Novel Accelerator Techniques

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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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✧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)

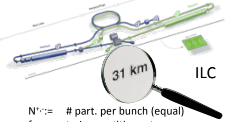
Systems powered/driven by:
✧Laser pulse(s)*
✧Relativistic, charged particle bunch(es)

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

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 average accelerating gradient (>1GeV/m)
- Accelerator(s) a few 100's-1000's m of meter long



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

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

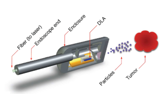
$N^{+,-}$:= # part. per bunch (equal)
f_{rep}:= train repetition rate
n_b:= # bunches per train
$\sigma^*_{x,y}$:= bunch transverse size @ waist
$\varepsilon_{x,y}$:= bunch emittance
E:= energy per particle
P_b:= average beam power $\approx n_b N f_{rep} E$

  - Focus on accelerator contribution (not final focus or interaction point)
  - Assume those are the same (bunch length?)
- Deliver the same average current with the same emittance (DWA, LWFA, PWFA)
- Deliver lower average current with lower emittance?? (DLA)

Applications

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

- 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)

Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Dielectric Wakefield Accelerator DWA	Plasma Wakefield Accelerator PWFA

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

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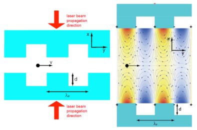
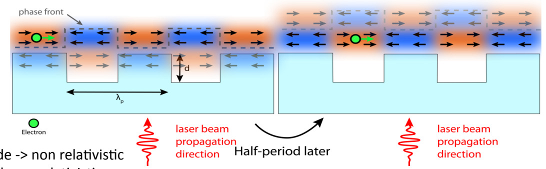
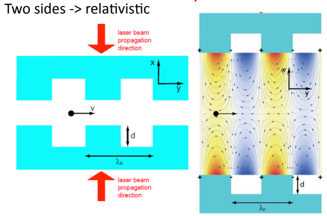
- Directly use the laser E-field in a ~λ³ (micro) structure
- Summary

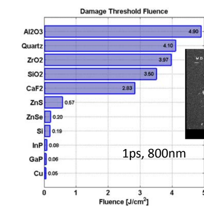


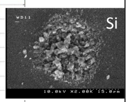
Dielectric Laser Accelerator (DLA)



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







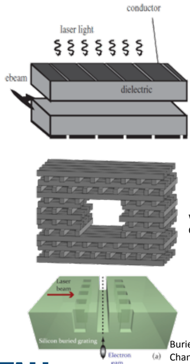
Soong, AIP Conf. Proc. 1507, 511 (2012)

- 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)

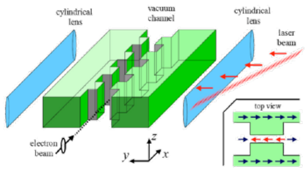
Proposed dielectric structures



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)

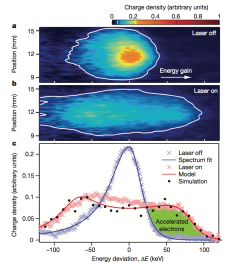
Courtesy P. Hommelhoff

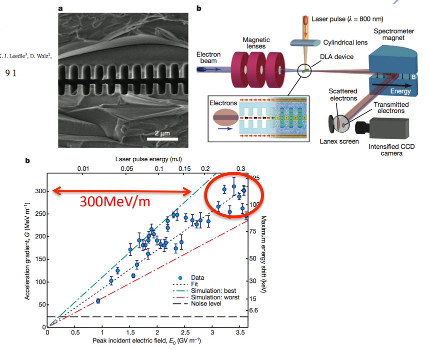
P. Hommelhoff, Accel. Med. Appl., Vösendorf, Austria, 2015

DLA RESULTS

Demonstration of electron acceleration in a laser-driven dielectric microstructure

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 — Non-relativistic

Courtesy of J. England

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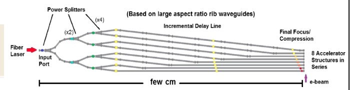


Peralta, AIP Proc. 1507, 169 (2012)

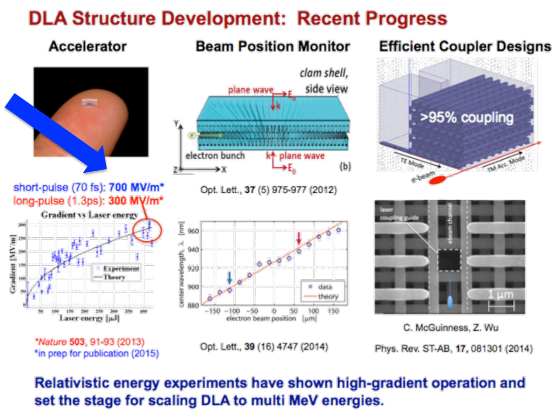
TABLE VII. Strawman parameters for the DLA Linear Collider.

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



Courtesy of J. England

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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 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)

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P. Muggli, CLIC 24/03/2017

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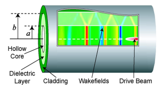
✧Cherenkov wakes in dielectric layers

✧Summary



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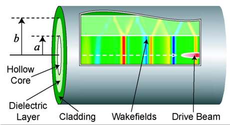
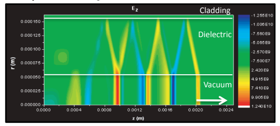
DIELECTRIC WAKEFIELD ACCELERATOR (DWA)





- 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)

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

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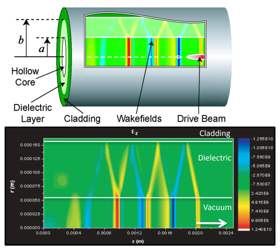
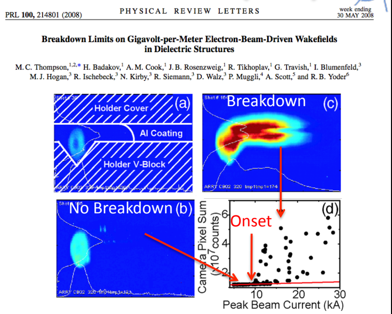
DiElectric Wakefield Accelerator (DWA)





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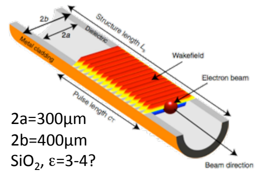
- Transformer ratio (unshaped beam)

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

✧ 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

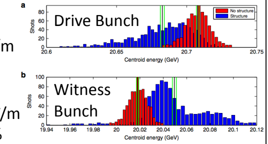
O'Shea et al., Nat . Comm. 7, 12763 (2016)

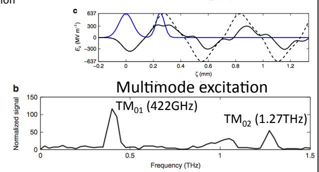


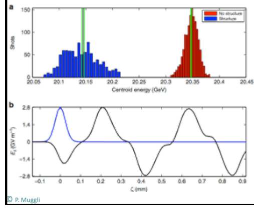
2a=300µm
2b=400µm
SiO$_2$, ε=3-4?
Cu cladding

