

Nanofotónica relativista: creando plasmas en condiciones extremas y fotones energéticos con láseres de pulsos ultracortos

Maria Gabriela Capeluto

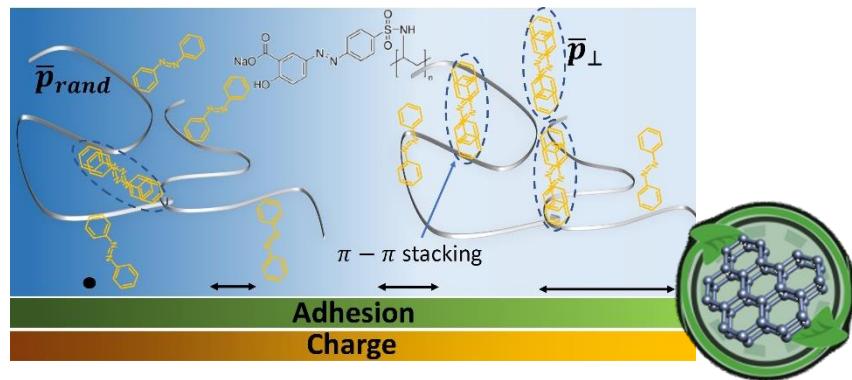
Laboratorio Óptica y Fotónica
Departamento de Física
Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires



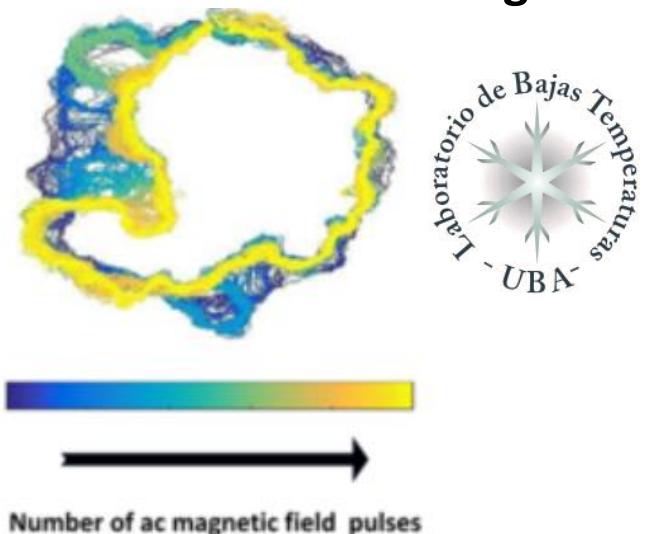
Colorado
State
University



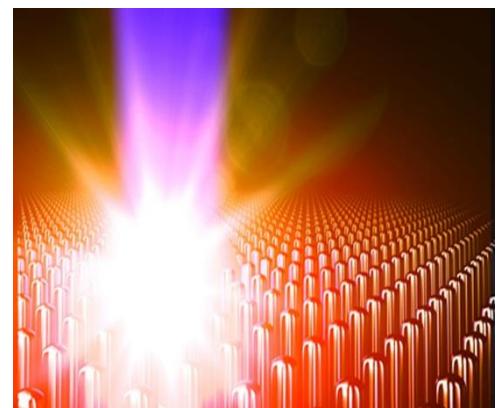
Materiales inteligentes



Dinámica AC en materiales magnéticos.

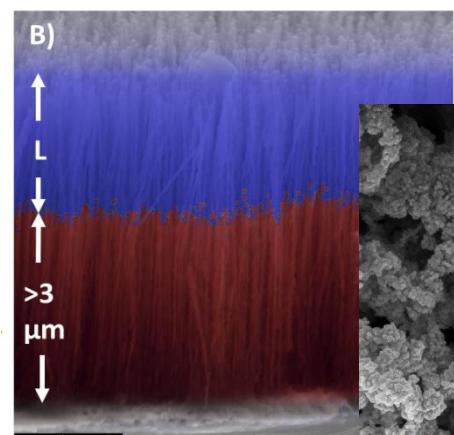


Plasmas con ultra alta densidad de energía

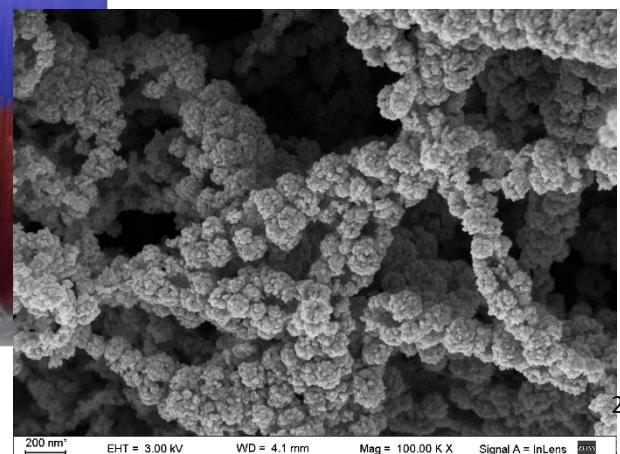


Colorado State
University

Nanomateriales para sensores y fuentes Fotónica electrodepositada



Mallas de ZnO



Nanofotónica relativista: creando plasmas en condiciones extremas y fotones energéticos con láseres de pulsos ultracortos

Maria Gabriela Capeluto ^{1,3}



R. Hollinger¹, V. N Shlyaptsev¹, A. Curtis¹, A. Moreau¹, C. Calvi¹, S. Kardorf¹, V. Kaymak², A. Pukhov², Y. Wang¹, S. Wang¹, A. Rockwood¹, C.S. Menoni¹, J.J. Rocca¹

¹ CSU, Fort Collins, Colorado, ² Heinrich-Heine-Universität Düsseldorf 3 DF. UBA, Argentina^{1,3}

Colorado State University



Advanced Beam Lab



LaserNetUS

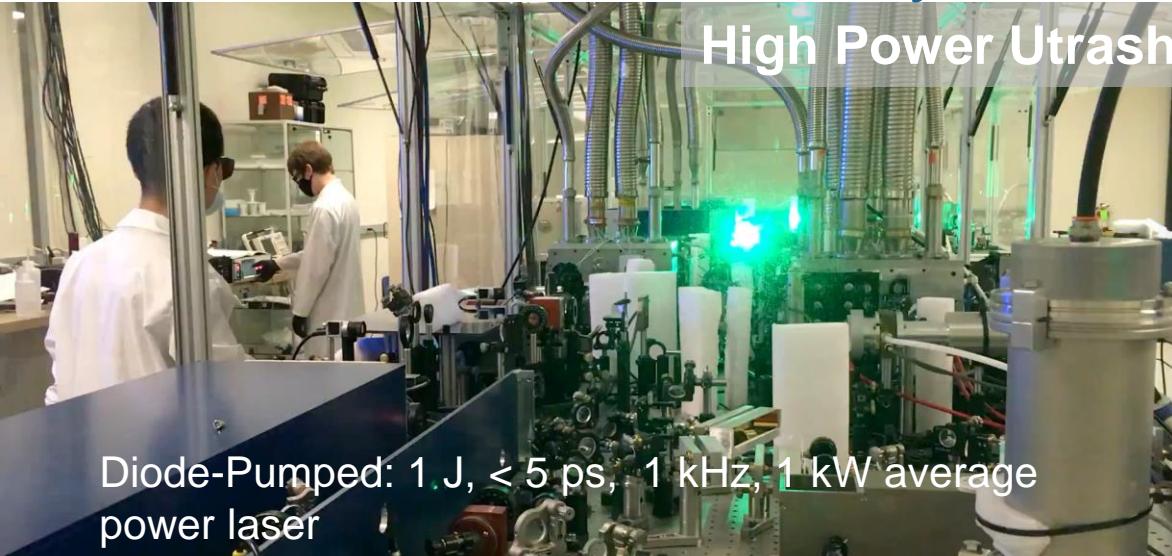


U.S. DEPARTMENT OF
ENERGY

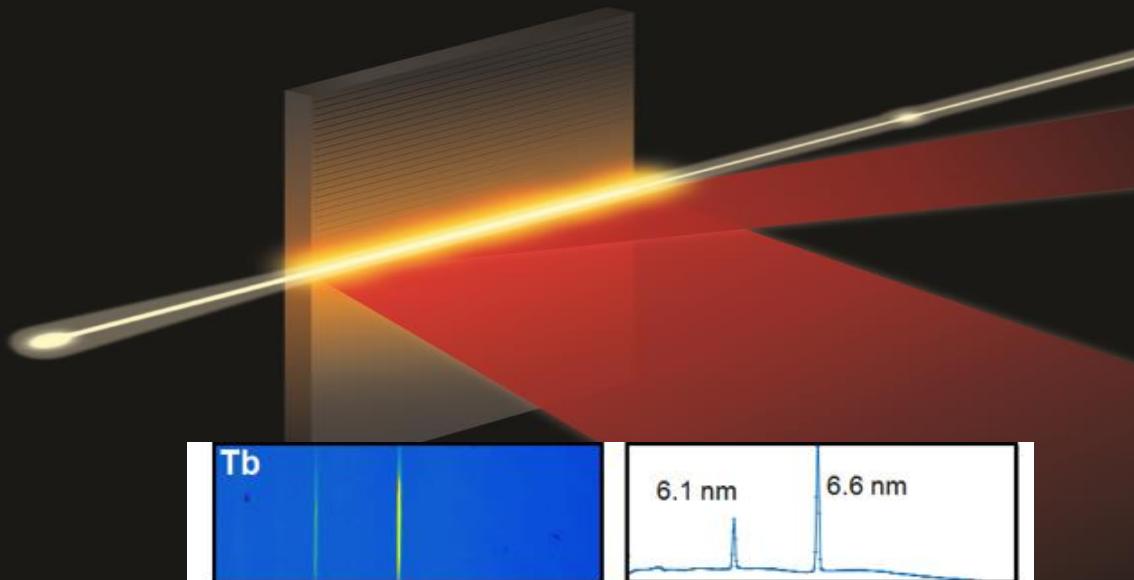
Office of
Science



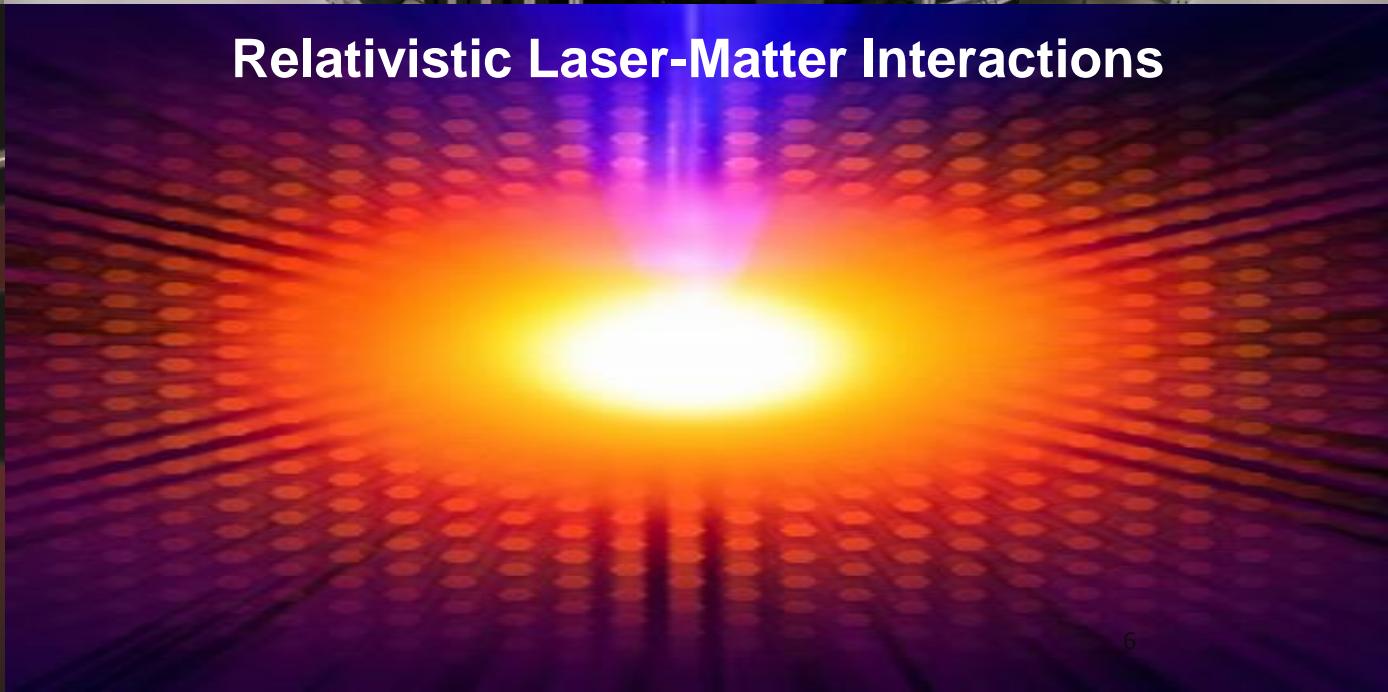
High Power Laser and ultra-Intense Laser-Matter Interaction at CSU's Advanced Beam Laboratory



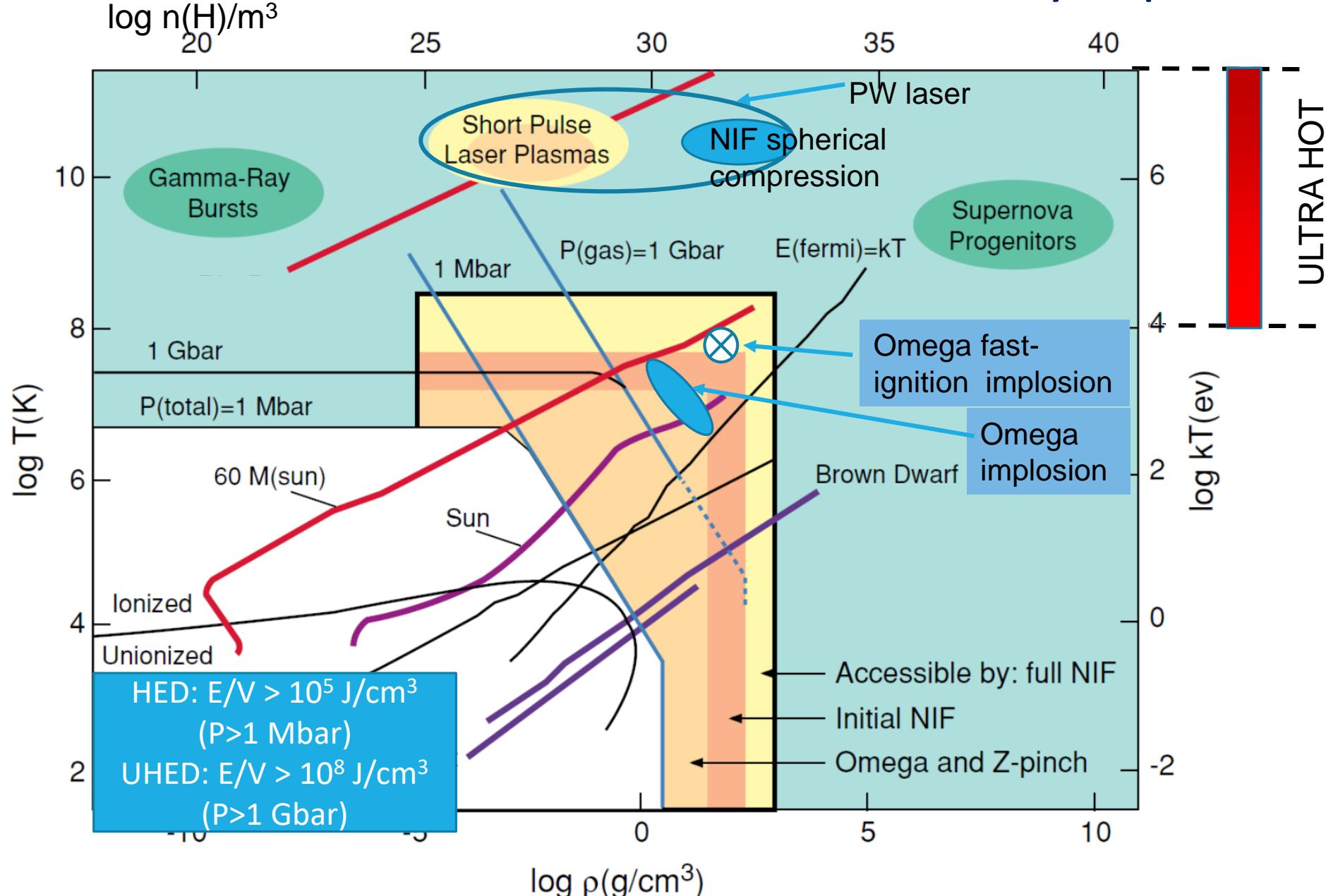
Soft x-ray lasers



Relativistic Laser-Matter Interactions



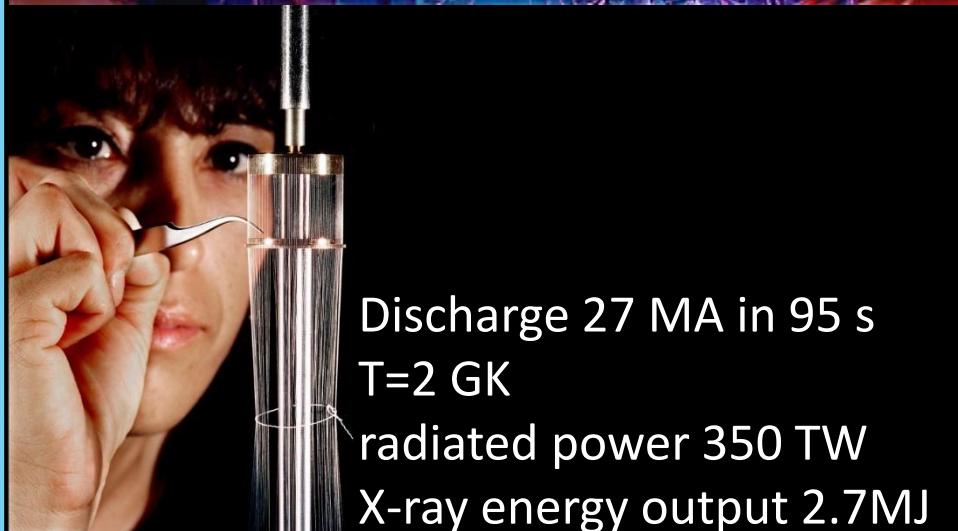
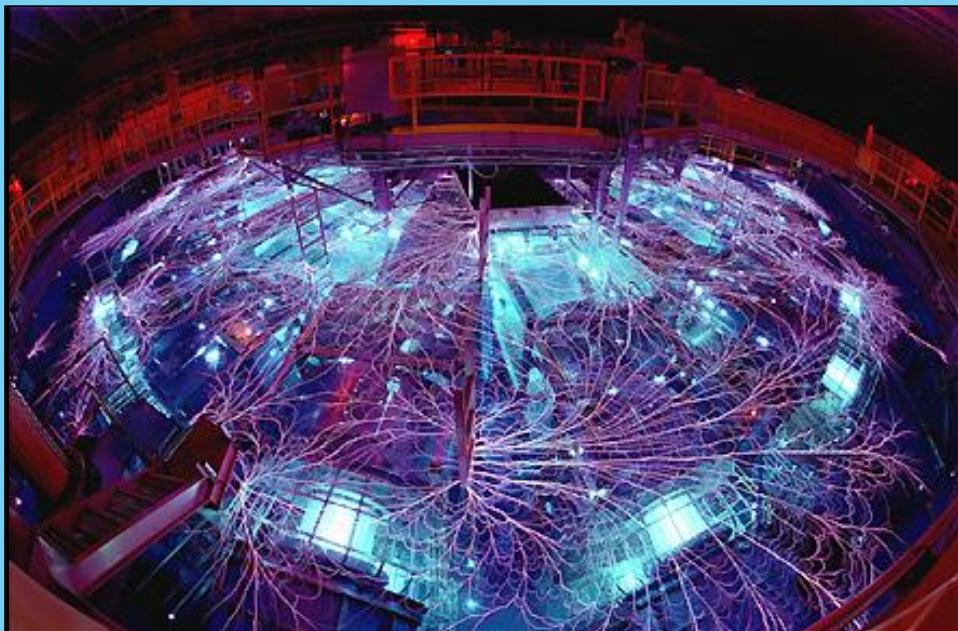
Condiciones de la materia UHED: naturaleza y experimentos



THE WAW! FACTOR: POTENCIA X TAMAÑO

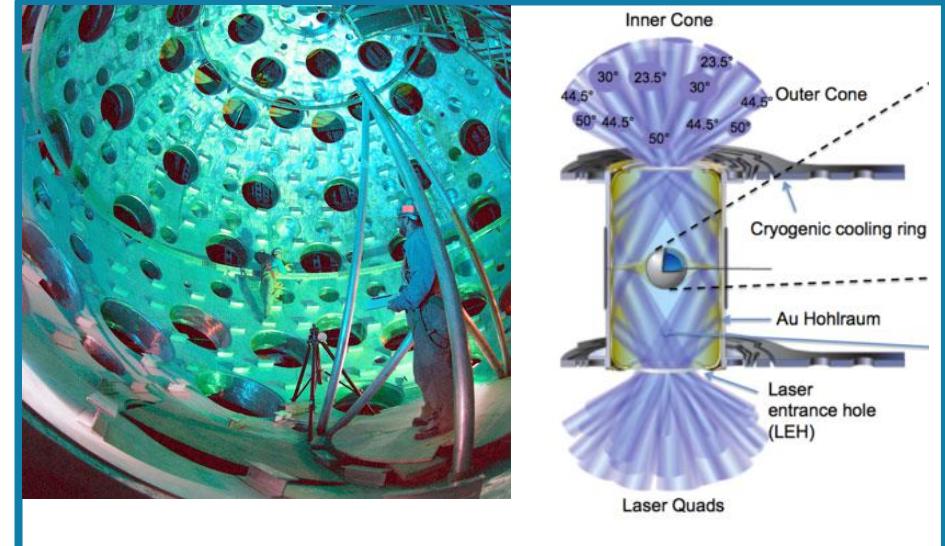
Z Pulsed Power Facility (Z machine)

Sandia National Lab



National ignition Facility

Lawrence Livermore National Lab



2MJ en 192 lasers @ 350nm
(500TW en target)



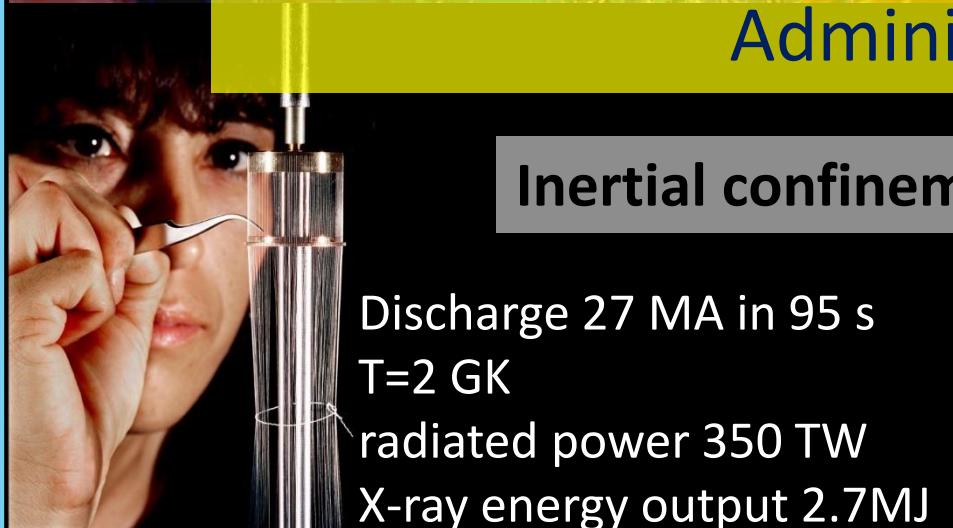
THE WAW! FACTOR: POTENCIA X TAMAÑO

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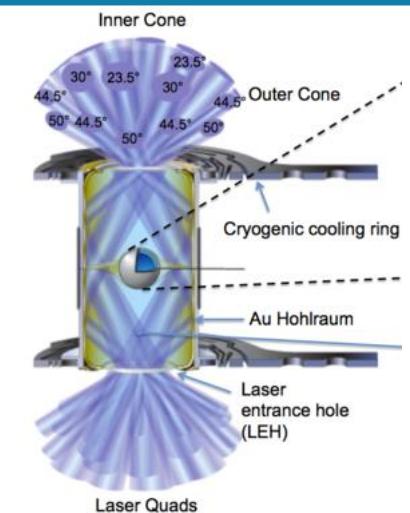
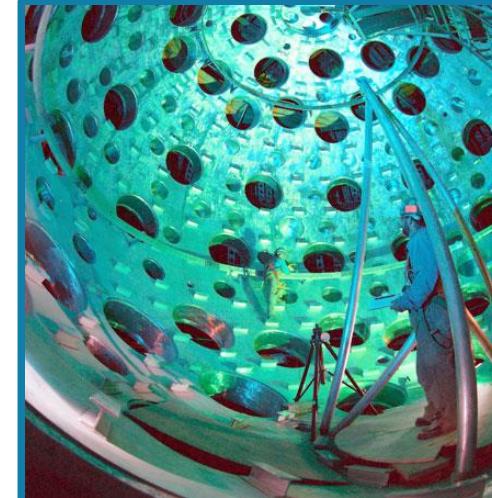


Department of Energy's National Nuclear Security Administration (NNSA)

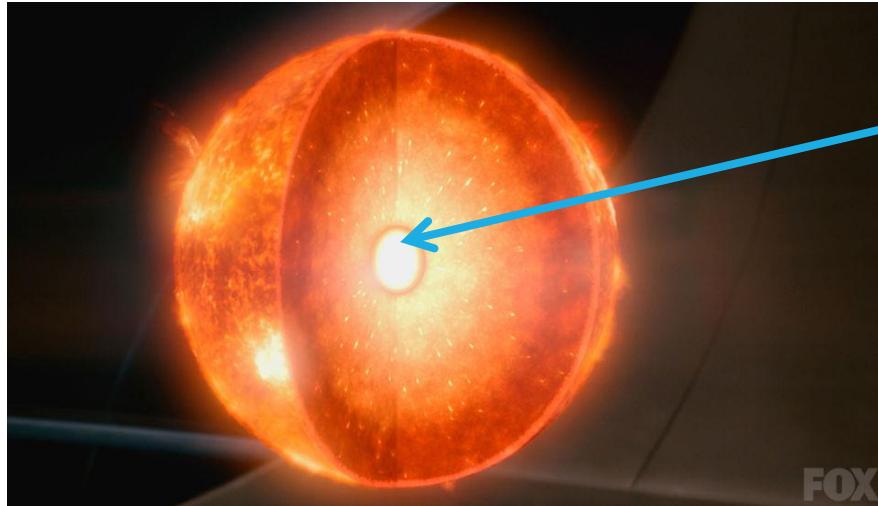


National ignition Facility

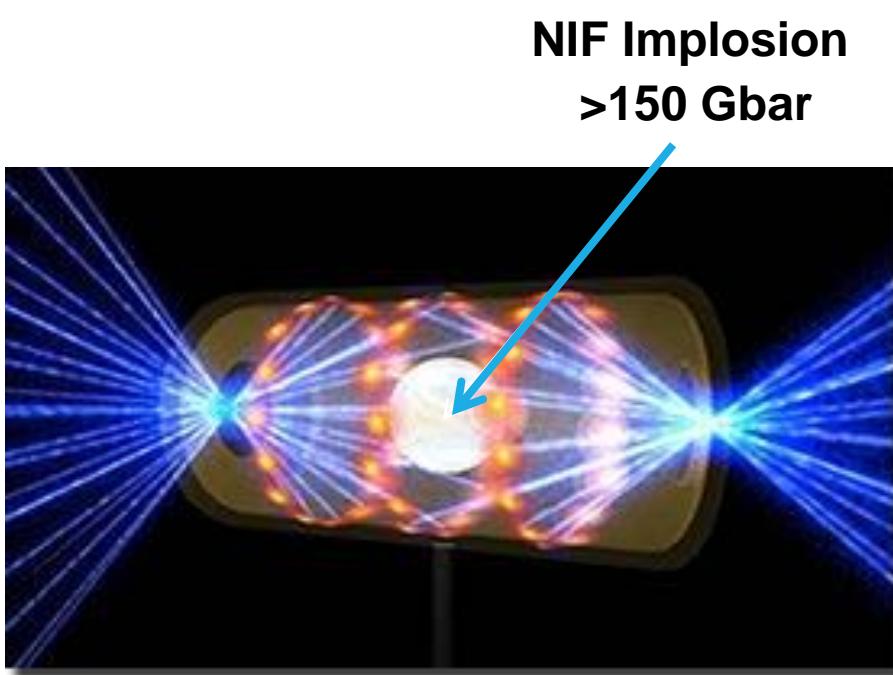
Lawrence Livermore National Lab



Un camino para obtener plasmas en condiciones extremas: irradiación de matrices de nanohilos alineados empleando laseres de intensidades relativistas

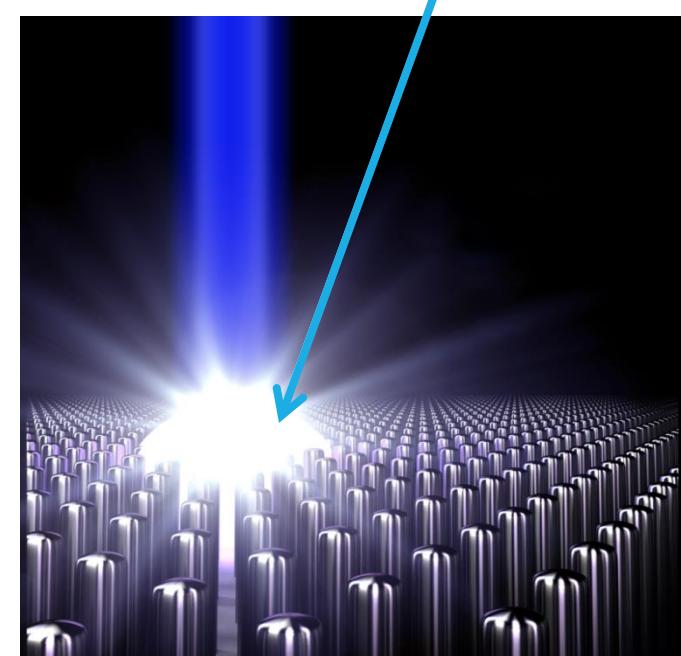


**Sun Core
240 Gbar**



**NIF Implosion
>150 Gbar**

Nanowire array plasma
 $I = 1 \times 10^{22} \text{ W cm}^{-2}$
 $> 300 \text{ Gbar}$ (estimación numérica)



UHED EN LABORATORIOS UNIVERSITARIOS

- Se podría llegar a condiciones de presión cercana a aquellas en el centro de las estrellas.
- Crear las condiciones para generar pulsos ultracortos rayos X con energías > 1 KeV con eficiencia record
- Crear fusión nuclear con gran eficiencia producción de neutrones
- Estudiar física atómica en condiciones de extrema temperatura y densidad (por ejemplo el transporte de radiación, opacidad, ecuaciones de estado)



INDICE

- Aleph: Advanced Laser for Extreme Photonics
- Interacción láseres de intensidad relativista y electrones
- Creación de plasmas altamente ionizados a partir de irradiación con láseres de intensidad relativista de blancos sólidos y blancos nanoestructurados.
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- Experimentos con intensidades “relativisticamente altas”
 - Nanohilos de polímero deuterado: energía y eficiencia de emisión de electrones, flujo de rayos gamma, rayos x y neutrones
 - Nanohilos metálicos: record en grado de ionización

3.3 Hz, 0.85 PW- Ti:Sapphire Laser System



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

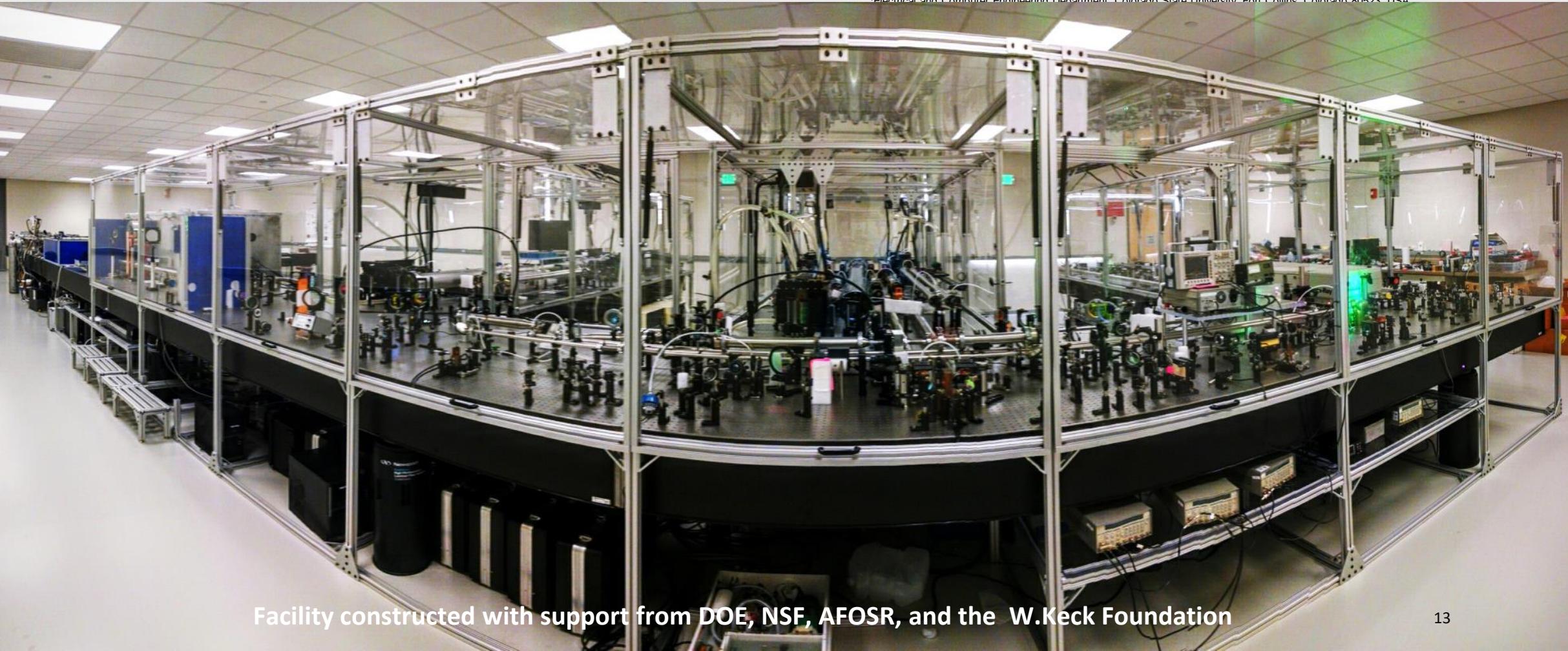
Letter

Optics Letters

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

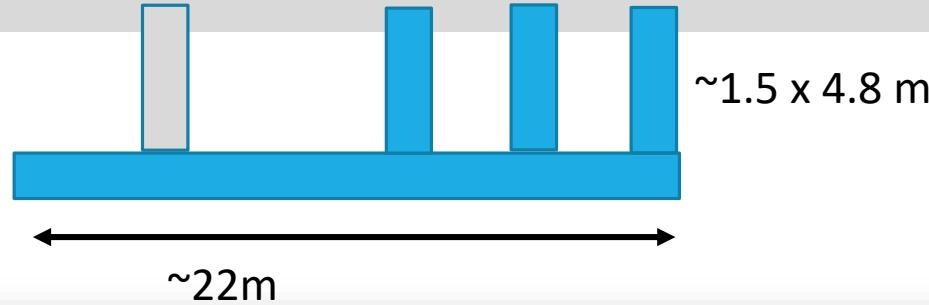
YONG WANG,^{1,†,*} SHOUJUN WANG,^{1,†} ALEX ROCKWOOD,^{2,†} BRADLEY M. LUTHER,³ REED HOLLINGER,¹
ALDEN CURTIS,¹ CHASE CALVI,² CARMEN S. MENONI,^{1,3} AND JORGE J. ROCCA^{1,2}

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



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

3.3 Hz, 0.85 PW- Ti:Sapphire Laser System

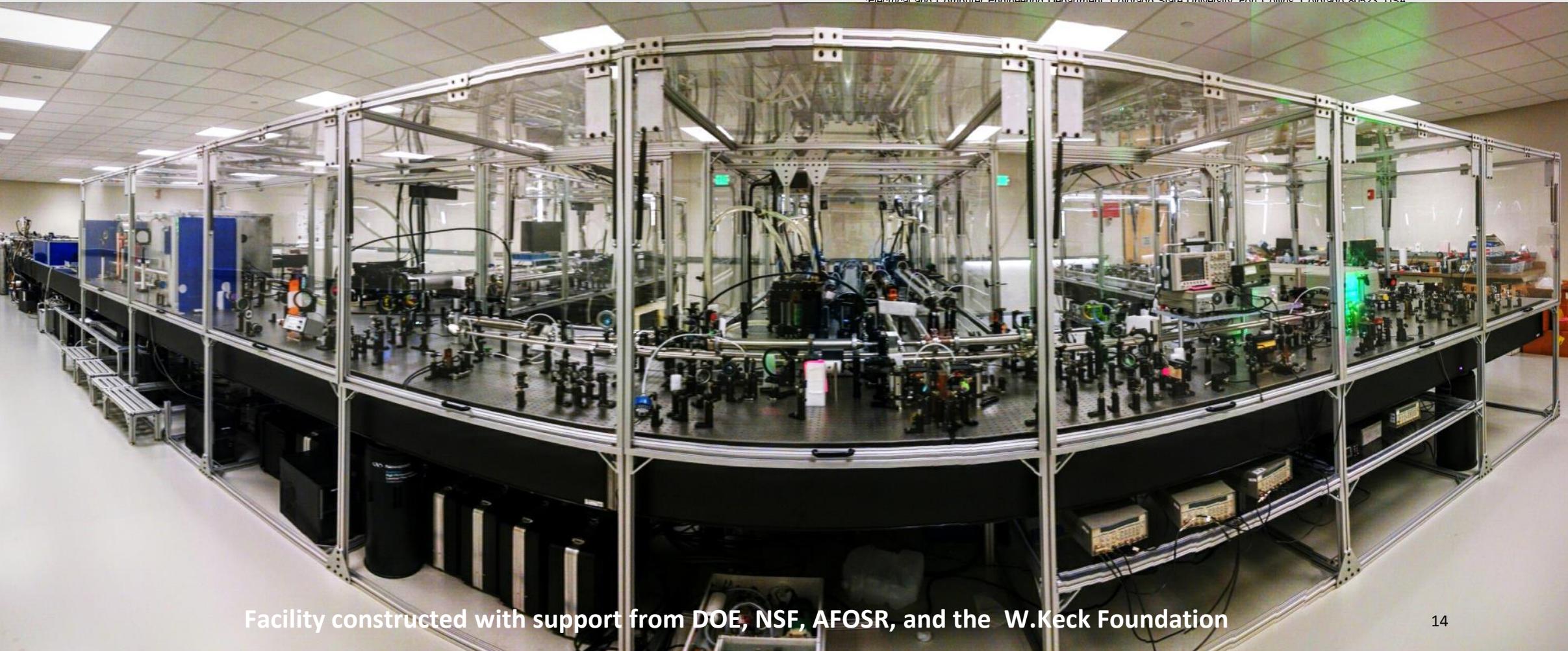


Optics Letters

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

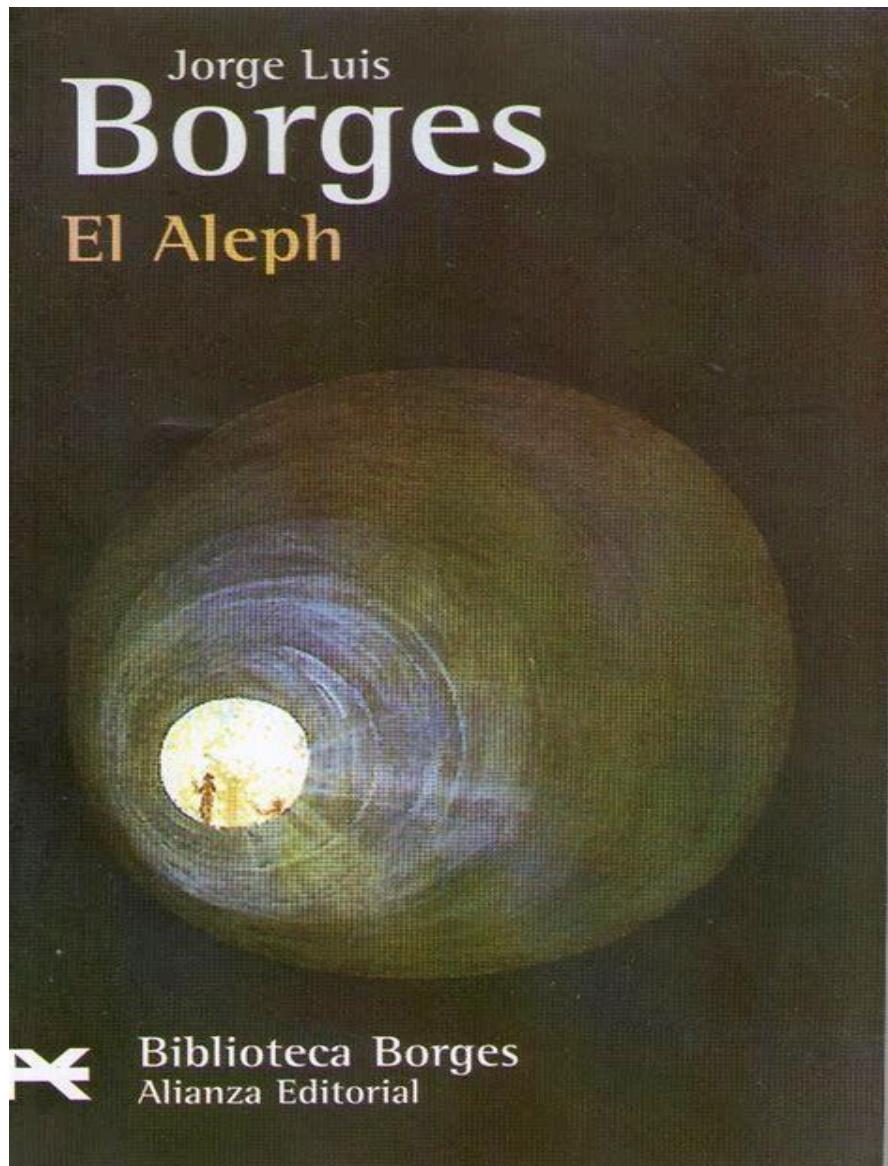
YONG WANG,^{1,†,*} SHOUJUN WANG,^{1,†} ALEX ROCKWOOD,^{2,†} BRADLEY M. LUTHER,³ REED HOLLINGER,¹ ALDEN CURTIS,¹ CHASE CALVI,² CARMEN S. MENONI,^{1,3} AND JORGE J. ROCCA^{1,2}

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ALEPH: Advanced Laser for Extreme Photonics



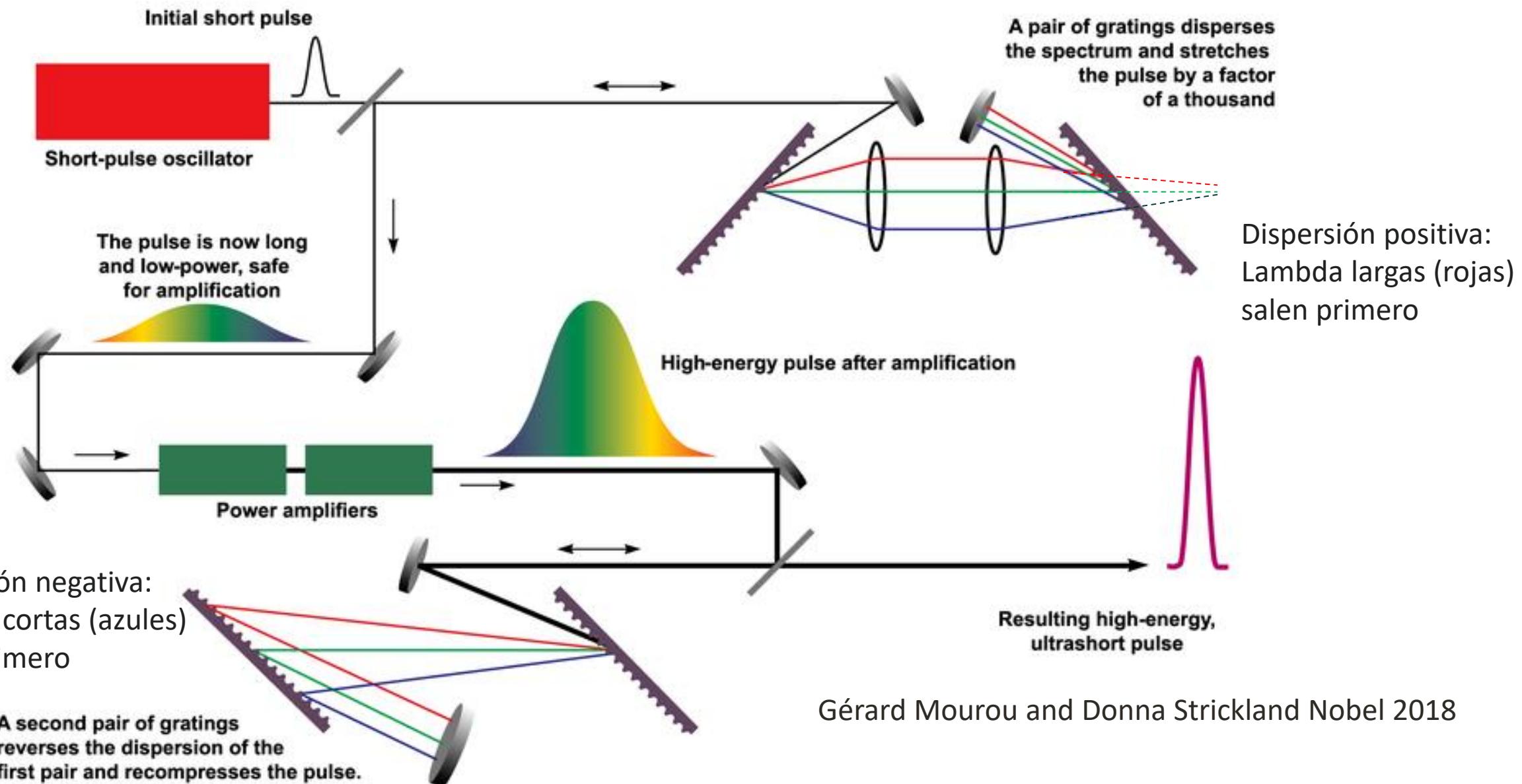
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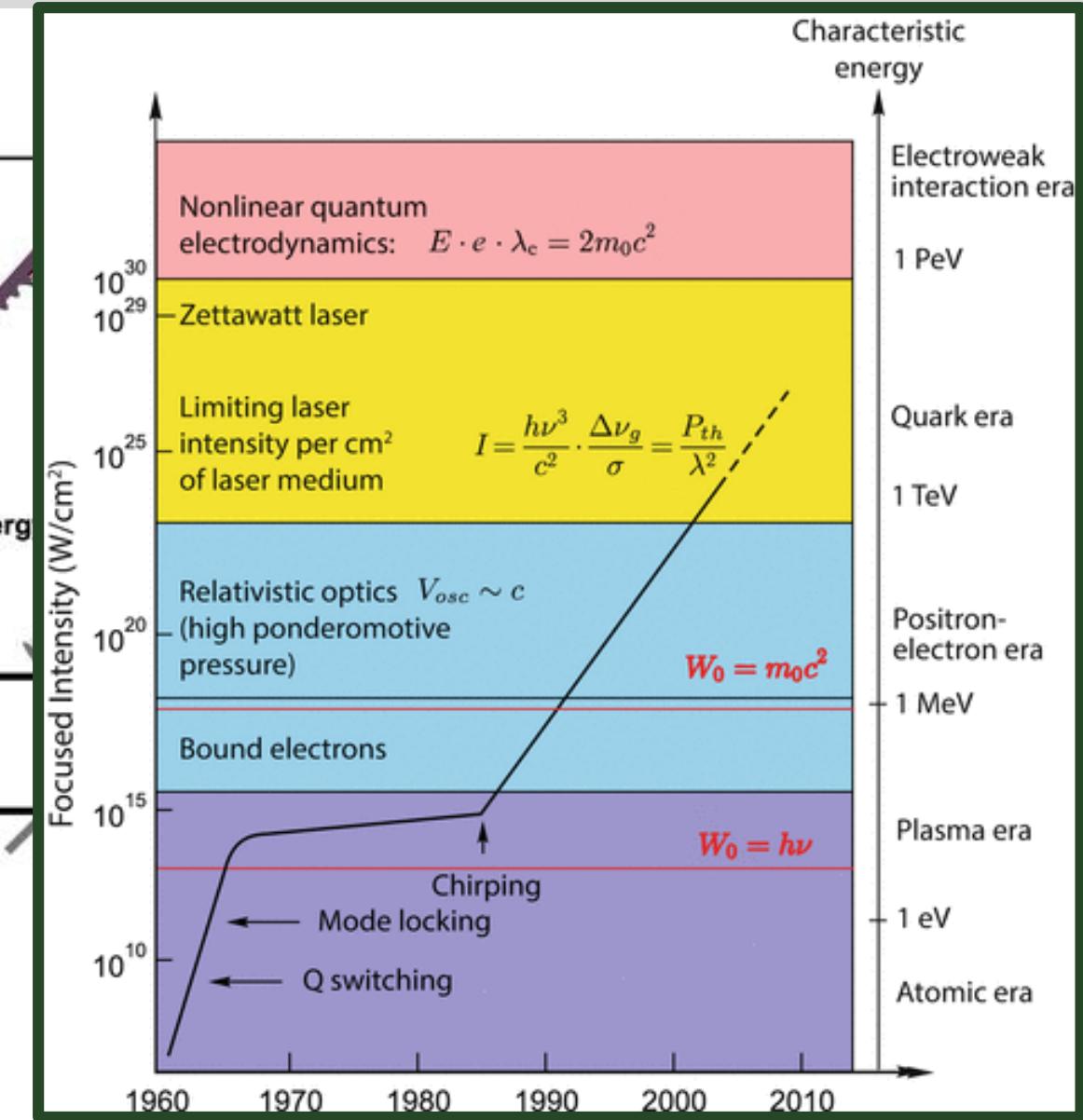
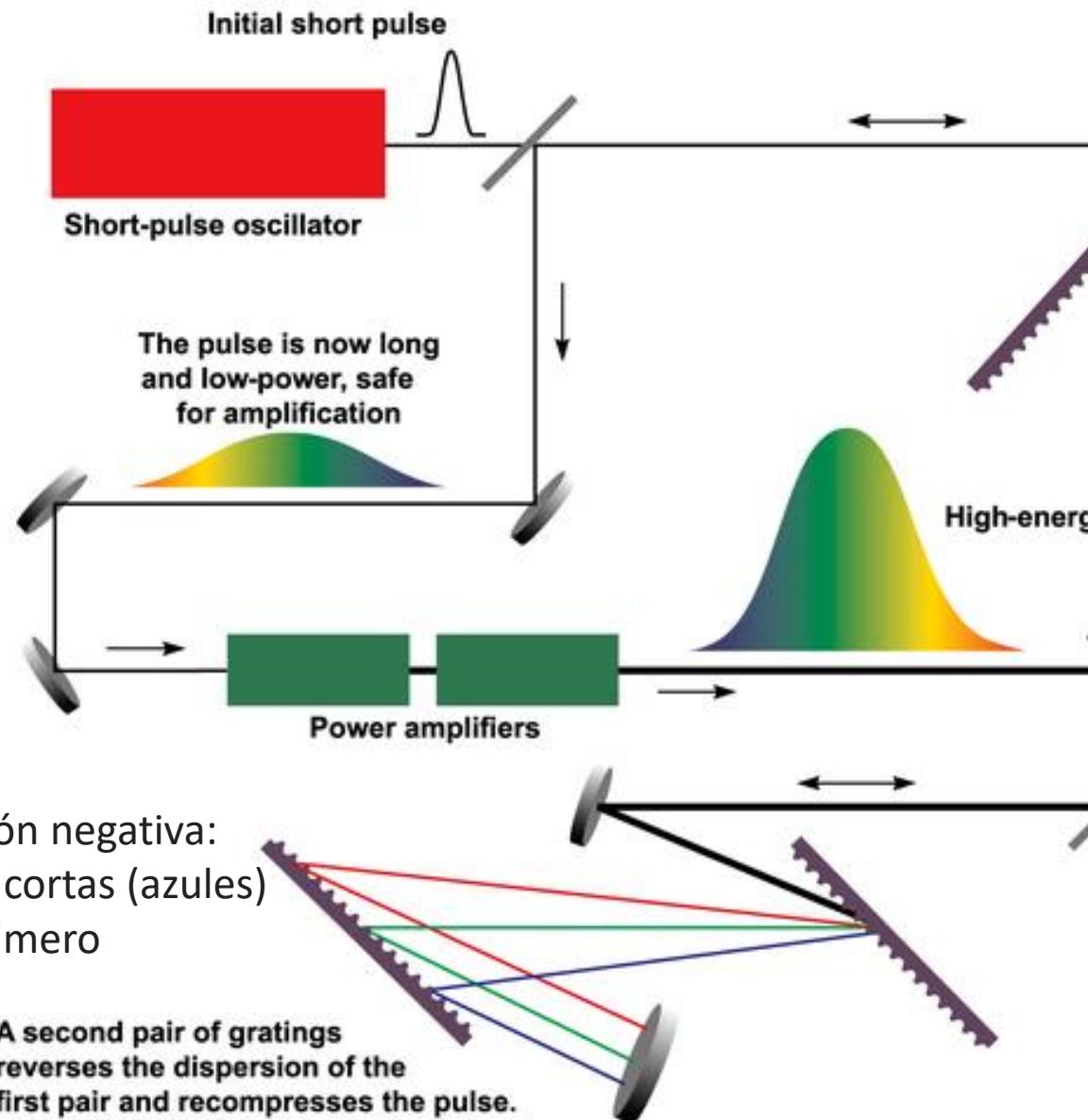
"vi una pequeña esfera tornasolada, de casi intolerable fulgor."

