Starting up AWAKE Run 2: operating the facility during LS2 and first results of the 2021 proton run

Giovanni Zevi Della Porta (CERN)

Accelerators and Technology Sector (ATS) Seminar

https://indico.cern.ch/event/1129691/

1 March 2022

Outline

- Introduction to AWAKE
    - Run 1 achievements
    - Plan for Run 2
- Run 2 preparation during the Long Shutdown 2 (2019-2020)
    - Laser ionization and plasma formation
    - Electron Beam: human and machine learning
    - Electron seeding in plasma: preparation for Run 2a
    - Performance: Alignment and Data Quality
- The 2021 proton run
    - Run 2a (2021-2022) physics goals
    - Preliminary results
- What's next?
    - 2022 proton run goals
    - Beyond Run 2: physics applications

Outline

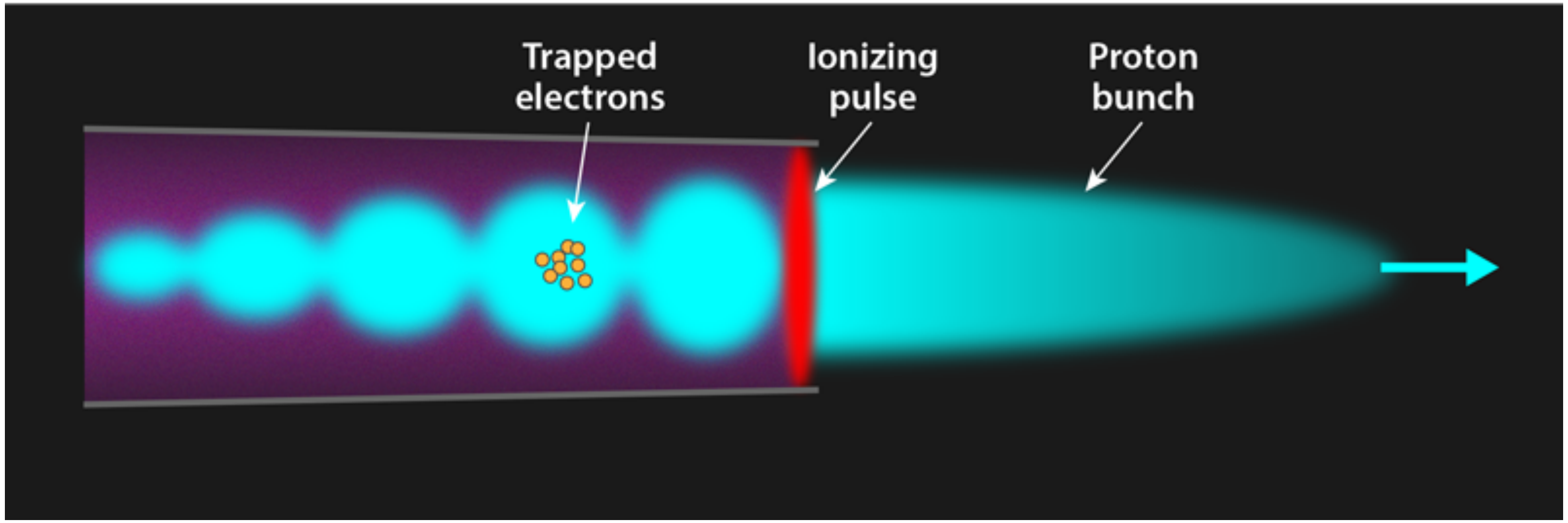
- Introduction to AWAKE
  - Run 1 achievements
  - Plan for Run 2
- Run 2 preparation during the Long Shutdown 2 (2019-2020)
  - Laser ionization and plasma formation
  - Electron Beam: human and machine learning
  - Electron seeding in plasma: preparation for Run 2a
  - Performance: Alignment and Data Quality
- The 2021 proton run
  - Run 2a (2021-2022) physics goals
  - Preliminary results
- What’s next?
  - 2022 proton run goals
  - Beyond Run 2: physics applications

Plasma wakefield acceleration, with a proton driver

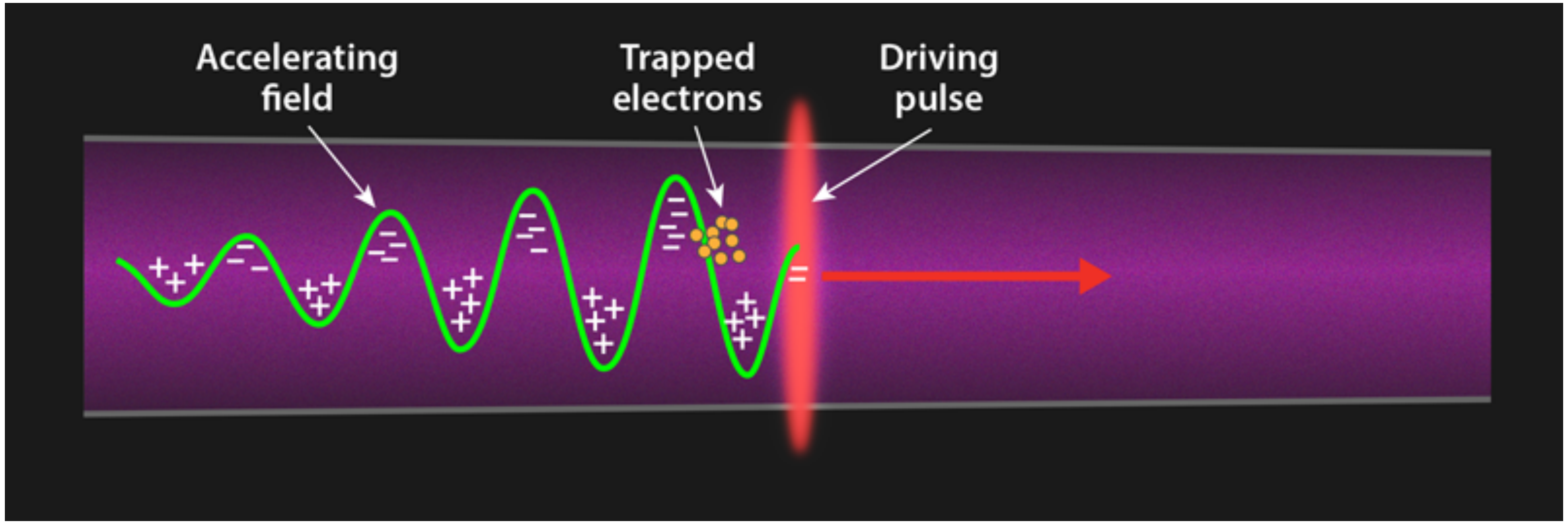
1) **Laser** ionizes gas, forming **plasma**

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

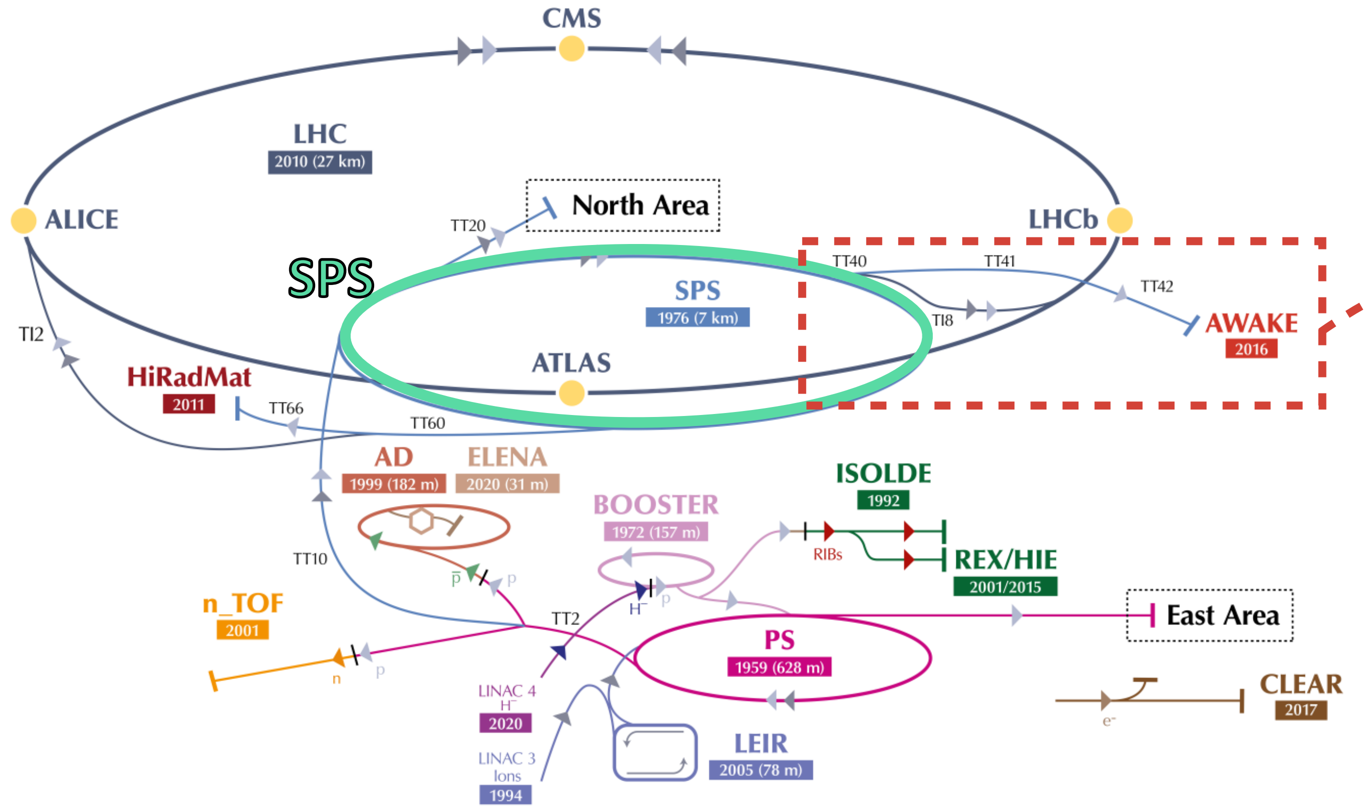
- Why plasma instead of a (superconducting) RF cavity?
  - **Higher fields**: can sustain more MV/m, leading to shorter accelerators
    - Metallic structures of RF accelerators break down at around 100 MV/m
  - **Self-focusing**: plasma can provide focusing fields, as well as accelerating

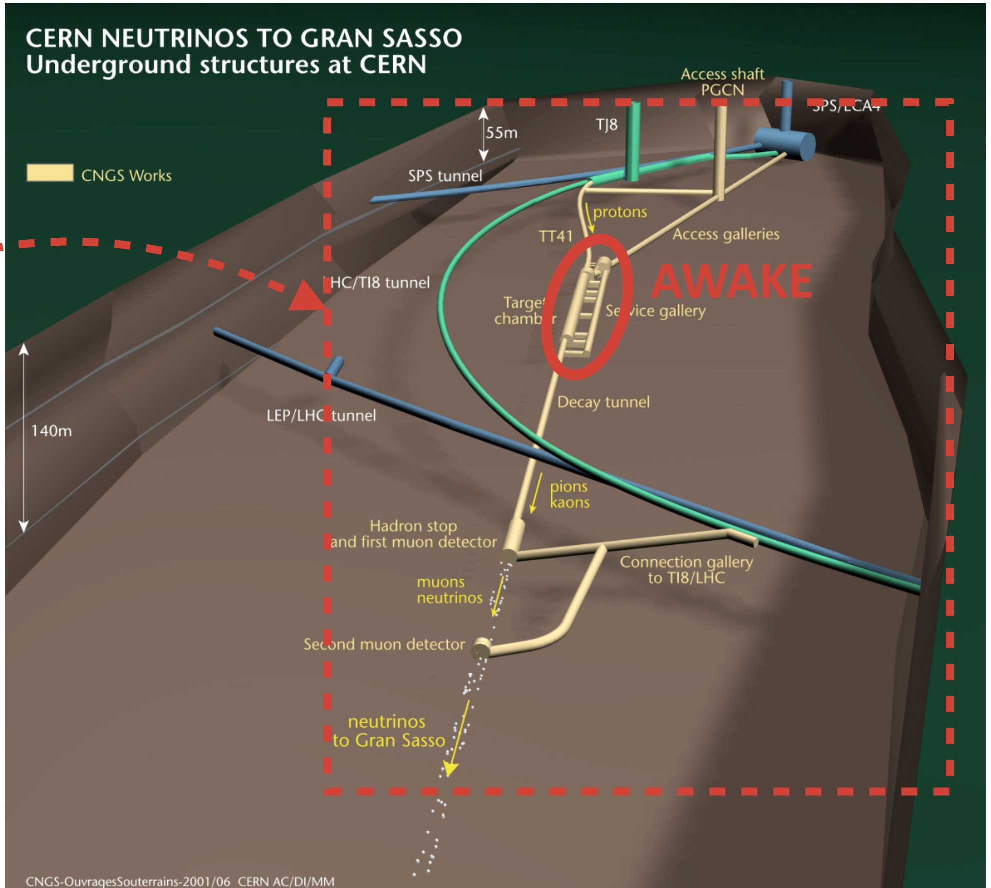
- Plasma wakefield acceleration has been studied since the 80's, but never with protons
  - Proton beams are rare, and the existing ones are very long, requiring self-modulation to scale their size down to the plasma wavelength
  - AWAKE is the only experiment exploring this possibility

- 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^-

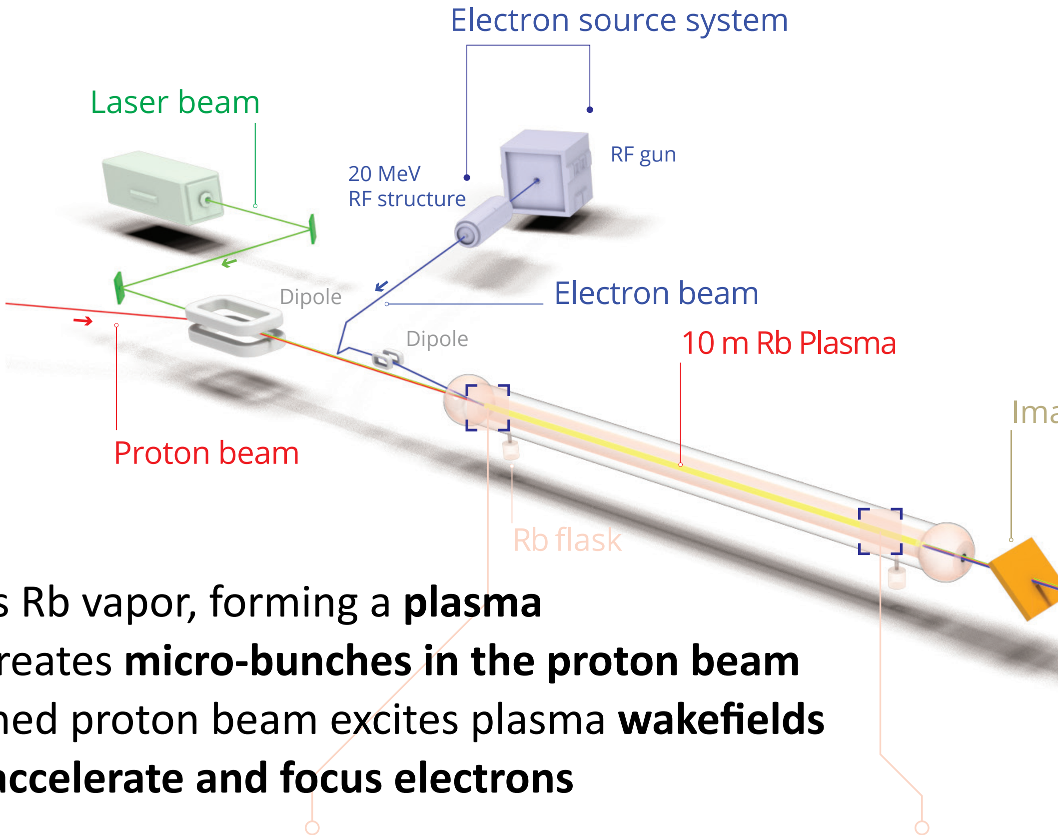
AWAKE at CERN

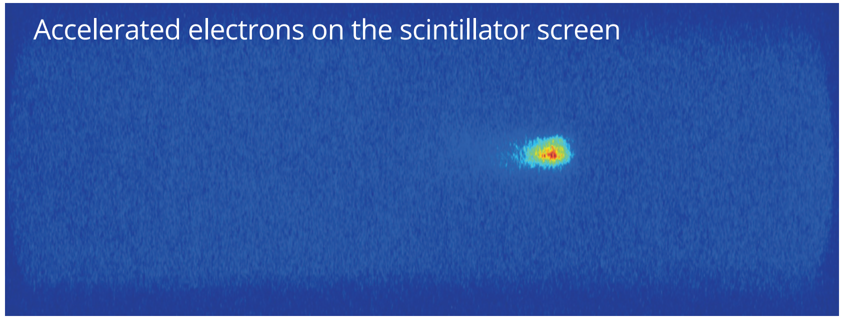
- AWAKE: **A**dvanced Proton Driven Plasma **Wake**field Acceleration Experiment
  - Proof of principle R&D experiment to study proton driven acceleration
  - 23 institutes, >100 people. Approved in 2013, electron acceleration in 2018



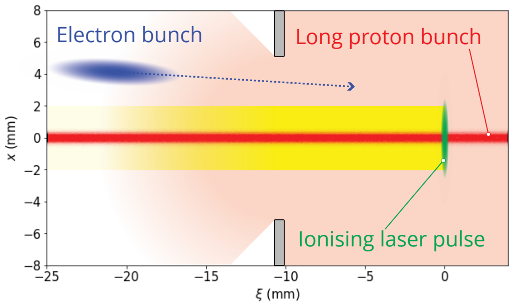


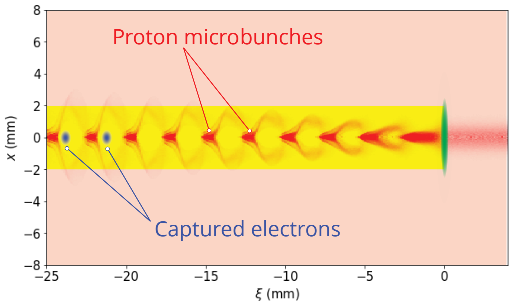
Experimental setup





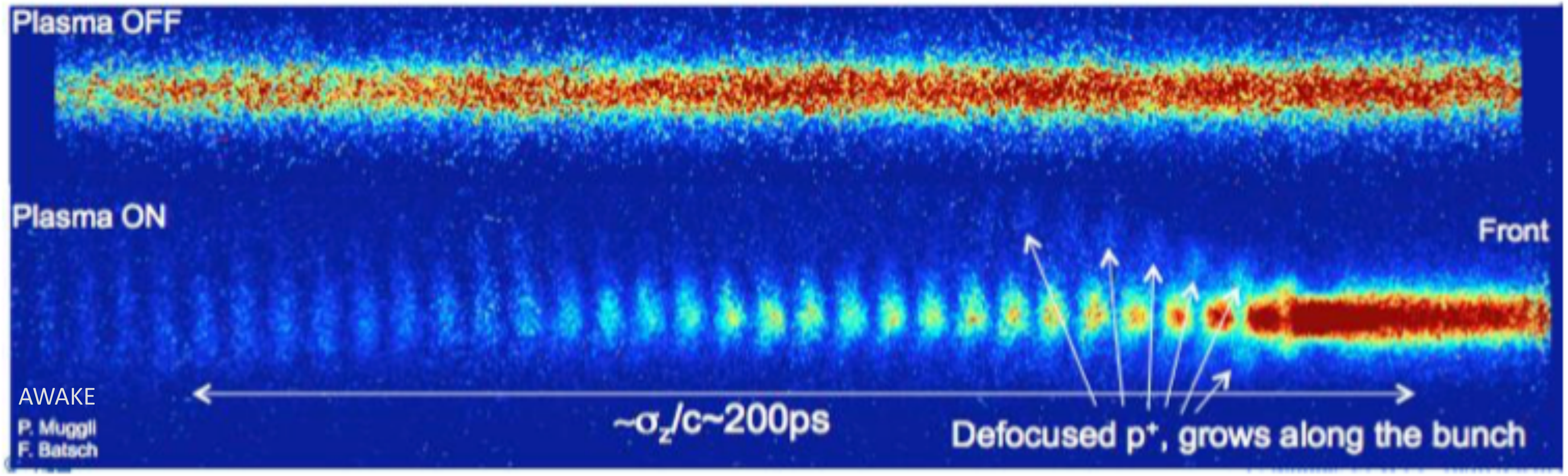
1) **Laser** ionizes Rb vapor, forming a **plasma**
2) Rb plasma creates **micro-bunches in the proton beam**
3) Micro-bunched proton beam excites plasma **wakefields**
4) Wakefields **accelerate and focus electrons**

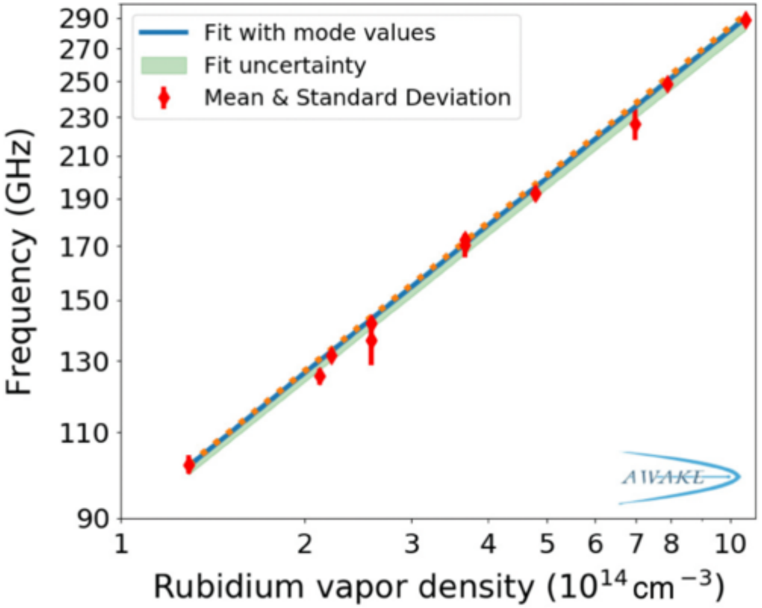




AWAKE Run 1: Milestone #1

- 2016/2017: SELF-MODULATION
  - First <u>seeded</u> self-modulation of a high energy proton bunch in plasma
  - <u>Phase-stability</u> and reproducibility are essential for electron acceleration!
  - —> SPS BUNCH CAN BE USED FOR ACCELERATION <—

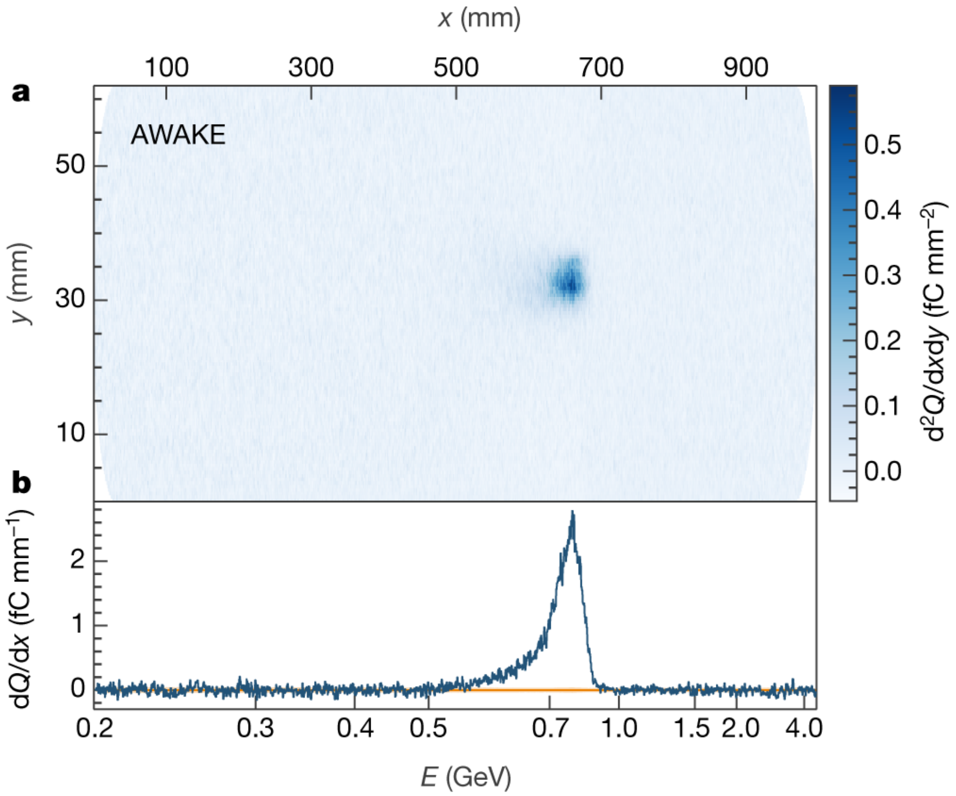


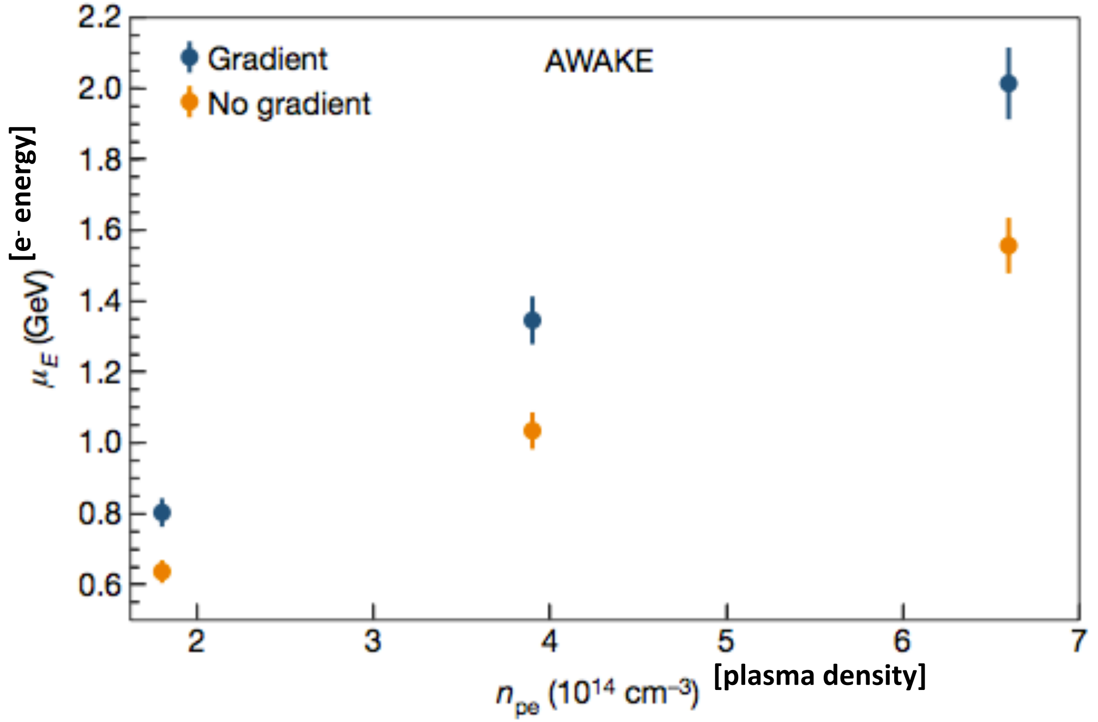


Phys. Rev. Lett. 122 (2019) 054801, 054802

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)





Nature 561, 363 (2018)

