Status of the Multi-bunch PWFA Experiment at ATF

AE31

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OUTLINE

- Motivation
- Brief into to the PWFA (Plasma Wakefield Accelerator)
- Experimental Setup
- 2-Bunch Results
- Multi-bunch Results (Preliminary)
- Summary and Future

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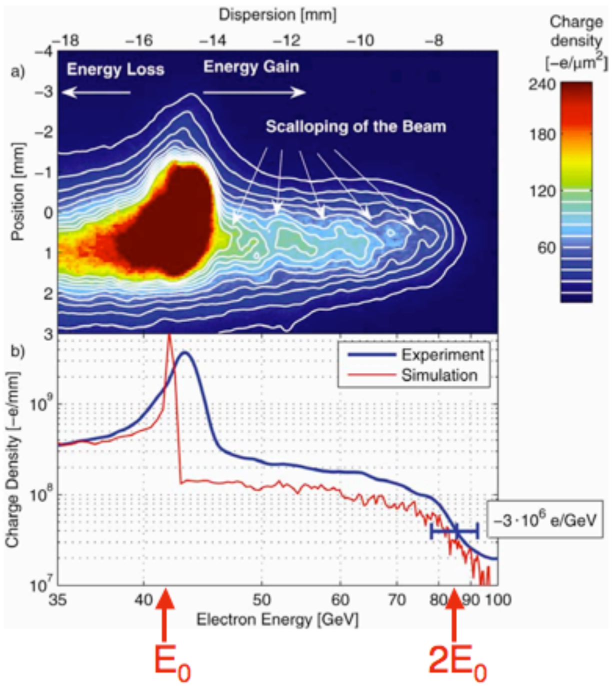
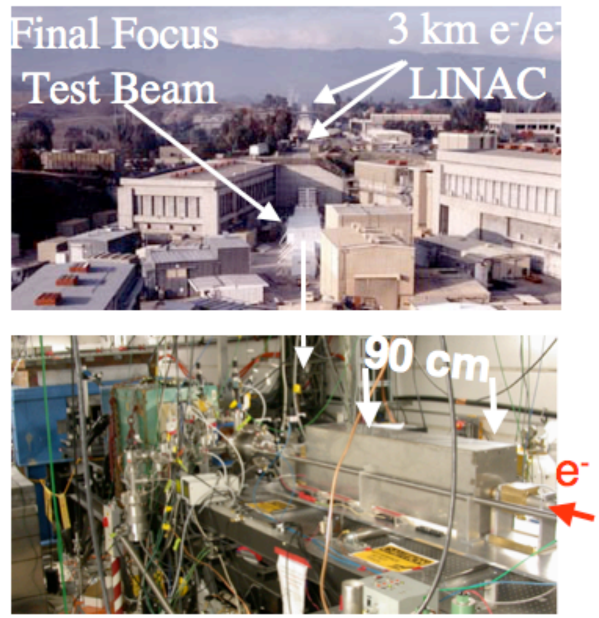
MOTIVATION

e^- ENERGY DOUBLING E_0=42 GeV

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



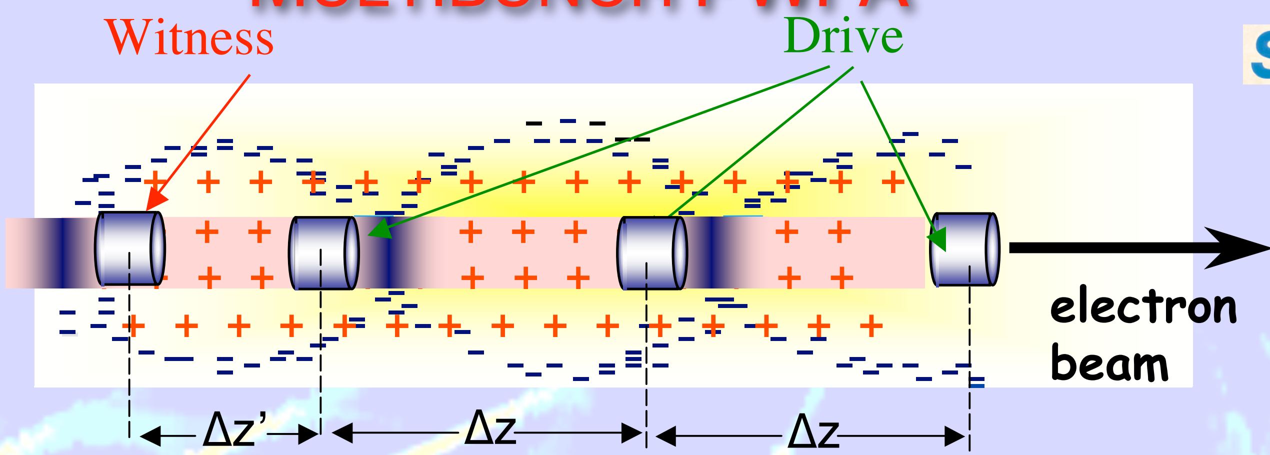


- Energy doubling of e^- over L_p≈85 cm, 2.7×10^{17} cm^{-3} plasma
- Unloaded gradient ≈52 GV/m (≈150 pC accel.)

P. Muggli, ICOPS 08, 06/17/08 25

- Tremendous progress with PWFA
- Need to accelerate a particle BUNCH
- Explore high transformer ratio scheme, beyond energy doubling

MULTIBUNCH PWFA



- Bunch spacing/plasma density condition:

  $\Delta z = \lambda_p$ (resonance) $\sigma_z \leq \lambda_p/2$

  $\Delta z' \approx (m+1/2)\lambda_p$

Plasma wavelength: $\lambda_p = \dfrac{2\pi c}{\omega_{pe}}$ Plasma angular frequency, density n_e: $\omega_{pe} = \left(\dfrac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$

- Wake fields add up (linear theory):

  $E_{z\ N\ bunches} = N \times E_{z\ 1\ bunch}$ (Maximize wakefield!)

- Maximize transformer ratio with "shaping" (beyond energy doubling!)

- Finite energy spread, beam acceleration

MULTIBUNCH PWFA

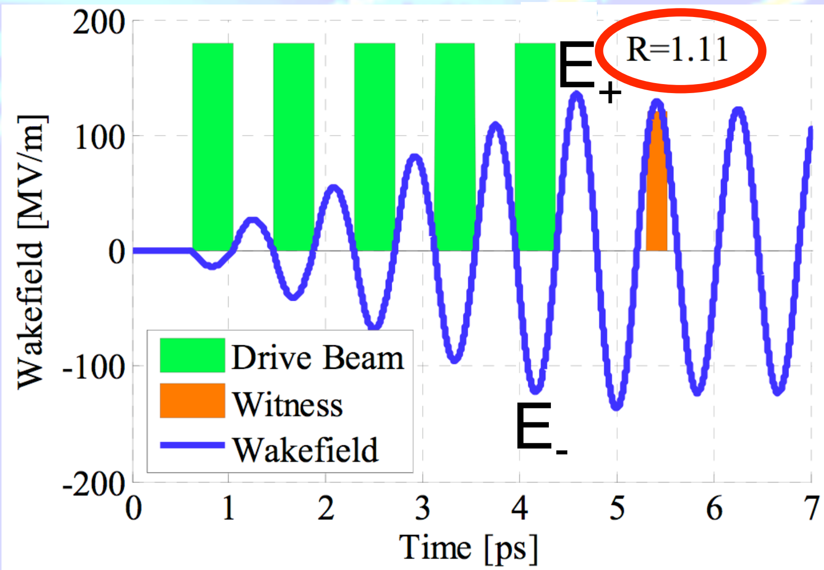
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

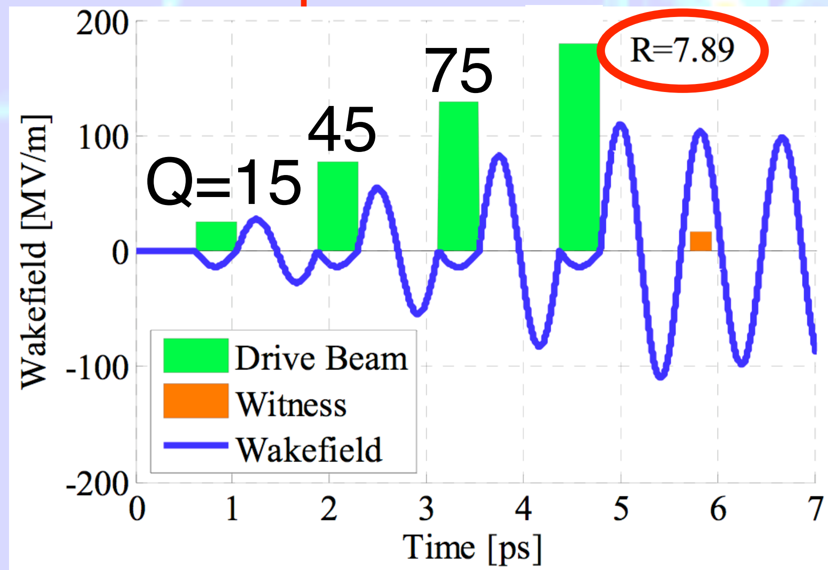
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 μm≈1.5λ_p

Ramped Bunch Train*



*Tsakanov, NIMA, 1999

➡ R=7.9 => multiply energy by ≈8 in a single PWFA stage!

2-BUNCH PWFA

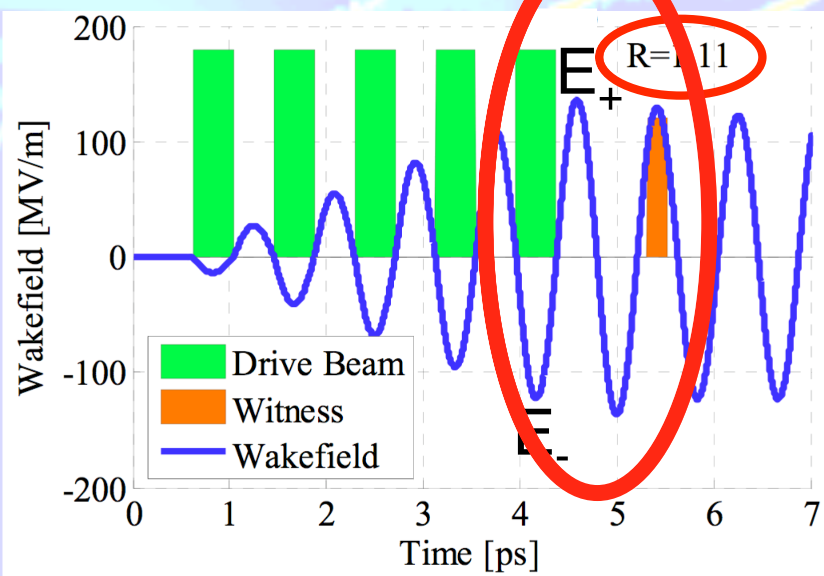
Transformer Ratio: $R = E_+ / E_-$ Energy Gain: $\leq RE_0$

