Overview of recent experimental results on Particle Wake Field Acceleration

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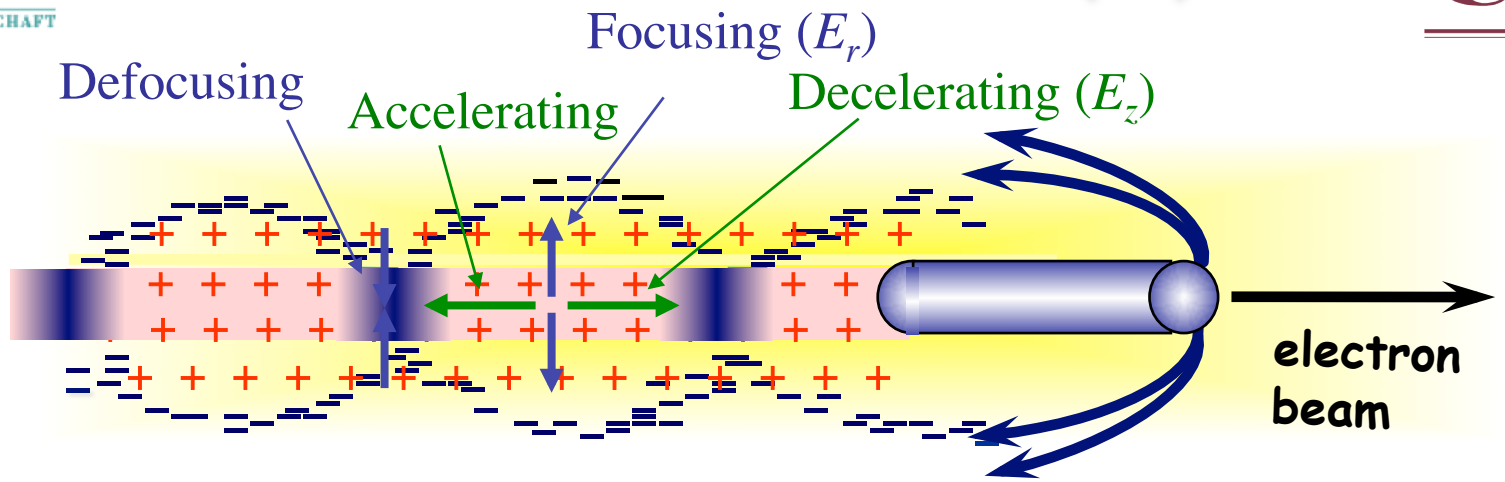
OUTLINE

- Motivation-Introduction to PWFA
- PWFA experimental results @ SLAC
  - e^- transverse dynamics, focusing, β-tron radiation
  - positrons
  - longitudinal dynamics, acceleration

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

- Multi-bunch, low energy PWFA results @ ATF-BNL
  - Resonant excitation of plasma wakefields
- Future proton driven PWFA @ CERN
- Summary and Conclusions

PLASMA WAKEFIELD (e^-)



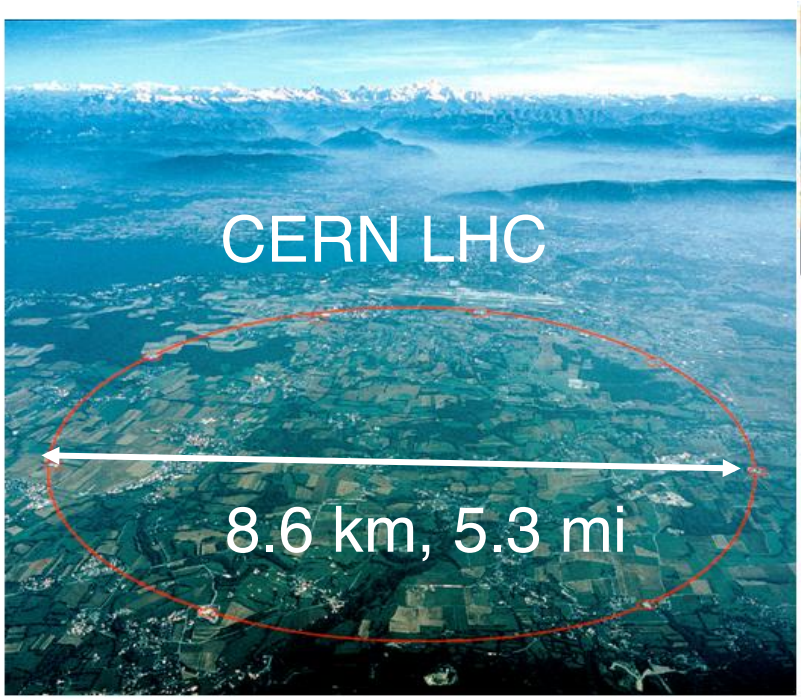
- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Plasma e^- rush back on axis => energy gain
- Optimize for acceleration, focusing (plasma lens), radiation (β-tron)
- Plasma Wakefield Accelerator (PWFA): high-frequency, high-gradient, strong focusing, co-linear, beam-driven accelerator

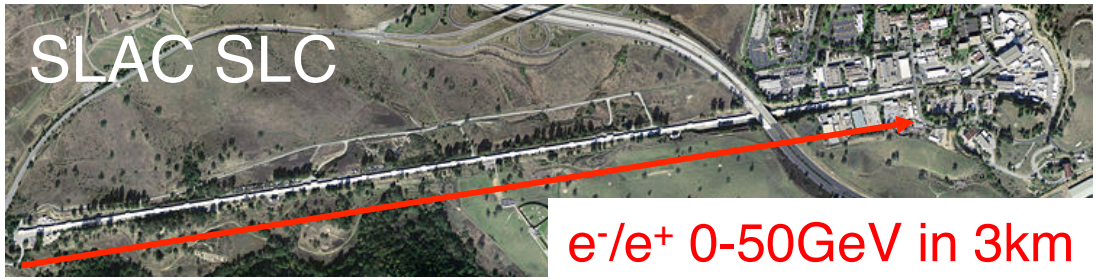
PARTICLE ACCELERATORS

- We are at the verge of significant physics discoveries
  - LHC@CERN: Higgs boson, super-symmetric particles, dark matter, dark energy, …
- Need precision machine (ie., lepton linear collider) to complement and further hadron collider discoveries
- SLAC-LCLS x-ray free electron laser (X-FEL) great success
- Short coherent x-ray pulses for biology, material science, warm dense mater, plasma studies, …
- X-FEL mushrooming: LCLS-2, DESY-Europe, Japan, Switzerland, …
- Continued interest in accelerators for basic science, technology, medicine, …
- But …

PARTICLE ACCELERATORS

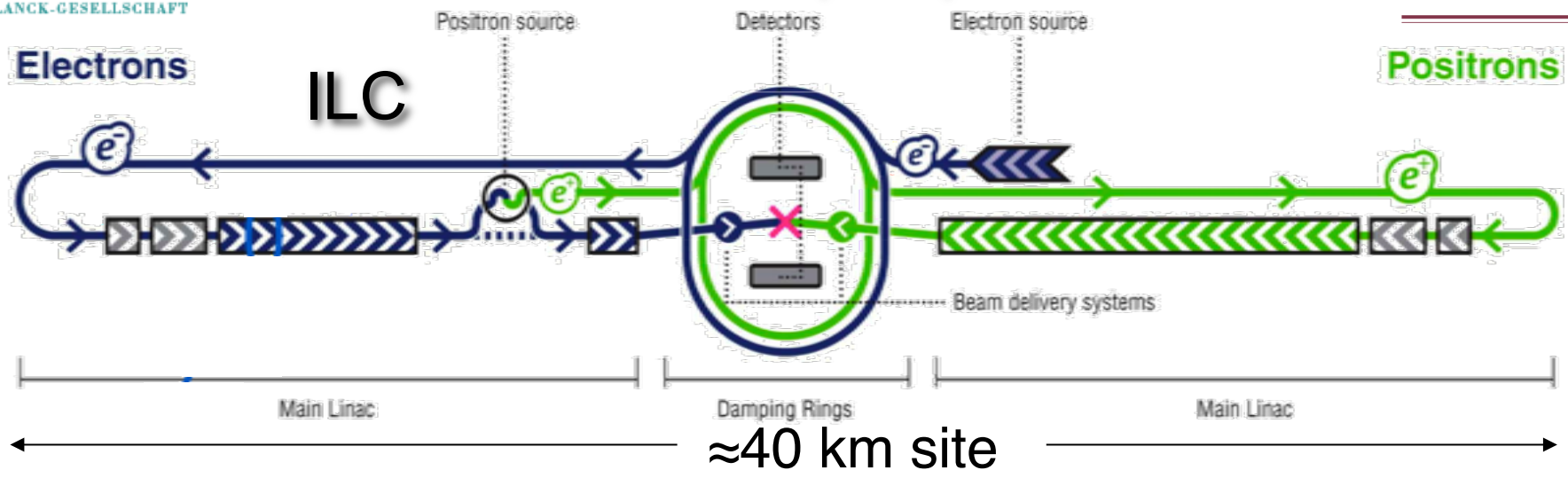
"The 2.4-mile circumference RHIC ring is large enough to be seen from space"





- 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?

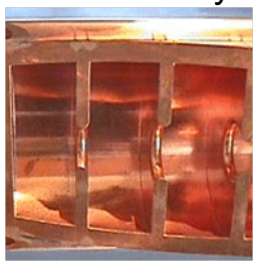
FUTURE LEPTON (e^-/e^+) COLLIDER



- 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:

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

Pillbox Cavity



<150MV/m?

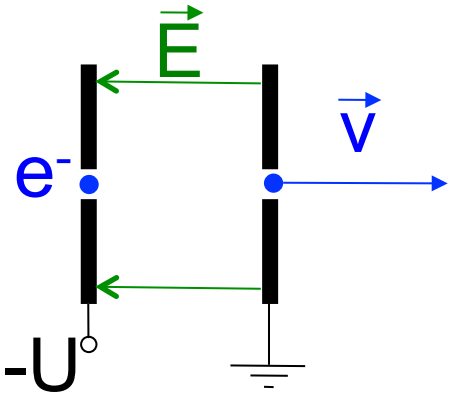
Is there a high-gradient alternative to rf technology?
Plasmas?

PARTICLE ACCELERATION

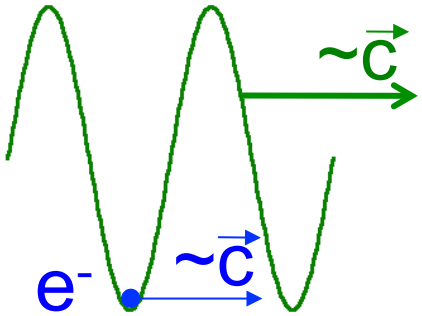
Requirements:

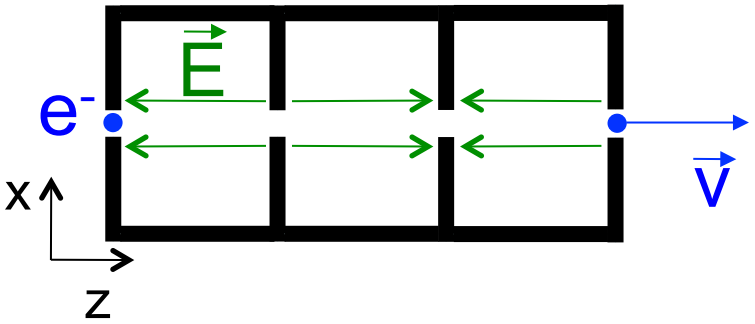
- Longitudinal (// to motion) electric field

DC field limited by breakdown

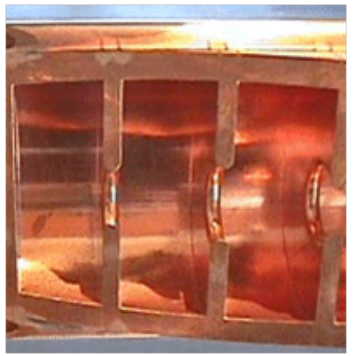


- Wave traveling at the particle velocity ($v_\phi \sim v_b \sim c$)





Pillbox Cavity



E_z=> TM cavity mode

Pillbox accelerating structure

Slow wave structure

WHAT ABOUT PLASMAS?

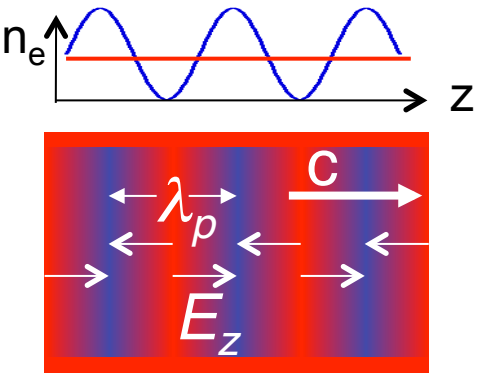
- Relativistic Electron Plasma Wave (Electrostatic, E_z):

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

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

"Cold Wavebreaking" Field

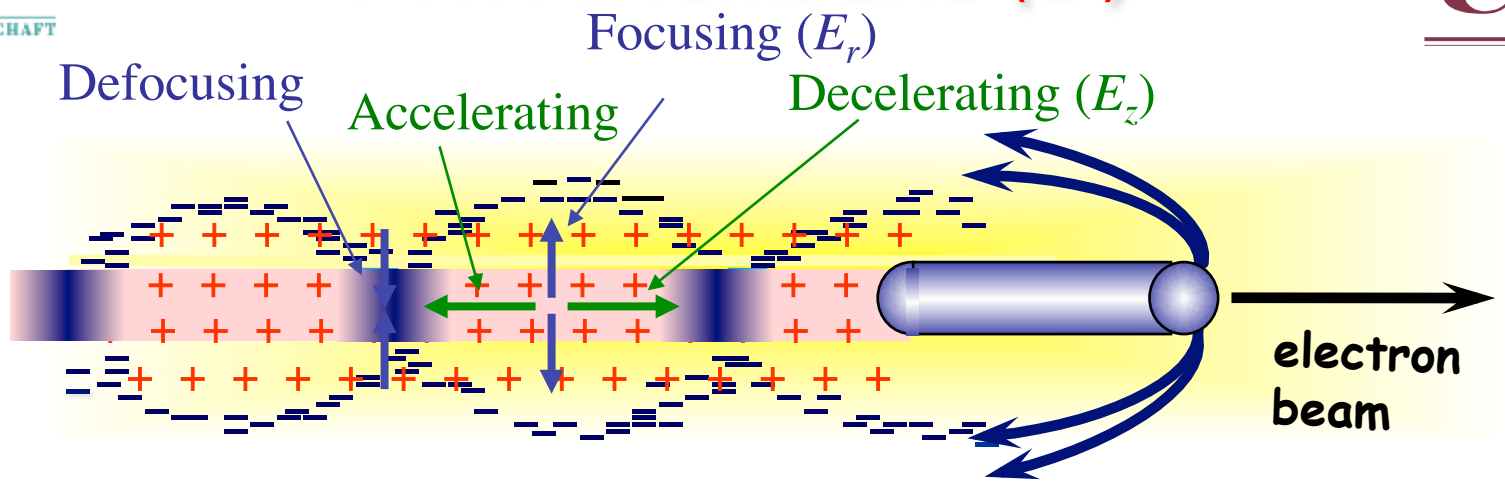
n_e=10^{14} cm^{-3}



LARGE
Collective response!

- Plasmas can sustain very large (collective) E_z-field, acceleration
- Wave, wake phase velocity = driver velocity (~c!)
- Plasmas are already (partially) ionized, difficult to "break-down"
- High gradient, high energy plasma accelerator? **Yes!**
- Plasmas wave or wake can be driven by:
  - Intense laser pulses (LWFA)
  - Short particle bunch (PWFA)

PWFA NUMBERS (e^-)



- Linear theory ($n_b << n_e$) scaling:

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

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

- Focusing strength:

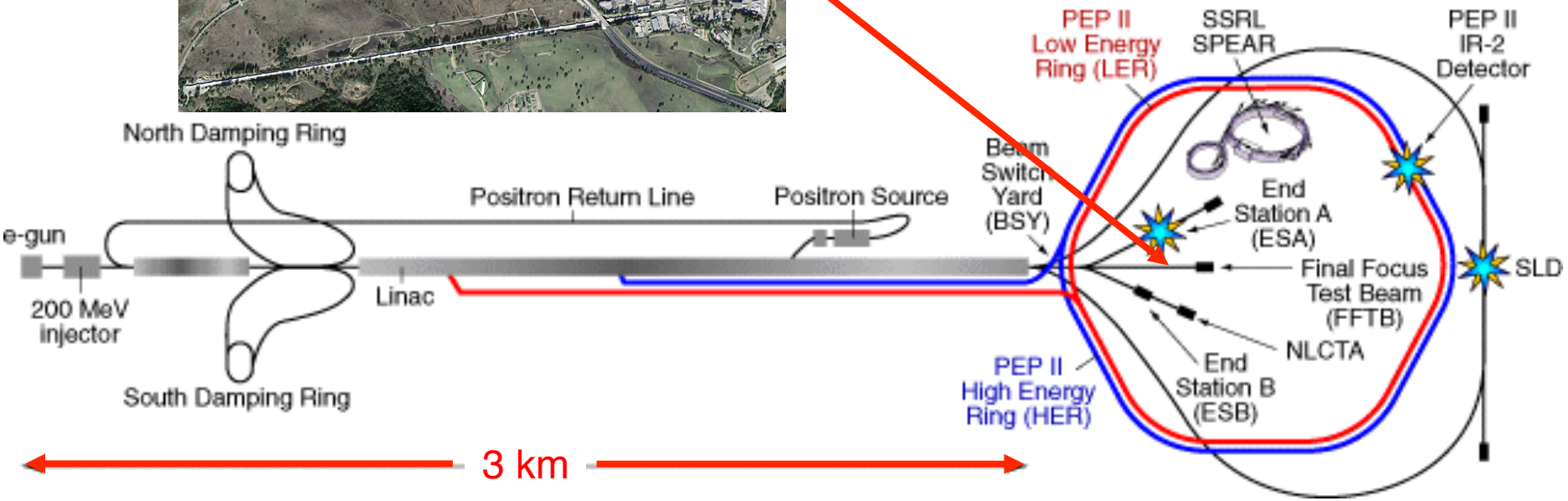
$$\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}\,cm^{-3}) \qquad (n_b > n_e)$$

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

PWFA ACOMPLISHMENTS & CHALLENGES

- ☑ Acceleration of electrons by 42GeV in 85cm of plasma!
- ☑ Excellent understanding of the PWFA (e^-)
- ☑ Demonstrated the acceleration and focusing of positrons by plasmas
- ☐ Acceleration of a bunch with finite energy spread
- ☐ Emittance preservation
- ☐ High-gradient acceleration of high quality positrons
- ☐ High energy efficiency acceleration
- ☐ Staging (or not!)
- ☐ Build a PWFA-based linear collider

PWFA EXPERIMENTS @ SLAC



Long-bunch Experiments

e^-/e^+ 28.5 GeV

$\sigma_z \approx 700\ \mu m$

$\sigma_r \approx 30\ \mu m$

$n_e \approx 2 \times 10^{14}\ cm^{-3}$

$L_p \approx 1.4$ m

Pre-ionized

N≈1.2-1.8x10^{10}/bunch

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

0.1-50 GV/m

Short-bunch experiments

e^- 28.5, 42 GeV

$\sigma_z \approx 30\text{-}20\ \mu m$

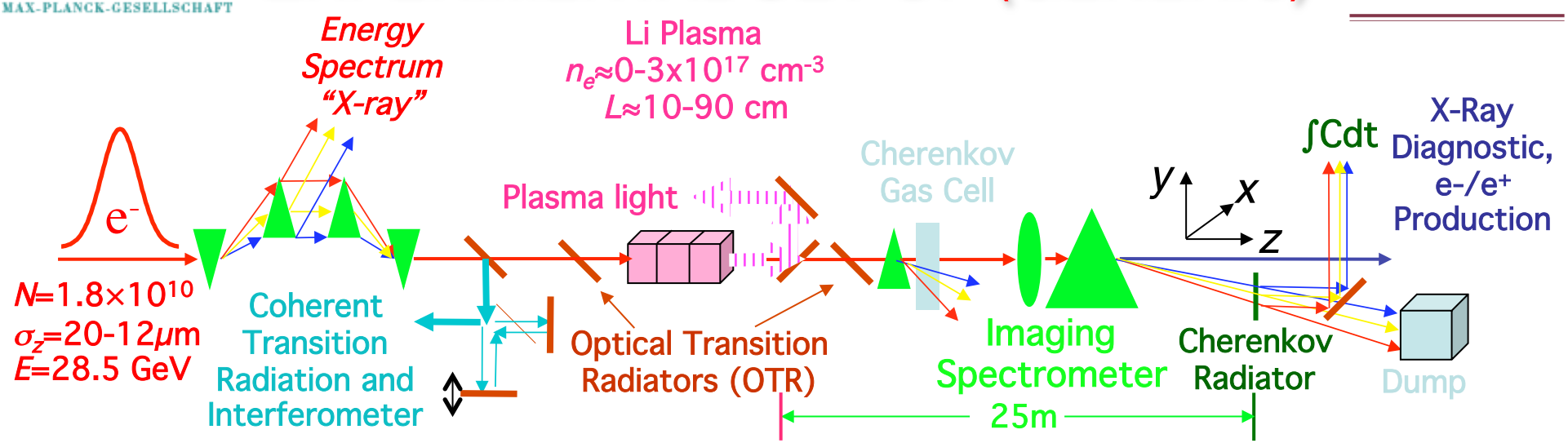
$\sigma_r \approx 10\ \mu m$

$n_e \approx 1\text{-}3 \times 10^{17}\ cm^{-3}$

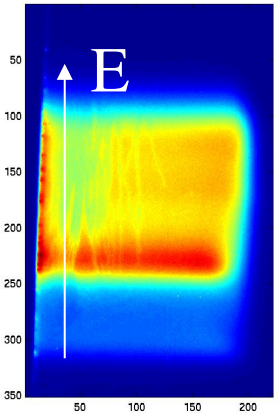
$L_p \approx 10, 20, 30, 60, 90, 120$ cm

