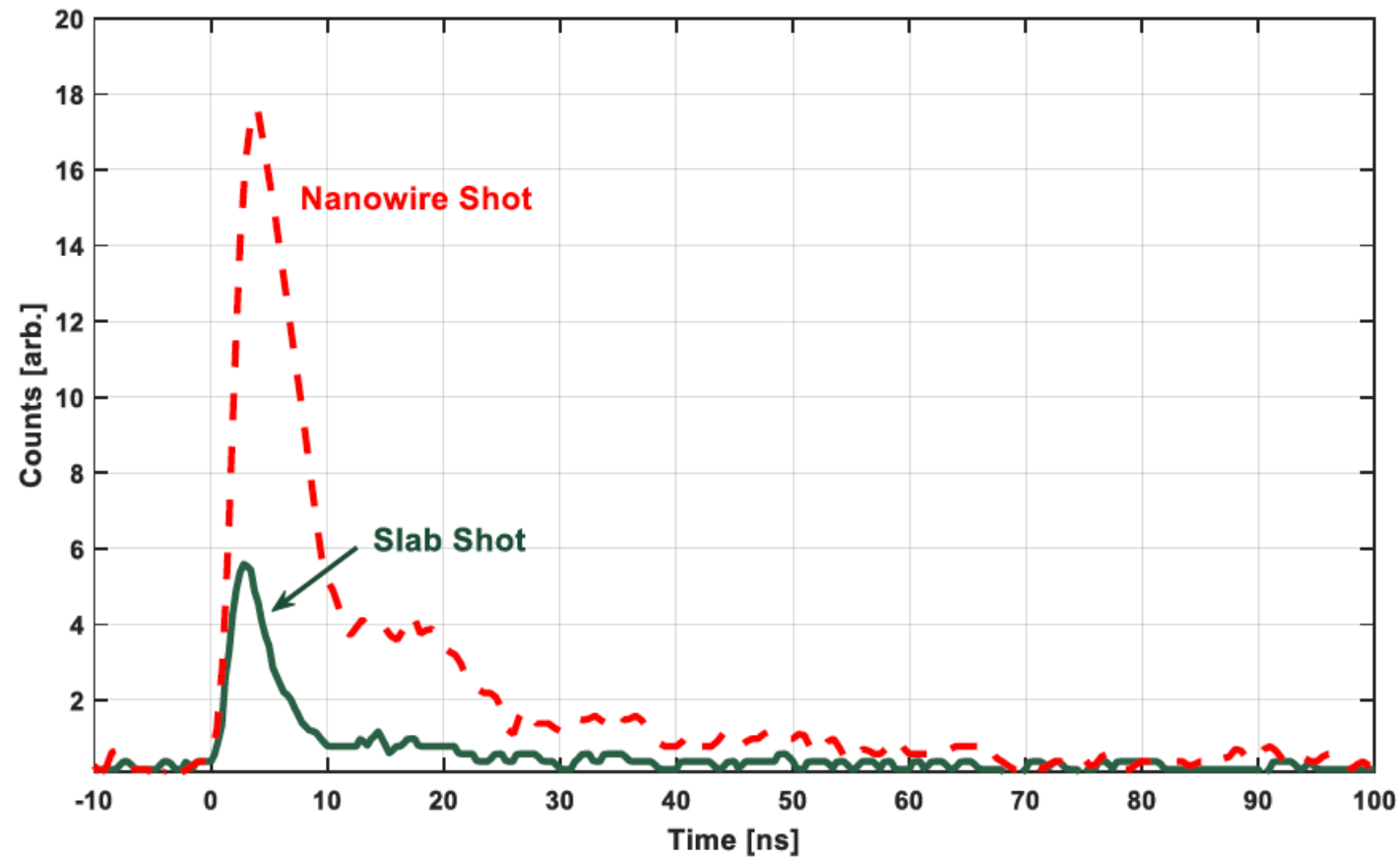
Relativistically Transparent Nanowire array target generates MeV electrons with increased energy and total flux

CD₂ Nanowire Array Electron Spectra (forward direction)



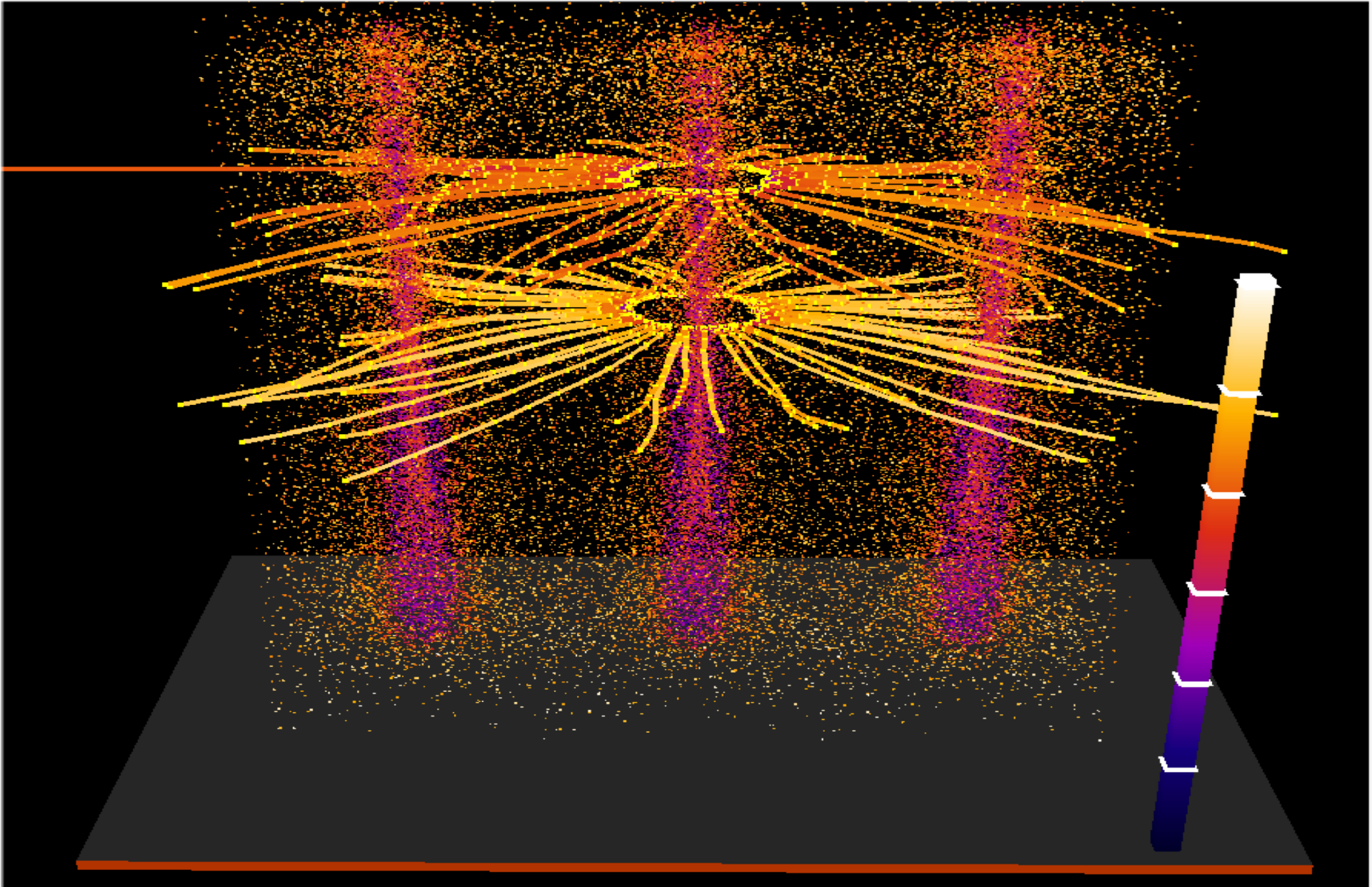
- Integrated flux enhanced **5x** for typical NW shot over solid
- Best shot flux enhanced **24.5x** over solid target

