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e4AWAKE: Next generation electron source for the Advanced Wakefield Experiment at CERN

Giovanni Zevi Della Porta (Max Planck Institute for Physics and CERN)

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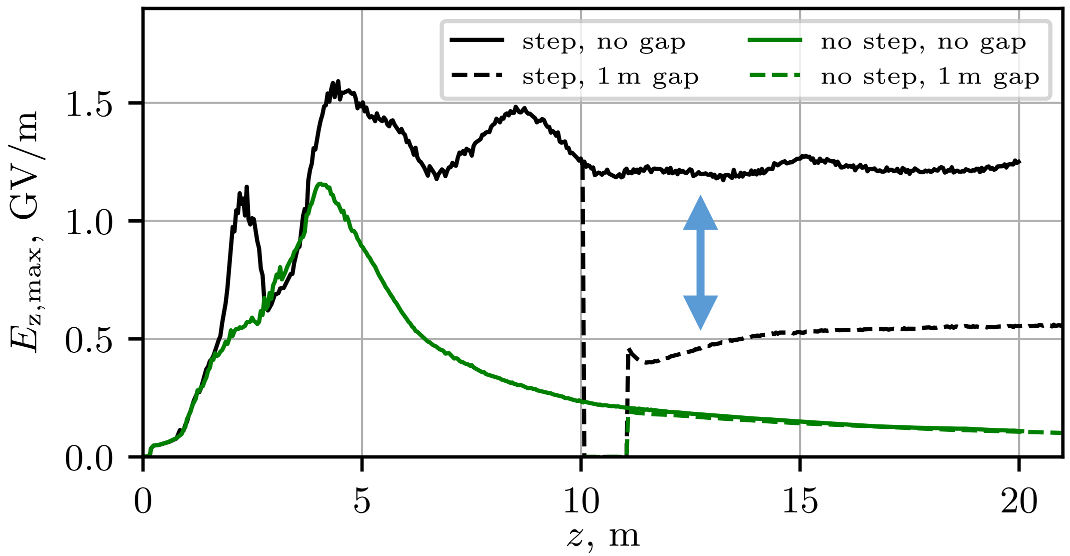
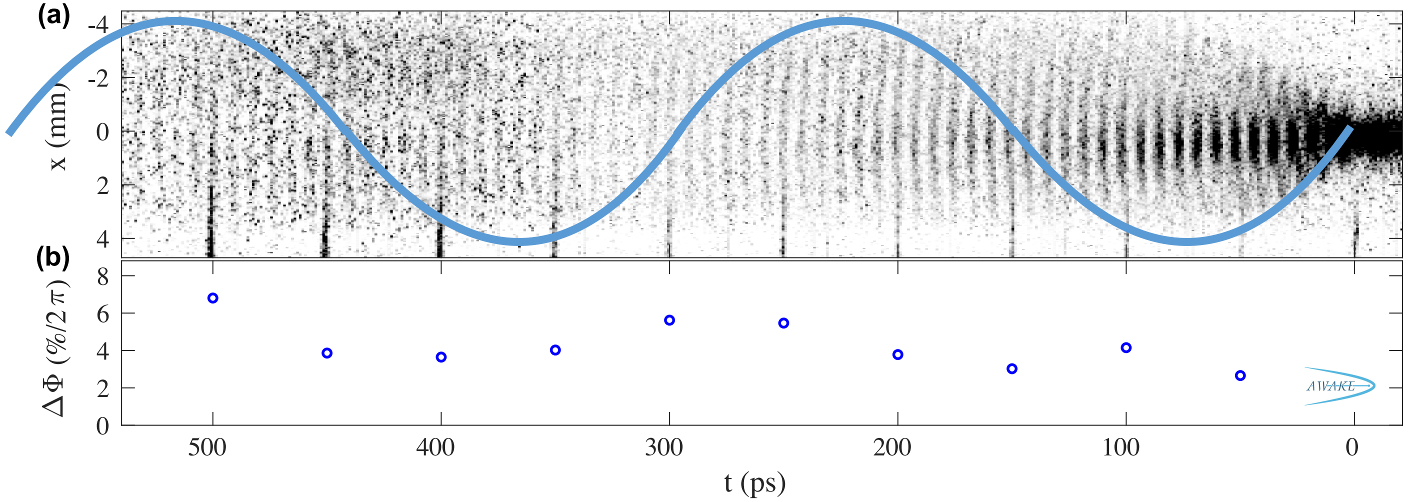
Baseline electron injection in AWAKE Run 2

- AWAKE plans to use an RF-based external injector for Run 2
  - Known technology to minimize risk
  - Achieves the challenging e^- beam requirements
- External injection requires a 1 meter gap in the plasma
  - Accelerating gradient (GV/m) is reduced by a factor of 2
  - Could we remove this gap?
- Proton driver forms a bunch-train, but difficult for an RF-based injector to provide an arbitrary train of witness electron bunches
  - ω_{pe} ~ 1.5 THz for n_{pe} = 7E14 cm^{-3}. Run 2 gun: RF ~ 3 GHz
  - Accelerated charge is less than its full potential
  - Can we explore this possibility by injecting multiple electron bunches?
- **Address these limitations to increase energy and luminosity**
  - **Increase physics reach of future experiments**

