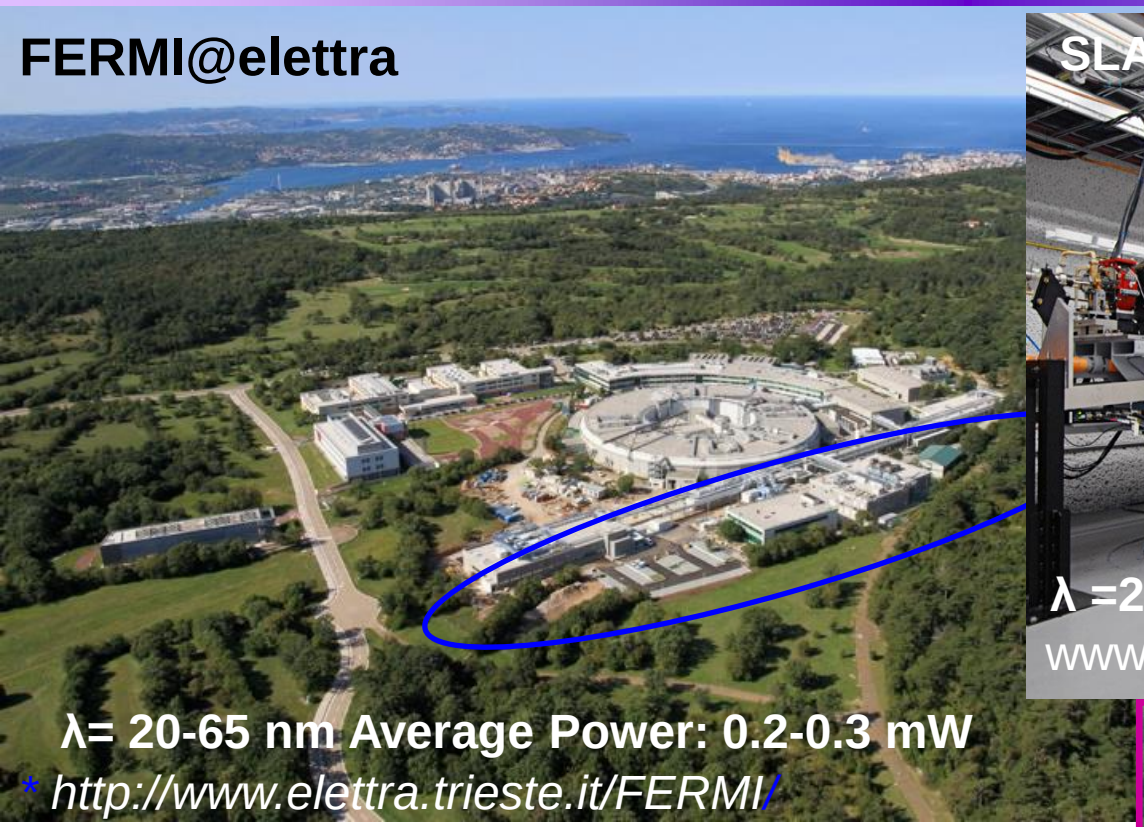
Intense Table-top Generation of Coherent and Incoherent X-ray Radiation from Dense Plasmas

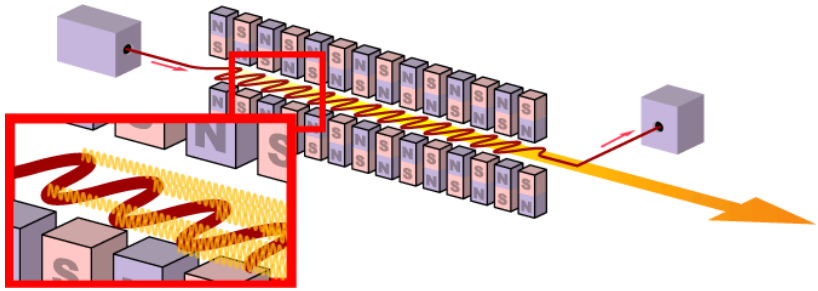
Jorge J. Rocca
Colorado State University
with V. Shlyaptsev and many collaborators

Work Supported thought the years by the the US Department of Energy DTRA, NSF, AFOSR

Intense X-ray sources are enabling tools for Science:

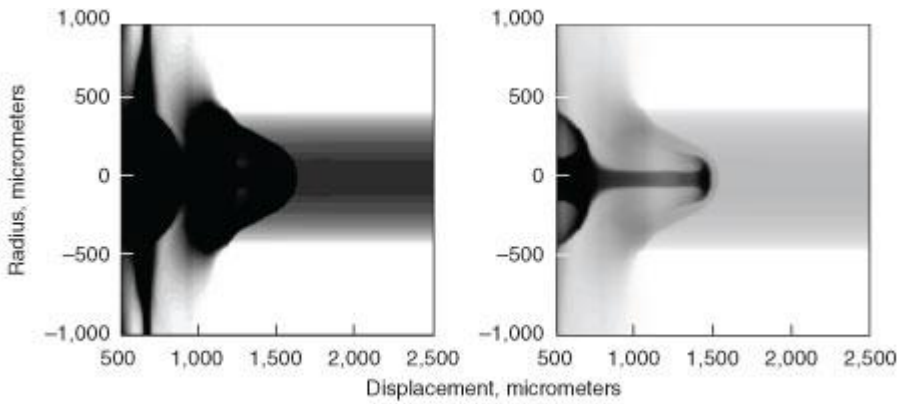
Free-electron lasers generate extremely bright x-ray beams





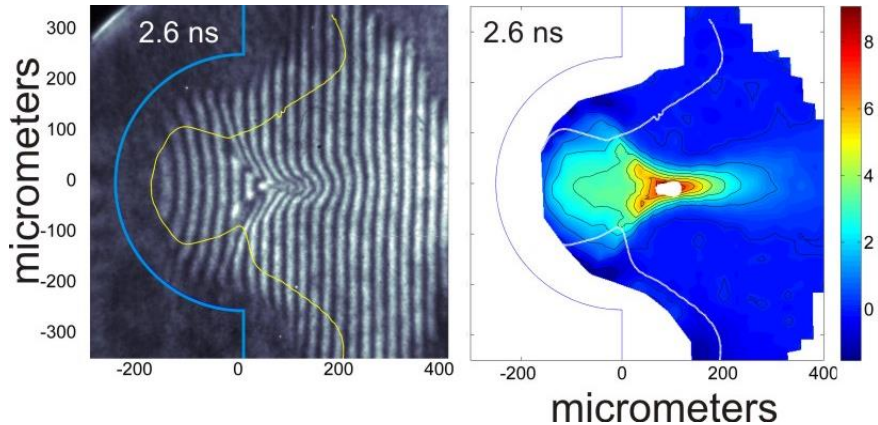
Motivation for plasma-based X-ray sources: Important applications require bright X-ray source on the site of the experiments

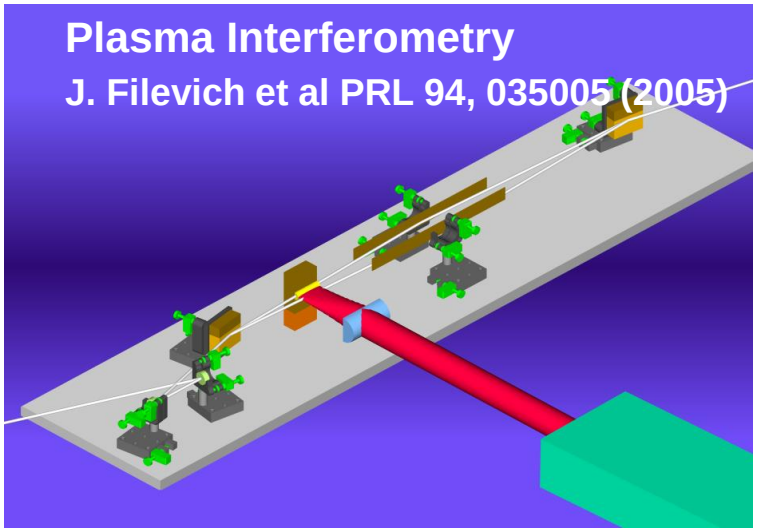
Improved radiography



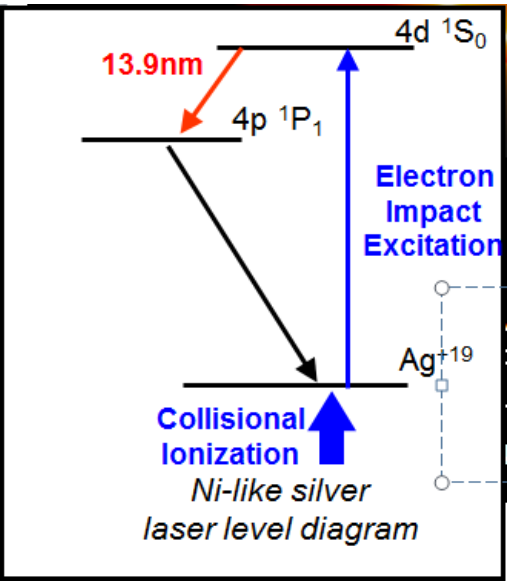
https://str.llnl.gov/Dec11/haefner.html

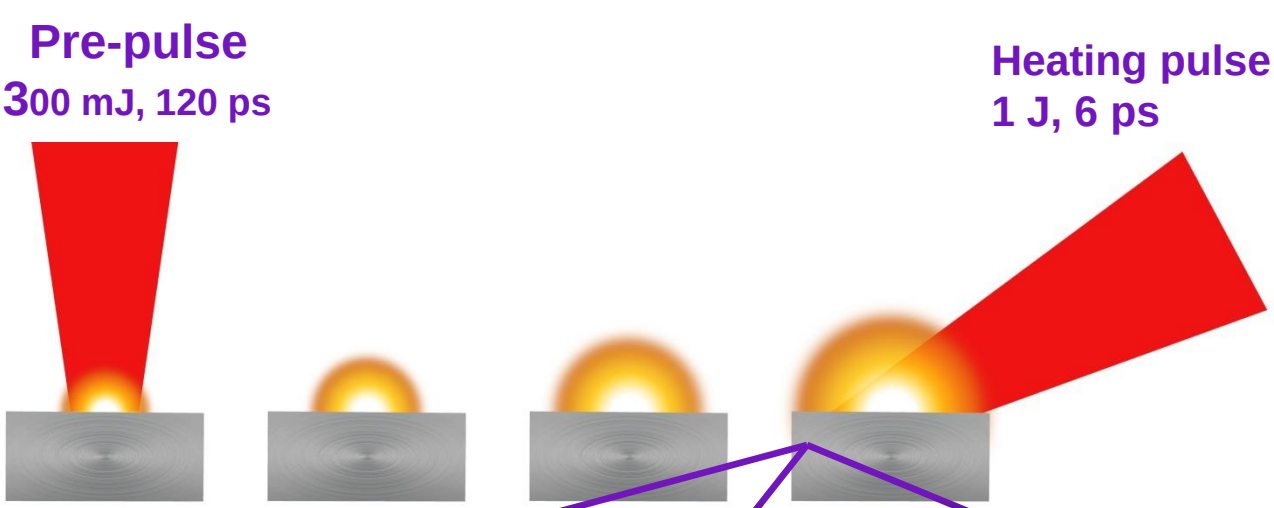
Soft X-ray laser dense plasma interferometry plasmas

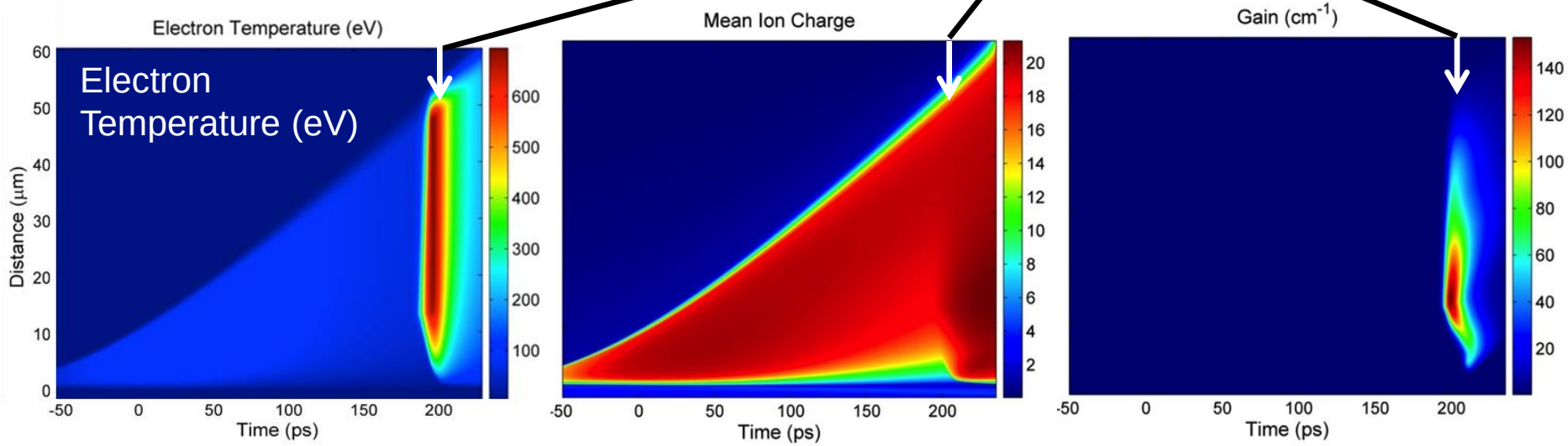




Soft x-ray laser amplification in dense plasmas



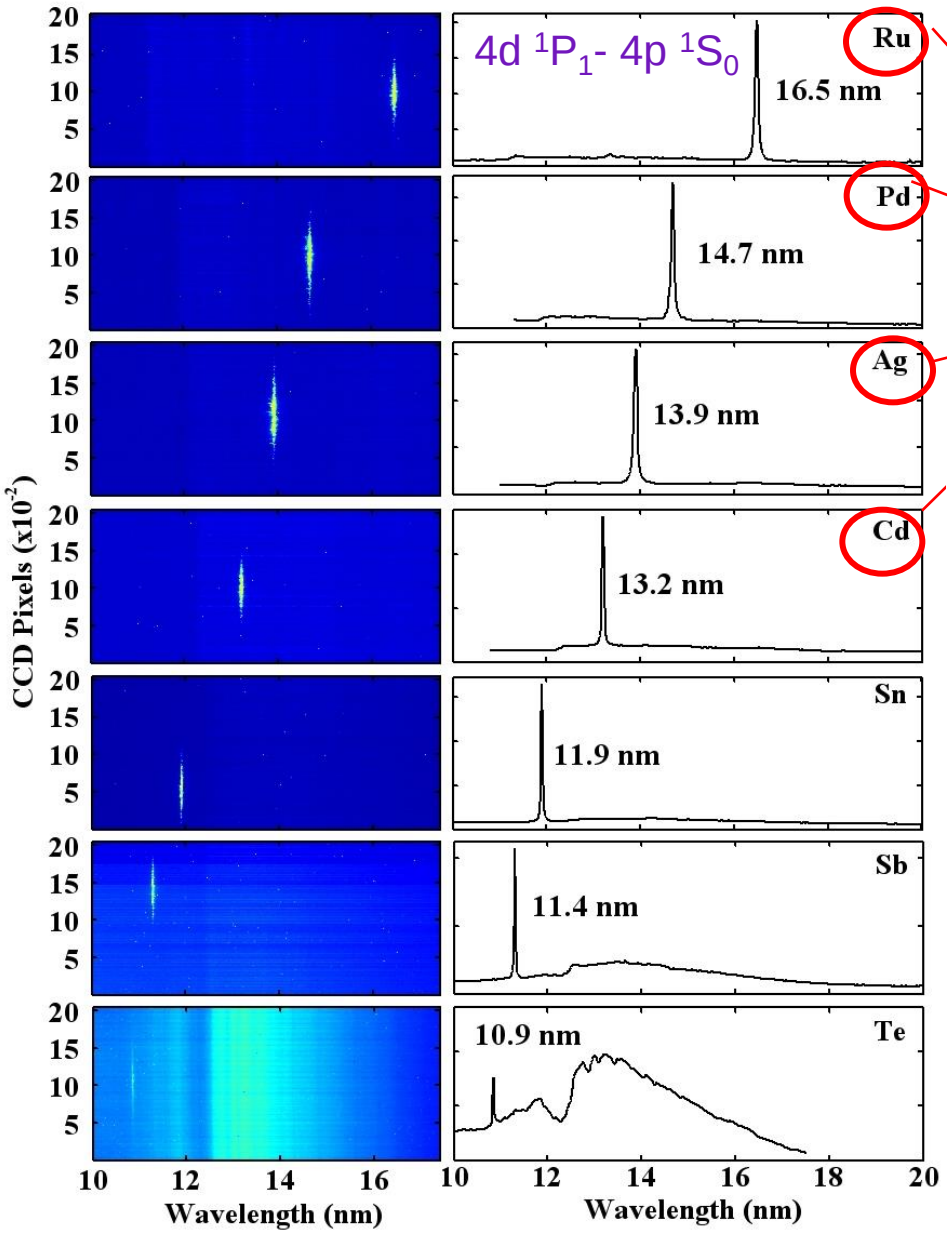




Modeling requires extensive accurate atomic data

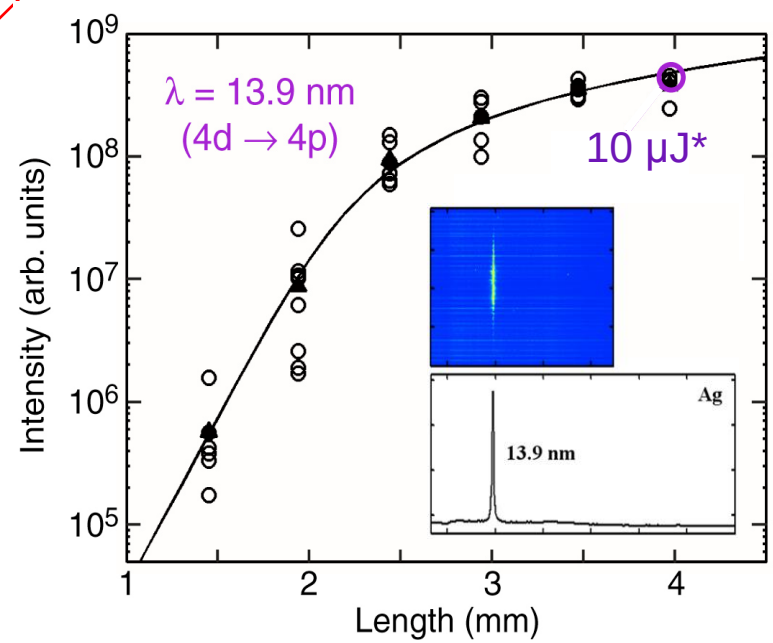
Simulations by Mark Berrill

High repetition rate table-top SXRL in transitions of Ni-like ions down to 10.9 nm



~ 1 J ps pulse excitation

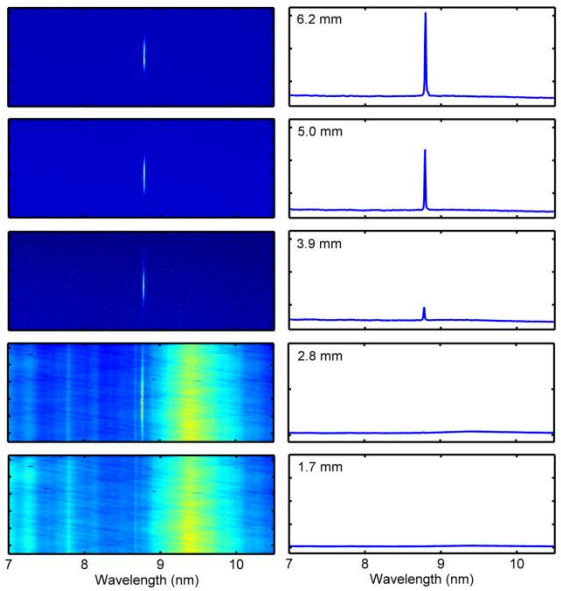
Gain saturated operation demonstrated



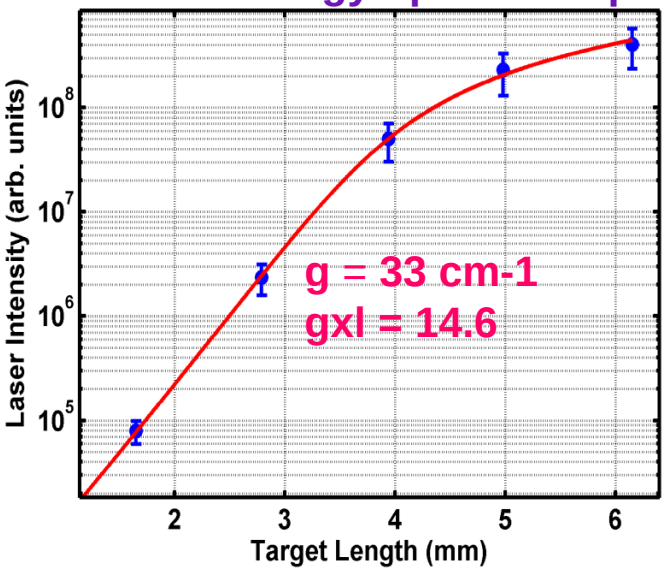
Y. Wang et al, Phys. Rev. A 72, 053807 (2005)
**D. Martz et al. Optics Lett. 35, 1632 (2010)*

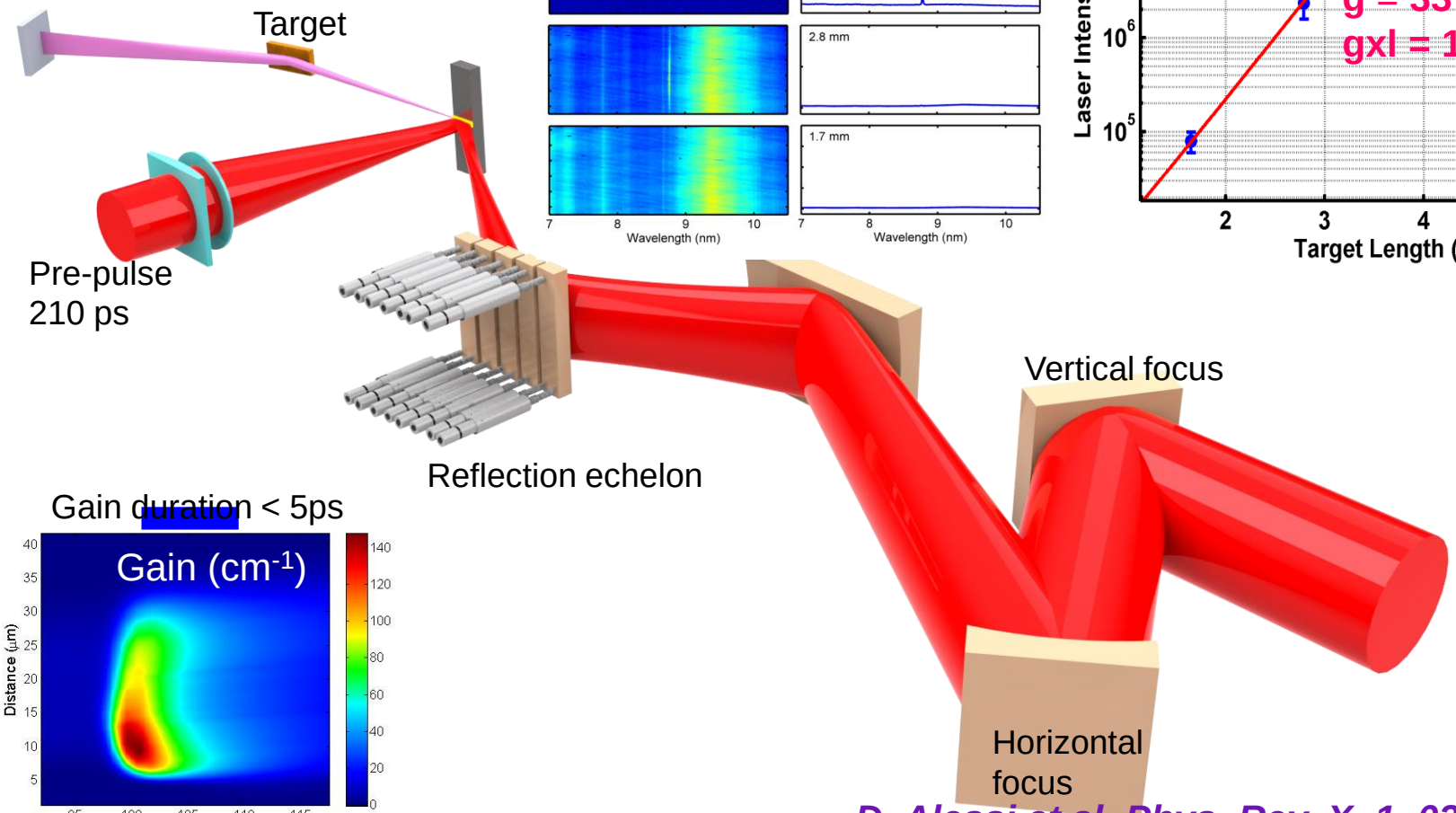
Gain-saturated table-top laser at 8.8 nm