Field-ionized

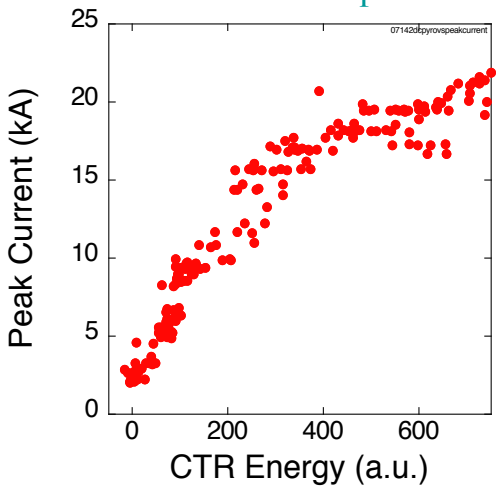
EXPERIMENTAL SET UP (GENERIC)



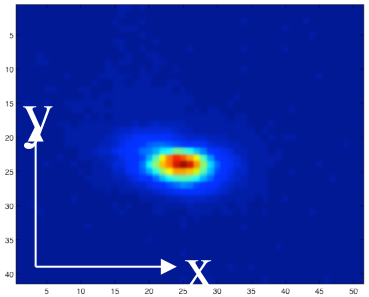
- X-ray Chicane



- Coherent Transition Radiation (CTR)
  - CTR Energy≈I_{peak}≈1/σ_z

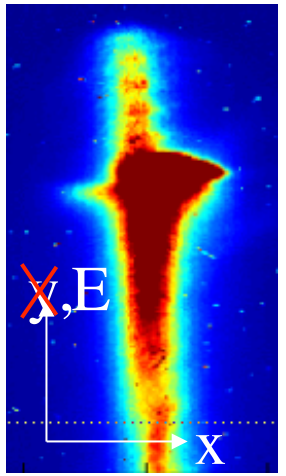


- OTR



-Spatial
-resolution ≈9 μm

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

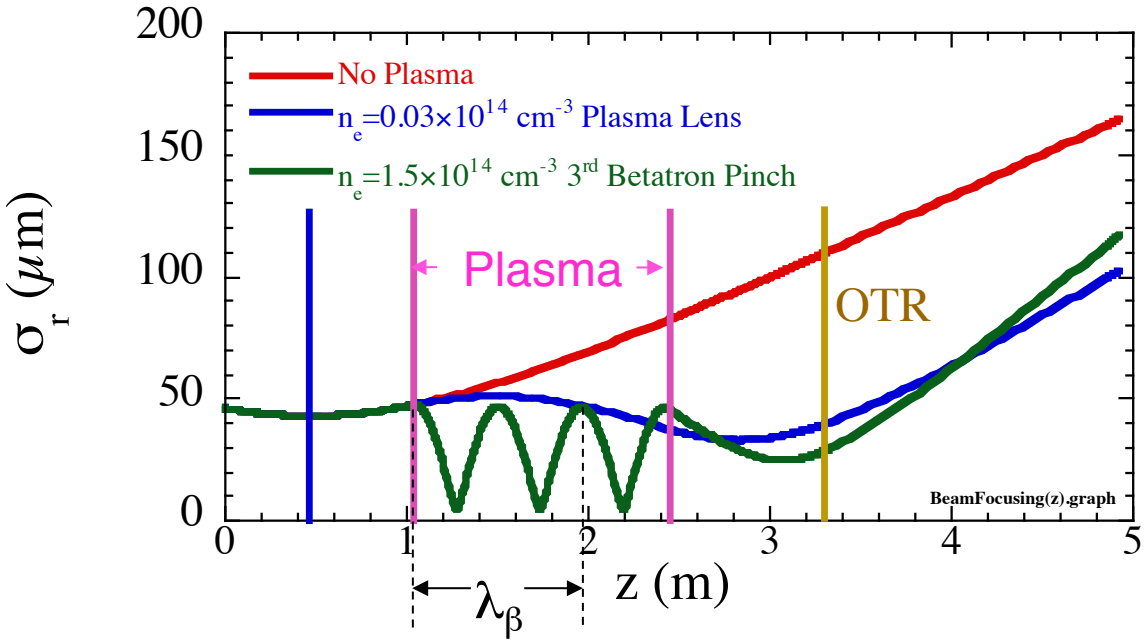


PLASMA FOCUSING OF e^-

Beam Envelope Model for Plasma Focusing

Plasma Focusing Force > Beam "Emittance Force"

($\beta_{beam}=1/K > \beta_{plasma}$)



Envelope equation:

$$\frac{\partial^2\sigma}{\partial z^2} + K^2\sigma = \frac{\varepsilon^2}{\sigma^3}$$

In an ion channel:

$$K = \frac{\omega_{pe}}{\sqrt{2\gamma}\,c} \propto (n_e)^{1/2}$$

with a focusing strength:

$$W = \frac{E_r}{rc} = \frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c}$$

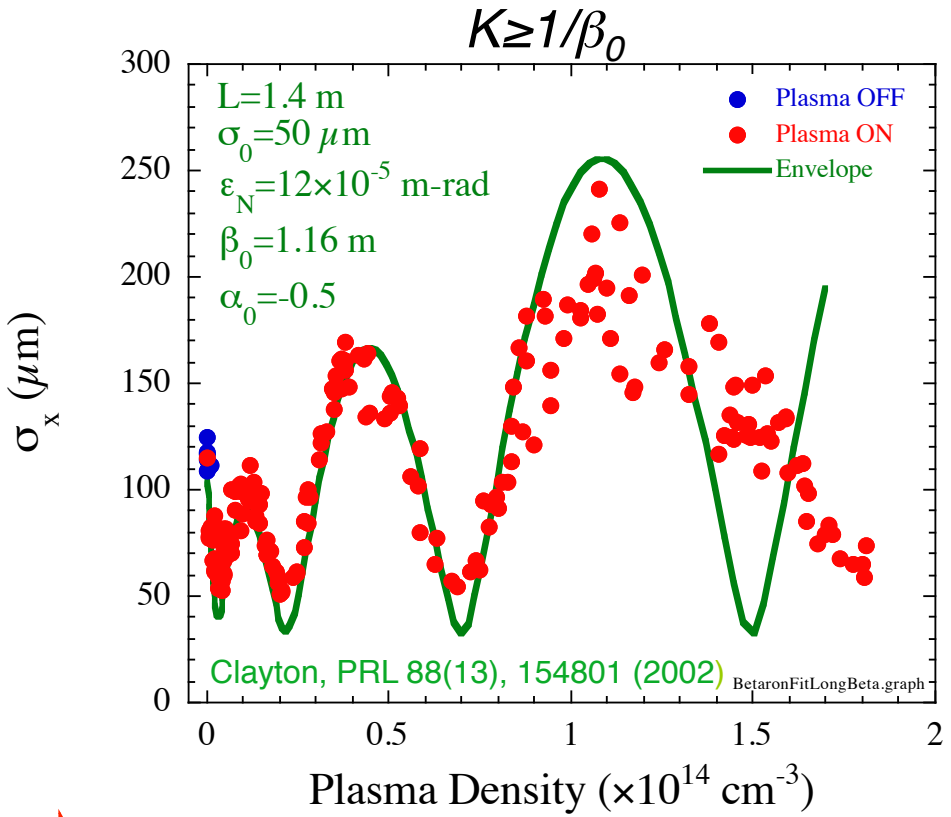
=6 kT/m
@ $n_e=2\times10^{14}$ cm^{-3}

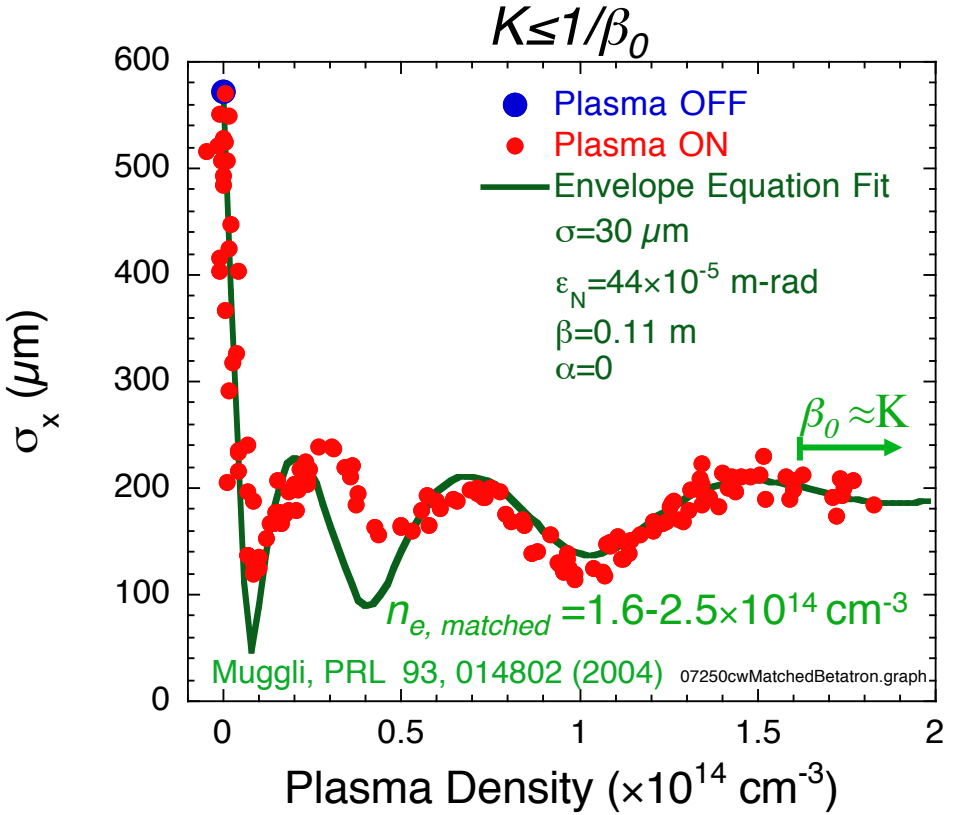
=6 MT/m
@ $n_e=2\times10^{17}$ cm^{-3}

- Multiple foci (betatron oscillation) within the plasma
- $\sigma_{x,y}(z)$ at fixed n_e => $\sigma_{x,y}(n_e)$ at fixed z
- Betatron radiation!

FOCUSING OF e^-

OTR Images ≈1m downstream from plasma





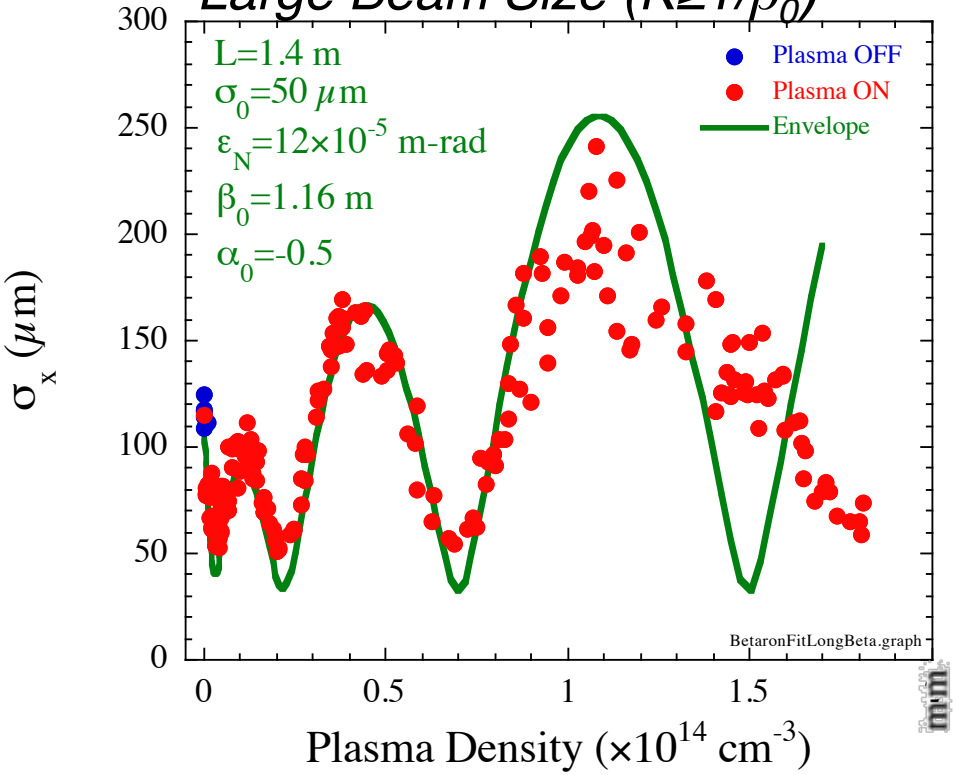
- Focusing of the beam well described by a simple model ($n_b > n_e$): Plasma = Ideal Thick Lens
- No emittance growth observed as n_e is increased
- Stable propagation over L=1.4 m up to as n_e =1.8×10^{14}cm^{-3}
- Channeling of the beam over 1.4 m or >12β_0

=> Matched Propagation over long distance!

β-TRON RADIATION IN PLASMAS

Wang, PRL 88, 2002

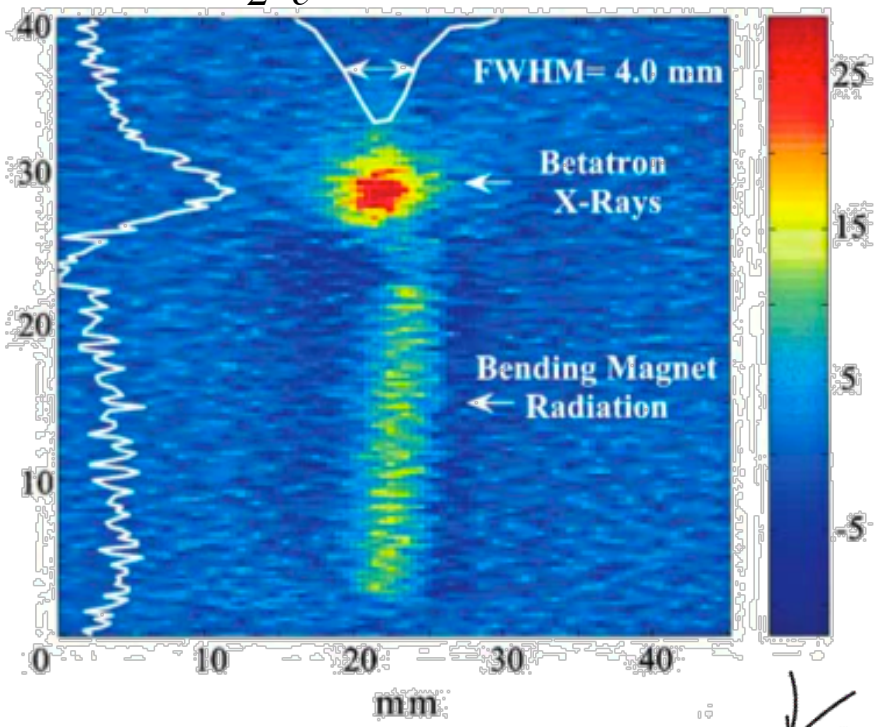
Large Beam Size ($K \geq 1/\beta_0$)



Ion column:

$$\lambda_\beta = \frac{\sqrt{8\gamma}\,\pi c}{\omega_{pe}} \propto \frac{1}{n_e^{12/2}}$$

$$\omega_c = \frac{3}{2}\frac{\gamma^3}{c}\omega_\beta^2 \sigma_r \propto n_e$$



$n_e = 1.5 \times 10^{14}\ cm^{-3}$ $\quad \lambda_\beta \cong 0.91\ m$ $\quad N_{\lambda_\beta} \cong 1.5$

$\hbar\omega_c \approx keV$ >6x10^5 photons @ 14.2±0.014 keV

- x-rays from a plasma wiggler (e^-)
- ~10keV @ n_e~10^{14}cm^{-3}, ~10MeV @ n_e~10^{17}cm^{-3} Johnson, PRL 97, 2006

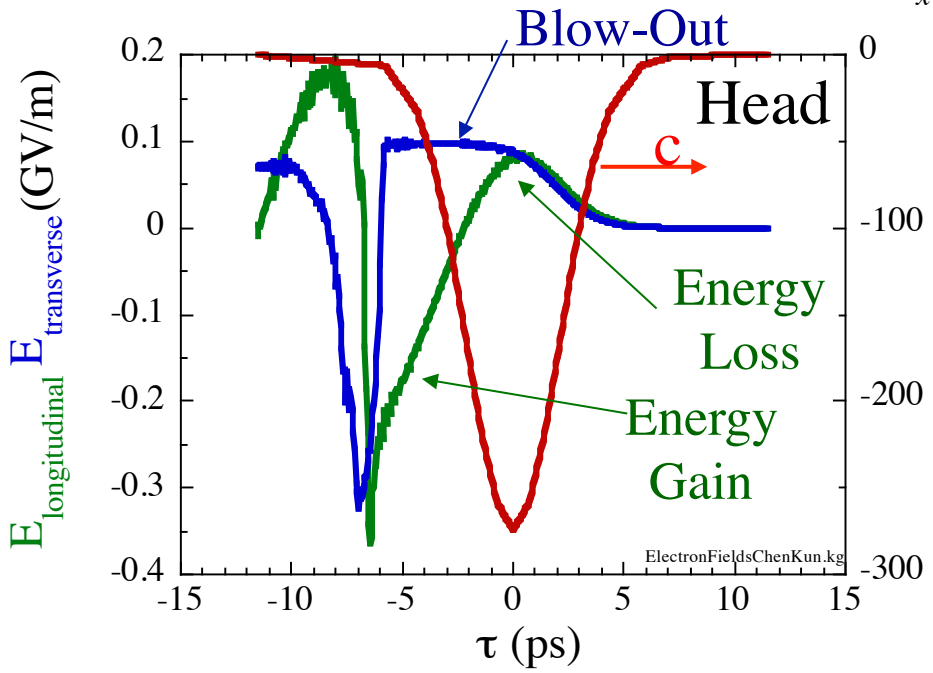
PLASMA WAKEFIELD FIELDS (e^-)

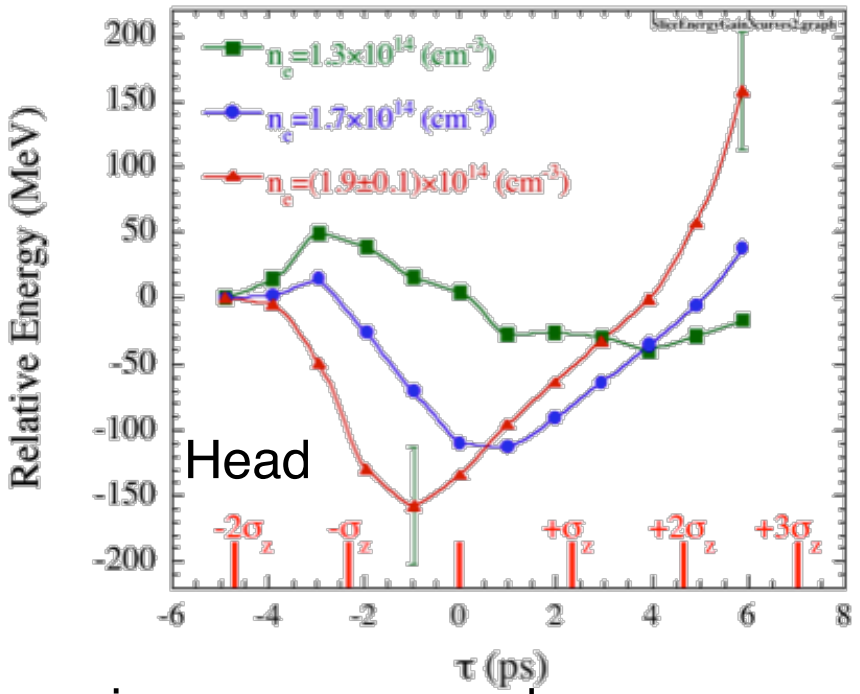
Muggli, Phys. Rev. Lett. 93, 014802 (2004).