JLB

Concepto general de funcionamiento: Pulsed chirped amplification

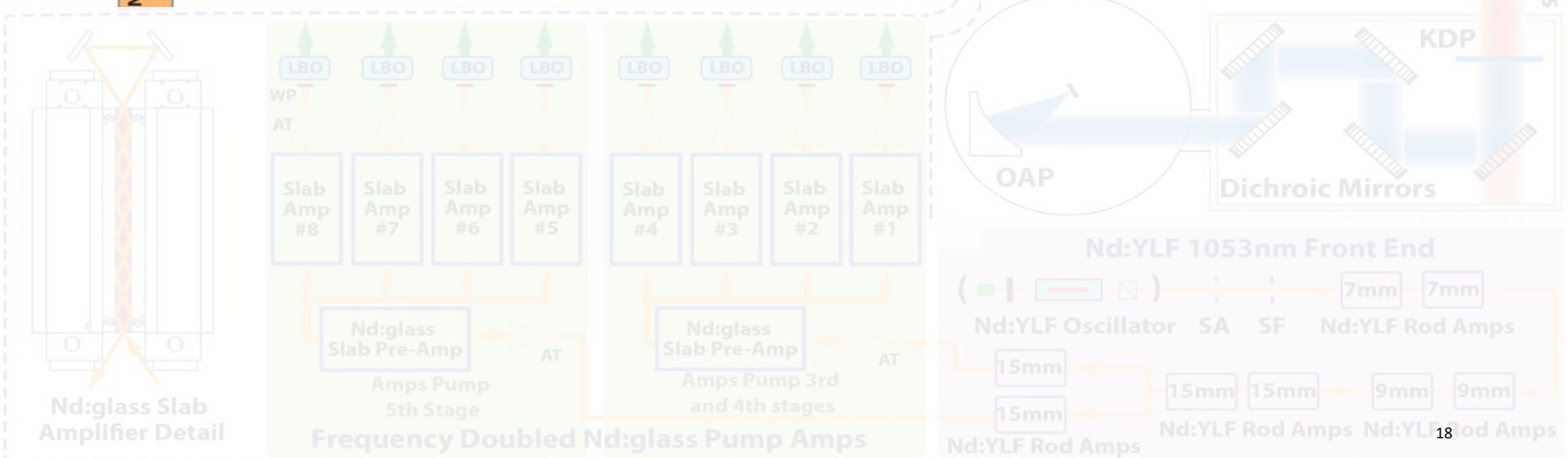
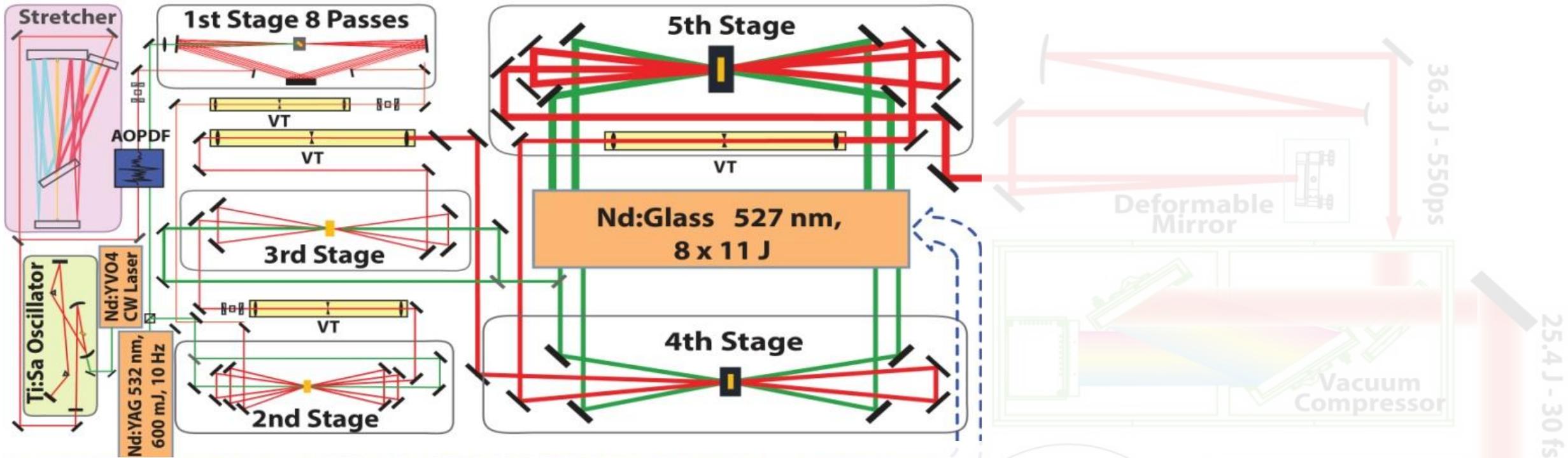


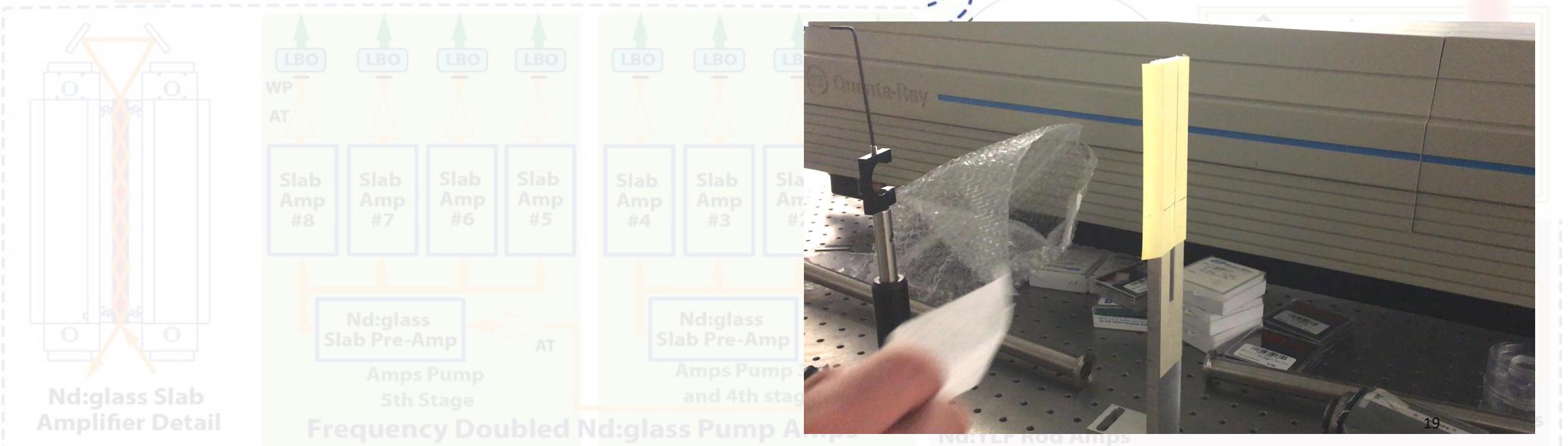
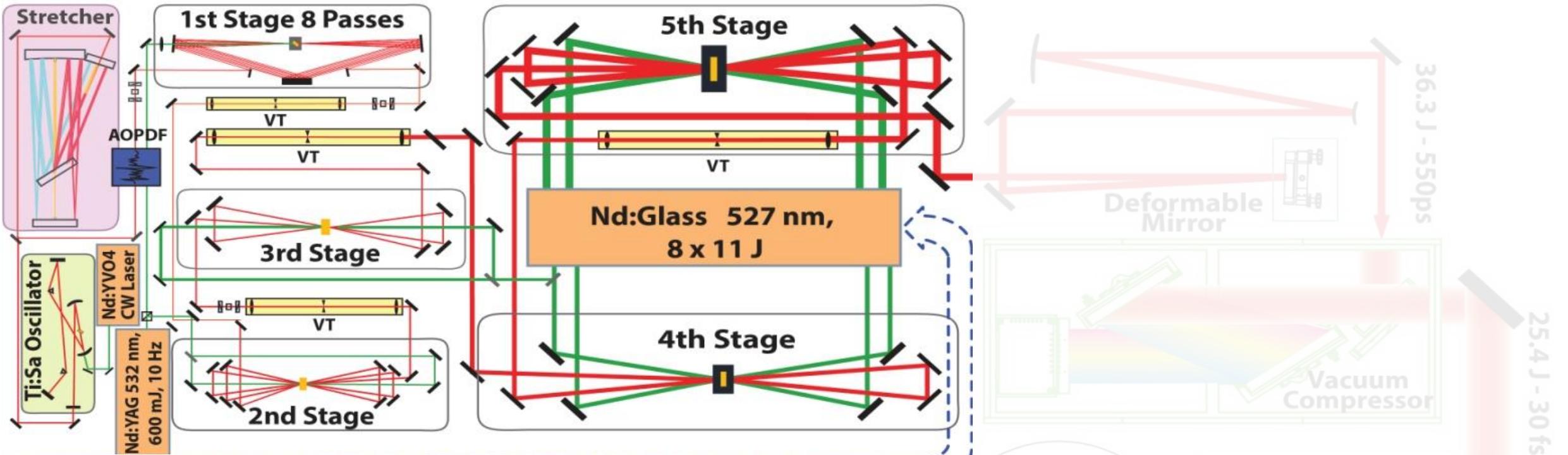
Concepto general de funcionamiento: Pulsed chirped amplification

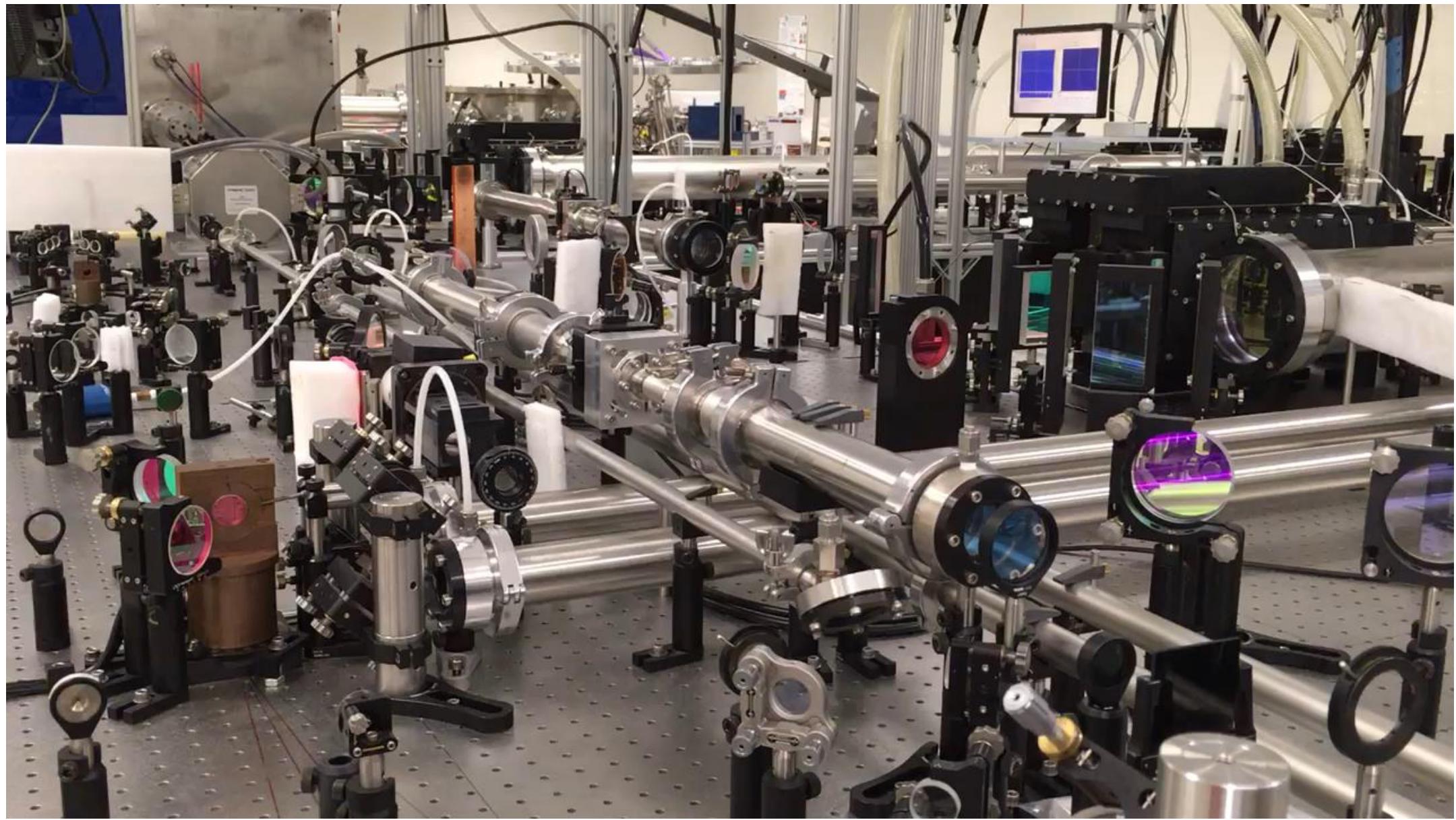


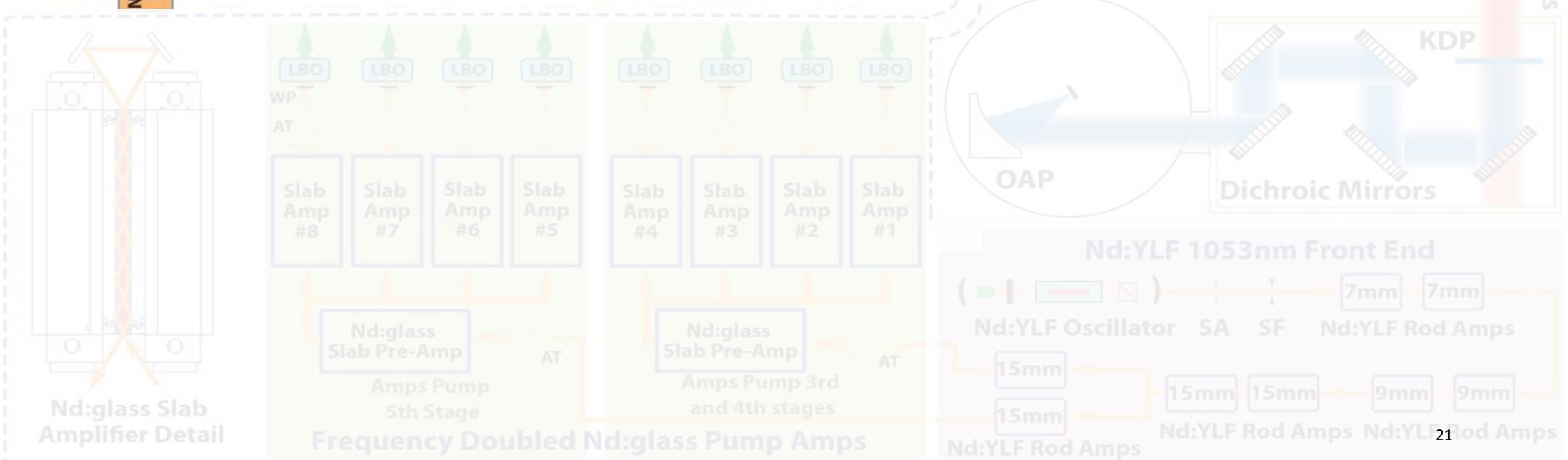
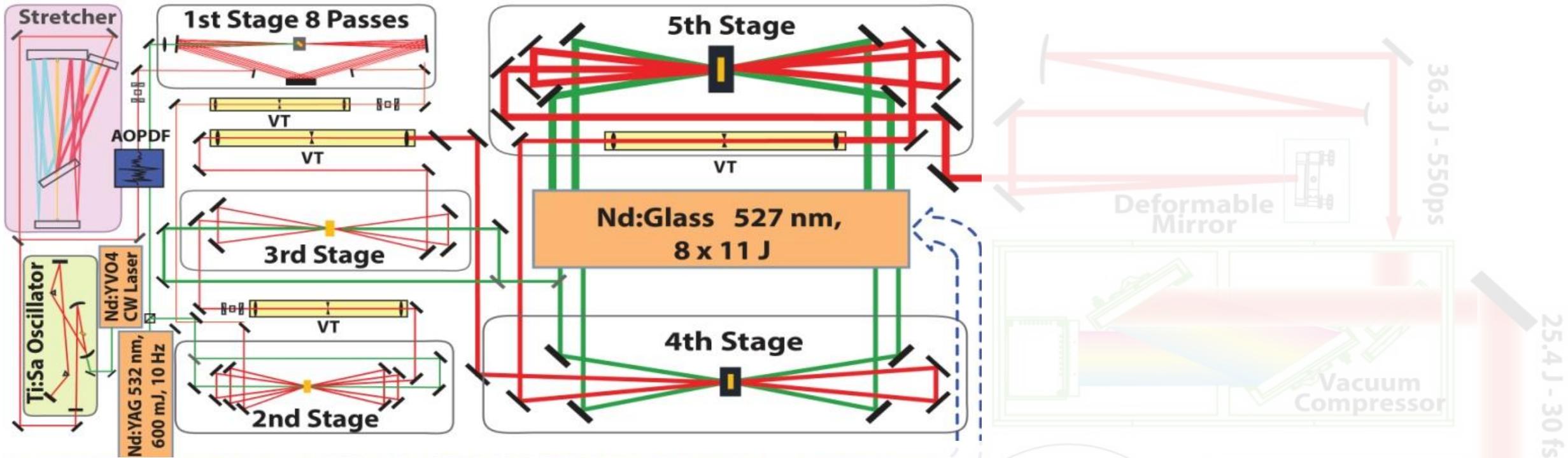
Dispersión negativa:
Lambda cortas (azules)
salen primero

A second pair of gratings
reverses the dispersion of the
first pair and recompresses the pulse.

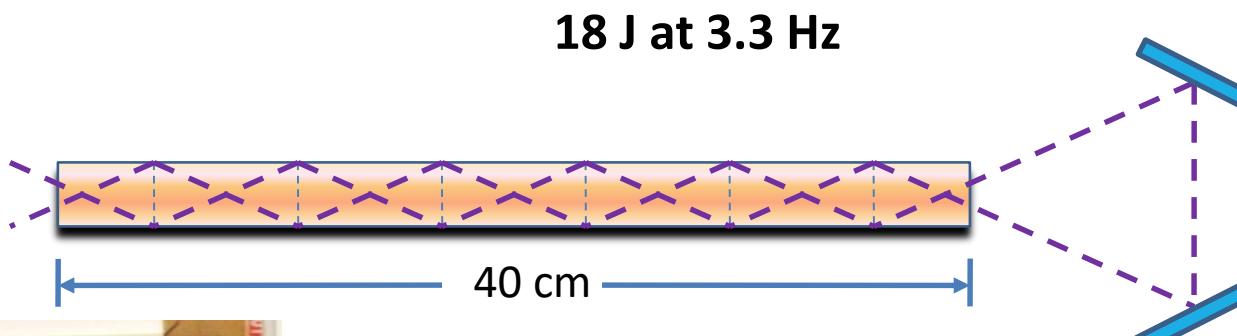
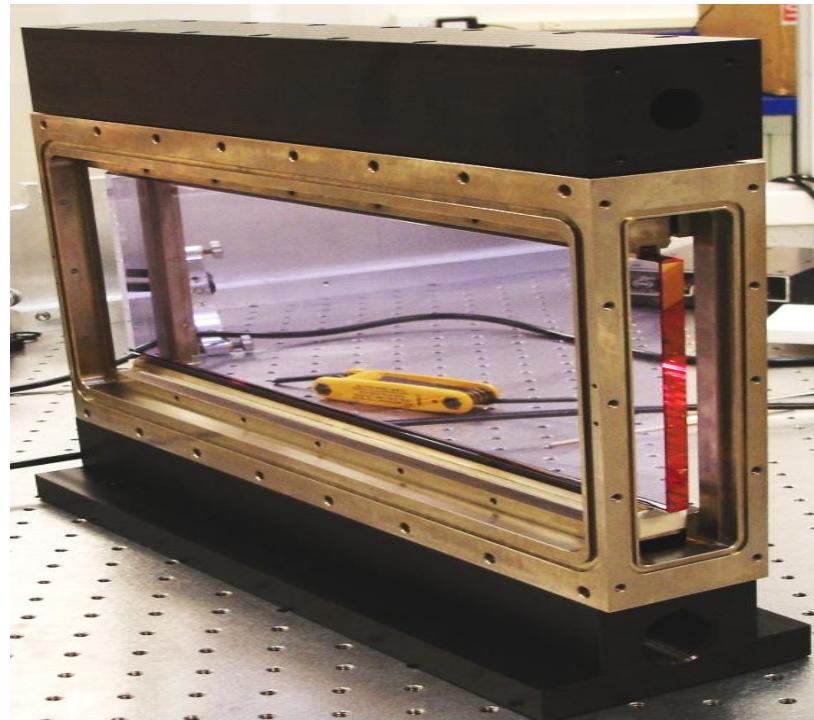




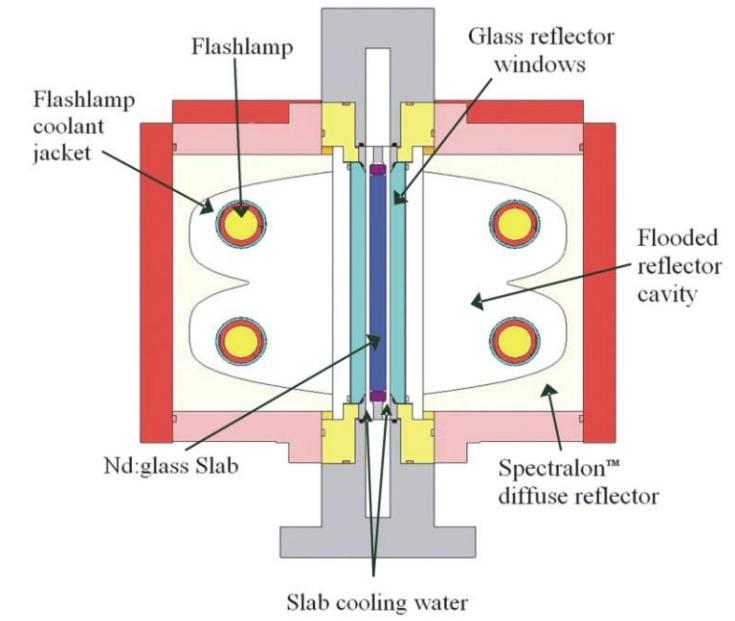
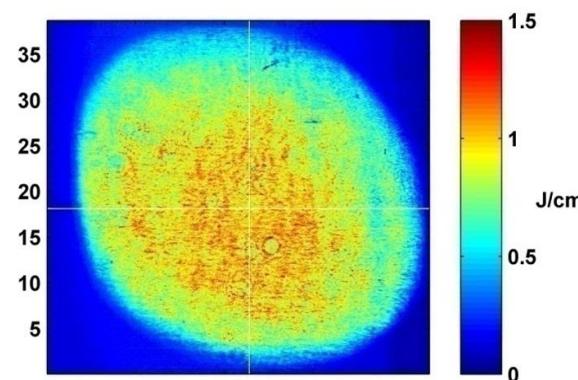




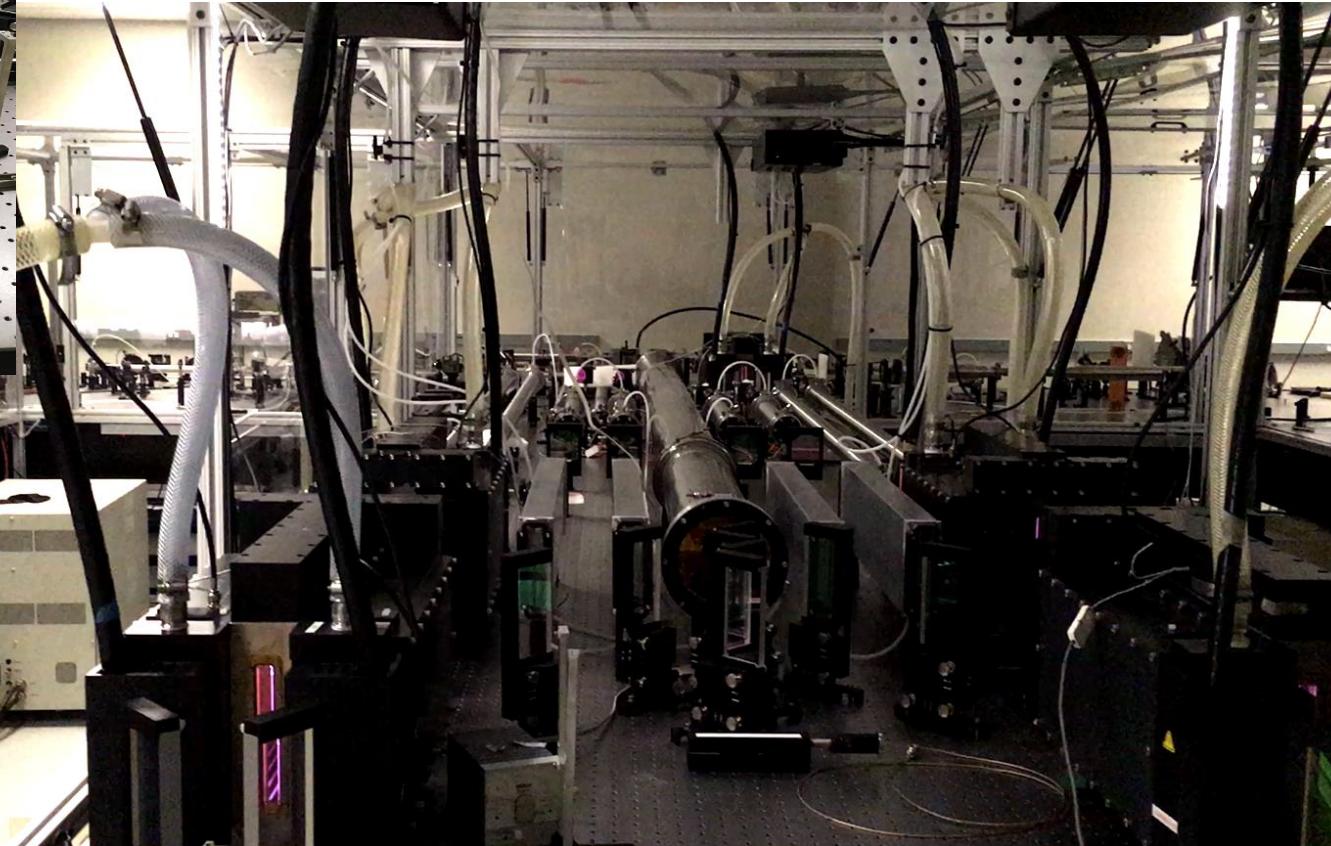
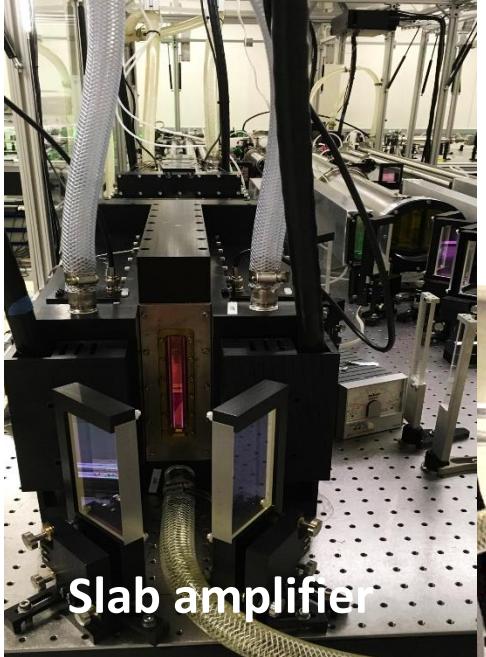
SLAB AMPLIFIER ON DOUBLE-PASS CONFIGURATION

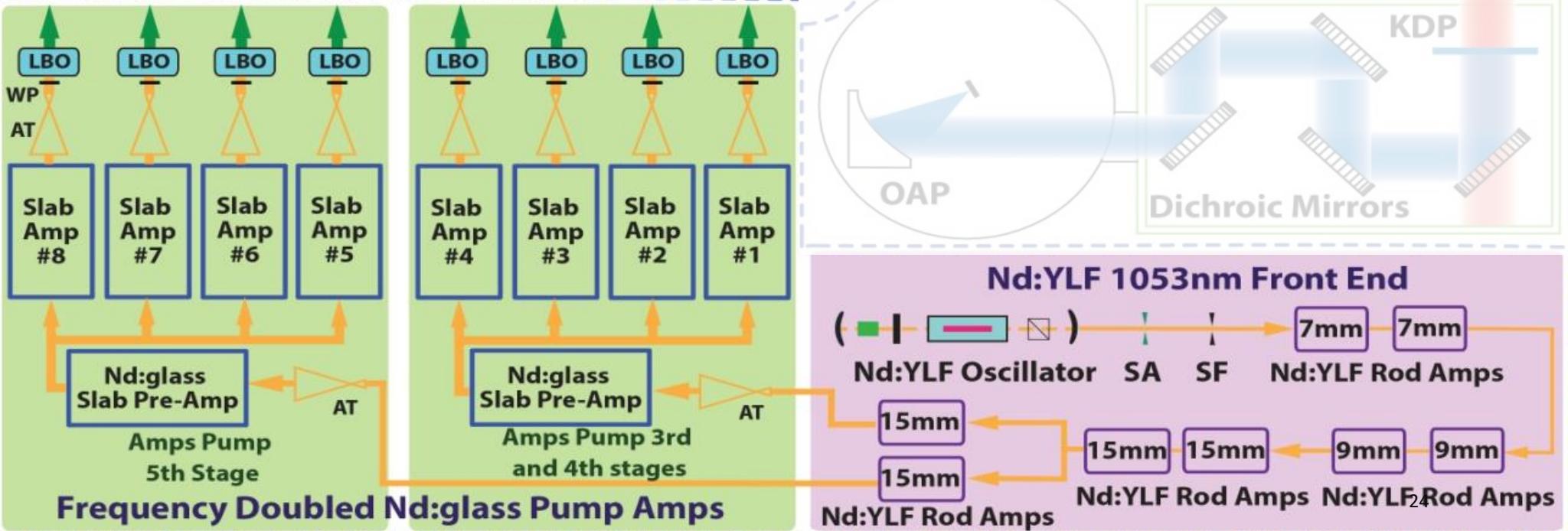
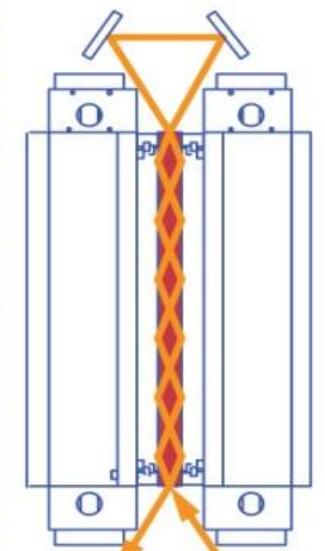
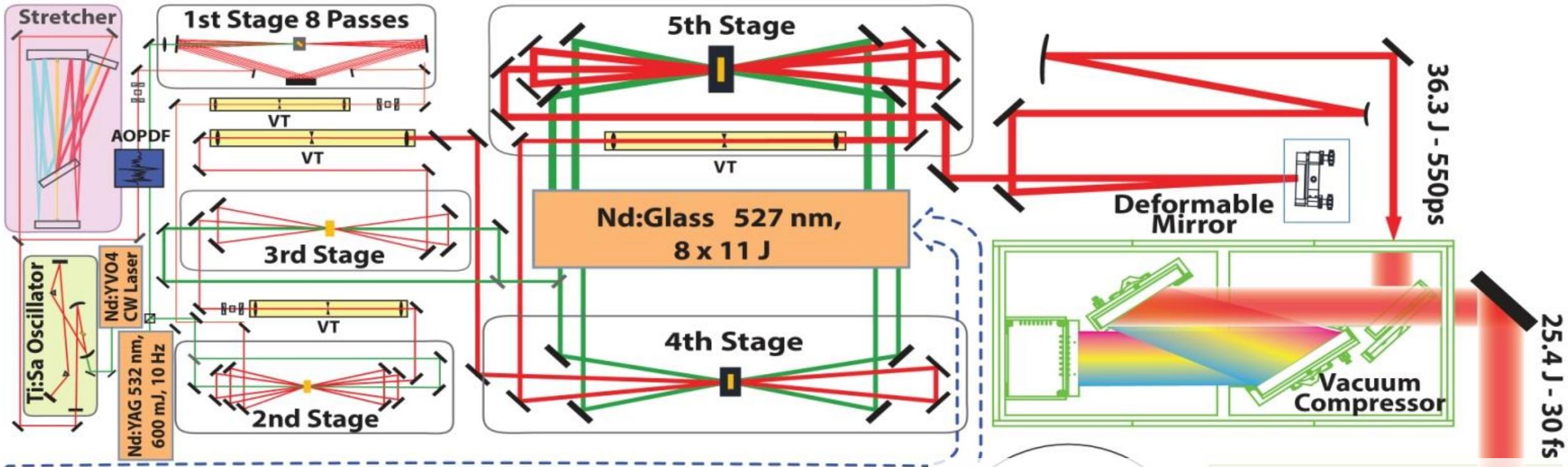


Good beam uniformity

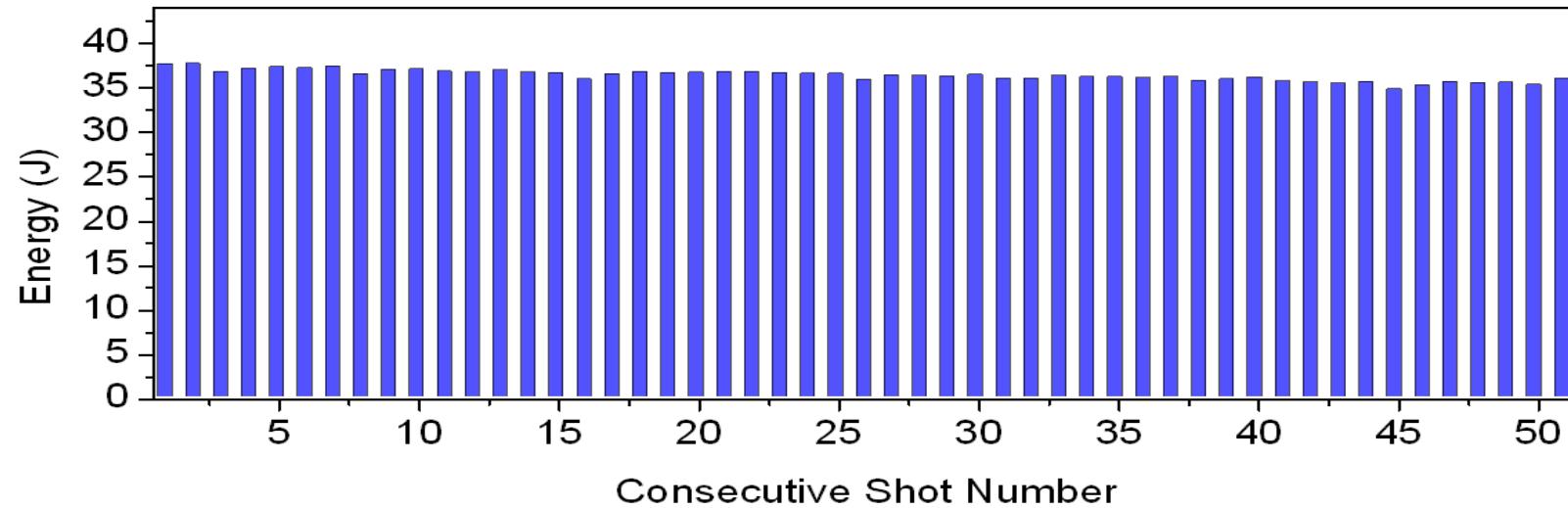


Pump laser slab amplifiers for 36 J ti:sapphire amplifier operating at 3.3 hz repetition rate

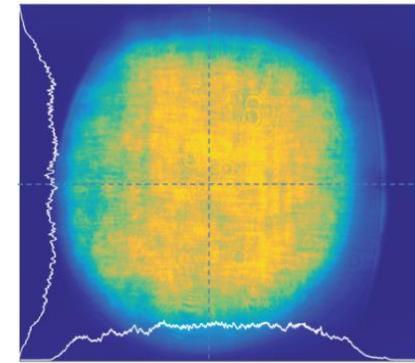




3.3 Hz laser run, 36.3 J average energy before compressor



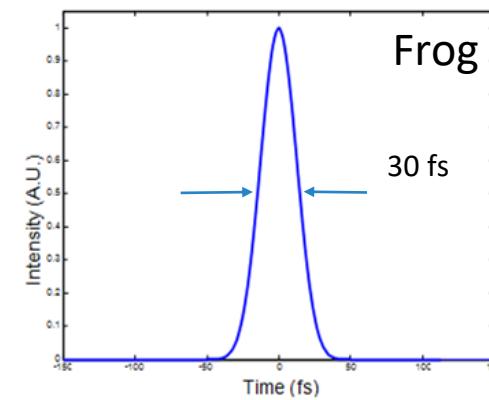
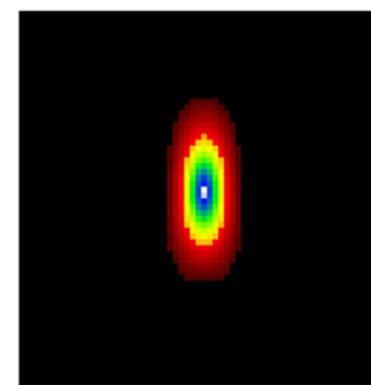
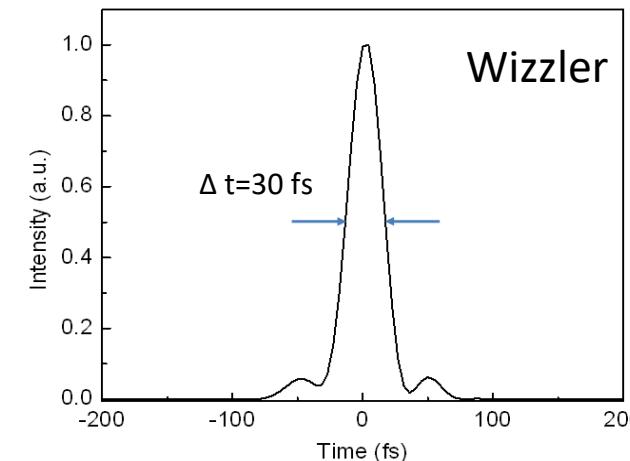
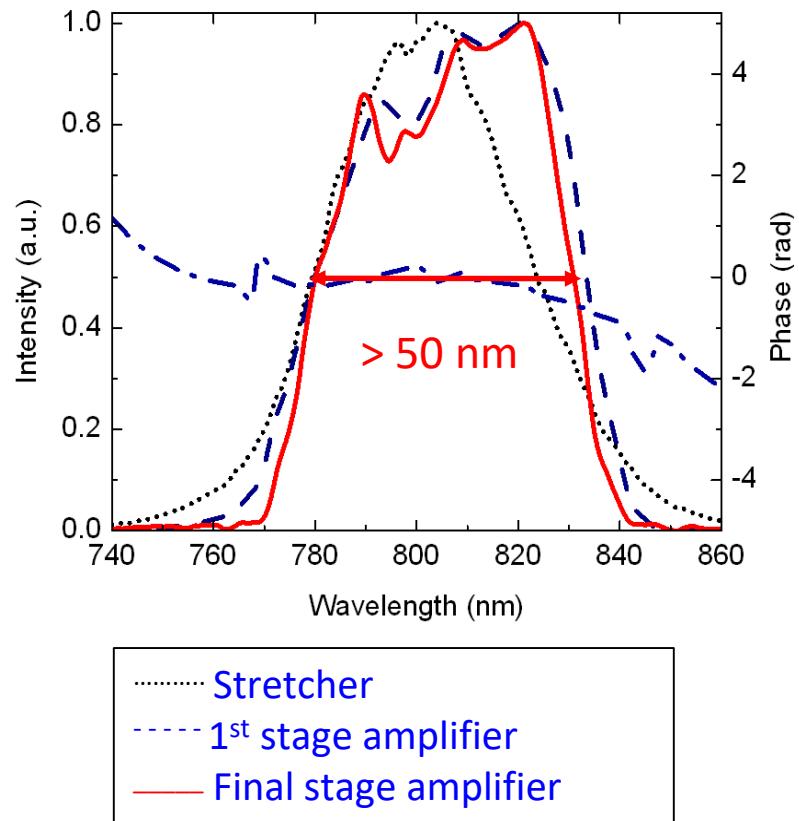
- Average pulse energy 36.3 J
- Shot-to-shot variation ~1.7% rms



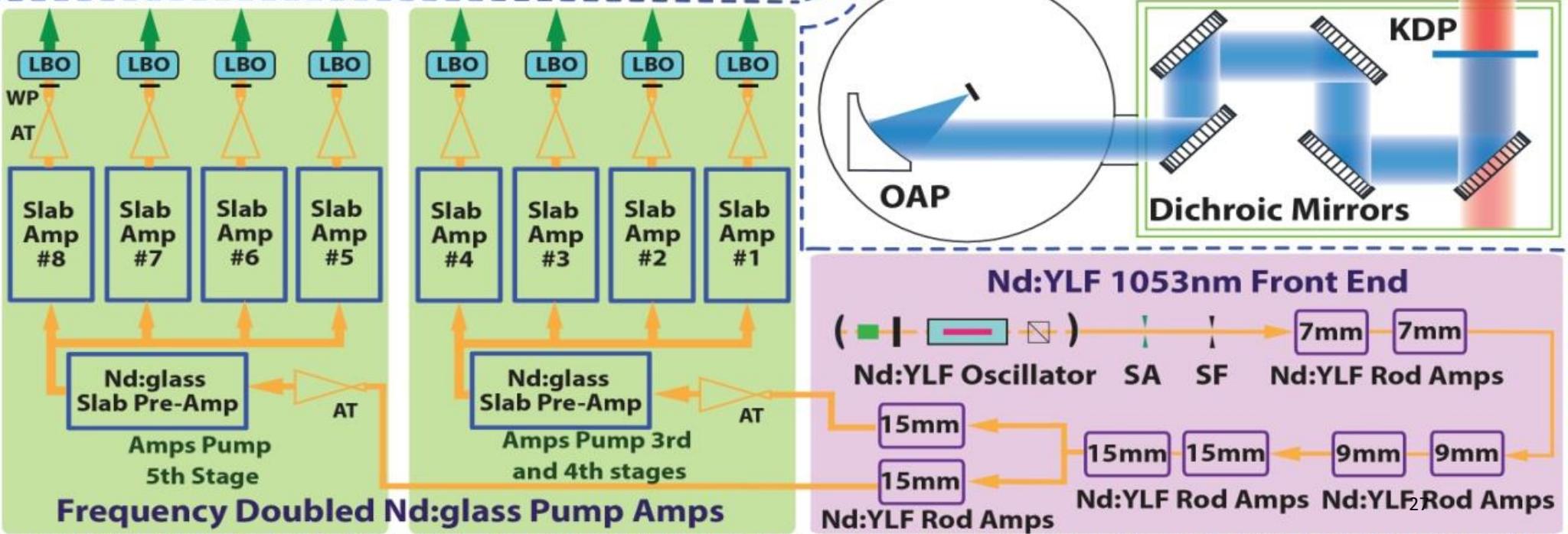
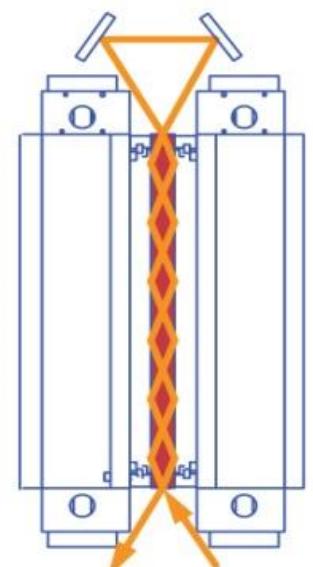
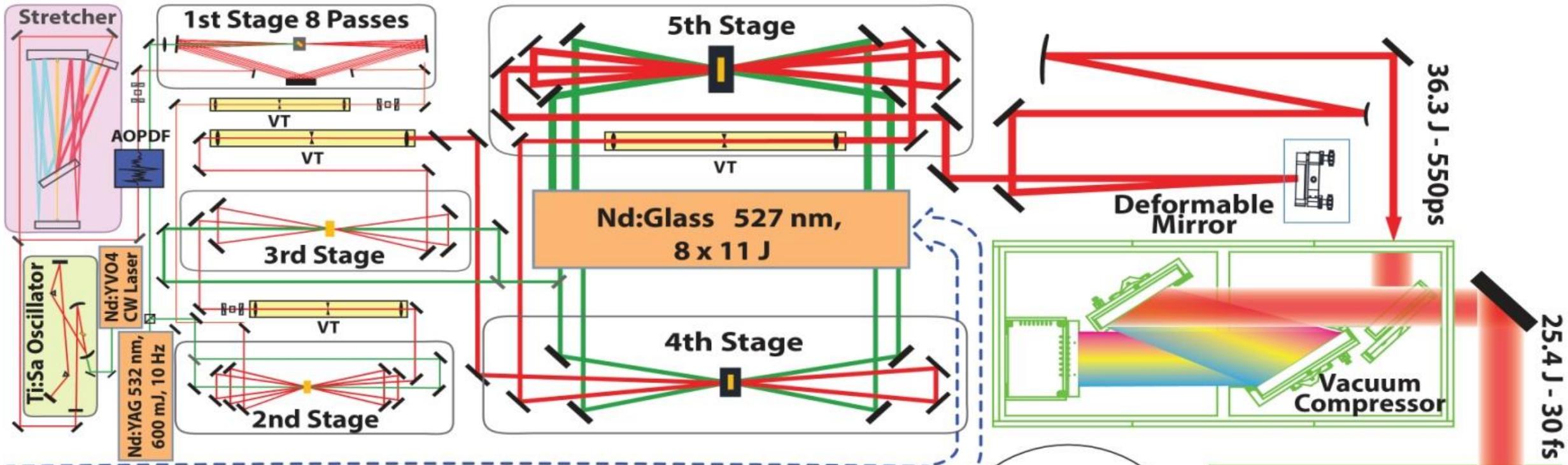
Spatial beam profile

