Plasma Wakefield Acceleration Experiments at ATF

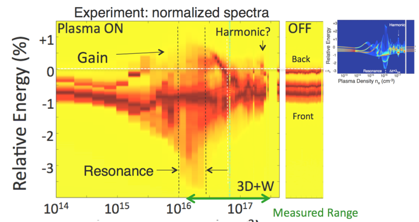
Patric Muggli
Max Planck Institute for Physics, Munich
muggli@mpp.mpg.de
B. Allen, Y. Fang
University of Southern California, Los Angeles CA 90089, USA

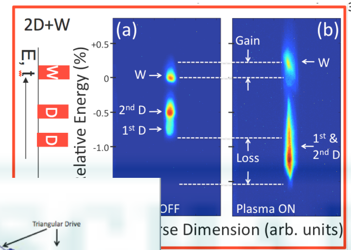
V. Yakimenko, M. Fedurin, K. Kusche, M. Babzien, C. Swinson, R. Malone
Brookhaven National Laboratory, Upton, NY 11973, USA

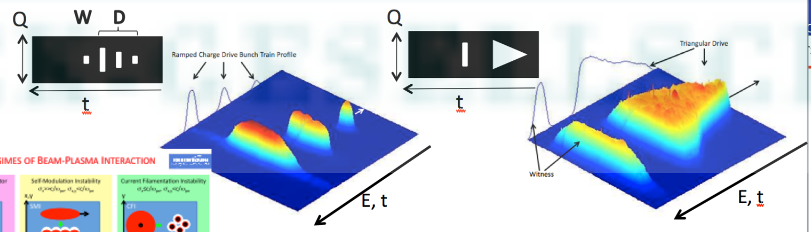
Work supported by US Dept. of Energy and NSF

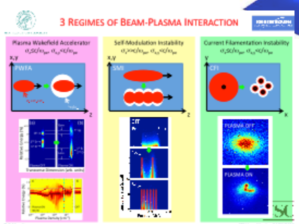
OUTLINE

- Multi-bunch, resonant PWFA results
- Shaped bunch for large transformer ratio (R) PWFA, access to weakly nonlinear PWFA regime (simulations)
- Plans for imaging of PWFA plasma density perturbation (FDH)
- Cool stuff at ATF
- Summary









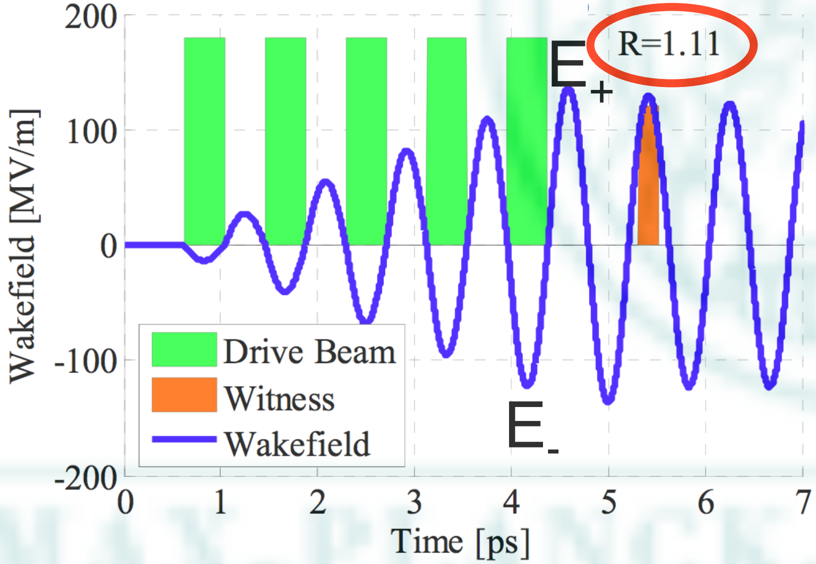
MULTIBUNCH PWFA

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

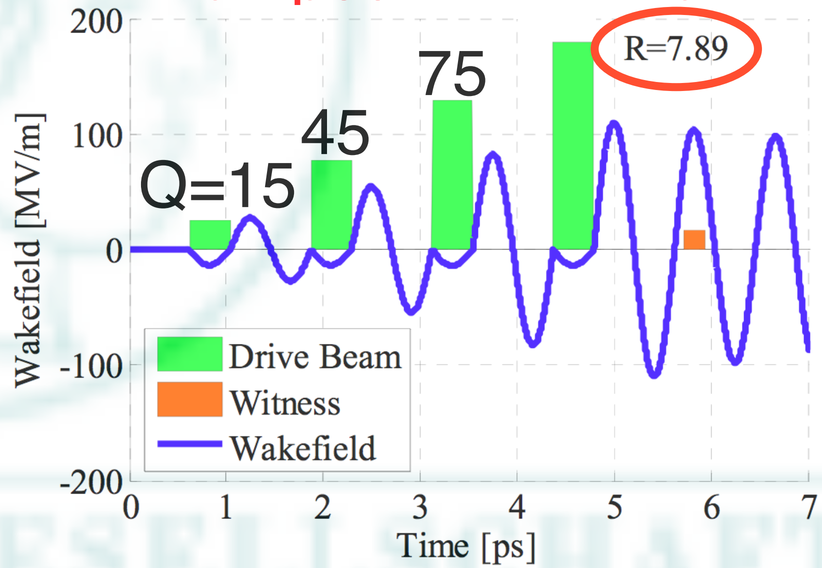
Bunch Train



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)

Demonstrated in GHz DLA in Jing, PRL 98, 144801 (2007), 2D+W

MULTIBUNCH PWFA

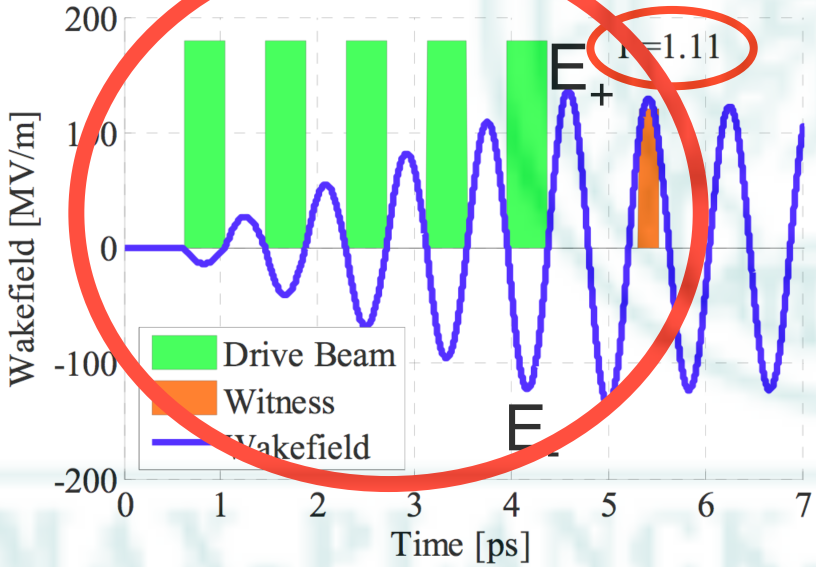
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

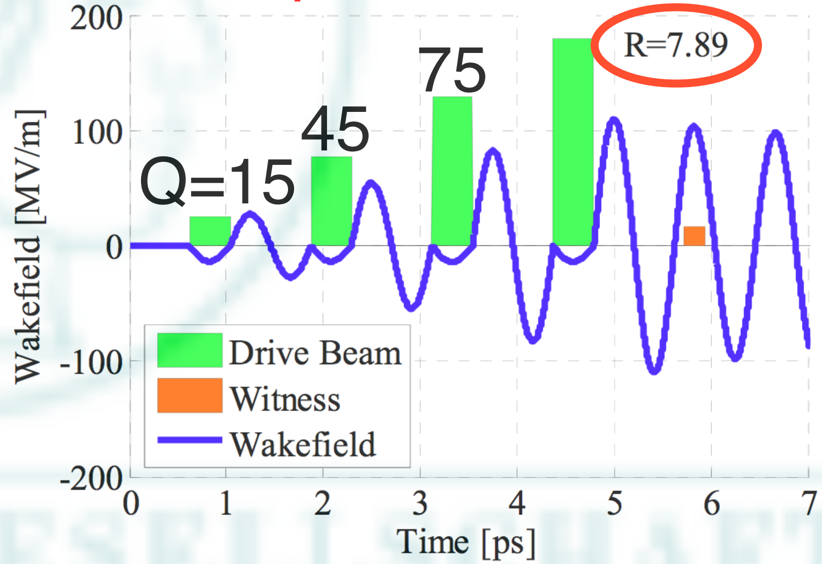
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*

