Seeding of the SMI with an electron bunch

A possible seeding concept for AWAKE Run 2?

Mathias Hüther

Max-Planck-Institute for Physics, Munich

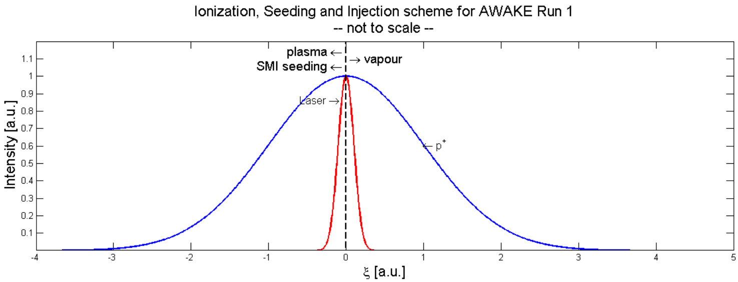
huether@mpp.mpg.de

May 5, 2017

2nd MPP-Wigner AWAKE Workshop
at Wigner Research Center for Physics, Budapest, Hungary

Outline

SMI Seeding Concept for Run 1



- 100 fs - laser beam is co-propagating in the centre of the proton bunch and causes an ionization front in the Rb vapour
- only proton beam behind the ionization front propagates through plasma
- sharp edge in the resulting proton distribution Q_{res} drives large wakefields
- external injection of electrons $\sim \frac{\lambda_{pe}}{2}$ behind the laser pulse

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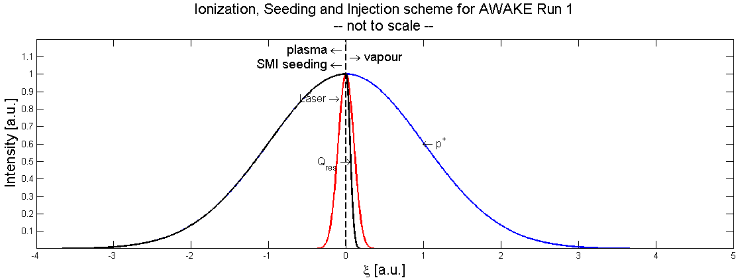

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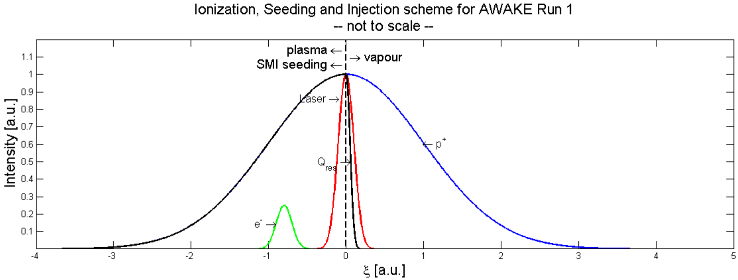

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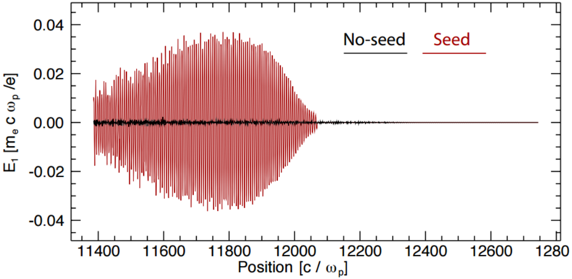
Why is a seeding of the SMI necessary?

- Simulation of Self-Modulation of a 12 cm long SPS proton beam:



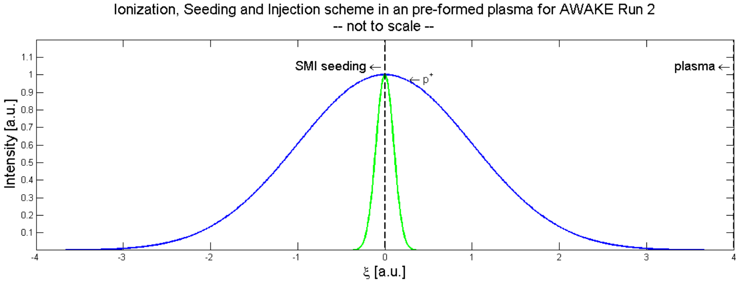
Comparison between unseeded and seeded SMI growth of a proton beam after beam propagation of $\sim 6.5\,\text{m}$ in a plasma with $N_b = 11.5 \cdot 10^{10}$. OSIRIS-Simulation, see *IPAC Proceedings 2013, Physics of the AWAKE Project*