Laser spectra, 30 fs pulse duration

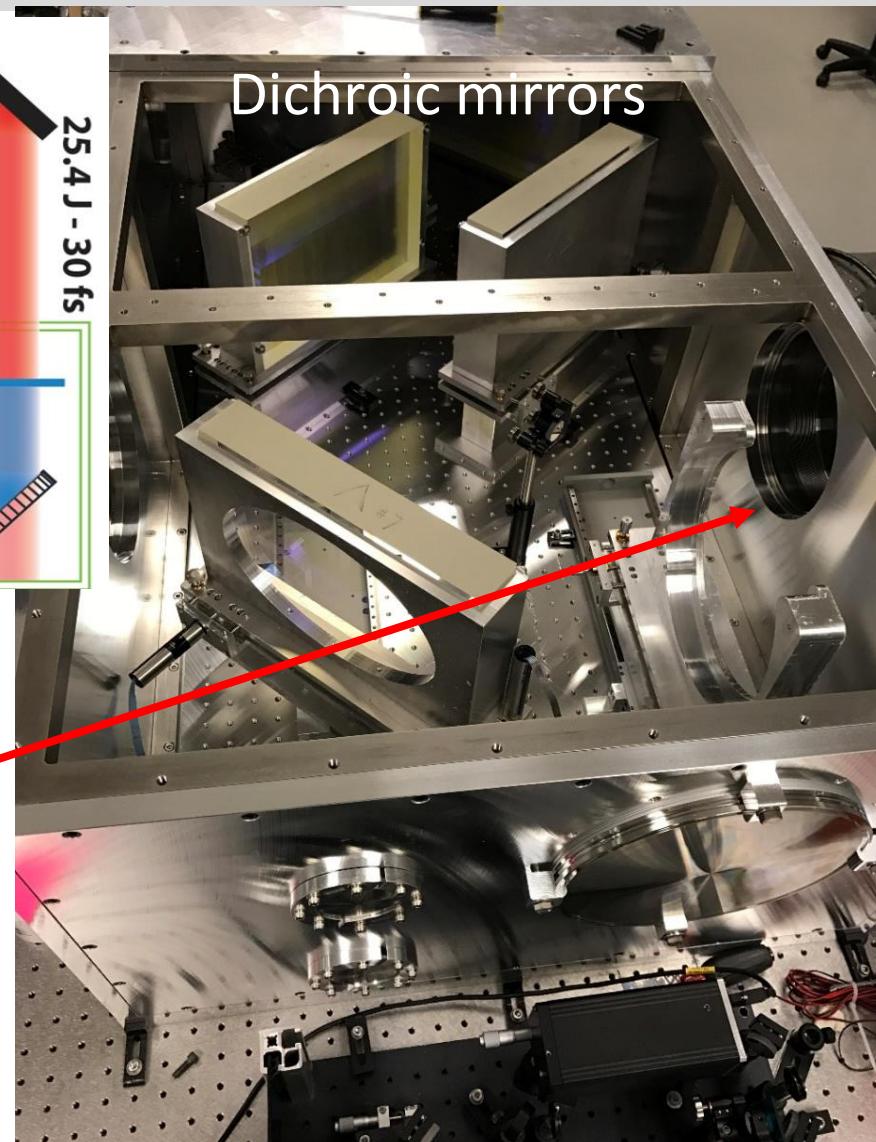
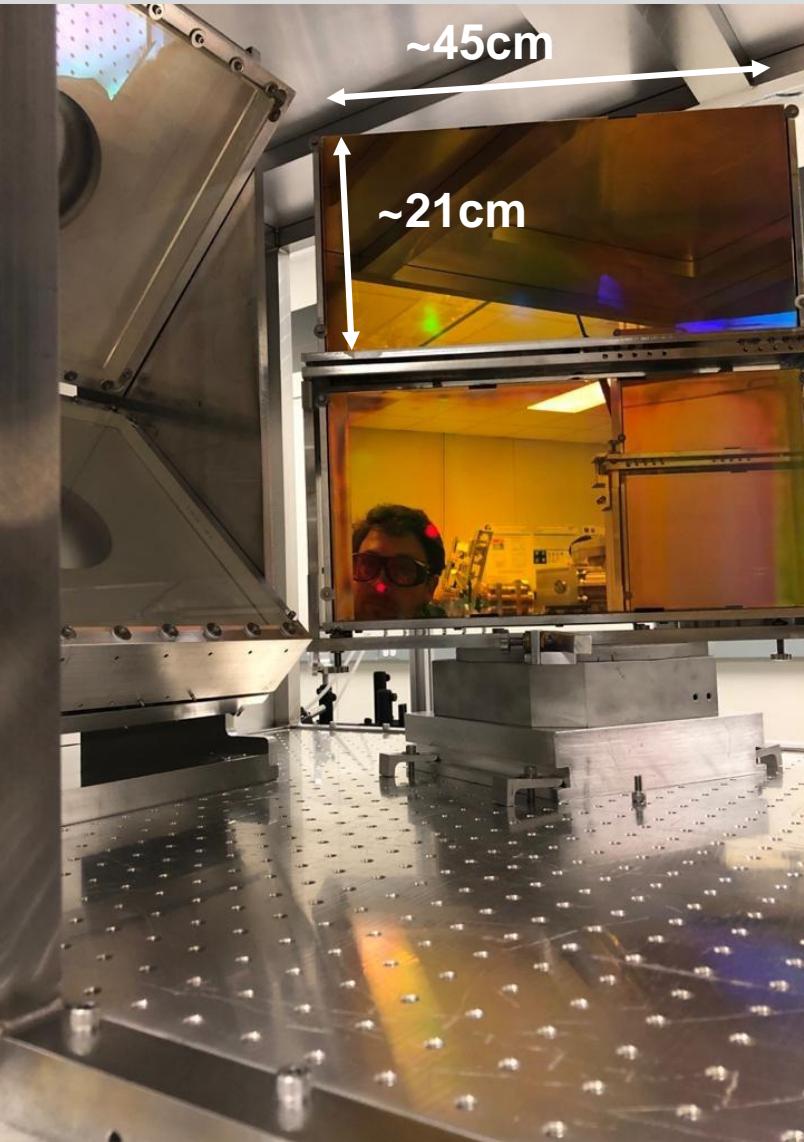
laser spectra through the system



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

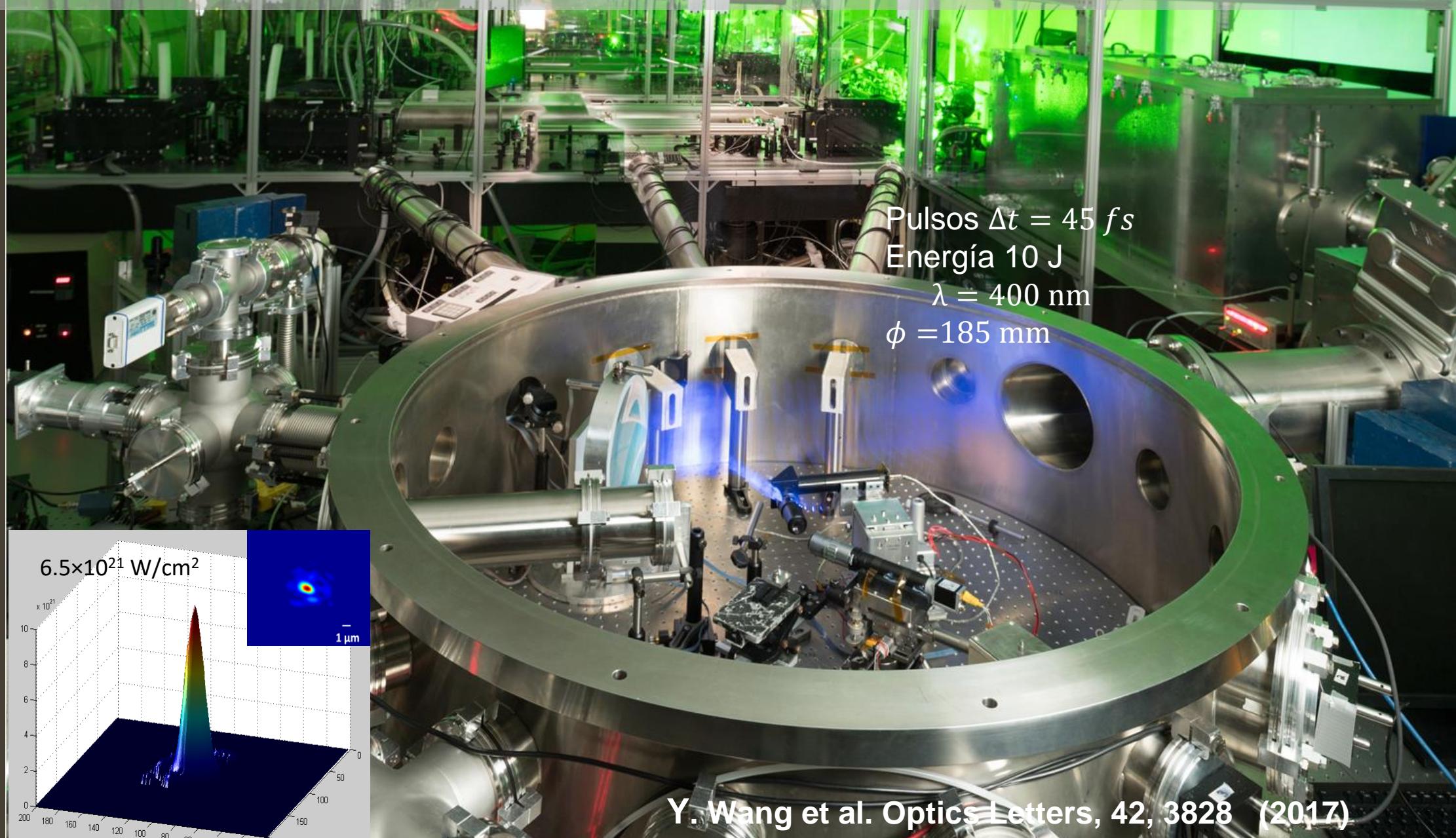


Ultra-high contrast pulses: $> 1 \times 10^{12}$ Frequency Doubling and filtering of fundamental beam



f/2 parabola achieves $6.5 \times 10^{21} \text{ W/cm}^2$ ($\gg I_R \sim 10^{19} \text{ W cm}^{-2}$ @400nm)

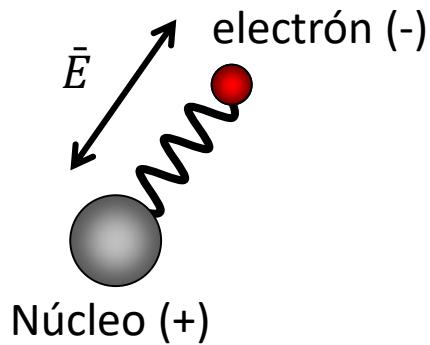
High contrast ($> 1 \times 10^{-12}$) in second harmonic beamline



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Fotónica lineal, no lineal y relativista

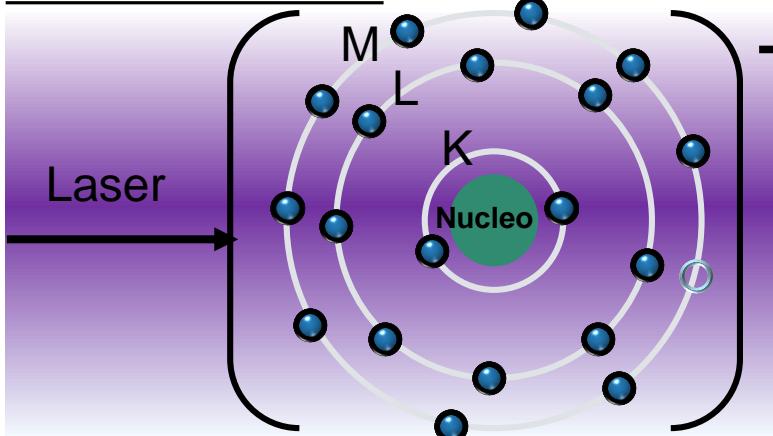


Fenómenos lineales

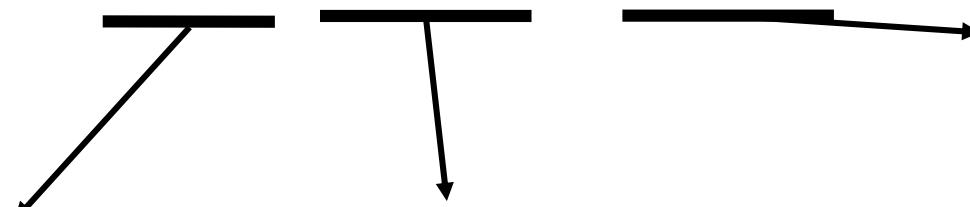
$$n(\omega) = \sqrt{\varepsilon(\omega)} = \sqrt{1 + \chi_{ij}^{(1)}(\omega)}$$

$$\omega = \frac{c}{\sqrt{\varepsilon(\omega)}} k$$

Fotónica relativista



$$P_j = \chi_{ij}^{(1)} E_j + \chi_{ijk}^{(2)} E_j E_k + \chi_{ijkl}^{(3)} E_j E_k E_l + \dots$$



Absorción de 2 fotones

Generación de tercer armónica

Auto modulación de fase

Auto-Enfoque

Mezclado de 4 ondas

...

Generación de segunda armónica

Suma de frecuencias

Diferencia de frecuencias

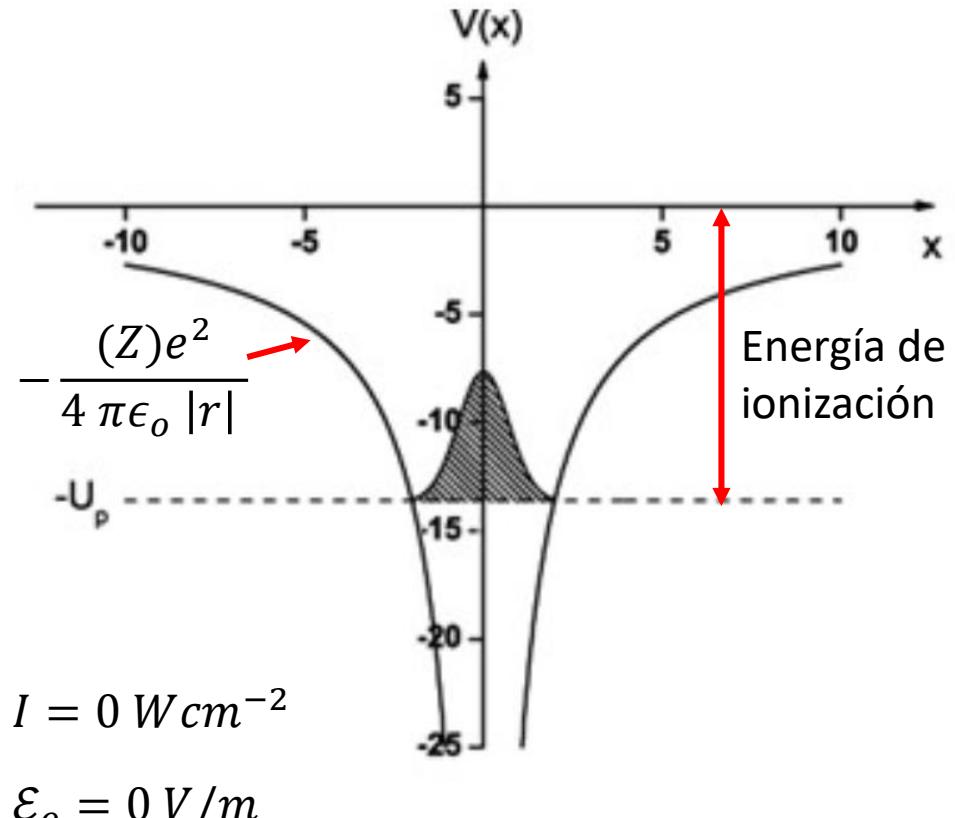
Rectificación óptica

$$E_\lambda \sim 3.1 \text{ eV} < E_{ion}$$

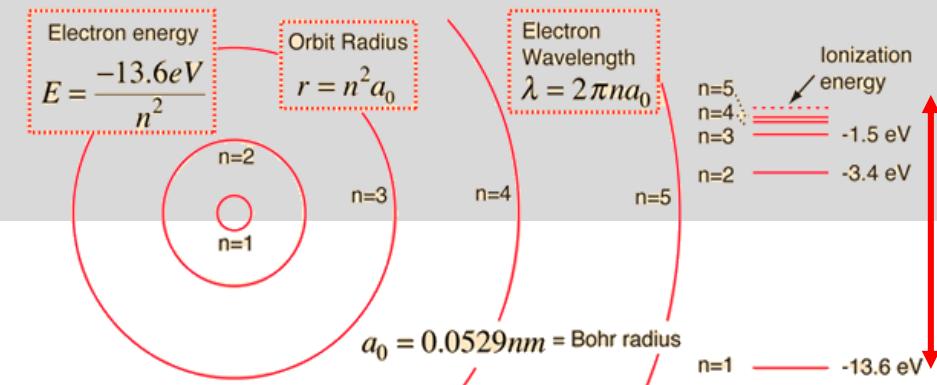
Cuales son los mecanismos de interacción y de ionización?

Mecanismos de ionización en átomos y moléculas

Átomo en ausencia de interacciones externas



Z: carga efectiva nuclear que ve el electrón



Campo eléctrico (1er radio de Bohr)

$$E_o = \frac{e}{4\pi\epsilon_0 a_0^2} \sim 5 \times 10^{11} \text{ V/m}$$

Campo óptico de igual amplitud

$$\mathbf{E}(r, t) = \hat{\mathbf{E}} e^{i(\omega t - \mathbf{k} \cdot \mathbf{r})}, I = \frac{1}{2} c \epsilon_0 \hat{\mathbf{E}} \cdot \hat{\mathbf{E}}^* \sim 3 \times 10^{16} \text{ W cm}^{-2}$$

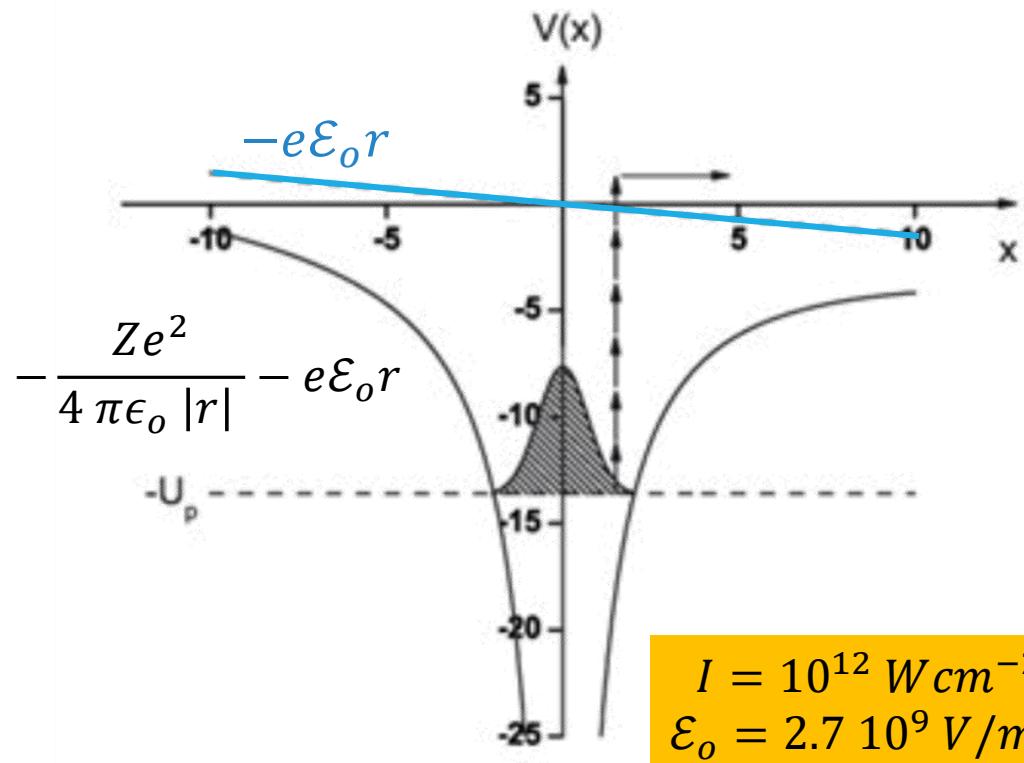
Energía de los fotones: $\lambda = 400 \text{ nm}$

$$E = h\nu = \frac{hc}{\lambda} = \frac{1240}{\lambda \text{ (nm)}} \text{ eV} = 3.1 \text{ eV} < E_{ion}$$

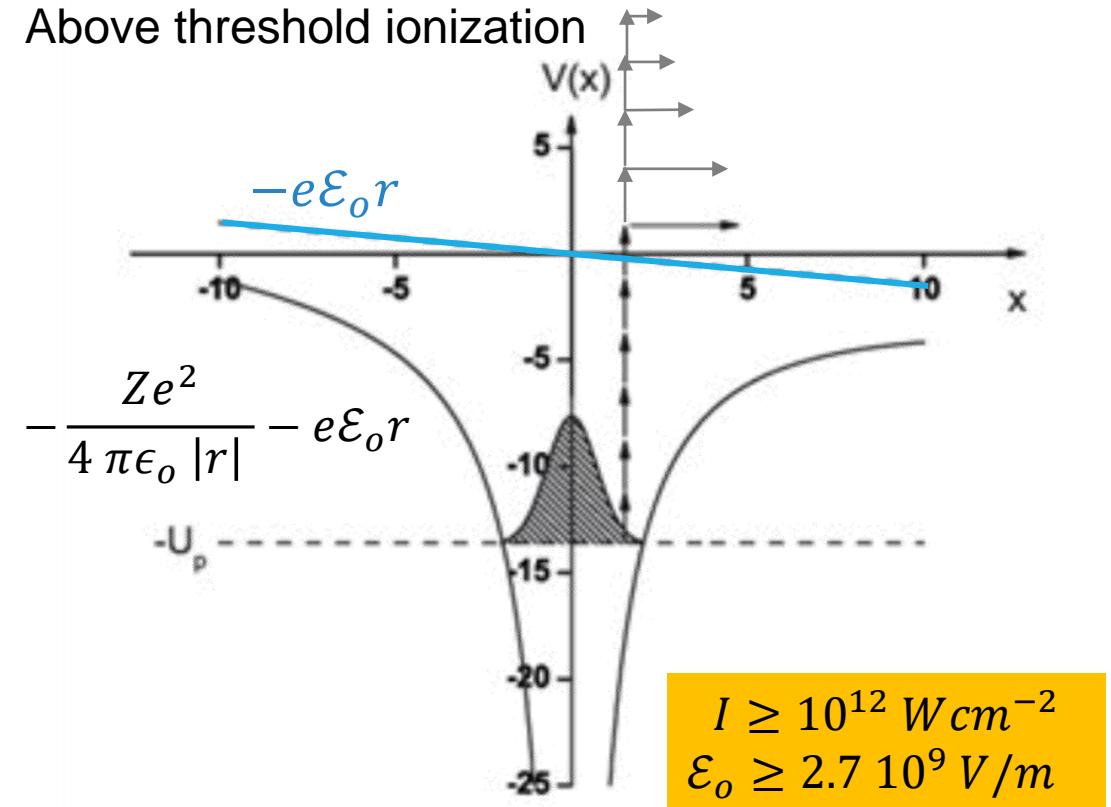
$A = (10 \mu\text{m})^2, \tau = 10 \text{ ps}$	$I \sim 3 \times 10^{16} \text{ W cm}^{-2}$	<u>State of the art lasers</u>
$P_W = I \cdot A$	$\sim 3 \times 10^{10} \text{ W}$	$\sim 1 \text{ PW}$
$\text{Energy} = P_W \cdot \tau$	$\sim 0.3 \text{ J}$	$\sim 10 \text{ kJ}$

Mecanismos de ionización en átomos y moléculas

Absorción multifotónica



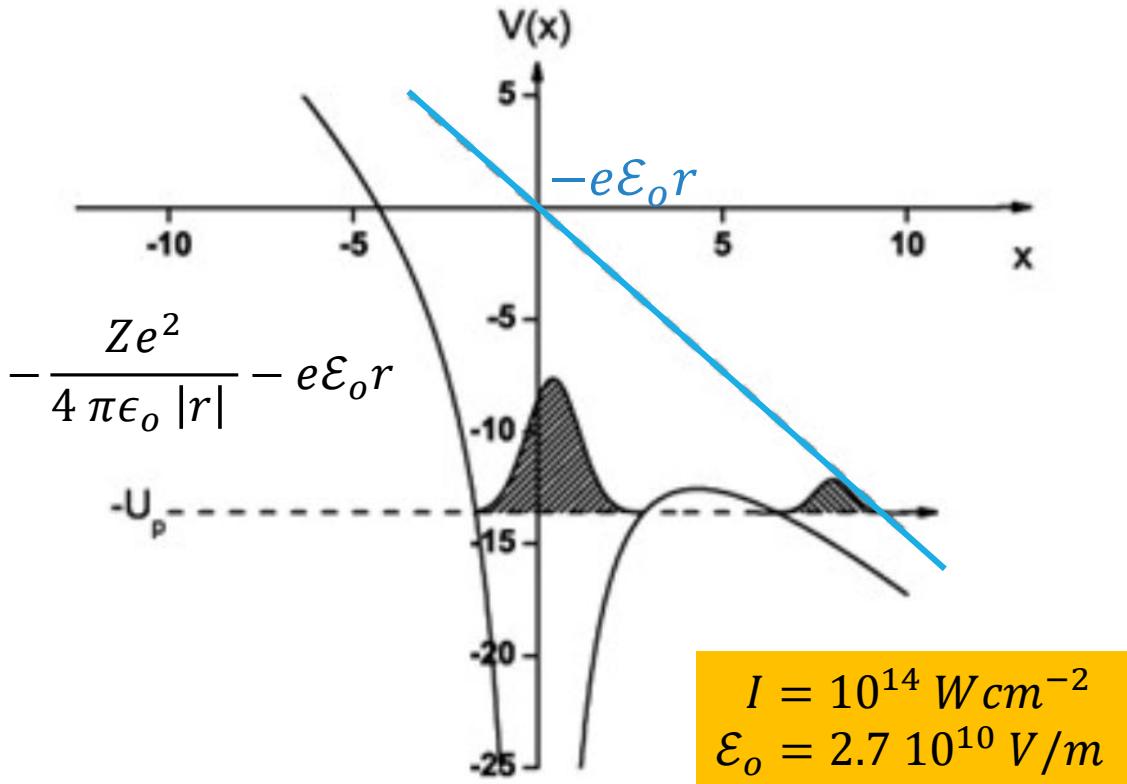
Above threshold ionization



$$E_0 \sim 5 \times 10^{11} \text{ V/m}$$
$$I \sim 3 \times 10^{16} \text{ W cm}^{-2}$$

Mecanismos de ionización en átomos y moléculas

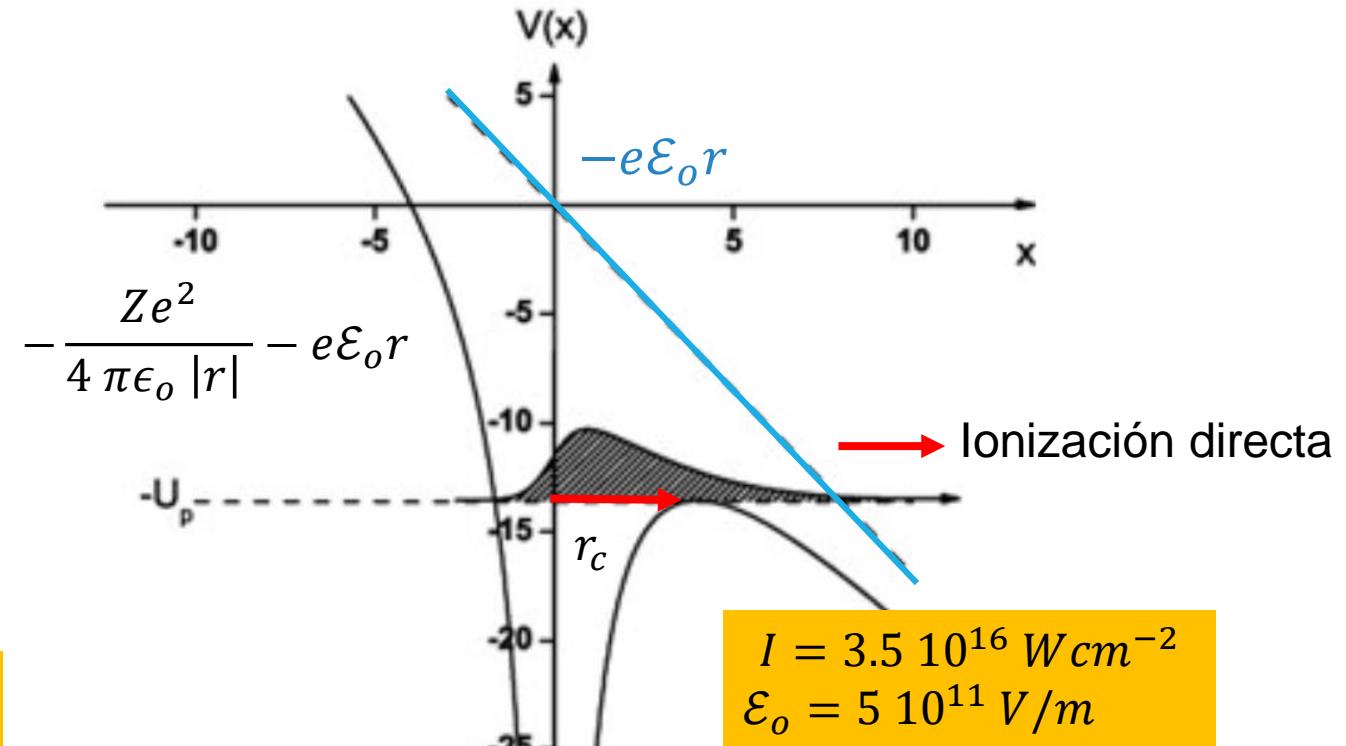
Efecto tunel



$$E_o \sim 5 \times 10^{11} \text{ V/m}$$

$$I \sim 3 \times 10^{16} \text{ W cm}^{-2}$$

Supresión de la barrera de potencial



$$r_c^2 = \frac{Ze}{4\pi\epsilon_0\epsilon_o}$$

$$\epsilon_{oc} = \frac{\pi\epsilon_0}{Ze^3} E_{ion}^2$$

$$I_{app} = \frac{1}{2} \epsilon_0 c \epsilon_{oc}^2$$

Interacciones de electrones y campos ópticos

Fuerza del campo electromagnético: caso onda plana

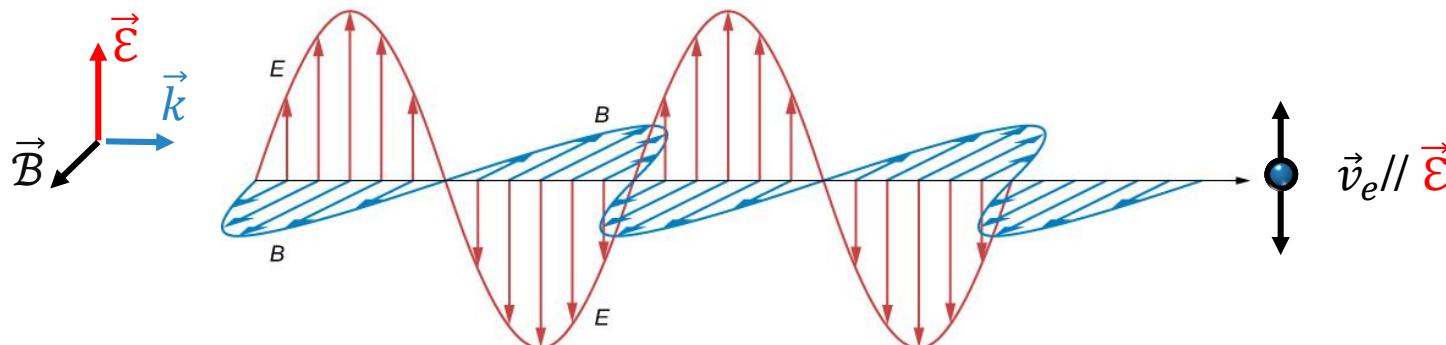
$$\frac{d\vec{p}}{dt} = \frac{d}{dt} (\gamma_e m_o \vec{v}_e) = -e \left[\vec{\mathcal{E}} + \frac{\vec{v}_e \times \vec{B}}{c} \right]$$

$$\gamma_e = \frac{1}{\sqrt{1 - \frac{v_e^2}{c^2}}} = \sqrt{1 + \frac{p^2}{m_o^2 c^2}}$$

Clásico

$v \ll c$

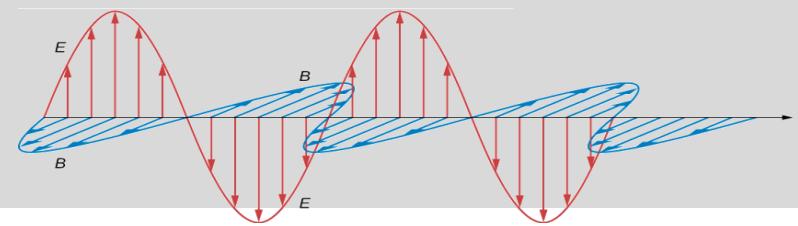
$$\begin{aligned} |\vec{v}_e \times \vec{B}| &\ll c \mathcal{E} \\ \gamma_e &\sim 1 \end{aligned}$$



Relativista $v \sim c$ $\gamma_e \gg 1$

No se puede despreciar $\vec{v}_e \times \vec{B}$
Ni la masa relativista $\gamma_e m_o$

Interacciones de electrones y campos ópticos



Fuerza del campo electromagnético: caso onda plana

$$\frac{d\vec{p}}{dt} = \frac{d}{dt} (\gamma_e m_o \vec{v}_e) = -e \left[\vec{\epsilon} + \frac{\vec{v}_e}{c} \times \vec{B} \right] \quad \gamma_e = \frac{1}{\sqrt{1 - v_e^2/c^2}} = \sqrt{1 + p^2/m_o^2 c^2}$$

$$\vec{a}(z, t) = \frac{e \vec{A}}{m_o c^2} = a_o \sin[k z - \omega t] \hat{x}, \quad \vec{\epsilon} = -\frac{d \vec{A}}{dt} \quad \vec{B} = \vec{\nabla} \times \vec{A}$$

$$a_o = \frac{e A_o}{m_o c^2} = \frac{e E_o / \omega}{m_o c} \quad I_o = \frac{1}{2} \epsilon_o c E_o^2 \quad a_o^2 = \frac{e^2 I_o \lambda_o^2}{2 \pi^2 \epsilon_o c^5 m_e^2} = \frac{(I_o/Wcm^{-2}) (\lambda_o/\mu m)^2}{1.37 \times 10^{18}}$$

$$\omega = ck$$

$$\gamma_e = 1 + \frac{p_x \text{ (quiver)}}{m_o c} = 1 + \frac{a^2}{2} \quad K = m_o c^2 (\gamma_e - 1) = m_o c^2 \frac{a^2}{2} \quad \begin{cases} K(\max) \sim m_o c^2 \\ a_o \sim 1 \end{cases} \quad \text{Límite relativista}$$

\vec{v}_e, γ_e, a crecen con I_o

$$I_R \lambda_o^2 \sim 1.37 \times 10^{18}$$

$$I_R \sim 10^{19} W cm^{-2} @ 400 nm$$

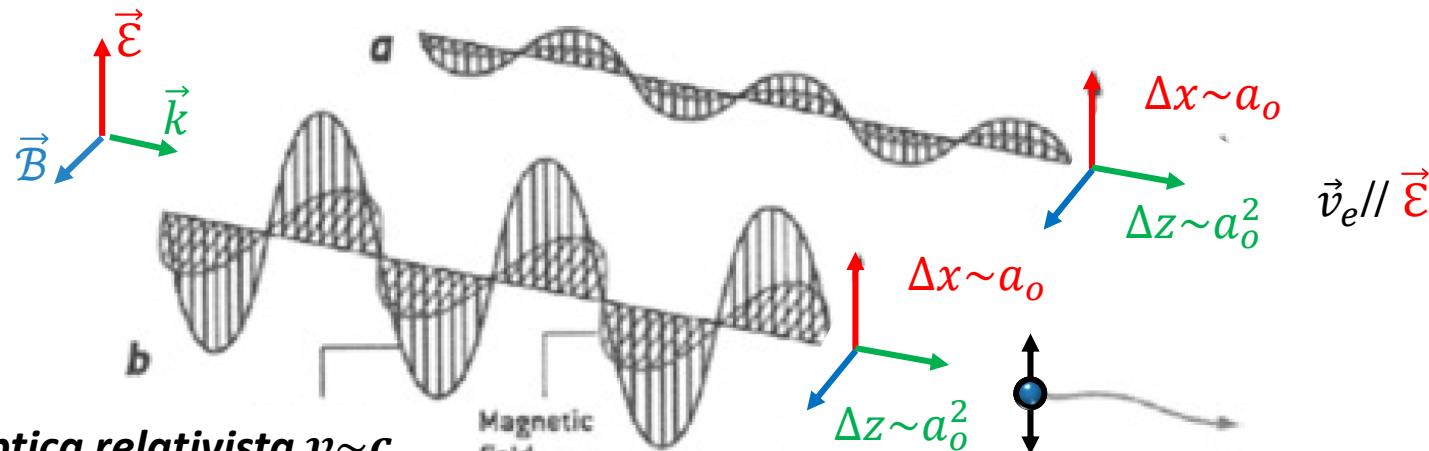
Interacciones de electrones y campos ópticos

$$a_o^2 = \frac{e^2 I_o \lambda_o^2}{2\pi^2 \epsilon_0 c^5 m_e^2} = \frac{(I_o/Wcm^{-2}) (\lambda_o/\mu m)^2}{1.37 \times 10^{18}}$$

Optica clásica $v \ll c$

$$a_o \ll 1, a_o^2 \ll a_o$$

El electron oscila en la dirección del campo $\vec{\mathcal{E}}$



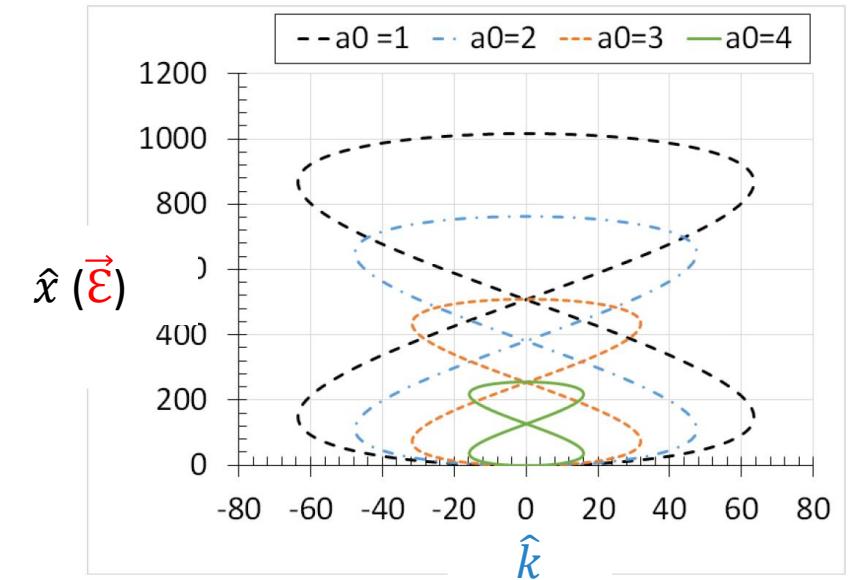
Optica relativista $v \sim c$

$$a_o \gg 1, a_o \ll a_o^2$$

$$\langle v_{drift} \rangle = c \frac{a_o^2}{a_o^2 + 4}$$

No hay transferencia neta de energía cinética

El electron se mueve en "ochos" en el plano $\vec{\mathcal{E}} \vec{k}$



Que le pasa a los fotones?

Generación de armónicos (8-type osc)

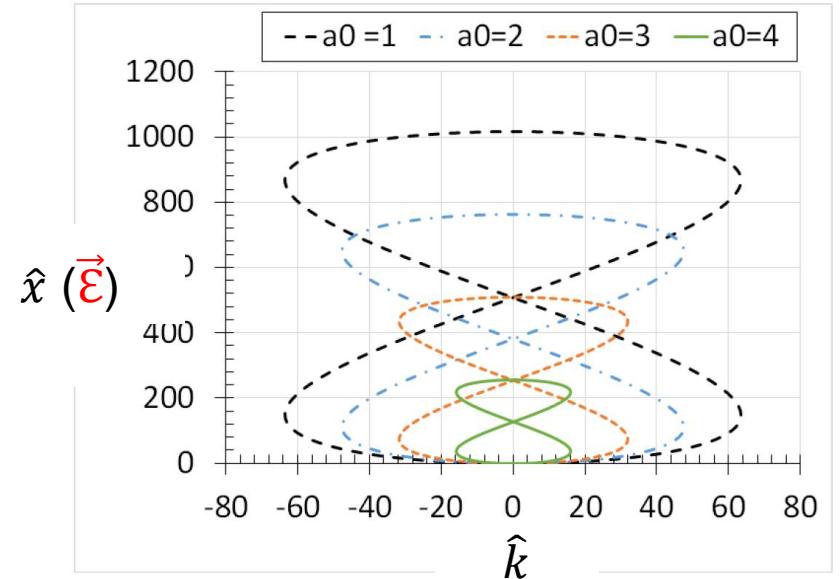
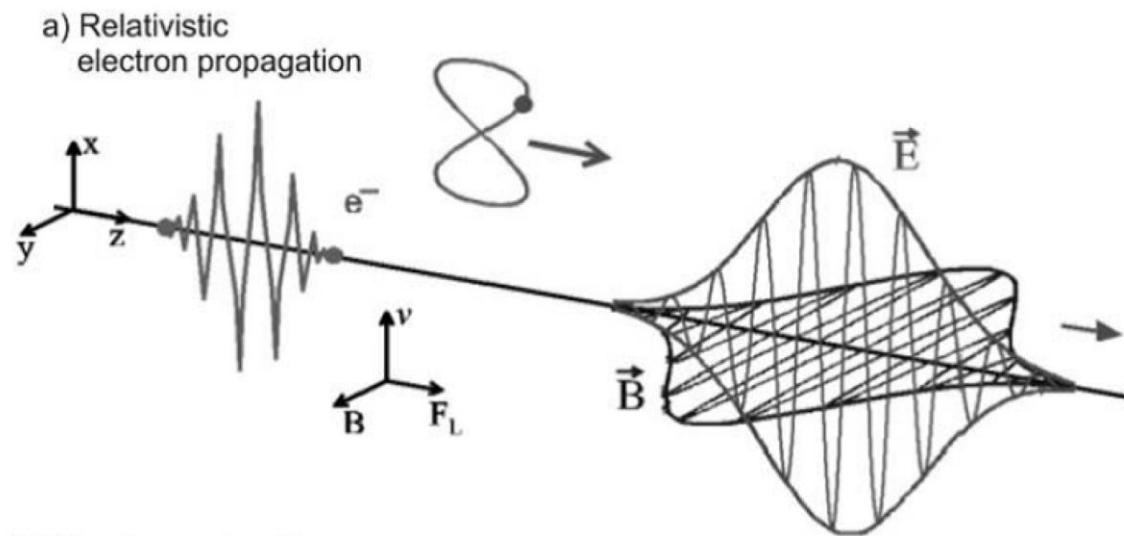
Corrimiento en frecuencia

Interacciones de electrones y campos ópticos

$$\vec{A} = \frac{e\vec{A}}{m_o c} = a_o \exp[-(t/\tau)] \sin[\omega t] \hat{x},$$

Optica relativista $v \sim c$

$$a_o \gg 1, a_o \ll a_o^2$$



No hay ganancia neta de energía cinética (solo en caso de electrón en vacío)
(pérdida de energía por radiación)

Interacciones de electrones y campos ópticos

Fuerza del campo electromagnético: pulso inhomogéneo $\vec{\mathcal{E}}(z, t) = \vec{\mathcal{E}}_s(z)\cos(\omega_o t)$

$$\vec{F}_p = -\nabla\Phi_p$$

$$\Phi_p(z) = \frac{e^2}{4m_o\langle\gamma_e\rangle\omega_o^2} \vec{\mathcal{E}}_s^2(z)$$

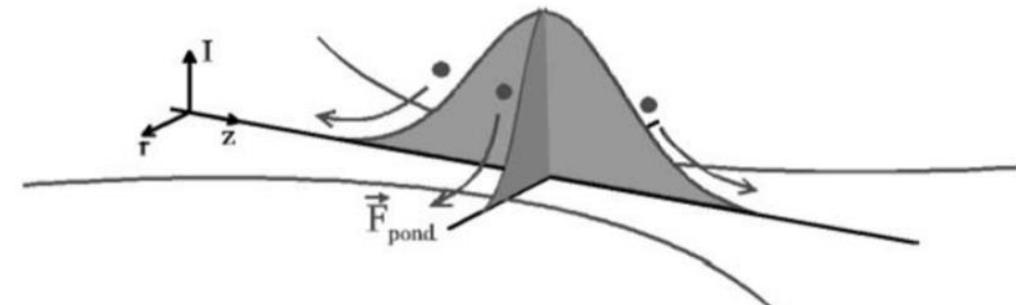
$$\langle\gamma_e\rangle^2 = 1 + a_o^2 = 1 + \frac{e^2 \lambda_o^2 I_o}{2\pi^2 m_o^2 \epsilon_o c^5}$$

- \vec{F}_p en la dirección que disminuye la intensidad
- $\vec{F}_p \propto \mathcal{E}_s^2$ (proporcional a la intensidad)
- La dirección no depende del signo de la carga

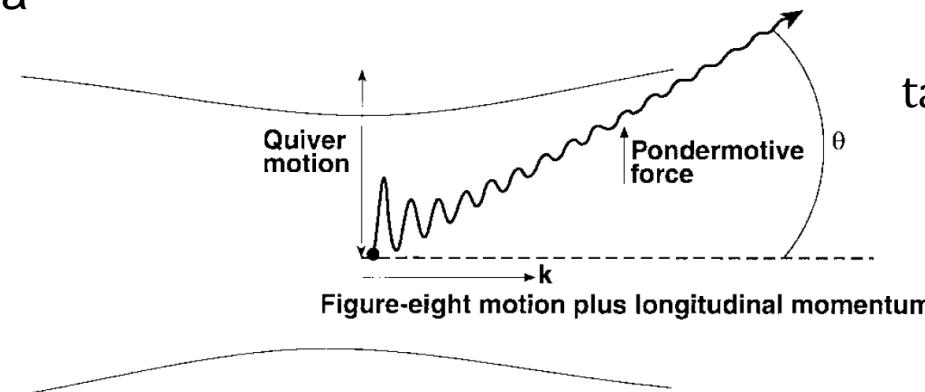
Velocidad máxima

$$\Phi_p^{max} = \langle K \rangle = m_e c^2 (\langle\gamma_e\rangle - 1)$$

$$\Phi_p^{max} = \frac{e^2}{4m_o\langle\gamma_e\rangle\omega_o^2} E_o^2 = m_o c^2 \frac{a_o^2}{4\langle\gamma_e\rangle}$$



En plasmas produce plasma wake (oscilaciones)