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

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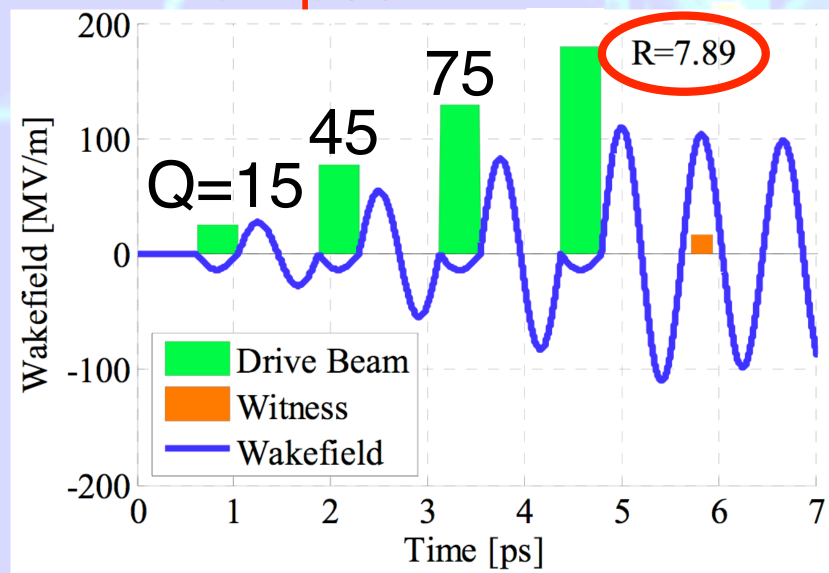
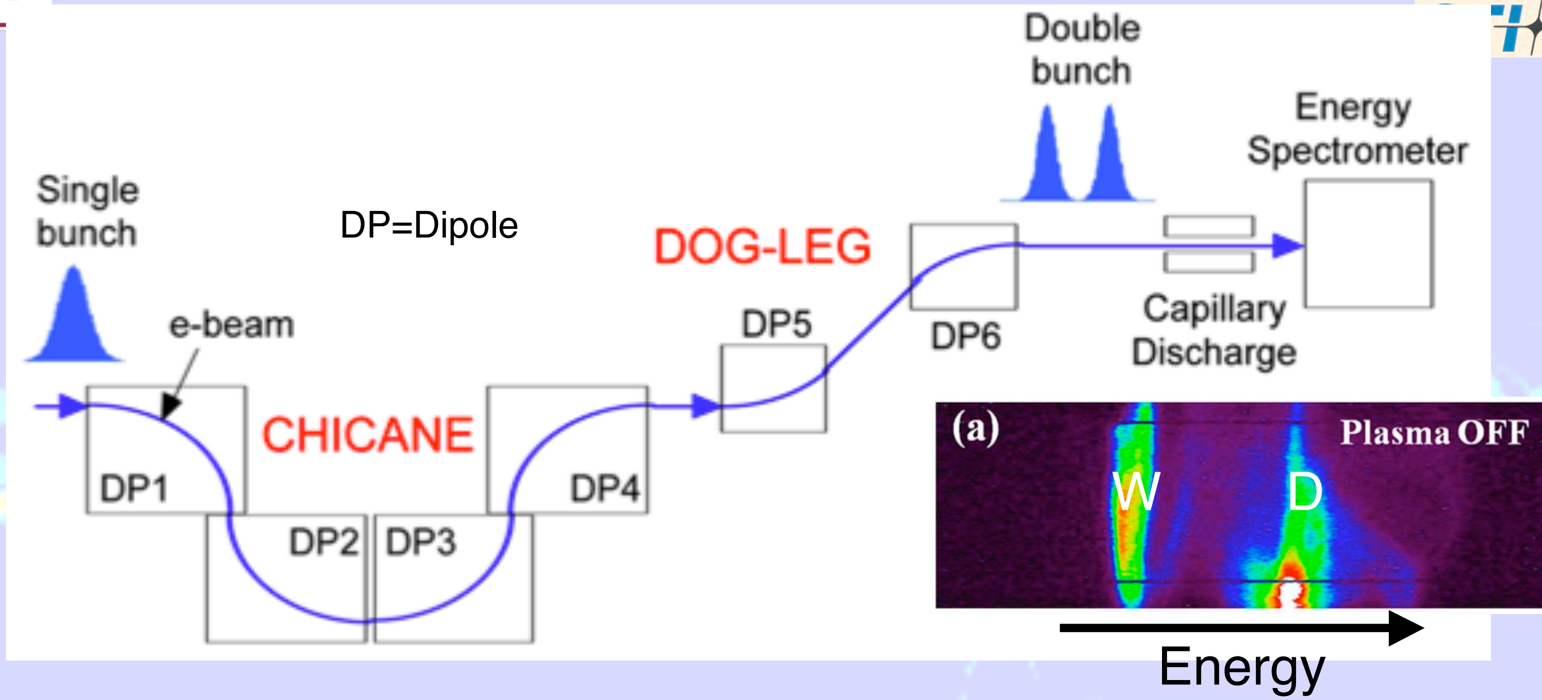


*Tsakanov, NIMA, 1999

➡ Acceleration of a witness bunch

2-BUNCH FORMATION

Gun
Linac



Incoming beam:
E_0=59 MeV
Q=500 pC
≈5.5ps or 1650 μm

	2-bunch	Drive	Witness
ΔE (MeV)	1.8	0.4+	0.4-
Δt (fs), Δz (µm)	500, 150	150, 45	90, 27
Q (pC)	480	300	180
n_b ($\times 10^{14}$ cm^{-3})	-	2.6	2.6

Kimura, AAC'06

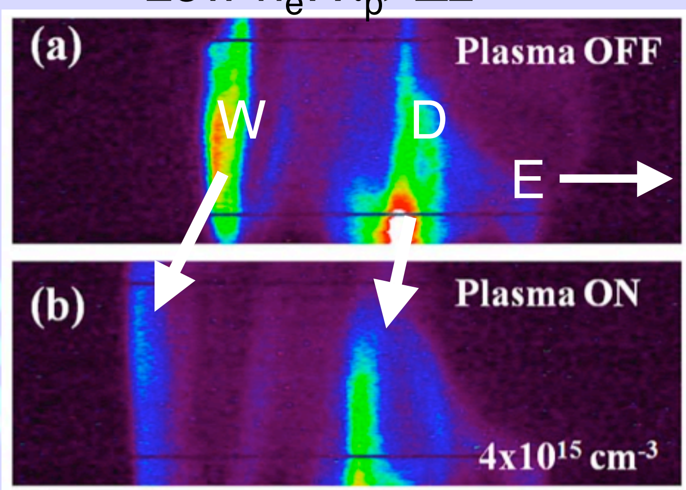
- Space charge and CSR break the bunch when over compressed
- PWFA linear regime for $n_e > n_b \approx 2.6 \times 10^{14}$ cm^{-3}

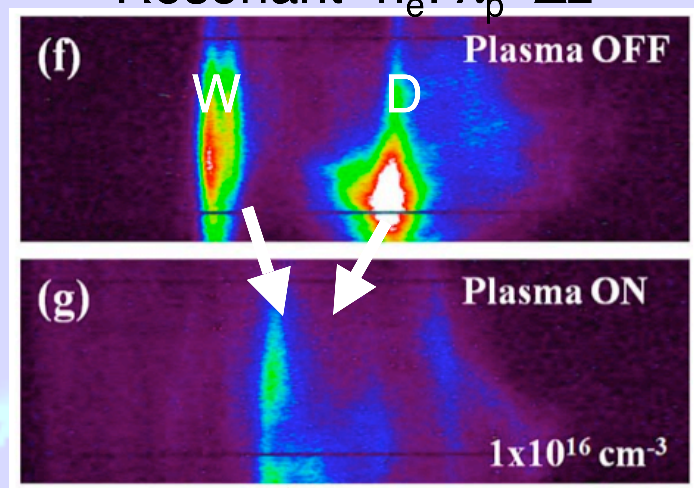
2-BUNCH RESULTS

Low n_e: $\lambda_p > \Delta z$

Kallos, PRL 2008

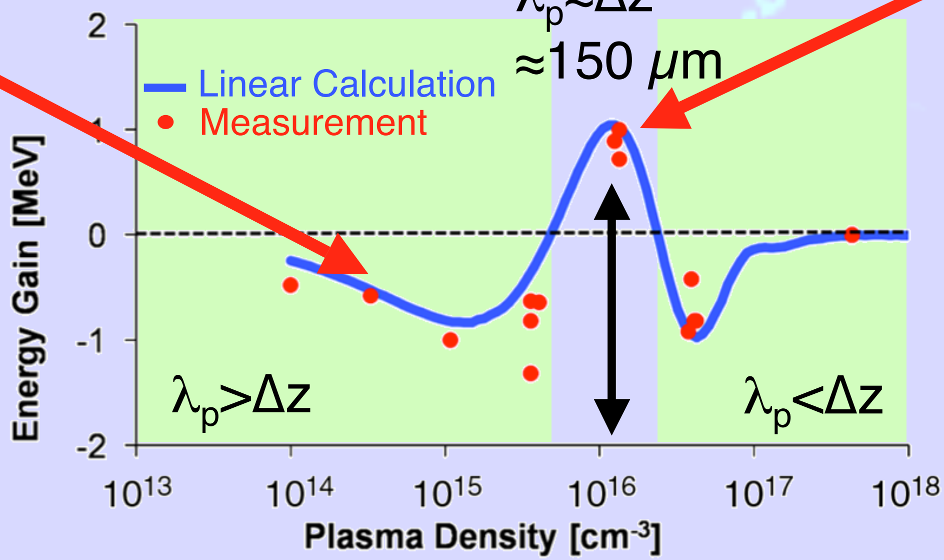
"Resonant" n_e: $\lambda_p \approx \Delta z$





