Run 2 of the Advanced Plasma Wakefield Experiment (AWAKE) at CERN

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for the AWAKE Collaboration

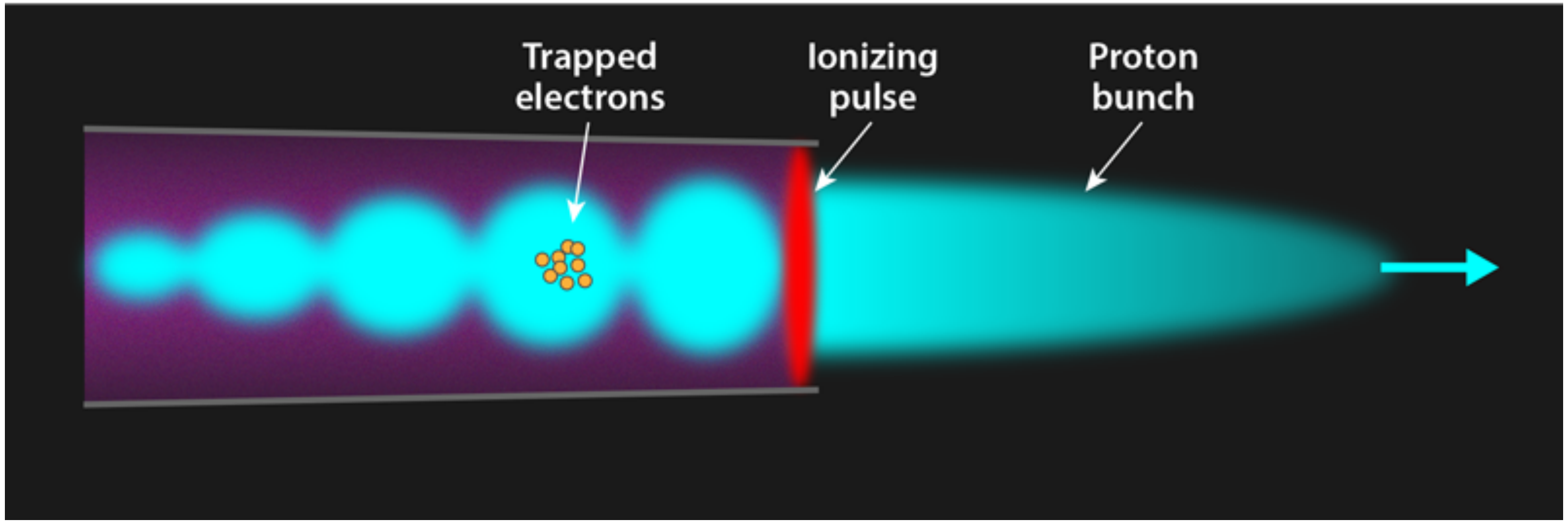
Liverpool, UK - 31 August 2022

Plasma wakefield acceleration, with a proton driver

1) **Laser** ionizes gas, forming **plasma**

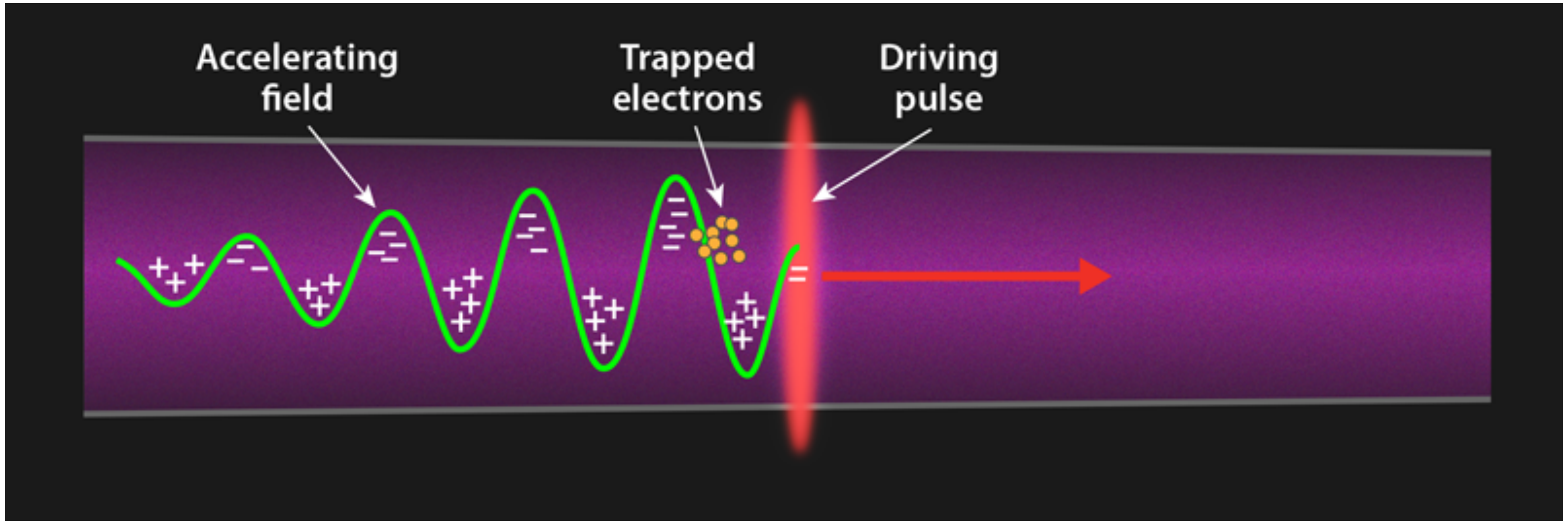
2) **Proton bunch** generates **wakefields** in the plasma, at its resonant frequency

3) **Micro-bunches form**, since plasma wavelength is smaller than proton bunch (**self-modulation** process)



APS/Alan Stonebraker

4) Proton **micro-bunches** act coherently to generate **wakefields** which **accelerate and focus electrons**



Plasma wakefield acceleration, with a proton driver

- Why plasma instead of a (superconducting) RF cavity?
  - **Higher fields**: can sustain more MV/m, leading to shorter accelerators
    - Metallic structures of RF accelerators break down at around 100 MV/m
  - **Self-focusing**: plasma can provide focusing fields (for e^-), as well as accelerating

Maximum E field in plasma (wave-breaking)
$E_{WB} \sim 96 \sqrt{n_{pe}}$ [V/m]
~ 2.5 GV/m for n_{pe} = 7E14 cm^{-3}

- Plasma wakefield acceleration has been studied since the 80's, but not with protons
  - Proton beams are rare, and the existing ones are very long, requiring **self-modulation to scale their size down to the plasma wavelength**
  - AWAKE is the only experiment currently exploring this possibility

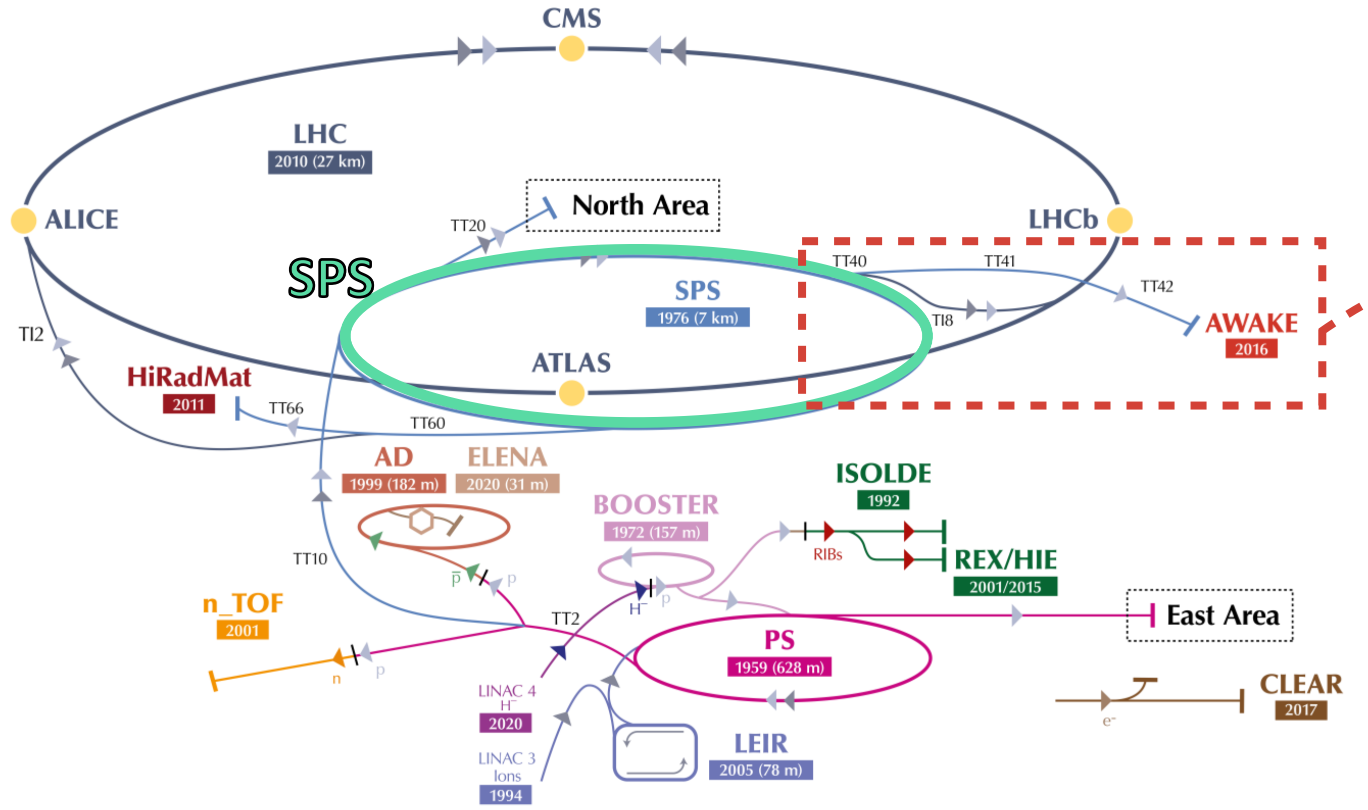
$$\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \varepsilon_0}} \qquad \lambda_{pe} = 2\pi \frac{c}{\omega_{pe}}$$