Ni-like Lanthanum
$4d^1S_0$- $4p^1P_1$



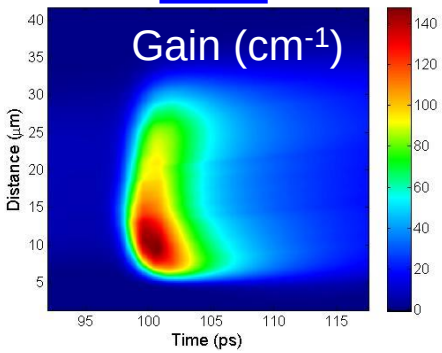
Pulse energy up to ~ 2.7 μJ





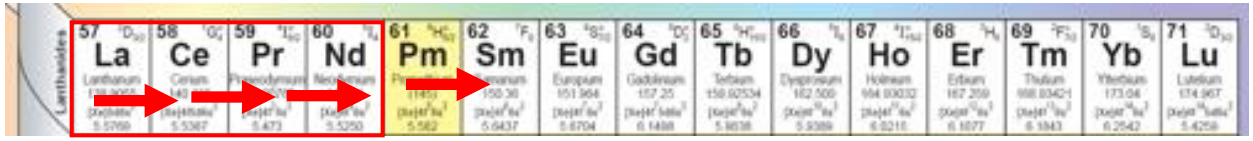
4.5 J, 2 ps

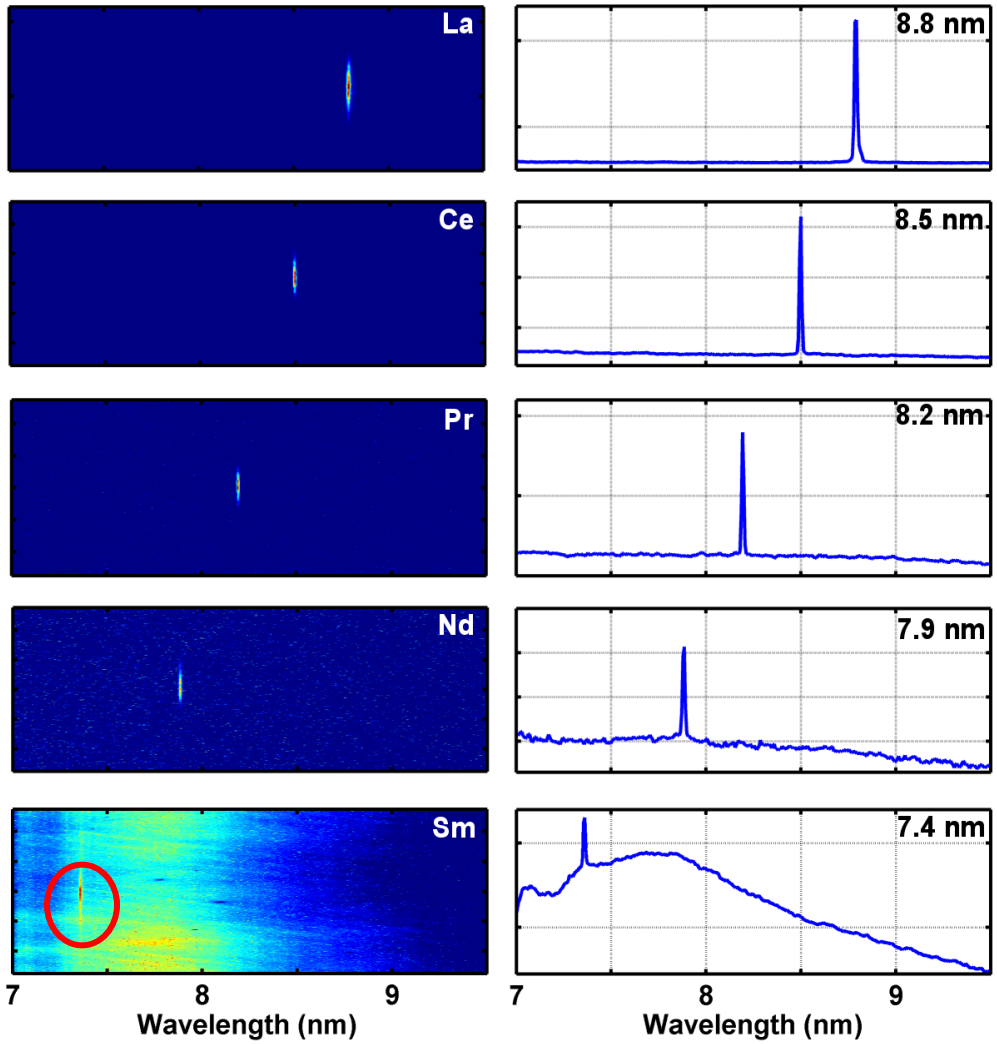
Gain duration < 5ps



D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

Extension of table-top SXRL to sub-10 nm wavelengths using lanthanide ions

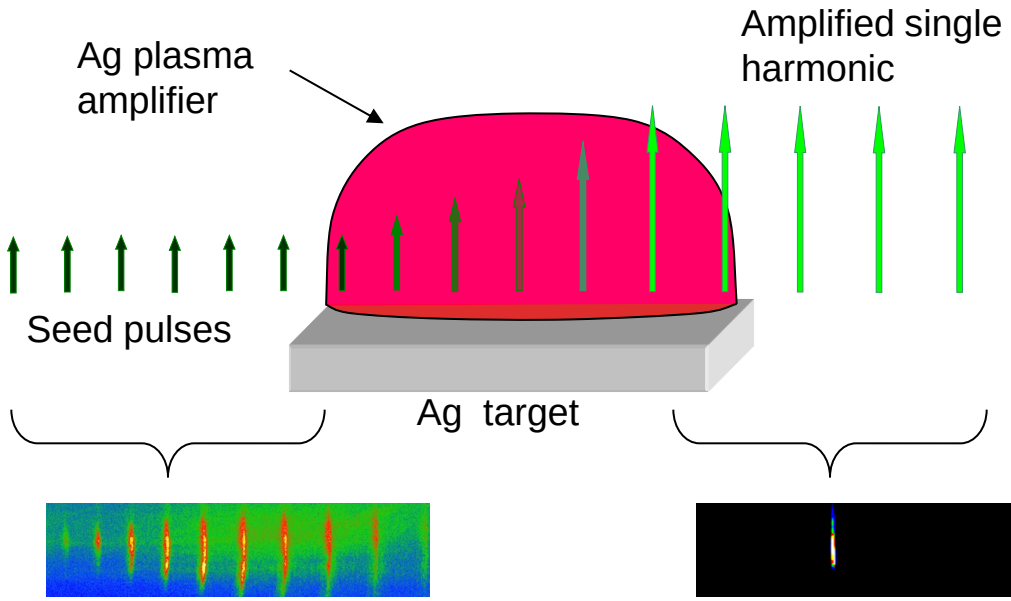




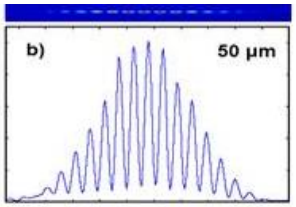
Nickel-like lanthanide ions $4d^1S_0$- $4p^1P_1$

D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

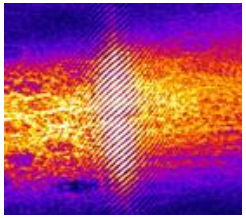
Injection-seeding SXR Lasers have full phase-coherence and shorter pulse width



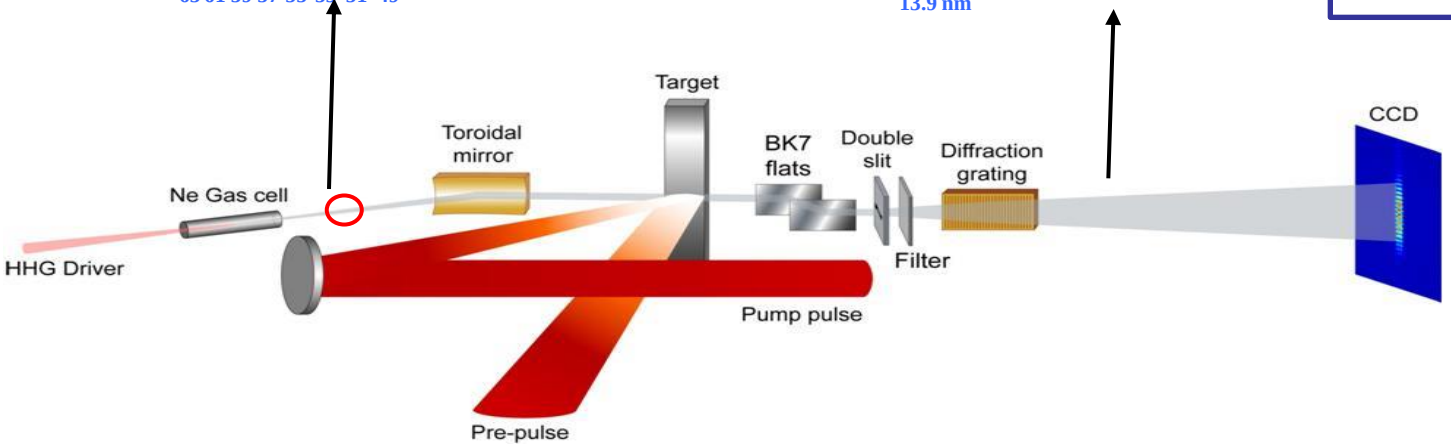
Full spatial coherence

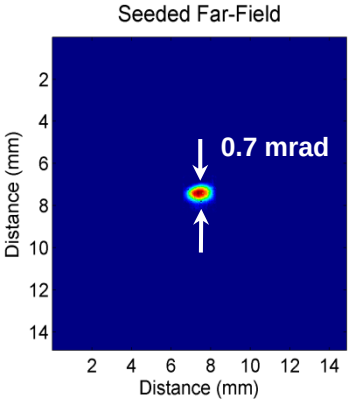


Full temporal coherence



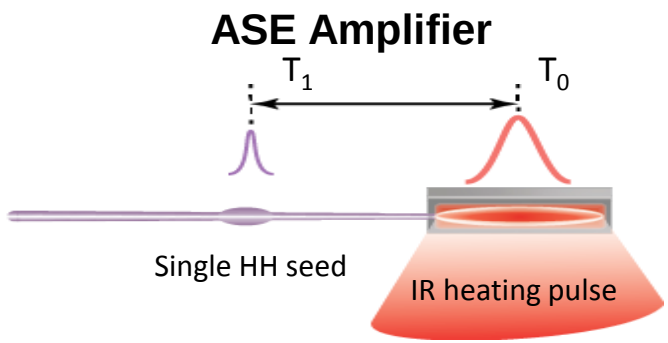
Shorter pulsewidth
(1.13±0.47)ps

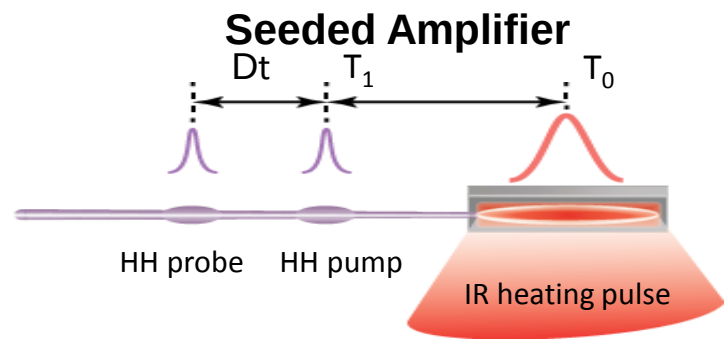


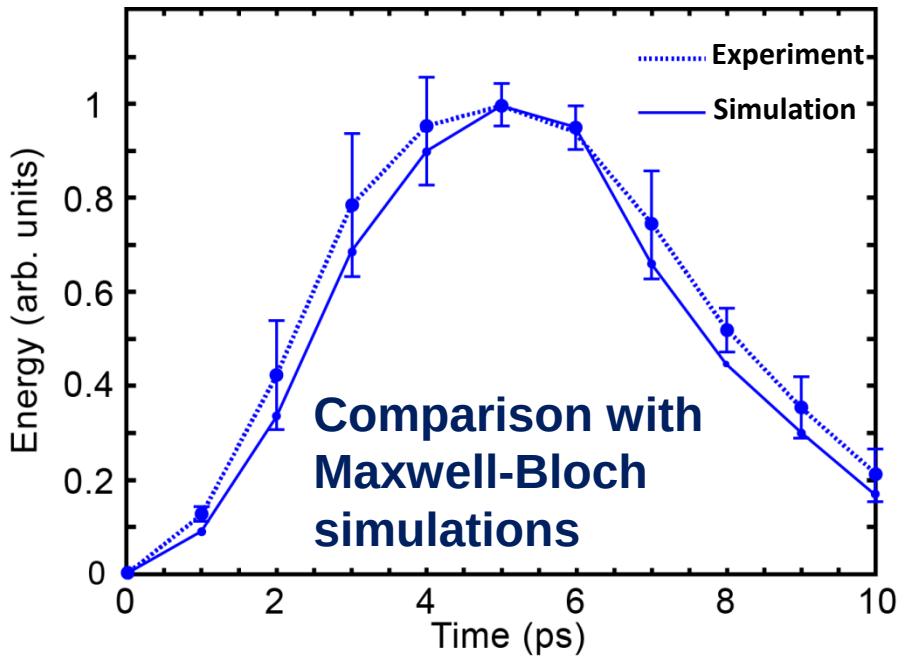


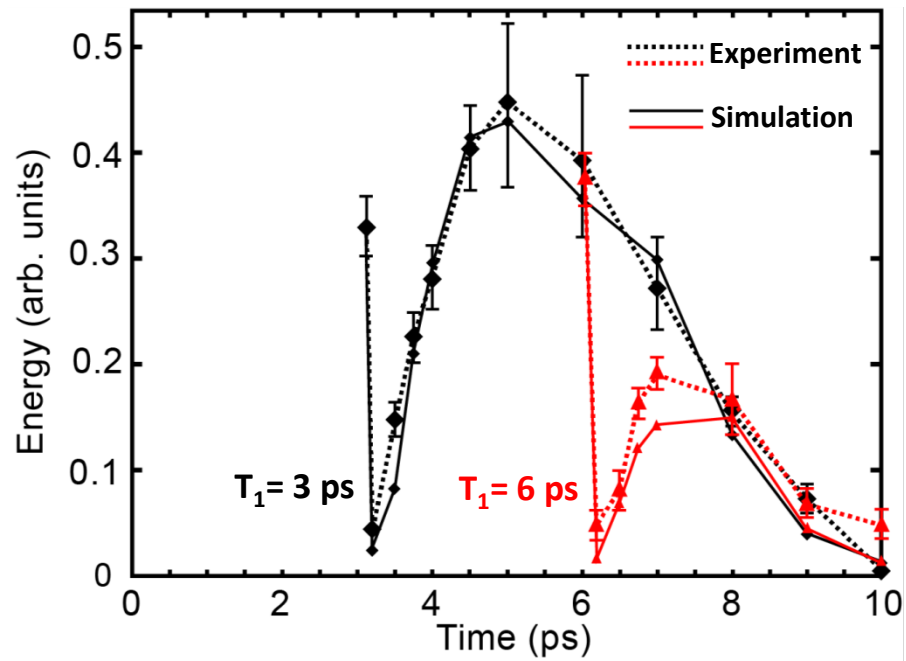
T. Ditmire et al. Phys. Rev. A. ***51****, R 4337, (1995); P. Zeitoun et al. Nature,* ***431****, 427, (2004) ;*
Y. Wang et al. Phys. Rev. Lett, ***97****, 123901 (2006) Y. Wang et al. Nature Photonics,* ***2****, 94, (2008)*

Pump-probe measurement of ultrafast population dynamics and gain in a SXRL plasma amplifier









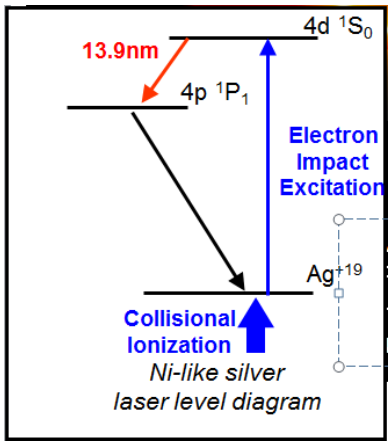
- **Following amplification of seed pulse the gain fully recovers in 1.5-1.75 ps**

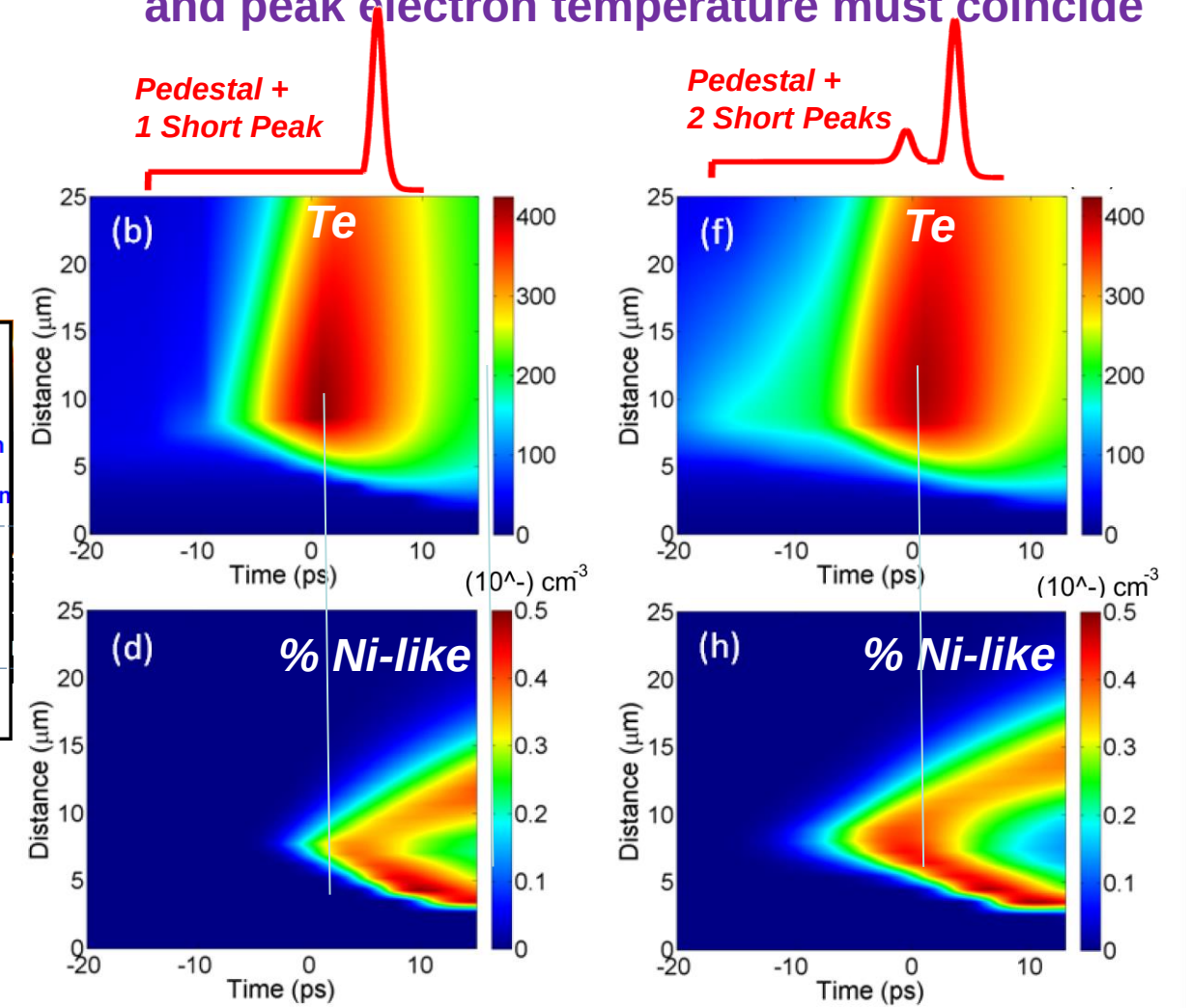
Y. Wang et al. Nature Photonics, 8, 381, (2014)

- **Result open possibility of CPA in soft x-ray plasma amplifier for ultra-bright fully coherent pulses.** *E. OLiva et al. Nature Photon.ics, 6, 766, (2012)*

SXRL efficiency can be significantly increased by tailoring the plasma generation

For maximum SXRL efficiency the time of peak Ni-like ion abundance and peak electron temperature must coincide

