Laser particle acceleration

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abstract

Two new technologies (coherent amplification network (CAN), thin film compression (TFC))

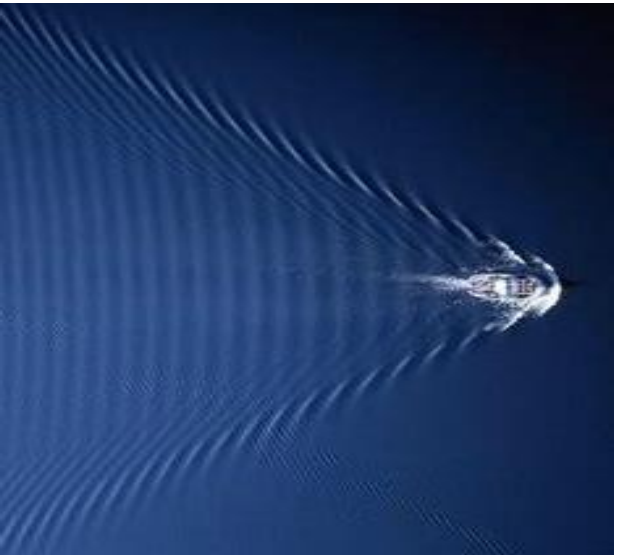
and 4 new innovations / applications (Laser-driven collider, γ-γ collider, SCLA proton acceleration, X-ray LWFA)

1. wakefield, relativistic coherence, and Tsunami
2. Laser-driven collider: 100 GeV over 1m, unit cells, stackup toward TeV based on CAN laser
3. Toward high reprate and high efficiency fiber laser (CAN)
4. γ-γ collider
5. Single-cycled laser and further coherency by TFC
6. Compact ion acceleration (short-lived isotope generation, ADS)
7. “TeV on a chip” (X-ray LWFA)

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed
maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0,
causes **wavebreak** and **turbulence**

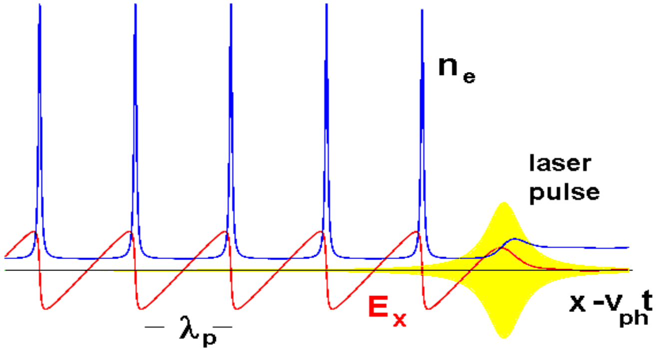


vs

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph}/e$

No wave breaks and wake **peaks** at v≈c

Wave **breaks** at v<c

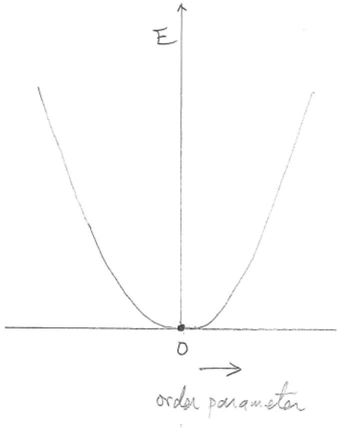


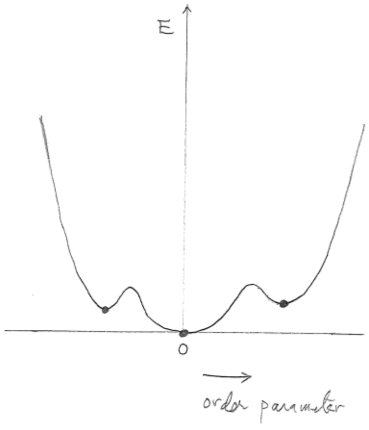
← relativity regularizes (***relativistic coherence***)

Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c/e$ (~ GeV/cm)

Wakefields and Higgs

Laundau-Ginzburg potential → BCS → Nambu → Higgs vacuum





Landau damping: decay of excited waves to equilibrium (left picture)

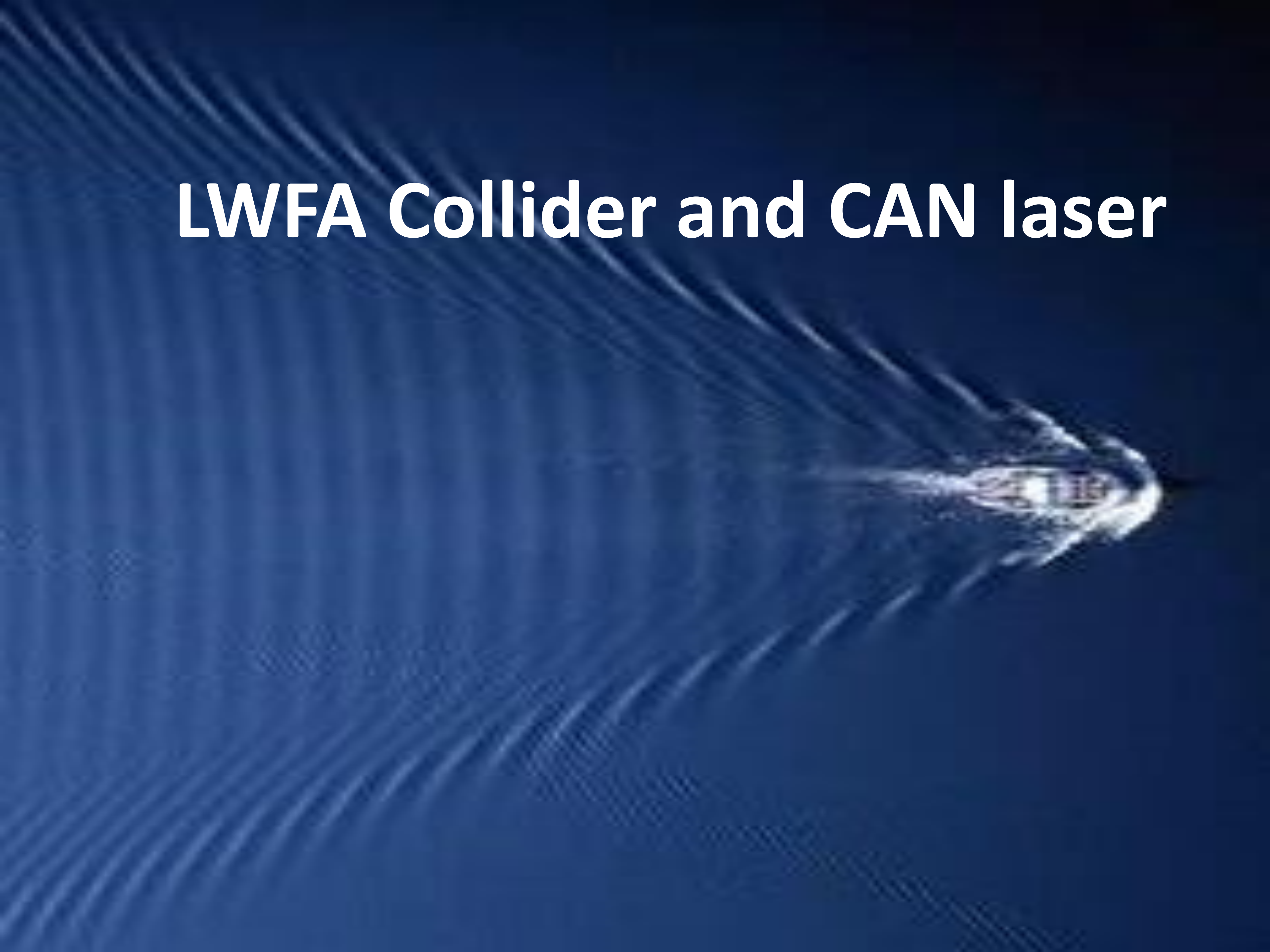
Wakefield: no damping; distinct excited <u>stable state</u> ←no particles to resonate (@ c)

= plasma's elevated Higgs state

| 0 > vs. | H > (cf . | H > → | 0 >)

thermo-equilibrium wakefield state tsunami onshore

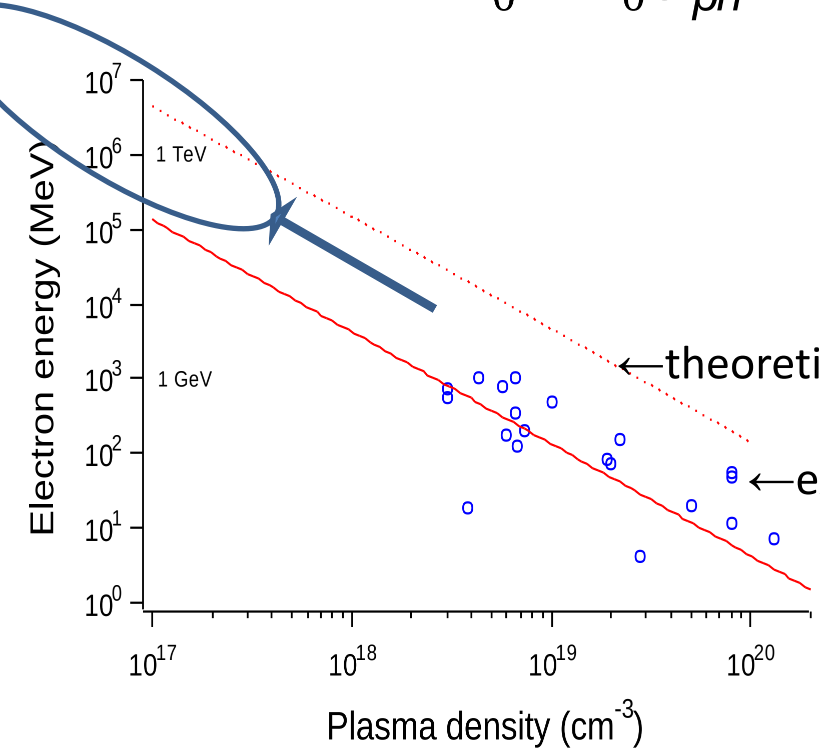
LWFA Collider and CAN laser



Theory of wakefield toward extreme energy

$$\Delta E \approx 2 m_0 c^2 a_0^2 \gamma_{ph}^2 = 2 m_0 c^2 a_0^2 \left(\frac{n_{cr}}{n_e} \right),$$