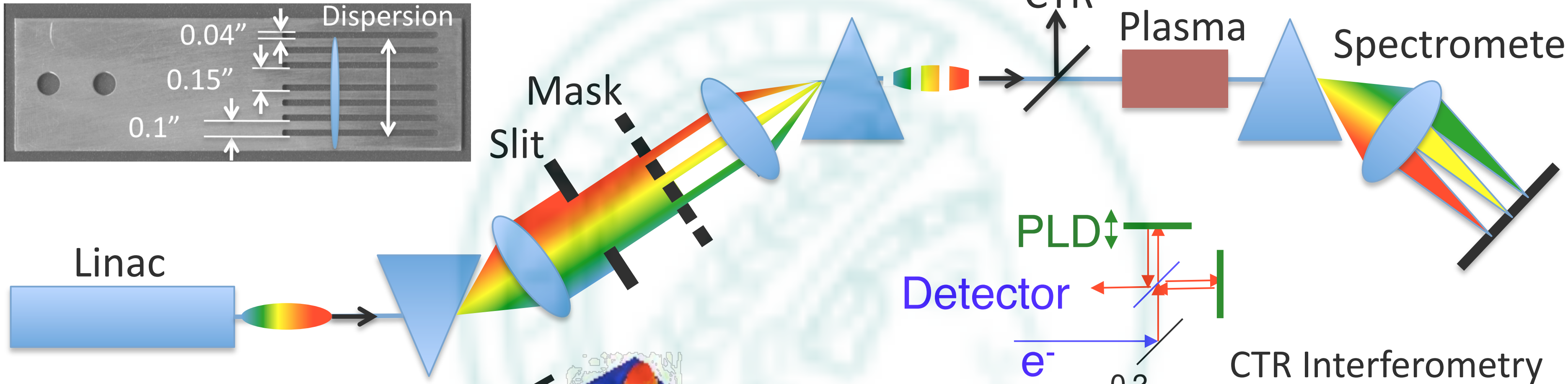


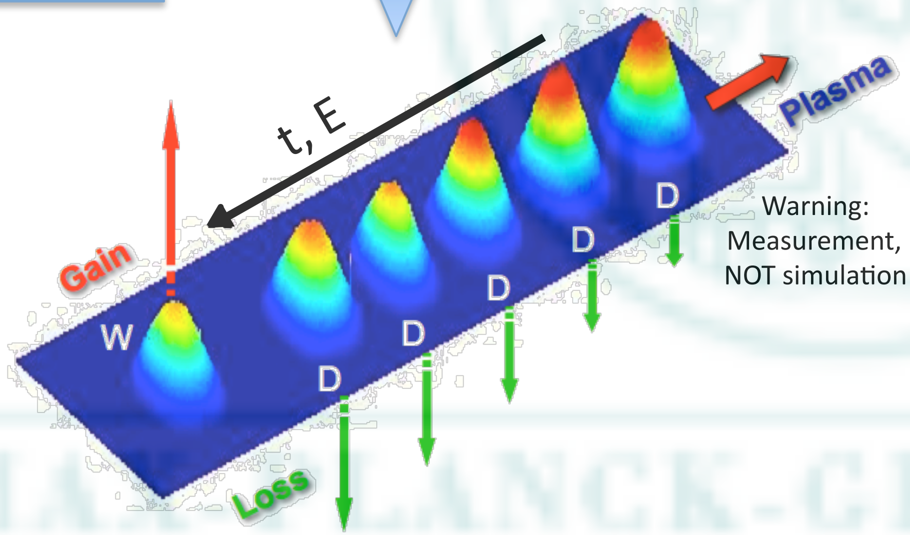
*Tsakanov, NIMA, 1999

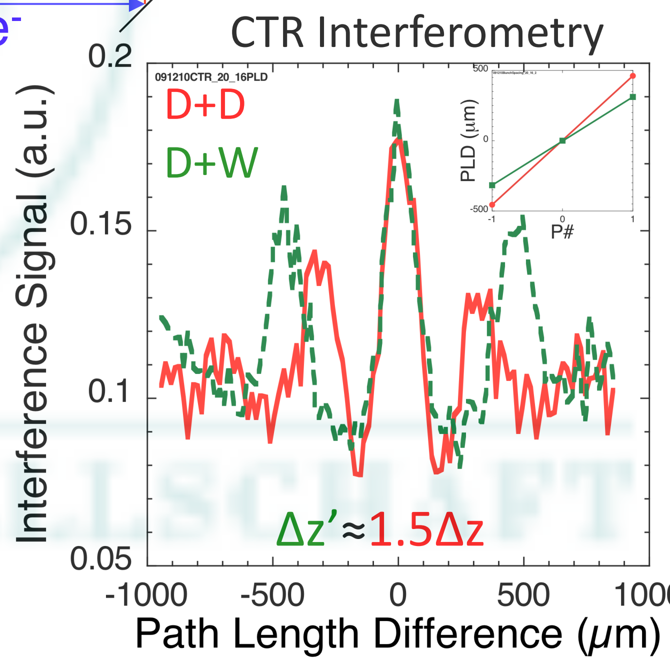
- Resonant excitation of wakefields
- Large transformer ratio and energy gain (>2)

MULTIBUNCH SOURCE-MASKING

Muggli, PRL 2008, PRST-AB 2010







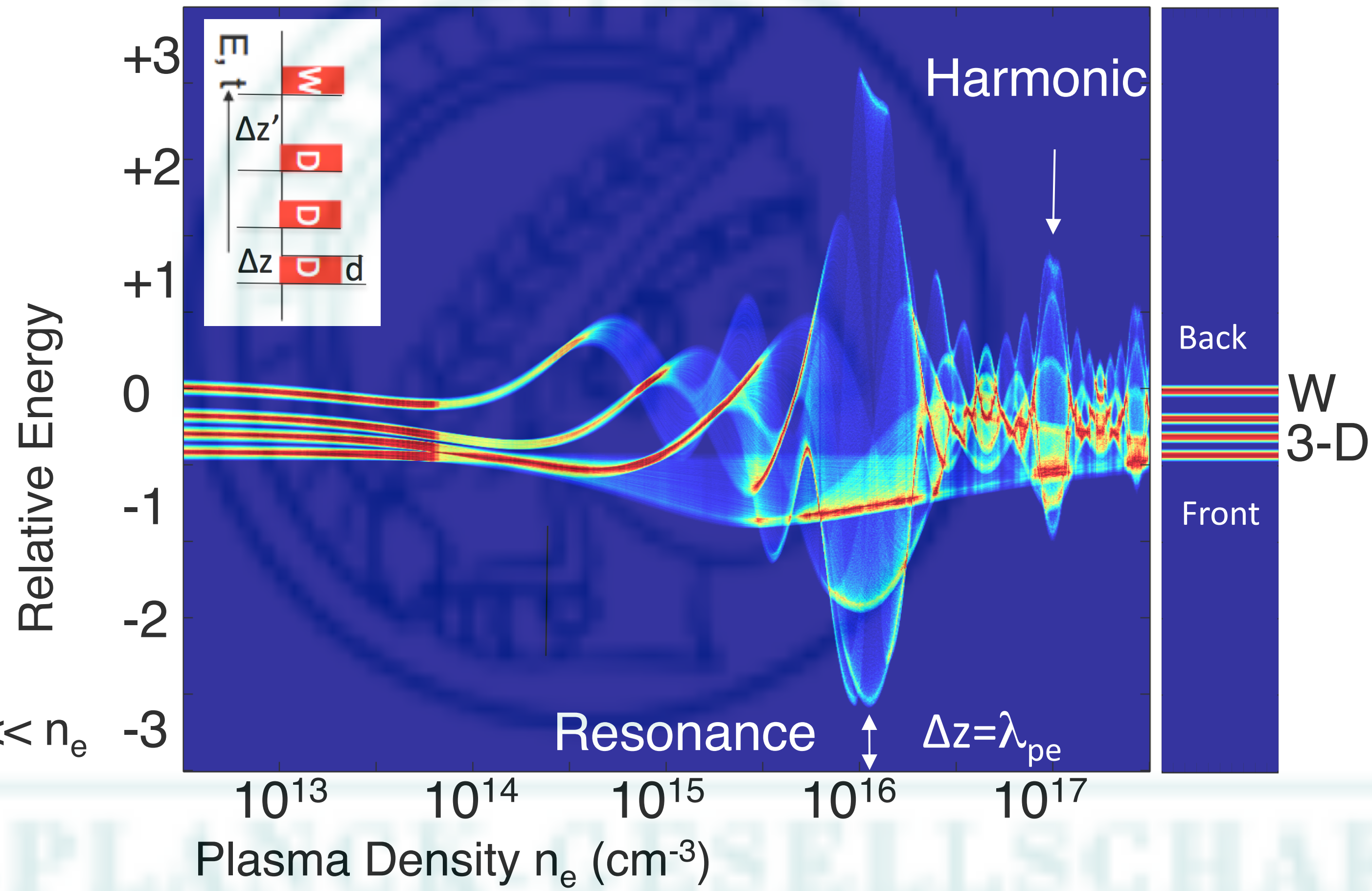
- Choose beam parameters with mask and beam parameters: N, Δz, σ_z, Q
- Same method used D+W bunches at FACET

ENERGY CHANGE

Linear calculation (2D): microbunches with equal charge

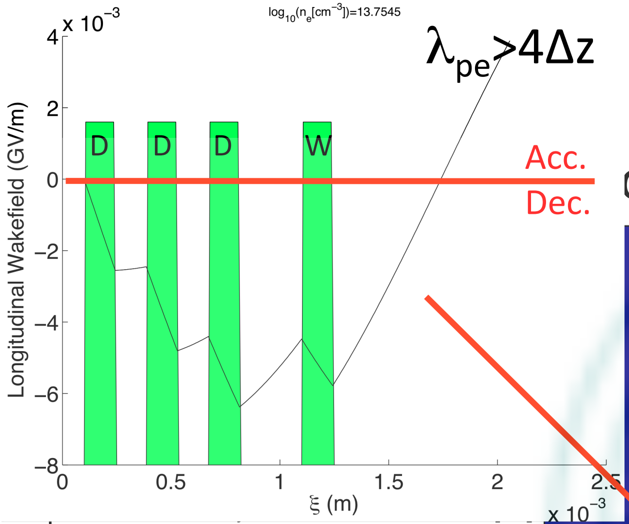
Experimental Parameters:

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
$n_b \approx 4x10^{13} cm^{-3} << n_e$
Linear Regime!

