Beam-Driven Plasma Wakefield Acceleration

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OUTLINE

- Motivation - Introduction to PWFA
- PWFA experimental results @ SLAC

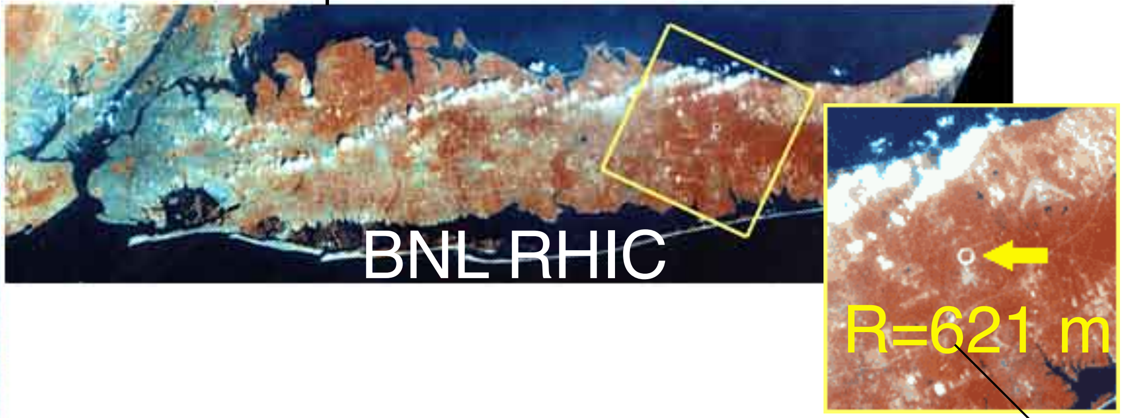
P. Muggli and M.J. Hogan, Comptes Rendus Physique, 10(2-3), 116 (2009).

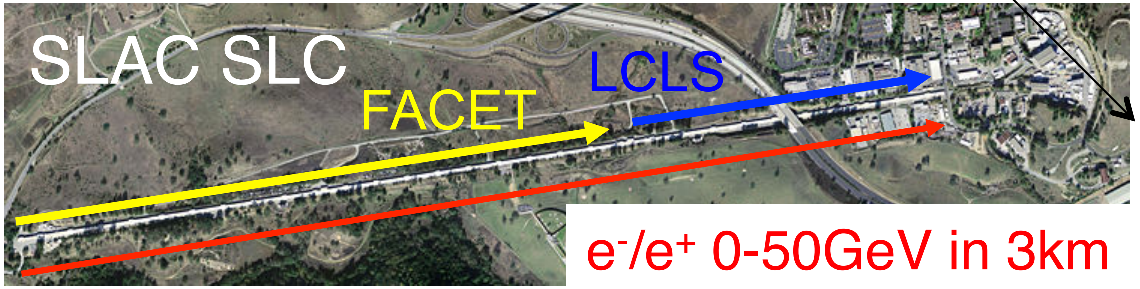
- Low energy PWFA @ ATF-BNL
- Proton driven PWFA @ CERN (for e^- acceleration)
- Summary and Conclusions

Focus on acceleration all the way through!

PARTICLE ACCELERATORS

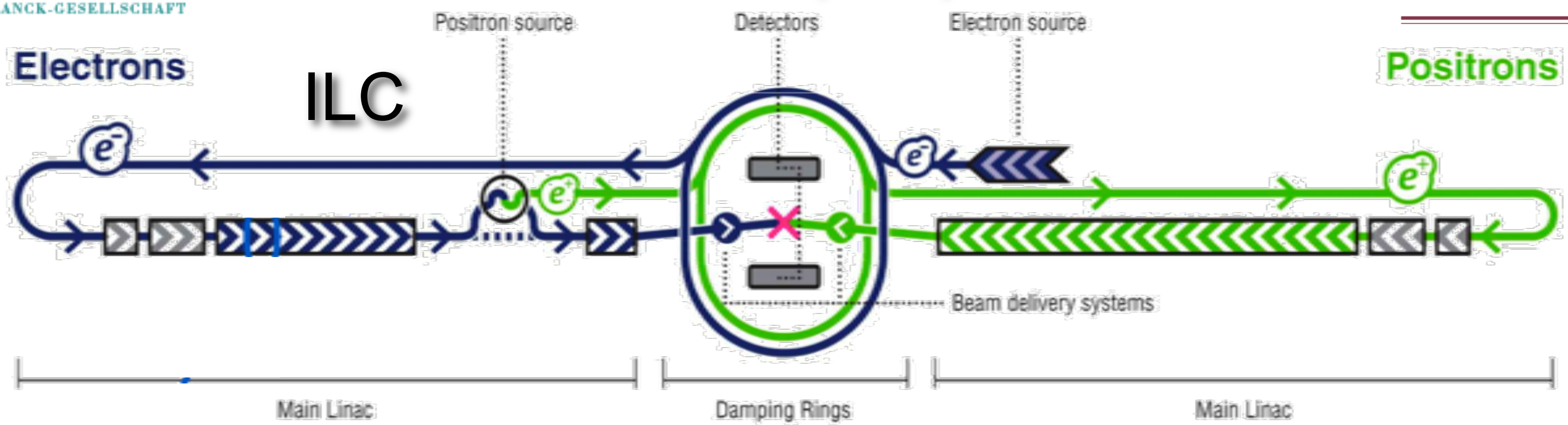
“The 2.4-mile circumference RHIC ring is large enough to be seen from space”





- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use rf technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

FUTURE LEPTON (e^-/e^+) COLLIDER

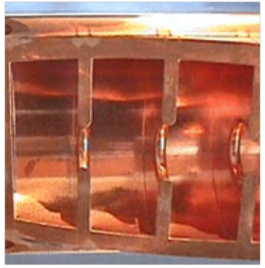


≈25 km site?

- Linear accelerator to avoid synchrotron radiation limitation ($\sim\gamma^4/r^2 \sim E^4/m^4r^2$)
- Energy frontier: 1-3 TeV, e^-/e^+
- Accelerator length with (cold) rf technology:

$$\frac{1\ \text{TeV}}{<50\ \text{MeV/m}} > 20\ \text{km}$$

Pillbox Cavity



<150MV/m?

Is there a <u>high-gradient</u> alternative to rf technology?
Plasmas?

WHAT ABOUT PLASMAS?

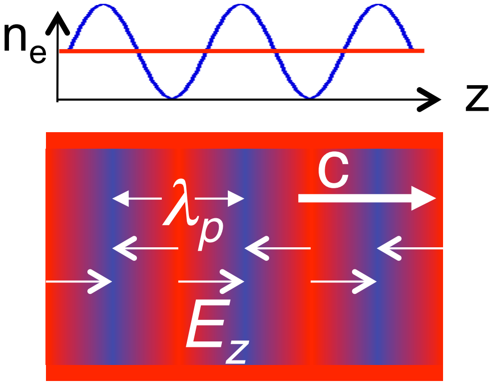
- Relativistic Electron Plasma Wave (Electrostatic, E_z):

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

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

Cold Plasma "Wavebreaking" Field

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

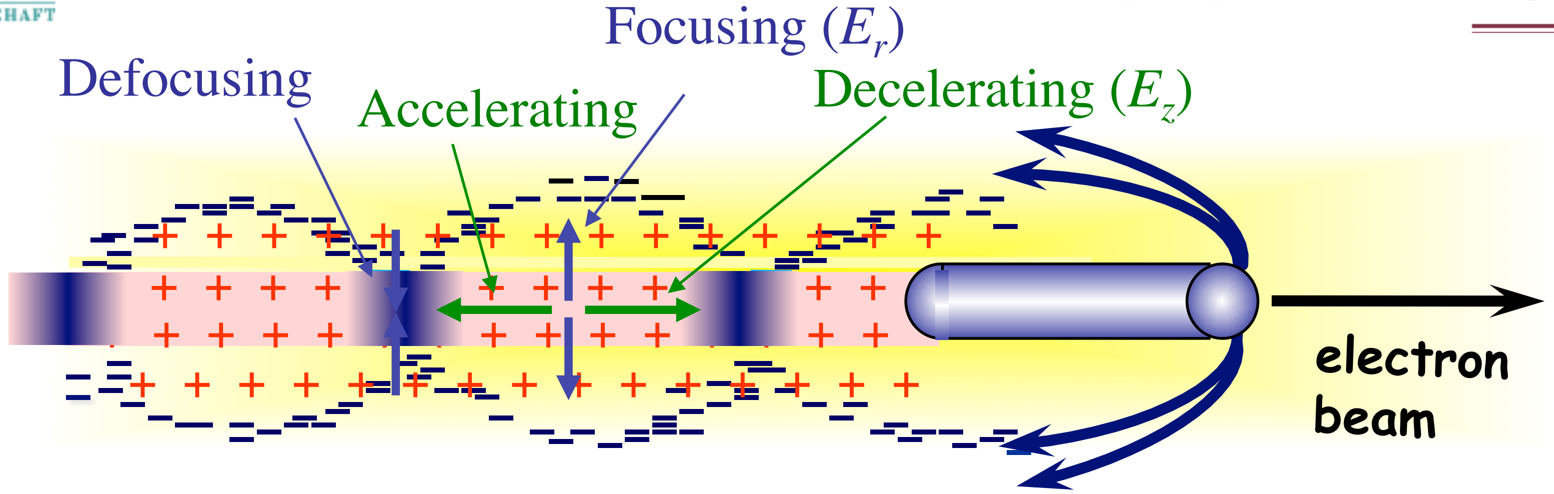


LARGE

Collective response!

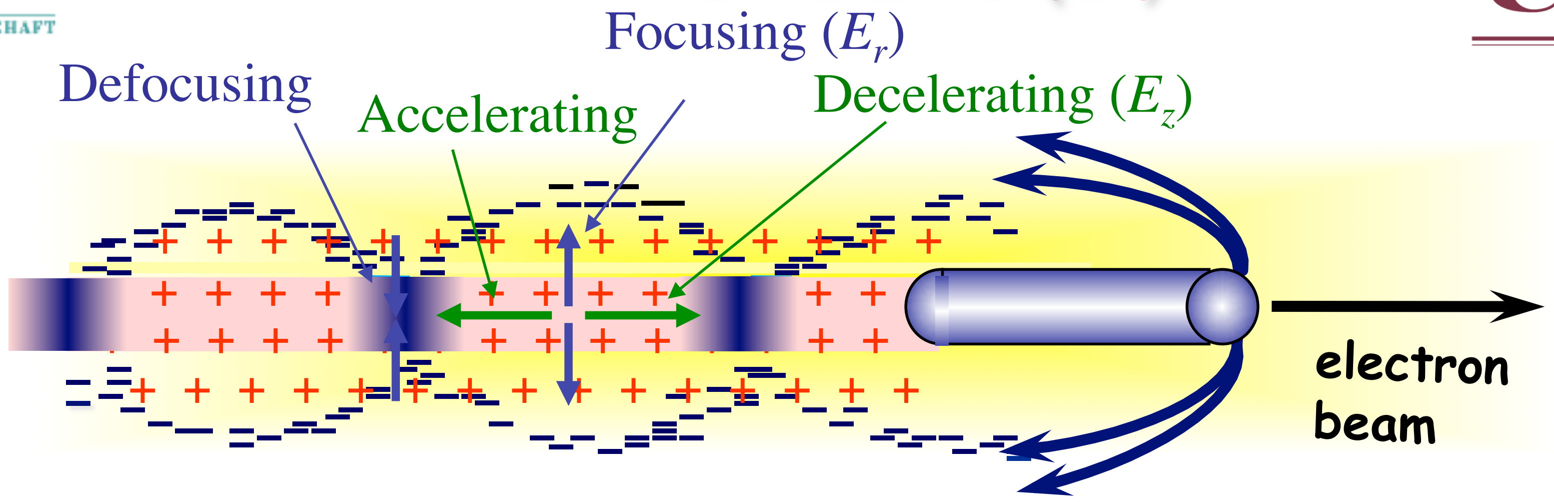
- Plasmas can sustain very large (collective) E_z-field, acceleration
- Wave, wake phase velocity = driver velocity (~c!)
- Plasma is already (partially) ionized, difficult to "break-down"
- Plasmas wave or wake can be driven by:
  - Intense laser pulses (LWFA)
  - Short particle bunch (PWFA)