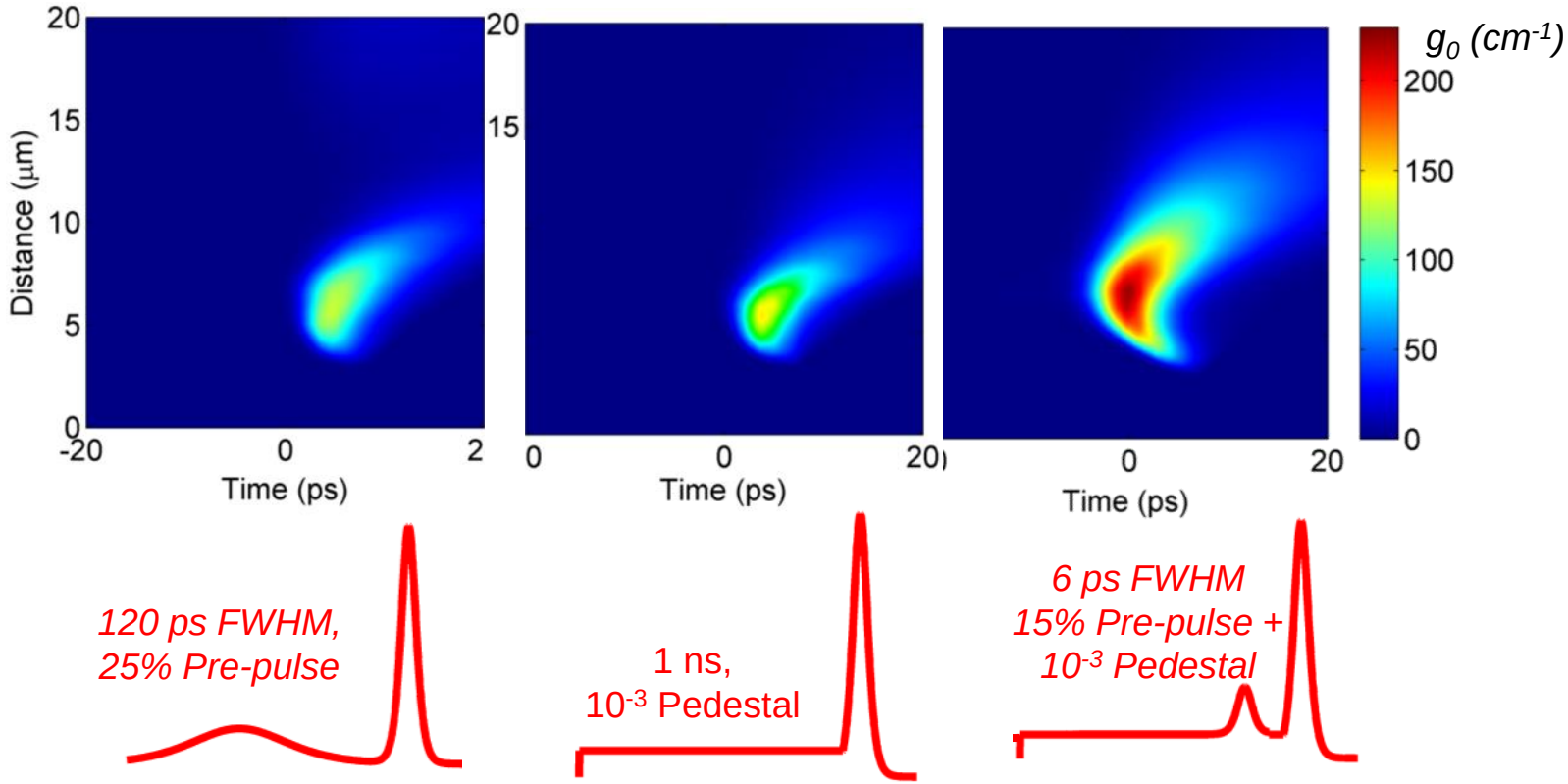




2-D hydrodynamic plasma amplifier model with detailed atomic physics

Pump laser pulse-shaping increases SXRL amplifier gain

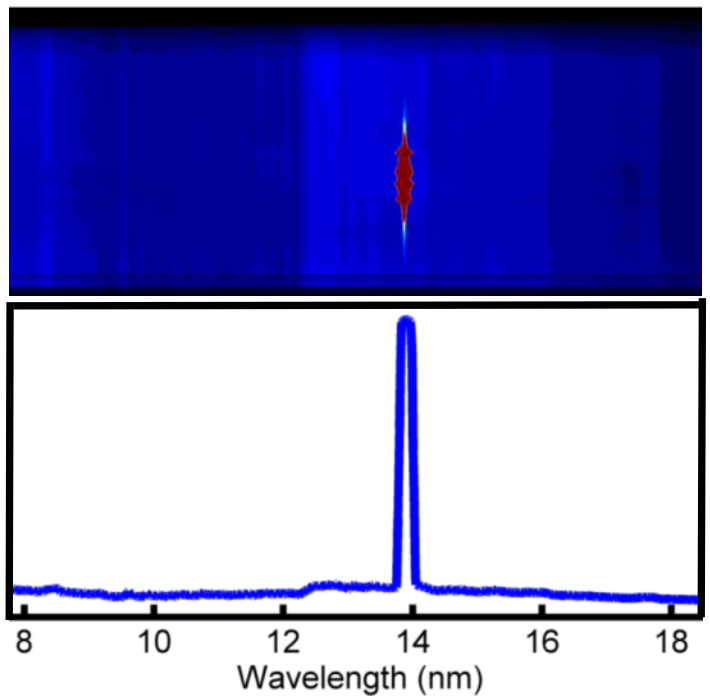
Simulated λ = 13.9nm small signal gain

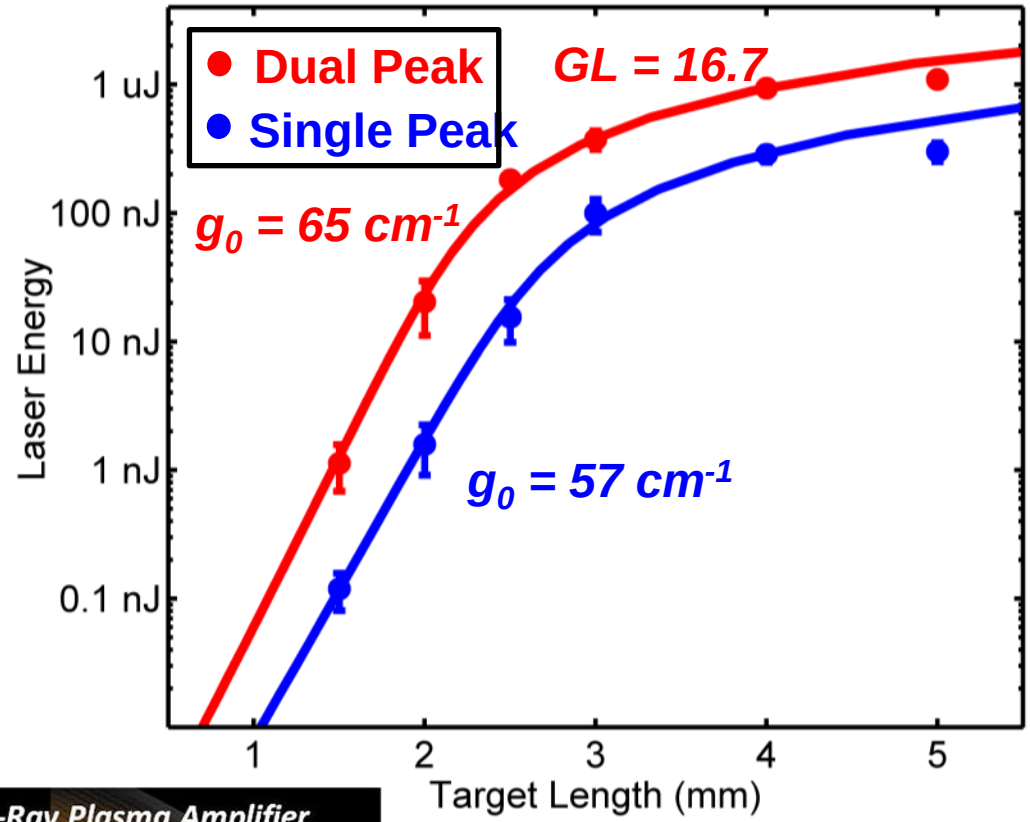


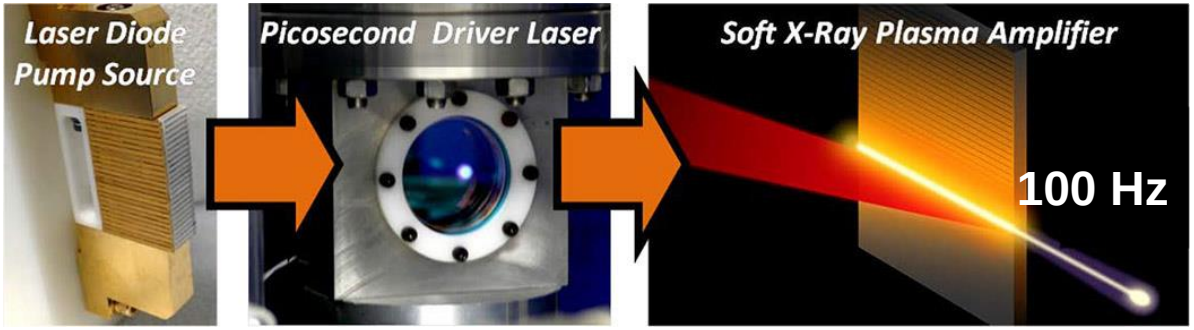
Short pre-pulse combined with low intensity pedestal results in a stronger amplification, longer gain duration and larger gain cross section

Gain-Saturated, λ = 13.9 nm Laser at 100 Hz Repetition Rate

3x λ = 13.9nm laser energy enhancement



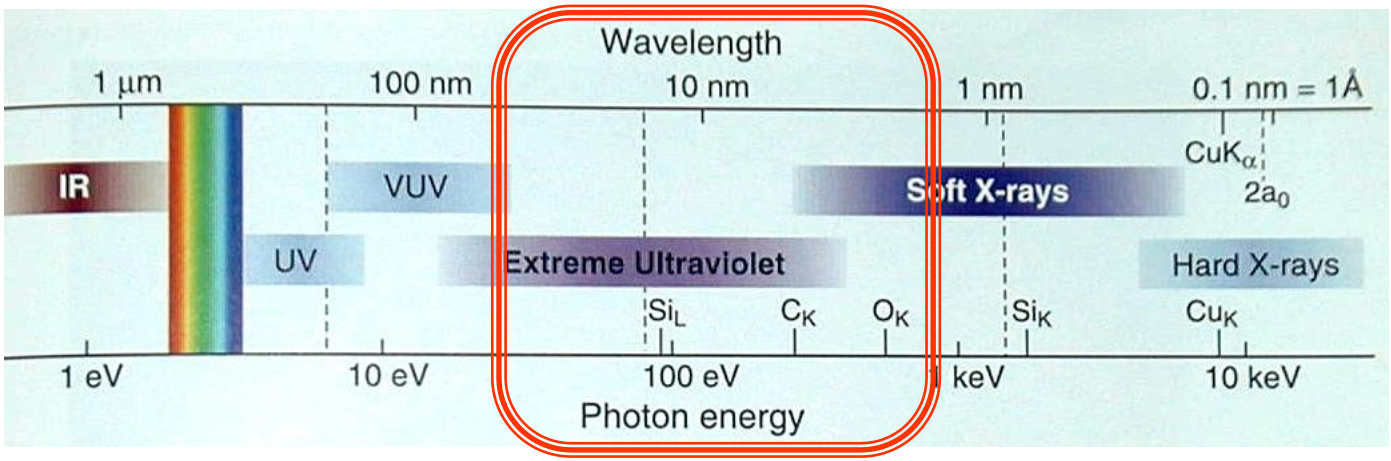


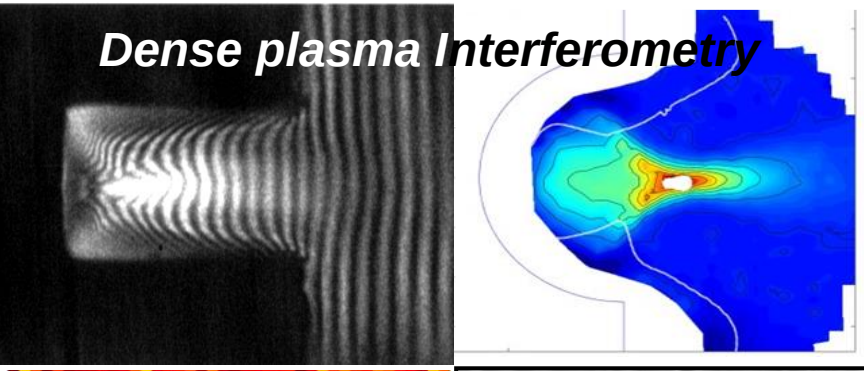


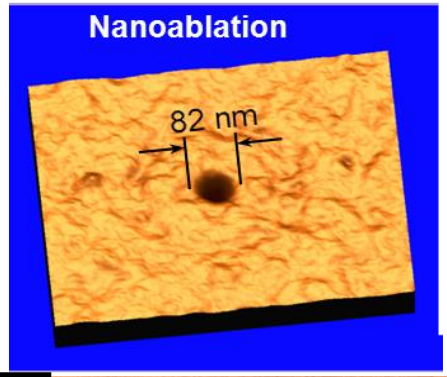
0.1 mW Average Power

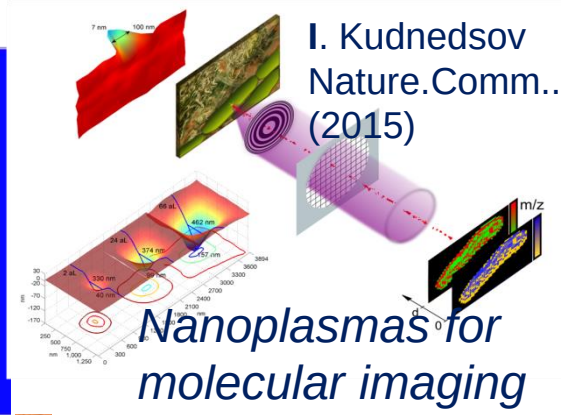
B.A. Reagan et al., Phys. Rev. A 89 , 053820, (2014).

Impact Inside and Outside Research Field: Intense soft x-ray laser beams can probe dense plasmas and explore/shape the nanoworld

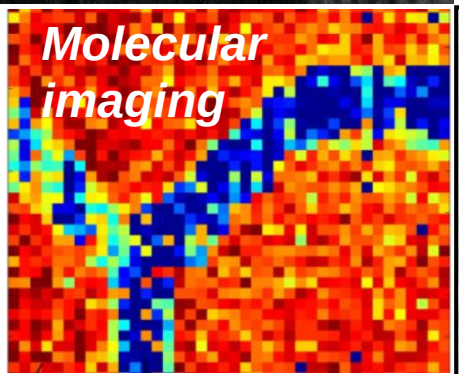


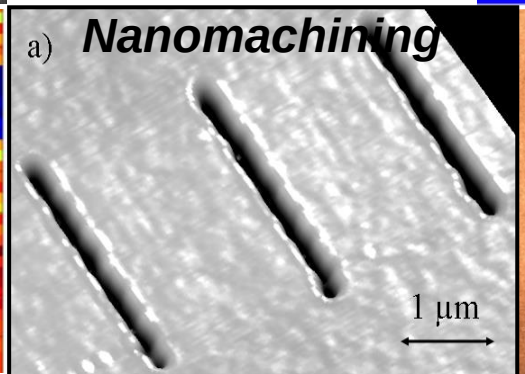


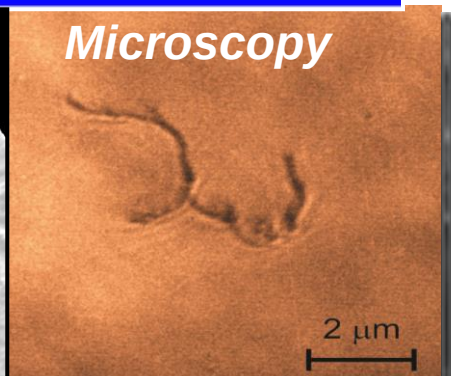


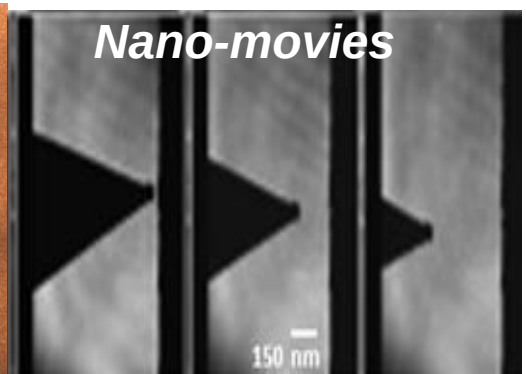


I. Kudnedsov Nature.Comm.. (2015)









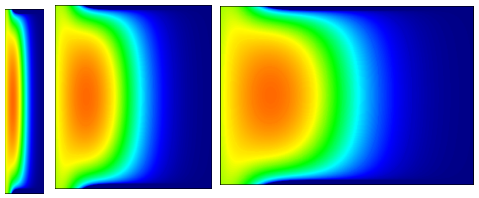
Bright incoherent X-ray sources: high X-ray yield requires simultaneous *high density and large plasma size*

Colorado State University

Radiative lifetime < Hydrodynamic time

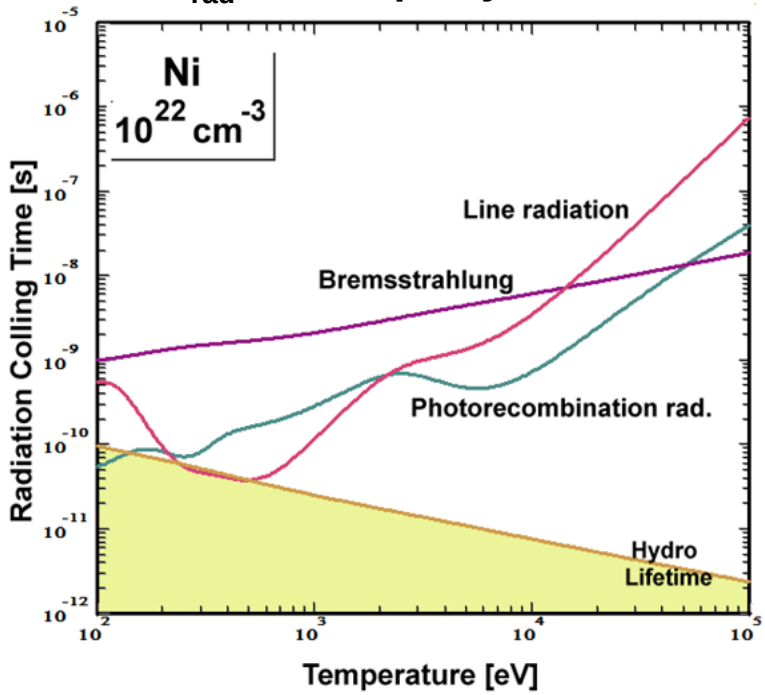
$$\tau_{rad} \propto \frac{1}{N_e} < \frac{\Delta L}{C_s} \propto \tau_{hydro}$$

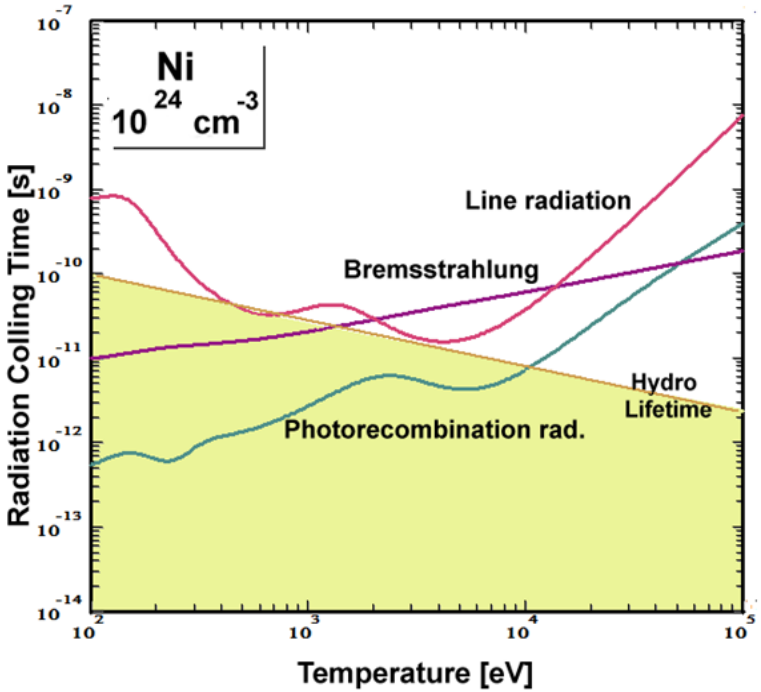
Large Plasma Density **Large Plasma Size**



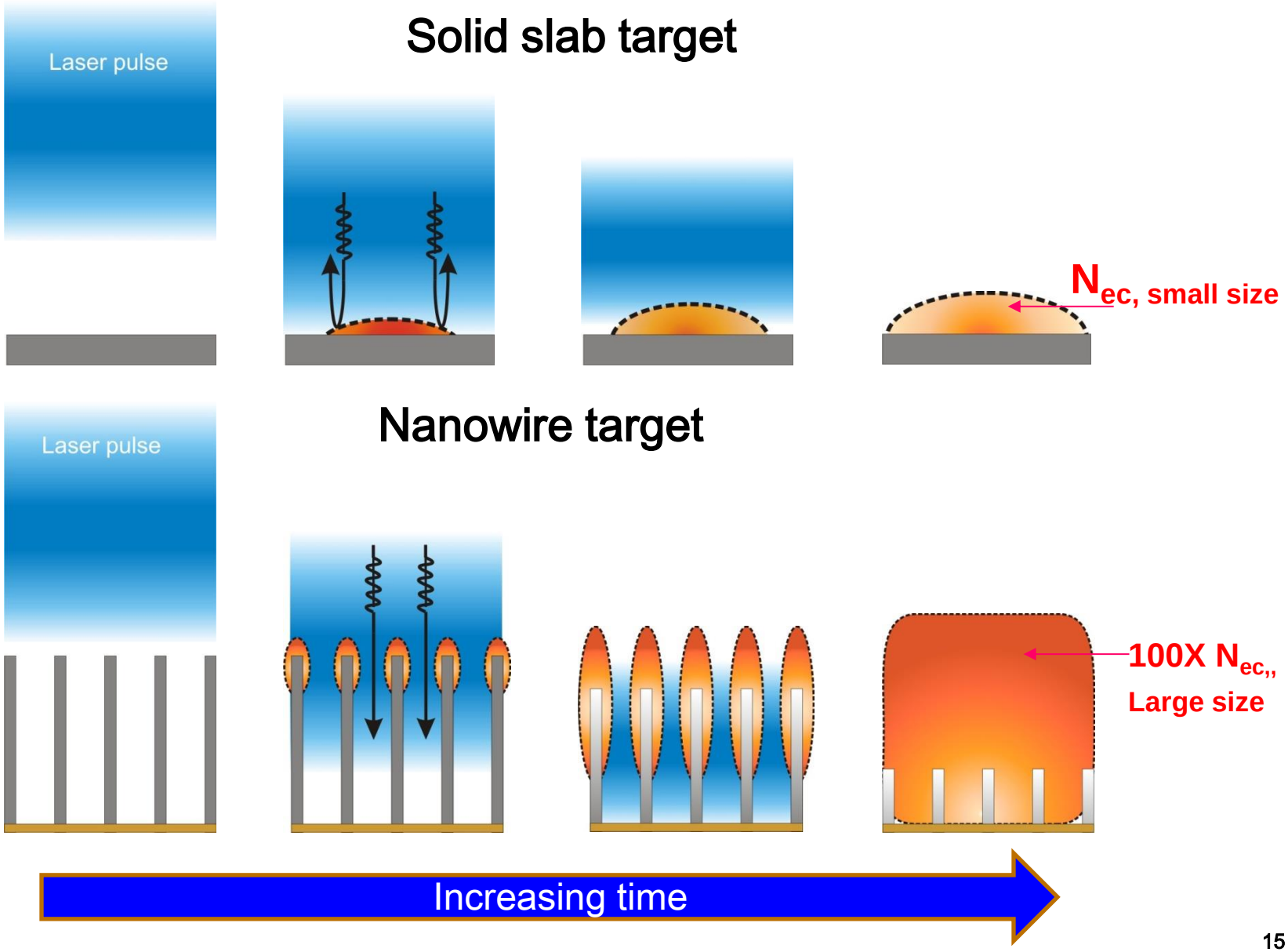
At 10^{24} cm^{-3} radiation cooling time decreases up to 100 X

τ_{rad} < 5-15 ps hydro lifetime ➔ high x-ray conversion efficiency



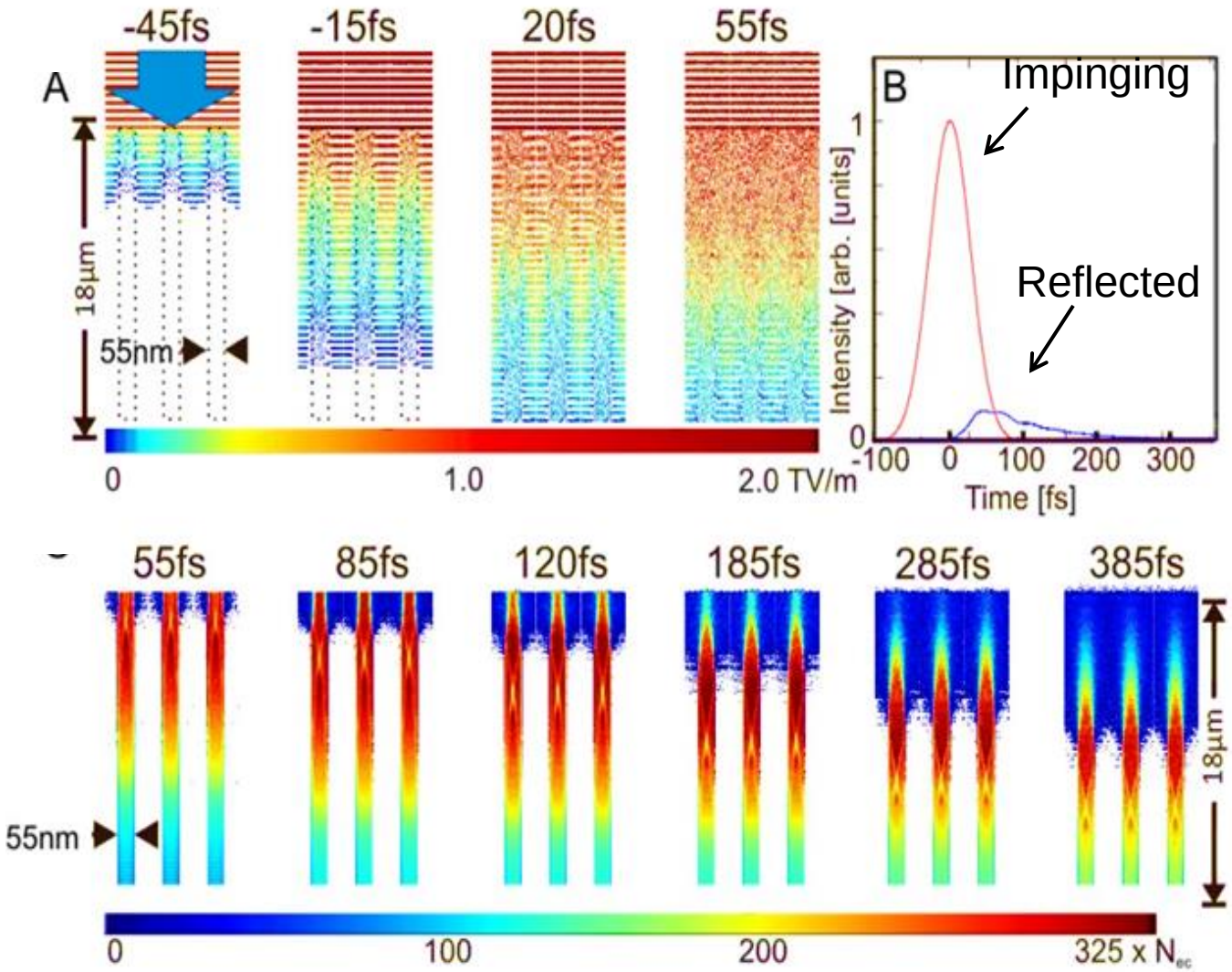


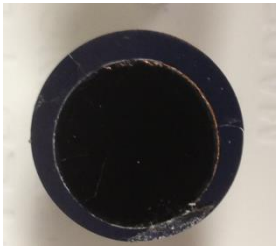
Plasma density and size can be both increased simultaneously > 100 X by irradiating aligned nanowire arrays with intense femtosecond laser pulses



