Worldwide Overview of

present and future

Plasma Wakefield Accelerator Experiments

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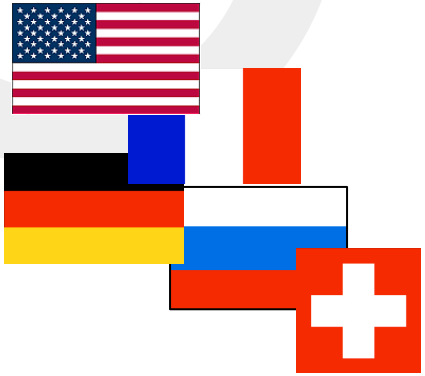

Work supported by US DoE

OUTLINE

Introduction

PWFA status and challenges

PWFA experiments

- Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF)
- SLAC National Accelerator Laboratory FACET
- SLAC Linear Collider Light Source (LCLS)
- MPP-CERN Proton-driven PWFA
- Budker Institute of Nuclear Physics, Novosibirsk, Russia

Summary

Renewed interest in PWFA sparked by SLAC results and availability of new beams

(c.f., WG4 attendance)

OUTLINE

USC UNIVERSITY OF SOUTHERN CALIFORNIA

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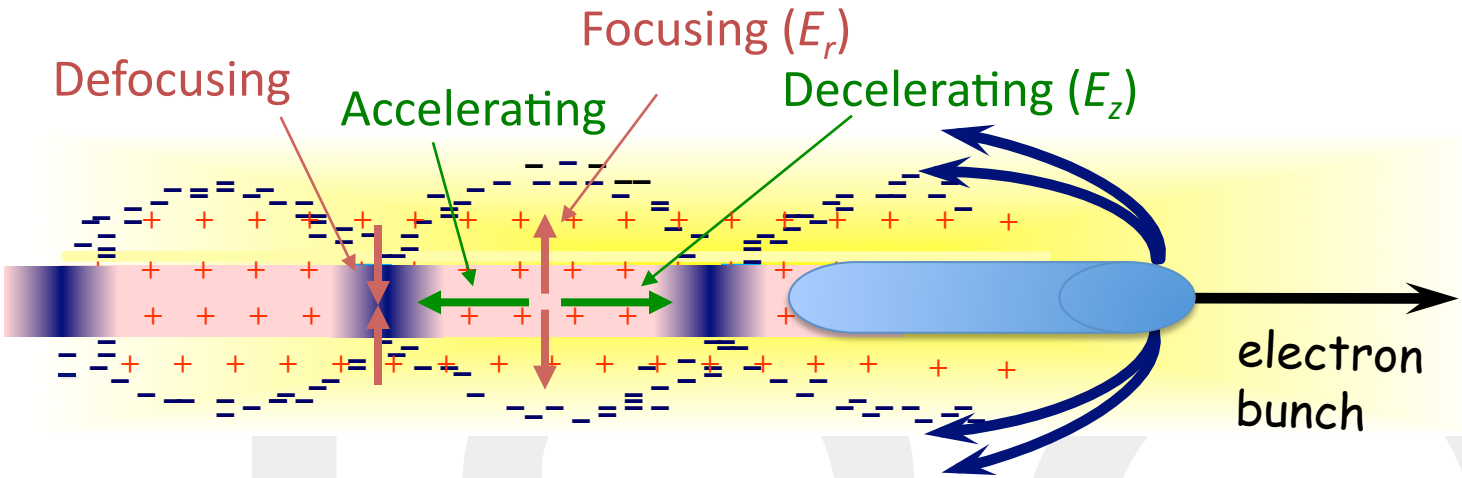
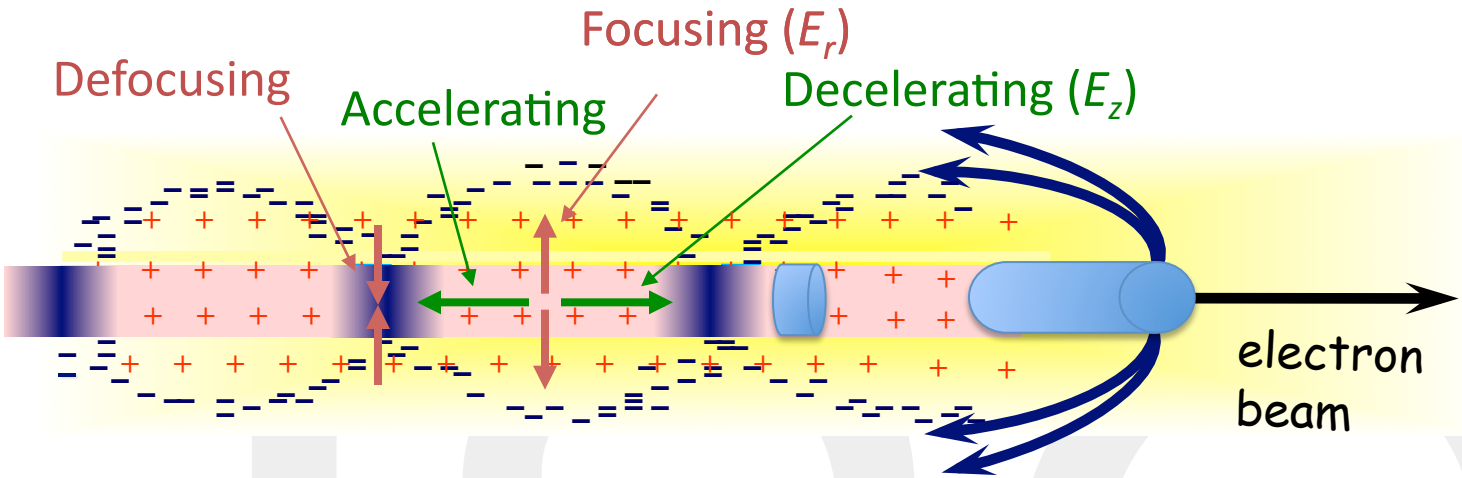
Summary

PWFA



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Plasma e^- rush back on axis => energy gain
- Can be optimized for acceleration, focusing, radiation, …
- Plasma Wakefield Accelerator (PWFA): high-frequency, high-gradient, strong focusing beam-driven, colinear accelerator

PWFA



- Plasma
- Plasma focusing
- Plasma
- Optimize
- Plasma radient, strong fo

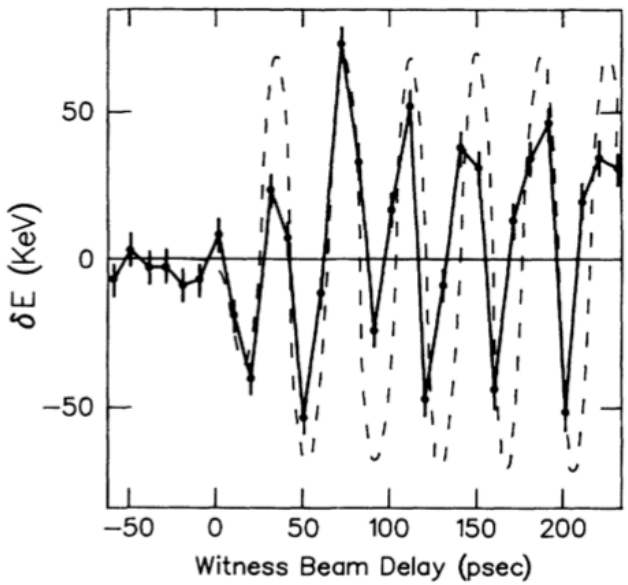
Single bunch for particle acceleration (ΔE/E~1)

Bunch train for bunch acceleration (ΔE/E<<1)

PWFA Milestones

PWFA proposed: Chen, PRL 54 (1985)

Rosenzweig, PRL 61, 98–101 (1988)



The demonstration!

$Q=2.1nC$

$E_0=21\text{-}15MeV$

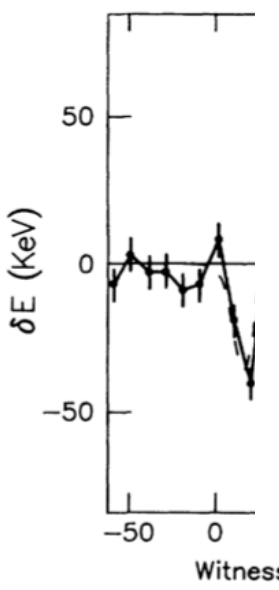
$\sigma_z=2.4mm$

$n_e=10^{12}\text{-}10^{13}cm^{-3}$

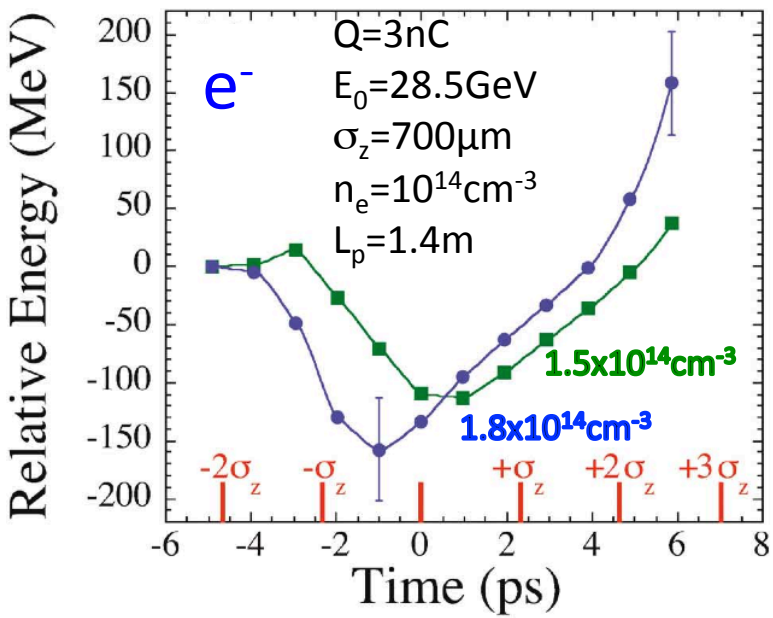
$L_p=20\text{-}35cm$

PWFA Milestones

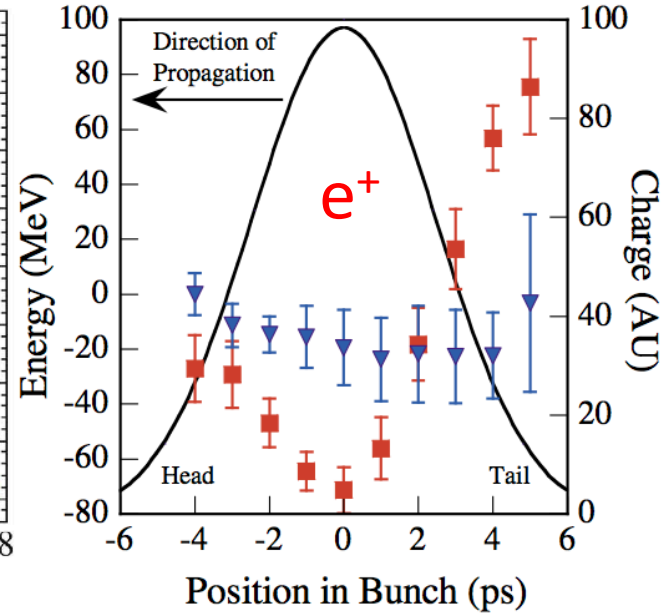
Rosenzweig,



Muggli PRL 93, 014802 (2004)

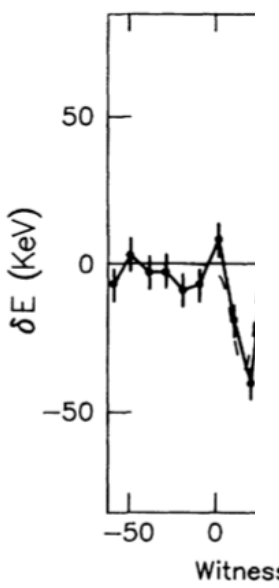


Blue PRL90, 214801 (2003).

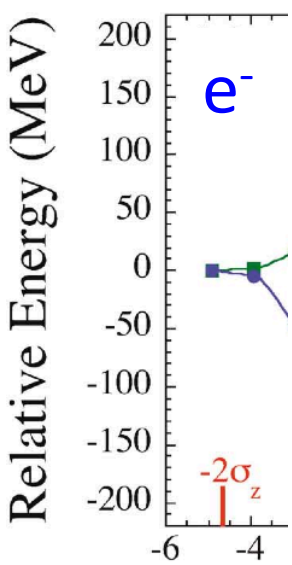


PWFA Milestones

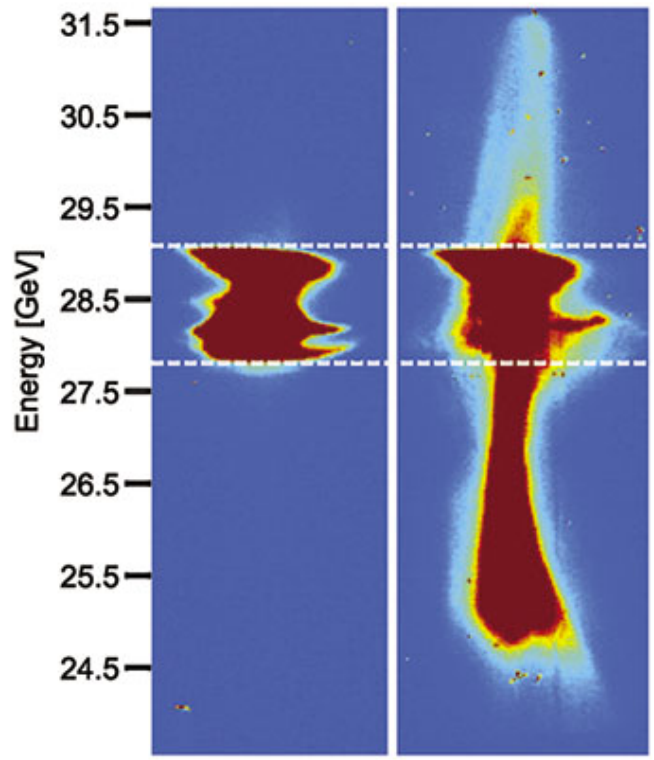
Rosenzweig,



Muggli



Hogan PRL 95, 054802 (2005)