2-D PIC Simulation QUICPICK

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

E_0	28.5 GeV	n_b	4×10^{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
σ_x=σ_y	70 μm		

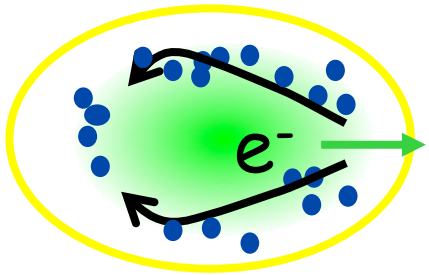


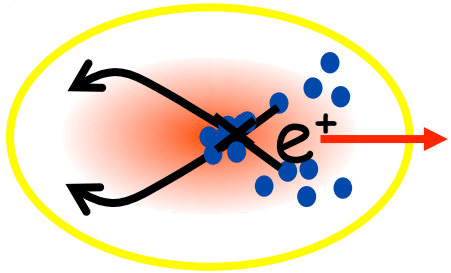


- Energy gain smaller than, hidden by, incoming energy spread
- Time resolution needed, but shows the physics
- Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

e^- & e^+ BEAM

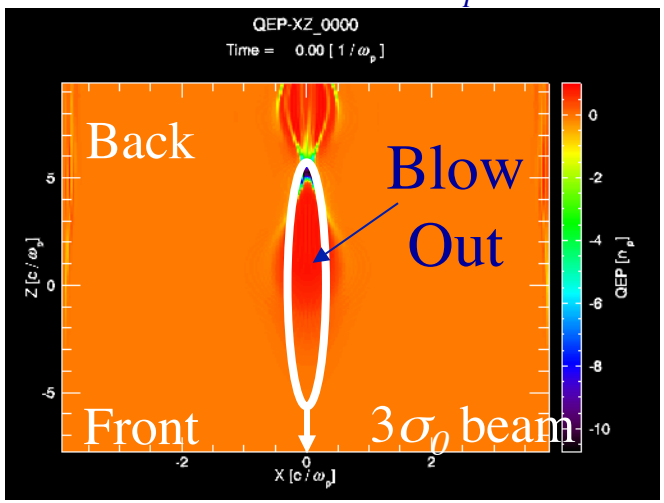
- Transverse dynamics, emittance preservation?





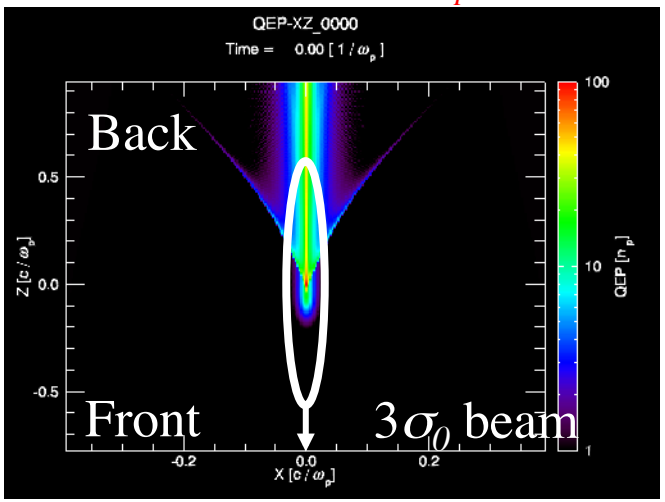
3-D QuickPIC simulations, plasma e^- density:

e^-: $n_{e0}=2\times10^{14}$ cm^{-3}, $c/\omega_p=375$ μm



$\sigma_r=35$ μm
$\sigma_r=700$ μm
$N=1.8\times10^{10}$
$L=2$ mm

e^+: $n_{e0}=2\times10^{12}$ cm^{-3}, $c/\omega_p=3750$ μm

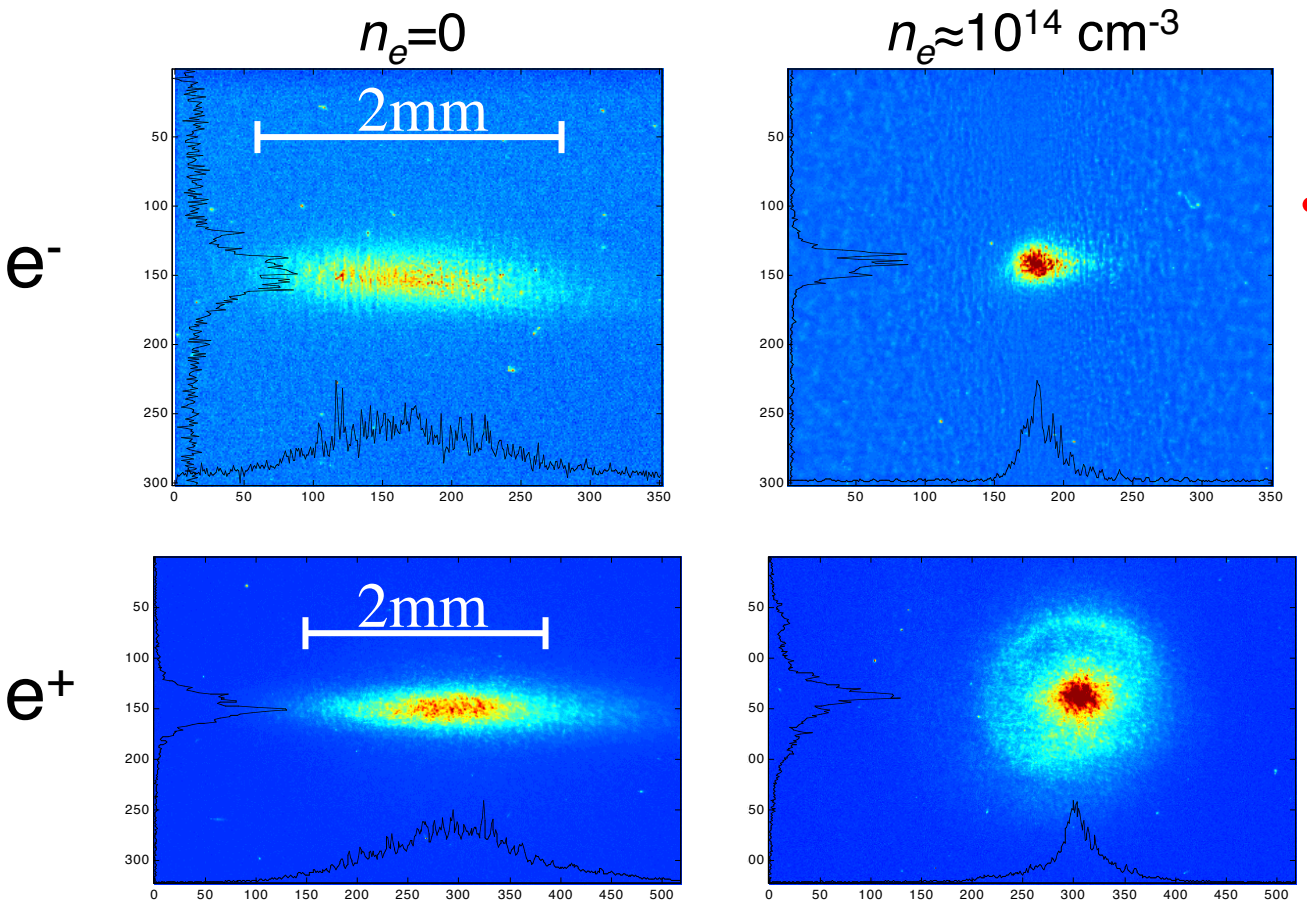


- Uniform focusing force (*r*,*z*)
- Free of geometric aberrations
- Emittance preserved

- Non-uniform focusing force (*r*,*z*)
- Emittance growth?

FOCUSING OF e^-/e^+

OTR images ≈1m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)
Single bunch experiments



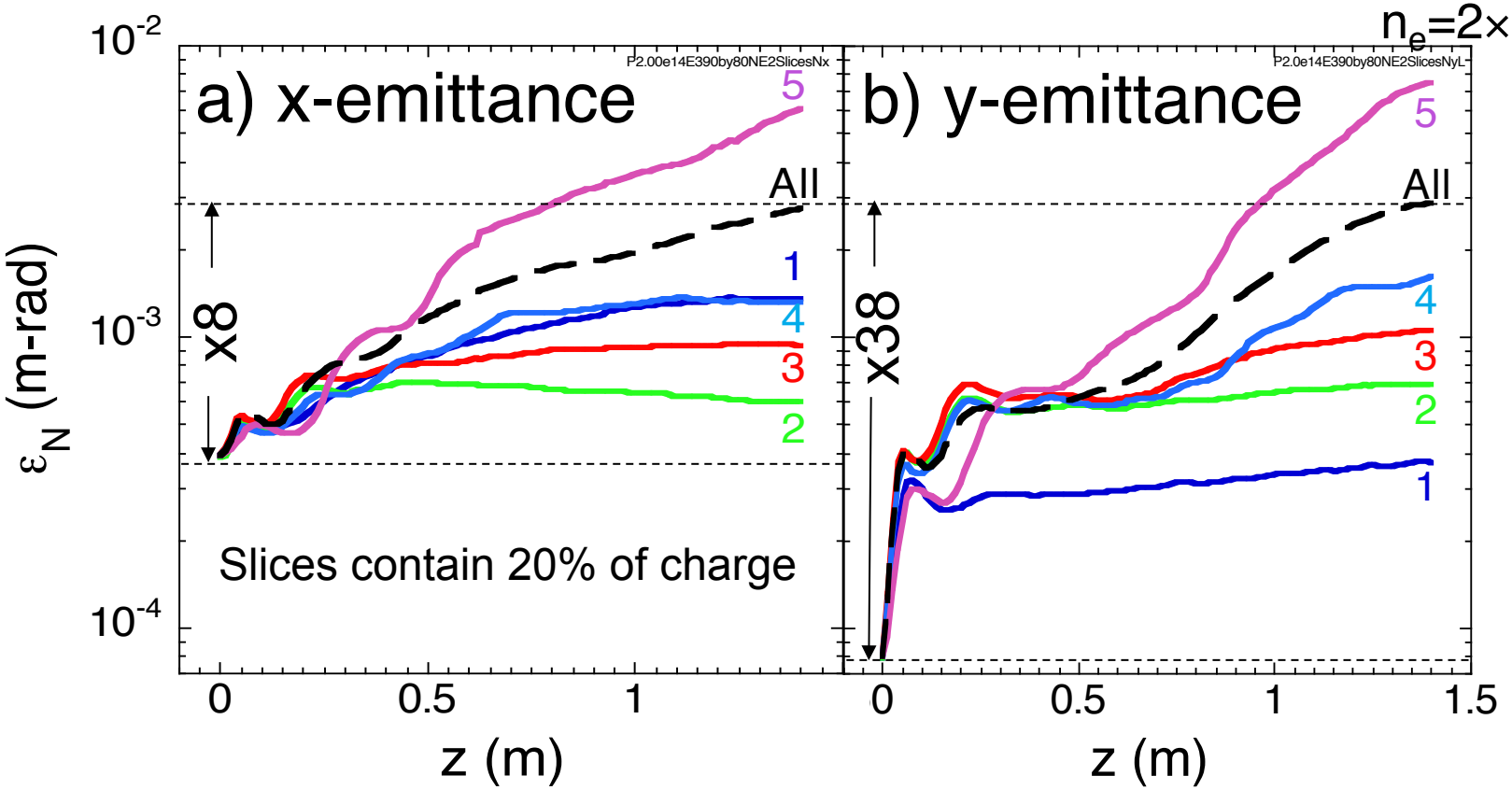
- Ideal Plasma Lens in Blow-Out Regime
- Plasma Lens with Aberrations, Halo Formation

➡ Focusing, but qualitative differences

e^+: SLICE EMITTANCE (SIMULATIONS)

$\sigma_{x0} \approx \sigma_{y0} \approx 25\ \mu m$, $\varepsilon_{Nx} \approx 390 \times 10^{-6}$, $\varepsilon_{Ny} \approx 80 \times 10^{-6}$ m-rad, $N = 1.9 \times 10^{10}$ e^+, $L \approx 1.4$ m

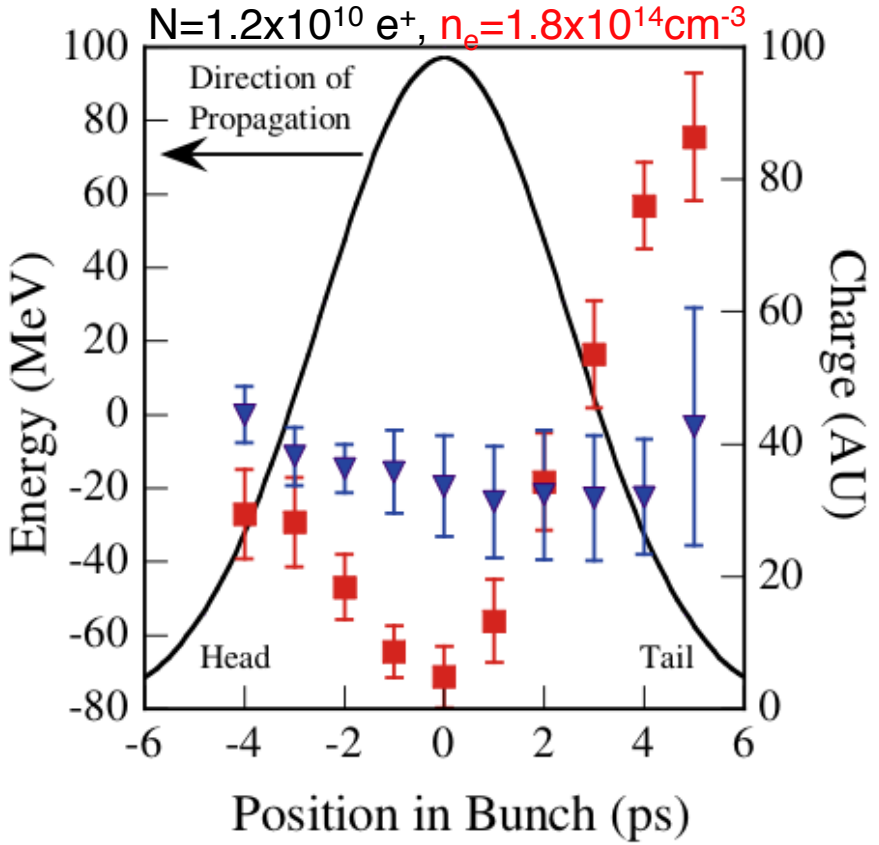
$n_e = 2 \times 10^{14}$ cm^{-3}

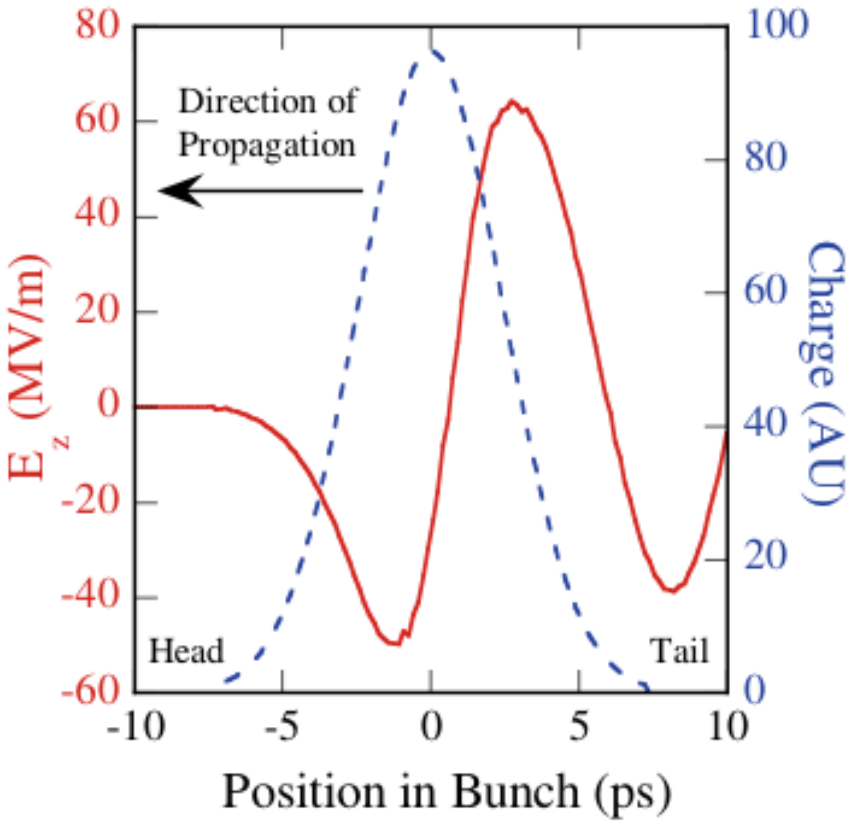


- Large emittance growth
- The e^+ beam exits the plasma with ≈equal emittances and ≈equal transverse sizes

Muggli, PRL 101, 055001 (2008).

e^+ ACCELERATION
PRE-IONIZED, LONG BUNCH

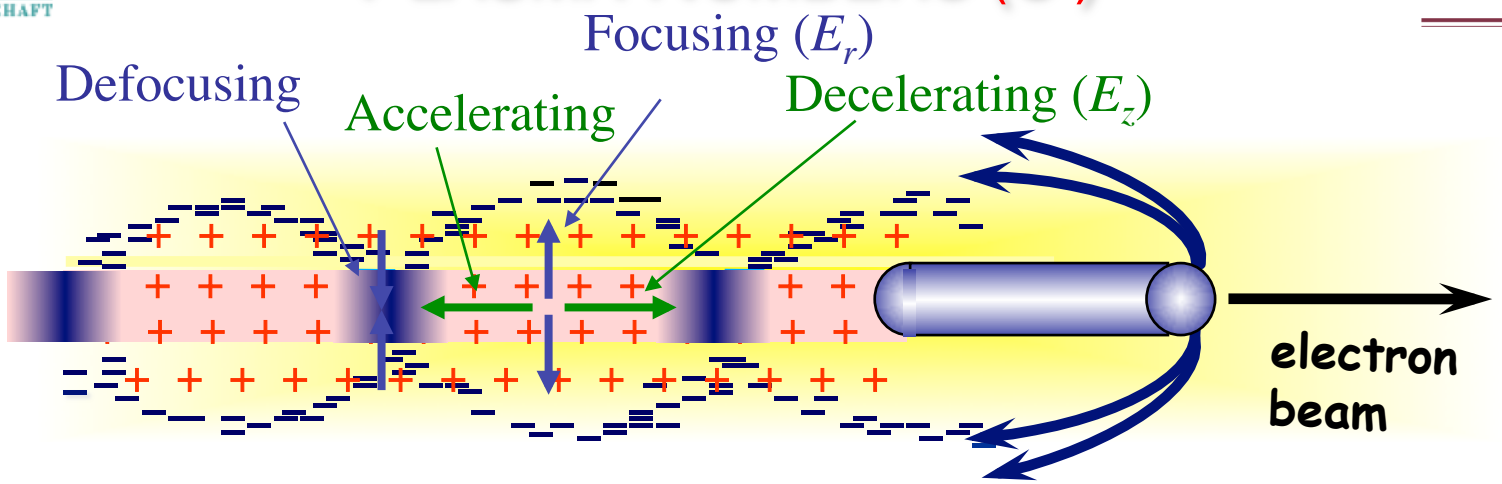




Blue, Phys. Rev. Lett. 90, 214801 (2003).

- Energy gain and loss ≈80 MeV over 1.4 m
- Good agreement with numerical simulations

PLASMA NUMBERS (e^-)



➡ Linear theory scaling:

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

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

Short Bunches!

➡ Focusing strength:

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

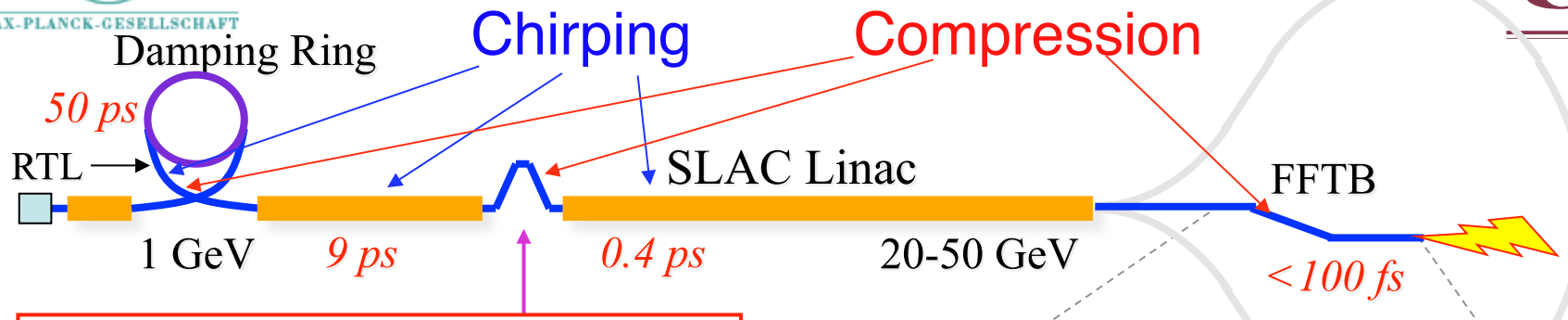
➡ N=2x10^{10}: σ_z=600 μm, n_e=2x10^{14} cm^{-3}, E_{acc}≈100 MV/m, B_θ/r=6 kT/m

σ_z= 20 μm, n_e=2x10^{17} cm^{-3}, E_{acc}≈ 10 GV/m, B_θ/r=6 MT/m

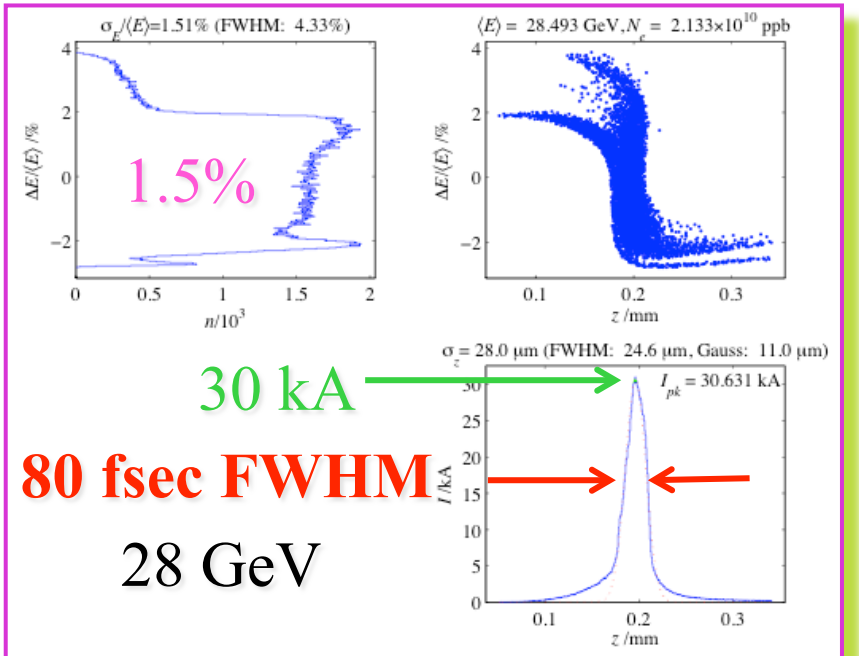
+plasma field ionization!