9.4x10^{9}e
G_d=252±14MeV/m

6x10^{9}e$^-$
G_a=320±17MeV/m
$E_{extraction}$=80%







2x10^{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

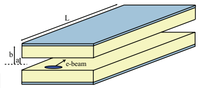
Acceleration in slab symmetric DWA

UCLA

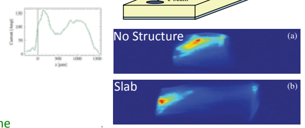
- Structure:
  - SiO2, planar geometry, beam gap 240µm
- BNL ATF
  - Flat beam
  - Long bunch structure with two peaks
- Acceleration of trailing peak
- Robust start-to-end simulations for benchmarking

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

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



SiO$_2$, Al
T_{SLAB}=240µm
T_{gap}=240µm
L_z=2cm
ε_N=2mm-mrad



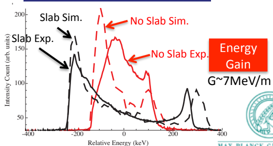
E_0=59MeV
Q=100-900pC
L_z~1.2mm
ε_N=2mm-mrad

Slab geometry allows for:
✧Reduced transverse wakefields
W'$_{per}$~k^3 -> 0 when $\sigma_{//}$>>a
✧More charge per bunch
✧Demonstration of energy gain!

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

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

Tremaine
PRE 56 7210 (1997)



G~7MeV/m

✧Appropriate for "flat" collider beams?

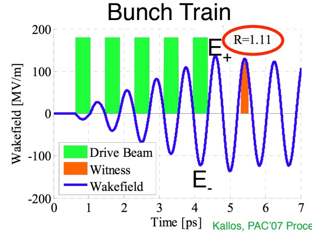
Courtesy G. Andonian

Multibunch PWFA

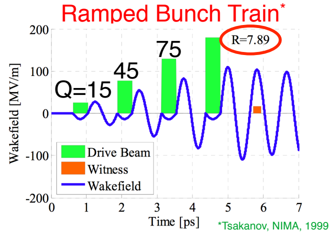
Transformer Ratio: $R = E_+/E_-$ Energy Gain: $\leq RE_0$

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 Δz=375 µm=1.5λ_p



Kallos, PAC'07 Proceedings

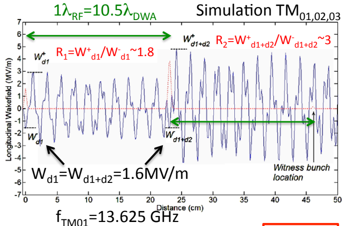


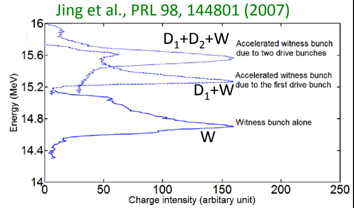
*Tsakanov, NIMA, 1999

- 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





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

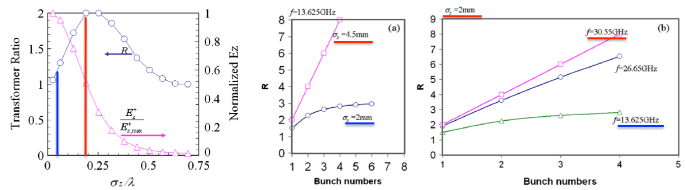
$$R_2/R_1 = \left(\frac{W^+_{d1+d2}}{W^-_{d1+d2}}\right)\Big/\left(\frac{W^+_{d1}}{W^-_{d1}}\right) = \frac{W^+_{d1+d2}}{W^+_{d1}} = 1.31 \pm 0.13.$$

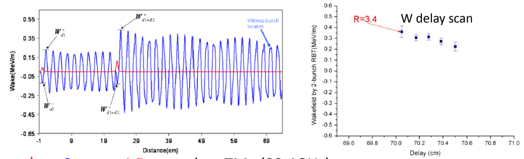
✧R=2.3 > 2!
✧Ramped bunch train increases R by 1.3
✧Demonstration of energy gain!
✧Other shapes: door step, double triangle, etc.

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

DWA RESULTS: R

✧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

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)

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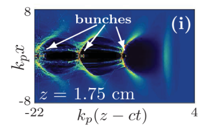
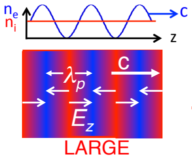
✧Intense laser pulse to drive wakefields in plasma

✧Summary



PLASMAS

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



$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \qquad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2} \text{ Plasma Frequency} \qquad k_p E_z = \frac{\omega_{pe}}{c}E_z = \frac{n_e e}{\varepsilon_0}$$

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

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

LARGE
Collective response!

Cold Plasma "Wavebreaking" Field

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

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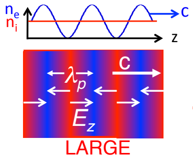

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$$E_{WB} = m_e c\omega_{pe}/e$$

✧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)

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PLASMAS

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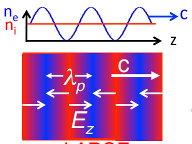

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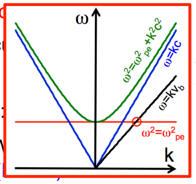
➢Dense particle bunch ([…]



Single mode system!

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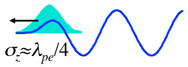
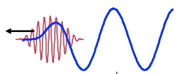
4 PLASMA-BASED ACCELERATORS*

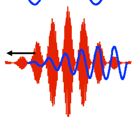
• Plasma Wakefield Accelerator (PWFA)
A high energy particle bunch (e^-, e^+, …)
P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)



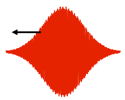
• Laser Wakefield Accelerator (LWFA)*
A short laser pulse (photons, ponderomotive)



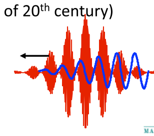
• Plasma Beat Wave Accelerator (PBWA)*
Two frequencies laser pulse, i.e., a train of pulses



• Self-Modulated Laser Wakefield Accelerator (SMLWFA)*
Raman forward scattering instability in a long pulse (LWFA of 20th century)



evolves into



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

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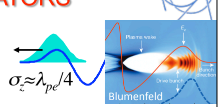

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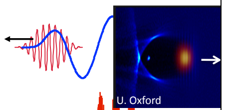
  A short laser pulse (photons, ponderomotive)



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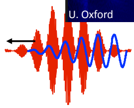

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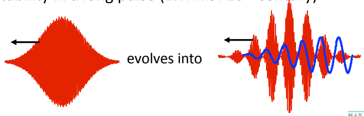
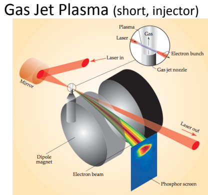
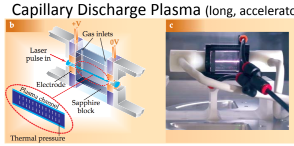


*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

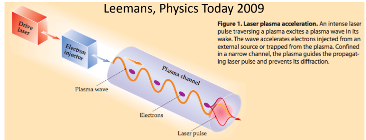
LASER WAKEFIELD ACCELERATOR (LWFA)

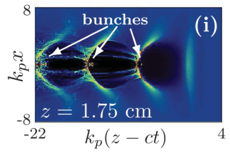
Gas Jet Plasma (short, injector) — Capillary Discharge Plasma (long, accelerator)

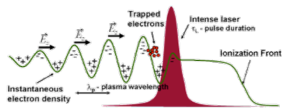




Leemans, Physics Today 2009







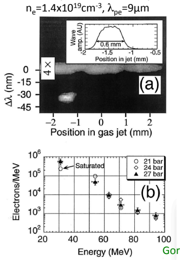
- ✧Most active field
- ✧Availability of TW Ti:Sapphire laser systems
- ✧Few TW for 10-100MeV e^- in a few mm
- ✧Acceleration, guiding
- ✧Self-trapping
- ✧Injection (plasma "gun")
- ✧Diagnostics
- ✧Radiation source
- ✧...

