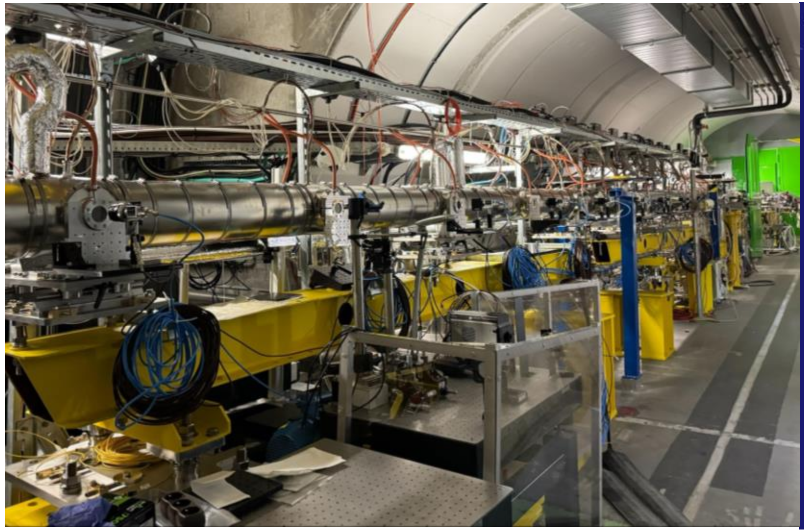
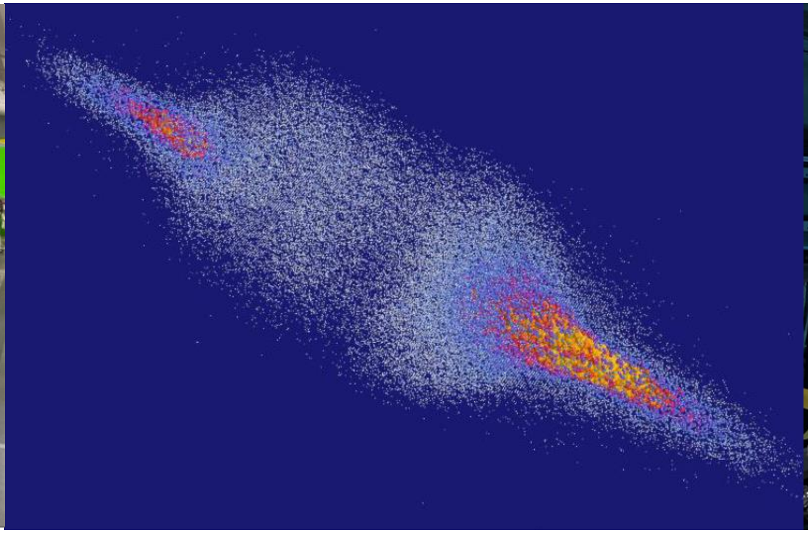




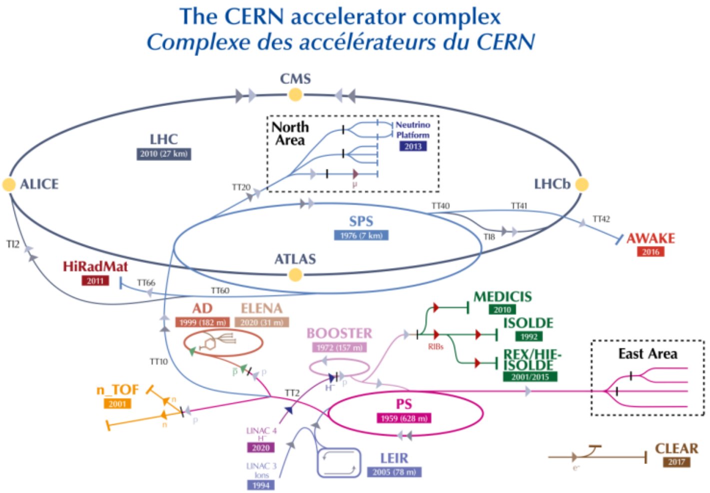
AWAKE: proton driven plasma wakefield acceleration for particle physics applications

M. Turner for the AWAKE Collaboration

The AWAKE experiment at CERN

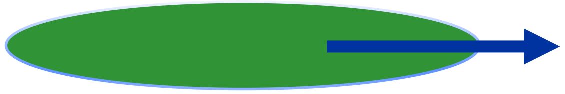
proton drivers

p+ bunches from the CERN SPS are delivered to the AWAKE facility



to excite wakefields in a (currently) 10 m long plasma

high energy drivers



driver parameters:

- **~20 kJ** → very high energy per bunch
- **400 GeV/c** high energy per particle
- enabling hundreds of GeV energy gain in single plasma (~TeV with LHC driver)

- low beam density **n_b~10^{12} cm^{-3}**
- very long (**σ_z~5 cm; ~100 λ_{pe}**)
- waist size σ_r~0.17 mm < c/ω_{pe}

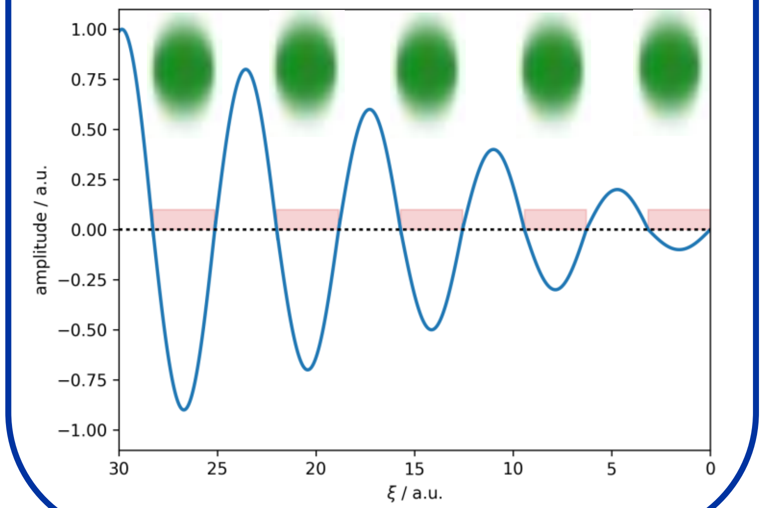
plasma parameters:

- plasma density: **n_{pe}1-10^{14} cm^{-3}**
- plasma wavelength **λ_{pe} ~3 – 1 mm**

resonant excitation

- to be able to excite ~GV/m fields → **self-modulation** (requires ~4-6m of plasma)

- multiple bunches → resonantly drive wakefield → large amplitude

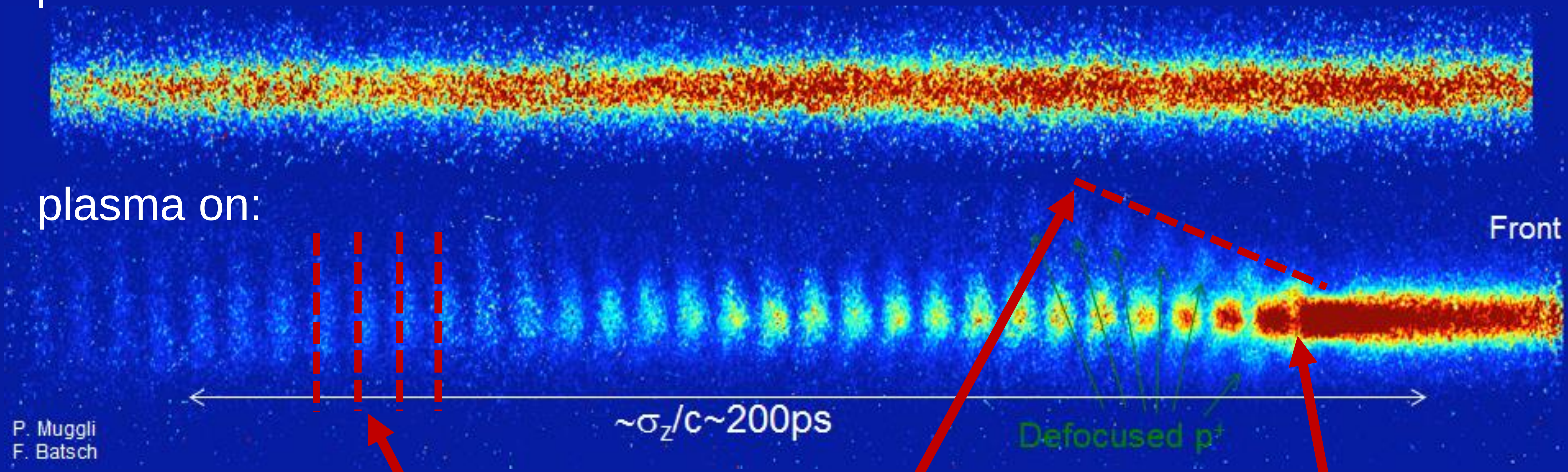


Self-modulation demonstrated

AWAKE, PRL 122, 054802 (2019)
M. Turner, (AWAKE coll.), PRL 122, 054801 (2019)
F. Braunmueller, (AWAKE coll.), PRL 125, 264801 (2020)
F. Batsch (AWAKE coll.), PRL 126 (2021)

plasma off:

plasma on:



frequency
$f=f_{pe}$

growth
$W_r > W_{r,seed}$

seed
→timing/phase reproducible

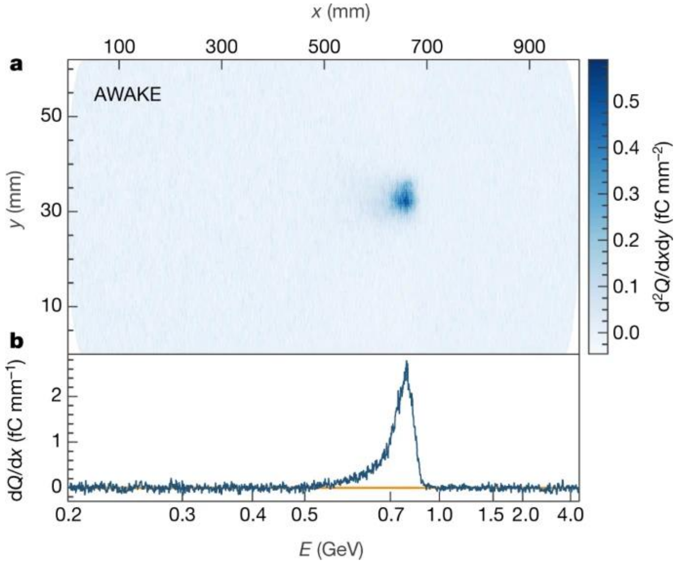
Proof-of-principle acceleration

external injection

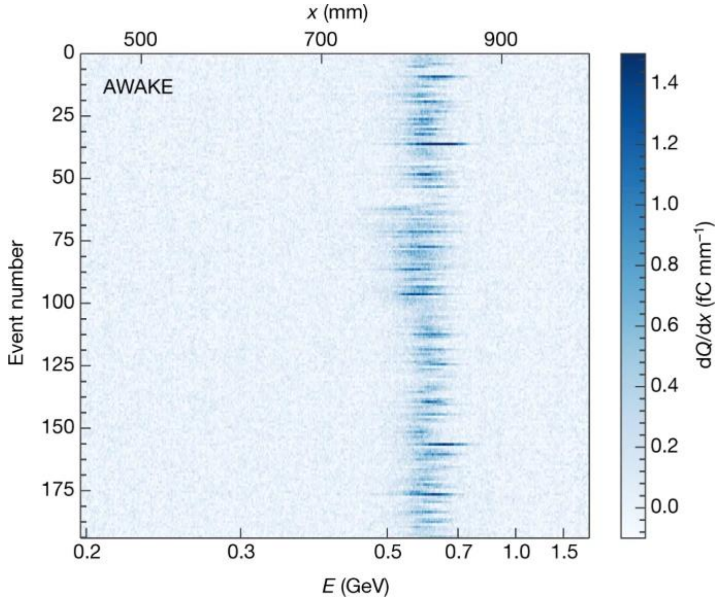
AWAKE Collaboration, Nature 2018

electrons accelerated

- finite energy spread

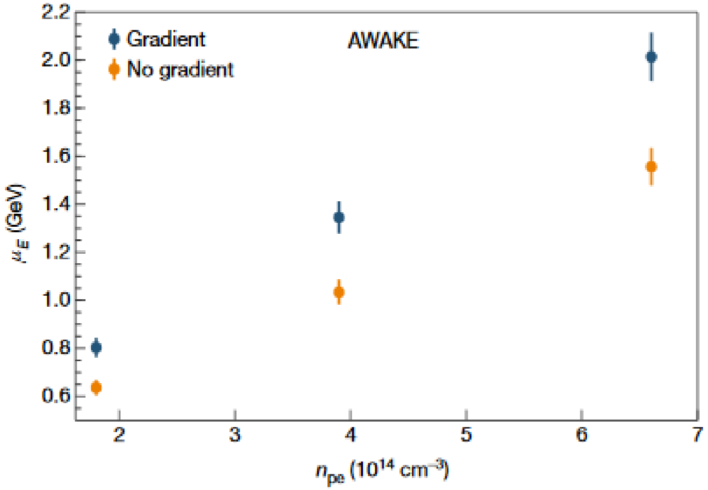


acceleration repeatable



plasma density scaling

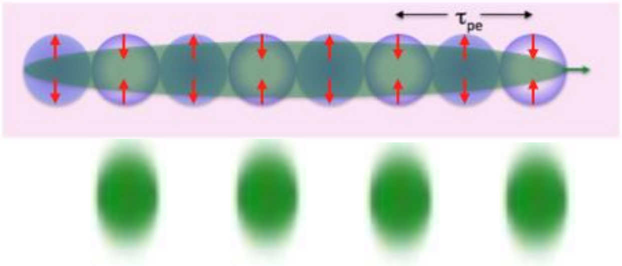
- increasing with increasing n_{pe}
- +20% higher energy with gradient