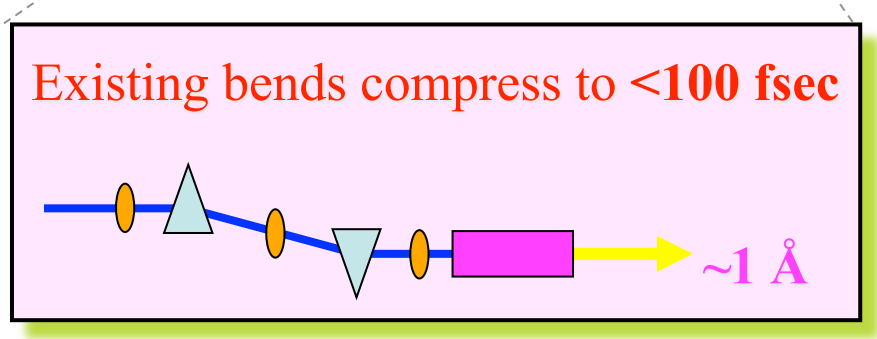
➡ Conventional: E_{acc}<150 MV/m, B_θ/r<2 kT/m

Short Bunch Generation In The SLAC Linac



Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)





- Bunch magnetic compression (N=cst) by a factor of ≈730/25≈29!

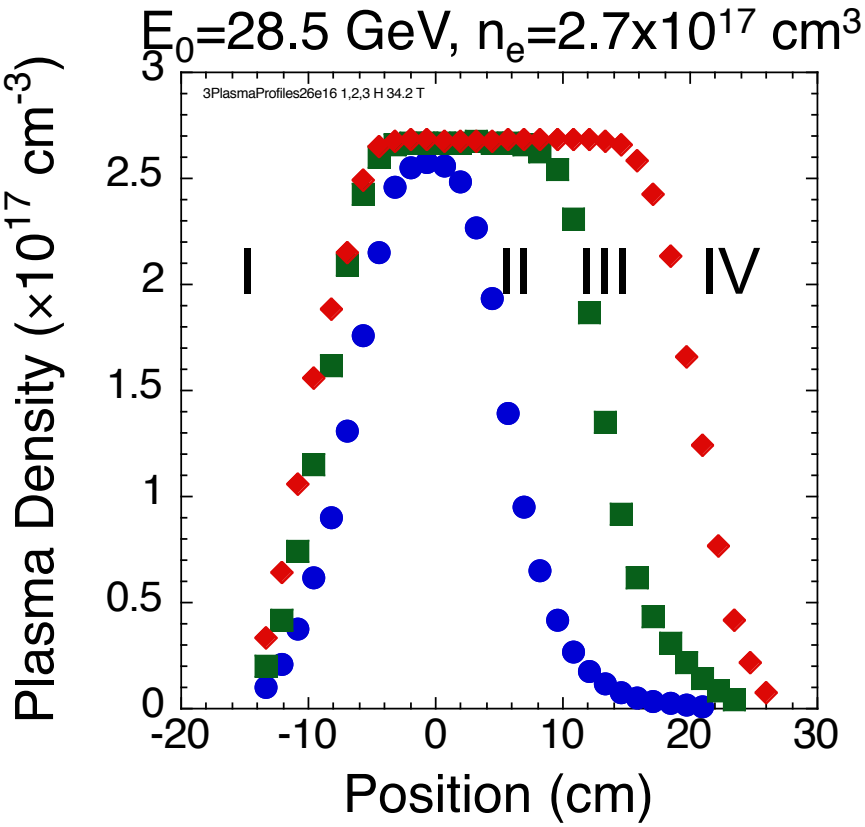
$$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2}$$

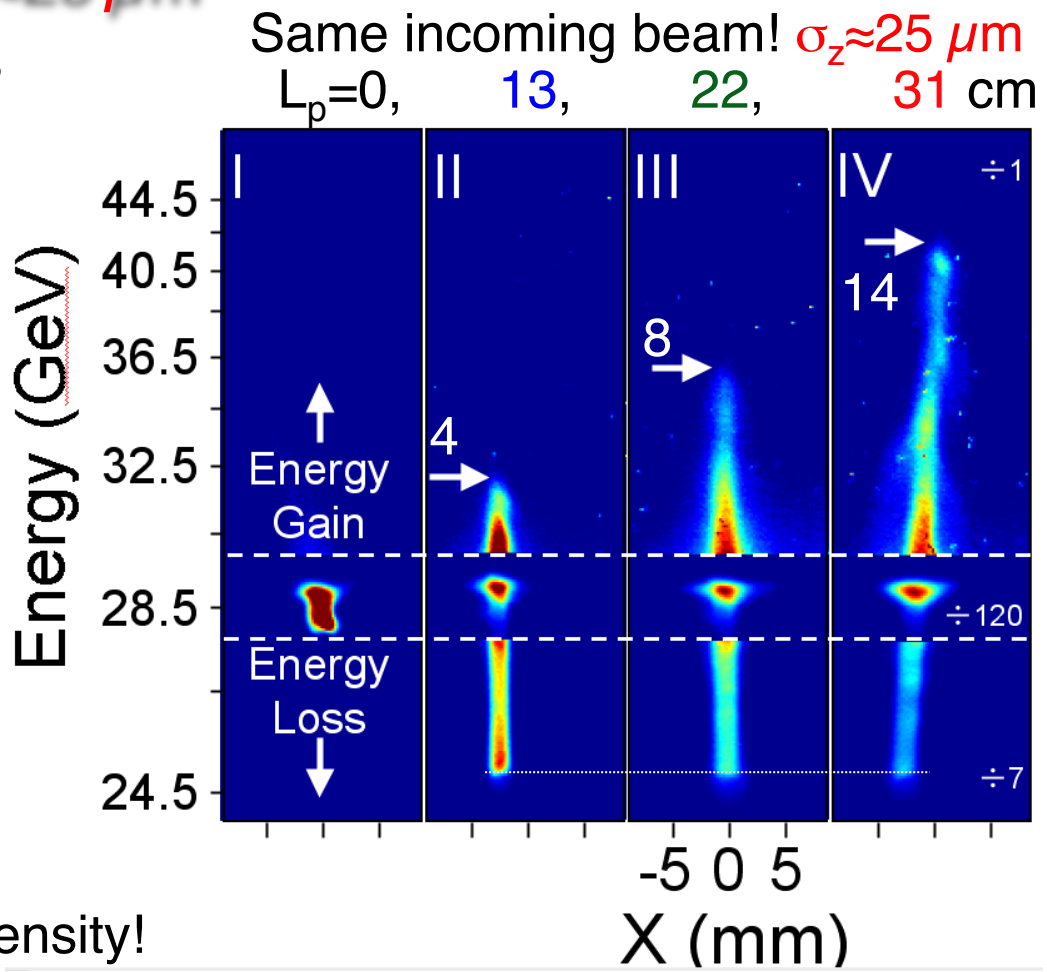
- $E_{r,\,bunch}$ > 6GV/m, filed-ionize Li!

Courtesy of SPPS

SCALING WITH PLASMA LENGTH

$\sigma_z \approx 25\ \mu m$





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

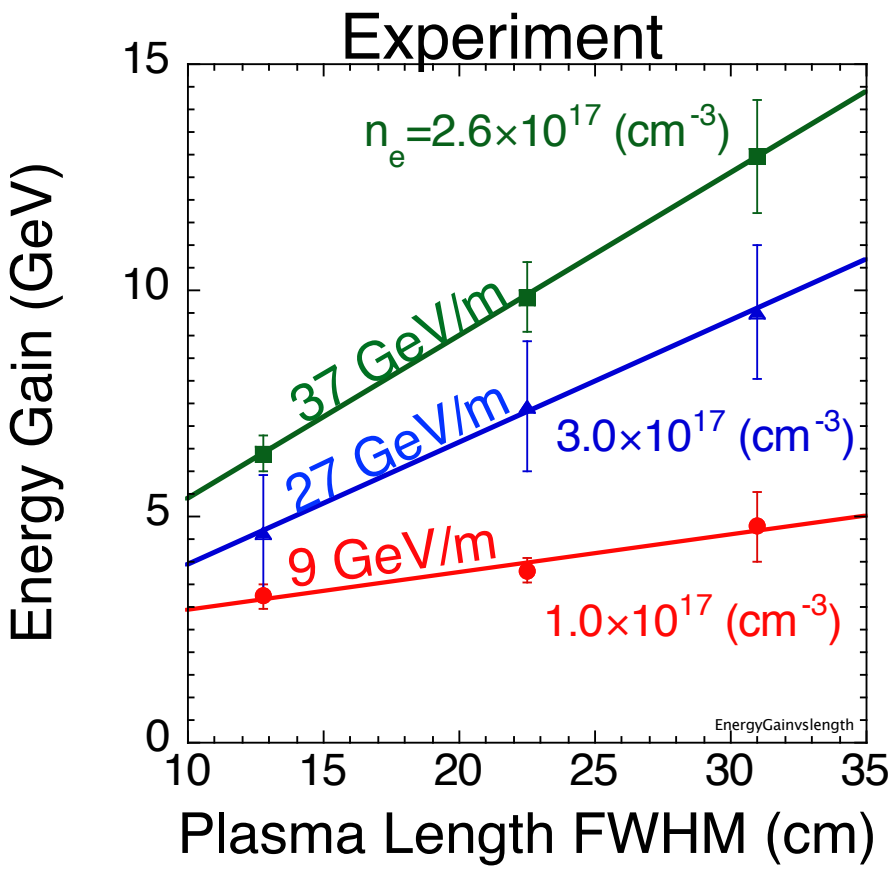
P. Muggli et al., New J. Phys. 12, 045022 (2010)

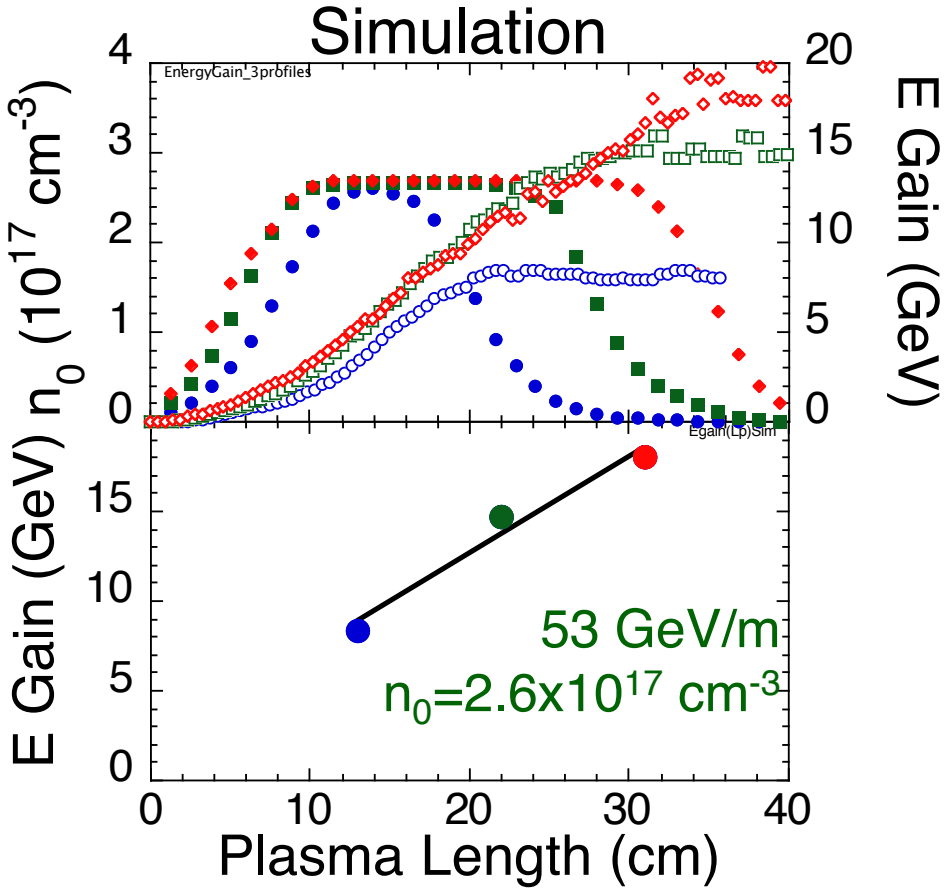
SCALING WITH PLASMA LENGTH

$$\text{Accelerating Gradient} = \frac{\text{Energy Gain}}{\text{Plasma Length}}$$

E_0=28.5 GeV

$\sigma_z \approx 25\ \mu m$

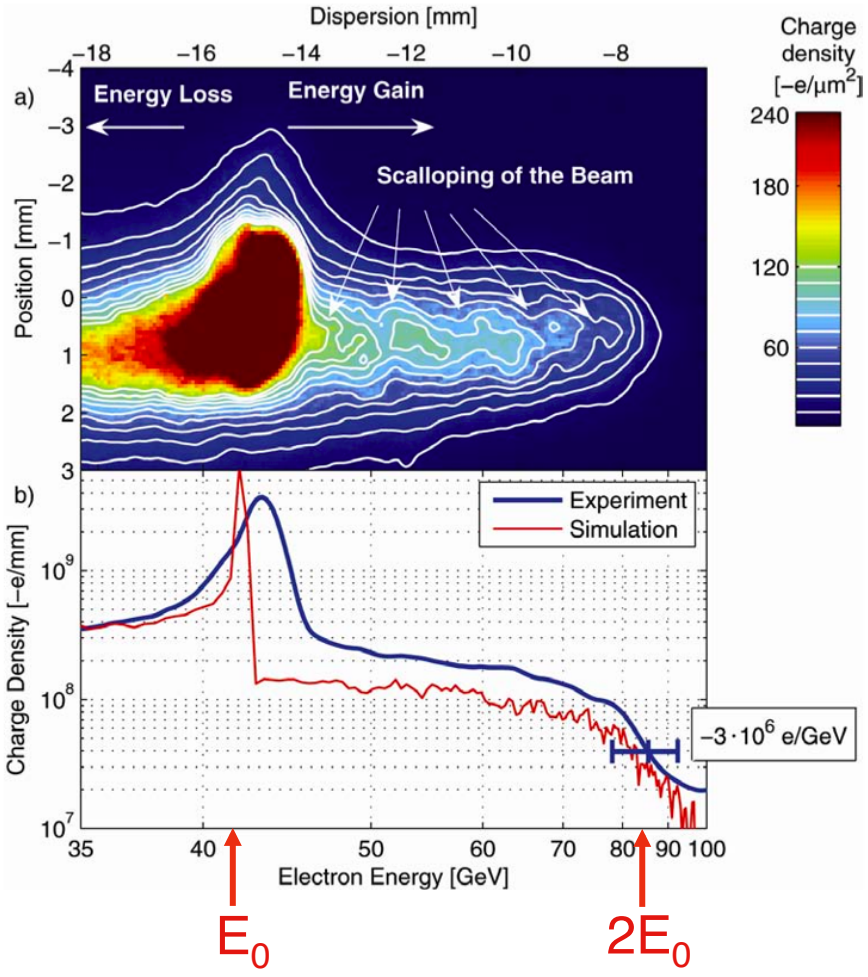




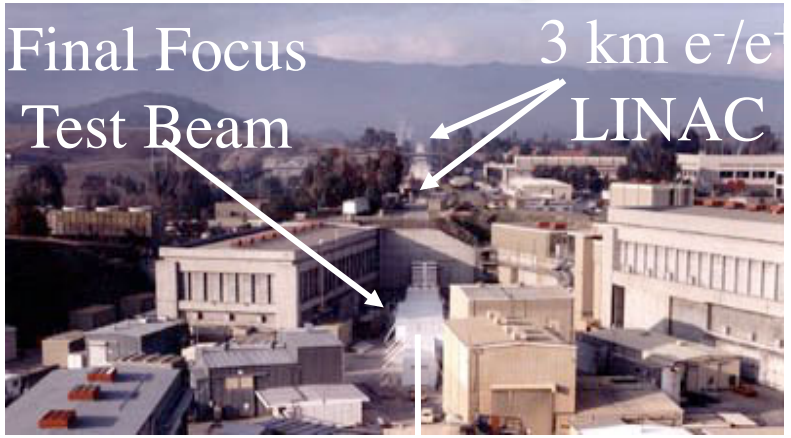
- Energy gain scales linearly with L_p, optimum $n_e \approx 2.6 \times 10^{17}$ cm^{-3}
- Experimental accelerating gradient: $E_{acc} \approx 37$ GeV/m (max. avg.)

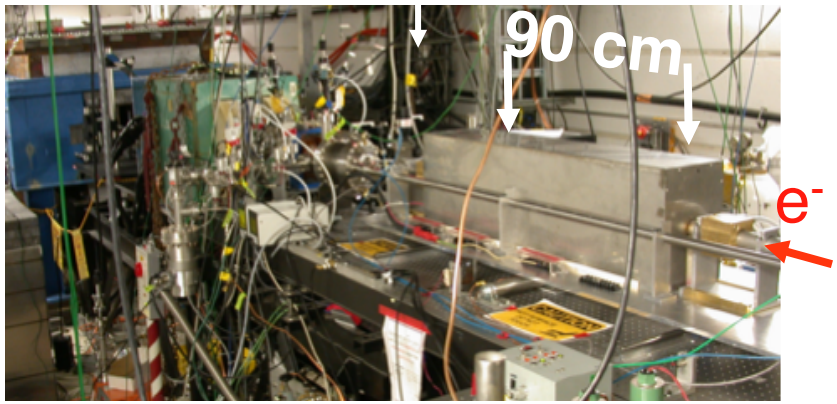
e^- ENERGY DOUBLING

I. Blumenfeld *et al.*, Nature 445, 2007



E_0=42 GeV

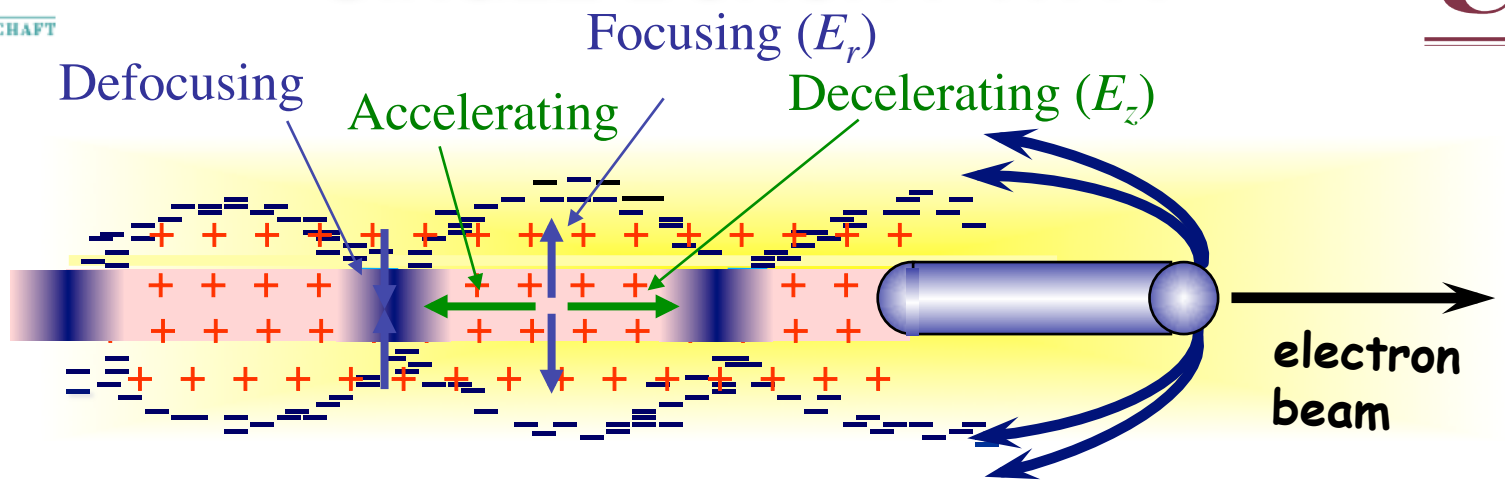




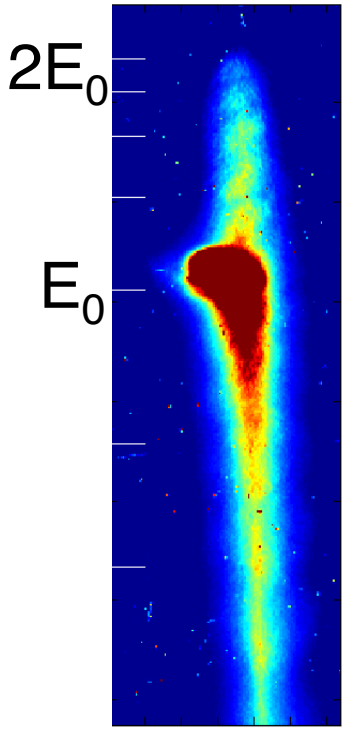
➡ Energy doubling of e^- over $L_p \approx 85$ cm, 2.7×10^{17} cm^{-3} plasma

➡ Unloaded gradient ≈52 GV/m (≈150 pC accel.)

