MAX-PLANCK-INSTITUT FÜR PHYSIK

AWAKE

Hosing of a long relativistic particle bunch induced by an electron bunch

T. Nechaeva[1], L. Verra[2], J. Pucek[1], M. Bergamaschi[1], L. Ranc[1], G. Zevi Della Porta[1,2] and P. Muggli[1]
on behalf of the AWAKE Collaboration

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[2] CERN, Geneva, Switzerland

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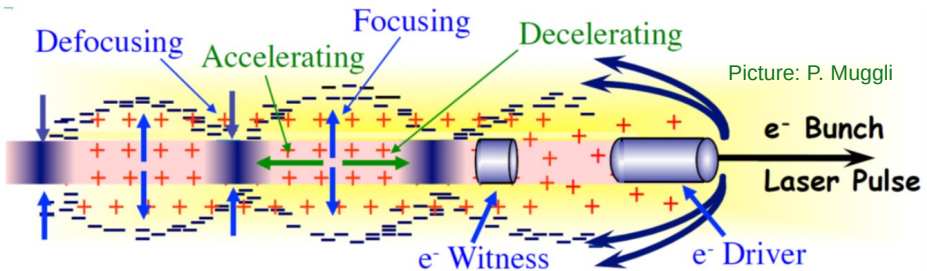
AAC Workshop, Nov. 6 – Nov. 11, 2022

Introduction: PWFA



- **Linear theory:**

$\sigma_t \leq 1/\omega_{pe}$

$\sigma_r \leq c/\omega_{pe}$ drive bunch

$$E_{WB} = \frac{m_e c \omega_{pe}}{e} \propto \sqrt{n_{pe}}$$

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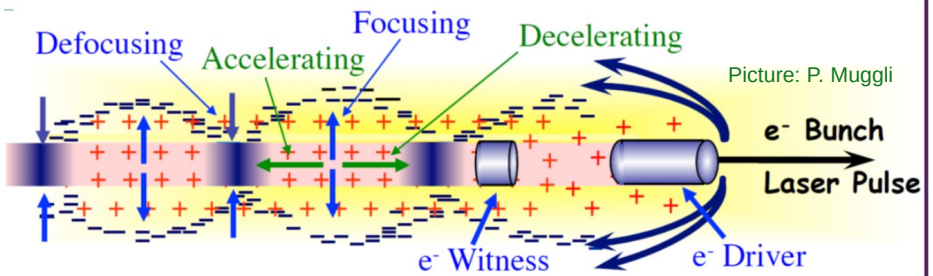

Gonsalves et al., Phys. Rev. Lett., **122** 084801 (2019)

~40 fs laser pulse, ~**40 J**

n_{pe} ~3*10^{17} cm^{-3}

~39 GeV/m

Blumenfeld et al., Nature **445** 741 (2007)

~60 fs e^- bunch, ~**50 J**

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short drivers

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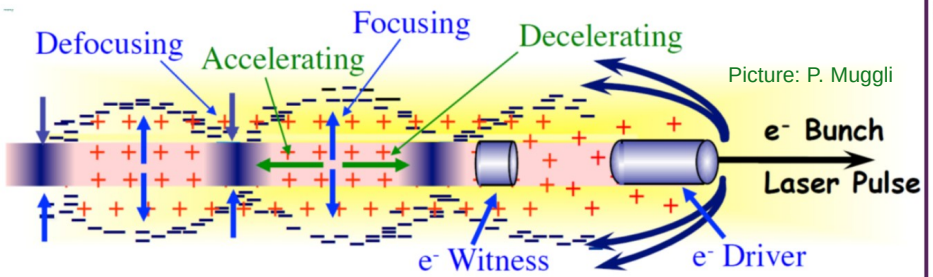

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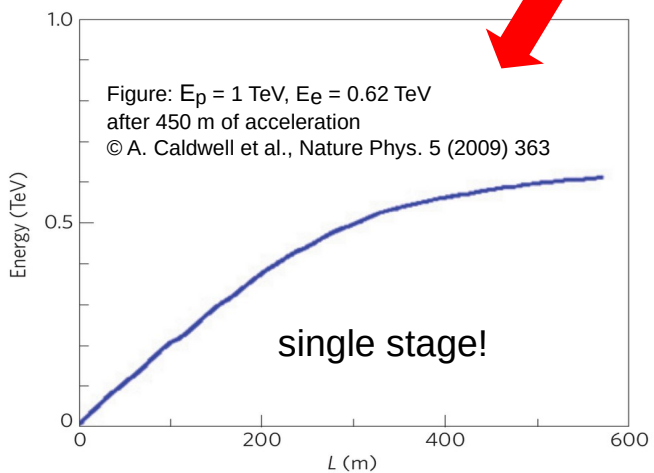
@ CERN:

SPS p^+ bunch → **19.2 kJ**

LHC p^+ bunch → **135 kJ**

- High energy
- Drives wakefields for long distance →
- No need for staging



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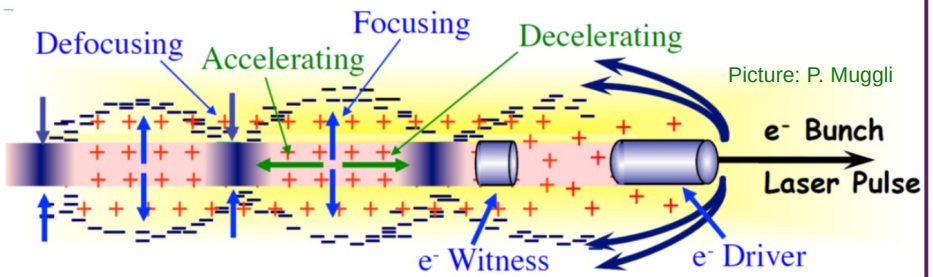

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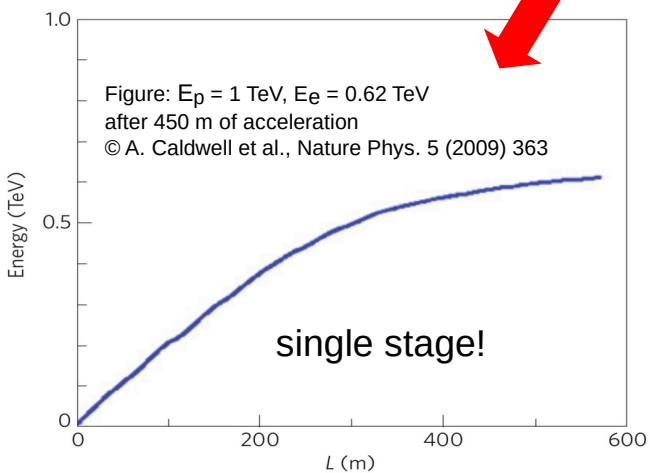

However: σ_t ~ 220 ps → long driver →
n_{pe} ~ 10^9 cm^{-3} → E_{WB} ~ MV/m

?

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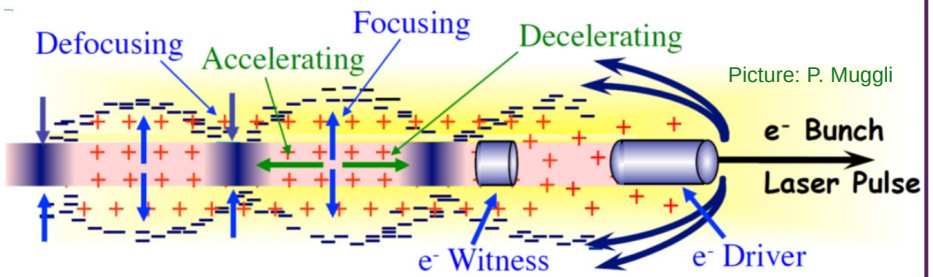

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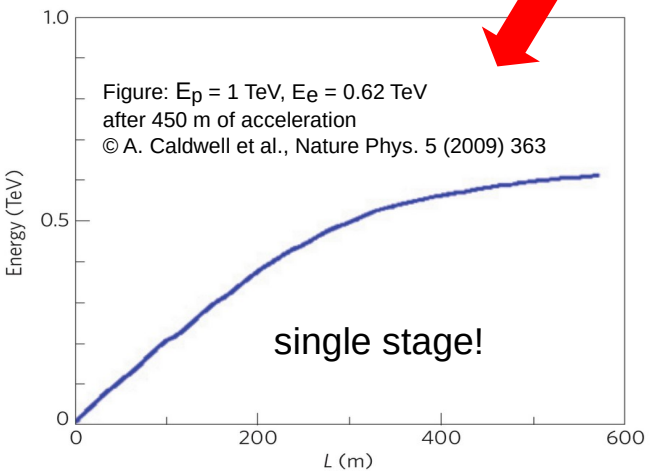

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Self-modulation!

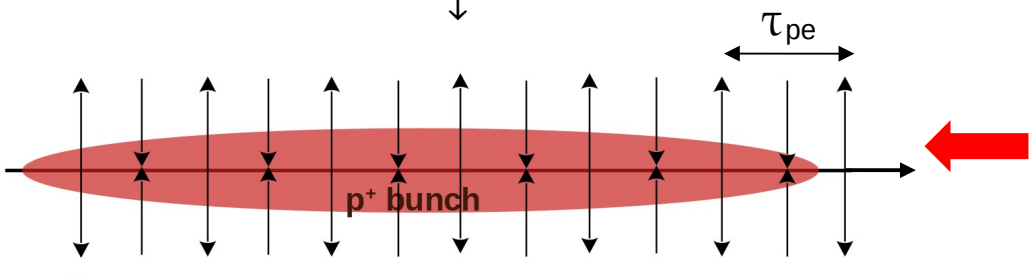
Self-Modulation

Long driver

↓

(over)dense plasma

↓



- Initial transverse wakefields →
- Periodic focusing/defocusing force →

Self-Modulation

Long driver

↓

(over)dense plasma

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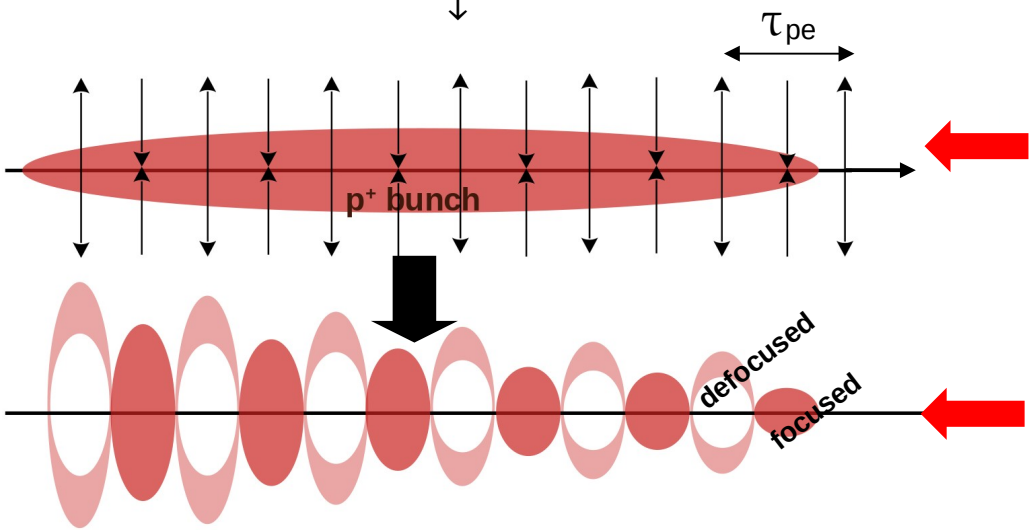
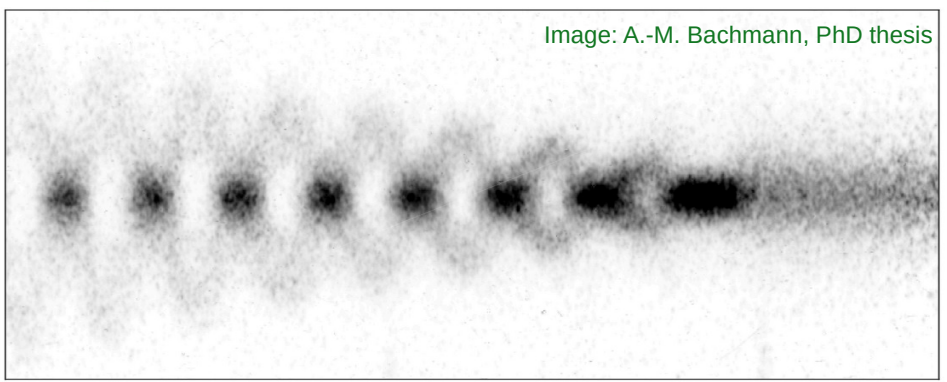




- Initial transverse wakefields →
- Periodic focusing/defocusing force →
- Bunch density modulation →
- Train of micro-bunches → period ~ τ_{pe}
- Micro-bunch length < τ_{pe} →