Loss

Gain



E_{gain}=+0.9 MeV

E_{loss}=-1.0 MeV

ΔE=+1.9 MeV

L_p=6 mm

$G_{unloaded}$=315 MeV/m

➡ First large gradient acceleration of a witness bunch

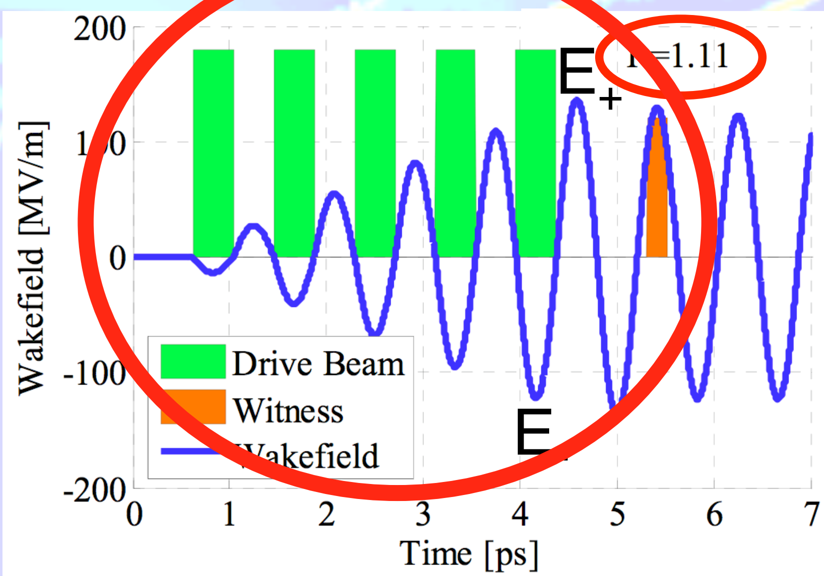
MULTIBUNCH PWFA

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 $\mu m \approx \lambda_p$

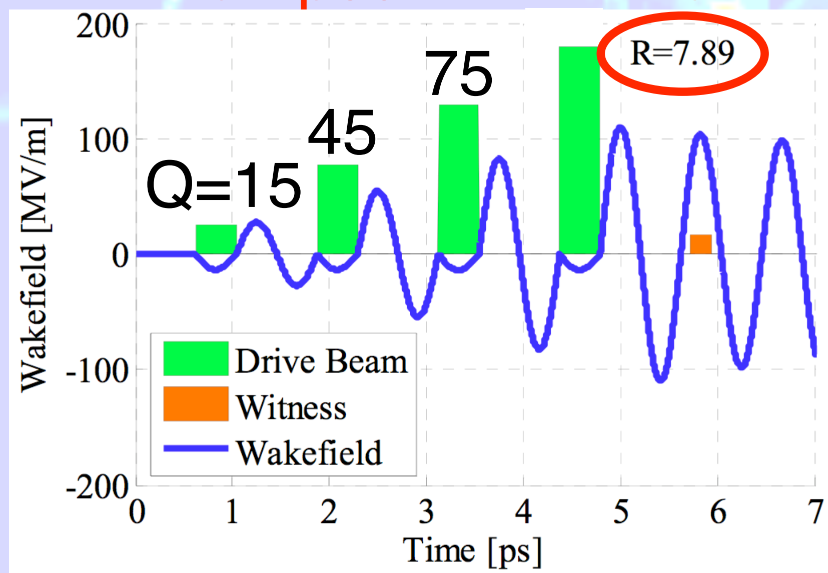
Bunch Train



Kallos, PAC'07 Proceedings

Δz=375 $\mu m \approx 1.5\lambda_p$

Ramped Bunch Train*

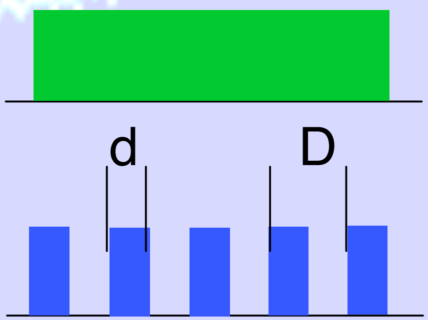


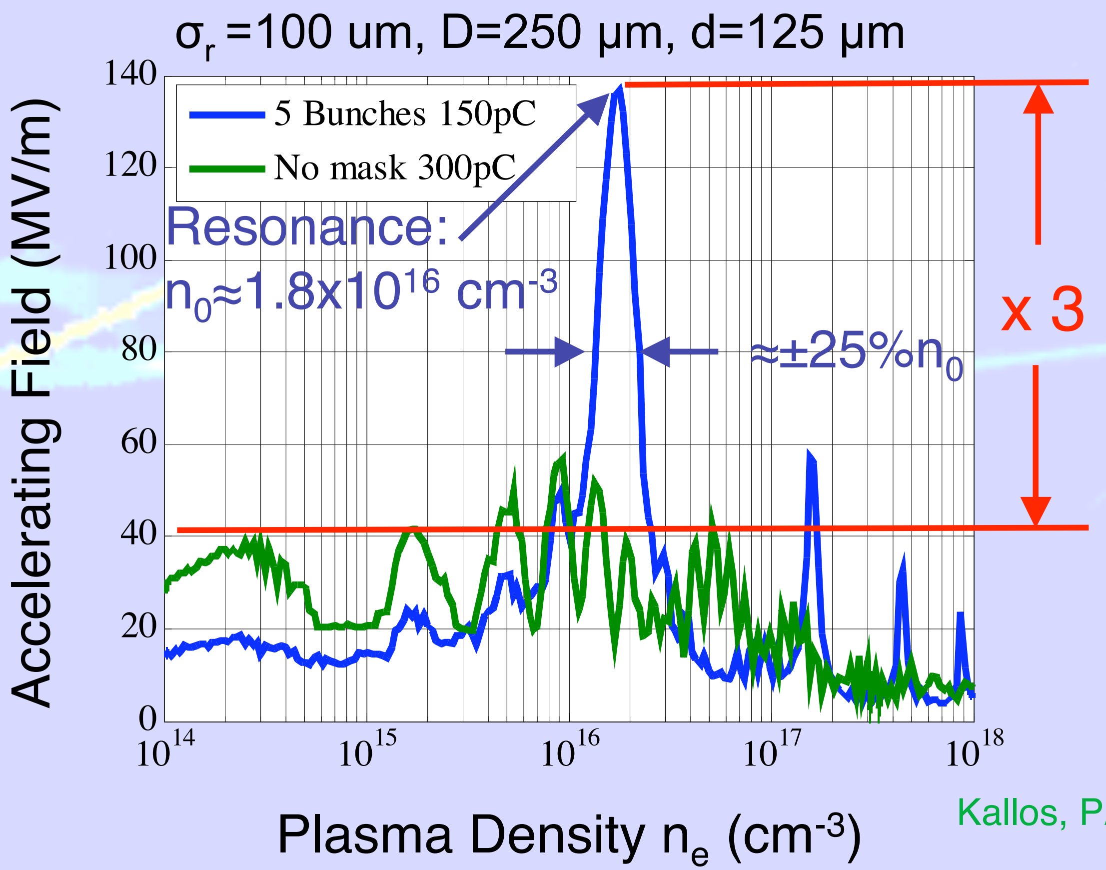
*Tsakanov, NIMA, 1999

➡ Resonant excitation of wakefields

ACCELERATING FIELD

Calculation microbunches with equal charge



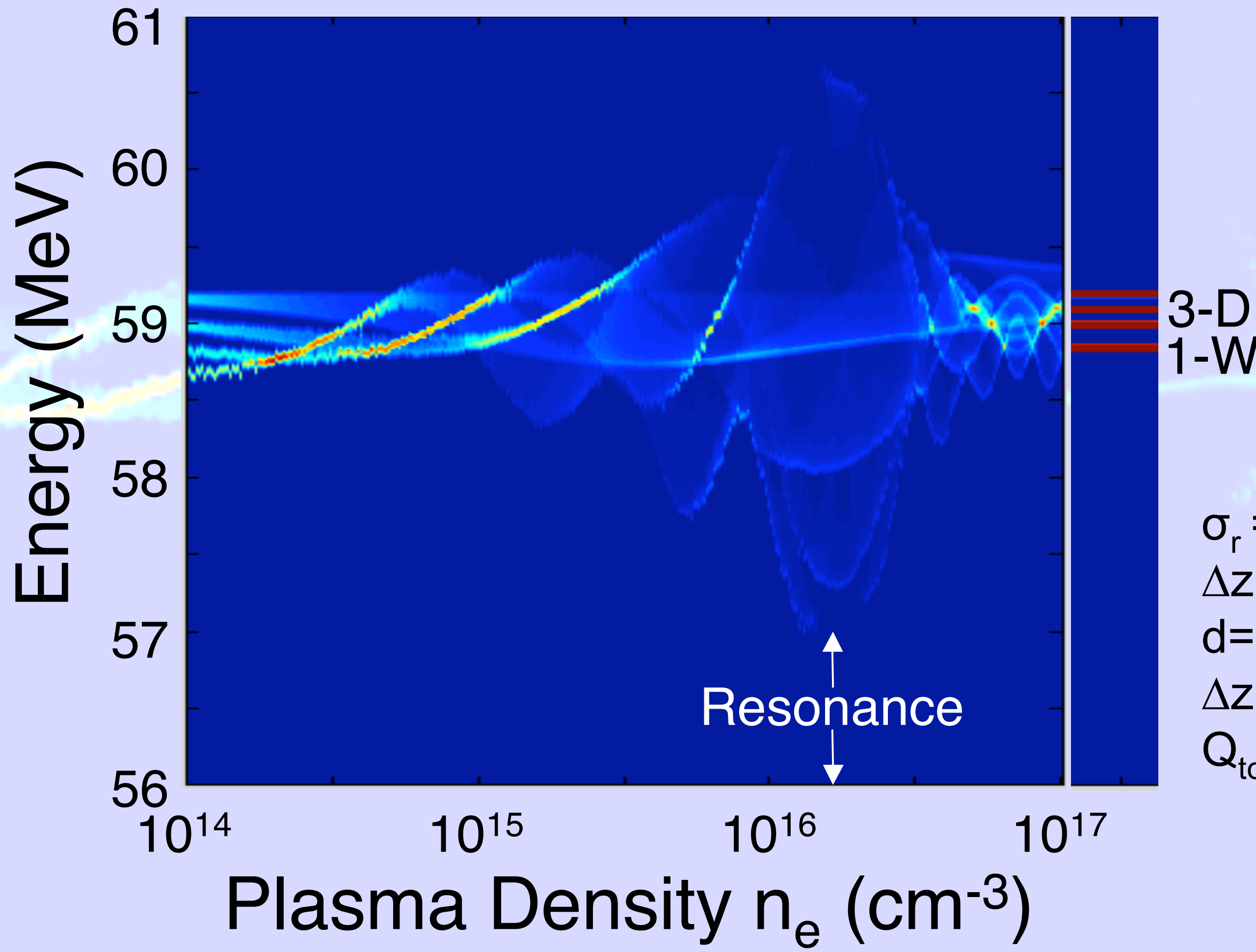


Kallos, PAC'07 Proceedings

- Expect ≈1.4 MeV energy gain/loss over 1 cm
- Microbunch resonance clear, and narrow

ENERGY CHANGE

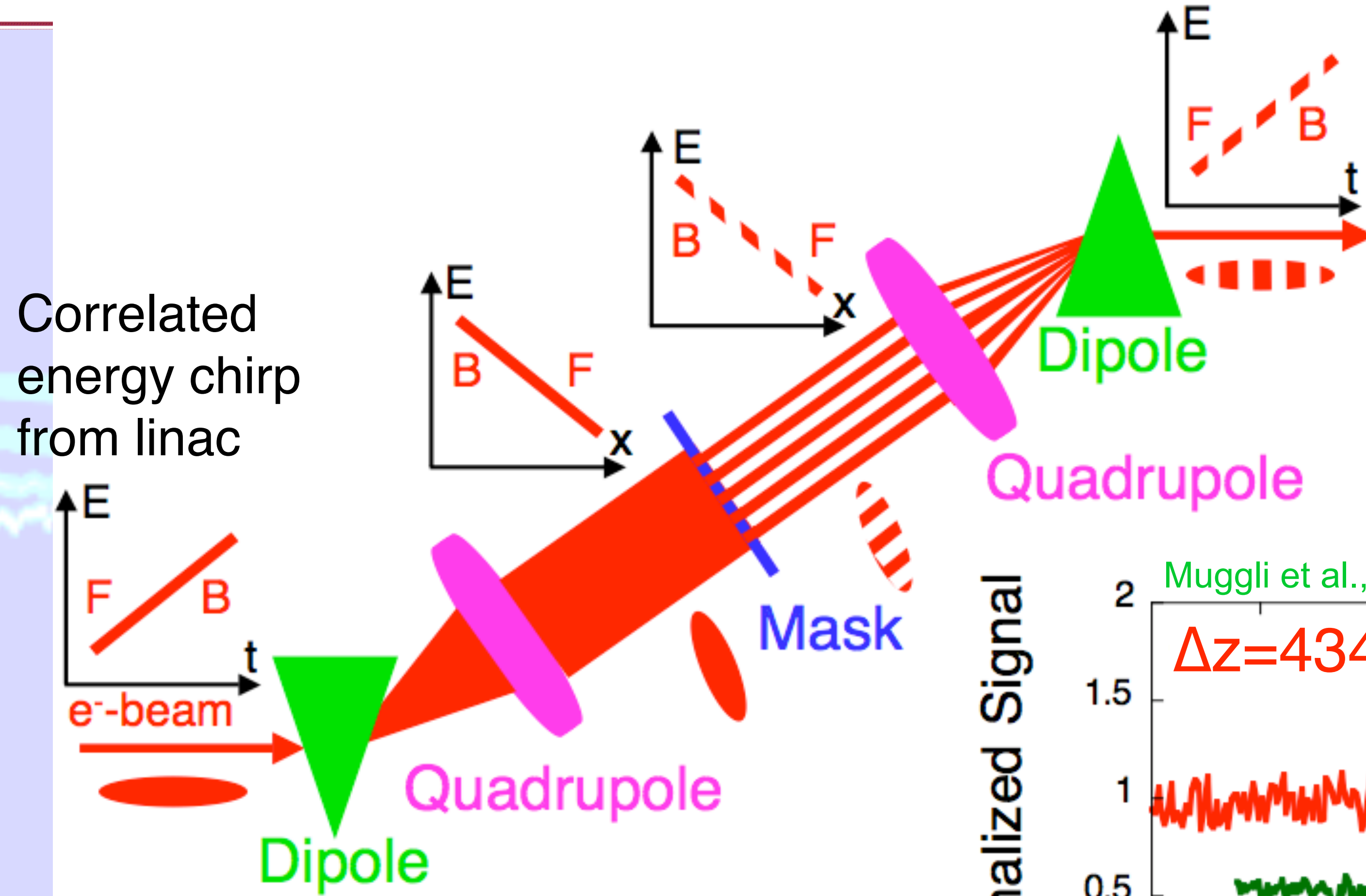
Linear calculation: microbunches with equal charge

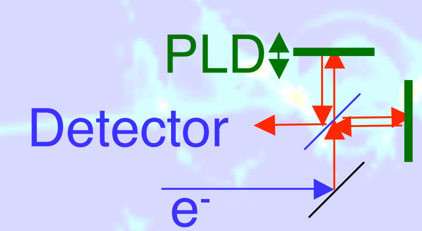


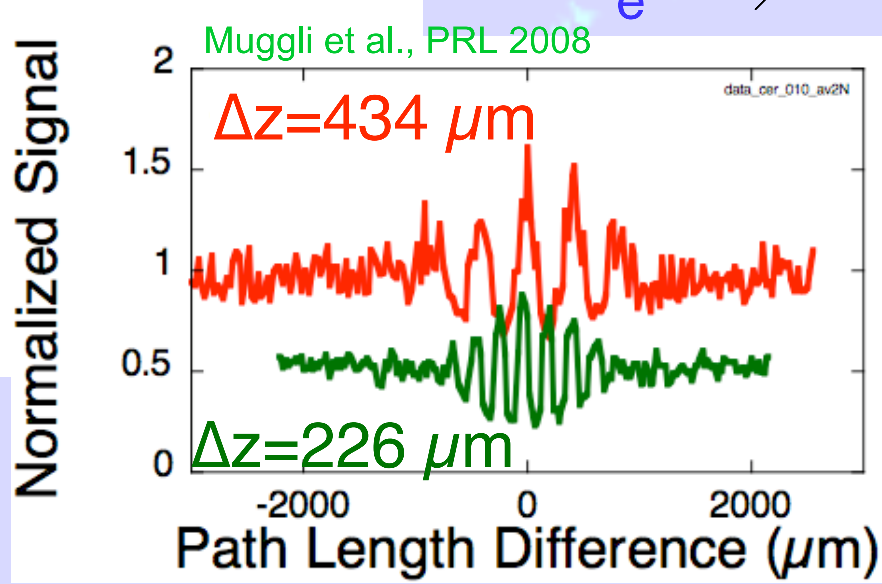
σ_r =100 um,
Δz=250 μm,
d=125 μm
Δz'=375 μm
Q_{tot}=150 pC

- Resonant excitation of wakefield is the main feature
- Note: case of witness bunch at lowest energy, WRONG CHIRP!

