



# 2025 Report to the SPSC



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**MAX-PLANCK-INSTITUT  
FÜR PHYSIK**

## ✧ Advanced WAKefield Experiment

### 19 Institutes Worldwide

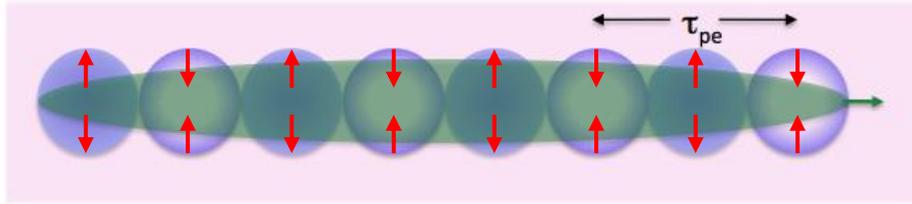
- *CERN, Geneva, Switzerland*
- *University of Manchester, Manchester, UK*
- *Cockcroft Institute, Daresbury, UK*
- *Lancaster University, Lancaster, UK*
- *Oxford University, UK*
- *Max Planck Institute for Physics, Munich, Germany*
- *Max Planck Institute for Plasma Physics, Greifswald, Germany*
- *UCL, London, UK*
- *UNIST, Ulsan, Republic of Korea*
- *Philipps-Universität Marburg, Marburg, Germany*
- *Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany*
- *University of Liverpool, Liverpool, UK*
- *ISCTE - Instituto Universitário de Lisboa, Portugal*
- *GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*
- *Ludwig-Maximilians-Universität, Munich, Germany*
- *University of Wisconsin, Madison, US*
- *Uppsala University, Sweden*
- *Wigner Institute, Budapest*
- *Swiss Plasma Center group of EPFL, Lausanne, Switzerland*



Experiment @

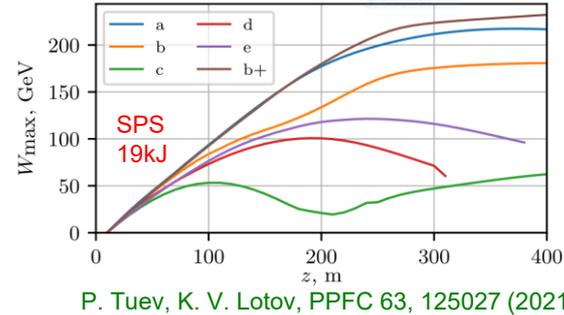
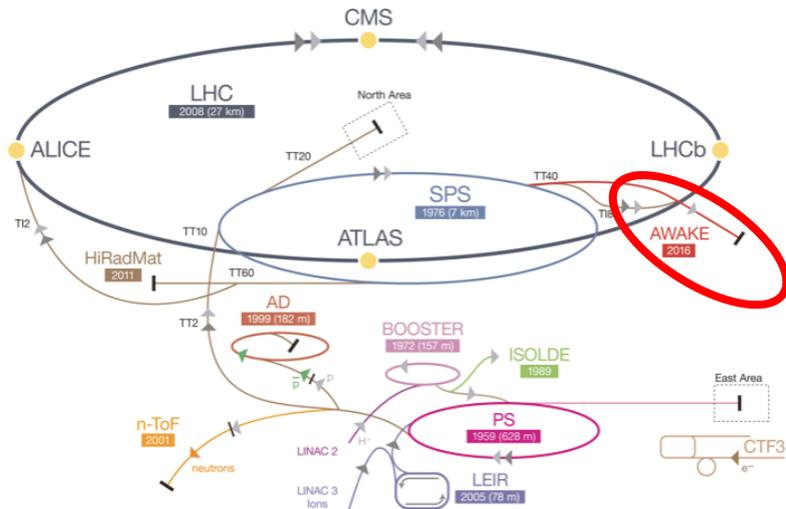


- ✧ Drive wakefields in plasma with a long proton ( $p^+$ ) bunch
- ✧ Accelerate externally-injected electrons ( $e^-$ ) to GeV (SPS) or TeV (LHC) energy scale
- ✧ Relativistic (100's GeV, TeV)  $p^+$  bunches with tens to hundreds of kJ are available





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SPS driver (400GeV, 19kJ):  
 ~200GeV in ~200m  
 ~ $10^9 e^-$

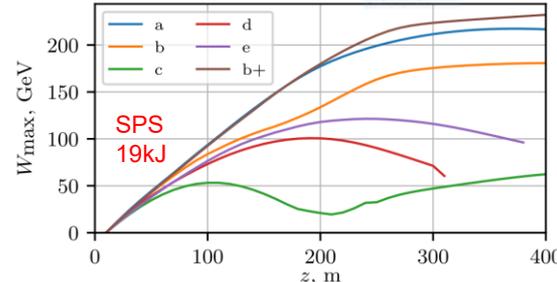
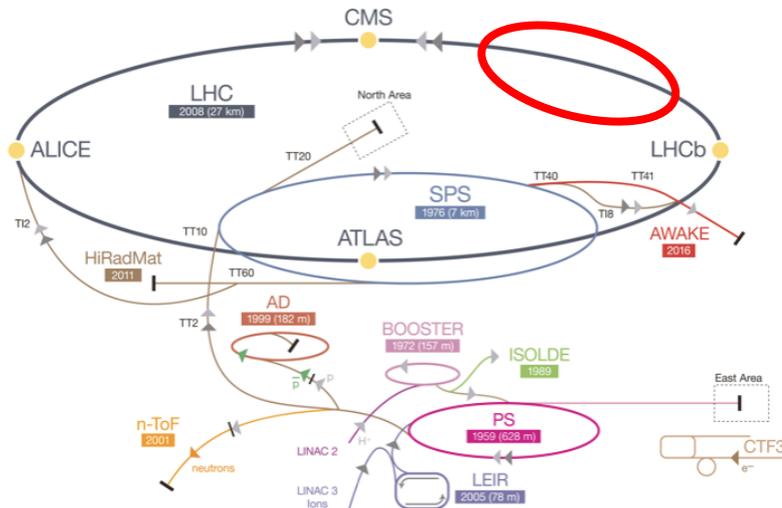
2D numerical simulation results



P. Tuv, K. V. Lotov, PFC 63, 125027 (2021)



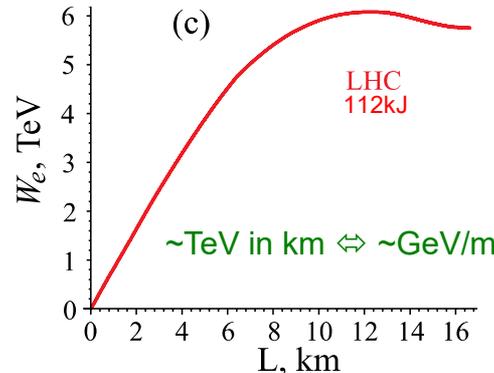
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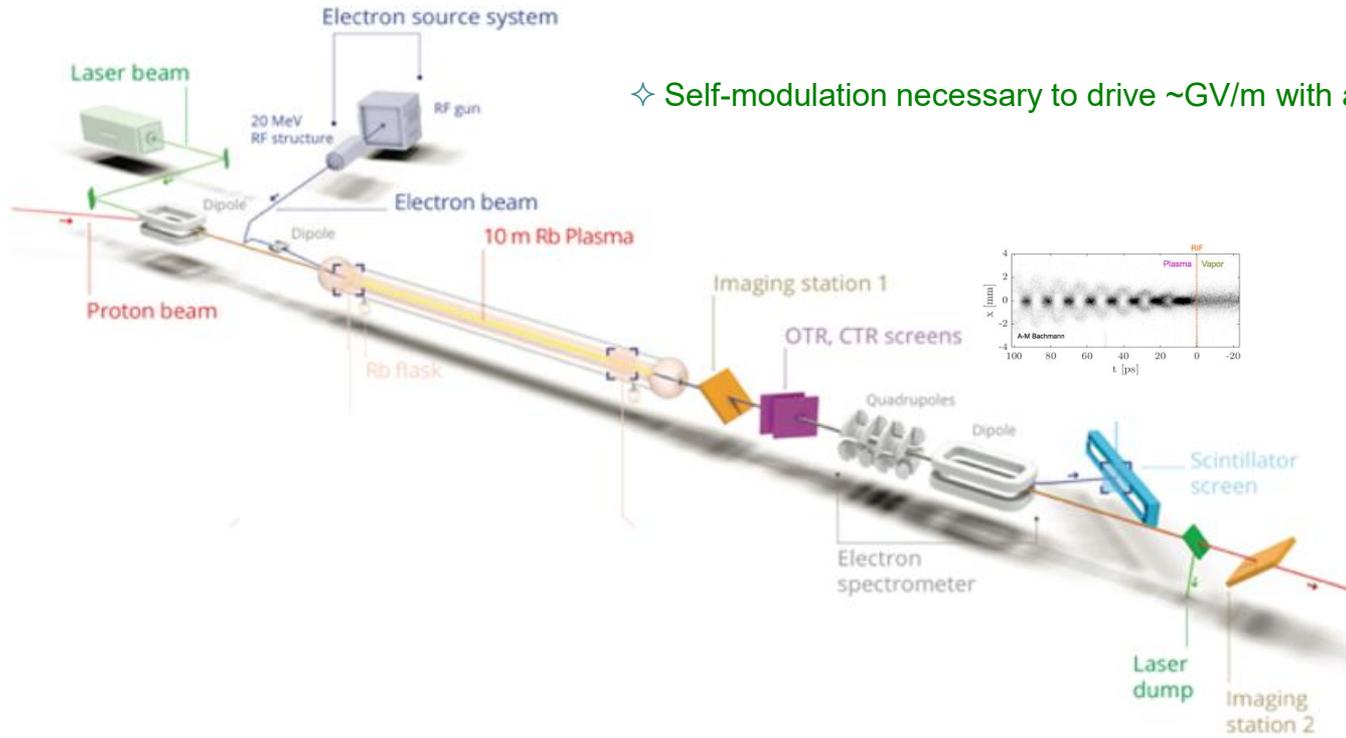
P. Tuev, K. V. Lotov, PFC 63, 125027 (2021)



LHC driver (7 TeV, 119 kJ):  
 $\sim 5$  TeV in  $\sim 7$  km  
 $\sim 10^9 e^-$

$\sim 1$  GeV/m!  
 200 m – 7 km!

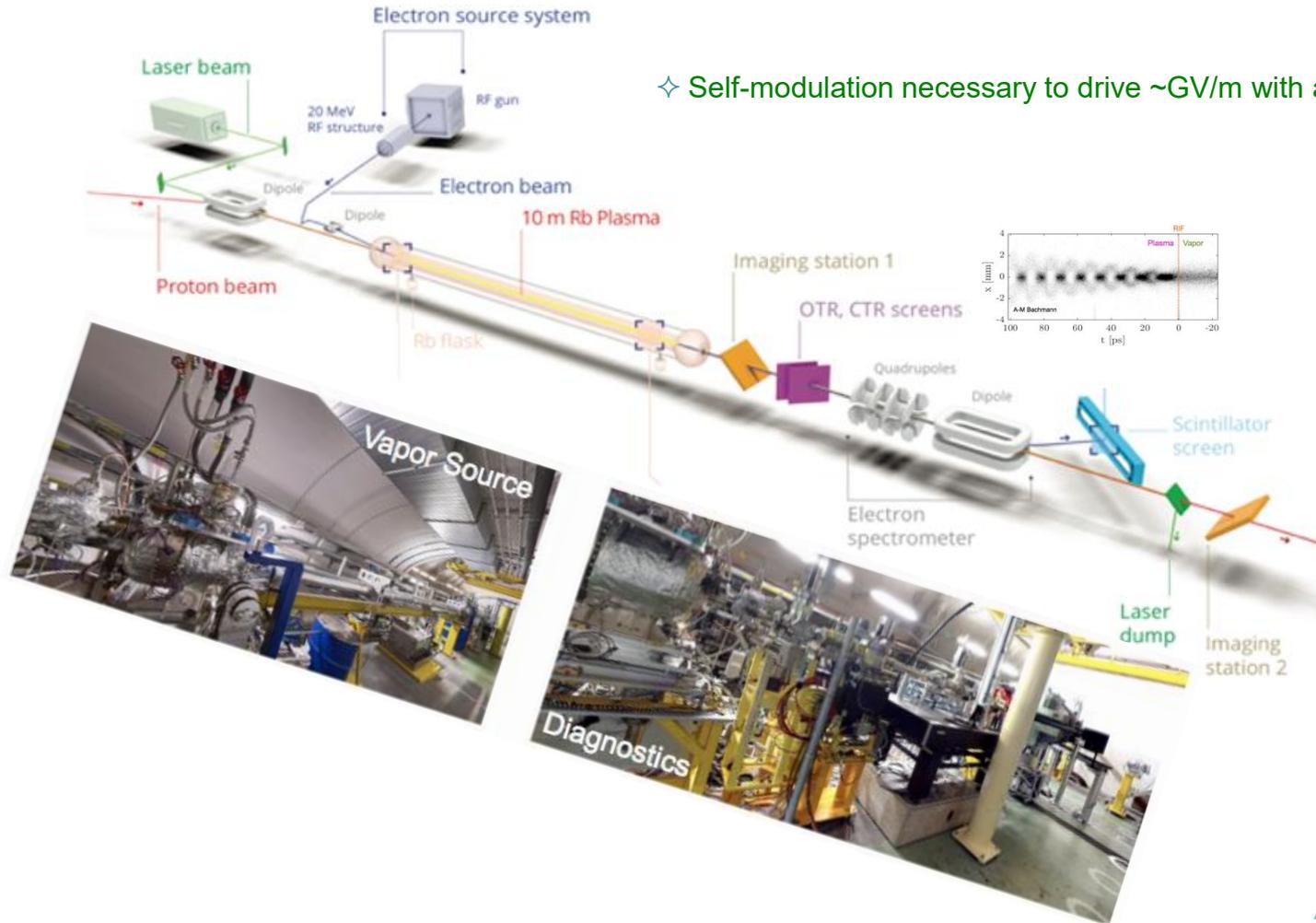
# RUNS 1, 2a,b: SELF-MODULATOR



✧ Self-modulation necessary to drive  $\sim$ GV/m with an SPS/LHC  $p^+$  bunch

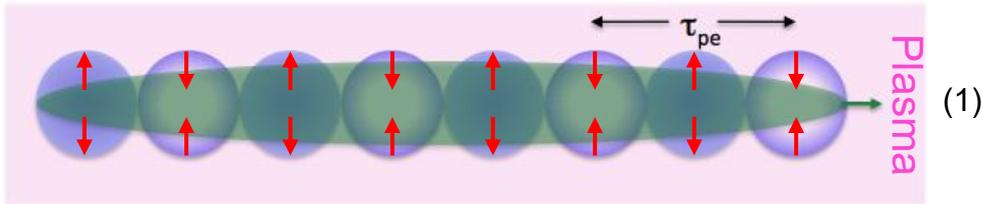
# RUNS 1, 2a,b: SELF-MODULATOR

✧ Self-modulation necessary to drive  $\sim$ GV/m with an SPS/LHC  $p^+$  bunch



# SELF-MODULATION

Long driver ( $p^+$ ),  $\sigma_t \gg 1/\omega_{pe}$ ,  $\sigma_r \sim c/\omega_{pe}$ , initially non-resonant



SPS  $p^+$  bunch, long  $\sigma_z \sim 5\text{cm}$  and narrow  $\sigma_r \sim 200\mu\text{m}$

Wakefields amplitude scaling:  $E_{acc} \sim 1/\sigma_z$  or  $1/\sigma_r$  in  $n_{e0} \sim 1/\sigma_z^2$  or  $1/\sigma_r^2$

**Choose:**  $E_{acc} \sim 1/\sigma_r$  in  $n_{e0} \sim 1/\sigma_r^2 \rightarrow \sigma_r \sim c/\omega_{pe}$

$\sigma_z \gg c/\omega_{pe} \leftrightarrow$  Self-modulation (SM) regime

$n_{e0} = 7 \times 10^{14} \text{cm}^{-3} \leftrightarrow E_{acc} \sim n_{e0}^{1/2} \sim 2.5 \text{GV/m}$

Plasma electron density:  $n_{e0}$ ,  $\omega_{pe} = (n_{e0} e^2 / \epsilon_0 m_e)^{1/2}$ ,  $\tau_{pe} = 2\pi / \omega_{pe}$

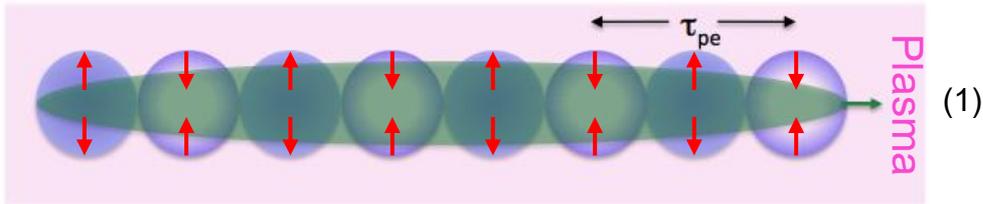
Wakefields: period and transverse size  $\sim$  plasma skin depth  $c/\omega_{pe} \sim n_{e0}^{-1/2}$

N. Kumar, Phys. Rev. Lett. 104, 255003 (2010)

$$E_{acc} \cong E_{WB} = \frac{m_e c^2 \sqrt{2}}{e \sigma_{z,r}} \cong \frac{723 \text{ MeV}}{\sigma [\text{mm}]}$$

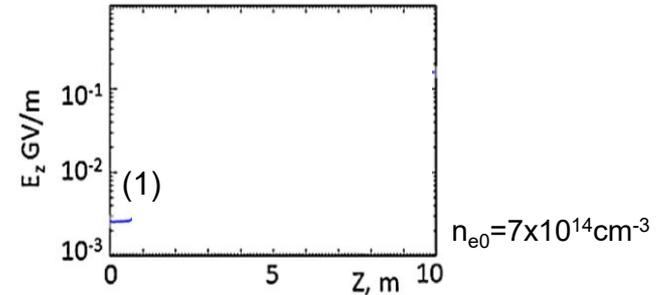
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Initial (transverse) wakefields (1)  
  
 Periodic focusing/defocusing

Pukhov, PRL107 145003 (2011)

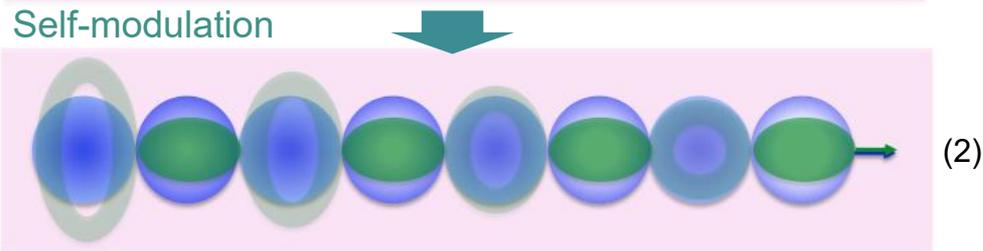
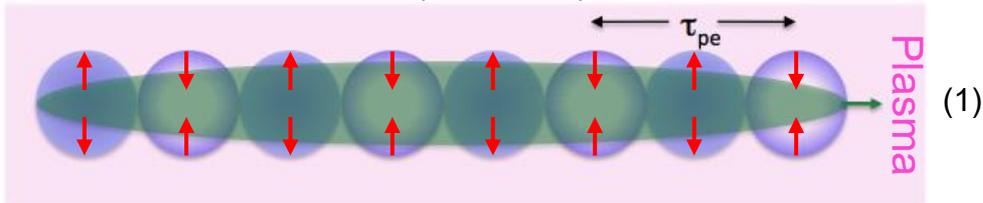


✧  $E_z$ -field along the plasma

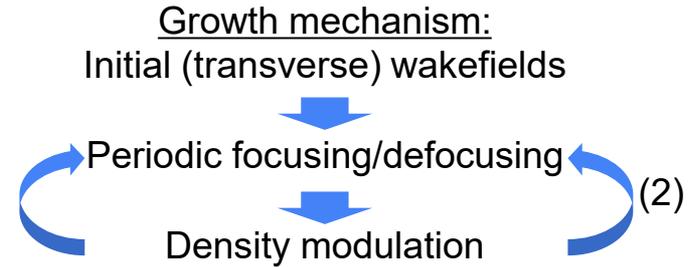
Relativistic particles do not (appreciably) dephase!  
 SM  $\leftrightarrow$  transverse effect!

# SELF-MODULATION

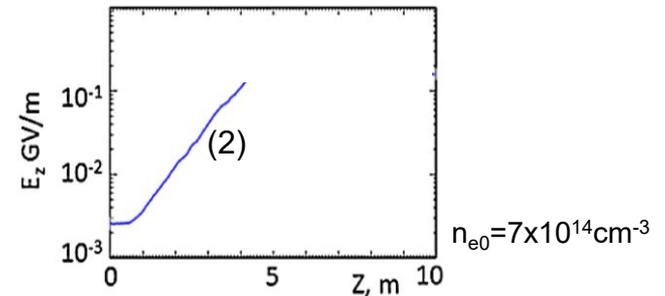
Long driver (p<sup>+</sup>),  $\sigma_t \gg 1/\omega_{pe}$ ,  $\sigma_r \sim c/\omega_{pe}$ , initially non-resonant



$$f_{mod} \cong \omega_{pe}/2\pi \propto n_{e0}^{1/2}$$



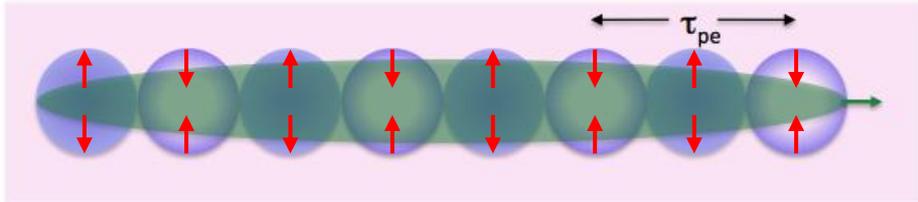
Pukhov, PRL107 145003 (2011)



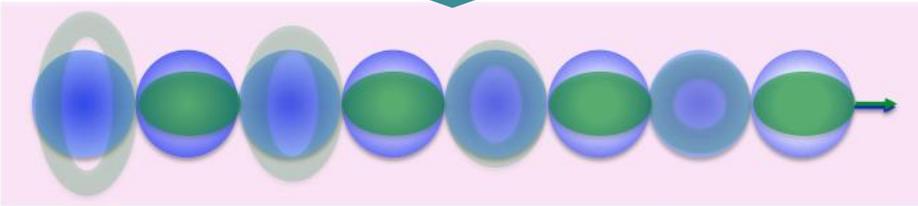
Growth along the bunch and plasma!

