Advanced Future Linear Collider Concepts

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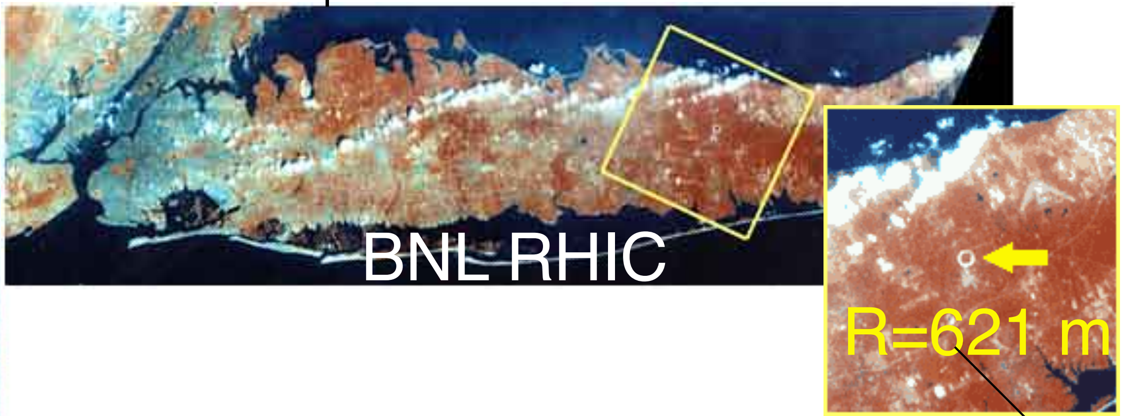
(Werner-Heisenberg-Institut)

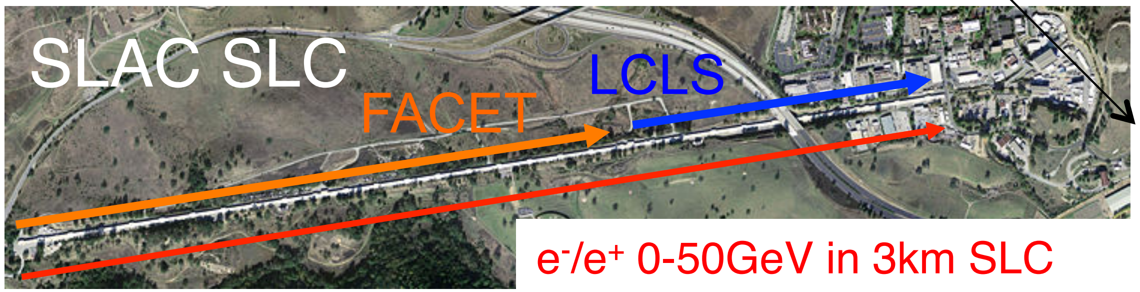
CERN

MAX-PLANCK-GESELLSCHAFT

PARTICLE COLLIDERS

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use radio frequency (RF) technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

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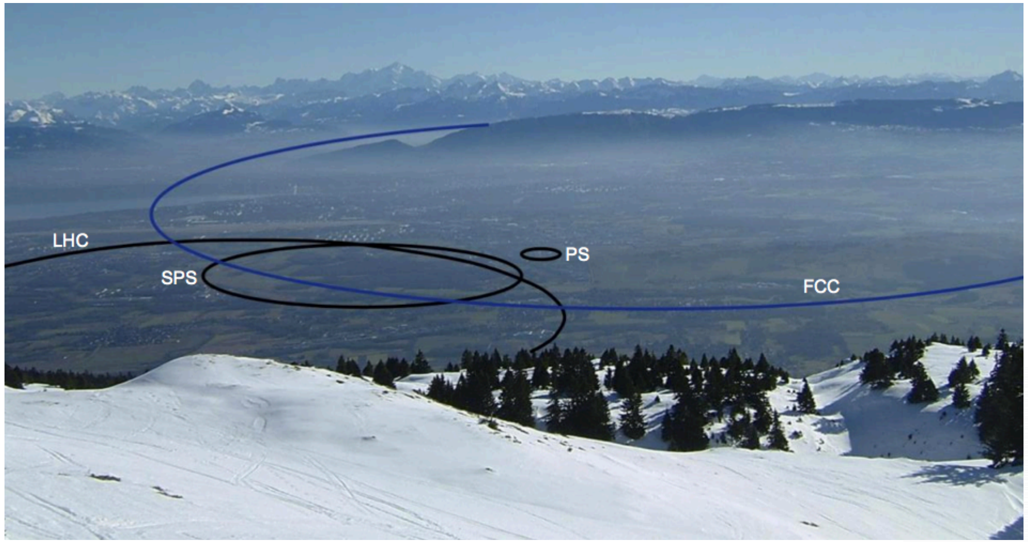
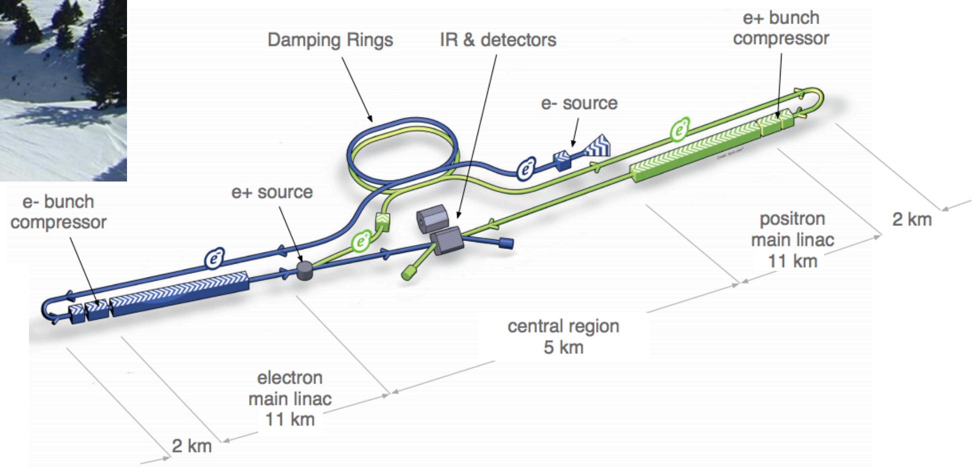
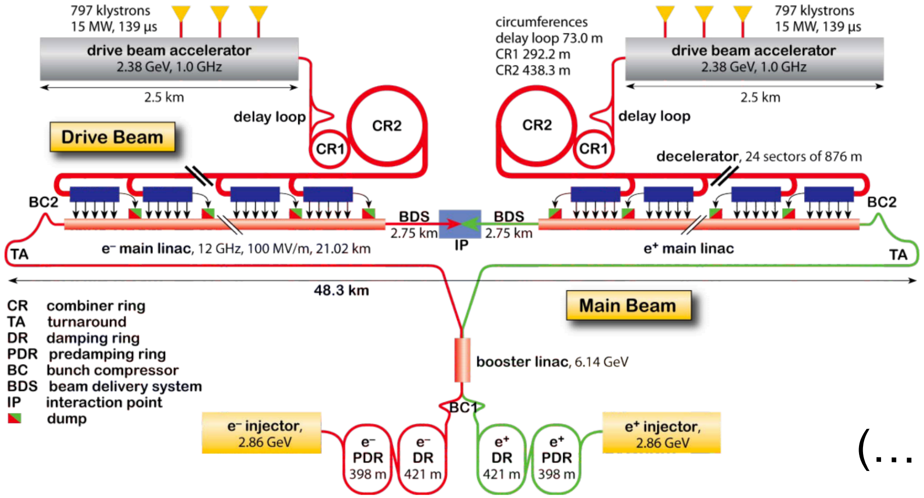
PARTICLE COLLIDERS

The future is …







… large and larger...

(… because of higher and higher energies)

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OUTLiNE

✧Introduction

✧Novel Acceleration Techniques

Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

✧Summary

OUTLINE

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PARTiCLE COLLiDERS

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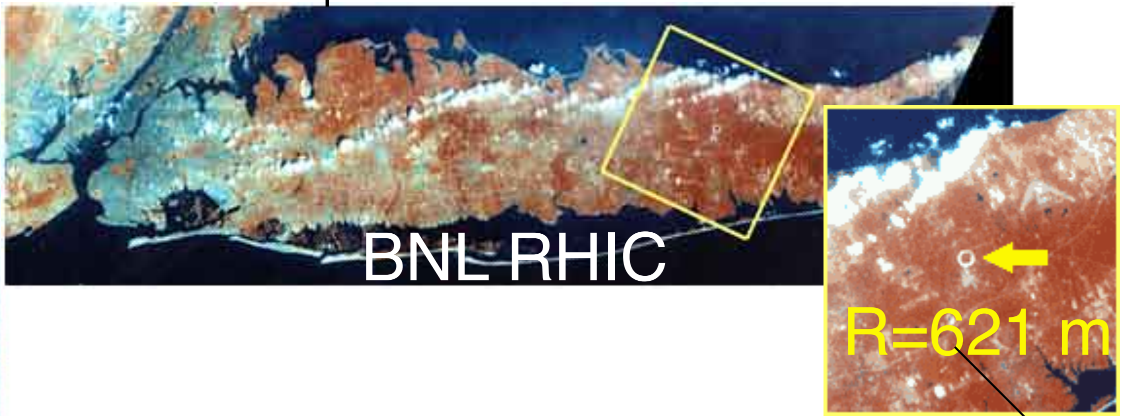

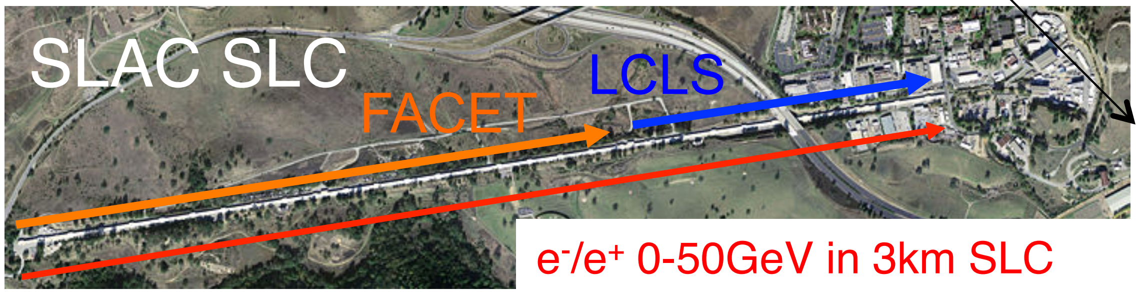

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PARTICLE COLLIDERS

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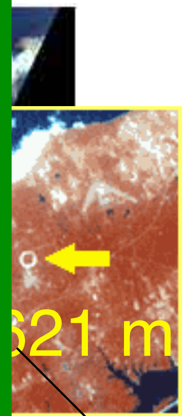


m SLC
m FACET
m LCLS

Hadron accelerators energy limited by magnetic field:

$$r_{Larmor} = \frac{\gamma mc}{qB_0} = r_{accelerator}$$

B_0~ 8T for LHC
(p^+, 7TeV, C=27km)

B_0~16T for FCC
(p^+, 50TeV, C=100km)

Lecture: Luca BOTTURA

- Some of the largest and most comp ... c instruments ever built!
- All use radio frequency (RF) techno
- Can we make them smaller (and cheaper) and with a higher energy?

PARTICLE COLLIDERS

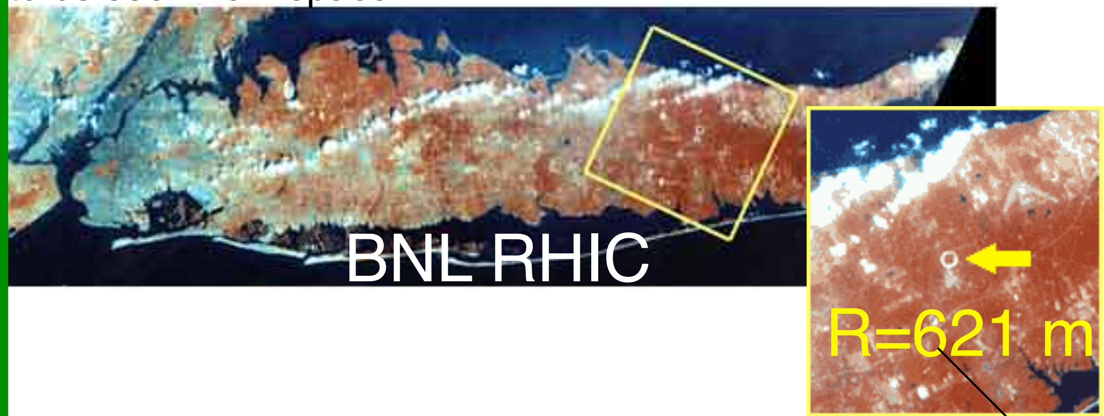
Light particles (e^-/e^+) accelerator
Limited by synchrotron radiation

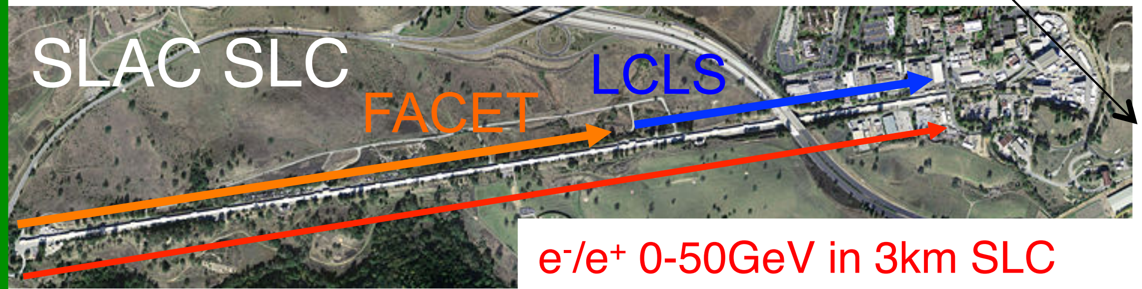
$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7} \frac{E^4}{R^2 m^4}$$

Linear for high energy!
Energy limited by the accelerating gradient:

$$\searrow \quad L = \frac{E(eV)}{G(eV/m)} \quad \nearrow$$

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





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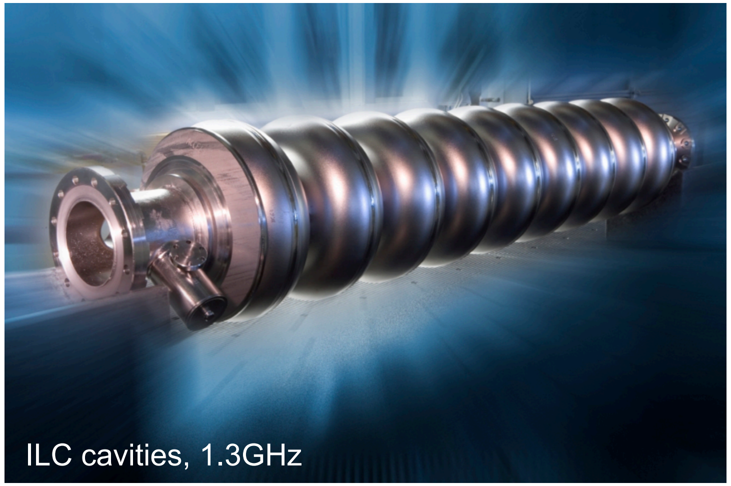
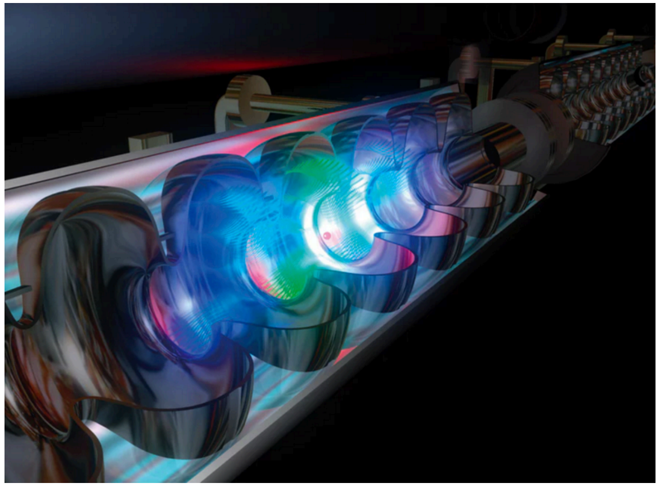
ACCELERATiNG STRUCTURES

✧All HEP accelerators use (metallic) RF structures … maximize gradient …

✧Cold, superconducting structures



ILC cavities, 1.3GHz

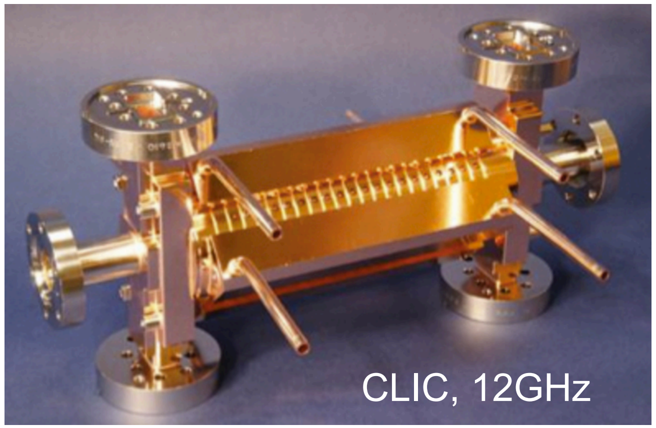


Field < 50MV/m

Lecture: Erk Jensen

✧Warm structures

SLAC, 2.856GHz



CLIC, 12GHz

CLIC, 12GHz

Lecture: Walter Wuensch

Field < 200MV/m

ACCELERATiNG FiELD/GRADiENT LiMiTATiONS

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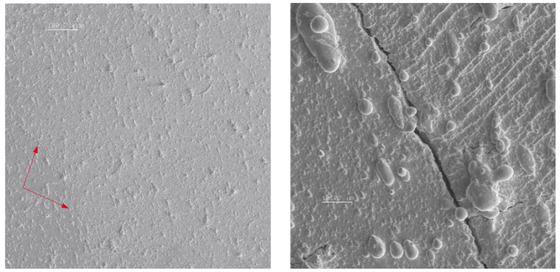
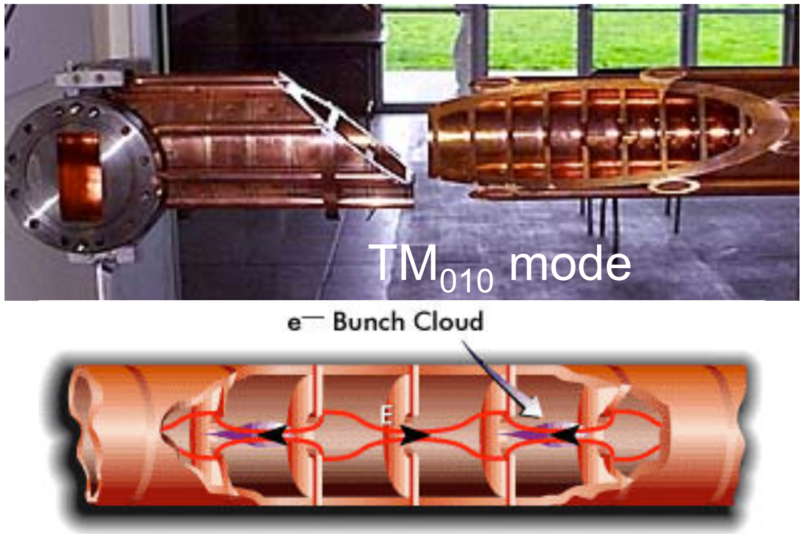
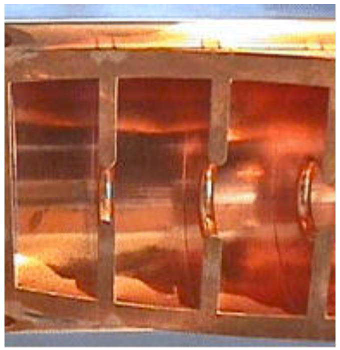
- ✧Gradient/field limit in (warm) RF structures: <100MV/m
- ✧RF break down (plasma!!) and pulsed heating fatigue
- ✧Accelerating field on axis, damage on the surface
- ✧Material limit, metals in the GHz freq. range (Cu, Mo, etc.)
- ✧Does not (seem to) increase with increasing frequency

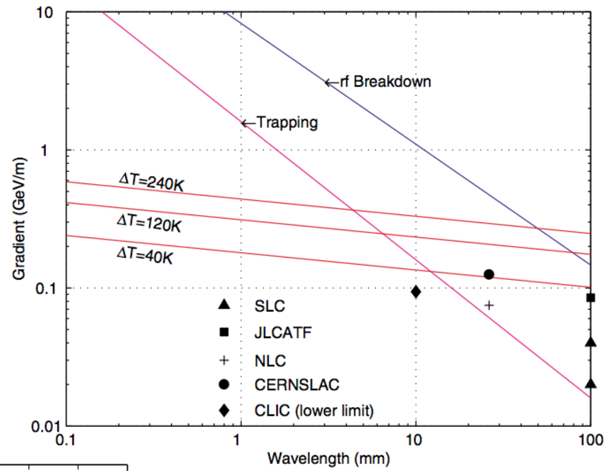
Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)

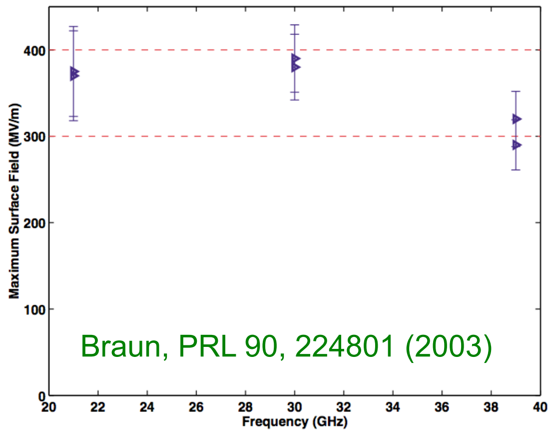








RF break down



Braun, PRL 90, 224801 (2003)