(when 1D theory applies)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = (n_{cr} / n_e)^{1/2}$$

$n_{cr} = 10^{21}$

$n_e = 10^{16}$

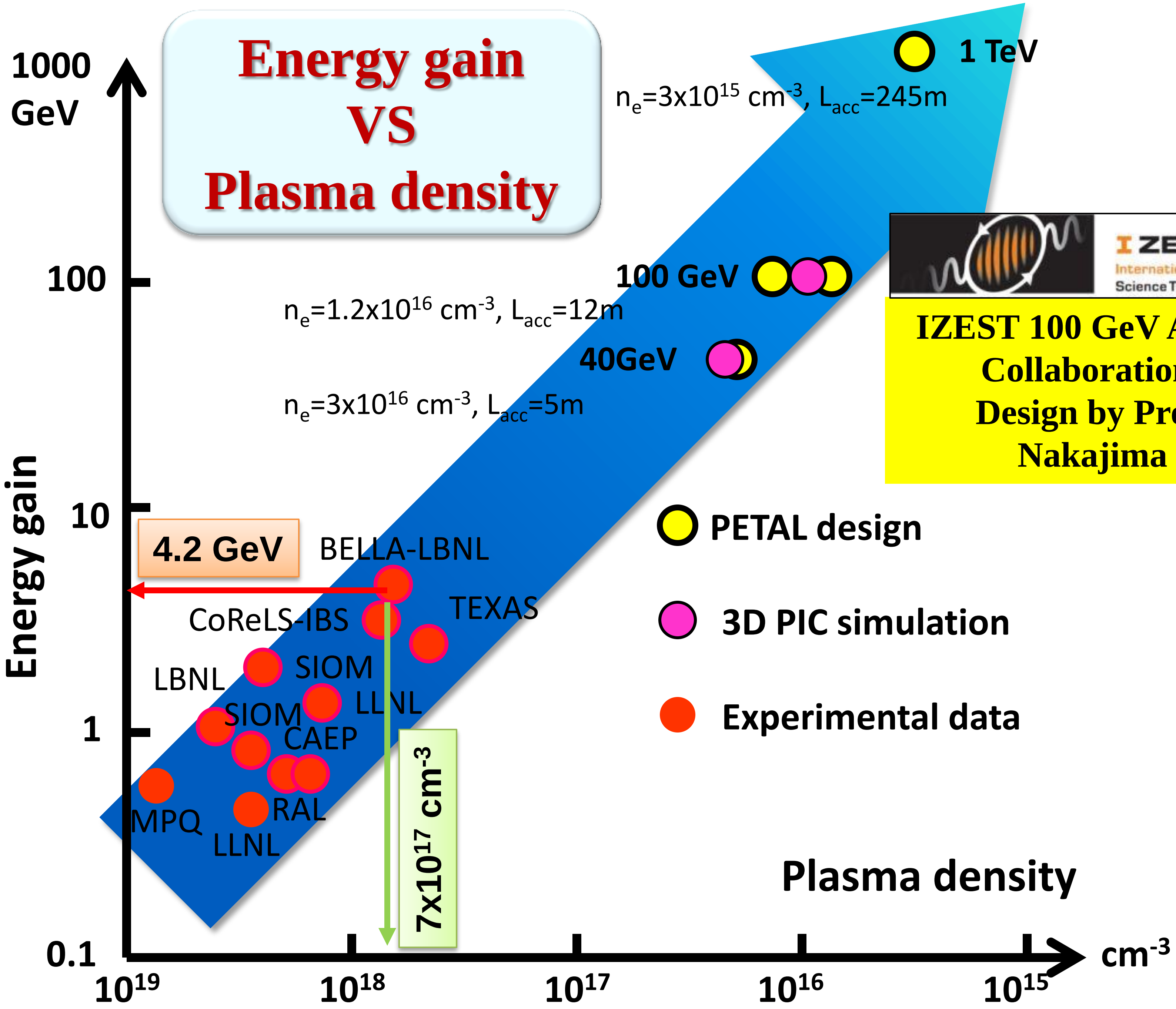
$$L_d = \frac{2}{\pi} \lambda_p a_0^2 \left(\frac{n_{cr}}{n_e} \right),$$

dephasing length

$$L_p = \frac{1}{3\pi} \lambda_p a_0 \left(\frac{n_{cr}}{n_e} \right),$$

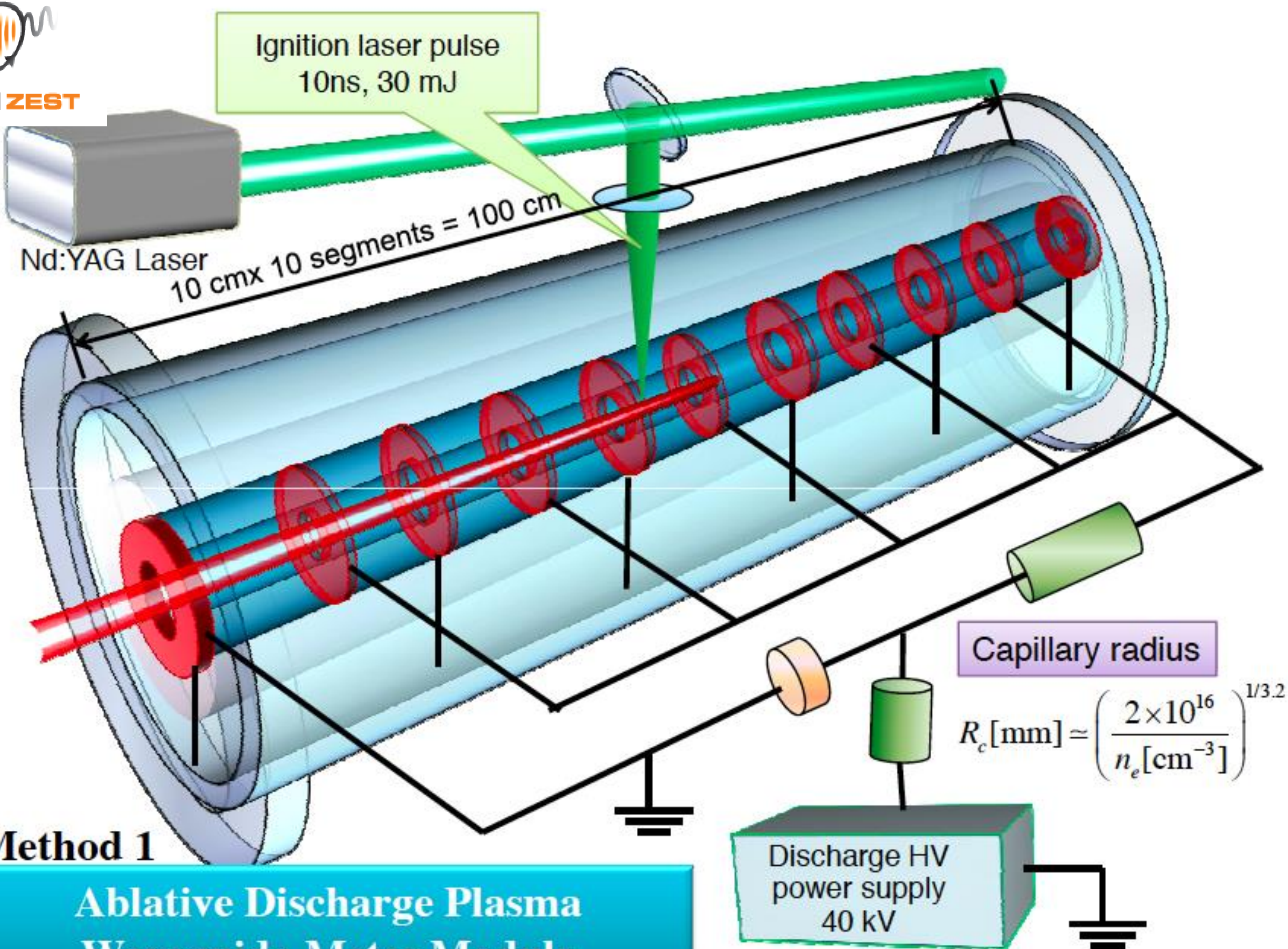
pump depletion length

Energy gain VS Plasma density



IZEST International Zeta-Exawatt Science Technology

IZEST 100 GeV Ascent Collaboration: Design by Prof. Nakajima



Ignition laser pulse
10ns, 30 mJ

Capillary radius

$$R_c[\text{mm}] \simeq \left(\frac{2\times10^{16}}{n_e[\text{cm}^{-3}]}\right)^{1/3.2}$$

