Beam-driven, Plasma-based Particle Acceleration

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Work supported by US Dept. of Energy

OUTLINE

- Motivation - Introduction to PWFA (Plasma Wakefield Accelerator)
- 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)
- Self-modulation-driven PWFA
- Summary and Conclusions

Focus on acceleration all the way through!

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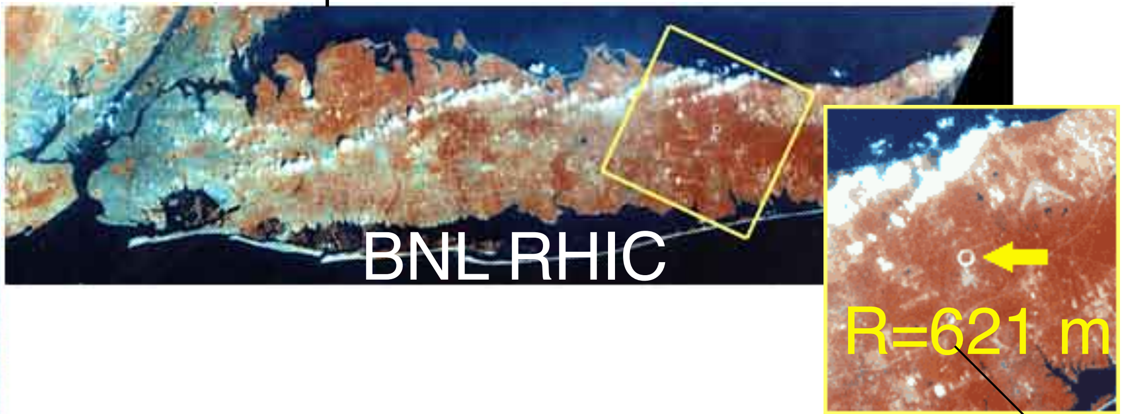
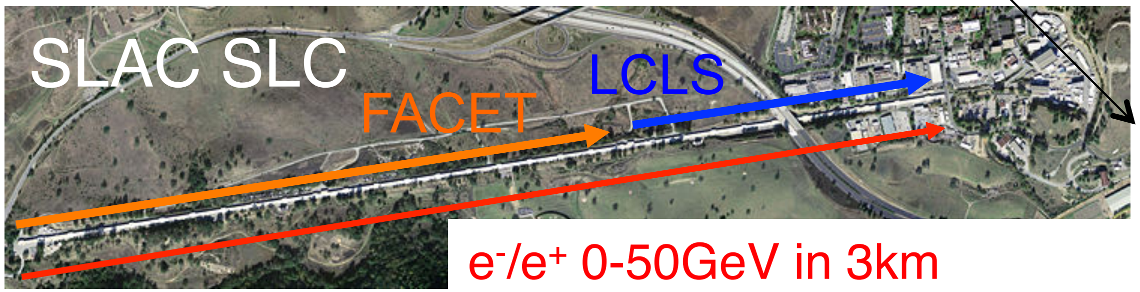
PARTICLE ACCELERATORS

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





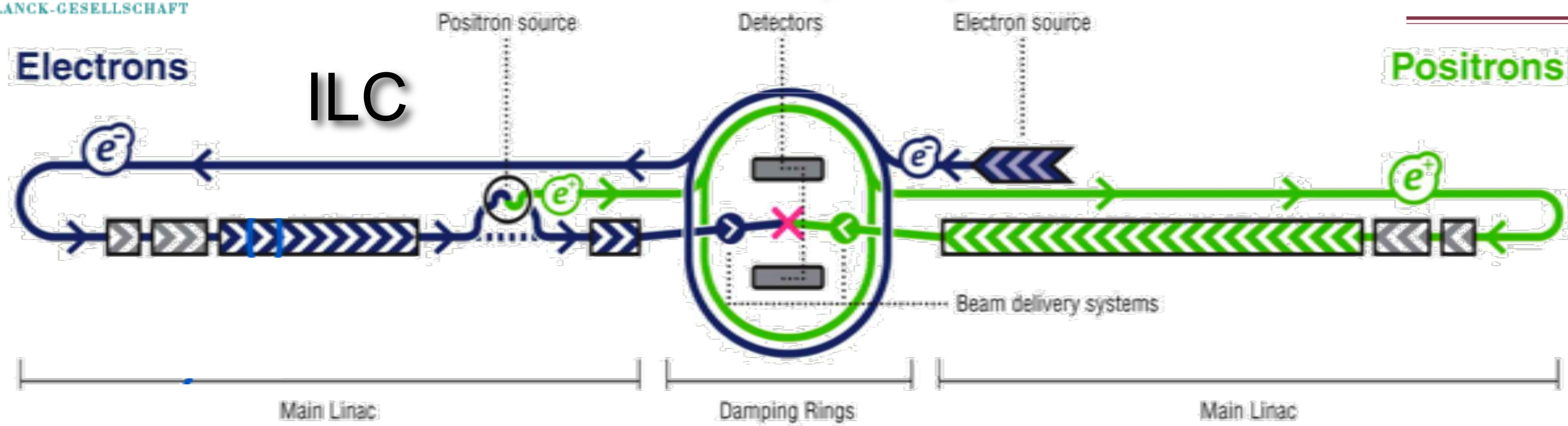
e^-/e^+ 0-50GeV in 3km

e^-/e^+ 0-23GeV in 2km FACET

e^- 0-14GeV in 1km LCLS

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

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

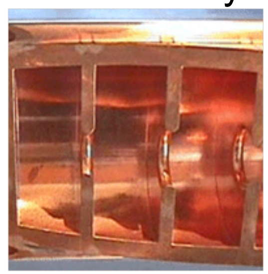


≈25 km site?

- Linear accelerator to avoid synchrotron radiation limitation ($\sim\gamma^4/r^2 \sim E^4/m^4r^2$)
- Energy frontier: 0.5-3 TeV, e^-/e^+
- Accelerator length with (cold) rf technology:

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

Pillbox Cavity



<150MV/m?

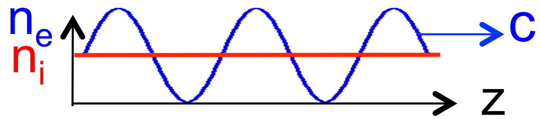
Is there a high-gradient alternative to rf technology?
Could it be plasmas?

WHAT ABOUT PLASMAS?

➡ Relativistic Electron Electrostatic Plasma Wave (Electrostatic, E_z):

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

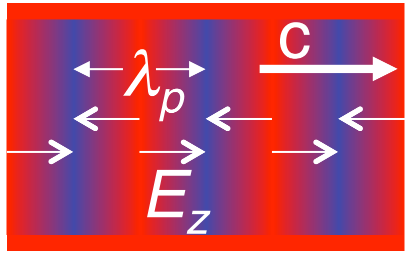
Plasma Frequency



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

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 when relativistic)

➡ Plasma is already (partially) ionized, difficult to "break-down"

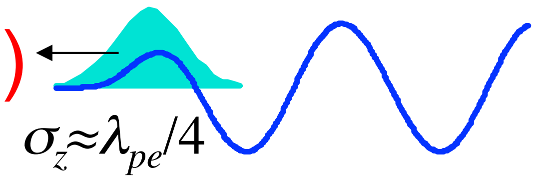
➡ Plasmas wave or wake can be driven by:

- Intense laser pulses (LWFA)
- Short particle bunch (PWFA)

4 PLASMA ACCELERATORS*

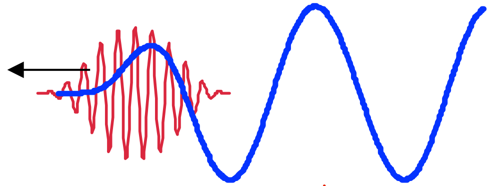
- Plasma Wakefield Accelerator (PWFA)

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



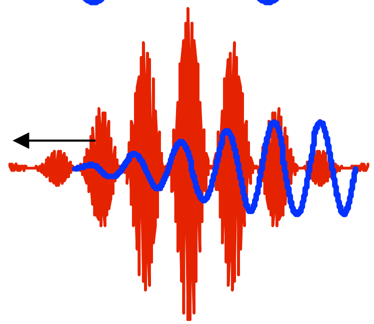
- Laser Wakefield Accelerator (LWFA)

  A short laser pulse (photons)



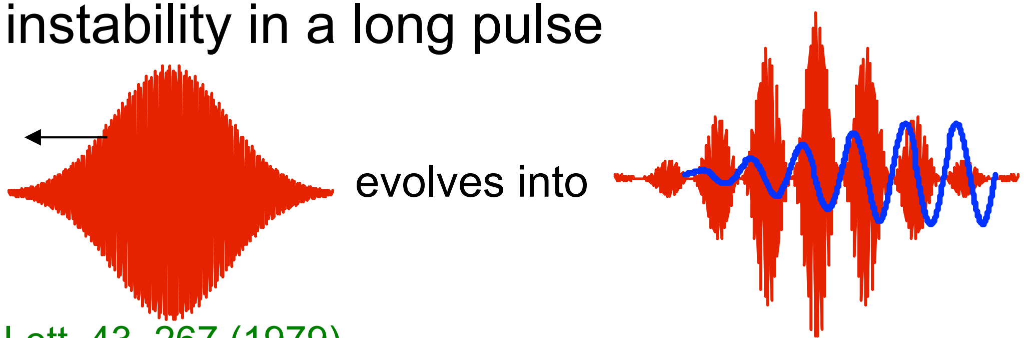
- Plasma Beat Wave Accelerator (PBWA)

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



- Self-Modulated Laser Wakefield Accelerator (SMLWFA)

  Raman forward scattering instability in a long pulse



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

4 PLASMA ACCELERATORS*

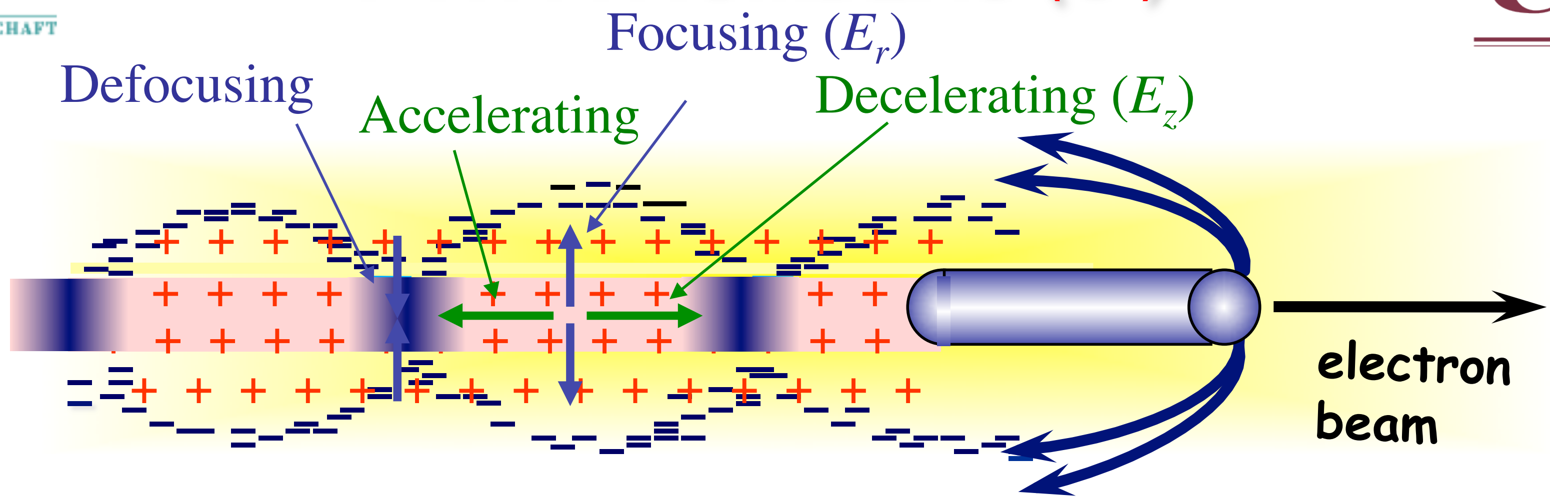
• Plasma Wakefield Accelerator (PWFA)

The plasma:

- Converts transverse into longitudinal fields (ES wave)
- Supports the relativistic (v_z~c) plasma wave with E_z=1-100GV/m
- Supports the accelerating structure
- Suppresses need for cavity fabrication
- Needs only one wave period
- Overcomes the breakdown limit

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

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 $k_{pe}\sigma_r << 1$)*

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

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

  σ_z= 20 μm, $n_e=2\times10^{17}$ cm^{-3}, E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

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

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

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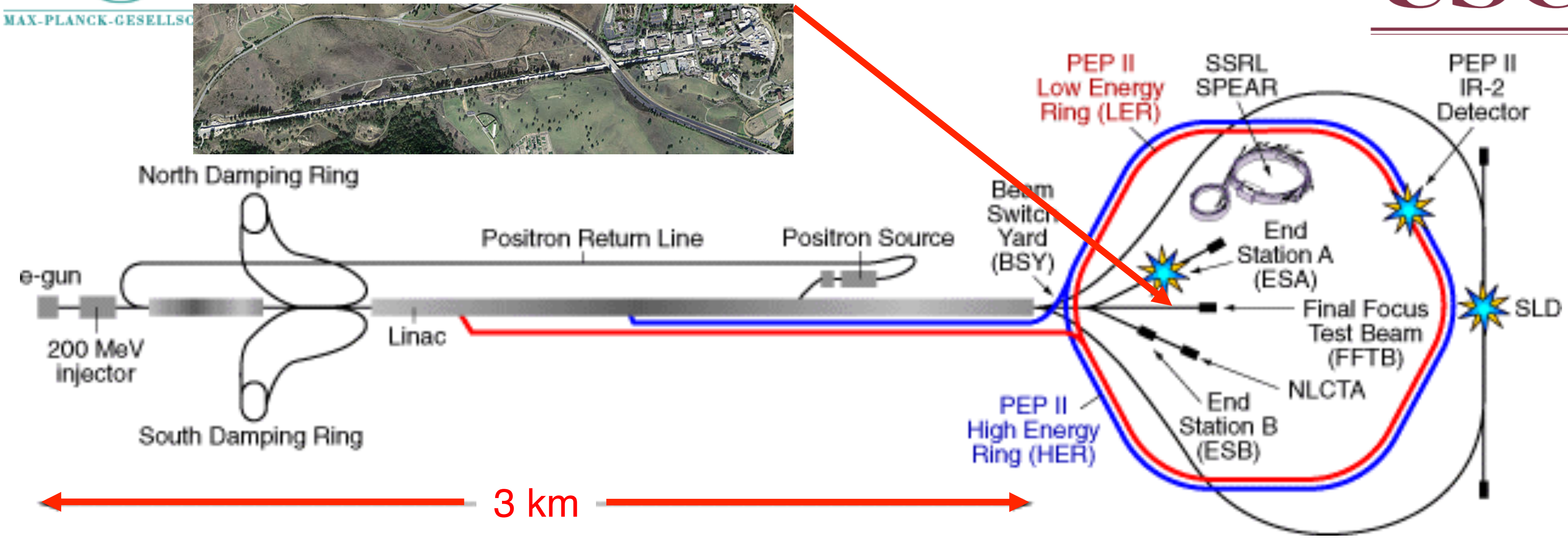
PWFA Experiments @ SLAC



