A method for obtaining 3D charge density distribution of a self-modulated proton bunch

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on behalf of the AWAKE Collaboration

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Conventional accelerators

- Synchrotron radiation in circular machines ~ $\frac{1}{m^4}$ – limitation for light particle colliders

- Modern RF cavities: limit on accelerating gradient ~ **100 MeV/m** (electric breakdown)

$$\Downarrow$$

- Increase acceleration length to increase particle energy

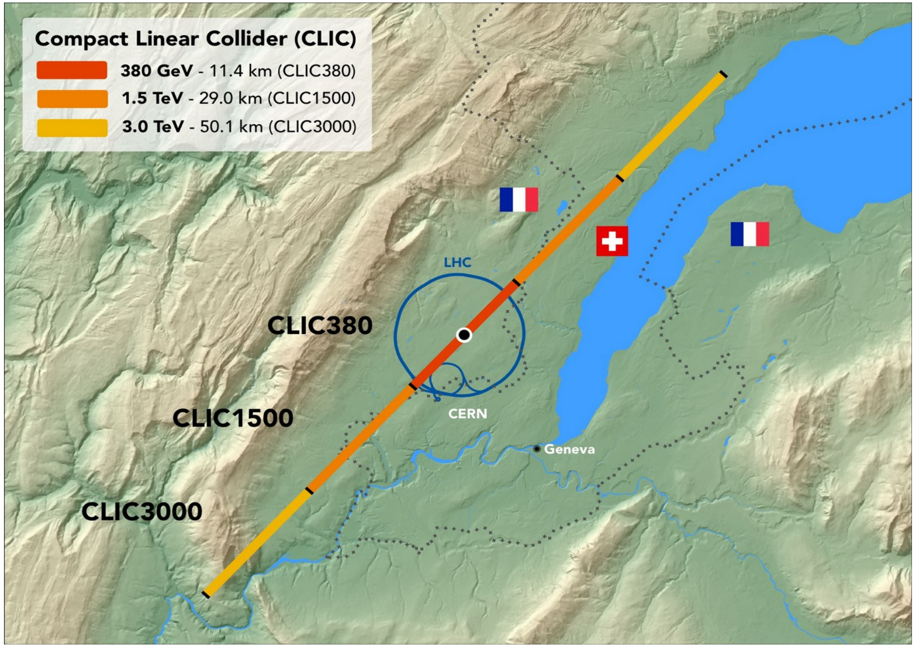


Image: CLIC – possible future linear collider at CERN.
© CERN

Image: Stanford Linear Accelerator (SLAC), USA; building covering the beam tube is ~3.2 km long!
© Wikipedia

Why PWFA?

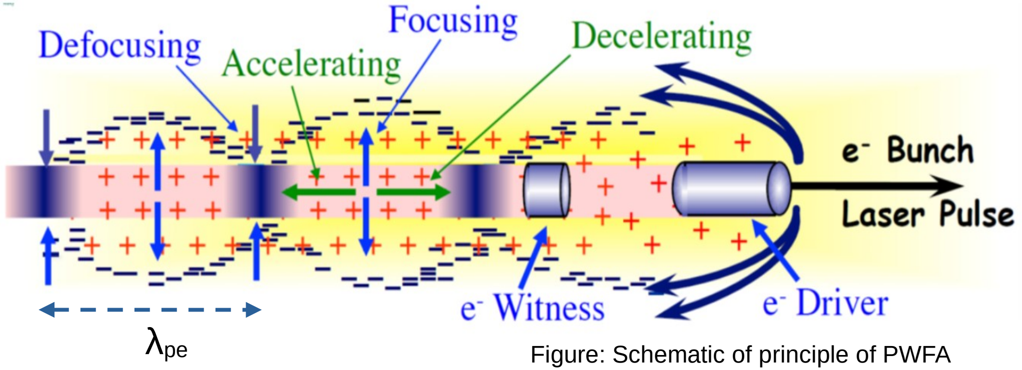


Figure: Schematic of principle of PWFA
© P. Muggli, MPP Munich, Germany

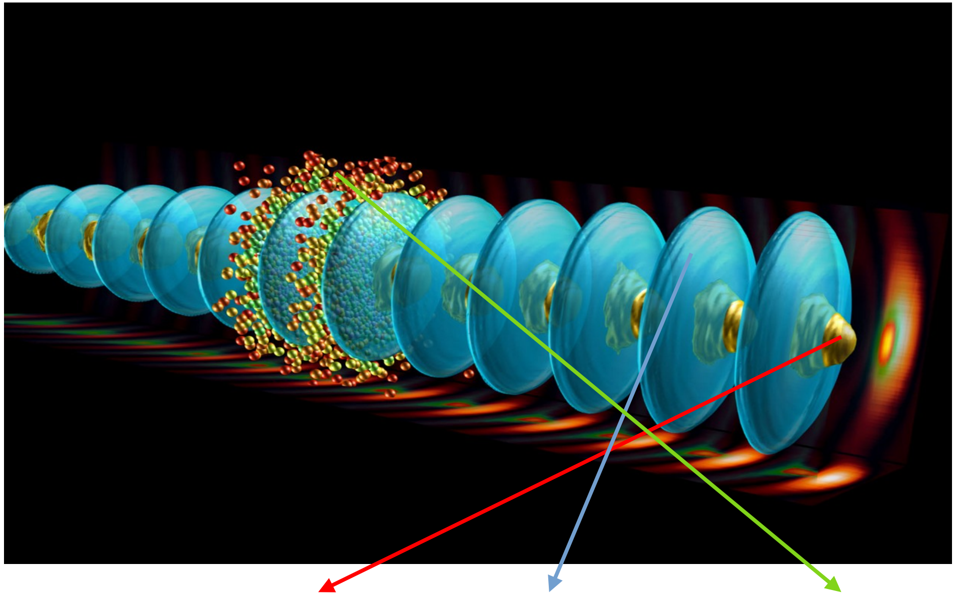


Image: drive bunch creates a plasma wave, which accelerates witness bunch
© J. Vieira, IST Lisbon, Portugal

Plasma-based acceleration (PWFA):

- Particle bunch or laser pulse propagates through plasma →
- Plasma electrons oscillation →
- Transverse and longitudinal electric and magnetic fields – wakefields
- Linear theory: wakefields – sinusoidal oscillations at ω_{pe}

Electric fields up to $E_{WB} = \frac{m_e c\, \omega_{pe}}{e}$, $\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{\varepsilon_0 m_e}}$

⇓

Accelerating gradient limit [eV/m] ~ $96\sqrt{n_{pe}}$ [cm^{-3}]

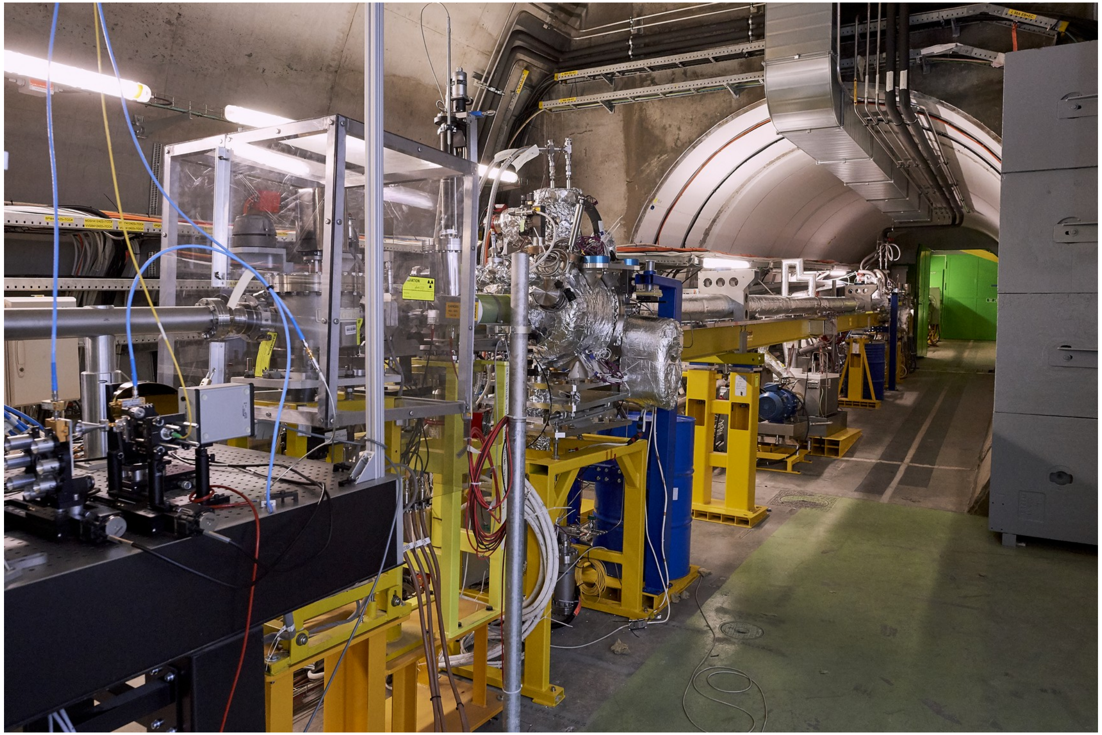
when $n_{pe} = 10^{18}$ cm^{-3} ⇒ gradient ~ **100 GeV/m**

AWAKE experiment

- AWAKE – Advanced Wakefield Experiment

- CERN-based R&D project – collaboration of ~20 institutes → proton driven PWFA studies