Challenge: controlling SM

to the level, where it can be used in an accelerator

- **transverse** wakefields dominate the SM process ($p_{p+,r}$~400 MeV)
  - $\Delta\gamma << \gamma$, → $\Delta L = (1/\gamma^2)(\Delta\gamma/\gamma) L < \lambda_{pe}$ → negligible longitudinal evolution of $p_{p+,z}$~400 GeV bunch



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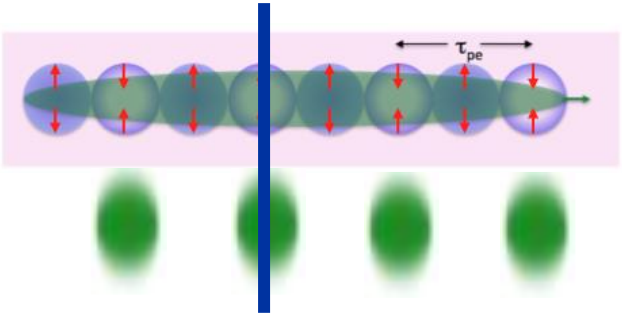

- **self-evolving:** SM instability → convective process
  - v_{ph} of the wakefields is evolving→ driver slices experiences different fields at different times

Challenge: controlling SM

to the level, where it can be used in an accelerator

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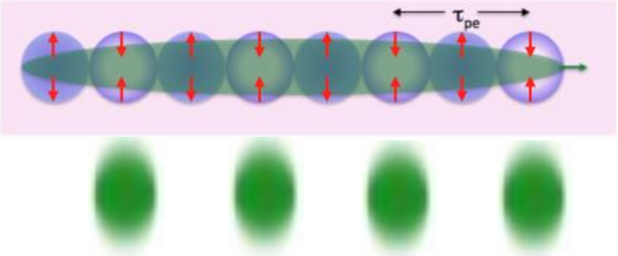

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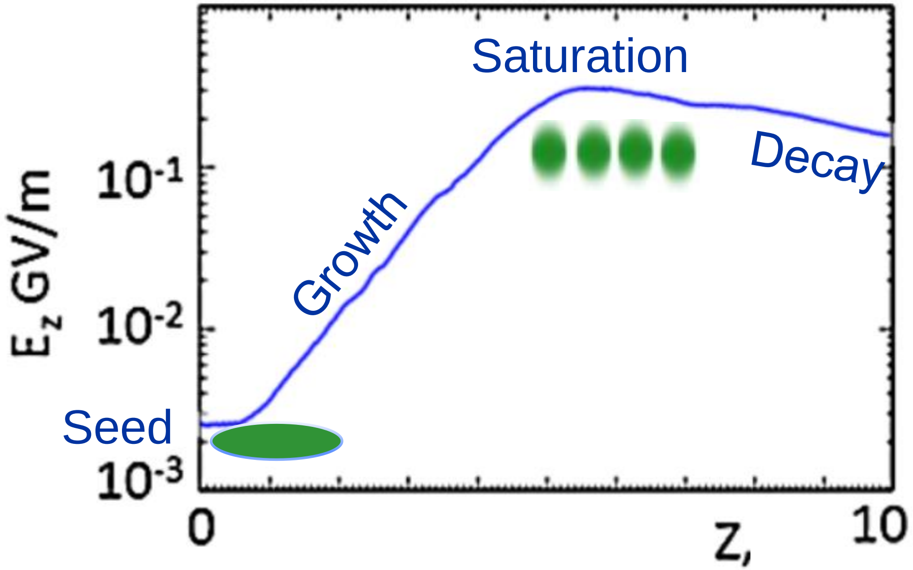
Pukhov, PRL 107 145003 (2011)



- **wakefield amplitude** → defined by driver
  - driver evolves → amplitude evolves

→ understand, control, tune the process

Outline

- **Latest AWAKE physics results**
  - discharge plasma source
    - wakefield growth, ion motion, filamentation instability
  - rubidium vapor source
    - amplitude stability, self-modulation instability suppression

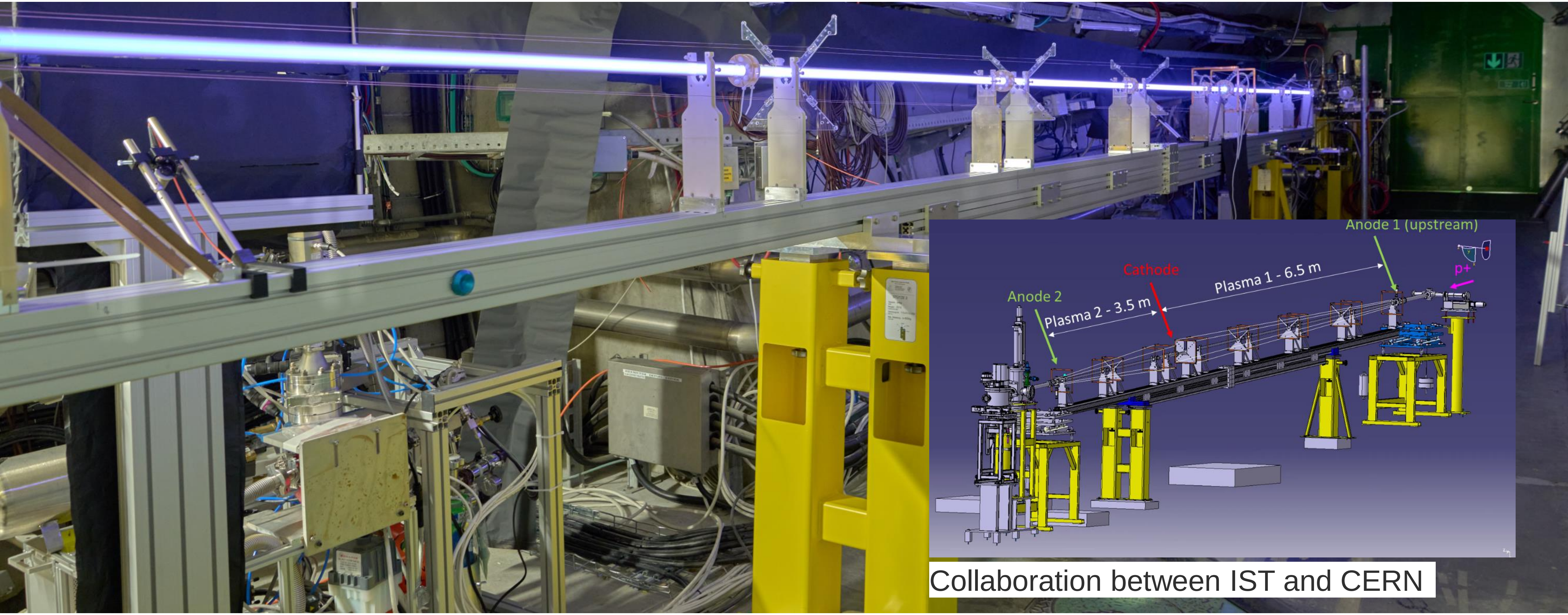
- **AWAKE's progress toward particle physics applications**
  - rubidium vapor source with plasma density step
  - approved AWAKE Run 2c/d programs

- **Summary and conclusions**

Discharge plasma source

talk + poster by
C. Amoedo, WG3

- **scalable** (50-200m) plasma source technology



Collaboration between IST and CERN

Plasma light shows wakefield growth

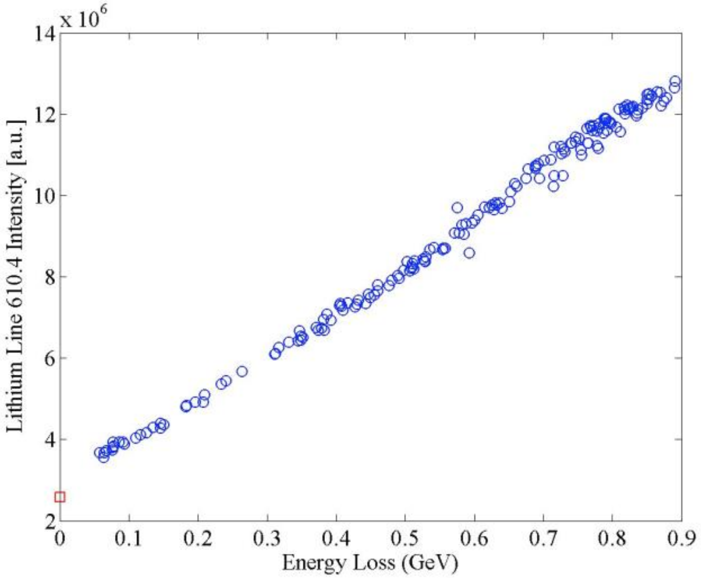
Poster by
J. Mezger

all captured light

plasma light
(from discharge)

wakefield light

expectation: wakefield light ↔ energy deposited



E. Oz, AIP Conf. Proc. 737, 708 (2004)

Plasma light shows wakefield growth

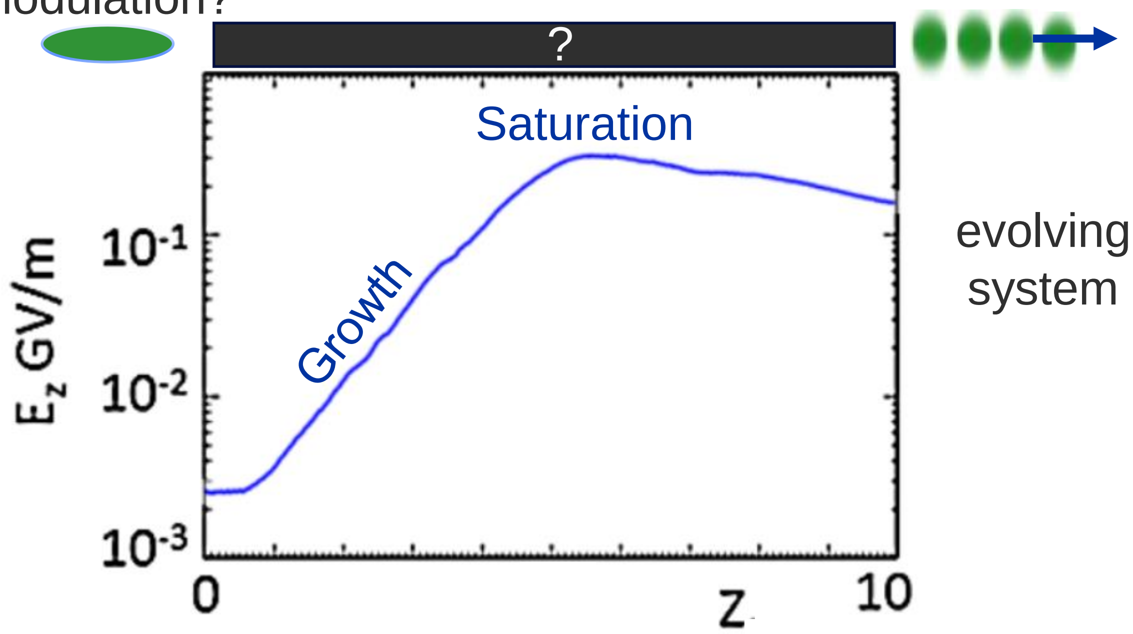
Poster by
J. Mezger

all captured light

plasma light
(from discharge)

wakefield light

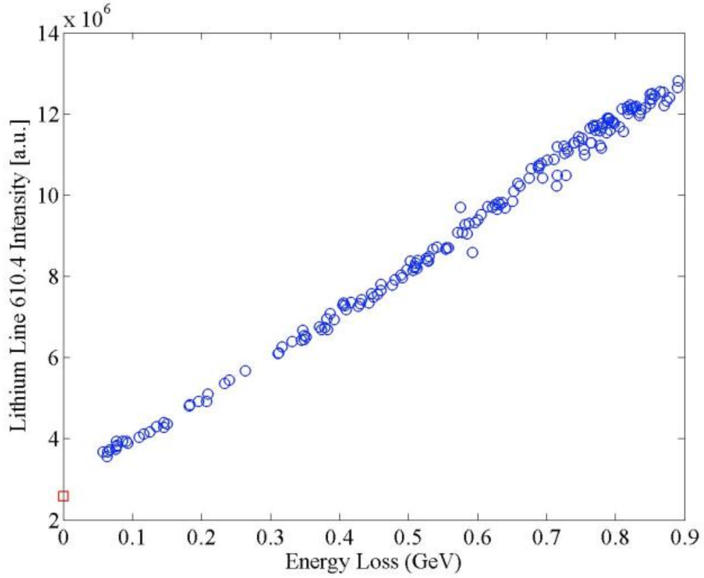
idea: wakefield light → show development of self-modulation?