Discharge HV
power supply
40 kV

Method 1

Ablative Discharge Plasma Waveguide-Meter Module

Nakajima, 2016

Areas of improvement in LA performance for various applications

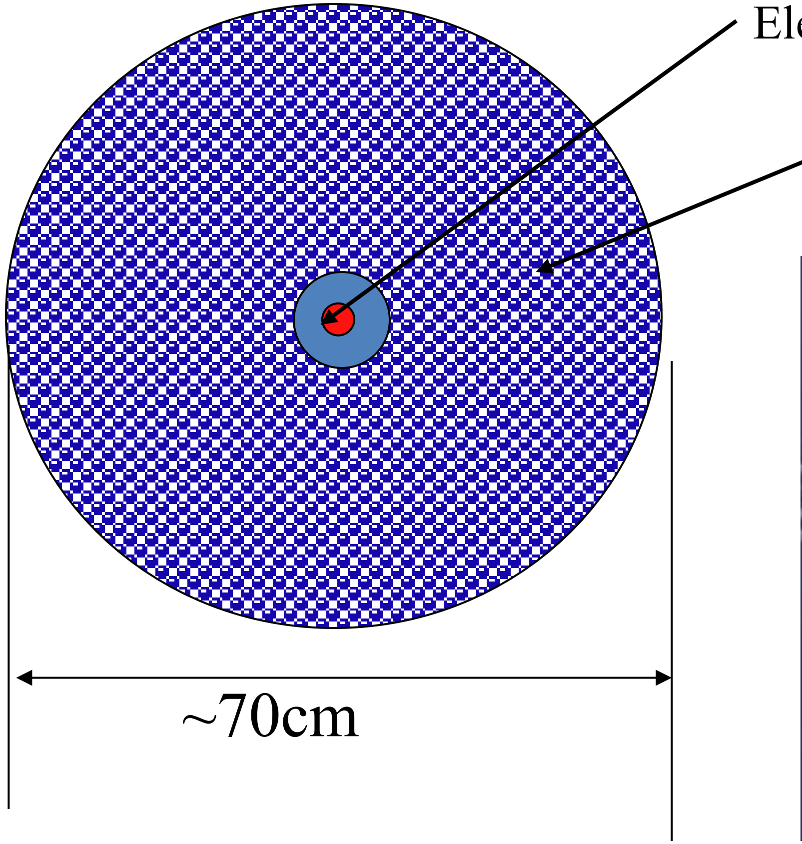
(from Darmstadt JTF workshop, 2010; also in Final Report of JTF: W. Leemans, W. Chou, M. Uesaka)

	THz	X-rays (betatron)	FEL (XUV)	Gamma-rays	FEL (X-rays)	Collider
Energy	✓	✓	✓	✓	↑	↑↑
ΔE/E	✓	✓	↓	↓	↓↓	↓↓
ε	✓	✓	✓	✓	✓	↓↓
Charge	✓	✓	✓	↑	✓	↑
Bunch duration	✓	✓	✓	✓	✓	✓
Avg. power	↑	↑	↑	↑	↑	↑↑

✓ : OK as is
↑: increase needed
↓: decrease needed

Need to Phase
32 J/1mJ/fiber~ 3x10^4 Phased Fibers!

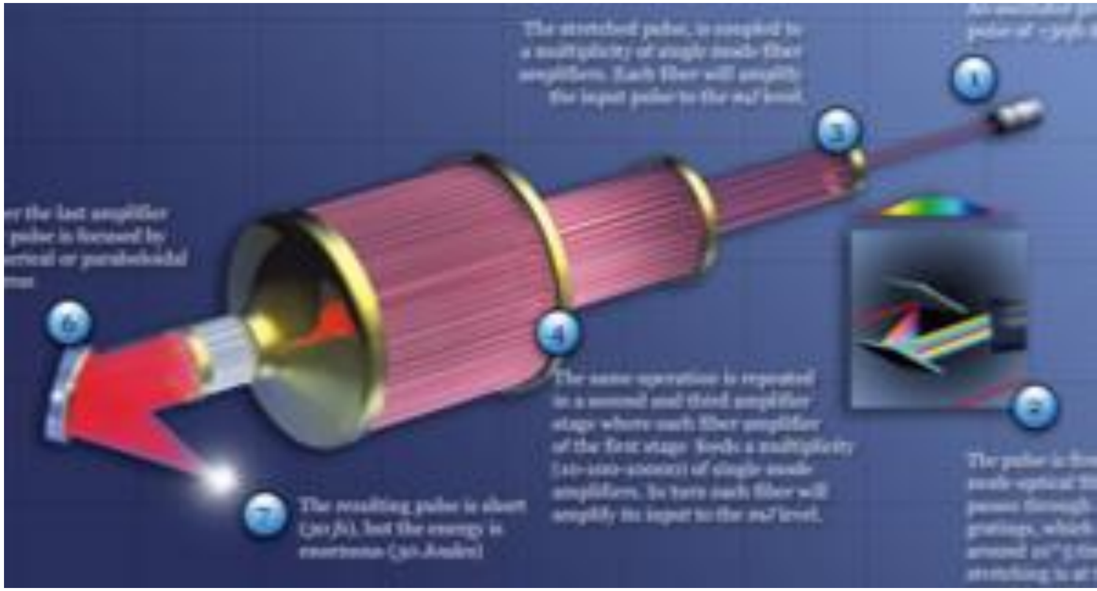
Mourou, Brocklesby, Tajima, Limpert,
Nature Photnics (2013)