Multi-bunch Source



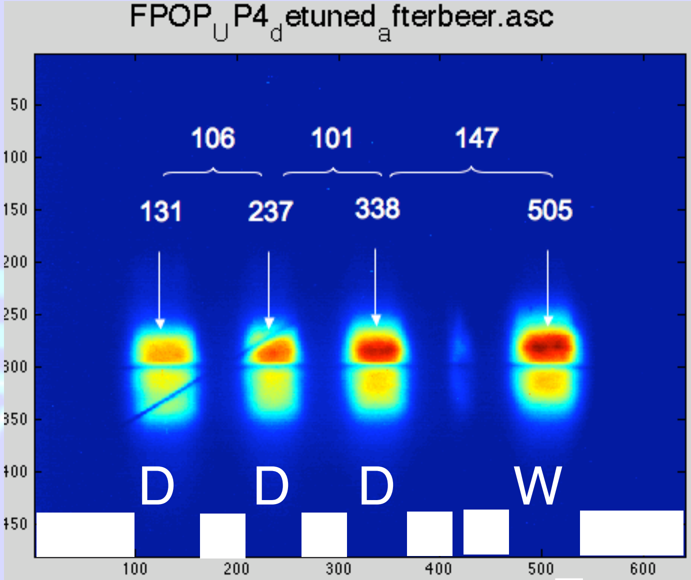


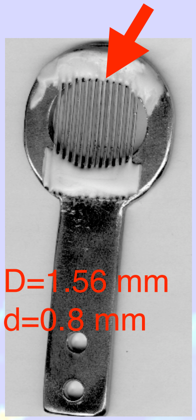


- Emittance selection
- Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σ_z, Q

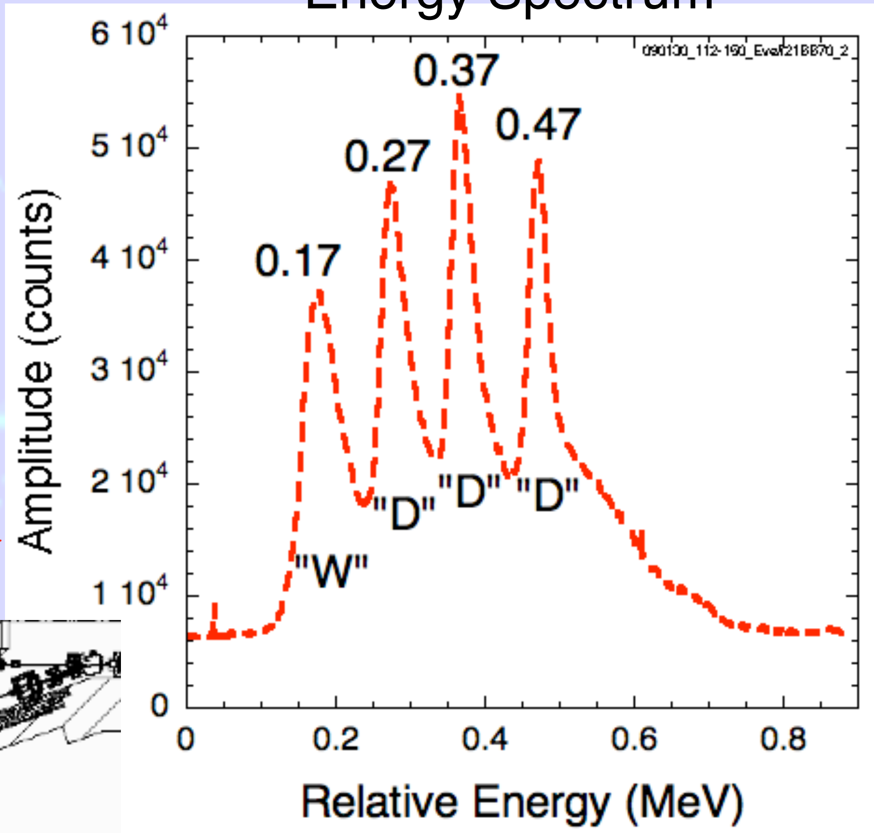
MULTI-BUNCH TRAIN FOR PWFA

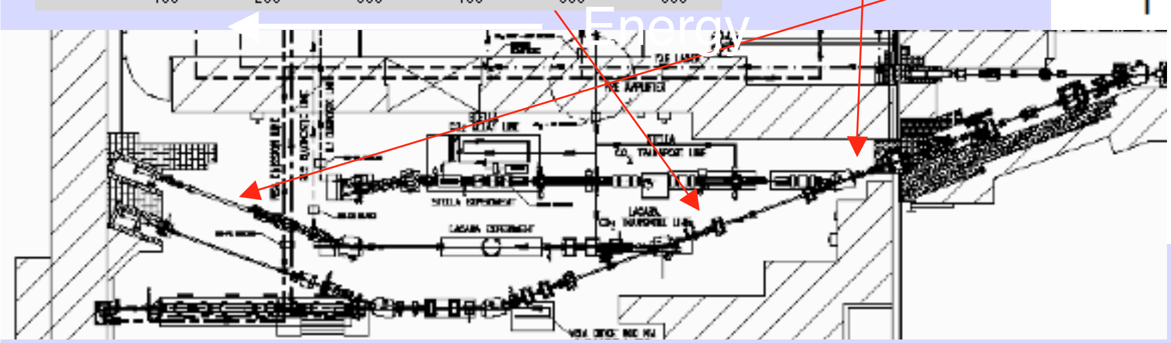
Mask Shadow





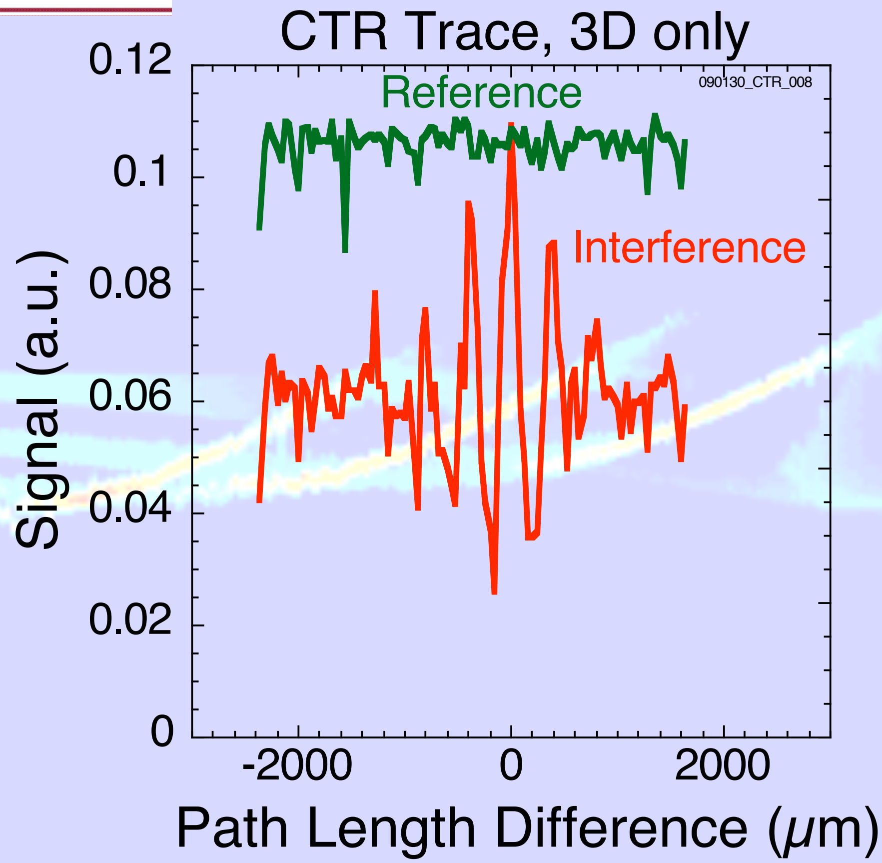
Energy Spectrum

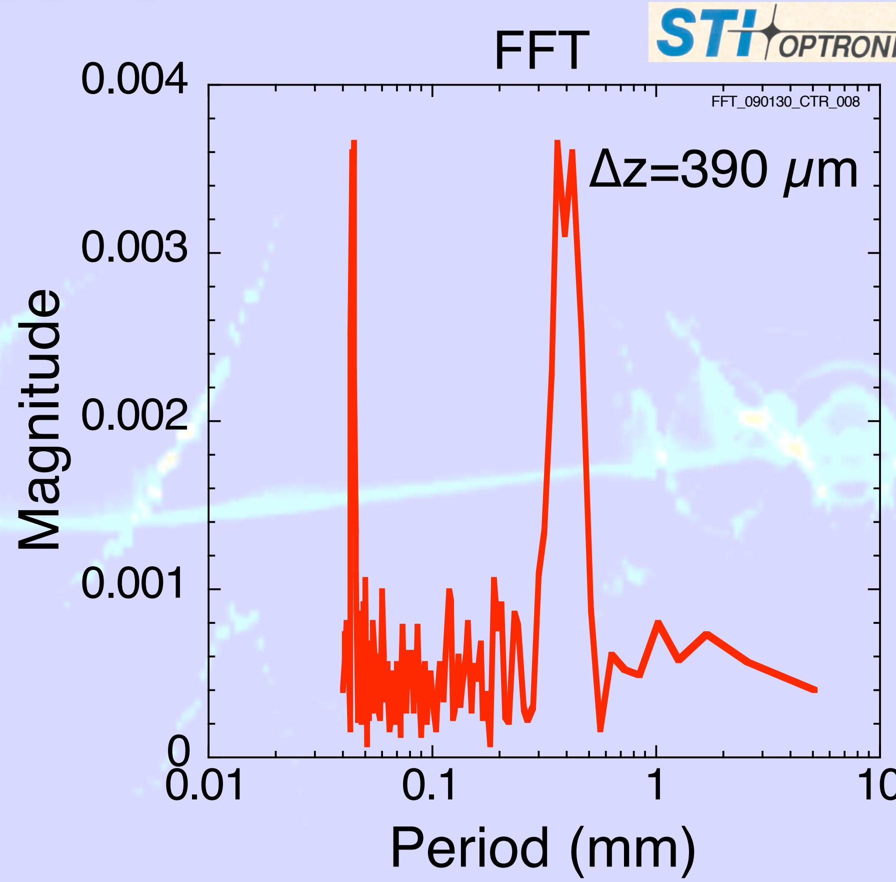




- Select number of drive bunches (high energy slit). Choose 3D+1W
- Witness bunch appears with drive bunch spacing on energy spectrometer
  CSR? See proposal by Alexei Fedotov

MULTI-BUNCH





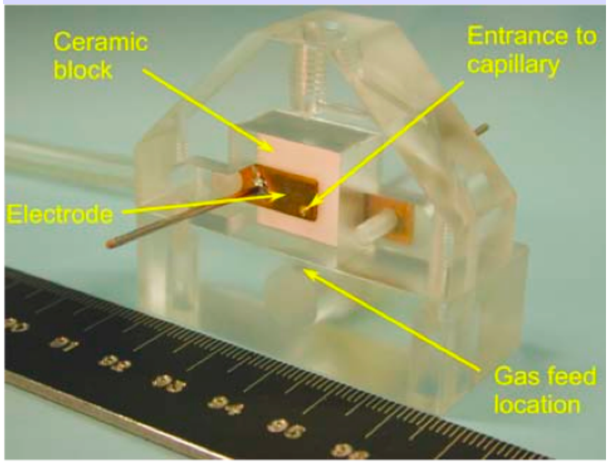
$$\omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{\frac{1}{2}} = k_{pe} c = \frac{2\pi c}{\lambda_{pe}} = \frac{2\pi c}{\Delta z} \longrightarrow n_e = \frac{\varepsilon_0 m_e}{e^2}\left(\frac{2\pi c}{\Delta z}\right)^2$$

