Fiber Accelerator: TVm^{-1} Crunch-in Wakefields

(Nanometric Wakefield Accelerator)

Aakash Sahai

Collaborators: Toshiki Tajima, Vladimir Shiltsev, Peter Taborek, Gerard Mourou

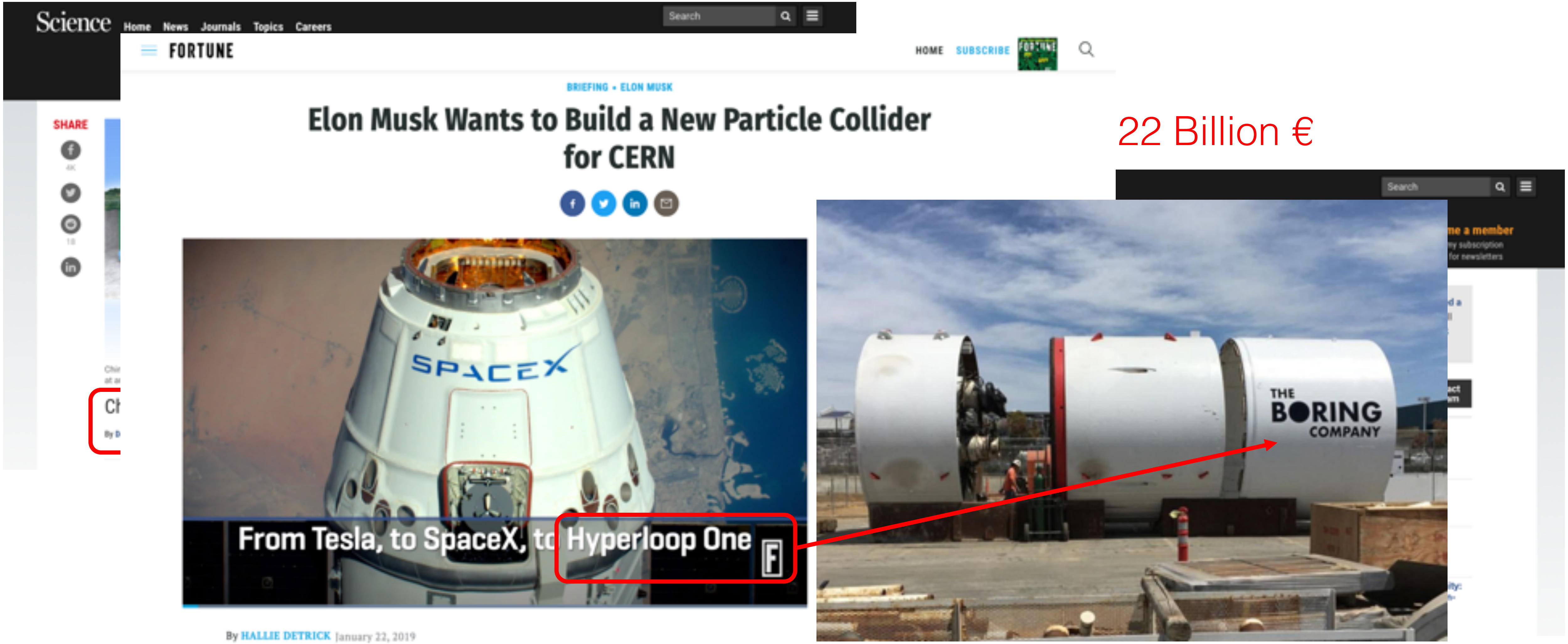
University of Colorado Denver

Fermilab

Outline

- Background & Motivation
- Nanometric **"crunch-in"** surface wave model
- 3D computational proof-of-principle - GeV in mm
- Nanometric beam envelope oscillations – O(100MeV) photons
- Conclusion & Future work

current RF Acc. workhorse of HEP



22 Billion €

CPA laser electron accelerator

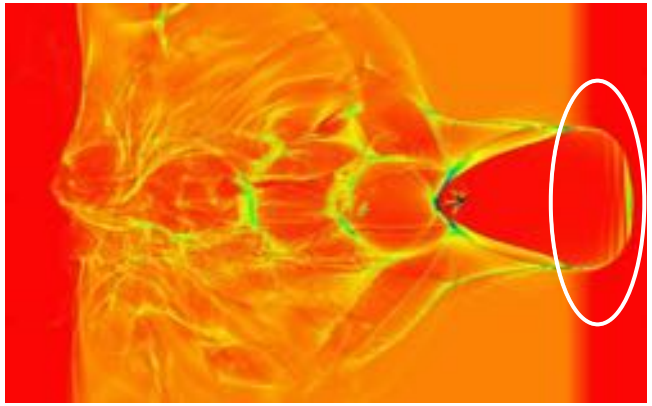
Giant strides in Laser Wake-Field Acceleration (LWFA) of electron beams

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024



electron density of strongly nonlinear LWFA

Laser-Plasma Collider effort

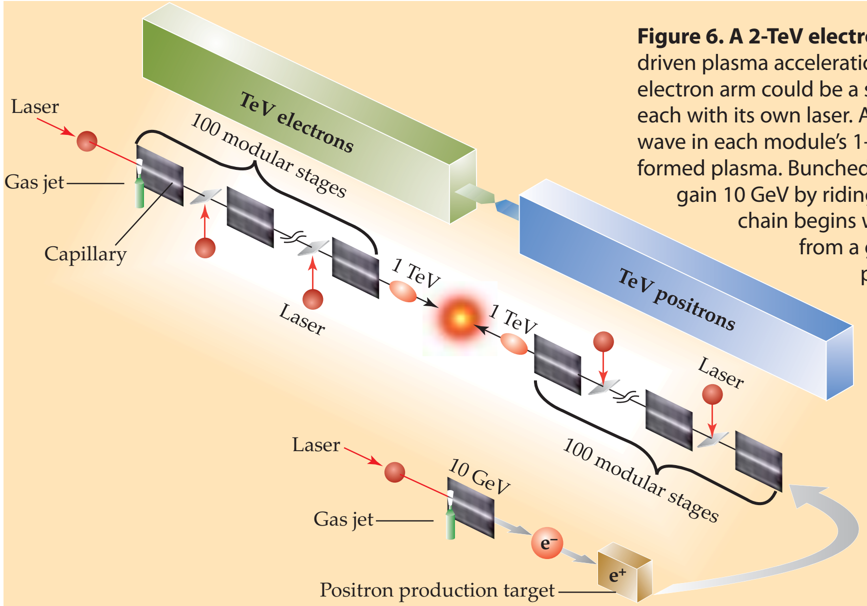


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

Laser-driven plasma-wave electron accelerators
Wim Leemans and Eric Esarey
Citation: Phys. Today **62**(3), 44 (2009); doi: 10.1063/1.3099645
View online: http://dx.doi.org/10.1063/1.3099645

Nanostructures electron dynamics

Proposed Solid-state plasma

Gaseous Plasma

electron density, $n_0 < 10^{21}$ cm^{-3}
(ionization required)

No Breakdown

Density - easier to control

Structure – quite difficult

Nanostructured "plasma"

$n_0 > 10^{21}$ cm^{-3}

now nanofabrication allows
tunable properties
nanostructured solids (*few atom layers*)

CB Fermi e^- gas: plasmon, surface plasmon, SP-polariton etc.

free e^- : nonlinear & relativistic collective oscillations

Time & Spatial scales

$$\omega_{pe}^{-1} = [4\pi n_0 e^2 m_e^{-1}]^{-1/2}$$

$$\lambda_{pe} = 2\pi c \omega_{pe}^{-1}$$

Gaseous Plasma

time scale :

$17.7(n_0[10^{18}\text{cm}^{-3}])^{-1/2}$ femtoseconds

spatial scale :

$33.3(n_0[10^{18}\text{cm}^{-3}])^{-1/2}$ μm

CPA laser & phase-space gym
made possible wakefield excitation

Solid-state Plasma

time scale :