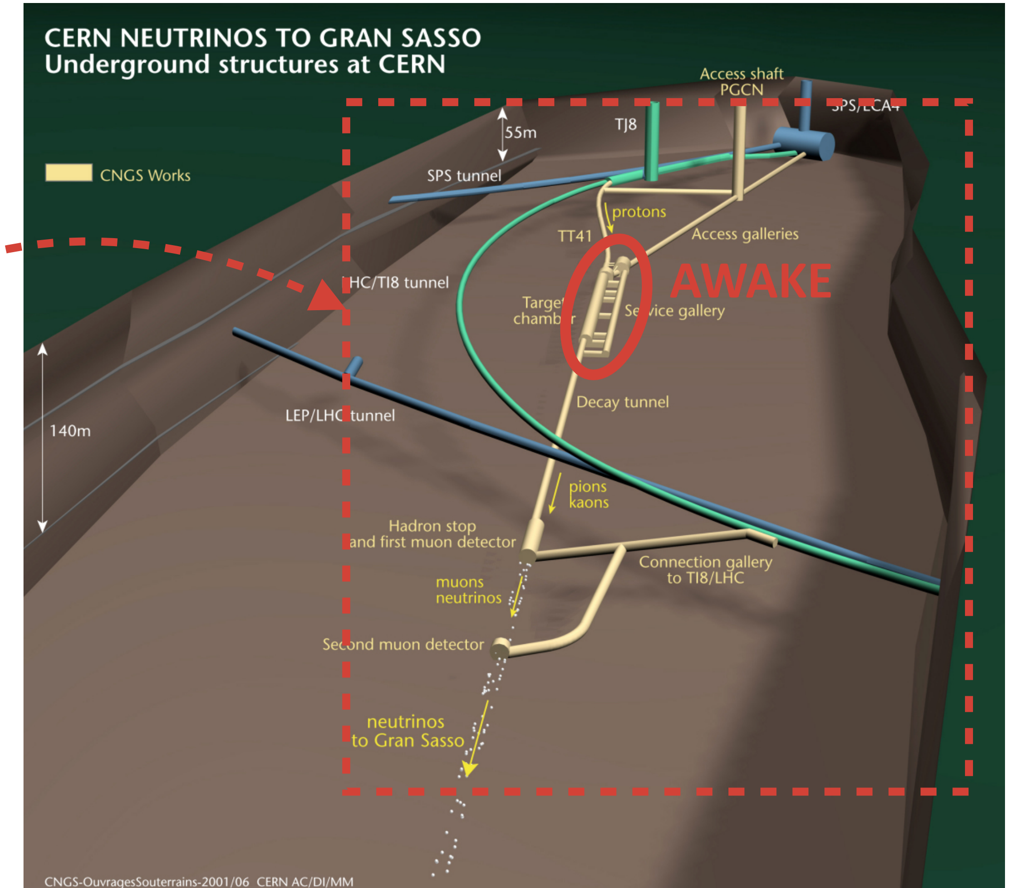
$\omega_{pe} \sim 56000 \sqrt{n_{pe}}$
$\omega_{pe} \sim$ 1.5 THz for n_{pe} = 7E14 cm^{-3}
$\lambda_{pe} \sim$ 1.2 mm for n_{pe} = 7E14 cm^{-3}

- Why protons, instead of electrons or lasers, to load the wakefields in the plasma?
  - **Highest stored energy per bunch** (SPS and LHC : 20 and 300 kJ/bunch)
  - **No need for "staging"** of multiple small accelerators, since $E_p >> E_e$
  - We can use **existing proton beams** to reach the **energy frontier with electrons**!
    - Simulations: SPS p^+ (450 GeV) can lead to 200 GeV e^-. LHC p^+ can yield to 3 TeV e^-

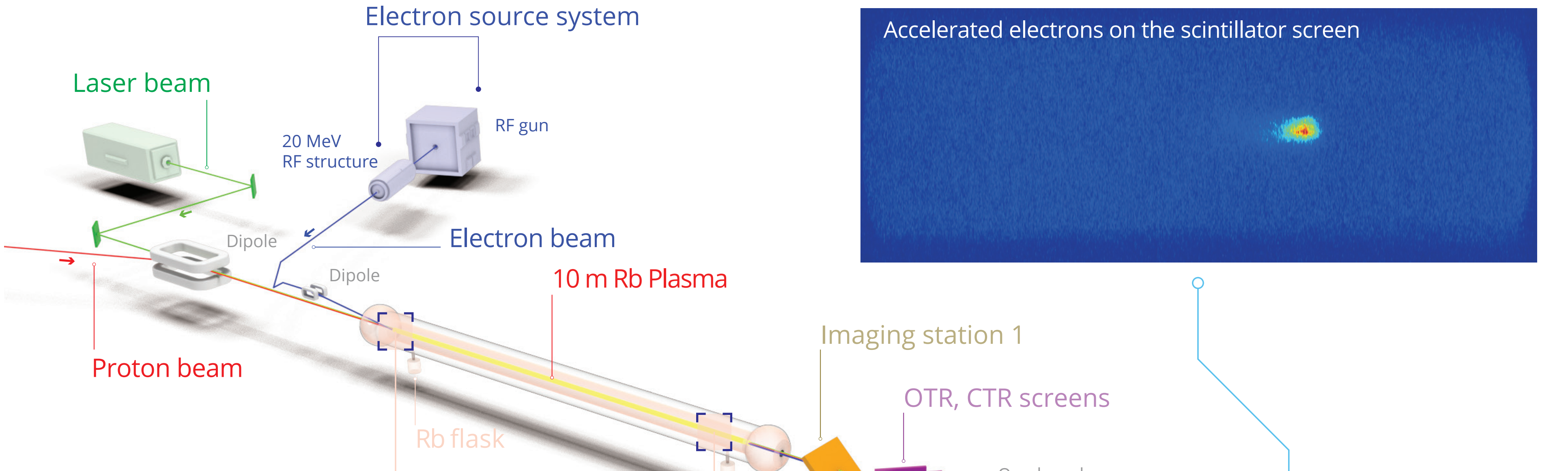
AWAKE at CERN

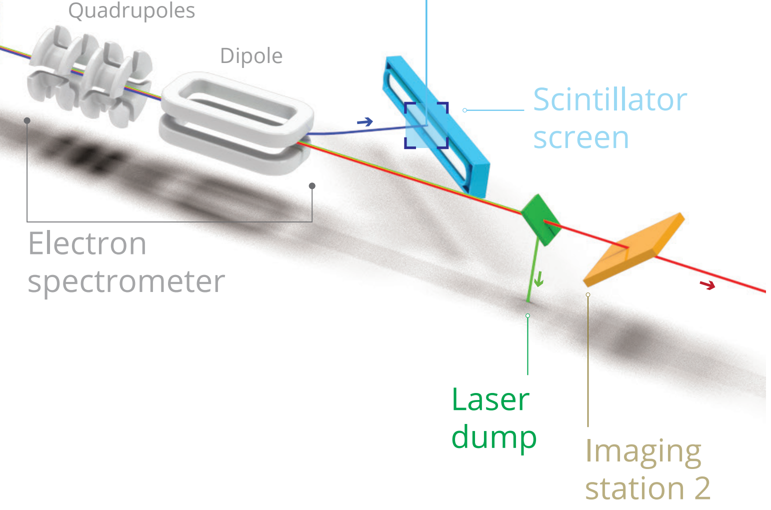
- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Proof of principle R&D experiment to study proton driven acceleration
  - 23 institutes, >100 people. Approved in 2013, electron acceleration in 2018



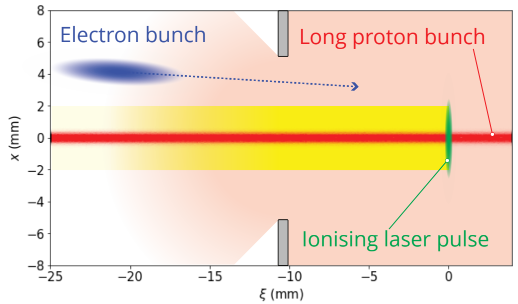


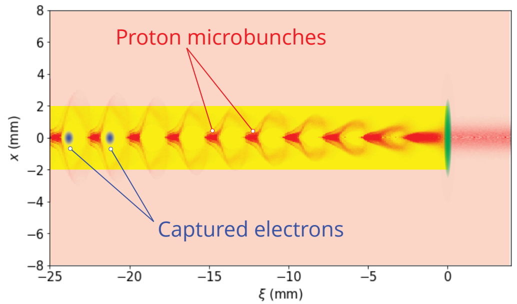
Experimental setup





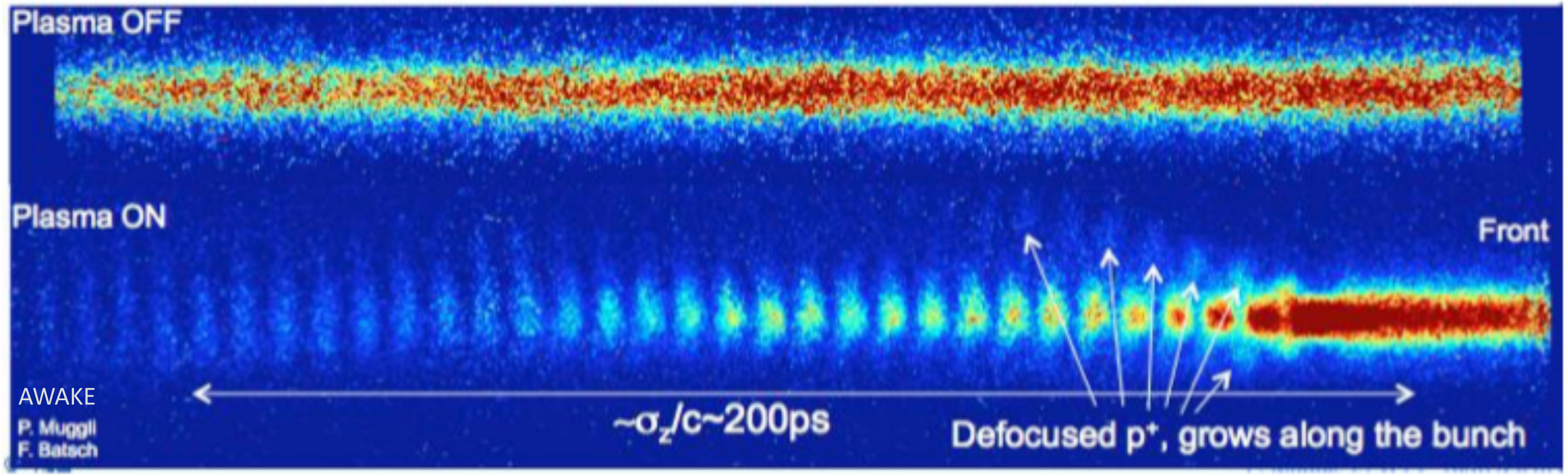
1) **Laser** ionizes Rb vapor, forming a **plasma**
2) Rb plasma creates **micro-bunches in the proton beam**
3) Micro-bunched proton beam excites plasma **wakefields**
4) Wakefields **accelerate and focus electrons**

