Novel Accelerator Techniques

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CERN

OUTLiNE

✧Novel Accelerator Techniques Applications

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

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OUTLINE

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✧Summary

NOVEL ACCELERATORS

"Novel"

⇕

"High-gradient"

⇕

>1GeV/m (ICFA-ANA)

⇕

Average gradient over m–scale

⇕

GeV to TeV e^- - e^+ (HEP)

Materials with higher damage threshold:

- Dielectrics (~GV/m)
- Plasmas (10-1000GV/m)

Systems powered/driven by:

- Laser pulse(s)*
- Relativistic, charged particle bunch(es)

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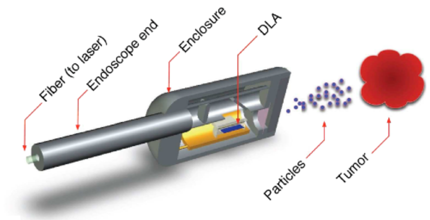
 *do not include laser vacuum/direct acceleration

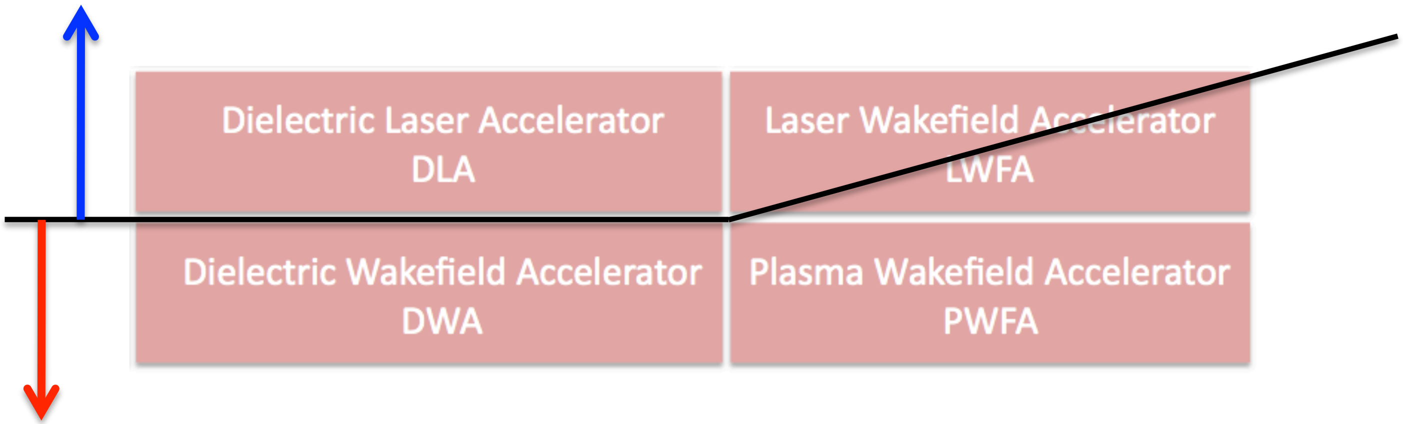
APPLiCATiONS

✧X-ray for radiography (advanced: phase contrast, etc.)
✧e^- for medical applications (10-300MeV)



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

✧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



✧Powerful radiation source, THz to γ-rays
✧X-ray FELs (pC in fs at 10GeV)
✧High-energy physics (HEP)

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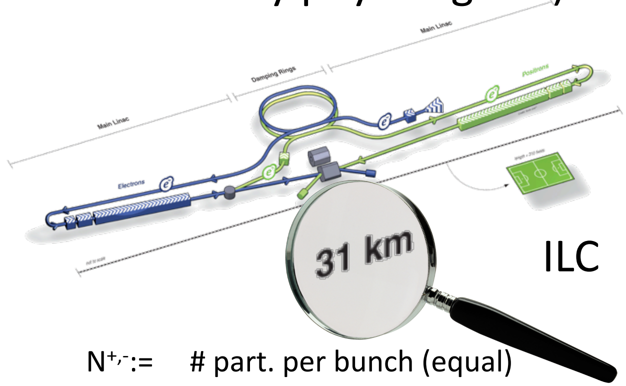
HEP APPLICATIONS

✧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-1000's m of meter long



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

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

$N^{+,-}$:= # 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 current with the same emittance (DWA, LWFA, PWFA)

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

OUTLINE

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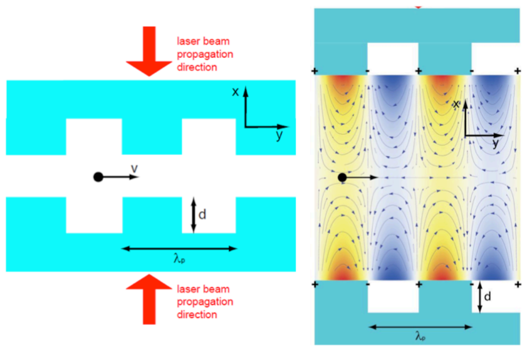
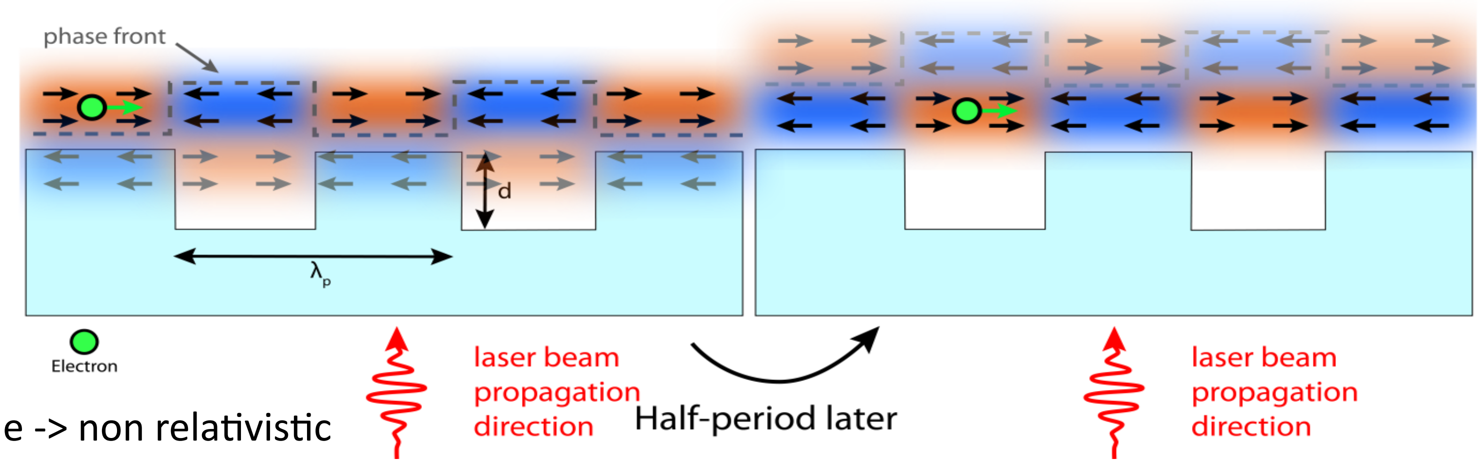
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

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

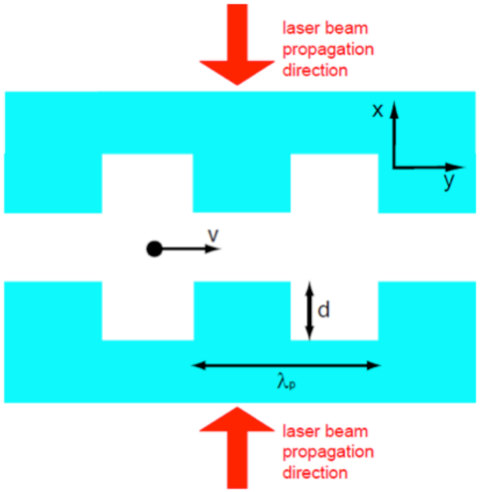
✧Summary

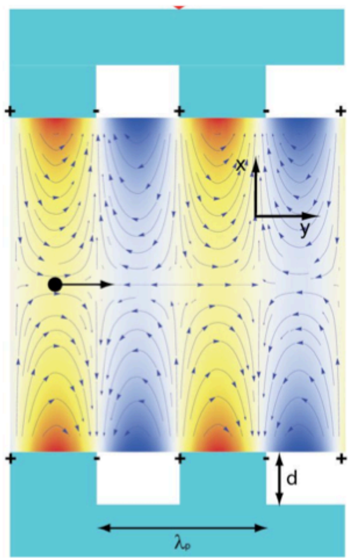


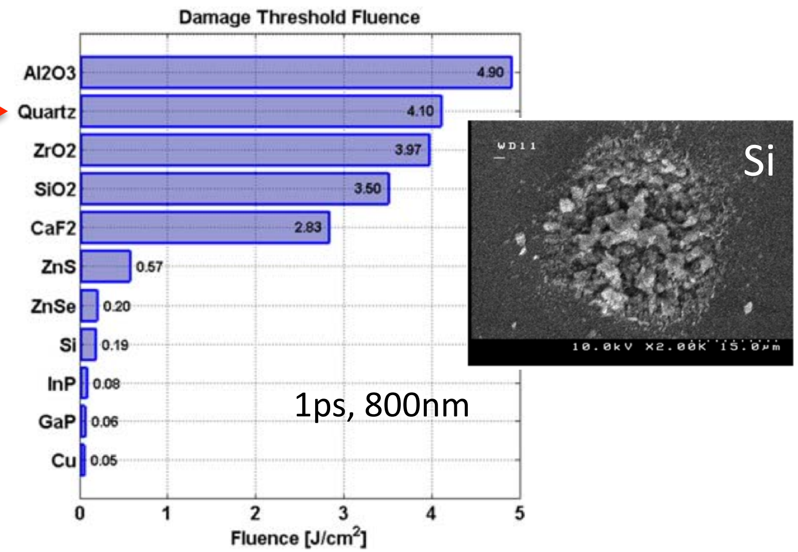
DiELECTRiC LASER ACCELERATOR (DLA)



✧ One side -> non relativistic
✧ Two sides -> relativistic







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

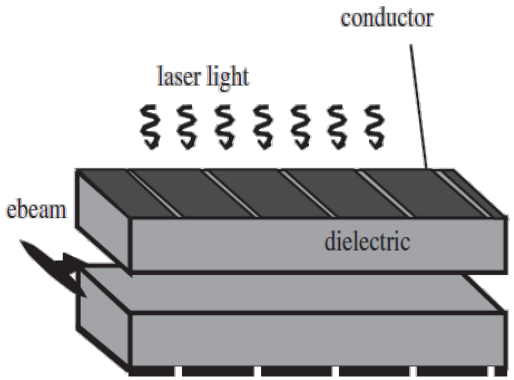
✧ Take advantage of large laser E-field
✧ Take advantage of large damage threshold (SiO_2, Si, etc.)
✧ Structure = phase mask for velocity matching

 Courtesy P. Hommelhoff

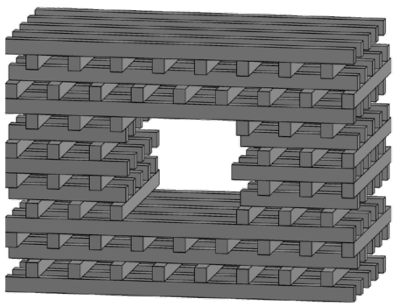
P. Hommelhoff, Accel. Med. Appl., Vösendorf, Austria, 2015

DiELECTRiC LASER ACCELERATOR (DLA)

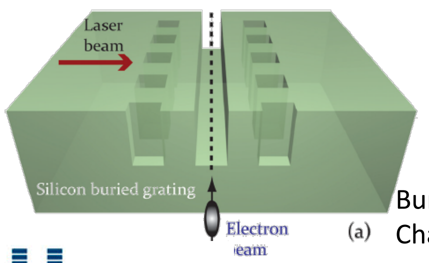
Proposed dielectric structures



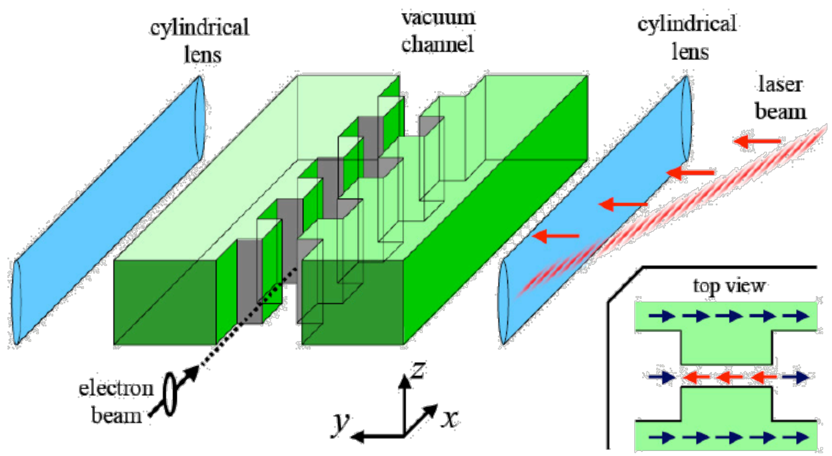
Yoder, Rosenzweig, 2005



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

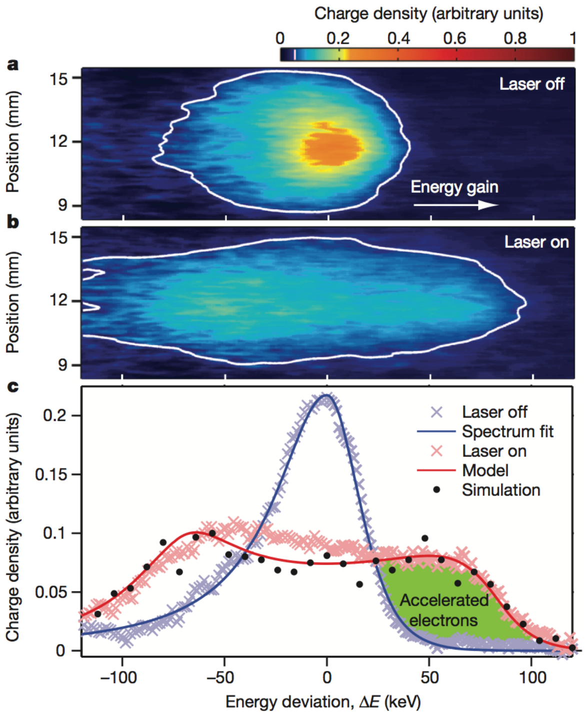
For a review and an extensive list of references, see: R. J. England et al., “Dielectric laser accelerators”, Rev. Mod. Phys. 86, 1337 (2014)

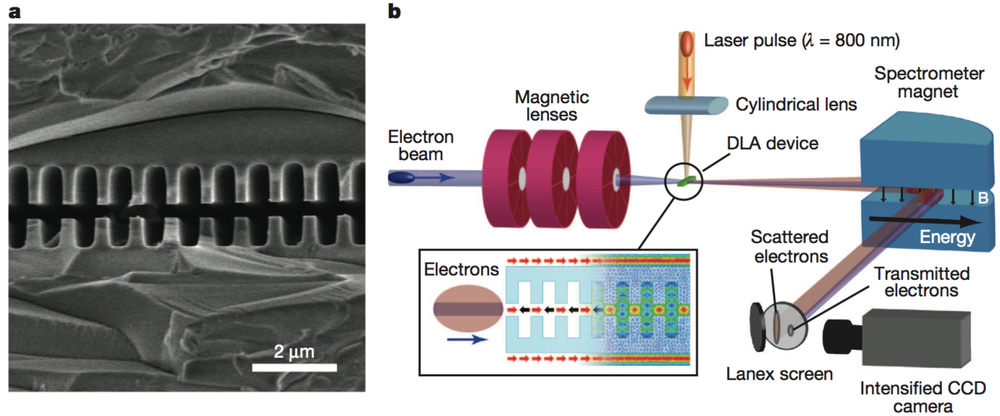
DLA Results

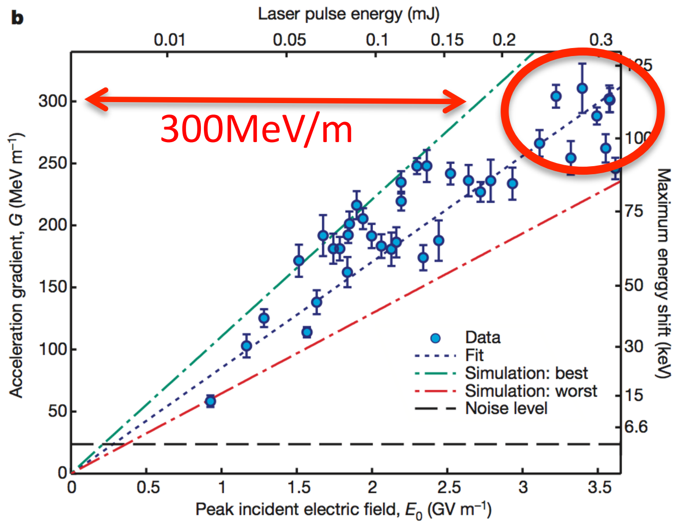
Demonstration of electron acceleration in a laser-driven dielectric microstructure

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





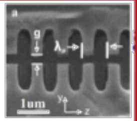
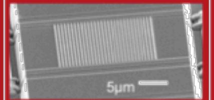
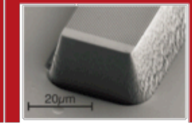


- ✧Beam not bunches at λ_{laser} scale -> broad spectrum … possible bunching: IFEL
- ✧Inferred accelerating gradient in excess of 300MV/m
- ✧Need sub-$(\lambda_{laser})^3$ beams, naturally low emittance and charge
- ✧Operate at very high rep-rate

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

Relativistic
“Accelerator”

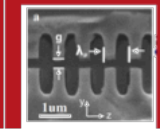
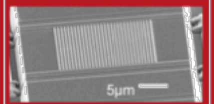
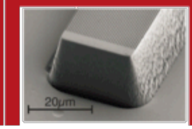
Non-relativistic
“Injector”

Courtesy of J. England

DLA RESULTS

Recent DLA Experiment Comparison

SLAC

Parameter	SLAC	Stanford	MQP/Erlangen
			
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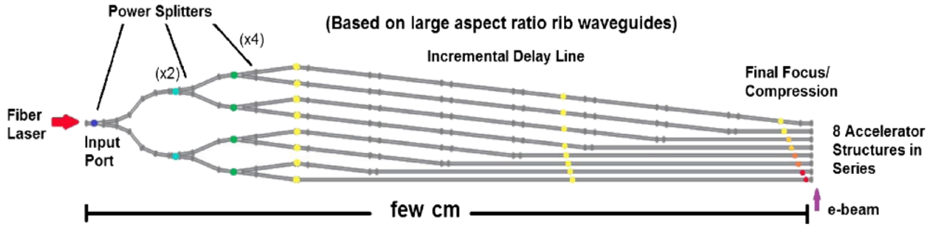
Relativistic "Accelerator"

Non-relativistic "Injector"



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

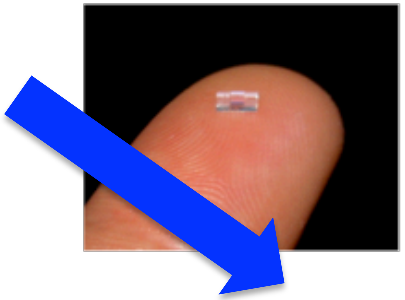
✧Deliver lower average current with lower emittance?? (DLA)

Courtesy of J. England

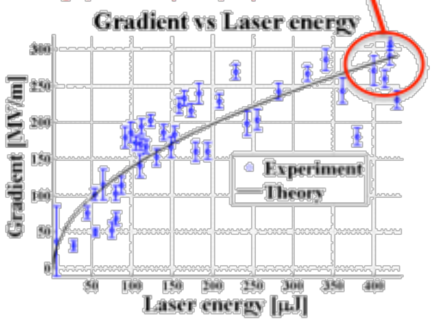
DLA RESULTS

DLA Structure Development: Recent Progress

Accelerator

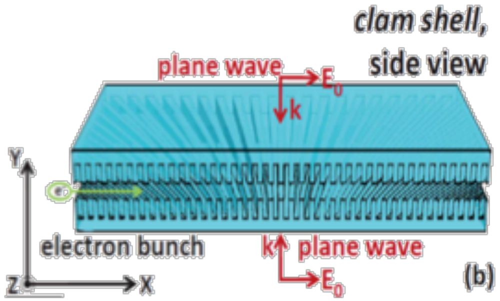


short-pulse (70 fs): **700 MV/m***
long-pulse (1.3ps): **300 MV/m***

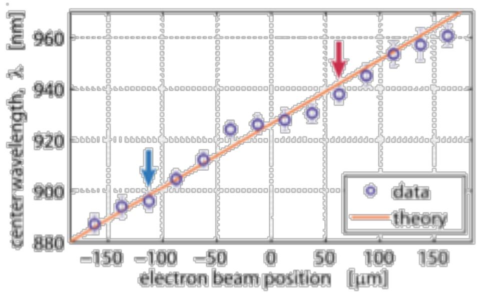


*Nature **503**, 91-93 (2013)
*in prep for publication (2015)

Beam Position Monitor

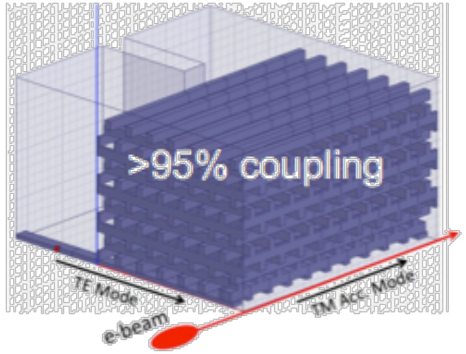


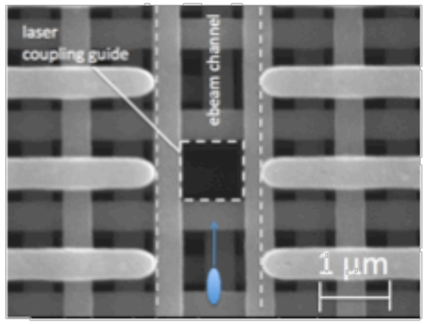
Opt. Lett., **37** (5) 975-977 (2012)



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

DiELECTRiC LASER ACCELERATOR (DLA)

A few general characteristics:

- ✧Requires very short e⁻ bunch(es) or train of bunches: λ_{laser}=1-2-10µm scale
- ✧Requires very low emittance for focusing to λ_{laser}=1-2-10µm scale
- ✧Very low charge per bunch
- ✧Potentially produces very low emittance beams
- ✧Can operate at very high rep. rate (MHz to GHz, laser)
- ✧Use efficient, well developed laser technology (diode pumped Thulium-doper fiber laser, or CO_2)
- ✧Injector (non-relativistic) + Accelerator (relativistic)
- ✧Linear and symmetric for e^- & e^+

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OUTLiNE

✧Novel Accelerator Techniques "Goals"

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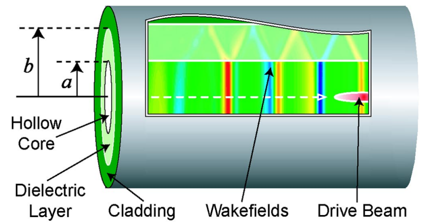
✧Cherenkov wakes in dielectric layers

✧Summary



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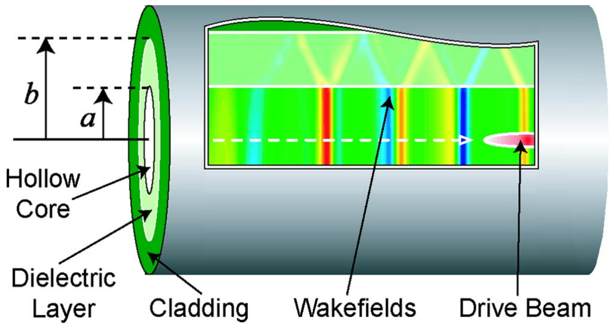
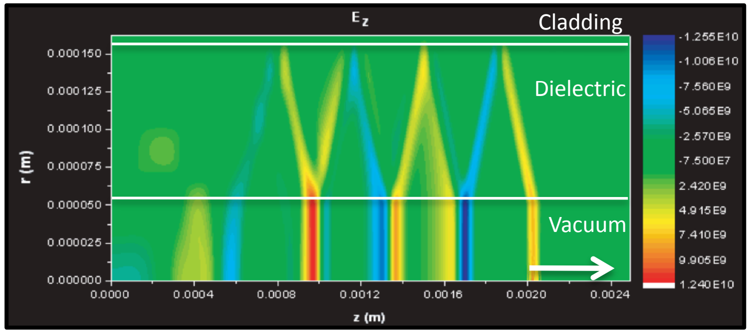
DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





- Peak decelerating field

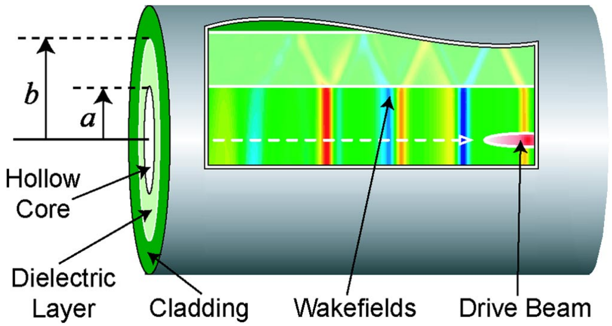
$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right]}$$

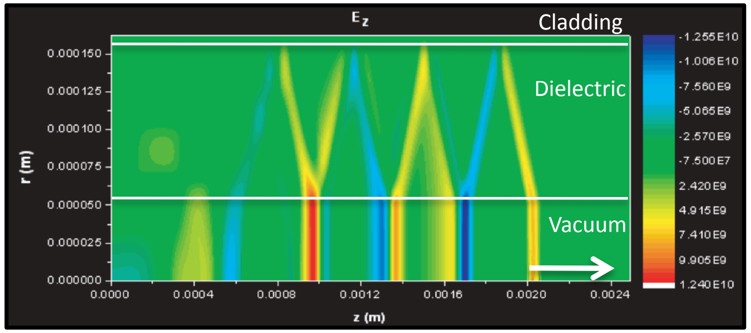
- Transformer ratio (unshaped beam)

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

 Detailed fields; Jing, RAST 09, 2016

DiELECTRiC WAKEFiELD ACCELERATOR (DWA)





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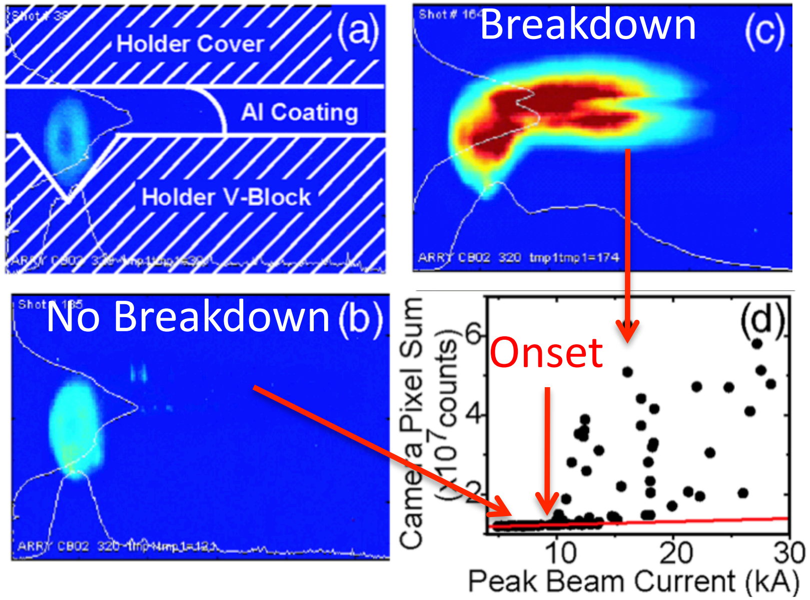
PRL 100, 214801 (2008) PHYSICAL REVIEW LETTERS week ending 30 MAY 2008