Increase of 3.6 X in > 1 MeV Gamma ray flux



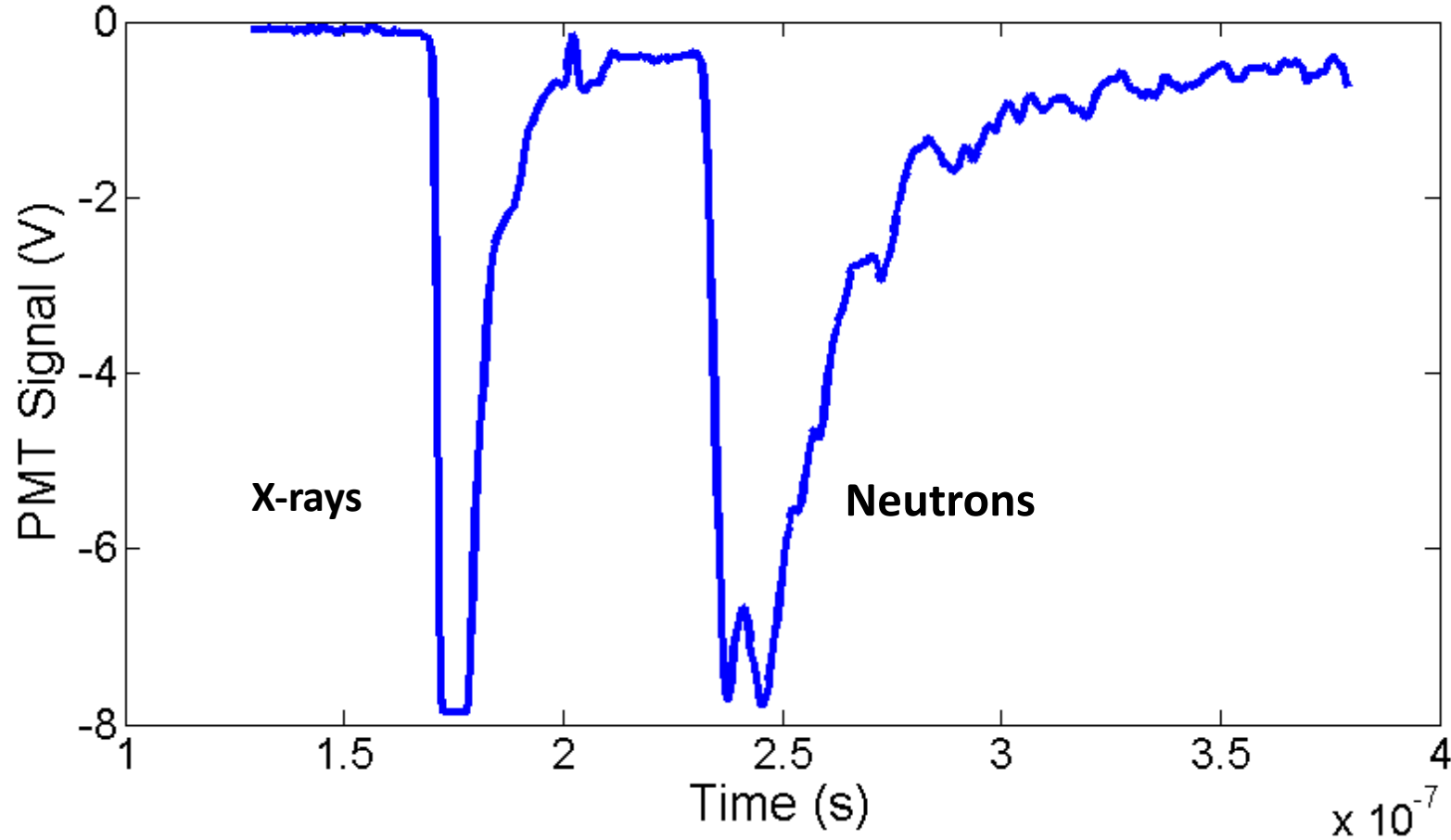
Ion Trajectories

CD₂ nanowires, $I = 5 \times 10^{21} \text{ W cm}^{-2}$



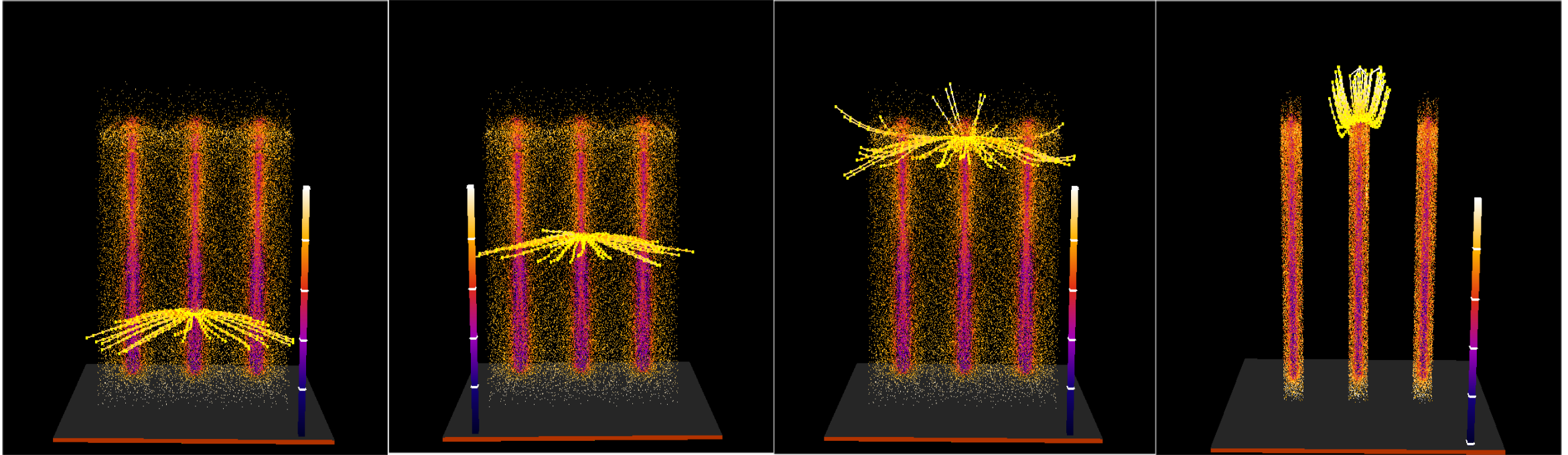
Neutron production increased to $> 2 \times 10^7$ n/shot

