Novel Accelerator Techniques

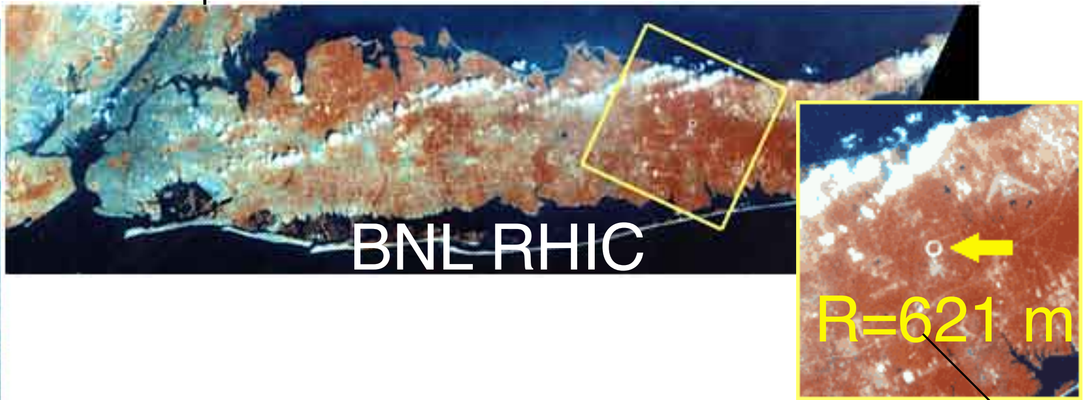
Patric Muggli
Max Planck Institute for Physics
Munich
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

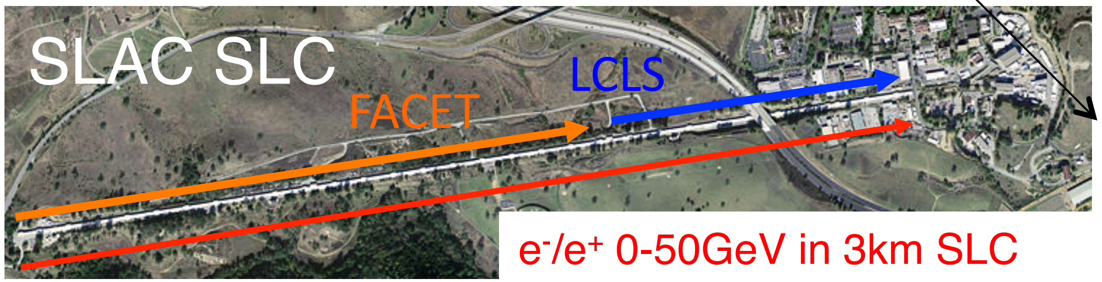
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MAX-PLANCK-GESELLSCHAFT

PARTICLE ACCELERATORS

"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 RF technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

PARTiCLE ACCELERATORS

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

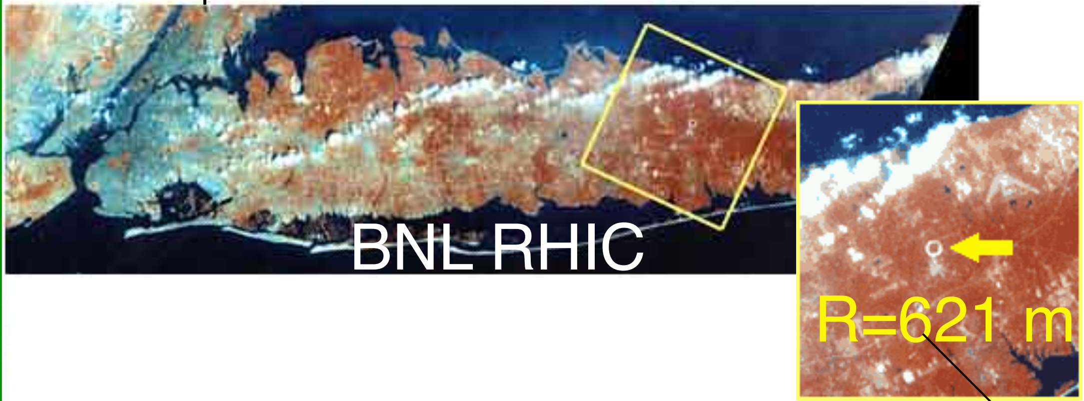
$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7} \frac{E^4}{R^2 m^4}$$

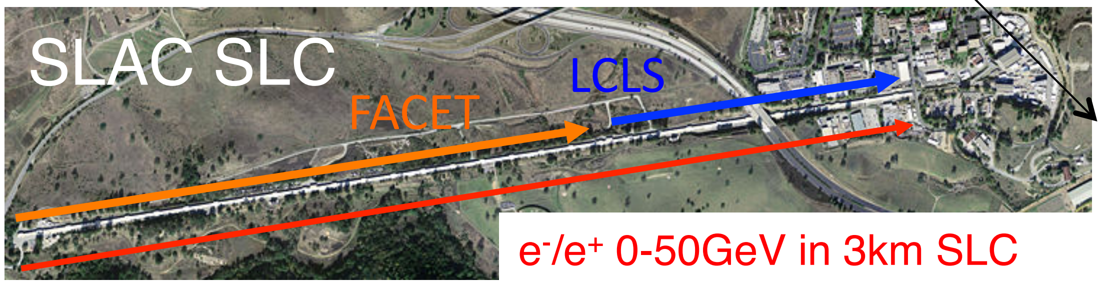
Must be linear and …

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

G : accelerating gradient

"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

complex (and most expensive) scientific

ate particles

➡ Can we make them smaller (and cheaper) and with a higher energy?

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

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 (>100MeV/m)
and reduce the size and cost
of a future e^-/e^+, e^-/p^+ collider
or of a x-ray FEL

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 RF technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

OUTLiNE

✧Novel Accelerator Techniques "Goals"

Driver \ Medium	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

✧Summary

OUTLiNE

✧Novel Accelerator Techniques "Goals"

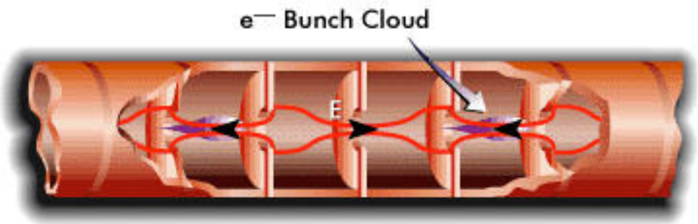
Driver \ Medium	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

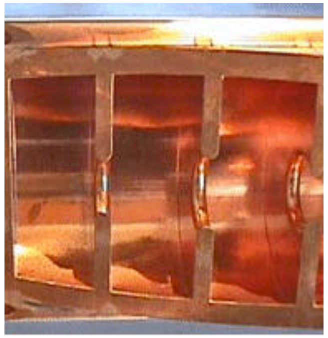
✧Summary

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

ACCELERATiNG FiELD/GRADiENT LiMiTATiONS

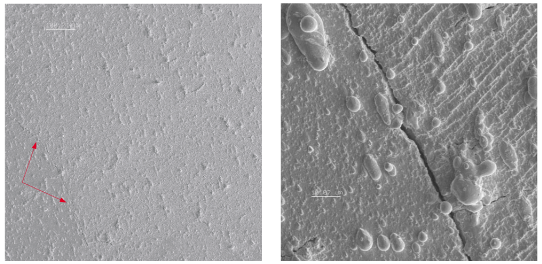
- ✧Gradient/field limit in (warm) RF structures: <100MV/m
- ✧RF break down (plasma!!) and pulsed heating fatigue
- ✧Accelerating field on axis, damage on the surface
- ✧Material limit, metals in the GHz freq. range (Cu, Mo, etc.)
- ✧Does not (seem to) increase with increasing frequency

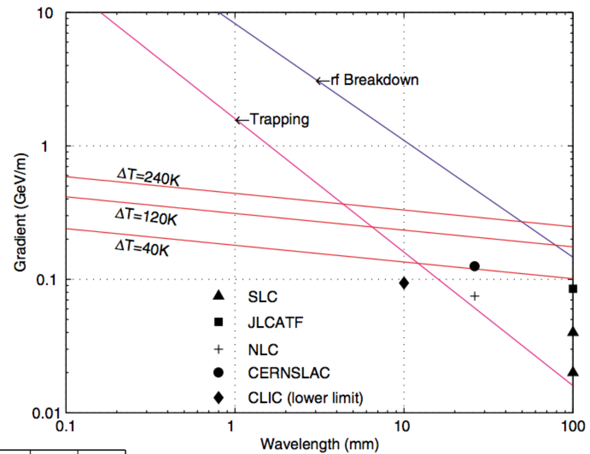




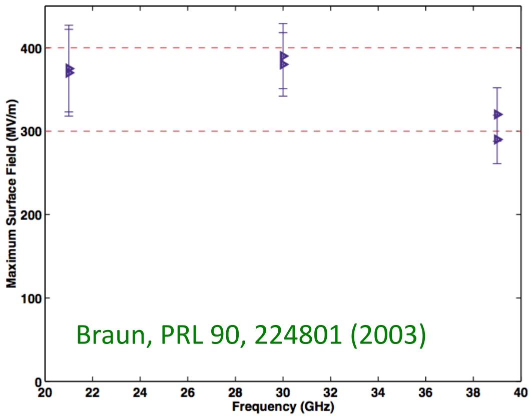
Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)





RF break down



Braun, PRL 90, 224801 (2003)

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

NOVEL ACCELERATORS

"Novel"
↕
"High-gradient"
↕
>1GeV/m
↕
Average gradient over m–scale
↕
GeV to TeV e^-/e^+

<u>Materials with higher damage threshold</u>:
- ✧Dielectrics (~GV/m)
- ✧Plasmas (10-100GV/m or ∞)

<u>Systems powered/driven by:</u>
- ✧Laser pulse(s)*
- ✧Charged particle bunch(es)

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

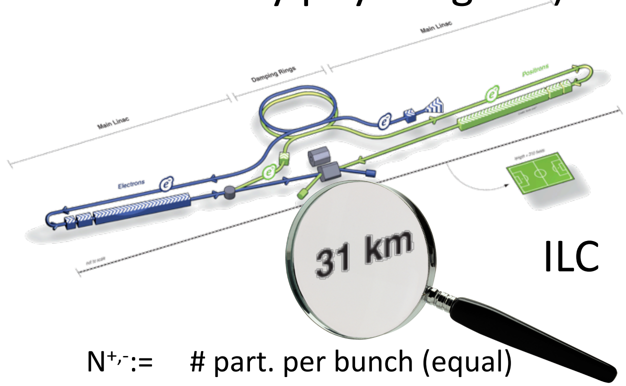
*do not include laser vacuum/direct acceleration

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

GOALS

✧Reaching final energy : >150GeV/beam for e^- and e^+ (determined by physics goals)
: up to 1-10TeV
: > 60GeV e^- (for e^-/p^+ collider, determined by physics goals)

✧Large <u>average</u> accelerating gradient (>1GeV/m)



✧Accelerator(s) a few 100's of meter long (not km's)

✧Reaching luminosity (e^-/e^+ or e^-/p^+, ions)

$$\mathcal{L} \propto \frac{N^+ N^- f_{rep} n_b}{\sigma_x^*(\varepsilon_x)\sigma_y^*(\varepsilon_y)} \Leftrightarrow \mathcal{L} \propto \frac{N P_b}{E\sigma_x^*(\varepsilon_x)\sigma_y^*(\varepsilon_y)}$$

$N^{+,-}$:= # part. per bunch (equal)
f_{rep}:= train repetition rate
n_b:= # bunches per train
$\sigma^*_{x,y}$:= bunch transverse size @ waist
$\varepsilon_{x,y}$:= bunch emittance
E:= energy per particle
P_b:= average beam power $\approx n_b N f_{rep} E$

- Focus on accelerator contribution (not final focus or interaction point)
- Assume those are the same (bunch length?)