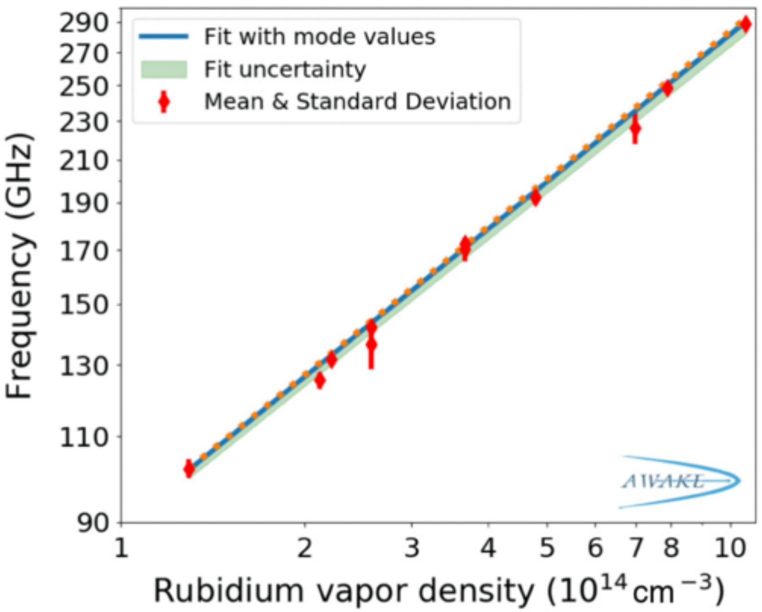




AWAKE Run 1: Milestone #1

- 2016/2017: SELF-MODULATION
  - First seeded self-modulation of a high energy proton bunch in plasma
  - Phase-stability and reproducibility are essential for electron acceleration!
  - —> Demonstration that SPS proton bunch can be used for acceleration <—



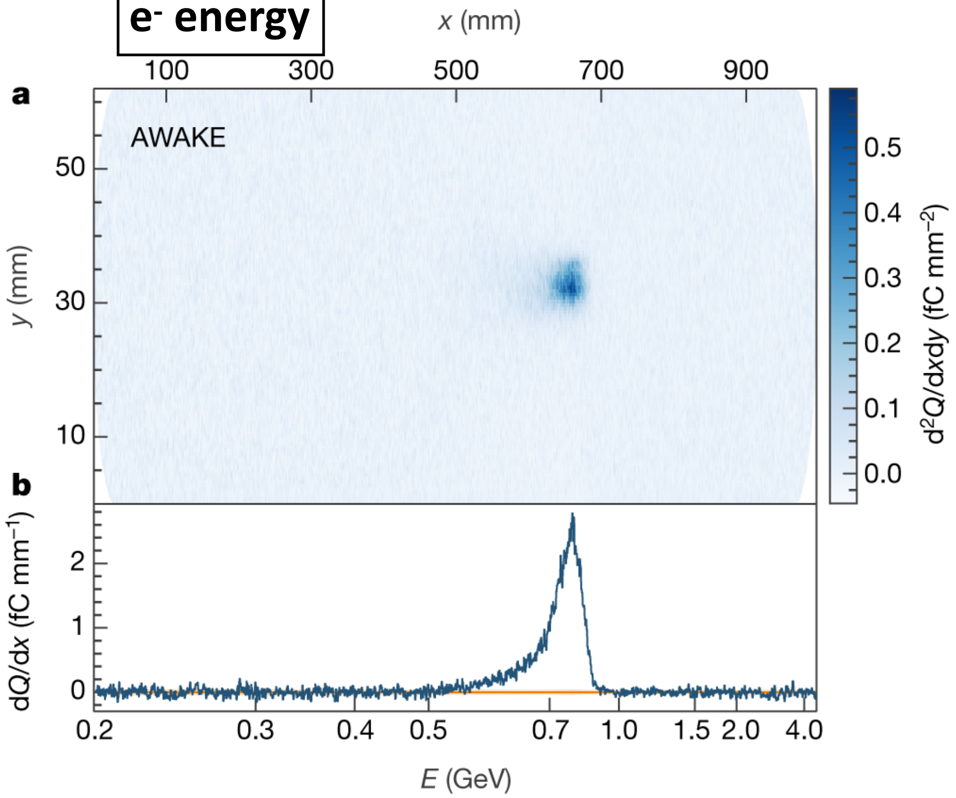


AWAKE Collaboration, Phys. Rev. Lett. 122 (2019) 054801, 054802

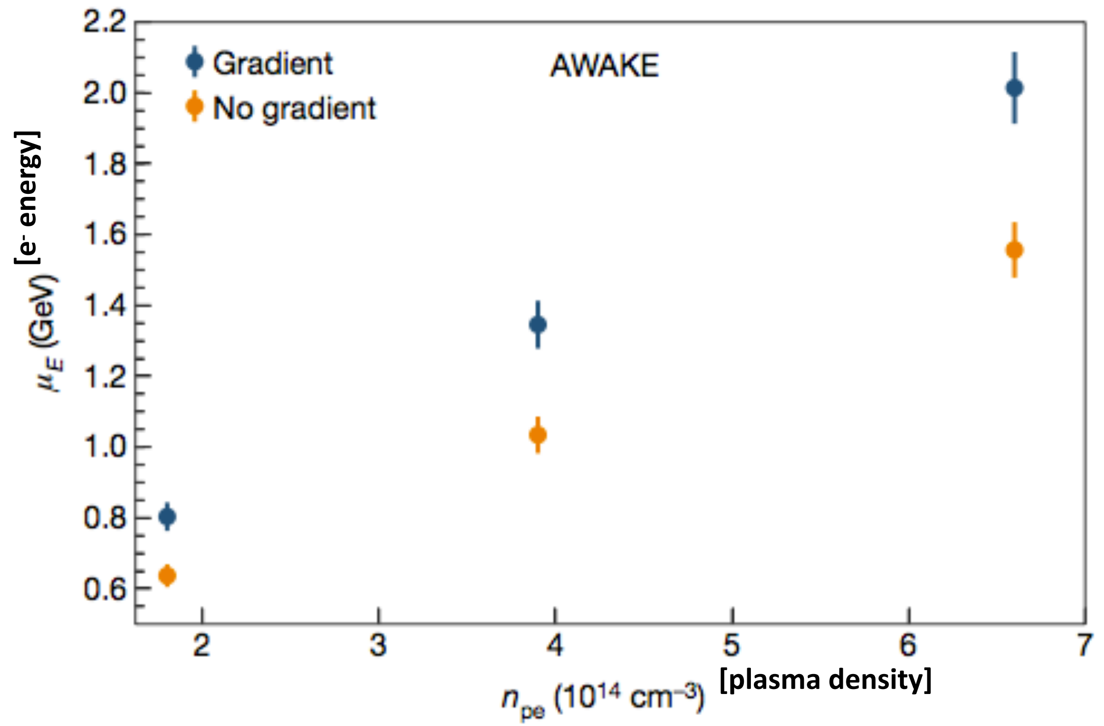
AWAKE Run 1: Milestone #2

- 2018: ACCELERATION: from 19 MeV to 2GeV
  - Inject e- and accelerate to GeV in the wakefield driven by the SPS protons
  - Maximum accelerated charge ~100 pC (~20% of injected)