# SELF-MODULATION

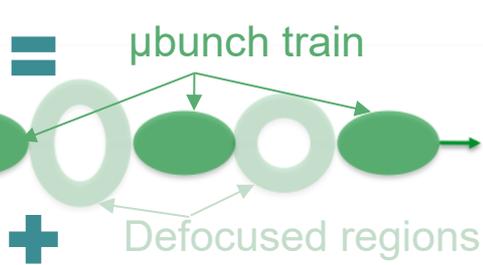
Long driver ( $p^+$ ), dense plasma,  $\sigma_t \gg 1/\omega_{pe}$ ,  $\sigma_t \sim c/\omega_{pe}$



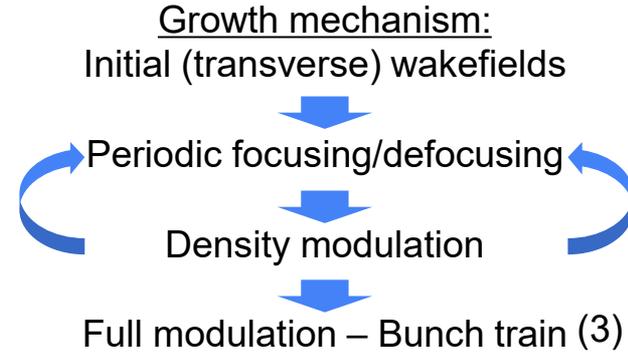
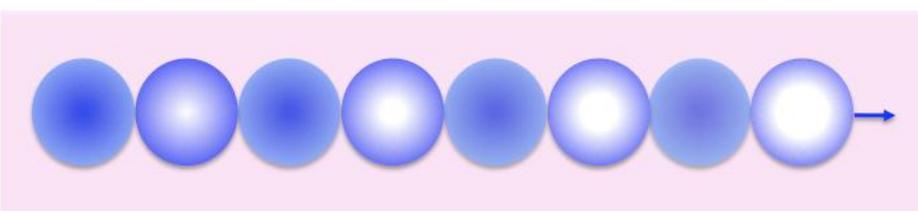
Self-modulation



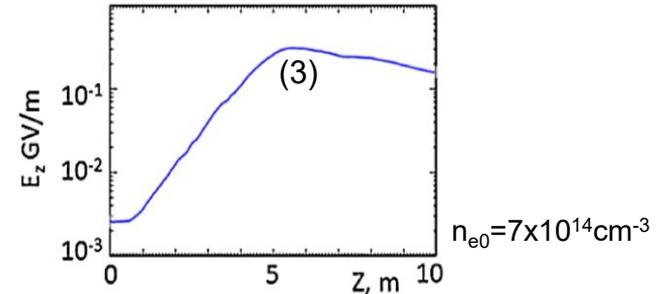
Self-modulated bunch



Plasma wakefields



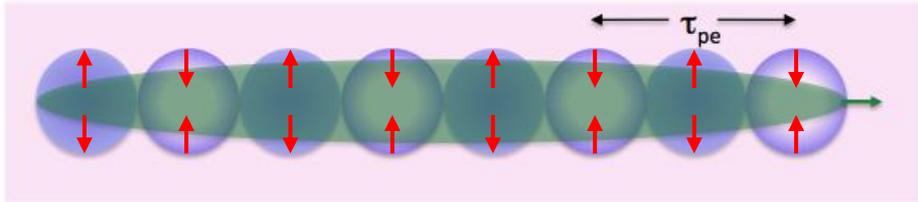
Pukhov, PRL107 145003 (2011)



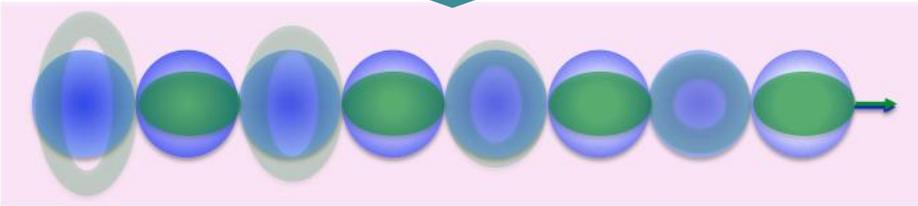
- (3) ✦ Train period  $\sim \tau_{pe} = 2\pi/\omega_{pe}$
- ✦  $\mu$ bunch length  $< \tau_{pe}$
- ✦ Resonantly drives wakefields to large amplitude
- ✦ Self-modulation necessary to drive  $\sim$ GV/m accelerating fields in  $\sim 10^{14} \text{cm}^{-3}$  density plasma

# SELF-MODULATION

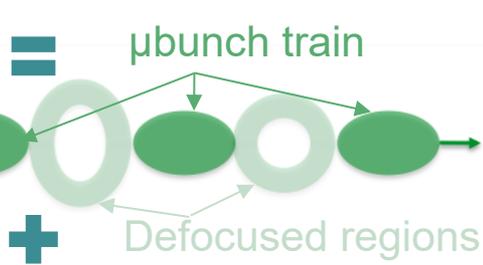
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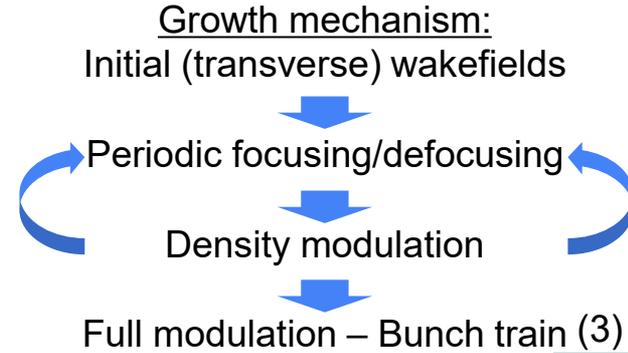
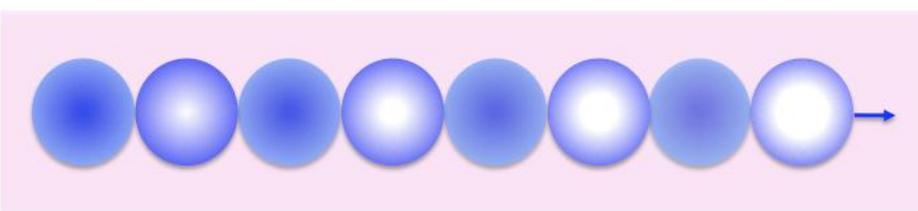
Self-modulation



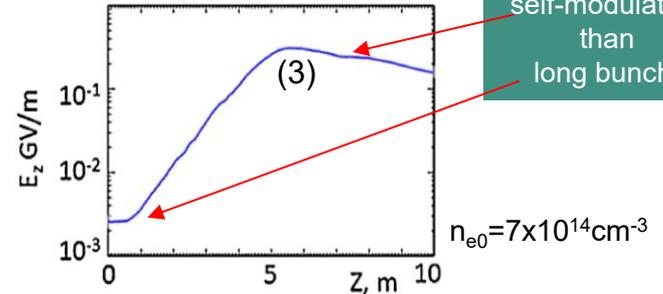
Self-modulated bunch



Plasma wakefields

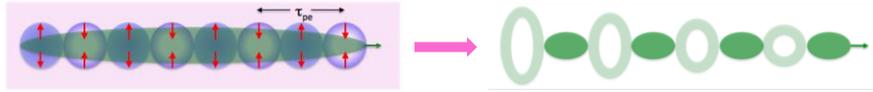


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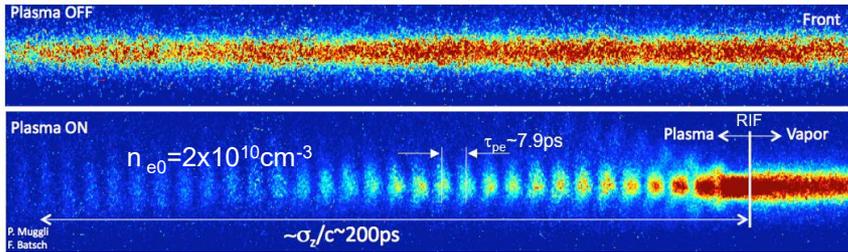
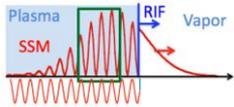


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# RUNS 1, 2a,b: SELF-MODULATOR



✧ SM occurs, and can be seeded (made reproducible)

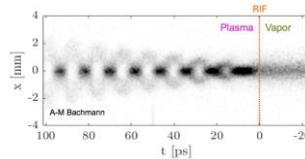


AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019)

M. Turner et al., AWAKE Coll., Phys. Rev. Lett. 122, 054801 (2019)

F. Batsch et al., AWAKE Coll., Phys. Rev. Lett. 126, 164802 (2021)

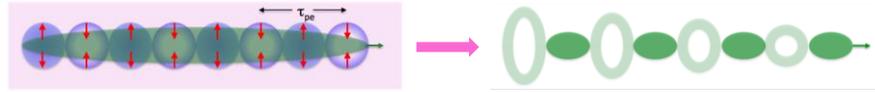
L. Verra et al., AWAKE Coll., Phys. Rev. Lett. 129, 024802 (2022)



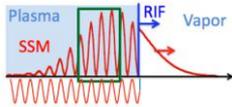
✧ Evidence for transverse wakefields

✧ All publications at: <https://twiki.cern.ch/twiki/bin/view/AWAKE/AwakePublic>

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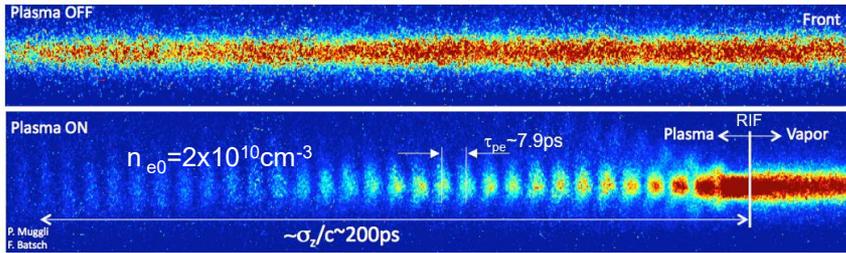
◇ SM occurs, and can be seeded (made reproducible)



◇ Acceleration of externally-injected test electrons (19MeV)

◇ Energy gain to 2GeV

◇ Larger gain with tailored plasma density

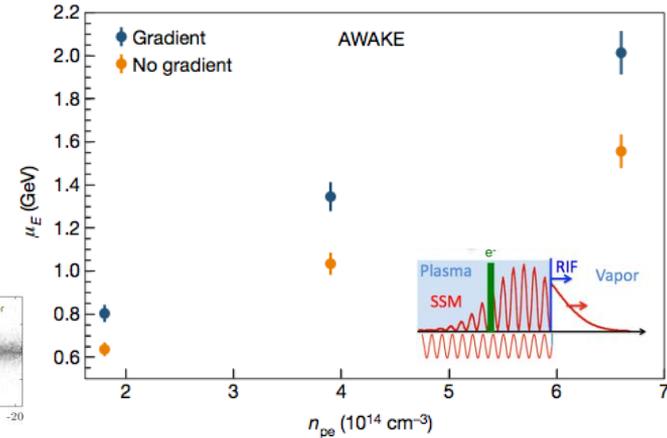
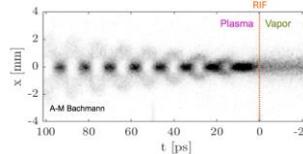


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AWAKE Coll., Nature 561, 363 (2018), Phil. Trans. R. Soc. A.37720180418 (2019)

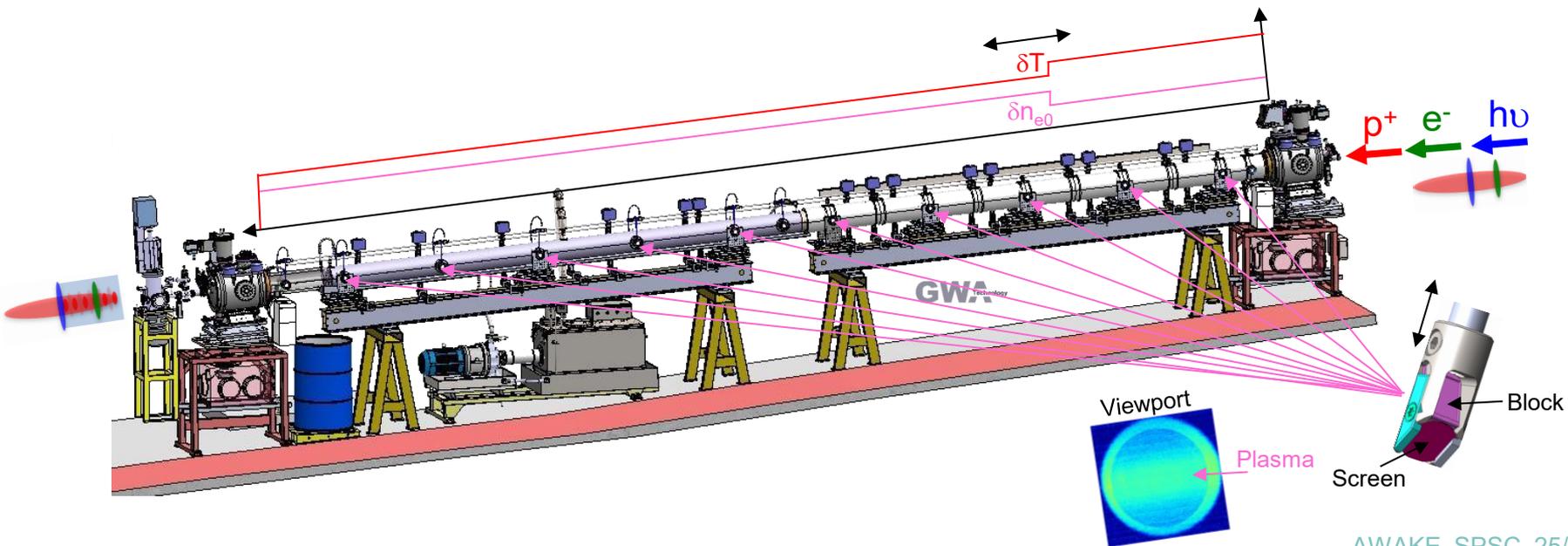
◇ Evidence for transverse wakefields

◇ Evidence for longitudinal wakefields

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# UPGRADE OF THE EXPERIMENT (2023-4)

- ✧ Plasma  $\leftrightarrow$  laser ionization of a rubidium (Rb) vapor
- ✧ Electrical heaters over the first 4.5m of the source
  - ✧ Apply step in **temperature**  $\leftrightarrow$  **vapor density**  $\leftrightarrow$  **plasma density**
- ✧ Optical viewports: light from plasma/wakefields
- ✧ Plungers with screens
  - ✧ Align  $e^-$  and  $p^+$  trajectories inside the source
  - ✧ Block ionizing laser pulse  $\leftrightarrow$  vary plasma length



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- 3 Run 2c preparation
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  - 4.3 Full driver/witness studies
  - 4.4 Beyond Run 2c
- 5 Particle physics applications of the AWAKE scheme
- 6 Publications and presentations
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  - 6.2 Conference presentations and posters

✧ Focus on accelerator development

✧ Expect:

✧ Ten publications

✧ Five PhD and one Master degrees

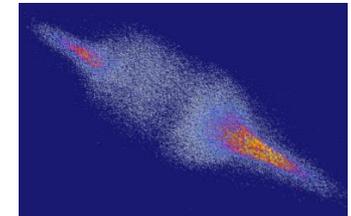


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## Experimental Observation of the Motion of Ions in a Resonantly Driven Plasma Wakefield Accelerator

[M. Turner](#)<sup>1</sup>, [E. Walter](#)<sup>2,3</sup>, [C. Amodeo](#)<sup>1</sup>, [N. Torrado](#)<sup>1,4</sup>, [N. Lopes](#)<sup>4</sup>, [A. Sublet](#)<sup>1</sup>, [M. Bergamaschi](#)<sup>5</sup>, [J. Pucek](#)<sup>5</sup>, [J. Mezger](#)<sup>5</sup> et al. (AWAKE Collaboration<sup>7</sup>)

Phys. Rev. Lett. **134**, 155001 – Published 17 April, 2025  
DOI: <https://doi.org/10.1103/PhysRevLett.134.155001>



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✧ Clear/strong plan for Run 2c and beyond



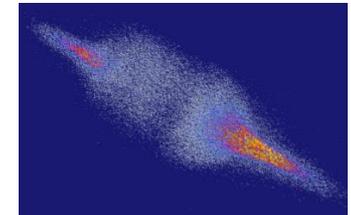
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Work in progress!

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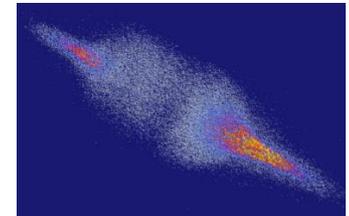


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DOI: <https://doi.org/10.1103/PhysRevLett.134.155001>



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  - 6.1 Publications by AWAKE and AWAKE Collaboration members on AWAKE-related topics
  - 6.2 Conference presentations and posters

- ✧ Focus on accelerator development
- ✧ Expect:
  - ✧ Ten publications
  - ✧ Five master degrees

**ONLY 14 slides left!**

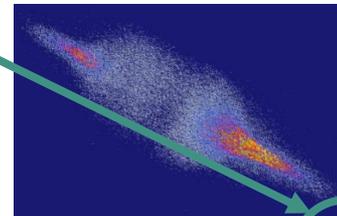
- ✧ Clear/strong plan for Run 2c and beyond



## Experimental Observation of the Motion of Ions in a Resonantly Driven Plasma Wakefield Accelerator

M. Turner<sup>1</sup>, E. Walter<sup>2,3</sup>, C. Amadio<sup>1</sup>, N. Torrado<sup>1,4</sup>, N. Lopes<sup>4</sup>, A. Sublet<sup>1</sup>, M. Bergamaschi<sup>5</sup>, J. Pucek<sup>5</sup>, J. Mezger<sup>5</sup> et al. (AWAKE Collaboration<sup>†</sup>)

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8/22

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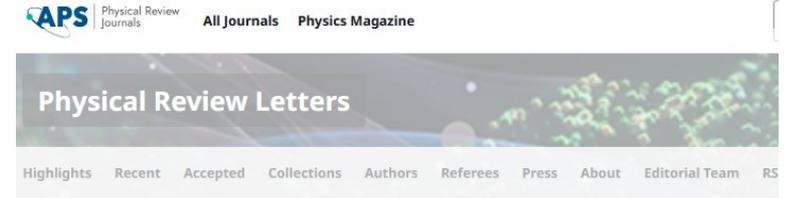
✧ Focus on accelerator development

✧ Expect:

✧ Ten publications

✧ Five PhD and one Master degrees

✧ Clear/strong plan for Run 2c and beyond

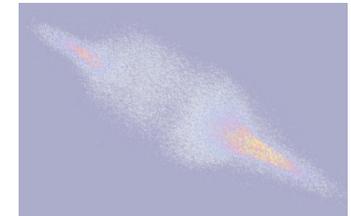


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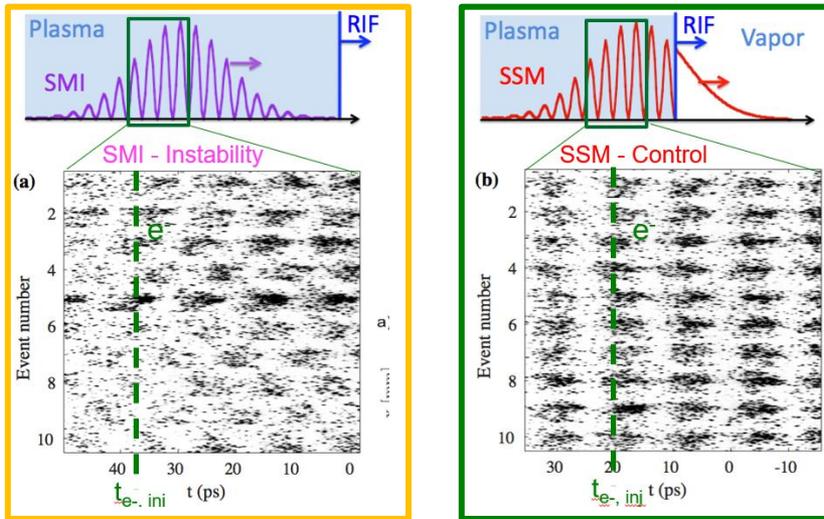
Phys. Rev. Lett. **134**, 155001 – Published 17 April, 2025  
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◇ Seeding → timing/phase reproducibility

No Seed

Seed



F. Batsch et al., AWAKE Coll., Phys. Rev. Lett. 126, 164802 (2021)

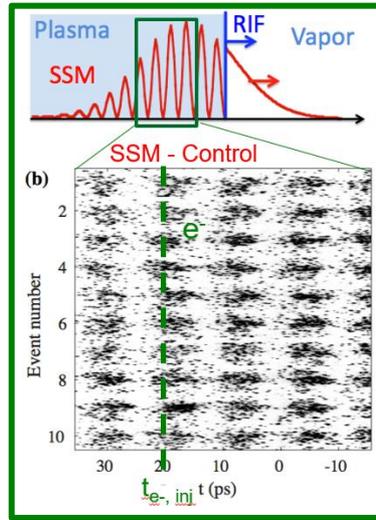
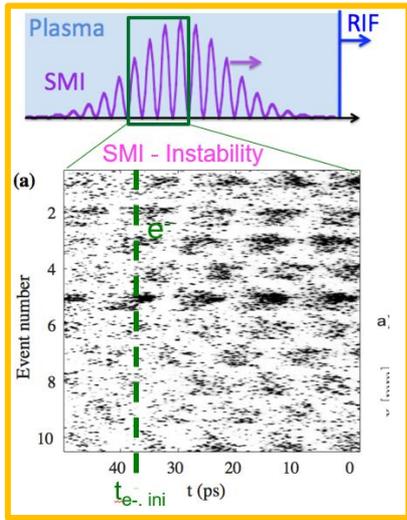
◇ Seeding makes timing/phase more reproducible

# SM\* REPRODUCIBILITY

◇ Seeding → timing/phase reproducibility

No Seed

Seed

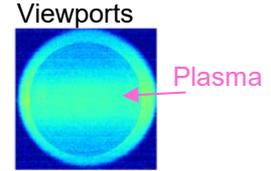
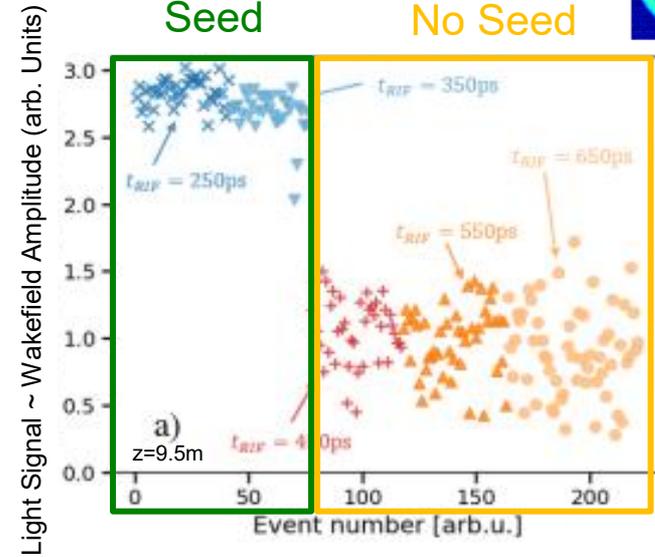


F. Batsch et al., AWAKE Coll., Phys. Rev. Lett. 126, 164802 (2021)

◇ Amplitude reproducibility?