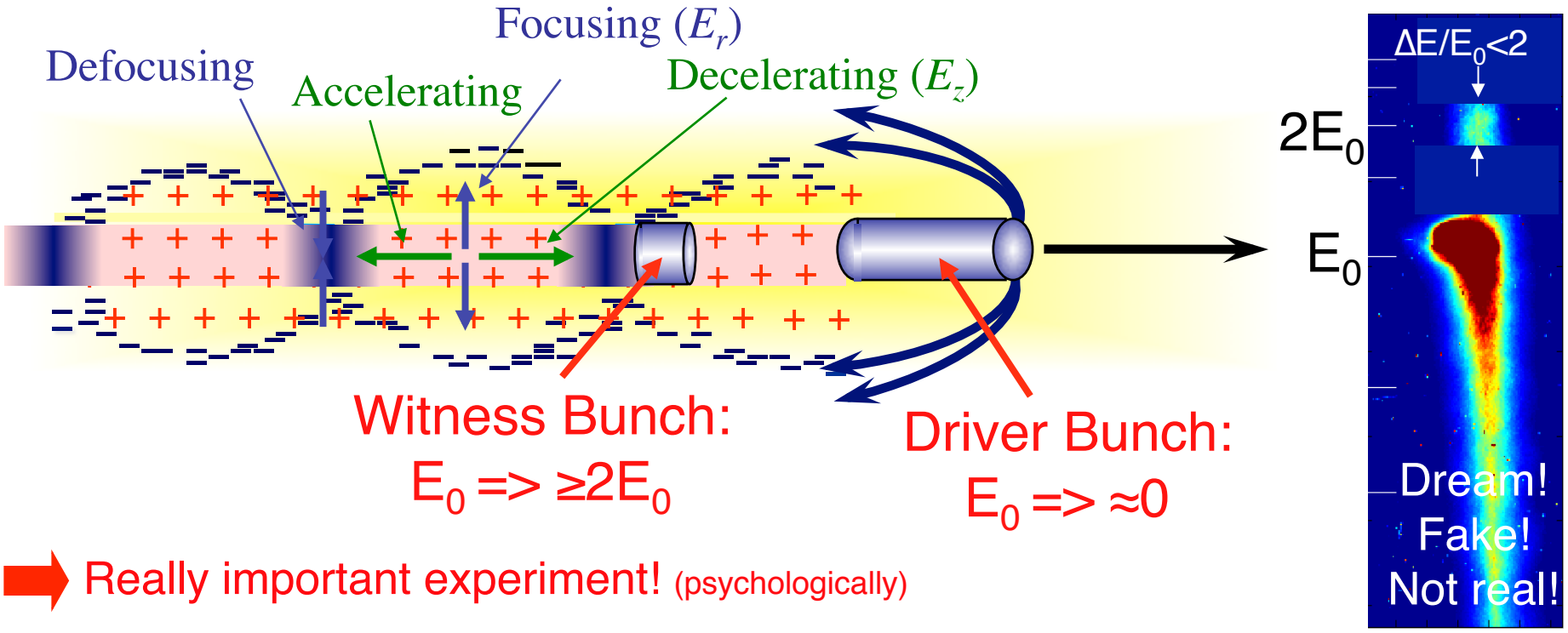
SINGLE BUNCH PWFA



- 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



2-BUNCH PWFA



- Really important experiment! (psychologically)
- Driver bunch: high-charge (*3N*), modest emittance, shaped?
- Witness bunch: lower charge (*N*), good emittance, shorter
  beam loading for *ΔE/E<<1*
- New facility: FACET@SLAC for 23GeV PWFA accelerator module
- Low energy physics experiments

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

MULTIBUNCH PWFA

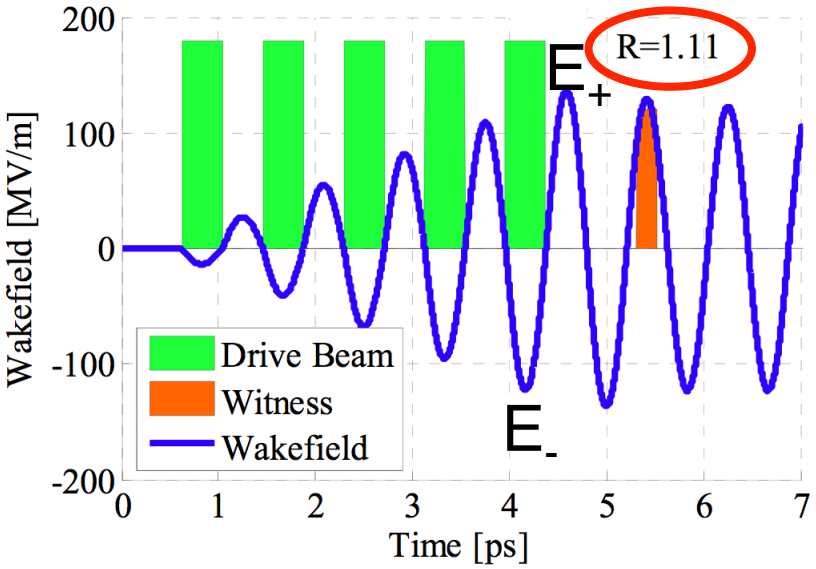
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

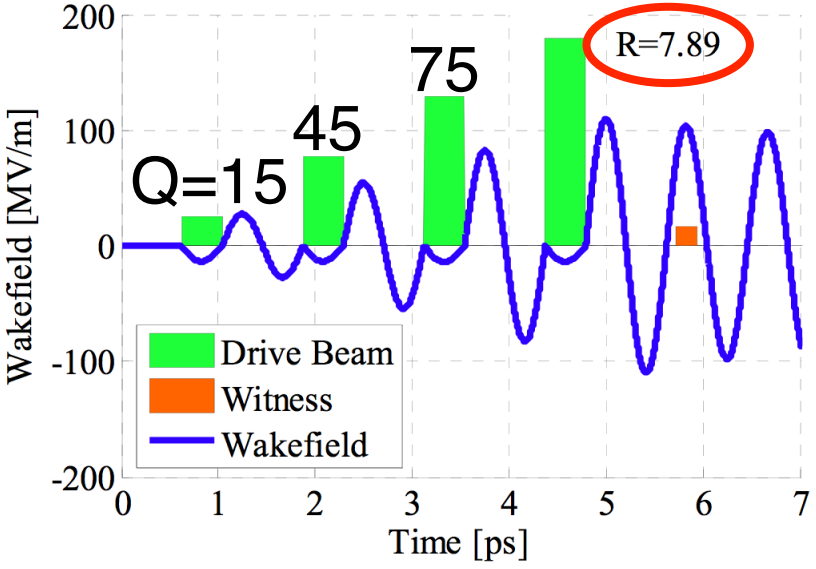
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



*Tsakanov, NIMA, 1999

- Linear (2D) theory for $n_b << n_e$!
- R=7.9 => multiply energy by ~8 in a single PWFA stage!

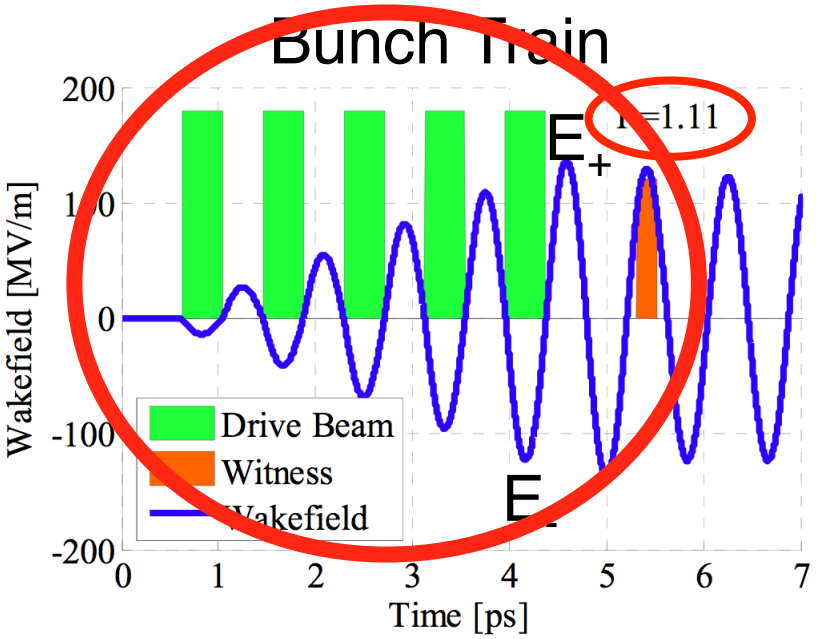
MULTIBUNCH PWFA

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

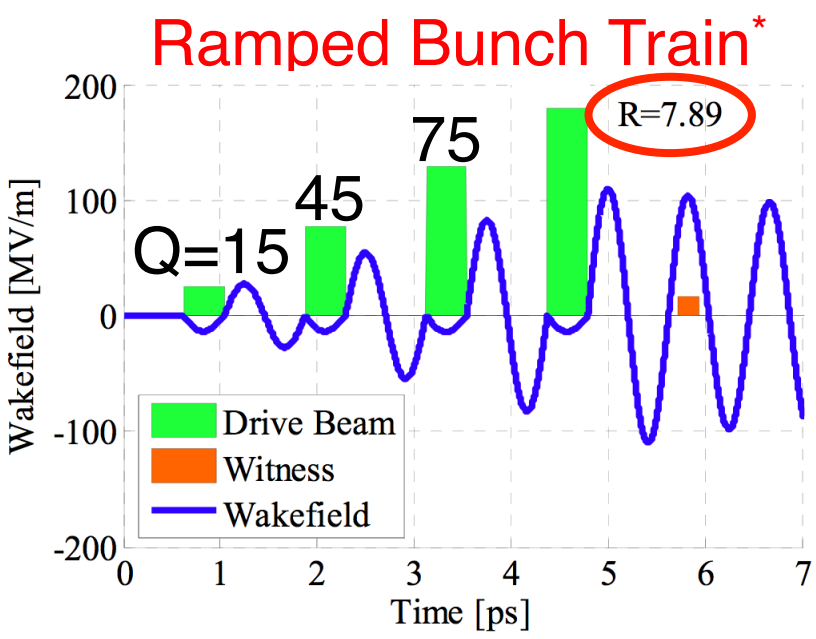
E_0: incoming energy

Q=30 pC/bunch, Δz=250 μm≈λ_p



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

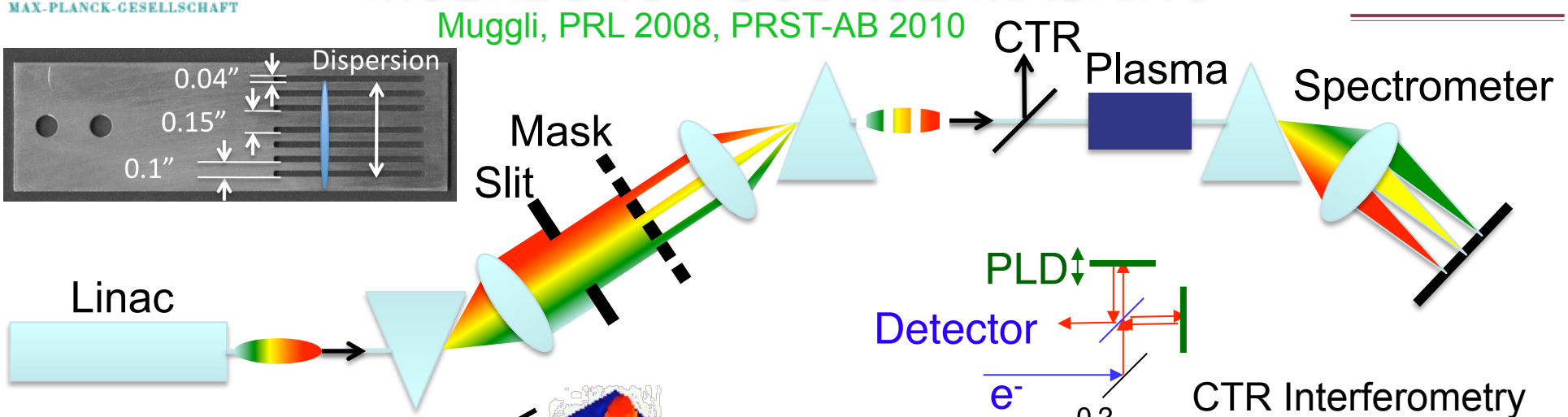


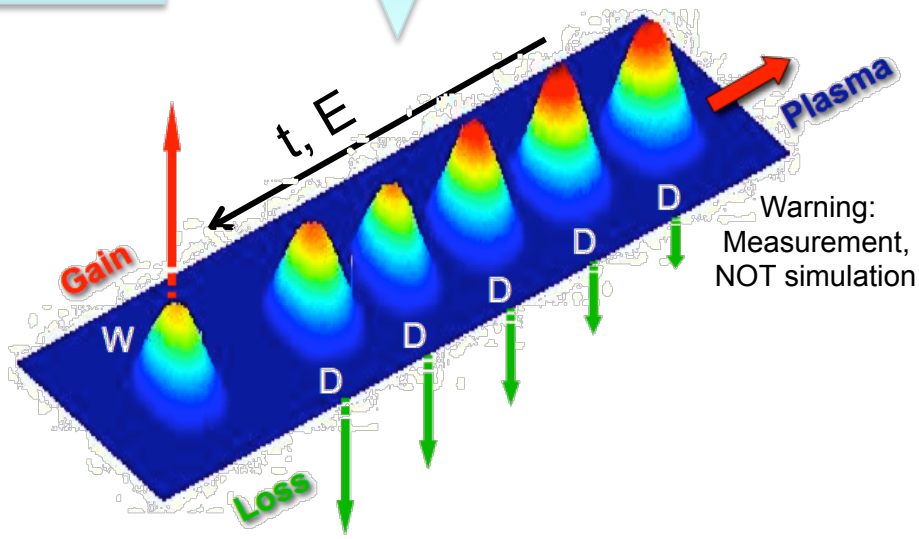
*Tsakanov, NIMA, 1999

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

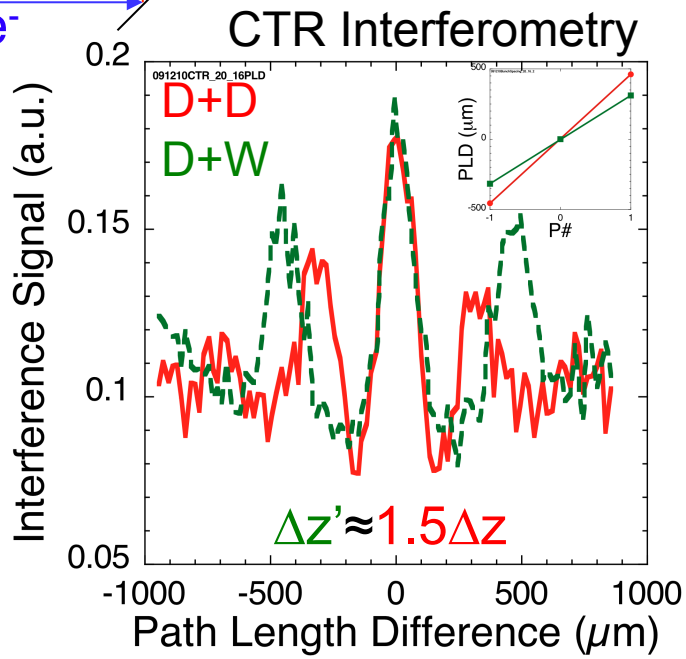
MULTIBUNCH SOURCE-MASKING

Muggli, PRL 2008, PRST-AB 2010





Warning:
Measurement,
NOT simulation

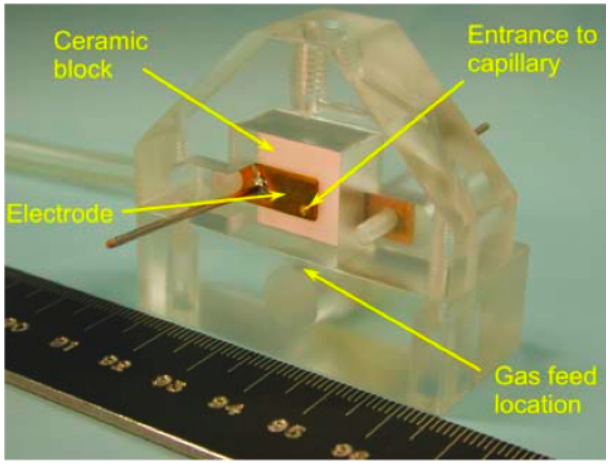


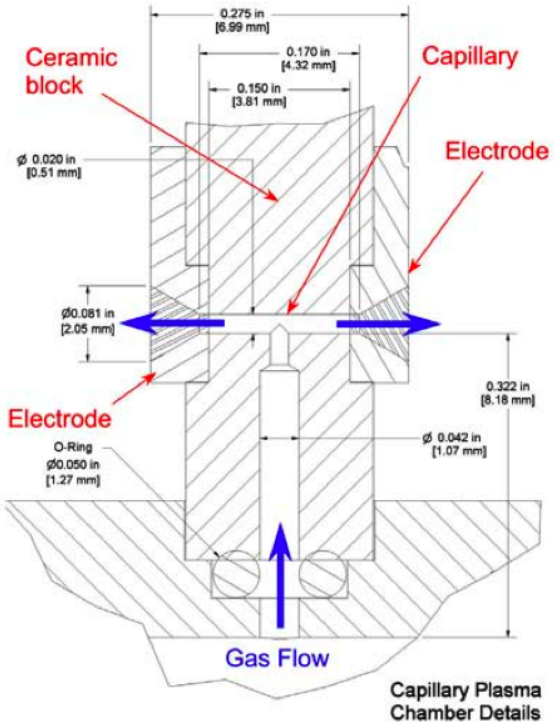
- Emittance selection
- Can choose the chirp, W at high energy
- Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σ_z, Q