- Final goal → quality-preserving high-energy electron beam accelerator



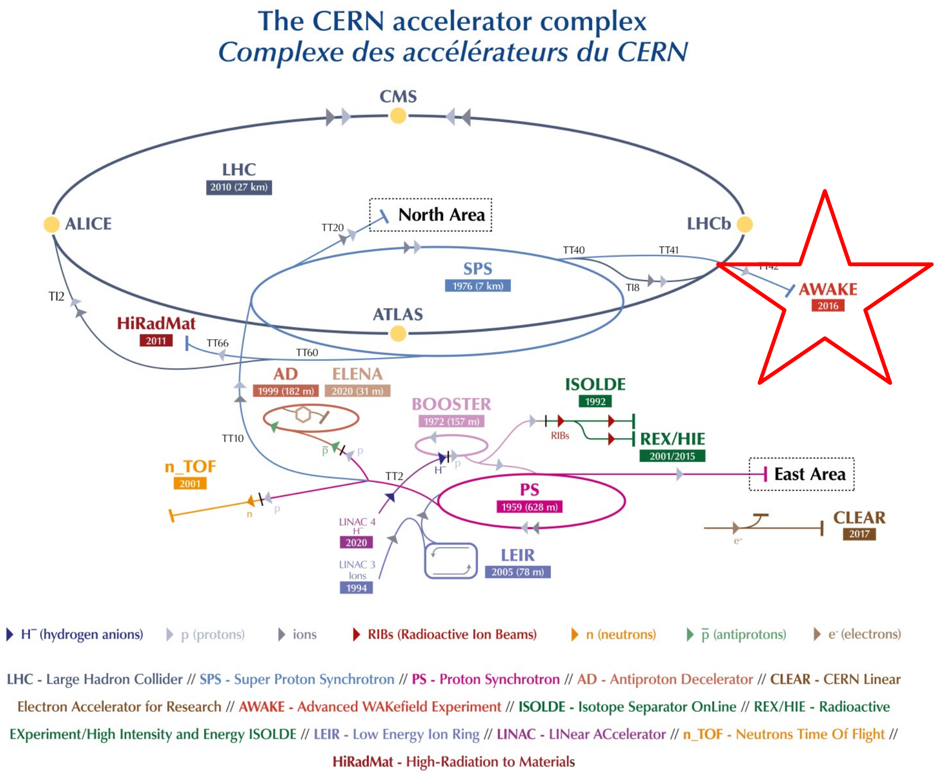


Image: AWAKE experimental setup
© M. Brice, CERN

Proton drive bunch

● Energy gain of witness bunch ≤ energy loss of drive bunch

● p^+ bunch → higher energies than laser pulses or e^- bunches:

SPS p^+ bunch (used in AWAKE) → ~19 kJ

SLAC e^- bunch → ~91 J

1 PW, 100 fs laser pulse → < 100 J

● p^+ bunch → drive wakefields over long distance → no need for staging

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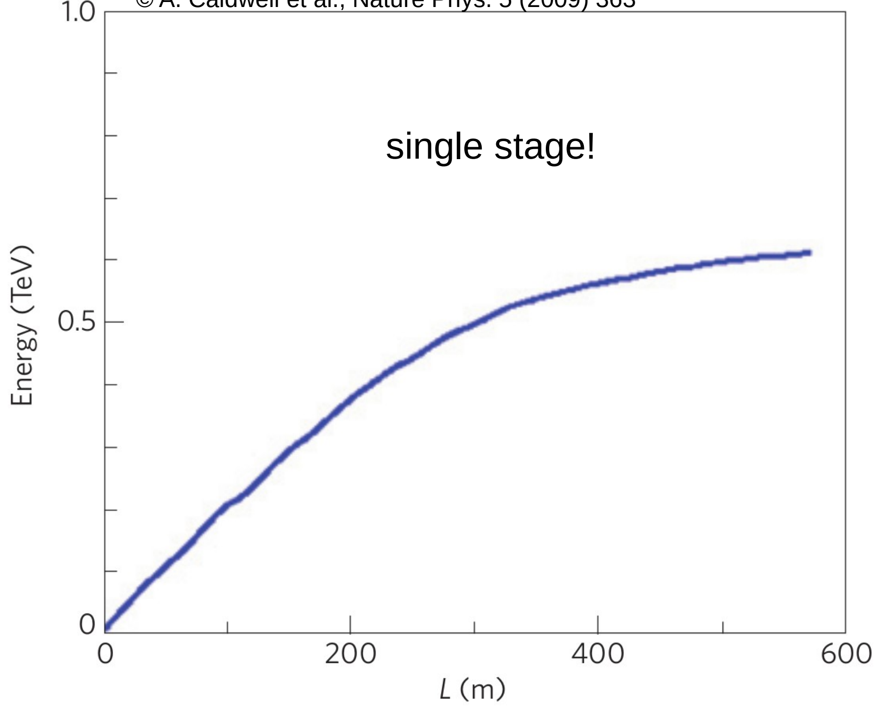
Figure: E_p = 1 TeV, E_e = 0.62 TeV after 450 m of acceleration.



Proton drive bunch

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- p^+ bunch → drive wakefields over long distance → no need for staging
- Theory: resonantly drive high-amplitude wakefields → bunch length $\sigma_z \sim \lambda_{pe}$; SPS p^+ bunch: $\sigma_z \sim 12$ cm $\gg \lambda_{pe}$
- Long p^+ bunch in plasma → self-modulation instability (SMI) → train of micro-bunches

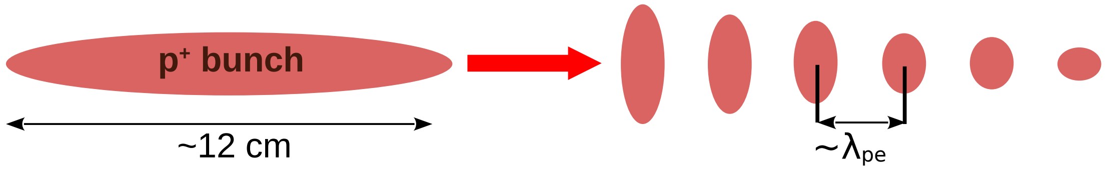
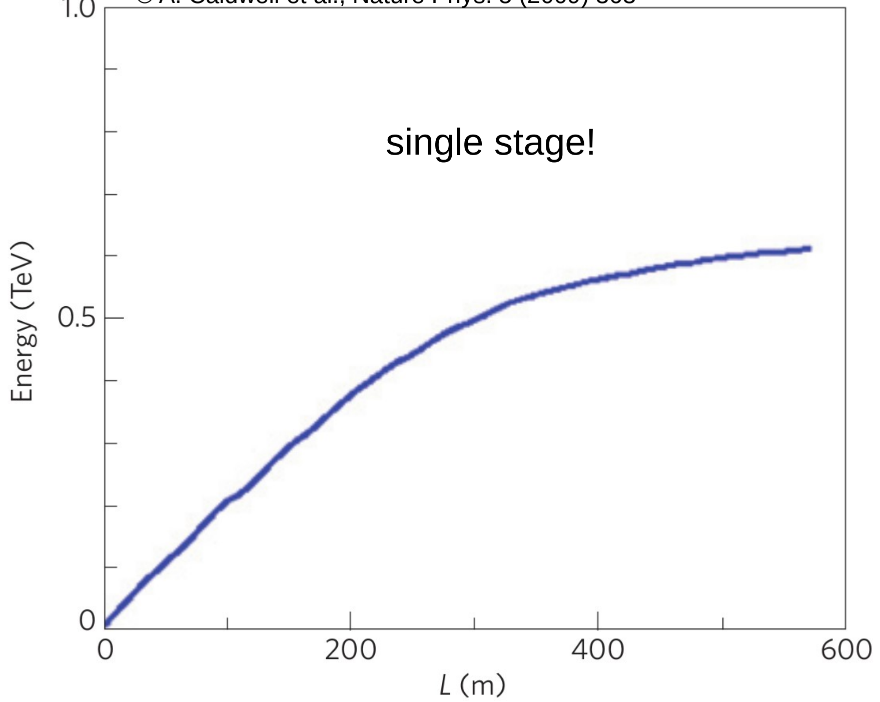
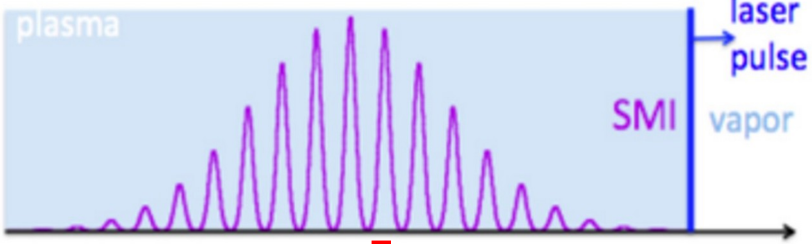


Figure: E_p = 1 TeV, E_e = 0.62 TeV after 450 m of acceleration.
© A. Caldwell et al., Nature Phys. 5 (2009) 363