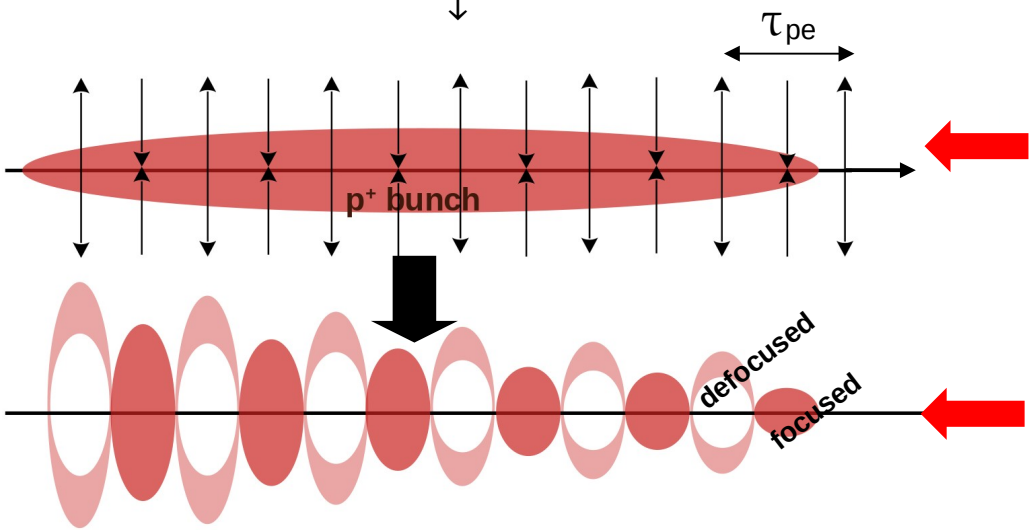
Self-Modulation

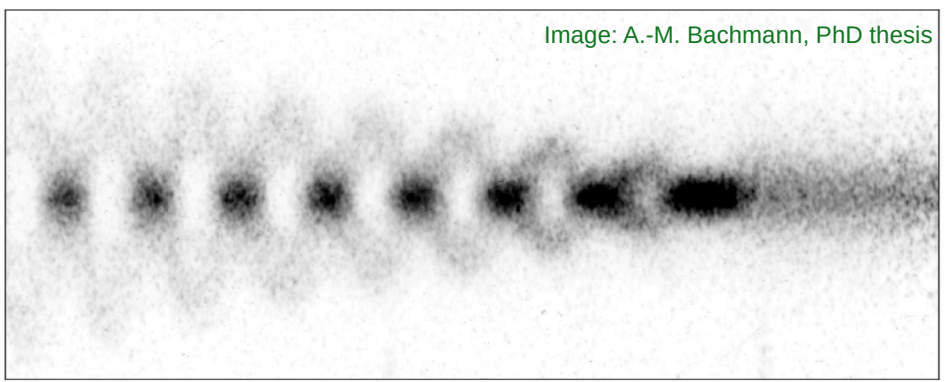
Long driver

↓

(over)dense plasma

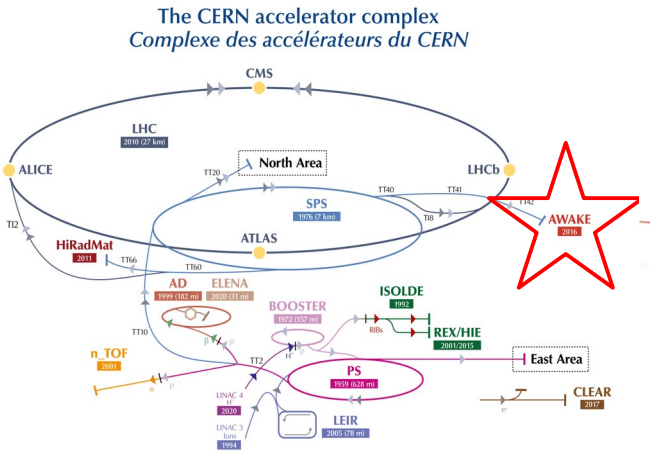
↓

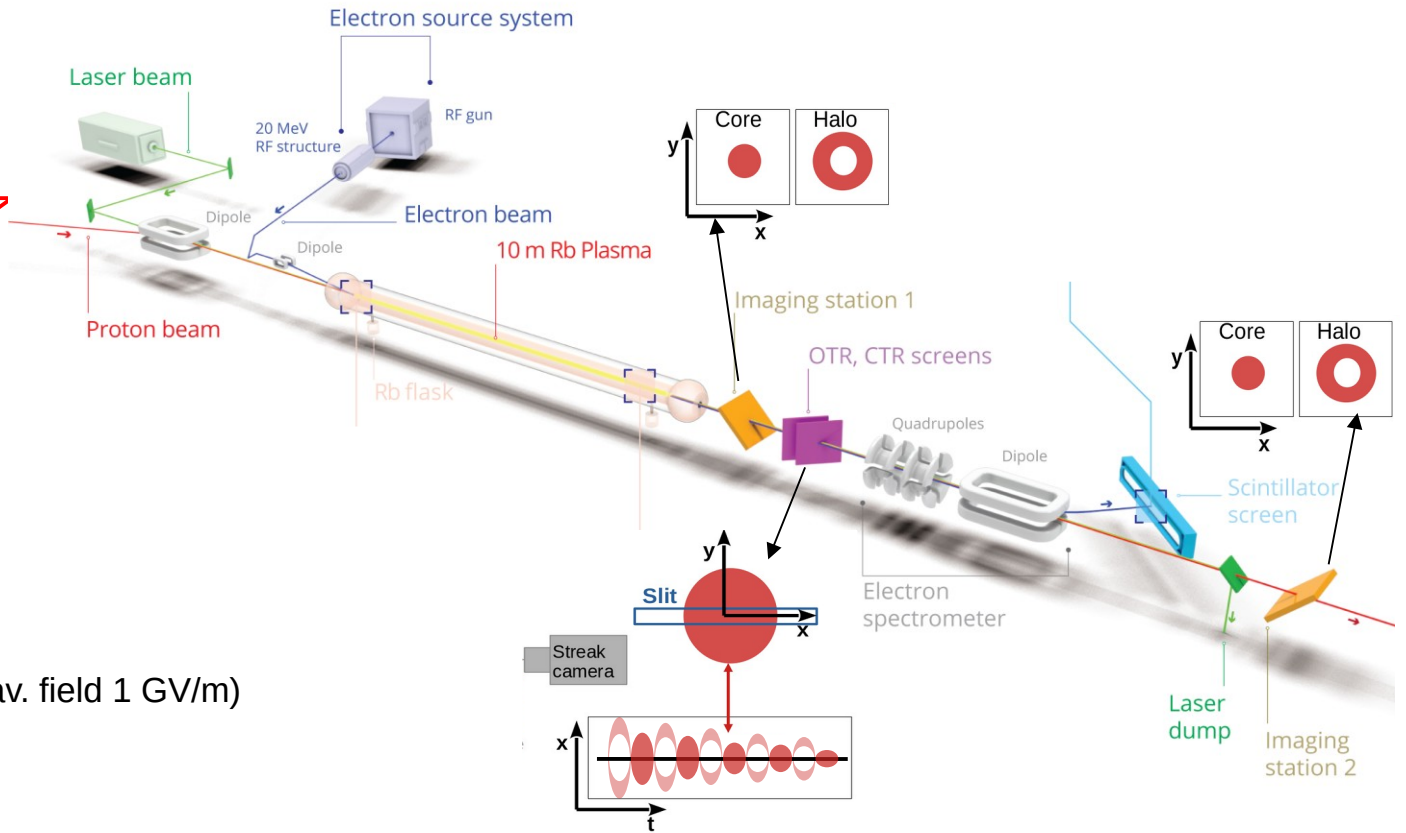




- Initial transverse wakefields →
- Periodic focusing/defocusing force →
- Bunch density modulation →
- Train of micro-bunches → period ~ τ_{pe}
- Micro-bunch length < τ_{pe} →
- **Resonant driving of large amplitude wakefields**

AWAKE Experiment



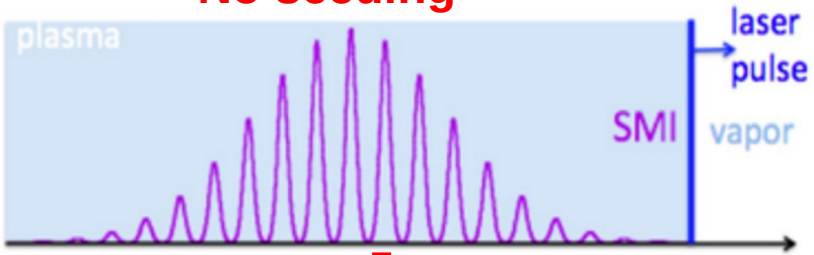


Goals:

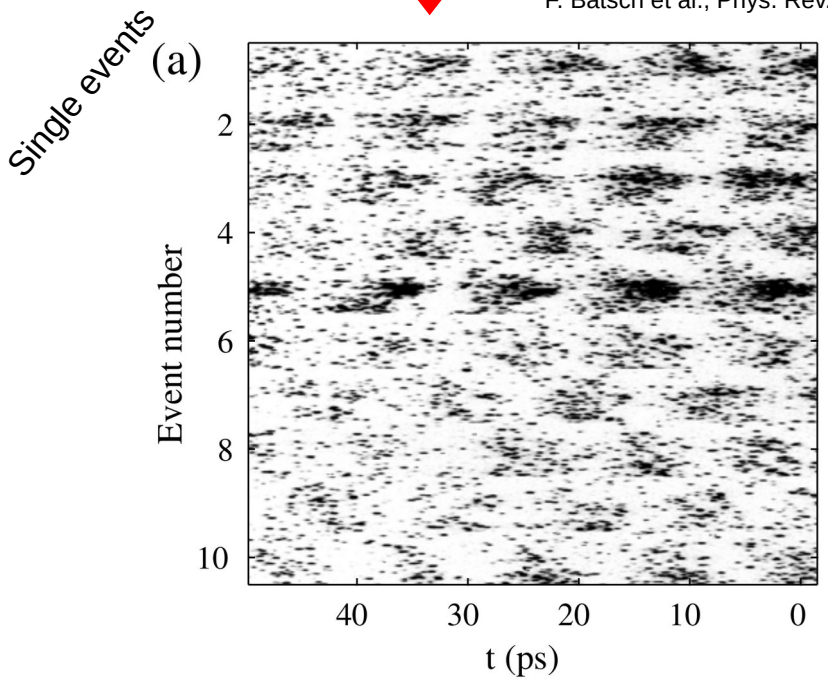
- Study SM of the p^+ bunch
- Study e^- bunch acceleration (with av. field 1 GV/m)
- External injection
- Bunch quality preservation at 10mm-mrad
- Scalability (two stages – modulator and accelerator)
- First HEP application → fixed target experiment

Self-modulation: instability → seeded

No seeding



F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)



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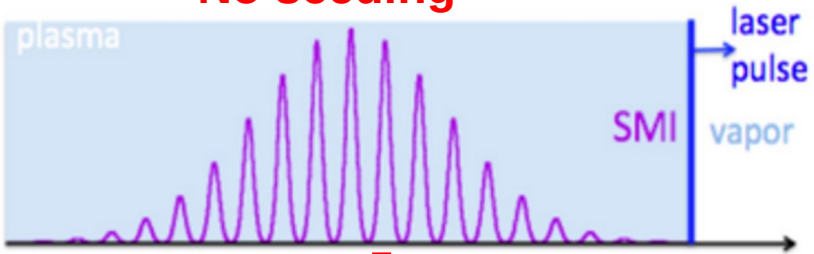
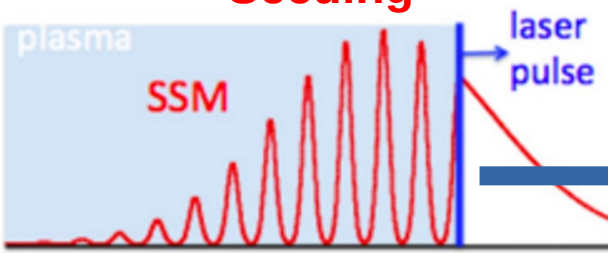


Seeding

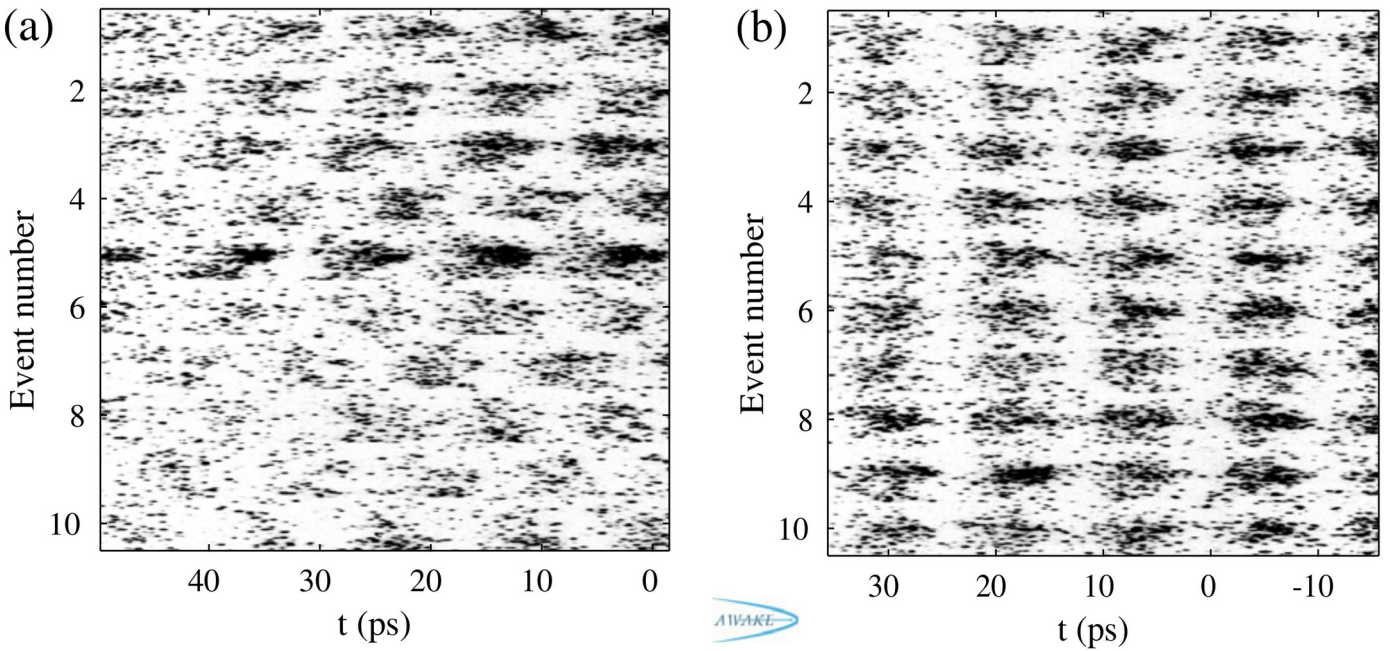


Relativistic ionization front (RIF) seeding

Sudden onset of beam-plasma interaction → seed wakefield

F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

Single events

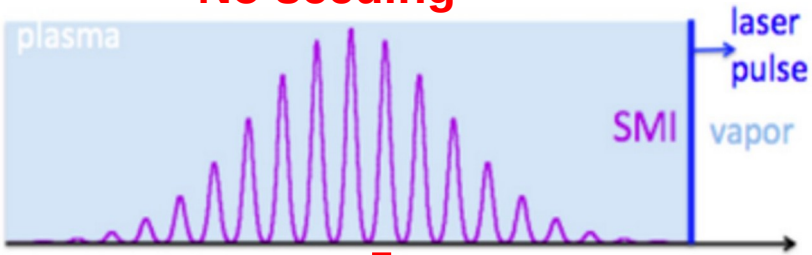


→ Reproducible outcome!

$\Delta t/\tau_{pe} \sim 6\ \%$,
$\tau_{pe} = 2\pi/\omega_{pe}$

Self-modulation: instability → seeded

No seeding



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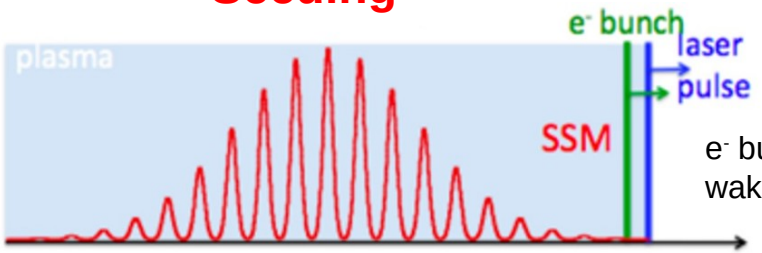

e⁻ bunch seeding

e⁻ bunch drives seed wakefields

L. Verra et al., Phys. Rev. Lett. 129 024802 (2022)

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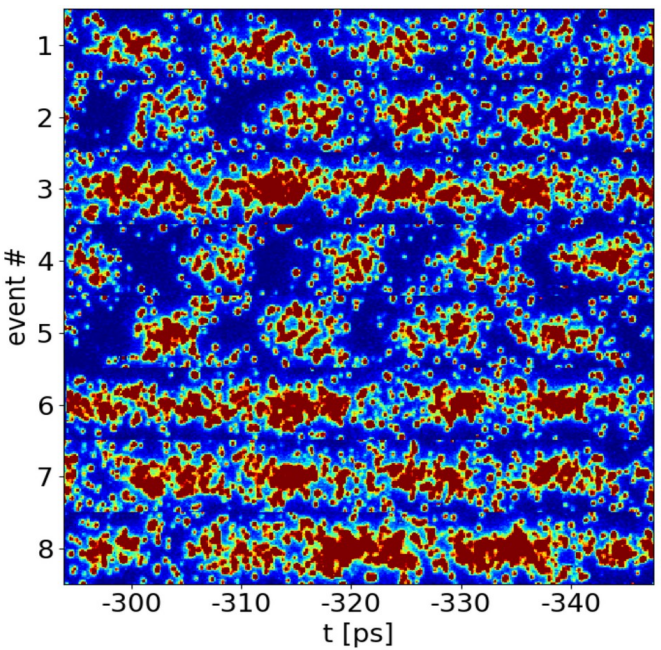

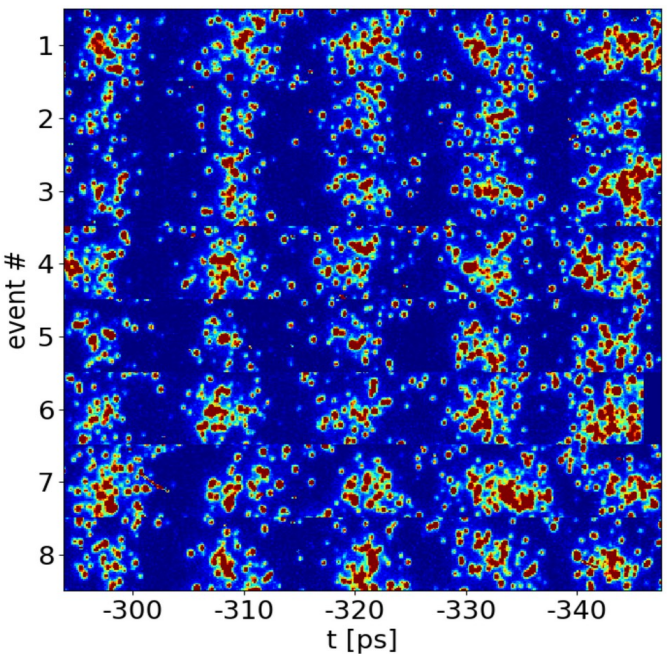

→ Reproducible outcome!

