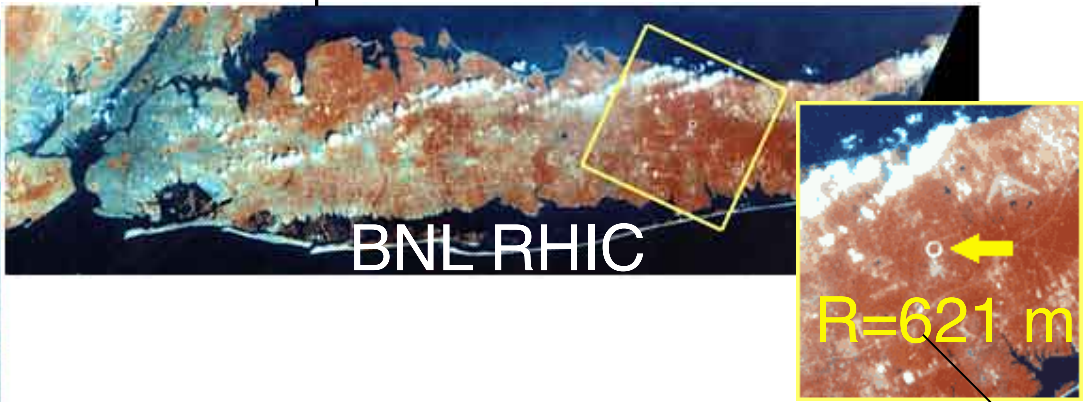
Advanced Accelerator Concepts

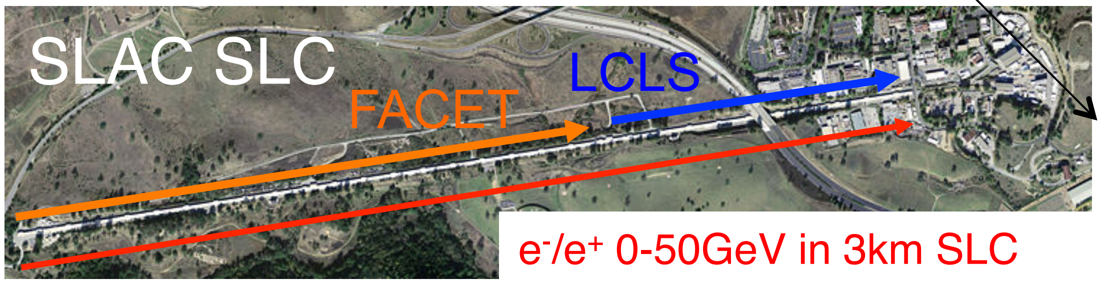
Patric Muggli
Max Planck Institute for Physics
Munich
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

MAX-PLANCK-INSTITUT
FÜR PHYSIK

PARTiCLE COLLiDERS

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



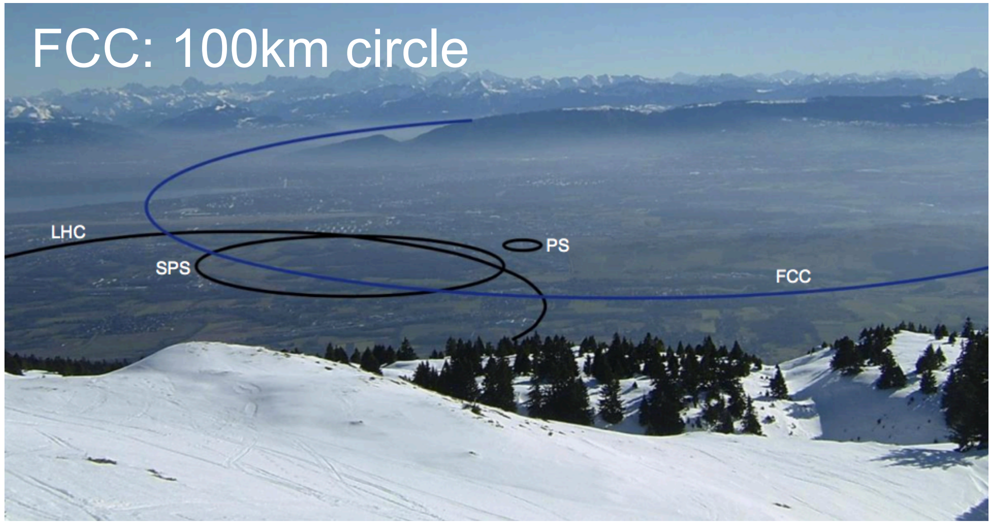


e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use radio frequency (RF) technology to accelerate particles

PARTiCLE COLLiDERS

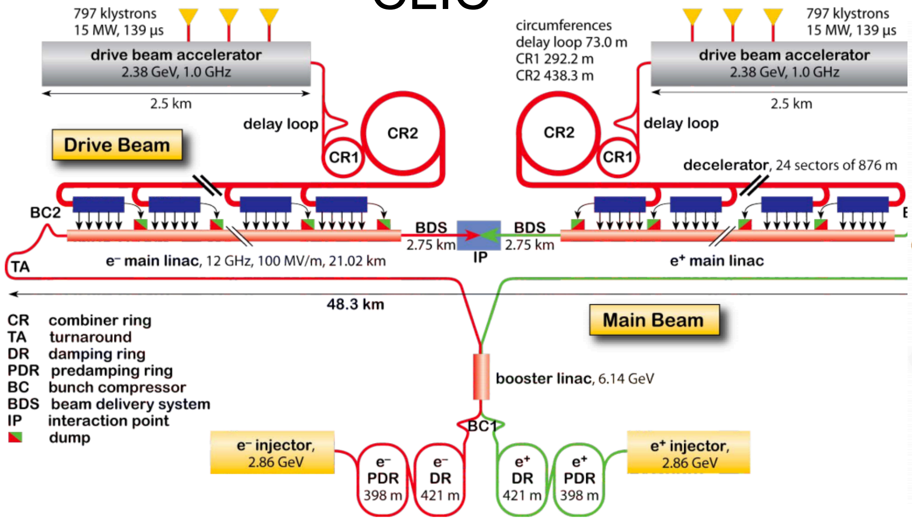
The future is …



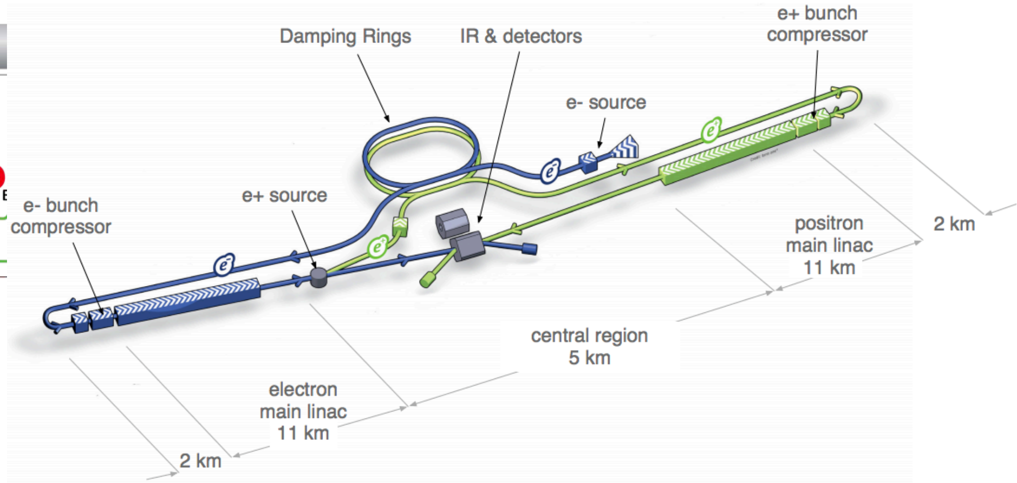
… large and larger…

(… because of higher and higher energies)

CLIC

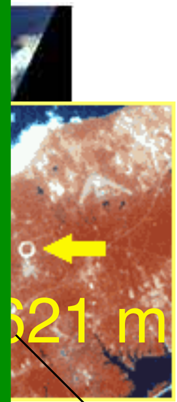


ILC



PARTiCLE COLLiDERS

“The 2.4-mile circumference RHIC ring is large enough to be



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)

m SLC
m FACET
m LCLS

- Some of the largest and most comp c instruments ever built!
- All use radio frequency (RF) technology to accelerate particles

MAX-PLANCK-INSTITUT FÜR PHYSIK

PARTICLE COLLIDERS

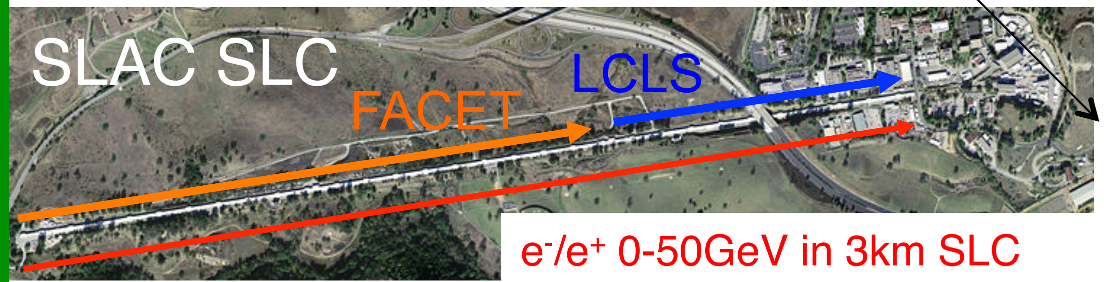
Light particles (e⁻/e⁺) accelerator
Limited by synchrotron radiation

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

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

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

"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

omplex (and most expensive) scientific

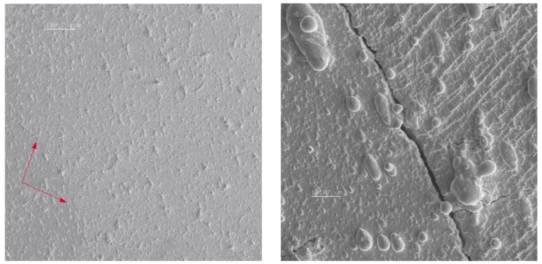
hnology to accelerate particles

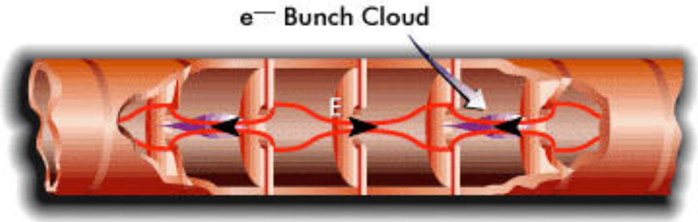
ACCELERATiNG FiELD/GRADiENT LiMiTATiONS

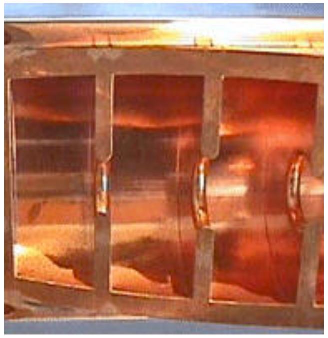
- ✧Gradient/field limit in (warm) RF structures: <1GV/m
- ✧RF break down (plasma!!) and pulsed heating fatigue
- ✧Accelerating field on axis, damage on the surface
- ✧Material limit, metals in the GHz freq. range (Cu, Mo, etc.)
- ✧Does not (seem to) increase with increasing frequency

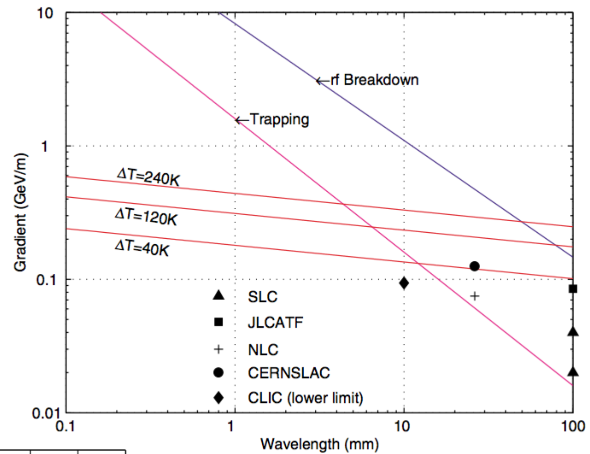
Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)







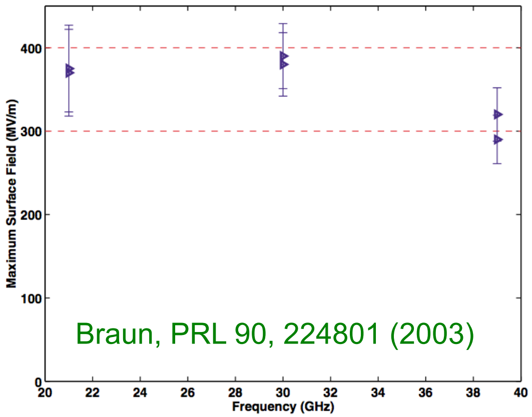


$$G_{\rm break} = \frac{1.1\ {\rm GeV/m}}{[\lambda({\rm cm})]^{7/8}},$$

$$G_{\rm trap} = \frac{1.6\ {\rm MeV}}{\lambda},$$

$$G_{\rm pulse} = (28\ {\rm MeV/m})\frac{\Delta T^{1/2}}{[\lambda({\rm mm})]^{1/8}}.$$

RF break down



Braun, PRL 90, 224801 (2003)

ACCELERATiNG FiELD/GRADiENT LiMiTATiONS

✧Gradient/field limit in (warm) RF structures: <1GV/m

✧RF break down (plasma!!) and pulsed heating fatigue

✧Accelerating f

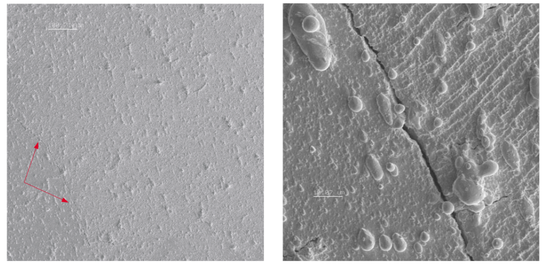
✧Material limit,)

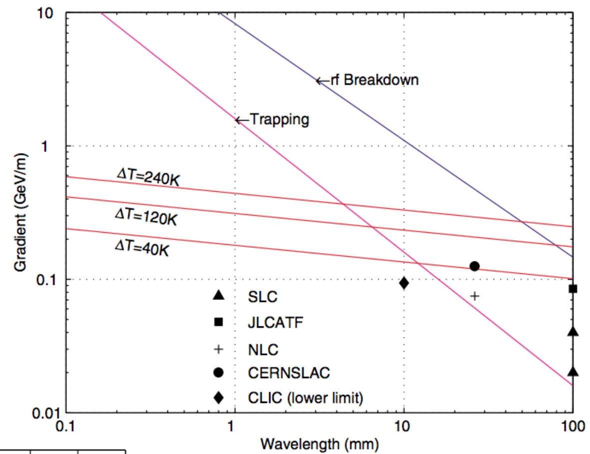
✧Does not (see

RF-accelerators:
Accelerating field limited to
<1GVm (low break-down rate)
by metal damage:
-RF-breakdown
-pulsed heating
Copper: low damage
threshold
Long RF pulses (high Q)

Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)





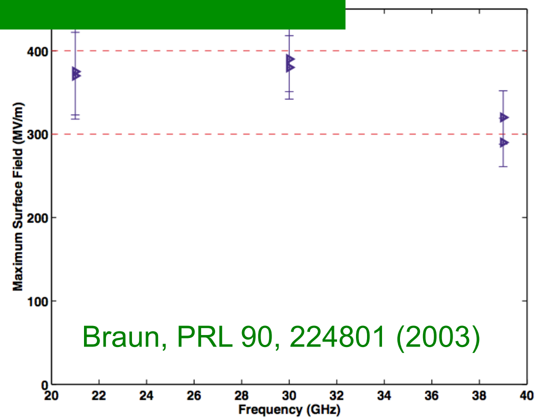
$$G_{\rm break} = \frac{1.1\ {\rm GeV/m}}{[\lambda({\rm cm})]^{7/8}},$$

$$G_{\rm trap} = \frac{1.6\ {\rm MeV}}{\lambda},$$

$$G_{\rm pulse} = (28\ {\rm MeV/m})\frac{\Delta T^{1/2}}{[\lambda({\rm mm})]^{1/8}}.$$

e⁻ Bu

n



PARTiCLE ACCELERATORS

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

Search for a new technology
to accelerate particles
at high-gradient (>1GeV/m)
and reduce the size and cost
of a future linear e^-/e^+ collider
or of an x-ray FEL …
… and low energy applications

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use radio frequency (RF) technology to accelerate particles

PARTICLE ACCELERATION

✧Acceleration: $\vec{F} \parallel \vec{v}$

✧The (RF, for high energy) accelerator converts (a fraction of the transverse) electric field of a (quasi) EM wave into a longitudinal component …

- ✧RF cavities: TE_{lmm}, TM_{lmn} modes (usually TM_{lmn})
- ✧Plasma, dielectrics convert transverse electric fields of a laser pulse or (relativistic) particle bunch into …

✧RF cavities: -large fields through high Q (quality factor), >>1
-store field => time for : - random ionization processes, cascade events, arcing
- pulsed heating

✧Plasma, dielectrics: -“instantaneous” high-fields (“Q”~1)
-wakefields …

PARTiCLE ACCELERATiON

✧Beam dynamics:

Transverse:

✧RF, dielectrics and magnets: -beam and fields "decoupled"

-β-function, long (RF)

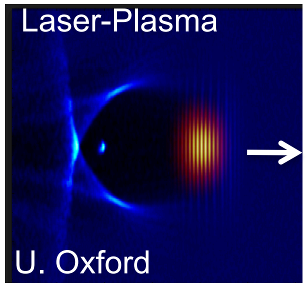
✧Laser beam, particle bunch: -strongly coupled to plasma, self-consistent system

-β-function, short (<<1m)

Longitudinal:

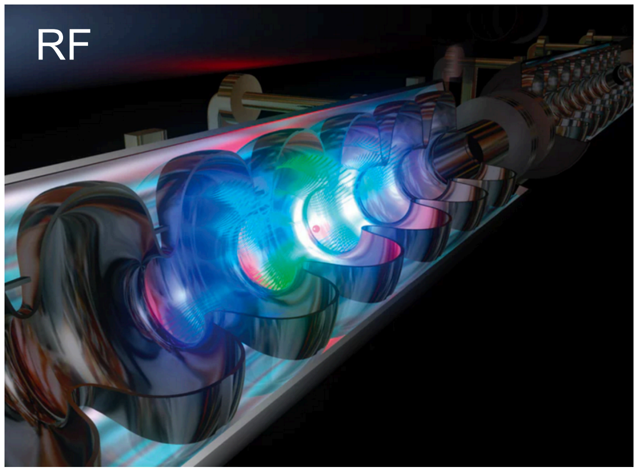
✧RF, longitudinal dynamics important (circular)

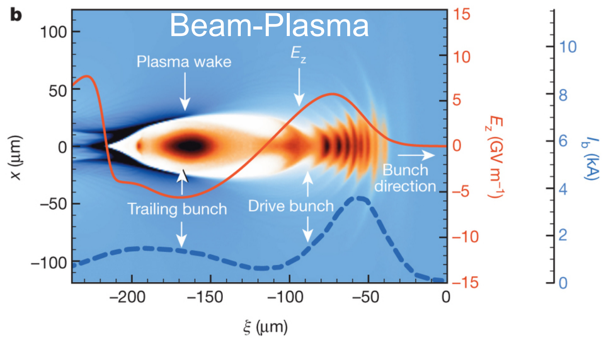
✧Plasma: relativistic wave, relativistic particles, "no longitudinal dynamics" (trapping)



~100µm

~10cm





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

✧Summary

✧General context: accelerators for high-energy, particle physics (>1GeV)
✧Many “low-energy” (<1GeV) applications, “small accelerators” (medical, imaging, security, etc.)