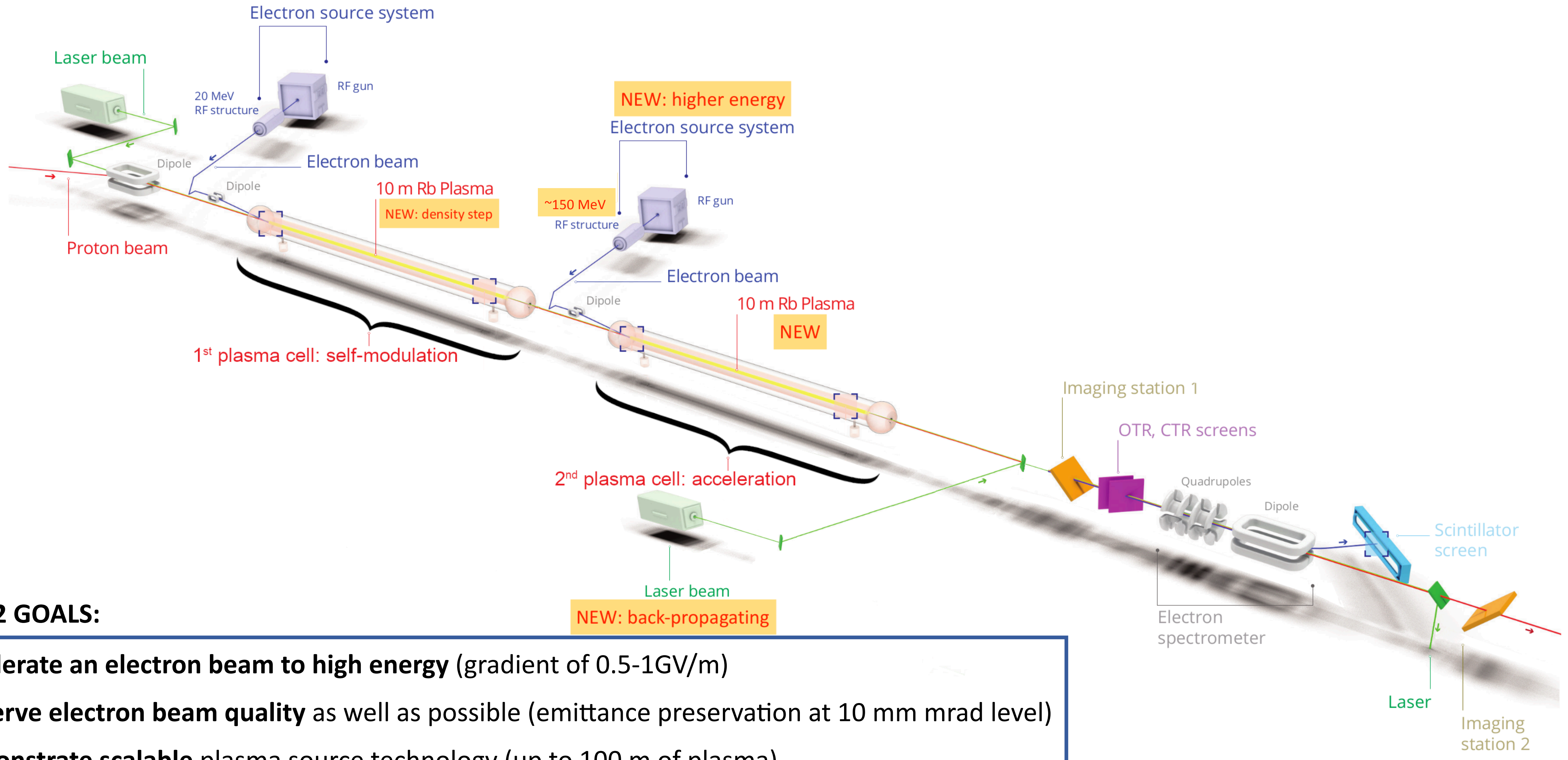
AWAKE Run 1: a broad scientific output

- Explore the large parameter space allowed by AWAKE
  - Characterize experimental setup (laser, e^- beam, diagnostics)
  - Understand how self-modulation starts and grows
  - Optimize charge and energy in electron acceleration

- Recent output (2018-2022)
  - ≥ 12 peer-reviewed journal papers by the AWAKE Collaboration
  - ≥ 30 peer-reviewed journal papers by subsets of AWAKE authors
  - ≥ 30 conference presentations/proceedings
  - ≥ 7 Master or PhD theses

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

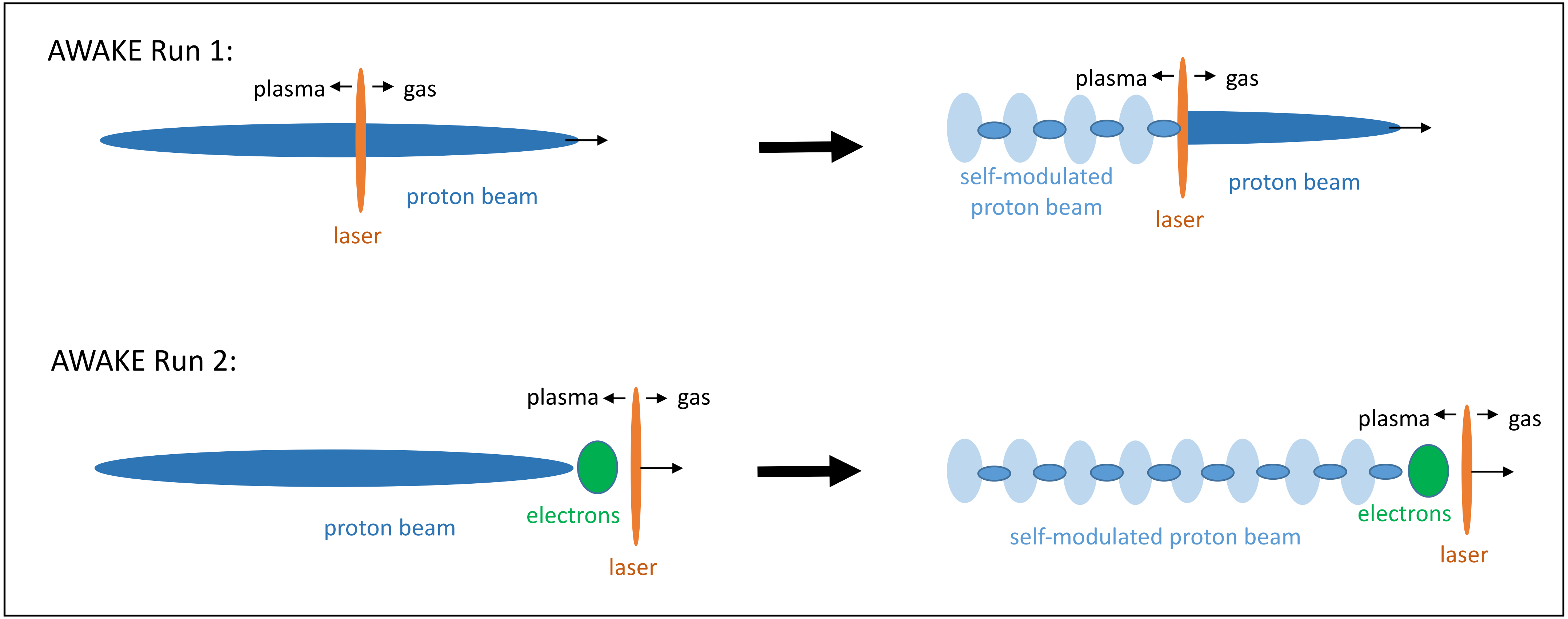
b. Demonstrate the stabilization of the micro-bunches with a density step in 1st plasma cell
    - Show levelling of strong acceleration field

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

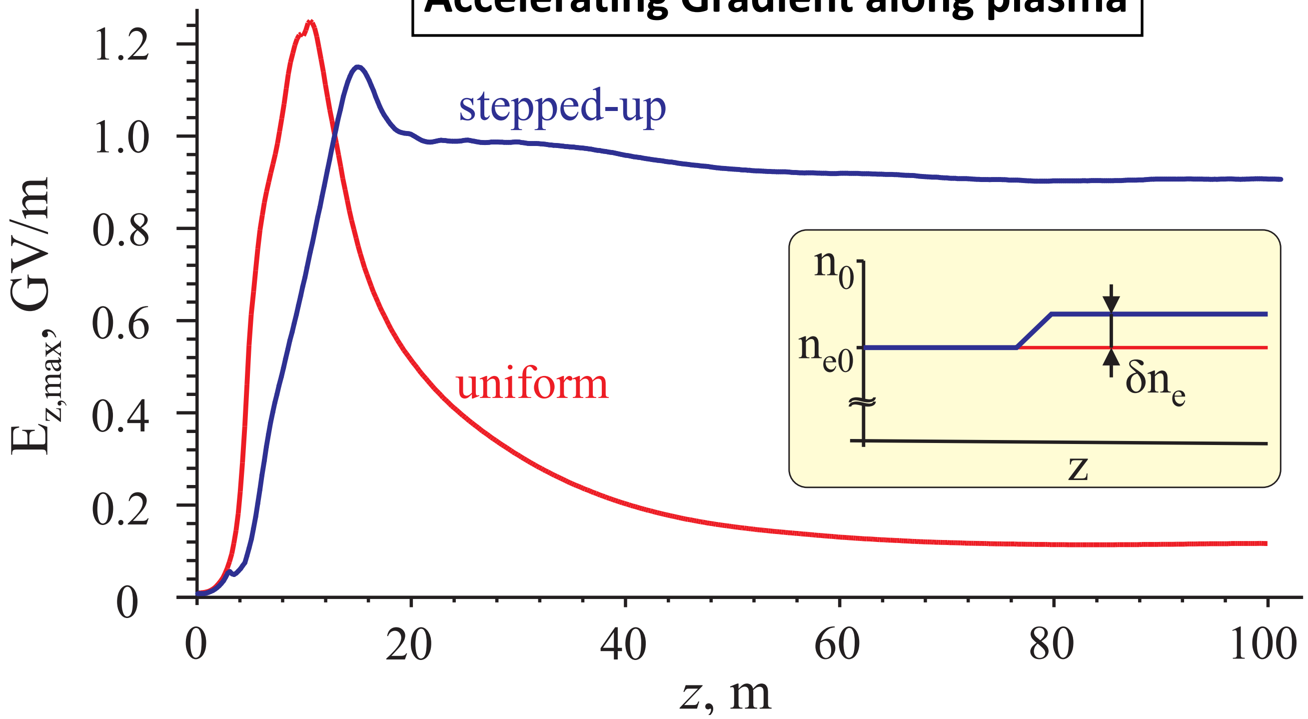


Run 2b: wakefields preservation

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

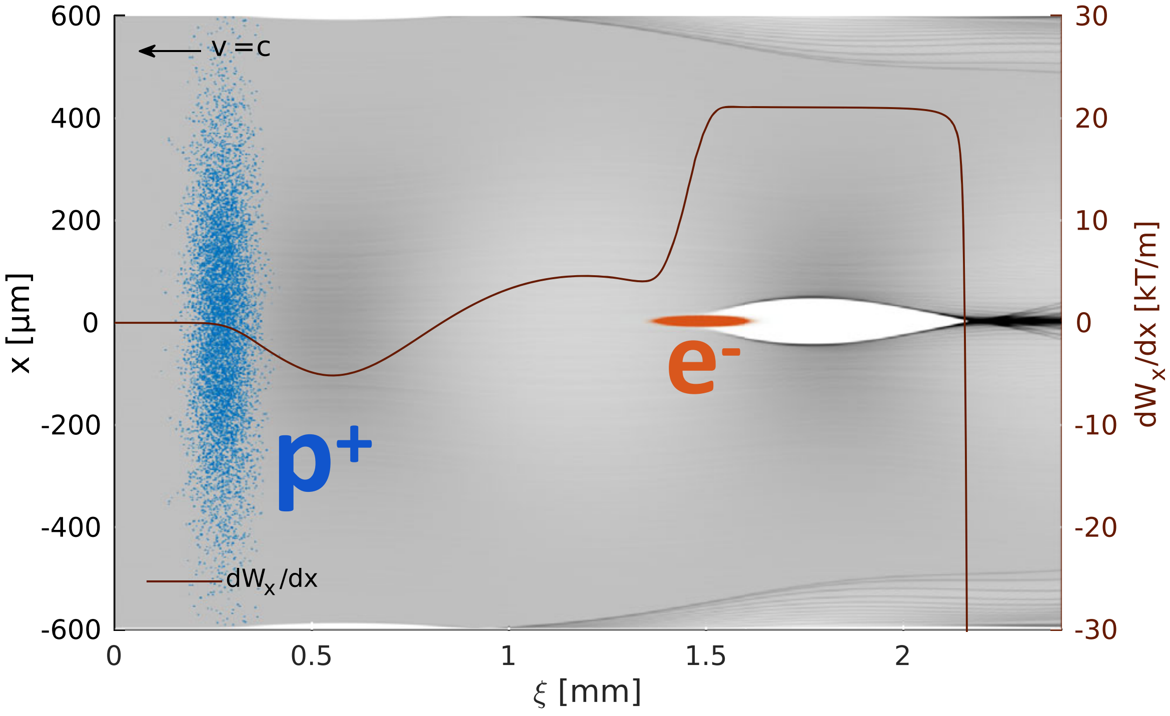


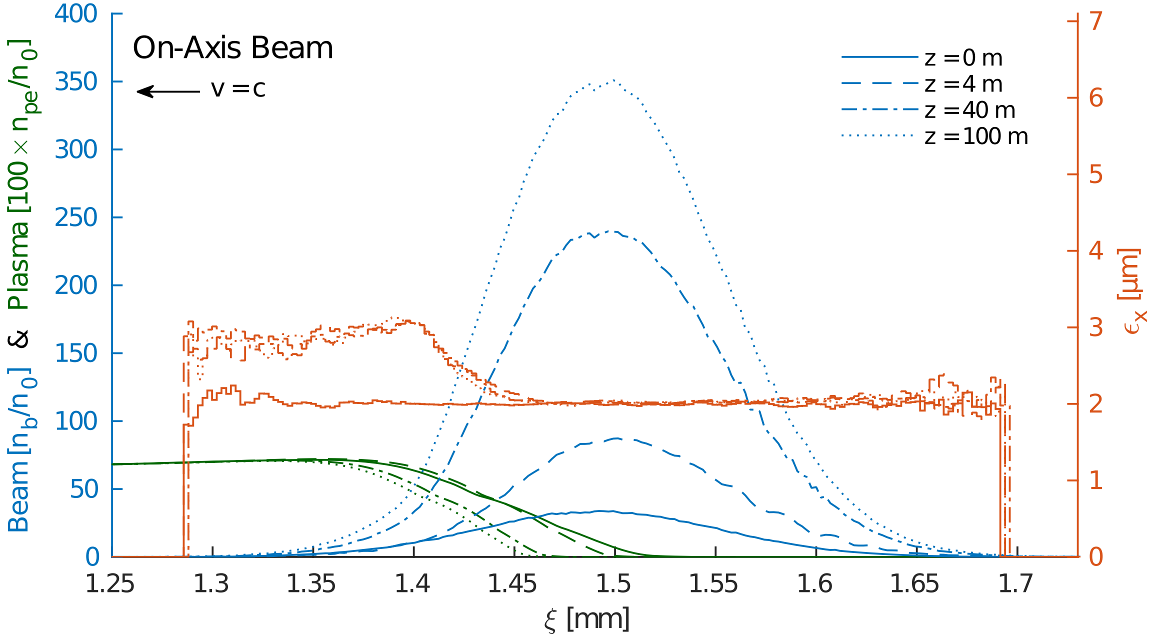
[A. Caldwell et al, *Nucl.Instrum.Meth.A* 829 (2016) 3-16]

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**



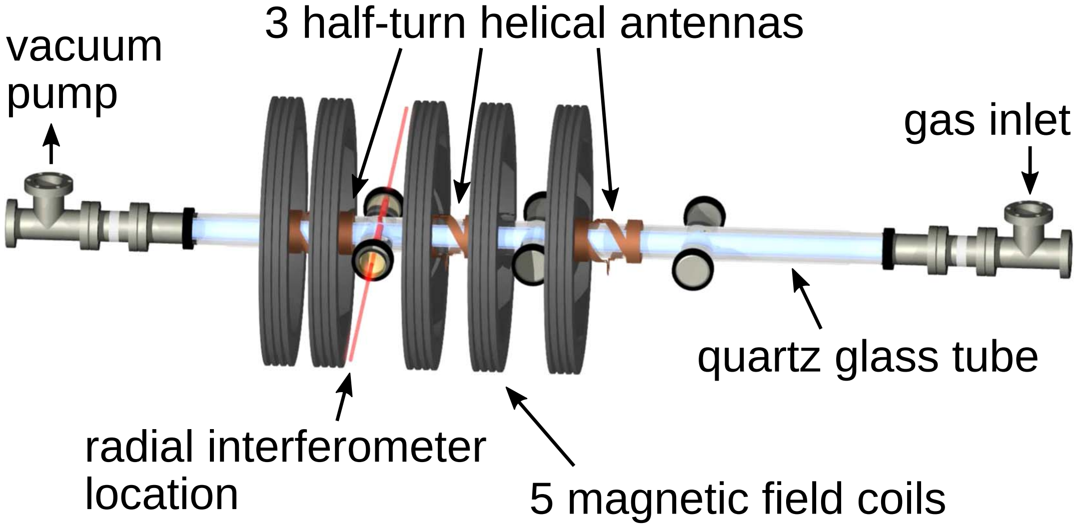


[V. K. Berglyd Olsen, E. Adli, P. Muggli, Phys. Rev. Accel. Beams 21, 011301 (2018)]

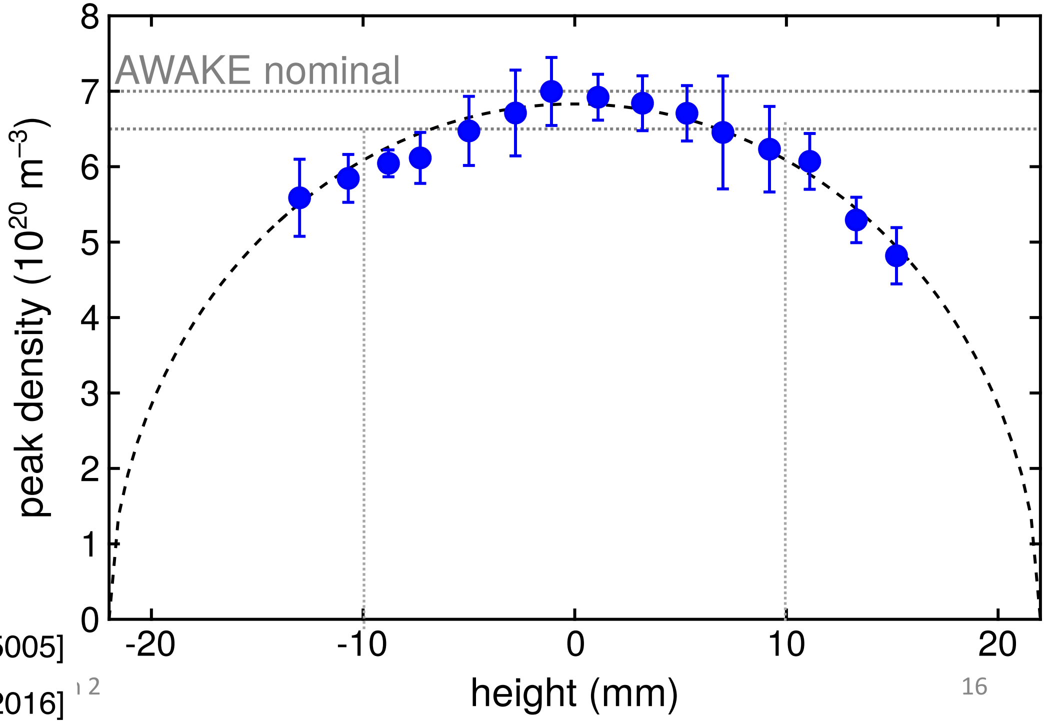
Run 2d: longer plasma

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



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

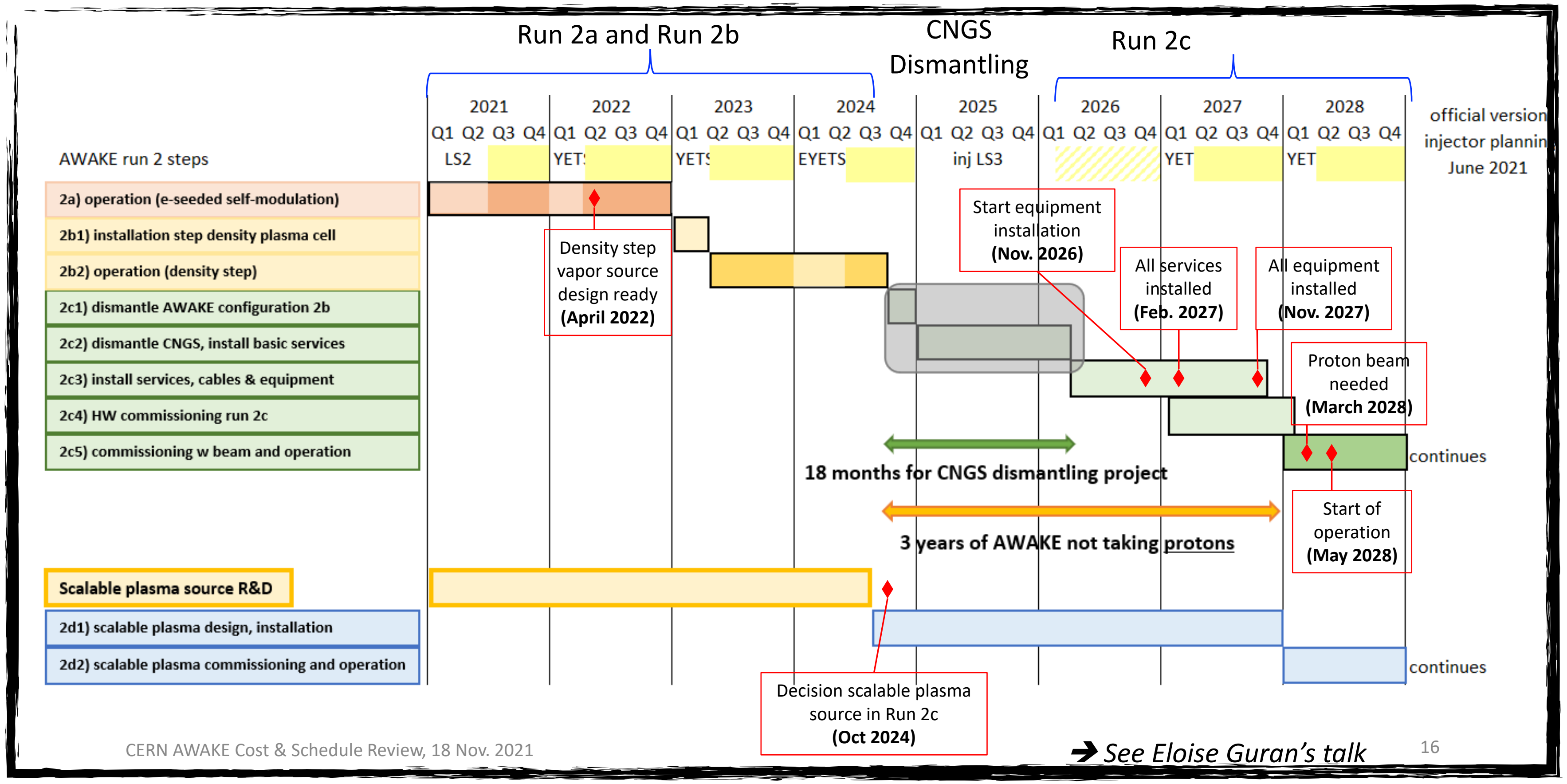


[B Buttenschön *et al* 2018 *Plasma Phys. Control. Fusion* **60** 075005]

[N. C. Lopes, Z. Najmudin, et al. CALIFES Workshop 2016]

Run 2 schedule

- In November 2021, Cost and Schedule for Run 2 were presented to a review panel
  - Run 2 program designed around injector schedule, with protons ≤ 2024 and ≥2028
  - Run 2 program requires emptying the CNGS tunnel to make room for equipment



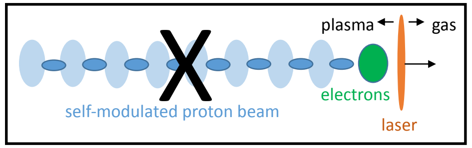
Outline

- Introduction to AWAKE
    - Run 1 achievements
    - Plan for Run 2
- Run 2 preparation during the Long Shutdown 2 (2019-2020)
    - Laser ionization and plasma formation
    - Electron Beam: human and machine learning
    - Electron seeding in plasma: preparation for Run 2a
    - Performance: Alignment and Data Quality
- The 2021 proton run
    - Run 2a (2021-2022) physics goals
    - Preliminary results
- What's next?
    - 2022 proton run goals
    - Beyond Run 2: physics applications

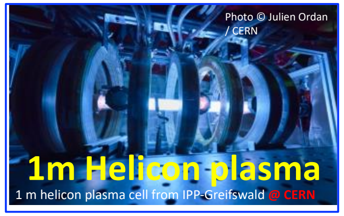
Long Shutdown 2: AWAKE without protons

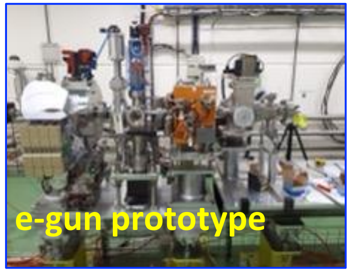
- The 2019-2021 years were extremely active, both in the AWAKE tunnel and on the surface

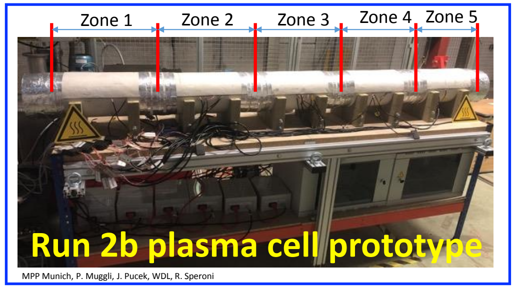
- I will focus on work in AWAKE/TAG41: 20 weeks of electron/laser beam in 2020, 11 weeks in 2021
  - Laser/Rubidium studies to improve the model of plasma formation
  - Electron beam studies to improve reproducibility, optics, trajectory and to test Machine Learning
  - Electrons-in-plasma studies to understand the electron-seeding process



- I will leave out all the studies, simulations and prototyping dedicated to the preparation for Run 2b/c/d:
  - Simulations to determine proton and electron beam parameters for Run 2c
  - Prototype of Run 2c electron gun and X-band in CTF2
  - Design of Run 2c laser, electron, proton lines
  - R&D on scalable plasma sources
  - Prototype for Run 2b plasma cell in EHN1
  - Tests at CLEAR of in-vapor diagnostics, high-frequency BPMs, bunch-length measurements with EOS

