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

Mario Galletti, Livio Verra
on behalf of SPARC_LAB Group

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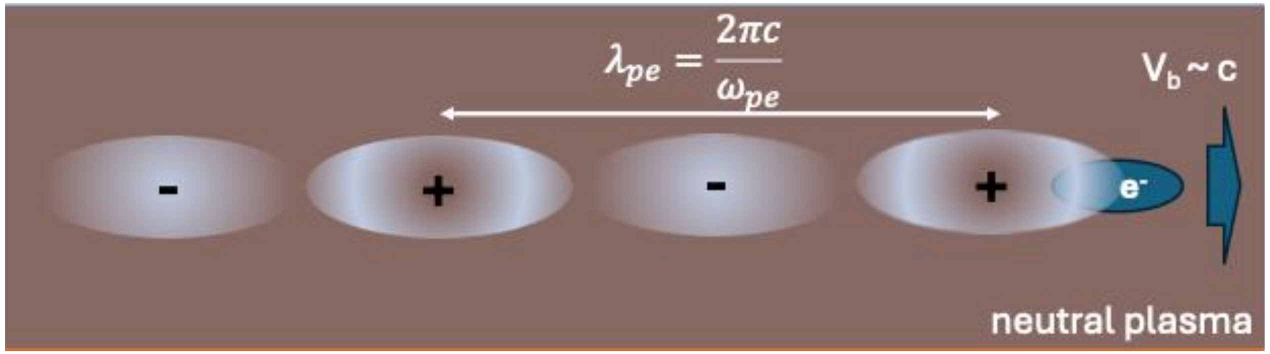
Introduction – Resonances in Plasma

- Plasma perturbation driven by charged particle bunches or laser pulses are periodic

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



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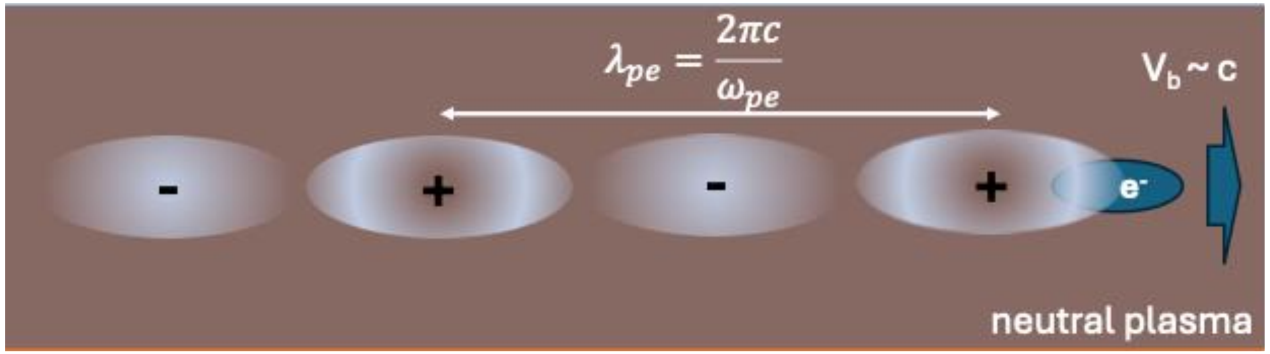
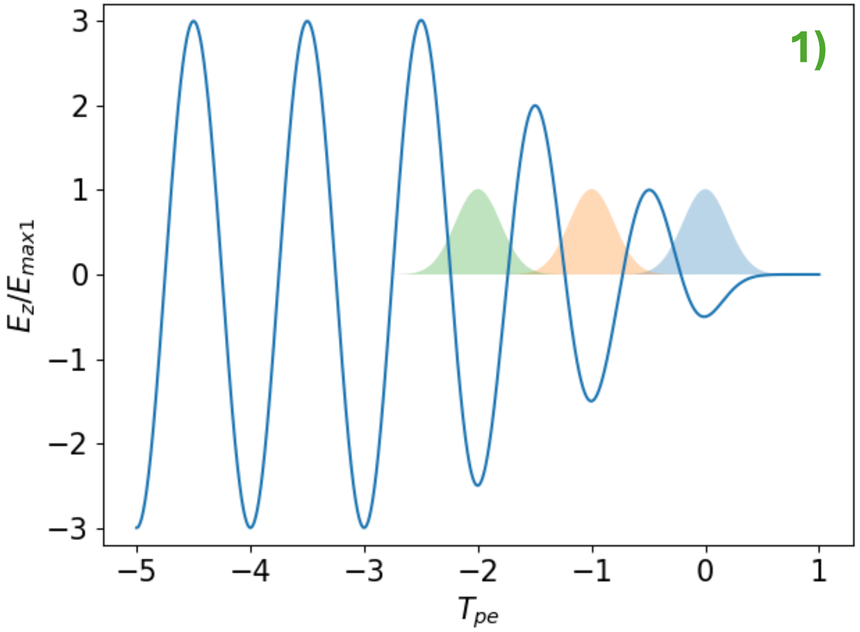
  1) Maximizing amplitude of longitudinal wakefields





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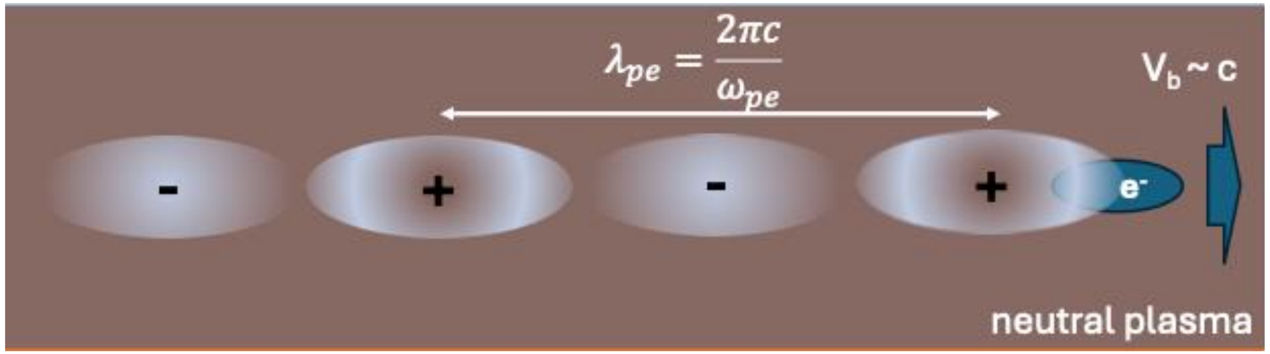
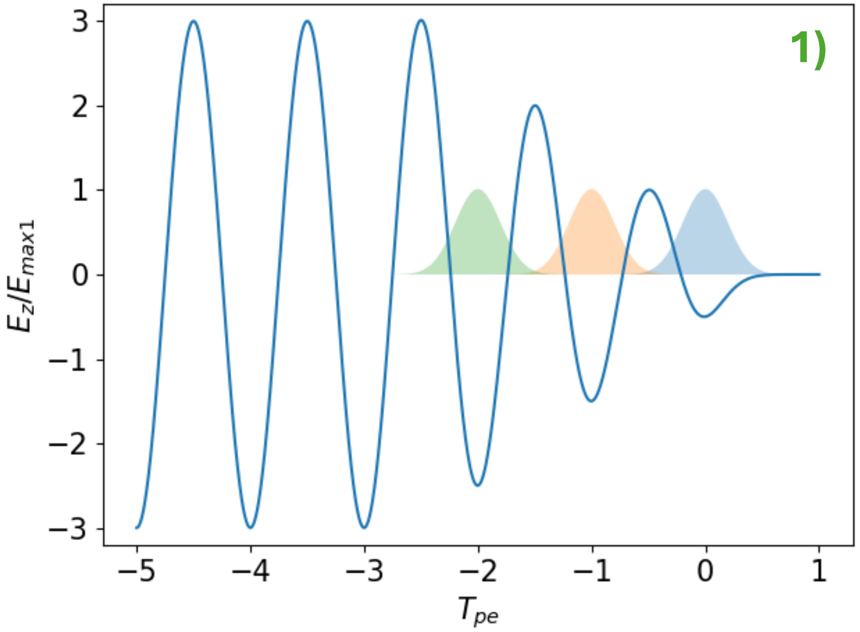
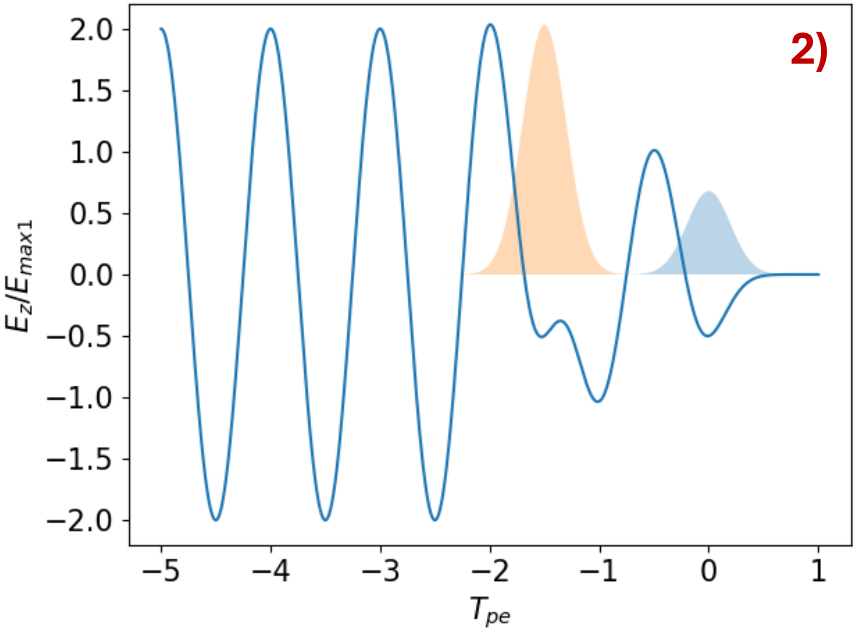
- Two ways of exploiting this property:
1) Maximizing amplitude of longitudinal wakefields
2) Maximizing the ratio between decelerating and accelerating (transformer ratio)

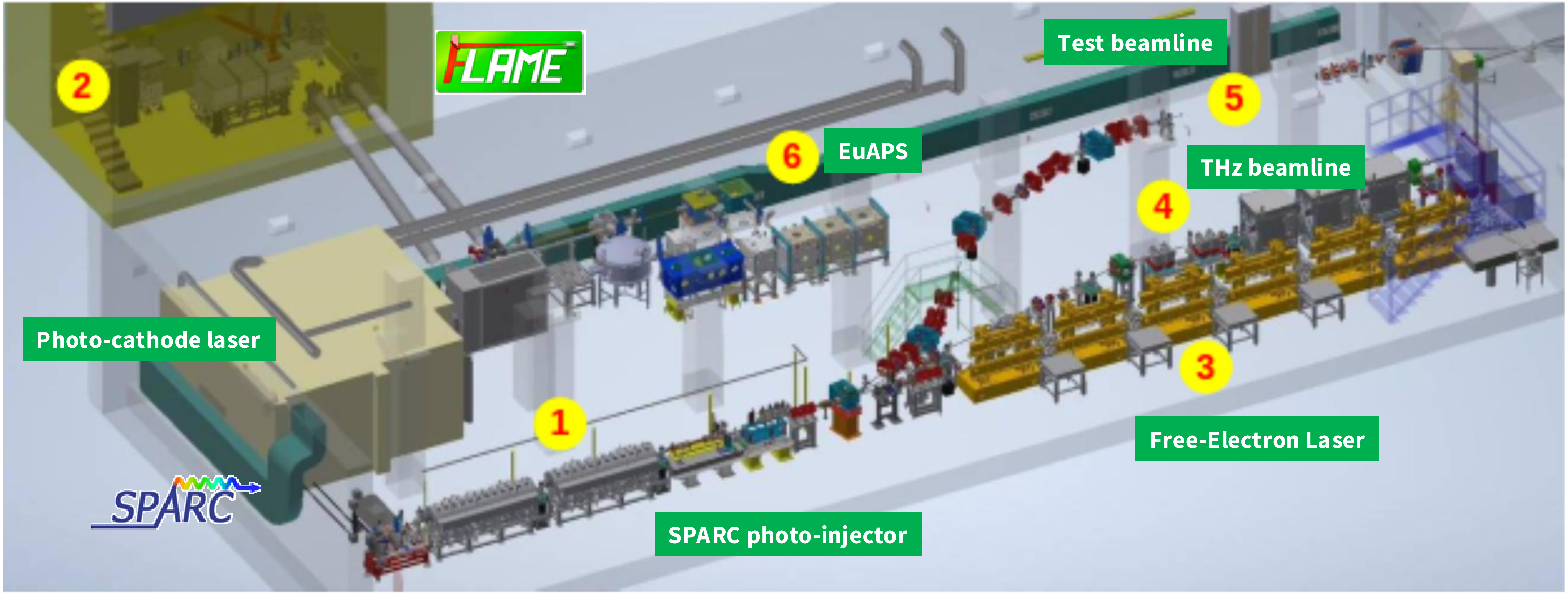
- Need a train of bunches with ~ps delay and adjustable relative charge







SPARC_LAB facility



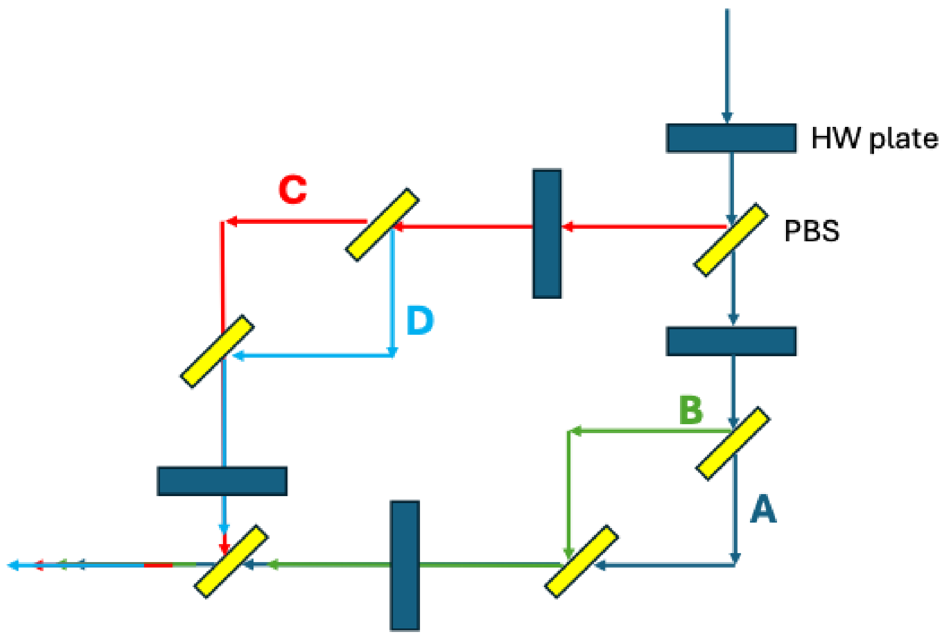
Layout of the SPARC_LAB facility. The bunker hosts the SPARC photo-injector (1), its photo-cathode laser and the three experimental beamlines: the FEL (3), the SABINA THz radiation source (4) and, finally, a test beamline (5) available for user experiments. The FLAME bunker (2) is connected to the SPARC one by means of an in-vacuum laser transport line and drives the EuAPS X-ray betatron source (6).

Pompili, R.; et al. The SPARC LAB facility for advanced acceleration and radiation experiments. **Phys. Rev. Accel. Beams 29, 051602 (2026)**

SPARC_LAB – Multiple Bunches configuration

- 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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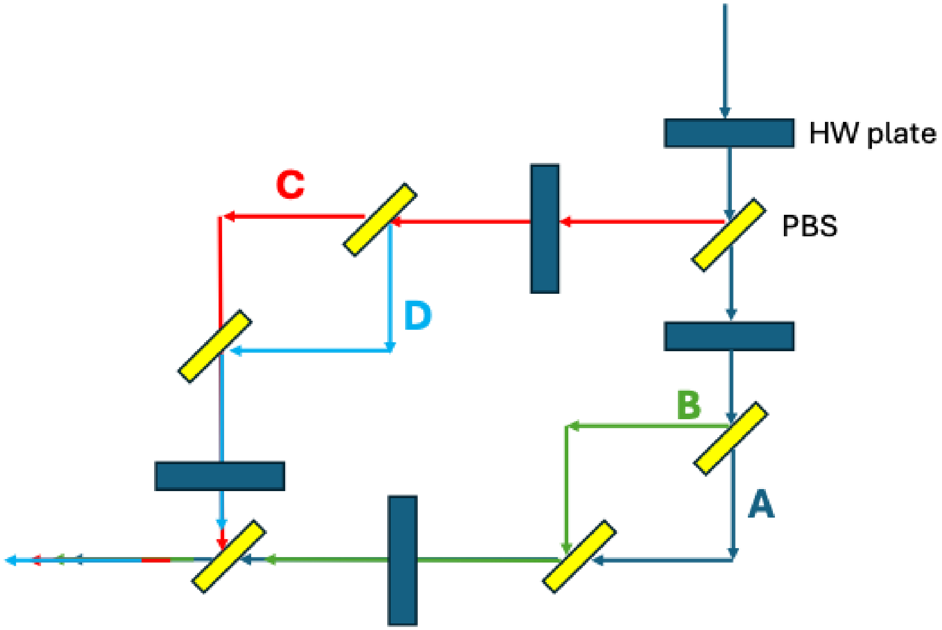
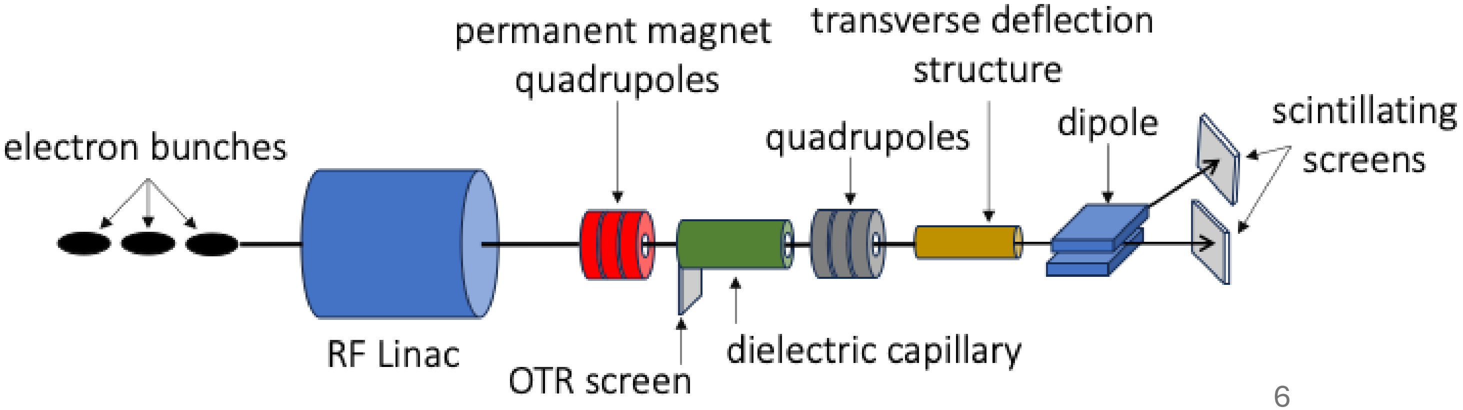
- Alignment of each trajectory with screens at plasma entrance and exit
- Plasma generated with discharge pulse in dielectric capillary





