X-ray Wakefield Accelerator on a Chip

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abstract

New technology thin film compression (TFC) [and coherent amplification network (CAN)] →

Leading to a new innovation X-ray LWFA (and single-cycled laser acceleration of ions)

1. Introduction to wakefield, relativistic coherence, and Tsunami
2. Toward high repreate and high efficiency fiber laser (CAN)
3. Single-cycled laser by TFC (Thin Film Compression) and further compression by relativistic compression
4. “TeV on a chip” (X-ray LWFA); coherent γ-ray laser, zeptosecond science
5. Compact ion acceleration (short-lived isotope generation, ADS)
Introduction to Wakefield
Laser Wakefield (LWFA):

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

Tsunami phase velocity becomes $\sim 0$, causes **wavebreak** and **turbulence**

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = \frac{m_0 v_{ph}}{e}$

No wave breaks and wake **peaks** at $v = c$

Wave **breaks** at $v < c$

**Relativistic coherence** enhances beyond the Tajima-Dawson field $E = \frac{m_0 c}{e}$ (~ 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 stable state ← no particles to resonate (@ c)

= plasma’s elevated Higgs state

| 0 > vs. | H >

thermo-equilibrium wakefield state tsunami onshore
Theory of \textbf{wakefield} toward extreme energy

\[ \Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right), \]  
\text{(when 1D theory applies)}

In order to avoid wavebreak, \[ a_0 < \gamma_{ph}^{1/2}, \]

where \[ \gamma_{ph} = \left(\frac{n_{cr}}{n_e}\right)^{1/2} \]

\[ n_{cr} = 10^{21} \]
\[ n_e = 10^{16} \]

\[ L_d = \frac{2}{\pi} \lambda_p a_0^2 \left(\frac{n_{cr}}{n_e}\right), \quad L_p = \frac{1}{3\pi} \lambda_p a_0 \left(\frac{n_{cr}}{n_e}\right), \]

dehasing length \quad pump depletion length
LWFA and CAN laser
IZEST 100 GeV Ascent Collaboration: Design by Prof. Nakajima

Energy gain VS Plasma density

- **PETAL design**
- **3D PIC simulation**
- **Experimental data**

- **BELLA-LBNL**
- **CoReLS-IBS**
- **TEXAS**
- **LBNL**
- **SIOM**
- **CAEP**
- **RAL**
- **LLNL**
- **MPQ**

- **n_e = 7 \times 10^{17} \text{ cm}^{-3}**
- **L_{\text{acc}} = 7 \text{ m}**

- **n_e = 3 \times 10^{15} \text{ cm}^{-3}**
- **L_{\text{acc}} = 245 \text{ m}**

- **n_e = 1.2 \times 10^{16} \text{ cm}^{-3}**
- **L_{\text{acc}} = 12 \text{ m}**

- **n_e = 3 \times 10^{16} \text{ cm}^{-3}**
- **L_{\text{acc}} = 5 \text{ m}**

- **1 TeV**

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**Experimental data**

**PETAL design**

**3D PIC simulation**

**Experimental data**
Method 1

Ablative Discharge Plasma Waveguide-Meter Module

IGNITION LASER PULSE
10 ns, 30 mJ

Nd:YAG Laser
10 cm x 10 segments = 100 cm

Capillary radius

\[ R_c[\text{mm}] \approx \left( \frac{2 \times 10^{16}}{n_e[\text{cm}^{-3}]} \right)^{1/3.2} \]

Discharge HV power supply
40 kV

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)

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<th>FEL (XUV)</th>
<th>Gamma-rays</th>
<th>FEL (X-rays)</th>
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✓: OK as is
↑: increase needed
↓: decrease needed
Coherent Amplification Network

Need to Phase

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

High rep-rated, efficient, digital control possible


Electron/positron beam

Transport fibers

~70cm

Length of a fiber ~2m Total fiber length~ 5 x 10^4 km
J. Bourderionnet, A. Brignon (Thales), C. Bellanger, J. Primot (ONERA)

**Coherent Fiber Combining**

1W PM EDFAs

1×2 splitters

1×16 splitters

16 × 4-channels PLZT phase modulators

Phase processing and feedback loop

2:1 image relay

QWLSI

lenslet array

fiber array

laser output

far-field observation

Laser diode 1.55µm

1W PM EDFA

polar. controller

Achievement 2011

→ 64 phase-locked fibers

→ XCAN project
Thin Film Compression and Relativistic Compression: ion accelerator as a short-term application
Single-cycle laser (new Thin Film Compression)

Laser power = energy / pulse length

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

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

F. Dollar, D. Farinella, T. Nguyen, TT
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 $\sigma$

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

Mourou et al. (2014)
Ultrarelativistic Mirror in the $\lambda^3$-laser Regime
(second step)

$\gamma = 10^3$
$\tau$  Pulse $\sim$ few zs
Pulse Power $\sim$ EW
Wavelength $\sim$ keV

Single Cycle Thin Film Compressor
10PW, 2fs, 100J, 1$\mu$m$^2$
Intensity $\sim 10^{25}$W/cm$^2$

Critical Surface Moving at $v \sim c$
$\gamma = 10^3$

Relativistic Compression
Even, isolated zeptosecond X-ray laser pulse possible
(simulation by N. Naumova, et al., 2014)

1PW optical laser $\rightarrow$ 10PW single osc. Optical laser $\rightarrow$ EW single osc. X-ray laser

Consistent with “Intensity-pulse-width Conjecture” (Mourou-Tajima, Science 331 (2011))
Brilliance of our Single Cycled X-ray Laser (SCXL)