e- energy



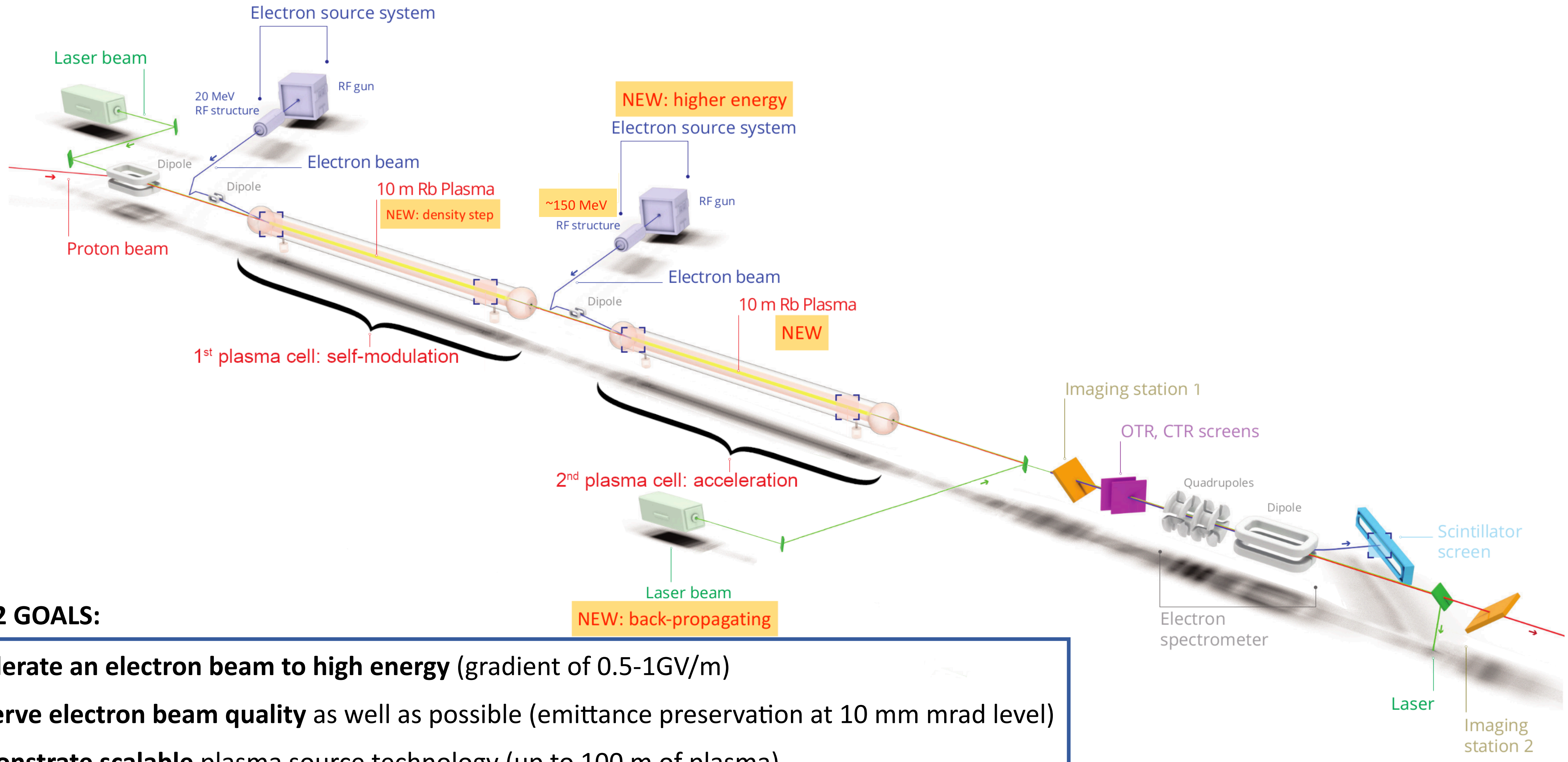
Energy vs plasma density



AWAKE Collaboration, Nature 561, 363 (2018)

The next step: AWAKE Run 2

Demonstrate the possibility to use the AWAKE scheme for high energy physics applications



RUN 2 GOALS:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (up to 100 m of plasma)

AWAKE Run 2: Phases

a. Demonstrate electron seeding of self-modulation in 1st plasma cell
   - Need self-modulation of the entire proton bunch

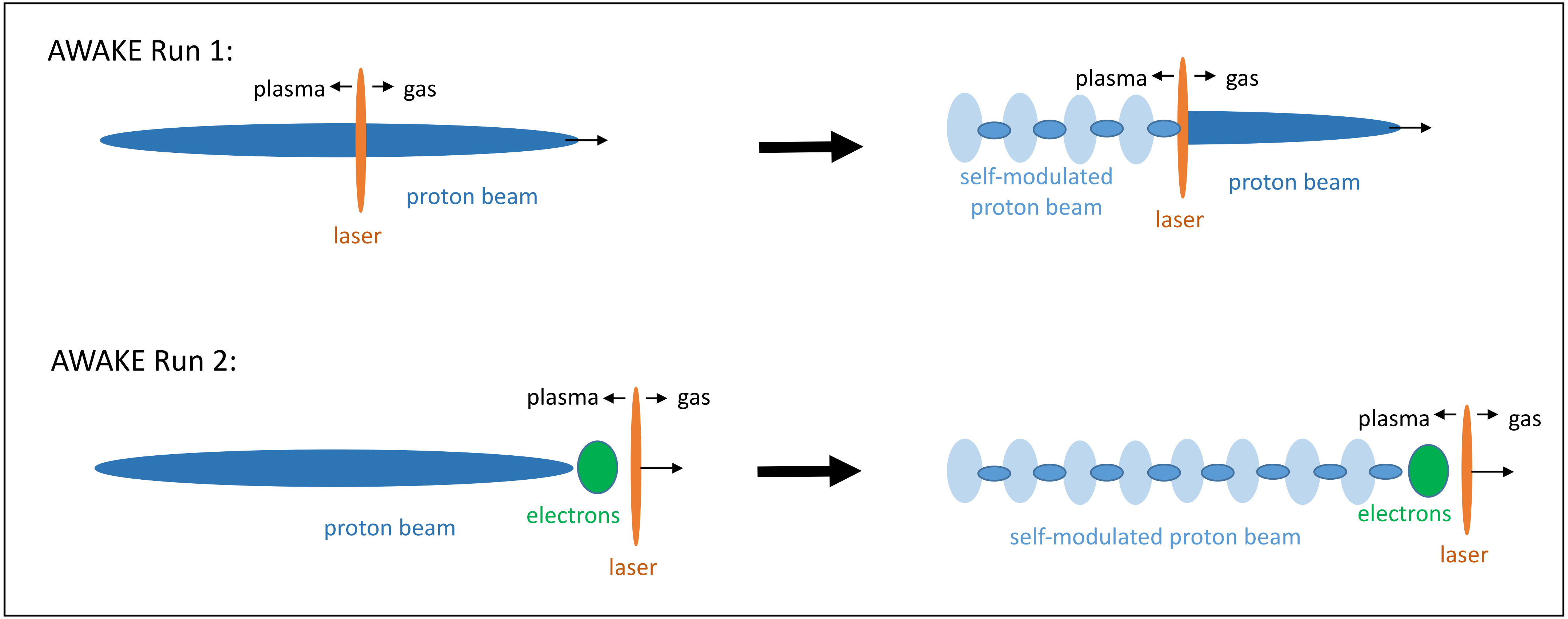
b. Demonstrate the stabilization of the micro-bunches with a density step in 1st plasma cell
   - Show leveling of strong acceleration field

c. Demonstrate electron acceleration and emittance preservation in 2nd plasma cell
   - Simultaneous energy gain and good emittance

d. Develop scalable plasma sources
   - Current method (laser ionization) cannot support O(100) m plasma cells

Run 2a: Self-modulation of entire bunch

a. Demonstrate electron seeding of self-modulation in 1st plasma cell
   - Need self-modulation of the entire proton bunch before entering 2nd cell, to prevent the head of the proton beam from disrupting the wakefields

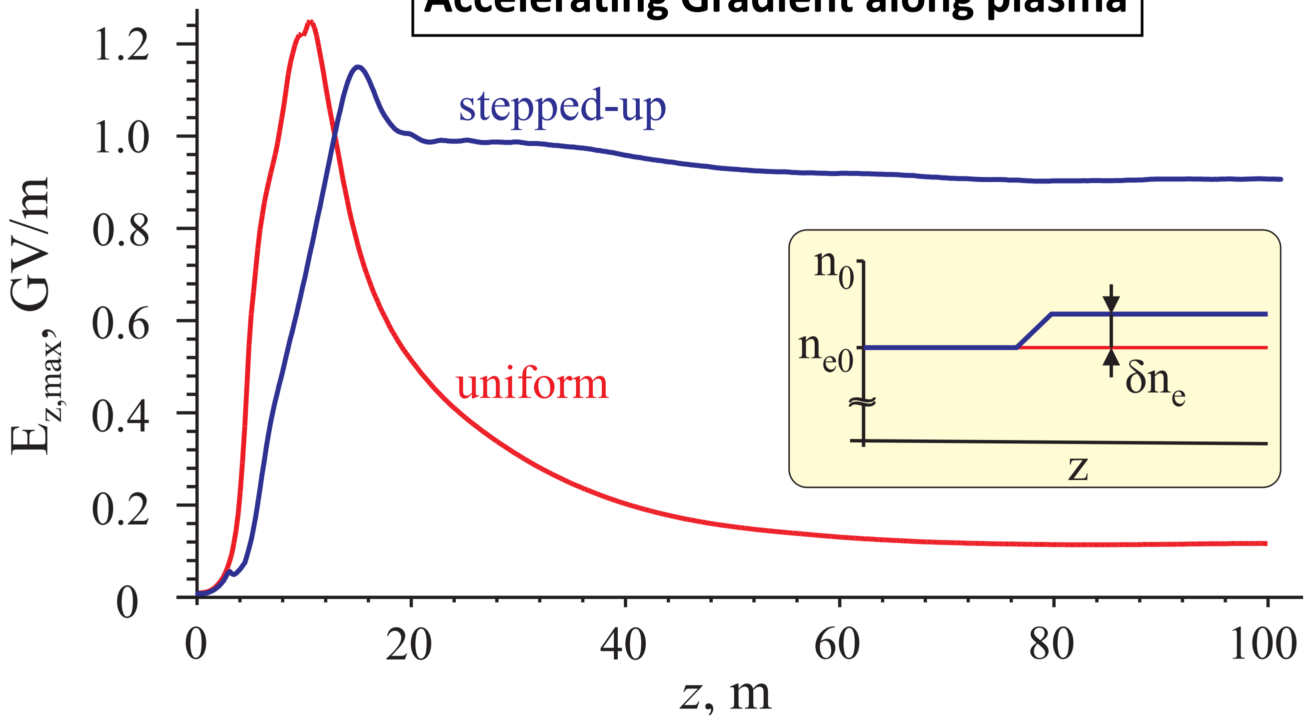


Run 2b: Wakefields preservation

b. Demonstrate the **stabilization** of the micro-bunches with a **density step in 1st plasma cell**

- Self-modulation can eventually destroy the beam
- Simulations predict that we can "freeze" the micro-bunching process by accurately choosing the plasma density profile