$177(n_0[10^{22}\text{cm}^{-3}])^{-1/2}$ attoseconds

spatial scale :

$333(n_0[10^{22}\text{cm}^{-3}])^{-1/2}$ nm

now experimentally realizable

Energy density

Tajima-Dawson limit
(or) Wavebreaking limit

$$E_{wb} = \frac{m_e c \omega_{pe}}{e}$$

Energy density of collective oscillations

$$\tilde{\mathcal{E}} = \frac{E_{wb}^2}{8\pi}$$

ultrashort laser pulse

energy density of ultrashort (σ_r , $\sigma_z \sim \lambda_{pe}$) laser pulse

$$\tilde{\mathcal{E}} = \frac{I}{2c}$$

$$\tilde{\mathcal{E}} = \frac{N_p \mathrm{E}_p}{(2\pi)^{3/2}\ (2\pi c/\omega_{pe})^3}$$

relativistic particle beam

field of ultrashort (σ_r , $\sigma_z \sim \lambda_{pe}$) particle bunch

$$E_{\mathrm{beam}} = \frac{eN_b}{2\pi(2\pi c/\omega_{pe})^2}$$

energy density of particle bunch

$$\tilde{\mathcal{E}} = \frac{E_{\mathrm{beam}}^2}{8\pi}$$

minimum particle number

Gaseous Plasma

$$E_{wb} \simeq 96(n_0[10^{18}\mathrm{cm}^{-3}])^{1/2}\ \mathrm{GVm}^{-1}$$

Solid-state Plasma

$$E_{wb} \simeq 9.6(n_0[10^{22}\mathrm{cm}^{-3}])^{1/2}\ \mathrm{TVm}^{-1}$$

need relativistic momentum of oscillation

Energy density considerations:

10 Joule class optical lasers ($a_0 > 1$)

~ nC charge in 30 μm beam

Energy density considerations:

mJ class keV x-ray lasers ($a_0 > 1$)

~ 100pC charge in ~100 nm beam

need relativistic intensity drive bunch

CPA laser & phase-space gym
made possible **wave-breaking** fields

now experimentally realizable

Mourou's attosecond x-ray laser

RC Relativistic Compression

TFC Thin-film Compression

Fig. 5a. Interaction of few cycle pulse in the relativistic γ regime. It shows the shaped mirror created by the enormous light pressure. In this time scale only the electrons have the time to move. The ions are to slow to follow.

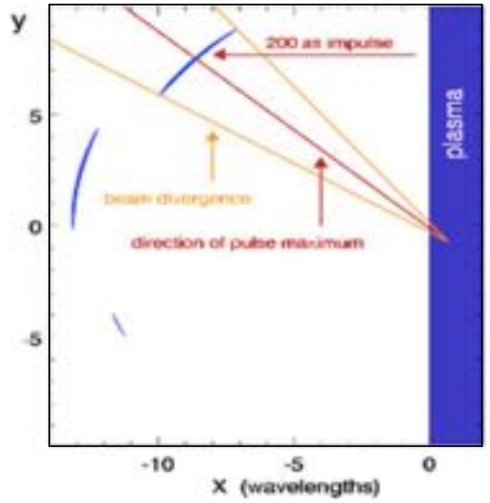
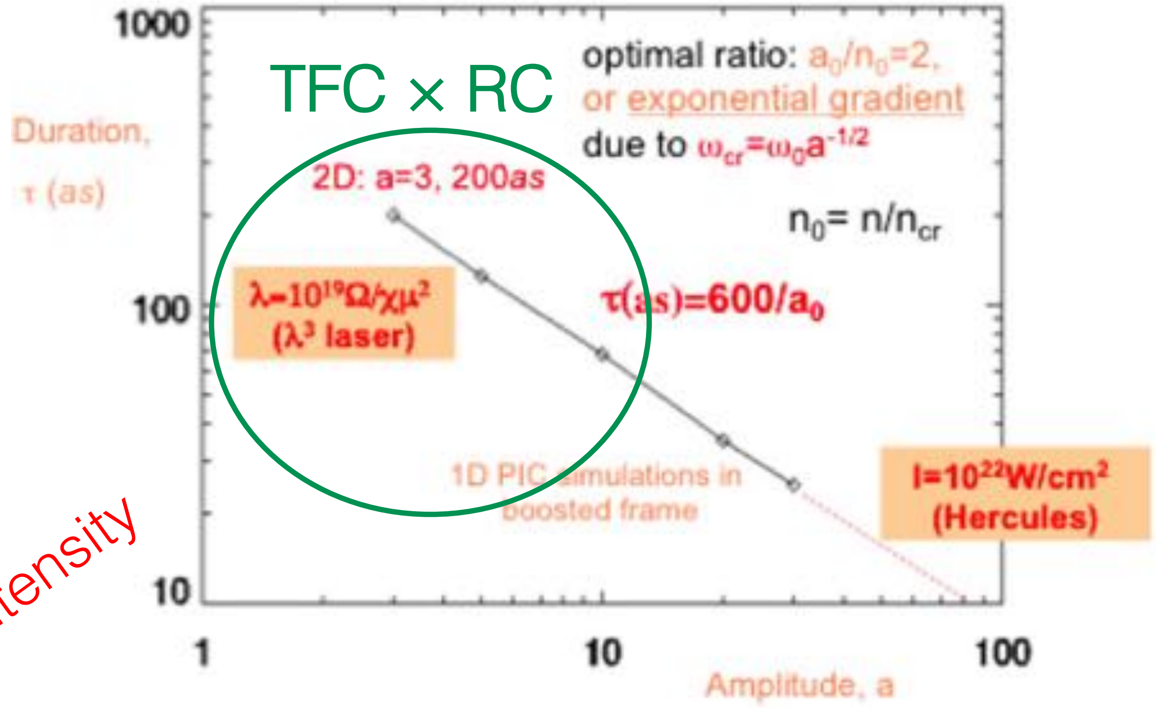


Fig. 5b. The reflection of an ultra relativistic pulse by a high Z target will broadcast the beam in specific way. The pulse is compressed by a factor proportional to a0. The pulses will be easily isolated.

Relativistic Intensity
x-ray laser



Eur. Phys. J. Special Topics **223**, 1181–1188 (2014)
© EDP Sciences, Springer-Verlag 2014
DOI: 10.1140/epjst/e2014-02171-5

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Naumova, N. M., Nees, J. A., Sokolov, I. V., Hou, B., Mourou, G. A., *Relativistic Generation of Isolated Attosecond Pulses in a λ^3 Focal Volume*, Phys. Rev. Lett. **92**, 063902 (2004)

Submicron near solid e⁻ bunch

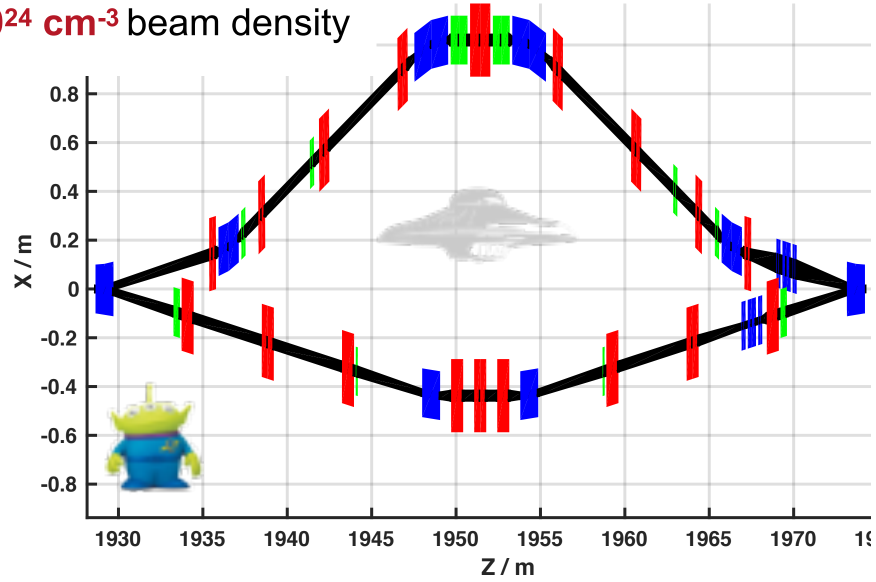
Phase-space gymnastics – 100nm compression - bunch length