Long-bunch Experiments		Short-bunch experiments
e^-/e^+ 28.5 GeV	$N\approx 1.2\text{-}1.8\times 10^{10}$/bunch	e^- 28.5, 42 GeV
$\sigma_z \approx 700\ \mu m$		$\sigma_z \approx 30\text{-}20\ \mu m$
$\sigma_r \approx 30\ \mu m$	$k_{pe}\sigma_z \approx \sqrt{2}$	$\sigma_r \approx 10\ \mu m$
$n_e \approx 2\times 10^{14}\ cm^{-3}$	0.1-100 GV/m	$n_e \approx 1\text{-}3\times 10^{17}\ cm^{-3}$
$L_p \approx 1.4$ m	Linear Theory	$L_p \approx 10, 20, 30, 60, 90, 120$ cm
Pre-ionized		Field-ionized

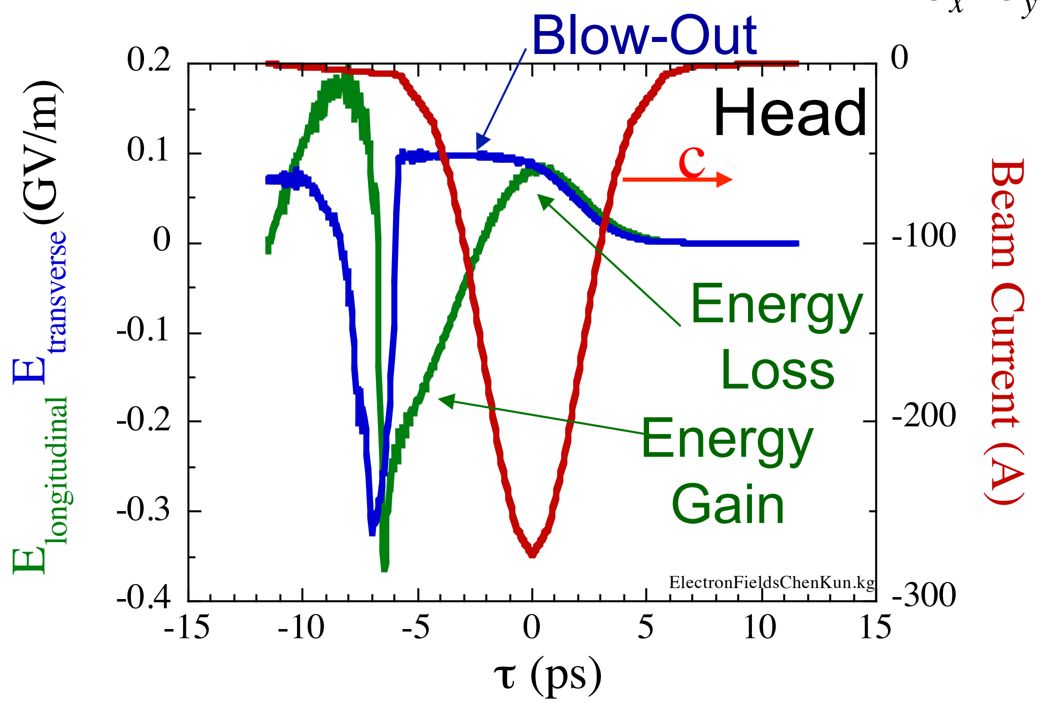
PLASMA WAKEFIELD FIELDS (e^-)
$\sigma_z \approx 700\ \mu m$

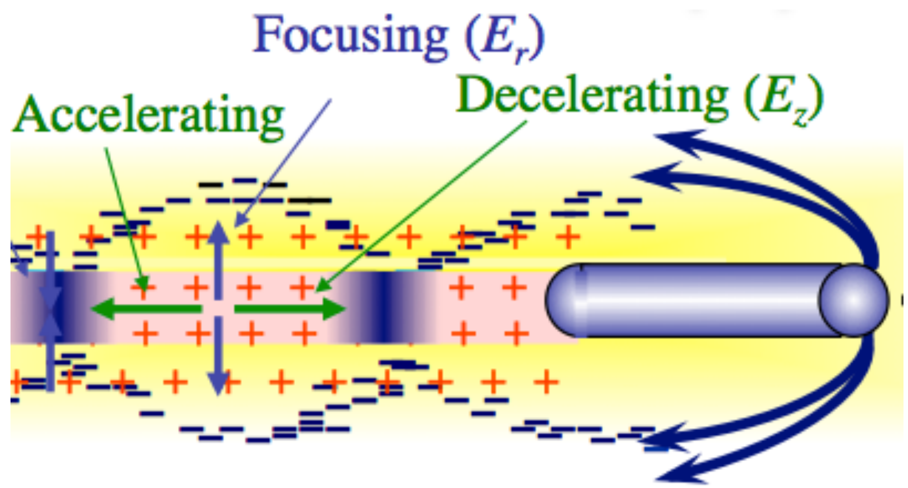
2-D PIC Simulation QUICPICK

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

$k_p\sigma_z \sim \sqrt{2}$

E_0	28.5 GeV	n_b	$4\times10^{14}\ cm^{-3}$
N	2×10^{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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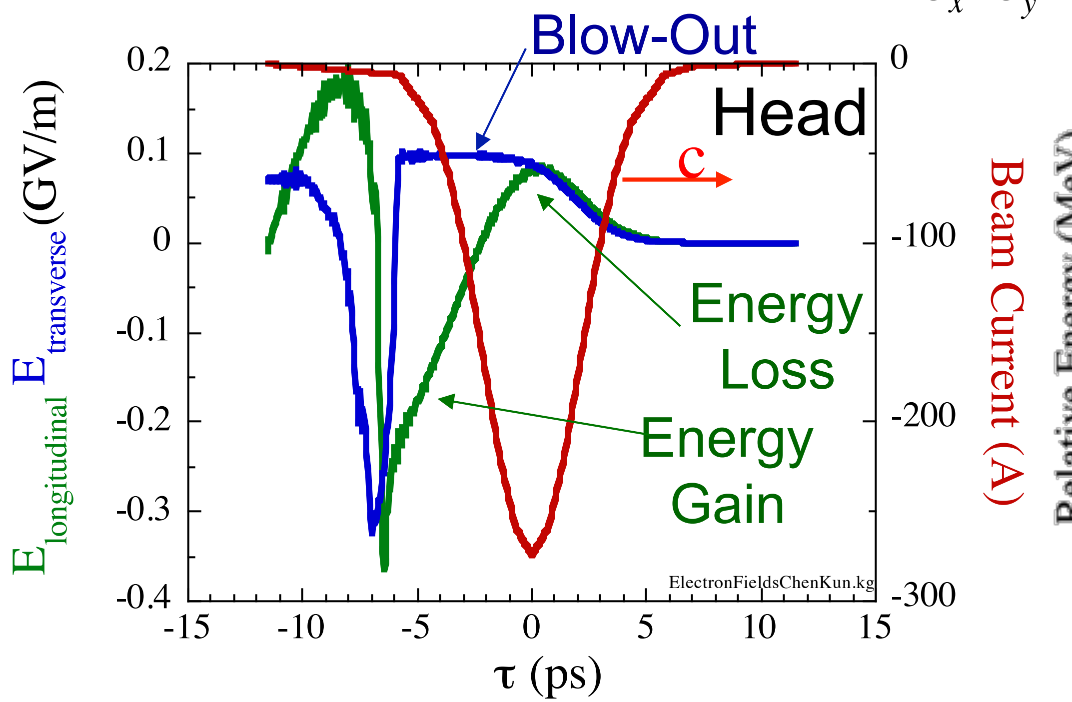
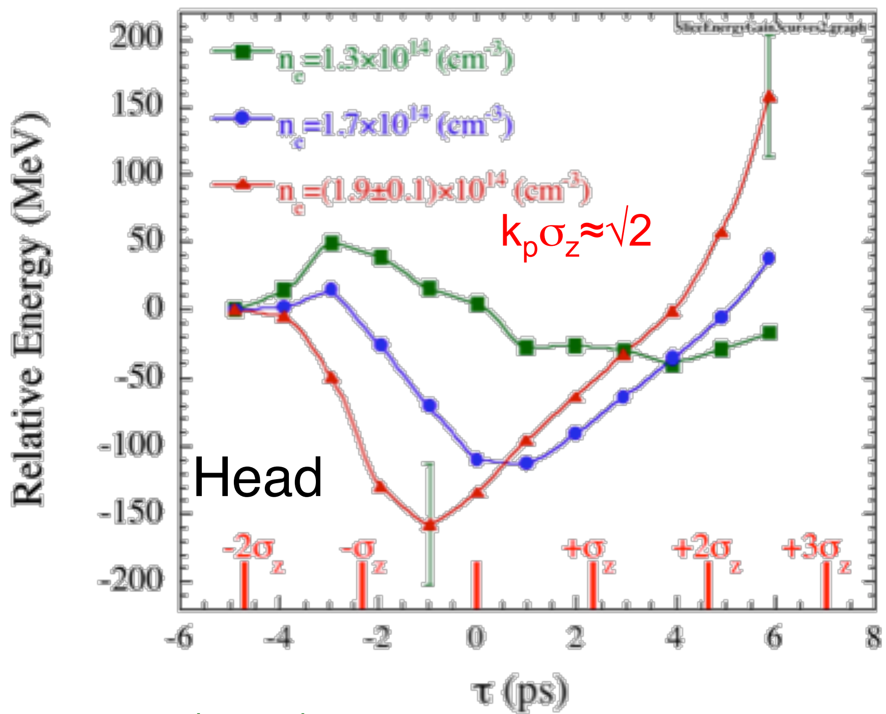
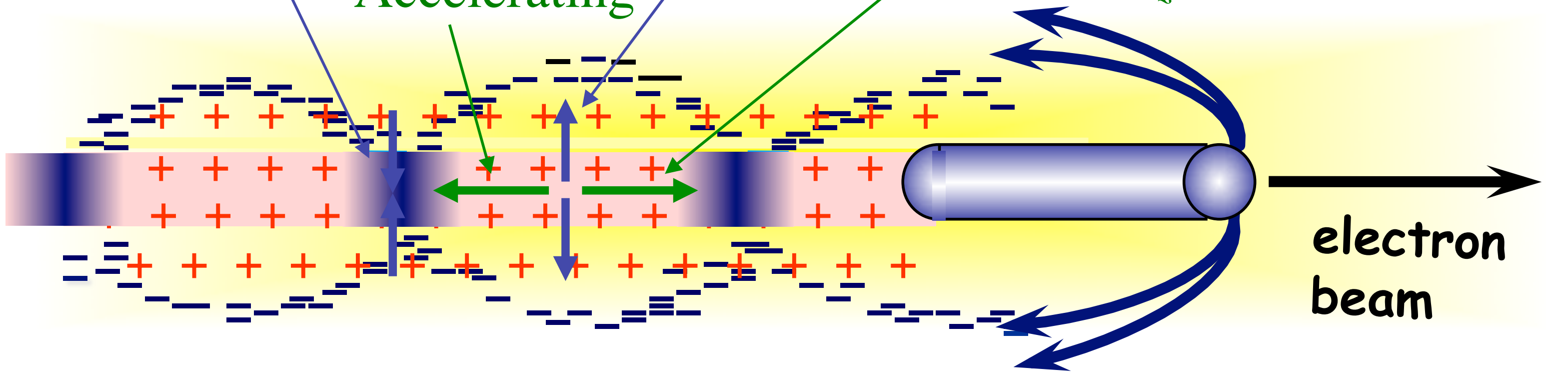




Muggli, Phys. Rev. Lett. 93, 014802 (2004).

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

$\approx N/\sigma_z^2$

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

Short Bunches (n_b>n_e) !