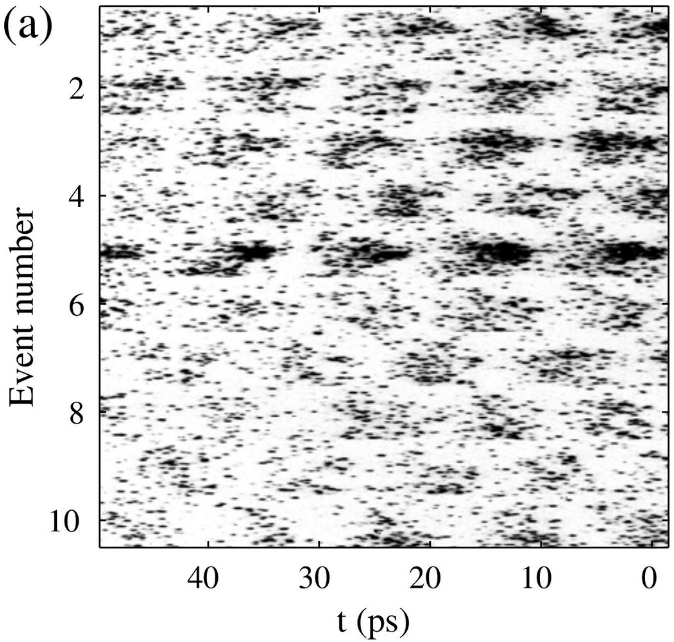


Self-modulation: instability → seeded

No seeding



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



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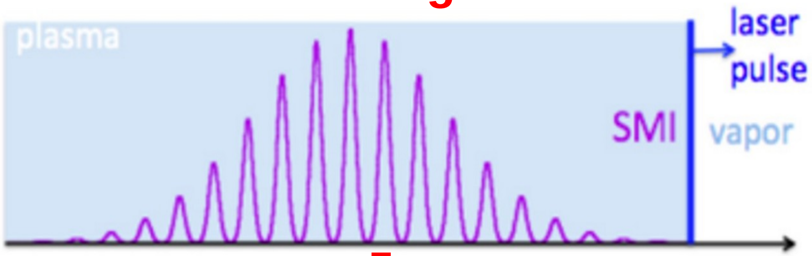
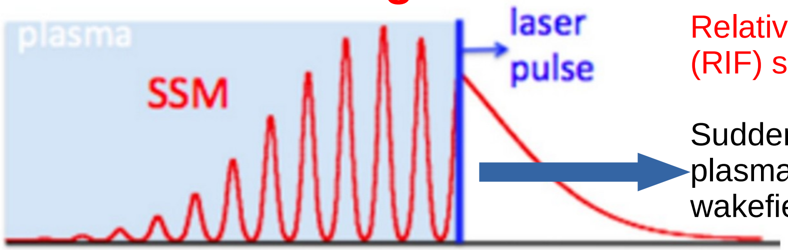


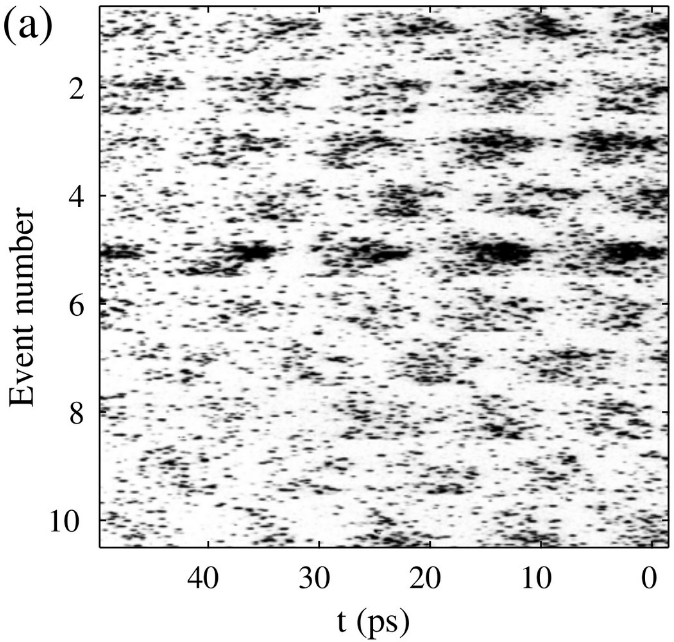
Seeding

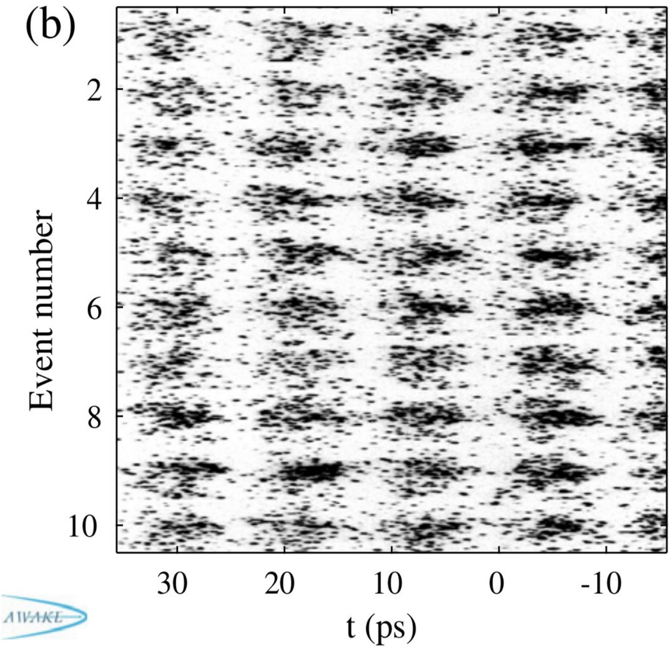


Relativistic ionization front (RIF) seeding

Sudden onset of beam-plasma interaction → seed wakefield

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



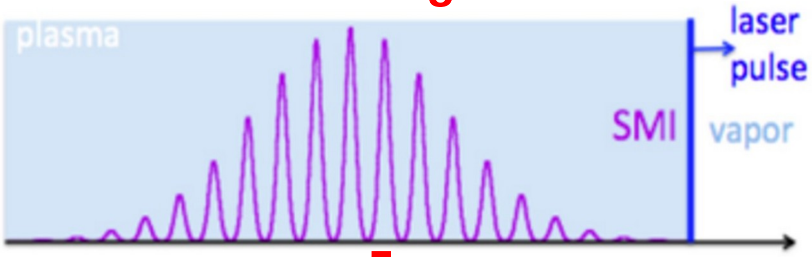


Reproducible outcome!

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

Self-modulation: instability → seeded

No seeding



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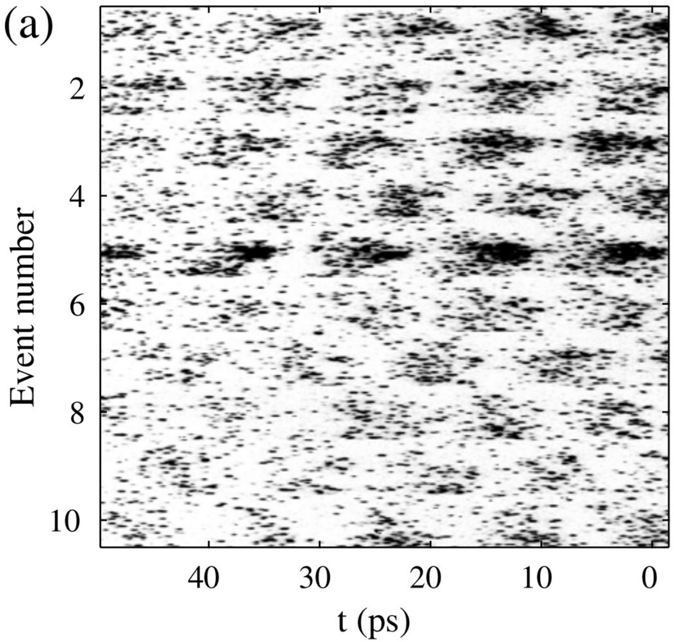
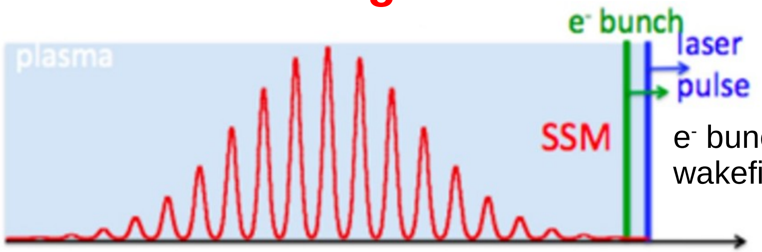