Q=3nC
E_0=28.5GeV
σ_z=20μm
n_e=2.7x10^{17}cm^{-3}
L_p=10cm

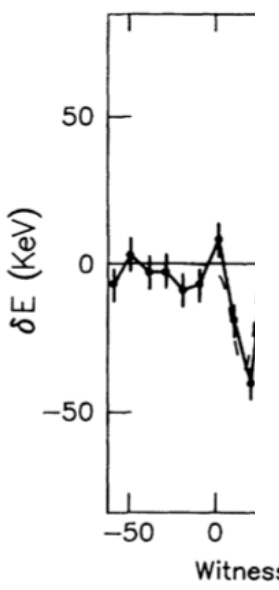
$$E_{acc.\ \max} \propto \frac{N}{\sigma_z^2}$$

$$n_e \propto \frac{1}{\sigma_z^2}$$

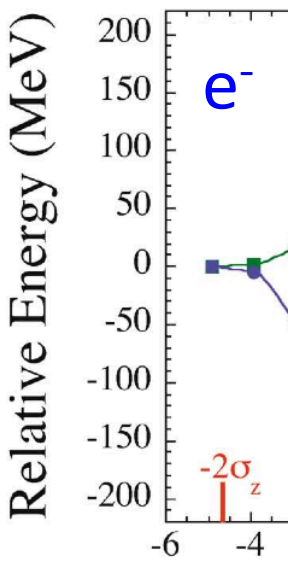
PWFA Milestones

Blumenfeld Nature 445, 741 (2007)

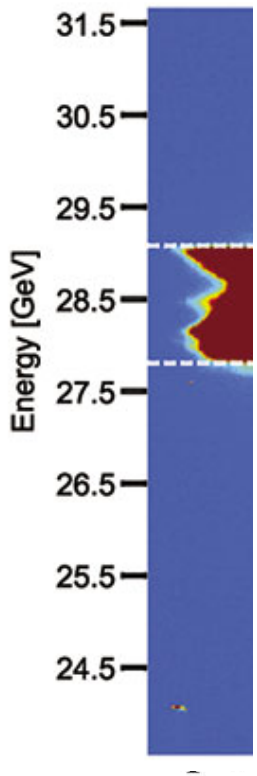
Rosenzweig,

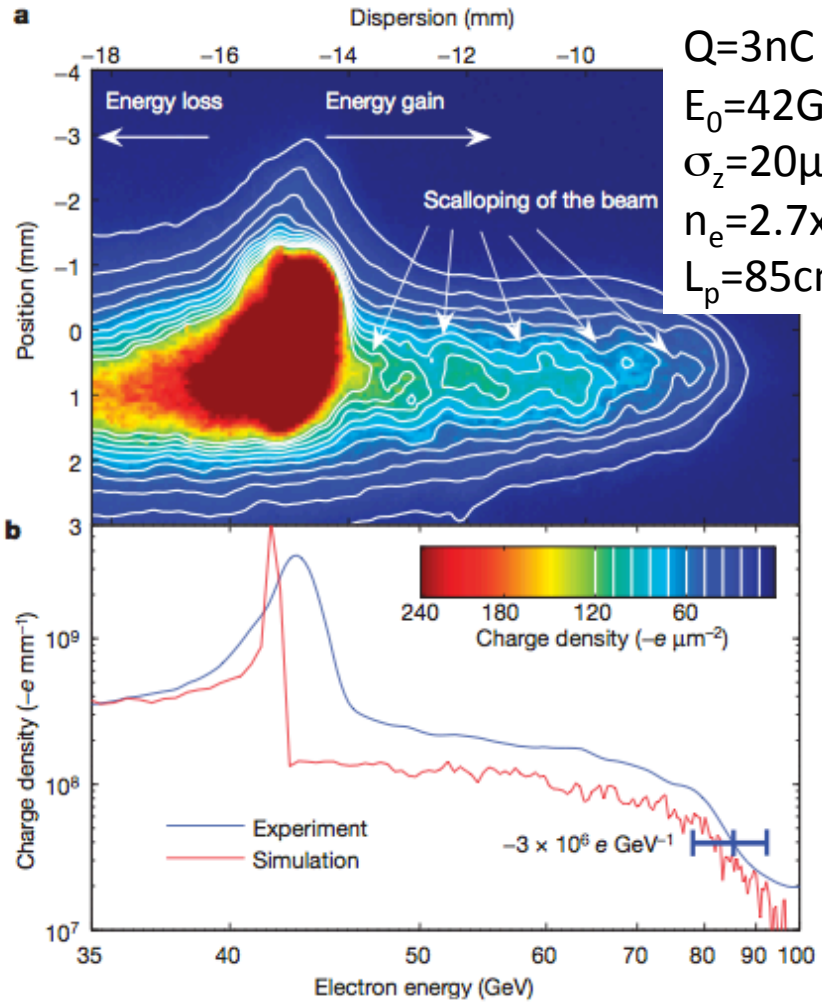


Muggli



Hogan





Q=3nC
E_0=42GeV
σ_z=20μm
n_e=2.7x10^{17}cm^{-3}
L_p=85cm

Significant progress
Large energy gain with a single bunch, particle acceleration

PWFA Recipe

Relativistic, short, dense bunch(es):

Accelerating gradient: $E_{z,accel}(V/m) \cong 2\times10^{-9}\frac{N}{\sigma_z^2}$ with $\frac{\sigma_z}{\lambda_{pe}} \cong \frac{1}{\sqrt{2\pi}}$ and $\frac{\sigma_r}{\lambda_{pe}} << 2\pi$

(max., single bunch, lin.)

Typically for 1GV/m: $N = 2\times10^{10}$ $\sigma_z \cong 200\mu m$ $\sigma_r << 137\mu m$ in $n_e = 1.4\times10^{15} cm^{-3}$

Blowout, nonlinear regime: $\frac{n_b}{n_e} > 1$ $(\sigma_r < 67\mu m)$

Pure ion column focusing: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c} \cong 42 kT/m$ free of geometric aberrations

Wavebreaking field: $E_{WB} = 3.6 GV/m$

Combination of large transverse focusing gradient and large accelerating field leads to large energy gain

All the beam particles and the wake are ultra-relativistic → no dephasing!

High energy (per particle) drive bunch

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PWFA STATUS: PROPAGATION

Beam-plasma matching condition: $\beta_0 = \frac{\sigma_r^2}{\varepsilon} = \frac{\gamma\sigma_r^2}{\varepsilon_N} = \frac{1}{k_\beta} = \frac{c\sqrt{2\gamma}}{\omega_{pe}}$ $\quad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$

Barov, PRL 80, 81 (1998)

Argone

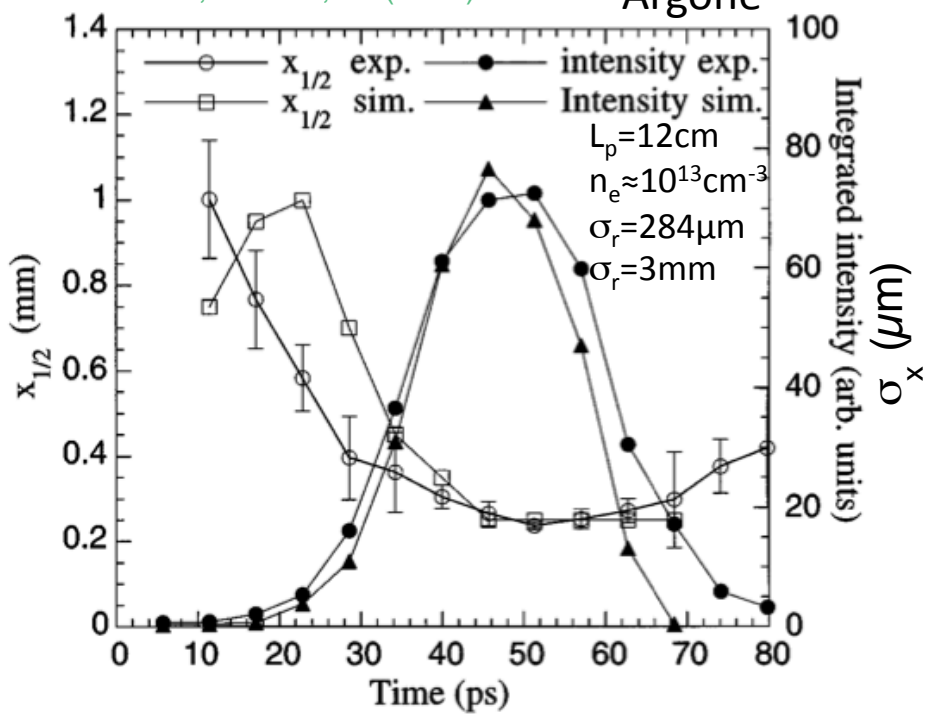
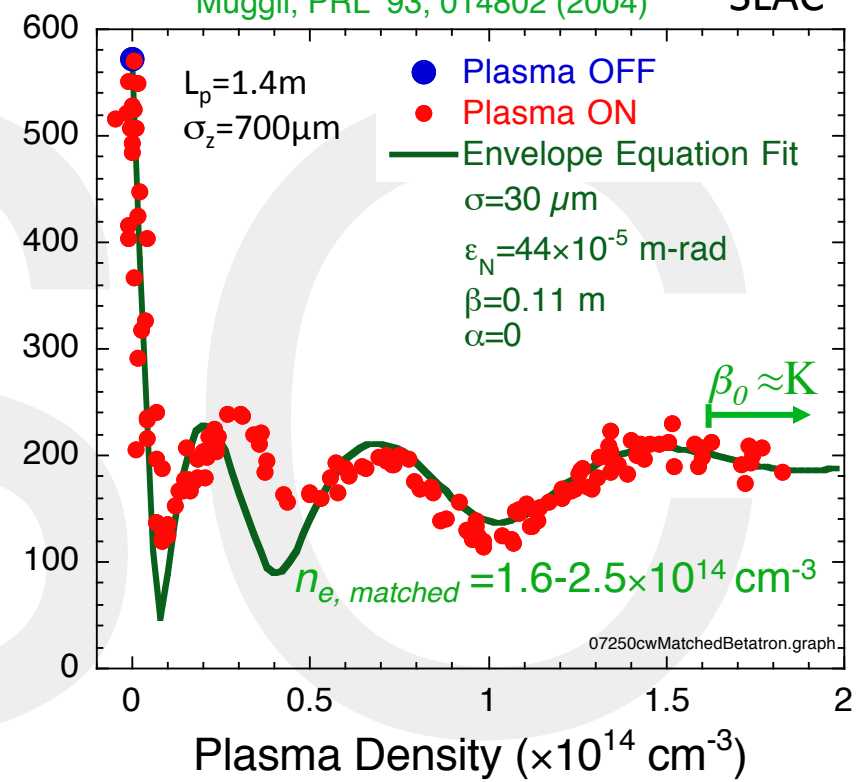


FIG. 5. Time-slice dependence of beam intensity and half-width, from experiment (exp.) and PIC simulation (sim.).

Muggli, PRL 93, 014802 (2004)

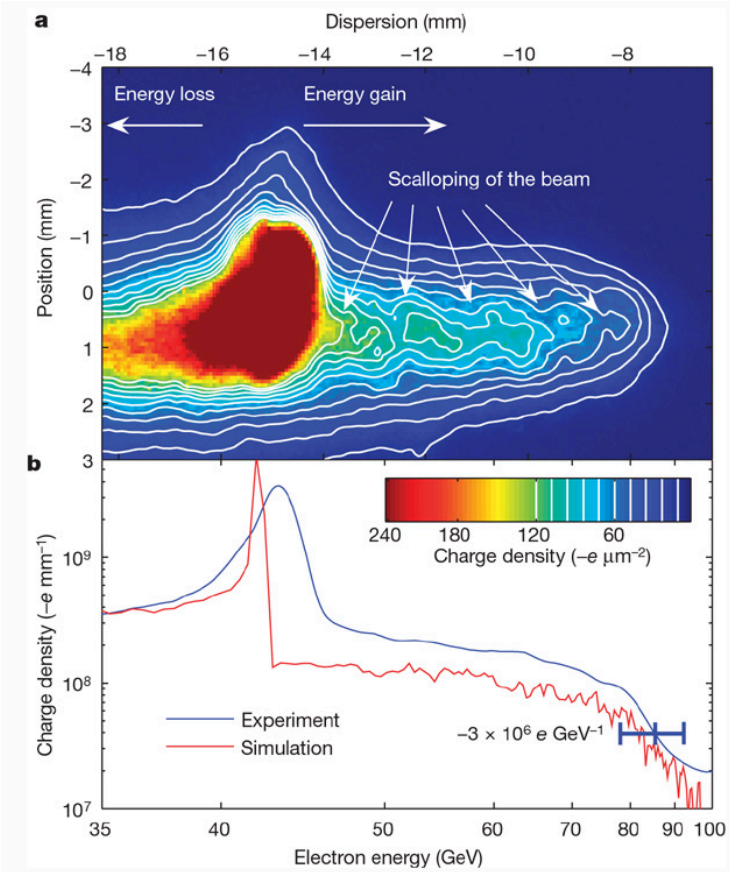
SLAC



Matched propagation over >10β_0 in both cases, m-long propagation

Transverse beam-plasma matching demonstrated

PWFA STATUS: ACCELERATION



Blumenfeld, Nature 445, 741 (2007)

SLAC

L_p=85cm

$n_e \approx 2.7\times10^{17}cm^{-3}$

σ_r=10μm

σ_z=15μm

N=1.8×10^{10}

Nonlinear regime

Yakimenko, 91, 014802 (2003)

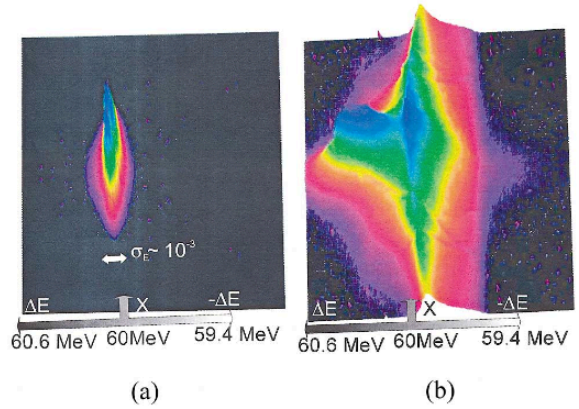


FIG. 4 (color). Spectrometer images, showing intensity in a combined false-color and contour plot. Energy is shown on the horizontal axis and transverse size in the vertical axis: (a) plasma off, (b) plasma on, $\Delta t = 3\ \mu s$.