- Focusing strength:

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

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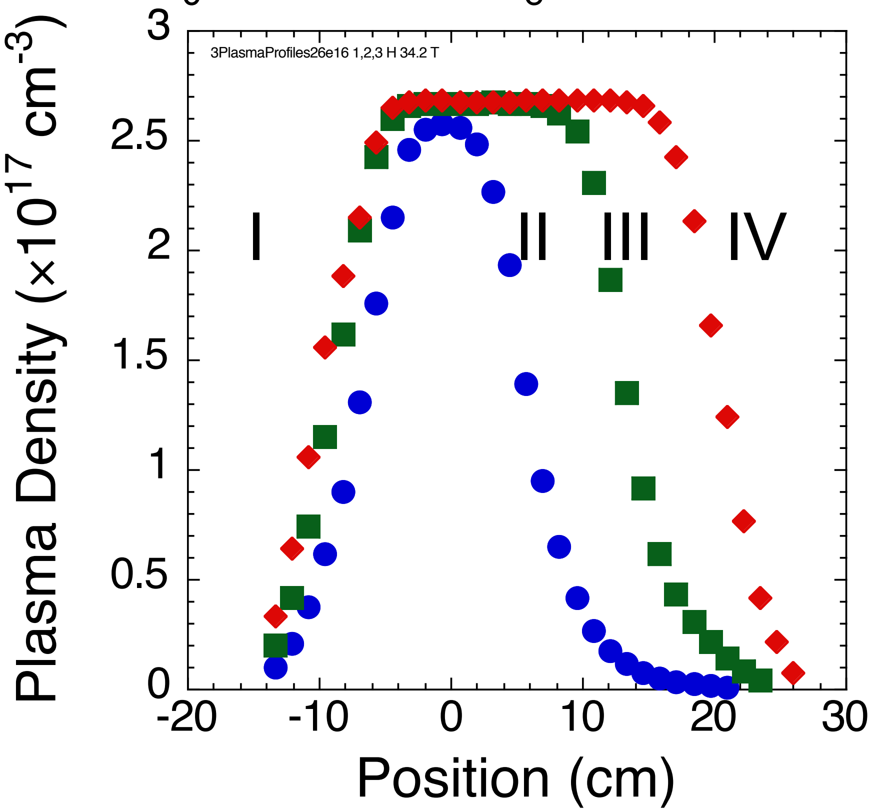
MAX-PLANCK-GESELLSCHAFT

USC

SCALING WITH PLASMA LENGTH

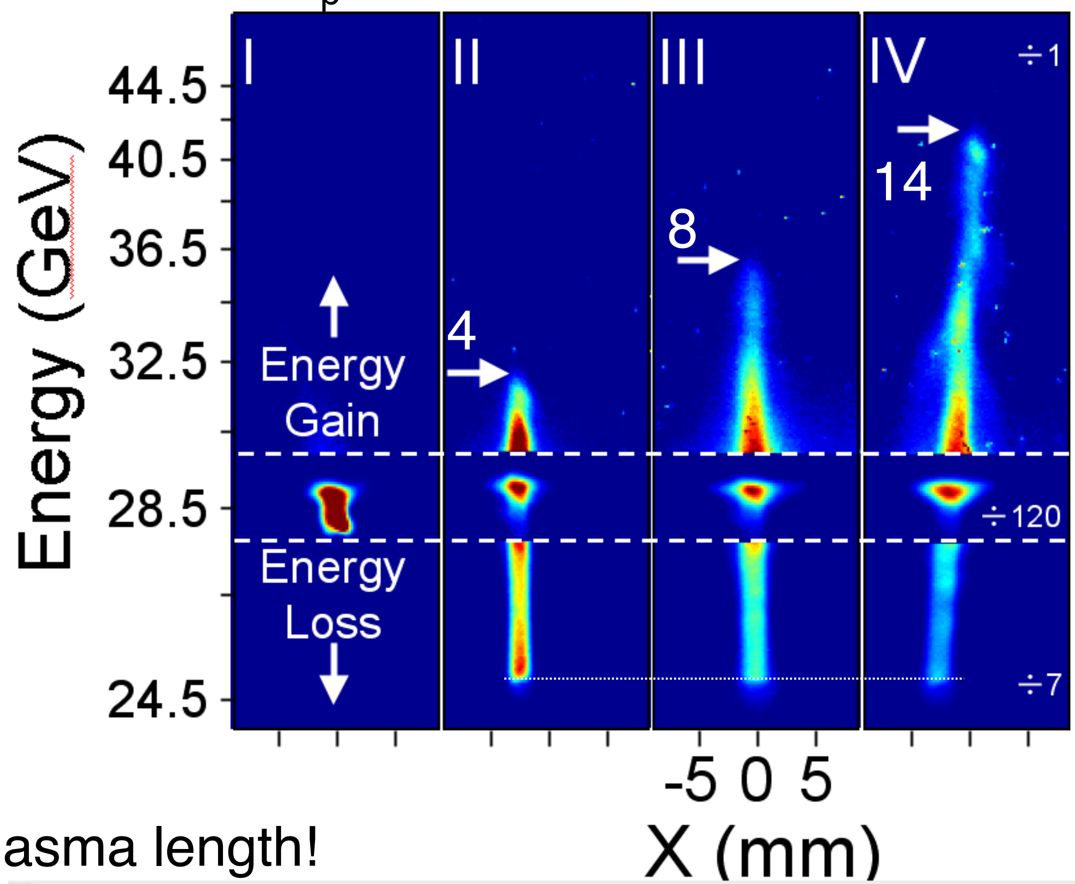
$\sigma_z \approx 25\ \mu m$

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



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

L_p=0, 13, 22, 31 cm



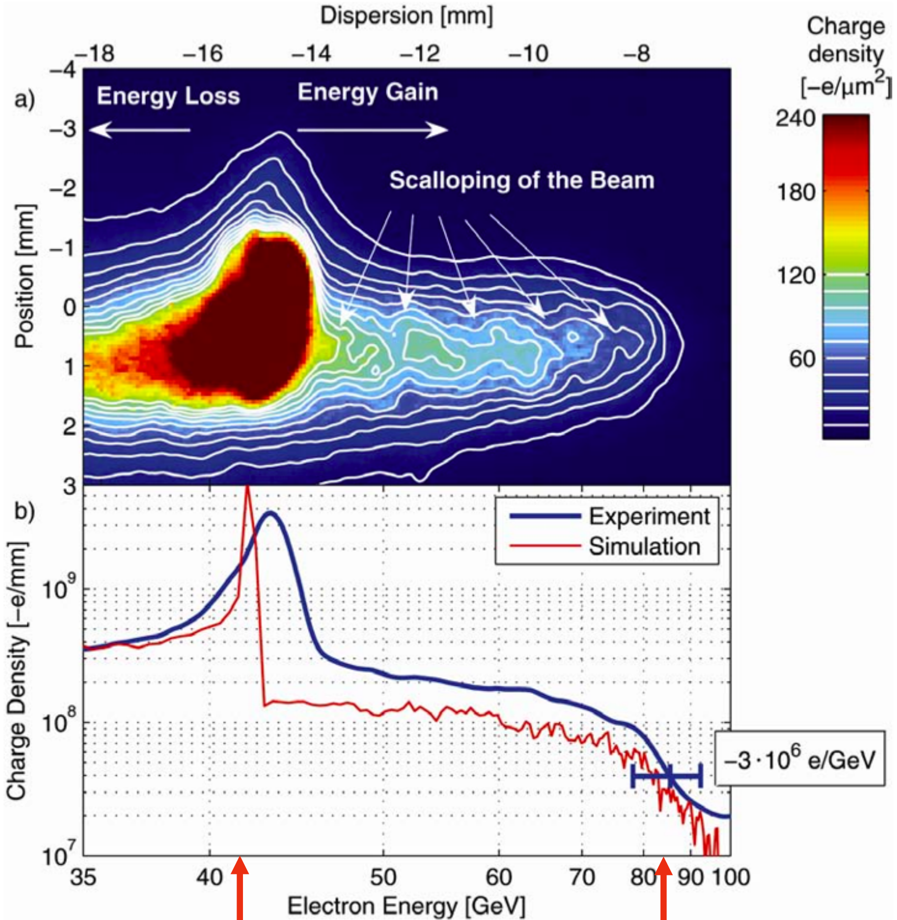
- Energy gain scales linearly with plasma length!
- Gain ≈14 GeV over (only!) L_p=31 cm!
- $E_{acc} \approx 45$ GV/m

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

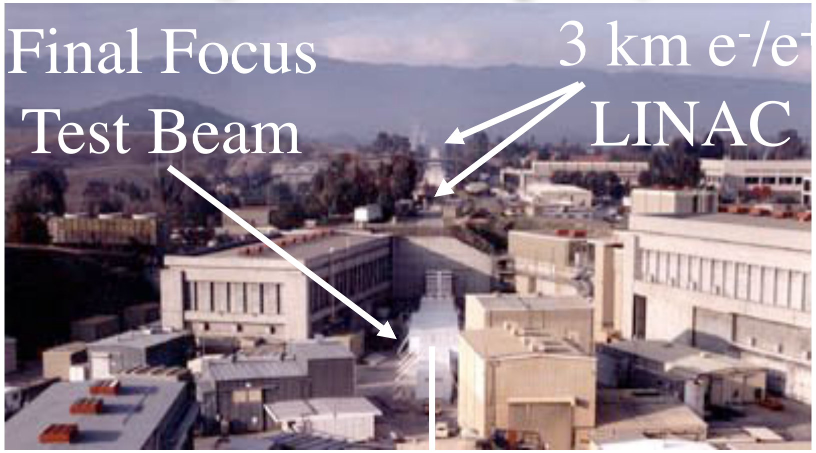
e^- ENERGY DOUBLING

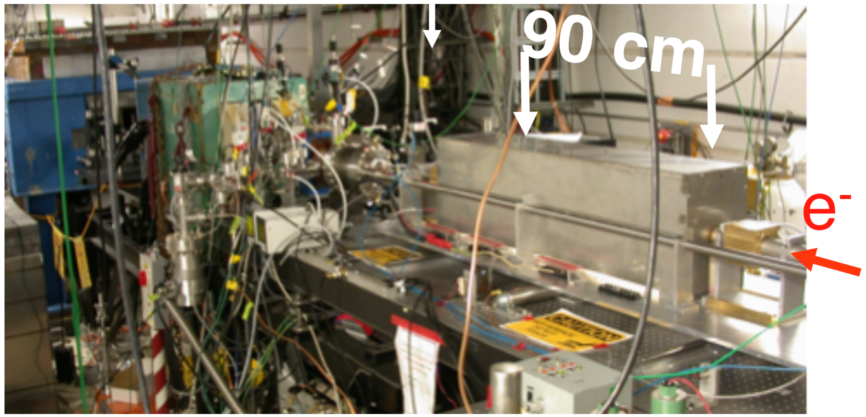
Blumenfeld, Nature 445, 2007

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



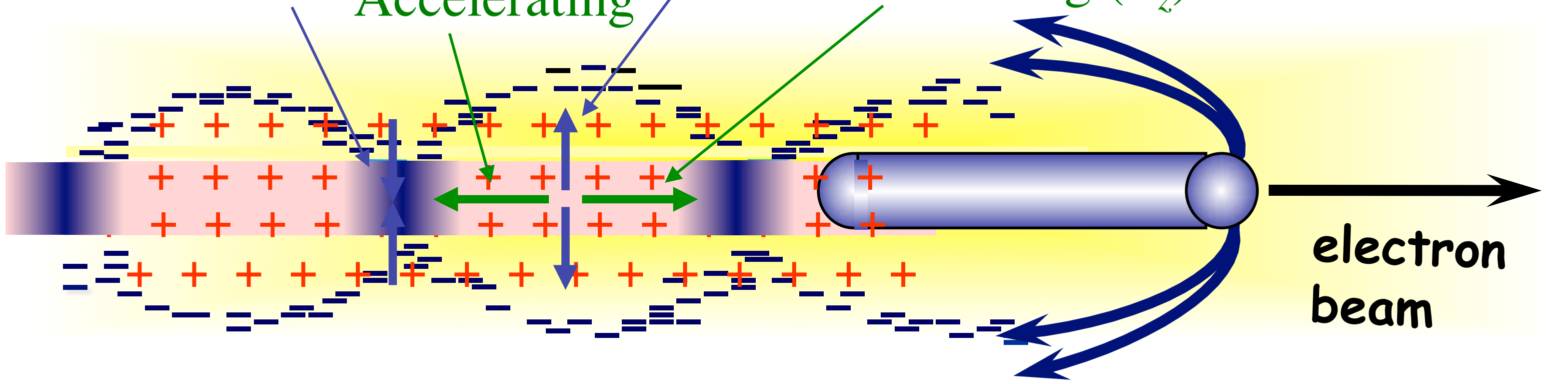
E_0 $2E_0$

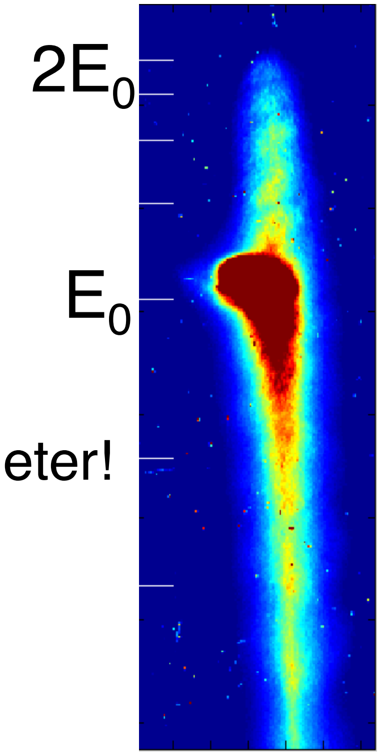




- Energy doubling of e^- over $L_p \approx 85$ cm, 2.7×10^{17} cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

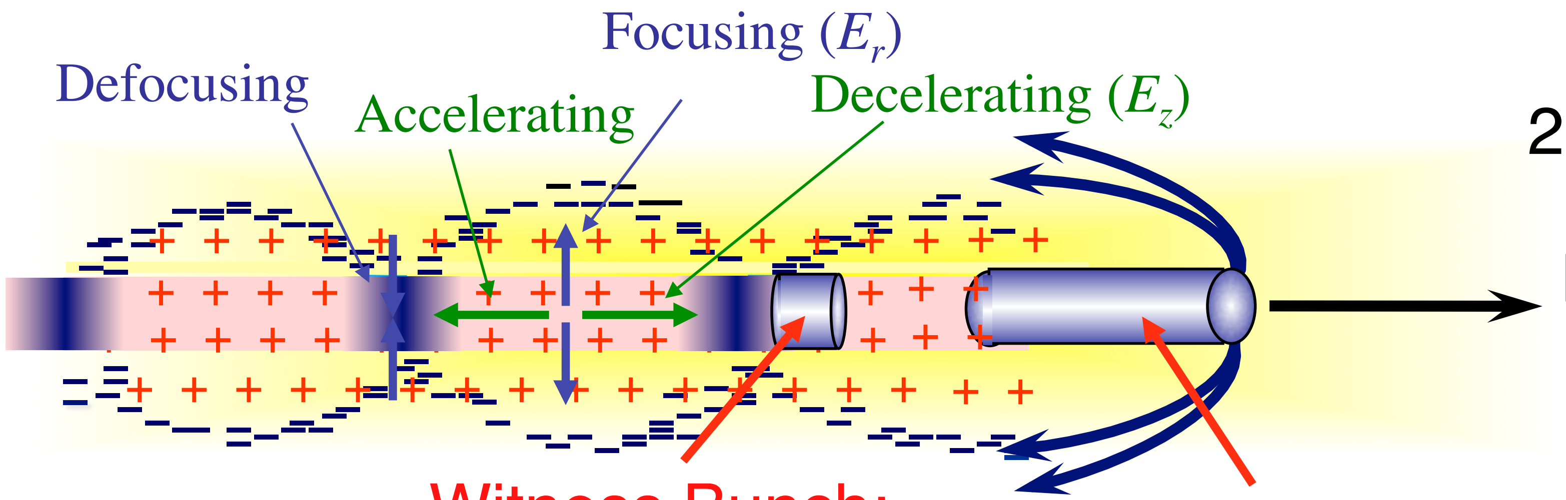
SINGLE BUNCH PWFA

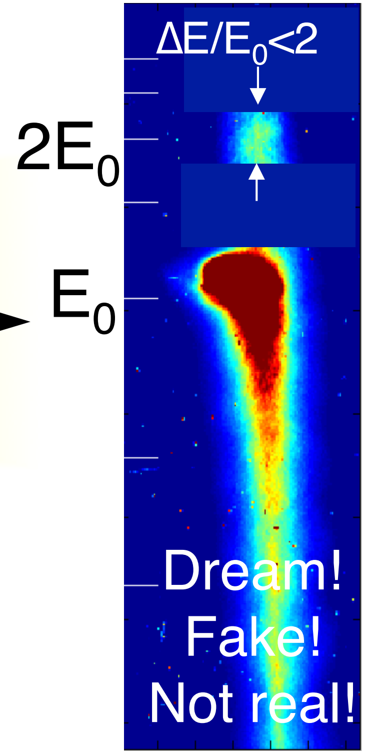




- Large energy gain (42GeV) in only 85cm, but …
- Particles at all phase, large energy spread (100%)
- Particle acceleration, not <u>bunch</u> acceleration,
  These wakefields exist and can be sustained over ~ meter!
- Need witness bunch injection behind a drive bunch