TOF detector at 2m with 10 cm lead shielding



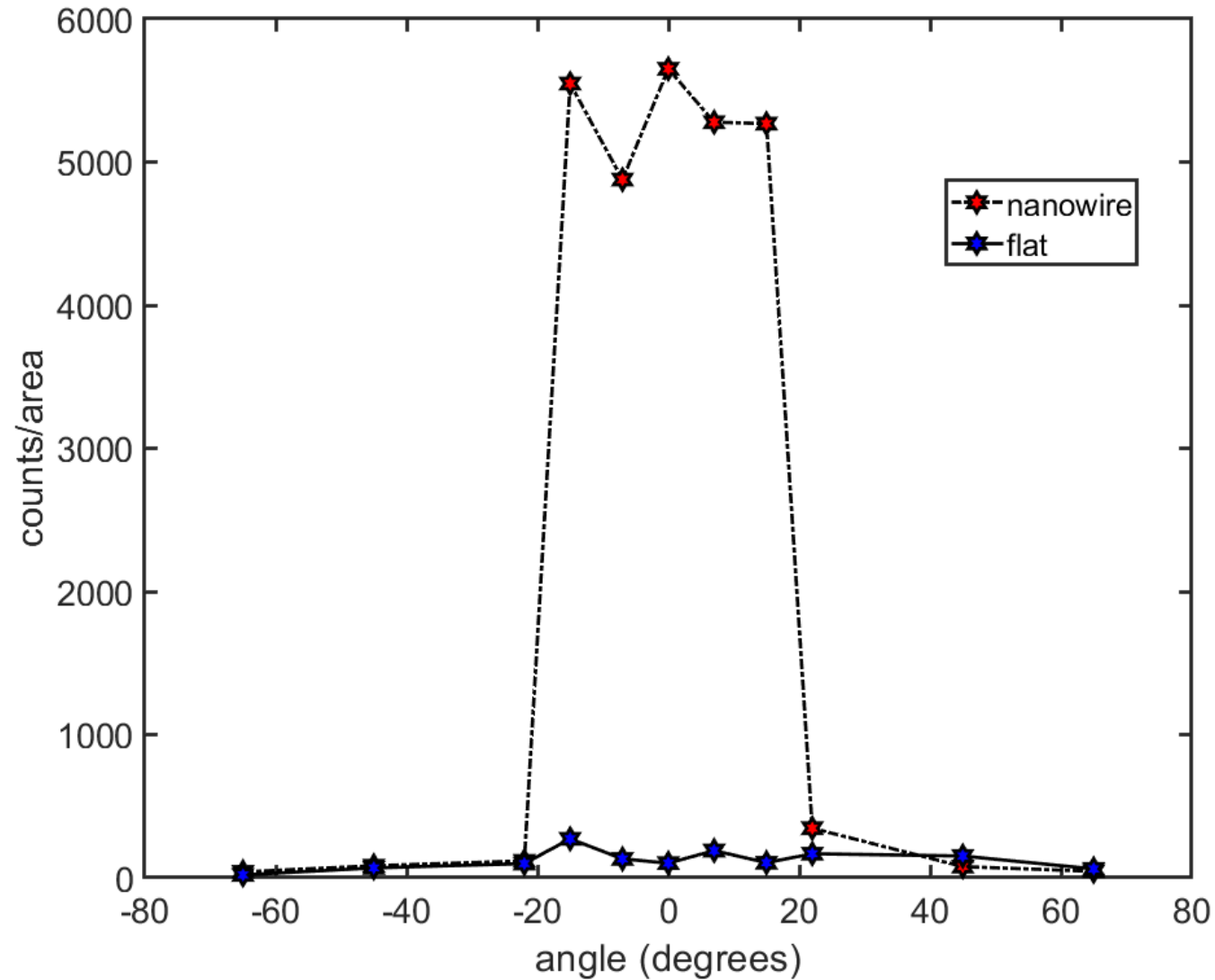
Ion trajectories

CD₂ Nanowires, 400 nm diameter, $5 \times 10^{21} \text{ W cm}^{-3}$

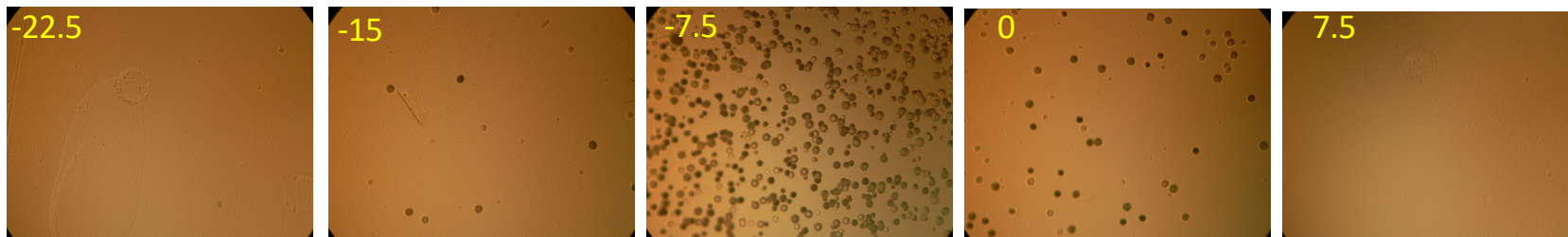
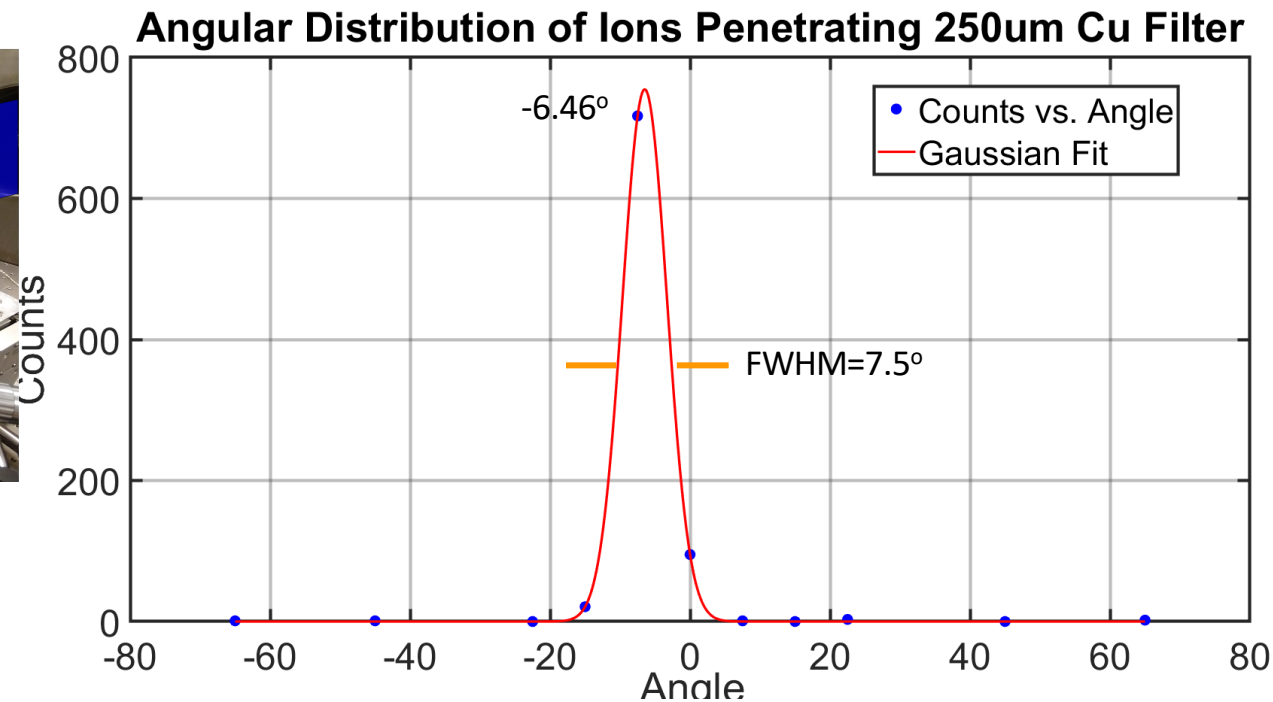
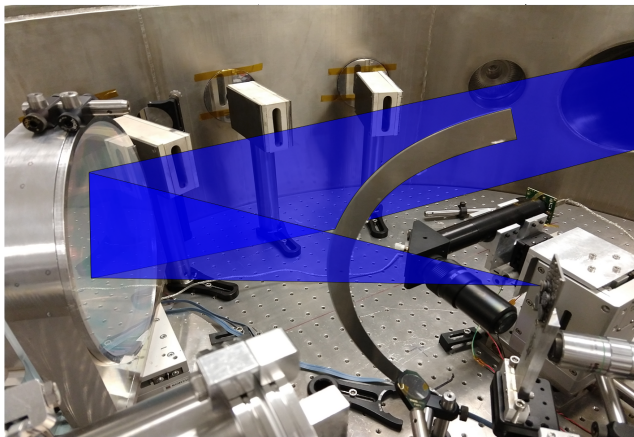


Ion beam in laser backward directions

Comparison with CD₂ flat solid target

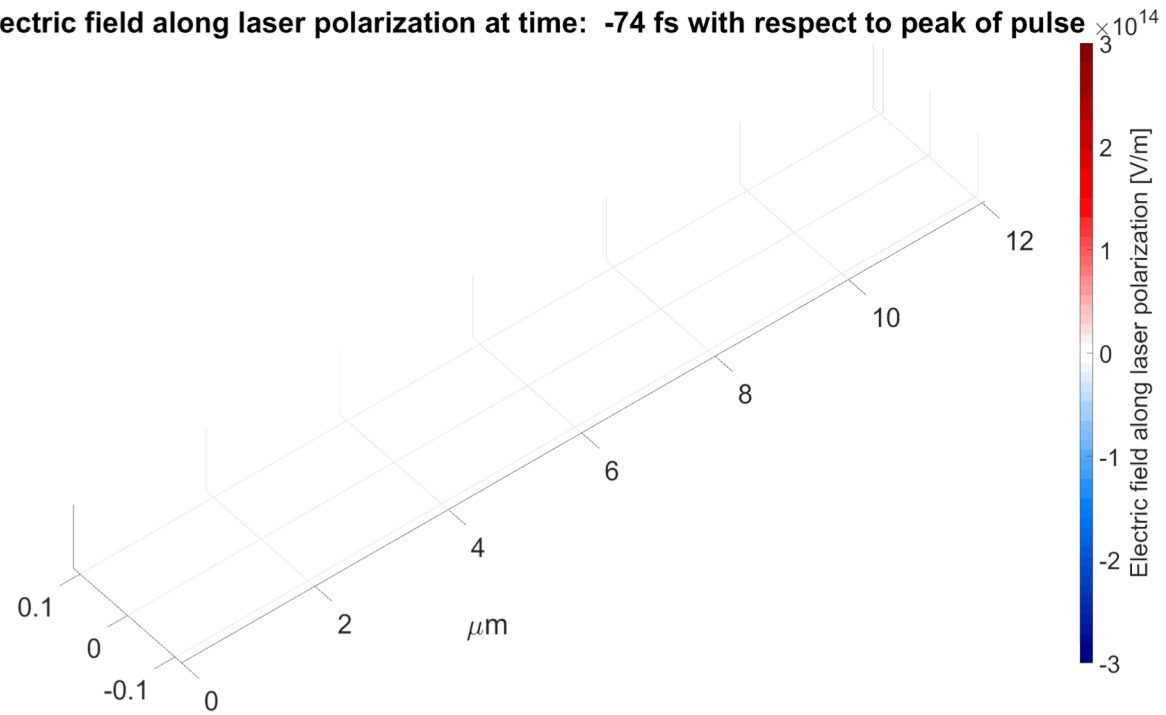


Angular Ion Distribution Measurement (> 13.3MeV D)