PLASMA WAKEFIELD (e^-)



- 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
- Optimize for acceleration, focusing (plasma lens), radiation (β-tron)
- Plasma Wakefield Accelerator (PWFA): high-frequency, high-gradient, strong focusing, co-linear, beam-driven accelerator

PWFA NUMBERS (e^-)



- Linear theory ($n_b<<n_e$) scaling: $E_{acc} \cong 110(MV/m)\dfrac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2}$ $\approx N/\sigma_z^2$

  $@\ k_{pe}\sigma_z \approx \sqrt{2}$ *(with $k_{pe}\sigma_r<<1$)*

- Focusing strength: $\dfrac{B_\theta}{r} = \dfrac{1}{2}\dfrac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}cm^{-3})$ ($n_b>n_e$)

- $N=2\text{x}10^{10}$: $\sigma_z=600\ \mu m$, $n_e=2\text{x}10^{14}\ cm^{-3}$, $E_{acc}\sim100$ MV/m, $B_\theta/r=6$ kT/m

  $\sigma_z=20\ \mu m$, $n_e=2\text{x}10^{17}\ cm^{-3}$, $E_{acc}\sim$ 10 GV/m, $B_\theta/r=6$ MT/m

- Frequency: 100GHz to >1THz, “structure” size 100 to 10μm

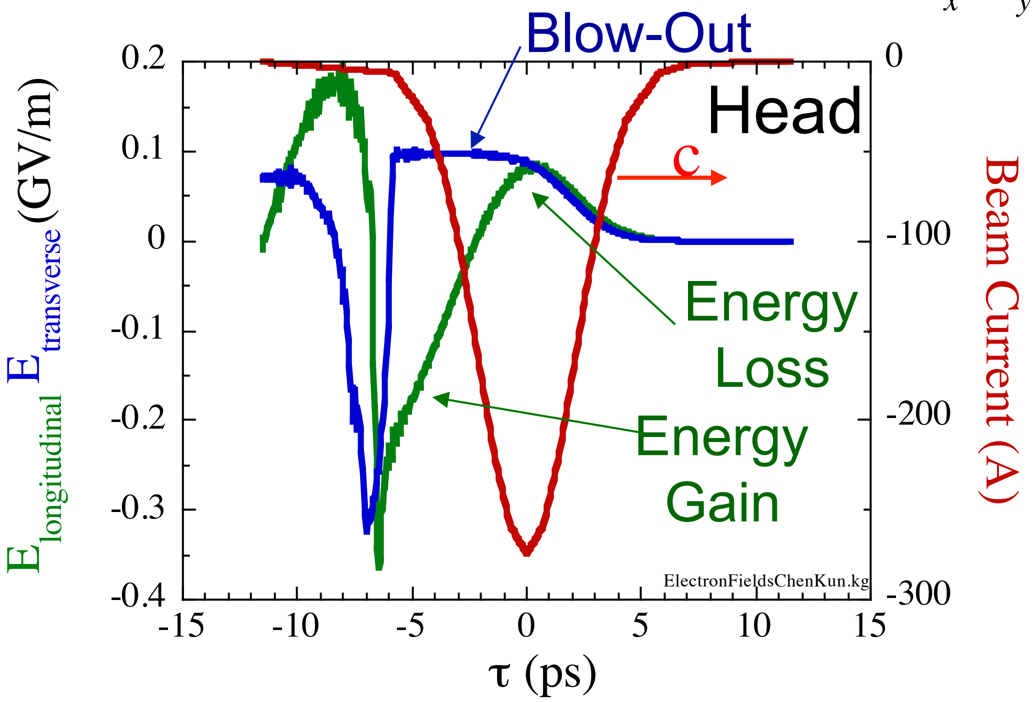
- Conventional accelerators: MHz-GHz, $E_{acc}<150$ MV/m, $B_\theta/r<2$ kT/m

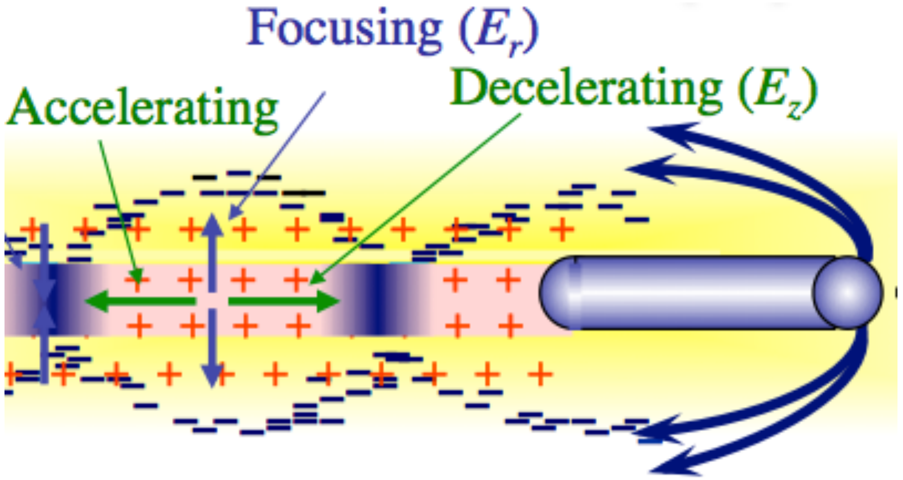
PLASMA WAKEFIELD FIELDS (e^-)
$\sigma_z \approx 700\ \mu m$

2-D PIC Simulation QUICPICK

$n_e = 1.5\times10^{14}\ cm^{-3}$, $N = 1.8\times10^{10}\ e^-$

E_0	28.5 GeV	n_b	$4\times10^{14}\ cm^{-3}$
N	$2\times10^{10}\ e^-$ or e^+	ε_{xN}	5×10^{-5} m-rad
σ_z	0.63 mm (2.1 ps)	ε_{yN}	0.5×10^{-5} m-rad
$\sigma_x=\sigma_y$	70 μm		





- Simulations - cartoon
- Experiment: measure energy gain/loss not wakefield amplitudes

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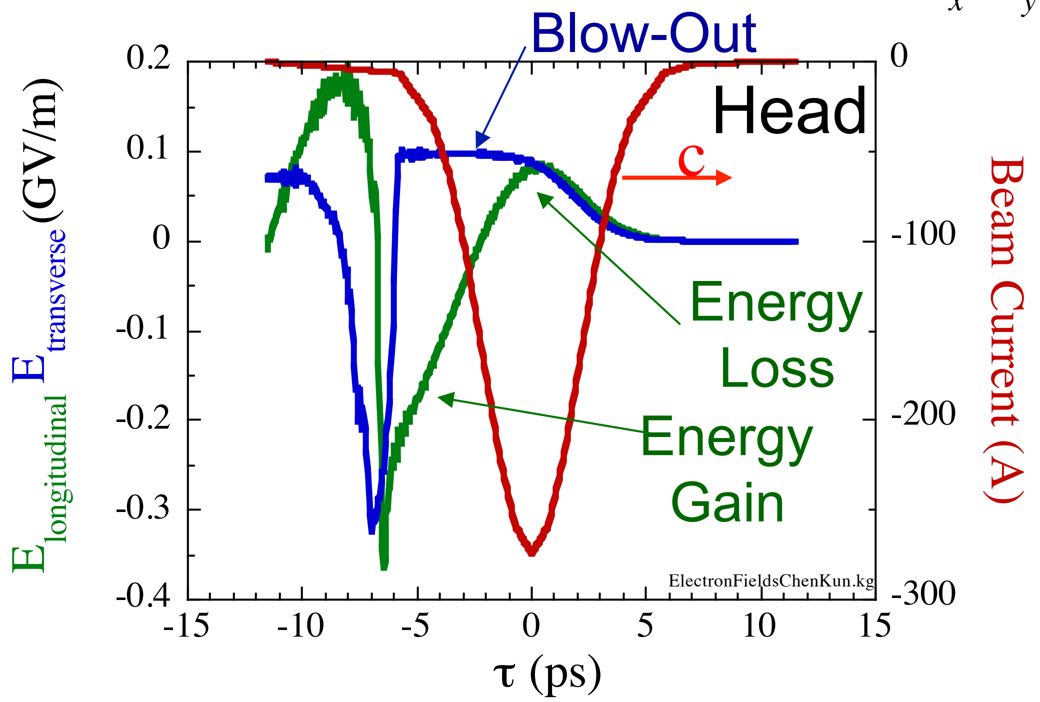
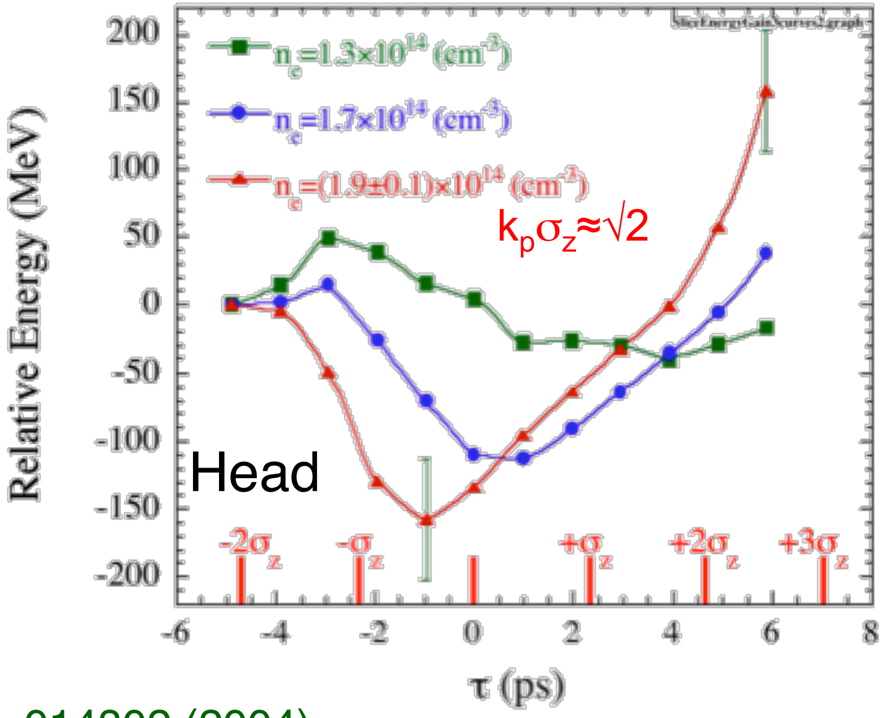
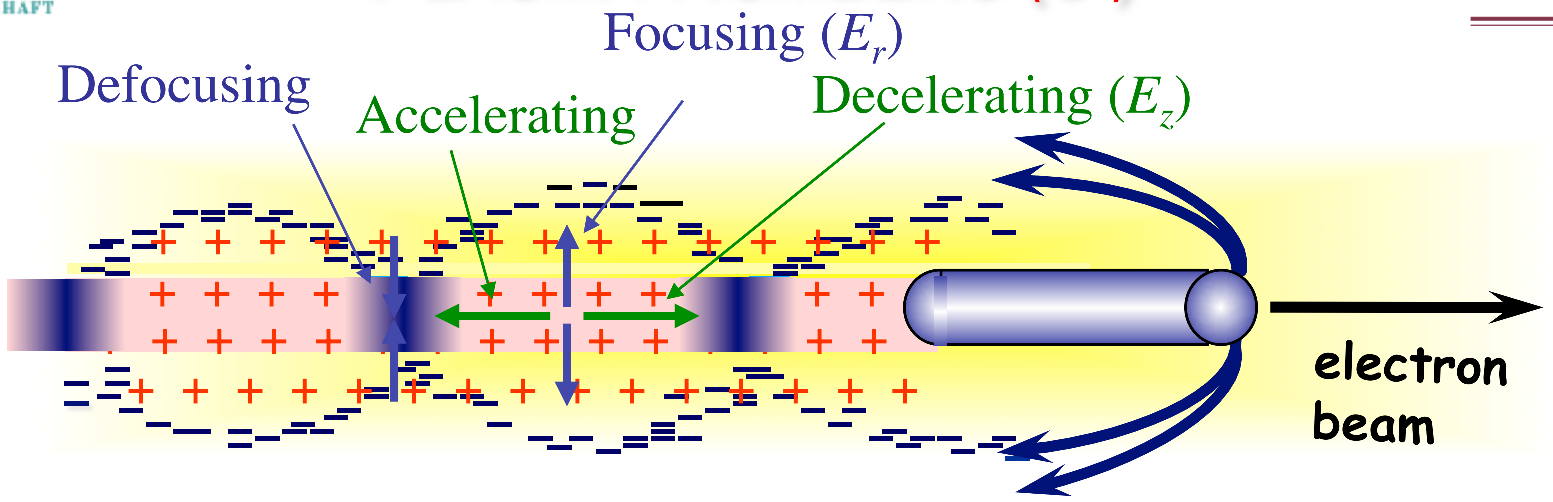