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

ADVANCED & NOVEL ACCELERATORS (ANAs)

"Advanced"

⇕

"High-gradient"

⇕

>1GeV/m (ICFA-ANA)

⇕

Average gradient over m–scale

⇕

GeV to TeV

 *do not include laser vacuum/direct acceleration

ADVANCED & NOVEL ACCELERATORS (ANAs)

MAX-PLANCK-INSTITUT FÜR PHYSIK

"Advanced"

"High-gradient"

>1GeV/m (ICFA-ANA)

Average gradient over m–scale

GeV to TeV

Novel materials with higher damage threshold:

- Dielectrics (~GV/m)
- Plasmas (10-100GV/m or ∞)

Novel drivers:

- Laser pulse(s)*
- Charged particle bunch(es)

 *do not include laser vacuum/direct acceleration

ADVANCED & NOVEL ACCELERATORS (ANAs)

MAX-PLANCK-INSTITUT FÜR PHYSIK

"Advanced"

⬍

"High-gradient"

⬍

>1GeV/m (ICFA-ANA)

⬍

Average gradient over m–scale

⬍

GeV to TeV

Novel materials with higher damage threshold:

- ✧Dielectrics (~GV/m)
- ✧Plasmas (10-100GV/m or ∞)

Novel drivers:

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

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

 *do not include laser vacuum/direct acceleration

ADVANCED & NOVEL ACCELERATORS (ANAs)

MAX-PLANCK-INSTITUT FÜR PHYSIK

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 ☺
Operate with "short pulses" … wakefields

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

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

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

 *do not include laser vacuum/direct acceleration

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^{11}W/cm^2

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

Charged Particle Bunch:

(tri-Gaussian, relativistic)

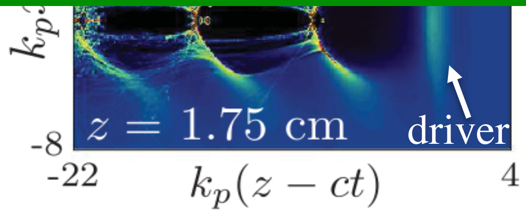
$$E_{\perp,\max} \approx \frac{1}{2(2\pi)^{3/2}}\frac{e}{\varepsilon_0}\frac{N}{\sigma_r \sigma_z}\left(1-e^{-1/2}\right)$$

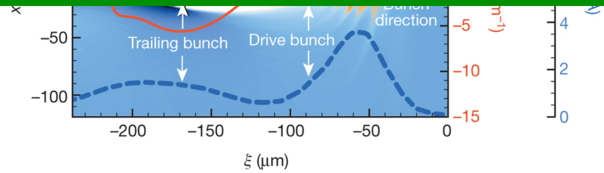
Example:
N=2×10^{10}e$^-$, σ_r=10µm, σ_z=20µm
$E_\perp$=11GV/m

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

Challenge / function of the accelerating structure:

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

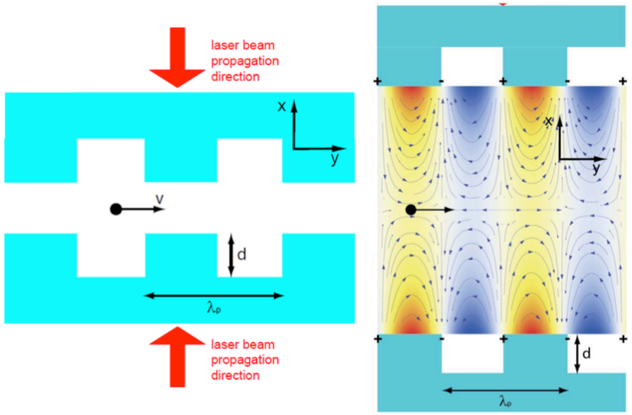




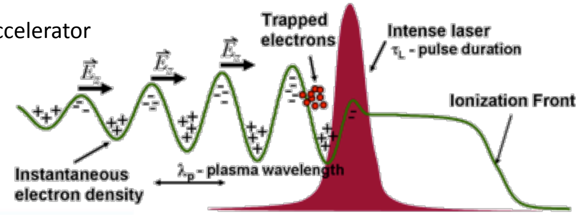
MAX-PLANCK-INSTITUT
FÜR PHYSIK

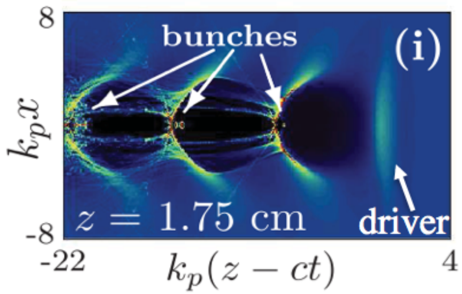
ADVANCED & NOVEL ACCELERATORS (ANAs)

Dielectric Laser Accelerator

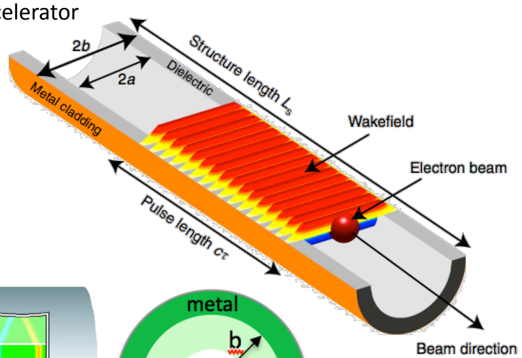


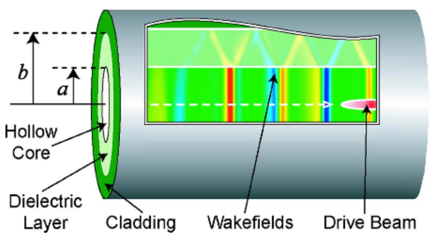
Laser WakeField Accelerator

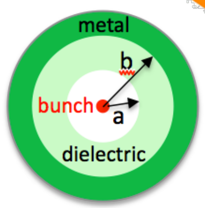




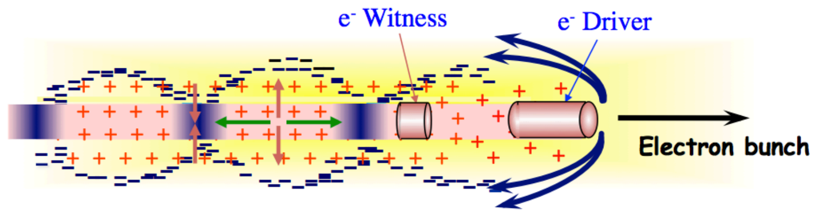
Structure WakeField Accelerator

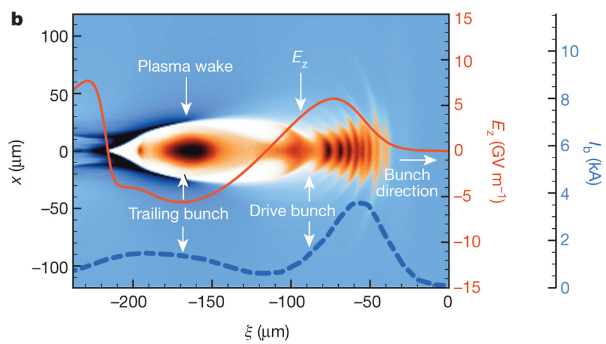






Plasma WakeField Accelerator





OUTLiNE

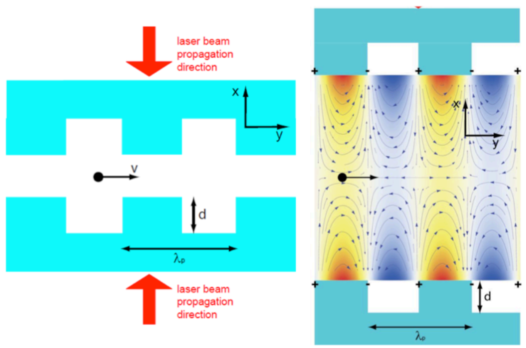
✧Introduction

✧Novel Acceleration Techniques

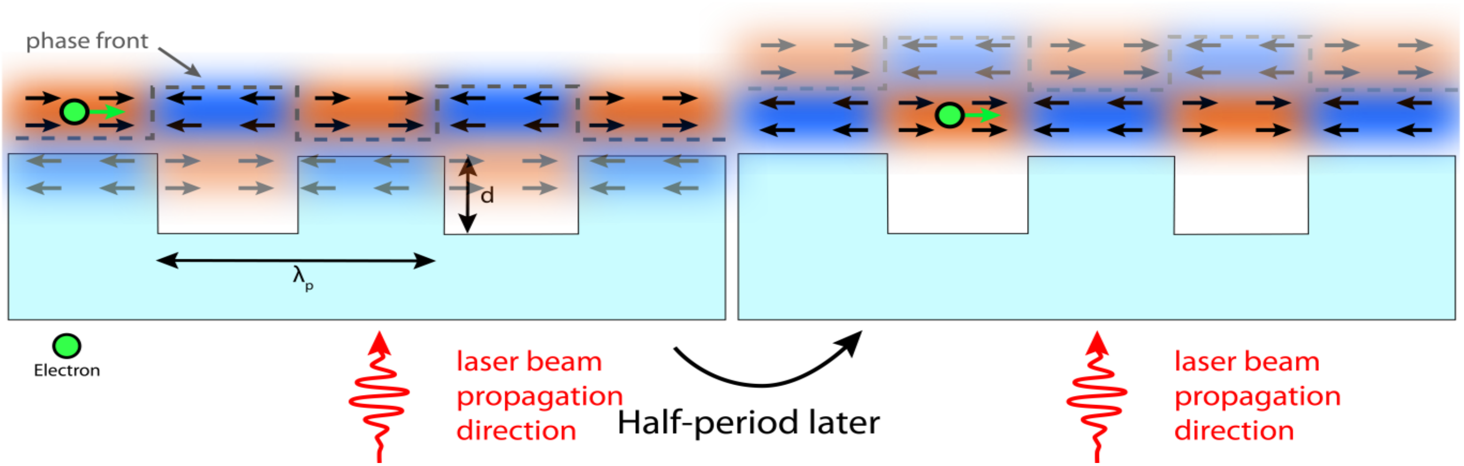
Medium / Driver	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

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

✧Summary

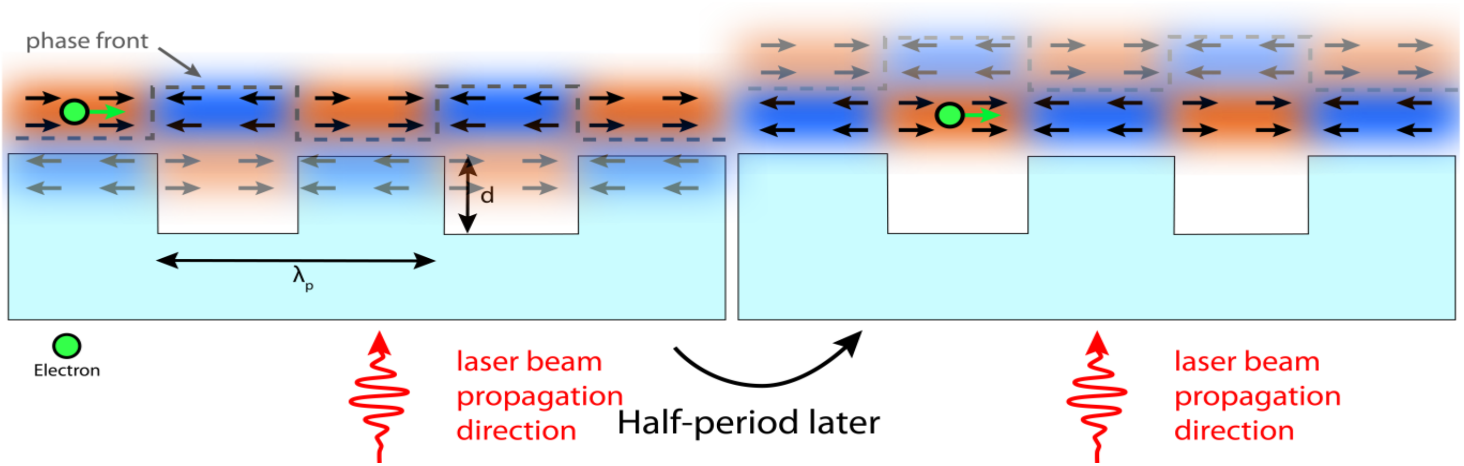


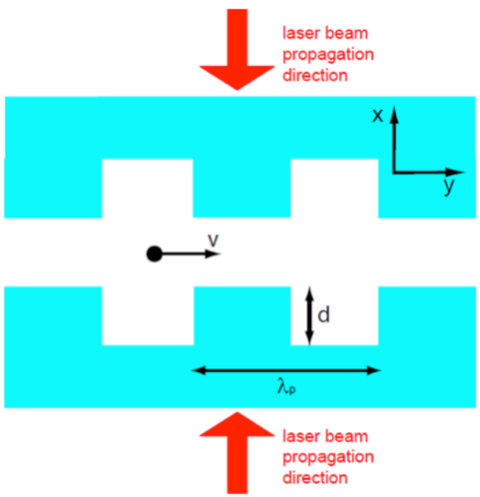
DiELECTRiC LASER ACCELERATOR (DLA)

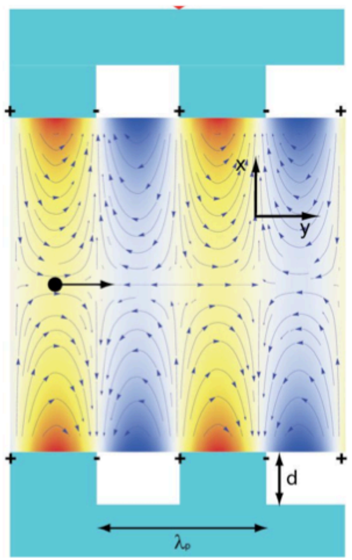


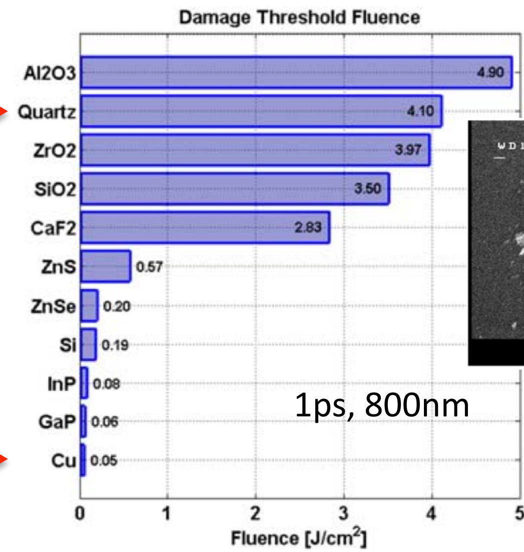
- ✧ Laser light: λ~1µm (or THz, 300µm)
- ✧ Structure features ~λ~1µm

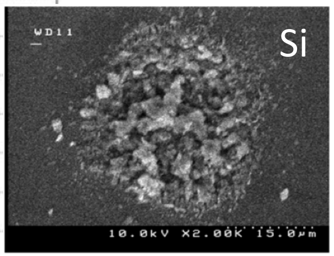
DiELECTRiC LASER ACCELERATOR (DLA)







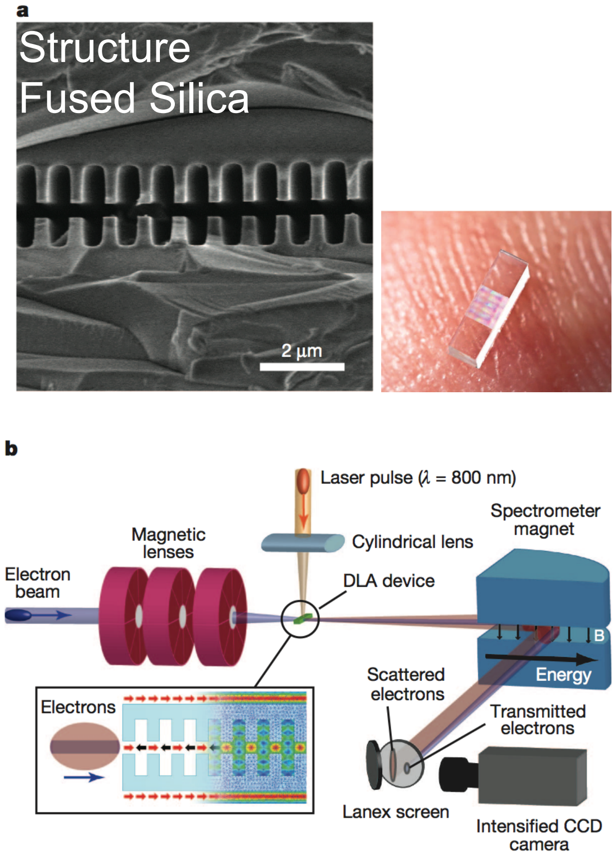




Soong, AIP Conf. Proc. 1507, 511 (2012)

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

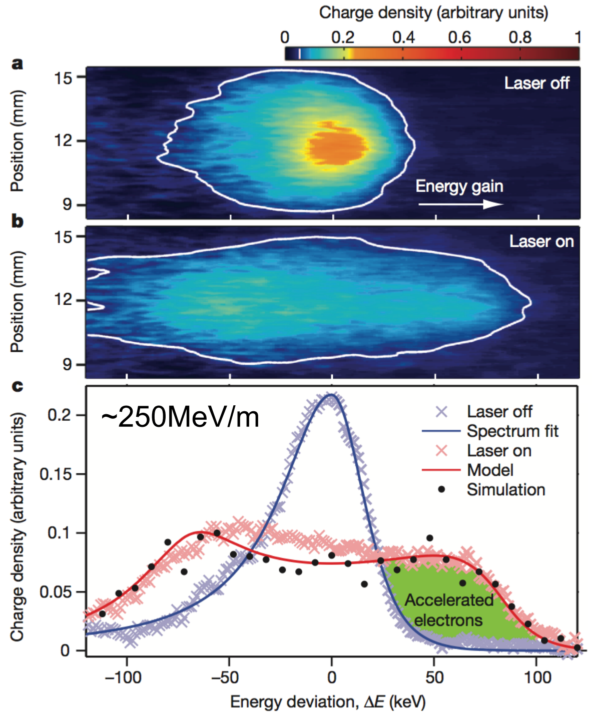
DLA Results



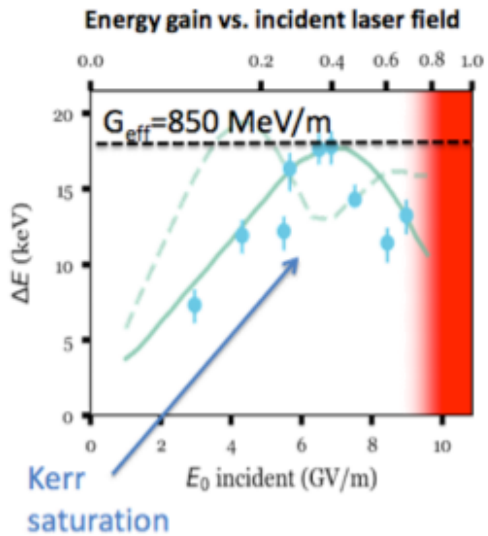
Demonstration of electron acceleration in a laser-driven dielectric microstructure