LASER WAKEFIELD ACCELERATOR (LWFA)

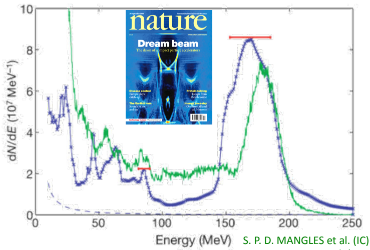
✧Wakefields driven by ponderomotive force of an intense laser beam

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

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}, λ_{pe}=9μm



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

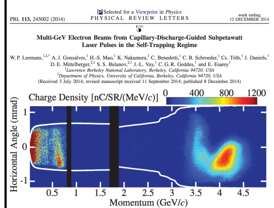


S. P. D. MANGLES et al. (IC)
C. G. R. GEDDES et al. (LBNL)
J. FAURE et al. (LOA)
Nature 431, 2004

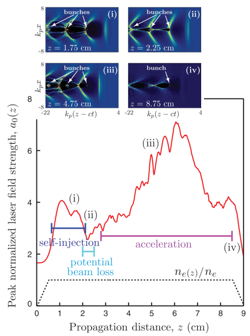
- ✧Forward Raman scattering (self-modulation)
- ✧Wave breaking injection
- ✧Nonlinear plasma wave
- ✧Acceleration beyond linear dephasing limit

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

LWFA RESULTS



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}=0.3PW
W=16J, σ_r=52μm, τ=42fs



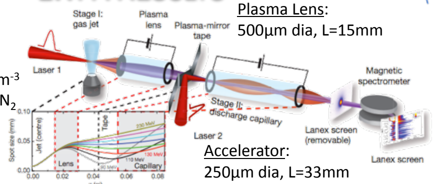
- ✧Peak energy gain 4.2GeV in <10cm
- ✧Self-trapped plasma e^-

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

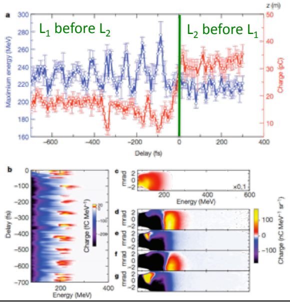
LWFA RESULTS

Plasma Lens:
500µm dia, L=15mm

Gas jet:
$n_e=5\times10^{18}cm^{-3}$
99%He+1%N_2
L=700µm

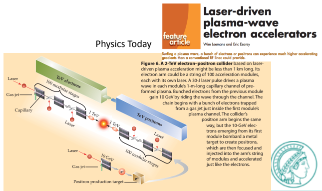


Accelerator:
250µm dia, L=33mm

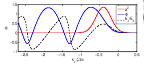


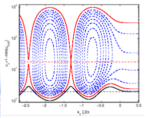
Steinke et al., Nature 530(11), 190, 2016

✧Staged acceleration (low energy)
✧Use of plasma optic and plasma mirror



LWFA INJECTORS (some)





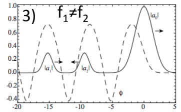
✧Wave breaking: drive the wave very non linear (Dawson, PRL,1956)

1)

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

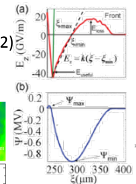
✧Three- two laser beams
(Umstadter PRL 76, 2073 (1996), Esarey, PRL 79, 2682 (1997))

3) $f_1 \neq f_2$



✧Density step (Suk PRL 86, 1011)

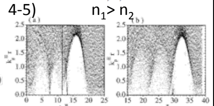
2)



✧Density down-ramp

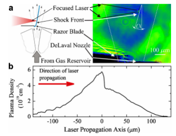
✧Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010)

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)

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."

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

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

✧The future is fiber lasers?

LASER WAKEFIELD ACCELERATOR (LWFA)

A few general characteristics:

✧High laser intensity: $I_0>10^{18}Wcm^{-2}$, P>40TW
✧Short laser pulse(?): 40fs $<\lambda_{pe}$
✧Large 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: $<\lambda_{pe}$
✧Provide ionization

✧$v_\phi \sim v_{g,\,laser}$<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, 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

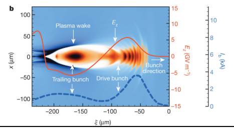
OUTLINE

✧Novel Accelerator Techniques "Goals"

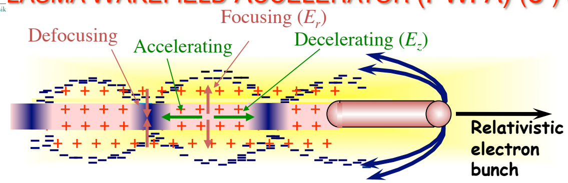
Driver \ Medium	Dielectric	Plasma
Laser Pulse	✧ Dielectric Laser Accelerator DLA	✧ Laser Wakefield Accelerator LWFA
Particle Bunch	✧ Dielectric Wakefield Accelerator DWA	✧ Plasma Wakefield Accelerator PWFA

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

✧Summary

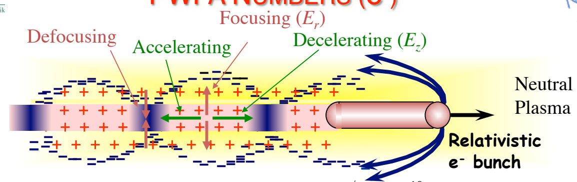


PLASMA WAKEFIELD ACCELERATOR (PWFA) (e^-)



- 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 $k_{pe}\sigma_r<<1$) $k_{pe} \sim n_e^{1/2}$

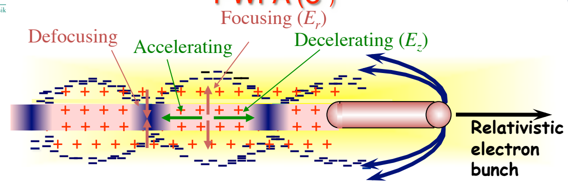
✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c}$ ($n_b>n_e$)

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

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

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

PWFA (e^-)



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

- 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

First PWFA Observation (e⁻)

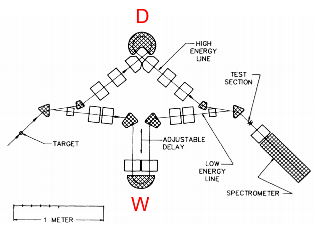


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

Rosenzweig, PRL 61, 98 (1988)