ACCELERATiNG FiELD/GRADiENT LiMiTATiONS

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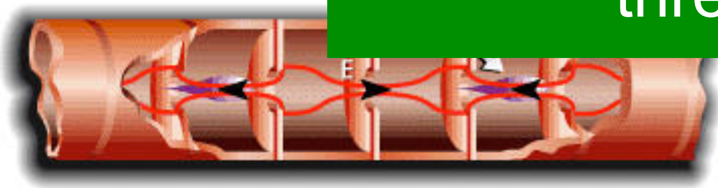
- ✧Gradient/field limit in (warm) RF structures: <100MV/m
- ✧RF break down (plasma!!) and pulsed heating fatigue
- ✧Accelerating f
- ✧Material limit,)
- ✧Does not (see

RF-accelerators:
Accelerating field limited to
<100MVm (low break-down rate)
by metal damage:
-RF-breakdown
-pulsed heating
Copper: low damage
threshold

e⁻ Bu



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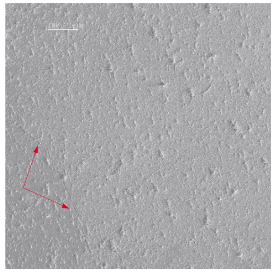
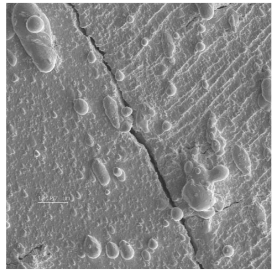
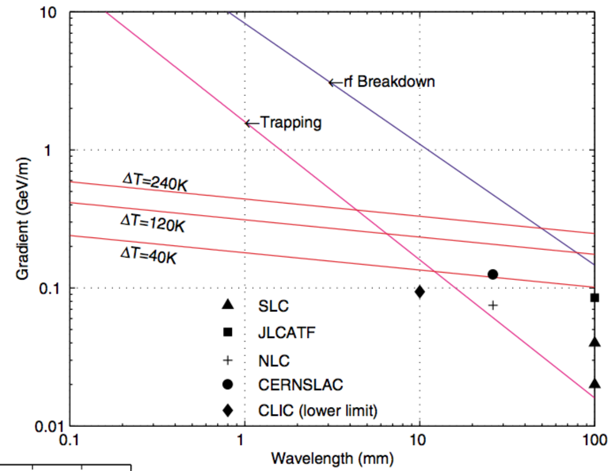
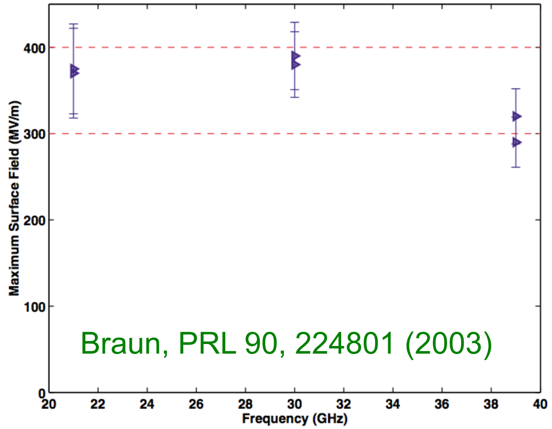
Pritzkau, PRSTAB 5, 112002 (2002)







RF break down



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PARTICLE ACCELERATORS

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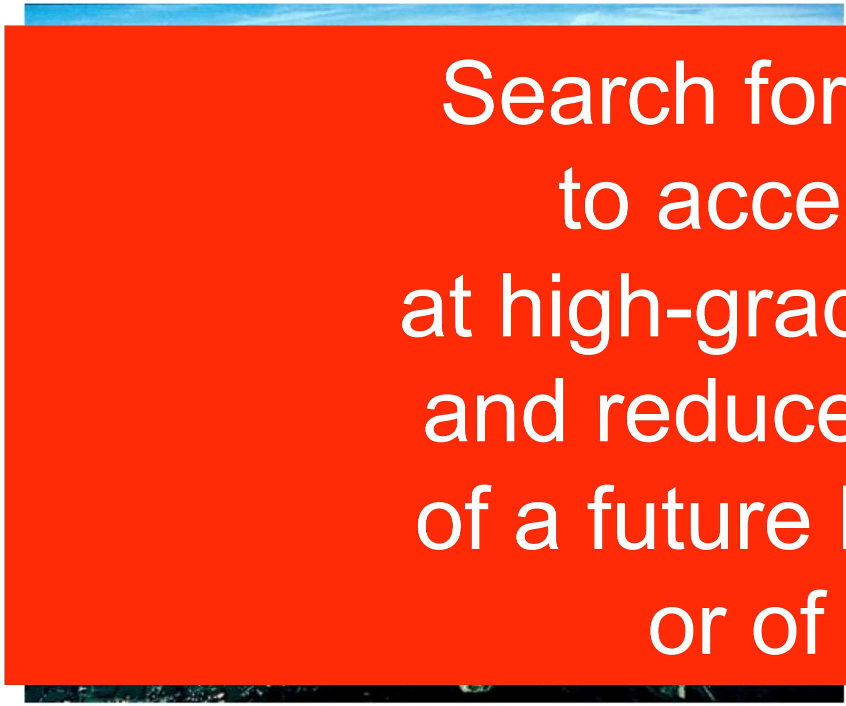

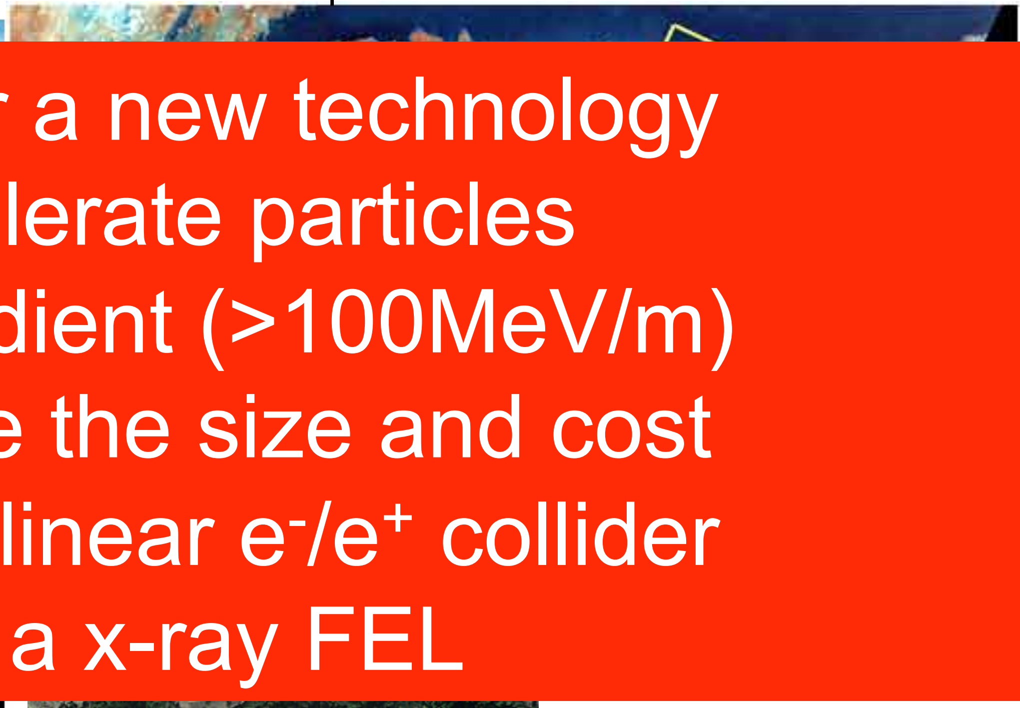

Search for a new technology to accelerate particles at high-gradient (>100MeV/m) and reduce the size and cost of a future linear e^-/e^+ collider or of a x-ray FEL

e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

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ADVANCED & NOVEL ACCELERATORS (ANAs)

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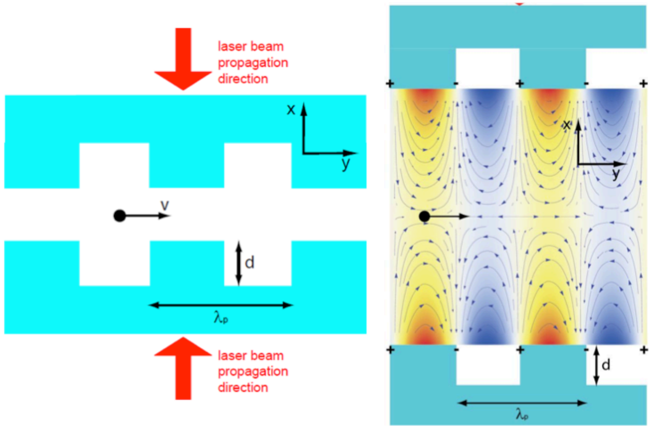
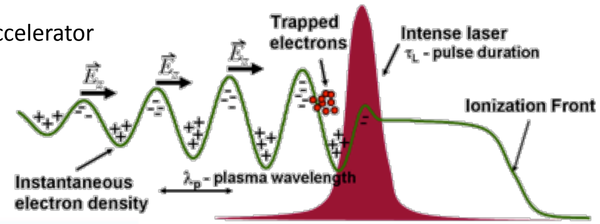
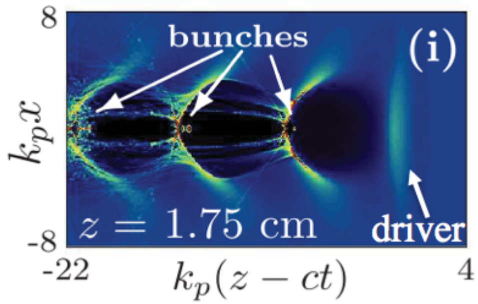
Dielectric Laser Accelerator

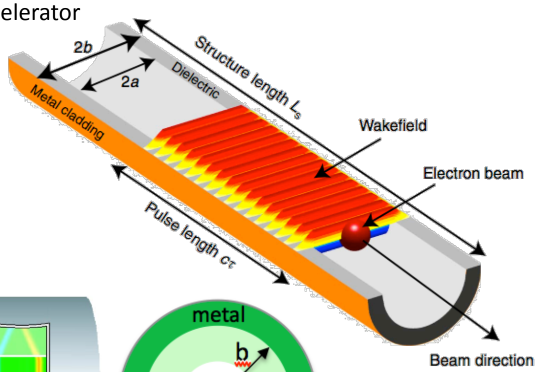


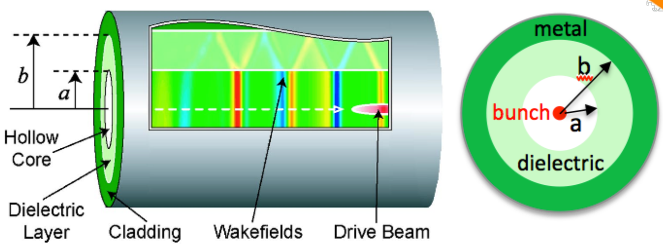
Laser WakeField Accelerator



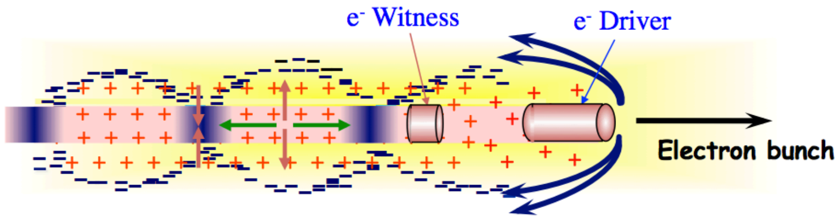


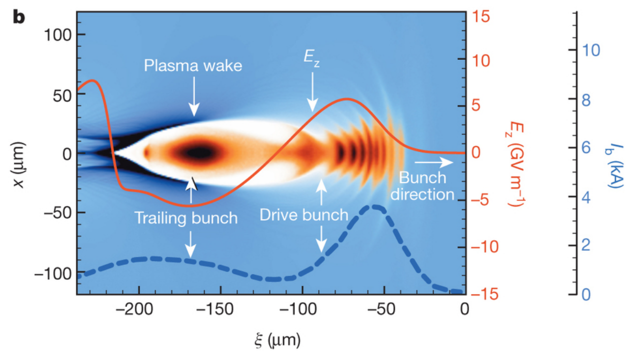
Structure WakeField Accelerator





Plasma WakeField Accelerator





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ADVANCED & NOVEL ACCELERATORS (ANAS)

"Advanced"

"High-gradient"

>1GeV/m (ICFA-ANA)

Average gradient over m–scale

GeV to TeV or beyond e^-/e^+

 *do not include laser vacuum/direct acceleration

ADVANCED & NOVEL ACCELERATORS (ANAs)

"Advanced"

⇕

"High-gradient"

⇕

>1GeV/m (ICFA-ANA)

⇕

Average gradient over m–scale

⇕

GeV to TeV or beyond e^-/e^+

Novel materials with higher damage threshold:
- ✧Dielectrics (~GV/m)
- ✧Plasmas (10-100GV/m or ∞)

Novel drivers:
- ✧Laser pulse(s)*
- ✧Charged particle bunch(es)

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ADVANCED & NOVEL ACCELERATORS (ANAs)

Role of the novel structure / challenge:
convert (some of) the transverse fields ($E_\perp$)
of the novel driver (laser pulse, particle bunch) into a
longitudinal (E_z) component for acceleration (E_z>1GV/m)
Advantage of novel material:
Sustain higher fields
- E~1-10GV/m for dielectrics
- E~100-∞GV/m for plasmas ☺

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ADVANCED & NOVEL ACCELERATORS (ANAs)

Laser Pulse:

(plane wave)

$$Intensity \approx \frac{1}{2}\varepsilon_0 c E_\perp^2$$

Example:
$E_\perp$=1GV/m
I~10^9W/cm^2

$$Poynting\ Vector: \langle \vec{S} \rangle = \frac{\langle \vec{E} \times \vec{B}^* \rangle}{\mu_0}$$

Charged Particle Bunch:

(tri-Gaussian, relativistic)

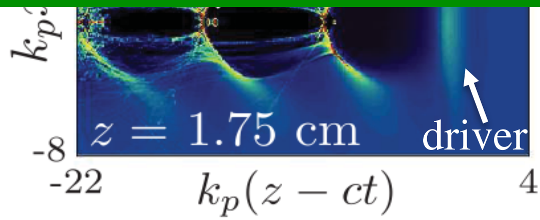
$$E_{\perp,\max} \approx \frac{1}{2(2\pi)^{3/2}} \frac{e}{\varepsilon_0} \frac{N}{\sigma_r \sigma_z} \left(1 - e^{-1/2}\right)$$

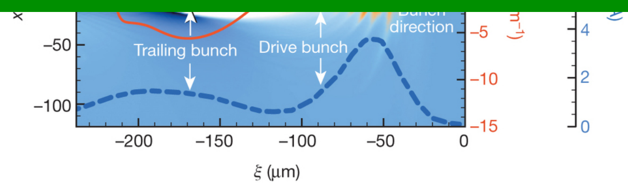
Example:
N=2x10^{10}e$^-$, σ_r=10µm, σ_z=20µm
$E_\perp$=11GV/m

$$E_r(r) \cong \frac{1}{2(2\pi)^{3/2}} \frac{e}{\varepsilon_0} \frac{N}{\sigma_z} \frac{\left(1 - e^{-r^2/2\sigma_r^2}\right)}{r}$$

Challenge / function of the accelerating structure:

Convert a fraction of $E_\perp$ into E_z (accel. ~$\int E_z dz$)





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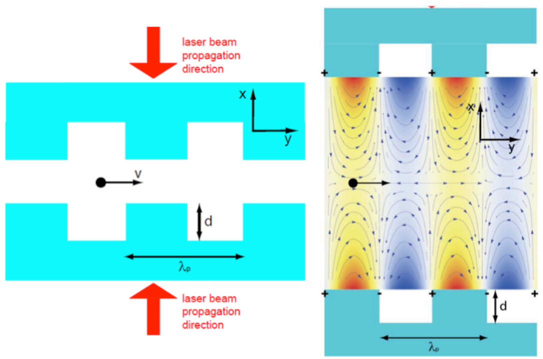
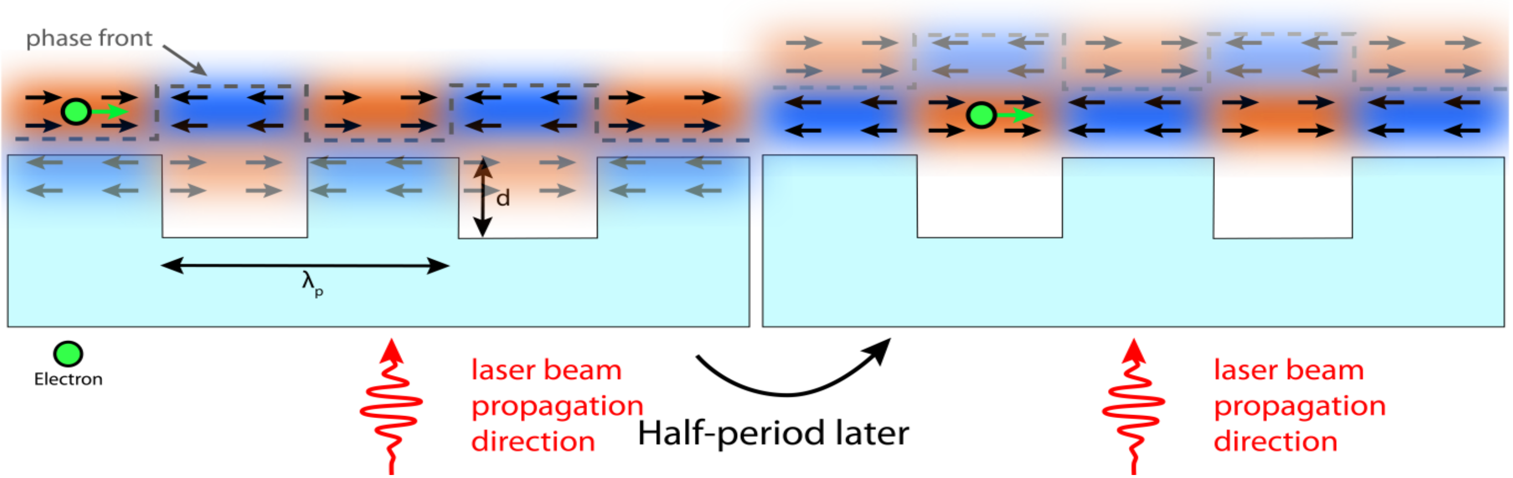
✧Directly use the laser E-field in a ~λ^3 (micro) structure

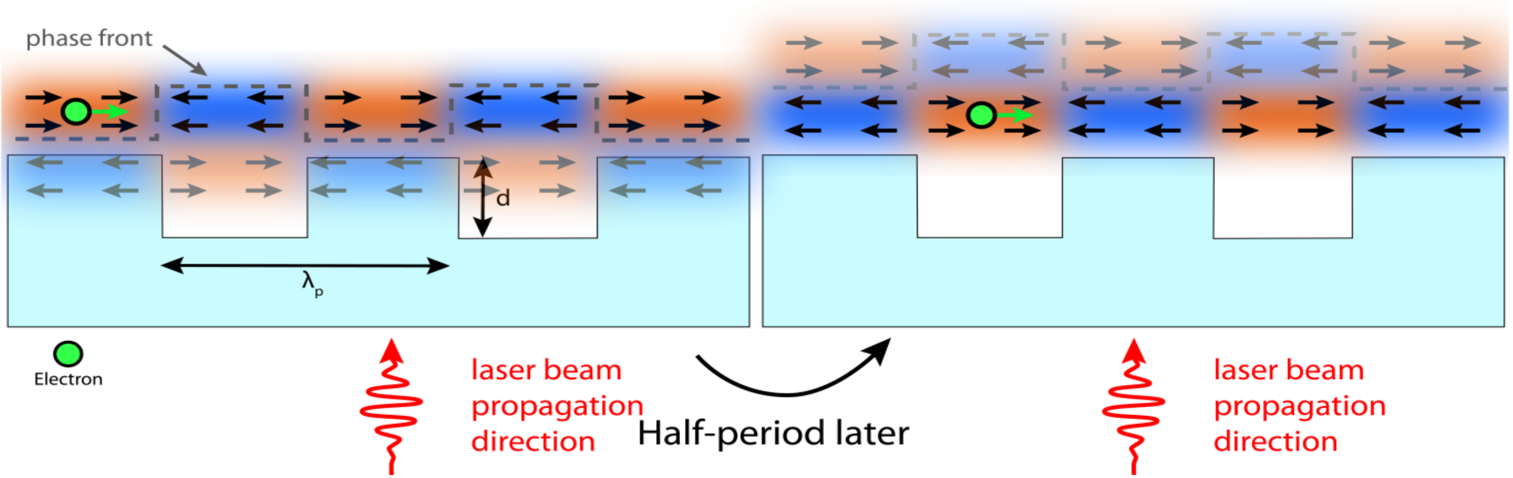
✧Summary

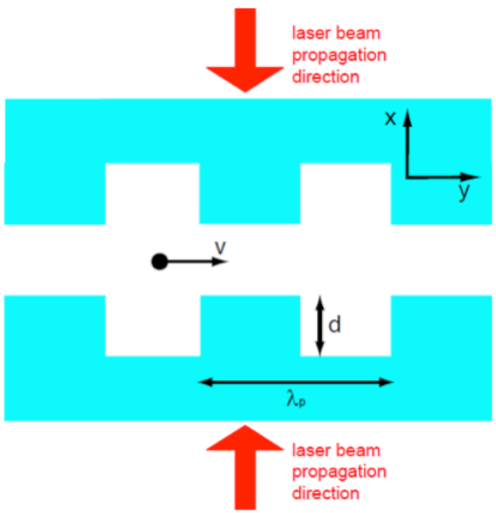


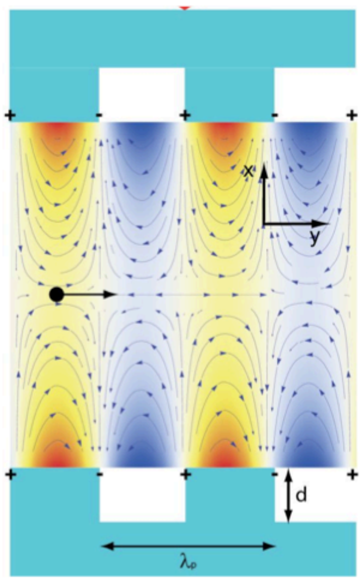
DiELECTRiC LASER ACCELERATOR (DLA)