evolving system

Pukhov, PRL 107 145003 (2011)

expectation: wakefield light ↔ energy deposited



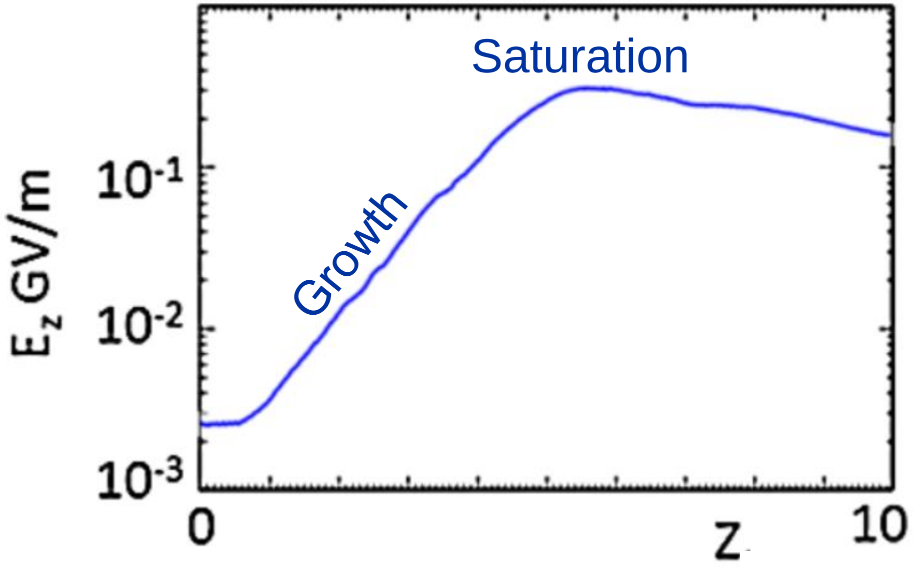
demonstrated in non-evolving system

E. Oz, AIP Conf. Proc. 737, 708 (2004)

Plasma light shows wakefield growth

Poster by
J. Mezger

- observed growth
- increases with n_{pe}



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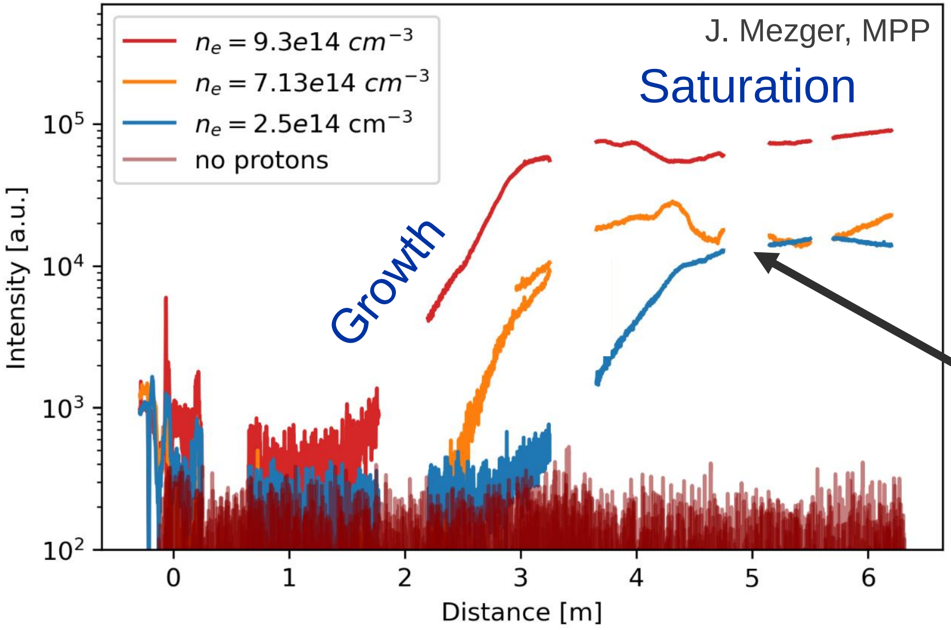
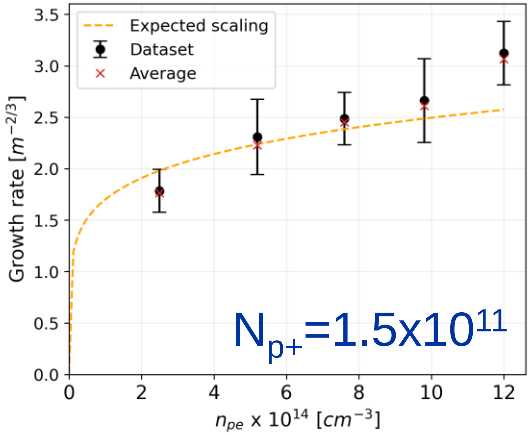


Gaps are
due to
holders

Plasma light shows wakefield growth

Poster by
J. Mezger

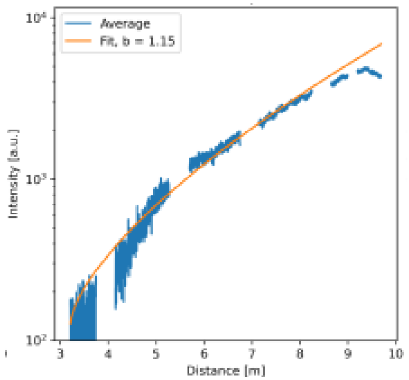
- Γ consistent with $n_{pe}^{1/6}$ scaling



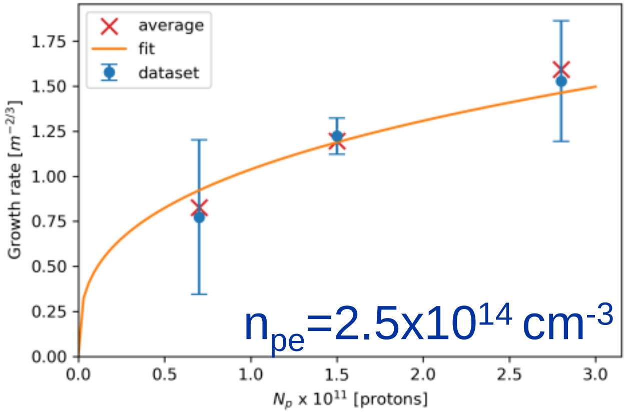
preliminary

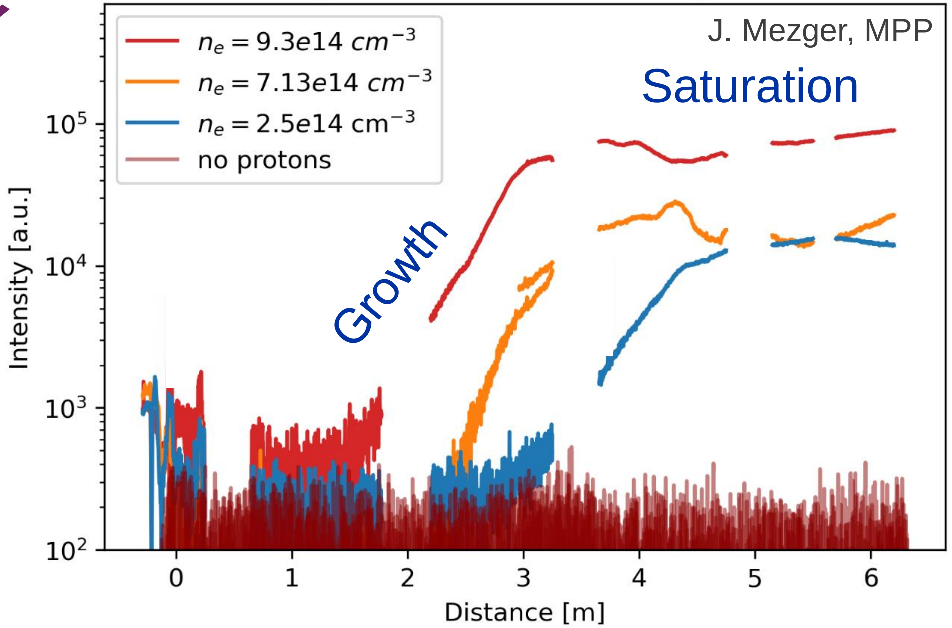
- fit growth rate Γ

$$\Gamma = \frac{3\sqrt{3}}{4}\omega_{pe}\left(\frac{n_{b0}m_e}{2n_{pe}m_p\gamma}\frac{\xi}{ct}\right)^{1/3}$$



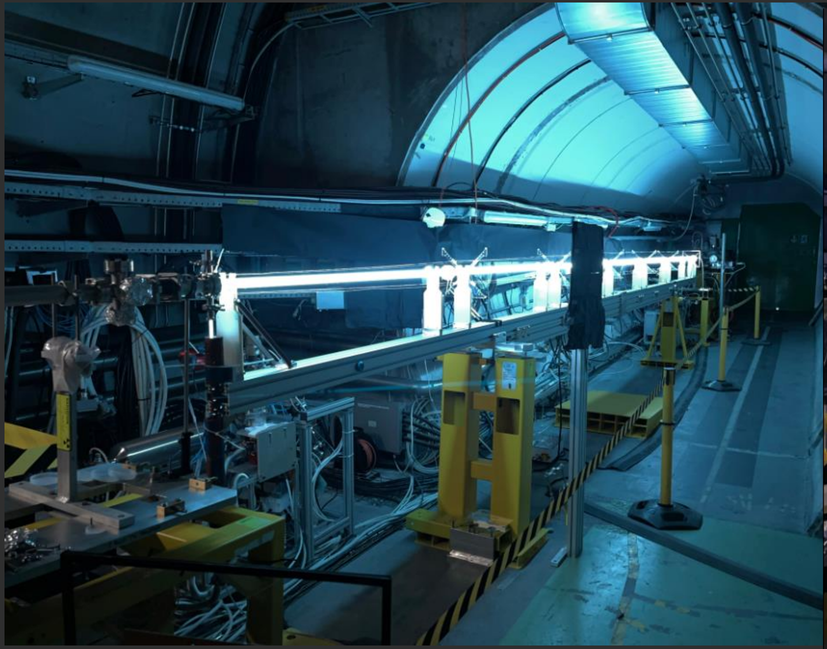
- Γ consistent with $n_{b0}^{1/3}$ scaling





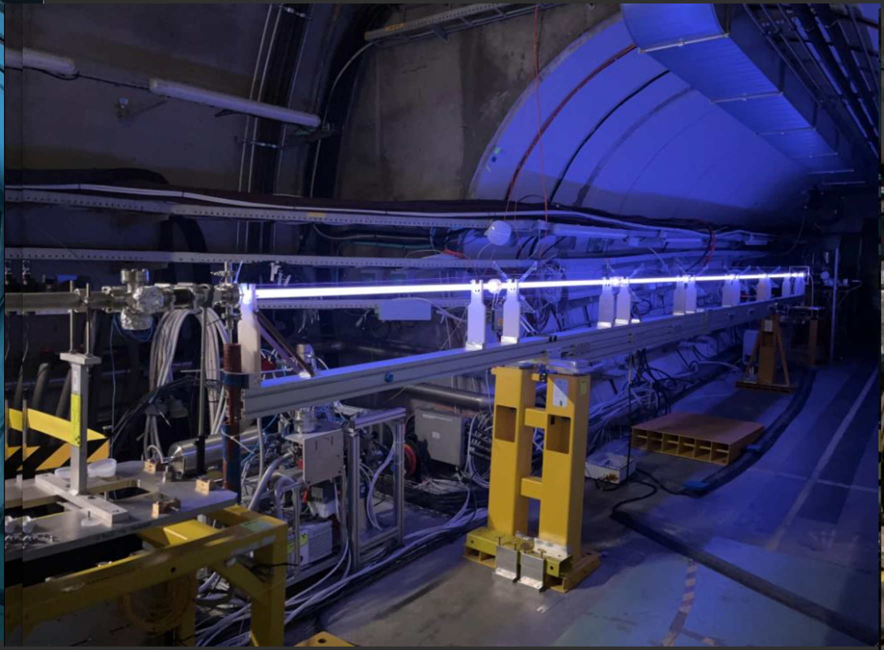
→ First time one sees SM evolution along the plasma xenon

A=131



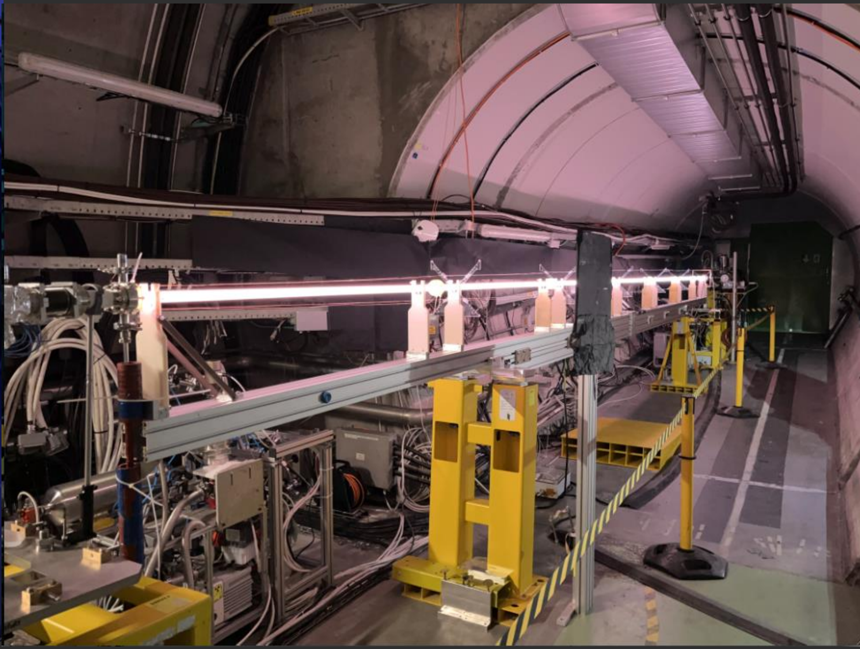
argon

A = 40



helium

A = 4



Motion of plasma ions

- broad interest:
    - uniform ion column → linear focusing force

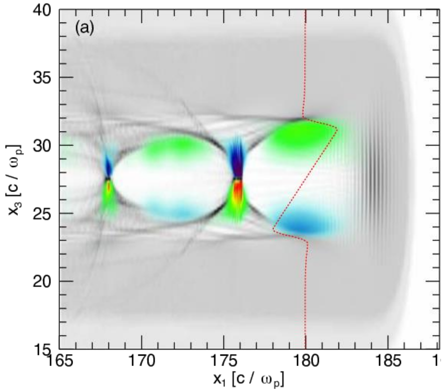


Image from Vieira, J. *et al* - arXiv:1607.03514

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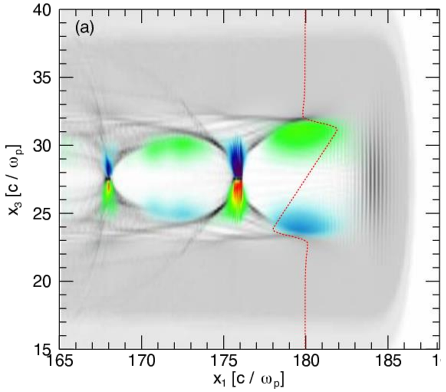