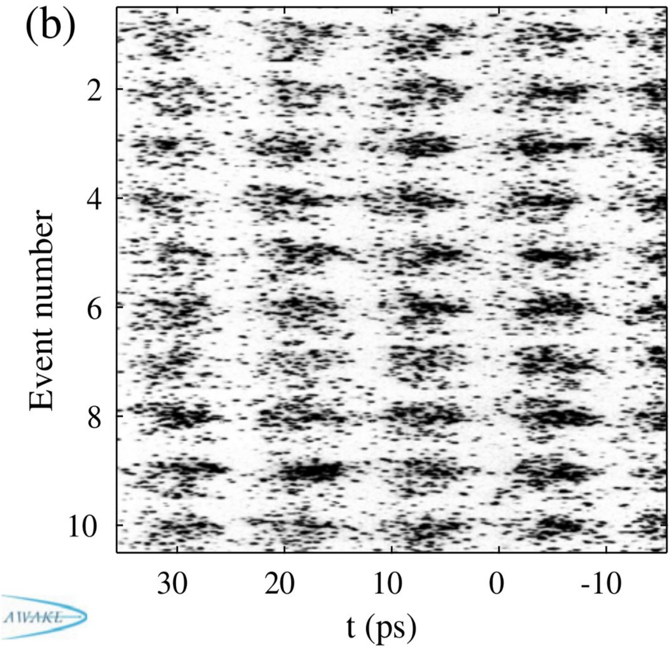
Seeding



e$^-$ bunch seeding

e$^-$ bunch drives seed wakefields

L. Verra et al., accepted for publication to Phys. Rev. Lett. (2022)



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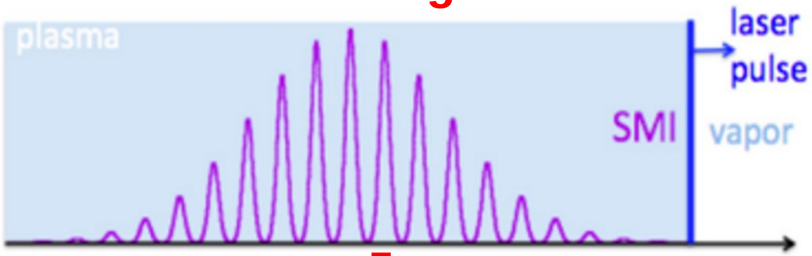
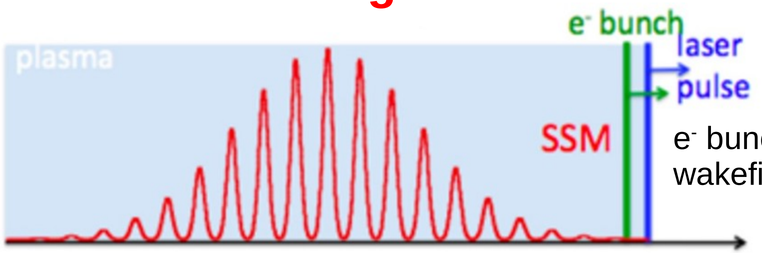


Seeding



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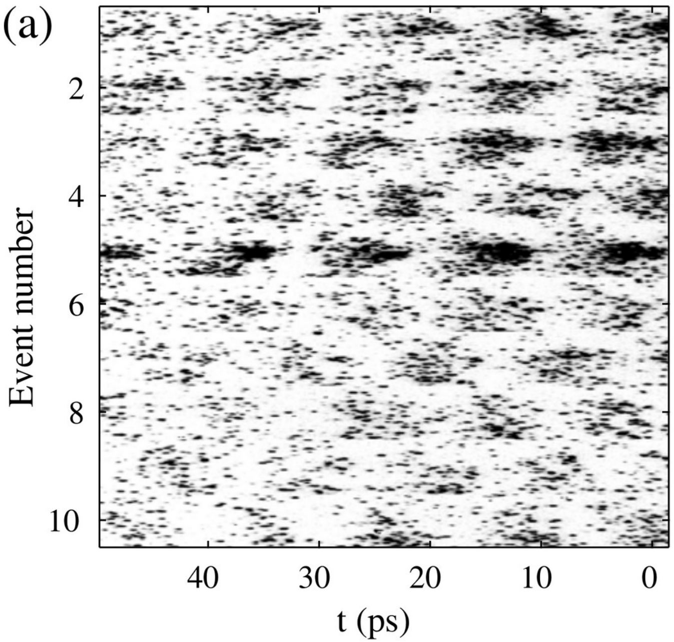
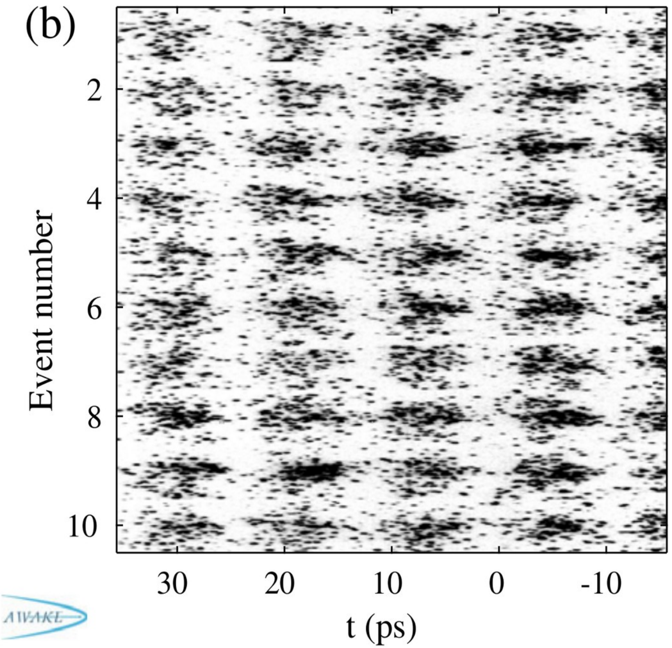
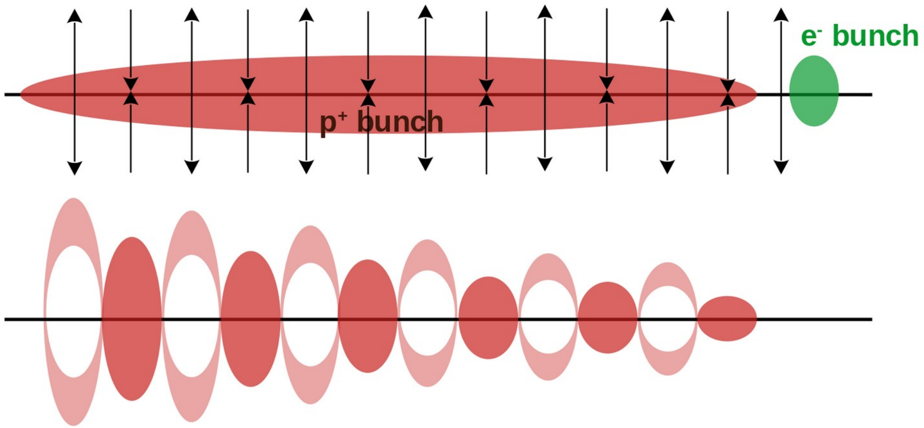




Reproducible outcome!

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

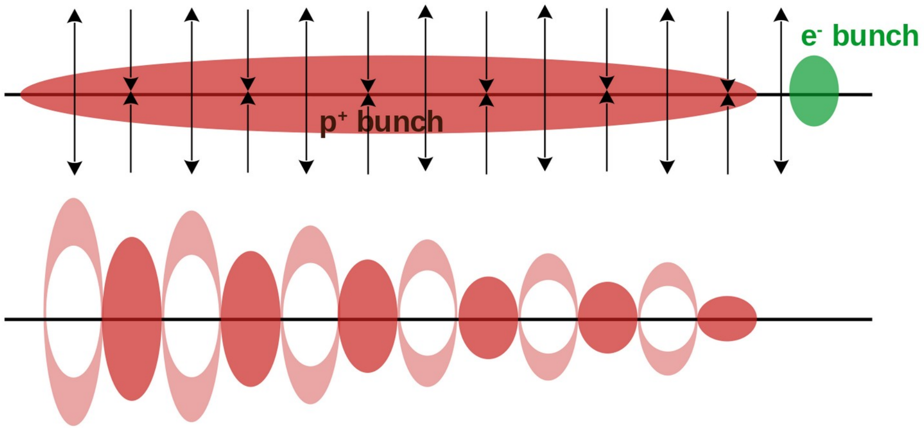
eSSM vs eSSM+Hosing



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

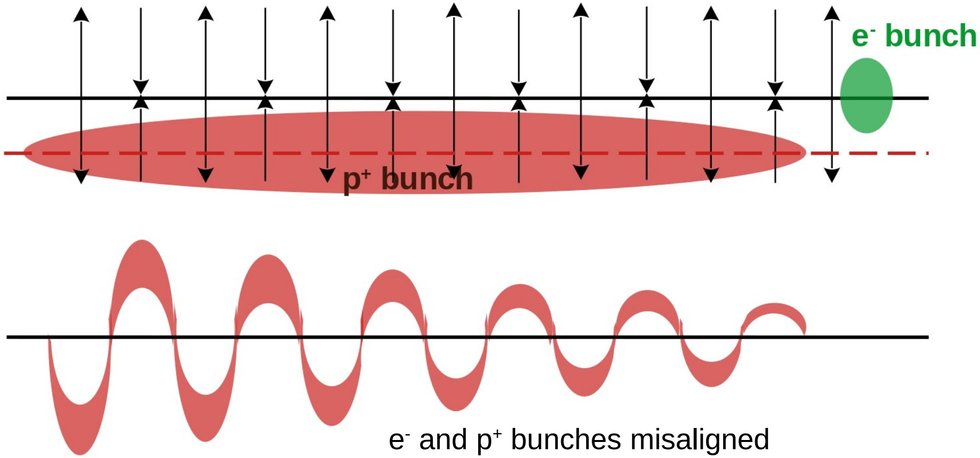
eSSM

eSSM vs eSSM+Hosing



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

eSSM



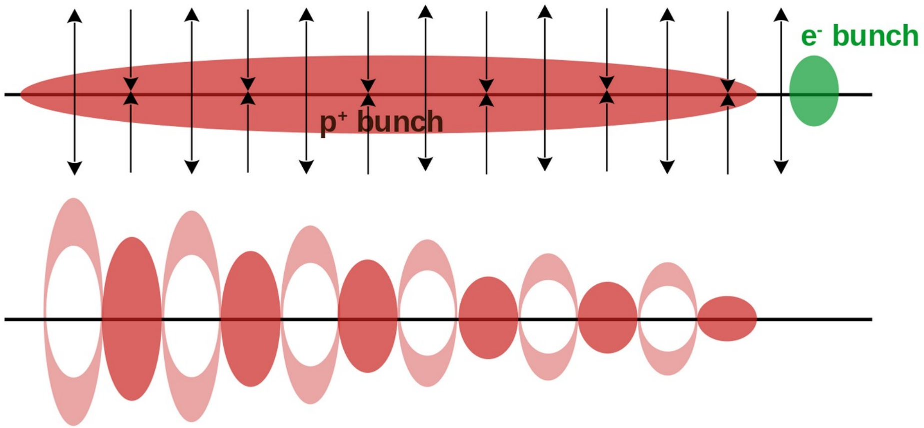
e$^-$ and p$^+$ bunches misaligned
force on p$^+$ bunch centroid ≠ 0 → hosing
force on p$^+$ bunch slice → focusing/defocusing