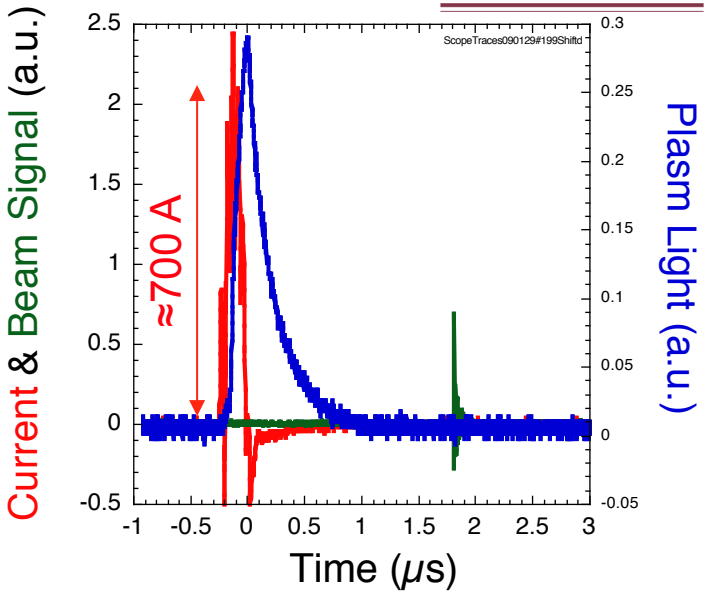
PLASMA SOURCE

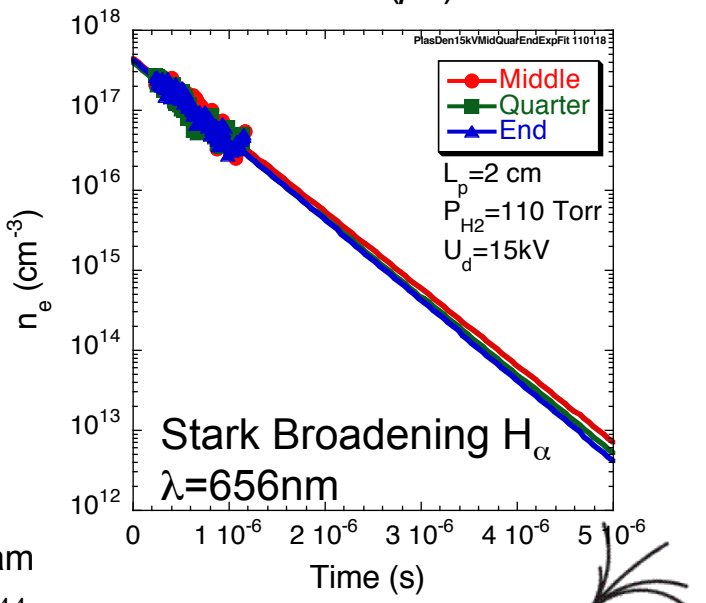
H_2-puff Capillary Discharge

Kimura, AAC'06 Proceedings







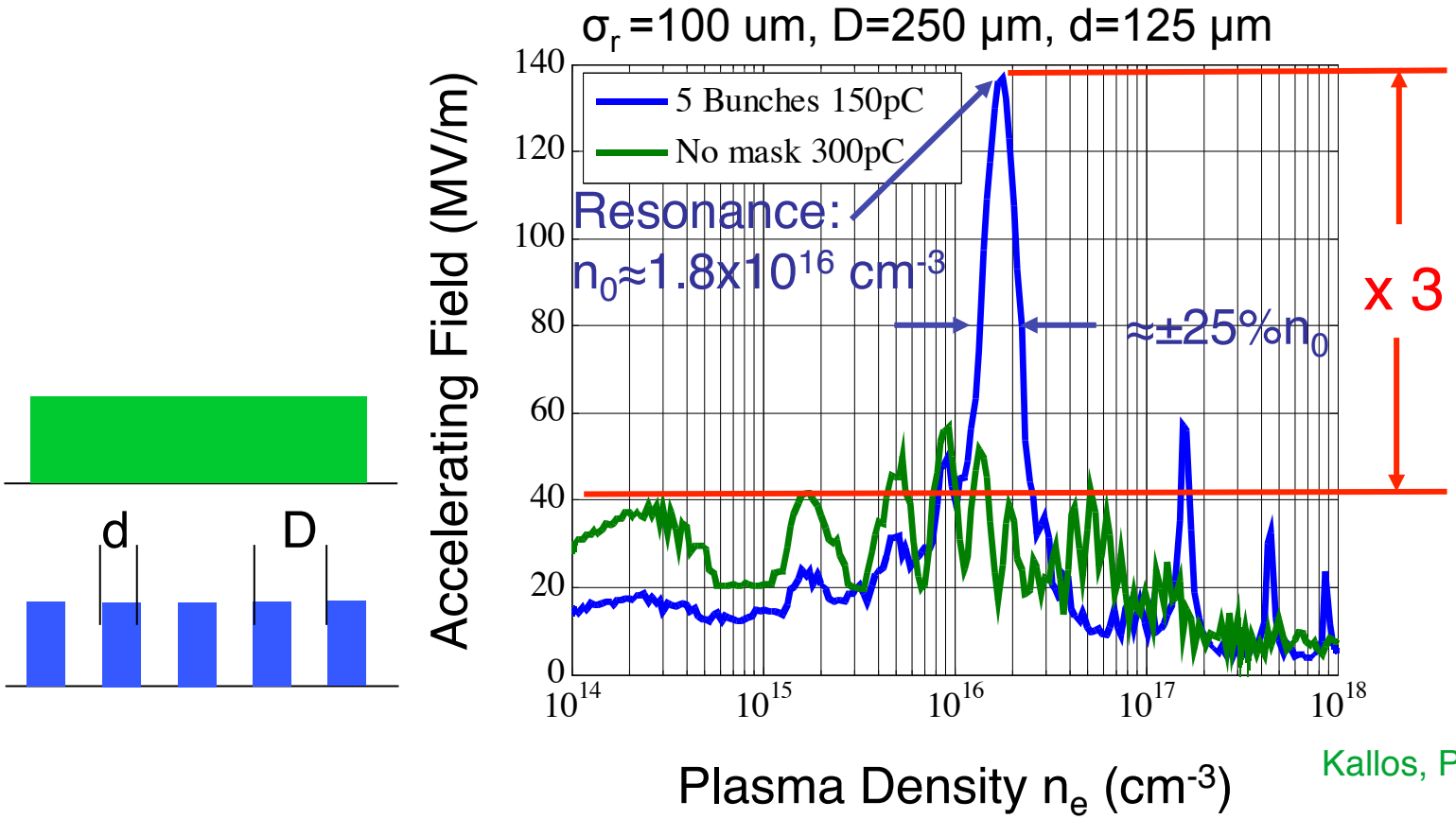


- U=15kV, P_{H2}=100Torr
- Plasma density n_e controlled through $\tau_{discharge\text{-}beam}$
- n_e fit and extrapolation $n_e(\tau) \cong 4.3 \times 10^{17} cm^{-3} e^{-\tau/444\,ns}$

$L_p \approx 2cm$

ACCELERATING FIELD

Linear calculation microbunches with equal charge



Kallos, PAC'07 Proceedings

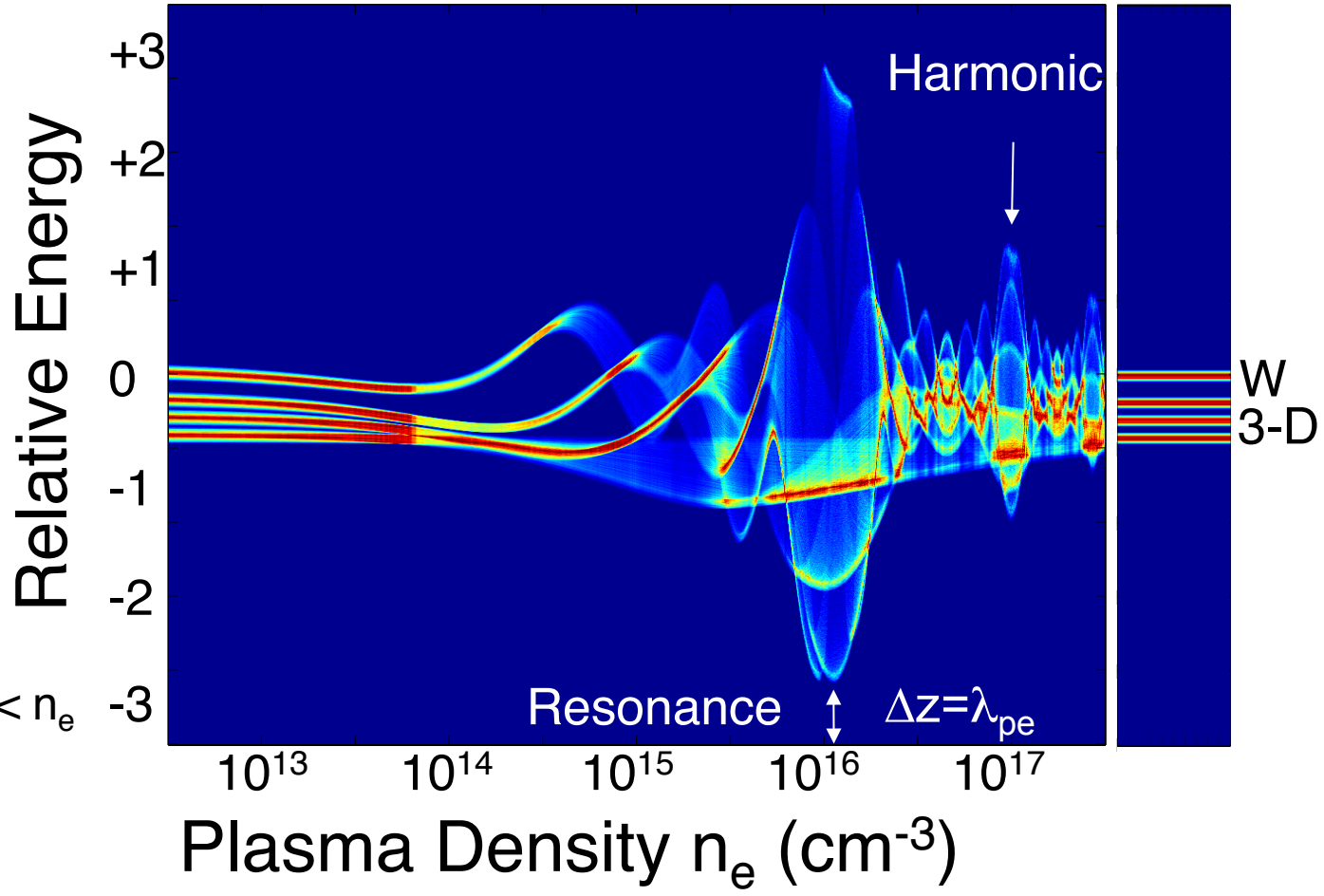
- Expect ≈MeV energy gain/loss over 1 cm
- Microbunch resonance clear, and narrow

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
$n_b \approx 4 \times 10^{13} cm^{-3} << n_e$
Linear Regime!



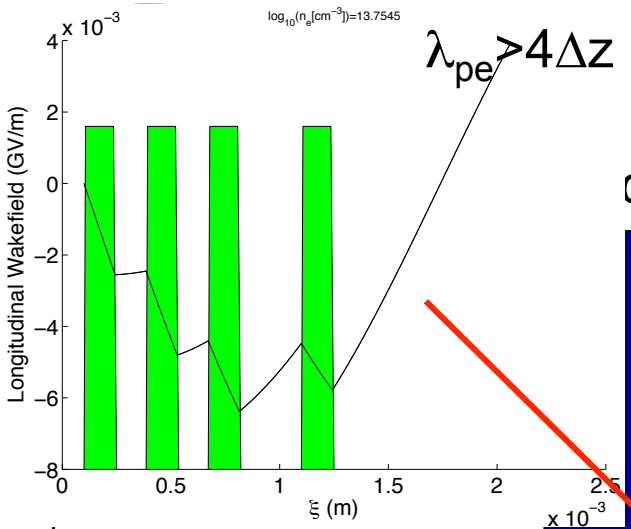
➡ Resonant excitation of wakefield is the main feature

➡ Chirp such that W enters with highest energy

➡ $n_{e,\,res} \approx 1.4 \times 10^{16}$ cm^{-3}

ENERGY CHANGE

culation (2D): microbunches with equal charge



$\lambda_{pe} > 4\Delta z$

Δz=284 μm,
d=142 μm
$\Delta z'$=426 μm
Q_{tot}=140 pC
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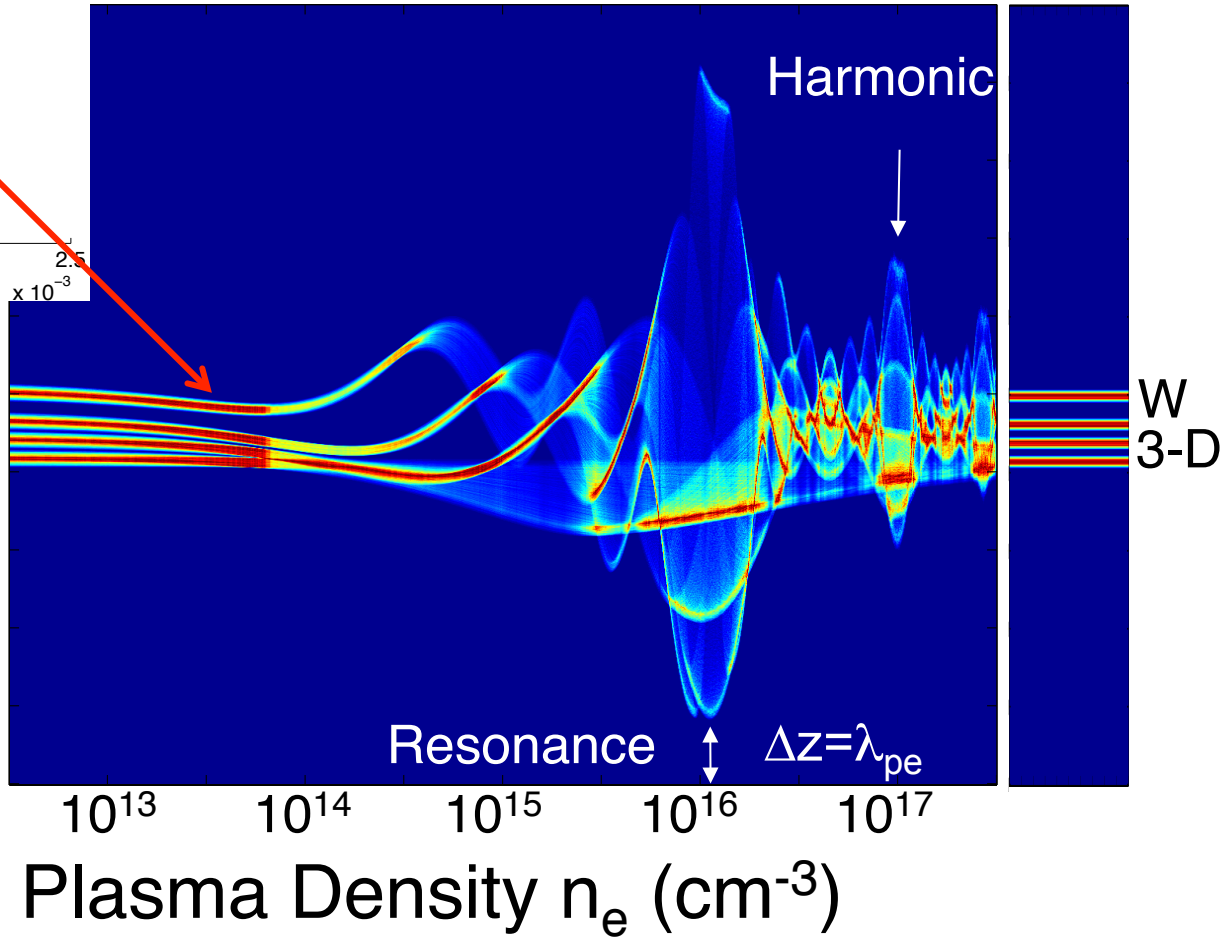

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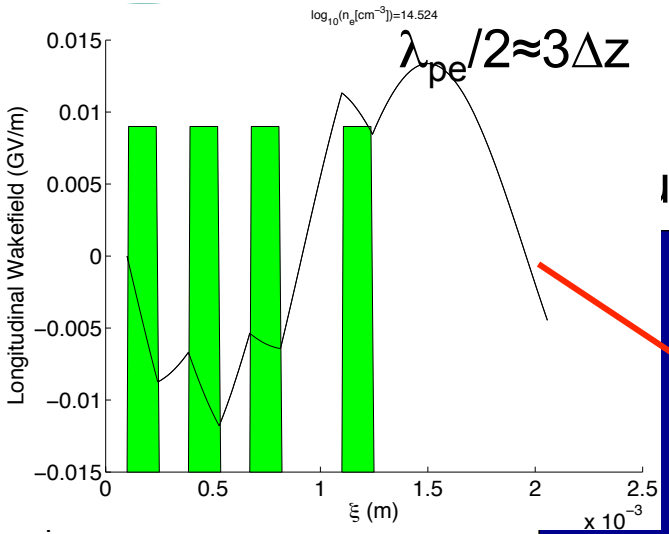
ENERGY CHANGE



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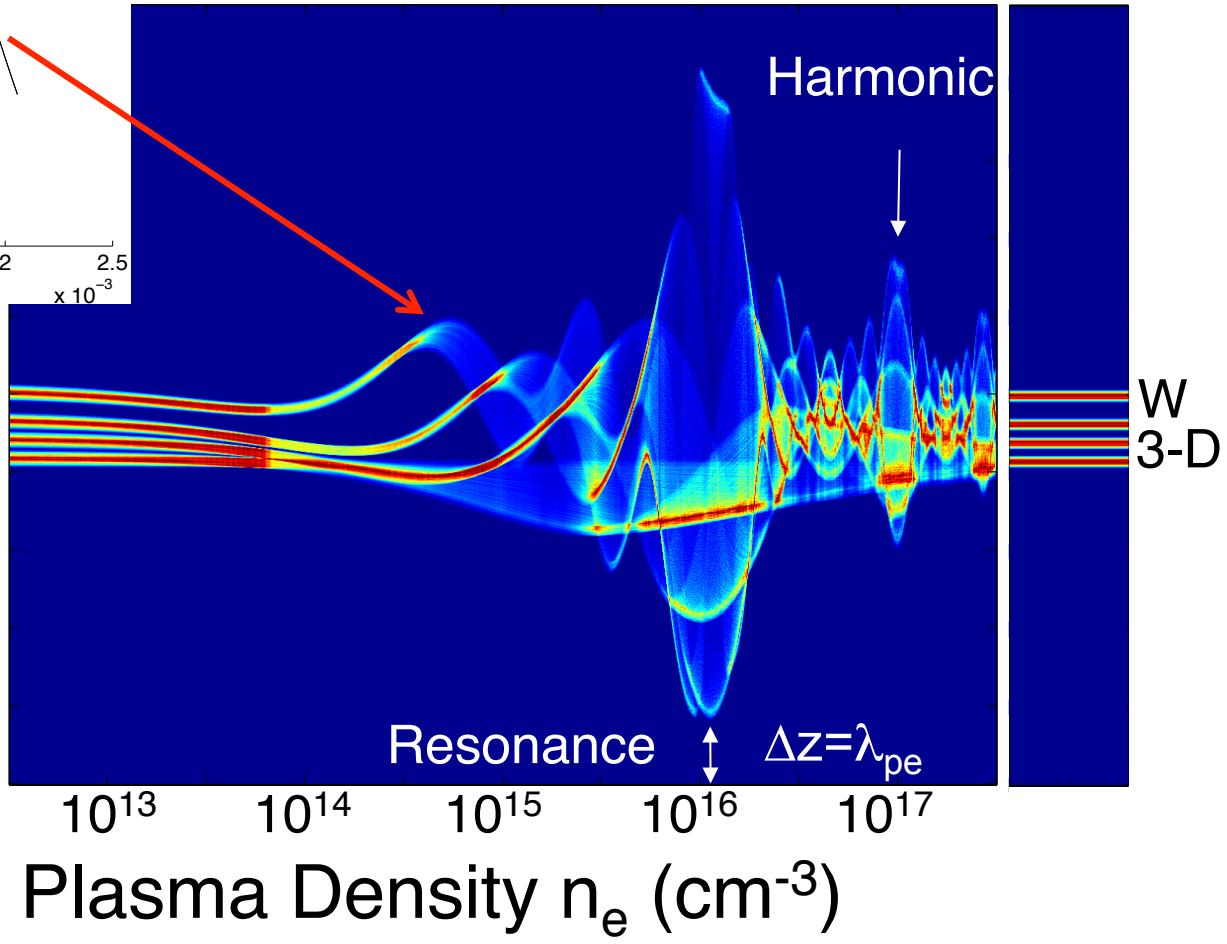

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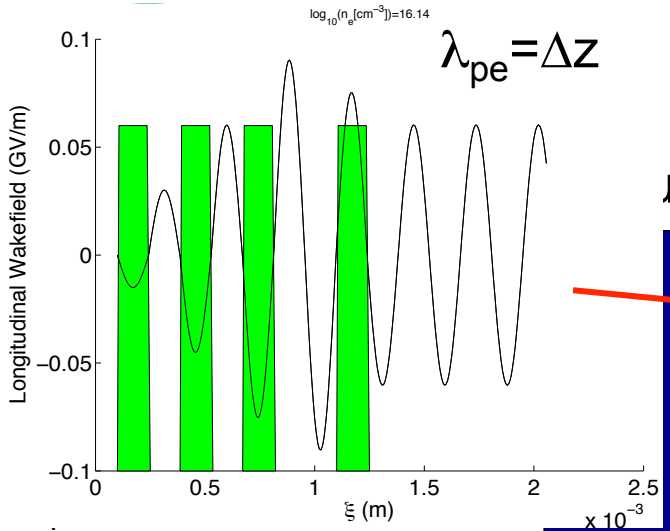
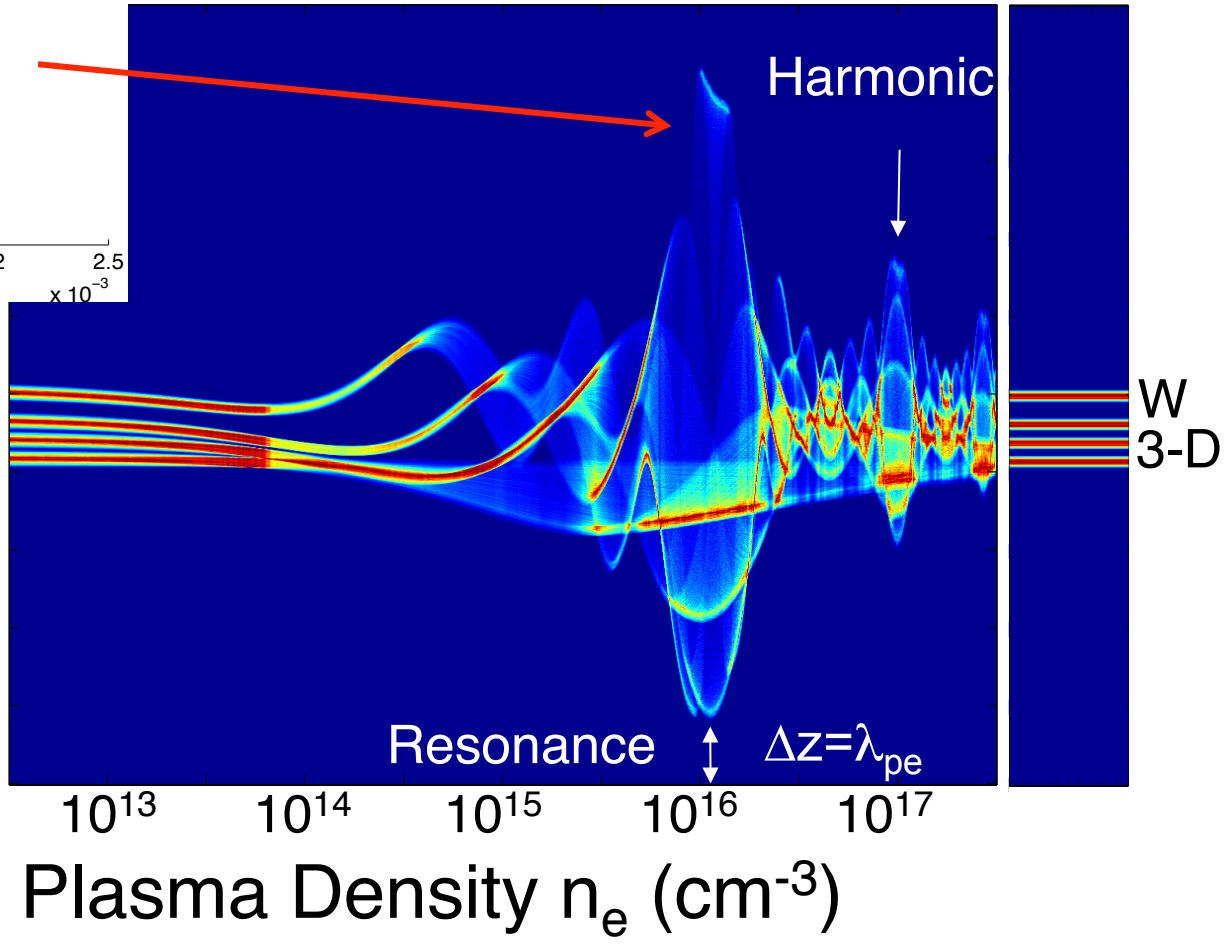
ENERGY CHANGE



ulation (2D): microbunches with equal charge



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Linear Regime!