Image from Vieira, J. *et al* - arXiv:1607.03514

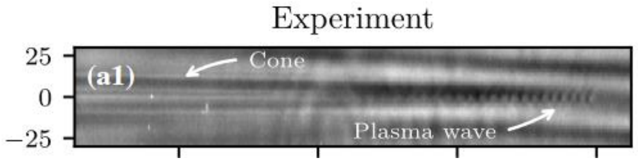
- motion of ions:
  - nonlinear focusing force
  - emittance growth

J. B. Rosenzweig et al., PRL 2005
Weiming An, et al., PRL 2017

- suggested to detune hosing resonance

T. J. Mehrling, et al, PRL 2018

Motion of plasma ions



M. F. Gilljohann, et al., Phys. Rev. X 9, 011046

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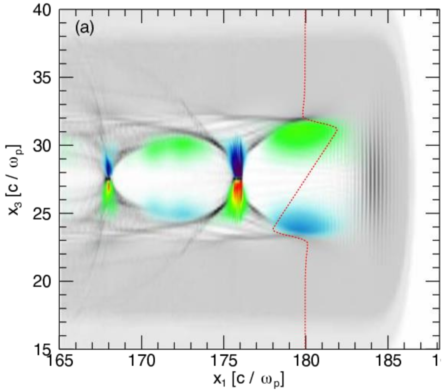

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J. B. Rosenzweig et al., PRL 2005
Weiming An, et al., PRL 2017

  - suggested to detune hosing resonance

T. J. Mehrling, et al, PRL 2018

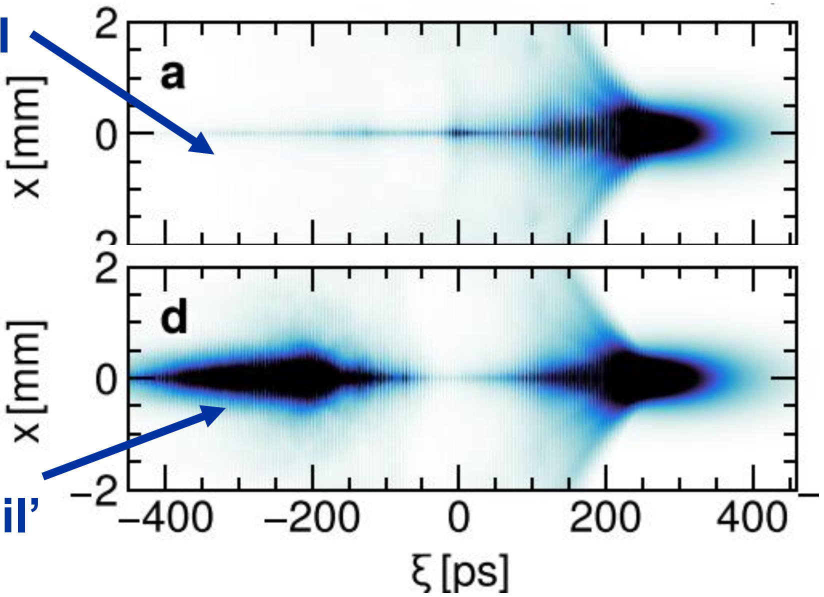
- motion of ions caused by:
  - fields of the driver
  - fields of the witness
  - **ponderomotive force of the wakefields**

$$\boldsymbol{F}_p \cong -\frac{e^2}{4m_e\omega_{pe}^2}\nabla\tilde{W}_r^{\,2}$$

- long bunch and SM (simulations)
  - formation of bunch tail

J. Vieira,et al., PRL. 2012
J. Vieira, et al., PoP, 2014
L. M. Gorbunov, et al., PoP, 2003

no tail



‘bunch tail’

immobile ions

mobile (‘light’) ions

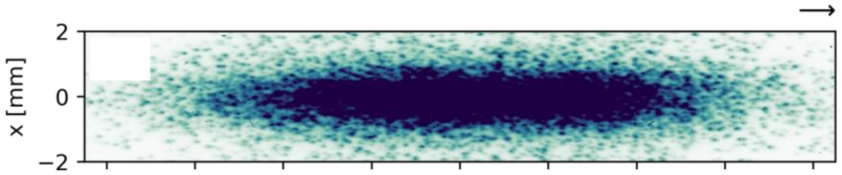
Motion of plasma ions

M. Turner, (AWAKE Collaboration), submitted

experiment

simulations

vacuum



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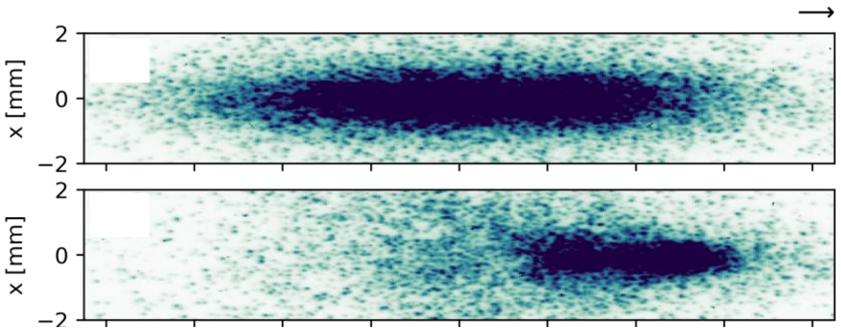
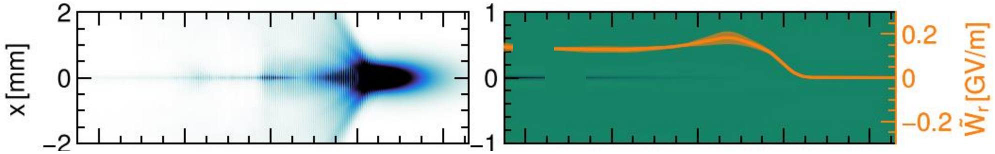
vacuum

xenon
A=131



simulations

n_{pe} = 4.8 x 10^{14} cm^{-3}, N_{p+} = 3x10^{11}



Motion of plasma ions

M. Turner, (AWAKE Collaboration), submitted

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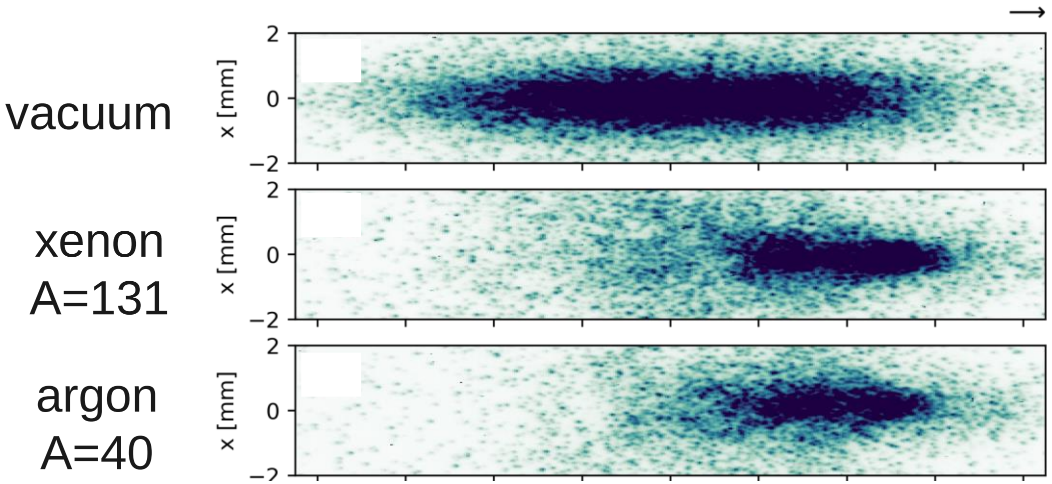

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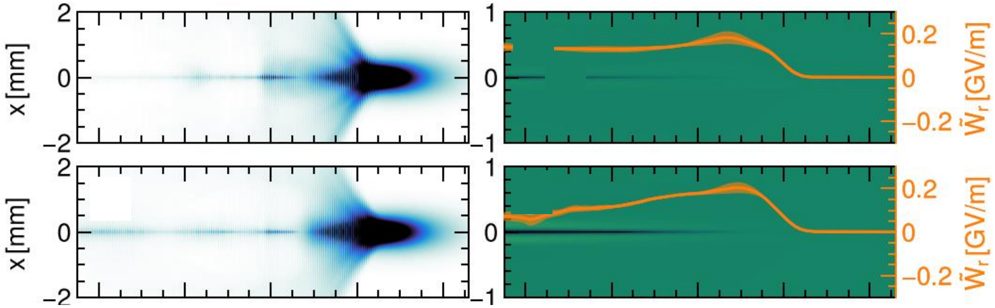


Motion of plasma ions

M. Turner, (AWAKE Collaboration), submitted

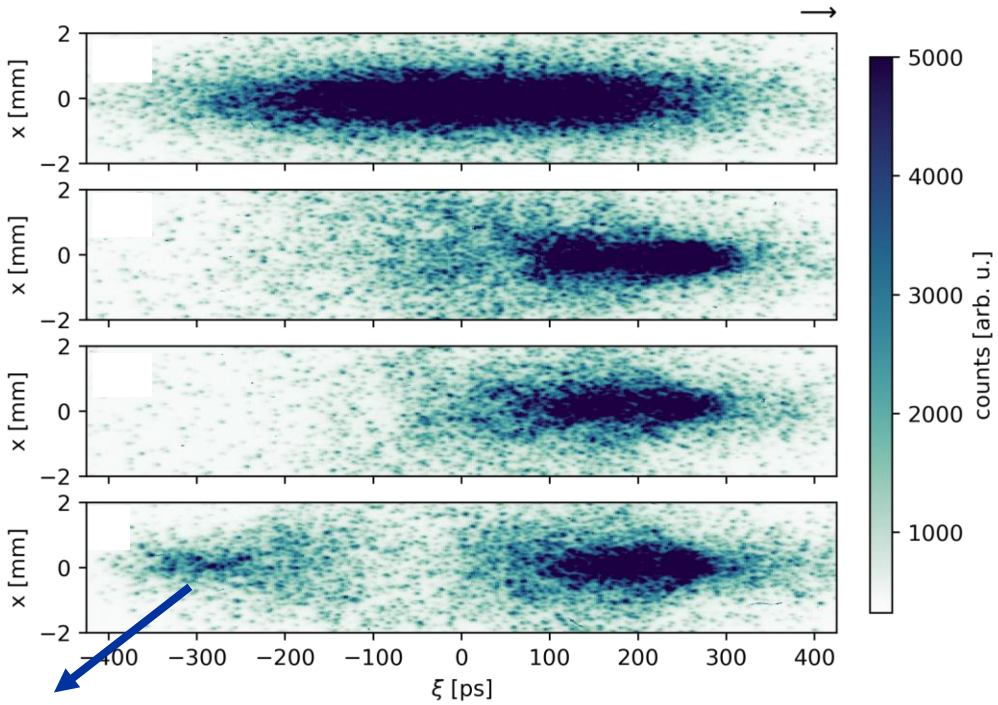
experiment

vacuum

xenon
A=131

argon
A=40

helium
A=4



‘bunch tail’

simulations

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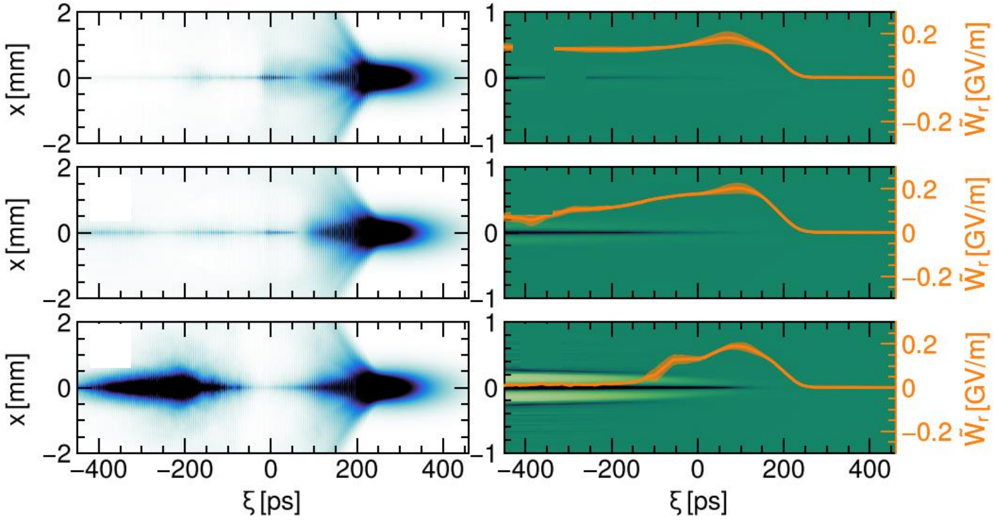
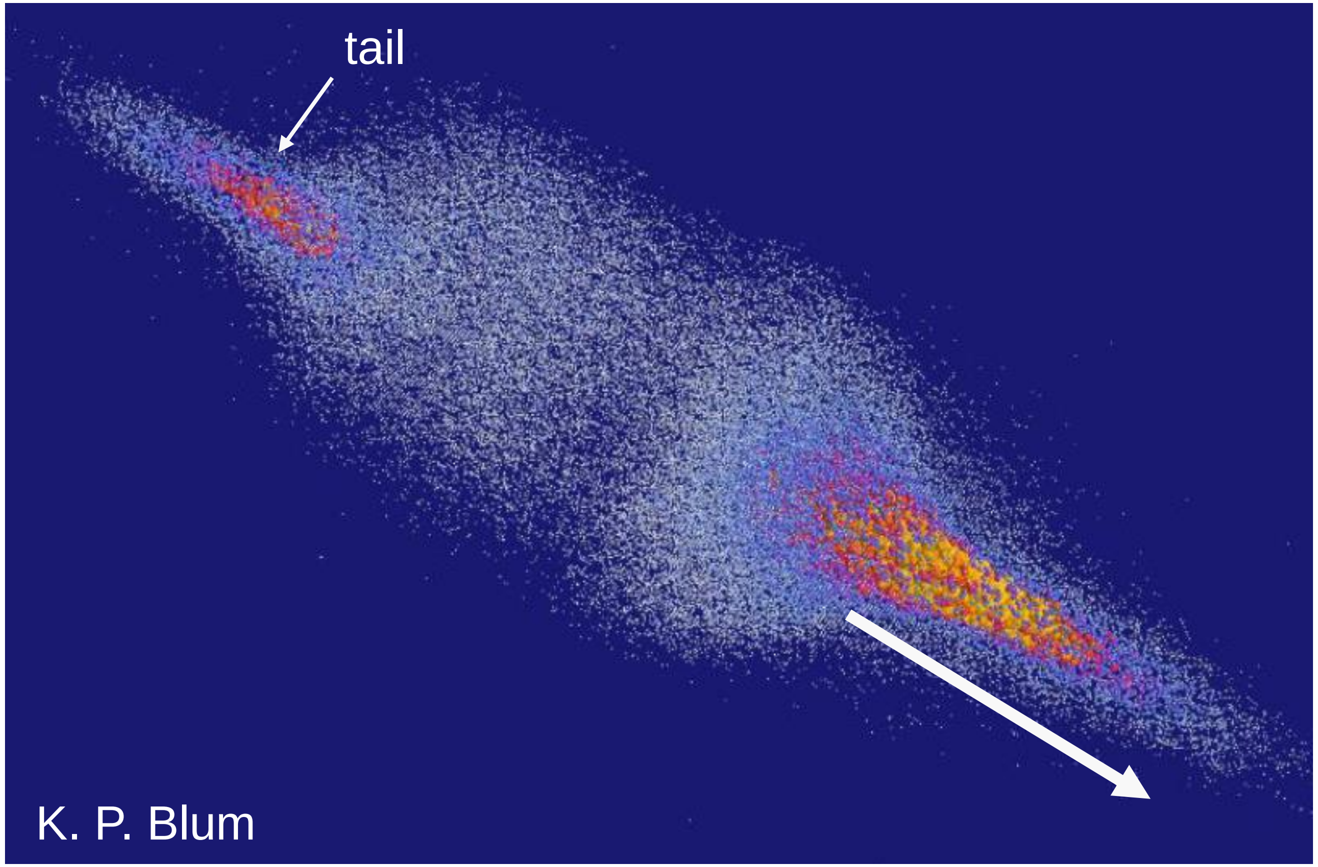