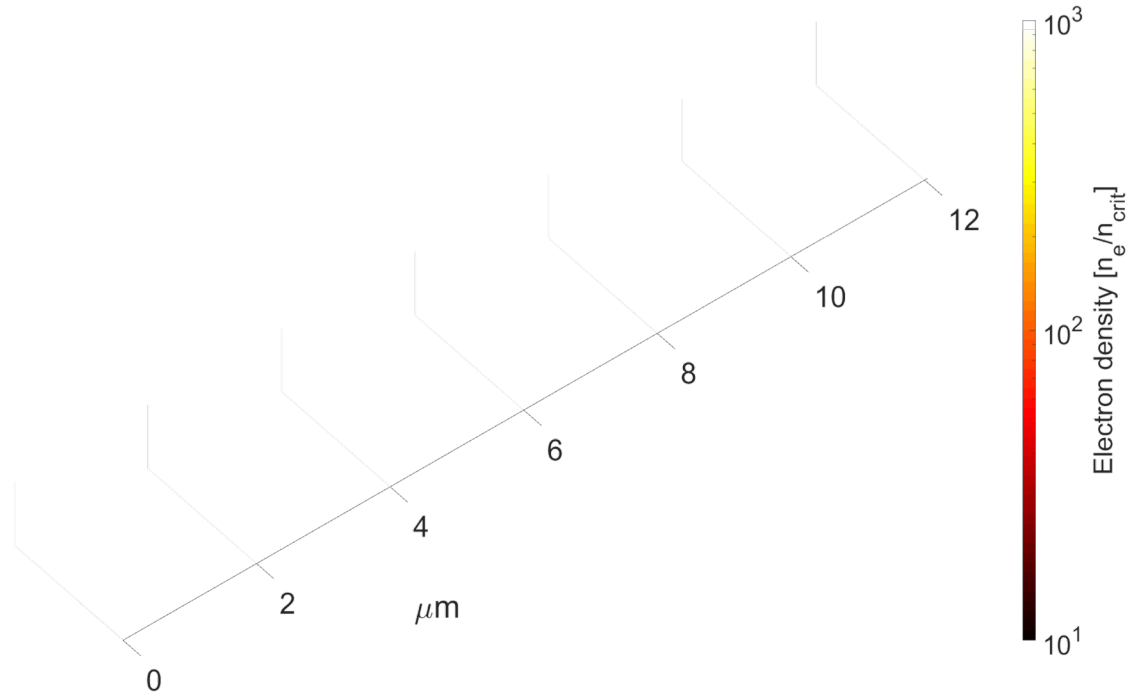


Au Nanowires

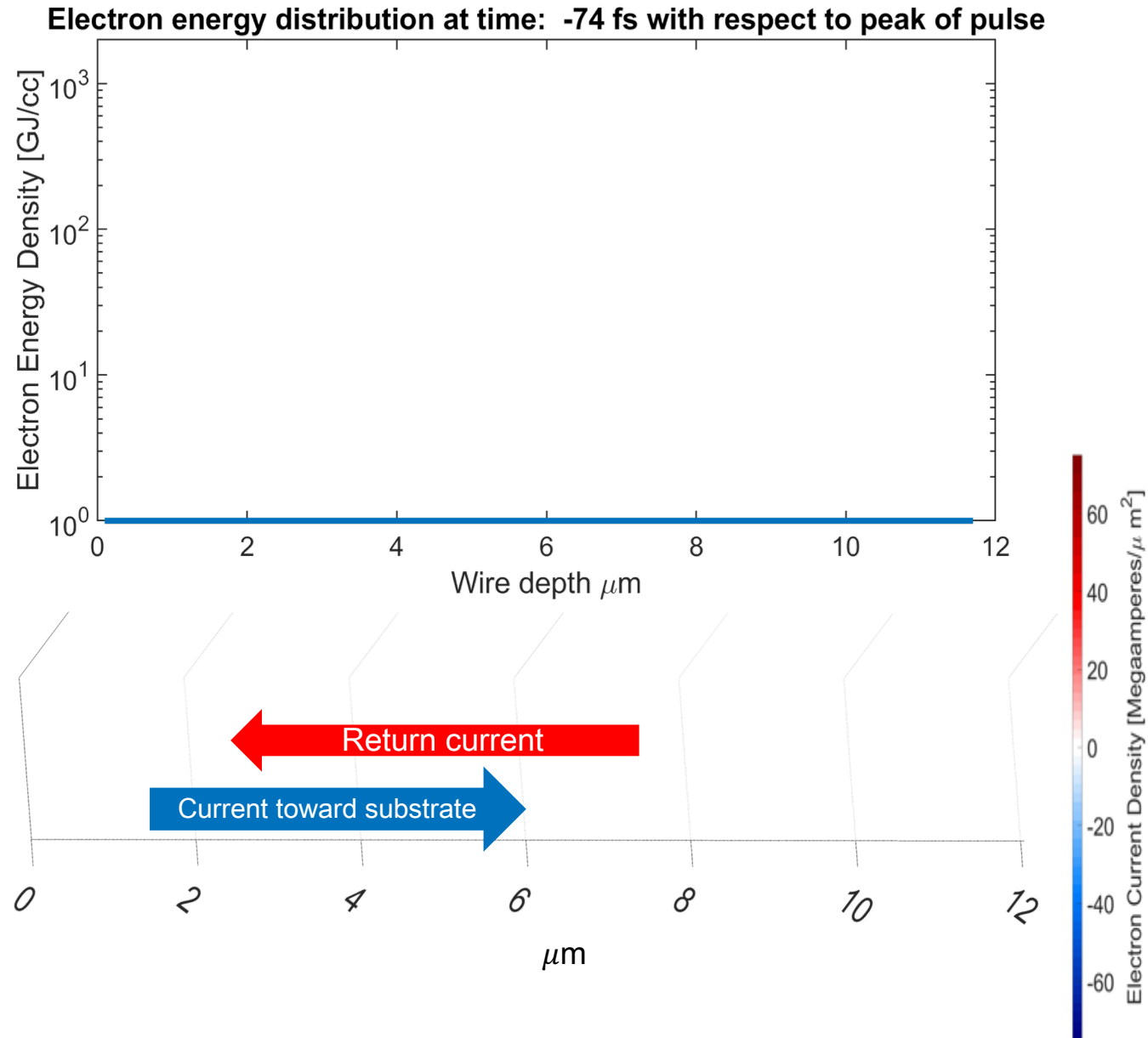
Electric field along laser polarization at time: -74 fs with respect to peak of pulse



$I = 4 \times 10^{21} \text{ W cm}^{-3}$
15 % solid density



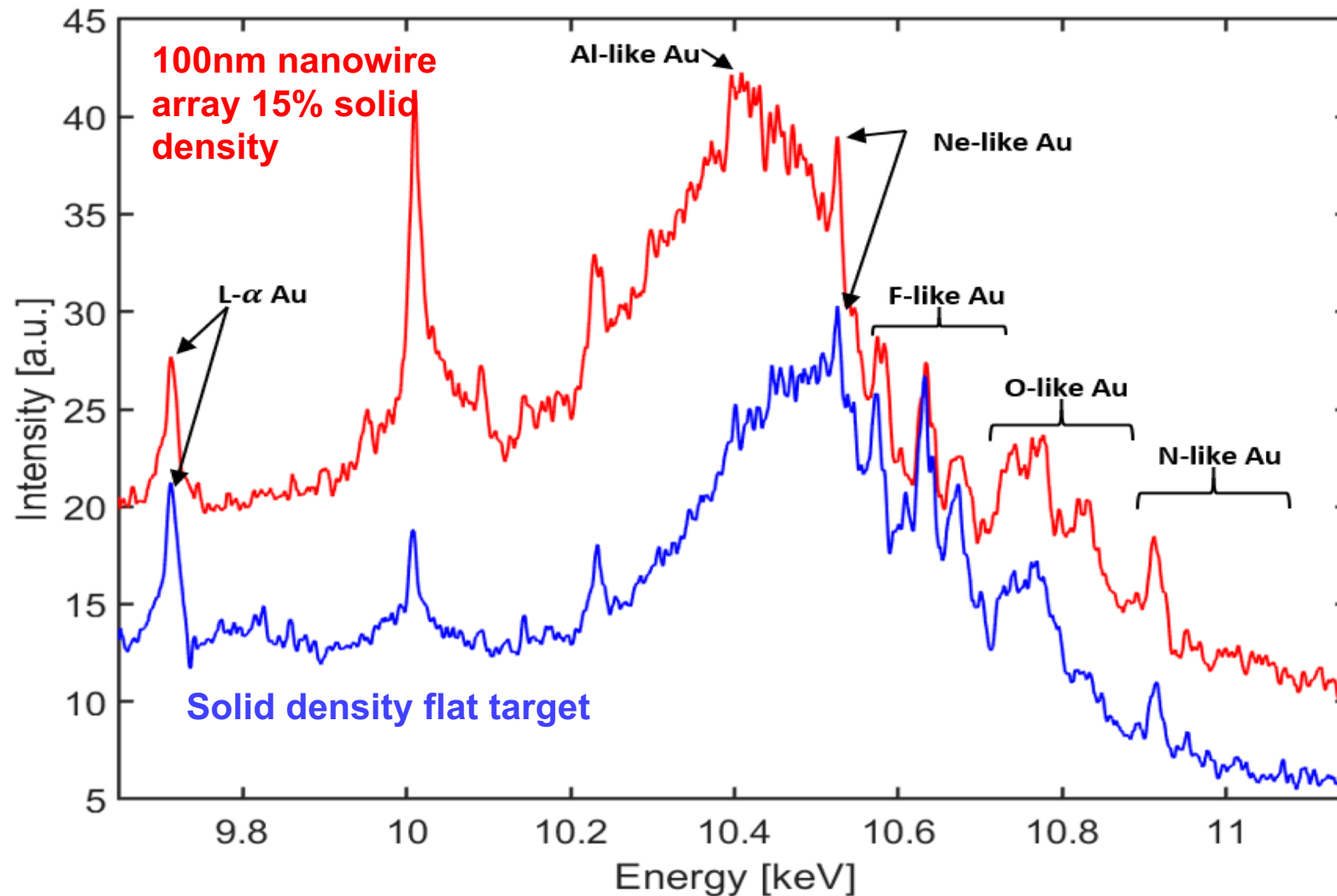
Laser drives hot electrons at tip of wire into plasma



