Resonant Excitation of Plasma Wakefields with a Train of Relativistic Particle Bunches

Livio Verra
(on behalf of SPARC_LAB Group)

European Advanced Accelerator Conference 2025
23.09.2025

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Introduction – Resonances in Plasma

- Plasma electrons and ions oscillate at natural frequencies in response to external disturbances:

$$\omega_{pe} = \sqrt{\frac{n_{pe}q^2}{\varepsilon_0 m_e}}, \quad \omega_{pi} = \sqrt{\frac{n_{pi}(zq)^2}{\varepsilon_0 m_i}}$$

- Important for:
  - Wave propagation ($\omega_0 > \omega_{pe}$)
  - Plasma diagnostics (e.g. n_{pe})
  - Energy transport and heating in fusion plasmas (e.g. Electron Cyclotron Resonance)
  - Instabilities
  - Effective wakefield excitation: disturbance coupled to oscillation

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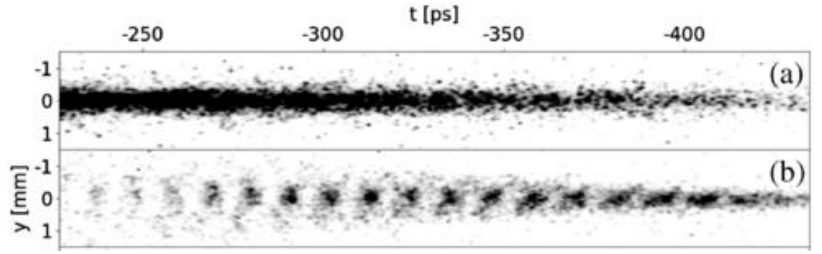
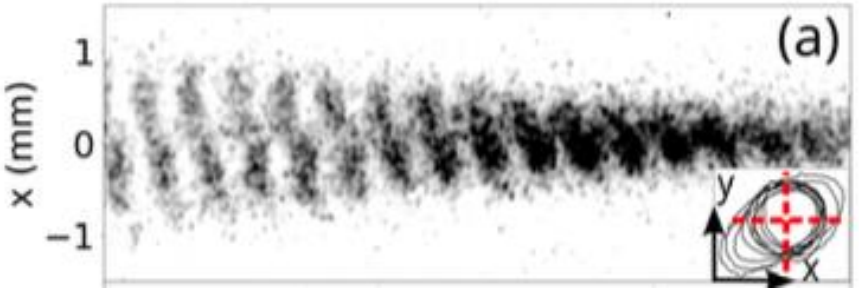


L. Verra et al. (AWAKE Coll.) PRL **129**, 024802 (2022)



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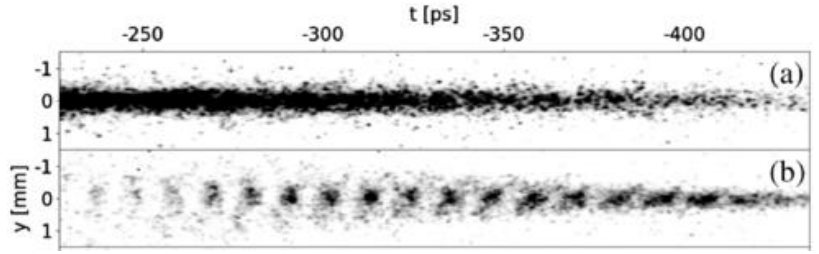

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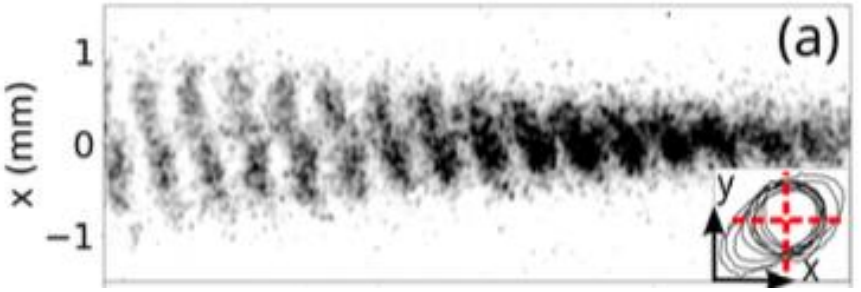

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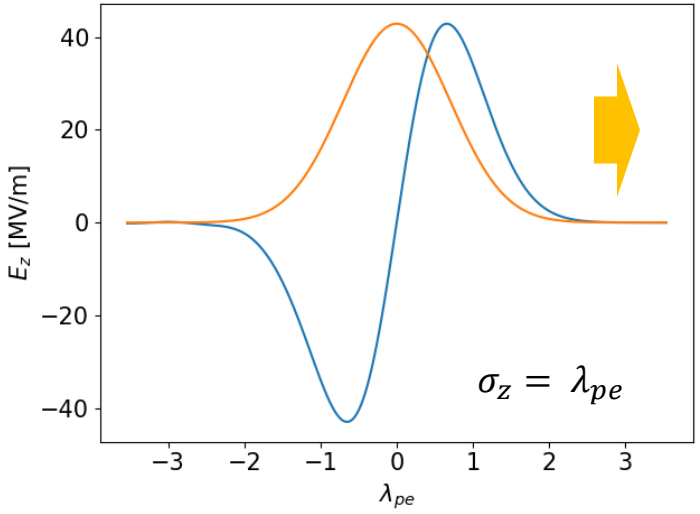

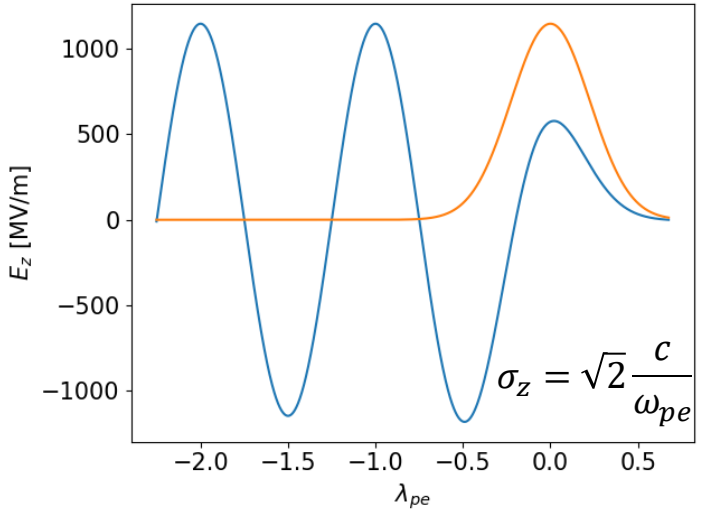

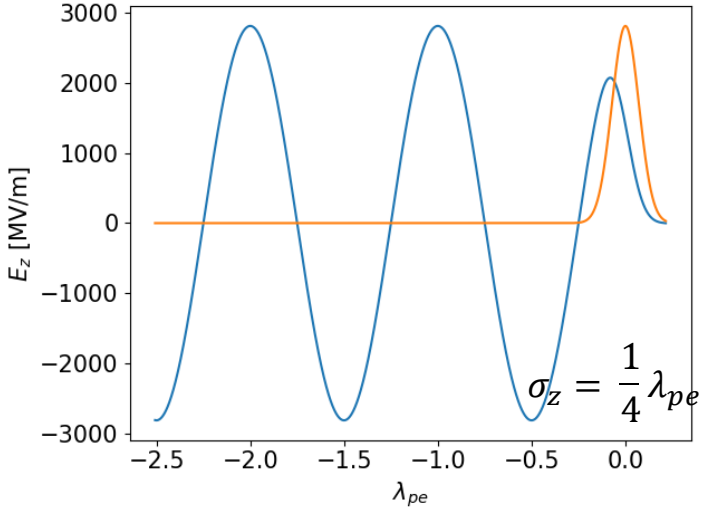

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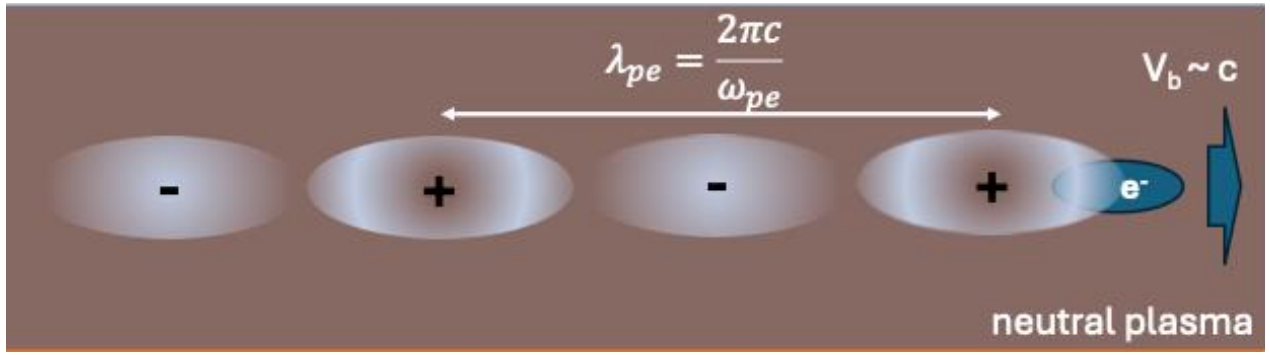
- Wakefields driven by successive bunches superpose
  → can be used to drive wakefields resonantly with multiple driver bunches



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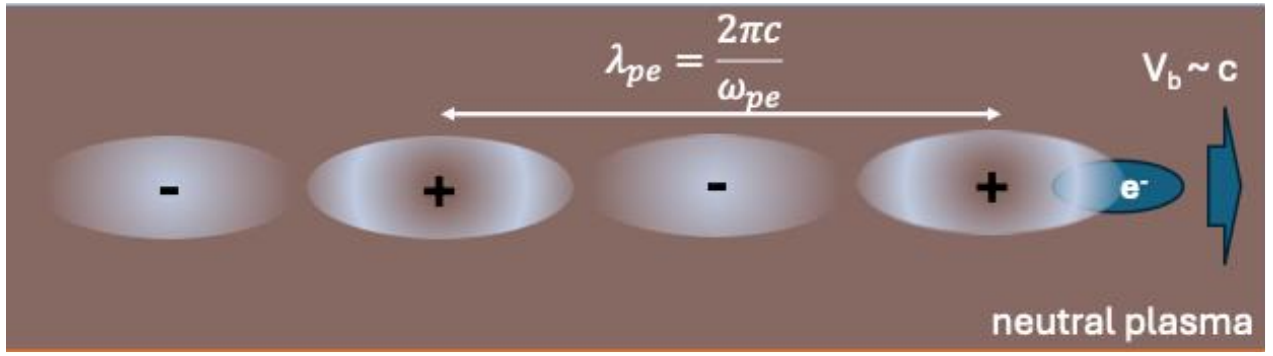
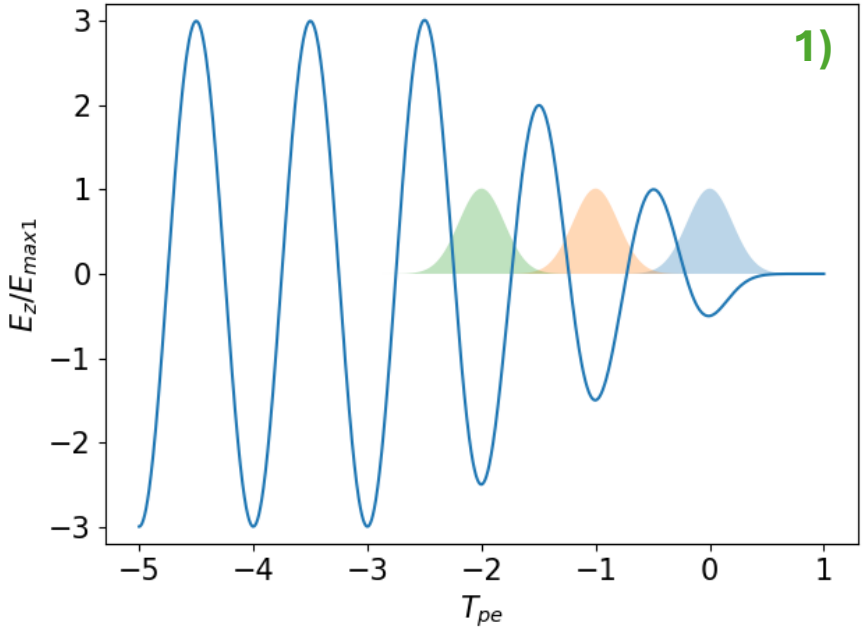
  1) Maximizing amplitude of longitudinal wakefields





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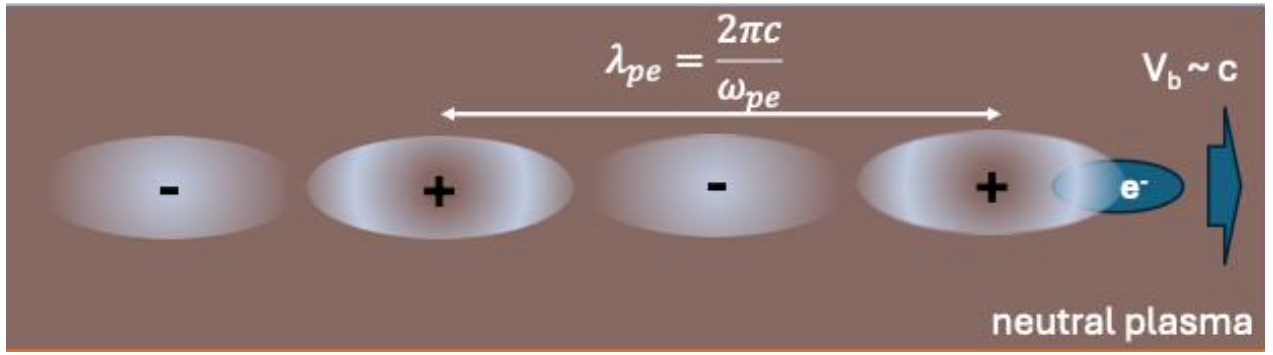
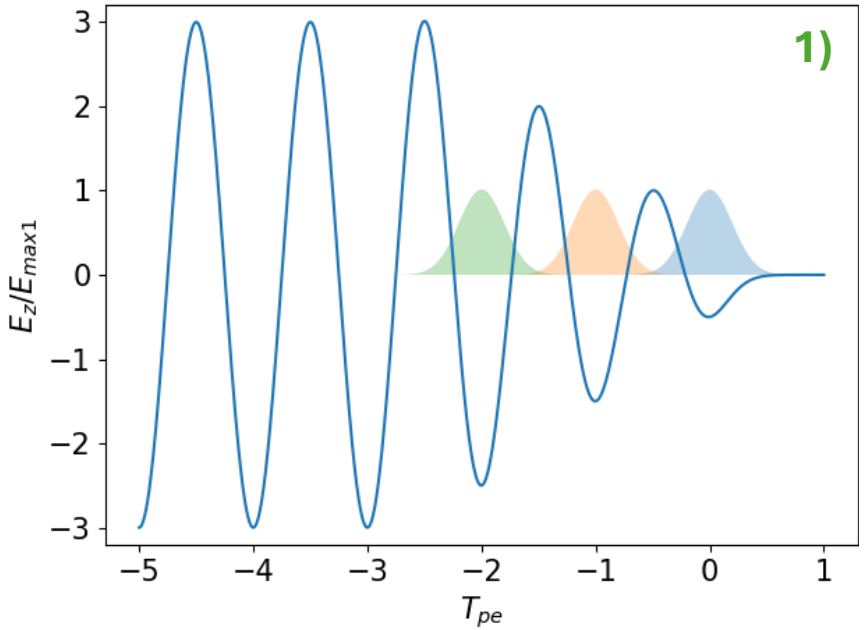
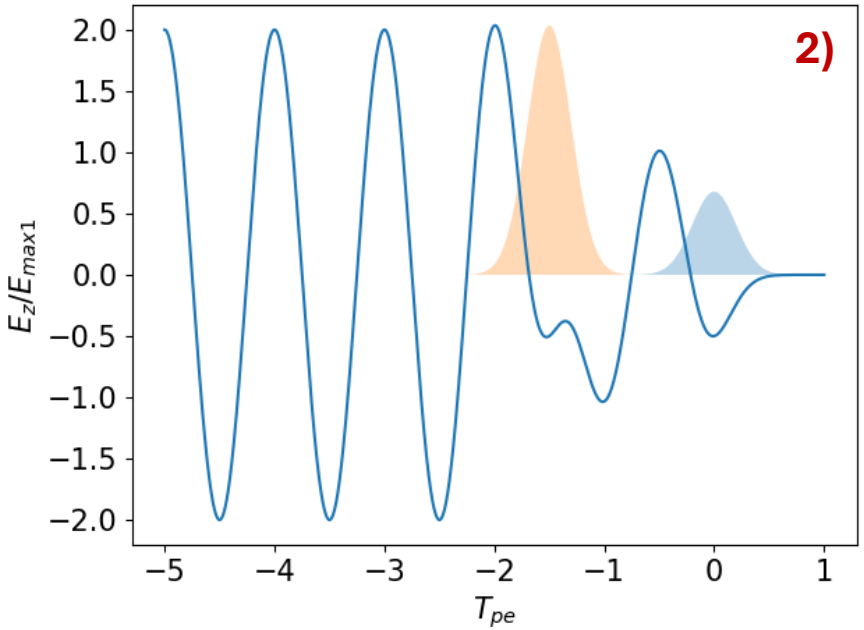
  2) Maximizing the ratio between decelerating and accelerating (transformer ratio)







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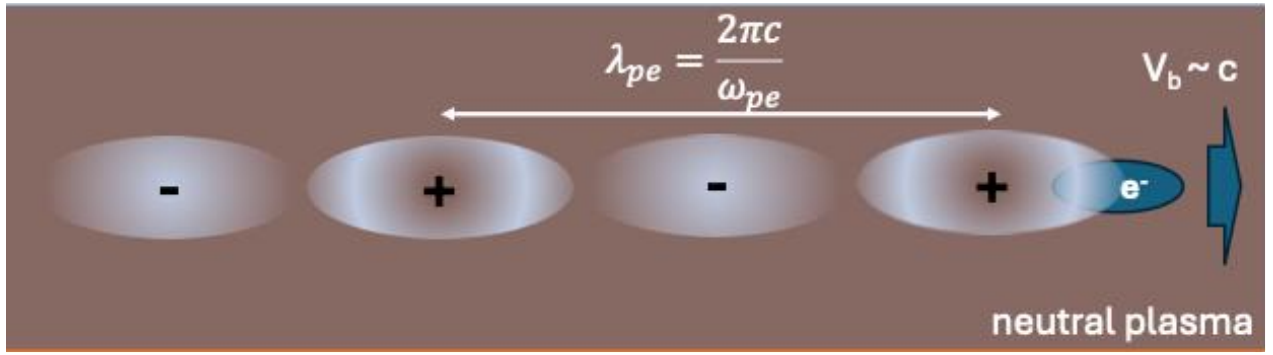

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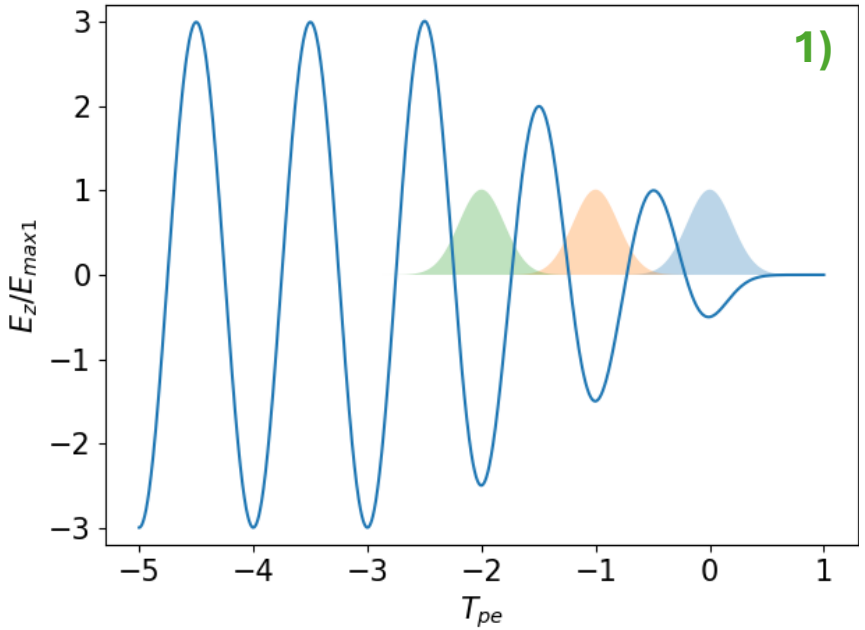
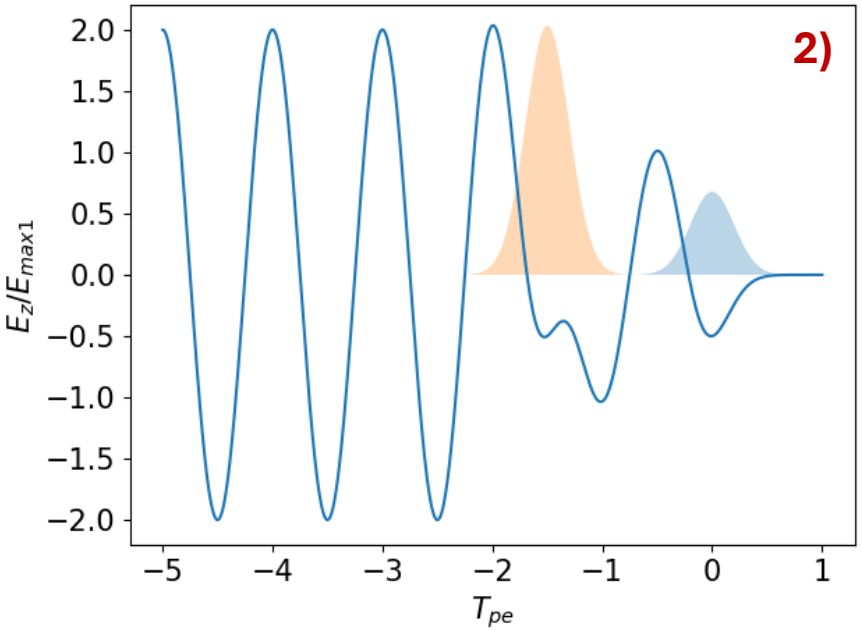
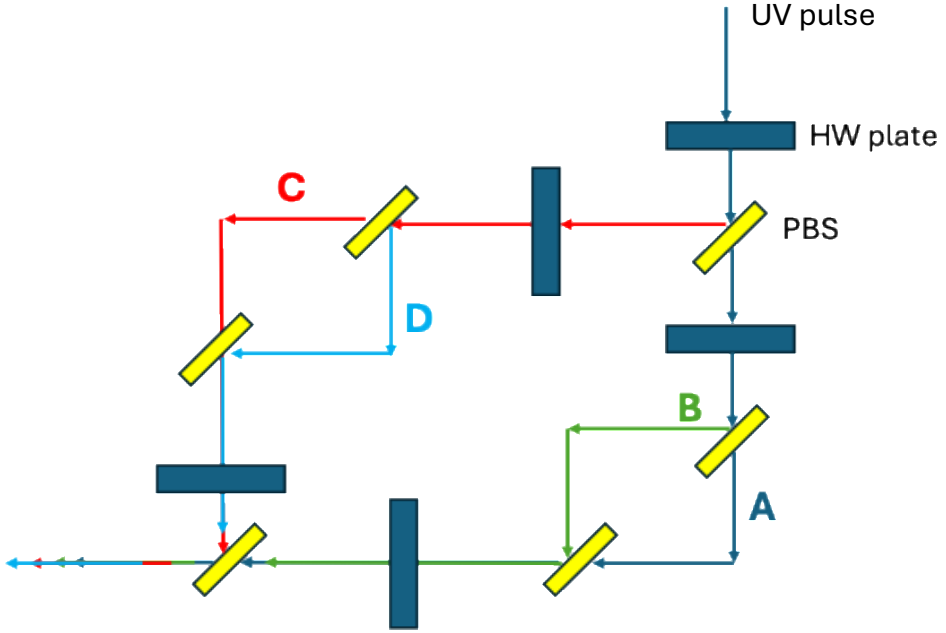
- Need a train of bunches with ~ps delay and adjustable relative charge





SPARC – Multiple Bunches

- Multiple UV pulses generated by splitting and delaying the initial pulse
- Combination of $\lambda/2$ plates and polarizing beam splitters → independent control of the charge and delay of each bunch



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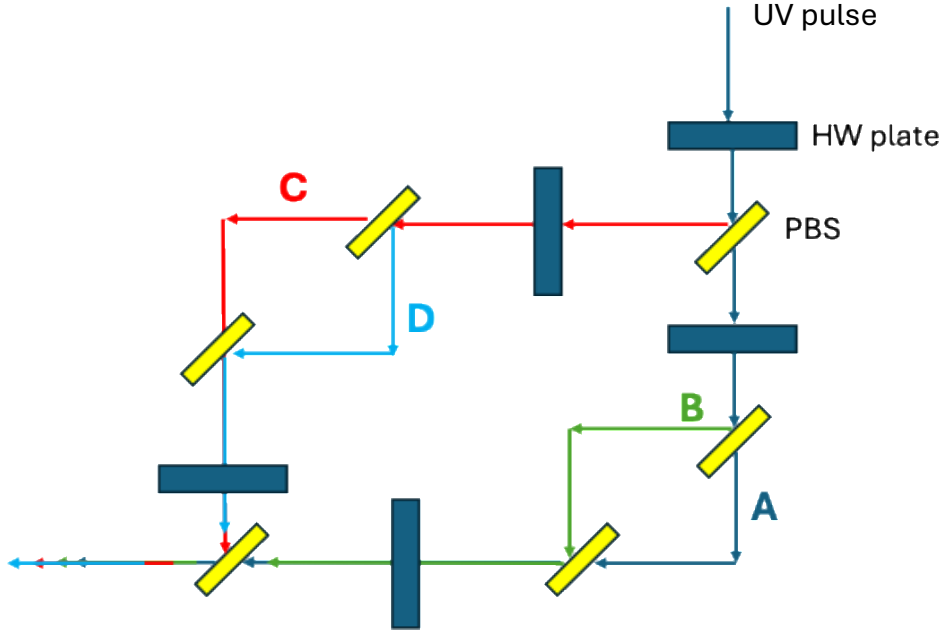