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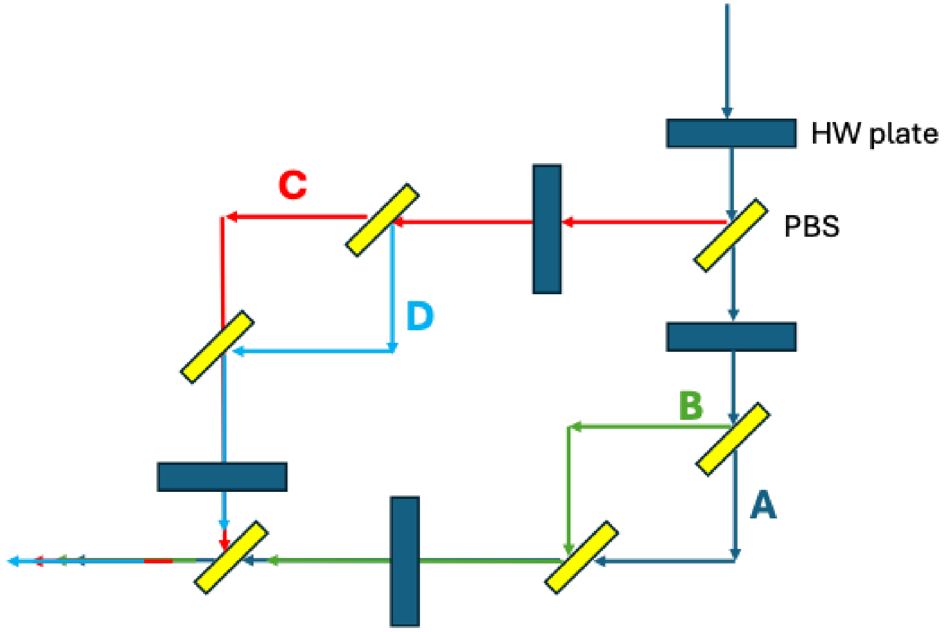
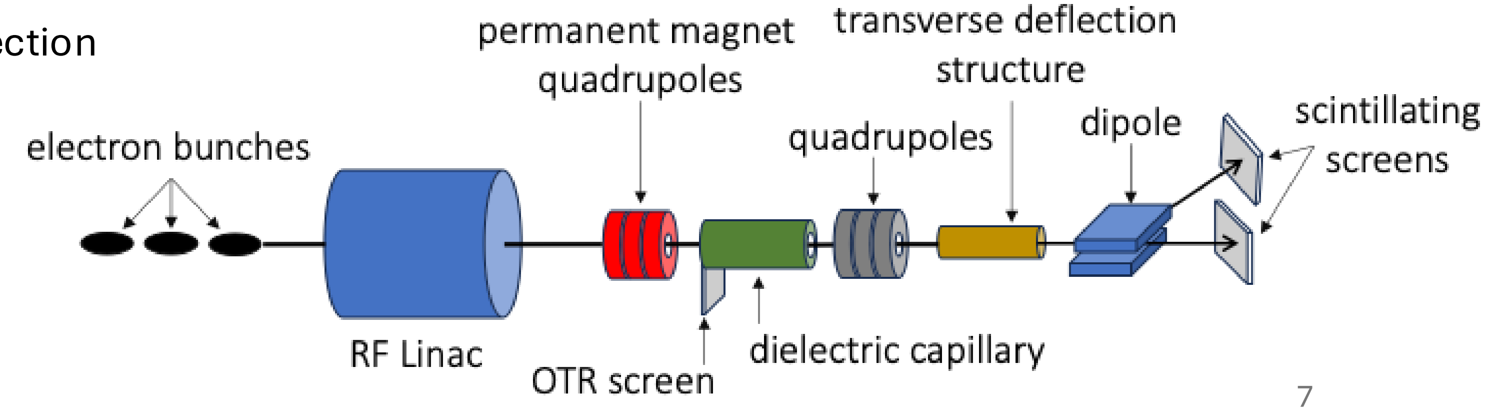
- Time resolved images obtained using transverse deflection structure (TDS)
- Longitudinal phase space using dipole + TDS



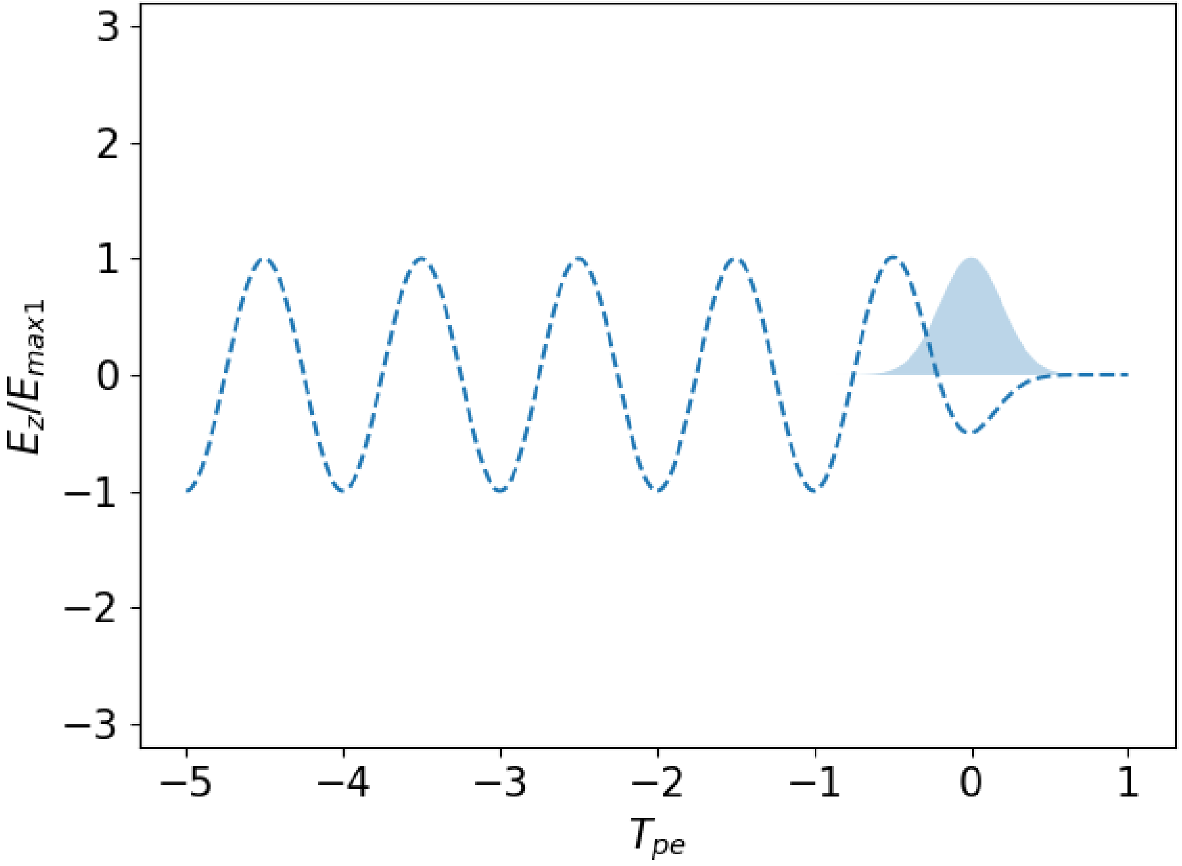


1) Maximizing the amplitude of the wakefields

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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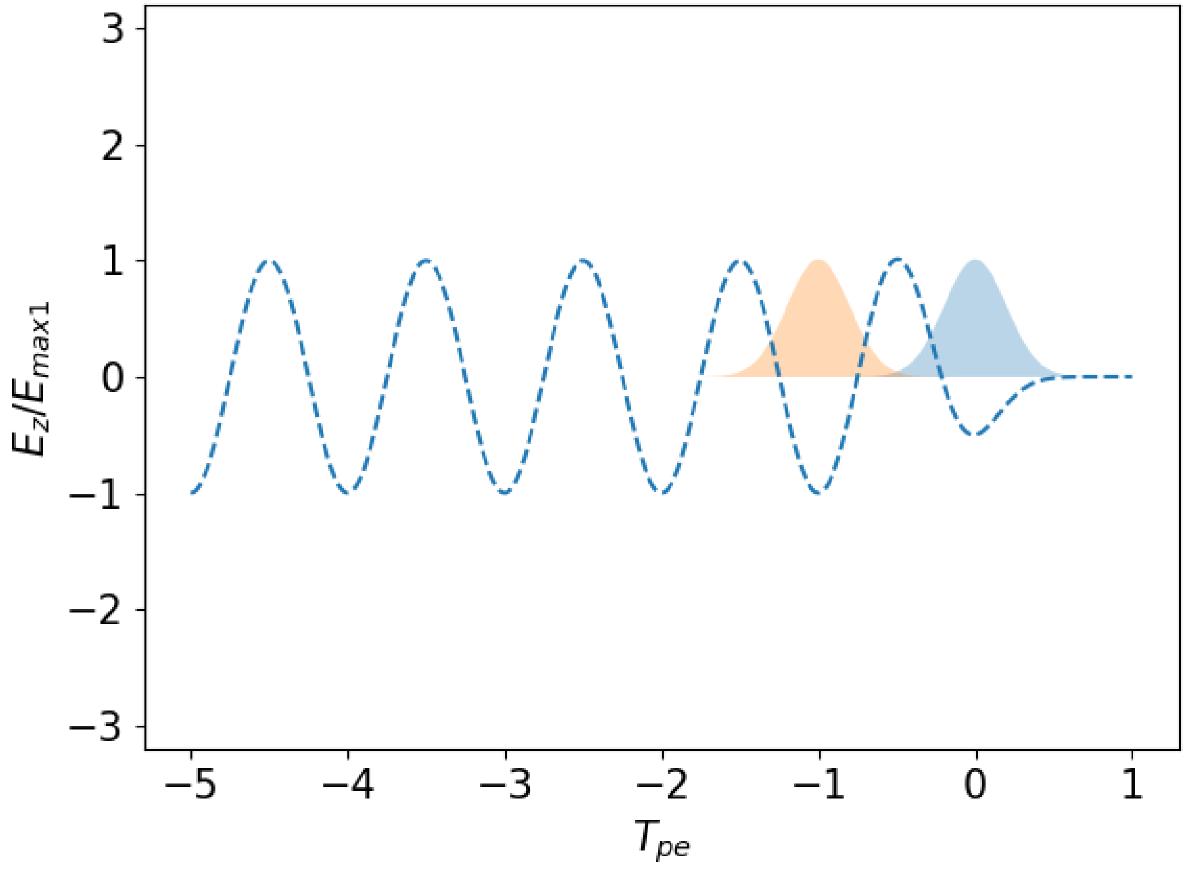

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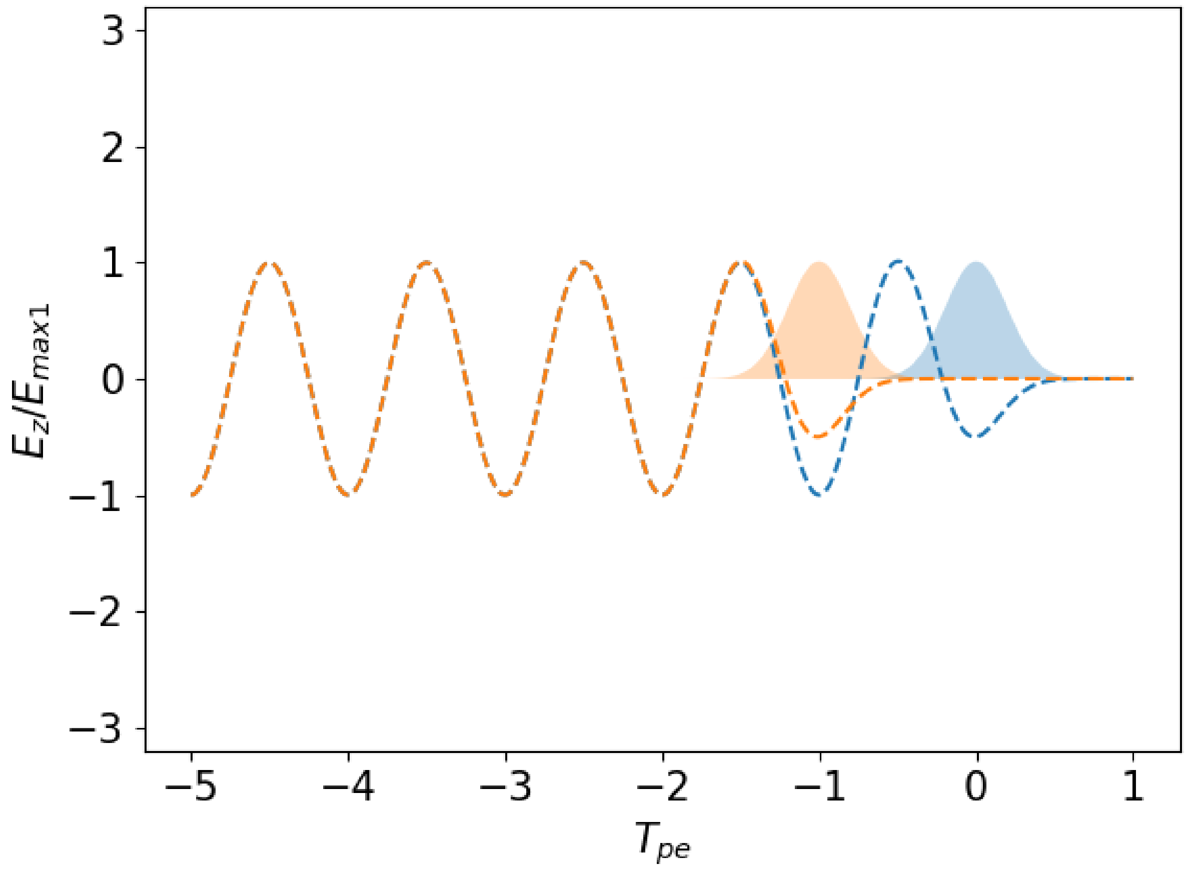

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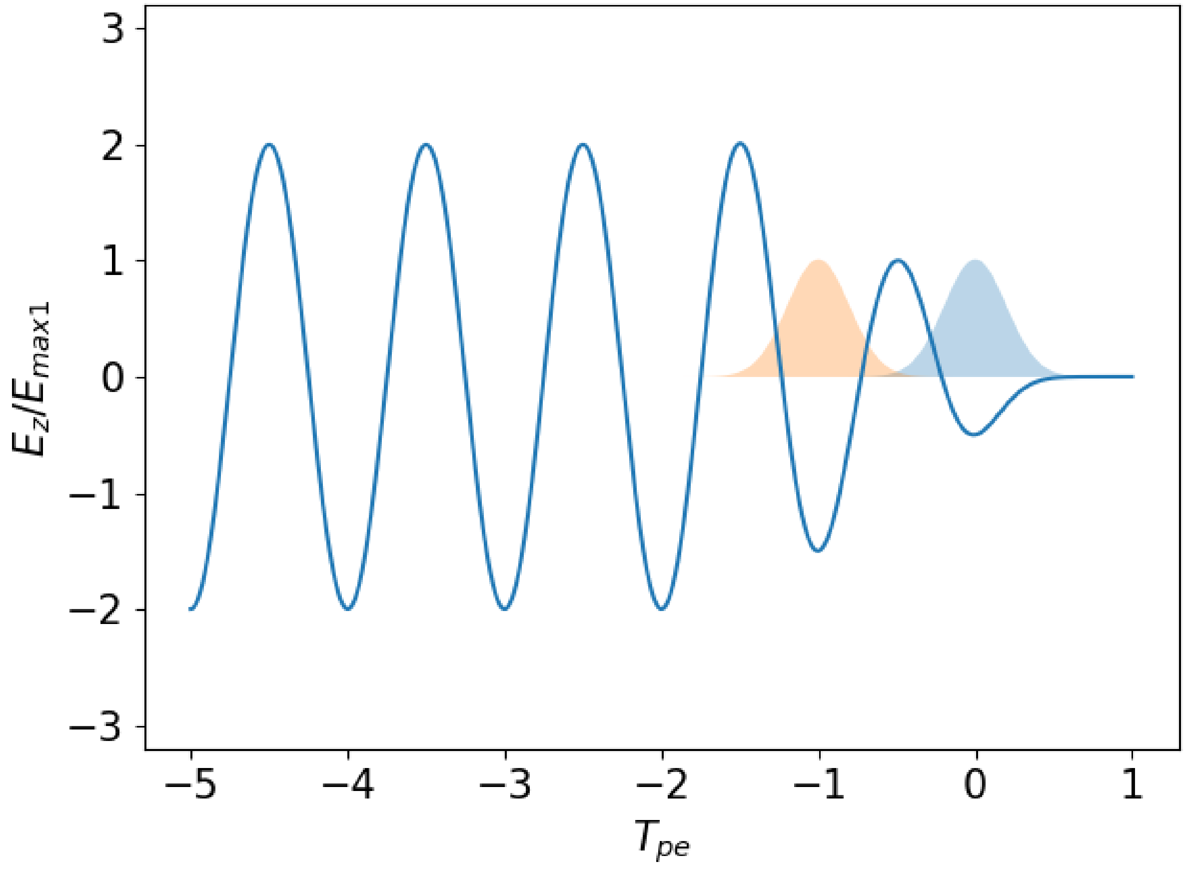