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 20GeV PWFA accelerator module
  Hogan et al., New J. Phys. 12, 055030 (2010)
- FACET program starting now
- Low energy physics experiments

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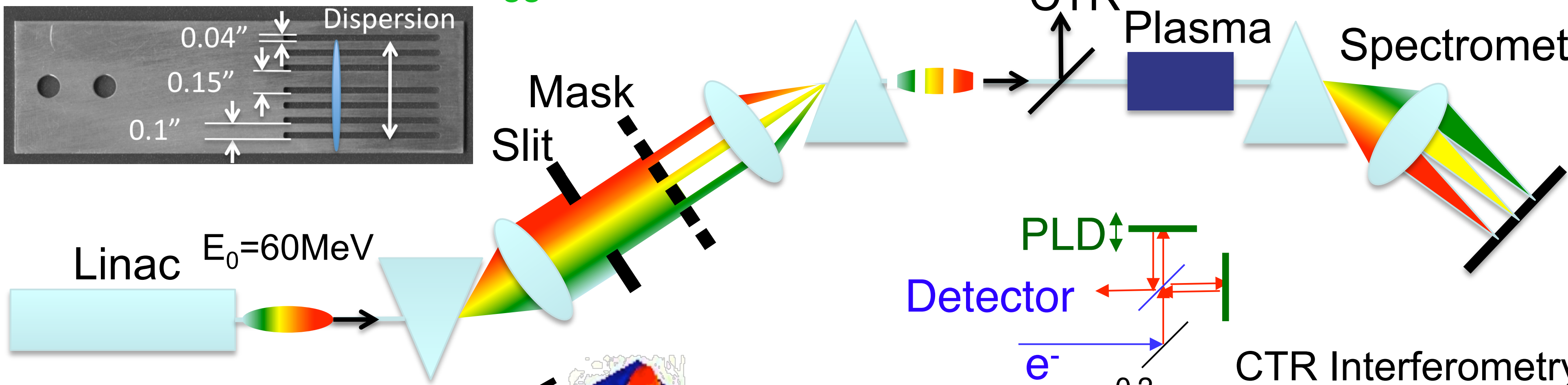
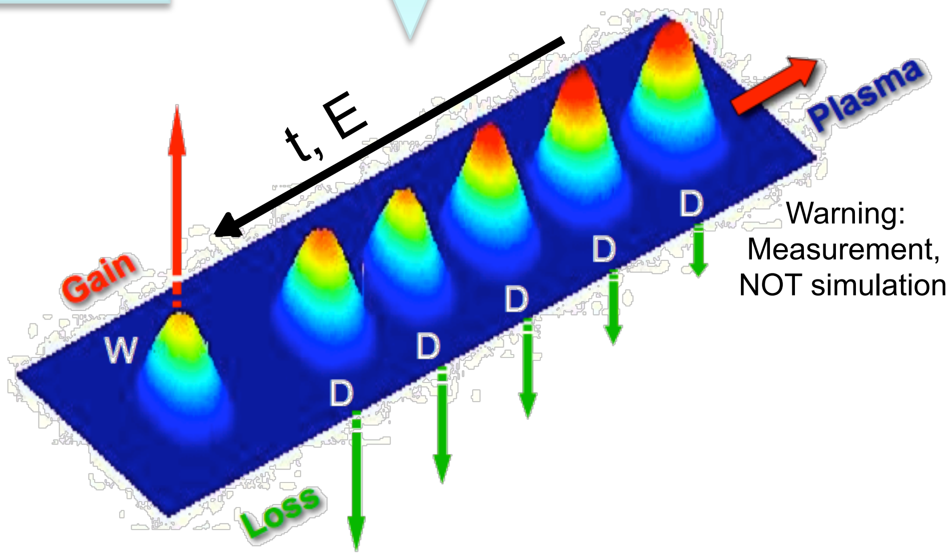
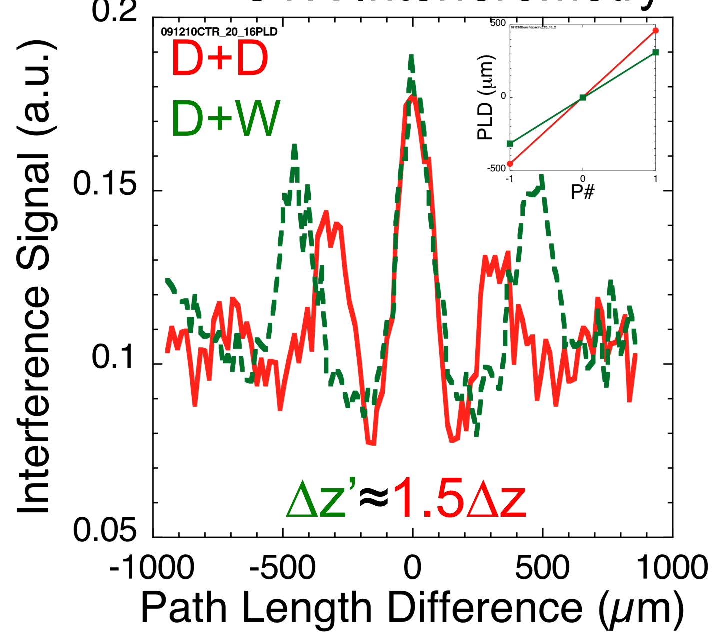
MULTIBUNCH SOURCE-MASKING

Muggli, PRL 2008, PRST-AB 2010







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

(similar to COMB@SPARC)

MULTIBUNCH PWFA

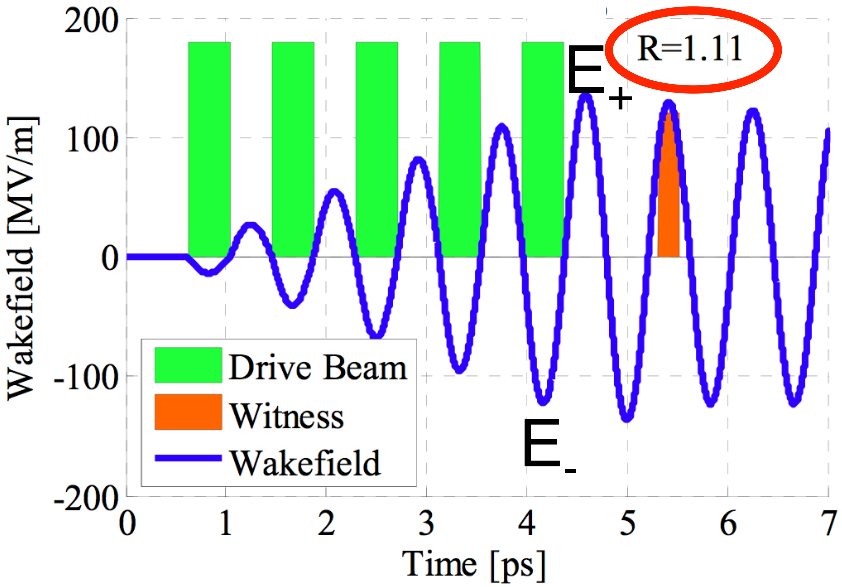
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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$\approx\lambda_p$

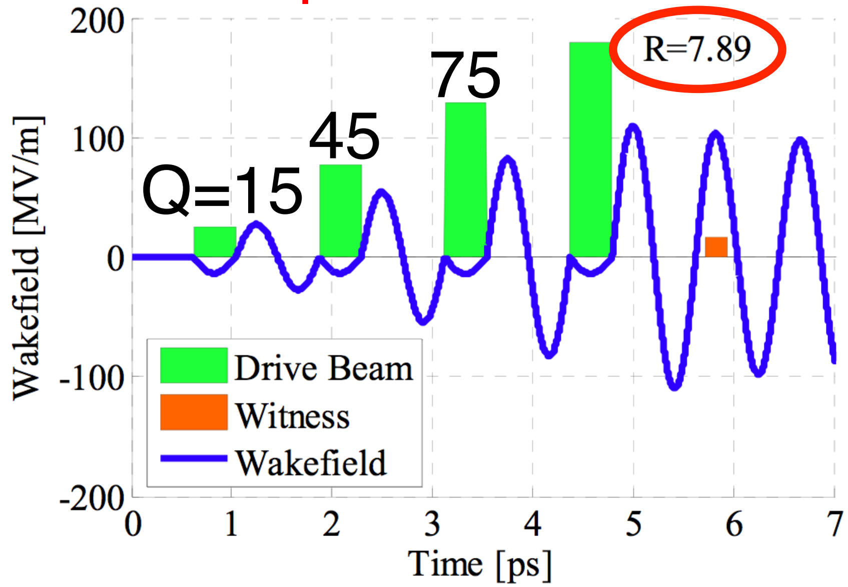
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm$\approx$1.5λ_p

Ramped Bunch Train*



*Tsakanov, NIMA, 1999

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

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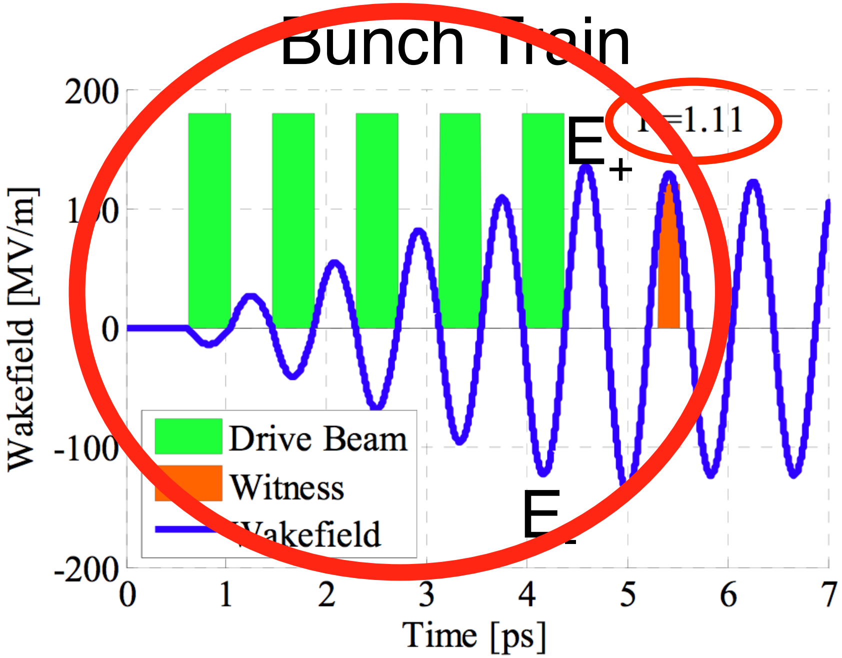
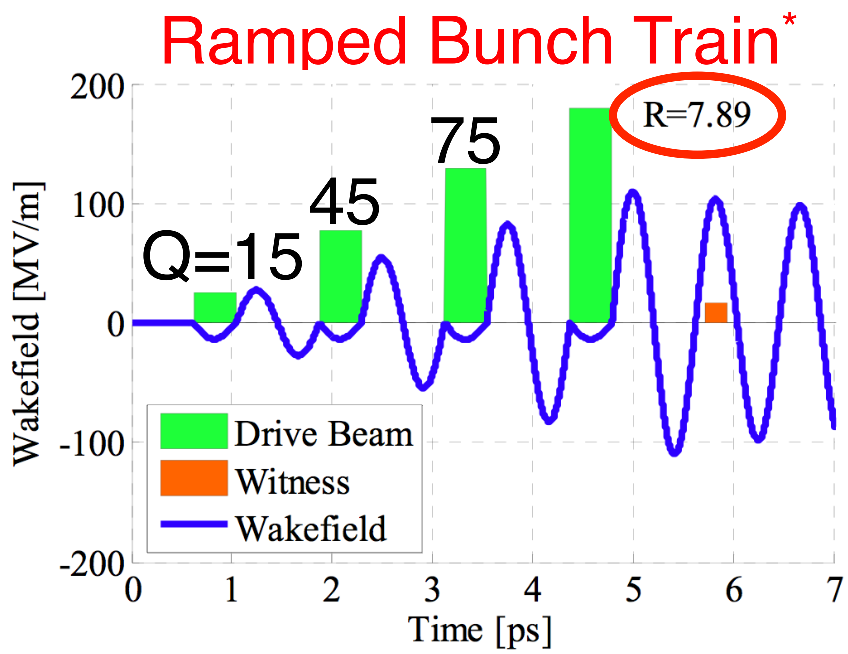


Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p



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- Resonant excitation of wakefields
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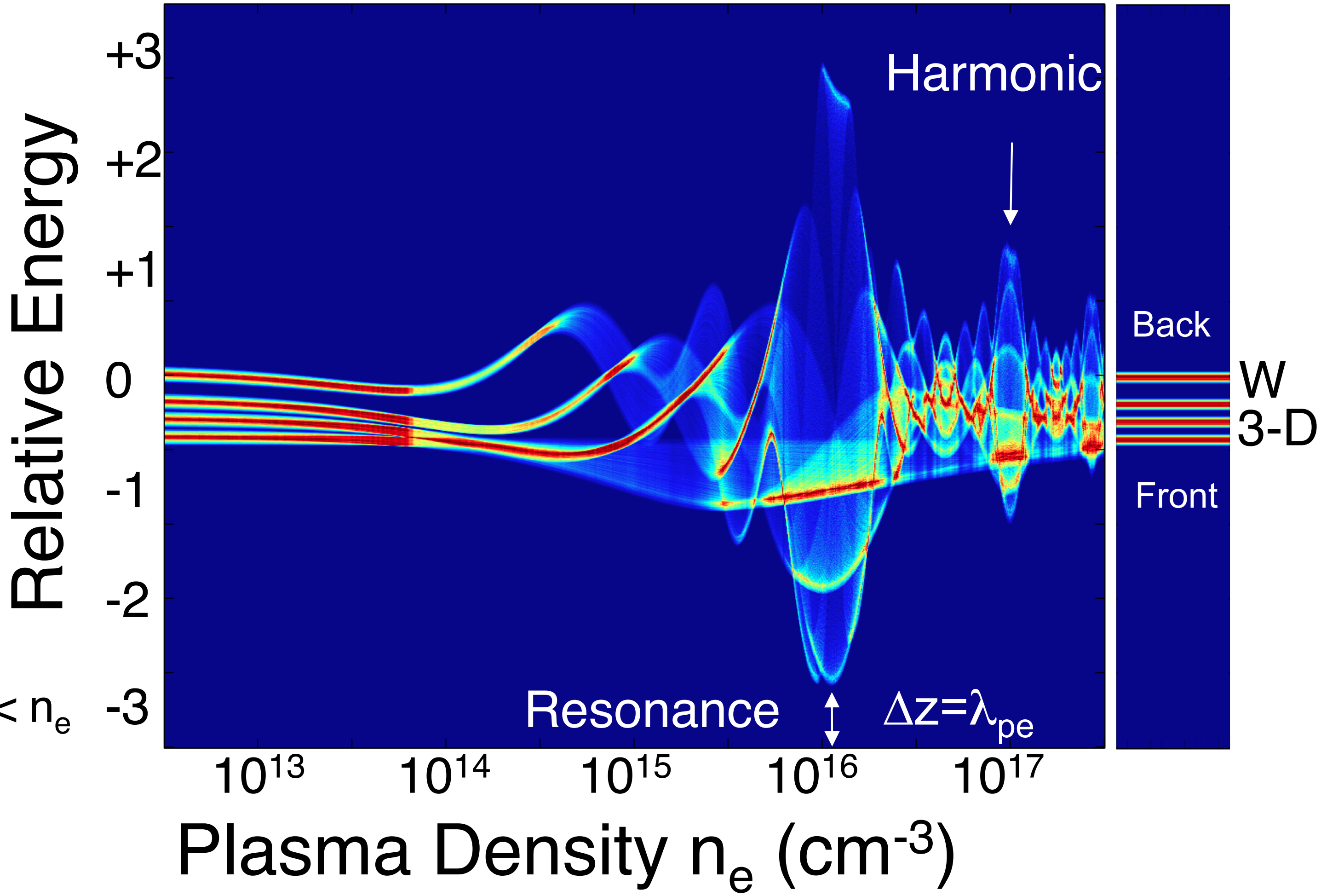
ENERGY CHANGE

Linear calculation (2D): microbunches with equal charge

Experimental Parameters:

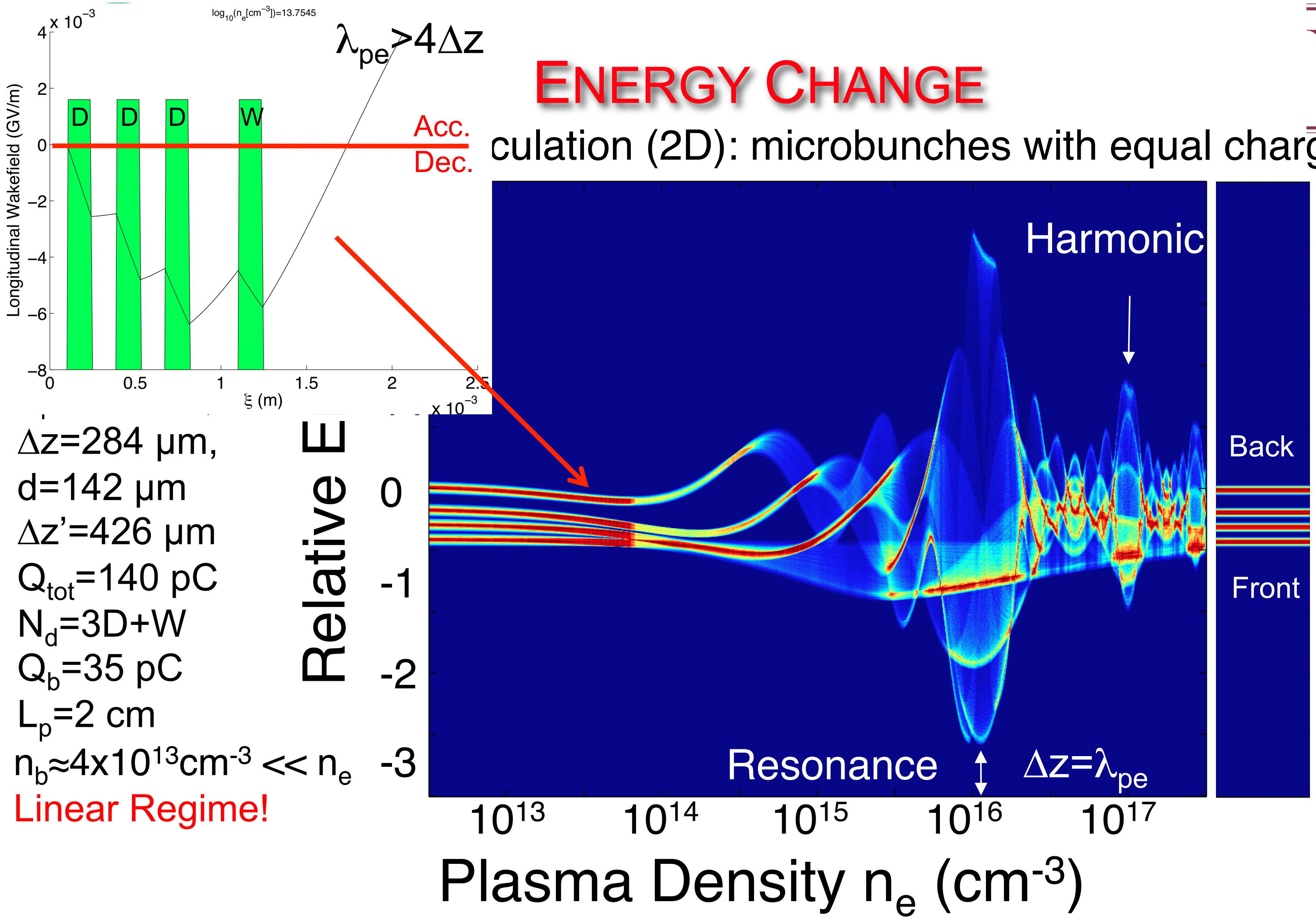
E_0=59 MeV
σ_r =100 um,
Δz=284 μm,
d=142 μm
$\Delta z'$=426 μm
Q_{tot}=140 pC
N_d=3D+W
Q_b=35 pC
L_p=2 cm
$n_b \approx 4\times10^{13}\text{cm}^{-3} \ll n_e$
Linear Regime!



- Resonant excitation of wakefield is the main feature
- Chirp such that W enters with highest energy
- $n_{e,\ res} \approx 1.4\times10^{16}$ cm^{-3} ⇔ $\lambda_{pe} \sim \Delta z$

ENERGY CHANGE

culation (2D): microbunches with equal charge



Δz=284 μm,
d=142 μm
$\Delta z'$=426 μm
Q_{tot}=140 pC
N_d=3D+W
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L_p=2 cm
$n_b \approx 4\times10^{13}$ cm^{-3} << n_e
Linear Regime!

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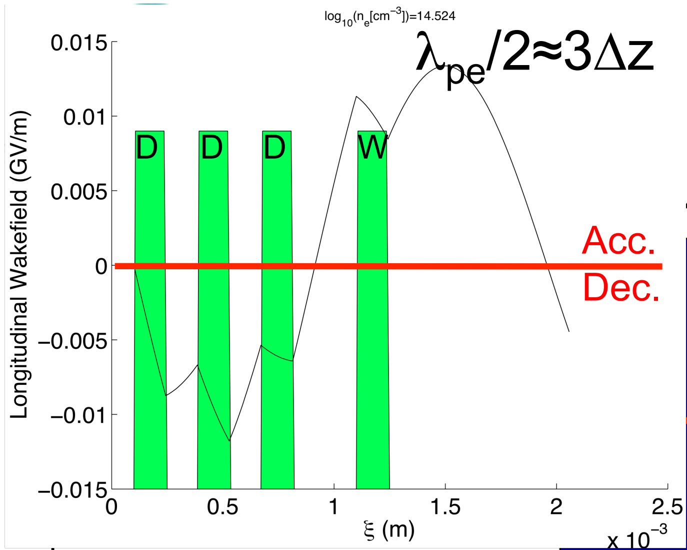

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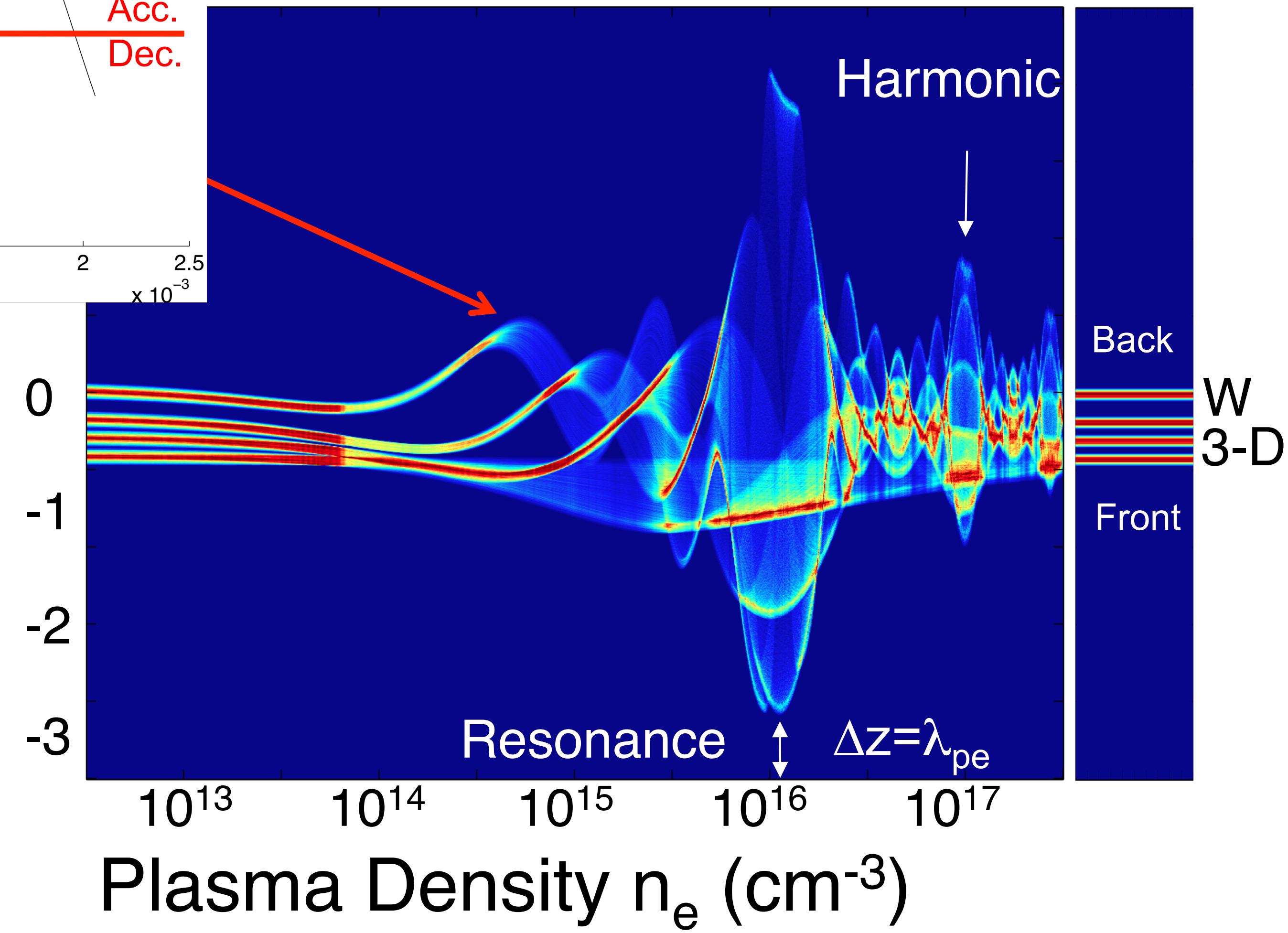