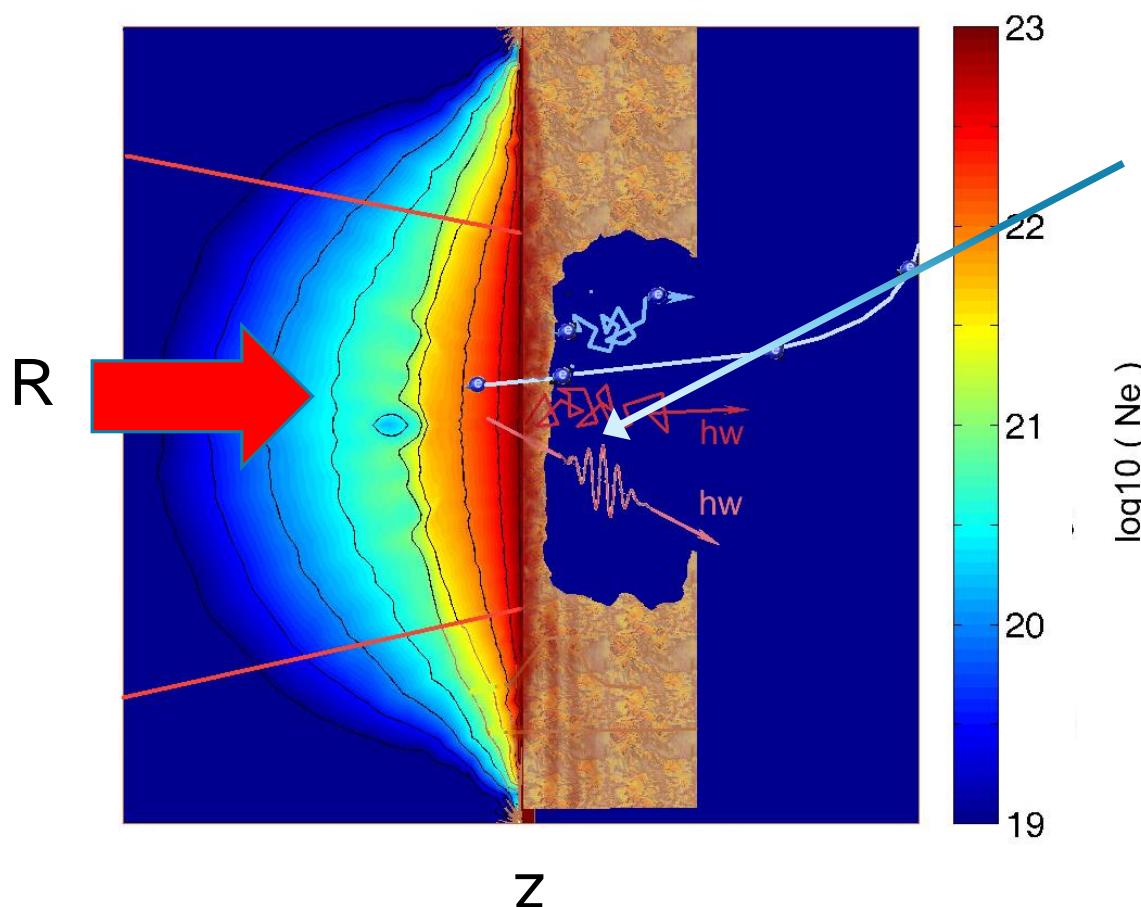


$$\tan(\theta) = \frac{p_{//}}{p_{\perp}} = \sqrt{\frac{2}{\gamma_e - 1}}$$

$$\begin{cases} \theta = \frac{\pi}{2} & v \ll c \\ \theta = 0 & v \sim c \end{cases}$$

CUANDO SE FORMA EL PLASMA, LOS MECANISMOS ABSORCIÓN DE CALOR CAMBIAN SUSTANCIALMENTE

El laser se absorbe primero en una capa de espesor del skin depth (ej Cu 2nm @ $\lambda = 1\mu\text{m}$)



Procesos que transfieren calor a la región supercrítica

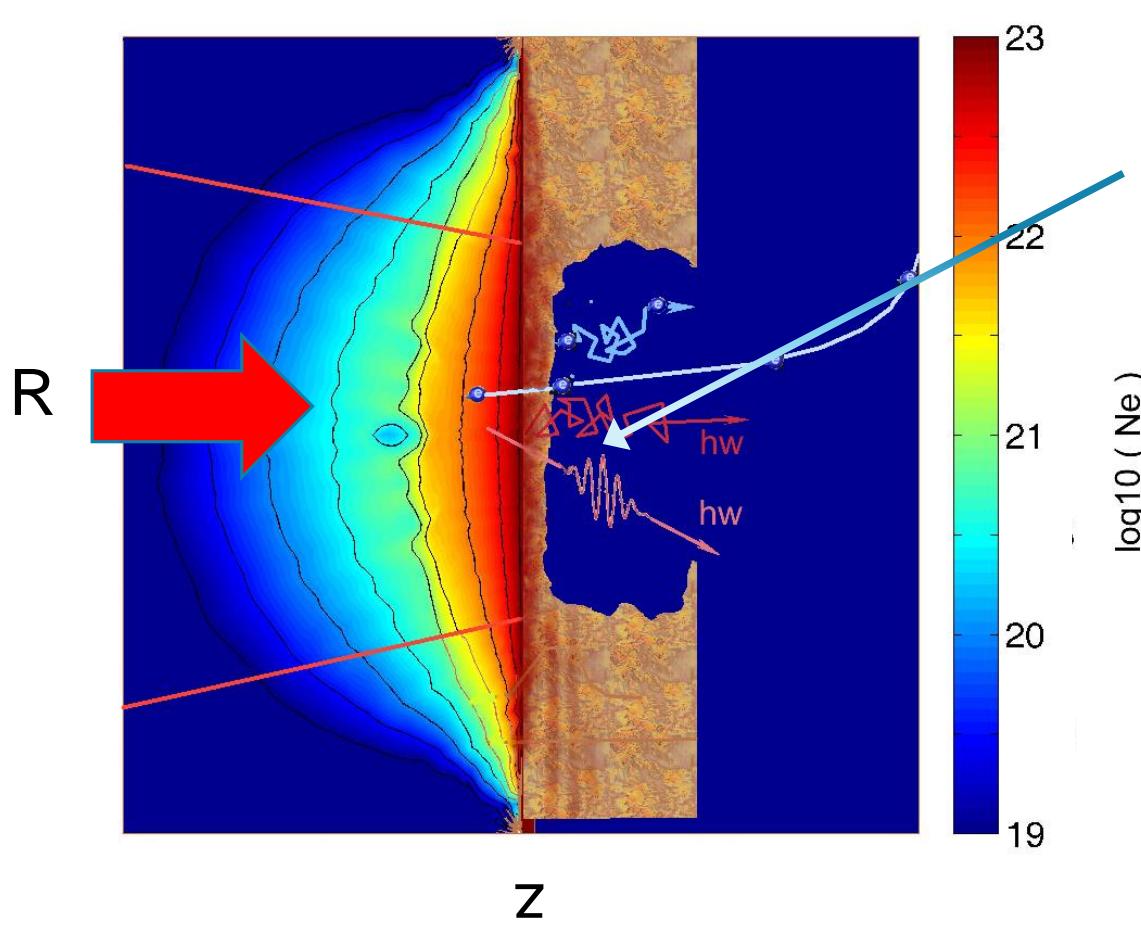
Ordenados por importancia

Cu ($I = 1 \times 10^{17} \text{ W/cm}^2$)

- Difusión térmica
- Electrones calientes/corriente de retorno
- Difusión de fotones de baja energía
- Absorción de fotones de alta energía
- Ondas de presión y shock

CUANDO SE FORMA EL PLASMA, LOS MECANISMOS ABSORCIÓN DE CALOR CAMBIAN SUSTANCIALMENTE

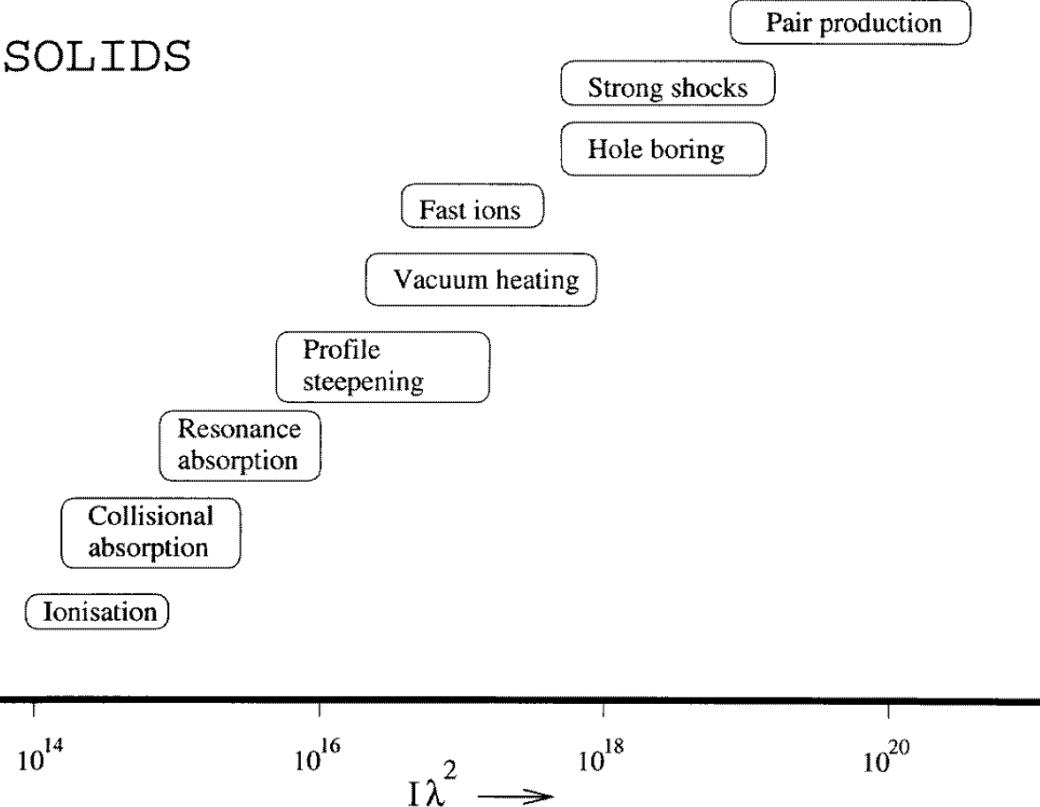
El laser se absorbe primero en una capa de espesor del skin depth (ej Cu 2nm @ $\lambda = 1\mu\text{m}$)



Procesos que transfieren calor a la región supercrítica

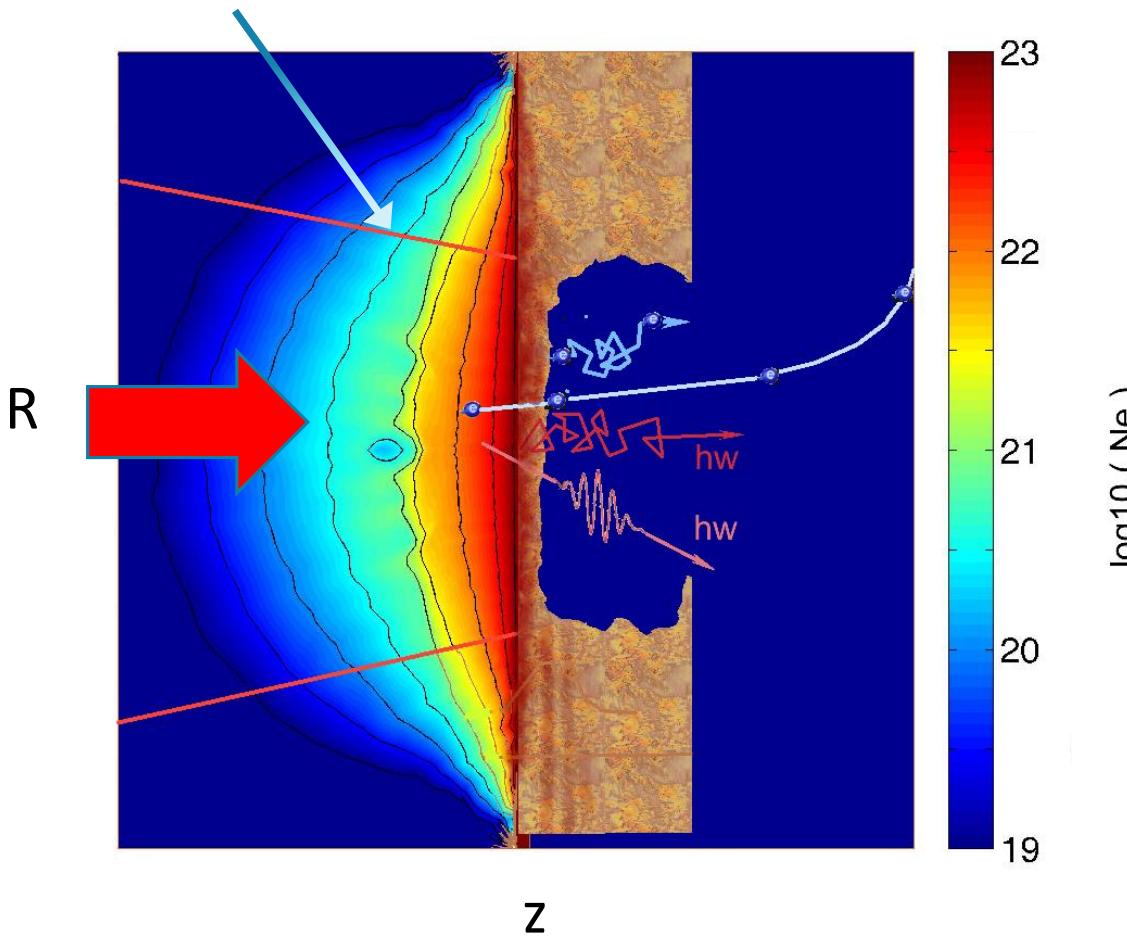
a)

SOLIDS



PROPAGACIÓN DE ONDAS EN PLASMAS: NO ES POSIBLE GENERAR PLASMAS EN VOLUMEN, SIMULTÁNEAMENTE DENSOS Y CALIENTES, IRRADIANDO BLANCOS SÓLIDOS

La **densidad critica** ($n_e = 1.1 \times 10^{21} \text{ cm}^{-3}$ @ $\lambda = 1\mu\text{m}$) es solo < 1% de la densidad del sólido



Relación de dispersión

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

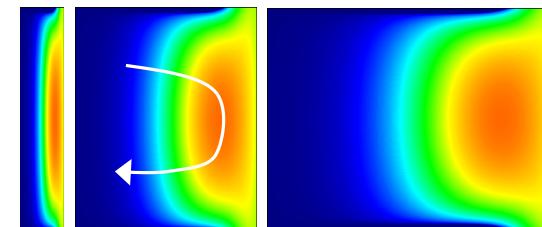
$$\omega_p^2 = \frac{e^2 n_e}{m_e \epsilon_0}$$

Índice de refracción $\frac{ck}{\omega} = \eta = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{\frac{1}{2}} = \left(1 - \frac{n_e}{n_{crit}}\right)^{\frac{1}{2}}$

$$n_{crit} = \frac{\pi c^2 m_e}{\lambda^2 e^2} = \frac{1.1 \times 10^{21}}{(\lambda[\mu\text{m}])^2}$$

haces propagantes $\omega > \omega_p \text{ o } n_e < n_{crit}$

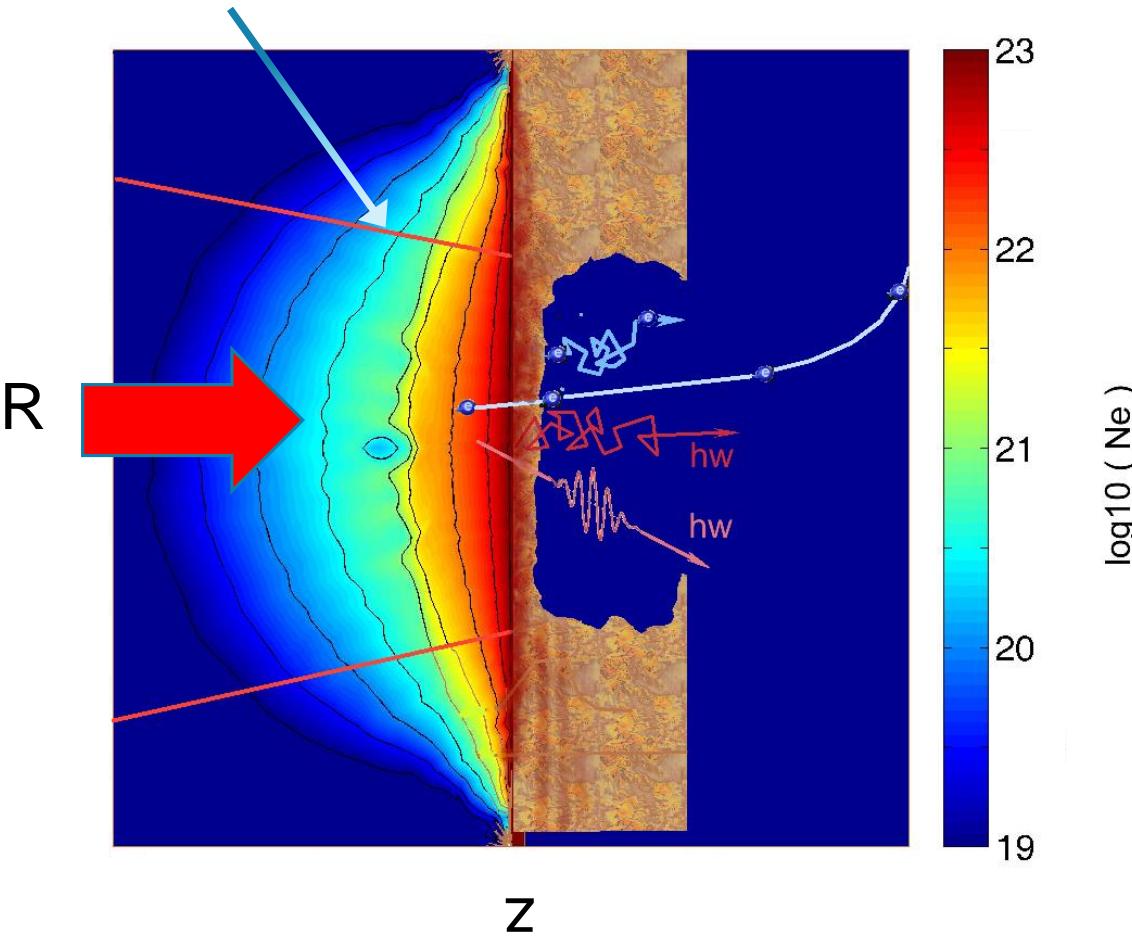
En otro caso las ondas se reflejan



$$n_{crit} (\lambda = 400\text{nm}) \sim 7 \times 10^{21} \text{ cm}^{-3}$$

PROPAGACIÓN DE ONDAS EN PLASMAS: EFECTOS RELATIVISTAS

La **densidad critica** ($n_e = 1.1 \times 10^{21} \text{ cm}^{-3}$ @ $\lambda = 1\mu\text{m}$) es solo < 1% de la densidad del sólido



Relación de dispersión

$$\omega^2 = \tilde{\omega}_p^2 + c^2 k^2$$

$$\tilde{\omega}_p^2 = \frac{\omega_p^2}{\langle \gamma_e \rangle}$$

$$\langle \gamma_e \rangle^2 = 1 + a_0^2 = 1 + \frac{e^2 I_o \lambda_o^2}{2\pi^2 \epsilon_o c^5 m_e^2}$$

Índice de refracción

$$\frac{ck}{\omega} = \eta = \left(1 - \frac{\tilde{\omega}_p^2}{\omega^2}\right)^{\frac{1}{2}} = \left(1 - \frac{\omega_p^2}{\omega^2 \langle \gamma_e \rangle}\right)^{\frac{1}{2}} = \left(1 - \frac{n_e}{\langle \gamma_e \rangle n_{crit}}\right)^{\frac{1}{2}}$$

$$\tilde{n}_{crit} = \langle \gamma_e \rangle n_{crit} > n_{crit}$$

Transparencia inducida relativísticamente

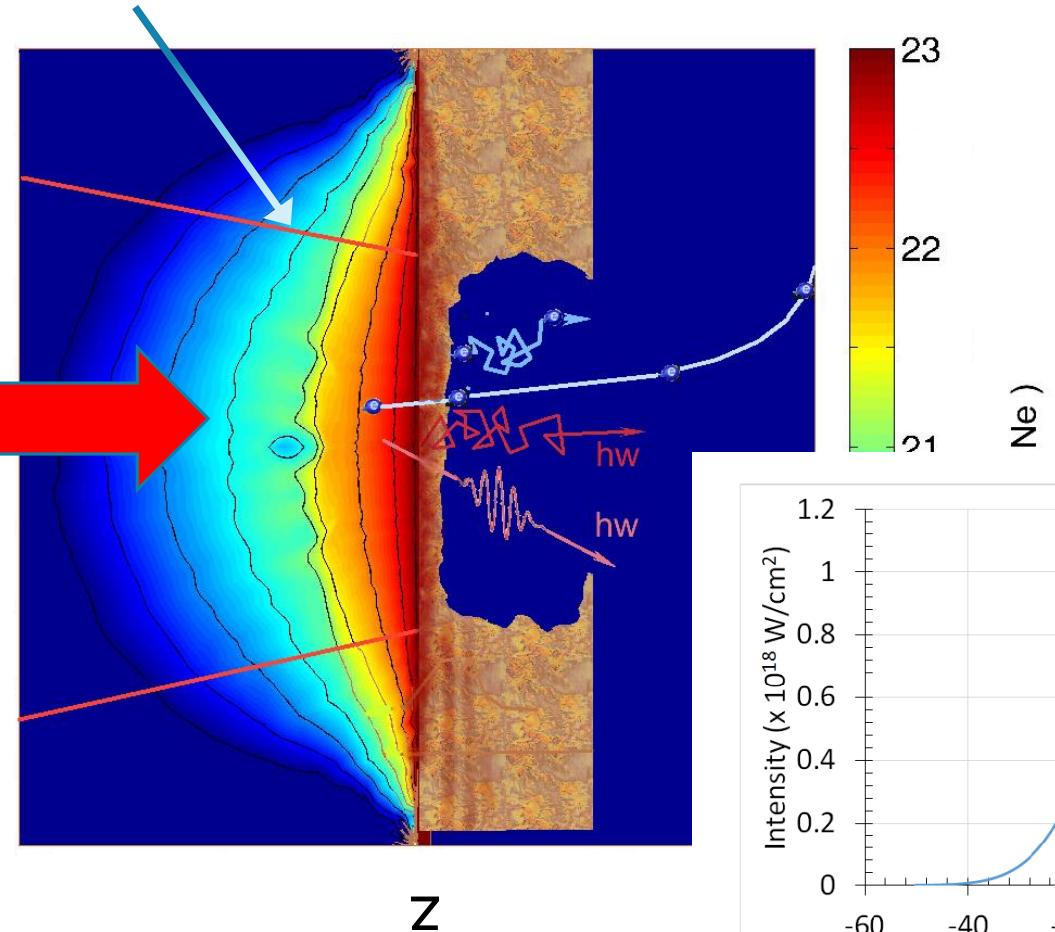
Haces propagantes hasta densidades electrónicas mayores

Efecto más importante cuando

$$I_o (\text{Wcm}^{-2}) \lambda_o^2 (\mu\text{m}^2) > 1.37 \times 10^{18}$$

PROPAGACIÓN DE ONDAS EN PLASMAS: EFECTOS RELATIVISTAS

La **densidad critica** ($n_e = 1.1 \times 10^{21} \text{ cm}^{-3}$ @ $\lambda = 1\mu\text{m}$) es solo < 1% de la densidad del sólido



$$\text{Relación de dispersión } \omega^2 = \tilde{\omega}_p^2 + c^2 k^2$$

$$\tilde{\omega}_p^2 = \frac{\omega_p^2}{\langle \gamma_e \rangle}$$

$$\langle \gamma_e \rangle^2 = 1 + a_o^2 = 1 + \frac{e^2 I_o \lambda_o^2}{2\pi^2 \epsilon_o c^5 m_e^2}$$

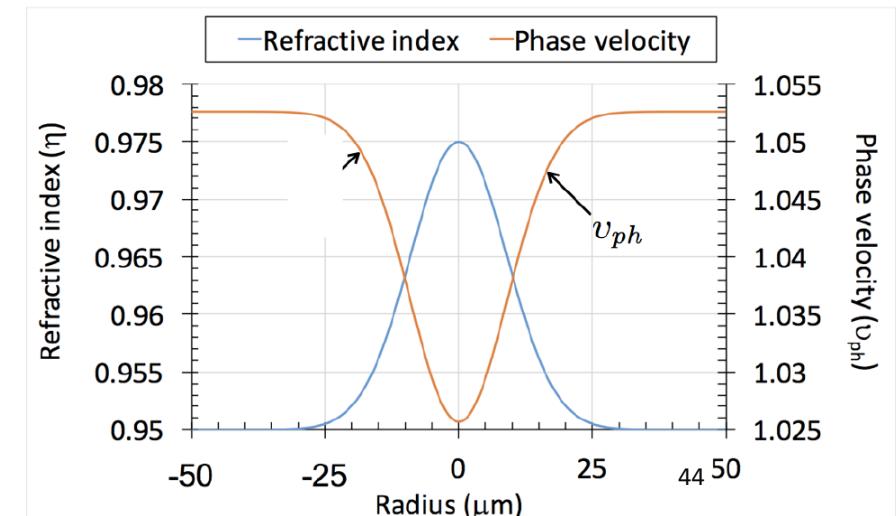
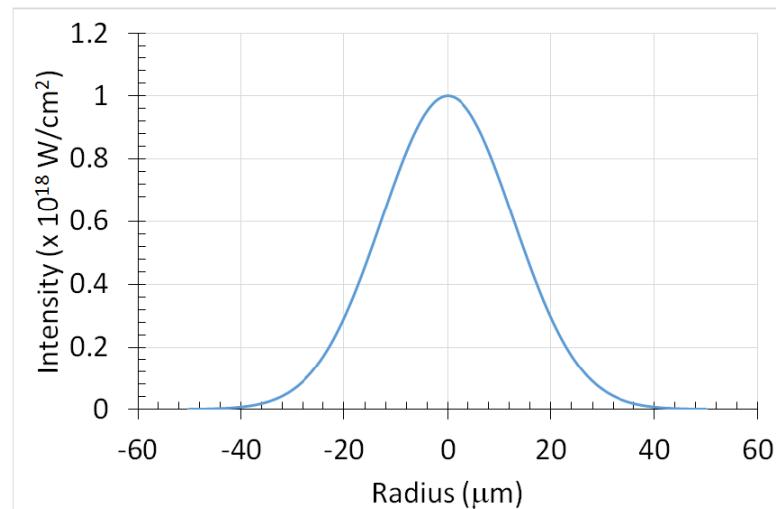
Índice de refracción

$$\frac{ck}{\omega} = \eta = \left(1 - \frac{\tilde{\omega}_p^2}{\omega^2}\right)^{\frac{1}{2}} = \left(1 - \frac{\omega_p^2}{\omega^2 \langle \gamma_e \rangle}\right)^{\frac{1}{2}} = \left(1 - \frac{n_e}{\langle \gamma_e \rangle n_{crit}}\right)^{\frac{1}{2}}$$

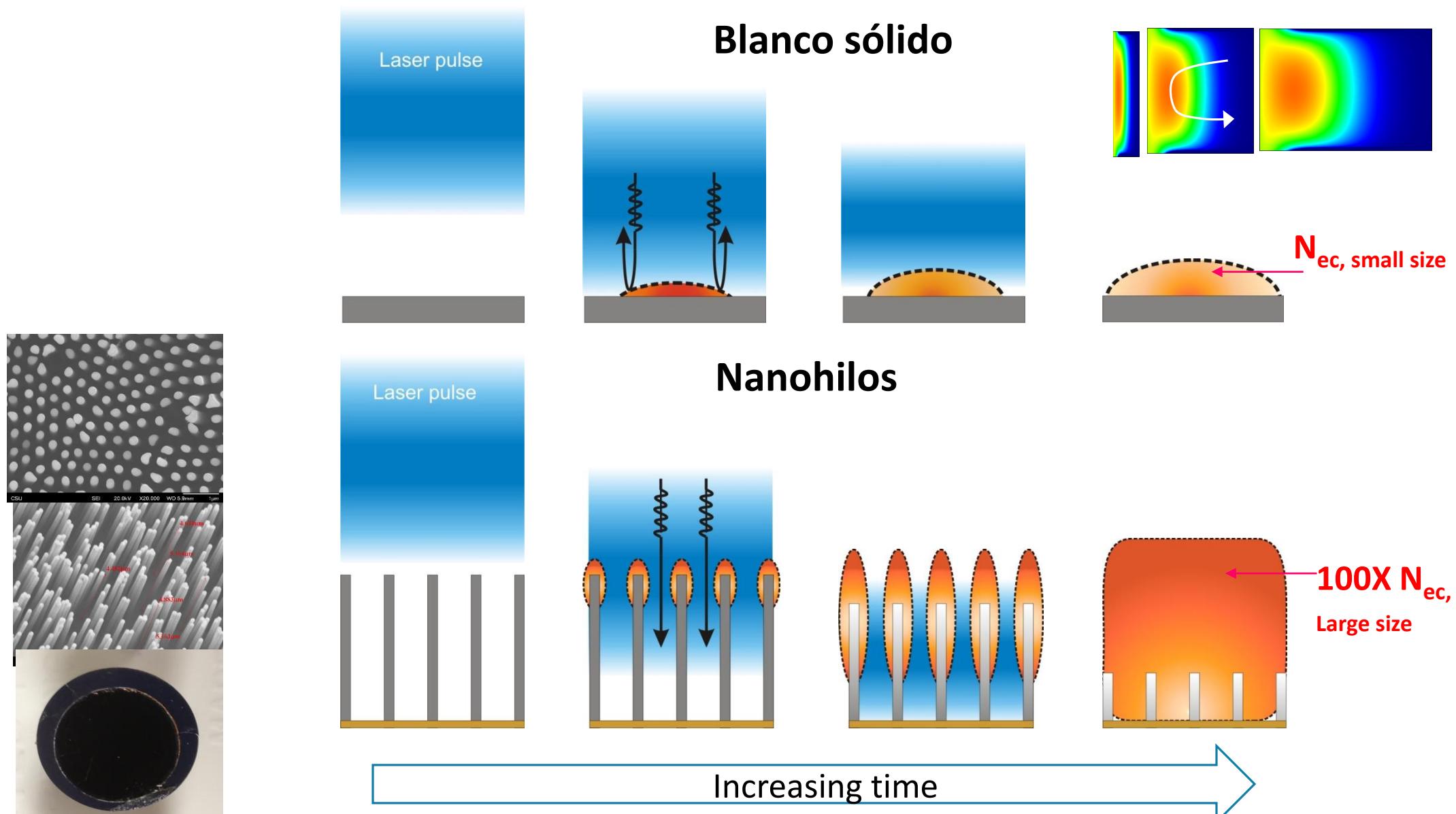
Autoenfoque relativista

η es mayor en las regiones de mayor $I_o \lambda_o^2$

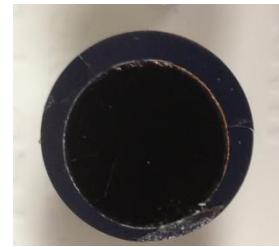
$$v_{ph} = \frac{c}{\eta}$$



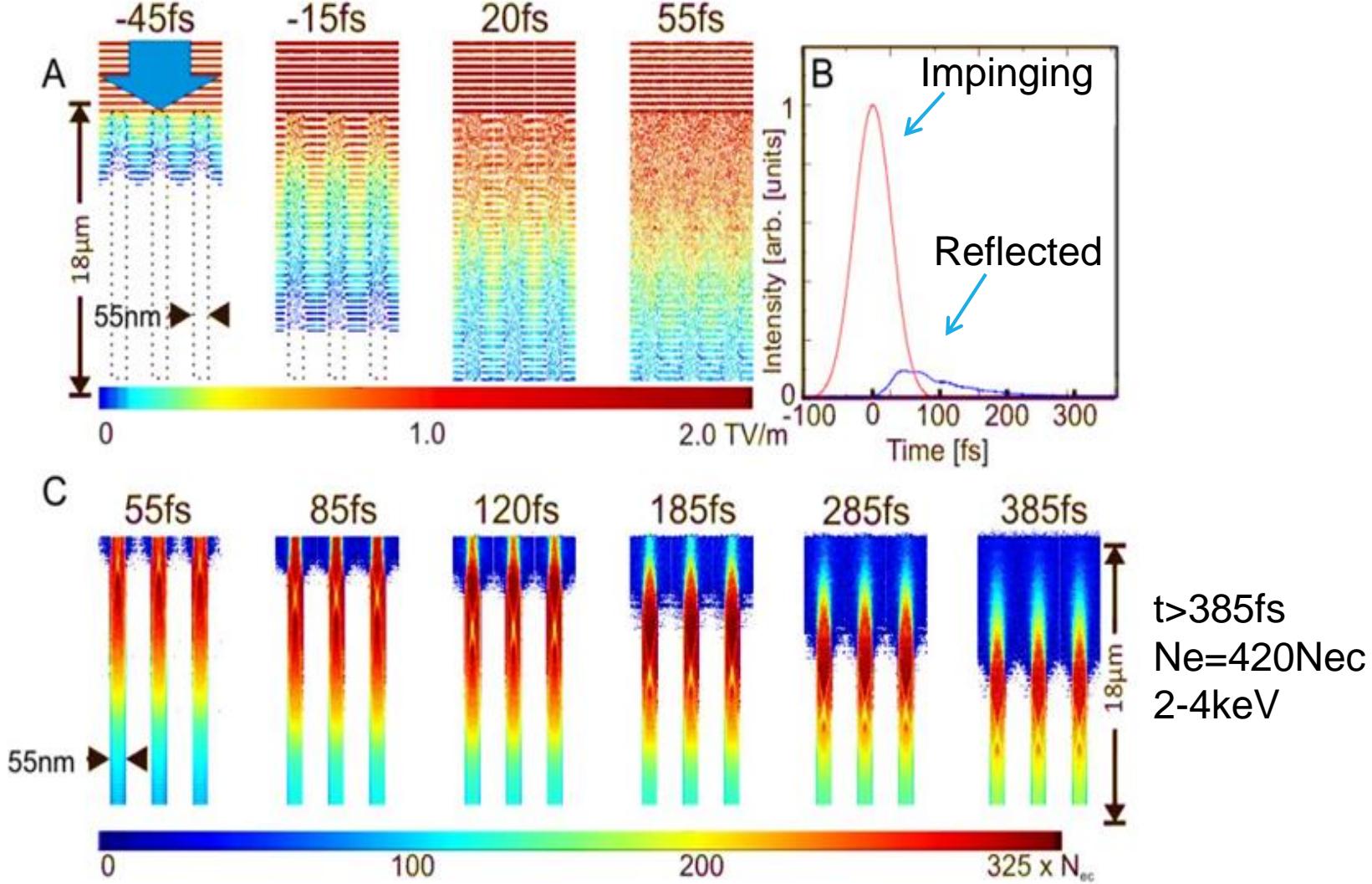
LA DENSIDAD Y EL TAMAÑO DEL PLASMA PUEDEN AUMENTARSE >100 VECES, IRRADIANDO
NANOHILOS VERTICALMENTE ALINEADOS CON LASERES PULSADOS EN FS



El calentamiento con láseres de matrices de nanohilos alineados, permite crear plasmas con temperaturas de varios keV y densidades mayores a 100 X Nec



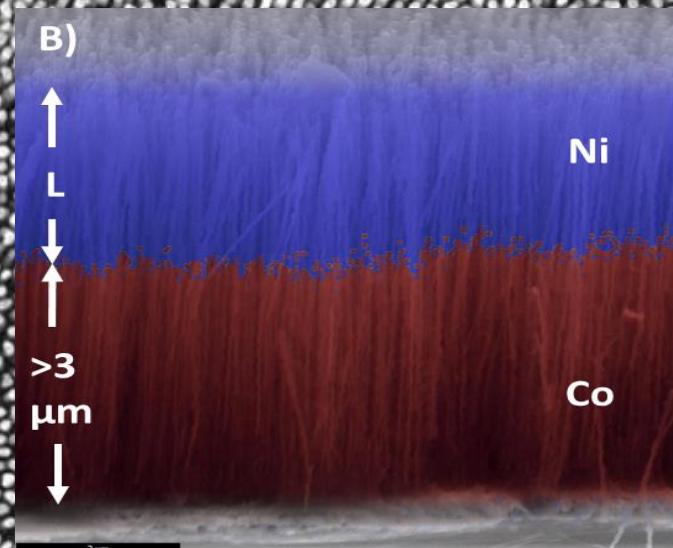
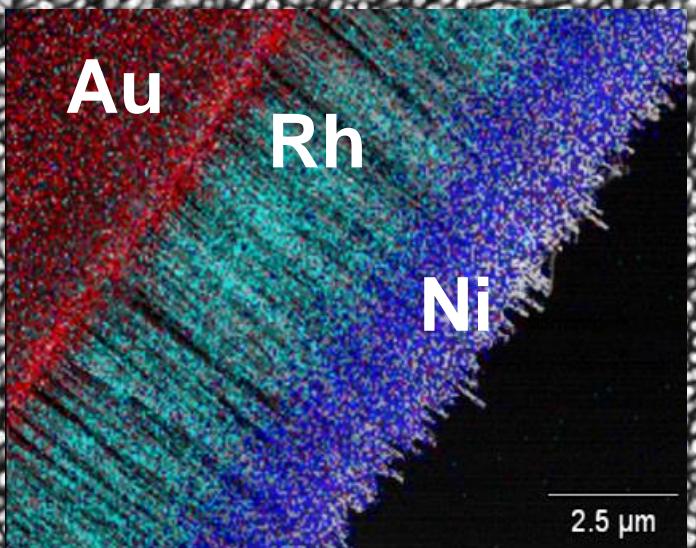
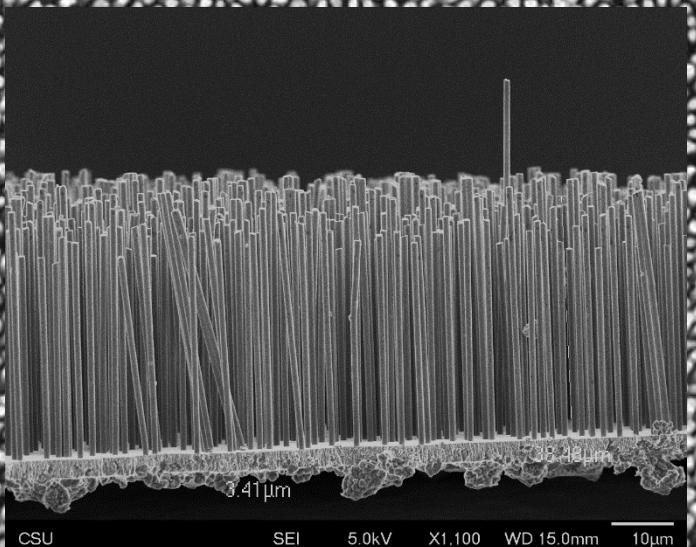
$I = 5 \times 10^{18} \text{ W cm}^{-2}$, Ni, diámetro=55 nm, densidad=0.12 sólido



PIC simulation: A. Pukhov

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

Nanohilos verticalmente alineados electrodepositados (SEM)



Templates: PC, AAO

Materials: Au, Ni, Co, Pd, Rh, Ag...

Radius: 50-1000 nm

Lengths: up to 20 μm

Density: 7% 15% 30% solid density

2 μm

INDICE

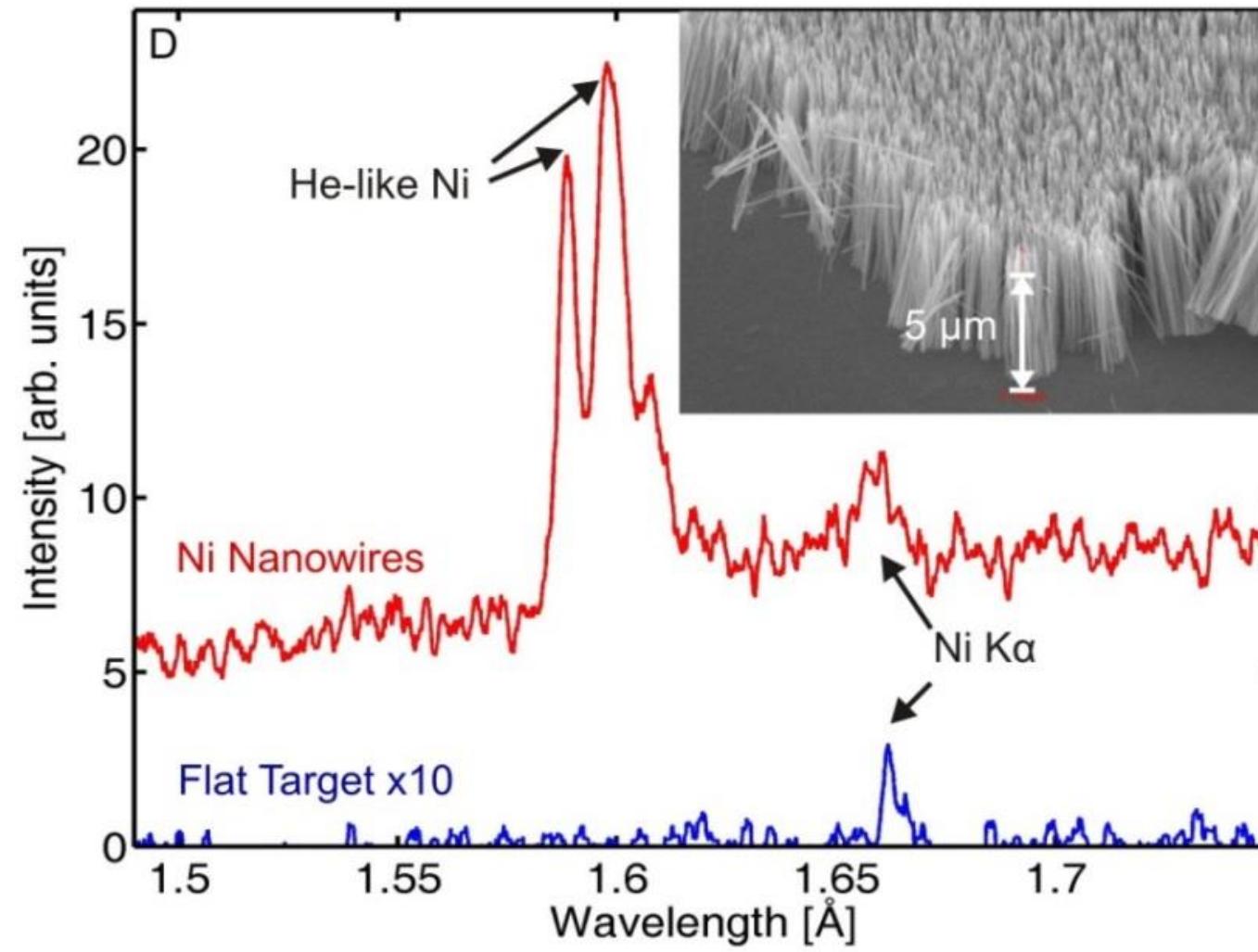
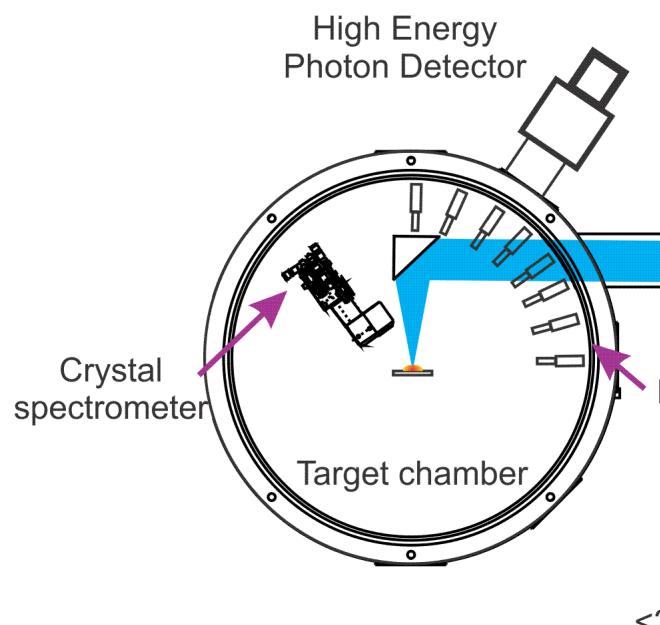
- Aleph: Advanced Laser for Extreme Photonics
- Interacción láseres de intensidad relativista y electrones
- Creación de plasmas altamente ionizados a partir de irradiación con láseres de intensidad relativista de blancos sólidos y blancos nanoestructurados.
- Experimentos con Intensidades “relativisticamente bajas”
 - Nanohilos metálicos: volumen del plasma, tiempo de formación del plasma, eficiencia en la emisión de rayos x)
 - Nanohilos polímero deuterado (experimentos de fusión nuclear de deuterio: energía de deuterones y neutrones, eficiencia de neutrones)
- Experimentos con intensidades “relativisticamente altas”
 - Nanohilos de polímero deuterado: energía y eficiencia de emisión de electrones, flujo de rayos gamma, rayos x y neutrones
 - Nanohilos metálicos: record en grado de ionización

LA EMISIÓN EN NICKEL HE _{α} EXCEDE A K _{α} CUANDO SE IRRADIA A $5 \times 10^{18} \text{ W cm}^{-2}$

28

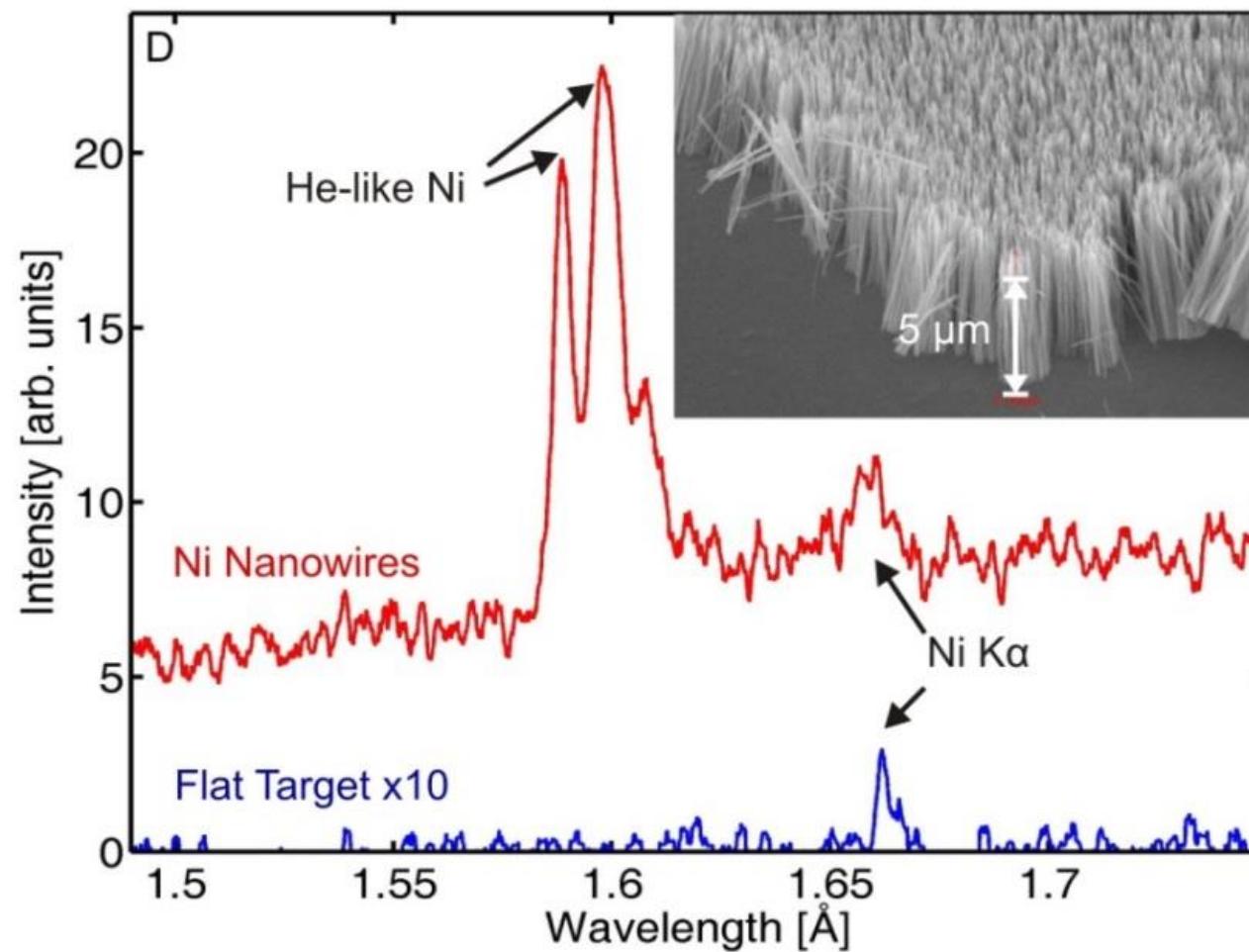
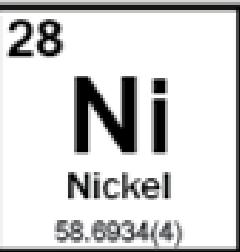
Ni

Nickel
58.6934(4)



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

LA EMISIÓN EN NICKEL HE _{α} EXCEDE A K _{α} CUANDO SE IRRADIA A $5 \times 10^{18} \text{ W cm}^{-2}$



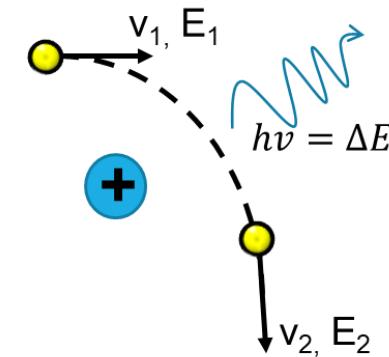
M. Purvis et al. *Nature Photonics*, 7, 796 (2013)