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

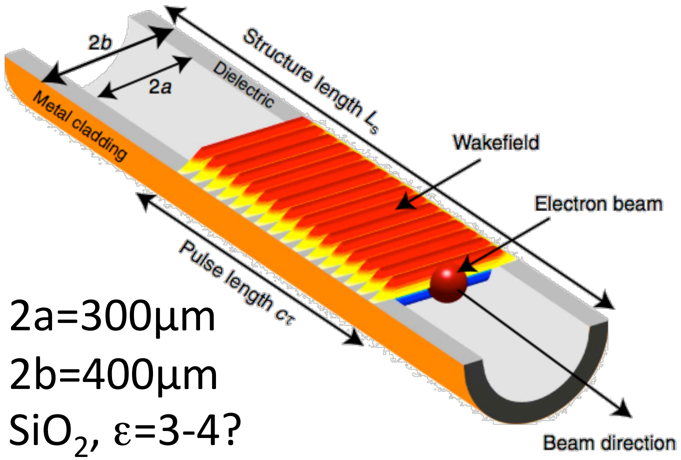
M. C. Thompson,[1,2,*] H. Badakov,[1] A. M. Cook,[1] J. B. Rosenzweig,[1] R. Tikhoplav,[1] G. Travish,[1] I. Blumenfeld,[3] M. J. Hogan,[3] R. Ischebeck,[3] N. Kirby,[3] R. Siemann,[3] D. Walz,[3] P. Muggli,[4] A. Scott,[5] and R. B. Yoder[6]



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

DWA RESULTS

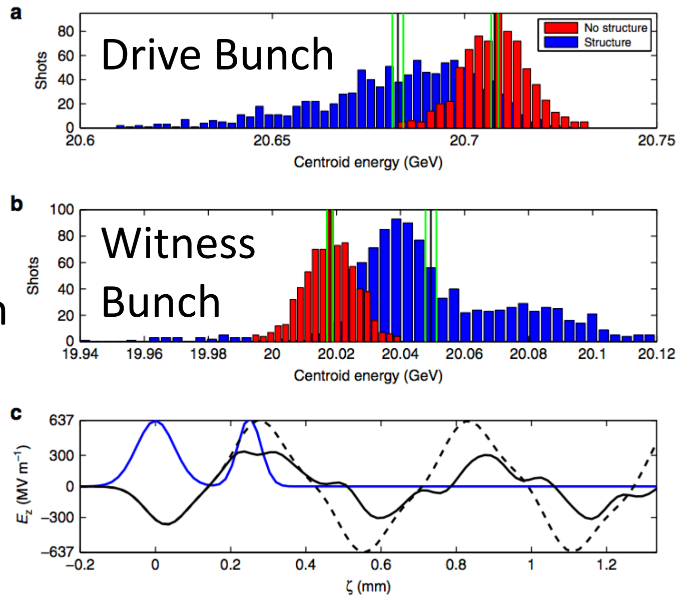
O'Shea et al., Nat . Comm. 7, 12763 (2016)



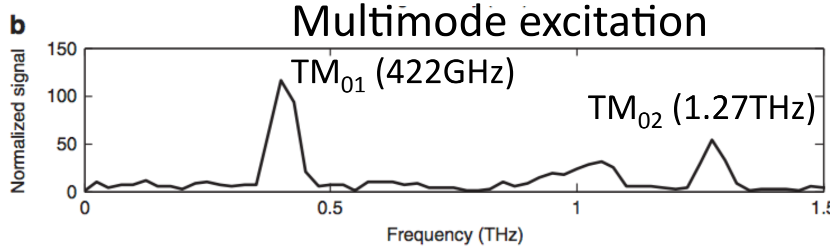
$2a$=300µm
$2b$=400µm
SiO_2, ε=3-4?
Cu cladding

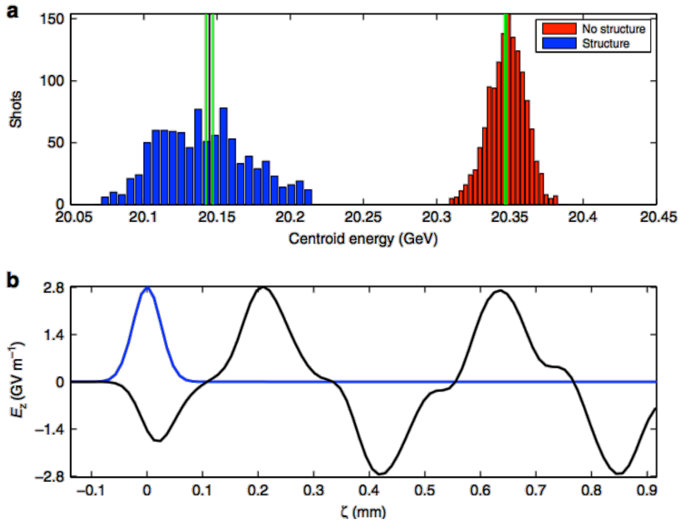
9.4×10^{9}e
G_d=252±14MeV/m

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



Multimode excitation





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

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

DWA RESULTS

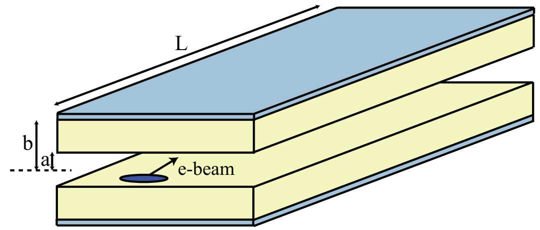
Acceleration in slab symmetric DWA

- 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

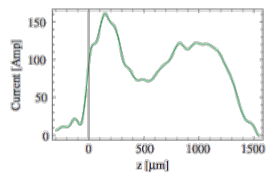
Slab geometry allows for:

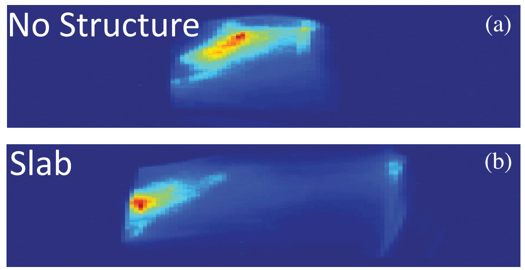
✧Reduced transverse wakefields

$W'_{per} \sim k^3 \to 0$ when $\sigma_{//} \gg a$

✧More charge per bunch

✧Demonstration of energy gain!



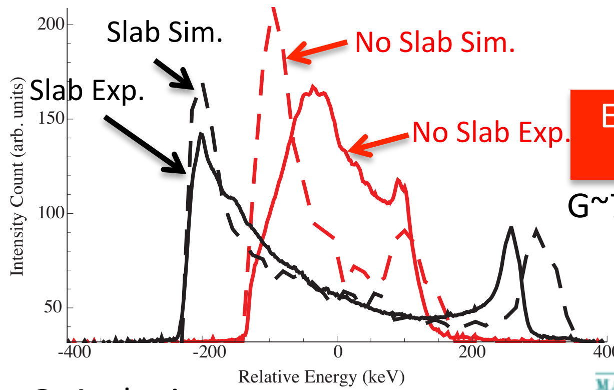


E_0=59MeV
Q=100-900pC
L_z~1.2mm
ε_N=2mm-mrad

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

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

Tremaine
PRE 56 7210 (1997)



Energy Gain

G~7MeV/m

✧Appropriate for "flat" collider beams?

Courtesy G. Andonian

MULTIBUNCH PWFA

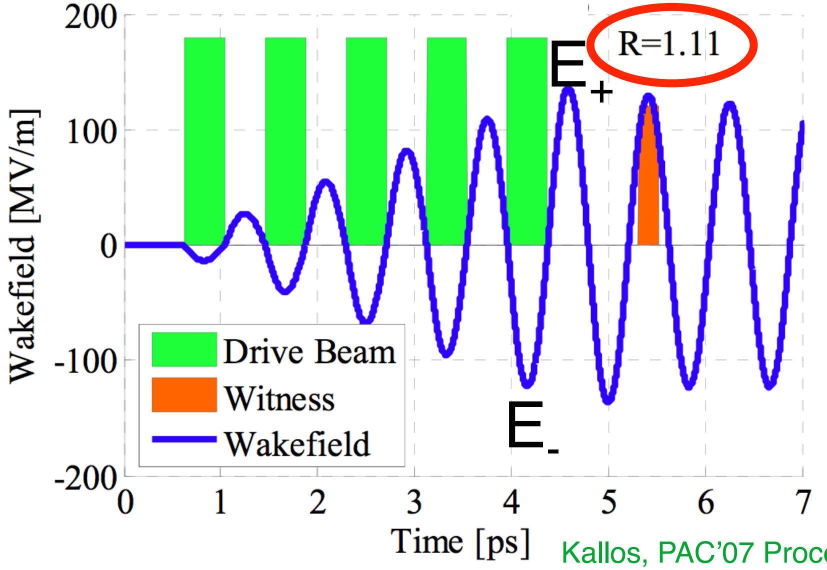
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

σ_r=125 μm, n_e=1.8x10^{16} cm^{-3}, λ_p=250 μm

E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm=λ_p

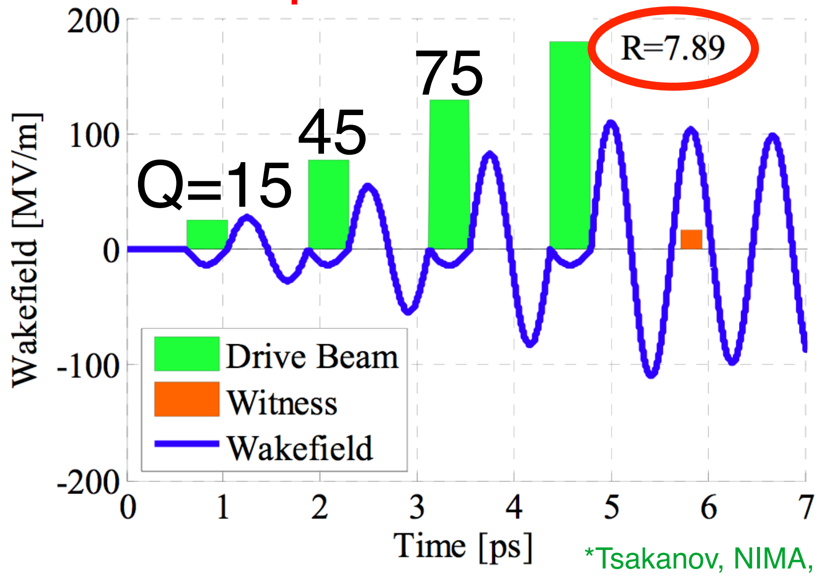
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm=1.5λ_p

Ramped Bunch Train*



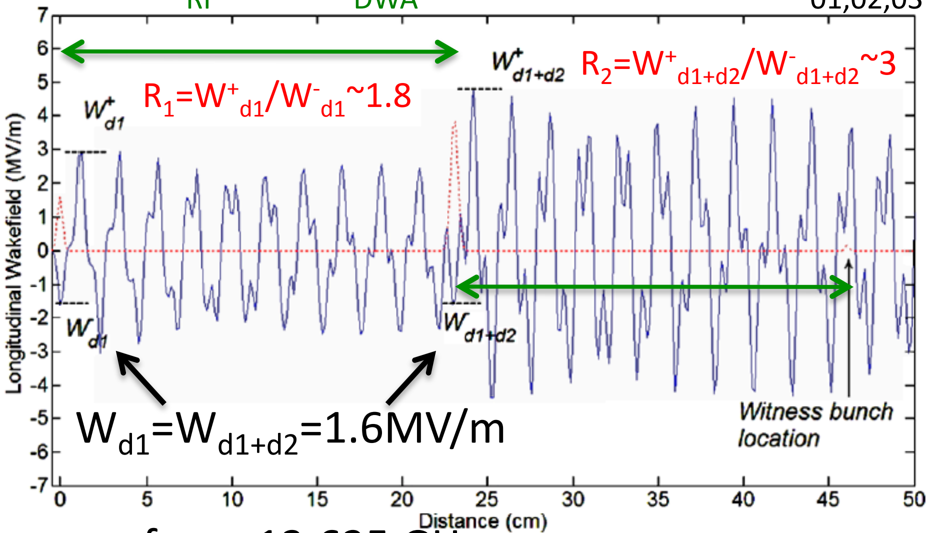
*Tsakanov, NIMA, 1999

- Single, symmetric bunch transformer ratio: R≤2
- Resonant excitation of wakefields
- Large transformer ratio and energy gain (>2)
- Energy conservation: $Q_W \Delta E_W \leq Q_D \Delta E_D$

DWA RESULTS: R

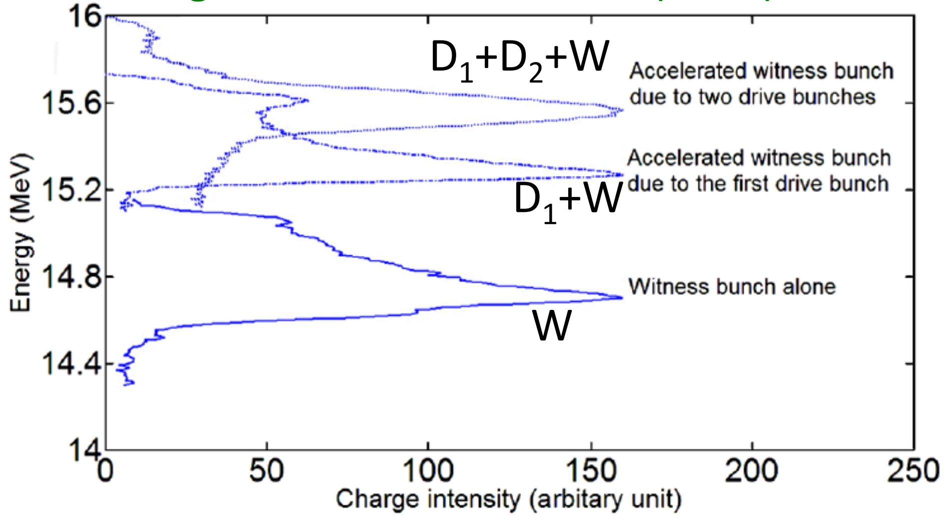
✧S-Band gun produces 2D+1W bunches in three buckets

$1\lambda_{RF}=10.5\lambda_{DWA}$ Simulation $TM_{01,02,03}$



$f_{TM01}=13.625$ GHz
$Q_{d1}=8nC$, $Q_{d2}=20nC$, $Q_w=1nC$ $R_2/R_1 1.6$
$\sigma_{d1}=1.5mm$, $\sigma_{d2}=2mm$

Jing et al., PRL 98, 144801 (2007)



$$R_2/R_1 = \left(\frac{W^+_{d1+d2}}{W^-_{d1+d2}}\right)/\left(\frac{W^+_{d1}}{W^-_{d1}}\right) = \frac{W^+_{d1+d2}}{W^+_{d1}} = 1.31 \pm 0.13.$$

2a=5mm
2b=6.35mm
Al_2O_3, ε=16
Cu tube

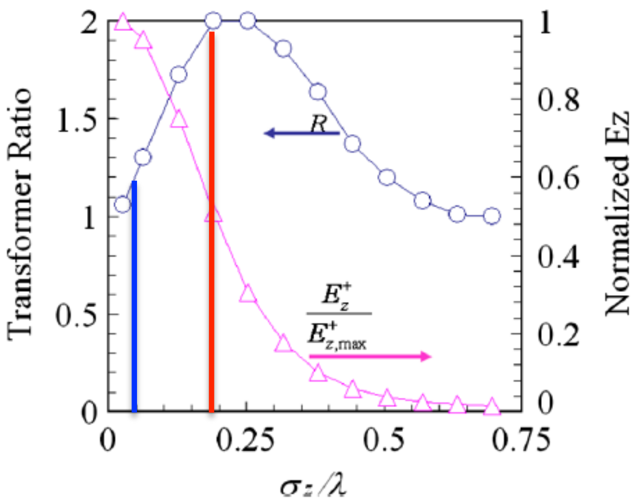
✧R=2.3 > 2!
✧Ramped bunch train increases R by 1.3
✧Demonstration of energy gain!
✧Other shapes: door step, double triangle, etc.

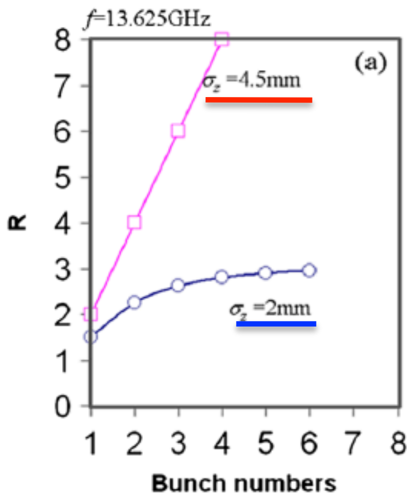
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

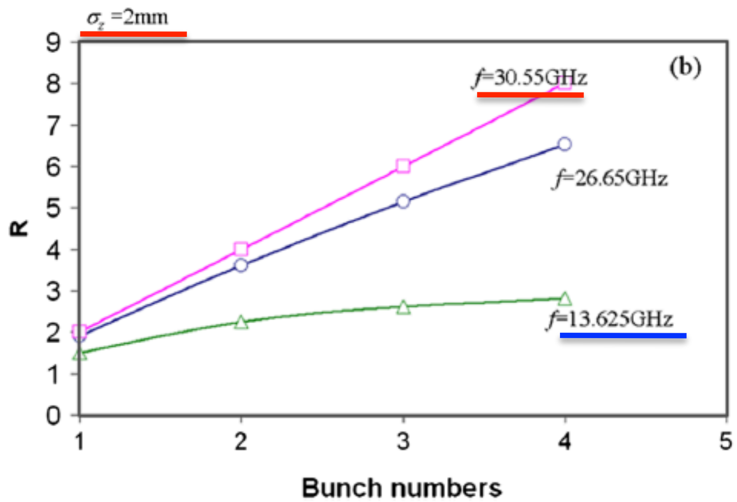
DWA RESULTS: R

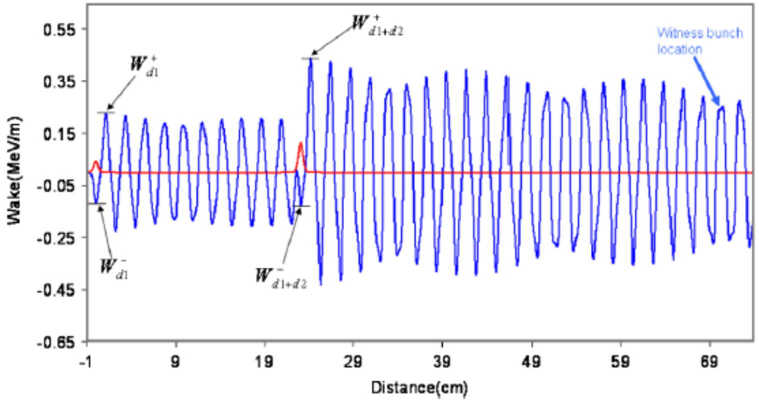
CERN

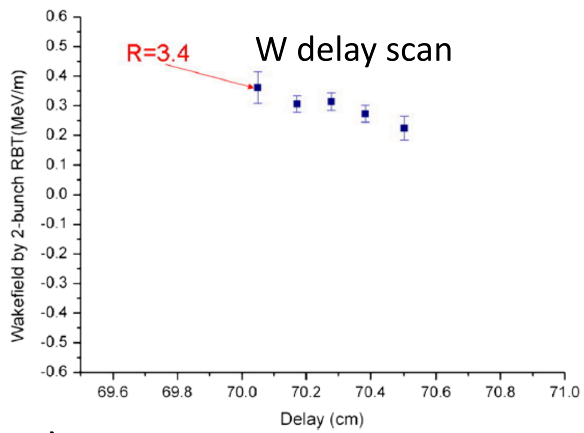
- ✧S-Band gun produces 2D+1W bunches in three buckets
- ✧f_{DWA}=13.625GHz => λ_{DWA}=22mm: σ_z=2mm -> 4.5mm











- ✧σ_z=2mm -> 4.5mm -> less TM_{02}(39.4GHz)
- ✧Q_1:Q_2=2. 7 (3.0) -> R_1=1.97 (2.0), R_2=3.4 (4.0), R_2/R_1=1.73 (2.0)
- ✧Better matched parameters -> better results

MAX-PLANCK-GESELLSCHAFT

DiELECTRiC WAKEFiELD ACCELERATOR (DWA)

A few general characteristics:

- ✧Driven by short e^- bunch(es)
- ✧GV/m possible
- ✧Short bunches for GV/m: (<100µm)
- ✧Linear and symmetric for e^- & e^+
- ✧Accommodate/prefer flat beams in planar structure
- ✧Can use diamond: low SEY, excellent thermal conductivity, etc.
- ✧Operate in the 10's to 100's GHz range
- ✧Multi-mode?

- ✧Extended structure without focusing? (ultra-low emittance)

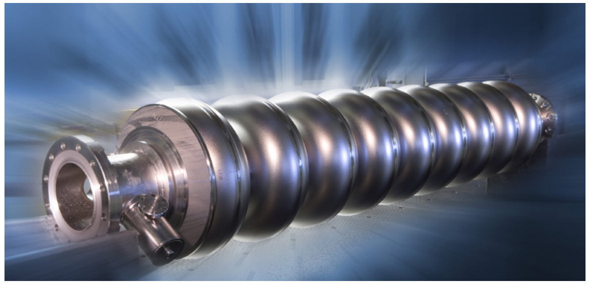
OUTLiNE

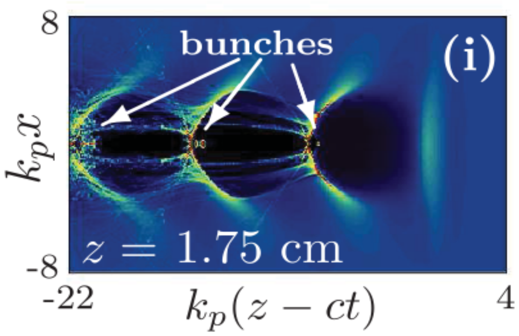
✧Novel Accelerator Techniques "Goals"

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

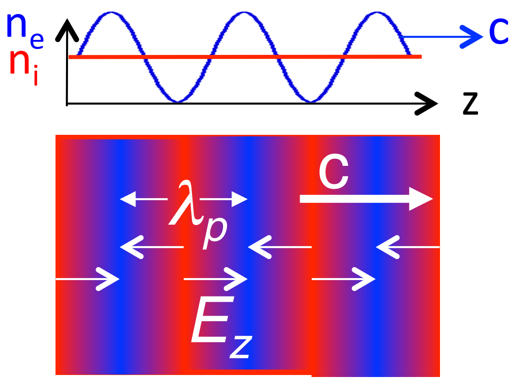
✧Summary





PLASMAS

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



LARGE

Collective response!

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

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

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

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

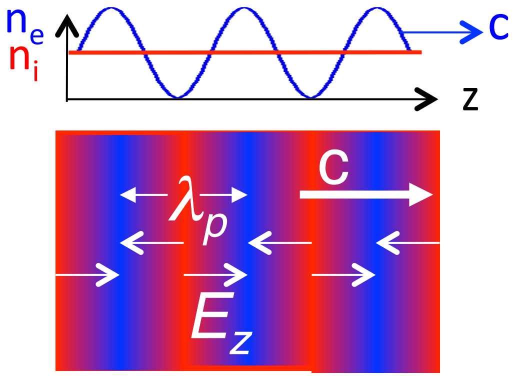
$n_e=10^{14}$ cm^{-3}

Cold Plasma "Wavebreaking" Field

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

PLASMAS

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



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Cold Plasma "Wavebreaking" Field

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

✧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 ….

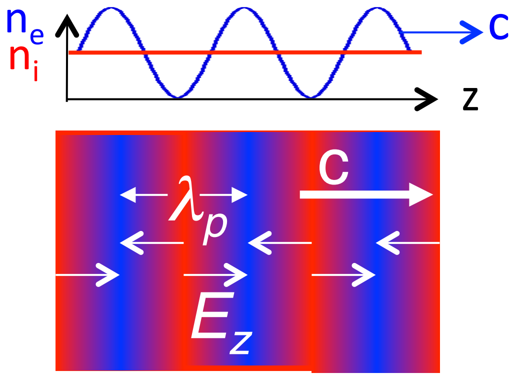
✧Plasmas wave or wake can be driven by:

➢Intense laser pulse (LWFA)

➢Dense particle bunch (PWFA)

PLASMAS

✧Relativistic Electron, Electrostatic Plasma Wave (E$_z$//k, B=0):



LARGE

Collective response!

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

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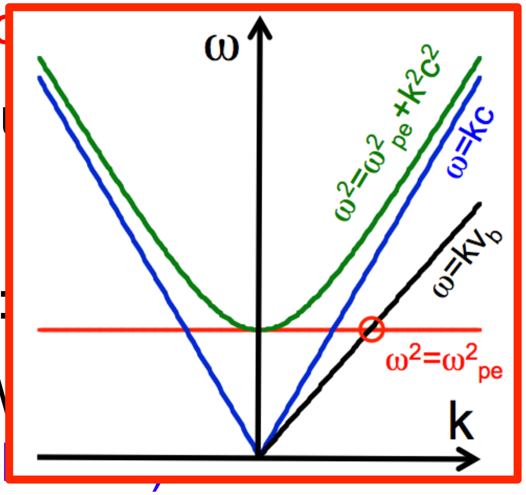


$\omega^2=\omega^2_{pe}$)

Single mode system!

✧Plasma is already (partially) ionized, diffic

✧No structure to build ….

✧Plasmas wave or wake can be driven by:

➢Intense laser pulse (LW

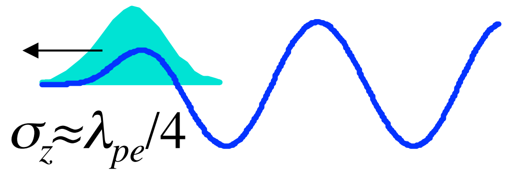
➢Dense particle bunch (

4 Plasma-based Accelerators*

- Plasma Wakefield Accelerator (PWFA)

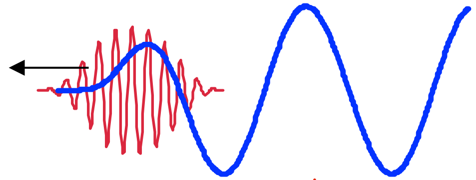
  A high energy particle bunch (e^-, e^+, ...)