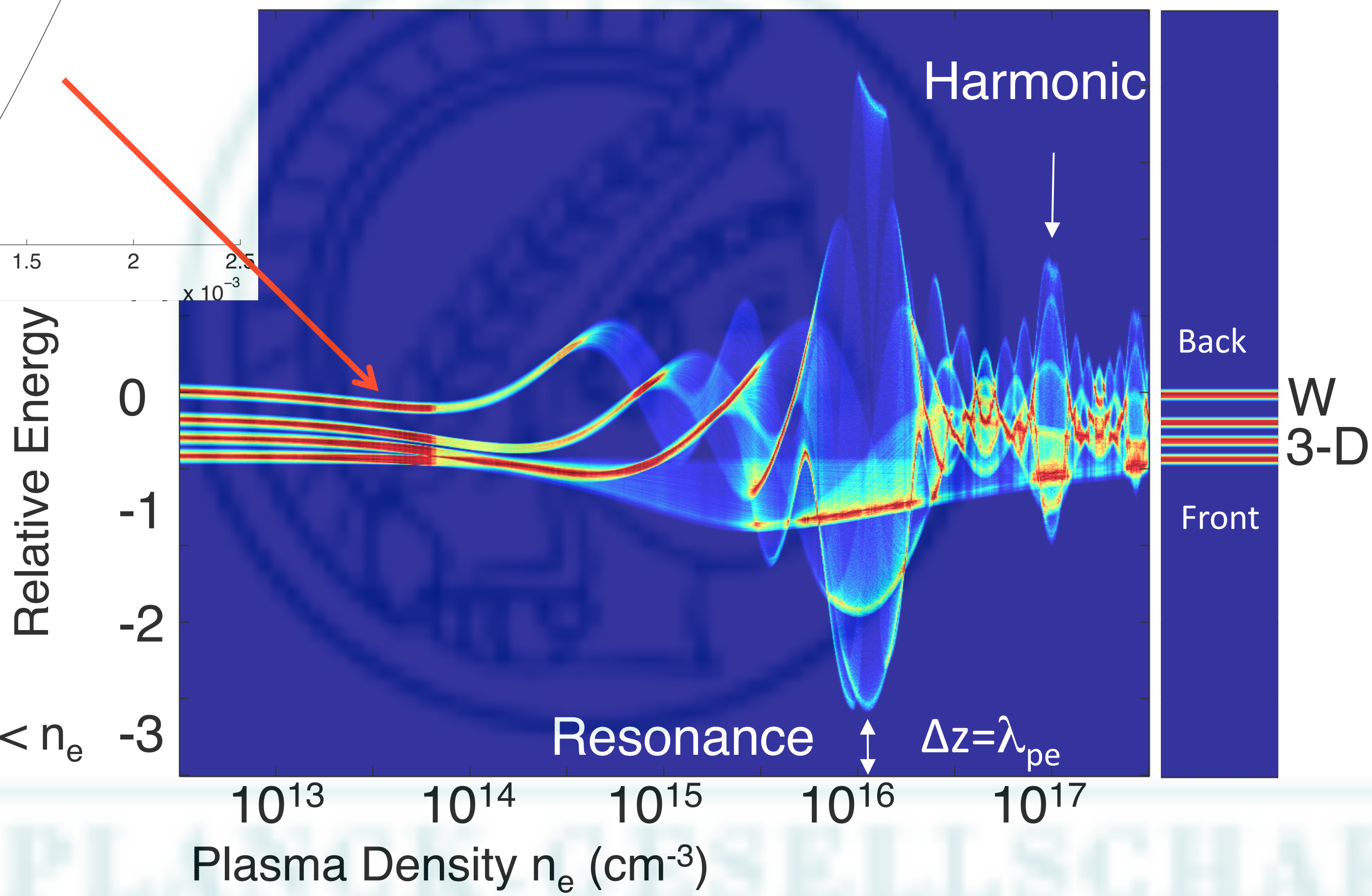


- Resonant excitation of PWFA in the linear regime
- Chirp such that W enters with highest energy
- $n_{e,\ res} \approx 1.4x10^{16}\ cm^{-3} \Leftrightarrow \lambda_{pe} \sim \Delta z$

ENERGY CHANGE



culation (2D): microbunches with equal charge

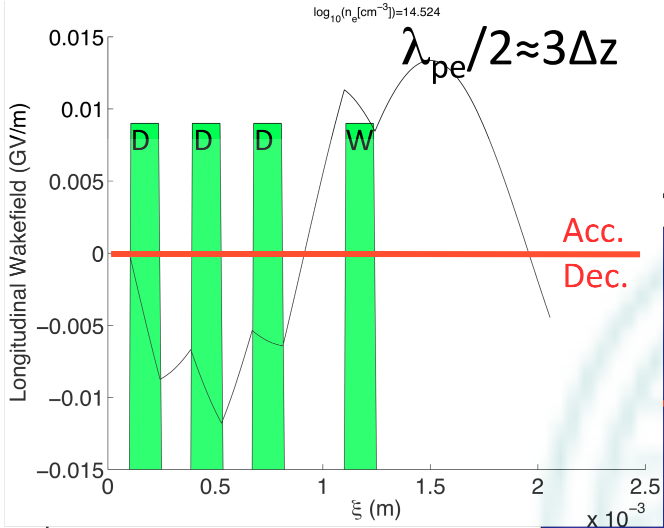


Δz=284 µm,
d=142 µm
$\Delta z'$=426 µm
Q_{tot}=140 pC
N_d=3D+W
Q_b=35 pC
L_p=2 cm
$n_b \approx 4\text{x}10^{13}\text{cm}^{-3} << n_e$
Linear Regime!

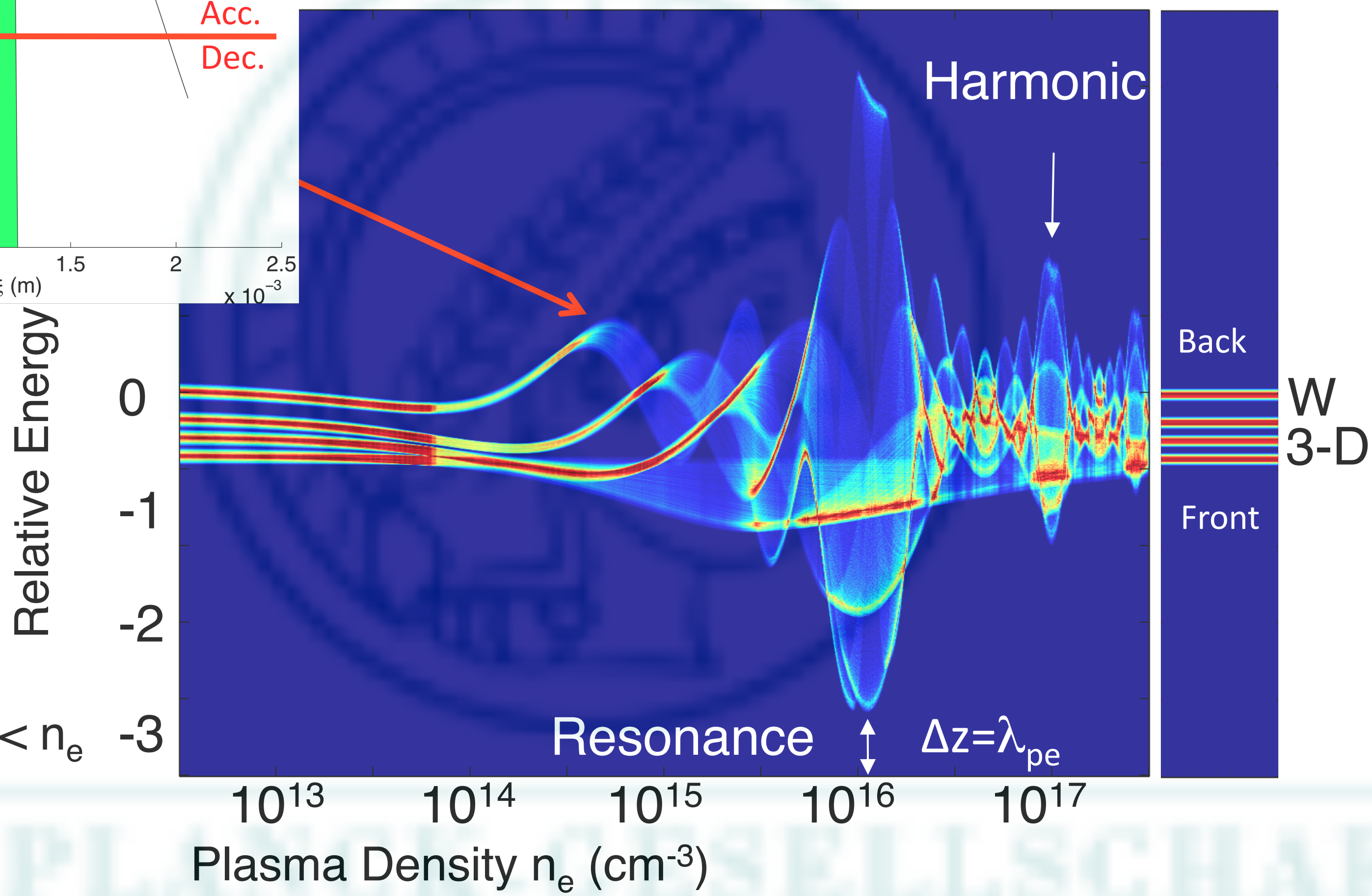
- ➡ Resonant excitation of PWFA in the linear regime
- ➡ Chirp such that W enters with highest energy
- ➡ $n_{e,\,res} \approx 1.4\text{x}10^{16}$ cm^{-3} ⇔ $\lambda_{pe} \sim \Delta z$

ENERGY CHANGE

ılation (2D): microbunches with equal charge

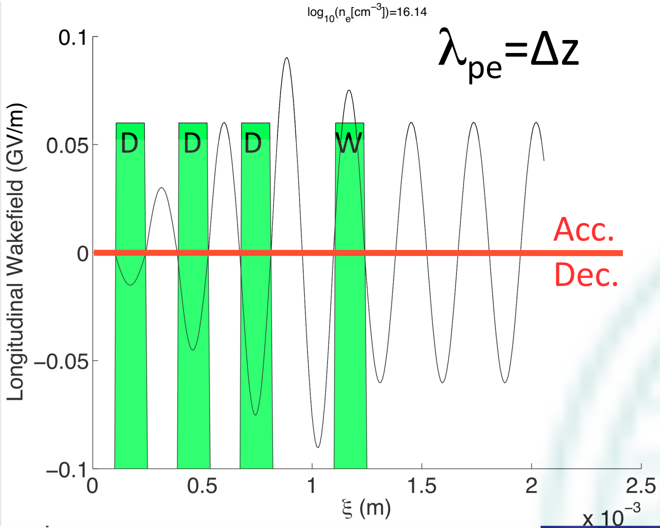


Δz=284 μm,
d=142 μm
$\Delta z'$=426 μm
Q_{tot}=140 pC
N_d=3D+W
Q_b=35 pC
L_p=2 cm
$n_b \approx 4 \times 10^{13}$cm^{-3} << n_e
Linear Regime!

