Towards Micron-scale electron accelerator at the tip of endoscopy – Source and delivery for compact LWFA

Weijian Sha

Discussions on fiber laser technology

for the "Endoscopic Accelerator" initiative

T. Tajima (LWFA)

J. Kuo, D. Roa, F. Tamanoi (medical applications)

J.-C. Chanteloup, W. Sha, D. Strickland (fiber lasers)

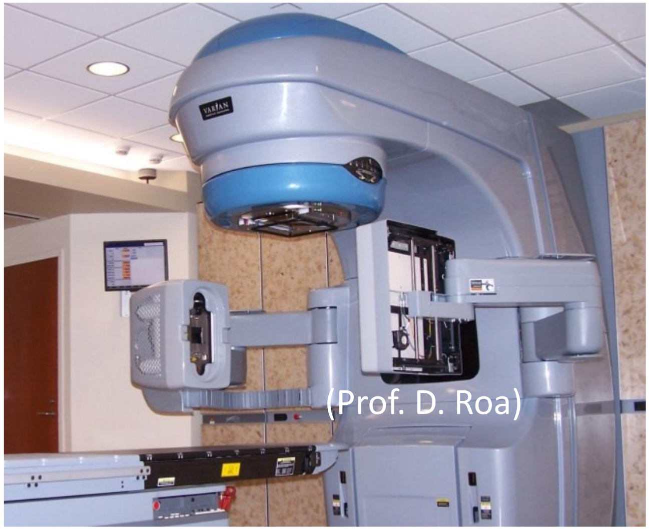
T. Kawachi, M. Mori, KPSI (LWFA experiments)

H. Lee (laser experiments and near critical density targeted)

…

Part 1. **Introduction**

External areal → Endoscopic "vector" treatment



Conventional radiotherapy:
Electron energies 6-20MeV by Linac or LWFA

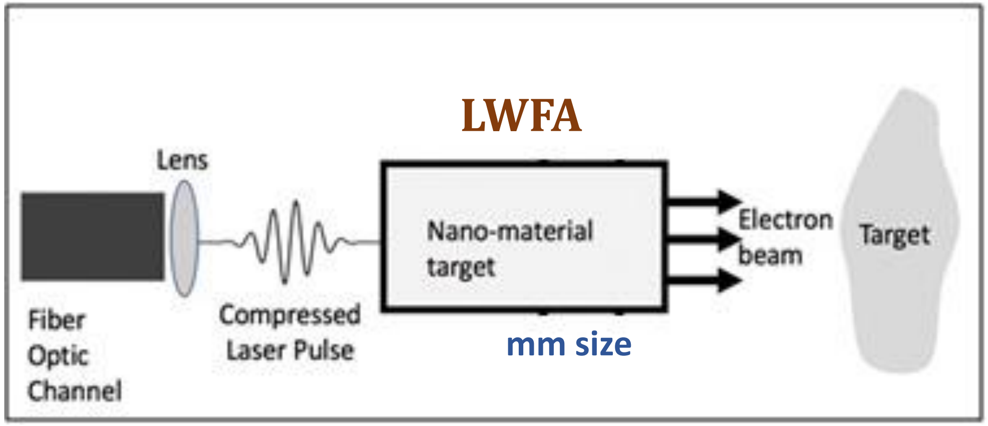
LWFA could provide high dose "FLASH" therapy

Furthermore, much tinier with **fiber**

L_e ~ 1 cm / 10MeV → 10 micron / 10keV

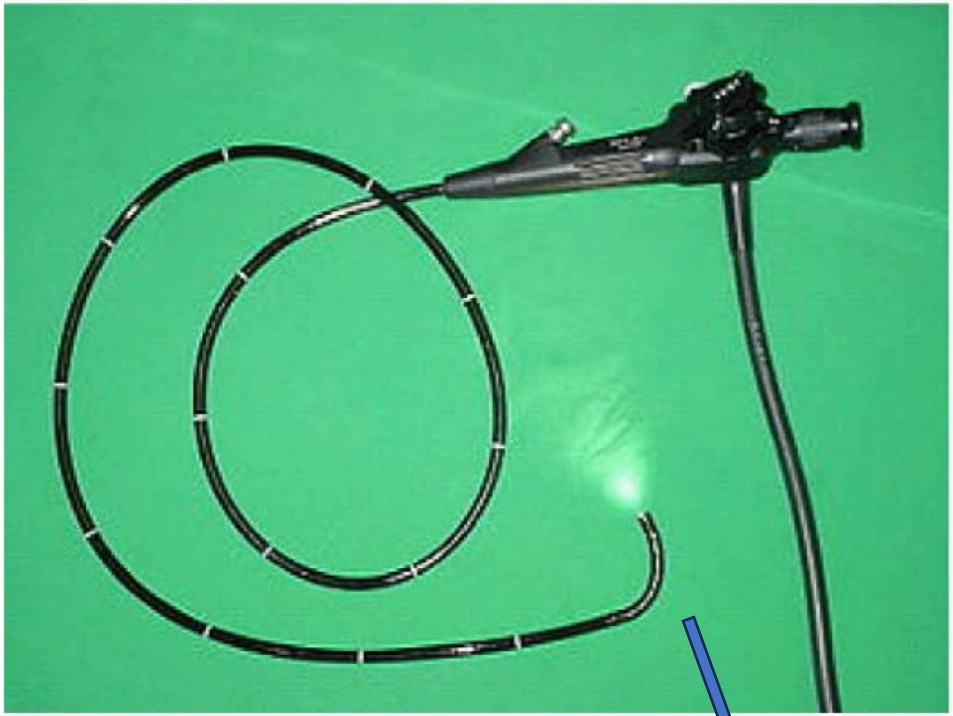
Body penetration ↑ Cancer cell size ↑

Endoscopic LWFA for electron radiotherapy

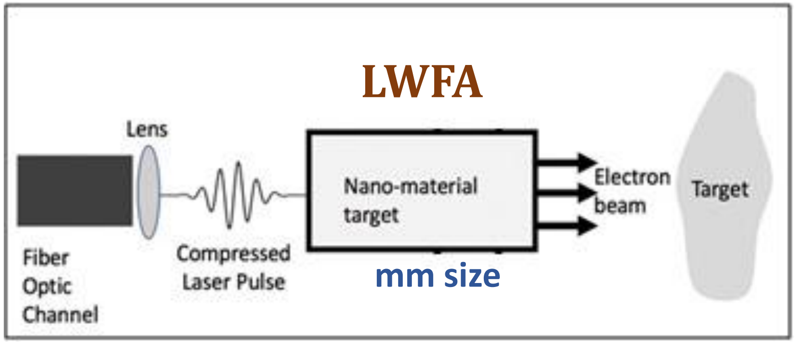


Roa, Kuo, Moyses, Taborek, Tajima, Mourou, and Tamanoi, Photonics (2022)

An Illustration of endoscope (or colonoscope)



Endoscopic LWFA for electron radiotherapy



Outline

Electron accelerator for endoscopic radiotherapy

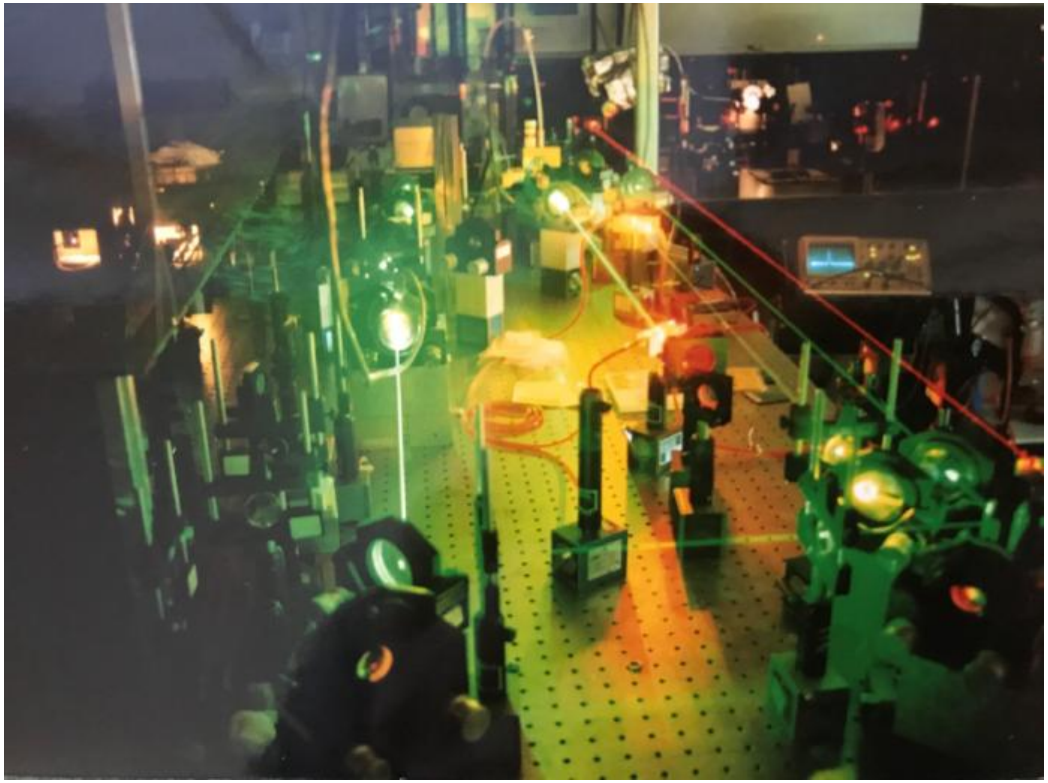
1. **Conventional accelerator for radio therapy → ** Compact **Accelerator** for **endoscopic** therapy