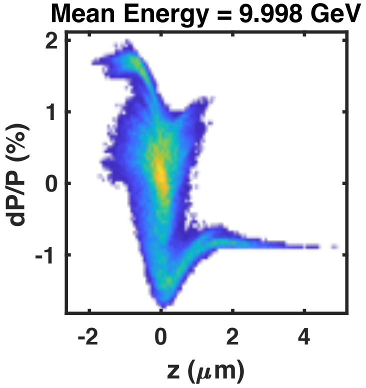
FACET-II Beam will Access New Regimes

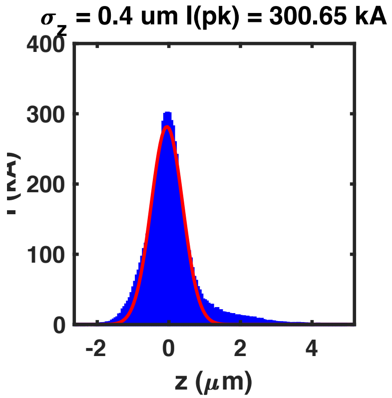
SLAC

Low-emittance (state of the art photoinjector) and ultra-short (improved compression) beam will generate:

- >300 kA peak current (~0.4 μm long)
- ~100 nm focus by plasma ion column
- **~10^{12} V/cm** radial electric field (Es=1.3x10^{16} V/cm)
- **~10^{24} cm^{-3}** beam density







V. Yakimenko, Workshop on Beam Acceleration in Crystals, June 24-25, 2019

13

Parameter	[Unit]	NPQED Collider	FACET-II	ILC	CLIC
Beam energy	[GeV]	125	10	250	1500
Bunch charge	[nC]	0.14–1.4	1.2	3.2	0.6
Peak current	[kA]	1700	300	1.3	12.1
Energy spread (rms)	[%]	0.1	0.85	0.12	0.34
Bunch length (rms)	[μm]	0.01–0.1	0.48	300	44
Bunch size (rms)	[μm]	0.01 0.01	3 2	0.47 0.006	0.045 0.001
Pulse rate ×	[Hz]×	100×	30×	5×	50×
Bunches/pulse	N_{bunch}	1	1	1312	312
Beamstrahlung	χ_{av}	969		0.06	5
Parameter	χ_{max}	1721		0.15	12
Disruption	$D_{x,y}$	0.001–0.1		0.3	0.15
Parameters		0.001–0.1		24.4	6.8
Peak electric field	[TV/m]	4500	3.2	0.2	2.7
Beam power	[MW]	0.002–0.02	10^{-4}	5	14
Luminosity	[cm^{-2} s^{-1}]	6×10^{30} -4×10^{32}		10^{34}	10^{34}

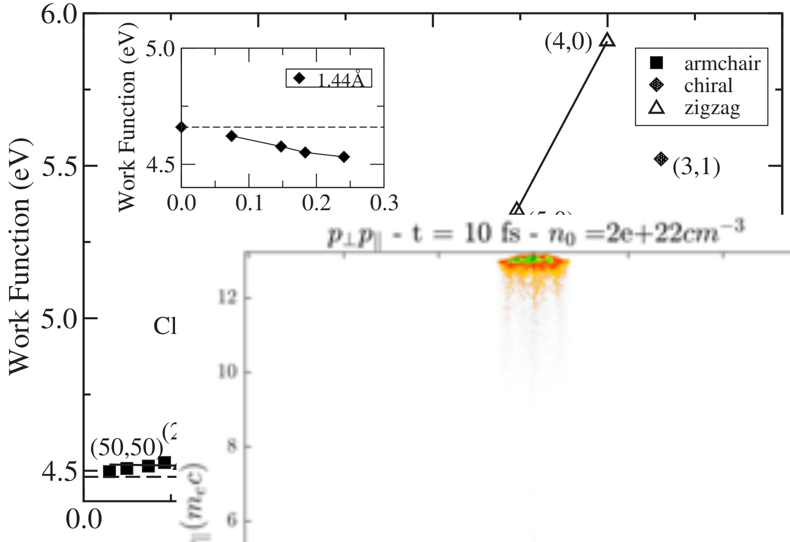
PHYSICAL REVIEW LETTERS **122,** 190404 (2019)

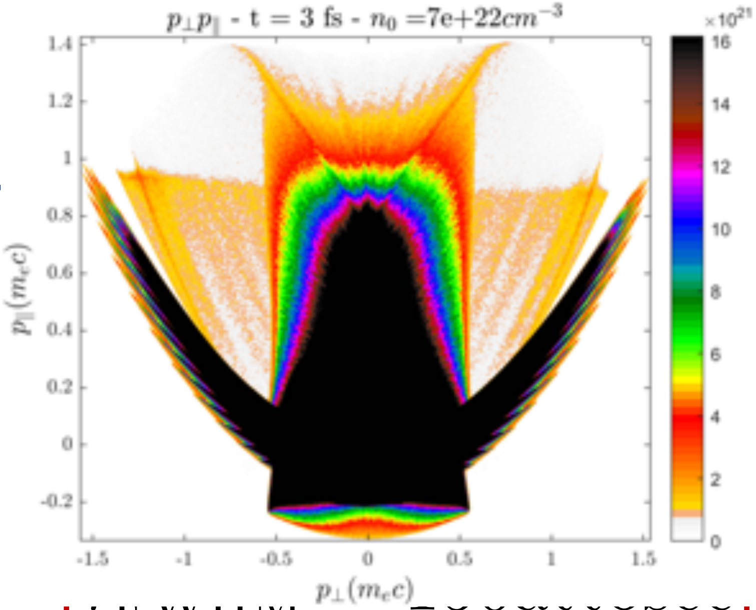
relativistic solid density electron “plasma”

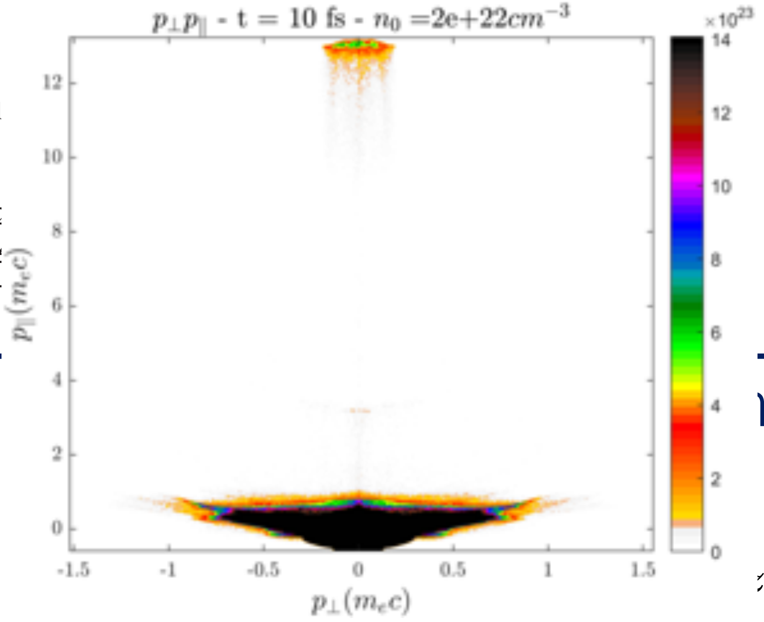
nanostructured tube

work function ~ 5eV

PHYSICAL REVIEW B **76**, 235413 (2007)