✧Deliver the same average (s) current with the same emittance (DWA, LWFA, PWFA)

✧Deliver lower average current with lower emittance?? (DLA)

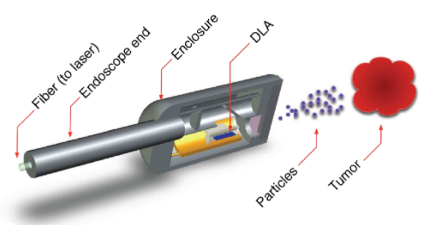
MAX-PLANCK-GESELLSCHAFT

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

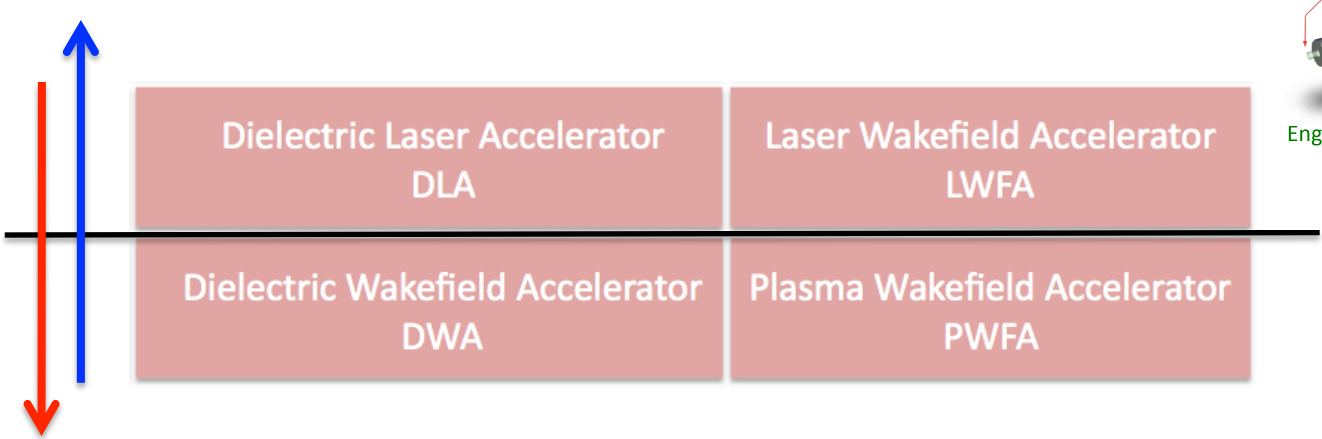
APPLICATIONS

- ✧X-ray for radiography (advanced: phase contrast, etc.)
- ✧e^- for medical applications

- ✧All require low energy <GeV
- ✧Can operate at very large peak gradient, mm-cm accelerator
- ✧Efficiency not an issue
- ✧Luminosity “not an issue”
- ✧Special characteristics: ultra-short, synchronized (laser), pump probe, etc.
- ✧Biological advantage …
- ✧Unique applications, compact



England, Rev. Mod. Phys., 86, 1337, (2014)



- ✧Powerful radiation source, THz to γ-rays
- ✧High-energy physics (HEP)

MAX-PLANCK-GESELLSCHAFT

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

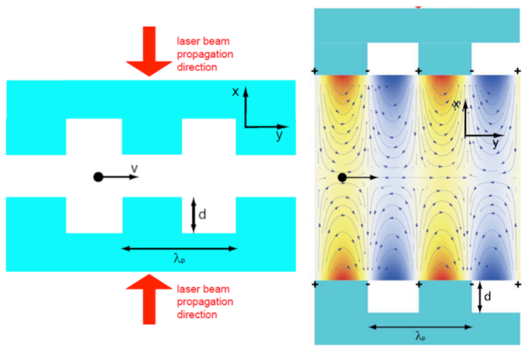
OUTLiNE

✧Novel Accelerator Techniques “Goals”

Medium / Driver	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

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

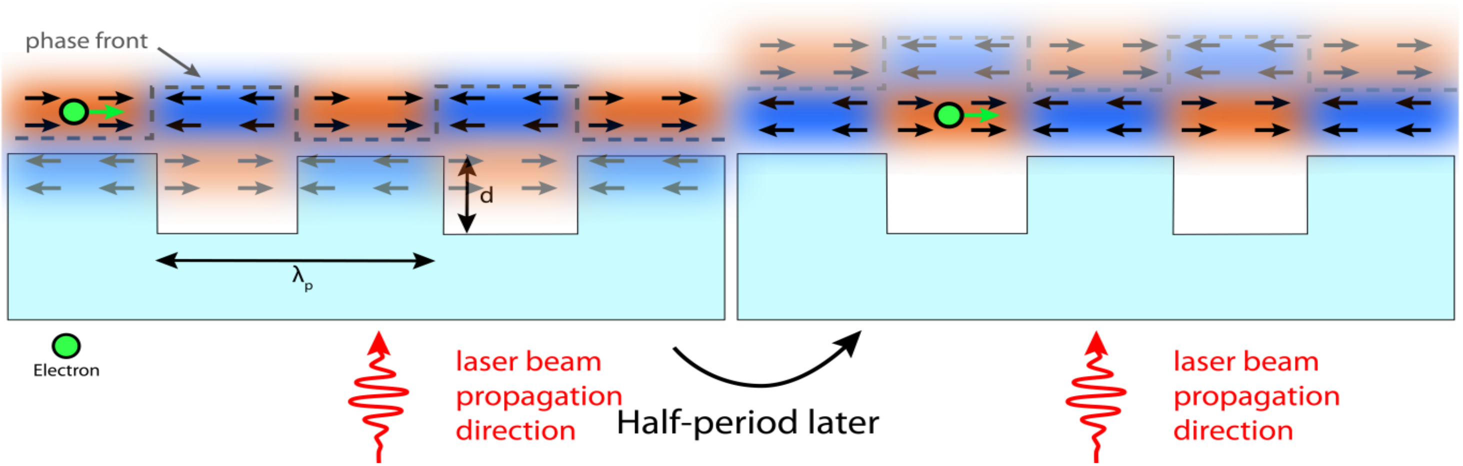
✧Summary

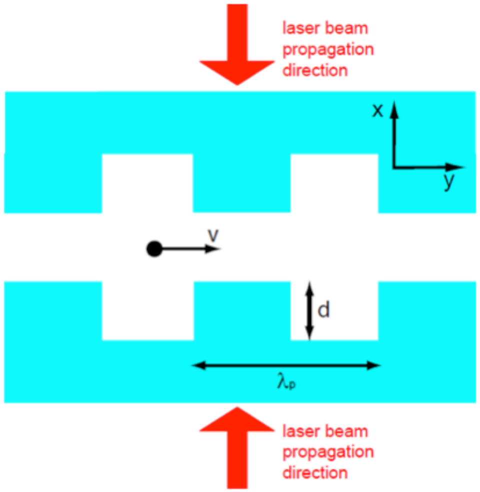


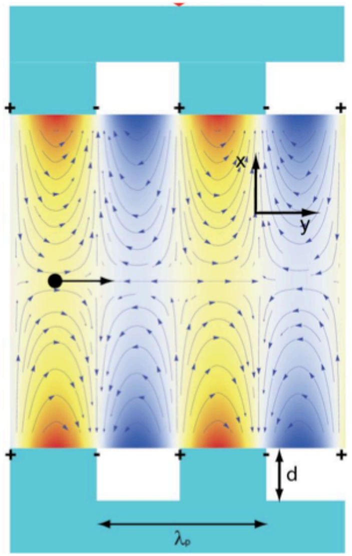
MAX-PLANCK-GESELLSCHAFT

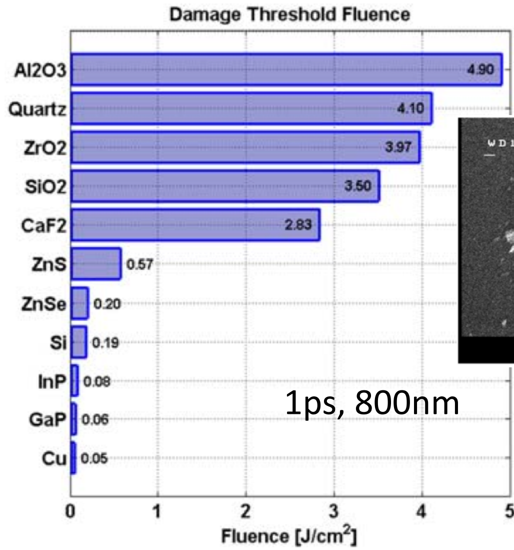
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

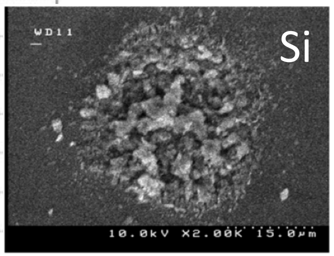
DiELECTRiC LASER ACCELERATOR (DLA)











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

- ✧ Take advantage of large laser E-field
- ✧ Take advantage of large damage threshold
- ✧ Structure = phase mask for velocity matching

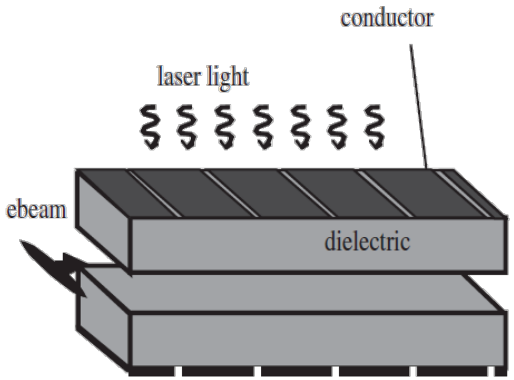
FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG

 Courtesy P. Hommelhoff

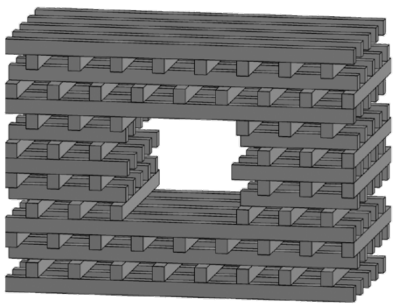
P. Hommelhoff, Accel. Med. Appl., Vösendorf, Austria, 2015

DiELECTRiC LASER ACCELERATOR (DLA)

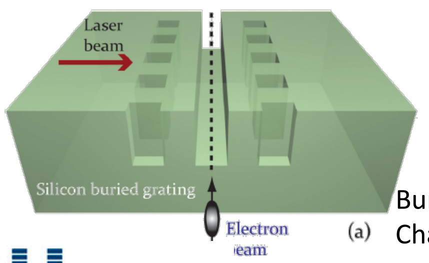
Proposed dielectric structures



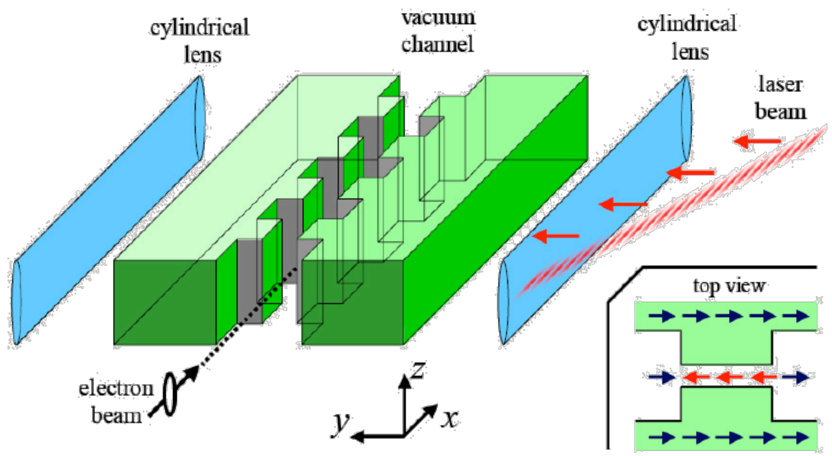
Yoder, Rosenzweig, 2005



Woodpile
Cowan, 2008



Buried Grating
Chang, Solgaard, 2014



Plettner, Lu, Byer, 2006

… and variants

- Goal: generate a mode that allows momentum transfer from laser field to electrons
- Use first order effect (efficient!)
- Second order effects (ponderomotive) too inefficient

For a review and an extensive list of references, see: R. J. England et al., “Dielectric laser accelerators”, Rev. Mod. Phys. 86, 1337 (2014)

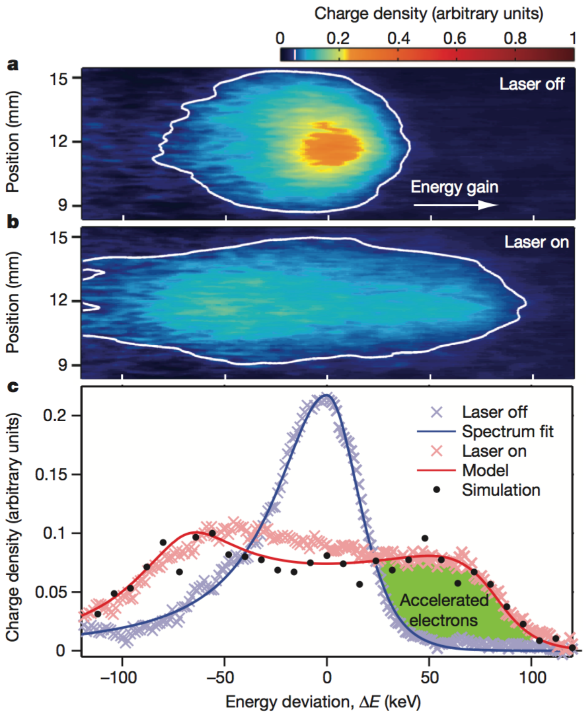
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

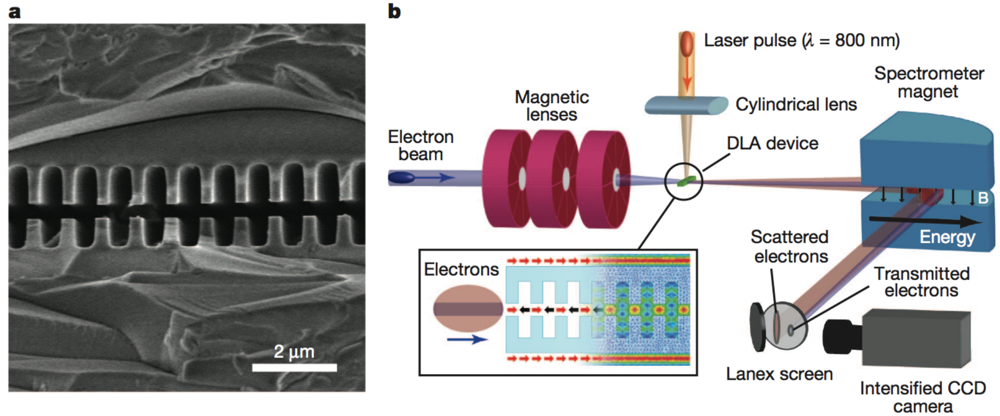
DLA RESULTS

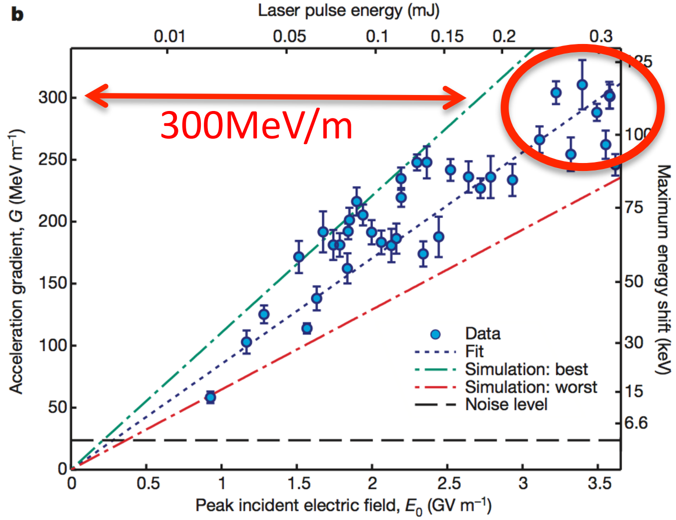
Demonstration of electron acceleration in a laser-driven dielectric microstructure