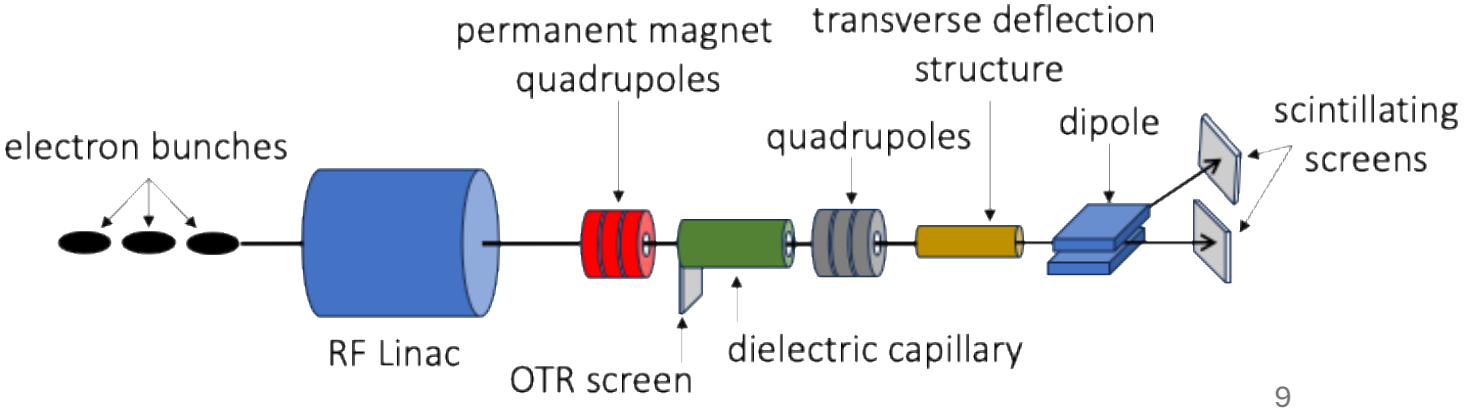

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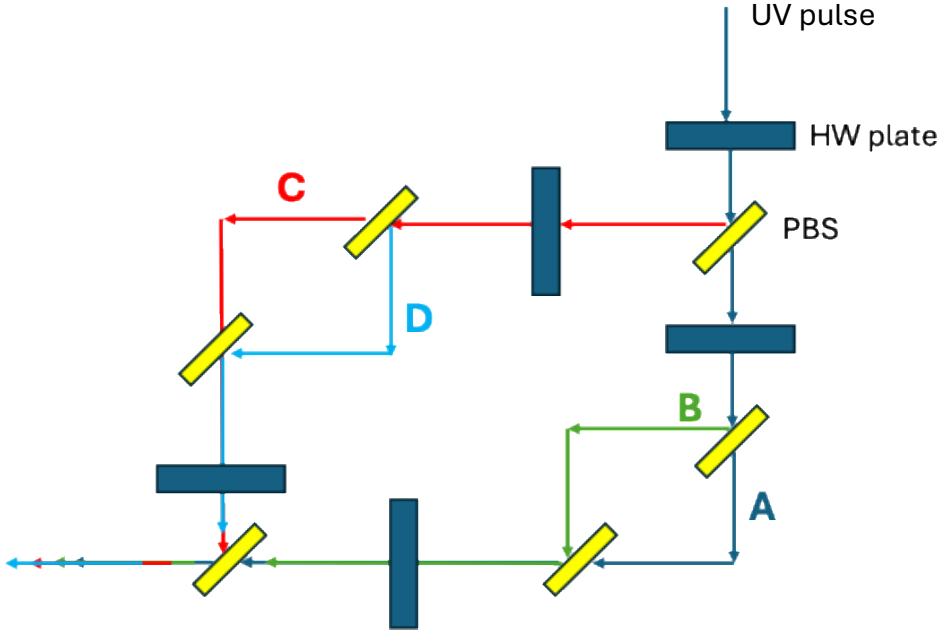

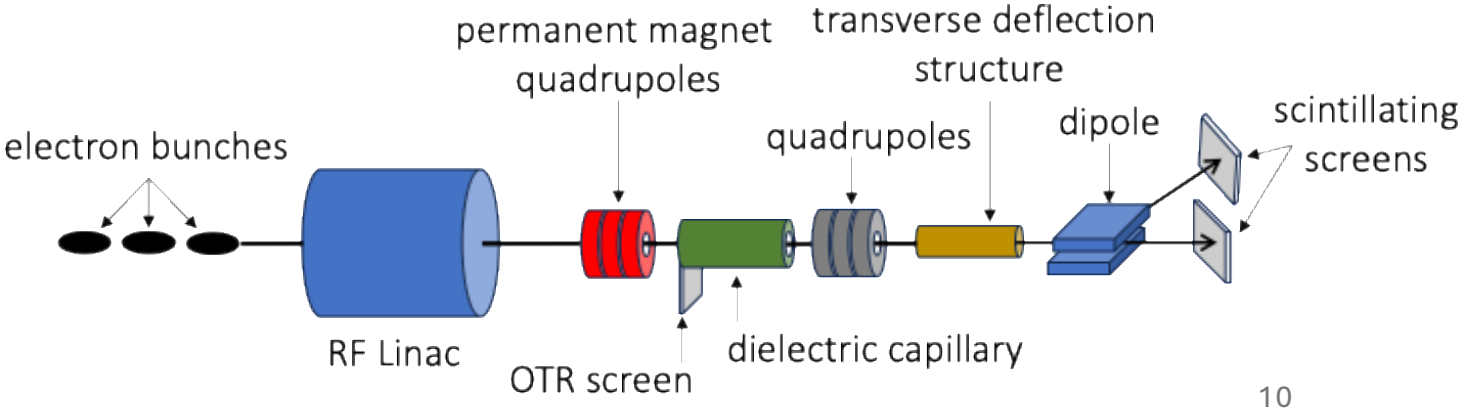

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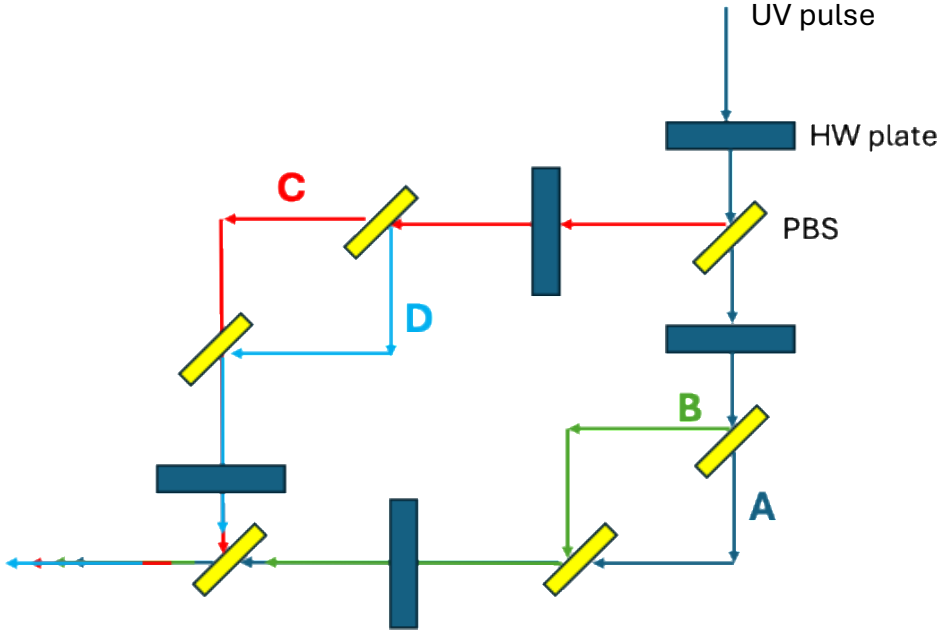

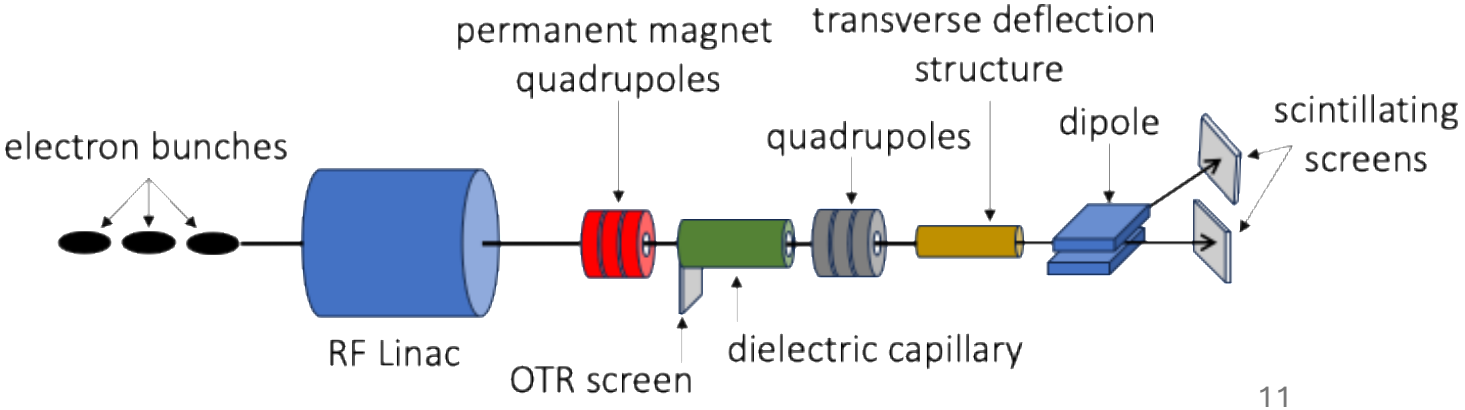

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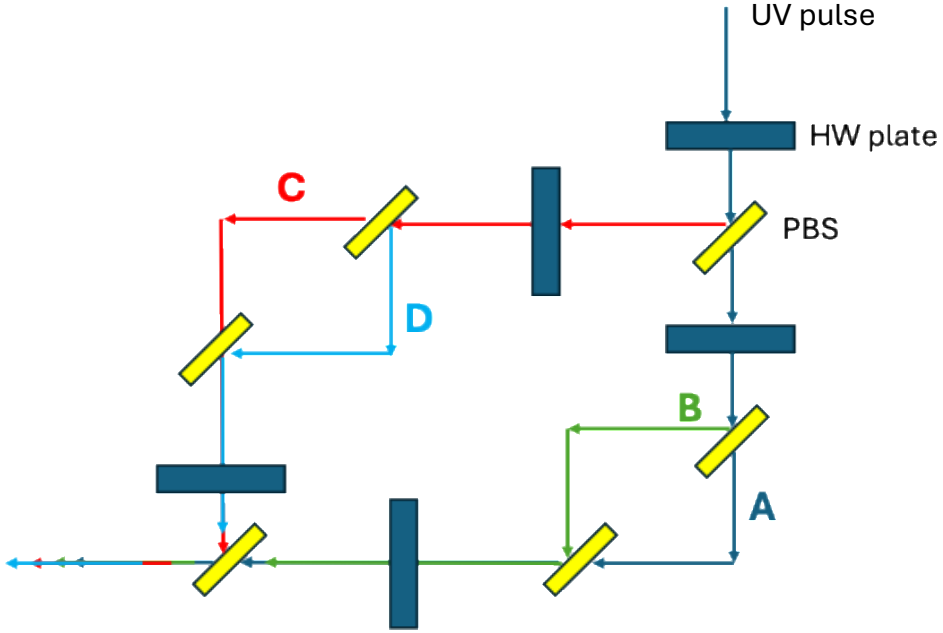

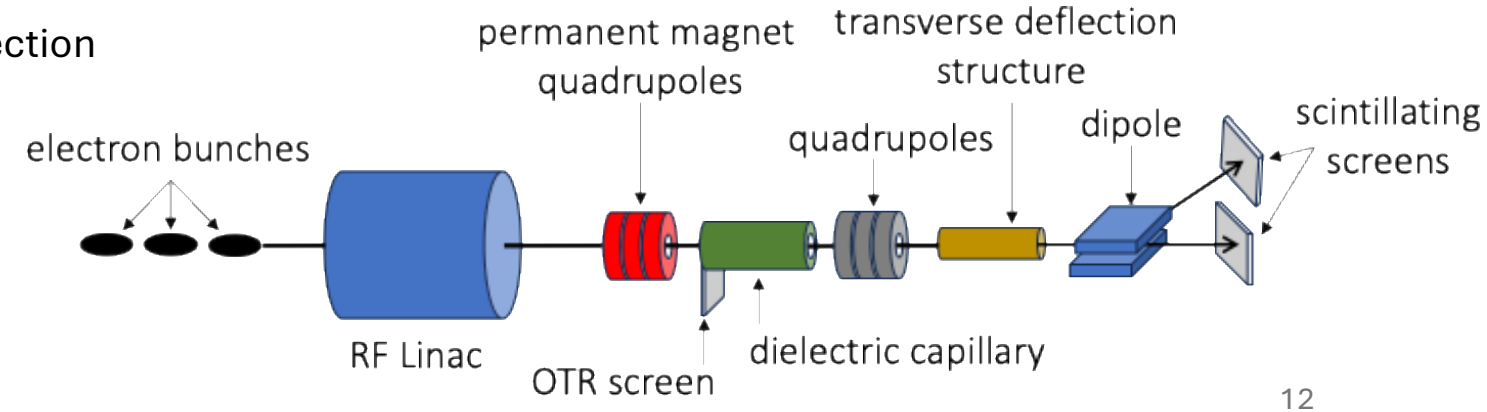

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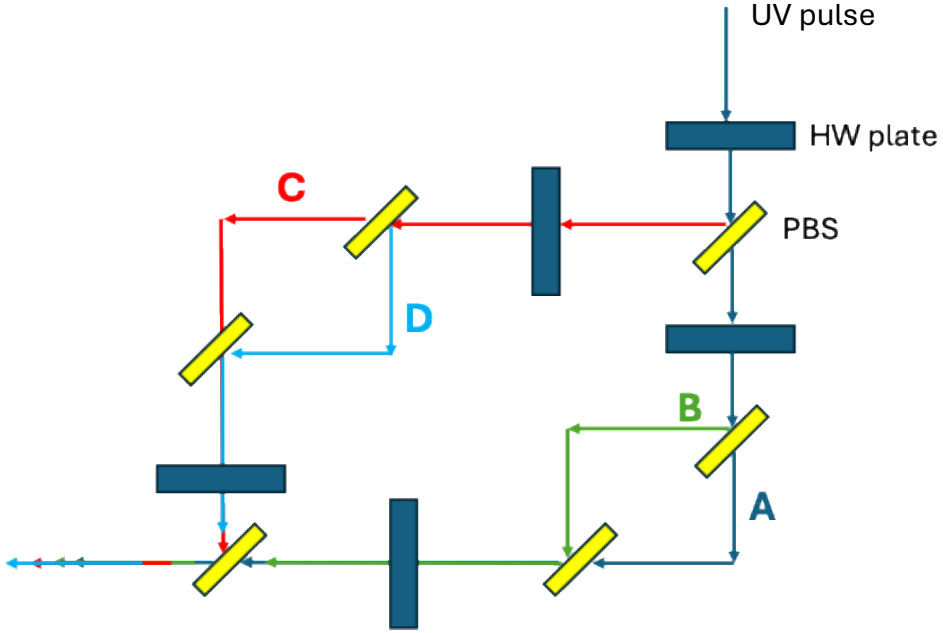
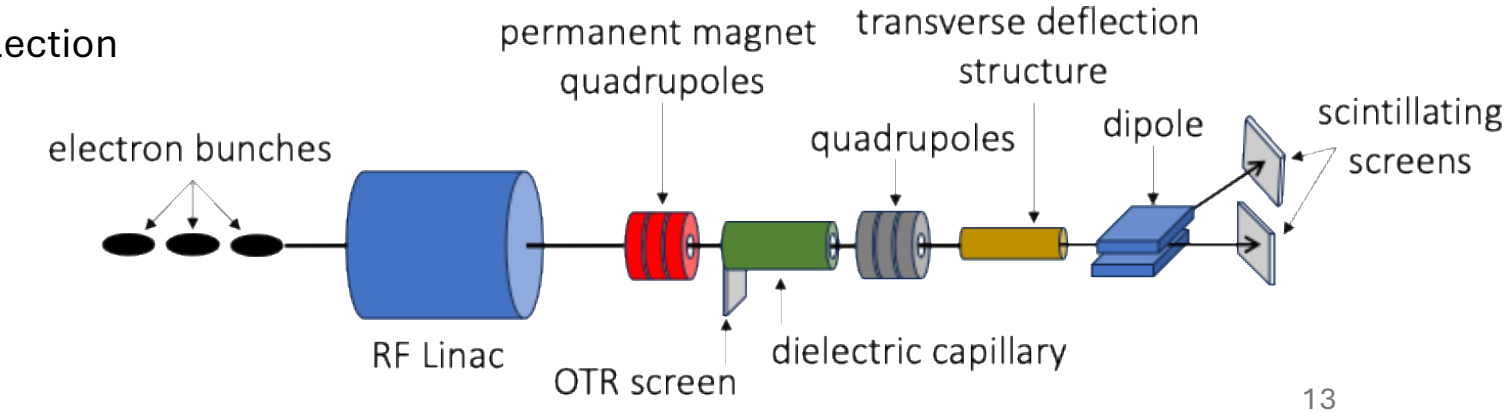
- Longitudinal phase space using dipole + TDS



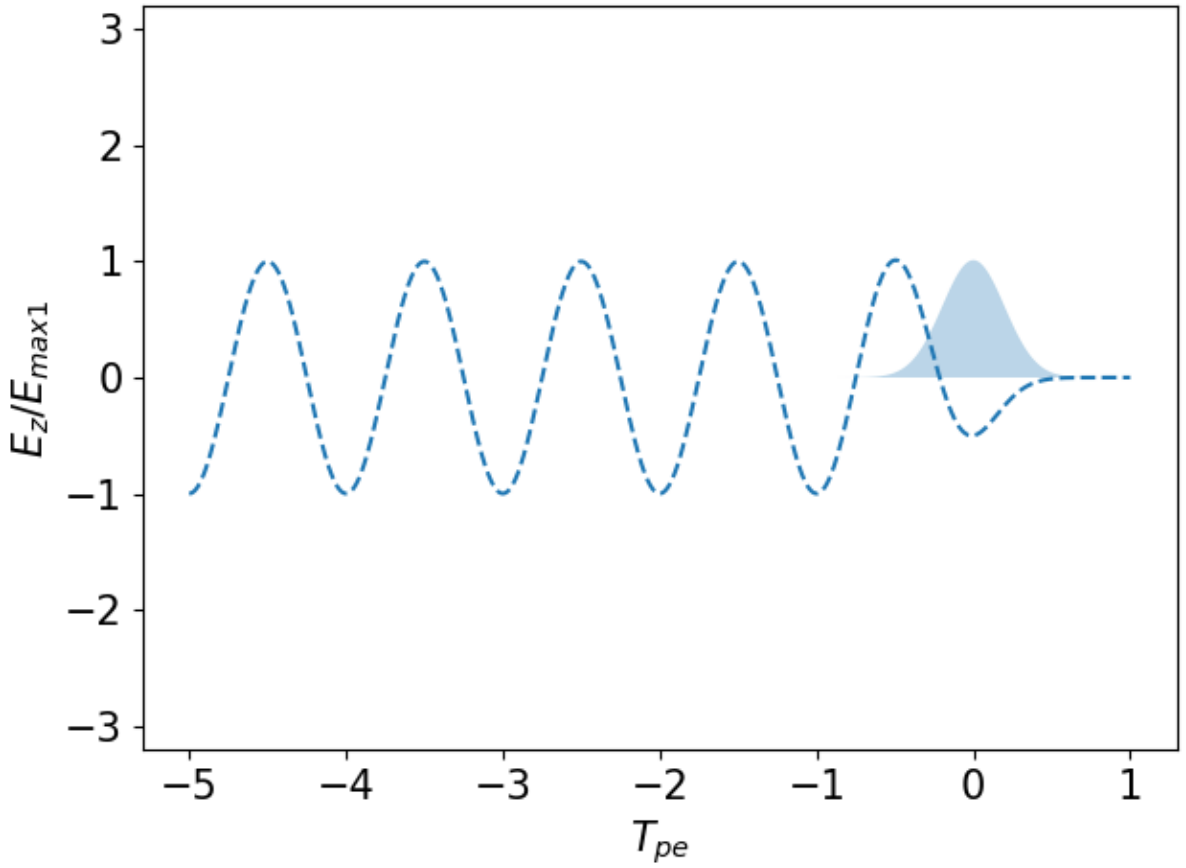


Maximizing the amplitude of the wakefields

Successive drivers positioned within the **decelerating phase** of the wakefields driven by the preceding ones

- Resonance when
  $\Delta t = T_{pe}$
  $f_{train} = f_{pe}$

e.g: $n_{pe} = 1.3 \cdot 10^{15}\ cm^{-3}$
$f_{pe} = 323\ GHz$
$T_{pe} = 3.1\ ps$



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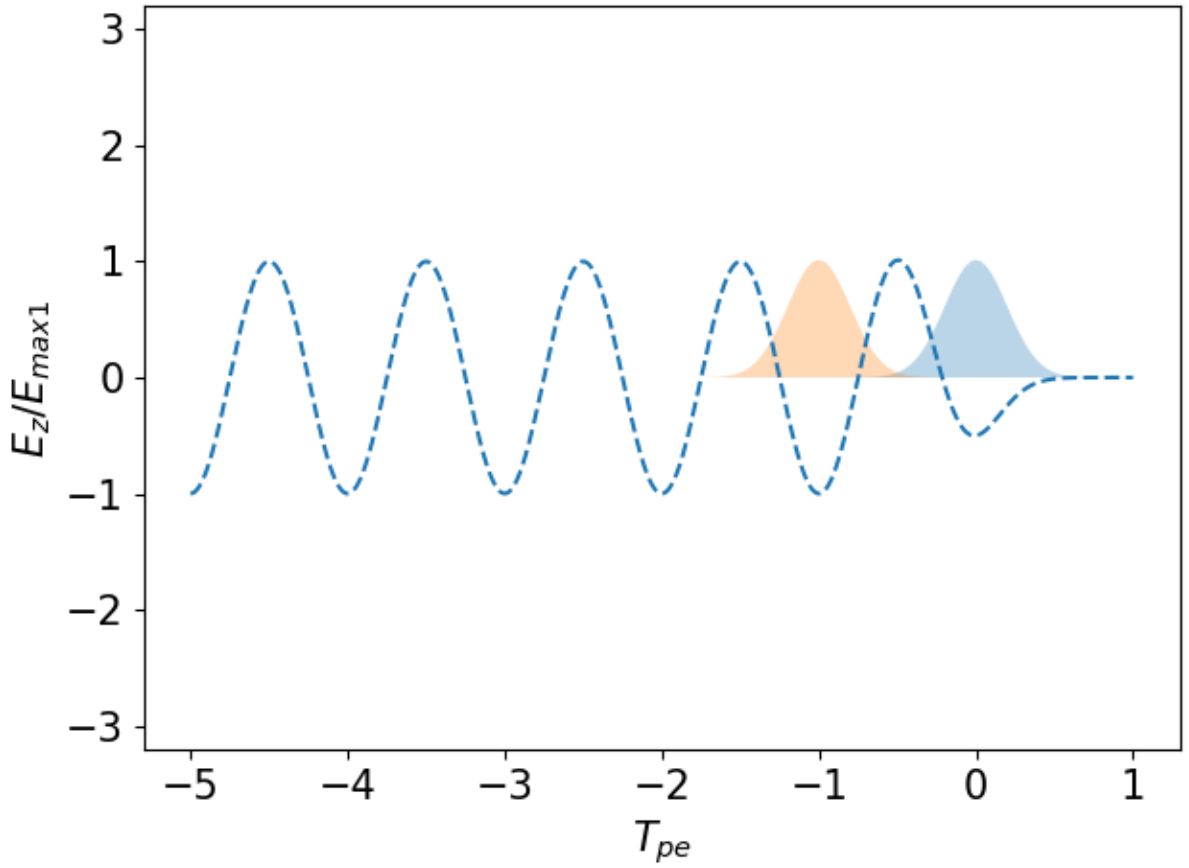

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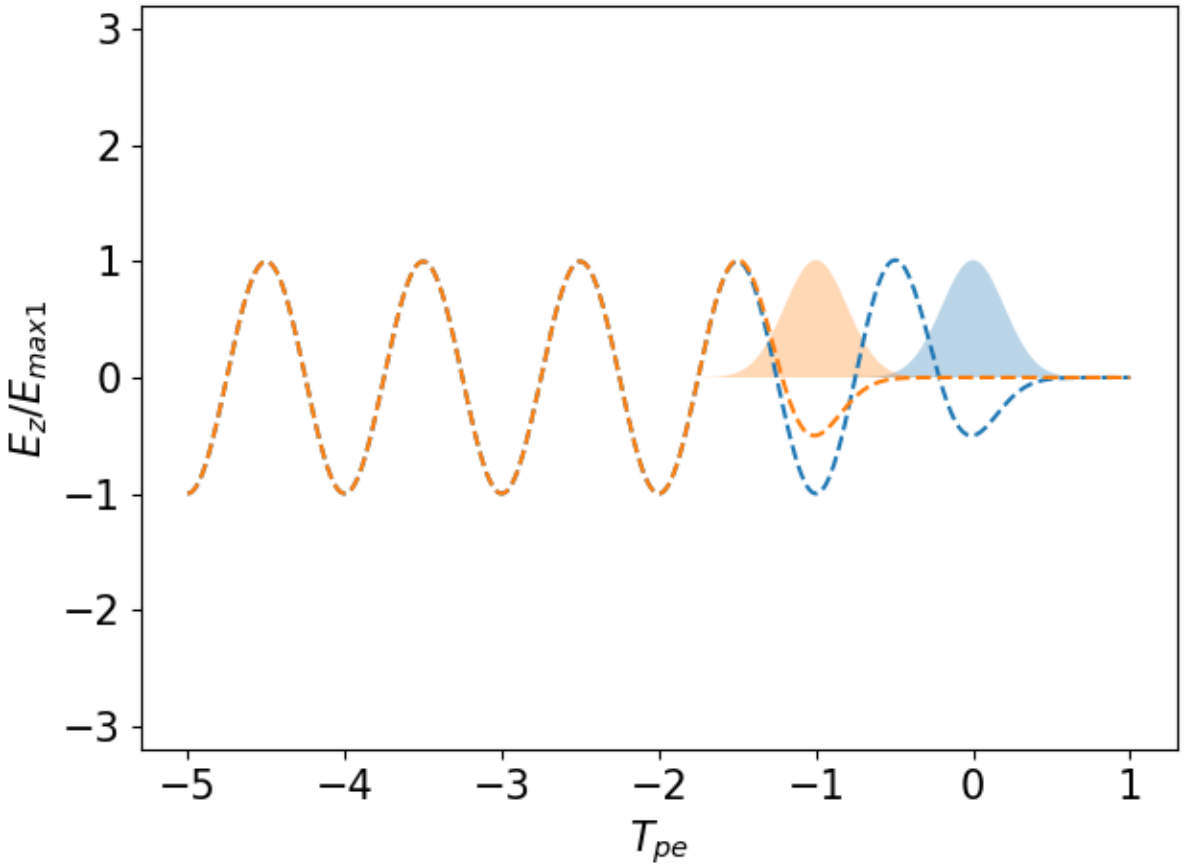