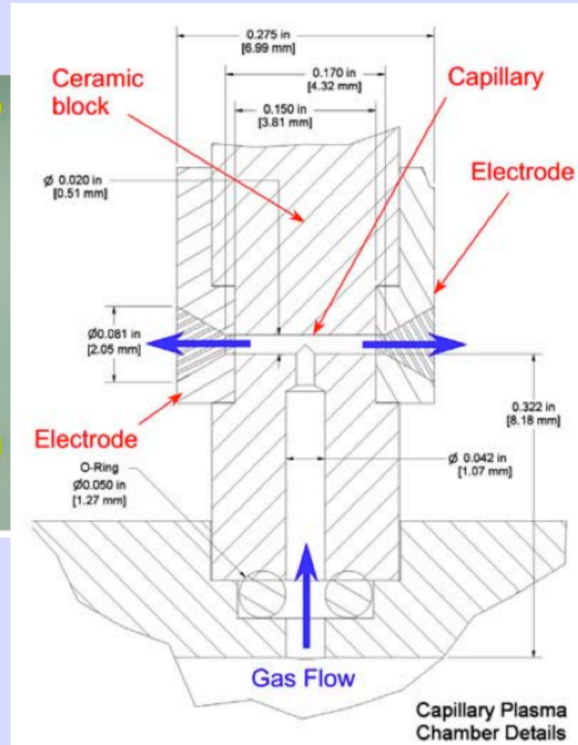
- Typical bunch separation: $\Delta z \approx 300\text{-}400\ \mu m$
- Expected plasma resonance: $\lambda_{pe}(n_e)=\Delta z$, $n_e \approx 1.2\text{-}0.7 \times 10^{16}\ cm^{-3}$

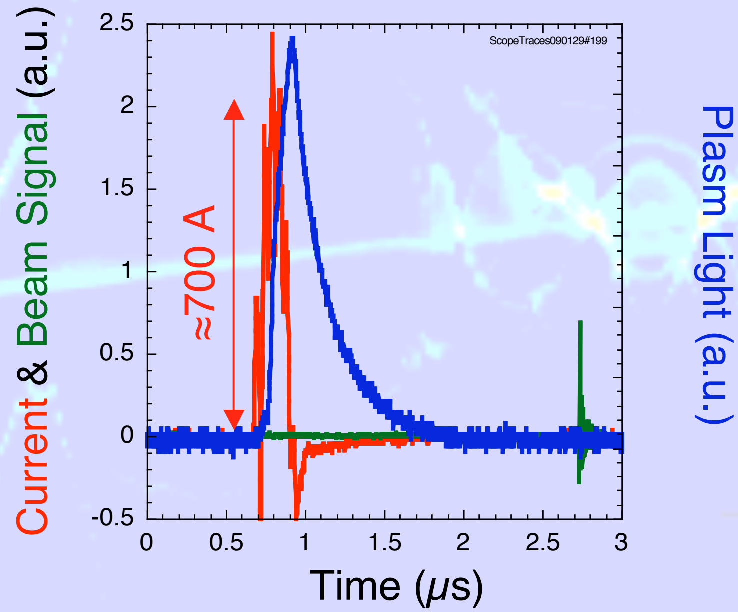
PLASMA SOURCE

H_2-puff Capillary Discharge

Kimura, AAC'06 Proceedings

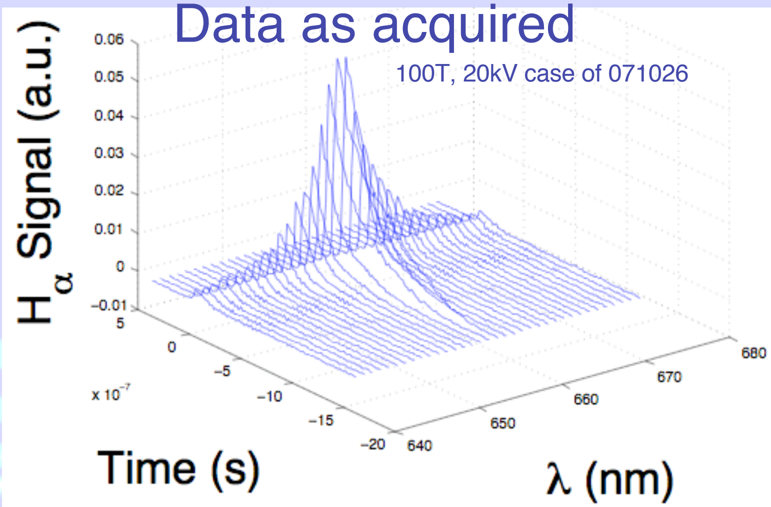


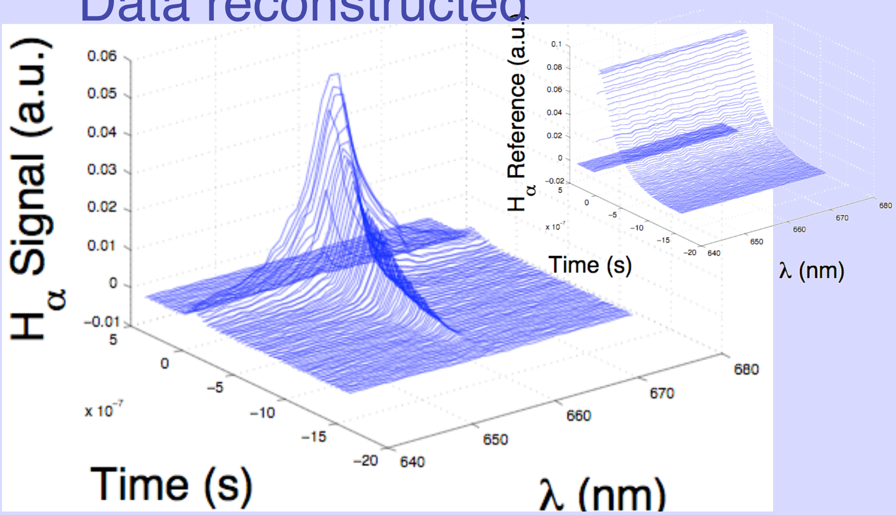




- Capillary discharge with puffed H_2
- Plasma density n_e controlled through P_{H2}, $V_{discharge}$, $\tau_{discharge\text{-}beam}$

PLASMA DENSITY VS TIME

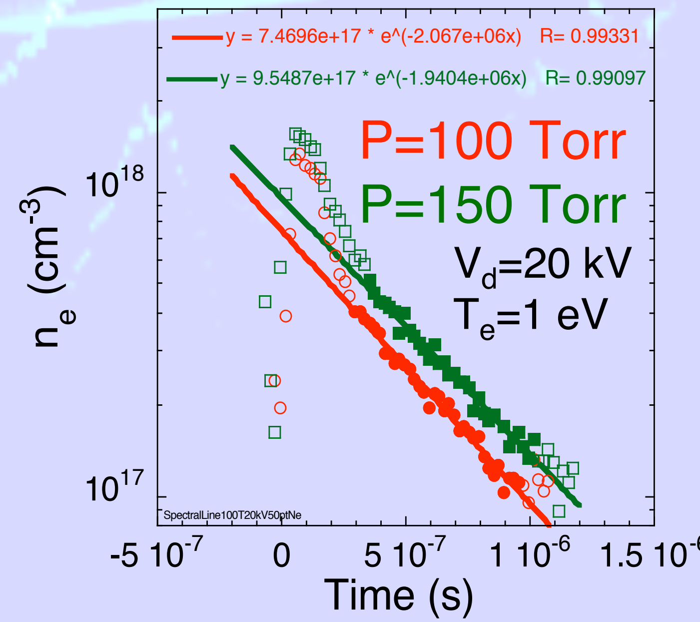




Time-resolved
Stark Broadening H_α line @ 656 nm

$$n_e\left[cm^{-3}\right] \cong 8\times 10^{12}\left(\frac{\Delta\lambda_{1/2}[A]}{\alpha_{1/2}}\right)^{3/2}$$

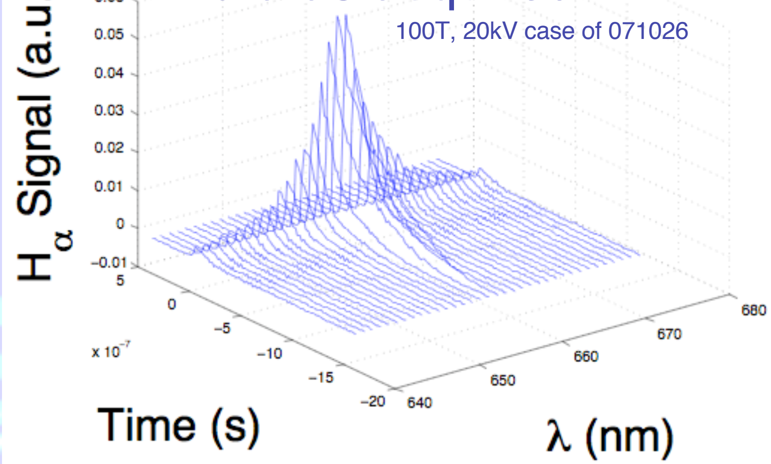
Griem, 1964



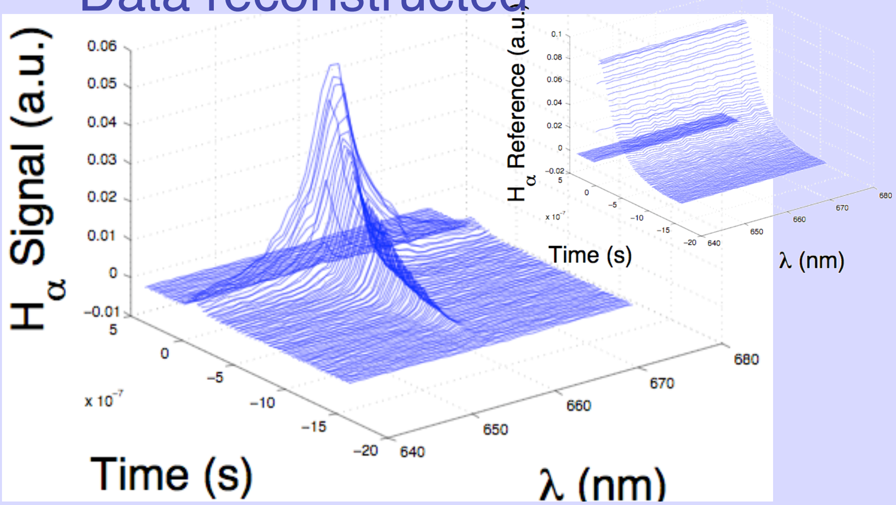
- Assume exponential decay of $n_e(t)$, large t
- Vary plasma density by varying discharge/beam timing