BNL-ATF

L_p=1.7cm

$n_e \approx 3.6\times10^{16}cm^{-3}$

σ_r=100μm

σ_z=450μm

Q=300pC

E_0=60MeV

Linear regime!

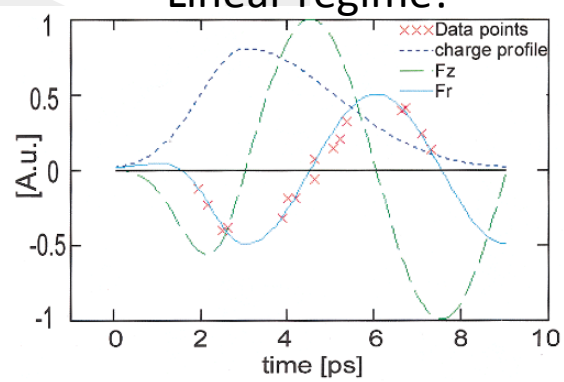


FIG. 6 (color). Expected phasing of longitudinal and transverse wake forces induced by the bunch, and experimental points reconstructed from the energy slices using double-Gaussian fit.

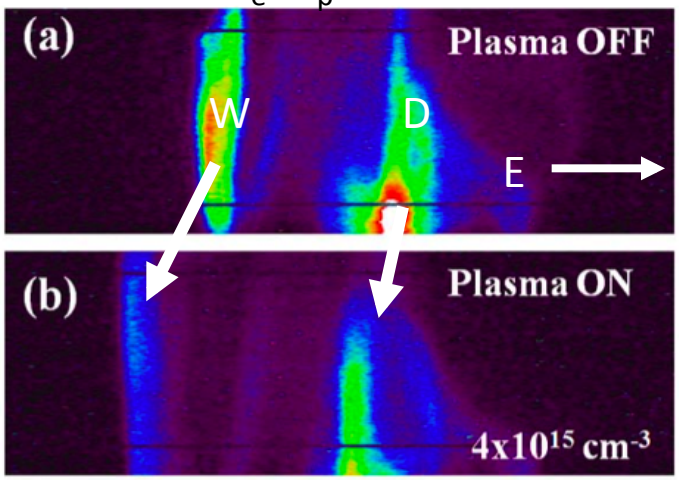
Large energy gain (42GeV) in large gradient (50GeV/m) meter-scale plasma

PWFA STATUS: ACCELERATION

Kallos, PRL 100, 074802 (2008)

Low n_e: $\lambda_p > \Delta z$

Optimum n_e: $\lambda_p \approx \Delta z$



BNL-ATF

σ_r=100µm

σ_{zD}=45µm

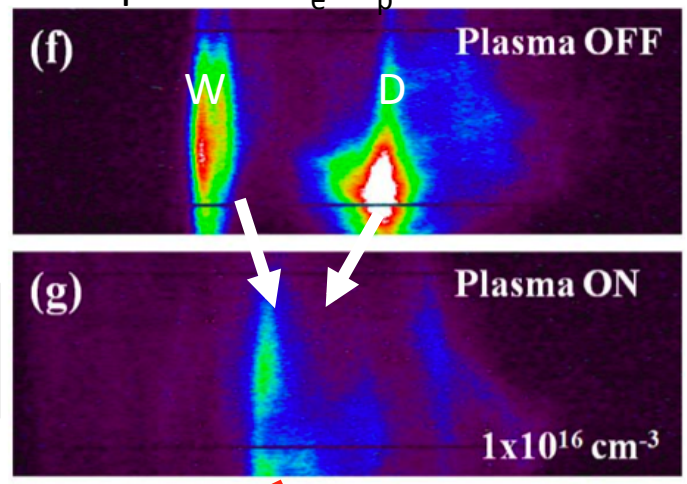
σ_{zW}=27µm

Δz=150µm

Q_{dD}=300pC

Q_{dD}=180pC

E_0=60MeV

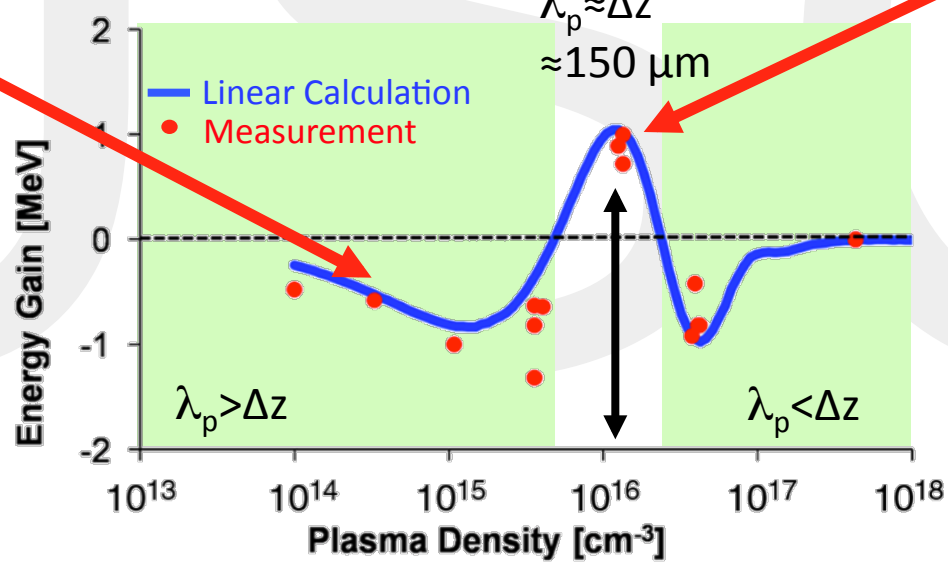


Loss

Gain

$\lambda_p \approx \Delta z$

$\approx$150 µm



E_{gain}=+0.9 MeV

E_{loss}=-1.0 MeV

ΔE=+1.9 MeV

L_p=6 mm

G_{loss} =-315 MeV/m

G_{loaded} =150 MeV/m

First large gradient acceleration of a witness bunch with beam loading

PWFA Status: Acceleration

Kallos, PRL 100, 074802 (2008)

The PWFA is well understood
Propagation and energy gain
Large energy gain by particles has been achieved

The wakefields exist!

Can they be used?

… and is there some fun physics to do?

First large gradient acceleration of a witness bunch with beam loading

PWFA Chalenges

Can the wakefields be used? For an e^-/e^+ collider?

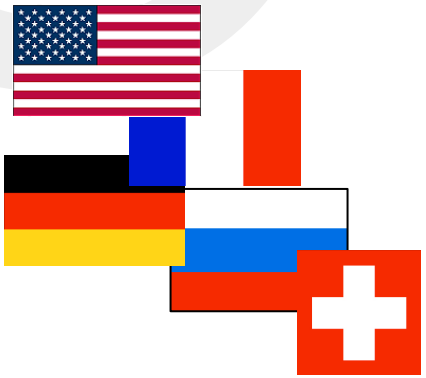
Generation of a bunch train: drive/witness

- Acceleration with a narrow energy spread
- Energy transfer efficiency
- Transformer ratio
- Beam loading
- Emittance preservation
- The positron bunch case

Staging

Energy frontier

e^-/e^+ collider



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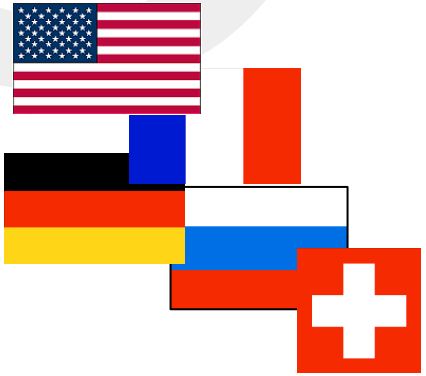
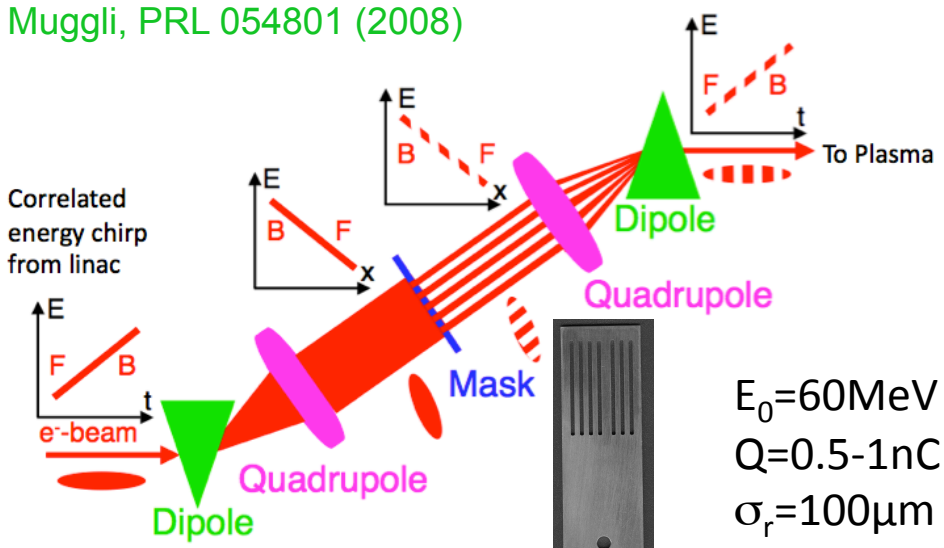
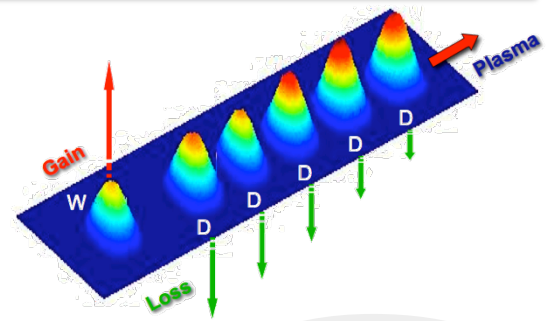


BNL-ATF

Muggli, PRL 054801 (2008)

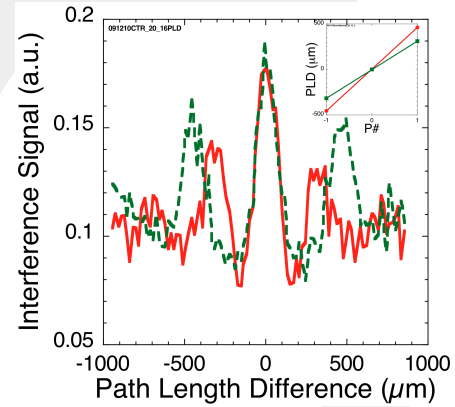




$\Delta z_{D\text{-}D}$=313µm $\Delta z'_{D\text{-}W}$=458µm

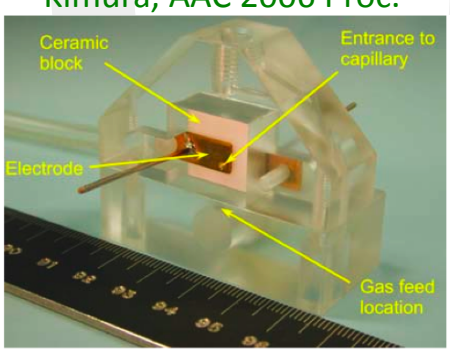
E_0=60MeV
Q=0.5-1nC
σ_r=100µm
σ_z=1.6mm
$n_b \approx 10^{13} cm^{-3}$

PWFA in linear regime



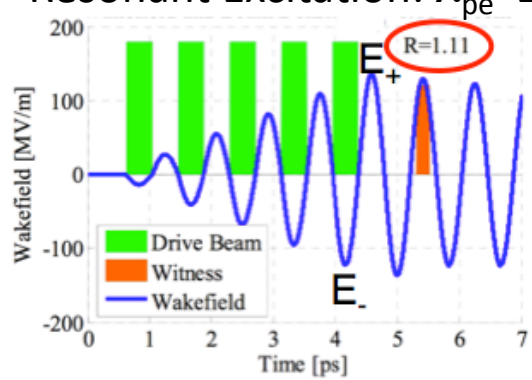
Capillary Discharge Plasma

Kimura, AAC 2006 Proc.