Accelerating Gradient along plasma

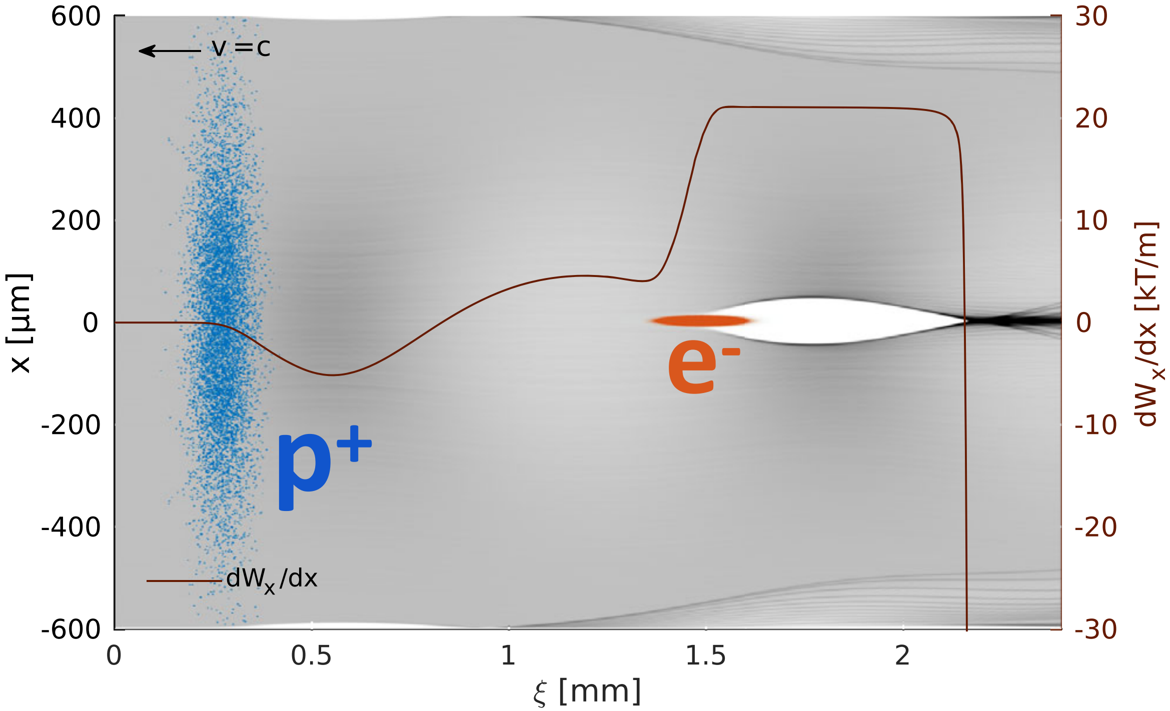


A. Caldwell et al, *Nucl.Instrum.Meth.A* 829 (2016) 3-16

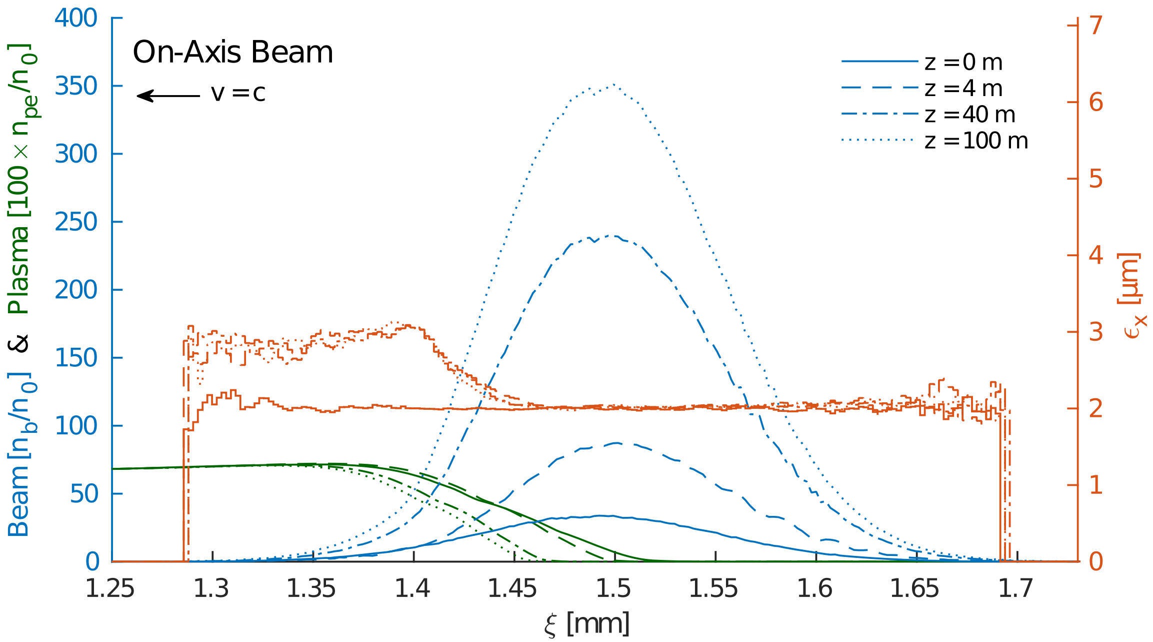
Run 2c: Beam quality

c. Demonstrate electron acceleration and emittance preservation in 2nd plasma cell

- 1: **Match e- beam** transverse properties to the plasma entrance: preserve emittance
- 2: **Blow out regime** (e- density >> Rb density): **linear focusing, ε preservation**
- 3: **Beam loading**: tune the charge/position of e- beam to reach **small δE/E**



Electron bunch emittance



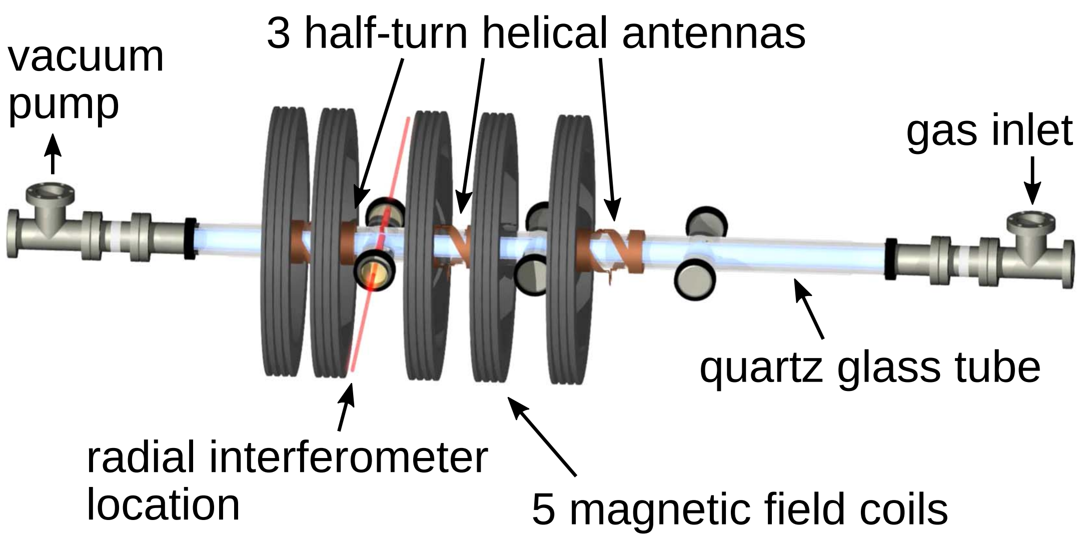
V. K. Berglyd Olsen, E. Adli, P. Muggli, Phys. Rev. Accel. Beams 21, 011301 (2018)

Run 2d: Longer plasma

d. Develop scalable plasma sources

- Current method (laser ionization) cannot support O(100) m plasma cells needed for O(100) GeV
- 'Helicon': low-frequency EM wave generated by RF antennas
- 'Discharge': high-current arc in plasma

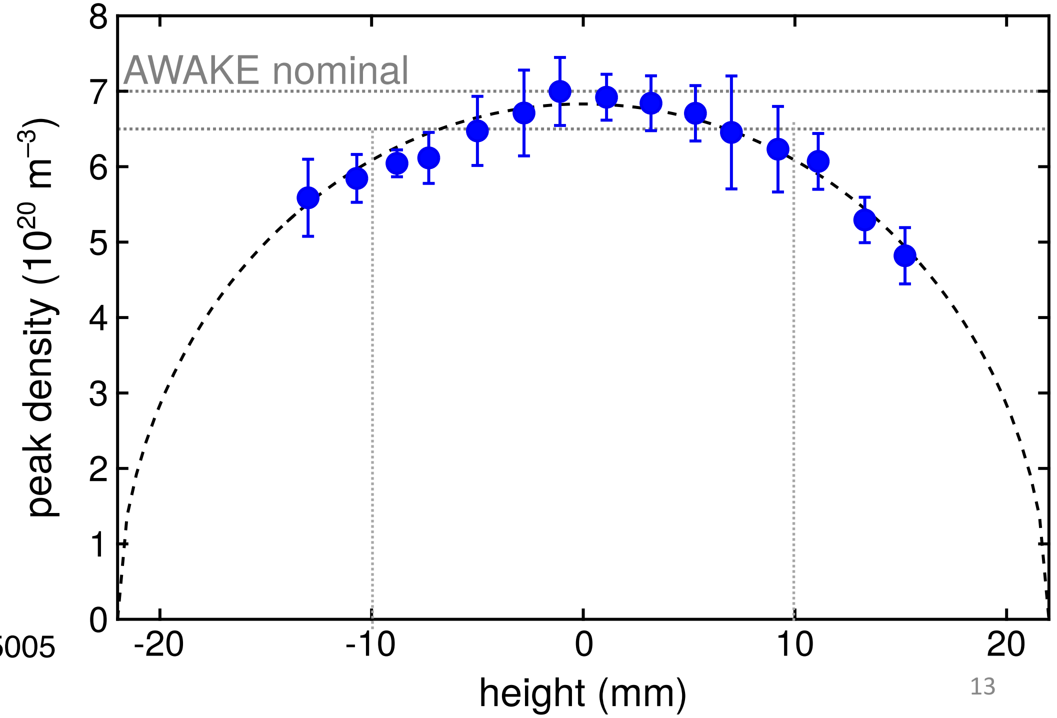
Helicon design



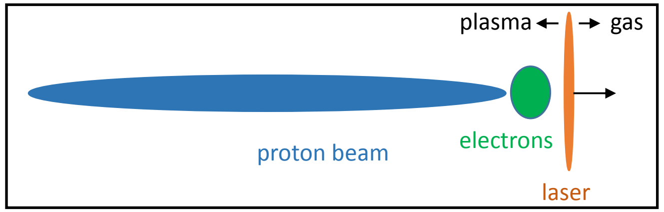
B Buttenschön *et al* 2018 *Plasma Phys. Control. Fusion* **60** 075005

N.E. Torrado et al, submitted for publication (2022)

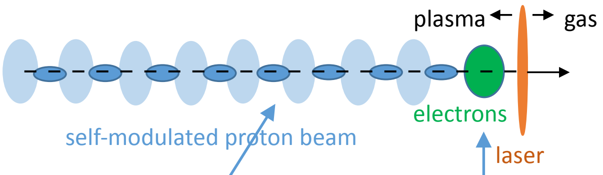
Helicon results: profile/density/timing in line with AWAKE requirements



Run 2a: what can we learn from eSSM?