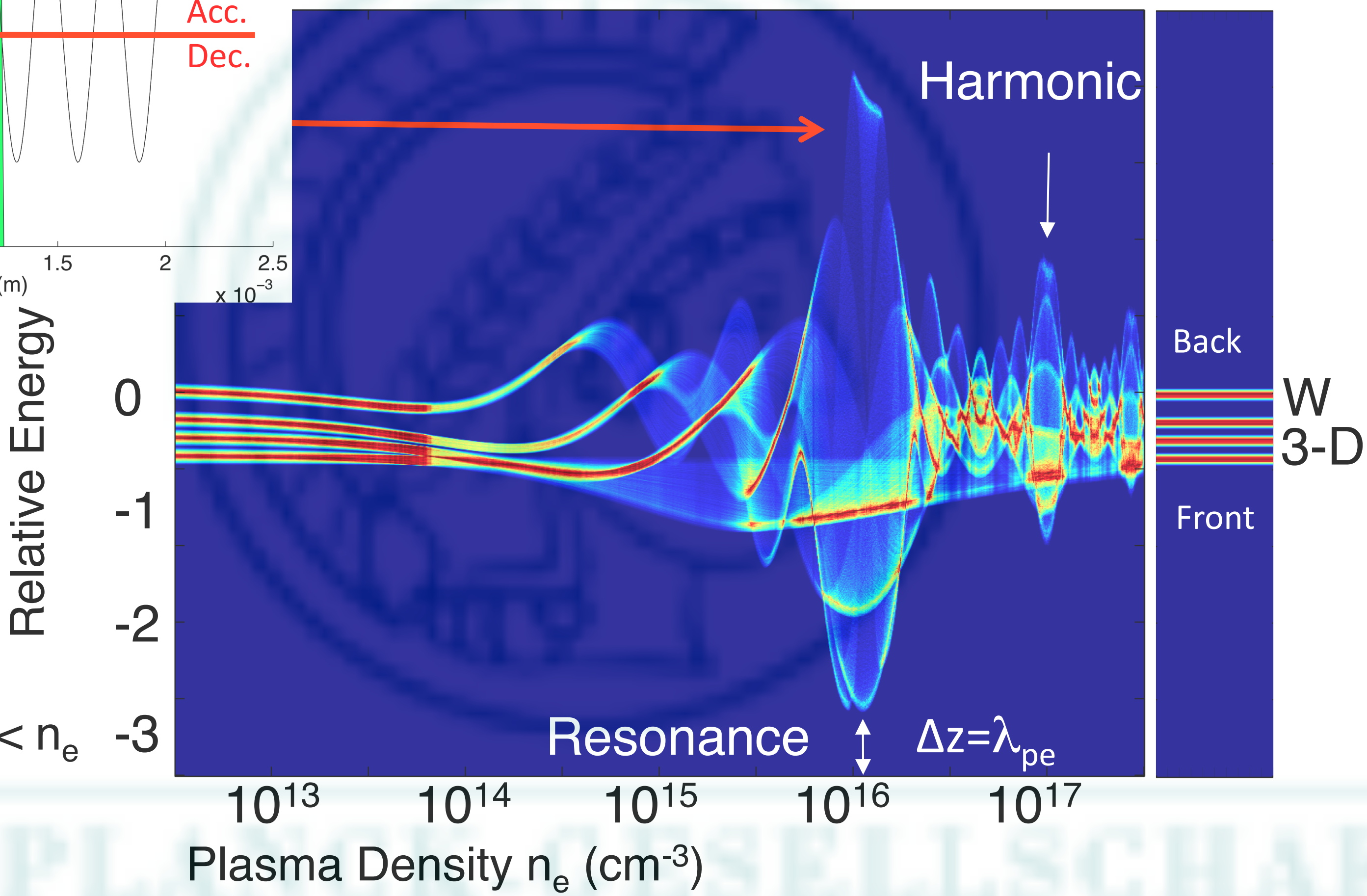


➡ Resonant excitation of PWFA in the linear regime
➡ Chirp such that W enters with highest energy
➡ $n_{e,\ res} \approx 1.4 \times 10^{16}$ cm^{-3} ⇔ $\lambda_{pe} \sim \Delta z$

ENERGY CHANGE



…ulation (2D): microbunches with equal charge

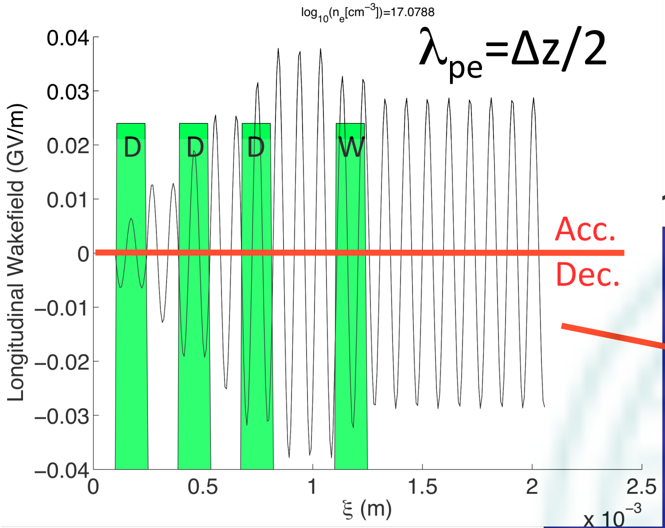


Δz=284 µm,
d=142 µm
$\Delta z'$=426 µm
Q_{tot}=140 pC
N_d=3D+W
Q_b=35 pC
L_p=2 cm
$n_b \approx 4\text{x}10^{13} cm^{-3} << n_e$
Linear Regime!

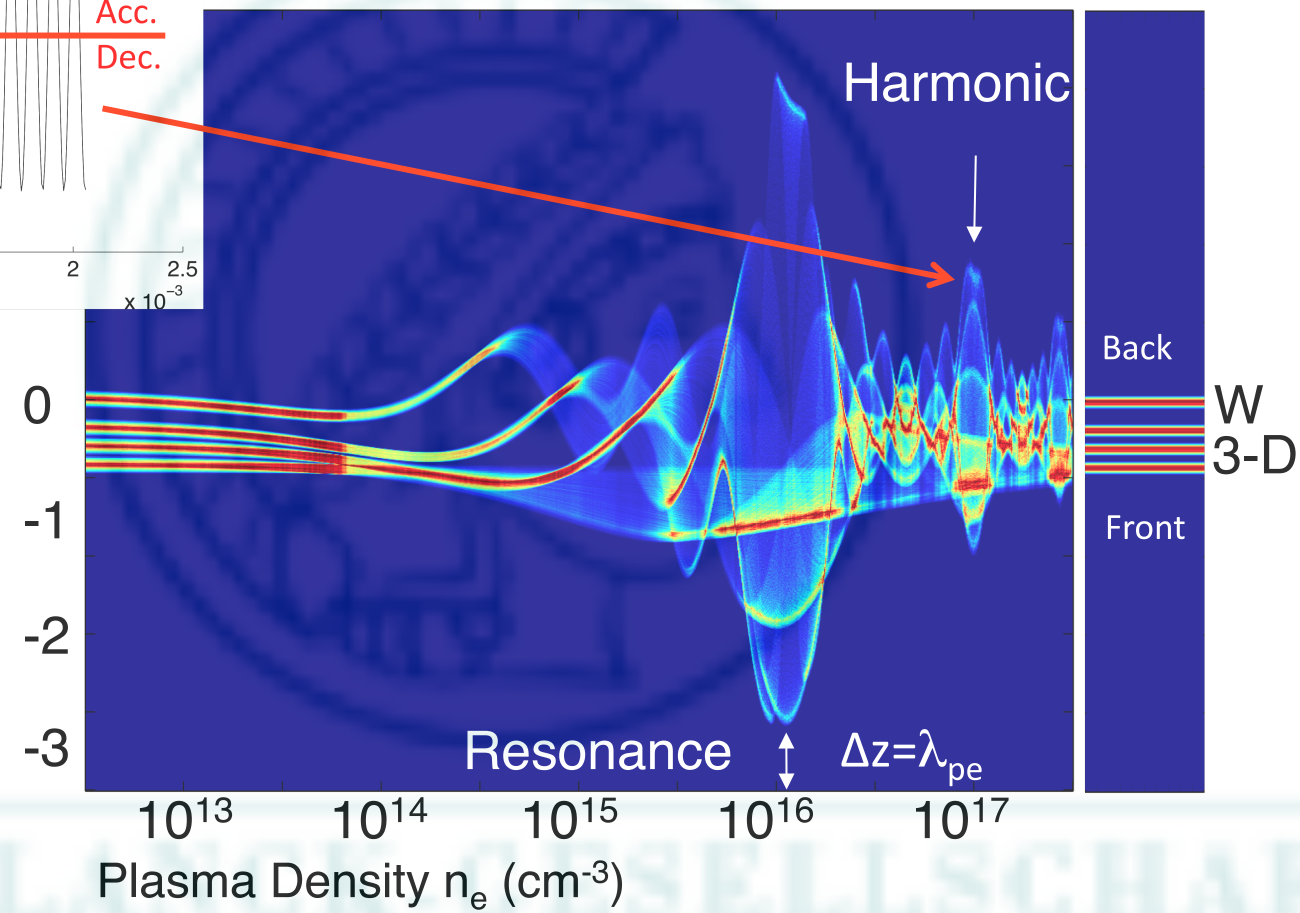
- Resonant excitation of PWFA in the linear regime
- Chirp such that W enters with highest energy
- $n_{e,\,res} \approx 1.4\text{x}10^{16}\ cm^{-3} \Leftrightarrow \lambda_{pe} \sim \Delta z$