SCXL added to T.J. Wang / R. X. Li (2016)
X-ray LWFA in Nanostructure

Tajima, EPJ 223 (2014)
Earlier works of X-ray crystal acceleration

- X-ray optics and fields (Tajima et al. PRL, 1987)
- Nanocrystal hole for particle propagation (Newberger, Tajima, et al. 1989, AAC; PR, ...)
- Particle transport in the crystal (Tajima et al. 1990, PA)

APPLICATION OF NOVEL MATERIAL IN CRYSTAL ACCELERATOR CONCEPTS

B. Newberger, T. Tajima, The University of Texas at Austin, Austin, Texas 78712
F. R. Huson, W. W. Mackay, Texas Accelerator Center, The Woodlands, Texas
B. C. Covington, J. R. Payne, Z. G. Zou, Sam Houston State University, Huntsville, Texas
N. K. Mahale, S. Ohnuma, University of Houston, Houston, Texas 77004

...which incorporate regular macroscopic features on the underlying crystal lattice are of potential application to crystal accelerators and coherent x-rays. We have recently begun an investigation of x-ray porous Si, in which pores of radii up to a lattice spacing are etched through thick x-volumes crystal. The potential reduction of losses to particu-
late-mented along the pores makes this a very material in crystal accelerators for relativistic, positive-charge particles. Our results on material properties which are...this context will be presented. The consequences transport will be discussed.

$D = \frac{\pi r_e^2 N Z_{\text{eff}} (m_e/m)^2}{\mu}$

where $r_e$ is the classical electron radius, $Z_{\text{eff}}$ is the effective atomic number, and $N$ is the number density of particles. Logarithmic dependencies on particle energy are neglected throughout. $L_n$ is a constant with a to...

Additional text on the effects of crystal accelerators, including the propagation of particles in x-ray fields, and the implications for future experiments in high-energy physics. Further discussion of the potential application of these techniques to particle transport and acceleration in x-ray crystal accelerators.
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);
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\textsuperscript{1,2}, A. H. Lumpkin\textsuperscript{2}, J. C. Thangaraj\textsuperscript{2}, R. M. Thurman-Keup\textsuperscript{2}, P. Piot\textsuperscript{1,2}, and V. Shiltsev\textsuperscript{2}

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

\textsuperscript{1} Northern Illinois Center for Accelerator and Detector Development (NICADD), Department of Physics, Northern Illinois University

\textsuperscript{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:**
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)

\[
\lambda = 1 \text{nm}, a_0 = 4, \sigma_L = 5 \text{nm}, \tau_L = 3 \text{nm} / c
\]

\[
n_{\text{tube}} = 5 \times 10^{24} / \text{cm}^3, \sigma_{\text{tube}} = 2.5 \text{nm}
\]
Wakefield comparison between the cases of a tube and a uniform density

X. M. Zhang
PIC simulation of X-ray wakefields in a nanomaterial tube: Density scaling

Photon energy = 1keV, tube radius = 5nm, $a_0=4$, a few-cycled laser (around $n_{cr}/n = 200$)

![Graph showing the relationship between wakefield $E_x$ and electron energy $E_e$ vs. tube density.](chart.png)

X. M. Zhnag (2016)
Wakefield scaling to the X-ray laser amplitude

\[ E_x \sim a_0^{1.875} \]

\[ E_e \sim a_0^{1.45} \]

X. M. Zhnag (2016)
Wakefields and the tube geometry

\[ E_x \sim \left( \frac{\sigma_{\text{tube}}}{\sigma_L} \right)^{-1.827} \]
With and without **optical phonon branch**

Model of optical phonon branch: *T. Tajima and S. Ushioda, PR B (1978)*

Without lattice force (i.e. plasma)
(when $\omega_{TO}$ is much smaller than $\omega_{pe}$, there is no noticeable difference from the below where $\omega_{TO} = 0$)

With lattice force (optical phonon branch present)

\[
\epsilon = 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{\Omega_p^2}{\omega^2 - \omega_{TO}^2}
\]

\[
\frac{\omega_{TO}}{\omega_{pe}} \approx 0.75 \quad \frac{\Omega_p}{\omega_{pe}} \approx \frac{1}{43}
\]

S. Hakimi, et al. (2017)

→ nanoplasmonics in X-ray regime
Wakefield on a chip
toward TeV over cm (beam-driven)
Conclusions

• A new direction of ultrahigh intensity: **zeptosecond lasers**
• **EW 10keV X-rays laser** from 1PW optical laser
• Single-cycled optical laser → More efficient and more coherent acceleration of ions
• Single-cycled X-ray laser pulse (relativistic compression)
• **X-ray LWFA in crystal**: accelerating gradient 1-10TeV/cm, accelerating length 1-10m, energy gain per stage PeV; **mini-accelerators** (mm-m; portable) for GeV, TeV, PeV (and beyond)
• **Crystal nanoengineering**: s.a. nanoholes, arrays, focus nano-optics for nano-accelerator
• **Zeptosecond nano-beams** of electrons, protons (ions), muons, coherent γ-rays to very high energies: new tools for nuclear science
• PIC (w/QED) simulation shows support of the X-ray wakefields
• Start of zeptoscience: ELI-NP zeptoproject (collaboration)---laser tools fit for nuclear phys. (←→ attoseconds for atoms)
• **Scales revolution**: eV→keV; PW→EW; as→zs; μm→nm; GeV/cm→TeV/cm; 100m→cm; μ-beam→nanobeam; $10^{18}$/cc → $10^{24}$/cc
Thank you!

(Y.Shin)