2. **High-Density Laser Wakefield Acceleration** (theory and experiment)
- e-beam (>10 keV) from laser $10^{14}\ \mathrm{W}/cm^2$

3. Ultrafast fiber laser
- Table-top lasers → Fiber lasers for miniature accelerator

4. Explore Innovations – target and flexible delivery
- Carbon nanotube
- Hollow core fiber & others

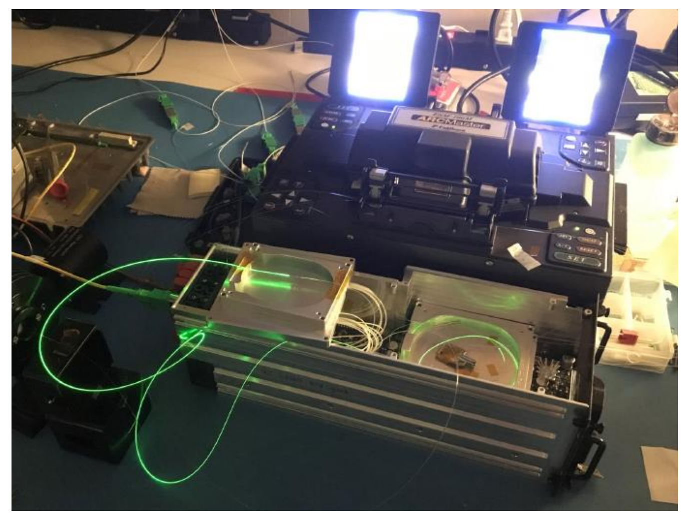
Compact Laser Source for Electron Accelerator at the tip of endoscope



Rochester/Michigan laser
100 fs, 20 μJ, 0.2 GW

To this size

→ ultrafast fiber laser/amplifier



(3-Watt fiber amplifier for optical communication)

My brief background (acamedic and industrial)

Started graduate study in LLE (U of Rochester)

PhD ultrafast lasers & spectroscopy (U of Michigan)

Post-doctoral researches in ultrafast science

Worked in industries in laser diodes, fiber lasers, fiber-optic communications

(SDL, General Atomics, CommScope)

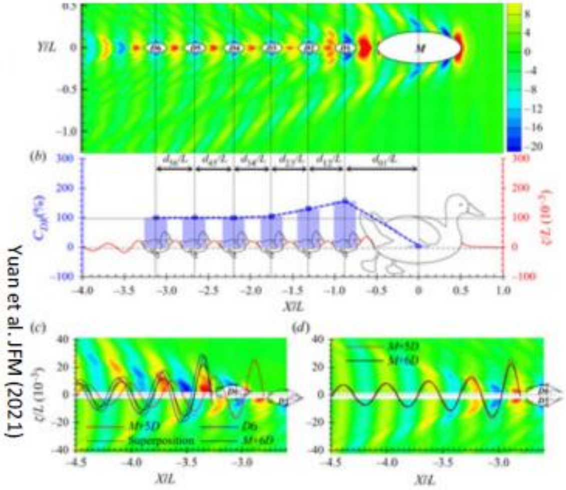
Part 2. High-Density
Laser Wakefield Acceleration (LWFA)
(theory guidance and experiments)

Laser Wakefield Acceleration

Wake

Wake by a duck

Nature (or mother duck) shows us.

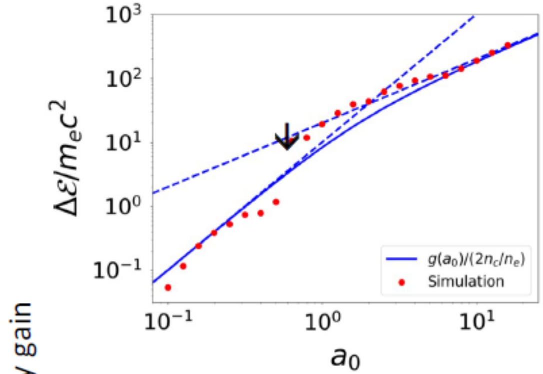


Yuan et al. JFM (2021)

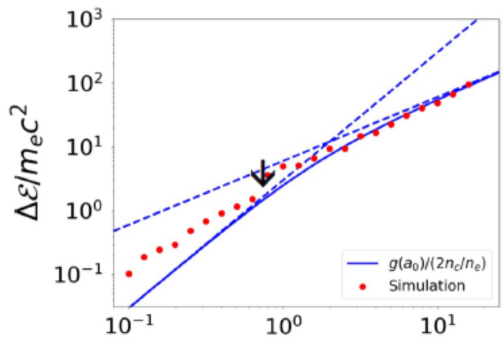
Transition to $a_0 < 1$ regime
Transition to near-critical density $n_e \sim n_{cr}$

v_g (group velocity of photon) = v_p (phase velocity of plasma wave) << c

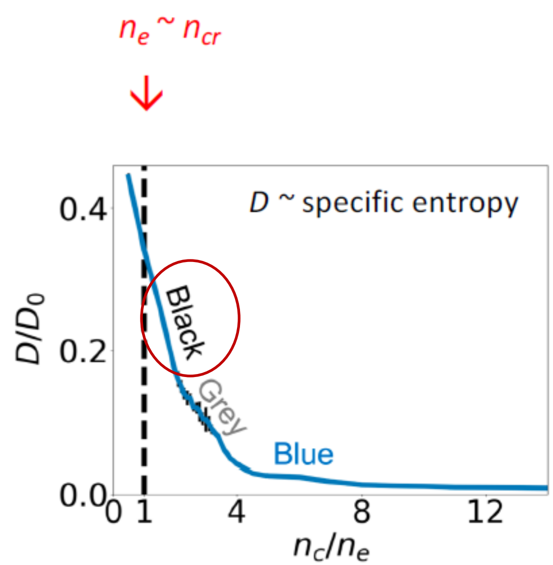
(S. Nicks, 2019)

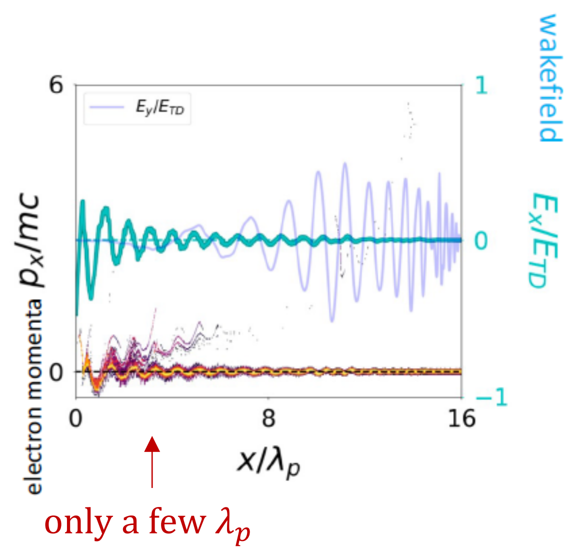


(a) E_{max} vs a_0 for fixed density ratio of 10



n_{cr} / n_e =3





For electron energy > MeV or GeV

- Low plasma density regime, $a_0 > 1$ or I >10^{18} W/cm^2. Table-top, or larger lasers > TW, PW