Muggli, Phys. Rev. Lett. 93, 014802 (2004).

- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m
- Shows the physics
- Similar results with positron bunch Blue, Phys. Rev. Lett. 90, 214801 (2003).

PLASMA NUMBERS (e$^-$)



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- Focusing strength: $\dfrac{B_\theta}{r} = \dfrac{1}{2}\dfrac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}\,cm^{-3})$

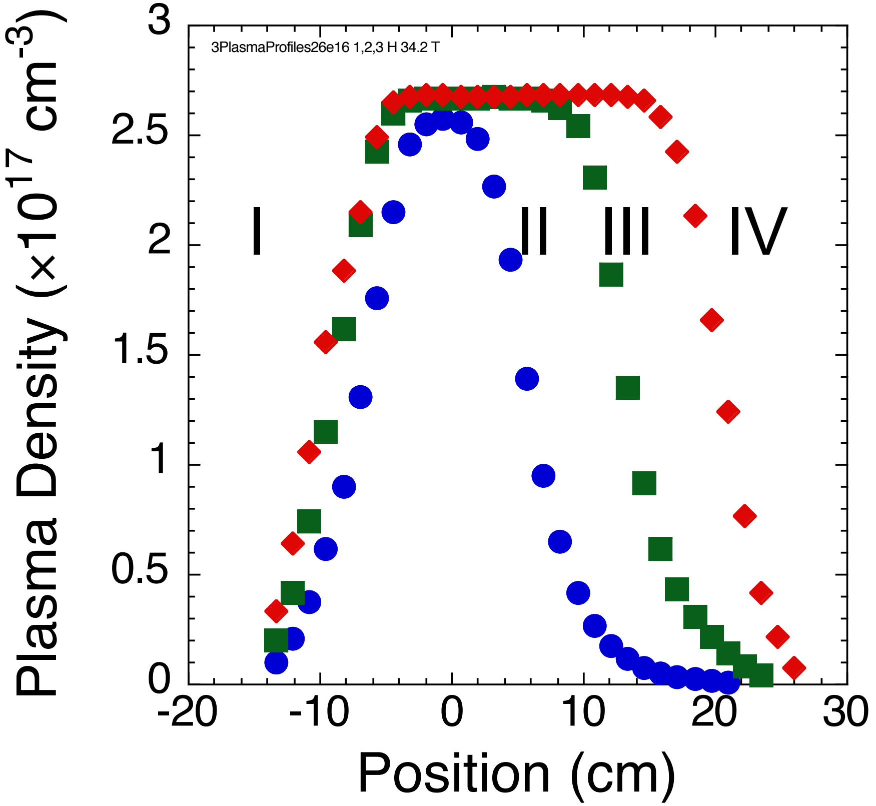
Short Bunches! ($n_b > n_e$)

- $N=2\times10^{10}$: σ_z=600 μm, $n_e=2\times10^{14}$ cm^{-3}, $E_{acc}\sim$100 MV/m, B_θ/r=6 kT/m
  σ_z= 20 μm, $n_e=2\times10^{17}$ cm^{-3}, $E_{acc}\sim$ 10 GV/m, B_θ/r=6 MT/m
- Frequency:100GHz to >1THz, “structure” size 100 to 10μm
- Conventional accelerators: MHz-GHz, E_{acc}<150 MV/m, B_θ/r<2 kT/m

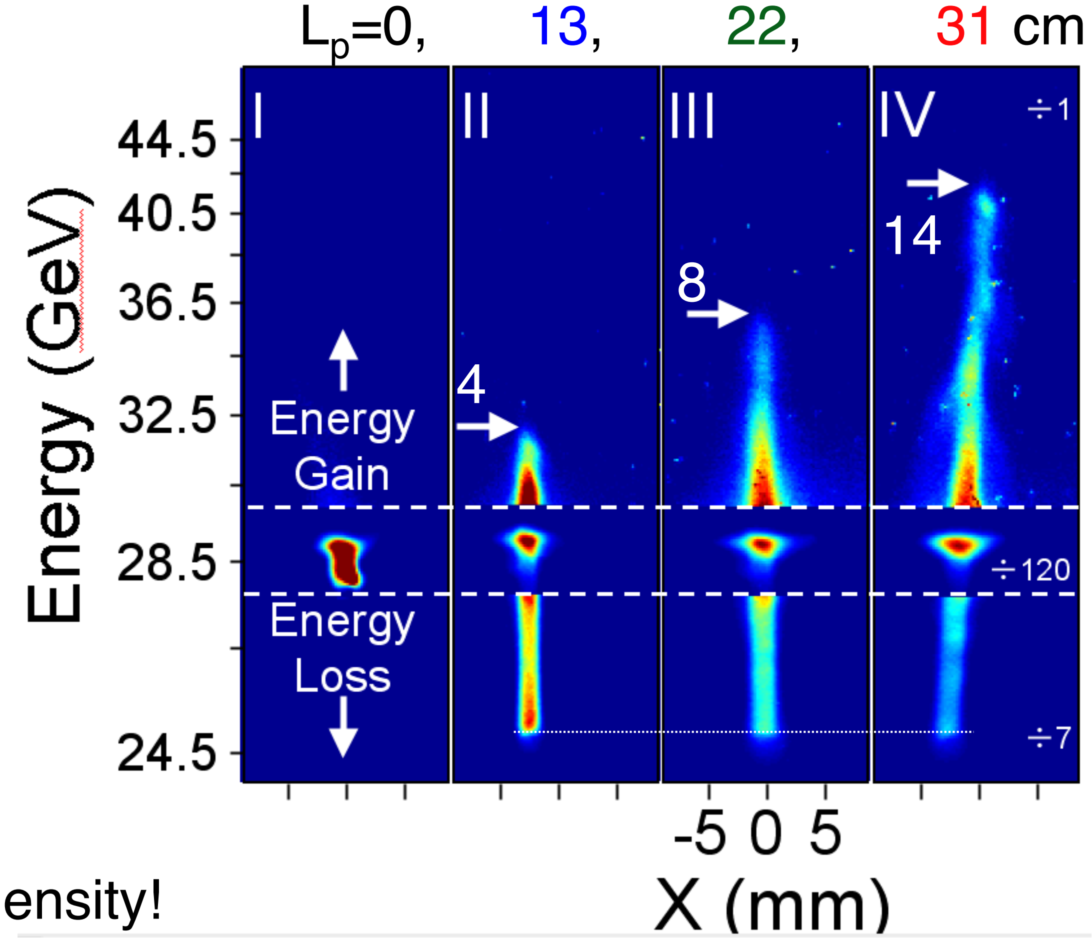
SCALING WITH PLASMA LENGTH

$\sigma_z \approx 25\ \mu m$

E_0=28.5 GeV, n_e=2.7x10^{17} cm^3



Same incoming beam! $\sigma_z \approx 25\ \mu m$

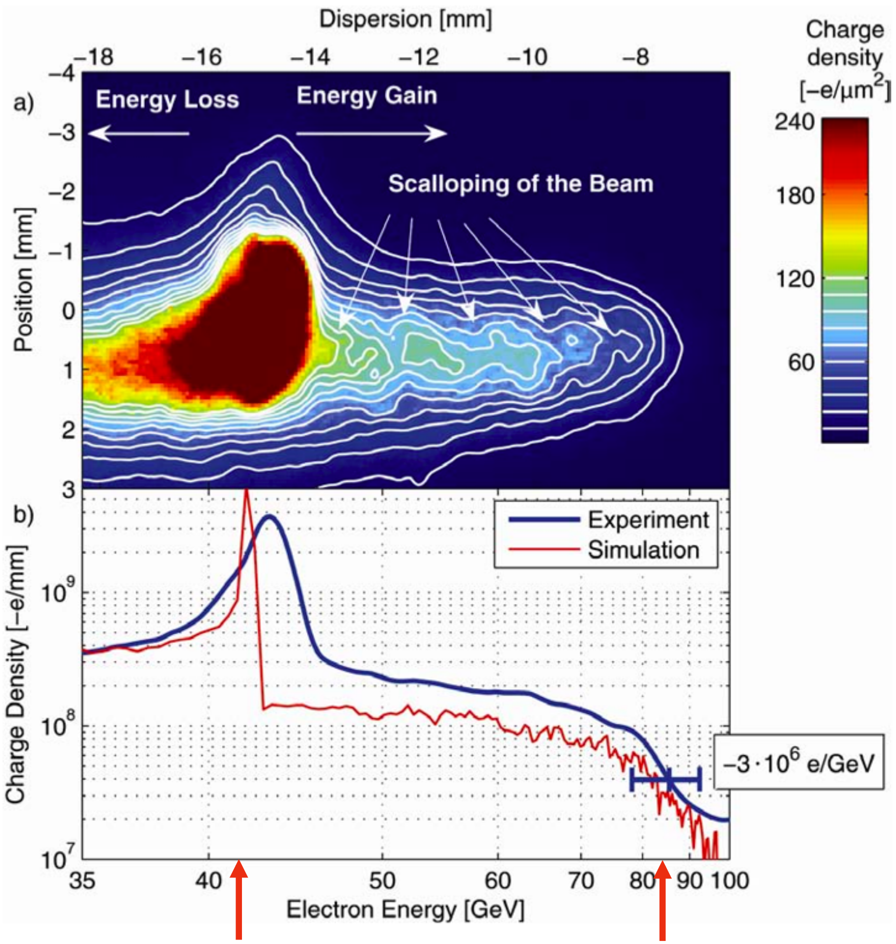


- Energy gain scales with plasma density!
- Gain ≈14 GeV over (only!) L_p=31 cm!
- E_{acc}≈45 GV/m