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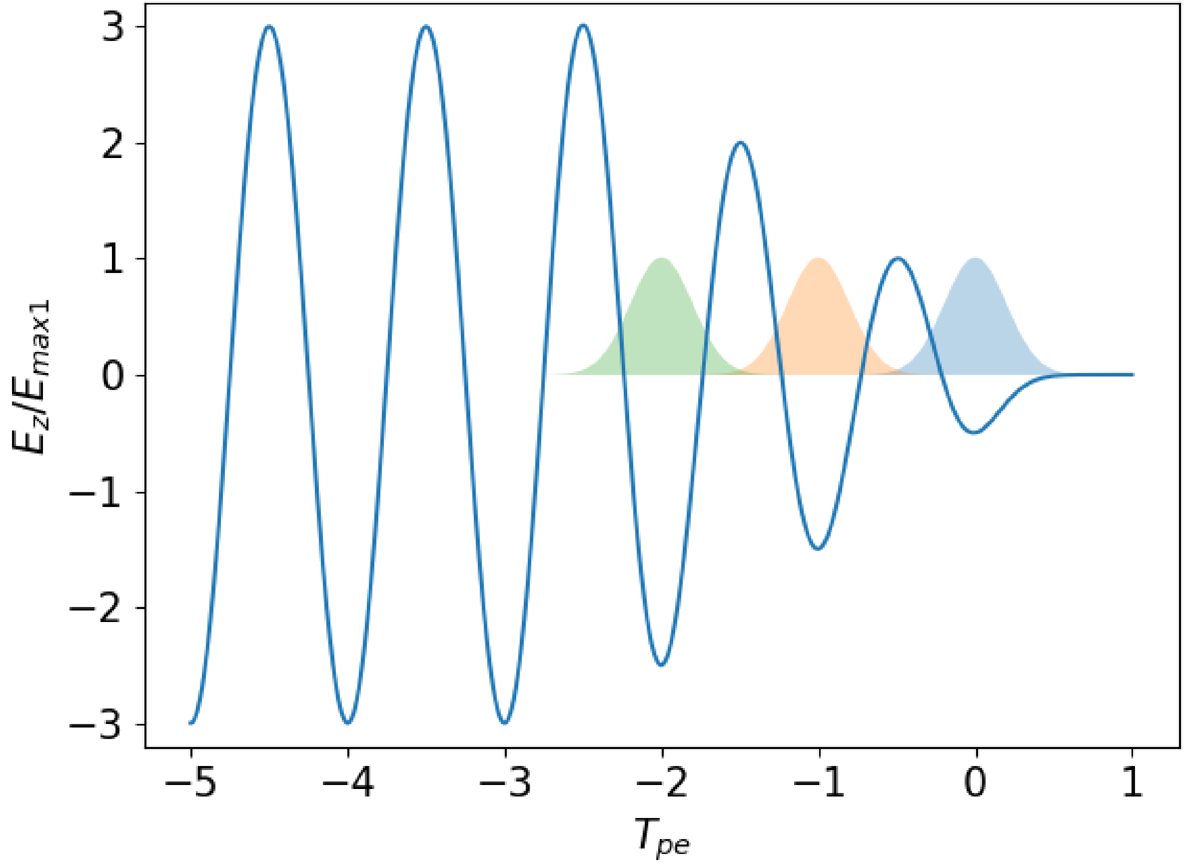
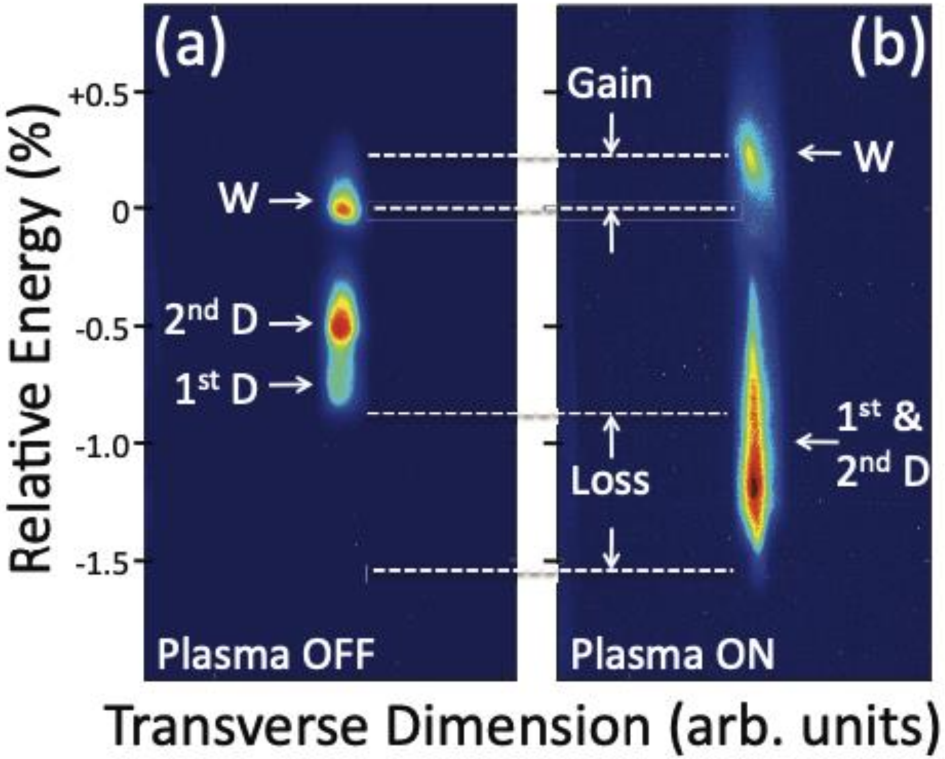
➔ **Observable at optimal coupling: increasing maximum energy loss of successive driver bunches**



1) Maximizing the amplitude of the wakefields – Previous Results

Acceleration with two driver bunches obtained 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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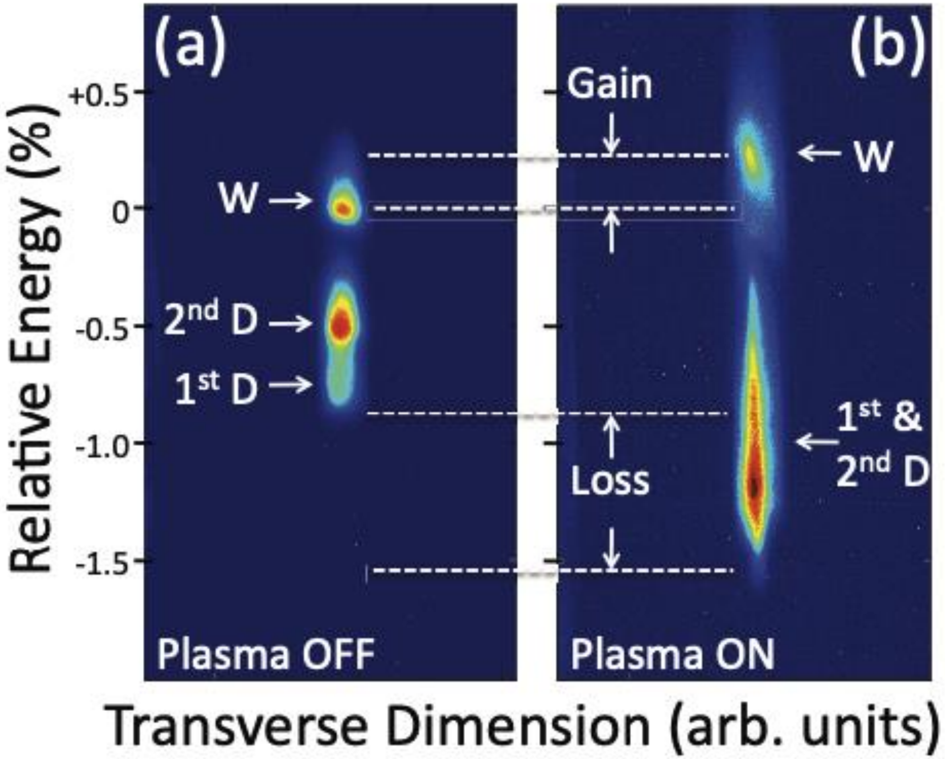

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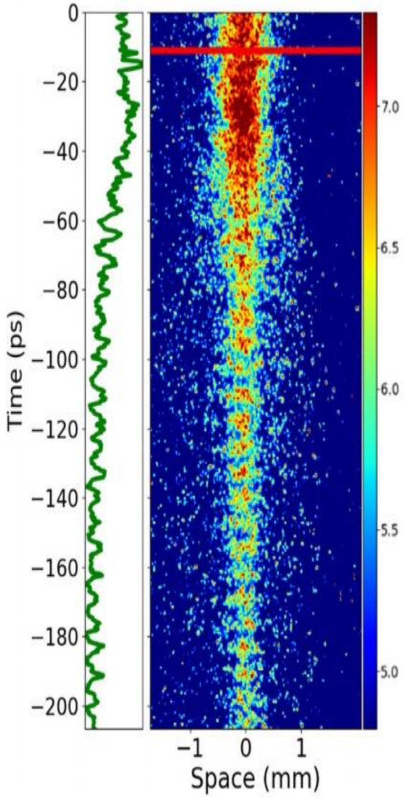
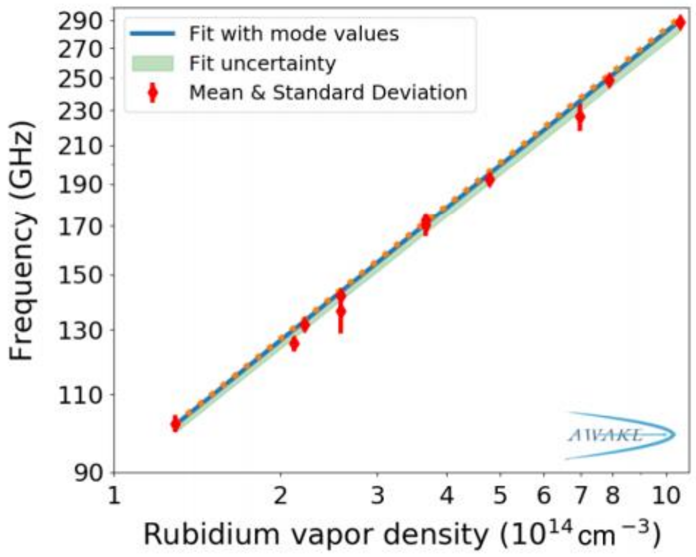
Acceleration with self-modulated p+ bunch (AWAKE)
- Periodic structure obtained by Self-Modulation
  → $f_{train} = f_{pe}$
  → only about half of initial charge contributes to driving final wakefields
  → need to wait for instability to saturate before injecting witness bunch

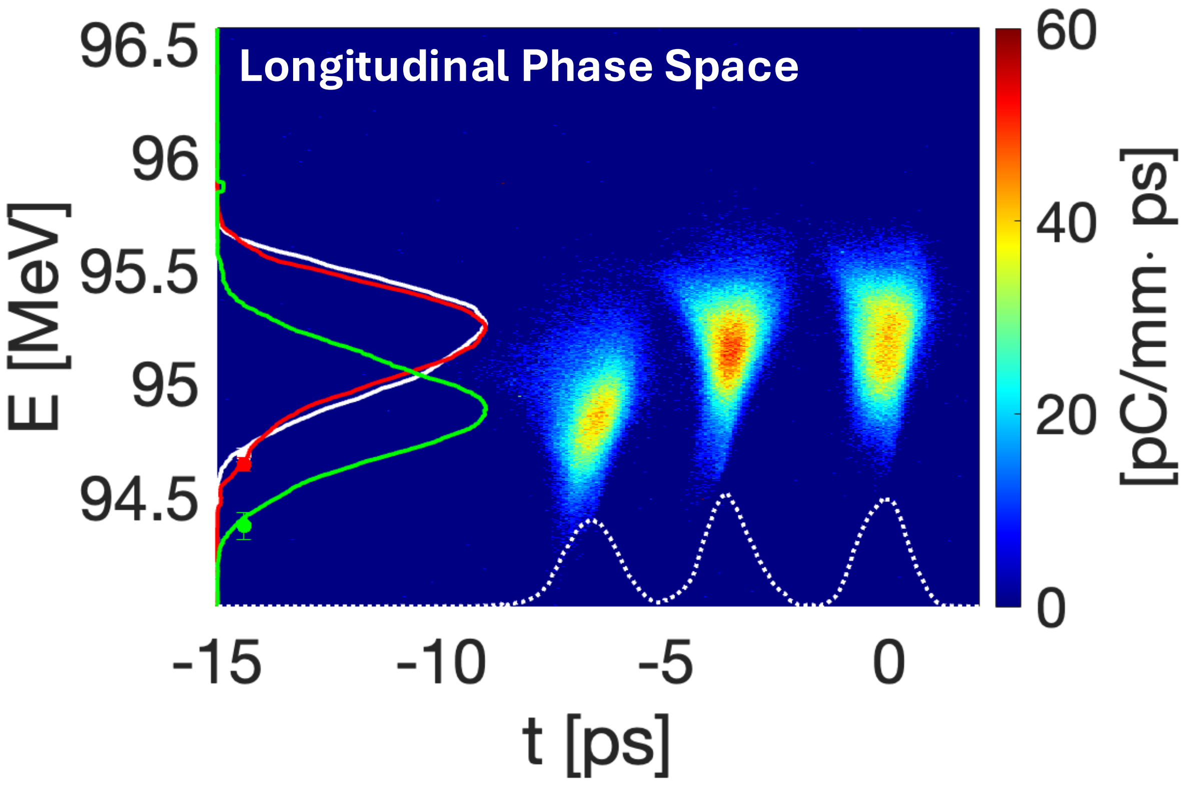




AWAKE Coll., Phys. Rev. Lett. 122, 054802 (2019)

1) 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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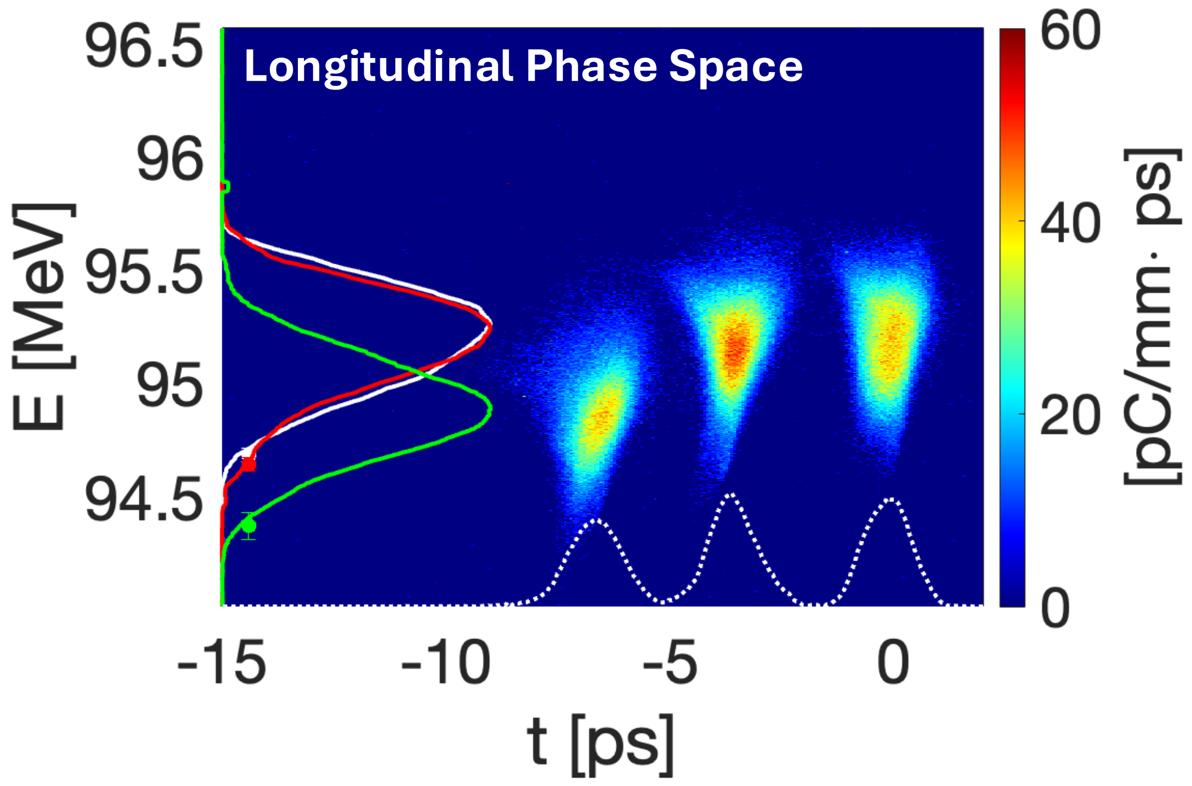
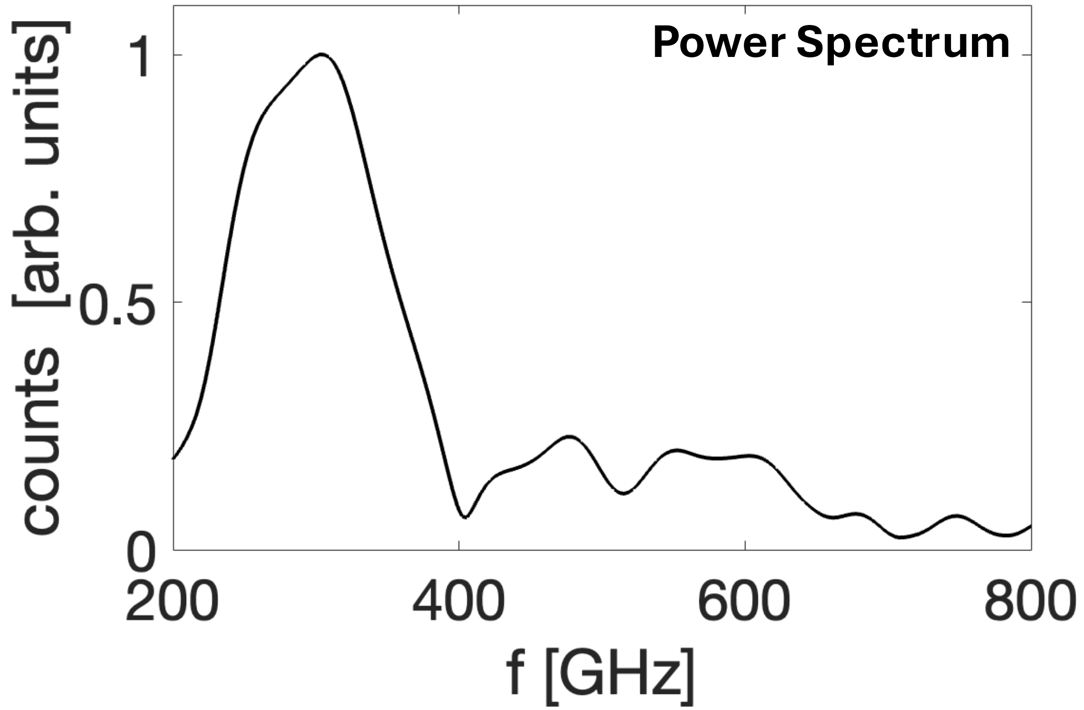
Discrete Fourier Transform

Peak at ~306 GHz
→ expected optimal coupling at
$n_{pe} \sim 1.2 \cdot 10^{15}\ cm^{-3}$
➔ $n_b \ll n_{pe}$: Linear regime