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



Presented by D. Cesar (UCLA)
@ EAAC 2017
Commun Phys **1,** 46 (2018)



- ✧Beam not bunched at λ_{laser}(800nm) 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

MAX-PLANCK-INSTITUT FÜR PHYSIK

OUTLiNE

✧Introduction

✧Novel Acceleration Techniques

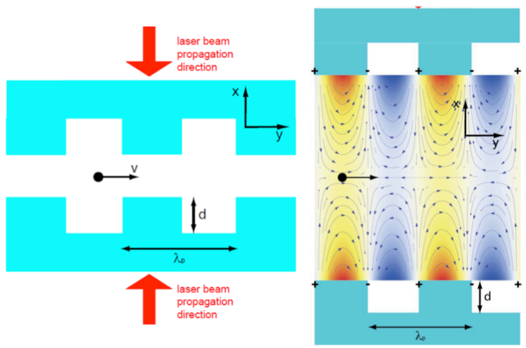
Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

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

✧Summary

R. England, Rev. Mod. Phys. 86, 1337

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



OUTLiNE

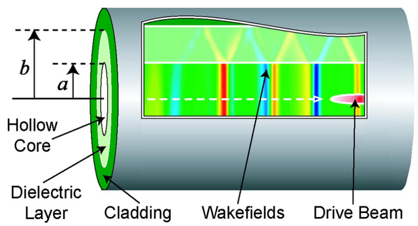
✧Introduction

✧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

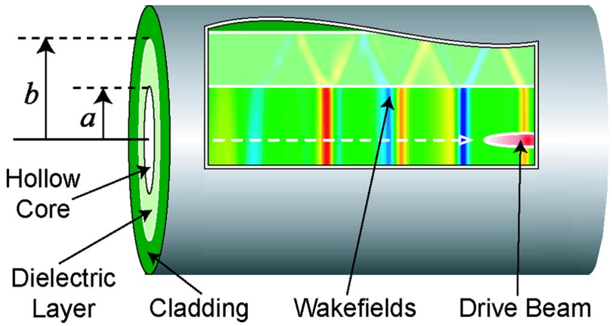
✧Cherenkov wakes in dielectric layers

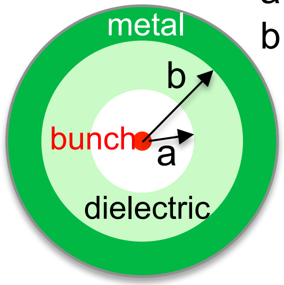
✧Summary



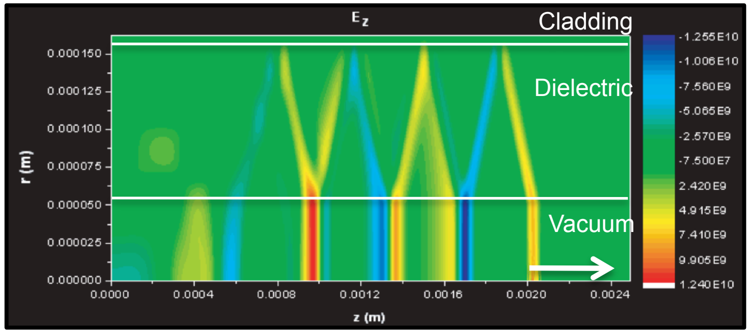
✧Colinear, not corrugated

DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





a: vacuum channel radius
b: dielectric outer radius

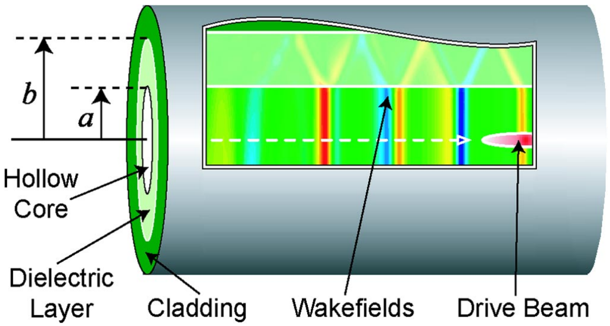


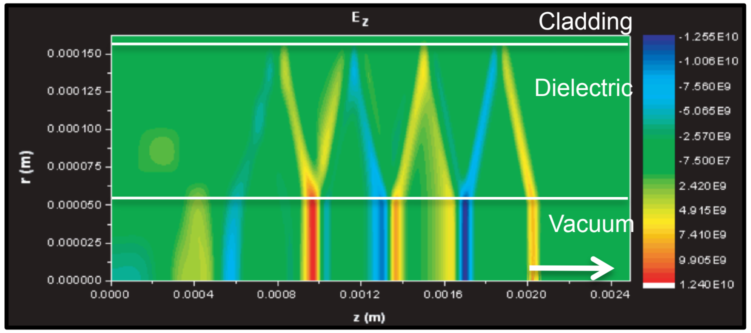
- Peak decelerating field

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

 Detailed fields; Jing, RAST 09, 2016

DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





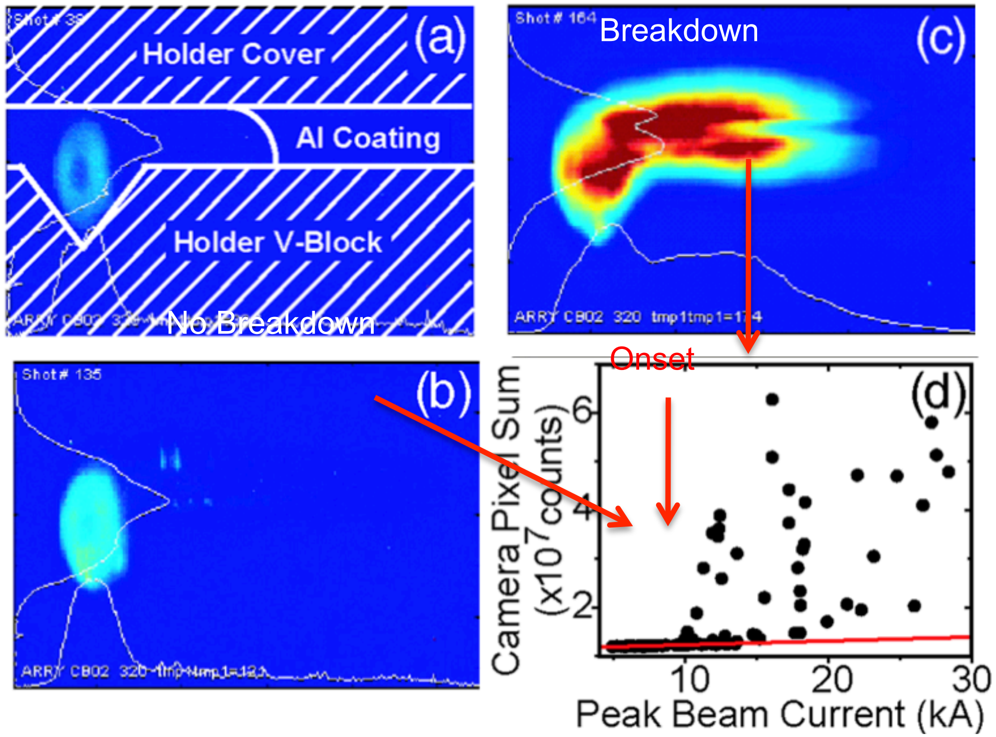
- Peak decelerating field

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

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]

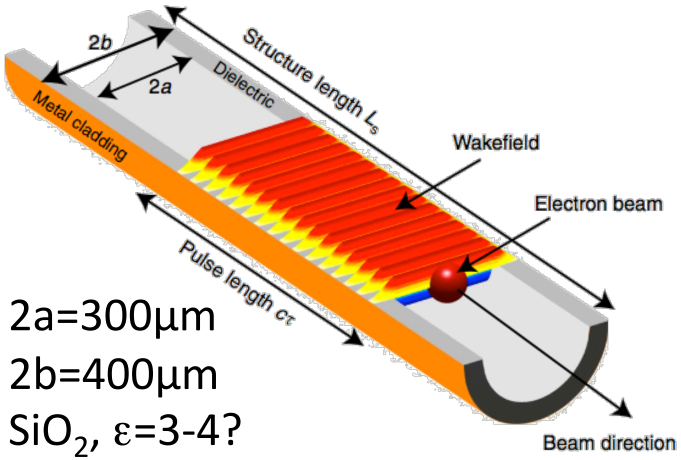


✧σ_z=100-10µm, N=2x10^{10} e$^-$
✧a=50µm, b=162µm, fused silica, ε~3, f_1~470GHz
✧Breakdown field at 13.8±0.7GV/m
✧Estimated max. decelerating field: 11GV/m
✧Estimated max. accelerating field: 17GV/m

 Detailed fields; Jing, RAST 09, 2016

DWA RESULTS

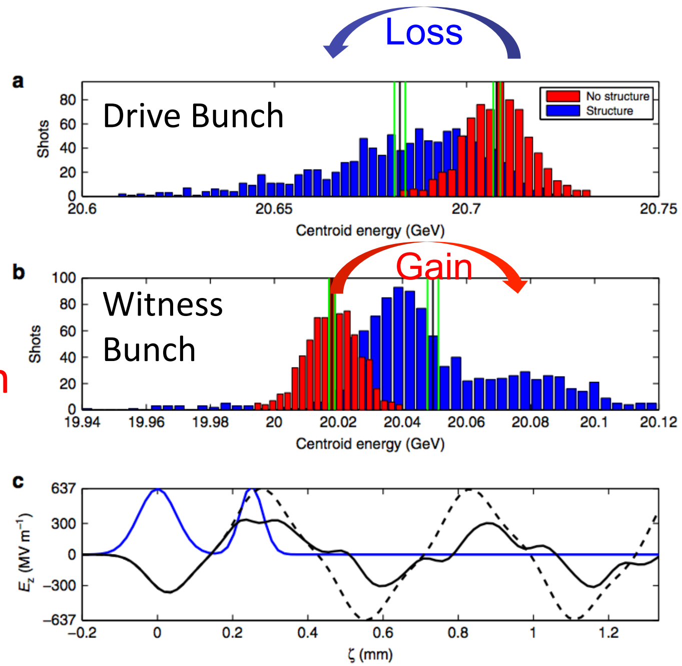
O'Shea et al., Nat . Comm. 7, 12763 (2016)

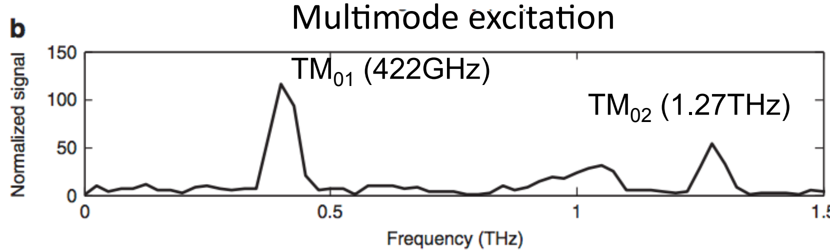


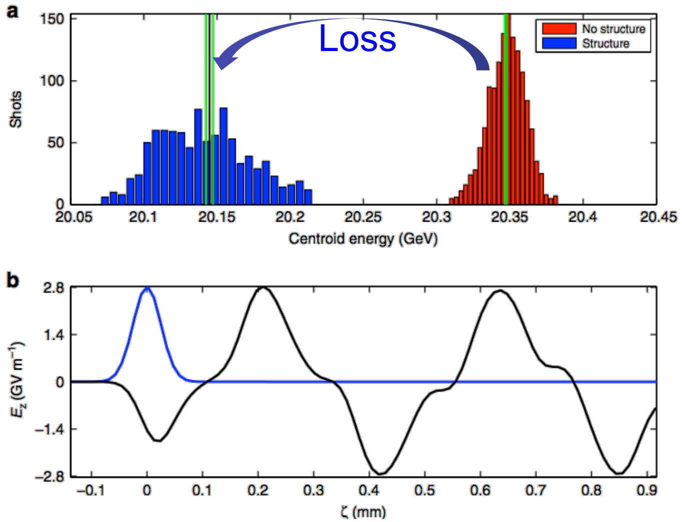
2a=300µm
2b=400µm
SiO_2, ε=3-4?
Cu cladding

9.4×10^9e
G_d=252±14MeV/m

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







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

- ✧"Large" gradient demonstrated
- ✧Energy gain by W bunch!
- ✧Lack of proper beams

DWA RESULTS

Acceleration in slab symmetric DWA

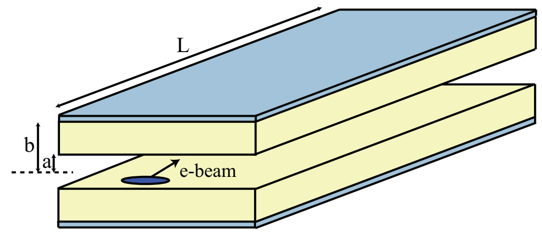
UCLA

- Structure:
  - SiO2, 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

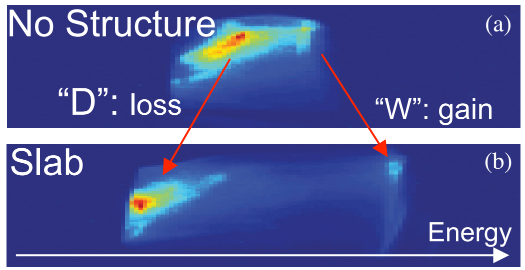
PRL **108**, 244801 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

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

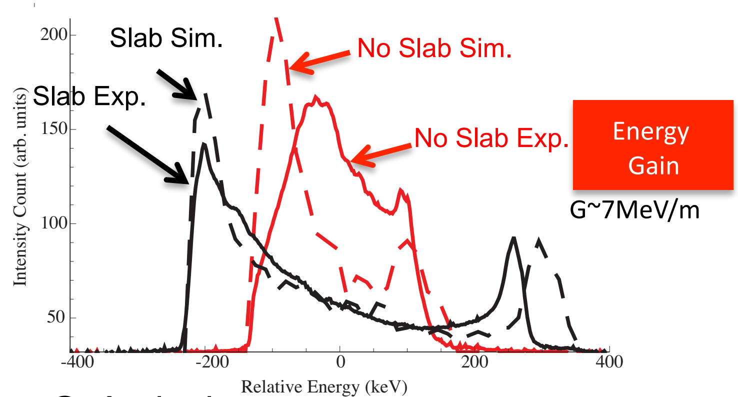
✧More charge per bunch

✧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)



G~7MeV/m

✧Appropriate for "flat" collider beams?

Courtesy G. Andonian

DWA RESULTS
Acceleration in slab symmetric DWA

MAX-PLANCK-INSTITUT FÜR PHYSIK

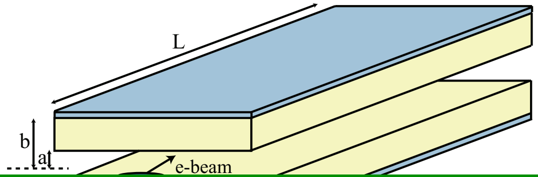
UCLA

- Structure:
  - SiO2, 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

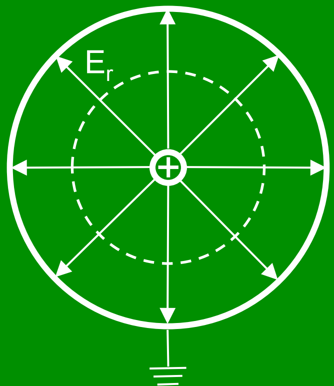
Dielectric Wakefield Acceleration of a Relativistic Electron Beam in a Slab-Symmetric Dielectric Lined Waveguide

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]



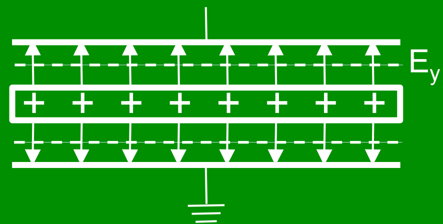
SiO_2, Al
T_{SLAB}=240µm
T_{gap}=240µm
L_z=2cm
ε_N=2mm-mrad

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:



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

✧Appropriate for "flat" collider beams?

Courtesy G. Andonian

OUTLiNE

✧Introduction

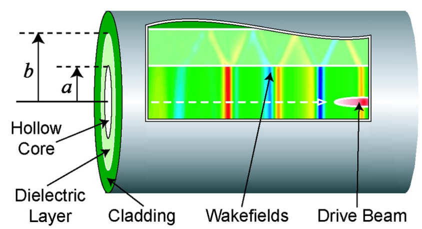
✧Novel Acceleration Techniques

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

✧Cherenkov wakes in dielectric layers

✧Summary

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



✧Colinear, not corrugated

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

✧Summary

MAX-PLANCK-INSTITUT FÜR PHYSIK

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

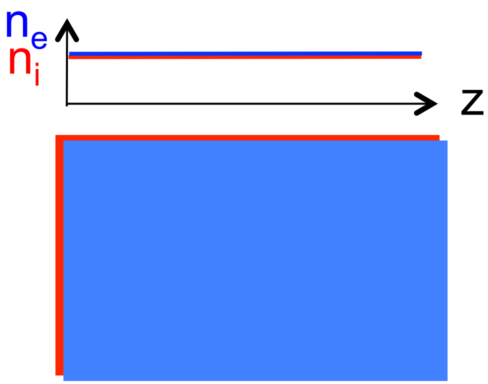
✧Summary

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

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

PLASMA

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



Wikipedia Plasma: (from Ancient Greek πλάσμα 'moldable substance')

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

✧First plasma wave discovered: Langmuir wave

✧Dispersion relation: $\omega^2 = \omega_{pe}^2 = \frac{n_{e0}e^2}{\epsilon_0 m_e}$

✧ ω_{pe} plasma electron (angular) frequency, n_{e0} plasma e^- density

✧Longitudinal electric field, E_z//k, B=0 – electrostatic wave

✧Erwin Langmuir, Nobel Prize in chemistry(!), 1932

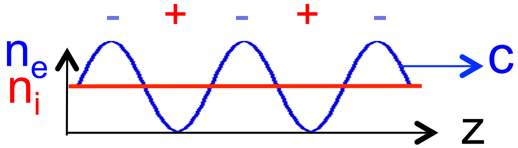
✧Hannes Alfvèn, 1970, MHD

✧Uniform plasma: on average ($\sim n_e^{-1/3}$ scale) no fields!

MAX-PLANCK-INSTITUT FÜR PHYSIK

PLASMA

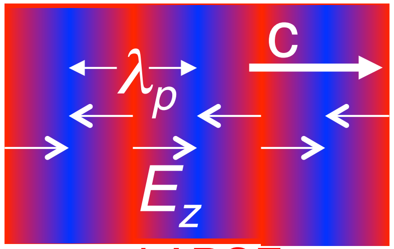
✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$

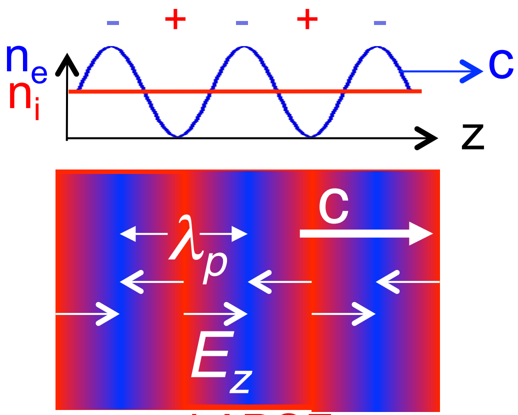
Plasma Electron Frequency



LARGE
Collective response!

PLASMA

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



LARGE
Collective response!