$\Delta t/\tau_{pe} \sim 7\ \%$,
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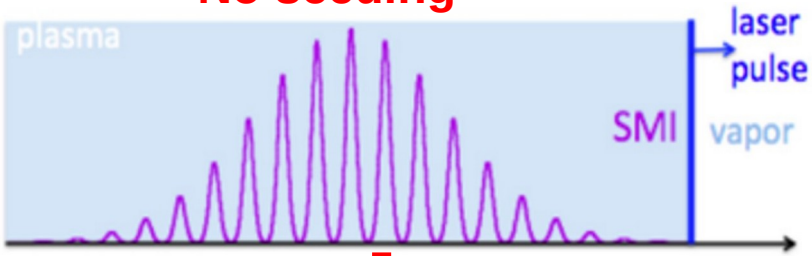
Self-modulation: instability → seeded

No seeding



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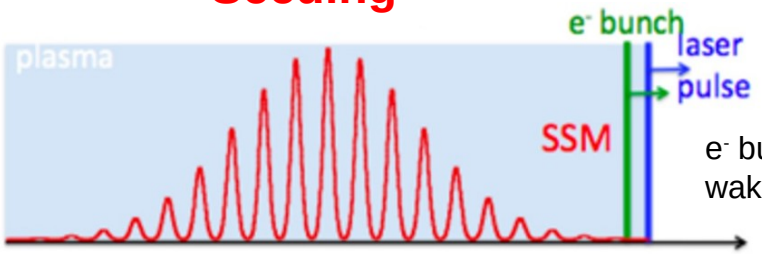

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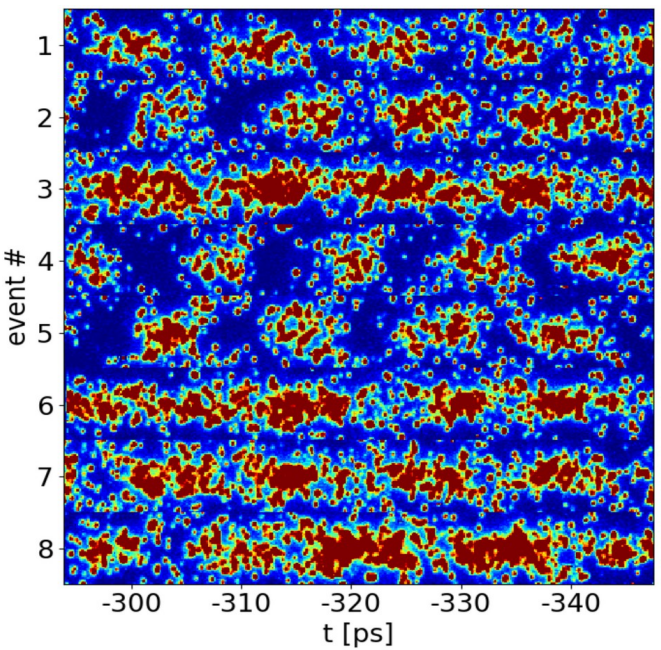

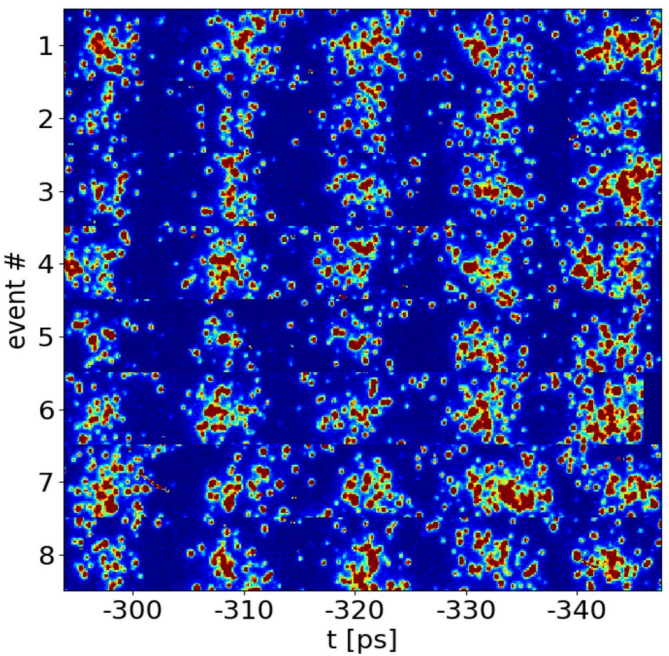

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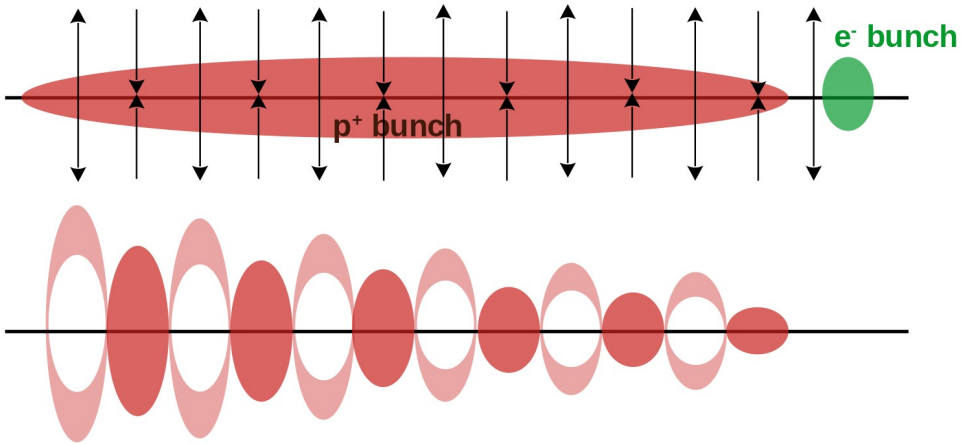
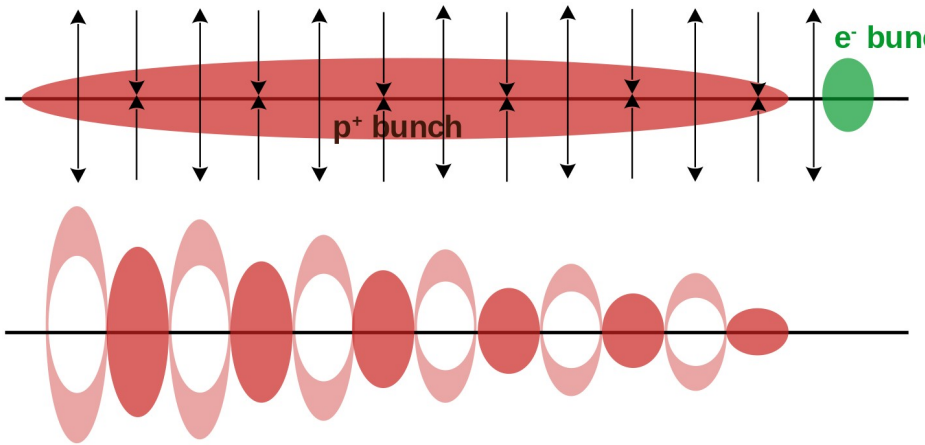
eSSM vs eSSM+Hosing



e^- and p^+ bunches aligned
force on p^+ bunch centroid = 0
force on p^+ bunch slice → focusing/defocusing

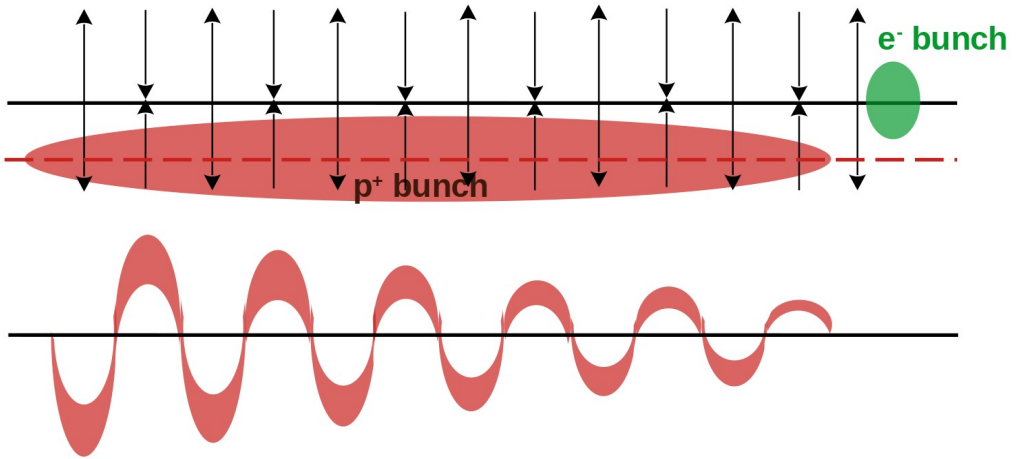
eSSM

eSSM vs eSSM+Hosing



e⁻ and p⁺ bunches aligned
force on p⁺ bunch centroid = 0
force on p⁺ bunch slice → focusing/defocusing

eSSM

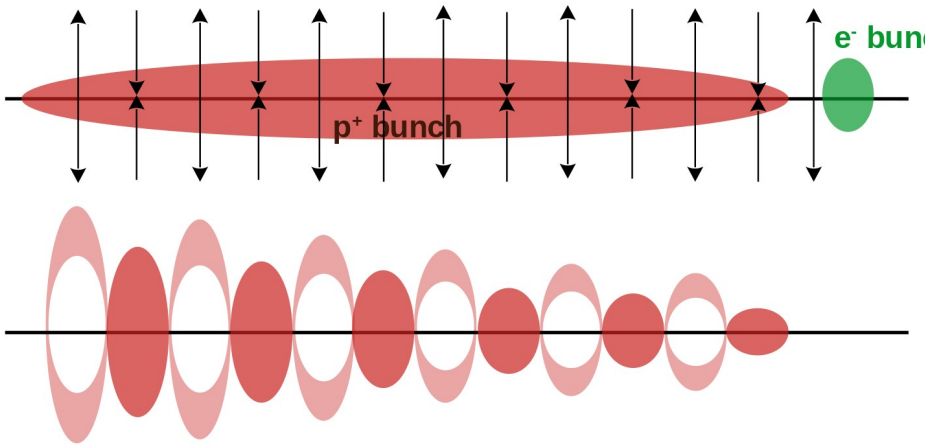


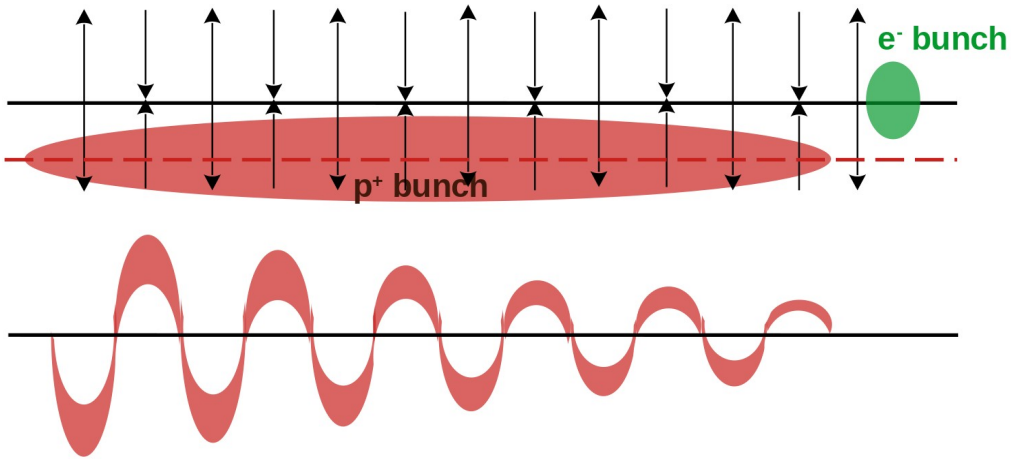
e⁻ and p⁺ bunches misaligned
force on p⁺ bunch centroid ≠ 0 → hosing-- **centroid position oscillation**
force on p⁺ bunch slice → focusing/defocusing

Hosing + eSSM

↓ ↓
one plane plane ⊥ hosing

eSSM vs eSSM+Hosing





e^- and p^+ bunches aligned
force on p^+ bunch centroid = 0
force on p^+ bunch slice → focusing/defocusing

eSSM

- Hosing occurs in the plane of misalignment
- eSSM → plane ⊥ hosing
- Hosing and eSSM caused by the same wakefields →
- Both processes are reproducible

e^- and p^+ bunches misaligned
force on p^+ bunch centroid ≠ 0 → hosing-- **centroid position oscillation**
force on p^+ bunch slice → focusing/defocusing

Hosing + eSSM

↓ one plane ↓ plane ⊥ hosing

Hosing in PWFA

- Hosing is **detrimental for acceleration process** →
- Important to study for the future PWFA →
- **Know how to suppress**
- Many studies on suppression

PRL **112,** 205001 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Hosing Instability Suppression in Self-Modulated Plasma Wakefields

J. Vieira,[1,3,*] W. B. Mori,[2] and P. Muggli[3]
[1]*GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[2]*Department of Physics and Astronomy, University of California Los Angeles, California 90095, USA*
[3]*Max-Plank-Institut für Physik, 80805 München, Germany*
(Received 13 December 2013; published 21 May 2014)

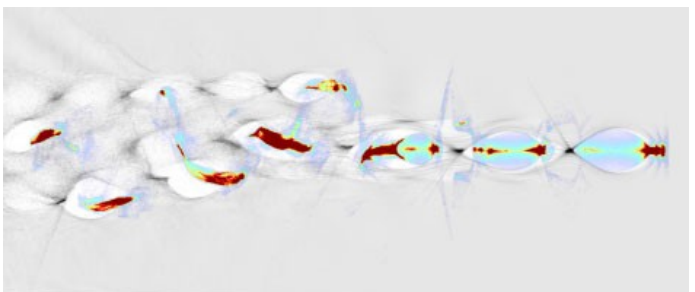


Figure: Beam breakup due to hosing growth in nonlinear blowout regime.
J. Vieira, W. Mori, P. Muggli, Phys. Rev. Lett. **112**, 205001 (2014)

Mitigation of the onset of hosing in the linear regime through plasma frequency detuning

Mariana Moreira,[1,*] Patric Muggli,[2,3] and Jorge Vieira[1]
[1]*GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[2]*Max Planck Institute for Physics, D-80805 Munich, Germany*
[3]*CERN, CH-1211 Geneva, Switzerland*

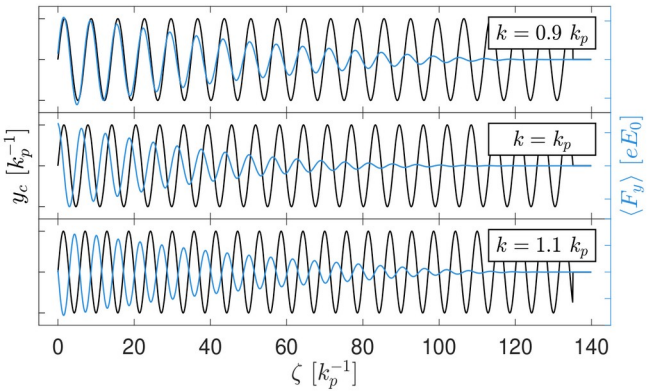


Figure: Initial centroid (black) and average transverse force (blue) for three different seed wavenumbers, obtained from 2D OSIRIS simulations at z = 0.
M. Moreira, P. Muggli, J. Vieira, arXiv: 2207.14763v1 (2022)

Towards experimental investigation of hosing instability mitigation at the PITZ facility