Muggli, IEEE-TPS 27, 791 (1999)
Muggli, New J. Phys. 12, 045022 (2010)

e^- ENERGY DOUBLING

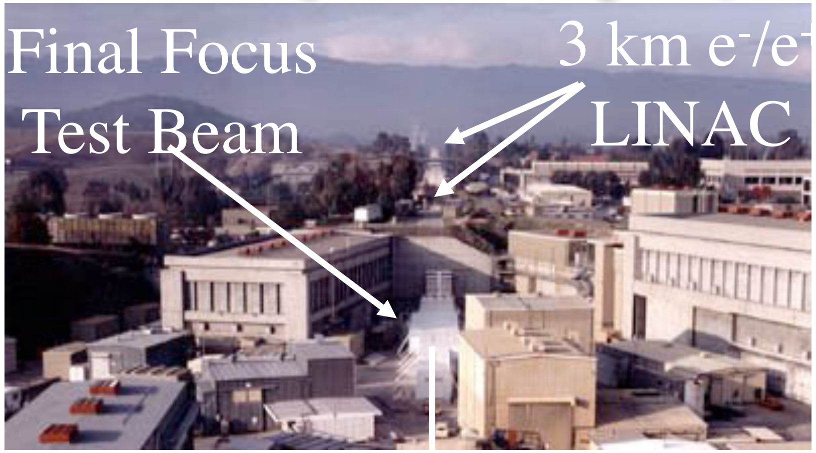
Blumenfeld, Nature 445, 2007

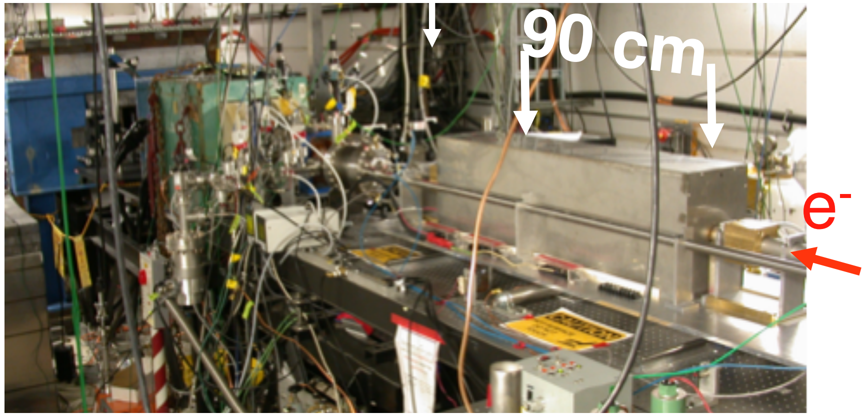


E_0

$2E_0$

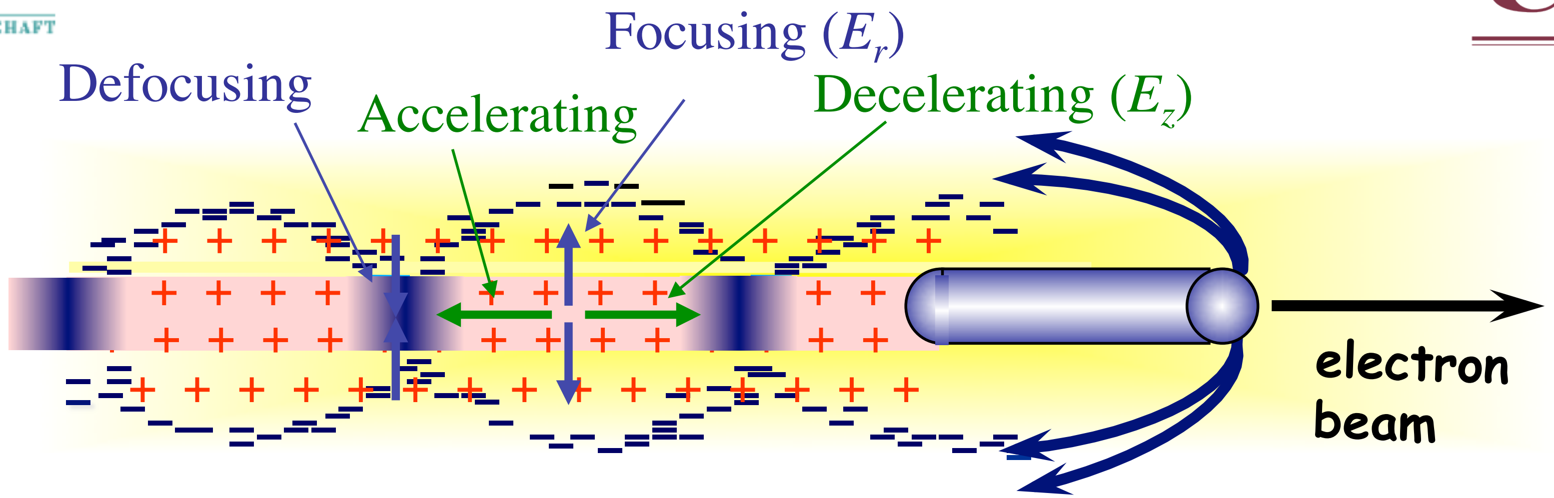
E_0=42 GeV, $\sigma_z \approx 25\ \mu m$



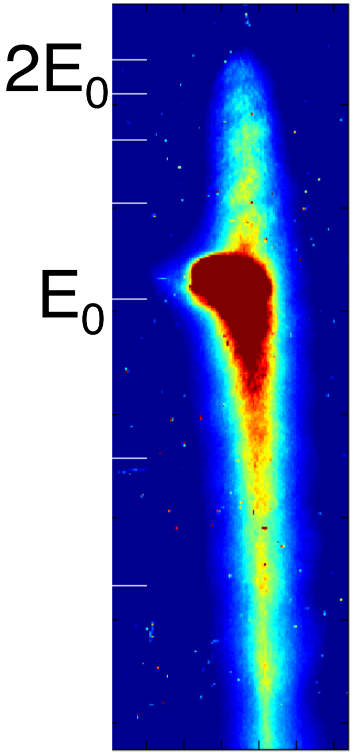


- Energy doubling of e^- over $L_p \approx 85$ cm, 2.7×10^{17} cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

SINGLE BUNCH PWFA

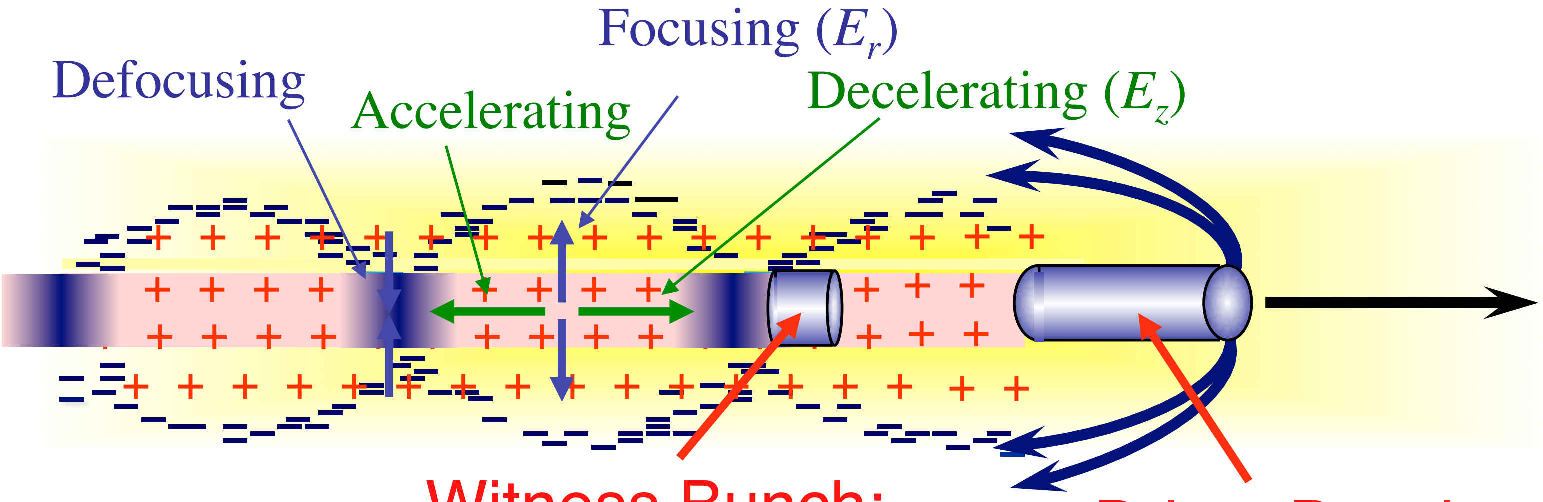


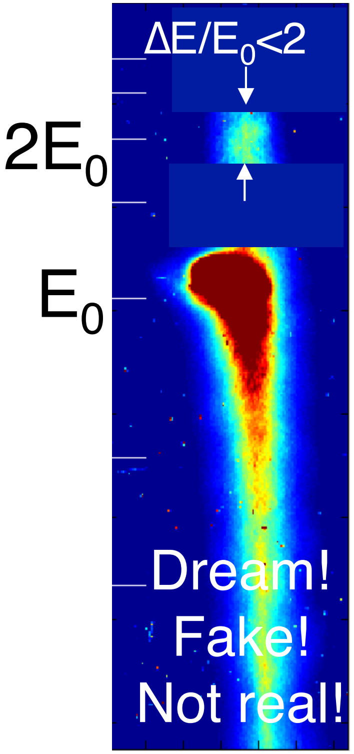
- Large energy gain (42GeV) in only 85cm, but …
- Particles at all phase, large energy spread (100%)
- Particle acceleration, not <u>bunch</u> acceleration
- Need witness bunch injection behind a drive bunch



© P. Muggli

2-BUNCH PWFA





Witness Bunch:
$E_0 \Rightarrow \geq 2E_0$

Driver Bunch:
$E_0 \Rightarrow \approx 0$

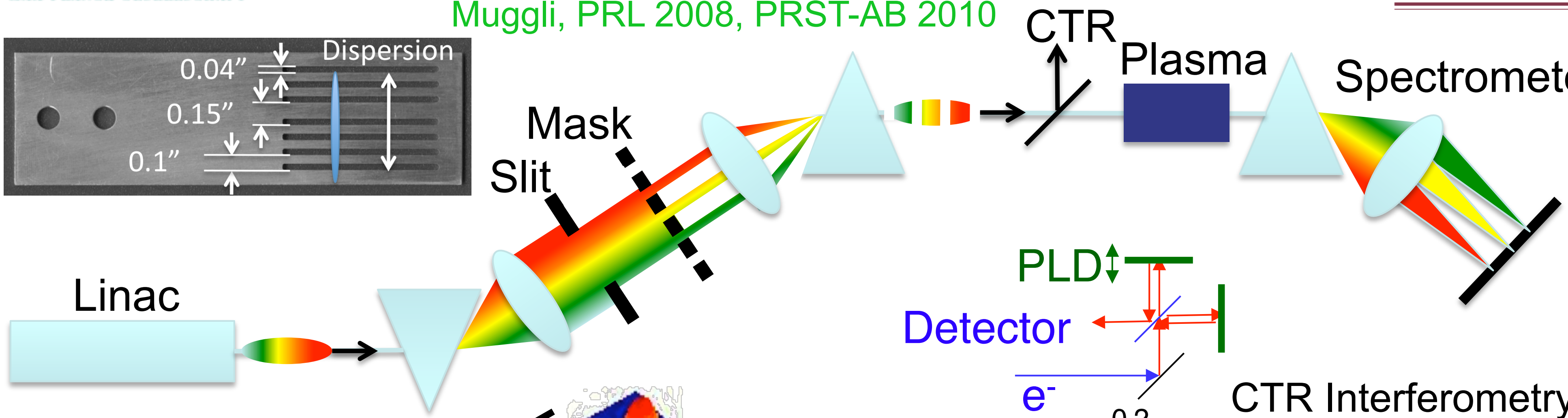
- Really important experiment! (psychologically)
- Witness bunch: lower charge (*N*), good emittance, shorter
  beam loading for $\Delta E/E<<1$
- New facility: FACET@SLAC for 23GeV PWFA accelerator module

