AWAKE Applications: Luminosity Considerations

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James Chappell

LEVERHULME TRUST

Outline

Discussion of limitations on the luminosity of a future AWAKE-like experiment:

Drive beam limitations.

- Extraction limits
- Machine limits
- Possible schemes for future AWAKE-like experiment.

Plasma limitations.

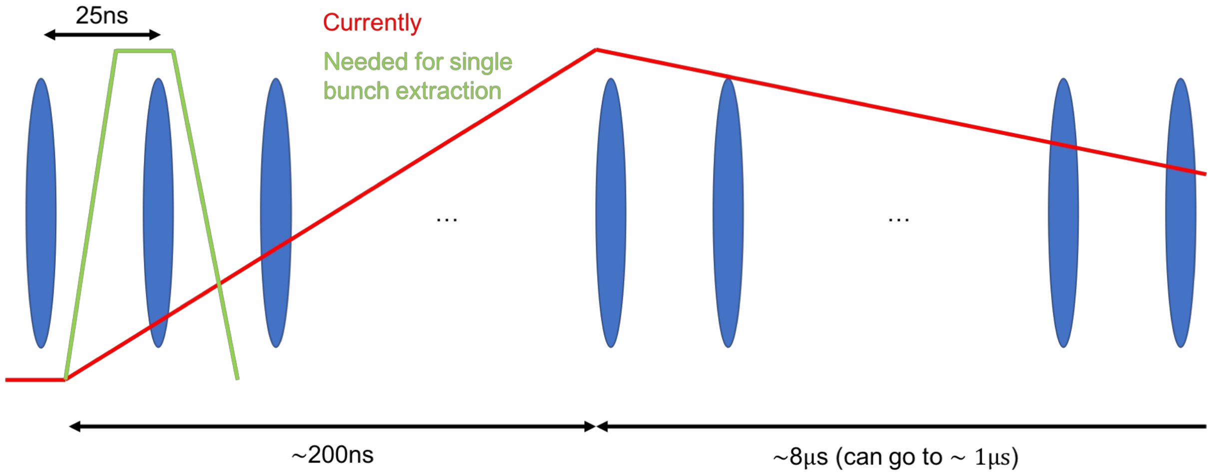
- Ion motion.
- Plasma source.
- Possible schemes for future AWAKE-like experiment.

Proton Beam Extraction Limitations

Current bunch extraction system:

- Time to charge extraction kicker $\sim 50ms$
- Extraction kicker rise time $\sim 200ns$
- Discharge currently $\sim 8\mu s$
  - Can be reduced to $\sim$ few μs (*Karel Cornelis*)

$\Rightarrow$ **Cannot take single bunch out of train as they are separated by 25ns.**



Proton Beam Extraction Limitations

Bunch extraction:

- SPS length: $22\mu s$
- Extraction kicker cycle length: $\sim 2\mu s$

$\Rightarrow$ For single bunch extraction, the maximum number of bunches allowed would be **10**.

SPS Injection Considerations

- PS length: $2\mu s$ $\Rightarrow$ 4 bunches are separated by 500ns. Would need to use "RF gymnastics" to equally space bunches around the SPS ring.
  - This is possible.

- Operate PSB in second harmonic to allow 2 bunches per booster ring.
  $\Rightarrow$ 8 proton bunches in single AWAKE cycle.
  $\Rightarrow$ Lower intensity & larger emittance, i.e. less ideal for driving a wakefield.

Longitudinal Bunch Compression

- Currently, the AWAKE proton bunch undergoes longitudinal compression before extraction from the SPS.

- Possible to perform “RF & Phase gymnastics” on each bunch separately if we have 8 equally separated bunches in the SPS *(Thomas Bohl).*
  ⇒ Could have 8 AWAKE proton bunches in a single cycle.

- Do we need to longitudinally compress bunches?
  - Gain 4x bunch density from smaller transverse size thanks to LIU upgrade.
  - If not, can use a bunch train from the LIU-SPS as is i.e. 72 bunches, each separated by 25ns (or 50ns) ⇒ **Plasma limitations**.