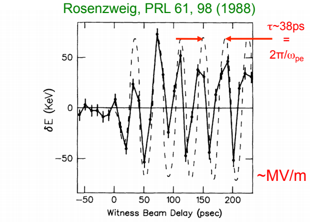


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q=2.1$ nC; plasma parameters $L=28$ cm and $n_e=8.6\times10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

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

Plasma Wakefield Fields (E-162, e⁻)

Typical parameters:

e⁻ beam:

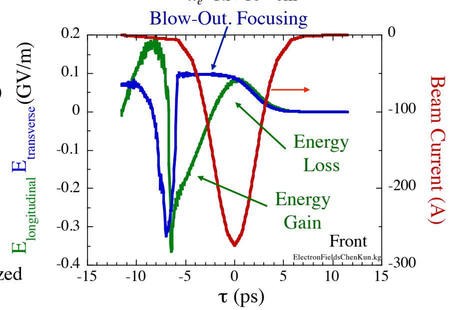
E	28.5 GeV
N	2×10^{10} e⁻
σ_z	0.63 mm (2.1 ps)
$\sigma_x=\sigma_y$	70 μm
n_b	4×10^{14} cm^{-3}
ε_{xN}	5×10^{-5} m-rad
ε_{yN}	0.5×10^{-5} m-rad

Plasma:

n_e	0-2×10^{14} cm^{-3}
L	1.4 m, laser ionized

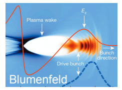
2-D PIC Simulation OSIRIS

$n_e=1.5\times10^{14}$ cm^{-3}

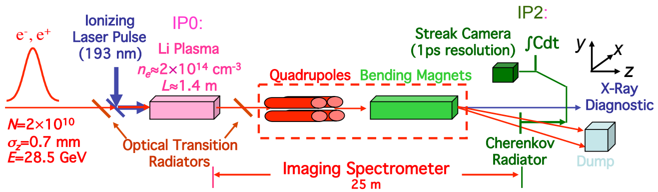


➡ Experiment: $n_b>n_e$ => non linear, blow-out regime

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



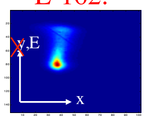
Experimental Set Up



- Plasma:
  Laser-ionized lithium vapor

- CHERENKOV (aerogel)

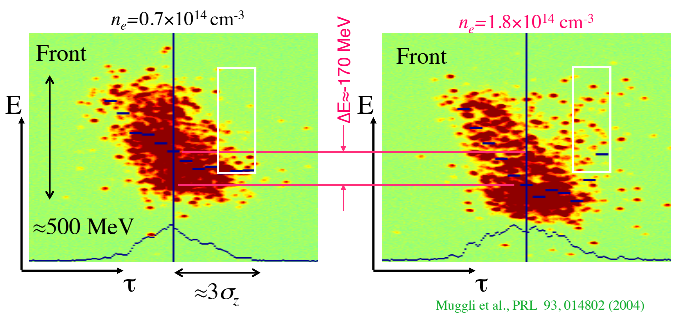
E-162:



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

USC

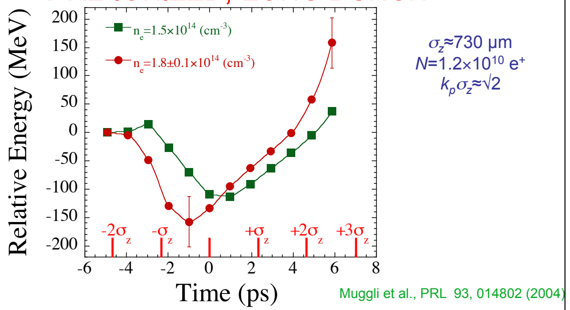
Slice Analysis Results Single Event



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)

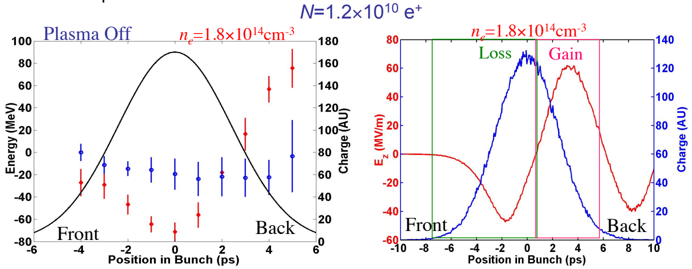
- Energy gain smaller than, hidden by, incoming energy spread
- Time resolution needed, but shows the physics
- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

Patric Muggli, HEEAUP05, 06/08/05 45

ENERGY LOSS/GAIN e+

B.E Blue, UCLA

Experiment — σ_z≈730 µm, N=1.2×10^10 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

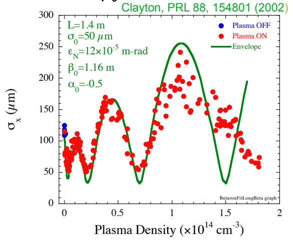
Excellent agreement!

Patric Muggli, HEEAUP05, 06/08/05 Blue et al., PRL 90, 214801, (2003) 46

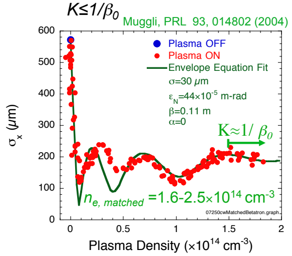
PROPAGATION OF e-

OTR Images ≈1m downstream from plasma

K≥1/β_0 Clayton, PRL 88, 154801 (2002)



K≤1/β_0 Muggli, PRL 93, 014802 (2004)

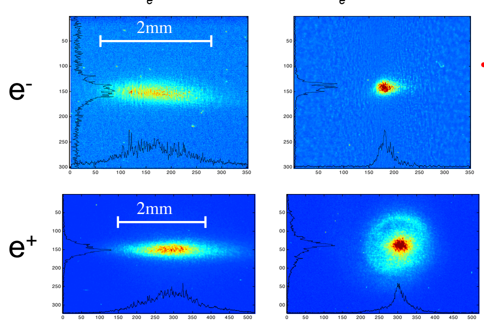


- Focusing of the beam well described by a simple model (n_b>n_e): Plasma = Ideal Thick Lens
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^14cm^-3
- Channeling of the beam over 1.4 m or >12β_0 => Matched Propagation over long distance!