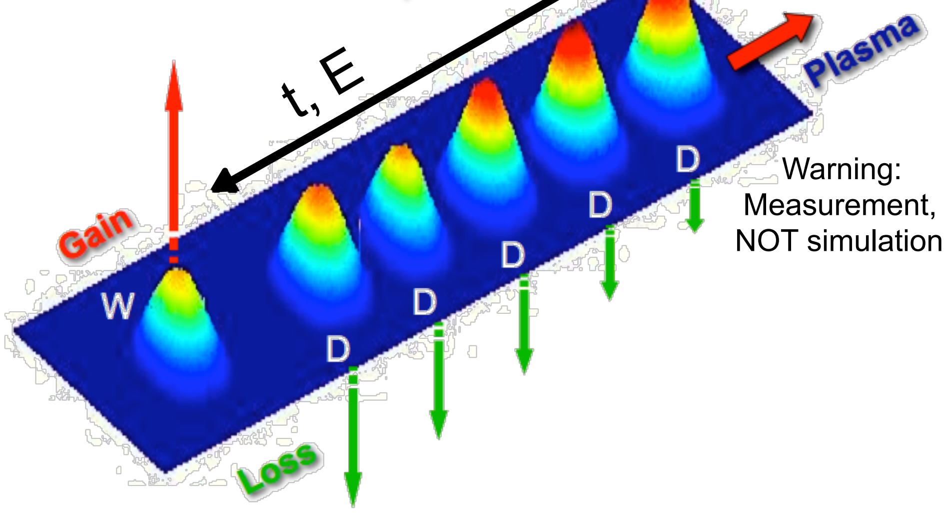
Hogan et al., New J. Phys. 12, 055030 (2010)

- Low energy physics experiments

MULTIBUNCH SOURCE-MASKING

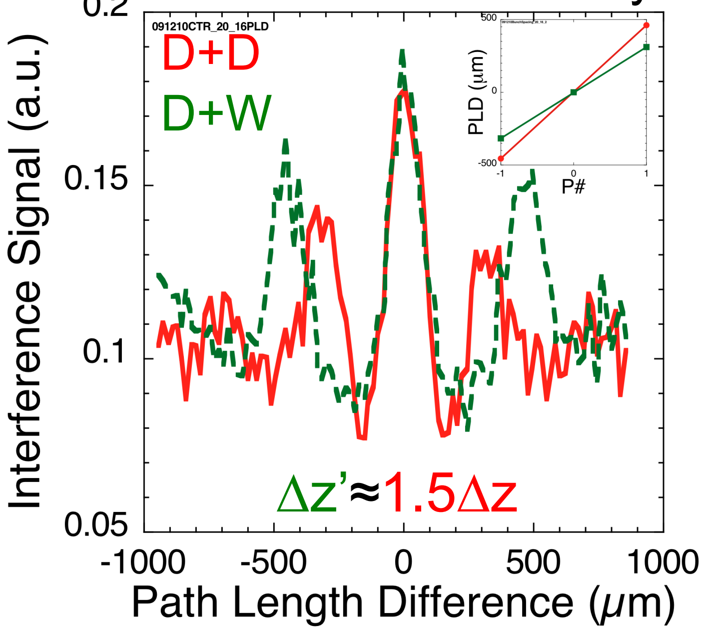
Muggli, PRL 2008, PRST-AB 2010





Warning: Measurement, NOT simulation

CTR Interferometry



- Choose beam parameters with mask and beam parameters: N, Δz, σ_z, Q
- Test bed for two bunches at FACET

MULTIBUNCH PWFA

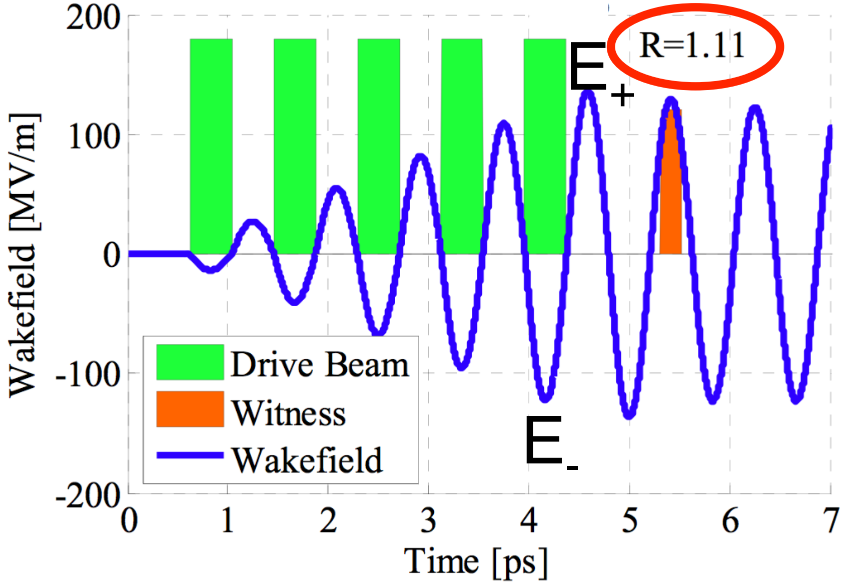
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p

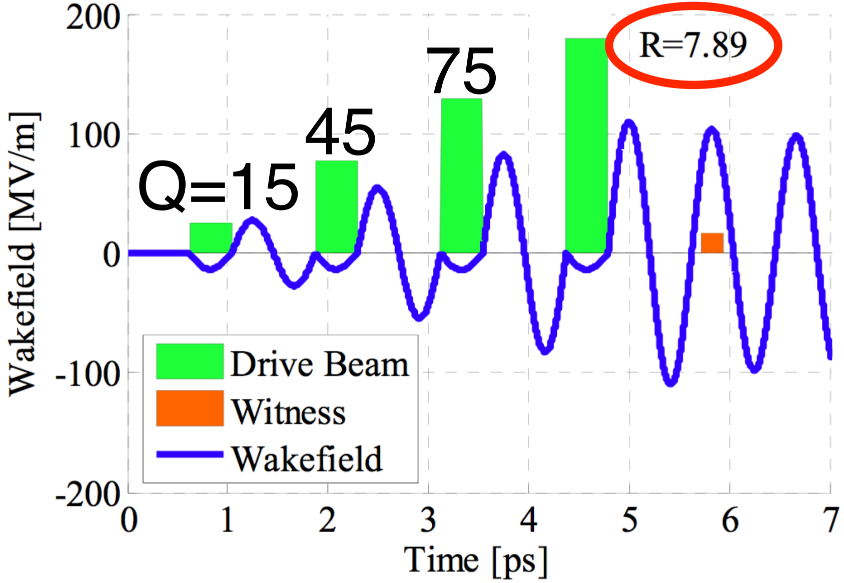
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



*Tsakanov, NIMA, 1999

- Resonant excitation of wakefields
- Large transformer ratio and energy gain (>2)

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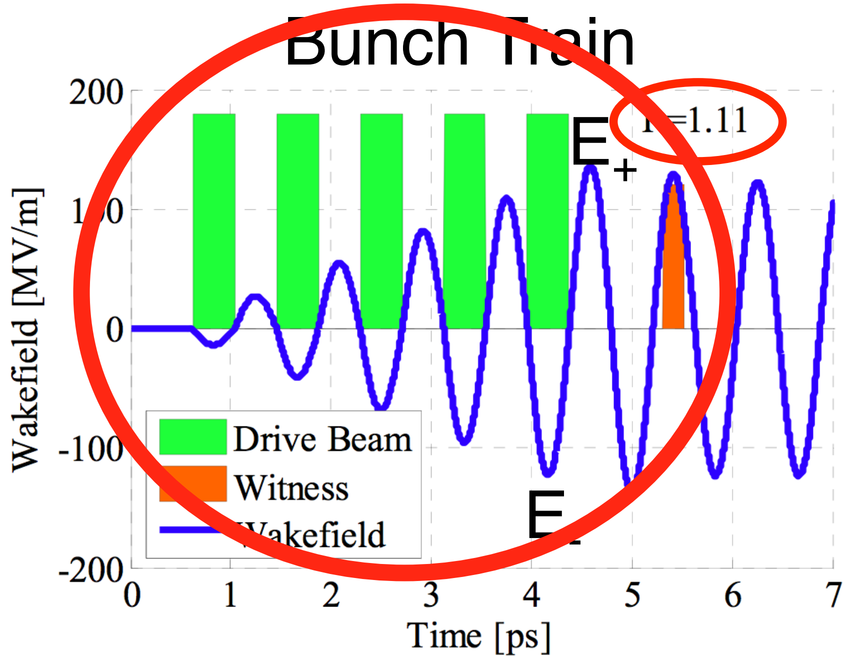

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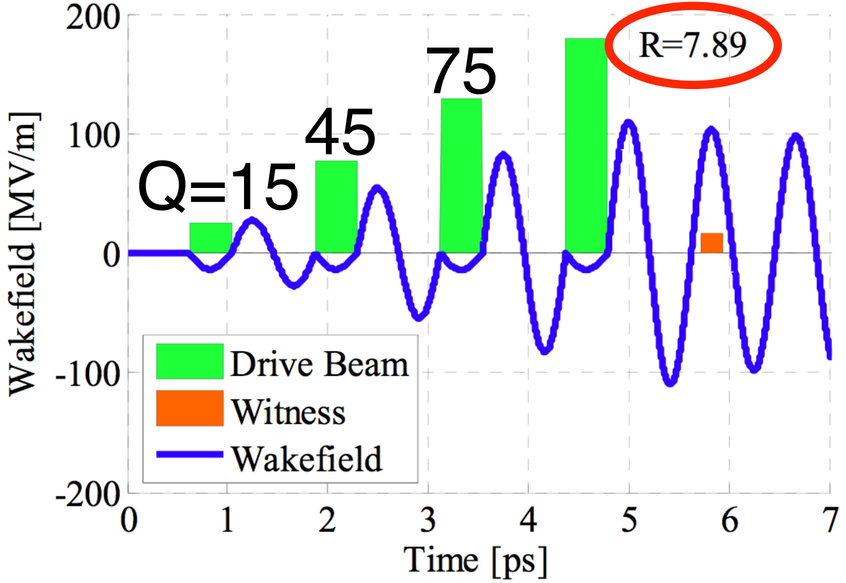