PIC simulations show heat penetrates depths of several µm creating multi- KeV temperature plasmas with densities up to 100 X critical

Intensity: 5 x 10 ^{18} W cm^{-2} , 55 nm diameter wires, 0.12 solid density target

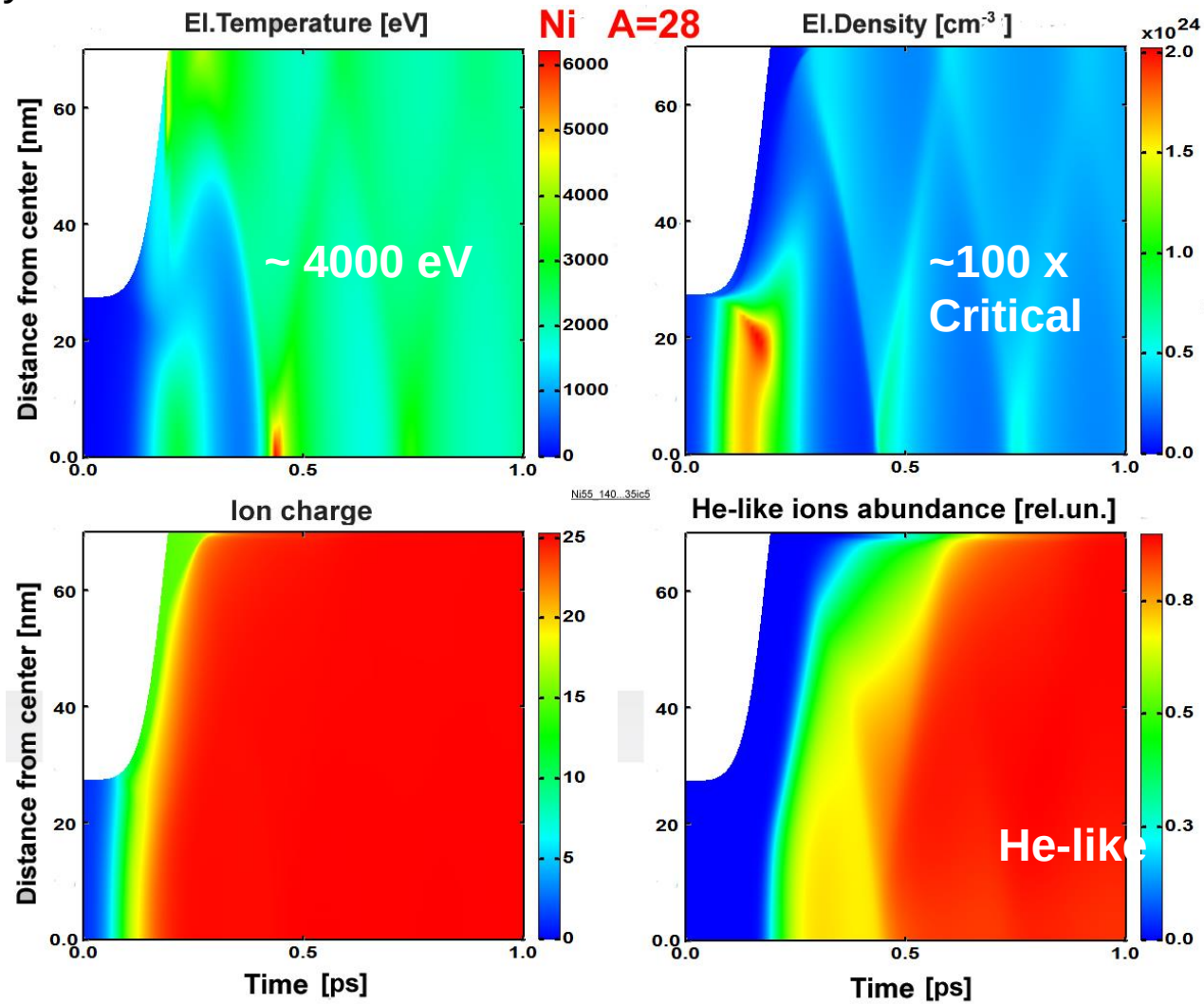




PIC simulation: A. Pukhov

Simulations predict volumetrically heated super-critical Ni plasmas ionized to He-like stage

Intensity: 5 x 10 ^{18} W cm^{-2} , 55 nm diameter wires, 0.12 solid density target



Simulations V.N Shlyaptsev

Experiment at CSU's Ti:Sapphire laser

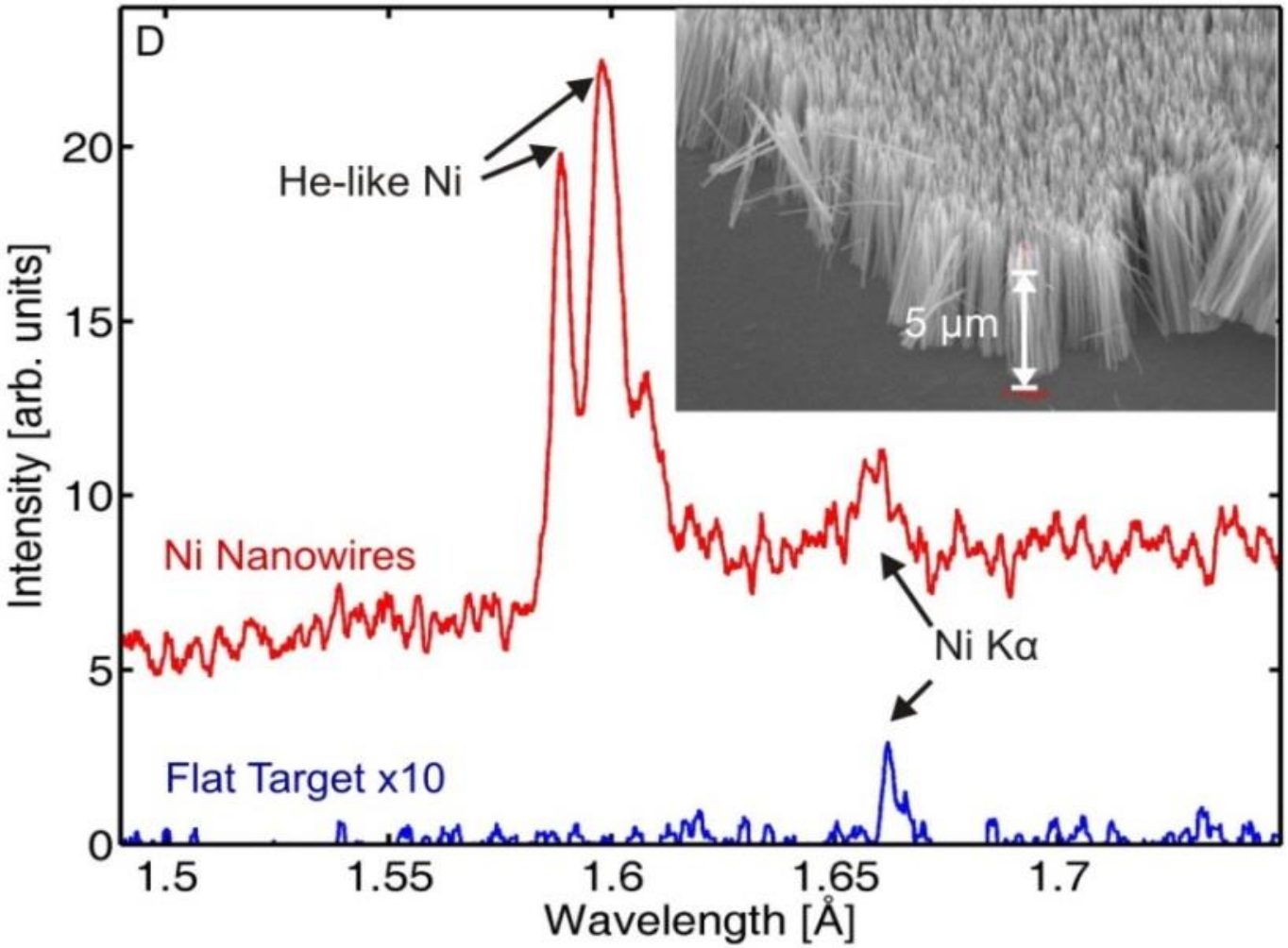
Experiments with 0.5 J (2ω) , 50-60 fs laser pulses

Laser upgraded to 32 J before compression

Ni nanowire array 12% solid density at 5 x 10 ^{18} W cm^{-2}

Irradiation with 0.5. J , 60 fs

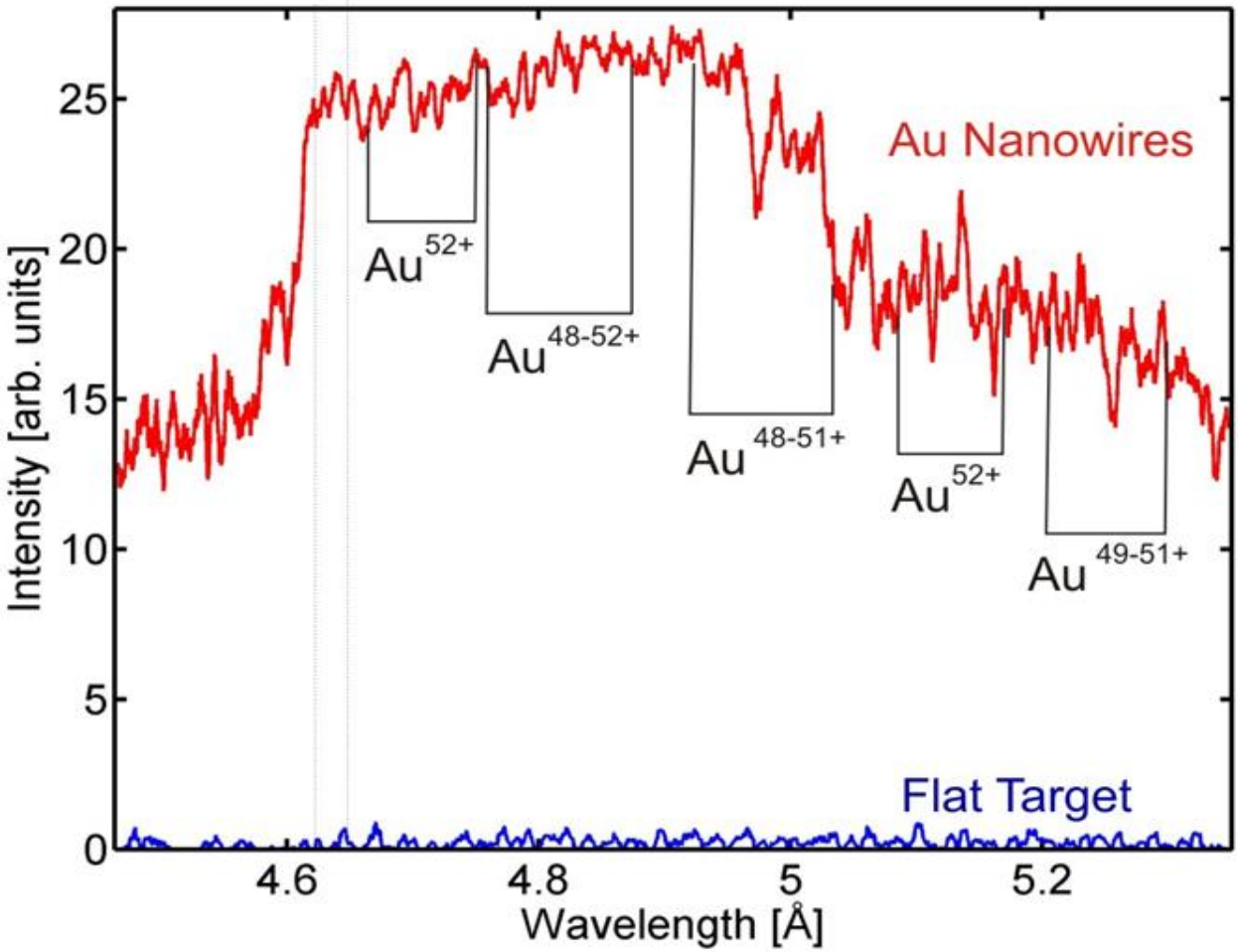
Nickel- Heα emission exceeds Kα

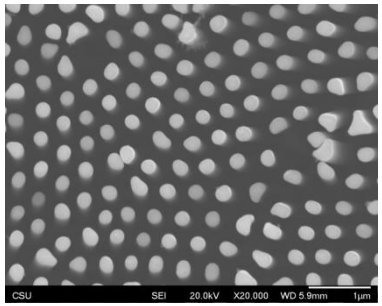


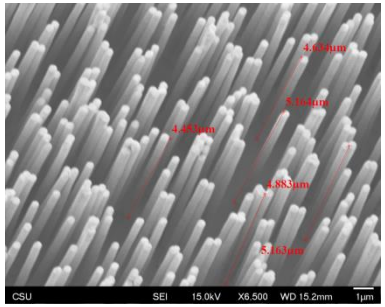
M. Purvis et al. *Nature Photonics 7,796, (2013)*

Gold ionized to Au^{+48-52}

5×10^{18} W cm^{-2} , 0.12 solid density target





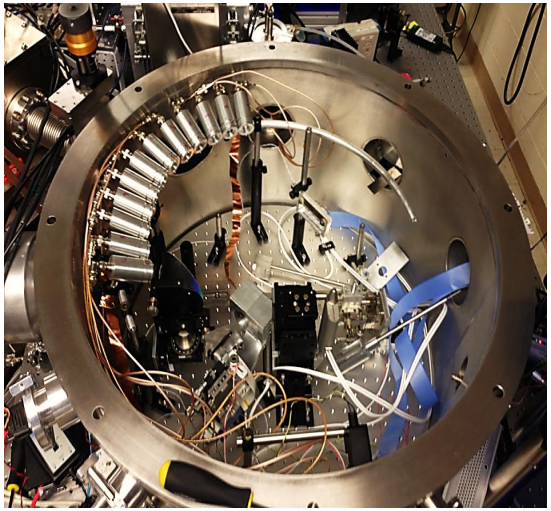


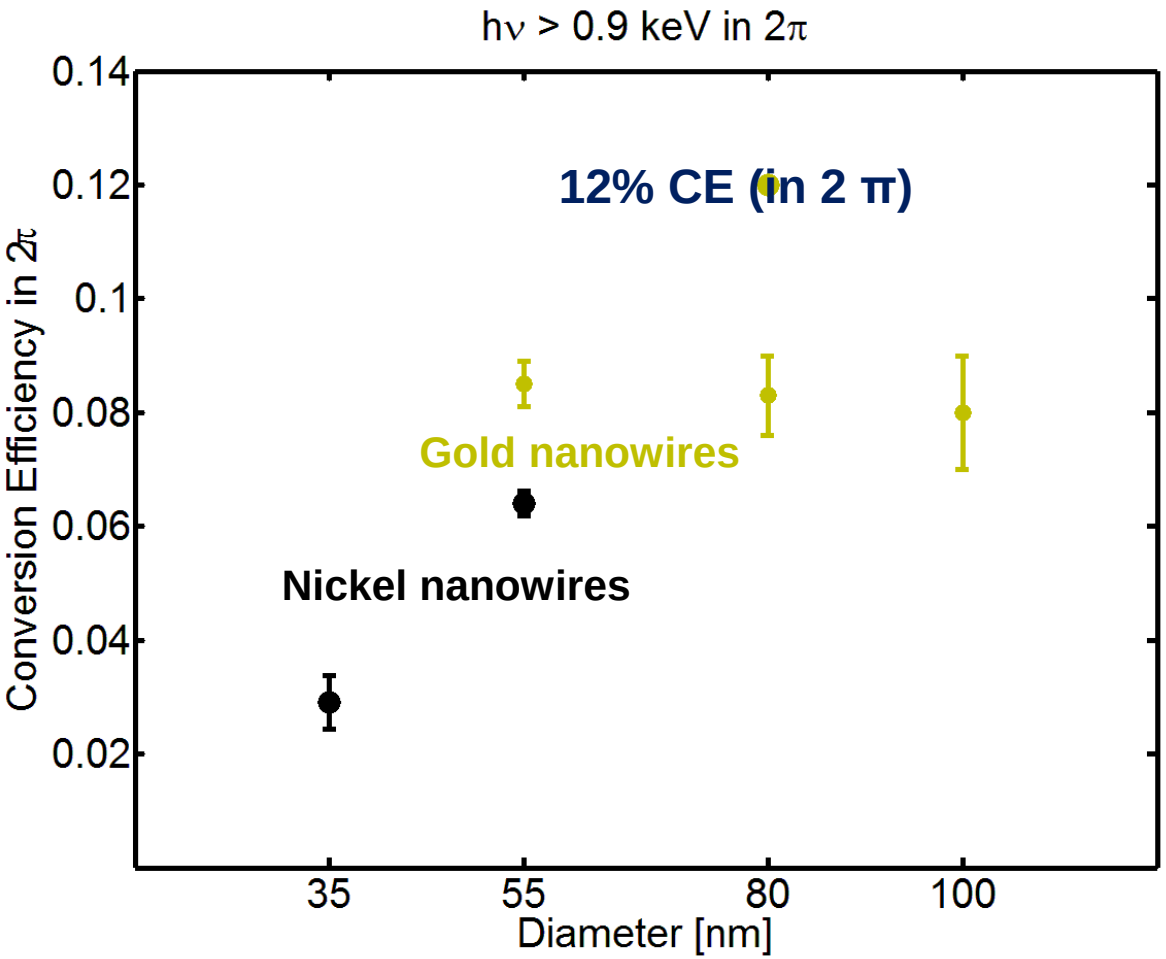
M. Purvis et al. *Nature Photonics*, ***7***,*796, (2013)*

Very High Conversion efficiency into > 1 KeV X-Rays

Irradiation intensity 2 x 10 ^{19} W Cm^{-2}

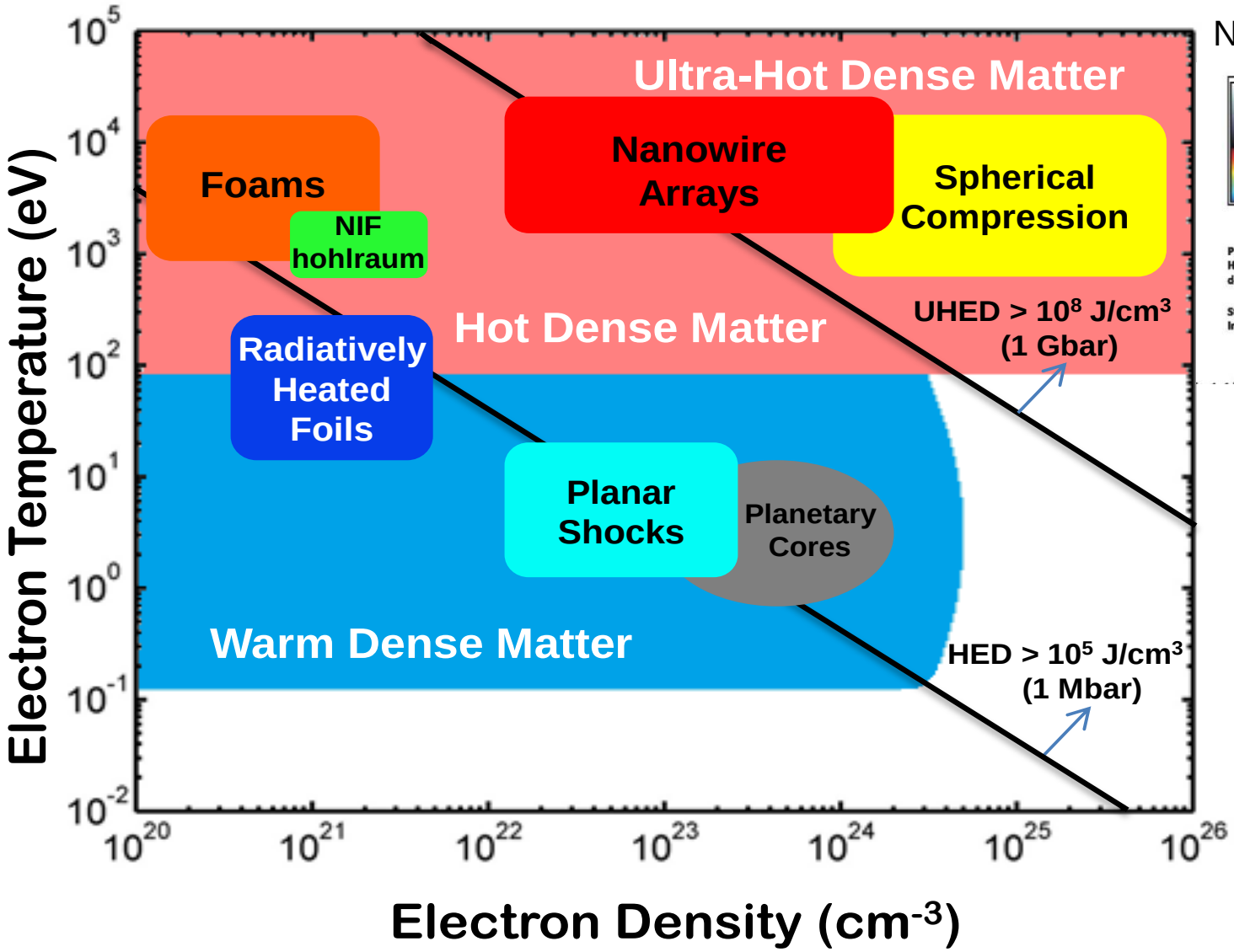
CE > 8 percent, with individual shots up to 12 % CE into 2π



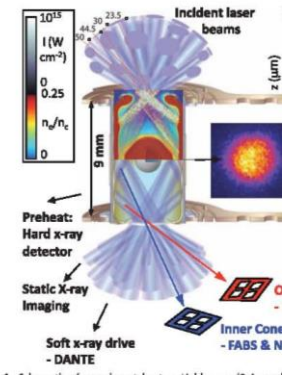


Creation of ultra-hot dense matter

Ultra High Energy Density (UHED) Plasmas



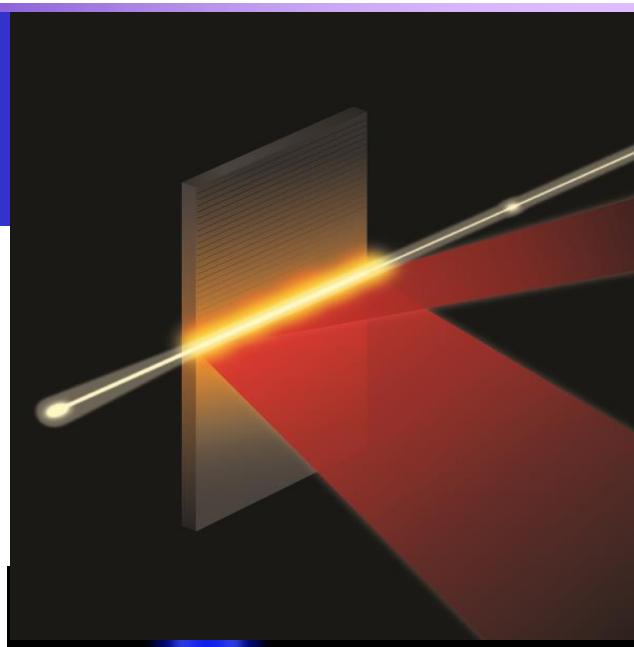
NIFcompression



S. Glenzer et al Science (2010)

Conclusions and Prospects

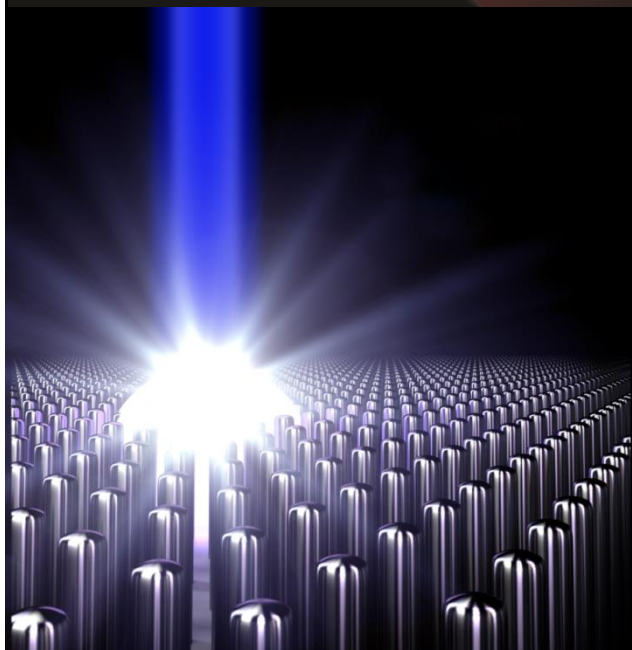
Plasmas can be tailored into bright sources of coherent and incoherent X-rays : enabling tools for plasma science and other fields