FOCUSING OF e-/e+

- OTR images ≈1m from plasma exit (ε_x≠ε_y)

n_e=0 — n_e≈10^14 cm^-3

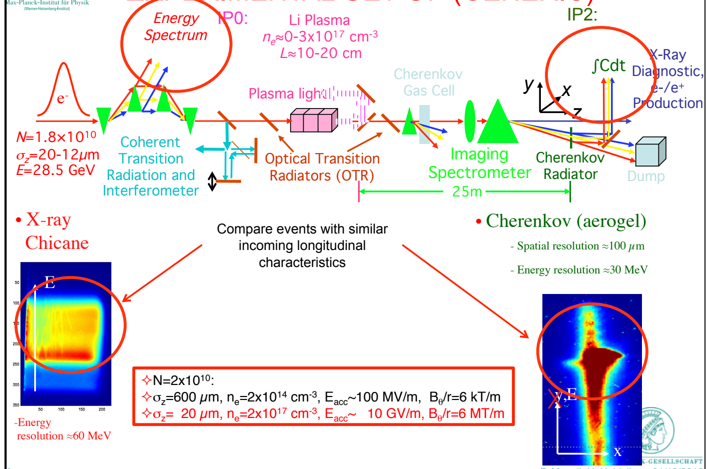


- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations

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

- Qualitative differences

EXPERIMENTAL SET UP (GENERIC)



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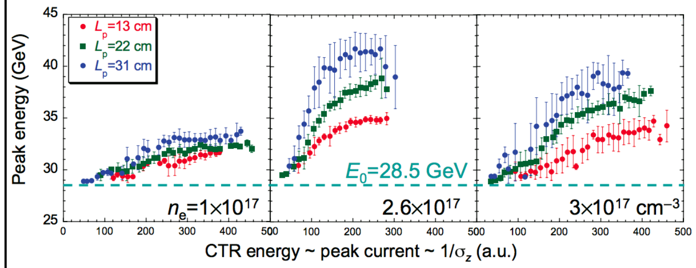
ENERGY GAIN VS. BUNCH LENGTH



- 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

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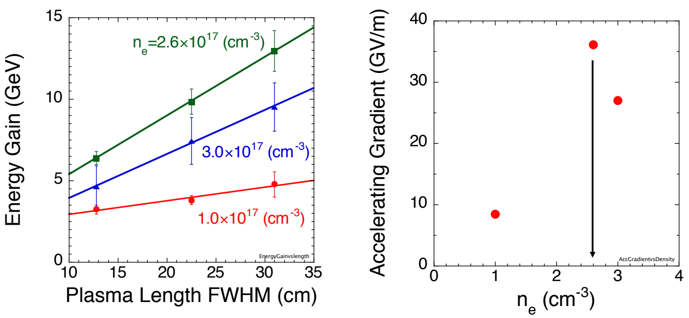
ENERGY GAIN VS. PLASMA LENGTH



- Largest gain with n_e=2.6×10^{17}cm^{-3} (• L_p, for σ_z≈20 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

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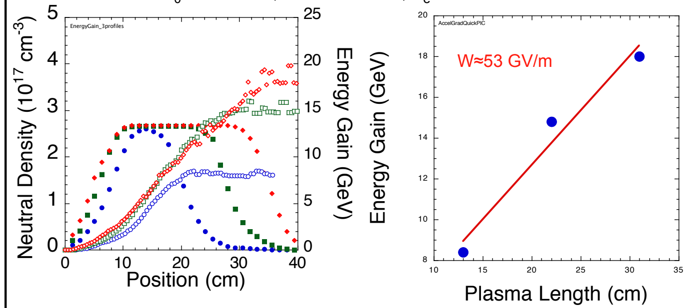
ENERGY GAIN VS. PLASMA LENGTH

3-D Simulations using QuickPIC

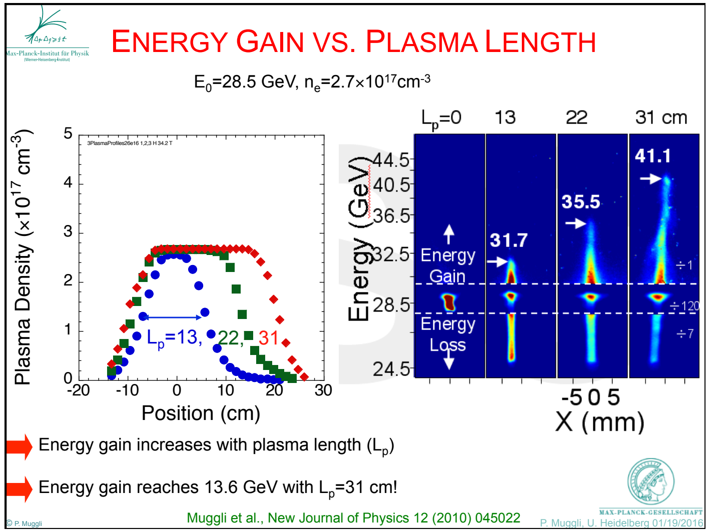
E_0=28.5 GeV, N=1.8×10^{10} e$^-$, n_e=2.7×10^{17}cm^{-3}

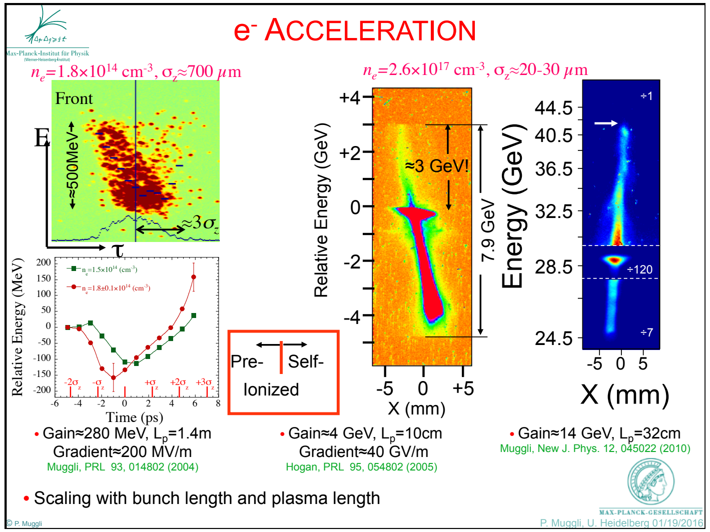


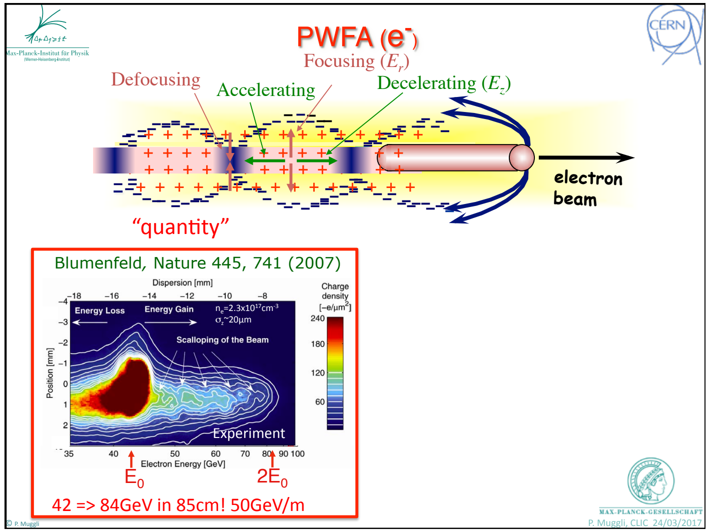
- Energy gain increases with plasma length (L_p)
- Gradient ≈53 GV/m