Effect of 1 meter gap on accelerating gradient



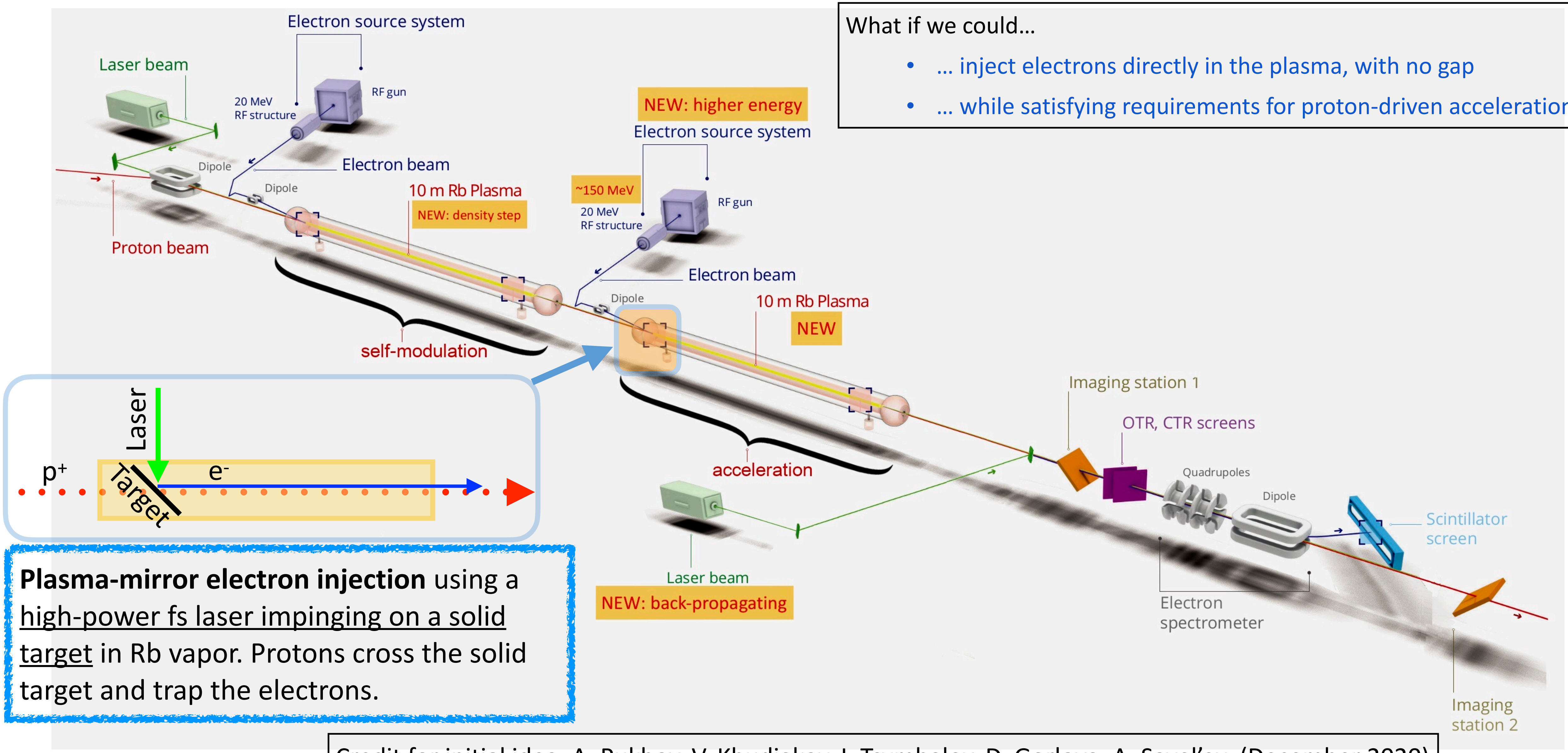
RF frequency vs proton bunch train structure



A possible alternative: e4AWAKE

What if we could…

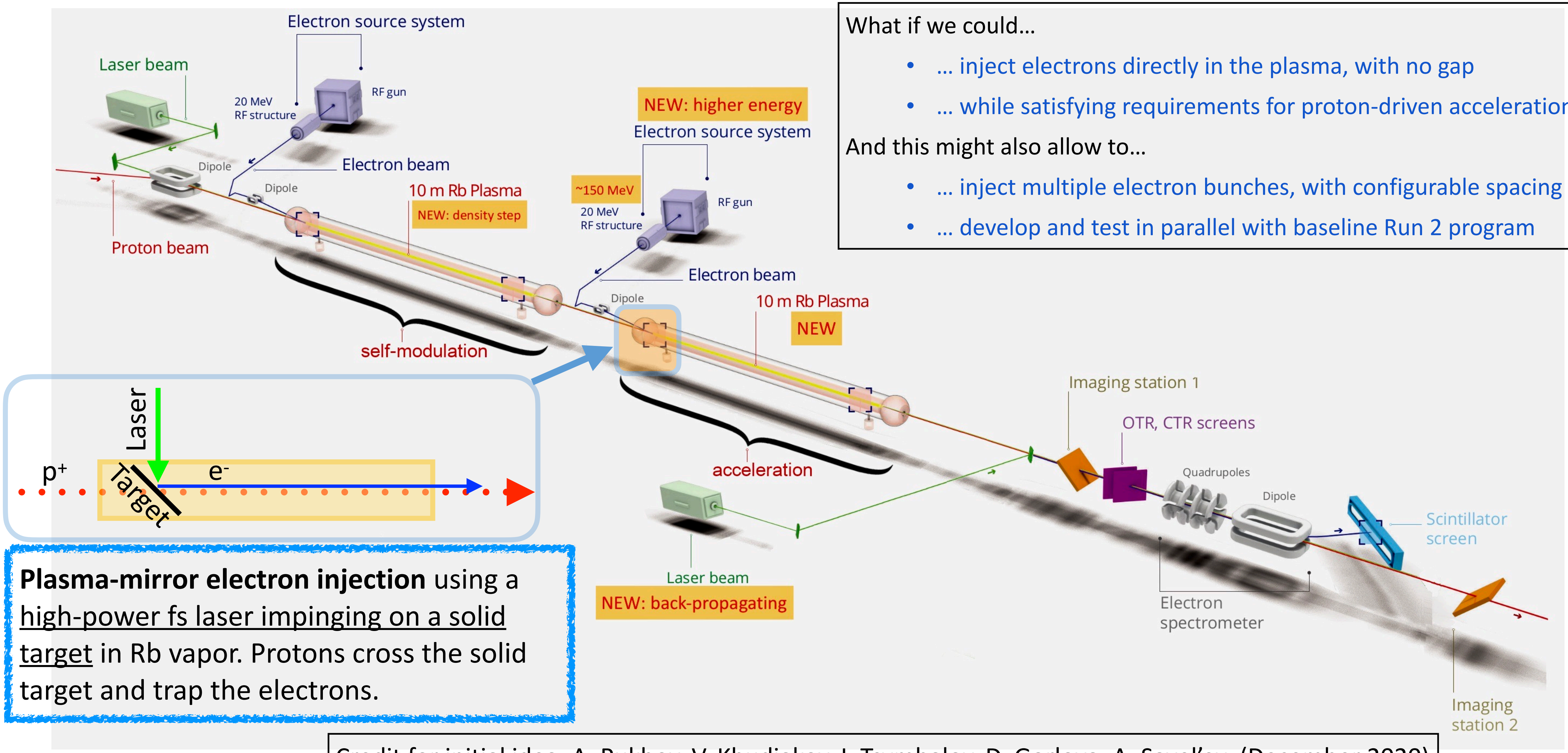
- … inject electrons directly in the plasma, with no gap
- … while satisfying requirements for proton-driven acceleration