Possible Schemes for AWAKE-like Accelerator

Parameter	AWAKE1 (Current)	LIU-SPS	LIU-AWAKE	HL-LHC
N_p	3×10^{11}	2.3×10^{11}	3×10^{11}	2.2×10^{11}
$E_p\ [GeV]$	400	450	$400\ or\ 450$	7000
$\sigma_{x,y}\ [\mu m]$	200	100	100	100
$\sigma_z\ [cm]$	6	7.55	6	7.55
n_b	1	288	8	2808
$\text{Max.}\ f_{rep}\ [Hz]$	0.139 (current AWAKE cycle: 7.2 seconds)	0.05 (time taken to fill SPS and accelerate ~20 seconds)	$0.16\ or\ 0.139$ (upgraded AWAKE cycle: 6 or 7.2 seconds)	31.6×10^6 (no. of bunches * crossing frequency)

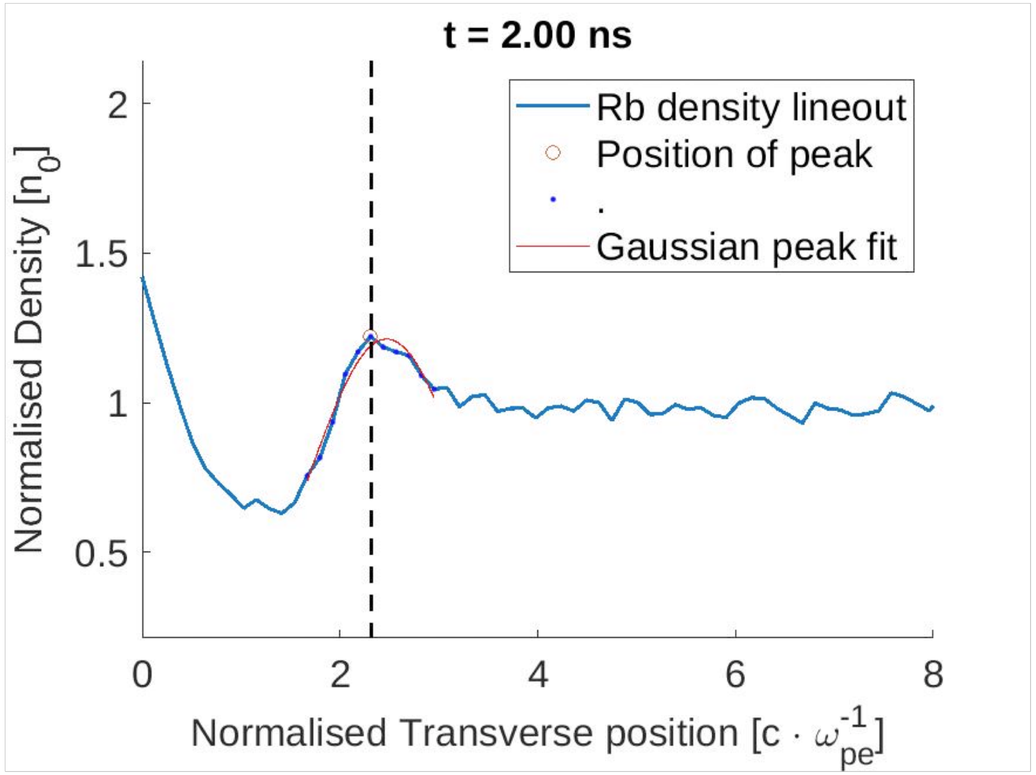
Plasma Limitations: Ion Motion

Plasma ion motion: $\sim 10s\ ns$

- Drive beam deposits large amount of energy into plasma which is transferred into the plasma electrons and ions.

- Causes transversely propagating ion soliton.

$\Rightarrow$ Plasma non-uniformity.