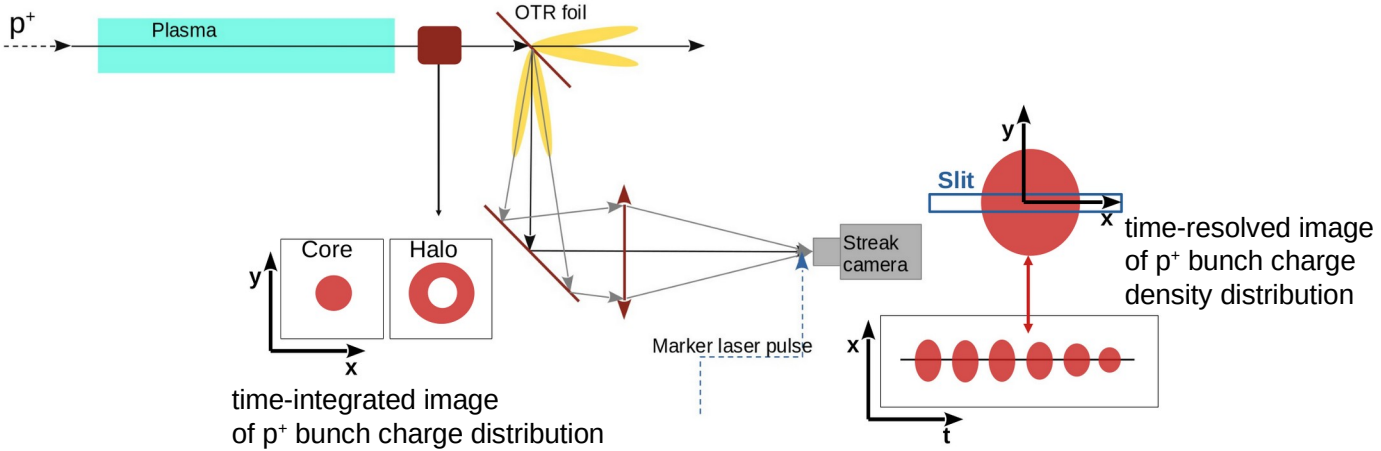
G Loisch *et al* 2020 *J. Phys.: Conf. Ser.* **1596** 012003

PHYSICAL REVIEW LETTERS **121,** 264802 (2018)

Suppression of Beam Hosing in Plasma Accelerators with Ion Motion

T. J. Mehrling,[*] C. Benedetti, C. B. Schroeder, E. Esarey, and W. P. Leemans
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

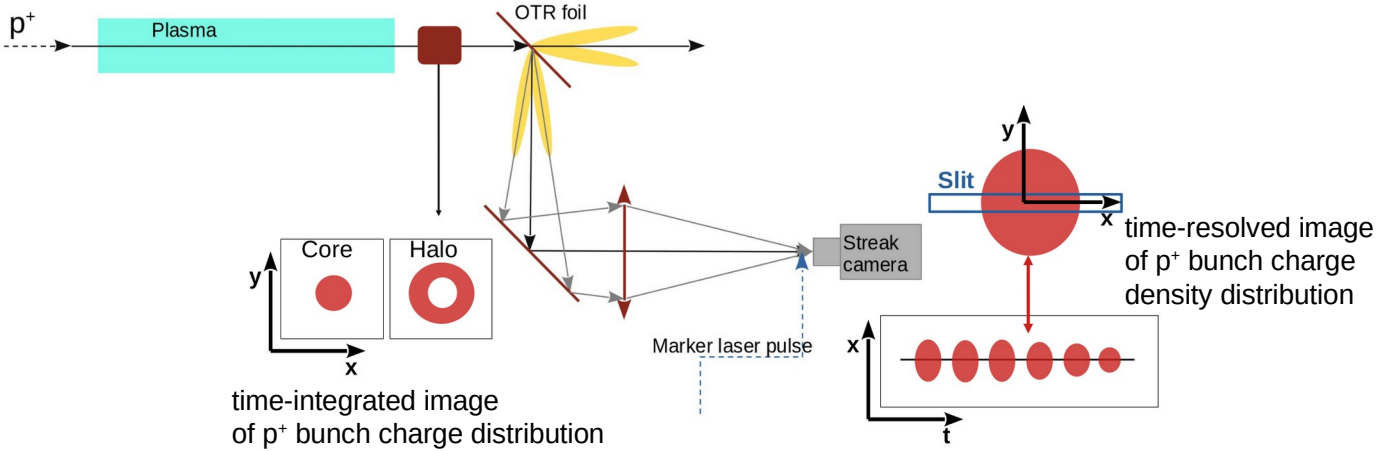
Hosing induced by electron bunch

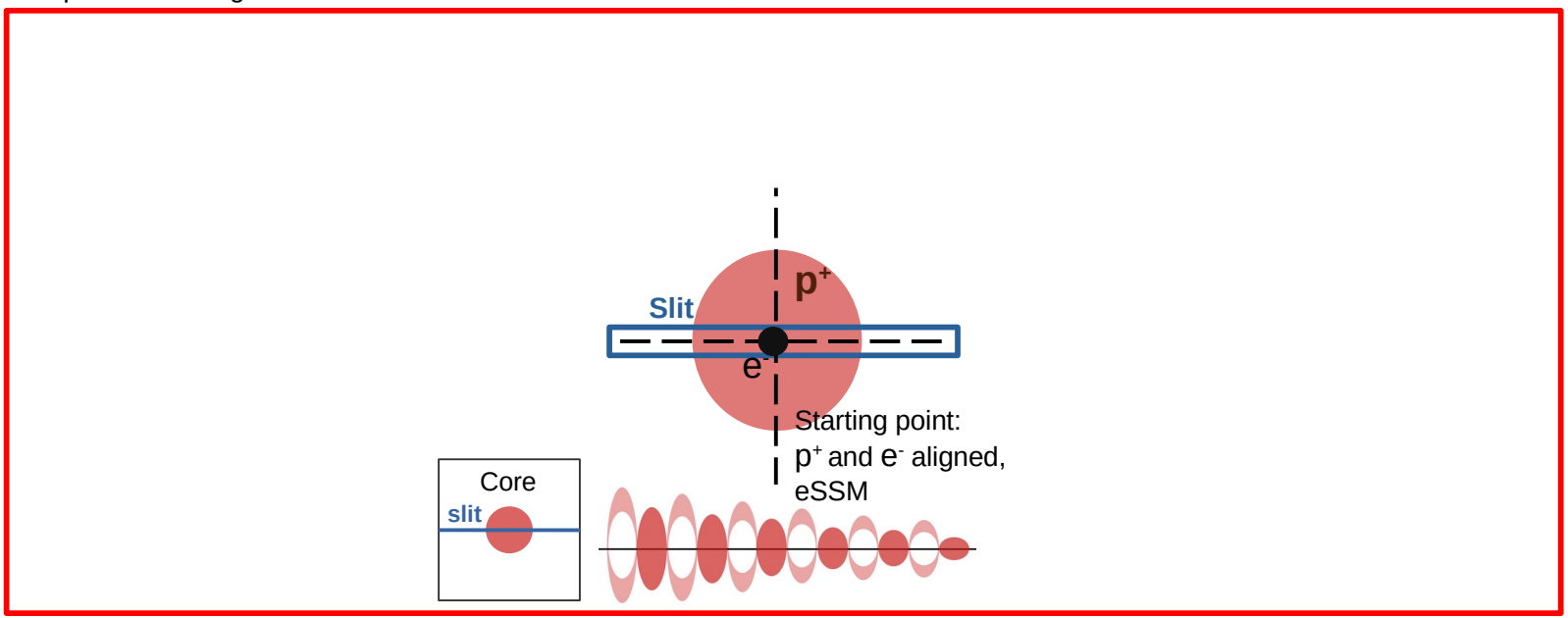


time-integrated image
of p^+ bunch charge distribution

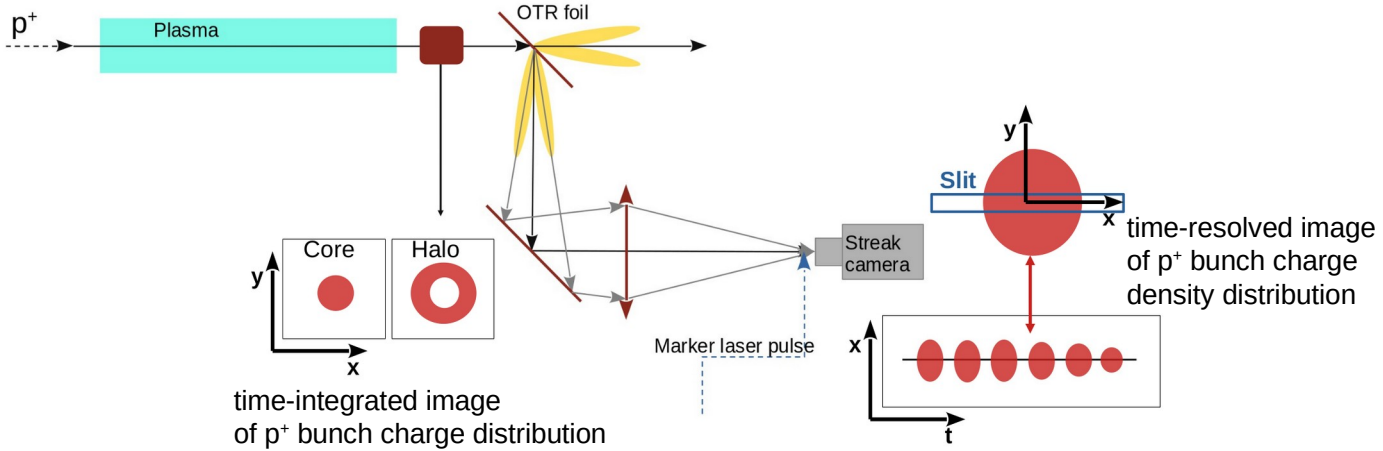
time-resolved image
of p^+ bunch charge
density distribution

Hosing induced by electron bunch



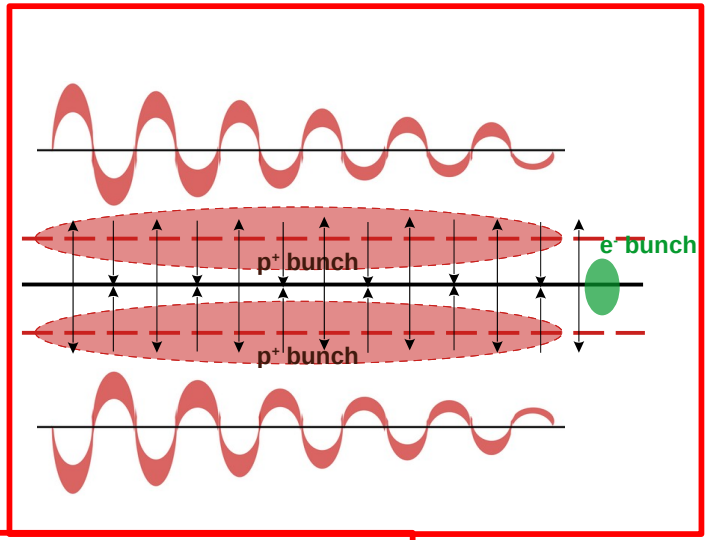


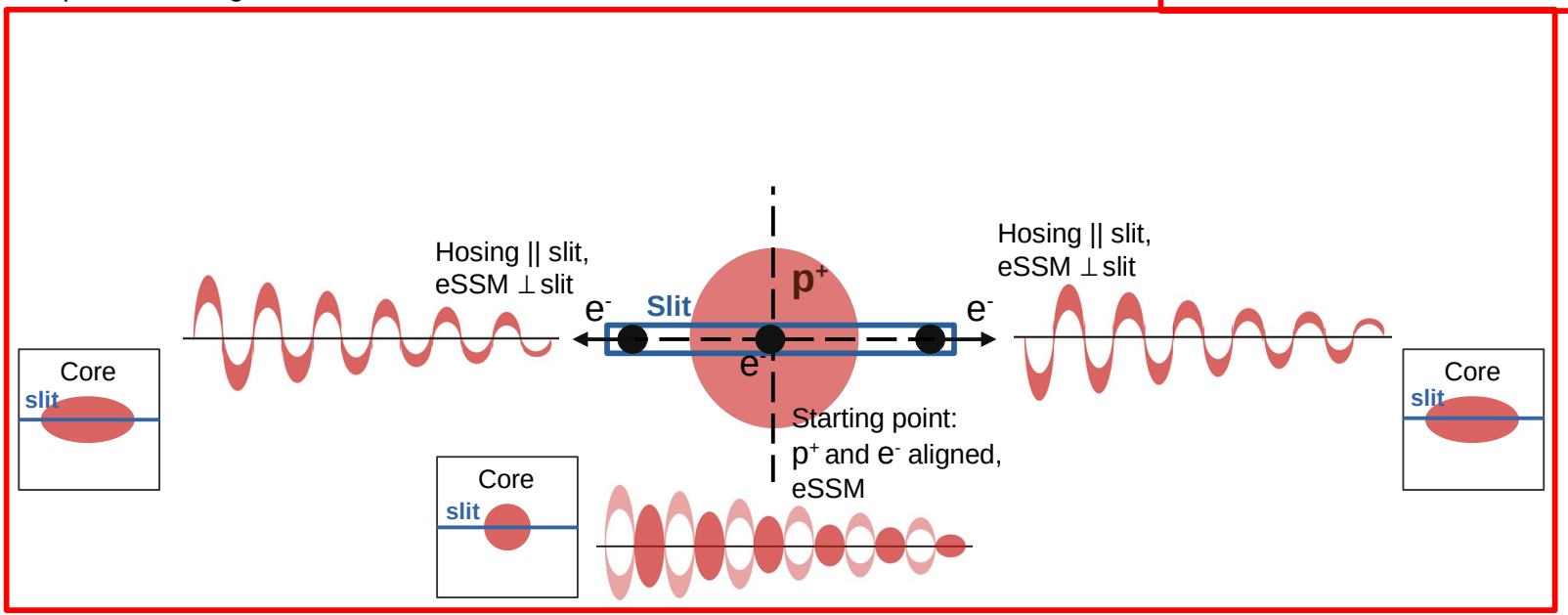
Hosing induced by electron bunch



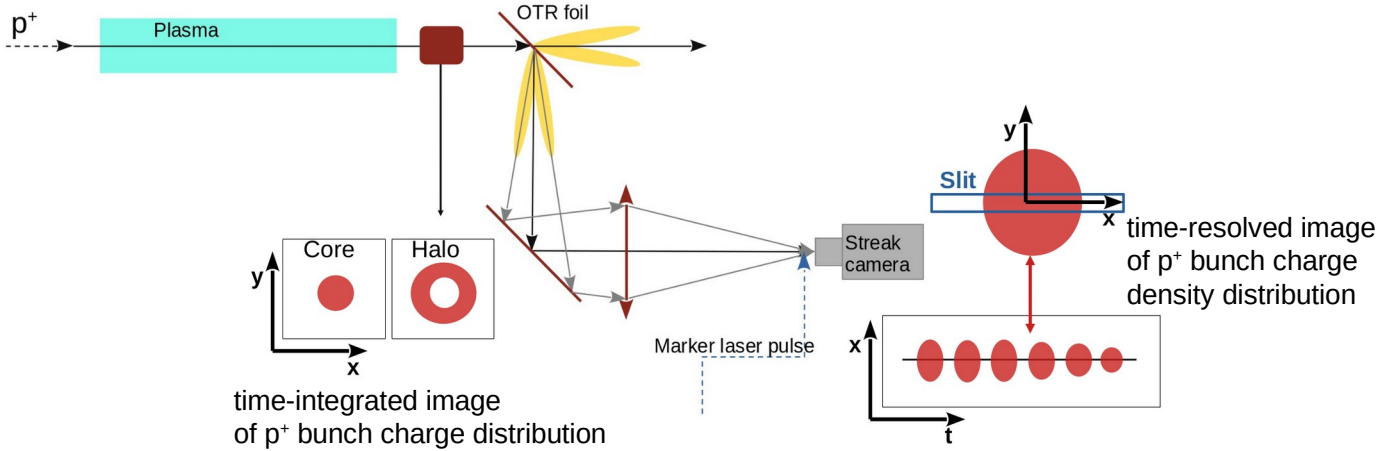
time-integrated image of p^+ bunch charge distribution