Seed

No Seed



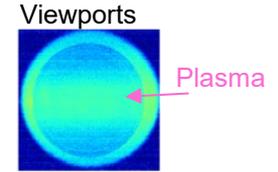
◇ Seeding makes timing/phase **and** amplitude of the wakefields more reproducible

◇ Light signal ~ amplitude of wakefields

◇ Small(er) RMS variations of light signal (i.e., wakefield amplitude) when seeded (SSM) than not seeded (SMI)

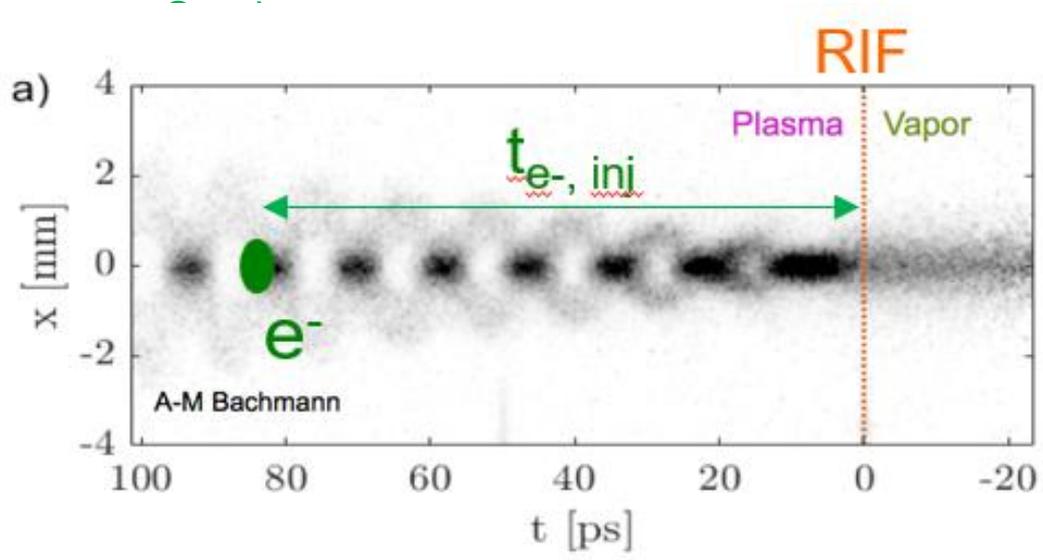
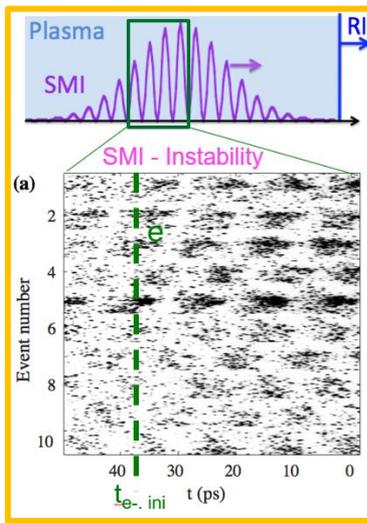
# SM\* REPRODUCIBILITY

◇ Amplitude reproducibility?

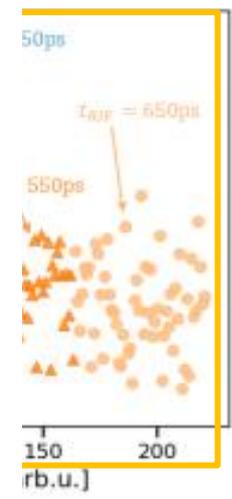


◇ Seeding → timing/phase reproducibility

No Seed



Seed



F. Batsch et al., AWAKE 2019, Phys. Rev. Lett. 123, 104801 (2019)

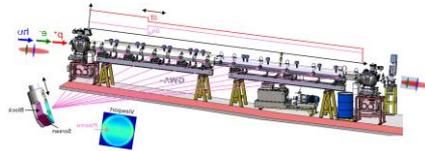
Phase AND amplitude reproducibility: ESSENTIAL for an accelerator!

◇ Light signal ~ amplitude of wakefields  
(i.e., wakefield amplitude) when seeded (SSM) than not seeded (SMI)

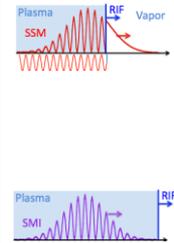
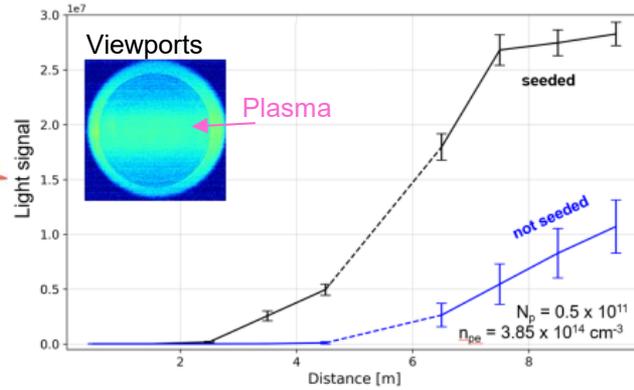
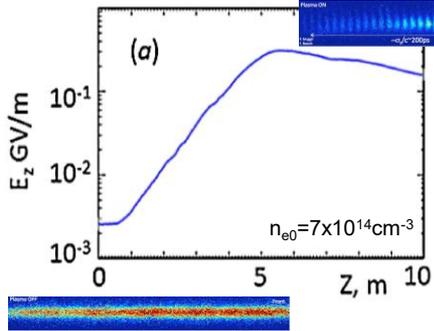
◇ Seeding makes timing/phase and amplitude of the wakefields more reproducible

# SM\* GROWTH / SATURATION

- Wakefields ↔ energy deposited in plasma
- Energy dissipation ↔ light emission



Numerical Simulations:  
Pukhov, PRL107 145003 (2011)

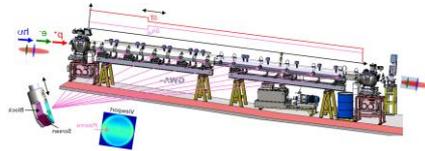


- Light signal and halo radius show:
  - Saturation of SM
  - Saturation length varies with  $n_{e0}$
  - Differences SSM (seeded) and SMI (not seeded, instability)

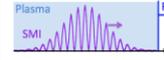
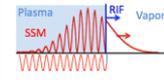
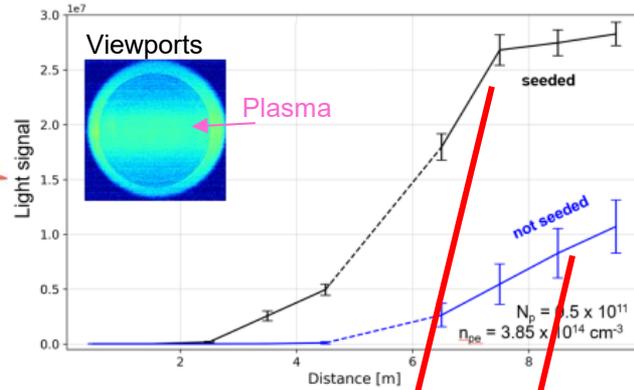
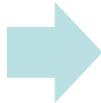
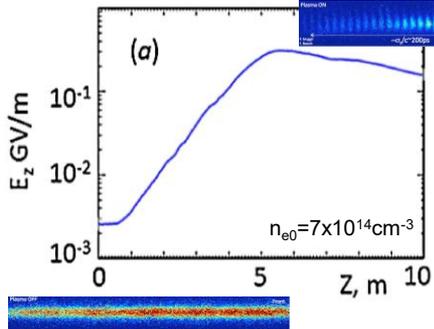
10m self-modulator length sufficient for Run 2c ( $< 5\text{m}$  with  $n_{e0} = 7 \times 10^{14} \text{ cm}^{-3}$ )

# SM\* GROWTH / SATURATION

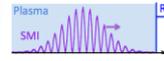
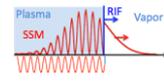
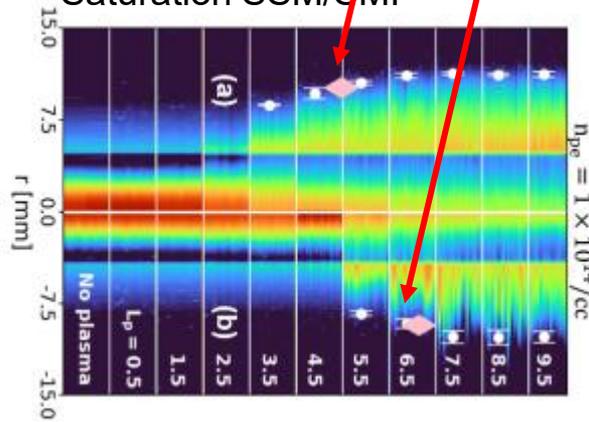
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- Energy dissipation ↔ light emission



Numerical Simulations:  
Pukhov, PRL107 145003 (2011)



## Saturation SSM/SMI

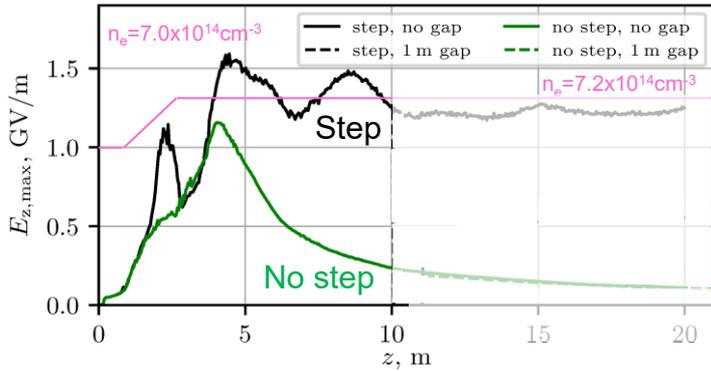


- Light signal and halo radius show:
  - Saturation of SM
  - Saturation length varies with  $n_{e0}$
  - Differences SSM (seeded) and SMI (not seeded, instability)
- 10m self-modulator length sufficient for Run 2c (<5m with  $n_{e0}=7 \times 10^{14} \text{cm}^{-3}$ )

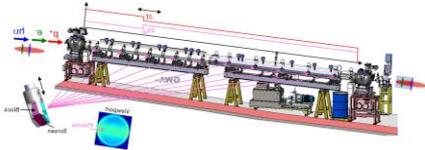
# ACCELERATION: DENSITY STEP

## ◇ Numerical simulation results:

- ◇ Uniform density plasma: wakefields saturate, reach low constant amplitude
- ◇ Step in density: wakefields maintain larger amplitude after saturation



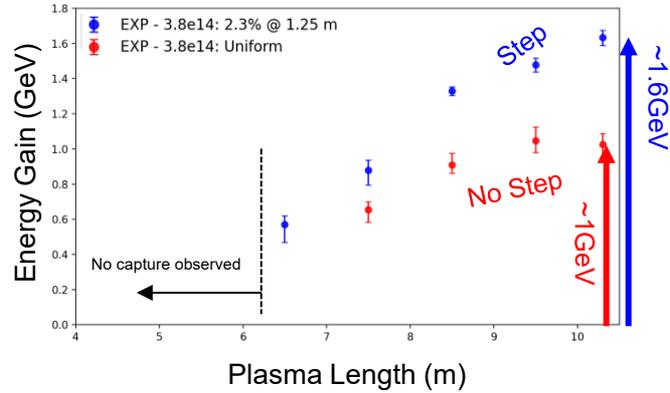
AWAKE Collaboration, *Symmetry* 2022, 14(8), 1680 (2022)



◇ Clearly observe expected effect of step in density: larger energy gain, larger gradient

## ◇ Experiment:

◇ Measure energy gain versus plasma length, side-injection, 19MeV e<sup>-</sup>

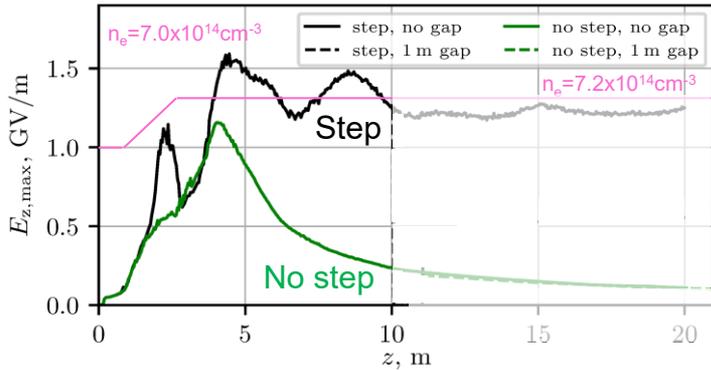


- ◇  $n_{e0} = 4 \times 10^{14} \text{cm}^{-3}$
- ◇ Larger energy gain w step:
  - ◇ 1 GeV  $\rightarrow$  1.6 GeV
- ◇ Charge capture < 10 pC (800 pc injected)
- ◇ Test e<sup>-</sup>

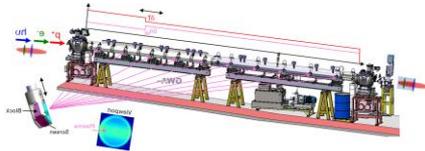
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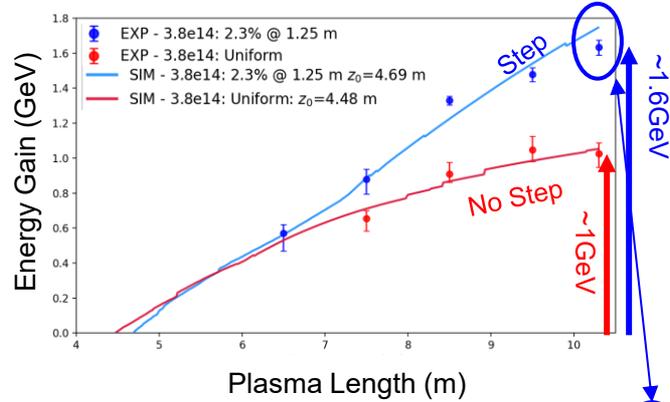
AWAKE Collaboration, *Symmetry* 2022, 14(8), 1680 (2022)



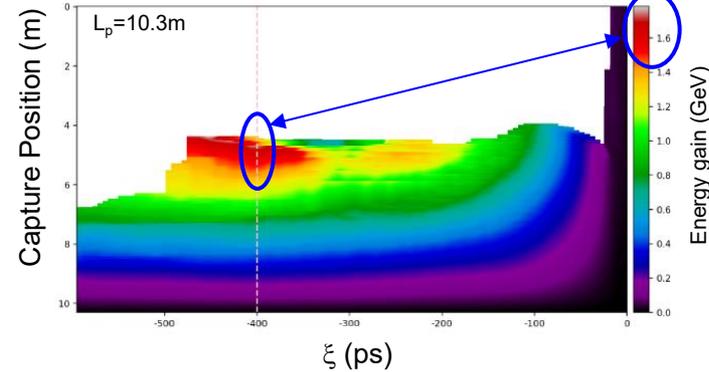
- ◇ Clearly observe expected effect of step in density: larger energy gain, larger gradient
- ◇ Agreement: experiment ↔ numerical simulations
- ◇ Similar observation with other  $n_{e0}$
- ◇ Optimization with long accelerator, injection on-axis → Run 2c

## ◇ Experiment:

◇ Measure energy gain versus plasma length, side-injection, 19MeV  $e^-$



- ◇  $n_{e0} = 4 \times 10^{14} \text{cm}^{-3}$
- ◇ Larger energy gain w step:  $1 \text{ GeV} \rightarrow 1.6 \text{ GeV}$
- ◇ Charge capture  $< 10 \text{ pC}$  (800pc injected)
- ◇ Test  $e^-$



- ◇ Energy gain from integral of wakefields
- ◇ Matches maximum gain
- ◇ Matches gain versus plasma length
- ◇ Capture  $e^-$  at  $z=4$  to  $5 \text{ m}$

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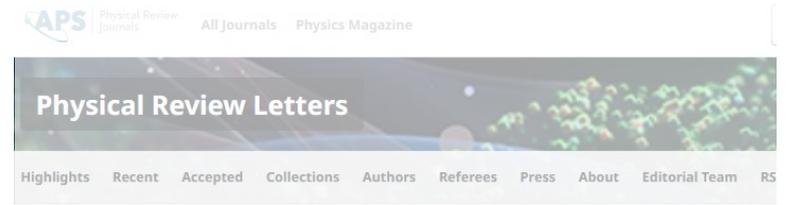
Well-understood

## ❖ Focus on accelerator development

Important for the accelerator:

- ❖ Timing/phase and amplitude of wakefields: reproducible
- ❖ Wakefields saturate over <10m
- ❖ Plasma density step increases energy gain

## ❖ Clear/strong plan for Run 2c and beyond



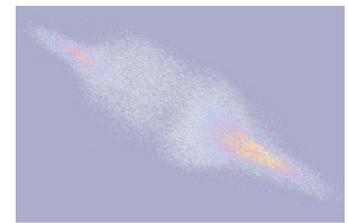
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Show more

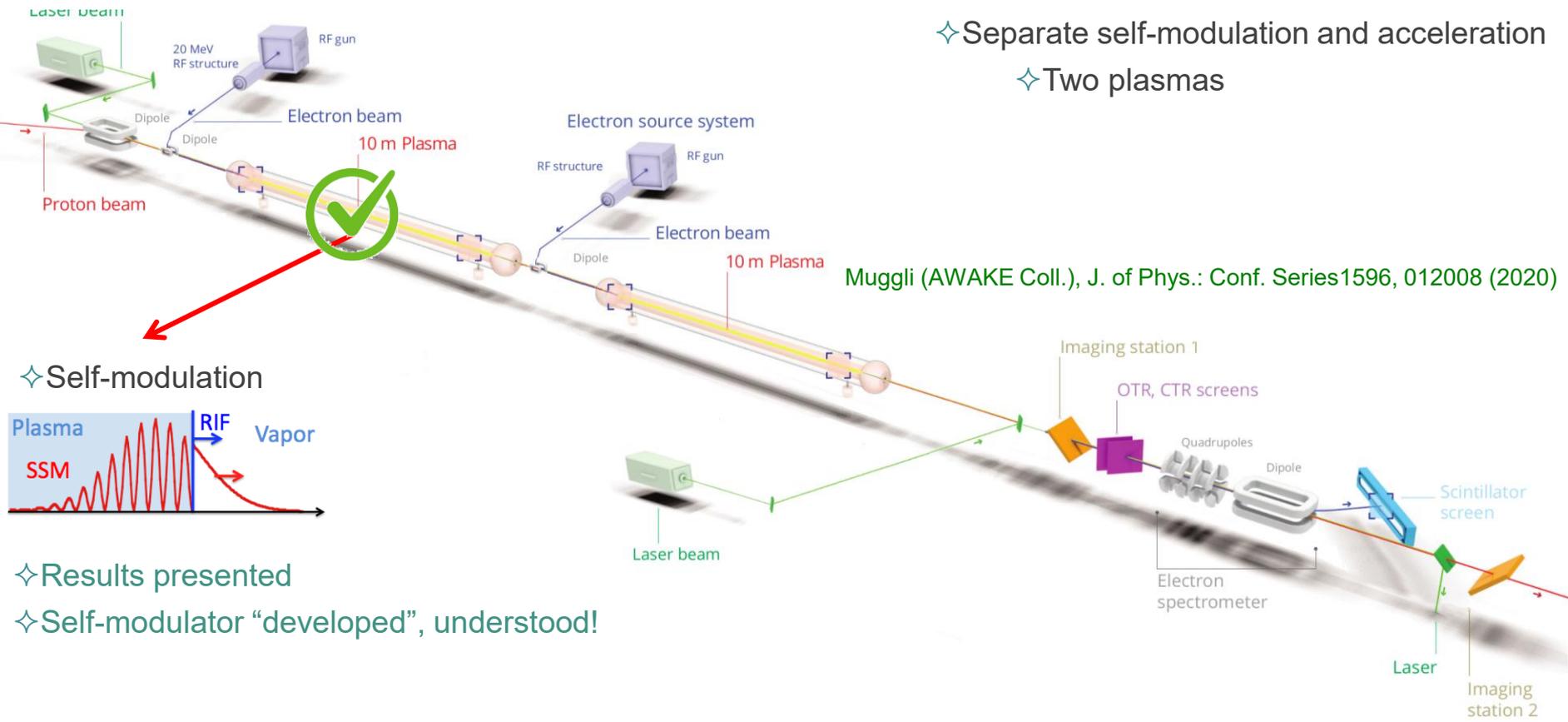
Phys. Rev. Lett. **134**, 155001 – Published 17 April, 2025  
DOI: <https://doi.org/10.1103/PhysRevLett.134.155001>