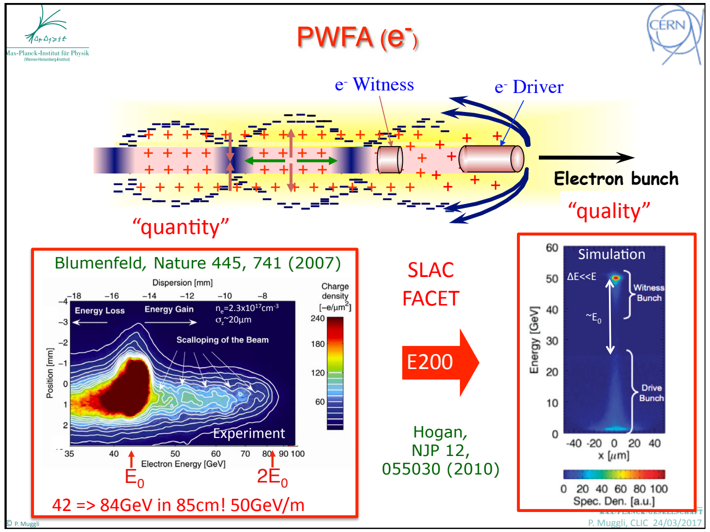
Muggli et al., New Journal of Physics 12 (2010) 045022

© P. Muggli   P. Muggli, U. Heidelberg 01/19/2016

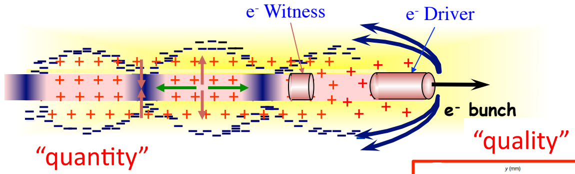

ENERGY GAIN VS. PLASMA LENGTH
E0=28.5 GeV, ne=2.7×10^17cm^-3
Plasma Density (×10^17 cm^-3)
Position (cm)
Lp=13, 22, 31
Lp=0 13 22 31 cm
Energy (GeV)
Energy Gain
Energy Loss
31.7
35.5
41.1
X (mm)
Energy gain increases with plasma length (Lp)
Energy gain reaches 13.6 GeV with Lp=31 cm!
Muggli et al., New Journal of Physics 12 (2010) 045022
P. Muggli, U. Heidelberg 01/19/2016


e- ACCELERATION
ne=1.8×10^14 cm^-3, σz≈700 µm
ne=2.6×10^17 cm^-3, σz≈20-30 µm
Front
≈500MeV
≈3σz
Relative Energy (MeV)
Time (ps)
Pre- Ionized
Self-
Relative Energy (GeV)
≈3 GeV!
7.9 GeV
X (mm)
Energy (GeV)
X (mm)
• Gain≈280 MeV, Lp=1.4m
Gradient≈200 MV/m
Muggli, PRL 93, 014802 (2004)
• Gain≈4 GeV, Lp=10cm
Gradient≈40 GV/m
Hogan, PRL 95, 054802 (2005)
• Gain≈14 GeV, Lp=32cm
Muggli, New J. Phys. 12, 045022 (2010)
• Scaling with bunch length and plasma length
P. Muggli, U. Heidelberg 01/19/2016

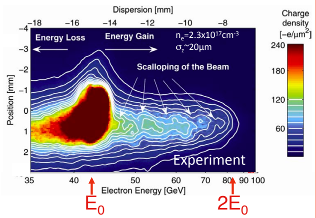

PWFA (e-)
Focusing (Er)
Defocusing
Accelerating
Decelerating (Ez)
electron beam
"quantity"
Blumenfeld, Nature 445, 741 (2007)
Dispersion [mm]
Energy Loss
Energy Gain
Scalloping of the Beam
Experiment
Electron Energy [GeV]
E0
2E0
42 => 84GeV in 85cm! 50GeV/m
P. Muggli, CLIC 24/03/2017


PWFA (e-)
e- Witness
e- Driver
Electron bunch
"quantity"
"quality"
Blumenfeld, Nature 445, 741 (2007)
Experiment
E0
2E0
42 => 84GeV in 85cm! 50GeV/m
SLAC FACET
E200
Hogan, NJP 12, 055030 (2010)
Simulation
Witness Bunch
Drive Bunch
Energy [GeV]
x [µm]
Spec. Den. [a.u.]
P. Muggli, CLIC 24/03/2017

Plasma Wakefield Accelerator (e^-)



Blumenfeld, Nature 445, 741 (2007)

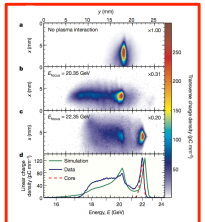


42 => 84GeV in 85cm! 50GeV/m

SLAC FACET

E200

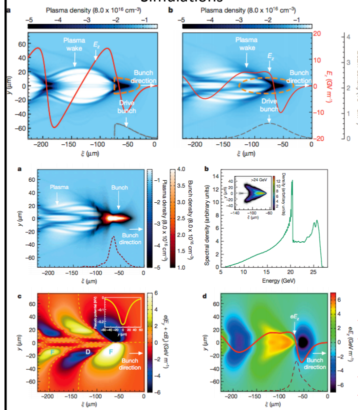
Litos, Nature 515(6),92 (2014)



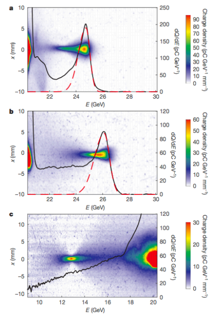
ΔE/E~%
η~30%

Plasma Wakefield Accelerator (e^+)

Simulations



Experiment



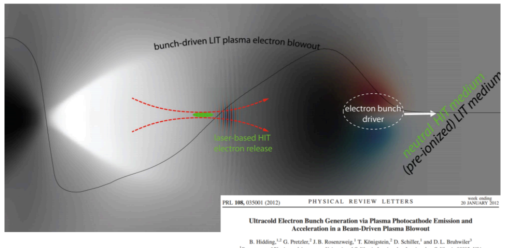
- $n_e=8\times10^{16}cm^{-3}$, $L_p=1.35m$
- $N=1.4\times10^{10}e^+$, $\sigma_r=70\mu m$, $\sigma_z=30\text{-}50\mu m$, $E_0=20.35GeV$, $n_b=(0.2\text{-}1)\times10^{16}cm^{-3}$,
- Peak in energy spectrum
- Plasma e- arrange themselves for focusing and self-loading

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

Low Emittance Injector

Underdense Photocathode PWFA

Trojan Horse Injection



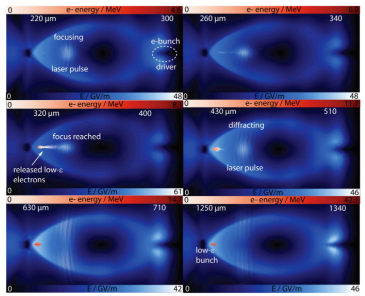
What's needed:
- LIT/HIT medium
- reliable electron bunch driver to set up LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout

- 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).

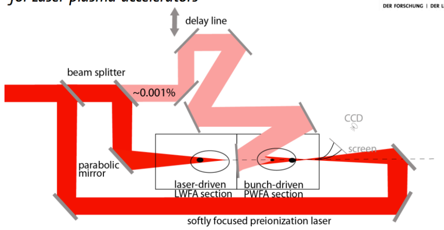


In contrast to LWFA schemes (~10^{18}-10^{19} W/cm²), here the laser pulse intensity is of the order of ~10^{14}-10^{15} W/cm², only.
→ Transverse momentum of bunch electrons is very low → direct consequences for divergence & emittance!