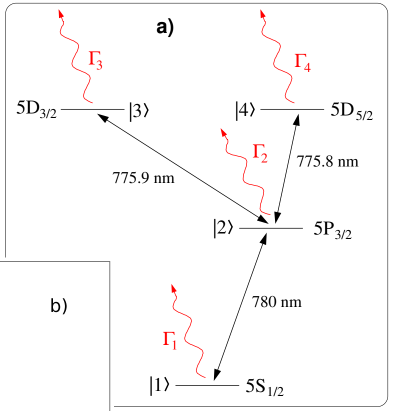




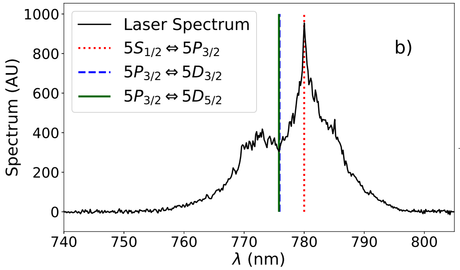


Laser studies of plasma channel formation

Atomic transition model

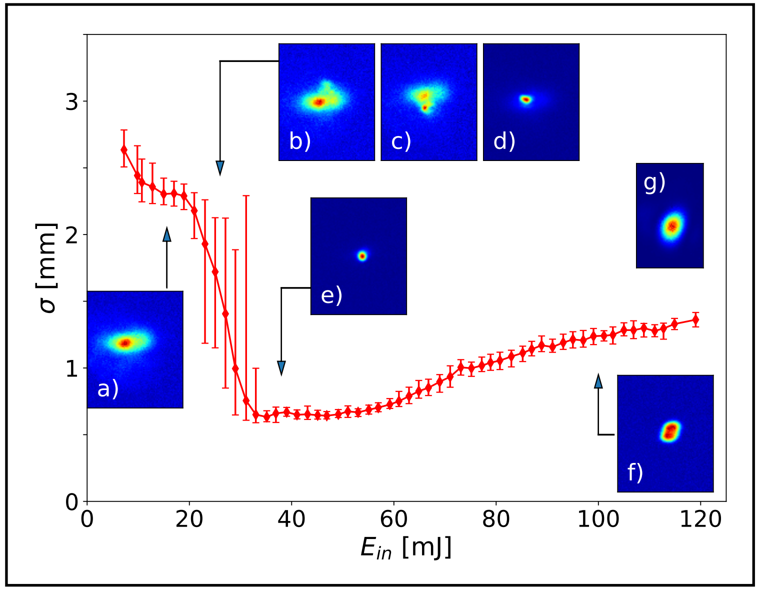


Laser spectrum

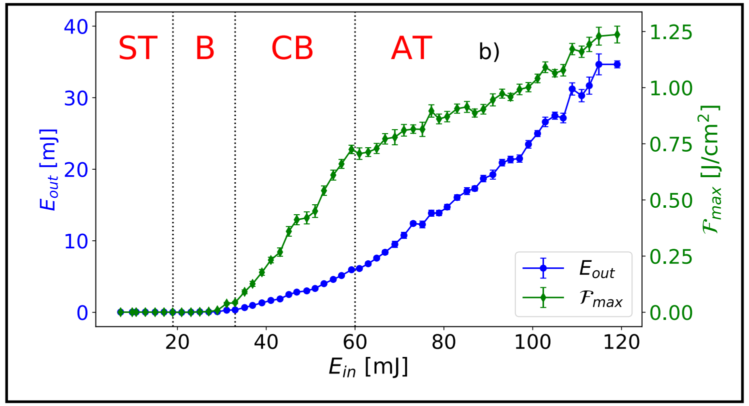


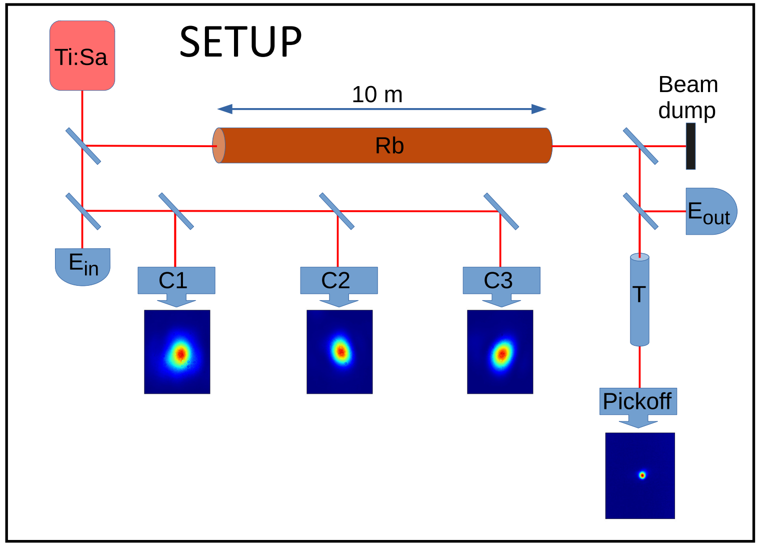
- Rb ionization: $E_1 = 4.18$ eV, $E_2 = 27.29$ eV
- Complex process: resonant nonlinear optical interaction, plasma becomes transparent to resonant frequency once the outermost electron is removed
- Laser (Ti:Sa) wavelength of ~780 nm is close to 3 resonances
- Experiment: measure size and energy of laser after 10 meters of propagation in Rb, as a function of laser input energy
  - Compare with different atomic transition models
- Next: explore role of resonance by scanning laser wavelength and measure extent of plasma channel

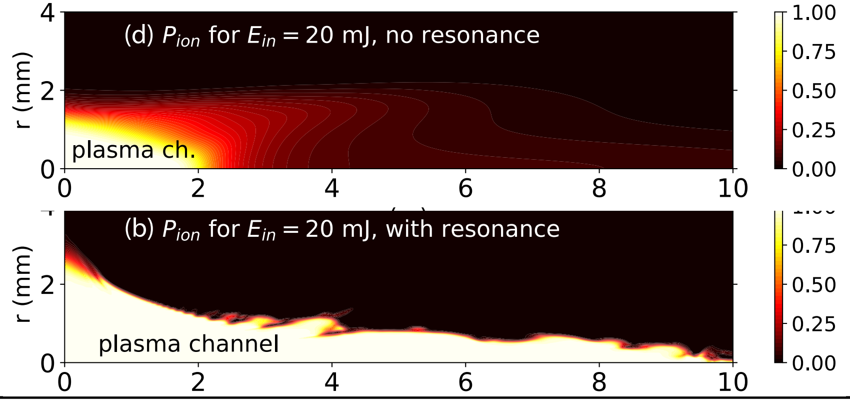
TRANSMITTED SIZE VS INPUT ENERGY



OUTPUT ENERGY VS INPUT ENERGY







G. Demeter et al, Long-range propagation of ultrafast ionizing laser pulses in a resonant nonlinear medium, Phys. Rev. A 104, 033506 (2021)

Improved control of e^- beam for seeding experiment

- In Run 1, the 18 MeV electron beam was used as “witness”, with the goal to accelerate *some* of its particles
- In Run 2, the 18 MeV beam was repurposed for electron seeding (the new ‘witness’ beam will be 150 MeV)
  - Simulations show that the *seed wakefield* depends strongly on the 6D phase space of the electron beam
  - To test this, we want to be able to scan parameters (charge, emittance, size) as widely as possible

Run 1 electron beam parameters*

Parameter	Value
Momentum [MeV/c]	10-20 ✅
Momentum spread $\Delta p/p$ [%]	0.5 ✅
Electrons per bunch [10^9]	1.2
Initial $\beta_{xi,yi}$ [m]	5 ✅
Initial $\alpha_{xi,yi}$ [rad]	0 ✅
R.M.S. normlalised emittance ε_n [mm mrad]	2
$\sigma_{xf,yf}$ at focal point [mm]	0.25

Run 2 requirements

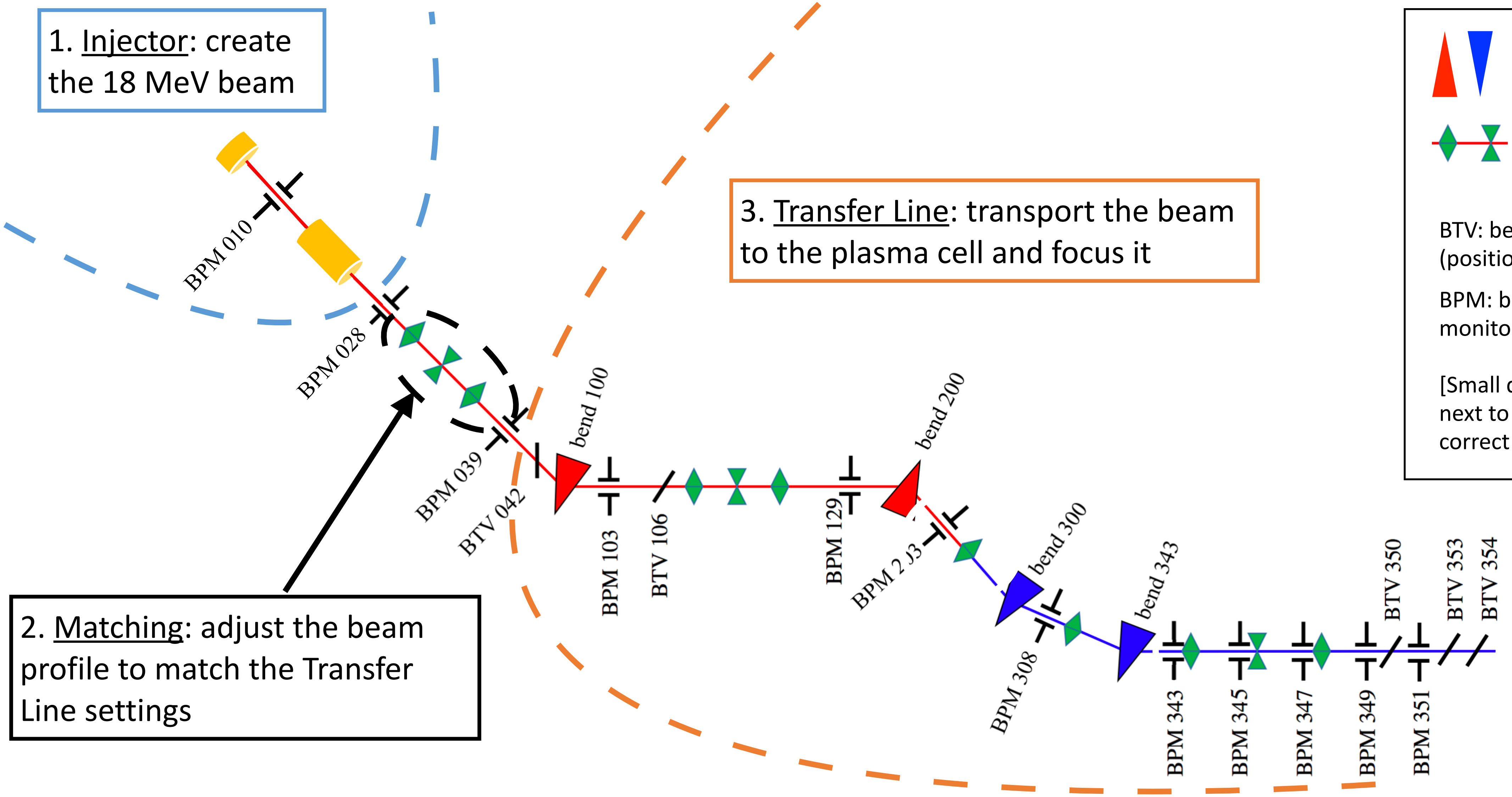
- Charge: vary from 1 to 4
- Emittance: vary from 1 to ~5
- Size: vary from 0.1 to 1

Parameters are correlated: improved control means learning to modify one without affecting others.

- By improving our control of the electron beam, we learn to control our seed wakefields
  - Determine which parameters are most crucial to seed the self-modulation

* C. Bracco et al., Systematic optics studies for the commissioning of the AWAKE electron beamline, in Proceedings of IPAC, 2019 (JACoW, Geneva, Switzerland, 2019), https://doi.org/10.18429/JACoW-IPAC2019-WEPMP029

The AWAKE Electron Beam



1. Injector: create the 18 MeV beam

2. Matching: adjust the beam profile to match the Transfer Line settings

3. Transfer Line: transport the beam to the plasma cell and focus it

Dipole magnets (bending)

Quadrupole magnets (focusing)

BTV: beam screeen (position and size data)

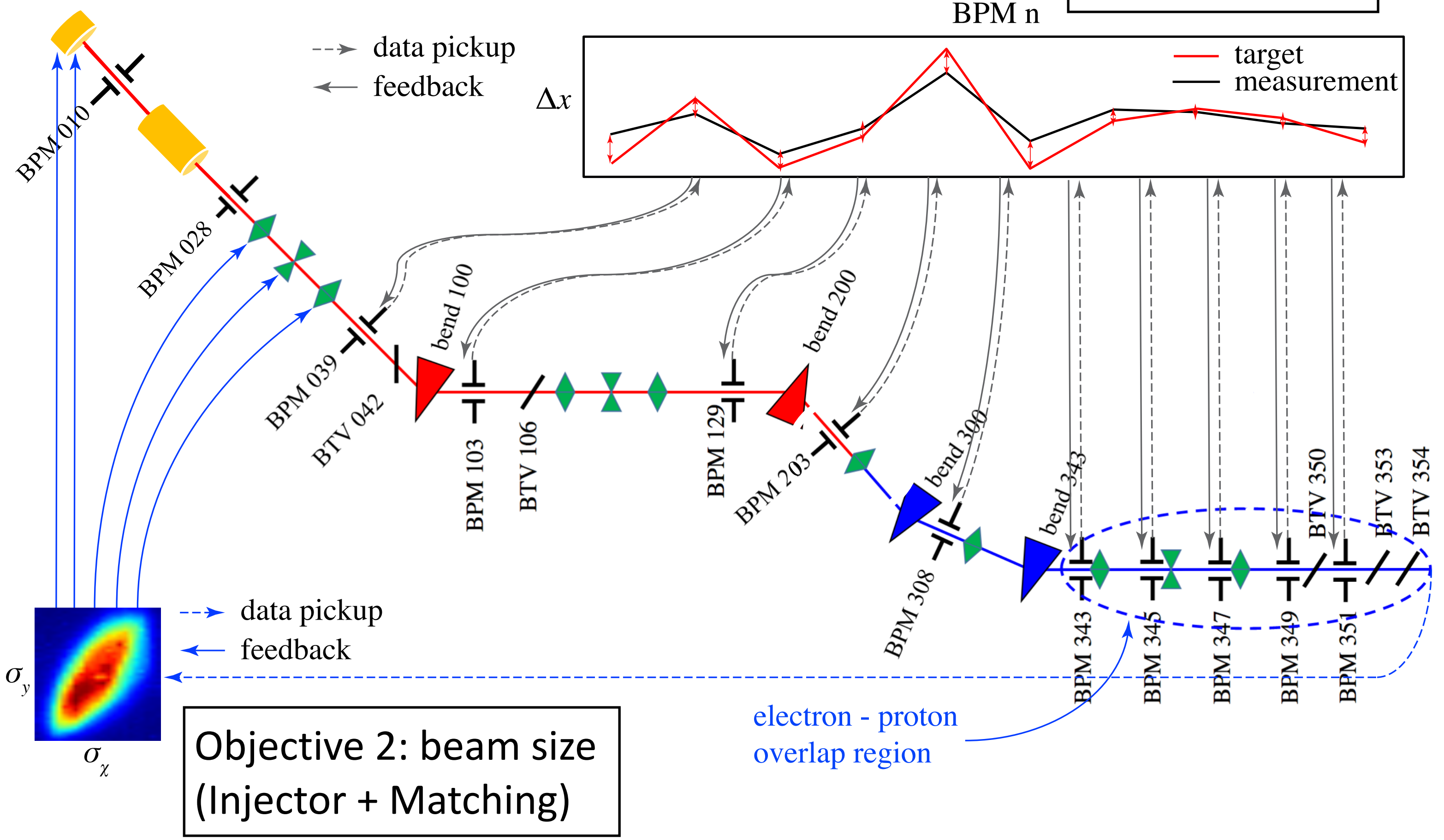
BPM: beam position monitor (position data)

[Small dipoles installed next to each BPM to correct trajectory]

Online multi-objective optimization

- Optimize competing objectives using adaptive feedback
  - Scheinker’s ES algorithm: model independent, effective for noisy and time varying systems with many coupled parameters
  - Use multiple competing feedback loops at various timescales

Objective 1:
beam trajectory

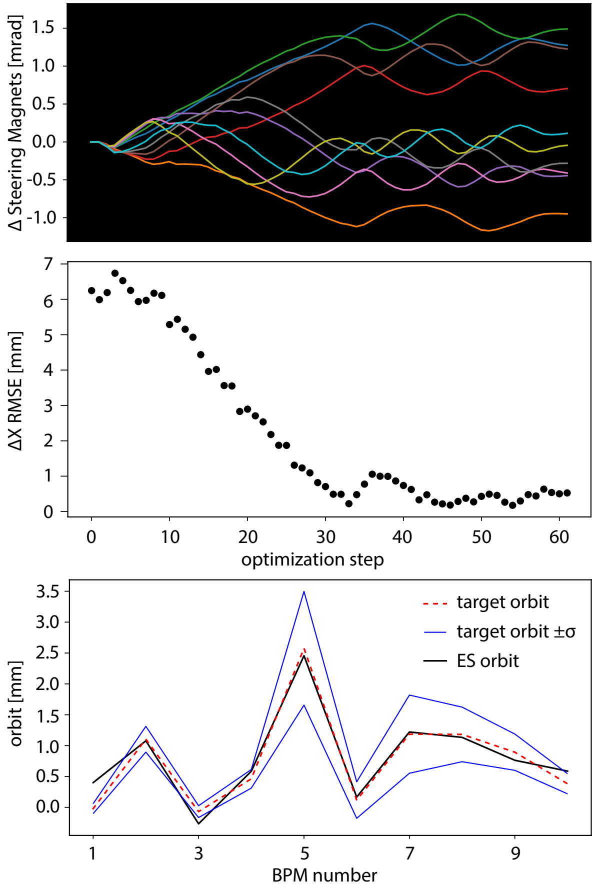


Online multi-objective particle accelerator optimization of the AWAKE electron beam line for simultaneous emittance and orbit control, A Scheinker et al., AIP Adv. 10 (2020) 5, 055320

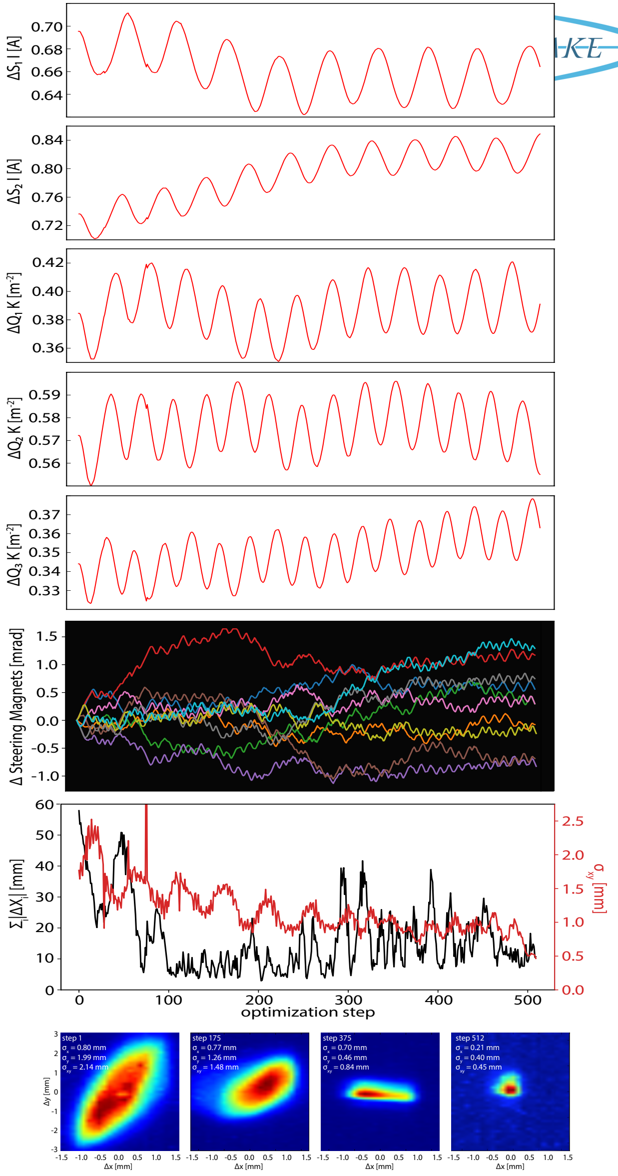
Online multi-objective optimization

- Optimize competing objectives using adaptive feedback
  - Scheinker’s ES algorithm: model independent, effective for noisy and time varying systems with many coupled parameters
  - Use multiple competing feedback loops at various timescales

- Optimization successful !
  - ~60 iterations to achieve objective 1
  - ~500 to achieve objectives 1+2
    - In AWAKE, 1 iteration ≈ 3 seconds



Objective 1: beam trajectory



Objectives 1+2: beam trajectory and beam size

Online multi-objective particle accelerator optimization of the AWAKE electron beam line for simultaneous emittance and orbit control, A Scheinker et al., AIP Adv. 10 (2020) 5, 055320

Reinforcement Learning: use ML to determine the best action

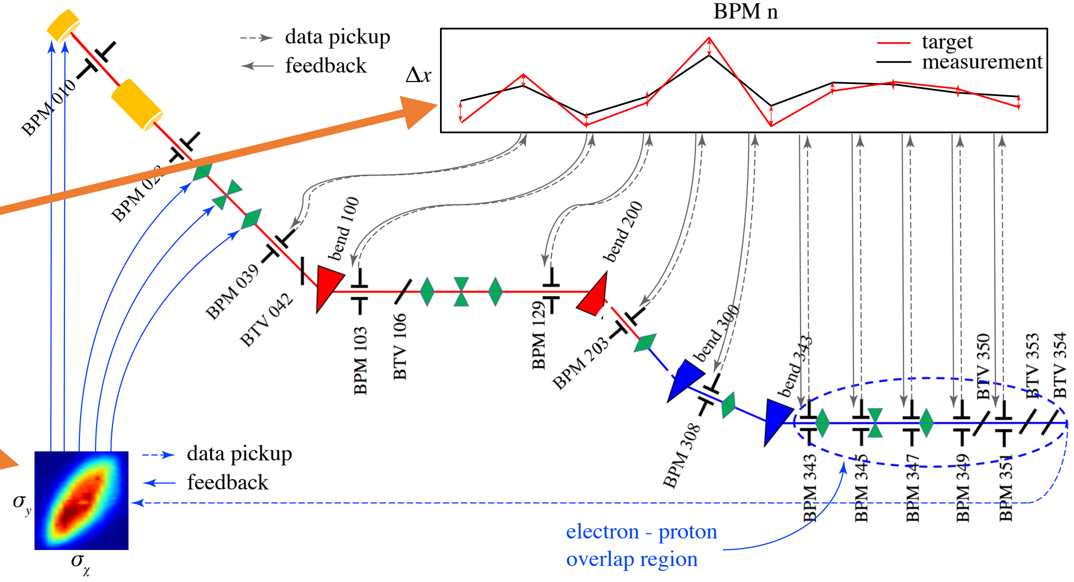
- An optimizer takes many iterations, every time: how can we get there faster?
  - Encode the system as a neural network (i.e. a function)
  - RL will use some time to ‘train’ (i.e. find the coefficients of the network that lead to best action, given initial states of the system) (i.e. build a model of the system)
  - After training, RL can directly take the ‘action’ required to solve the problem
  - REQUIREMENT: full set of observables ($x_1, \ldots, x_n$) to distinguish between states
  - ASSUMPTIONS: constant response and no hidden observables

- Test RL by learning to solve individual problems
  - Trajectory optimization

Sample-efficient Reinforcement Learning for CERN accelerator control,
V Kain et al., Phys. Rev. Accel. Beams 23, 124801 (2020)

  - Match Injector to Transfer Line

Automatic setup of 18 MeV electron beamline using machine learning,
F Velotti et al., Submitted to PRAB



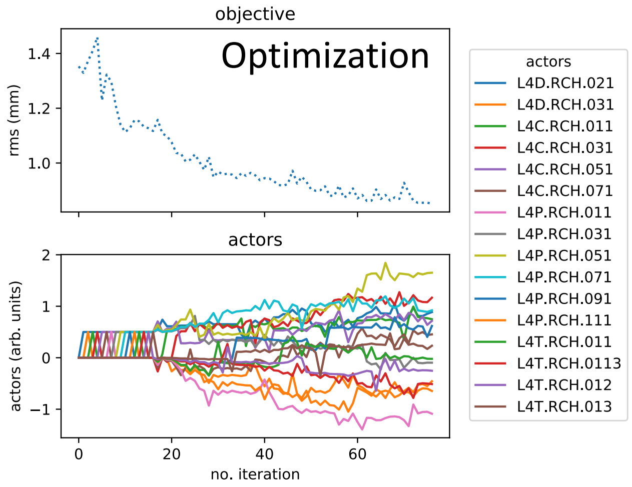
Reinforcement Learning: use ML to determine the best action

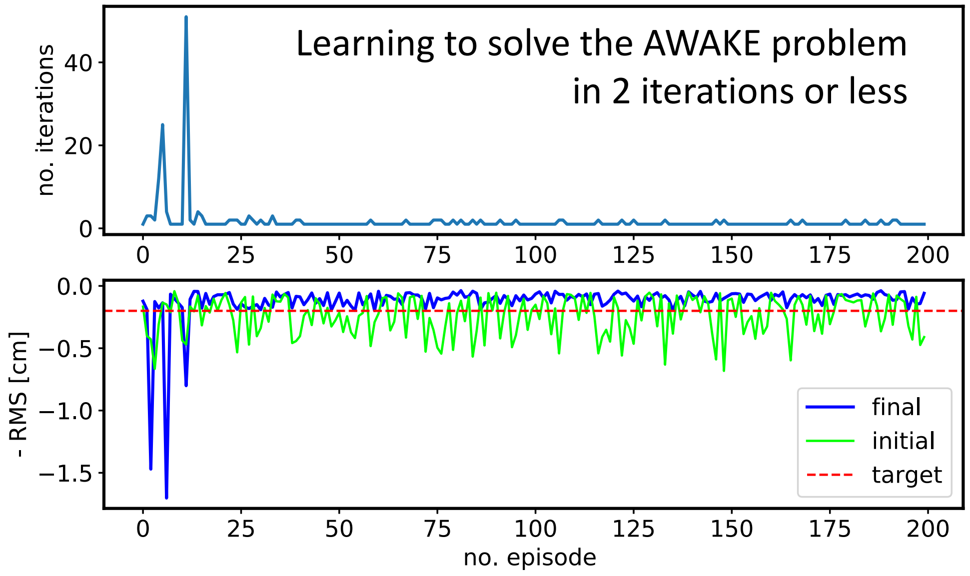
Trajectory Optimization

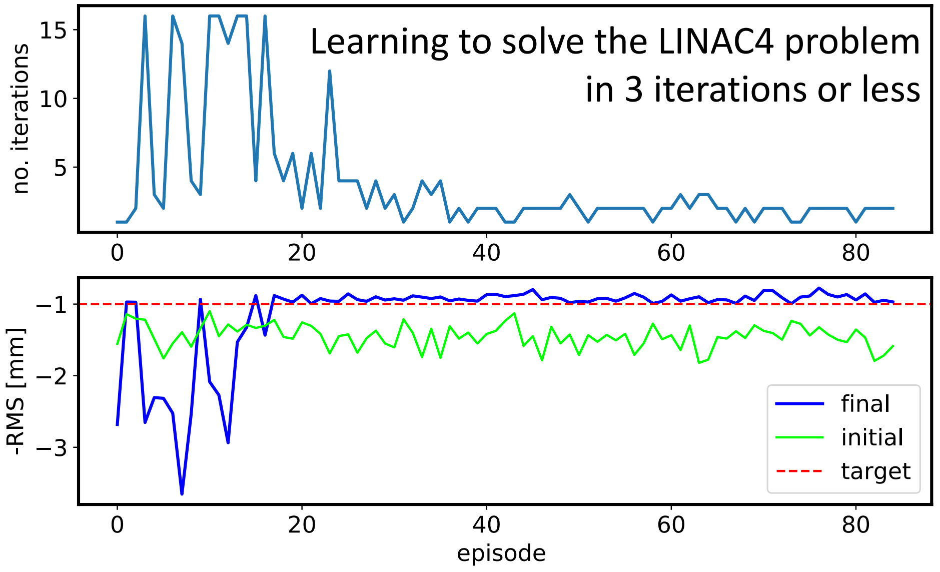
V Kain et al., Sample-efficient Reinforcement Learning for CERN accelerator control, Phys. Rev. Accel. Beams 23, 124801 (2020)

- Proof-of-principle: AWAKE
  - Online model of beam-line is available, so trajectory optimization can be done using standard tools (YASP)
  - With no knowledge of the online model, RL is able to solve problem with ≤ 2 iterations, after training for ~100 iterations
  - Training still valid after 3 months
  - Training on simulated model also effective

- Real challenge: CERN's LINAC4
  - Online model was not yet available at the time of study
  - Simple optimizer requires 70 iterations
  - RL can train for ~130 iterations, and afterwards find the trajectory with ≤ 3 iterations







Reinforcement Learning: use ML to determine the best action

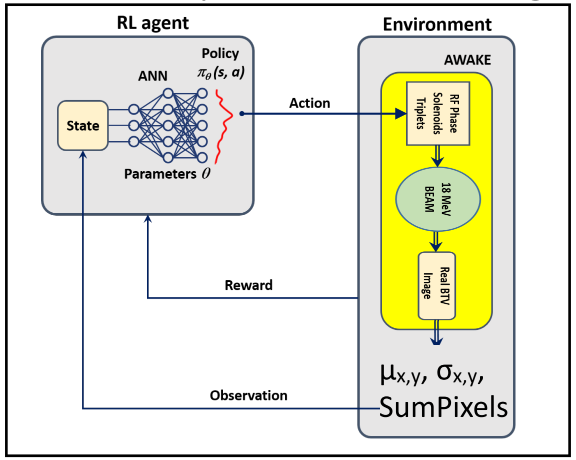
Matching Injector to Transfer Line

F Velotti et al., Automatic setup of 18 MeV electron beamline using machine learning, Submitted to PRAB

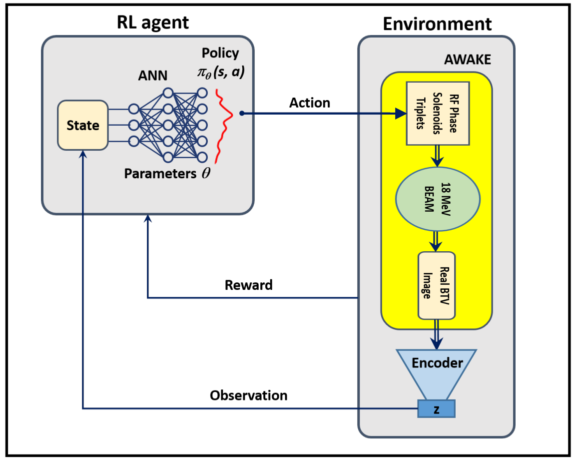
- Real challenge: AWAKE
  - Online models not available: manual tuning to optimize beam size and intensity!
  - Multi-objective: **beam size (80%)** and intensity (20%) from a 2D BTV image
  - Highly non-linear response
  - Numerical optimizer requires > 100 iterations to converge
- Different approaches used to describe the 2D “state” information for RL:
  - “Explicit”: Gaussian fits ($\mu_{x,y}$, $\sigma_{x,y}$) and total intensity
  - “Implicit”: Let a variational autoencoder (VAE) compress image to 5 parameters
- Training the VAE gives the ability to produce synthetic data and train a synthetic model of AWAKE. How does the RL on the synthetic model?