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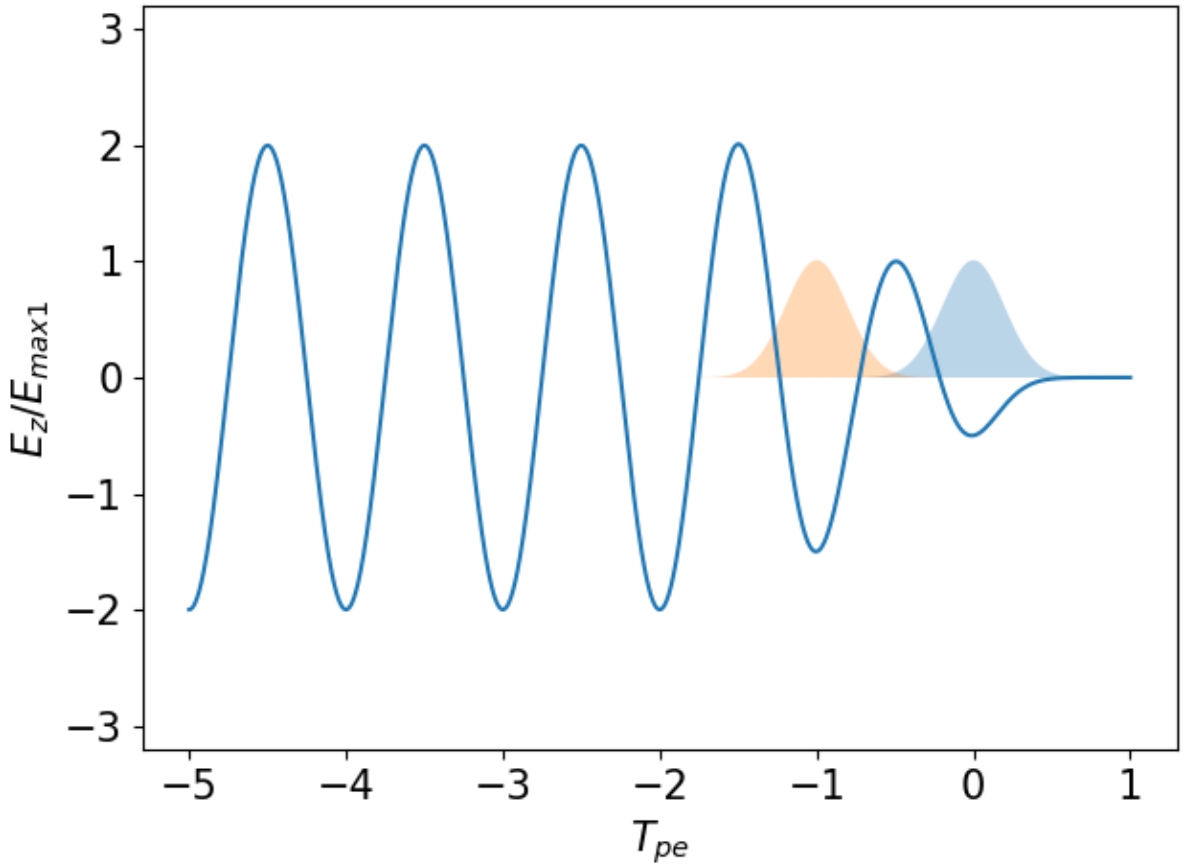

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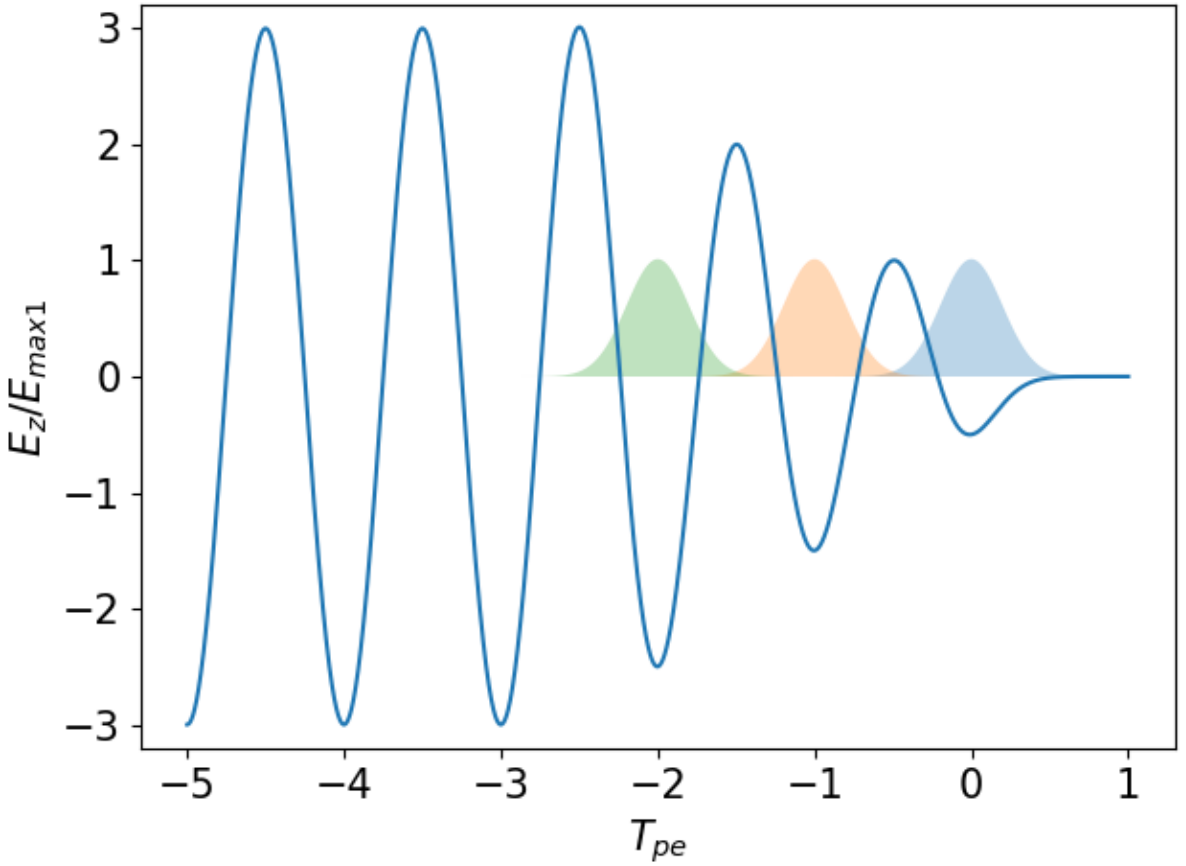
- Potentially larger amplitude than single bunch with equal total charge

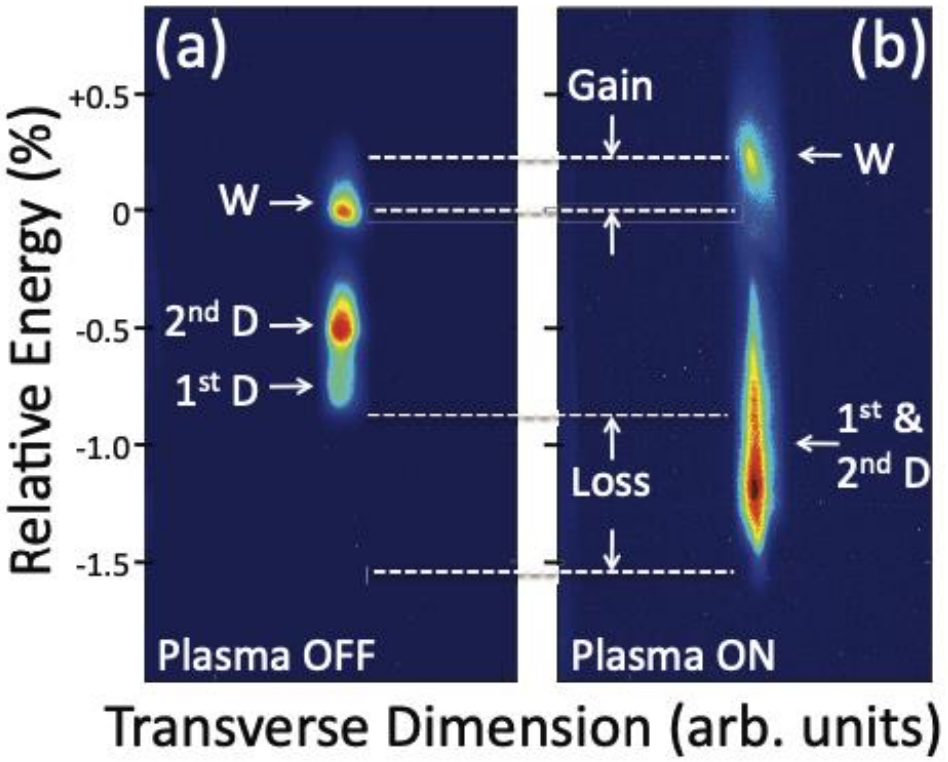
➔ **Observable at optimal coupling: increasing maximum energy loss of successive driver bunches**



Maximizing the amplitude of the wakefields – Previous Results

Acceleration with two driver bunches at BNL/ATF:

- Bunches obtained with mask in dispersive section
  → Charge loss during the transport



P. Muggli et al., Proceedings of PAC 2011

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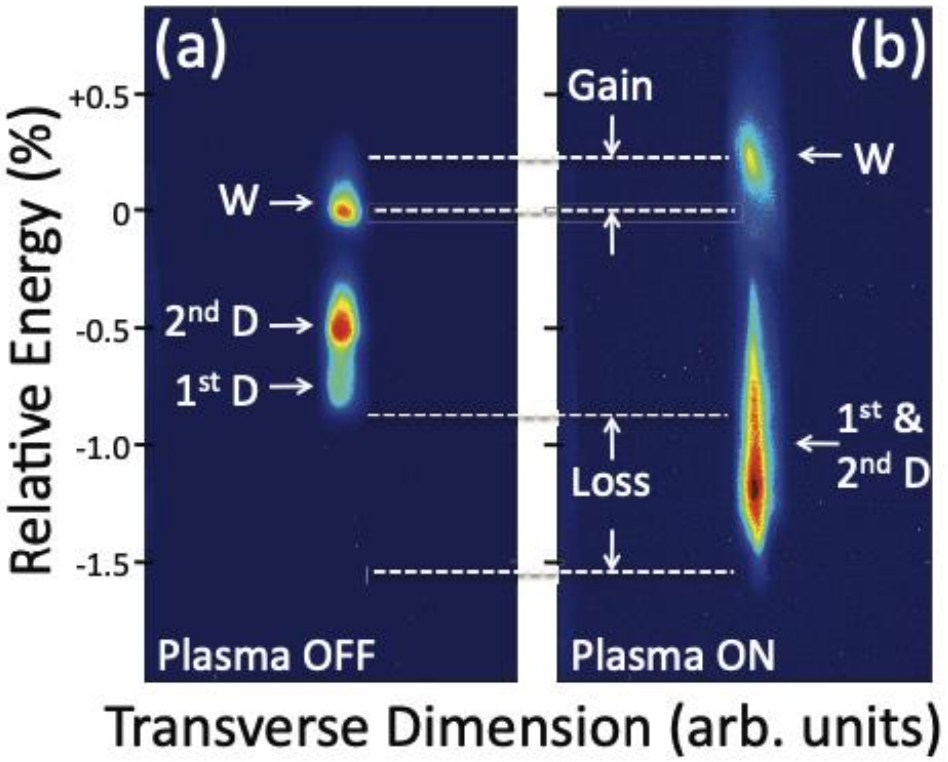

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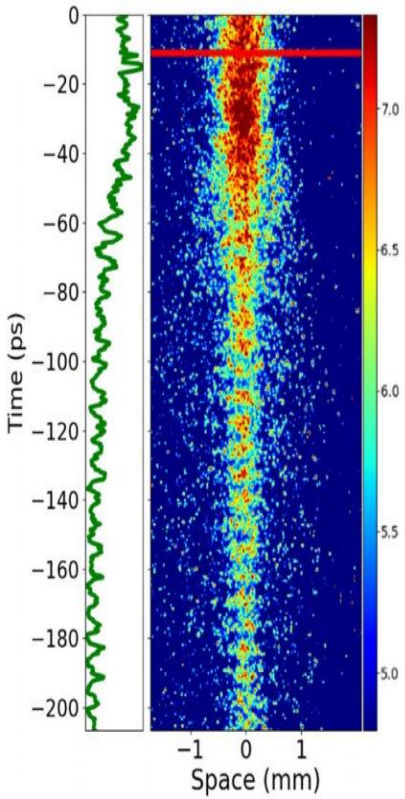
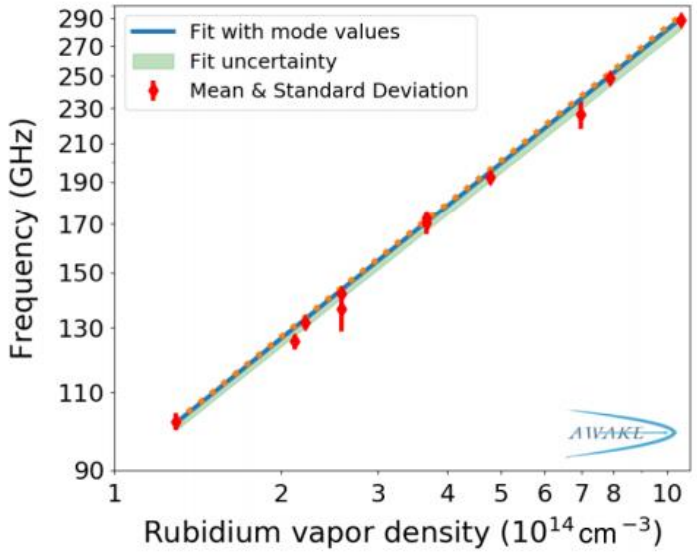
Acceleration with self-modulated p+ bunch (AWAKE)

- Periodic structure obtained by Self-Modulation
  → $f_{train} = f_{pe}$
  → only about half of initial charge contributes to driving final wakefields
  → need to wait for instability to saturate before injecting witness bunch

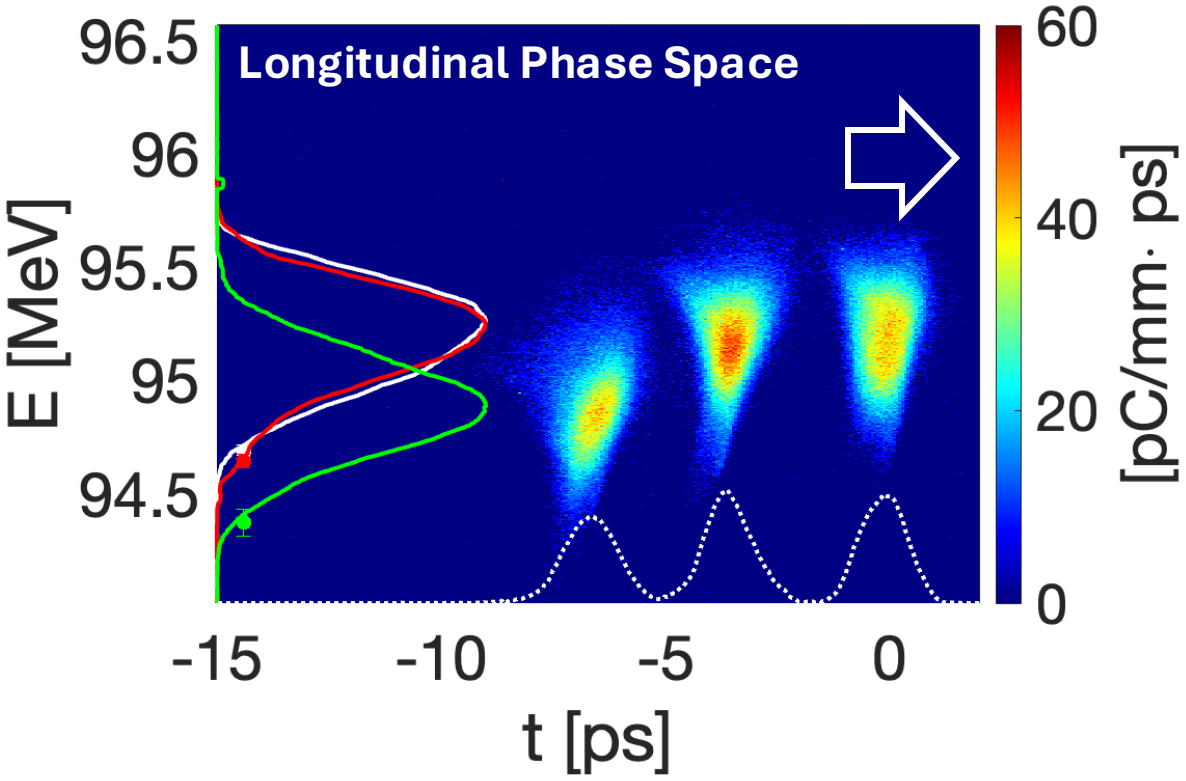




AWAKE Coll., Phys. Rev. Lett. 122, 054802 (2019)

Maximizing the amplitude of the wakefields - Results

- We set up three driver bunches with equal charge and equal delay between successive bunches
- On-crest RF acceleration
  → $\sigma_t \sim 1ps$
  → $\sigma_r \sim 30\mu m$
  ➔ $n_b = 4 \cdot 10^{13}\ cm^{-3}$



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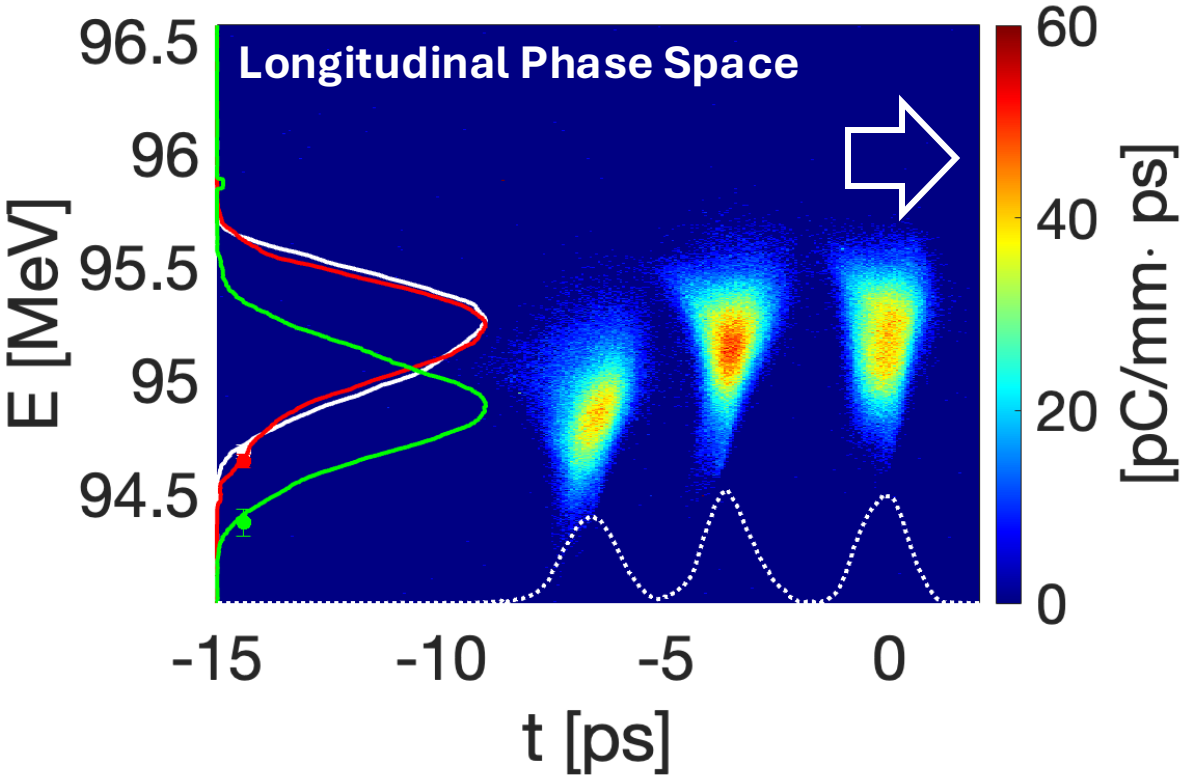
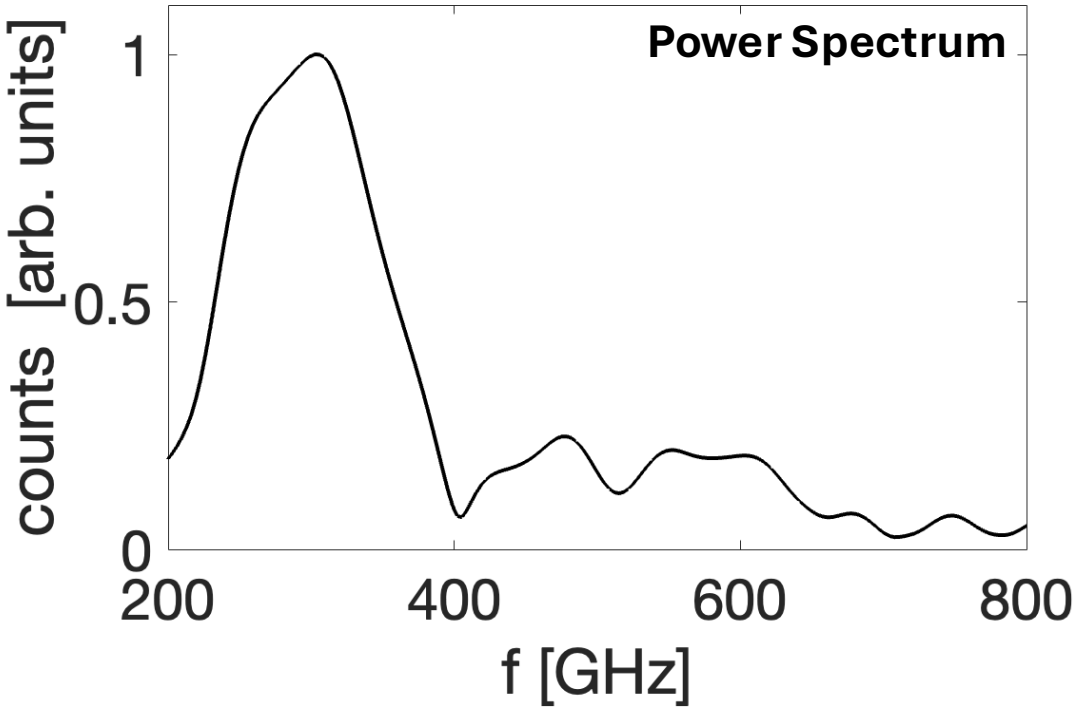
Discrete Fourier Transform



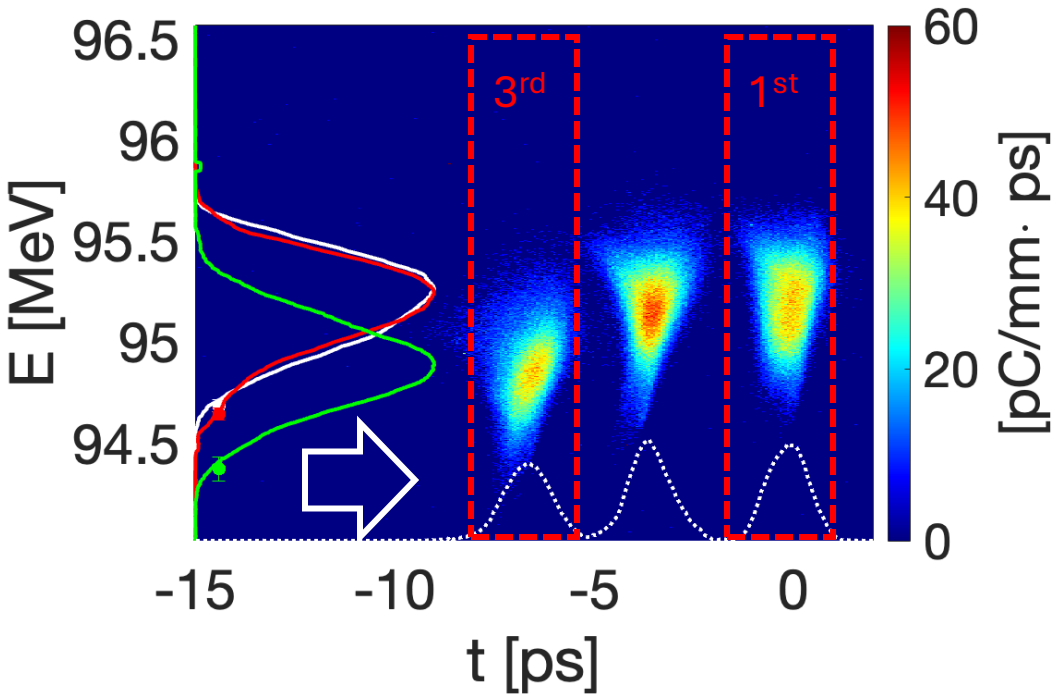
Peak at ~315 GHz
→ expected optimal coupling at $n_{pe} \sim 1.2 \cdot 10^{15}\ cm^{-3}$
➔ $n_b \ll n_{pe}$: Linear regime