Motion of plasma ions

M. Turner, (AWAKE Collaboration), submitted



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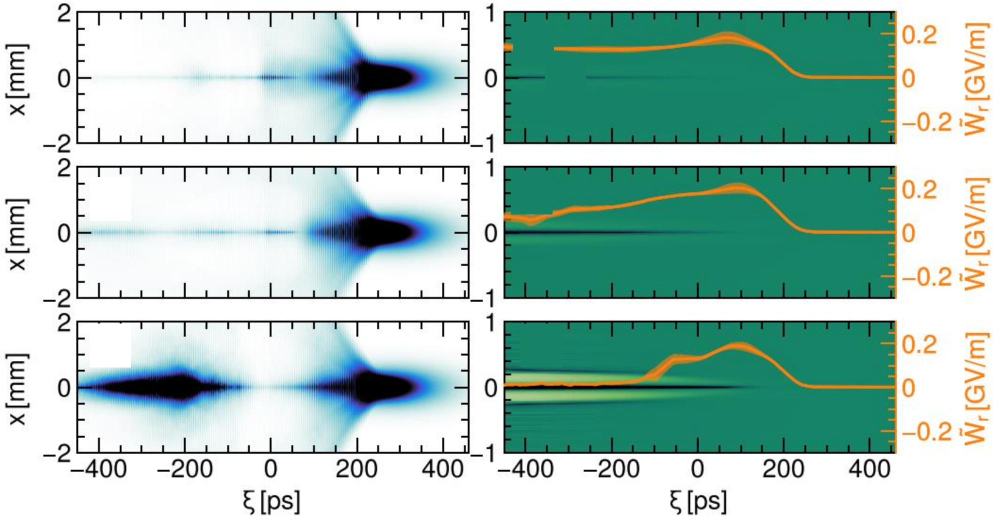
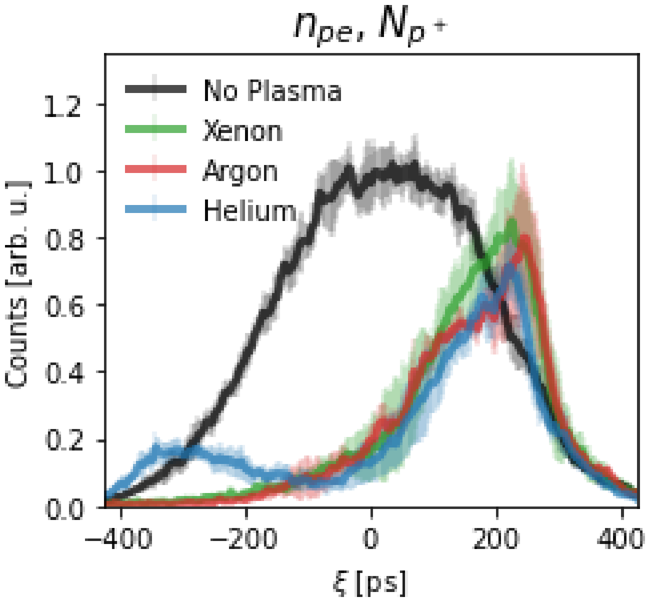


- bunch tail observed, reproducible → effect of motion of ions on the bunch
  - at this wakefield amplitude (n_{pe} and N_{p+}) only with helium
- confirms expected inverse mass dependency