- no significant growth of SMI due to noise over the length of the plasma cell

$\rightarrow$ external seeding necessary

- perturbation of the ionization front seeds the SMI
- seeding concept could in general also be used for AWAKE Run 2

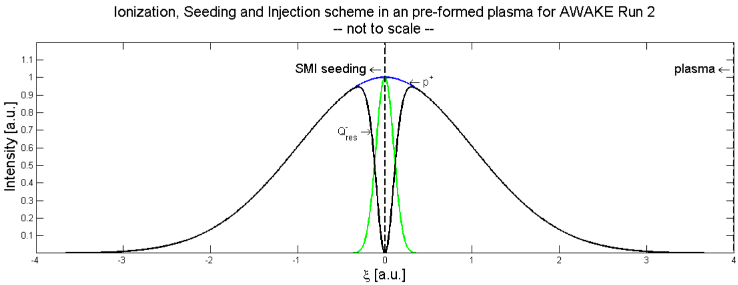
Idea of an alternative seeding concept for Run 2



Alternative Seeding Concept for AWAKE Run 2

- send proton bunch through a pre-formed plasma
- injection of a short electron bunch at the maximum of the proton beam
- cancellation of charges, resulting in a sharp edge in the absolute density of positive charges Q_{res}

Idea of an alternative seeding concept for Run 2



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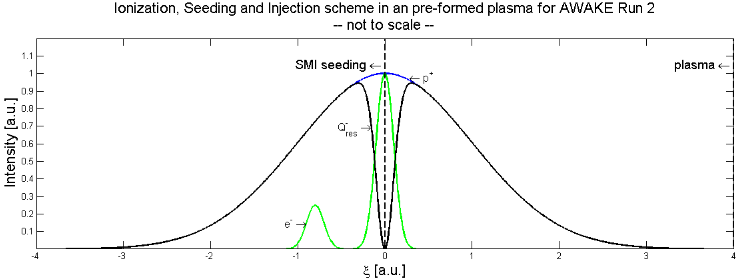

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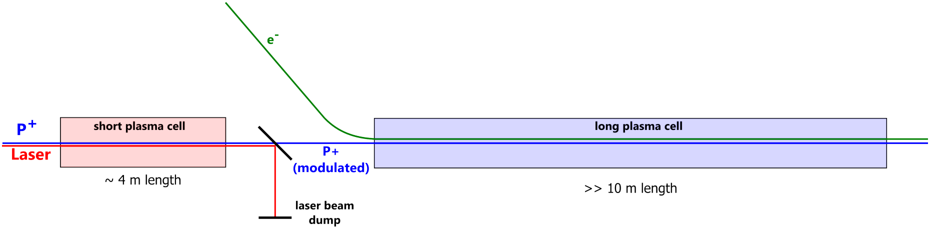
A seeding concept for Run 2 – A possible setup



Possible Setup for AWAKE Run 2, with a short and a long plasma cell. Short plasma cell filled with Rubidium vapour, ionization with high-power laser

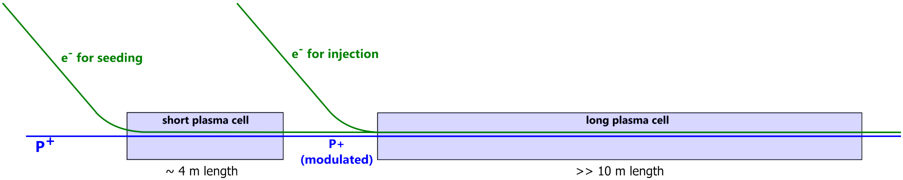
Short plasma cell:

- seeding the SMI
- modulation of the proton beam
- similar to AWAKE Run 1

Long plasma cell:

- acceleration of electrons
- pre-modulated proton bunch
- plasma could be created by a Discharge Ionisation or with a Helicon Source

An alternative seeding concept for Run 2 – Advantages



Possible Setup for AWAKE Run 2, with a short and a long plasma cell without need of a laser or Rubidium vapour

- → no need of a high-power laser beam for ionsization and SMI seeding any more
- → Rb vapour plasma cell could be completely replaced by Discharge or Helicon Plasma sources (Ar plasma)
- → no need of complicated Rb handling any more

Idea of a seeding concept for Run 2 – Upcoming Questions

- Can the SMI also be seeded by an electron bunch?
- What would be the optimal shape of this electron bunch for an effective seeding of the SMI?
- Which charge density would be needed?
- Are the wakefields driven by the front part of the proton beam negligible compared to the trailing part with the sharp edge
- Is there a significant effect of direct electron-proton interactions?
- Could this scheme be an alternative concept for AWAKE Run 2?