- Laser drives hot electrons at tip of wire into plasma
- Peak electron energy density of $>1\text{TJ/cc}$ at tip of wire
- Electrons deposit energy through the volume ending with an energy density of $\sim 100\text{ GJ/cc}$
- Large current density causes $\mathbf{J} \times \mathbf{B}$ force to pinch the wire

Au L shell spectra from solid and near solid density plasmas show emission from ions up to N-like Au⁷²⁺

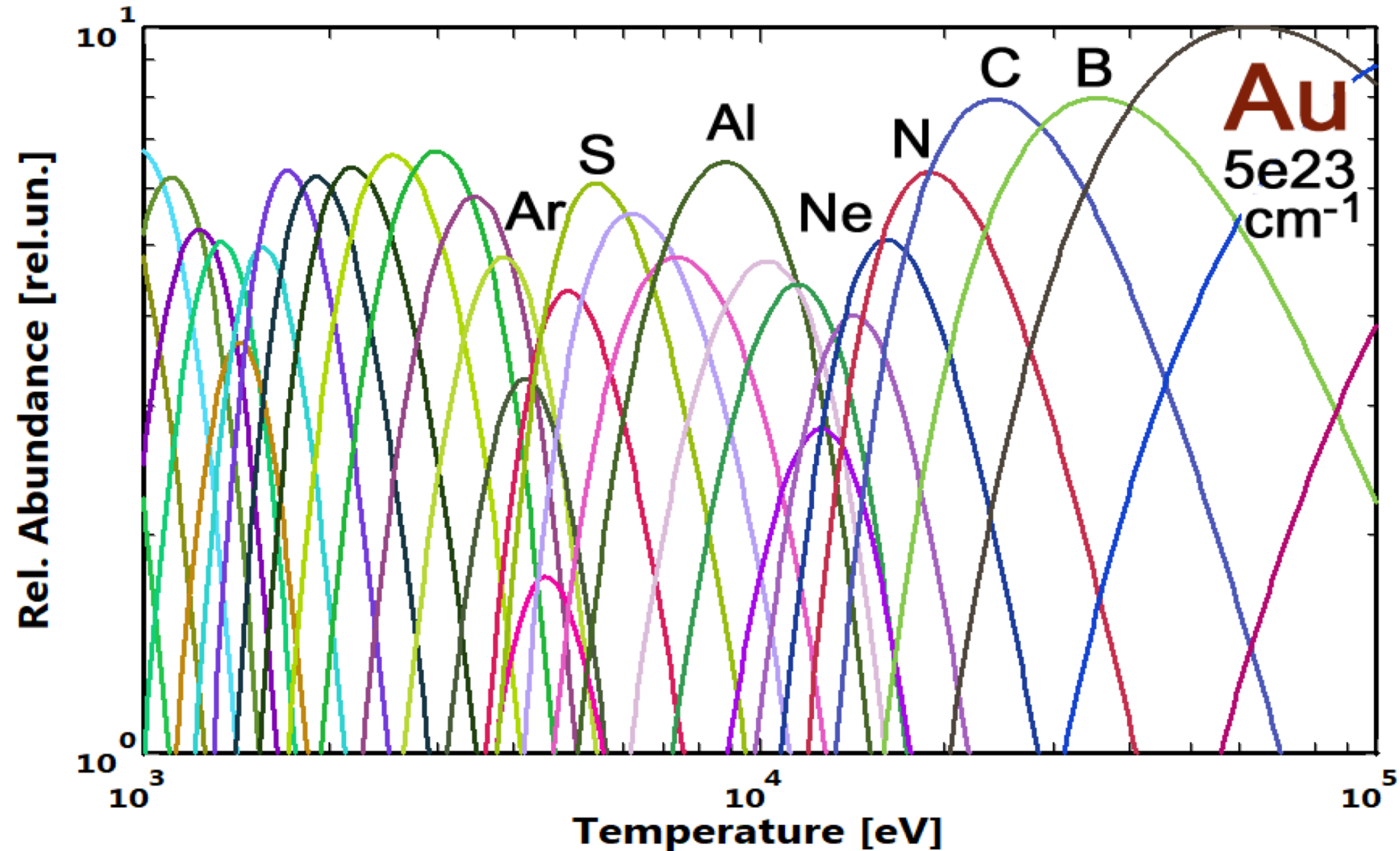
$$I = 3 \times 10^{21} \text{ Wcm}^{-2} (a_0 = 21)$$



R. Hollinger et al., Nature Photonics, 14, 607, (2020)

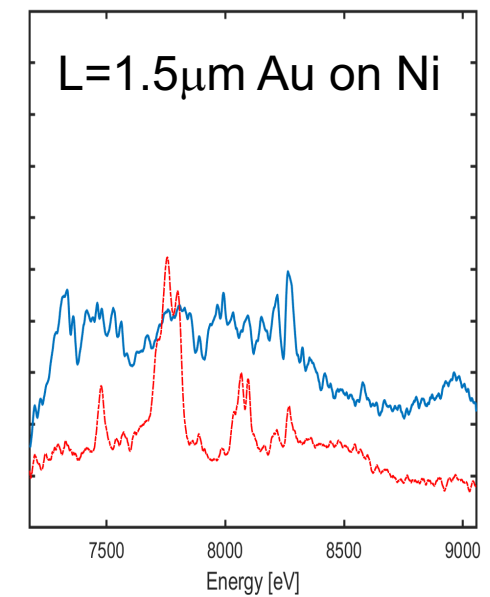
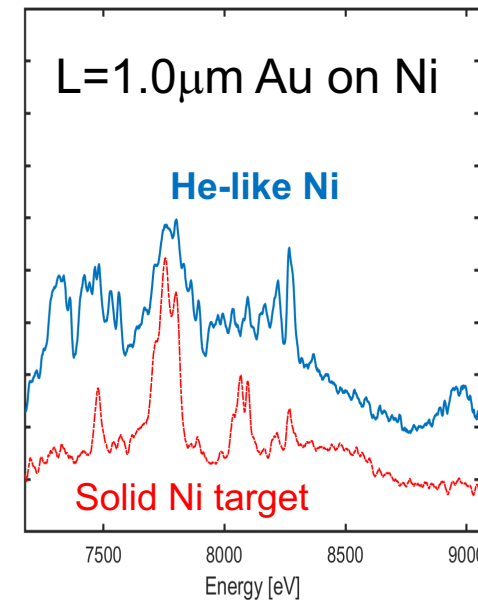
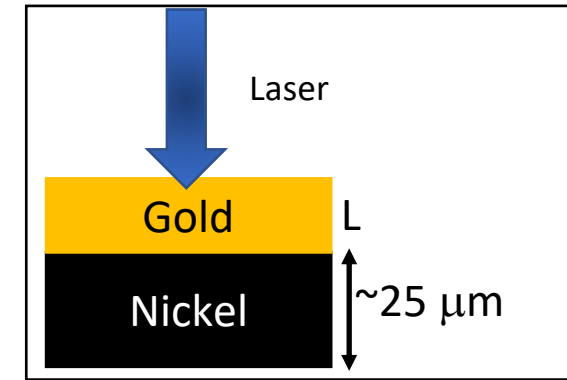
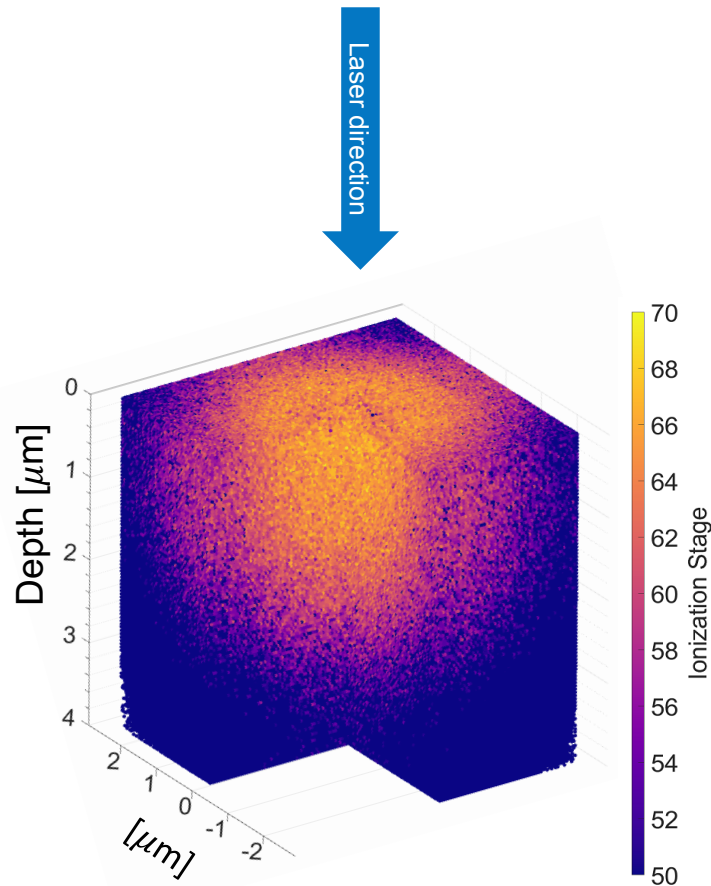
- Both targets show emission up to N-like Au⁷²⁺
- Nanowire target charge state peaks around Al-like Au⁶⁶⁺
- Solid target is peaks around Ne-like Au⁶⁹⁺