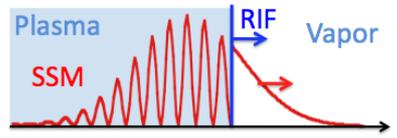
# RUN 2c,d: ACCELERATE e<sup>-</sup> BUNCH, QUALITY

- ✧ Separate self-modulation and acceleration
- ✧ Two plasmas



Muggli (AWAKE Coll.), J. of Phys.: Conf. Series 1596, 012008 (2020)

✧ Self-modulation

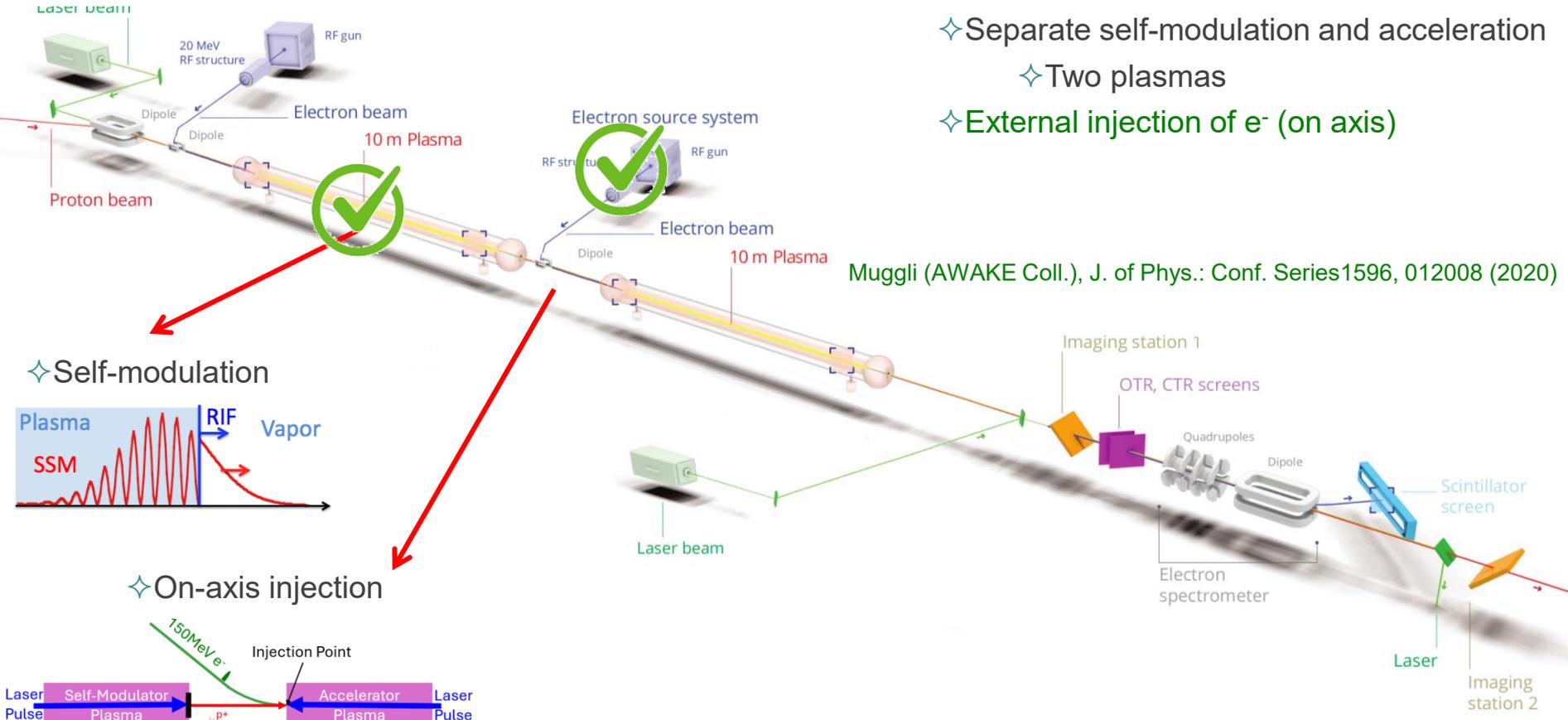


✧ Results presented

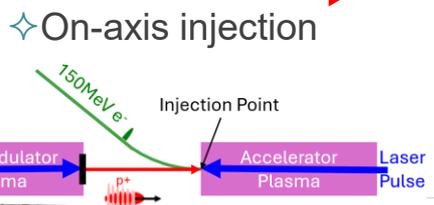
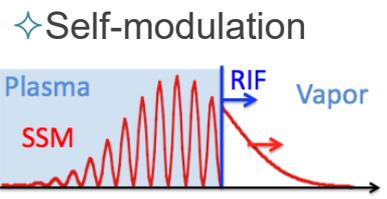
✧ Self-modulator “developed”, understood!



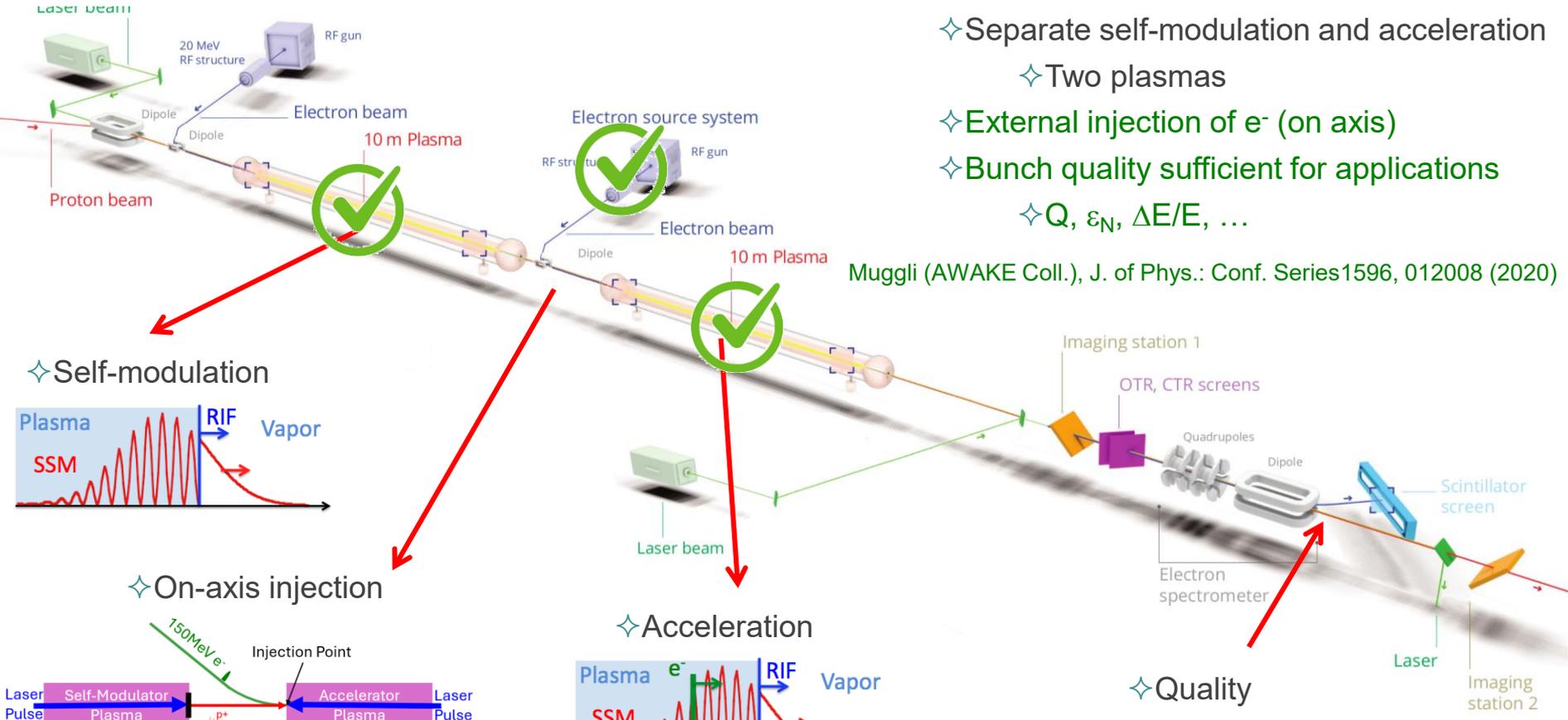
# RUN 2c,d: ACCELERATE $e^-$ BUNCH, QUALITY



- ✧ Separate self-modulation and acceleration
- ✧ Two plasmas
- ✧ External injection of  $e^-$  (on axis)

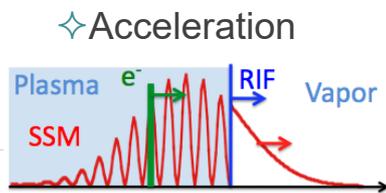
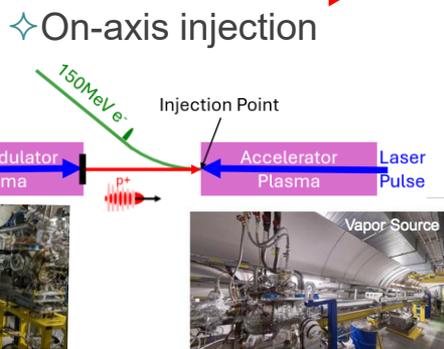
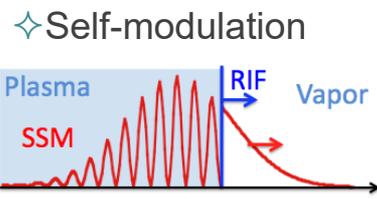


# RUN 2c,d: ACCELERATE $e^-$ BUNCH, QUALITY



- ✧ Separate self-modulation and acceleration
- ✧ Two plasmas
- ✧ External injection of  $e^-$  (on axis)
- ✧ Bunch quality sufficient for applications
  - ✧  $Q$ ,  $\epsilon_N$ ,  $\Delta E/E$ , ...

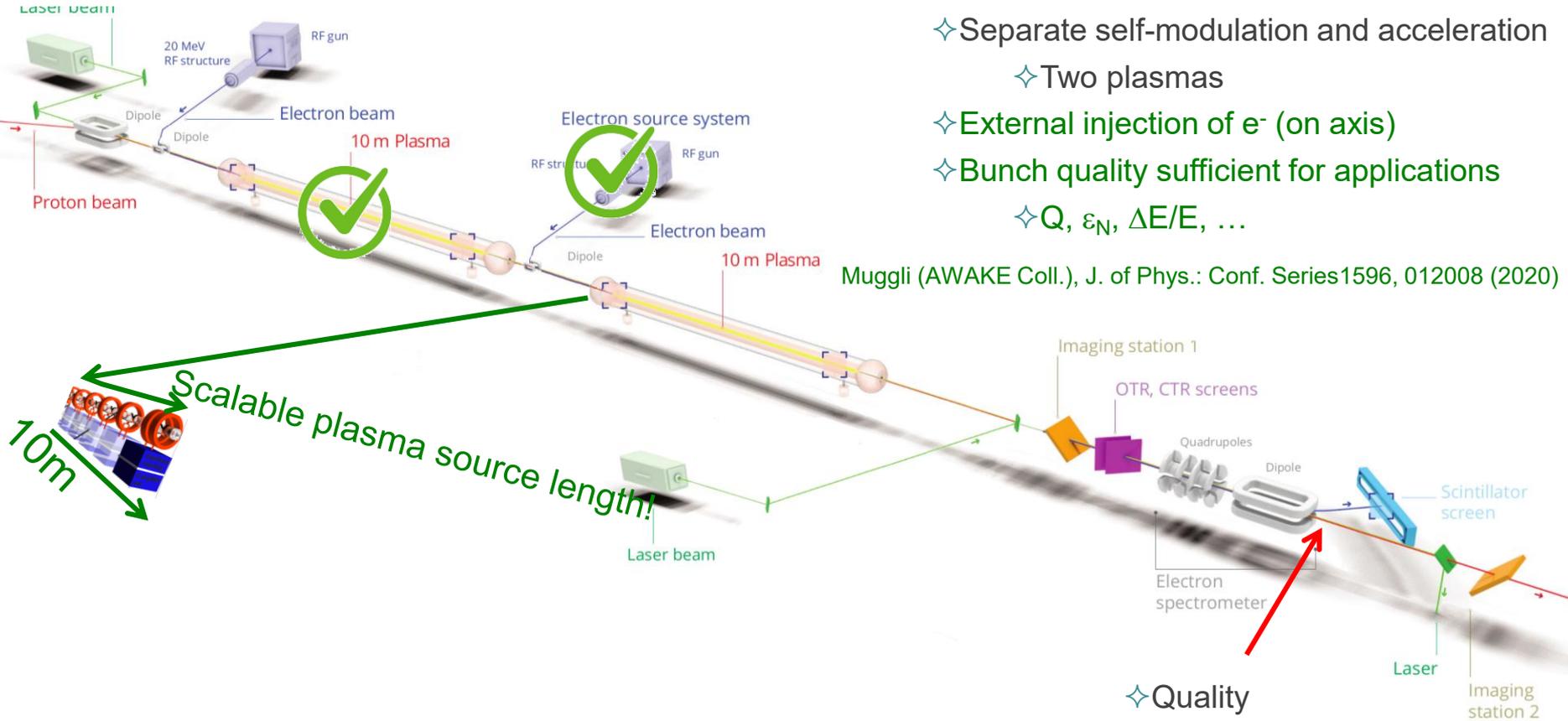
Muggli (AWAKE Coll.), J. of Phys.: Conf. Series 1596, 012008 (2020)



✧ 10m plasma: 4-10GeV

- ✧ Quality
- ✧ Application!

# RUN 2c,d: ACCELERATE $e^-$ BUNCH, QUALITY



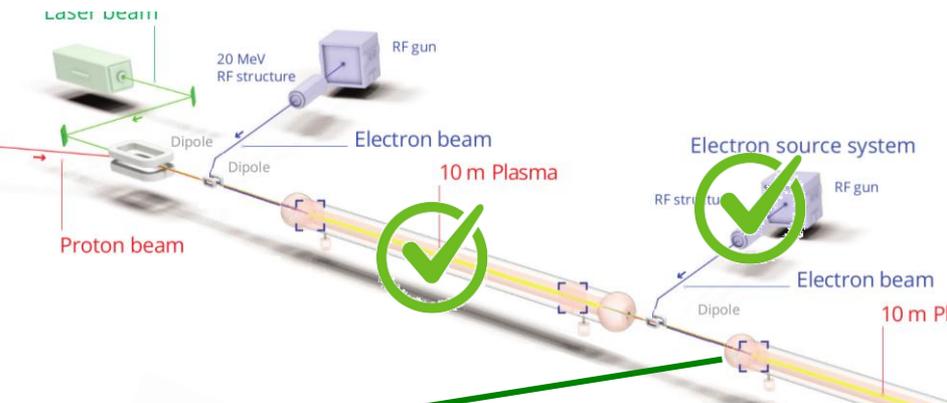
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Muggli (AWAKE Coll.), J. of Phys.: Conf. Series 1596, 012008 (2020)

- ✧ Quality
- ✧ Application!
- ✧ **HIGH ENERGY  $e^-$**
- ✧ **50-100GeV**

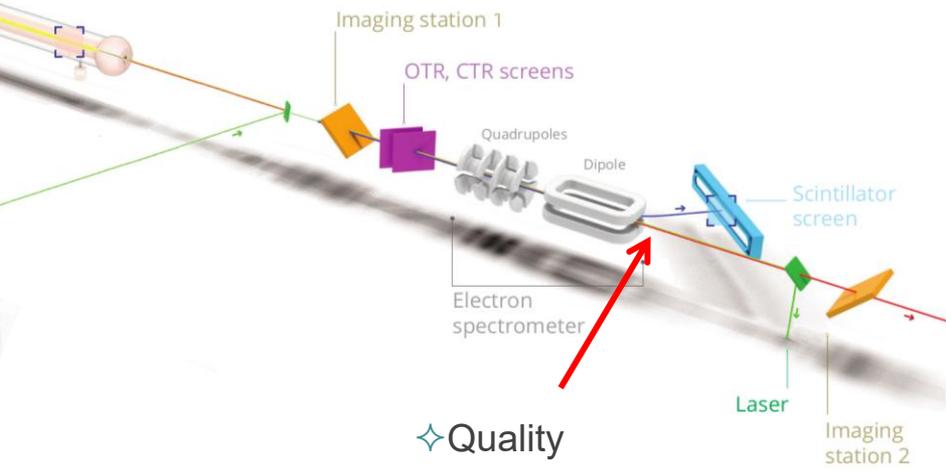
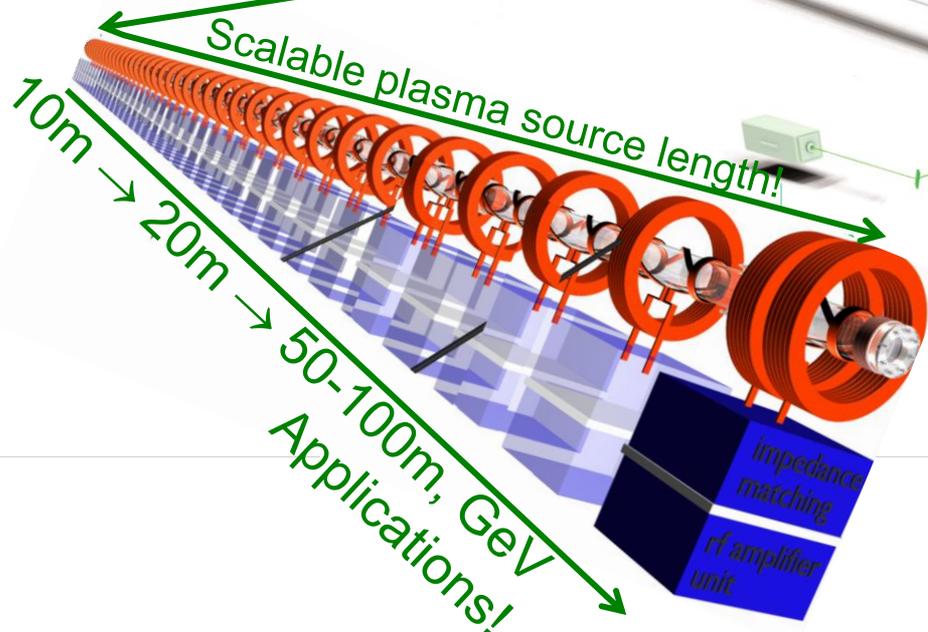


# RUN 2c,d: ACCELERATE $e^-$ BUNCH, QUALITY



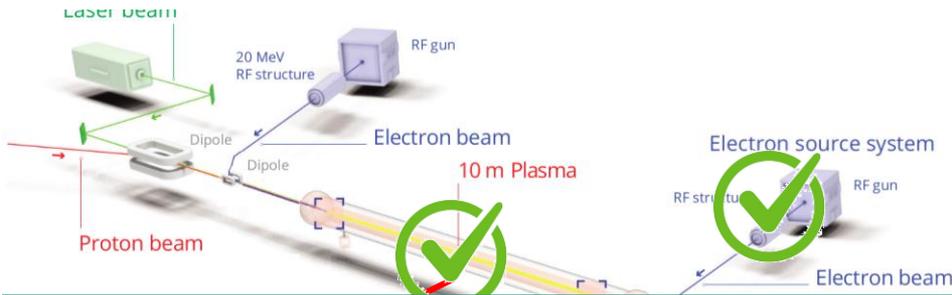
- ✧ Separate self-modulation and acceleration
  - ✧ Two plasmas
- ✧ External injection of  $e^-$  (on axis)
- ✧ Bunch quality sufficient for applications
  - ✧  $Q$ ,  $\epsilon_N$ ,  $\Delta E/E$ , ...