Hosing + eSSM

↓ one plane

↓ plane ⊥ hosing

eSSM vs eSSM+Hosing



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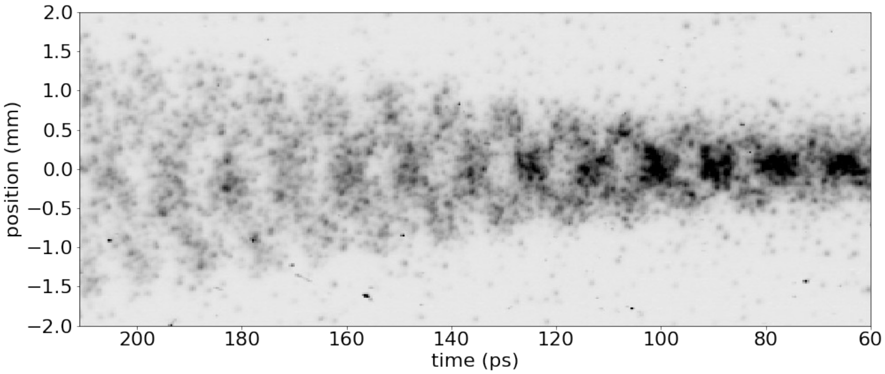
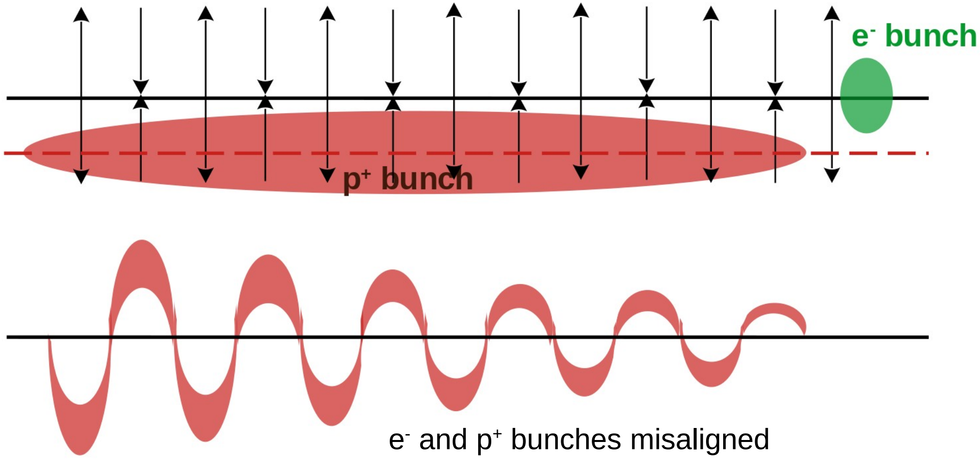
eSSM





e^- and p^+ bunches misaligned
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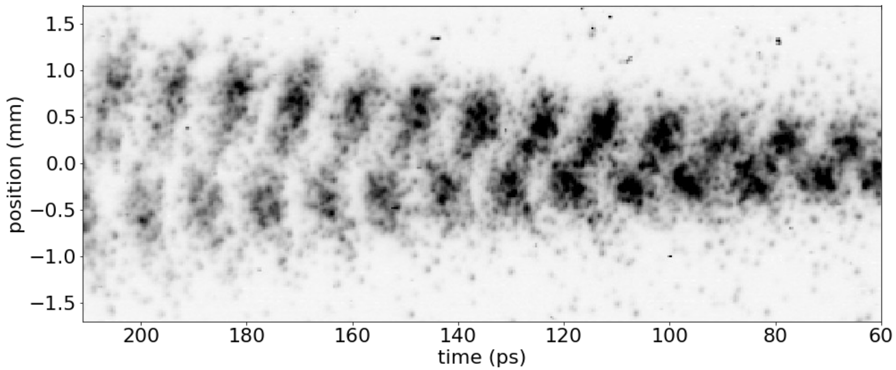
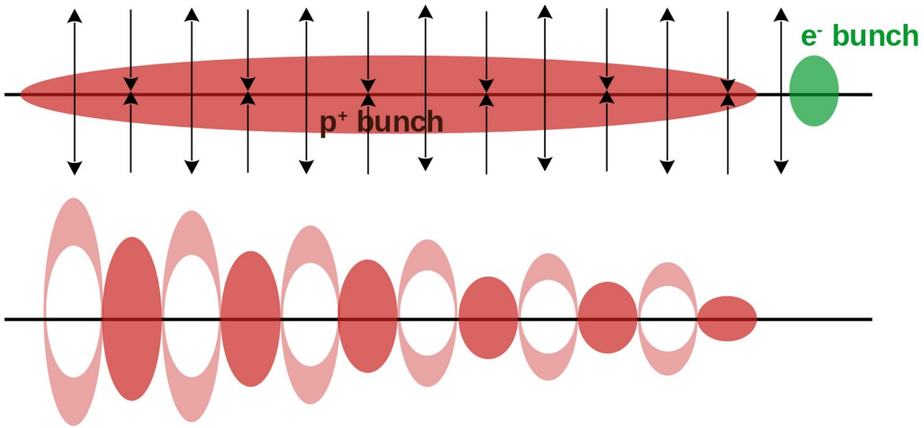
Hosing + eSSM
↓ ↓
one plane plane ⊥ hosing



eSSM vs eSSM+Hosing



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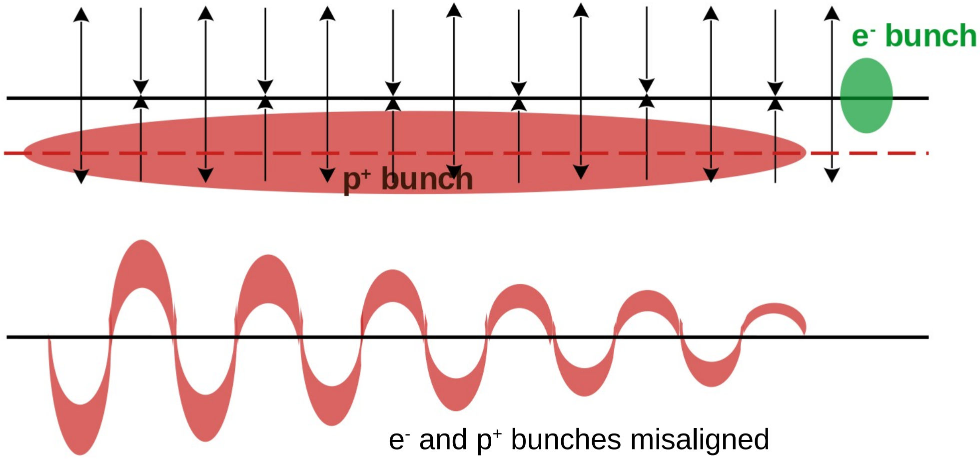
eSSM



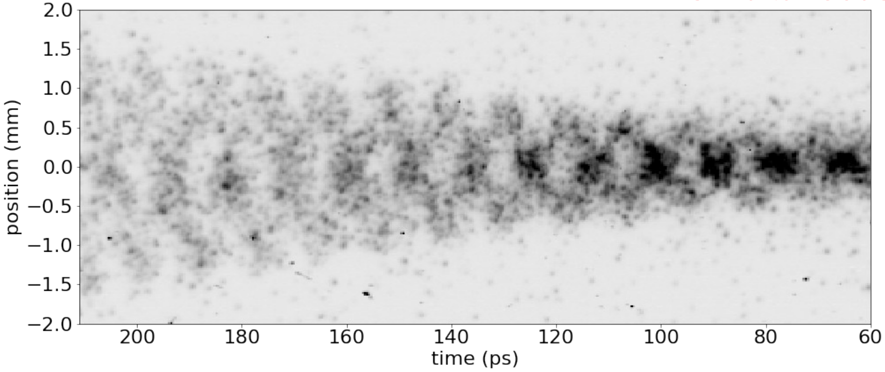
e^- and p^+ bunches misaligned
force on p^+ bunch centroid ≠ 0 → hosing
force on p^+ bunch slice → focusing/defocusing

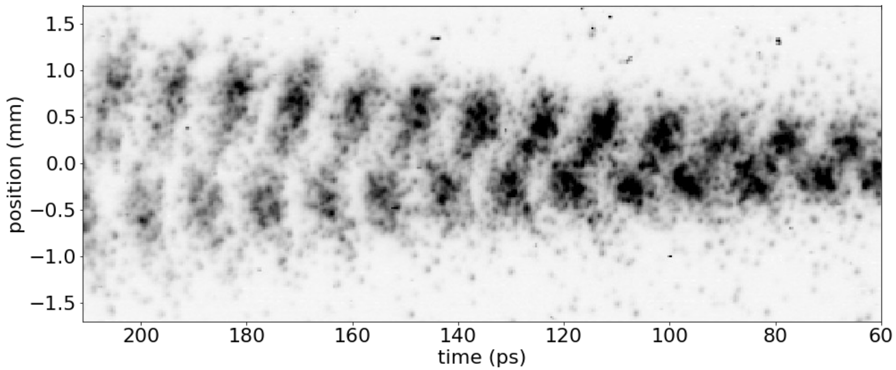
Hosing + eSSM
↓ one plane
↓ plane ⊥ hosing

- Hosing occurs in the plane of misalignment
- Plane of misalignment ≠ main plane of observation?