ENERGY CHANGE

…lation (2D): microbunches with equal charge



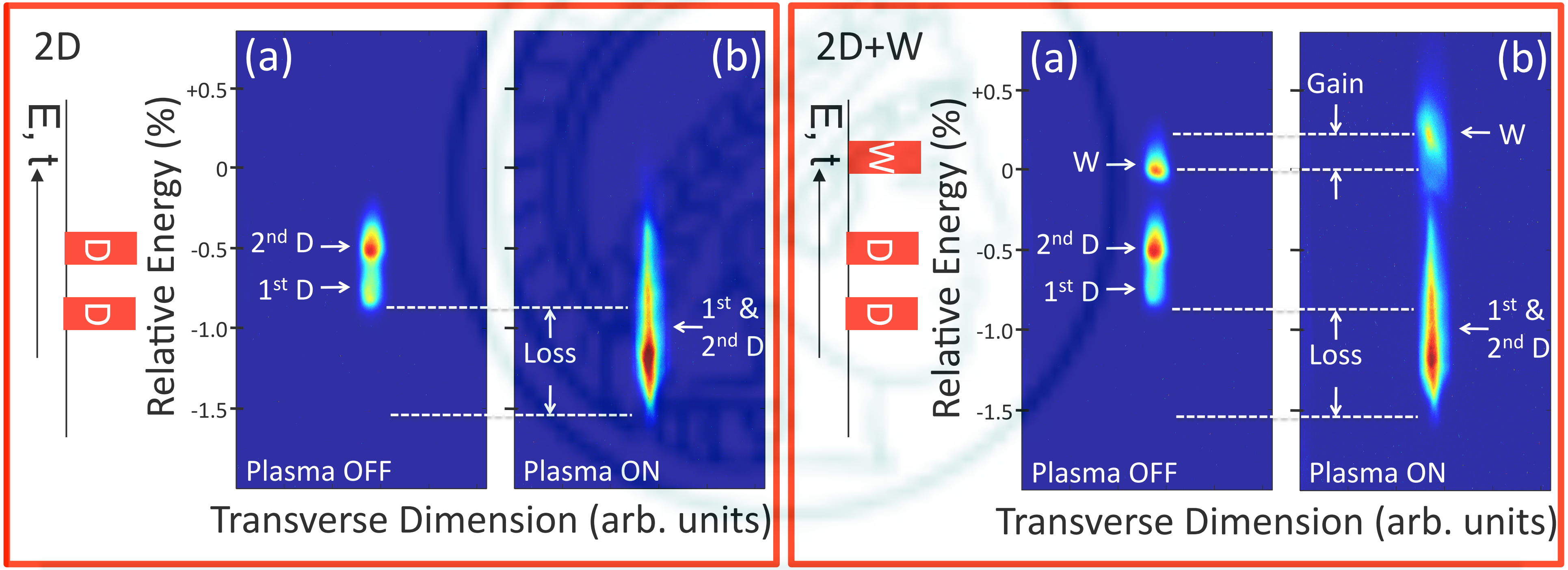
$\Delta z=284\ \mu m$,
$d=142\ \mu m$
$\Delta z'=426\ \mu m$
$Q_{tot}=140$ pC
$N_d=3D+W$
$Q_b=35$ pC
$L_p=2$ cm
$n_b \approx 4\times10^{13} cm^{-3} << n_e$
Linear Regime!



- Resonant excitation of PWFA in the linear regime
- Chirp such that W enters with highest energy
- $n_{e,\,res} \approx 1.4\times10^{16}\ cm^{-3} \Leftrightarrow \lambda_{pe} \sim \Delta z$

WITNESS BUNCH ACCELERATION

Experiment: $n_e \approx 8 \times 10^{15}$ cm^{-3}



Muggli, Proc. PAC 2011

- Acceleration of witness bunch (also with 3D+W)
- Large energy loss, ~0.42MeV or ~21MeV/m (over 2cm)
- Energy gain, 0.12MeV or ~6MeV/m

Low R!!

n_e variation?

MULTIBUNCH PWFA

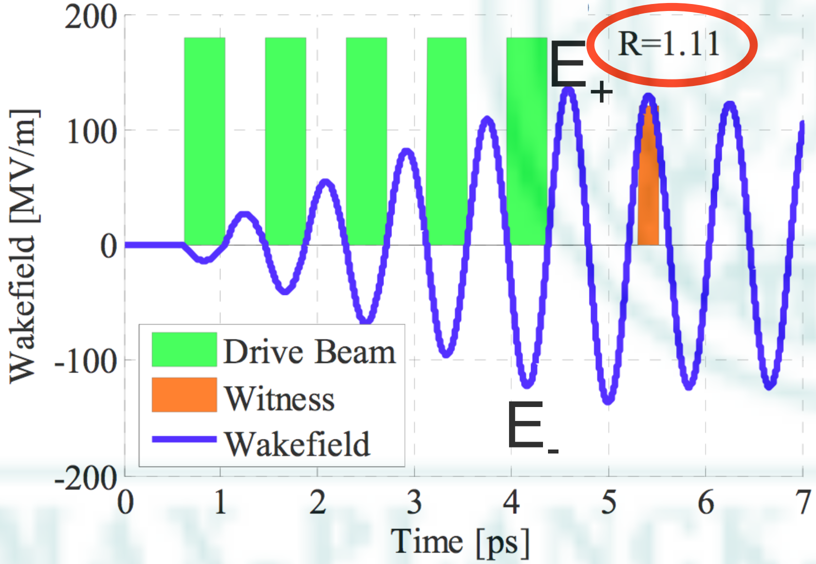
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

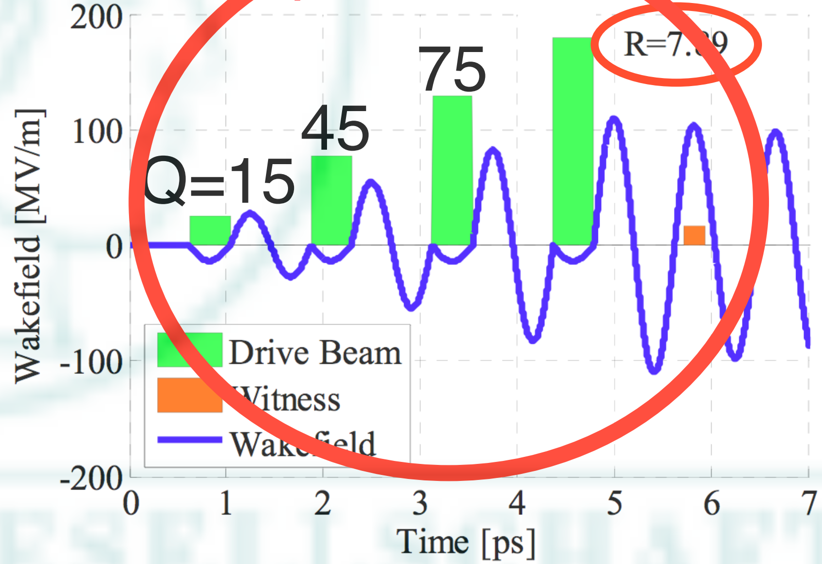
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



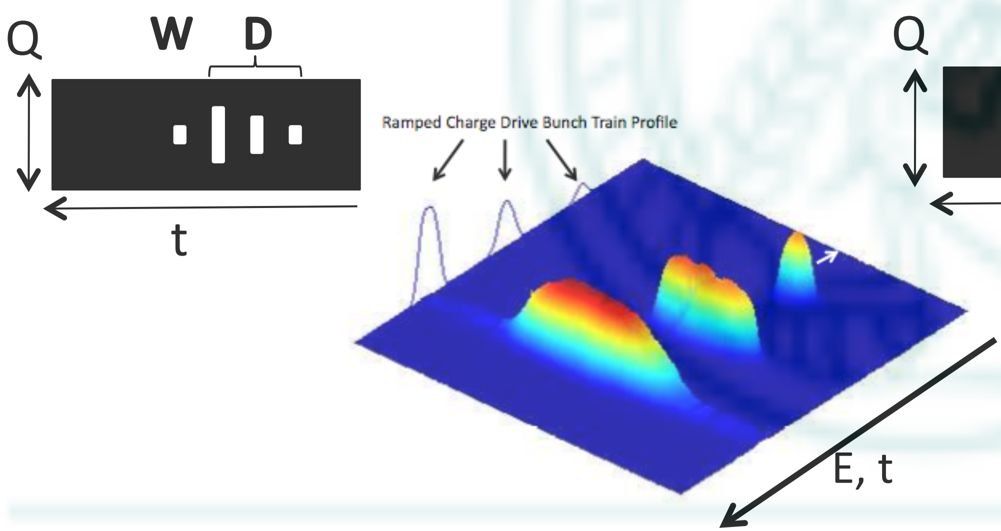
*Tsakanov, NIMA, 1999

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

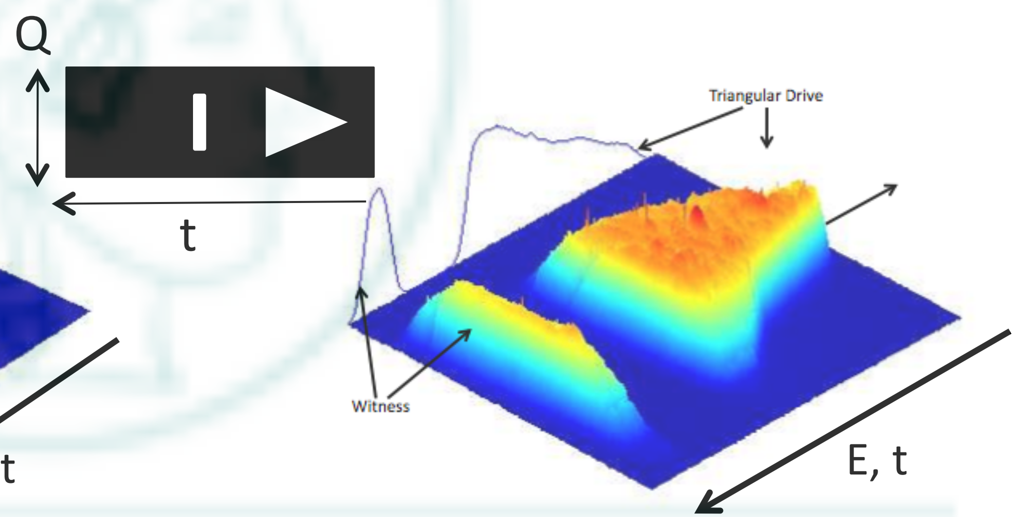
CURRENT-SHAPED BUNCHES

- Mask technique to tailor both time and charge/current structure

- Ramped bunch train



- Triangular bunch

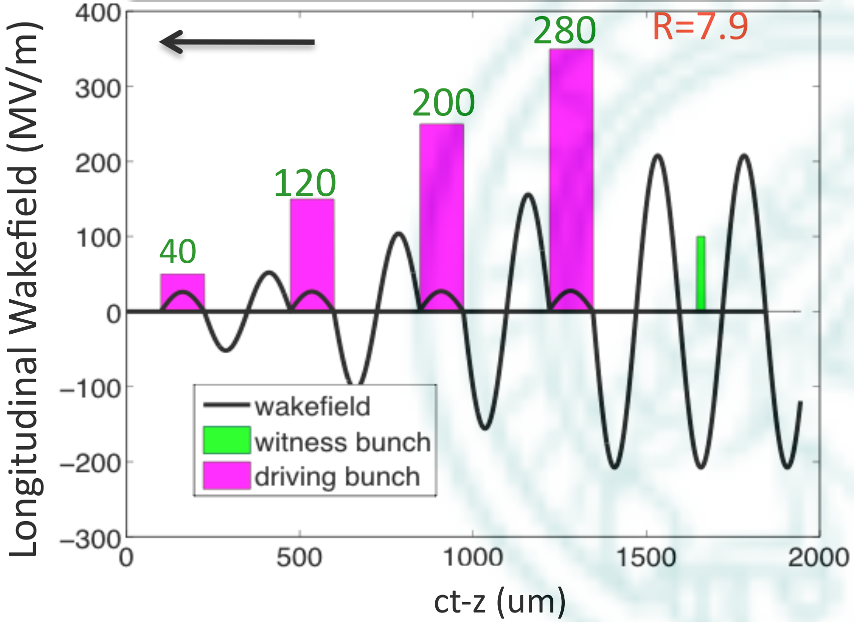


- Wakefields amplitude also depends on σ_r!