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







✧Inferred accelerating gradient in excess of 300MV/m, can be increased

✧Need sub-$(\lambda_{laser})^3$ beams, naturally low emittance and charge

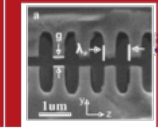
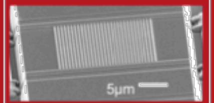
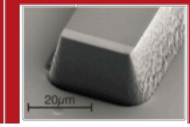
✧Operate at very high rep-rate

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

DLA RESULTS

Recent DLA Experiment Comparison

SLAC

Parameter	SLAC 	Stanford 	MQP/Erlangen 
Year	2013	2015	2013
Material	Fused Silica	Silicon	Fused Silica
Beam Energy	60 MeV	96.3 keV	30 keV
β = v/c	0.9996	0.54	0.33
Laser Pulse Energy	330 μJ	5.2 nJ	160 nJ
Pulse Duration	1.1 ps	130 fs	110 fs
Interaction Length	360 μm	5.6 μm	11 μm
Max Energy Gain	100 keV	1.22 keV	275 eV
Max Gradient	309 MV/m	220 MV/m	25 MV/m

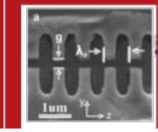
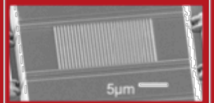
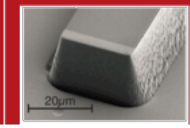
Courtesy of J. England

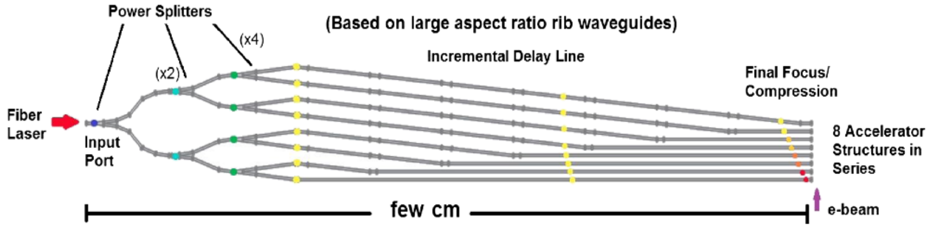
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

DLA RESULTS

Recent DLA Experiment Comparison

SLAC

Parameter	SLAC 	Stanford 	MQP/Erlangen 
Year	2013	2015	2013
Material	Fused Silica	Silicon	Fused Silica
Beam Energy	60 MeV	96.3 keV	30 keV
β = v/c	0.9996	0.54	0.33
Laser Pulse Energy	330 µJ	5.2 nJ	160 nJ
Pulse Duration	1.1 ps	130 fs	110 fs
Interaction Length	360 µm	5.6 µm	11 µm
Max Energy Gain	100 keV	1.22 keV	275 eV
Max Gradient	309 MV/m	220 MV/m	25 MV/m



Peralta, AIP Proc. 1507, 169 (2012)

TABLE VII. Strawman parameters for the DLA Linear Collider.

Parameter	Units	CLIC	DLA 3 TeV	DLA 250 GeV
Center-of-mass energy	GeV	3000	3000	250
Bunch charge	e	3.7×10^9	30 000	38 000
Bunches per train		312	159	159
Train repetition rate	MHz	5.0×10^{-5}	20	60
Bunch train length	ps	26 005	1.0	1.0
Single bunch length	μm	34.7	0.0028	0.0028
Design wavelength	μm	230 609	2.0	2.0
Invariant X emittance	μm	0.66	0.0001	0.002
Invariant Y emittance	μm	0.02	0.0001	0.002
IP X spot size	nm	45	1	2
IP Y spot size	nm	1	1	2
Beamstrahlung energy loss	%	28.1	1.0	0.6
Enhanced luminosity/top 1%	cm^{-2}/s	2.0×10^{34}	3.2×10^{34}	1.3×10^{34}
Beam power	MW	14.1	22.9	7.3
Wall-plug efficiency	%	4.8	12.2	9.5
Wall-plug power	MW	582	374	152
Gradient	MV/m	100	1000	1000
Total linac length	km	42.0	3.0	0.3

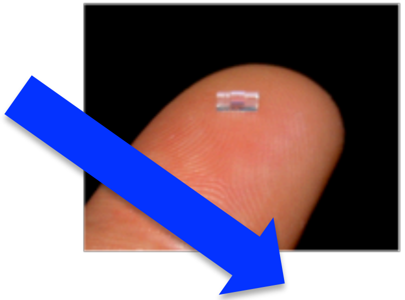
✧Deliver lower average current with lower emittance?? (DLA)

Courtesy of J. England

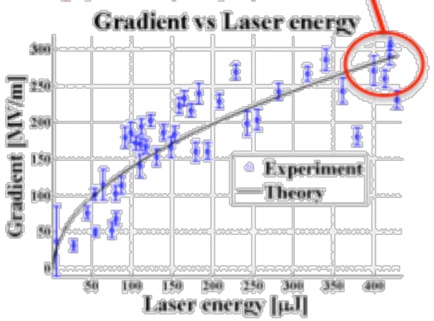
DLA RESULTS

DLA Structure Development: Recent Progress

Accelerator

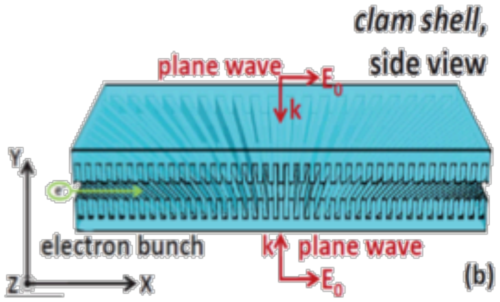


short-pulse (70 fs): **700 MV/m***
long-pulse (1.3ps): **300 MV/m***

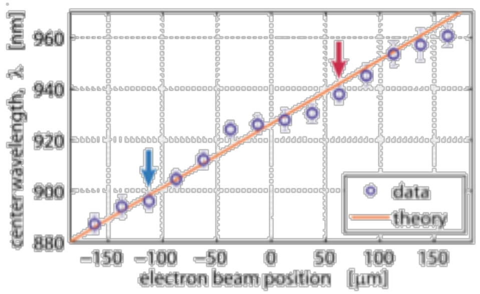


Nature* **503, 91-93 (2013)
*in prep for publication (2015)

Beam Position Monitor

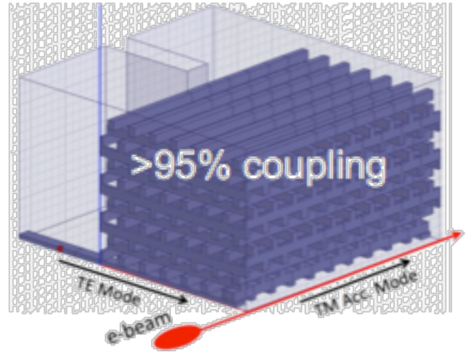


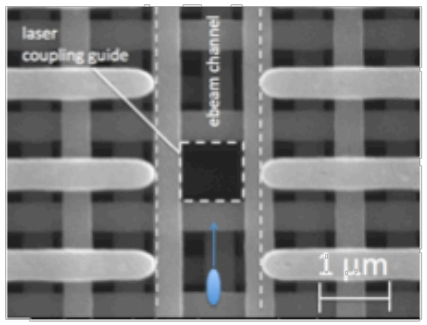
Opt. Lett., **37** (5) 975-977 (2012)



Opt. Lett., **39** (16) 4747 (2014)

Efficient Coupler Designs





C. McGuinness, Z. Wu

Phys. Rev. ST-AB, **17**, 081301 (2014)

Relativistic energy experiments have shown high-gradient operation and set the stage for scaling DLA to multi MeV energies.

Courtesy of J. England

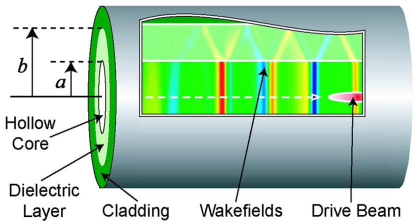
OUTLiNE

✧Novel Accelerator Techniques "Goals"

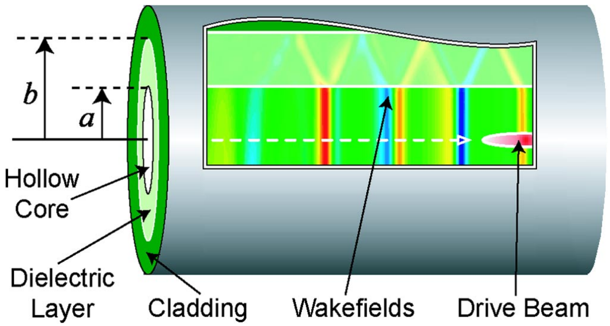
Driver \ Medium	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

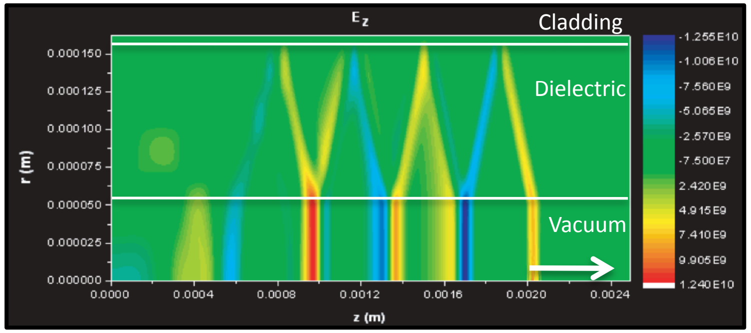
✧Cherenkov wakes in dielectric layers

✧Summary



DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





- Peak decelerating field

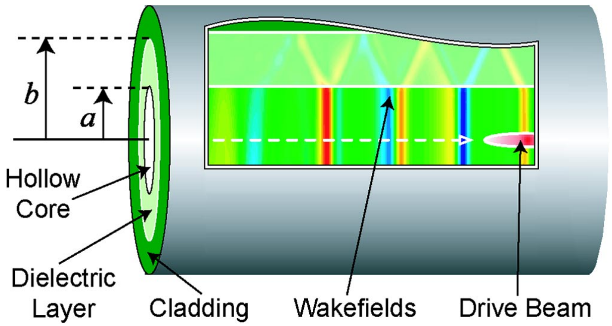
$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

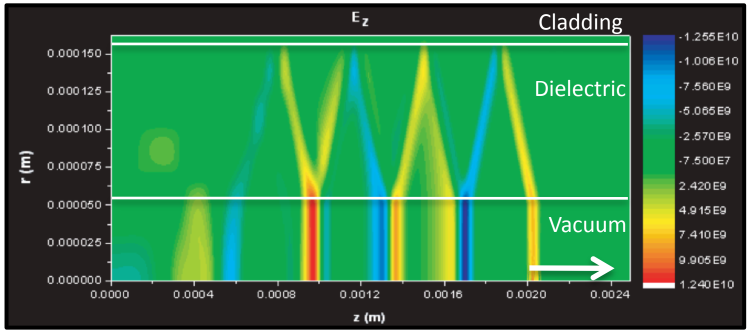
- Transformer ratio (unshaped beam)

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

DiELECTRiC WAKEFiELD ACCELERATOR (DWA)

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





- Peak decelerating field

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

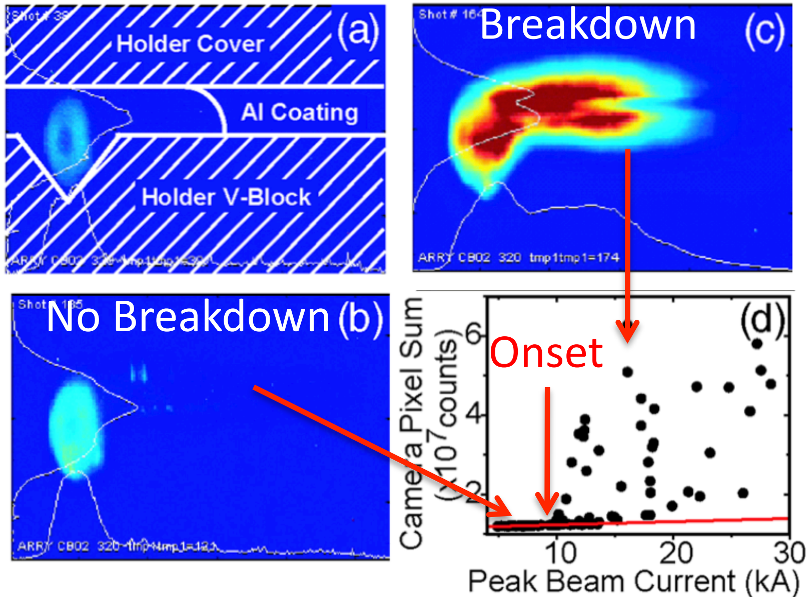
- Transformer ratio (unshaped beam)