In steady state ionization equilibrium Neon-like ions
appear at temperatures > 10 KeV



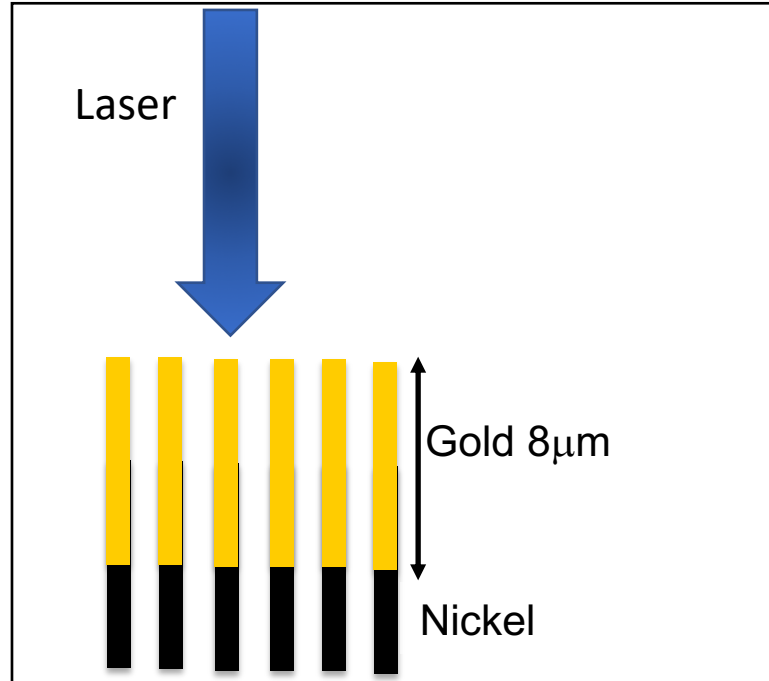
Simulation of solid target heat penetration depth agrees with experiment

+500fs after peak of laser pulse

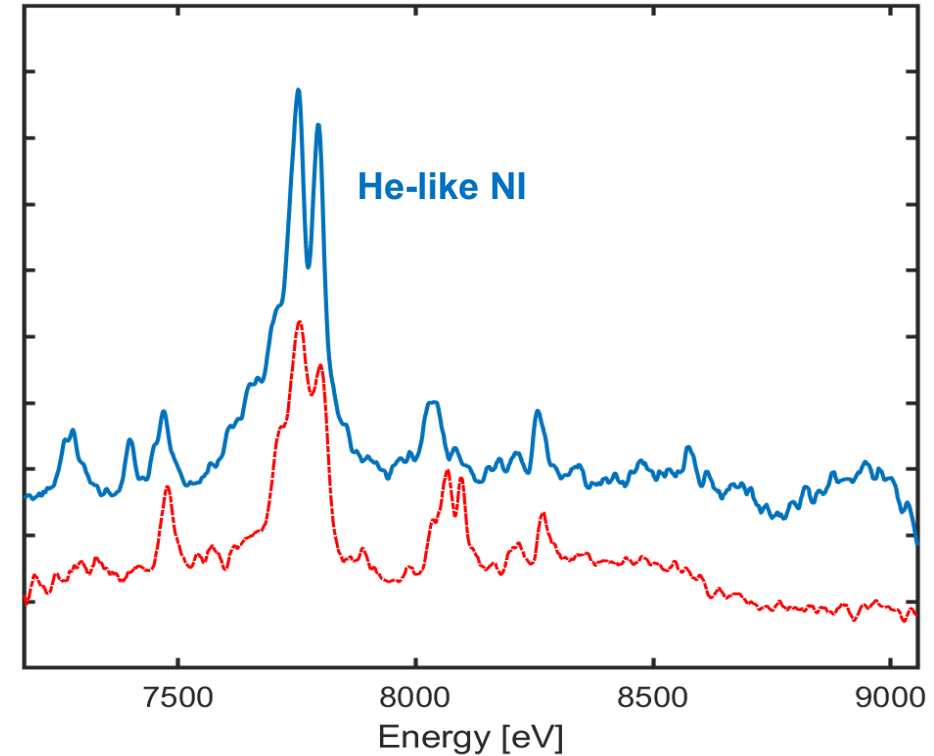


Buried Ni tracer reveals heat penetration in nanowire array exceeds 8 micrometers