time-resolved image of p^+ bunch charge density distribution



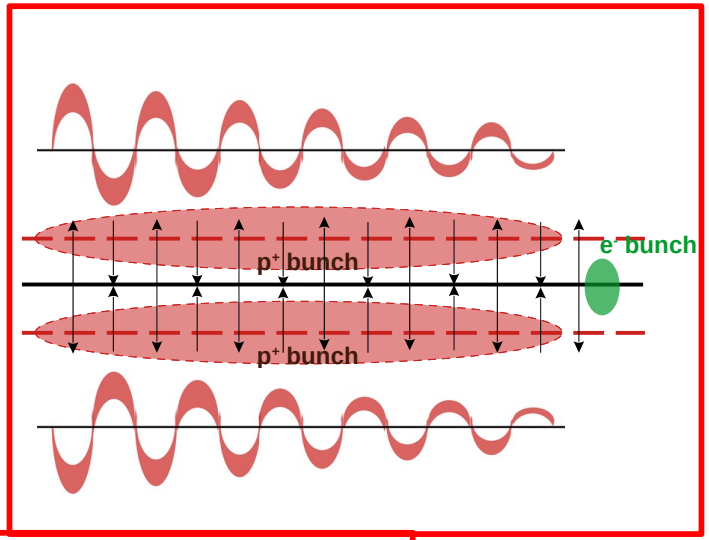


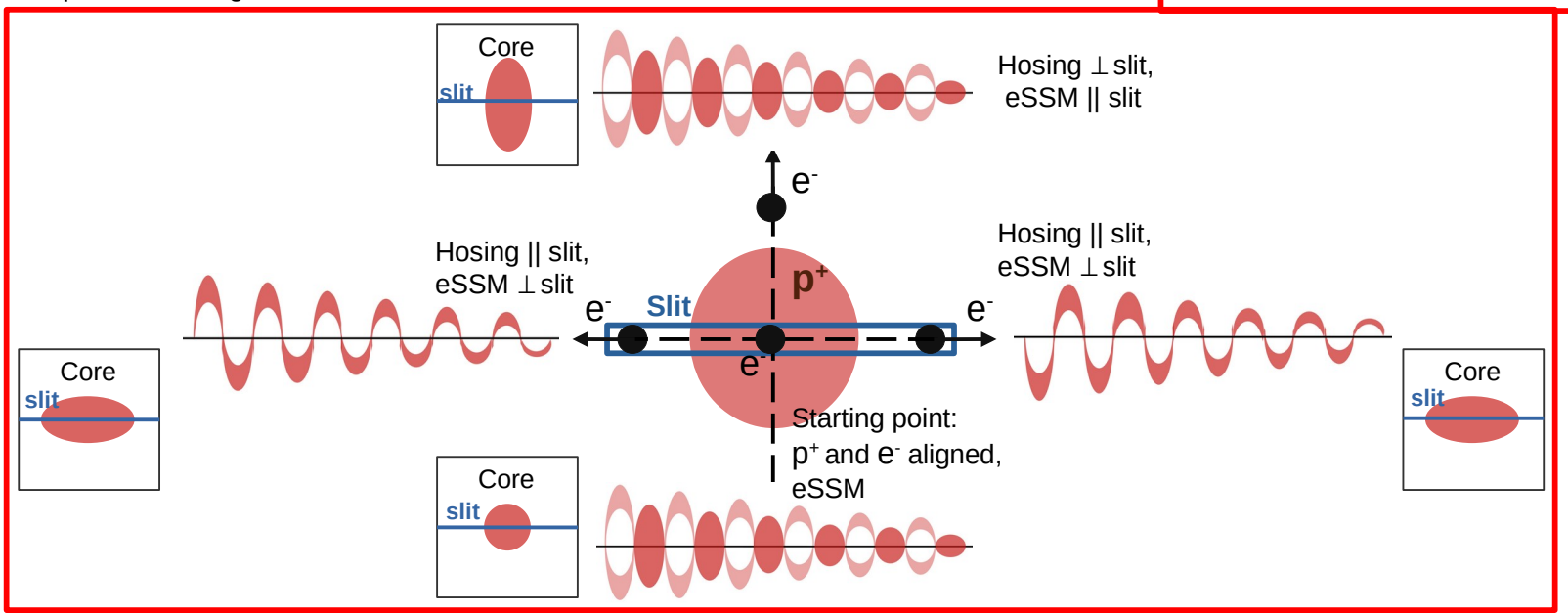
Hosing induced by electron bunch



time-integrated image of p^+ bunch charge distribution

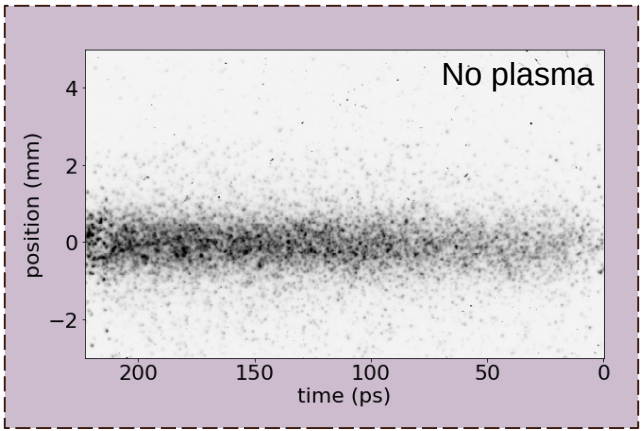
time-resolved image of p^+ bunch charge density distribution

