External Electron Injection for the Advanced Wakefield Experiment (AWAKE) Run 2b

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Abstract: We summarise and explain plans for witness particle beam injection into wakefields for the AWAKE Run 2b experiments. In AWAKE plasma wakefields are driven by a self-modulating relativistic proton bunch. For Run 2b, we use a novel rubidium vapour source that allows for a plasma density step. To demonstrate that the density step can stabilise the wakefield amplitude and to probe the longitudinal fields, we plan on injecting a 19MeV electron bunch produced by a photo-injector. We highlight the experimental challenges of this injection process and present our plans for the near future.

AWAKE RUN 1 : (2016-2018)

- PLASMA: Uniform 10m Rb vapour + ionising laser pulse
- DRIVER: 400GeV proton bunch ➔ self-modulates (instability SMI or seeded SSM) ➔ micro-bunch train drives plasma electron wave resonantly ➔ experimentally demonstrated
- WITNESS: Electron bunches injected with ~19MeV accelerated up to 2GeV energies ➔ experimentally demonstrated

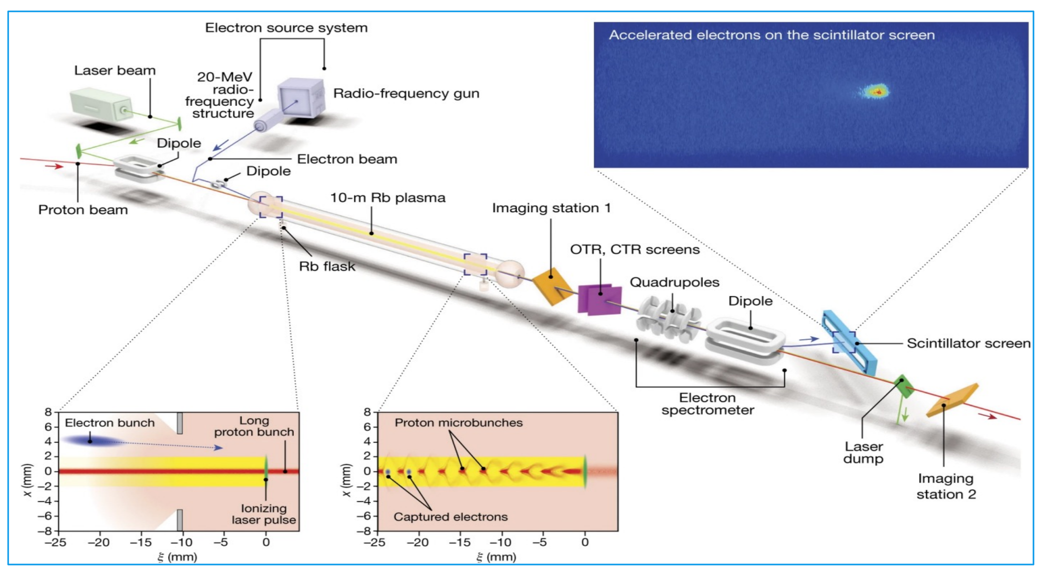

Figure 1: Schematic of current setup (taken from ref. [1]); ionising laser and driving proton bunch are merged before the plasma source. A beam of 19MeV electrons is injected at the entrance of the plasma source.

COUNTERACTING SSM INDUCED DEPHASING:

IDEA: plasma density step ➔ to rephase microbunches in wakefields

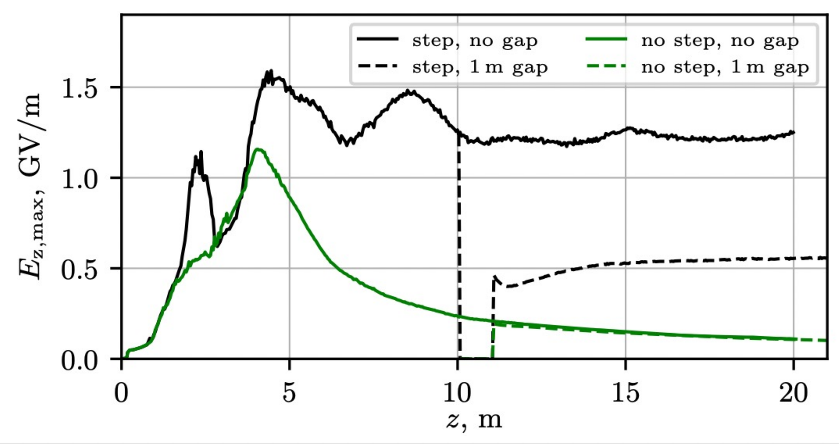

Figure 2: The effect of a density step on the wakefield amplitude $E_{z,max}$ see [1]; Gap refers to the plan for Run 2c where two plasma sections are considered (modulator + accelerator)).

ELECTRON INJECTION:

- External: only option due to high wakefield phase velocity
- Off-axis injection: due to density ramp & defocusing of electron bunch at entrance on axis

AWAKE RUN 2b: (2022-2024)

- **New vapour source allows for density step** (adjustable heating sections 0.25-4.25m)
  ➔ stabilise wakefield amplitude leading to higher witness energies
- More diagnostics along 15m beam line allow for better control and insight: <=> dipole & quadrupole magnets, beam screens (BTVs) & beam position monitors (BPMs) (Figure 4)
- Asymmetric entrance aperture
  ➔ more flexibility for electron injection

Goals:

➔ optimise wakefields by optimising density step height and z-location

➔ external, off-axis electron injection to directly measure wakefield evolution along the plasma

Experimental Parameters:

Driver	
Type	Protons from the SPS (CERN)
Length	~6-8cm r.m.s
Energy	~400GeV
Ionising laser	
Type	Central wavelength: 780µm
Pulse duration	~120fs
Energy	~100mJ

Plasma	
Type	Rubidium vapour source
Length	10m
Densities	10^{14}-10^{15}cm^{-3}
Density steps	Density steps; up to +9% at 0.25-4.25m along the plasma
Additional characteristic	µ-metal around vapour source
Entrance aperture	-Dimensions in Figure 6 -Centre offset from proton beam trajectory (Figure 5)

Injected Witness [3]	
Type	Electrons produced by S-band RF-photo-injector
UV laser spot size	~1mm on Cs2Te cathode
Bunch charge	100-700pC
Normalized transverse emittance	1-6mm·mrad
Bunch length σ_z	2-5ps
Energy prior to booster	~5MeV
Injector/Booster	3GHz by a 30 MW klystron, 10Hz
Energy after 1m booster	~19MeV

Measurement Goal:

CONTROLLED WITNESS INJECTION AT VARIOUS Z-LOCATIONS ALONG THE PLASMA TO PROBE AVERAGE LONGITUDINAL WAKEFIELDS

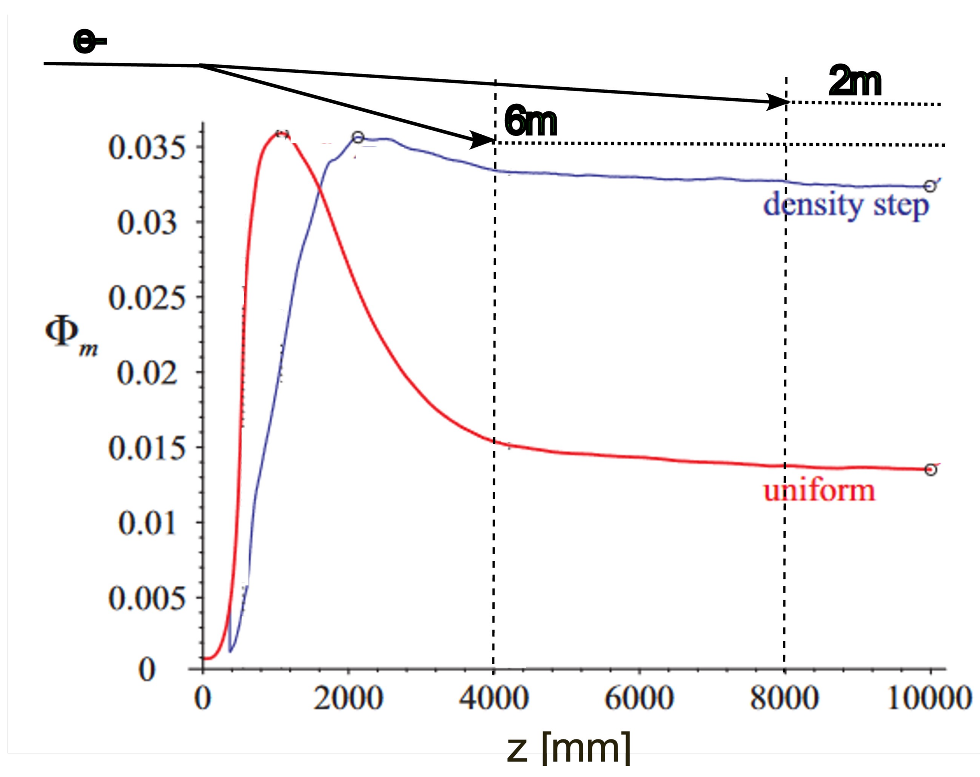

Figure 3: Sketch of possible injection scheme to probe wakefields. Depicted is the maximum wakefield amplitude Φ_m as a function of propagation distance, z, for uniform plasma (red lines) and plasma with an optimum density step (blue lines) from [2]. Injection points of interest: with vs, without density step and with varying acceleration distances.