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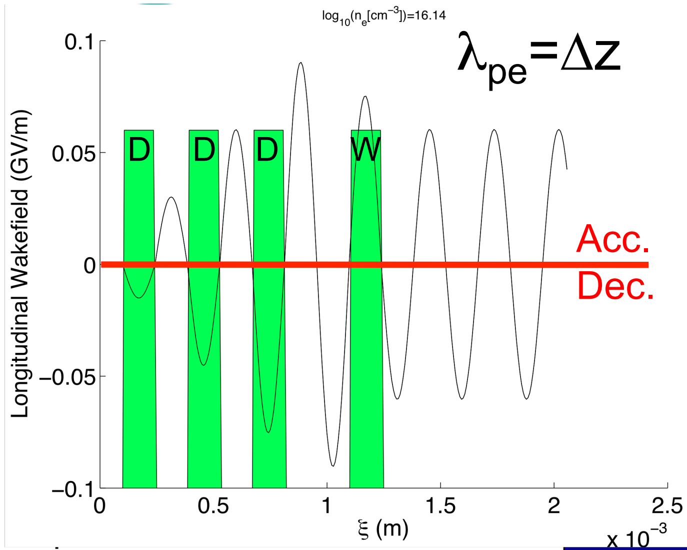
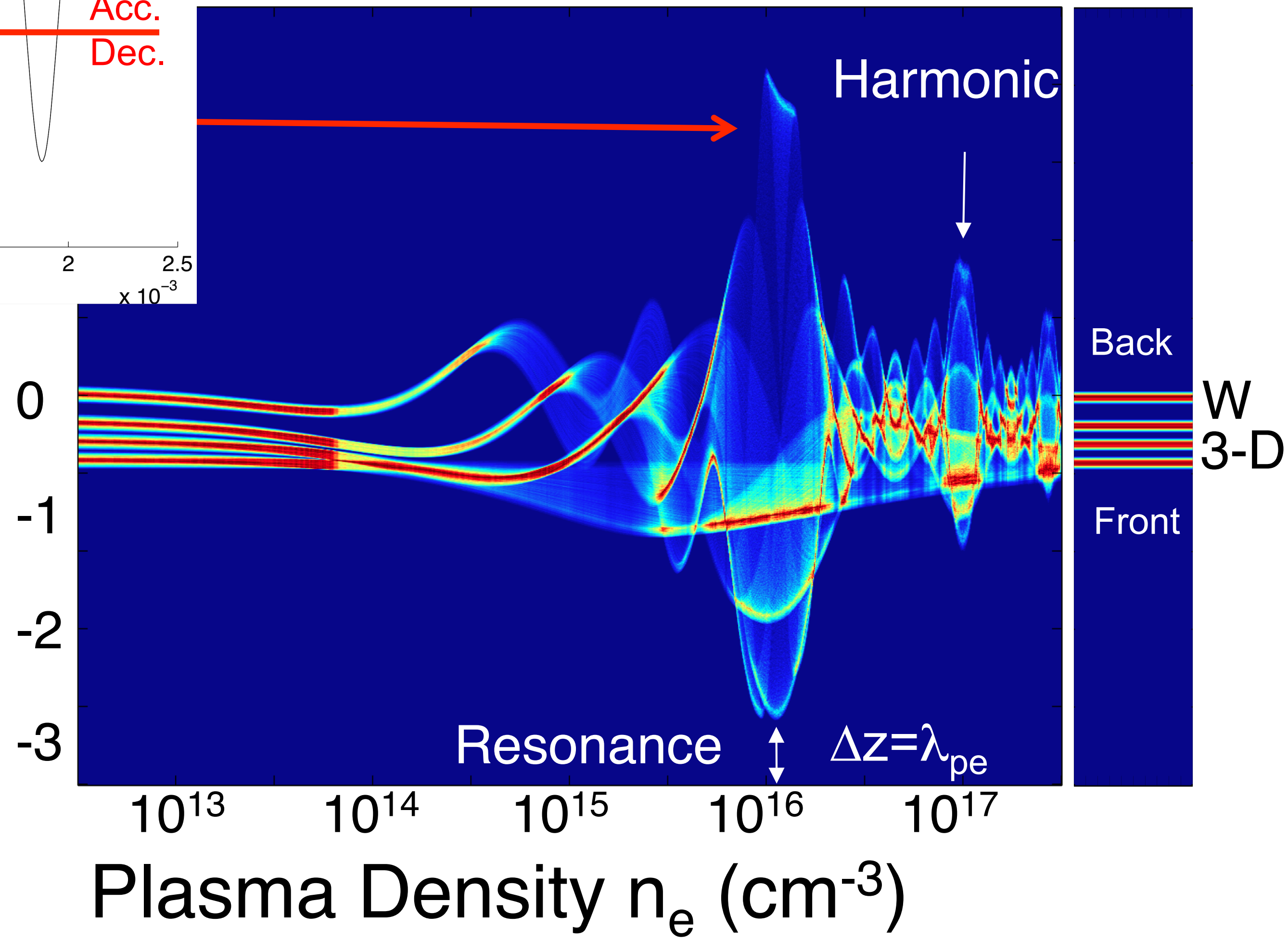
ENERGY CHANGE



ulation (2D): microbunches with equal charge

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
$n_b \approx 4\times10^{13} cm^{-3} << n_e$
Linear Regime!



- Resonant excitation of wakefield is the main feature
- Chirp such that W enters with highest energy
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ENERGY CHANGE

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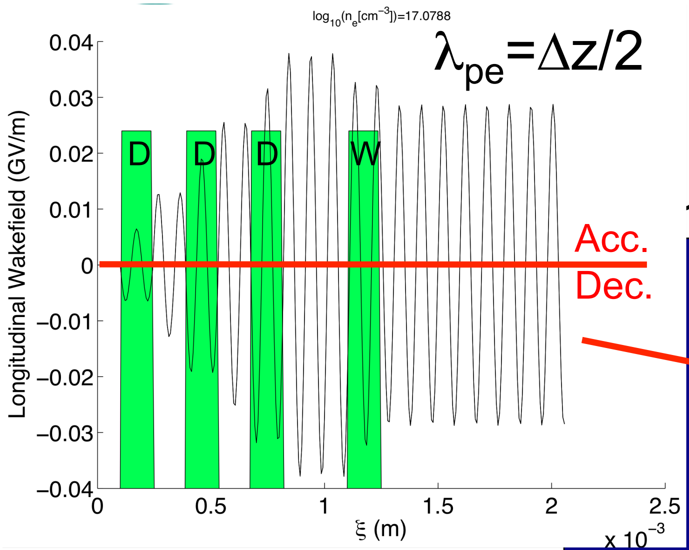

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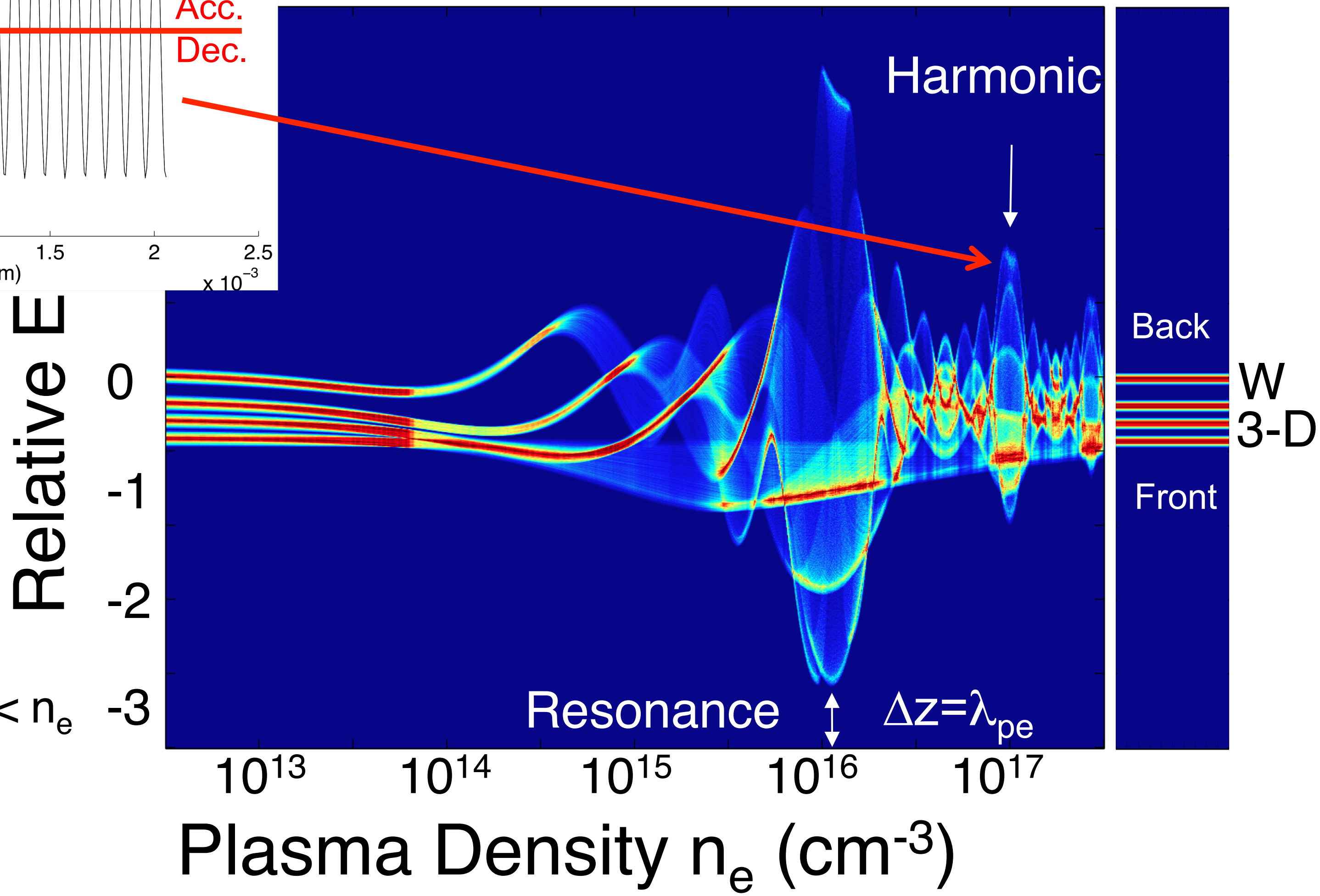

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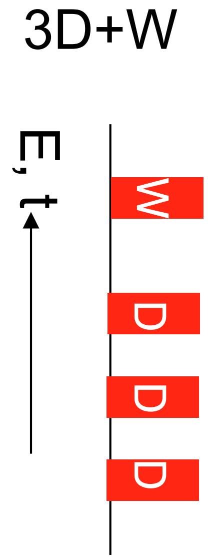
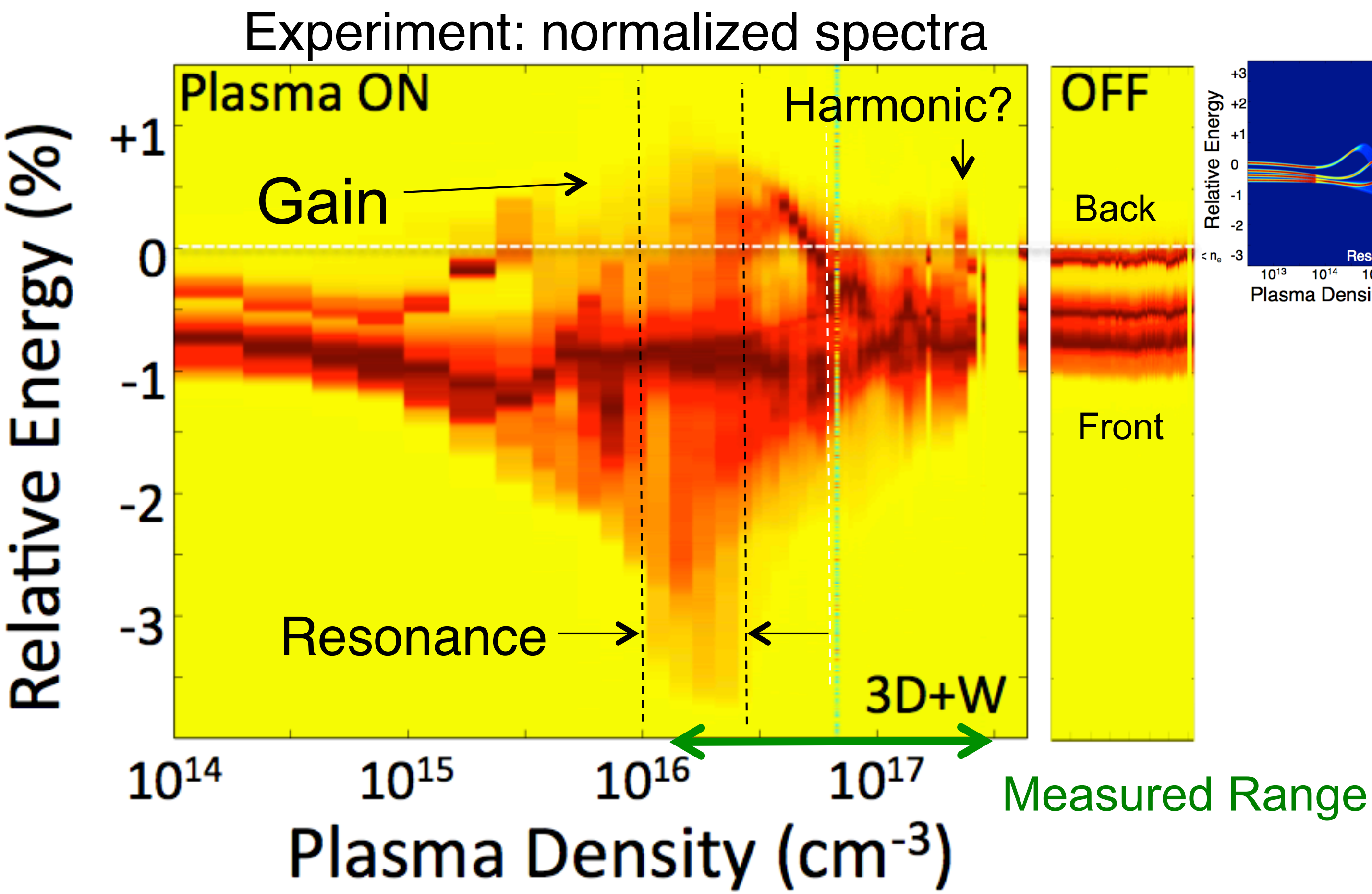
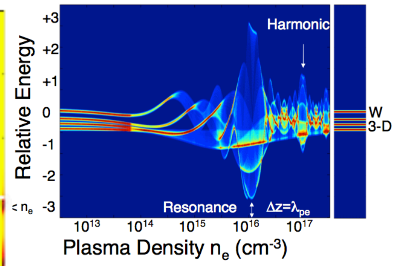


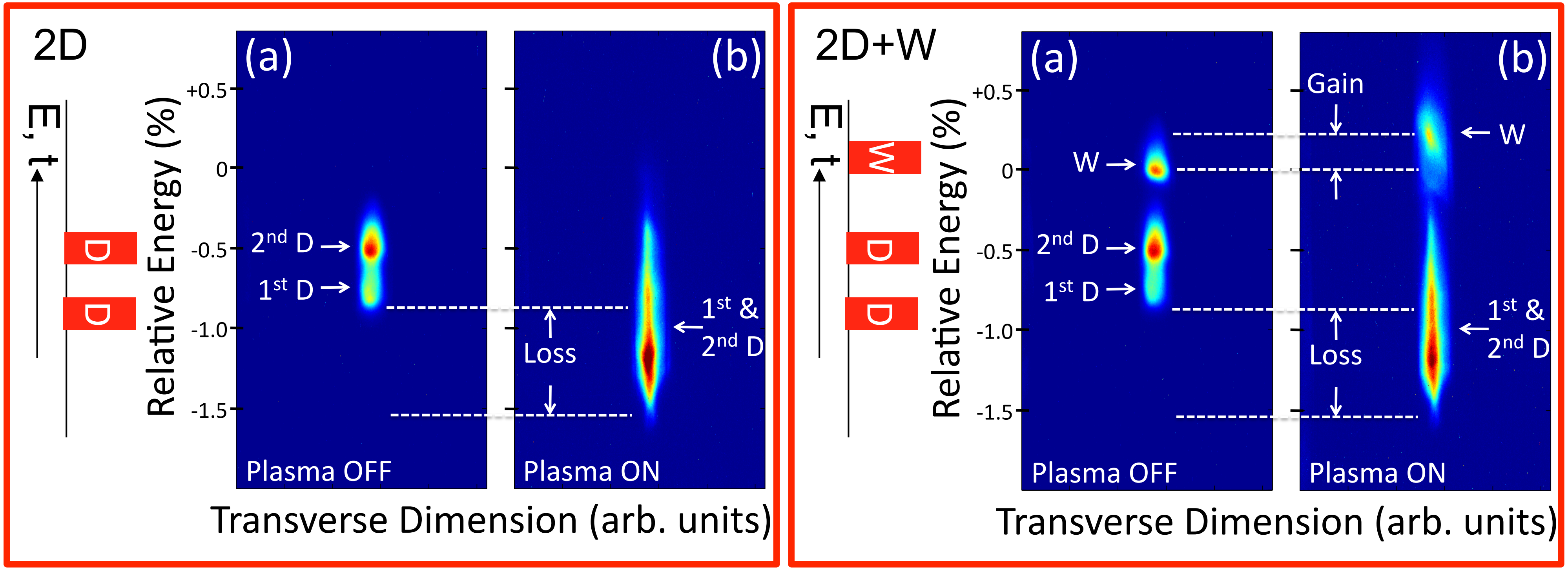




- Resonance clearly observed ⇔ λ_{pe}~Δz
- Large energy loss, ~1.95 MeV or ~97MeV/m (over 2cm)
- Energy gain, 0.74MeV or ~37MeV/m

WITNESS BUNCH ACCELERATION

Experiment: $n_e \approx 8\text{x}10^{15}\,\text{cm}^{-3}$



- Acceleration of witness bunch
- Large energy loss, ~0.42MeV or ~21MeV/m (over 2cm)
- Energy gain, 0.12MeV or ~6MeV/m

OUTLINE

- Motivation - Introduction to PWFA (Plasma Wakefield Accelerator)
- 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)
- Self-modulation-driven PWFA
- Summary and Conclusions

Focus on acceleration all the way through!