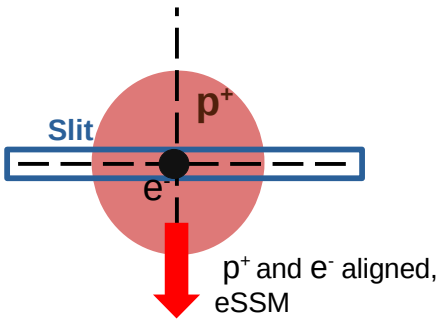


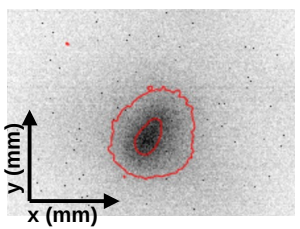


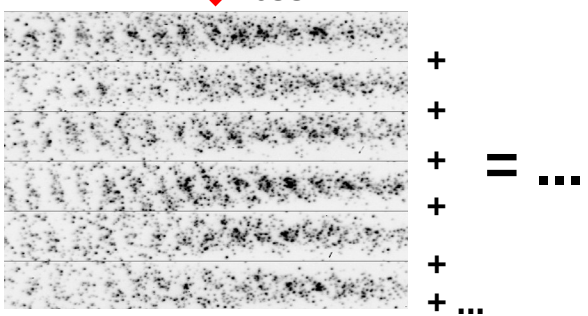
Results

preliminary





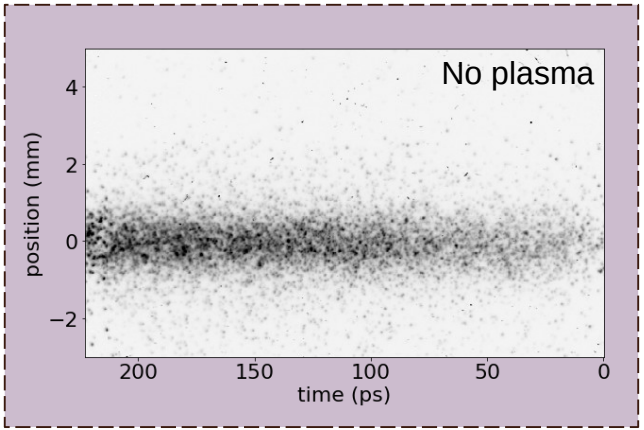


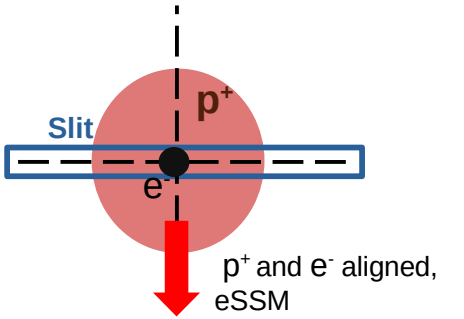


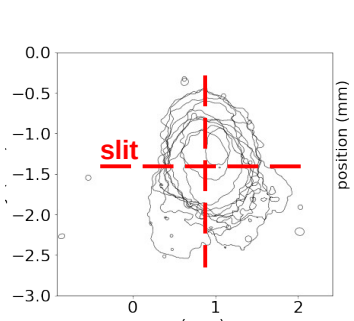
Results

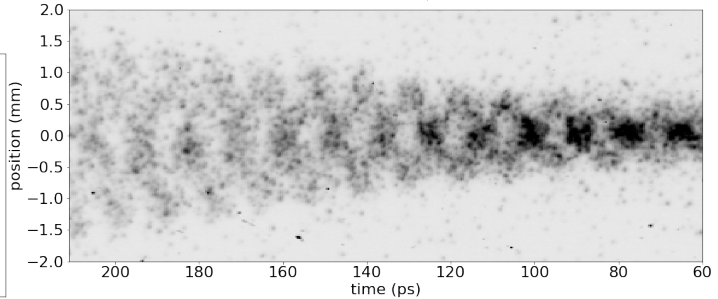
Images – averages of ~10 events

preliminary





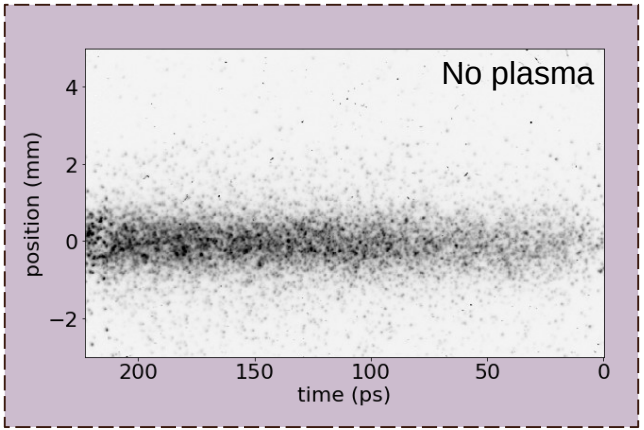


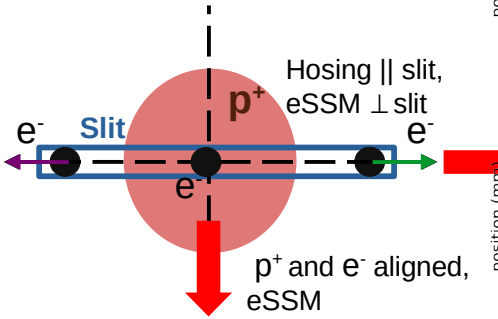


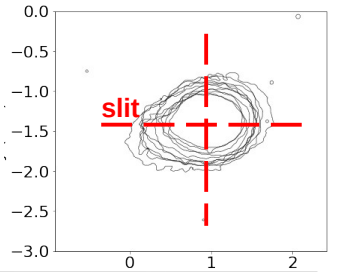
Results

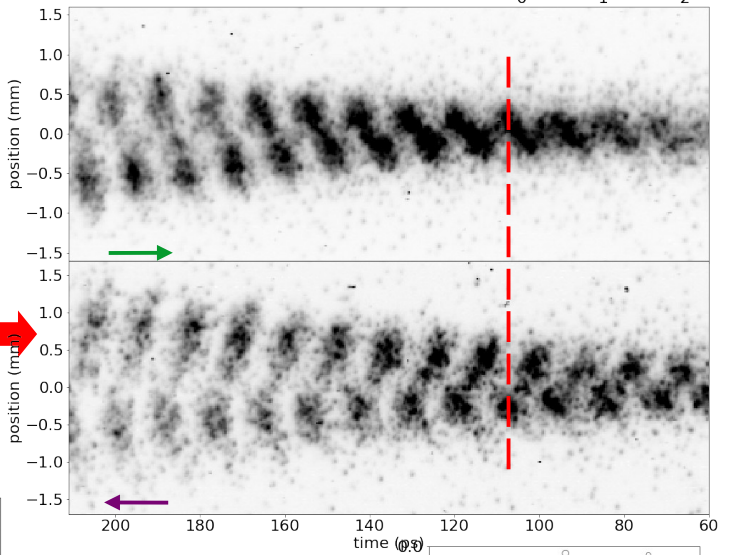
Images – averages of ~10 events

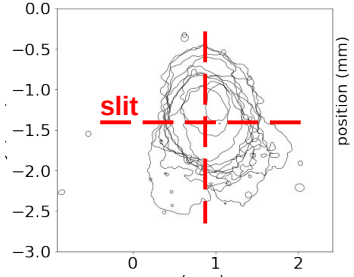
preliminary

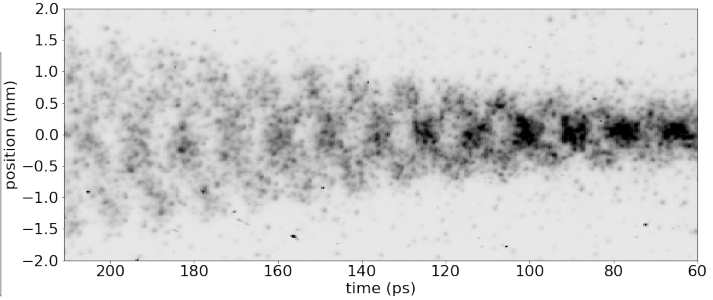


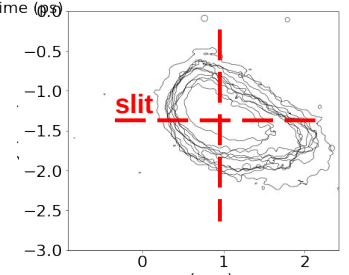








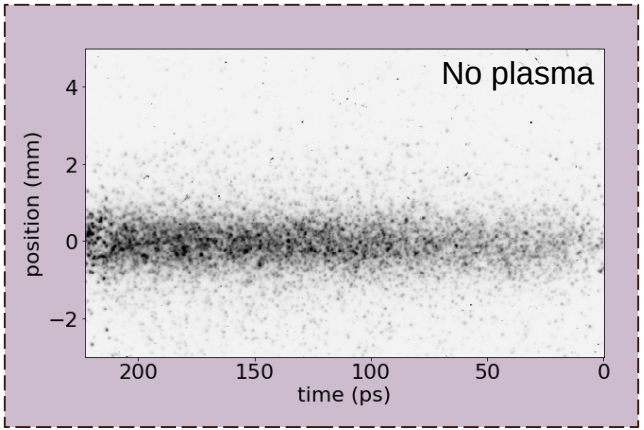


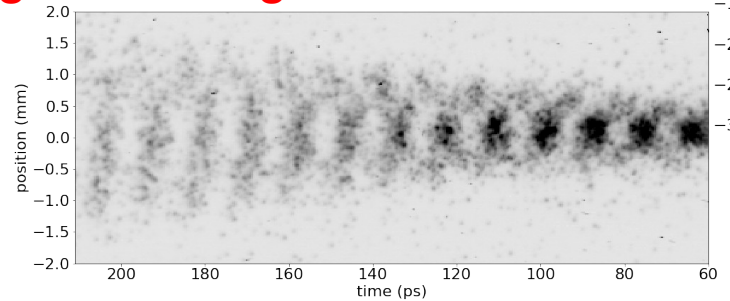


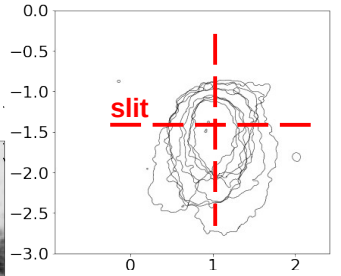
Results

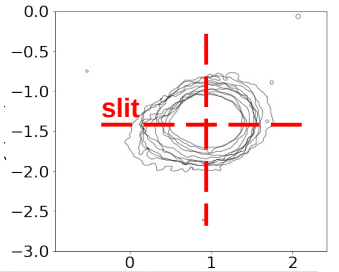
Images – averages of ~10 events

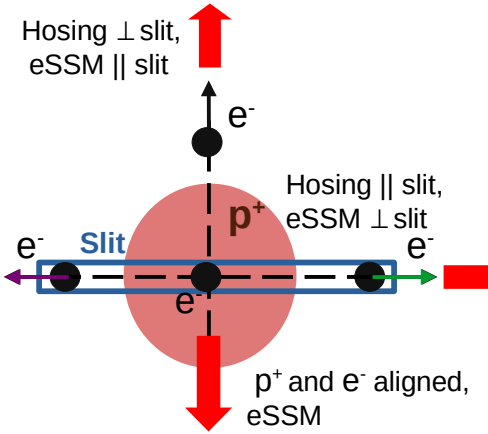
preliminary

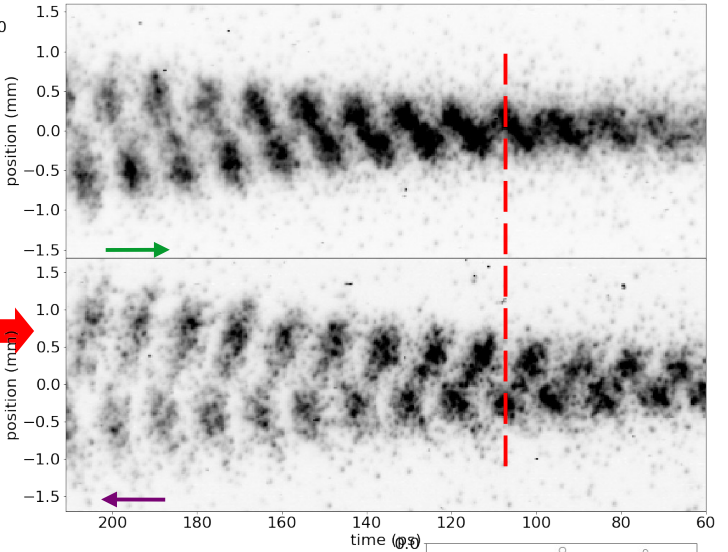


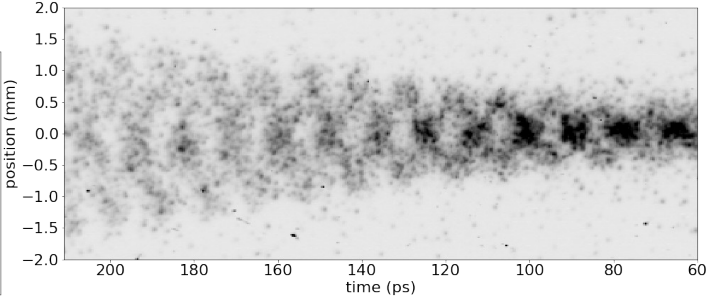


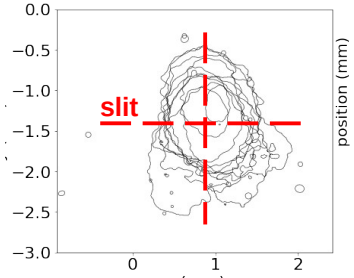


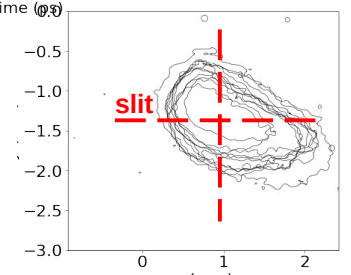










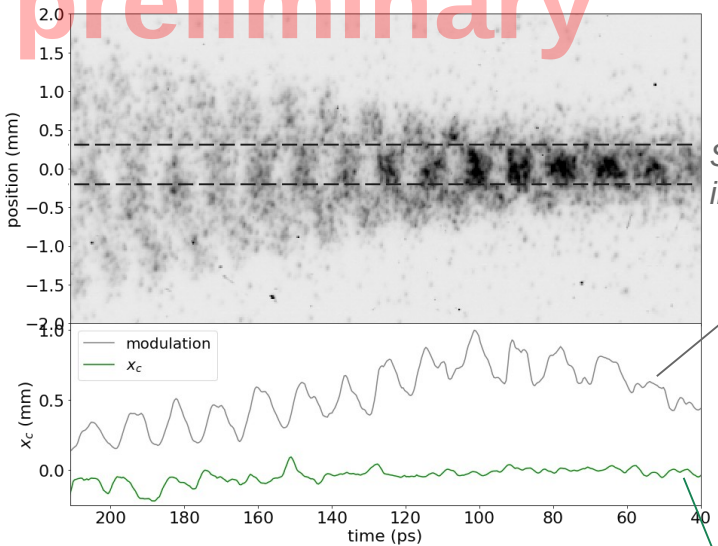


Frequency analysis

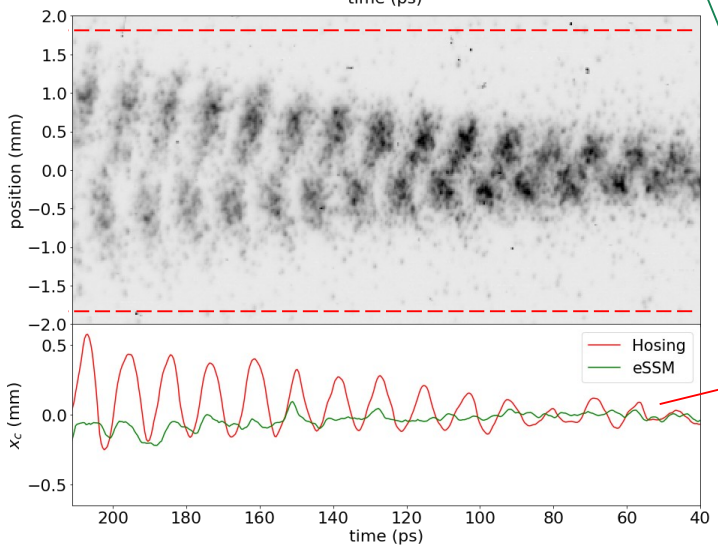
preliminary

Plasma e⁻ frequency $f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_{pe}e^2}{\epsilon_0 m_e}}$

$n_{pe} \sim 0.96*10^{14}$ cm^{-3}



Summed charge density in the bunch core



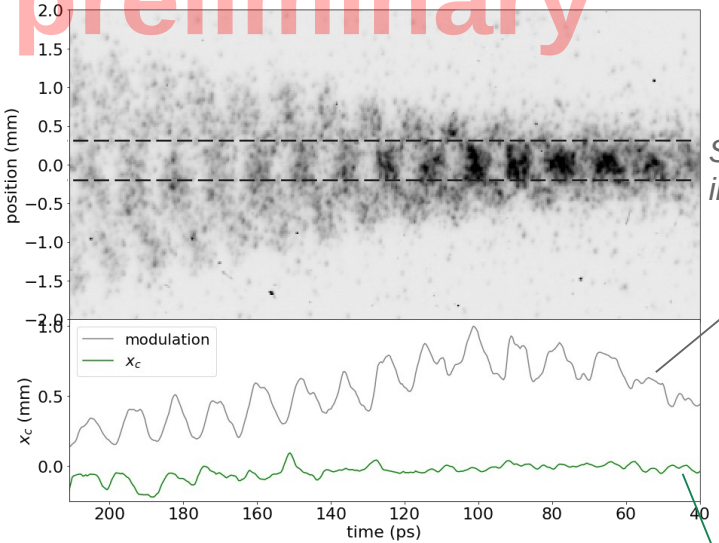
Center of mass of each transverse bunch slice

Frequency analysis

preliminary

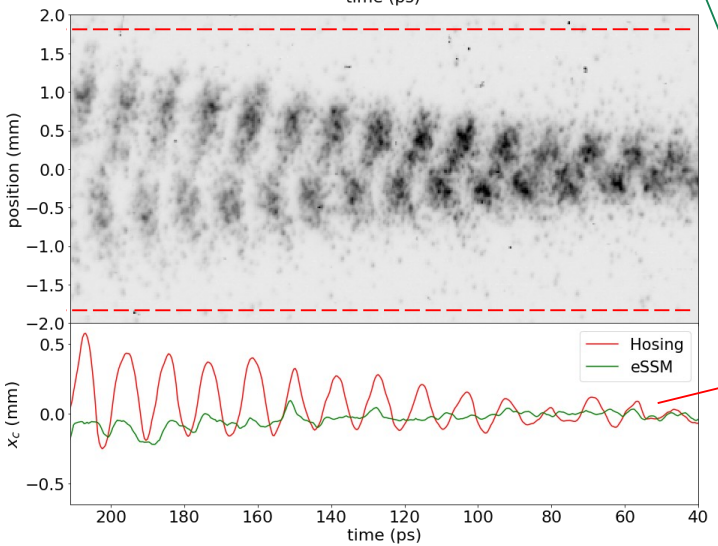
Plasma e⁻ frequency $f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_{pe}e^2}{\epsilon_0 m_e}}$

n_{pe} ~ 0.96*10^{14} cm^{-3}

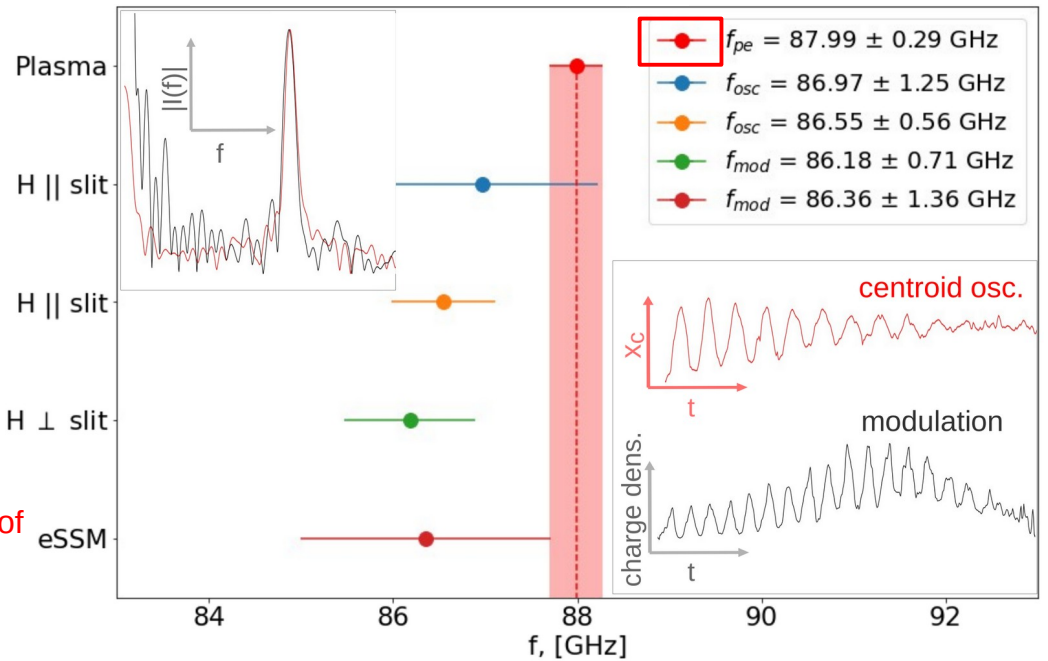


Summed charge density in the bunch core

DFT



Center of mass of each transverse bunch slice



Frequency analysis

preliminary

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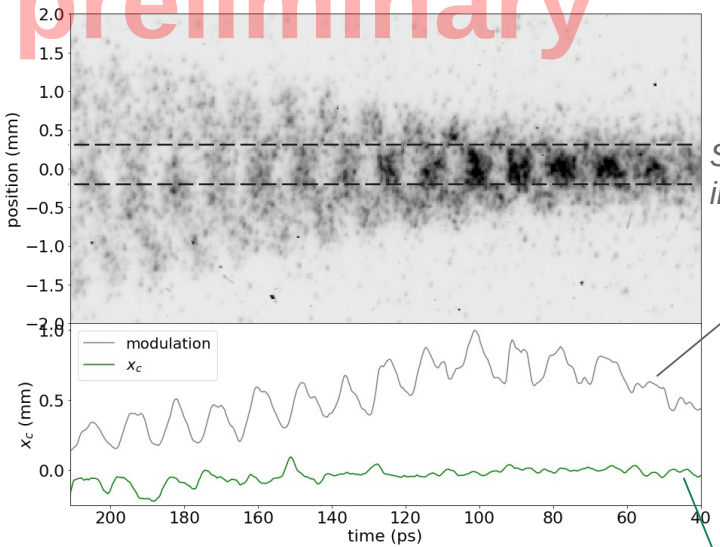
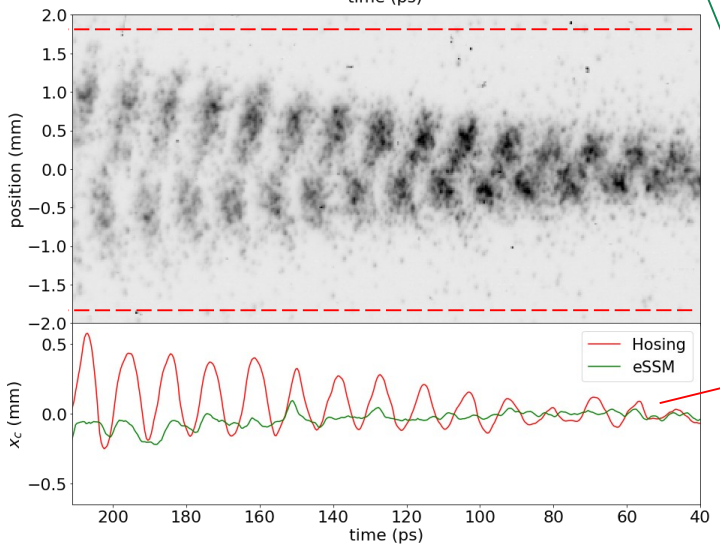
n_{pe} ~ 0.96*10^{14} cm^{-3}



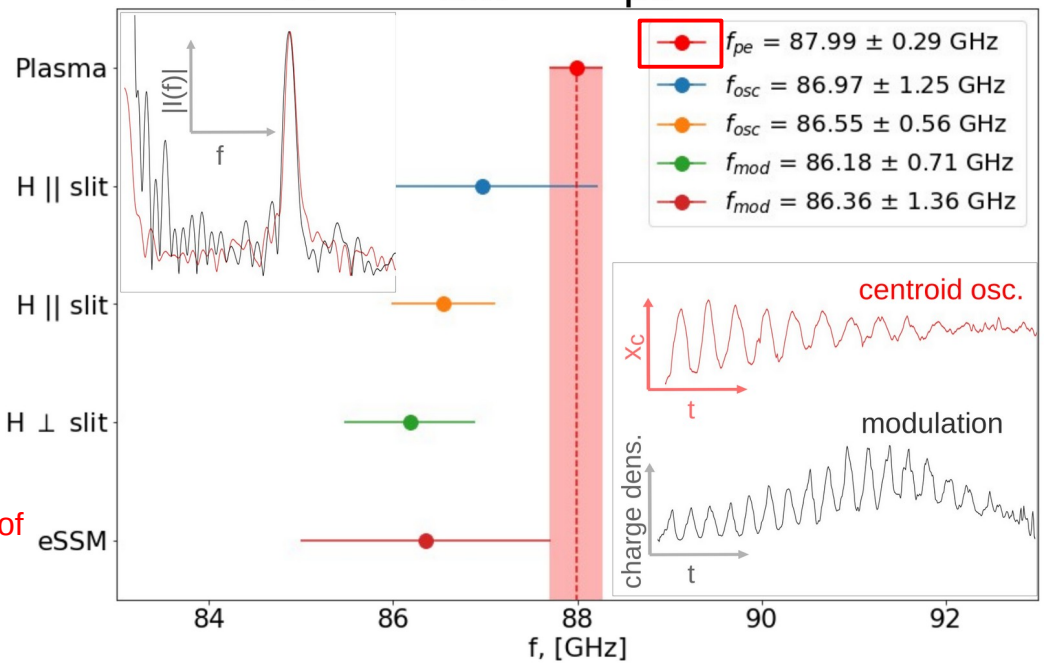
Summed charge density in the bunch core

DFT



Center of mass of each transverse bunch slice

$f_H \simeq f_{SM} \simeq f_{pe}$



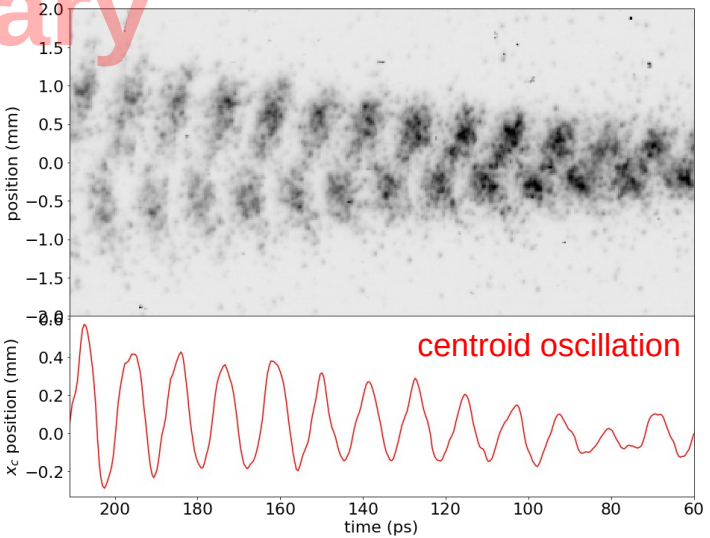
Frequency analysis

preliminary

Plasma e- frequency $f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_{pe}e^2}{\epsilon_0 m_e}}$