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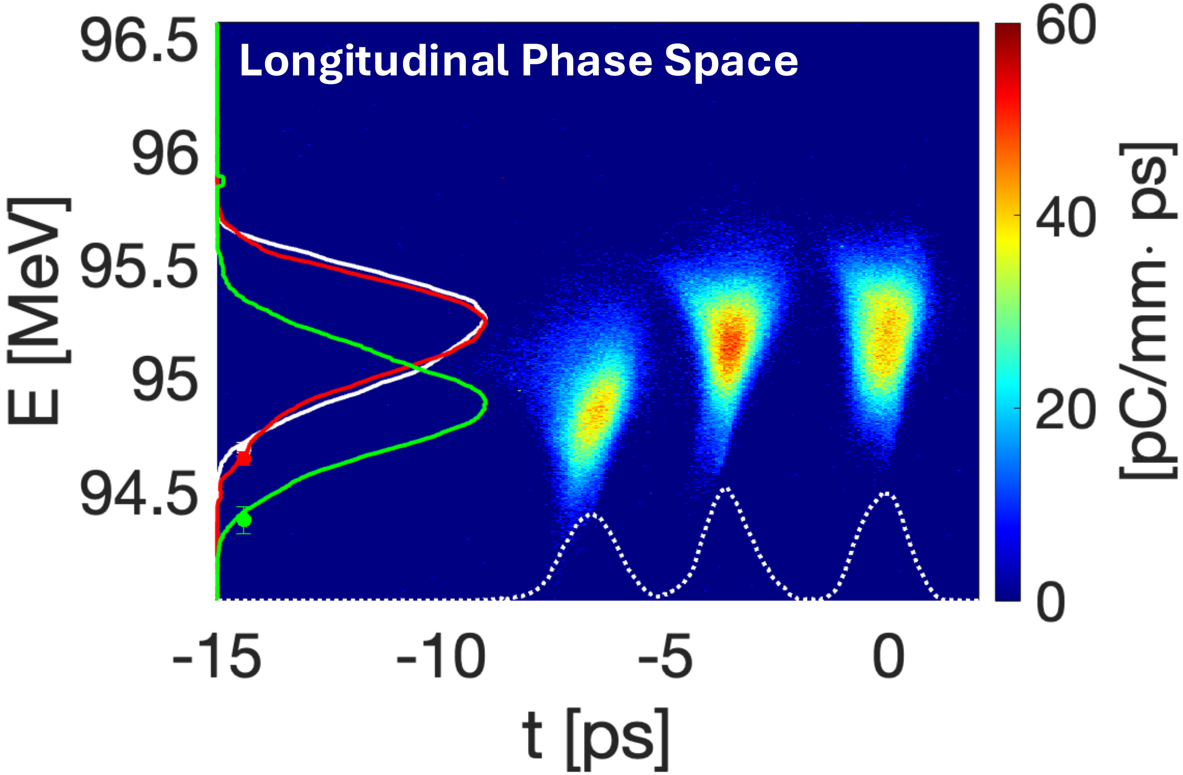
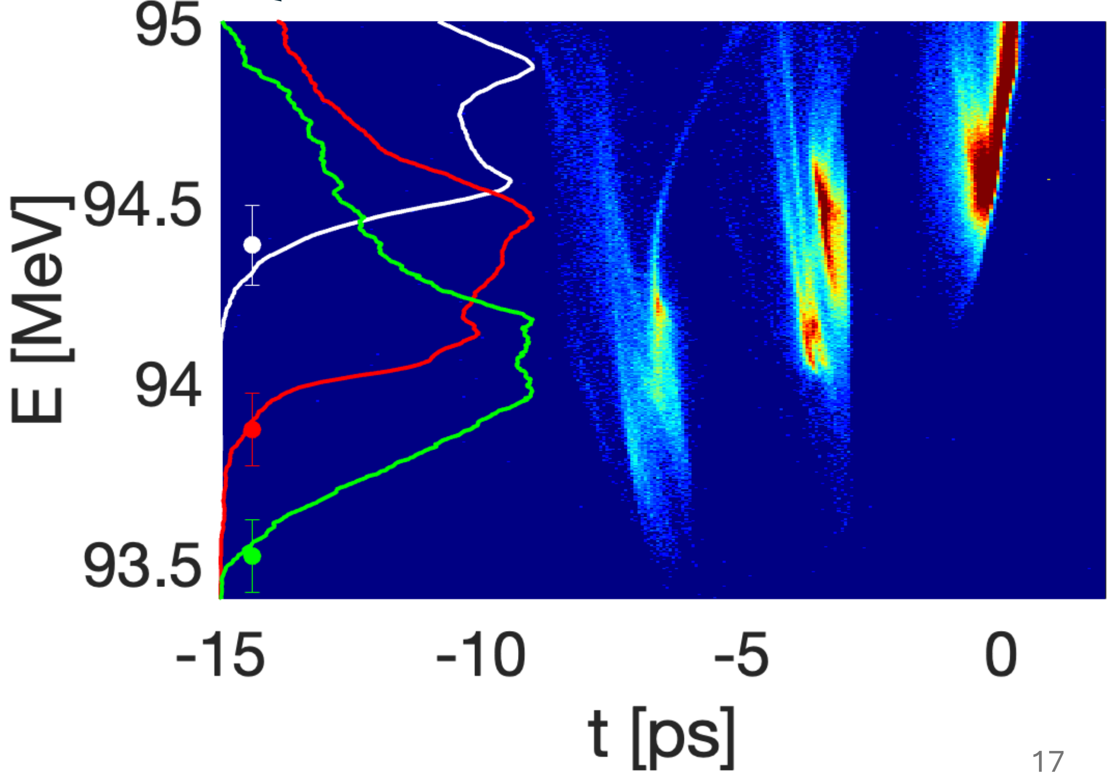
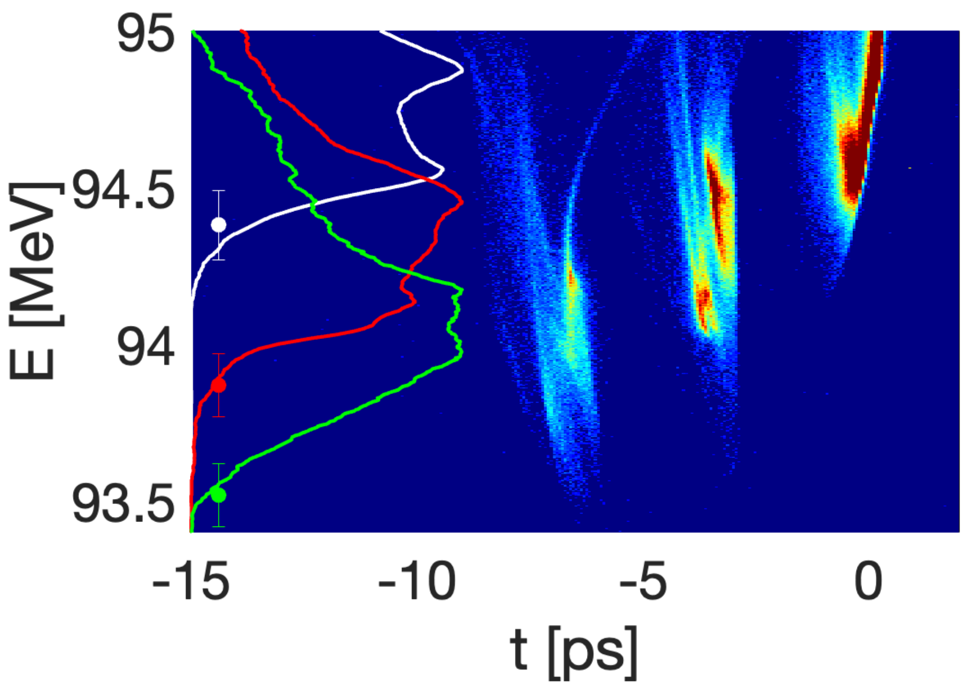




1) Maximizing the amplitude of the wakefields - Results

- 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

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



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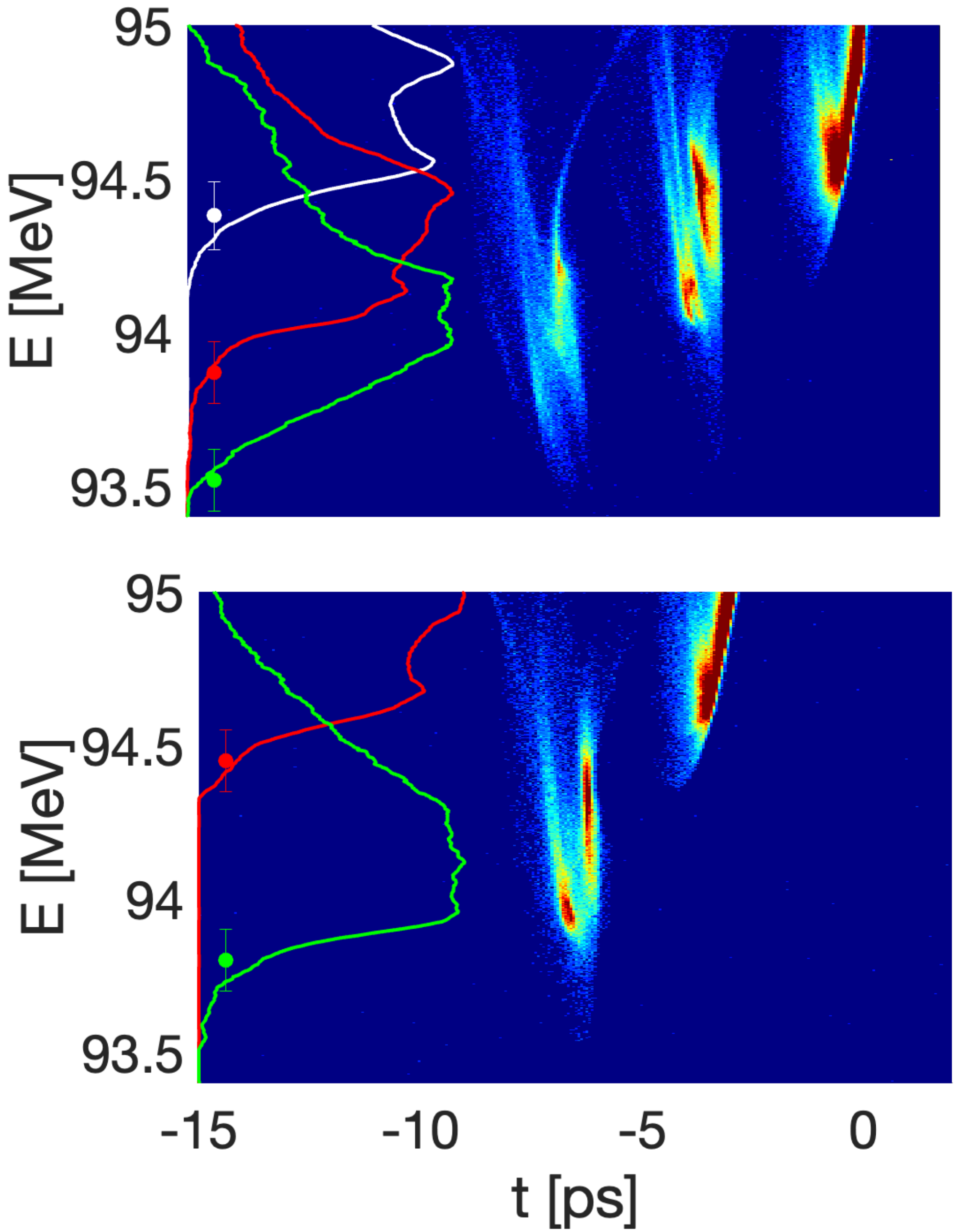

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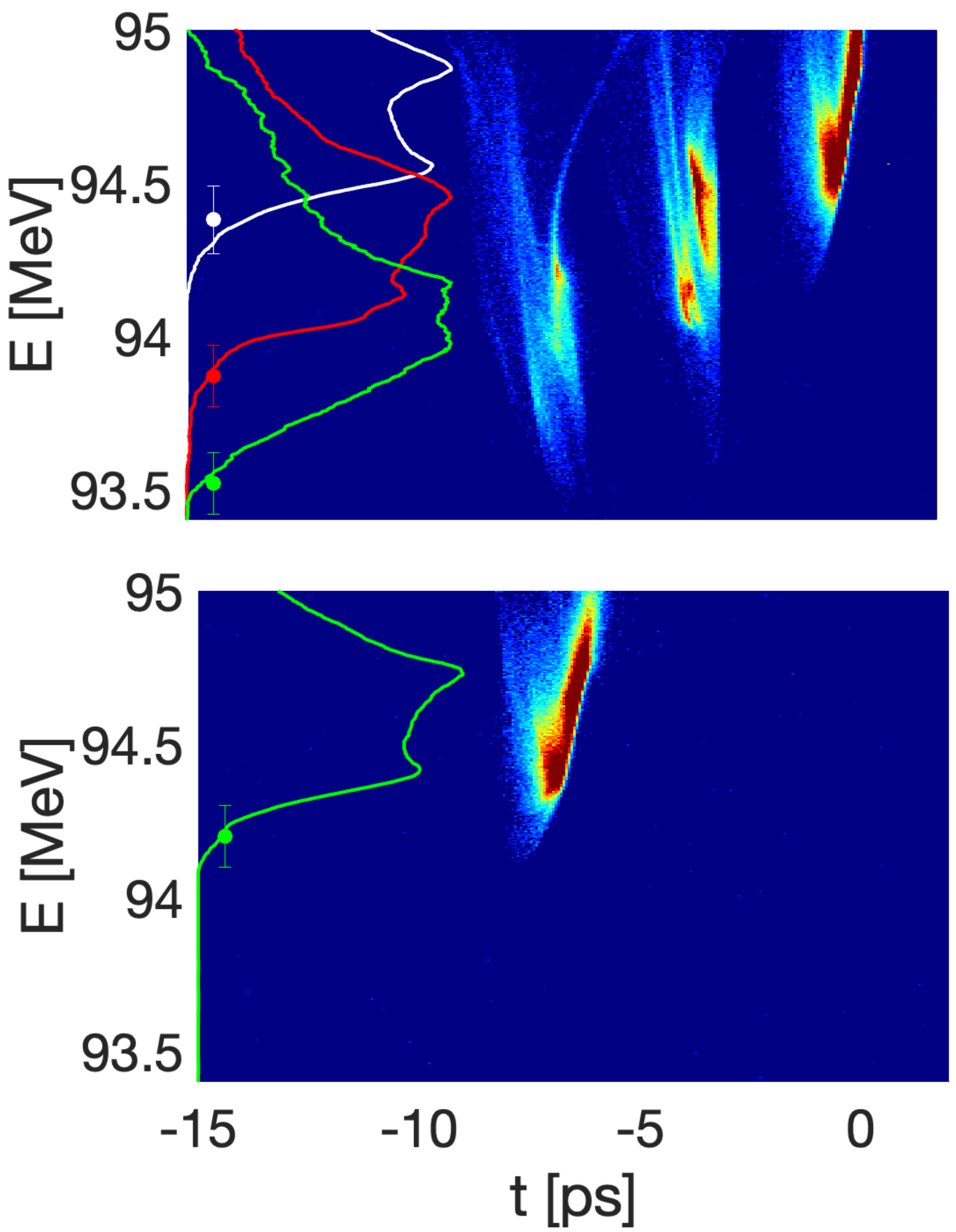

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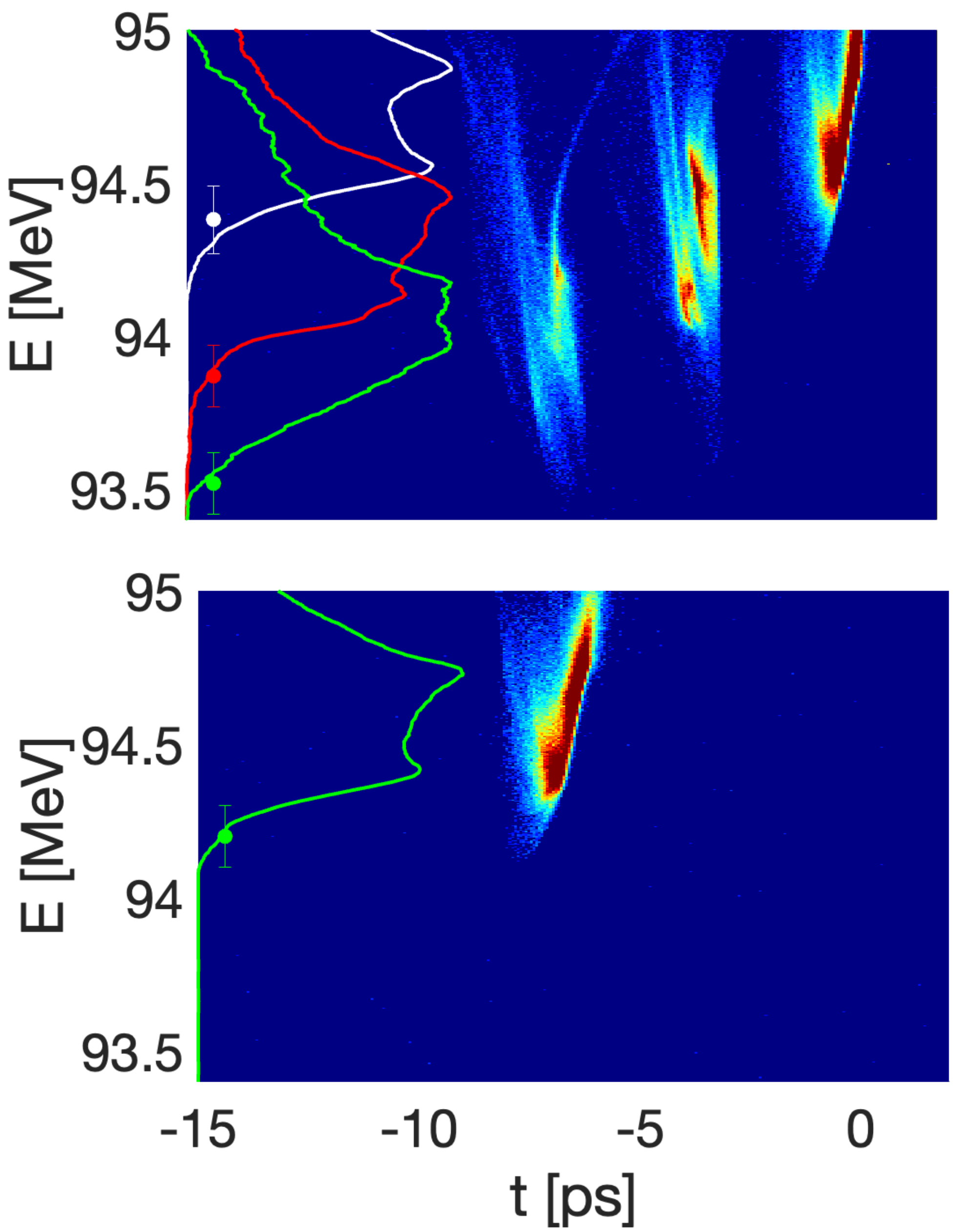
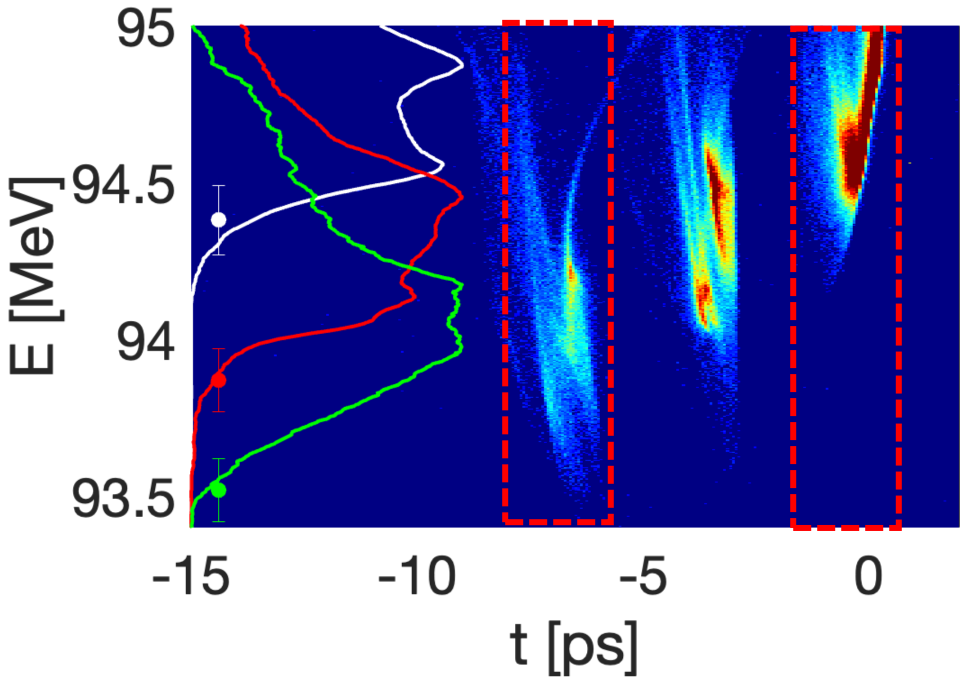
- The sum of each contribution gives the final energy loss:
  $\boldsymbol{\Delta E^-_3 = (0.7 - 0.2) + (0.4 - 0.2) + 0.2 = 0.9}$ **MeV**
  ➔ The wakefields driven by each bunch superpose linearly