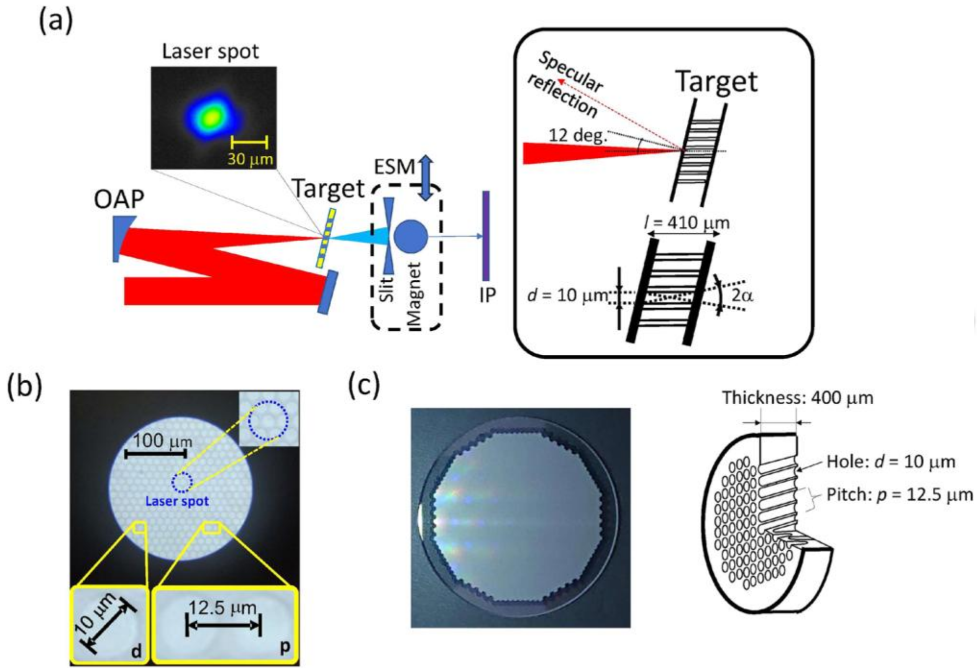
Micron-scale electron accelerator at the tip of endoscopy: > 10 keV

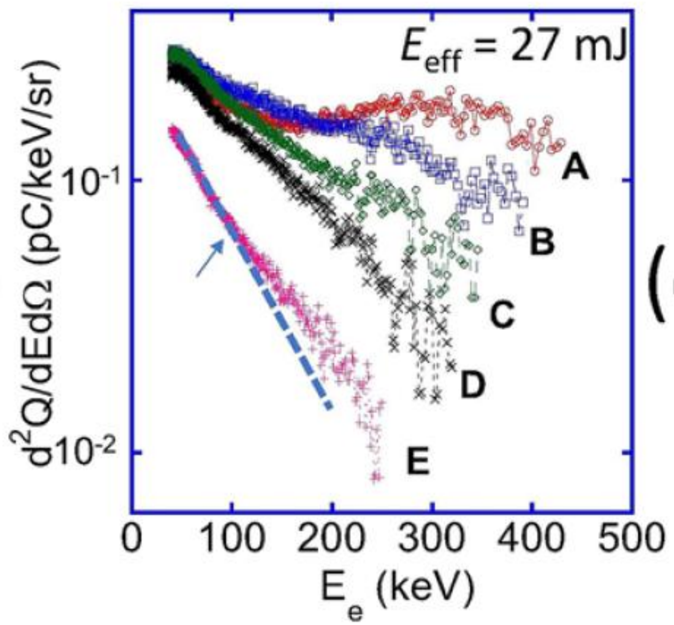
- Near-critical density regime, 10^{14} W/cm^2, GW or sub-GW, compact fiber laser

Experimental Realization of near-critical density LWFA

50 keV to 400 keV electron beam

(KPSI QST) M. Mori, T. Kawachi *et al*, AIP Advances (2024)

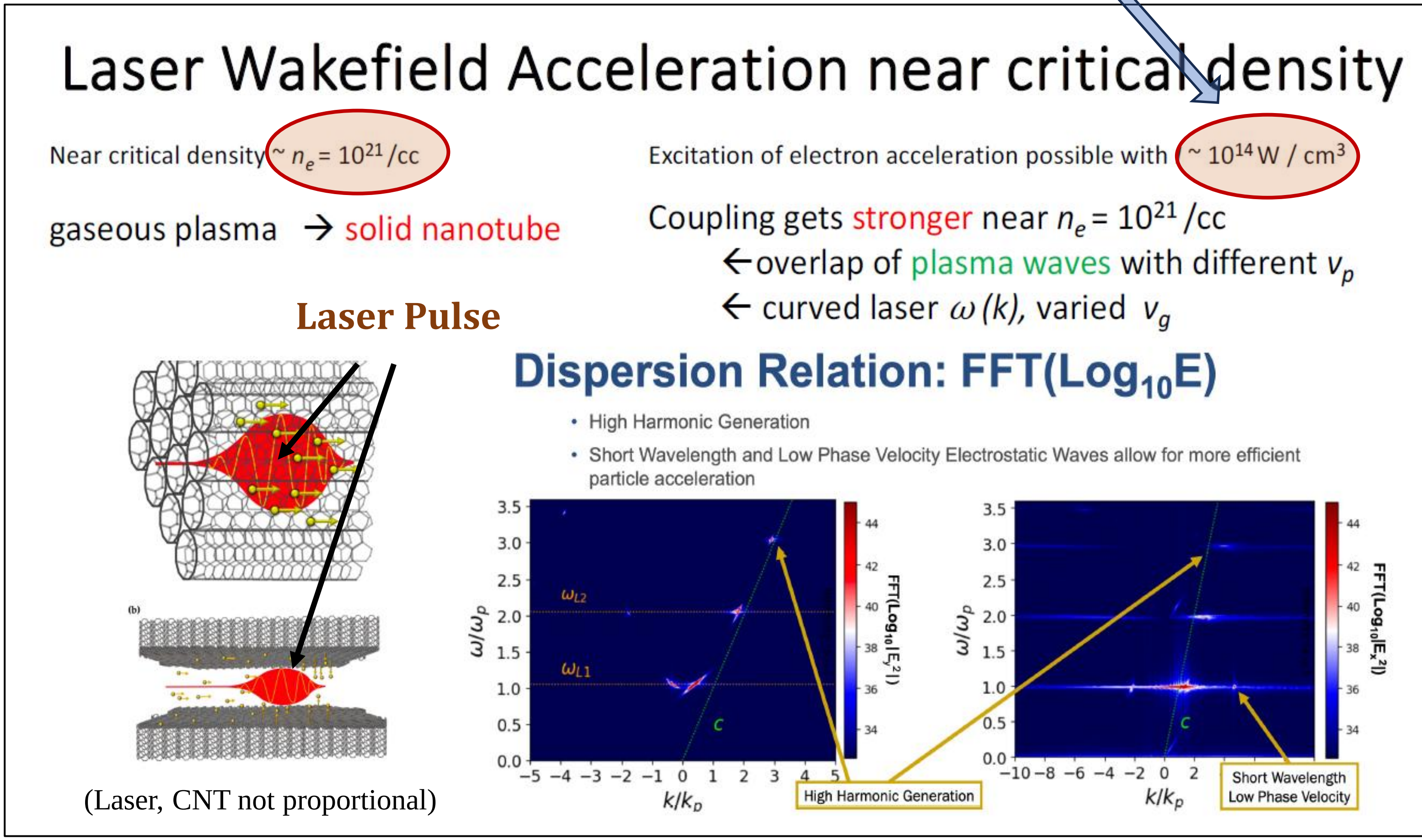




- Glass microcapillary target 400 μm thickness
- Ti:Sapphire CPA laser
- Target ablated by laser, produce plasma at or near critical density
- Measured electron energy over a range of laser intensity
- > 50 keV at $10^{16} W/cm^2$