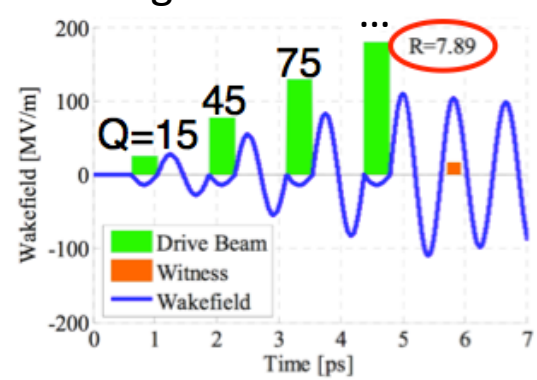
$n_e=10^{14}\text{-}10^{17} cm^{-3}$
L_p=1-2cm

Resonant Excitation: $\lambda_{pe}=\Delta z$



Kallos, PAC'07 Proceedings

Large Transformer Ratio

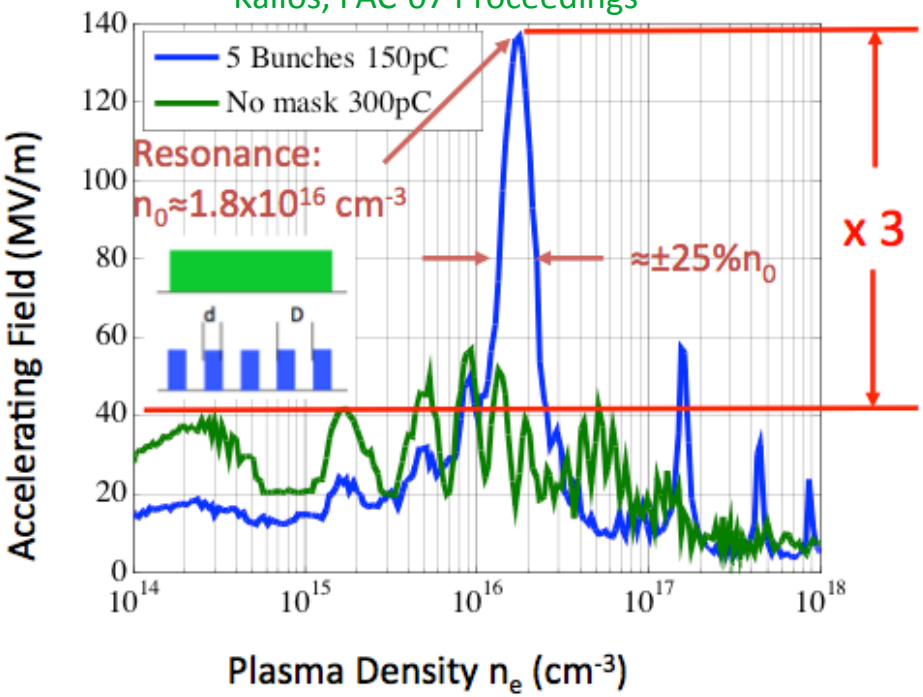


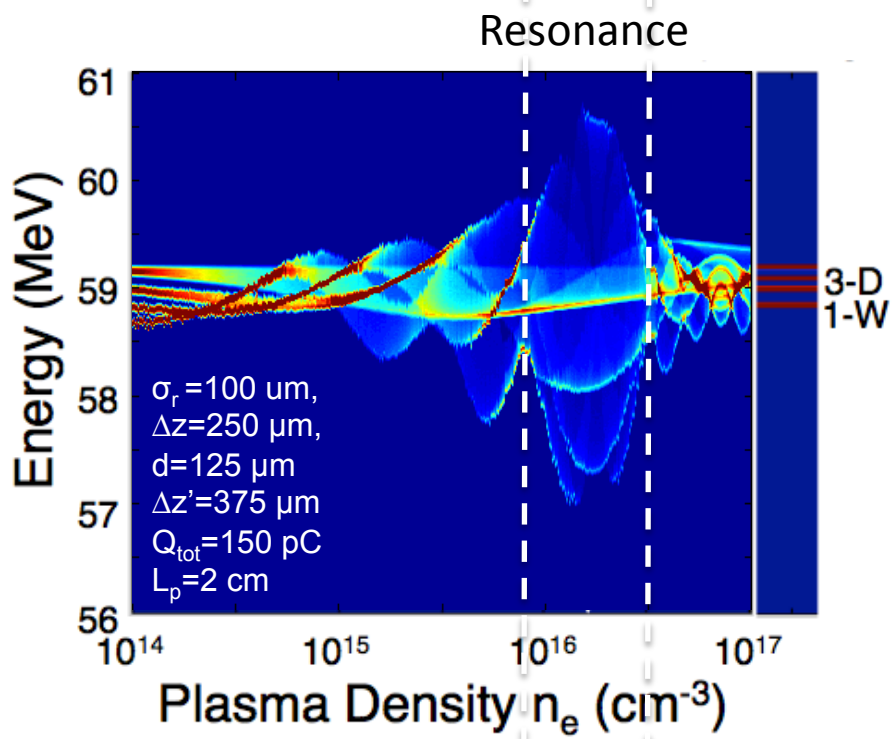
*Tsakanov, NIMA, 1999

BNL-ATF: CALCULATIONS

2D linear calculation microbunches with equal charge

Kallos, PAC'07 Proceedings





Expect ≈MeV energy gain/loss over 1-2 cm

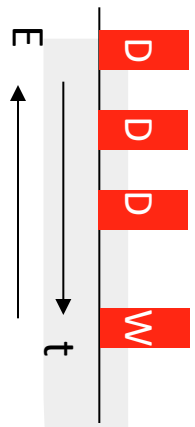
Resonance clear, and narrow

BNL-ATF

Experimental

=100 um,
z=350 μm

0.7 MeV



Preliminary!

- Vary # drive bunches
- Block witness bunch
- Reverse train chirp

Plasma Density n_e (cm^{-3})

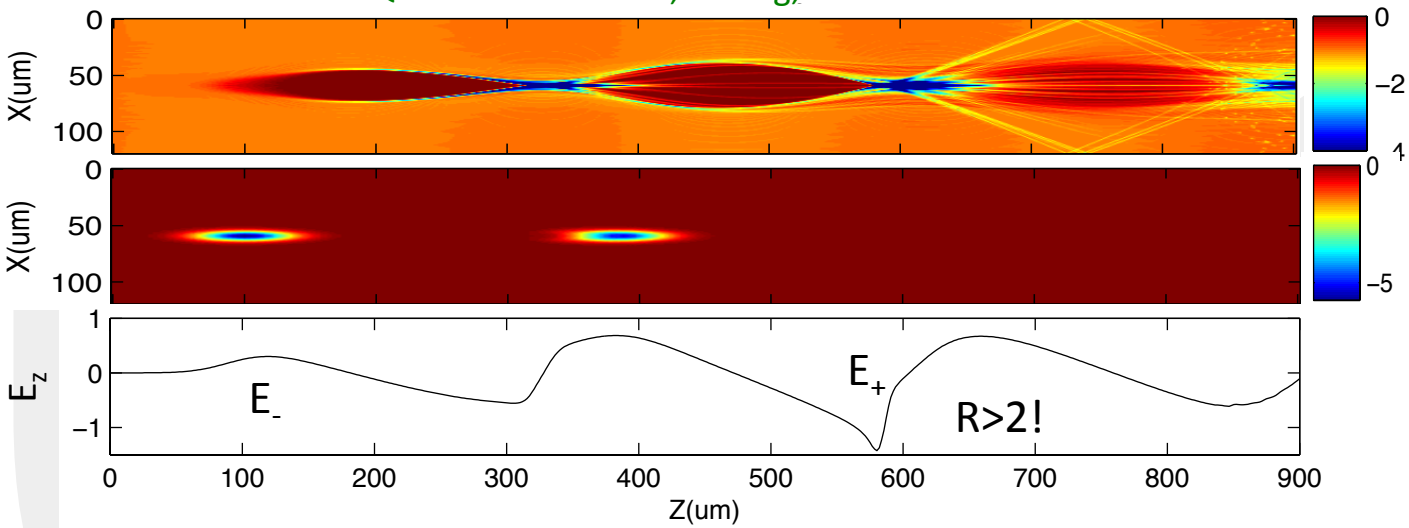
Energy gain, up to 0.7 MeV?

Stability of $\Delta E/E_0$ => stability of Δz!

BNL-ATF

With tight focusing the ATF beam can reach "nonlinear" PWFA regime

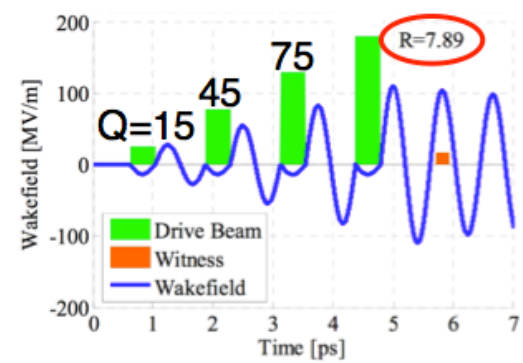
QuickPIC simulation, Y. Fang, USC



σ_r=3um
σ_z=25um
Q=40pC
$n_b=7.06*10^{16}cm^{-3}$
Δz=282um
E_0=59MeV (γ=115.3)
$n_e=1.24x10^{16}cm^{-3}$
$\varepsilon_N=10^{-6}$m-rad

E_{wb}=11GV/m!

Can study large transformer ratio from ramped bunch train
not in the linear case,
or in the "weakly nonlinear case" (W. Lu)
or in the "quasi-nonlinear case" (J. Rosenzweig)
for application to a collider case



*Tsakanov, NIMA, 1999

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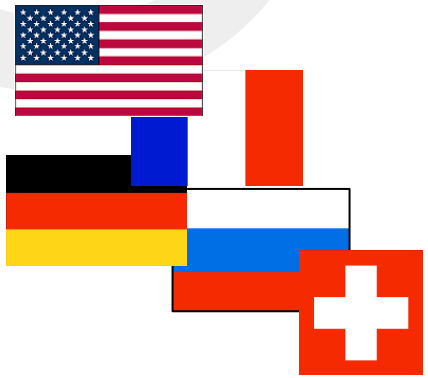

FACET @ SLAC: 2nd Generation PWFA Experiments

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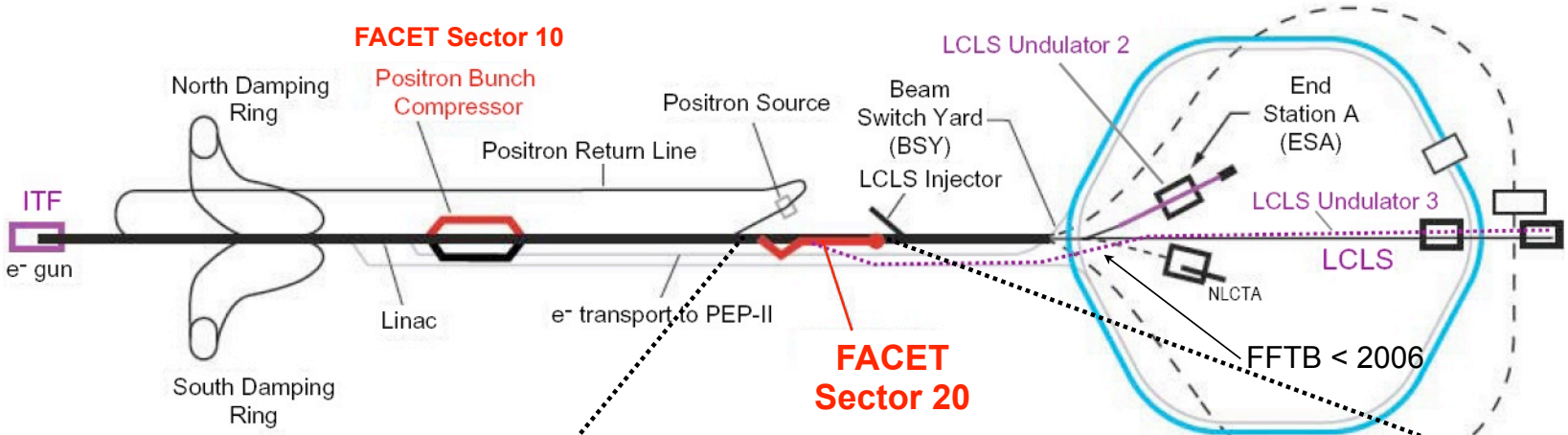
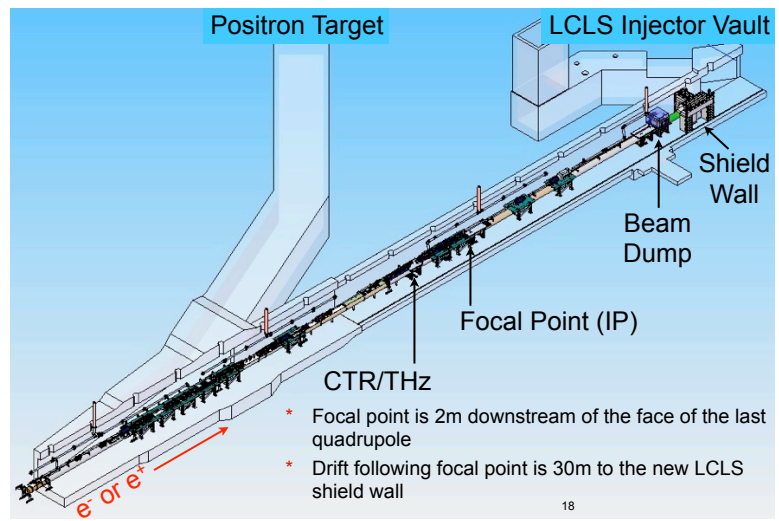


Nominal
FACET Beam Parameters

Energy	23 GeV
Charge	3 nC
Sigma z	14 μm
Sigma r	10 μm
Peak Current	22 kAmps
Species	e^- & e^+

e^-/e^- & train e^+/e^+ masking technique
&
e^-/e^+ train
"Sailboat" chicane
High-gradient acceleration of high-quality bunches