1) Maximizing the amplitude of the wakefields - Results

- By varying the delay between discharge and bunches, we vary n_{pe} and therefore T_{pe} due to plasma recombination
- We investigate the resonant behavior by varying the plasma density while measuring the LPS of each bunch



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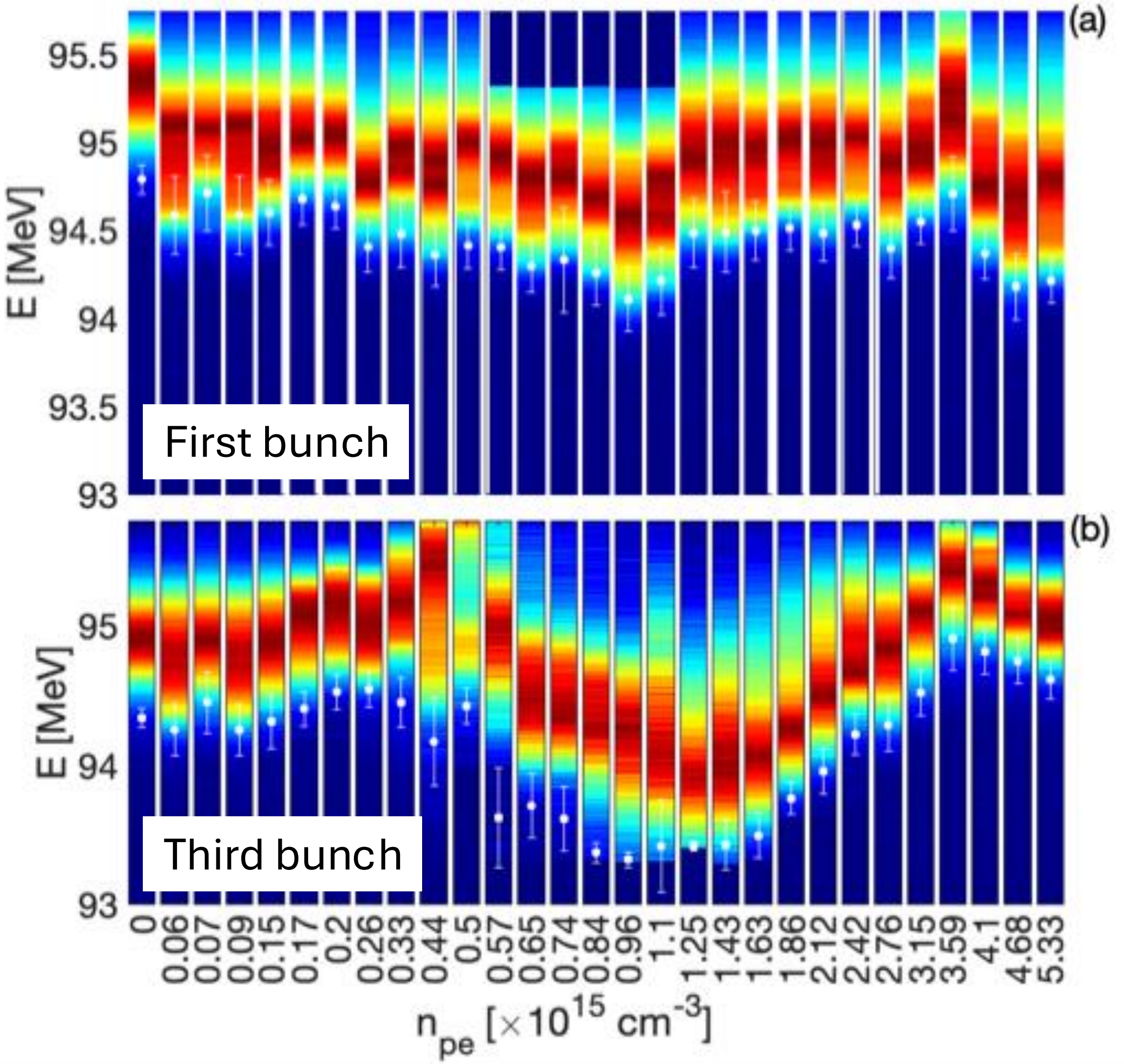
- Clear enhancement at optimal coupling for the third bunch



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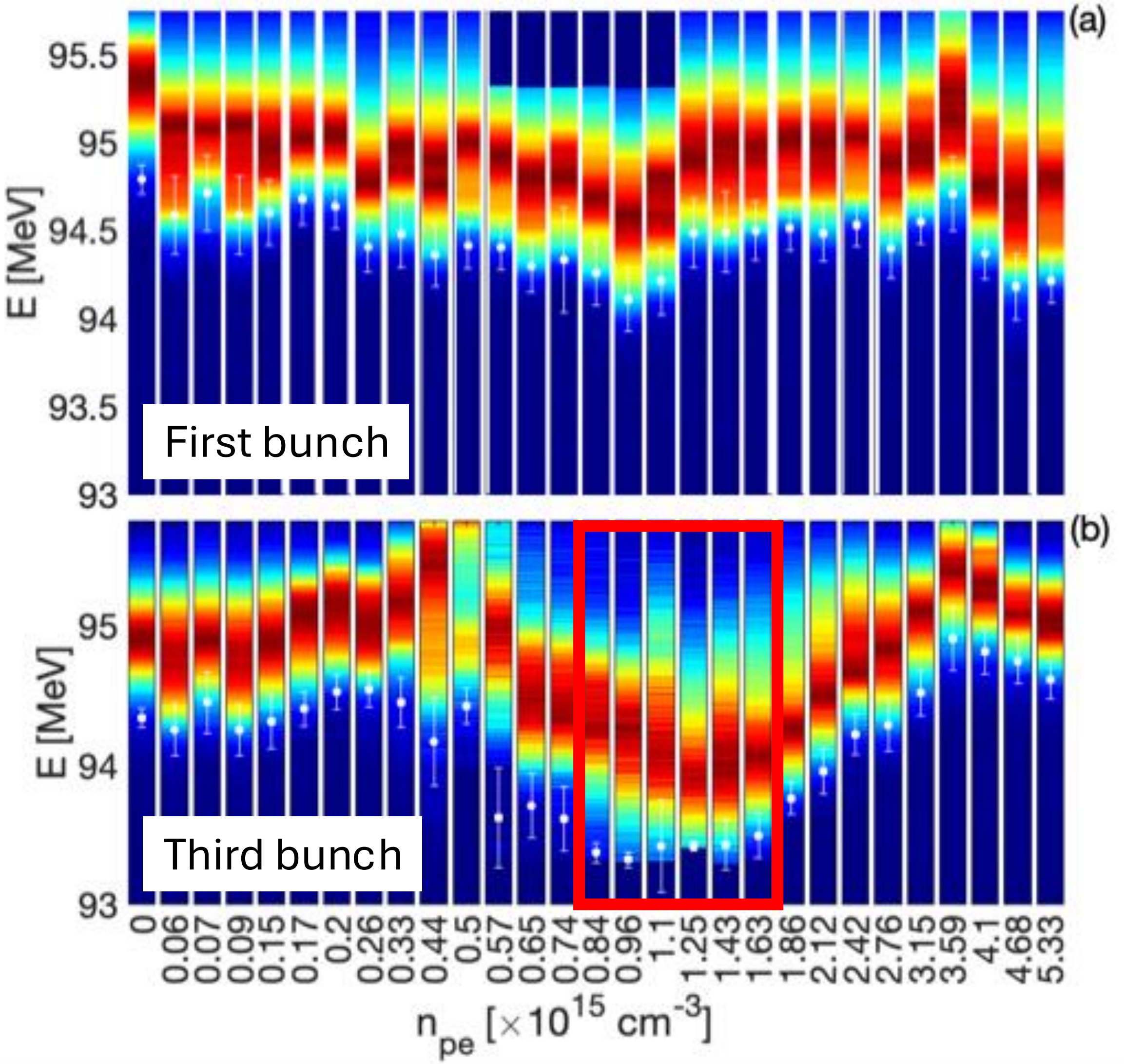
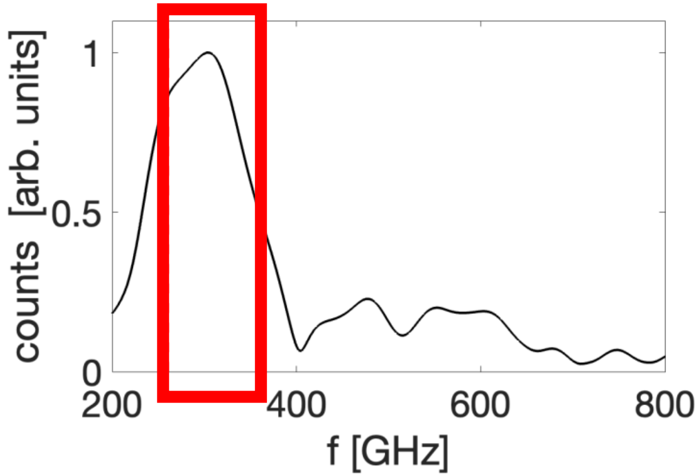
- Maximum energy loss when train is coupled in frequency with plasma





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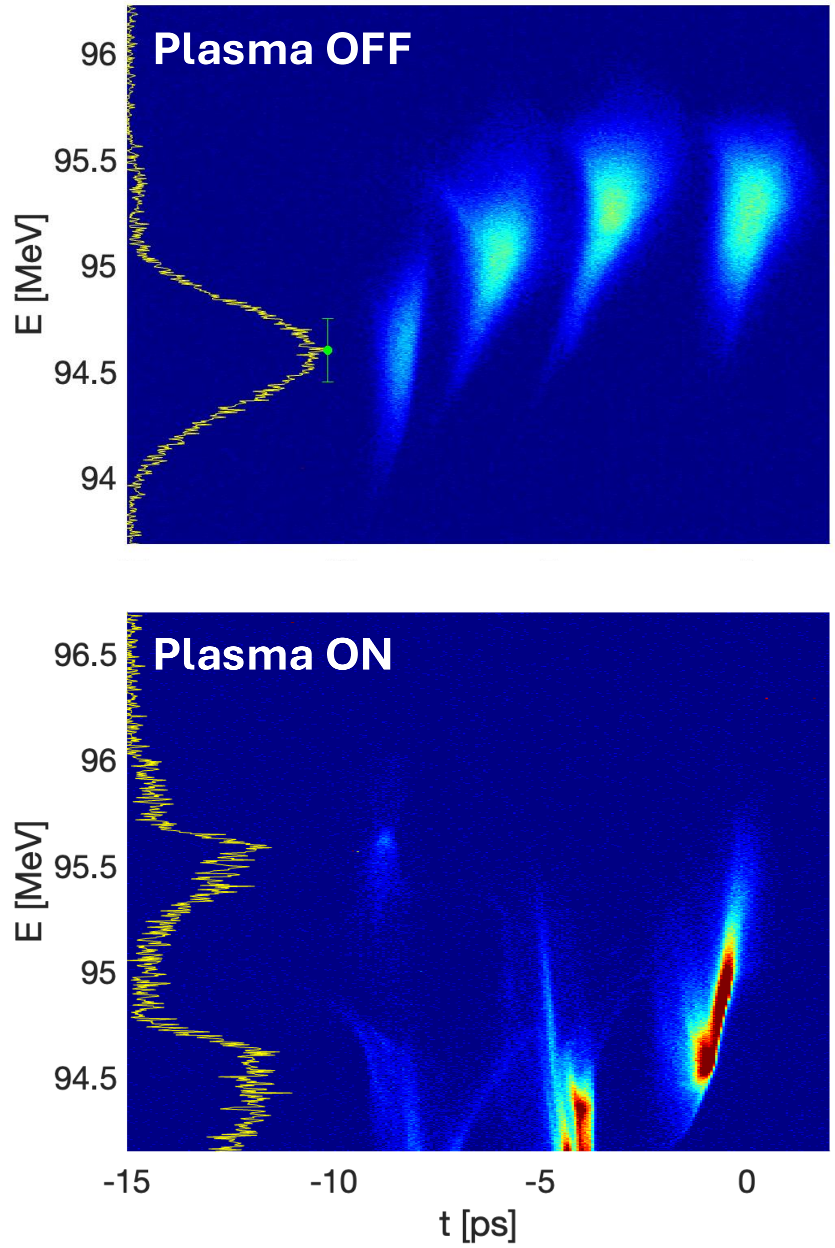
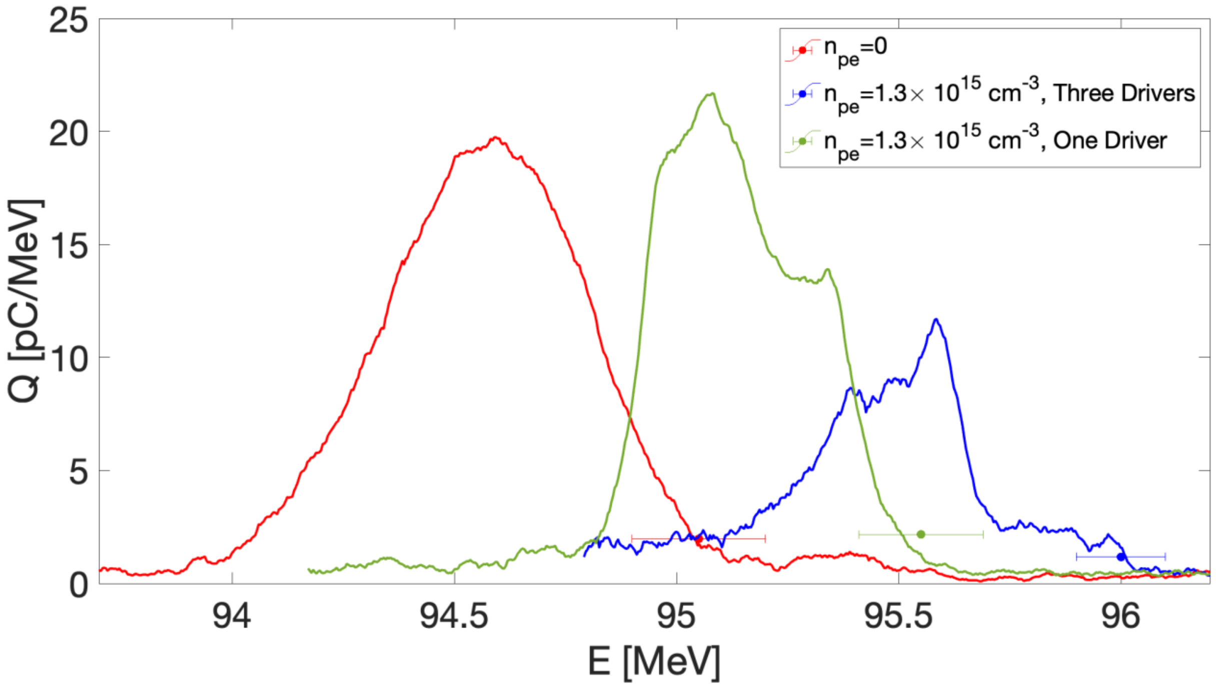
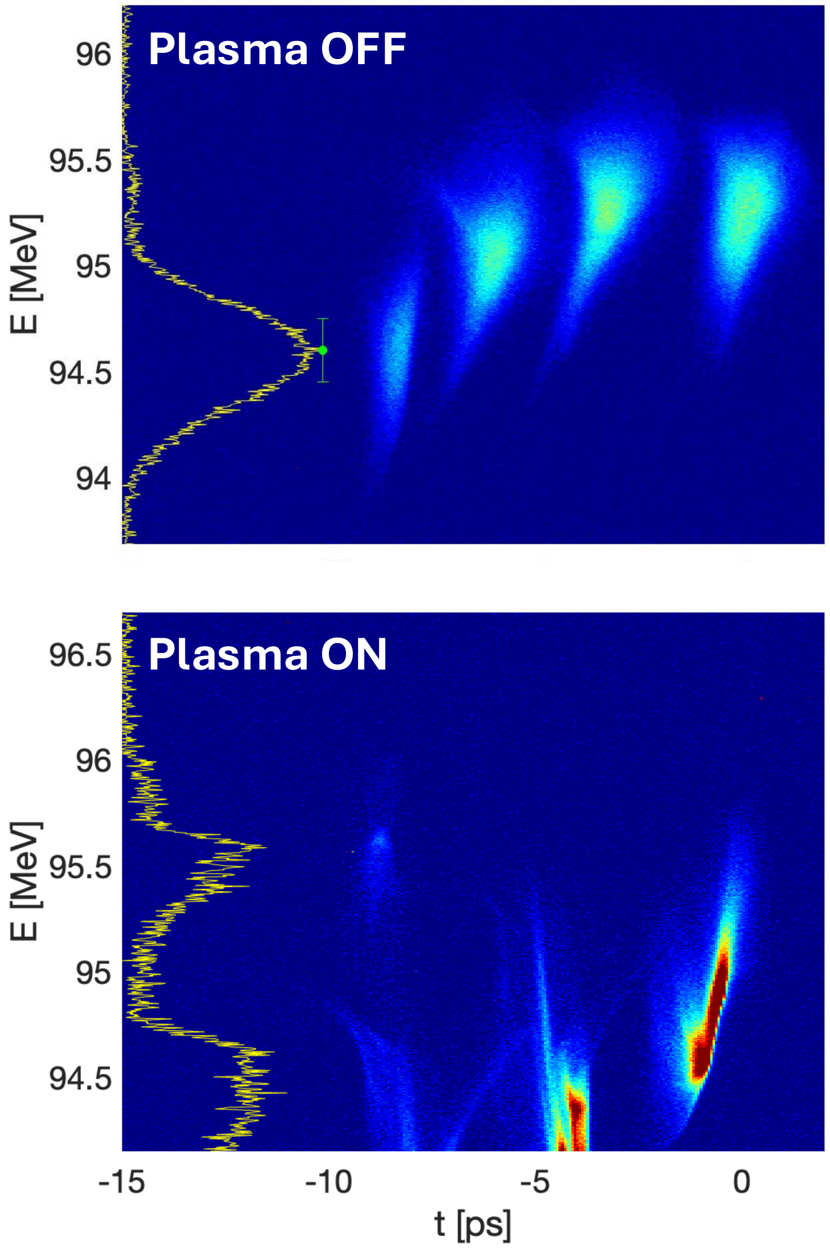