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$ Plasma Electron Frequency

$$k_{pe}E_z = \frac{\omega_{pe}}{c}E_z = \frac{n_{e0}e}{\epsilon_0}$$

Cold Plasma "Wavebreaking" Field

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

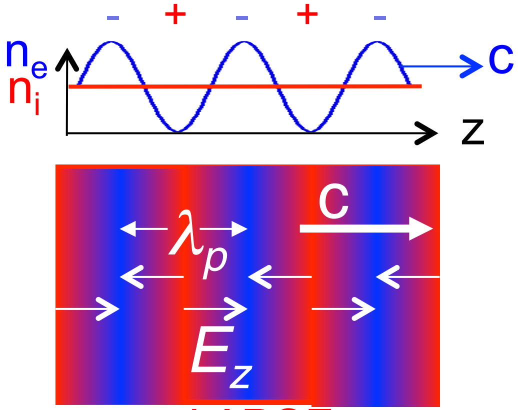
Dawson, PRL (1959)

$$E_{WB} = \left(\frac{m_e c^2}{\epsilon_0}\right)^{1/2} n_{e0}^{1/2} \cong 100\sqrt{n_{e0}[cm^{-3}]} \cong 1GV/m$$

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

PLASMA

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



LARGE
Collective response!

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\epsilon_0}$$

$$\omega_{pe}=\left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$ Plasma Electron Frequency

$$k_{pe}E_z=\frac{\omega_{pe}}{c}E_z=\frac{n_{e0}e}{\epsilon_0}$$

Cold Plasma "Wavebreaking" Field

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

Dawson, PRL (1959)

$$E_{WB}=\left(\frac{m_e c^2}{\epsilon_0}\right)^{1/2} n_{e0}^{1/2}\cong 100\sqrt{n_{e0}[cm^{-3}]}\cong 1GV/m$$

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

✧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 …

Single mode system!

✧Plasmas wave or wake can be driven by:

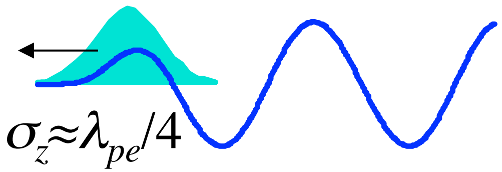
- ➢Intense laser pulse (LWFA)
- ➢Dense particle bunch (PWFA)

4 PLASMA-BASED ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

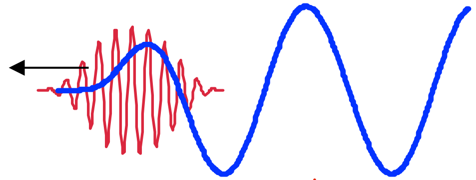
  A high energy particle bunch (e^-, e^+, ...)

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



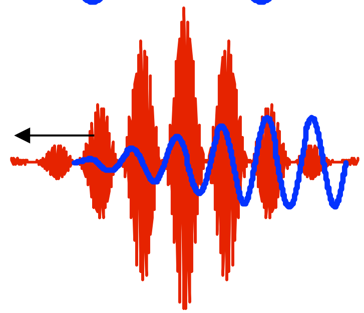
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



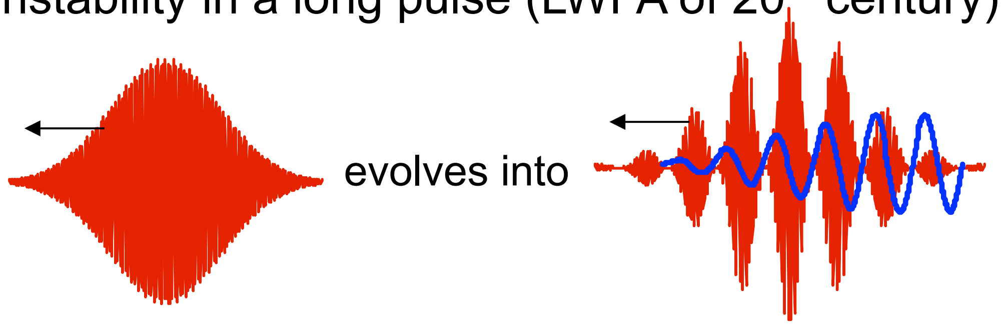
- Plasma Beat Wave Accelerator (PBWA) *

  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 20^{th} century)



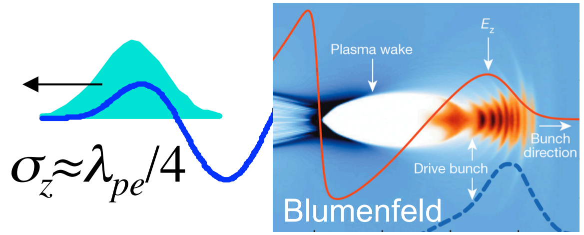
*Pioneered by J.M. Dawson (Tajima, Dawson, Phys. Rev. Lett. 43, 267 (1979))

4 PLASMA-BASED ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

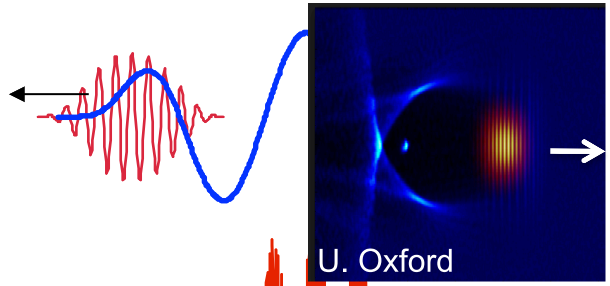
  A high energy particle bunch (e^-, e^+, ...)

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



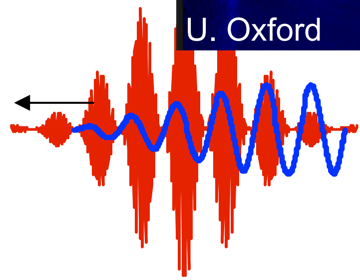
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



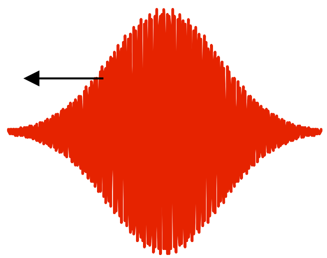
- Plasma Beat Wave Accelerator (PBWA) *

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

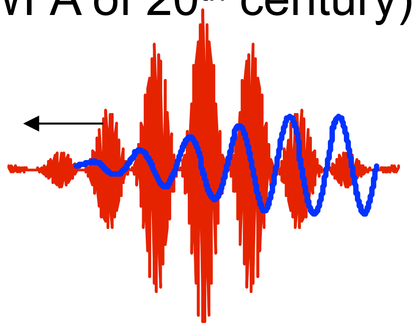


- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

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



evolves into



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

OUTLiNE

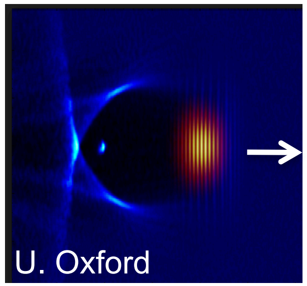
✧Introduction

✧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

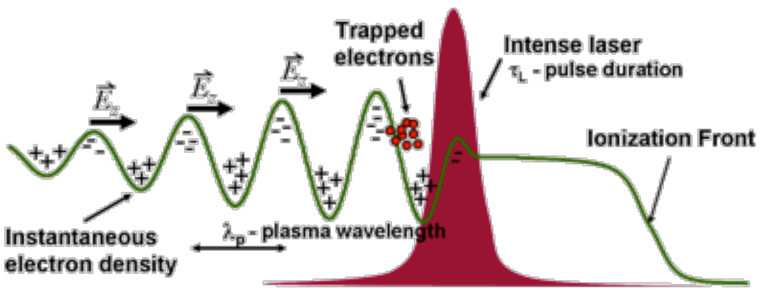
✧Intense laser pulse to drive wakefields in plasma

✧Summary



LASER WAKEFIELD ACCELERATOR (LWFA)

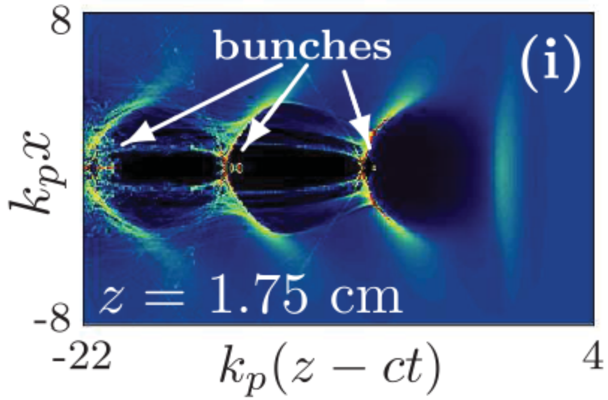
✧Laser pulse ponderomotive force (~light pressure) drives the wakefields

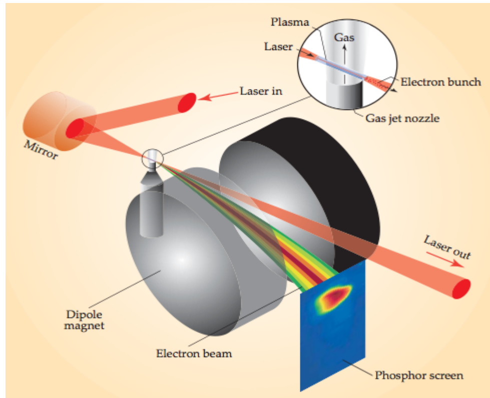


Typical parameters:

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

Plasma: $n_e=10^{16}$-10^{20}cm^{-3}





Gas Jet Plasma
(short, injector)

✧Most active field

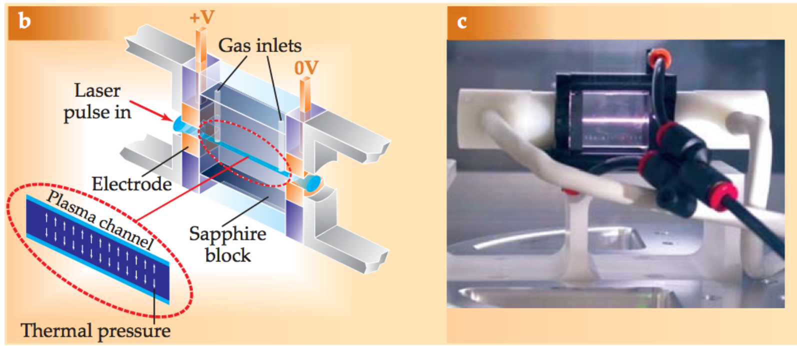
✧Availability of TW Titanium:Sapphire laser systems

✧Laser pulse provides the plasma (ionization)

✧Few TW for 10-100MeV e^- in a few mm

✧Medical, THz/x-ray source, …

✧PW for multi-GeV energy gain



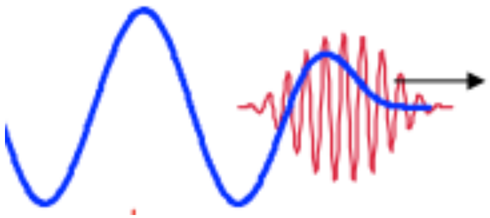
Capillary Discharge Plasma (long, accelerator)

LASER WAKEFiELD ACCELERATOR (LWFA)

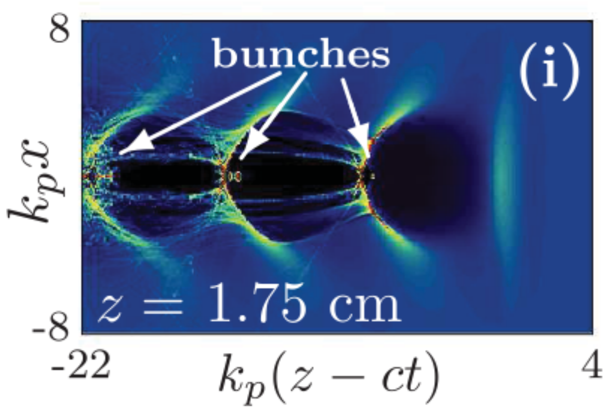
✧Wakefields driven by ponderomotive force of an intense laser beam

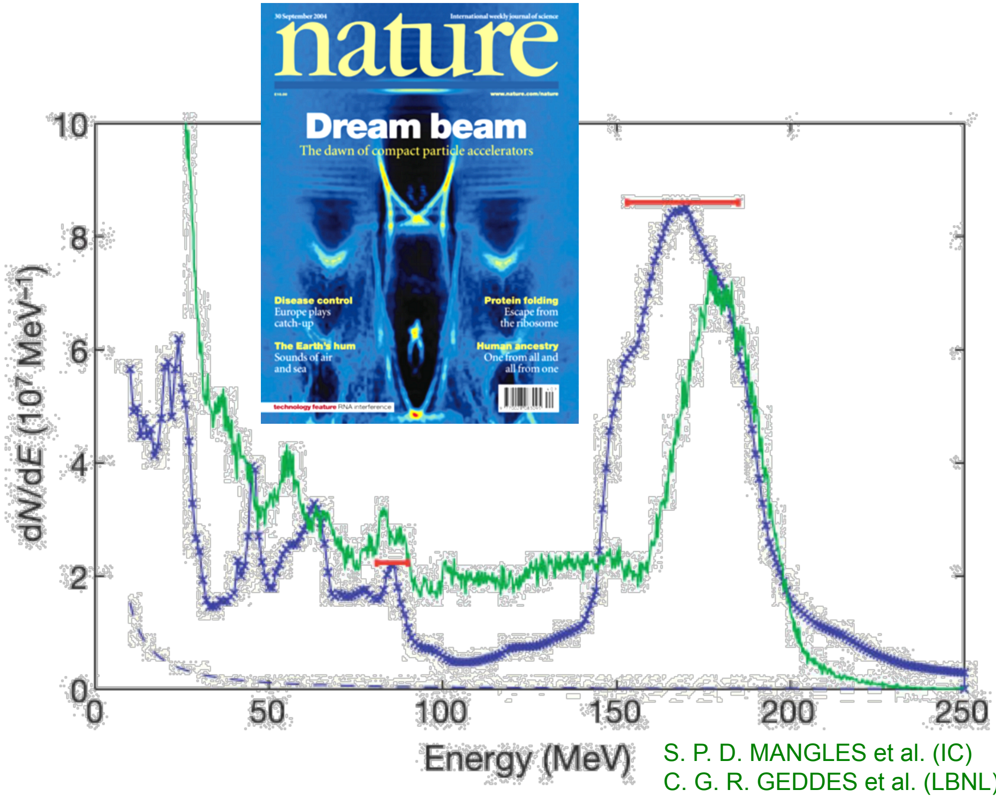
$a_0=v_{osc}/c=eE_0/mc\omega_0^2$~1 $a_0=v_{osc}/c=8.5\times10^{-10}\lambda_0[\mu m]\ I_0^{1/2}[Wcm^{-2}]$

"Forced" or "bubble" regime



a_0~1





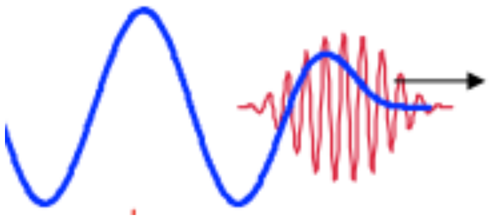
S. P. D. MANGLES et al. (IC)
C. G. R. GEDDES et al. (LBNL)
J. FAURE et al. (LOA)
Nature 431, 2004

✧""Monoenergetic"" bunches (self-trapped)
✧Previously: continuous, thermal energy spectrum
✧Short laser pulse (a_0>1)

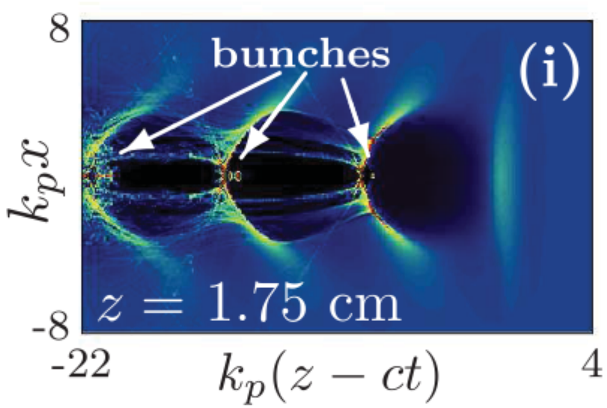
LASER WAKEFIELD ACCELERATOR (LWFA)

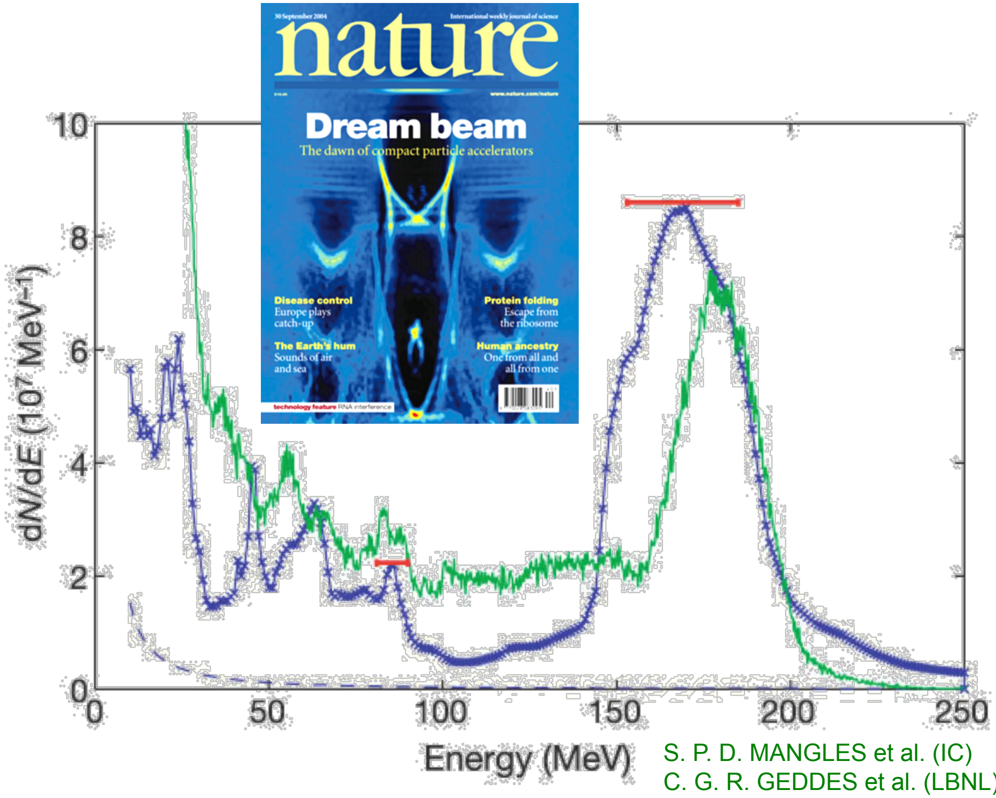
Finite energy spread with the “forced” or “bubble” regime

“Forced” or “bubble” regime



a_0~1

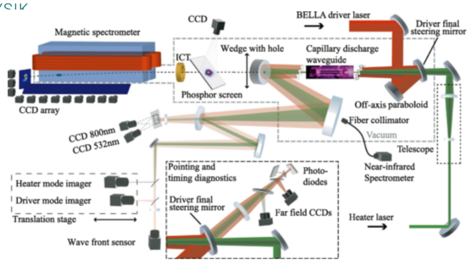




S. P. D. MANGLES et al. (IC)
C. G. R. GEDDES et al. (LBNL)
J. FAURE et al. (LOA)
Nature 431, 2004

- ✧“”Monoenergetic”” bunches (self-trapped)
- ✧Previously: continuous, thermal energy spectrum
- ✧Short laser pulse (a_0>1)