PWFA DRIVER

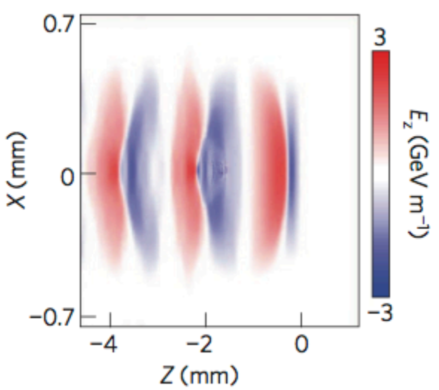
Energy considerations (PWFA = energy transformer):

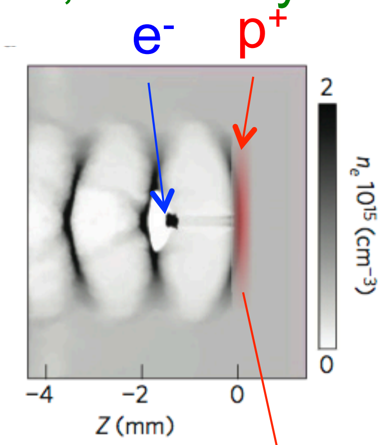
- A SLAC, 28.5GeV bunch with $2\times10^{10}e^-$ caries ~90J
  An ILC, 0.5TeV bunch with $2\times10^{10}e^-$ caries ~1.6kJ
- A SLAC-like driver for staging (FACET, +25GeV)
- A SPS, 450GeV bunch with $10^{11}p^+$ caries ~7.2kJ
  A LHC, 7TeV bunch with $10^{11}p^+$ caries ~112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- Long plasmas required (~100's m)
- Requires short (~100µm) p+ bunch

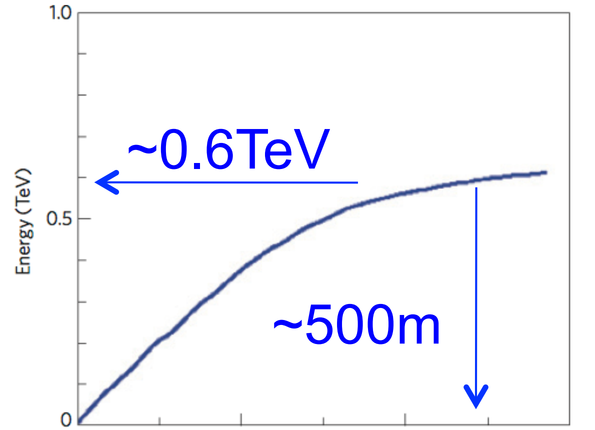
PROTON-DRIVEN PWFA @ CERN

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

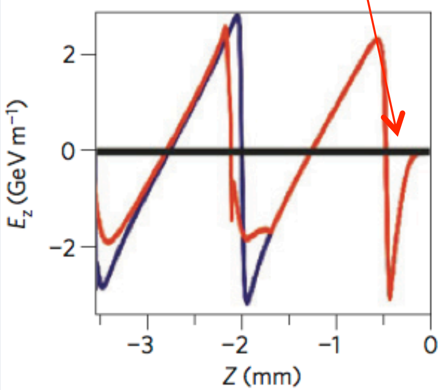
p+:
E_0=1TeV
σ_z=100µm
N=10^{11}
e-:
E_0=1GeV
N=1.5x10^{10}

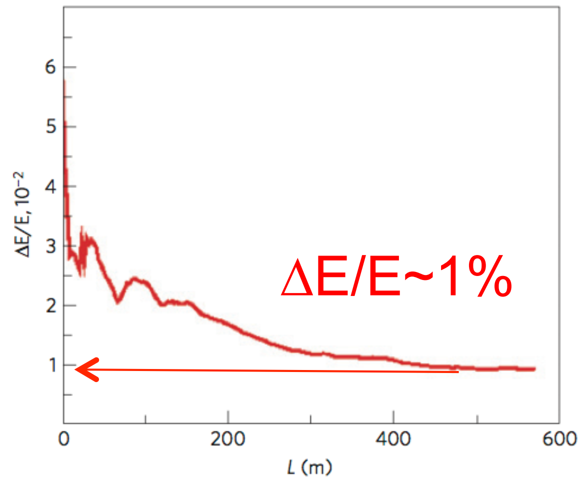






Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons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

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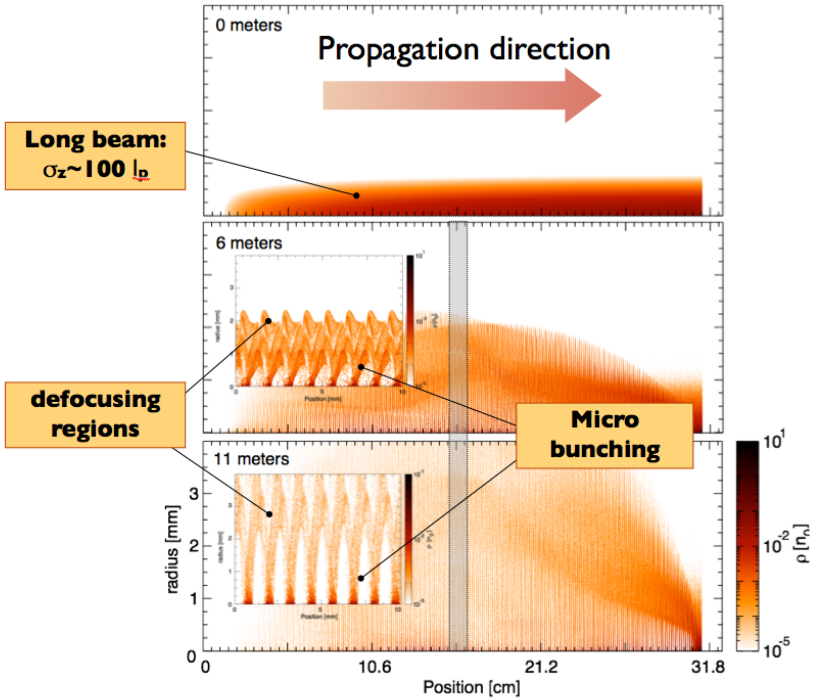
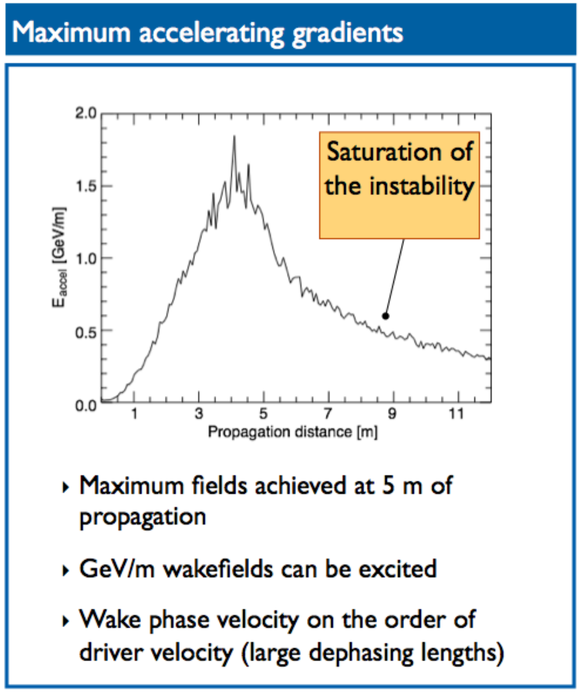
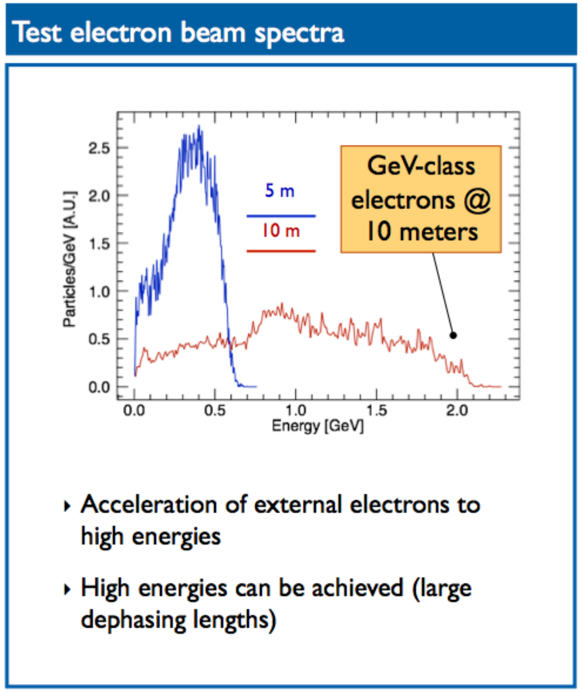
PROTON-DRIVEN PWFA @ CERN

- Self modulation of long (~12cm), 450GeV SPS bunch in λ_p=1.5mm plasma



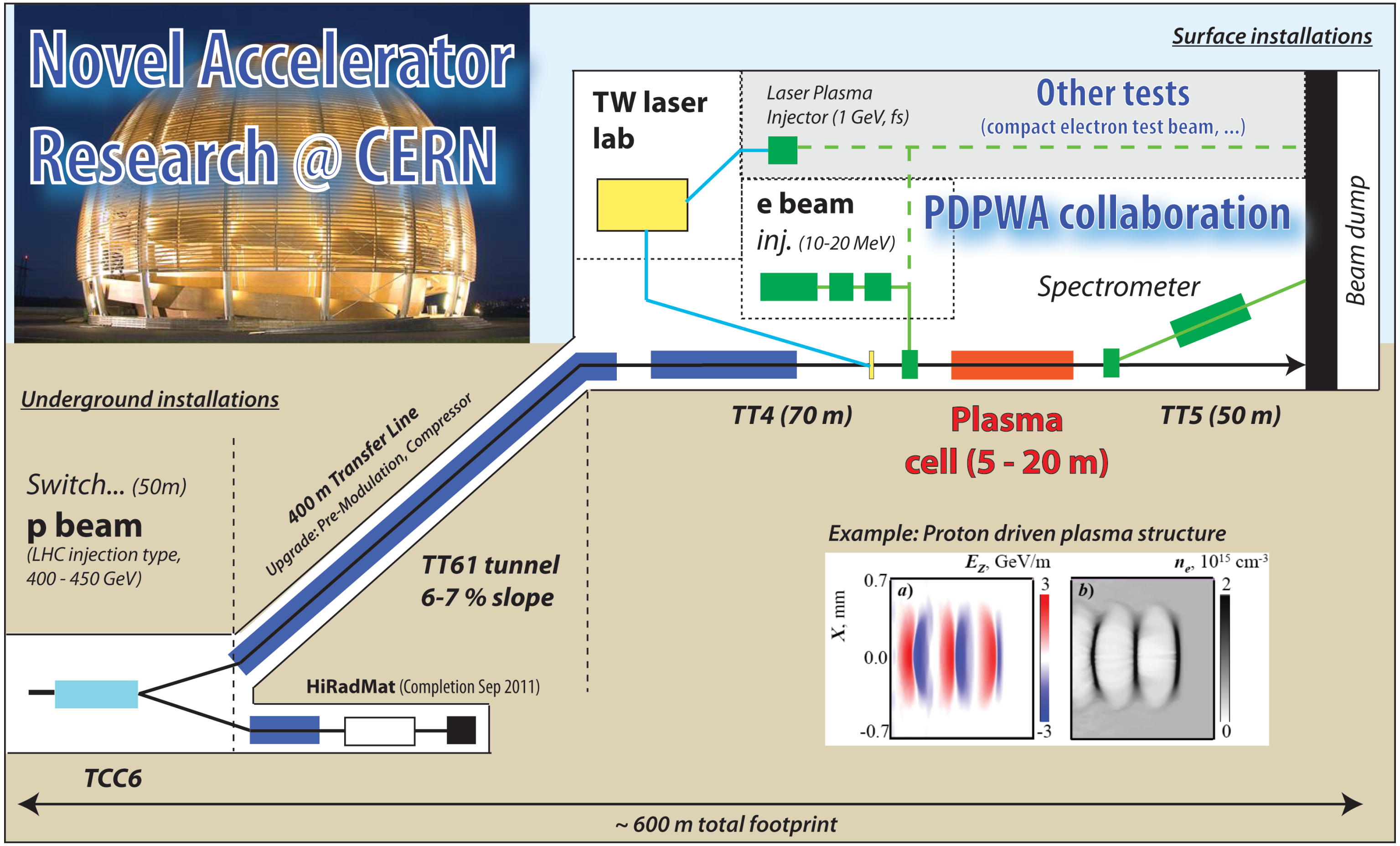




Simulations: J. Vieira

- Growth of instability / p^+ density modulation / E_z
- Resonantly drives large amplitude (1-2GV/m) accelerating fields
- Injected e^- gain ~1GeV in 5-10m plasma
- Injected of short e^- bunch would produce narrow $\Delta E/E$