1) Maximizing the amplitude of the wakefields - Results

- 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





➔ Resonant excitation allows for enhancement of accelerating gradient

2) 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

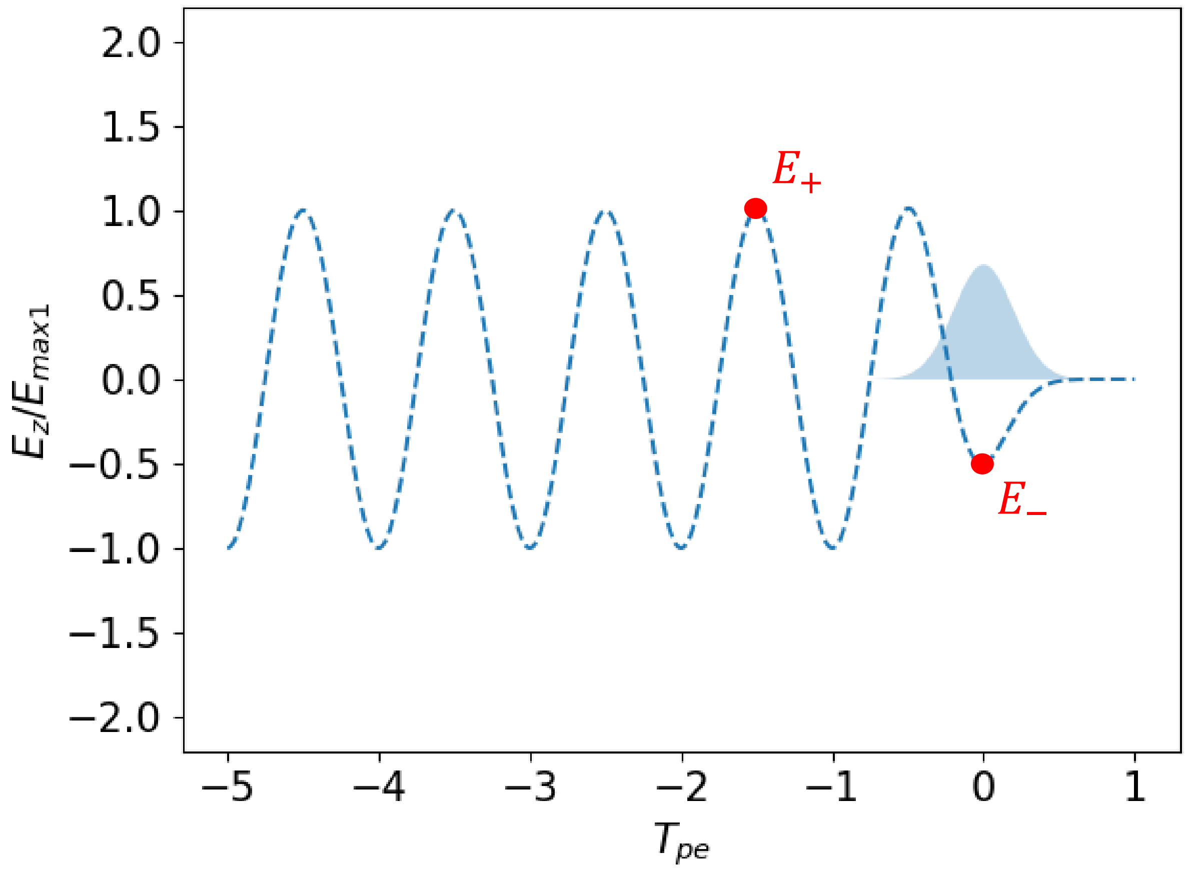
→ Increasing R means: longer depletion length

➔ **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

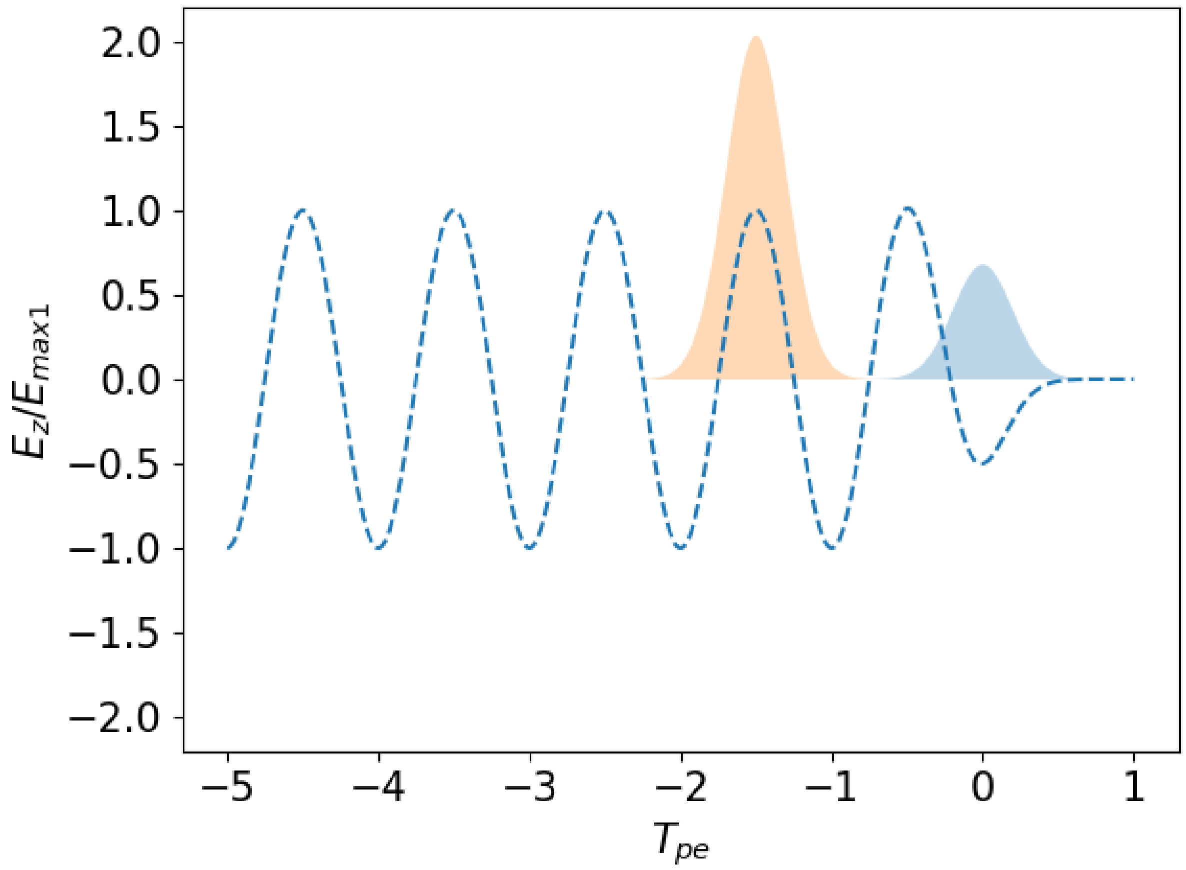


2) Maximizing the transformer ratio

→ 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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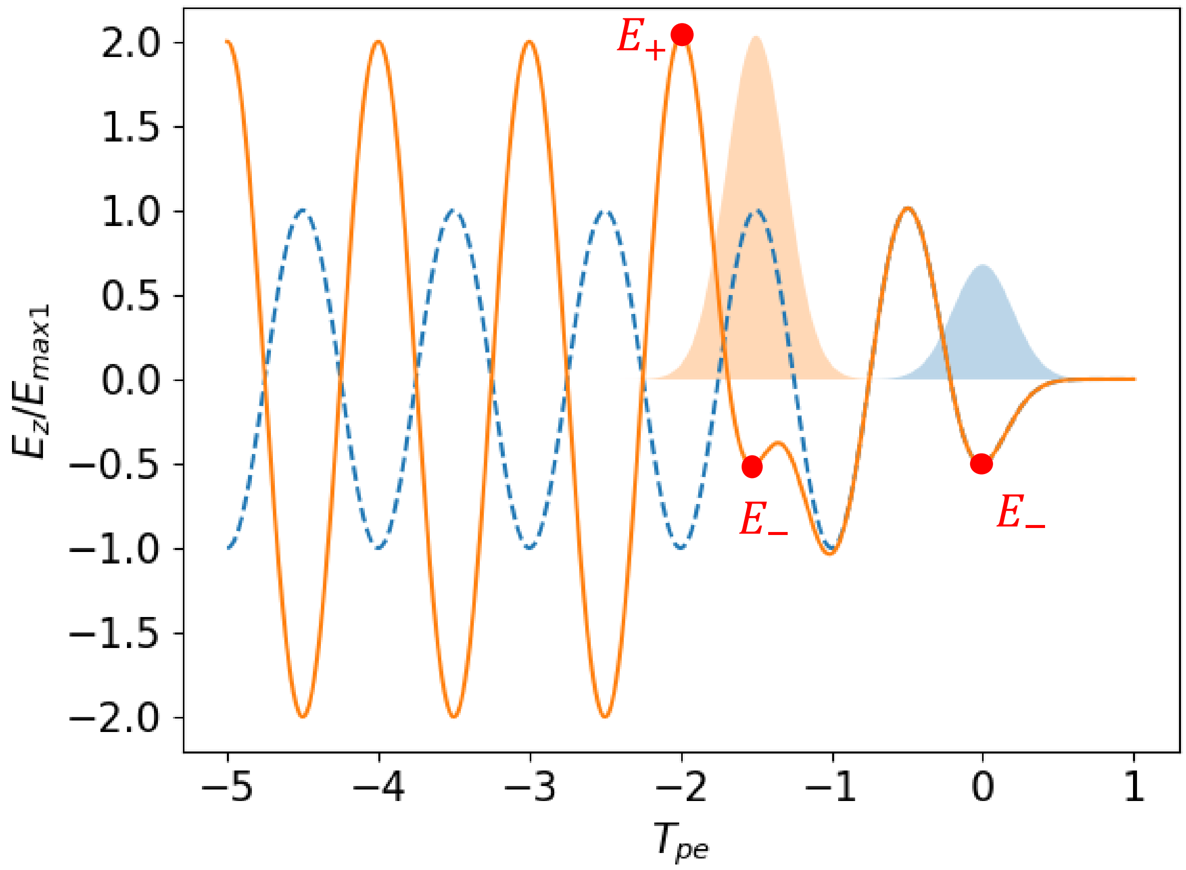
→ Superposition gives equal E_- within the drivers

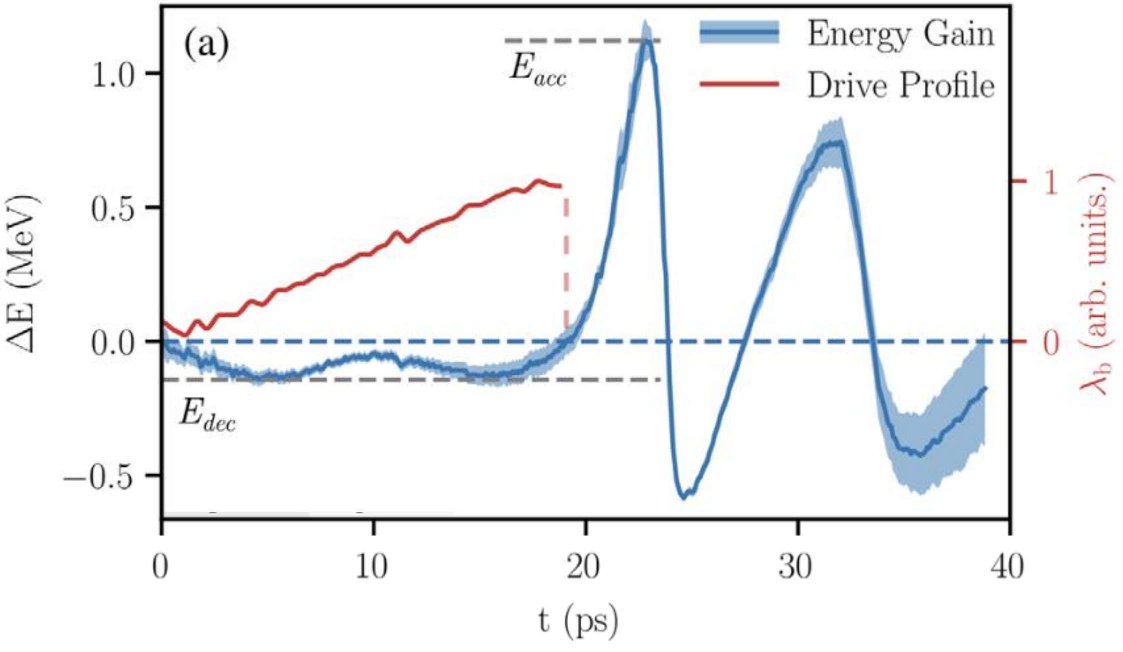
→ **Enhanced $\boldsymbol{R}$ meaning** $R_N = N \cdot R_1$

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



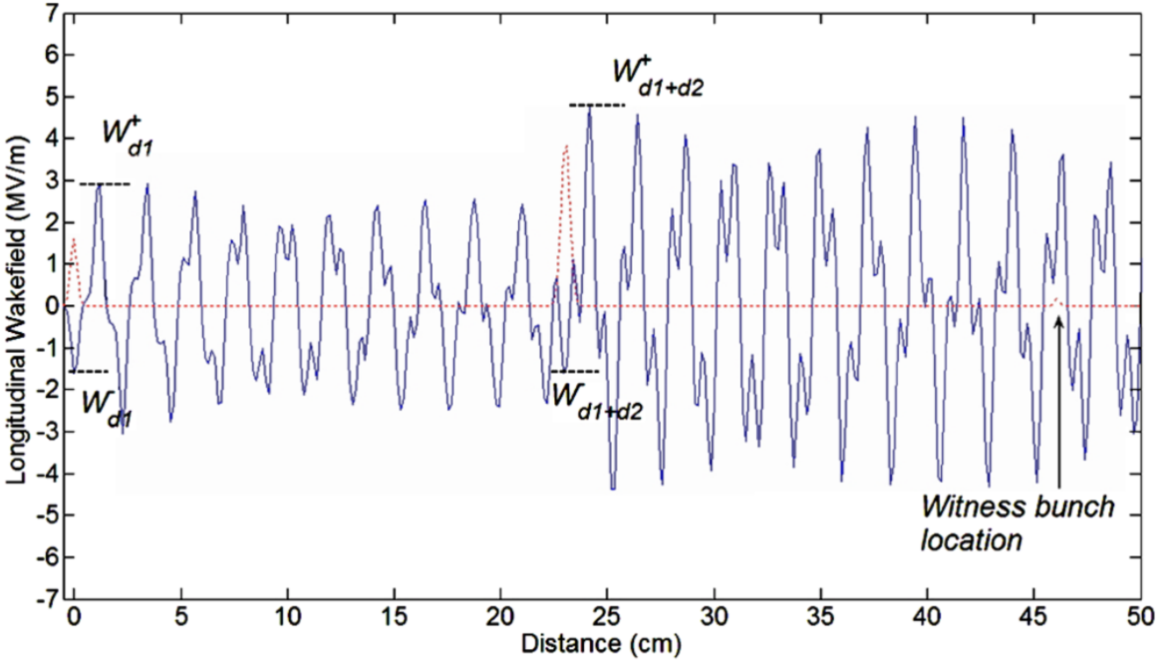
2) Maximizing the transformer ratio – Previous results

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)

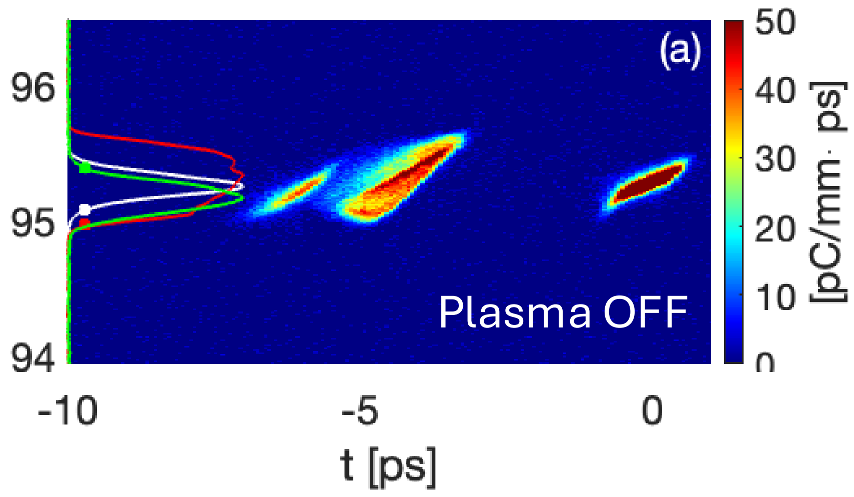
Ramped train of bunches in dielectric-loaded wakefield accelerator



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

2) Maximizing the transformer ratio - Results

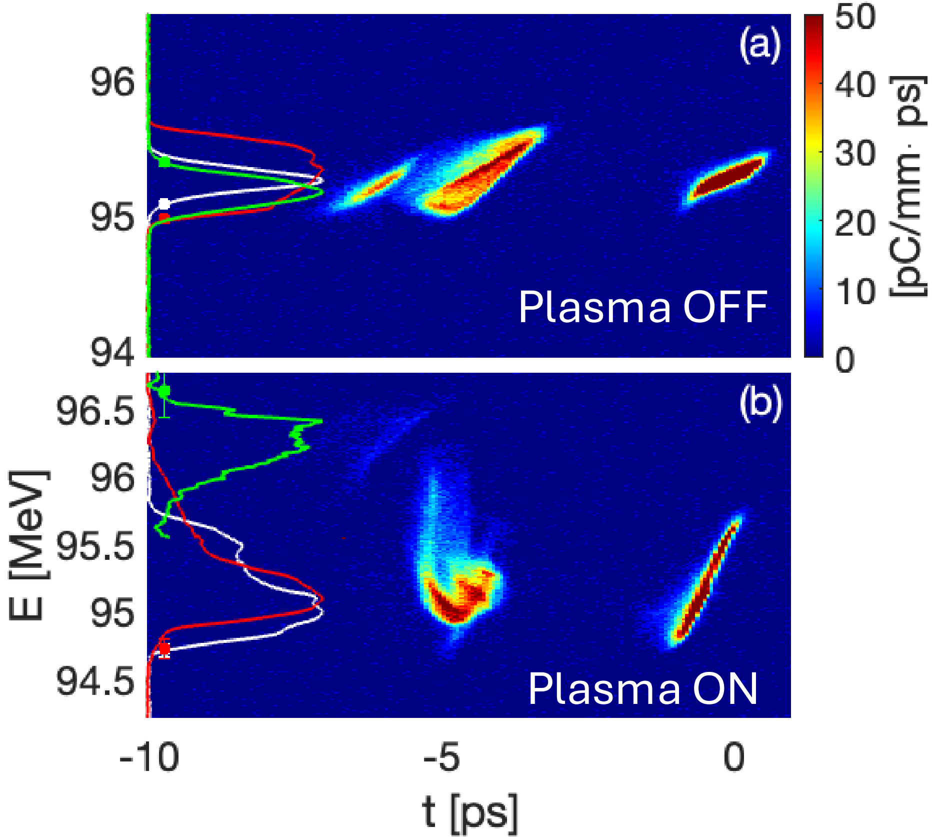
- Two driver bunch delayed by 1.5 T_{pe}