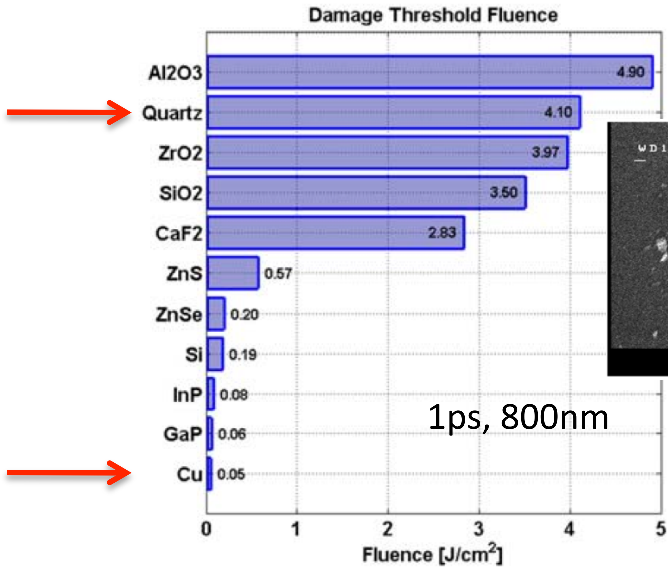


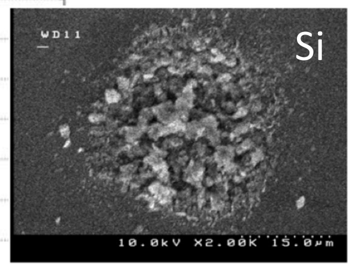
DiELECTRiC LASER ACCELERATOR (DLA)











Soong, AIP Conf. Proc. 1507, 511 (2012)

- ✧ Take advantage of large laser E-field
- ✧ Take advantage of large damage threshold (SiO_2, Si, etc.)
- ✧ Structure = phase mask for velocity matching

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 Courtesy P. Hommelhoff

P. Hommelhoff, Accel. Med. Appl., Vösendorf, Austria, 2015

DLA RESULTS

Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]

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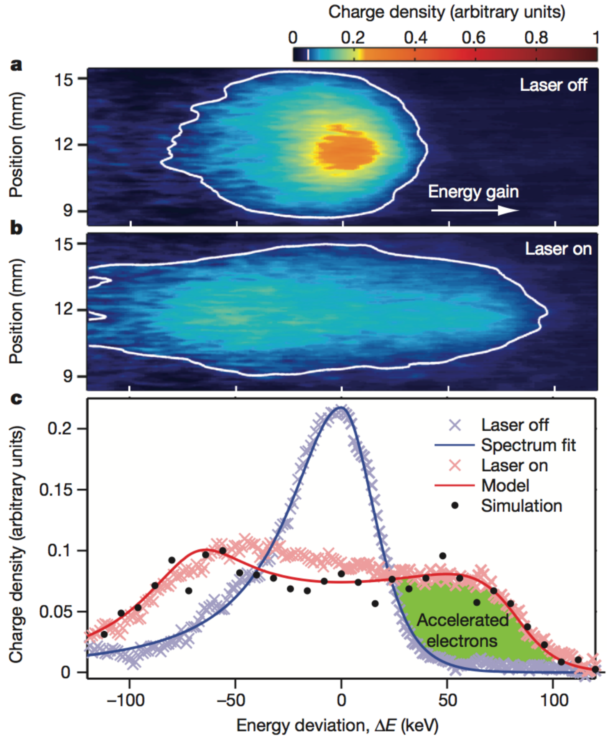
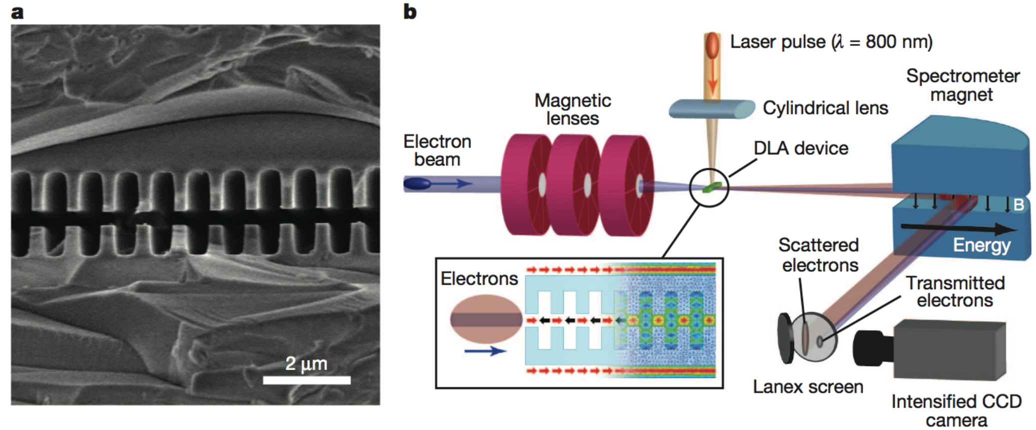
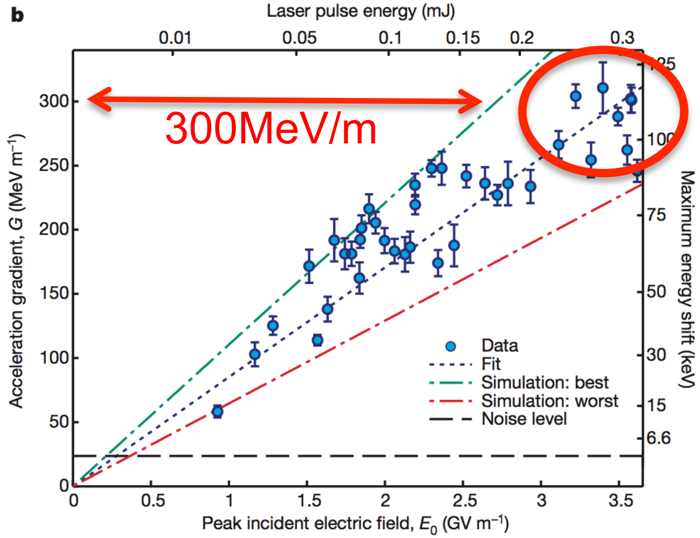






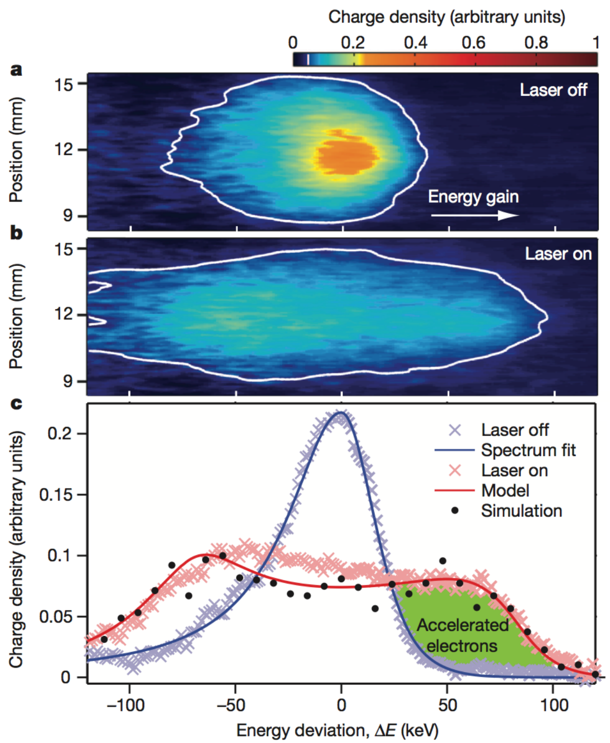
- ✧Beam not bunches at λ_{laser} scale -> broad spectrum … possible bunching: IFEL
- ✧Inferred accelerating gradient in excess of 300MeV/m
- ✧Need sub-$(\lambda_{laser})^3$ beams, naturally low emittance and charge
- ✧Operate at very high rep-rate

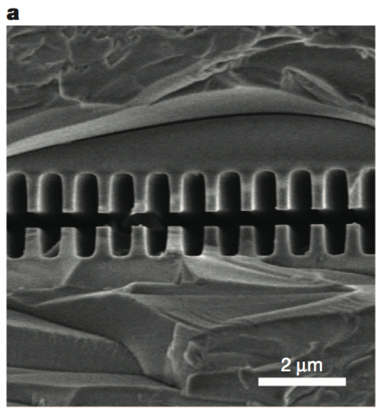
DLA RESULTS

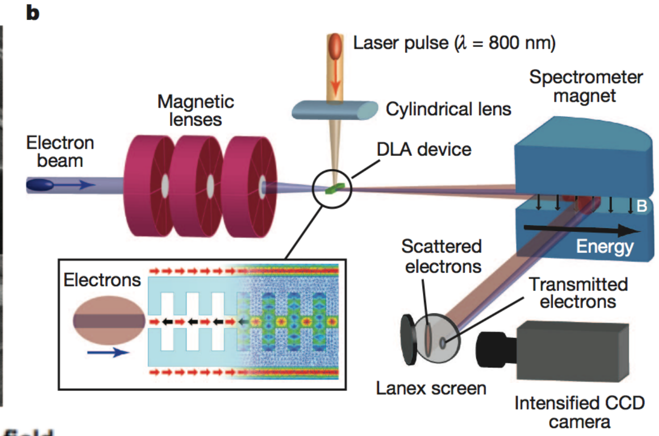
Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]

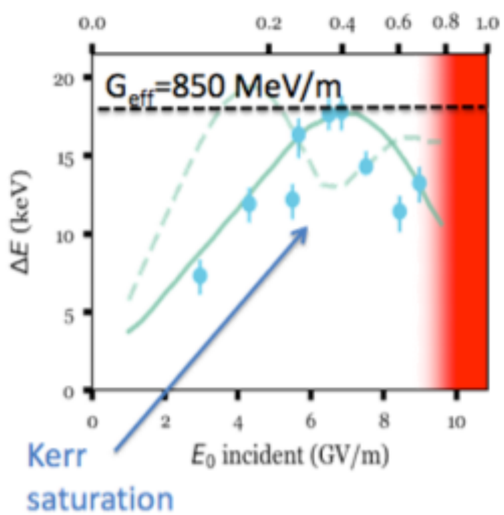
7 NOVEMBER 2013 | VOL 503 | NATURE | 91







Energy gain vs. incident laser field



Presented by D. Cesar (UCLA) @ EAAC 2017

- ✧Beam not bunches at λ_{laser} scale -> broad spectrum … possible bunching: IFEL
- ✧Inferred accelerating gradient in excess of 800MeV/m
- ✧Need sub-$(\lambda_{laser})^3$ beams, naturally low emittance and charge
- ✧Operate at very high rep-rate

OUTLiNE

✧Introduction

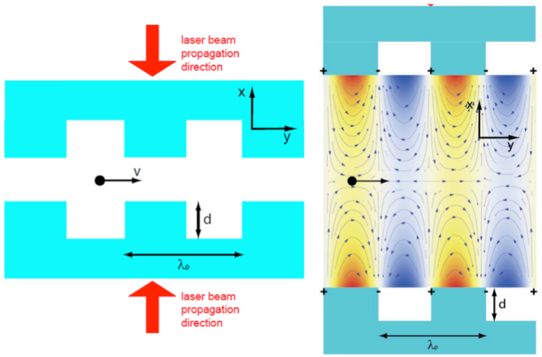
✧Novel Acceleration Techniques

Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

✧Directly use the laser E-field in a ~λ^3 (micro) structure

✧Summary

- ✧ Demonstrated ~1GeV/m
- ✧ Takes advantage of μ-fabrication
- ✧ Takes advantage of rapid progress in fiber lasers
- ✧ Symmetric e^-/e^+
- ✧ Low emittance, low charge, high rep. rate



OUTLiNE

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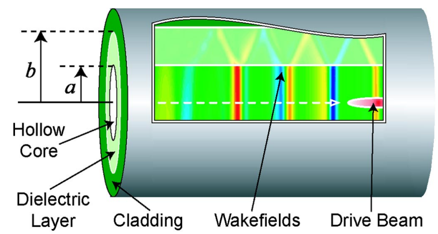
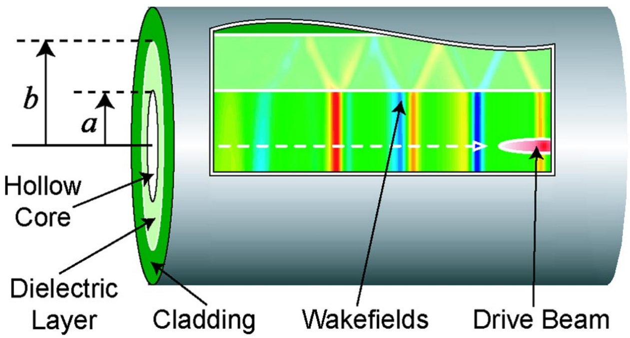
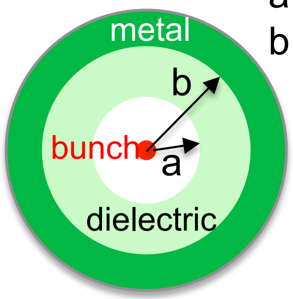
✧Cherenkov wakes in dielectric layers

✧Summary

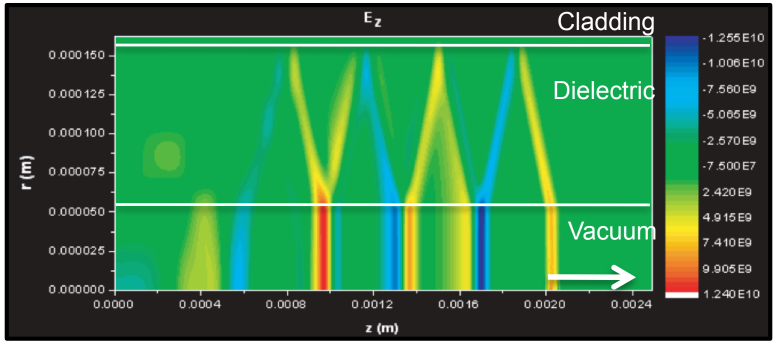


DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





a: vacuum channel radius
b: dielectric outer radius



- Peak decelerating field

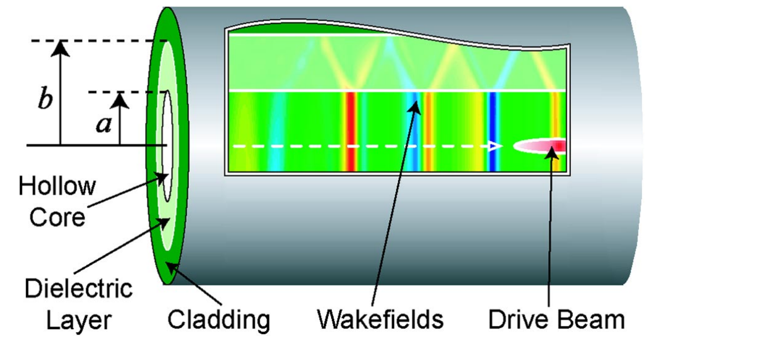
$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

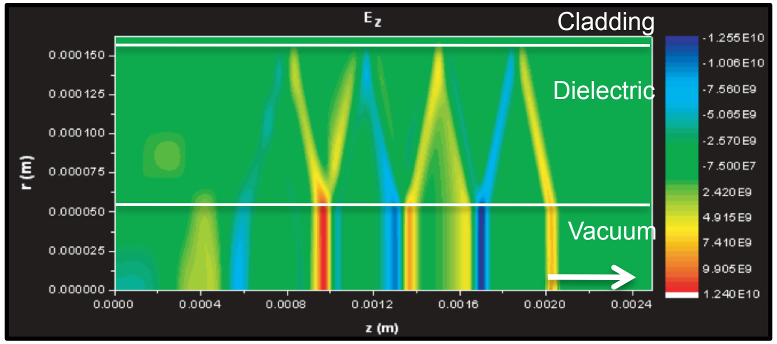
- Transformer ratio (unshaped beam)

$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$

Detailed fields; Jing, RAST 09, 2016

DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





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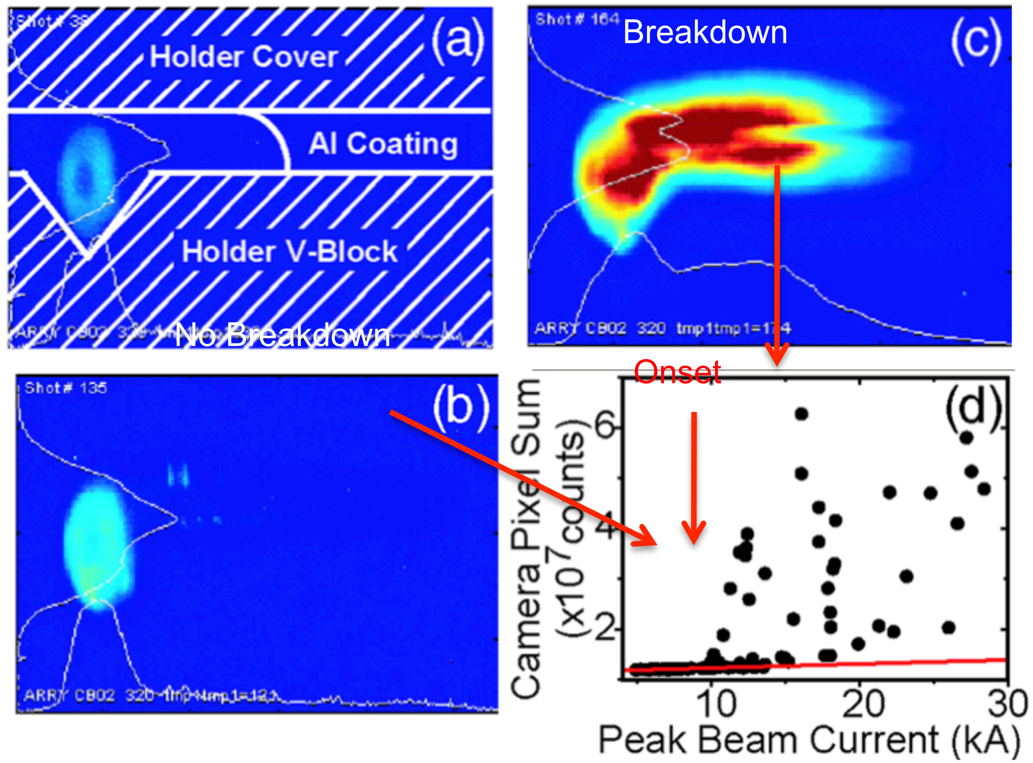
PRL 100, 214801 (2008) PHYSICAL REVIEW LETTERS week ending 30 MAY 2008

Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures

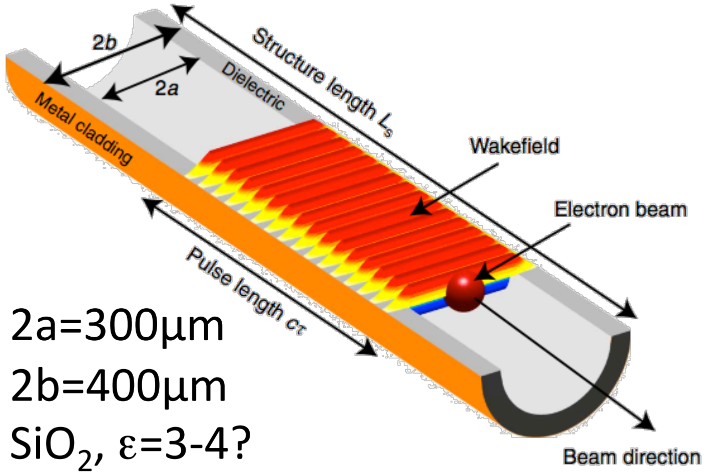
M. C. Thompson,[1,2,*] H. Badakov,[1] A. M. Cook,[1] J. B. Rosenzweig,[1] R. Tikhoplav,[1] G. Travish,[1] I. Blumenfeld,[3] M. J. Hogan,[3] R. Ischebeck,[3] N. Kirby,[3] R. Siemann,[3] D. Walz,[3] P. Muggli,[4] A. Scott,[5] and R. B. Yoder[6]



✧σ_z=100-10µm, N=2x10^{10} e$^-$
✧a=50µm, b=162µm, fused silica, ε~3, f_1~470GHz
✧Breakdown field at 13.8±0:7GV/m
✧Estimated max. decelerating field: 11GV/m
✧Estimated max. accelerating field: 17GV/m

DWA RESULTS

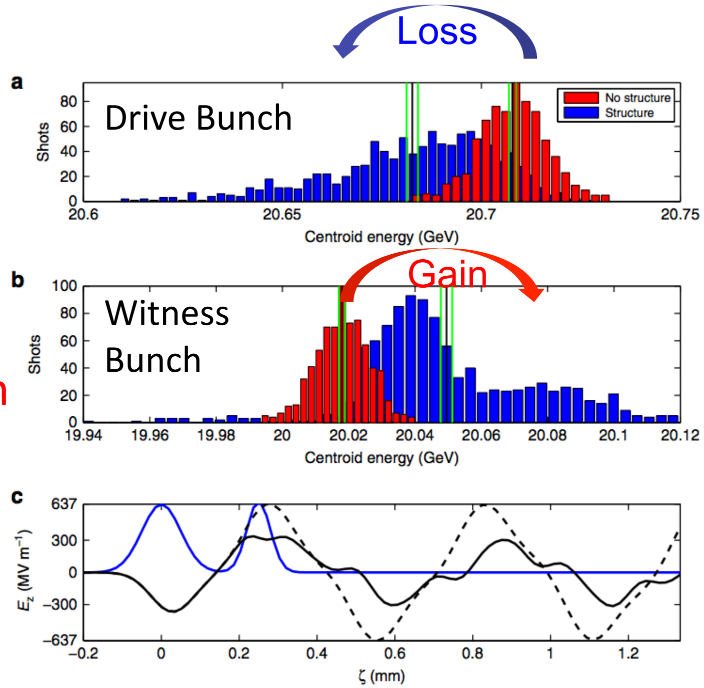
O'Shea et al., Nat . Comm. 7, 12763 (2016)