Electron/positron beam

Transport fibers

~70cm

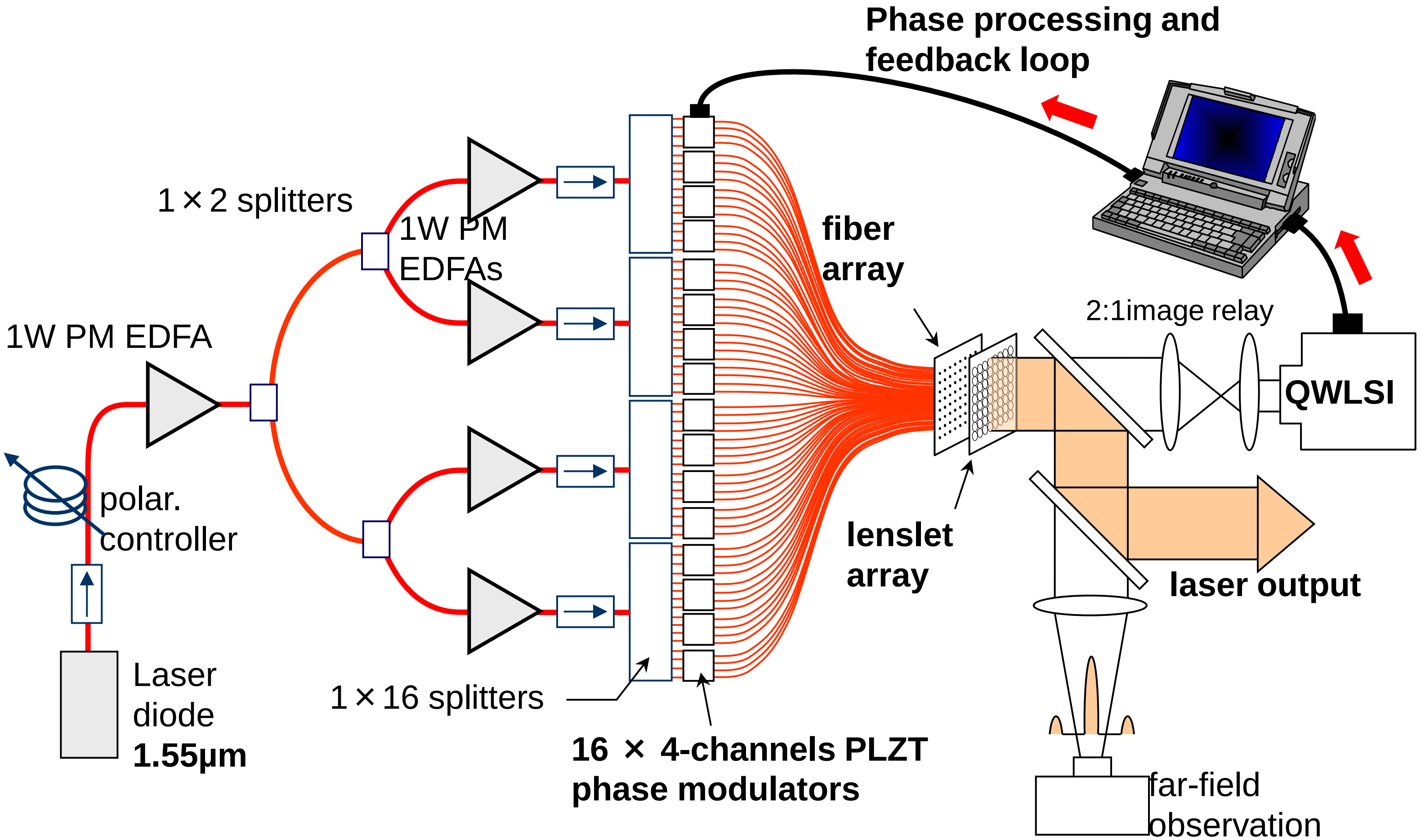


Length of a fiber ~2m

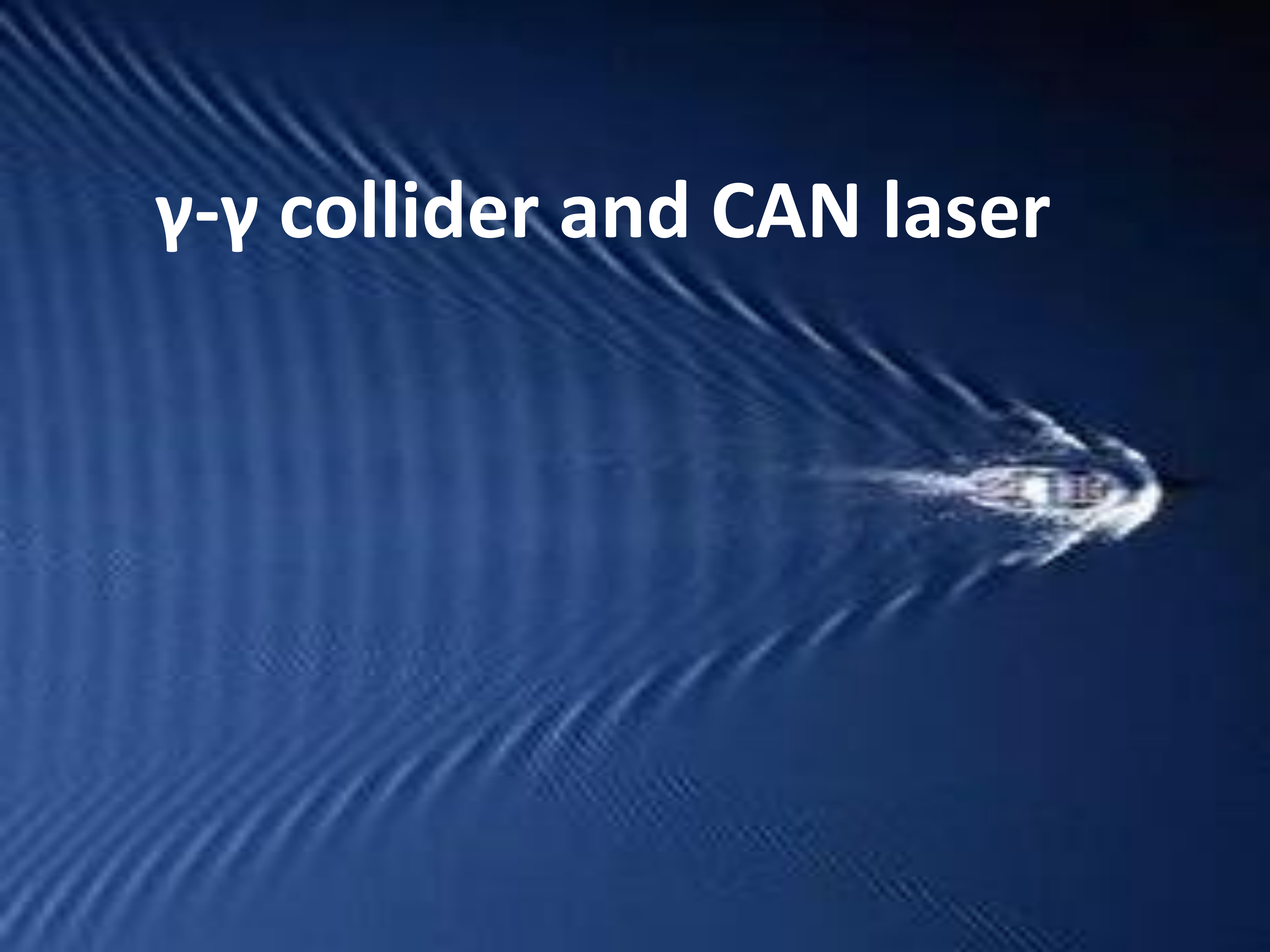
Total fiber length~ 5 10^4km

J. Bourderionnet, A. Brignon (Thales), C. Bellanger, J. Primot (ONERA)

Coherent Fiber Combining



Achievement 2011
→ 64 phase-locked fibers

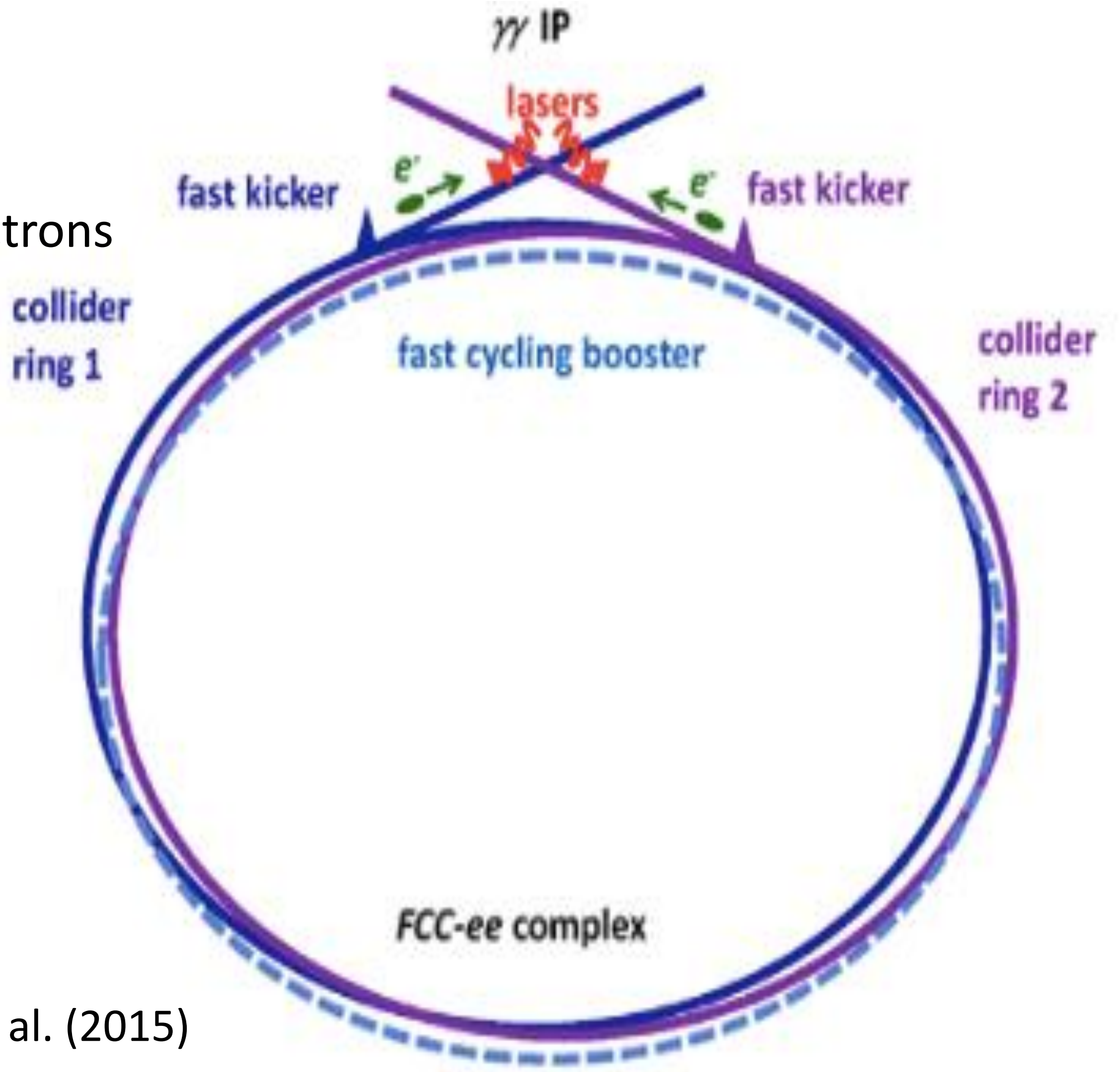


γ-γ collider and CAN laser

γ-γ collider and XCAN fiber laser

One option of FCC of CERN:

- **γ-γ collider**
- lasers that backscatter off electrons
  - CAN fiber laser
    (high rep-rate,
    high fluence,
    high efficiency)



R. Aleksan, et al. (2015)

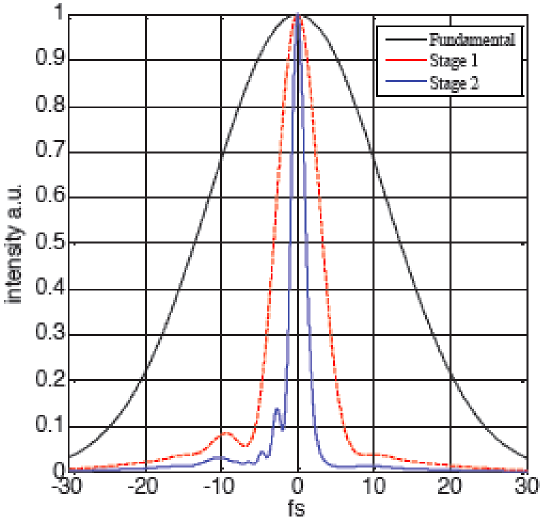
Thin Film Compression and ion accelerator

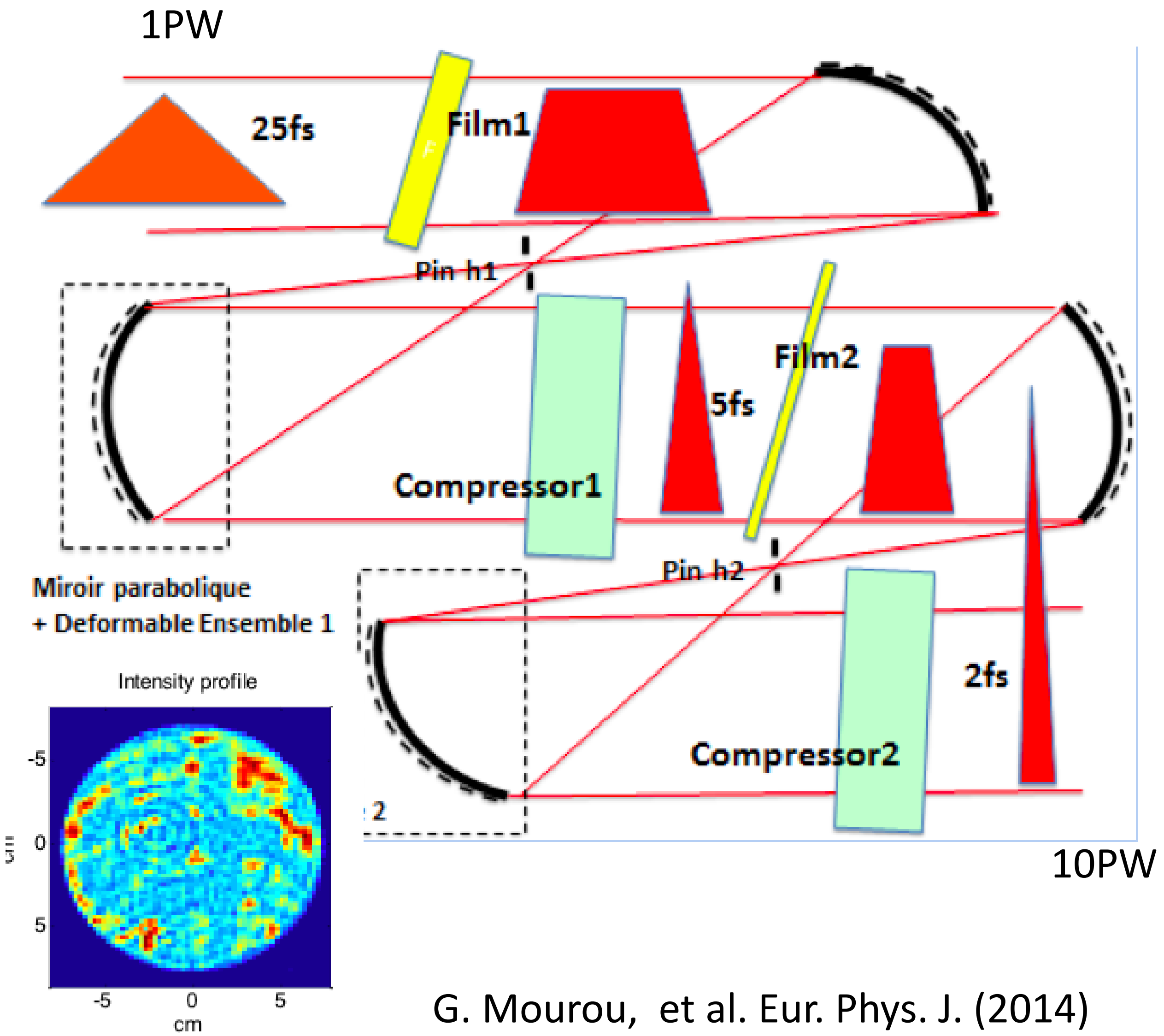
Tajima, EPJ 223 (2014)