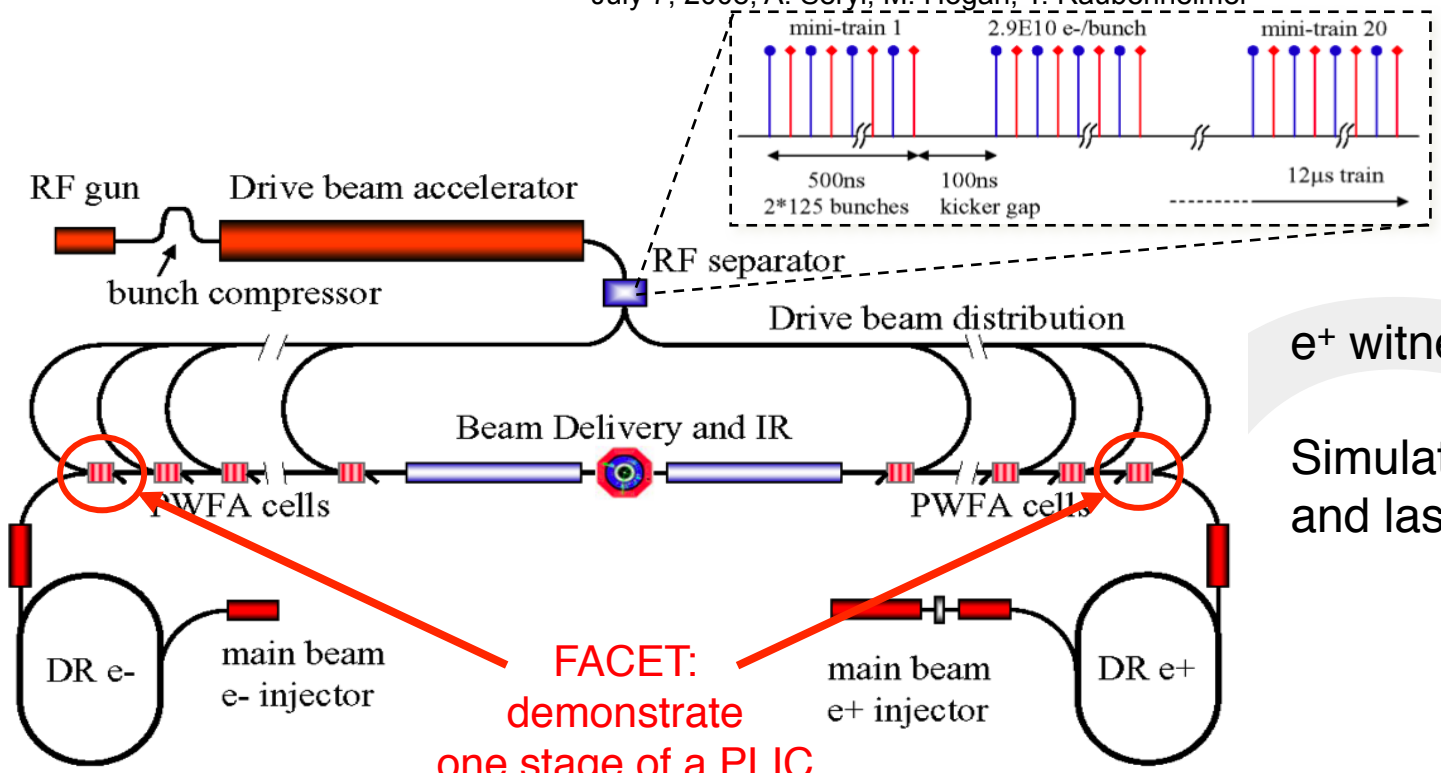


SLAC/UCLA/USC

Adapted from M. Hogan slides

FACET @ SLAC

July 7, 2008, A. Seryi, M. Hogan, T. Raubenheimer



FACET:
demonstrate
one stage of a PLIC
23 GeV e^-/e^+

e^+ witness on e^- wake

Simulations of first and last e^- stage ✓

Concept to be developed …

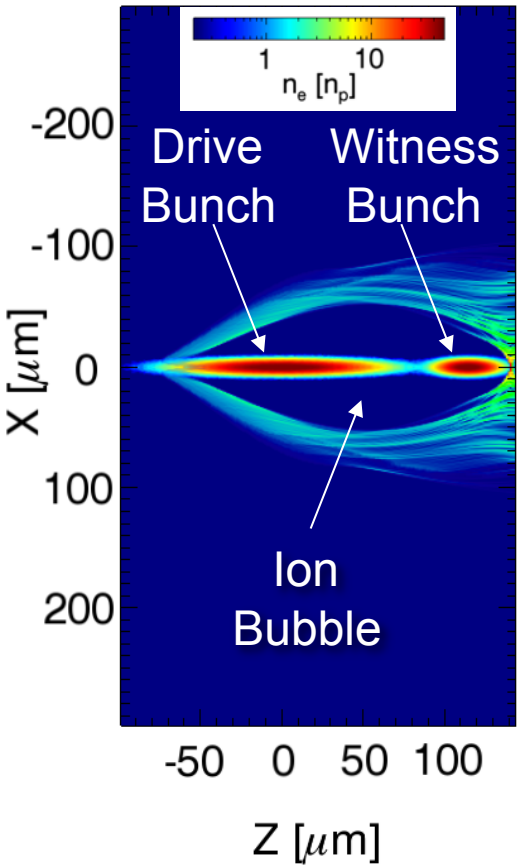
Second generation PWFA experiments: -2-bunch generation
-acceleration with narrow energy spread
-energy transfer efficiency, beam loading
-high gradient, high quality positron bunch acceleration

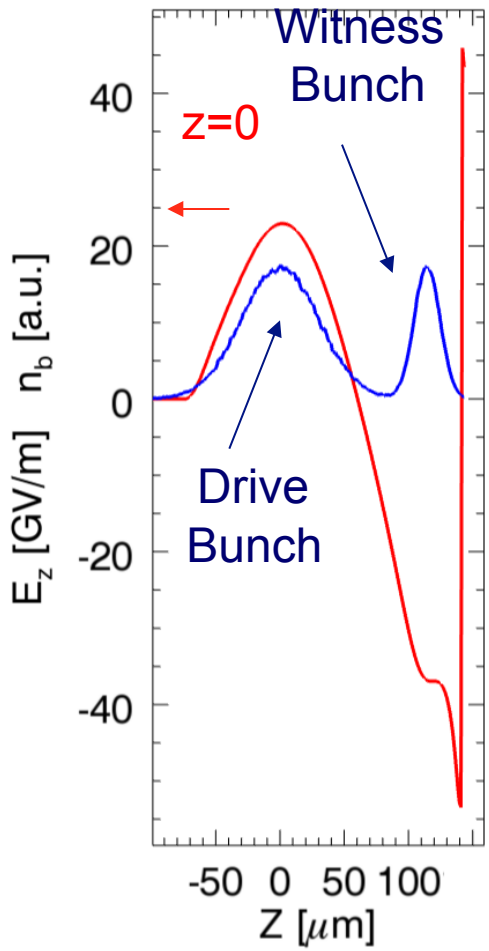
Third generation: -staging

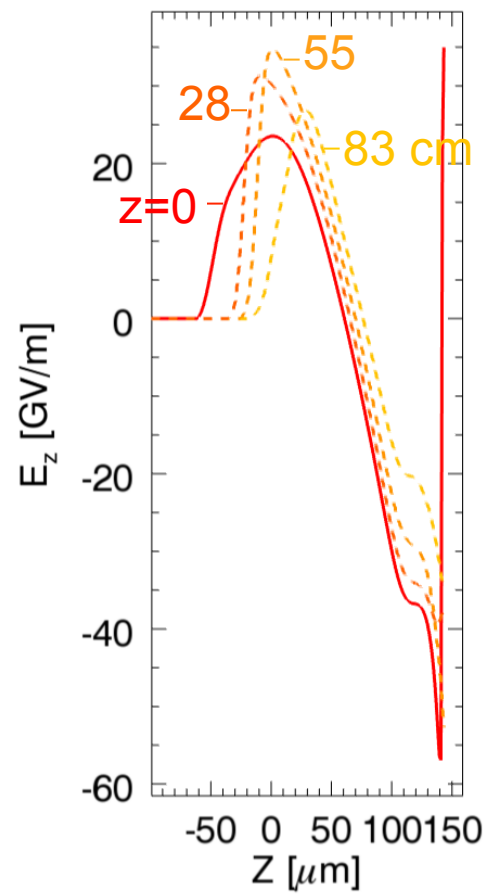
FACET @ SLAC: BUNCH ACCELERATION

QuickPIC simulation, D: σ_z=30μm, N=3x10^{10}e$^-$
W: σ_z=10μm, N=1x10^{10}e$^-$, σ_{r0}=3μm

Δz=115μm, n_e=10^{17}cm^{-3}





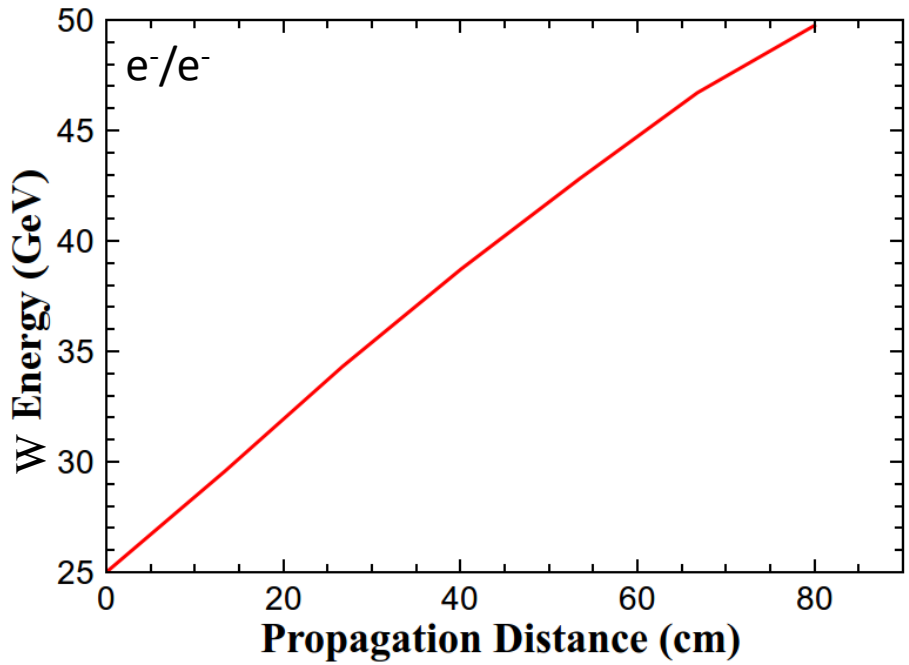


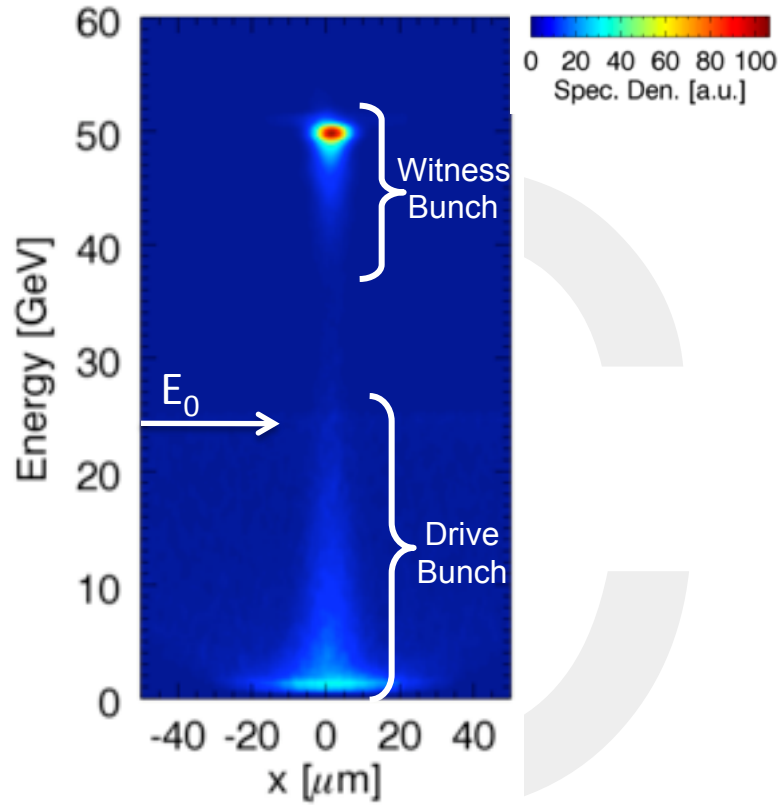
Beam loading @ 37GV/m (z=0)
Wake evolution due to bunch head erosion, but no dephasing

Hogan, New J. Phys. 12, 055030 (2010)

FACET @ SLAC: BUNCH ACCELERATION

QuickPIC simulation, D: σ_z=30μm, N=3x10^{10}e$^-$
W: σ_z=10μm, N=1x10^{10}e$^-$, σ_{r0}=3μm
Δz=115μm, n_e=10^{17}cm^{-3}, E_0=25GeV





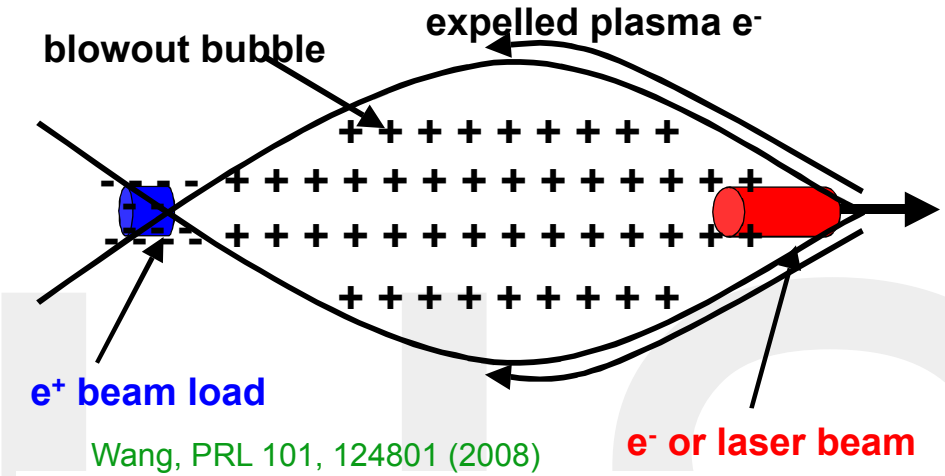
Wake evolution "bends" energy gain

L_p=80cm, gain 25GeV, $\Delta E/E_0 \approx 3\%$, BUNCH ACCELERATION!