Experiment planned at $10^{14}\mathrm{W/cm^2}$

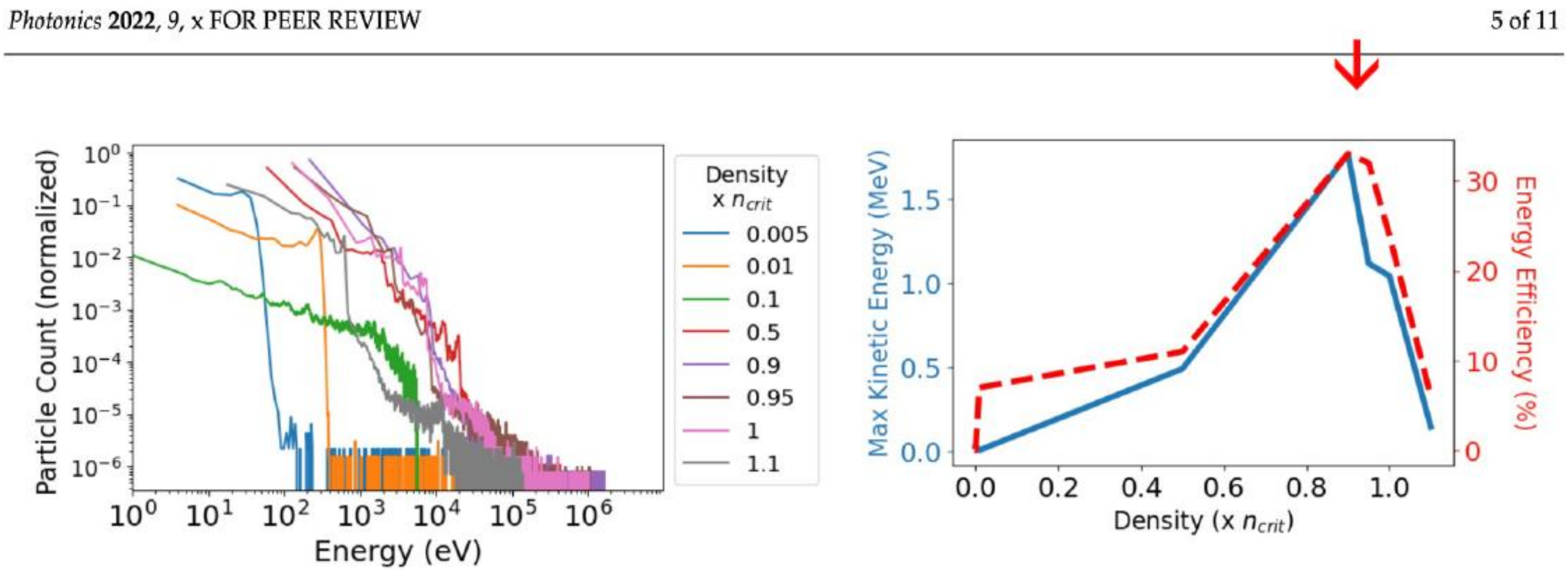
Carbon Nanotube for endoscopic LWFA –
Intended for low intensity compact laser source



B. Nicks et al., Photonics (2021)
Chattopadhyay, S., Mourou, G., Shiltsev, V., and Tajima, T. *Beam acceleration in Crystals and Nanostructures* (World scientific 2020)

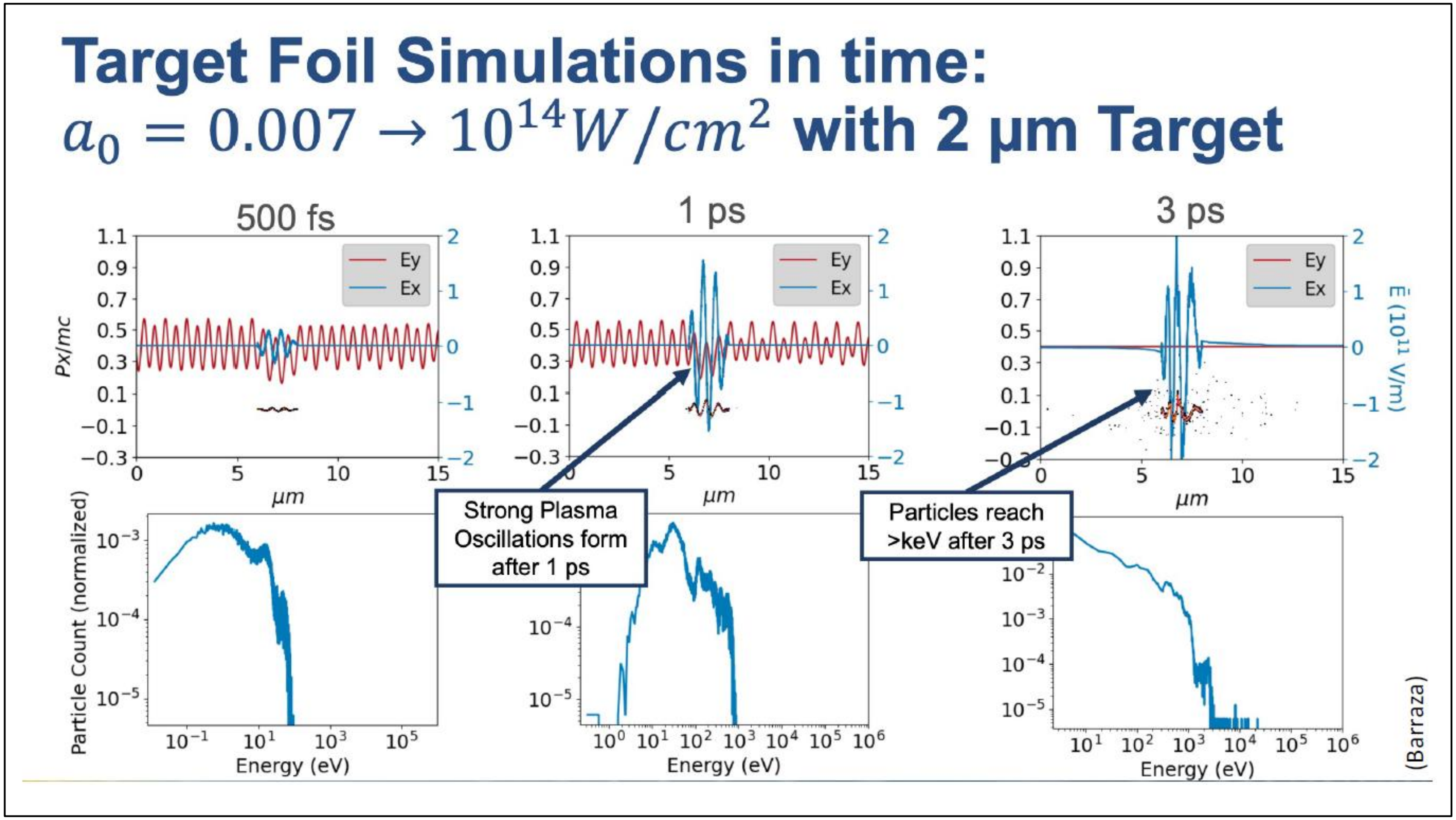
Near-critical density LWFA – High conversion efficiency

Barraza, Tajima, Strickland, Roa (Photonics, 2022)



- > 10 keV electrons with 10^{14} W/cm^2
- High conversion efficiency 30% at near critical density

Beatwave LWFA for endoscopic accelerator



Beatwave 1ω and 2ω, pulse width ~ 2 ps

Ernesto Barraza, Private comm. (2023)