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

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

MAX-PLANCK-GESELLSCHAFT

DWA RESULTS

Acceleration in slab symmetric DWA

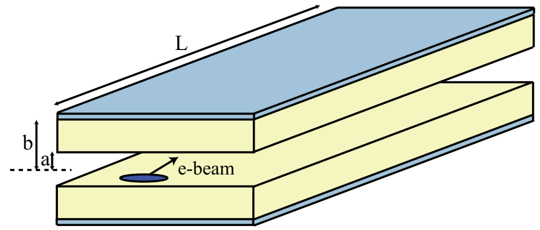
UCLA

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

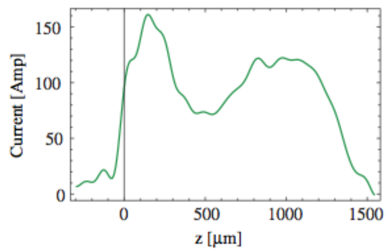
Dielectric Wakefield Acceleration of a Relativistic Electron Beam in a Slab-Symmetric Dielectric Lined Waveguide

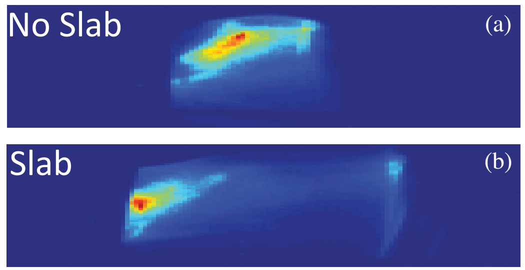
G. Andonian,[1] D. Stratakis,[1] M. Babzien,[2] S. Barber,[1] M. Fedurin,[2] E. Hemsing,[3] K. Kusche,[2] P. Muggli,[4] B. O'Shea,[1] X. Wei,[1] O. Williams,[1] V. Yakimenko,[2] and J. B. Rosenzweig[1]

- 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



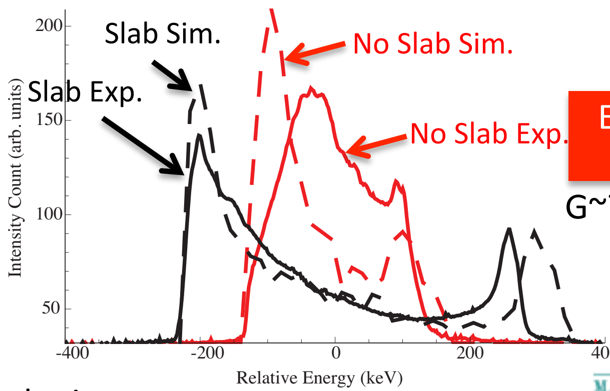
SiO_2, Al
T_{SLAB}=240μm
T_{gap}=240μm
L_z=2cm
ε_N=2mm-mrad





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

Slab geometry allows for:
✧More charge per bunch
✧Reduced transverse wakefields
✧Demonstration of energy gain!



Energy Gain

G~7MeV/m

Courtesy G. Andonian

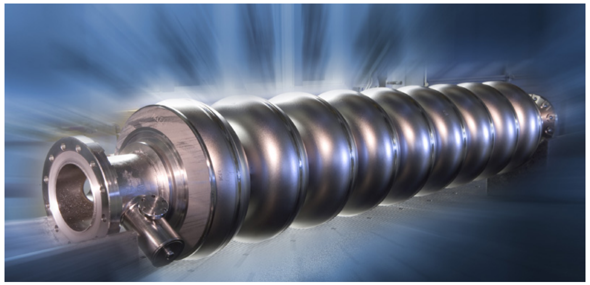
OUTLiNE

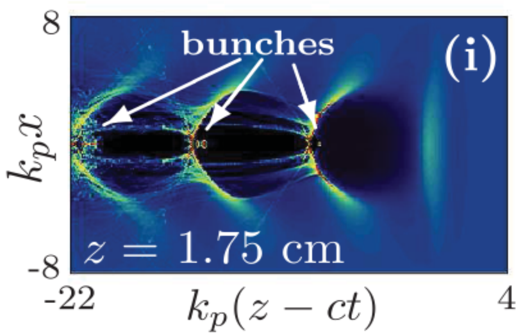
✧Novel Accelerator Techniques "Goals"

Driver \ Medium	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

✧Intense laser pulse to drive wakefields in plasma

✧Summary

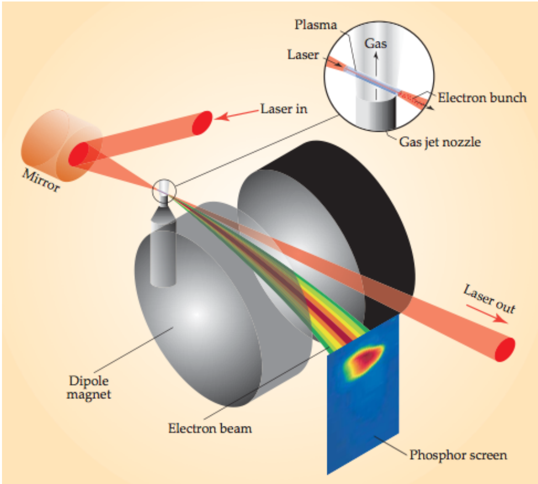


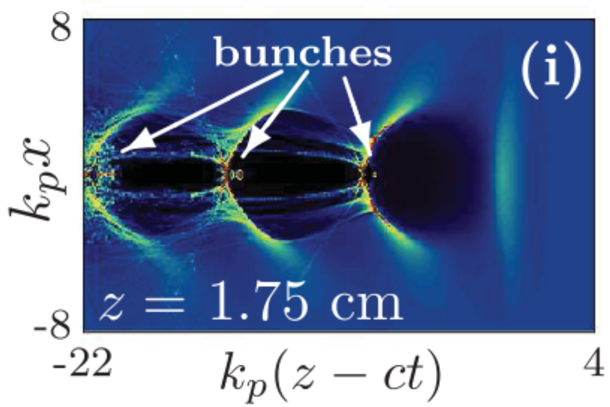


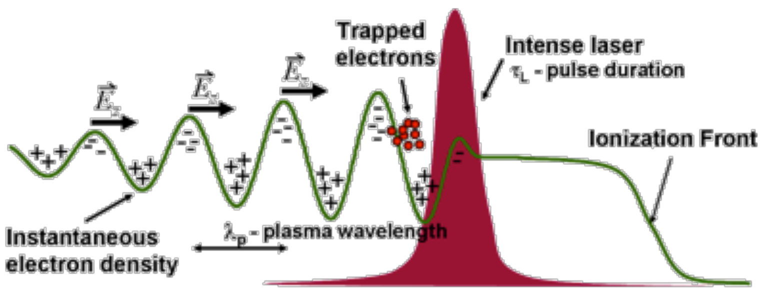
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

LASER WAKEFIELD ACCELERATOR (LWFA)

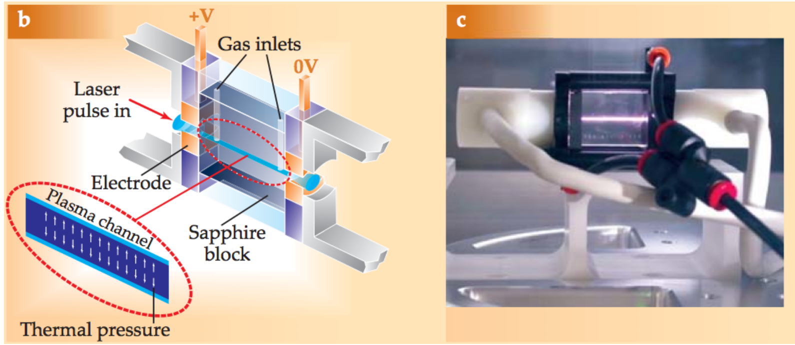
Gas Jet Plasma (short, injector)







Capillary Discharge Plasma (long, accelerator)



Leemans, Physics Today 2009

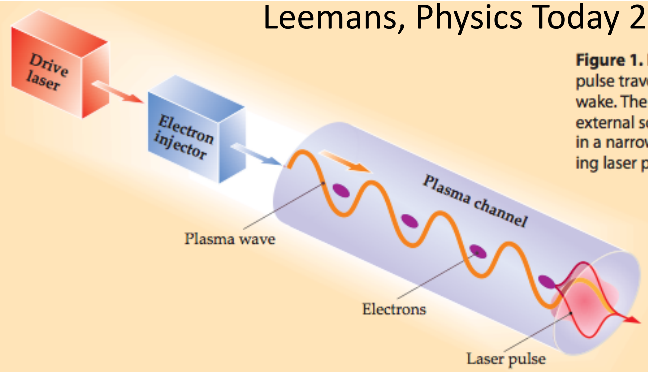
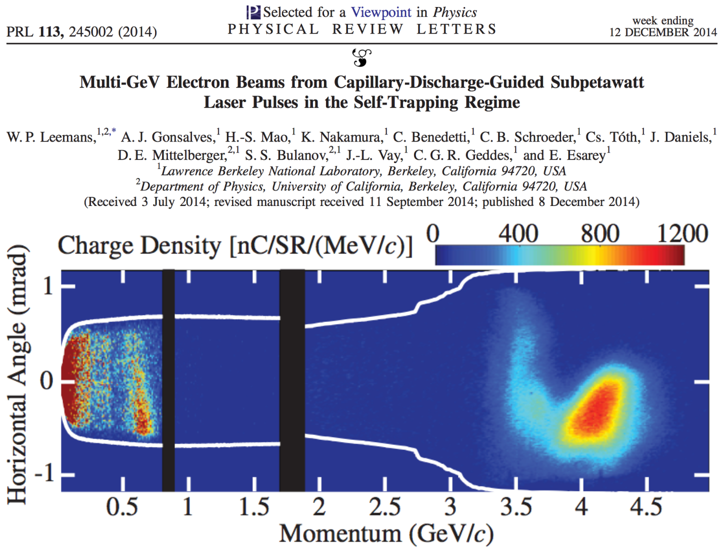


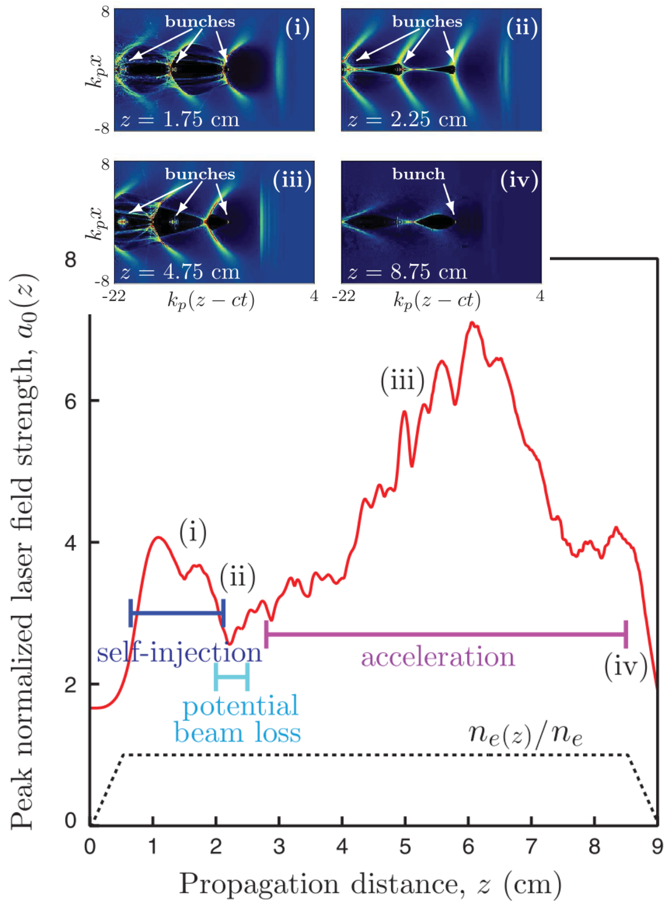
Figure 1. Laser plasma acceleration. An intense laser pulse traversing a plasma excites a plasma wave in its wake. The wave accelerates electrons injected from an external source or trapped from the plasma. Confined in a narrow channel, the plasma guides the propagating laser pulse and prevents its diffraction.

- ✧Most active field
- ✧Availability of TW Ti:Sapphire laser systems
- ✧Few TW for 10-100MeV e^- in a few mm
- ✧Acceleration, guiding
- ✧Self-trapping
- ✧Injection (plasma "gun")
- ✧Diagnostics
- ✧Radiation source
- ✧…

LWFA



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}
$P_{laser} \approx$0.3PW
W=16J, $\sigma_r \approx$52µm, $\tau \approx$42fs



- ✧Peak energy gain 4.2GeV in <10cm
- ✧Self-trapped plasma e$^-$

- ✧Needed: controlled external injection
- ✧100TW laser pulse with joules (i.e., not too short)

LWFA Laser Development

✧International Committee on Ultra-high Intensity Lasers (ICUIL)

- "Our mission is to stimulate, strengthen and expand ultra-intense laser science and related technologies."

ICUIL The International Committee on Ultra-High Intensity Lasers

✧The International Coherent Amplification Network (ICAN)

- "The network is looking into existing fiber laser technology, which we believe has fantastic potential for accelerators"
- "CERN's contribution to the ICAN project is part of a wider strategy to encourage the development of laser acceleration technologies. By supporting ICAN and similar research projects, CERN will be contributing to the R&D of potentially ground-breaking accelerator technologies."

ICAN

ican International Coherent Amplification Network

✧Strong effort to develop high peak power/high average power, short pulse lasers

✧The future is fiber lasers?