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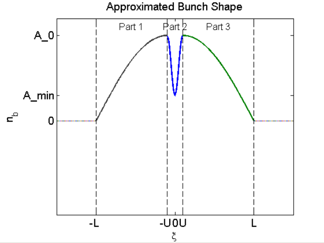
- Can we test this concept already with our AWAKE setup from Run 1?

Analytic Calculations in Linear Theory

Ansatz: cos-approximation of bunch shape



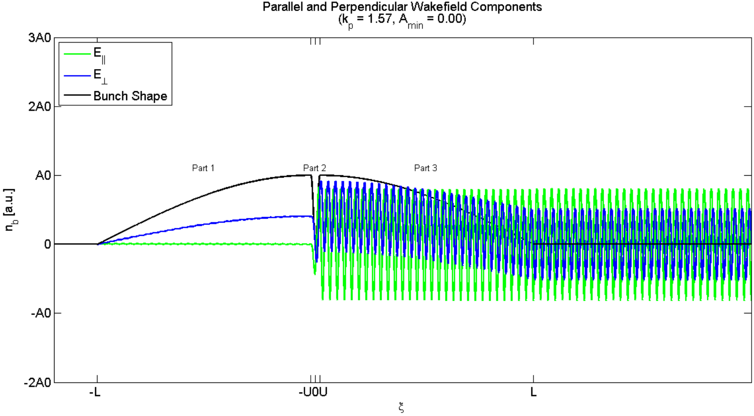
cos-approximation of $n_{b||}$

$$n_{b||}(\xi') = \begin{cases} A_0 \cdot \sin\left(\frac{\pi\cdot(\xi'+L)}{2(L-U)}\right) & \xi \in [-L, -U] \\ \frac{A_{min}-A_0}{2} \cdot \cos\left(\frac{\pi\xi'}{U}\right) + \frac{A_{min}+A_0}{2} & \xi \in [-U, U] \\ A_0 \cdot \cos\left(\frac{\pi\cdot(\xi'-U)}{2(L-U)}\right) & \xi \in [U, L] \\ 0 & \text{else} \end{cases}$$

- different parts can just be added due to the superposition principle!

Example for an AWAKE-like case

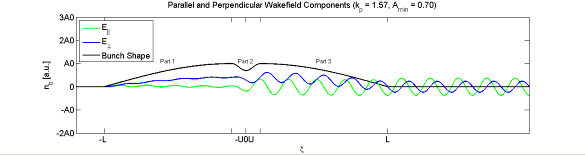
$\sigma_{z,p^+} = 12\,\text{cm},\ \sigma_{z,e^-} = 0.25\,\text{cm},\ |Q_{p^+}| = |Q_{e^-}|$ for $[-U, U]$, $k_p = \frac{\pi}{2}$



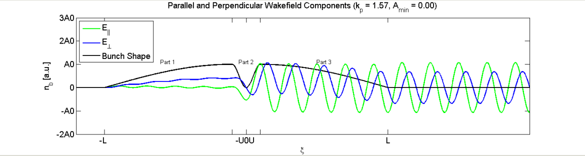
AWAKE-like case: Long proton bunch and short electron bunch. The resulting "gap" in the positive charge, drives large parallel and longitudinal wakefields

Electron Density A_{min}

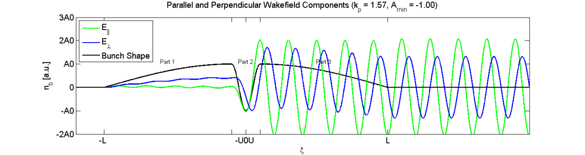
3 different cases ($k_p = \frac{\pi}{2},\ \frac{U}{L} = \frac{1}{10}$):