LWFA RESULTS



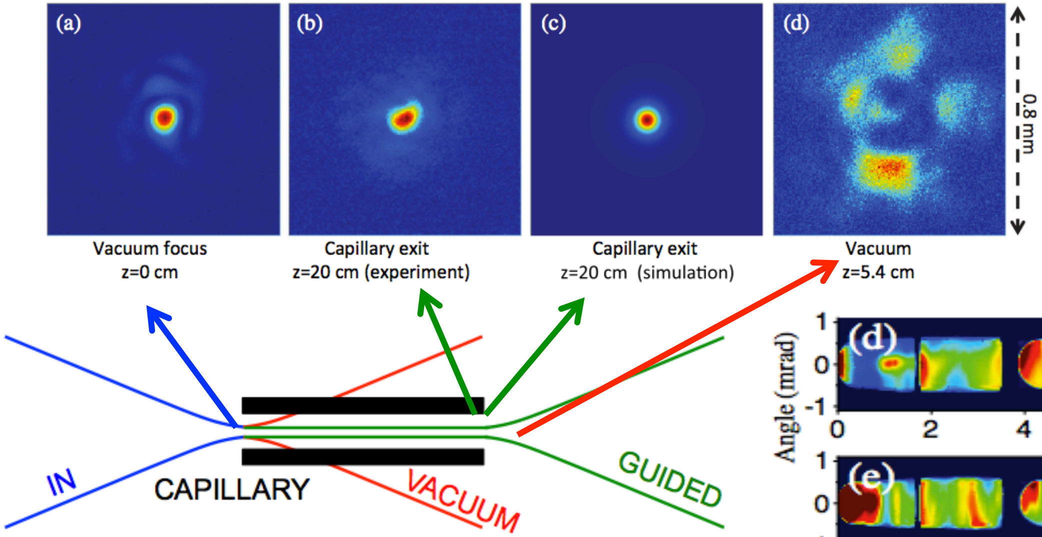
PHYSICAL REVIEW LETTERS 122, 084801 (2019)

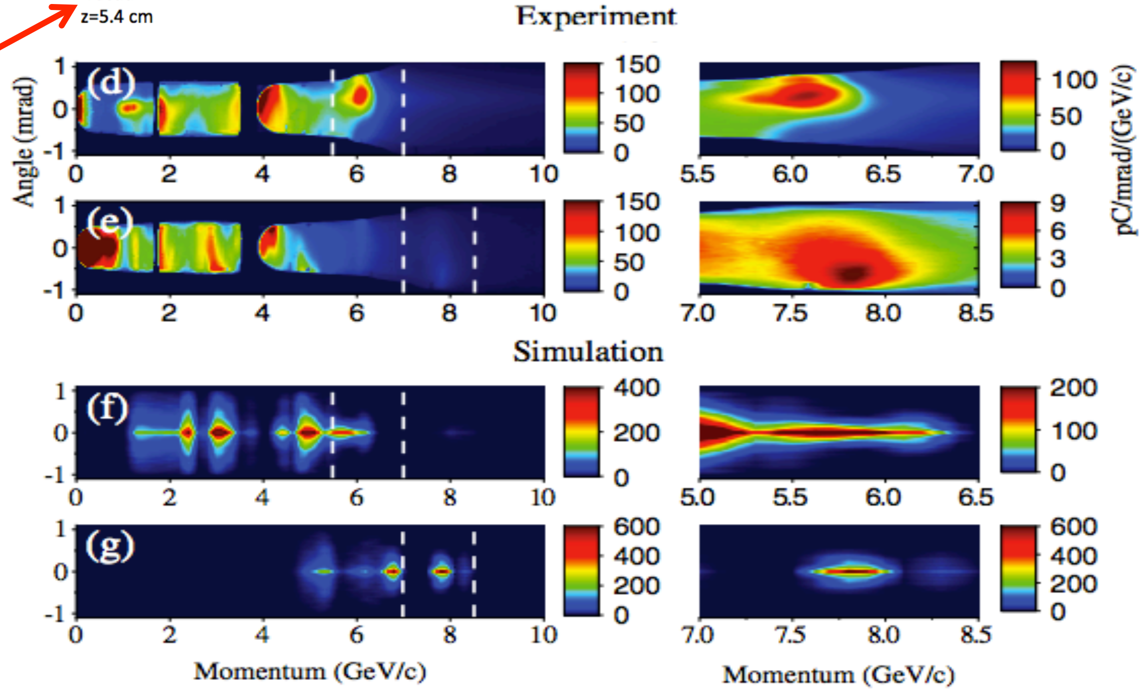
Editors' Suggestion   Featured in Physics

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

A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]

(e)
E_{av}=7.8 GeV
Q=5 pC
Θ_{rms}=0.2 mrad
L_p=20cm, $n_{e0}\approx 2.7\times10^{17}cm^{-3}$
Capillary discharge, heater
$P_{laser}\approx$850TW
W=31J, $\sigma_r\approx$61µm, $\tau\approx$35fs





✧PW laser pulse (850TW)
✧Peak energy gain 7.8GeV in 20cm
✧Laser guiding essential
✧Plasma optical fiber
✧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))

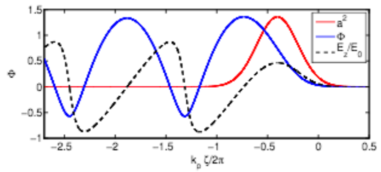
3) Three- two laser beams
(Umstadter PRL 76, 2073 (1996), Esarey, PRL 79, 2682 (1997)

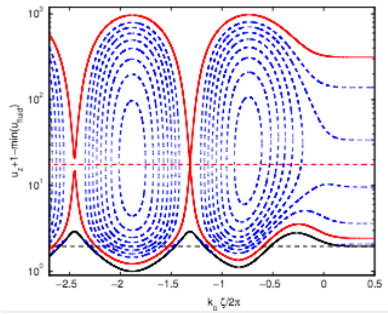
4) Density step (Suk PRL 86, 1011)

5) Density down-ramp

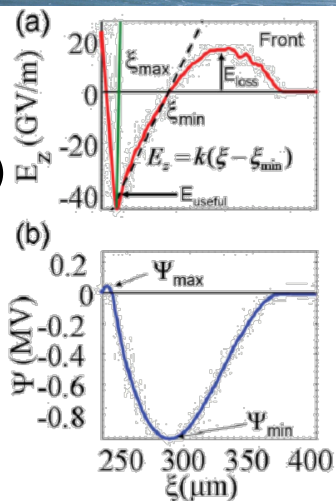
6) Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010)

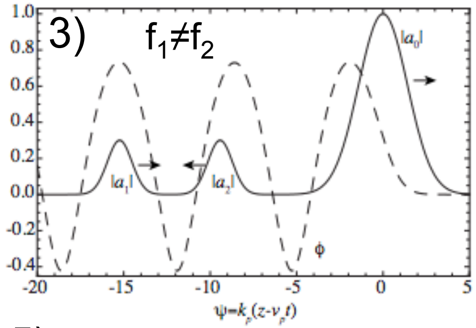
7) External injection





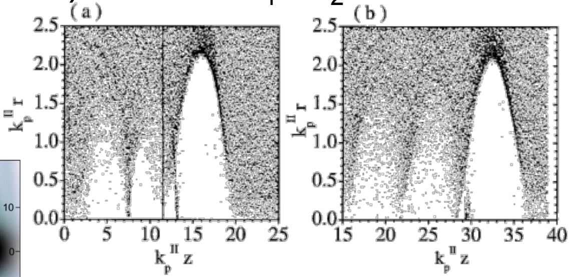
2)



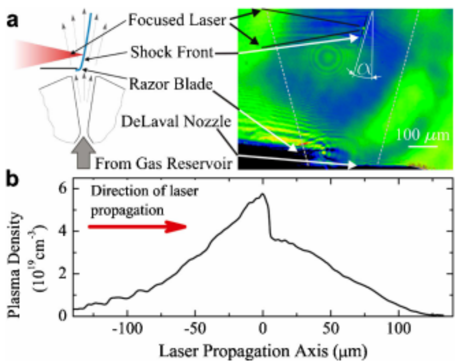


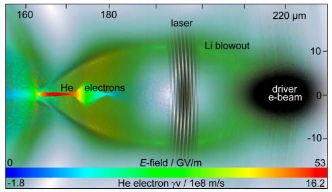
4-5)

$n_1 > n_2$



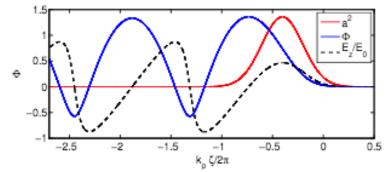
5-6)

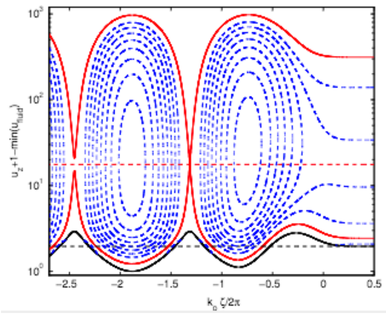




Physics of laser-driven plasma-based electron accelerators, E. Esarey et al., Rev. Mod. Phys. 81, 1229 (2009)
Overview of plasma-based accelerator concepts, E. Esarey et al., IEEE TPS, 24(2), 252 (1996)

LWFA INJECTORS (some)





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

1)

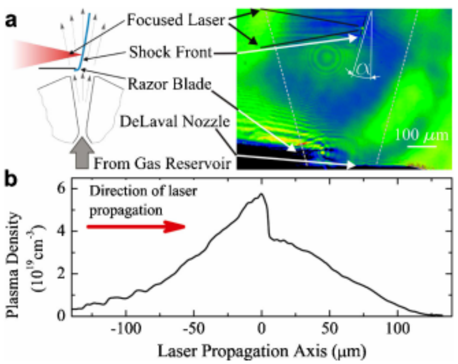
2) Ionization trapping
(Oz, PRL 98, 084801 (2007), Hidding, PRL 108 035001 (2012))

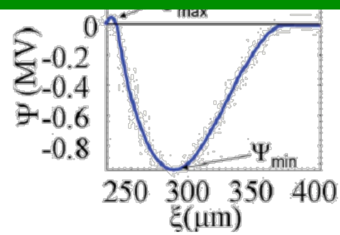
3) Three- two laser beams
(Umstadter PRL 76, 2073 (1996), Esarey, PRL 79, 2682 (1997)

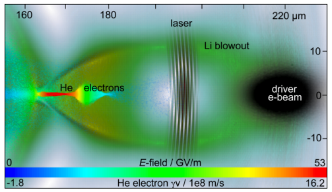
LWFA is also an e^- injector
Plasma as beam optic (plasma lens)
➡ All laser + plasma accelerator!!

7) External injection

5-6)



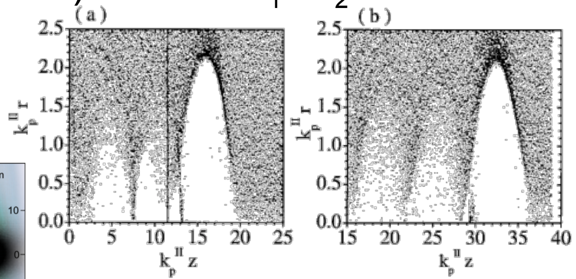




4-5)

$\psi = k_p(z - v_p t)$

$n_1 > n_2$



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)

OUTLINE

✧Introduction

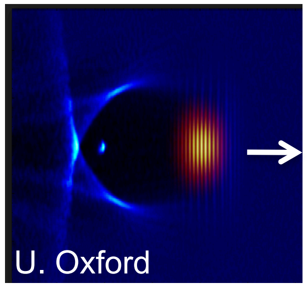
✧Novel Acceleration Techniques

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 plasma

✧Summary

- ✧ No structure to fabricate
- ✧ Demonstrated >100GeV/m
- ✧ Demonstrated large energy gain (~8GeV, 20cm)
- ✧ LWFA is also the injector (e^-)
- ✧ All plasma accelerator!
- ✧ Not symmetric e^-/e^+



OUTLINE

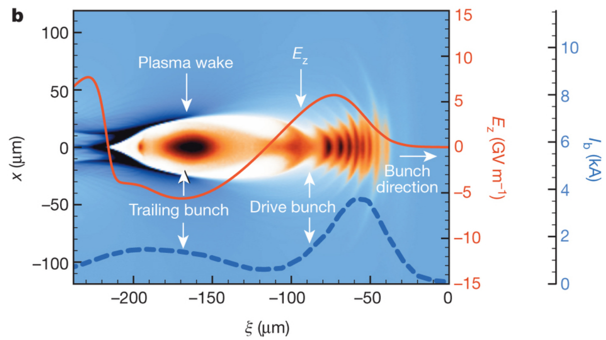
✧Introduction

✧Novel Acceleration Techniques

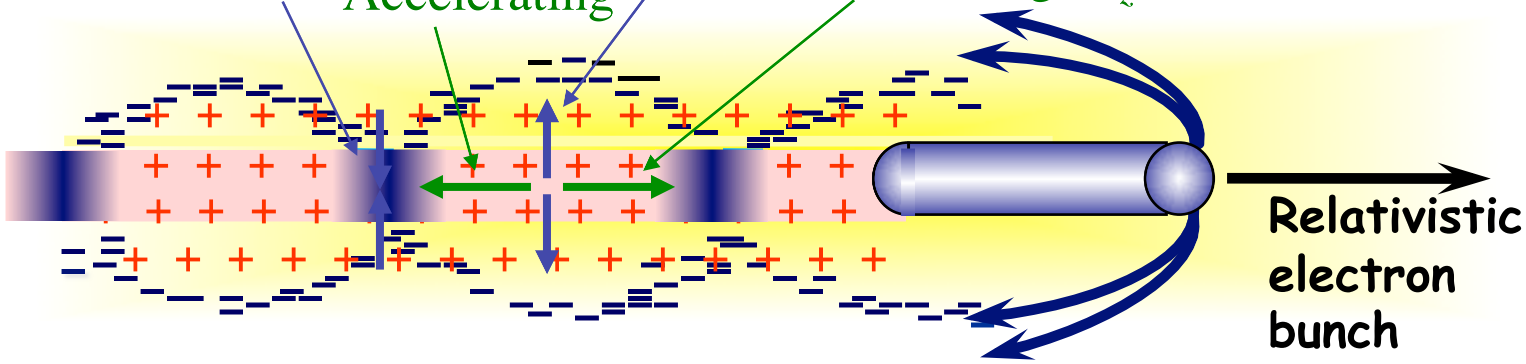
Driver \ Medium	Dielectric	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA

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

✧Summary

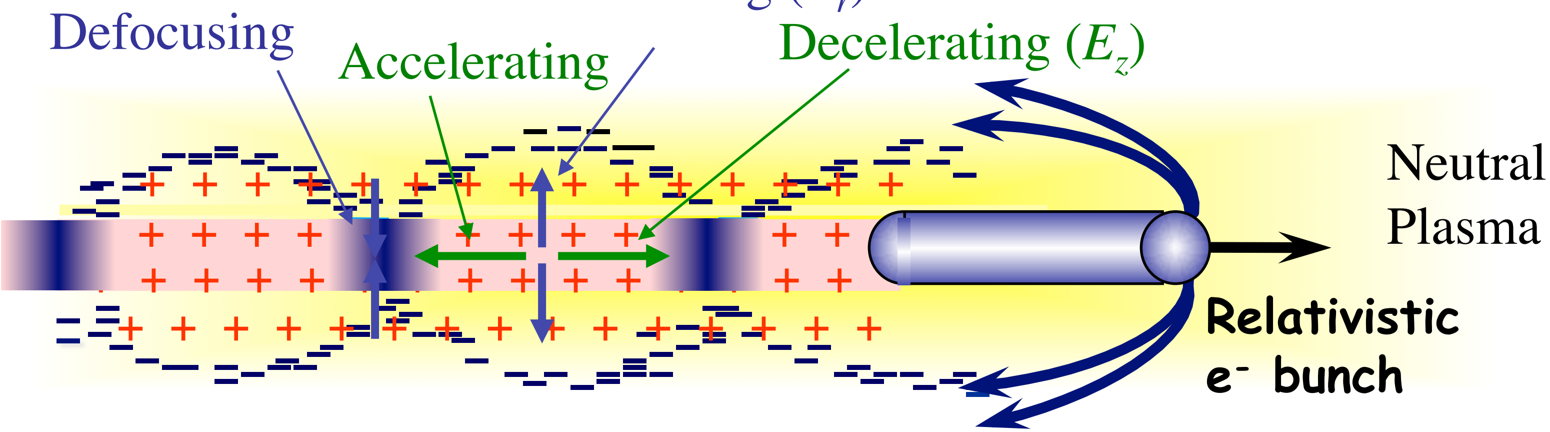


PLASMA WAKEFIELD ACCELERATOR (e^-)



- 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 $\beta^*=\sigma^{*2}/\varepsilon_g$~cm, m)
- Acceleration physics identical PWFA, LWFA

PWFA NUMBERS (e^-)



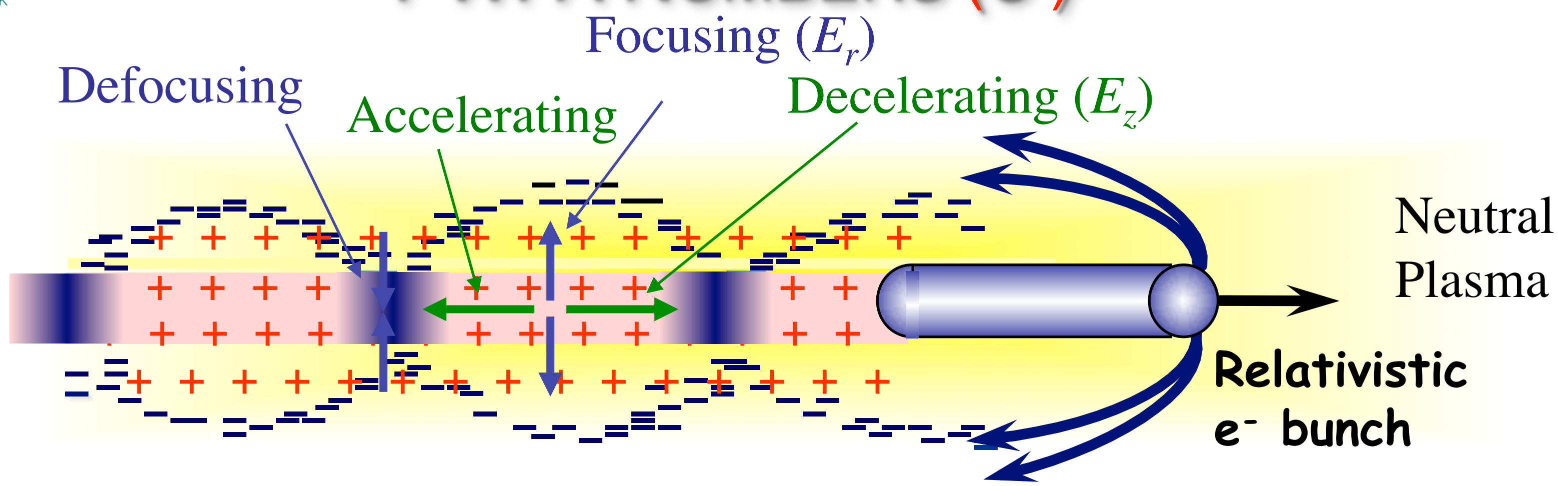
✧Linear theory ($n_b << n_{e0}$) scaling:

$$E_{acc} \cong 100[MV/m]\frac{N/2\times 10}{(\sigma_z/0.6mm)^2} \propto \frac{N}{\sigma_z^2}$$

$$@k_{pe}\sigma_z \cong \sqrt{2}, k_{pe}\sigma_r \ll 1 \qquad k_{pe} = \omega_{pe}/c \propto n_{e0}^{1/2}$$

✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_{e0}e}{\epsilon_0 c}$ ($n_b > n_{e0}$)

PWFA NUMBERS (e$^-$)



✧Linear theory (n_b<<n_{e0}) scaling:

$$E_{acc} \cong 100[MV/m]\frac{N/2\times 10}{(\sigma_z/0.6mm)^2} \propto \frac{N}{\sigma_z^2}$$

$$@k_{pe}\sigma_z \cong \sqrt{2}, k_{pe}\sigma_r \ll 1 \qquad k_{pe} = \omega_{pe}/c \propto n_{e0}^{1/2}$$

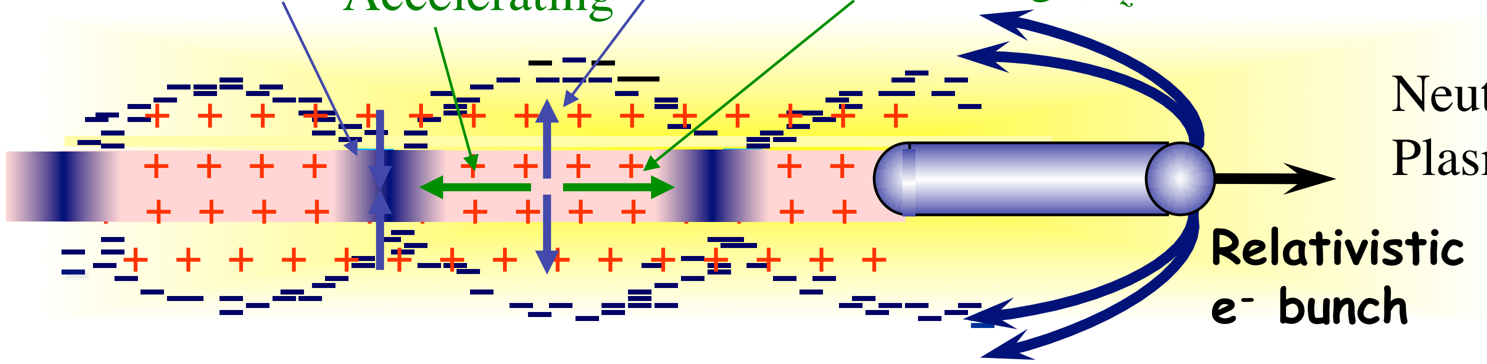
✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_{e0}e}{\epsilon_0 c}$ (n_b>n_{e0})

✧N=2x10^{10}: σ_z=600 μm, n_e=2x10^{14} cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
σ_z= 20 μm, n_e=2x10^{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^-)



✧Linear theory (n_b<<n_{e0}) scaling:

$$E_{acc} \cong 100[MV/m]\frac{N/2\times 10}{(\sigma_z/0.6mm)^2} \propto \frac{N}{\sigma_z^2}$$

$$@k_{pe}\sigma_z \cong \sqrt{2}, k_{pe}\sigma_r \ll 1 \qquad k_{pe} = \omega_{pe}/c \propto n_{e0}^{1/2}$$

✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_{e0}e}{\epsilon_0 c}$ (n_b>n_{e0})

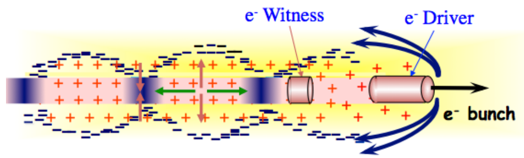
✧N=2x10^{10}: σ_z=600 μm, n_e=2x10^{14} cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
σ_z= 20 μm, n_e=2x10^{17} cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

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

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

FIRST PWFA OBSERVATION (e^-)

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



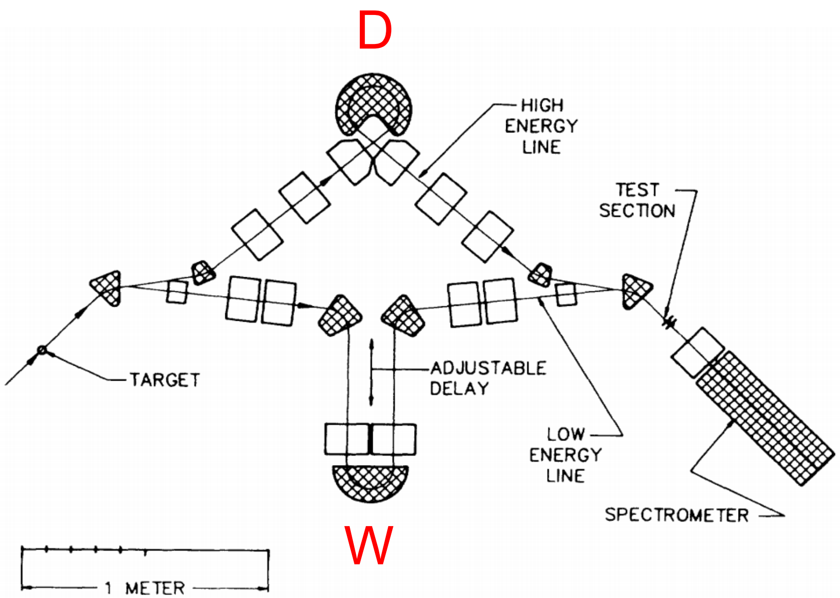


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

Rosenzweig, PRL 61, 98 (1988)

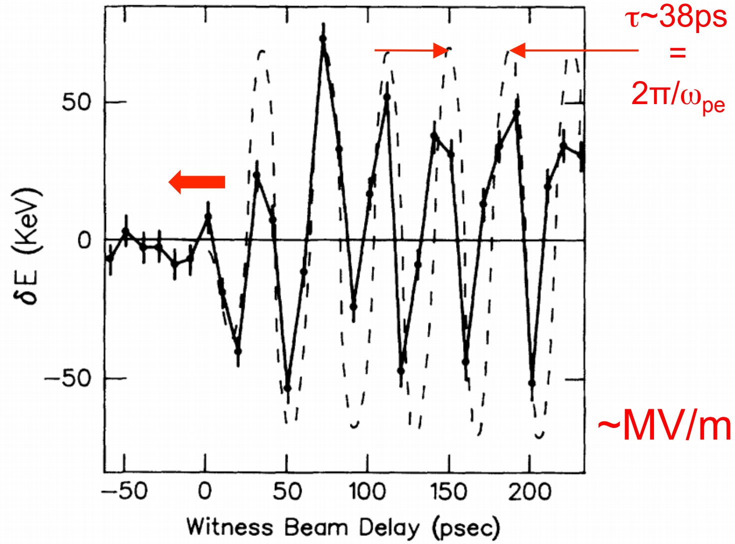
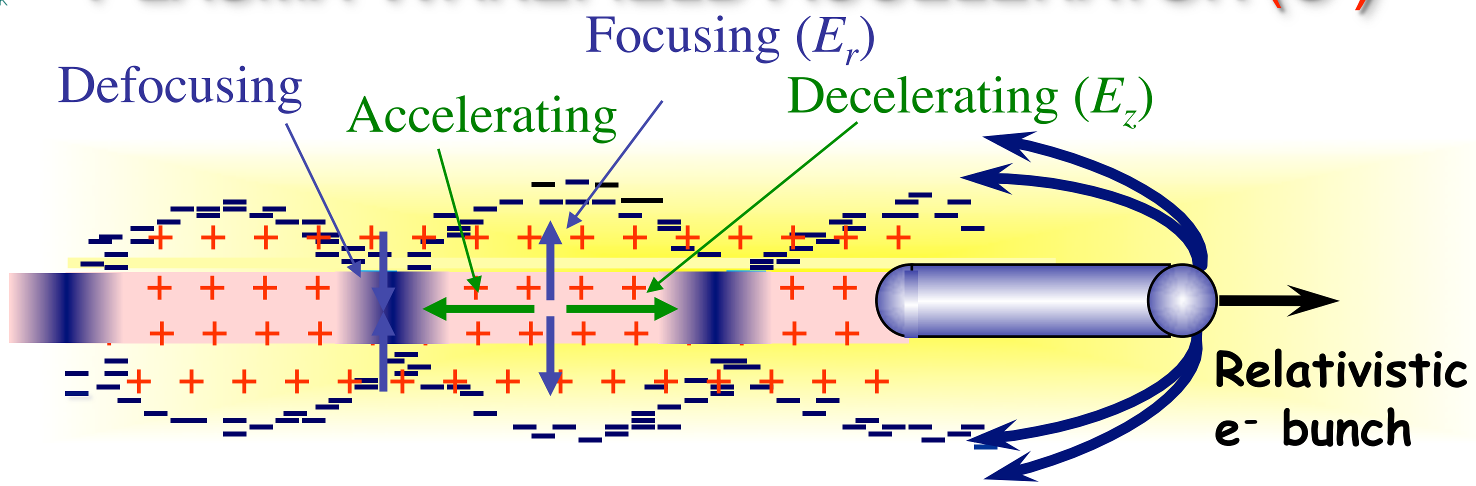


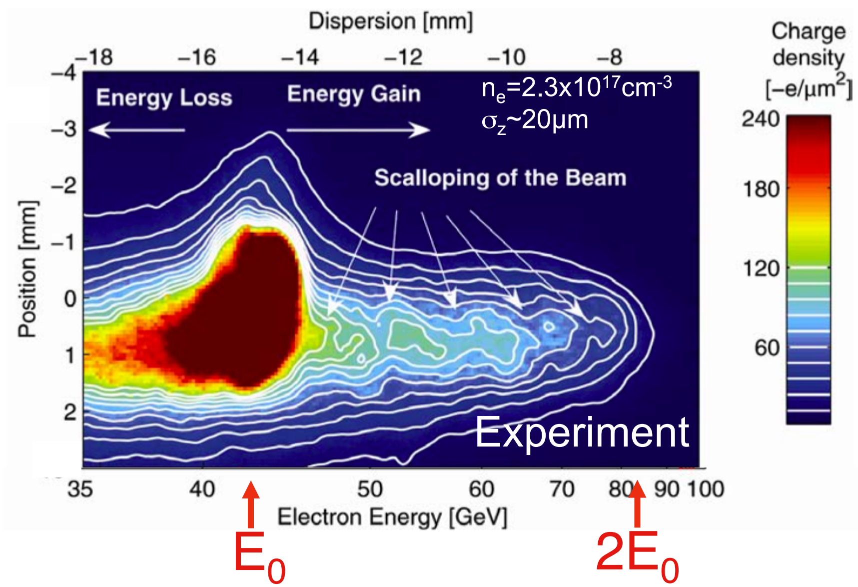
FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6 \times 10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

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

PLASMA WAKEFIELD ACCELERATOR (e^-)



Blumenfeld, Nature 445, 741 (2007)

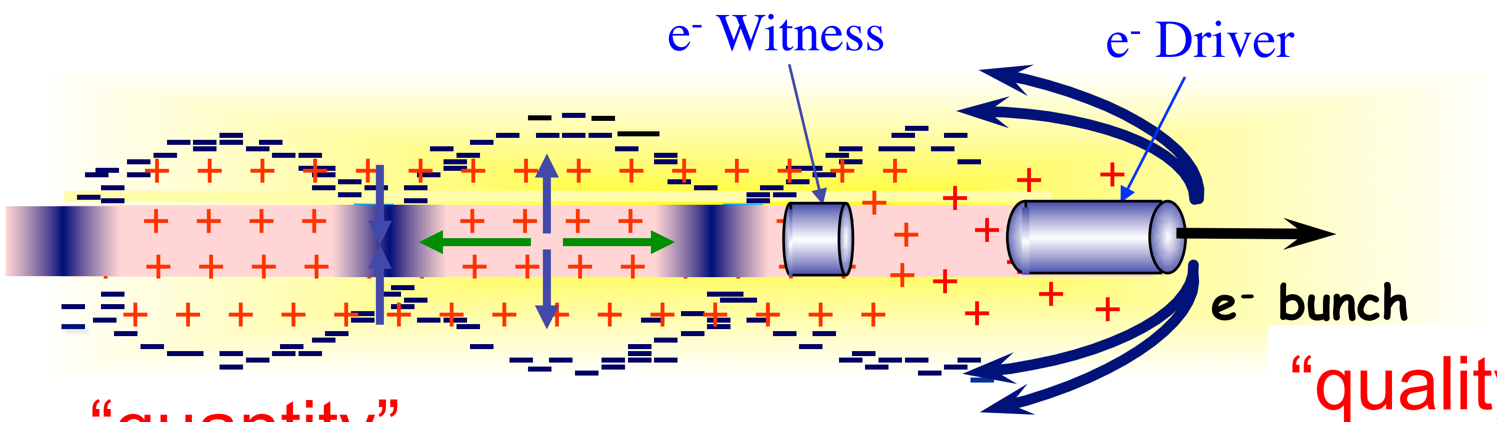


42 => 84GeV in 85cm! 50GeV/m

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

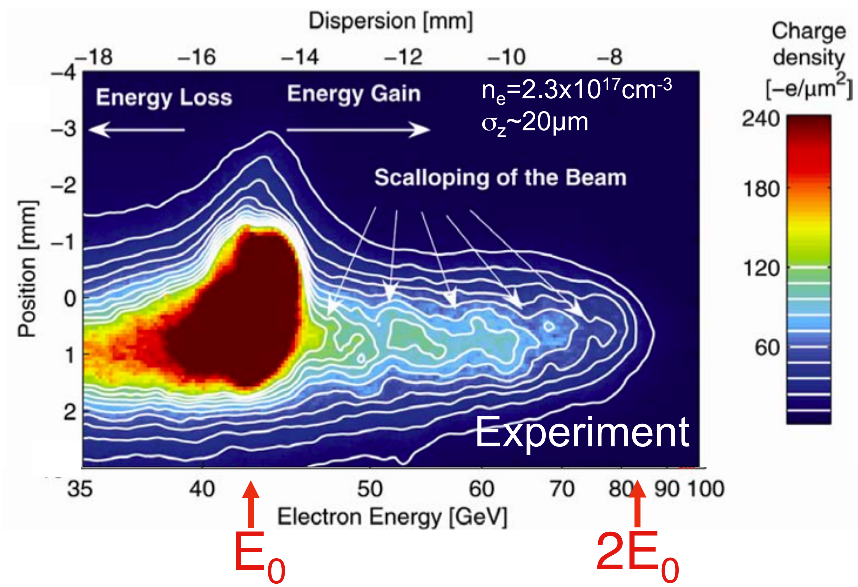
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

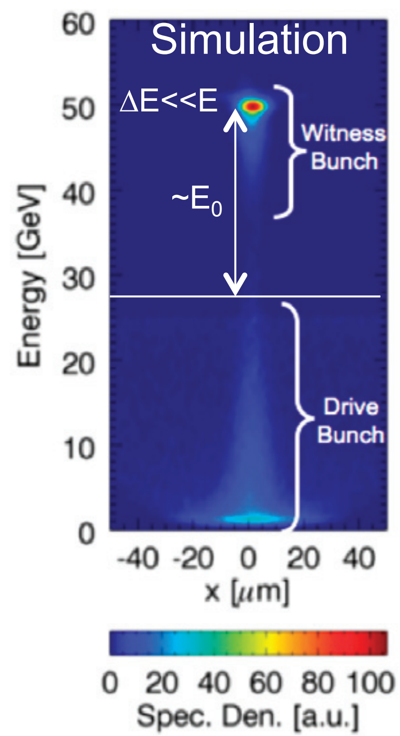
Blumenfeld, Nature 445, 741 (2007)



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

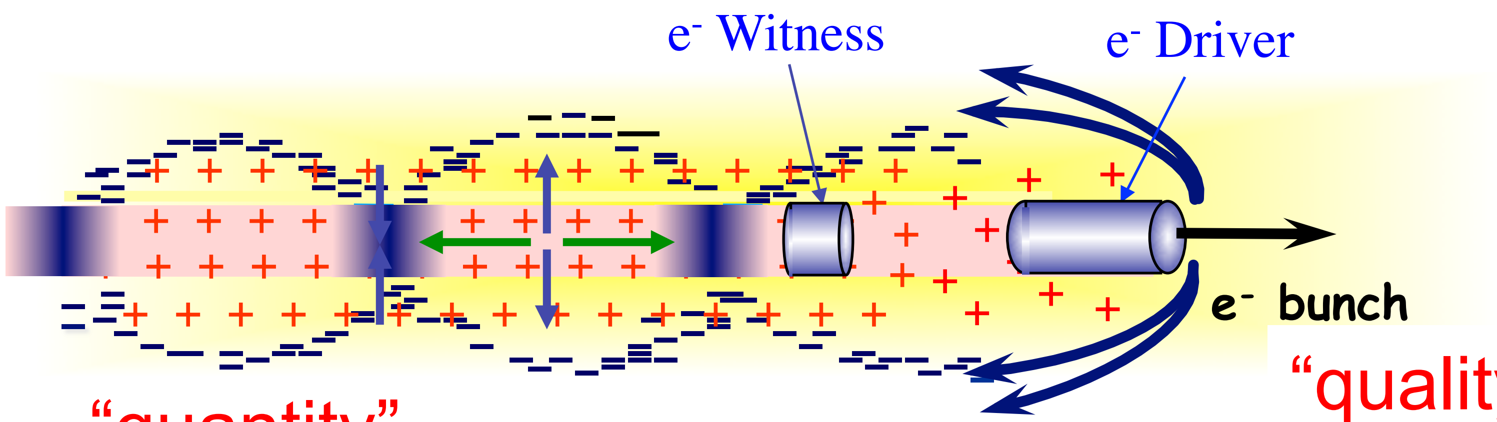
SLAC FACET

Hogan, NJP 12, 055030 (2010)



MAX-PLANCK-INSTITUT FÜR PHYSIK

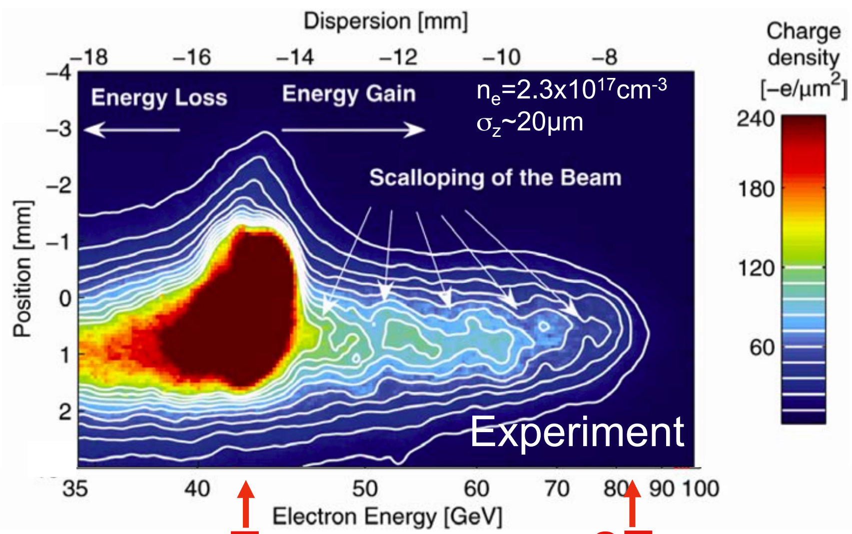
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)

