“TeV on a Chip”: A New Perspective of Wakefield Acceleration

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1. New compression of laser

2. Nanometric wakefield accelerator driven by X-ray laser = “TeV on a Chip”

3. Nanotube driven by e-beam

4. e-beam modulation and XFEL in nanotube

5. Astrophysical wakefields

6. Nanotube wakefield cancer therapy
Motivation:

1. Invention of **Thin Film Compression** (TFC, 2013) opened up **Laser Wakefield Acceleration** (LWFA, 1979) in X-ray regime,

\[ E_{TD} = m \omega_{pe} \frac{c}{e}; \quad \Delta \varepsilon = 2mc^2 a_0^2 \left( \frac{n_{cr}}{n} \right) \]

compactifying further by $10^3$ over the gas plasma LWFA

2. X-ray frequency exceeds the nanomaterial’s plasma frequency $\omega_{pe}$

→ carbon-nanotubes

higher than 10TV/m wakefield (2014)

→ Explore X-ray wakefield accelerator in nanotube = “TeV on a Chip”
Plasma (nanomaterial) accelerator driven by beam/pulse

Collective force $\sim N^2$ (nonlinear $\leftrightarrow$ linear force $\sim N$)
Coherent and smooth structure (not stochastic)

Plasma (nanomatter) accelerator driven by laser (coherent photons)

compactification by $10^3 - 10^4$ (now even by $10^6$) $>>$ conventional accelerators
enabled by laser technology (laser compression (Mourou et al.1985))
Laser Wakefield (LWFA):

Wake phase velocity $\gg$ 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: $E = m\omega v_{ph}/e$

No wave breaks and wake peaks at $v \approx c$

Wave breaks at $v < c$

Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c/e$ ($\sim \text{GeV/cm}$)
At ICTP Summer School (1981), Prof. Salam summoned me and discussed about laser wakefield acceleration.

Salam: ‘Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged’. (1981)

He organized the Oxford Workshop on laser wakefield accelerator in 1982.

Effort: many scientists over many years to realize his vision / dream
High field science: spawned

(NB: Prof. C. Rubbia et al. discovered his bosons at CERN, 1983)
Enabling technology: **laser revolution**

G. Mourou invented **Chirped Pulse Amplification** (1985)

**Laser** intensity exponentiated since, to match the required intensity for Tajima-Dawson’s **LWFA** (1979)
Laser-driven Bow and Wake

Density: $n_e = 1.14 \times 10^{18} \text{ cm}^{-3}$

Wakefield acceleration

(Bulanov, Esirkepov)

Wake Wave

Bow Wave

Ponderomotive acceleration
Theory of **wakefield** toward extreme energy

\[ \Delta E \approx 2 m_0 c^2 a_0^2 \gamma_{ph}^2 = 2 m_0 c^2 a_0^2 \left( \frac{n_{cr}}{n_e} \right), \tag{when 1D theory applies} \]

In order to avoid wavebreak,

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

where

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

\[ n_{cr} = 10^{21} / \text{cc} \text{ (1eV photon)} \]

\[ 10^{29} \text{ (10keV photon)} \]

\[ n_e = 10^{16} \text{ (gas)} \rightarrow 10^{23} / \text{cc (solid)} \]

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

dephasing length

pump depletion length
CAN Laser:
Need to Phase
32 J/1mJ/fiber~ $3 \times 10^4$ Phased Fibers!

Electron/positron beam
Transport fibers

Mourou, Brockesby, Tajima, Limpert (2013)

~70cm

Length of a fiber ~2m Total fiber length~ $5 \times 10^4$km
Thin Film Compression

Mourou G, et al., 2014
Single-cycled laser and “TeV on a chip”
Next Generation X-ray Lasers
(on Thin Film Compression)

Earlier works of X-ray crystal acceleration

-X-ray optics and fields (Tajima et al., 1987)
-particle transport in the crystal (Tajima et al. 1990)

APPLICATION OF NOVEL MATERIAL IN CRYSTAL ACCELERATOR CONCEPTS

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which incorporate regular macroscopic features on the underlying crystal lattice are of potential application to crystal accelerators and coherent sources. We have recently begun an investigation of partial holes in which the periodic structure is etched through finite volumes of crystal. The potential reduction of losses to partially etched crystals makes this a very interesting approach to crystal accelerators for relativistic charged particles. Our results on material properties which are the subject of this paper will be presented. The consequences of transport will be discussed.