- Resonant excitation of wakefield is the main feature
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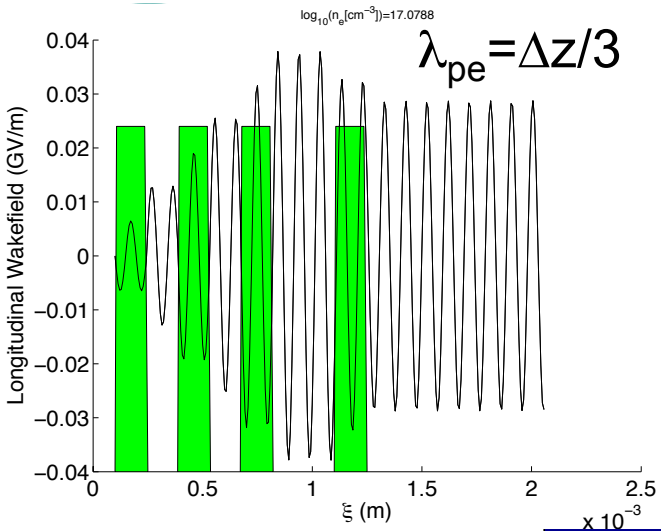
ENERGY CHANGE



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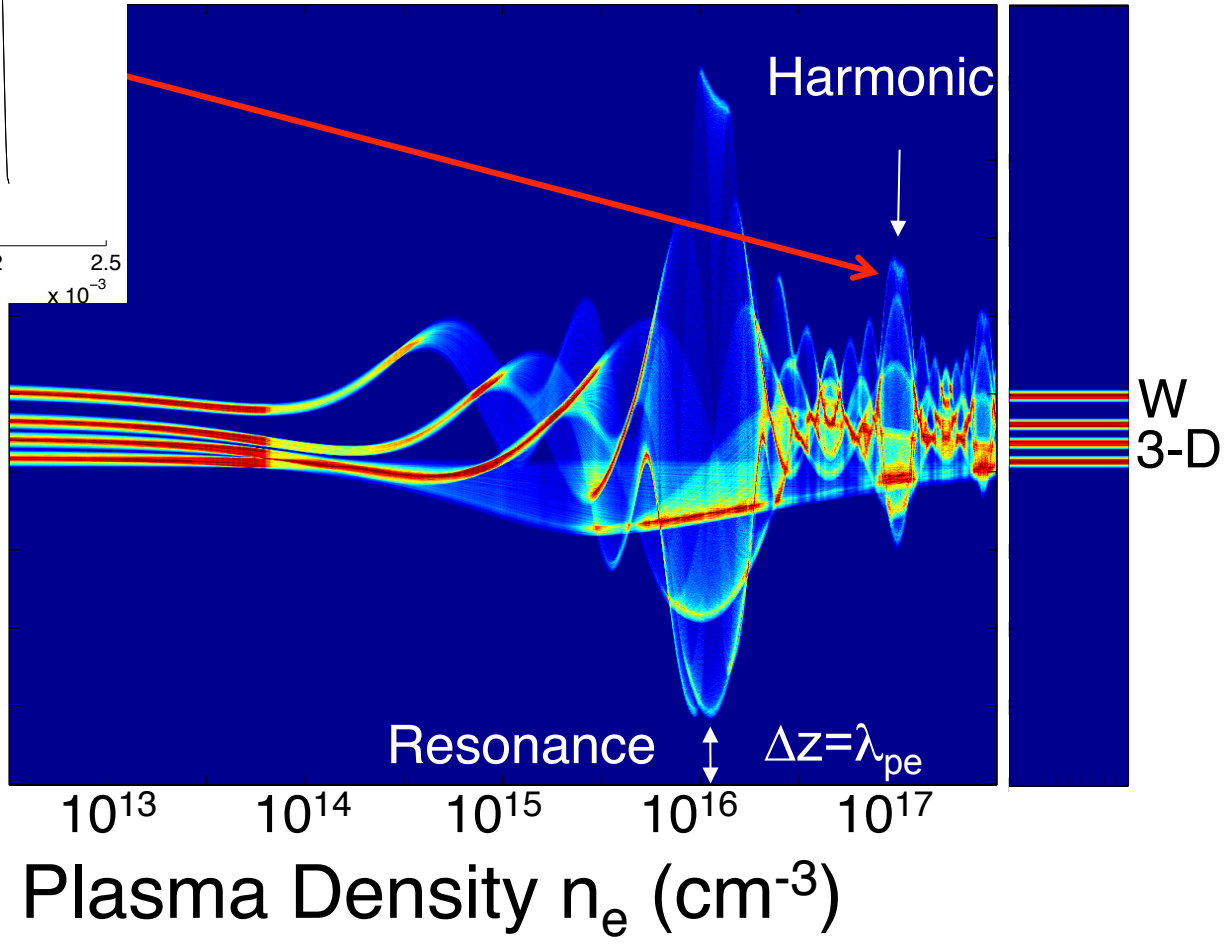

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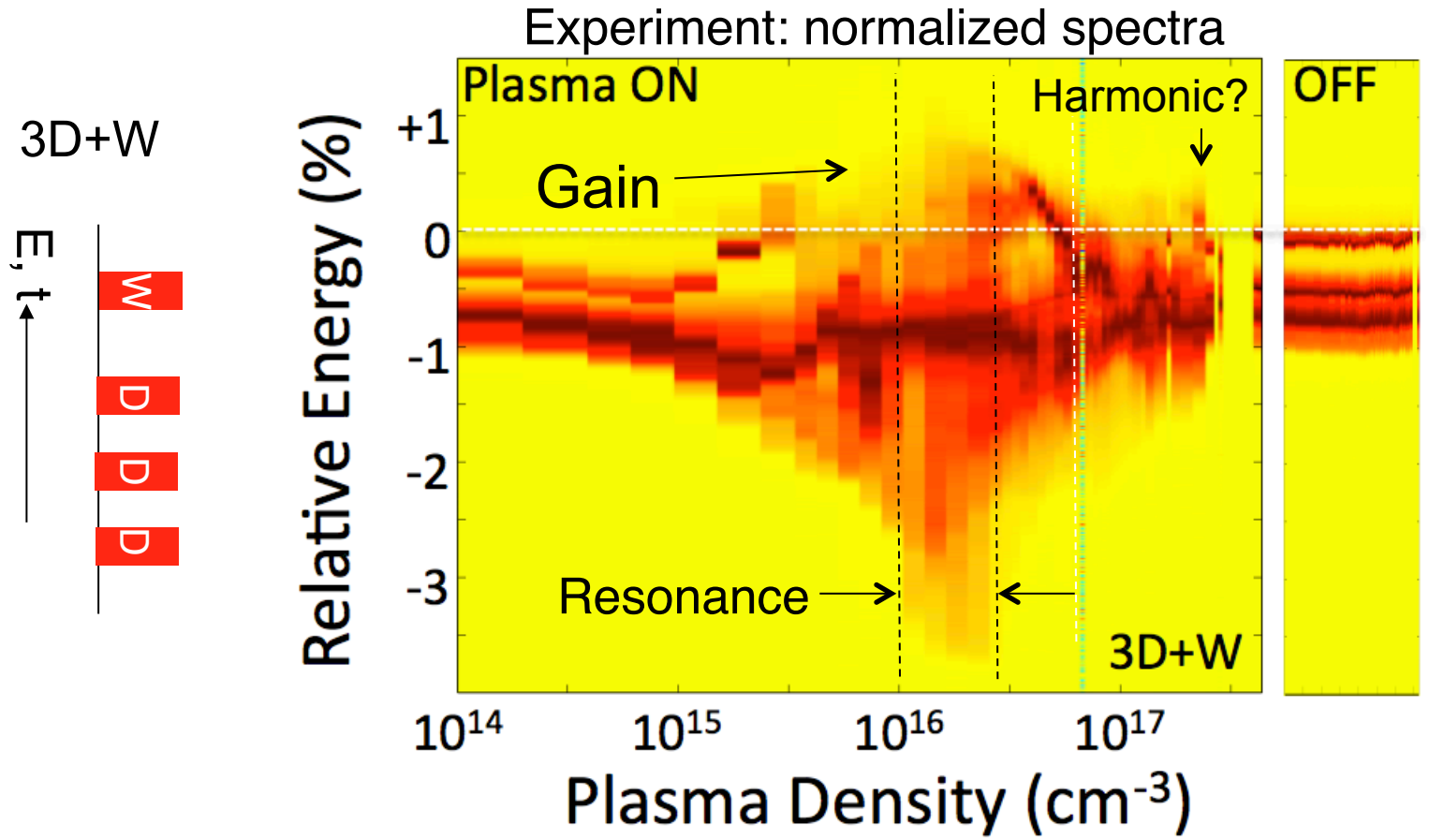
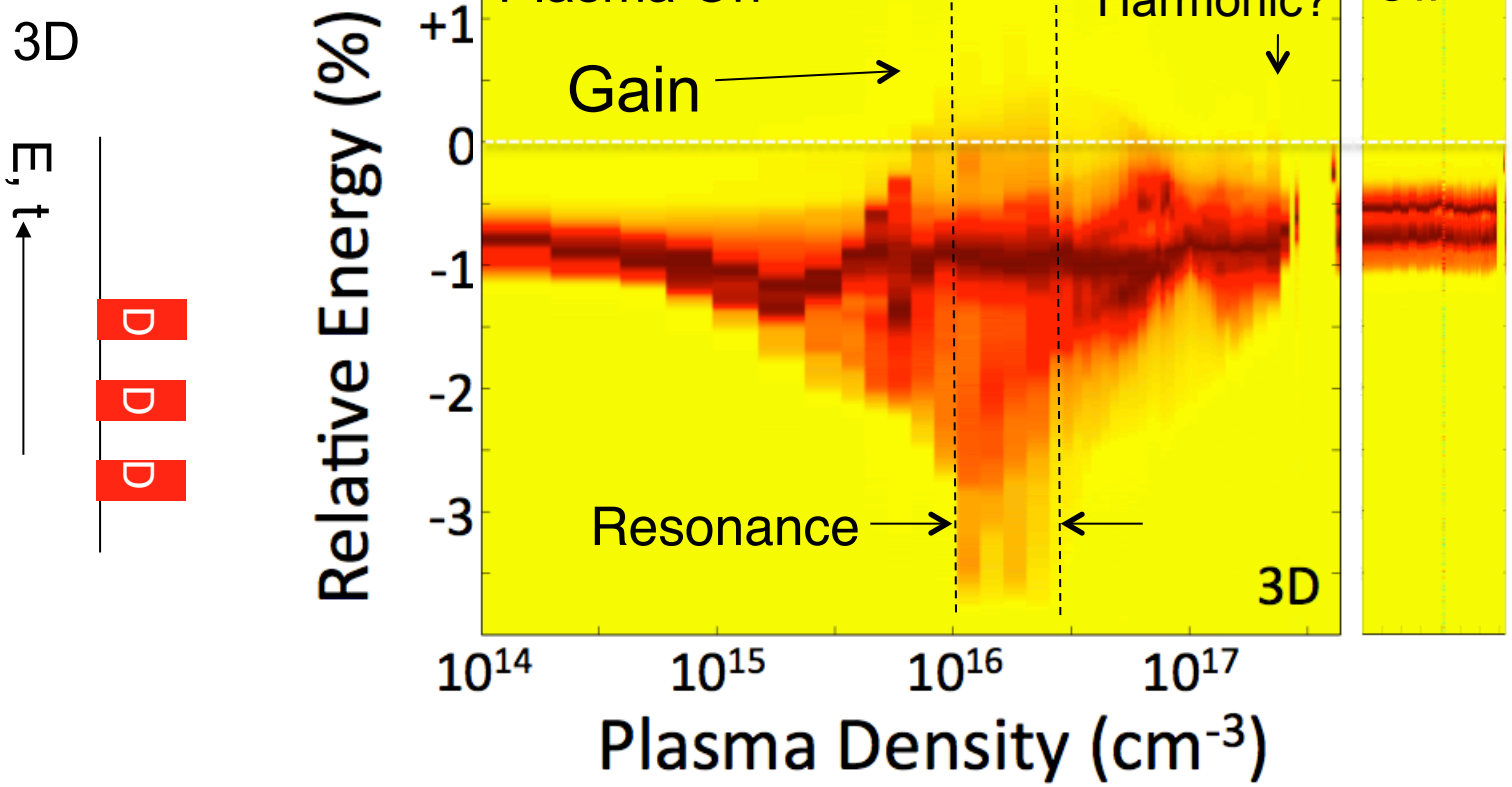
ENERGY CHANGE



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

ENERGY CHANGE



- Resonance clearly observed
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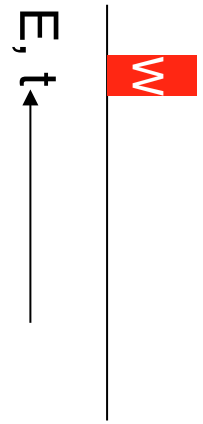
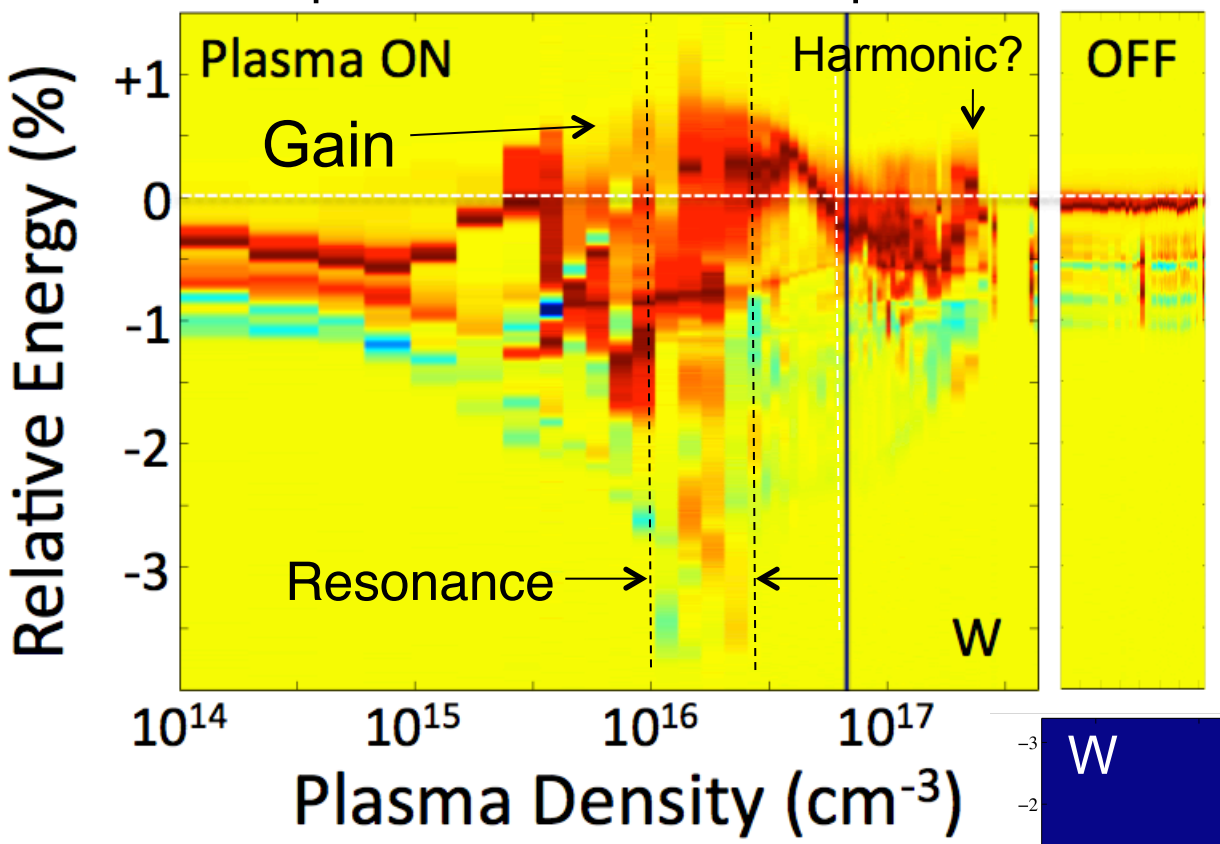
ENERGY CHANGE

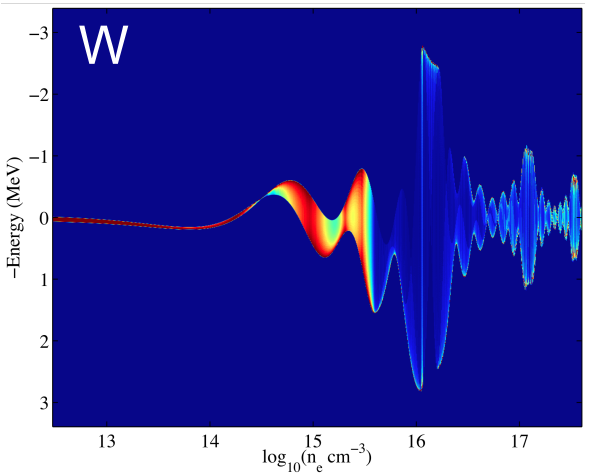
3D+W
-3D
= W



Experiment: normalized spectra



+: red
-: blue-green



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- Large energy loss, ~1.95 MeV or ~97MeV/m (over 2cm)
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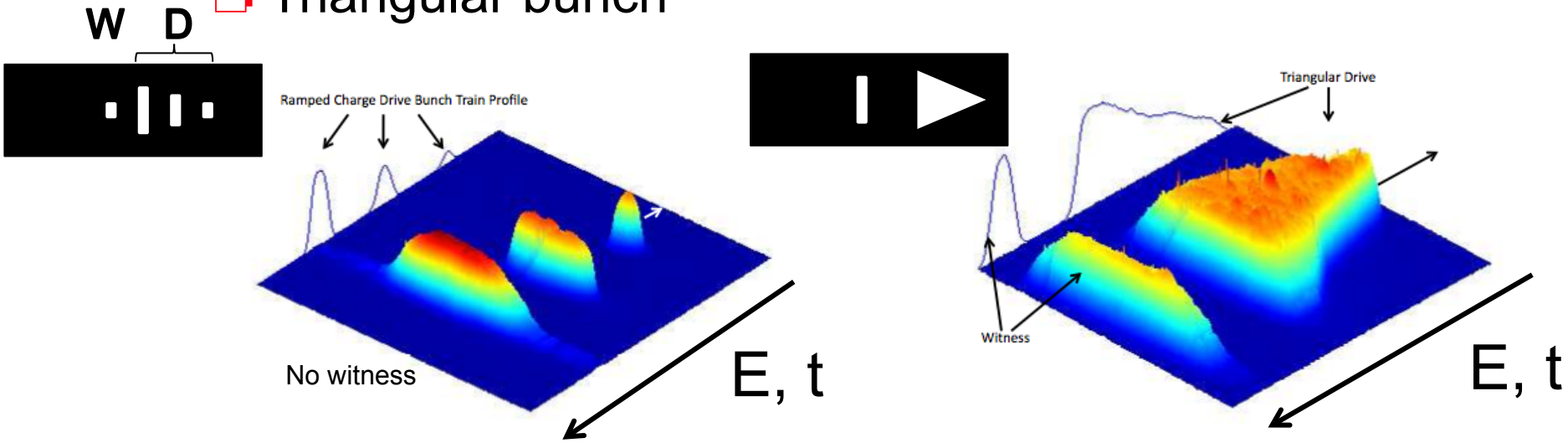
Other Low Energy Experiments