n_{pe} ~ 0.96*10^{14} cm^{-3}

f_{pe} ~ 87.9 GHz

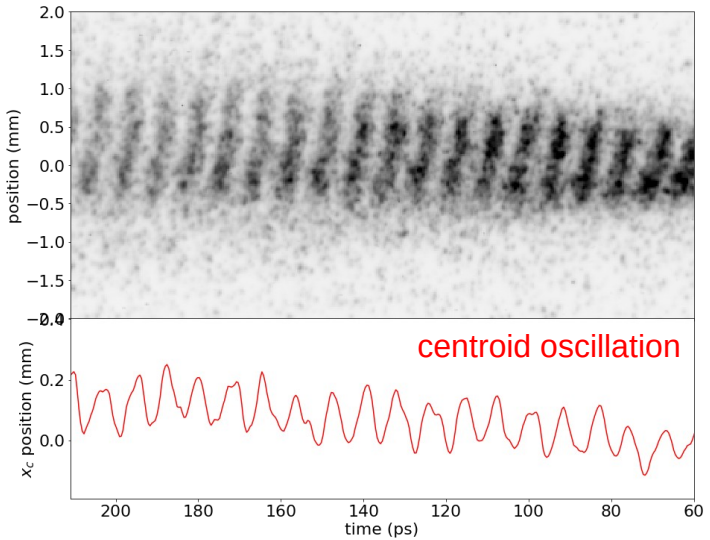


f_H = 86.97 GHz

T_H ~ 11.4 ps

n_{pe} ~ 2.03*10^{14} cm^{-3}

f_{pe} ~ 127.8 GHz



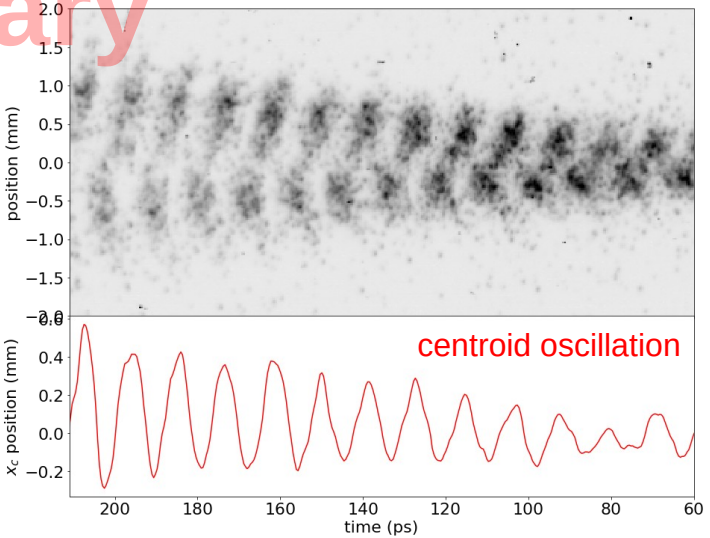
f_H = 123.5 GHz

T_H ~ 8 ps

Frequency analysis

preliminary

n_{pe} ~ 0.96*10^{14} cm^{-3}
f_{pe} ~ 87.9 GHz

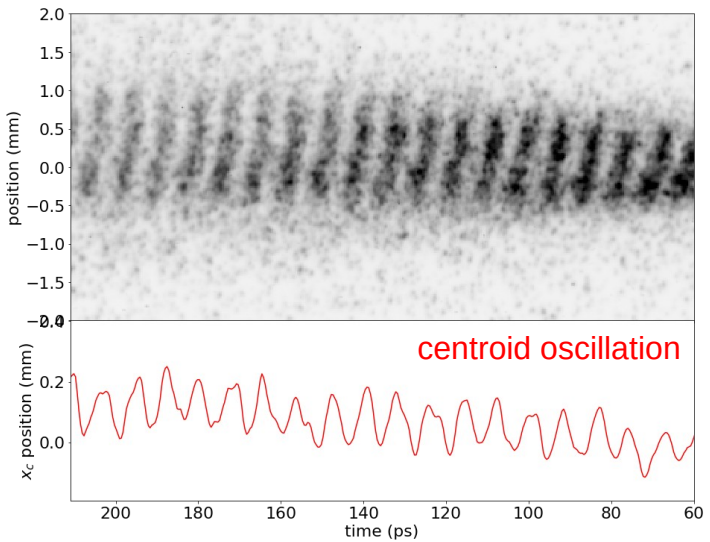


Plasma e$^-$ frequency $f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_{pe}e^2}{\epsilon_0 m_e}}$

f_H = 86.97 GHz

T_H ~ 11.4 ps

n_{pe} ~ 2.03*10^{14} cm^{-3}
f_{pe} ~ 127.8 GHz



f_H = 123.5 GHz

T_H ~ 8 ps

- n_{pe} increases ⇒ f_{pe} increases ⇒
- $f_{H,\,SM}$ increases
- $f_{H,\,SM} \approx f_{pe}$

Amplitude of oscillations vs p+ bunch charge

$$x_c = \delta_c \frac{e^{N_h}}{N_h^{1/2}} \frac{3^{1/4}}{(8\pi)^{1/2}} \cos\left(\pi/12 - k_p \xi - N_h/\sqrt{3}\right)$$ *

δ_c = f(e$^-$ parameters) – initial amplitude

N_h = f(p$^+$ parameters) – growth rate

* C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

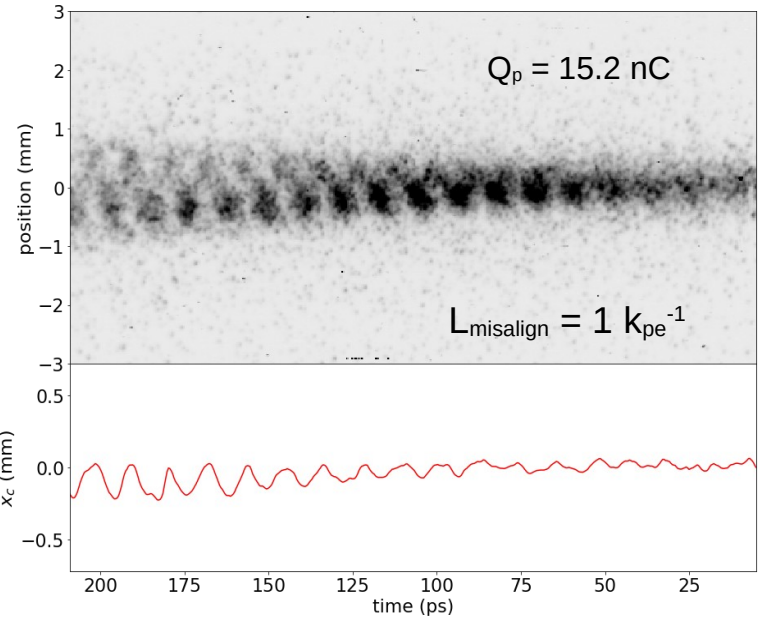
Amplitude of oscillations vs p+ bunch charge

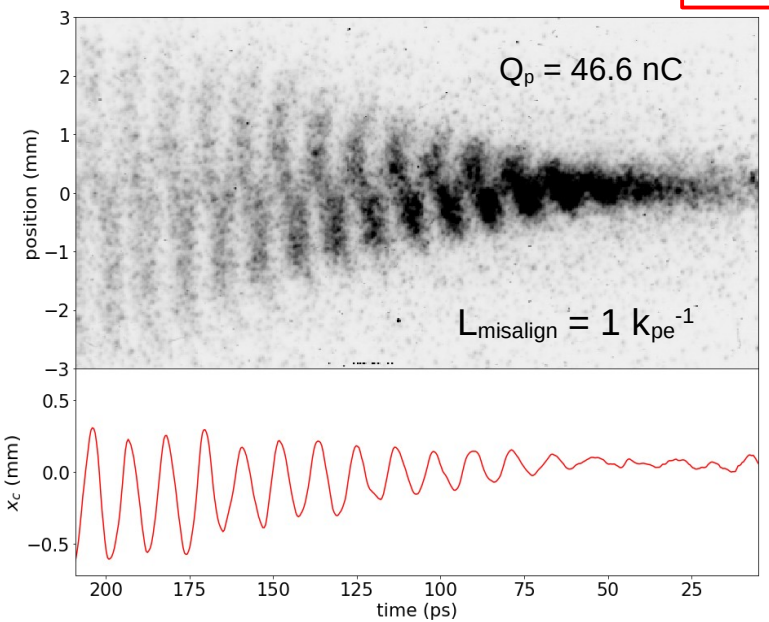
preliminary

$$x_c = \delta_c \frac{e^{N_h}}{N_h^{1/2}} \frac{3^{1/4}}{(8\pi)^{1/2}} \cos\left(\pi/12 - k_p \xi - N_h/\sqrt{3}\right)$$ *

δ_c = f(e⁻ parameters) – initial amplitude

N_h = f(p⁺ parameters) – growth rate





- **Linear theory:**
- **$N_h = f(n_b)$**
- $n_p = f(Q_p)$:
  Q_p increases → n_p increases

* C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

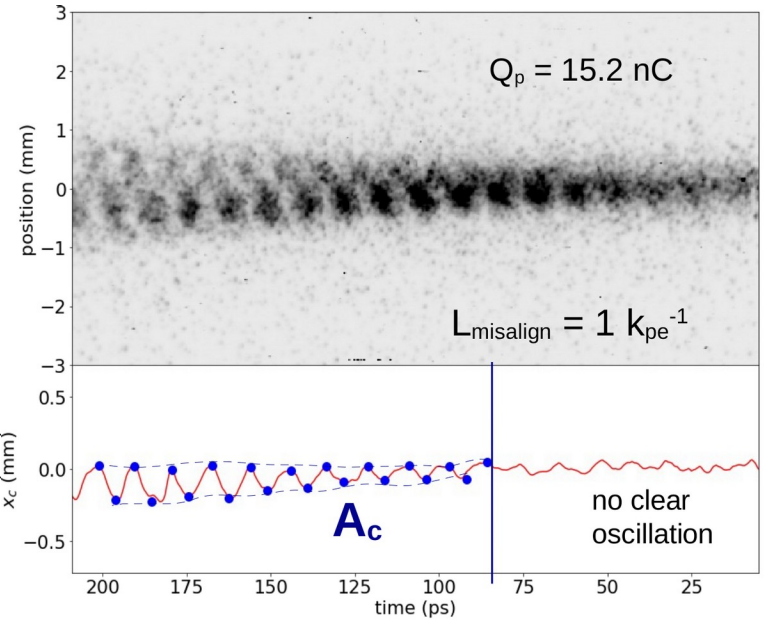
Amplitude of oscillations vs p+ bunch charge

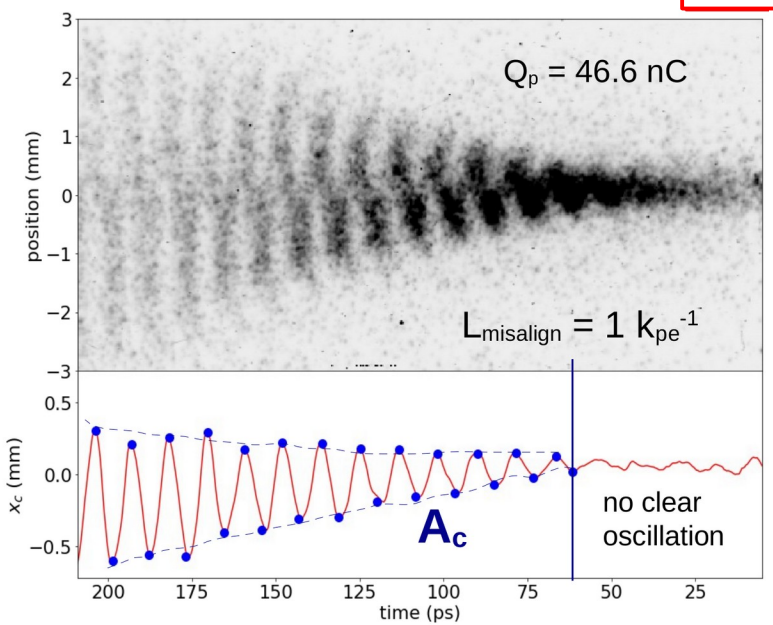
preliminary

$$x_c = \delta_c \frac{e^{N_h}}{N_h^{1/2}} \frac{3^{1/4}}{(8\pi)^{1/2}} \cos\left(\pi/12 - k_p \xi - N_h/\sqrt{3}\right)$$ *

δ_c = f(e⁻ parameters) – initial amplitude

N_h = f(p⁺ parameters) – growth rate





- **Linear theory:**
- **$N_h = f(n_b)$**
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  Q_p increases → n_p increases

* C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

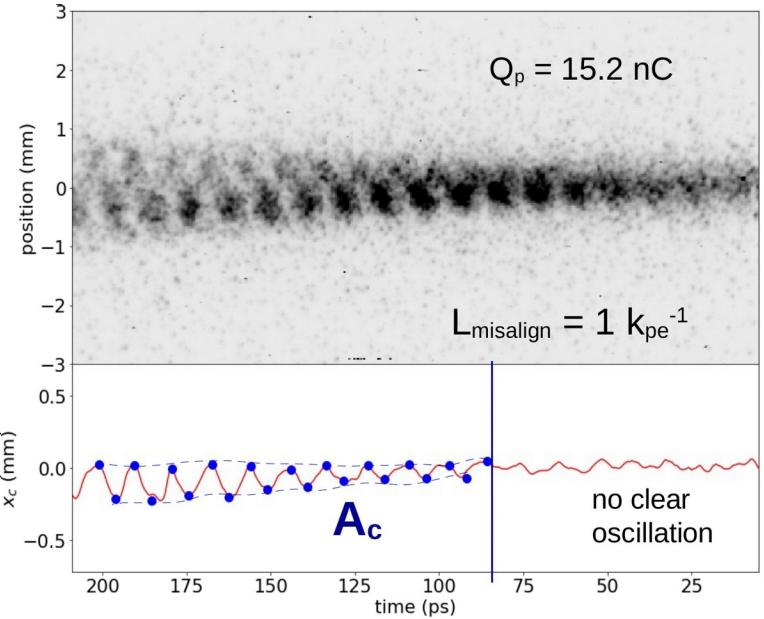
Amplitude of oscillations vs p+ bunch charge

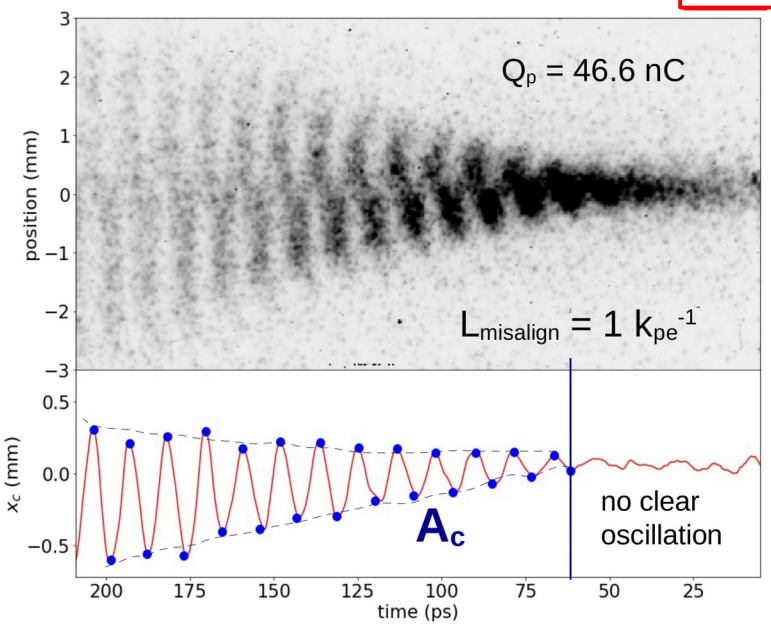
preliminary

$$x_c = \delta_c \frac{e^{N_h}}{N_h^{1/2}} \frac{3^{1/4}}{(8\pi)^{1/2}} \cos\left(\pi/12 - k_p \xi - N_h/\sqrt{3}\right) \quad *$$

δ_c = f(e⁻ parameters) – initial amplitude

N_h = f(p⁺ parameters) – growth rate





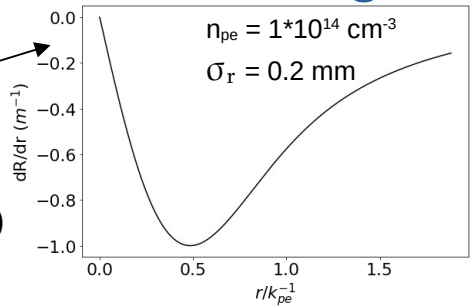
- **Linear theory:**
- **$N_h = f(n_b)$**
- $n_p = f(Q_p)$:
  Q_p increases → n_p increases