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series 1596, 012008 (2020)



- ✧ Quality
- ✧ Application!
- ✧ **HIGH ENERGY  $e^-$**
- ✧ **50-100GeV**

# RUN 2c,d: ACCELERATE $e^-$ BUNCH, QUALITY

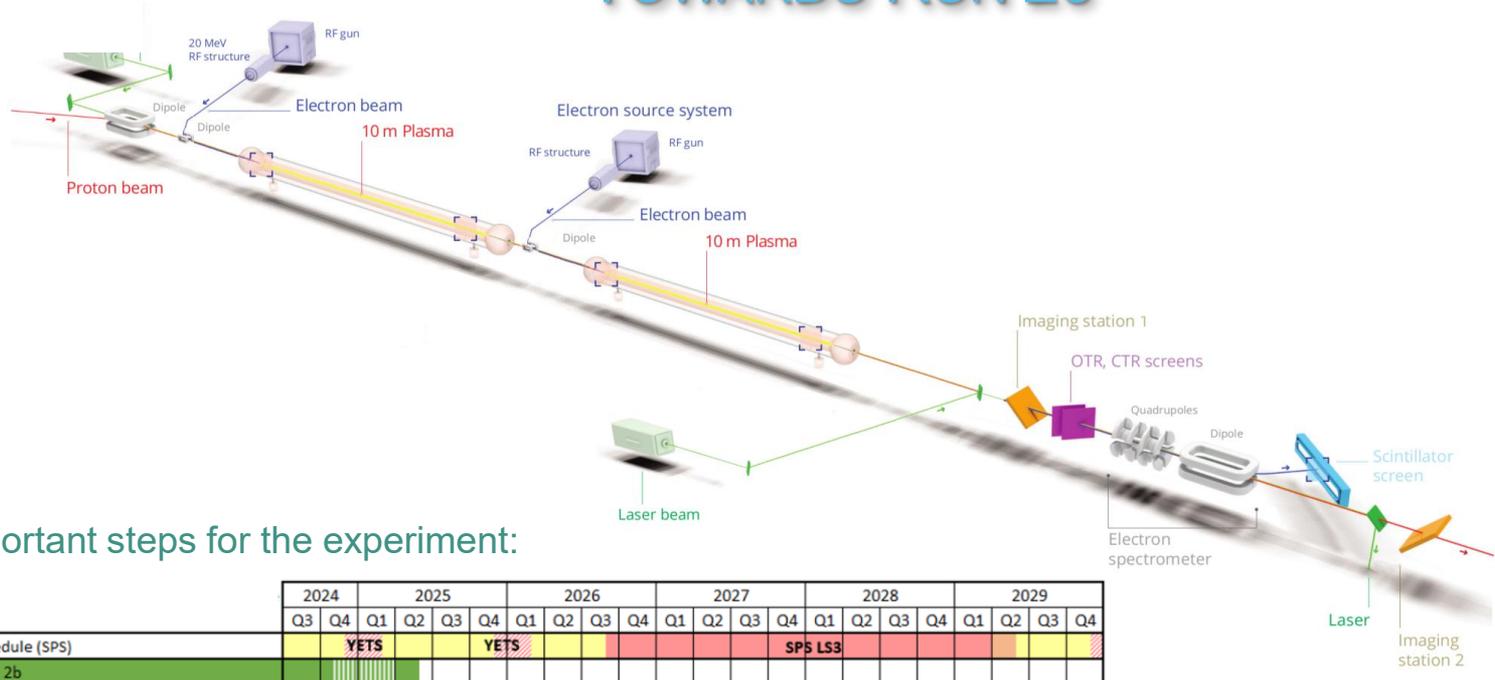


- ✧ Separate self-modulation and acceleration
  - ✧ Two plasmas
- ✧ External injection of  $e^-$  (on axis)
- ✧ Bunch quality sufficient for applications
  - ✧  $Q$ ,  $\varepsilon_N$ ,  $\Delta E/E$ , ...

Clear plans towards/for Runs 2c and 2d:

- ✧ Extension of the AWAKE facility (CNGS target area dismantling (CTD))
- ✧ Development of the 2c/2d experimental setup
  - ✧ Re-use plasma sources Runs 1 & 2, 20MeV injector, diagnostics, ...
- ✧ → 2c: injection experiments in 10m plasma: bunch quality,  $Q$ ,  $\varepsilon_N$ ,  $\Delta E/E$ , ...
- ✧ → 2d: scalability of acceleration in 20m scalable (in length) plasma source: discharge or helicon source
- ✧ Development of scalable plasma source(s)

# TOWARDS RUN 2c



## ✦ Important steps for the experiment:

	2024				2025				2026				2027				2028				2029			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
Injector schedule (SPS)			YETS			YETS								SPS LS3										
AWAKE Run 2b																								
B.697 SCE works																								
B.697 services installation																								
Run 2b removal																								
Awake decabling																								
CTD - set-up of the area																								
CTD - main works																								
CTD - decontamination & cleaning																								
Handover to AWAKE																								
Run 2c - Installation services, cables																								
Run 2c - Equipment installation																								
Run 2c - Hardware commissioning																								
Run 2c - Beam commissioning																								
Run 2c - 150MeV Beam commissioning																								
Run 2c - Commissioning with beam & operation																								

Stop experiments  
CNGS target area  
dismantling

Equipment Install

p<sup>+</sup> beam!

✦ Detailed plan not shown ...

Slide: Ans Pardon, for EN and ACE annual meeting input from EN-ACE-OSS

## CTD Preparation (CTD: CNGS target area dismantling)

	2024		2025			
	Q3	Q4	Q1	Q2	Q3	Q4
Building construction						
Building services installation						
AWAKE 2b removal						
AWAKE decabling						

### AWAKE removal and decabling



E-source & Klystron  
Exp. Area & Klystron  
e- and p+ beamlines

### Storage

- Buffer zone
- Storage for
- ~300m<sup>2</sup> floor area is ...
- Insulated, HVAC system, Overhead crane 10t
- Shielded with 80 cm thick concrete blocks
- Shielded storage & shielded TREC area inside



Next: Nuclear dismantling CNGS: Q1-Q4 2026

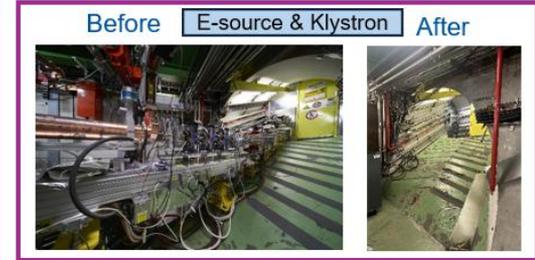
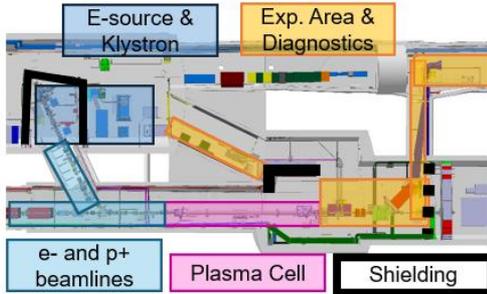
✧ Dismantling of CNGS target area advancing well!

Slide: Ans Pardon, for EN and ACE annual meeting input from EN-ACE-OSS

## CTD Preparation (CTD: CNGS target area dismantling)

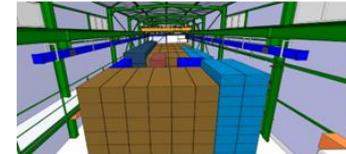
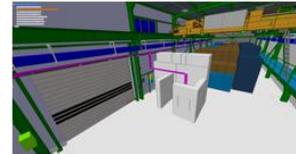
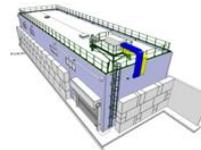
	2024		2025			
	Q3	Q4	Q1	Q2	Q3	Q4
Building construction						
Building services installation						
AWAKE 2b removal						
AWAKE decabling						

### AWAKE removal and decabling



### Storage building (B.697)

- Buffer zone for waste items
- Storage for reusable blocks
- ~300m<sup>2</sup> floor surface, ~200m<sup>2</sup> surface under crane
- Insulated, HVAC system, Overhead crane 10t
- Shielded with 80 cm thick concrete blocks
- Shielded storage & shielded TREC area inside



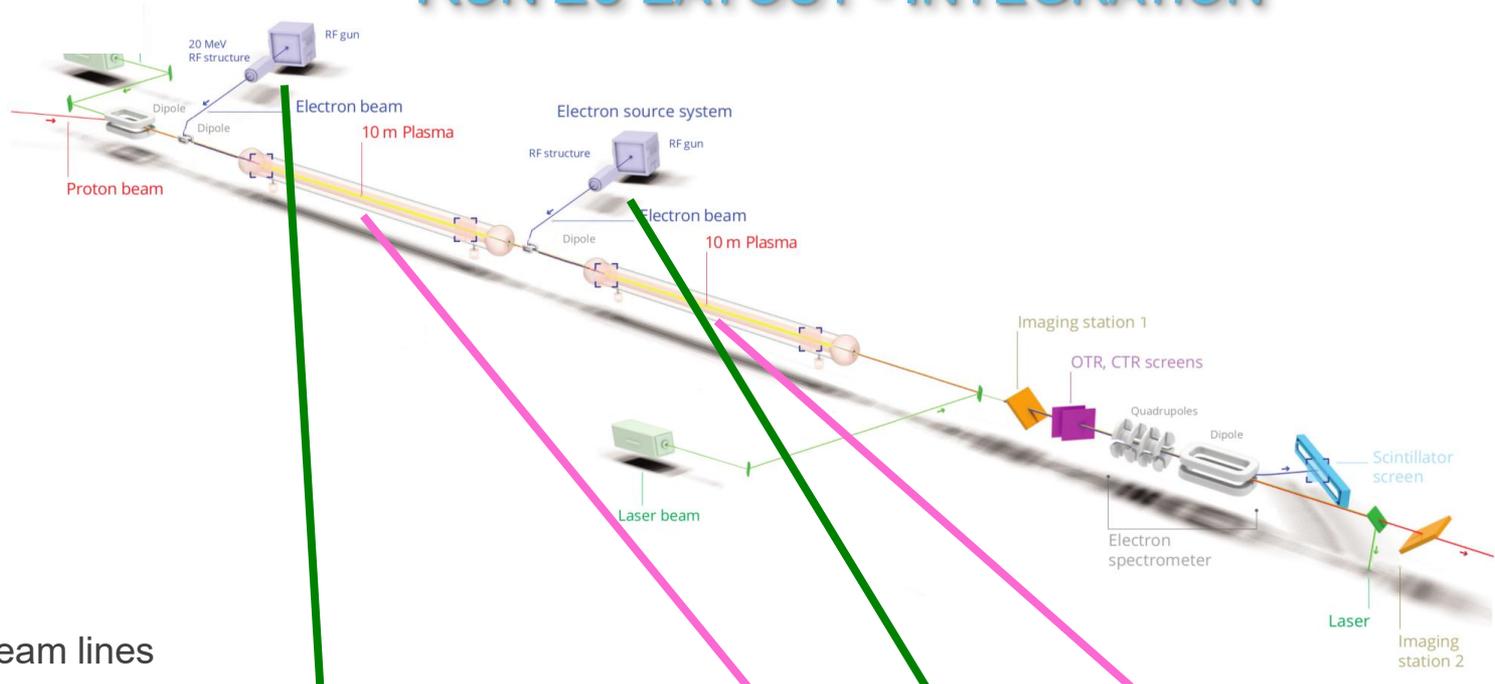
Courtesy A. Kosmicki, EN-ACE-INT



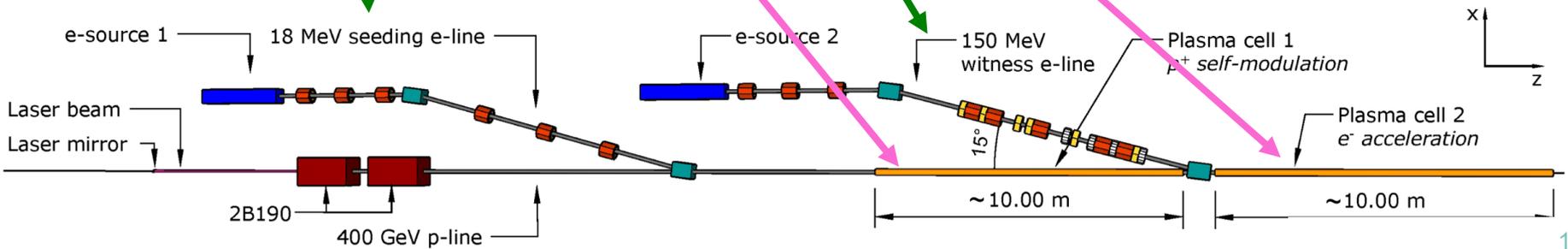
**Next: Nuclear dismantling CNGS: Q1-Q4 2026**

✧ Dismantling of CNGS target area advancing well!

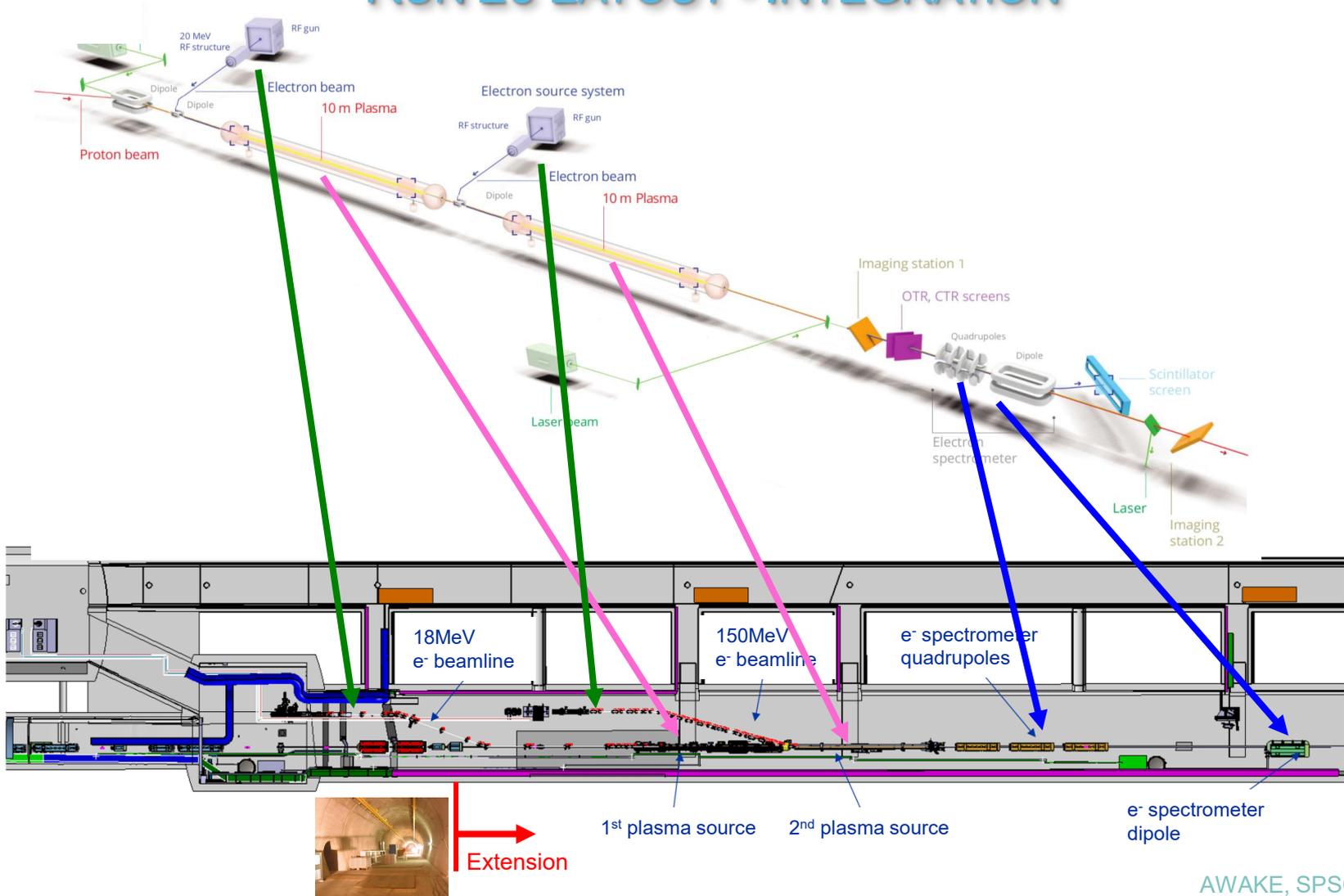
# RUN 2c LAYOUT - INTEGRATION



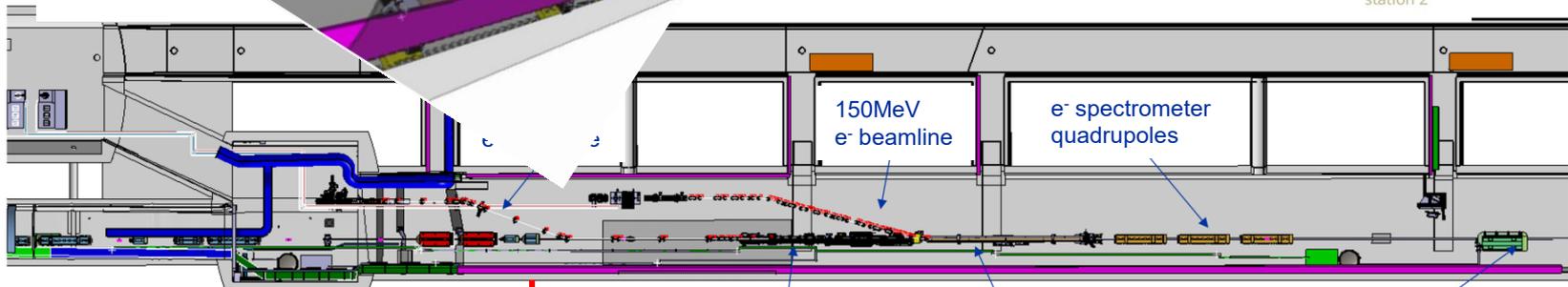
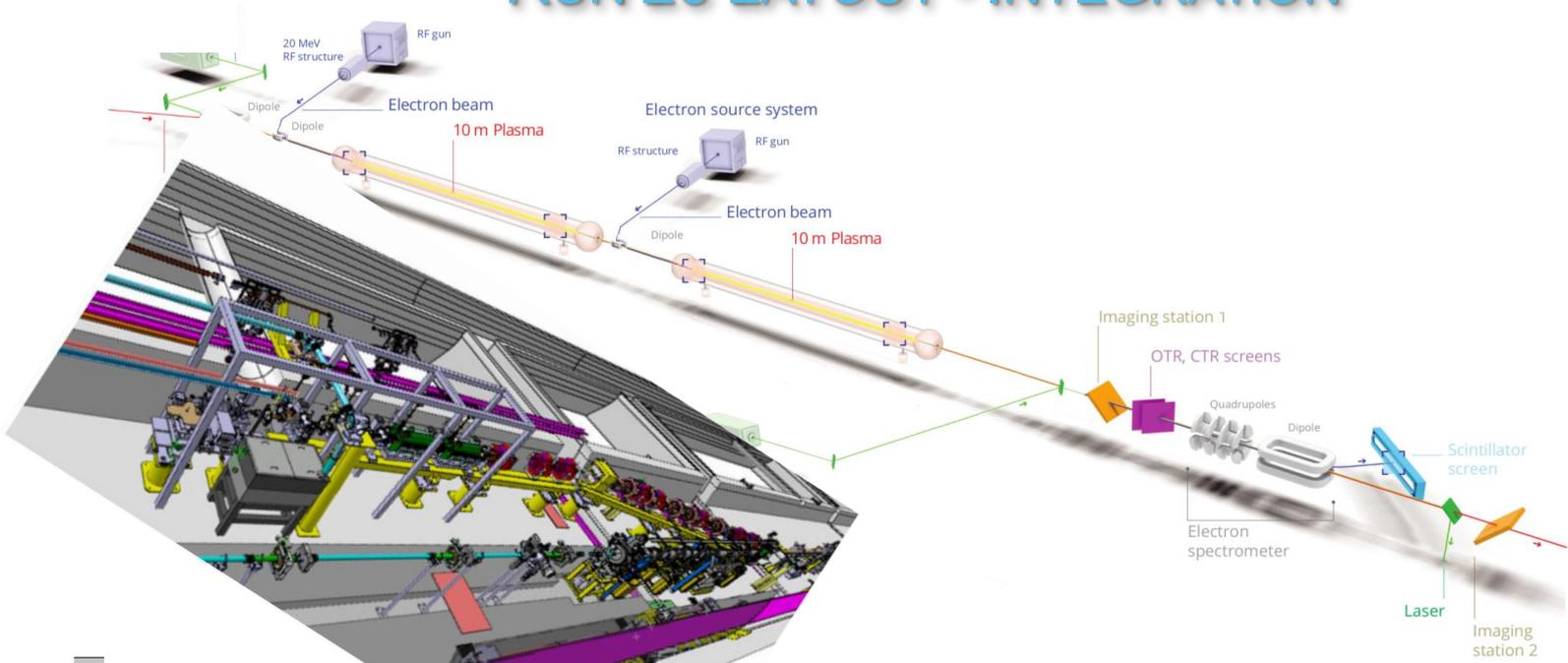
## ✧ Beam lines