Radiación continua

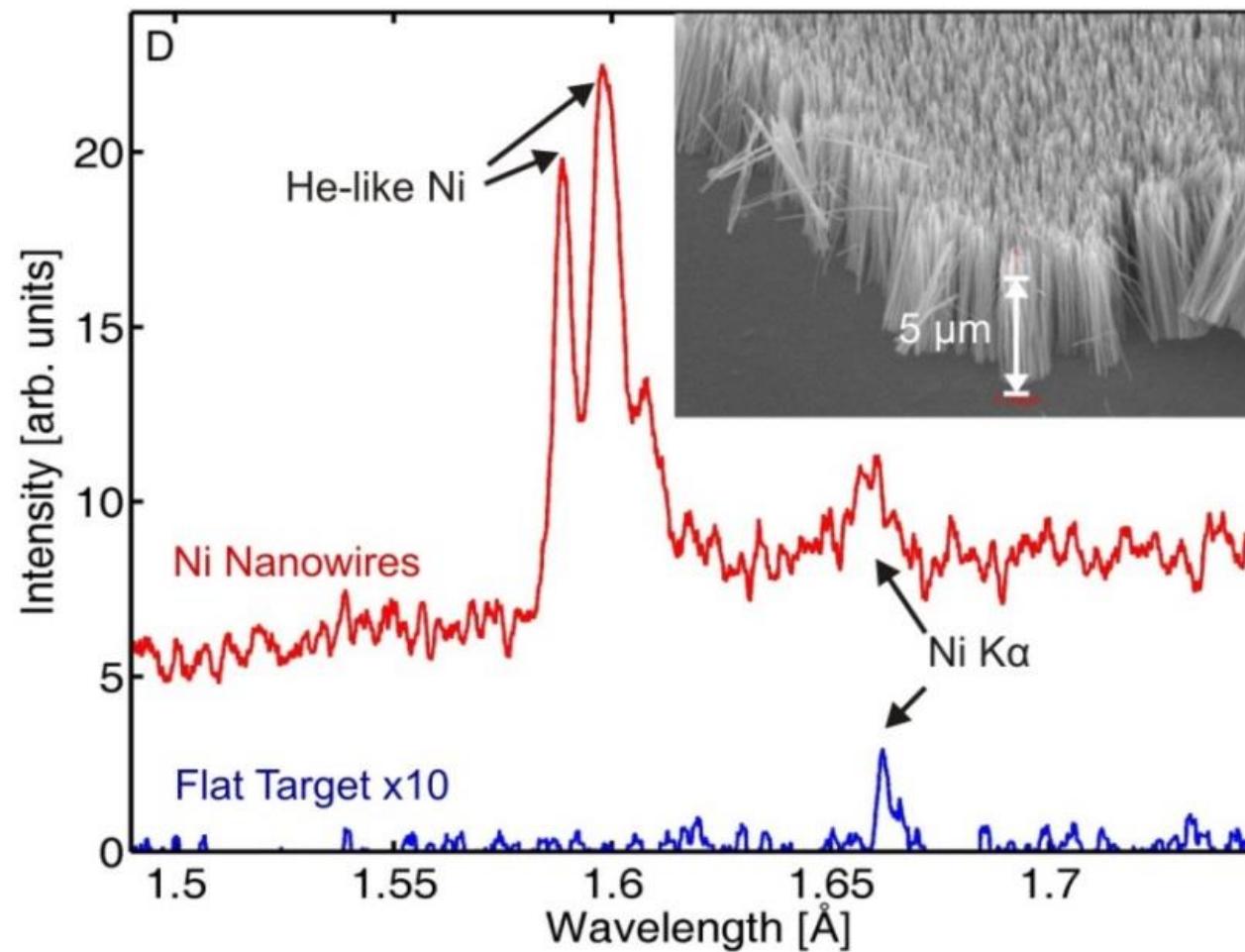
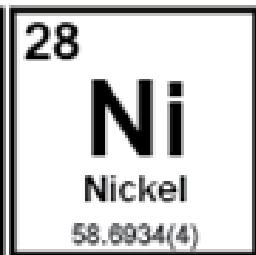
- bremsstrahlung
(free-free transitions)
- recombinación
(free-bound transitions)

bremsstrahlung

bremsen "to brake"
Strahlung "radiation"; i.e.
"radiación de frenado"



LA EMISIÓN EN NICKEL HE _{α} EXCEDE A K _{α} CUANDO SE IRRADIA A $5 \times 10^{18} \text{ W cm}^{-2}$



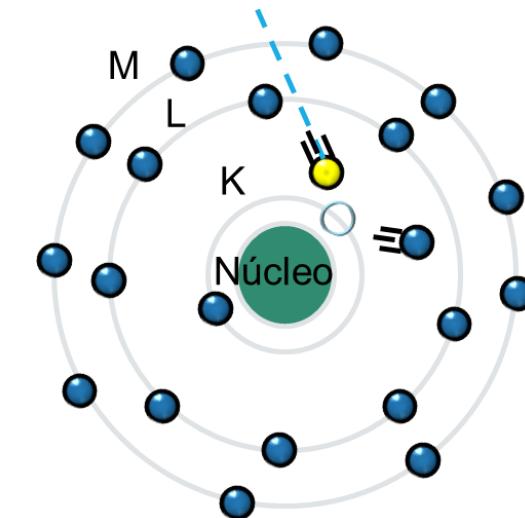
M. Purvis et al. *Nature Photonics*, 7, 796 (2013)

Radiación continua

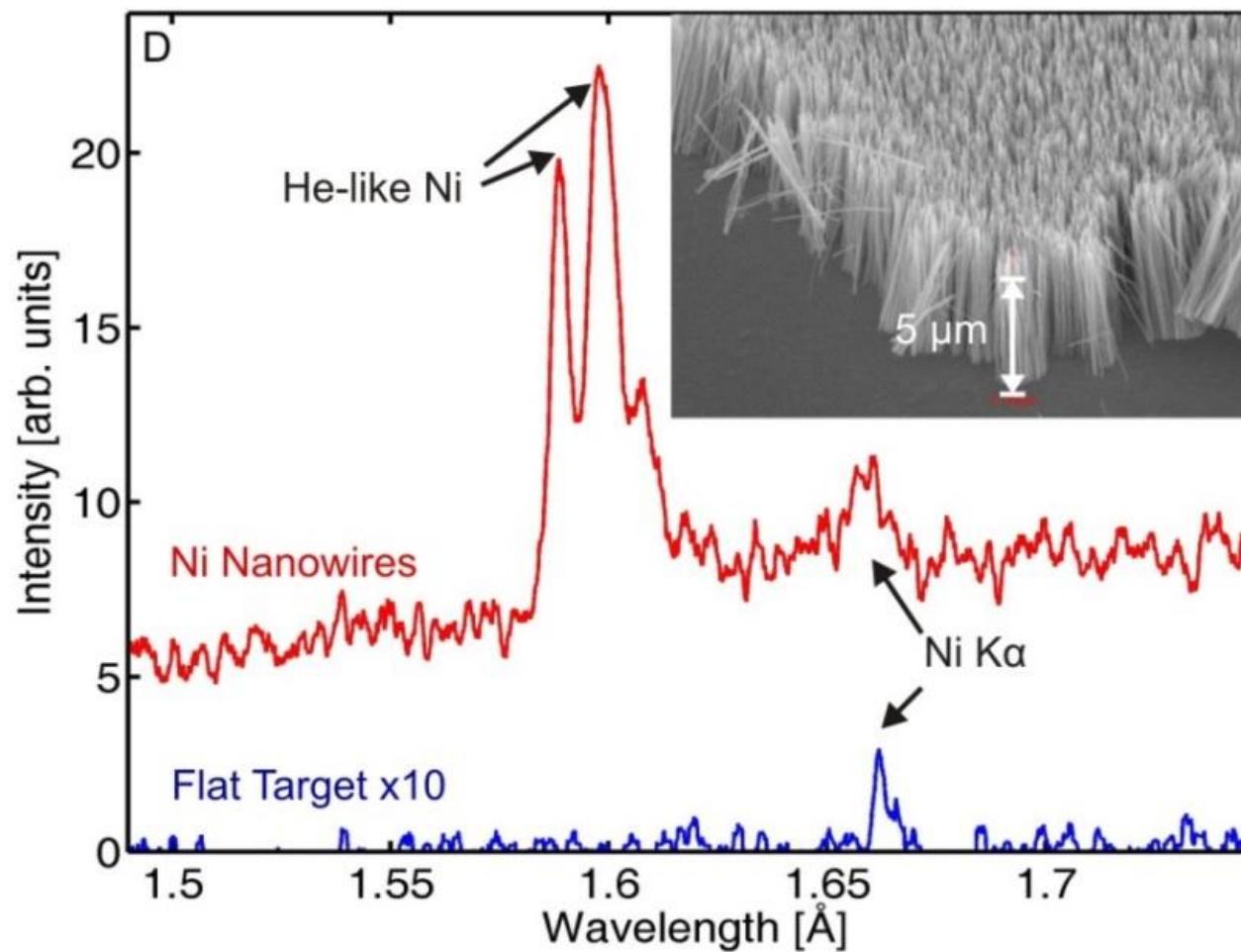
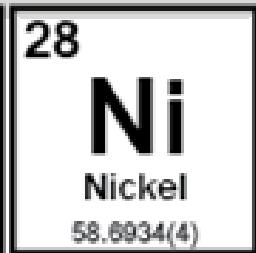
- bremsstrahlung
- (free-free transitions)
- recombinación
- (free-bound transitions)

Transiciones internas o de línea

- (bound-bound transitions)



LA EMISIÓN EN NICKEL HE _{α} EXCEDE A K _{α} CUANDO SE IRRADIA A $5 \times 10^{18} \text{ W cm}^{-2}$



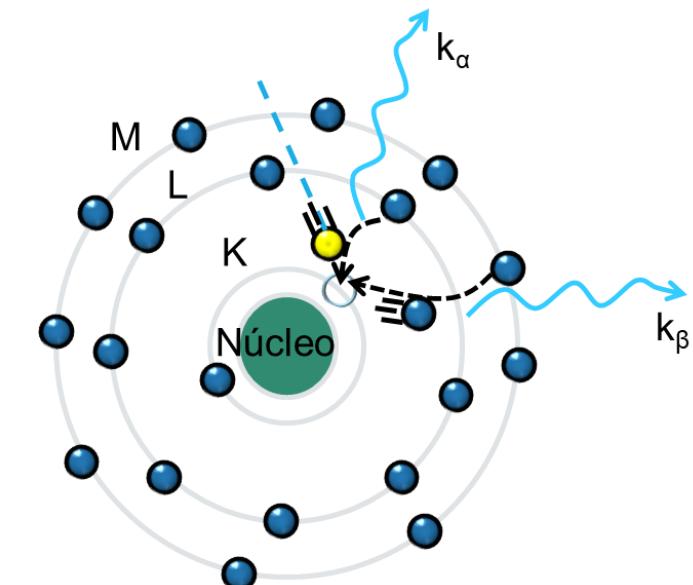
M. Purvis et al. *Nature Photonics*, 7, 796 (2013)

Radiación continua

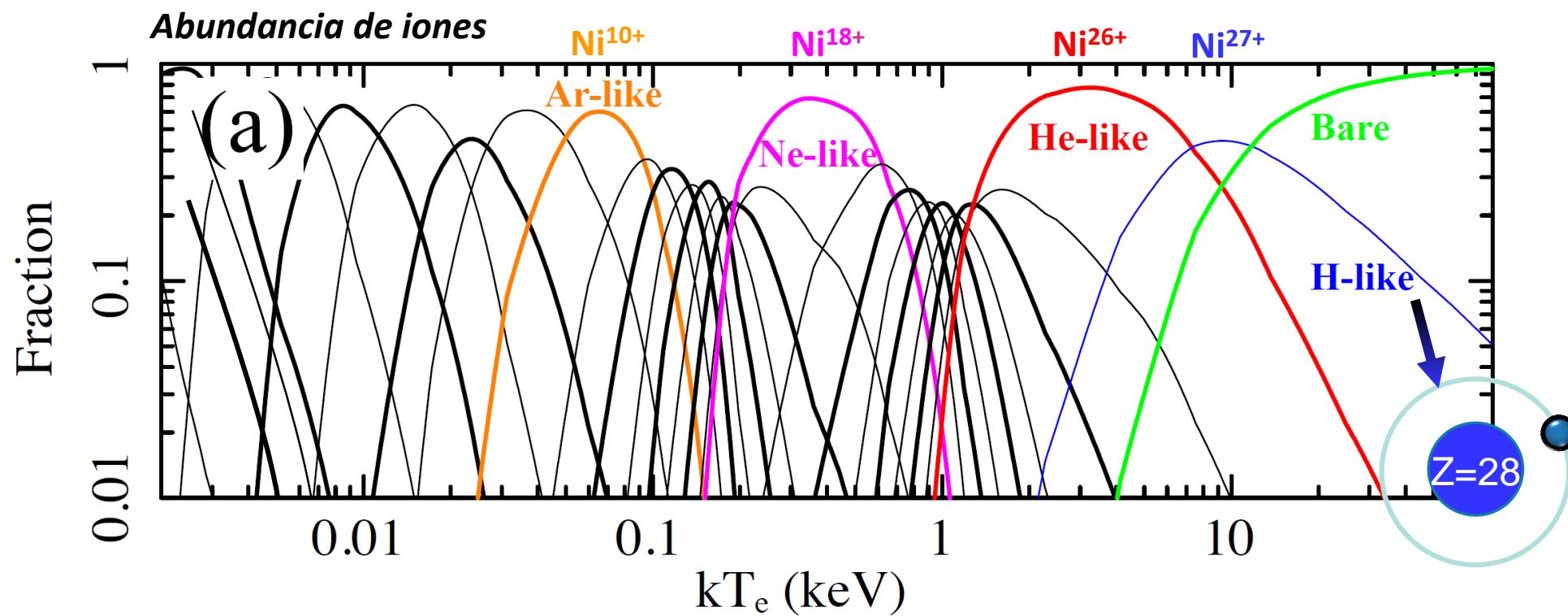
- bremsstrahlung
(free-free transitions)
- recombinación
(free-bound transitions)

Transiciones internas o de línea

(bound-bound transitions)



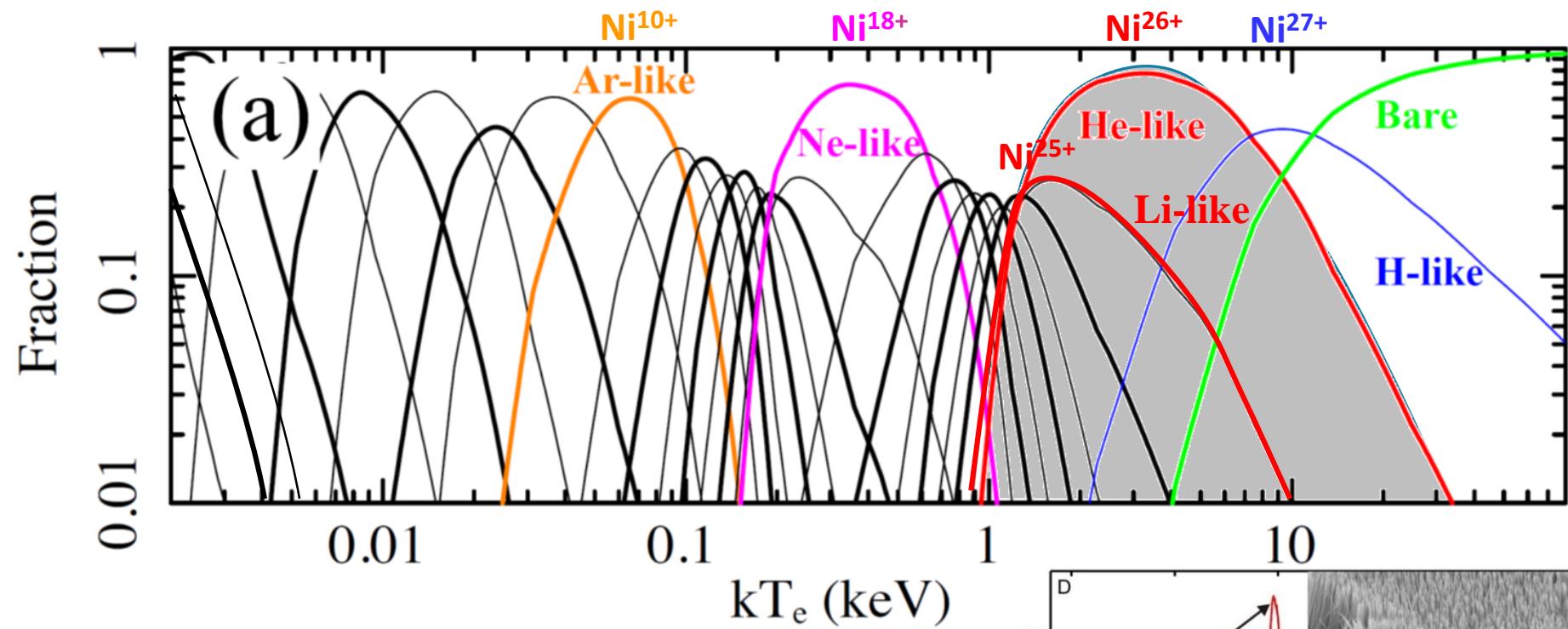
EN UN PLASMA EN EQUILIBRIO, A MAYOR TEMPERATURA ELECTRONICA (T_e), LOS ATOMOS COEXISTEN CON GRADOS DE IONIZACION MAYORES.



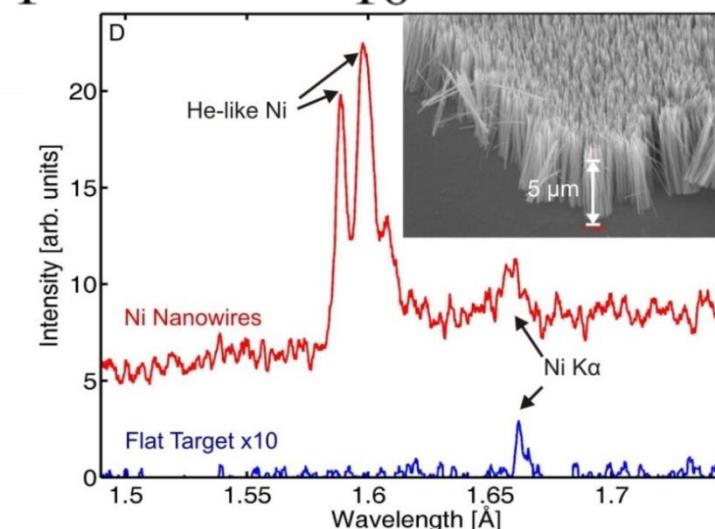
Periodic Table of the Elements

1 IA 1A																			18 VIIIA 8A
H Hydrogen [1.008; 1.008]																			He Helium [4.002602; 4.002602]
Li Lithium [6.938; 6.997]	Be Beryllium [9.012183(5)]	Na Sodium [22.98976928(2)]	Mg Magnesium [24.304; 24.307]	Sc Scandium [44.95908(5)]	Ti Titanium [47.867(1)]	V Vanadium [50.9415(1)]	Cr Chromium [51.9961(6)]	Mn Manganese [54.938045(5)]	Fe Iron [55.845(2)]	Co Cobalt [58.933194(4)]	Ni Nickel [58.6934(4)]	Cu Copper [63.546(3)]	Zn Zinc [65.38(2)]	Ga Gallium [69.723(1)]	Ge Germanium [72.630(8)]	As Arsenic [74.921595(6)]	Se Selenium [78.971(8)]	Br Bromine [79.901; 79.907]	Kr Krypton [83.798(2)]
<small>Atomic mass values reflect the IUPAC accepted values as of 09/2013. Masses expressed in [a,b] format show the lower and upper limit of atomic mass depending on the physical and chemical history of the element. Masses expressed in <> format are the mass numbers of the longest-lived isotope for elements with no stable nucleus.</small>																			<small>Atomic Number Symbol Name Atomic Mass</small>

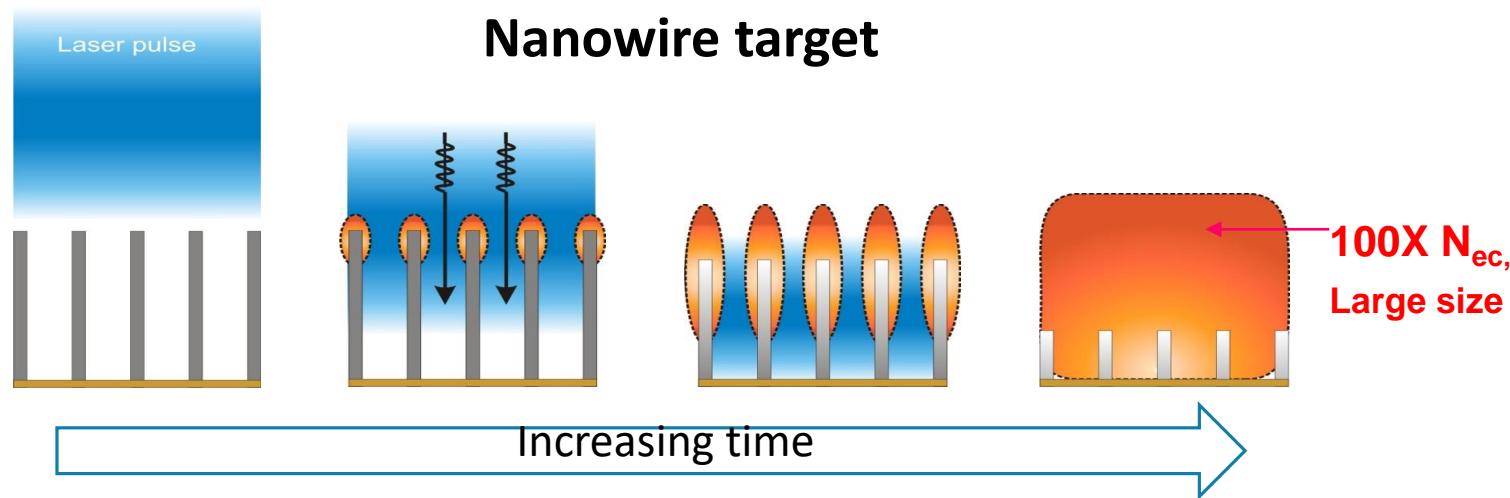
EN UN PLASMA EN EQUILIBRIO, A MAYOR TEMPERATURA ELECTRONICA (T_e),
LOS ATOMOS COEXISTEN CON GRADOS DE IONIZACION MAYORES.



A partir del espectro de rayos X: Te, Ne,
abundancia de iones

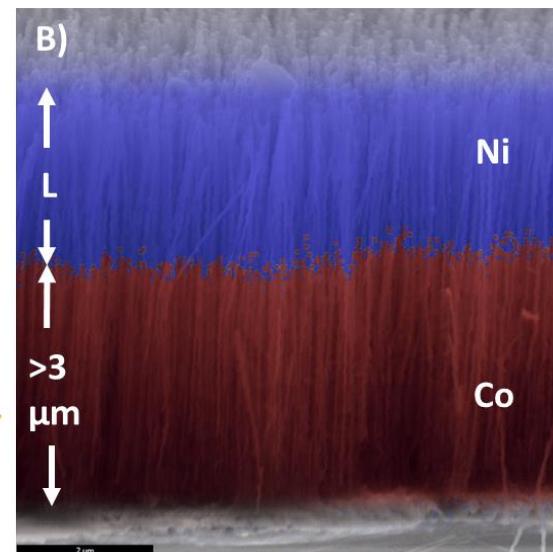
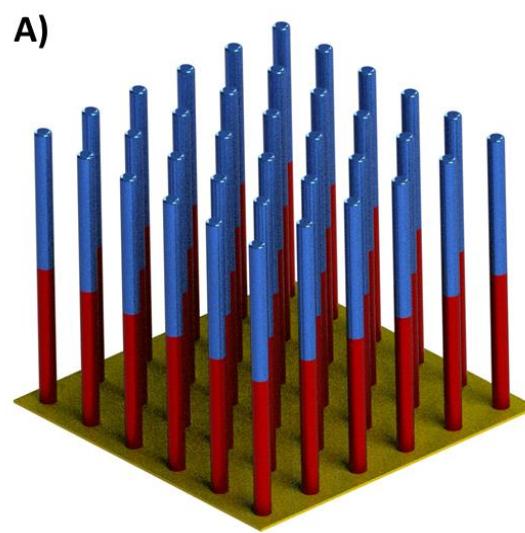


Mediciones del volumen del plasma

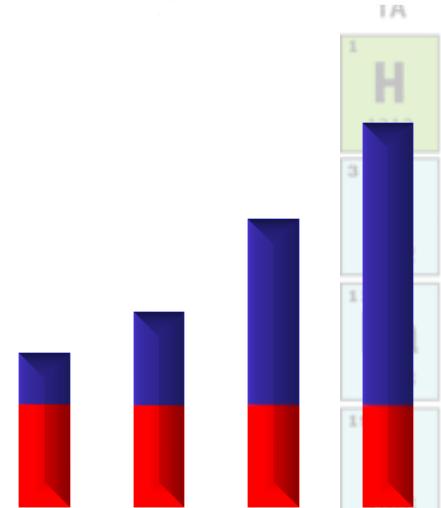
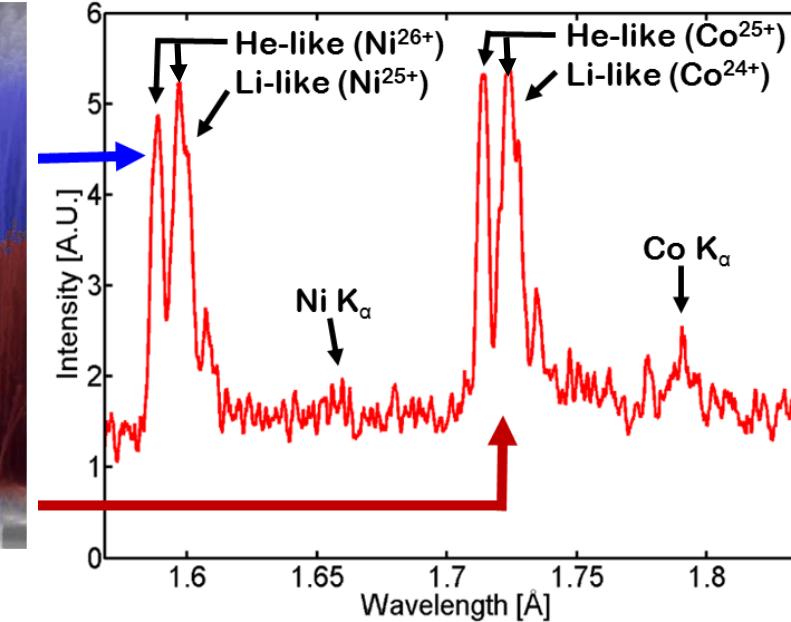


MEDICION DE LA LONGITUD DE PENETRACION DEL CALOR, MONITOREANDO A EMISION DE TRAZAS ENTERRADAS

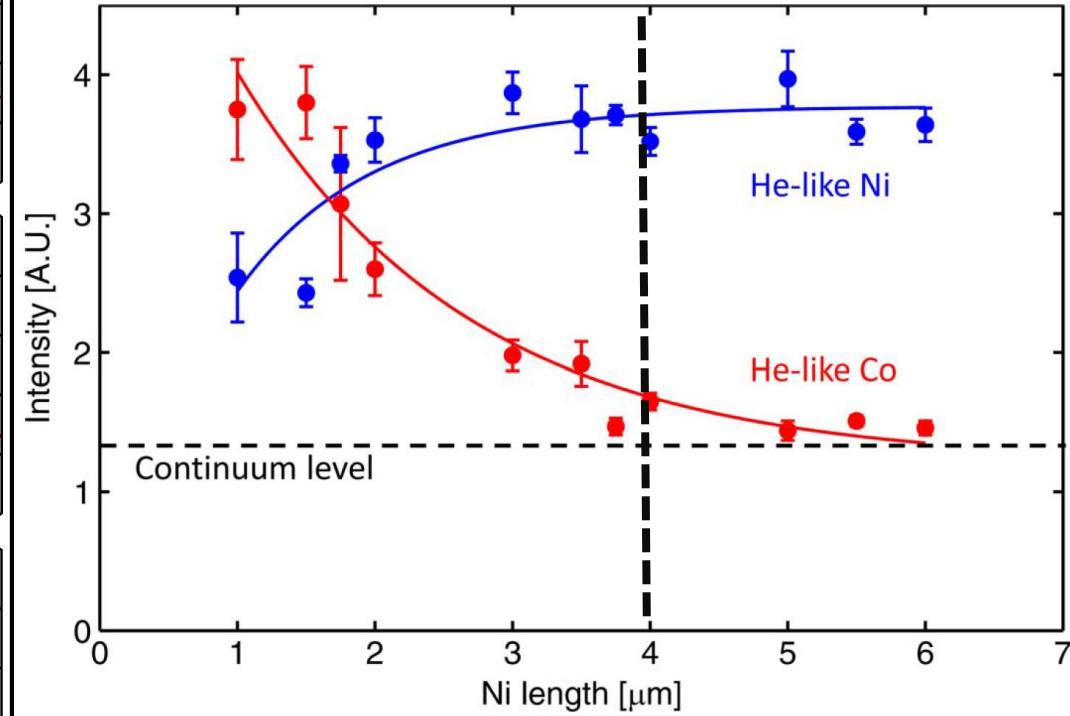
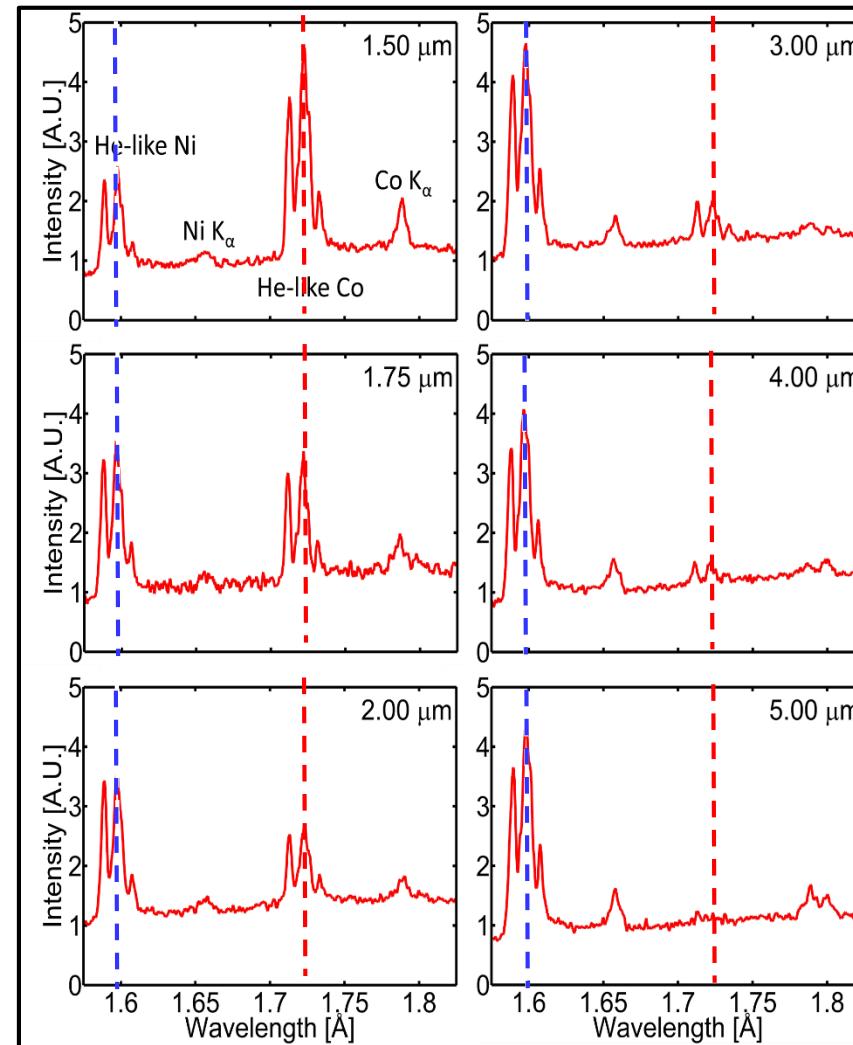
Energy Dispersive Spectroscopy



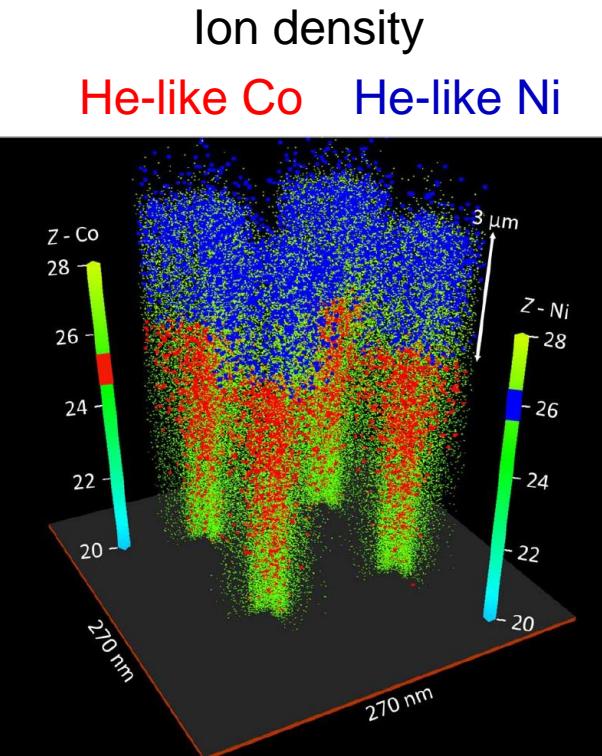
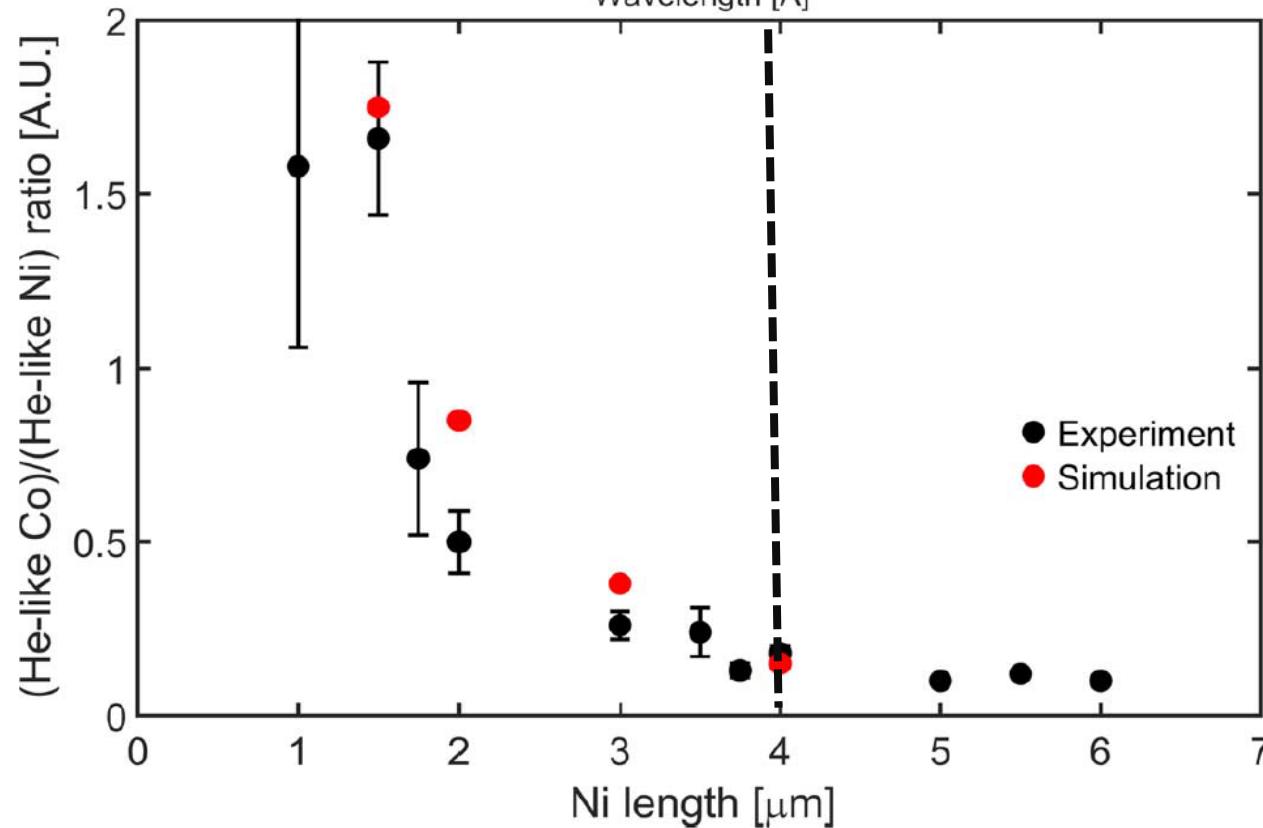
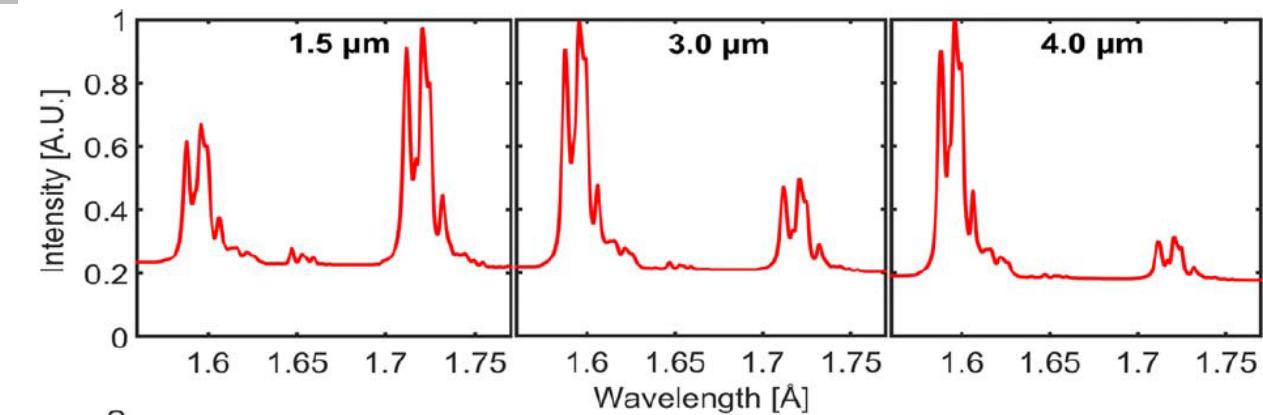
55nm diameter
13% solid density



EL CALENTAMIENTO VOLUMETRICO PERMITE OBSERVAR IONES HE-LIKE CO HASTA PROFUNDIDADES DE $4\mu\text{m}$



LOS RESULTADOS ESTÁN DE ACUERDO CON LAS SIMULACIONES 3D RELATIVISTAS/ FÍSICA ATÓMICA

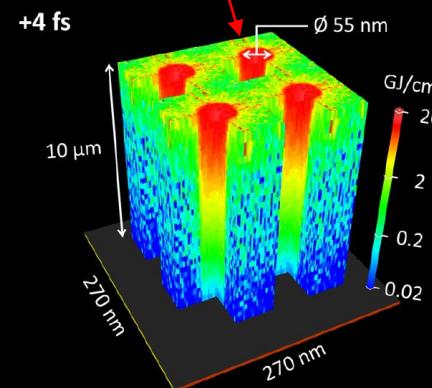


EL CALENTAMIENTO VOLUMETRICO DE NANOHILOS ALINEADOS PRODUCE DENSIDADES DE ENERGIA EXTREMAS EN EXPERIMENTOS COMPACTOS

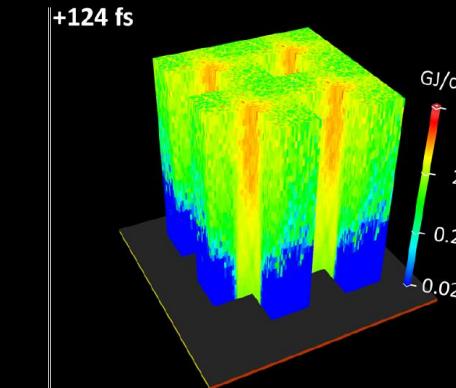
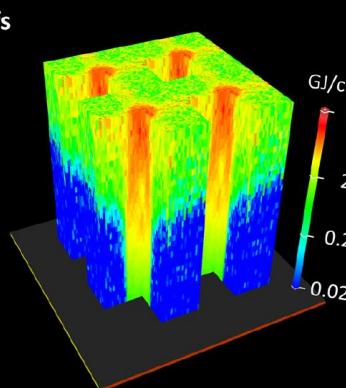
$N_e > 10^{24} \text{ cm}^{-3}$

$P > 100 \text{ Gbar}$

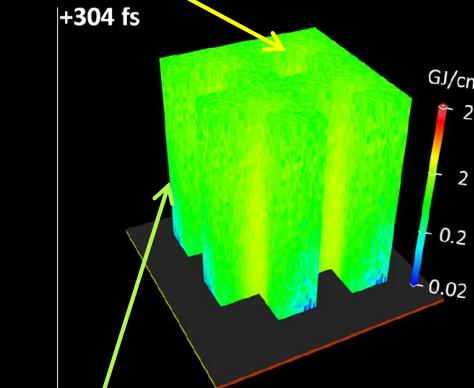
Energy Density 22 GJ cm^{-3}



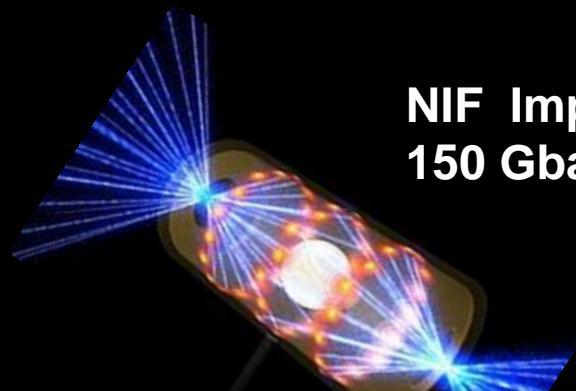
$I = 4 \times 10^{19} \text{ W cm}^2 - 55 \text{ fs}$



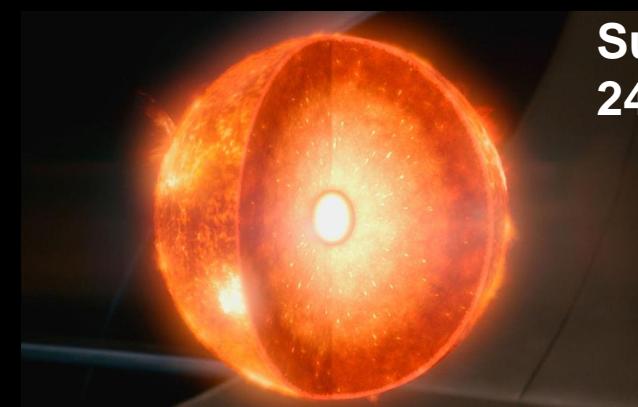
$>10 \text{ Gbar}$



$N_e > 3 \times 10^{23} \text{ cm}^{-3}, T_e \sim 14 \text{ keV}$
 $P \sim 7 \text{ Gbar}, \text{ Energy Density } 1 \text{ GJ cm}^{-3}$



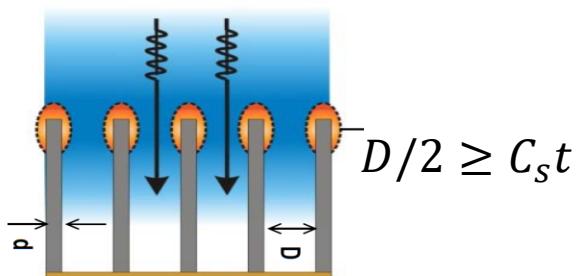
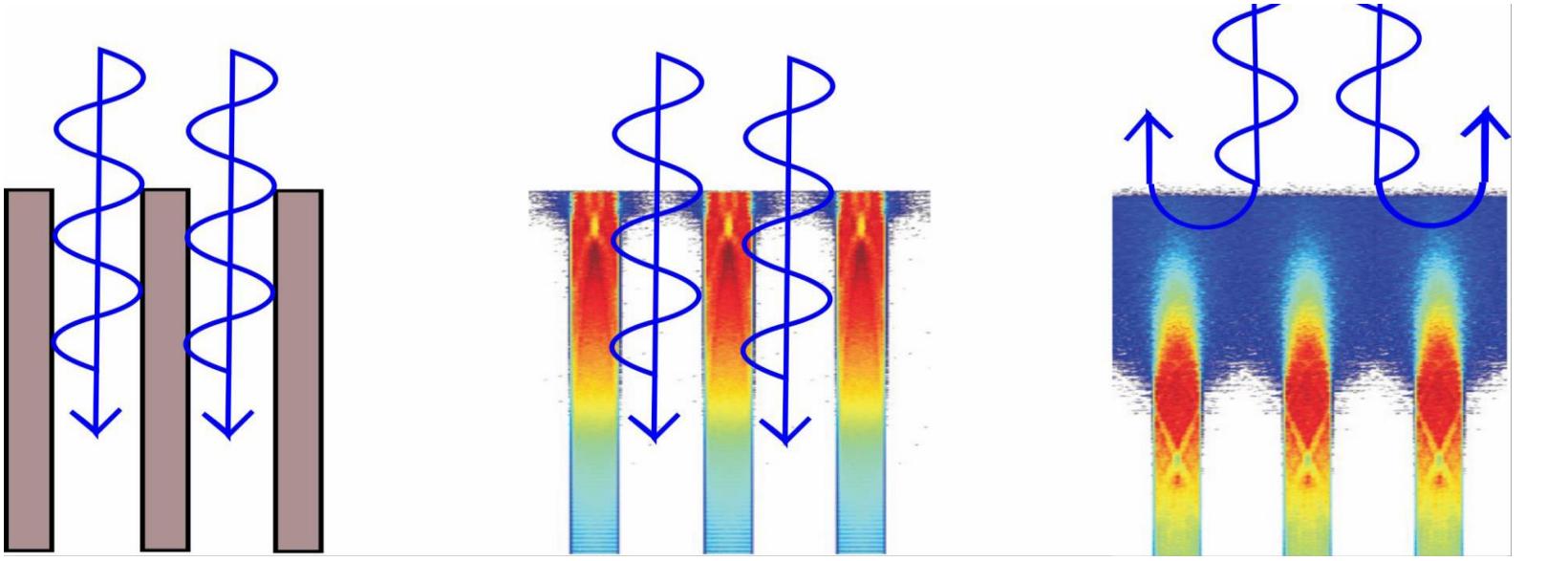
NIF Implosion
150 Gbar



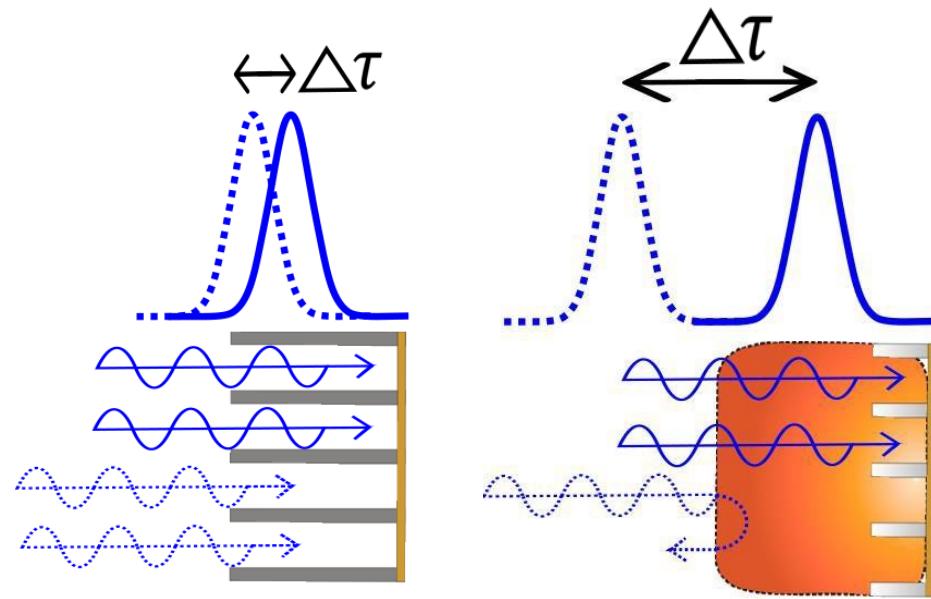
Sun Core
240 Gbar

Cuán rápido se cierran los gaps?

La formación de la superficie de densidad crítica impide acoplar la energía del laser en un volumen de plasma con T_e y N_e grandes.