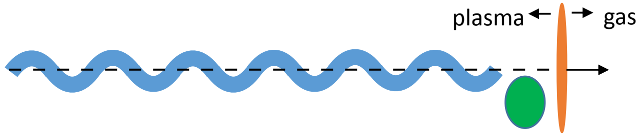
Seeding and growth of **self-modulation**



scan *proton* bunch *charge*

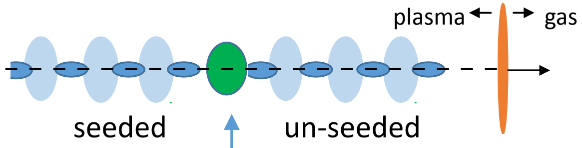
scan *electron* bunch *charge*

Seeding and growth of **hosing**



scan electron bunch *transverse position*

Interplay of **seeded and unseeded** self-modulation



scan electron bunch *longitudinal position*

Key Result of Run 2a

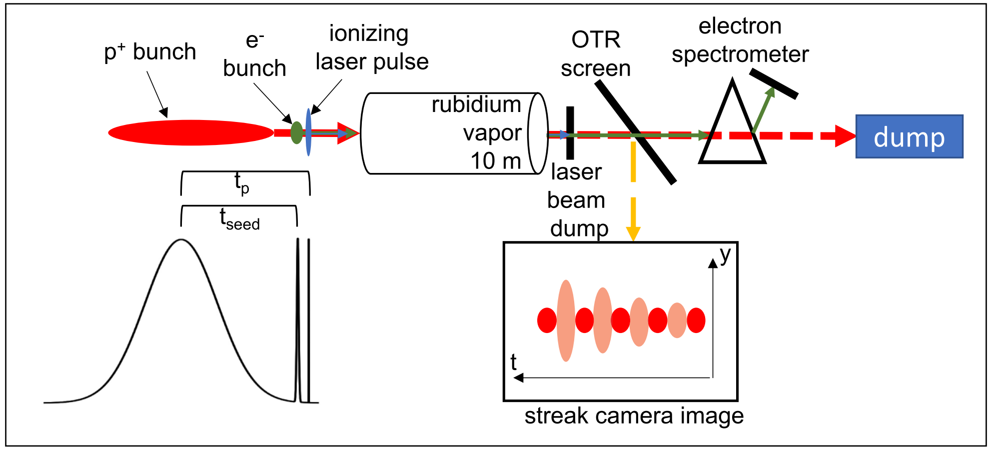
Electron bunch seeding: Reproducibility of SM

- 1) Seeding: transverse wakefields generated by the e^- bunch in plasma
  - Studied in simulations and in experiments without protons

K. Moon *et al*., *Proc. 47th EPS Conference on Plasma Physics*, 2021, http://ocs.ciemat.es/EPS2021PAP/pdf/P3.2014.pdf
L. Verra *et al*., *Proc. 47th EPS Conference on Plasma Physics*, 2021, arXiv:2106.12414
GZDP *et al*., *Proc. IPAC'21*, doi:10.18429/JACoW-IPAC2021- TUPAB160

  - Electron bunch pinches in first few cm, then generates wakefields in the first few meters

- 2) Electron bunch stabilizes SM growth and removes event-to-event phase variations
  - Micro-bunches appear at the same time in consecutive events (r.m.s(ϕ) ~ 7%)
  - Phase (i.e. timing) can be controlled by delaying the electron bunch

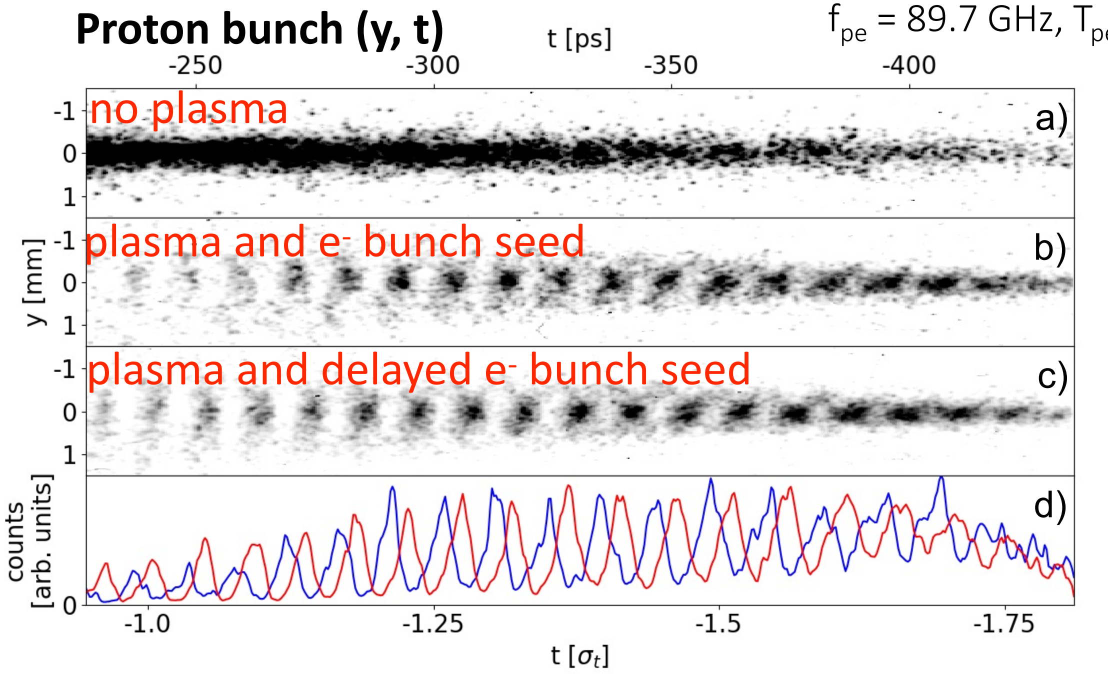


electron bunch:
- Q = 220 pC
- $\varepsilon_N \sim 1$ µm
- $\sigma_r = 0.2$ mm
- $\sigma_t \sim 5$
- E = 19 MeV

proton bunch:
- $N_p = 1\text{-}3 \cdot 10^{11}$
- $\sigma_r = 0.1 - 0.2$ mm
- $\varepsilon_N \sim 1.5\text{-}3.5$ µm
- $\sigma_t \sim 250$ ps
- p = 400 GeV/c

plasma:
$n_{pe} = 1 \cdot 10^{14}$ cm^{-3}

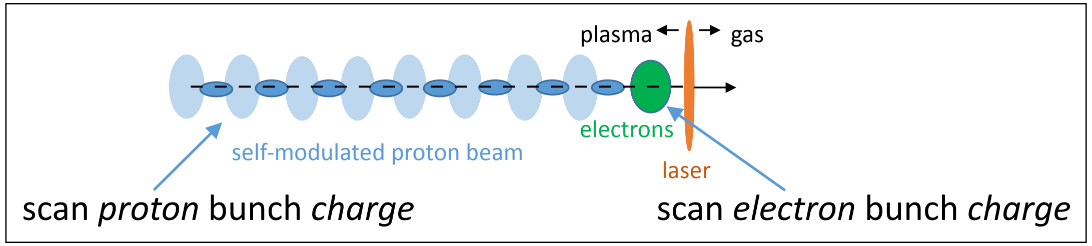
$f_{pe} = 89.7$ GHz, $T_{pe} = 11.1$ ps



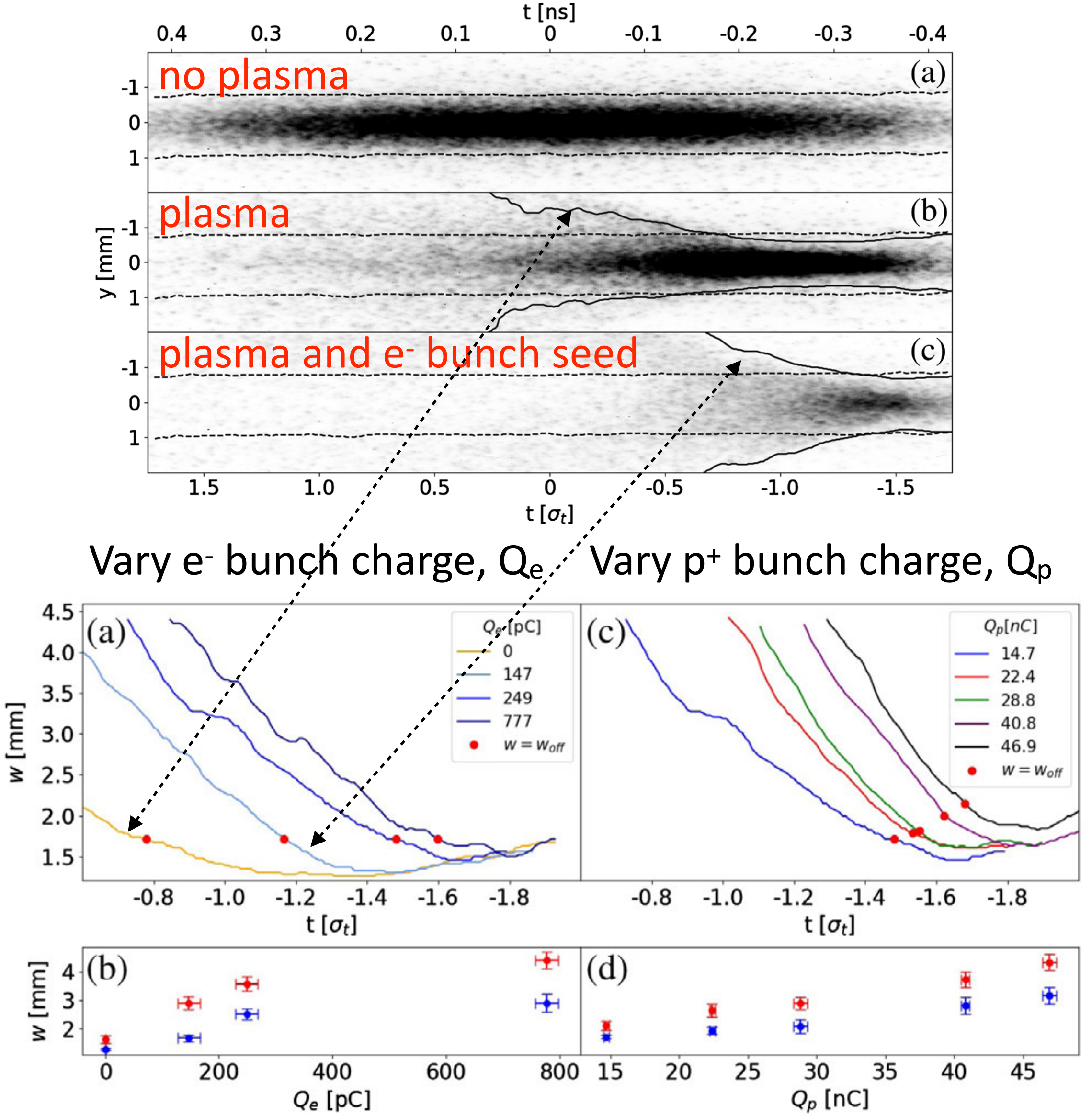
L. Verra, GZDP, *et al*. (AWAKE Collaboration), "Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma", *Phys. Rev. Lett*. 129, 024802 (2022)