2) 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

➔ $\boldsymbol{R = 3.2 \pm 0.5}$



2) Maximizing the transformer ratio - Results

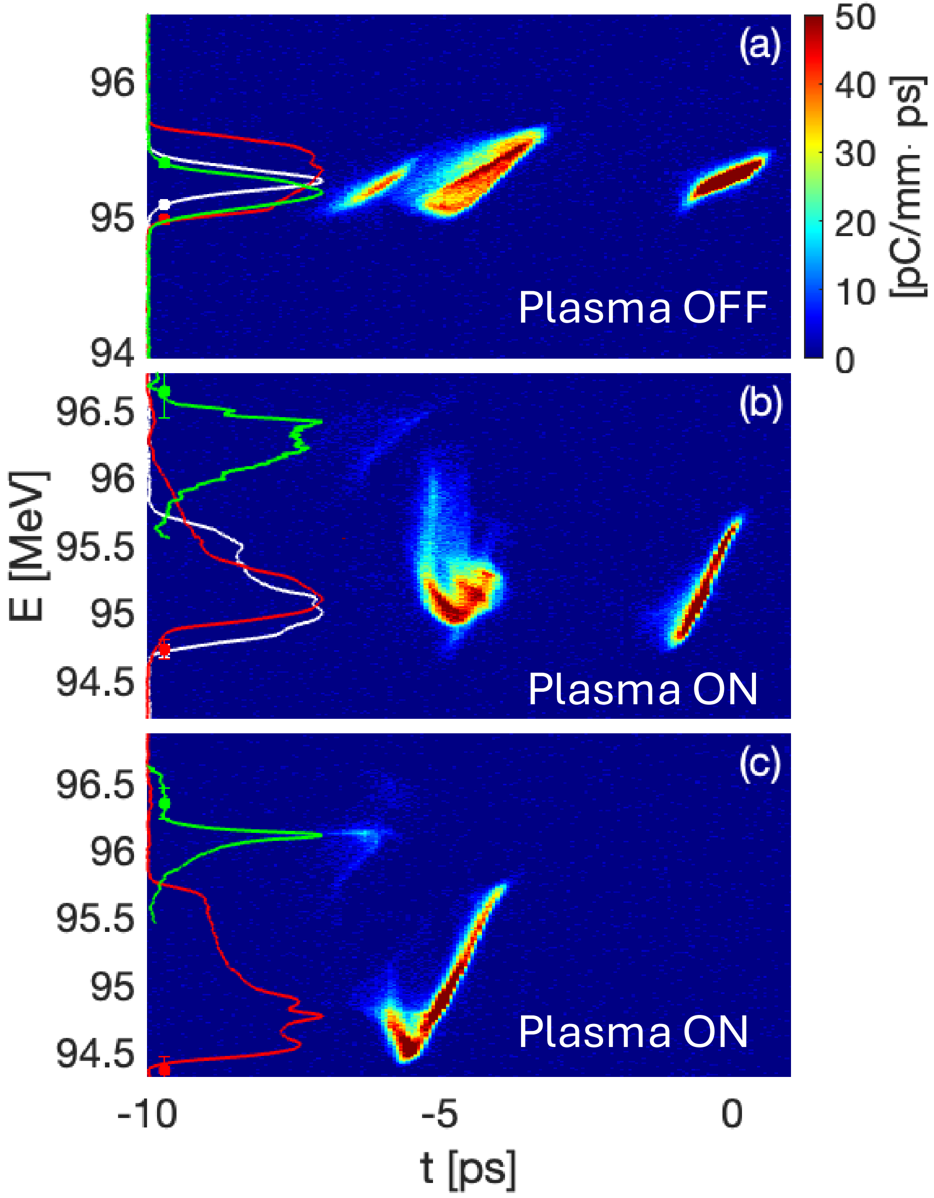
- Two driver bunch delayed by 1.5 T_{pe}
- Charge of the second driver increased to have energy loss nearly equal to the first driver: $\Delta E^- = 0.37$ MeV
- Witness bunch accelerated with $\Delta E^+ = 1.2$ MeV

➔ $\boldsymbol{R = 3.2 \pm 0.5}$

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

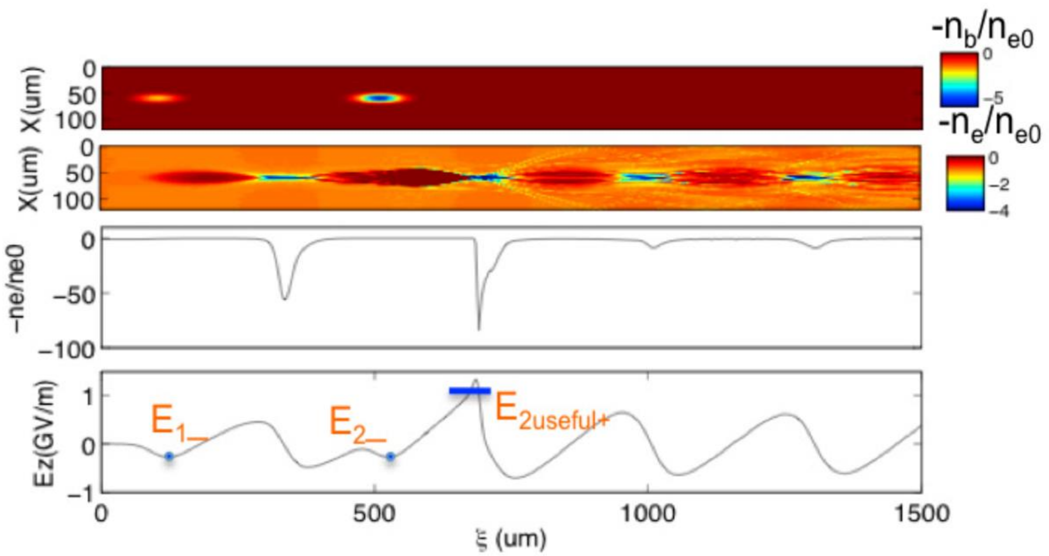
➔ $\boldsymbol{R = 1.5 \pm 0.3}$

➔ Enhancement of transformer ratio when two bunches are present!



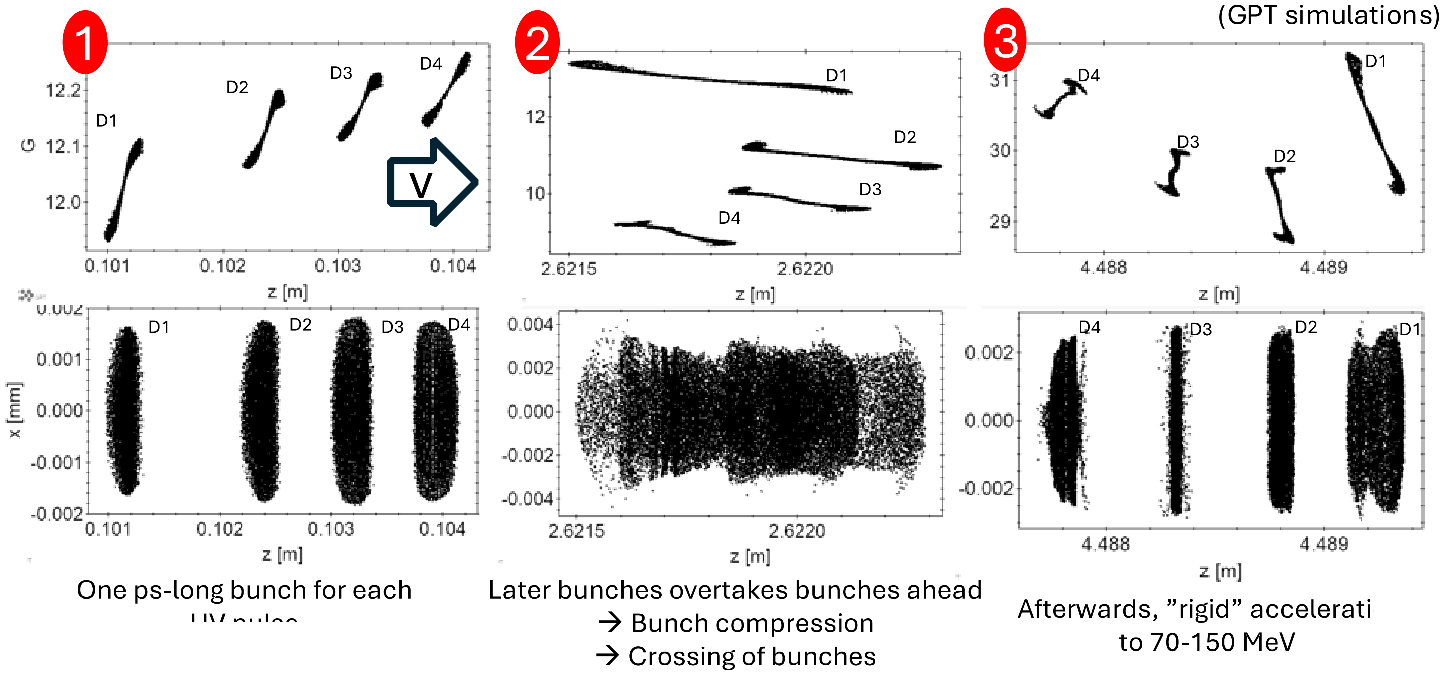
Future @SPARC_LAB

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



Fang et al., Proceedings PAC 2011

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



One of the proposed experiments for this year

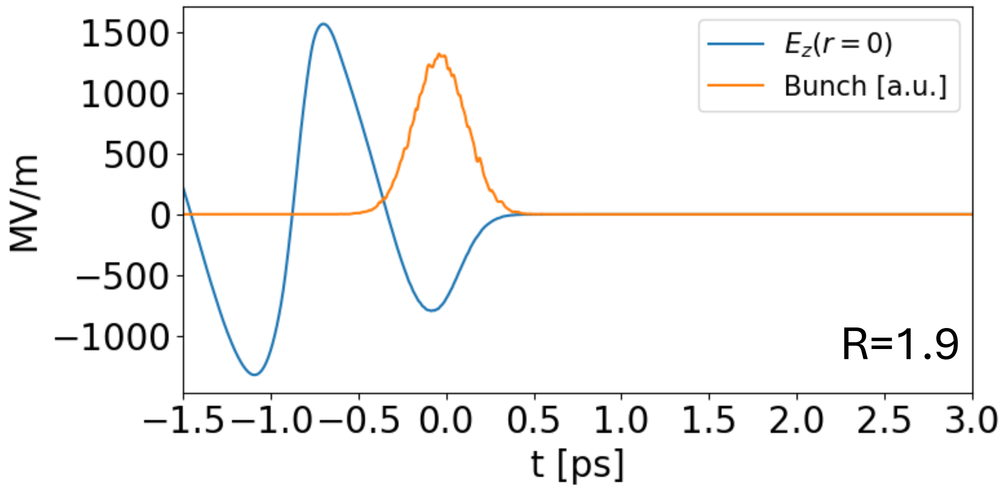
Future @EuPRAXIA

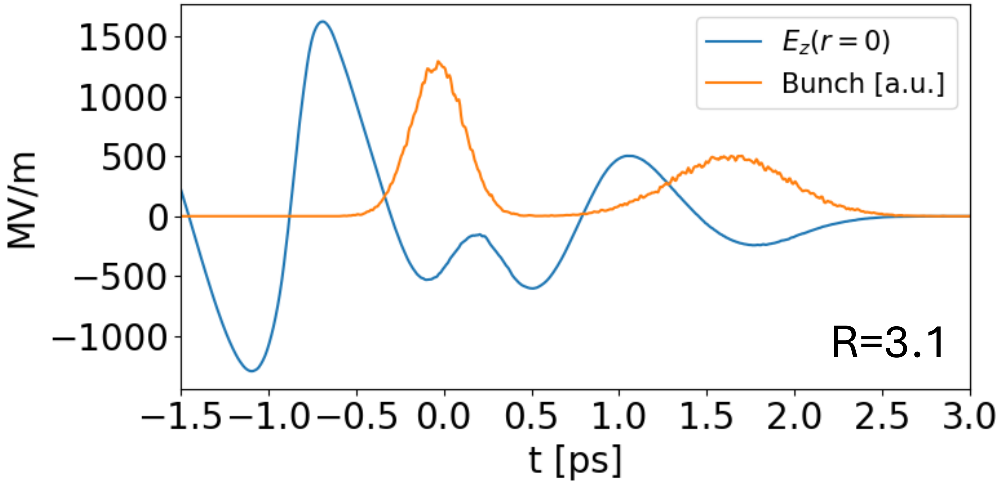
- The non-linear, high-transformer-ratio configuration could be used at EuPRAXIA@SPARC_LAB to maximize the final energy reach of the witness bunch towards 5 GeV

- 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**

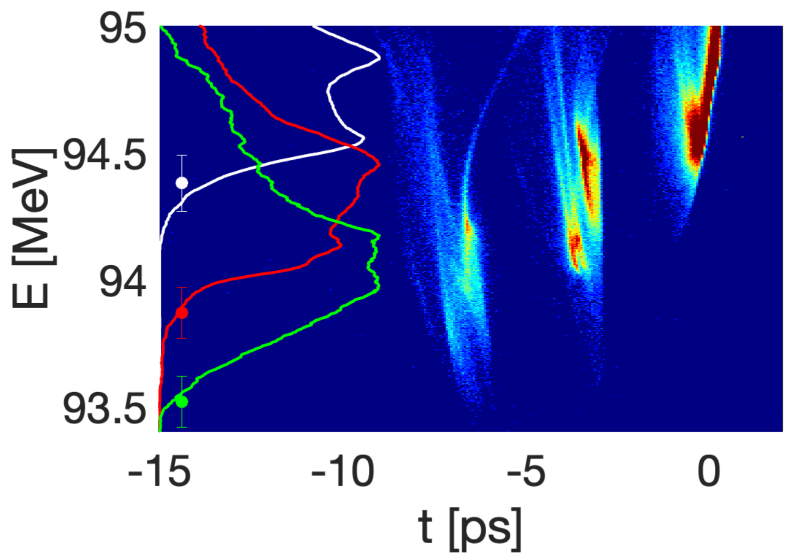
➔ **Lasing at shorter wavelength**

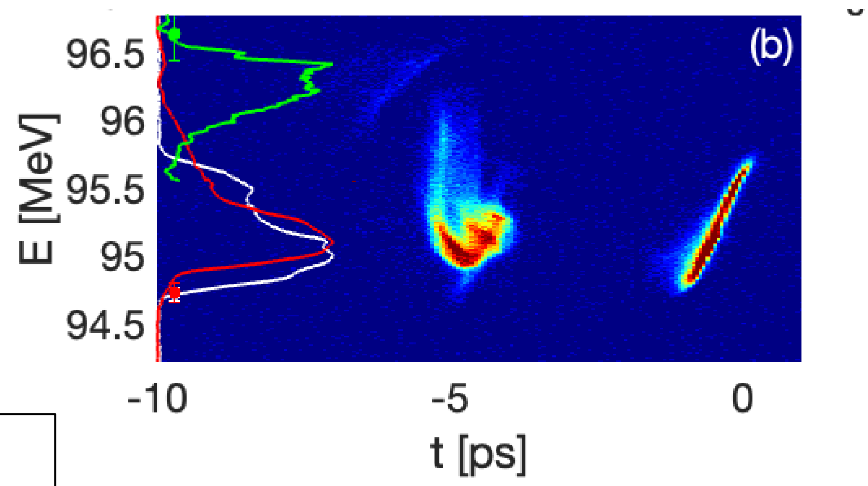




Conclusions

- We demonstrated resonant wakefield excitation in plasma with trains of pre-formed electron bunches
- In linear regime, wakefields superpose linearly
  → growth along the train
- Configuration with delay = integers of T_{pe}
  → Wakefield Amplitude enhancement
- Configuration with delay = half-integers of 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





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

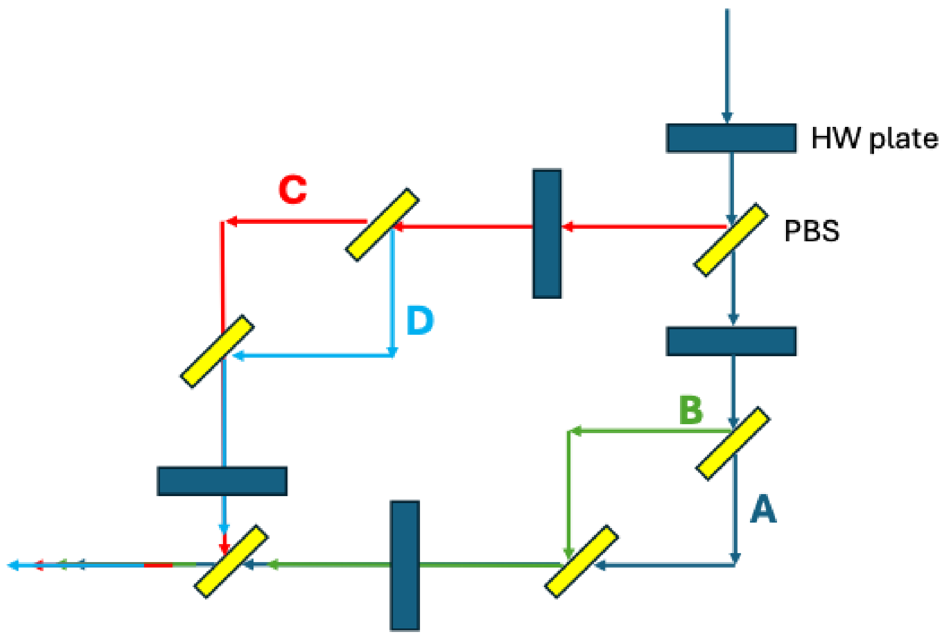
L. Verra,[1,*] M. Galletti,[1] M.P. Anania,[1] A. Biagioni,[1] M. Carillo,[1] E. Chiadroni,[2] A. Cianchi,[3,4,5] G. Costa,[1] L. Crincoli,[1] A. Del Dotto,[1] M. Del Giorno,[1] R. Demitra,[1] G. Di Pirro,[1] A. Giribono,[1] V. Lollo,[1] M. Opromolla,[1] G. Parise,[1] D. Pellegrini,[1] R. Pompili,[1] S. Romeo,[1] G. Silvi,[1] F. Stocchi,[1,3] F. Villa,[1] and M. Ferrario[1]

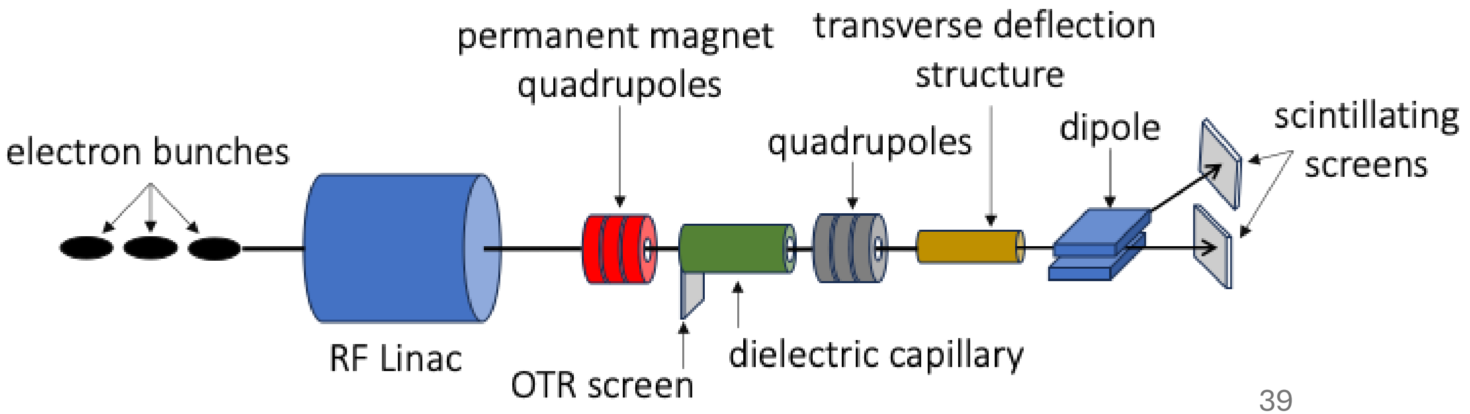
Thank you!