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

LWFA-BASED COLLIDER CONCEPT

Schroeder , PRSTAB, 13, 101301 (2010)

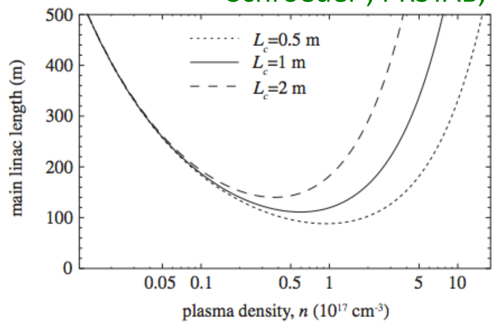


FIG. 3. Main single-linac length versus plasma density n for several laser in-coupling distances L_c, for $E_b = 0.5$ TeV and $a_0 = 1.5$.

feature article

44 March 2009 Physics Today

Laser-driven plasma-wave electron accelerators

Wim Leemans and Eric Esarey

Surfing a plasma wave, a bunch of electrons or positrons can experience much higher accelerating gradients than a conventional RF linac could provide.

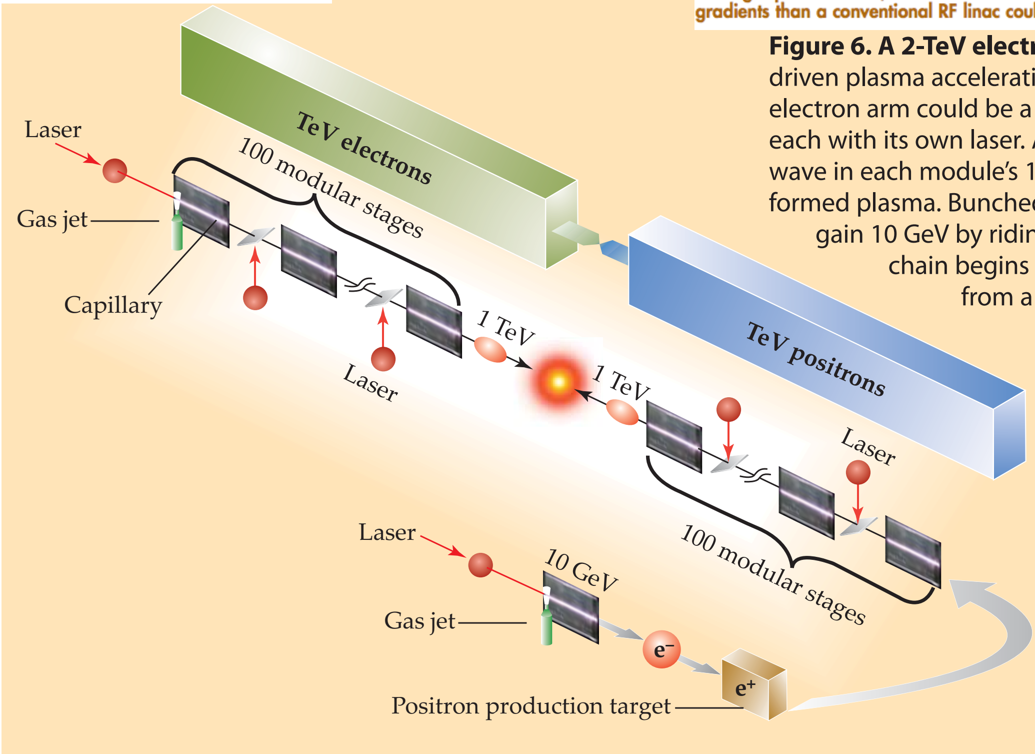


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed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

✧Effort (particularly at LBNL, Cilex) towards an e^-/e^+ collider

MAX-PLANCK-GESELLSCHAFT

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

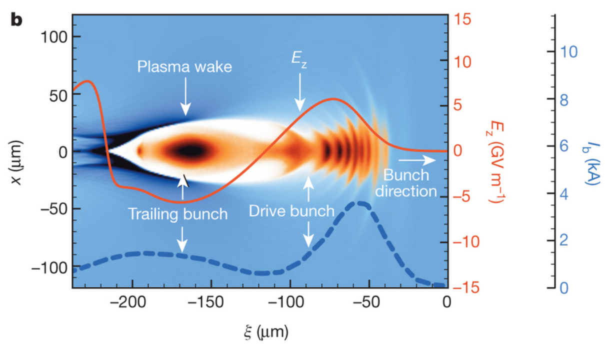
OUTLINE

✧Novel Accelerator Techniques “Goals”

Medium / Driver	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

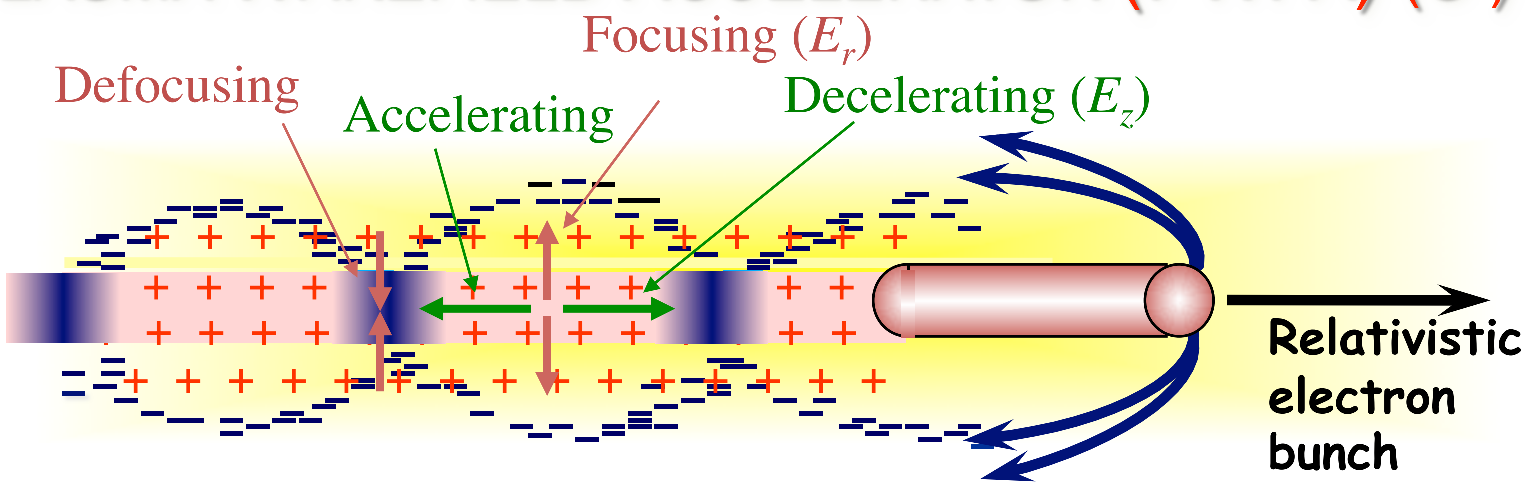
✧Dense, relativistic particle bunch to drive wakefields in a plasma

✧Summary



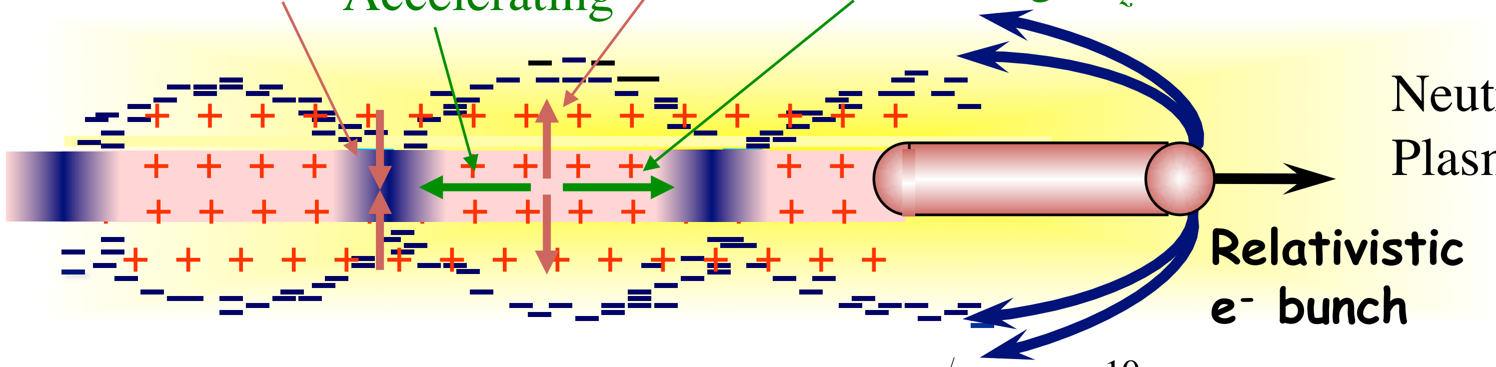
MAX-PLANCK-GESELLSCHAFT

PLASMA WAKEFIELD ACCELERATOR (PWFA) (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 $\beta^*=\sigma^{*2}/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

PWFA NUMBERS (e^-)



✧Linear theory ($n_b<<n_e$) scaling:

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

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

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

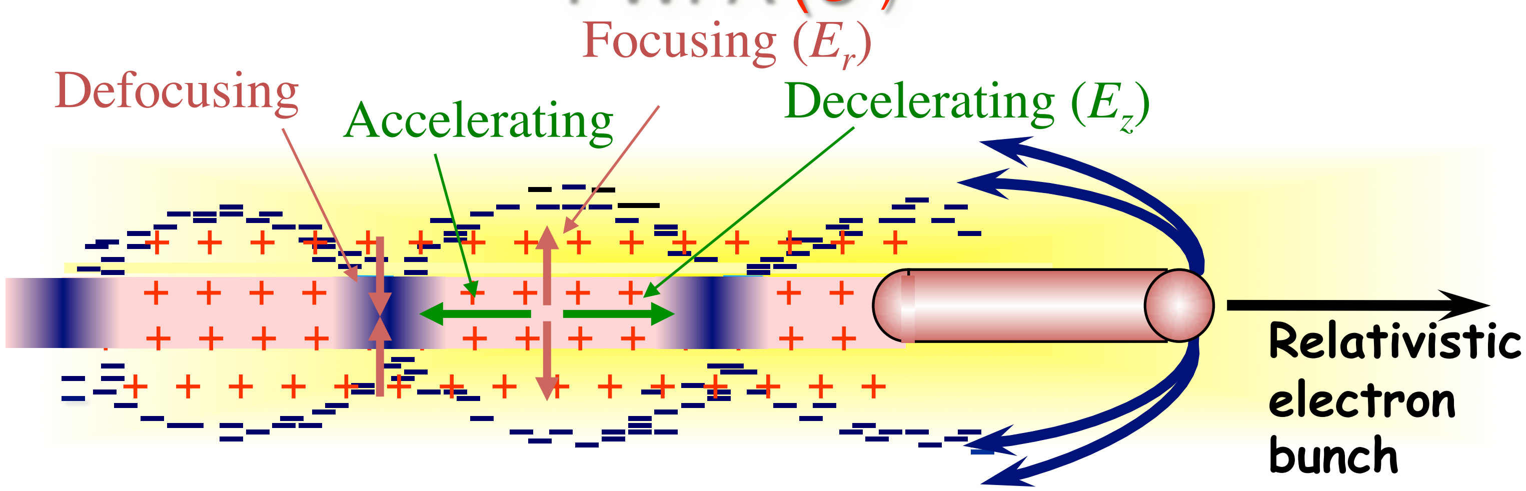
✧N=2×10^{10}: σ_z=600 μm, $n_e=2\times10^{14}$ cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
σ_z= 20 μm, $n_e=2\times10^{17}$ cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

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

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

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

PWFA (e^-)



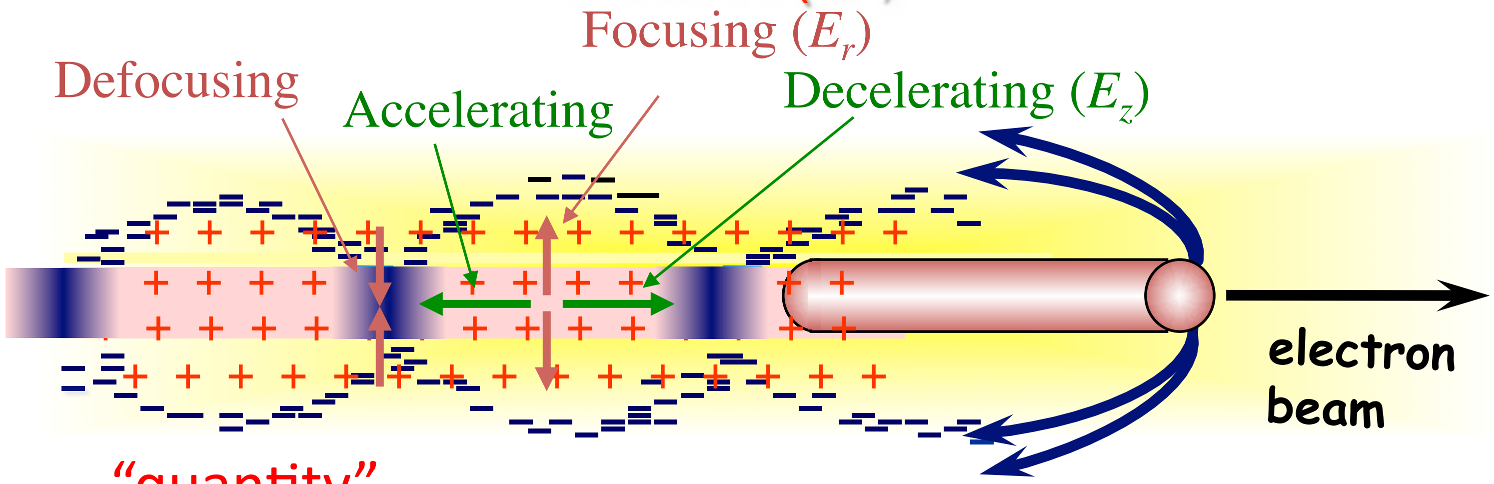
- Plasma wave/wake excited by a relativistic particle bunch
- by space charge force => deceleration + focusing (MT/m)
- k on axis => acceleration, GV/m
- ver => ultra-relativistic wake
  => no dephasing
- ave long Rayleigh lengths”
  $^2/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

Very large energy gain possible with short, high-energy relativistic bunches!