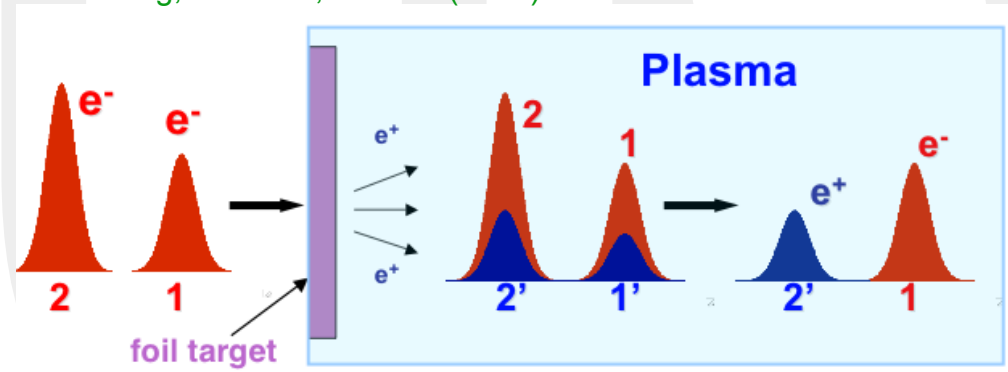
D to W energy transfer efficiency ≈30%

Hogan, New J. Phys. 12, 055030 (2010)

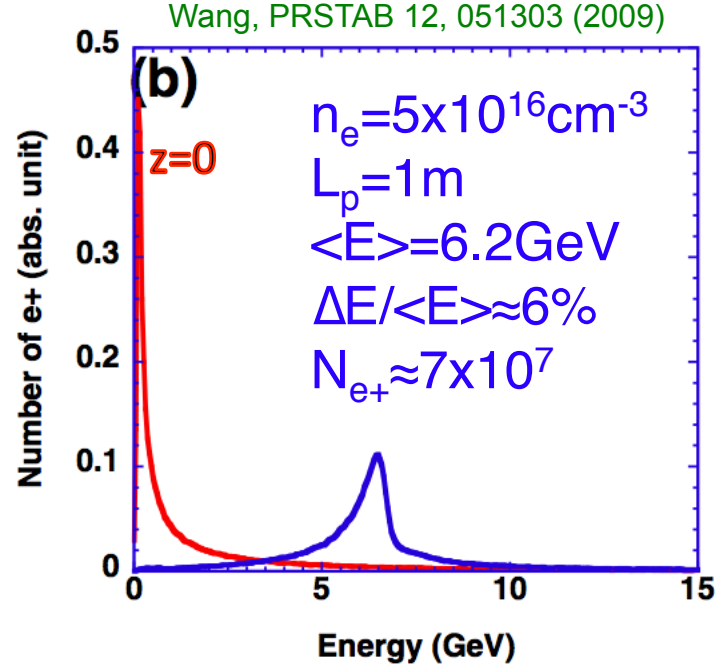
FACET @ SLAC: e+ ACCELERATION



Wang, PRL 101, 124801 (2008)

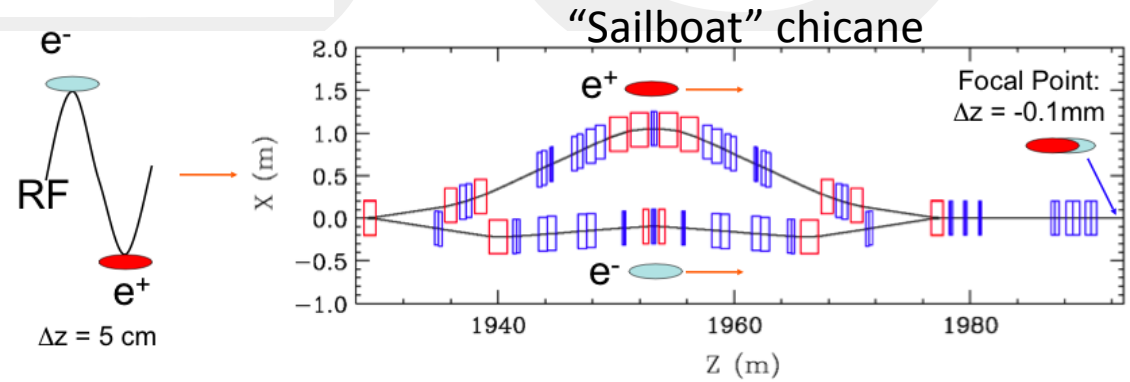


Wang, PRSTAB 12, 051303 (2009)



Test of e+ acceleration on e- wake before …

Wide open field for solution …



OUTLINE

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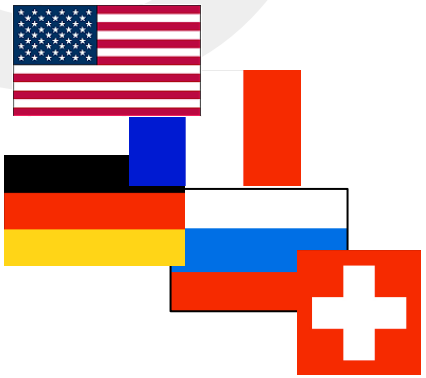

PWFA WITH LCLS BEAM

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Measurements and Simulations for 20-pC Bunch at 14 GeV

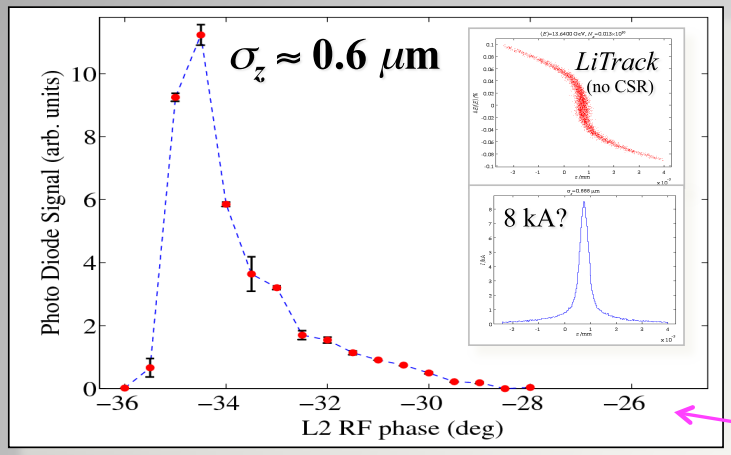
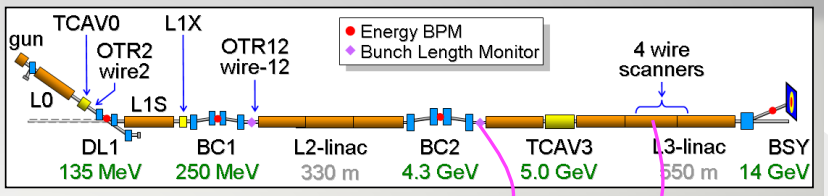
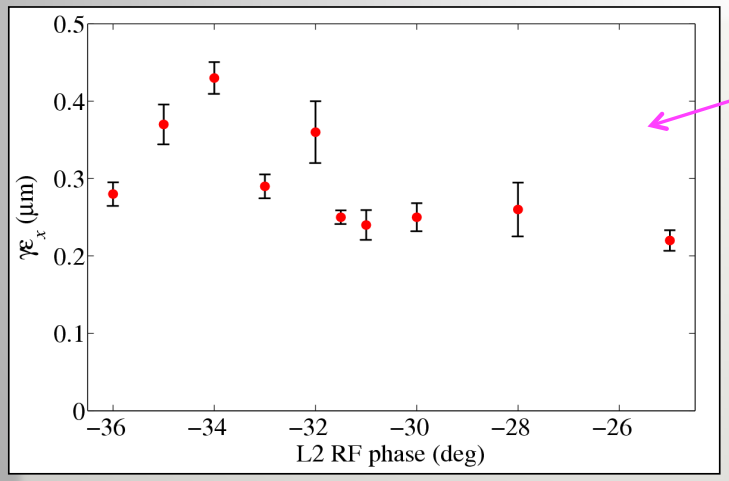
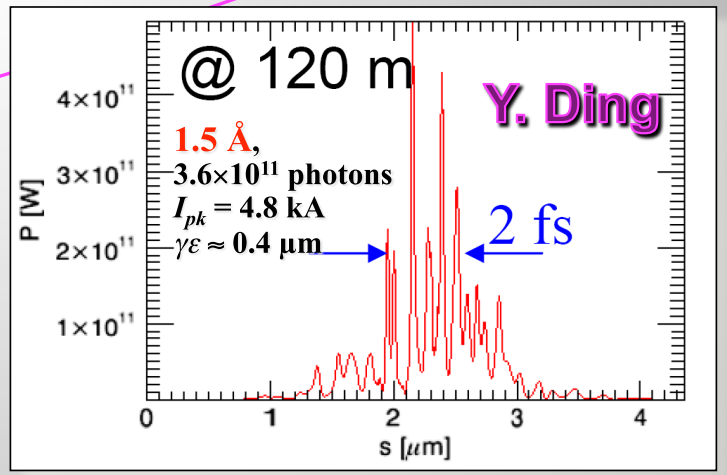


Photo-diode signal on OTR screen after BC2 shows minimum compression at L2-linac phase of -34.5 deg.





Horizontal projected emittance **measured** at 10 GeV, after BC2, using 4 wire-scanners.



LCLS FEL **simulation** at 1.5 Å based on measured injector beam and *Elegant* tracking, with CSR, at 20 pC.

Courtesy J.B. Rosenzweig

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Optimized excitation at LCLS

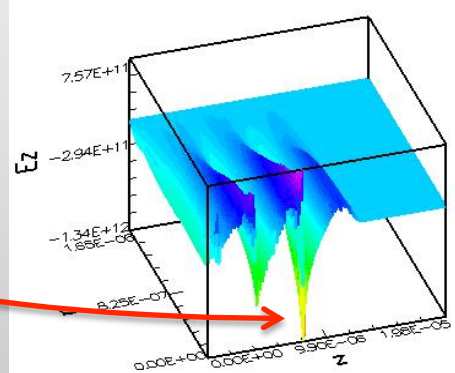
- Beam must be short and narrow compared to plasma skin depth $\sigma_r < k_p^{-1}$ $\sigma_z < k_p^{-1}$
- In this case $\tilde{Q} > 1$ implies $n_b > n_0$, blowout $\tilde{Q} \equiv \frac{N_b k_p^3}{n_0}$
- With 2 fs LCLS beam we should choose $n_0 = 7 \times 10^{19}$ cm^{-3}

  σ_r<600nm!
- For 20 pC beam, we have $\tilde{Q} = 7$
- Linear "Cerenkov" scaling

$$eE_{z,dec} = e^2 N_b \int \frac{n(k)-1}{n(k)} dk \Rightarrow = e^2 N_b k_p^2 \qquad eE_{z,dec} \cong \frac{4e^2 N_b}{\sigma_z^2}$$

- *1 TV/m fields* (!)
- Collaboration initiated
  - UCLA-SLAC-USC

OOPIC simulation of LCLS case



Courtesy J.B. Rosenzweig

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What are the experimental issues?

- Length of plasma: ~1 mm
  - ~1 GeV energy change, perturbative at beginning
- Plasma formation
  - ~3 atm gas jet (for $n_e \approx 7 \times 10^{19} cm^{-3}$)
  - Ionization via LCLS X-rays? Not highly relevant
  - Beam-induced ionization (PHysics with capital PH)
- Beam focusing
  - Need few hundred nm beam
  - Use strong-field mini-beta insertion
  - Easily installable, minimal disruption
- Ion collapse
- Beam diagnostics in new regime

Courtesy J.B. Rosenzweig

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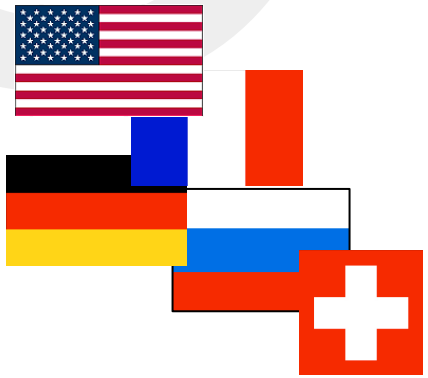
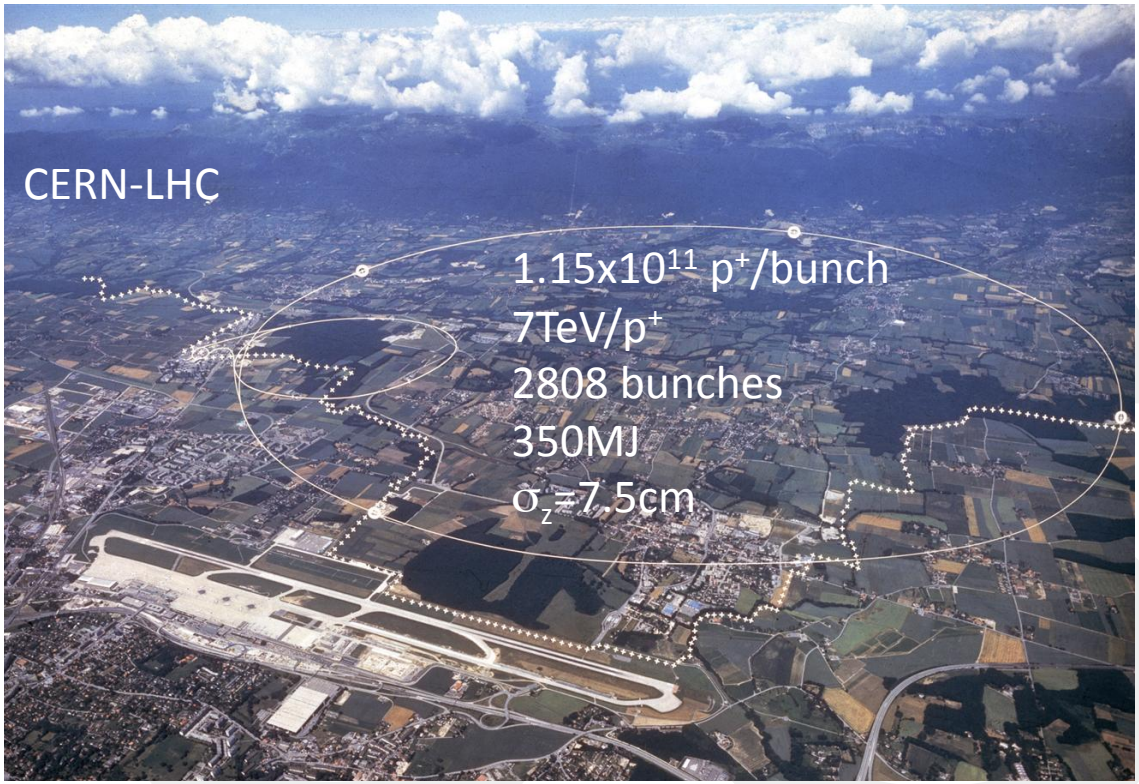
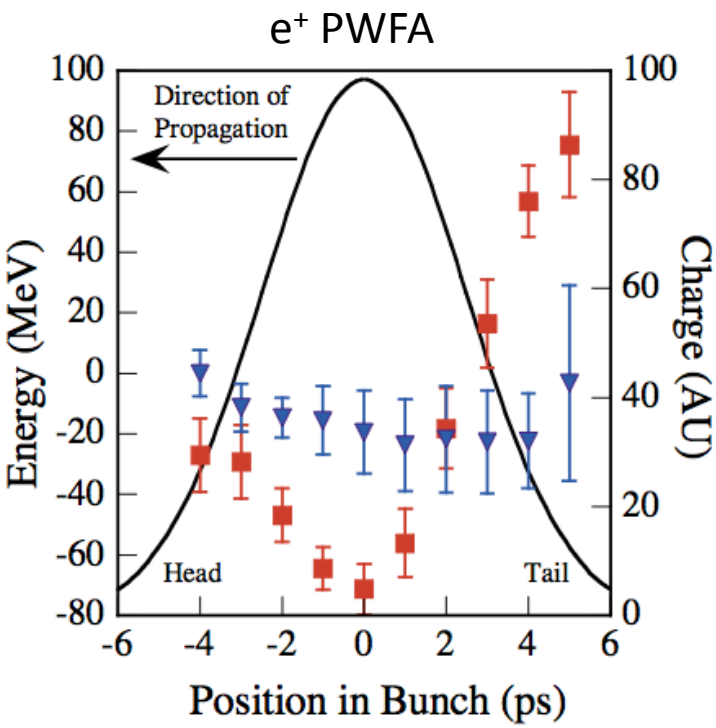


PROTON-DRIVEN PWFA



Blue, PRL 214801 (2003)



Proton beam could be potential high energy drivers to accelerate e^-/e^+ bunches in PWFAs

Single LHC 7TeV bunch, 1.15×10^{11} p^+, carries 140kJ!
Single ILC 1TeV bunch, 2×10^{10} e^-/e^+, bunch carries only 3kJ!
Can p^+ drivers be recycled?