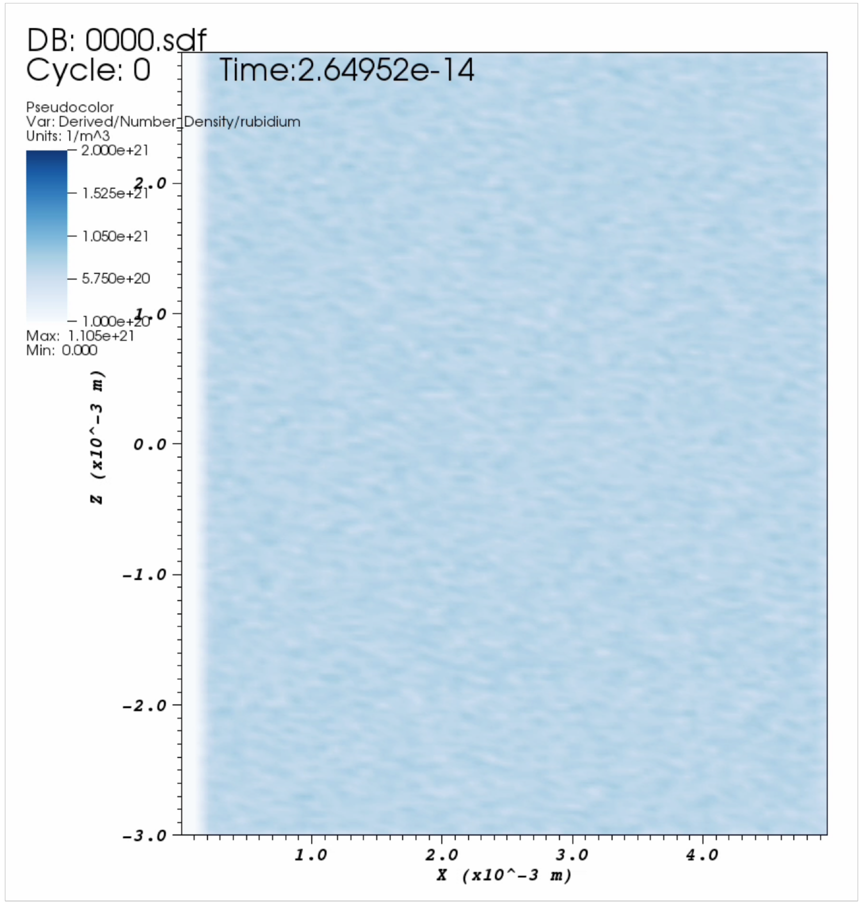
Plasma Limitations: Ion Motion

- Must wait for the ion energy to dissipate and uniformity to be reached before the plasma can be used to accelerate electrons again.

- This places a fundamental maximum repetition rate on any plasma-based accelerator.

- Repetition rate can be optimised through careful choice of plasma ion species.

- More research needs to be undertaken…



Plasma Limitations: Vapour source

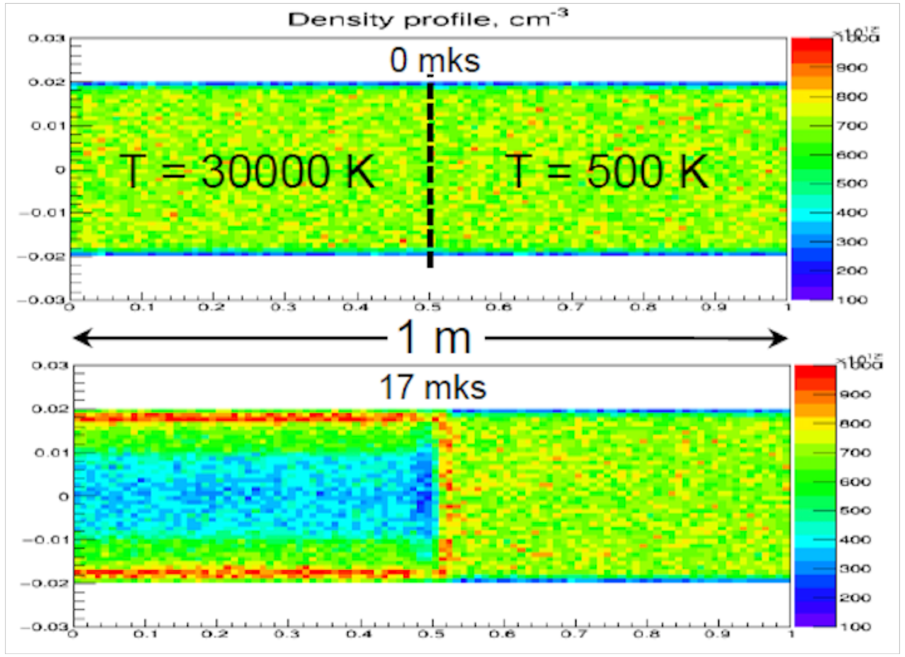
AWAKE currently uses a laser-ionised vapour source for plasma.