Single-cycle laser (new Thin Film Compression)

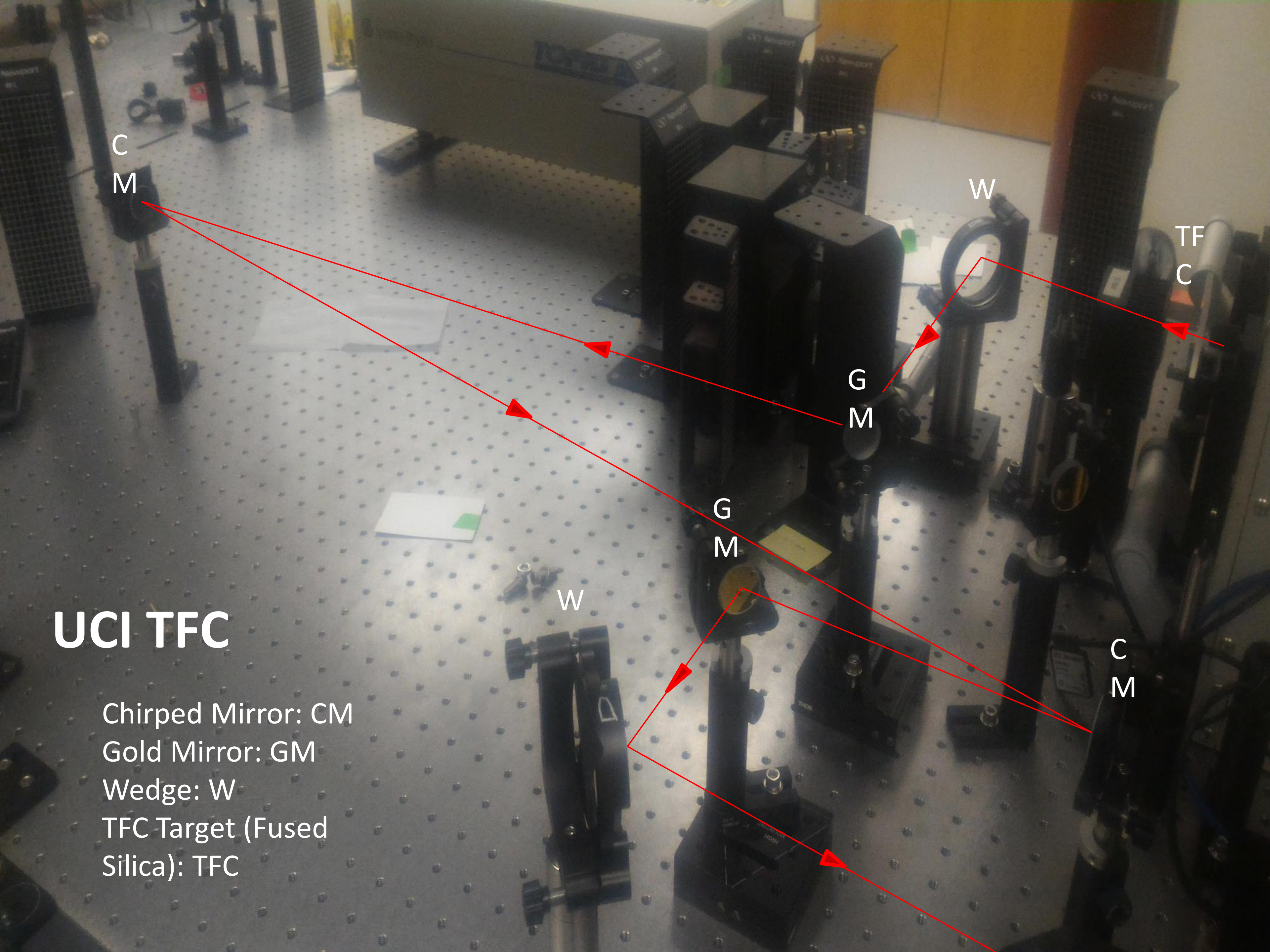
Laser power = energy / pulse lnegth

Optical nonlinearity of thin film → pulse frequency width bulge, pulse compression





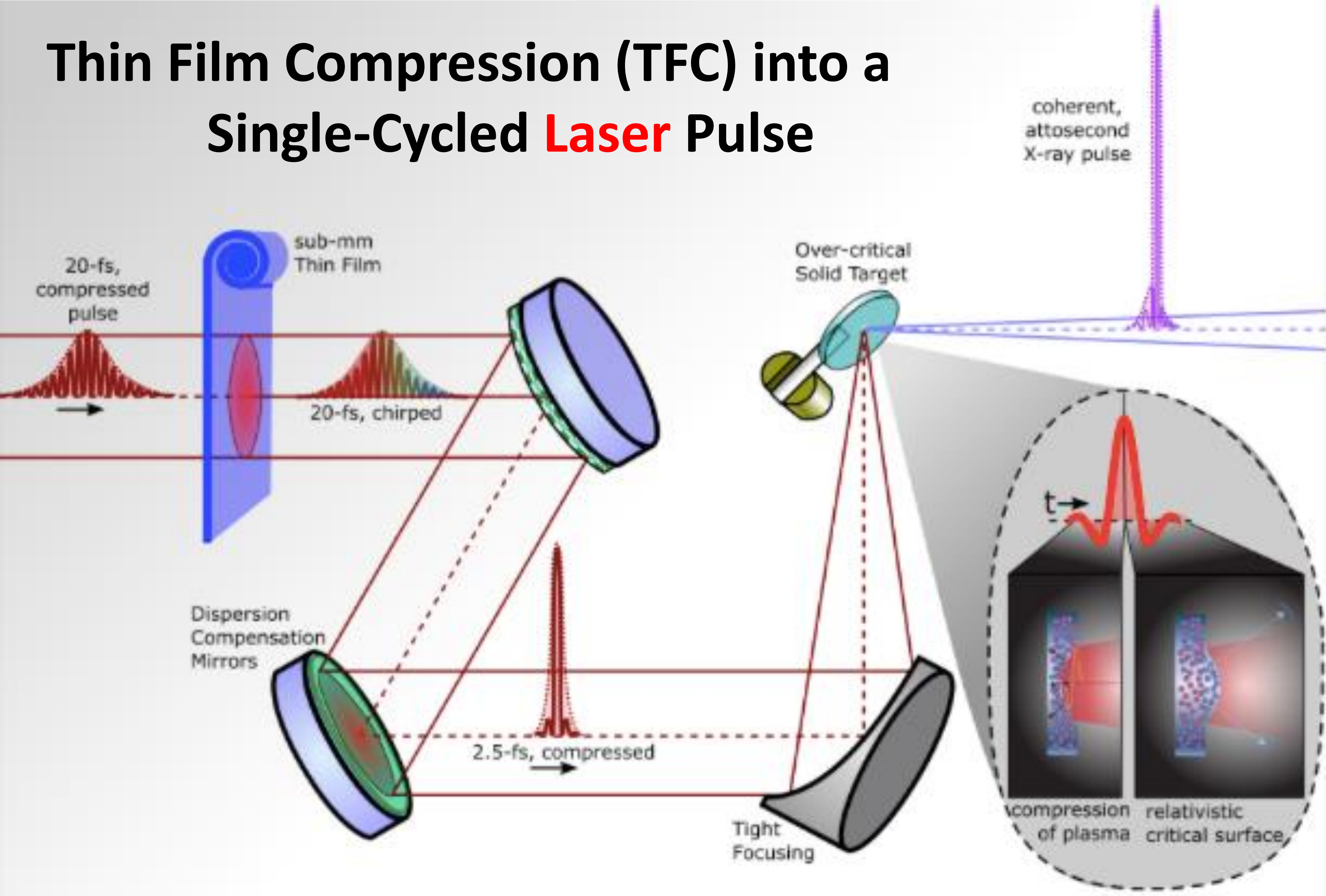
G. Mourou, et al. Eur. Phys. J. (2014)