PROTON-DRIVEN PWFA

Acceleration of e^- on p^+ wake

β=~14m

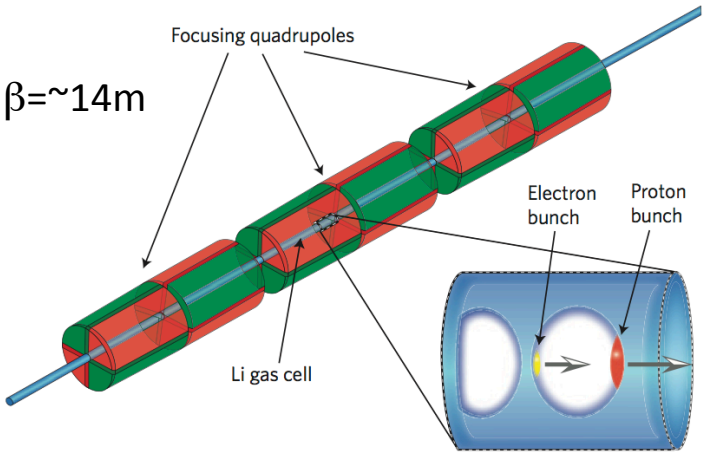
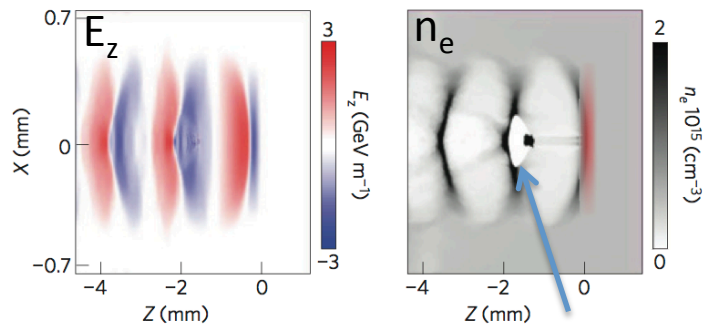


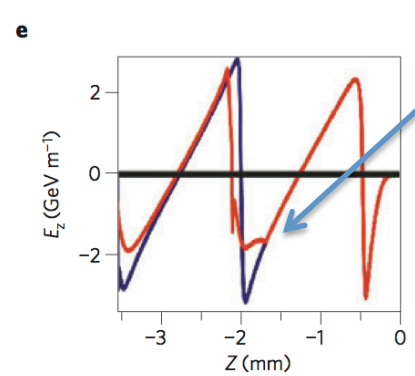
Table 1 | Table of parameters for the simulation.

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

Single stage p^+ PWFA require external focusing for bunch head confinement

Short and wide p^+ bunch drives non-linear wakefields





Beam Loading

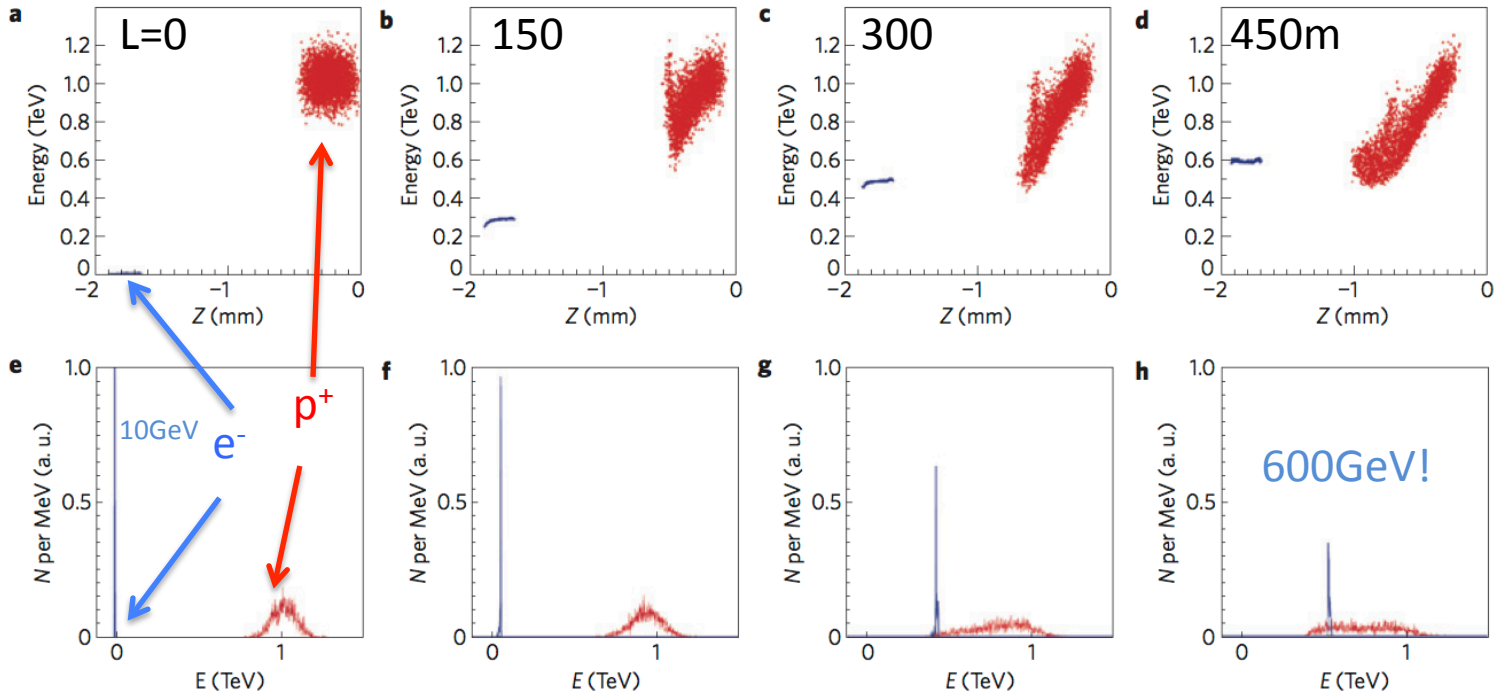
wo W

w W≈2GV/m

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

PROTON-DRIVEN PWFA

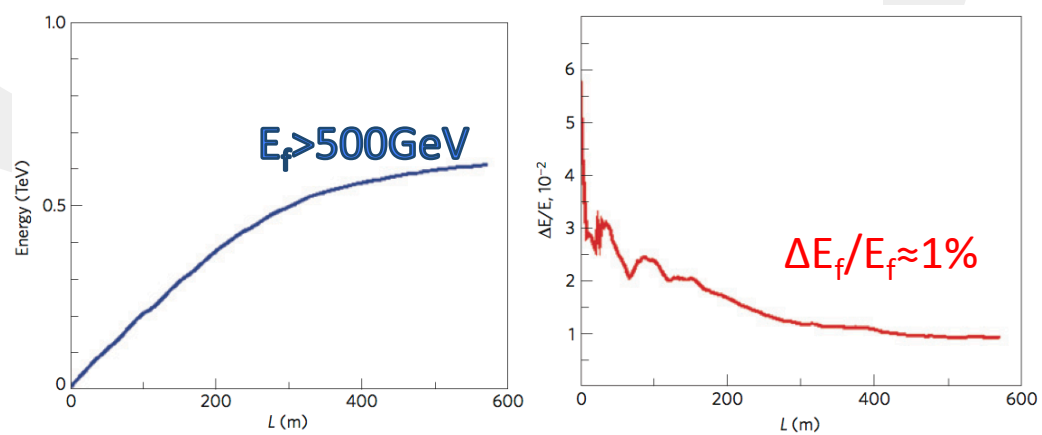
2-D simulations



γ_0=1000,
L=500m,
Dephasing!

Generate 0.6TeV e^-
in ≈500m p^+-driven PWFA

Major issues:
Transverse hose instability?
Existing p^+ bunches are long!



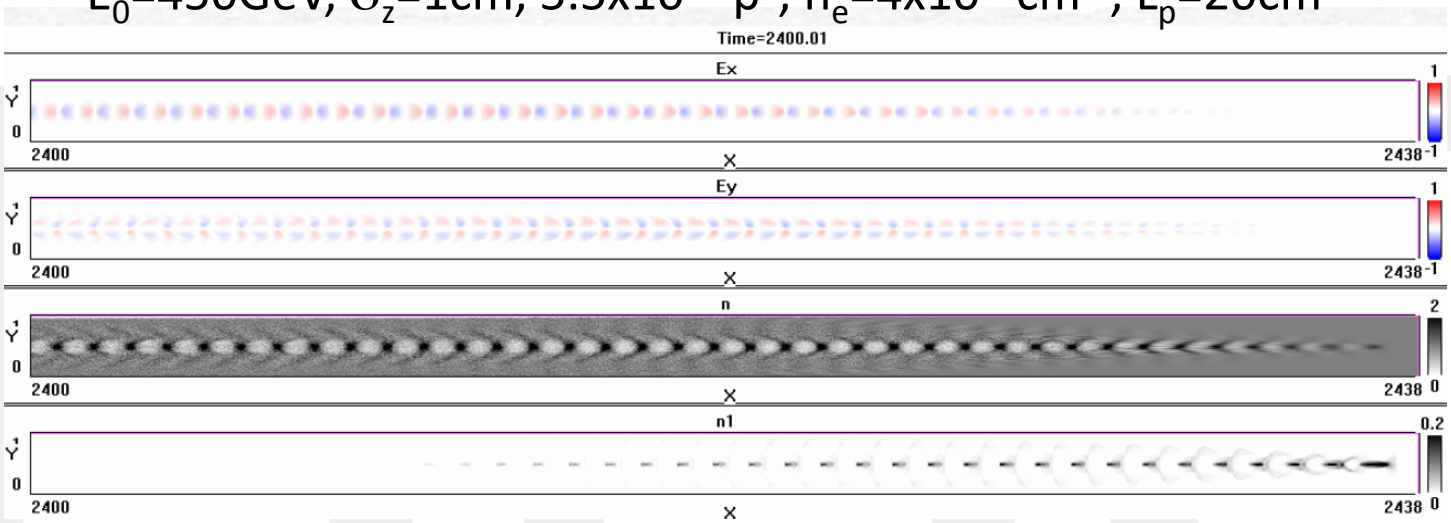
Caldwell, Nat. Phys. 5, 363 (2009)

PROTON-DRIVEN PWFA

Short p^+ bunches do not exist yet

Use self modulation of long bunch due to (radial) two-stream instability
(similarity to early self-modulated LWFA)

E_0=450GeV, σ_z=1cm, 5.5x10^{10} p^+, n_e=4x10^{15}cm^{-3}, L_p=20cm



E_x accelerating

E_y focusing

n_e

n_b

Simulations show peak accelerating field in the 200-500MV/m

Simulations A. Pukhov

Experimental goals (A. Caldwell):

- Near-term plan is to use the extracted p^+ beam from the PS or SPS to demonstrate an energy gain of 1 GeV within 5 m of plasma
- These experiments should also lead to a scheme to achieve 100 GeV energy gain per 100 m plasma

Plasma source: helicon or UCLA/USC/SLAC lithium vapor?