- Results
  - Able to solve problem with ≤ 2 iterations, after training for 200 iterations
  - Good results on Explicit/Implicit/Synthetic Data
- Problem: system has a slowly-changing response
  - RL trained on Day 1 does not work on Day 2
  - Additional efforts needed to incorporate residual state information (i.e. 2D image is not enough)

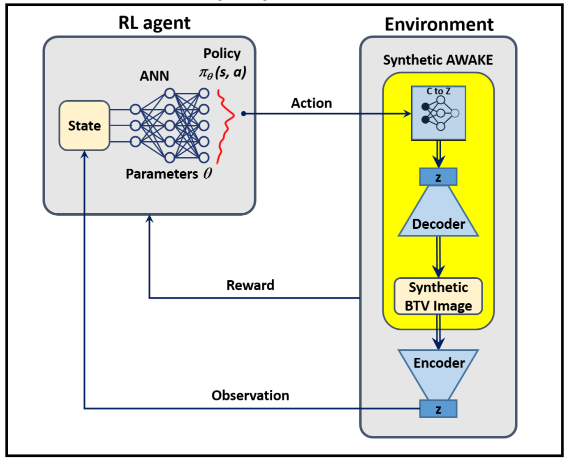
RL with explicit state encoding



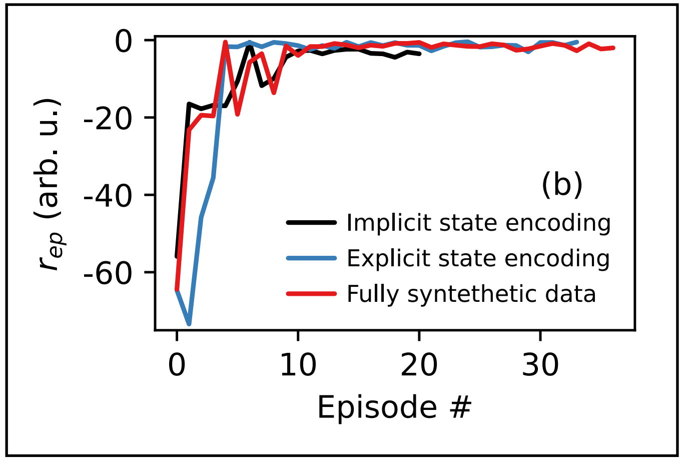
RL with implicit state encoding



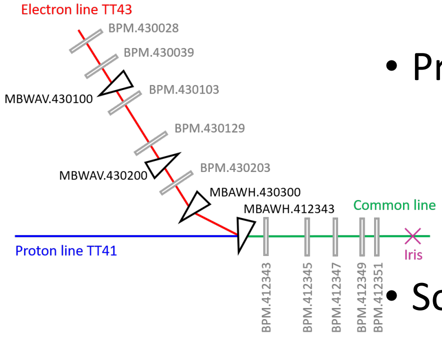
RL with fully synthetic data



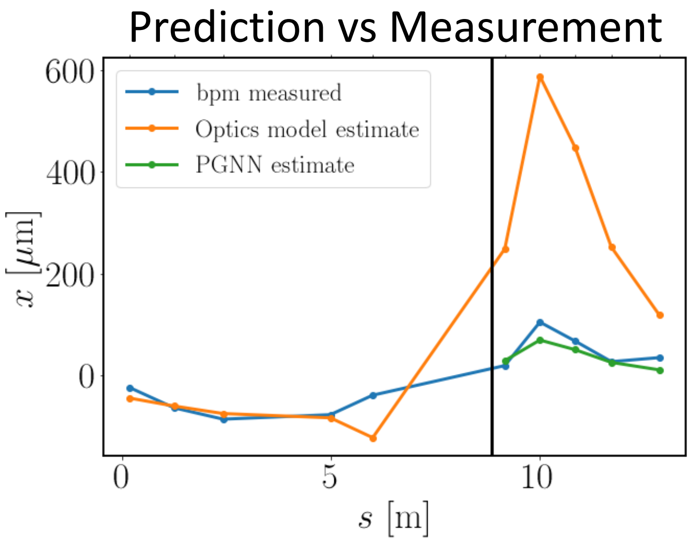
All three approaches work well

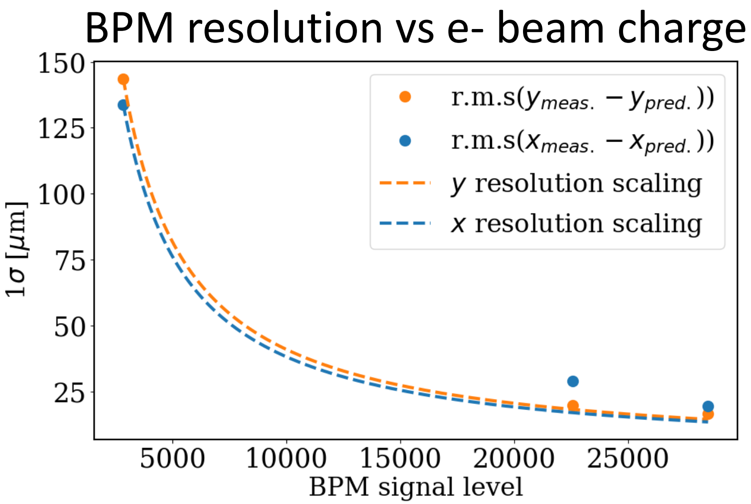


Beam trajectory reconstruction using neural networks



- Problem: no direct measurement of e⁻ trajectory in p⁺ events
  - BPMs overwhelmed by higher charge of proton
  - Hardware solutions, under development: Cherenkov Diffraction Radiation BPMs and HF BPMs
- Solution: can we solve this in software, using the first half of the electron line?
  - In Run 1, attempted to use optics model, with insufficient results
  - Idea: teach a Physics Guided Neural Network (PGNN) to correct the estimates of the optics model
- Results: PGNN works well when BPM resolution is good
  - Measurement of PGNN performance is limited by BPM resolution
  - When BPM resolution is poor (i.e. low-charge e⁻ beam), it is difficult to estimate the PGNN performance
  - Good news: jitter for low-charge beam is small low, so PGNN is not needed and a simple average trajectory works well



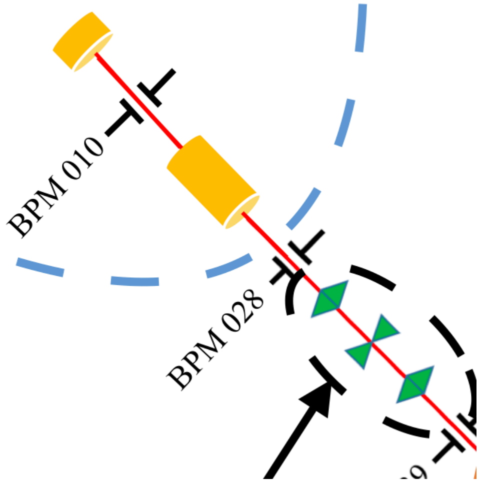


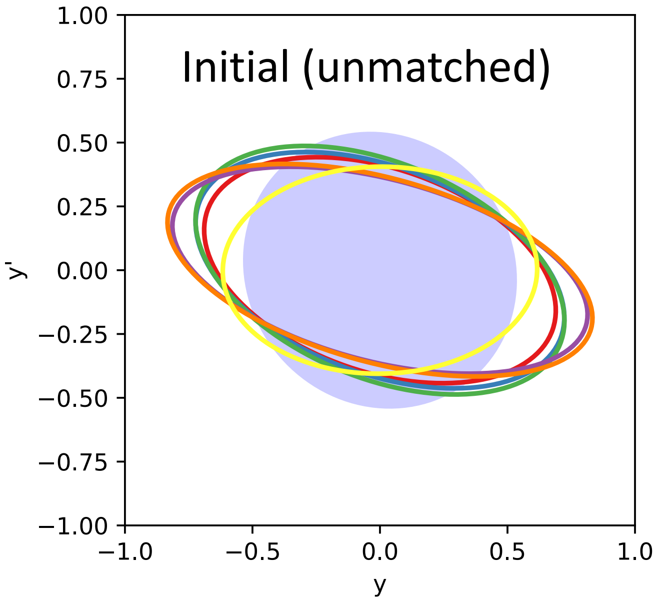
BPM	Position jitter [μm]			Optics model r.m.s error [μm]			PGNN r.m.s error [μm]		
	low	medium	high	low	medium	high	low	medium	high
412343	175.5	97.5	73.5	147.2	32.9	69.6	136.7	19.7	15.1
412345	184.6	94.6	28.4	148.2	25.0	46.4	143.4	19.1	15.4
412347	247.4	165.5	142.9	189.3	39.5	89.4	165.4	22.5	21.1
412349	224.8	131.9	242.3	188.2	57.6	95.2	152.1	21.1	18.7
412351	233.9	42.9	148.0	180.2	56.4	62.3	143.7	19.6	16.6

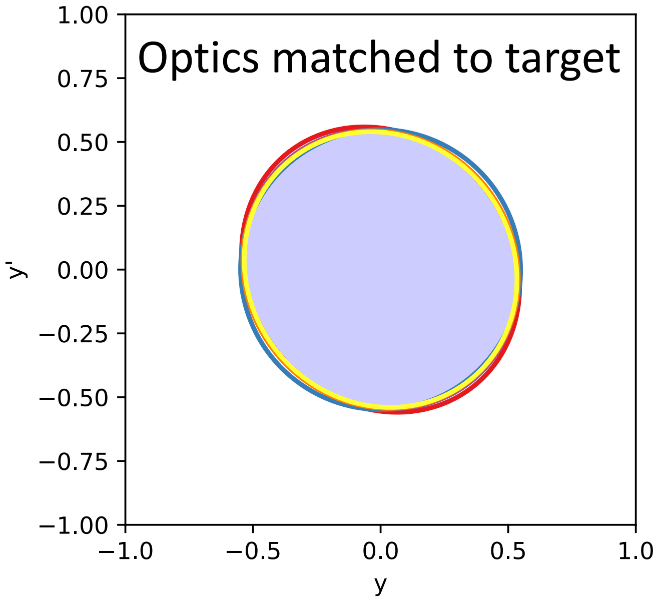
R. Ramjiawan et al., Design of the AWAKE Run 2c transfer lines using numerical optimizers, To be submitted

Analytic solutions and manual tuning (Human Learning)

- Tuning the Injector system:
  - Injector parameters cannot be moved continuously, so Optimizers and ML are not (yet) a solution
- Matching Injector to Transfer Line:
  - Reinforcement Learning cannot (yet) solve this: slowly changing response
  - In parallel to ML program, we developed an ‘analytic’ solution
    - 1) Measure beam optics (4D) out of the Injector
    - 2) Solve system of equations predicting what the best currents for the ‘matching’ magnets





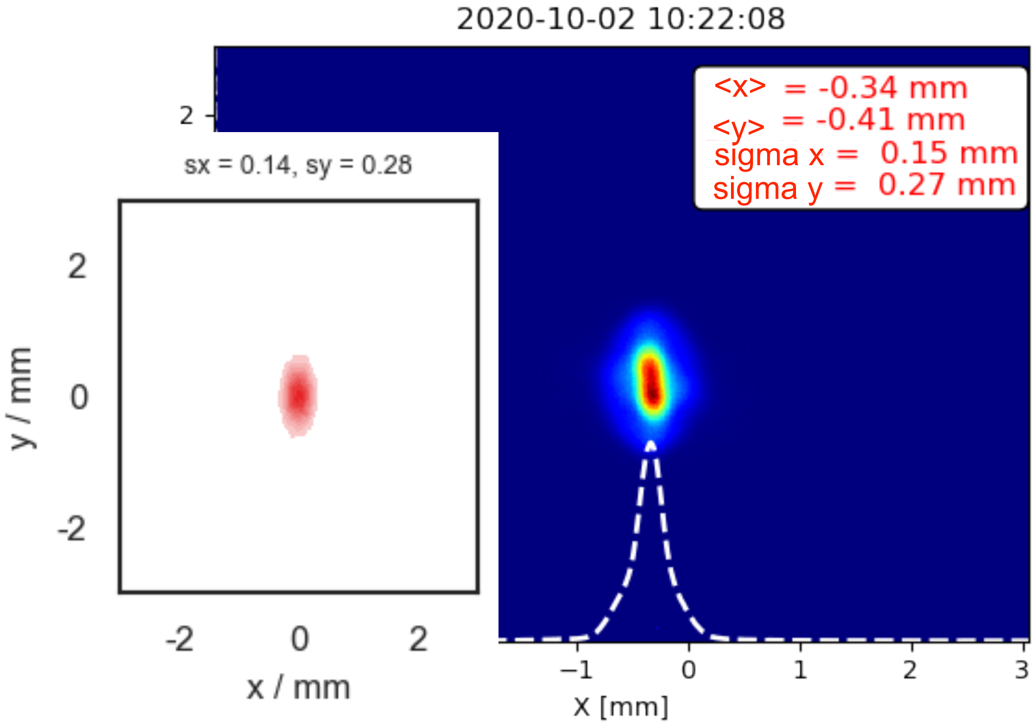


G. Zevi Della Porta et al. APS Division of Plasma Physics Meeting 2020, BO03.002

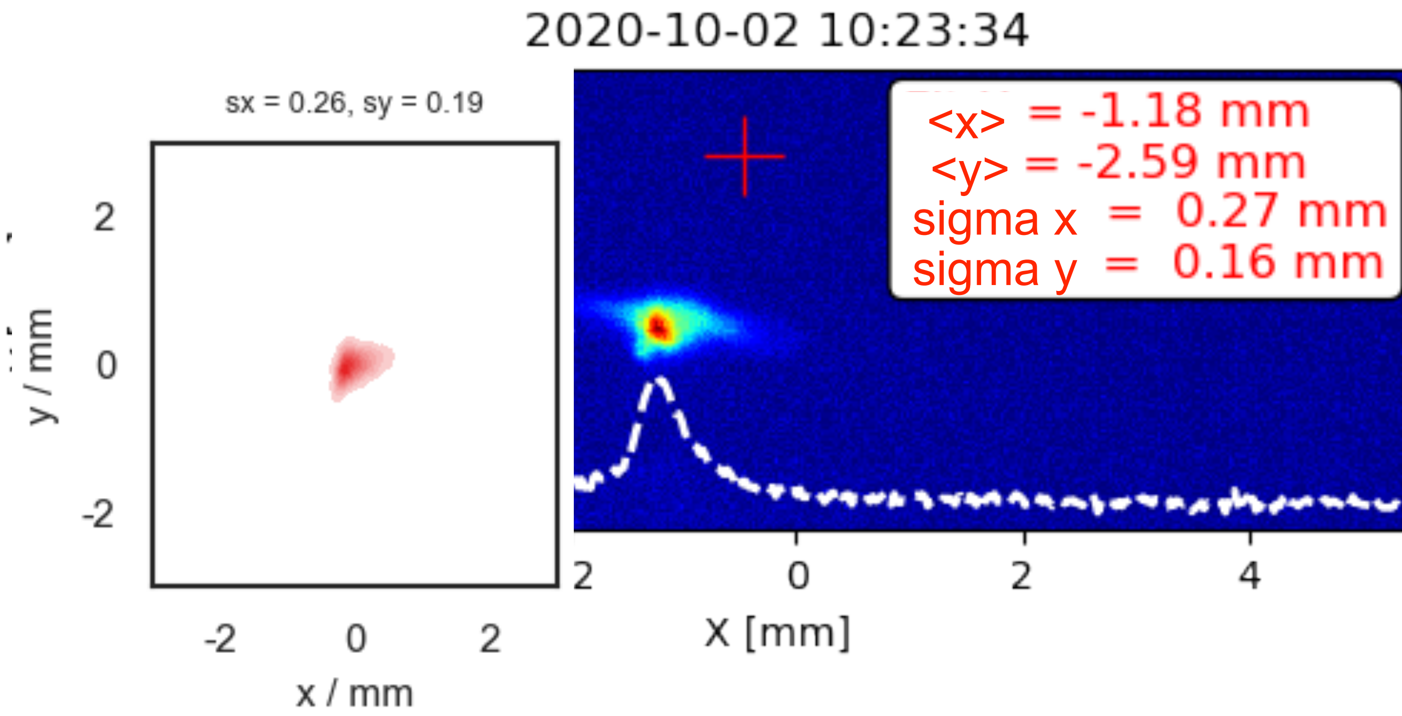
Simulations: Transfer Line

- Full model of Transfer Line available
  - Good agreement with data, as long as injector optics variations are taken into account
  - Allowed to develop alternative focusing (i.e. changing beam size to affect e$^-$ bunch density while keeping charge fixed)
- Necessary tool since the beam size estimate at plasma entrance relies fully on simulation in 2021
  - BTV @ plasma entrance added in early 2022, undergoing commissioning

BEGINNING (BTV42)



END (BTV54)



G. Zevi Della Porta et al. APS Division of Plasma Physics Meeting 2020, BO03.002

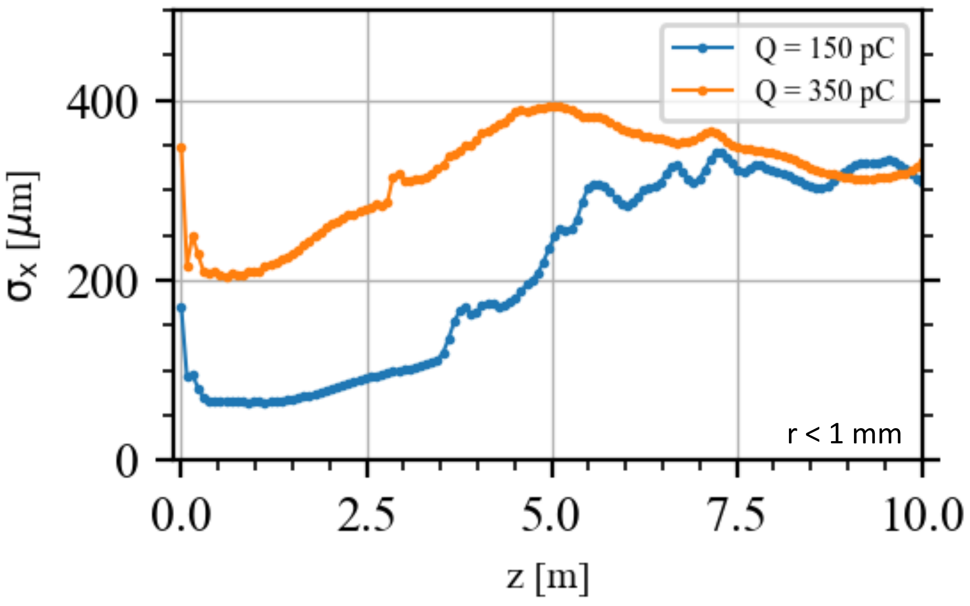
Outline

- Introduction to AWAKE
  - Run 1 achievements
  - Plan for Run 2
- Run 2 preparation during the Long Shutdown 2 (2019-2020)
  - Laser ionization and plasma formation
  - Electron Beam: human and machine learning
  - Electron seeding in plasma: preparation for Run 2a
  - Performance: Alignment and Data Quality
- The 2021 proton run
  - Run 2a (2021-2022) physics goals
  - Preliminary results
- What's next?
  - 2022 proton run goals
  - Beyond Run 2: physics applications

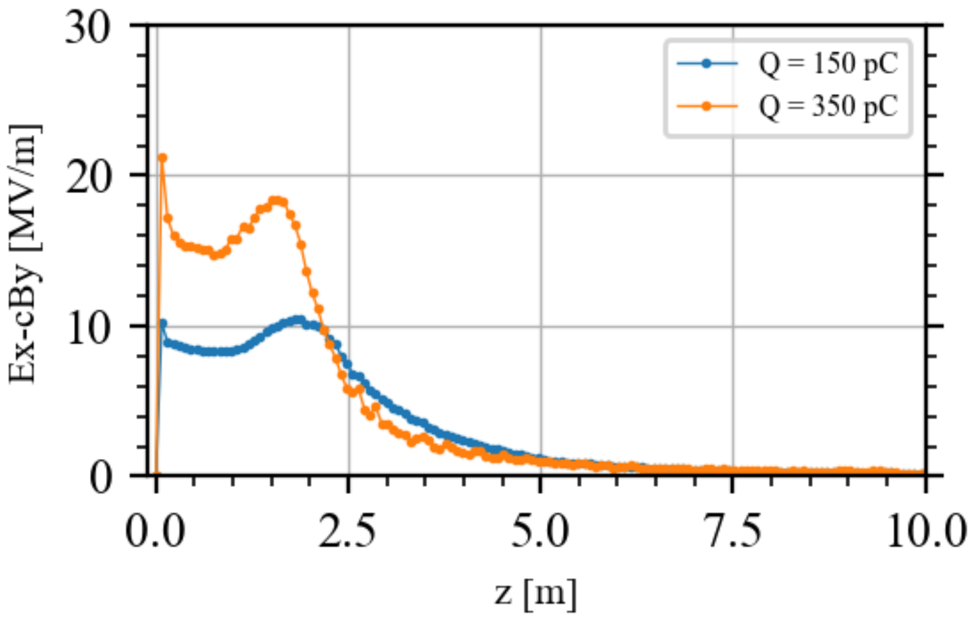
Electron seeding: e- bunch energy deposited in plasma

- Seeding relies on transverse wakefields generated by e- bunch in the first meters of plasma
  - Size: e- bunch pinches in the first few cm and remains small for several meters
  - Wakefield: while the e- bunch is small, large wakefields are sustained for the first two meters
- We cannot yet measure seed wakefields directly, but we can measure the e- bunch properties after the plasma

Electron bunch size evolution



Max transverse wakefield at r = 200 µm



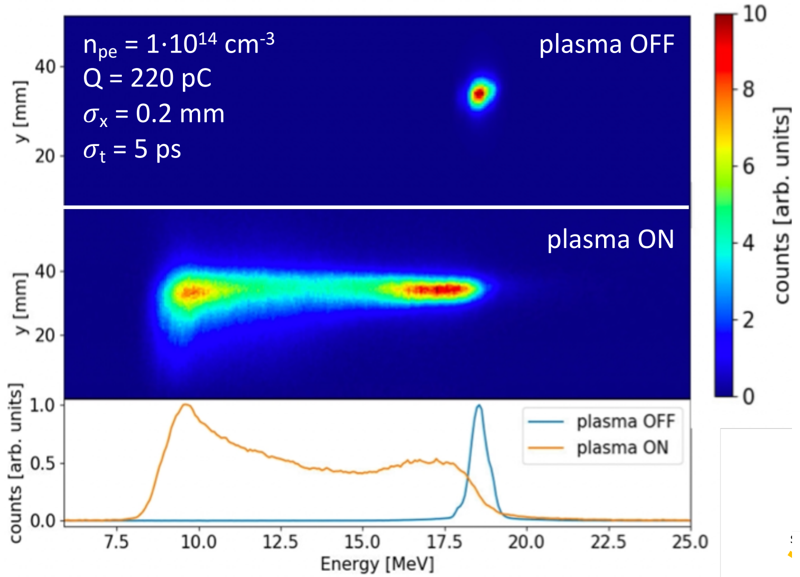
FBPIC (Fourier-Bessel Particle-In-Cell)

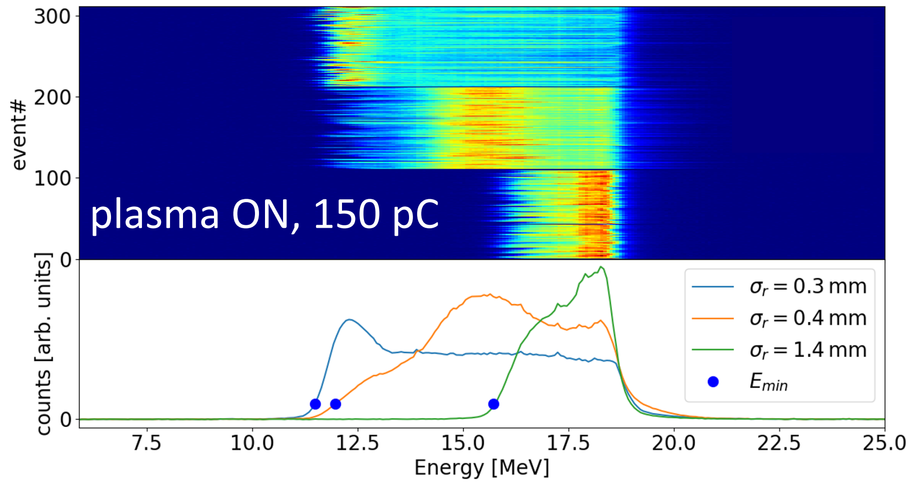
R. Lehe, M. Kirchen, I. A. Andriyash, B. B. Godfrey, and J.-L. Vay, "A spectral, quasi-cylindrical and dispersion-free particle-in-cell algorithm," *Computer Physics Communications*, vol. 203, pp. 66–82, 2016, ISSN: 0010-4655. DOI: https://doi.org/10.1016/j.cpc.2016.02.007.