Maximizing the amplitude of the wakefields - Results

- We investigate the resonant behavior by varying the plasma density while measuring the LPS of each bunch

- By varying the delay between discharge and bunches, we vary n_{pe} and therefore T_{pe} due to plasma recombination



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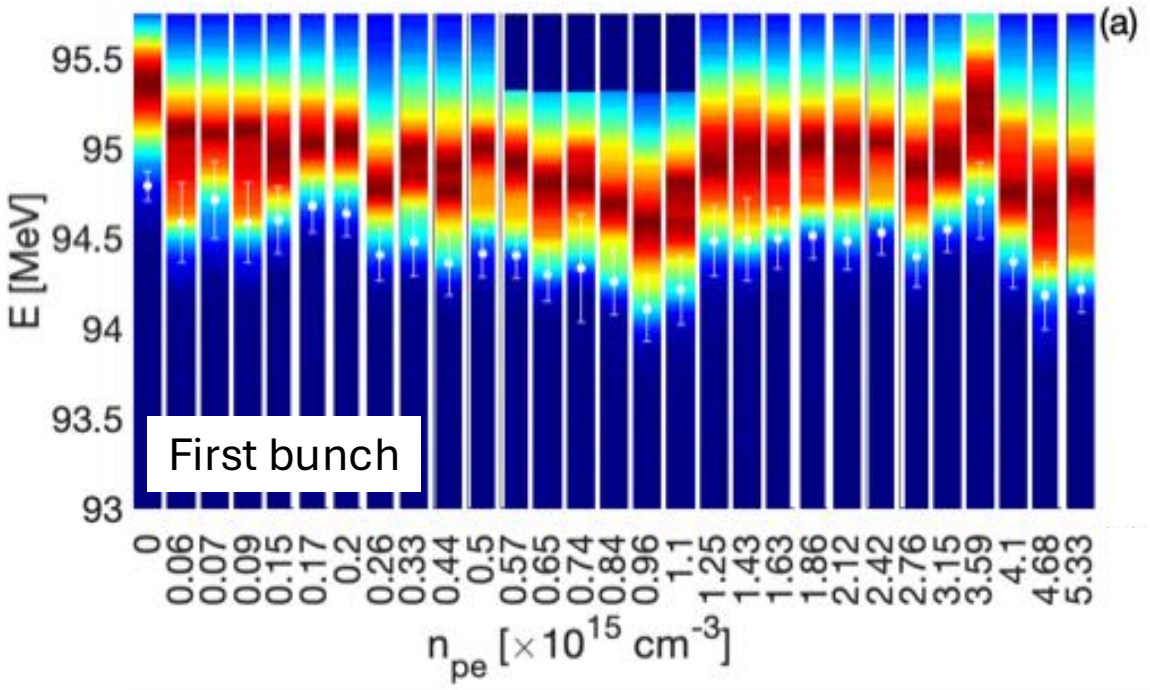

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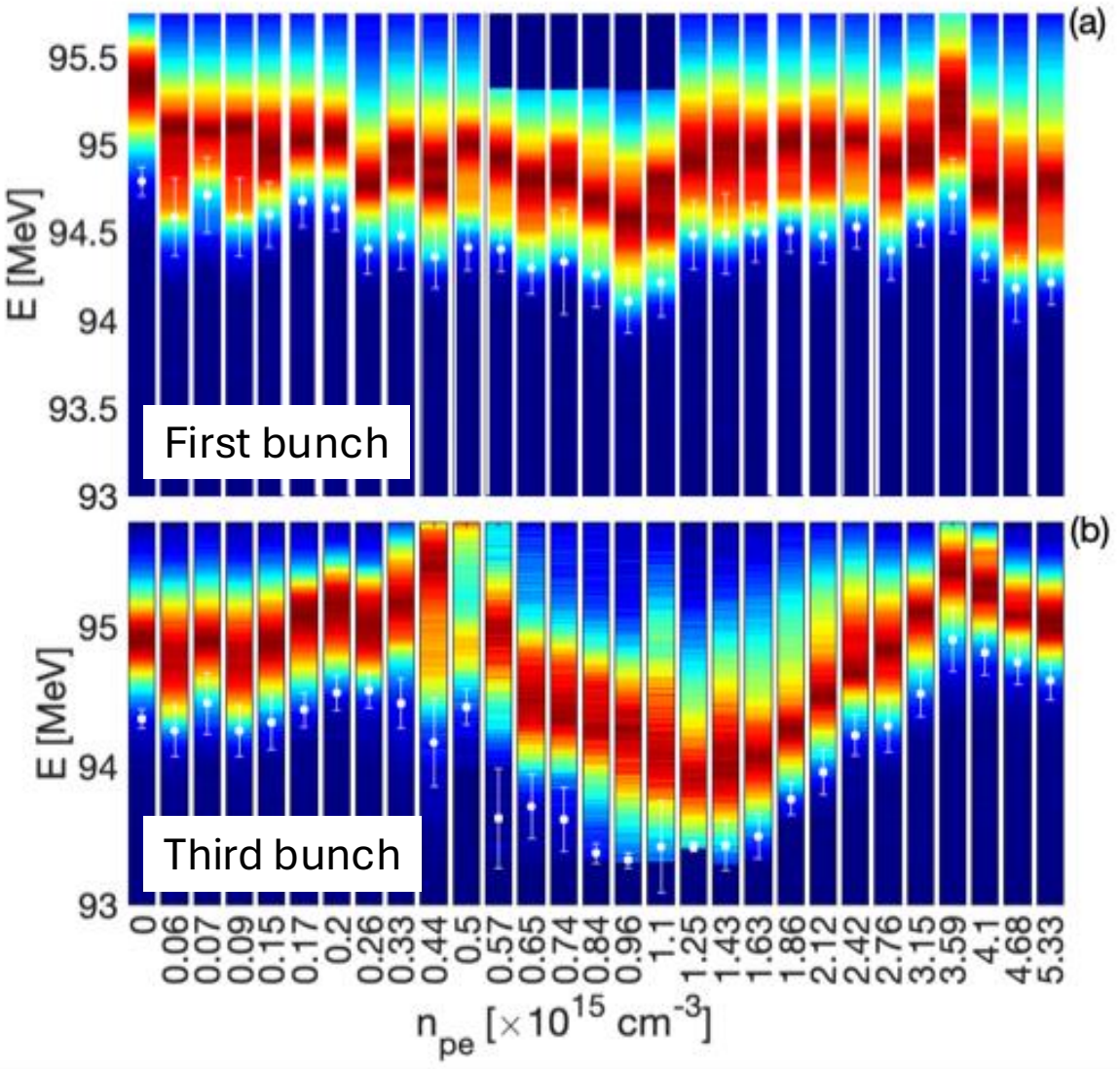

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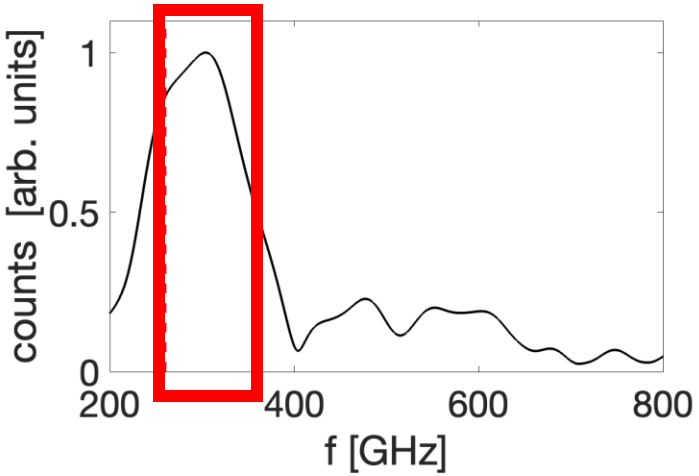
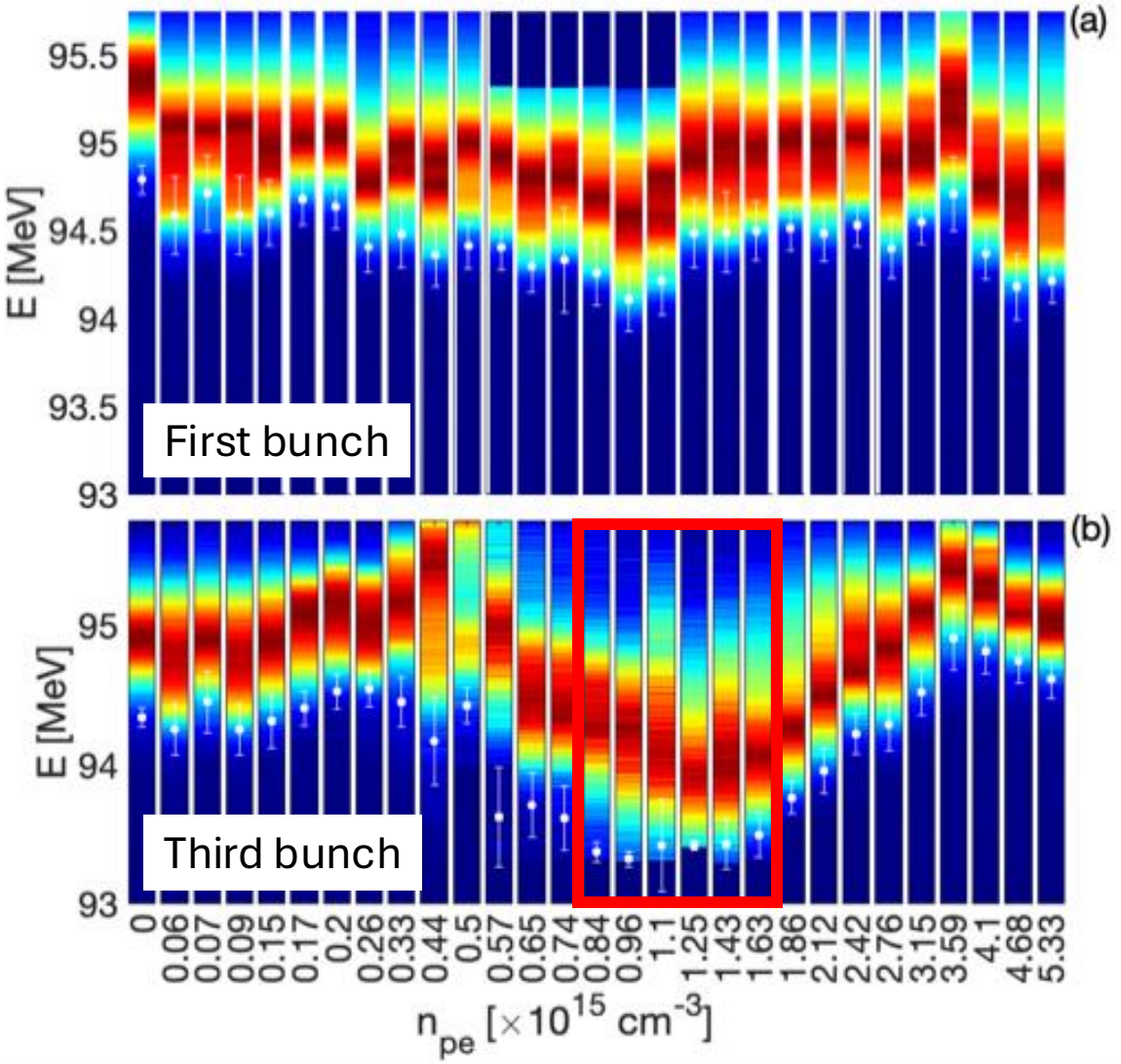
- Maximum energy loss when train is coupled in frequency with plasma





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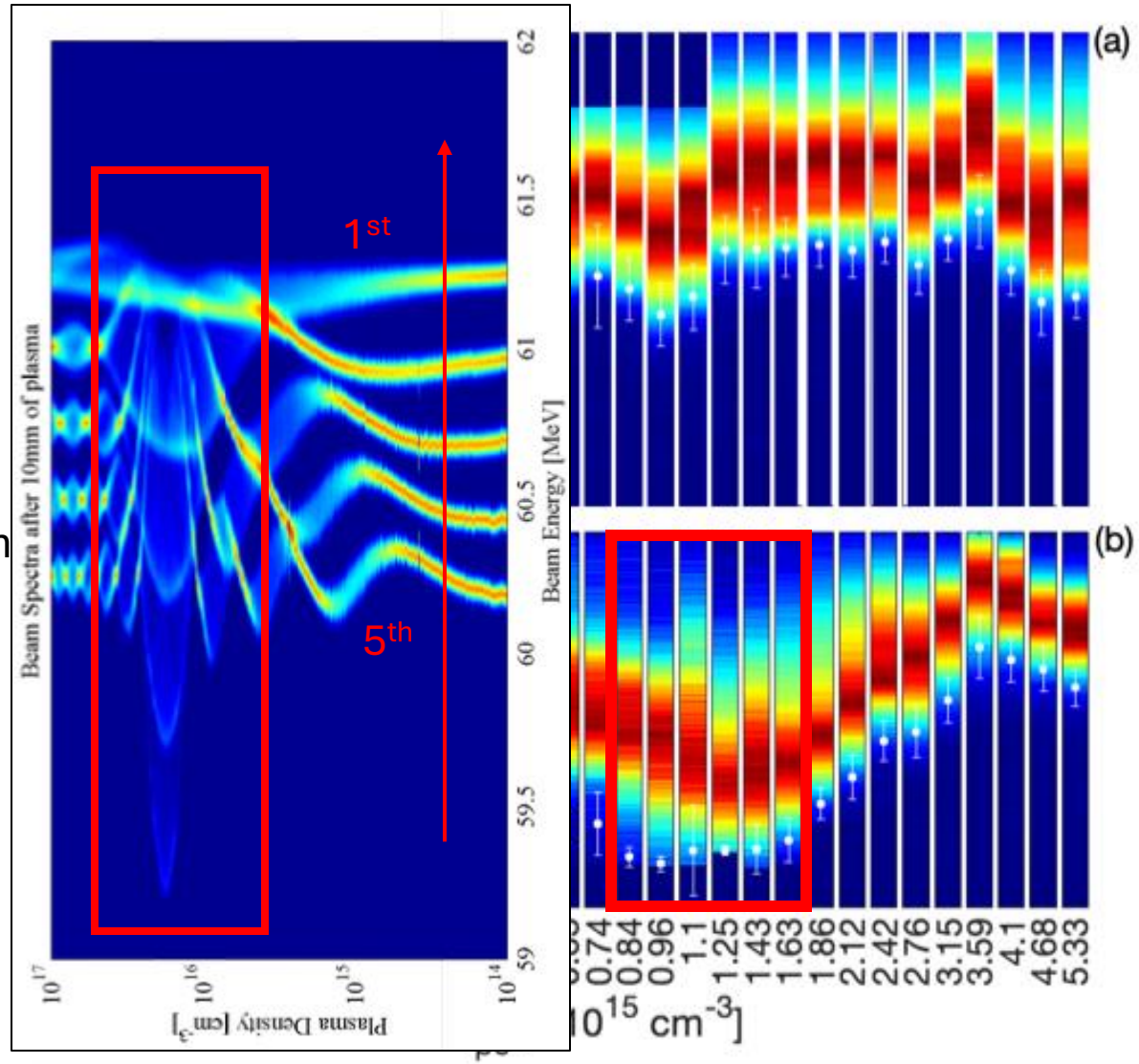
- Maximum energy loss when train is coupled in frequency with plasma
- Same behavior as expected from simulations



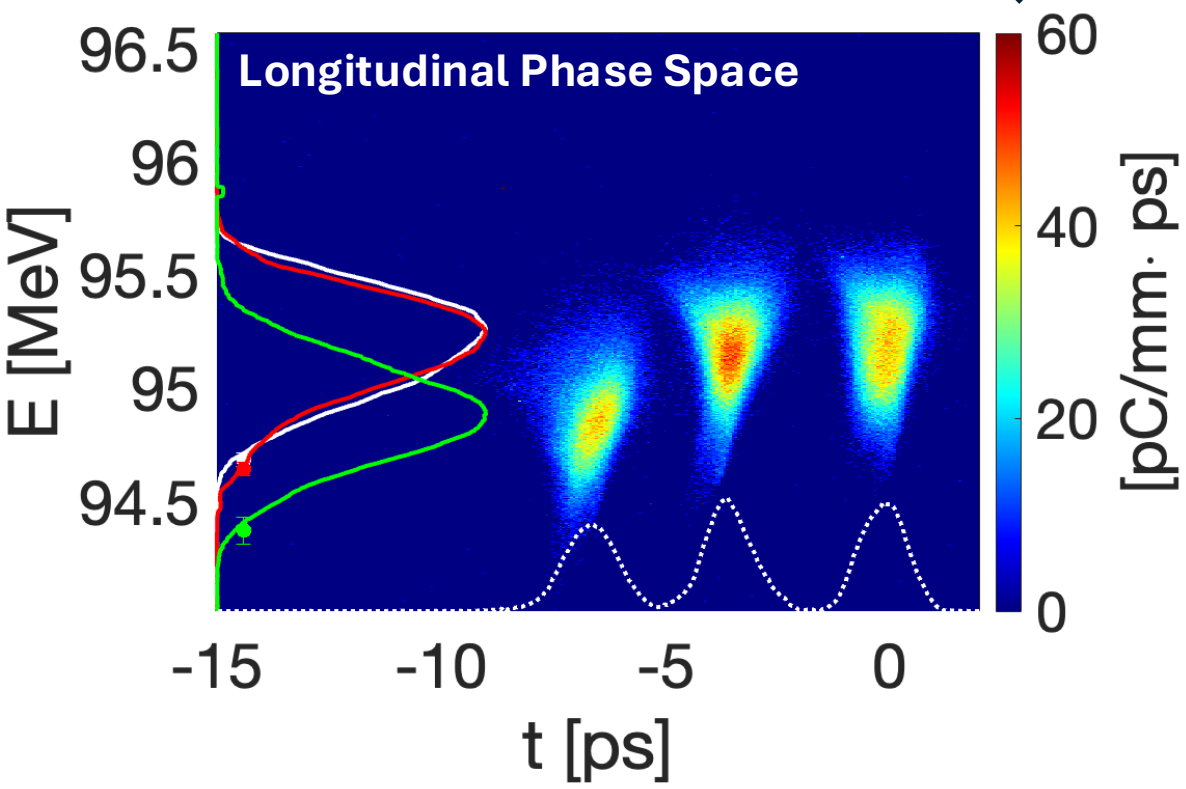
E. Kallos, PhD thesis (2008)

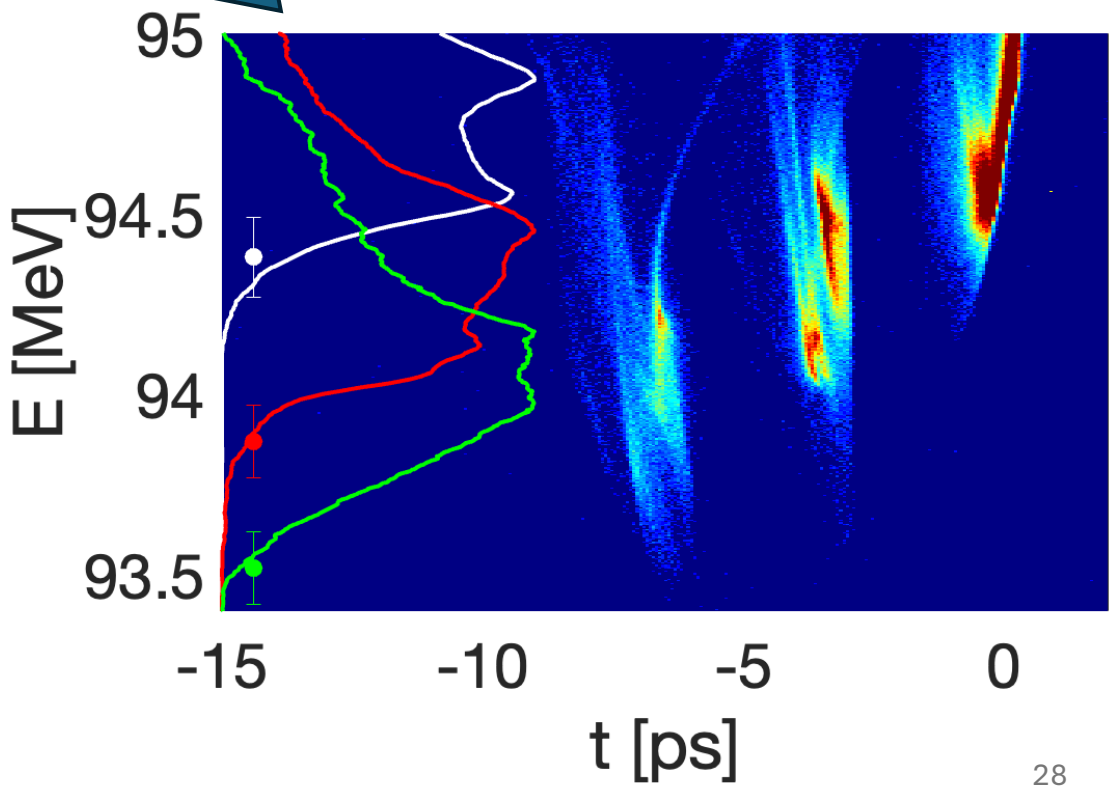
Maximizing the amplitude of the wakefields - Results

- We set up three driver bunches with equal charge and equal delay between successive bunches
- On-crest RF acceleration
  → $\sigma_t \sim 1ps$
  → $\sigma_r \sim 30\mu m$
  ➔ $n_b = 4 \cdot 10^{13}\ cm^{-3}$

Plasma ON

Peak at ~315 GHz
→ expected optimal coupling at $n_{pe} \sim 1.2 \cdot 10^{15}\ cm^{-3}$
➔ $n_b \ll n_{pe}$: Linear regime

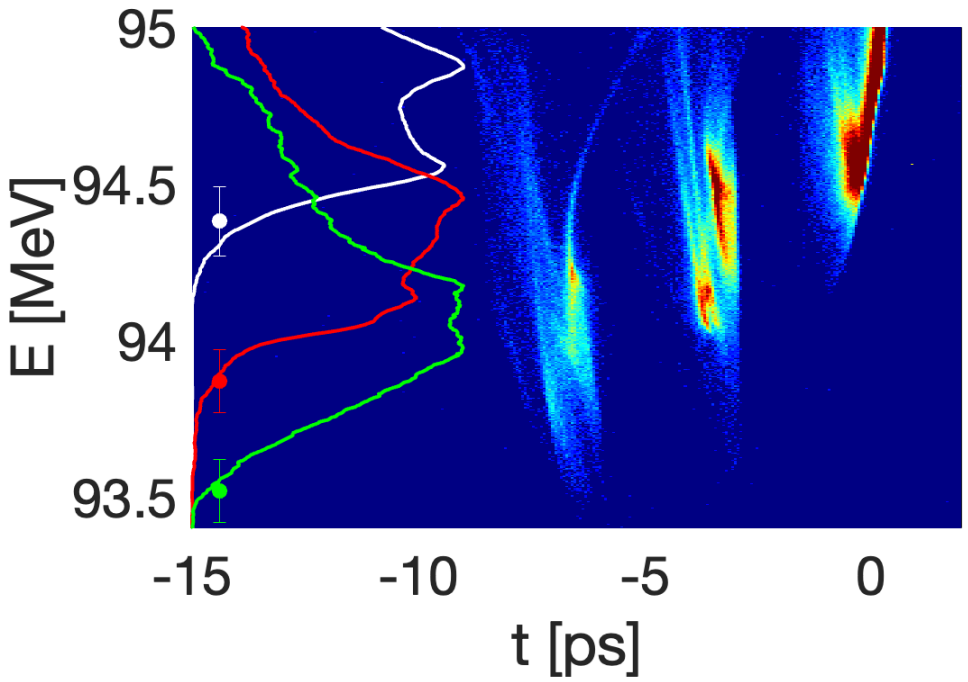




Maximizing the amplitude of the wakefields - Results

- Minimum energy of each bunch calculated as the value where the amplitude of the energy distribution reaches 10% of maximum

- Energy loss increasing along the train after propagation in plasma
  $\Delta E^{-}_{1,2,3} = (0.3, 0.7, 0.9) \pm 0.1$ MeV