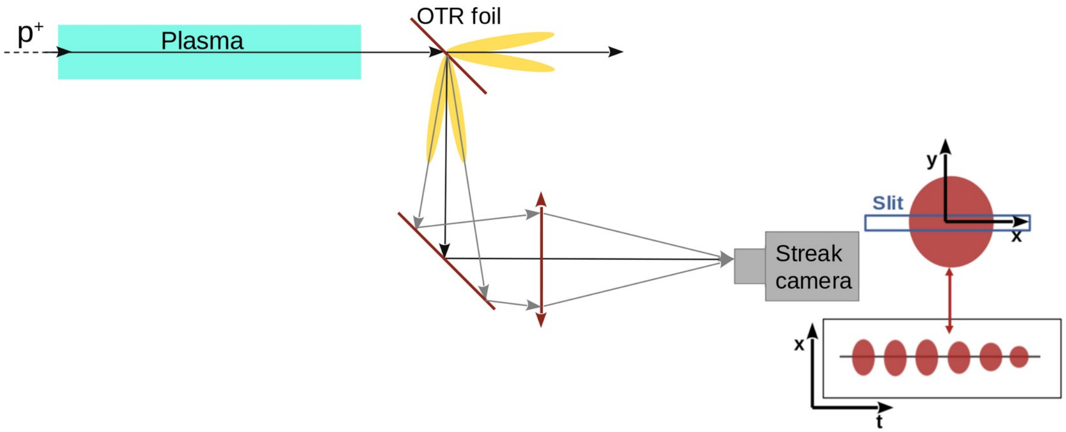
⇓

- Need a method to look at two (or more) planes simultaneously



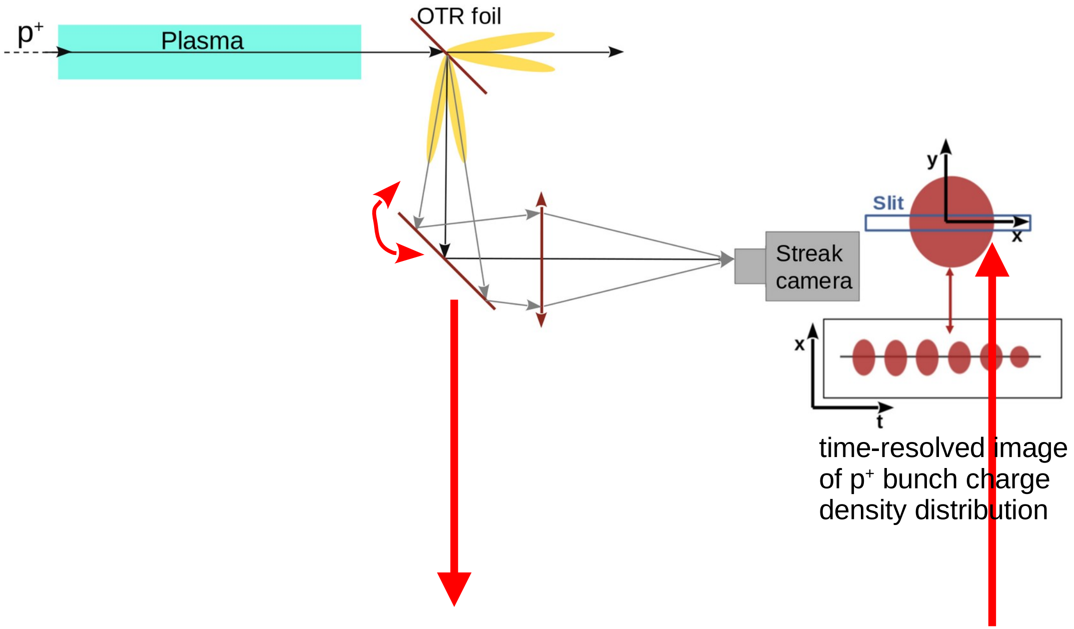


Method



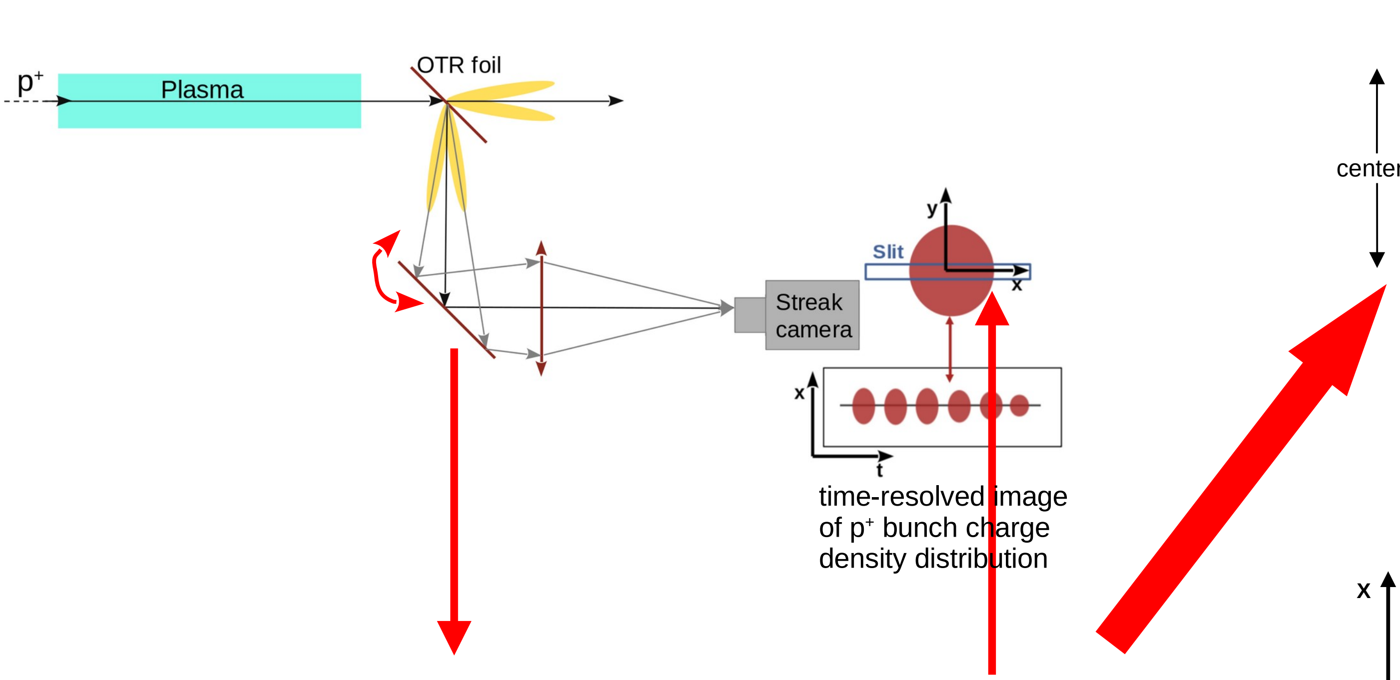
time-resolved image
of p+ bunch charge
density distribution

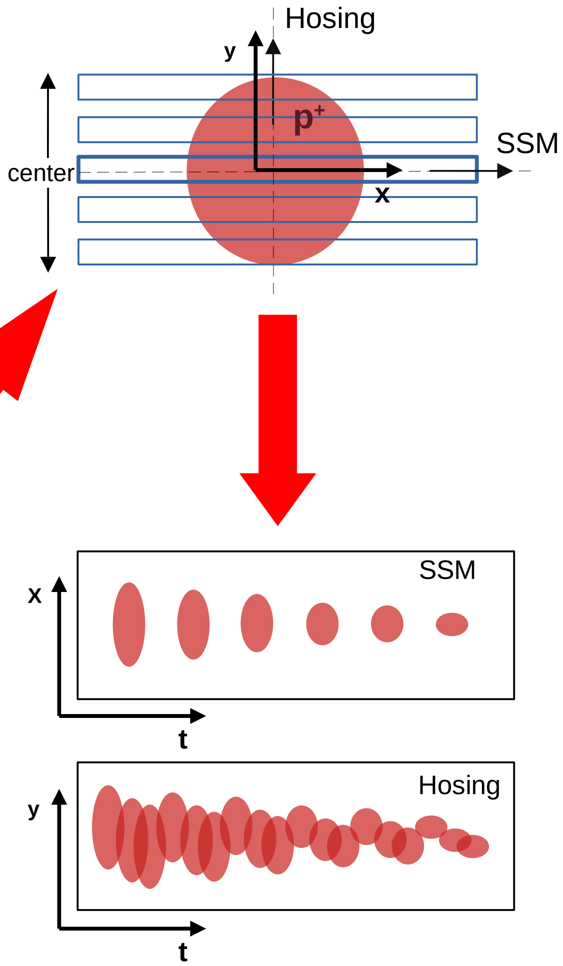
Method



Vary the mirror angle ↔ vary streak camera slit position across p+ bunch transverse distribution