$$I=4 \times 10^{21} \text{ Wcm}^{-2} (a_0 = 21)$$

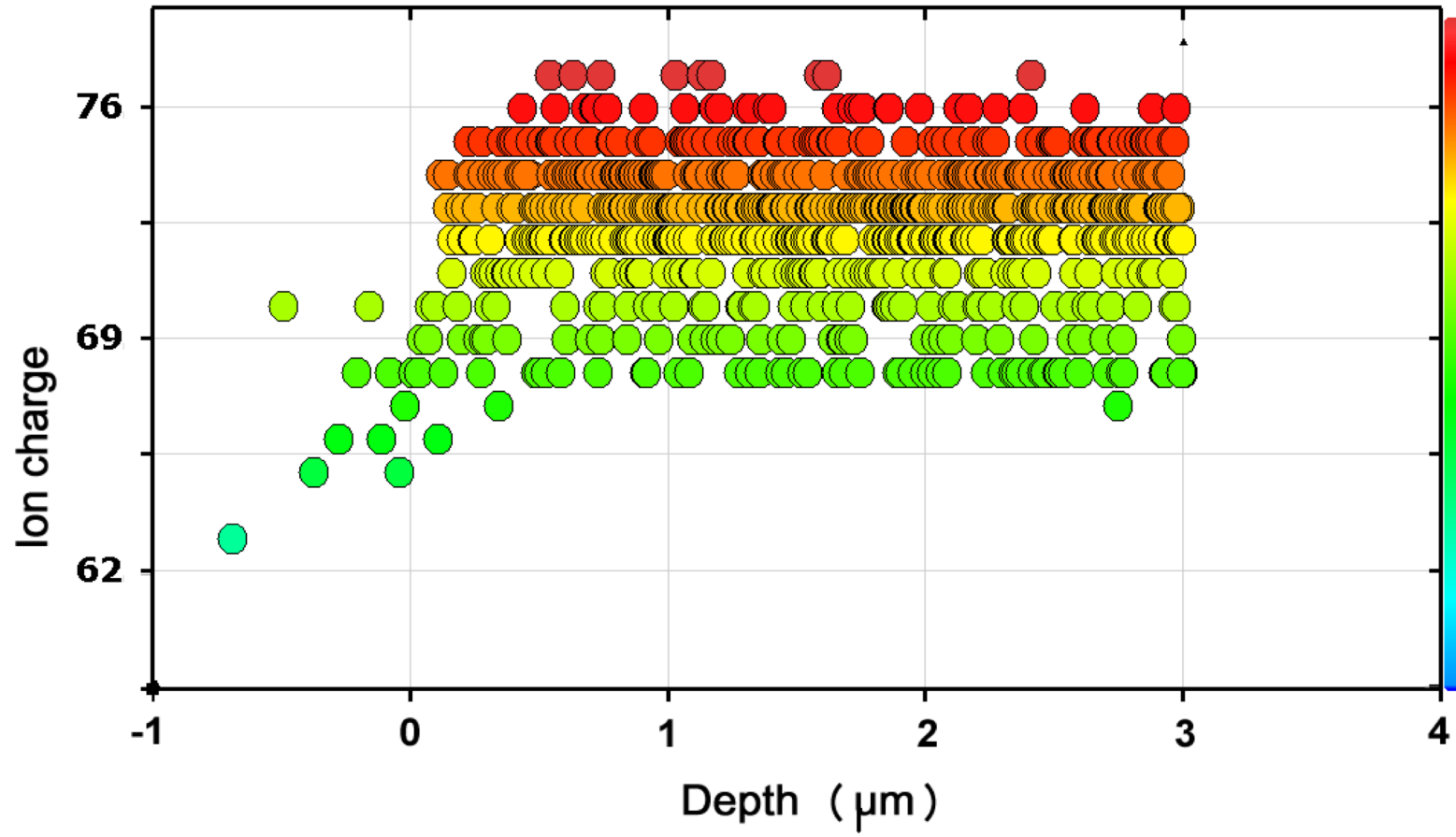


~8μm Au on Ni 100nm 15% NW



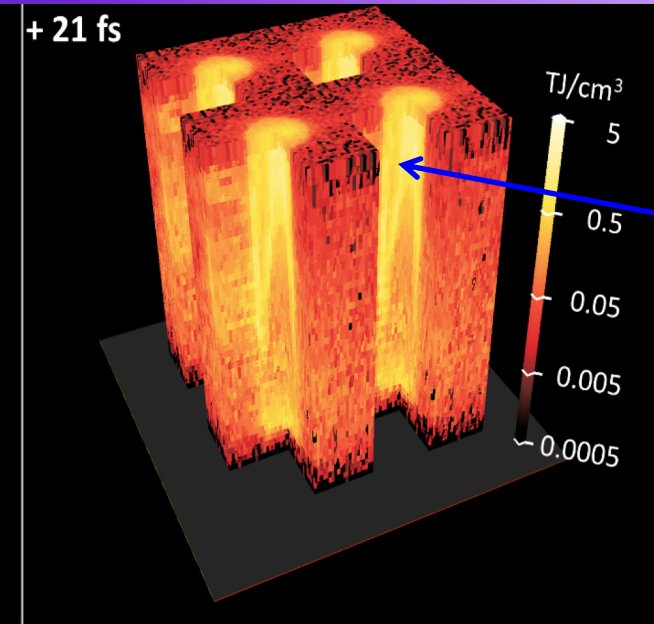
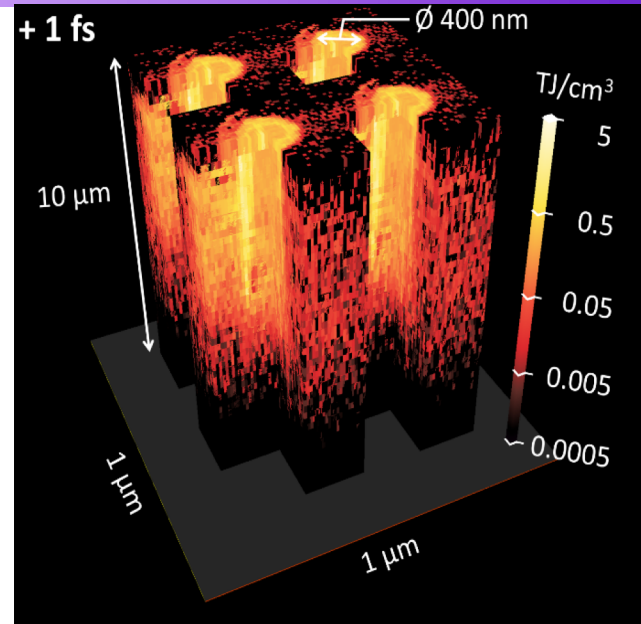
He-Like Au^{+77} solid density plasma predicted

$4 \times 10^{21} \text{ Wcm}^{-2}$ with a $5 \mu\text{m}$ FWHM diameter focal spot



Scaling to $1 \times 10^{22} \text{ W cm}^{-3}$ ($a_0 = 34$)

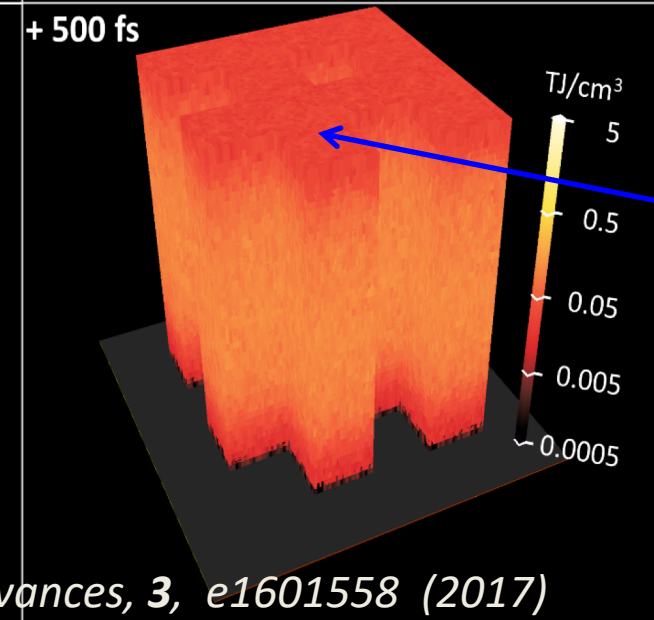
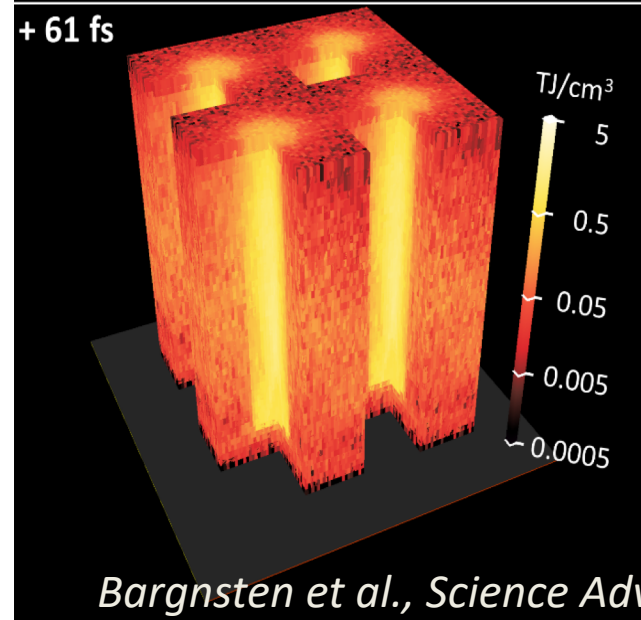
55 nm diameter Au nanowires, 13% solid density, 400 nm, 30 fs



$N_e = 2 \times 10^{25} \text{ cm}^{-3}$

2 TJ cm^{-3}

7 Tbar



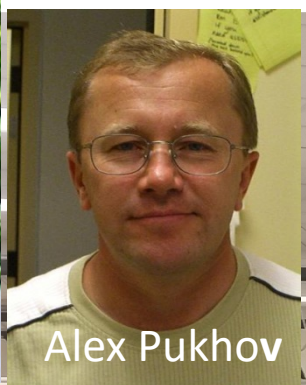
80 GJ cm^{-3}

0.35 Tbar

Contributors:



Vyacheslav
Shlyaptsev



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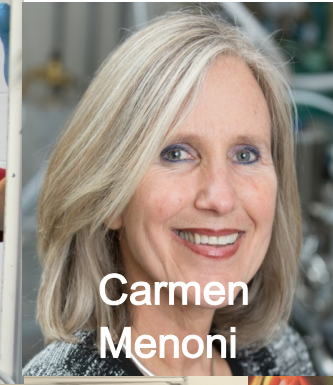
Yong Wang