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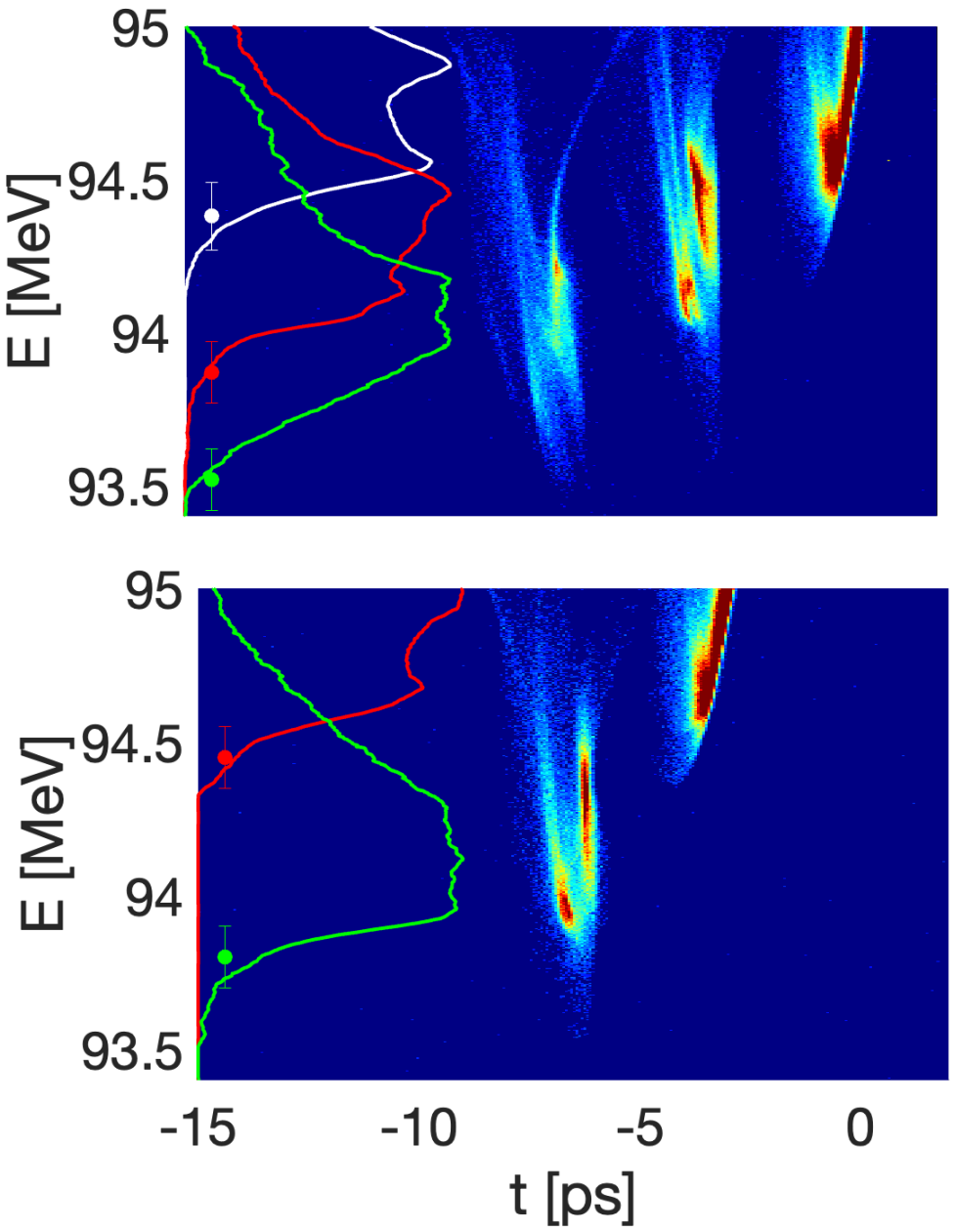

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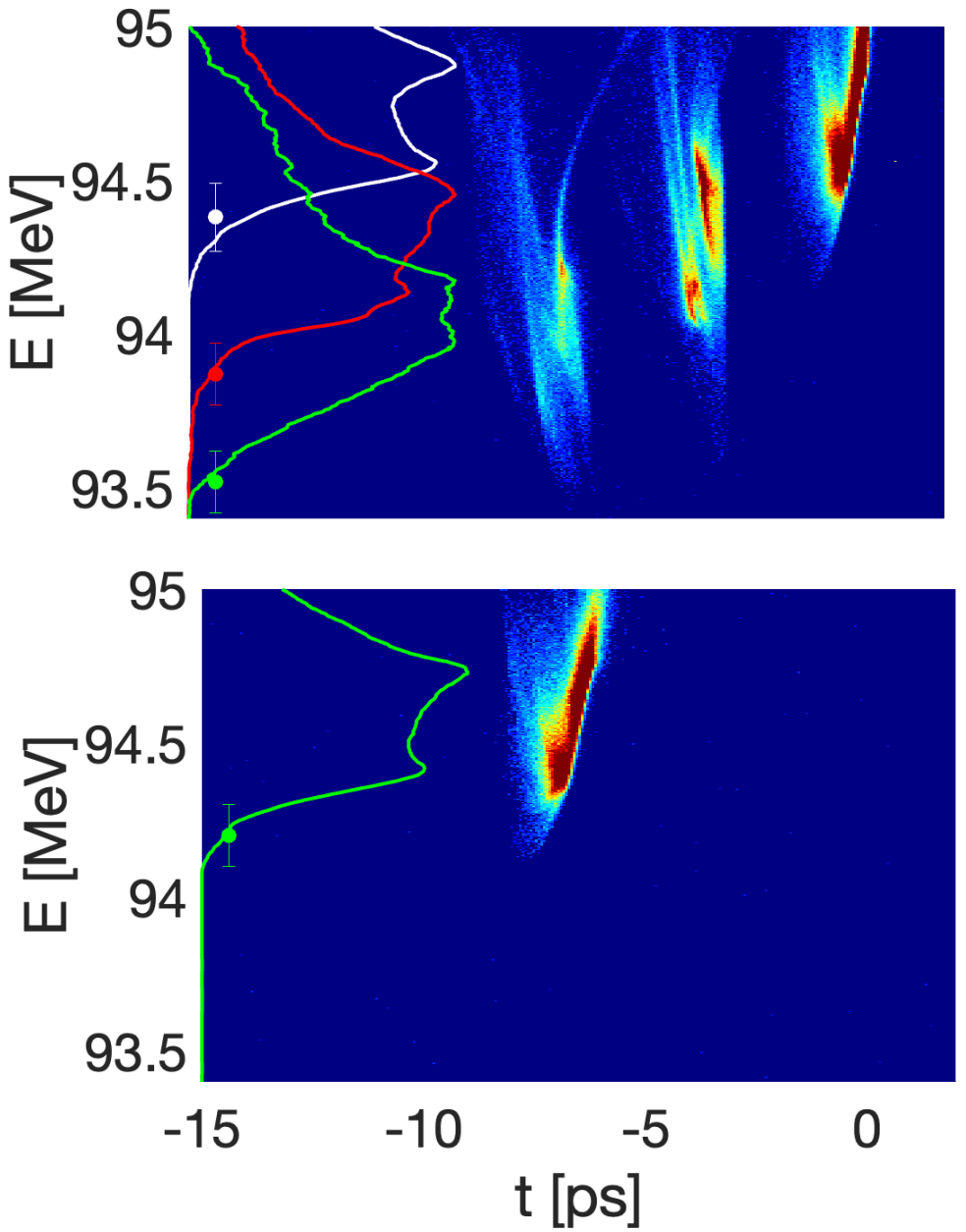

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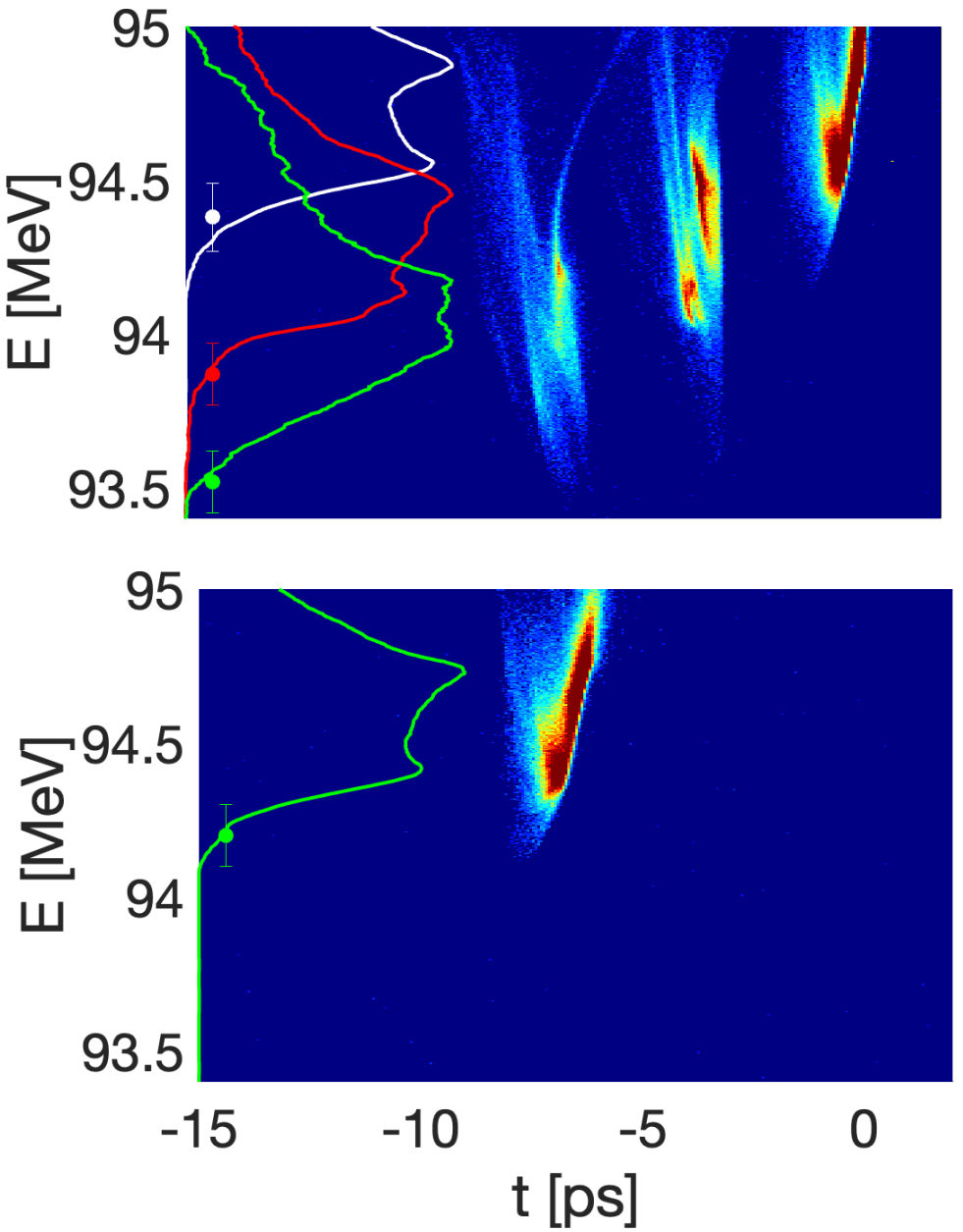
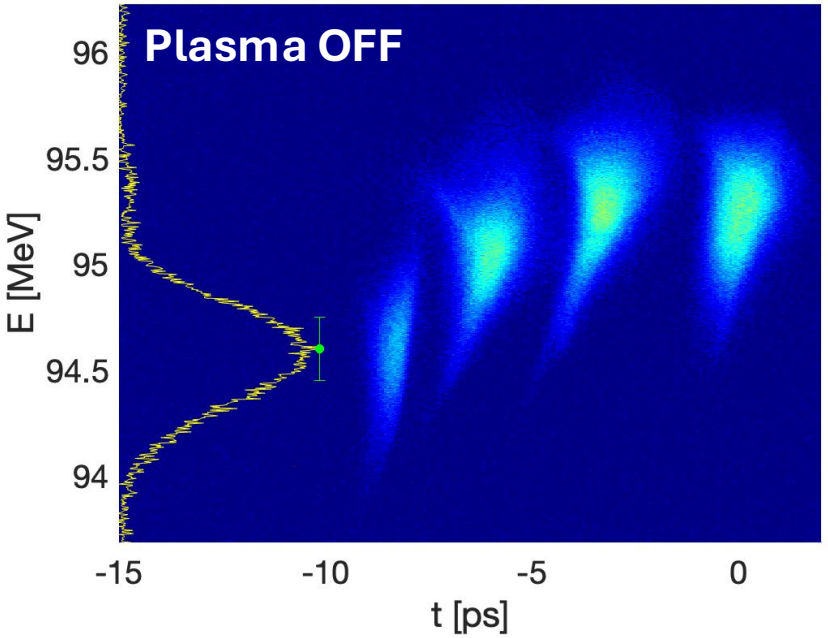
- The sum of each contribution gives the final energy loss:
  $\mathbf{\Delta E^{-}_{3} = (0.7 - 0.2) + (0.4 - 0.2) + 0.2 = 0.9\ MeV}$
  ➔ The wakefields driven by each bunch superpose **linearly**



Maximizing the amplitude of the wakefields - Results

- We sample the longitudinal wakefields by injecting a witness bunch (small charge) in the accelerating phase



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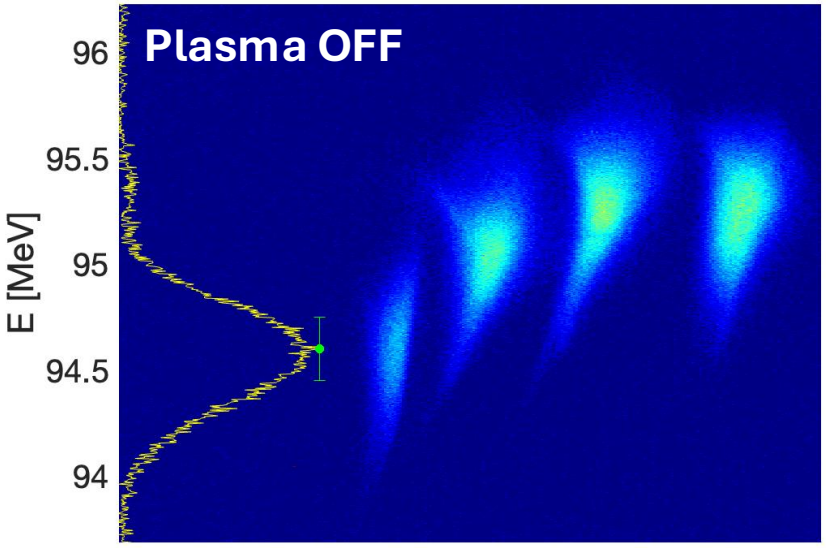
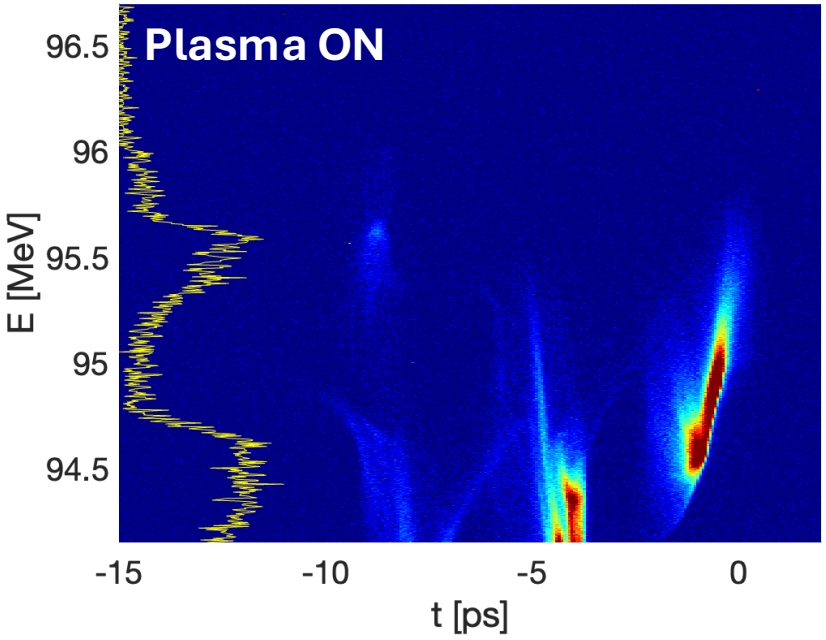
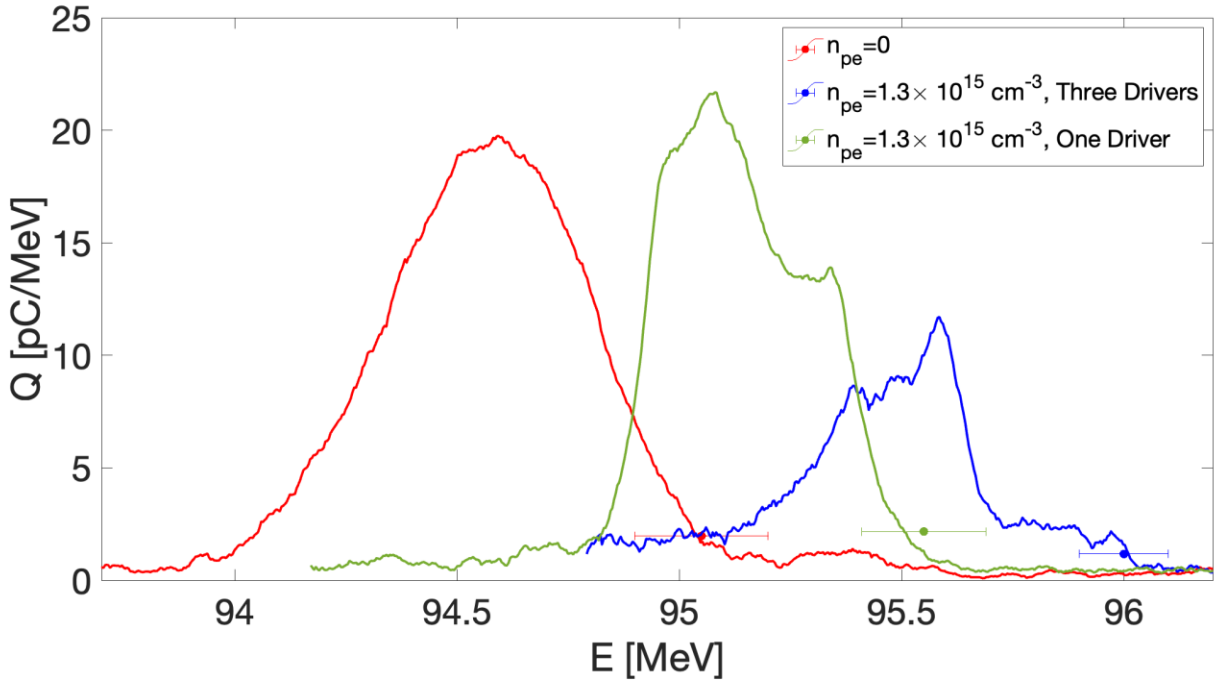




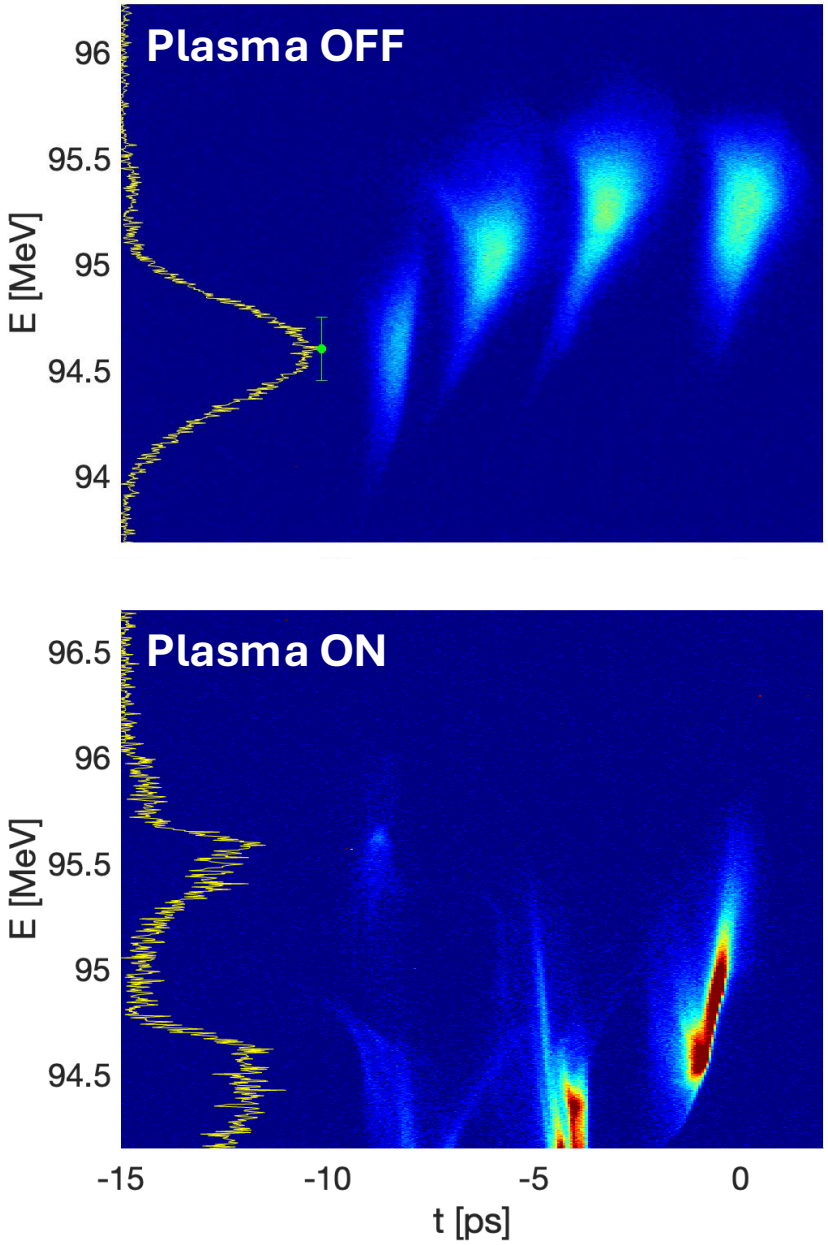
Maximizing the amplitude of the wakefields - Results

- We sample the longitudinal wakefields by injecting a witness bunch (small charge) in the accelerating phase

- Larger accelerating gradient when more driver bunches are present (more charge contributing the wakefields)



➔ Resonant excitation may allow for enhancement of accelerating gradient with respect to single bunch with all charge



Maximizing the transformer ratio

Transformer ratio defined as:

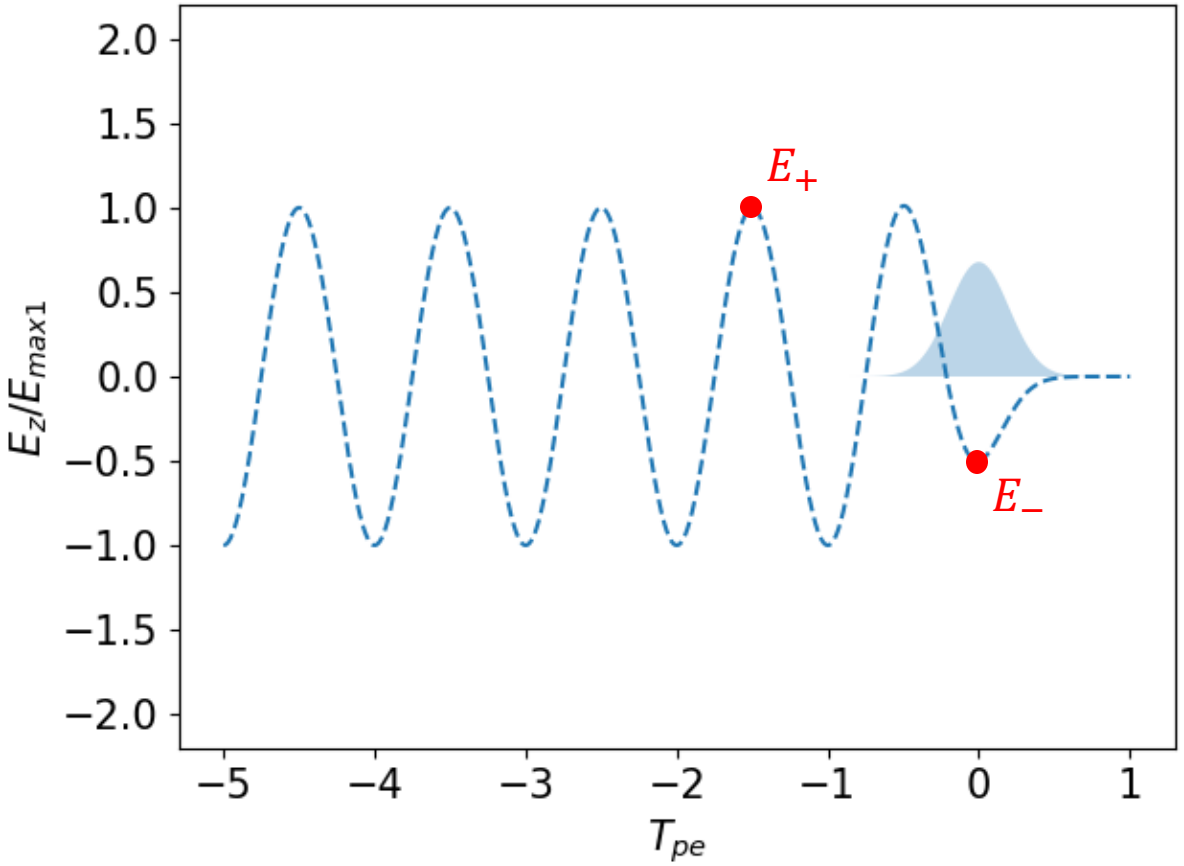
$$R = \frac{E_+}{E_-}$$

Limited to R<2 for symmetric driver bunches by the fundamental theorem of beam loading

→ Increasing R means: longer depletion length
➔ larger final energy gain

→ Desirable for more efficient energy transfer

→ This can be achieved with:
- Asymmetric drivers (e.g. triangular current profile)
- Train of bunches with increasing charge

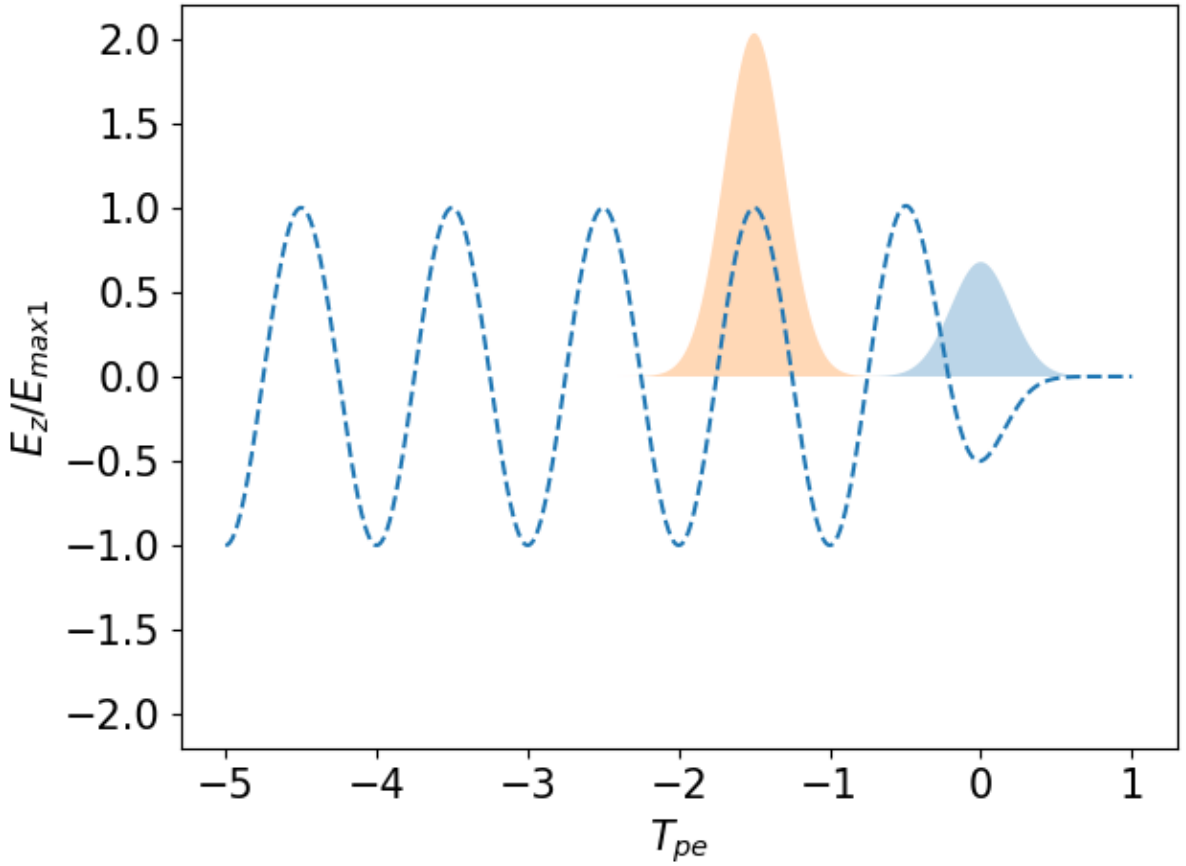


Maximizing the transformer ratio

→ Using a ramped bunch or a ramped bunch train allows for R>2

→ Second bunch positioned within the accelerating phase of the wakefields driven by the first one (half-integer of T_{pe})