and \( k = \frac{m_0}{2m_N} \), is the “spring constant of the channel well. Its specific form depends on the size of the channel potential and the string of atomic purposes it suffices to take a typical value of \( 2 \times 10^4 \) is the multiple scattering velocity space “diffusion” We have used \( D = z^2 e_N Z_{\text{mol}} \left( \frac{m_e}{m_N} \right)^2 L_n \), where \( e_N \) is the classical electron radius, \( Z_{\text{mol}} \) is the number density of valence electrons, and \( N \) is the number density of atoms. Logarithmic dependencies on particle energy detection throughout: \( I \) is a constant with a value

Beam Transport in the Crystal X-ray Accelerator

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Abstract A Fokker-Planck model of charged particle transport in crystal channels which includes the effect of strong accelerating gradients has been developed\(^1\) for application to...
Why Nanotubes

- High density ↔ Higher acceleration gradient (~ TeV / cm)
- Provides external structure to guide laser and electron beam
- No slowdown of electrons by collisions
- Intact for time of ionization (fs)

(b) Lazarowich RJ, Taborek P, Yoo BY, Myung NV. 2007
X-ray LWFA in a tube vs. uniform solid

A few-cycled 1keV X-ray pulse ($a_0 \sim O(1)$), causing 10TeV/m wakefield in the tube more strongly confined in the tube cf: uniform solid

X. Zhang (2016)
Ion lattice modes (s.a. polaritons) Included*):

basically all actions via plasmons

(S. Hakimi et al., 2019)

\[
\epsilon(k, \omega) = 1 - \frac{\omega_{pi}^2}{\omega^2 - \omega_{D}^2} - \frac{\omega_{pe}^2}{\omega^2 - k_z^2 v_e^2} \cdot 1
\]

(Tajima and Ushioda, 1978)
Effects of Optical Phonons

without optical phonon

with optical phonon

Hakimi S, et al. 2018
X-ray in nanotube ↔ optical laser in mm plasma guide

Acceleration process are self-similar: X-ray in micron (short), while optical laser in mm (longer)

But beam emittance and betatron radiation: quite different (not self-similar)

Distributions of (a)(b) wakefield and (c)(d) electron energy induced by (a)(c) the X-ray laser pulse and (b)(d) optical laser in a tube when $a_0=10$
(a)(b) Photon energy distributions and (c)(d) photon energy spectrum in the (a)(c)X-ray driven case and (b)(d) 1eV optical laser driven case in a tube.
(a) The space distribution \((x, y)\) and (b) the transverse phase space \((y, p_y/p_x)\)
Wakefield strength: tube size, wall density, laser intensity

\( E_x \sim (\sigma_{\text{tube}}/\sigma_L)^{-1.827} \)

\( E_x \sim a_0^{1.875} \)
Nanotube $\leftrightarrow \rightarrow$ no hole

Nanotube (5 nm radius)  
No nanotube

Zhang X, Tajima T, Farinella et al., PRAB, 2016
Nanotube $\leftrightarrow$ No tube

Zhang X, 2016
Fermi’s PeV Accelerator

Now

TeV on a chip $\rightarrow$ PeV over 10m $\rightarrow$ check superstring theory?
Beam-driven nanotube wakefields: accelerator X-ray FEL in gamma-ray regime
E-Beam driven case

Multi channeled nanotubes

Beam-driven wakefield

(A. Sahai, 2020)
E-beam driven wakefield in nanotube

A. Sahai, (2020) supported by U. Colorado at Denver, Boulder RMACC
Strong self-focus and self-modulation of electron beam in nanotube

A. Sahai, 2020 (supported by UC Denver, Boulder RMAAC)
Nature’s wakefield accelerator in cosmos
Ultrahigh Energy Cosmic Rays (UHECR)

Fermi mechanism runs out of steam beyond $10^{19}$ eV due to synchrotron radiation. Wakefield acceleration comes in rescue prompt, intense, linear acceleration. small synchrotron radiation radiation damping effects?
Cen A

- Distance: 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets
Discovery of Blackhole and Prediction

M87 blackhole: by Event Horizon Telescope (2019)

Prediction: Tajima and Shibata “Plasma Astrophysics” (1997)
Nature’s LWFA: Blazar jets
- extreme high energy cosmic rays ($\sim 10^{21}$ eV)
- episodic $\gamma$-ray bursts observed consistent with LWFA theory

Ebisuzaki-Tajima (2014)