Plasma-mirror electron injection using a <u>high-power fs laser impinging on a solid target</u> in Rb vapor. Protons cross the solid target and trap the electrons.

Credit for initial idea: A. Pukhov, V. Khudiakov, I. Tsymbalov, D. Gorlova, A. Savel'ev (December 2020)

A possible alternative: e4AWAKE



What if we could…

- … inject electrons directly in the plasma, with no gap
- … while satisfying requirements for proton-driven acceleration

And this might also allow to…

- … inject multiple electron bunches, with configurable spacing
- … develop and test in parallel with baseline Run 2 program

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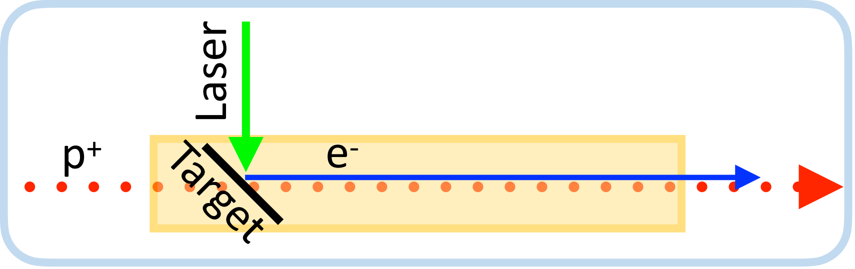
Questions towards a possible implementation

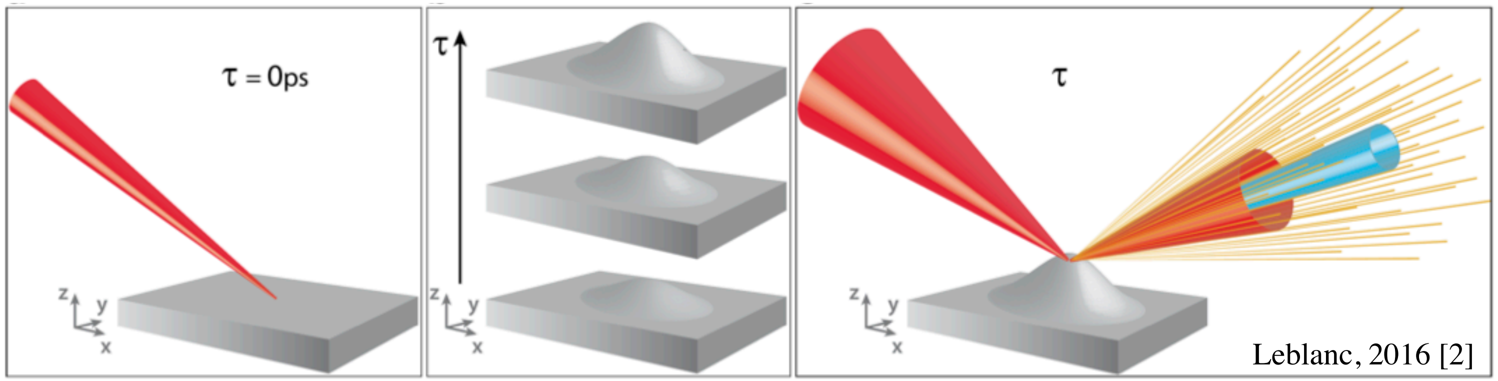


- Plasma-mirror electron injection: how does it work?
  - Could we use the existing laser of AWAKE?
- How does the electron bunch compare with the RF one?
  - Will the e- bunch be trapped by proton-driven wakefields?
- Could proton-driven wakefields drive multiple e- bunches, in theory?
- How would we implement this, in practice?
  - Would the timeline fit with AWAKE Run 2?