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- Resonant excitation of wakefields
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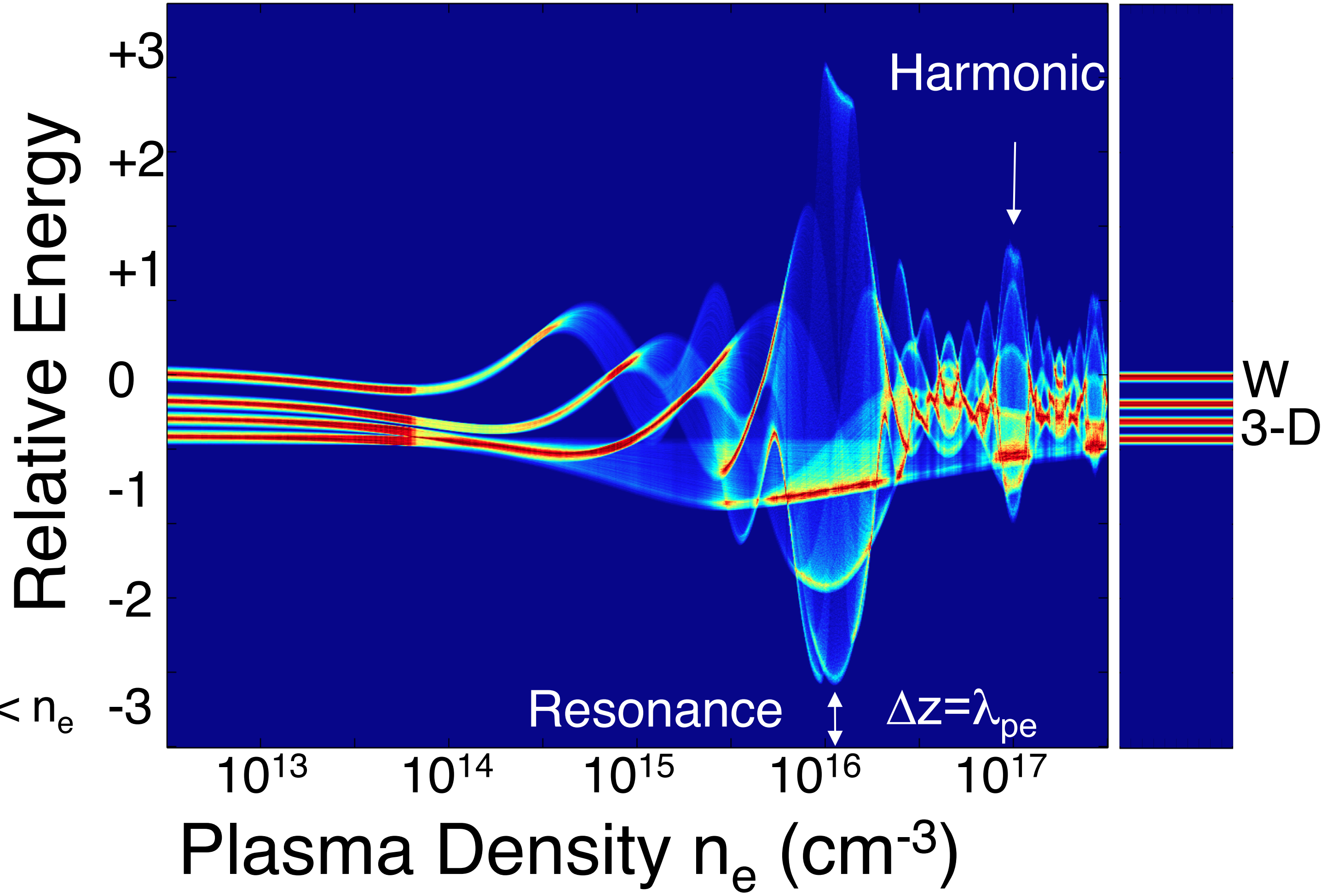
ENERGY CHANGE

Linear calculation (2D): microbunches with equal charge

Experimental Parameters:

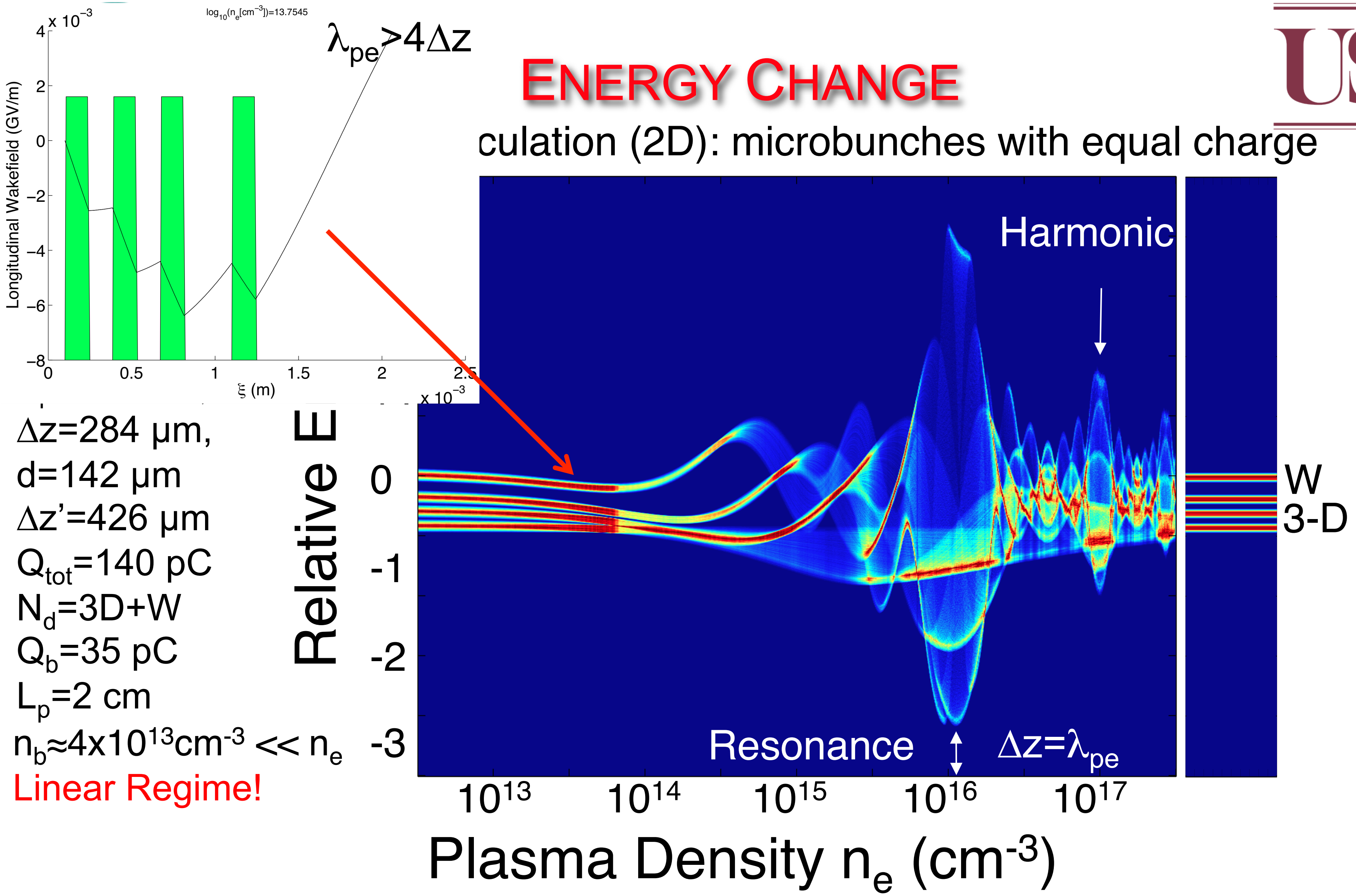
E_0=59 MeV
σ_r =100 um,
Δz=284 µm,
d=142 µm
$\Delta z'$=426 µm
Q_{tot}=140 pC
N_d=3D+W
Q_b=35 pC
L_p=2 cm
$n_b \approx 4\text{x}10^{13}\text{cm}^{-3} << n_e$
Linear Regime!



- Resonant excitation of wakefield is the main feature
- Chirp such that W enters with highest energy
- $n_{e,\ res} \approx 1.4\text{x}10^{16}\ \text{cm}^{-3} \Leftrightarrow \lambda_{pe} \sim \Delta z$

ENERGY CHANGE

culation (2D): microbunches with equal charge



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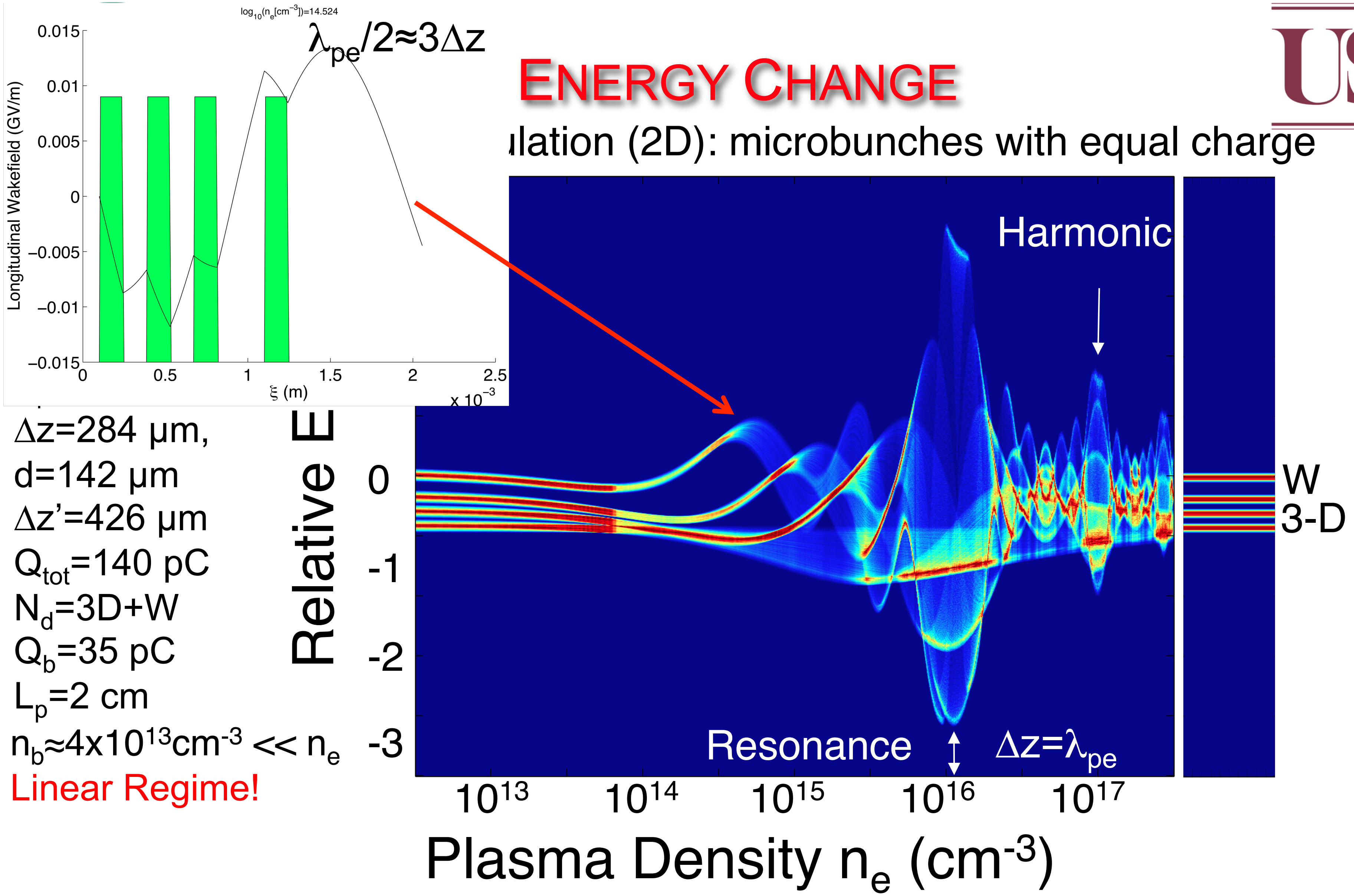