# RUN 2c LAYOUT - INTEGRATION



# RUN 2c LAYOUT - INTEGRATION



Extension

1<sup>st</sup> plasma source

2<sup>nd</sup> plasma source

e<sup>-</sup> spectrometer dipole

# RF GUN – 150MeV e<sup>-</sup> BEAMLINE

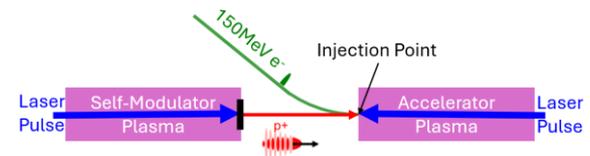
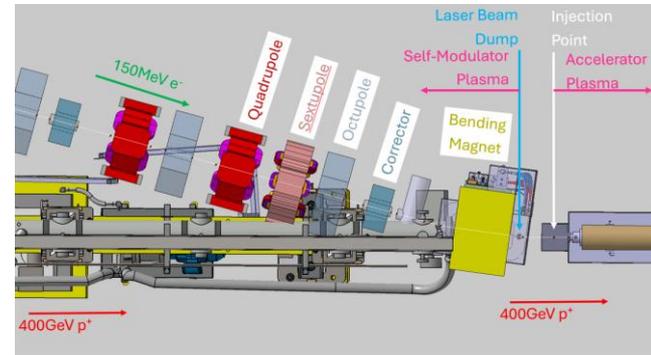
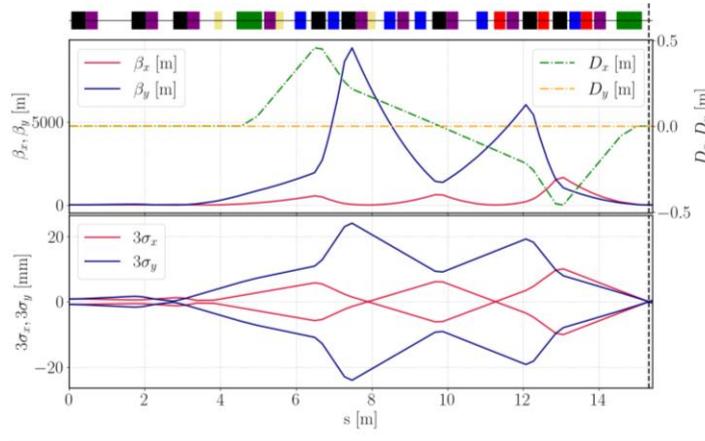
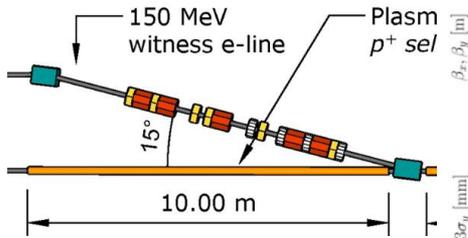
✧ S-band RF gun (ARTI) under test @ CTF2

✧ X-band RF structure under test



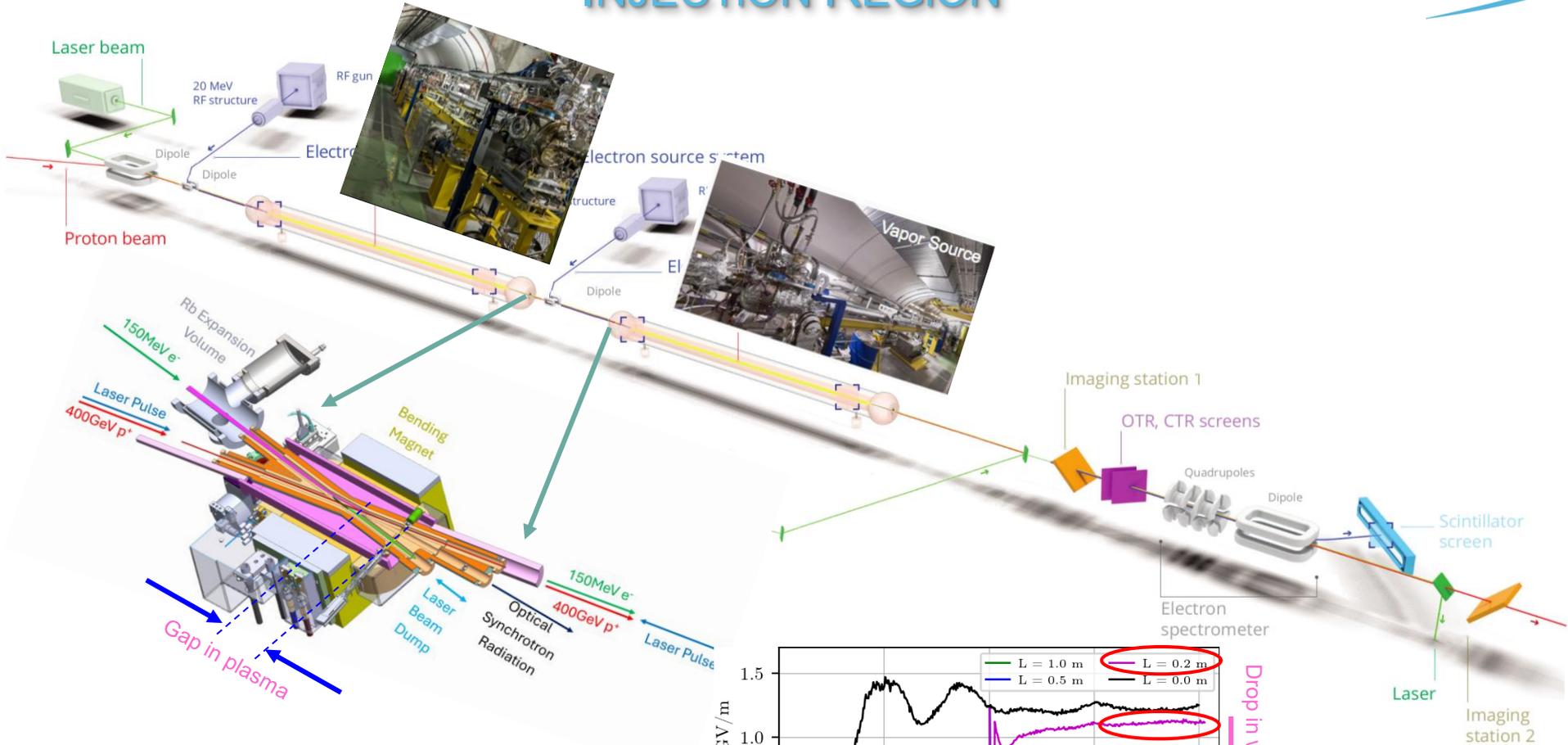
- ✧ Development of S-band gun, X-band linac advancing well!
- ✧ 150MeV e<sup>-</sup> bunch for injection:
  - ✧ Transverse size matched to plasma focusing force:  $\sigma_{\text{matched}} = 5.75\mu\text{m}$ !
  - ✧ Bunch duration:  $\sigma_{\text{matched}} = 200\text{fs}$
  - ✧ e<sup>-</sup> capture:  $\gamma_e \approx 294 \approx \gamma_p \approx 427$

## ✧ Beamline

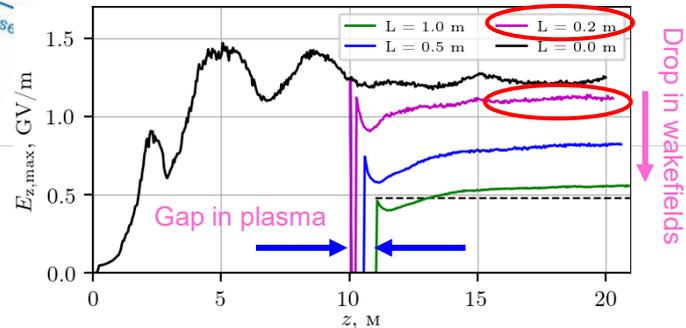


- ✧ Produces desired beam/bunch parameters
- ✧ Fits the experimental layout
- ✧ Tolerance studies under way

# INJECTION REGION

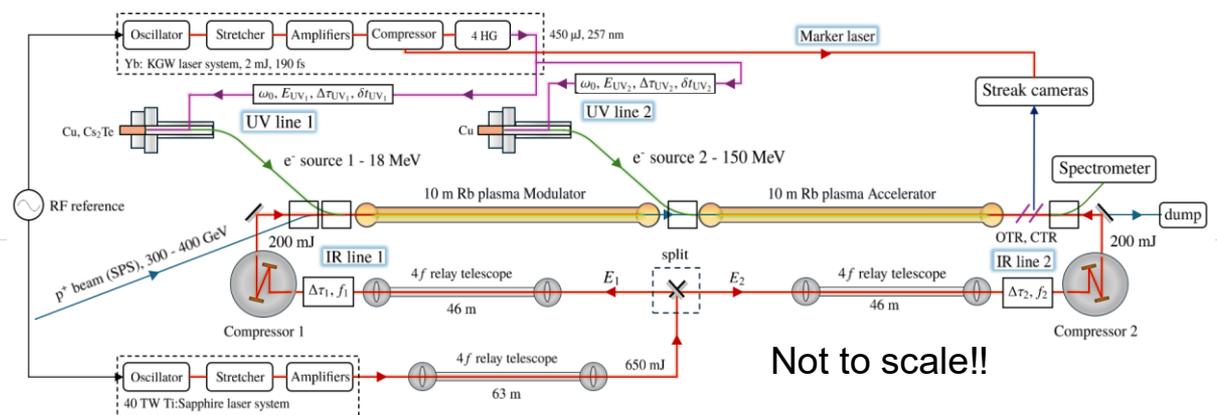
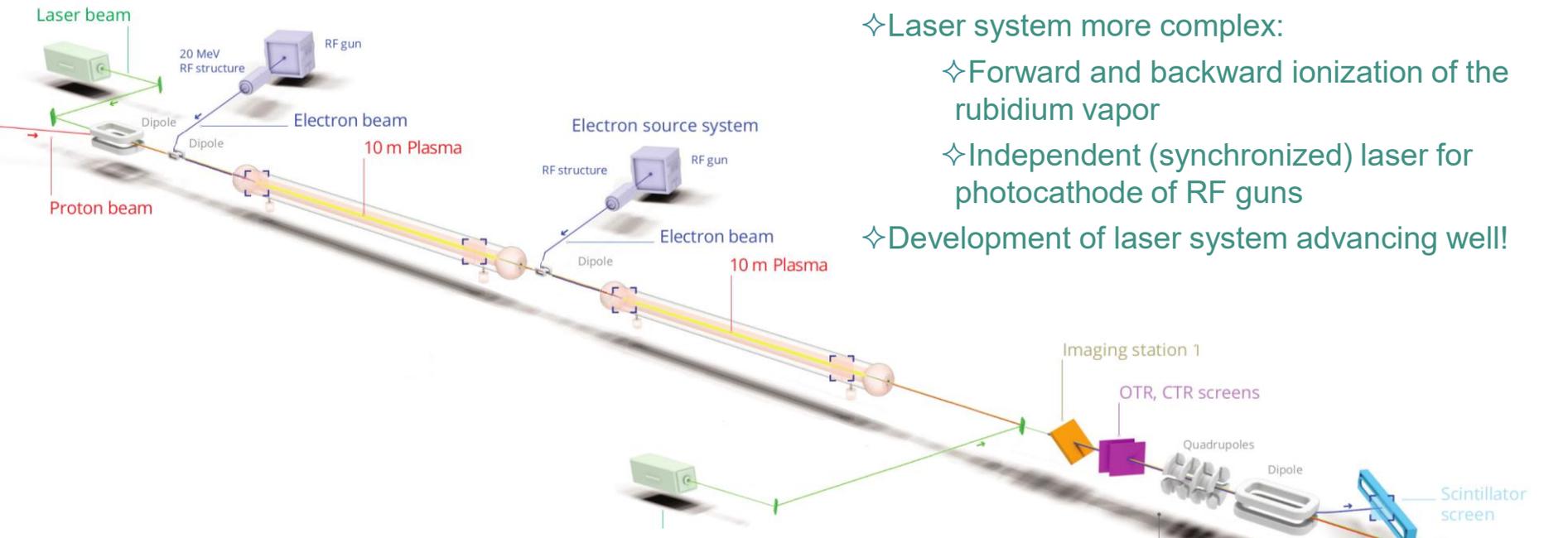


- ✧ Minimize gap length!
- ✧ Maintain temperature/density uniformity
- ✧ Include diagnostics



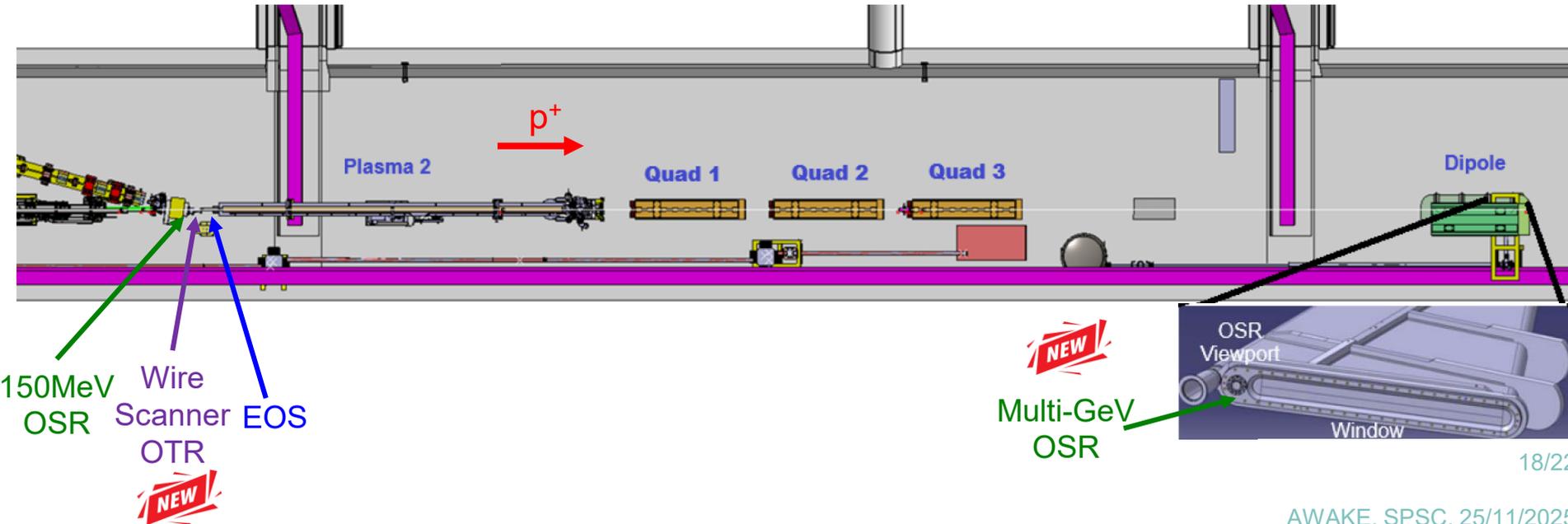
# LASERS: IONIZATION & e<sup>-</sup>

- ✧ Laser system more complex:
  - ✧ Forward and backward ionization of the rubidium vapor
  - ✧ Independent (synchronized) laser for photocathode of RF guns
- ✧ Development of laser system advancing well!



# DIAGNOSTICS

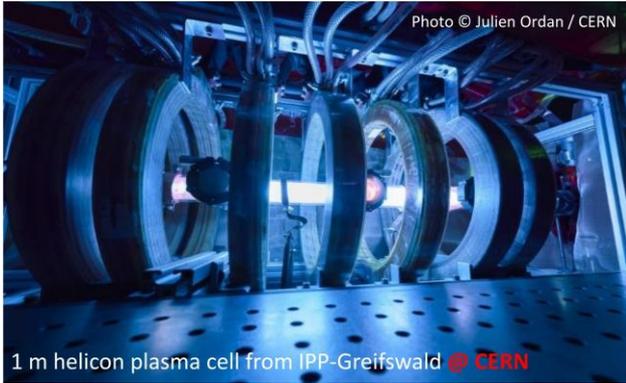
- ✧ Runs 1 and 2a,b diagnostics: streak cameras, OTR and screens, etc.
- ✧ New magnetic spectrometer for higher  $e^-$  bunch energies:  $\rightarrow >10\text{GeV}$ 
  - ✧ Single/multi/shot emittance measurements
- ✧ New diagnostics:
  - ✧ **O**ptical **S**ynchrotron **R**adiation: 150MeV  $e^-$  beam size, position; accelerated  $e^-$  bunch emittance
  - ✧ **E**lectro **O**ptical **S**ampling: 150MeV  $e^-$  bunch duration :  $\sigma_t=200\text{fs}$ !
  - ✧ **W**ire **S**canner: 150MeV  $e^-$  beam size:  $\sigma_{\text{matched}}=5.75\mu\text{m}$ !



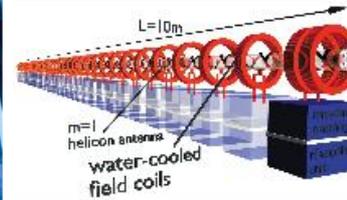
# TOWARDS RUN 2d: SCALABILITY

- ✧ Laser ionization does not scale to long plasma lengths (20-100m-1km): laser pulse energy depletion!
- ✧ Scalability: plasma source  $\leftrightarrow$  energy gain
- ✧ Plasma source development laboratory at CERN

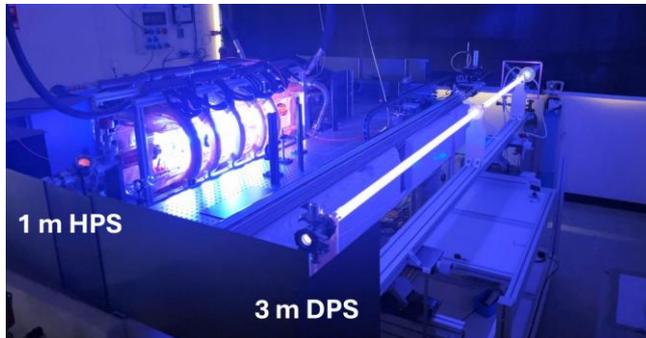
## ✧ Helicon plasma source (HPS): magnetized RF discharge



Buttenschön, PPFC 60(7), 075005 (2018)  
Zepp, Phys. Plasmas 31, 070704 (2024)



## ✧ Discharge plasma source (DPS)



Torrado, IEEE-TPS 51(12) (2023)

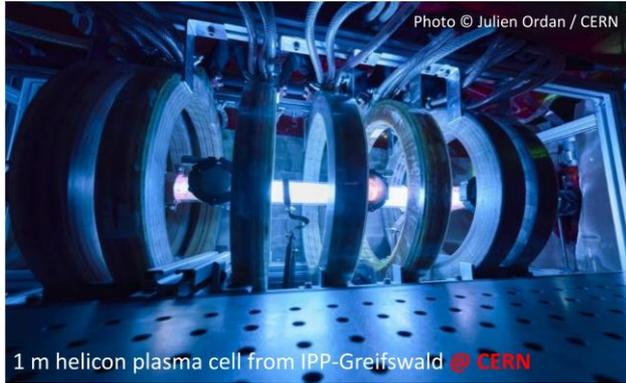
- ✧ Diagnostic challenge: demonstration of plasma density uniformity!

$$\Delta n_e/n_{e0} < 1/4N_{\mu b}, N_{\mu b} \sim 100 \rightarrow \Delta n_e/n_{e0} < 0.25\%$$

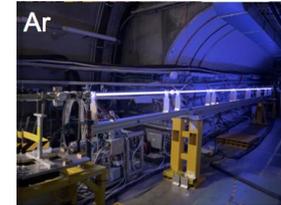
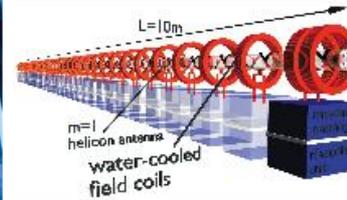
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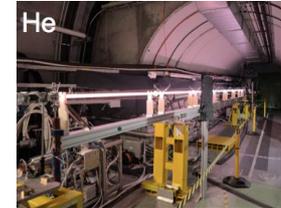


Buttenschön, PPFC 60(7), 075005 (2018)  
Zepp, Phys. Plasmas 31, 070704 (2024)



❖ 10m DPS tested with  $p^+$  beam in 2023

L. Verra et al., AWAKE Collaboration, Phys. Rev. E 109, 055203 (2024)

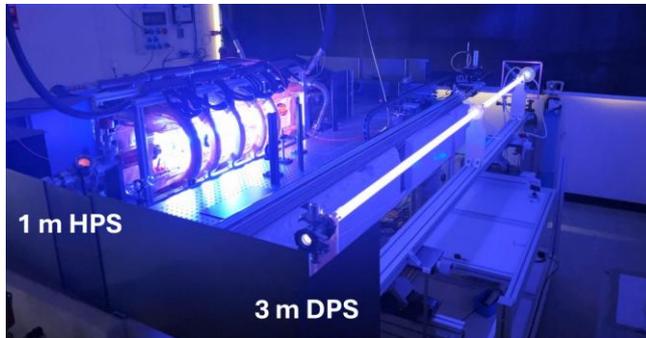


M. Turner et al., AWAKE collaboration, Phys. Rev. Lett. 134, 155001(2025)



C. Amoedo et al., AWAKE collaboration, to be submitted

## ❖ Discharge plasma source (DPS)



Torrado, IEEE-TPS 51(12) (2023)

❖ Diagnostic challenge: demonstration of plasma density uniformity!

$$\Delta n_e/n_{e0} < 1/4N_{\mu b}, N_{\mu b} \sim 100 \rightarrow \Delta n_e/n_{e0} < 0.25\%$$

# TABLE OF CONTENT



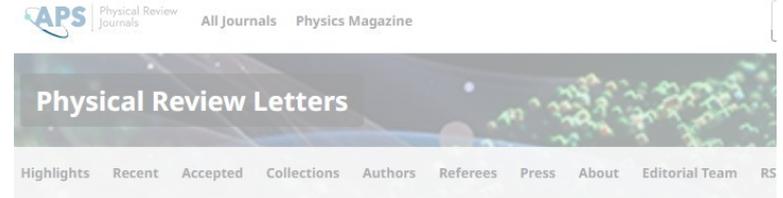
- 1 Executive summary
- 2 Run 2b experimental results
  - 2.1 Light measurements
  - 2.2 Saturation of SM
  - 2.3 SM amplitude reproduction
  - 2.4 Hosing
  - 2.5 Energy spread reduction step
  - 2.6 Phase stability of wakefields
  - 2.7 Scaling of SM at high plasma density
  - 2.8 Scherren measurement of "plasma" radius
  - 2.9 SM suppression
  - 2.10 SM in discharge plasma source
- 3 Run 2c preparation
  - 3.1 CNGS target area dismantling
  - 3.2 Layout and integration
  - 3.3 New electron source
  - 3.4 LLRF
  - 3.5 Beam transport
  - 3.6 Beamline beamlines
  - 3.7 Instrumentation
  - 3.8 Injection region
  - 3.9 Scalable plasma source
- 4 Numerical Simulations
  - 4.1 Proton beam studies
  - 4.2 Witness studies
  - 4.3 Full driver/witness studies
  - 4.4 Beyond Run 2c
- 5 Particle physics applications of the AWAKE scheme
- 6 Publications and presentations
  - 6.1 Publications by AWAKE and AWAKE Collaboration members on AWAKE-related topics
  - 6.2 Conference presentations and posters