PLASMA DENSITY VS TIME

Data as acquired



Data reconstructed



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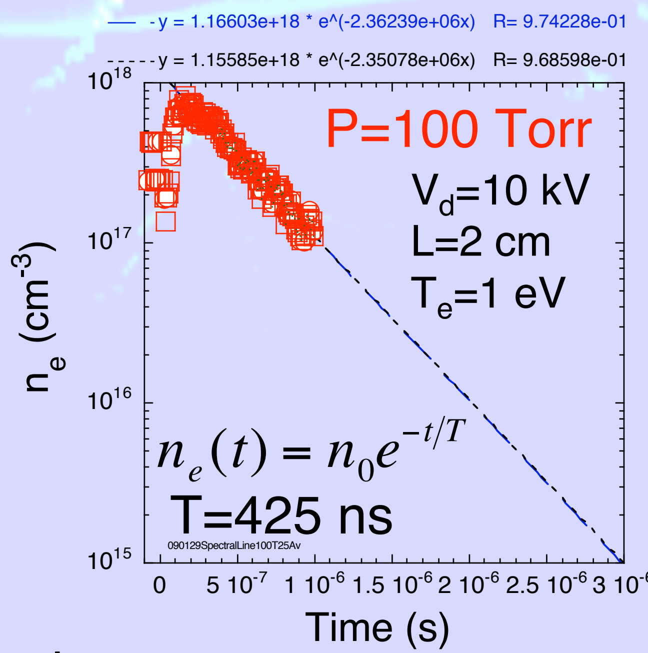
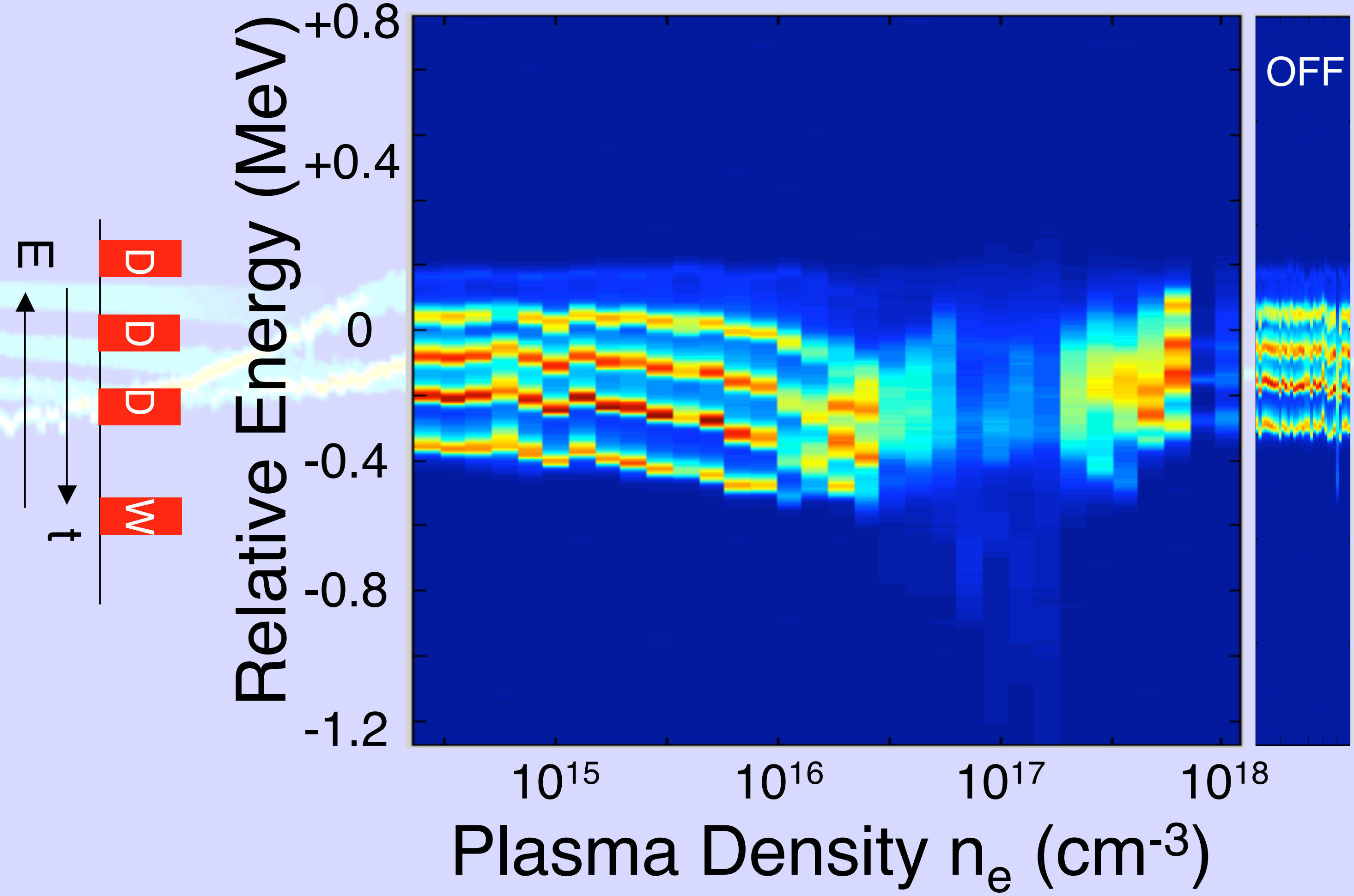
Griem, 1964



- Assume exponential decay of $n_e(t)$, large t
- Vary plasma density by varying discharge/beam timing

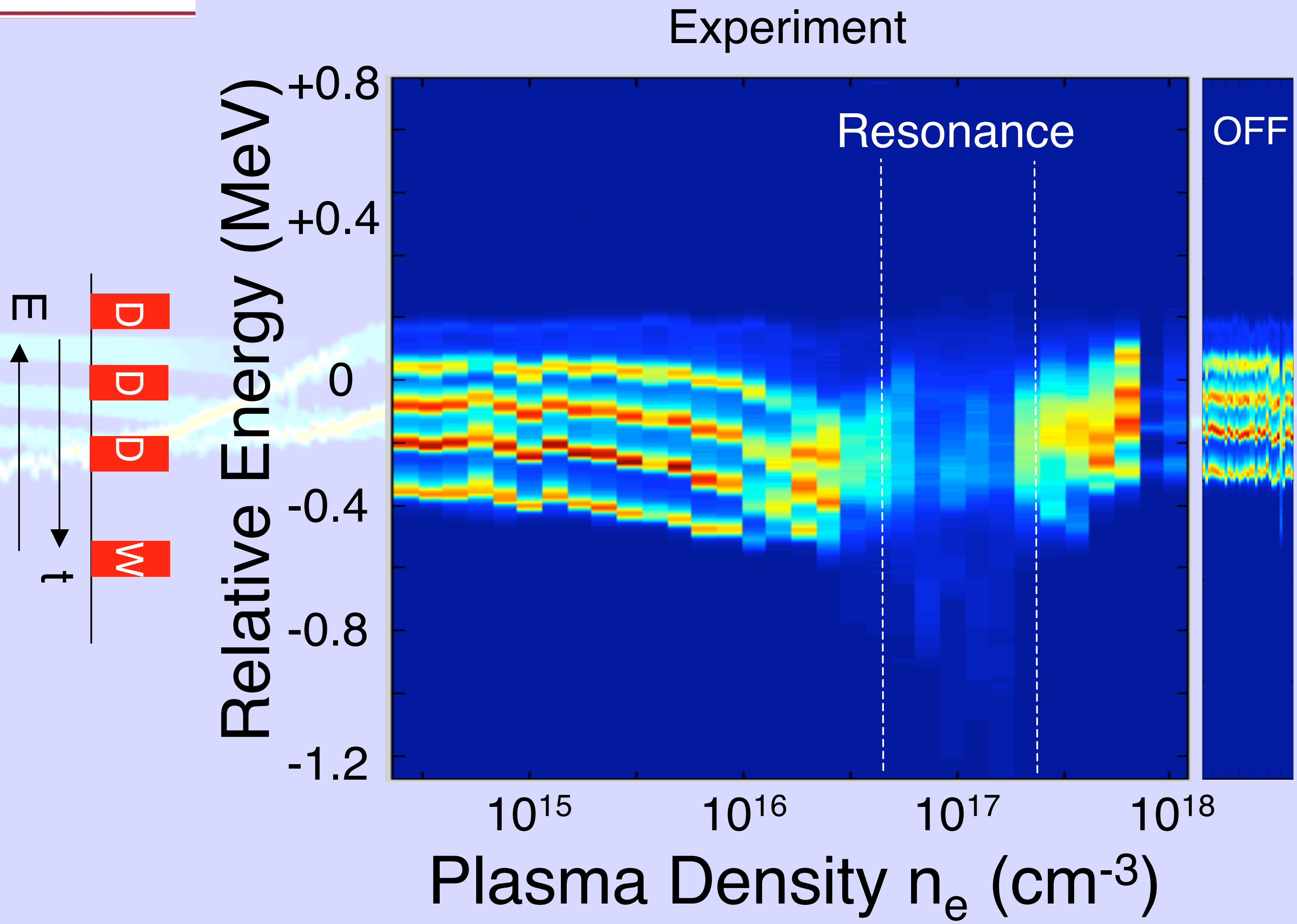
ENERGY CHANGE

Experiment



- Resonance clearly observed
- Large energy loss, >0.8 MeV or >40MeV/m
- Energy gain?

ENERGY CHANGE



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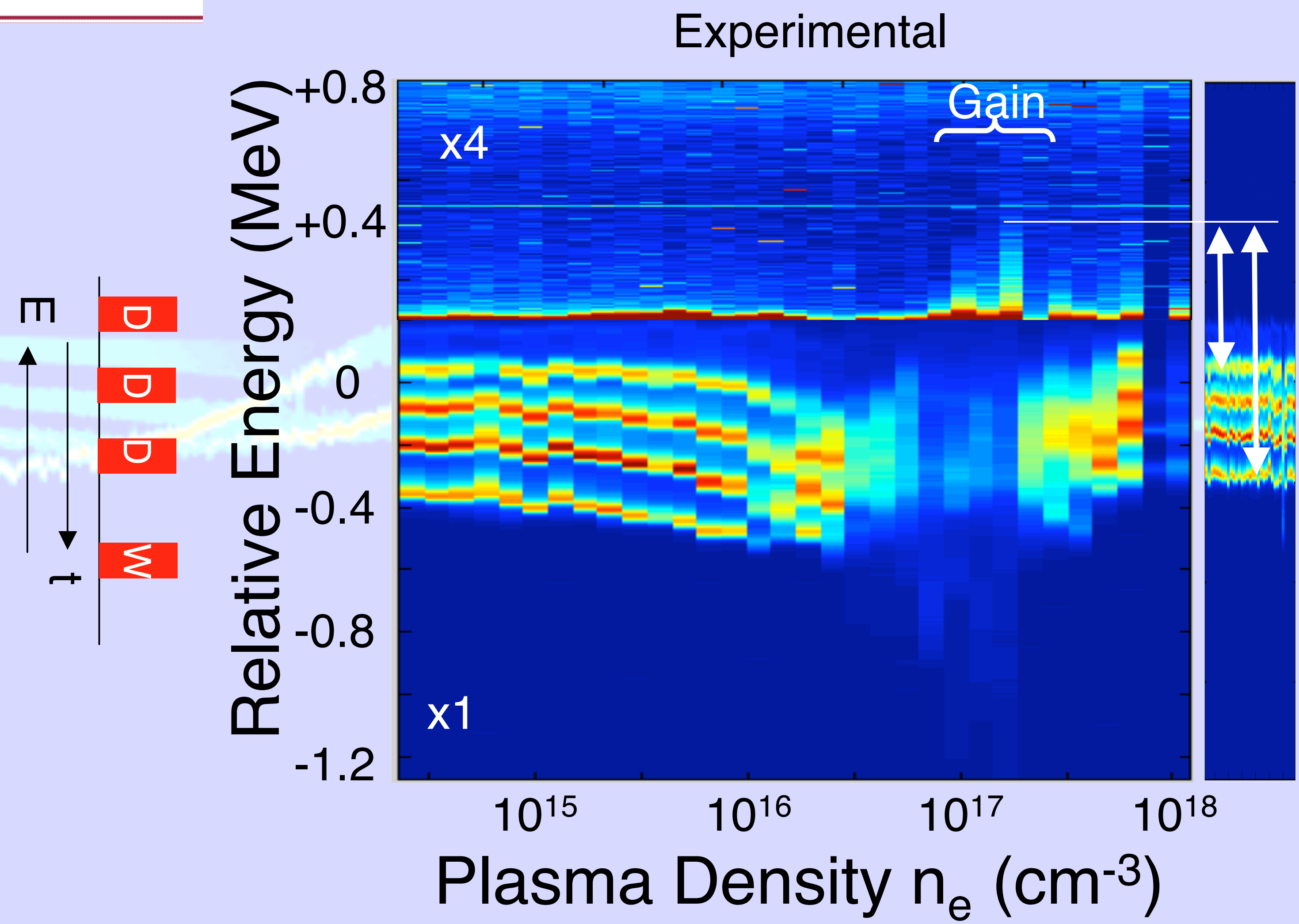
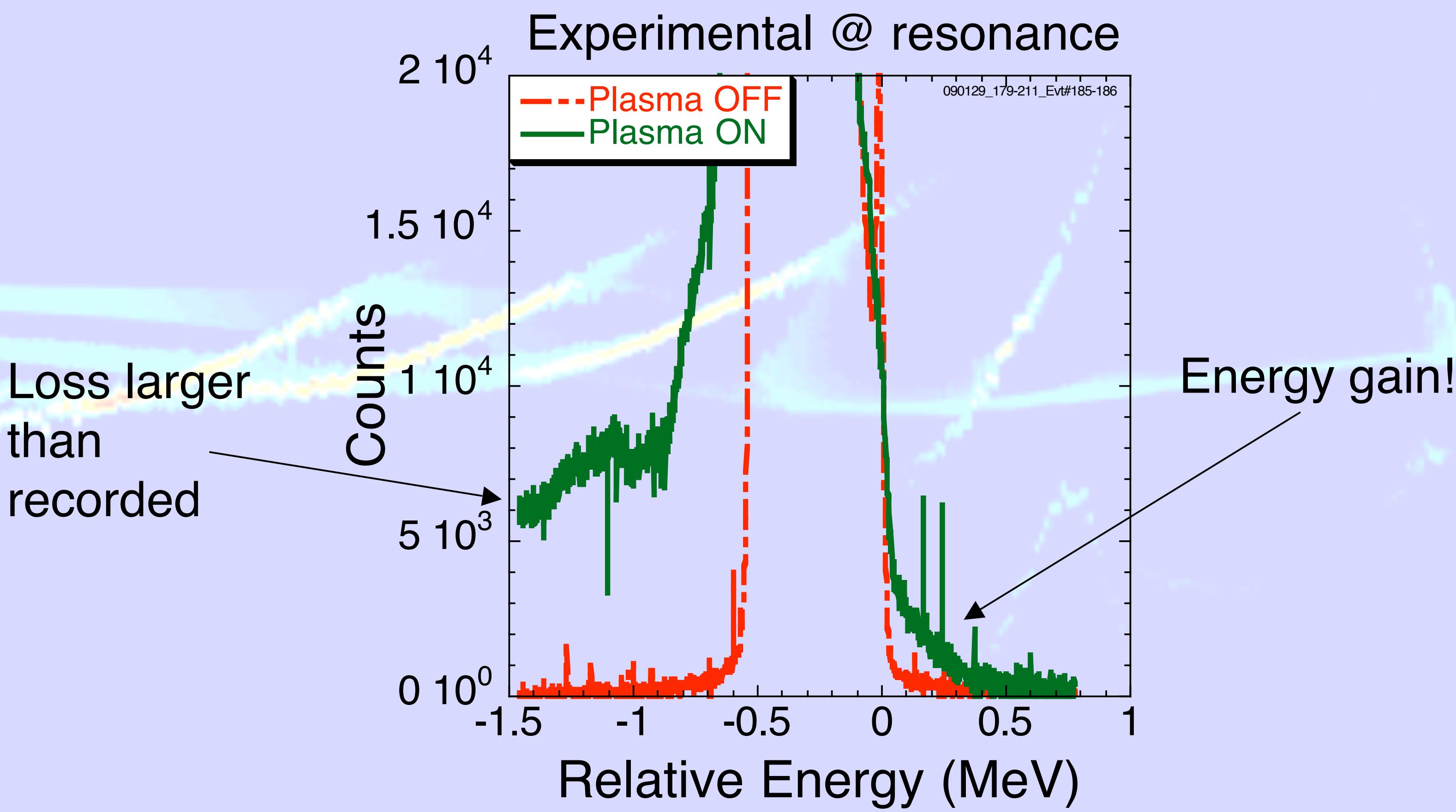
ENERGY CHANGE