Scaling with wakefield amplitude

M. Turner, (AWAKE Collaboration), submitted

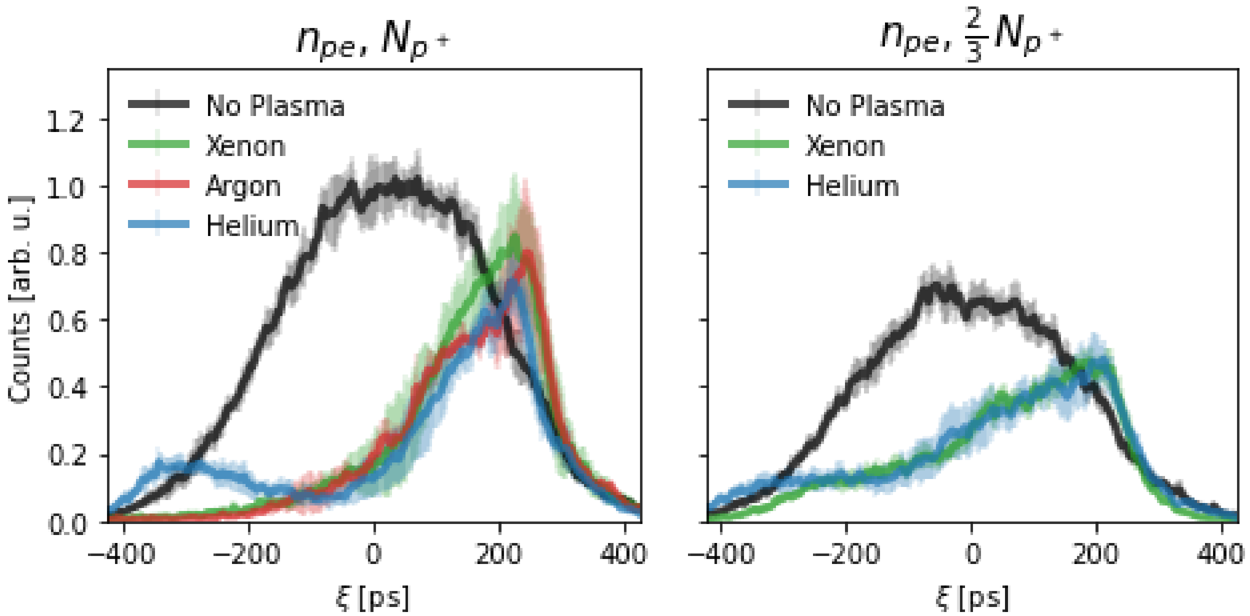


Peak field ~600 MV/m

$$\lambda_{pe} = 152 \mu m$$

Scaling with wakefield amplitude

M. Turner, (AWAKE Collaboration), submitted



Peak field ~600 MV/m

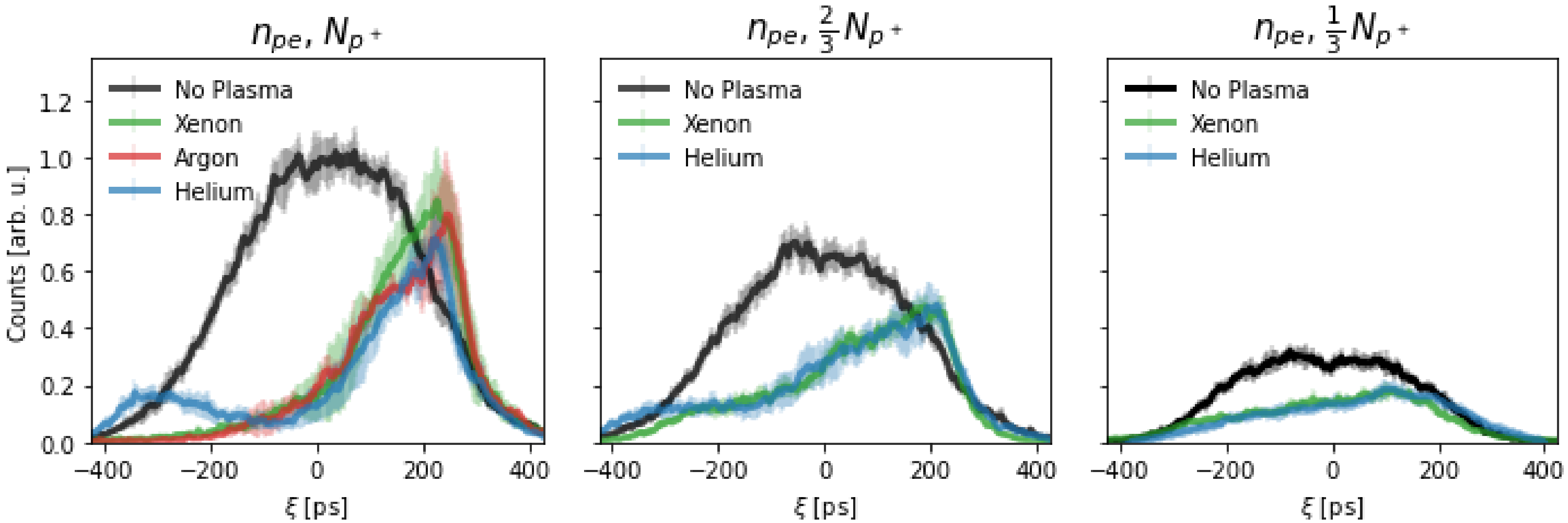
$\lambda_{pe} = 152\mu m$

Peak field ~390 MV/m

$\lambda_{pe} = 152\mu m$

Scaling with wakefield amplitude

M. Turner, (AWAKE Collaboration), submitted



Peak field ~600 MV/m

$\lambda_{pe} = 152\mu m$

Peak field ~390 MV/m

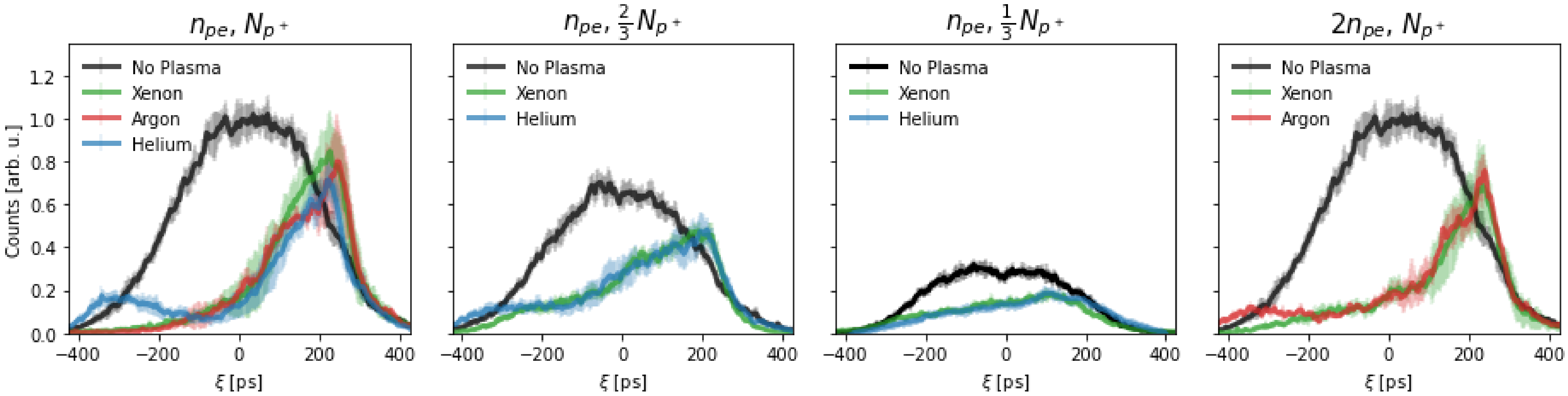
$\lambda_{pe} = 152\mu m$

Peak field ~260 MV/m

$\lambda_{pe} = 152\mu m$

Scaling with wakefield amplitude

M. Turner, (AWAKE Collaboration), submitted



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Peak field ~390 MV/m

$\lambda_{pe} = 152\mu m$

Peak field ~260 MV/m

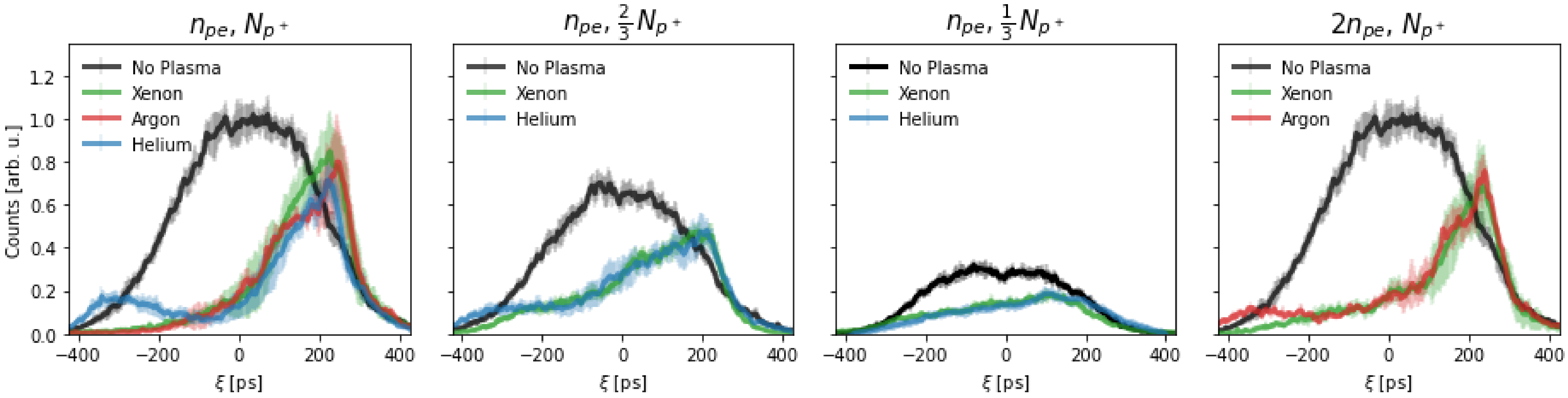
$\lambda_{pe} = 152\mu m$

Peak field ~930 MV/m

$\lambda_{pe} = 109\mu m$

Scaling with wakefield amplitude

M. Turner, (AWAKE Collaboration), submitted



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$\lambda_{pe} = 152\mu m$

Peak field ~260 MV/m

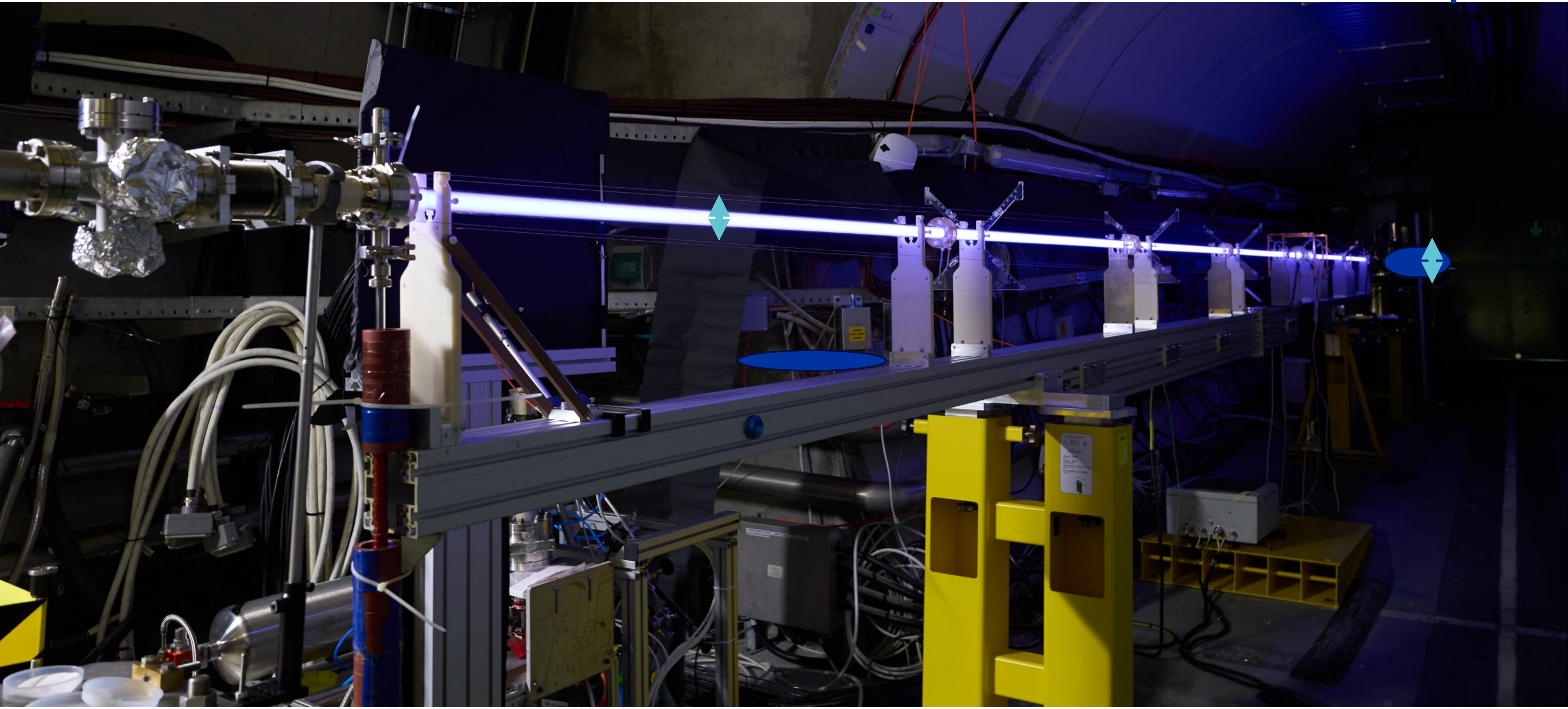
$\lambda_{pe} = 152\mu m$

Peak field ~930 MV/m

$\lambda_{pe} = 109\mu m$

- effect also scales with wakefield amplitude (n_{pe} and N_{p+}) $\boldsymbol{F}_p \cong -\frac{e^2}{4m_e\omega_{pe}^2}\boldsymbol{\nabla}\tilde{W_r}^2$
- important validation of the model/scalings that will be used to inform collider designs

Wide plasma (~cm) + wide proton bunch ($\sigma_{r0} >> c/\omega_{pe}$)



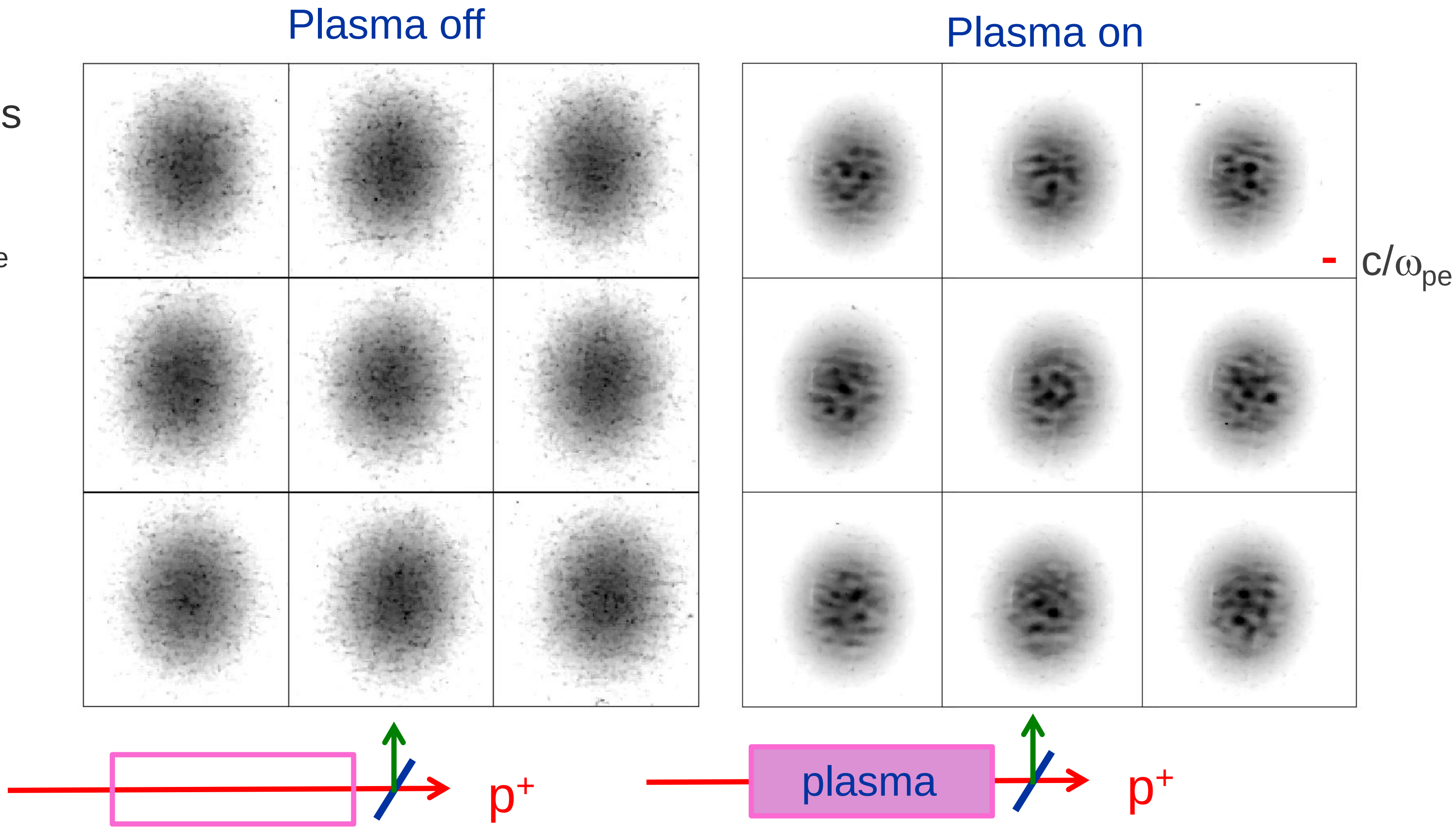
Filamentation instability

‘Astrophysics in the lab’

- $\sigma_{r0}<c/\omega_{pe}$: optimum for wakefield generation
  - ’one filament’
- $\sigma_{r0}>>c/\omega_{pe}$: filamentation instabilities can develop …
  - observed filaments at the c/ω_{pe} scale

Talk by L. Verra, WG3

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



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  - observed filaments at the c/ω_{pe} scale

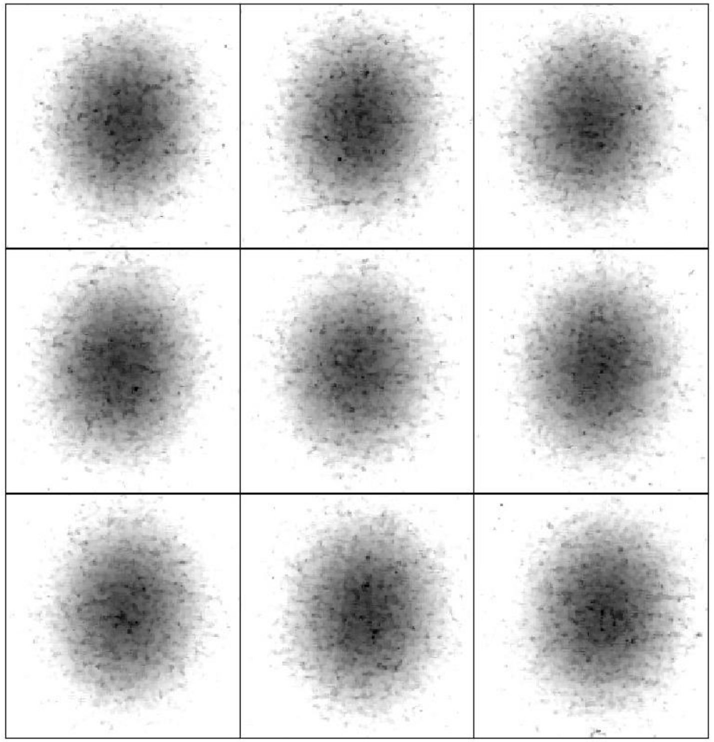
Talk by L. Verra, WG3

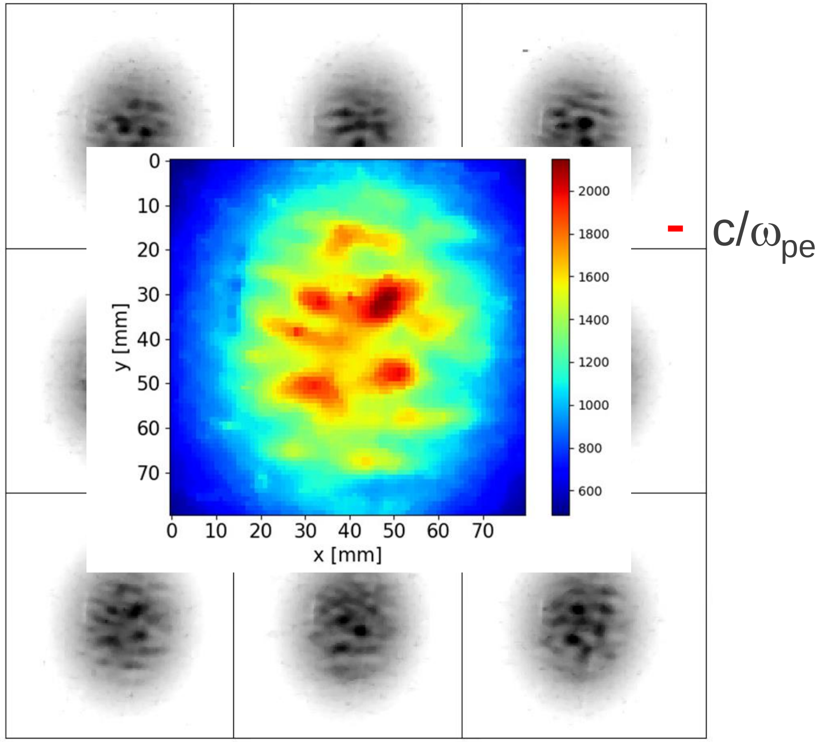
L. Verra et al.,(AWAKE Collaboration)
Phys. Rev. E 109, 055203