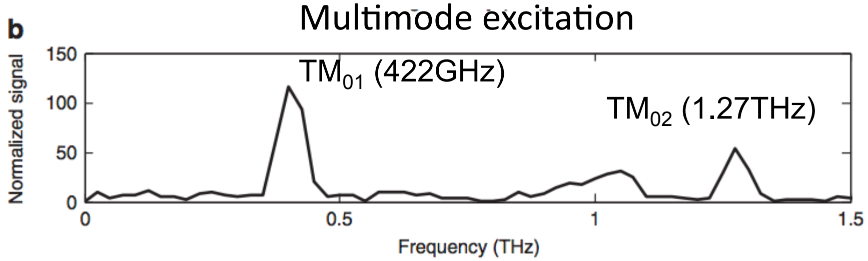


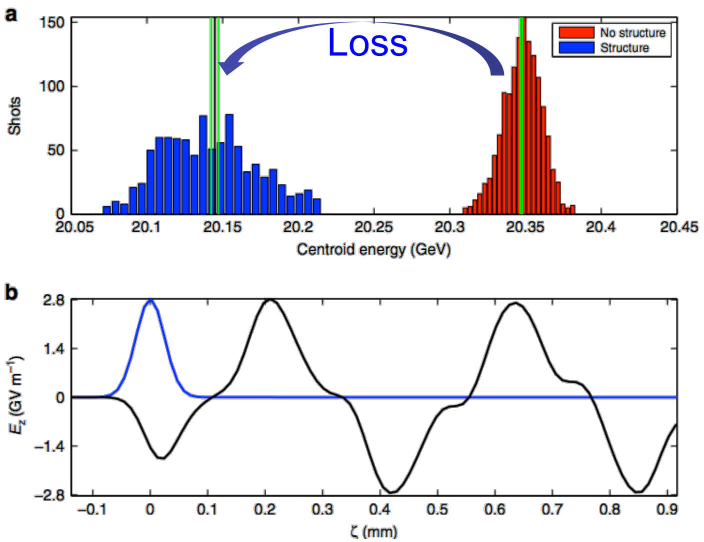
2a=300µm
2b=400µm
SiO_2, ε=3-4?
Cu cladding

9.4×10^9e
G_d=252±14MeV/m

$6\times10^9 e^-$
G_a=320±17MeV/m
$E_{extraction}$=80%







$2\times10^{10} e^-$
ΔE=220±3MeV in 15 cm
-> G=1.347±0.020GeV/m

- ✧GV/m demonstrated
- ✧Energy gain by W bunch!
- ✧Lack of proper beams

DWA RESULTS

Acceleration in slab symmetric DWA

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

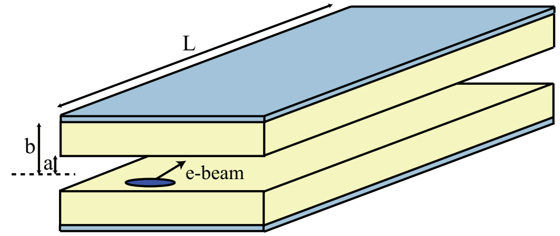
UCLA

- Structure:
  - SiO_2, planar geometry, beam gap 240µm
- BNL ATF
  - Flat beam
  - Long bunch structure with two peaks
- Acceleration of trailing peak
- Robust start-to-end simulations for benchmarking

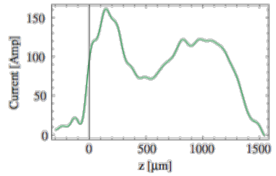
PRL 108, 244801 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

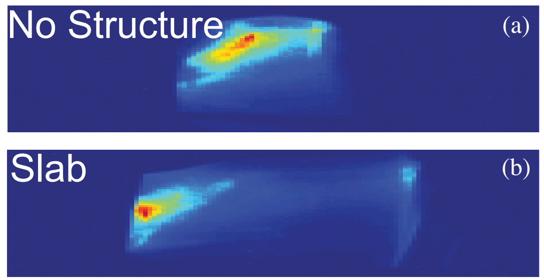
Dielectric Wakefield Acceleration of a Relativistic Electron Beam in a Slab-Symmetric Dielectric Lined Waveguide

G. Andonian,[1] D. Stratakis,[1] M. Babzien,[2] S. Barber,[1] M. Fedurin,[2] E. Hemsing,[3] K. Kusche,[2] P. Muggli,[4] B. O'Shea,[1] X. Wei,[1] O. Williams,[1] V. Yakimenko,[2] and J. B. Rosenzweig[1]



SiO_2, Al
T_{SLAB}=240µm
T_{gap}=240µm
L_z=2cm
ε_N=2mm-mrad





E_0=59MeV
Q=100-900pC
L_z~1.2mm
ε_N=2mm-mrad

Slab geometry allows for:

✧Reduced transverse wakefields

W'_{per}~k^3 -> 0 when $\sigma_{//}$>>a

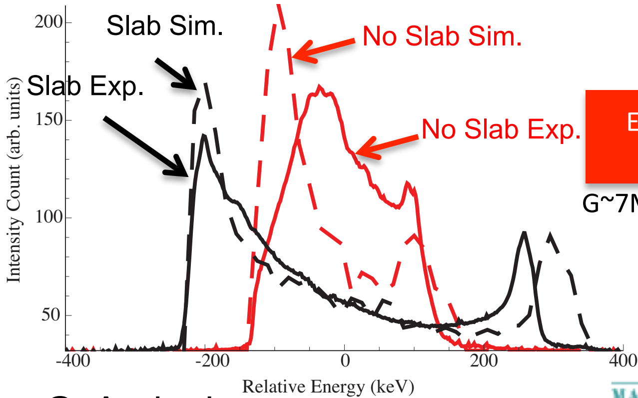
✧More charge per bunch

✧Demonstration of energy gain!

TABLE I. Comparison multibunch BBU of a cylindrical and slab-symmetric linear accelerator with an average accelerating gradient of 1 GeV/m, fundamental wavelength $\lambda_0=2\pi/k_0=10.6\ \mu m$, $a=2.5\ \mu m$, and beam loading quality factor $Q=1000$; only the lowest frequency dipolelike mode is considered, with $\sigma_x=100\ \mu m$ in the slab case. Comparison parameters: average current eNc/λ_0, transverse wake strength $W'_\perp/eN$, and BBU growth length L_g.

	Slab case	Cylindrical case
Average current	490 mA	16 mA
Transverse wake (dominant dipole)	30 V/(mm^2 fC)	10^5 V/(mm^2 fC)
Multibunch BBU growth length	15 cm	1.4 cm

Tremaine
PRE 56 7210 (1997)



Energy Gain

G~7MeV/m

✧Appropriate for "flat" collider beams?

Courtesy G. Andonian

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(Werner-Heisenberg-Institut)

DWA RESULTS

Acceleration in slab symmetric DWA

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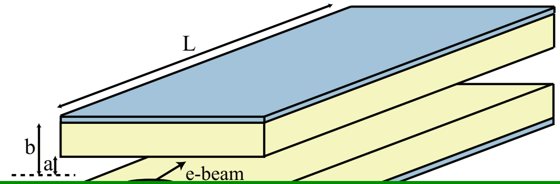
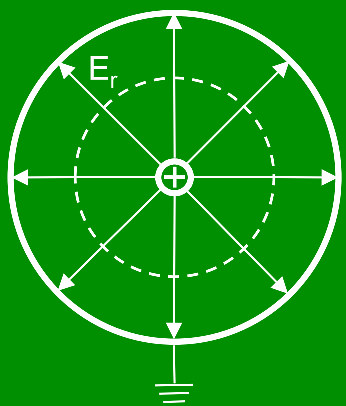


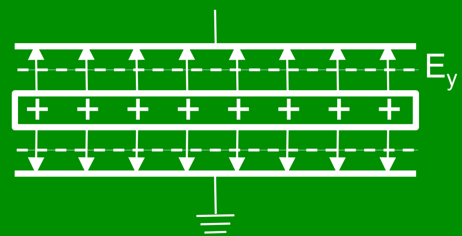
SiO_2, Al
T_{SLAB}=240µm
T_{gap}=240µm
L_z=2cm
ε_N=2mm-mrad

In cylindrical coordinates the field decreases as 1/r:



$$E_r(r) = \frac{1}{2\pi\varepsilon_0} Q_{lin} \frac{1}{r}$$

In Cartesian coordinates the field is constant:



$$E_y(x) = \frac{1}{\varepsilon_0} Q_{lin} = cst$$

-400 -200 0 200 400
Relative Energy (keV)

✧Appropriate for "flat" collider beams?

Courtesy G. Andonian

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OUTLINE

✧Introduction

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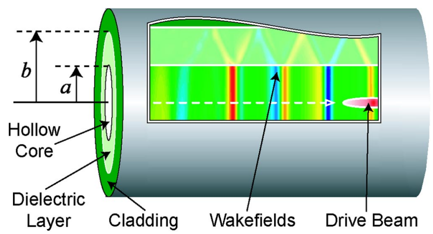
✧Cherenkov wakes in dielectric layers

✧Summary

✧ Simple structure to fabricate
✧ Demonstrated >1GeV/m
✧ Demonstrated energy transfer efficiency
✧ Symmetric e^-/e^+
✧ Dielectric "CLIC"



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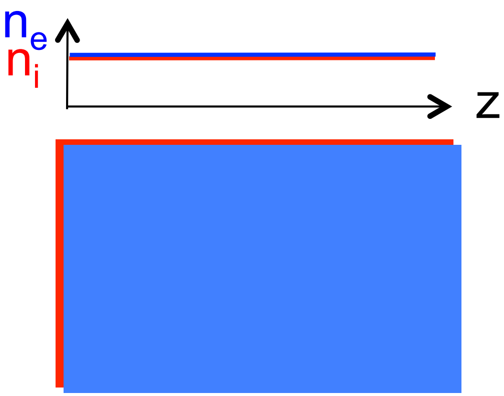
✧Summary

✧Mmmmm … plasmas, is there anything they can't do?
(adapted from H. J. Simpson)

http://simpsons.wikia.com/wiki/Mmm...

PLASMAS

✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



Wikipedia Plasma: (from Greek πλάσμα, "anything formed"[1]) is one of the four fundamental states of matter, the others being solid, liquid, and gas. A plasma has properties unlike those of the other states.

Plasma: "Gas" of charged (ionized) particles (e^-, ions) that exhibits a collective behavior (screening, waves, etc.)

- ✧First plasma wave discovered: Langmuir wave
- ✧Dispersion relation: $\omega^2=\omega_{pe}^2=n_e e^2/\varepsilon_0 m_e$, ω_{pe} plasma frequency, n_e plasma e^- density
- ✧Longitudinal electric field, E_z//k, B=0 – electrostatic wave
- ✧Erwin Langmuir, Nobel Prize in chemistry(!), 1932
- ✧Hannes Alfvèn, 1970, MHD

[1] b) the body, as fashioned by the Creator
c) of a story which is fictitious but possible
d) pretence

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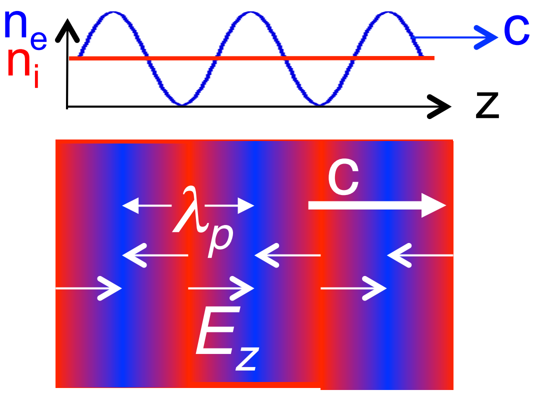
PLASMAS

✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



LARGE
Collective response!

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0}$$

$$\omega_{pe}=\left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$$ Plasma Frequency

$$k_p E_z=\frac{\omega_{pe}}{c}E_z=\frac{n_e e}{\varepsilon_0}$$

$$E_z=\left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2}\cong 100\sqrt{n_e\left(cm^{-3}\right)}=1\,GV/m$$

n_e=10^{14} cm^{-3}

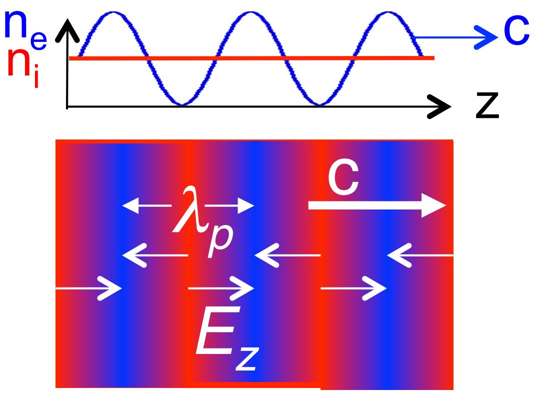
Cold Plasma "Wavebreaking" Field

$$E_{WB}=m_e c\omega_{pe}/e$$

Dawson, PRL (1959)

PLASMAS

✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



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Dawson, PRL (1959)

✧Plasmas can sustain very large (collective) E_z-field, acceleration

✧Wave, wake phase velocity = driver velocity (~c when relativistic, $\omega^2=\omega^2_{pe}$)

✧Plasma is already (partially) ionized, difficult to “break-down”

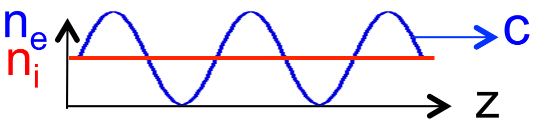
✧No structure to build …. Wave in a uniform medium …

✧Plasmas wave or wake can be driven by:

➢Intense laser pulse (LWFA)
➢Dense particle bunch (PWFA)

PLASMAS

✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



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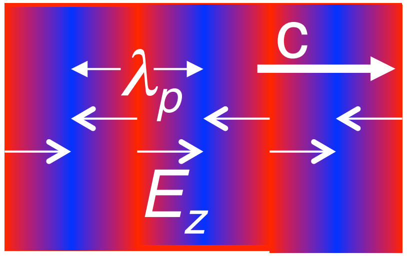

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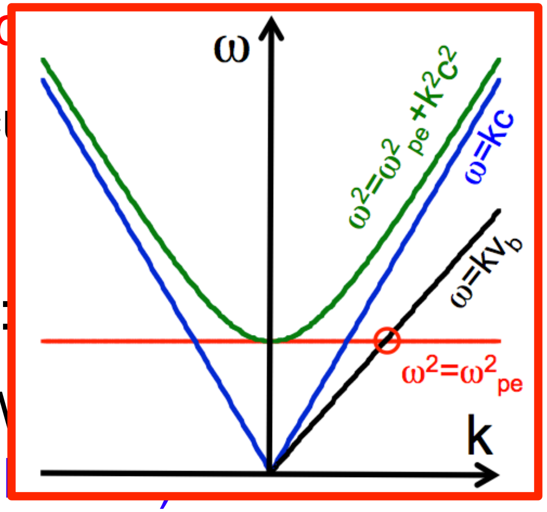


Single mode system!

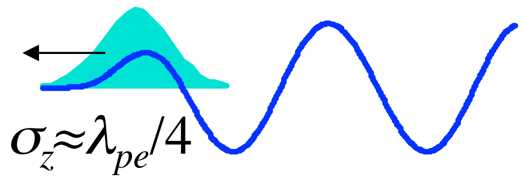
➢Intense laser pulse (LW
➢Dense particle bunch (

4 PLASMA-BASED ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

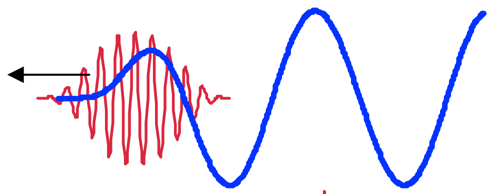
  A high energy particle bunch (e^-, e^+, ...)

  P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)



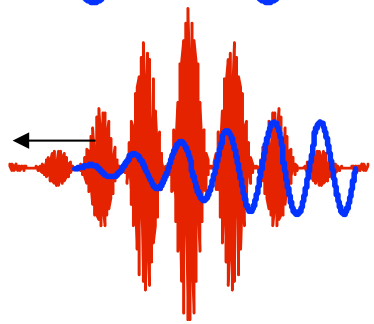
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



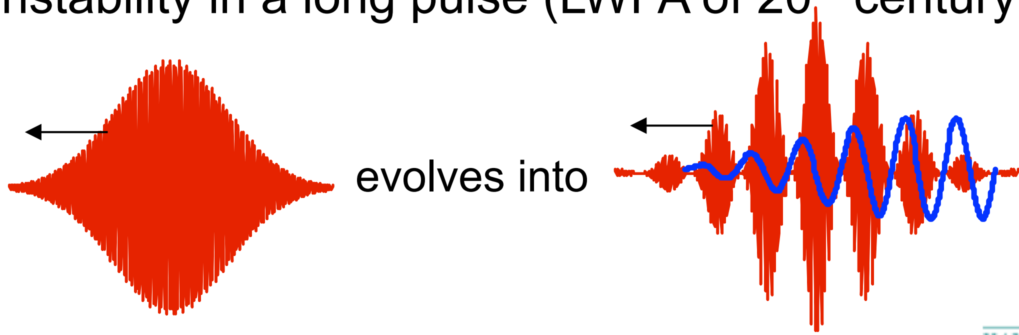
- Plasma Beat Wave Accelerator (PBWA) *

  Two frequencies laser pulse, i.e., a train of pulses



- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

  Raman forward scattering instability in a long pulse (LWFA of 20th century)



*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

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  A high energy particle bunch (e^-, e^+, ...)

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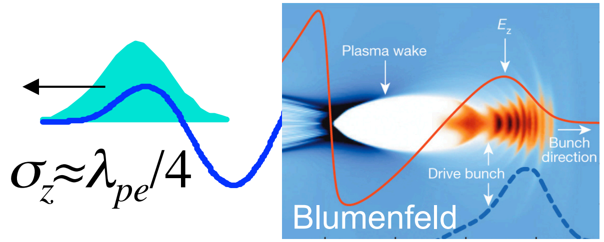

- Laser Wakefield Accelerator (LWFA) *

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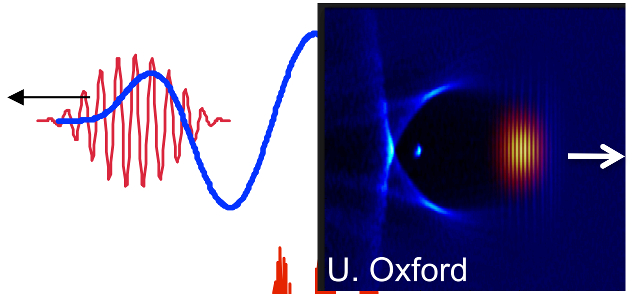
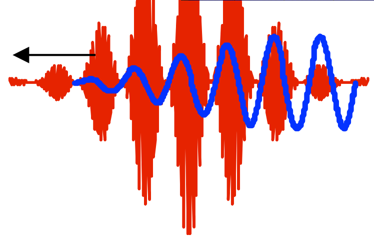


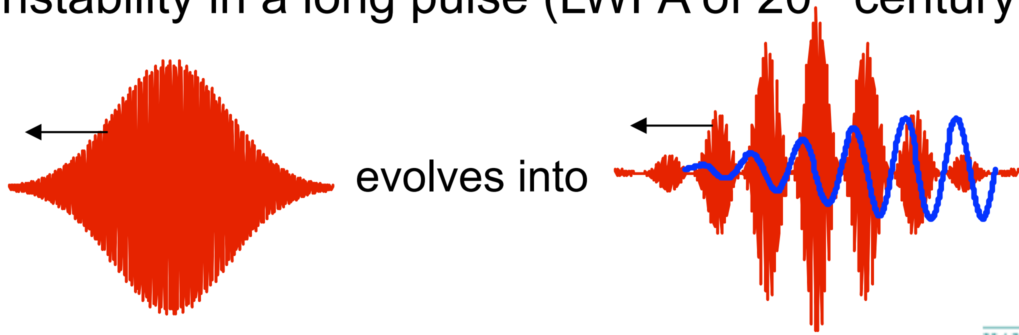
- Plasma Beat Wave Accelerator (PBWA) *

  Two frequencies laser pulse, i.e., a train of pulses



- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

  Raman forward scattering instability in a long pulse (LWFA of 20th century)



*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

OUTLiNE

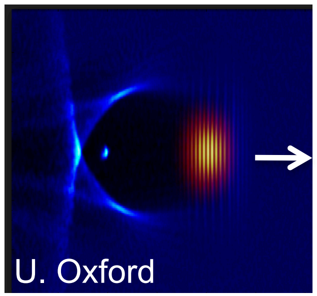
✧Introduction

✧Novel Acceleration Techniques

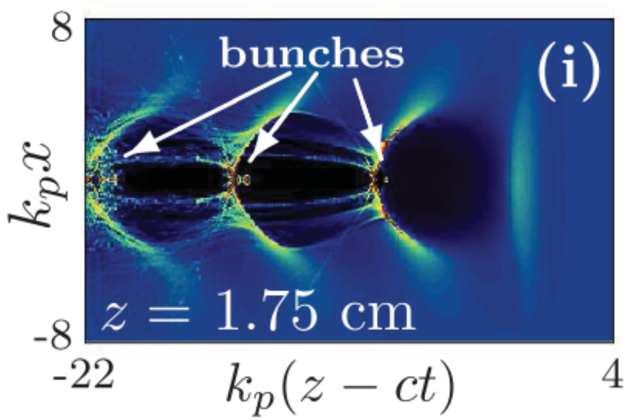
Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