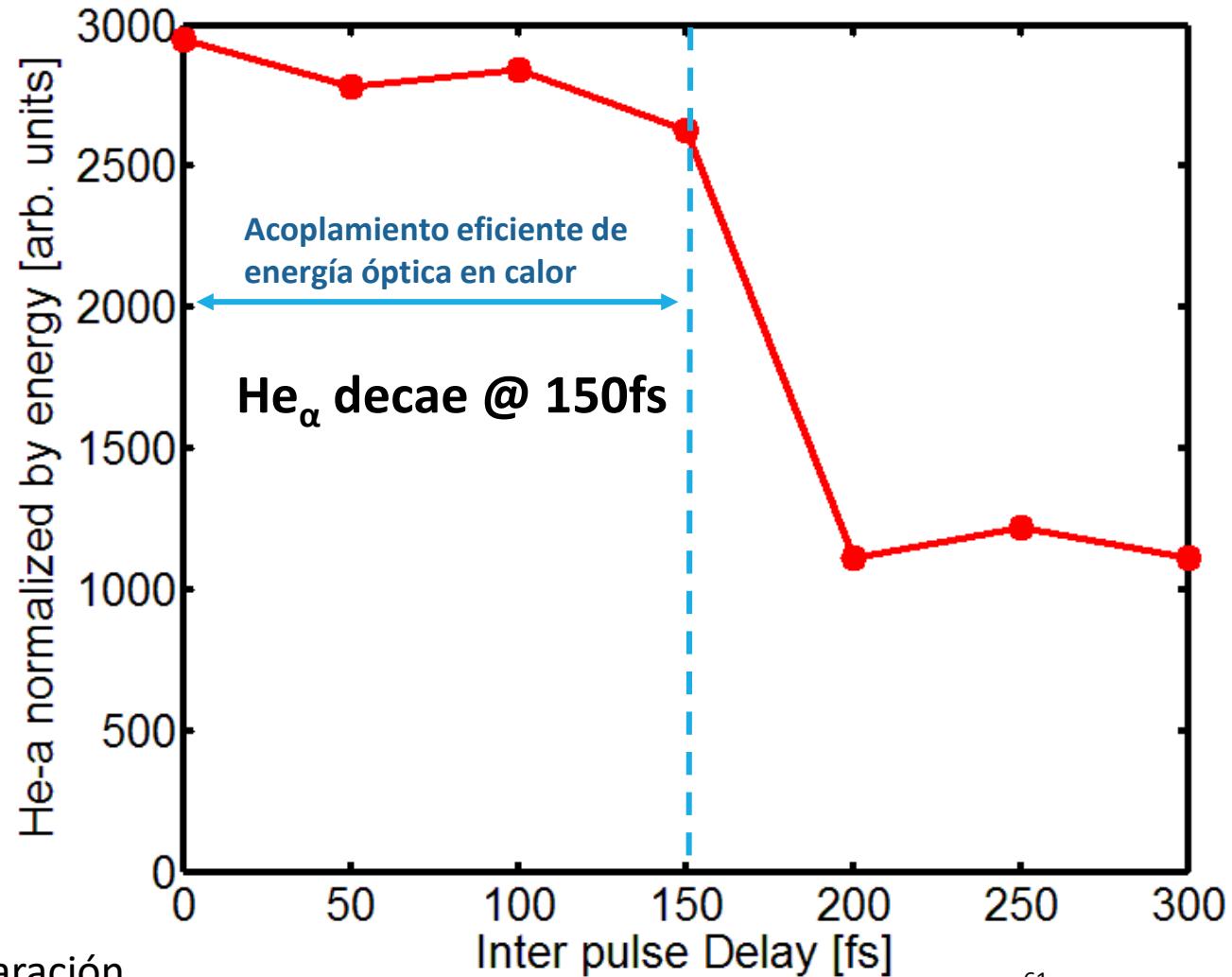


MEDICIÓN DEL ACOPLAMIENTO DE ENERGÍA USANDO DOS PULSOS QUE ARRIBAN EN DISTINTOS TIEMPOS



$I=4 \times 10^{19} \text{ Wcm}^{-2} - 1 \times 10^{20} \text{ Wcm}^{-2}$.

Ni diámetro: 80nm, 12% densidad sólido



PLASMAS CON DENSIDAD ELECTRÓNICA (NE) Y TAMAÑO (L) SIMULTÁNEAMENTE GRANDES, EMITEN RAYOS X EFICIENTEMENTE

Tiempo de vida radiativo

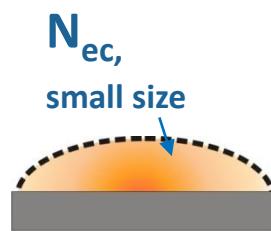
$$\tau_{rad} \propto \frac{1}{\langle \sigma v \rangle N_e} < \frac{\Delta L}{C_s} \propto \tau_{hydro}$$

Densidad electrónica grande

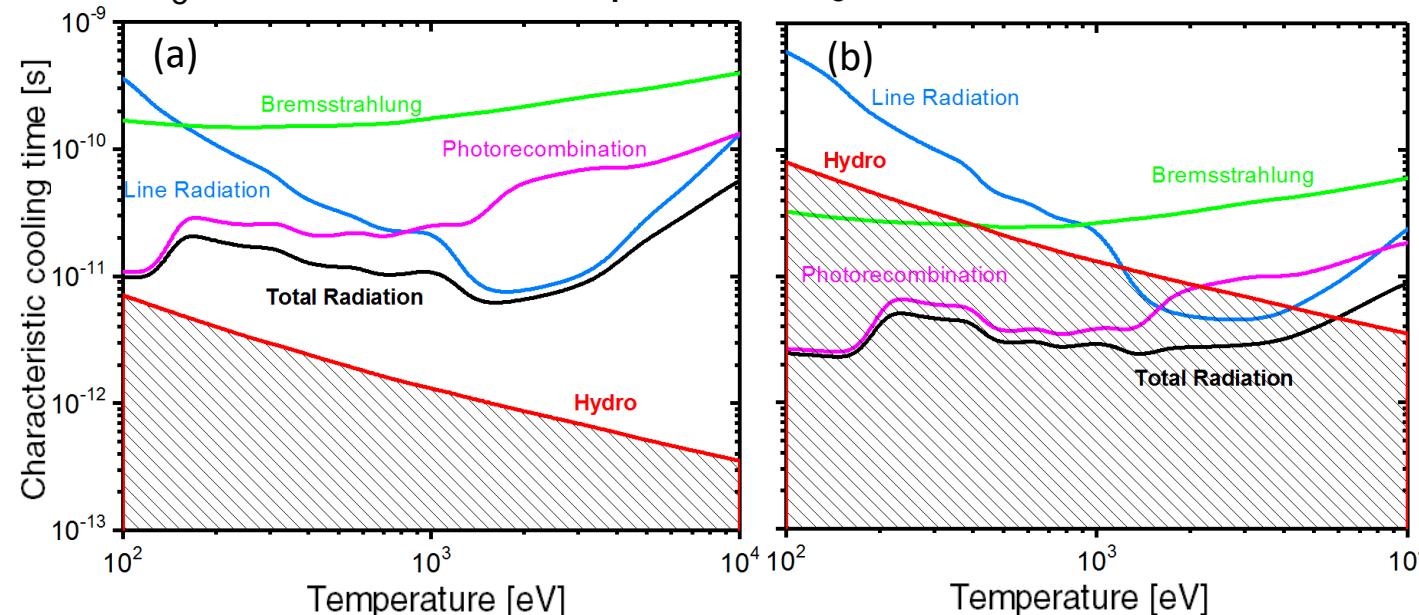
Tiempo de expansión Hidrodinámica

Tamaño del plasma grande

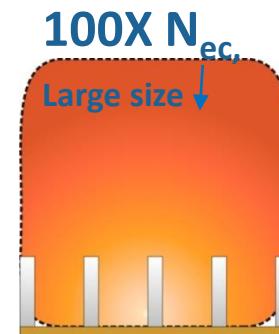
Optica 4 (11), 1344-1349 (2017)



Au Solid target
 $N_e = 6 \times 10^{22} \text{ cm}^{-3}$, $L = 0.2 \mu\text{m}$

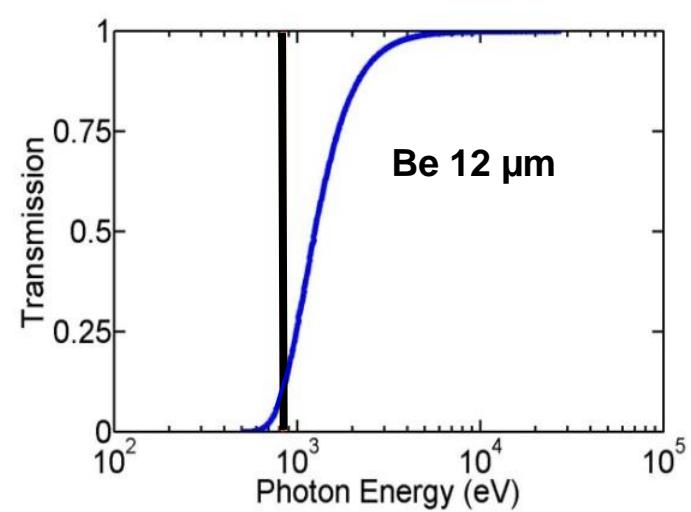
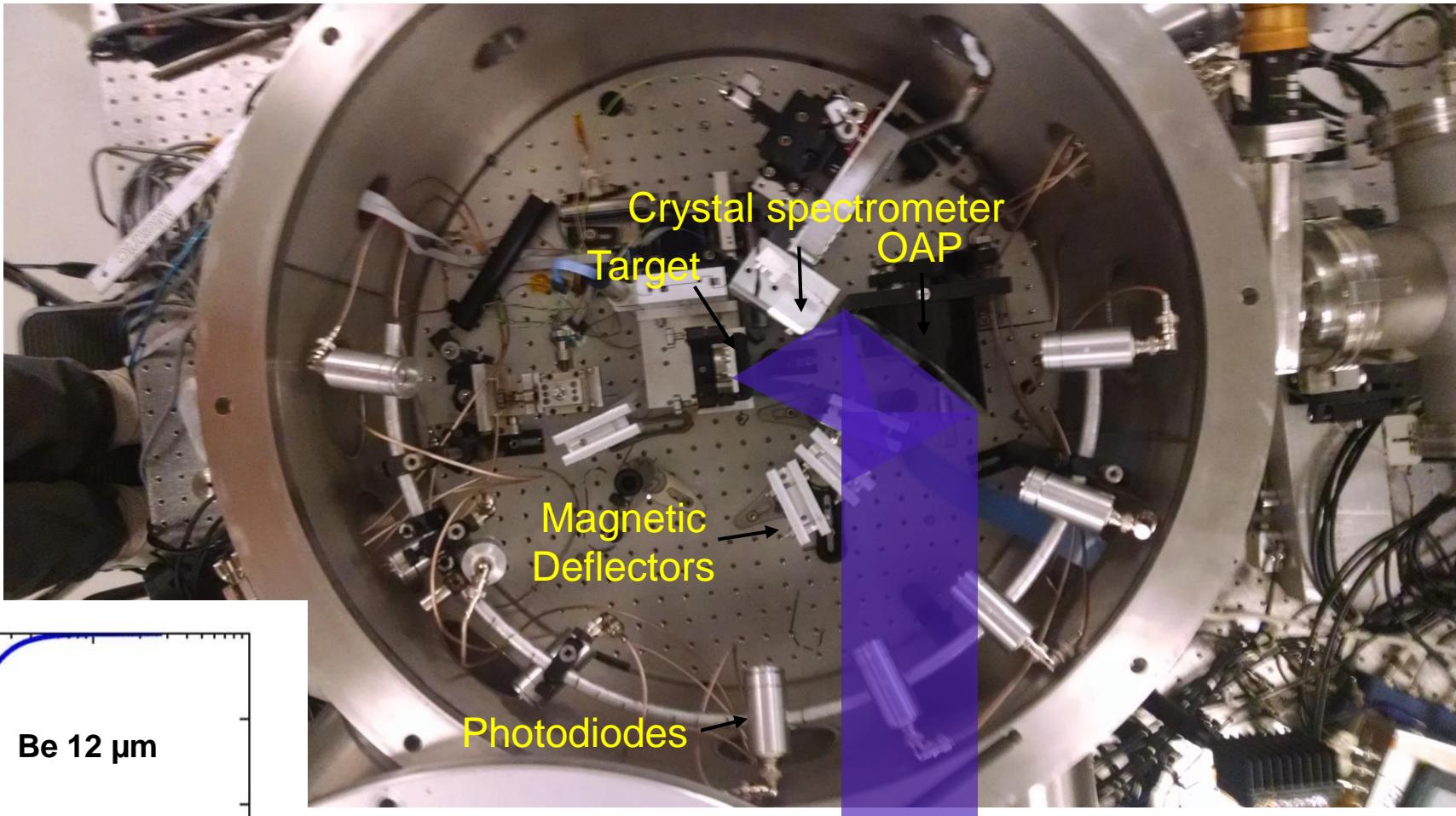


Au Nanowire array
 $N_e = 4 \times 10^{23} \text{ cm}^{-3}$, $L = 4 \mu\text{m}$



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)

EFICIENCIA DE CONVERSIÓN EN RAYOS X Y OTROS EXPERIMENTOS....

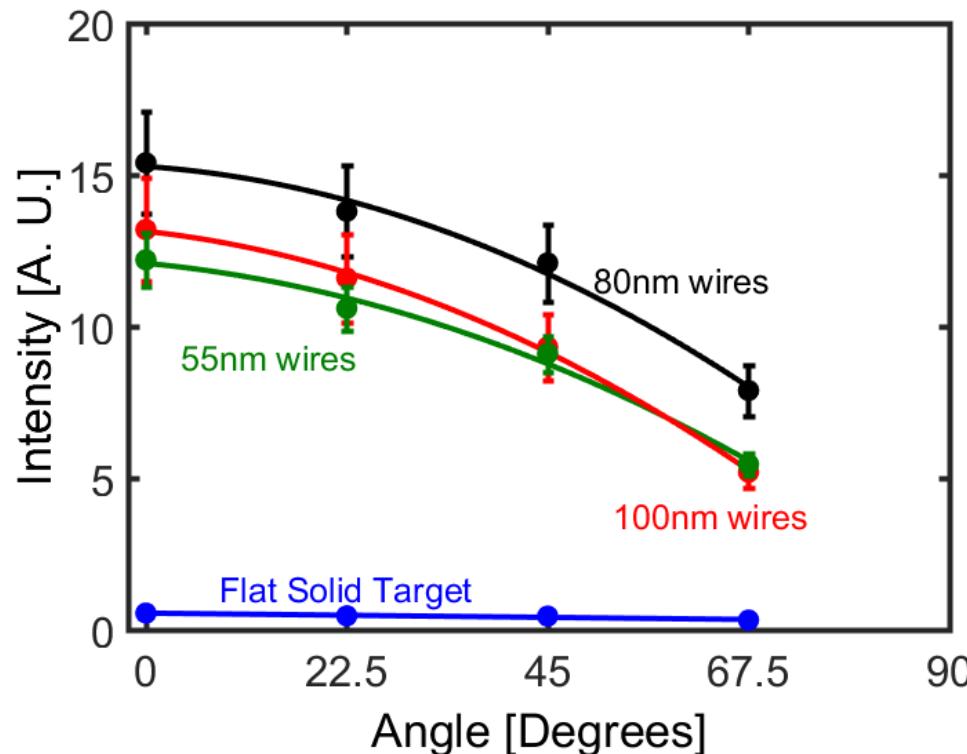


Optica 4 (11), 1344-1349 (2017)

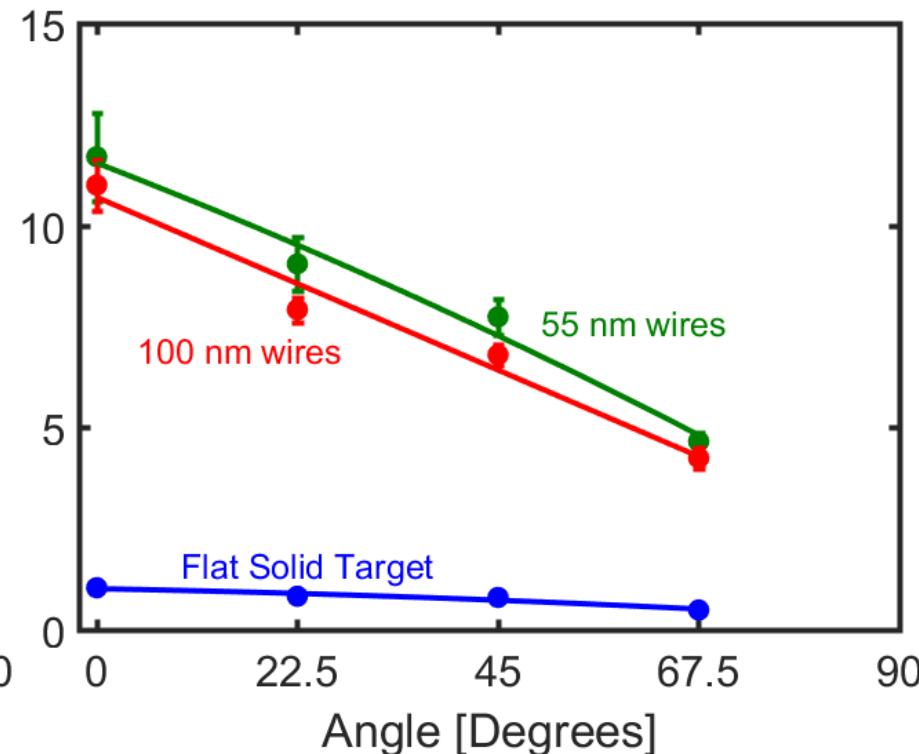
LOS NANOHILOS PRODUCEN FOTONES CON $h\nu > 1 \text{ keV}$ CON UNA EFICIENCIA ENTRE 10 Y 100 VECES MAYOR QUE LOS BLANCOS SOLIDOS

$I = 4 \times 10^{19} \text{ W cm}^{-2}$; 55 fs pulses

Au nanowires

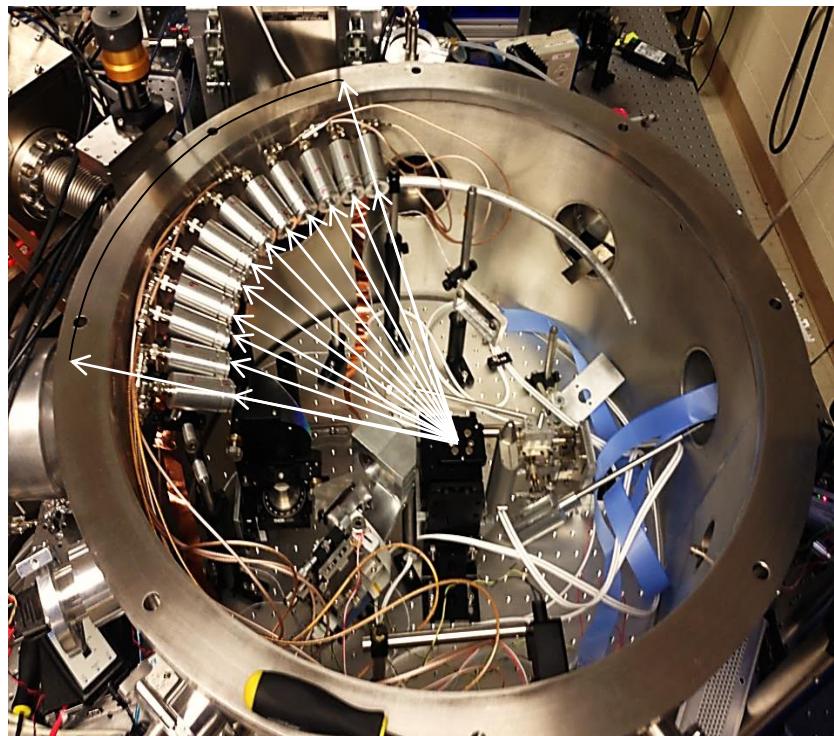


Nickel nanowires

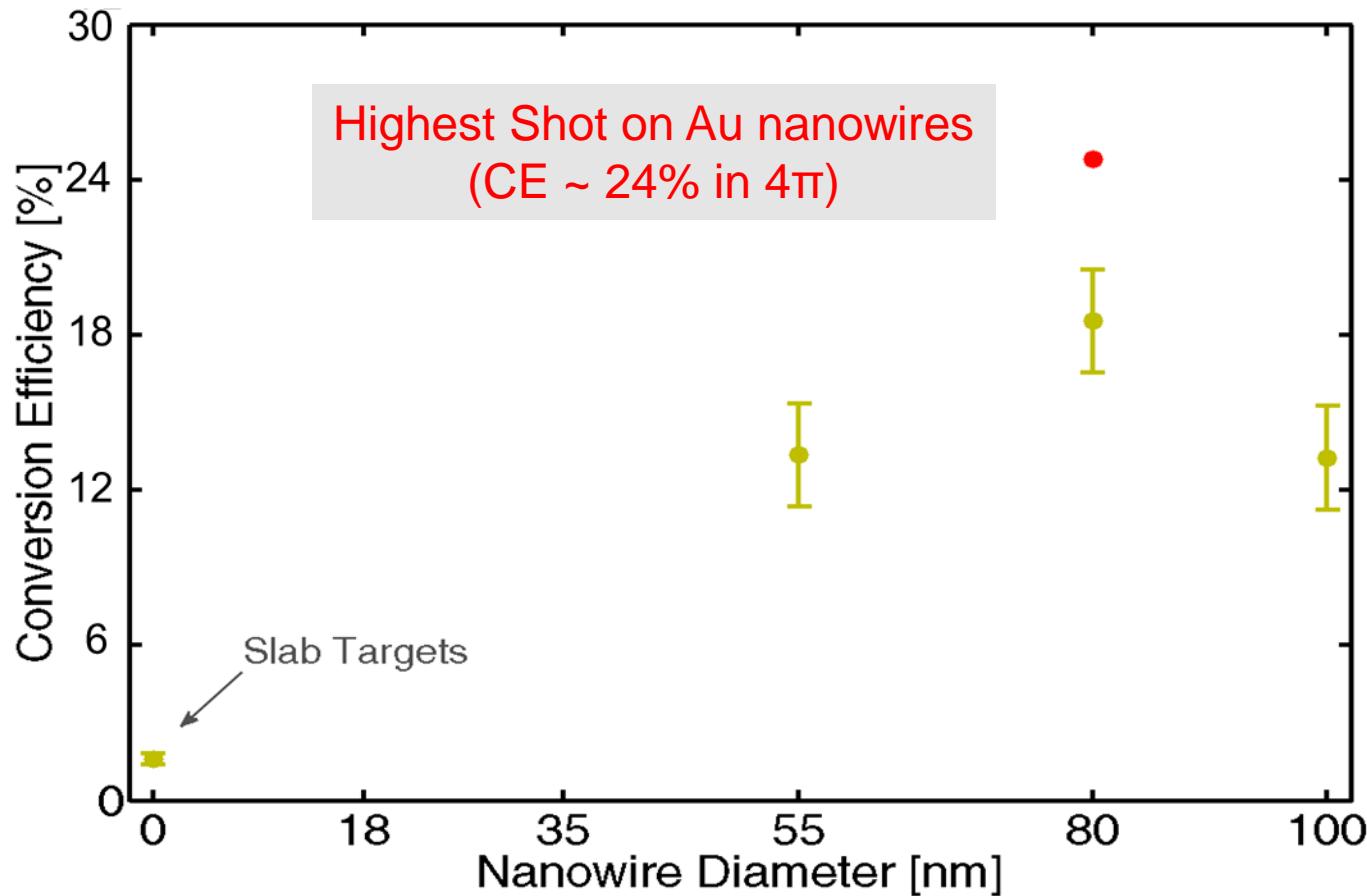


LOS NANOHILOS PRODUCEN FOTONES CON $h\nu > 1 \text{ keV}$ CON UNA EFICIENCIA ENTRE 10 Y 100 VECES MAYOR QUE LOS BLANCOS SOLIDOS

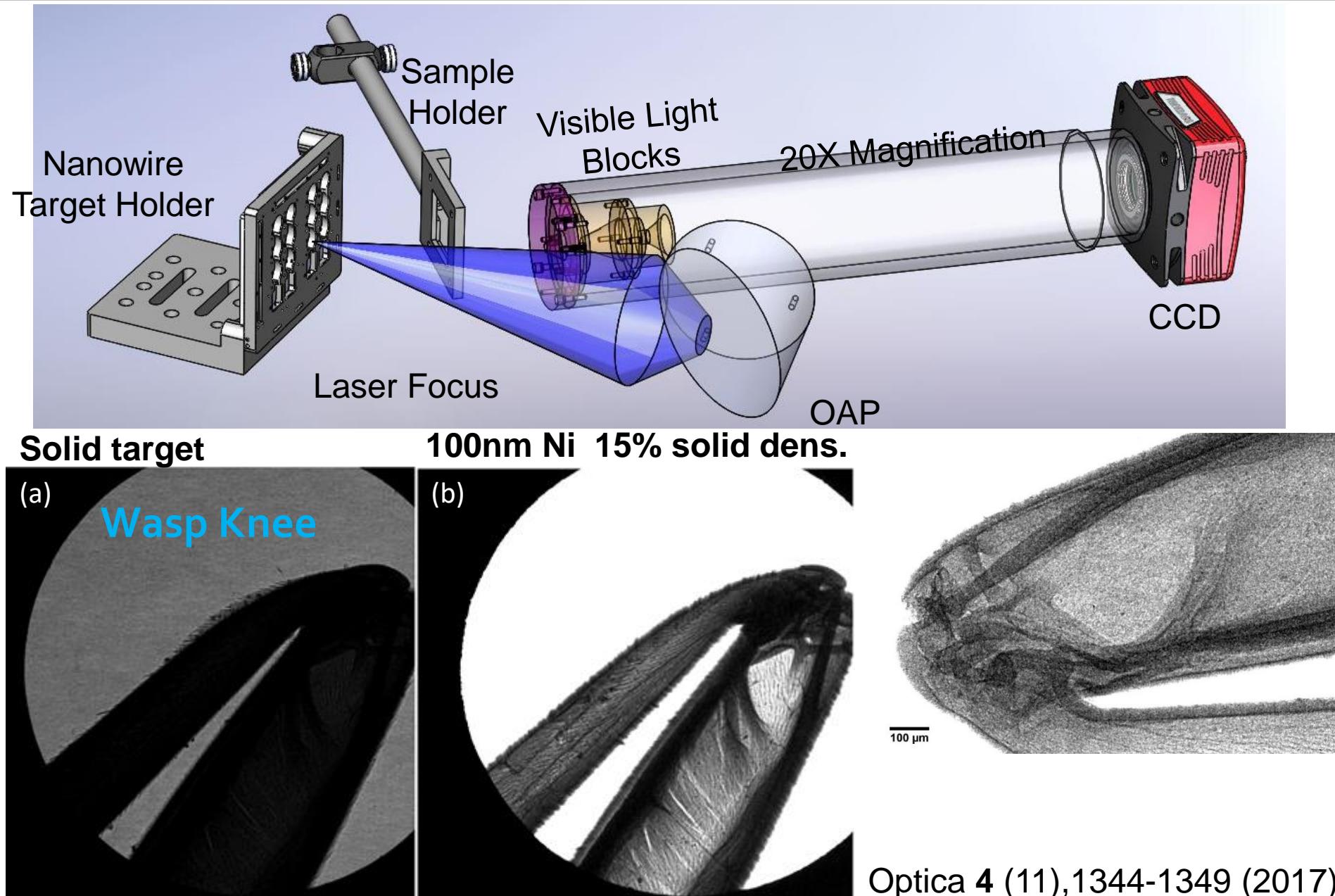
CE (record)~ 20 %, (hasta 24% disparos individuales) en 4π



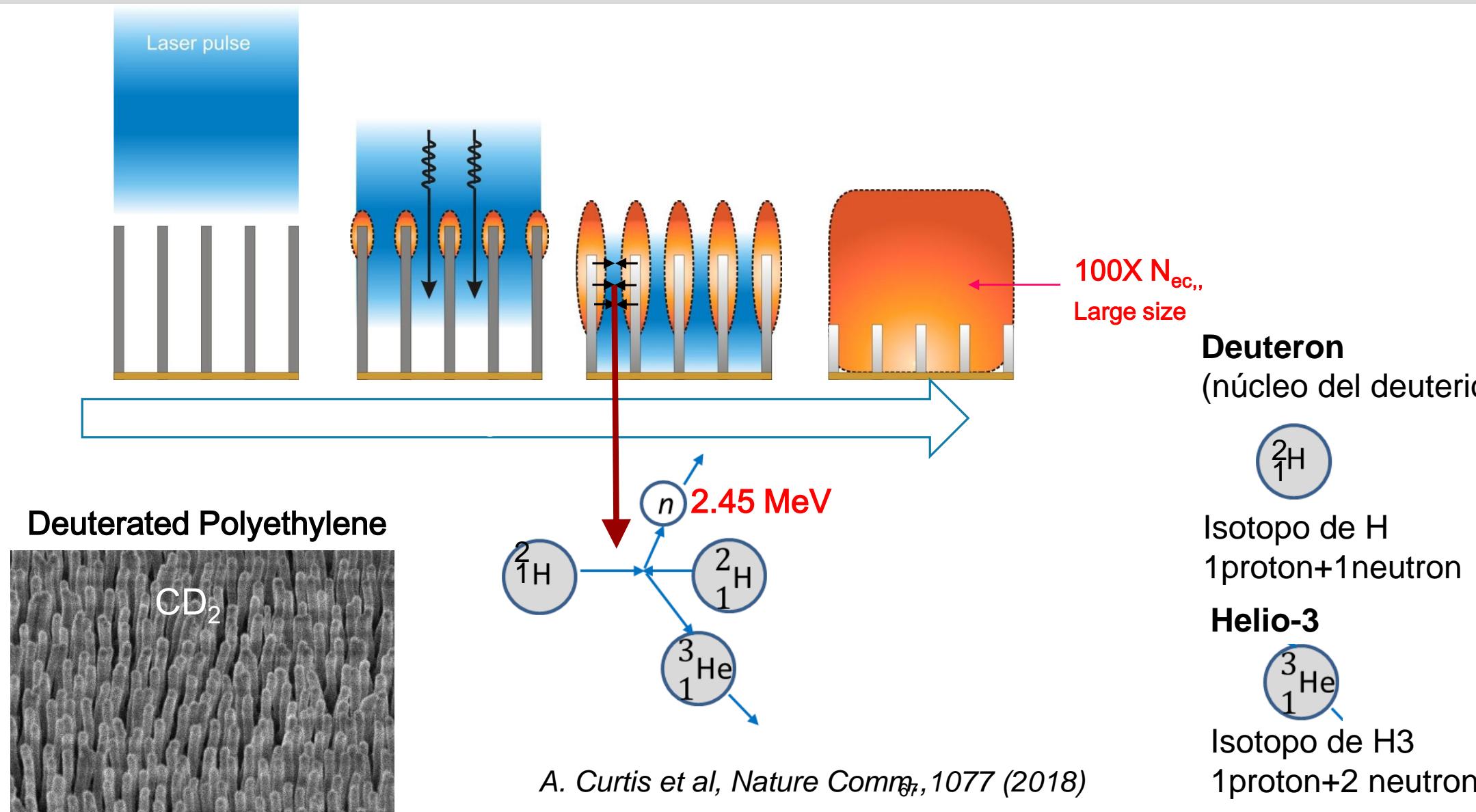
$I = 4 \times 10^{19} \text{ W cm}^{-2}$ 55 fs pulses



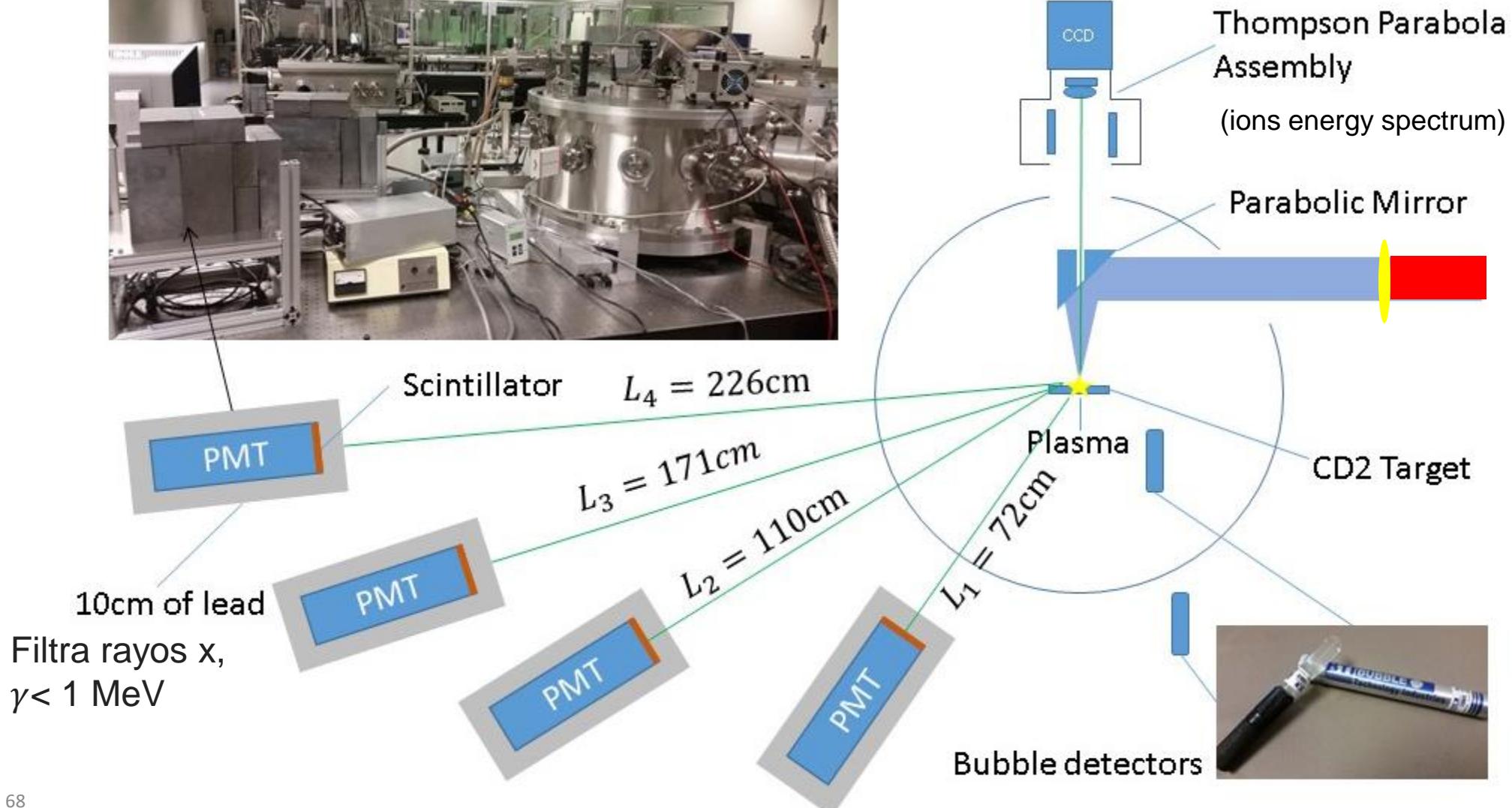
RADIOGRAFIA PRODUCIDA POR UN UNICO DISPARO DE UN PULSO DE RAYOS X



Deuterium ion acceleration and neutron production in deuterated nanowires



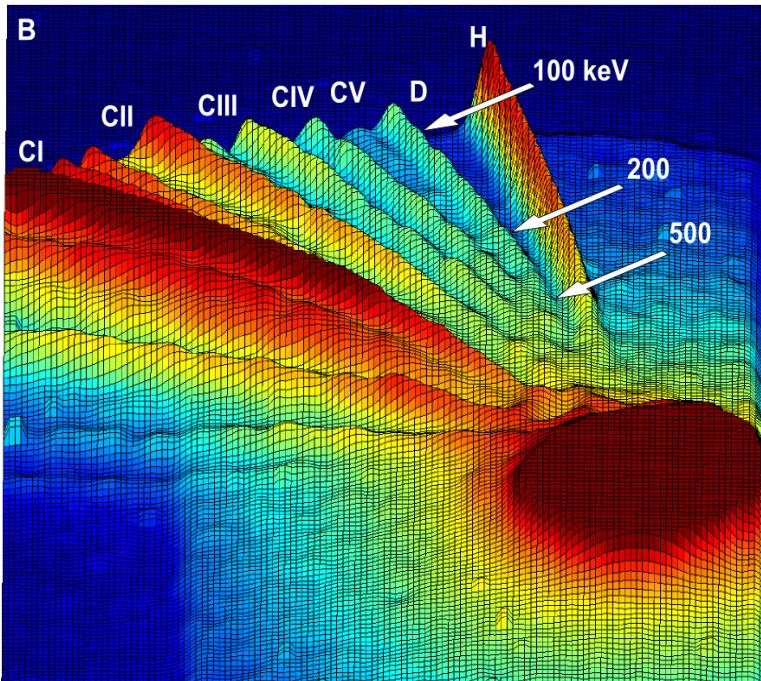
Deuteron and Neutron Detection Setup



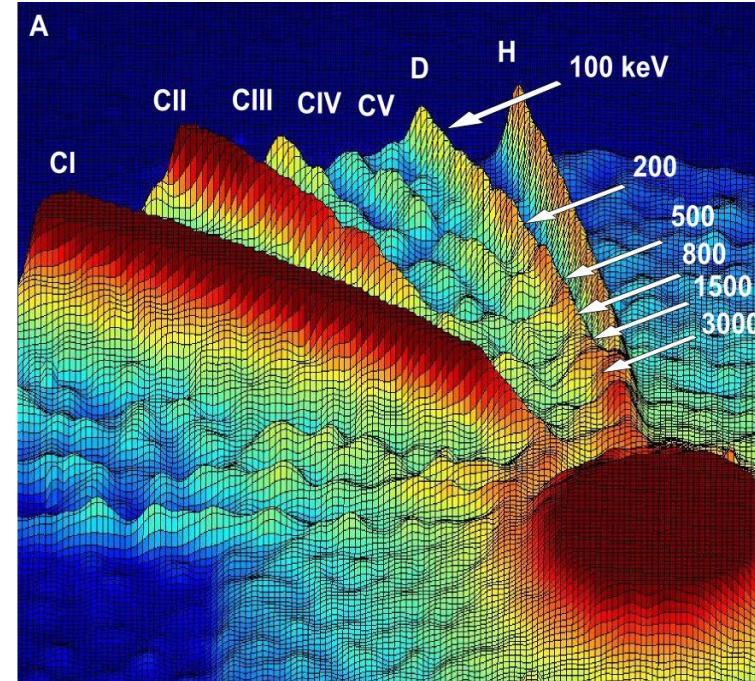
Deuteron energies up to 3 MeV measured

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

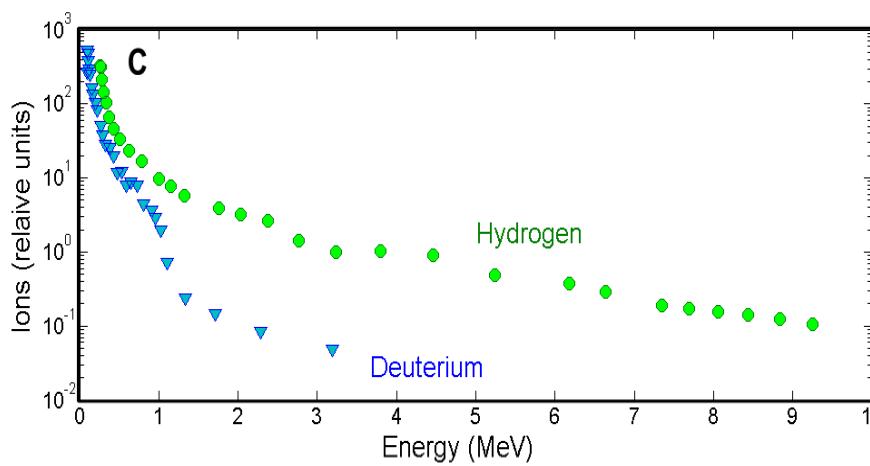
Flat Target



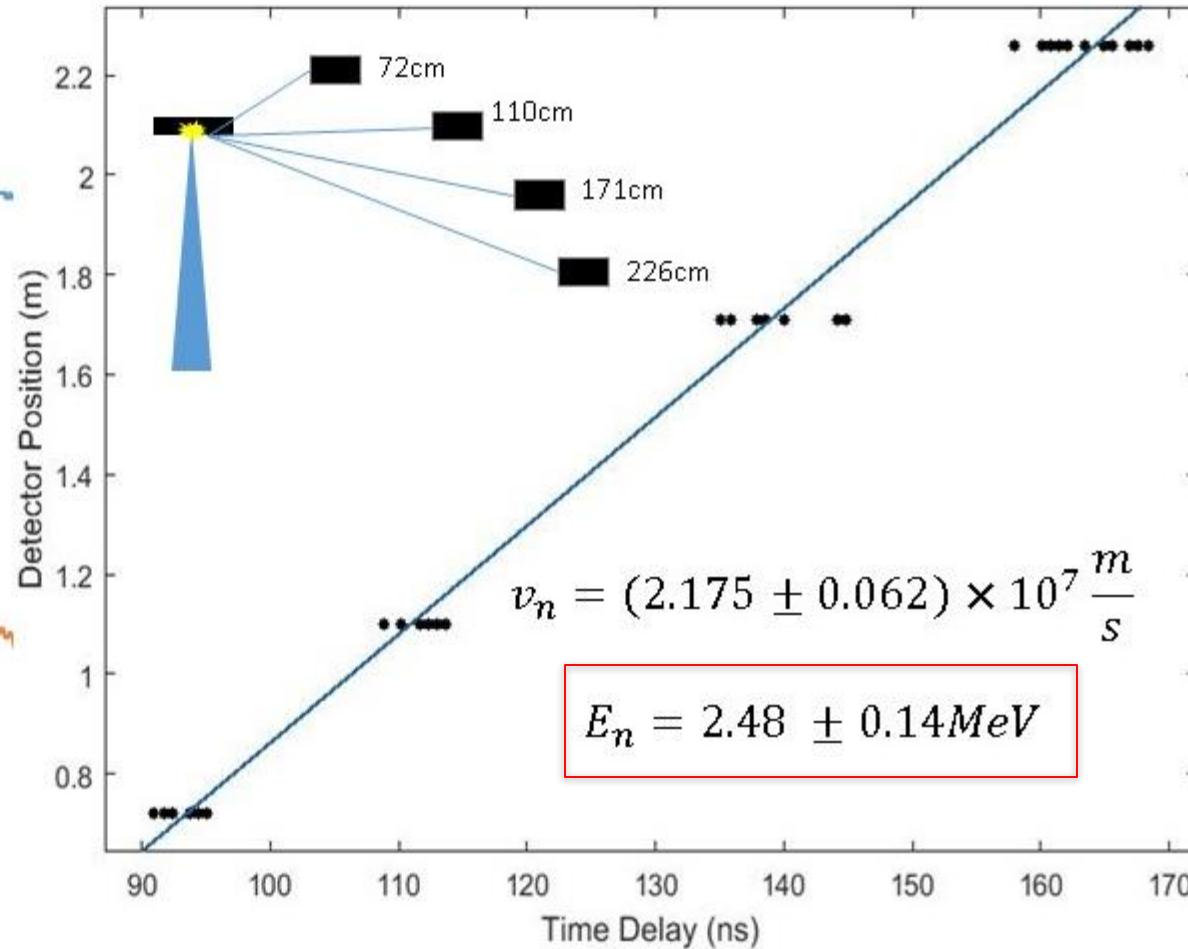
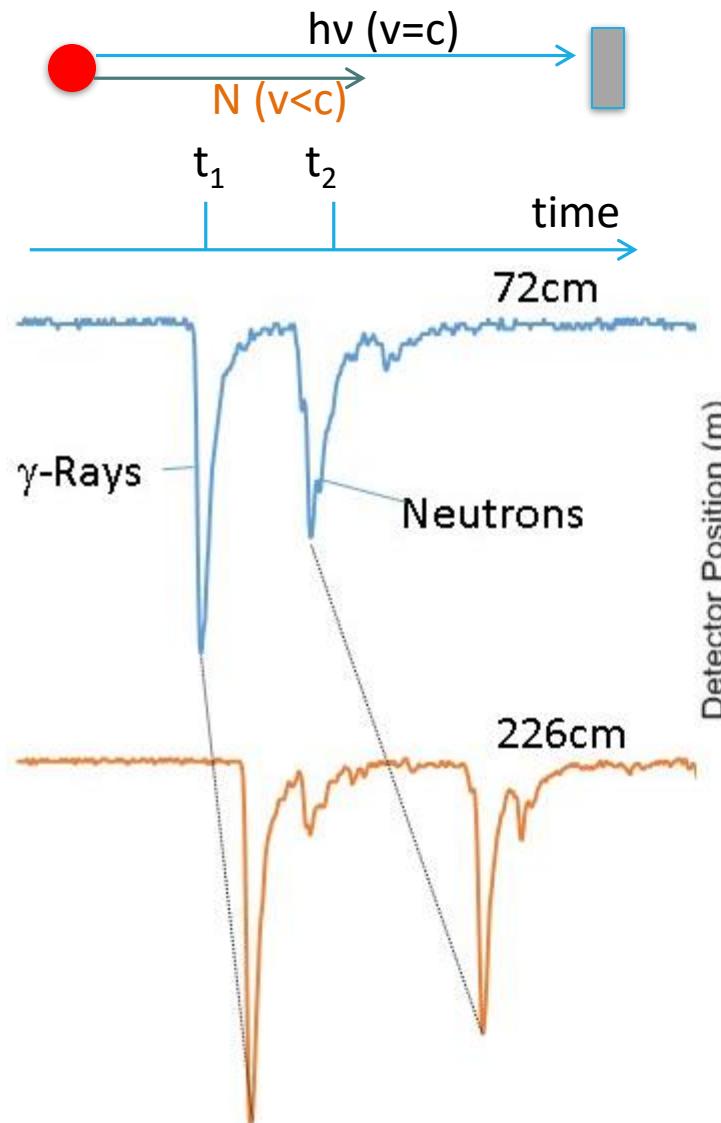
Nanowire



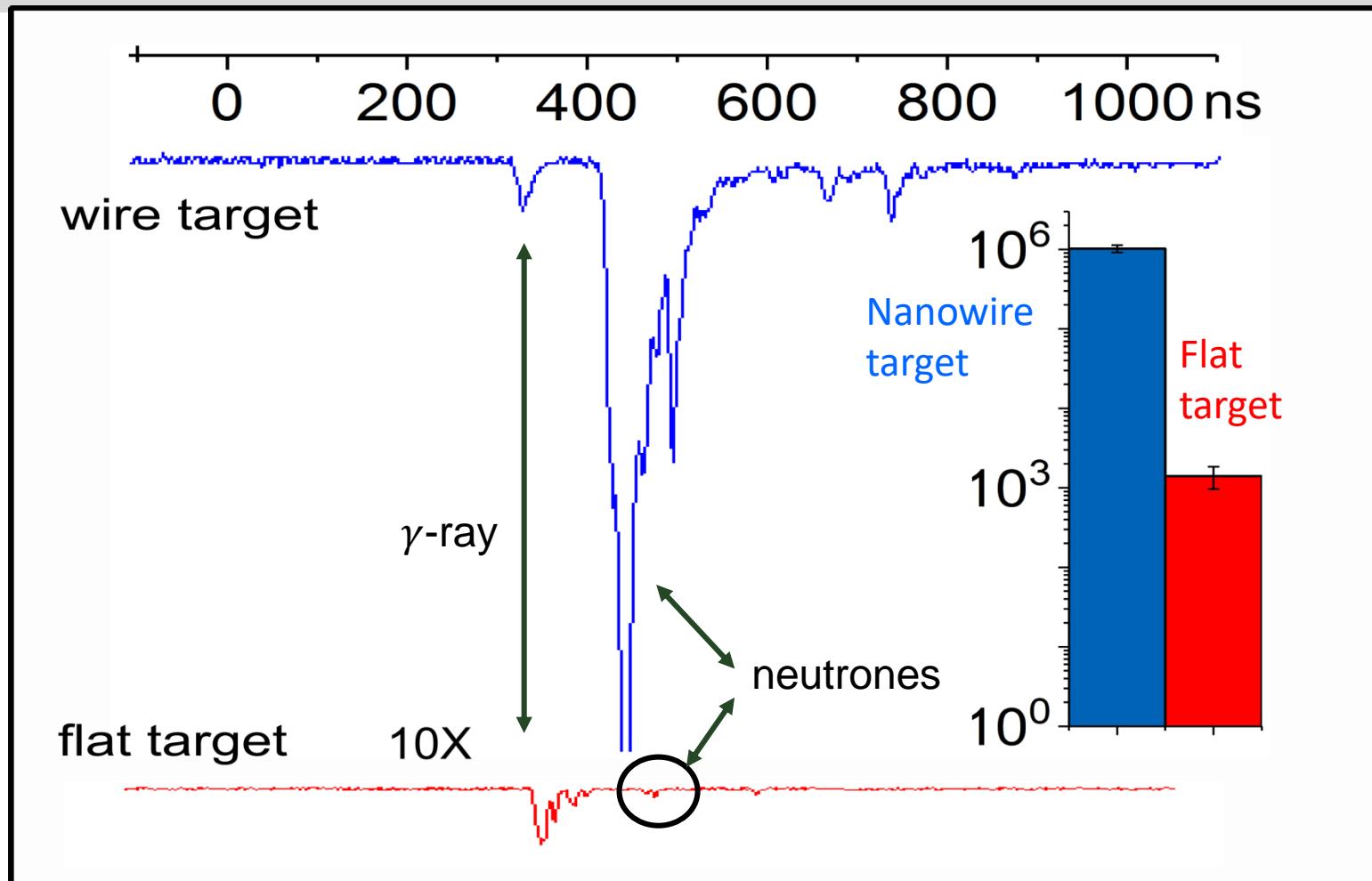
Deuterium flat
0.5MeV



Neutron Time of Flight: D-D Fusion Neutrons



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)

INDICE

- Aleph: Advanced Laser for Extreme Photonics
- Interacción láseres de intensidad relativista y electrones
- Creación de plasmas altamente ionizados a partir de irradiación con láseres de intensidad relativista de blancos sólidos y blancos nanoestructurados.

- Experimentos

- Nanohilos de polímero deuterado. Energía y eficiencia de emisión de electrones, flujo de rayos gamma, rayos x y neutrones

- Nanohilos metálicos: record en grado de ionización

SUBAMOS LA INTENSIDAD!