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



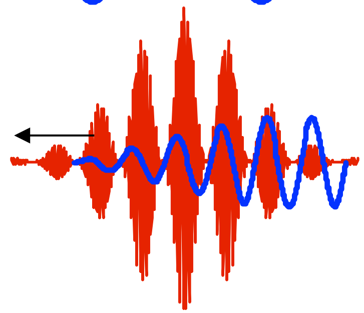
- Laser Wakefield Accelerator (LWFA) *

  A short laser pulse (photons, ponderomotive)



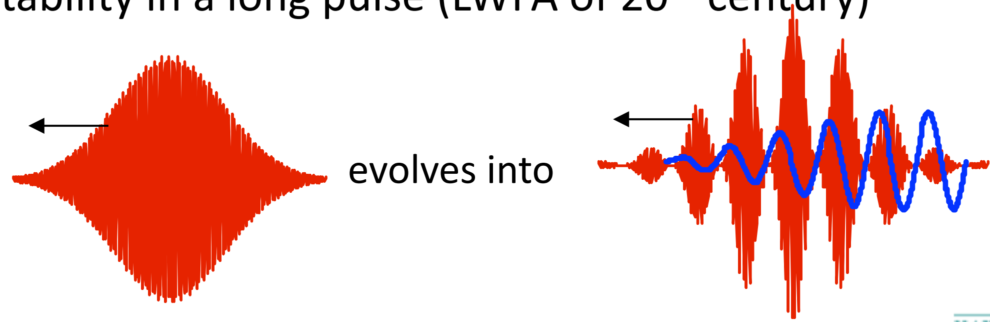
- Plasma Beat Wave Accelerator (PBWA) *

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



- Self-Modulated Laser Wakefield Accelerator (SMLWFA) *

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



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

4 PLASMA-BASED ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

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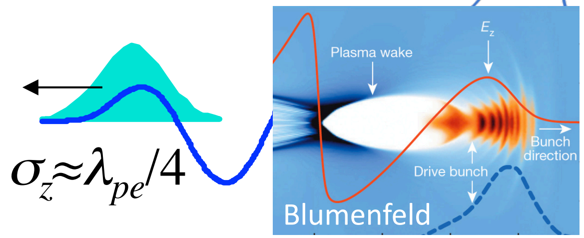

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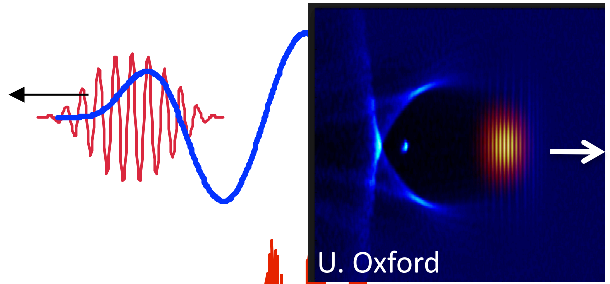

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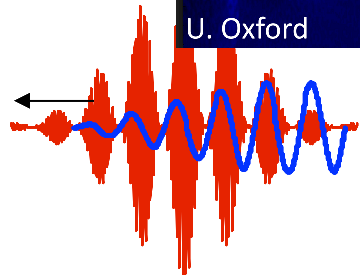

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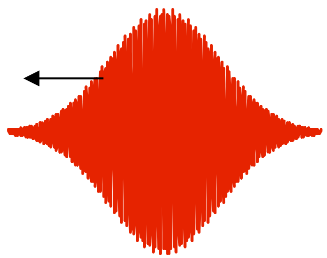
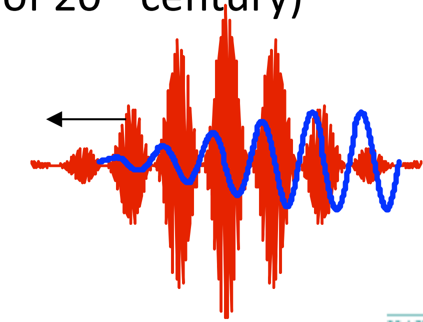


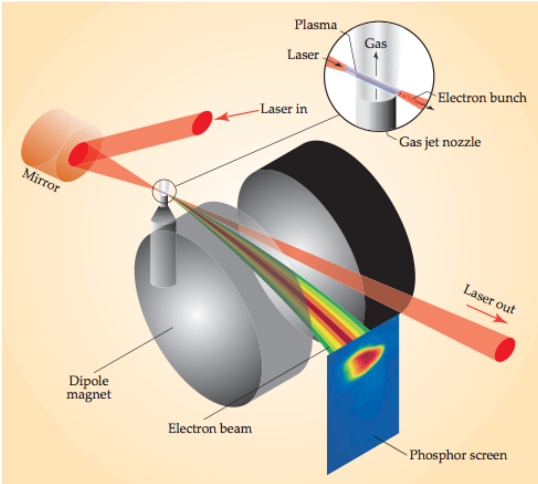
evolves into



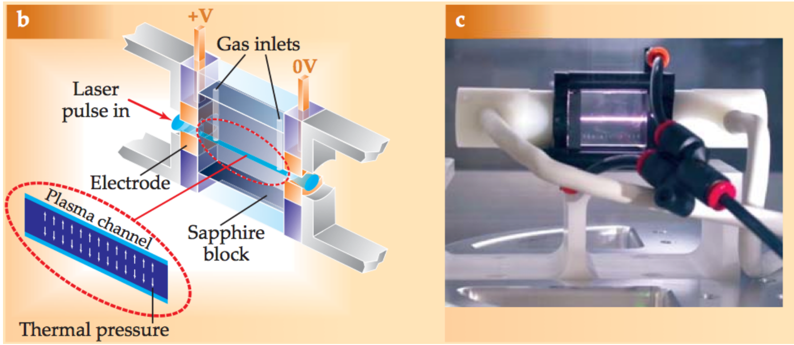
*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

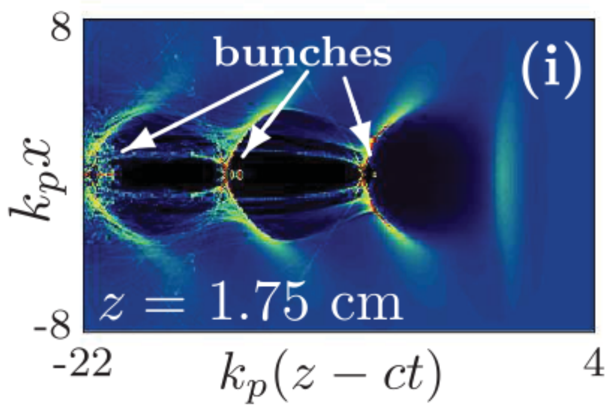
LASER WAKEFIELD ACCELERATOR (LWFA)

Gas Jet Plasma (short, injector)



Capillary Discharge Plasma (long, accelerator)





Leemans, Physics Today 2009

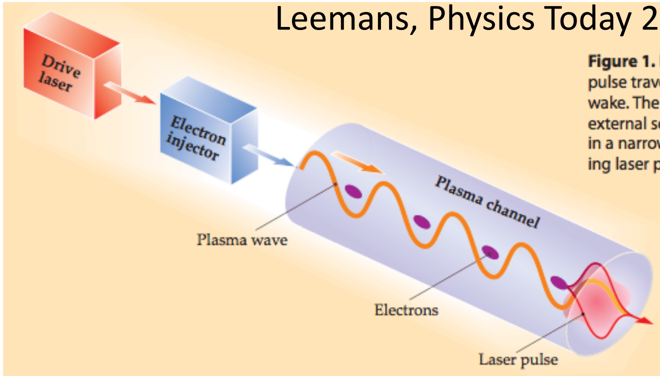
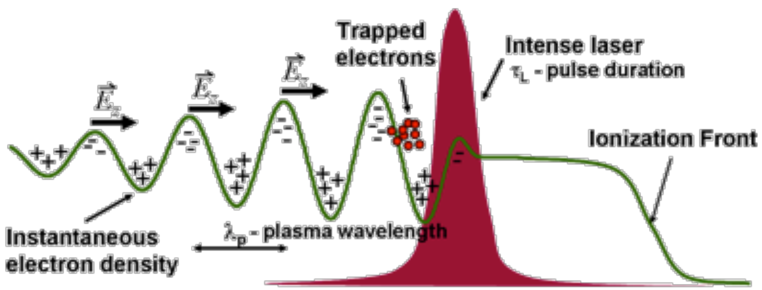


Figure 1. Laser plasma acceleration. An intense laser pulse traversing a plasma excites a plasma wave in its wake. The wave accelerates electrons injected from an external source or trapped from the plasma. Confined in a narrow channel, the plasma guides the propagating laser pulse and prevents its diffraction.

- ✧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
- ✧…

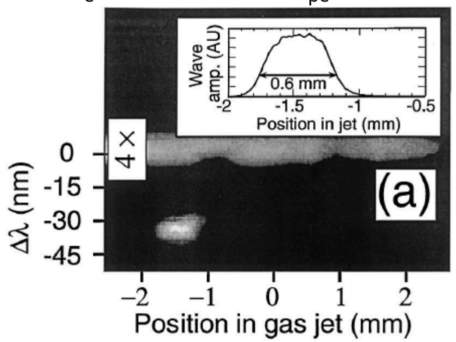


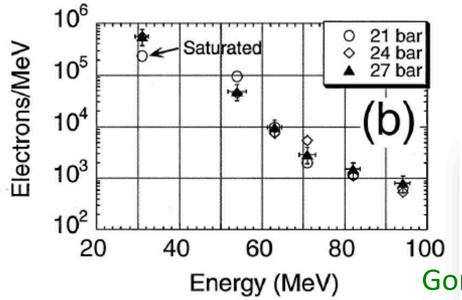
LASER WAKEFIELD ACCELERATOR (LWFA)

✧Wakefields driven by ponderomotive force of an intense laser beam

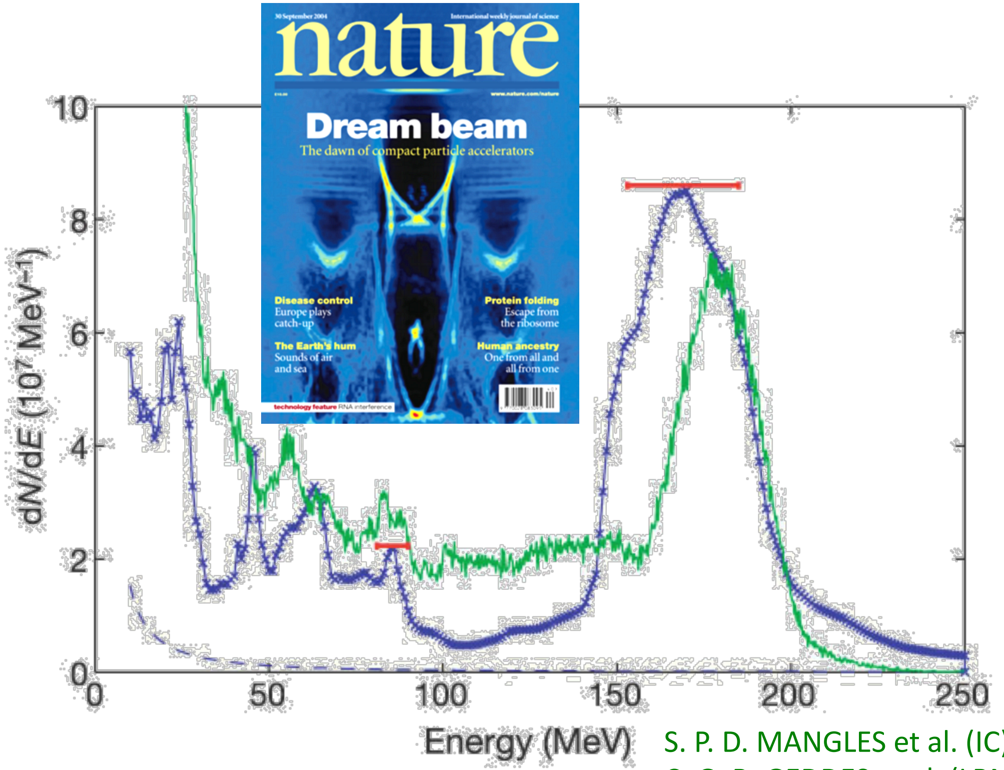
$a_0=v_{osc}/c=eE_0/mc\omega_0^2\sim1$ $\qquad$ $a_0=v_{osc}/c=8.5\times10^{-10}\,\lambda_0[\mu m]\,I_0^{1/2}[Wcm^{-2}]$

20J, 1ps, 20TW, 1.053μm
20μm dia, $I_0=6\times10^{18}W/cm^{-2}$, $a_0=2$
$n_e=1.4\times10^{19}cm^{-3}$, $\lambda_{pe}=9\mu m$





Gordon et al., PRL 80, 2133 (1998)

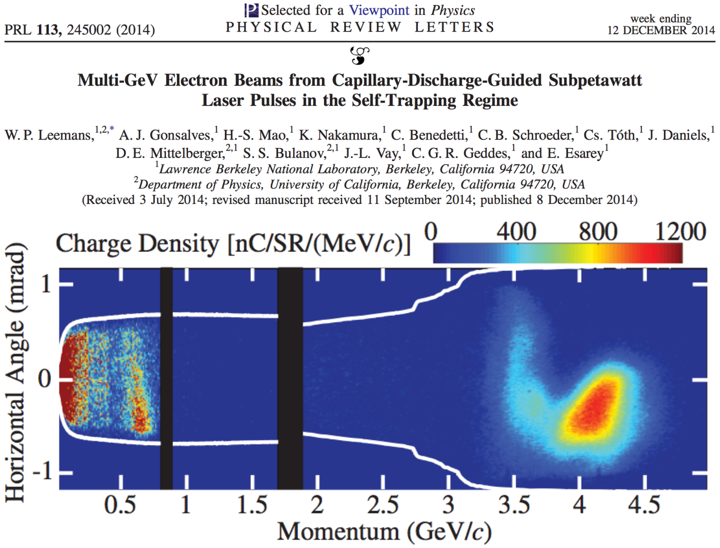


S. P. D. MANGLES et al. (IC)
C. G. R. GEDDES et al. (LBNL)
J. FAURE et al. (LOA)
Nature 431, 2004

✧Forward Raman scattering (self-modulation)
✧Wave breaking injection
✧Nonlinear plasma wave
✧Acceleration beyond linear dephasing limit

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

LWFA Results


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

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

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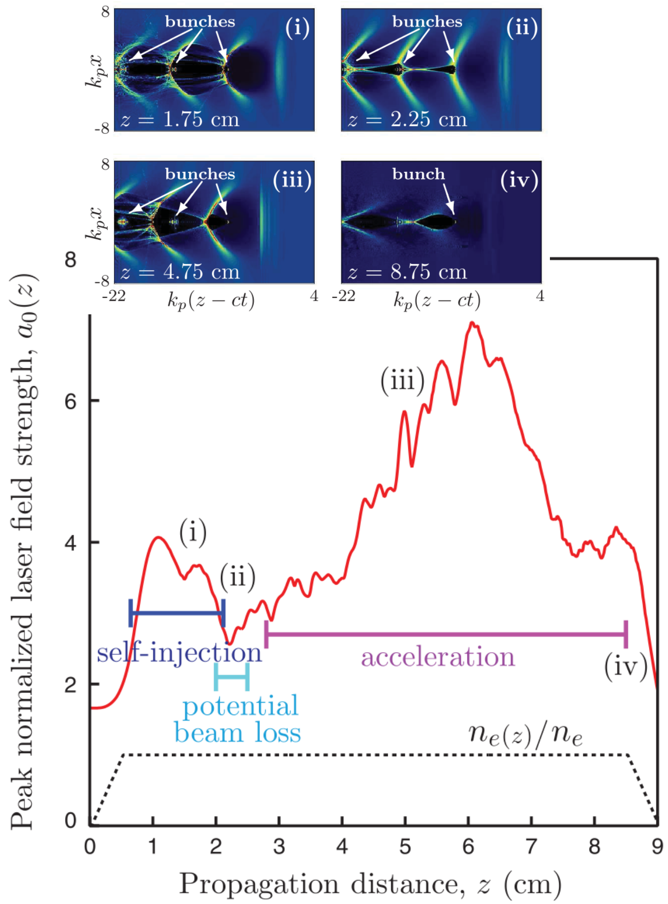
(Received 3 July 2014; revised manuscript received 11 September 2014; published 8 December 2014)

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



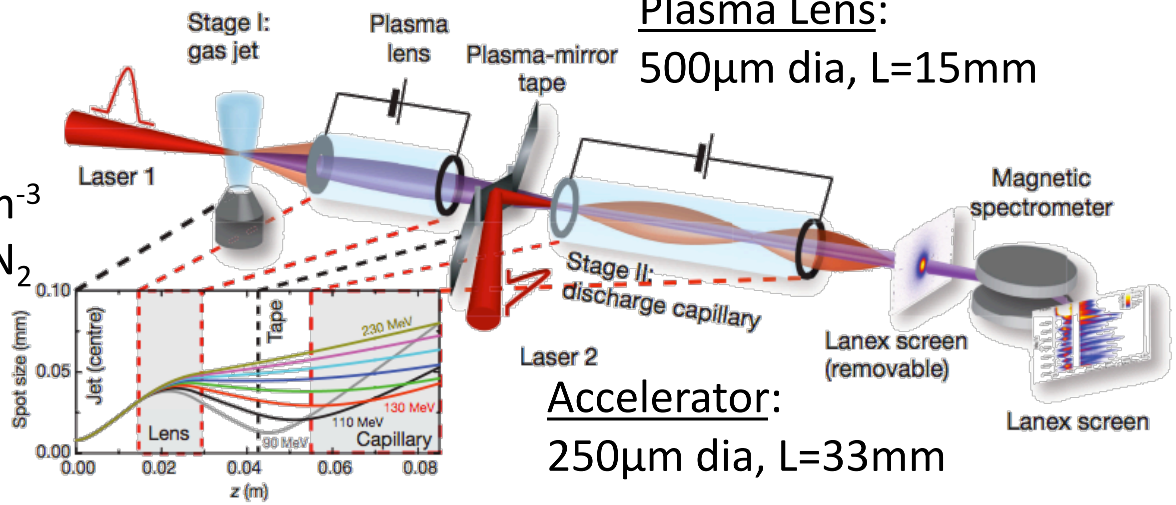
- ✧Peak energy gain 4.2GeV in <10cm
- ✧Self-trapped plasma e^-

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

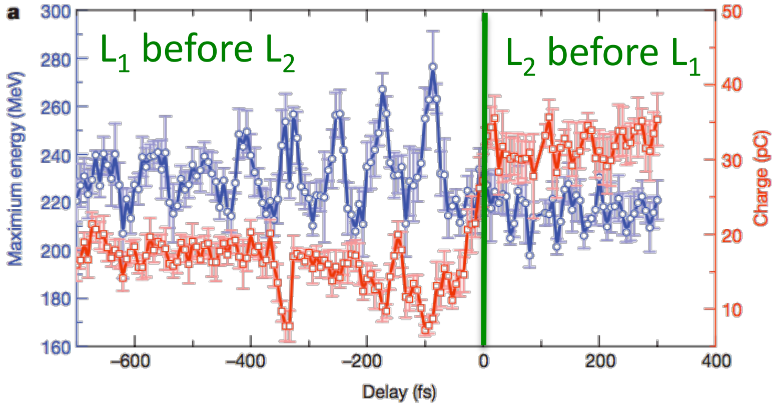
LWFA RESULTS

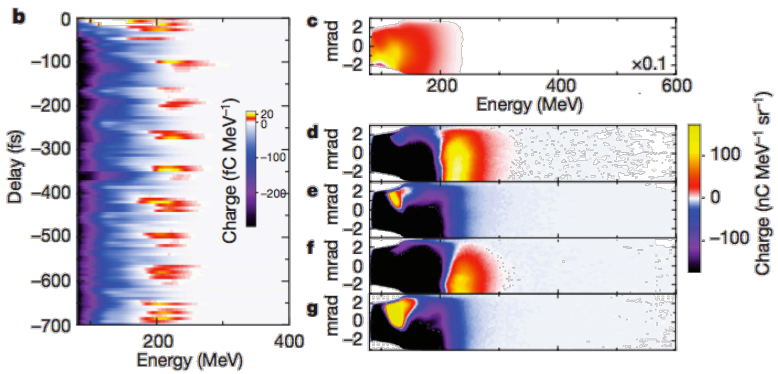
Gas jet:
n_e=5x10^{18}cm^{-3}
99%He+1%N_2
L=700µm

Plasma Lens:
500µm dia, L=15mm



Accelerator:
250µm dia, L=33mm



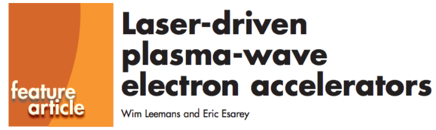


Steinke et al., Nature 530(11), 190, 2016

✧Staged acceleration (low energy)

✧Use of plasma optic and plasma mirror

Physics Today


feature article

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.

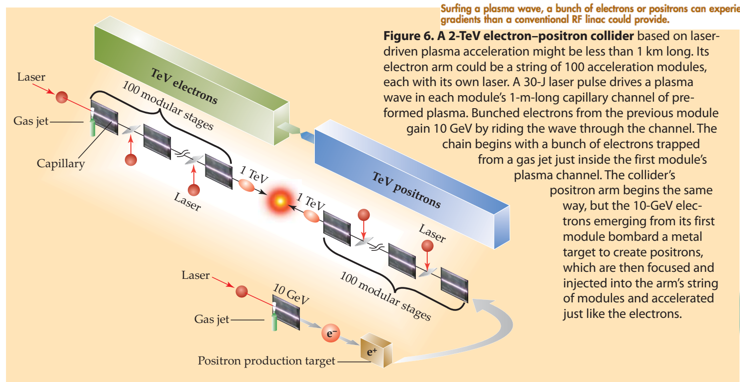


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed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

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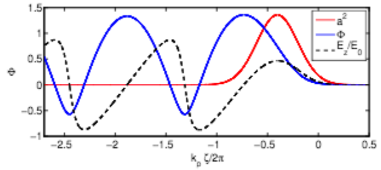
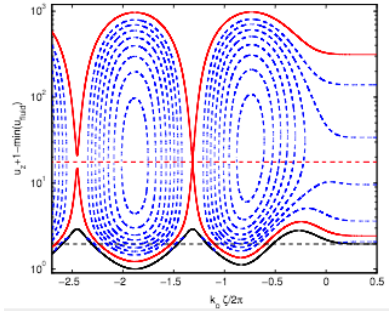
LWFA iNJECTORS (some)





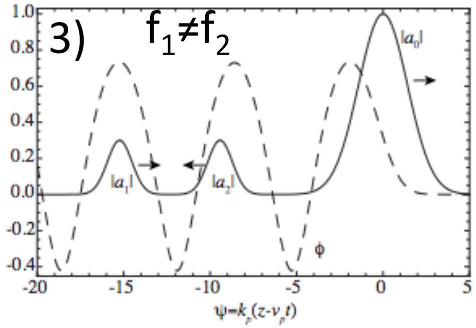
✧Wave breaking: drive the wave very non linear (Dawson, PRL,1956)

1)

✧Ionization trapping (Oz, PRL 98, 084801 (2007))

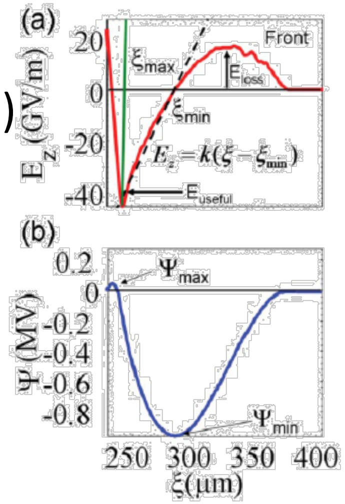
✧Three- two laser beams
(Umstadter PRL 76, 2073 (1996), Esarey, PRL 79, 2682 (1997))

3) $f_1 \neq f_2$



✧Density step (Suk PRL 86, 1011)

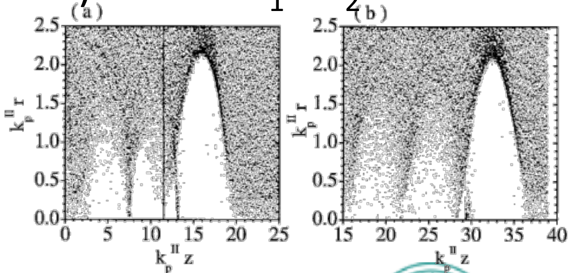
2)



✧Density down-ramp

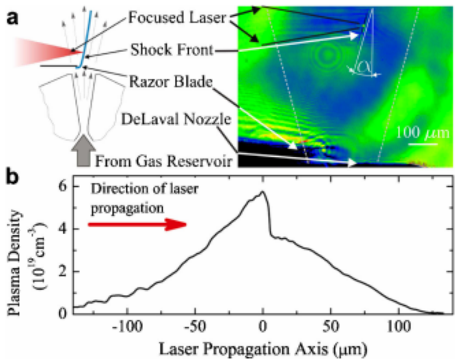
✧Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010))

4-5) $n_1 > n_2$



✧External injection

5-6)



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

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LWFA LASER DEVELOPMENT

CERN

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

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

✧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

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

✧The future is fiber lasers?