Plasma-mirror electron injection

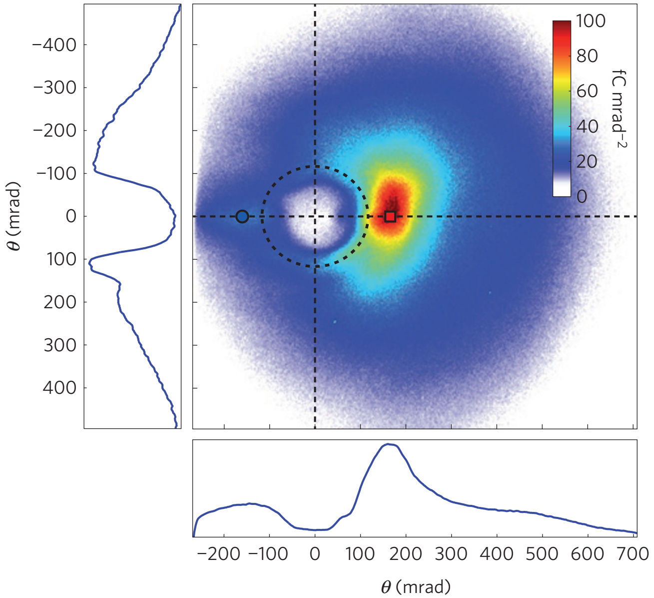
Step 1: Create a plasma-mirror with a lower-intensity laser

Step 2: Shine a high-intensity laser onto the plasma-mirror, extracting plasma electrons and accelerating them



Leblanc, 2016 [2]

Electron beam divergence and momentum distribution



A few recent papers:

[1] M. Thévenet, A. Leblanc, S. Kahaly, et al. *Vacuum laser acceleration of relativistic electrons using plasma mirror injectors*. Nature Phys 12, 355–360 (2016).

[2] A. Leblanc. *Miroirs et réseaux plasmas en champs lasers ultra-intenses : génération d'harmoniques d'ordre élevé et de faisceaux d'électrons relativistes*. Physique des plasmas [physics.plasm-ph]. Université Paris Saclay (COmUE), 2016.

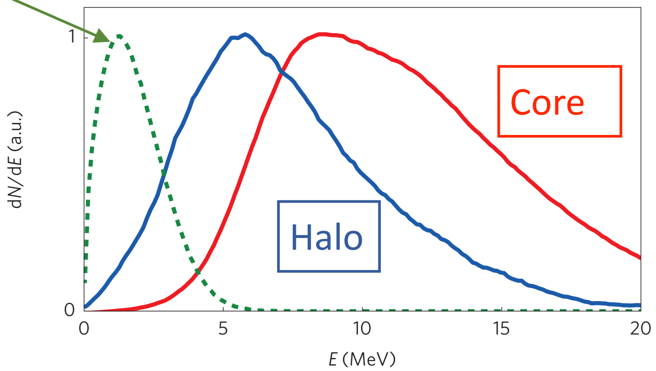
[3] N. Zaïm, et al. *Few-cycle laser wakefield acceleration on solid targets with controlled plasma scale length*. Physics of Plasmas 26, 033112 (2019).

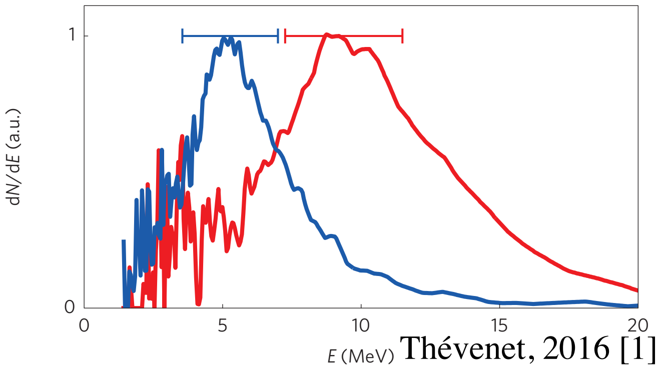
[4] L. Chopineau, et al. *Identification of Coupling Mechanisms between Ultraintense Laser Light and Dense Plasmas*. Phys. Rev. X 9, 011050 (2019)

[5] I. Tsymbalov, et al. *Well collimated MeV electron beam generation in the plasma channel from relativistic laser-solid interaction*. Plasma Phys. Control. Fusion 61 075016 (2019).

[6] V. Khudiakov and A. Pukhov. *Optimized laser-assisted electron injection into a quasilinear plasma wakefield*. Phys. Rev. E 105, 035201 (2022).

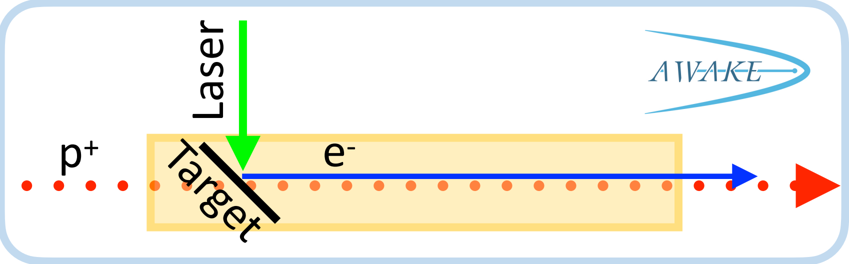
Energy after ejection from plasma mirror or relativistic-oscillating mirror (ROM)





Thévenet, 2016 [1]