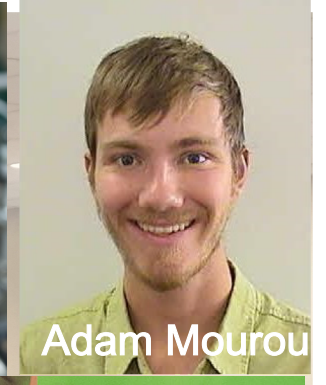
Maria Gabriela
Capeluto



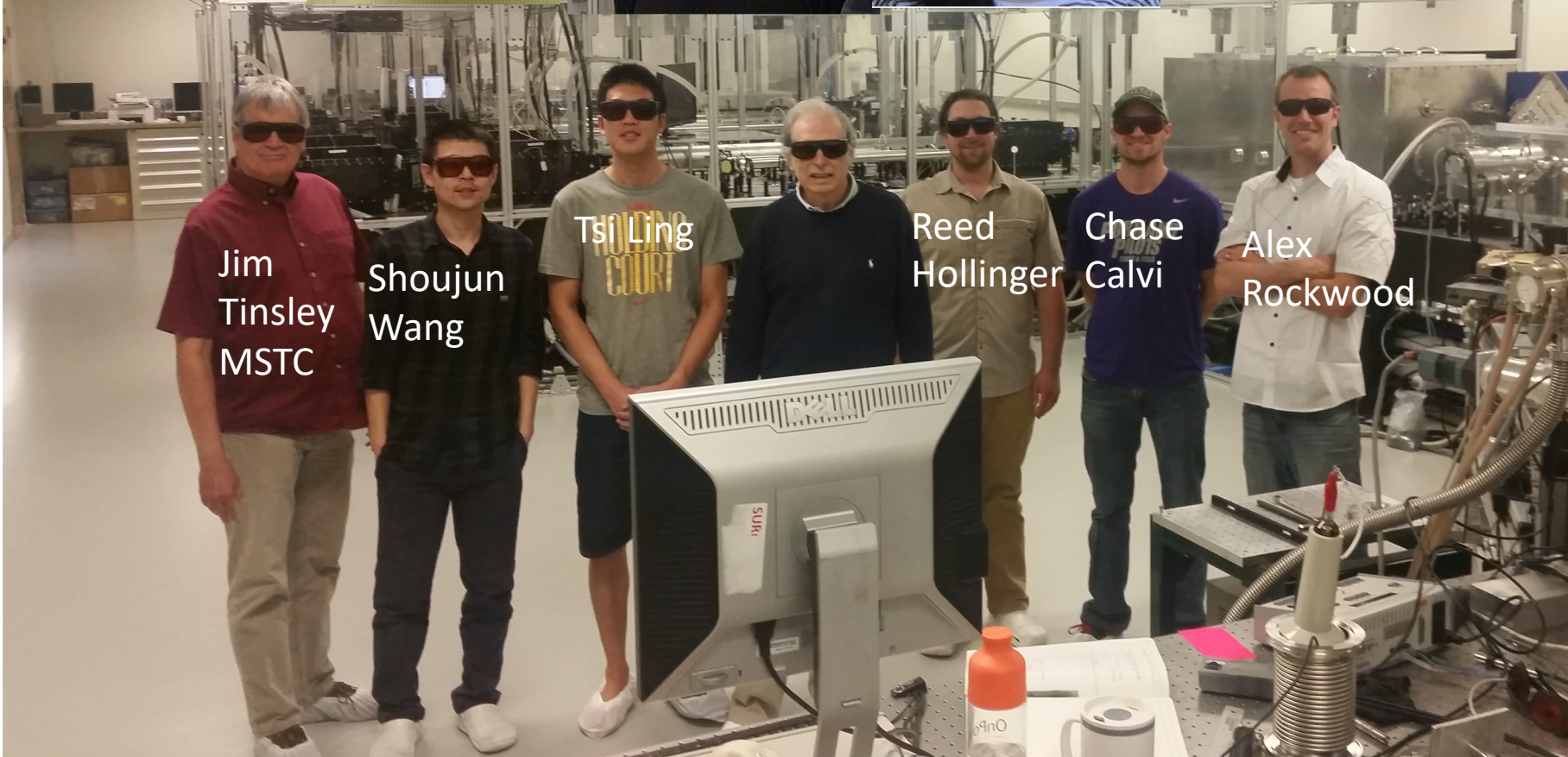
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Carmen
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Tsi Ling

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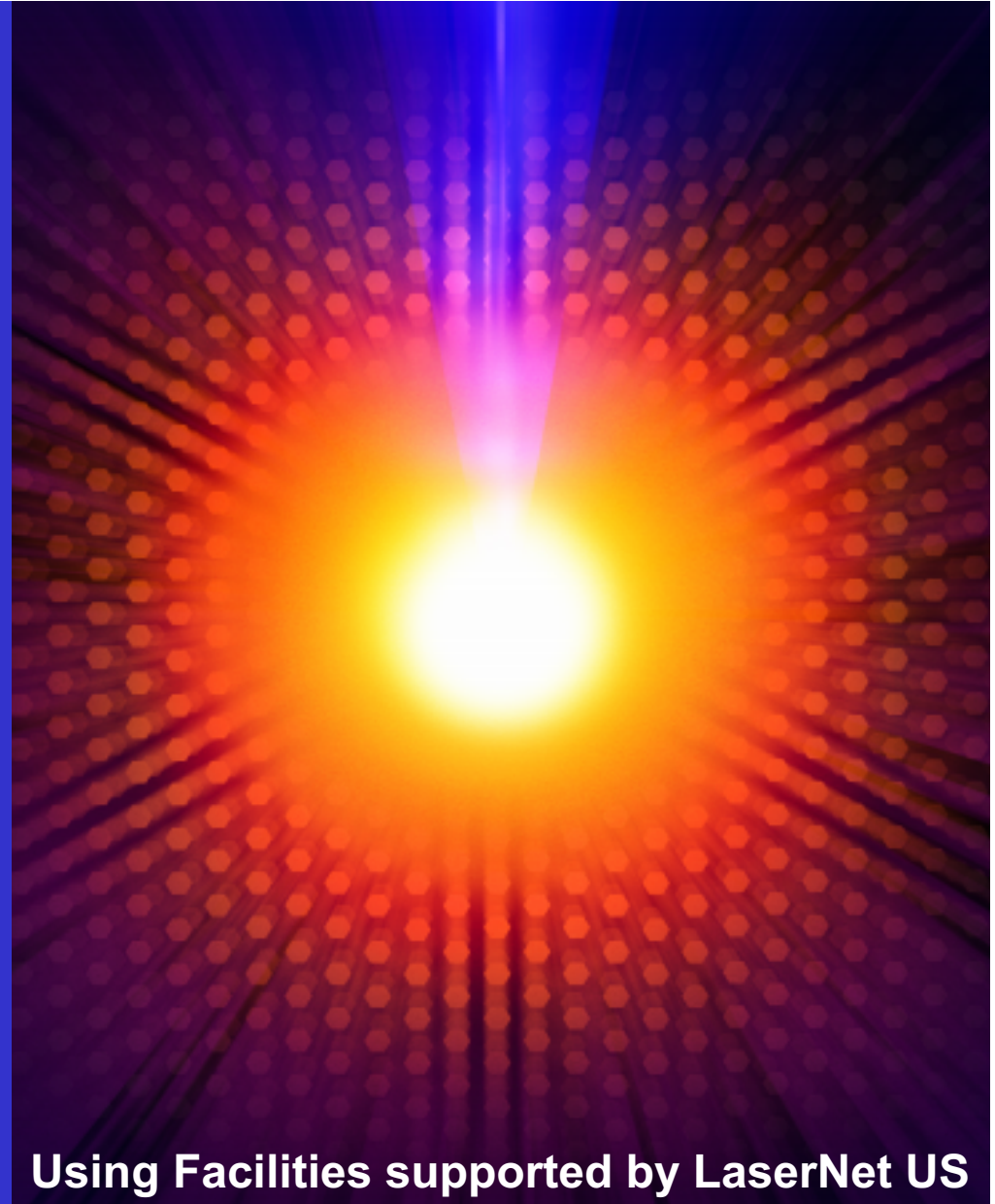
Mario Marconi

Conclusions:

Interaction of highly relativistic ultrashort laser pulses with nanostructures

- Interactions of high contrast, relativistic laser pulses with nanostructures creates ultra high energy density plasmas with extreme conditions.
- Demonstrated Au plasmas with extraordinary degree of ionization, N-like Au line emission.
- Measured record conversion efficiency optical laser light into picosecond x-ray pulses of up to 20% for $h\nu > 1$ keV
- Measured increased flux and energy of fast electron and ions
- Generated flashes of quasi monoenergetic neutrons from D-D fusion

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Using Facilities supported by LaserNet US



Colorado State University Advanced Beam Laboratory

Work supported by DOE ,AFOSR, and ONR