Method





Vary the mirror angle ↔ vary streak camera slit position across p^+ bunch transverse distribution

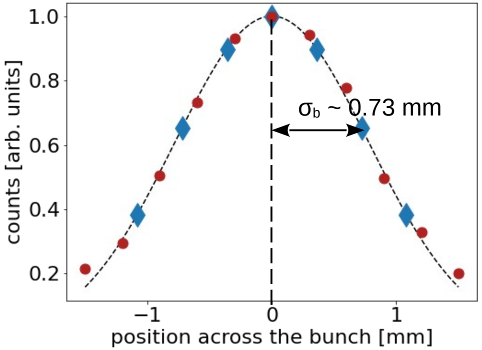
Results

1. ● Vary mirror angle →

● Time-integrated p^+ bunch charge density distribution as a function of position across the bunch →

● Find central point

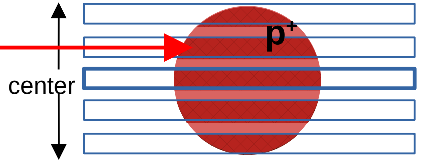
● Determine positions where to take data



● – summed charge density

♦ – positions where slices of

p^+ bunch charge density distribution are recorded



Step size – $0.5\sigma_b$

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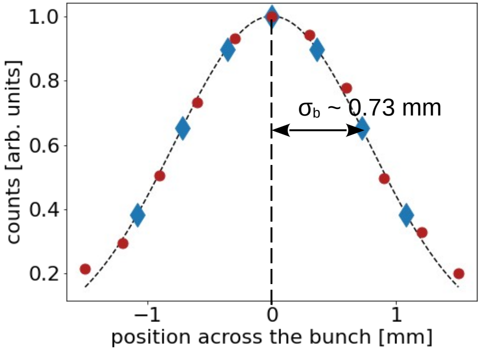
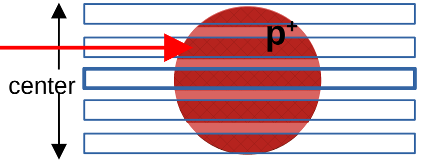




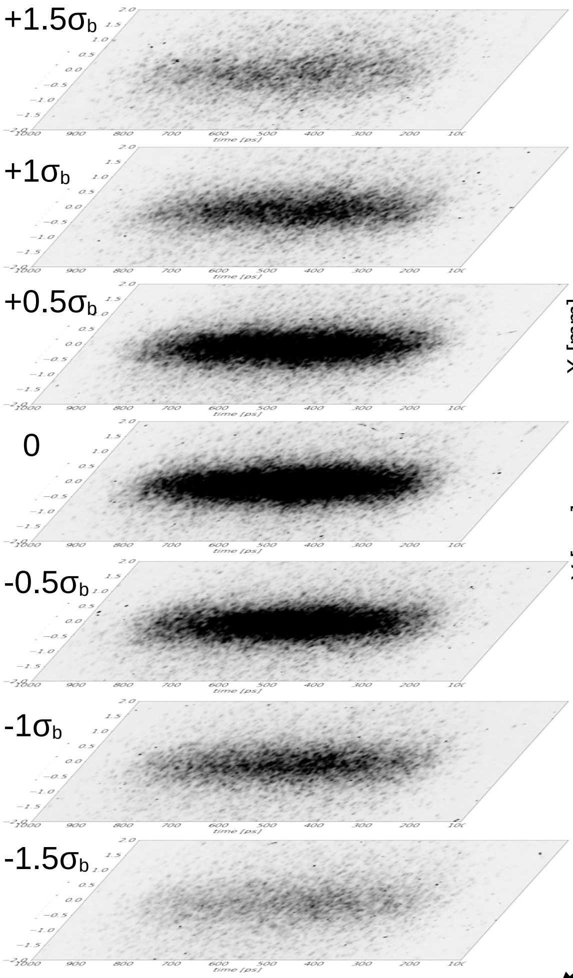
● – summed charge density

♦ – positions where slices of p^+ bunch charge density distribution are recorded

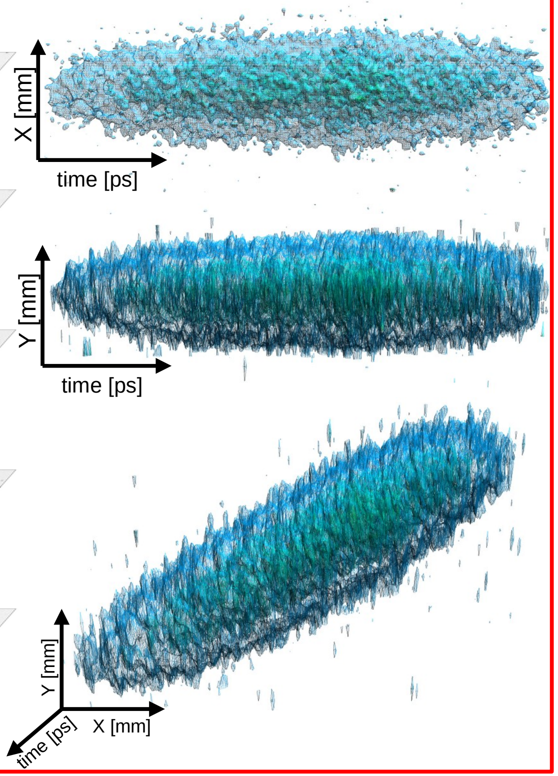
Step size – $0.5\sigma_b$

2. • Do a test →

• Incoming p^+ bunch (propagating as if in vacuum)



• Slices placed in linear rectangular grid → 3D distribution



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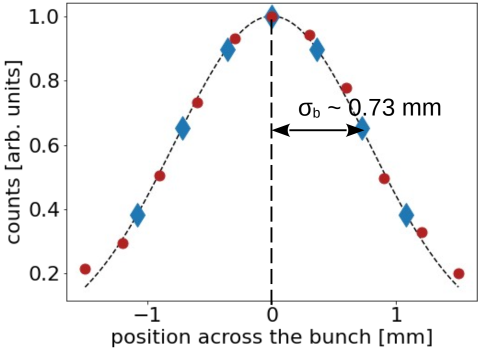
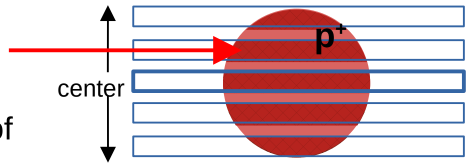