Laser parameters

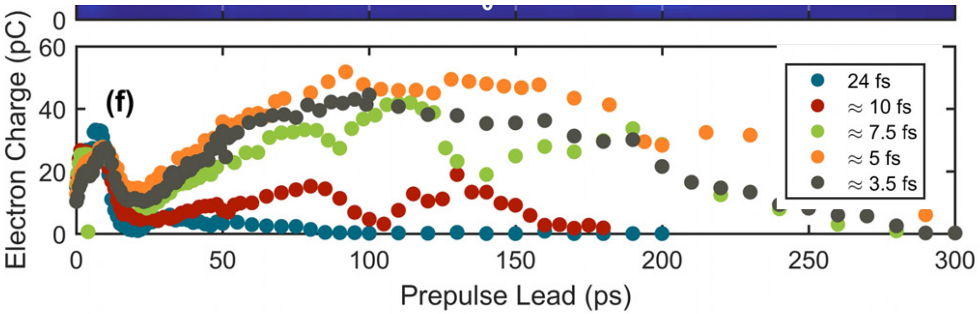


- Plasma-mirror injector could use a fraction of AWAKE's laser
  - Sufficient energy, but need to improve compression, contrast and focus

	Thévenet 2016 [1]	Zaïm 2019 [3]	Tsymbalov 2019 [5]	Khudiakov [6] (Simulation)	Current AWAKE
Wavelength [nm]	800	800	800	800	780
Energy [mJ]	700	2.6	50	4, 15, 60	450
Pulse length [fs]	25	[24, 3.5]	50	50	120
Focus size [µm]	5.5	1.75	3	4	700
Intensity [W/cm²]	2E+19	[2.3E18, 1.6E19]	5E+18	5E17, 2E18, 9E18	1E+13
Signal-to-noise (ps scale)	10^{12}	10^{10}	10^{7}	N.A.	10^{7}

- Using AWAKE's laser allows to focus immediately on physics and operation challenges
  - Operation in Rb and Ar atmospheres
  - Multi-bunch performance

Zaïm 2019 [3]: charge extraction for O(100) ps (single shot)



Electron bunch parameters

Beam parameters: RF vs plasma-mirror

	Charge [pC]	Length [fs]	Transverse Size [µm]	Normalized Emittance [mm mrad]	Energy [MeV]	Energy spread
Run 2 RF e- source	100	200	5.75	2	150	0.2%
Thévenet 2016 [1]	300	25	5.5	~10 (*)	10	~50%
Tsymbalov 2019 [5]	30	50	15	~1.5 (*)	1	~50%

(*) Based on divergences of 100 mrad [1] and 50 mrad [2], assuming mono-energetic beam and $\varepsilon_N = \beta\gamma \langle x \rangle \langle x' \rangle$

Ideal conditions for witness bunch (i.e. baseline)

1. Bunch density ~35*plasma electron density
   i. Generates blowout for linear focusing
   ii. Loads the wakefield, for constant acceleration along the bunch
2. Match γ to proton (i.e. ~200 MeV) to maintain phase w.r.t. wakefields
3. Matched to plasma focusing: σ/ε/γ satisfy matching condition

$$\sigma_{x,y,eb} = \left(\frac{2c^2 \epsilon_N^2 m_e \varepsilon_0}{n_{pe} e^2 \gamma} \right)^{1/4}$$

Plasma mirror electron injector

→ Small transverse size and pulse length: high charge density

→ Low energy, but acceleration can still take place if trapping conditions are satisfied (next slide)

→ Biggest difference is in γ, which has the smallest exponent. Matching conditions not satisfied exactly, so some evolution is expected (next slide)