K. Moon et al. IPAC2021 - TUPAB160

Electrons in plasma: Run 2a without protons

- Preliminary experimental results
- Plasma-off measurements (propagation in vacuum)
  - No energy loss, as expected
- Plasma-on measurements
  - Significant energy and charge loss
  - Reproducible event-to-event
  - Energy loss (i.e. seed strength) depends on electron beam properties
- Dedicated analysis and comparison with simulation ongoing
  - Decided to measure electron energy loss also during proton run





L. Verra et al., 47th EPS Conference on Plasma Physics (2021), P3.2011

Performance challenges and improvements

- Largest operational challenge: aligning the 3 beams to < 50 µm
  - **Laser**: σ ~ 700 µm, position jitter ~ 200 µm
  - **Protons**: σ ~ 200 µm, position jitter ~ 40 µm
  - **Electrons**: σ ~ 200 µm, position jitter ~ 20 µm

BPM resolution:
Protons: ~ 100 µm
Electrons: ~ 200 µm

Alignment requires averaging many shots to beat jitter and resolution

- Laser: adapted Run 1 alignment code, using analog BTVs (1 Hz)
  - Set up a moving average on 10 Hz digital cameras along a parallel laser line
  - **2022**: finish commissioning parallel line to align at 10 Hz without interrupting proton beam

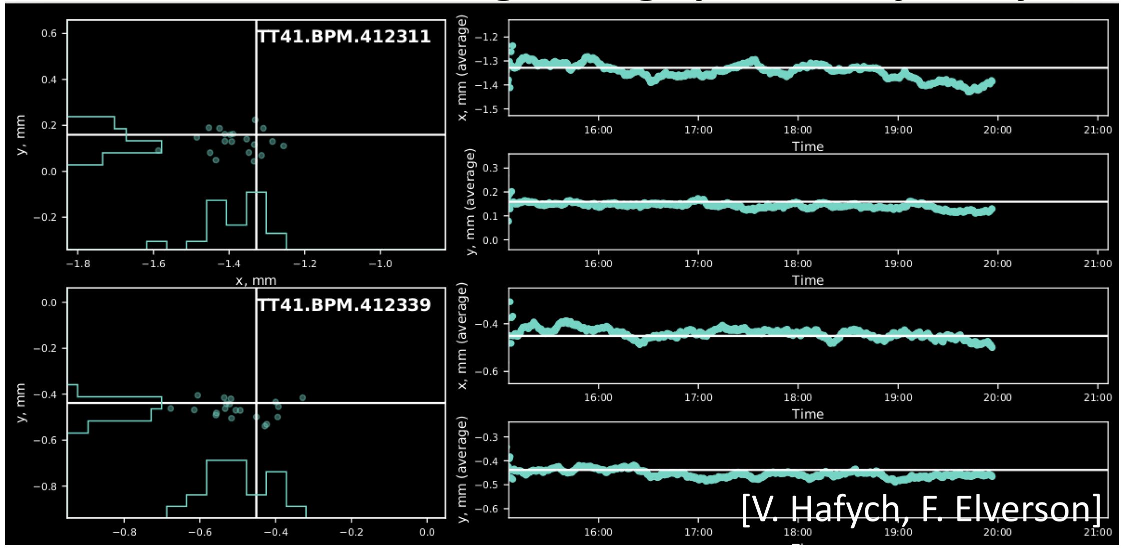
- Electrons: developed simple code to calculate offset/angle based on BPM average over ~400 events at 10 Hz
  - Can reach golden trajectory in only a few minutes
  - But lengthy alignment is still required to find the proton beam (since proton alignment is limited)
  - **2022**: Improvement expected with the installation of a BTV screen at the plasma entrance

- Protons: developed simple code averaging BPMs over 20 events (10 minutes!)
  - Longer average would be needed, but 10+10 minutes of beam time is already a lot
  - Alignment affected by SPS interruption, super-cycle changes, drift.
  - **2022**: consider transitioning to BTV for higher resolution, allowing to use fewer shots

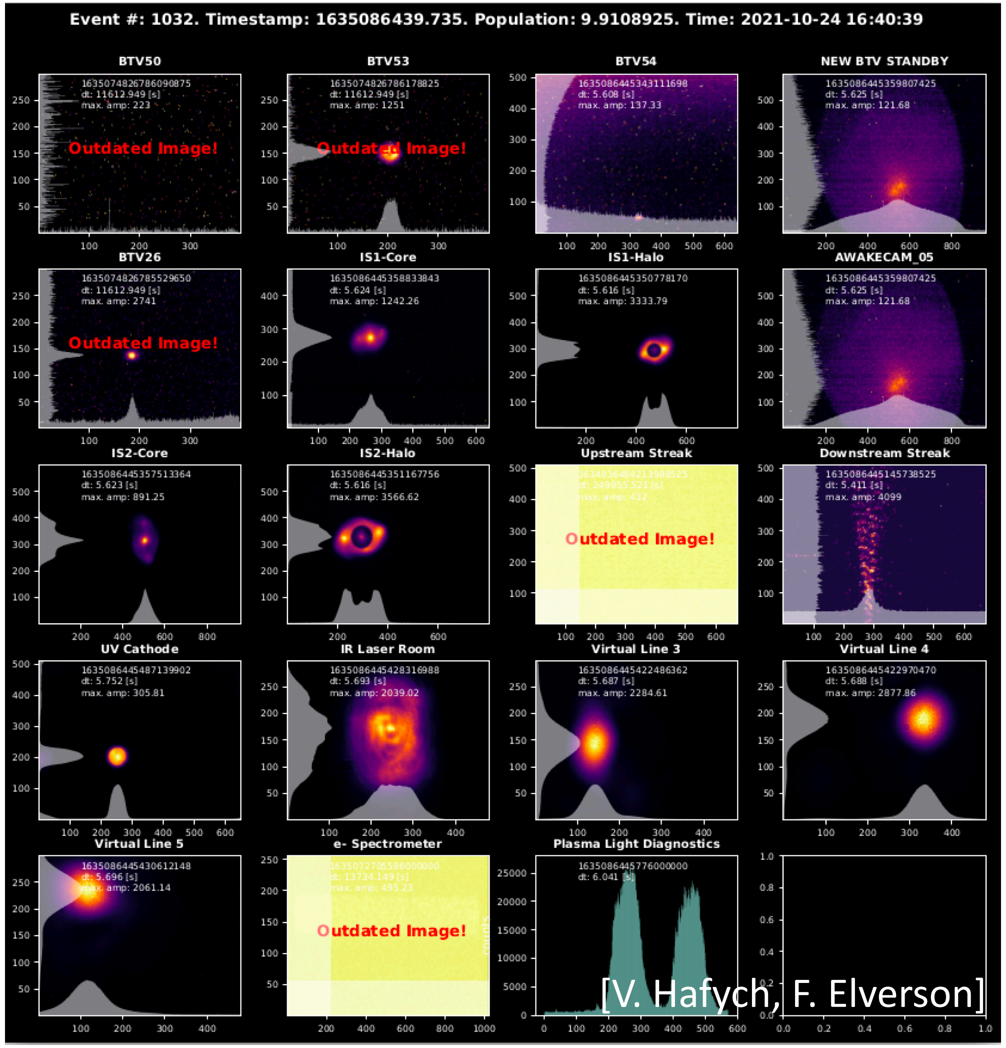
New for Run 2: Data Quality Monitoring

- A lesson from the LHC experiments: reduce downtime by catching problems as early as possible with basic data monitoring
  - Constant monitoring of timestamp and errors for all data written to disk (250 variables, 50 MB per event).
  - Trajectory monitoring for 3 beams (moving averages to overcome jitter and resolution)
- Further improvements ongoing to improve reliability.

Timeline of moving average proton trajectory



Single event summary (main diagnostics)

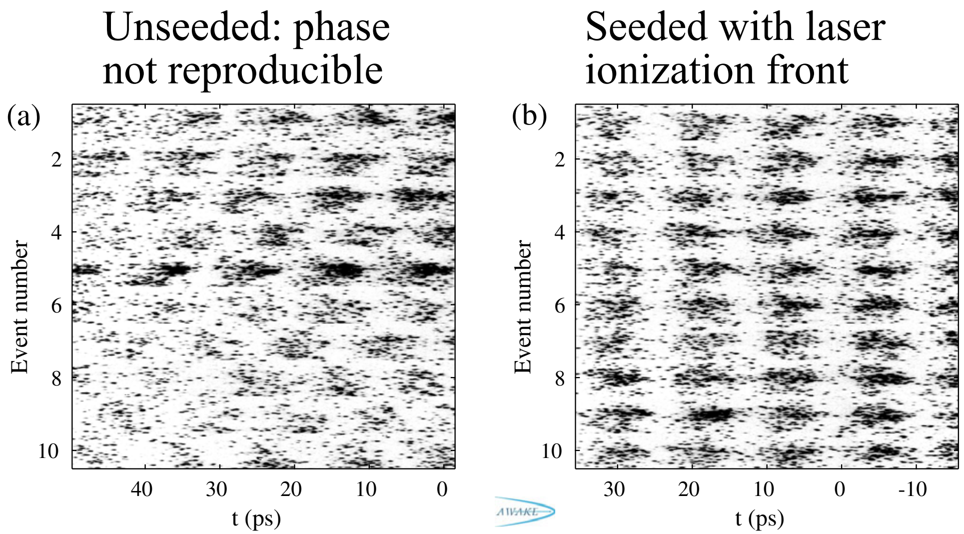


Outline

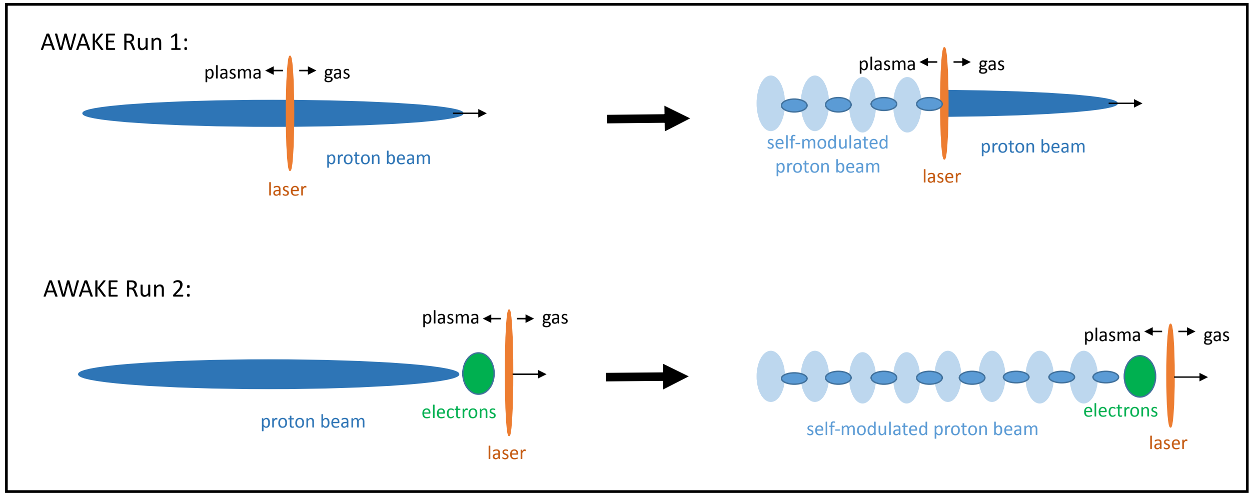
- Introduction to AWAKE
  - Run 1 achievements
  - Plan for Run 2
- Run 2 preparation during the Long Shutdown 2 (2019-2020)
  - Laser ionization and plasma formation
  - Electron Beam: human and machine learning
  - Electron seeding in plasma: preparation for Run 2a
  - Performance: Alignment and Data Quality
- The 2021 proton run
  - Run 2a (2021-2022) physics goals
  - Preliminary results
- What's next?
  - 2022 proton run goals
  - Beyond Run 2: physics applications

Run 2a: electron seeding of self-modulation (eSSM)

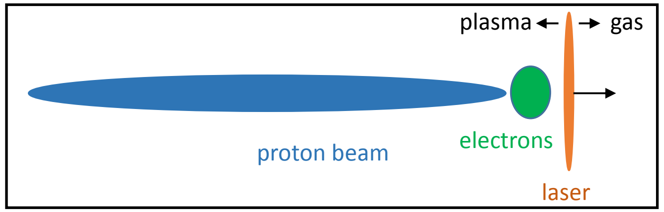
- ‘Seeding’ the proton bunch self-modulation is required for reproducible acceleration
  - Only electrons injected at a precise <u>phase</u> of the micro-bunch train can accelerate and remain focused
  - Actively seeding the self-modulation allows <u>phase-reproducible</u> micro-bunch trains
- In Run 1, self-modulation seeded by a <u>laser ionization front</u> (i.e. the plasma starts in the *middle* of the proton bunch)
  - The <u>head of the proton bunch remains unmodulated</u>
- In Run 2, the <u>entire proton bunch needs to be modulated before entering the 2nd cell</u>, to prevent the bunch head from modulating at a different phase and affecting the wakefields
  - **Primary goal of Run 2a: <u>demonstrate</u> that an electron bunch can seed self-modulation in the 1st plasma cell**



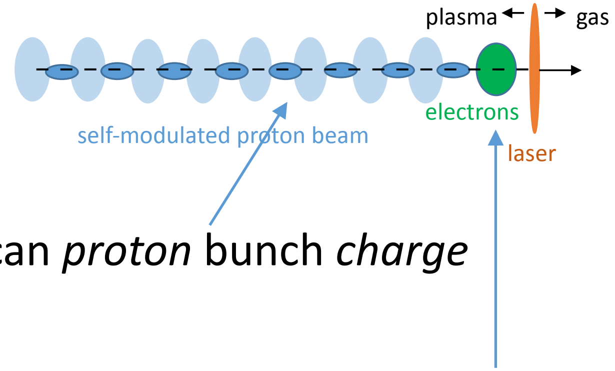
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).



Run 2a: what can we learn from eSSM?



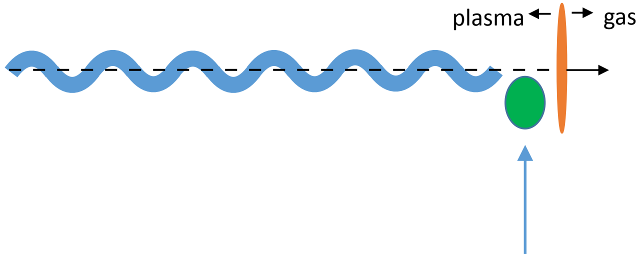
Seeding and growth of
self-modulation



scan *proton* bunch *charge*

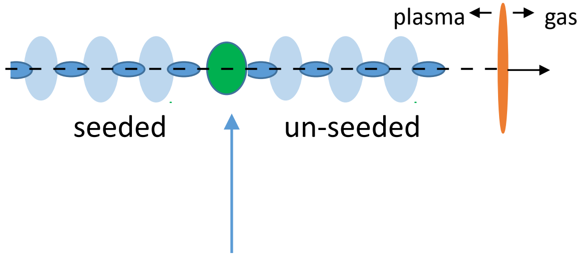
scan *electron* bunch *charge*

Seeding and growth of
hosing



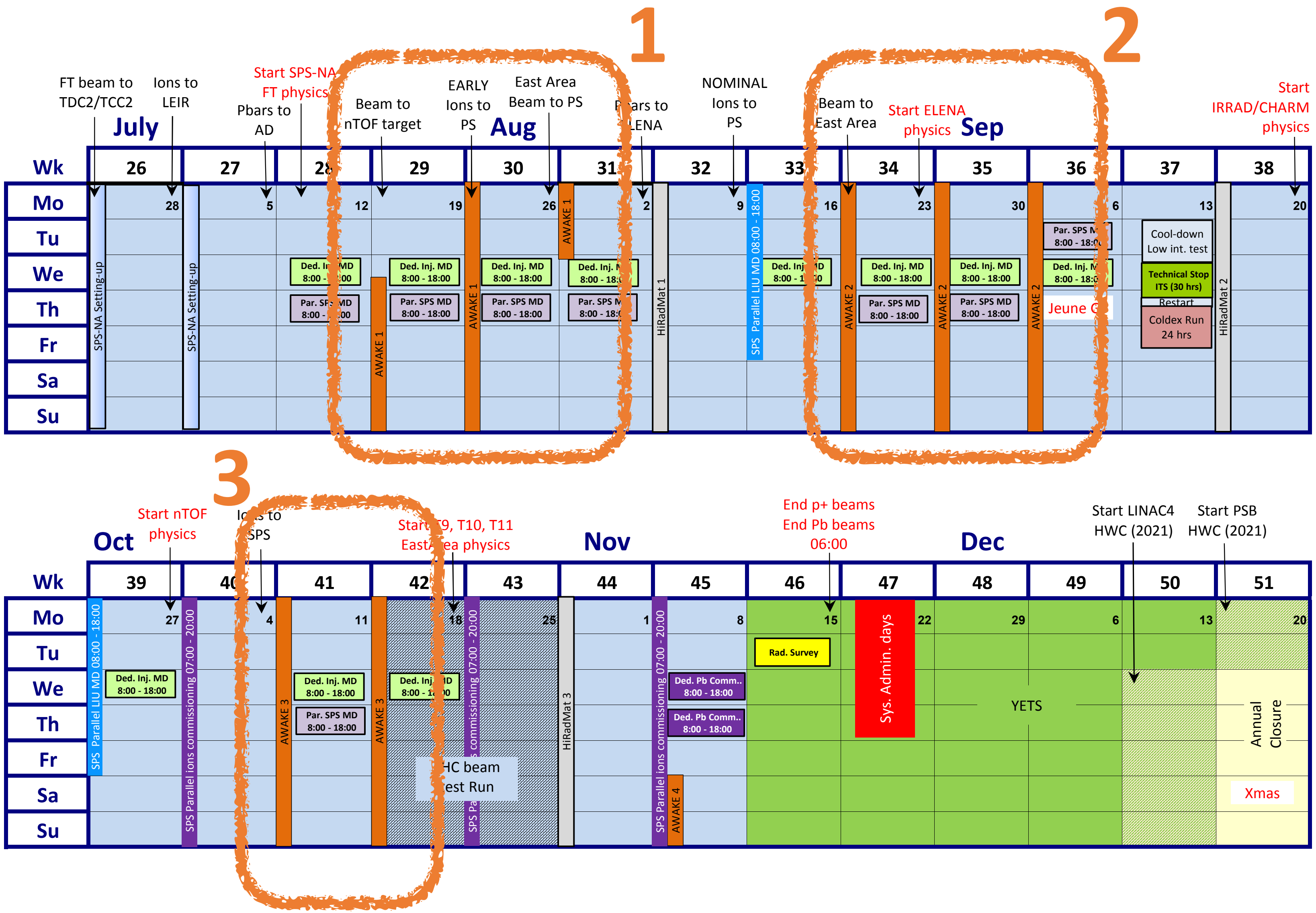
scan electron bunch
transverse position

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

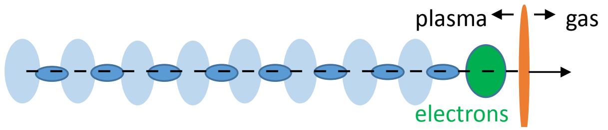


scan electron bunch
longitudinal position

2021 AWAKE proton run: 2+3+2 weeks (+ 2 days)

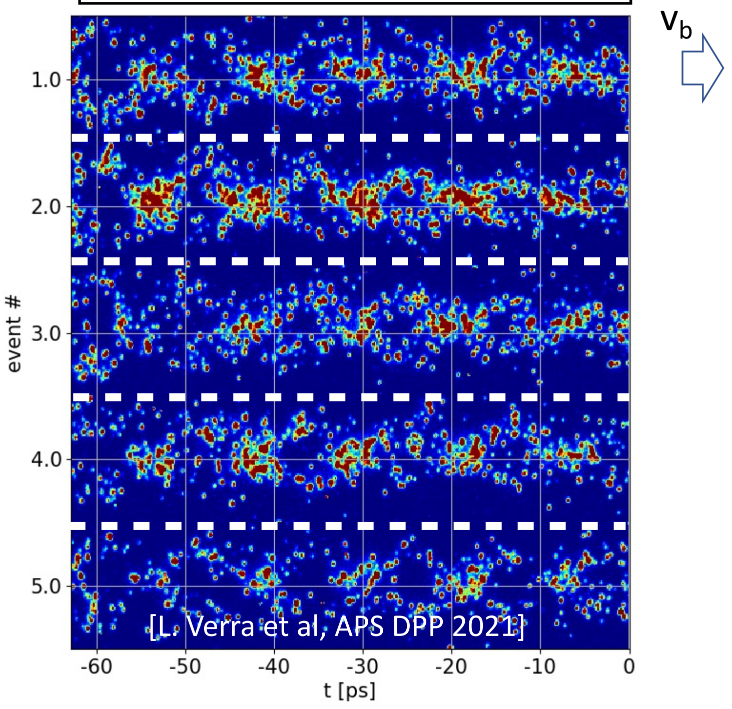


First run (July 21, 2 weeks)

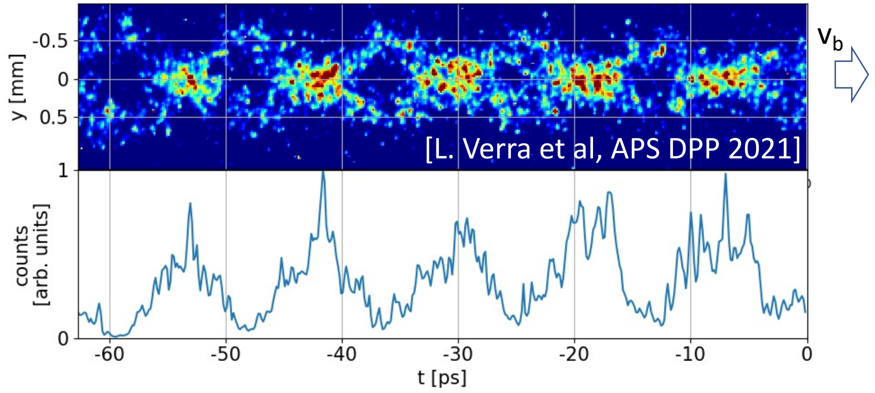


- First observation of electron-seeded self-modulation
  - Observed with low electron beam charge, allowing to study effect of increased charge

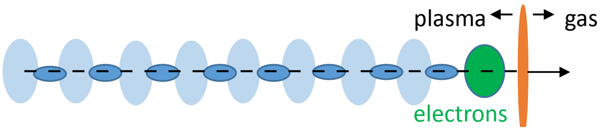
Phase-reproducibility in consecutive events



Sum of 10 consecutive events

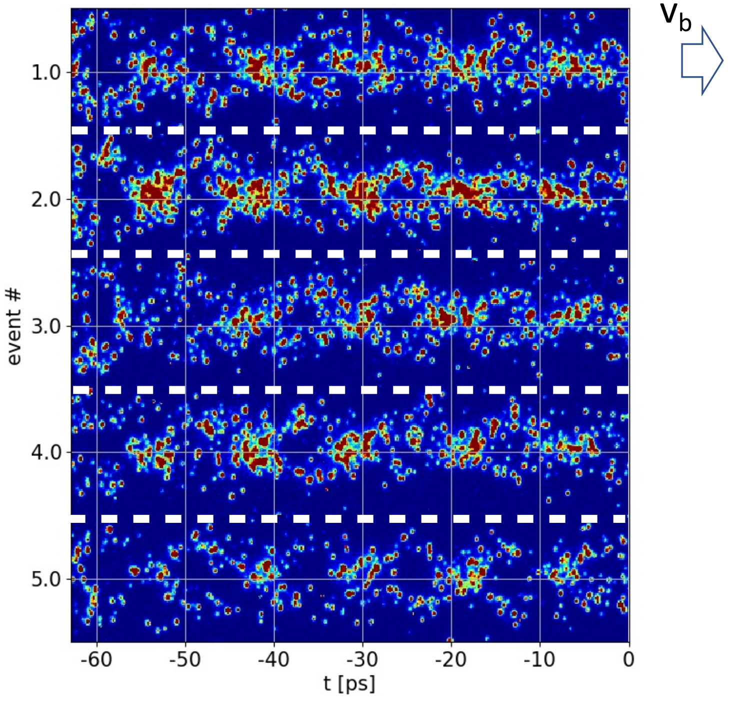


First run (July 21, 2 weeks)

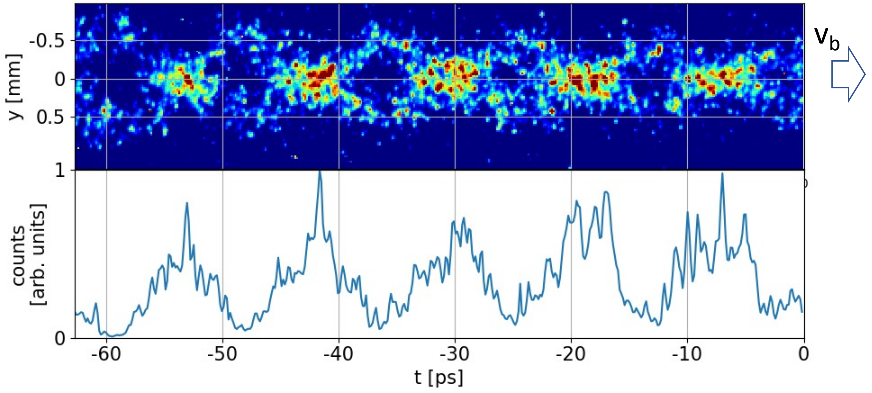


- First observation of electron-seeded self-modulation
  - Observed with low electron beam charge, allowing to study effect of increased charge

Phase-reproducibility in consecutive events

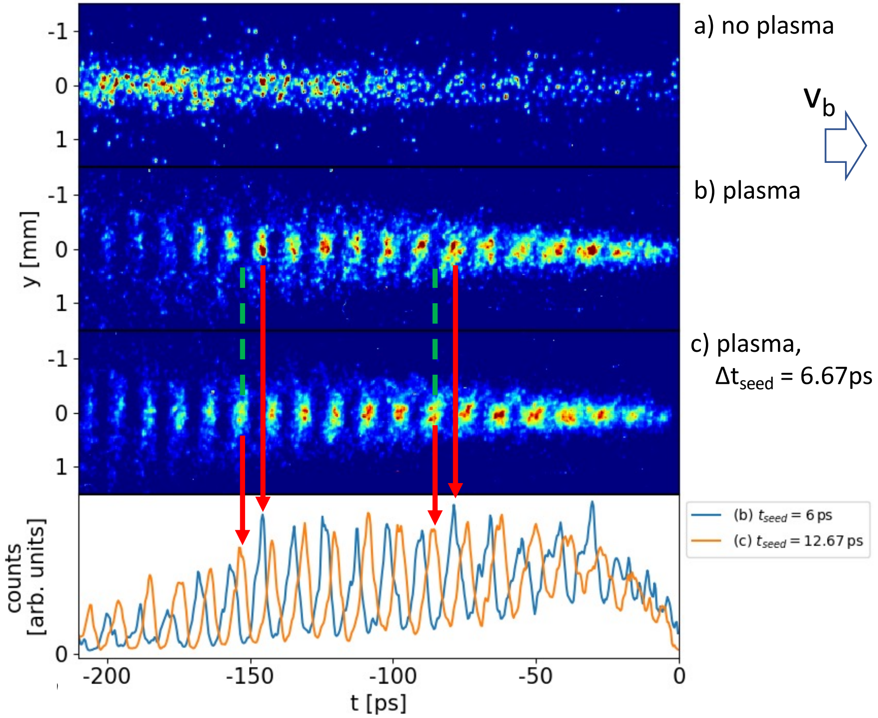


Sum of 10 consecutive events



Control of the eSSM process: shifting the electron bunch position shifts the proton micro-bunches by the same Δt