$$|Q_{p^+}| > |Q_{e^-}|$$
$$A_{min} > 0$$



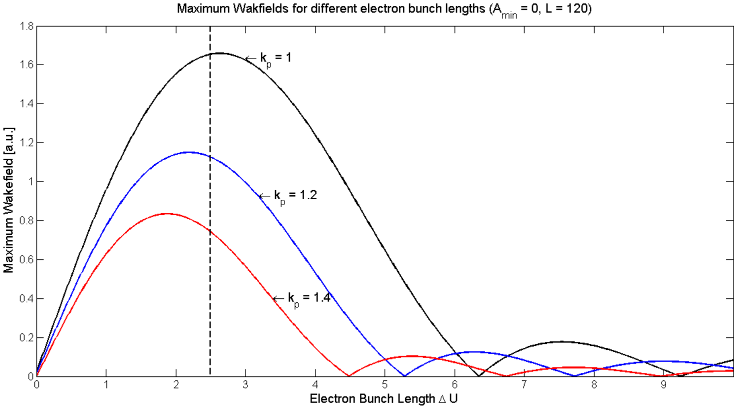
$$|Q_{p^+}| = |Q_{e^-}|$$
$$A_{min} = 0$$



$$|Q_{p^+}| < |Q_{e^-}|$$
$$A_{min} < 0$$

→ Wakefields scale linearly with A_{min}, the higher the electron density the larger the wakefields

Electron Bunch Length ΔU



→ for a given configuration of A_{min}, L and k_p there exists an ideal electron bunch length which yields maximal parallel and perpendicular wakefields.

Optimal Bunch Shape

- for the experiment the electron bunch should be considered as Gaussian shaped, as it is produced by an Gaussian laser beam on the photo-cathode, whereas the longitudinal SPS proton bunch profile is following a $\left[1-4\left(\frac{\tau}{\tau_L}\right)^2\right]^q$ distribution (with $q \approx 1-2$)
- this limits the possibilities of shaping the electron bunch, as electron density and the slope of its gradient are no longer independent
- still some degrees of freedom left as proton shape can also be controlled by varying the UV-beam to the photo-cathode

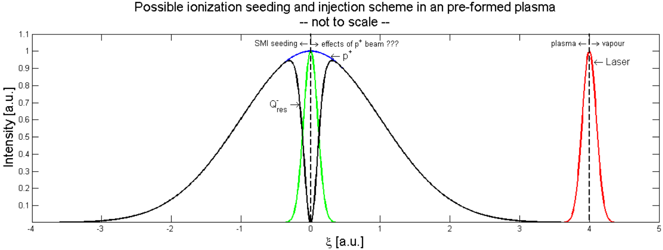
Questions to be solved by Simulations

To get a deeper understanding of the processes OSIRIS-simulations of the proton bunch are necessary:

- For a plasma cell $\gg 10$ m, the leading part of the proton bunch might eventually also allow the SMI to grow out of noise
  - the complete proton-bunch has to be simulated
  - the longer size of the plasma cell has to be taken into account
  - to avoid overwhelming large data, reduced parameters (like e.g. $\sigma_{z,p} = 1.2$ cm; $\sigma_{z,e} = 0.1$ cm; $N_{b,p} = 1 \cdot 10^{11}$ cm^{-3}) will be defined for OSIRIS-simulations
- Energy depletion of injected electrons
  - ~ 20 MeV electrons will loose energy inside the plasma much faster than the protons
  - this results in a back-drift of the electrons w.r.t. the center of the proton beam and eventually to a dephasing of the wakefields
- Defocusing of electrons in focusing fields for protons

Experimental Investigation with current AWAKE Setup

The setup of the AWAKE experiment which will be ready by the end of 2017 can be used in order to test the proposed seeding mechanism:



Experimental test of alternative seeding concept using the current AWAKE setup and the laser for ionization of the Rb plasma

1. the delay of the laser with respect to the proton beam has to be shifted in order to have the laser beam before the proton beam
2. the delay of the electron gun with respect to the proton beam has to be shifted to have the electron bunch at the same time as the peak of the proton beam
3. OTR and/or CTR measurement of the (modulated) proton beam

Summary & Conclusion

- We presented an idea for a different seeding concept for AWAKE Run 2 and its experimental test with the setup of AWAKE Run 1
- The SMI of the proton beam would be seeded by a step in the effective positive charge density caused by the external injection of an electron beam. This would no longer require a high-power laser nor a Rubidium plasma cell
- Analytic calculations in linear theory allow a first approximation of the required charge and shape of the electron bunch
- A more detailed investigation on the e^- bunch charge and shape as well as effects from merging an electron and a proton beam has to be subject of PIC simulations
- The concept can be experimentally tested with the setup of AWAKE Run 1 by only changing the delay of the laser beam and the electron gun

Thank you for your attention!