Electron bunch seeding: Controlled growth of SM

Key Result of Run 2a



- Longitudinal image of entire proton bunch (at 1 ns timescale) allows to study how SM grows along the bunch
- Defocused protons exit the plasma and propagate in vacuum
  - Their radial extent carries information on the transverse momentum they acquire from wakefields during SM growth
  - Study the "transverse extent" of each time slice, *w*, defined as distance between points reaching 20% max amplitude
- Amplitude of transverse wakefield along bunch and along the plasma :
  - $W_{\perp}(t,z) = W_{\perp 0} \exp\left(\Gamma(t,z) z\right)$
  - Seed wakefield depends on e⁻ bunch charge: $W_{\perp 0}(Q_e)$
  - Growth rate depends on p+ bunch charge: $\Gamma(Q_p)$
  - Use *w* to study $W_{\perp}$
  - *w* increases along the bunch and when increasing either Q_p or Q_e
  - Defocusing starts earlier in the bunch when increasing Q_p and Q_e



L. Verra, GZDP, *et al*. (AWAKE Collaboration), "Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma", *Phys. Rev. Lett*. 129, 024802 (2022)

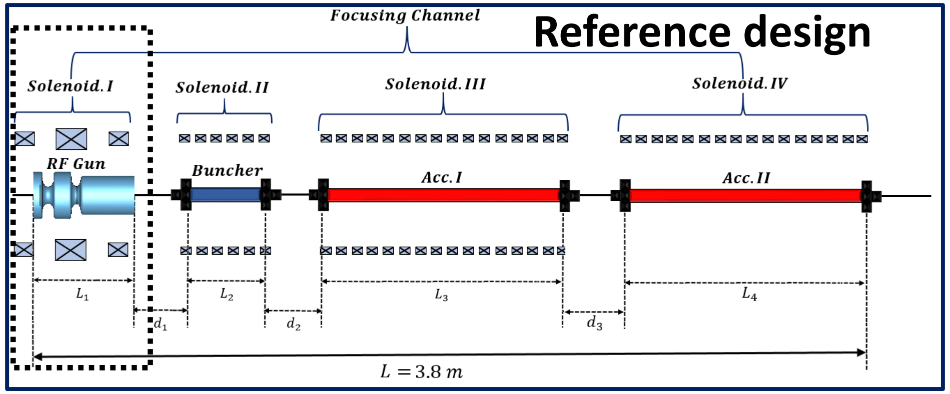
Run 2c e⁻ Source Design

- Stringent electron beam parameters to satisfy blow-out, beam-loading, optical matching as required by Run 2c
  - E: 150 MeV, ΔE/E < 0.2 %
  - Normalized Emittance: 2 mm mrad
  - Bunch length: 200 fs

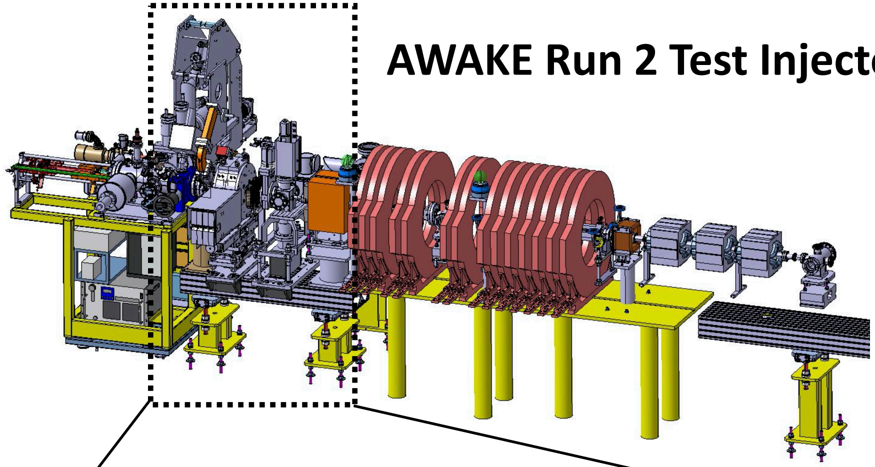
- Reference design:
  - Electron gun: S-band RF gun developed by INFN
  - RF Buncher: 25 cm X-band (2 ps —> 200 fs)
  - Accelerator: two 1 m X-band structures with 80 MV/m, embedded in solenoidal B field
- Details of design optimization:

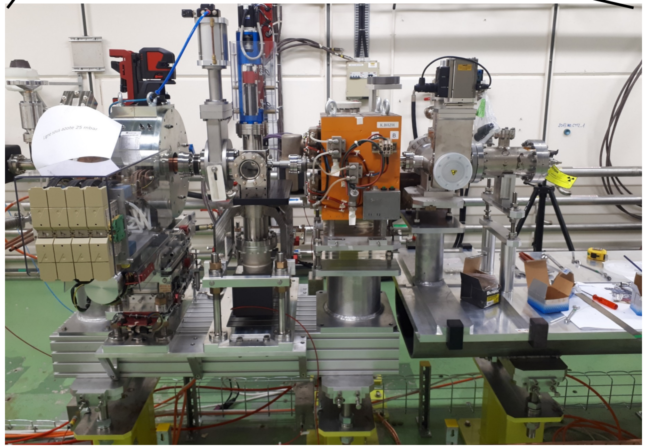
Poster and proceedings by J. M. Arnesano and S. Doebert (TUPOPA24)

"Design of an X-Band Bunching and Accelerating System for the AWAKE Run 2"



AWAKE Run 2 Test Injector

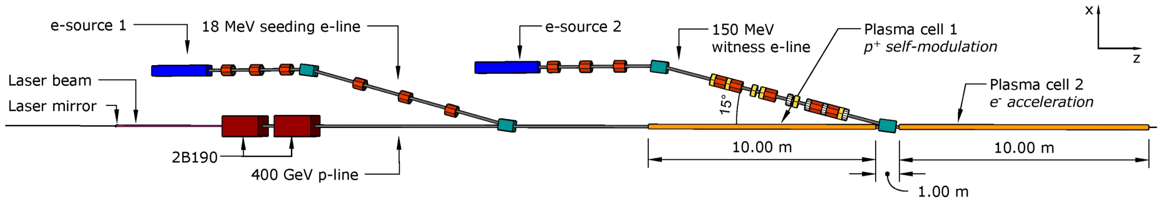




D. Alesini *et al.*, *Phys. Rev. Accel. Beams* 21, 112001 (2018)

K. Pepitone *et al.*, *NIM-A* 909, 102-106 (2018). doi:10.1016/j.nima.2018.02.044

Run 2c e- Beamline Design

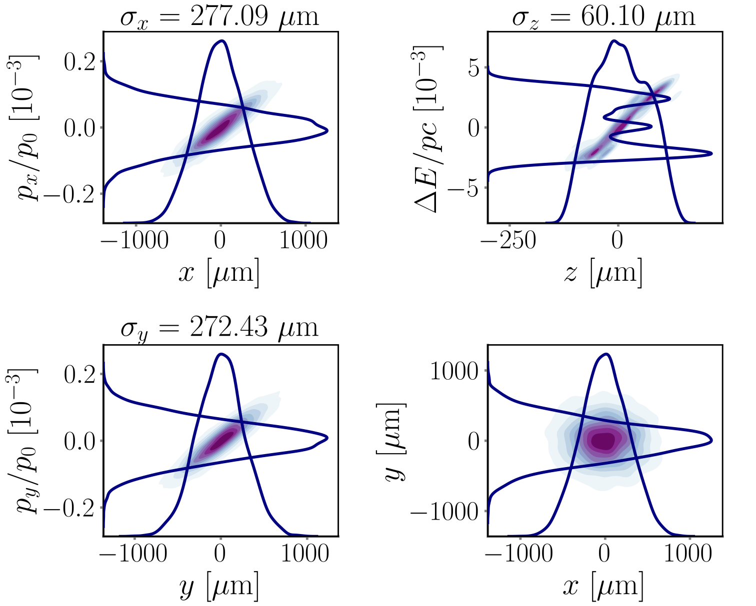


- 25 m transfer line with 15º dog-leg
- Simulation: electron source simulation output sent to 6D particle tracking in MAD-X
- Optimization, part 1: Genetic Algorithm for initial design (2 dipoles, 8 quadrupoles)
  - + : bunch is shortened (initial ΔE/z correlation from e- source)
  - - : bunch is widened due to chromatic effects