Part 3. Ultrafast fiber laser as compact source

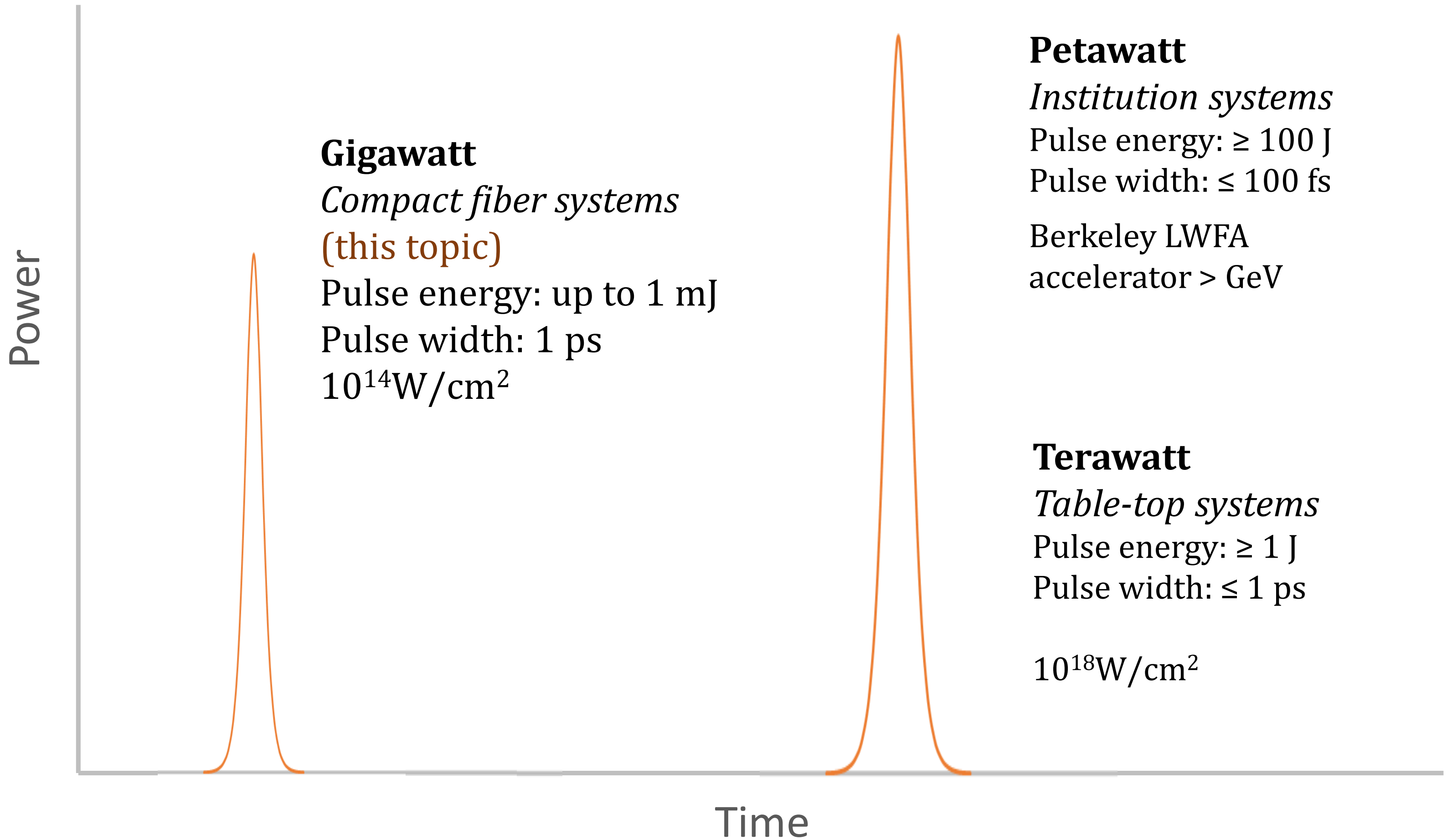
For microscopic laser accelerator

e-beam (>10 keV) from laser $10^{14}\ W/cm^2$

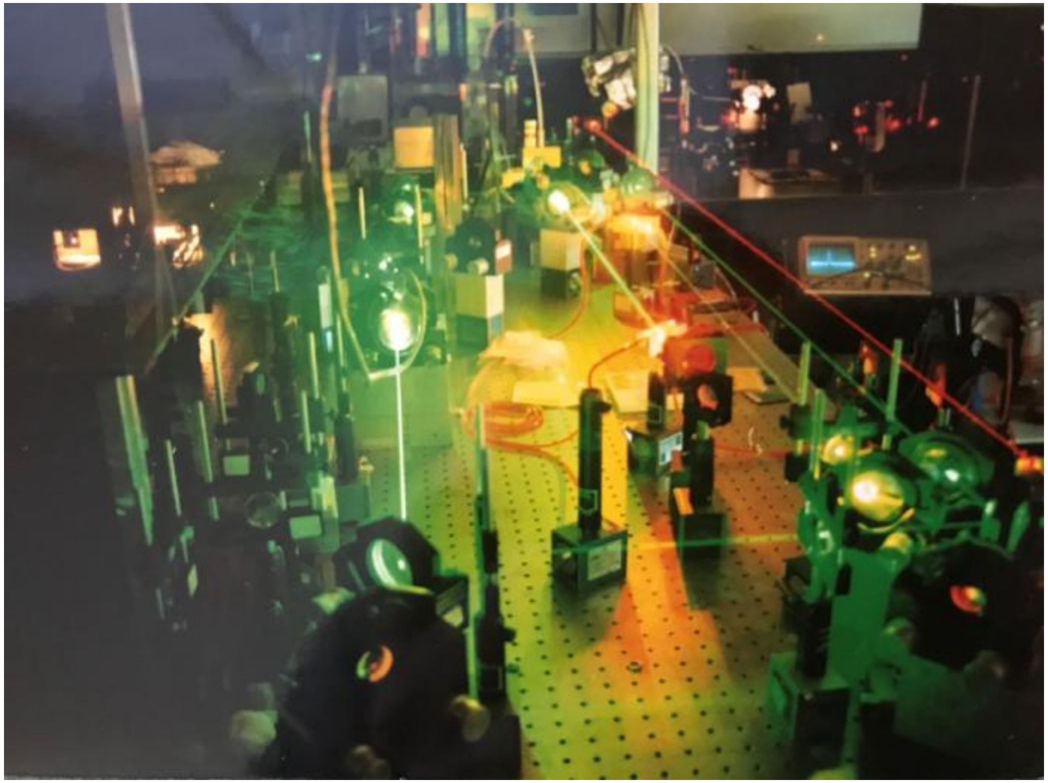

Free-Space Laser System
(lenses, mirrors, alignment)

Concentrating light energy onto picosecond/femtosecond pulses

Peak Power: Giga (10^9), Tera (10^{12}), Peta Watt (10^{15})

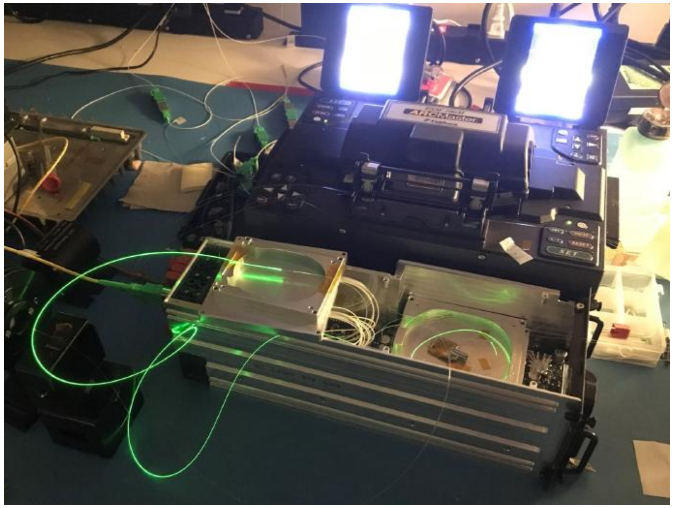


Compact Laser Source for Electron Accelerator at the tip of endoscope



Rochester/Michigan laser
100 fs, 20 μJ, 0.2 GW

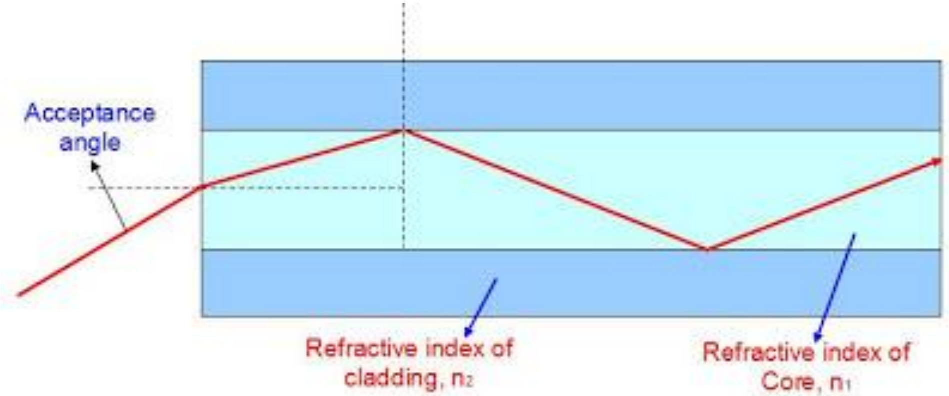
To this size



→ ultrafast fiber laser/amplifier

(3-Watt fiber amplifier for optical communication)

Power of Optical Fiber – Light Guiding



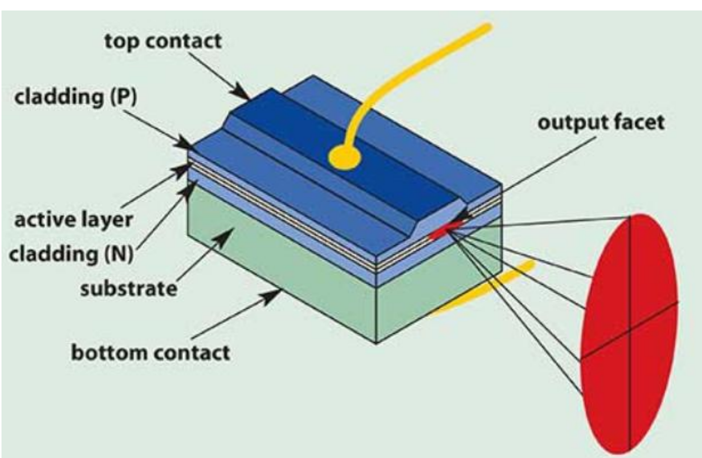
Numerical Aperture

$$NA = \sqrt{n_1^2 - n_2^2}$$

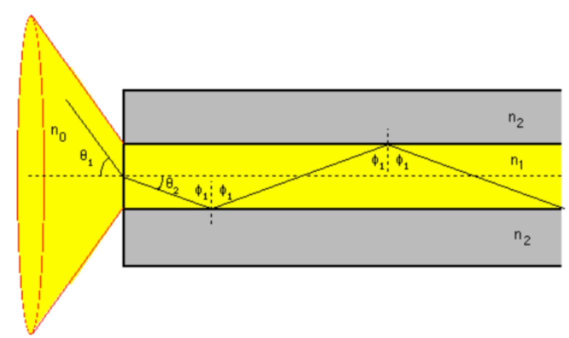
Total internal reflection from Snell's law, at angles close to 90°