→ Larger charge density to overload the longitudinal wakefields



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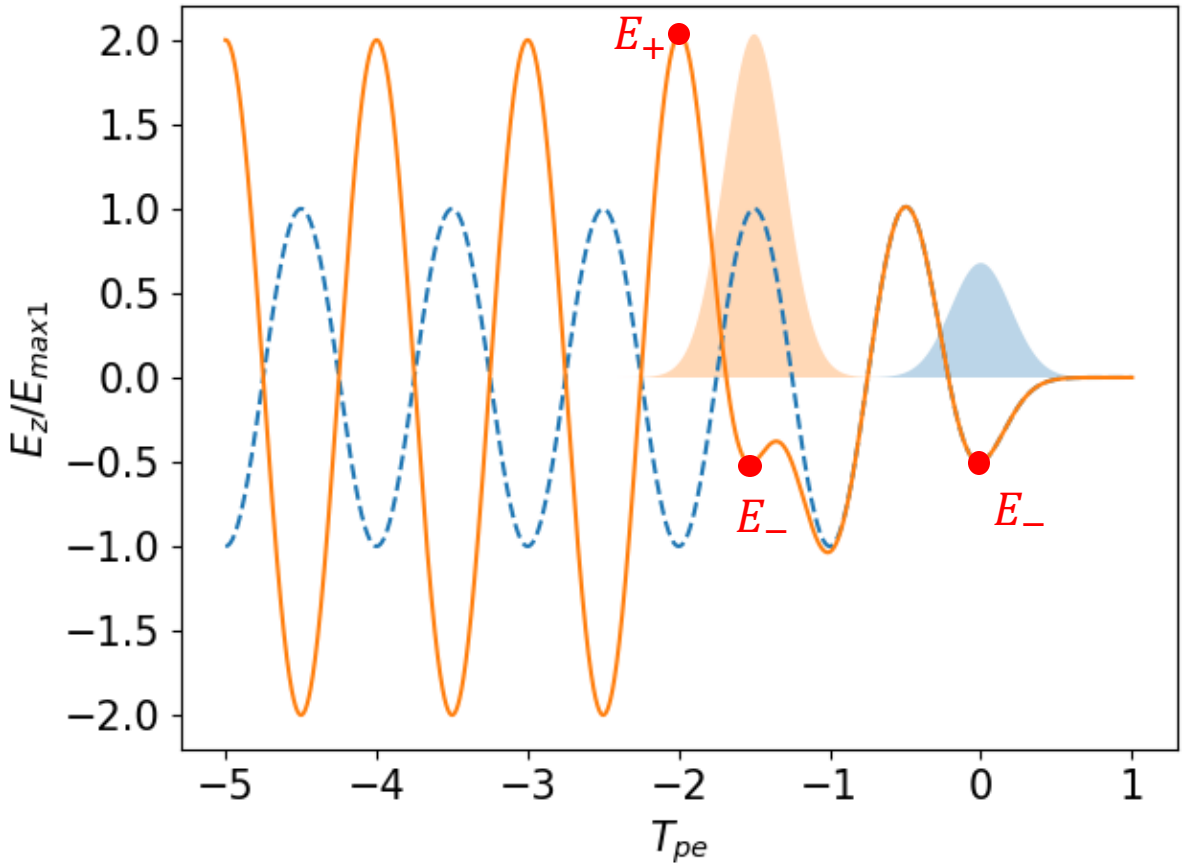
→ Superposition gives equal E_- within the drivers

➔ Enhanced R → $R_N = N \cdot R_1$



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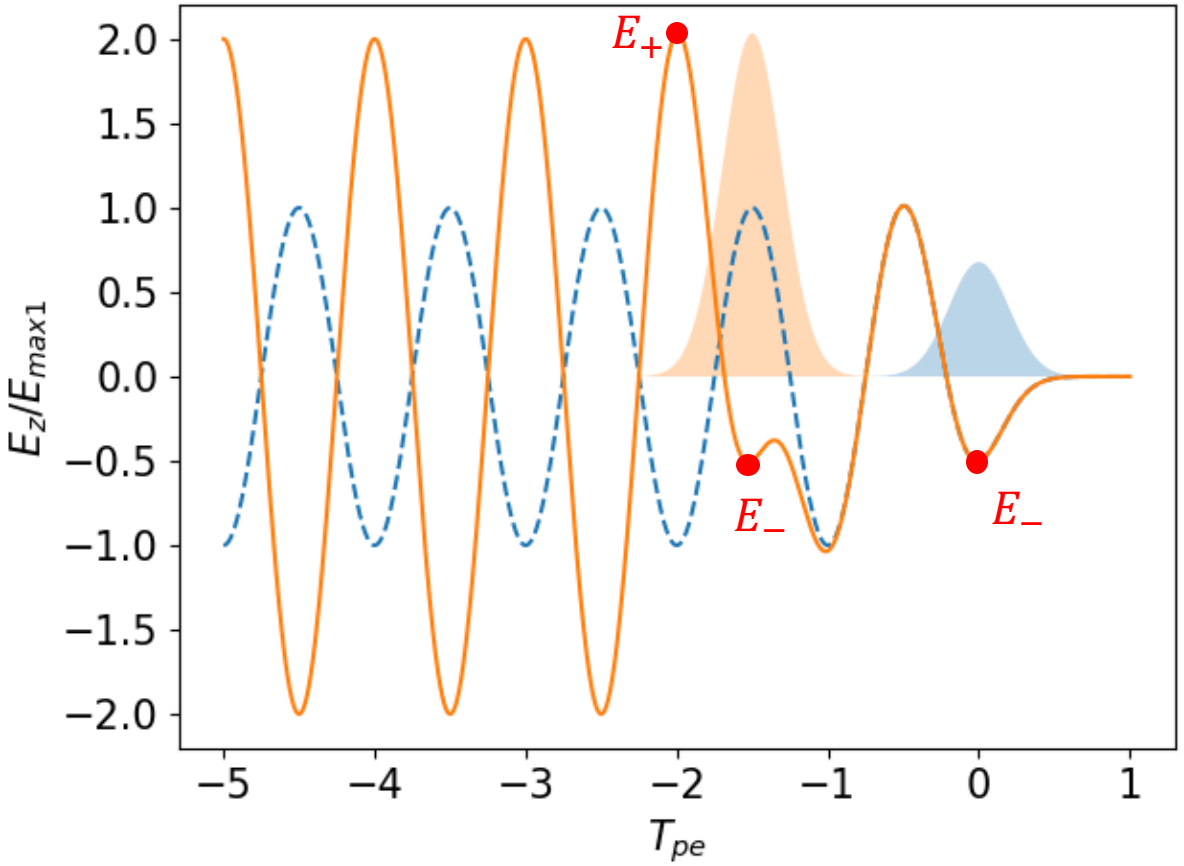
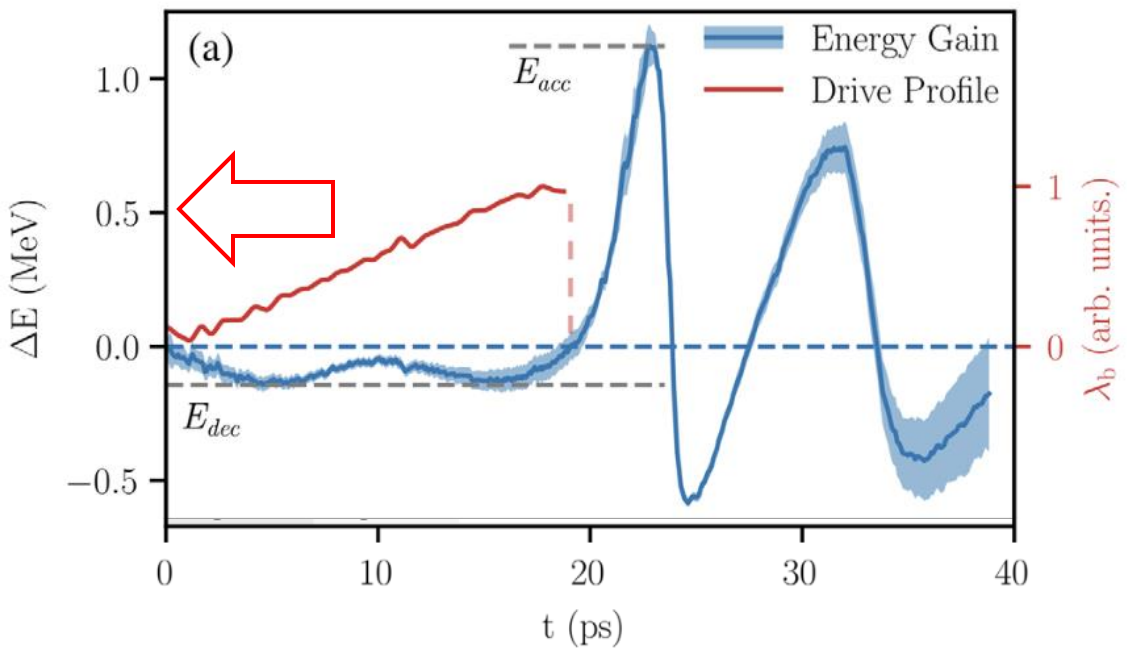
➔ **Observable at optimal coupling:**
increasing $R = \frac{E_+}{E_-} = \frac{\Delta E^+}{\Delta E^-}$ when both drivers are present



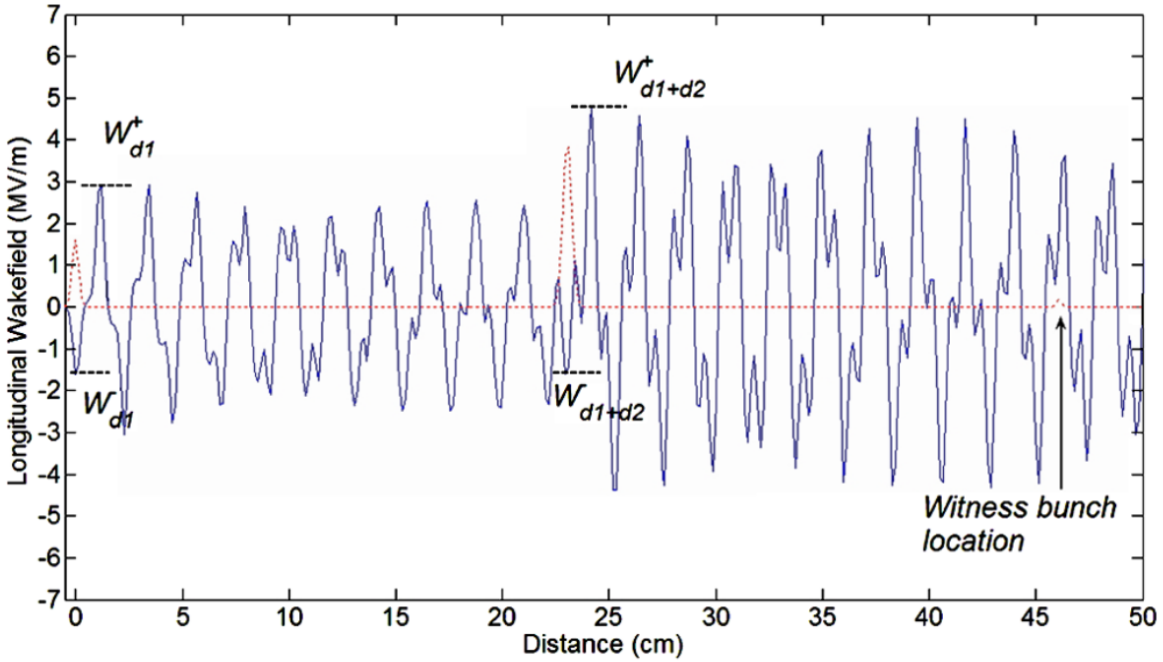
Maximizing the transformer ratio – Previous results

Single bunch with triangular current profile in non-linear regime



Loisch et al., Phys. Rev. Lett. 121, 064801 (2018)
Roussel et al., Phys. Rev. Lett. 124, 044802 (2020)

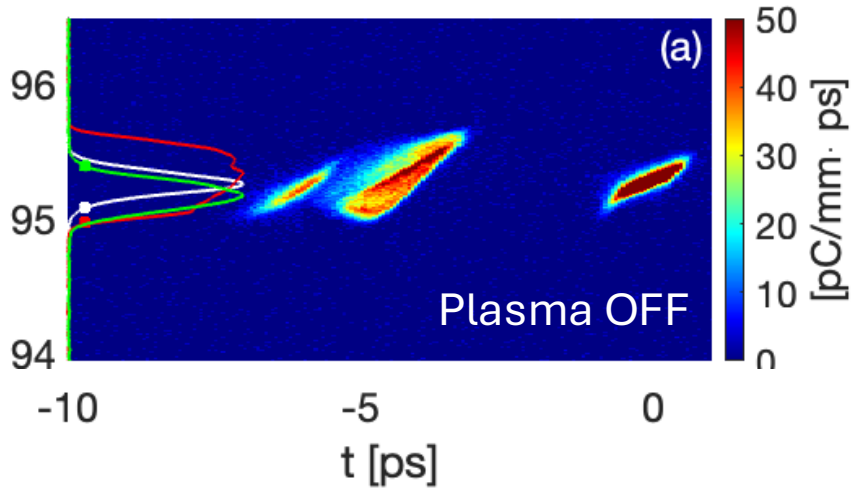
Ramped train of bunches in dielectric-loaded wakefield accelerator



Jing et al., Phys. Rev. Lett. 98, 144801 (2007)

Maximizing the transformer ratio - Results

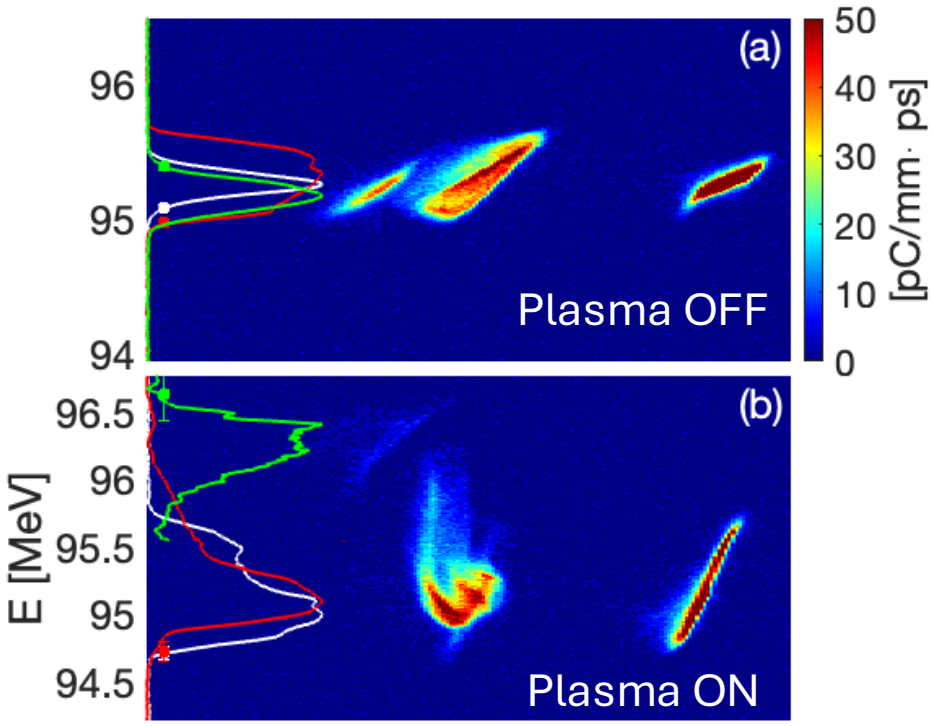
- Two driver bunch delayed by 1.5 T_{pe}



Maximizing the transformer ratio - Results

- Two driver bunch delayed by 1.5 T_{pe}
- Charge of the second driver increased to have energy loss nearly equal to the first driver: $\Delta E^{-} = 0.37$ MeV
- Witness bunch accelerated with $\Delta E^{+} = 1.2$ MeV

➔ $R = 3.2 \pm 0.5$



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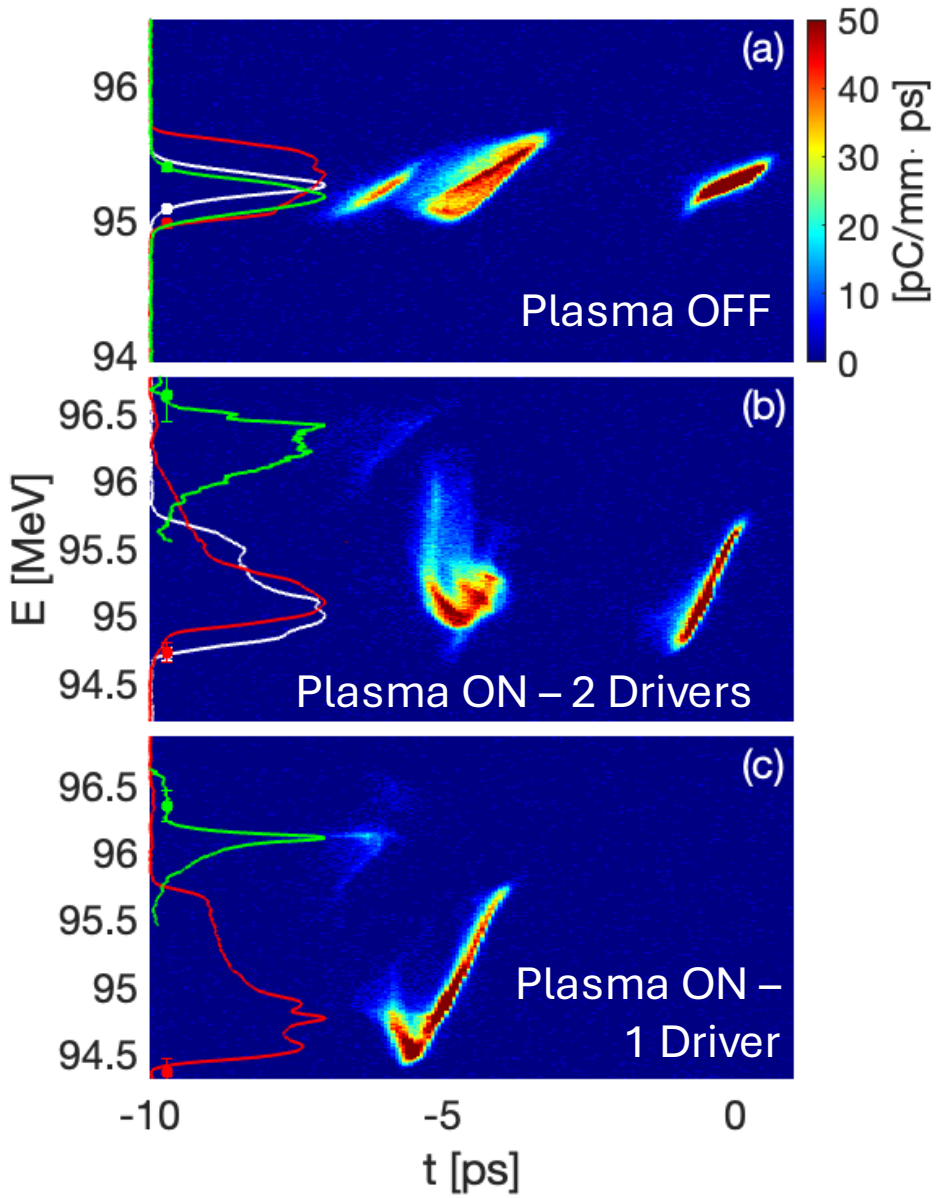
- When only the second driver is present $\Delta E^- = 0.6$ MeV, $\Delta E^+ = 0.9$ MeV

➔ $R = 1.5 \pm 0.3$

➔ Enhancement of transformer ratio when two bunches are present!



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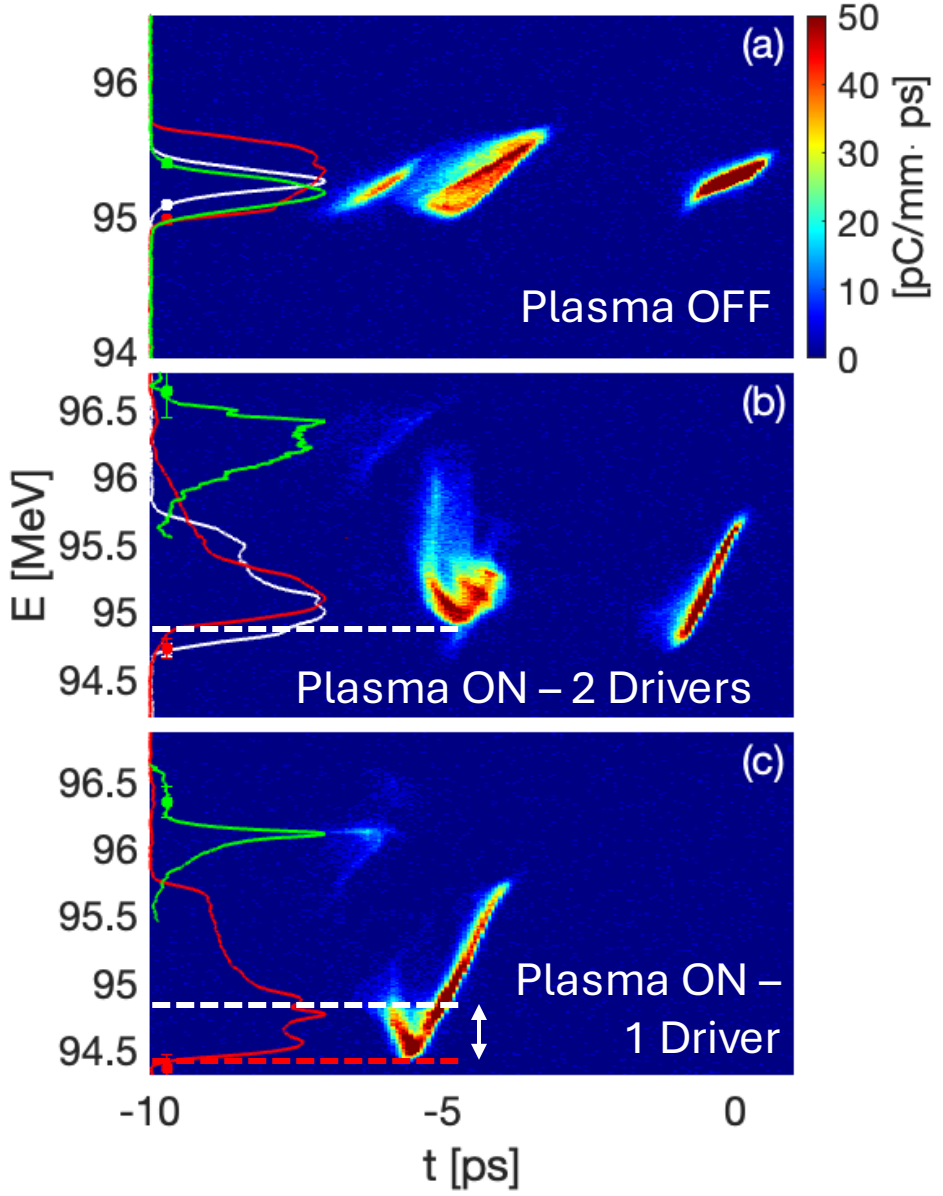
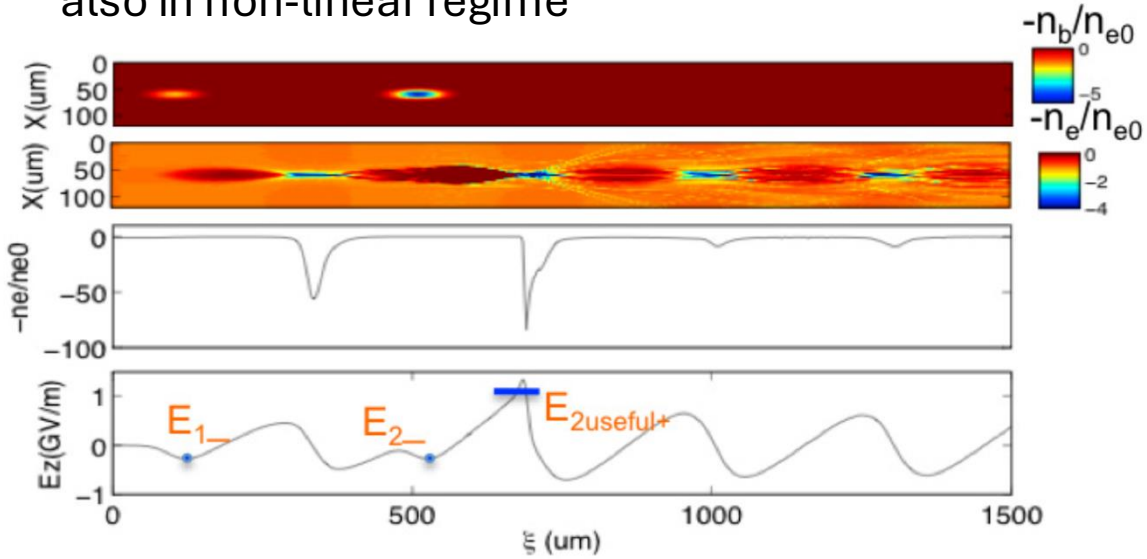
➔ Enhancement of transformer ratio when two bunches are present!
➔ Mostly due to reduced energy loss