Q_p increases → A_c increases

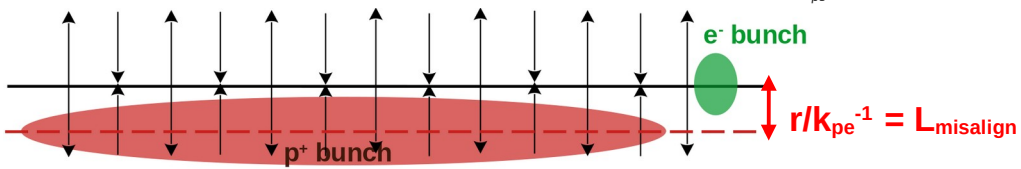
***** C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

Amplitude of oscillations vs misalignment extent

- **Linear theory**: $W_r \rightarrow W_{\perp,\,seed}$ depends on r as



- Amplitude of oscillations = f(misalignment extent ($L_{misalign}$))



$$x_c = \delta_c \frac{e^{N_h}}{N_h^{1/2}} \frac{3^{1/4}}{(8\pi)^{1/2}} \cos\left(\pi/12 - k_p \xi - N_h/\sqrt{3}\right) \quad *$$

δ_c = f(e⁻ parameters) – initial amplitude

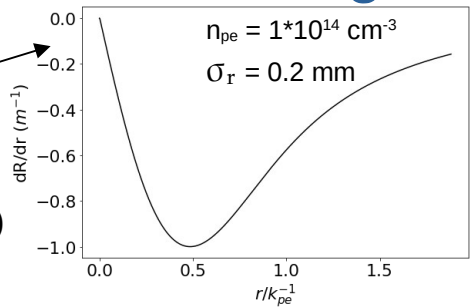
N_h = f(p⁺ parameters) – growth rate

* C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

Amplitude of oscillations vs misalignment extent

preliminary

- **Linear theory**: $W_r \rightarrow W_{\perp,\,seed}$ depends on r as



- Amplitude of oscillations = f(misalignment extent ($L_{misalign}$))

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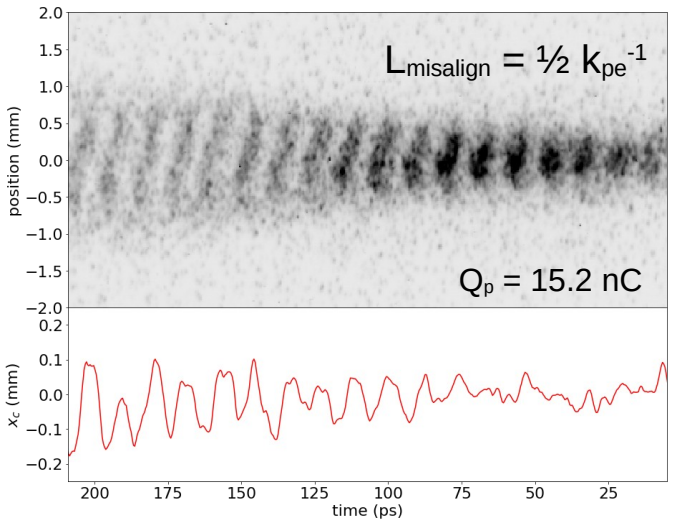

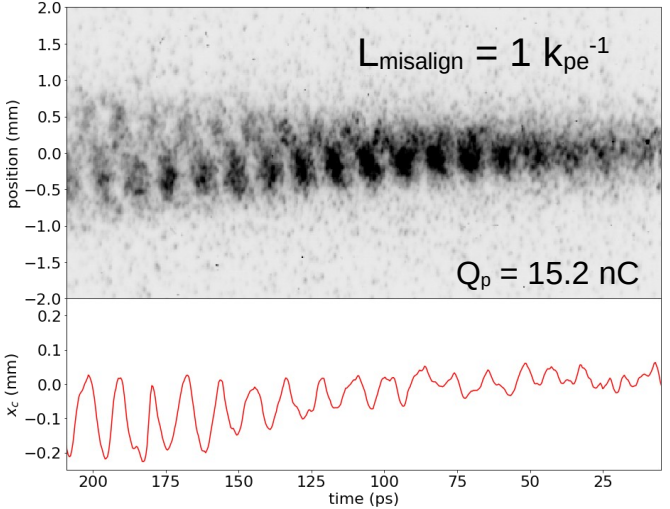

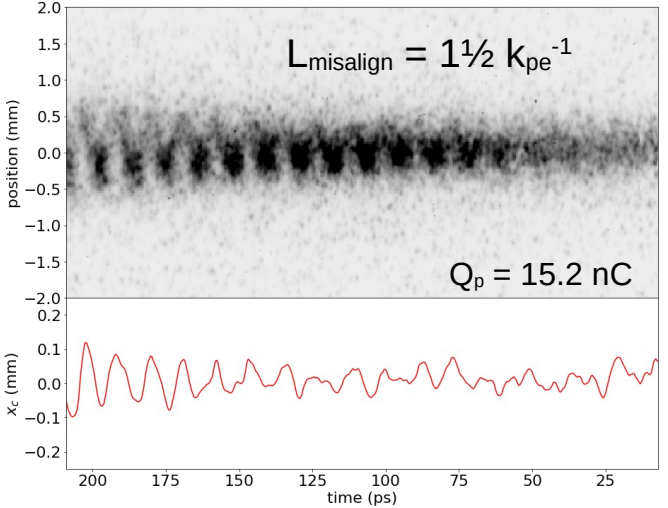

* C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

Amplitude of oscillations vs misalignment extent

preliminary

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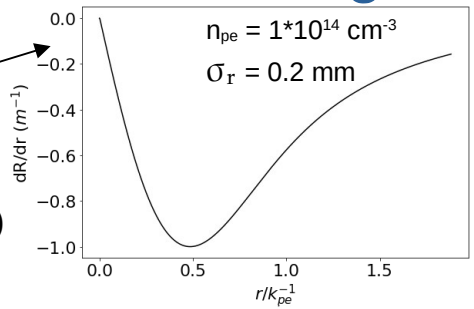

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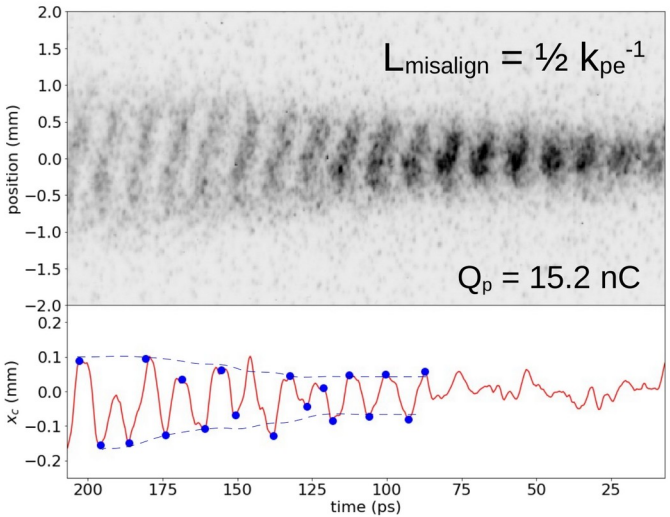

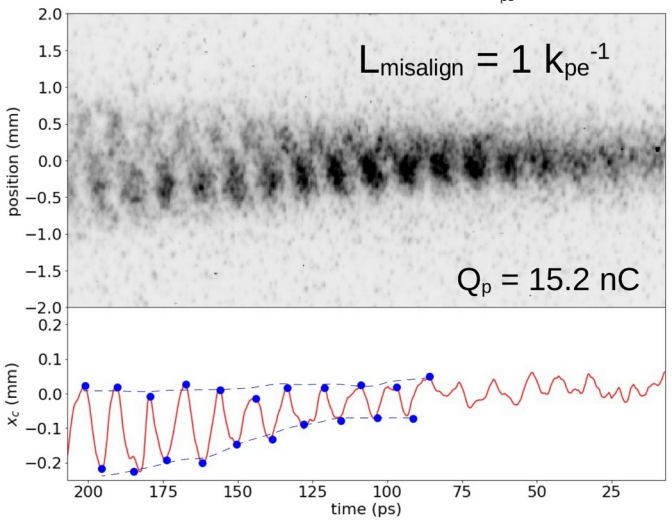

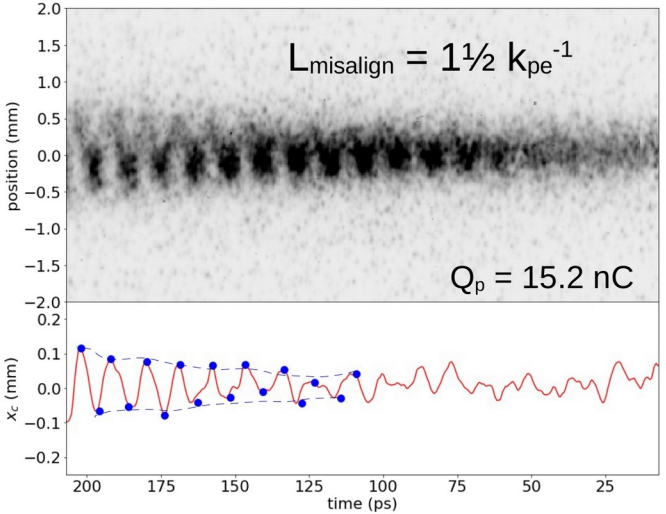

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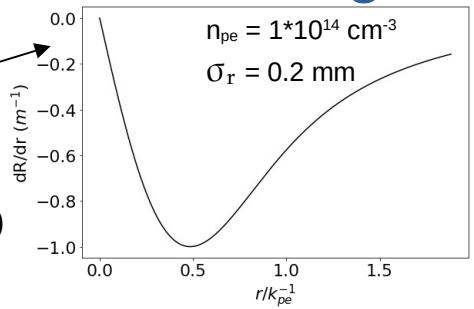

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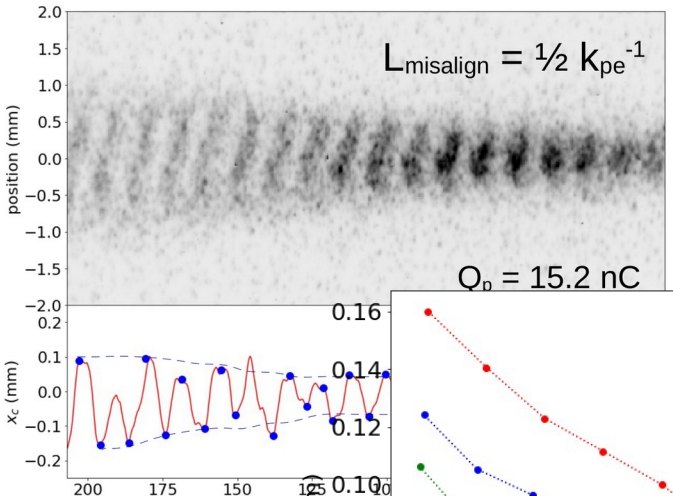

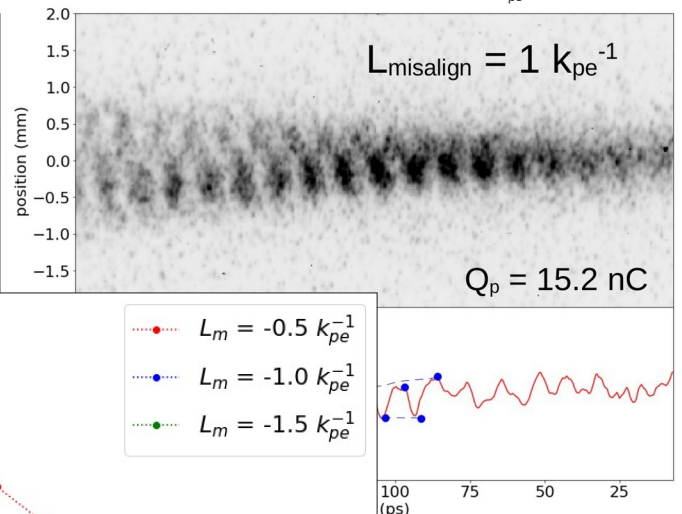

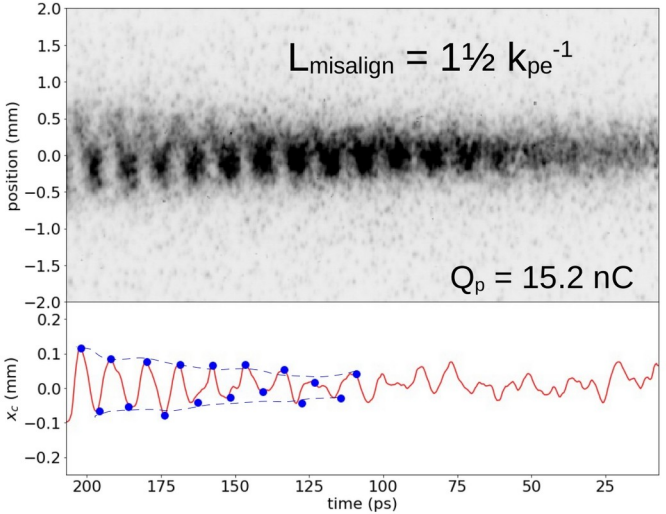

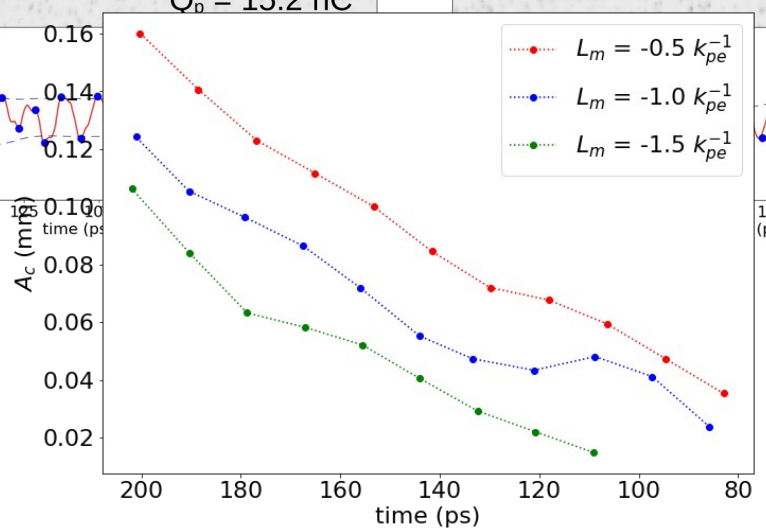

$L_{misalign}$ increases → A_c decreases

***** C. Schroeder, *Phys. Rev.* E **86**, 026402 (2012)

Conclusion and outlook

- Understanding hosing is important for PWFA (LWFA)
- Hosing @ AWAKE: can occur in the 1st stage → might grow further in the 2nd stage →
- Study hosing → know how to suppress it
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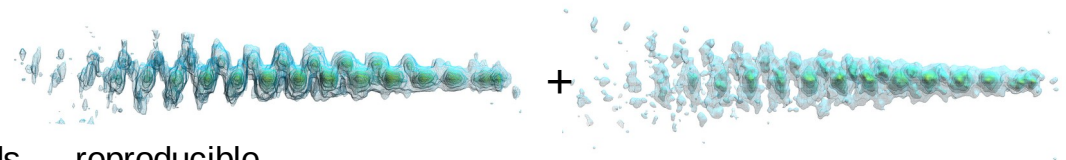
  - Occurs at the same time as eSSM (in ⊥ planes) 
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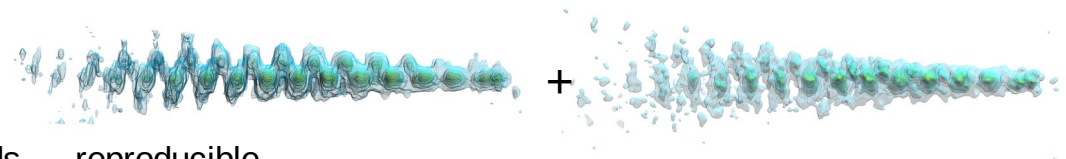
  - Occurs at the same time as eSSM (in ⊥ planes) 
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Thank you for your attention!