MAX-PLANCK-GESELLSCHAFT

LASER WAKEFIELD ACCELERATOR (LWFA)

A few general characteristics:

- High laser intensity: I_0>10^{18}Wcm^{-2}, P>40TW
- Short laser pulse(?): 40fs <λ_{pe}
- High plasma density: n_e>$10^{18}$$cm^{-3}$?
- λ_0~1µm: $Z_R=\pi w_0^2/\lambda_0$=314µm for w_0=10µm
- Tight focus: <λ_{pe}
- Provide ionization

- v_ϕ~$v_{g,\ laser}$<c: dephasing …
- Does not trap plasma e^- for n_e<$10^{18}$$cm^{-3}$ (wave too fast, field too low)
- Need external guiding for large energy gain: self-guiding, radial density depletion (capillary), etc.
- External injection in low density plasma (n_e~$10^{17}$$cm^{-3}$) in glass capillary (Wojda, PRE 80, 066403 2009)
- Energy loss to wakefields leads to spectral modifications and evolution

- Matched laser/plasma: high energy, long pulse (ps) laser pulse

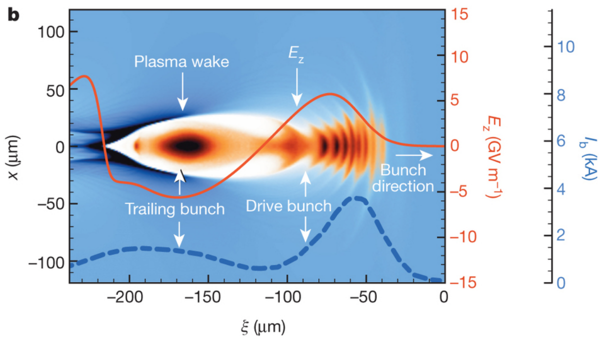
OUTLiNE

✧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

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

✧Summary



PLASMA WAKEFIELD ACCELERATOR (PWFA) (e^-)

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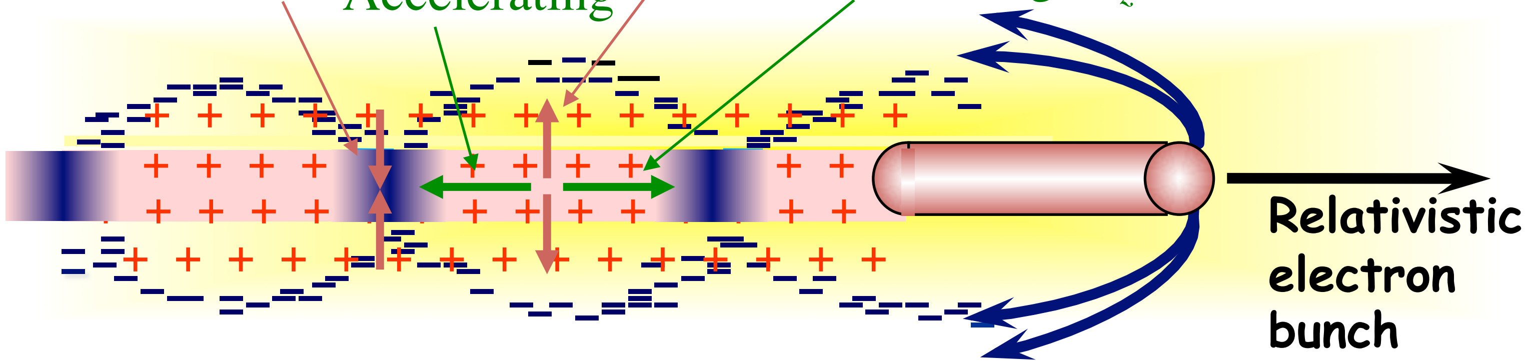

- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge force => deceleration + focusing (MT/m)
- Plasma e^- rush back on axis => acceleration, GV/m
- Ultra-relativistic driver => ultra-relativistic wake
  => no dephasing
- Particle bunches have long "Rayleigh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

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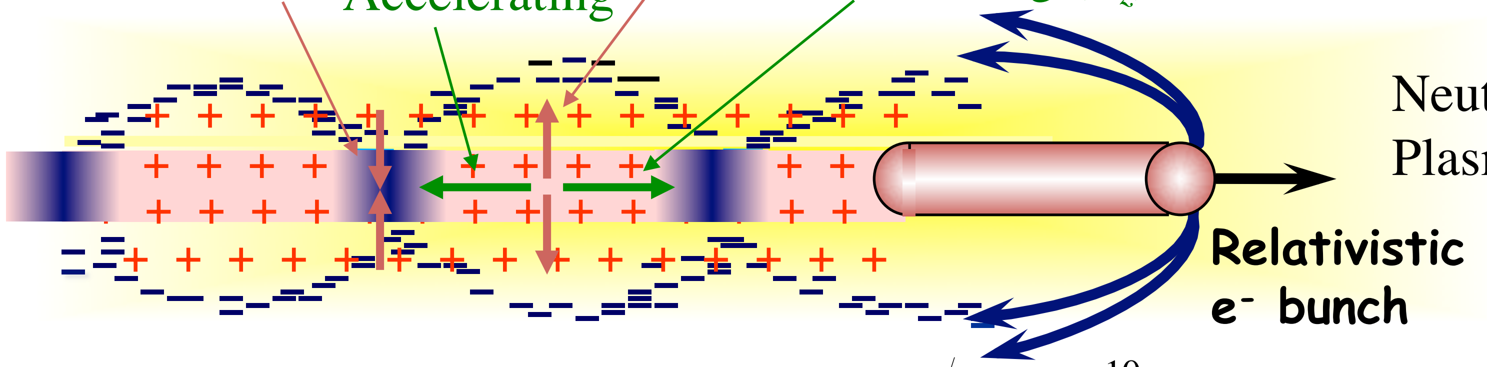
PWFA NUMBERS (e⁻)



✧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) $\quad k_{pe} \sim n_e^{1/2}$

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

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

σ_z= 20 μm, n_e=$2\text{x}10^{17}$ cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

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

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

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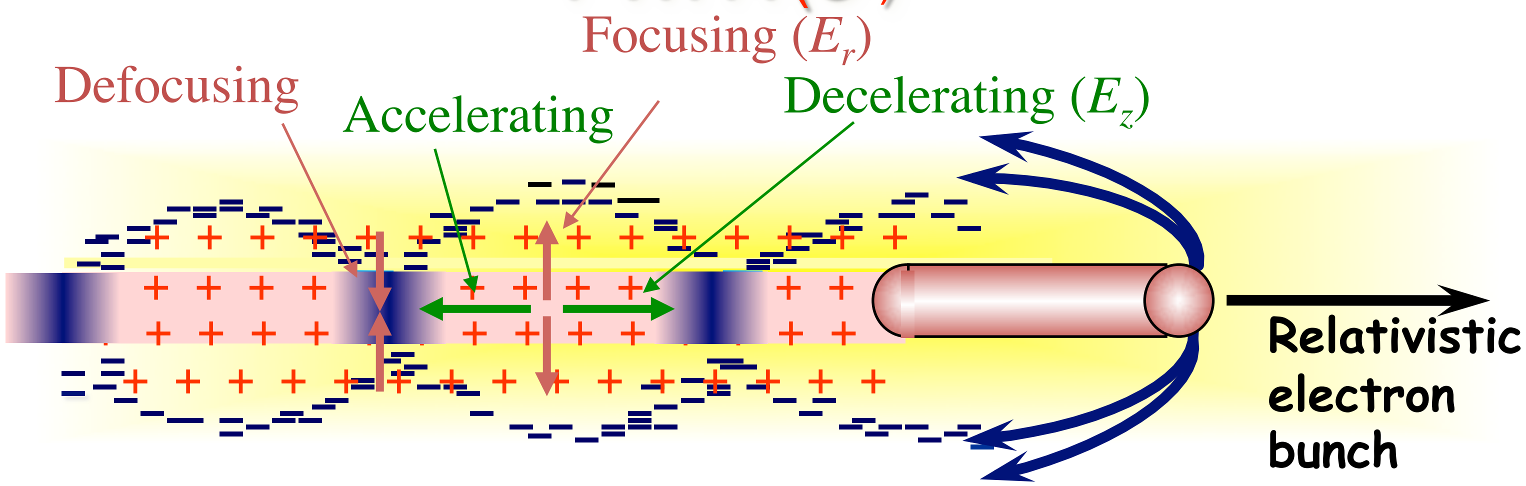
PWFA (e^-)



- 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}/ε~cm, m)
- Acceleration physics identical PWFA, LWFA

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

FIRST PWFA OBSERVATION (e^-)

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

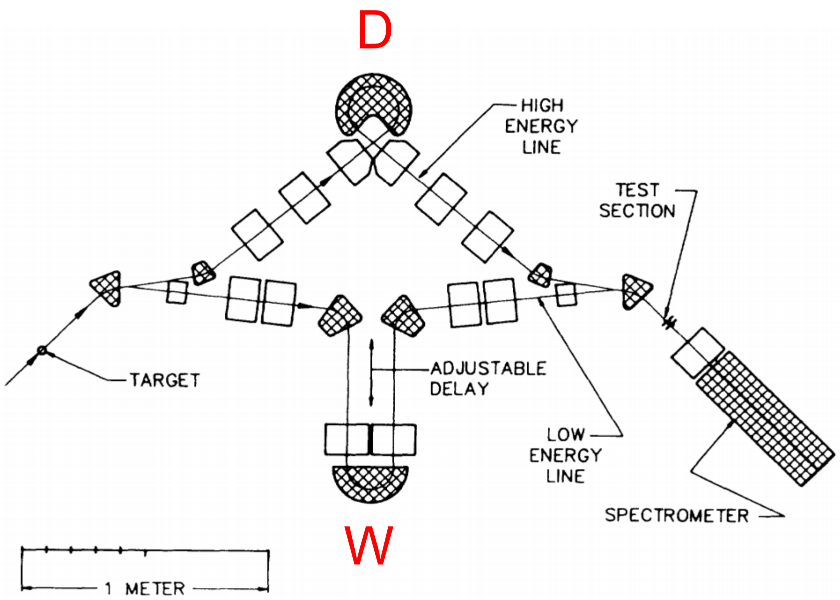


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

Rosenzweig, PRL 61, 98 (1988)

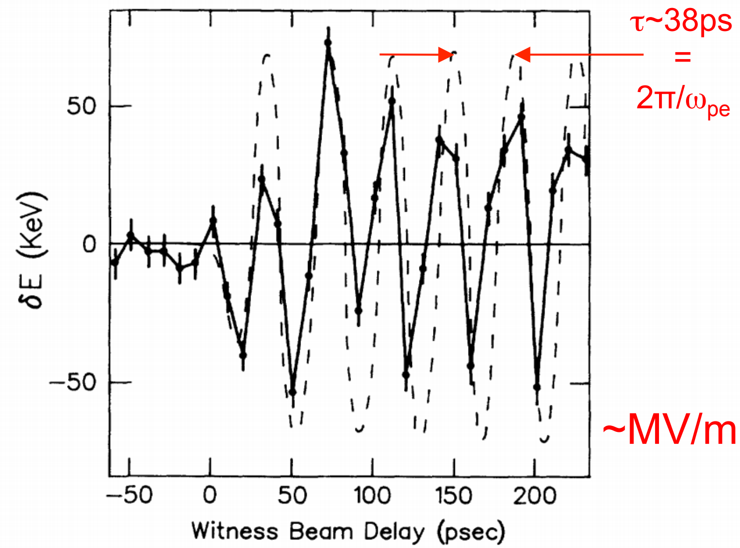
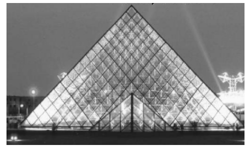


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q=2.1$ nC; plasma parameters $L=28$ cm and $n_e=8.6\times10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

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

PLASMA WAKEFIELD FIELDS (E-162, e⁻)



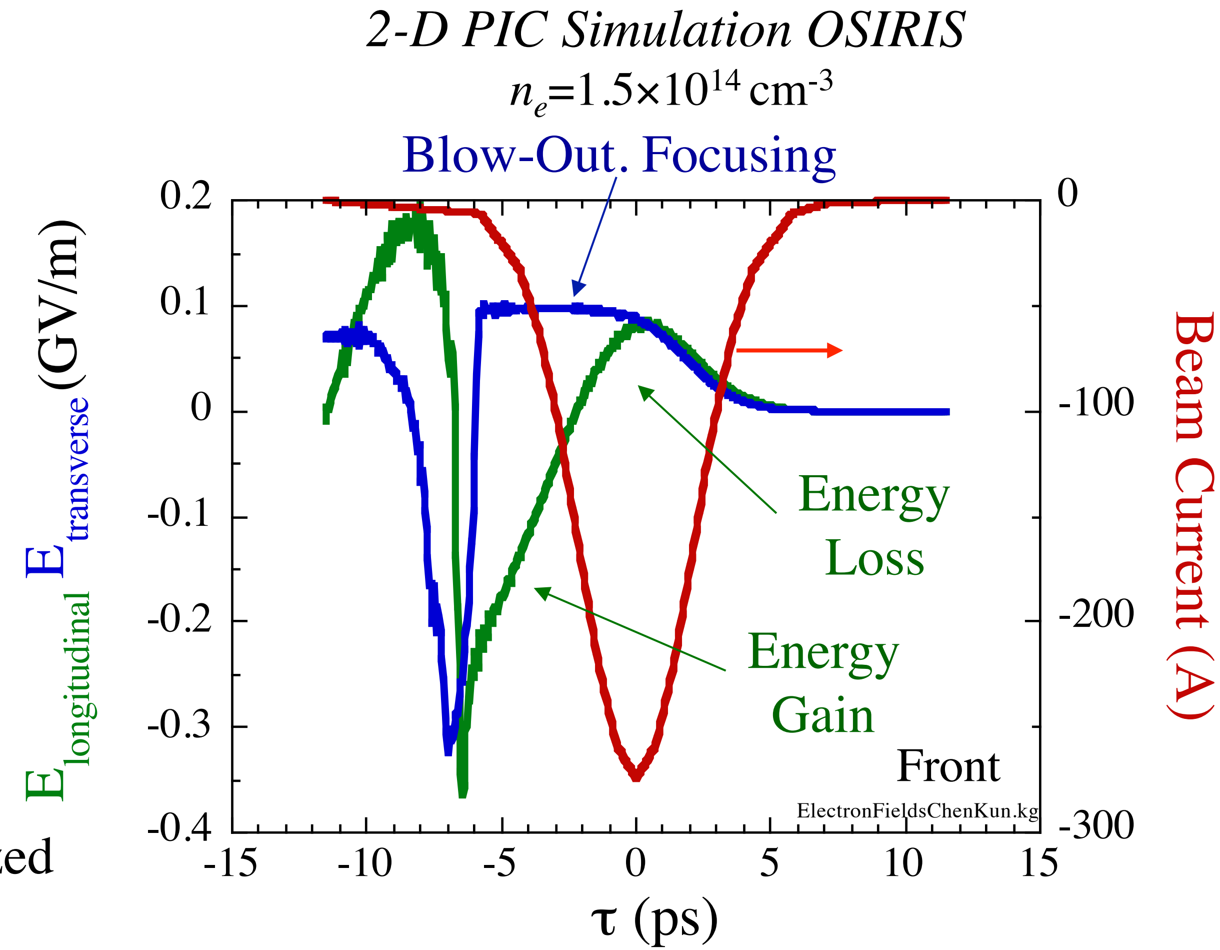
Typical parameters:

e⁻- beam:

E	28.5 GeV
N	2×10^{10} e⁻
σ_z	0.63 mm (2.1 ps)
$\sigma_x=\sigma_y$	70 μm
n_b	4×10^{14} cm^{-3}
ε_{xN}	5×10^{-5} m-rad
ε_{yN}	0.5×10^{-5} m-rad

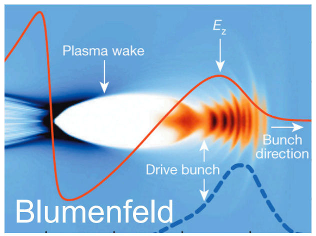
Plasma:

n_e	$0\text{-}2\times10^{14}$ cm^{-3}
L	1.4 m, laser ionized

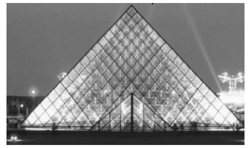


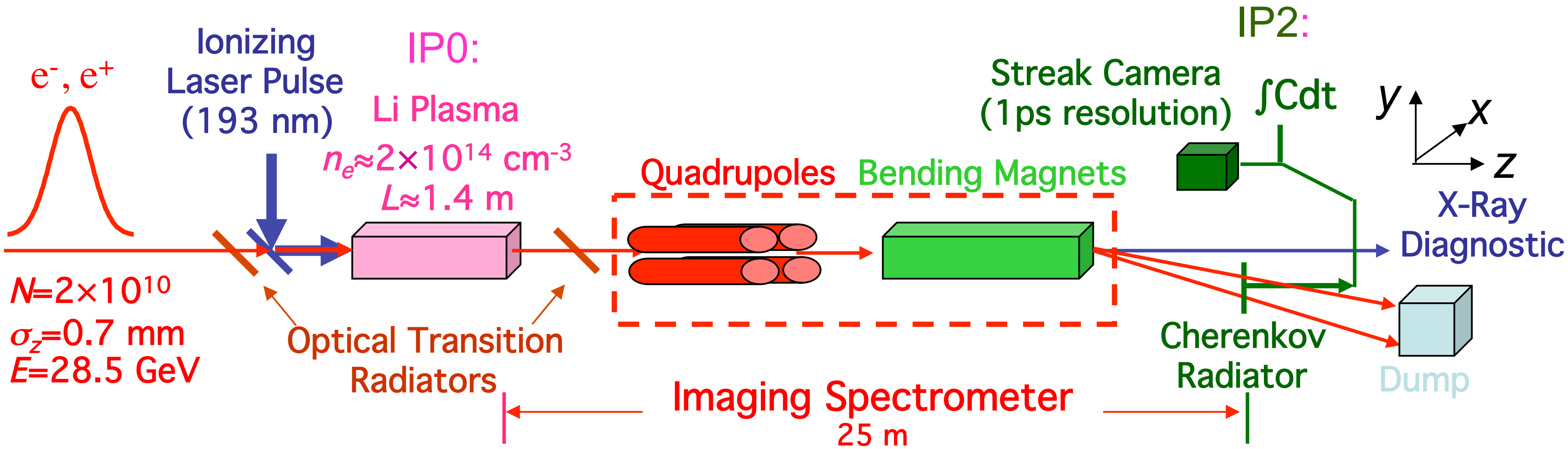
Experiment: $n_b > n_e$ => non linear, blow-out regime

- Uniform focusing field (r,z)
- Large decelerating/accelerating fields



EXPERIMENTAL SET UP

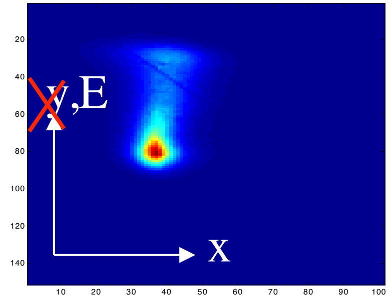




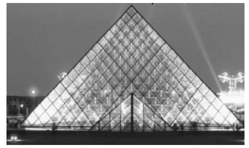
- Plasma:
  Laser-ionized lithium vapor

- CHERENKOV (aerogel)

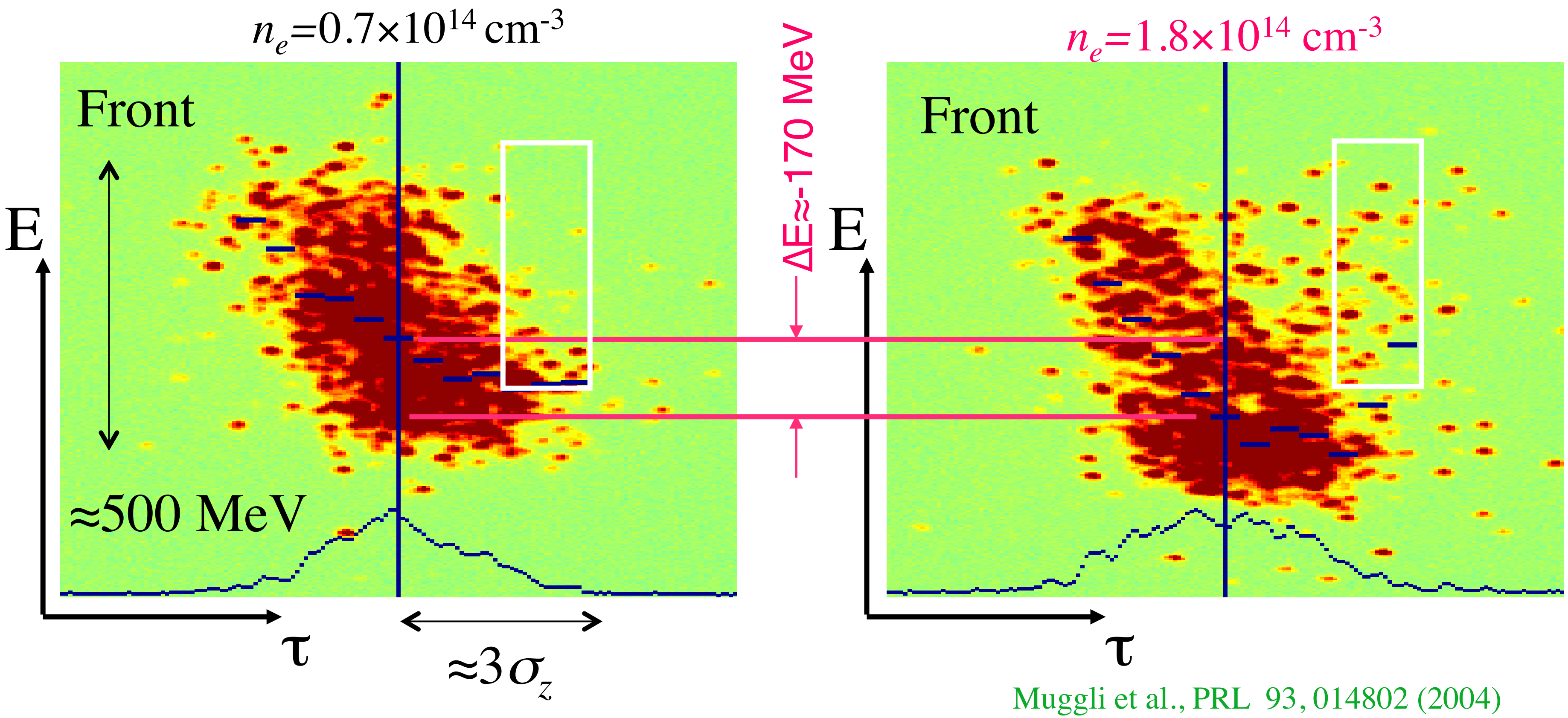
E-162:



- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV
- Time resolution: ≈1 ps



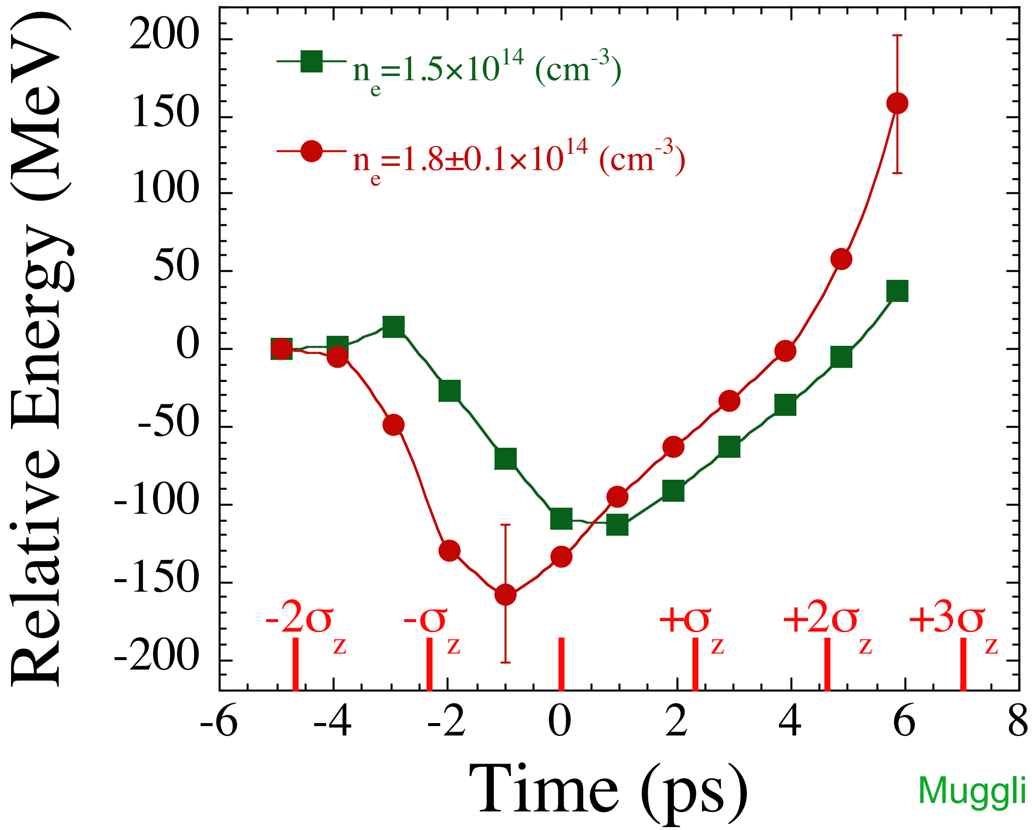
SLICE ANALYSIS RESULTS
SINGLE EVENT



Muggli et al., PRL 93, 014802 (2004)

- Select events by n_e, and by position on the streak camera slit
- Use low n_e events as “plasma off”

e^- ACCELERATION PRE-IONIZED, LONG BUNCH



σ_z≈730 µm
N=1.2×10^{10} e^+
$k_p\sigma_z$≈√2

Muggli et al., PRL 93, 014802 (2004)

- Energy gain smaller than, hidden by, incoming energy spread
- Time resolution needed, but shows the physics
- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

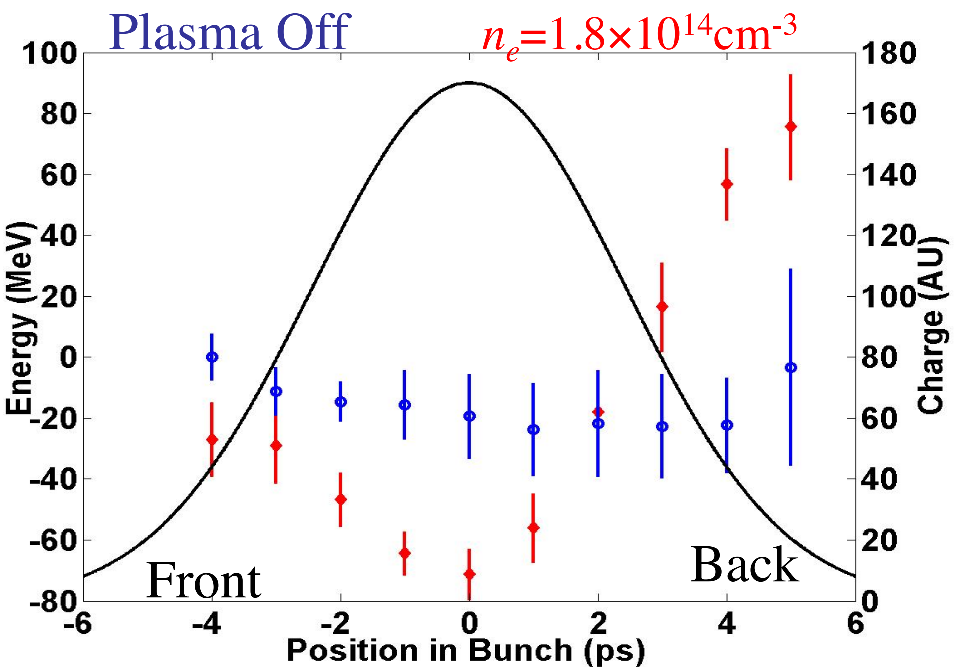
ENERGY LOSS/GAIN e^+

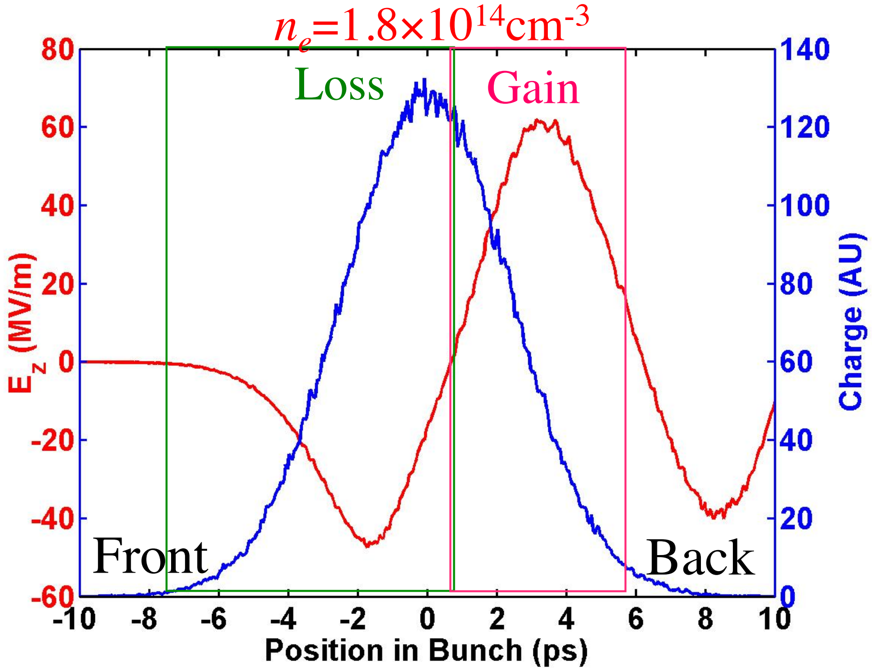
B.E Blue, UCLA

Experiment

$\sigma_z \approx 730$ µm
$N = 1.2 \times 10^{10}$ e^+

2-D Simulation





- Loss ≈ 70 MeV
- Gain ≈ 75 MeV

(over 1.4 m)

- Loss ≈ 45 MeV/m × 1.4 m=63 MeV
- Gain ≈ 60 MeV/m × 1.4 m=84 MeV

➡ Excellent agreement!