(like skipping a stone on water surface)

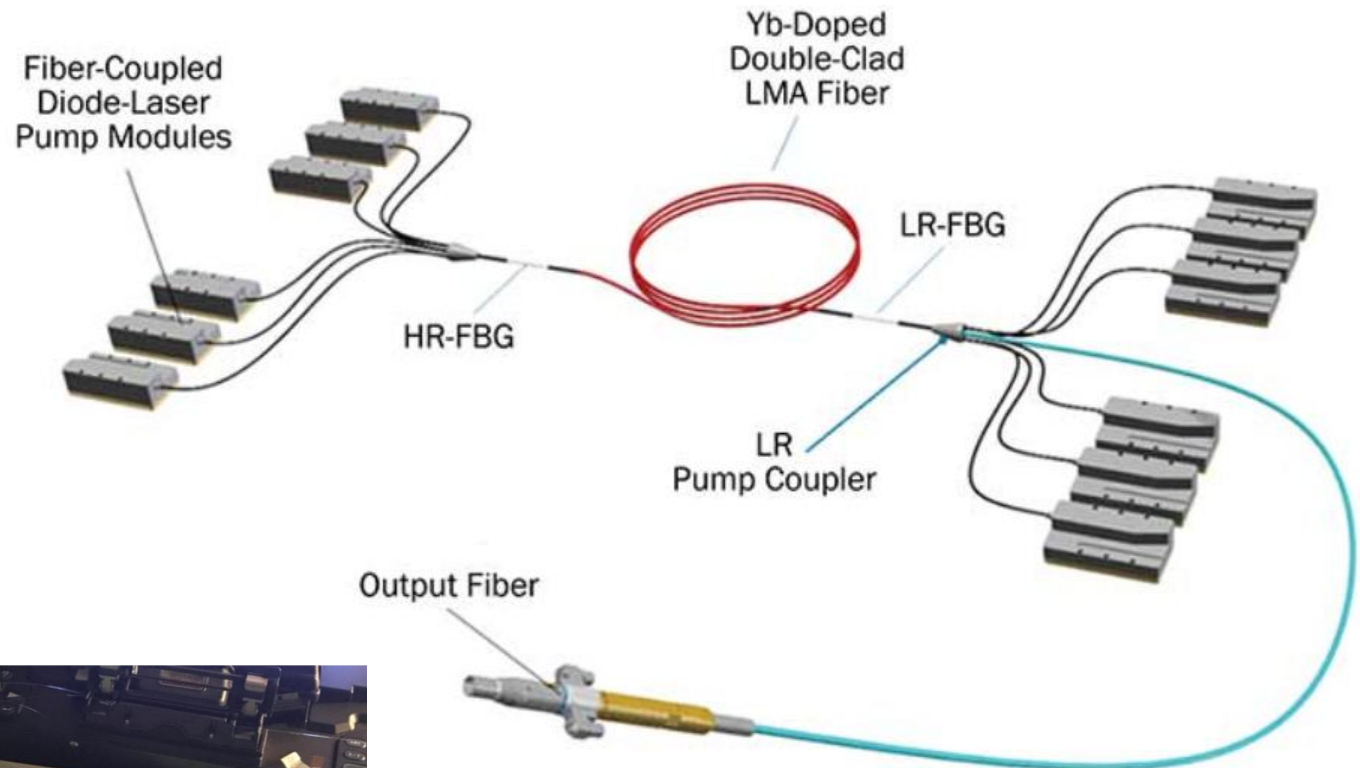
The effect is astounding: 1% difference in $\Delta n = n_2 - n_1$ is sufficient to guide light.

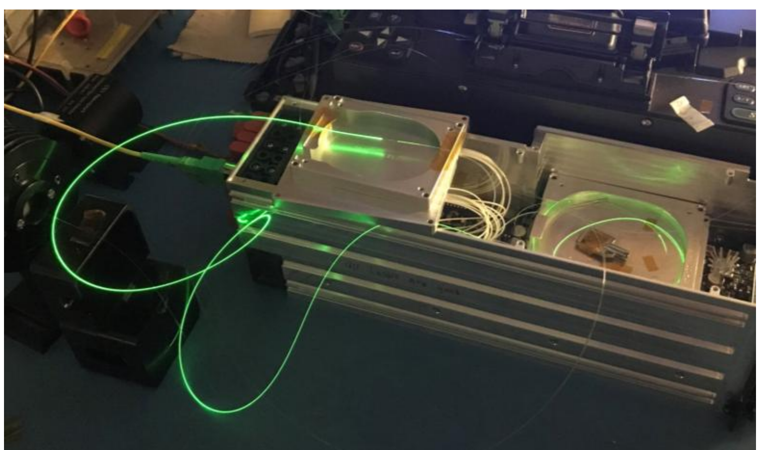


Acceptance angle > 60° for coupling divergent laser diodes.



Fiber Laser Construction, Example





Fiber Laser Technology & Applications

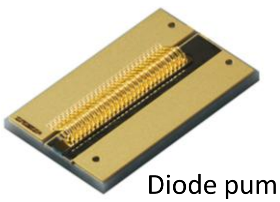
Application	Average Power	Pulse Width	Peak Power	Spatial Mode	Focused Intensity
Metal cutting (heat)	1 to 100 kW	Continuous	same as average	MM[1]	10^7 W/cm^2 (CW)
Semiconductor Processing	10 to 1000 W	1 to 100 ns	MW (10^6 W)	MM/SM[2]	10^9 W/cm^2 (peak)
Glass cutting (cold ablation)	> 10 W	≤ 0.5 ps	Hundreds of MW	SM	≥ 10^{13} W/cm^2 (peak)
Portable LWFA (>10 keV electrons)	1 to 10 W	≤ 1 ps	≥ GW (10^9 W)	SM	≥ 10^{14} W/cm^2 (peak)

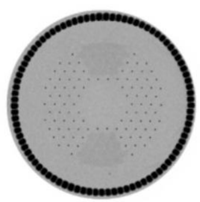
[1]MM: multi-mode (spatial) [2]SM: single mode

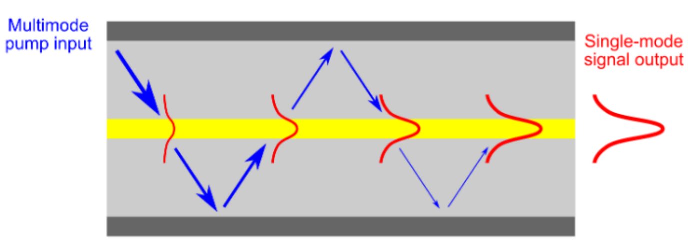
Femtosecond Ophthalmology

Under Collaboration with Prof. Donna Strickland on going;