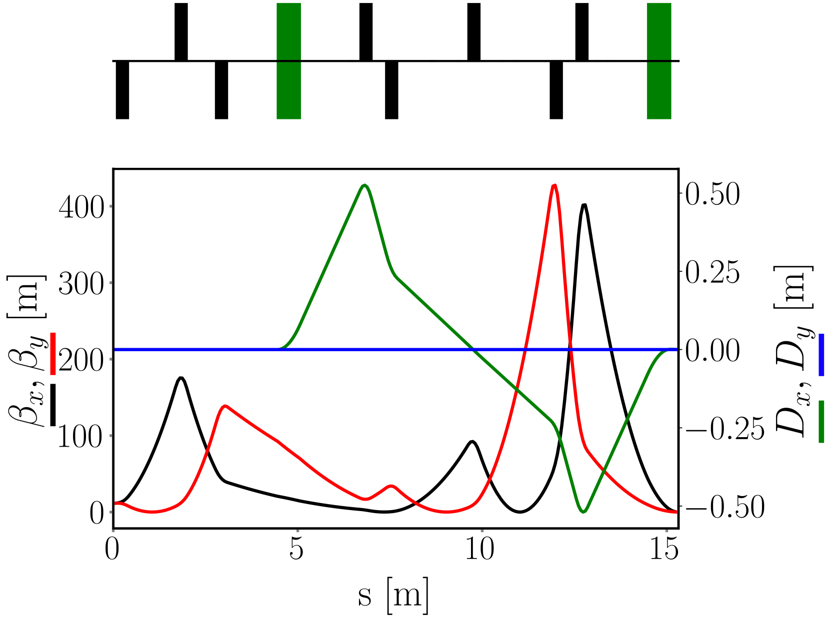
Design parameters at injection

Parameter	Specification
$\beta_{x,y}$	4.87 mm
$\alpha_{x,y}$	0.0
$D_{x,y}$	0 m
$\sigma_{x,y}$	5.75 µm
σ_z	60 µm
$\epsilon_{x,y}$	2 mm mrad

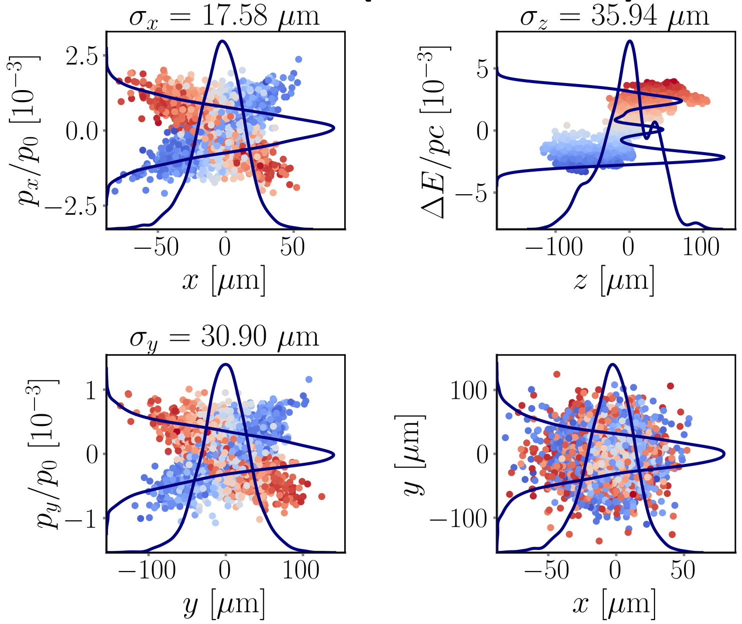
INPUT (from e- source simulation)



Optics, beta, dispersion along the line

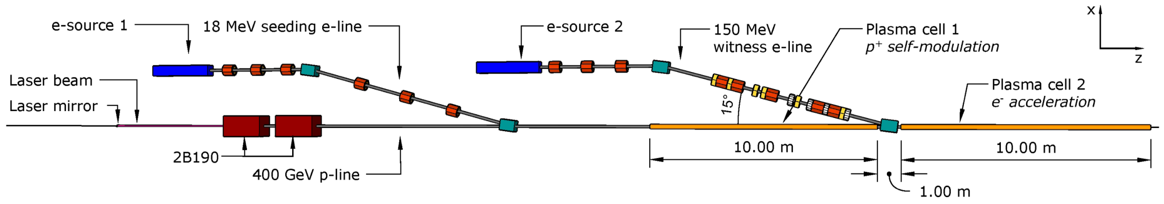


OUTPUT (from MAD-X)



R. Ramjiawan *et al.*, submitted for publication (2022). arXiv:2203.01605

Run 2c e- Beamline Design

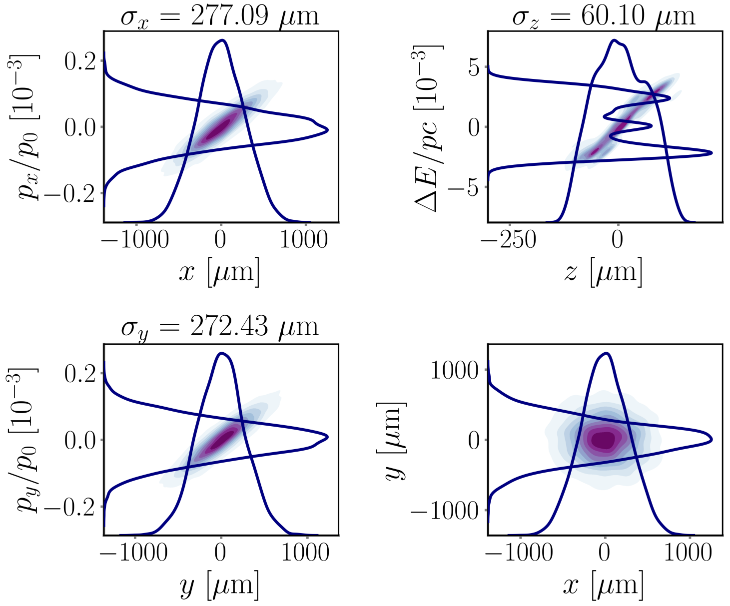


- Optimization, Part 2: sextupoles and octupoles
  - Address chromatic effects
  - Position and strength optimized numerically (Powell algorithm)
- Estimated effect of misalignments of all optical elements, and developed 1 µm level alignment procedure to avoid $\sigma_{x,y}$ growth
- —> Achieved the challenging experimental requirements for Run 2c <—

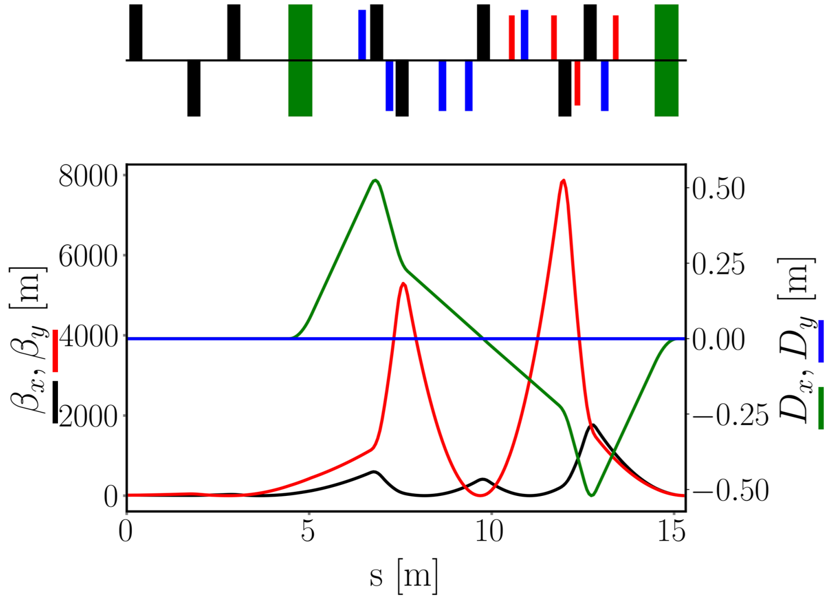
Design parameters at injection

Parameter	Specification
$\beta_{x,y}$	4.87 mm
$\alpha_{x,y}$	0.0
$D_{x,y}$	0 m
$\sigma_{x,y}$	5.75 µm
σ_z	60 µm
$\epsilon_{x,y}$	2 mm mrad

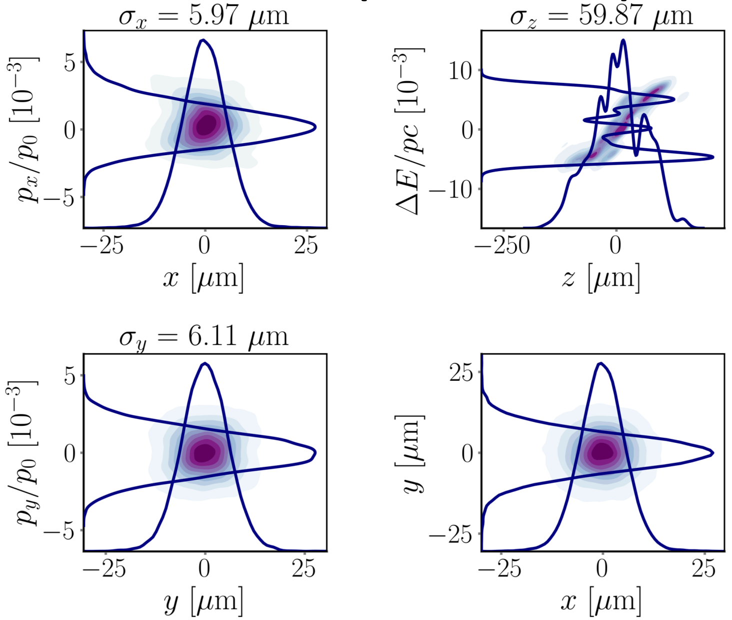
INPUT (from e- source simulation)



Optics, beta, dispersion along the line



OUTPUT (from MAD-X)



R. Ramjiawan *et al.*, submitted for publication (2022). arXiv:2203.01605

Conclusions

- AWAKE was created to test a new idea for electron acceleration
  - Use plasma to transfer energy from protons to electrons and potentially reach the electron energy frontier
- So far, in Run 1 and Run 2a, all expectations have been met
  - The rest of Run 2 aims to demonstrate the possibility to use the AWAKE scheme for high energy physics applications
- AWAKE Run 2 is the path towards future physics applications
  - First: fixed target experiments, i.e. search for dark photon
  - Next step: electron-proton or electron-ion colliders
  - Complementary to other plasma wakefield projects/experiments: European Strategy for Particle Physics "Accelerator R&D Roadmap"