MAX-PLANCK-GESELLSCHAFT

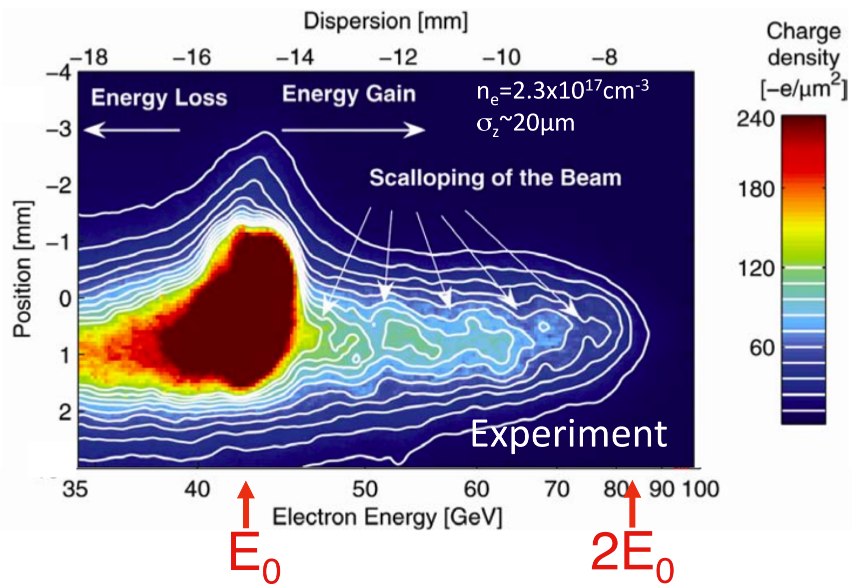
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

PWFA (e^-)



"quantity"

Blumenfeld, Nature 445, 741 (2007)

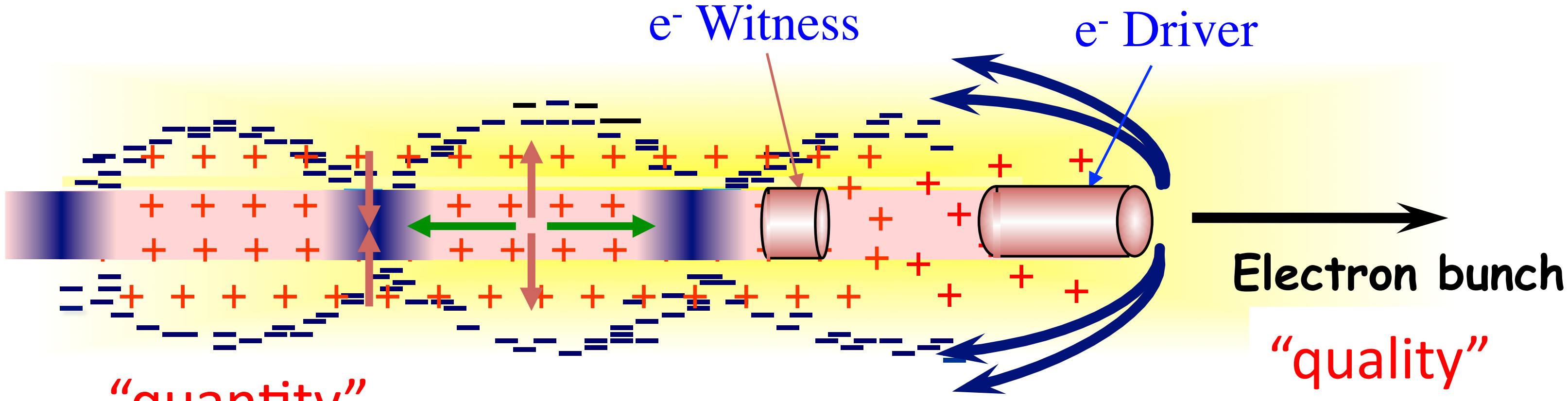


42 => 84GeV in 85cm! 50GeV/m

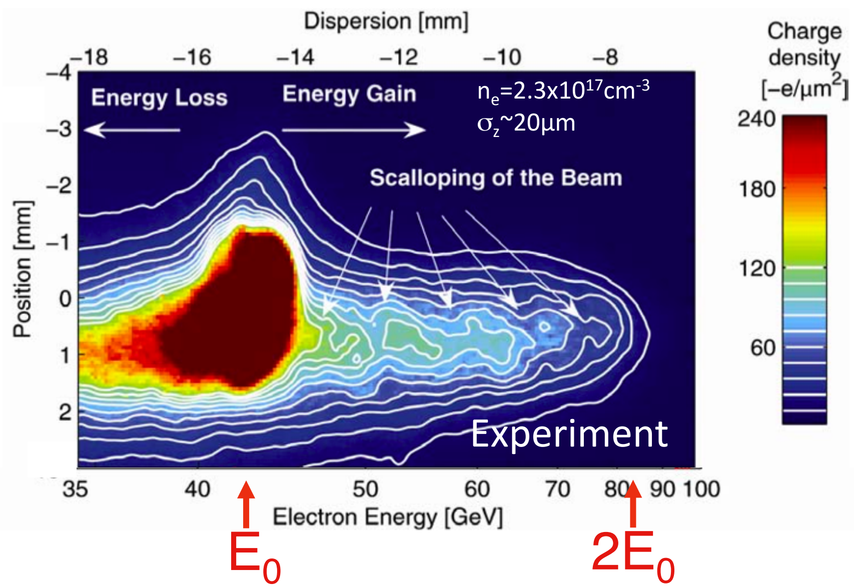
MAX-PLANCK-GESELLSCHAFT

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

PWFA (e⁻)



Blumenfeld, Nature 445, 741 (2007)

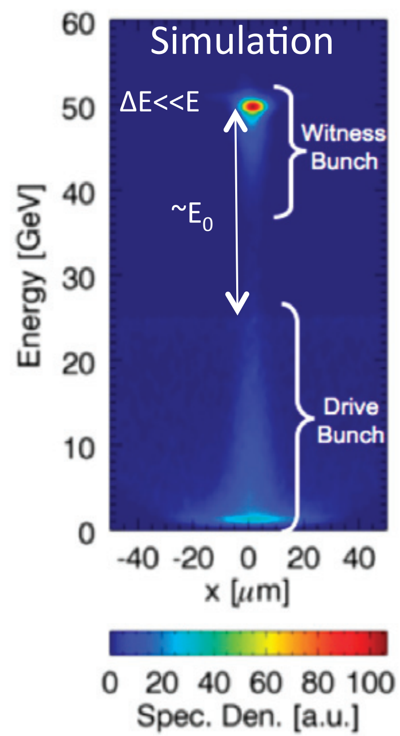


42 => 84GeV in 85cm! 50GeV/m

SLAC
FACET

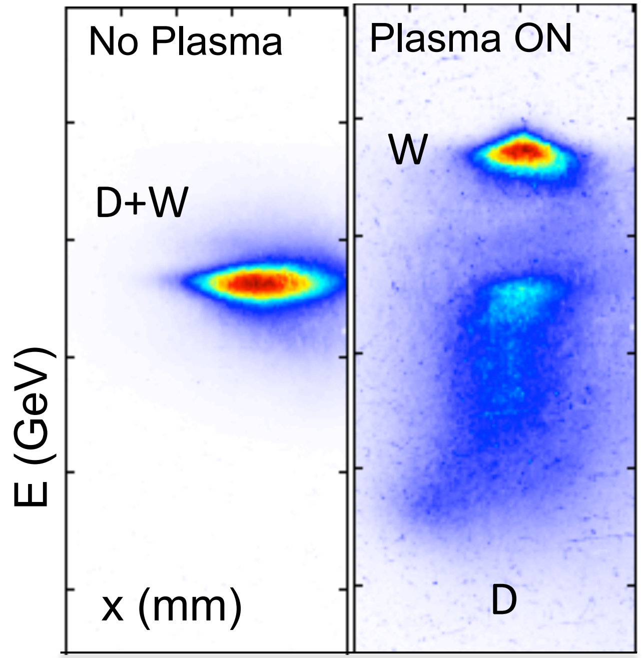
E200

Hogan,
NJP 12,
055030 (2010)

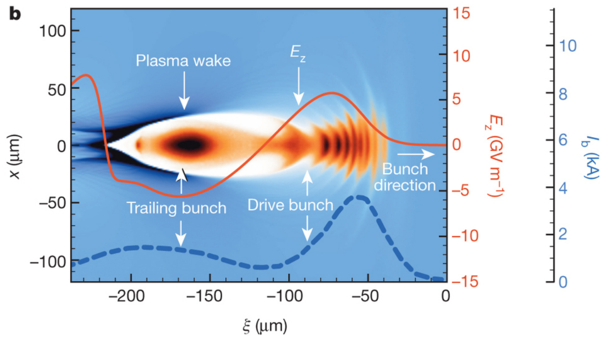


High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

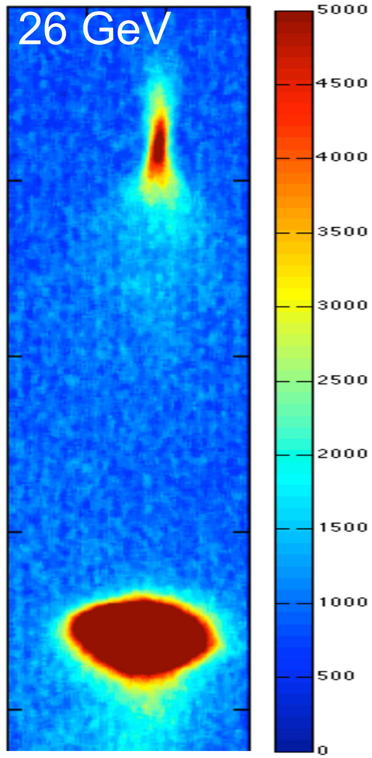
- Focus on energy gain, efficiency, optimization of accelerated beam quality
- Measure, repeat/confirm, publish, improve…



2 GeV Energy Gain (~30cm)
~2% dE/E
~30% efficiency



Nature ***515***, *92-95 (November 2014)*



Single shot with
6 GeV Energy Gain (~1m)

Optimization of electron PWFA in H_2 plasma is the focus of ongoing run

Courtesy M.J. Hogan, SLAC

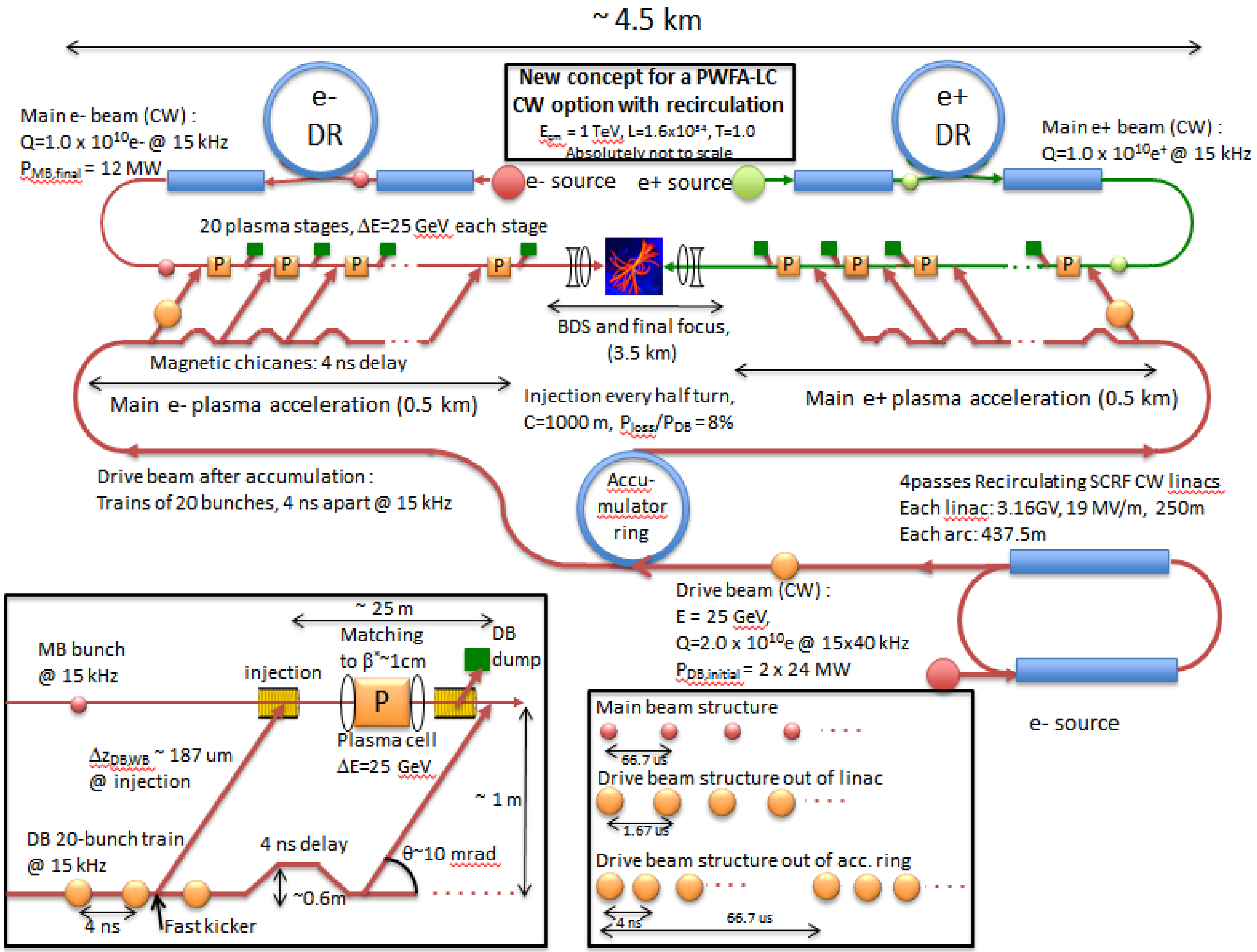
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

