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

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Conventional accelerators

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

- Modern RF cavities: limit on accelerating gradient $\sim 100$ MeV/m (electric breakdown)

  $\Downarrow$

- Increase acceleration length to increase particle energy

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

Image: CLIC – possible future linear collider at CERN. © CERN
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 $\omega_{pe}$

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

$\downarrow$

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

when $n_{pe} = 10^{18}$ cm$^{-3}$ ⇒ gradient $\sim 100$ 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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- Theory: resonantly drive high-amplitude wakefields $\rightarrow$ bunch length $\sigma_z \sim \lambda_{pe}$; SPS $p^+$ bunch: $\sigma_z \sim 12$ cm $\gg \lambda_{pe}$

- Long $p^+$ bunch in plasma $\rightarrow$ self-modulation instability (SMI) $\rightarrow$ 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

$p^+$ bunch $\sim 12$ cm
Self-modulation: instability → seeded

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No seeding

Seeding

Relativistic ionization front (RIF) seeding

Sudden onset of beam-plasma interaction → seed wakefield

Reproducible outcome!

Δt/τ_{pe} ~ 6 %,
τ_{pe} = 2π/ω_{pe}
Self-modulation: instability → seeded

No seeding

Seeding

\[ \Delta t / \tau_{pe} \sim 6 \% \]
\[ \tau_{pe} = \frac{2\pi}{\omega_{pe}} \]

Reproducible outcome!


L. Verra et al., accepted for publication to Phys. Rev. Lett. (2022)
Self-modulation: instability $\rightarrow$ seeded

No seeding

Seeding

- $e^-$ bunch seeding
- $e^-$ bunch drives seed wakefields

Reproducible outcome!

$\Delta t/\tau_{pe} \sim 6\%,$

$\tau_{pe} = 2\pi/\omega_{pe}$
e\textsuperscript{−} and p\textsuperscript{+} bunches aligned
force on p\textsuperscript{+} bunch centroid = 0
force on p\textsuperscript{+} bunch slice → focusing/defocusing

eSSM vs eSSM+Hosing
eSSM vs eSSM+Hosing

**e and p bunches aligned**

- Force on p bunch centroid = 0
- Force on p bunch slice → focusing/defocusing

**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

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
↓
hosing

position (mm)

-2.0  -1.5  -1.0  -0.5  0.0  0.5  1.0  1.5  2.0

-200  180  160  140  120  100  80  60
time (ps)

position (mm)

-2.0  -1.5  -1.0  -0.5  0.0  0.5  1.0  1.5

-200  180  160  140  120  100  80  60
time (ps)
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.

-eSSM

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

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force on p⁺ bunch centroid ≠ 0 → hosing
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Hosing + eSSM
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one plane
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Method

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

$\sigma_b \sim 0.73$ mm

- summed charge density
- positions where slices of $p^+$ bunch charge density distribution are recorded

Step size – $0.5\sigma_b$
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

   \[ \sigma_b \approx 0.73 \text{ mm} \]

2. ● Do a test →
   ● Incoming $p^+$ bunch (propagating as if in vacuum)
   ● Slices placed in linear rectangular grid → 3D distribution

   \[ +1.5\sigma_b \]
   \[ +1\sigma_b \]
   \[ +0.5\sigma_b \]
   \[ 0 \]
   \[ -0.5\sigma_b \]
   \[ -1\sigma_b \]
   \[ -1.5\sigma_b \]

   ● – summed charge density
   ✷ – positions where slices of $p^+$ bunch charge density distribution are recorded

Step size \( \approx 0.5\sigma_b \)
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

   ![Graph showing summed charge density and central point](image)

   ● 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 $\perp$ slit

   ![Diagram showing eSSM $\parallel$ slit and Hosing $\perp$ slit](image)
Conclusion

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

- $e^-$-$p^+$ 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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- $e^-p^+ \text{ aligned} \rightarrow e\text{SSM}$ → in all planes

- $e^-p^+ \text{ misaligned} \rightarrow \text{Hosing} + e\text{SSM}$

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

- Test with the $p^+$ bunch in plasma: Hosing $\perp$ slit and eSSM $\parallel$ slit
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- Apply to future studies of simultaneous occurrence of hosing and eSSM

- Is eSSM-only possible?
Conclusion

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Thank you for your attention!