- 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?)

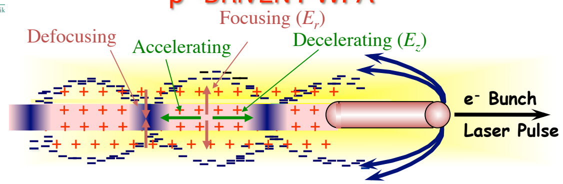
PLASMA WAKEFIELD ACCELERATOR (PWFA)

A few general characteristics:

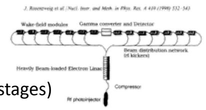
✧Relativistic bunch γ_0>1
✧Short bunch: <1mm < λ_{pe}
✧Dense bunch n_b>n_e>10^{16}cm^{-3}
✧Tight focus: <λ_{pe}
✧Does not provide ionization, in general
✧Negatively charged bunches …

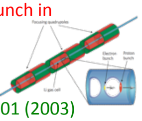
✧$v_\phi=v_{bunch}=(1-1/\gamma_0^2)^{1/2}c\sim c$: no dephasing …
✧Plasma provides focusing, no external guiding necessary(?)
✧Large β-function
} Long accelerator (m)
✧Large energy loss possible with little drive bunch evolution (e.g.: e^-, γ_0=40'000->1'000)

p^+-DRIVEN PWFA



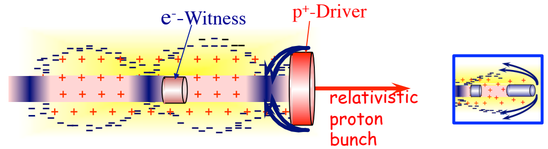
✧ILC, 0.5TeV bunch with 2x10^{10}e$^-$ ~1.6kJ
✧SLAC, 20GeV bunch with 2x10^{10}e$^-$ ~60J
✧SLAC-like driver for staging (FACET= 1 stage, collider 10+ stages)
✧SPS, 400GeV bunch with 10^{11}p$^+$ ~6.4kJ
LHC, 7TeV bunch with 10^{11}p$^+$ ~112kJ
✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
✧Large average gradient! (≥1GeV/m, 100's m)
✧Wakefields driven by e+ bunch: Blue, PRL 90, 214801 (2003)





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

p^+-DRIVEN PWFA



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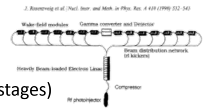
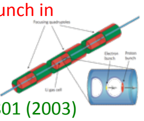
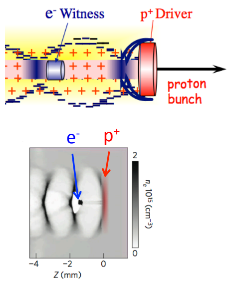




Caldwell, Nat. Phys. 5, 363, (2009)

p+-DRiVEN PWFA

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

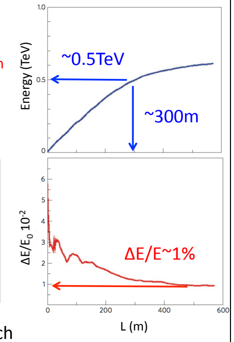


e-: E_0=10GeV, N=10^{10}

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

Single Stage: W_0=16J → W_f=1kJ

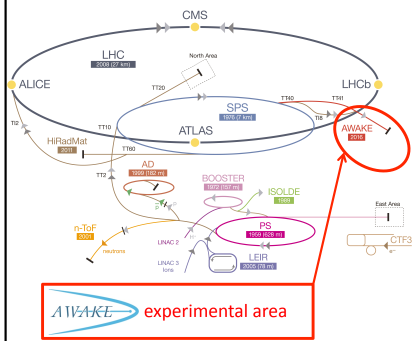
Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons 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

σ_z=12cm!!

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

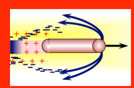
pROTON bEAMS @ CERN

CERN's Accelerator Complex

CMS

Parameter	PS	SPS	SPS Opt

Scaling



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

σ_z=12cm~λ_{pe} → n_e~$8\times10^{10}cm^{-3}$

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

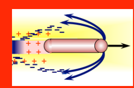
pROTON bEAMS @ CERN

CERN's Accelerator Complex

CMS

Parameter	PS	SPS	SPS Opt

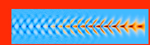
Scaling



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

σ_z=12cm~λ_{pe} → n_e~$8\times10^{10}cm^{-3}$

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



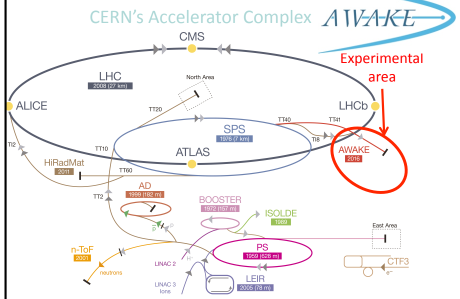
→Use self-modulation instability (SMI)

→σ_z~12cm train with period ~1.2mm

→n_e~$7\times10^{14}cm^{-3}$, ($k_{pe}\sigma_r$~1), L_p=10m

→E_{WB}~1GV/m, f_{pe}~237GHz

p⁺-DRiVEN PWFA



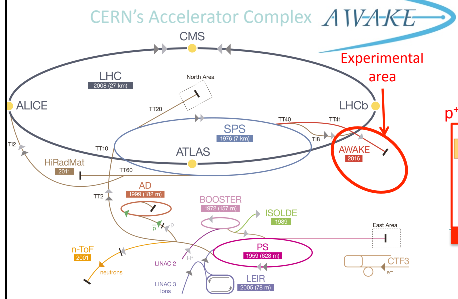
✧SPS beam: high energy, small σ_r*, long β*

✧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

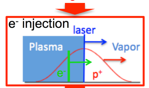
AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014)

p⁺-DRiVEN PWFA

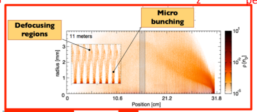


3×10^{11}, 400GeV SPS p⁺

10m plasma, n_e=1-10×10^{14}cm^{-3}

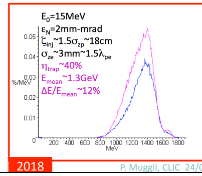


p⁺ bunch self-modulation: σ_z~$100\lambda_{pe}$



2016-17

GeV energy gain by externally injected e^-



2018

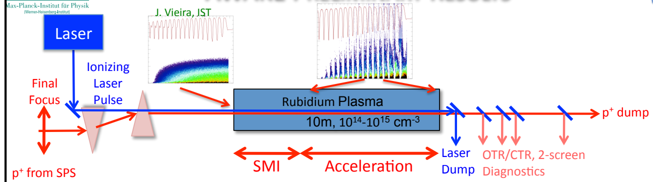
✧SPS beam: high energy, small σ_r*, long β*

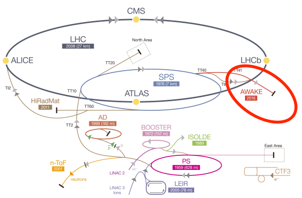
✧Initial goal: ~GeV gain by externally injected e^-,in 5-10m of plasma in self-modulated p⁺ driven PWFA