Backup Slides

Analytic Calculations in Linear Theory

Parallel Wakefields:

- Part 1: $$E_{1,\|}(\xi) = \begin{cases} 0 & \text{if } \xi < -L \\ \frac{A_0}{2k_p}\left[-(C_+ + C_-)\left[\cos\left(\frac{\pi(\xi+L)}{2(L-U)}\right) + \cos\big(k_p(\xi+L)\big)\right]\right] & \text{if } -L \le \xi \le -U \\ \frac{A_0}{2k_p}\left[-(C_+ - C_-)\sin\big(k_p(\xi+U)\big) + (C_+ + C_-)\cos\big(k_p(\xi+L)\big)\right] & \text{if } \xi > -U \end{cases}$$
- Part 2: $$E_{2,\|}(\xi) = \begin{cases} 0 & \text{if } \xi < -L \\ \frac{A_1}{2k_p}\left[(D_+ + D_-)\sin\left(\frac{\pi\xi}{U}\right) - (D_+ - D_-)\sin\big(k_p(\xi+U)\big)\right] & \\ + \frac{A_2}{k_p^2}\sin\big(k_p(\xi+U)\big) & \text{if } -U \le \xi \le U \\ \frac{A_1}{2k_p}\left[(D_+ - D_-)\sin\big(k_p(\xi-U)\big) - (D_+ - D_-)\sin\big(k_p(\xi+U)\big)\right] & \\ - \frac{A_2}{k_p^2}\left[\sin\big(k_p(\xi-U)\big) - sin(k_p(\xi+U))\right] & \text{if } -U \le \xi \le U \end{cases}$$
- Part 3: $$E_{3,\|}(\xi) = \begin{cases} 0 & \text{if } \xi < U \\ \frac{A_0}{2k_p}\left[(C_+ + C_-)\sin\left(\frac{\pi(\xi-U)}{2(L-U)}\right) + (C_+ - C_-)\sin\big(k_p(\xi-U)\big)\right] & \text{if } U \le \xi \le L \\ \frac{A_0}{2k_p}\left[(C_+ + C_-)\cos\big(k_p(\xi-L)\big) + (C_+ - C_-)\sin\big(k_p(\xi-U)\big)\right] & \text{if } \xi > L \end{cases}$$
- pre-factors: $C_\pm = \frac{1}{\frac{\pi}{2(L-U)} \pm k_p}$, $D_\pm = \frac{1}{\frac{\pi}{U} \pm k_p}$, $A_1 = \frac{A_{min} - A_0}{2}$, $A_2 = \frac{A_{min} + A_0}{2}$

Analytic Calculations in Linear Theory

Perpendicular Wakefields:

- Part 1: $E_{1,\perp}(\xi) = \begin{cases} 0 & \text{if } \xi < -L \\ \frac{A_0}{2}\left[(C_+ - C_-)\sin\left(\frac{\pi(\xi+L)}{2(L-U)}\right) + (C_+ + C_-)\sin\left(k_p(\xi+L)\right)\right] & \text{if } -L \leq \xi \leq -U \\ \frac{A_0}{2}\left[(C_+ - C_-)\cos\big(k_p(\xi+U)\big) + (C_+ + C_-)\sin\big(k_p(\xi+L)\big)\right] & \text{if } \xi > -U \end{cases}$
- Part 2: $E_{2,\perp}(\xi) = \begin{cases} 0 & \text{if } \xi < -L \\ \frac{A_1}{2}\left[(D_+ + D_-)\cos\left(\frac{\pi\xi}{U}\right) - (D_+ - D_-)\cos\big(k_p(\xi+U)\big)\right] \\ \quad + \frac{A_2}{k_p}\left[1 - cos(k_p(\xi+U))\right] & \text{if } -U \leq \xi \leq U \\ \frac{A_1}{2}\left[(-D_+ + D_-)\cos\big(k_p(\xi-U)\big) + (D_+ - D_-)\cos\big(k_p(\xi+U)\big)\right] \\ \quad - \frac{A_2}{k_p}\left[\cos\big(k_p(\xi+U)\big) - \cos\big(k_p(\xi-U)\big)\right] & \text{if } -U \leq \xi \leq U \end{cases}$
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