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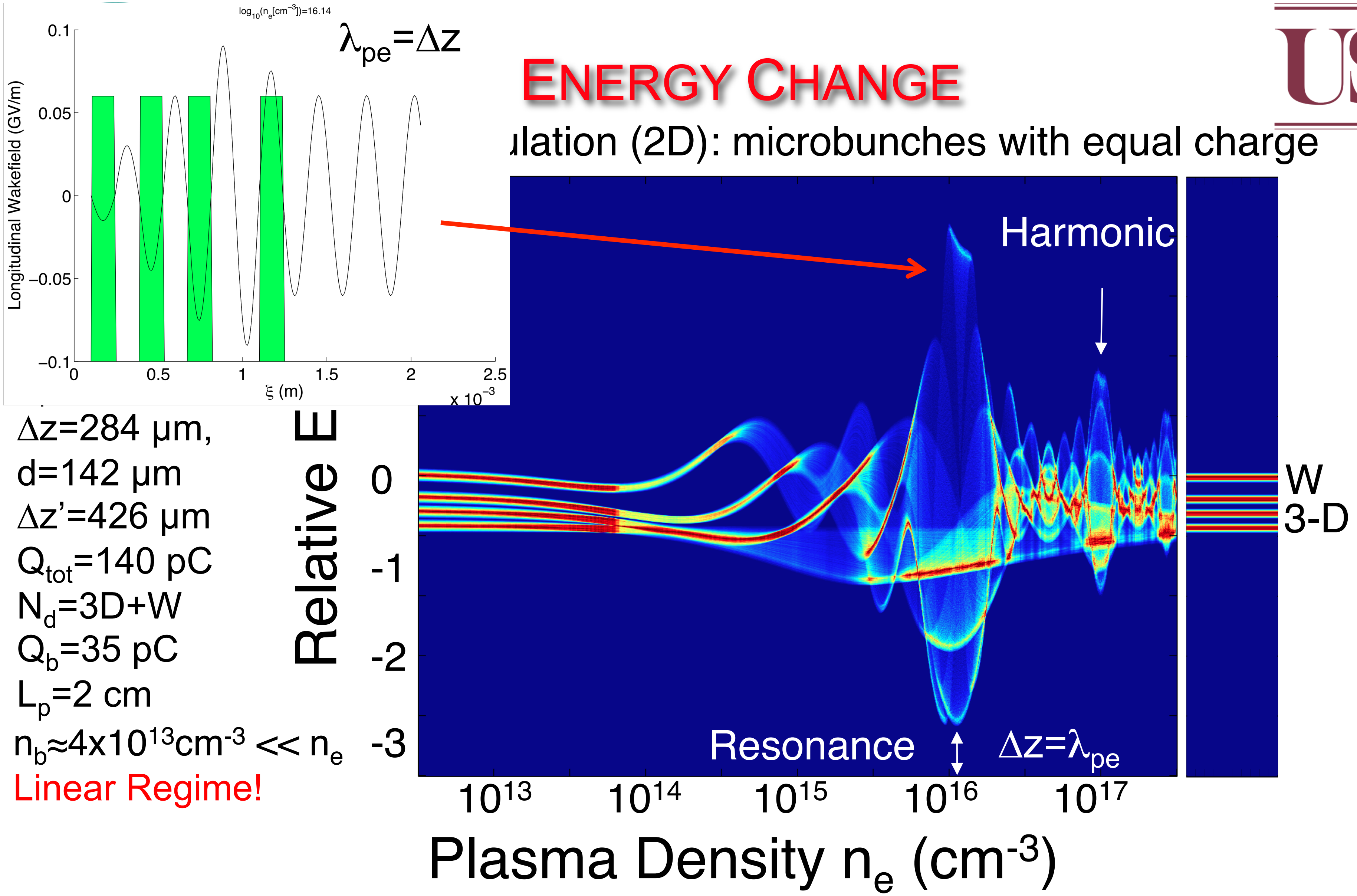

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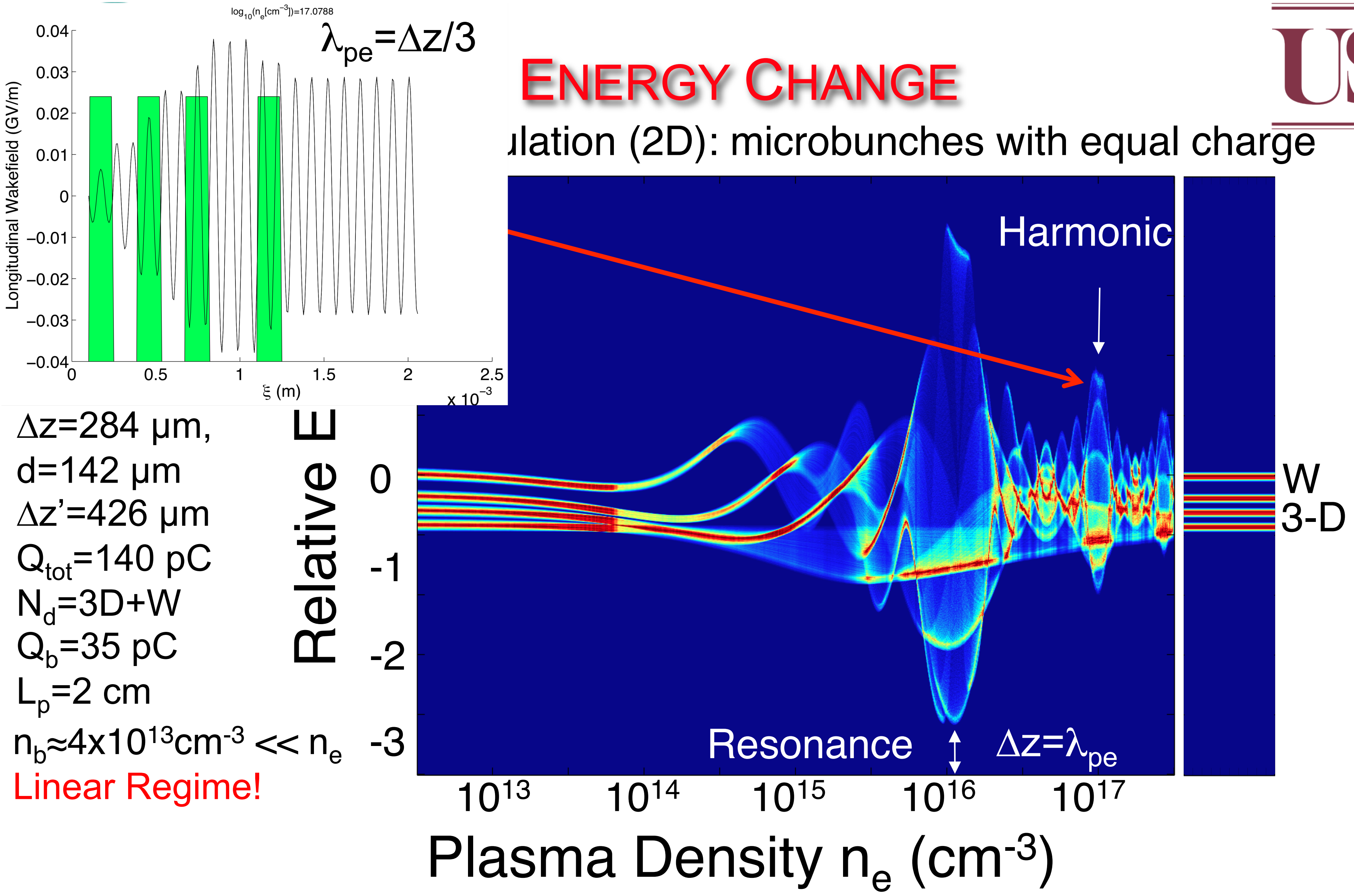

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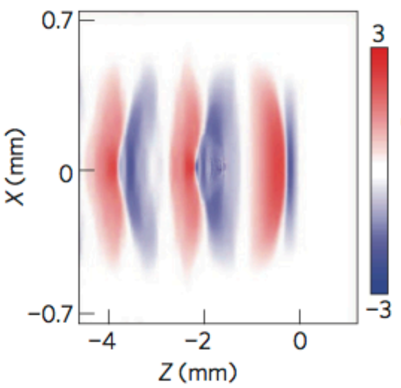
PROTON-DRIVEN PWFA @ CERN

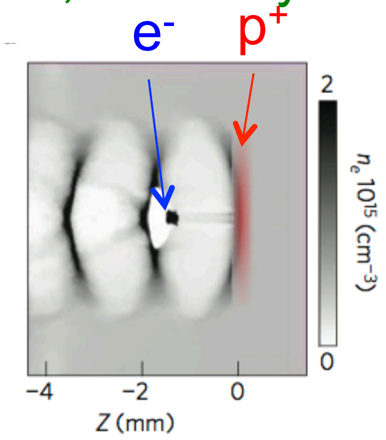
- A SLAC, 28.5GeV bunch with 2x10^{10}e^{-} caries ~90J
  An ILC, 0.5TeV bunch with 2x10^{10}e^{-} caries ~1.6kJ
- A SLAC-like driver for staging (FACET, +25GeV)
- A SPS, 450GeV bunch with 10^{11}p^{+} caries ~7.2kJ
  A LHC, 7TeV bunch with 10^{11}p^{+} caries ~112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- Long plasmas required (~100's m)
- Requires short (~100μm) p+ bunch

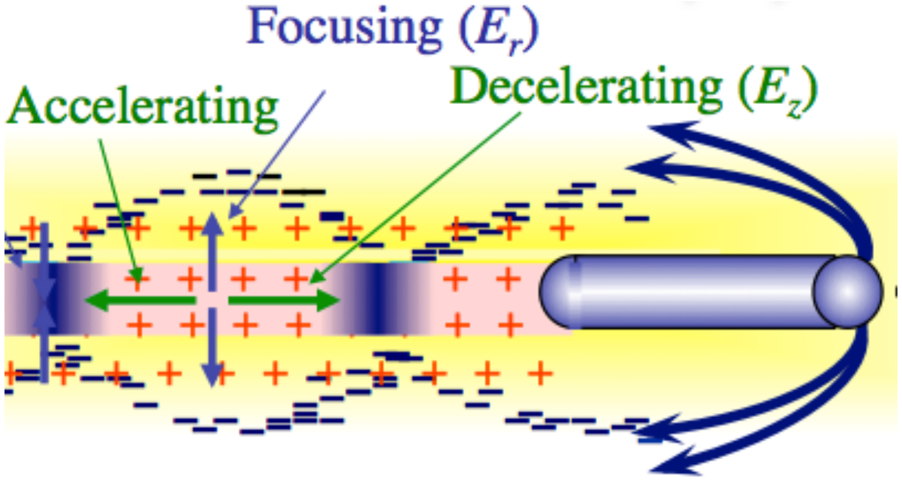
PROTON-DRIVEN PWFA @ CERN

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

p+:
E_0=1TeV
σ_z=100µm
N=10^{11}
e-:
E_0=1GeV
N=10^{11}

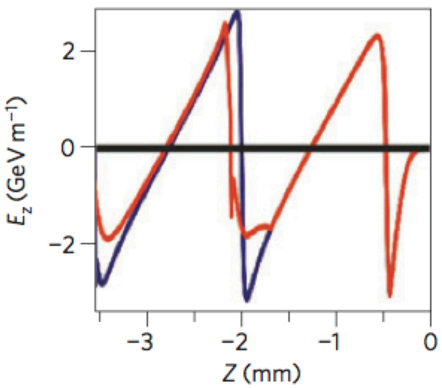






Phase difference!

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

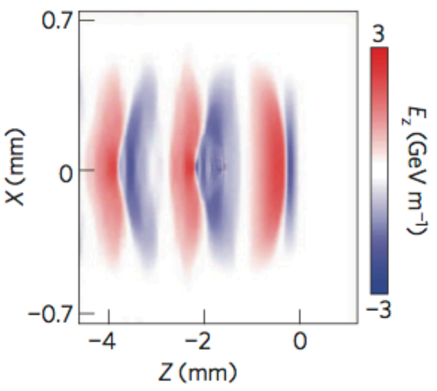


- ❐ Use “pancake” p$^+$ bunch to drive non-linear wake (cylinder for e$^-$ driver)
- ❐ Gradient ~1.5GV/m (av.)