Current Status

- **Table top SXR Lasers down to 8 nm (gain saturated)**
- **100 Hz repetition rate, 0.1 mW, @ λ=13.9 nm**
- **Incoherent ps keV x-rays efficiently generated from volumetric heating of ordered nanostructures:**

  a new UHED regime (100 x ne_c, keV temperatures)



Frontiers:

- **Sub- 5 nm table-top x-ray lasers**
- **Femtosecond table-top x-ray lasers**
- **Fully coherent table-top SXR Lasers with average powers similar to present SXR FELs**
- **X-ray conversion efficiency into picosecond incoherent pulses > 80%**
- **Tools needed: High energy ultrashort pulse high repetition rate lasers**

Collaborators

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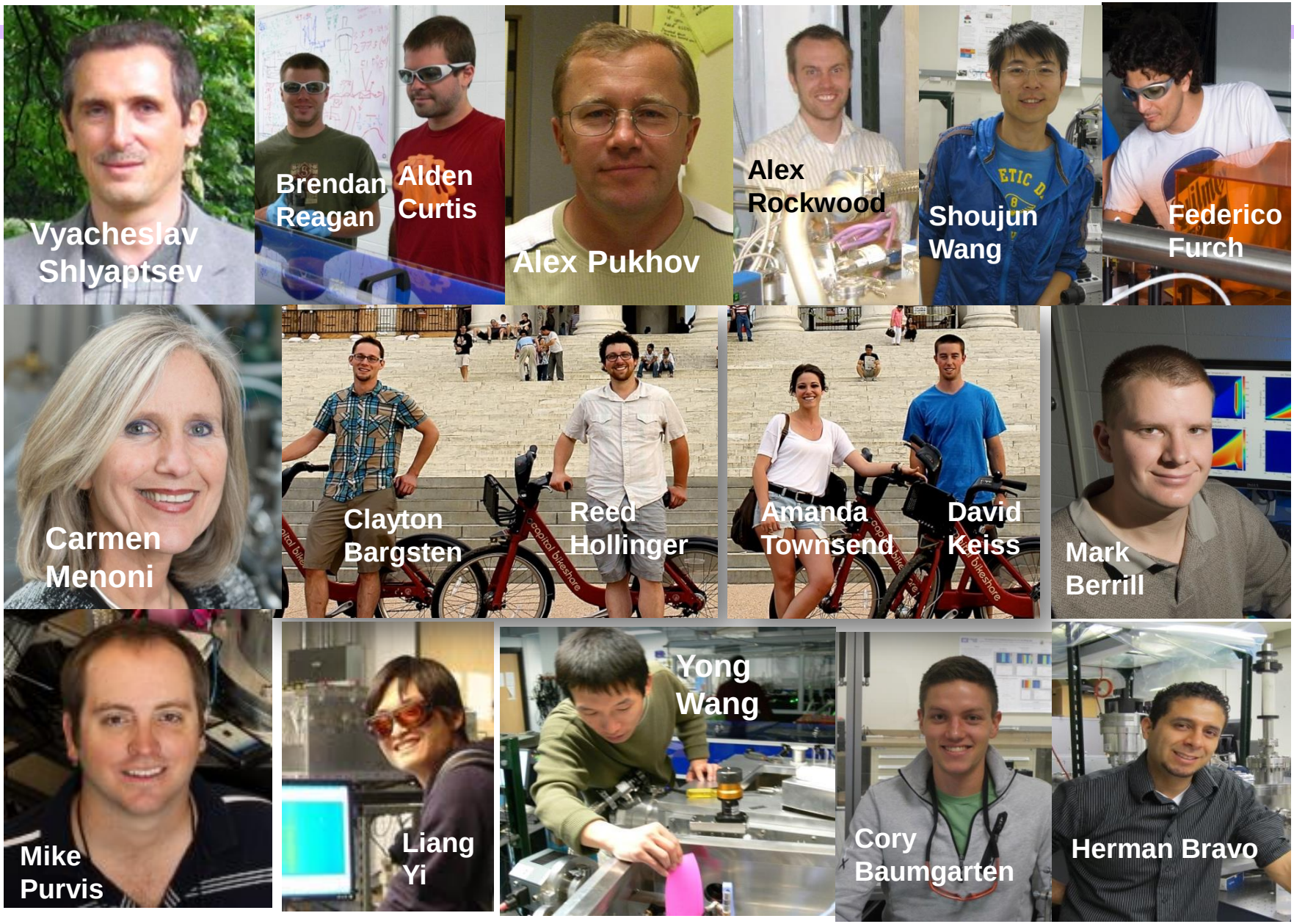
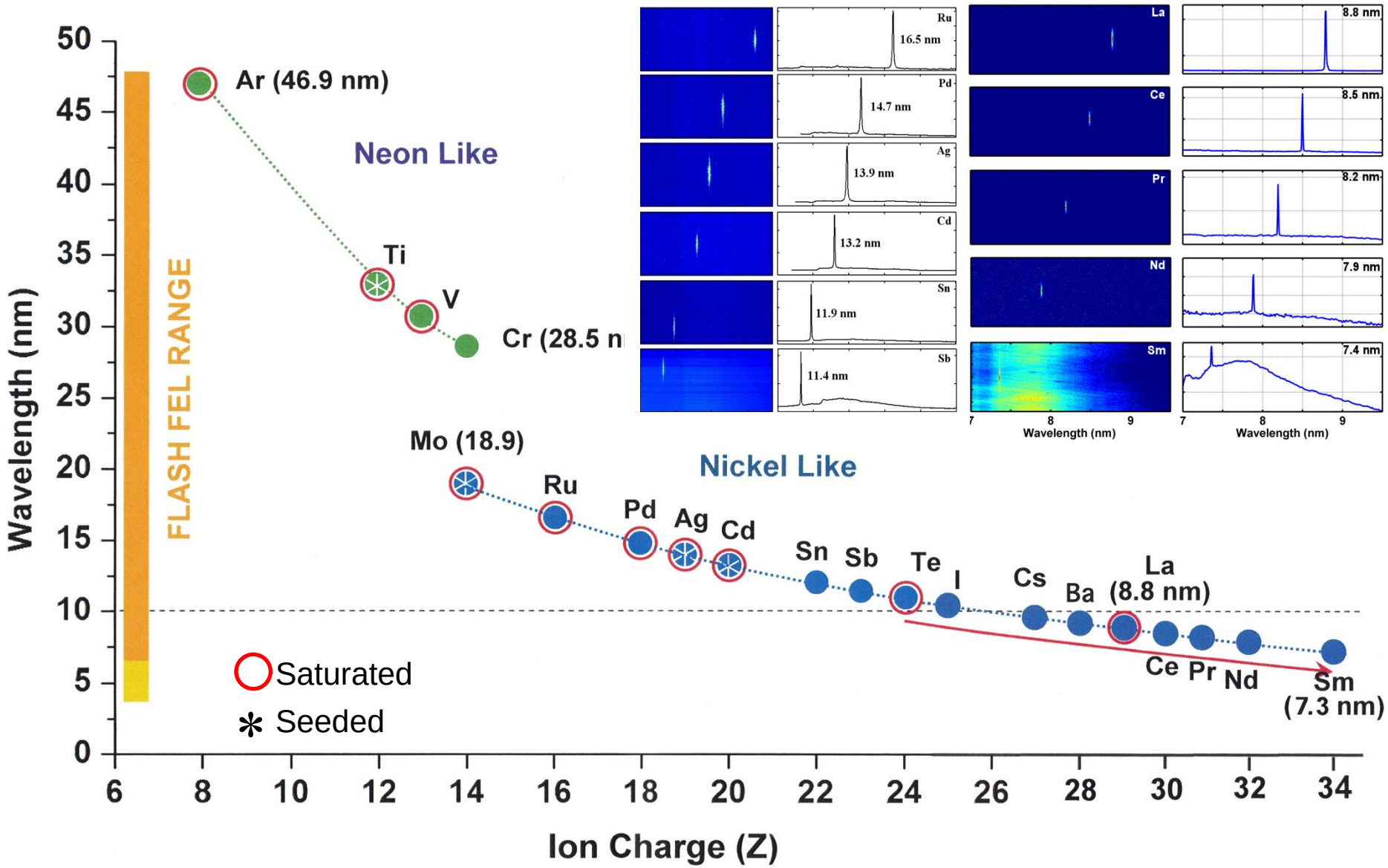
Work Supported thought the years by DOE, NSF, DTRA, AFOSR

Contributors:

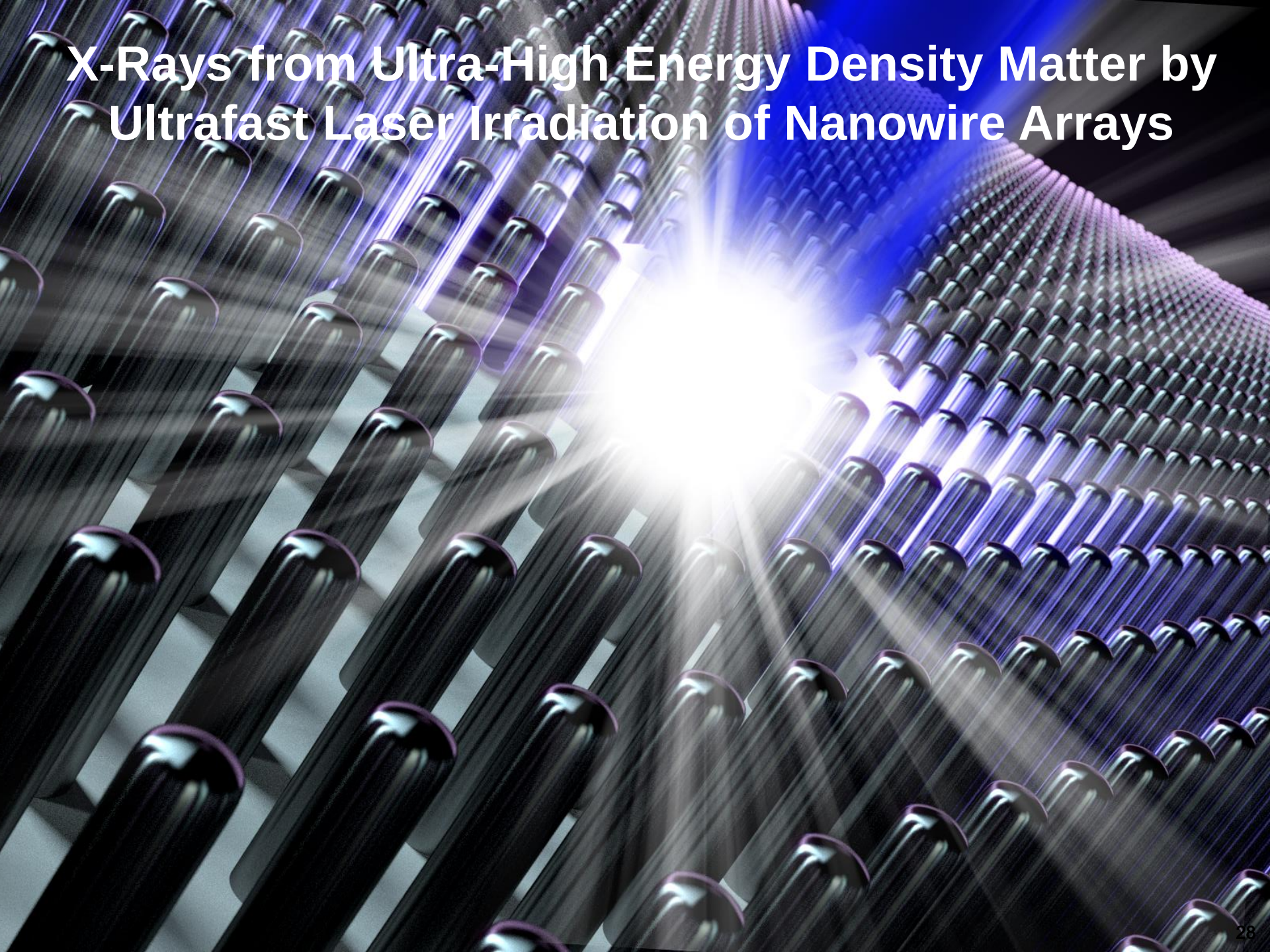


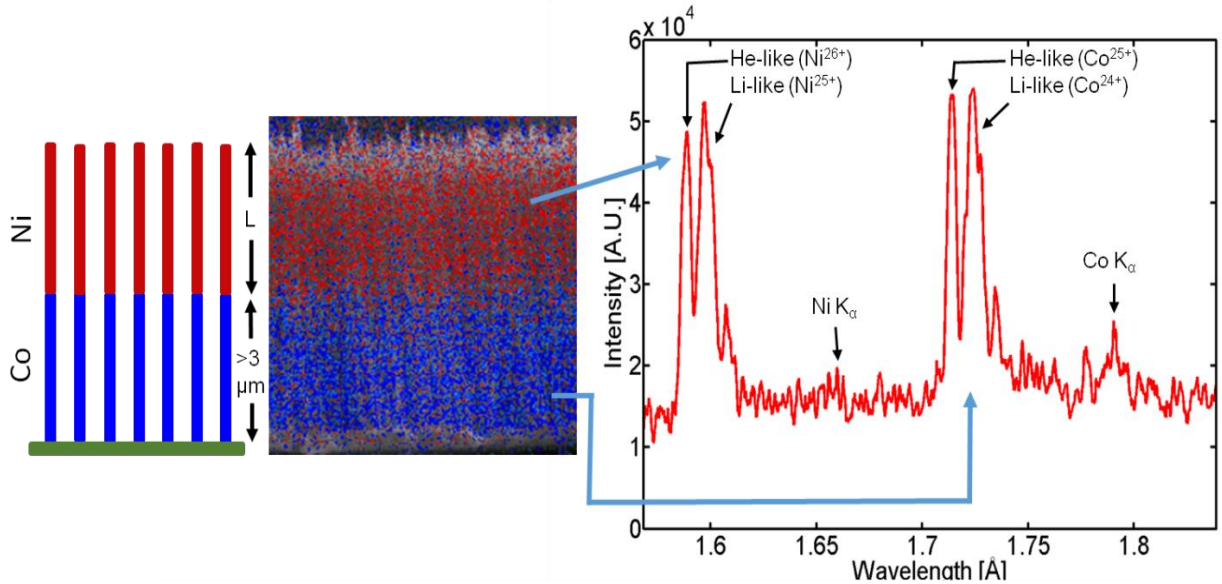
Gain-saturated table-top SXRLs cover 8.8 nm - 47 nm wavelength region

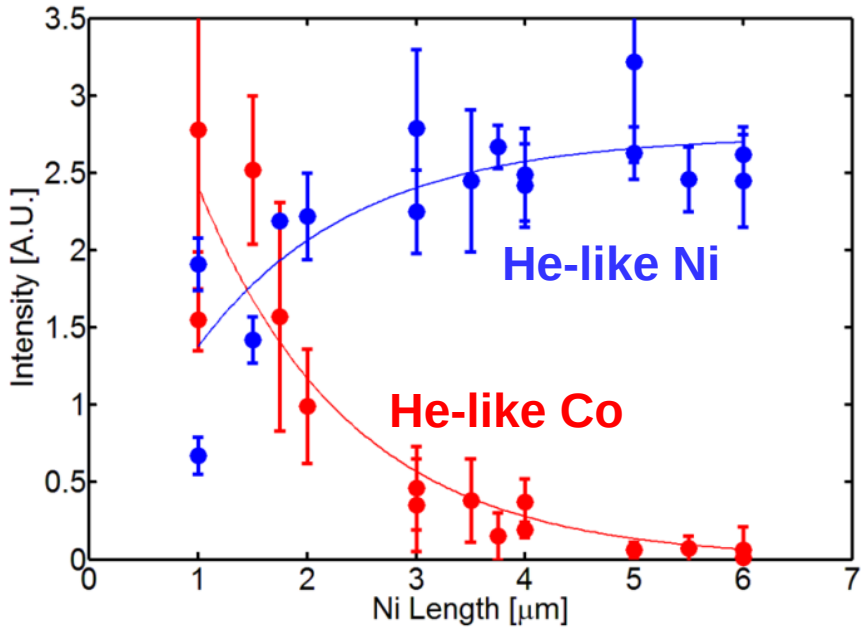


D. Alessi et al. Phys. Rev X, 1, 021023, (2011)

X-Rays from Ultra-High Energy Density Matter by Ultrafast Laser Irradiation of Nanowire Arrays

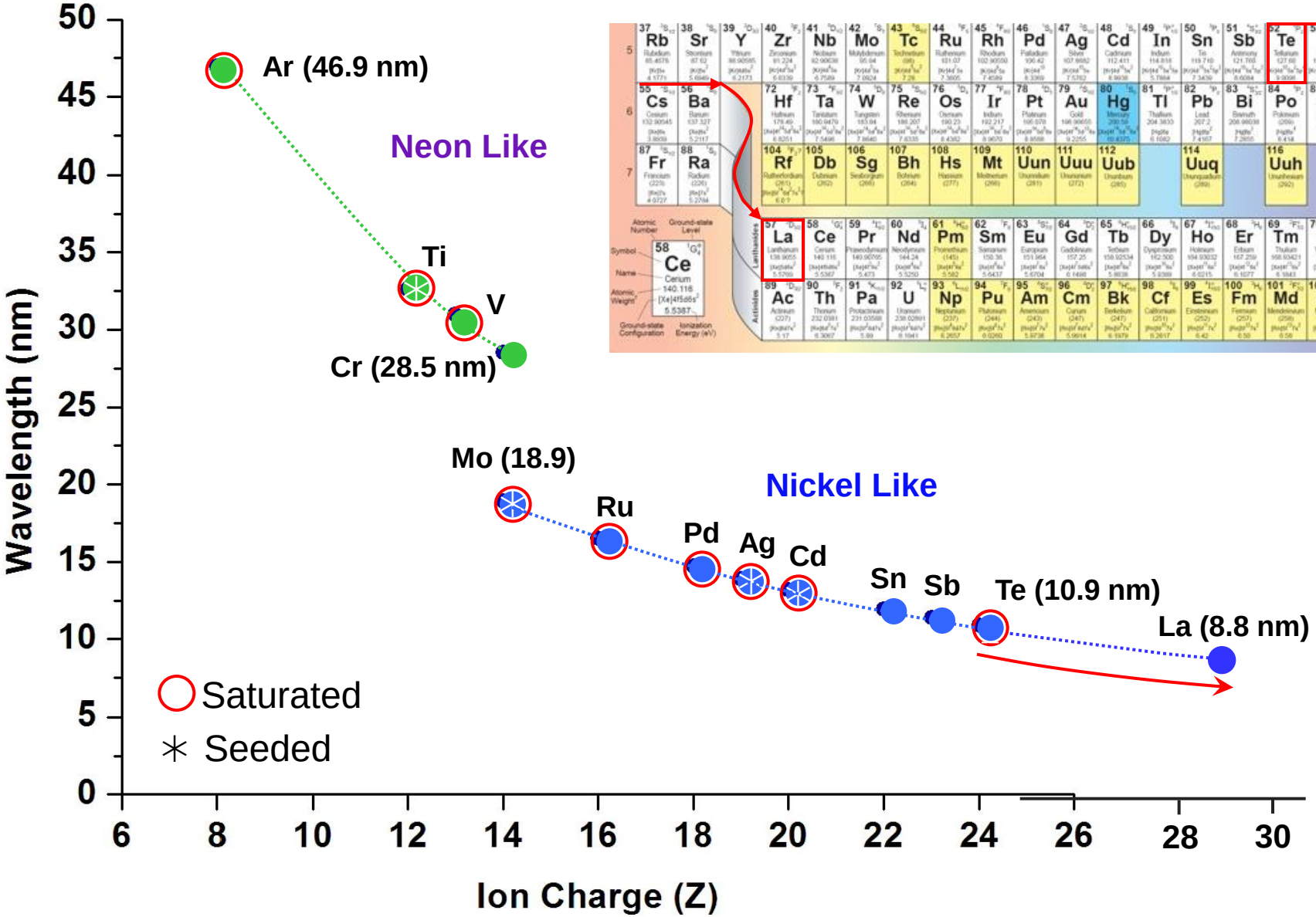



Ni
Co
L
>3 μm
x 10^4
He-like (Ni^26+)
Li-like (Ni^25+)
He-like (Co^25+)
Li-like (Co^24+)
Ni Kα
Co Kα
Intensity [A.U.]
Wavelength [Å]

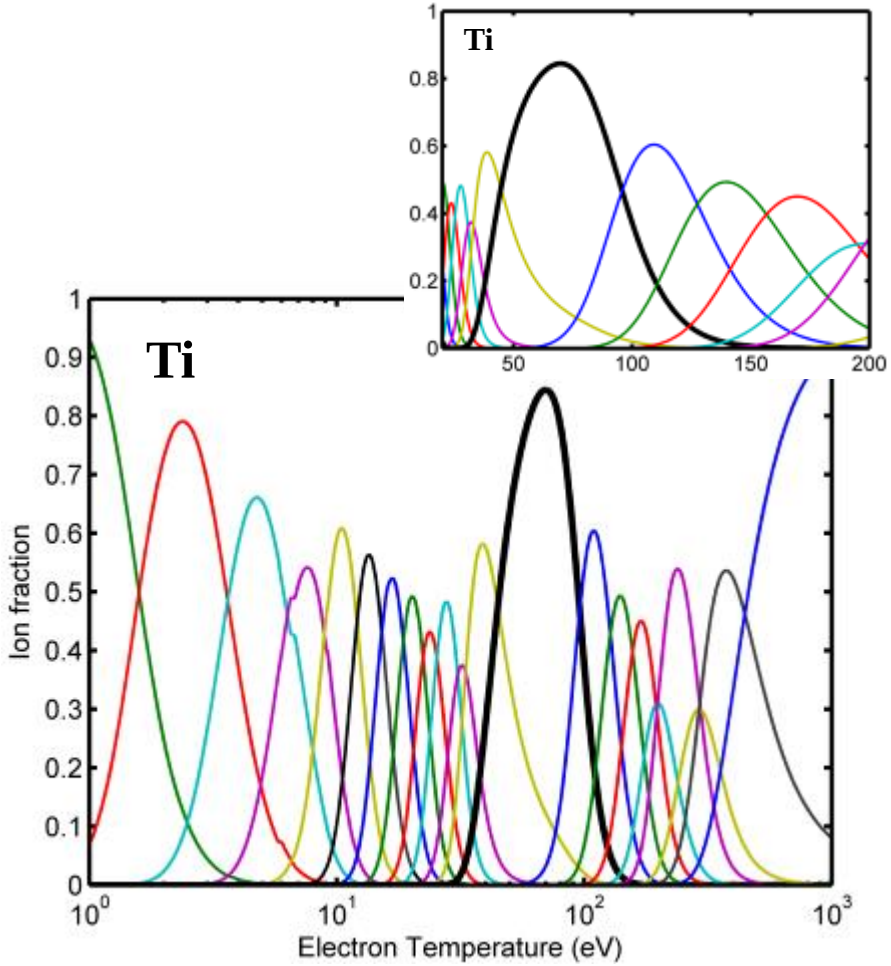

He-like Ni
He-like Co
Intensity [A.U.]
Ni Length [μm]

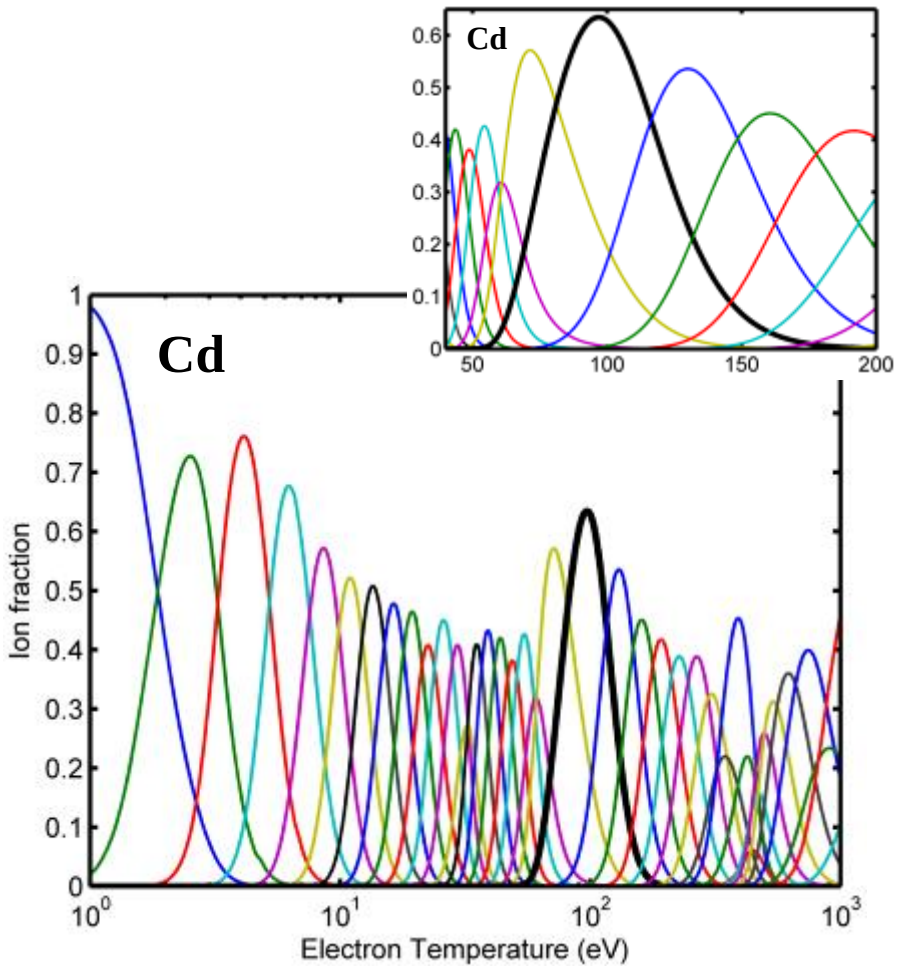
Extension of gain-saturated table-top SXRL to sub-10 nm wavelengths using lanthanide ions