✧Setup a comprehensive PWFA program at CERN

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

AWAKE PRELiMiNARY RESULTS





2016-17: self-modulation instability (SMI) studies

Three observables

✧Defocused p⁺

✧p⁺ bunch modulation at λ_{pe}

✧Emission of coherent transition radiation at λ_{pe}

2018: acceleration of 16MeV e^-

✧Energy gain ~1GeV

✧Few % ΔE/E

✧SPS bunch: 400GeV, 3×10^{11}p⁺,

✧10m, laser ionized Rb plasma 1-10×10^{14}cm^{-3}

Rb VAPOR/PLASMA SOURCE

✧1×10^{14}<n_e<1×10^{15}cm^{-3}

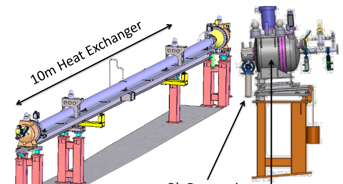
✧Very uniform density: $\Delta n_{Rb,e}/n_{Rb,e}$<0.2%

✧Sharp ramps: a few cm

✧Heat exchanger + free expansion of Rb

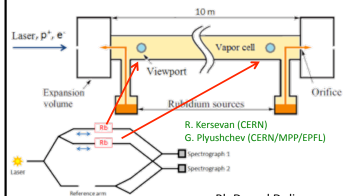
✧Laser field ionization

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



E. Oz, F. Batsch (MPP) WDL

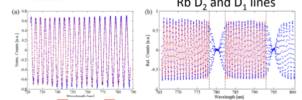
E. Oz & P. Muggli., NMA 740(11), 197 (2014).



R. Kersevan (CERN)

G. Plyushchev (CERN/MPP/EPFL)

Rb D_2 and D_1 lines

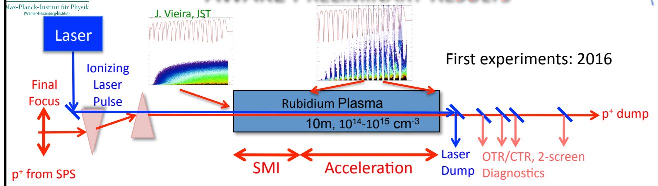


$S(\lambda) = \tilde{A}\cdot\cos\left(\frac{2\pi}{\lambda}\left[\overline{nl}\frac{r_e f_1 \lambda_1^3}{4\pi(\lambda-\lambda_1)} + \overline{nl}\frac{r_e f_2 \lambda_2^3}{4\pi(\lambda-\lambda_2)} + \frac{\tau}{c}\right]\right)$ Öz et al., NIMA 829, 321 (2016)

✧Meet density requirements

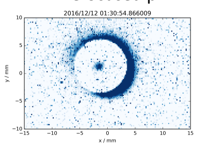
✧Measure n_{Rb} with <0.5% accuracy

AWAKE PRELIMINARY RESULTS



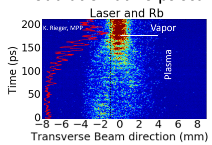
First experiments: 2016

✧Defocused p+



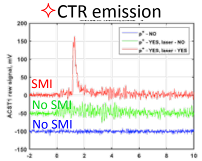
M. Turner, CERN

✧Modulation at 10 ps scale



K. Rieger, MPP

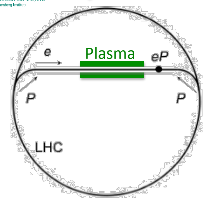
✧CTR emission



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

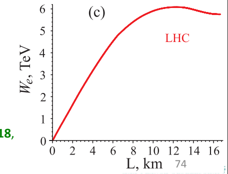


- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable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

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

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"

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

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 (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 physics roadblocks/show stoppers

SUMMARY

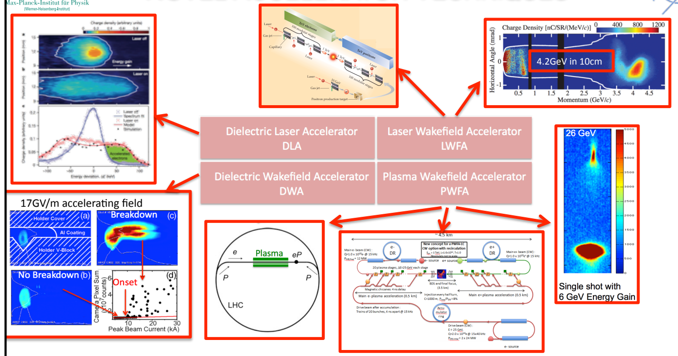
- Number of technical challenges towards collider beams (last talk): a priori solvable
- Some e^+-symmetric schemes (DLA, DWA), some applications need not e^+ (e^-/p^+)
- "Large scale" experiments: FACET, DESY Flash Forward, INFN SPARC_LAB, CERN AWAKE, BELLA, CILEX, ELI, etc.
- Need facility(ies) dedicated 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)

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

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

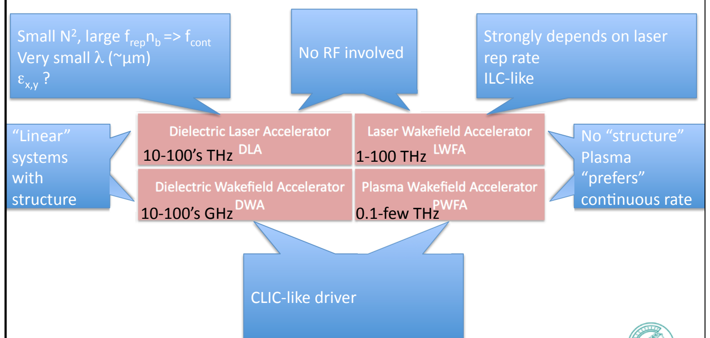
NOVEL ACCELERATOR TECHNIQUES



- 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

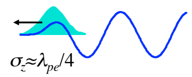
TECHNIQUES

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



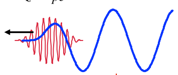
5 PLASMA-BASED ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)
  A high energy particle bunch (e^-, e^+, ...)
  P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)

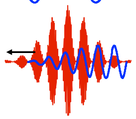


$\sigma_z \approx \lambda_{pe}/4$

- 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

- Self-Modulated PWFA (sMPPWFA)

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

LWFA-BASED COLLIDER CONCEPT

Schroeder , PRSTAB, 13, 101301 (2010)

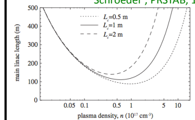


FIG. 3. Main single-linac length versus plasma density n for several laser in-coupling distances L_c, for $E_b = 0.5$ TeV and $a_0 = 1.5$.

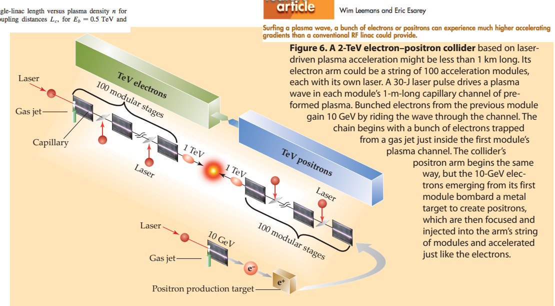


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed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