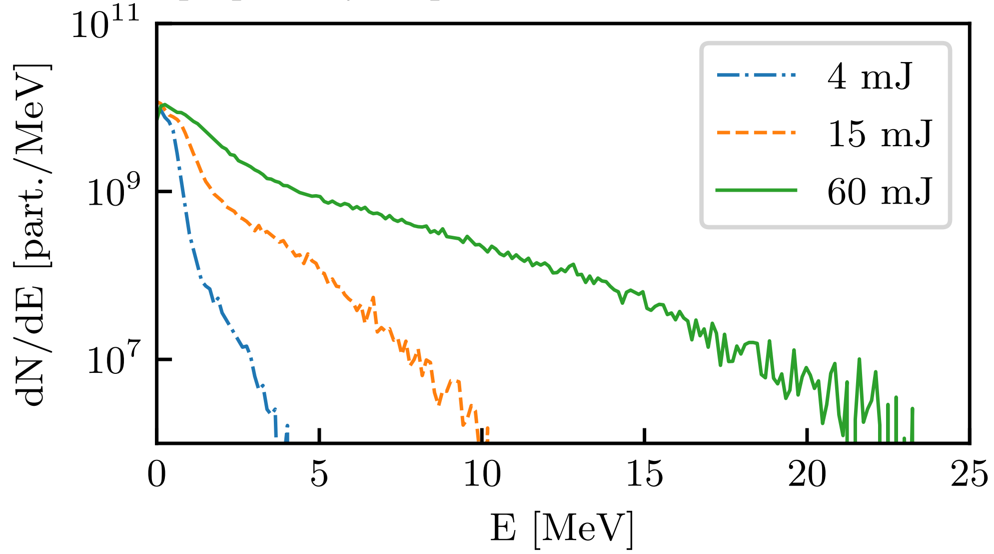
Trapping and acceleration

2-step VLPL 3D **simulation**: e- source and acceleration

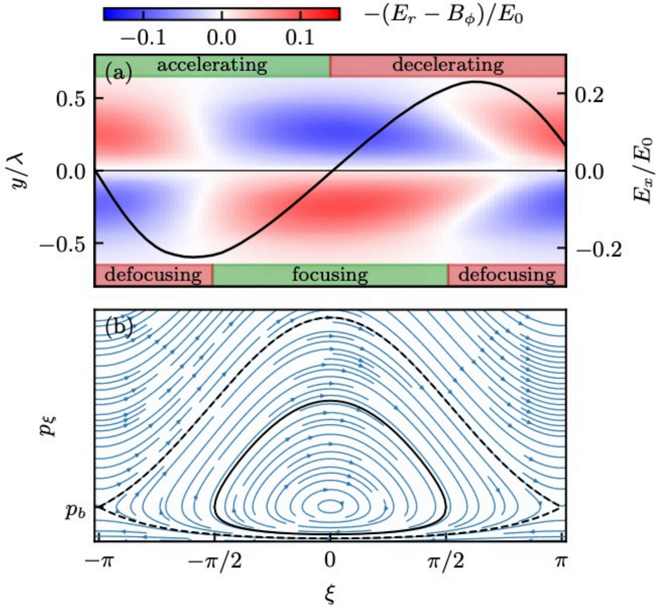
Compatibility of the plasma-mirror electron source with the proton wakefields of AWAKE evaluated analytically and with simulations.

Final charge/emittance depend on electron source, while **final energy** is determined by accelerating gradient and plasma length.

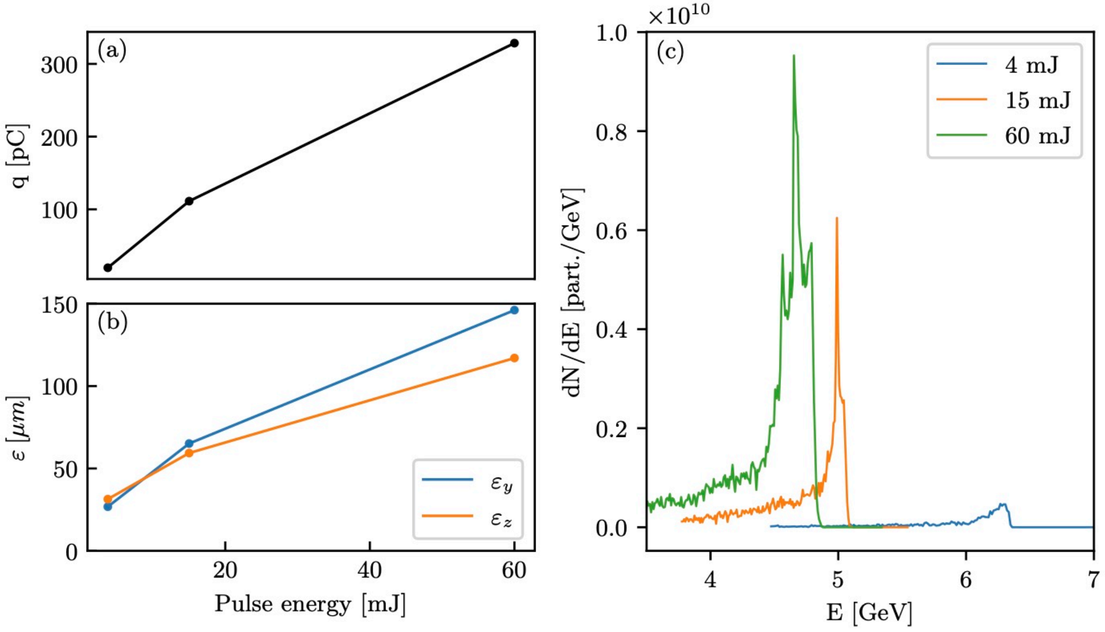
<u>Initial properties</u> from plasma-mirror e- source