Blue et al., PRL 90, 214801, (2003)

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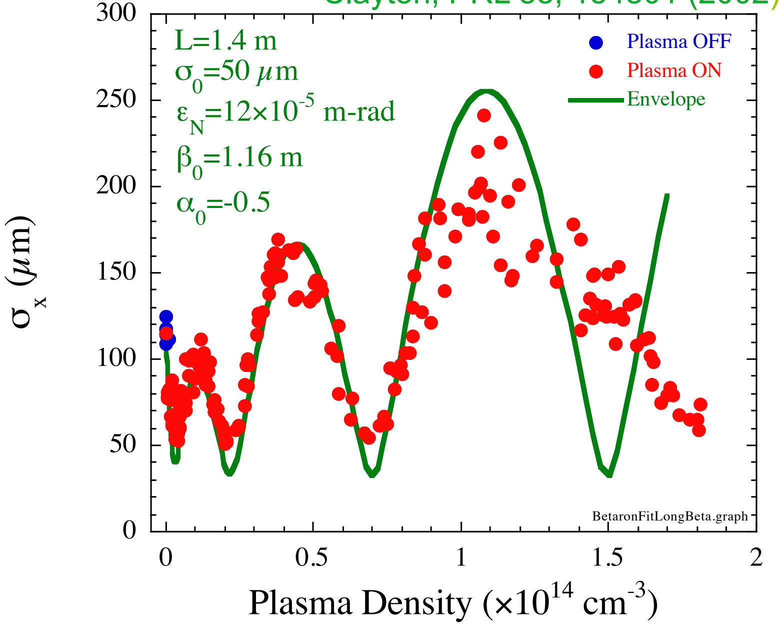
PROPAGATION OF e^-

OTR Images ≈1m downstream from plasma

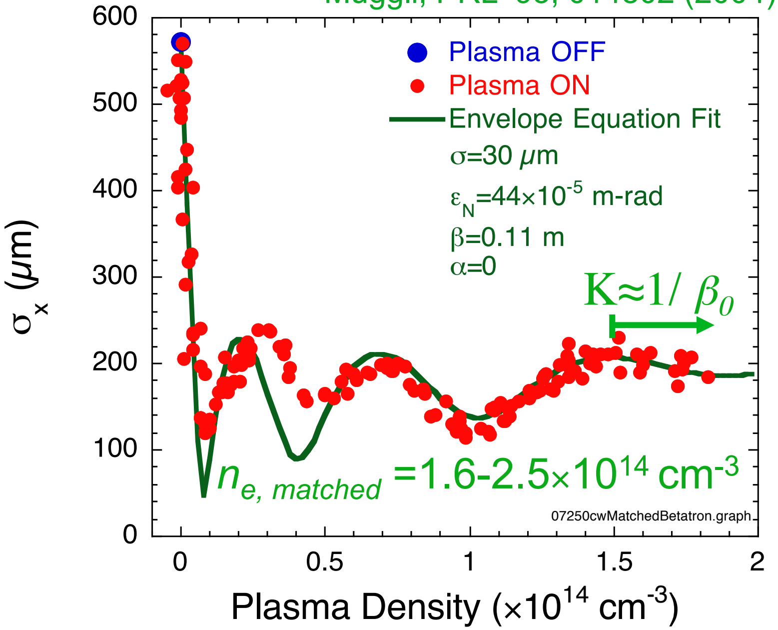
K≥1/β₀

Clayton, PRL 88, 154801 (2002)



K≤1/β₀

Muggli, PRL 93, 014802 (2004)



- Focusing of the beam well described by a simple model ($n_b>n_e$): Plasma = Ideal Thick Lens
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^{14}cm^{-3}
- Channeling of the beam over 1.4 m or >12β_0
  => Matched Propagation over long distance!

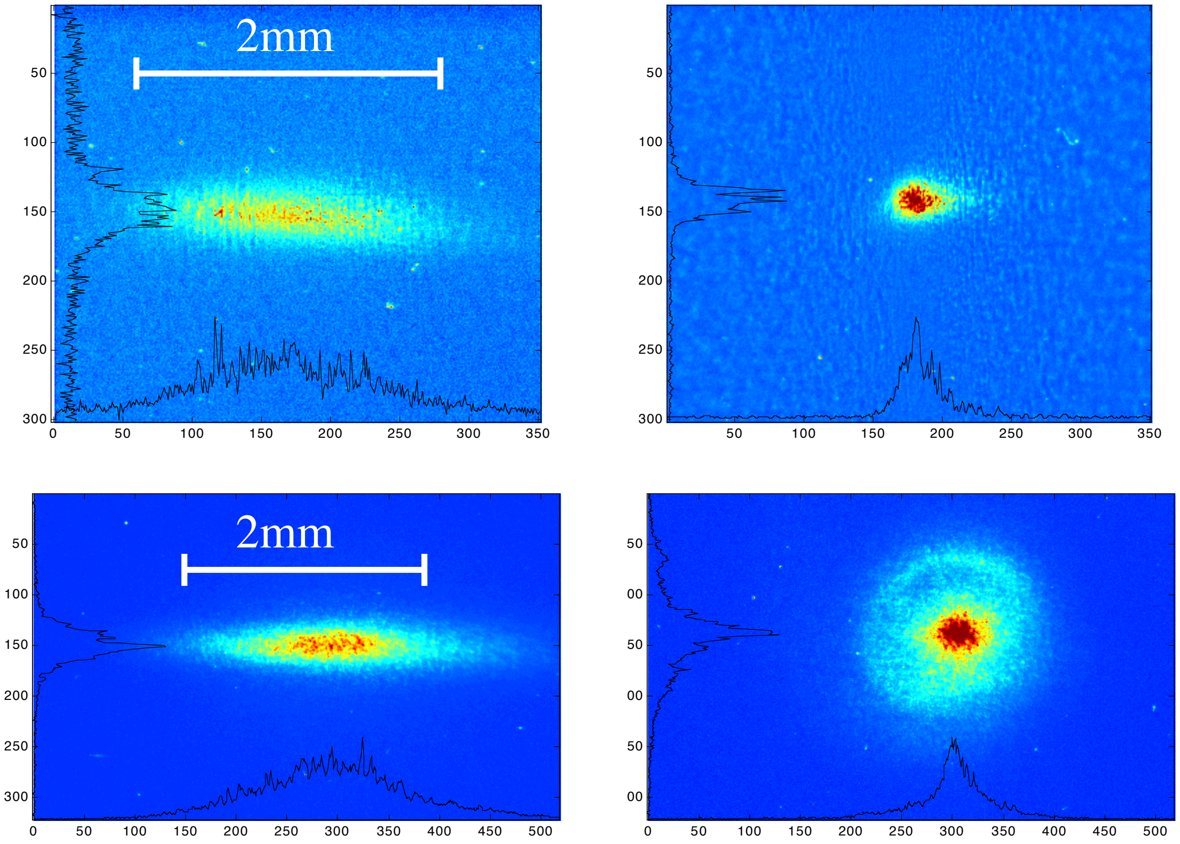
FOCUSING OF e^-/e^+

- OTR images ≈1m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)

n_e=0 | n_e≈10^{14} cm^{-3}

e^-

e^+

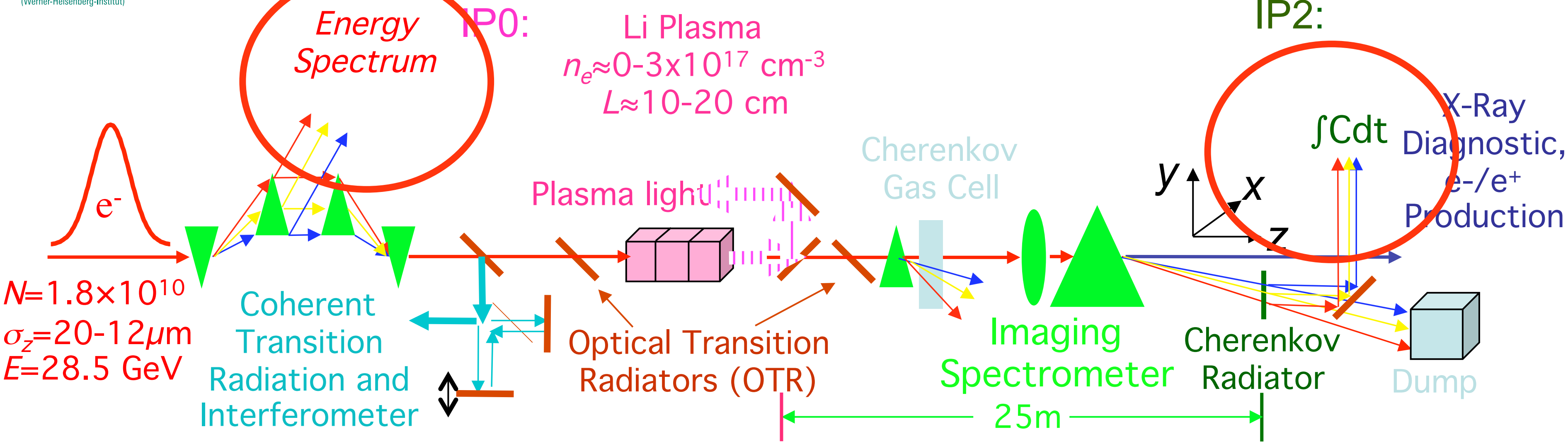


- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

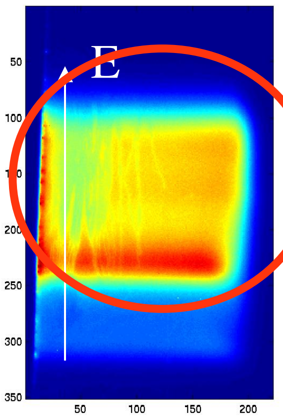
Muggli et al., Phys. Rev. Lett. 101, 055001 (2008).

➡ Qualitative differences

EXPERIMENTAL SET UP (GENERIC)



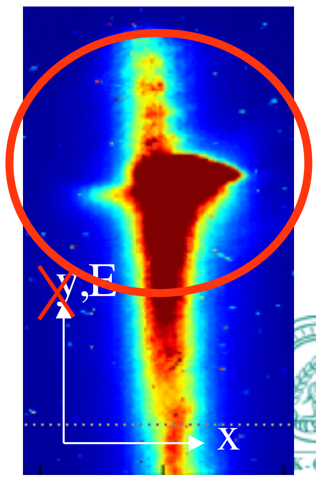
- X-ray Chicane



-Energy resolution ≈60 MeV

Compare events with similar incoming longitudinal characteristics

- Cherenkov (aerogel)
  - Spatial resolution ≈100 μm
  - Energy resolution ≈30 MeV

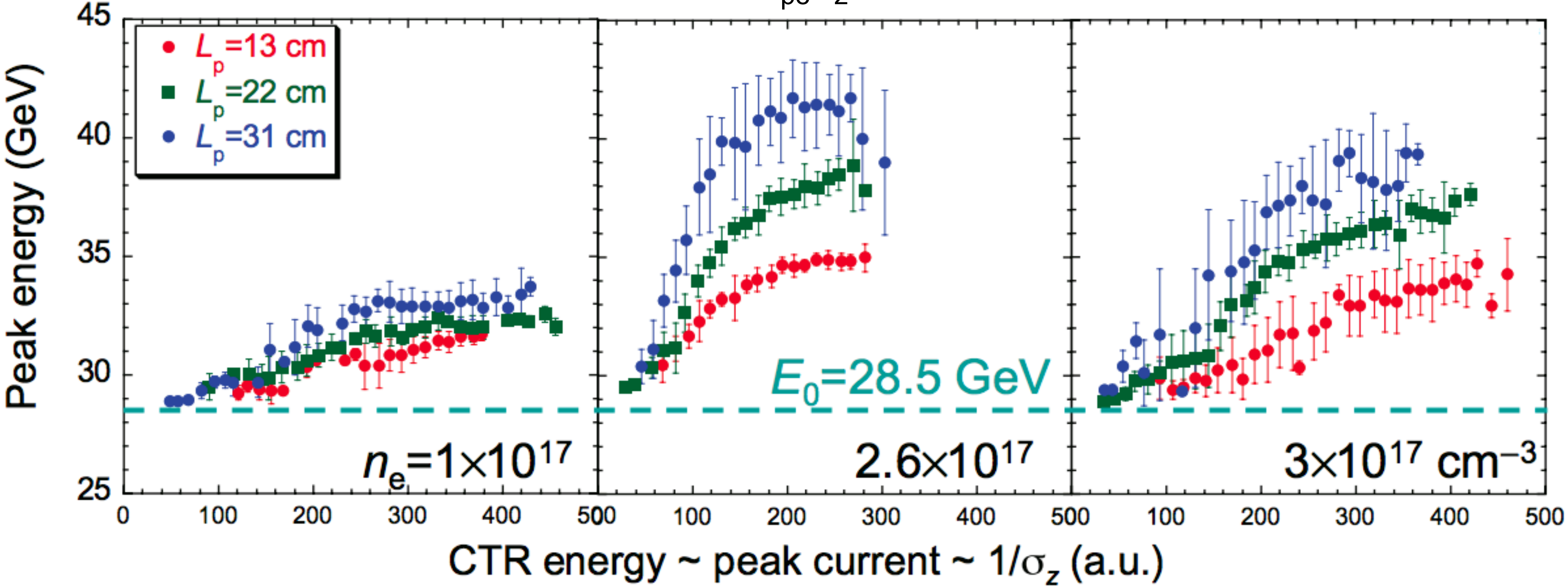


✧N=2x10^{10}:
✧σ_z=600 μm, n_e=2x10^{14} cm^{-3}, E_{acc}~100 MV/m, B_θ/r=6 kT/m
✧σ_z= 20 μm, n_e=2x10^{17} cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

$k_{pe}\sigma_z$~√2 <-> $\sigma_z/n_e^{1/2}$~cst

Energy Gain vs. Bunch Length

$k_{pe}\sigma_z \sim \sqrt{2}$



- Energy gain increases bunch peak current or σ_z^{-1}
- Energy gain reaches 13? GeV with L_p=31 cm!

Muggli et al., New Journal of Physics 12 (2010) 045022

ENERGY GAIN VS. PLASMA LENGTH

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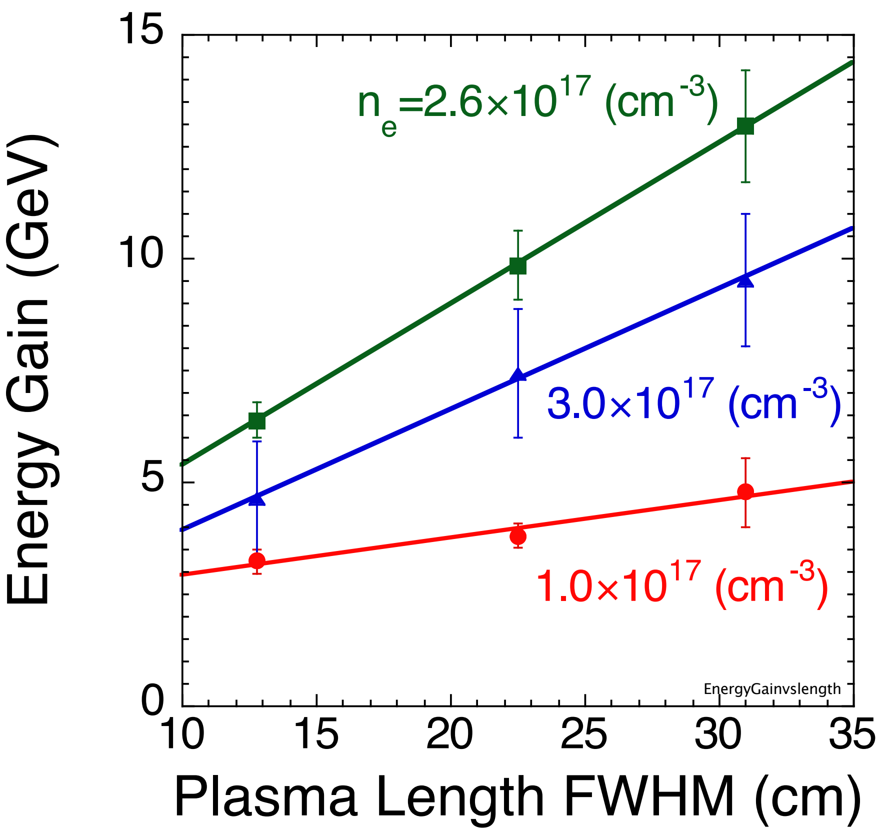
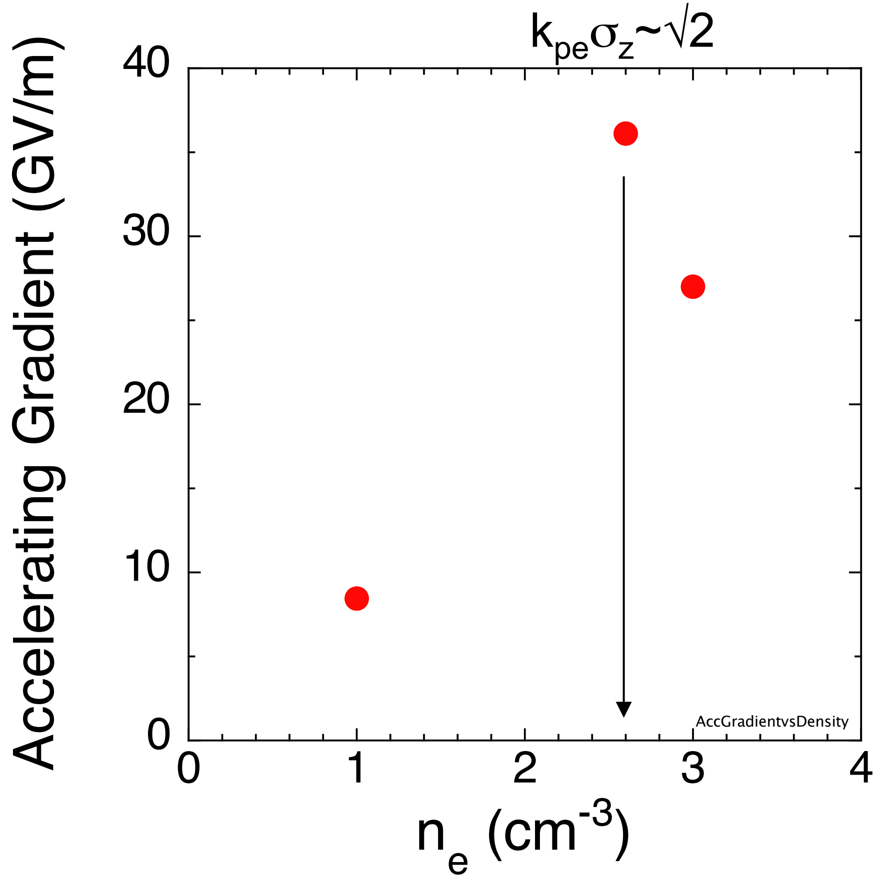


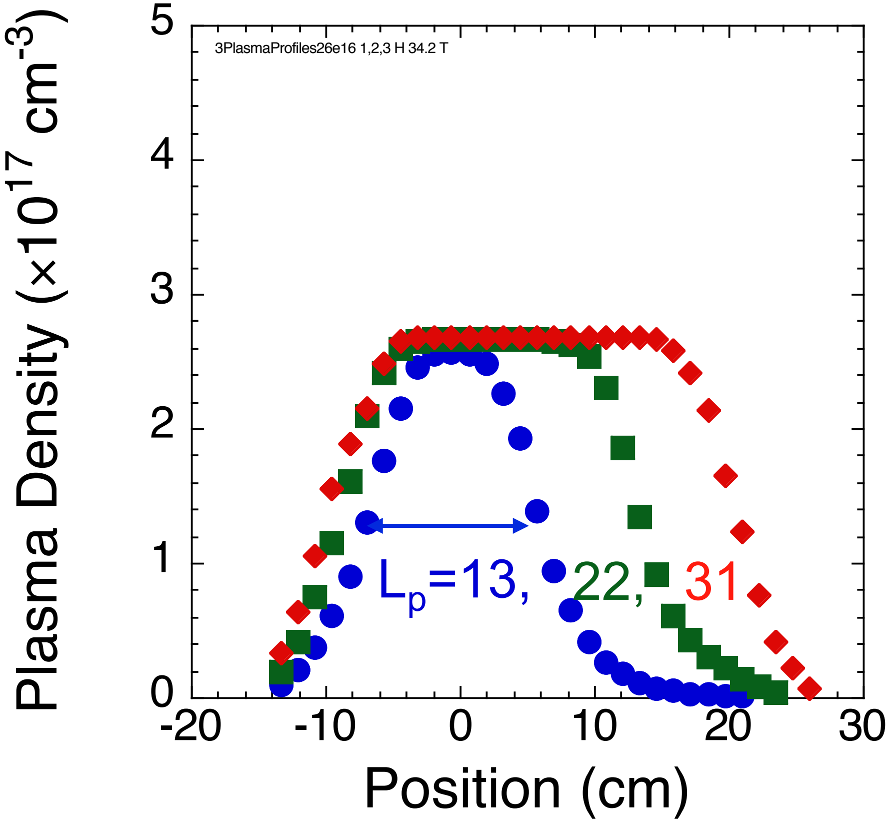


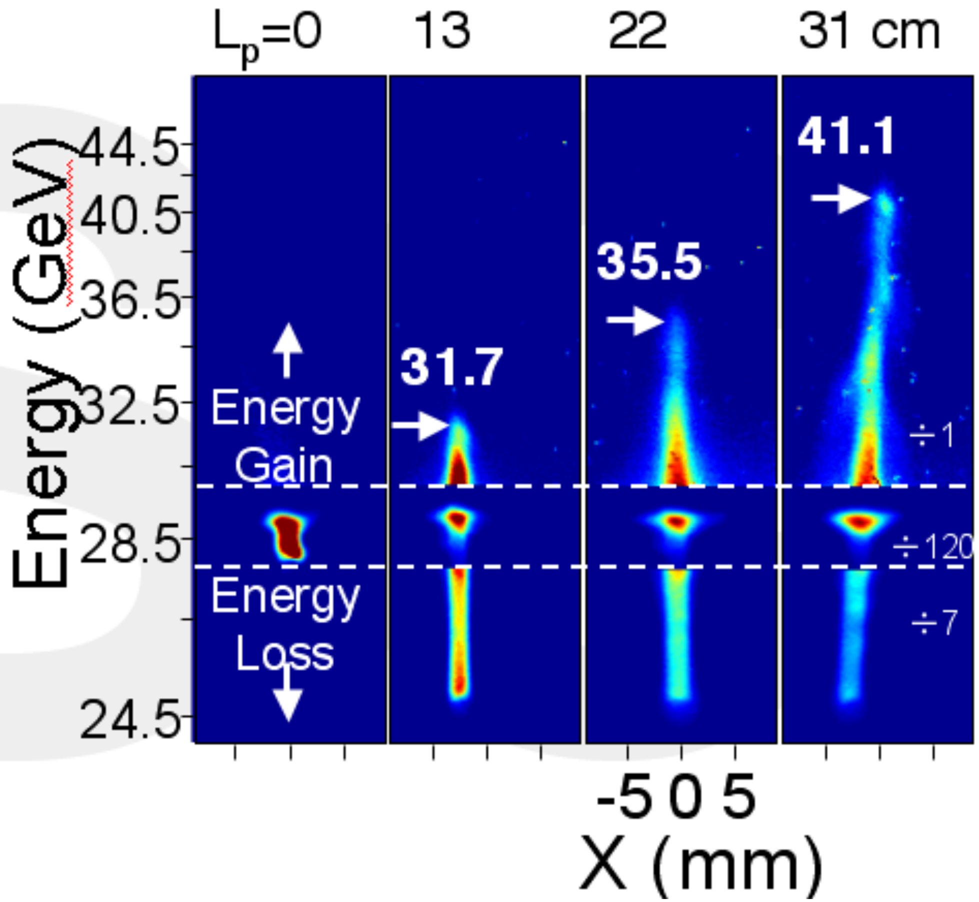
- Largest gain with $n_e=2.6\times10^{17}$cm^{-3} (• L_p, for $\sigma_z\approx20$ µm)
- Accelerating gradient of 36 GV/m over L_p=31 cm (unloaded: 7% accelerated charge)

Muggli et al., New Journal of Physics 12 (2010) 045022

ENERGY GAIN VS. PLASMA LENGTH

E_0=28.5 GeV, n_e=2.7×10^{17}cm^{-3}





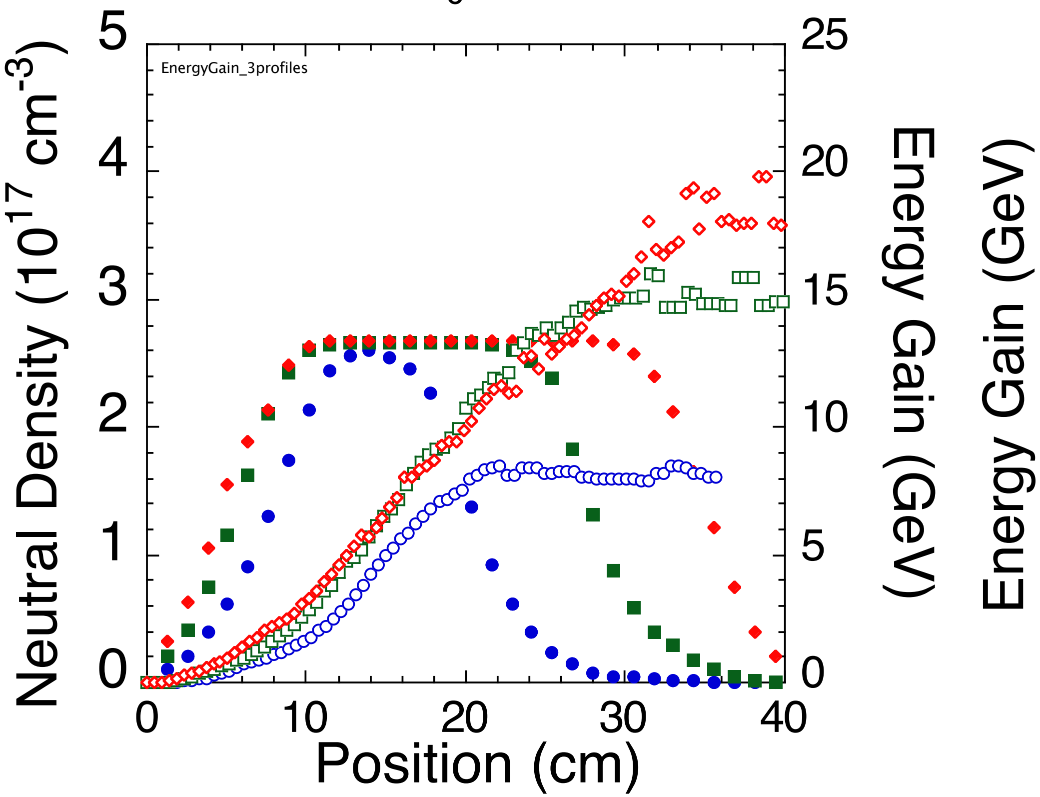
- Energy gain increases with plasma length (L_p)
- Energy gain reaches 13.6 GeV with L_p=31 cm!