$\rightarrow a_0 \sim 3$

$E_{\text{beam}}(n_{b0}=$ … $= 400\text{nm})$

$\simeq 0.1\text{TV/m}$

$V_{\text{beam}}(\text{inter}-\text{atomic}) = E_{\text{beam}} \times 10\text{Å} = 100\text{V}$

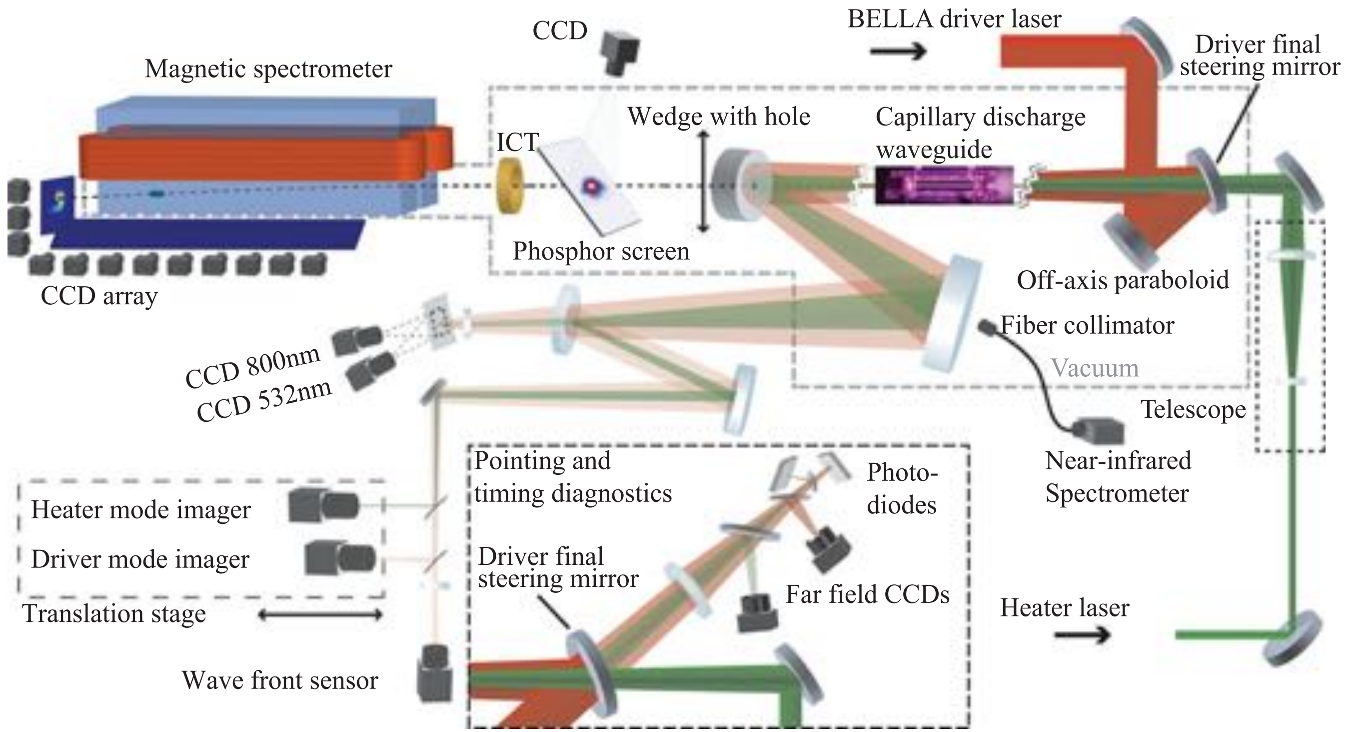
structured “plasma”

hollow gaseous fiber accelerator

D. C., Kurki-Suonio, T., Tajima, T., *Laser Self-Trapping for the Plasma Fiber Accelerator*, IEEE Transactions on Plasma Science, **15**, iss.2, April 1987

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide



- hollow tube in gaseous plasma
- guide & self-focus high-intensity laser pulse
- difficult to create such channels
- But, higher energies need good quality channels