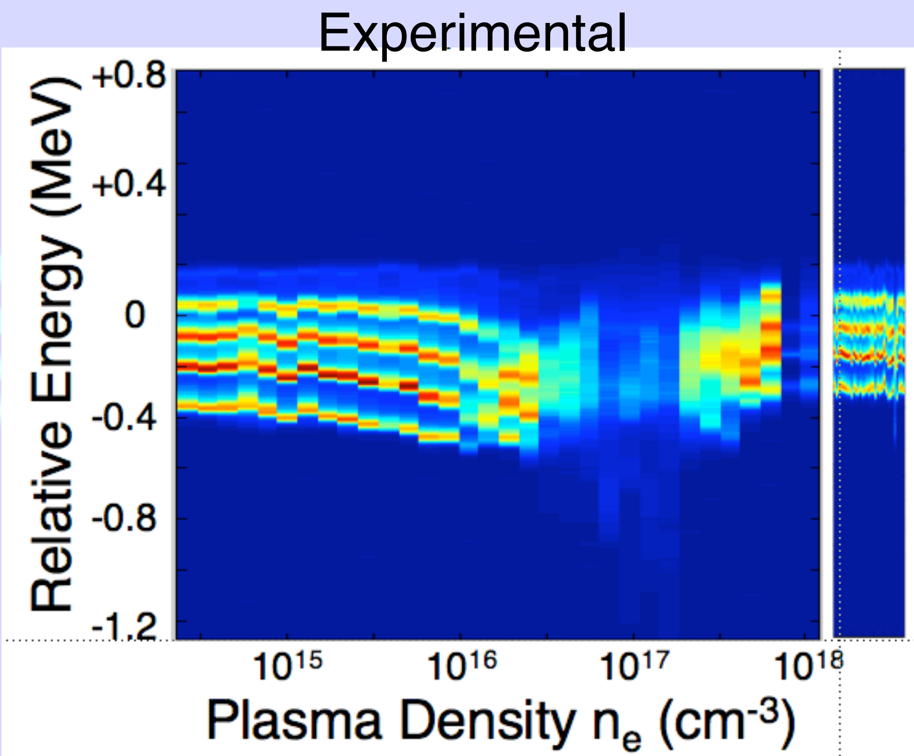
- Energy gain, up to 0.7 MeV?
- Stability of $\Delta E/E_0$ => stability of Δz!

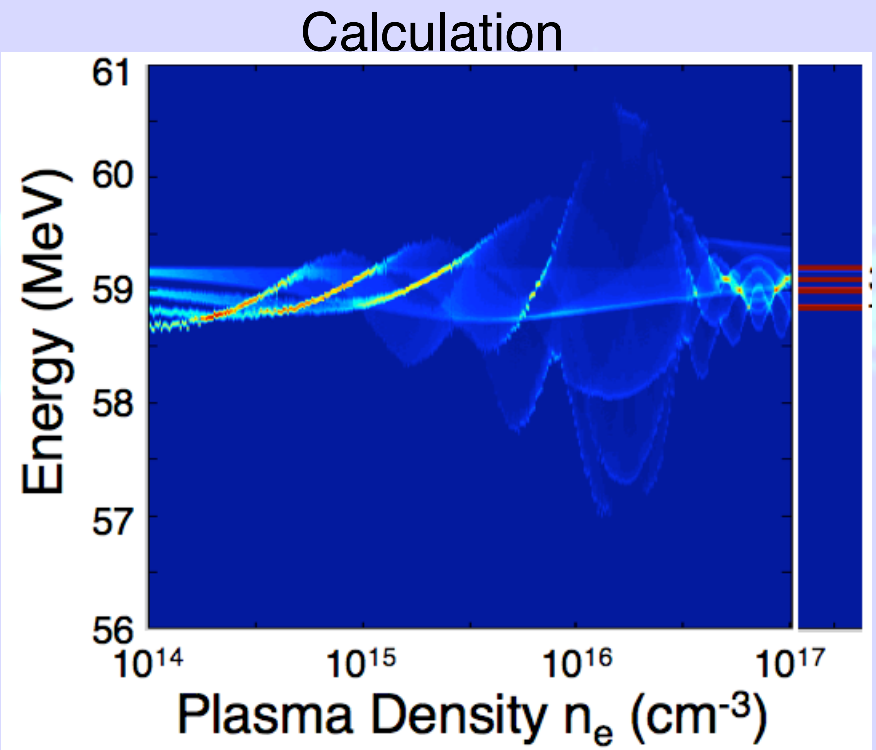
ENERGY CHANGE



- Can test energy gain from witness bunch by blocking it
- Smeared gain because μbunch length ≈ $\lambda_{pe}/2$
- Large loss, >1 MeV, L_p=2 cm, G_{-}>50 MeV/m

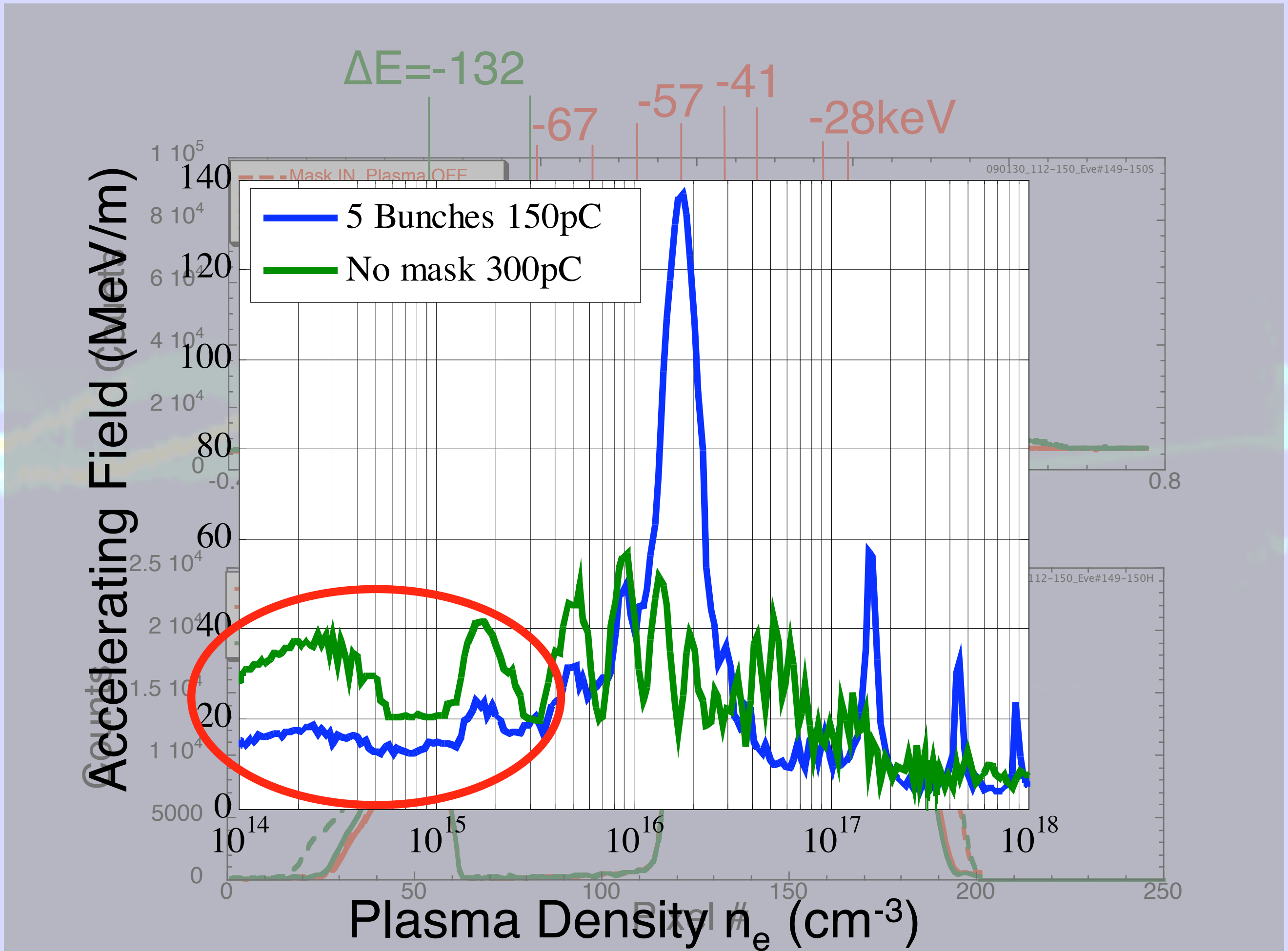
ENERGY CHANGE





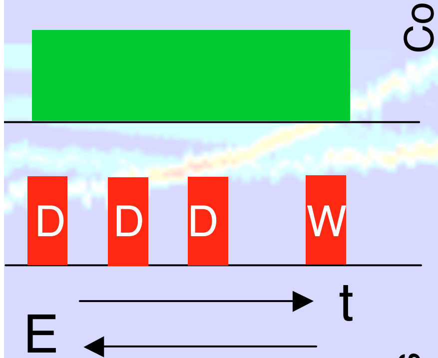
- Very suggestive!
- Microbunch resonance very clear
- Revisit $n_e(t)$ measurement