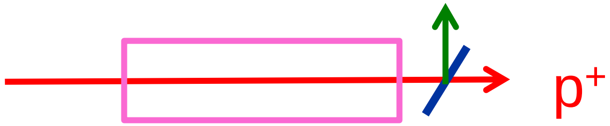
Plasma off

σ_{r0}~$3.2c/\omega_{pe}$

Plasma on

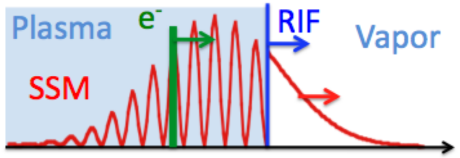


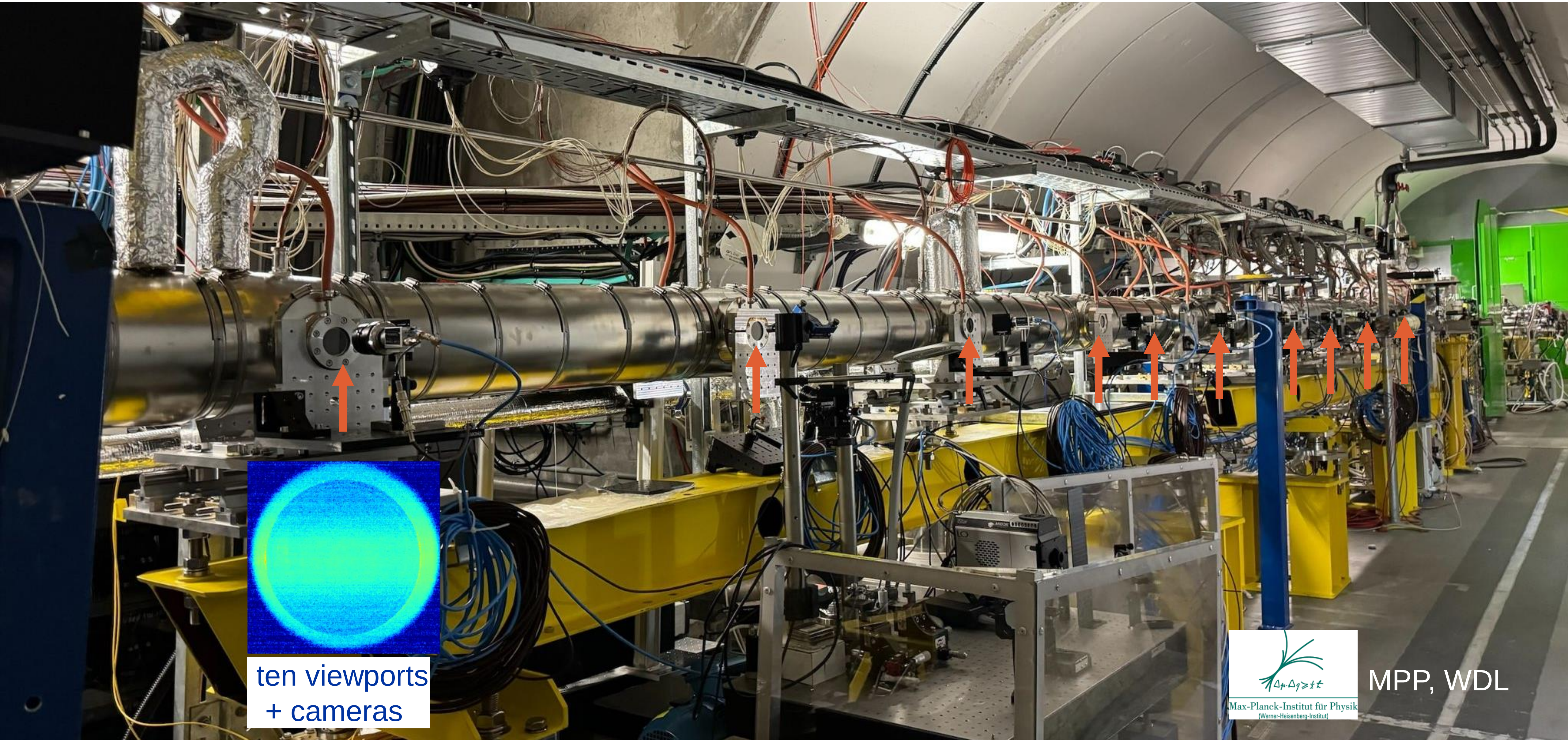




Rubidium vapor source

laser ionized → allows for relativistic ionization front (RIF) seeding




ten viewports
+ cameras

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

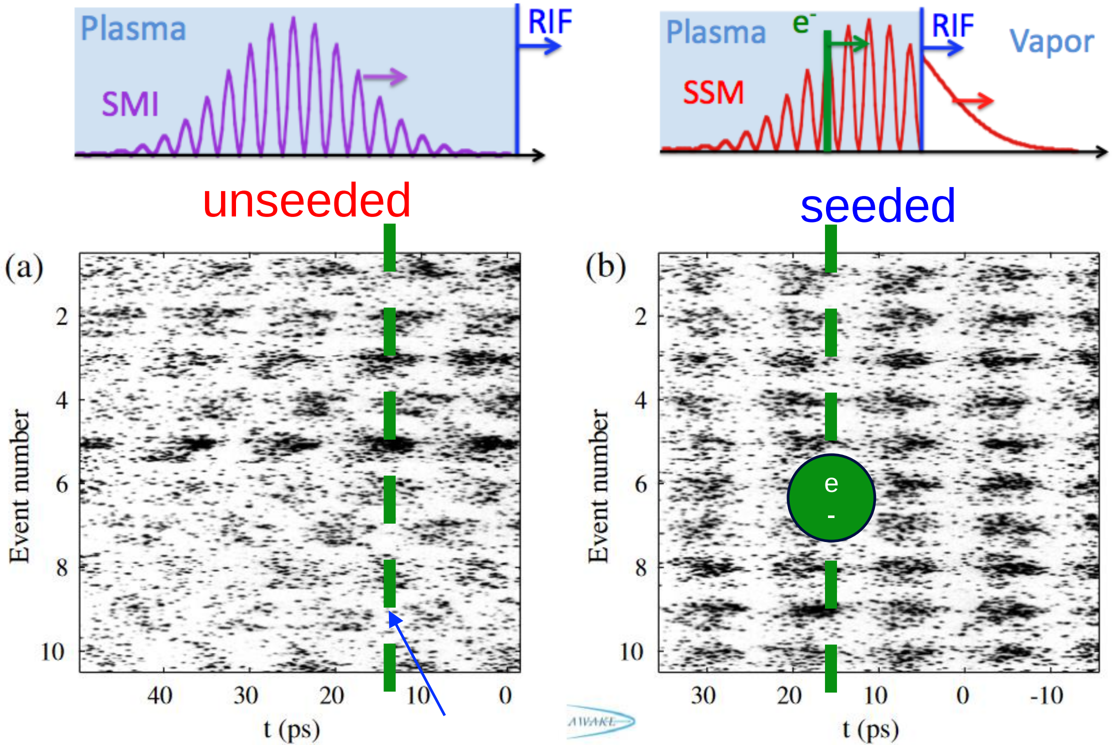
MPP, WDL

Wakefield amplitude reproducibility

Poster by
A. Clairembaud

To build a reproducible accelerator, the phase and amplitude of the wave must be reproducible

previously: seeding → phase stability



random timing/phase

stable timing/phase

F. Batsch et al., (AWAKE Coll.), Phys. Rev. Lett. 126, 164802 (2021)
L. Verra, et al., (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

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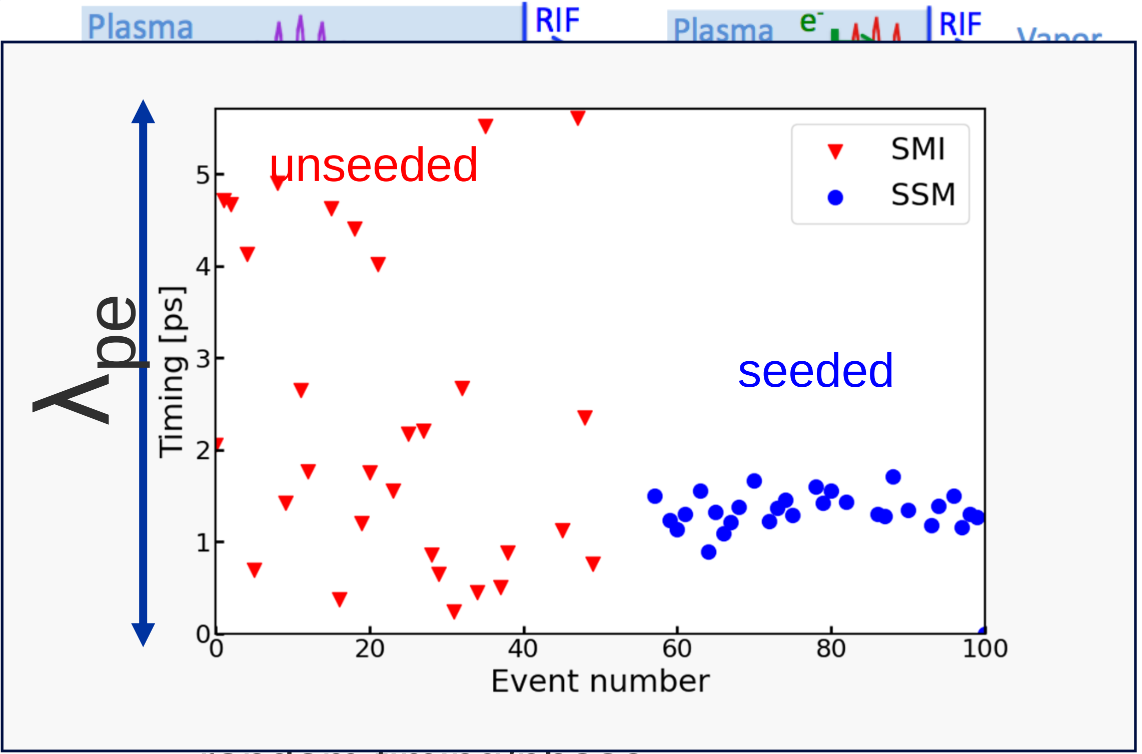

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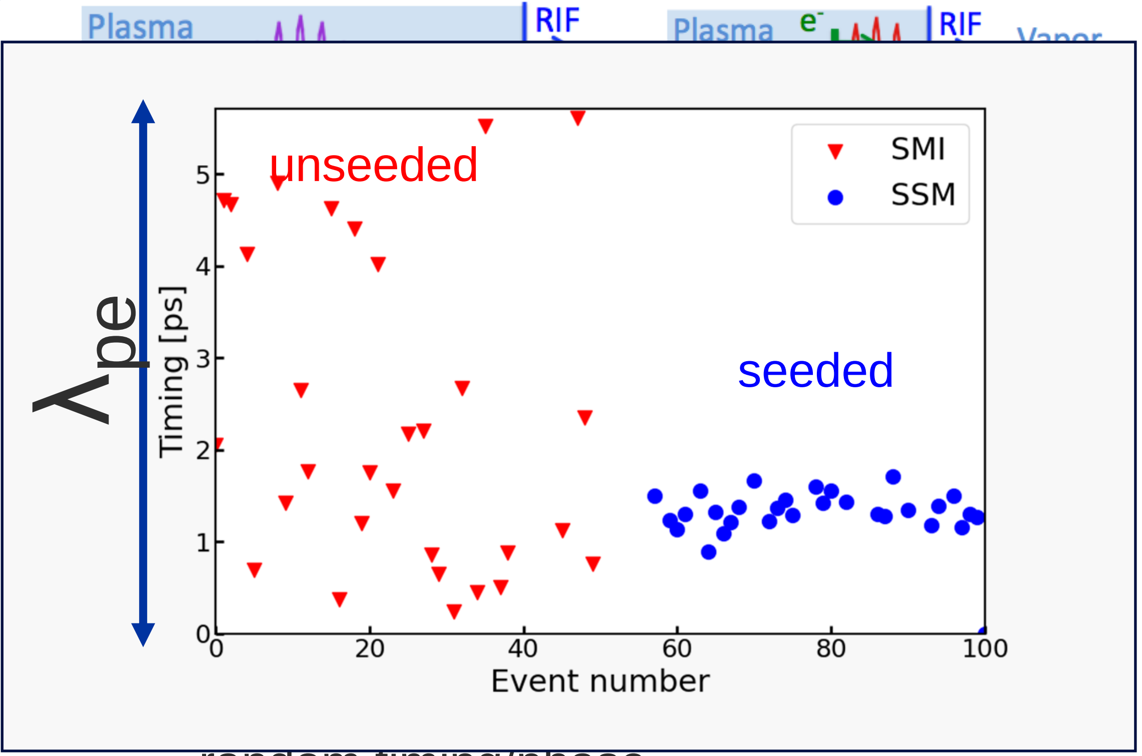
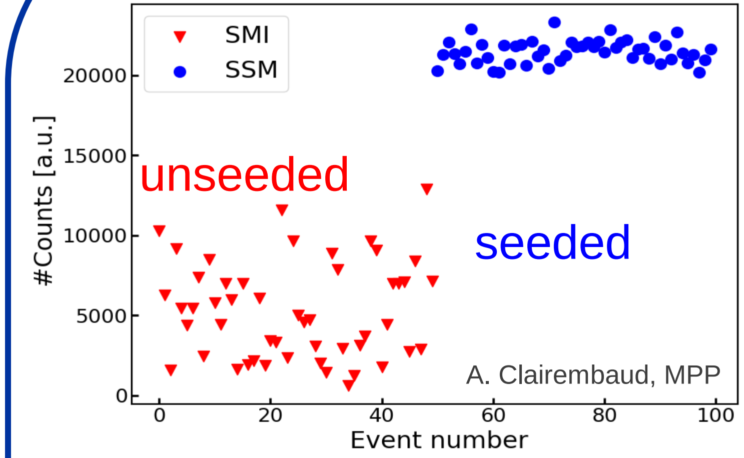


random timing/phase

stable timing/phase

F. Batsch et al., (AWAKE Coll.), Phys. Rev. Lett. 126, 164802 (2021)
L. Verra, et al., (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