EXPERIMENTOS Y SIMULACIONES QUE MUESTRAN EFEKTOS RELATIVISTAS EN INTERACCIÓN DE LA LUZ CON LOS MATERIALES

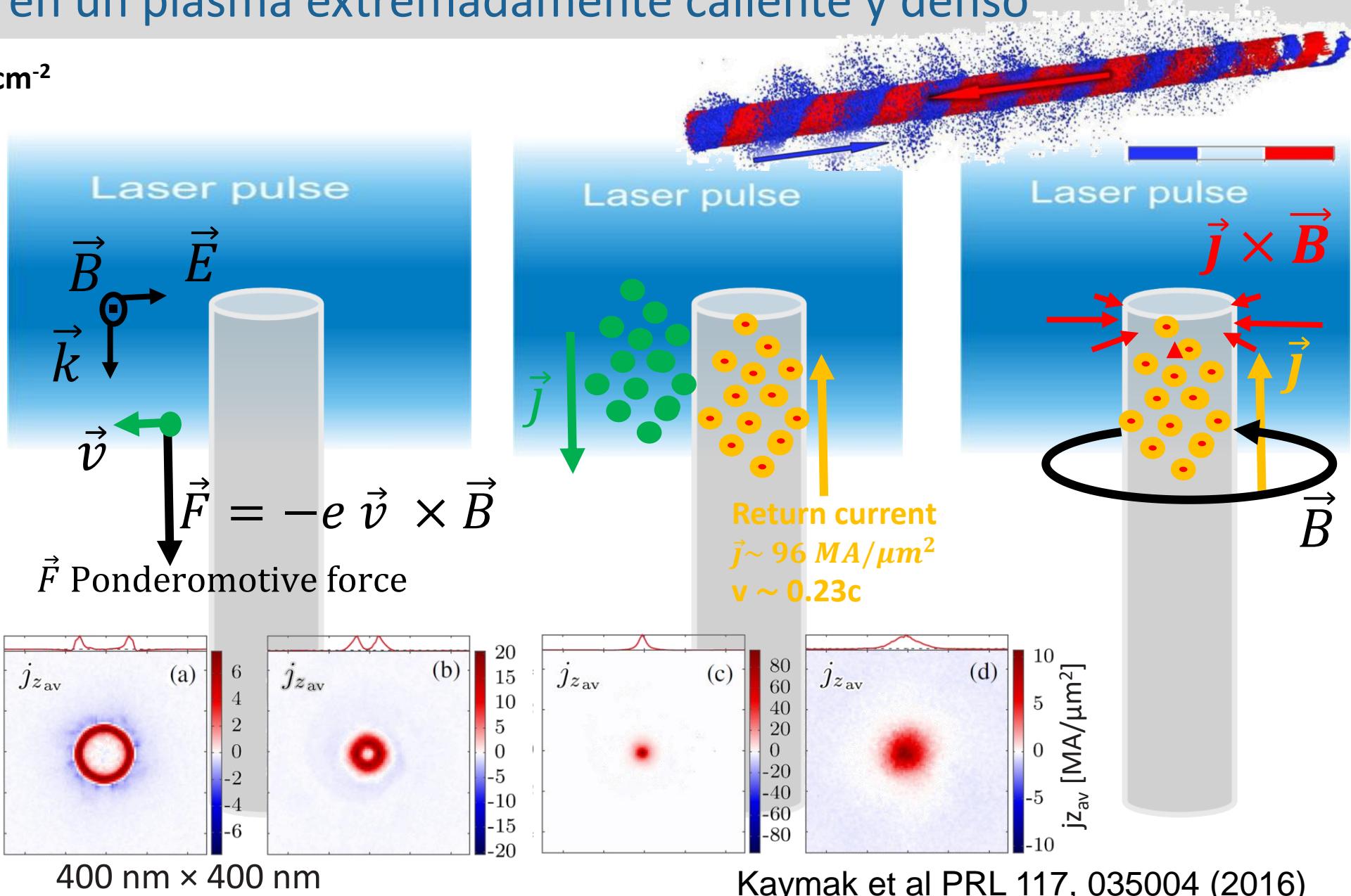
- Experimentos

- Nanohilos de polímero deuterado. Energía y eficiencia de emisión de electrones, flujo de rayos gamma, rayos x y neutrones

- Nanohilos metálicos: record en grado de ionización

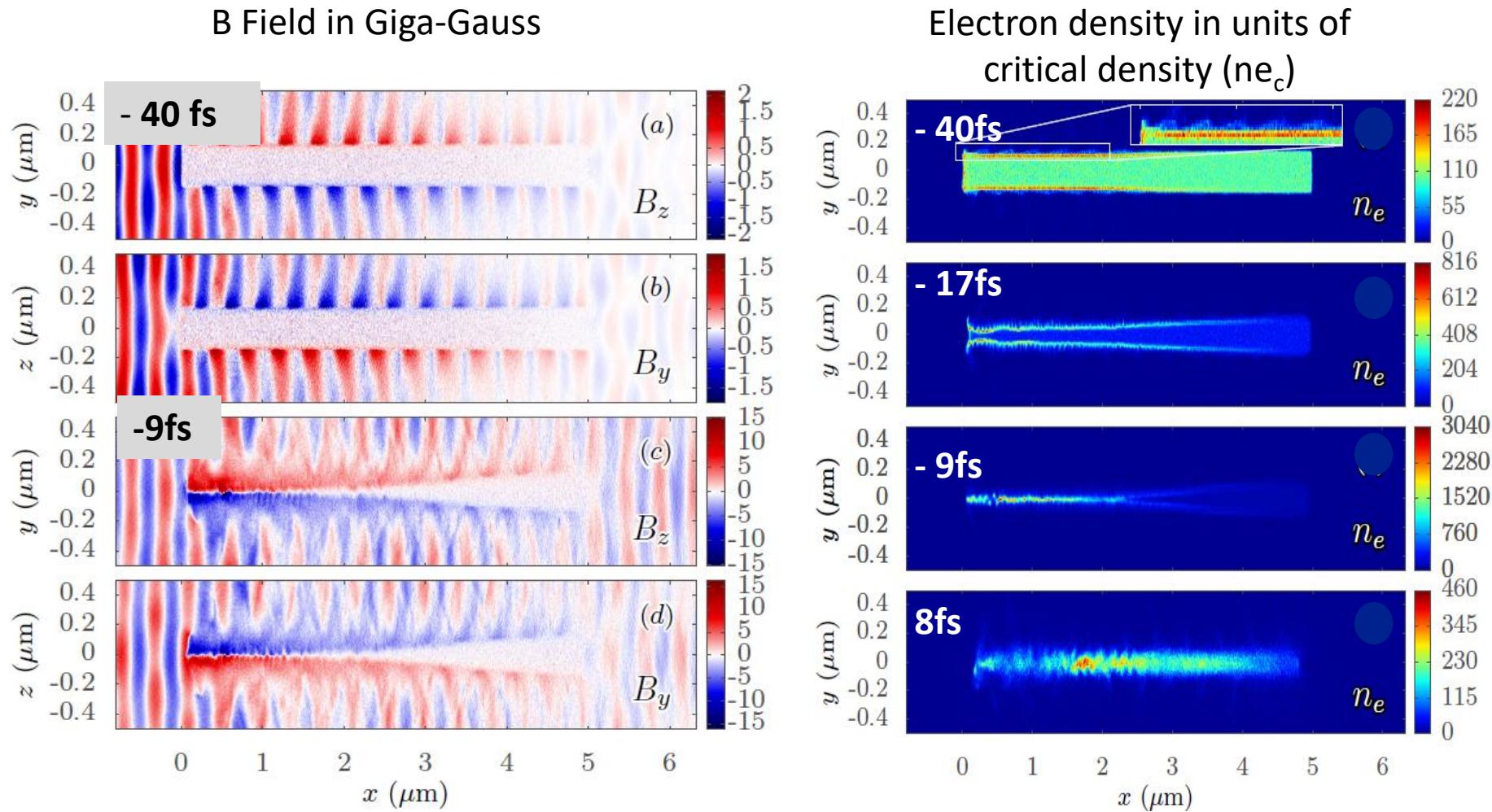
El Nanopinch relativista inducido por la corriente de retorno comprime a los nanohilos en un plasma extremadamente caliente y denso

$I \sim 5 \times 10^{21} \text{ W cm}^{-2}$



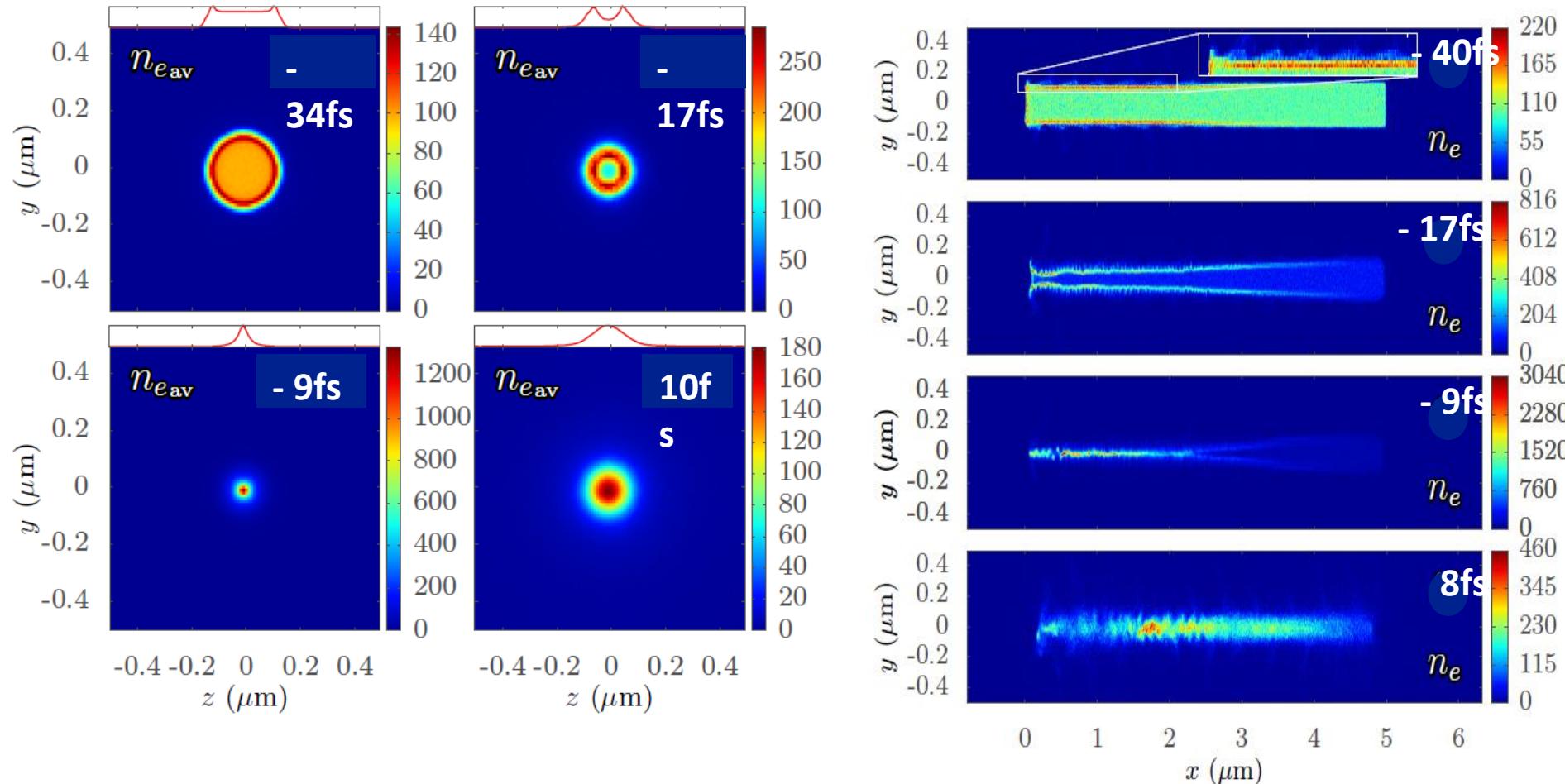
The large return current generates a Giga-Gauss azimuthal magnetic field and nano-scale Z-pinch with > 1000 times n_e

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



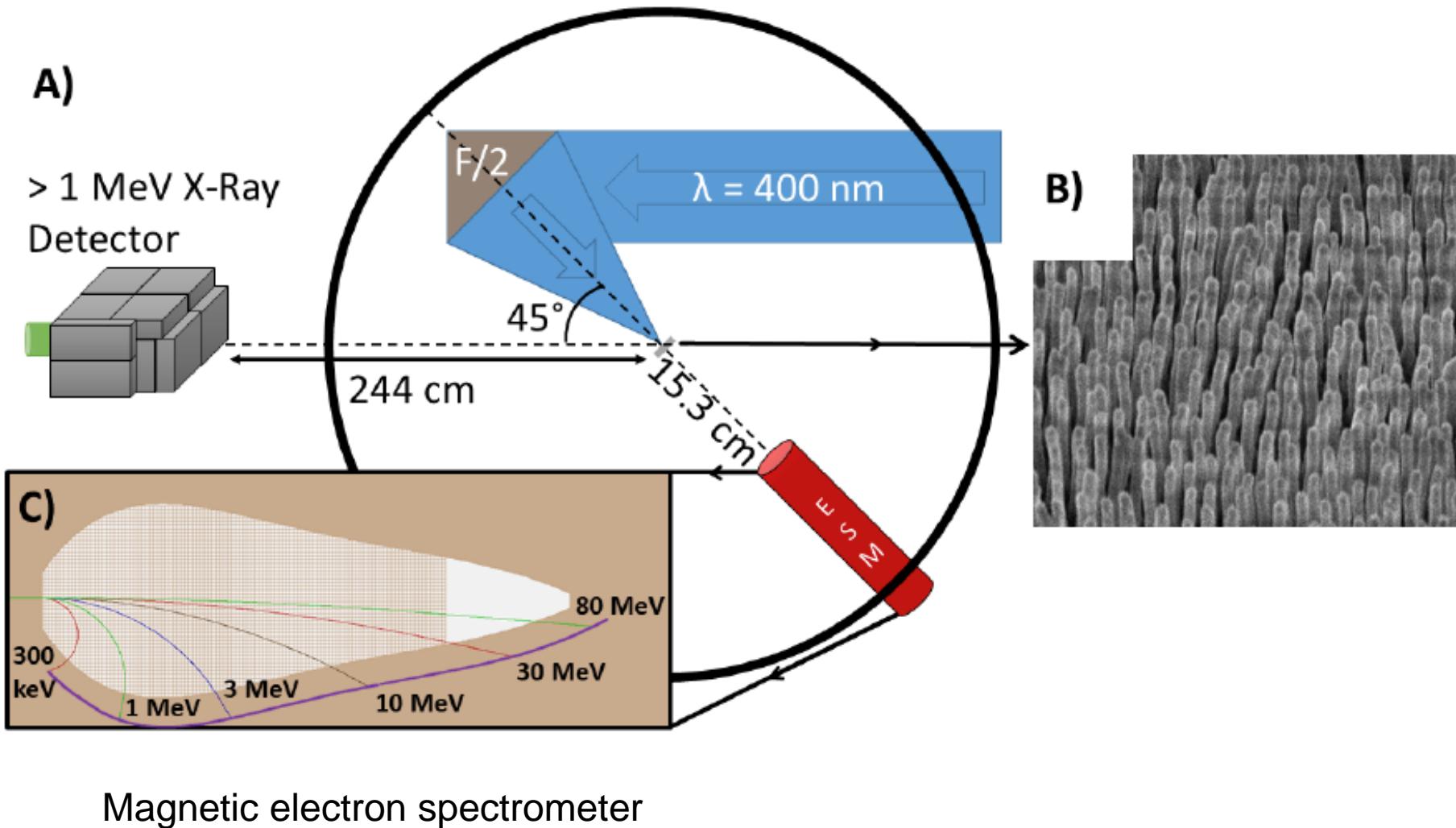
Self-generated quasi-static azimuthal magnetic field pinches nanowires into hot plasmas with $n_e > 9 \times 10^{24} \text{ cm}^{-3}$, > 1000 times the critical density

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

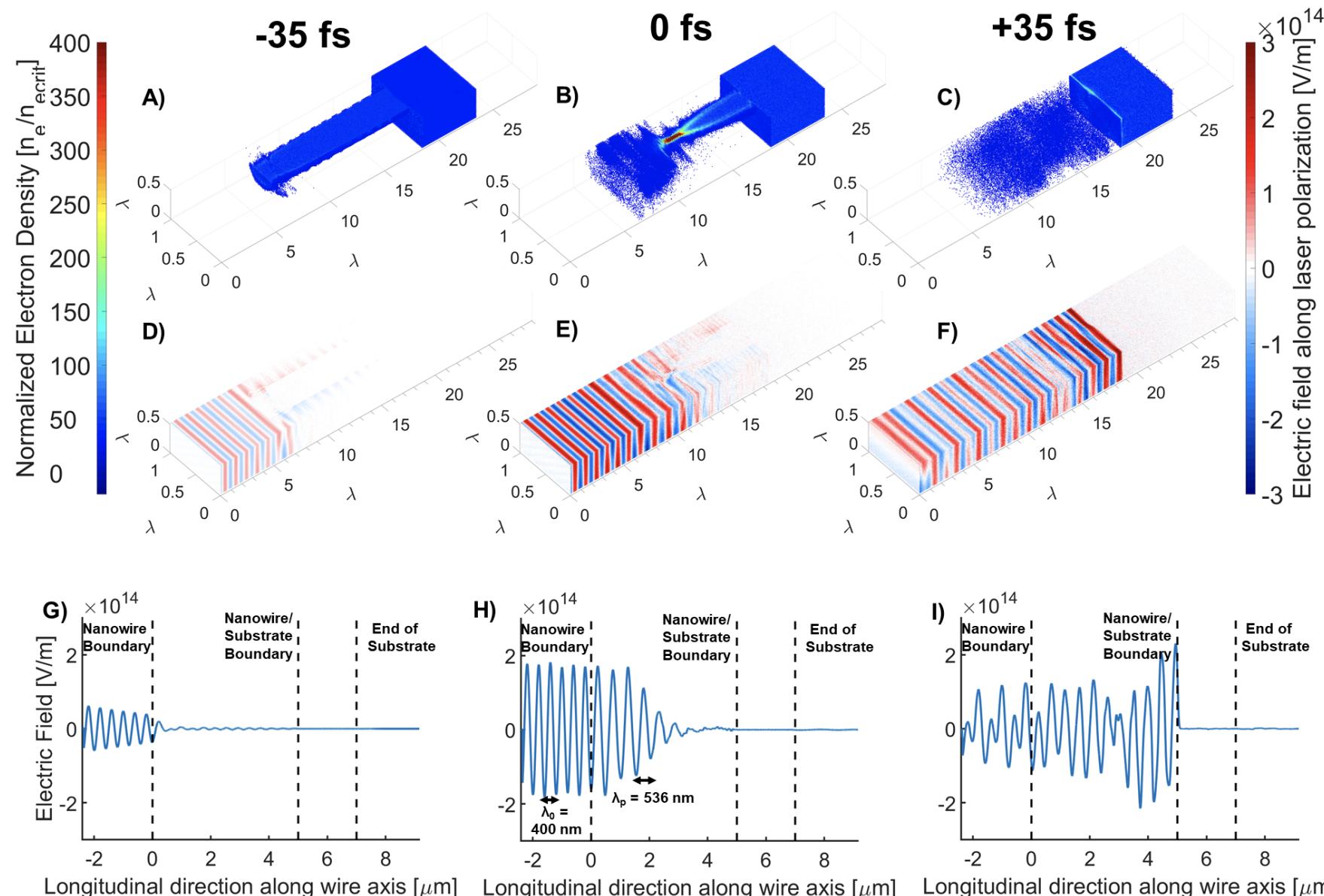


Relativistic Induced Transparency and Electron Acceleration in Dense CD₂ Nanowire array

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

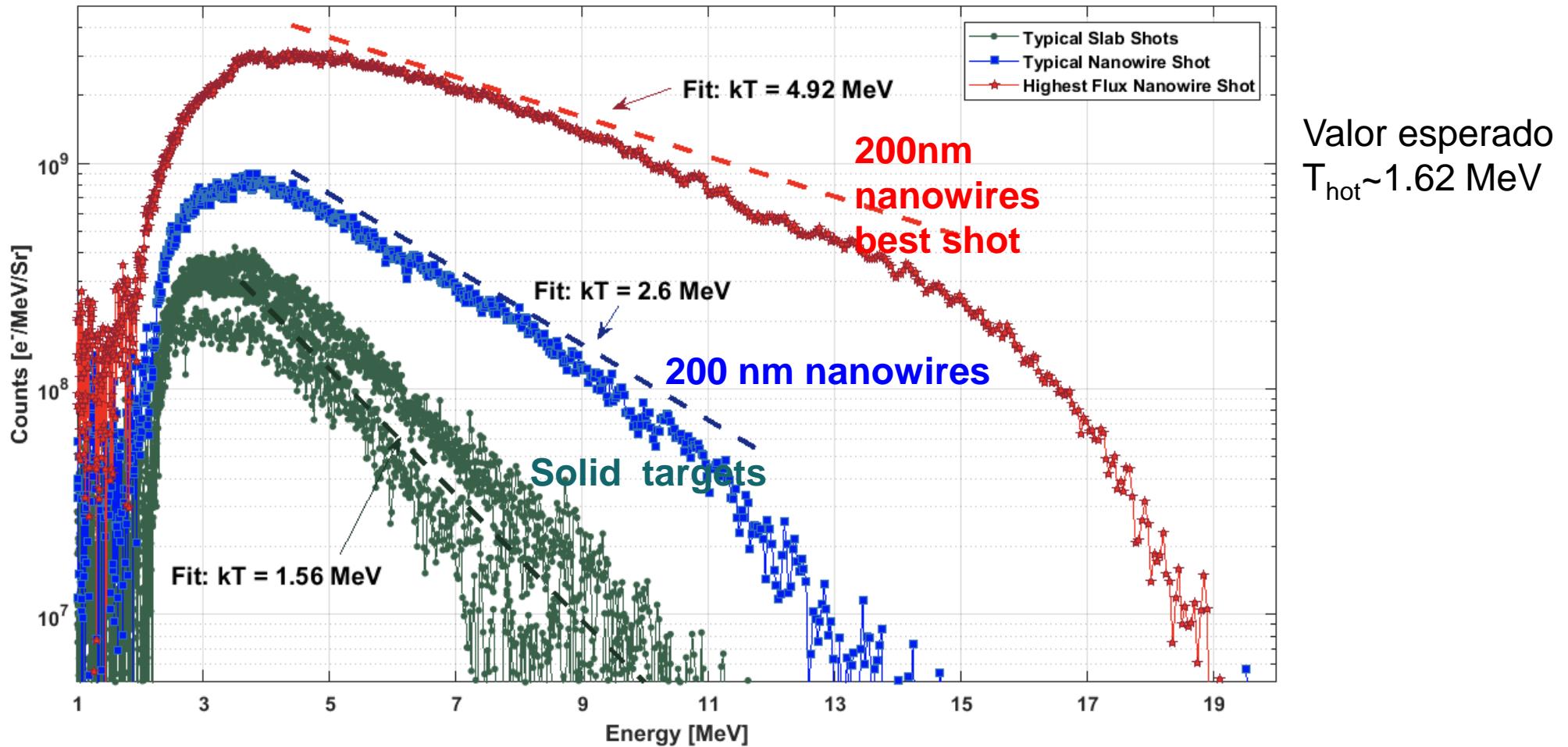


Relativistically induced transparency allows for deep laser pulse propagation into overdense CD₂ plasma



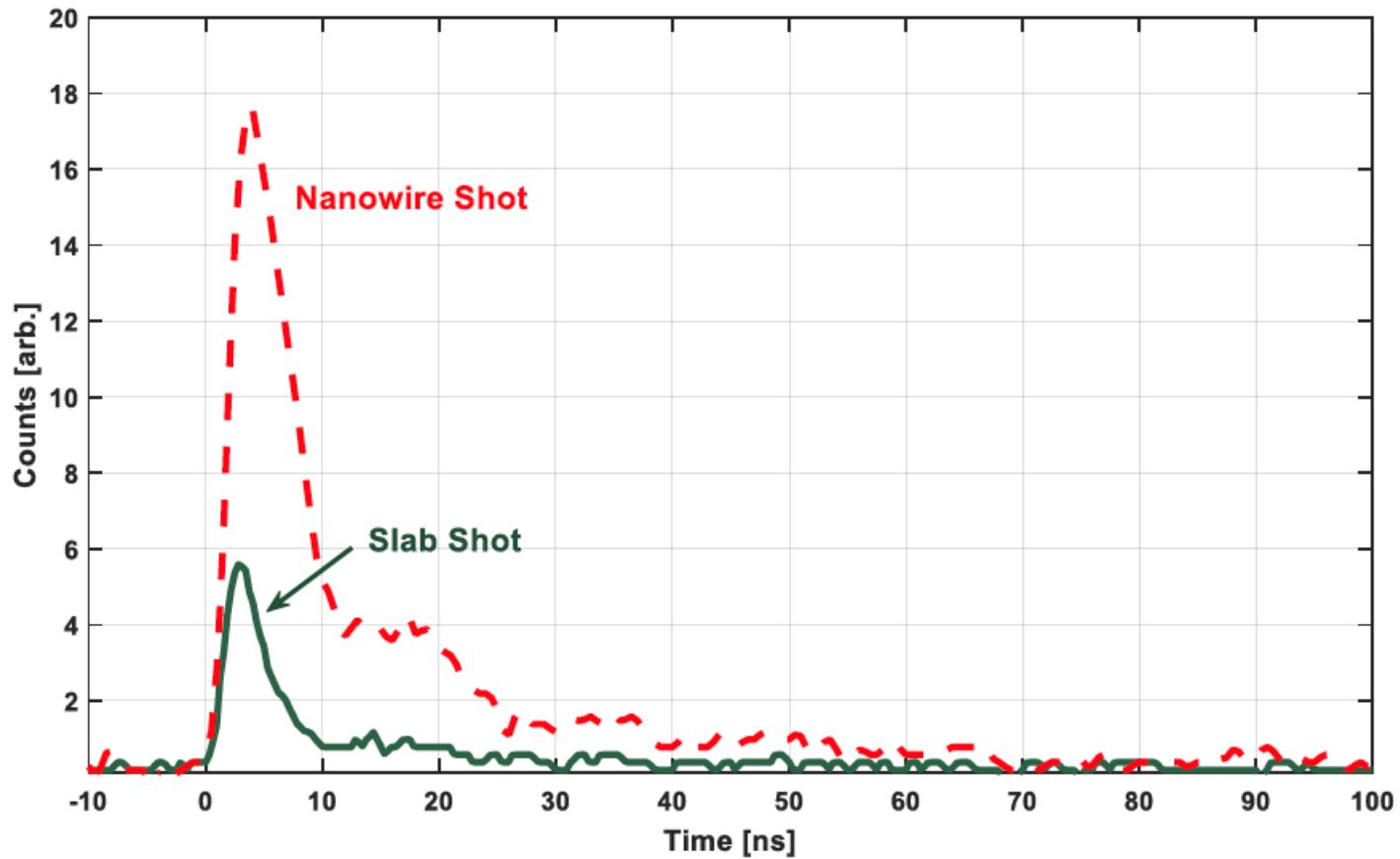
Relativistically Transparent Nanowire array target generates MeV electrons with increased energy and total flux

CD₂ Nanowire Array Electron Spectra (forward direction)



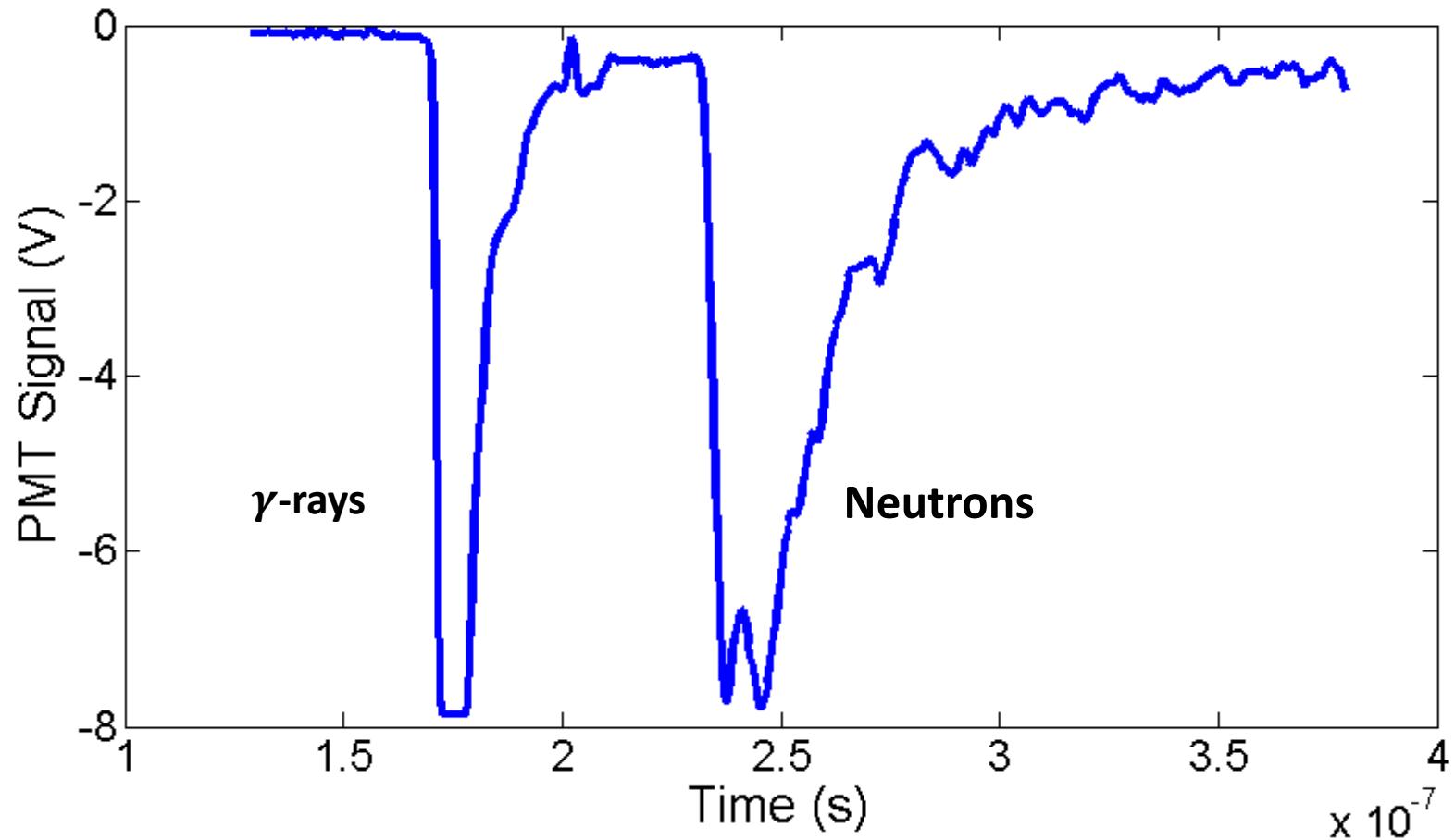
- Integrated flux enhanced **5x** for typical NW shot over solid
- Best shot flux enhanced **24.5x** over solid target

Increase of 3.6 X in > 1 MeV Gamma ray flux



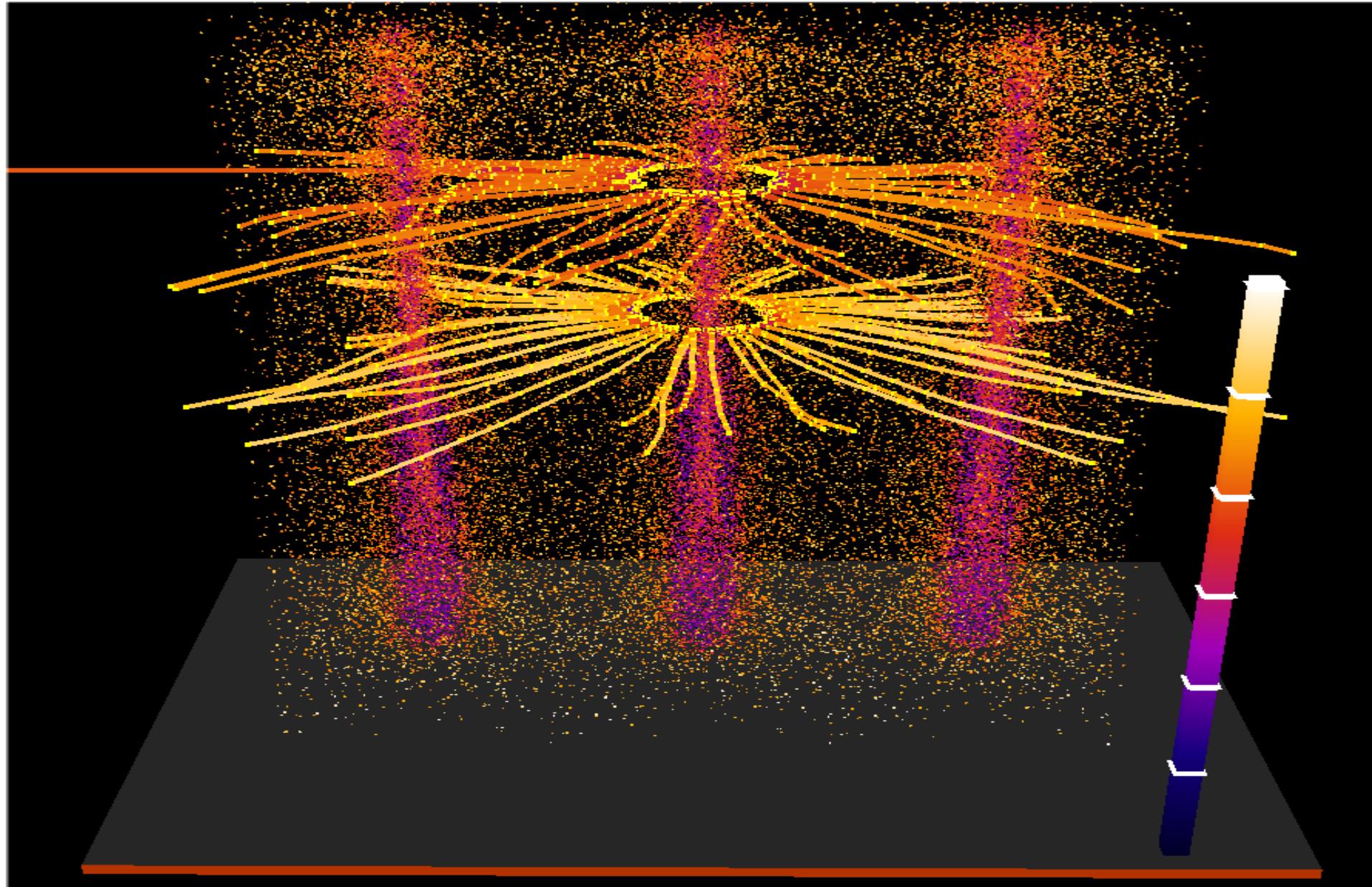
NEUTRON PRODUCTION INCREASED TO $> 2 \times 10^7$ N/SHOT

TOF detector at 2m with 10 cm lead shielding



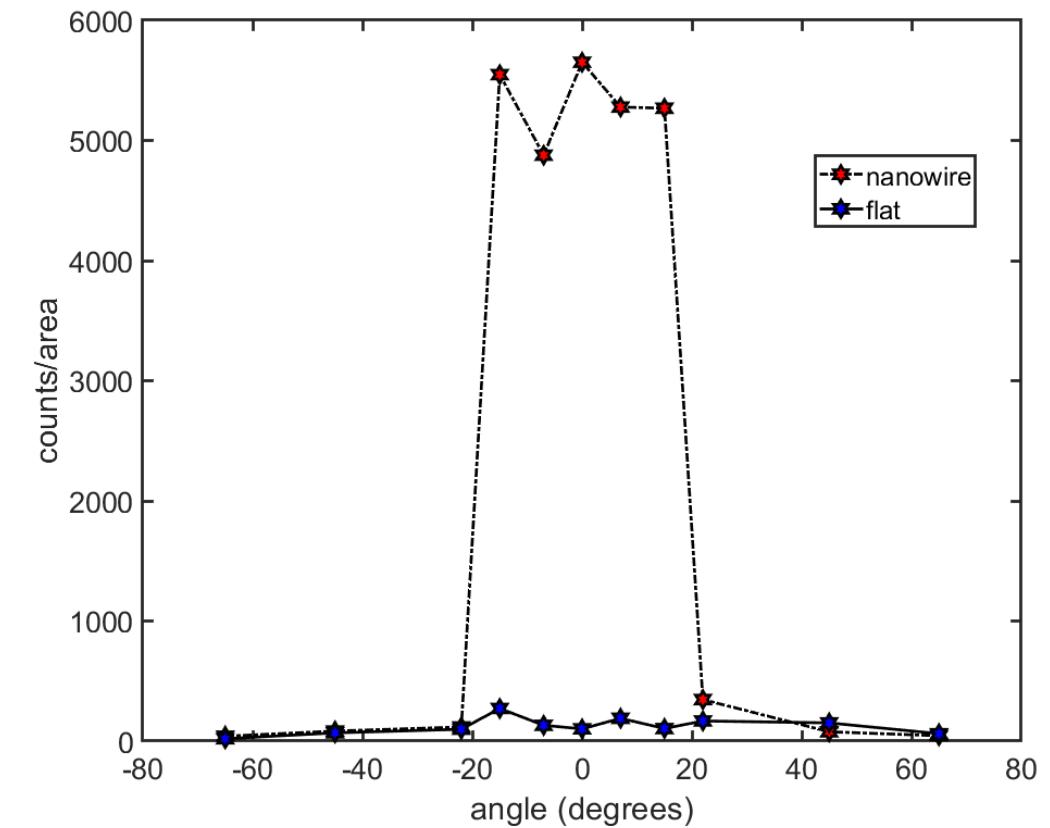
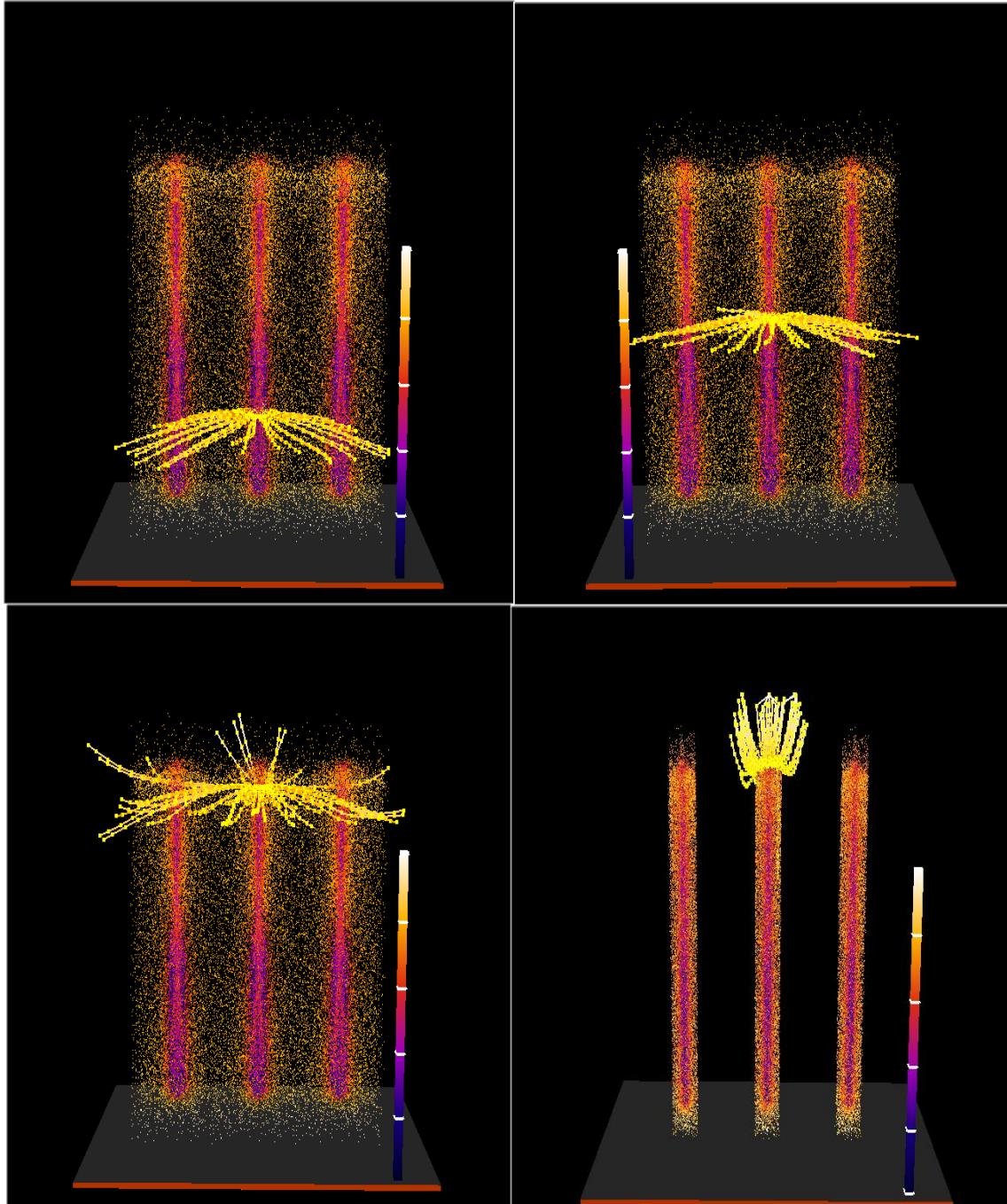
Ion Trajectories

CD_2 nanowires, $I = 5 \times 10^{21} \text{ W cm}^{-2}$

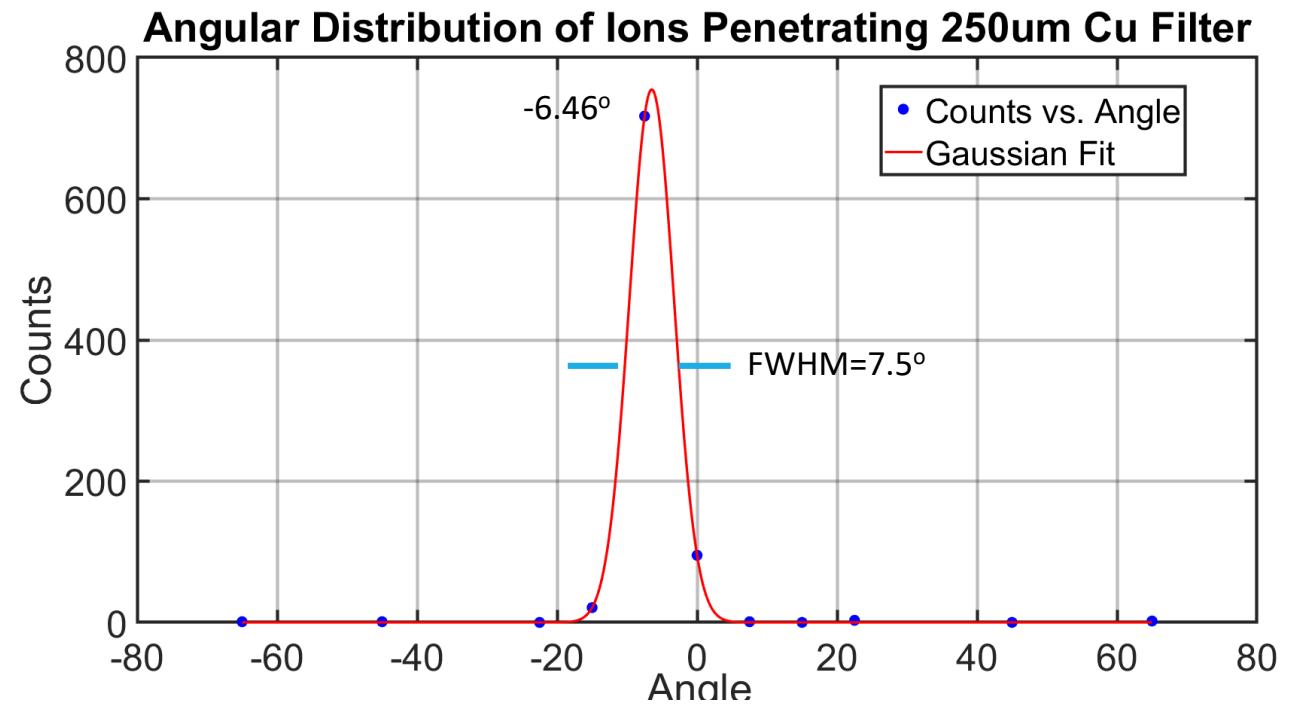


Ion trajectories

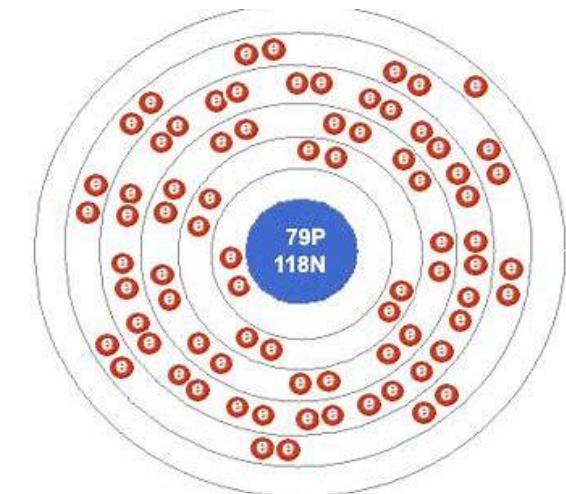
CD₂ Nanowires, 400 nm diameter, $5 \times 10^{21} \text{ W cm}^{-3}$



ANGULAR ION DISTRIBUTION MEASUREMENT (> 13.3MEV D)



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



Ne-like
Au

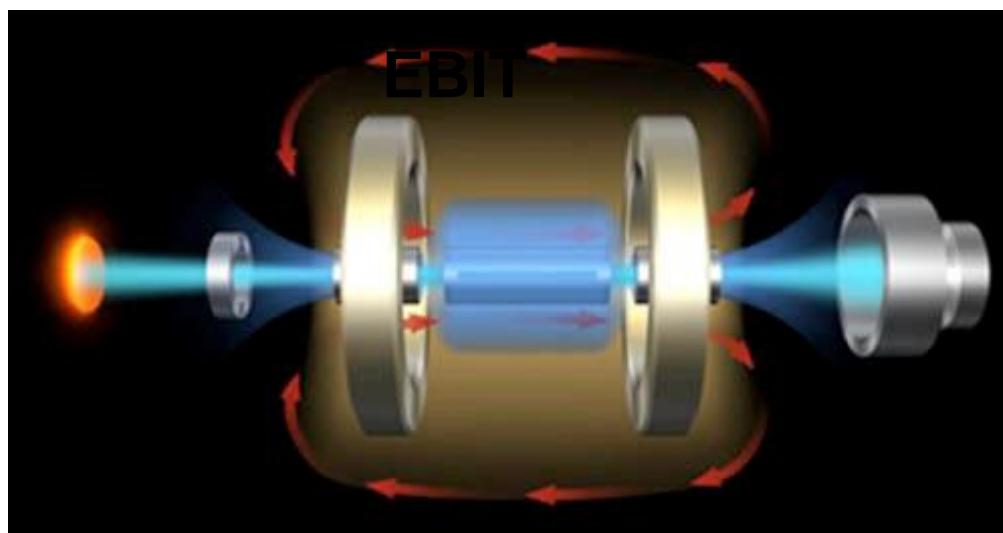
\uparrow

17900 eV

\uparrow

Au^{+68}

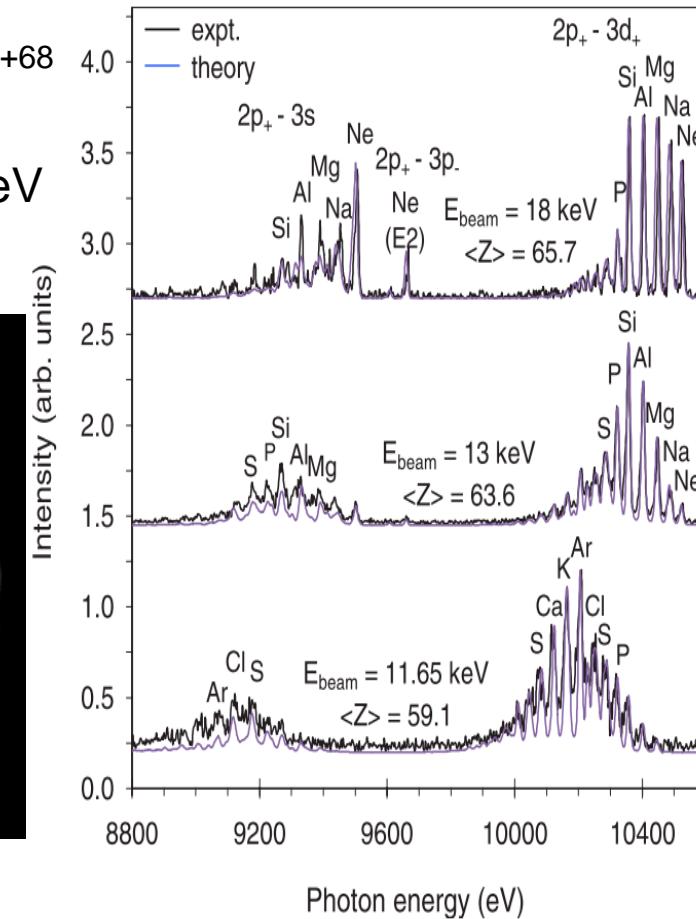
$>100 \text{ keV}$



Densities > 10 orders of magnitude below solid density

LLNL Super EBIT

$\text{Ne} = 10^{12} \text{ cm}^{-3}$



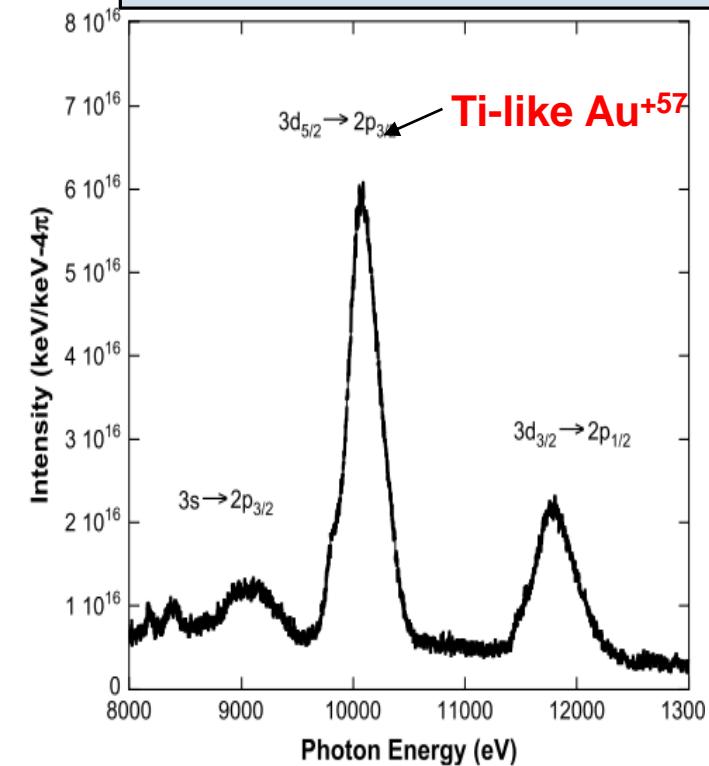
G.V. Brown et al Physical Review E 77, 066406 (2008)