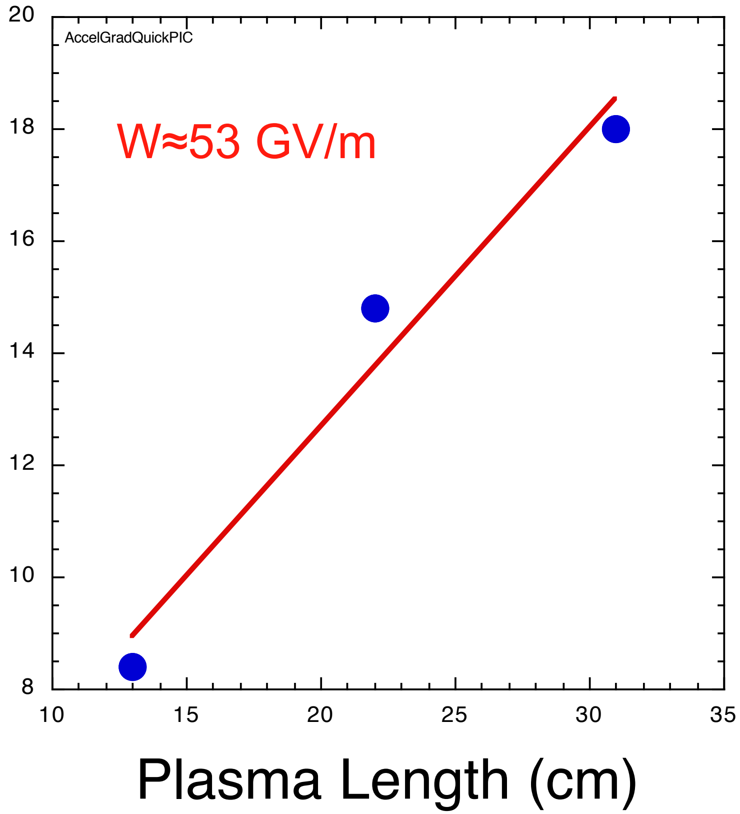
Muggli et al., New Journal of Physics 12 (2010) 045022

ENERGY GAIN VS. PLASMA LENGTH

3-D Simulations using QuickPIC

E_0=28.5 GeV, N=1.8×10^{10} e$^-$, n_e=2.7×10^{17}cm^{-3}





- Energy gain increases with plasma length (L_p)
- Gradient ≈53 GV/m

Muggli et al., New Journal of Physics 12 (2010) 045022

e^- ACCELERATION

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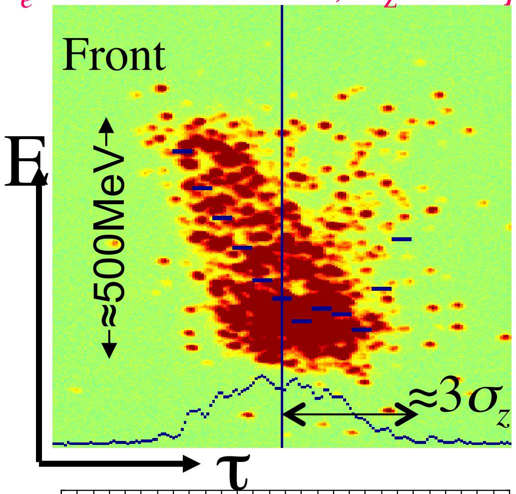
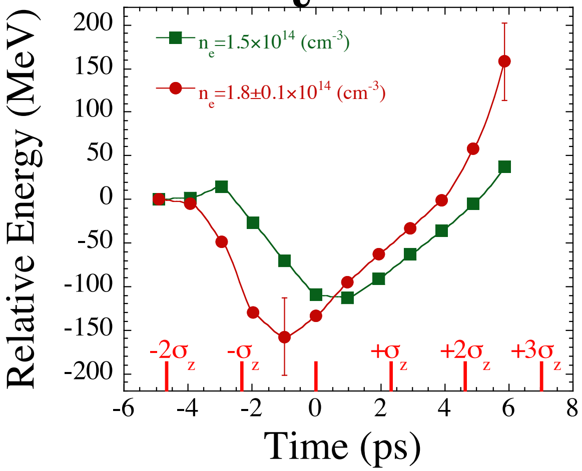
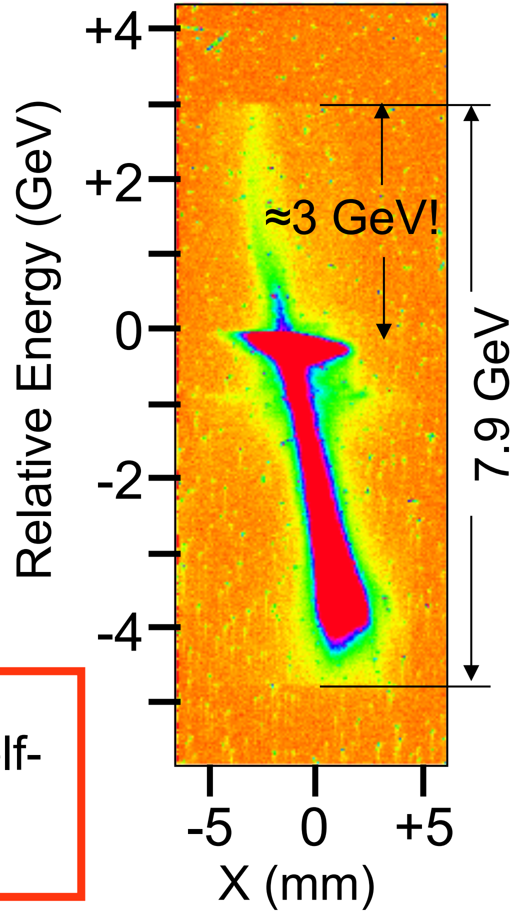
n_e=1.8×10^{14} cm^{-3}, σ_z≈700 μm

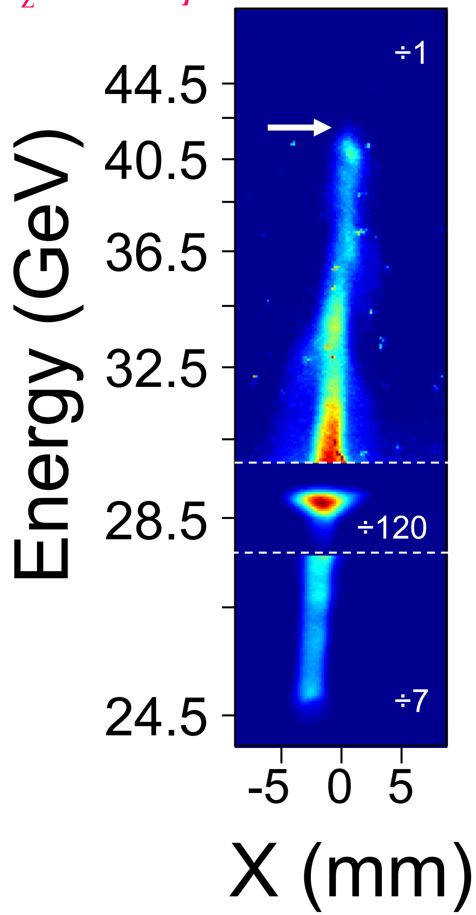




Pre- | Self-
Ionized

n_e=2.6×10^{17} cm^{-3}, σ_z≈20-30 μm





- Gain≈280 MeV, L_p=1.4m
  Gradient≈200 MV/m
  Muggli, PRL 93, 014802 (2004)

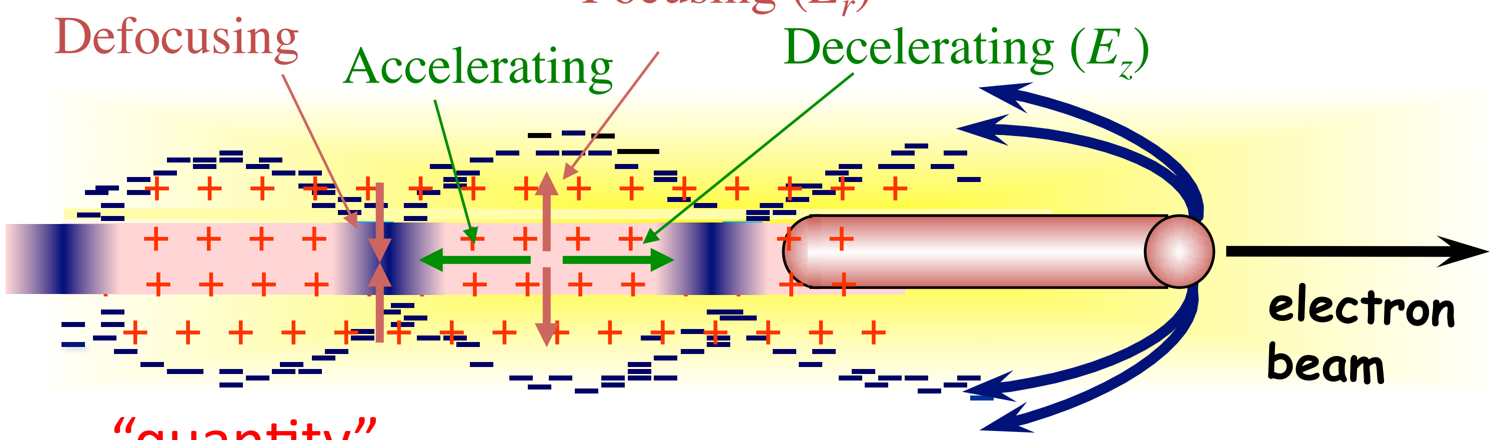
- Gain≈4 GeV, L_p=10cm
  Gradient≈40 GV/m
  Hogan, PRL 95, 054802 (2005)

- Gain≈14 GeV, L_p=32cm
  Muggli, New J. Phys. 12, 045022 (2010)

- Scaling with bunch length and plasma length

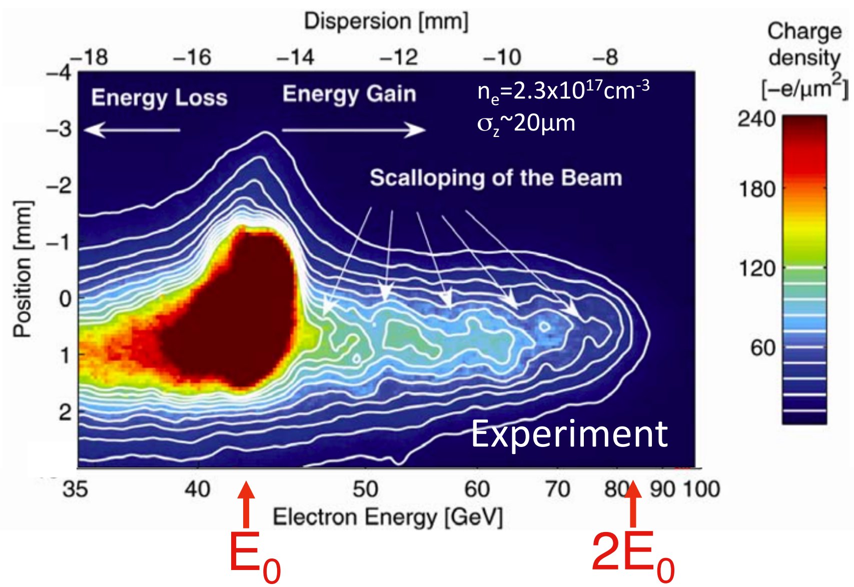
MAX-PLANCK-GESELLSCHAFT

PWFA (e^-)



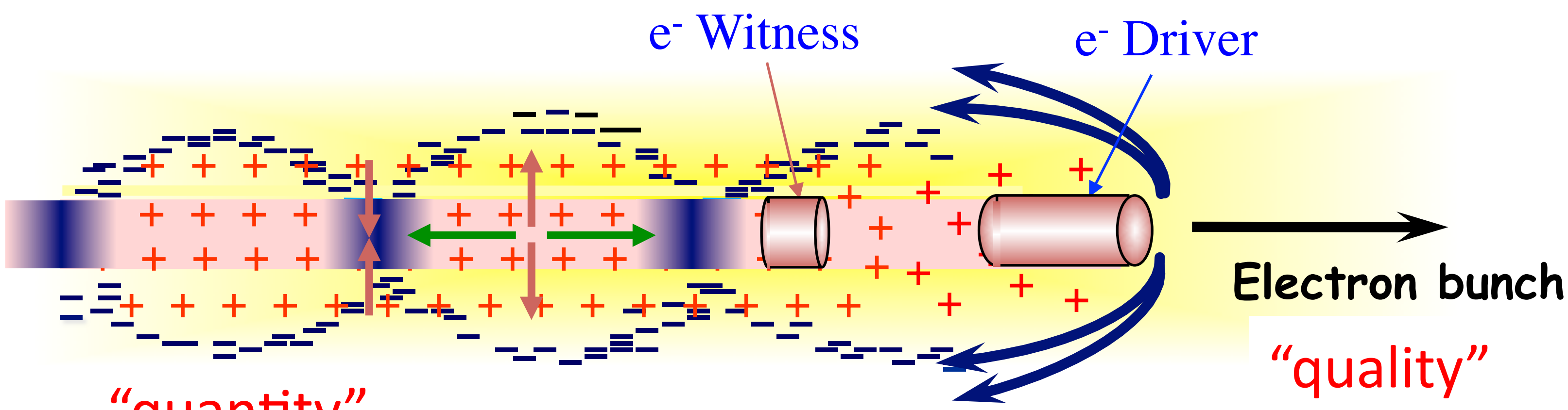
"quantity"

Blumenfeld, Nature 445, 741 (2007)



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

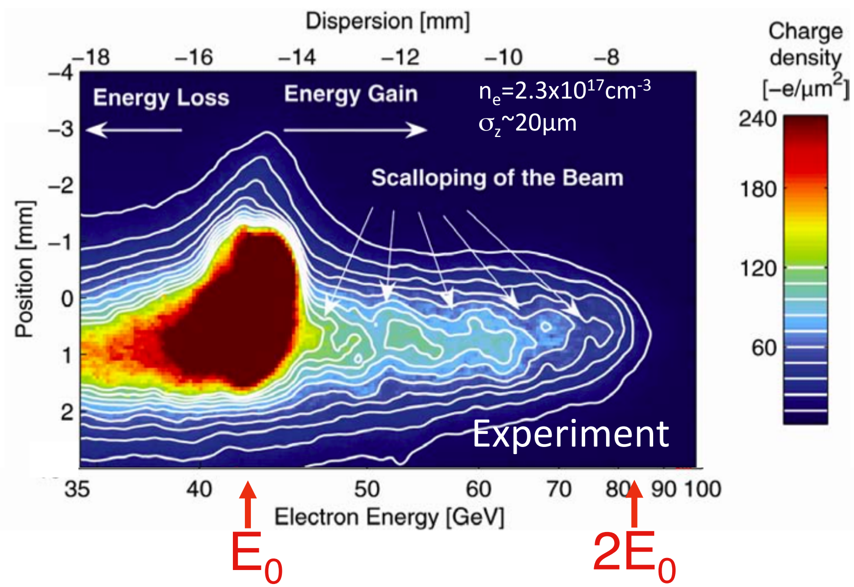
PWFA (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)

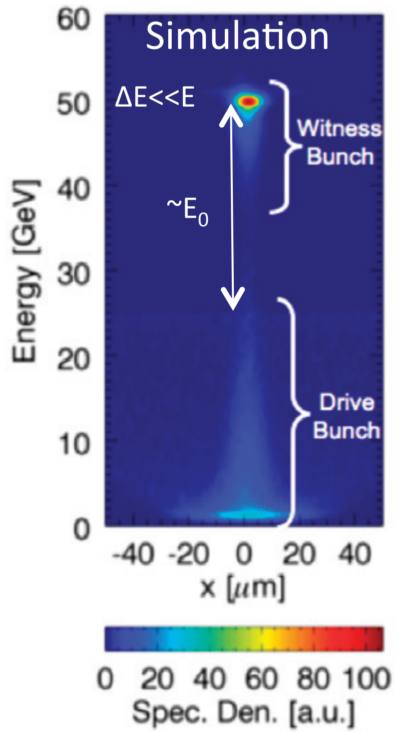


42 => 84GeV in 85cm! 50GeV/m

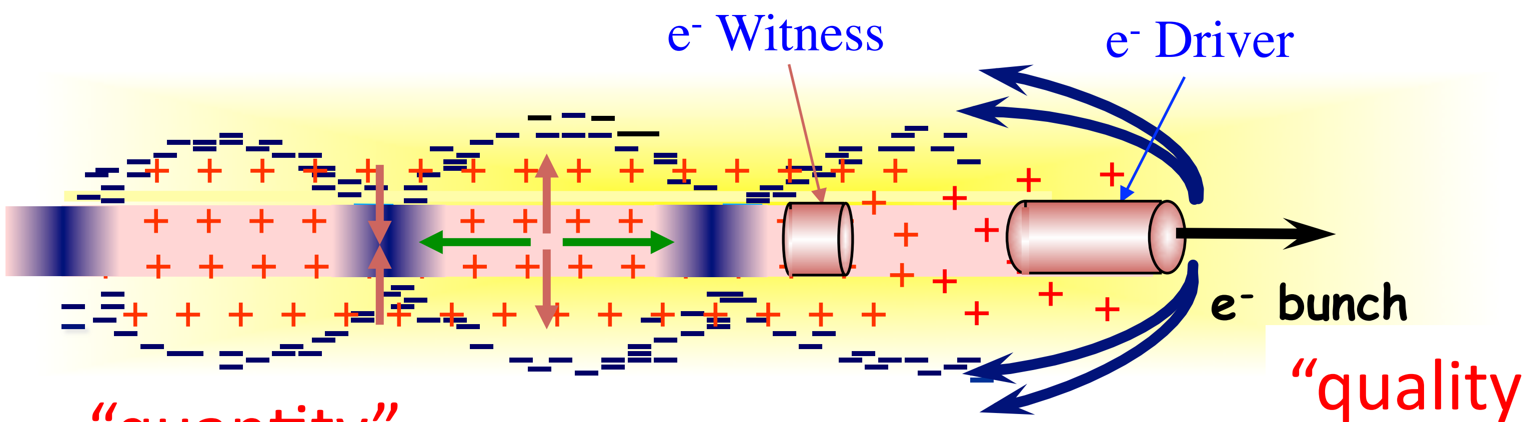
SLAC FACET

E200

Hogan, NJP 12, 055030 (2010)



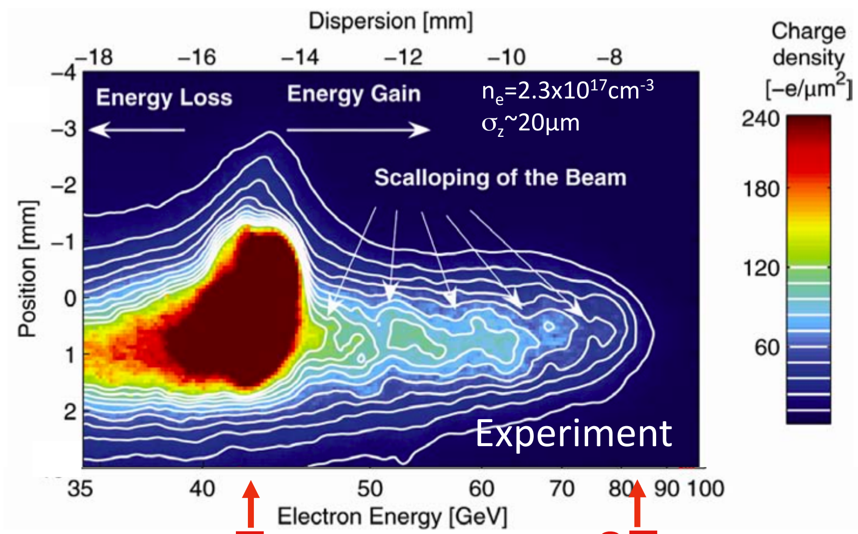
PLASMA WAKEFIELD ACCELERATOR (e^-)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)



E_0 $2E_0$

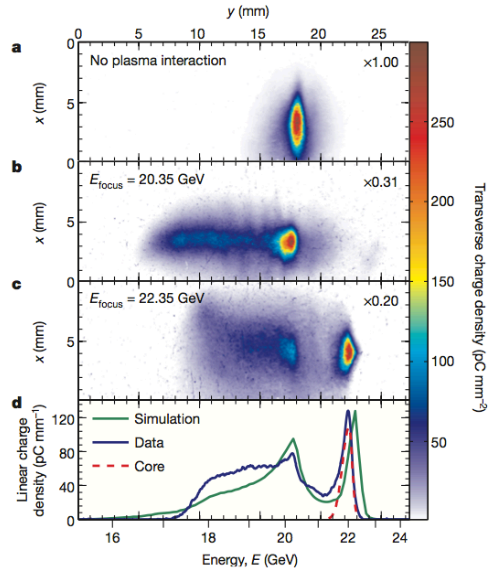
42 => 84GeV in 85cm! 50GeV/m

SLAC

FACET

E200

Litos, Nature 515(6),92 (2014)



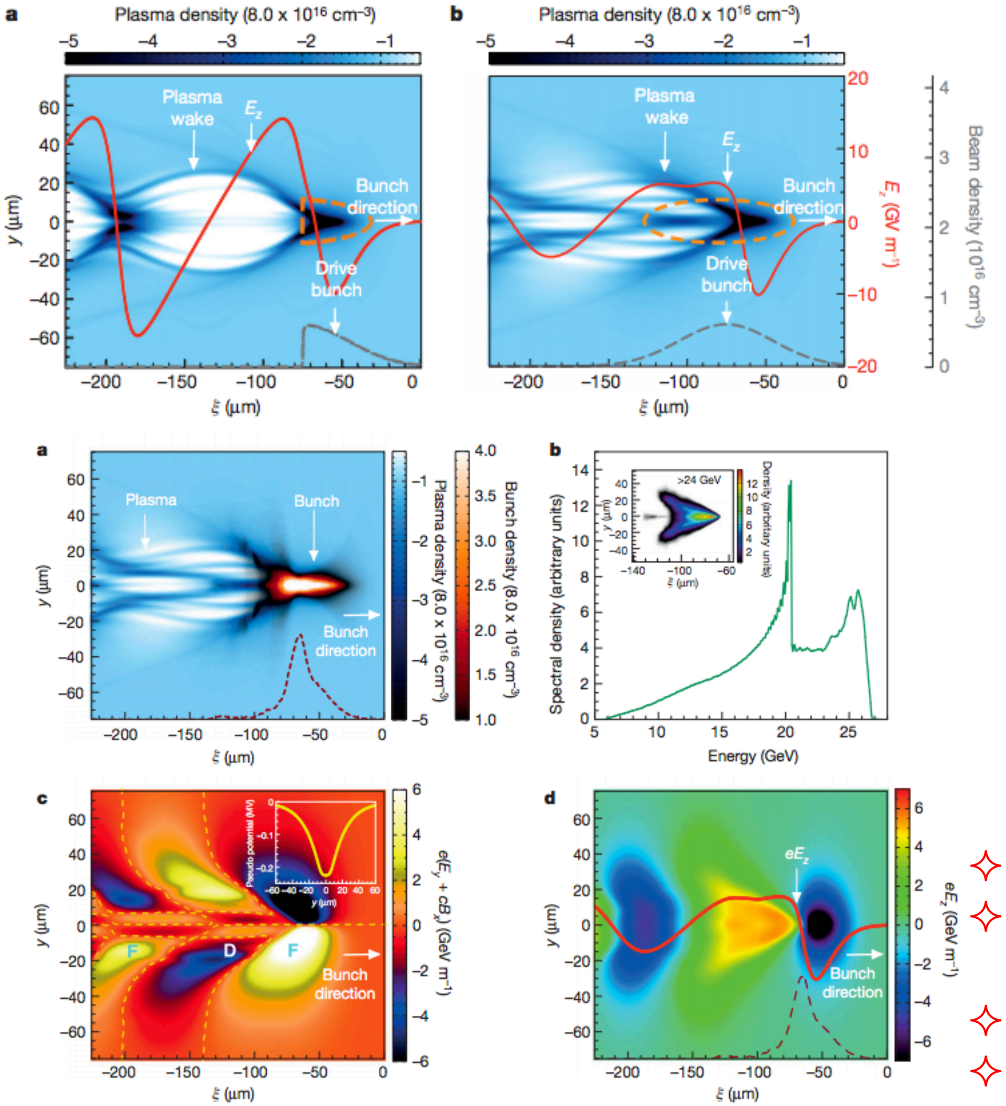
$\Delta E/E$~%

η~30%

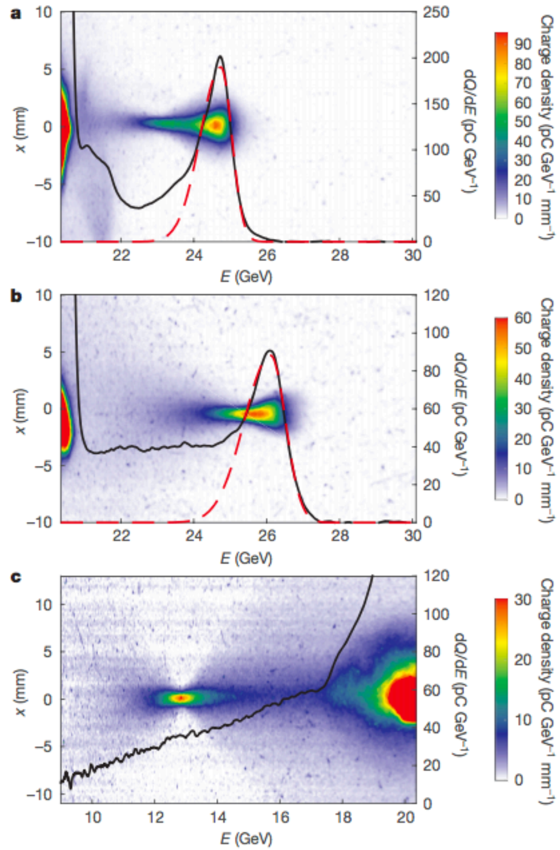
PLASMA WAKEFIELD ACCELERATOR (e^+)

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

Simulations



Experiment



- n_e=8x10^{16}cm^{-3}, L_p=1.35m
- N=1.4x10^{10}e$^+$, σ_r=70μm, σ_z=30-50μm, E_0=20.35GeV, n_b=(0.2-1)x10^{16}cm^{-3},
- Peak in energy spectrum
- Plasma e^- arrange themselves for focusing and self-loading

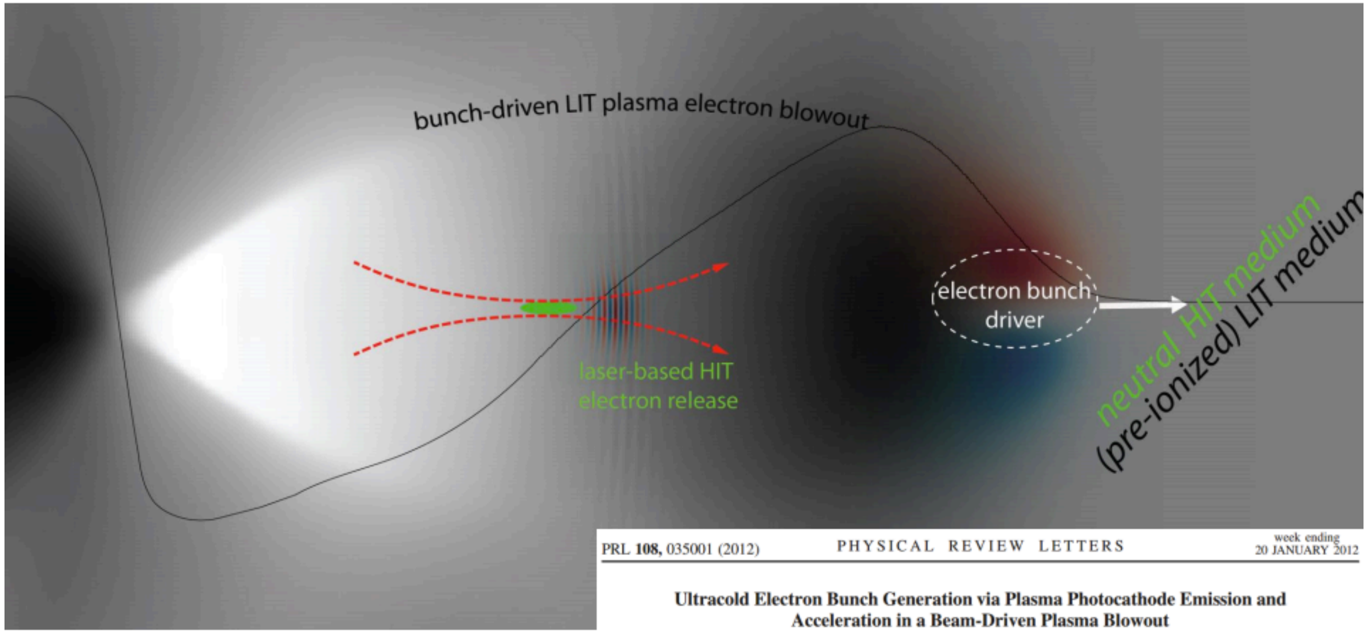
Corde et al., Nature 524, 442 (2015)

MAX-PLANCK-GESELLSCHAFT

LOW EMiTTANCE iNJECTOR

Underdense Photocathode PWFA

Trojan Horse Injection



PRL 108, 035001 (2012) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2012

Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout

B. Hidding,[1,2] G. Pretzler,[2] J. B. Rosenzweig,[1] T. Königstein,[2] D. Schiller,[1] and D. L. Bruhwiler[3]
[1]*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA*
[2]*Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*
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(Received 30 March 2011; published 17 January 2012)

What's needed:

- **LIT/HIT medium**
- **reliable electron bunch driver to set up LIT blowout**
- **synchronized, low-intensity laser pulse to release HIT electrons within blowout**

✧e^- born in large E_z field (GV/m)

✧Born from low laser intensity (~10^{14}Wcm^{-2})

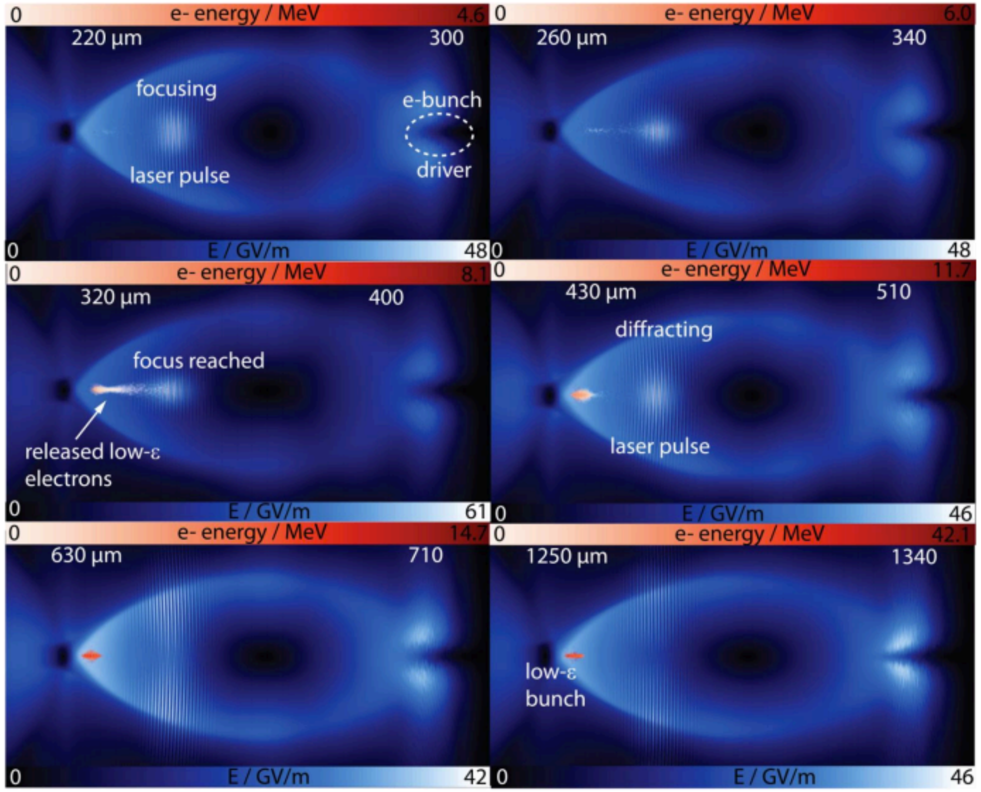
✧Ultra-low (nm-rad) emittance (at low charge?)