- Large transformer ratio PWFA
  - Ramped bunch train
  - Triangular bunch



- Application to dielectric loaded accelerator (DLA)
- Access to nonlinear regime with tight focusing
- Access to beam current filamentation instability with relevance to plasma physics, astrophysics, ICF

PROTON-DRIVEN PWFA @ CERN

- A SPS, 450GeV bunch with $10^{11}p^+$ caries 7.2kJ
  A LHC, 7TeV bunch with $10^{11}p^+$ caries 11.2kJ
  An ILC, 0.5TeV bunch with $2x10^{10}e^-$ caries 1.6kJ

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

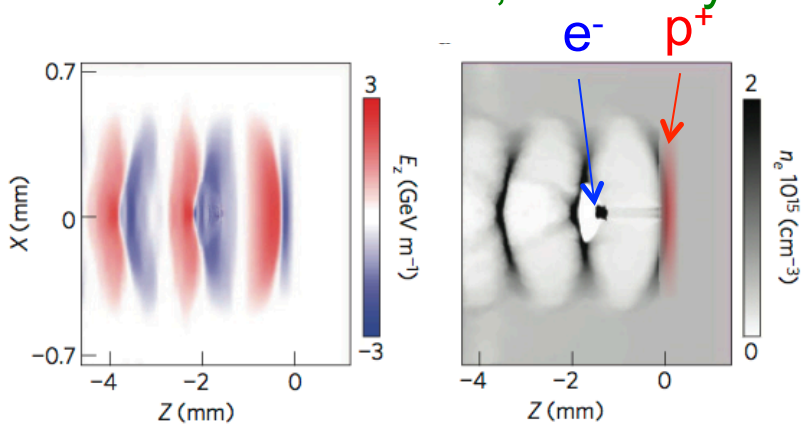
- These p^+ are not very relativistic => dephasing

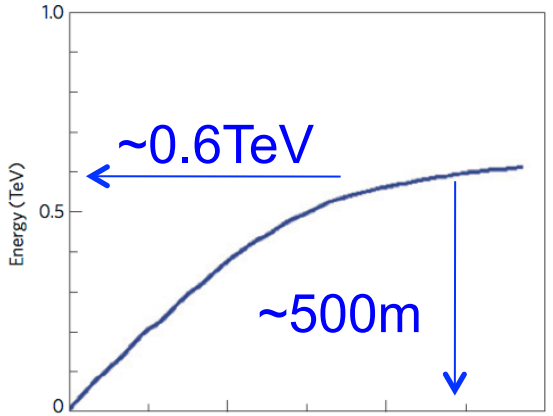
- Long plasmas may be required (~100's m)

- Short (~100μm) bunches do not exist!

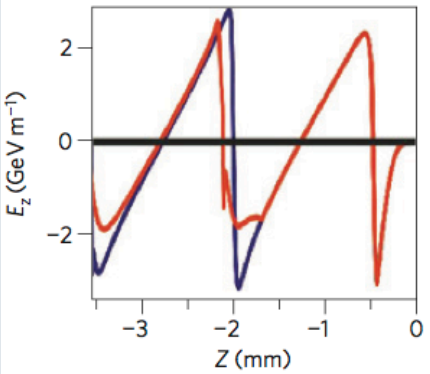
PROTON-DRIVEN PWFA @ CERN

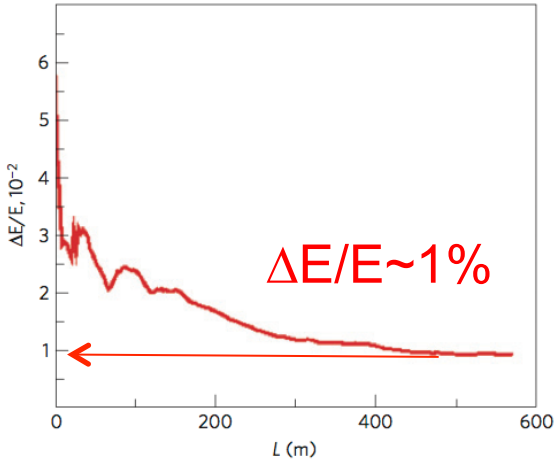
Caldwell, Nat. Phys. 5, 363, (2009)





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, efficiency ~ 10%
- ILC-like e^- bunch from a single p^+-driven PWFA

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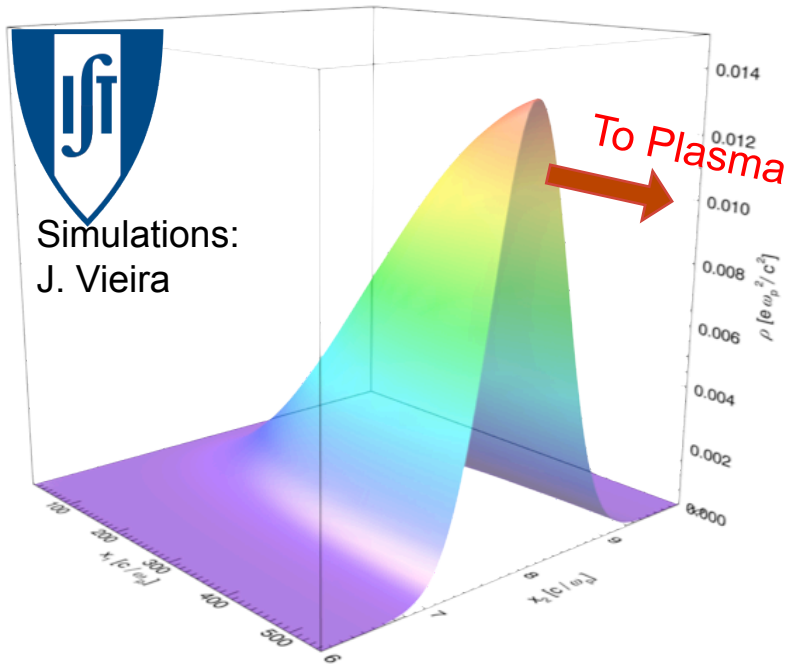
- Short p+ bunches not available
  => self modulation of long (~12cm~100λ_{pe}), 450GeV SPS bunch

Proton bunch	Electron bunch
$\sigma_{\|}$ = 12 cm $\sigma_{\perp}$ = 200 μm n_b/n_0 = 0.00217 (linear PWFA) γ = 479.6 N = 11.5x10^{10} (30.0x10^{10})	$\sigma_{\|}$ = 100 mm $\sigma_{\perp}$ = 200 μm n_b/n_0 = 1.32x10^{-7} γ = 20 (10 MeV)
Plasma	**Box**
n_0 = 7x10^{14} cm^{-3} λ_p = 1.2 mm ~ $\sigma_{\|}$ /100 Uniform density Immobile ions Length = up to15 meters	$n_{\perp}$ = 425 cells $n_{\|}$ = 18000 cells 4 particles per cell quadratic splines



- Simulations assume seeding of the instability (cut p$^+$ bunch, short laser pulse, e$^-$ bunch, …)

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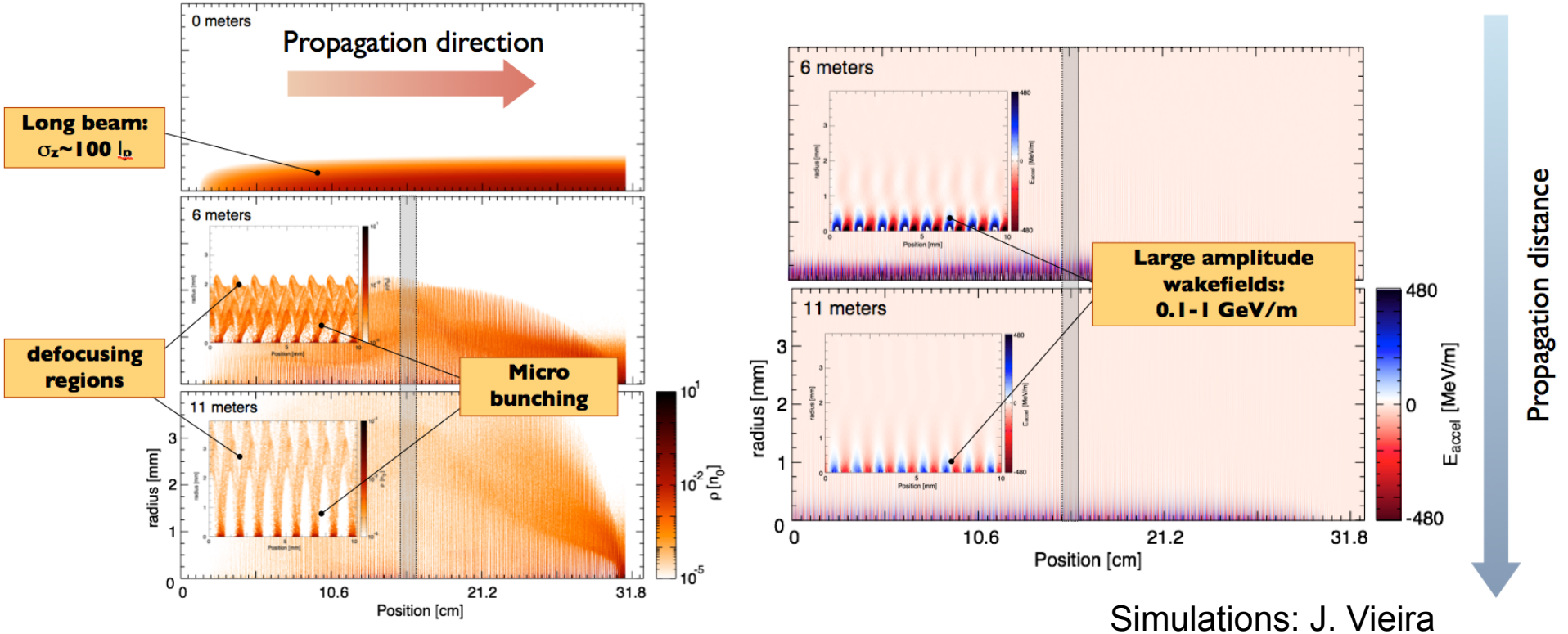
- Transverse two-stream instability
  => self modulation of long (~12cm), 450GeV SPS bunch @λ_p

N. Kumar et al., Phys. Rev. Lett. 104, 255003 (2010).



Simulations: J. Vieira

- Drives large amplitude (0.1-1GV/m) accelerating fields
- E_z (acceleration) sampled by injecting (~10MeV) e^- bunch

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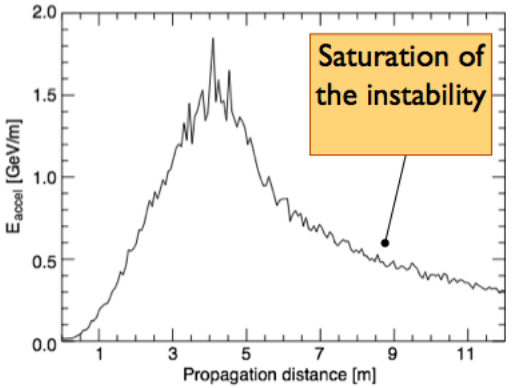
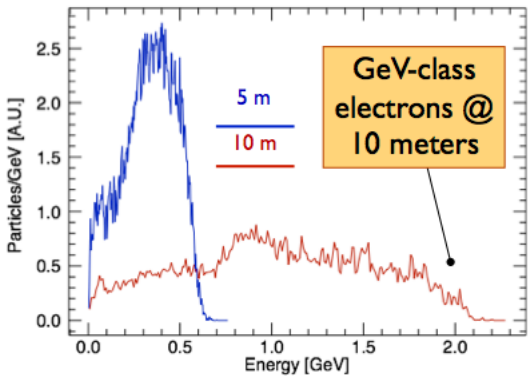
- Self modulation of long (~12cm), 450GeV SPS bunch

Maximum accelerating gradients



- Maximum fields achieved at 5 m of propagation
- GeV/m wakefields can be excited
- Wake phase velocity on the order of driver velocity (large dephasing lengths)

Test electron beam spectra



- Acceleration of external electrons to high energies
- High energies can be achieved (large dephasing lengths)

- Growth of instability / p^+ density modulation / E_z
- Injected e^- gain ~1GeV in 5-10m plasma
- Injected of short e^- bunch would produce narrow $\Delta E/E$

Simulations: J. Vieira

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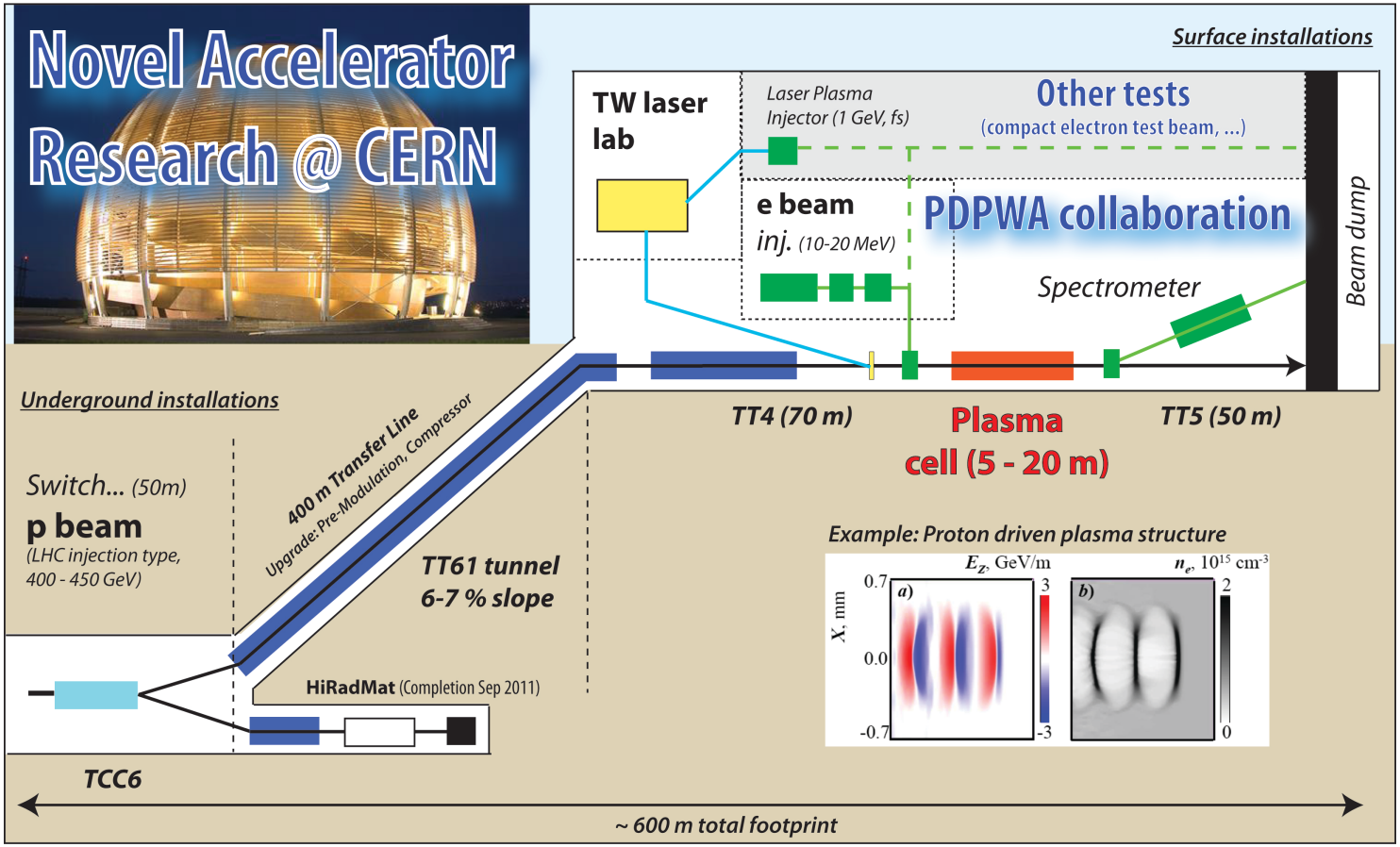

- Letter of intent submitted to CERN for self-modulated p^+-driven PWFA experiments
- Experiments 2015-… for 1GeV in 1m
- Program for TeV class e- from p^+-driven PWFA, driven by MPP

Summary and Conclusions

- PWFA made remarkable progress
  - 42GeV energy gain in 85cm of plasma
- Low energy experiments study PWFA physics
- PWFA is well understood
- Many more results: multi-GeV trapped e^-, emittance, …
- FACET@SLAC will address PWFA collider issues
  - Acceleration of witness bunch ($\Delta E/E_0$~1%)
  - e^+ …
  - Single, e^-/e^+, +25 GeV PWFA stage
- Proton-driven PWFA to be proposed to CERN, PWFA at DESY and in Japan, about to start at INFN, DESY-Zeuthen, …
- PWFA is a possible technology candidate for future more compact (cheaper) collider and light sources
- Watch for laser-driven plasma-based accelerators (LWFA)

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Thank you!

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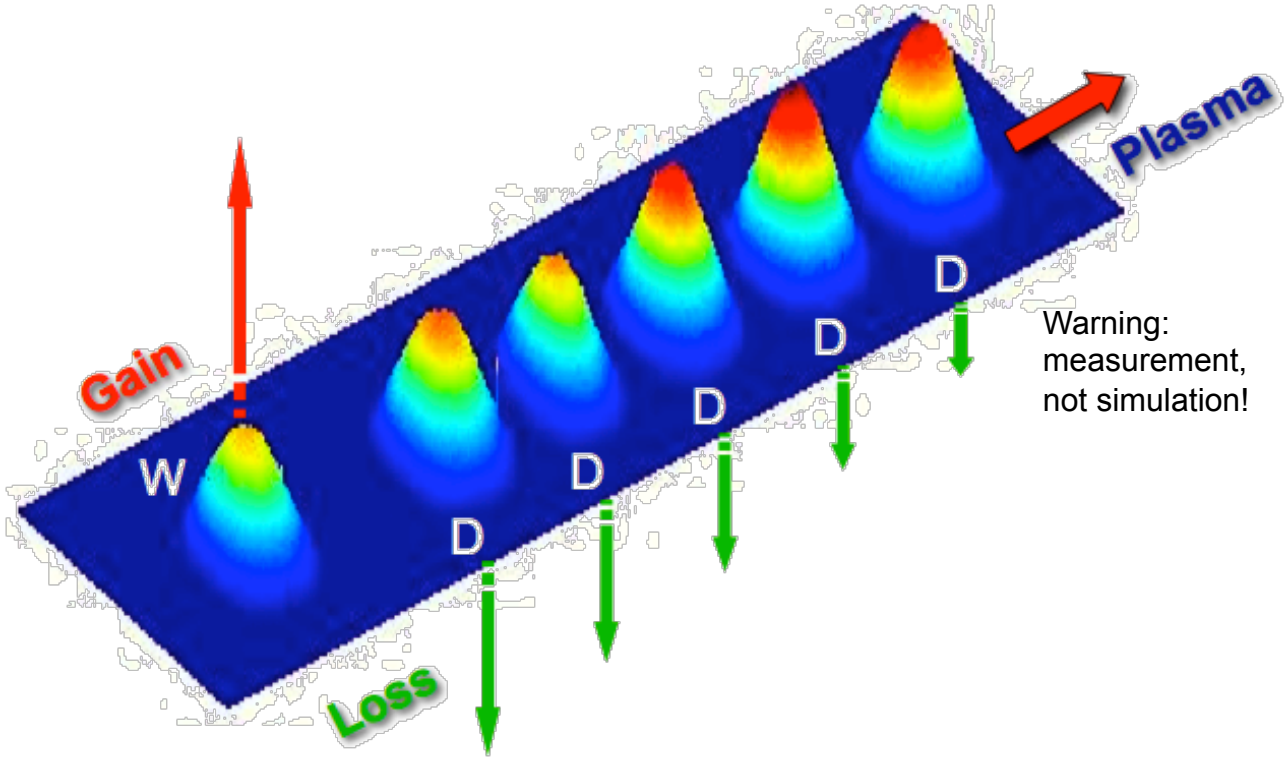
Thank You!



Warning:
measurement,
not simulation!

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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