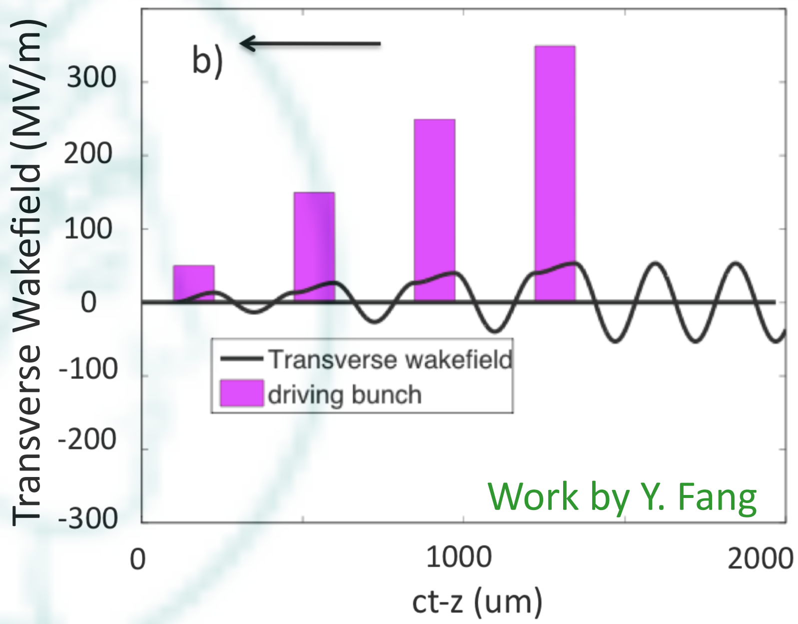
- Shaped bunch for large R PWFA and seeding of SMI

LINEAR REGIME

Longitudinal Wakefield



Transverse Wakefield



✧Same decelerating wakefields, but different focusing fields

✧Density ratio (1:3:5:7) not maintained during propagation for "large" energy gain, i.e., long propagation (all same σ_r)

Weakly Nonlinear Regime

Fields add

Blowout -> same focusing field $E_r \sim r$

-> E_z weakly dependent on σ_r

Rosenzweig, AIP Conf. Proc. 1299, 2011

Y. Fang, PAC2011 Proc., 391

Best of both lin. and nonlin.!

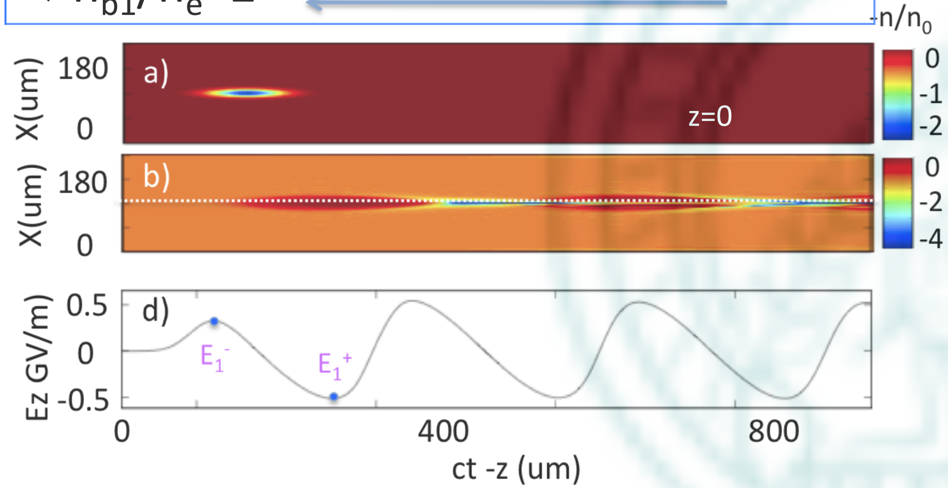
ACCESS WEAKLY NONLINEAR REGIME

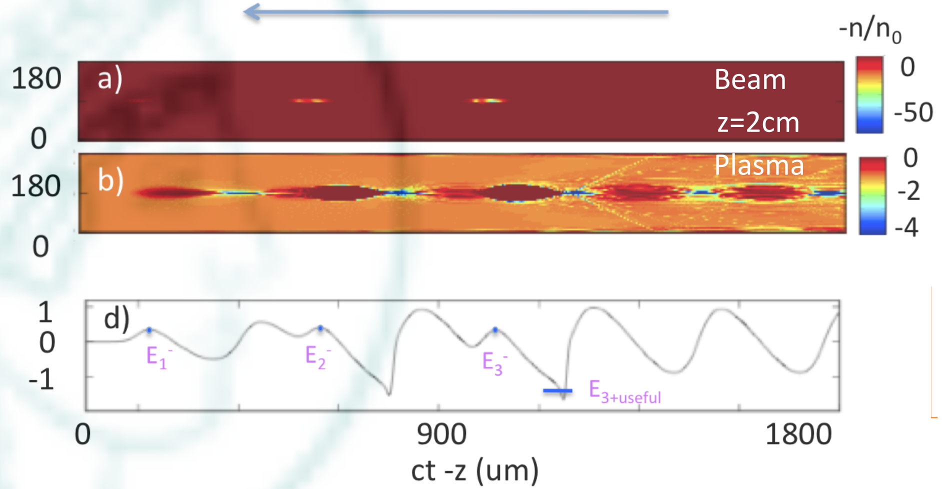
MAX-PLANCK-GESELLSCHAFT

BROOKHAVEN NATIONAL LABORATORY

- Q_1=50pC, σ_z=25µm, σ_r=5µm
- $n_{b1}=2.5\times10^{16}cm^{-3}$, $n_e=1.24\times10^{16}cm^{-3}$
- n_{b1}/n_e~2

- $Q_1:Q_2:Q_3$=1:2.6:3.8 *vs.* 1:2.5:3.3, lin. theo.
- $\Delta\xi=1.3\lambda_{pe}$ *vs.* $1.5\lambda_{pe}$, lin. theo.





- Blow-out ➡ weakly nonlinear
- $R_1=E_1^+/E_1^-$=**1.52** (R_1=2, square bunch)

Y. Fang, PAC2011 Proc., 391

- $R_3=E_{3+useful}/E_{3-}\approx$**4.2** (z=0) ➡ **4.0** (z=2cm)
- R almost constant!

E_1^-=0.38 GV/m
E_2^-=0.43GV/m
E_3^-=0.35GV/m
$E_{3useful}^+$=1.61GV/m

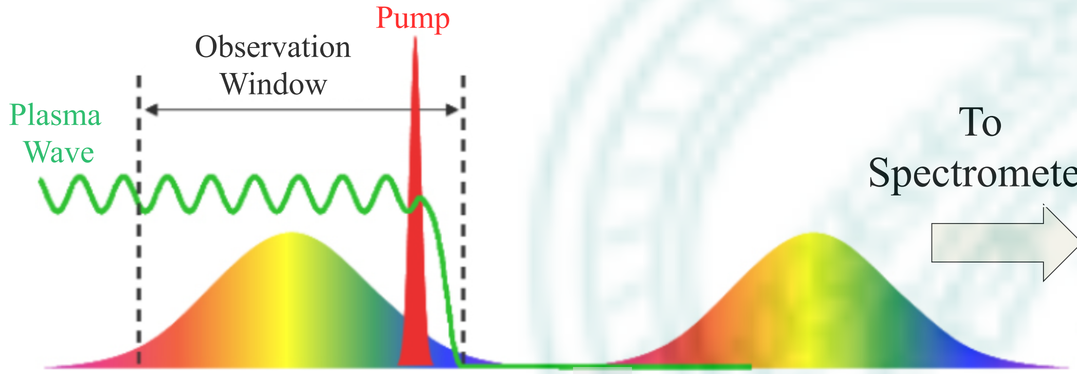
+32MeV over 2cm!