Well-understood

Clear plan  
Significant progress

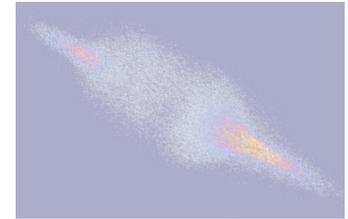
- ✧ Focus on accelerator development
- ✧ Expect:
  - ✧ Ten publications
  - ✧ Five PhD and one Master theses

✧ Clear/strong plan for Run 2c and beyond

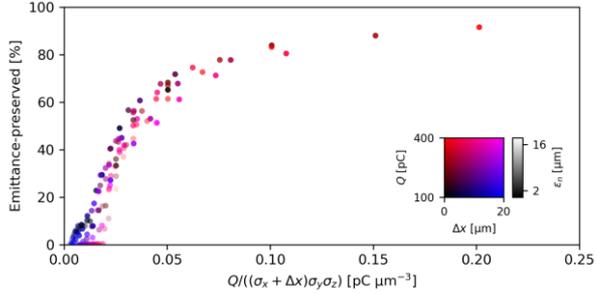


OPEN ACCESS | GO MOBILE | ACCESS BY CERN LIBRARY  
**Experimental Observation of the Motion of Ions in a Resonantly Driven Plasma Wakefield Accelerator**  
[M. Turner](#)<sup>1</sup>, [E. Walter](#)<sup>2,3</sup>, [C. Amoedo](#)<sup>1</sup>, [N. Torrado](#)<sup>1,4</sup>, [N. Lopes](#)<sup>4</sup>, [A. Sublet](#)<sup>1</sup>, [M. Bergamaschi](#)<sup>5</sup>, [J. Pucek](#)<sup>5</sup>, [J. Mezger](#)<sup>5</sup> et al. (AWAKE Collaboration<sup>7</sup>)

Phys. Rev. Lett. **134**, 155001 – Published 17 April, 2025  
DOI: <https://doi.org/10.1103/PhysRevLett.134.155001>

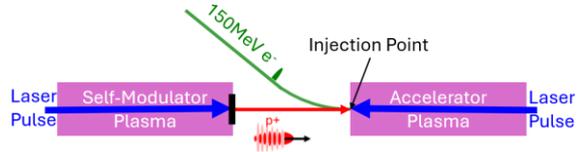


## ✧ Injection tolerance studies

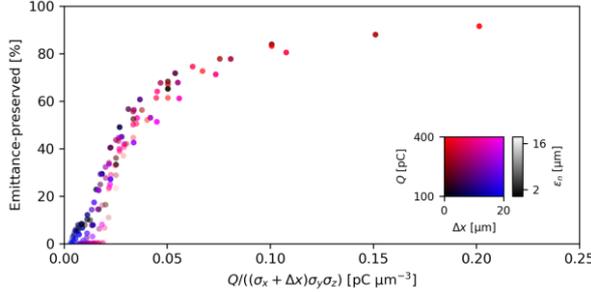


✧ Misalignment  $\Delta x, y \sim$  tens of  $\mu\text{m}$  @ accelerator entrance

✧ Tight tolerances!

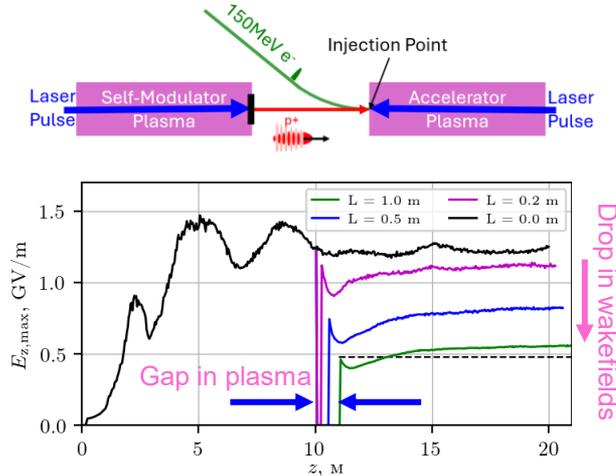


## Injection tolerance studies



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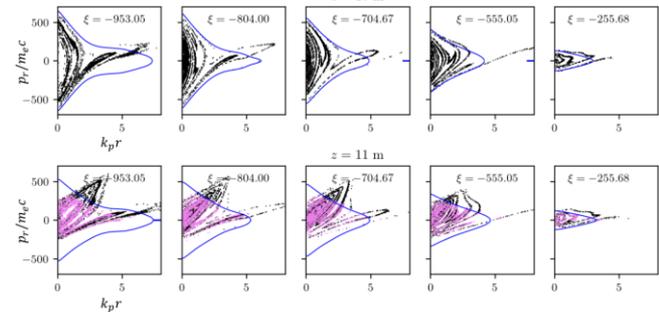
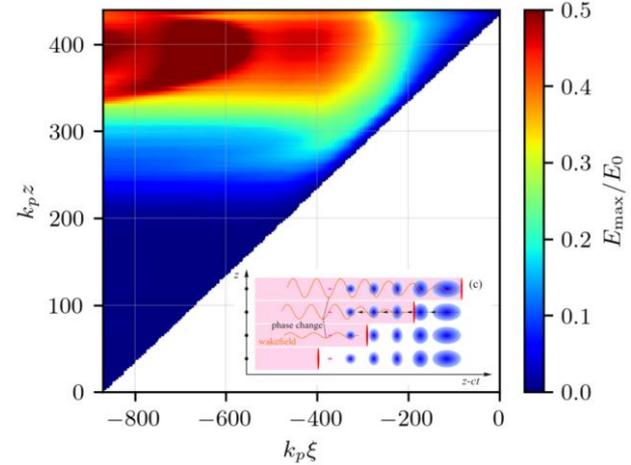
✧ Tight tolerances!



✧ Many more results ...

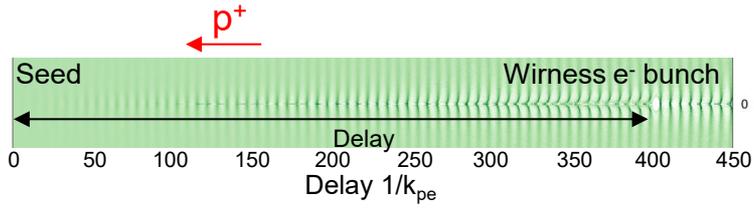
✧ Choice and consistency of parameters

## Injection: backward propagating laser/pulse/boundary

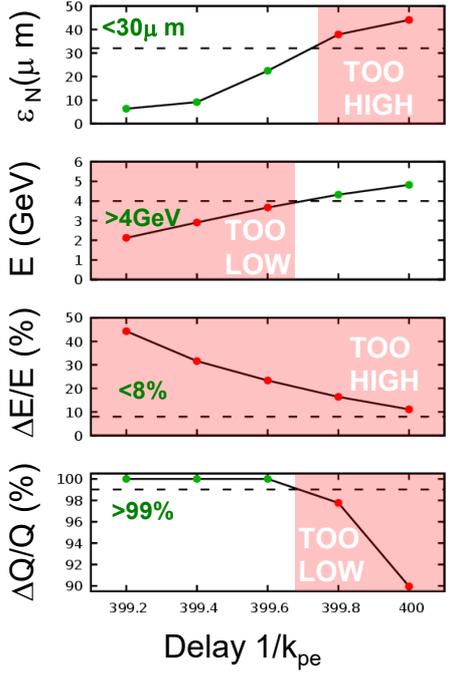


✧ No significant impact on final  $e^-$  bunch parameters

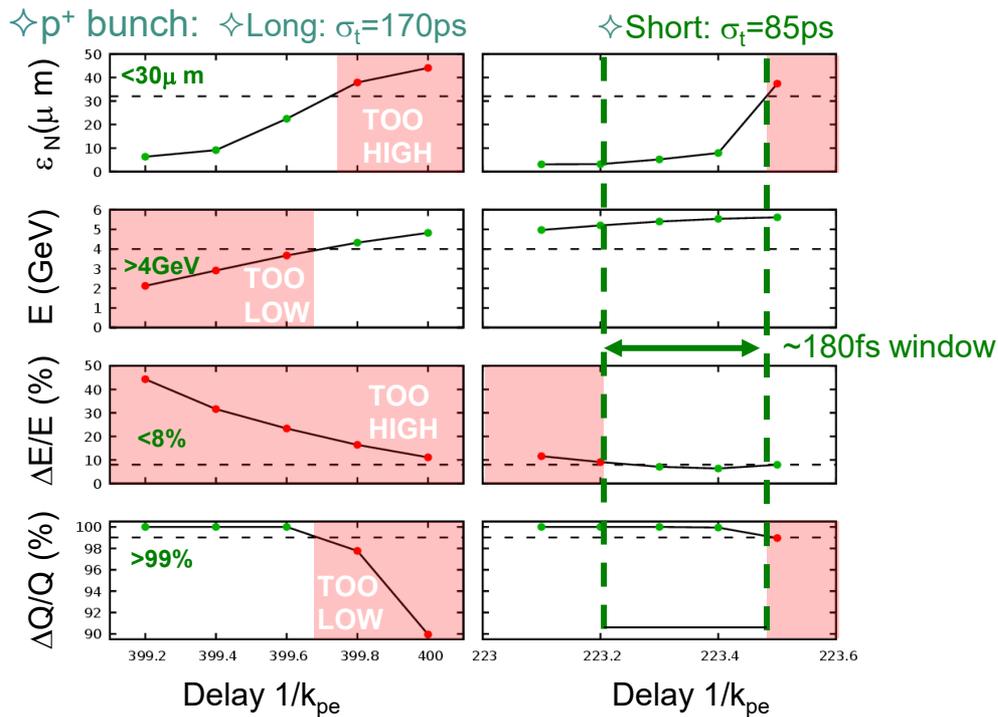
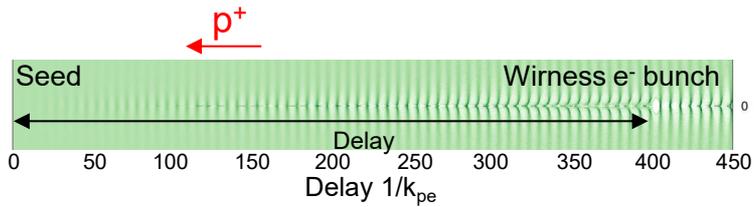
# BEAM TIME REQUEST FOR 2026



◇ p<sup>+</sup> bunch: ◇ Long:  $\sigma_t=170\text{ps}$

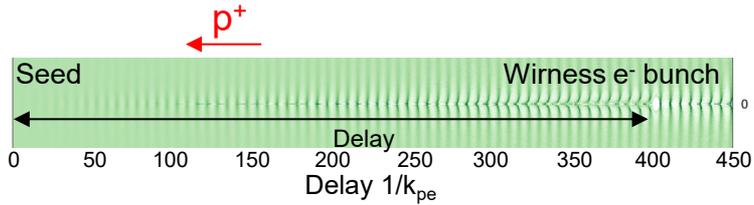


# BEAM TIME REQUEST FOR 2026



◇ Better e<sup>-</sup> bunch quality with short p<sup>+</sup> bunch  
 $\sigma_t=170\text{ps} \rightarrow 85\text{ps}$

# BEAM TIME REQUEST FOR 2026



Proposed plan for p<sup>+</sup> bunch compression:

Phase 1:

✧ LN4-PSB-PS: beginning 2026

✧ Recover longitudinal emittances similar to 2024 measurements

✧ Explore minimum stable longitudinal emittance for  $4 \times 10^{11}$  particles per bunch

✧ Demonstrate long-term reproducibility (3-4, 6-hour slots)

Phase 2:

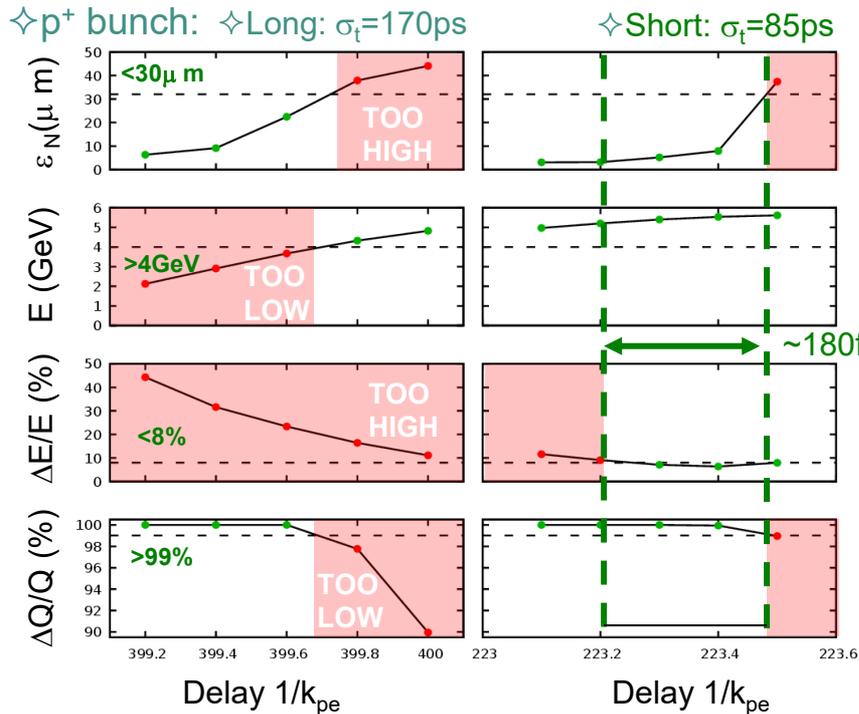
✧ LN4-PSB-PS-SPS: mid 2026

✧ Recover 90ps rms bunch length at the SPS extraction

✧ Studies with bunch lengths below 90ps are beyond the capabilities of present acquisition systems

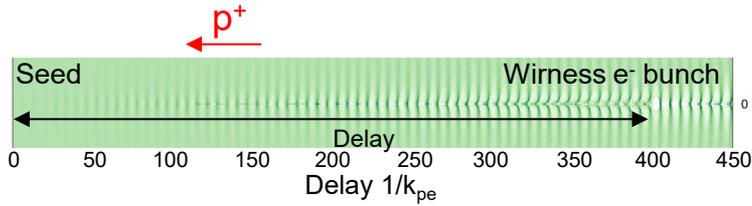
✧ Demonstrate long-term reproducibility (2-3, 6-hour slots)

✧ AWAKE cycles need to be commissioned in 2026, although they are not required for operation



✧ Better e<sup>-</sup> bunch quality with short p<sup>+</sup> bunch  
 $\sigma_t=170\text{ps} \rightarrow 85\text{ps}$

# BEAM TIME REQUEST FOR 2026



Proposed plan for  $p^+$  bunch compression:

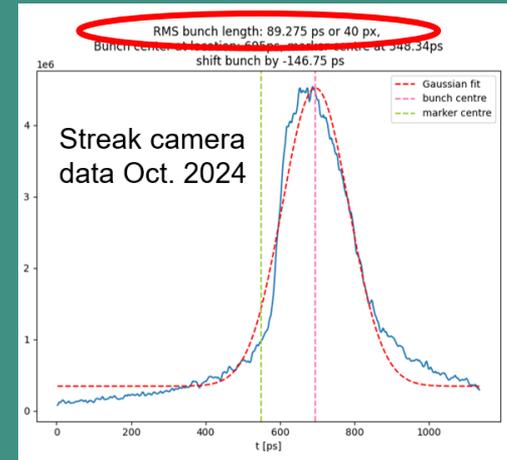
Phase 1:

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✧ Recover longitudinal emittances similar to 2024 measurements

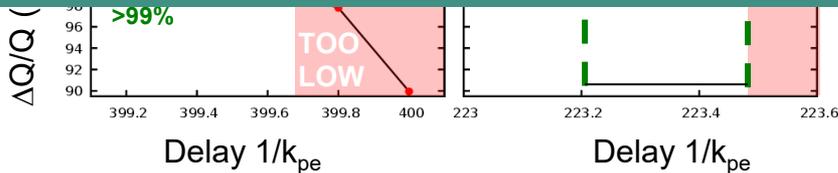
✧  $p^+$  bunch: ✧ Long:  $\sigma_t=170\text{ps}$  ✧ Short:  $\sigma_t=85\text{ps}$

- ✧ Request MD time for short  $p^+$  bunch production in 2026
- ✧  $\sigma_t=170\text{ps} \rightarrow 85\text{ps}$  for  $e^-$  bunch quality
- ✧ Ease requirement on plasma density uniformity  $\sim 1/\sigma_t$
- ✧ “Short parallel MD”  $\rightarrow$  low impact on SPS schedule
- ✧ 2024 preliminary results show  $\sigma_t \sim 90\text{ps}$  possible
  - ✧ Demonstrate reproducibility



✧ Demonstrate long-term reproducibility (2-3, 6-hour slots)

✧ AWAKE cycles need to be commissioned in 2026, although they are not required for operation



✧ Better  $e^-$  bunch quality with short  $p^+$  bunch  
 $\sigma_t=170\text{ps} \rightarrow 85\text{ps}$

# Our report:

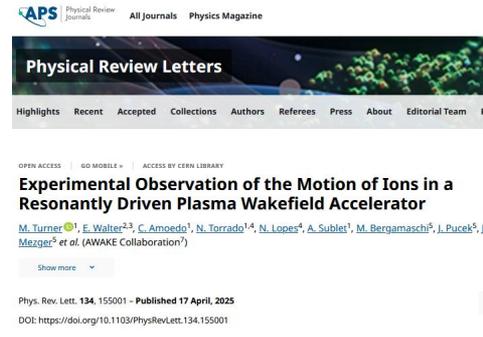
- 1 Executive summary
- 2 Run 2b experimental results
  - 2.1 Light measurements
  - 2.2 Saturation of SM
  - 2.3 SM amplitude reproduction
  - 2.4 Hosing
  - 2.5 Energy spread reduction step
  - 2.6 Phase space wakefields
  - 2.7 Self-amplified SM at high plasma density
  - 2.8 Scherren measurement of "plasma" radius
  - 2.9 SM suppression
  - 2.10 SM in discharge plasma source
- 3 Run 2c preparation
  - 3.1 CNGS target area dismantling
  - 3.2 Layout and integration
  - 3.3 New electron gun
  - 3.4 LLRF
  - 3.5
  - 3.6
  - 3.7
  - 3.8 Injection region
  - 3.9 Scalable plasma source
- 4 Numerical Simulations
  - 4.1 Proton beam
  - 4.2 With
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  - 4.98
  - 4.99
  - 4.100
- 5 Particle physics applications of the AWAKE scheme
- 6 Publications and presentations
  - 6.1 Publications by AWAKE and AWAKE Collaboration members on AWAKE-related topics
  - 6.2 Conference presentations and posters

Well-understood

Clear plan  
Significant progress

Consistency of parameters

# SUMMARY



- ✦ Quite some progress
- ✦ Focus on accelerator development
- ✦ Expect:
  - ✦ Ten publications
  - ✦ Five PhD and one Master theses

- ✦ Mariana Moreira, John Dawson  
Doctoral Thesis Prize,
- ✦ Laser Plasma Accelerator  
Workshop, Sept. 2025
- ✦ C. Amoedo, Poster Prize
- ✦ European Advanced  
Accelerators Conference,  
Sept. 2025



✦ Clear/strong plan for Run 2c and beyond

# Thank you to my collaborators



# Thank you!

<http://www.mpp.mpg.de/~muggli>

muggli@mpp.mpg.de

## Our report:

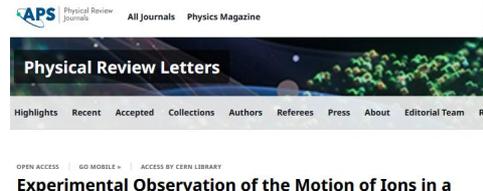
- 1 Executive summary
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  - 2.2 Saturation of SM
  - 2.3 SM amplitude reproduction
  - 2.4 Hosing
  - 2.5 Energy spread

understood

## SUMMARY

✧ Quite some progress

✧ Focus on accelerator development



## 2026:

# MD beam time request for short $p^+$ bunch production

- 3.7 L<sub>1</sub> diagnostics
- 3.8 Injection region
- 3.9 Scalable plasma source

- 4 Numerical Simulations
  - 4.1 Proton beam
  - 4.2 Wakefield
- 5 Particle physics applications of the AWAKE scheme
- 6 Publications and presentations

Consistency of parameters

✓ Clear/strong plan for Run 2c and beyond



- 6.1 Publications by AWAKE and AWAKE Collaboration members on AWAKE-related topics
- 6.2 Conference presentations and posters

22/22

# OUTLINE



✧ Accelerate,  $e^-$ ,  $p^+$ , ions, etc.