Colorado State University

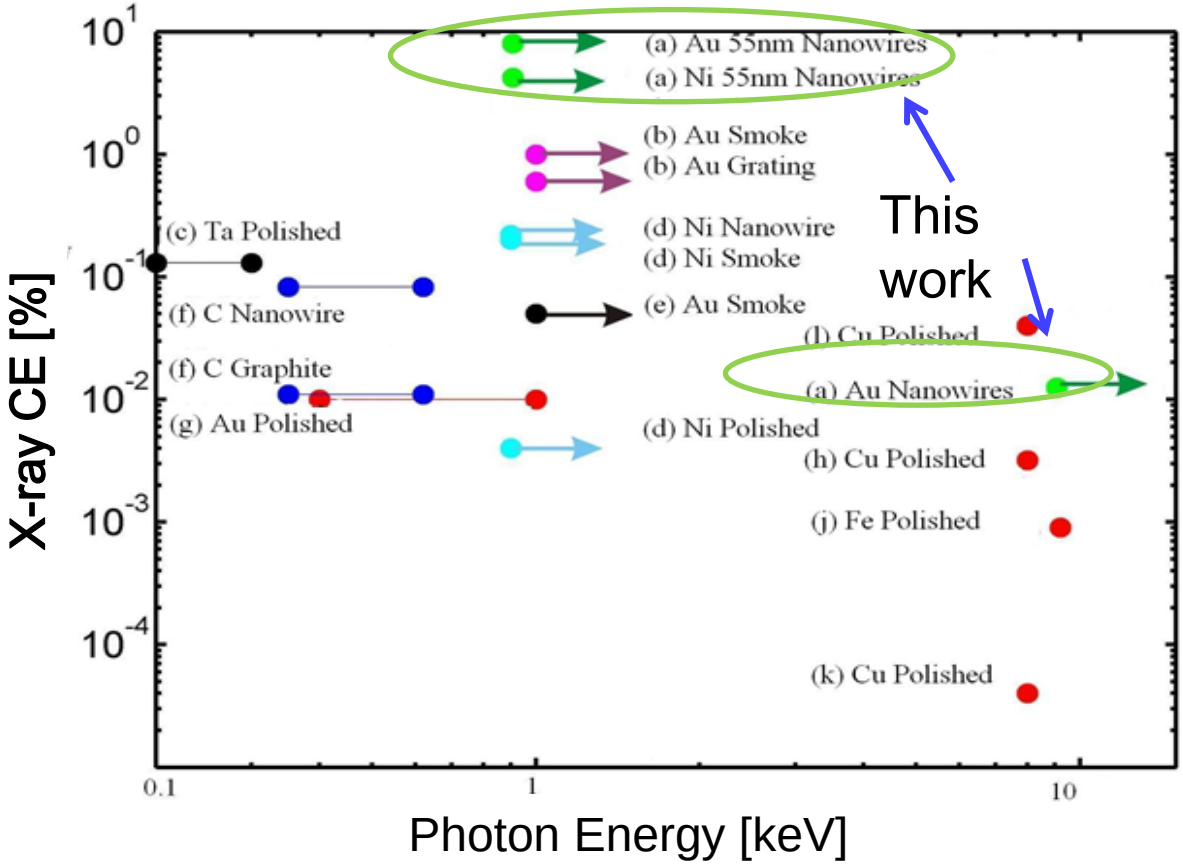


Collisional X-ray lasers make use of closed-shell ion stability over a large range of temperature and plasma density



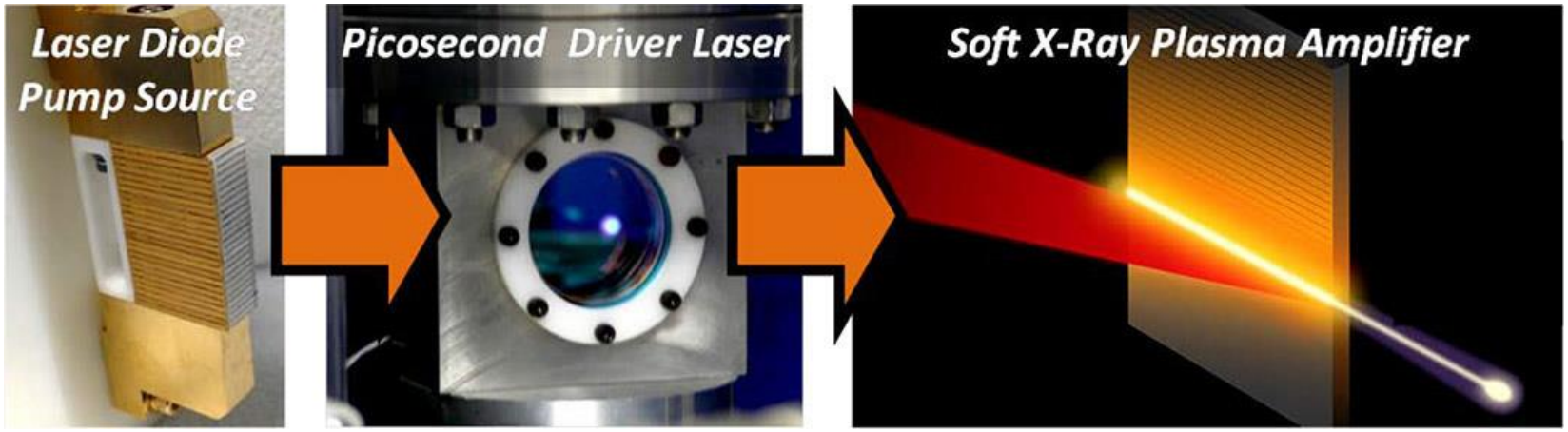


X-ray yield from ultra-shot pulse irradiated targets



a) Purvis et al. Nature Photonics, (2013)
b) Murnane et al., App. Phys. B (1994).
c) Pelletier et al. Optics Letters (1996).
d) Kulcsar et al. Phys. Rev. Lett. (2000).
e) Gordon et al. Optics Letters (1994).
f) Nishikawa et al. App. Phys. B. (2004).
g) Stern et al., Phys. Rev. A (1988).
h) Serbanescu et al. Rev. Sci. Inst. (2007).
i) Eder, et al. Appl. Phys. B. (2000).
j) Zhavorankov, et al. Optics Letts. (2002).
k) Thogerson, et al. App. Phys. A. (2001).

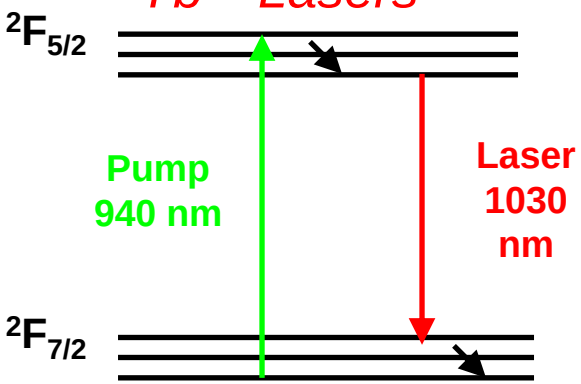
High repetition rate, diode-pumped table-top soft x-ray lasers.



Laser Diode Pumping Advantages

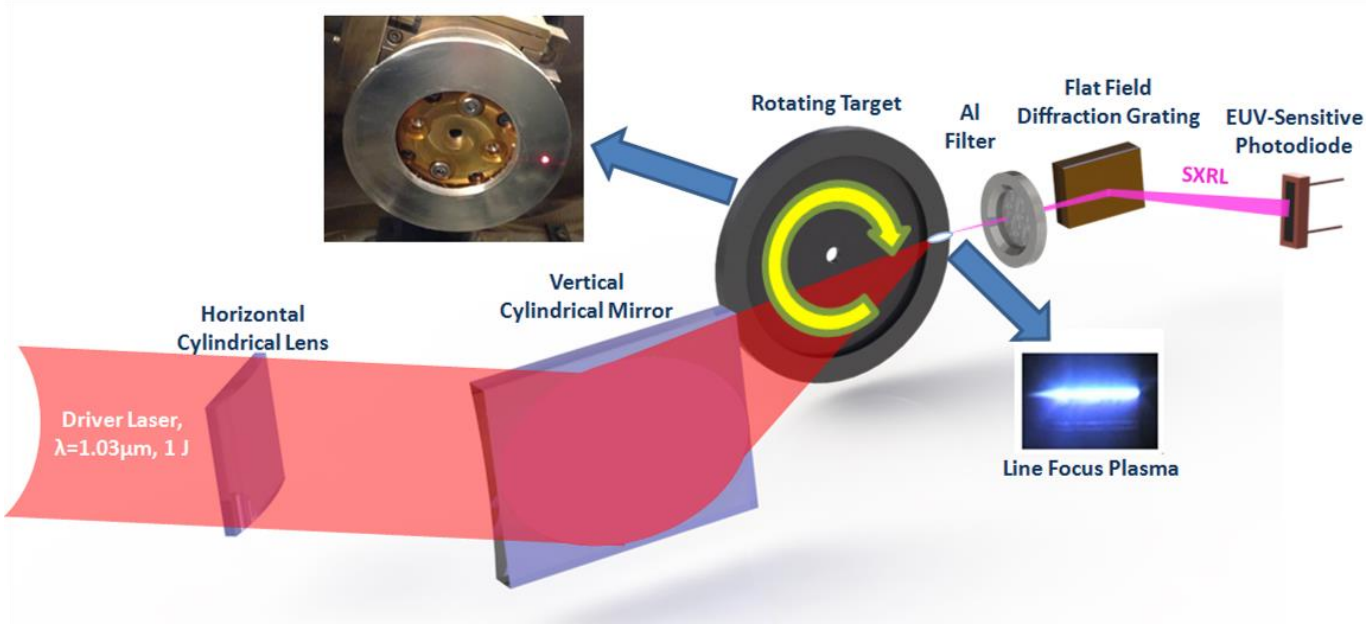
- Highly efficient
  - >50% Electrical efficiency
- Narrow bandwidth
  - Efficiently pump a single transition
- Directional
  - End-pumping
- Very high average power
  - Allow high repetition rate
- Compact

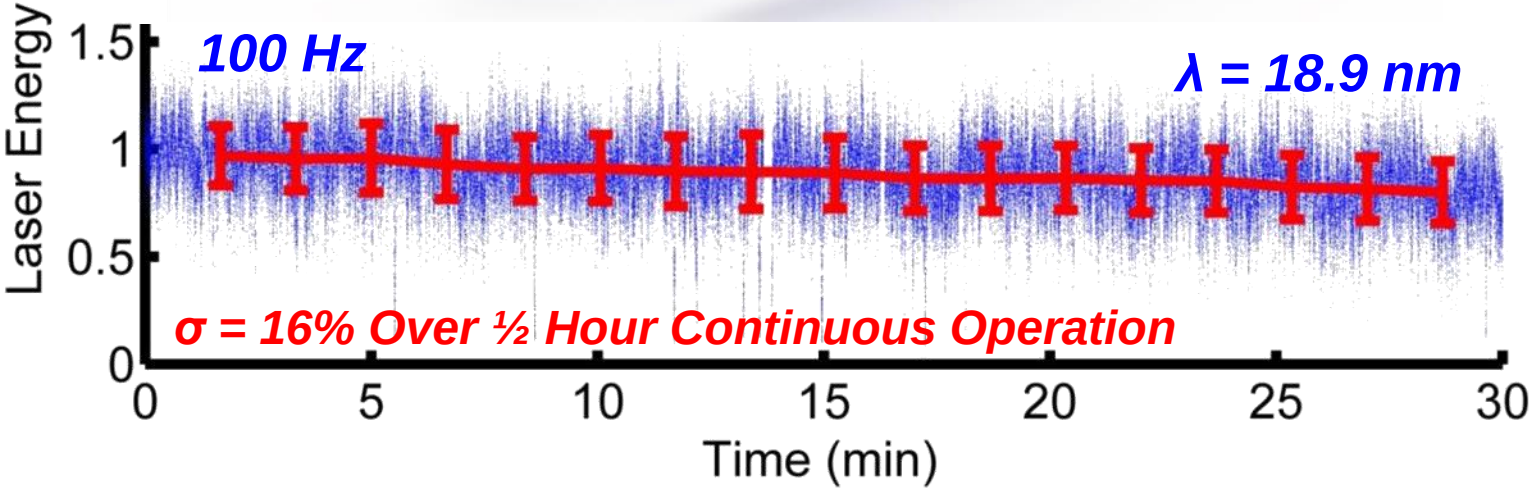
Yb^{+3} Lasers



- Absorption bands at InGaAs wavelengths
- Small quantum defect (<10%)
- Long lifetime for high energy storage

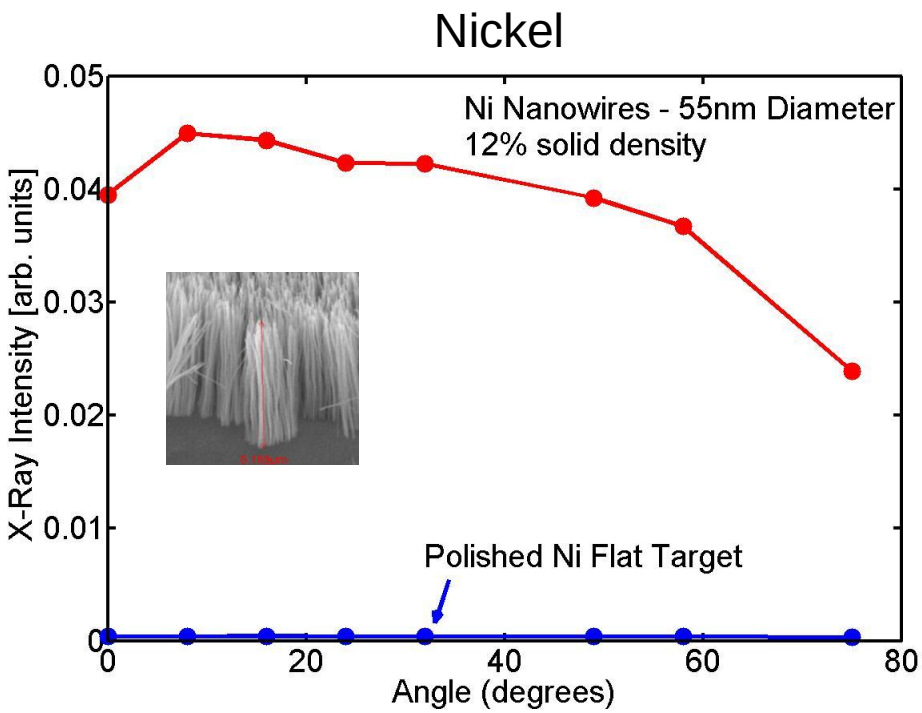
1.8 x 10^5 Consecutive Soft X-Ray Laser Shots

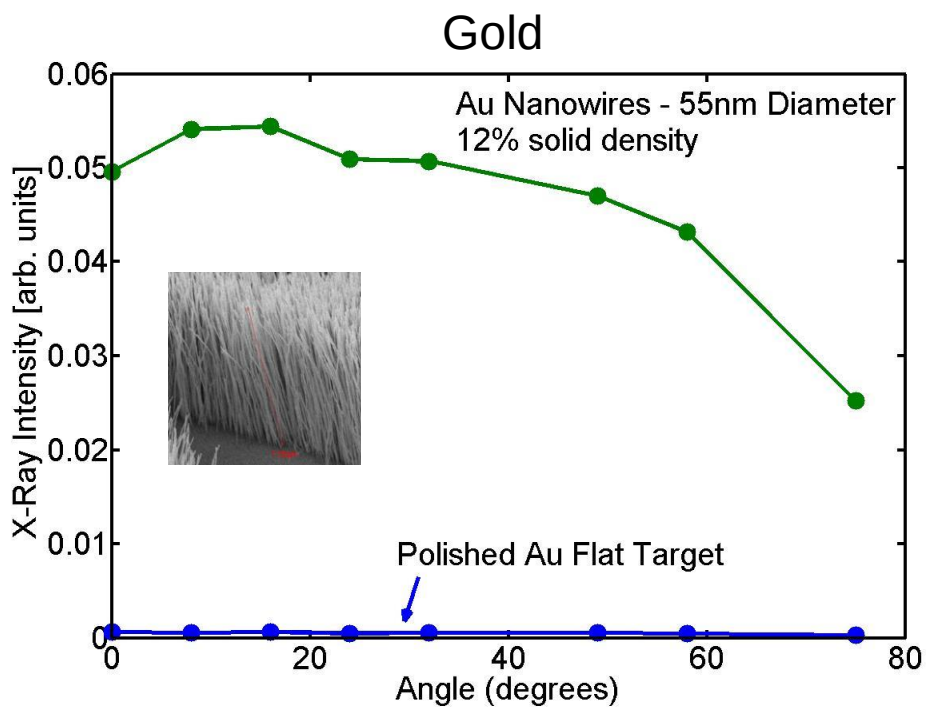


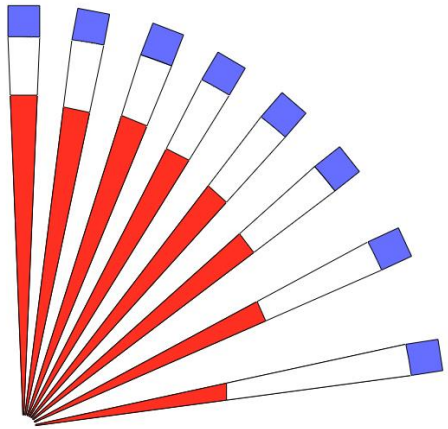


B.A. Reagan et al., Opt. Expr. ***21****, 28380, (2013).*

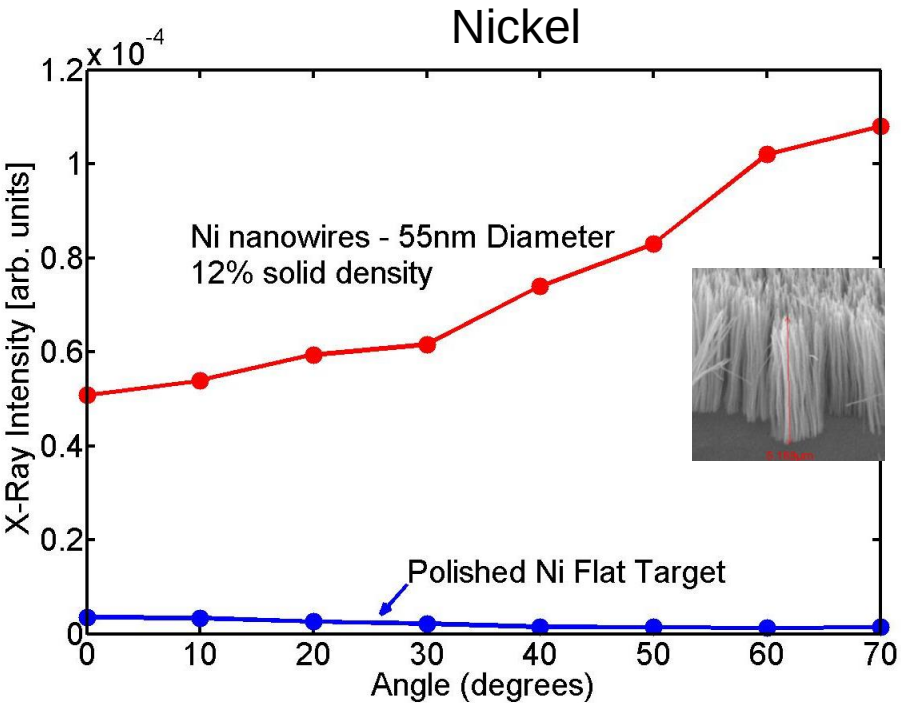
Angular distribution of > 0.9 KeV X-ray emission

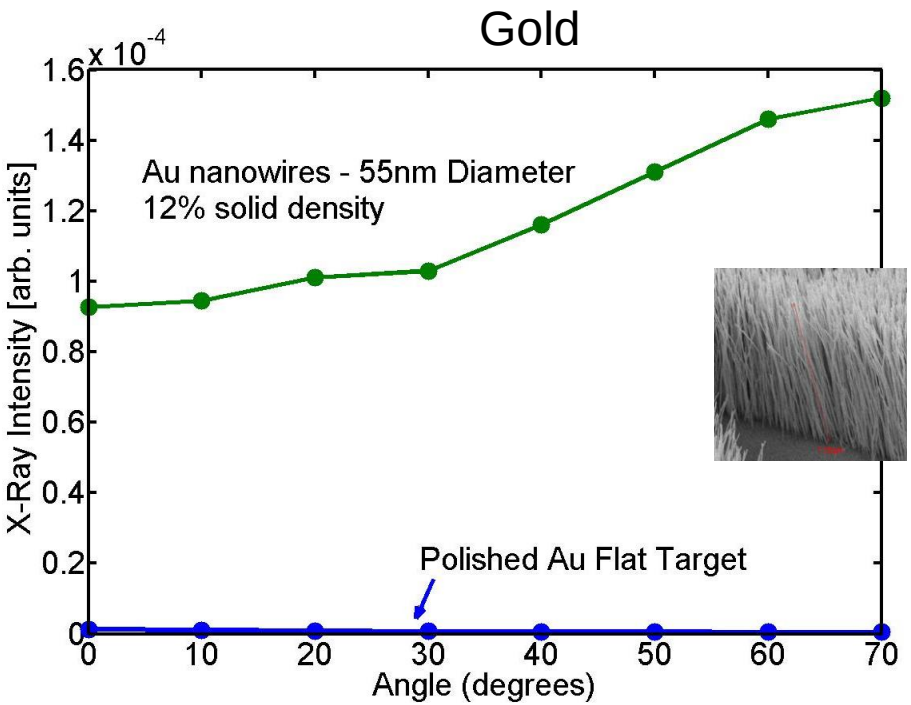


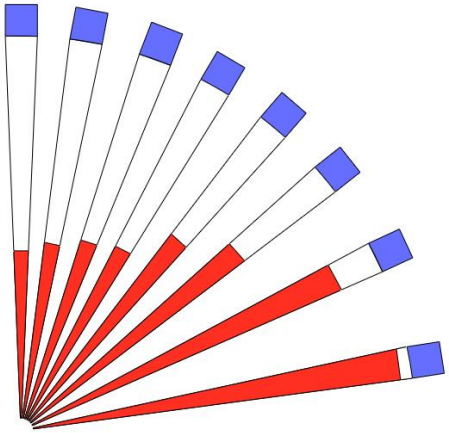




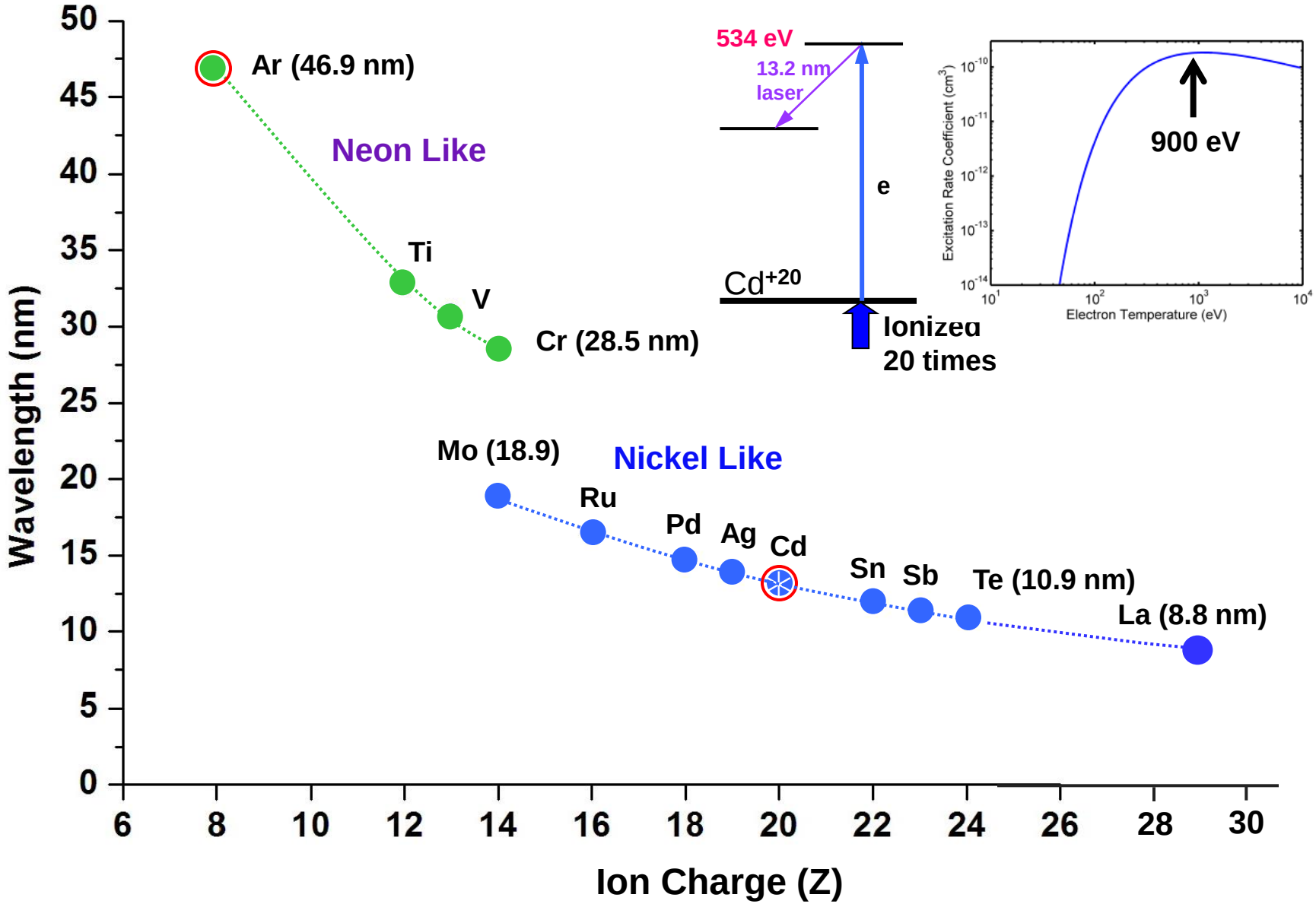
> 9 KeV X-ray emission profile increases at large angles