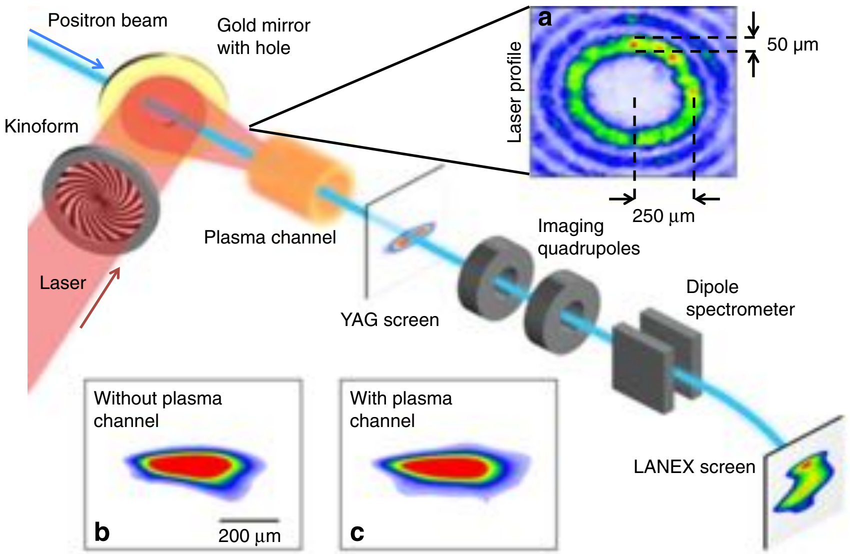
beam-driven hollow channel plasma

PURELY EM mode

nature COMMUNICATIONS

ARTICLE

Received 17 Nov 2015 | Accepted 27 Apr 2016 | Published 2 Jun 2016



un-ionized gas within the channel

e^+-beam -driven

$r_{ch} = 16\ c/\omega_{pe}$

$n_b = 1.3\ n_0$
$\sigma_z = 1.5\ c/\omega_{pe}$
$\sigma_r = 0.3\ c/\omega_{pe}$

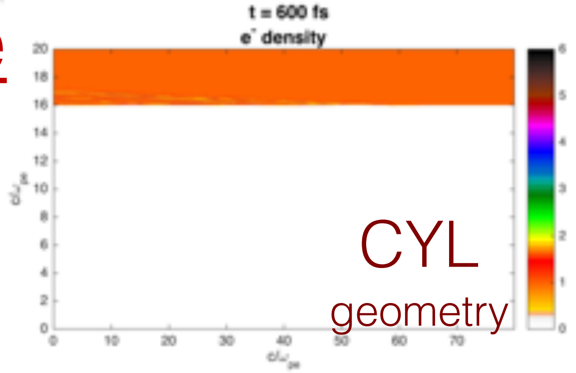
$\gamma_b = 1000$

NO focusing forces

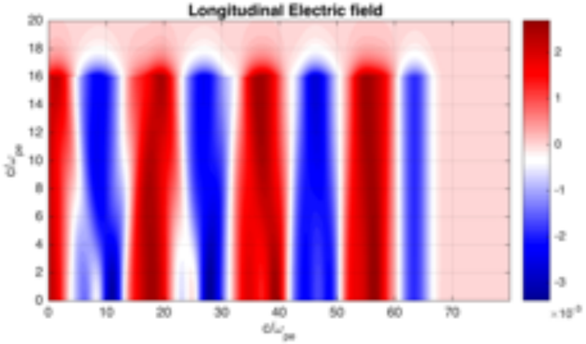
currents in the wall

EM acc. fields leak into the channel

$10^{-2}\ E_{WB}$



CYL geometry



$n_0 = 8 \times 10^{16}\ cm^{-3}$

obs. field = **220MV/m**

WB field ~ **20 GV/m**

nano-tubes – hollow crystal channels

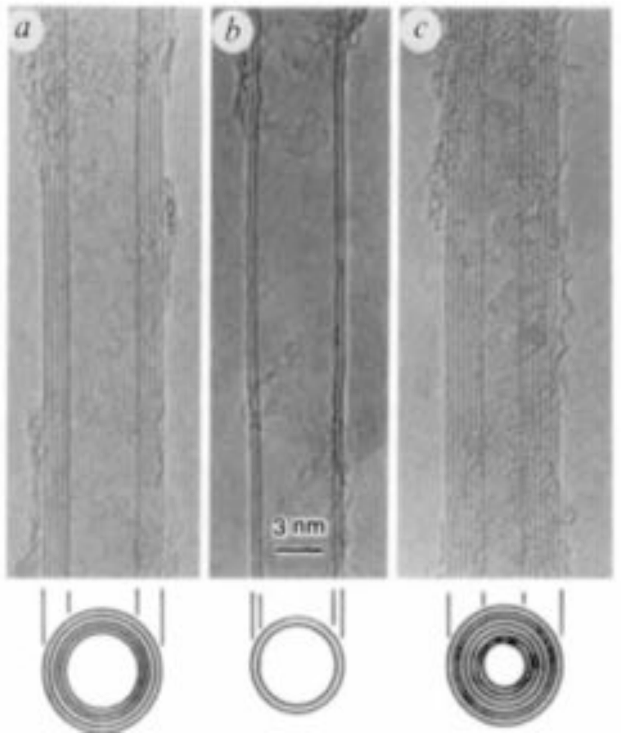


FIG. 1 Electron micrographs of microtubules of graphitic carbon. Parallel dark lines correspond to the (002) lattice images of graphite. A cross-section of each tubule is illustrated. *a*, Tube consisting of five graphitic sheets, diameter 6.7 nm. *b*, Two-sheet tube, diameter 5.5 nm. *c*, Seven-sheet tube, diameter 6.5 nm, which has the smallest hollow diameter (2.2 nm).

LETTERS TO NATURE

Helical microtubules of graphitic carbon

Sumio Iijima

NEC Corporation, Fundamental Research Laboratories, 34 Miyukigaoka, Tsukuba, Ibaraki 305, Japan

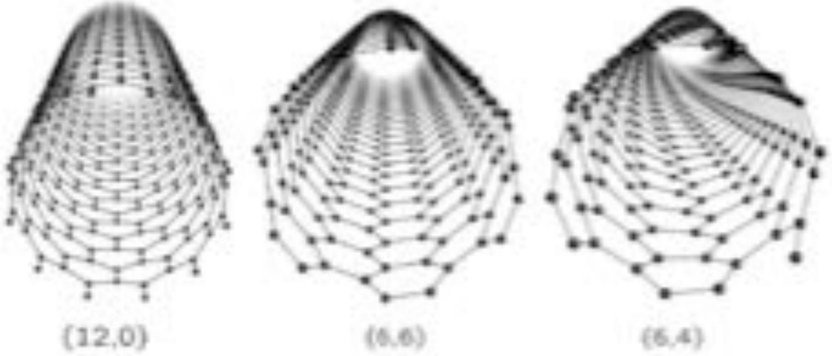
NATURE · VOL 354 · 7 NOVEMBER 1991

density ~ 10^{21} - 10^{22} cm^{-3}

$\lambda_{\mathrm{mfp}} \simeq \mu\ m$ collision-less e$^-$ over few ten fs

PRL **98,** 186808 (2007)

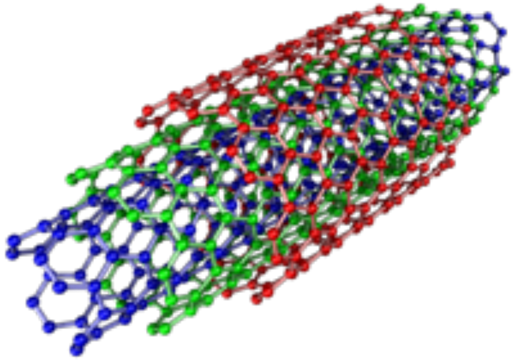
single-walled nanotubes (SWNT)



zigzag armchair chiral

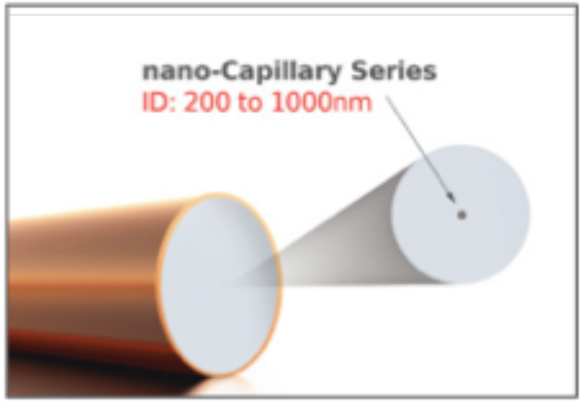
SWNT diameter – 0.3nm to 4nm

multi-walled nanotubes (MWNT)



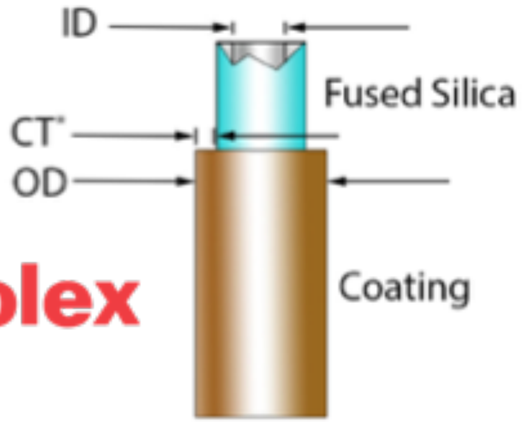
MWNT diameter – 1.5nm to 100nm

Commercial Silica Capillaries



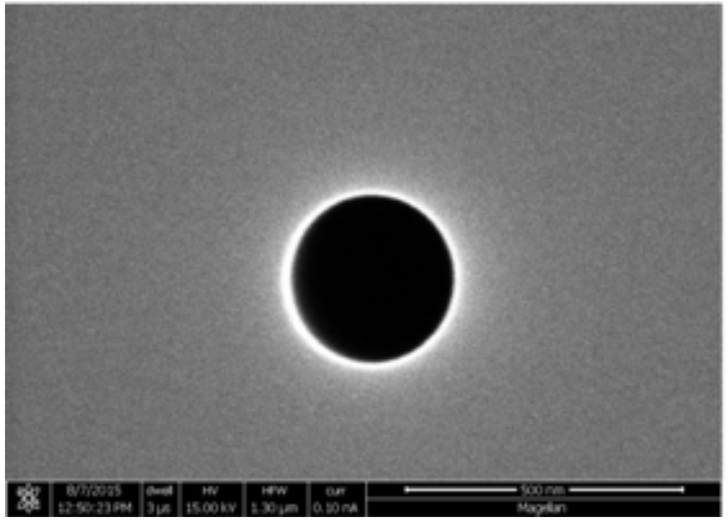
Polymicro nano-Capillary Tubing

Polymicro
nano-Capillary
Fused Silica Capillary Tubing

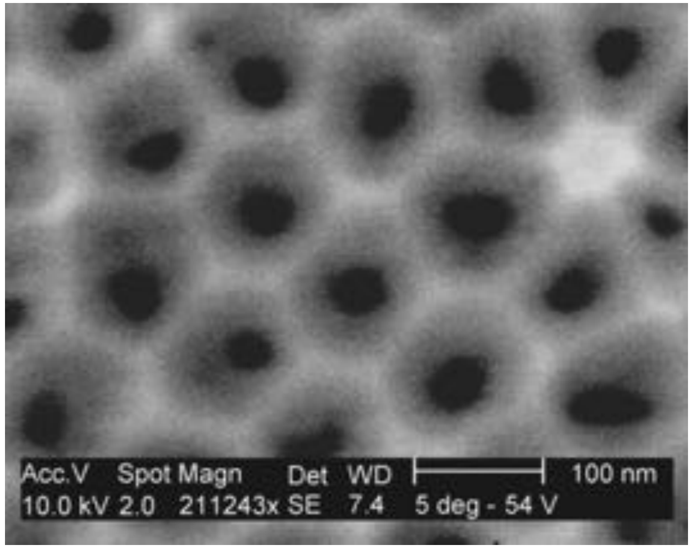


molex

Polymicro Fused Silica Capillary Diagram



SEM characterization
courtesy: P. Taborek



Lazarowich, R. J., Taborek, P., Yoo, B. Y., Myung, N. V., *Fabrication of porous alumina on quartz crystal micro-balances* J. Appl. Phys. **101**, 104909 (2007)