A Beam Driven Plasma-Wakefield Linear Collider: From Higgs Factory to Multi-TeV

Summarized for CSS2013

E. Adli, J.P.Delahaye, S.J.Gessner, M.J. Hogan, T. Raubenheimer (SLAC)
W.An, C. Joshi, W.Mori (UCLA)

Figure 1: Layout of a 1 TeV PWFA Linear Collider



PWFA-BASED COLLIDER CONCEPT

Table 1: Main parameters at various beam collision energies

E at IP, CM	**GeV**	250	500	1000	3000	6000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10
Main beam bunches / train		1	1	1	1	1	1
Main beam bunch spacing,	**nsec**	3.33E+04	5.00E+04	6.67E+04	1.00E+05	1.43E+05	2.00E+05
Repetition rate,	**Hz**	30000	20000	15000	10000	7000	5000
n exp.bunch/sec,	**Hz**	30000	20000	15000	10000	7000	5000
Avg current in exp beam	**uA**	48.06	32.04	24.03	16.02	11.21	8.01
peak current in exp beam	**A**	4.81E-05	3.20E-05	2.40E-05	1.60E-05	1.12E-05	8.01E-06
Power in exp. beam	**W**	6.0E+06	8.0E+06	1.2E+07	2.4E+07	3.4E+07	4.0E+07
Effective accelerating gradient	**MV/m**	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Overall length of each linac	**m**	125	250	500	1500	3000	5000
BDS (both sides)	**km**	2.00	2.50	3.50	5.00	6.50	8.00
Overall facility length	**km**	2.25	3.00	4.50	8.00	12.50	18.00
IP Parameters							
Exp. bunch gamepsX,	**m**	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Exp. bunch gamepsY,	**m**	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08
beta-x,	**m**	1.10E-02	1.10E-02	1.10E-02	1.10E-02	1.10E-02	1.10E-02
beta-y,	**m**	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
sigx,	**m**	6.71E-07	4.74E-07	3.35E-07	1.94E-07	1.37E-07	1.06E-07
sigy,	**m**	3.78E-09	2.67E-09	1.89E-09	1.09E-09	7.72E-10	5.98E-10
sigz,	**m**	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Y		8.44E-02	2.39E-01	6.75E-01	3.51E+00	9.93E+00	2.14E+01
Dx		1.03E-02	1.03E-02	1.03E-02	1.03E-02	1.03E-02	1.03E-02
Dy		1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00	1.83E+00
Uave		0.17	0.48	1.35	7.00	19.79	42.59
delta_B	**%**	2.75	6.66	12.76	23.10	27.67	29.88
P_Beamstrahlung [W]	**W**	1.7E+05	5.3E+05	1.5E+06	5.6E+06	9.3E+06	1.2E+07
ngamma		0.57	0.73	0.88	1.05	1.11	1.14
Hdx		1.00	1.00	1.00	1.00	1.00	1.00
Hdy		4.62	4.62	4.62	4.62	4.62	4.62
Hd		1.7	1.7	1.7	1.7	1.7	1.7
Geometric Lum (cm-2 s-1)		9.41E+33	1.25E+34	1.88E+34	3.76E+34	5.27E+34	6.27E+34
Total Luminosity (cm-2 s-1)		**1.57E+34**	**2.09E+34**	**3.14E+34**	**6.27E+34**	**8.78E+34**	**1.05E+35**
Integrated Lum. (fb-1 per 1E7s)		**157**	**209**	**314**	**627**	**878**	**1045**
Lum1%		**9.41E+33**	**1.15E+34**	**1.57E+34**	**2.51E+34**	**3.07E+34**	**3.14E+34**

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

PWFA-BASED COLLIDER CONCEPT

Table 1: Main parameters at various beam collision energies

E at IP, CM	**GeV**	250	500	1000	3000	6000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10

E at IP, CM	**GeV**	250	500	1000	3000	6000	10000

- Various energy scenarios

MAX-PLANCK-GESELLSCHAFT

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

PWFA-BASED COLLIDER CONCEPT

Table 1: Main parameters at various beam collision energies

E at IP, CM	GeV	250	500	1000	3000	6000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10
E at IP, CM	GeV	250	500	1000	3000	6000	10000
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	1.43E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	7000	5000

- Various energy scenarios
- CW beam rate for plasma "recovery", use SC RF for drive beam linac

MAX-PLANCK-GESELLSCHAFT

PWFA-BASED COLLIDER CONCEPT

Table 1: Main parameters at various beam collision energies

E at IP, CM	GeV	250	500	1000	3000	6000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10

E at IP, CM	GeV	250	500	1000	3000	6000	10000
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	1.43E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	7000	5000
Avg current in exp beam	uA	48.06	32.04	24.03	16.02	11.21	8.01
peak current in exp beam	A	4.81E-05	3.20E-05	2.40E-05	1.60E-05	1.12E-05	8.01E-06
Power in exp. beam	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	3.4E+07	4.0E+07

- ✧Various energy scenarios
- ✧CW beam rate for plasma “recovery”, use SC RF for drive beam linac
- ✧Reasonable beam current and power

PWFA-BASED COLLIDER CONCEPT

Table 1: Main parameters at various beam collision energies

E at IP, CM	GeV	250	500	1000	3000	6000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10

E at IP, CM	GeV	250	500	1000	3000	6000	10000
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	1.43E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	7000	5000
Avg current in exp beam	uA	48.06	32.04	24.03	16.02	11.21	8.01
peak current in exp beam	A	4.81E-05	3.20E-05	2.40E-05	1.60E-05	1.12E-05	8.01E-06
Power in exp. beam	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	3.4E+07	4.0E+07
Effective accelerating gradient	MV/m	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Overall length of each linac	m	125	250	500	1500	3000	5000
BDS (both sides)	km	2.00	2.50	3.50	5.00	6.50	8.00
Overall facility length	km	2.25	3.00	4.50	8.00	12.50	18.00

- ✧Various energy scenarios
- ✧CW beam rate for plasma "recovery", use SC RF for drive beam linac
- ✧Reasonable beam current and power
- ✧Average gradient ~1GeV/m (~8GeV/m peak), reasonable linac lengths

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

PWFA-BASED COLLIDER CONCEPT

Table 1: Main parameters at various beam collision energies

E at IP, CM	GeV	250	500	1000	3000	6000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10	1.0E+10

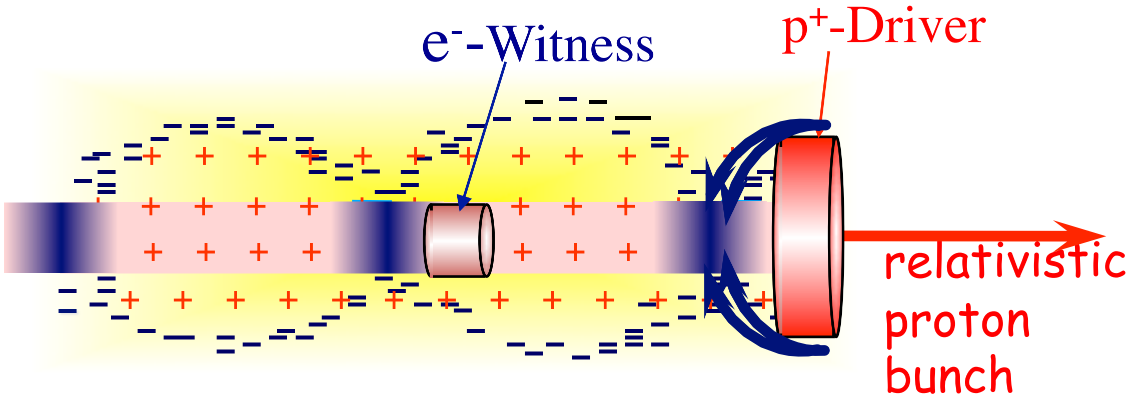
E at IP, CM	GeV	250	500	1000	3000	6000	10000
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	1.43E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	7000	5000
Avg current in exp beam	uA	48.06	32.04	24.03	16.02	11.21	8.01
peak current in exp beam	A	4.81E-05	3.20E-05	2.40E-05	1.60E-05	1.12E-05	8.01E-06
Power in exp. beam	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	3.4E+07	4.0E+07
Effective accelerating gradient	MV/m	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00
Overall length of each linac	m	125	250	500	1500	3000	5000
BDS (both sides)	km	2.00	2.50	3.50	5.00	6.50	8.00
Overall facility length	km	2.25	3.00	4.50	8.00	12.50	18.00
Geometric Lum (cm-2 s-1)		9.41E+33	1.25E+34	1.88E+34	3.76E+34	5.27E+34	6.27E+34
Total Luminosity (cm-2 s-1)		**1.57E+34**	**2.09E+34**	**3.14E+34**	**6.27E+34**	**8.78E+34**	**1.05E+35**
Integrated Lum. (fb-1 per 1E7s)		**157**	**209**	**314**	**627**	**878**	**1045**

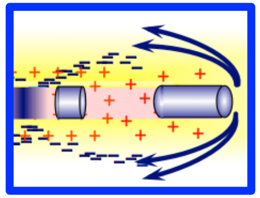
- Various energy scenarios
- CW beam rate for plasma "recovery", use SC RF for drive beam linac
- Reasonable beam current and power
- Average gradient ~1GeV/m (~8GeV/m peak), reasonable linac lengths
- Reasonable luminosities

MAX-PLANCK-GESELLSCHAFT

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

p^+-DRiVEN PWFA



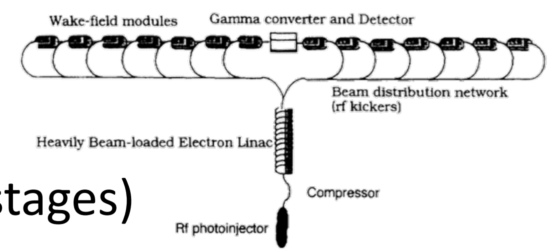


✧ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ

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

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

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

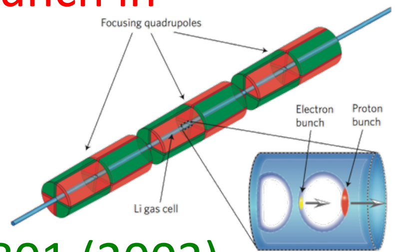


✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ

✧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)

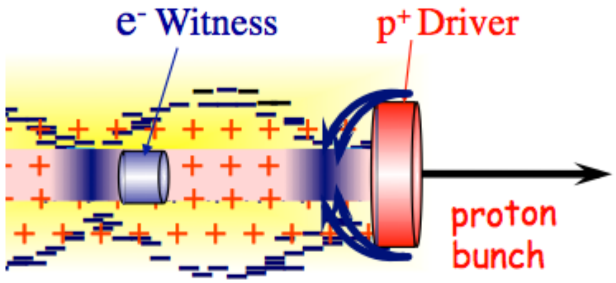


Caldwell, Nat. Phys. 5, 363, (2009)

MAX-PLANCK-GESELLSCHAFT

p^+-DRiVEN PWFA

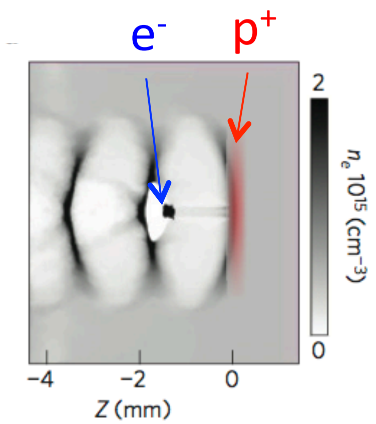
Caldwell, Nat. Phys. 5, 363, (2009)