✧Intense laser pulse to drive wakefields in a plasma

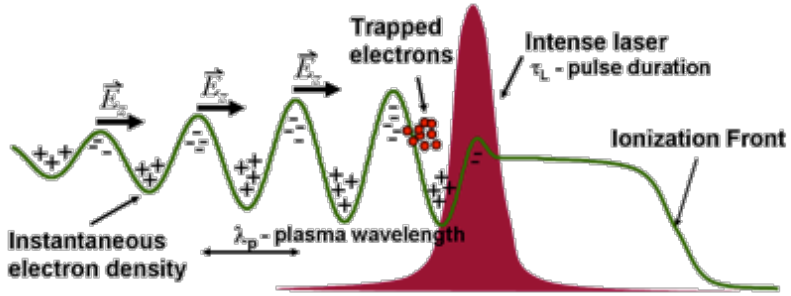
✧Summary



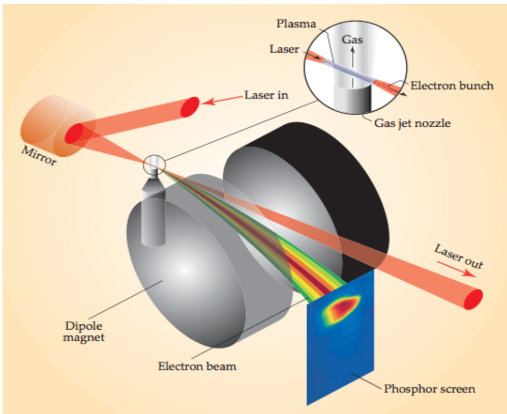
LASER WAKEFiELD ACCELERATOR (LWFA)



Laser pulse ponderomotive force (~light pressure) drives the wakefields

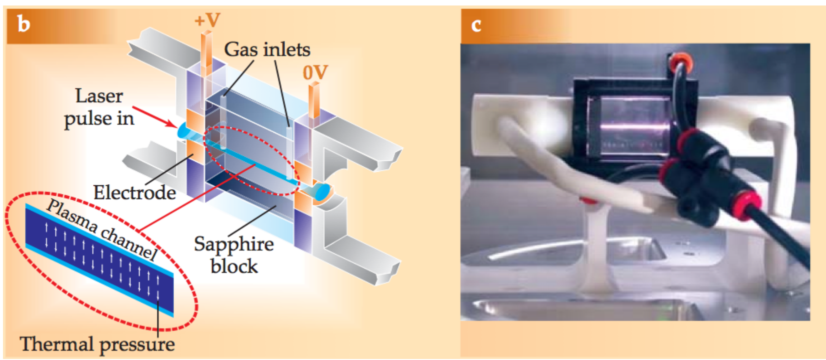


Typical parameters:
Laser: $I=10^{18}$-10^{20}W/cm^2, ~40fs, w_0=10µm
Plasma: $n_e=10^{18}$-10^{20}cm^{-3}



Gas Jet Plasma
(short, injector)

✧Most active field
✧Availability of TW Ti:Sapphire laser systems
✧Few TW for 10-100MeV e$^-$ in a few mm
✧Medical, THz/x-ray source, …



Capillary Discharge Plasma (long, accelerator)

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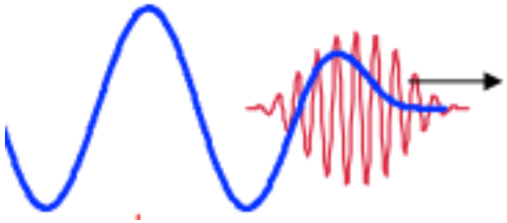
Laser Wakefield Accelerator (LWFA)

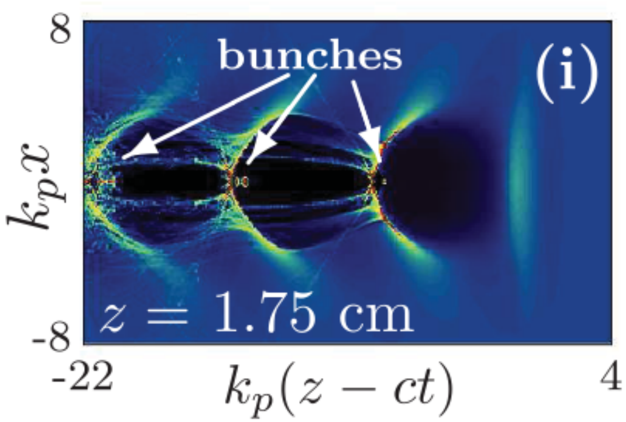
✧Wakefields driven by ponderomotive force of an intense laser beam

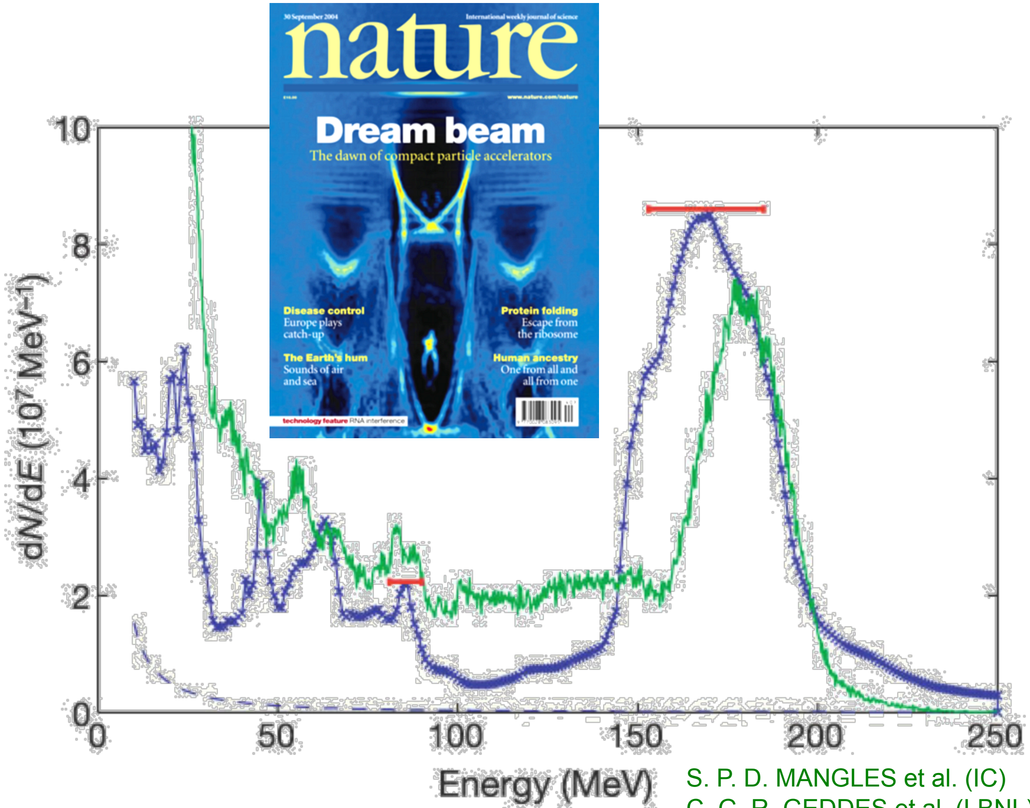
$a_0=v_{osc}/c=eE_0/mc\omega_0^2\sim1$ $a_0=v_{osc}/c=8.5\times10^{-10}\,\lambda_0[\mu m]\ I_0^{1/2}[Wcm^{-2}]$

"Forced" or "bubble" regime



$a_0\sim1$





S. P. D. MANGLES et al. (IC)
C. G. R. GEDDES et al. (LBNL)
J. FAURE et al. (LOA)
Nature 431, 2004

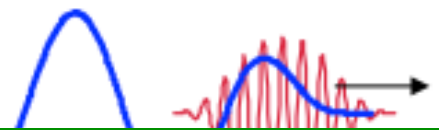
✧""Monoenergetic"" bunches (self-trapped)
✧Short laser pulse (a_0>1)

LASER WAKEFiELD ACCELERATOR (LWFA)

✧Wakefields driven by ponderomotive force of an intense laser beam

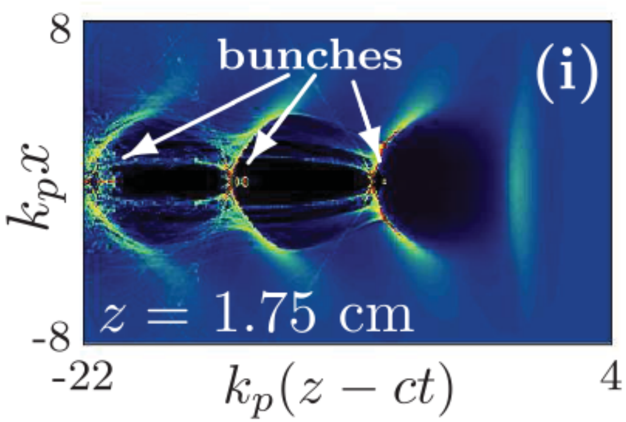
$a_0=v_{osc}/c=eE_0/mc\omega_0^2\sim 1$ $a_0=v_{osc}/c=8.5\text{x}10^{-10}\,\lambda_0[\mu m]\;I_0^{1/2}[Wcm^{-2}]$

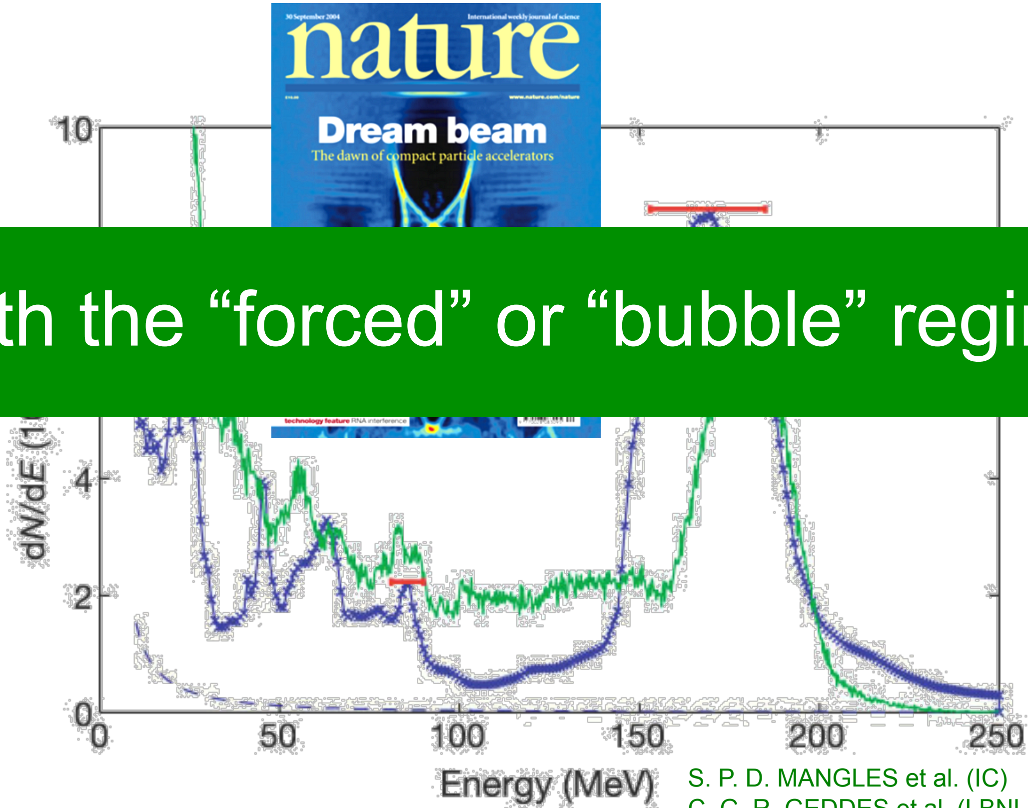
"Forced" or "bubble" regime



Finite energy spread with the "forced" or "bubble" regime

a_0 1





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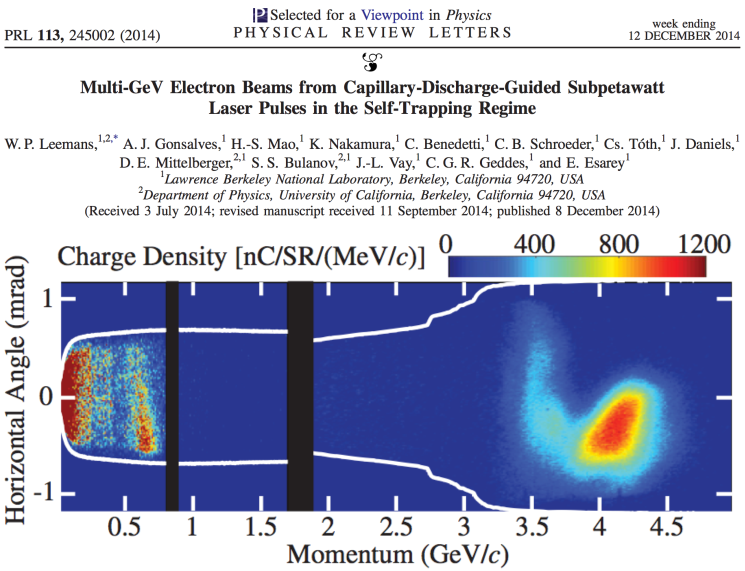
✧Short laser pulse (a_0>1)

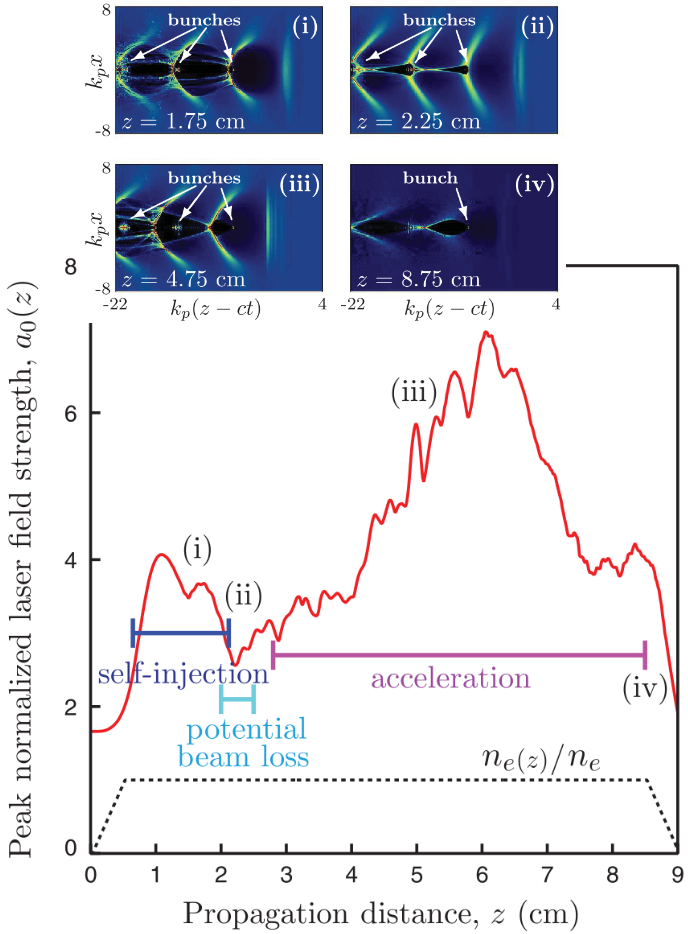
LWFA RESULTS


Selected for a Viewpoint in Physics
PRL 113, 245002 (2014) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2014

Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime

W. P. Leemans,[1,2,*] A. J. Gonsalves,[1] H.-S. Mao,[1] K. Nakamura,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. Daniels,[1] D. E. Mittelberger,[2,1] S. S. Bulanov,[2,1] J.-L. Vay,[1] C. G. R. Geddes,[1] and E. Esarey[1]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

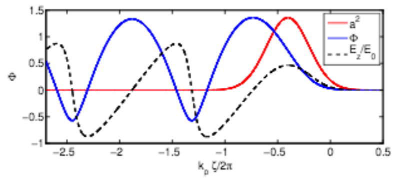
E_{av}=4.2 GeV, $\Delta E/E_{RMS}$=6%
Q=6 pC
Θ_{rms}=0.3 mrad
L_p=9cm, $n_e \approx 7\times10^{17}$cm^{-3}
Capillary discharge
$P_{laser} \approx$0.3PW
W=16J, $\sigma_r \approx$52µm, $\tau \approx$42fs

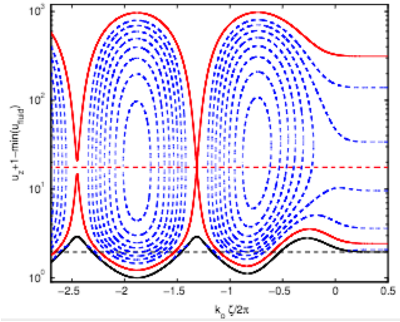


✧PW laser pulse (300TW)
✧Peak energy gain 4.2GeV in <10cm
✧Self-trapped plasma e^-

✧LWFA does NOT need conventional injector
✧e^- trapped from the plasma

LWFA INJECTORS (some)





1) Wave breaking: drive the wave very non linearly (Dawson, PRL,1956)

2) Ionization trapping
(Oz, PRL 98, 084801 (2007), Hidding, PRL 108 035001 (2012))

3) Three- two laser beams
(Umstadter PRL 76, 2073 (1996), Esarey, PRL 79, 2682 (1997)

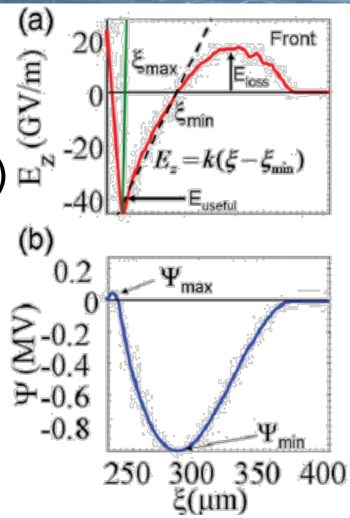
4) Density step (Suk PRL 86, 1011)

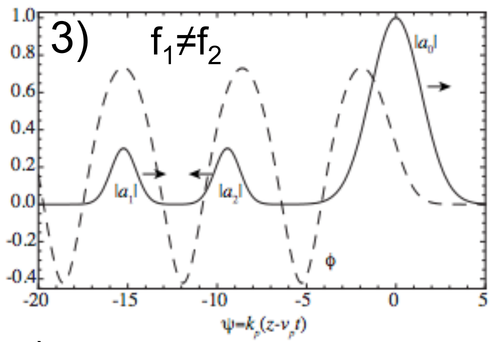
5) Density down-ramp

6) Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010)

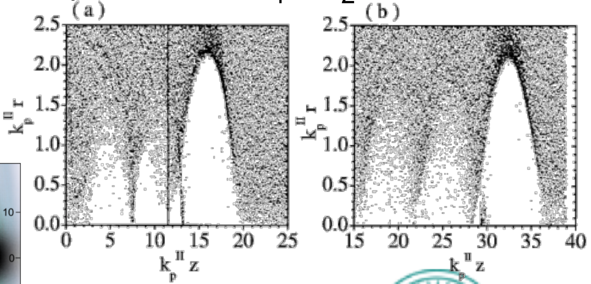
7) External injection

2)

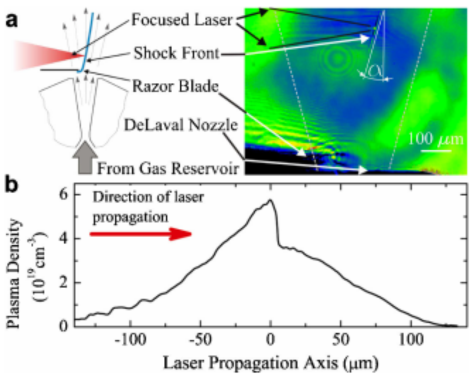


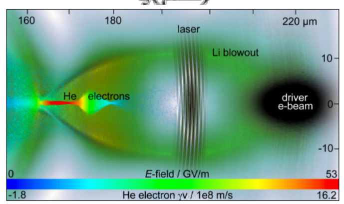


4-5) $n_1 > n_2$



5-6)





Physics of laser-driven plasma-based electron accelerators, E. Esarey et al., Rev. Mod. Phys. 81, 1229 (2009)
Overview of plasma-based accelerator concepts, E. Esarey et al., IEEE TPS, 24(2), 252 (1996)

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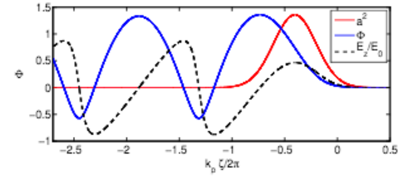
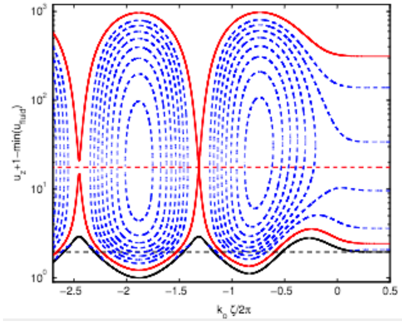
LWFA INJECTORS (some)





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3) Three- two laser beams
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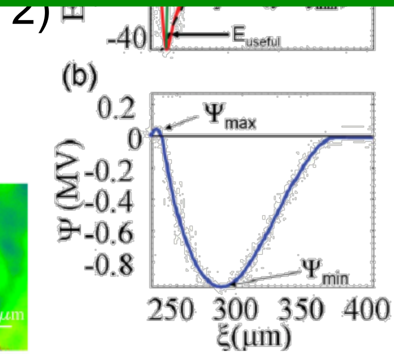
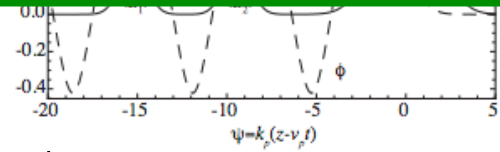
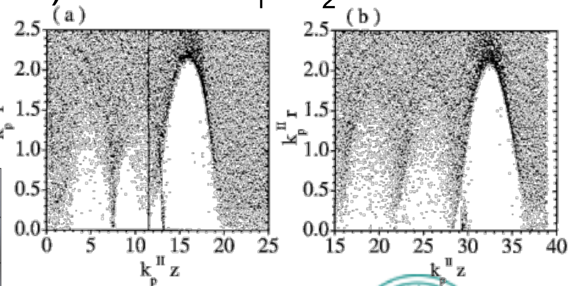
LWFA is also an e^- injector