Materials Today • Volume 17, Number 5 • June 2014
A brief review of atomic layer deposition: from fundamentals to applications

of three or more elements by ALD is very useful in optoelectronic materials such as photovoltaics as it enables a means to control-lably vary properties as band gap, density, conductivity, energy band levels, and morphology. An example of this is the ALD-

Nanostructured material wakefield model

solid-state nanostructured tube wakefield

- **Tunable** density, structure, composition
- **Collisions** can be controlled
- **guided** and **focused** - x-ray laser and particle beam
- **Nonlinear** & **Relativistic** Surface Plasmon Polariton
- **wave-breaking** fields accessible

beam-driven crunch-in surface mode

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 081004 (2017)

Excitation of a nonlinear plasma ion wake by intense energy sources with applications to the crunch-in regime

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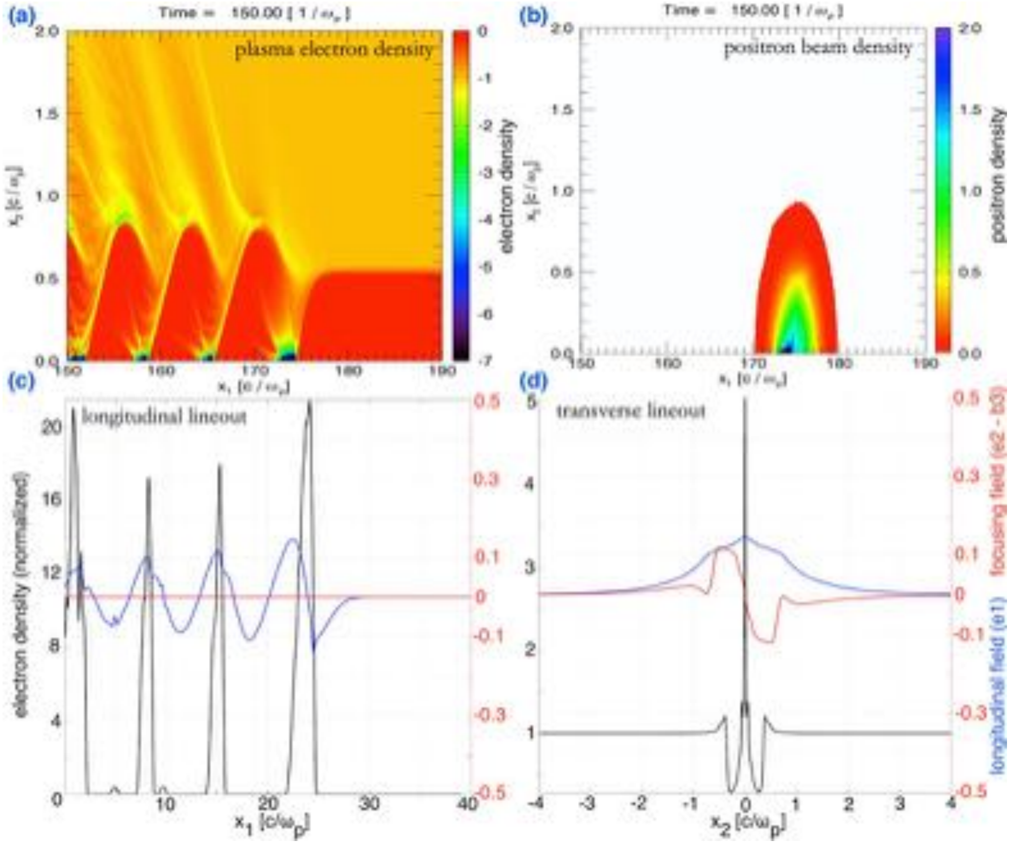
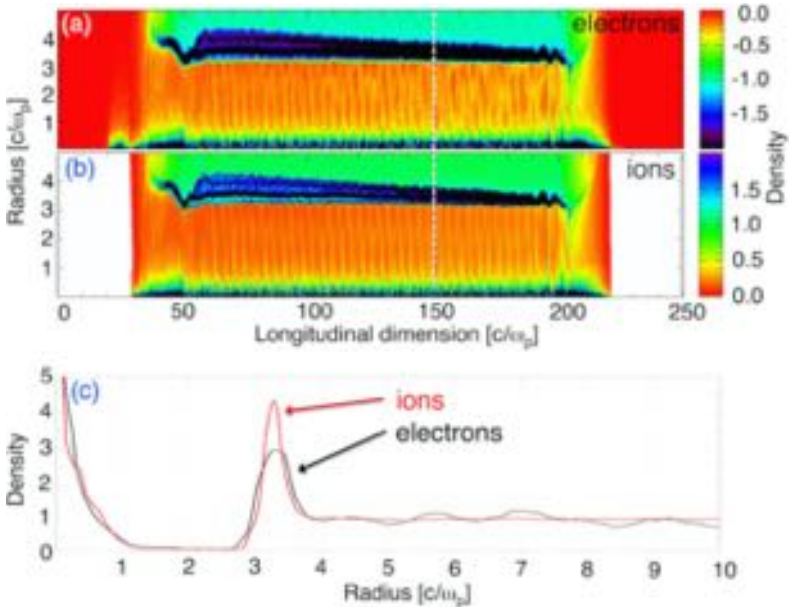
(Received 5 February 2017; published 23 August 2017)