Fermi’s ‘Stochastic Acceleration’
(large synchrotron radiation loss)

↓

Coherent wakefield acceleration
(no limitation of the energy)
Astrophysical **wakefield** acceleration: Superintense **Alfvén Shock** in the Blackhole Accretion Disk toward ZeV Cosmic Rays \(a_0 \sim 10^6 - 10^{10}, \text{large spatial scale}\)

\[a_0 = \frac{eE_0}{mc\omega_0} \gg 1\]

\(E_0: \text{modest}\)
\(\omega_0: \text{extremely small}\)

Ebisuzaki and Tajima, Astropart. Phys.(2014)
Comic ray acceleration and $\gamma$-ray emission: Summary

\[ \log (L_{\text{tot}} / \text{erg s}^{-1}) \text{ vs. } \log m \]

- $W_{\text{max}} = 10^{24}$ eV
- $W_{\text{max}} = 10^{20}$ eV
- $W_{\text{max}} = 10^{16}$ eV
- $W_{\text{max}} = 10^{12}$ eV

Ebisuzaki, Tajima
EPJ 223, 1113(2014)
Blazar shows anti-correlation between $\gamma$ burst flux and spectral index

Blazar: A00235+164
$M \sim 10^8 M_{\text{Sun}}$

Rise time < week (less than a unit),
Period between bursts $\sim > 10$ weeks
Spectral index $\Rightarrow 2$
($\sim$ Ebisuzaki/Tajima theory)

$\Rightarrow$ all quantitatively consistent with Wakefield theory

N. Canac, K. Abazajian (2019)
Again, Anti-correlation even in a bigger blazar

Blazar: 3C454.3
$M \sim 10^9 M_{\text{Sun}}$

Same anti-correlation as AO0235+164

The rise time and burst periods a lot longer (by an order of magnitude)

Quantitative agreement and correct scaling with Blazar mass with (broader sense of) Wakefield theory (Ebisuzaki/Tajima) period $\sim M$; luminosity $\sim M$

N. Canac, K. Abazajian (2019)
Nanotube cancer therapy
High density **wakefields** for medicine

- **Micron accelerator** (in body?) by **optical laser**
- **Nanomaterials** target: density $\sim 10^{21} \text{ cm}^{-3}$

**Critical density wakefield acceleration** ($< \text{MeV}$) : e.g. skin cancer

Nicks et al. (2019)
Beatwave wakefield acceleration of electron acceleration in low intensity laser

- Two laser pulses, each $a_0 = 0.03$
- $a_0 = 0.03 \rightarrow 1.2 \times 10^{15} \text{ W/cm}^2$
- Wavelength: $\lambda_0 = 1 \mu\text{m}$
- $\omega_1 = \omega_0 + \omega_p/2$, $\omega_2 = \omega_0 - \omega_p/2$
- Pulse length: $\approx 300 \text{ fs}$

\[ \text{Tajima-Dawson (1979)} \]

Very low intensity laser with nanotubes $\rightarrow$ no vacuum necessary

S. Nicks, et al. (2020)
Conclusions

• **1994-LWFA** Demonstrated: **ultrafast** pulses, **coherent collective** (robust) **intense** (GeV/cm) accelerators.
• **TFC → Single-cycled laser → single-cycled X-ray laser** (also high density e-bunch)
• **Wakefield in nanostructure** (TeV/cm): **TeV on a chip accessible**
• Toward PeV (~10-100m)
• **Wakefields**: Nature’s favored acceleration for UHECR, **gamma ray** bursts from Blazars
• Applications: tiny **LWFA** radiotherapy of cancer

* Book: “Beam Acceleration in Crystals and Nanostructures” (WSP, 2020)
Recent advancements in generation of intense X-ray laser ultrashort pulses open opportunities for particle acceleration in solid-state plasmas. Wakefield acceleration in crystals or carbon nanotubes shows promise of unmatched ultra-high accelerating gradients and possibility to shape the future of high energy physics colliders. This book summarizes the discussions of the “Workshop on Beam Acceleration in Crystals and Nanostructures” (Fermilab, June 24–25, 2019), presents next steps in theory and modeling and outlines major physics and technology challenges toward proof-of-principle demonstration experiments.

Thank you!

“Accelerator
Unprecedented and huge
Curious baby
Embraced by Mother Mountain
Where’s her beautiful white coat?”
(Toshiki, Geneva, Feb. 13, 2020)