✧Potential game changer: no need for damping ring …

LOW EMiTTANCE iNJECTOR

Laser pulse intensity is crucial

Focus laser pulse intensity has to be just above the ionization threshold of the HIT medium (here, helium).

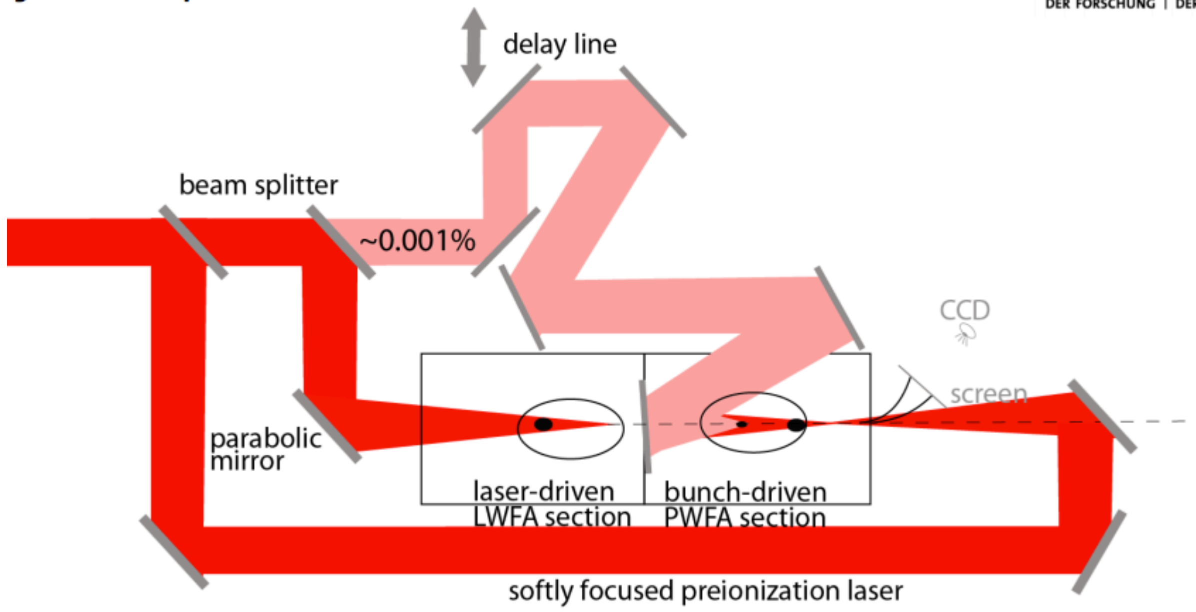


In contrast to LWFA schemes (~10^{18}-10^{19} W/cm²), here the laser pulse intensity is of the order of ~10^{14}-10^{15} W/cm², only.
→ Transverse momentum of bunch electrons is very low → direct consequences for divergence & emittance!

- ✧ e^- born in large E_z field (10's GV/m)
- ✧ Ultra-low (nm-rad) emittance (at low charge?)
- ✧ Correlation charge/emittance?

LOW EMITTANCE INJECTOR

Beam brightness transformer and stabilizer for Laser-plasma-accelerators



- Bunch quality transformer: energy, energy spread (see "Monoenergetic energy doubling", PRL 140195002, 2010), emittance
- e.g., LPA: $\Delta E_1 = 20\,\%$, $\varepsilon_{n1} \sim 10^{-6}$ m rad → TROJAN: $\Delta E_2 = 0.1\,\%$, $\varepsilon_{n2} \sim 10^{-8}$ m rad

✧ e^- born in large E_z field (GV/m)

✧ Ultra-low (nm-rad) emittance (at low charge?)

PLASMA WAKEFIELD ACCELERATOR (PWFA)

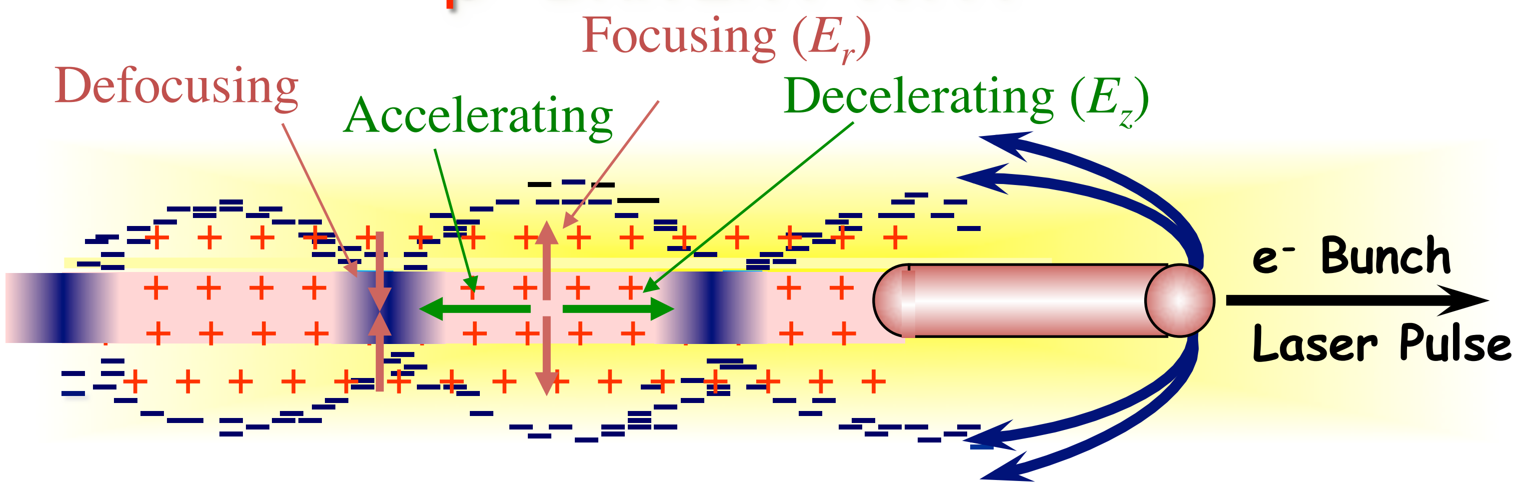
A few general characteristics:

- Relativistic bunch γ_0>1
- Short bunch: <1mm < λ_{pe}
- Dense bunch n_b>n_e>10^{16}cm^{-3}
- Tight focus: <λ_{pe}
- Does not provide ionization, in general
- Negatively charged bunches …

- $v_\phi=v_{bunch}=(1-1/\gamma_0^2)^{1/2}c\sim c$: no dephasing …
- Plasma provides focusing, no external guiding necessary(?)

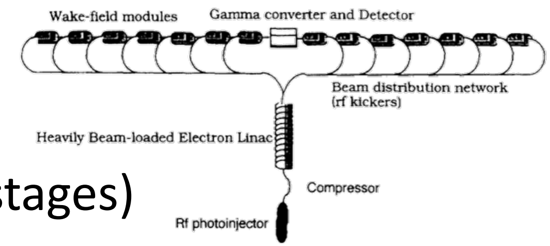
  } Long accelerator (m)
- Large β-function
- Large energy loss possible with little drive bunch evolution (e.g.: e^-, γ_0=40'000->1'000)

p⁺-DRiVEN PWFA



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

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

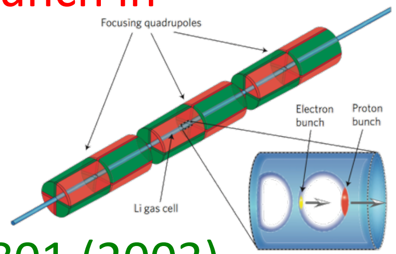


✧SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J

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

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

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

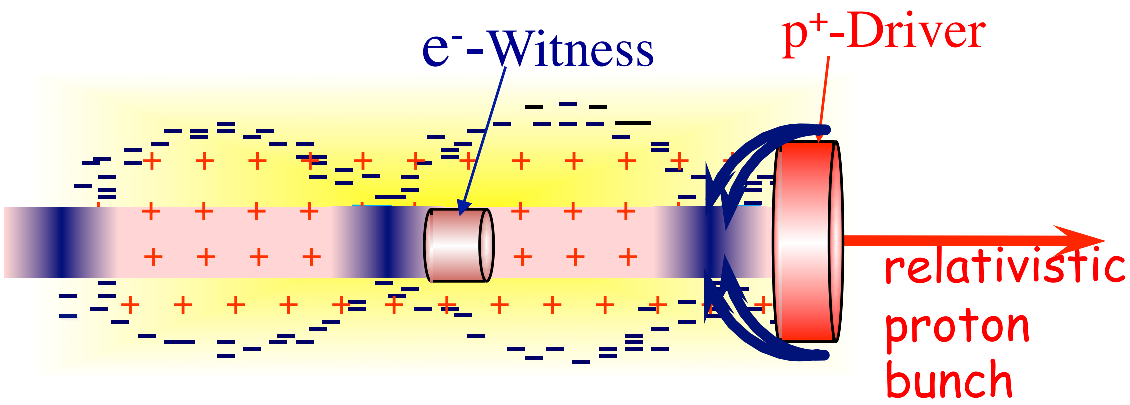


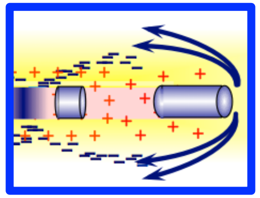
Caldwell, Nat. Phys. 5, 363, (2009)

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

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

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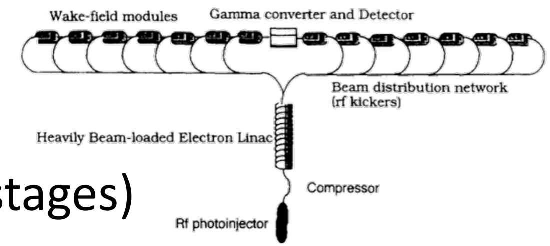
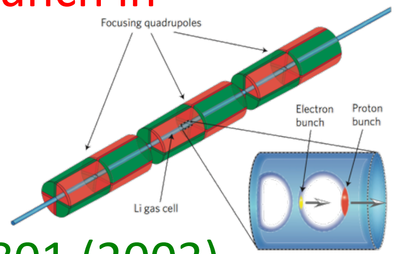
J. Rosenzweig et al. / Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543

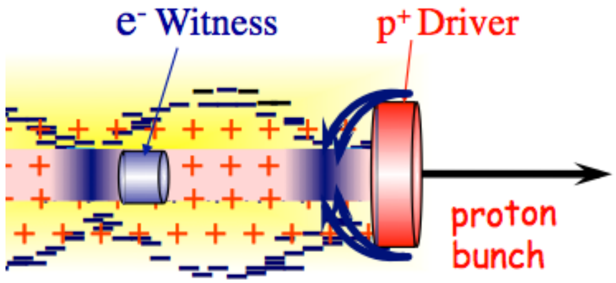




Caldwell, Nat. Phys. 5, 363, (2009)

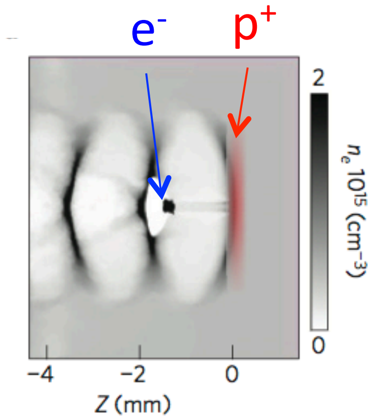
p^+-DRiVEN PWFA

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

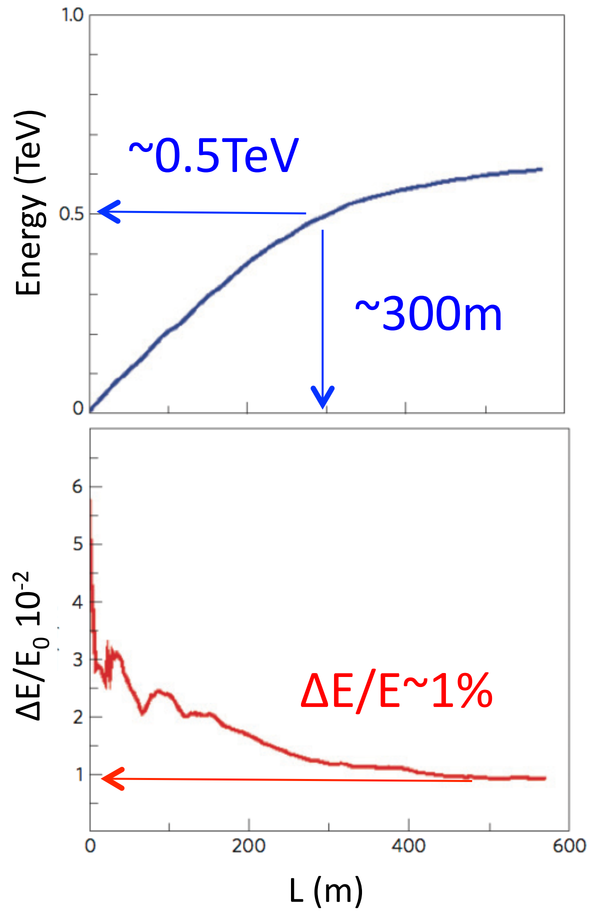


e^-:	p^+:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
N=10^{10}	N=10^{11}
W_0=16J	W_0=16kJ
W_f=1kJ	

Single Stage



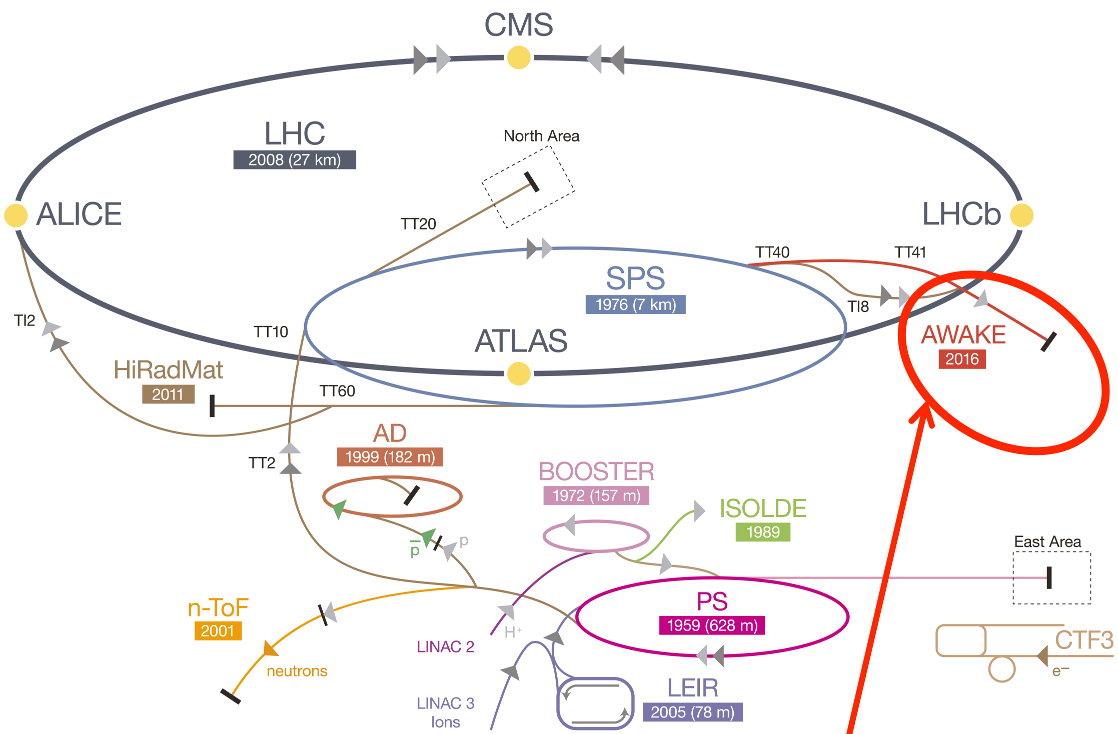
Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_P/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons 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 (average!!!)
- ✧Operate at lower n_e ($6\times10^{14}cm^{-3}$), larger $(\lambda_{pe})^3$, easier life …

PROTON BEAMS @ CERN

CERN's Accelerator Complex



Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	400	400
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (µm)	400	200	200
β^* (m)	1.6	5	5

AWAKE experimental area

σ_z=12cm!!

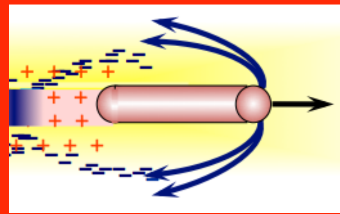
✧SPS beam: high energy, small σ_r^*, long β^*

pROTON bEAMS @ CERN

CERN's Accelerator Complex

Parameter	PS	SPS	SPS Opt

Scaling



$\lambda_{pe}=2\pi c/\omega_{pe}=2\pi c/(n_e e^2/\varepsilon_0 m_e)^{1/2}$

$\sigma_z=12cm\sim\lambda_{pe} \rightarrow n_e\sim 8x10^{10}cm^{-3}$

$\rightarrow E_{WB}=mc\omega_{pe}/e=2\pi mc^2/e\lambda_{pe} \sim 27MV/m$

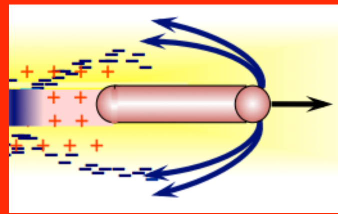
pROTON bEAMS @ CERN

CERN's Accelerator Complex

CMS

Parameter	PS	SPS	SPS Opt

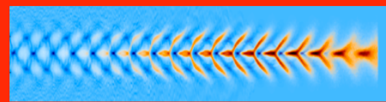
Scaling



$\lambda_{pe}=2\pi c/\omega_{pe}=2\pi c/(n_e e^2/\varepsilon_0 m_e)^{1/2}$

$\sigma_z=12cm\sim\lambda_{pe}$ $\rightarrow$ $n_e\sim8x10^{10}cm^{-3}$

$\rightarrow E_{WB}=mc\omega_{pe}/e=2\pi mc^2/e\lambda_{pe}$ ~27MV/m



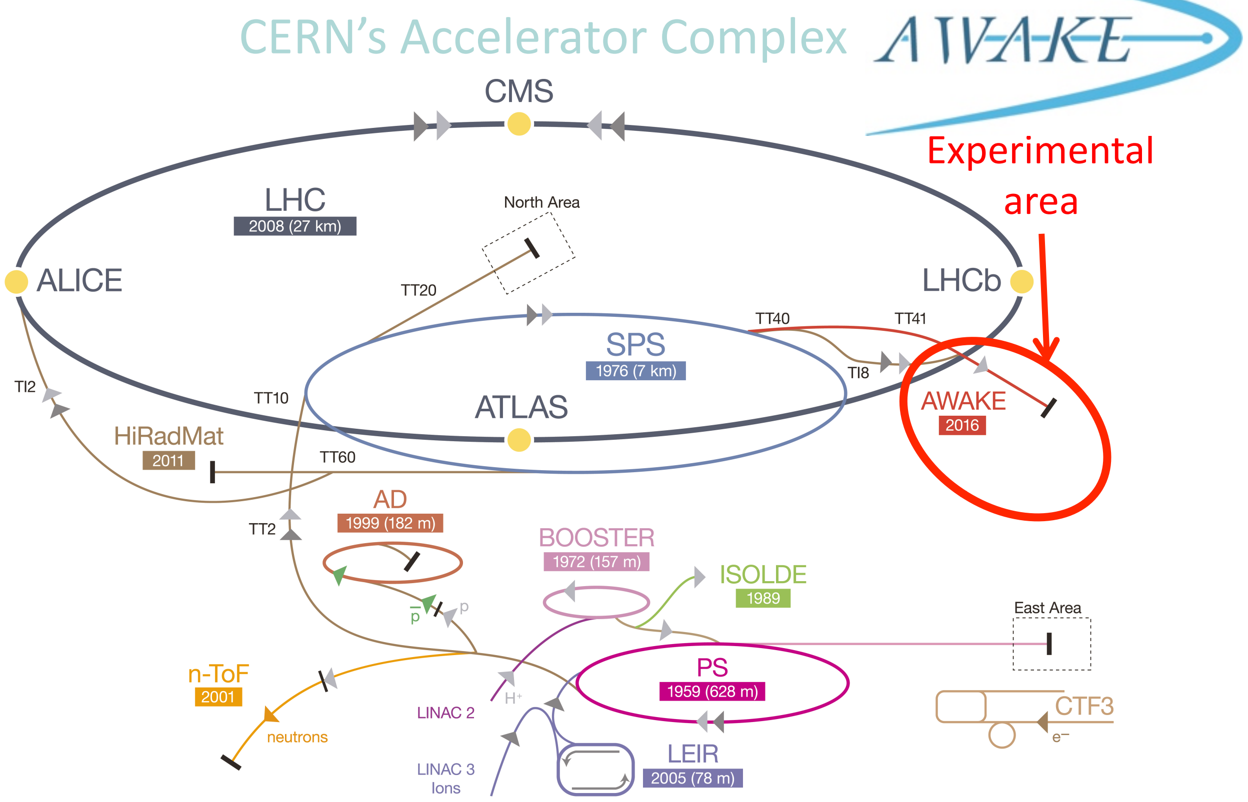
$\rightarrow$Use self-modulation instability (SMI)

$\rightarrow\sigma_z$~12cm train with period ~1.2mm

$\rightarrow n_e\sim7x10^{14}cm^{-3}$, $(k_{pe}\sigma_r\sim1)$, $L_p=10m$

$\rightarrow E_{WB}\sim1GV/m$, $f_{pe}\sim237GHz$

p^+-DRiVEN PWFA



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

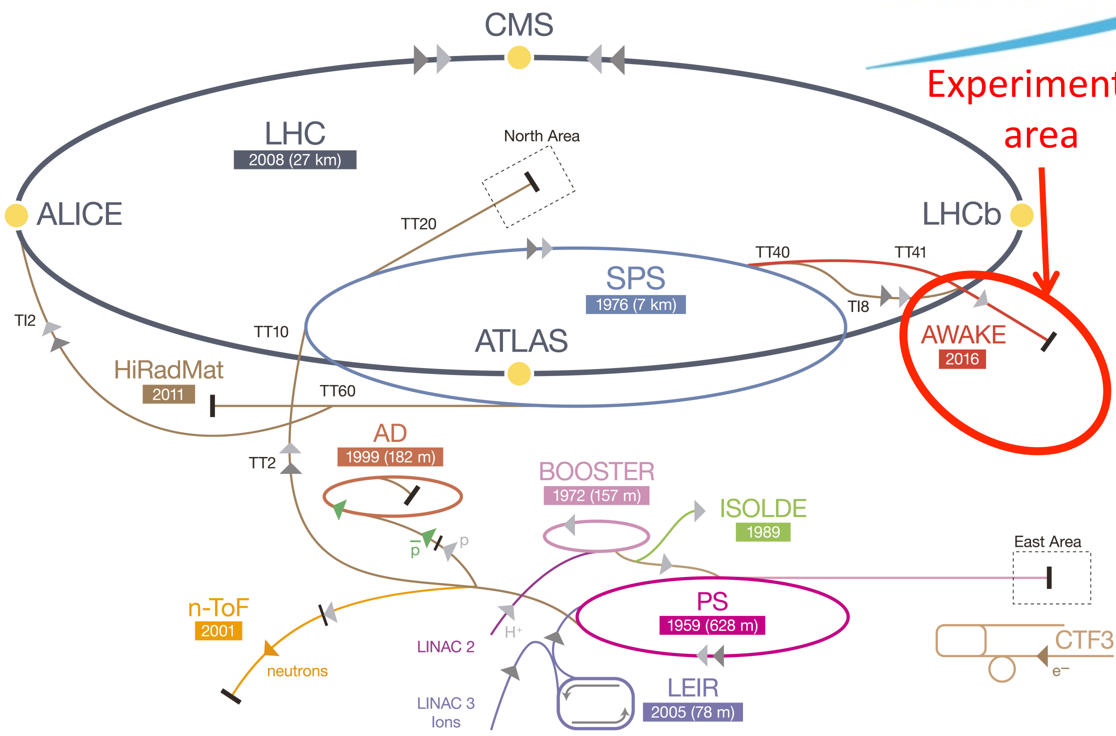
✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p^+ driven PWFA