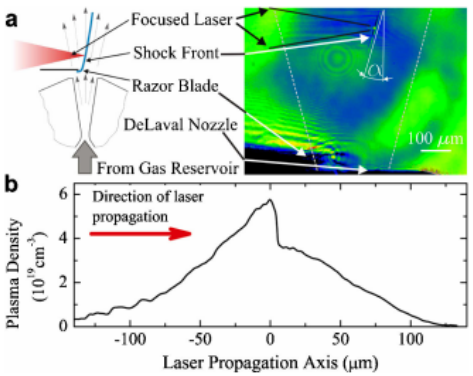
6) Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010)

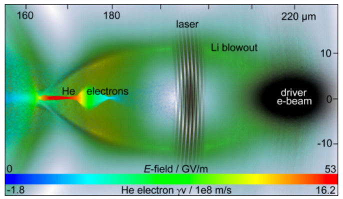
4-5) $n_1 > n_2$



7) External injection

5-6)





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OUTLINE

✧Introduction

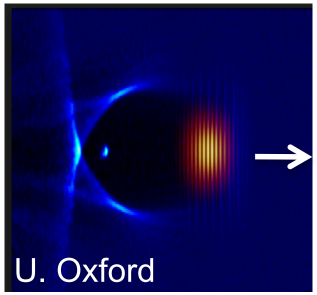
✧Novel Acceleration Techniques

Medium / Driver	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

✧Intense laser pulse to drive wakefields in a plasma

✧Summary

- ✧No structure to fabricate
- ✧Demonstrated >100GeV/m
- ✧Demonstrated large energy gain
- ✧LWFA is also the injector (e^-)
- ✧Not symmetric e^-/e^+



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OUTLINE

✧Introduction

✧Novel Acceleration Techniques

Medium / Driver	Dielectric	Plasma
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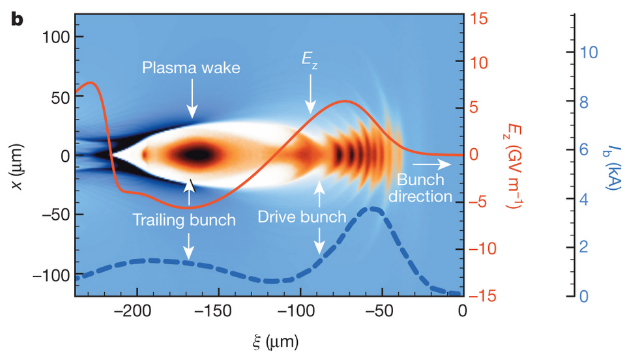
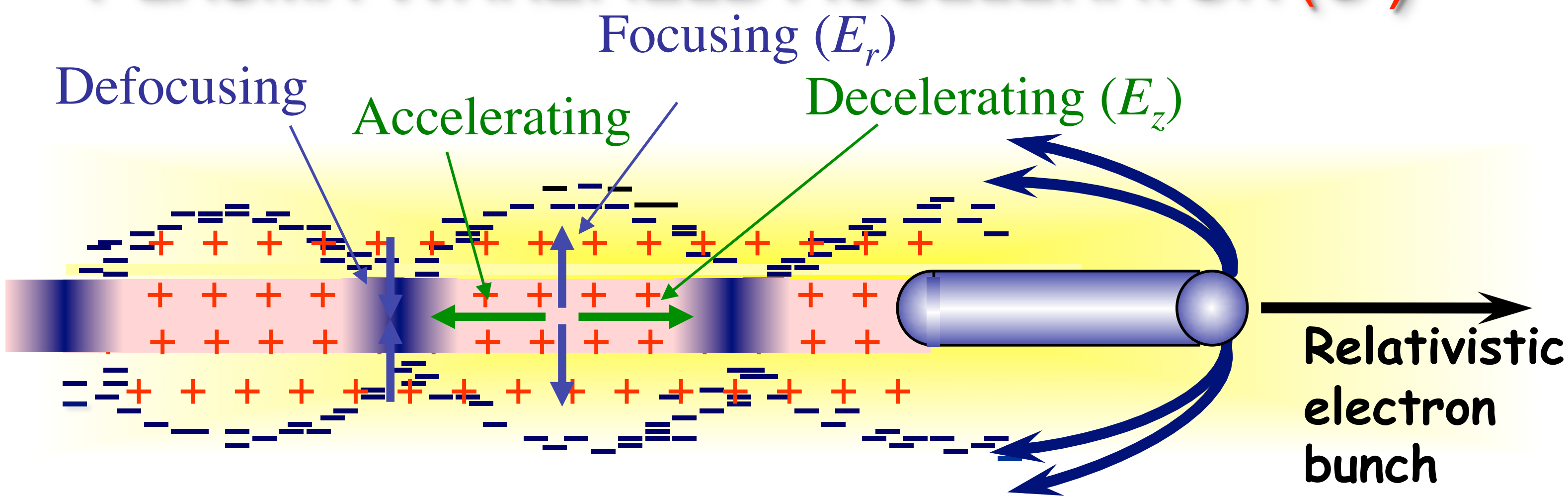
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

✧Dense, relativistic particle bunch (e^-, e^+, p^+, …) to drive wakefields in plasma

✧Summary

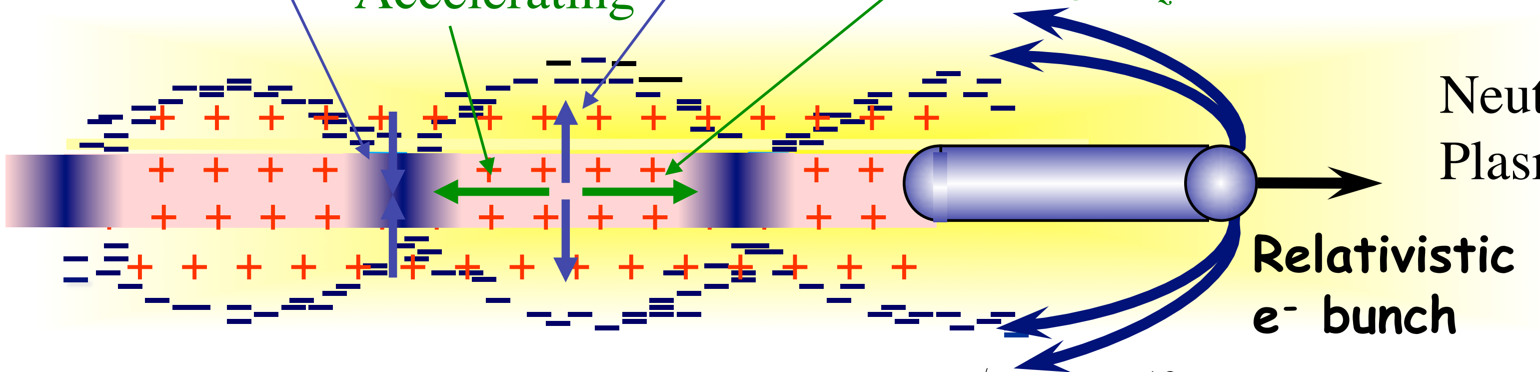


PLASMA WAKEFIELD ACCELERATOR (e^-)



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge force => deceleration + focusing (MT/m)
- Plasma e^- rush back on axis => acceleration, GV/m
- Ultra-relativistic driver => ultra-relativistic wake
  => no dephasing
- Particle bunches have long "Rayleigh length"
  (beta function $\beta^*=\sigma^{*2}/\varepsilon\sim$cm, m)
- Acceleration physics identical PWFA, LWFA

PWFA NUMBERS (e^-)



✧Linear theory (n_b<<n_e) scaling:

$$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2} \approx N/\sigma_z^2$$

$@\ k_{pe}\sigma_z \approx \sqrt{2}$ (with $k_{pe}\sigma_r$ <<1) $\qquad k_{pe} = \omega_{pe}/c \propto n_e^{1/2}$

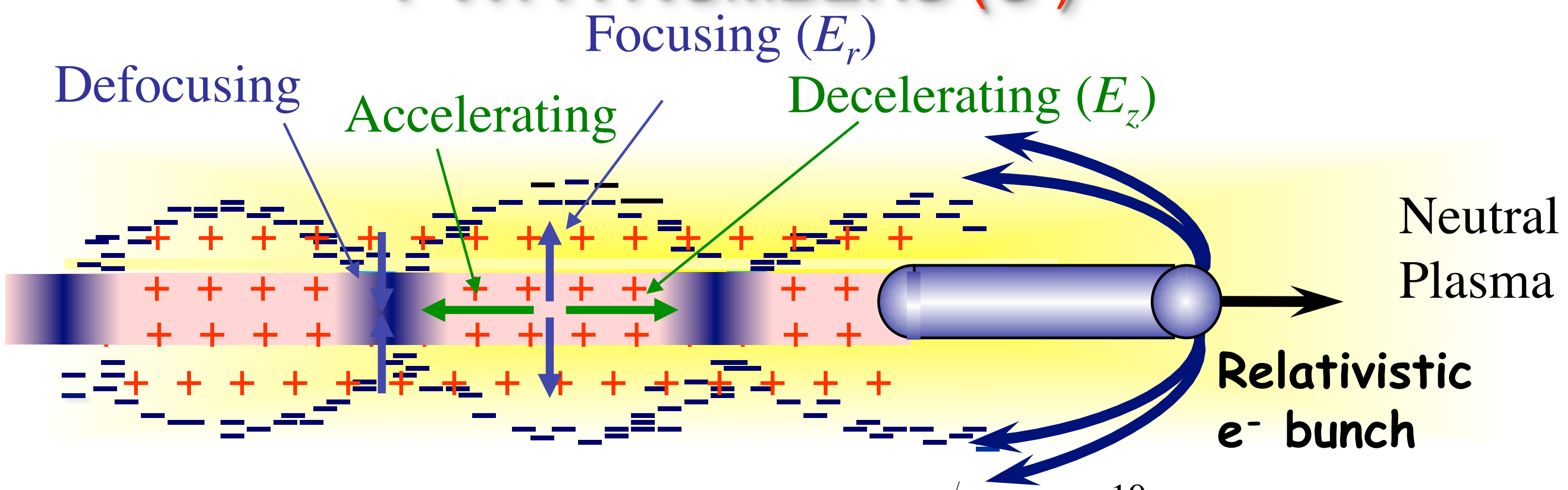
✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c}$ $\quad$ (n_b>n_e)

✧N=2×10^{10}: σ_z=600 μm, n_e=2×10^{14} cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
σ_z= 20 μm, n_e=2×10^{17} cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

✧Frequency: 100GHz to >1THz, "structure" size 1mm to 100μm

✧Conventional accelerators: MHz-GHz, E_{acc}<150 MV/m, B_θ/r<2 kT/m

PWFA NUMBERS (e^-)



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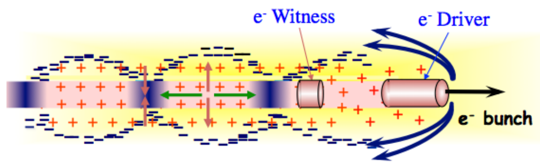
FIRST PWFA OBSERVATION (e^-)



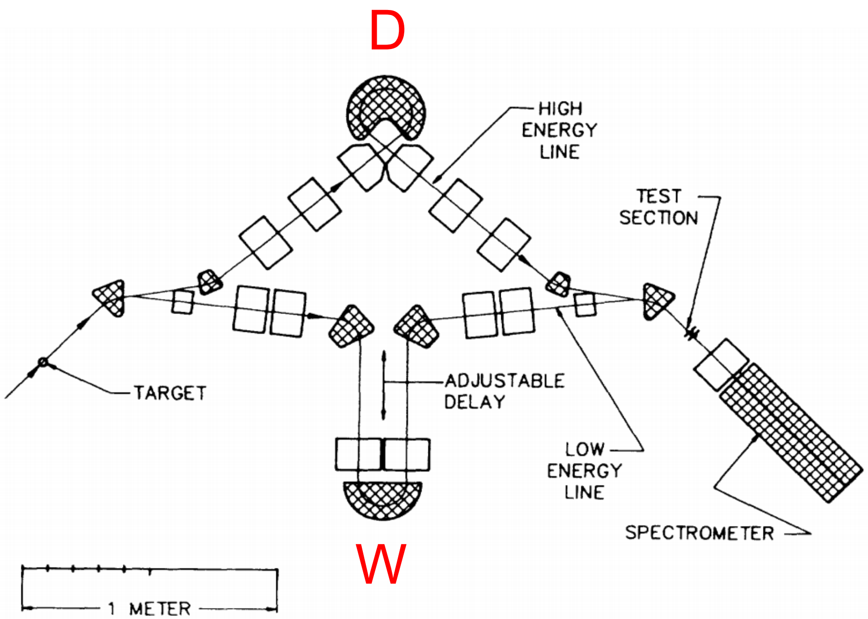


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

Rosenzweig, PRL 61, 98 (1988)

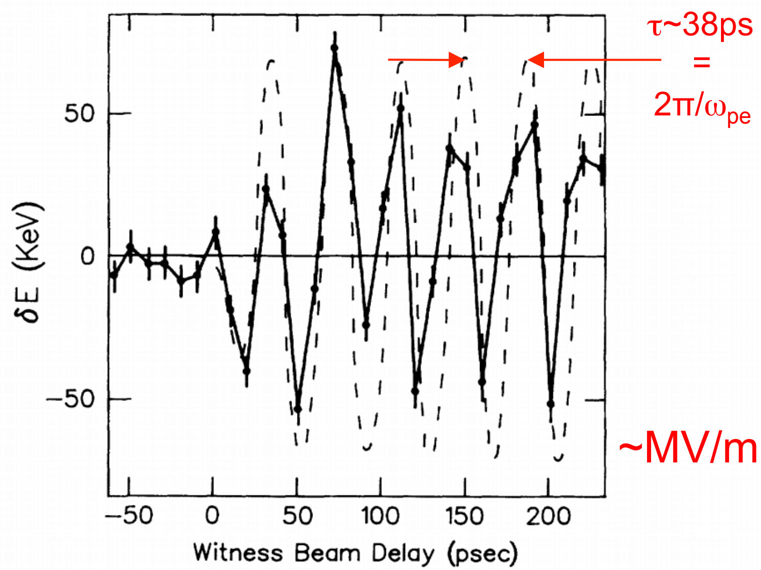
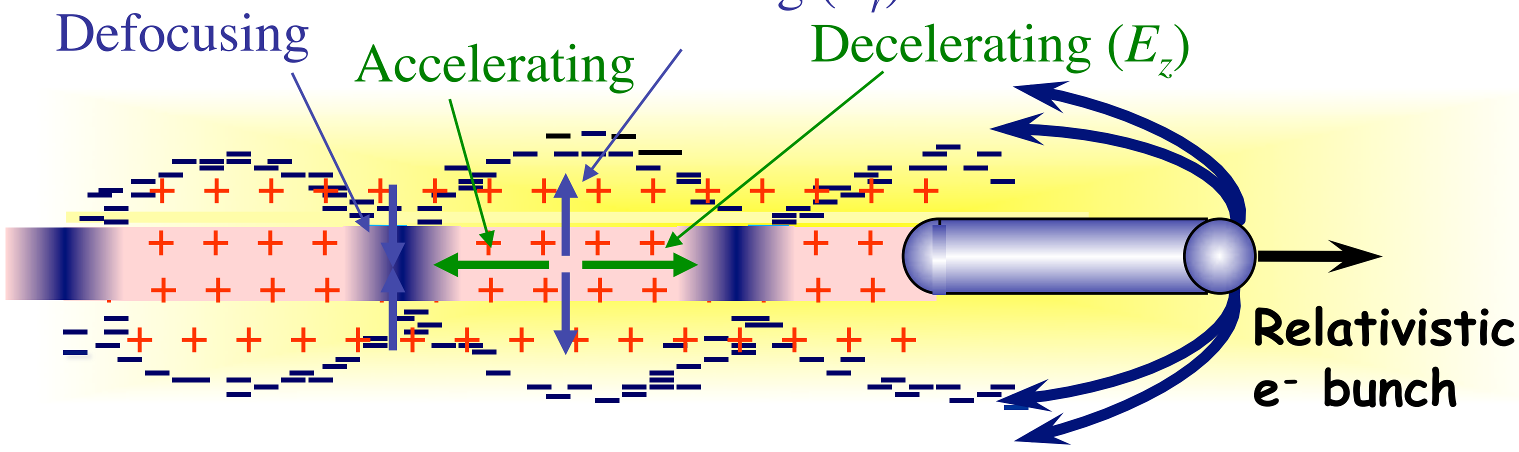


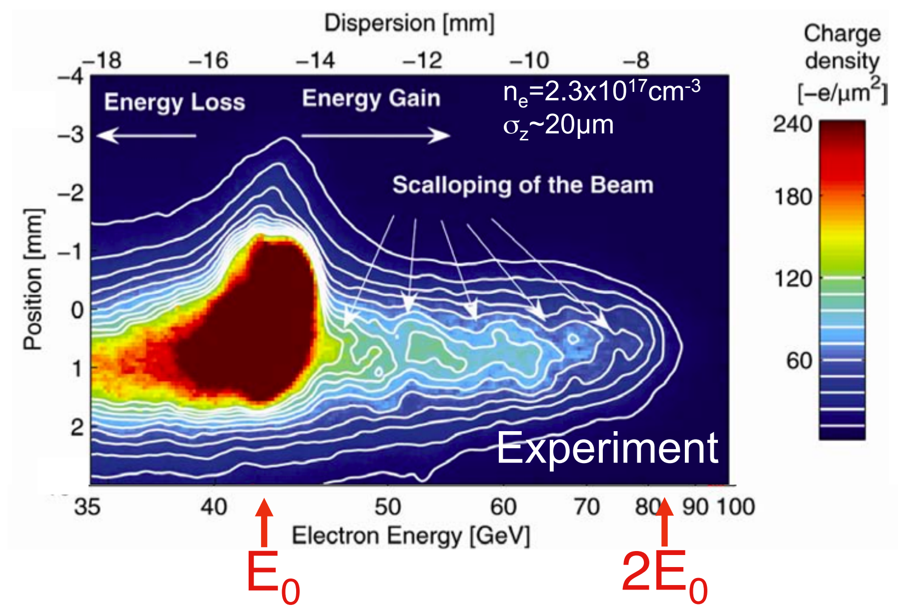
FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6 \times 10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

- ✧Drive/witness bunch experiment
- ✧Low wakefield amplitudes (low n_e, long bunches, …)

Plasma Wakefield Accelerator (e^-)



Blumenfeld, Nature 445, 741 (2007)



42 => 84GeV in 85cm! 50GeV/m

Muggli, Phys. Rev. Lett. 93, 014802 (2004)
Hogan, Phys. Rev. Lett. 95, 054802 (2005)
Muggli, Hogan, Comptes Rendus Physique, 10 (2-3), 116 (2009)
Muggli, New J. Phys. 12, 045022 (2010)

n_e=2.3x10^{17}cm^{-3}
σ_z~σ_r~20µm
N=2x10^{10}
E_0=42GeV
I~10kA

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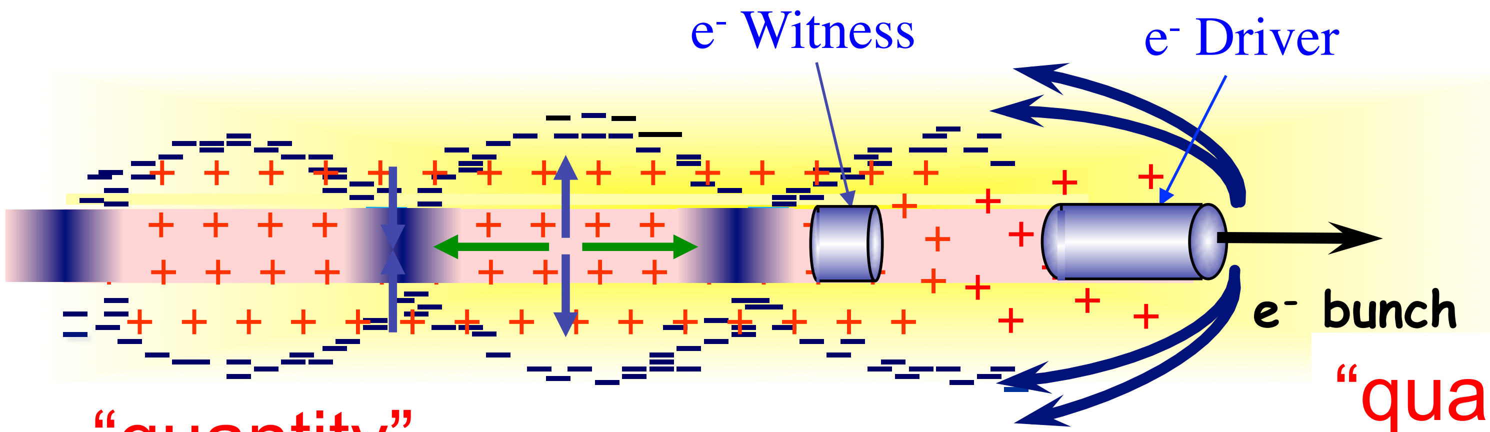
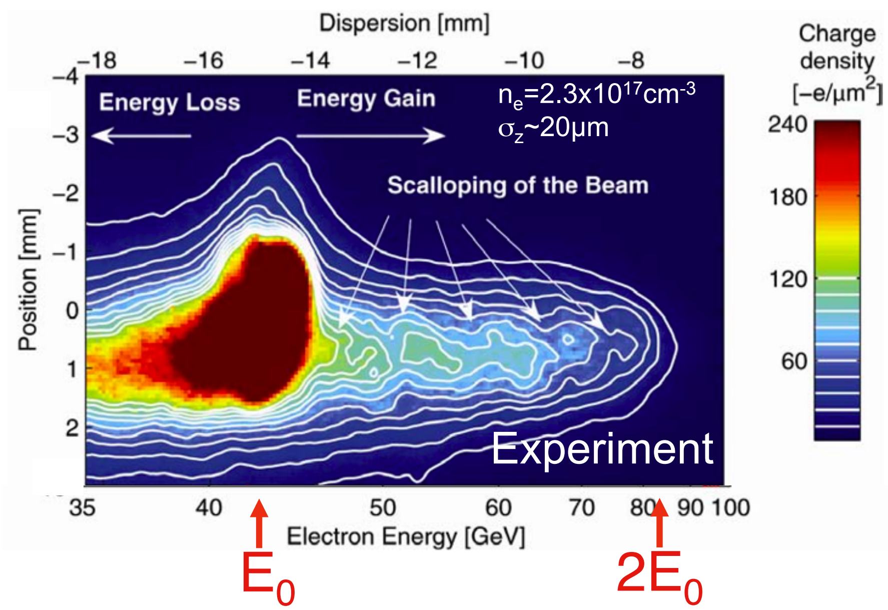
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)