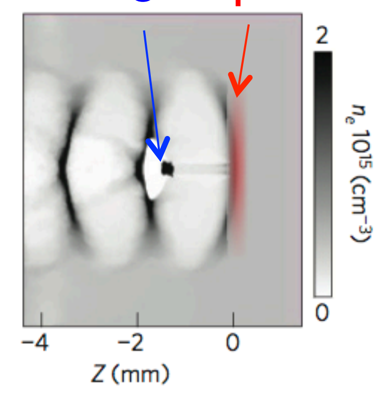
PROTON-DRIVEN PWFA @ CERN

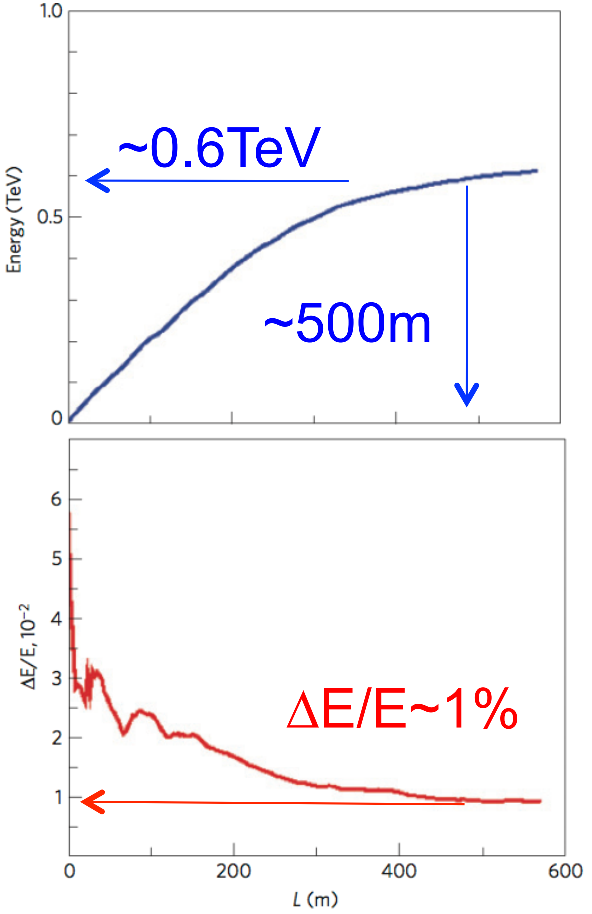
Caldwell, Nat. Phys. 5, 363, (2009)

p+:
E_0=1GeV
σ_z=100µm
N=10^{11}
e-:
E_0=1GeV
N=10^{11}



e- p+

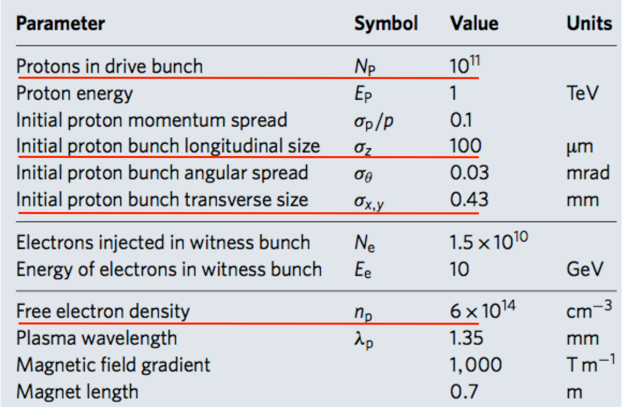




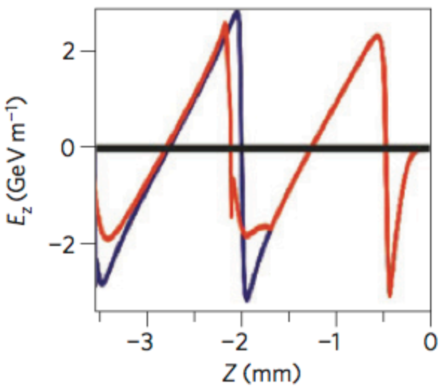
~0.6TeV

~500m

ΔE/E~1%

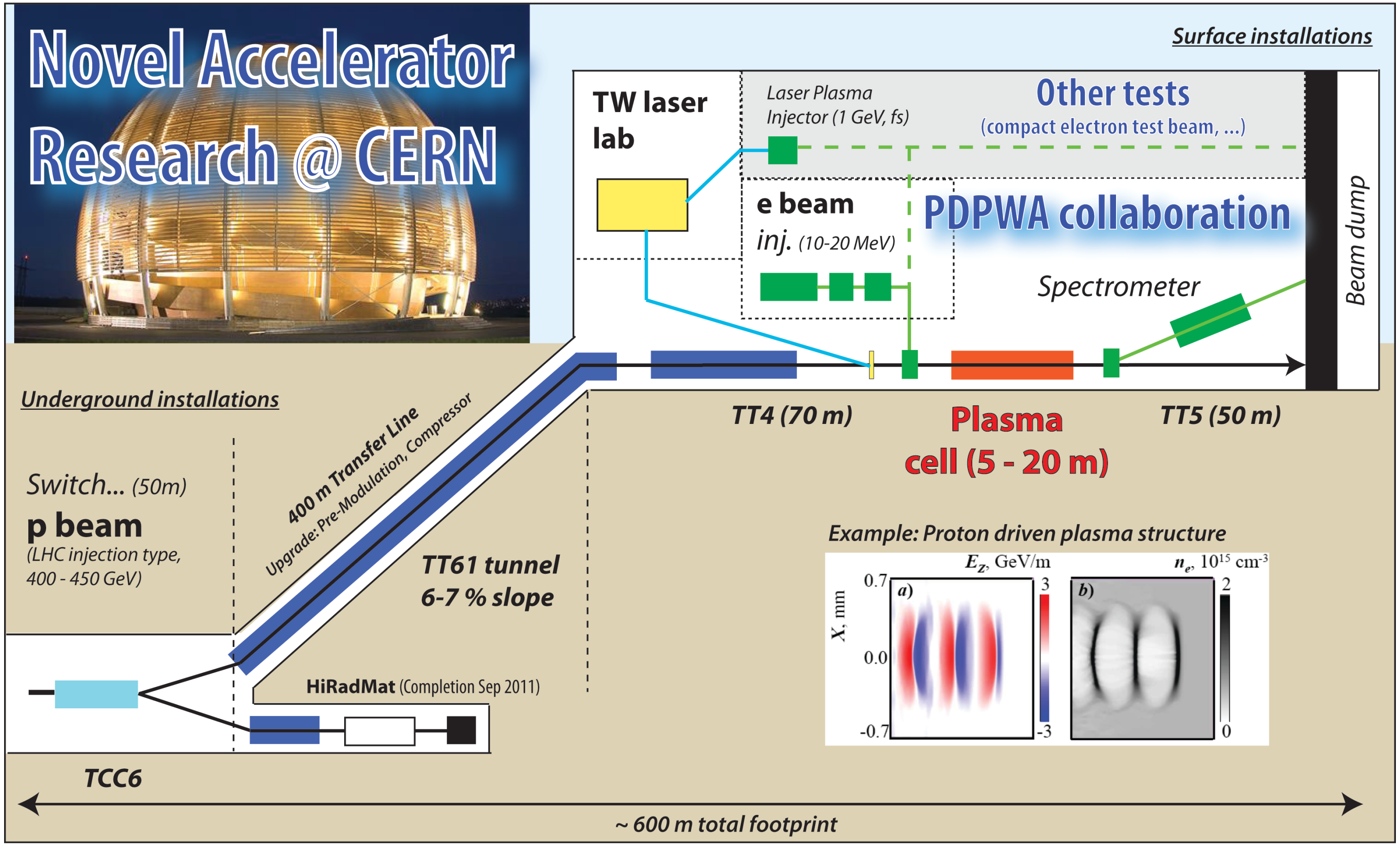


Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons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



- Use “pancake” p^+ bunch to drive non-linear wake (cylinder for e^- driver)
- Gradient ~1.5GV/m (av.), efficiency ~ 10%
- ILC-like e^- bunch from a single p^+-driven PWFA

PROTON-DRIVEN PWFA @ CERN



- Letter of intent submitted to CERN for self-modulated p$^+$-driven PWFA experiments, verdict in October …
- Experiments 2015-… for 1GeV in a few meters, self modulated
- Program for TeV class e- from p$^+$-driven PWFA, driven by MPP

SUMMARY AND CONCLUSIONS

- PWFA made remarkable progress
  - 42GeV energy gain in 85cm of plasma @ SLAC
- PWFA is well understood
- FACET@SLAC will address PWFA collider issues
  - Acceleration of witness bunch ($\Delta E/E_0$~1%)
  - e^+ …
  - Single, e^-/e^+, +25 GeV PWFA stage
- Test the physics in low energy experiments (BNL-ATF)
- Proton-driven PWFA to be proposed to CERN, by MPP, first PWFA experiment in EU, only p^+ in the world
- PWFA at DESY, in Japan, Italy, …
- PWFA could be a possible technology candidate for future more compact (cheaper) colliders and light sources

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Thank you!

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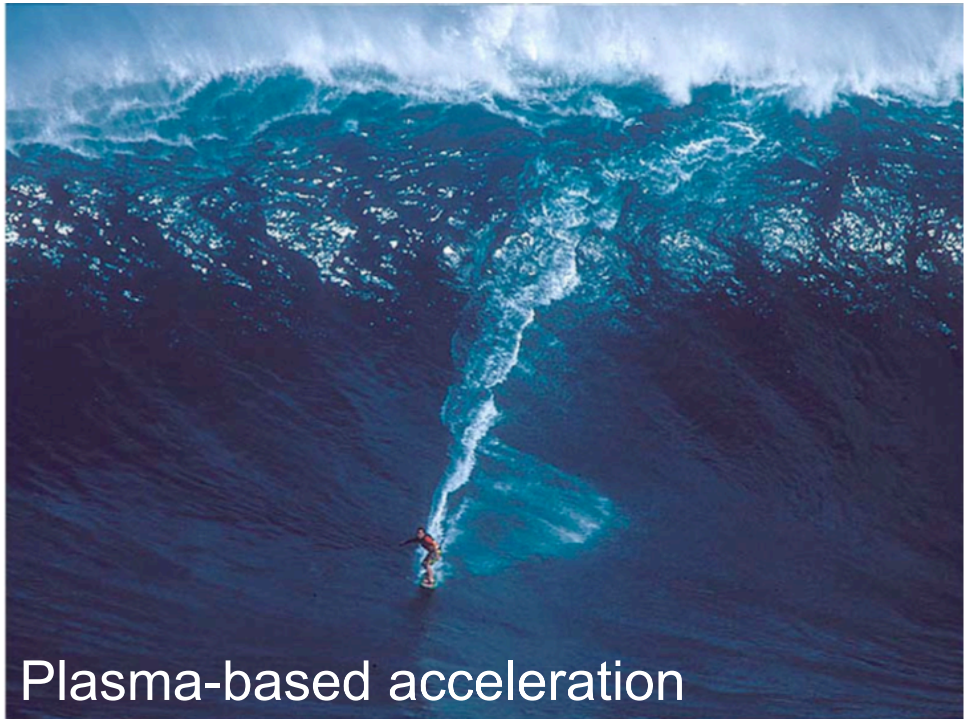
Thank You!

Turn this …

RF-based acceleration

… into that!



Plasma-based acceleration

Review of High-energy Plasma Wakefield Experiments:
P. Muggli and M.J. Hogan, Comptes Rendus Physique, 10(2-3), 116 (2009).

Related publications at: www-http://www-rcf.usc.edu/~muggli/publications.html

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