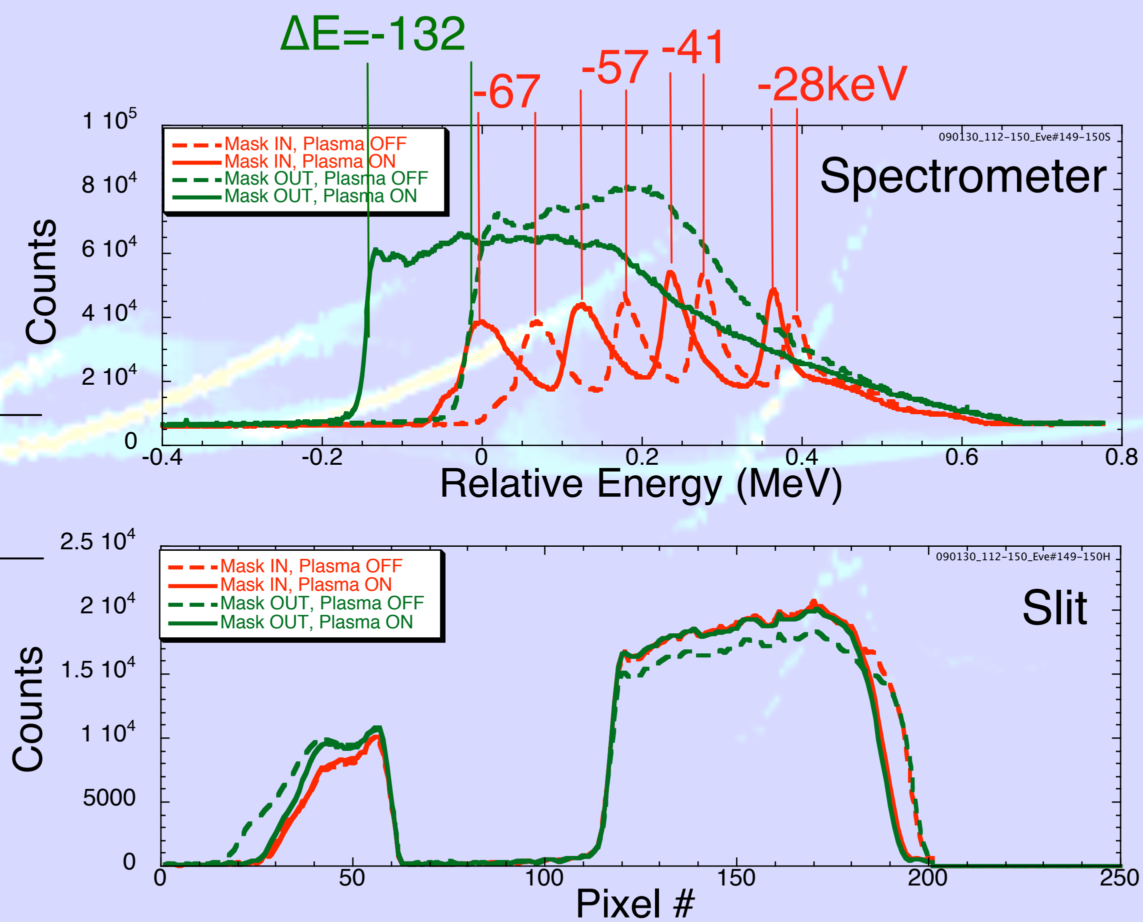
LOW DENSITY INTERACTION



- Similar spectra on slit ⇔ similar Δz
- Low n_e, l_p>Δz, off resonance, more loss without mask
- Interact with 'envelope", more charge without mask

LOW DENSITY INTERACTION





- Similar spectra on slit ⇔ similar Δz
- Low n_e, $l_p > \Delta z$, off resonance, more loss without mask
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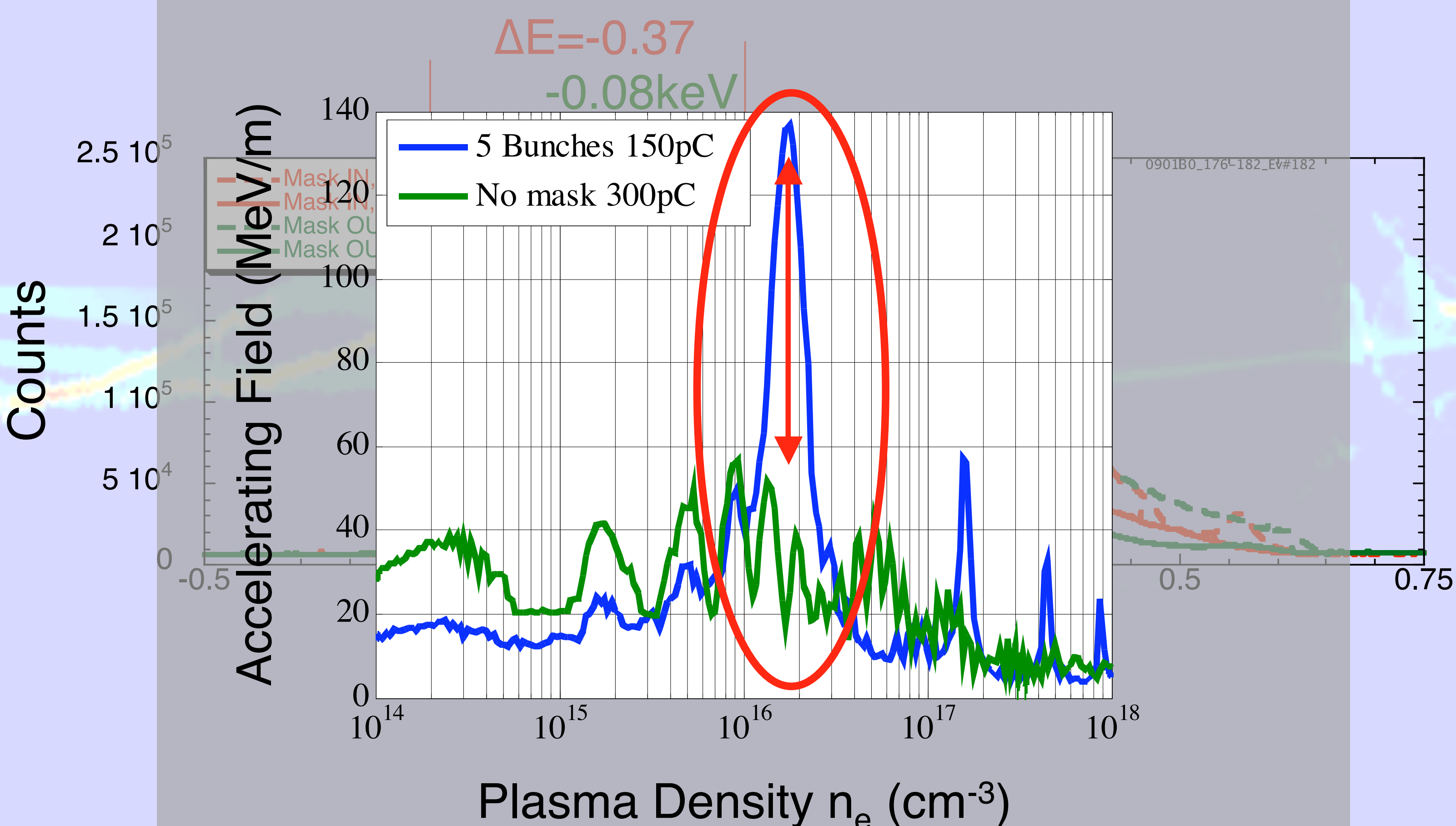
USC

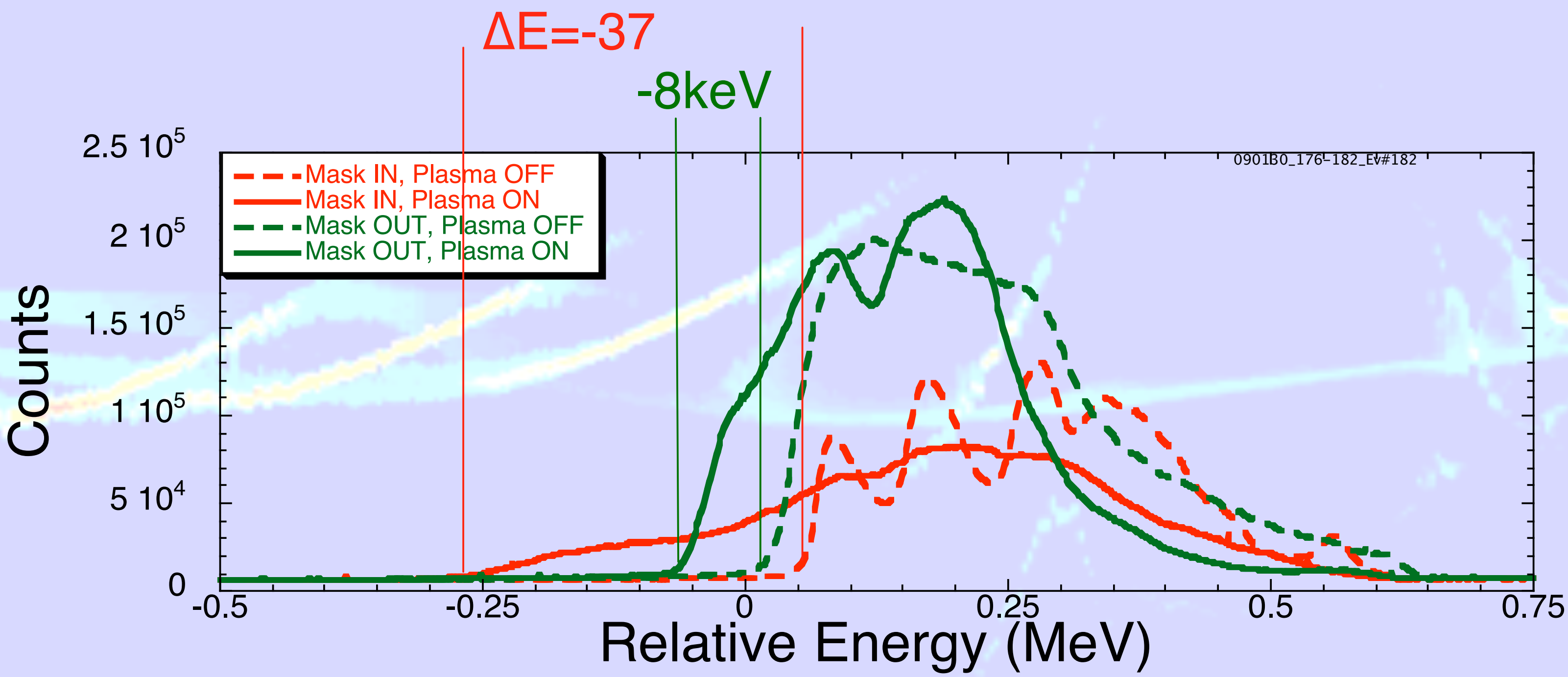
Resonant Density Interaction

BROOKHAVEN NATIONAL LABORATORY
STI OPTRONICS



- Much larger loss with microbunches at resonance
- Decelerating gradient ≈18 MV/m

RESONANT DENSITY INTERACTION



- Much larger loss with microbunches at/near resonance
- Drive large wakefield with half the charge and large n_e
- Decelerating gradient with μbunches ≈18 MV/m

CONCLUSION

- Resonance excitation of PWFA with multi-bunch train observed
- Main feature: large energy loss, loss of bunch structure, energy gain
- Single-bunch/multi-bunch effect
- More interesting experiments to do:
  - vary # drive bunch
  - block witness bunch
  - shaping for transf. ratio
- Questions:
  - effect of CSR on bunch spacing
  - $\lambda_{pe}=\Delta z$? $n_e(t)$=???
  - stability of Δz or $\Delta E/E_0$
- Larger gradient with compressed train, x-band cavity
  Rotation of phase space, W on high energy side!
- Arguably the most interesting PWFA physics experiment!

Thank you!

AND

Thank you <u>very much</u> to every one at ATF!