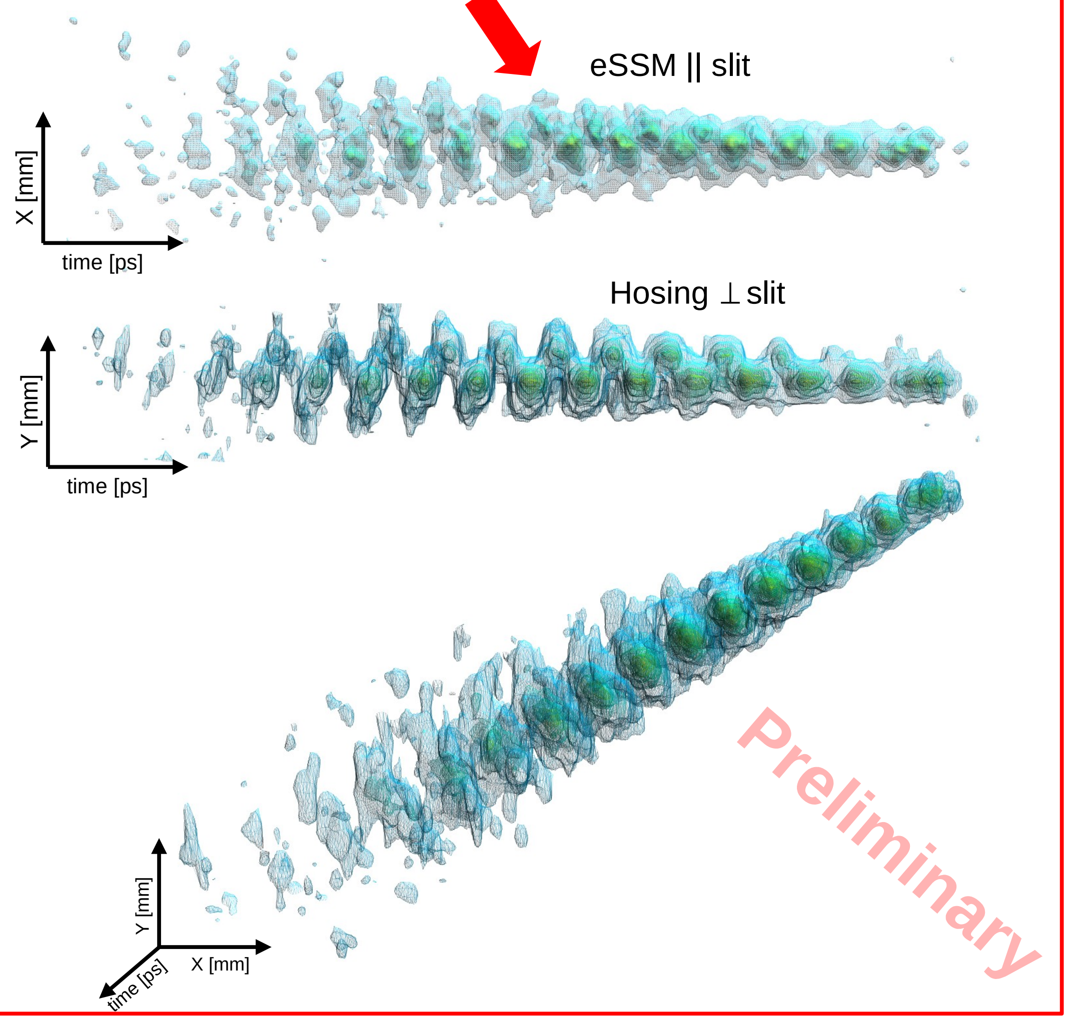
● – summed charge density

♦ – positions where slices of p^+ bunch charge density distribution are recorded

Step size – $0.5\sigma_b$

3. ● p^+ bunch in plasma →

● Misalign e^- bunch ⊥ slit



Conclusion

- AWAKE: seeding of self-modulation with e^- bunch → alignment-sensitive

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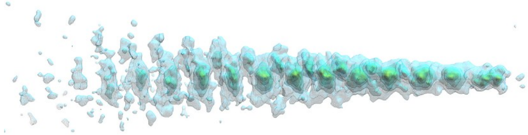
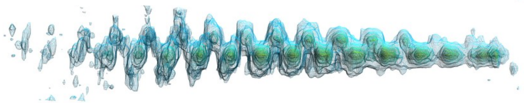
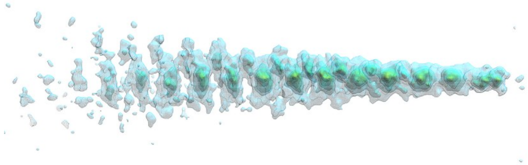
- e^--p^+ aligned → eSSM  → in all planes

- e^--p^+ misaligned → Hosing + eSSM  + 

- Hosing occurs in the plane of misalignment → if not main plane of observation → can be unnoticed

⇓

Conclusion

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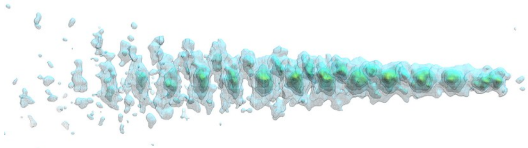
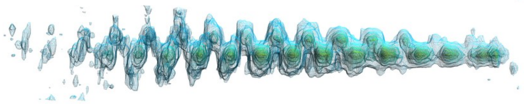
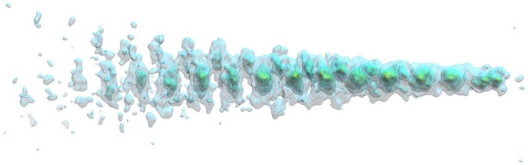
- e^--p^+ aligned → eSSM  → in all planes

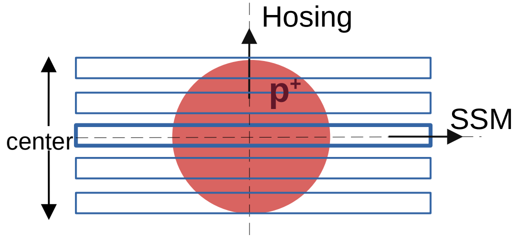
- e^--p^+ misaligned → Hosing + eSSM  + 

- Hosing occurs in the plane of misalignment → if not main plane of observation → can be unnoticed

⇓

- Develop a method for simultaneous observation of two (or more) planes

- Do a “streak camera slit scan” across the transverse p^+ bunch charge density distribution



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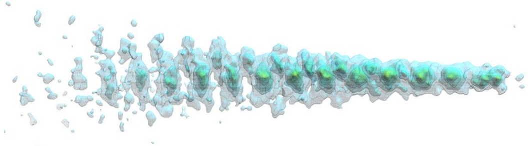
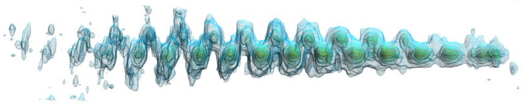
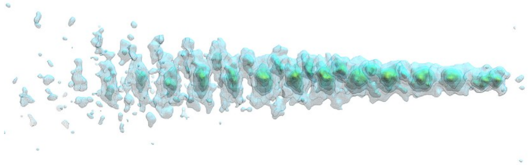


→ in all planes

- e^--p^+ misaligned → Hosing + eSSM



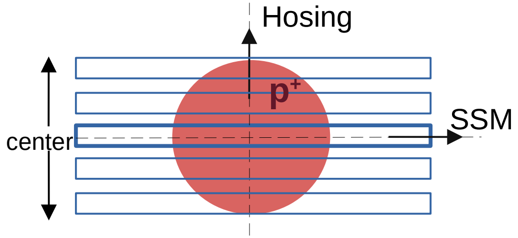
+



- Hosing occurs in the plane of misalignment → if not main plane of observation → can be unnoticed

⇓

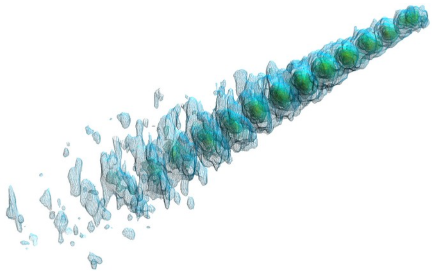
- Develop a method for simultaneous observation of two (or more) planes



- Do a “streak camera slit scan” across the transverse p^+ bunch charge density distribution

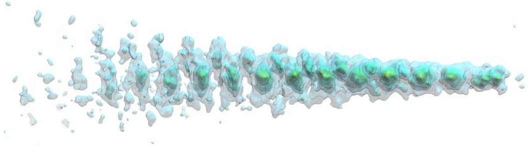
- Test with the incoming p^+ bunch (no plasma)

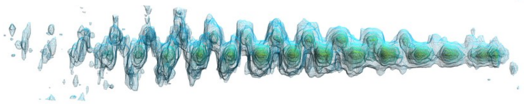
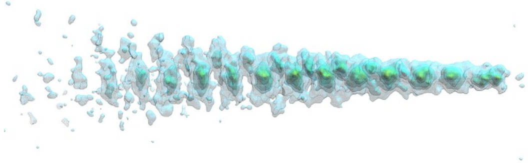
- Test with the p^+ bunch in plasma: Hosing ⊥ slit and eSSM || slit



Conclusion

- AWAKE: seeding of self-modulation with e^- bunch → alignment-sensitive

- e^--p^+ aligned → eSSM  → in all planes

- e^--p^+ misaligned → Hosing + eSSM  + 

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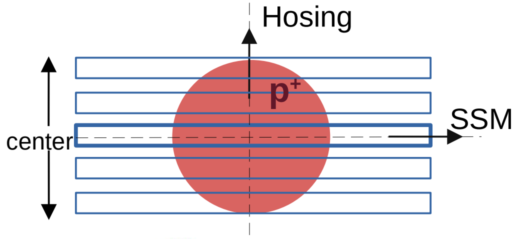

- Do a “streak camera slit scan” across the transverse p^+ bunch charge density distribution

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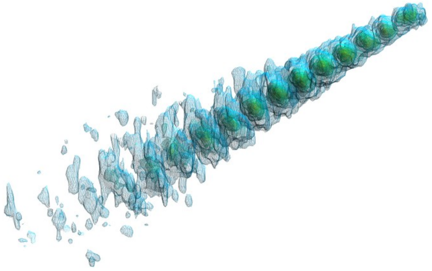

- Test with the p^+ bunch in plasma: Hosing ⊥ slit and eSSM || slit

- Apply to future studies of simultaneous occurrence of hosing and eSSM

- Is eSSM-only possible?

Conclusion

- AWAKE: seeding of self-modulation with e^- bunch → alignment-sensitive

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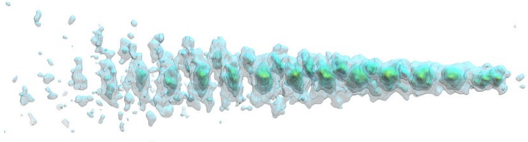
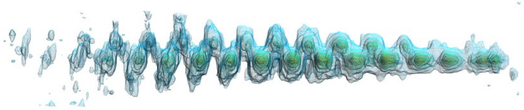
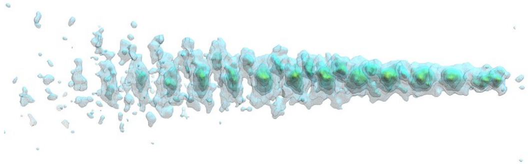


→ in all planes

- e^--p^+ misaligned → Hosing + eSSM



\+



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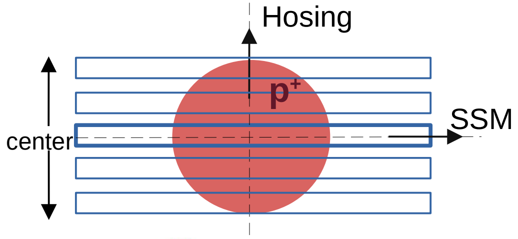

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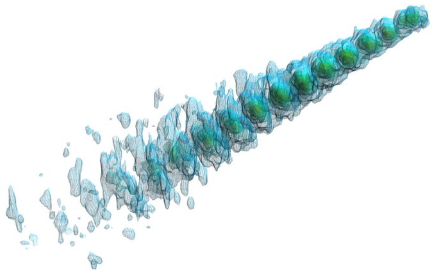

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- Is eSSM-only possible?

Thank you for your attention!