✧Setup a comprehensive PWFA program at CERN

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

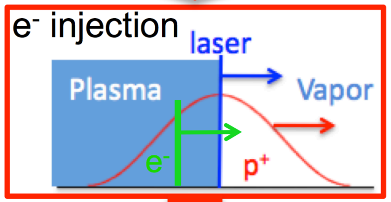
p^+-DRiVEN PWFA

CERN's Accelerator Complex

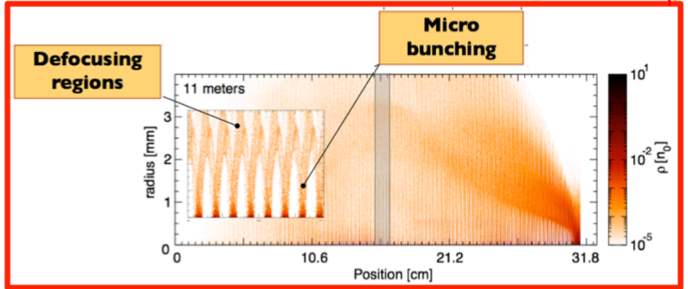


Experimental area

3×10^{11}, 400GeV SPS p^+
10m plasma, n_e=1-10x10^{14}cm^{-3}

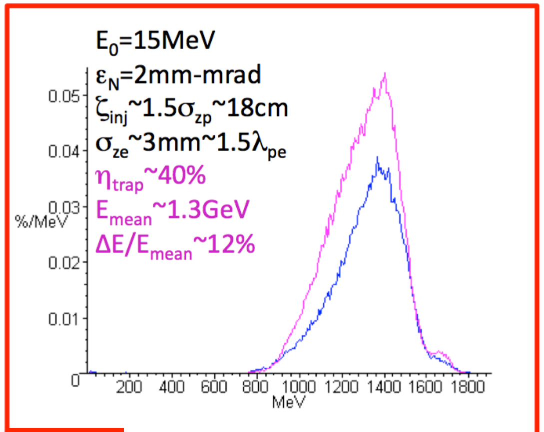


p^+ bunch self-modulation: $\sigma_z \sim 100\lambda_{pe}$



2016-17

GeV energy gain by externally injected e^-



2018

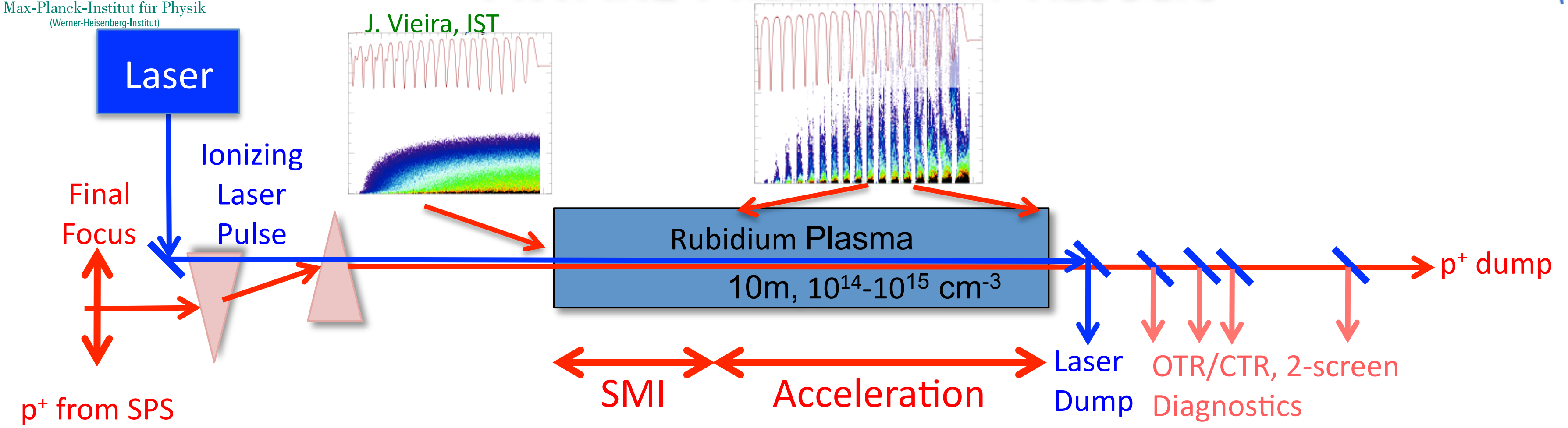
- ✧SPS beam: high energy, small σ_r^*, long β^*
- ✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p^+ driven PWFA
- ✧Setup a comprehensive PWFA program at CERN

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

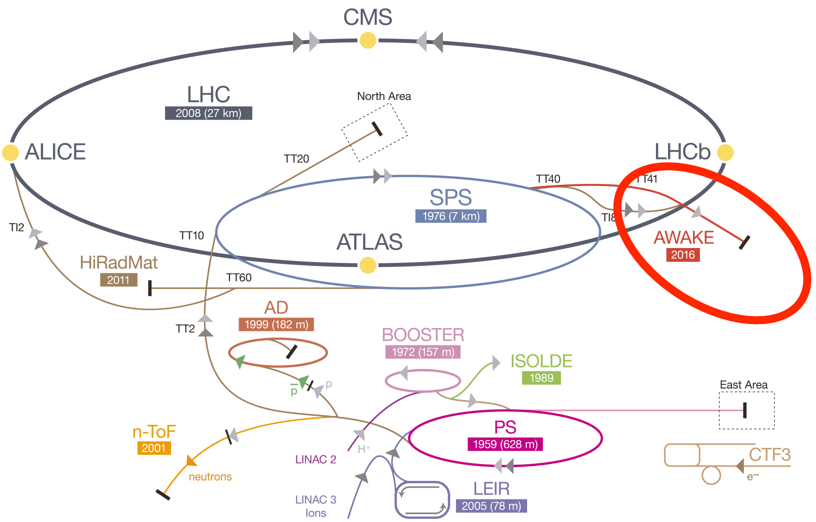
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

CERN

AWAKE PRELIMINARY RESULTS



CERN's Accelerator Complex



<u>2016-17: self-modulation instability (SMI) studies</u>

Three observables

- ✧Defocused p^+
- ✧p^+ bunch modulation at λ_{pe}
- ✧Emission of coherent transition radiation at λ_{pe}

<u>2018: acceleration of 16MeV e^-</u>

- ✧Energy gain ~1GeV
- ✧Few % $\Delta E/E$

- ✧SPS bunch: 400GeV, $3x10^{11}p^+$,
- ✧10m, laser ionized Rb plasma $1\text{-}10x10^{14}cm^{-3}$

MAX-PLANCK-GESELLSCHAFT

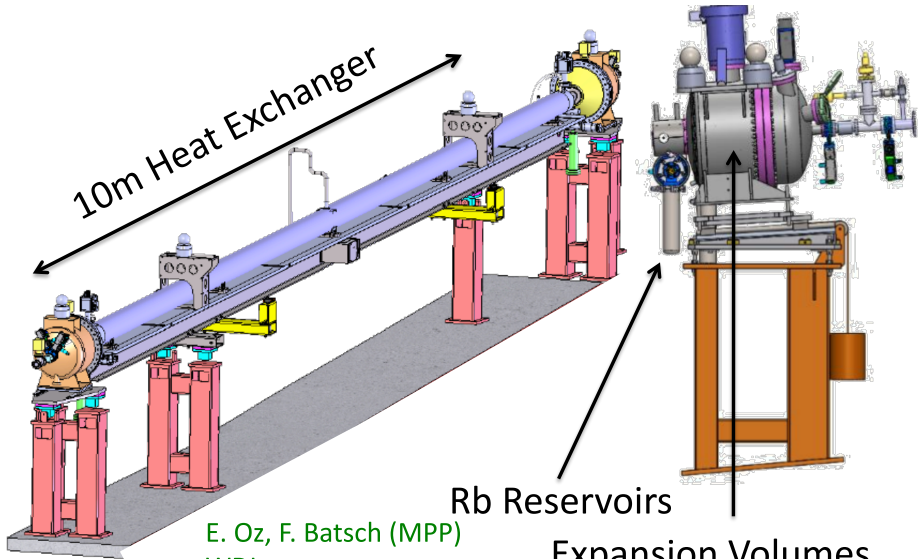
Rb VAPOR/PLASMA SOURCE

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

CERN

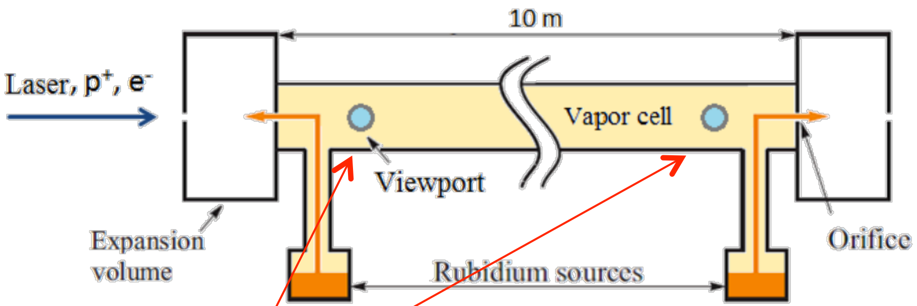
- ✧ $1\times10^{14} < n_e < 1\times10^{15}\,cm^{-3}$
- ✧ Very uniform density: $\Delta n_{Rb,e}/n_{Rb,e} < 0.2\%$
- ✧ Sharp ramps: a few cm
- ✧ Heat exchanger + free expansion of Rb
- ✧ Laser field ionization

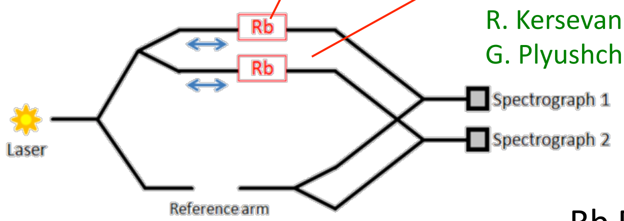
J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN



E. Oz, F. Batsch (MPP)
WDL

E. Oz & P. Muggli., NMA 740(11), 197 (2014).

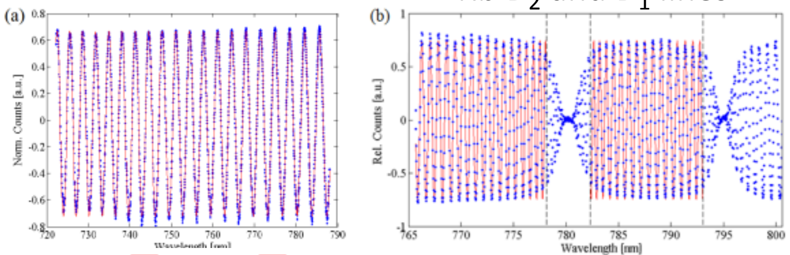




R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)

- ✧ Meet density requirements
- ✧ Measure n_{Rb} with <0.5% accuracy

Rb D_2 and D_1 lines

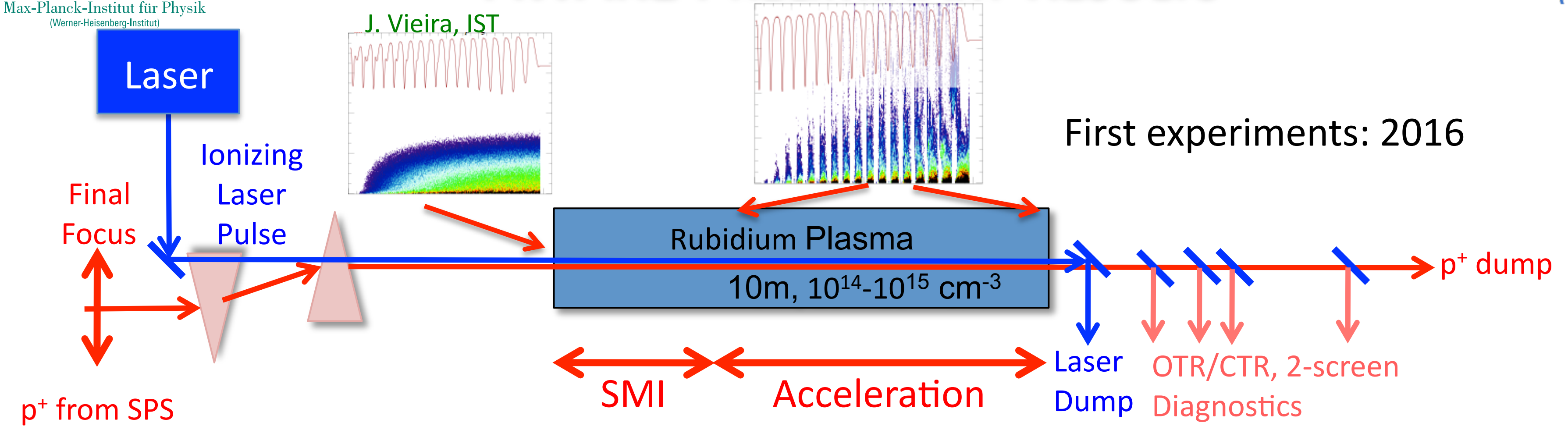


$$S(\lambda) = \tilde{A}\cdot\cos\left(\frac{2\pi}{\lambda}\cdot\left[\frac{\tilde{n}l\, r_0 f_1 \lambda_1^3}{4\pi(\lambda-\lambda_1)} + \frac{\tilde{n}l\, r_0 f_2 \lambda_2^3}{4\pi(\lambda-\lambda_2)} + \tilde{\xi}\right]\right)$$

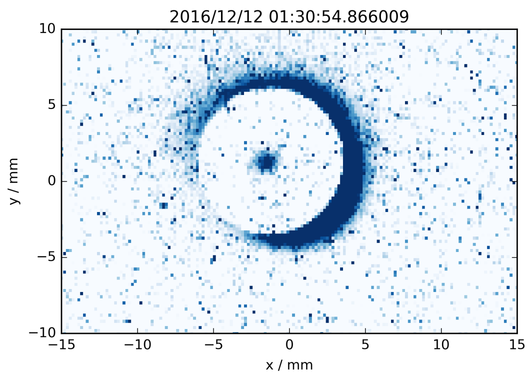
Öz et al., NIMA 829, 321 (2016)

AWAKE PRELiMiNARY RESULTS

First experiments: 2016

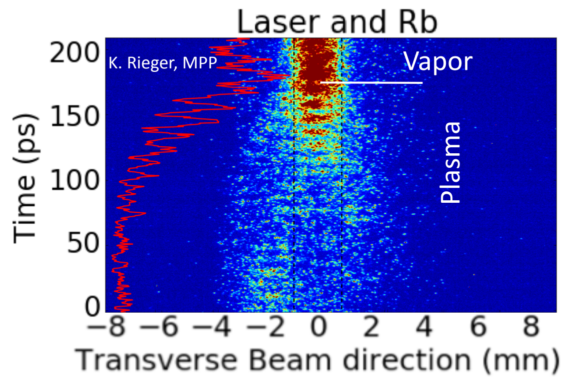


✧Defocused p^+



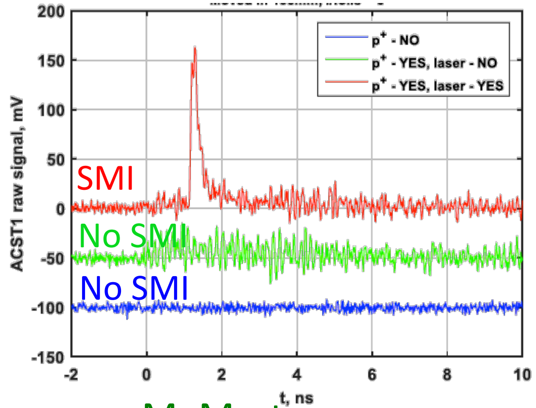
M. Turner, CERN

✧Modulation at 10 ps scale



K. Rieger, MPP

✧CTR emission



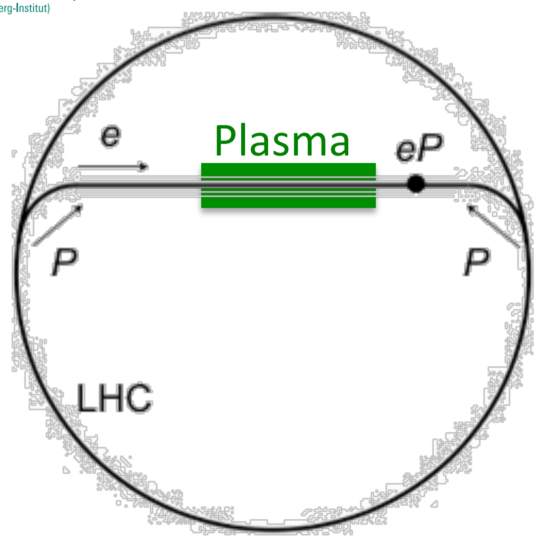
M. Martyanov
F. Braunmueller, MPP

✧Successful first SMI physics run: 48h

✧Operation at low plasma density: 1.5x10^{14}cm^{-3}

✧SMI signal detected on all three diagnostics

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

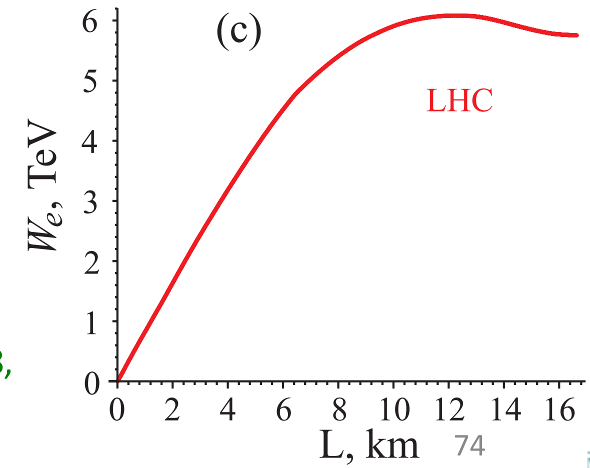


- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable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

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

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

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)

✧Staging in LWFA (low energy)

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

- Complex experiments for small groups

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

✧No physics roadblocks/show stoppers

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SUMMARY

CERN

- Number of technical challenges towards collider beams (last talk): a priori solvable
- Some e^+-symmetric schemes (DLA, DWA), some applications need not e^+ (e^-/p^+)
- "Large scale" experiments: FACET, DESY Flash Forward, INFN SPARC_LAB, CERN AWAKE, BELLA, CILEX, ELI, etc.
- Need facility(ies) dedicated with optimum parameters … witness bunch …
- Need to apply CLIC-like optimization process to each concept (this group?)
- Strengthen collaboration between lab/university groups
  - "The next collider will not be built by faculties at universities", J. Someone, US DoE
- Efficiency, reproducibility, stability, reliability, etc.
- Field mature for accelerator laboratories to adopt a concept and take it to the limit …

Reviews of Accelerator Science and Technology Vol. 09 (2016)
Proceedings of the 2014 CAS-CERN Accelerator School: Plasma Wake Acceleration (2016)

MAX-PLANCK-GESELLSCHAFT

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muggli@mpp.mpg.de

*Luckily I did not present a significant number of other very interesting topics …

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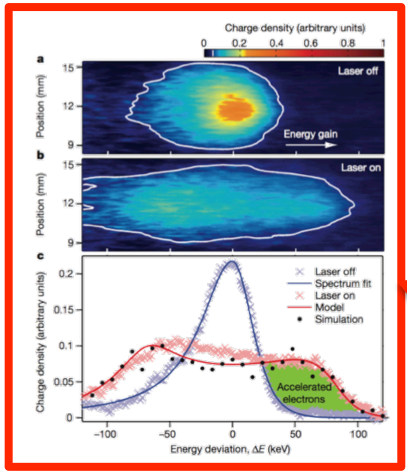
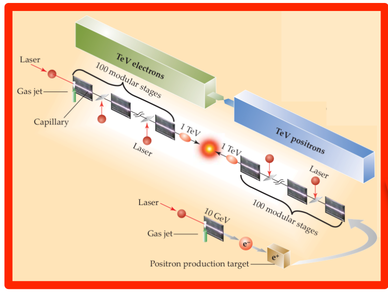
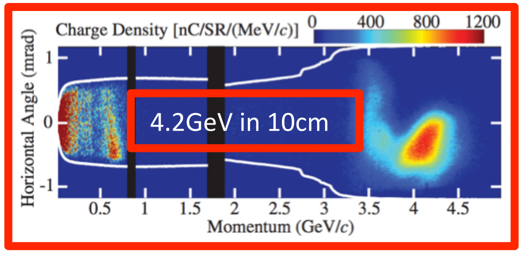
NOVEL ACCELERATOR TECHNiQUES





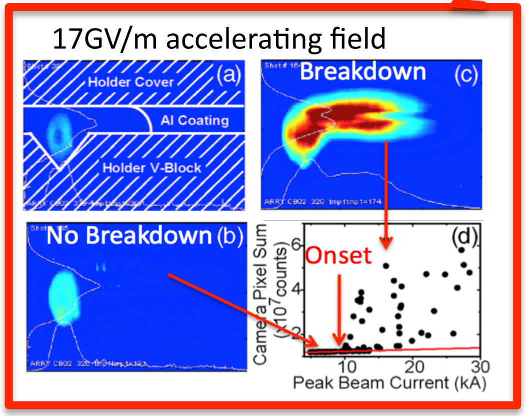


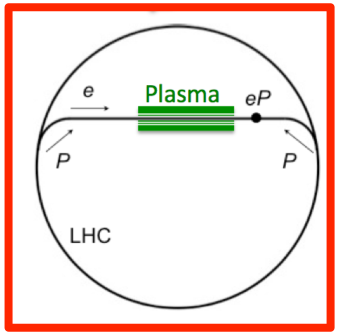
Dielectric Laser Accelerator DLA

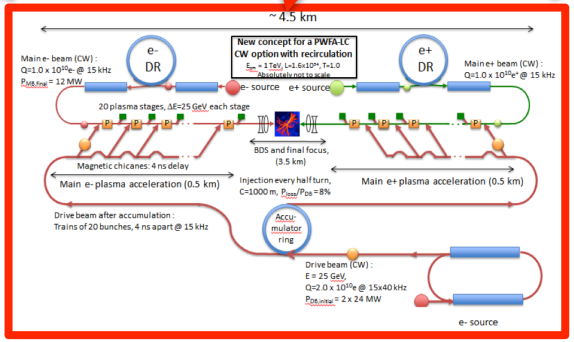
Laser Wakefield Accelerator LWFA

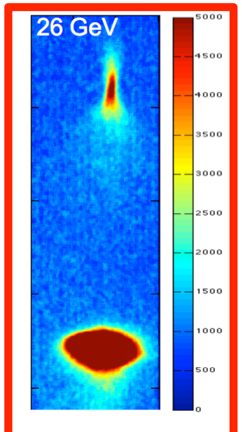
Dielectric Wakefield Accelerator DWA

Plasma Wakefield Accelerator PWFA









Single shot with 6 GeV Energy Gain

- ✧Very active field that has demonstrated large accelerating gradients: 1-10GeV/m
- ✧Very large energy gains (4-20GeV) in <1m in plasmas
- ✧No physics showstoppers towards high energy, high luminosity accelerator
- ✧Straw man “designs” for HEP colliders exist: e^-/e^+ and e^-/p^+ colliders
- ✧Field mature for accelerator laboratory to take it to the limit

TECHNIQUES

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

Small N^2, large $f_{rep}n_b$ => f_{cont}
Very small λ (~μm)
$\varepsilon_{x,y}$?

No RF involved

Strongly depends on laser rep rate
ILC-like

"Linear" systems with structure

No "structure"
Plasma "prefers" continuous rate

Dielectric Laser Accelerator DLA 10-100's THz	Laser Wakefield Accelerator LWFA 1-100 THz
Dielectric Wakefield Accelerator DWA 10-100's GHz	Plasma Wakefield Accelerator PWFA 0.1-few THz

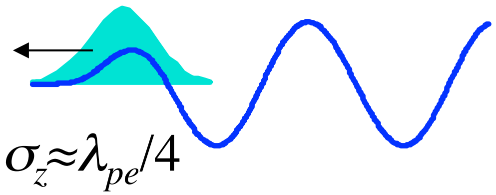
CLIC-like driver

~~4~~ 5 PLASMA-BASED ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

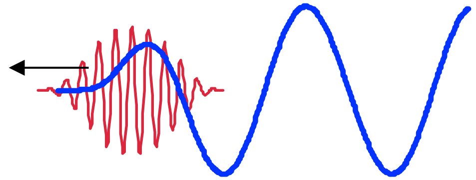
  A high energy particle bunch (e^-, e^+, ...)

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



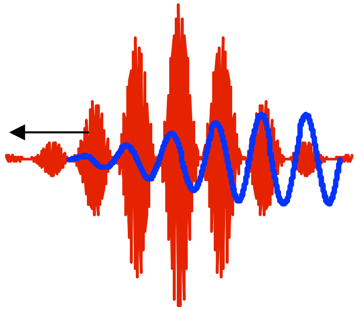
- Laser Wakefield Accelerator (LWFA)

  A short laser pulse (photons)



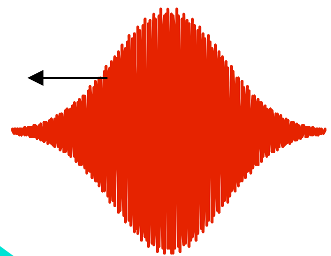
- Plasma Beat Wave Accelerator (PBWA)

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

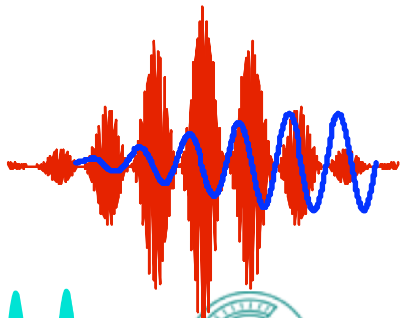


- Self-Modulated Laser Wakefield Accelerator (SMLWFA)

  Raman forward scattering instability in a long laser pulse

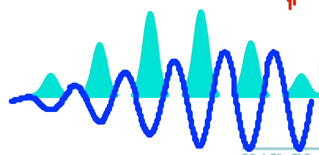


evolves into



- Self-Modulated PWFA (sMPPWFA)

evolves into



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

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LWFA-BASED COLLIDER CONCEPT

Schroeder , PRSTAB, 13, 101301 (2010)

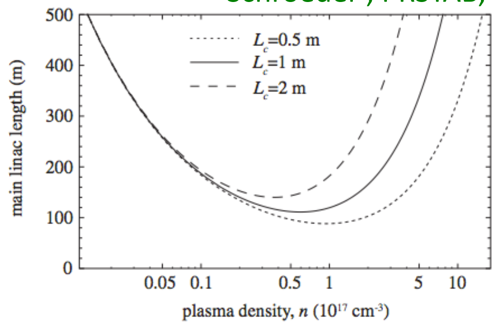

FIG. 3. Main single-linac length versus plasma density n for several laser in-coupling distances L_c, for $E_b = 0.5$ TeV and $a_0 = 1.5$.

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.

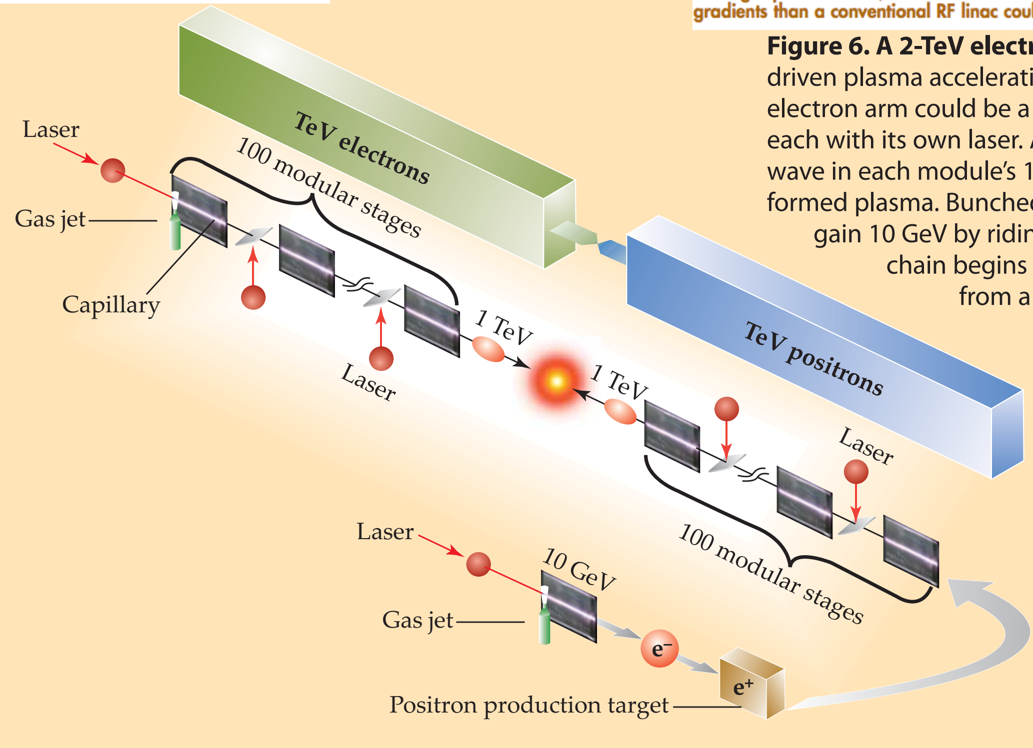

Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed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