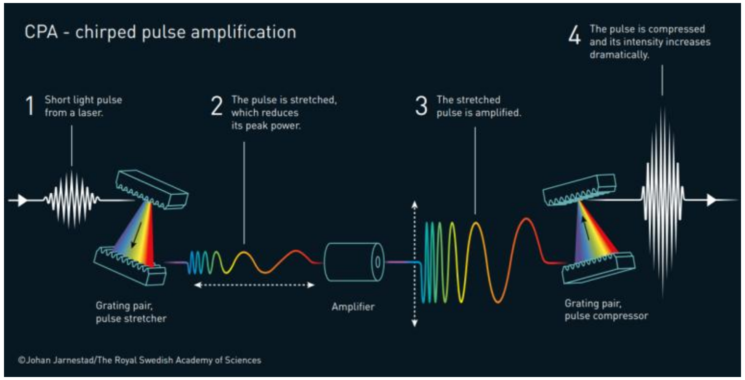
+ This Discussion


Diode pump laser


Large-mode-area doped fiber



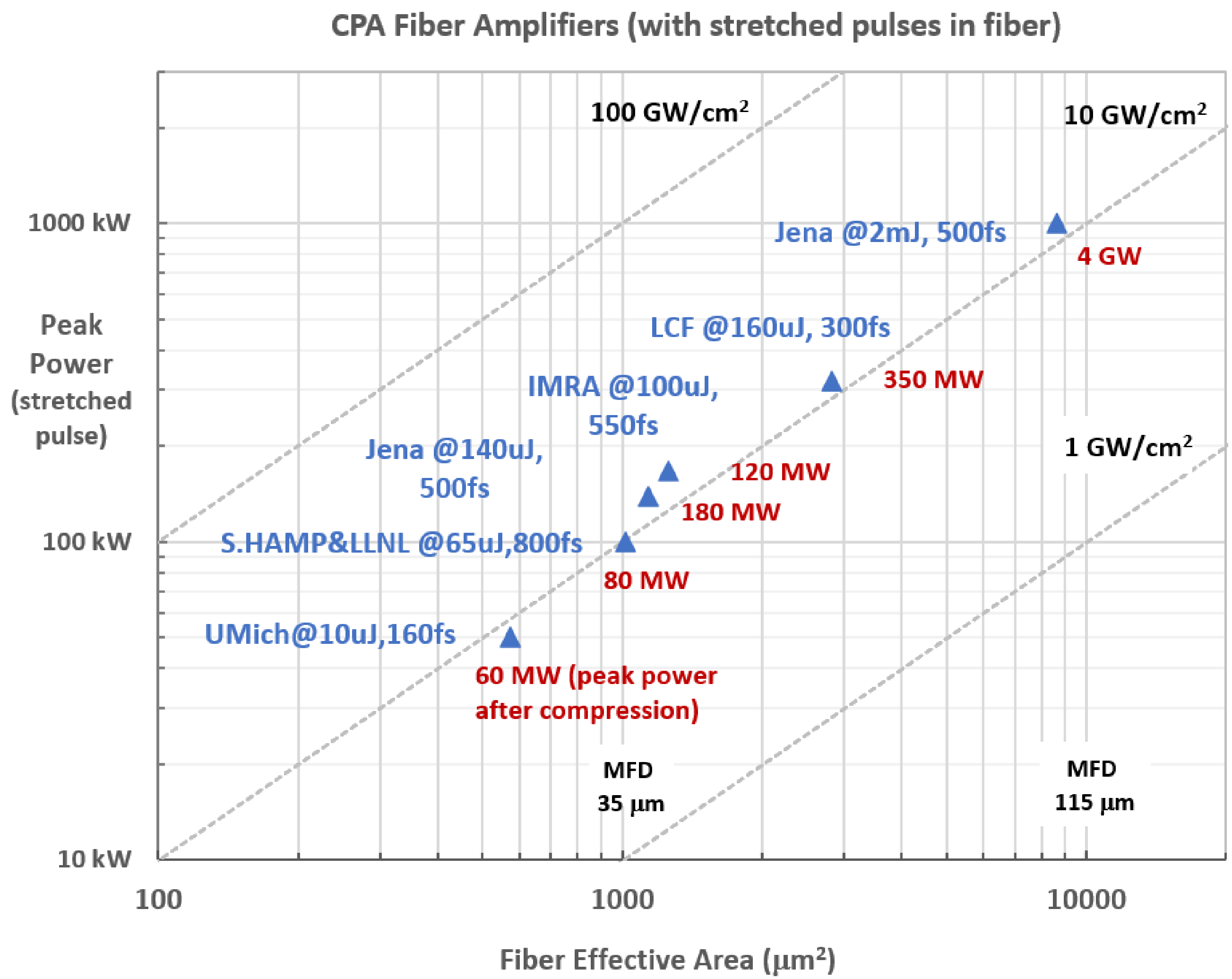
Double-clad fiber technology



Chirped pulse amplification

W. Sha, J.-C. Chanteloup, G. Mourou, Photonics 2022, 9, 423

Nonlinearity limit 10 GW/cm^2 of ultrafast pulse amplification in fiber



nonlinear phase accumulation

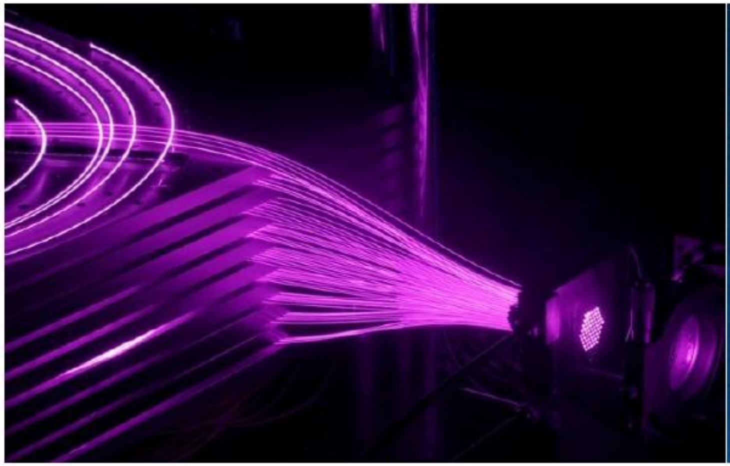
$$\varphi_{nl} = \gamma\ P\ L$$

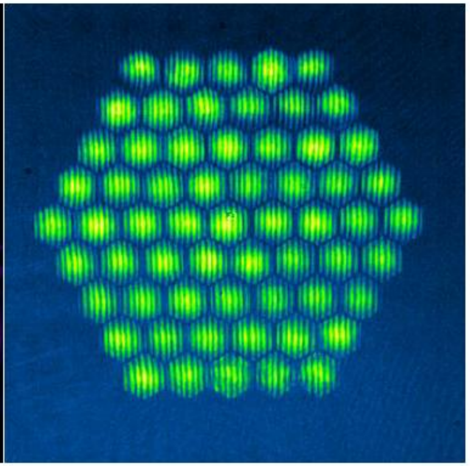
fiber length: meters long

$\gamma = 2\pi n_2 / \lambda A_{eff}$
Larger fiber core size for single-mode

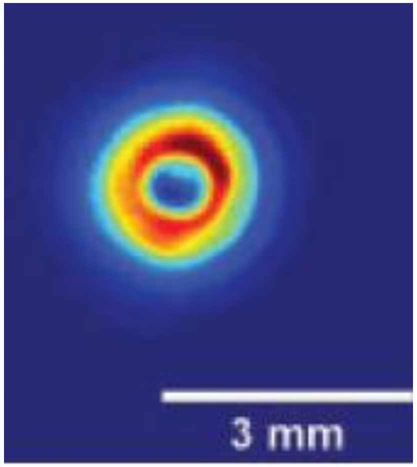
Chirped Pulse (CPA) peak power reduced by >1,000

XCAN – Coherently Beam Combined Laser (61 fiber lasers)





61 fiber lasers



Coherently Combined

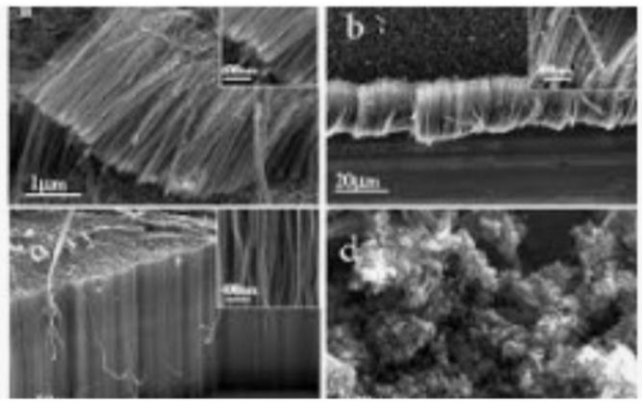
École Polytechnique

J.-C. Chanteloup et al., *Laser Focus World 2021*

Part 4. Fiber delivery for LWFA at tip of endoscope

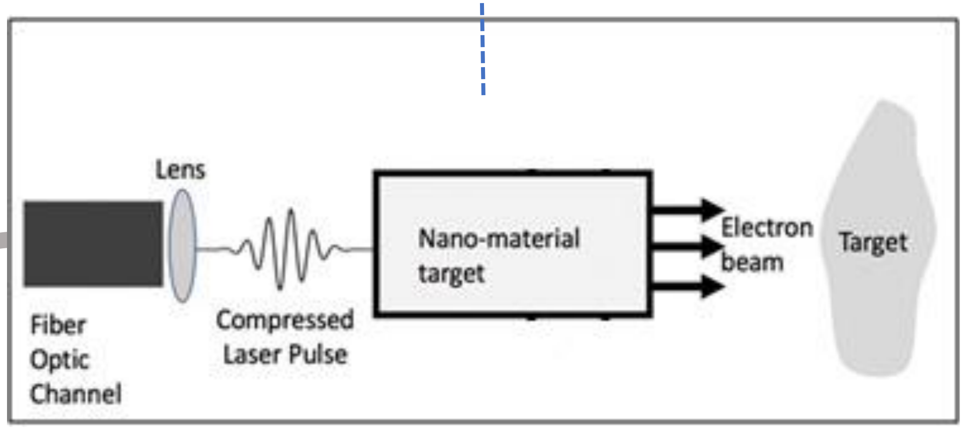
Fiber delivery for LWFA at tip of endoscope

Carbon nanotubes on a substrate:
→ toward Carbon Nanoforest (instead of plasma w/vacuum)



Pick CNT diameter
→ Critical density $10^{21}/cm^3$
(1 μm laser)

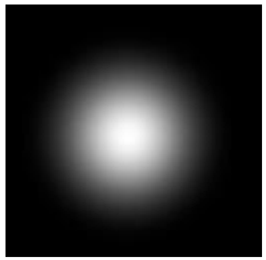
Flexible Light Pipe



Roa, Kuo, Moyses, Taborek, Tajima, Mourou, and Tamanoi, Photonics (2022).