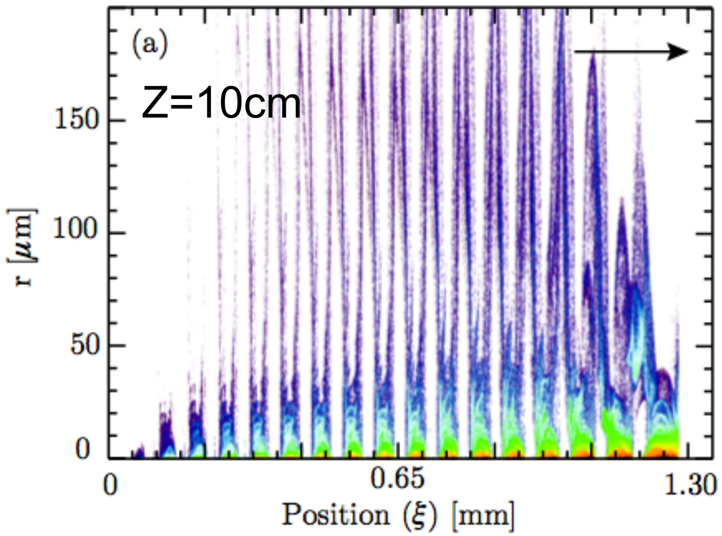
PROTON-DRIVEN PWFA @ CERN

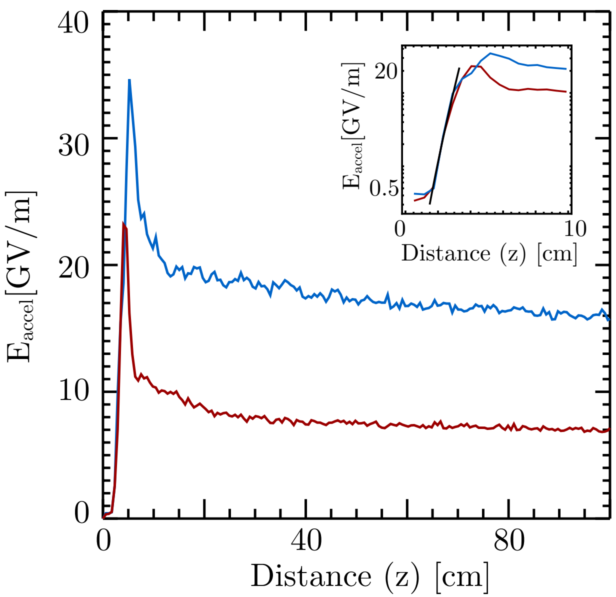


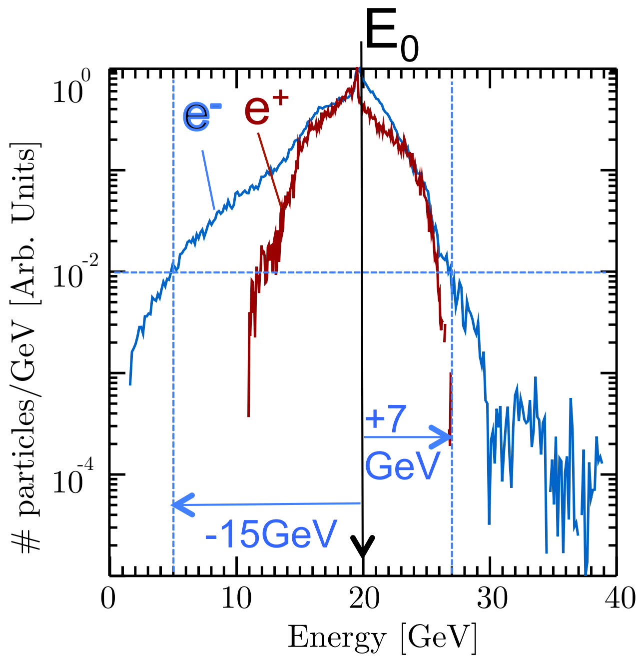
- Letter of intent favorably reviewed by CERN SPSC
- Detailed technical proposal due in one year
- Experiments 2015-… for 1GeV in a few meters, self modulated
- Program for TeV class e- from p^+-driven PWFA, driven by MPP

TEST SELF-MODULATION @ SLAC

- Send long SLAC e^- bunches (σ_z~700µm) in plasma for short bunches (n_e~$10^{17}cm^{-3}$)
- E_0=20GeV, σ_r~10µm, N=$2x10^{10}$





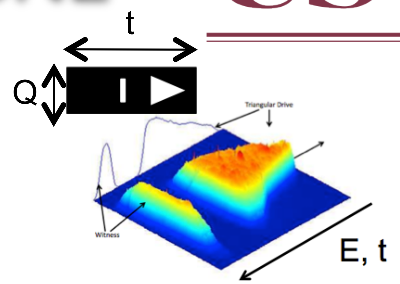


- S-M after <10cm
- E_z>20MV/m
- Reach "blowout"
- Multi-GeV gain/loss

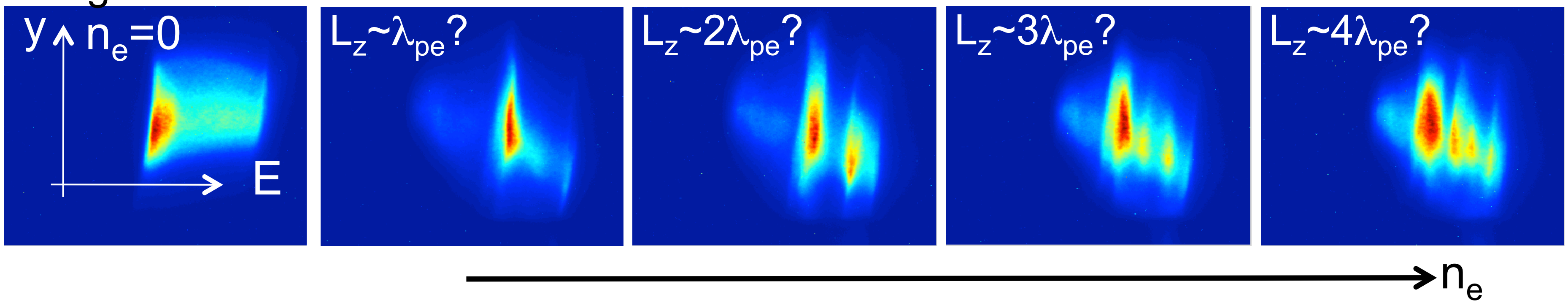
- Experiment will be proposed to SAREC for experiments in Summer 2012
- All components available (tinker toy experiment)

TEST SELF-MODULATION @ ATF-BNL

- E_0=60MeV, σ_r~100µm, N~4x10^9, L_z~1500µm



Triangular Bunch



- First evidence of self-modulation (in energy) in a plasma?
- Coherent transition radiation energy (~1/σ_z) measurements indicate S-M
- Encouraging preliminary results
- Will repeat next week ….

TEST SELF-MODULATION @ ATF-BNL

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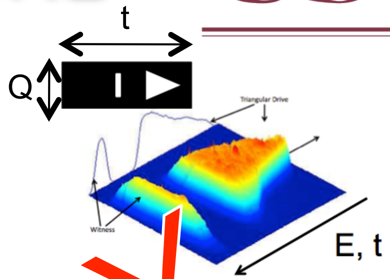

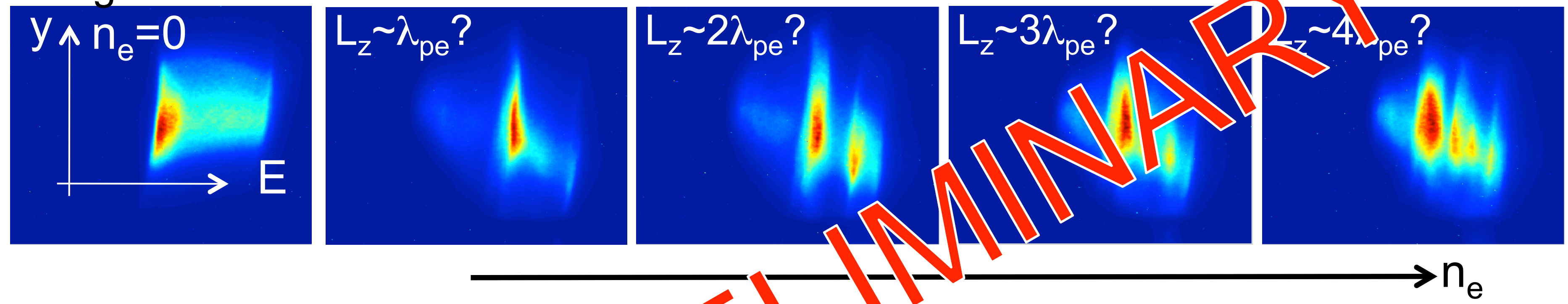

VERY PRELIMINARY

- First evidence of self-modulation (in energy) in a plasma?
- Coherent transition radiation energy (~1/σ_z) measurements indicate S-M
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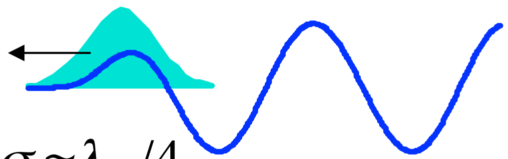
Focus on acceleration all the way through!

5 ~~4~~ PLASMA ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

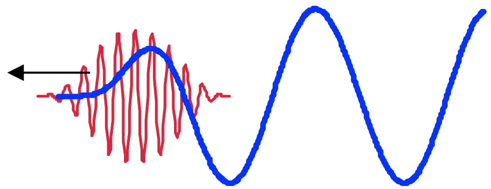
  A high energy particle bunch (e^-, e^+, ...)



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

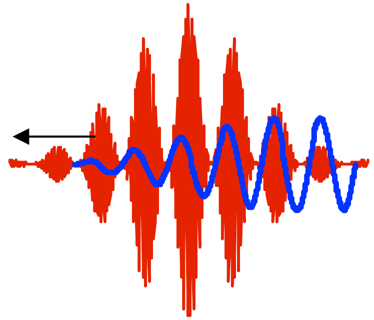
- Laser Wakefield Accelerator (LWFA)

  A short laser pulse (photons)



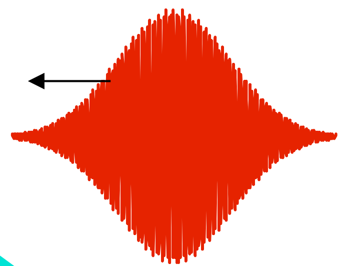
- Plasma Beat Wave Accelerator (PBWA)

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

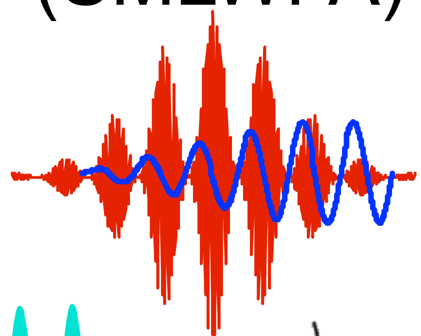


- Self-Modulated Laser Wakefield Accelerator (SMLWFA)

  Raman forward scattering instability in a long laser pulse

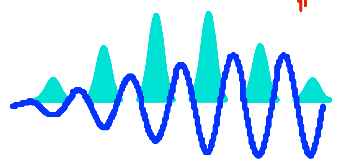


evolves into



- Self-Modulated PWFA (SMPPWFA)

evolves into



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

SUMMARY AND CONCLUSIONS

- PWFA made remarkable progress
  - 42GeV energy gain in 85cm of plasma @ SLAC
- PWFA is well understood (http://www-rcf.usc.edu/~muggli/publications.html)
- 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 proposed to CERN, by MPP, first PWFA experiment in EU, only p^+ PWFA in the world (Fermilab???)
- PWFA at DESY, in Japan, Italy (COMB@Frascati), …
- p^+-PWFA will use self-modulation initially
- Exciting new self-modulation experiments with e^- (SLAC-FACET, ATF, DESY, Diamond (UK), Russia. …)
- PWFA could be a technology candidate for future more compact (cheaper) colliders and light sources

Collaborations:

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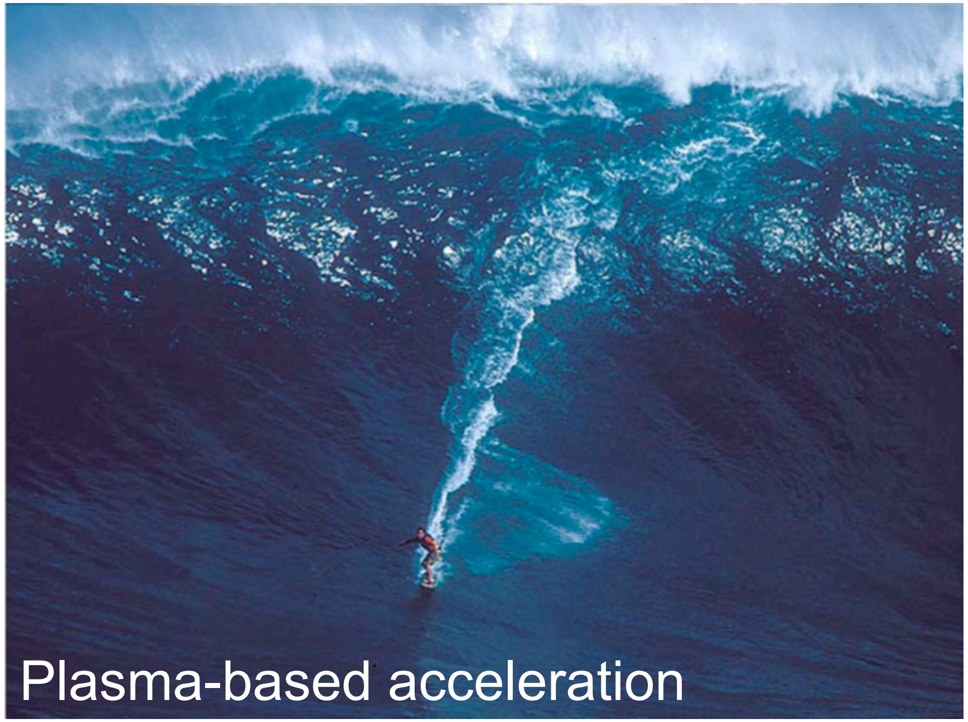
Thank you!

* Principal Investigators

Thank You!

The PWFA:

turning this … … into that!



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

Work supported by US Dept. of Energy