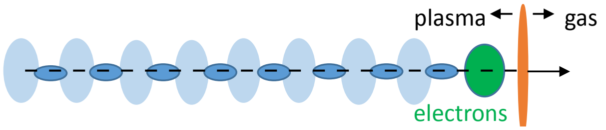
210 ps-scale streak camera images



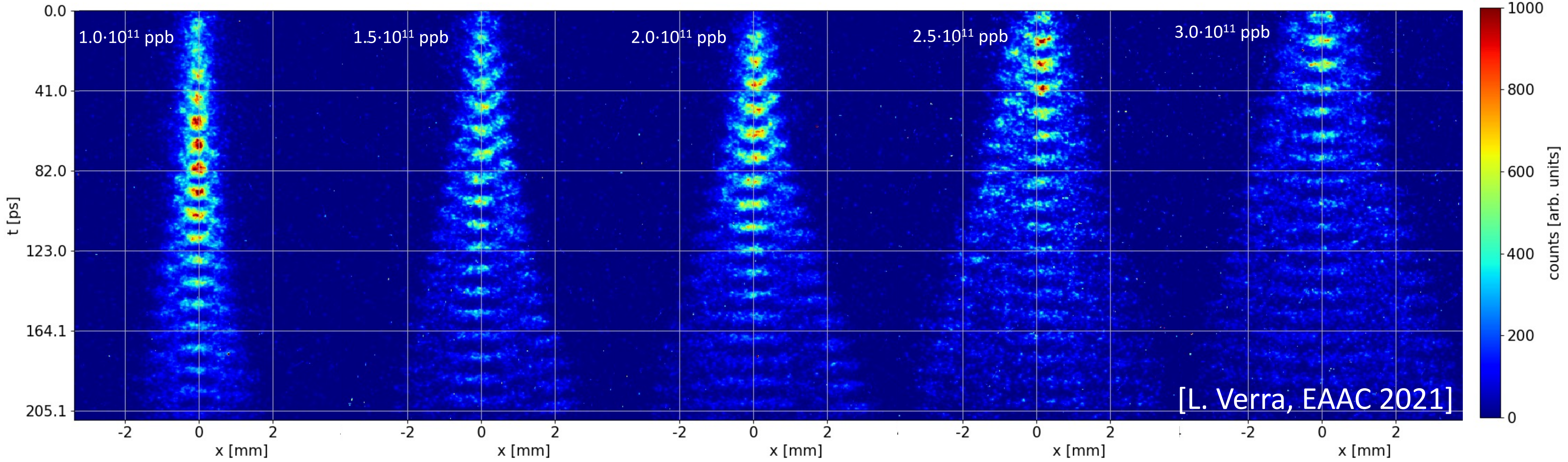
[L. Verra et al, APS DPP 2021]

Second run (August 23, 3 weeks)

- eSSM observed up to 3E11 proton intensity (AWAKE nominal)
- Study self-modulation dependence on:
  - Electron bunch charge, i.e. seed wakefield amplitude
  - Proton bunch charge, i.e. self-modulation growth rate



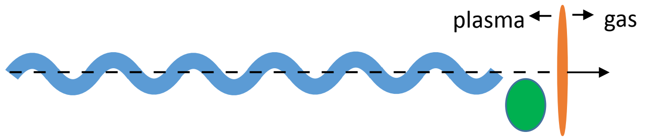
Proton bunch, 210 ps scale (plasma and electron seed). Different proton bunch charges



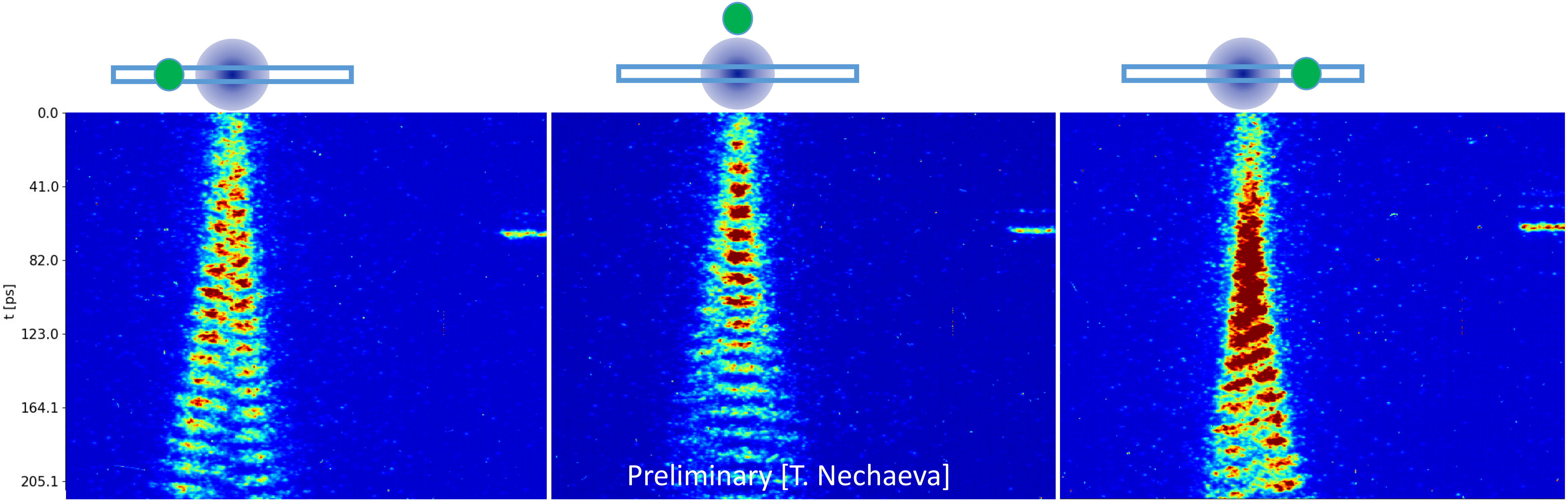
*All images are sums of O(10) events

Second run (August 23, 3 weeks)

- Study hosing dependence on misalignment axis
  - Control the direction of hosing w.r.t. the streak camera slit

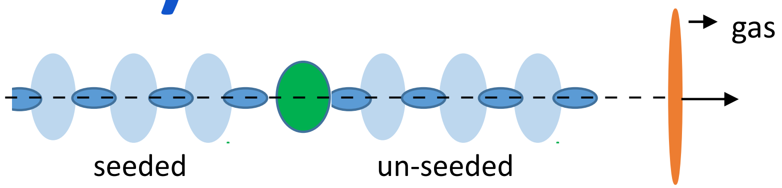


Proton bunch, 210 ps scale (plasma and electron seed). Different electron bunch alignments

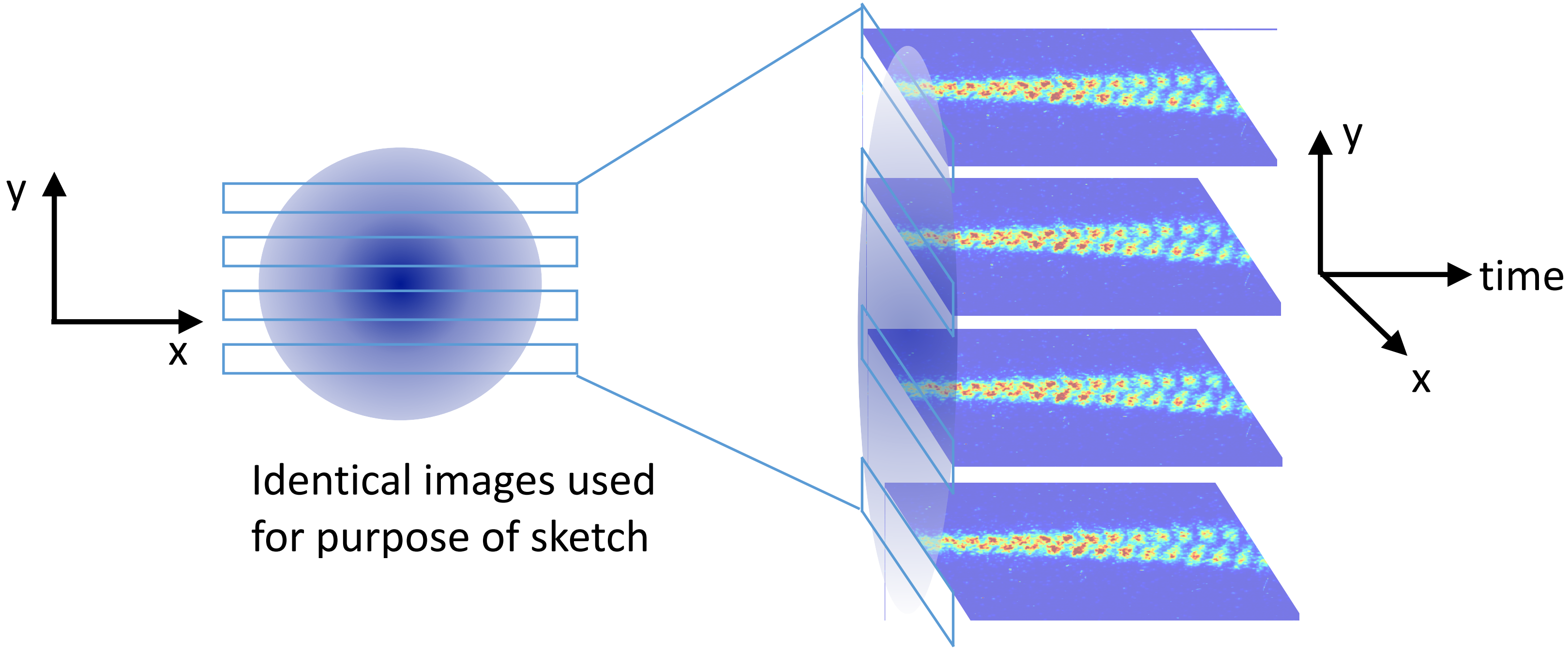


*All images are sums of O(10) events

Third run (September 11, 2 weeks)



- First scans of longitudinal electron position
  - How does the unseeded front of the proton bunch affect the seeded back of the bunch?
  - Important to understand the role of electron-seeding in Run 2c
- Study 3D features of beam by moving image on streak camera slit
  - Requires shot-to-shot reproducibility for O(100) consecutive shots, or O(1) hour
  - Interesting to understand both self-modulation and hosing configurations



Identical images used for purpose of sketch

Summary for 2021 proton run

- Run 2a started in July 2021, with an ambitious program
  - Prove electron-seeded self-modulation of proton bunch
  - Use electron-seeding to understand the physics of self-modulation and hosing

- Very good results from the 7 weeks of proton beam received in 2021
  - Early observation of electron-seeding: already started advanced studies and scans
  - Sufficient stability for long scans to explore full 3D beam profile

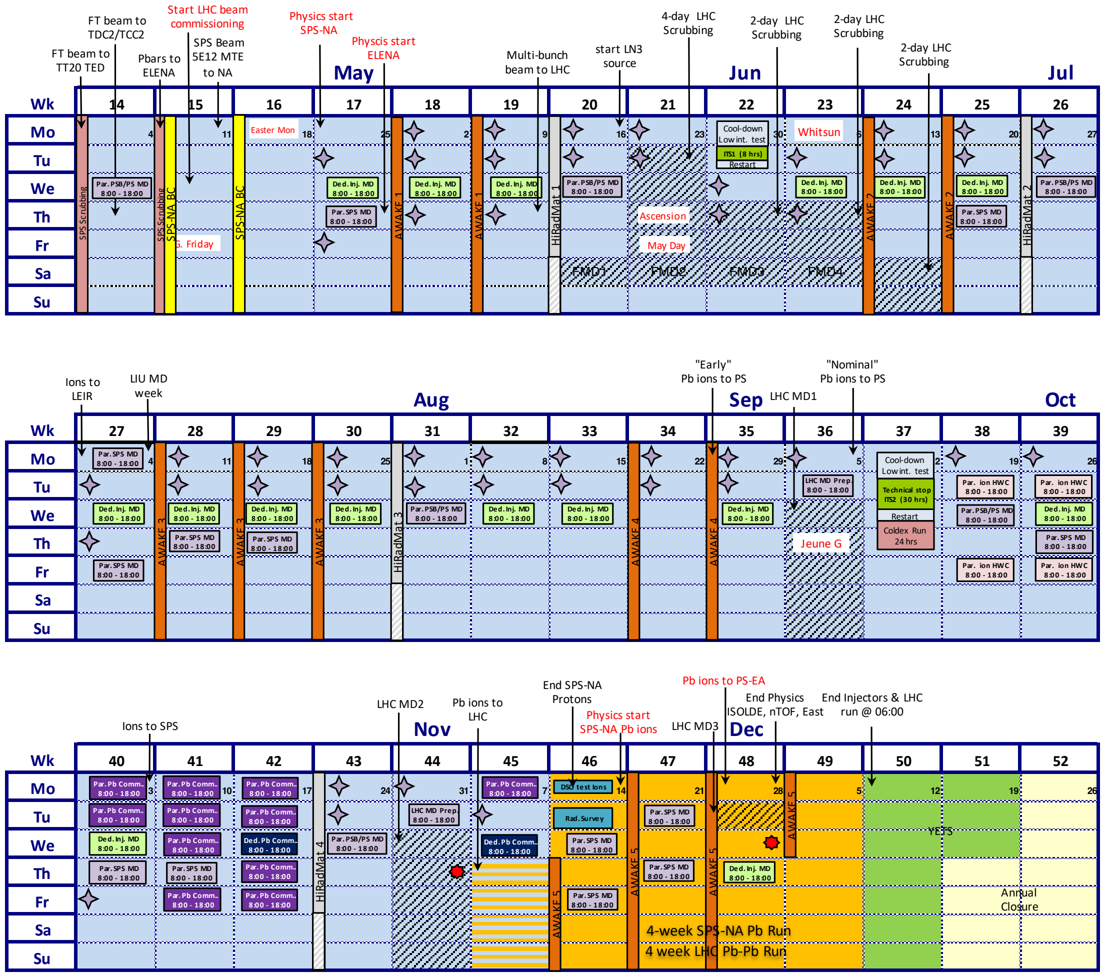
- These results would not have been possible without the support and dedication of:
  - The control room team: Livio Verra, Jan Pucek, Tatiana Nechaeva, Michele Bergamaschi, Joshua T. Moody, Miklos Kedves, Eugenio Senes, Eloise Guran, Vasyl Hafych, Samuel Wyler, Francesca Elverson, Edda Gschwendtner and Patric Muggli
  - The SPS operation team and the support and service teams of the AWAKE facility

Outline

- Introduction to AWAKE
  - Run 1 achievements
  - Plan for Run 2
- Run 2 preparation during the Long Shutdown 2 (2019-2020)
  - Laser ionization and plasma formation
  - Electron Beam: human and machine learning
  - Electron seeding in plasma: preparation for Run 2a
  - Performance: Alignment and Data Quality
- The 2021 proton run
  - Run 2a (2021-2022) physics goals
  - Preliminary results
- What's next?
  - 2022 proton run goals
  - Beyond Run 2: physics applications

Next step: 2022 proton run

- 12 weeks of beam time foreseen for 2022
- AWAKE and SPS operations
  - Improve laser and electron alignment, using new BTV and improved software
  - Work with SPS to improve proton beam alignment, stability (for long scans), and to extract beam during LHC filling
- Physics program
  - Continue scans to explore the physics of eSSM and electron-seeded hosing
  - [Tentative] Use new spectrometer cameras to measure size/emittance of accelerated beam



Beyond Run 2: Roadmap for Particle Physics Applications

- The AWAKE scheme can provide **high-energy (> 50 GeV) high-charge electron bunches**
  - Switch from R&D to particle physics experiments!
- Step 1: produce e^- bunches for fixed target experiments (standalone, least stringent)
  - Build upon AWAKE Run 2, extend plasma from 10 m to ~100 m
  - Physics: dark photons, strong-field QED, …
- Step 2: re-inject electron beam for e-p (or e-ion) collisions
  - Move AWAKE on a transfer line feeding back into the LHC, use SPS or LHC protons
  - Physics: explore proton/ion structure, pγ cross section, leptoquarks, …
- And beyond: e^+e^-, polarized beams, muons, …

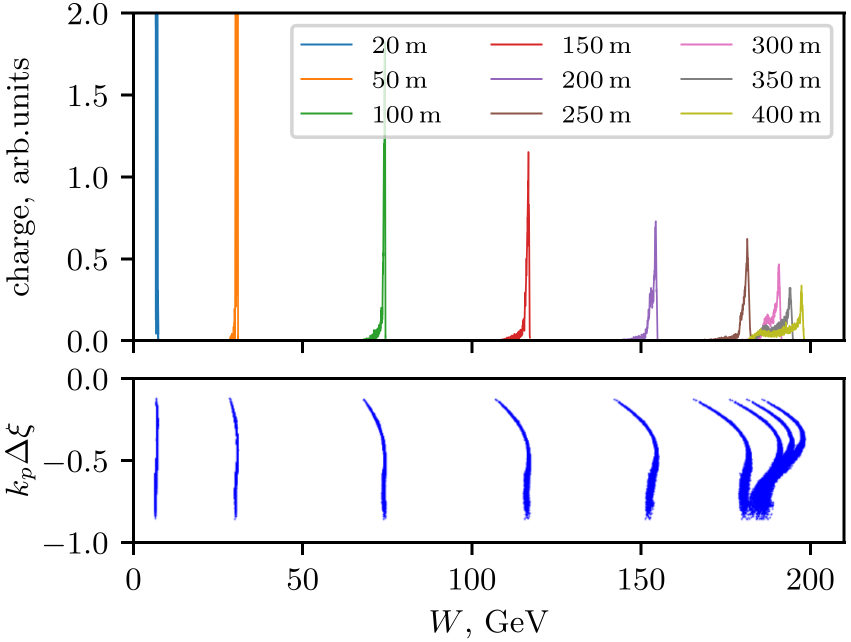
Active participation in Physics Beyond Colliders workshop and European Strategy Update

- arXiv:1812.11164, arXiv:1812.08550, CERN-PBC-REPORT-2018-005 and 007

Step 1: produce e⁻ bunches for fixed target experiments

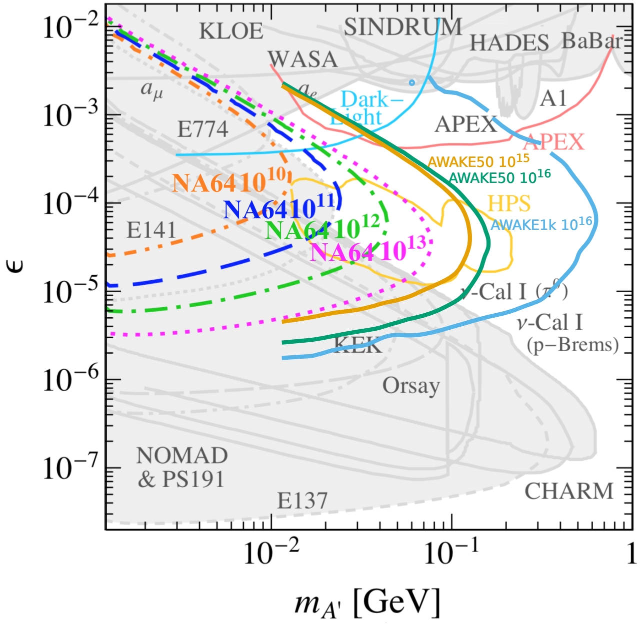
- Fixed target requirements: energy & flux important, relaxed emittance
  - Recent simulations show a maximum energy of 200 GeV with SPS protons!
  - Energy and electrons on target competitive with state-of-the-art (NA64)

AWAKE energy using the SPS beam



K.V. Lotov and P.V. Tuev, Plasma wakefield acceleration beyond the dephasing limit with 400 GeV proton driver, *Plasma Phys. Control. Fusion*, **63**, 2021, 125027.

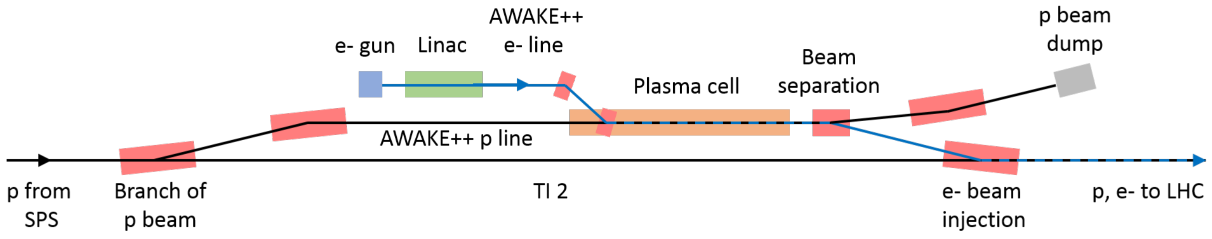
Dark photon mass/coupling reach



R. Alemany et al., Summary Report of Physics Beyond Colliders at CERN, arXiv:1902.00260, 2019.

Step 2: re-inject electron beam for e-p (or e-ion) collisions

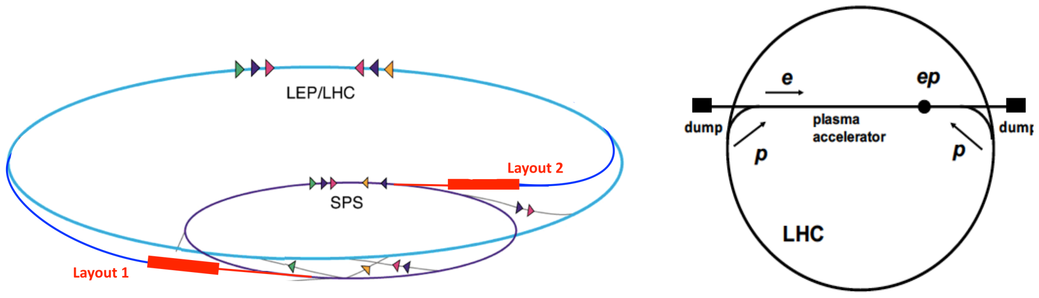
- Explore QCD scaling laws at high center of mass energy, leptoquark searches
  - Limited luminosity, but very high energy



PEPIC: √s = 1.3 TeV, SPS-driven

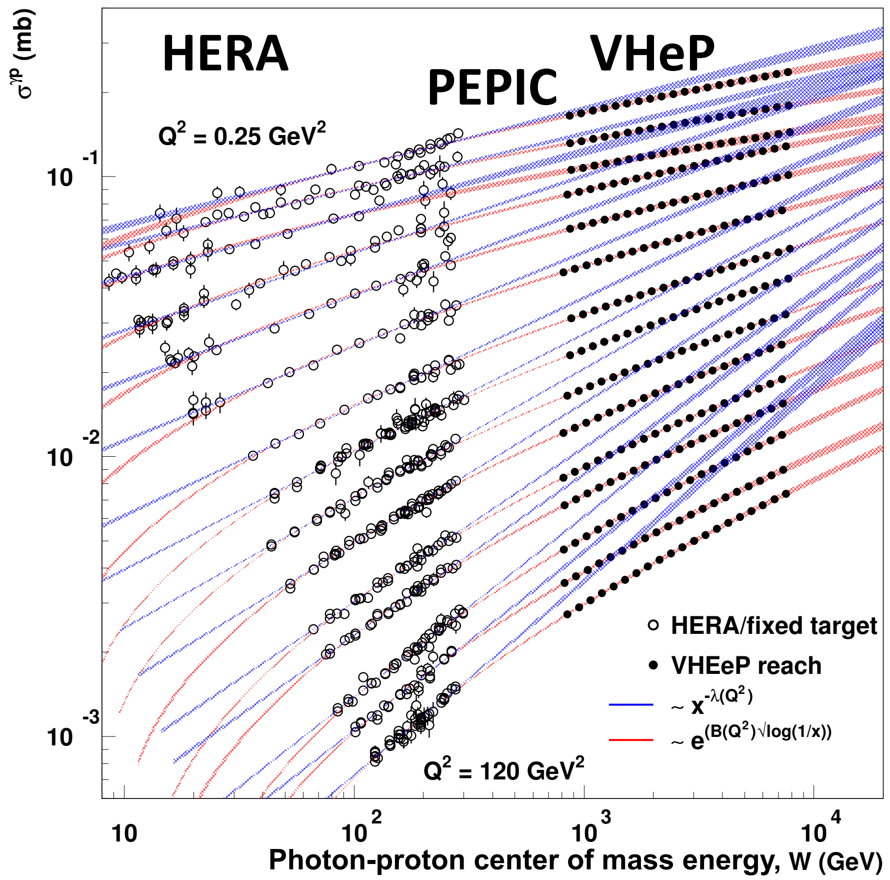
(Plasma electron-proton/ion collider)

VHeP: √s = 9 TeV, LHC-driven



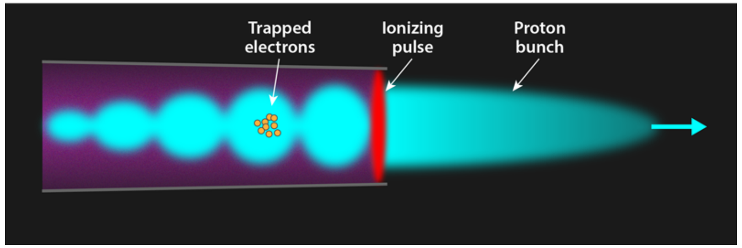
G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

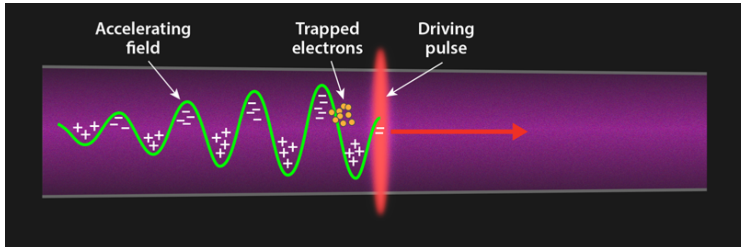
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463



Conclusions

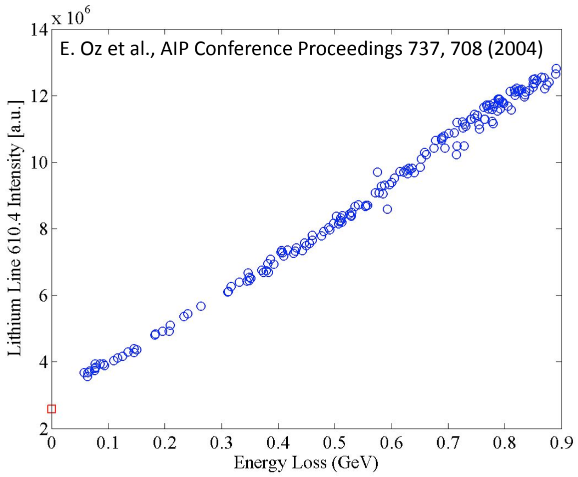
- AWAKE was created to test a new idea for electron acceleration
  - Use plasma to transfer energy from protons to electrons and potentially reach the electron energy frontier
- So far, in Run 1 and Run 2a, all expectations have been met
  - The rest of Run 2 aims to demonstrate the possibility to use the AWAKE scheme for high energy physics applications
- AWAKE is actively thinking about future physics applications
  - Began with Physics Beyond Colliders discussion
  - Most recently in the context of the European Strategy for Particle Physics "Accelerator R&D Roadmap"