UCI TFC

Chirped Mirror: CM
Gold Mirror: GM
Wedge: W
TFC Target (Fused Silica): TFC

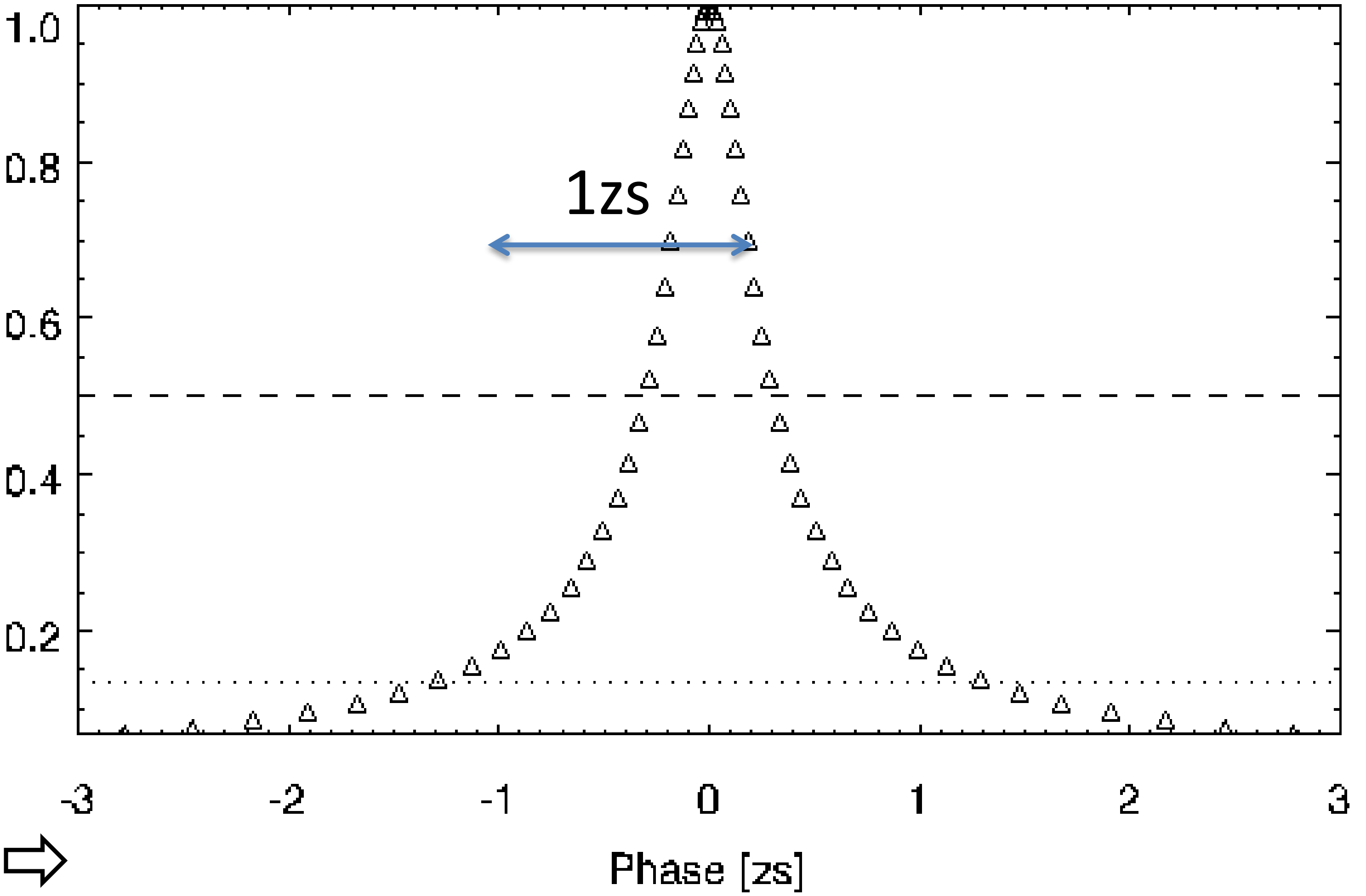
Thin Film Compression (TFC) into a Single-Cycled Laser Pulse



Mourou et al. (2014)

Even,isolated zeptosecond X-ray laser pulse possible

(simulation by N. Naumova, et al., 2014)



⇨

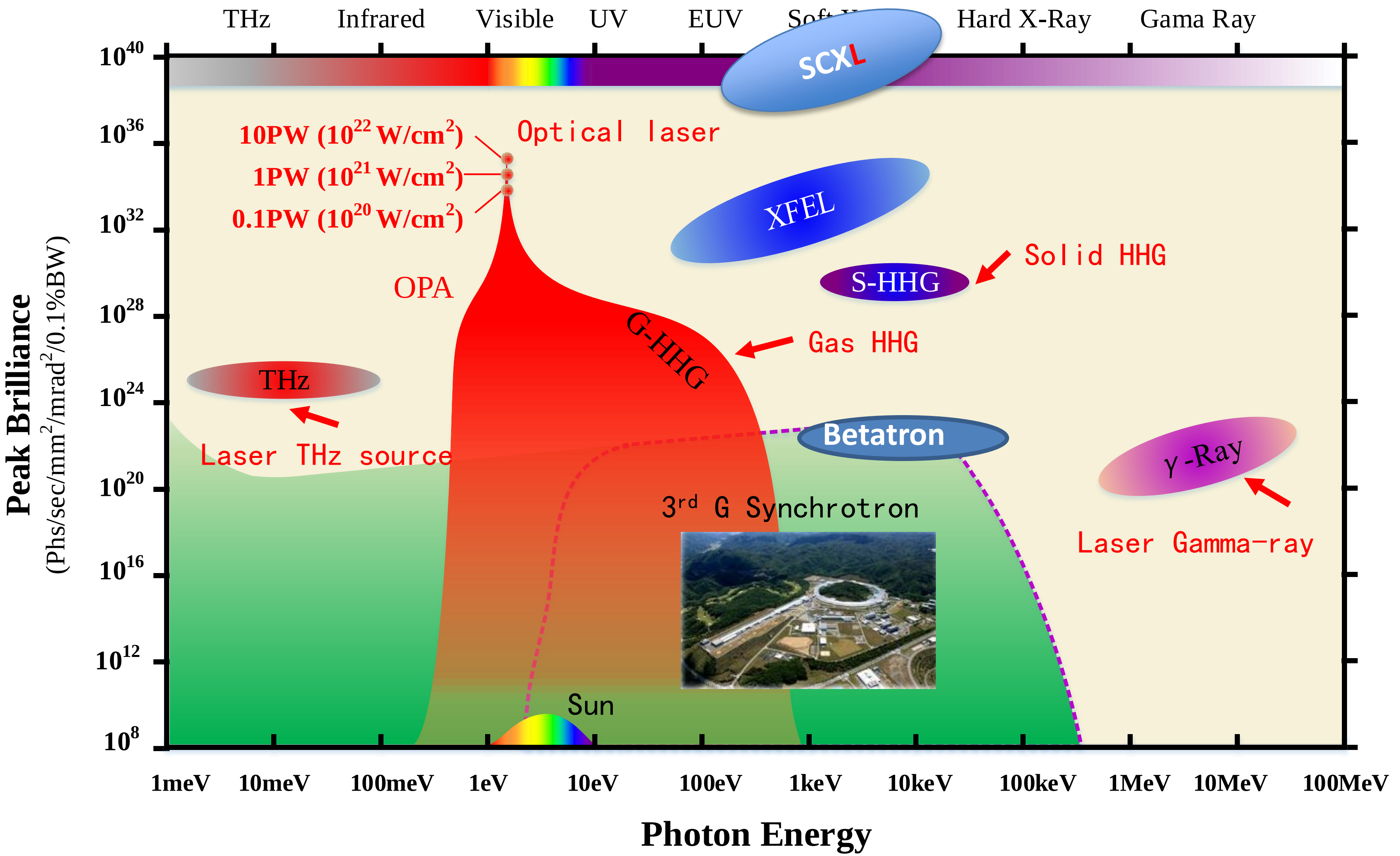
1PW optical laser → 10PW single osc. Optical laser

→ EW single osc. X-ray laser

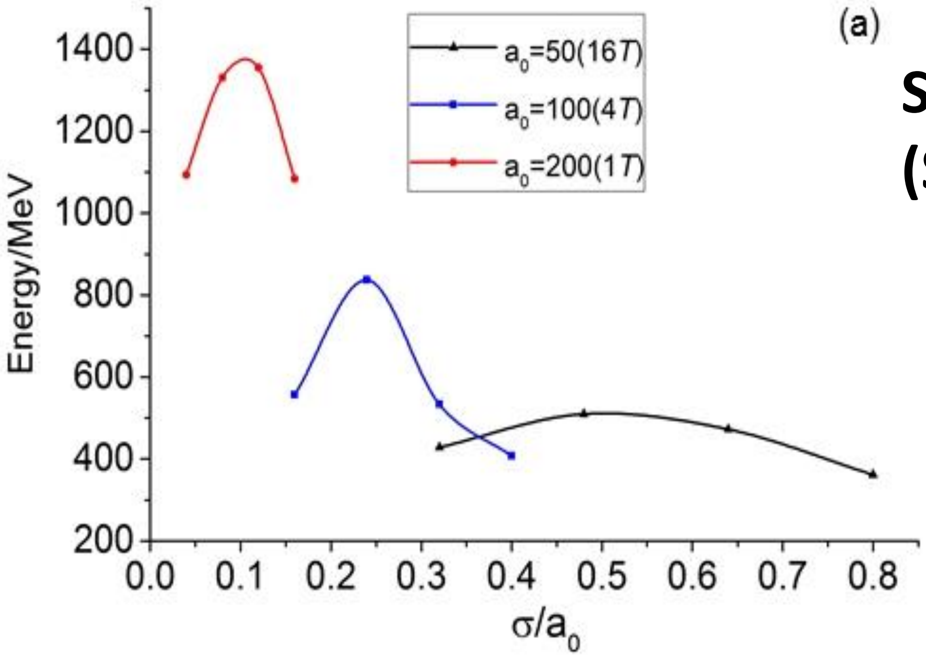
Consistent with “Intensity-pulse-width Conjecture” (Mourou-Tajima, Science **331** (2011))

Petawatt laser / secondary rays vs SR, XFEL, and SCXL

Brilliance of our Single Cycled X-ray Laser (SCXL)