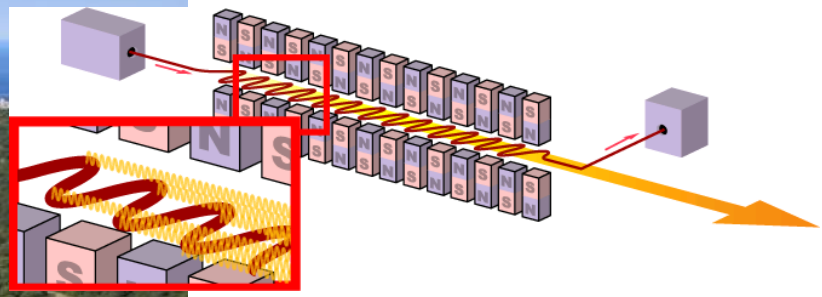


Scaling to shorter wavelengths requires hotter-denser plasmas



Free-electron lasers generate very bright soft x-ray beams with high pulse energy and high average power

FERMI @elettra — Free Electron Laser for Multidisciplinary Investigations



PHOTON BEAM PARAMETERS TO DATE *

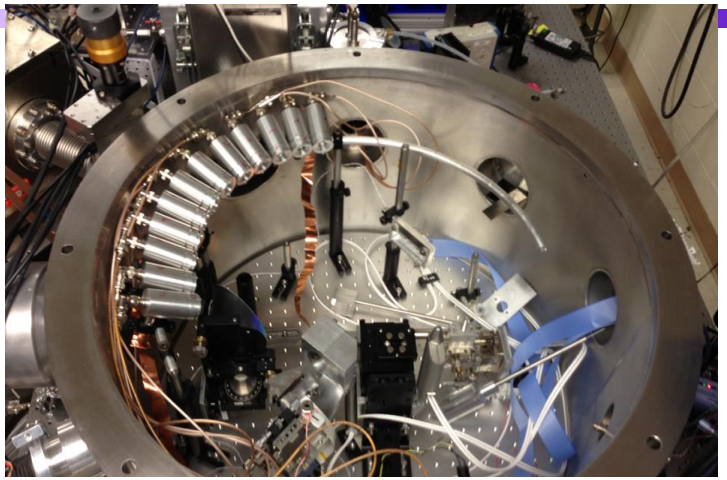
PARAMETER	VALUE	UNITS
Photon energy range (at present no third harmonic)	19-62 20-65	eV nm
Energy/pulse	20-30	µJ
Repetition rate	10	Hz
Estimated pulse length FWHM	<150	fs
FEL bandwidth $\Delta E/E$	$6\ 10^{-4}$	

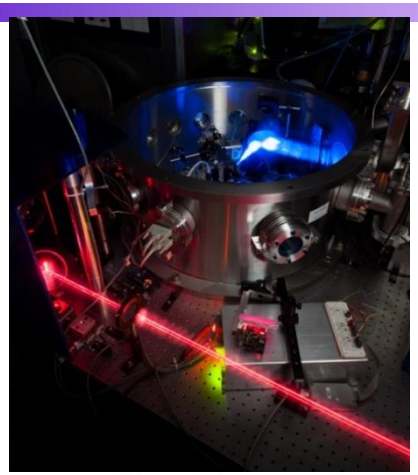
2.5 10 ^{12} photons/pulse @ 20 nm

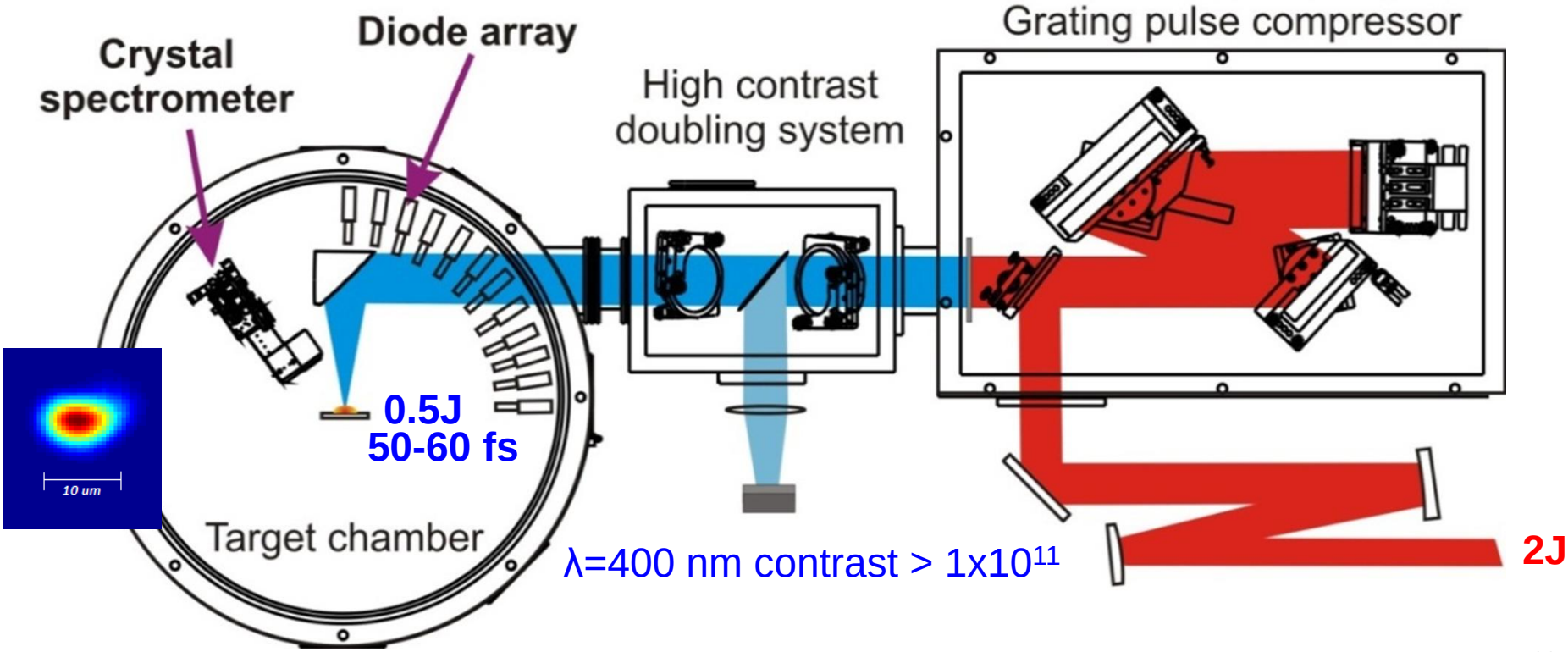
Average Power: 0.2-0.3 mW

** http://www.elettra.trieste.it/FERMI/*

Experimental setup

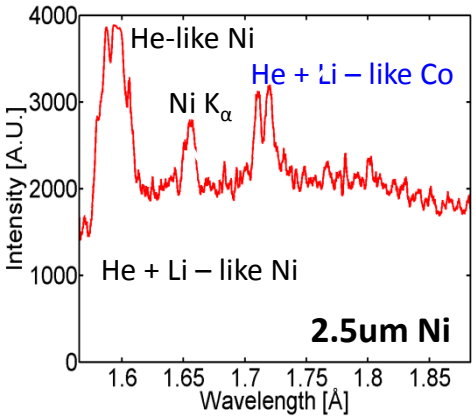


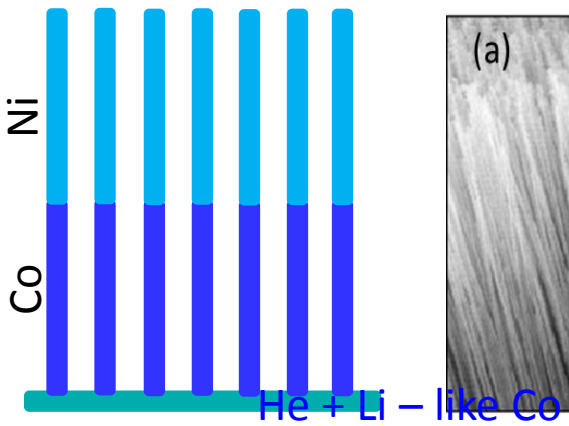


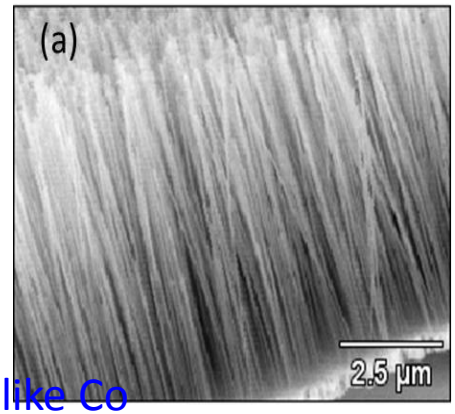


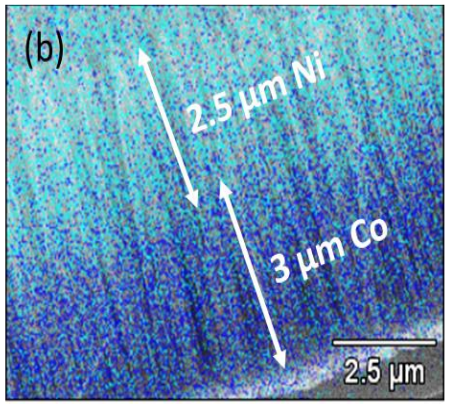
New result:

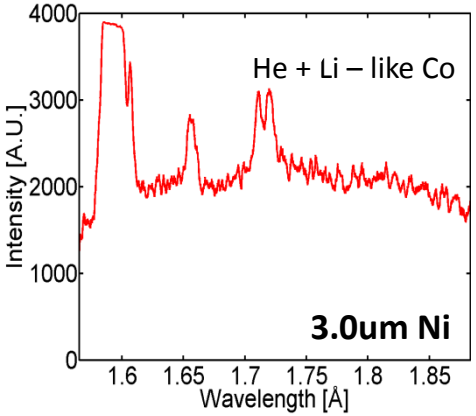
Measurement of heat penetration depth using X-ray spectroscopy of dual-composition nanowire arrays

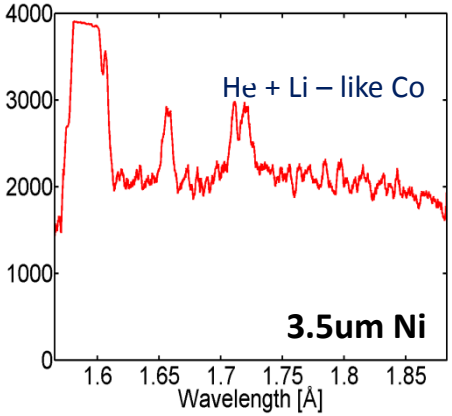


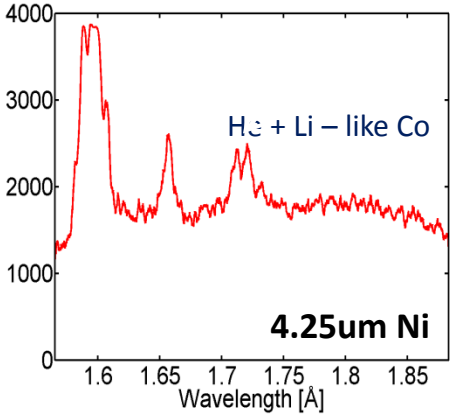


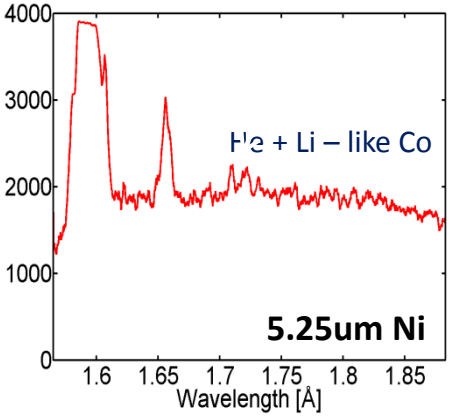




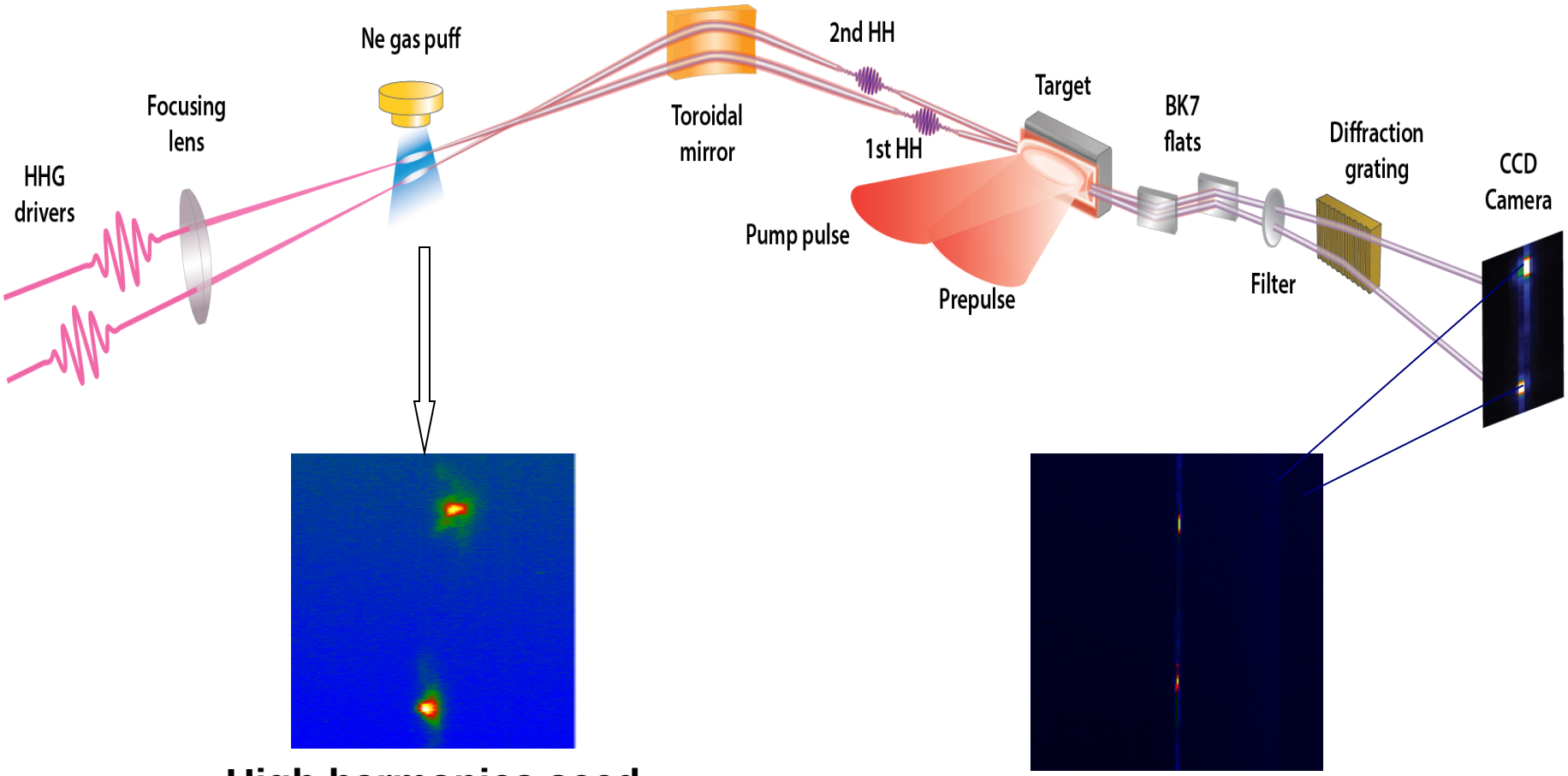








Gain dynamics of ASE and seeded soft x-ray amplifiers



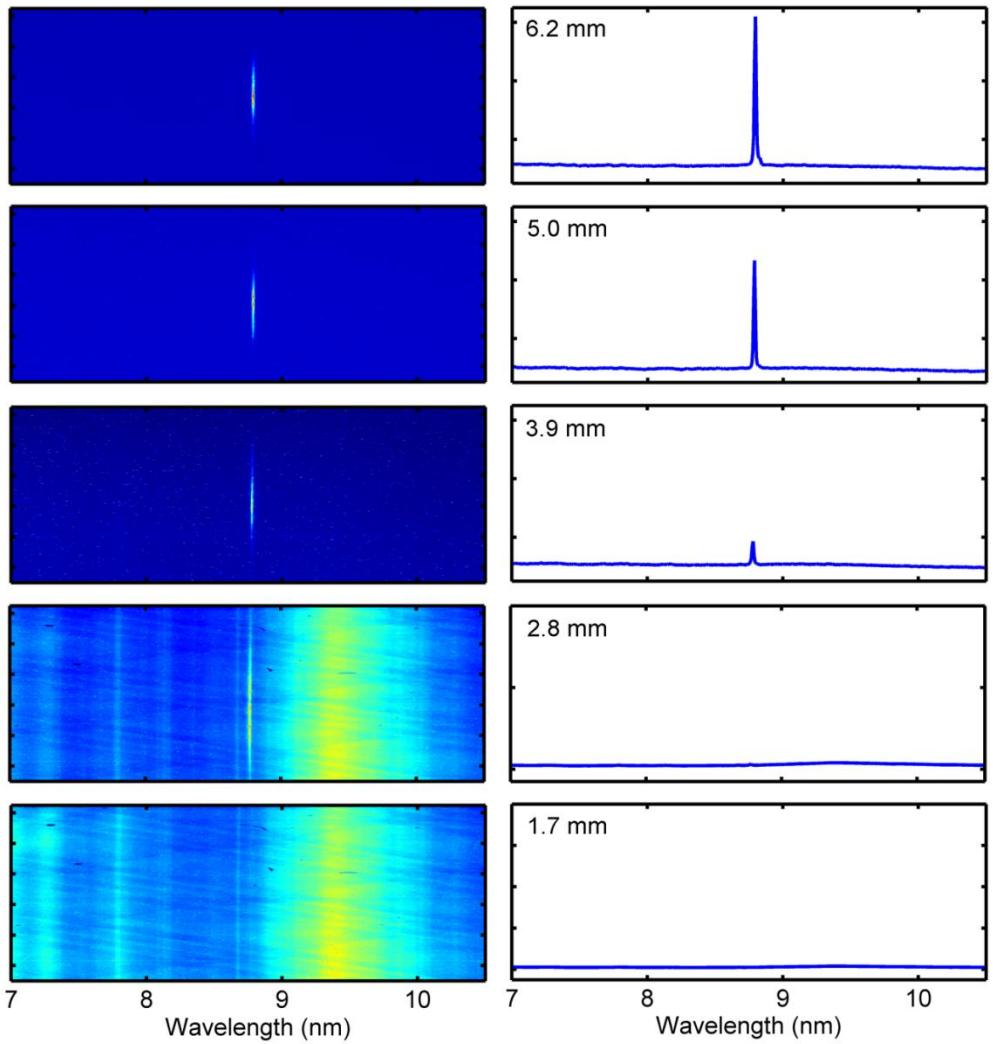
High harmonics seed pulses with time delay

Amplified Seed pulses

Y. Wang et al. Nature Photonics, 8, 381, (2014)

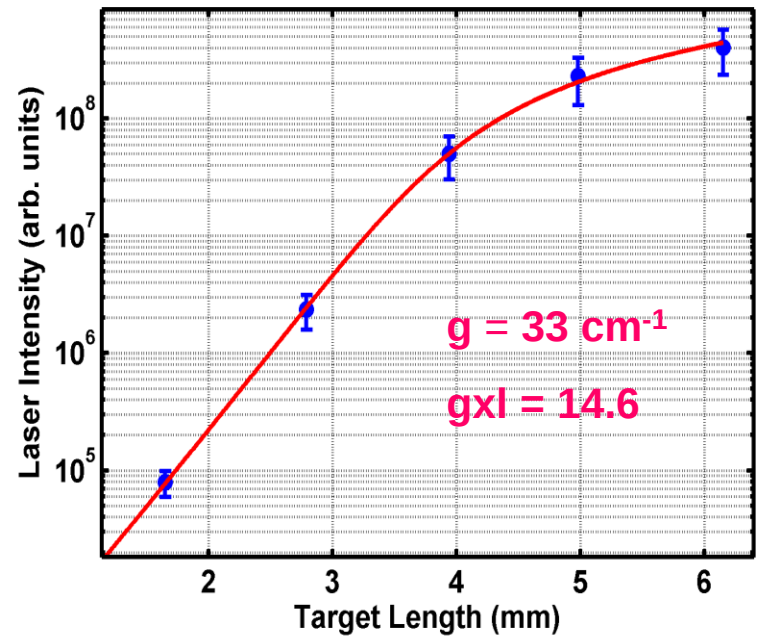
Demonstration of Gain-saturated table-top laser at 8.8 nm at 1 Hz repetition rate