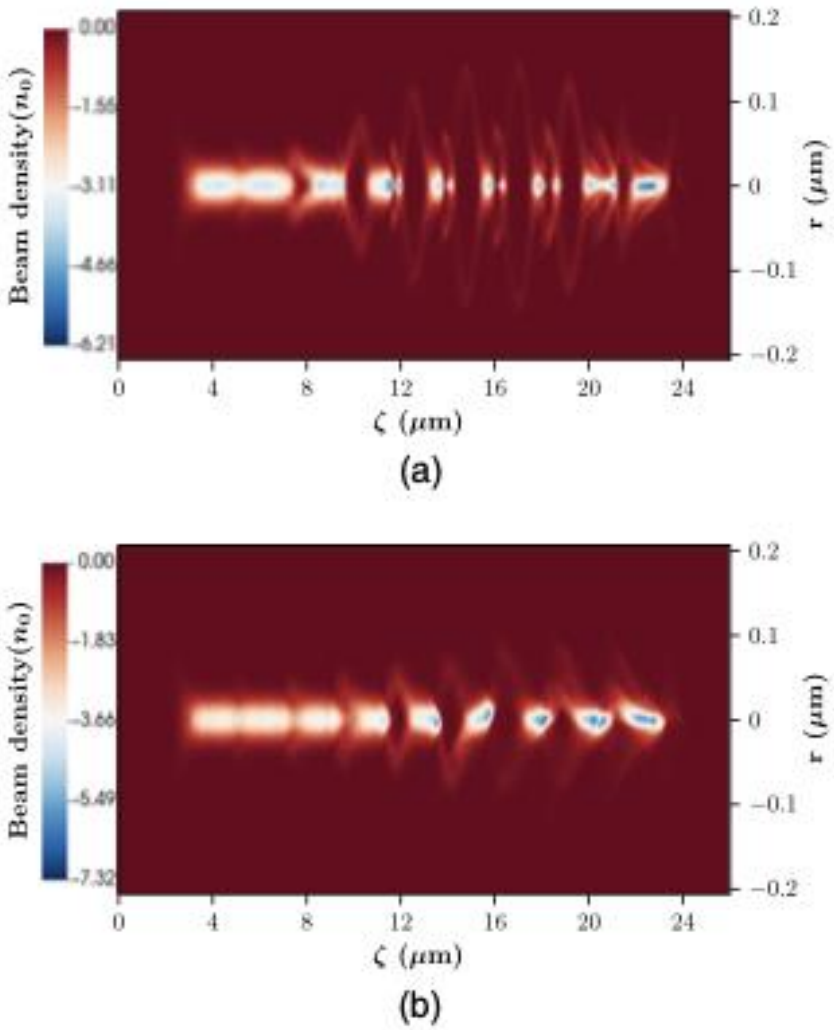
Future - SPARC

- Ramped charge train could be used to maximize R also in non-linear regime



Fang et al., Proceedings PAC 2011

- Investigation of "beam destruction" and hosing



Manwani et al., PRAB **24**, 051302 (2021)

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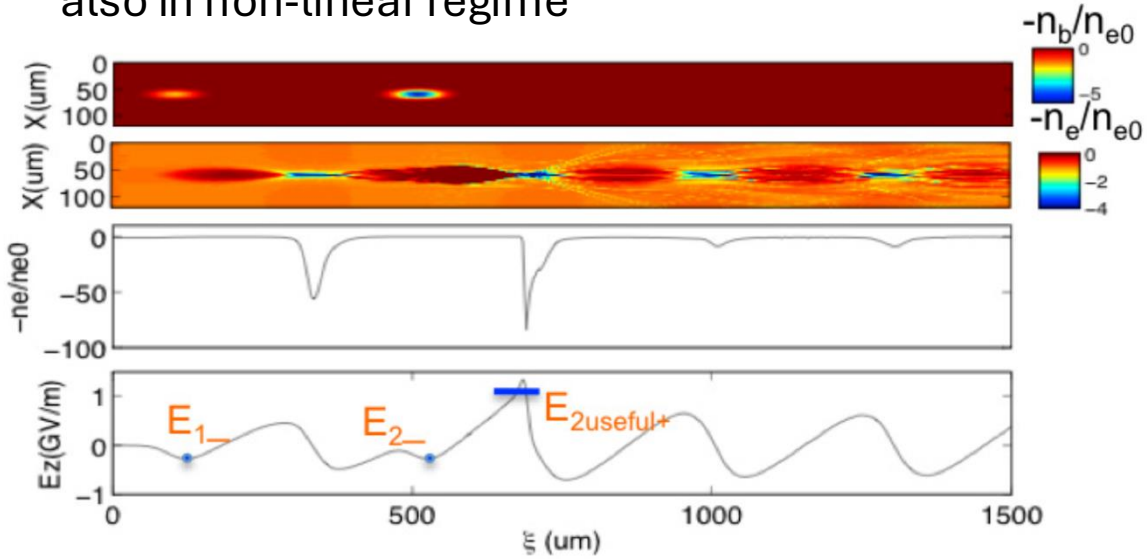
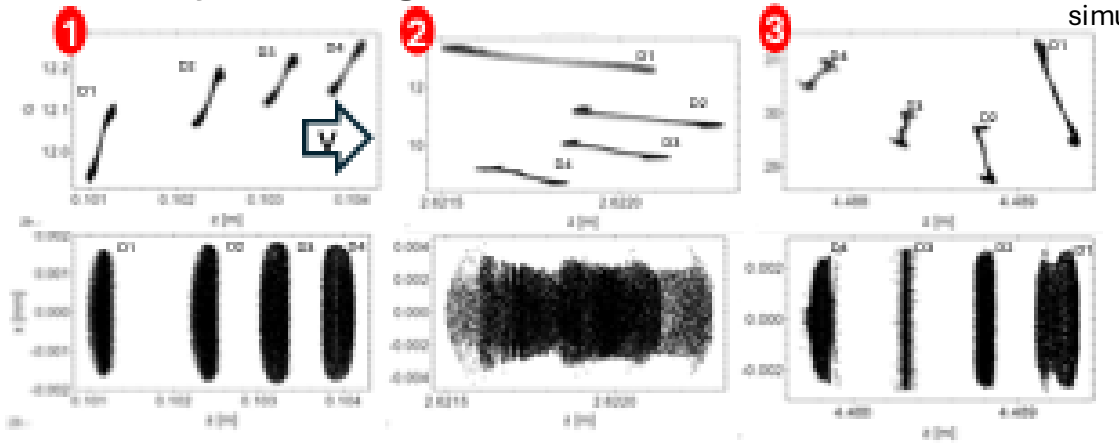


Fang et al., Proceedings PAC 2011

- To reach blowout, need for bunch compression → Velocity bunching

(GPT simulations)



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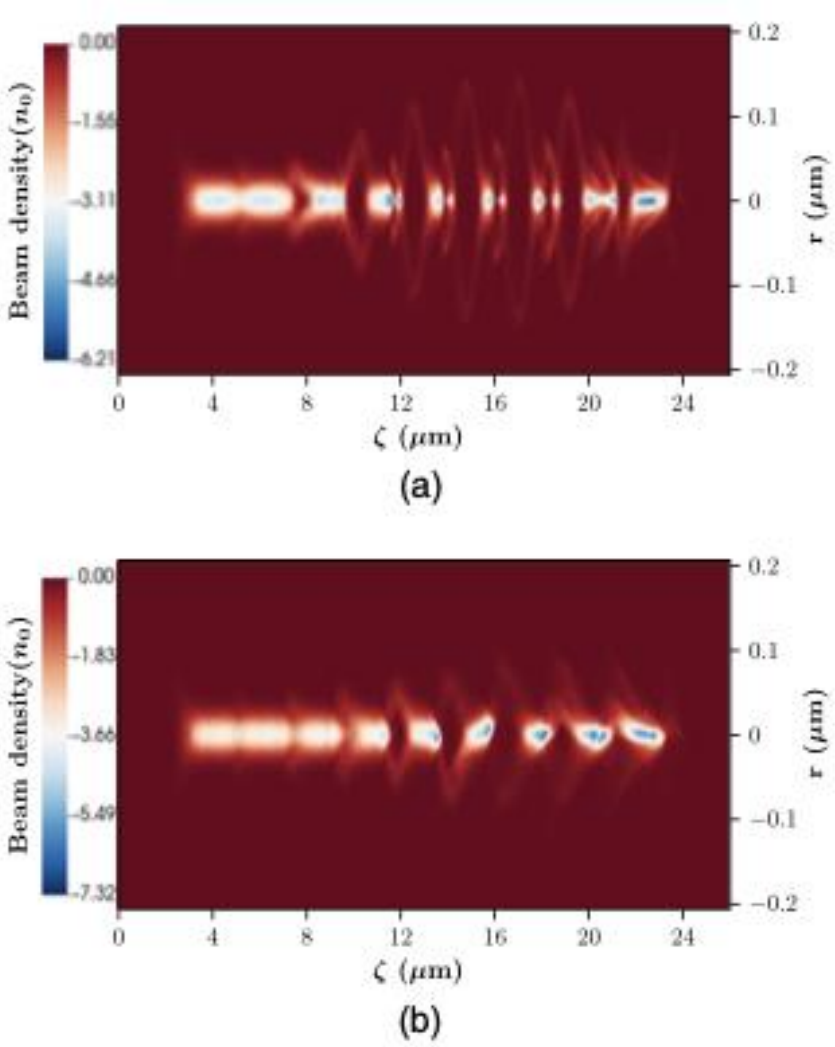


Manwani et al., PRAB **24**, 051302 (2021)

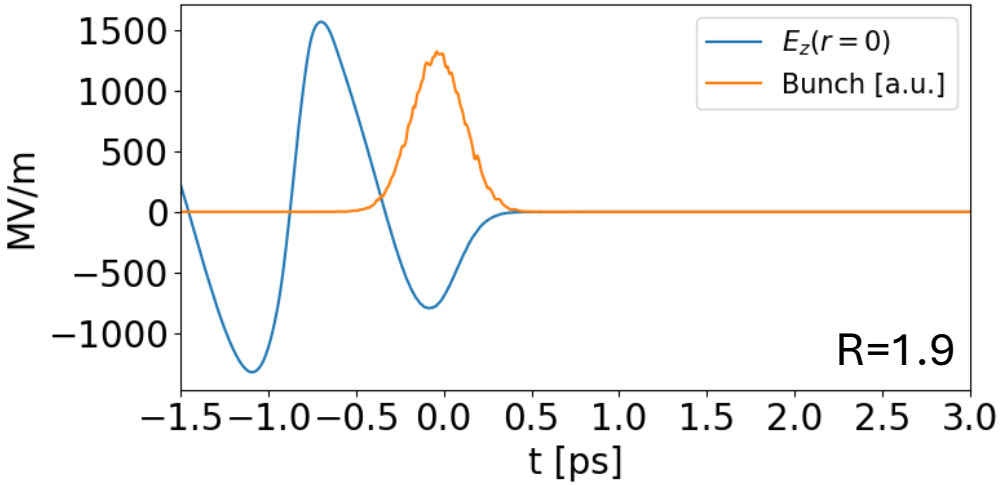
Future - EuPRAXIA

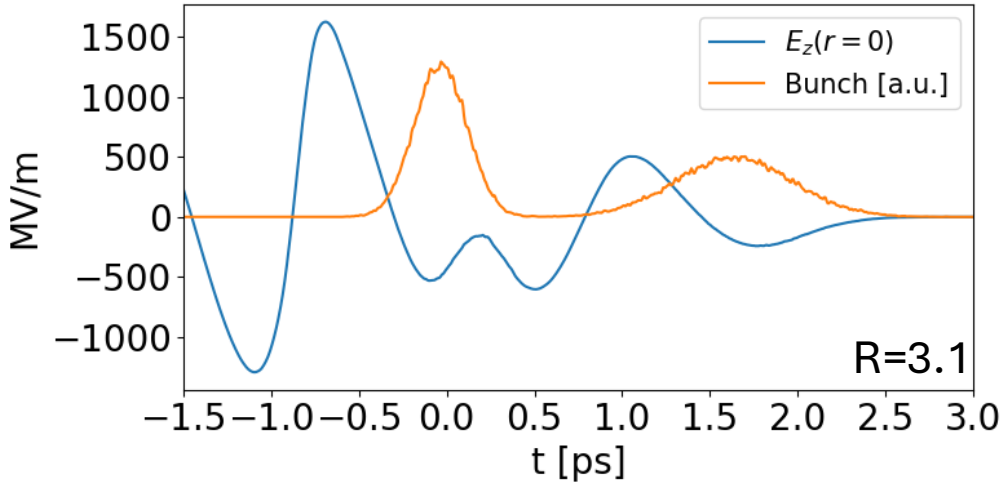
- The non-linear, high-transformer-ratio configuration could be used at EuPRAXIA@SPARC_LAB to maximize the final energy reach of the witness bunch towards 5 GeV

- Low-charge driver bunch ahead of the main driver ”jump-starts” the wakefields, reducing E^-within drivers
  → R enhancement

➔ Higher final energy with the same main driver bunch

➔ Lasing at shorter wavelength





EuPRAXIA@SPARC_LAB

Conclusions

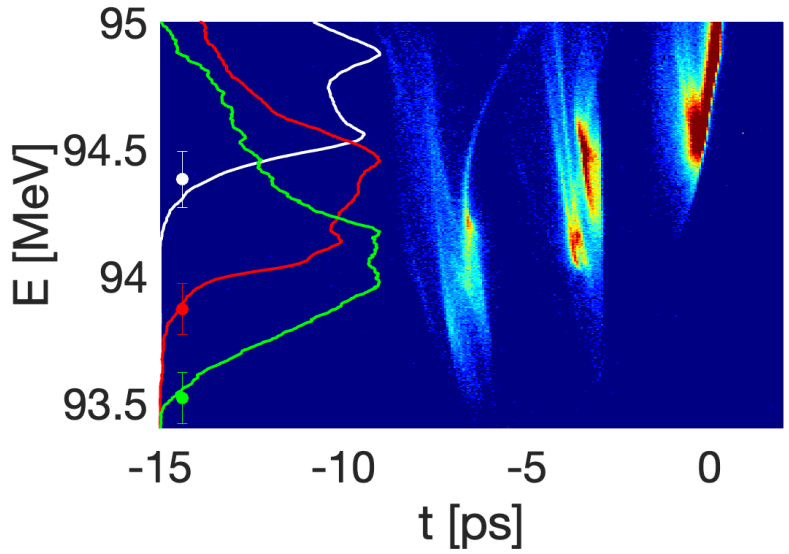
- We demonstrated resonant wakefield excitation in plasma with trains of pre-formed electron bunches

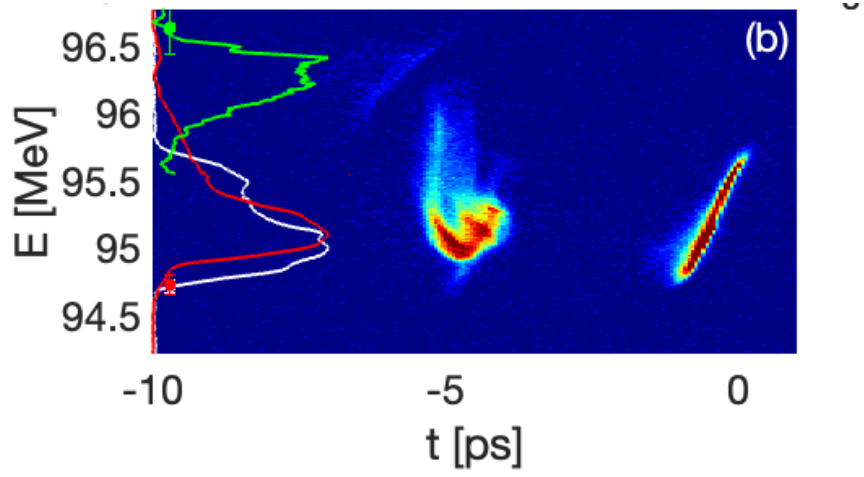
- In linear regime, wakefields superpose linearly
- Configuration with $\Delta t = N \cdot T_{pe}$
  → Amplitude growth along the train

- Configuration with $\Delta t = \frac{N}{2} \cdot T_{pe}$ and ramped charge
  → Transformer ratio enhancement

- Future: upgrade to "bunch compression" setup with velocity bunching to study non-linear, high-transformer-ratio acceleration
  → Possible impact on EuPRAXIA@SPARC_LAB

- Manuscript accepted for publication on Phys. Rev. E:
  L. Verra et al., https://doi.org/10.21203/rs.3.rs-6115160/v1





ACCEPTED PAPER

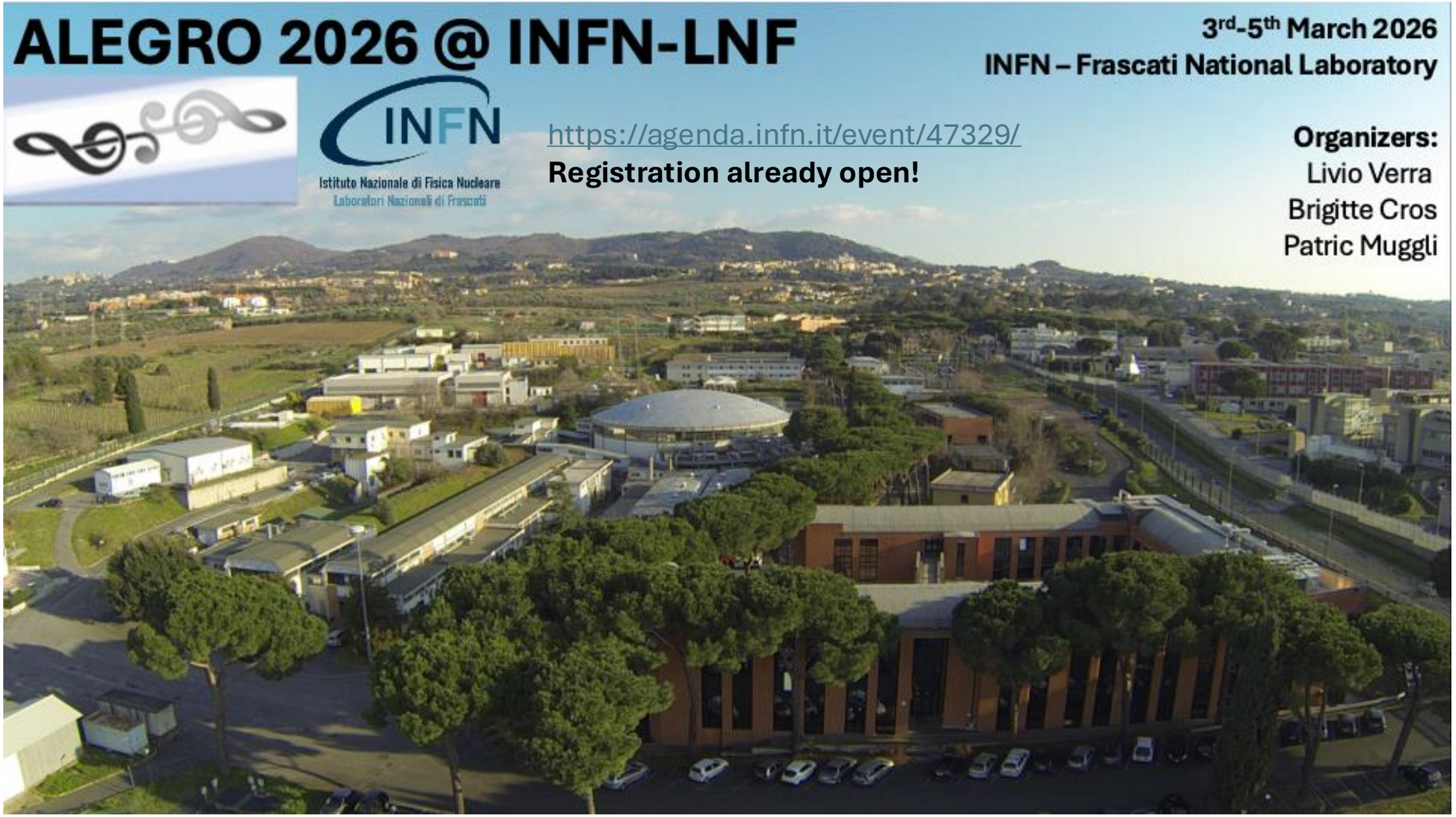
Resonant excitation of plasma wakefields with a train of relativistic particle bunches

L. Verra, M. Galletti, M. P. Anania, A. Biagioni, M. Carillo, E. Chiadroni, A. Cianchi, G. Costa, L. Crincoli, A. Del Dotto, M. Del Giorno, R. Demitra, G. Di Pirro, A. Giribono, V. Lollo, M. Opromolla, G. Parise, D. Pellegrini, R. Pompili, S. Romeo, G. Silvi, F. Stocchi, F. Villa, and M. Ferrario

Phys. Rev. E - **Accepted** 19 September, 2025
DOI: https://doi.org/10.1103/x4xl-4fnp

Export Citation

ALEGRO 2026


ALEGRO 2026 @ INFN-LNF
3rd-5th March 2026
INFN – Frascati National Laboratory
INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
https://agenda.infn.it/event/47329/
Registration already open!
Organizers:
Livio Verra
Brigitte Cros
Patric Muggli

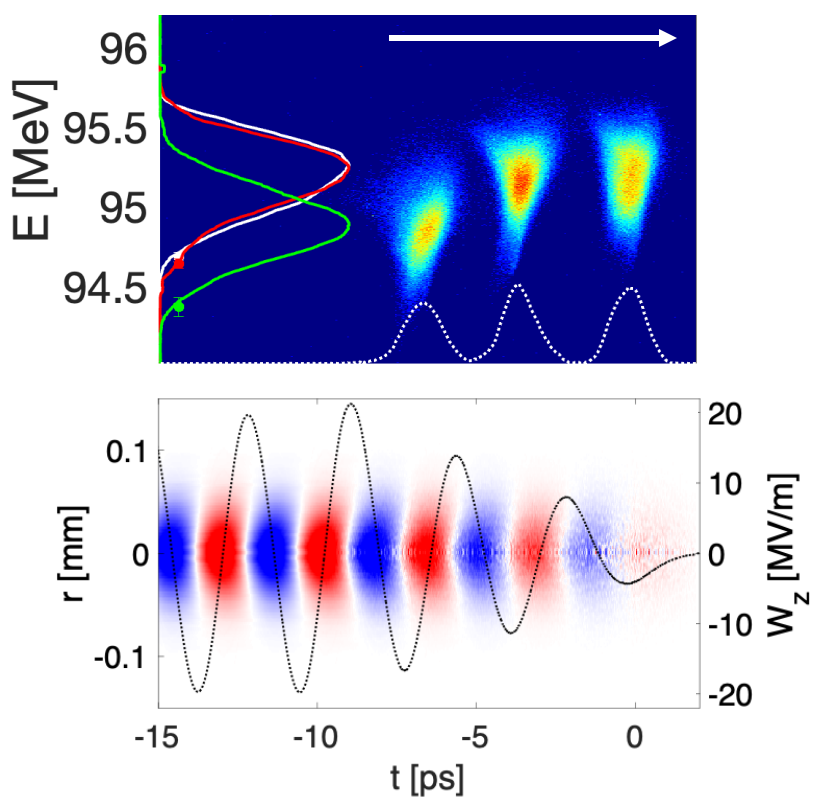
INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

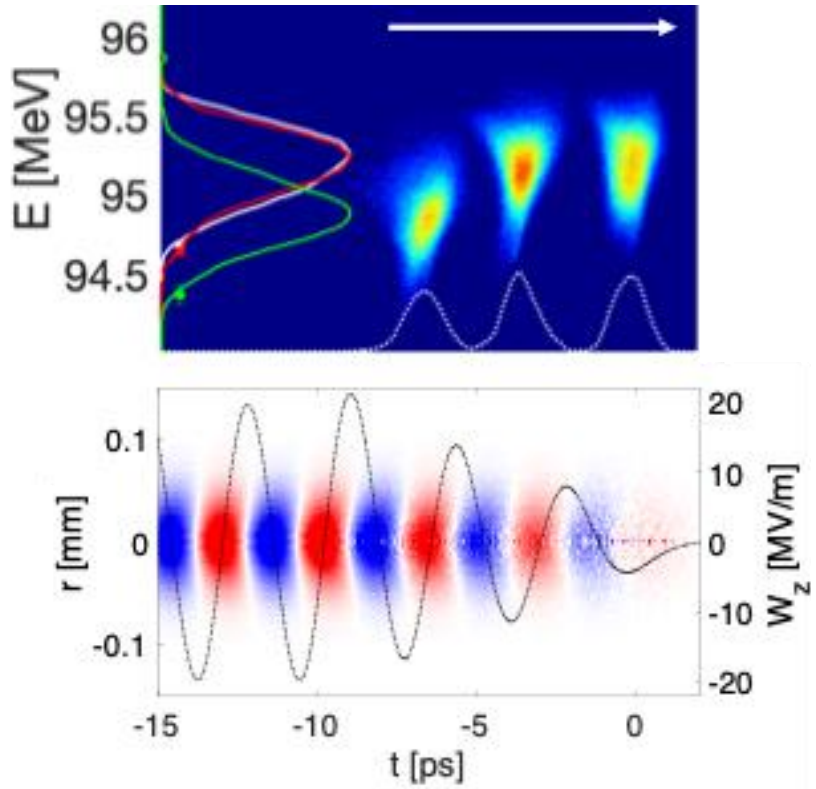
EuPRAXIA
EuPRAXIA@SPARC_LAB

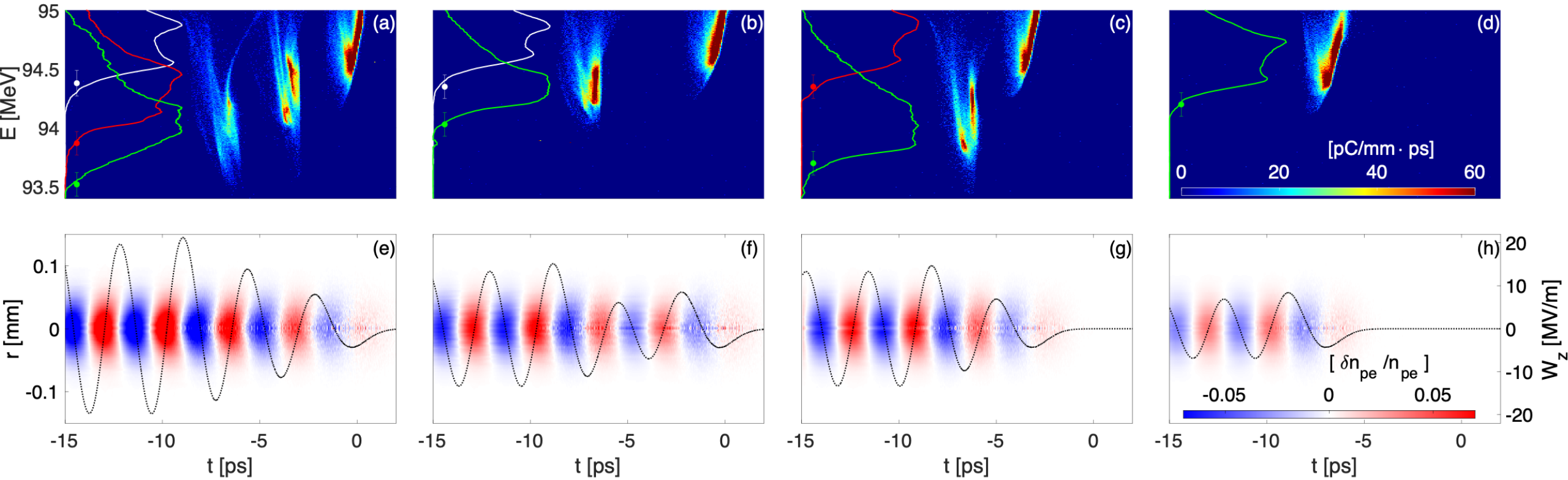
Thank you!