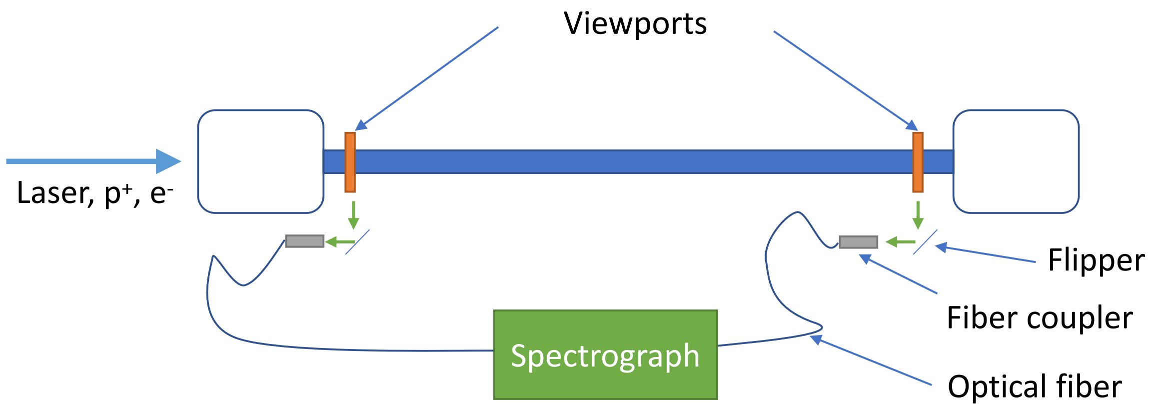


BACKUP

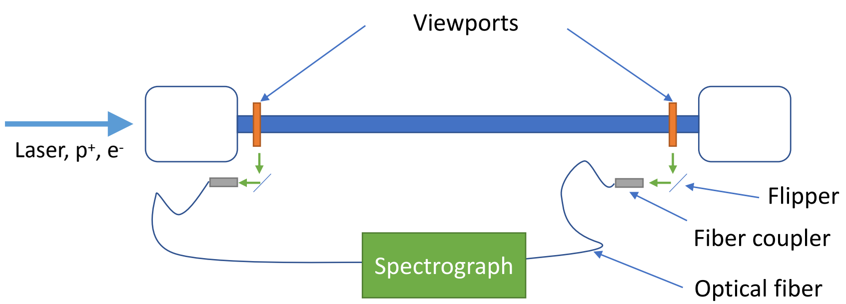
Run 2a goals: Plasma light as a measurement of wakefields



- Inspiration: SLAC E-164-X PWFA experiments (2004)
  - Clear indication that plasma light is proportional to wakefields
  - Explanation: wakefields sustained by plasma e^- oscillations dissipate in plasma. Plasma recombination produces light.
- Setup @ AWAKE:
  - Optical fibers from 2 viewports to spectrograph used at 0^{th} order
  - Data: laser-only, add electrons, protons or both
- Simple analysis to measure wakefields:
  - Use timing to reject laser pulse light, and use laser-only images for background subtraction

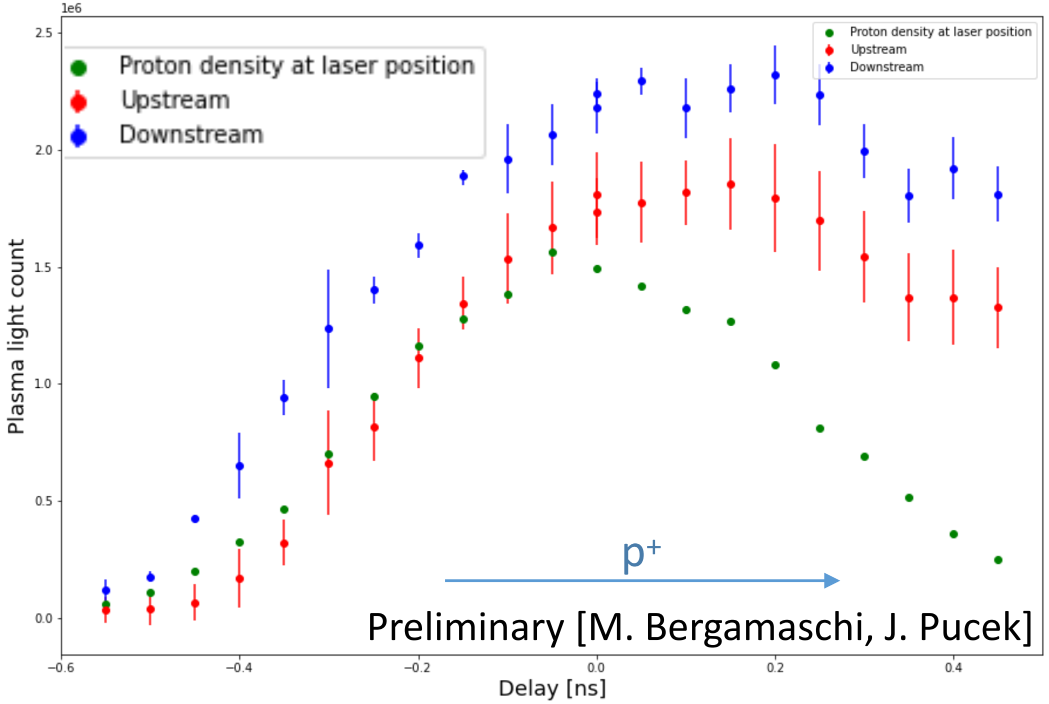


Second run (August 23, 3 weeks)



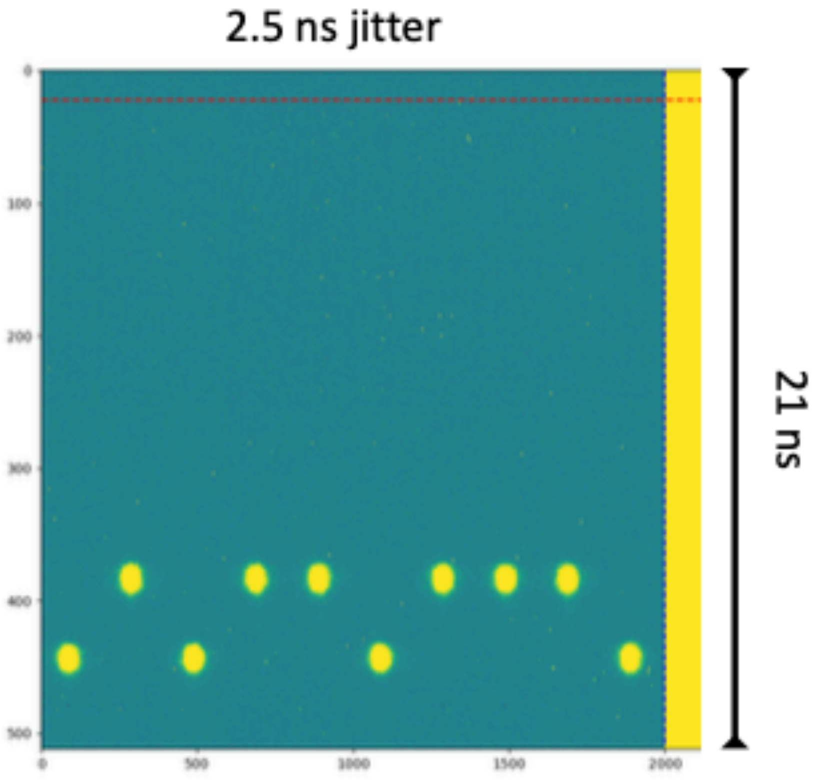
- Study plasma light with laser + protons
  - Focus on proton wakefields (~10 times larger than electron ones)
  - Upstream viewport: wakefields driven by local proton density
  - Downstream viewport: wakefields result from 10m evolution of self-modulation

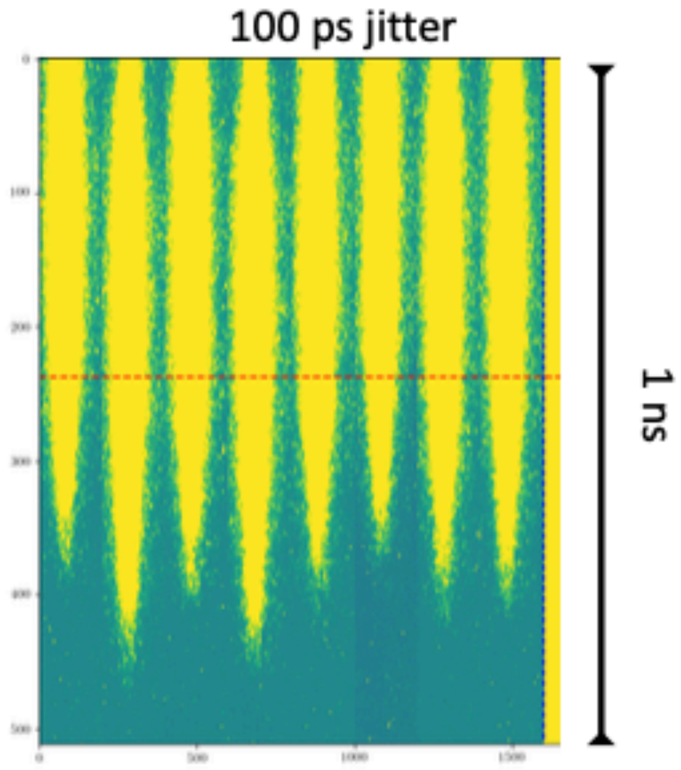
- Promising results
  - Upstream: Correlation between plasma light and proton density at laser position
  - Correlation between two viewports
  - Measurements active for most of the run: laser+electrons and laser+protons+electrons



Highlights of the first proton run (July 22 - Aug 3)

- July 29-30: proton timing jitter
  - Different RF issues causing proton jitter on different scales

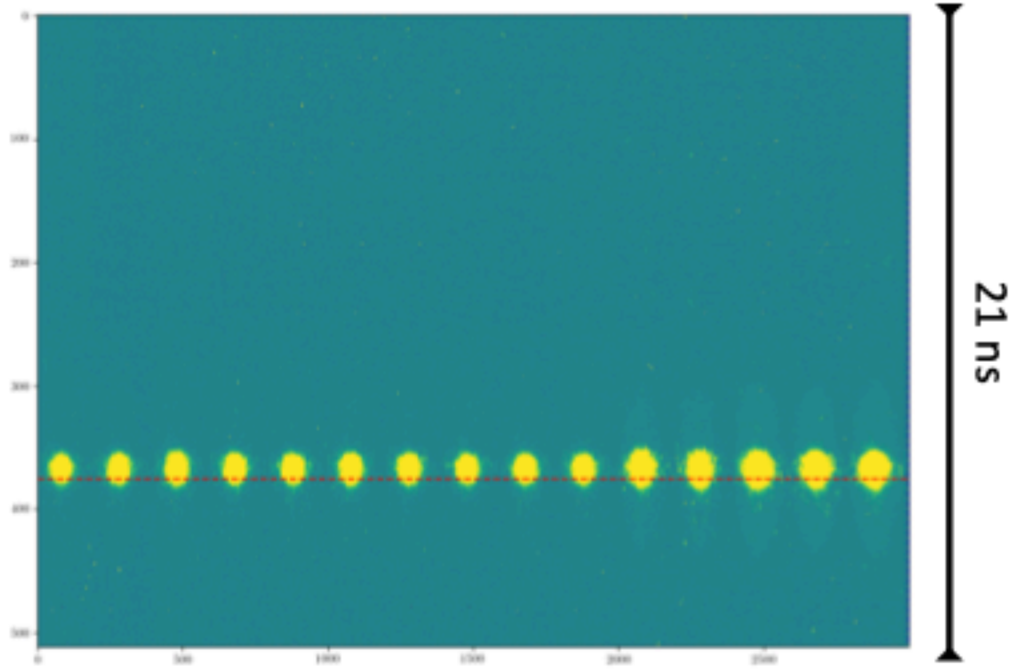




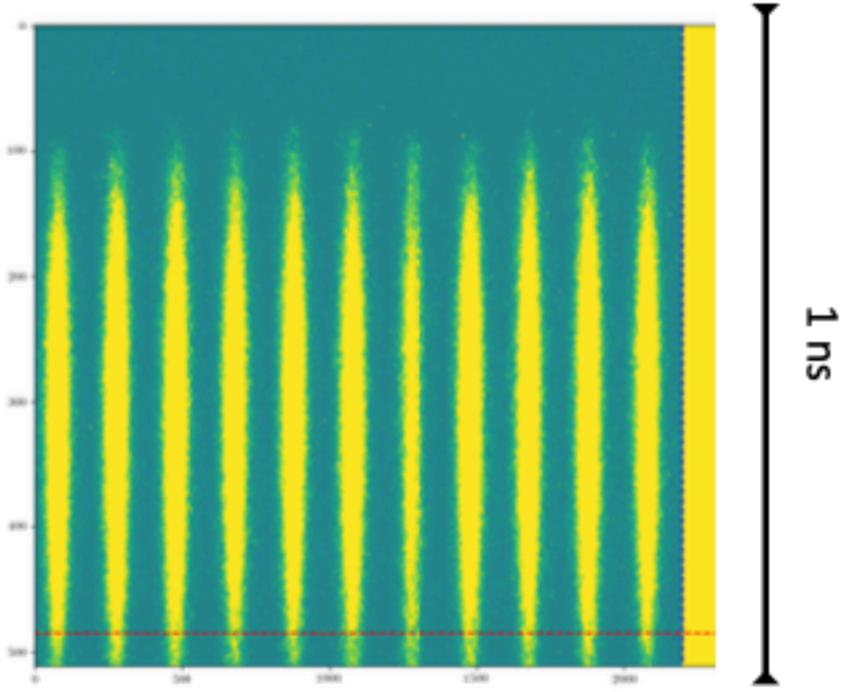
Highlights of the first proton run (July 22 - Aug 3)

- July 29-30: proton timing jitter
  - 2.5 ns jitter solved next-day, and 100 ps reduced
  - 100 ps jitter fully solved by beginning of second proton run

No 2.5 ns jitter



No 100 ps jitter

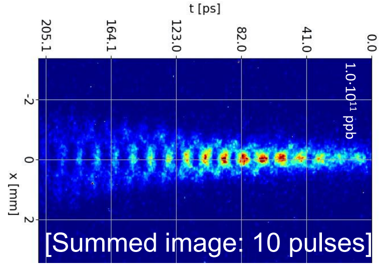


AWAKE feedback to SPS

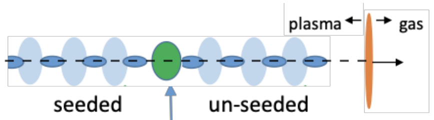
- Reported at *Injectors and Experimental Facilities Workshop* in December
  - https://indico.cern.ch/event/1063281/timetable/

AWAKE challenges (from the injector complex)

- **Experiments are centered on reproducibility**
  - Need for **reproducible wakefields**
  - A longitudinal profile requires ~10 summed images
- **Data-taking consists of parameter scans**
  - 1 "data point" requires 10-15 consecutive pulses
  - **10-point scan** requires **1 hour**



Only possible with stable beam conditions



scan electron bunch *longitudinal position*

- **The biggest challenge comes from interruptions**

  Beam is interrupted for **more than a few cycles:** need to realign proton beam and restart scan

- **Current diagnostic insufficient for the necessary alignment precision**

  Searching 'good alignment' by manually looking at self-modulation images. **Hours of physics time lost.**

AWAKE feedback to SPS

- Reported at *Injectors and Experimental Facilities Workshop* in December
  - https://indico.cern.ch/event/1063281/timetable/

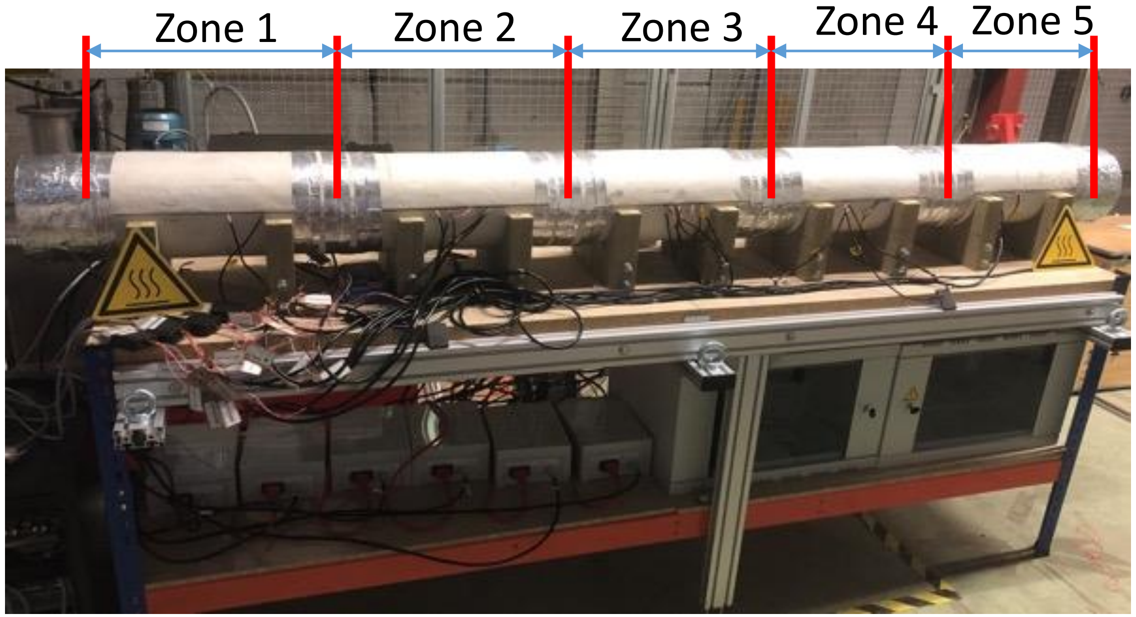
- **Feedback 1: the ALIGNMENT issue. *Should SPS take over proton beam alignment?***
  - Currently alignment is calculated by AWAKE operators based on BPM averages, and **mm/mrad** corrections are given to SPS operators. Do we want to change the procedure? Could/should SPS take this over?
- **Feedback 2: the STABILITY issue. *Can we think out of the box to improve it?***
  - **Restart of a scan (> 1 hour):** every time there is a few-minute interruption
  - **Speed up scans:** more frequent extractions (4 per super-cycle) in stable conditions?
  - **Anticipate less stable injector conditions:** give up the beam altogether in these situations?
  - **Improve communication:** not just with SPS but also with LHC and injectors to see if potentially disruptive tests or procedures are expected?
- **Feedback 3: the LHC FILLING issue. *Can AWAKE take protons during LHC filling?***
  - **Not possible** during Run 1 (2016-2018). What is the situation now? Showstoppers?
  - Since we suffer from upstream issues during the MDs on Wednesday and Thursday, additional interruptions from LHC filling in 2022
- **Feedback 4: the FLEXIBILITY issue. *Could there be flexibility when changing conditions?***

  Sometimes an experiment **is not yet finished**, when physics is stopped to change the cycle, begin an LHC fill, or make other active changes.
  - **Improve communication:** an early heads-up would already help to plan accordingly
  - **Evaluate priorities:** A “Could we have N more minutes?” card to occasionally postpone disruptive changes

Studies and experiments towards Run 2 b, c, d

[Run 2 b] New plasma cell with density steps

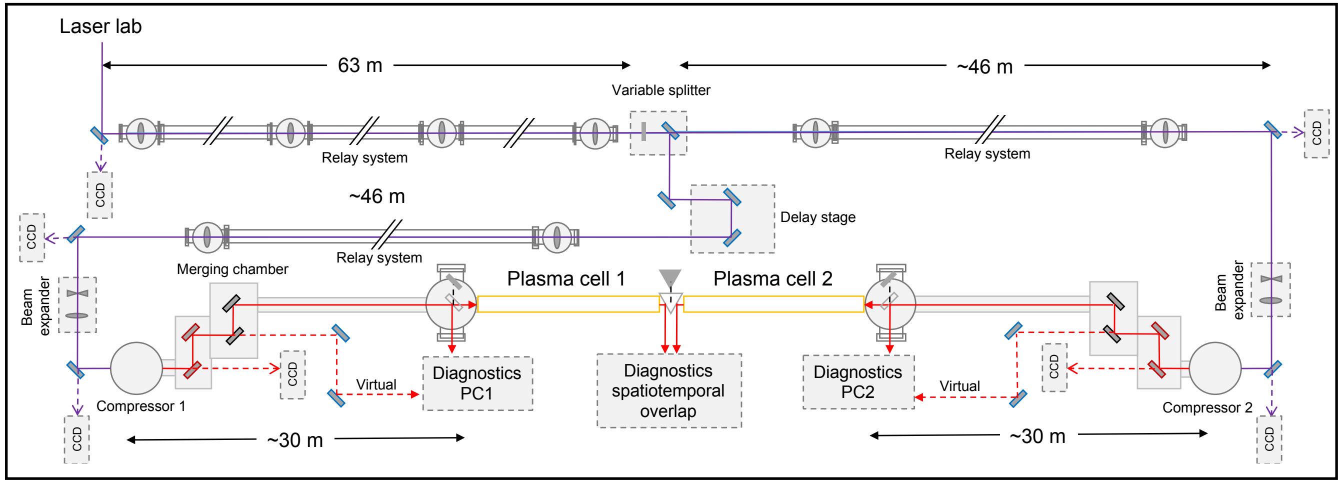
Prototype setup in test stand in EHN1!
System connected to Siemens control system
Good results for performance and control



MPP Munich, P. Muggli, J. Pucek, WDL, R. Speroni

[Run 2 c] New UV and IR laser lines

UV laser for 2nd electron source
Counter-propagating IR for ionization of second plasma cell



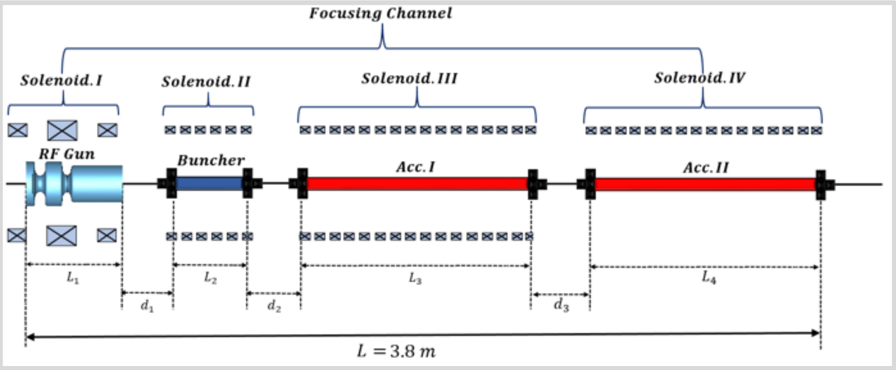
V. Fedosseev, E. Granados, H. Panuganti,
J. Moody, MPP

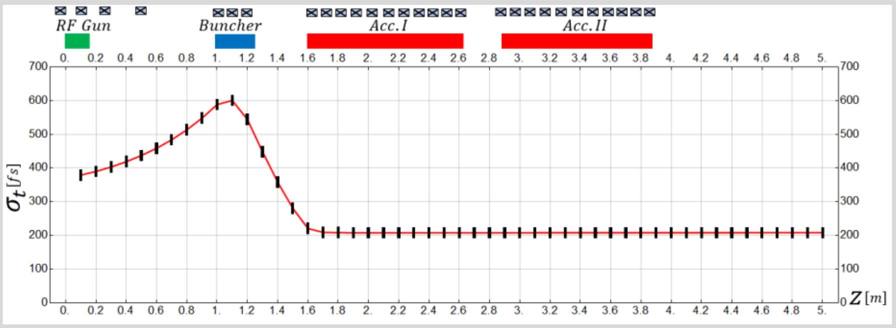
For more details, see E. Gschwendtner SPSC report: https://indico.cern.ch/event/962697/contributions/4050037/

Studies and experiments towards Run 2 b, c, d

[Run 2 c] New 150 MeV e⁻ source

→ based on X-band
→ Well advanced design
→ Prototyping together with CLEAR

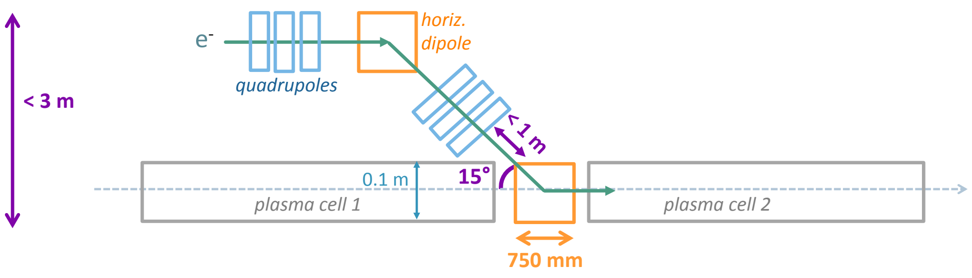


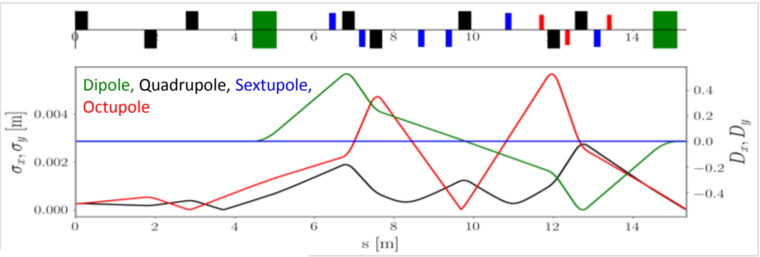


S. Doebert, M. Dayyani Kelisani, L. Garolfi

[Run 2 c] New e- line

→ Requirement of β = 5 mm at injection.
→ Require a module which is achromatic, with no bunch lengthening.
→ Limit of ~ 3m width set by tunnel width
→ Dipole bending angle > 15° so beam-pipe doesn't hit plasma cell
→ Dipole-quadrupole spacing > 1 m





R. Ramjiawan, F. Velotti

Design optimised to meet matching condition at plasma merge-point:

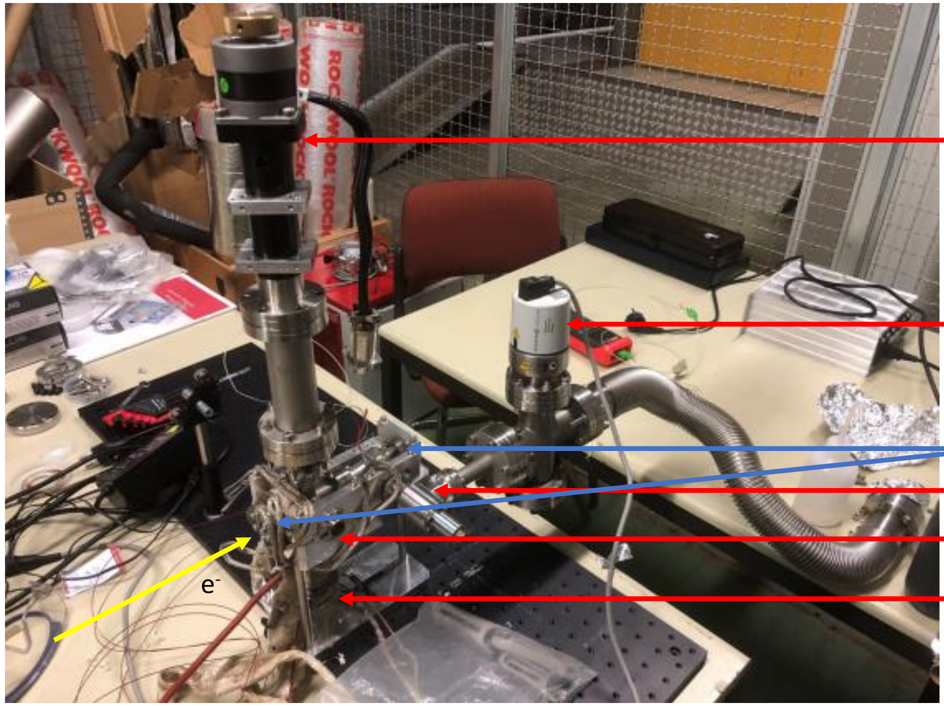
$$\sigma = \sqrt{4.87\ \text{mm} \times \epsilon}$$

For more details, see E. Gschwendtner SPSC report: https://indico.cern.ch/event/962697/contributions/4050037/

Studies and experiments towards Run 2 b, c, d

[Run 2 b] Diagnostics: beam screens in Rb vapor

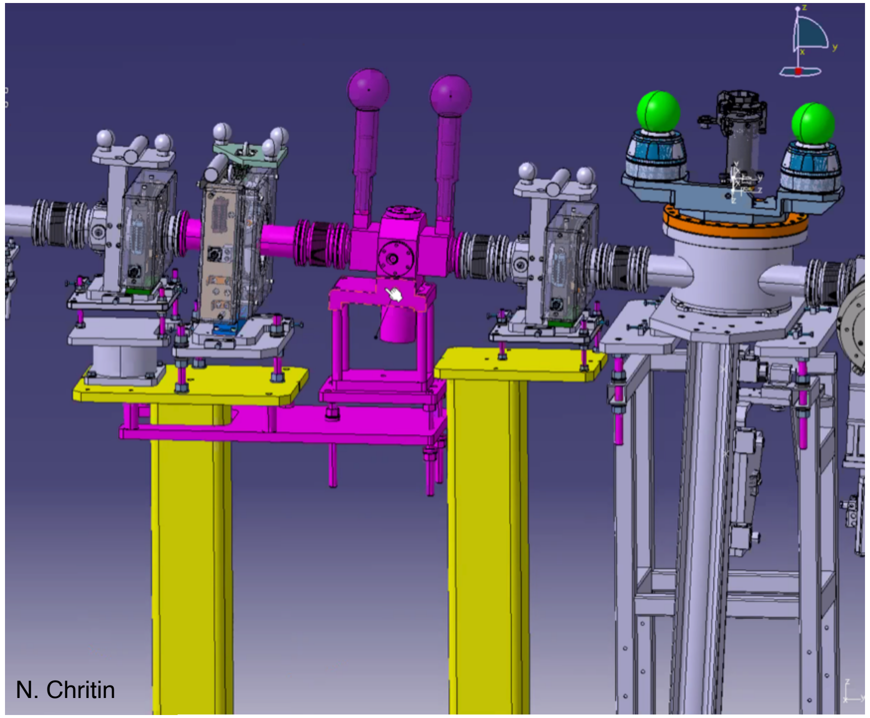
Study screen installation inside the vapor source expansion volume
Test screen performance in CLEAR



J. Pucek

[Run 2 b] Diagnostics: Cherenkov diffraction radiation (ChDR) BPMs

Preparing for prototype installation ~April 2021, with the goal to test it with protons during Run 2a. Full system for Run 2b.