Backup slides

SPARC_LAB – Multiple Bunches configuration

- 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
- UV pulses at photocathode inside RF gun within an RF period

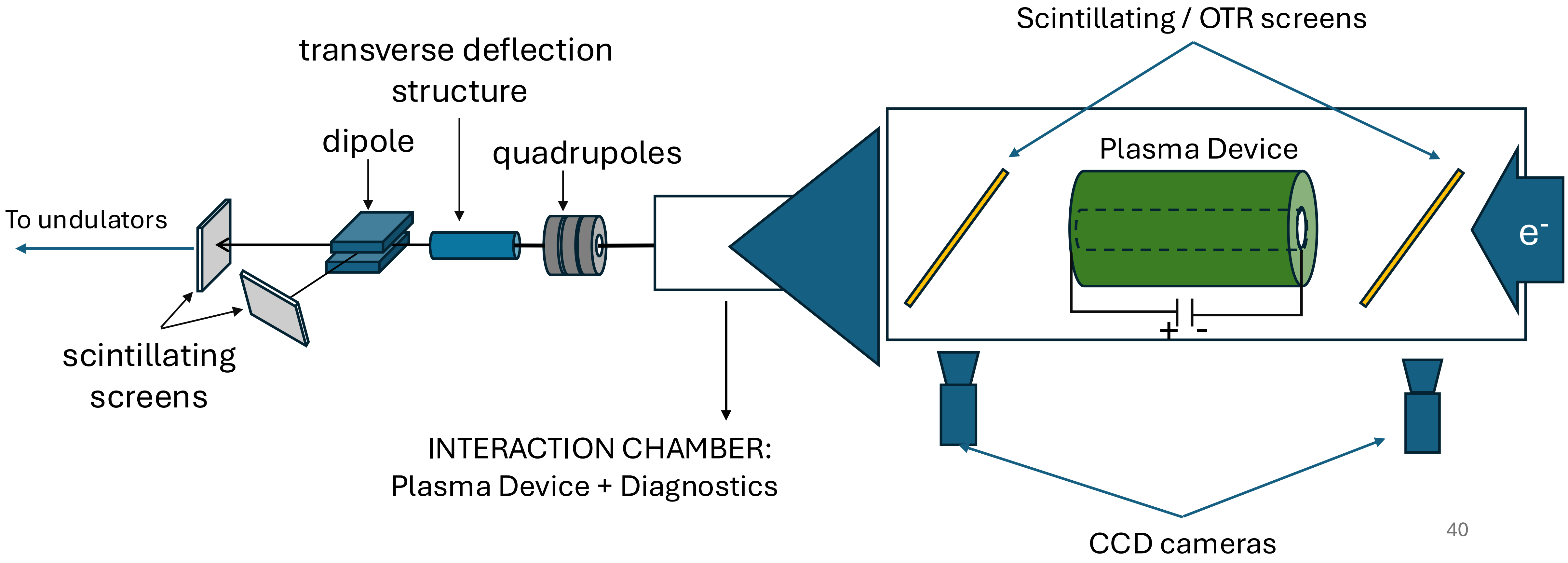




0b. SPARC - Setup

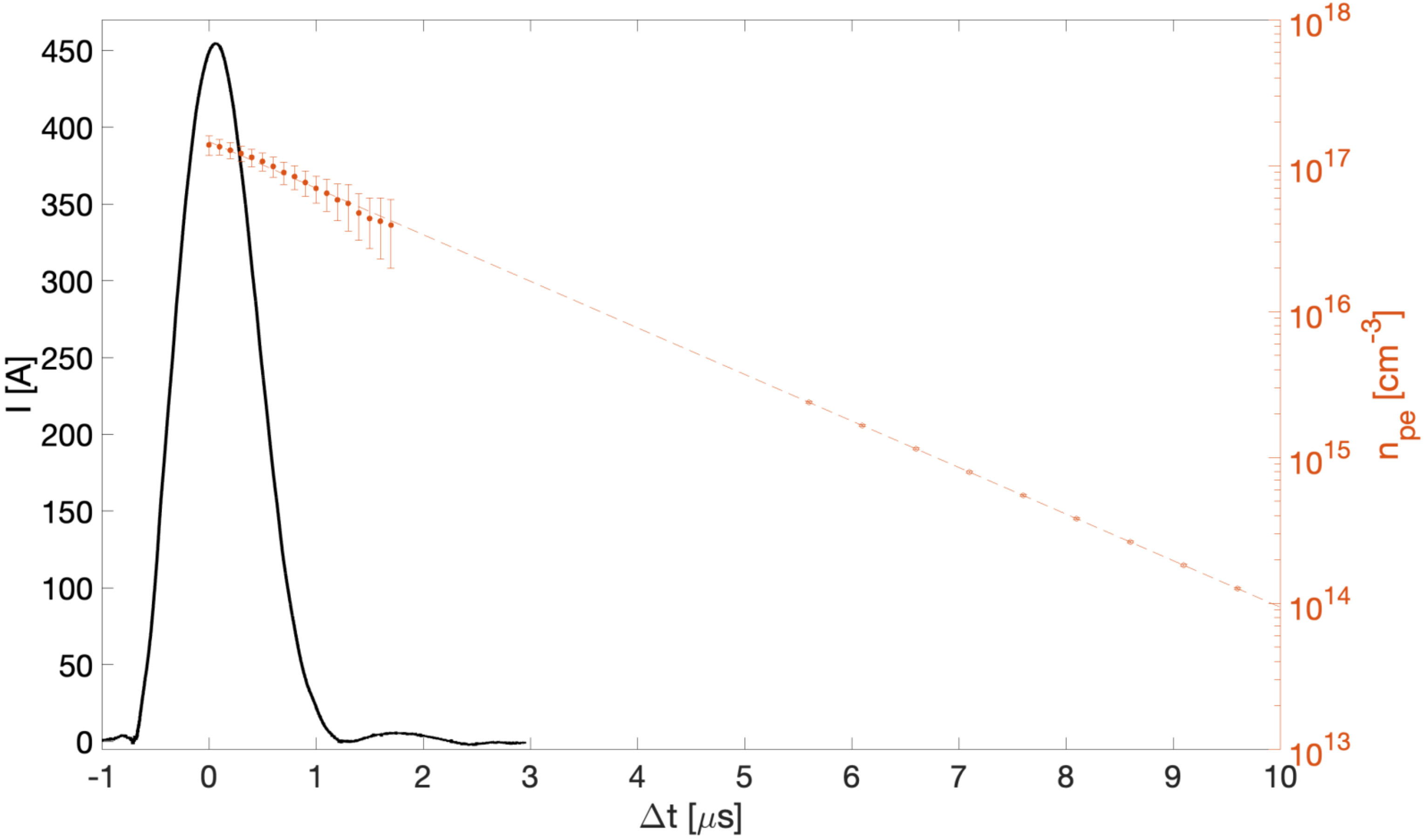
- Photoinjector + Linac
    - Acceleration and bunch compression (<20 fs)
    - Velocity Bunching
- Discharge Plasma Capillary
- Diagnostics (Charge, Energy, Emittance, etc..)
- Undulators

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

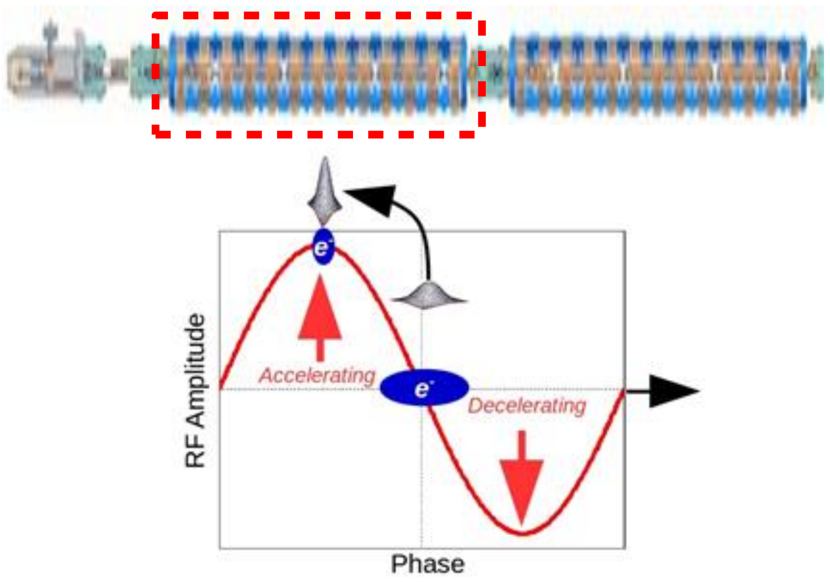


450
400
350
300
250
200
150
100
50
0
I [A]
-1
0
1
2
3
4
5
6
7
8
9
10
Δt [μs]
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
n_{pe} [cm^{-3}]

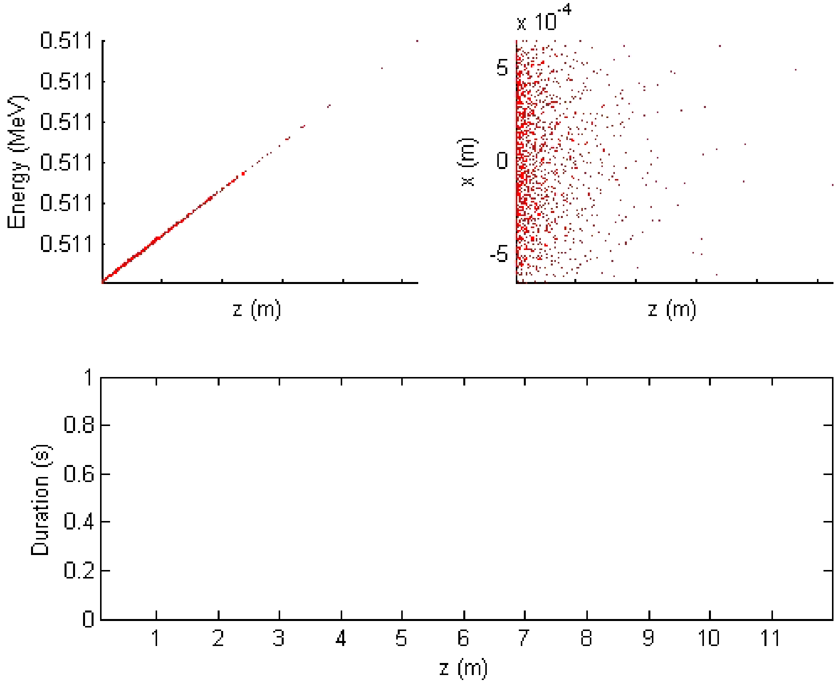
Velocity bunching

Alternative technique to magnetic compression in chicanes / doglegs.

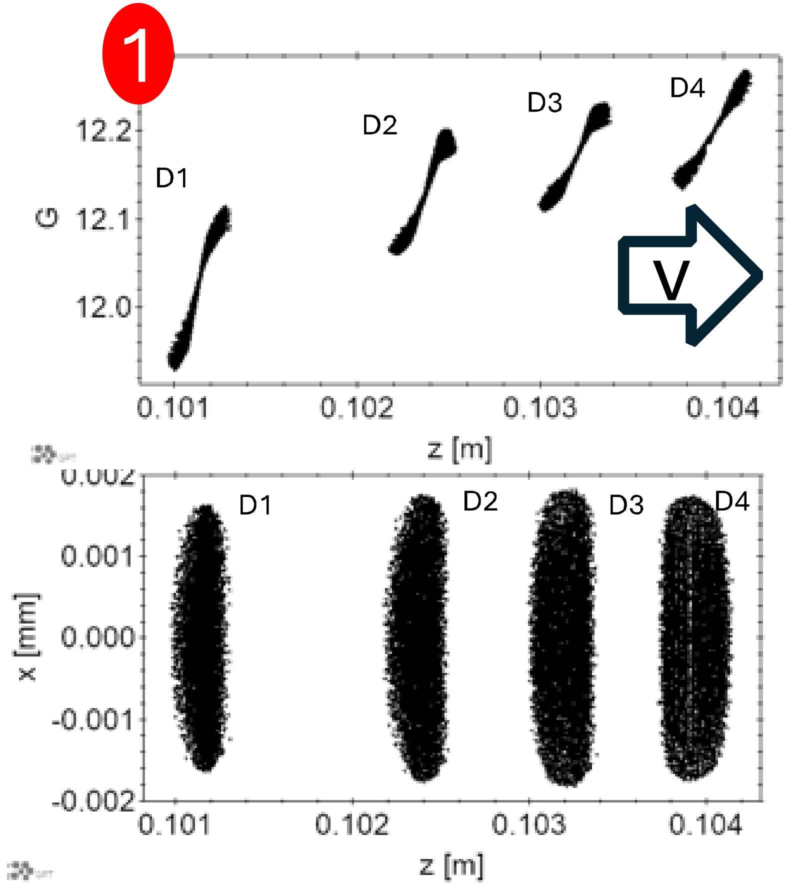
Velocity bunching compression

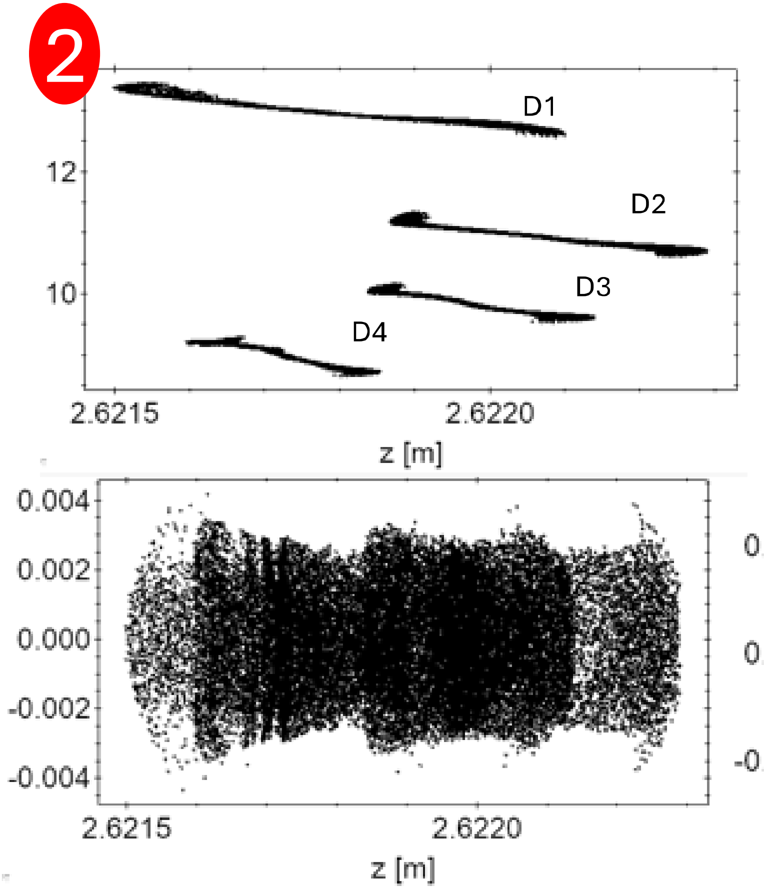


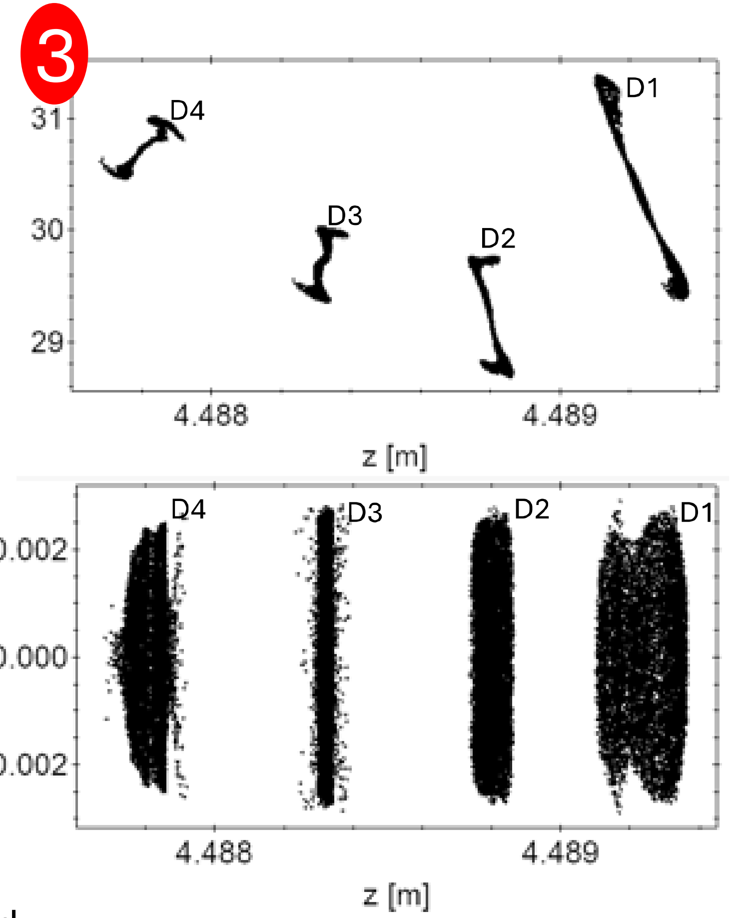
200+20 pC GPT simulation



- It simultaneously accelerate and compress the electron bunches, making the photo-injector very compact.







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