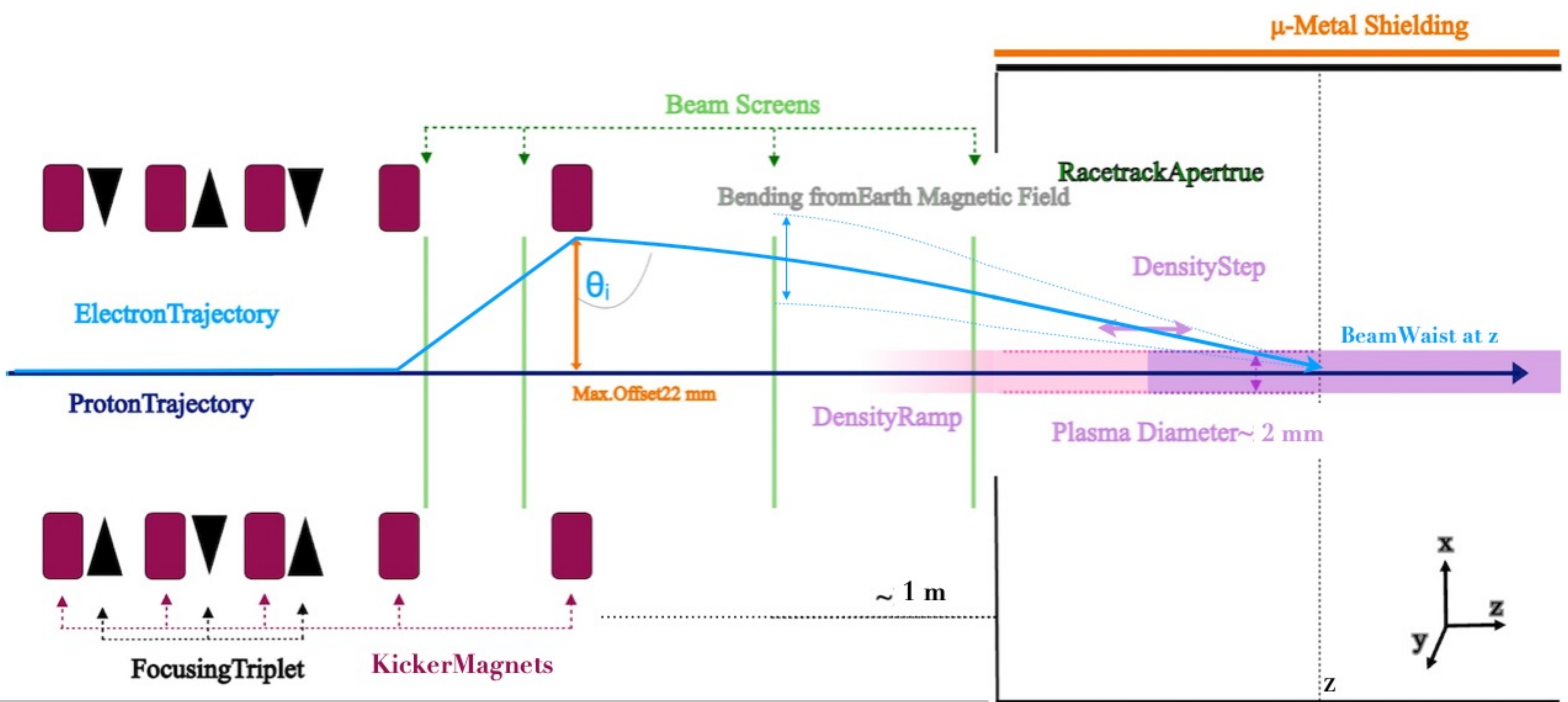

Figure 4: Schematic drawing of the injection region showing the trajectories of the proton and electron bunches and laser pulse. Also shown are positions of BTVs, kicker magnets and the focusing quadrupole triplet. Drawing not to scale.

Challenges:

- Entrance aperture for laser pulse, driver & witness bunch creates plasma density ramp that can defocus electrons prior to capture by the wakefields➔ off-axis injection
- Witness must cross wakefields at the same z-location in both axes, no diagnostics at injection location
- Ideally, injection location **after** density step and SSM saturation, to avoid dephasing
- Witness beam size should be smaller than aperture, otherwise charge is lost
- Earths' magnetic field affects the trajectory of the low energy witness bunch significantly ➔ need to adjust injection trajectory

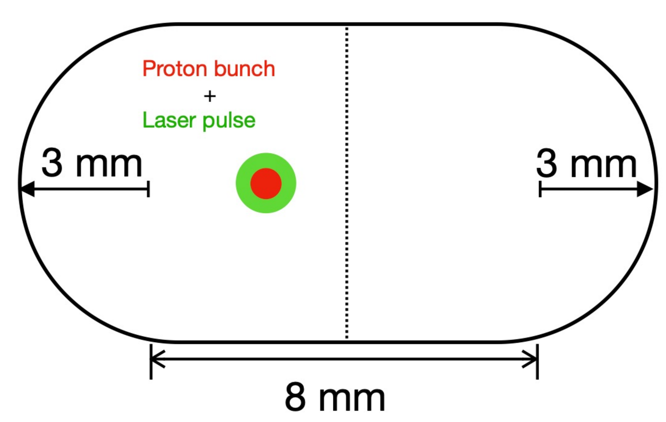

Figure 5: Vapour source entrance aperture; racetrack shape allows for larger injection angles than circular shape with same area (Run 1).

References:

[1]: Gschwendtner, E.; Lotov, K.; Muggli, P.; Wing, M.; et al. The AWAKE Run 2 Programme and Beyond. *Symmetry* **2022**, *14*, 1680. https://doi.org/10.3390/sym14081680
[2]: Lotov, K. V. "Physics of beam self-modulation in plasma wakefield accelerators", *Physics of Plasmas* 22.10 (2015). https://arxiv.org/pdf/1503.05104.pdf
[3]: Verra, L., Della Porta, G. Z., Moon, K. J., Bachmann, A. M., Gschwendtner, E., & Muggli, P. (2021). Seeding of proton bunch self-modulation by an electron bunch in plasma. *arXiv preprint arXiv:2106.12414.*