S. Mazzoni, E. Senes, M. Bergamaschi, C. Pakuza, +UK, TRIUMF

For more details, see E. Gschwendtner SPSC report: https://indico.cern.ch/event/962697/contributions/4050037/

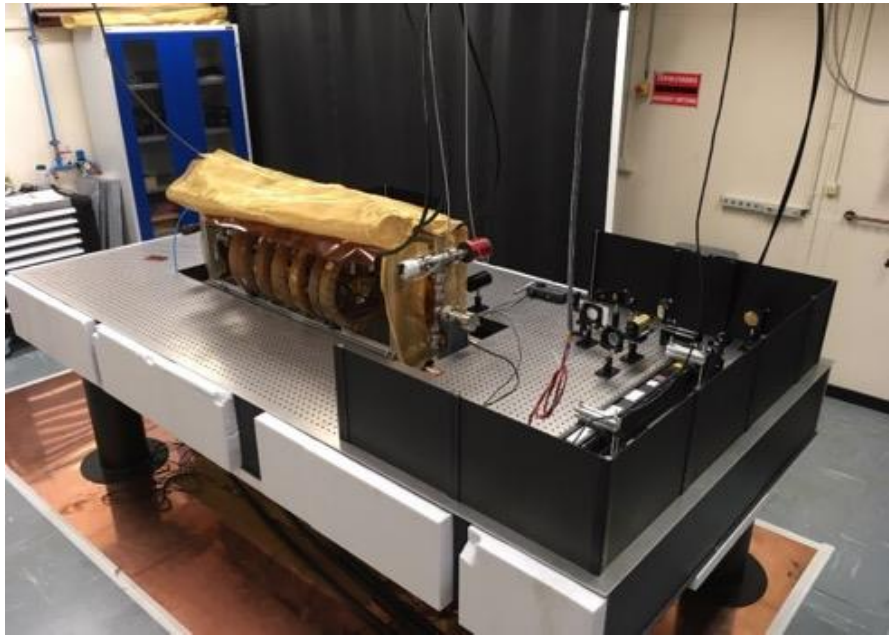
Studies and experiments towards Run 2 b, c, d

[Run 2 d] Develop scalable plasma sources

Current method (laser ionization) cannot support O(100) m plasma cells
2 parallel developments

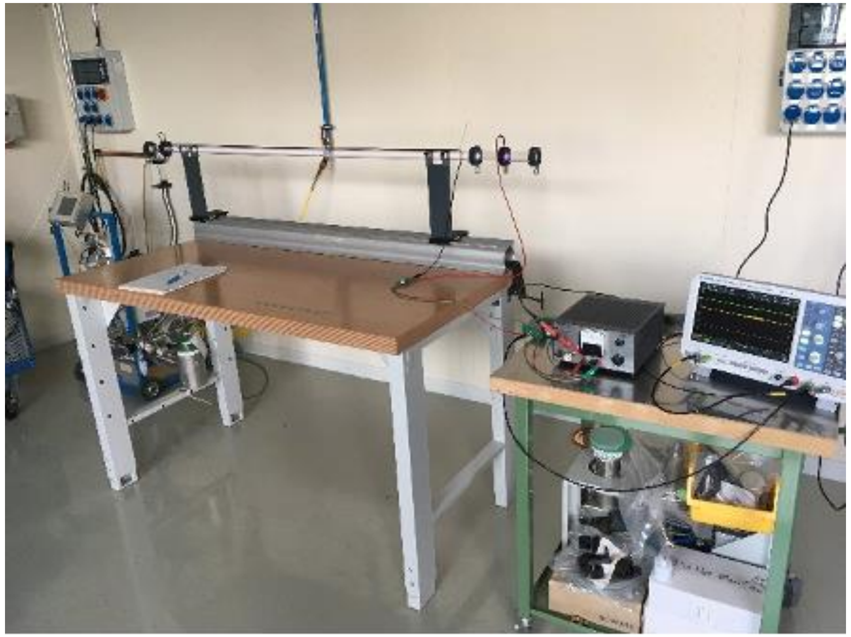
‘**Helicon**’: low-frequency EM wave generated by RF antennas
Prototype (1m) moved to CERN in 2019, tests started

1 m helicon plasma source at CERN



‘**Discharge**’: high-current arc plasma

1.6m discharge plasma cell setup at CERN



A. Sublet, + IPP Greifswald, SPC Lausanne, Univ. Wisconsin, IST Lisbon

For more details, see E. Gschwendtner SPSC report: https://indico.cern.ch/event/962697/contributions/4050037/

Step 1: produce e⁻ bunches for fixed target experiments

- Fixed target requirements: energy & flux important, relaxed emittance
  - Simulations show parameter ranges for SPS-based beams
  - Energy and electrons on target competitive with state-of-the-art

proton energy	**plasma length**	**electron energy**	**electron charge**
400 GeV	50 m	33 GeV	107 pC
400 GeV	100 m	54 GeV	134 pC
450 GeV	130 m	70 GeV	134 pC

Parameter	**AWAKE-upgrade-type**	**HL-LHC-type**
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (s)	40	40
Electrons per cycle N_e	2×10^9	5×10^9
Number of electrons on target per 12 weeks run	4.1×10^{15}	2×10^{17}

* Assumes a 12 week experimental period with a 70% SPS duty cycle.

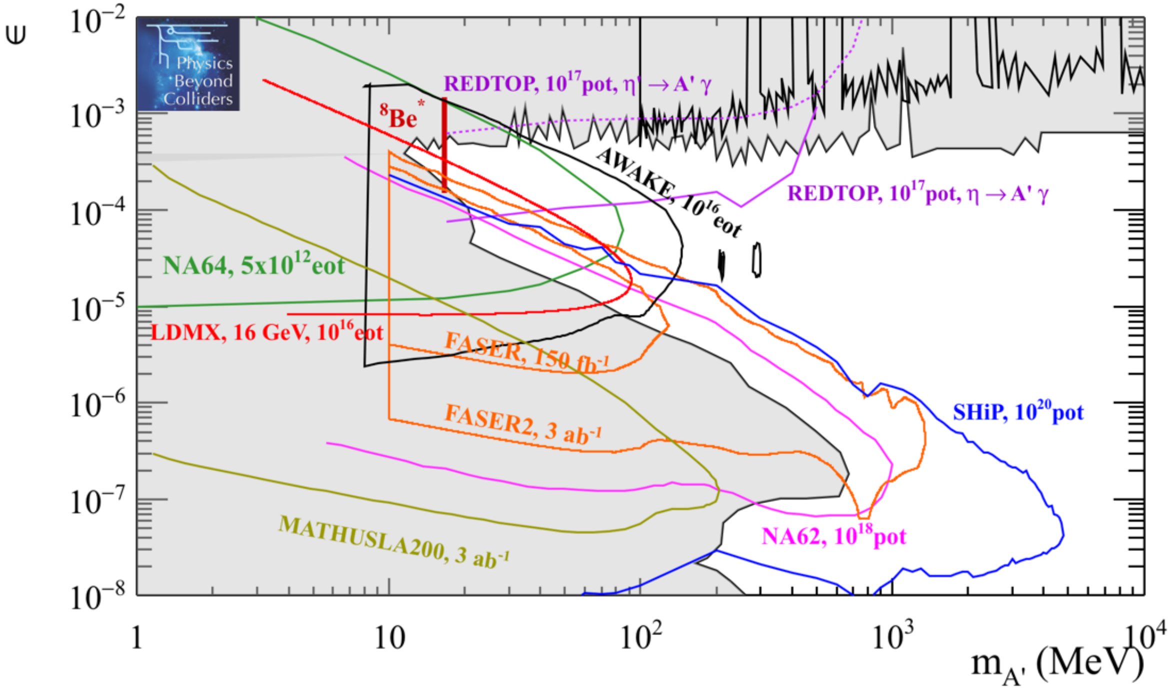
Reference: NA64 experiment @ CERN
- 100 GeV
- 3×10^{12} electrons for entire lifetime

- arXiv:1812.11164, arXiv:1812.08550, CERN-PBC-REPORT-2018-005 and 007

Step 1: produce e- bunches for fixed target experiments

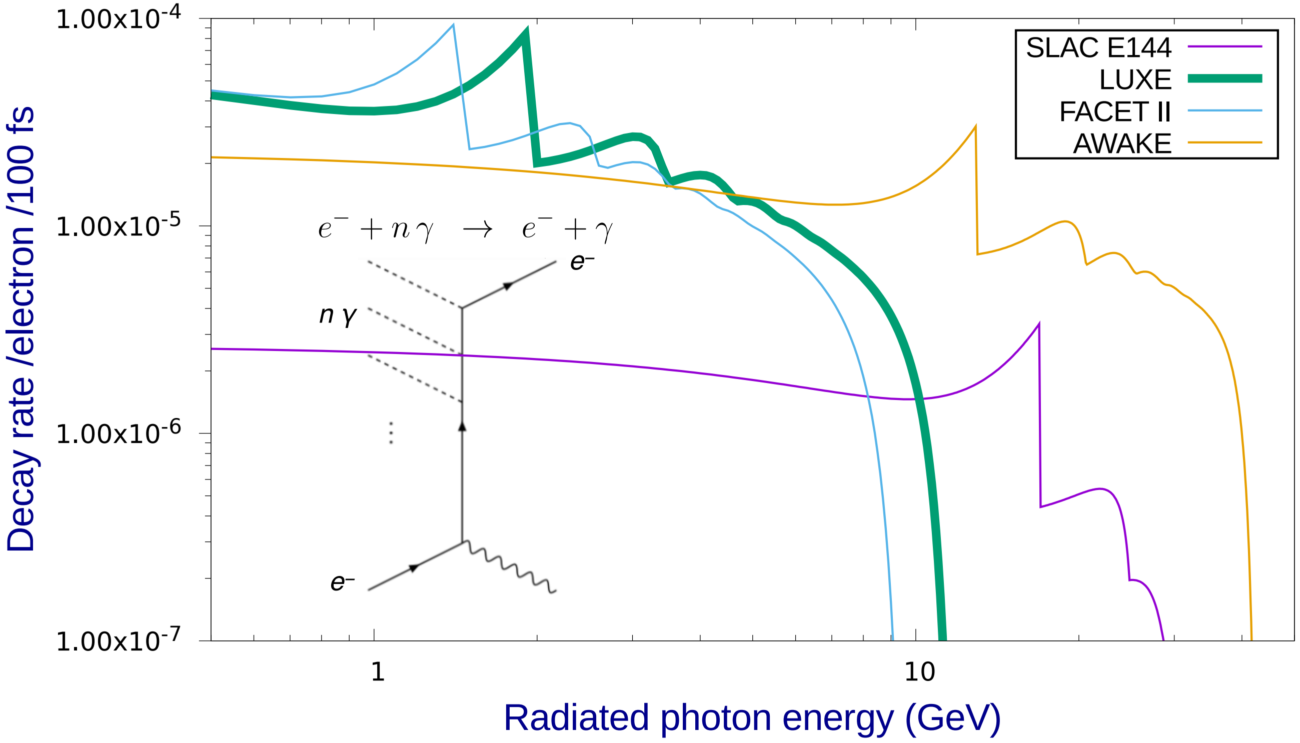
- Significant extension in physics reach using an AWAKE-like electron beam

Dark photon search (NA64-like)



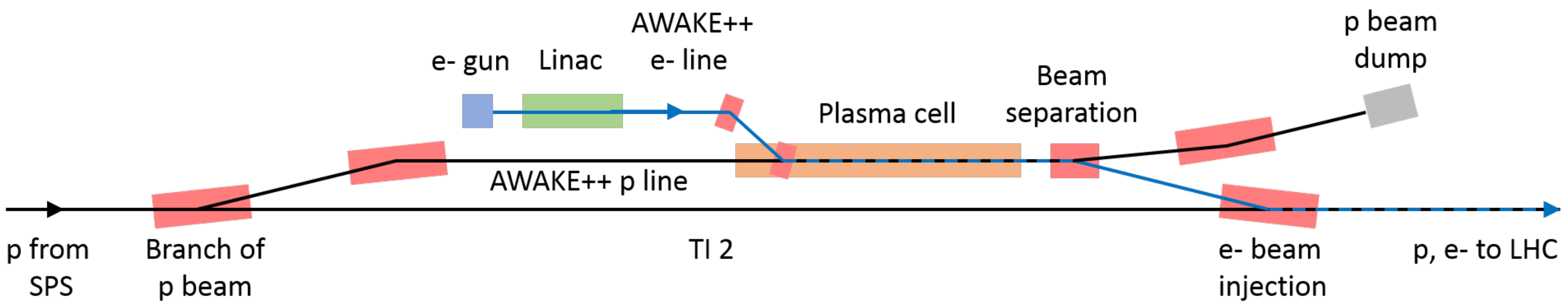
[CERN-PBC-REPORT-2018-007]

Strong-field QED tests (e-/laser interactions)



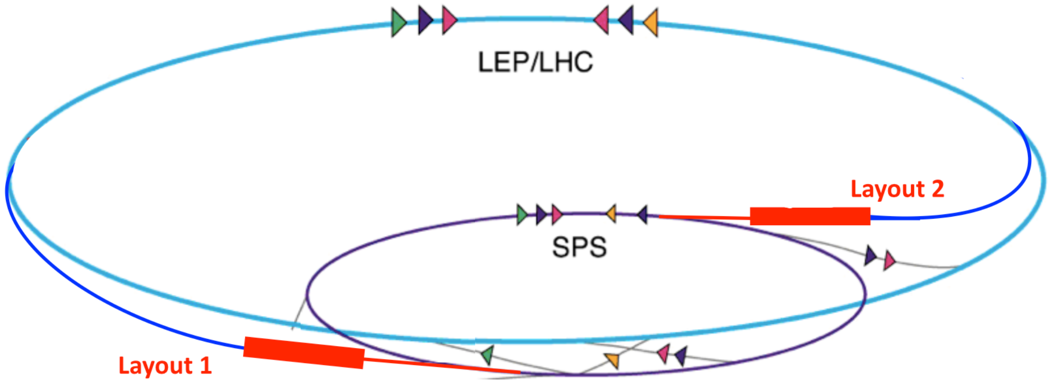
[A. Hartin, IJMP A33 1830011 (2018), M. Altarelli et al. arXiv:1905.00059]

Step 2: re-inject electron beam for e-p (or e-ion) collisions



PEPIC: √s = 1.3 TeV, SPS-driven

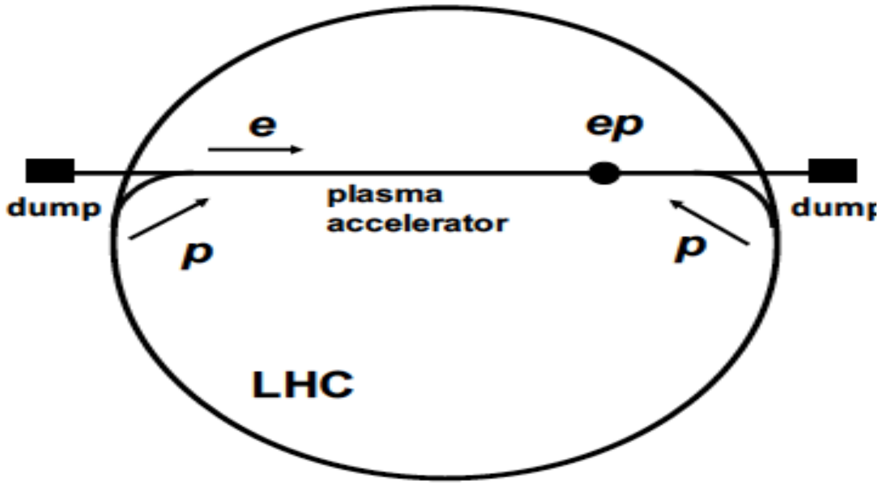
(Plasma electron-proton/ion collider)



G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

VHeP: √s = 9 TeV (LHC-driven)

(Very high energy eP collider)



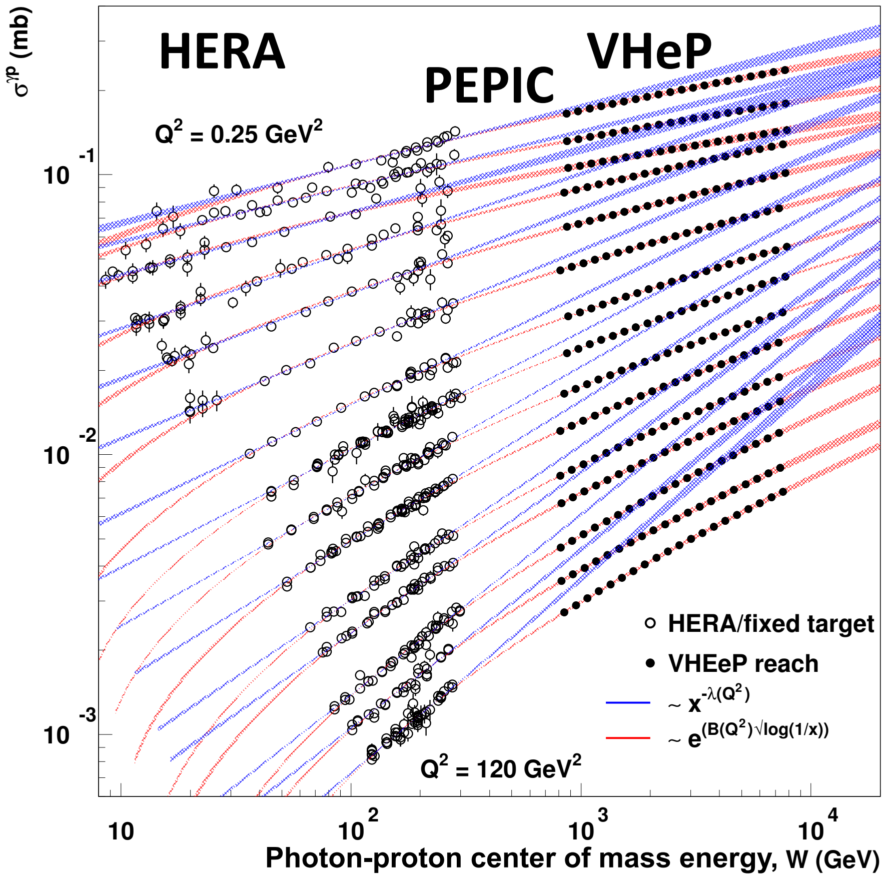
VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Beyond CERN: RHIC-EIC proposal for 18 GeV electron beam [J. Chappel et al, *PoS* DIS2019 (2019) 219]

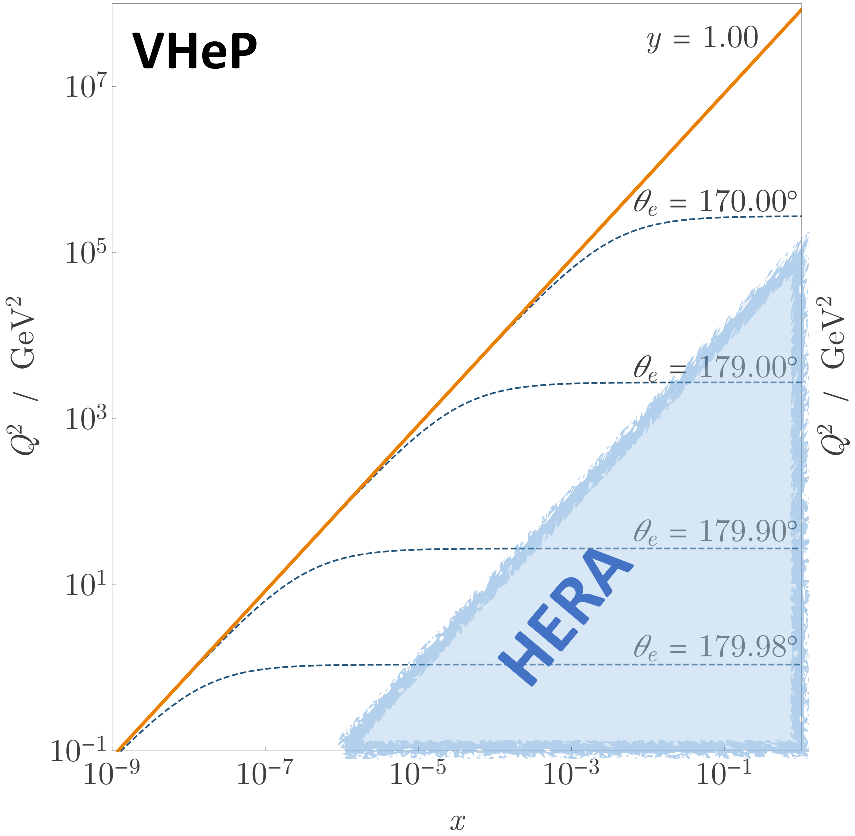
Step 2: re-inject electron beam for e-p (or e-ion) collisions

- New energy regime for Deep Inelastic Scattering

Test scaling laws at high c.m.e.

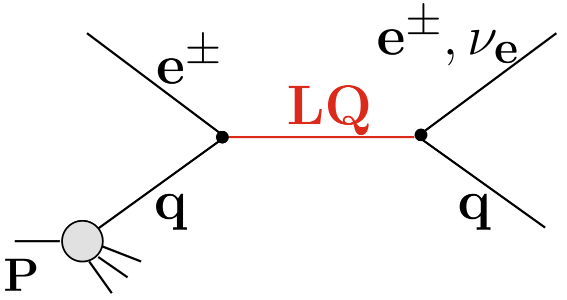


Higher c.m.e. —> larger cross sections, higher photon Q^2 , lower parton x w.r.t. HERA

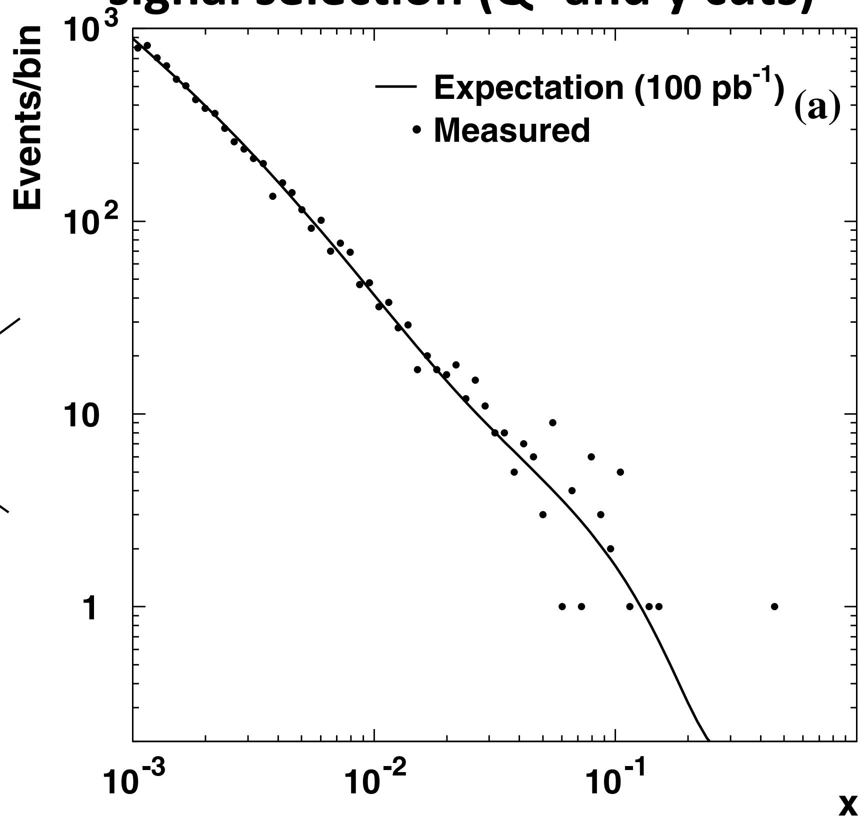


Step 2: re-inject electron beam for e-p (or e-ion) collisions

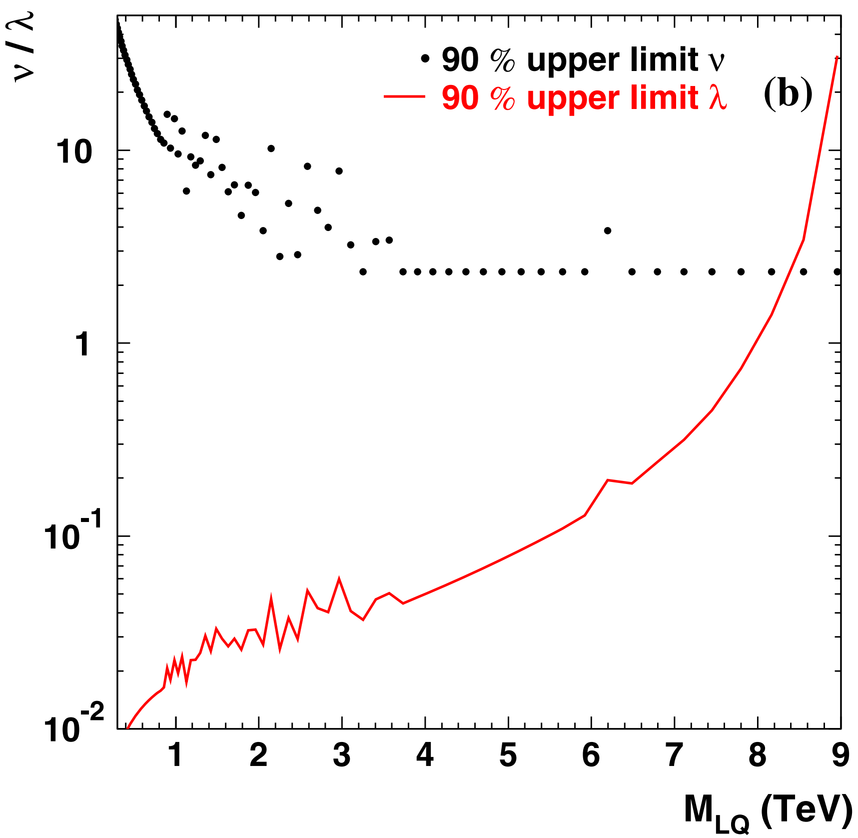
- New energy regime for Leptoquark searches



Expected $N^{background}$ events after signal selection (Q^2 and y cuts)



Upper limit on N^{signal} events ν and coupling λ



VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463