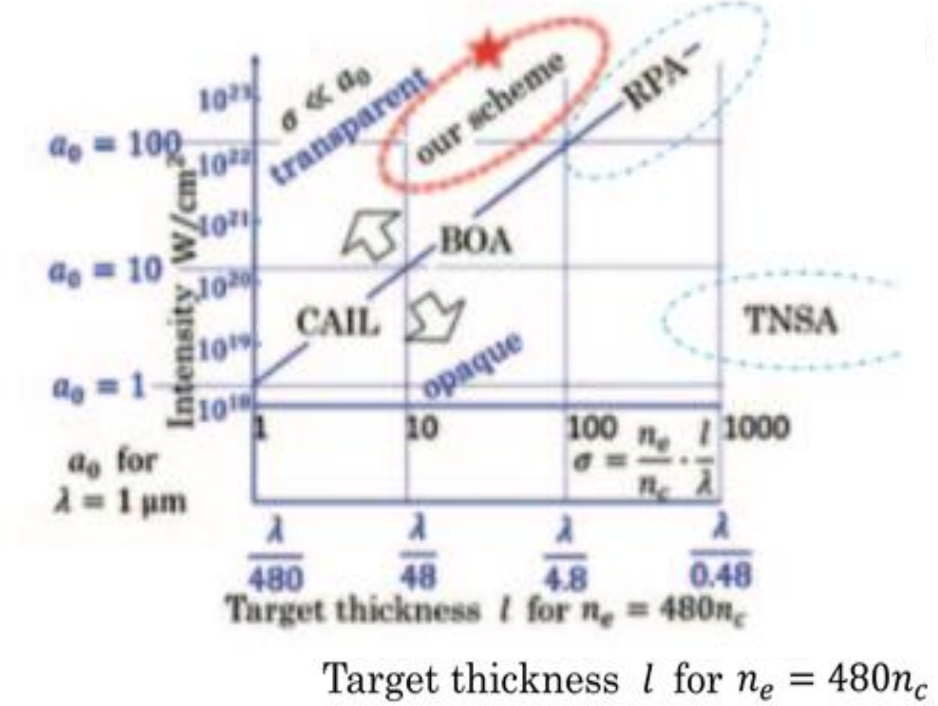


SCXL added to T.J. Wang / R. X. Li (2016): see M3.1



Single-Cycled Laser Acceleration (SCLA)

more coherent acceleration under same laser energy: more energies proportional to a_0



Domain map of various ion accelerations in a_0 and σ

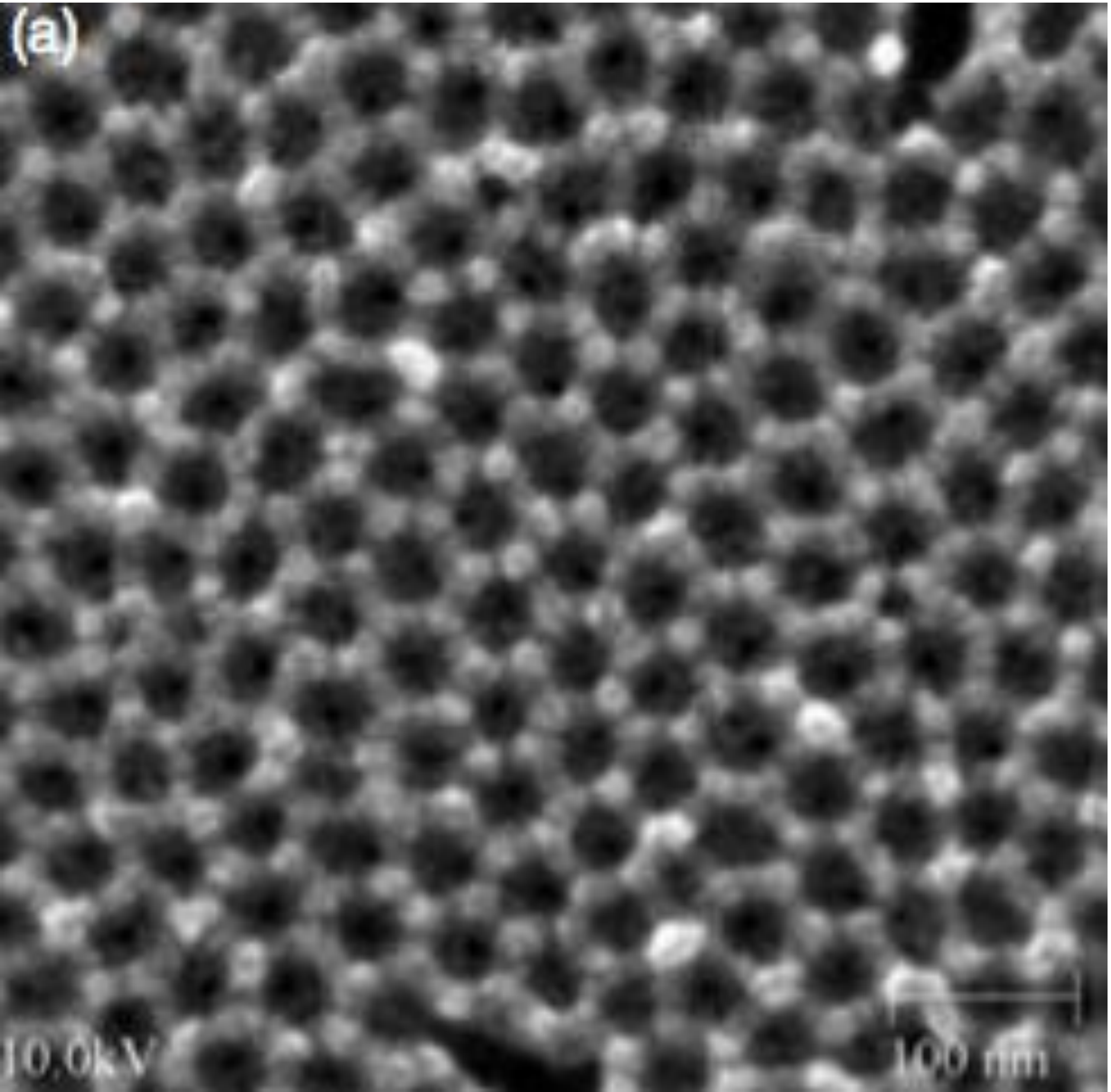
Zhou et al. PoP (2016)

X-ray LWFA in Nanostructure

Tajima, EPJ 223 (2014)

Porous Nanomaterial:

rastering possible



Nano holes:

reduce the stopping power

keep strong wakefields

➔ Marriage of *nanotech* and *high field science*

Spatia (nm), time(as-zs), density 10^{24} /cc), photon (keV) scales:
Transverse and longitudinal **structure of nanotubes**: act as e.g., accelerator structure (the structure intact in time of ionization, material breakdown times fs > x-ray pulse time zs-as)

Porous alumina on Si substrate
Nanotech. **15**, 833 (2004);
P. Taborek (UCI): porous alumina (2007)

UCI/Fermilab efforts on nanostructure wakefield acceleration

16th Advanced Accelerator Concept Workshop (AAC2014)

TeV/m Nano-Accelerator

Current Status of CNT-Channeling Acceleration Experiment

Y. M. Shin[1,2], A. H. Lumpkin[2], J. C. Thangaraj[2], R. M. Thurman-Keup[2], P. Piot[1,2], and V. Shiltsev[2]

Thanks to X. Zhu, D. Broemmelsiek, D. Crawford, D. Mihalcea, D. Still, K. Carlson, J. Santucci, J. Ruan, and E. Harms

[1]Northern Illinois Center for Accelerator and Detector Development (NICADD), Department of Physics, Northern Illinois University

[2]Fermi National Accelerator Laboratory (FNAL)

X-ray wakefield acceleration in nanomaterials tubes

T. Tajima, EPJ (2014)

X-ray laser with short length and small spot:

NB: electrons in outers-shell bound states, too, interact with X-rays

Simulation:

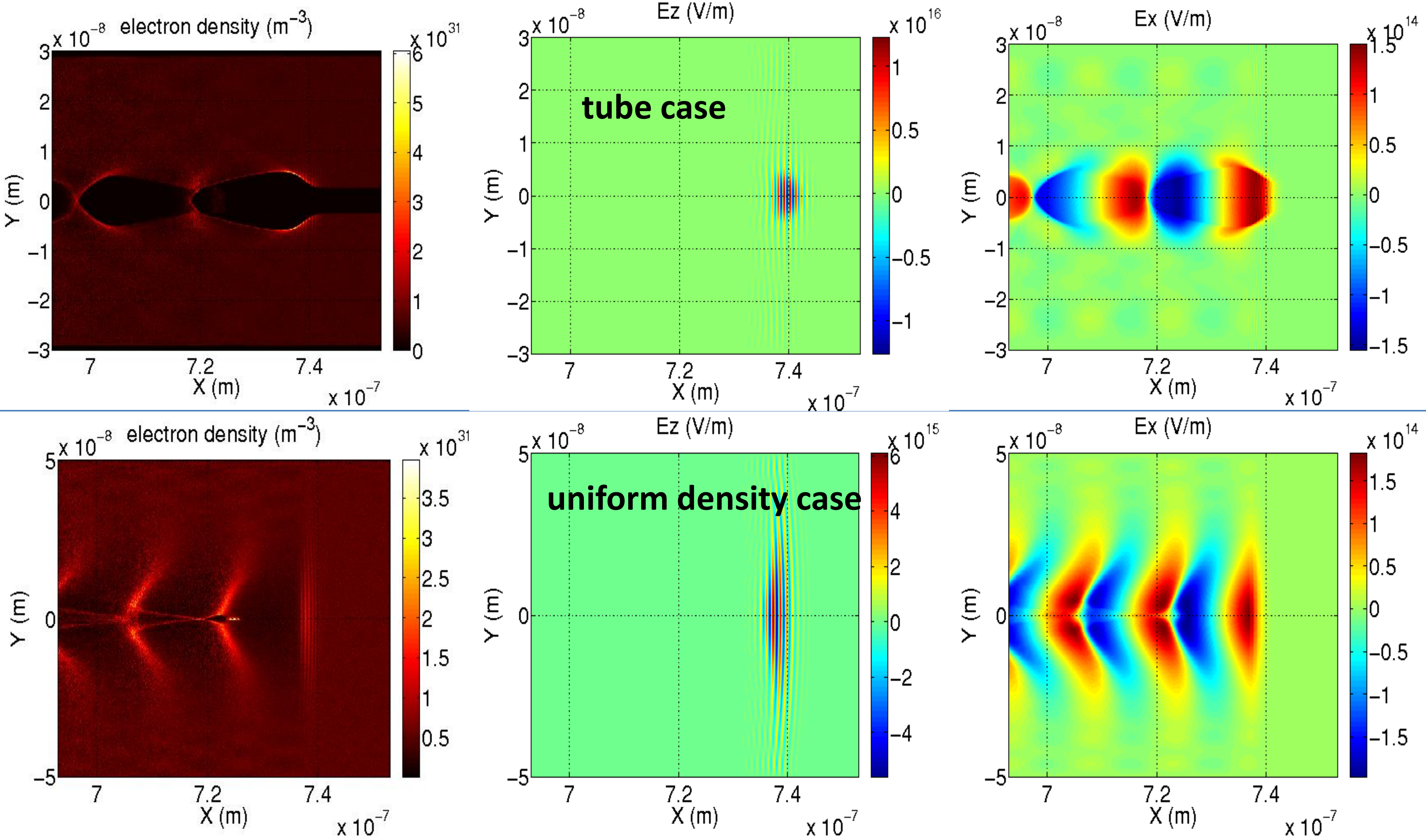
X.M. Zhang, et al. (2016)