coherent radial oscillations
e^- collapse to the channel axis

Coherent acc. fields ~ **0.4 E_{WB}**

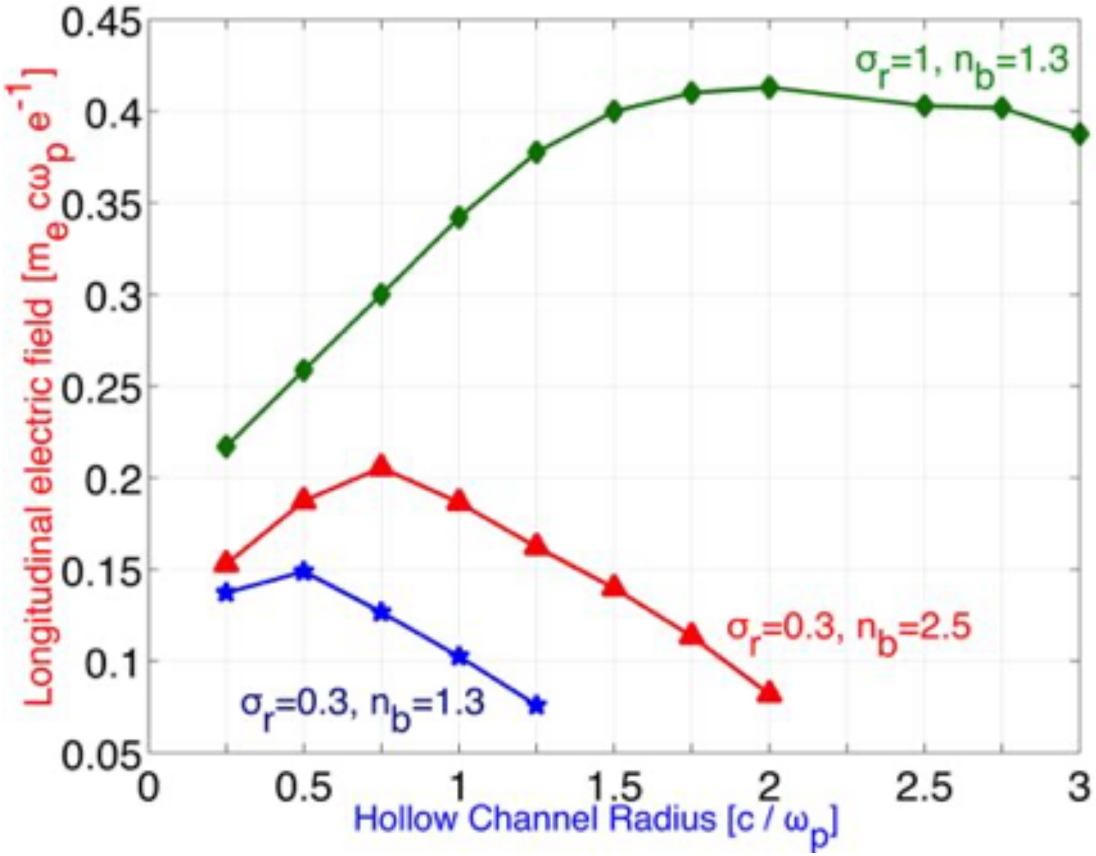
Chapter 8

Sahai, A. A., *On Certain Non-linear and Relativistic Effects in Plasma-based Particle Acceleration*, Ph.D. dissertation submitted to the Duke university graduate school, July 2015

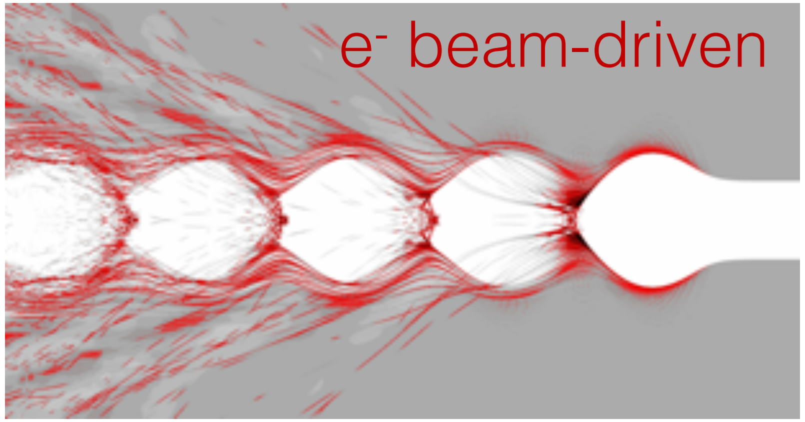
beam-driven crunch-in surface mode

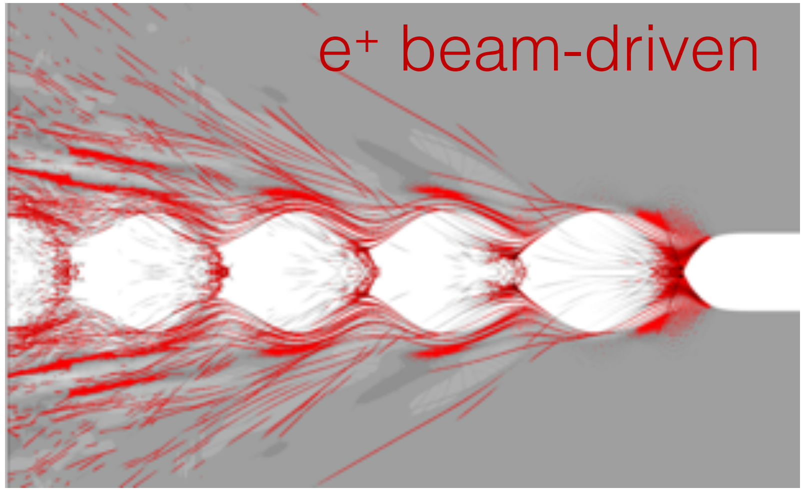
Chapter 8

Sahai, A. A., *On Certain Non-linear and Relativistic Effects in Plasma-based Particle Acceleration*, Ph.D. dissertation submitted to the Duke university graduate school, July 2015



cartesian CRUNCH-IN mode





x-ray laser tube crunch-in mode

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 101004 (2016)

Particle-in-cell simulation of x-ray wakefield acceleration and betatron radiation in nanotubes

Xiaomei Zhang,[1,2] Toshiki Tajima,[2] Deano Farinella,[2] Youngmin Shin,[3] Gerard Mourou,[4] Jonathan Wheeler,[4] Peter Taborek,[2] Pisin Chen,[5] Franklin Dollar,[2] and Baifei Shen[1]

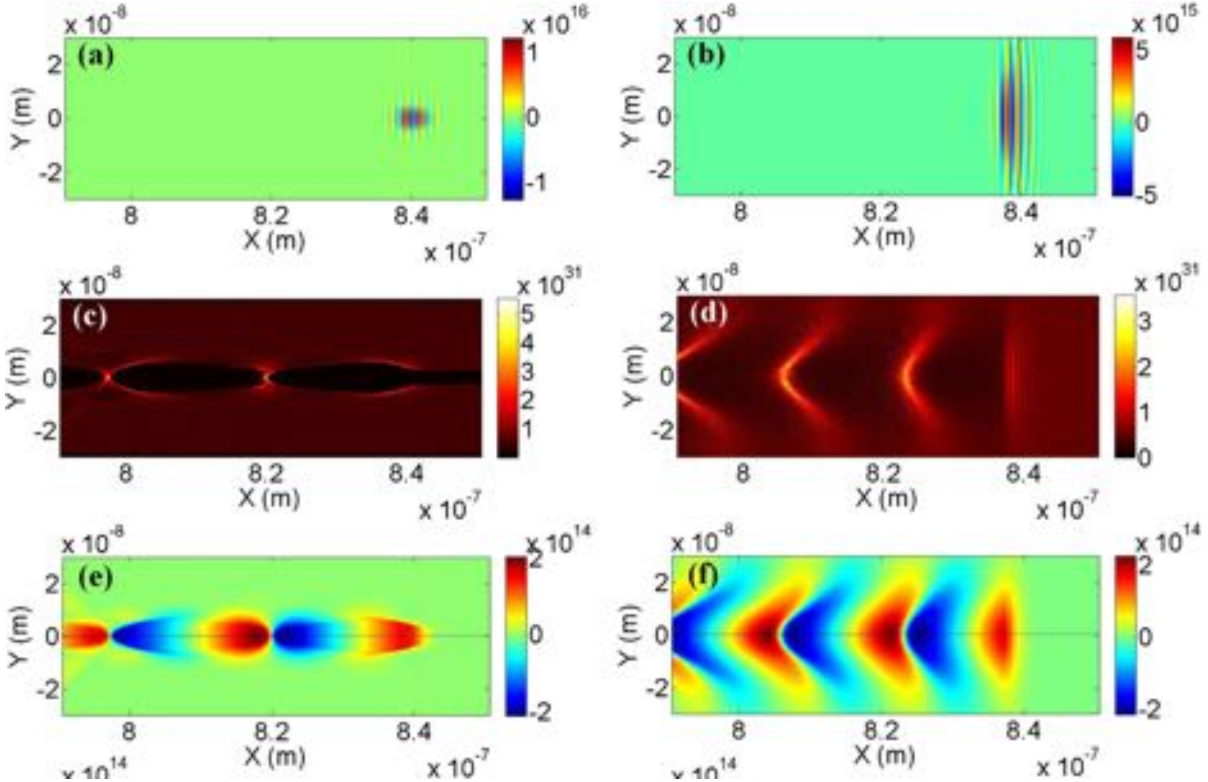
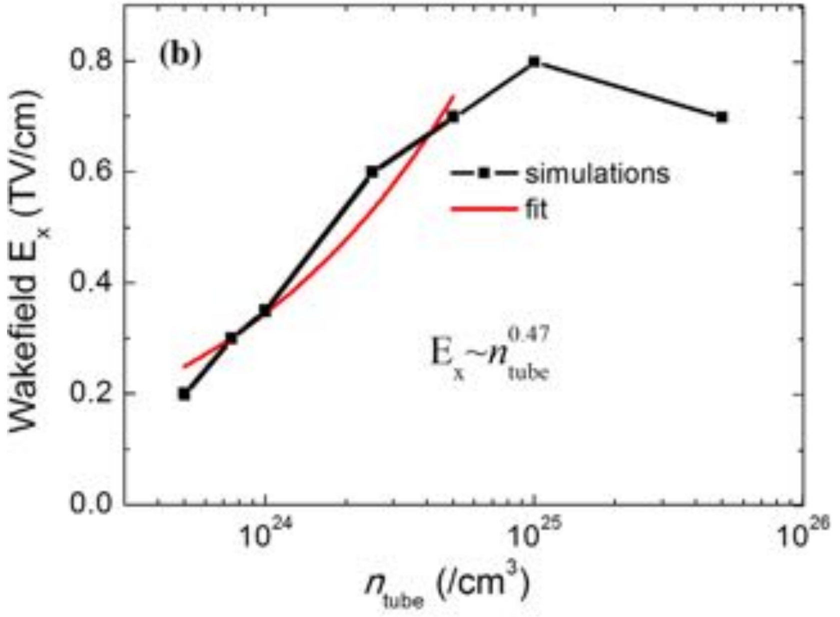