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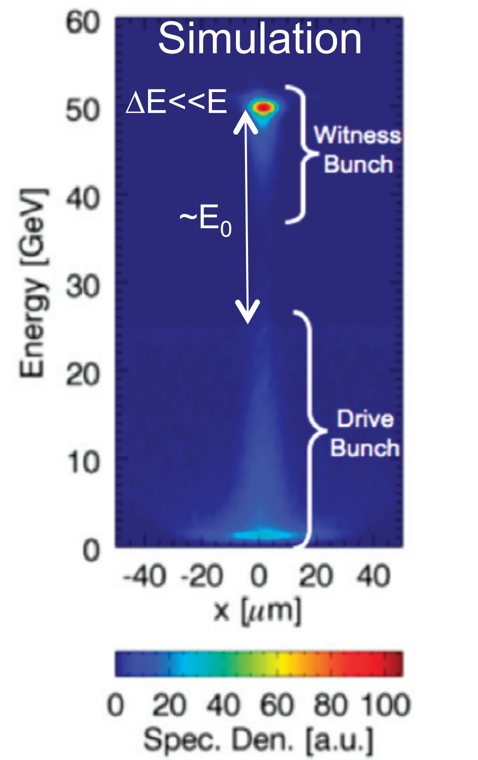
SLAC
FACET

E200

Hogan,
NJP 12,
055030 (2010)



PLASMA WAKEFIELD ACCELERATOR (e^-)

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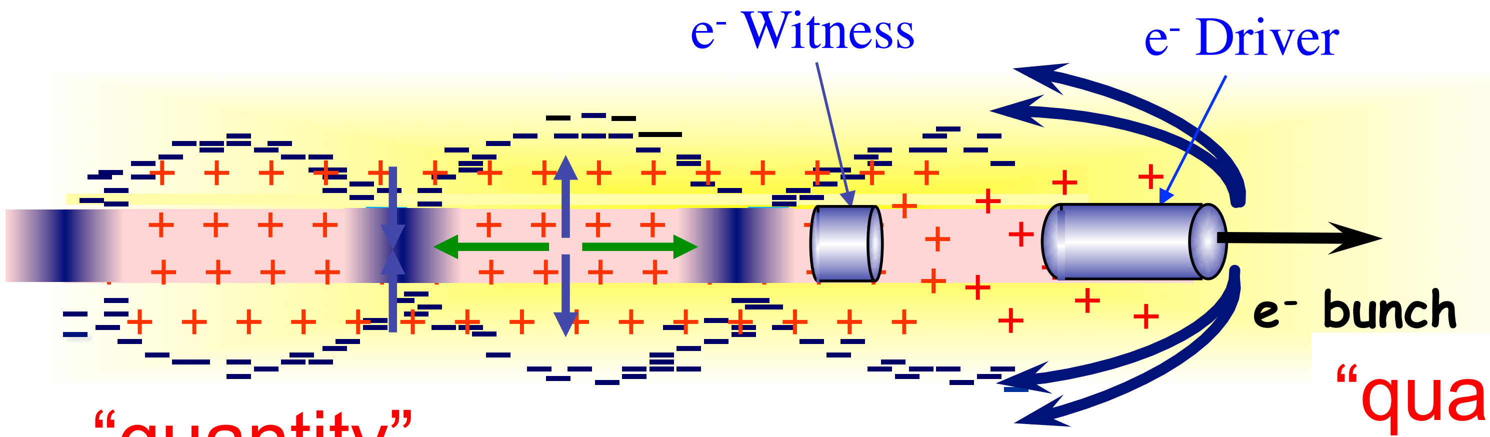

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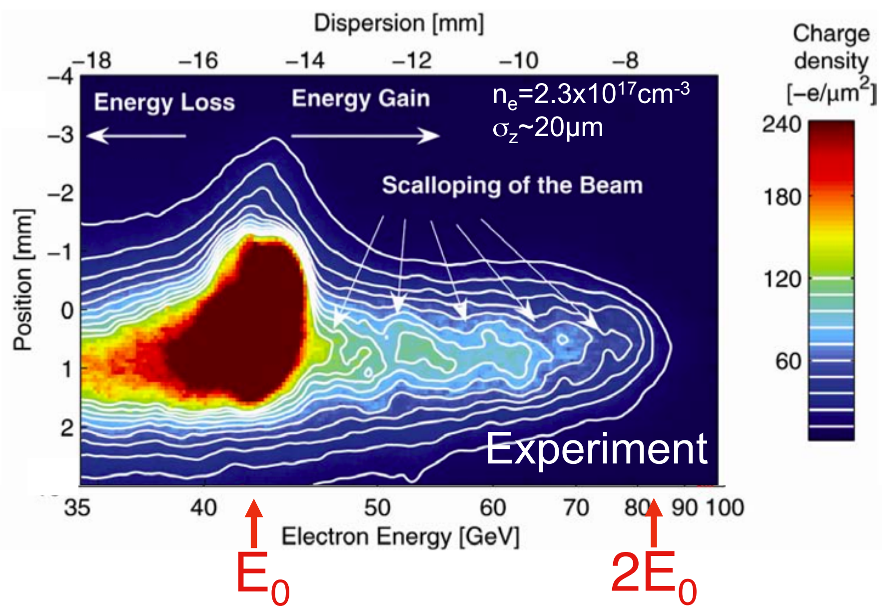

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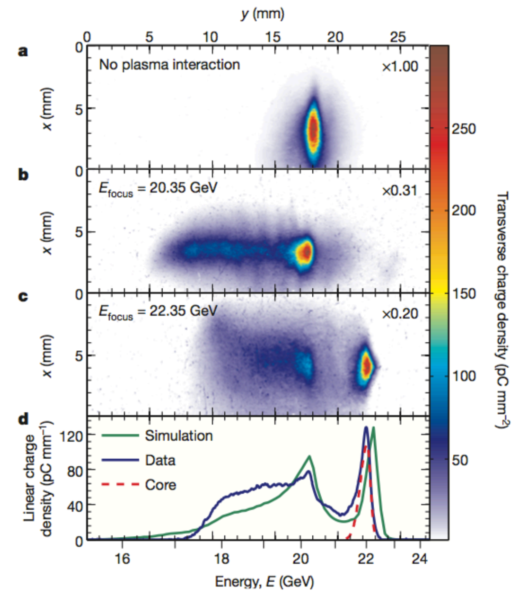
SLAC FACET

E200

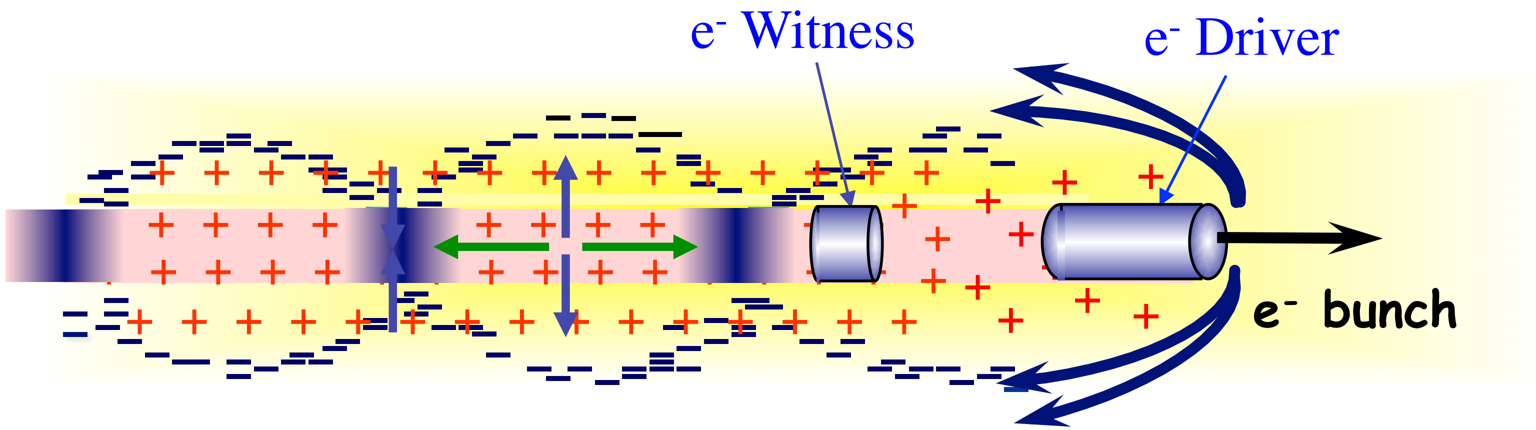
Litos, Nature 515(6) 92 (2014)



$\Delta E/E$~%

η~30%

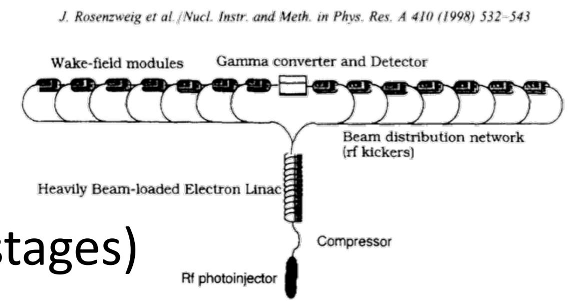
e⁻-DRiVEN PWFA



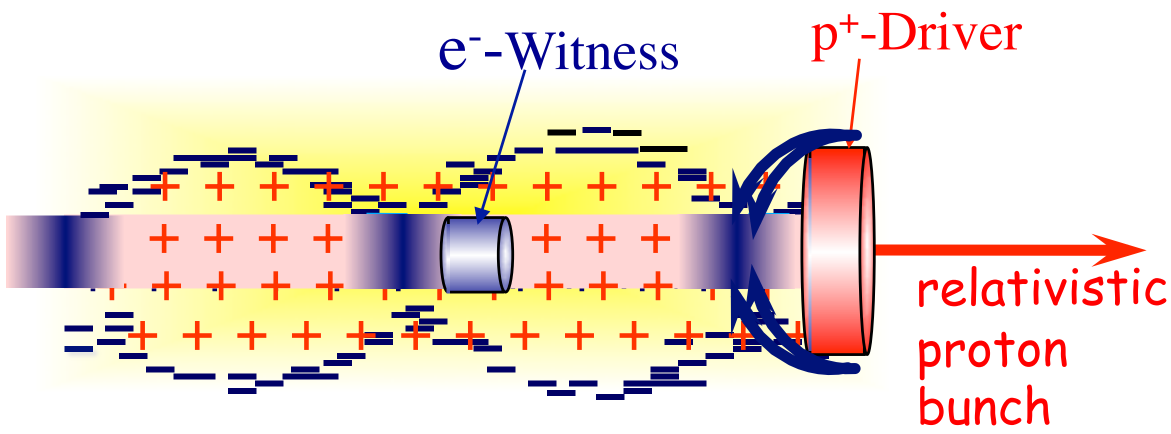
✧ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ

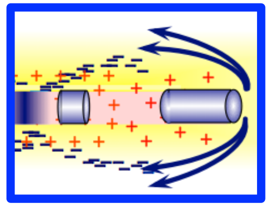
✧SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J

✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)



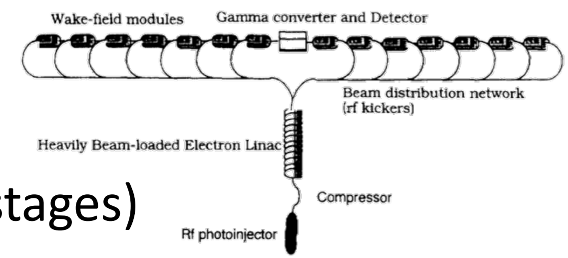
p+-DRiVEN PWFA? YES BUT WHY?





✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ

J. Rosenzweig et al. /Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543

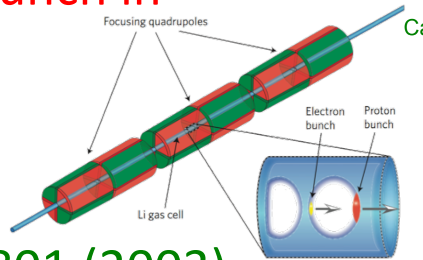


✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J

✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ

✧A single SPS or LHC bunch could produce an ILC bunch in a <u>single</u> PWFA stage!



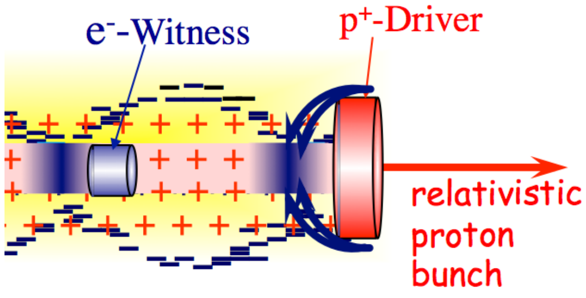
Caldwell, Nat. Phys. 5, 363, (2009)

✧Large <u>average</u> gradient! (≥1GeV/m, 100's m)

✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)

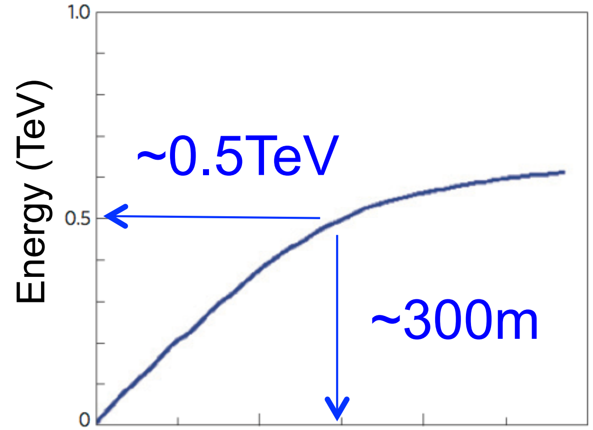
PROTON-DRIVEN PWFA

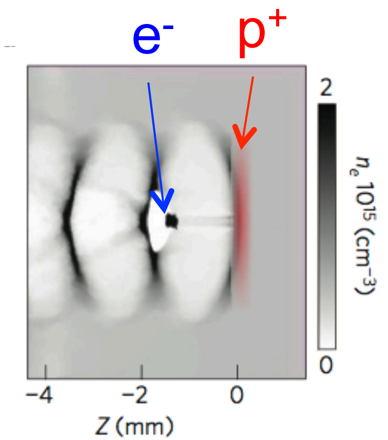
Caldwell, Nat. Phys. 5, 363, (2009)



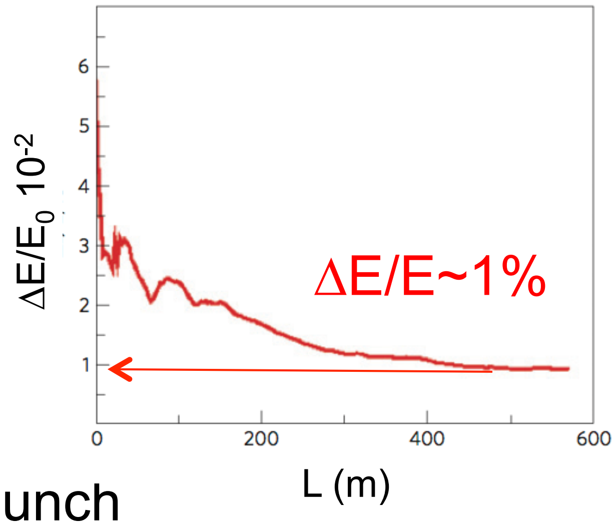
e⁻:	p⁺:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
N=10^{10}	N=10^{11}
W_0=16J	W_0=16kJ
W_f=1kJ	

Single Stage





Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	T m^{-1}
Magnet length		0.7	m



- ✧Accelerate an e⁻ bunch on the wakefields of a p⁺ bunch
- ✧Single stage, no gradient dilution
- ✧Gradient ~1 GV/m over 100's m
- ✧Operate at lower n_e (6×10^{14}cm^{-3}), larger $(\lambda_{pe})^3$, easier life …

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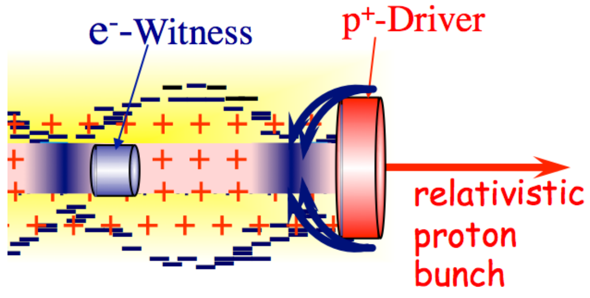
PROTON-DRIVEN PWFA

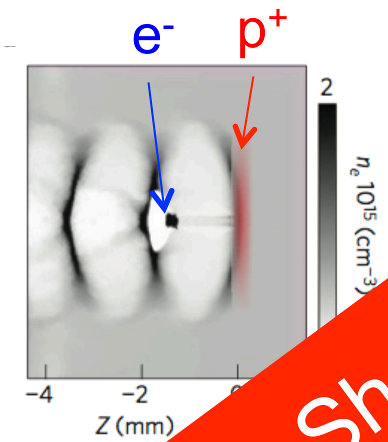
Caldwell, Nat. Phys. 5, 363, (2009)

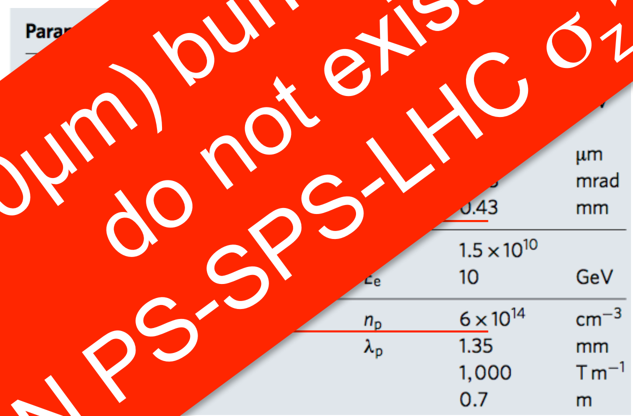


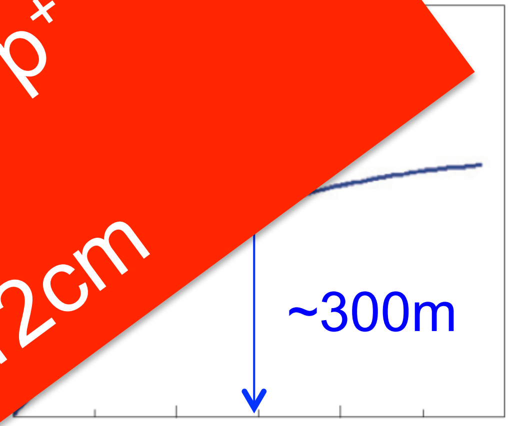
e^-:
E_0=10GeV
N=10^{10}
W_0…

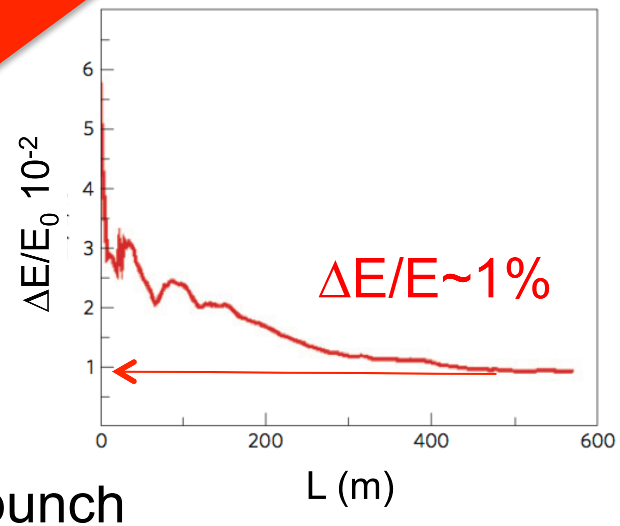
p^+:
E_0=1T…

Single
Stage









Short (100µm) bunches with 10^{11} p^+
do not exist!!!
CERN PS-SPS-LHC σ_z~6-12cm

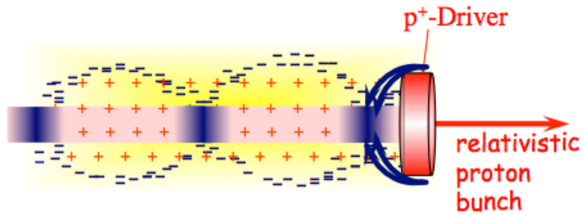
- ✧ … n the wakefields of a p^+ bunch
- ✧ … ient dilution
- ✧ Gr… n over 100's m
- ✧ Ope… ower n_e ($6x10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