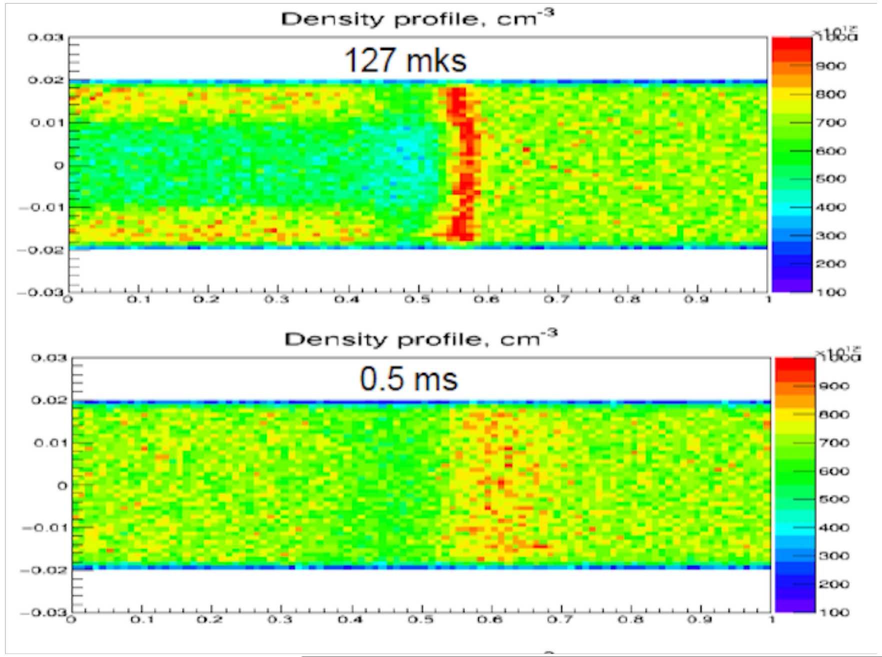
- Recombination of plasma $> 50\mu s$

  (see "Update on Plasma Decay Analysis", S. Gessner, AWAKE Collaboration meeting, March 2018)

- Subsequent dissipation of temperature gradient in vapour $\sim ms$

  (see "Rb Flow in AWAKE", G. Plyushchev, 12th AWAKE Physics Board Meeting, August 2015)





Plasma Limitations

- Using current vapour source, minimum separation between proton bunches is $\sim ms$
  - $\Rightarrow$ Limits maximum repetition rate to $\sim 100Hz$
- If we could have a continuous plasma (e.g. helicon source), the limitation is the plasma ion motion and relaxation $\sim 10s\ ns$
  - $\Rightarrow$ Maximum repetition rate $\sim MHz$
  - $\Rightarrow$ Would need a different method to seed self-modulation
    (e.g. electron bunch, see DOI: 10.1016/j.nima.2018.02.084)

UCL

Example: AWAKE for NA64

For reference, NA64 in its current setup hopes to accumulate $\sim 3\times10^{12}$ electrons on target in its lifetime.

Parameter	LIU-SPS with upgraded extraction kickers (Once per SPS super-cycle*)	LIU-SPS (Once per SPS super-cycle*)	LIU-AWAKE @ 400GeV (Twice per SPS super-cycle*)
N_p	3×10^{11}	2.3×10^{11}	3×10^{11}
$E_p\ [GeV]$	450	450	400
$\sigma_{x,y}\ [\mu m]$	100	100	100
$\sigma_z\ [cm]$	7.55	7.55	6
n_b (per SPS-SC)	320	288	16
$f_{rep}\ [Hz]$	0.025	0.025	0.025
N_e	5×10^9	2×10^9	5×10^9
$E_e\ [GeV]$	60	60	50
Number of electrons on target per year:**	$\mathbf{2.0 \times 10^{17}}$	$\mathbf{7.3 \times 10^{16}}$	$\mathbf{1.0 \times 10^{16}}$

* Have assumed an SPS super-cycle takes 40 seconds. ** Have assumed a twelve week run with a 70% SPS duty cycle.

Example: PEPIC

Parameter	Original assumption	AWAKE Run II based setup	Best case scenario
N_e	$1.15{\times}10^{10}$	$1{\times}10^{9}$	$5{\times}10^{9}$
E_e	$100GeV$	$50GeV$	$60GeV$
n_b	288	1	320
f_{rep}	$15Hz$	$0.17Hz$ (Once every 6s)	$0.05Hz$ (Cycle length of 20s)
Luminosity		$\mathbf{5.92{\times}10^{24}cm^{-2}s^{-1}}$	$\mathbf{2.79 \times 10^{27}cm^{-2}s^{-1}}$

These are calculated assuming that the electron beam is colliding with a HL-LHC proton beam taken from: "HL-LHC Parameters v4.2.1" (13/11/2015). See here.

The best case scenario calculation assumes upgraded extraction kickers that allow us to use a single proton bunch (3e11 protons) every 25ns for driving the wakefield.

Further study

- Need to understand plasma limitations in more detail, in particular the ion motion and how this varies with density, species, drive beam etc.

- Need to investigate whether the wakefield driven by non-longitudinally compressed LIU-SPS proton bunch can be used for electron acceleration.

- Need to investigate new methods for seeding proton self-modulation in plasma.