- ➡ Access QNL or weakly nonlinear regime at ATF
- ➡ Reach R>2 with 3 bunches, maintained over 2cm
- ➡ Must explore collider beam parameters
- ➡ Experiments planned with J. Rosenzweig's group

Work by Y. Fang

USC

FDH – Frequency Domain Holography

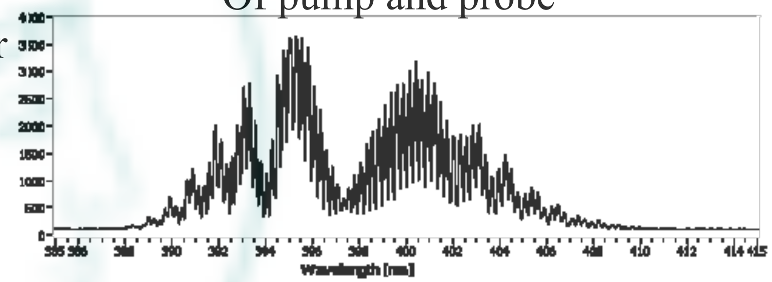


Chirped Probe
captures snapshot of
several plasma wavelengths

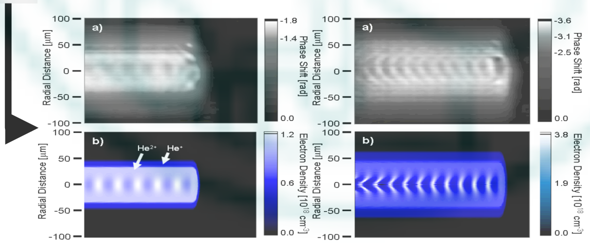
Chirped Reference

To Spectrometer

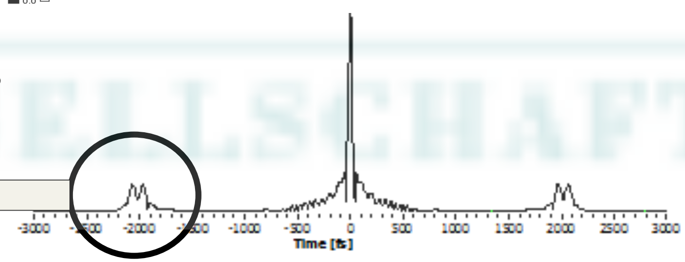
Frequency domain interference
Of pump and probe



FFT



N. H. Matlis, et al., "Snapshots of laser wakefields", *Nature Physics*, **2**, 749 - 753 (2006)



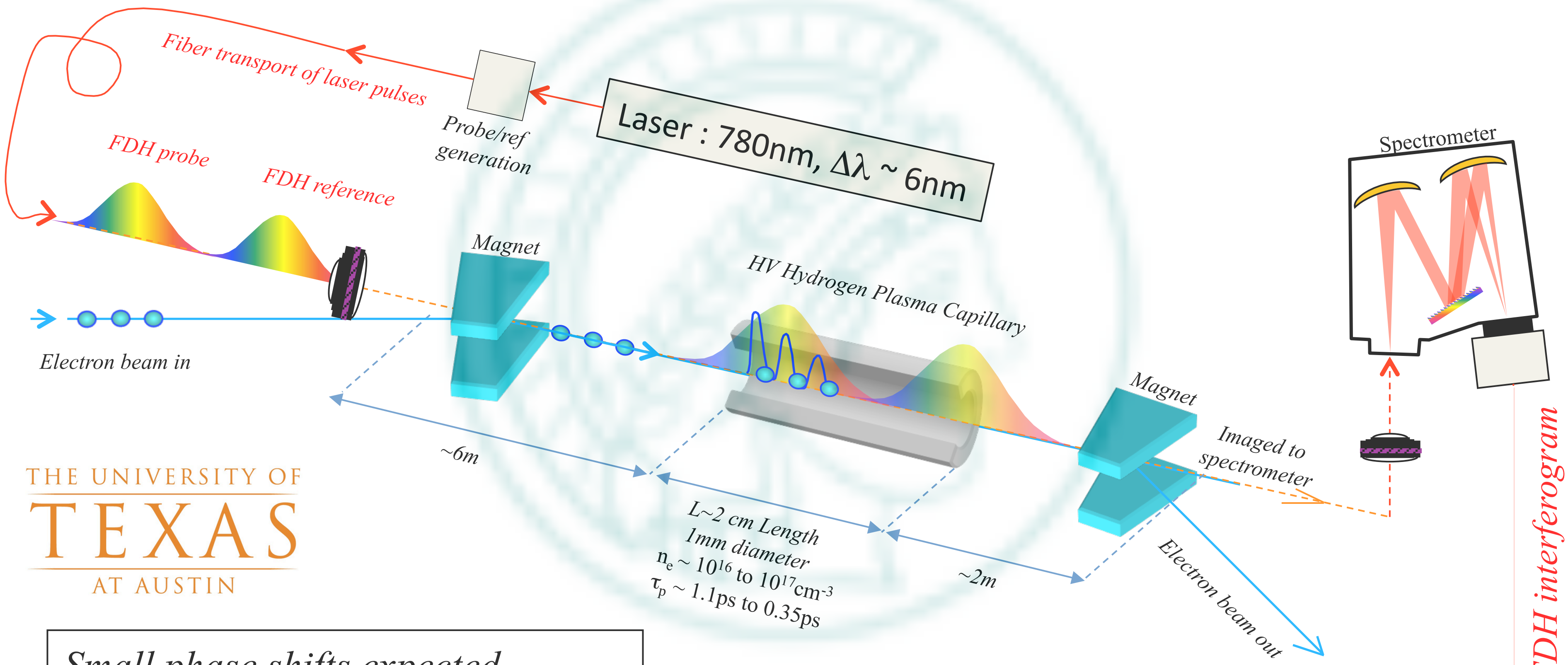
Probe phase encoded in sidebands

Map of plasma wave

THE UNIVERSITY OF TEXAS AT AUSTIN

USC

Schematic setup of FDH at ATF

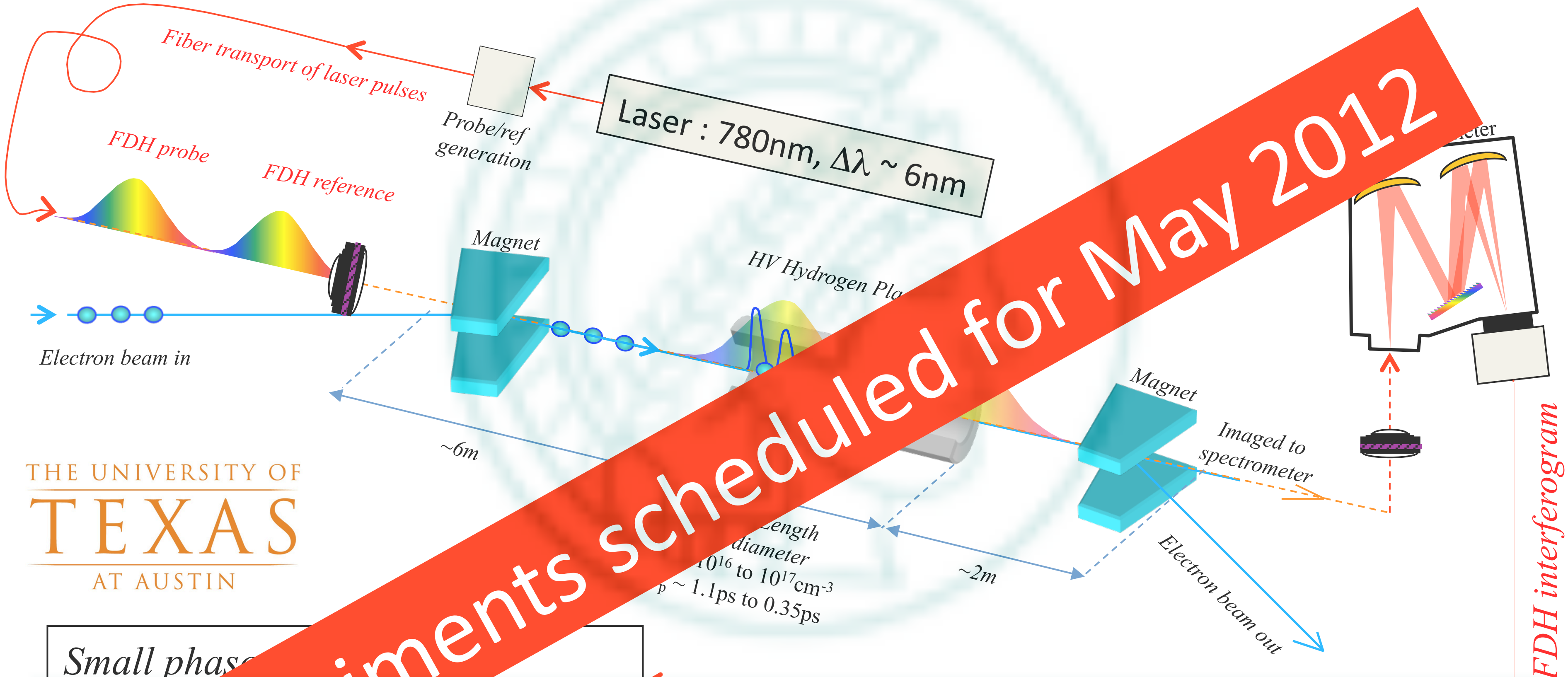


Small phase shifts expected
$\Delta\varphi = (2\pi/\lambda_{pr})\Delta nL \sim 10^{-3}$ *to* 10^{-2} *rad*

Larger phase shifts were observed in previous visualization experiments of LWFA. However, here there is no background from intense laser driver.

	$\Delta\varphi$	
Siders	$\sim 10^{-2}$ *rad*	- *Multishot FDI of LWFA,* Siders *et al.*, PRL **76**, 3570 (96)
Matlis	$\sim 10^{-1}$ *rad*	- *Single shot FDH of LWFA,* N. H. Matlis, et al., *Nature Physics*, **2**, 749 - 753 (2006)

Schematic setup of FDH at ATF



Experiments scheduled for May 2012

Small phas

Δφ = (*to* 10^{-2} *rad*

Larg *ifts were observed in previous visualization experiments of LWFA. However, here there is no* *ground from intense laser driver.*

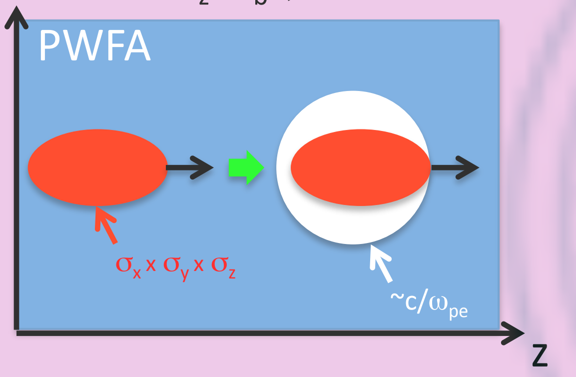
	$\Delta\varphi$		
Siders	*~*10^{-2} *rad*	-	*Multishot FDI of LWFA,* Siders *et al.*, PRL **76**, 3570 (96)
Matlis	*~*10^{-1} *rad*	-	*Single shot FDH of LWFA,* N. H. Matlis, et al., *Nature Physics*, **2**, 749 - 753 (2006)