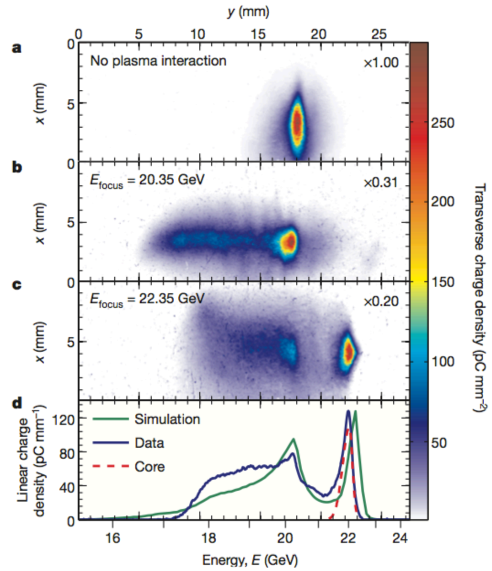


E_0 $2E_0$

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

SLAC FACET

Litos, Nature 515(6) 92 (2014)

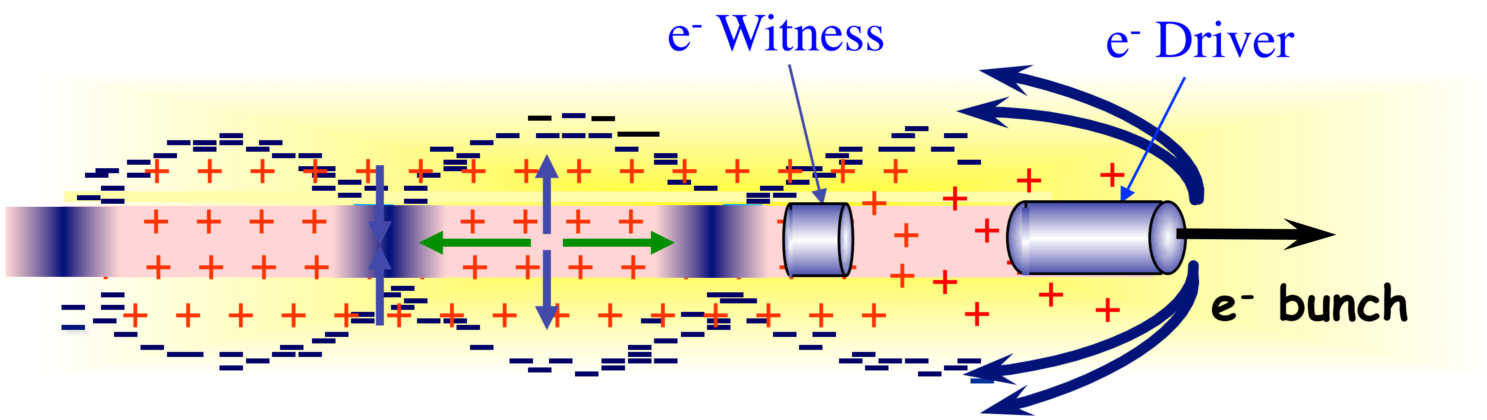


~2GeV in ~36cm

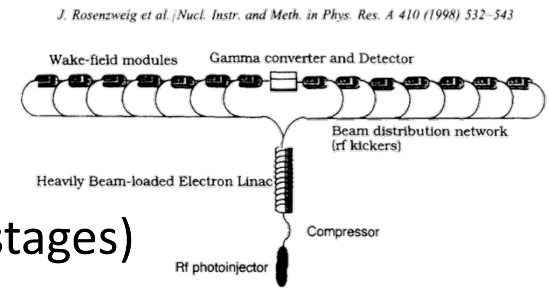
$\Delta E/E$~%

η_{W-W}~30%

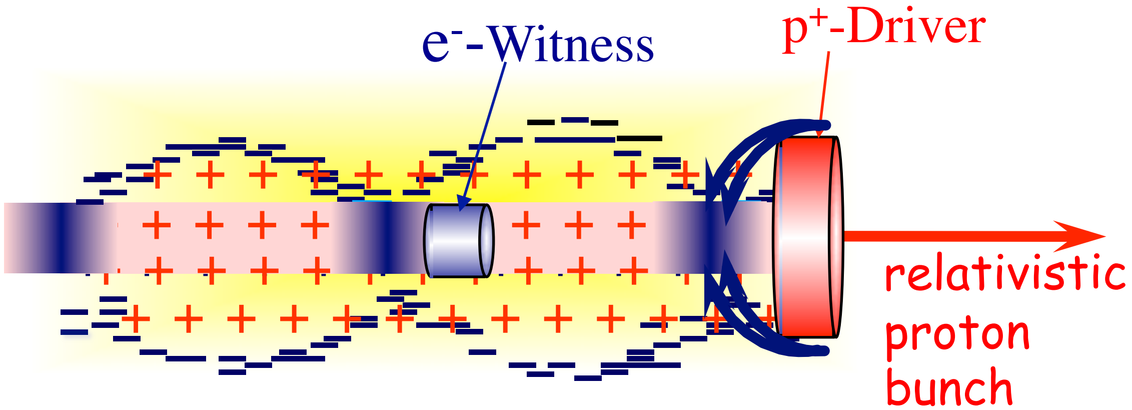
PWFA, TeV COLLiDER

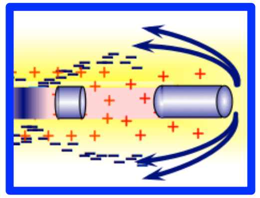


- ✧ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ
- ✧SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J
- ✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

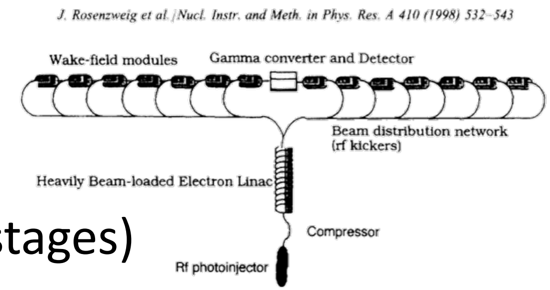


p^+-DRiVEN PWFA? YES BUT WHY?

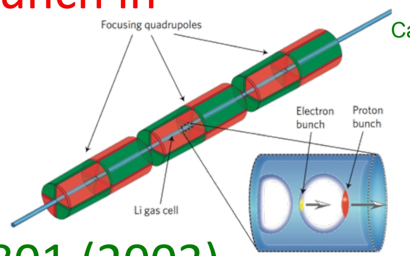




- ✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ



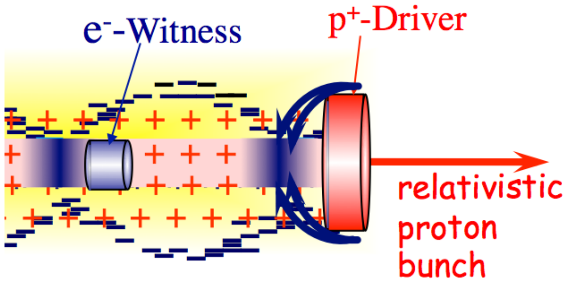
- ✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J
- ✧SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)
- ✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- ✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- ✧Large average gradient! (≥1GeV/m, 100's m)
- ✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)



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

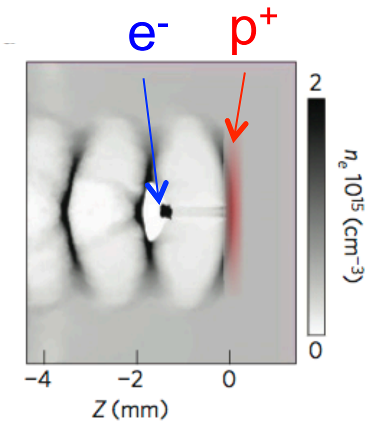
PROTON-DRIVEN PWFA

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

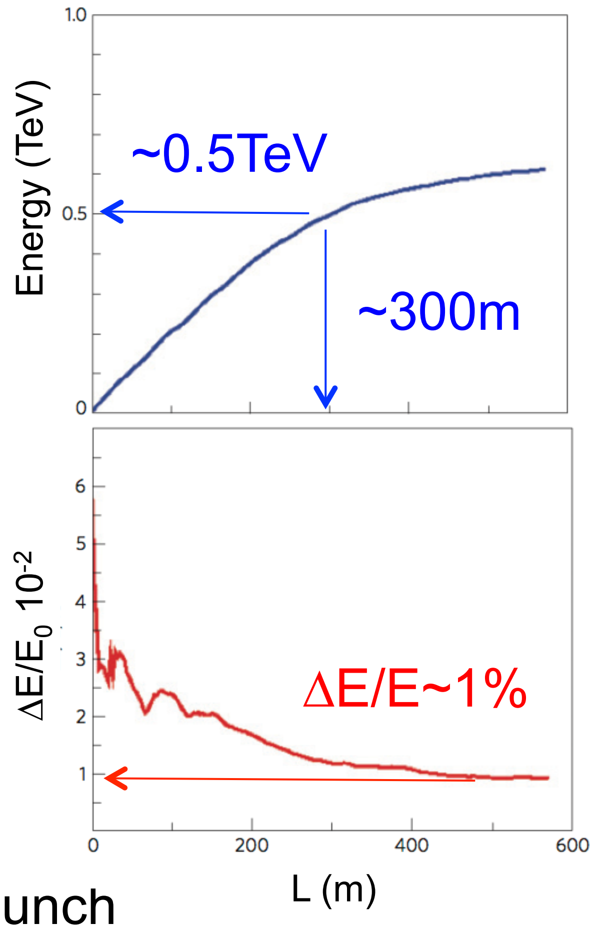


e^-:	p^+:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
N=10^{10}	N=10^{11}
W_0=16J	W_0=16kJ
W_f=1kJ	

Single Stage



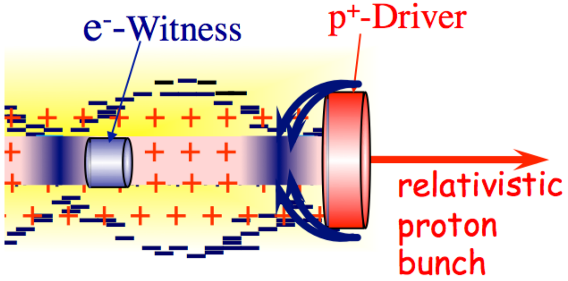
Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_P/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons 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 ($6\text{x}10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

PROTON-DRIVEN PWFA

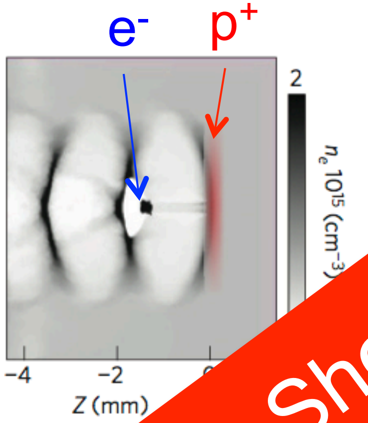
Caldwell, Nat. Phys. 5, 363, (2009)



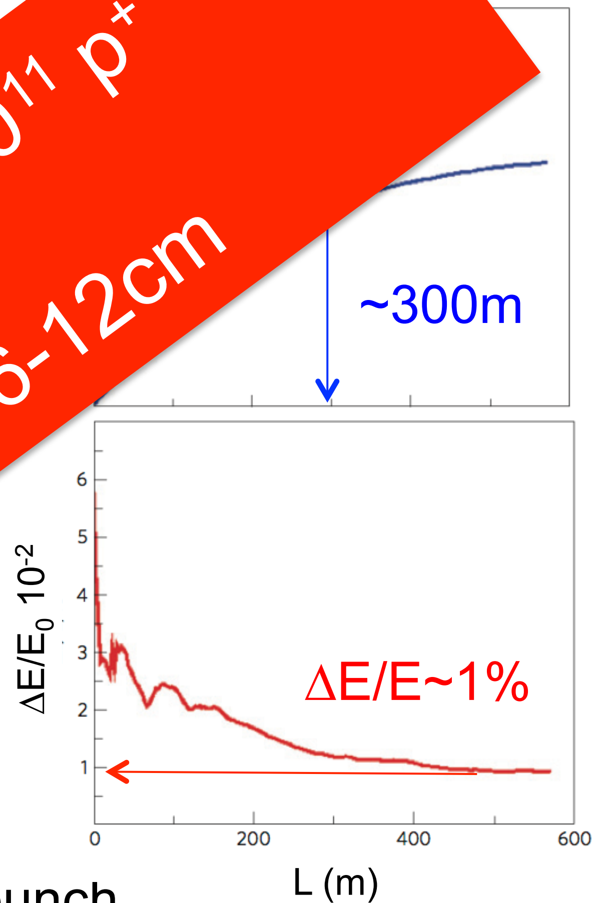
Single Stage

e^-:
E_0=10GeV
N=10^{10}
W_0...

p^+:
E_0=1T...



Para...		
		μm
		mrad
	0.43	mm
	1.5×10^{10}	
E_e	10	GeV
n_p	6×10^{14}	cm^{-3}
λ_p	1.35	mm
	1,000	$T\,m^{-1}$
	0.7	m

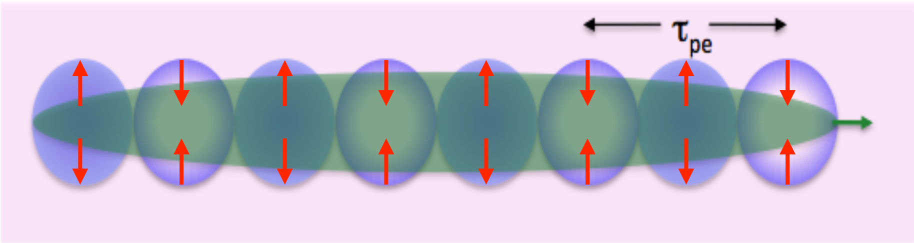


Short (100µm) bunches with 10^{11} p^+ do not exist!!!
CERN PS-SPS-LHC σ_z~6-12cm

- ✧ ... the wakefields of a p^+ bunch
- ✧ ...dient dilution
- ✧ Gr... m over 100's m
- ✧ Ope... lower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

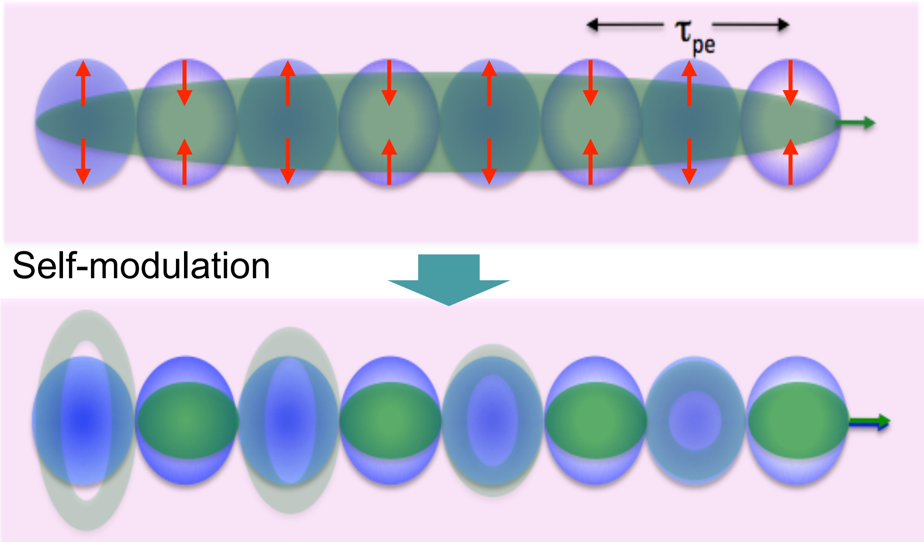
SELF-MODULATiON

✧Long driver (e^-), dense plasma, $\sigma_t >> 1/\omega_{pe}$, $\sigma_t \sim c/\omega_{pe}$



SELF-MODULATION

✧Long driver (e^-), dense plasma, $\sigma_t >> 1/\omega_{pe}$, $\sigma_t \sim c/\omega_{pe}$



Growth mechanism:

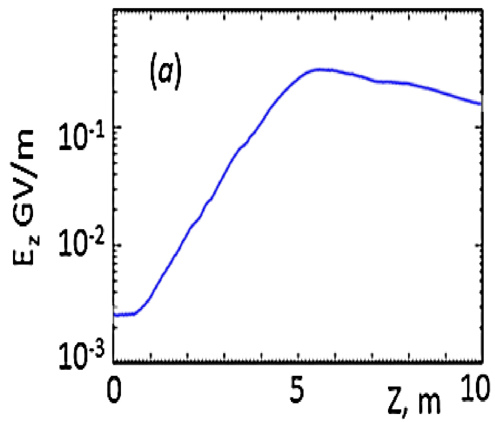
Initial (transverse) wakefields

Periodic focusing/defocusing

Density modulation

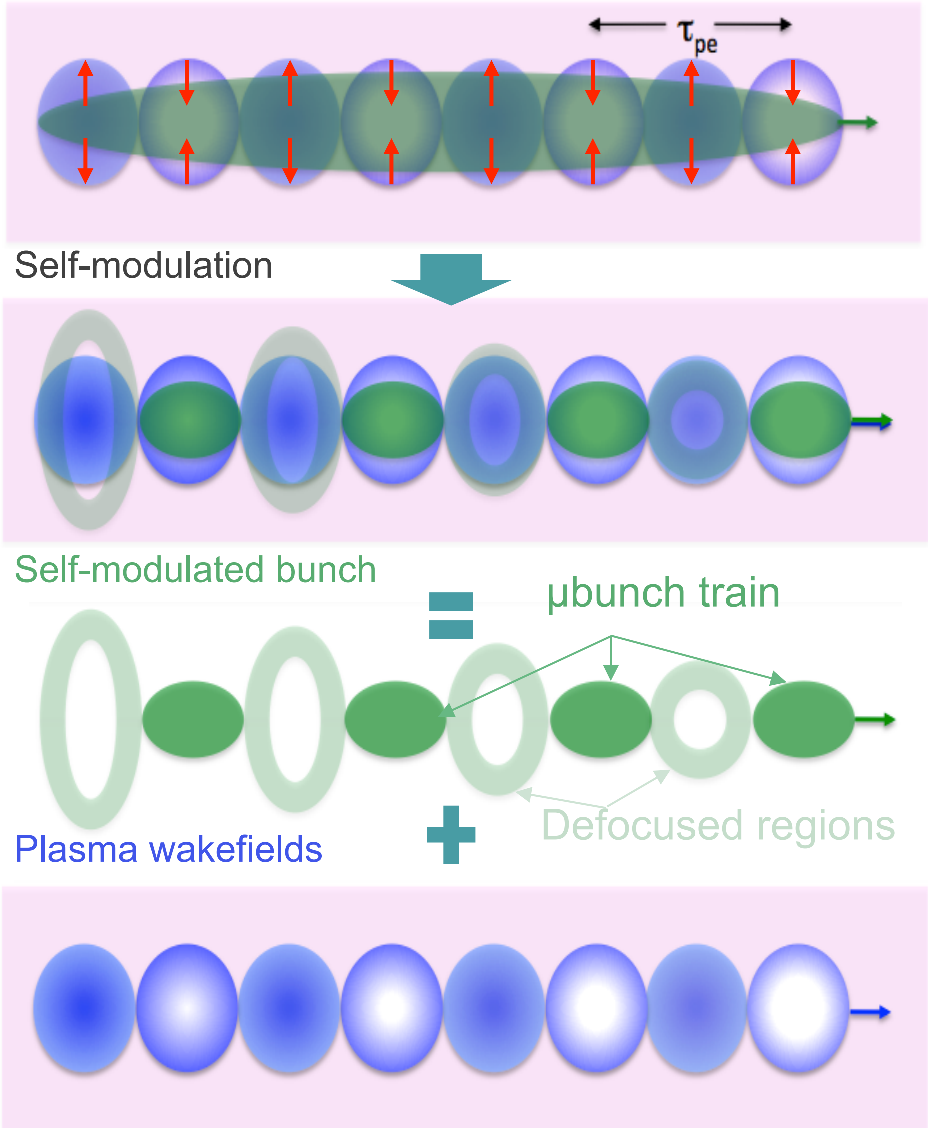
Full modulation - bunch train

Pukhov, PRL107 145003 (2011)