Laser pulse with small spot can be well controlled and guided with a tube. Such structure available e.g. with **carbon nanotube**, or **alumina nanotubes** (typical simulation parameters)

$$\lambda = 1nm, a_0 = 4, \sigma_L = 5nm, \tau_L = 3nm/c$$

$$n_{tube} = 5\times10^{24}/cm^3, \sigma_{tube} = 2.5nm$$

Wakefield comparison between the cases of a tube and a uniform density

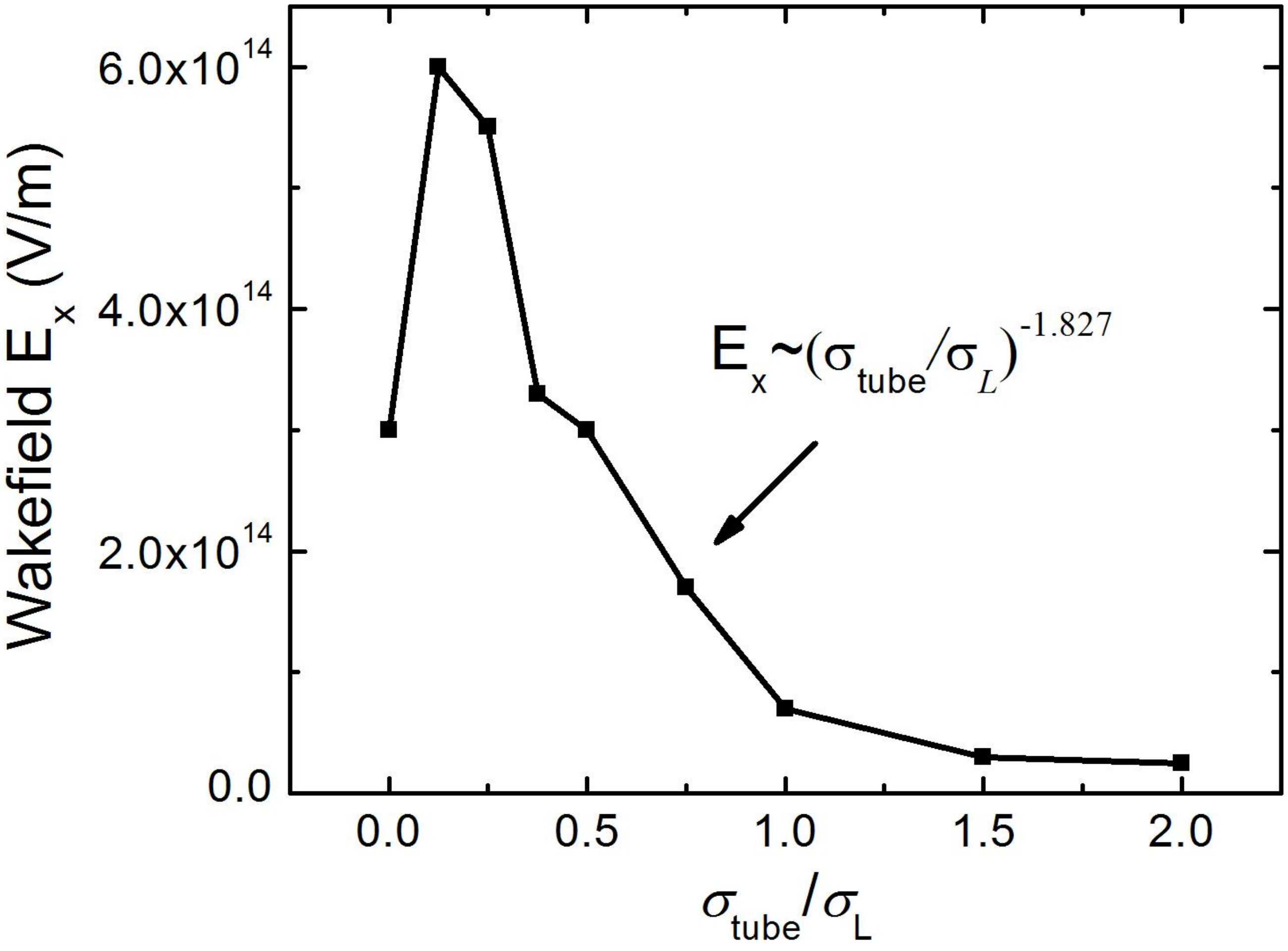


tube case

uniform density case

X. M. Zhang, et al. PR AB (2016)

Wakefields and the tube geometry

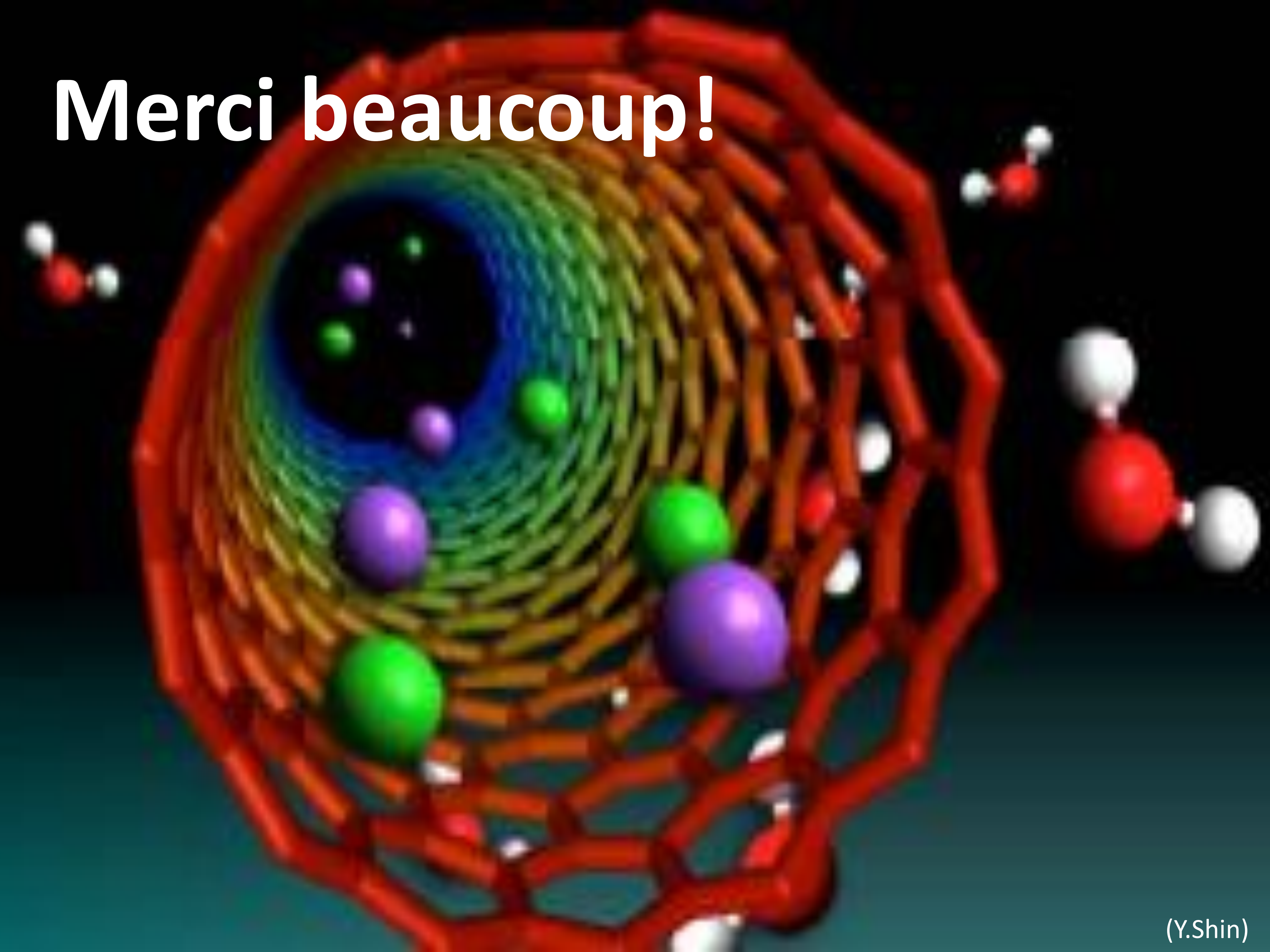


X. M. Zhang (2016)

conclusions

- Laser wakefield accelerators with CAN→ a **collider**
- Fiber laser revolution: High reprate, high efficiency---collab with CERN---**γγ collider**
- Further innovation in laser with TFC : single-cycled laser's promise—New technological window
- Efficient proton acceleration: **isotope production, ADS**
- Single-cycled X-ray laser --→ "**TeV on a chip**"

Merci beaucoup!



(Y.Shin)