Laser Beam Quality and Focal Intensity 10^{14} W/cm^2

Flexible Light Pipe: Single mode

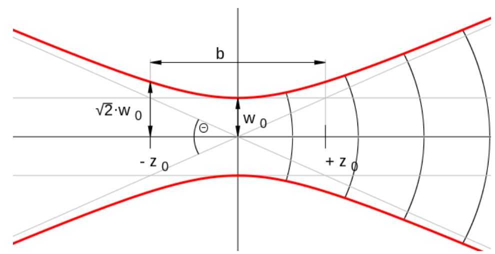


Focus-ability, Beam-Parameter Product (M^2)

Waist radius $w_{0,}$ far-field divergence half angle θ

$$w_0 \cdot \theta = M^2 \frac{\lambda}{\pi}$$

(M = 1.0 for single-mode)



Application	Pulse Energy →	Pulse Width →	Peak Power	Power Factor	Focal Diameter	Focal Area cm^2	Focused Intensity	≥ 10^{14} W/cm^2
Compact LWFA (5 µm focus)	50 µJ	1 ps	50 MW	1E+06	5 µm	2.E-07	2.5E+14	yes
10 µm focus	200 µJ	1 ps	200 MW	1E+06	10 µm	8.E-07	2.5E+14	yes
20 µm focus	1 mJ	1 ps	1 GW	1E+09	20 µm	3.E-06	3.2.E+14	yes

Flexible Fiber for Pulse Delivery (endoscope)

Nonlinearity limits in fiber amplifier: $\mathbf{10^{10}\ W/cm^2}$

Glass **breakdown threshold** due to instantaneous E field in laser**:** $\mathbf{\sim 10^{13}\ W/cm^2}$

Solid-core fiber (conventional fiber) <u>cannot</u> transmit the ultrafast pulses

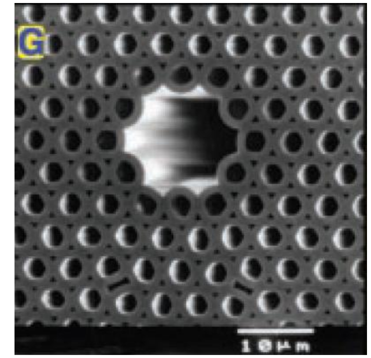
200 MW peak power, 20 μm mode-field → $\mathbf{5{\times}10^{13}\ W/cm^2}$

Much above nonlinearity and damage thresholds

Hollow-core fiber for light pulse delivery

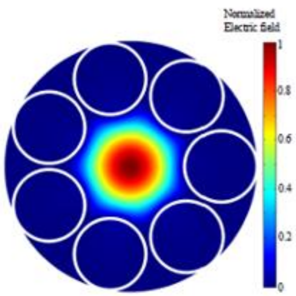
"Photonic bandgap guiding" instead of TIR

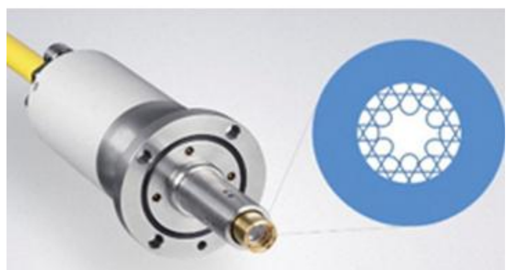
Anti-resonant in cladding, light guiding in hollow core:
damage ↓↓, nonlinearity ↓↓↓



P. Russell, *Science* 2003

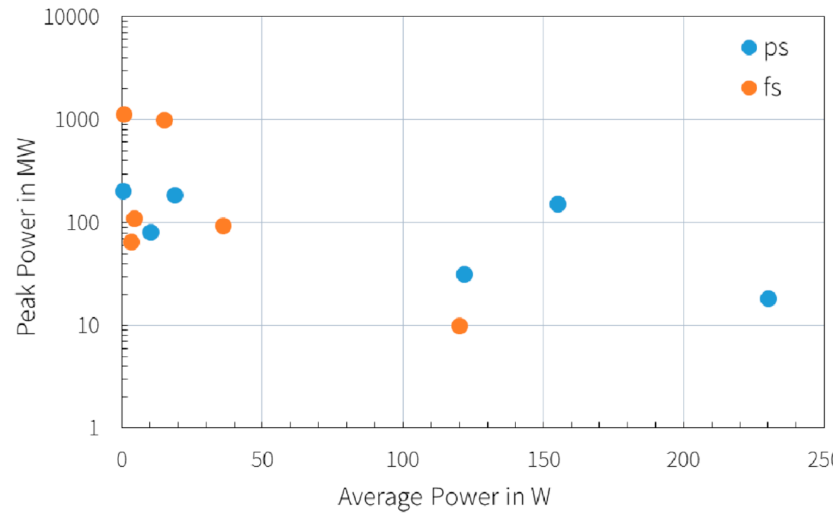
PT photonics product catalog





Bending radius 25 cm

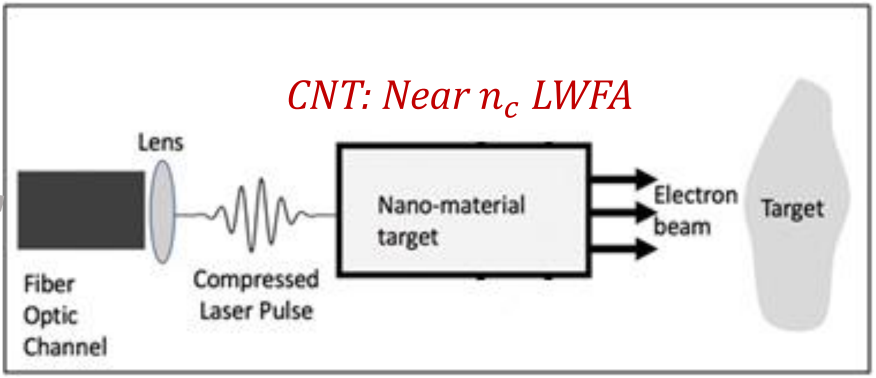
Hollow-core delivery up to GW peak power



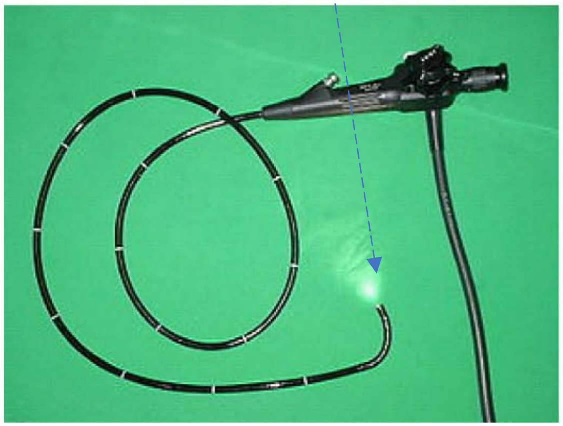
Eilzeret al., MDPI *Fibers*, 2018

Micron-Scale Electron Accelerator at the tip of endoscope

Flexible
Hollow-core fiber



Compact Fiber Laser
Up to GW peak power



Summary:
Micron-scale electron accelerator at the tip of endoscopy

1. Near-critical density Laser Wakefield Acceleration → low energy electrons (>10 keV, < MeV) at endoscopic treatment site
2. Fiber laser as compact source up to Gigawatt
3. Explore innovations flexible light transport to deliver 10^{14} W/cm^2 to micro-electron accelerator

Recent publications:

T. Tajima and P. Chen, eds. Progress of Laser Accelerator and Future Prospects (MDPI, Basel, 2023).
https://www.mdpi.com/journal/photonics/special_issues/Laser_Accelerator