SELF-MODULATION

- Long driver (e^-), dense plasma, $\sigma_t >> 1/\omega_{pe}$, $\sigma_t \sim c/\omega_{pe}$



Growth mechanism:

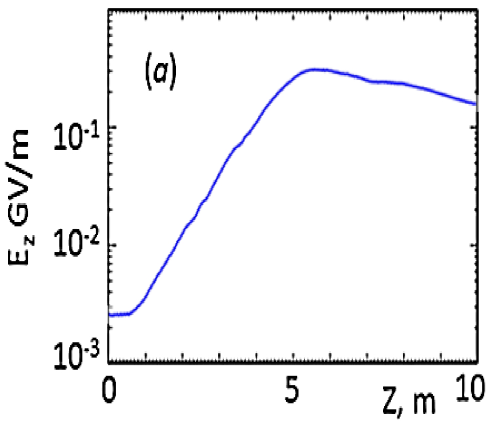
Initial (transverse) wakefields

Periodic focusing/defocusing

Density modulation

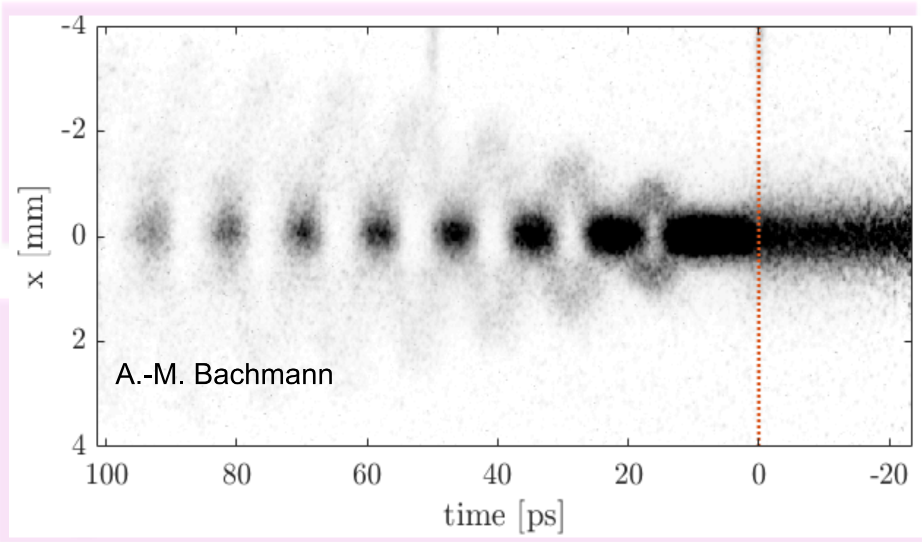
Full modulation - bunch train

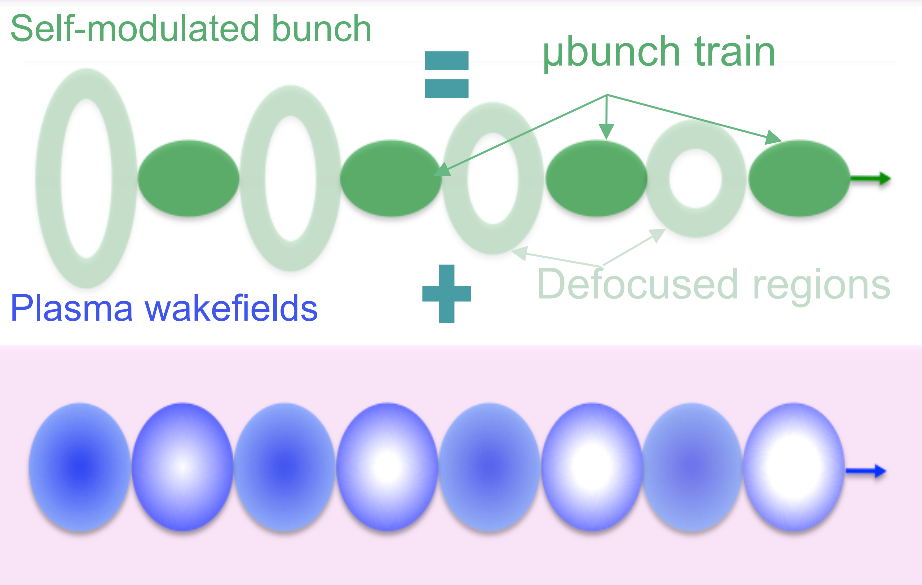
Pukhov, PRL107 145003 (2011)



SELF-MODULATiON

✧Long driver (e^-), dense plasma, $\sigma_t >> 1/\omega_{pe}$, $\sigma_t \sim c/\omega_{pe}$





Growth mechanism:

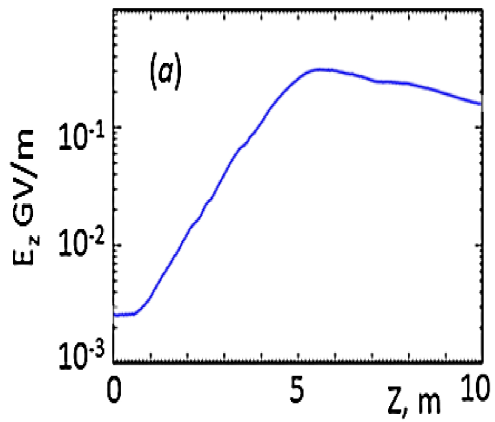
Initial (transverse) wakefields

Periodic focusing/defocusing

Density modulation

Full modulation - bunch train

Pukhov, PRL107 145003 (2011)



✧Train period $\sim\tau_{pe}=2\pi/\omega_{pe}$

✧µbunch length < τ_{pe}

✧Resonantly drives wakefields to large amplitude

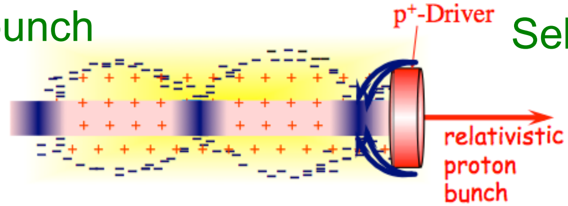
MAX-PLANCK-INSTITUT FÜR PHYSIK

AWAKE @ CERN

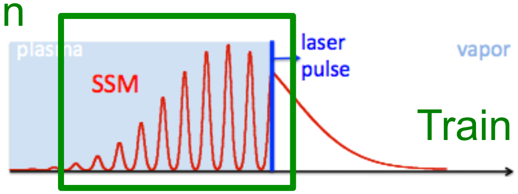
✧Use a long ($\sigma_z >> \lambda_{pe}$), relativistic (400GeV/p^+), high energy (~20kJ) p^+ bunch to resonantly drive large amplitude wakefields (E_z~1GV/m) in a long (~10^+m) plasma

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

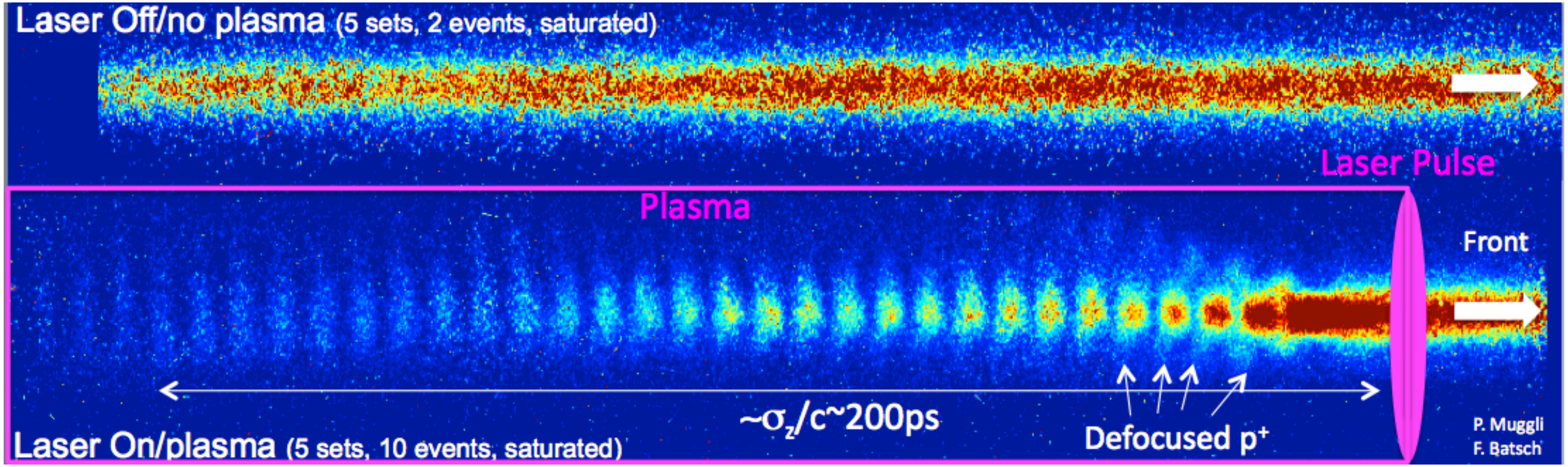
Single short bunch



Self-Modulation
SM



Train of μbunches

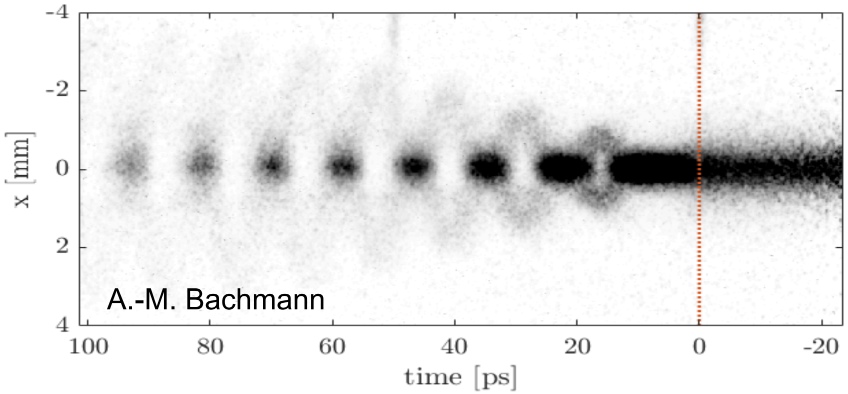


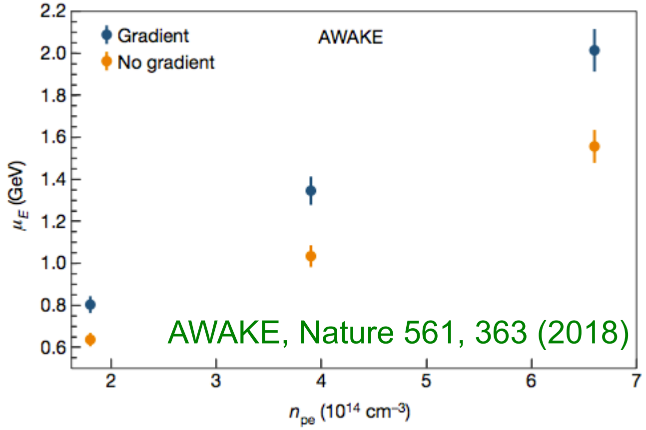
AWAKE, PRL 122, 054802 (2019)
Turner et al. PRL 122, 054801 (2019)
Braunmueller, PRL 125, 264801 (2020)
Batsch, PRL 126, 164802 (2021)

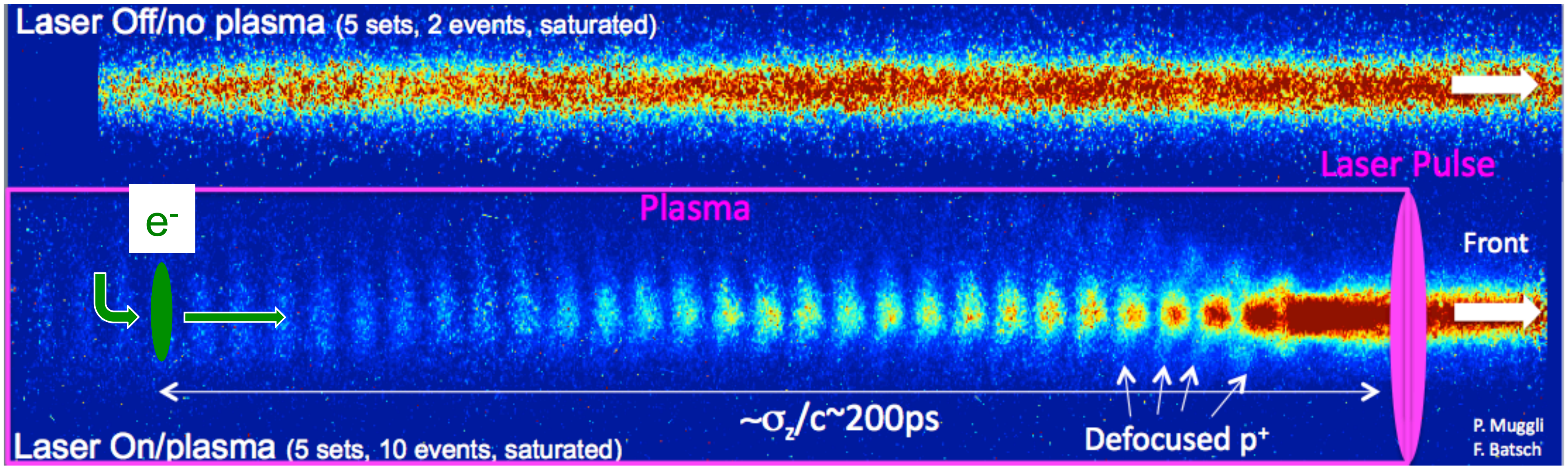
AWAKE @ CERN

✧Acceleration of externally-injected e^-

✧19MeV -> 2GeV







✧External injection of e^- for acceleration

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

AWAKE, PRL 122, 054802 (2019)
Turner et al. PRL 122, 054801 (2019)
Braunmueller, PRL 125, 264801 (2020)
Batsch, PRL 126, 164802 (2021)

MAX-PLANCK-INSTITUT
FÜR PHYSIK

OUTLINE

✧Introduction

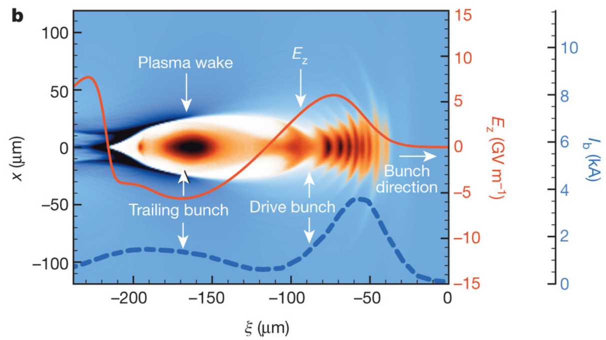
✧Novel Acceleration Techniques

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

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

✧Summary

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



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

✧Summary

PWFA FOR e⁻/e⁺ COLLIDER

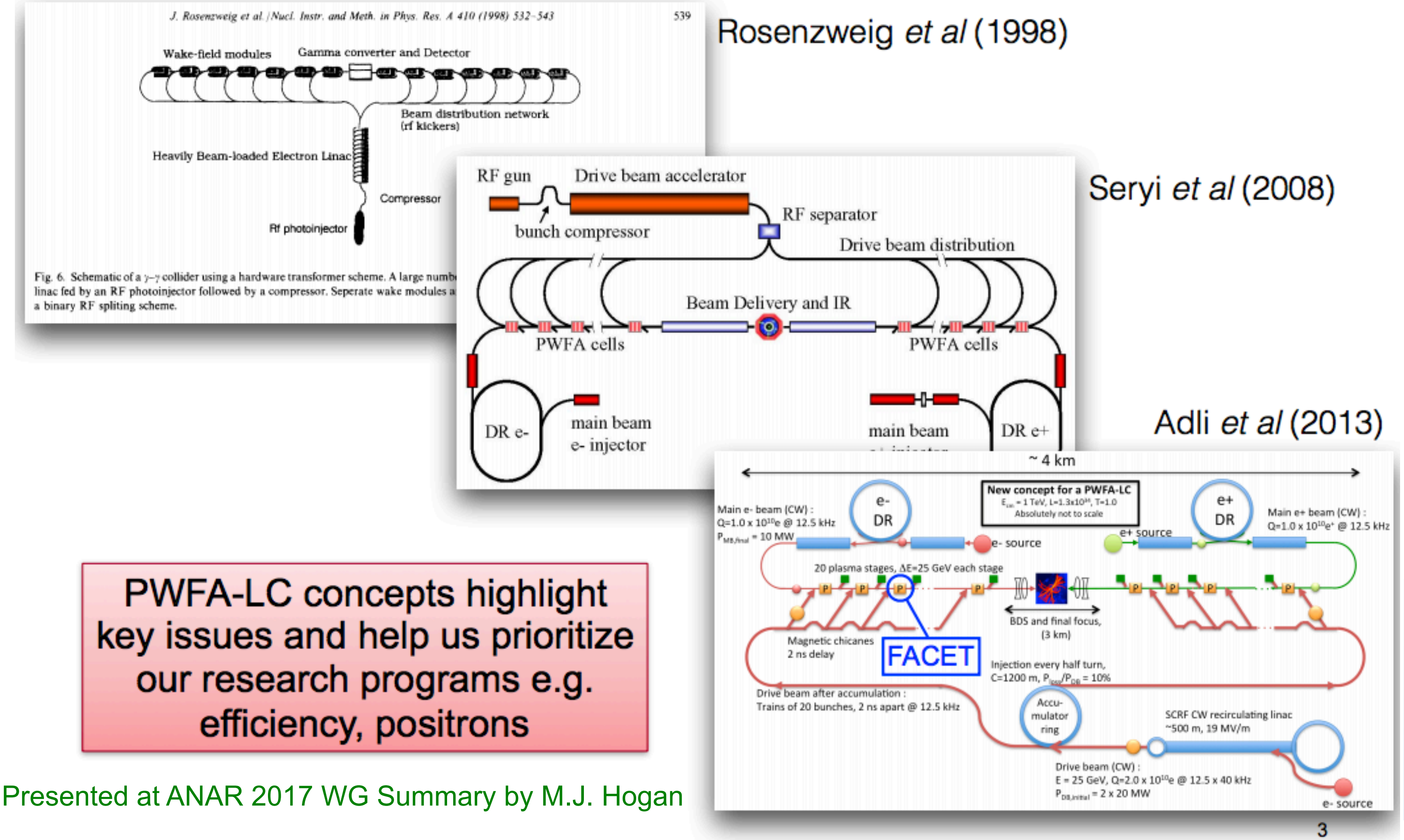
PWFA Research Roadmap for Electron Driver:
Goal is to Get to a TeV Scale Collider for High Energy Physics

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

Print ISSN: 1793-6268
Online ISSN: 1793-8058

✧ Staging also required for LWFA

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

SUMMARY

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

- ✧ Large energy gains have been achieved:

  0-7.8GeV in ~ 20cm plasma (LWFA, LBL)
  42-84GeV in ~ 85cm plasma (PWFA, SLAC)
  0.019-2.0GeV in <10m (SM-PWFA, AWAKE)

- ✧ 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 km-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, e.g., injector
  - ✧ ANAs need to meet all challenges of colliders

- ✧ Exciting research field since in its discovery phase … opportunities …

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