# POSSIBLE APPLICATIONS



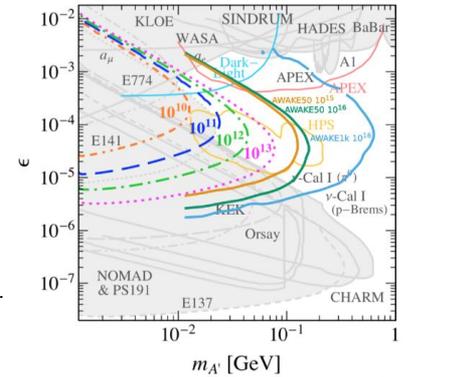
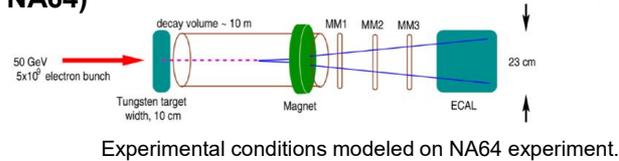
## First application: SPS driver

→ Requirements on emittance are moderate for fixed target experiments → first experiments in not-too far future!

## Search for dark photons

- **50-100 GeV  $e^-$  bunch**
- Decay of dark photon into visible particles (e.g.  $e^+e^-$ )
- $10^{16}$   $e^-$  on target with AWAKE-like beam (**1000 more than NA64**)

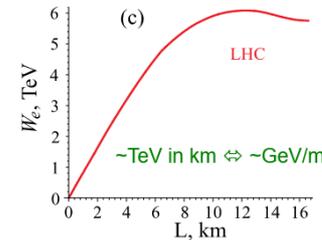
Deep inelastic scattering  
Strong field QED



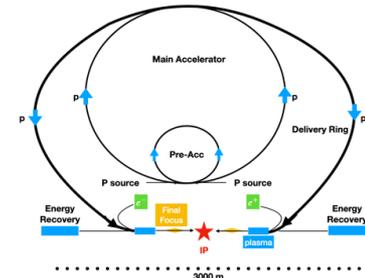
→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

## Collider Applications: LHC driver

- Collision of TeV-range  $e^-$  with an LHC  $p^+$  bunch: lower luminosity measurements in  $e^-/p^+$  or  $e^-$ /ion collisions
- Proton-driven Higgs factory (ALIVE):  $e^+/e^-$  collider 250 GeV CoM
- Strong field QED



A. Caldwell, Phys. Plasmas **18**, 13101 (2011)

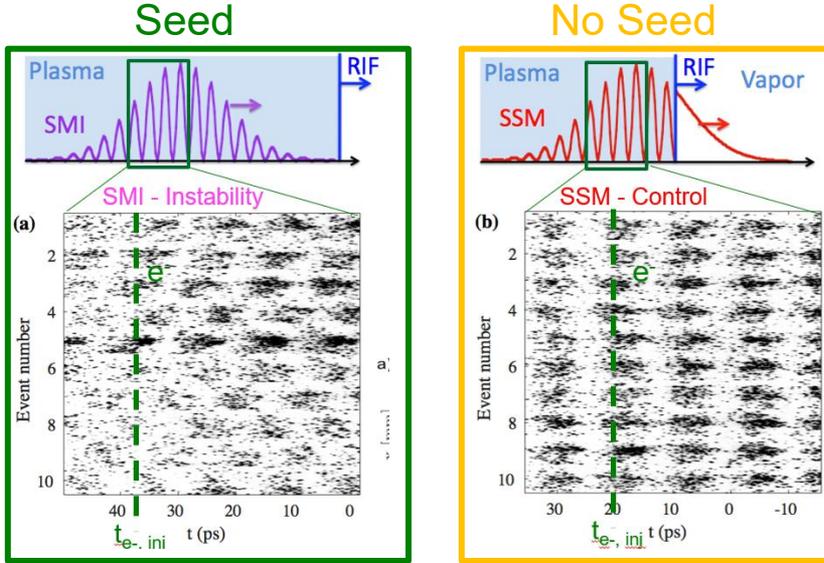


J Farmer et al 2024 New J. Phys. **26** 113011

→ From exploratory studies ...

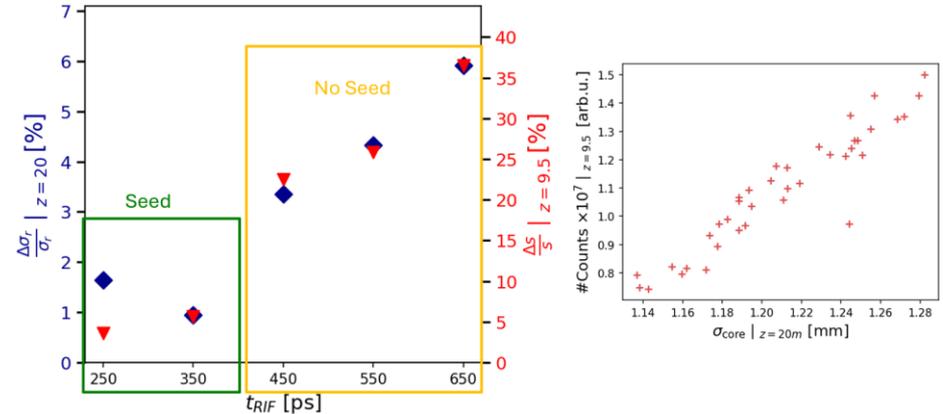
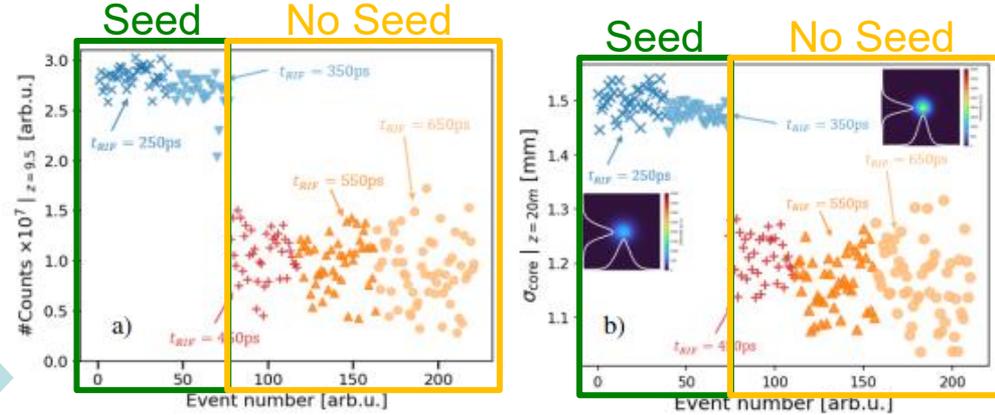
# SM REPRODUCIBILITY

◇ Seeding → timing/phase reproducibility



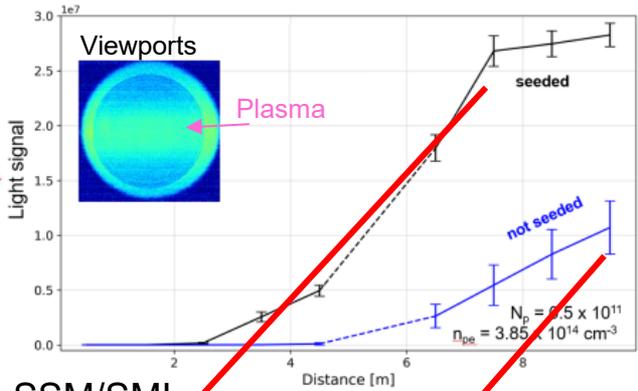
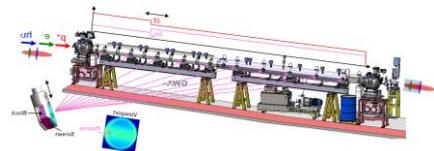
F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

◇ Amplitude reproducibility?

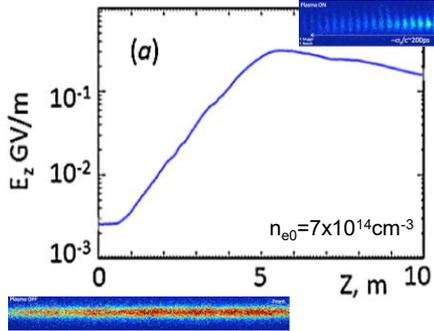


# SM\* GROWTH / SATURATION

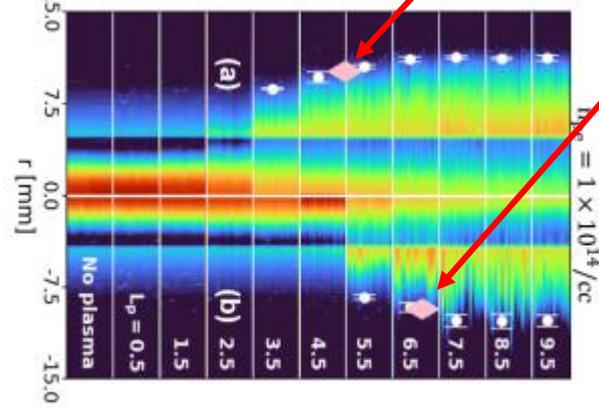
- Wakefields ↔ energy deposited in plasma
- Energy dissipation ↔ light emission



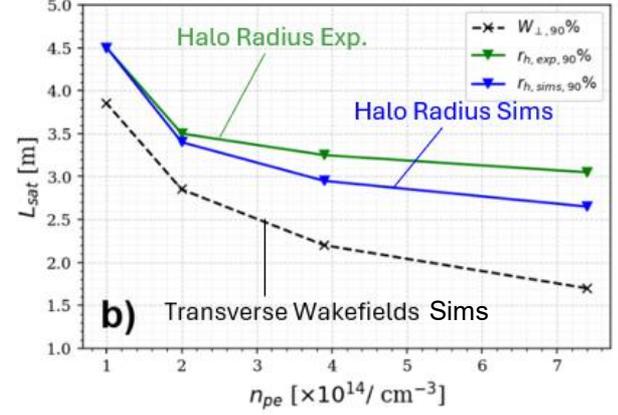
Numerical Simulations:  
Pukhov, PRL107 145003 (2011)



## Saturation SSM/SMI



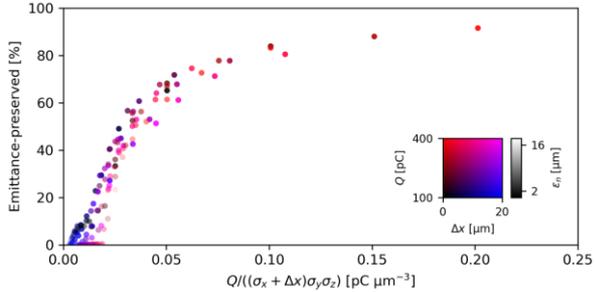
## Saturation length vs plasma density



- Light signal and halo radius show:
  - Saturation of SM
  - Saturation length varies with  $n_{e0}$
  - Differences SSM (seeded) and SMI (instability)
- 10m self-modulator length sufficient for Run 2c (<5m with  $n_{e0} = 7 \times 10^{14} \text{ cm}^{-3}$ )

# NUMERICAL SIMULATIONS EXAMPLES

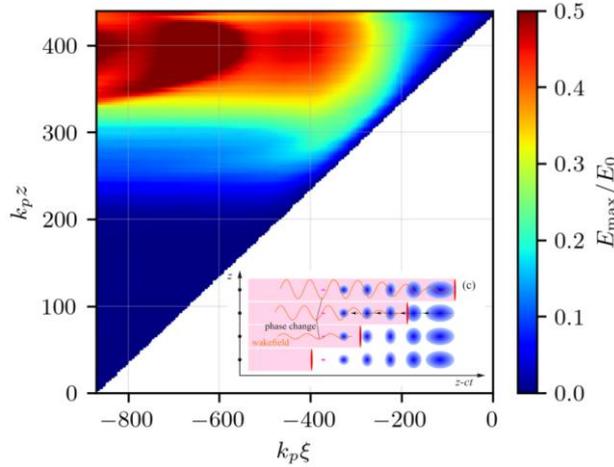
## Injection tolerance studies



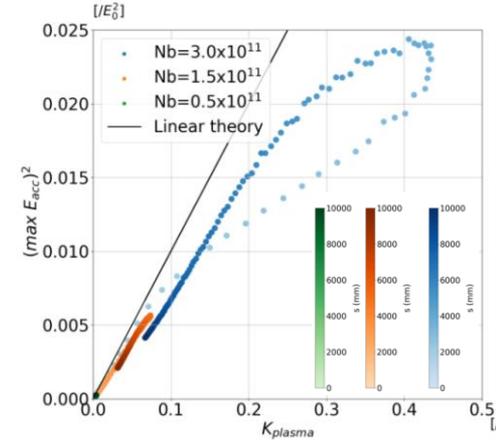
Δx, y ~ tens of μm @ accelerator entrance

Tight tolerances!

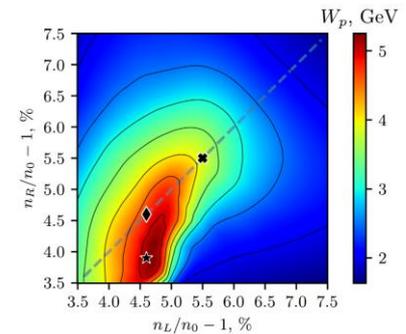
## Injection: backward propagating laser/pulse/boundary



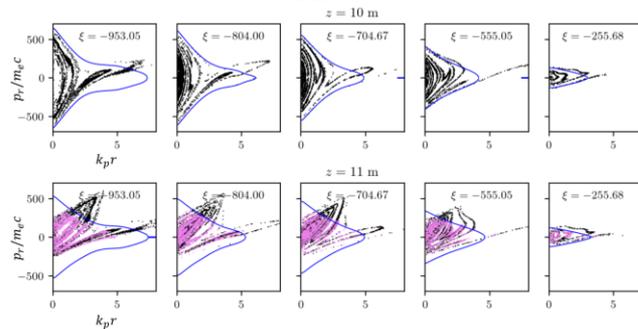
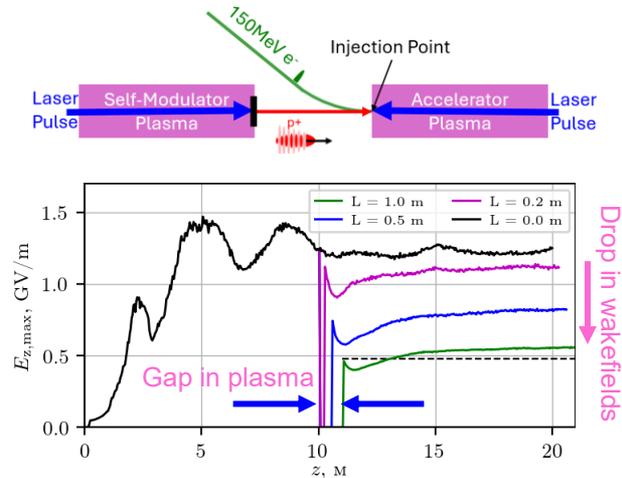
## Wakefield energy



## Energy gain optimization



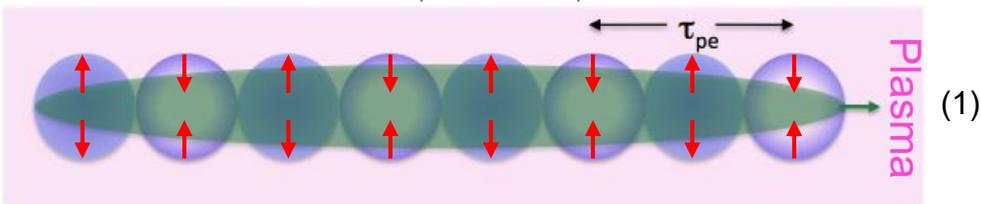
Two plasma densities?



No significant issue at accelerator entrance

# SELF-MODULATION

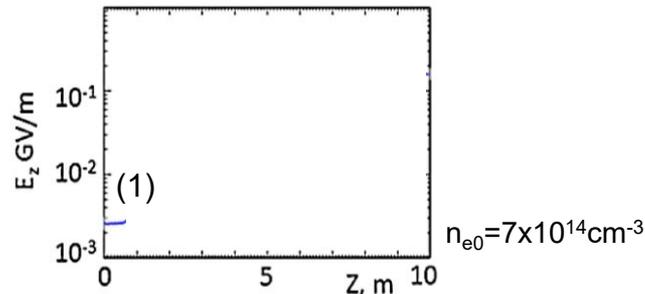
Long driver ( $p^+$ ),  $\sigma_t \gg 1/\omega_{pe}$ ,  $\sigma_r \sim c/\omega_{pe}$ , initially non-resonant



Initial (transverse) wakefields  
  
 Periodic focusing/defocusing (1)

SPS  $p^+$  bunch, long  $\sigma_z \sim 5\text{cm}$  and narrow  $\sigma_r \sim 200\mu\text{m}$   
 Plasma electron density:  $n_{e0}$ ,  $\omega_{pe} = (n_{e0}e^2/\epsilon_0 m_e)^{1/2}$ ,  $\tau_{pe} = 2\pi/\omega_{pe}$   
 Wakefields: period and transverse size  $\sim c/\omega_{pe} \sim n_{e0}^{-1/2}$   
 Choose:  $n_{e0}$  such that  $c/\omega_{pe} \sim \sigma_r$   
 $\sigma_z \gg c/\omega_{pe} \leftrightarrow$  Self-modulation (SM) regime  
 $n_{e0} = 7 \times 10^{14} \text{cm}^{-3} \leftrightarrow E_{acc} \sim n_{e0}^{1/2} \sim \text{GV/m}$

Pukhov, PRL107 145003 (2011)

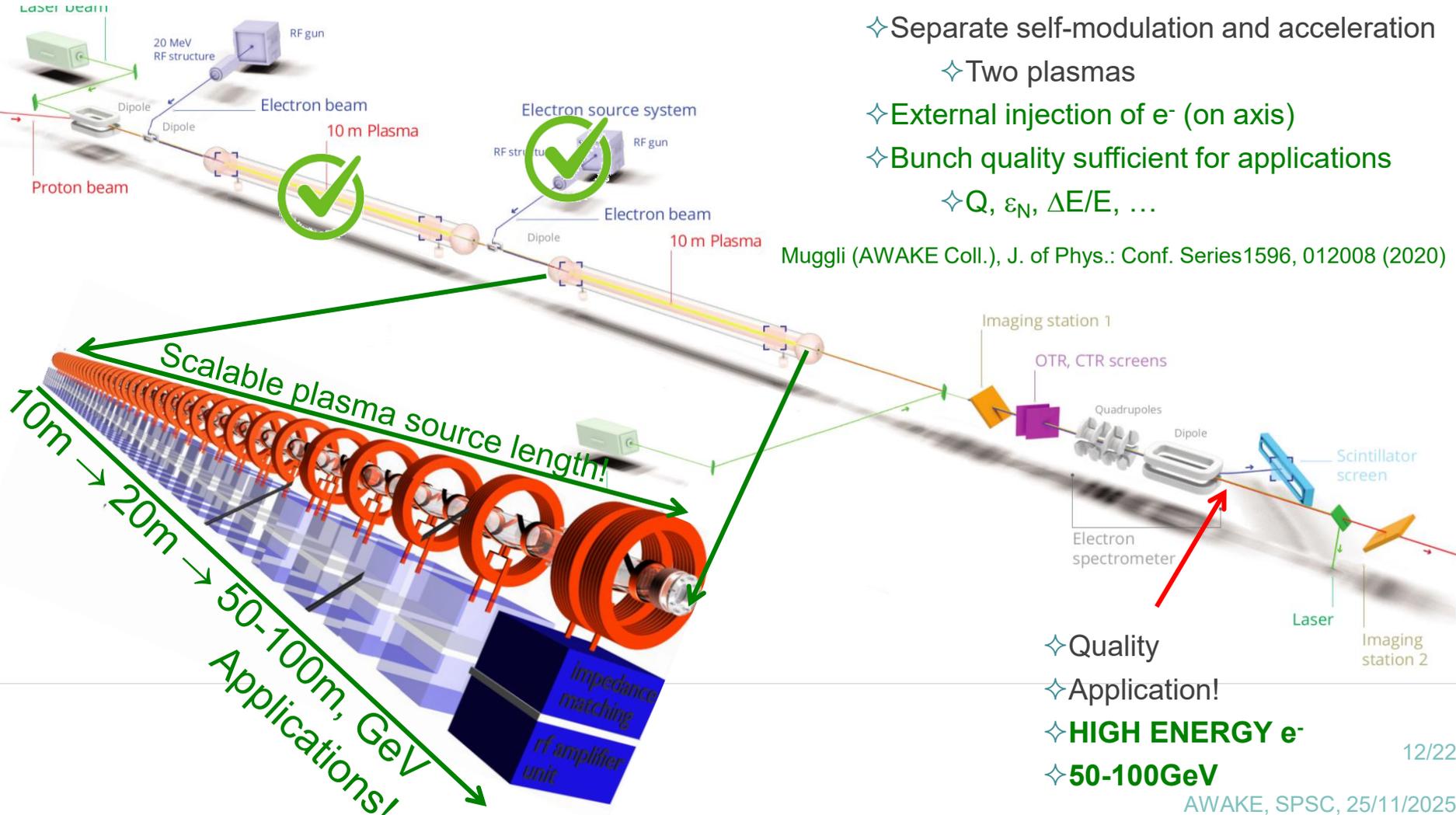


✧  $E_z$ -field along the plasma

N. Kumar, Phys. Rev. Lett. 104, 255003 (2010)

Relativistic particles do not (appreciably) dephase!  
 SM  $\leftrightarrow$  transverse effect!

# RUN 2c,d: ACCELERATE e<sup>-</sup> BUNCH, QUALITY



- ✧ Separate self-modulation and acceleration
- ✧ Two plasmas
- ✧ External injection of e<sup>-</sup> (on axis)
- ✧ Bunch quality sufficient for applications
  - ✧  $Q$ ,  $\epsilon_N$ ,  $\Delta E/E$ , ...

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series 1596, 012008 (2020)

- ✧ Quality
- ✧ Application!
- ✧ **HIGH ENERGY e<sup>-</sup>**
- ✧ **50-100GeV**