TABLE I. Summary of the laser and plasma parameters for our base case.

Laser wavelength λ_L	Peak amplitude a_0	Width radius σ_L	Length radius σ_x	Plasma density n_{tube}	Tube radius σ_{tube}
1 nm	4	5 nm	3 nm	5×10^{24} W/cm^3	2.5 nm/0 nm
1 μm	4	5 μm	3 μm	5×10^{18} W/cm^3	2.5 μm/0 μm



Nanometric wakefield model

crunch-in kinetic theoretical model - IV

Tube wakefield

peak radial field

$$E_{t-r}(\xi_{r-min})\ 2\pi r_{\rm min}\ dz = 4\pi\ \delta Q_{\rm max}$$

$$\boxed{E_{t-r}(\xi_{r-min}) = -\alpha\ n_t\ 2\pi r_t\ \left(\frac{e n_{b0}\ 2\pi\sigma_r^2}{n_t\pi(r_t+\Delta w)^2 - n_{b0}\ 2\pi\sigma_r^2}\right)}$$

Panofsky-Wenzel theorem

$$\frac{E_{t-r}}{\Delta\xi} = \frac{E_{t-z}}{\Delta r}$$

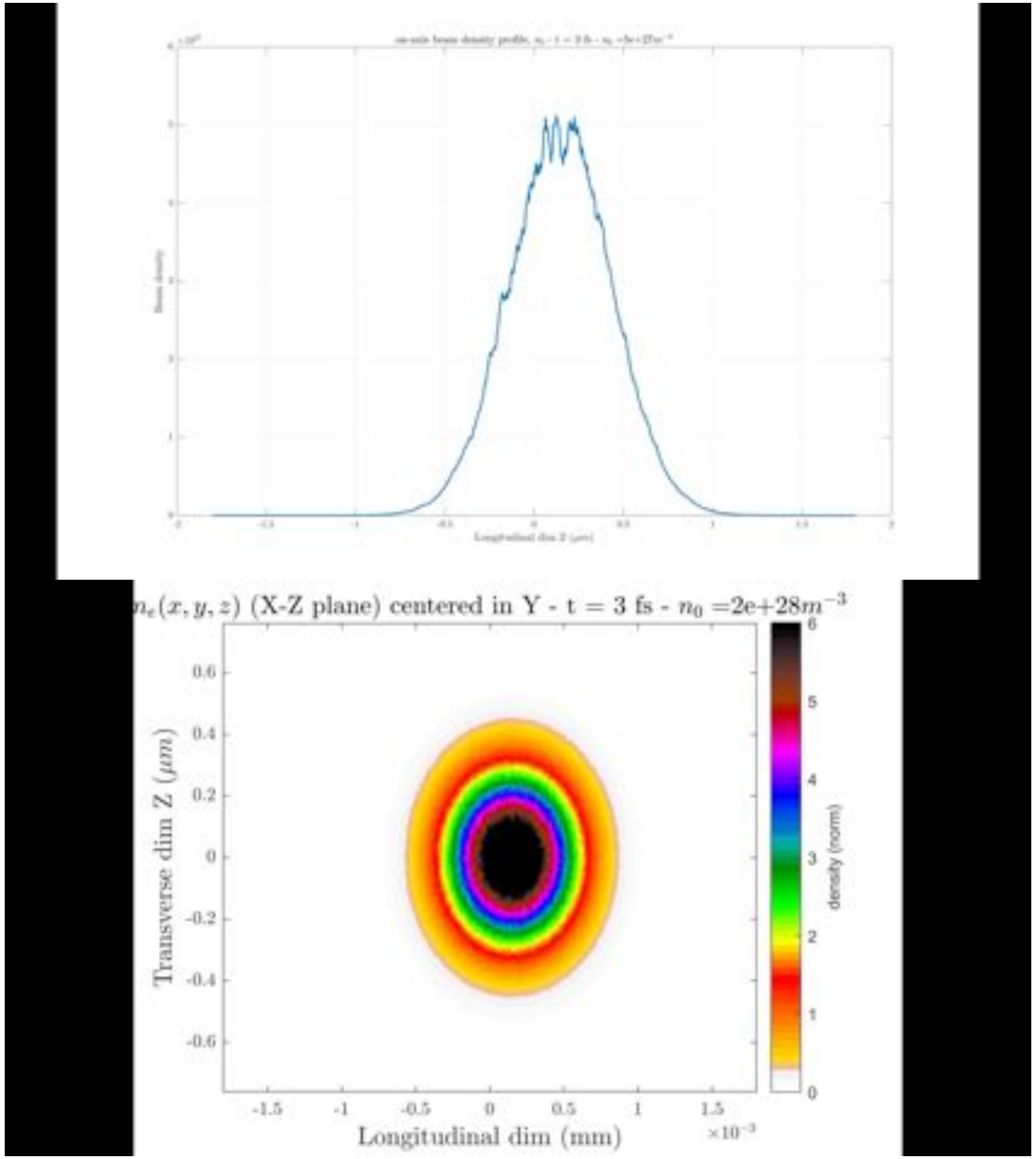
$$E_{t-z} = \frac{E_{t-r}}{\Delta\xi}\Delta r = E_{t-r}\ \frac{r_{min}}{\kappa\ 2\pi c}\ \frac{\omega_{pe}(n_t)}{\sqrt{\gamma_e}}$$

Tube wakefield

peak acc. field

$$\boxed{E_{t-z} = -\frac{2.03}{\kappa}\ \frac{\sqrt{n_t[10^{22}\mathrm{cm}^{-3}]}}{\sqrt{r_t[100\mathrm{nm}]}}\ \sqrt{Q_b[\mathrm{pC}]}\ \frac{\sigma_r}{\sigma_z}\ \left(\left(\frac{r_t+\Delta w}{r_t}\right)^2 - 2\frac{n_{b0}}{n_t}\frac{\sigma_r^2}{r_t^2}\right)^{-1}\ \frac{\mathrm{TV}}{\mathrm{m}}}$$

3D Particle-In-Cell modeling



3D PIC simulation
on-axis beam density profile

initialized Gaussian

2D slice density profile

Conclusion & Future Work

Nanometric Wakefield Acceleration

- **Ready to be prototyped:**
  1 GeV in ~100 μm
- Several **related details** being characterized:
  attosecond ionization, ion motion, etc.
- Extend the **module** to higher energies

Towards

TeV on a Chip !

- Self-focusing & nano-modulation
  of ultra-relativistic beam
- controlled O(100MeV) photon production

Gamma-ray

FEL on a Chip !!