Trapping Conditions of Proton Wakefields



<u>Final properties</u> of electron bunches after plasma wakefield acceleration



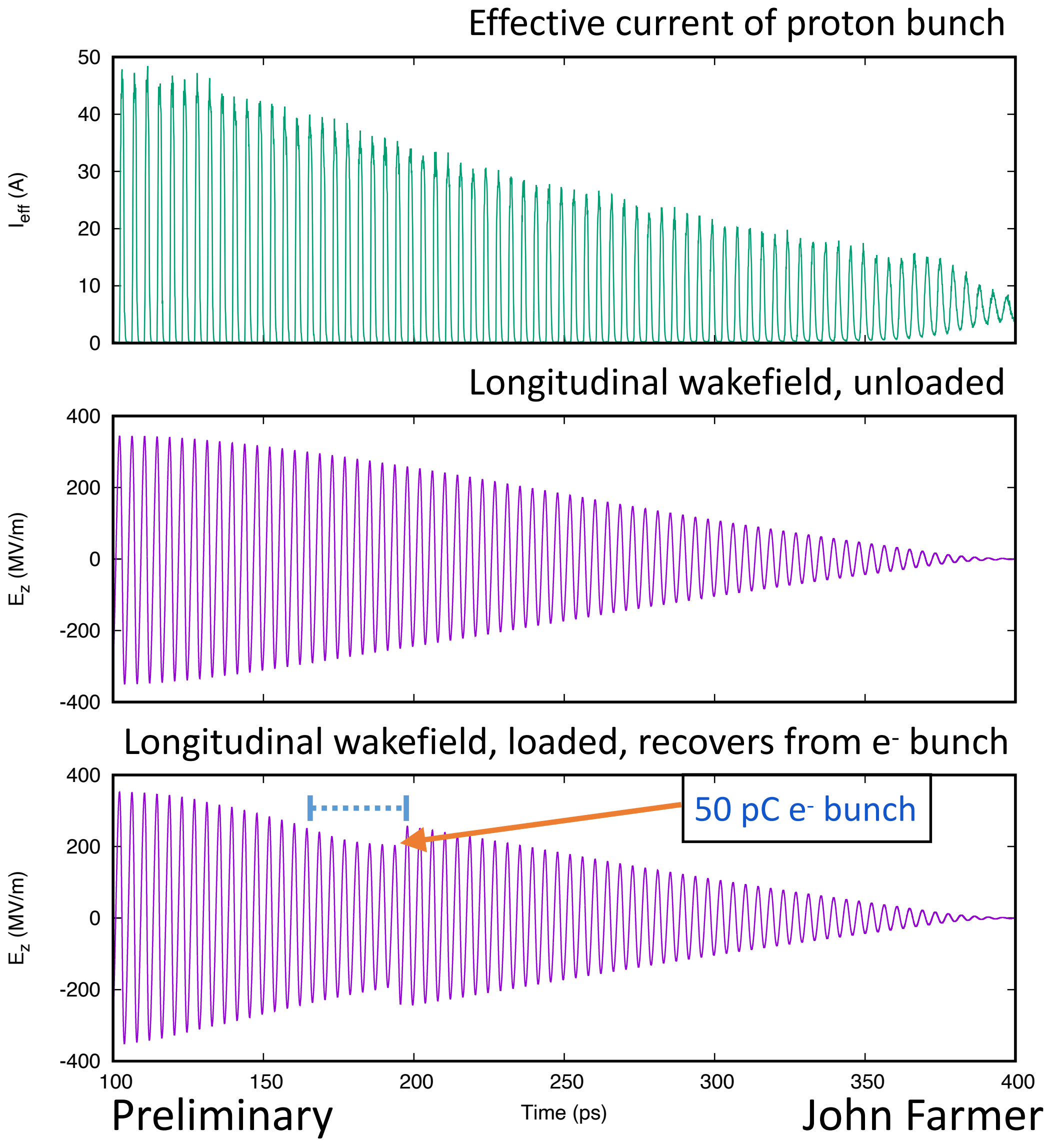
Charge and Energy comparable with Run 2 baseline, but larger emittance at high charges.

Promising basis for further studies.

V. Khudiakov and A. Pukhov. *Optimized laser-assisted electron injection into a quasilinear plasma wakefield*. Phys. Rev. E 105, 035201 (2022).

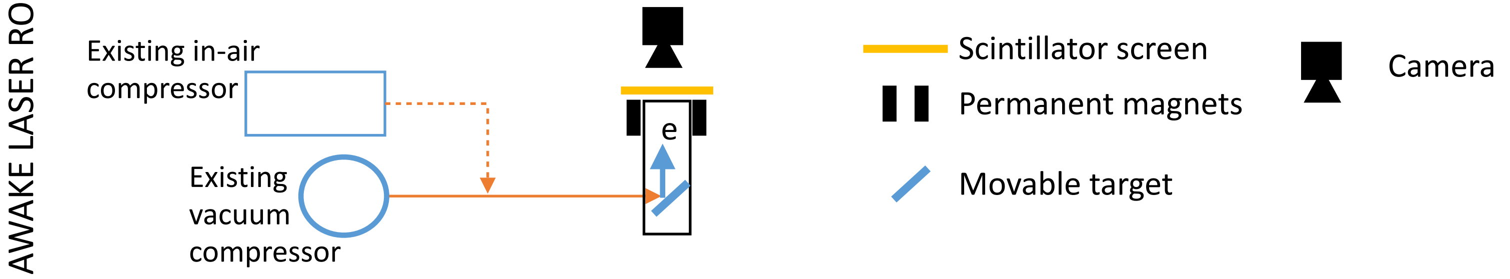
Wakefield recovery

- AWAKE luminosity is constrained by its repetition rate
  - A proton bunch every 7-20 s
- The proton driver forms a micro-bunch-train: can it be loaded with multiple electron bunches?
  - **e4AWAKE injector could provide the flexibility to test this**
  - Other possibilities with other injectors …
- Not trivial to predict longitudinal wakefields recovery after e^- injection in acceleration plasma
  - 2D simulations (LCODE) based on AWAKE Run 2 parameters
  - 3E11 proton bunch, 12 cm σ_z, 7E14/cm3 plasma, 50 pC e^- bunch, density step in self-modulation plasma
- **Encouraging preliminary result:**
  - **Wakefield recovers fully after ~10 micro-bunches**
  - **Potential to inject a second electron bunch**



Implementation: standalone and integrated

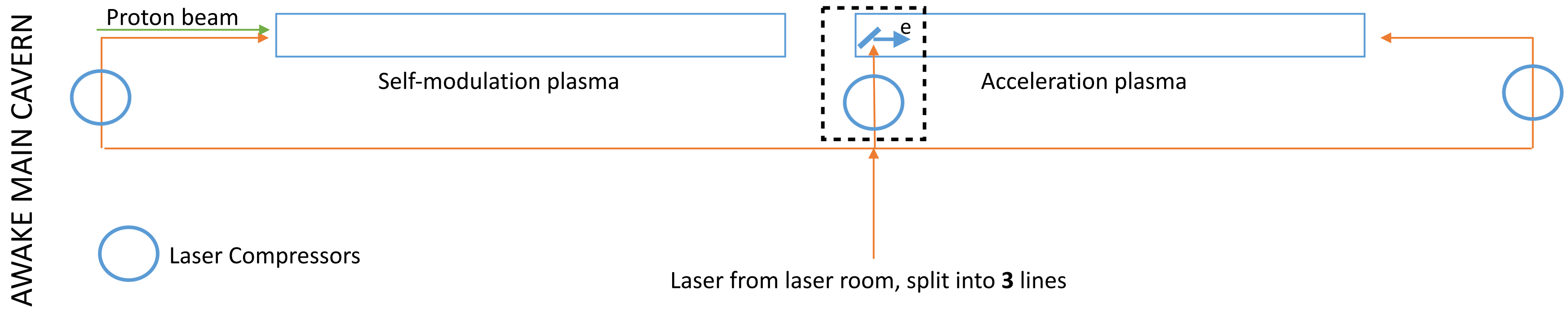
- Step 1: Build a standalone electron gun



GOAL 1: Build a plasma-mirror electron source operating in vacuum and characterize its properties when producing a single bunch and a 2-bunch train.