Courtesy A. Caldwell

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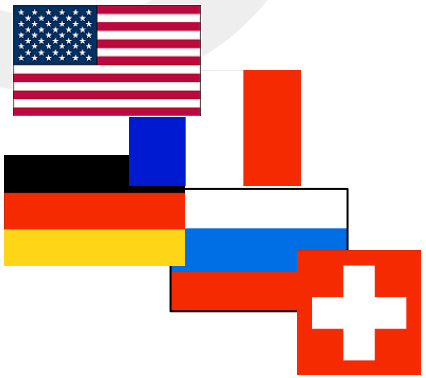

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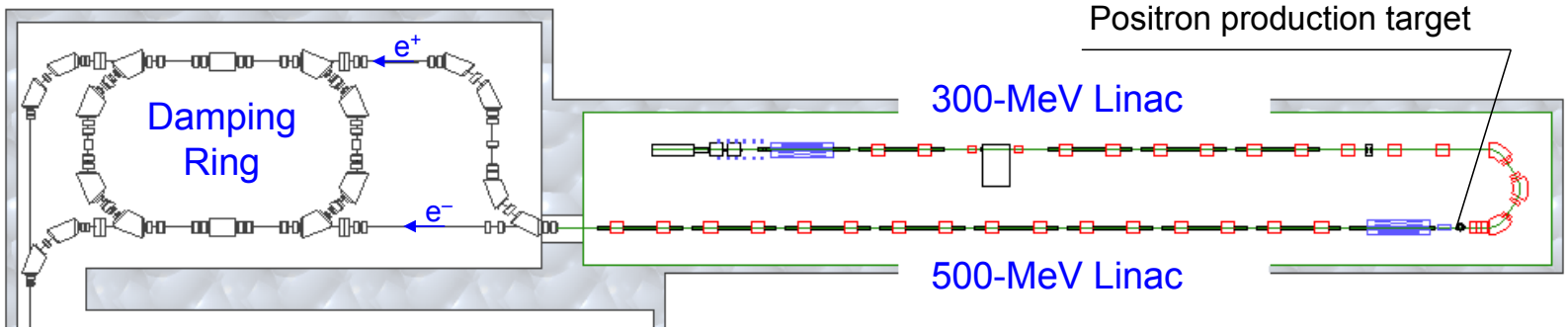
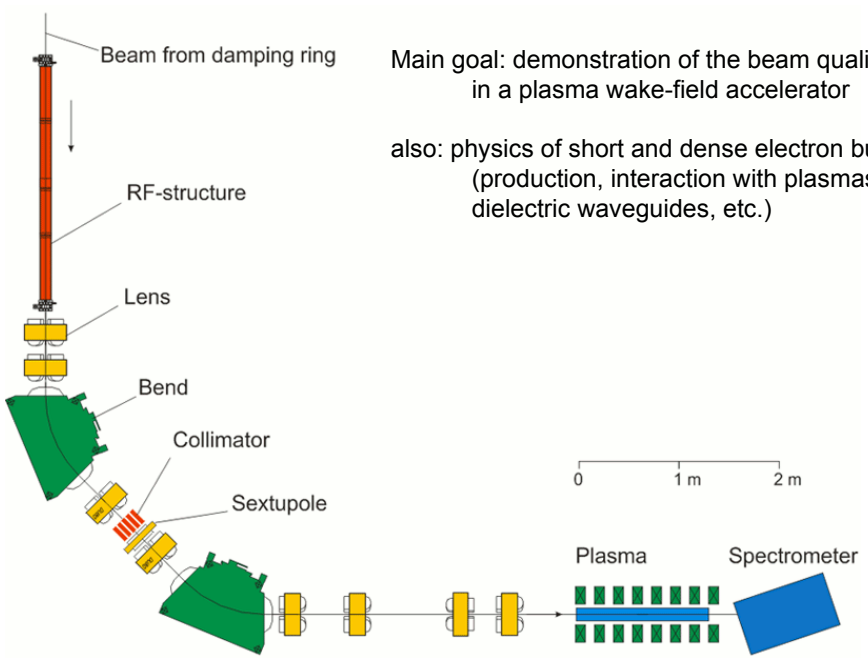
VEPP-5 Injection Complex



PWFA experiment at Budker INP



Main goal: demonstration of the beam quality in a plasma wake-field accelerator

also: physics of short and dense electron bunches (production, interaction with plasmas, dielectric waveguides, etc.)

Electron beam obtained in the damping ring:

E = 200 … 400 MeV
$N(e^-)$ = $2 \cdot 10^{10}$
σ_S = 8 mm (I_{peak} = 50 A)

Will produce e^- and e^+

Positron beam commissioning is scheduled for 2011

Courtesy Alexey Petrenko

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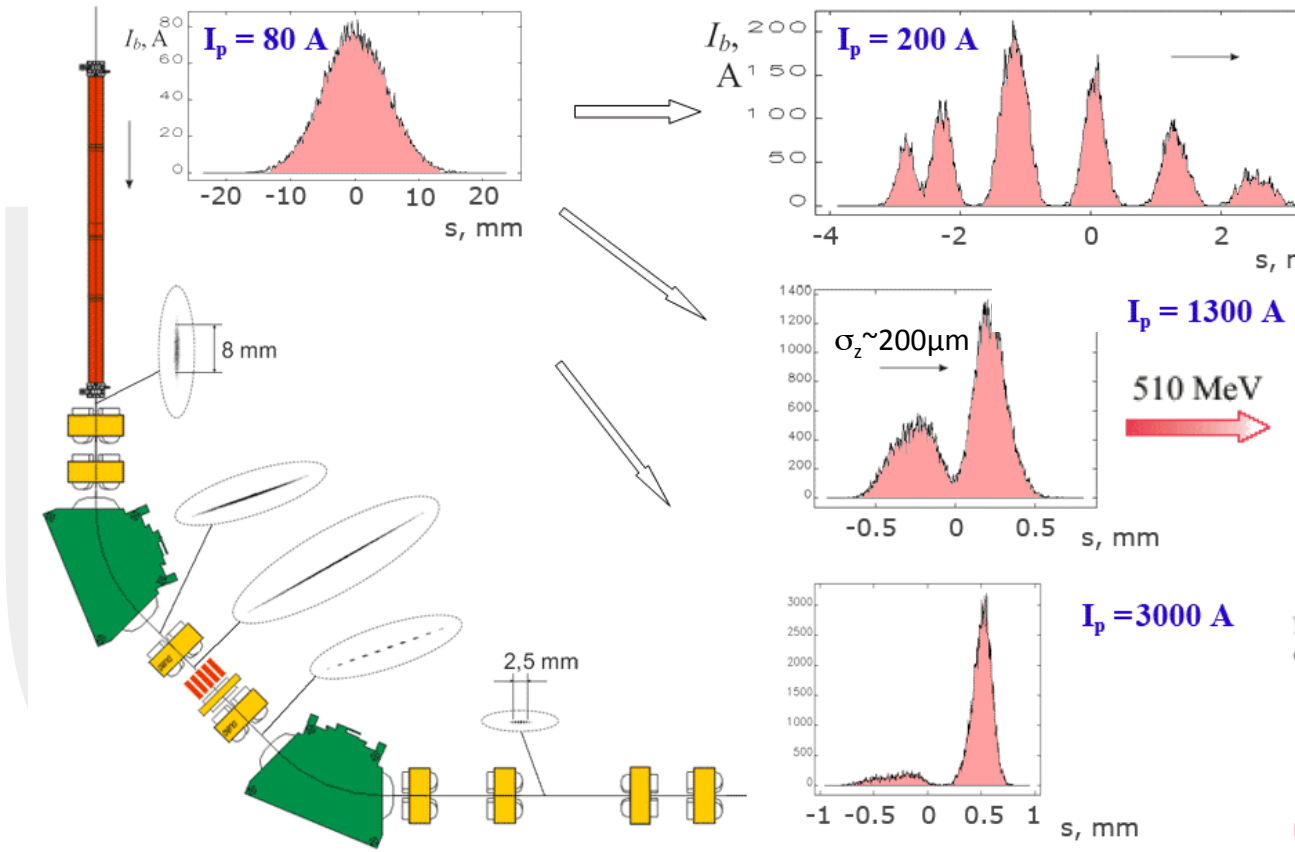
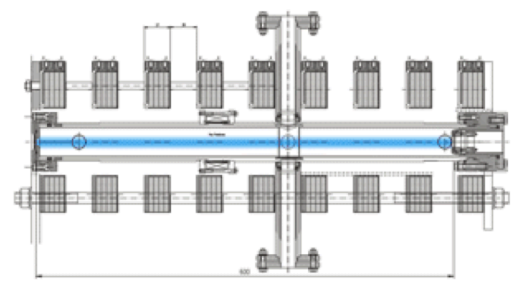
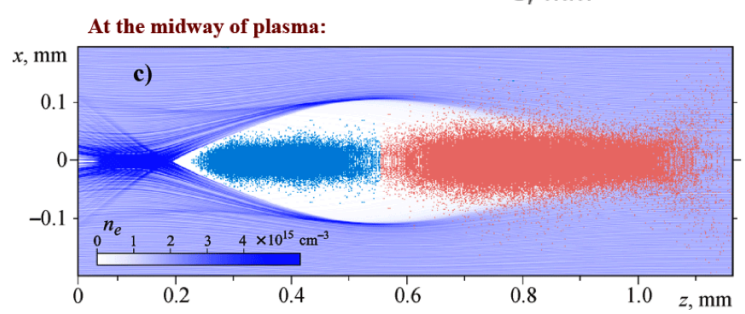
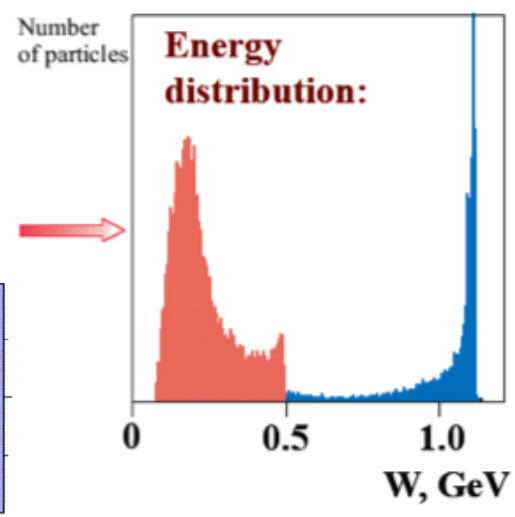
Beam compression (ELEGANT tracking including CSR)



Pulsed plasma: 40cm, ~10^{15}cm^{-3}





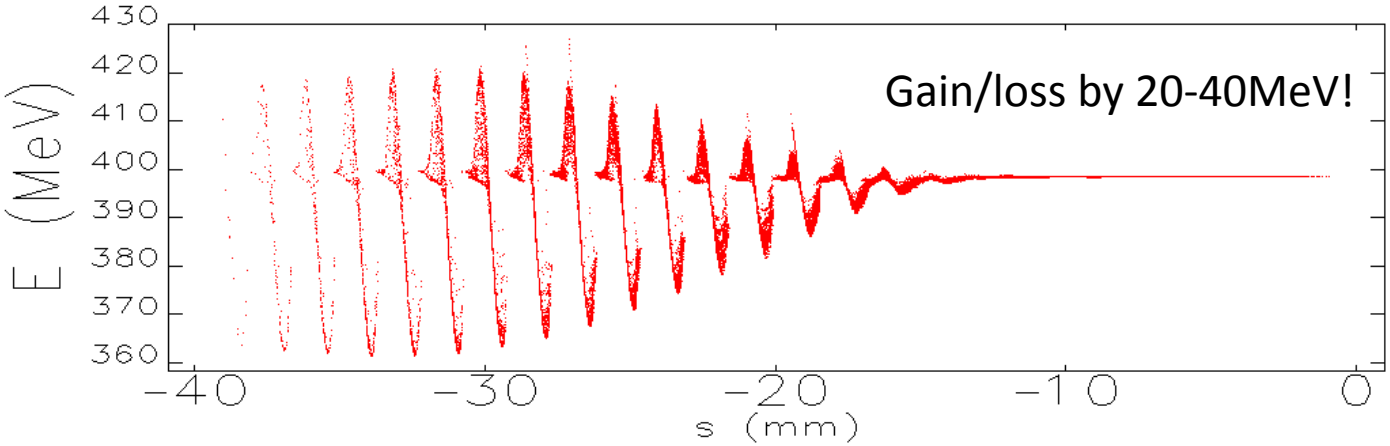


Budker Institute of Nuclear Physics, Novosibirsk, Russia

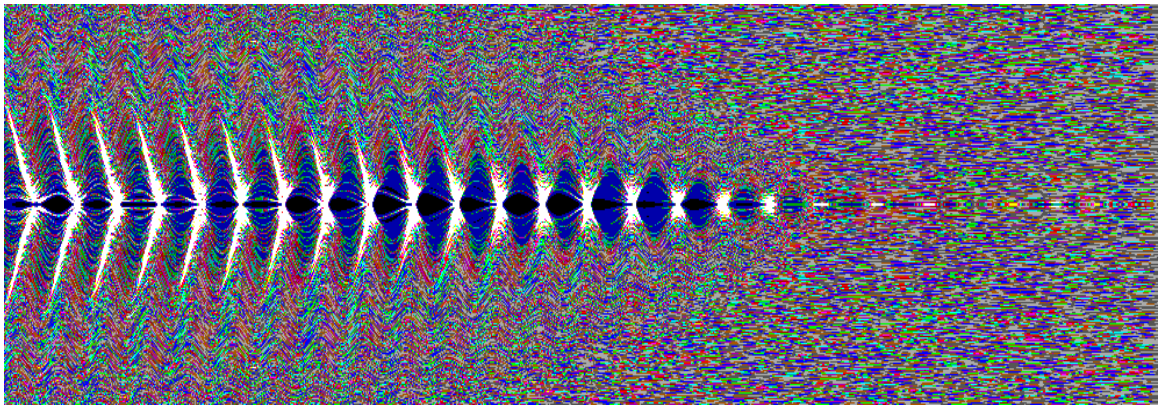
However, before compression becomes available:

σ_z~8mm, radial two stream instability

Beam particle energy vs longitudinal position:



Electron plasma density:



Later: experiments with e^- and e^+ bunch trains

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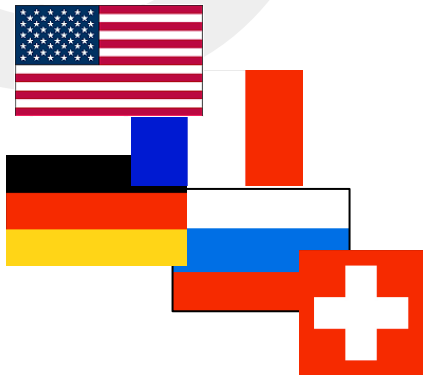

SUMMARY

Renewed interest in PWFA sparked by SLAC results and availability of new beams

Experiments running at Brookhaven ATF

- Basic PWFA physics, resonant excitation, high transformer ratio, etc.

FACET is being built a SLAC and will come online next year for 2nd generation experiments

- Add ~E_0 to a bunch in meter-scale plasma
- Narrow final energy spread bunch
- Beam loading, transformer ratio, energy transfer efficiency, …
- The e^+ case (e^+ on e^- wake)

TV/m possible with LCLS short (2fs) bunches

- XXL wakefields
- Ultrafast ionization physics

p^+-driven PWFA at CERN

- Driver for TeV-range e^- acceleration

Budker Institute of Nuclear Physics, Novosibirsk, Russia

- Program similar to FACET's, with e^- and e^+

Other possible experiments at SPARC-X, DESY, CLIC, Fermilab, …

PWFA experiments with LWFA e^- beams…

Application to light sources …

Experiments will address accelerator issues

Thank You!

Thank you for the slides:
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