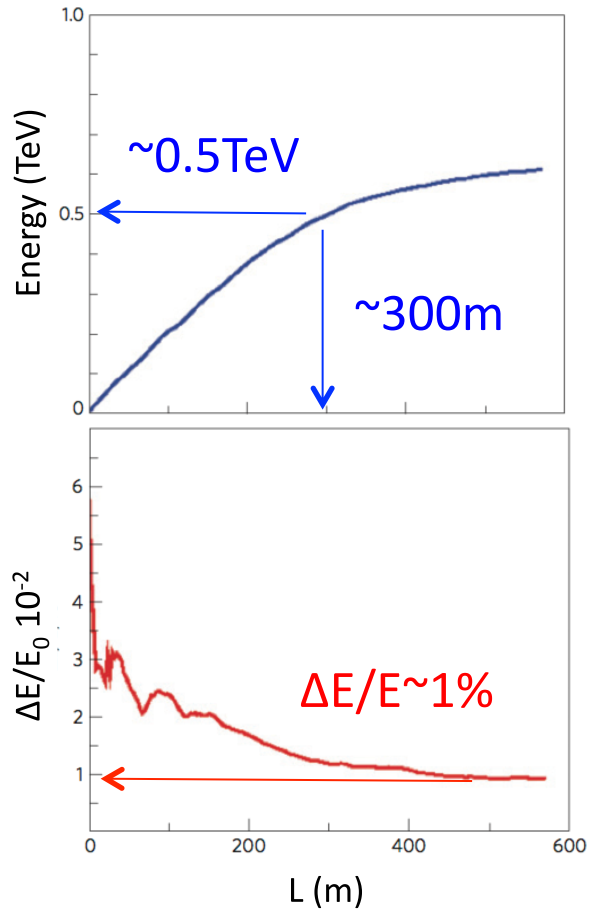
e^-:
E_0=10GeV
N=10^{10}
W_0=16J
W_f=1kJ

p^+:
E_0=1TeV
σ_z=100µm
N=10^{11}
W_0=16kJ

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

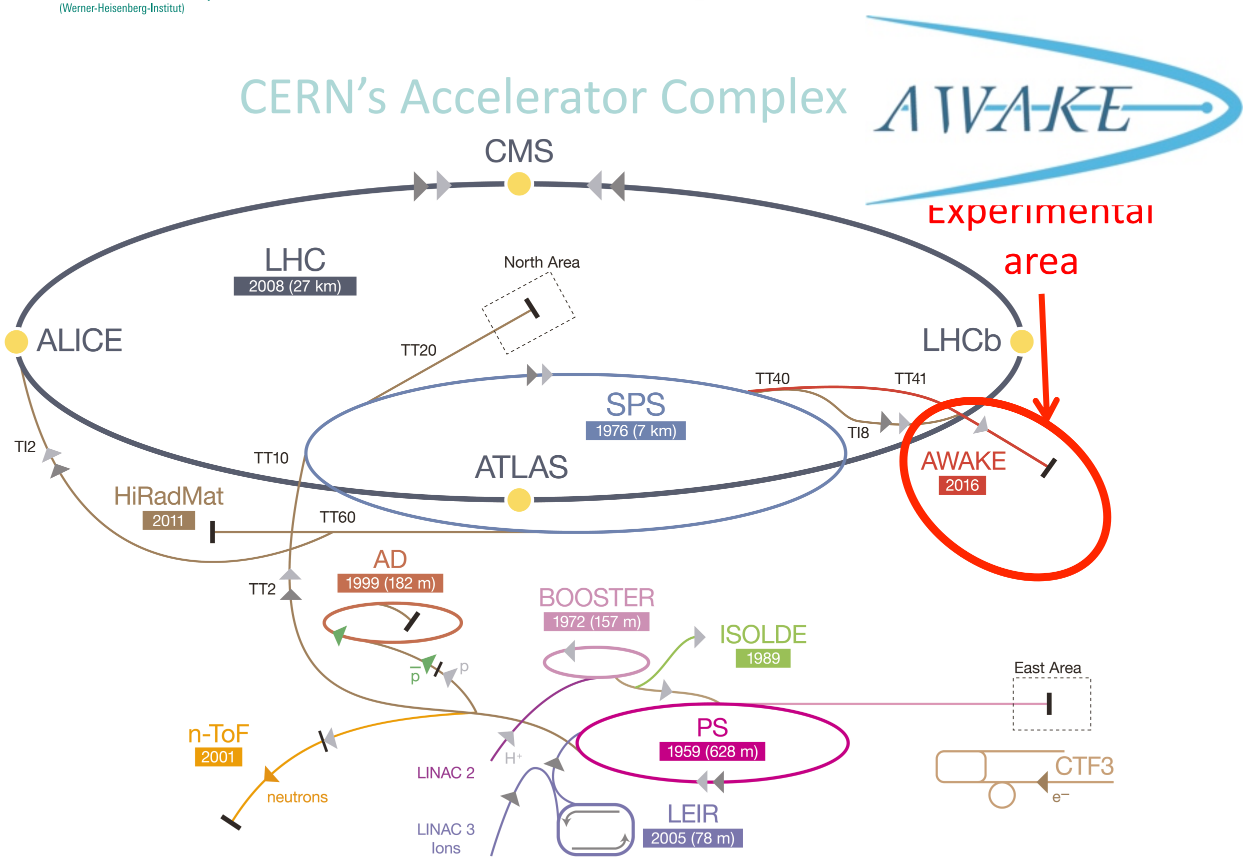


- ✧Accelerate an e^- bunch on the wakefields of a p^+ bunch
- ✧Single stage, no gradient dilution
- ✧Gradient ~1 GV/m over 100's m (average!!!)
- ✧Operate at lower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
MAX-PLANCK-GESELLSCHAFT

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

p⁺-DRiVEN PWFA



✧SPS beam: high energy, small σ_r*, long β*

✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p^+ driven PWFA

✧Setup a comprehensive PWFA program at CERN

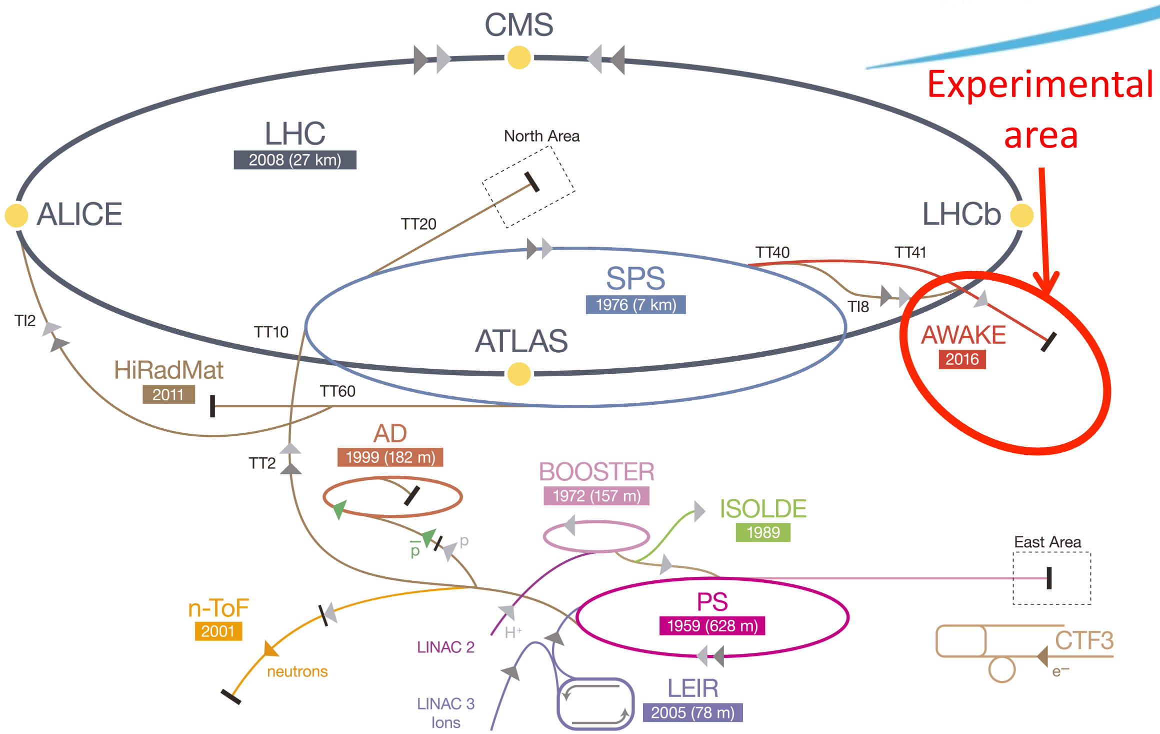
AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)

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

p^+-DRiVEN PWFA

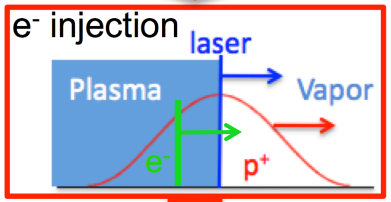
CERN's Accelerator Complex

AWAKE

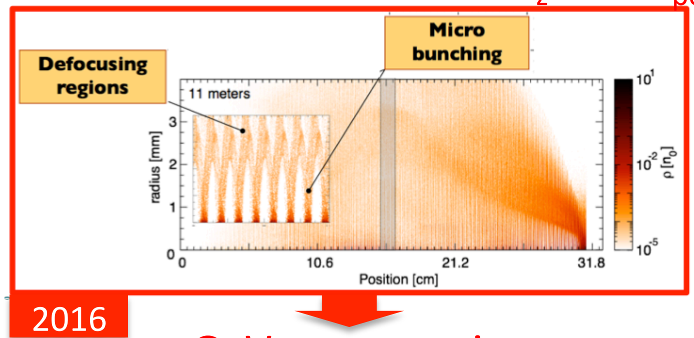


3x10^{11}, 400GeV SPS p^+

10m plasma, n_e=1-10x10^{14}cm^{-3}

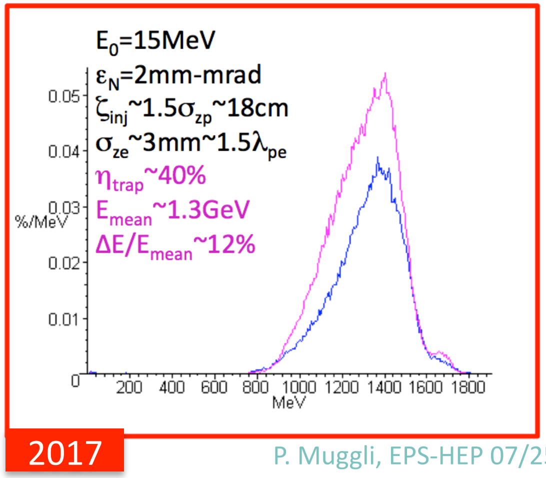


p^+ bunch self-modulation: σ_z~100λ_{pe}



GeV energy gain

by externally injected e$^-$



✧SPS beam: high energy, small σ_r*, long β*

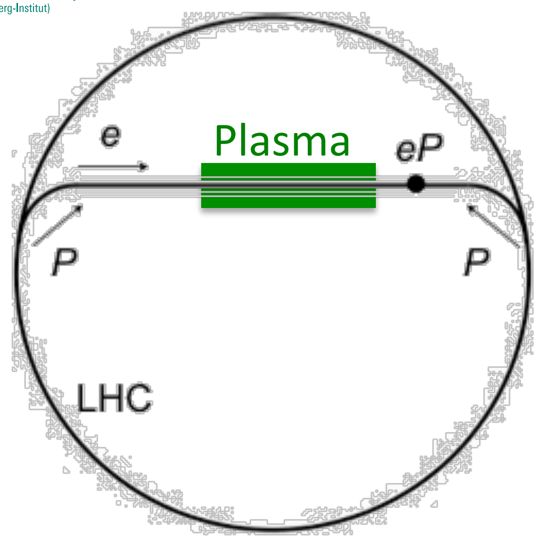
✧Initial goal: ~GeV gain by externally injected e$^-$,in 5-10m of plasma in self-modulated p^+ driven PWFA

✧Setup a comprehensive PWFA program at CERN

AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)

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

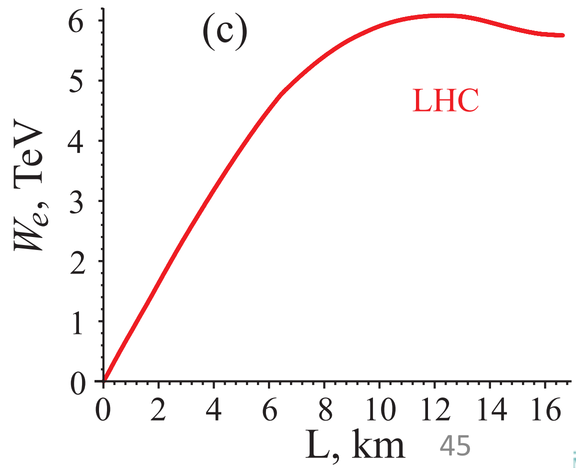
p^+-DRIVEN PWFA FOR e^-/p^+ COLLIDER



$$\mathcal{L} = f\frac{N_e \cdot N_p}{4\pi\sigma_x \cdot \sigma_y} \approx 5 \cdot 10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- 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)

Courtesy A. Caldwell

OUTLINE

✧Novel Accelerator Techniques "Goals"

Medium / Driver	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

✧Summary

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

SUMMARY

✧Number of possible novel techniques: dielectrics/plasmas, laser/particle beams

✧All have demonstrated accelerating gradients large than 700MeV/m!!! Novel!!!

✧Very large gradients reached (>100GV/m)

✧Very large energy gains achieved (>4GeV in ~10cm LWFA, >40GeV in 85cm PWFA)

✧Witness bunch acceleration, transfer efficiency (30% bunch to bunch) demonstrated (PWFA)

✧Next milestones: high quality acceleration (ΔE/E, ε small), staging/long accelerator

- Complex experiments for small groups

✧Concepts for "collider-like" accelerators exist for 1GeV/m (average gradient, all)

✧No <u>physics</u> roadblocks/show stoppers

MAX-PLANCK-GESELLSCHAFT

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

SUMMARY

✧Number of technical challenges towards collider beams: a priori solvable

✧"Large scale" experiments: FACET, DESY Flash Forward, INFN SPARC_LAB, CERN AWAKE, BELLA, CILEX, ELI, etc.

✧Strengthen collaboration between lab/university groups

- "The next collider will not be built by faculties at universities"

✧Efficiency, reproducibility, stability, reliability, etc.

✧Field mature for accelerator laboratories to adopt a concept and take it to the limit …

Thank you to my collaborators!

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

muggli@mpp.mpg.de

Thank you to P. Hommelhoff, J. England, M. Hogan, G. Andonian, A. Caldwell for material