GOAL 2: Measure the electron source properties when operating in argon and rubidium gases matching the AWAKE densities.

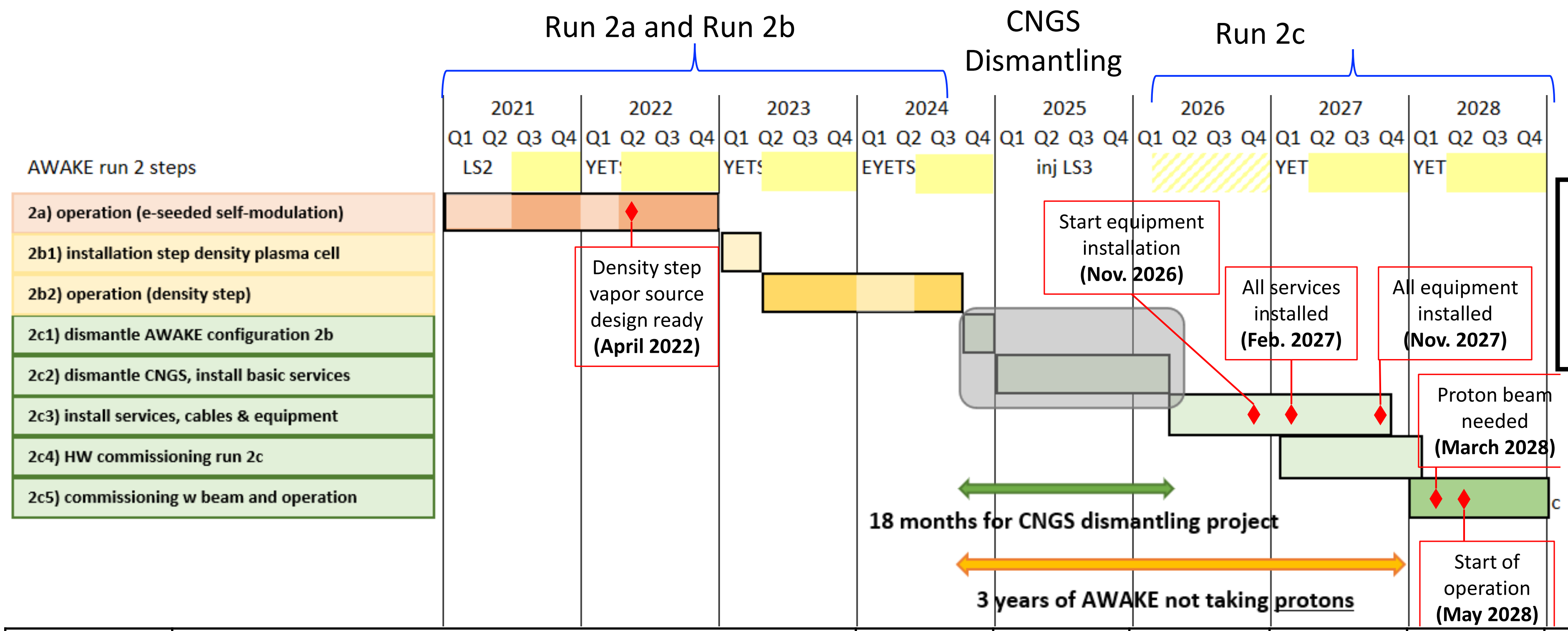
- Step 2: Integrate an electron gun in the Run 2c design



GOAL 3: Demonstrate the compatibility of the electron source with proton-driven acceleration and compare the properties of accelerated beams using the RF-based electron source.

GOAL 4: Study the acceleration of a 2-bunch train with different inter-bunch distances.

Timeline compatible with AWAKE Run 2



Take advantage of 2025-2026 downtime to work on standalone system in the laser room.

Phases	Steps	2024	25	26	27	28	Goal
1	1: Design standalone electron source						1
	2: Install and commission standalone electron source						1
	3: Experiments with electron source in vacuum						1
	4: Experiments with electron source in argon and rubidium gas						2
2	1: Design AWAKE plasma cell modification						3
	2: Install in AWAKE (as part of Run 2c installation)						3
	3: Experiments with proton-driven acceleration						3
	4: Experiments with 2-bunch train						4

Outlook

- Interesting to explore the limitations and possible extensions of AWAKE Run 2
  - Removing the 1-meter gap would increase the gradient by a factor of 2
  - Injecting multiple e^- bunches would increase luminosity
  - *These are key parameters in designing physics experiments beyond Run 2*

- Plasma-mirror electron injection has advantages and challenges
  - +: satisfies geometrical constraints, uses existing laser, test in parallel with Run 2
  - - : unknown performance in Rb/Ar and with multi-bunches, target motion after each shot, imperfect matching conditions, difficult alignment and diagnostic, …

- Interested in exploring other options as we think about the future
  - For multiple electron bunches at ~10 ps scale (RF or Plasma)
  - For shortening 1 meter gap (injection in plasma or other solutions)
  - For a fully plasma-based accelerator: see next talk