High energy lasers ionizes gold to Au⁺⁵⁷

OMEGA LASER (U. Rochester)

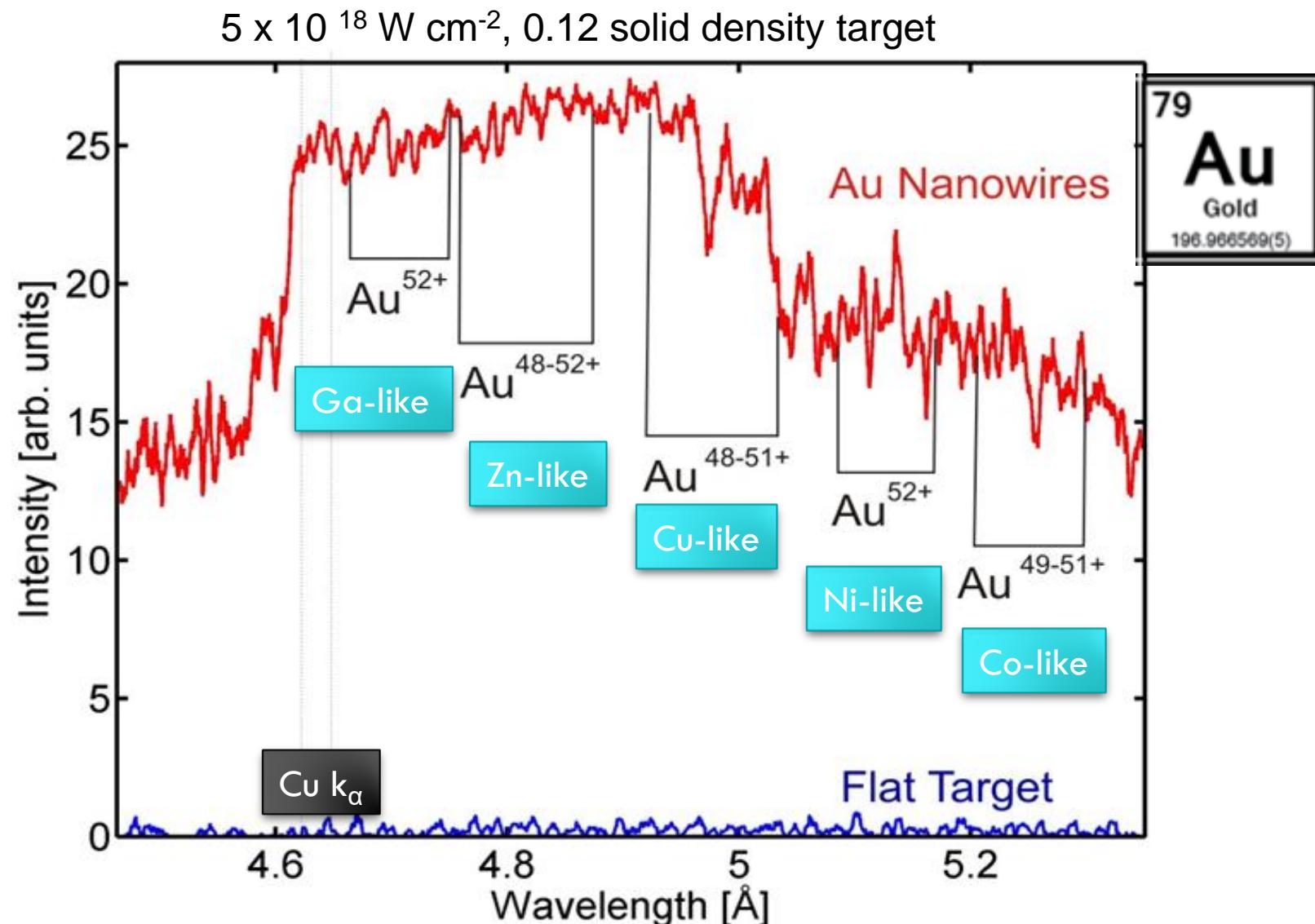


'Hot' hohlraum OMEGA
Ne = 10^{21} cm⁻³



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

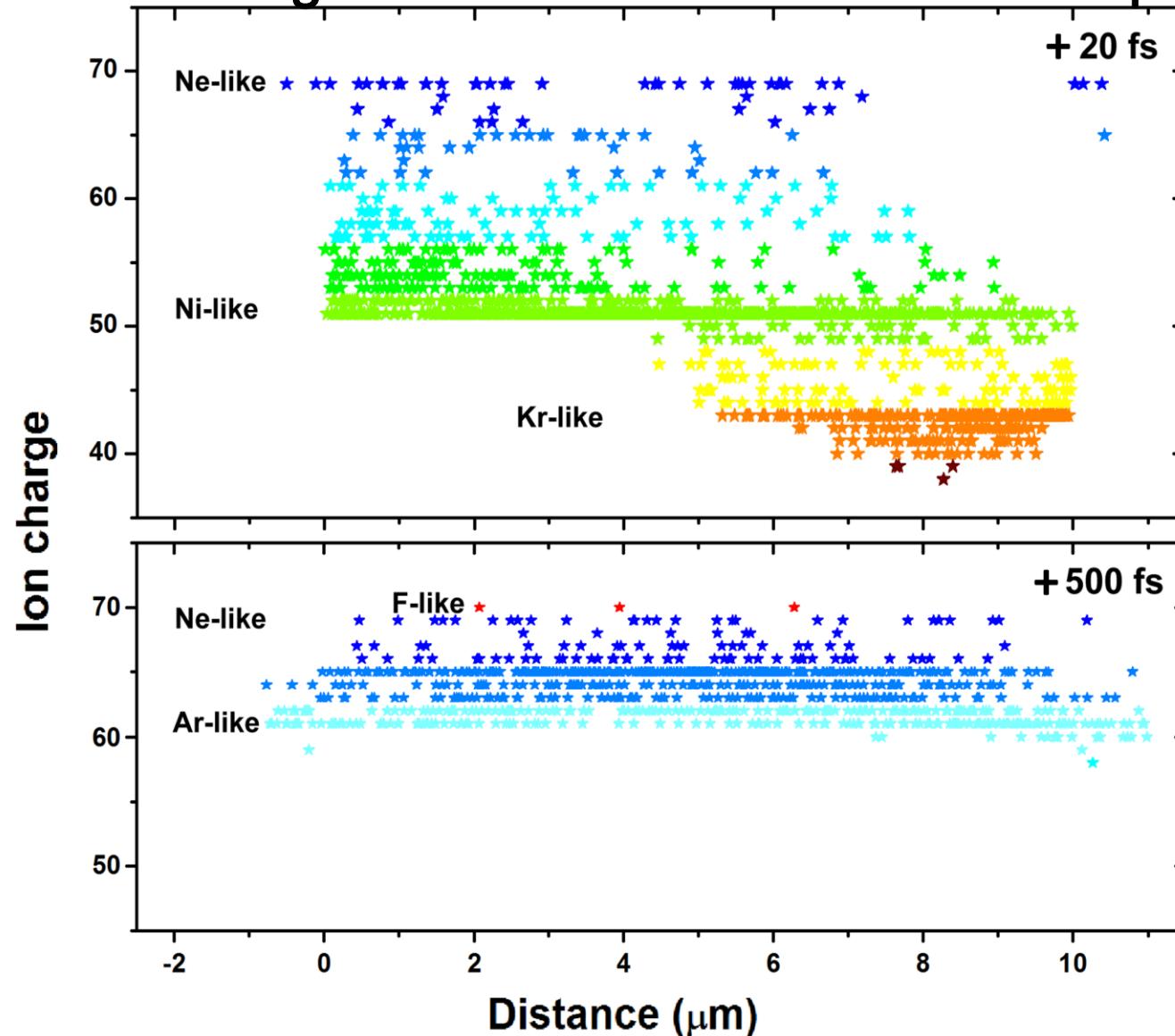
IRRADIANDO CON $5 \times 10^{18} \text{ W cm}^{-2}$ NANOHILOS DE ORO SE PRODUCE UN PLASMA EN VOLUMEN CON IONES Au⁺⁴⁸⁻⁵²



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

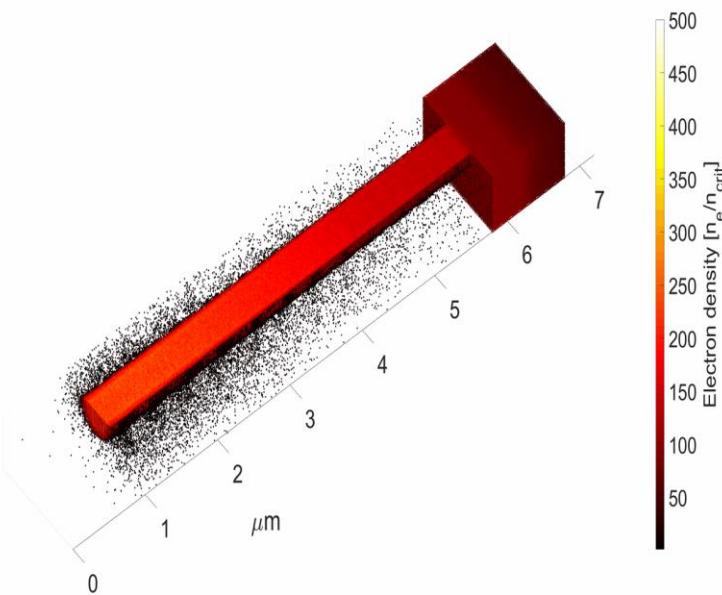
Irradiation intensity of $1 \times 10^{22} \text{ W cm}^{-3}$ predicted to create extreme ionization states in Au (eg. F-like Au)

Ion charge distribution as a function of depth:

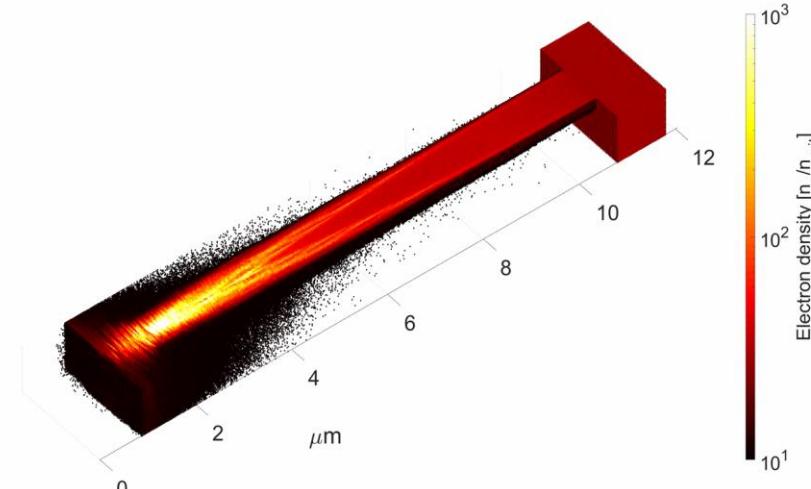


Incremento de la densidad electronica al aumentar la intensidad

$$5 \times 10^{18} \text{ W cm}^{-2}$$

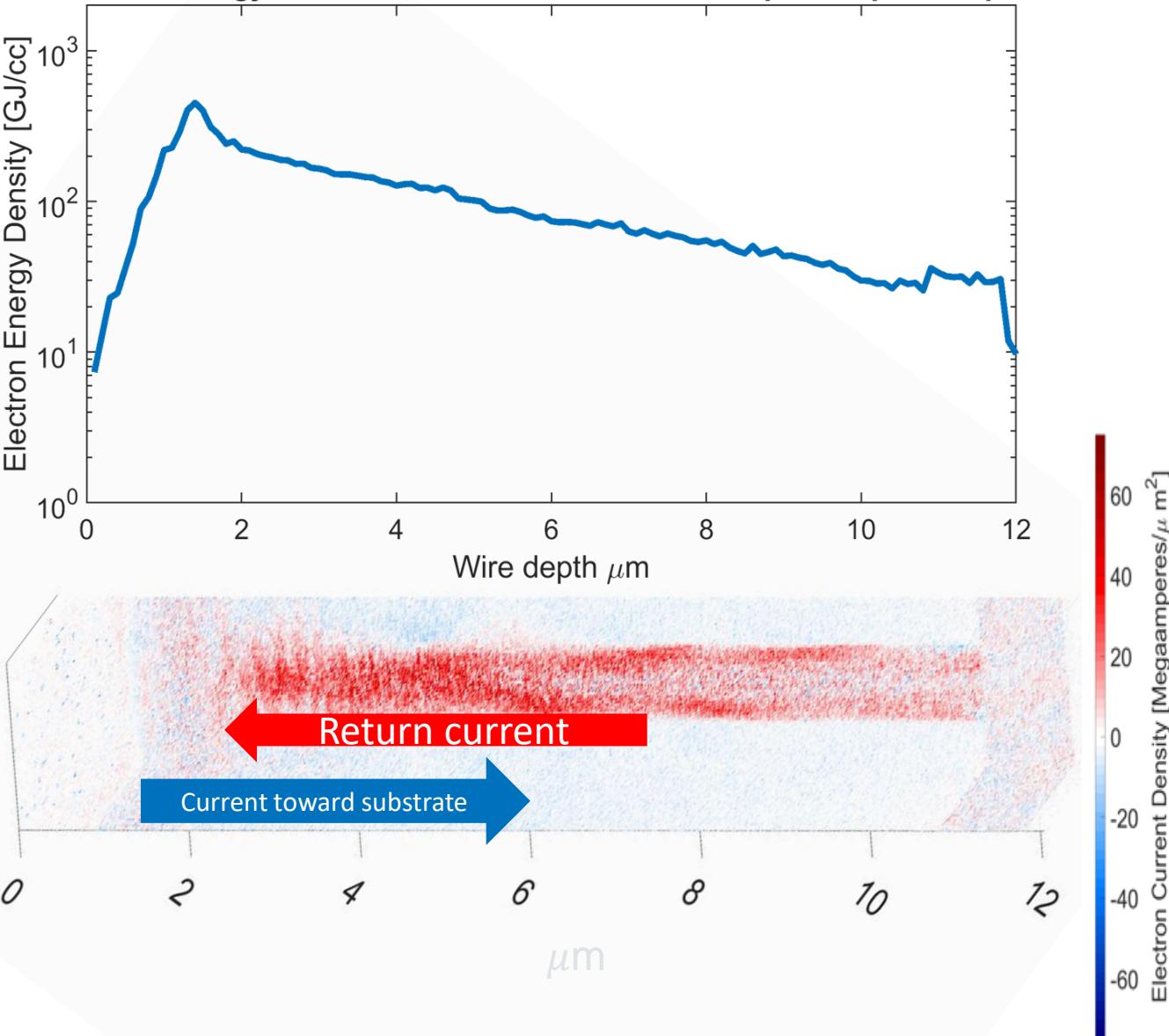


$$I = 4 \times 10^{21} \text{ W cm}^{-3}$$



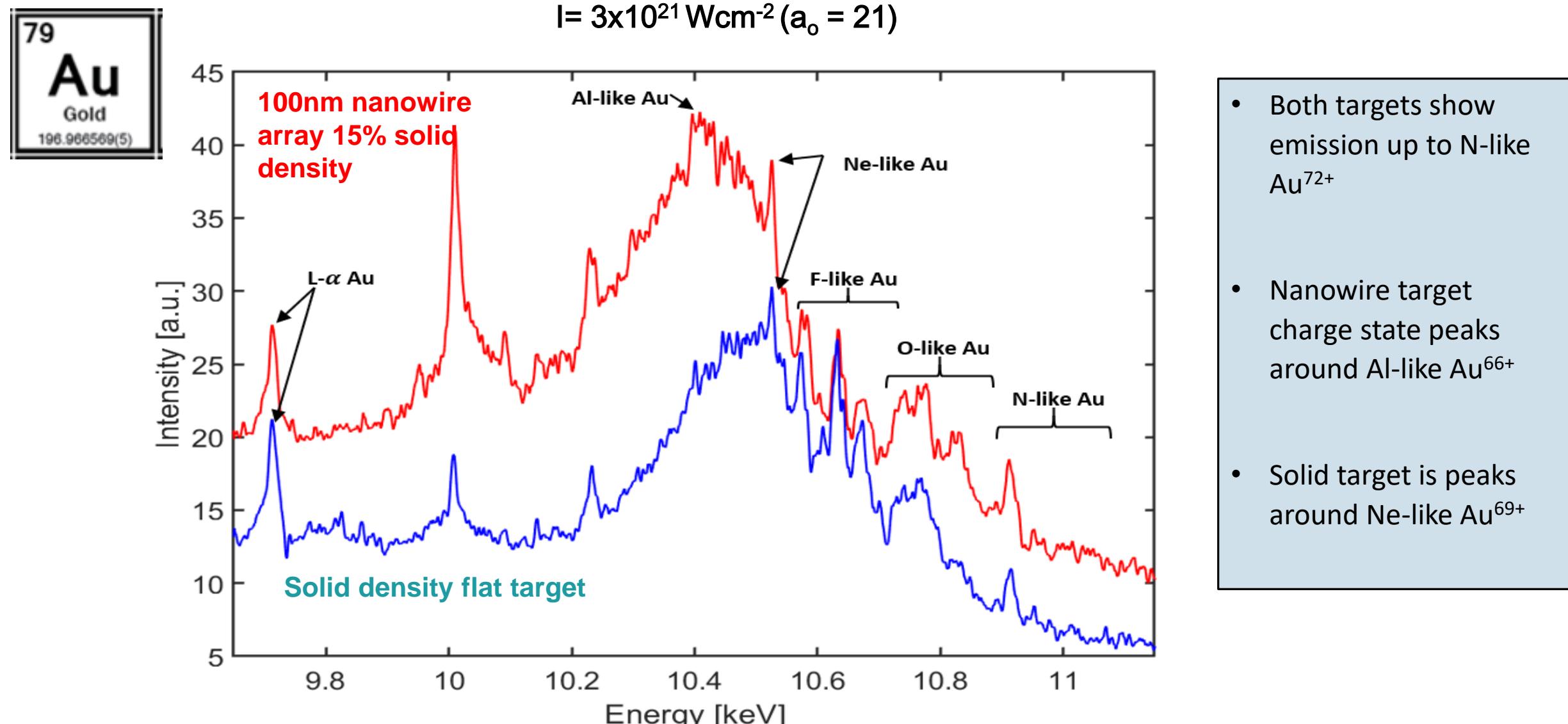
Laser drives hot electrons at tip of wire into plasma

Electron energy distribution at time: 30 fs with respect to peak of pulse

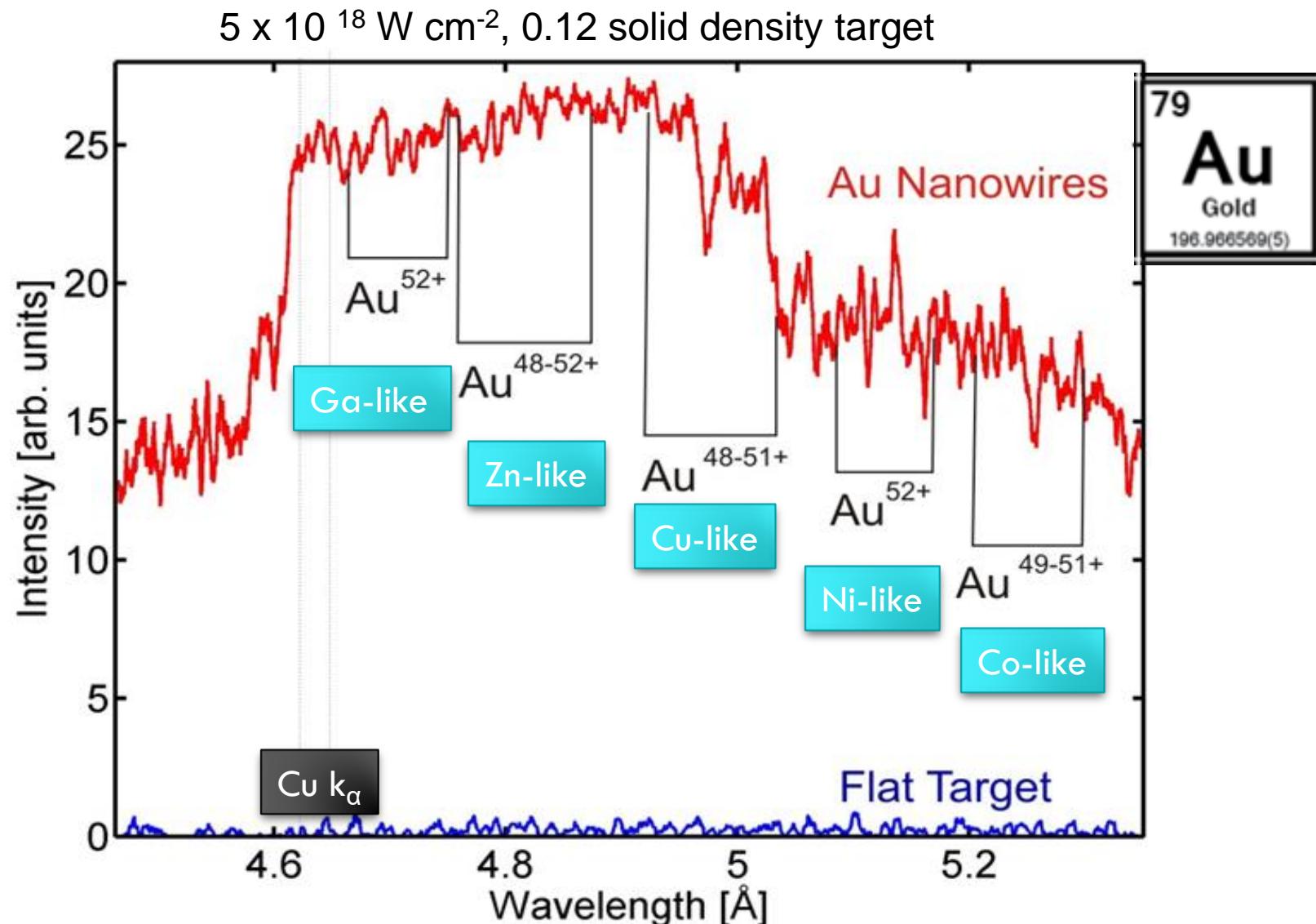


- Laser drives hot electrons at tip of wire into plasma
- Peak electron energy density of $>1\text{ TJ}/\text{cc}$ at tip of wire
- Electrons deposit energy through the volume ending with an energy density of $\sim 100\text{ GJ}/\text{cc}$
- Large current density causes $\mathbf{J} \times \mathbf{B}$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

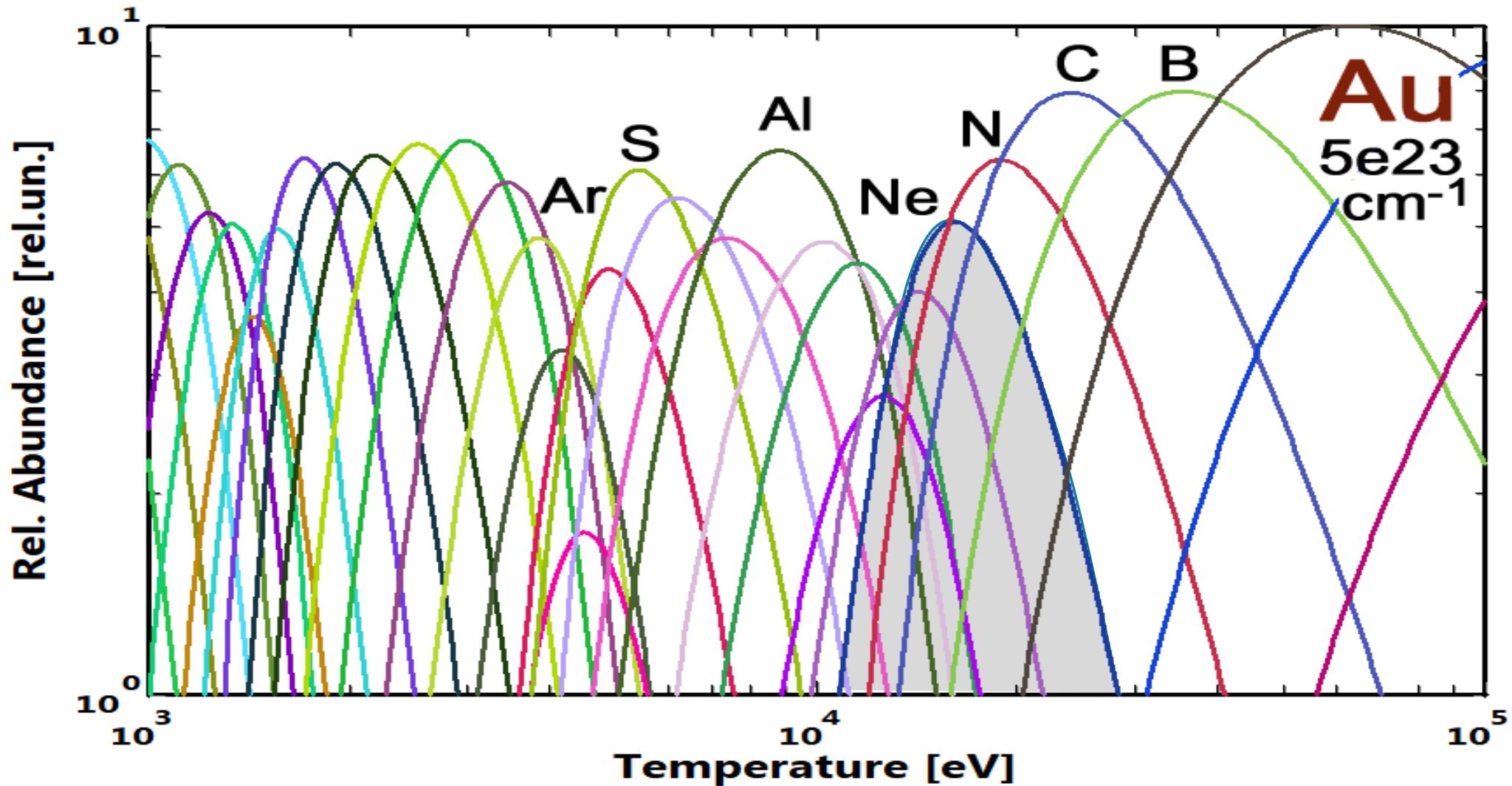


IRRADIANDO CON $5 \times 10^{18} \text{ W cm}^{-2}$ NANOHILOS DE ORO SE PRODUCE UN PLASMA EN VOLUMEN CON IONES Au⁺⁴⁸⁻⁵²



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

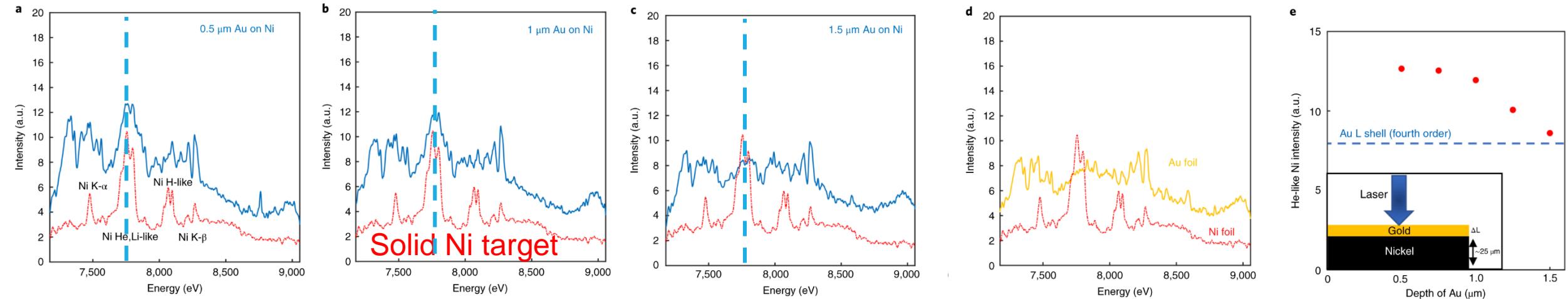
En el estado de ionización de equilibrio, los iones Ne-like aparecen en temperaturas > 10 KeV



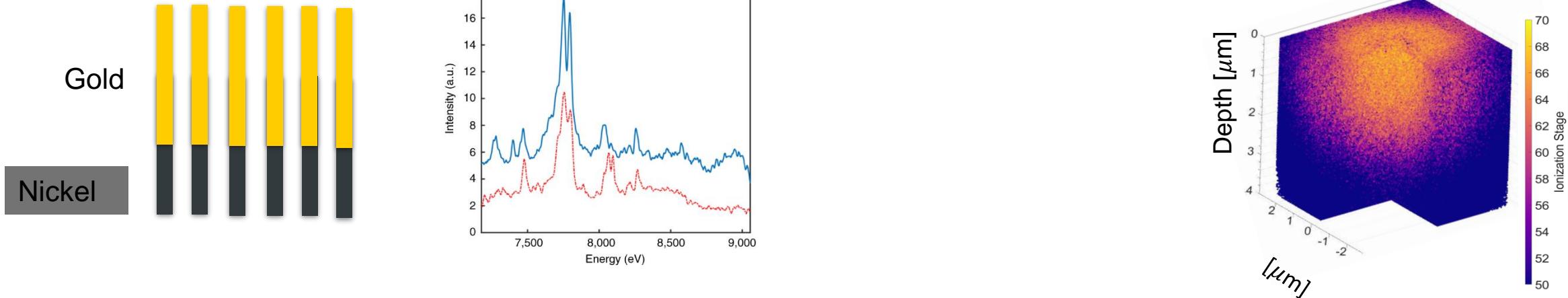
Buried Ni tracer reveals heat penetration in nanowire array exceeds 8 micrometers

$$I = 4 \times 10^{21} \text{ W cm}^{-2} (a_o = 21)$$

Flats

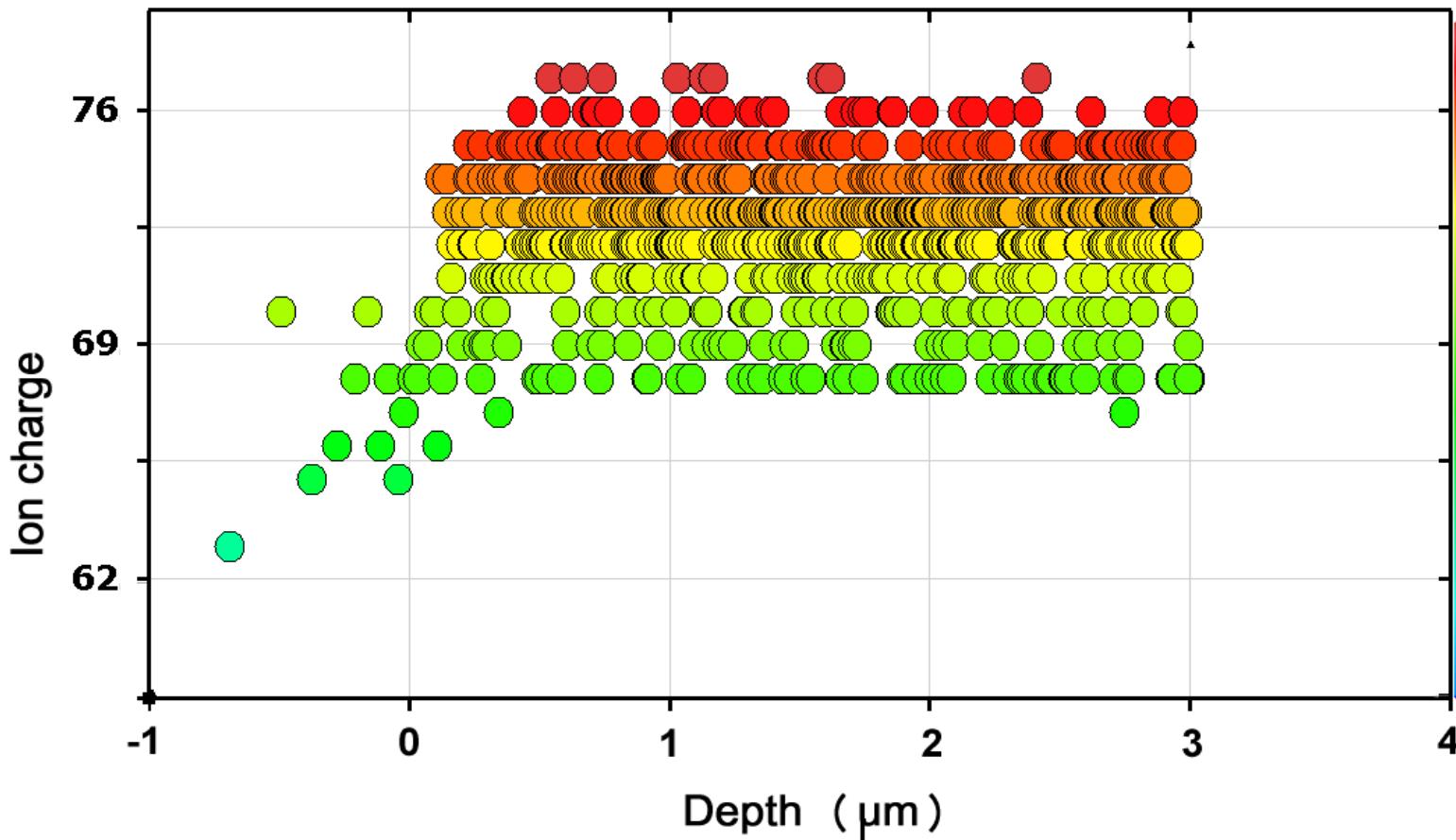


Nanowires



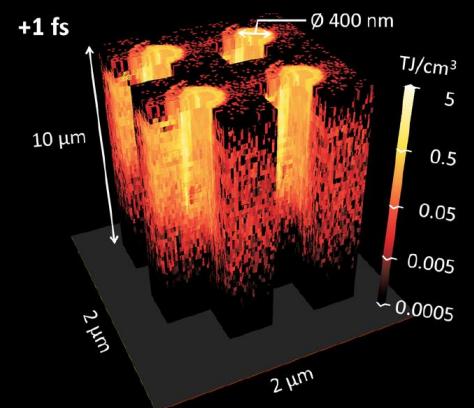
He-Like Au⁺⁷⁷ solid density plasma predicted

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

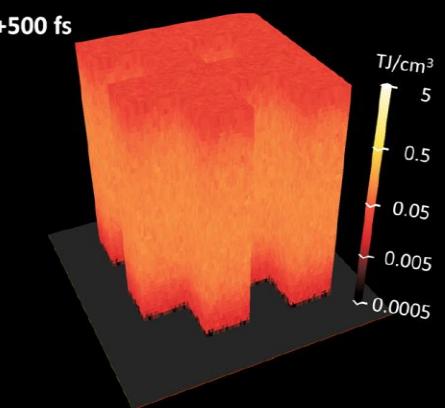
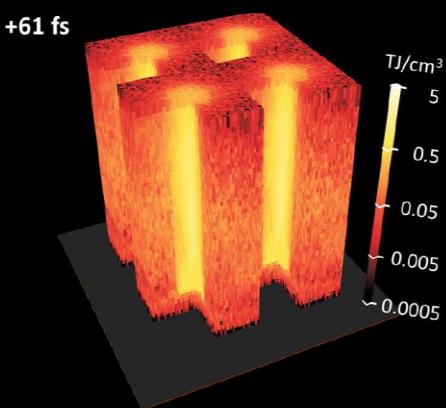
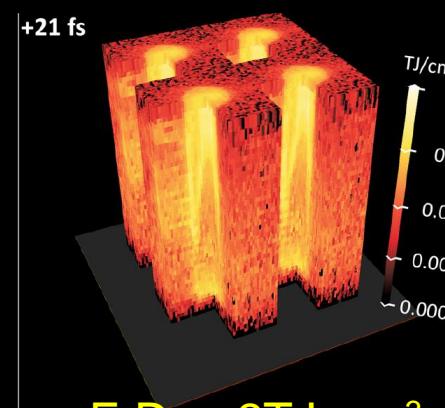


Aumentar la intensidad hasta $2 \times 10^{22} \text{ W cm}^{-2}$ ($a_0 = 34$) se obtendrían densidades de energía y presiones sin precedentes

400 nm Au nw
12% solid density

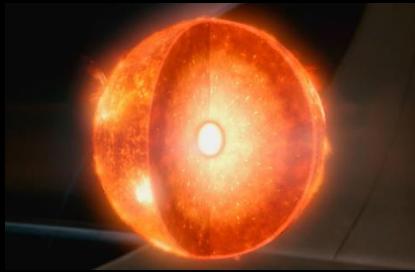


$$I = 2 \times 10^{22} \text{ W cm}^{-2} \quad a_0 = 34 - 30 \text{ fs}$$

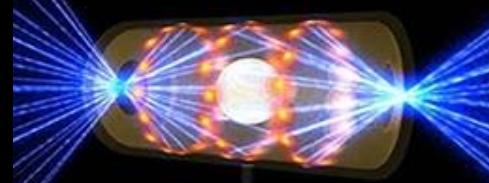


E.D. 80 GJ cm⁻³
P~0.35 Tbar
Te~500 keV

Sun Core 240 Gbar

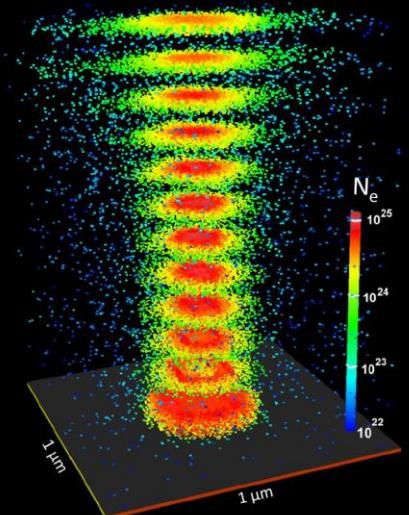


NIF Implosion 150 Gbar



$N_e \sim 1 \times 10^{26} \text{ cm}^{-3}$
MJ power laser

+40 fs Nano pinch compression



$N_e \sim 2 \times 10^{25} \text{ cm}^{-3} = 3200 \times N_{\text{ec}}$

Plasmas con UHED por irradiación con láseres de intensidad relativista

ALEPH PW (850 TW) laser

Experimento

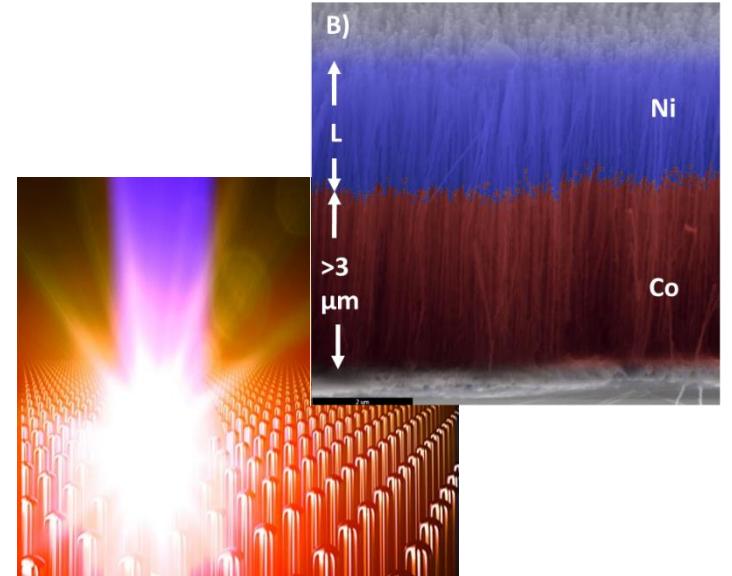
Colorado State University



Modelado

Lawrence Livermore National Laboratory

Heinrich Heine
Universität Düsseldorf



Hercules
300TW laser



M

Aceleración de
protons Au NW
PPCF 61 (6), 065016
(2019)

Orion
PW (10^3 TW) laser



Ps Xrays, T~keV Ni
NW
arXiv:2007.10410

Jupiter (Titan)
PW (10^3 TW) laser



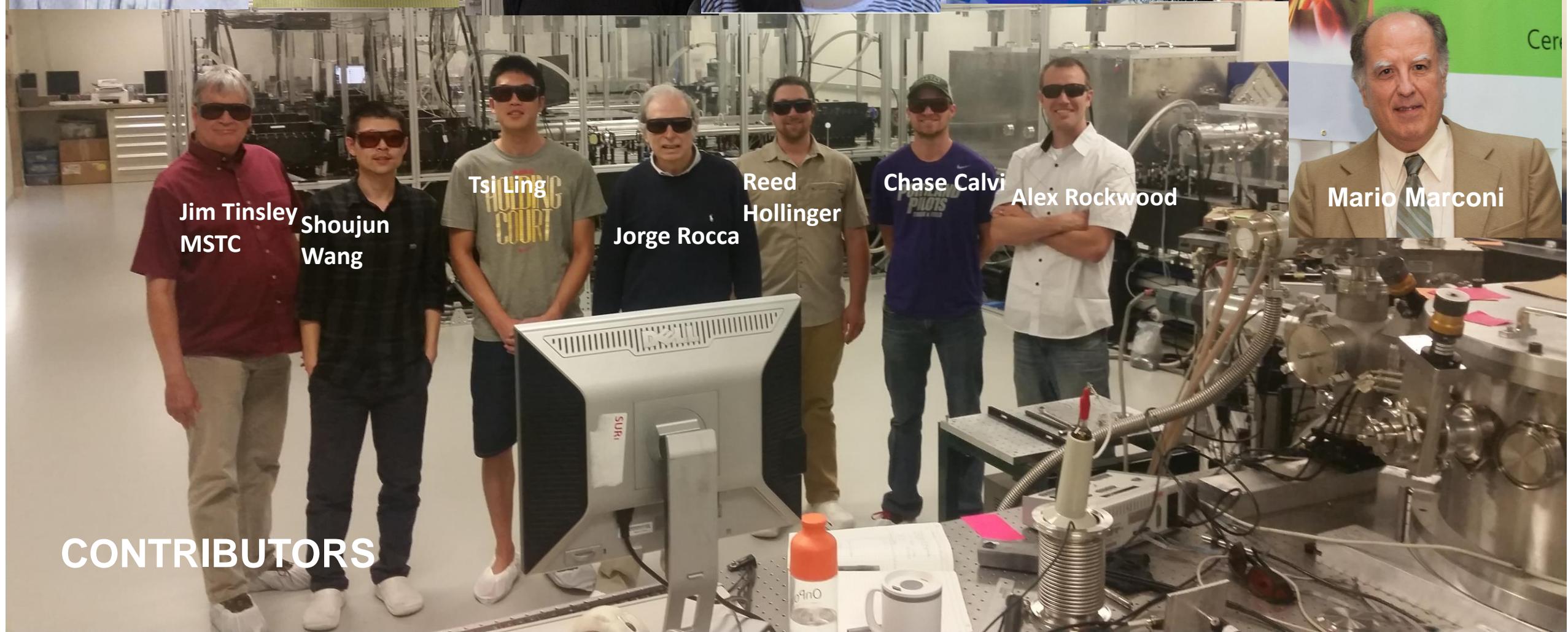
Ni, Au, Ag,
incremento Rx y T
En preparación

PHELIX
PW (500 TW)



GSI Helmholtzzentrum für
Schwerionenforschung GmbH

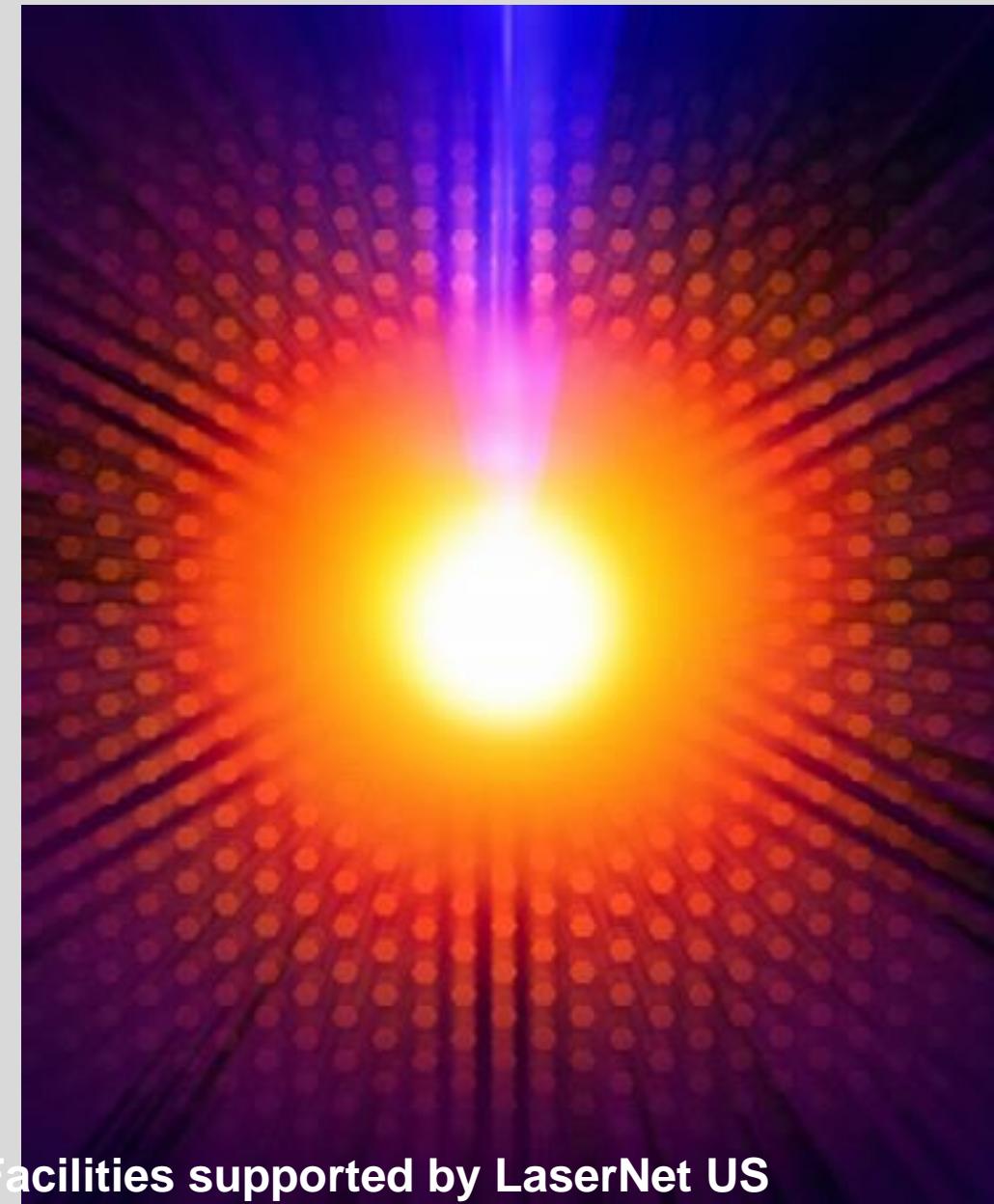
Aceleración de
iones (C^{6+}) y protones
(Co NW)
PRE 102(2) 021201,(2020)



Conclusiones:

Interacción de pulsos láseres ultracortos altamente relativistas con nanoestructuras

- La interacción de láseres de pulsos ultracortos con intensidades relativistas con nanoestructuras permite obtener plasmas con ultra alta densidad de energía en condiciones extremas de presión y temperatura
- Se generaron plasmas de Au con grados de ionización extraordinarios, emisión N-like Au line.
- Se midió una eficiencia de conversión record de pulsos ópticos en pulsos de rayos x de picosegundos de hasta 20% para $h\nu > 1 \text{ keV}$
- Se midió un incremento de flujo y energía de electrones rápidos e iones
- Se generaron flashes de neutrones quasi monoenergéticos a partir de reacciones de fusión D-D



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Colorado State University Advanced Beam Laboratory

Ph.D Opportunities Available. Contract: Prof. Jorge Rocca; jorge.rocca@colostate.edu



Work supported by DOE ,AFOSR, and ONR