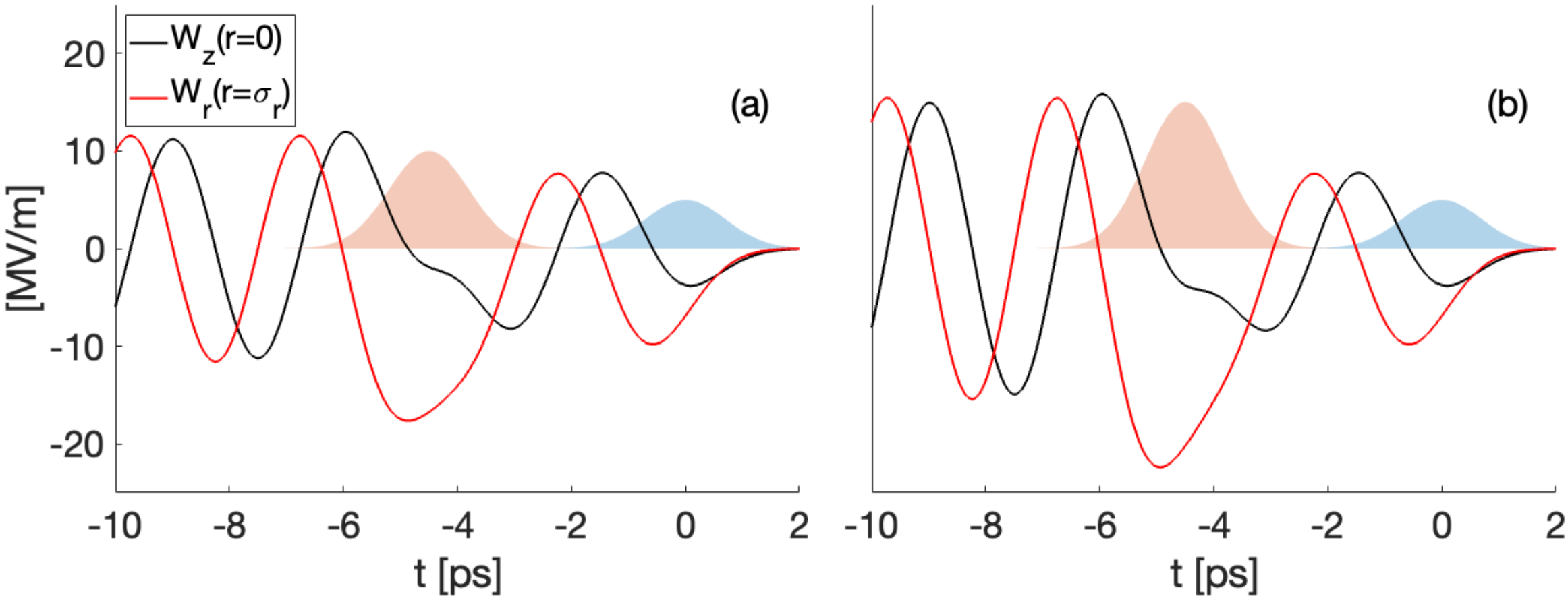
SPARC
LAB

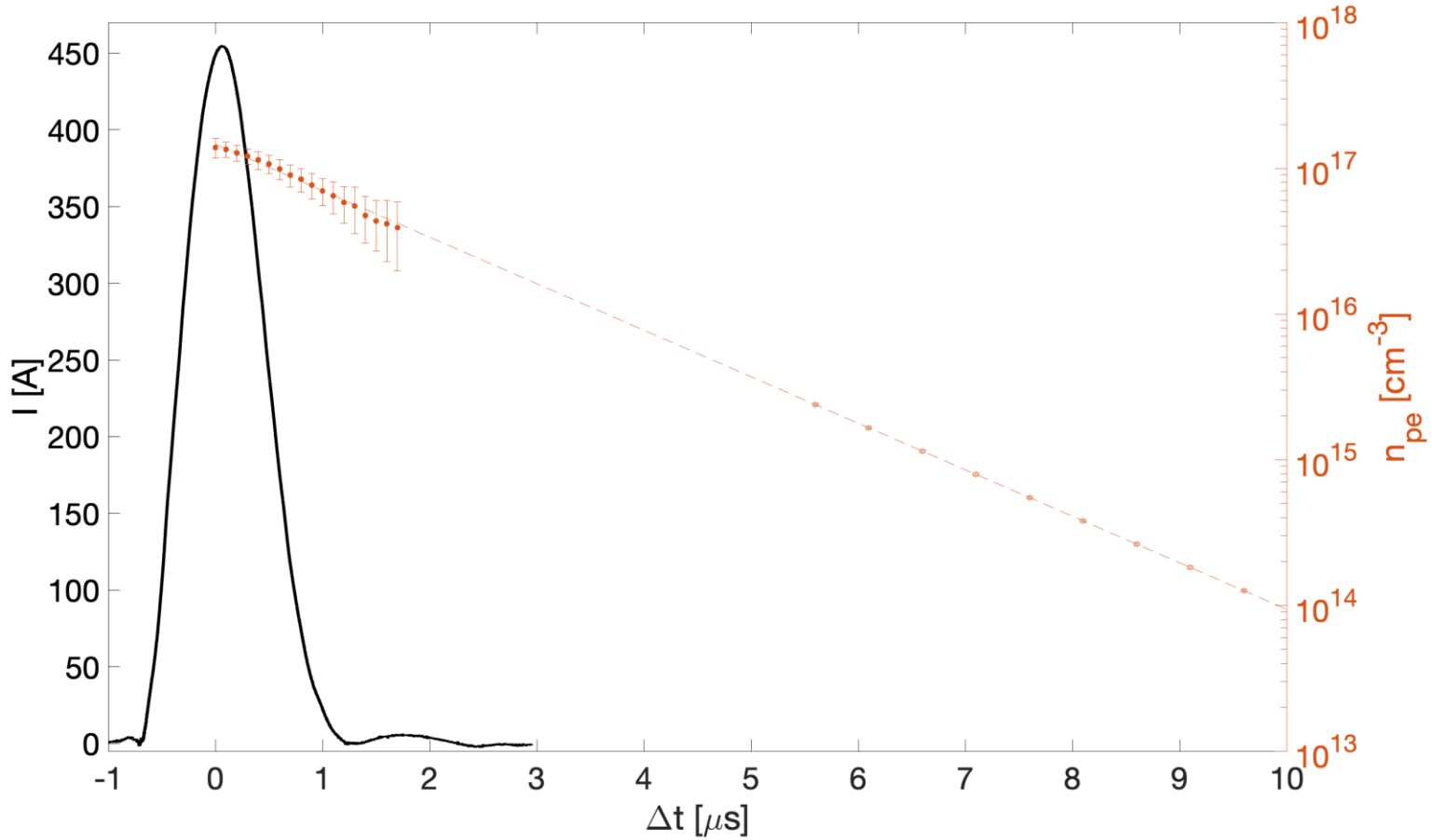
Backup slides


E [MeV]
96
95.5
95
94.5
r [mm]
0.1
0
-0.1
-15
-10
-5
0
t [ps]
20
10
0
-10
-20
W_z [MV/m]


E [MeV]
96
95.5
95
94.5
r [mm]
0.1
0
-0.1
-15
-10
-5
0
t [ps]
20
10
0
-10
-20
W_z [MV/m]


95
94.5
94
93.5
E [MeV]
(a)
(b)
(c)
(d)
[pC/mm · ps]
0
20
40
60
(e)
(f)
(g)
(h)
0.1
0
-0.1
r [mm]
[δn_pe /n_pe]
-0.05
0
0.05
20
10
0
-10
-20
W_z [MV/m]
-15
-10
-5
0
t [ps]

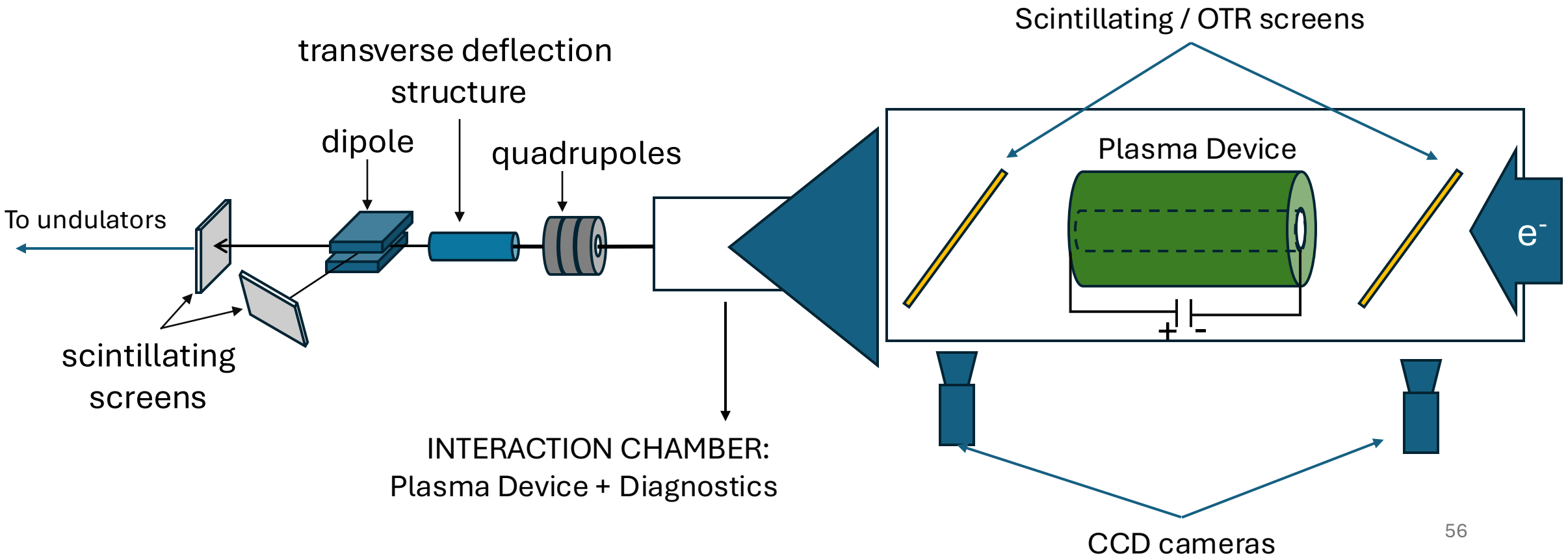

W_z(r=0)
W_r(r=σ_r)
(a)
(b)
[MV/m]
20
10
0
-10
-20
-10
-8
-6
-4
-2
0
2
t [ps]


I [A]
450
400
350
300
250
200
150
100
50
0
-1
0
1
2
3
4
5
6
7
8
9
10
Δt [μs]
10^18
10^17
10^16
10^15
10^14
10^13
n_pe [cm^-3]

0b. SPARC - Setup

- Photoinjector + Linac
  - Acceleration and bunch compression (<20 fs)
  - Velocity Bunching
- Discharge Plasma Capillary
- Diagnostics (Charge, Energy, Emittance, etc..)
- Undulators

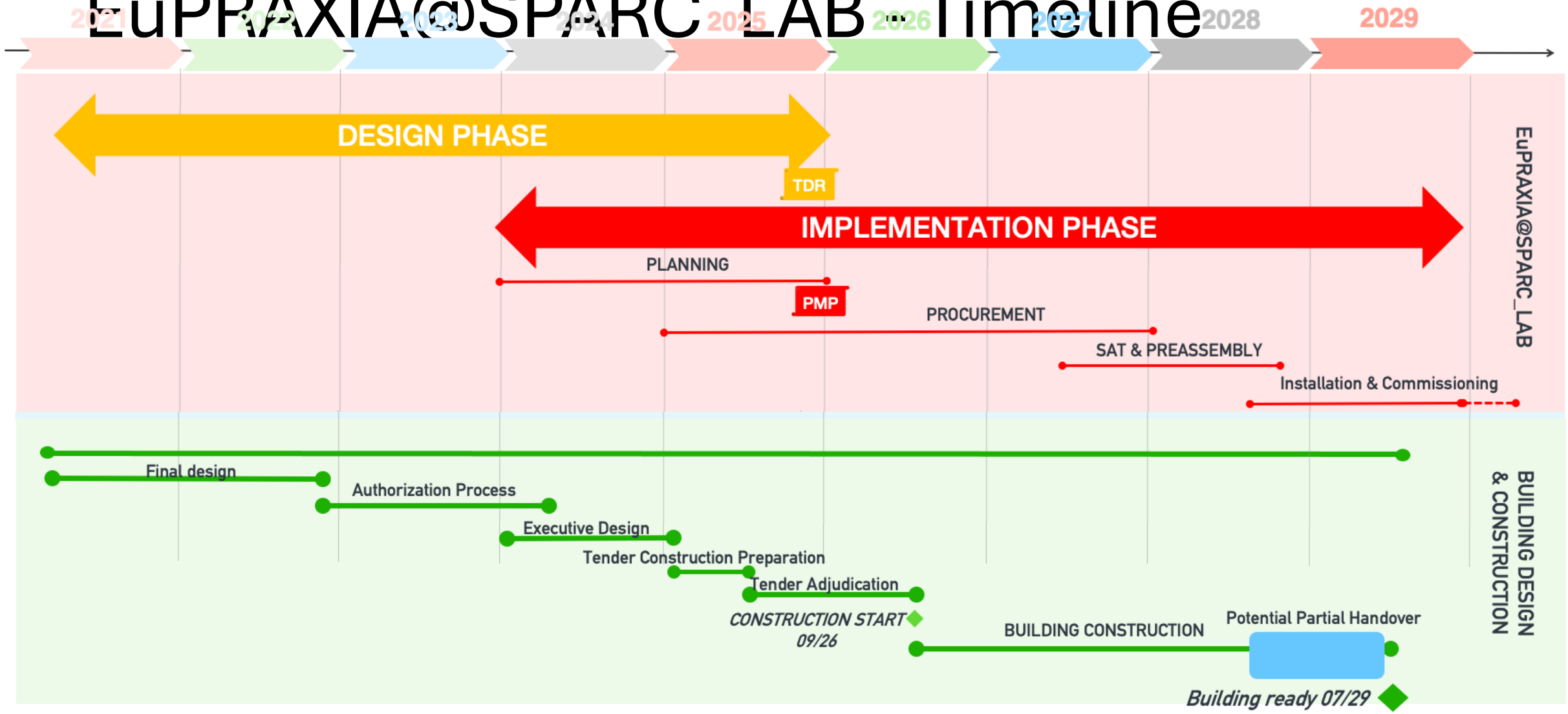
Charge (total)	20 – 1000 pC
Energy	70 – 150 MeV
Normalized Emittance	~ 1 mm mrad
Bunch Duration (rms)	0.02 – 3 ps
Bunch Transverse size (rms)	0.1 – 0.5 mm



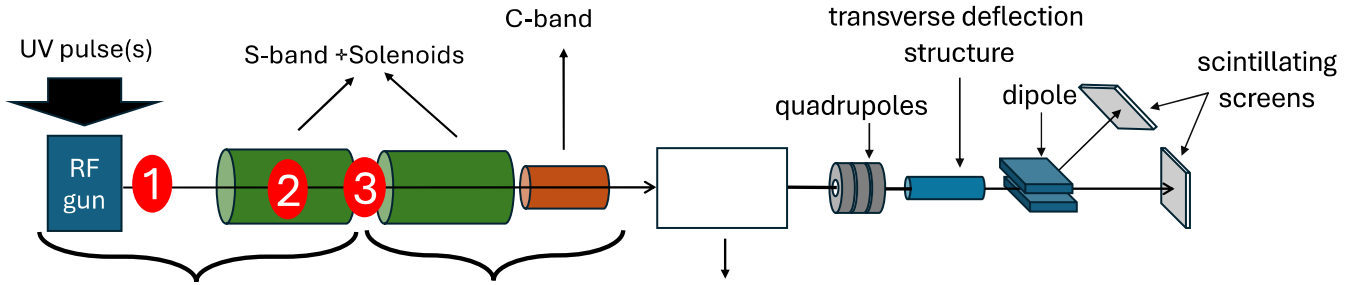
EuPRAXIA@SPARC_LAB

- Soft X-ray (2-4 nm) FEL based on Plasma Wakefield Acceleration (PWFA) at Frascati
- 500 MeV, 30 pC electron bunch boosted to 1 GeV in 60-cm-long plasma

EuPRAXIA@SPARC_LAB Timeline



SPARC LINAC



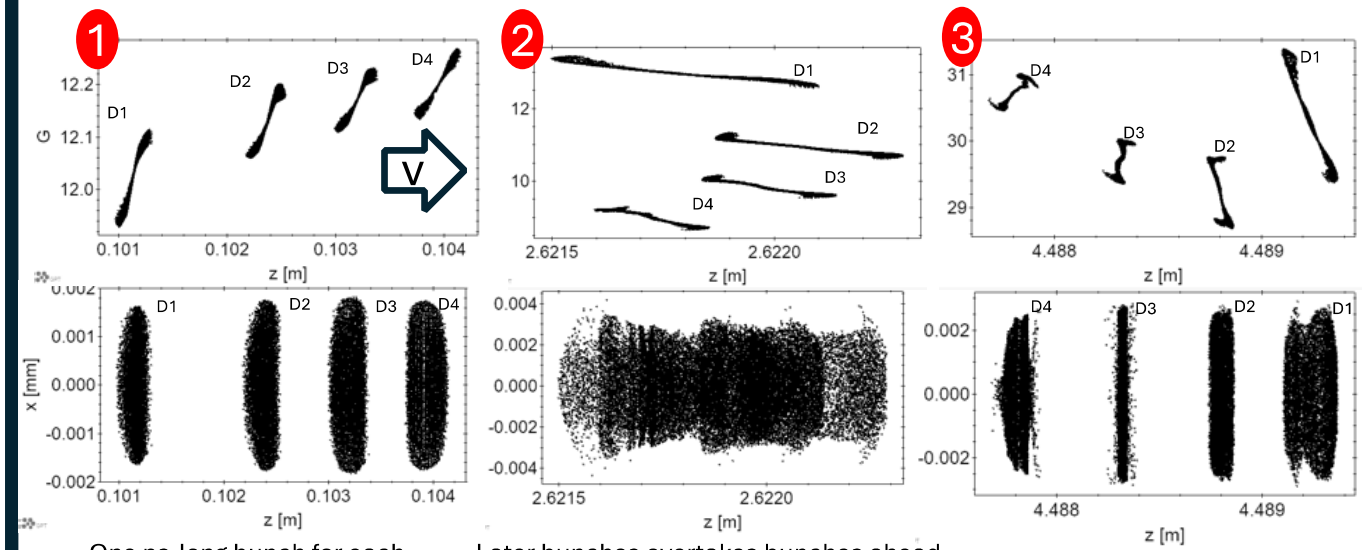
- Bunch compression
- Final bunch spacing
- Emittance control

- Energy spread tuning
- Final energy

INTERACTION CHAMBER:
Final focusing + discharge capillary + Capture System + Diagnostics

Train of compressed bunches generated via velocity bunching

L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87–106 (2001)



One ps-long bunch for each UV pulse

Later bunches overtakes bunches ahead
→ Bunch compression
→ Crossing of bunches

Afterwards, ”rigid” acceleration to 70-150 MeV

GPT Simulations

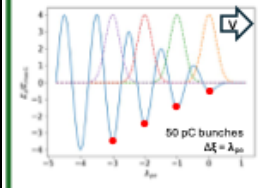
Multiple-Drive-Bunch Plasma Wakefield Acceleration

L. Verra[1], M. Galletti[1], R. Pompili[1], A. Biagioni1, M. Carillo[1], A. Cianchi[2], L. Crincoli[1], A. Curcio[3], A. Del Dotto[1], F. Demurtas[2], G. Di Pirro[1], V. Lollo[1], G. Parise[1], D. Pellegrino[1], S. Romeo[1], G. Silvi[1], F. Villa[1], and M. Ferrario[1]
[1]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[2]University of Rome Tor Vergata, Rome, Italy
[2]University of Rome Sapienza, Rome, Italy

Abstract

The space-charge field of a relativistic bunch is screened in plasma due to the presence of mobile charge carriers. We experimentally investigate such screening by measuring the effect of dielectric wakefields driven by the bunch in an uncoated dielectric capillary where the plasma is confined. We show that the plasma screens the space-charge field when the distance between the bunch and the dielectric surface is much larger than the plasma skin depth, and that, otherwise, the effects of dielectric and plasma wakefields are present simultaneously.

Resonant Configuration



Superposition of wakefields driven by each bunch

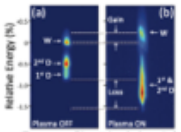
→ Resonance when distance = plasma wavelength

→ Potentially larger amplitude than single bunch with equal total charge

Previous Results:

Resonant wakefields driven by self-modulated p^+ bunch (AWAKE)

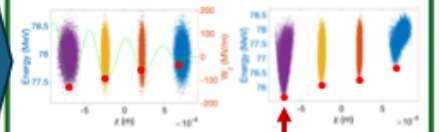
L. Verra et al. (AWAKE Coll.), PRL 129, 024802 (2022)
AWAKE Coll., PRL 122, 054802(2019)
AWAKE Coll., Nature 561, 363 (2018)



Witness bunch acceleration

P. Muggli et al., Proceedings of PAC 2011

Linear theory calculations

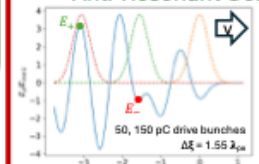


Bunch distribution from GPT
$\Delta\xi = 5\ \mu m$
→ Resonance at $n_{pe} = 5.5 \cdot 10^{15}\ cm^{-3}$

$n_b << n_{pe}$ for all bunches ($\sigma_r = 100\mu m$)
→ Linear regime

Observable:
Energy loss increases along the train

Anti-Resonant Configuration



Concept proven in dielectric wakefield accelerator

C. Jing et al., PRL 98, 144801 (2007)

Superposition of wakefields driven by each bunch

→ Equal decelerating field within all drive bunches

→ Enhanced transformer ratio $R = \frac{E_+}{E_-}$

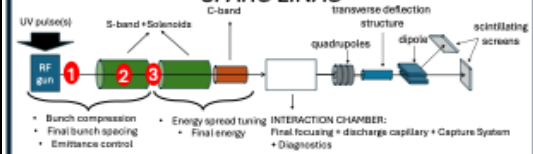
→ More efficient energy transfer

→ Longer depletion length

Experimental Plan:

- Setup Multi-Bunch Configuration (UV + LINAC)
- Demonstrate resonant wakefield excitation (increased energy loss along the train)
- Demonstrate enhanced transformer ratio acceleration using ramped bunch train

SPARC LINAC



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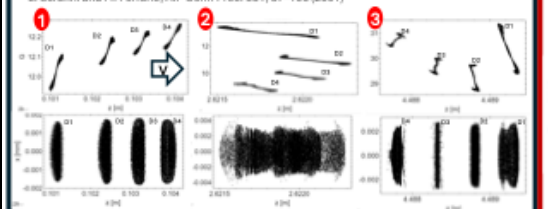

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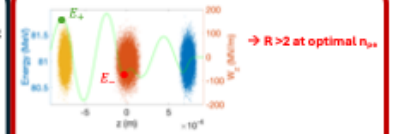
→ Crossing of bunches

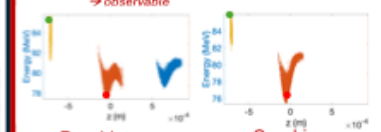
Afterwards, "rigid" acceleration to 70-150 MeV

GPT Simulations



Bunch distribution from GPT
$\Delta\xi = 720\ \mu m$
→ Resonance at $n_{pe} = 3.8 \cdot 10^{15}\ cm^{-3}$

Effect of ramps reduces the final value or R_+ but: enhancement with two ramped drive bunches
→ observable



Two drivers: R = 1.4 > One driver: R = 0.87

(Further optimization and additional driver to reach R>2)