Ni-like Lanthanum $4d^1S_0$- $4p^1P_1$



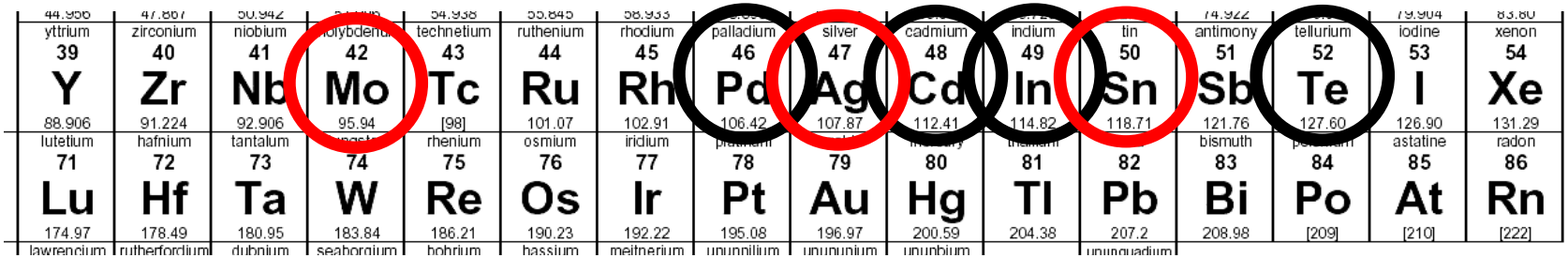
7.5 J Total Pump Energy

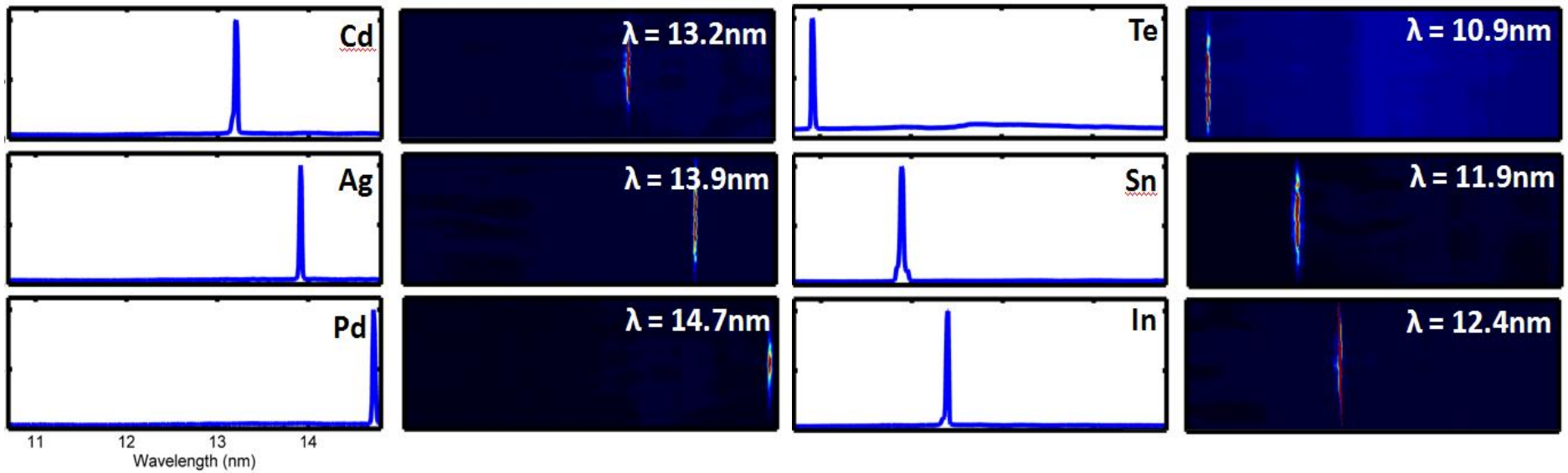
Pulse energy up to ~ 2.7 μJ



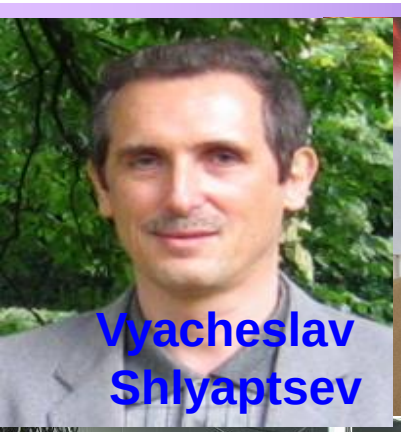
D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

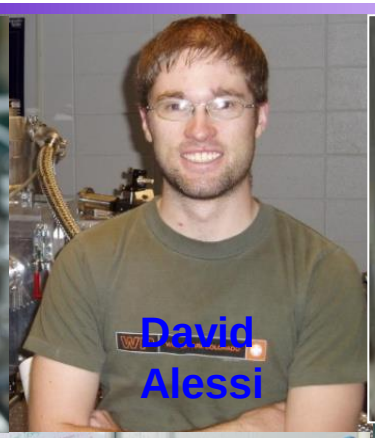
Extending diode-pumped lasers to λ = 10.9 nm

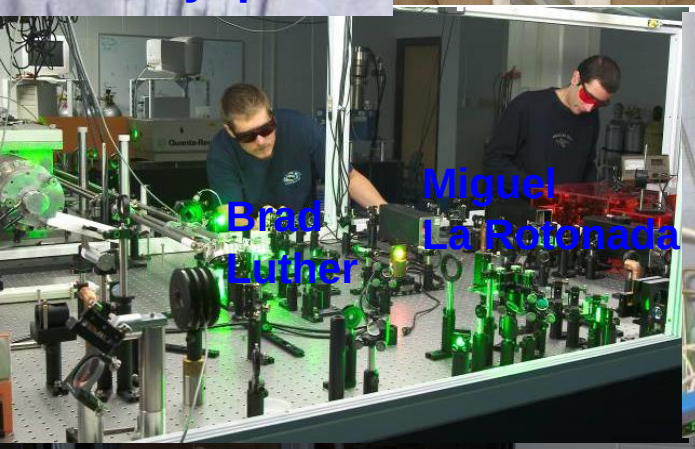




Acknowledgement

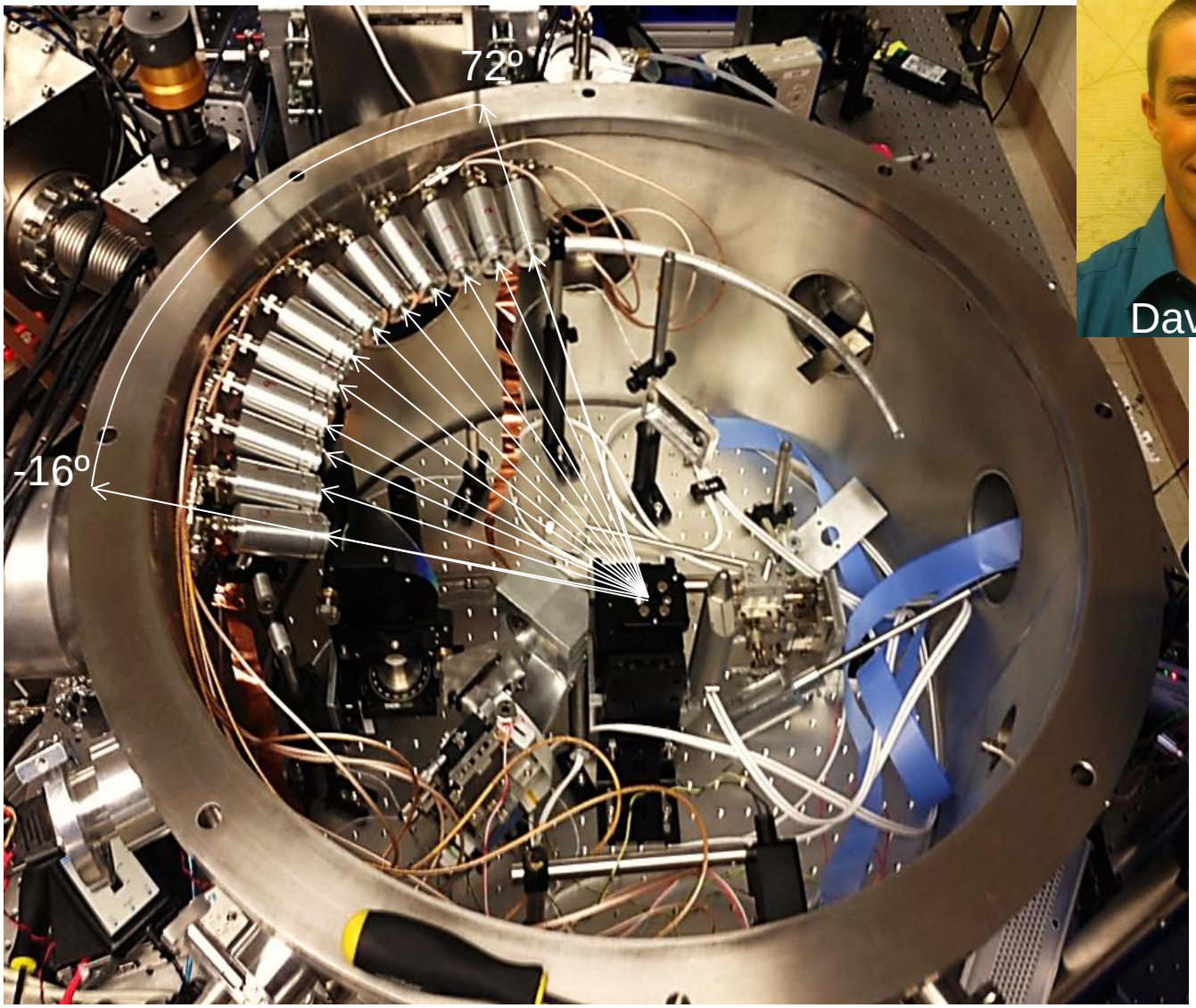






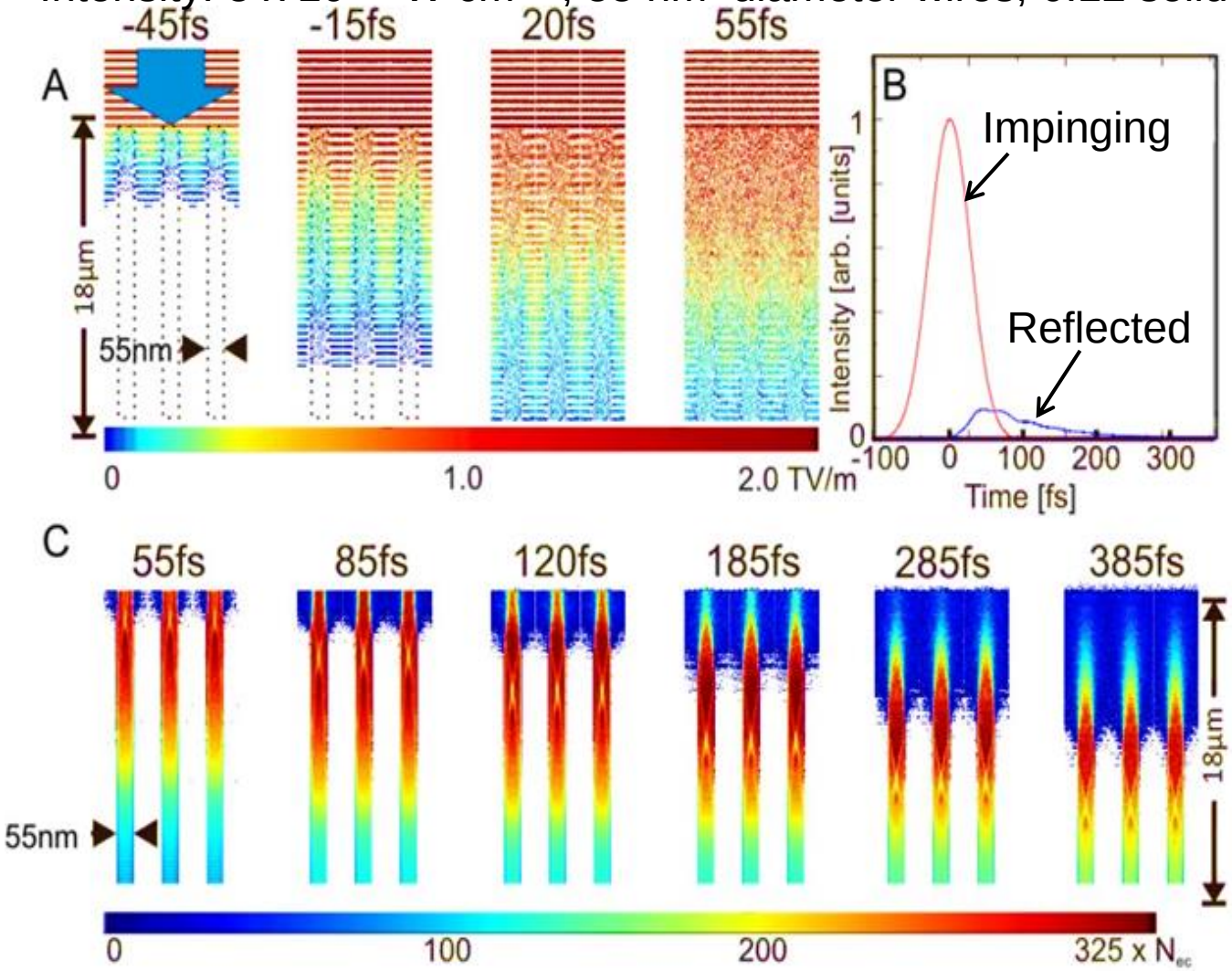
X-ray yield measurements

Array of 12 filtered X-ray filtered photodiodes



PIC simulations show heat penetrates depths of several µm creating KeV temperature plasmas with densities up to 100 X critical

Intensity: 5 x 10 ^{18} W cm^{-2} , 55 nm diameter wires, 0.12 solid density target



Energy density deposited at core ~ 2 GJ/cm^3

Transformed in average thermal energy 0.3 GJ/cm^3

Core thermal pressure: 10 Gbar

Average thermal pressure 1-2 Gbar

Average KTe ~ 4 KeV

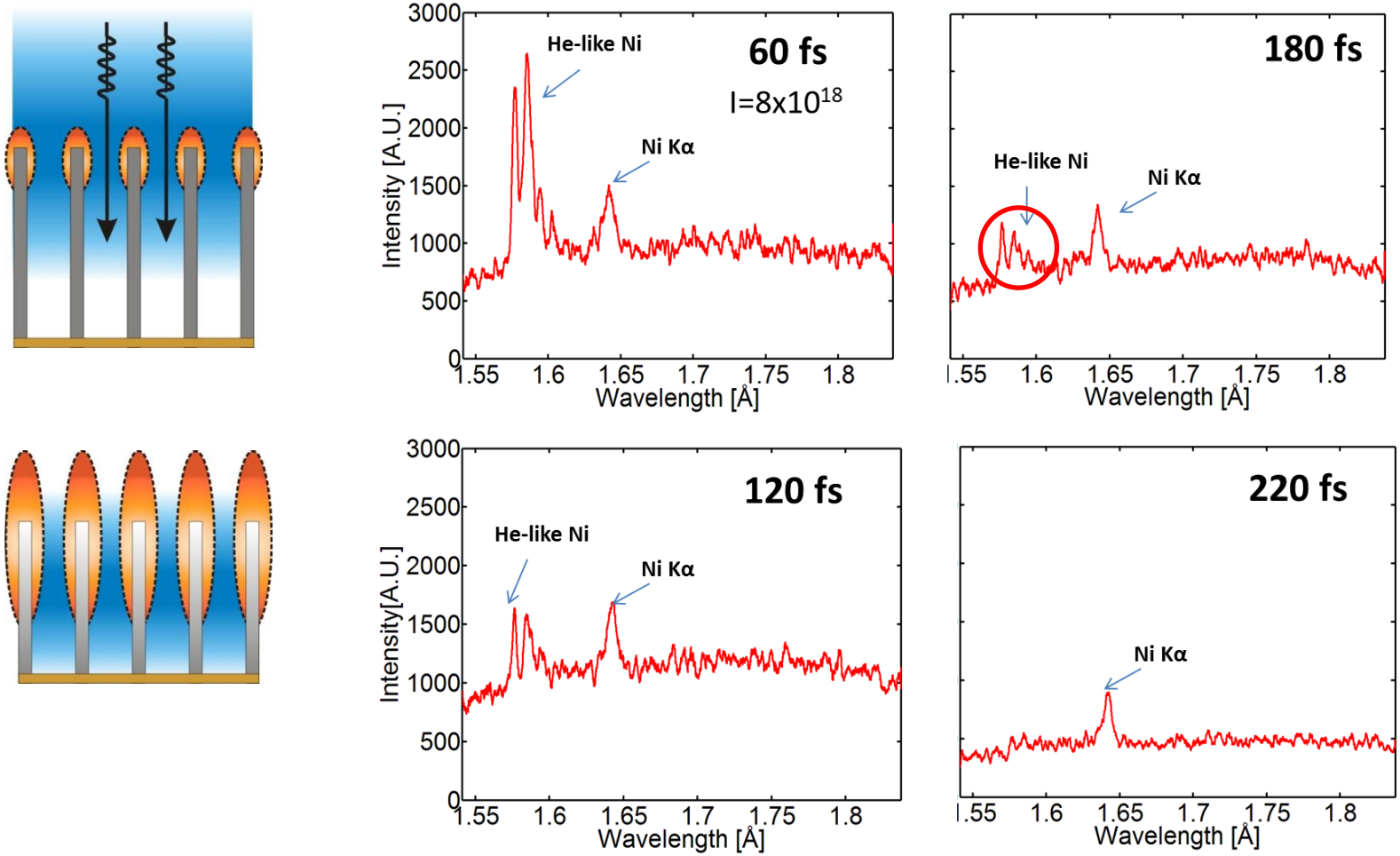
PIC simulation: A. Pukhov

Scaling laser pulse length: what laser pulse lengths are effective ? Impacts future implementation at large facilities

Ni nanowires 55nm diameter ; 13% solid density, I~ 5×10^{18} cm^{-2}

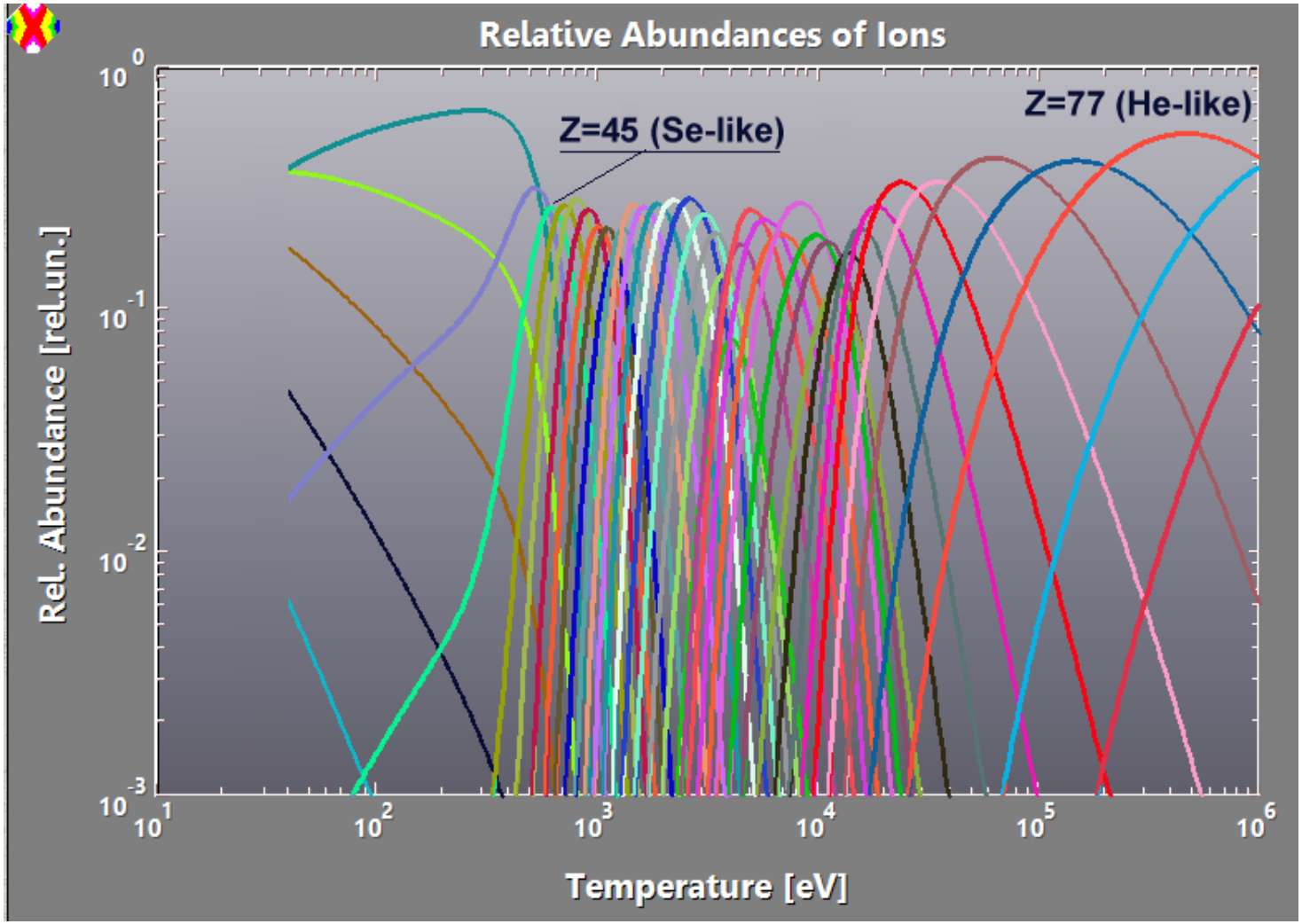
X-Ray emission from He-like observed with laser pulse length up to 180 fs

Increase pulse duration at constant pulse energy

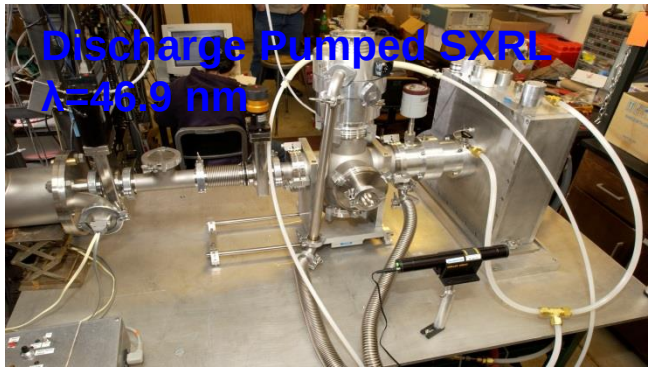


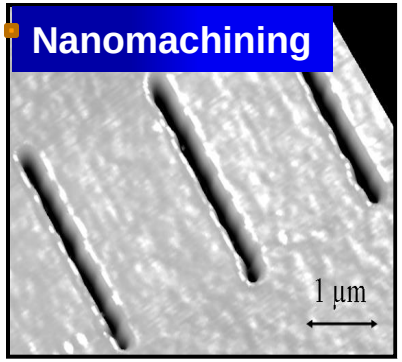
Au array irradiated with 50 J, 500 fs pulse (LLNL Titan) predicted to reach He-like Au

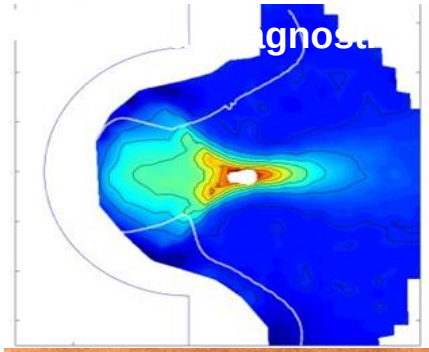
Tunneling ionization will produce charge states exceeding Z=50, subsequent collisional ionization will lead to Z up to 77.

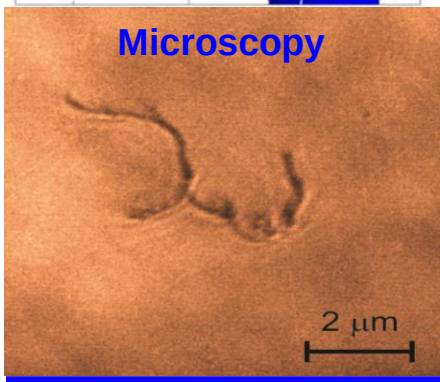


Compact plasma-based soft x-ray lasers can be installed at the application's site

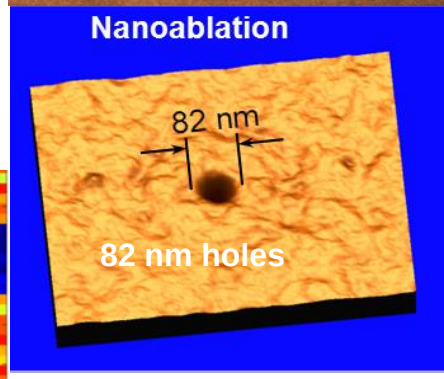
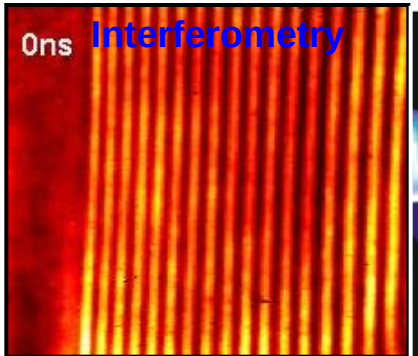
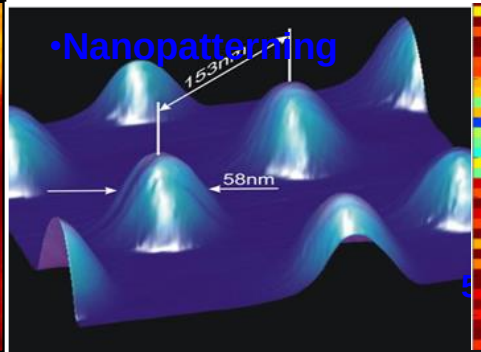
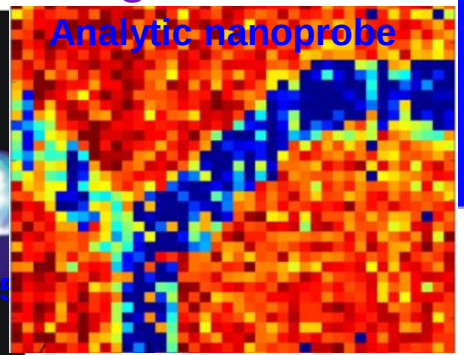








- High pulse energy (µJ-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness



Microscopy