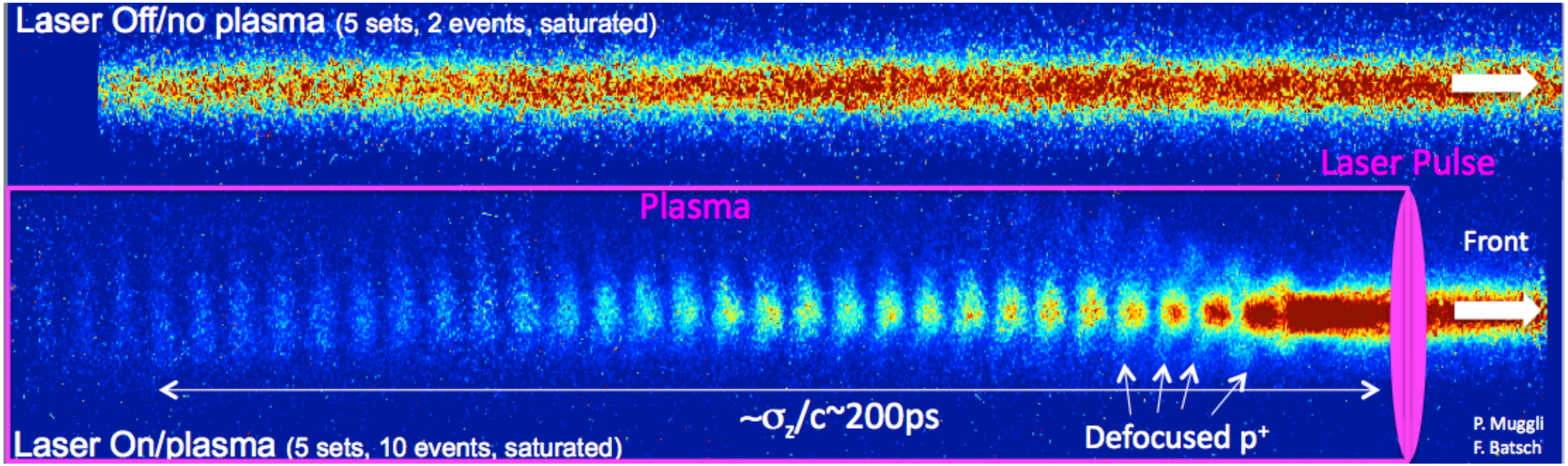
MAX-PLANCK-GESELLSCHAFT

AWAKE @ CERN

✧Use a long ($\sigma_z >> \lambda_{pe}$), relativistic (400GeV/p^+), high energy (~20kJ) p^+ bunch to resonantly drive large amplitude wakefields (E_z~1GV/m) in a long (~10^+m) plasma

✧Demonstrated self-modulation of the long proton bunch by the plasma wakefields





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✧Use a long (σ_z>>λ_{pe}), relativistic (400GeV/p^+), high energy (~20kJ) p^+ bunch to resonantly drive large amplitude wakefields (E_z~1GV/m) in a long (~10⁺m) plasma

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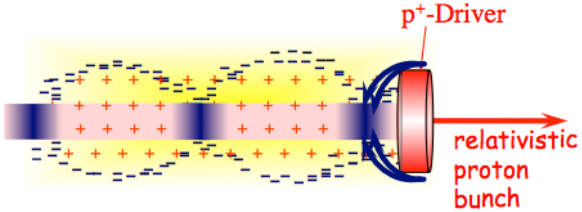

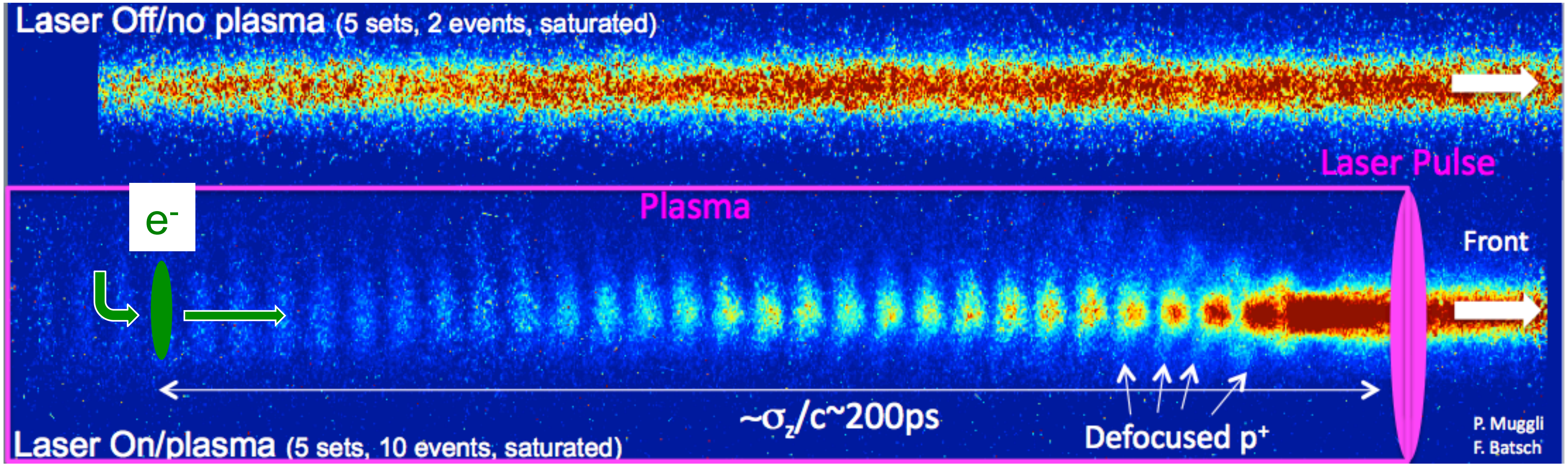

✧External injection of e^- for acceleration

✧Development of a physics case and e^-/p^+ collider design

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OUTLINE

✧Introduction

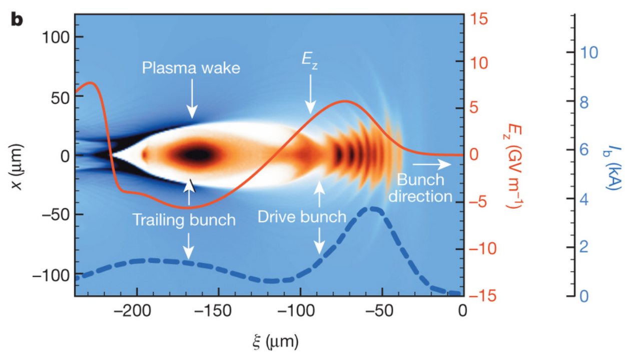
✧Novel Acceleration Techniques

Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

✧Dense, relativistic particle bunch (e^-, e^+, p^+, …) to drive wakefields in plasma

✧Summary

- ✧ No structure to fabricate
- ✧ Demonstrated >50GeV/m
- ✧ Demonstrated large energy gain
- ✧ Not symmetric e^-/e^+
- ✧ Application to e^-/e^+ and e^-/p^+ colliders



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OUTLINE

✧Introduction

✧Novel Acceleration Techniques

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✧Summary

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SUMMARY

- Advance and novel accelerators (ANAs) have demonstrated very high gradient acceleration (1-100GeV/m)

- Large energy gains have been achieved:
  0-4.2GeV in ~ 9cm plasma (LWFA)
  42-84GeV in ~85cm plasma (PWFA)

- Schemes based on dielectrics are symmetric for the acceleration of e^- and e^+

- Challenges remain in producing beams of collider quality

- Concepts/straw-man design of ANA-based colliders exist …
  - e^-/e^+ collider, Higgs physics
  - e^-/p^+ collider, QED, p^+ structure physics
  - Reduction in length by a factor of a few

- Long term possibility:
  - ANA part of an energy upgrade of a linear collider (CLIC, ILC)
  - ANA replaces “conventional” accelerator parts
  - ANAs need to meet all challenges of colliders

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p^+-DRIVEN PWFA FOR e^-/p^+ COLLIDER

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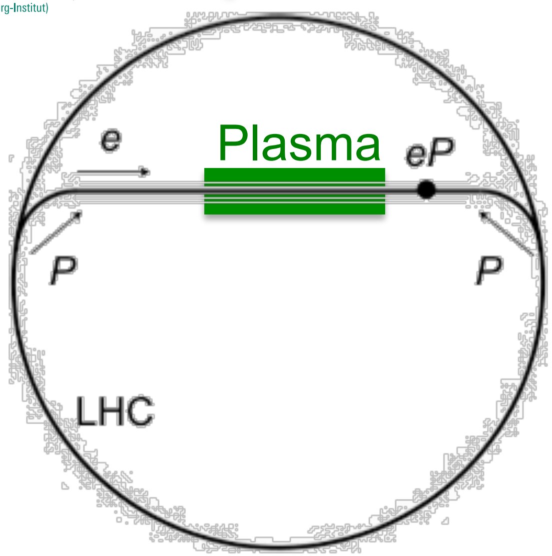
AWAKE



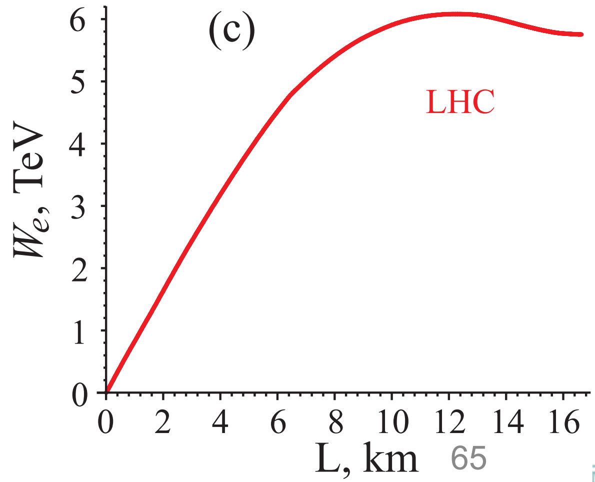
$$\mathcal{L} = f \frac{N_e \cdot N_p}{4\pi\sigma_x \cdot \sigma_y}$$

$$\approx 5 \cdot 10^{28} \text{cm}^{-2}\text{s}^{-1}$$

- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
  - *~3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

simulation of existing LHC bunch in plasma with trailing electrons …

A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)



A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

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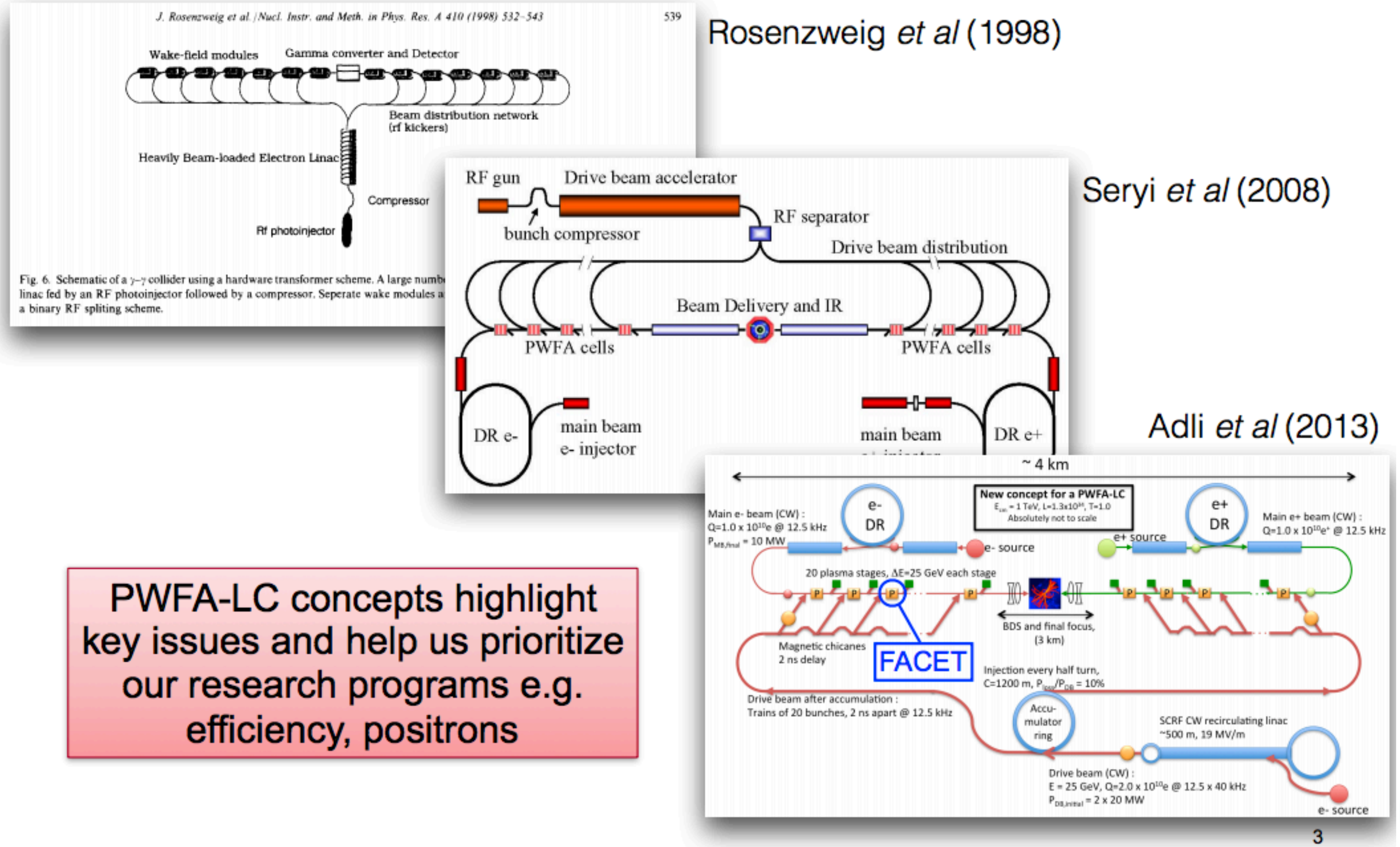
PWFA FOR e^-/e^+ COLLIDER

PWFA Research Roadmap for Electron Driver: Goal is to Get to a TeV Scale Collider for High Energy Physics

SLAC



Rosenzweig *et al* (1998)

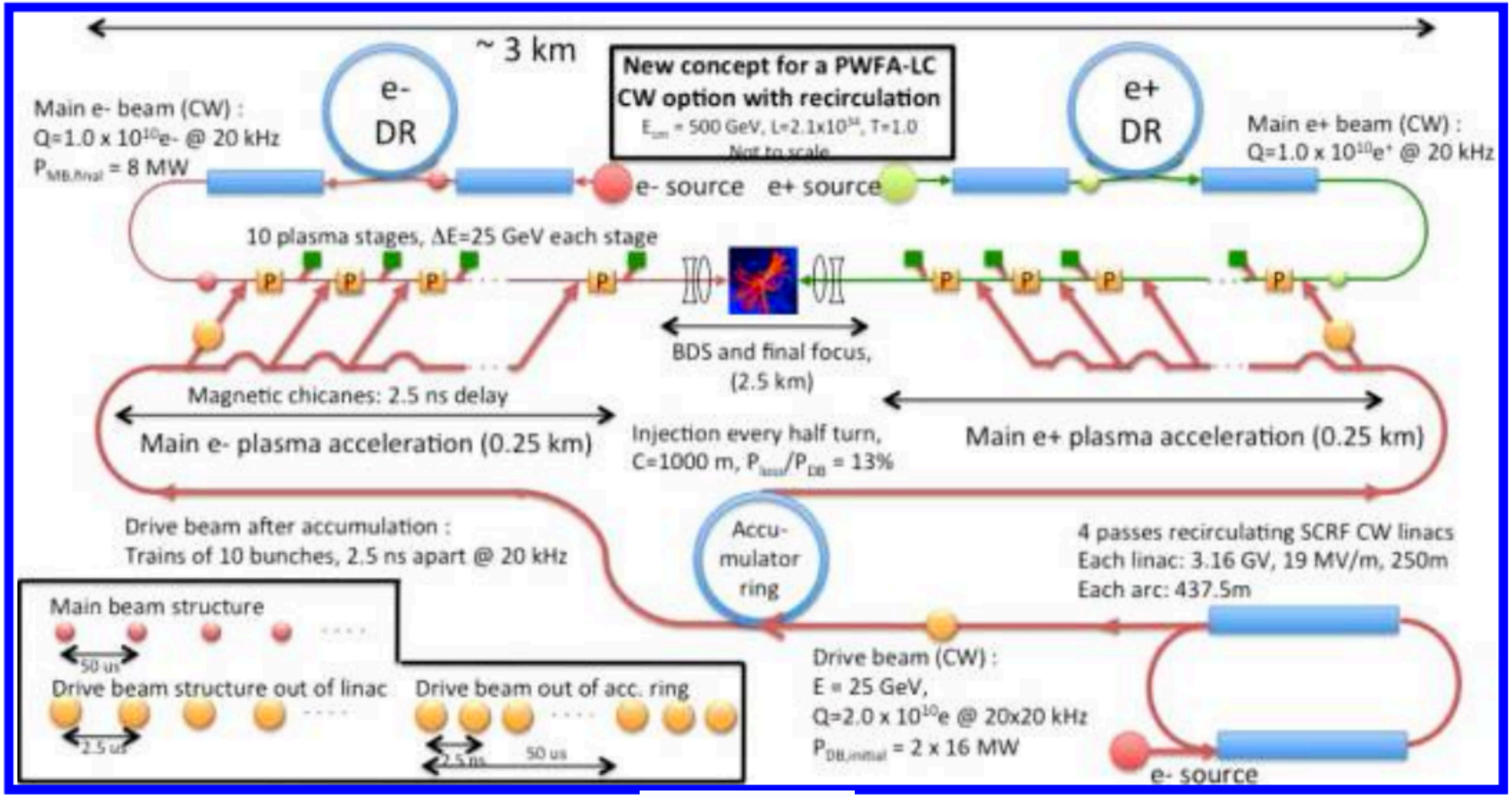
Seryi *et al* (2008)

Adli *et al* (2013)

PWFA-LC concepts highlight key issues and help us prioritize our research programs e.g. efficiency, positrons

Presented at ANAR 2017 WG Summary by M.J. Hogan

PWFA FOR e^-/e^+ COLLIDER



Mark J. Hogan, Rev. Accl. Sci. Tech., 09, 63 (2016)

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Online ISSN: 1793-8058

2016, Vol. 16
on Advanced
Accelerators

LWFA FOR e^-/e^+ COLLIDER

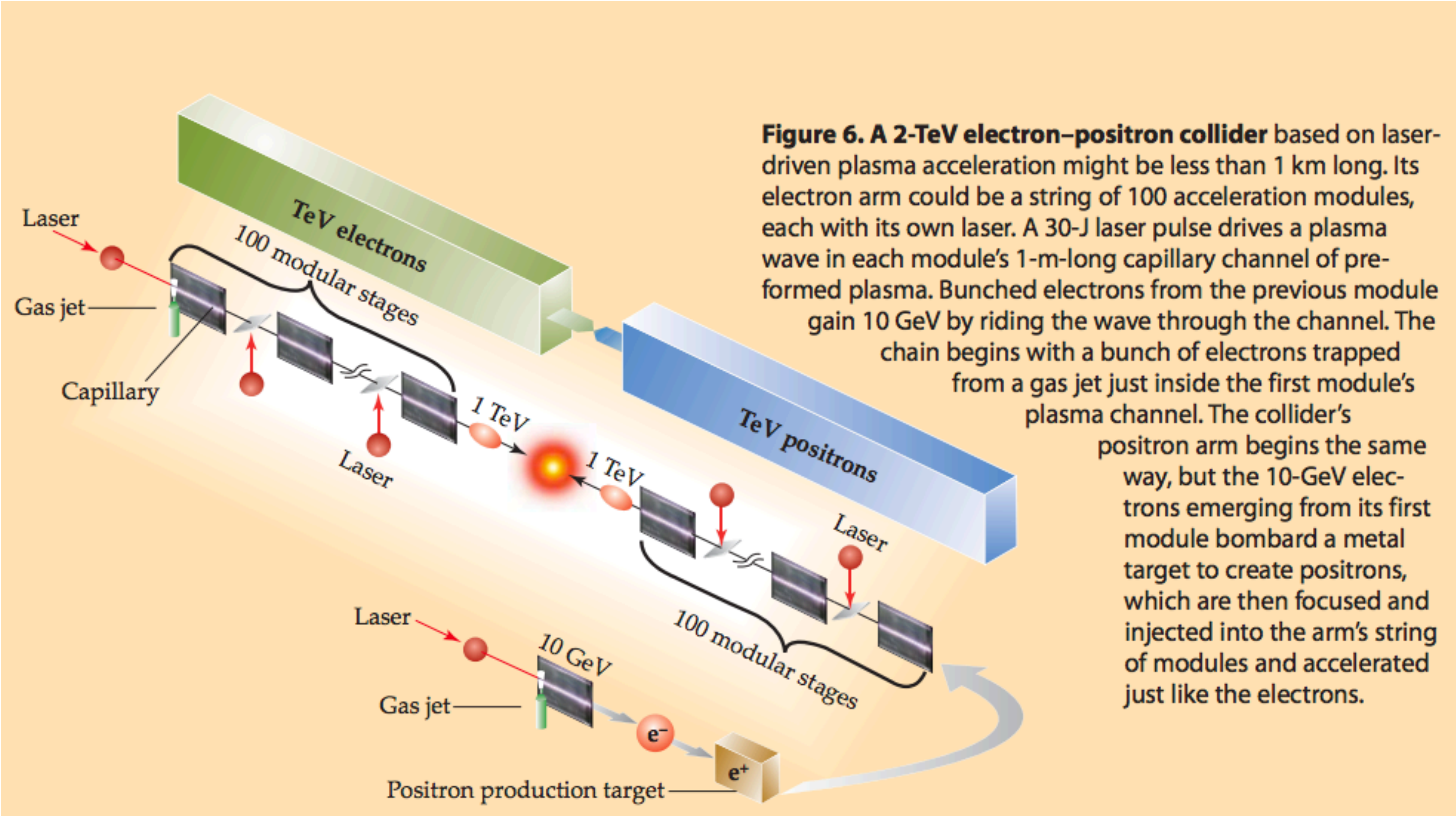

Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of preformed 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.

Lemmans, Physics Today 62, 3, 44 (2009)

… and concepts for SWFA and DLA also exist …

Plasma WakefiEld Accelerator

RF-based acceleration …

… plasma-based acceleration

I. Blumenfeld

Yeah, it's kinda like that …

… it will change your life!

http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de