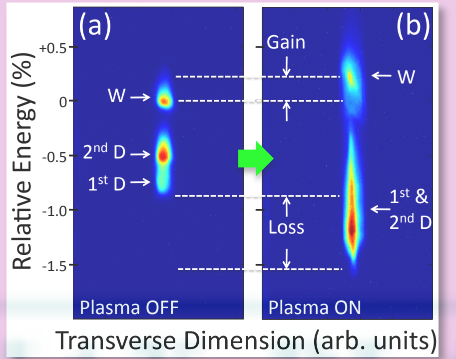
3 Regimes of Beam-Plasma Interaction

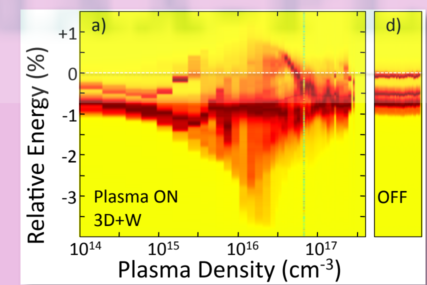
Plasma Wakefield Accelerator

$\sigma_z \le c/\omega_{pe}$, $\sigma_{x,y} \le c/\omega_{pe}$

$E_z \sim n_b^{\alpha}$, $\alpha<1$



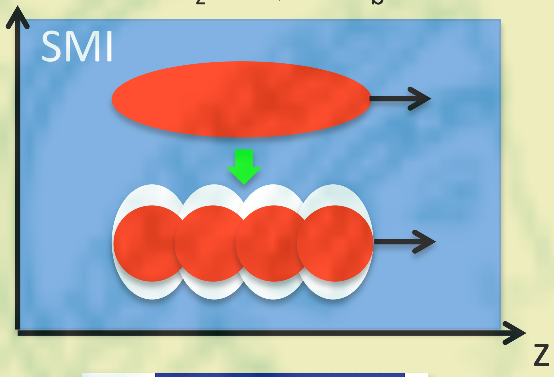


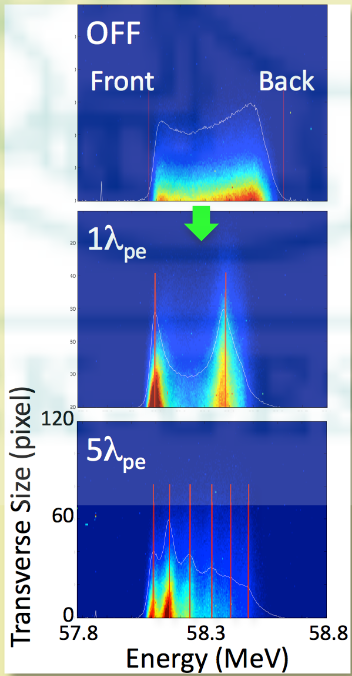


Self-Modulation Instability

$\sigma_z >> c/\omega_{pe}$, $\sigma_{x,y} \le c/\omega_{pe}$

$E_z \sim e^{\Gamma z}$, $\Gamma \sim n_b$

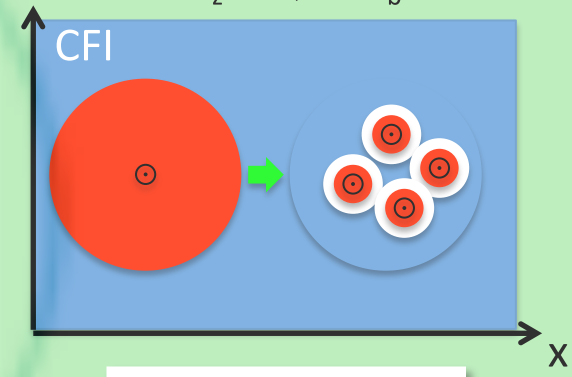


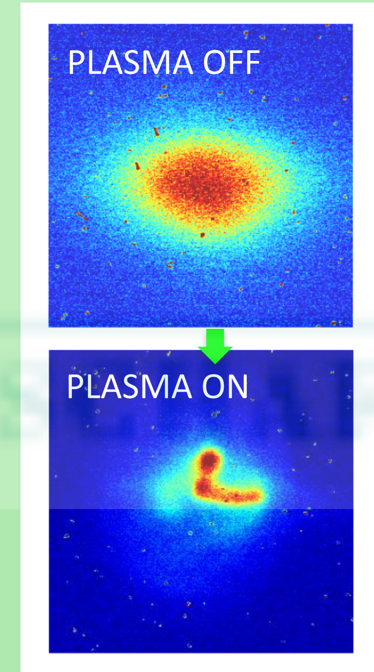


Current Filamentation Instability

$\sigma_z \le c/\omega_{pe}$, $\sigma_{x,y} > c/\omega_{pe}$

$E_z \sim e^{\Gamma z}$, $\Gamma \sim n_b$



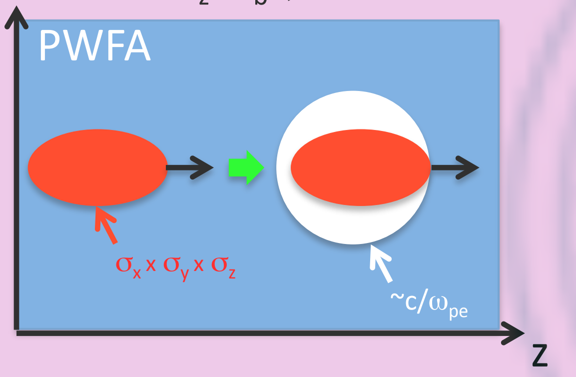


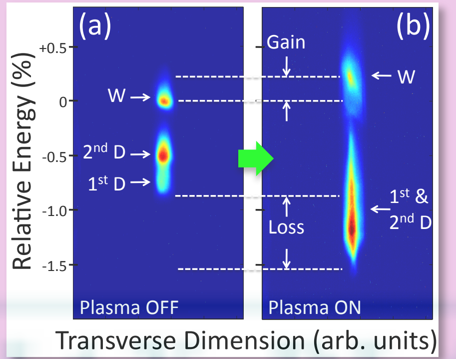
3 Regimes of Beam-Plasma Interaction

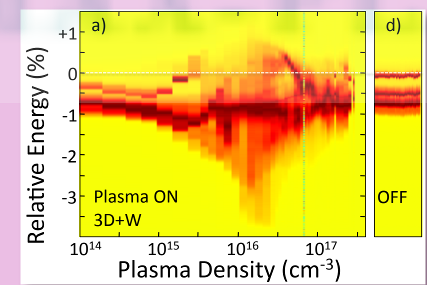
Plasma Wakefield Accelerator

$\sigma_z \leq c/\omega_{pe}$, $\sigma_{x,y} \leq c/\omega_{pe}$

$E_z \sim n_b^{\alpha}$, $\alpha<1$



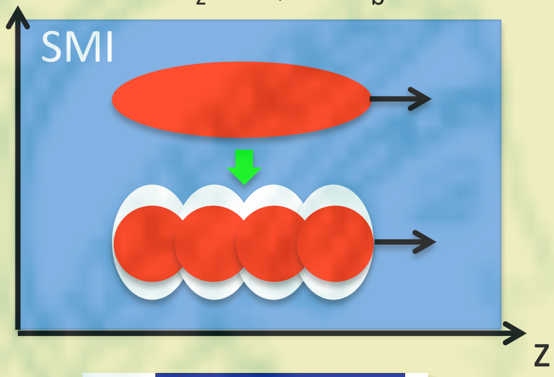


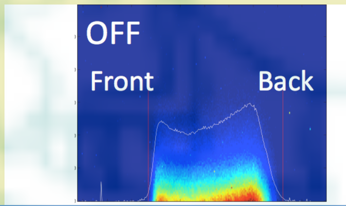


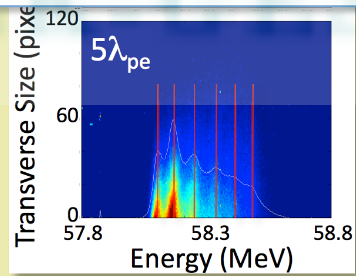
Self-Modulation Instability

$\sigma_z >> c/\omega_{pe}$, $\sigma_{x,y} \leq c/\omega_{pe}$

$E_z \sim e^{\Gamma z}$, $\Gamma \sim n_b$



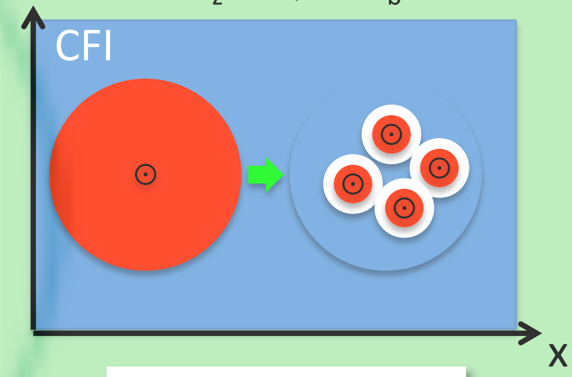


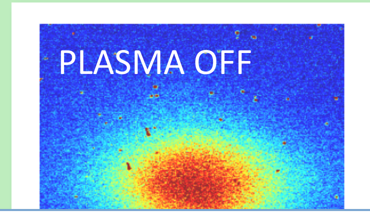


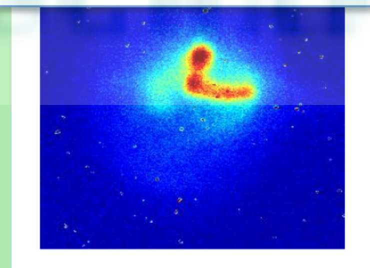
Current Filamentation Instability

$\sigma_z \leq c/\omega_{pe}$, $\sigma_{x,y} > c/\omega_{pe}$

$E_z \sim e^{\Gamma z}$, $\Gamma \sim n_b$







Next talks by Y. Fang and B. Allen!

SUMMARY

- Much interesting e$^-$-beam/plasma interaction physics can be done at ATF Resonant PWFA, large R, PWFA wake imaging, SMI, CFI. …
- Bunch shaping in time and charge using masking technique enables PWFA physics experiments (as well as DLA experiments, UCLA, Euclid TechLabs, …)
- Resonant PWFA excitation by a bunch train observed
- Large R experiments planned with RBT and triangular bunches
- Access to QNL-PWFA regime planned (with J. Rosenzweig's group, UCLA)
- Imaging of PWFA plasma density modulation planned using laser interferometry and Fourier domain holography (FDH) (soon with M. Downer's group, UT)

Thank you!

Thank you very much to ATF!

Work supported by US Dept. of Energy and NSF (CFI)

Thank you!