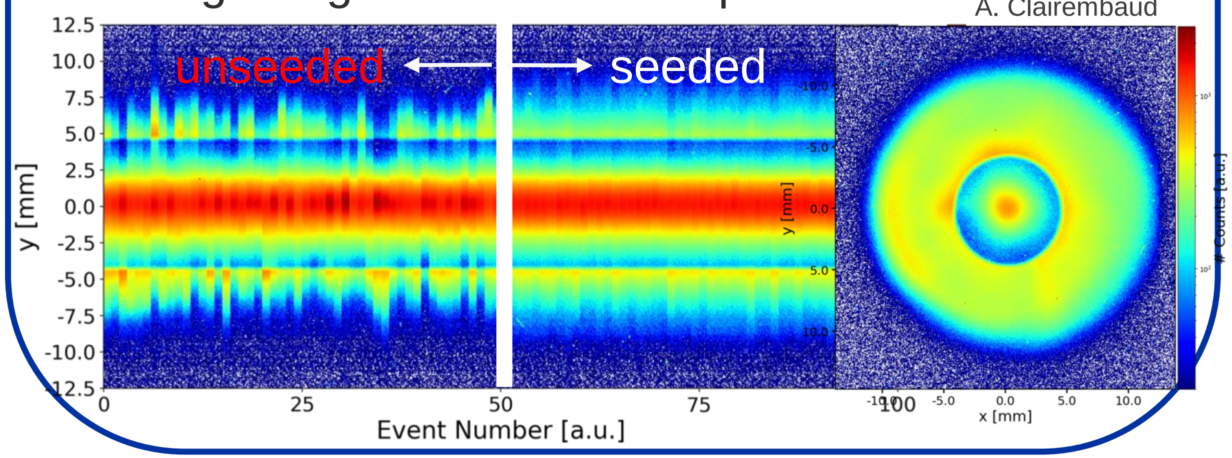
now: seeding → amplitude stability



- ➢ plasma light and halo more reproducible when SM seeded

preliminary

during SM growth defocused protons

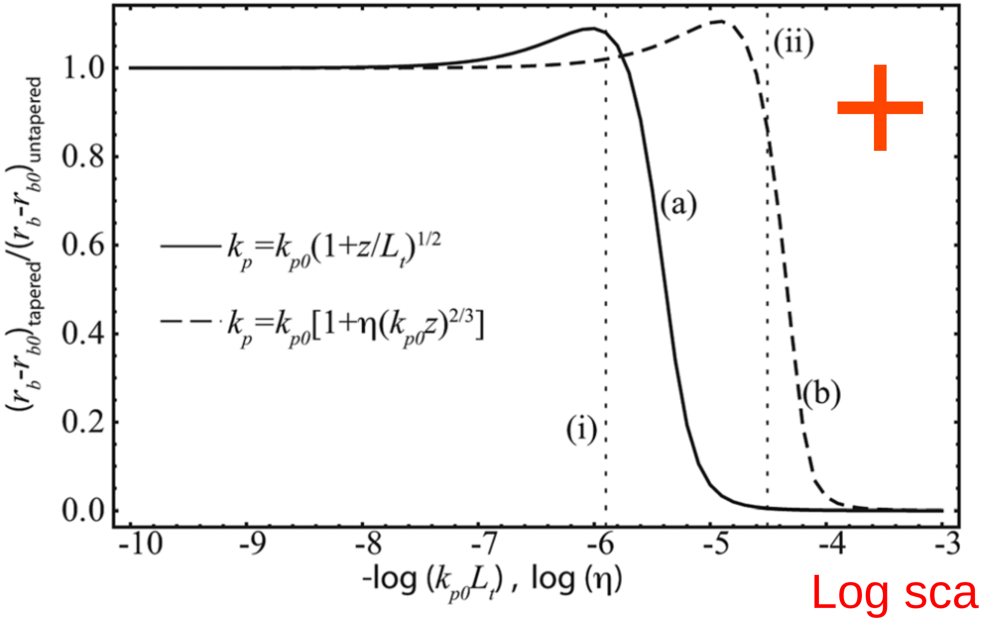


Self-modulation instability suppression

Poster by
J. Mezger

prediction from theory

C. B. Schroeder, et al., *Phys. Plasmas* 19, 010703 (2012)

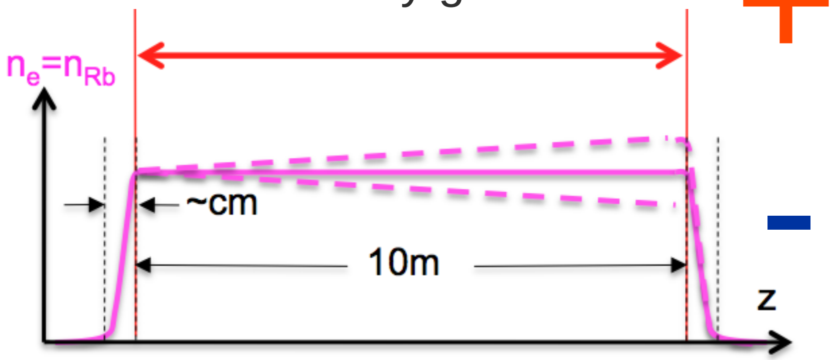


+

Log scale

- ➢ vapor source allows for linear density gradients

+



-

- ➢ relative radial modulation of the bunch vs. linear density gradient (log scale)
- ➢ SM suppression at large gradient, because resonance is detuned ⟷ feedback loop affected

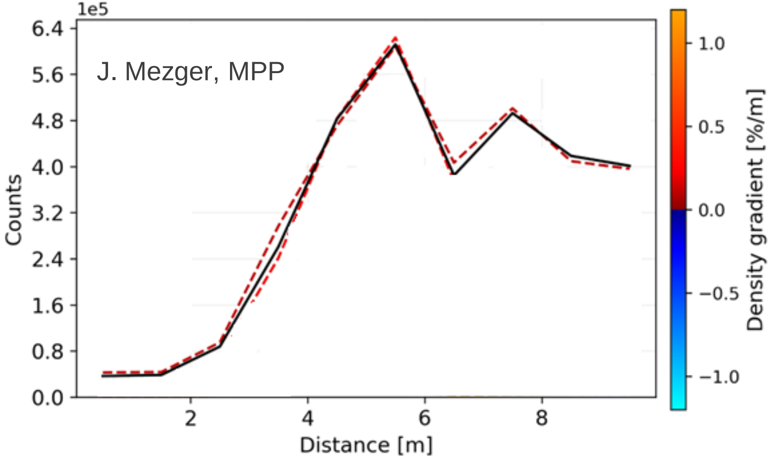
Self-modulation instability suppression

Poster by
J. Mezger

prediction from theory: positive gradients **suppress** the development of the SM

C. B. Schroeder, et al.,
Phys. Plasmas 19, 010703 (2012)

wakefield light along the plasma



preliminary

Self-modulation instability suppression

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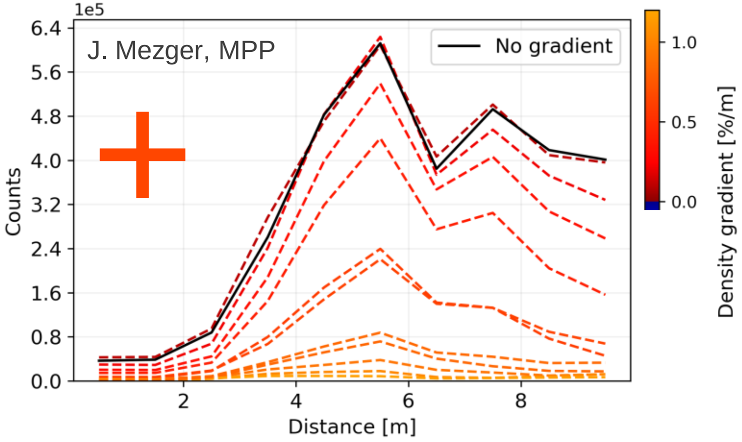
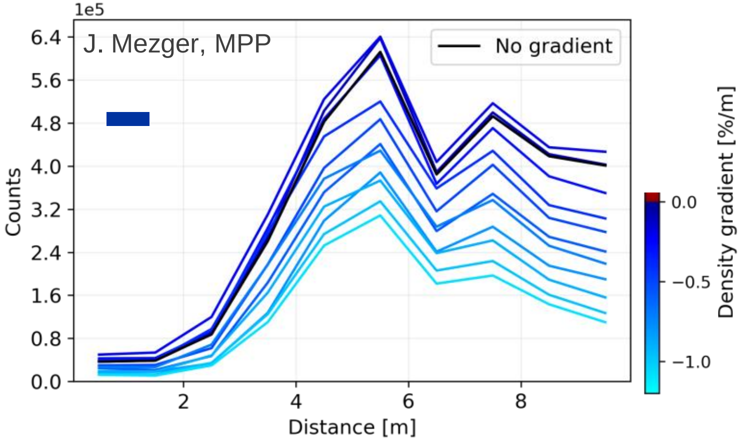
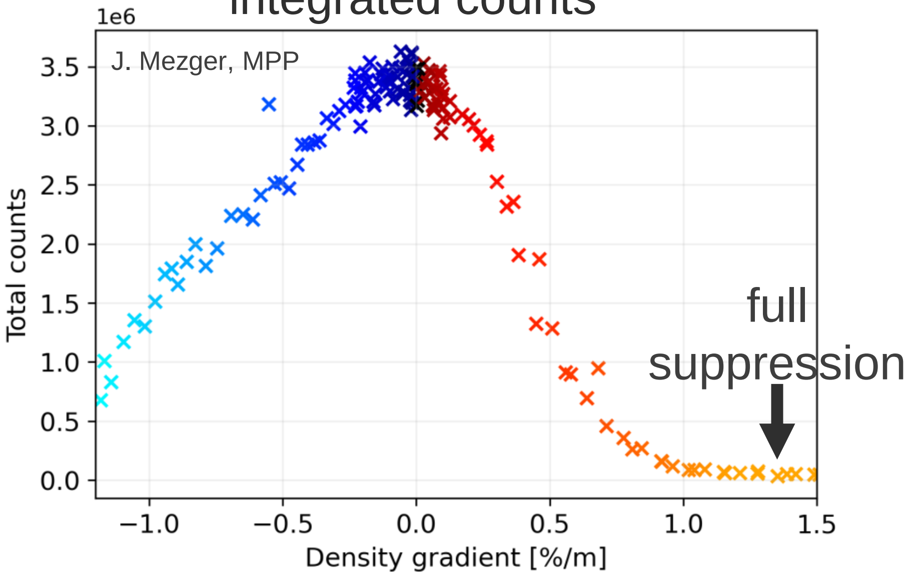




n_{pe} =2x10^{14} cm^{3,}
N_{p+}=0.5x10^{11} per bunch
RIF=+200 ps

preliminary

integrated counts



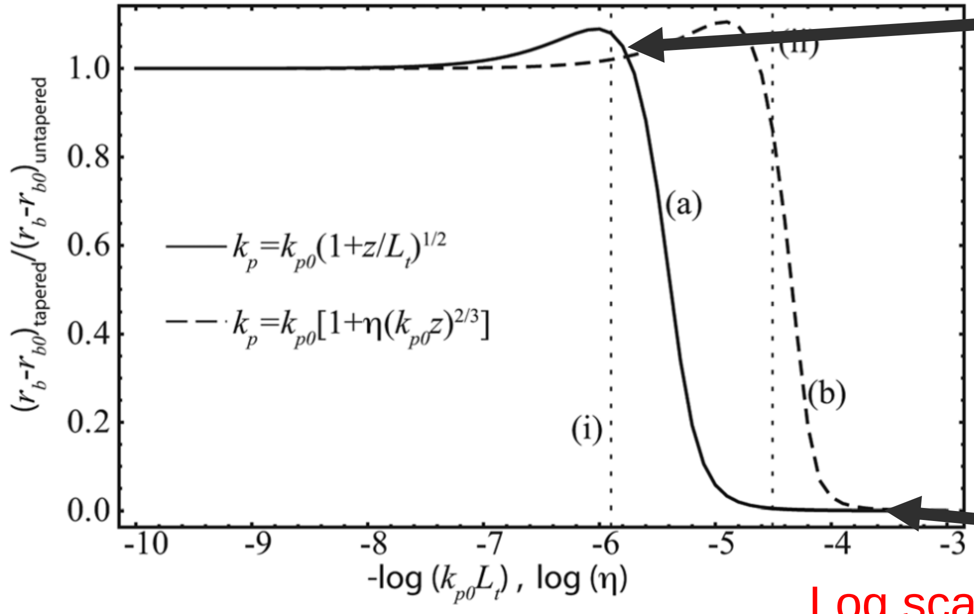
- ➢ less wakefield light for large positive and negative gradients

Self-modulation instability suppression

Poster by
J. Mezger

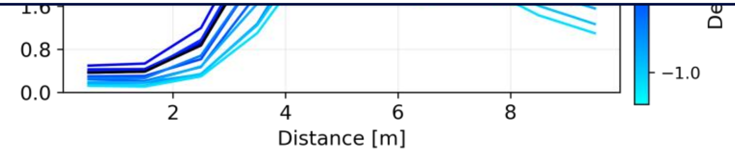
prediction from theory: positive gradients **suppress** the development of the SM

measurement of the plasma light



Log scale

C. B. Schroeder, et al., *Phys. Plasmas* 19, 010703 (2012)

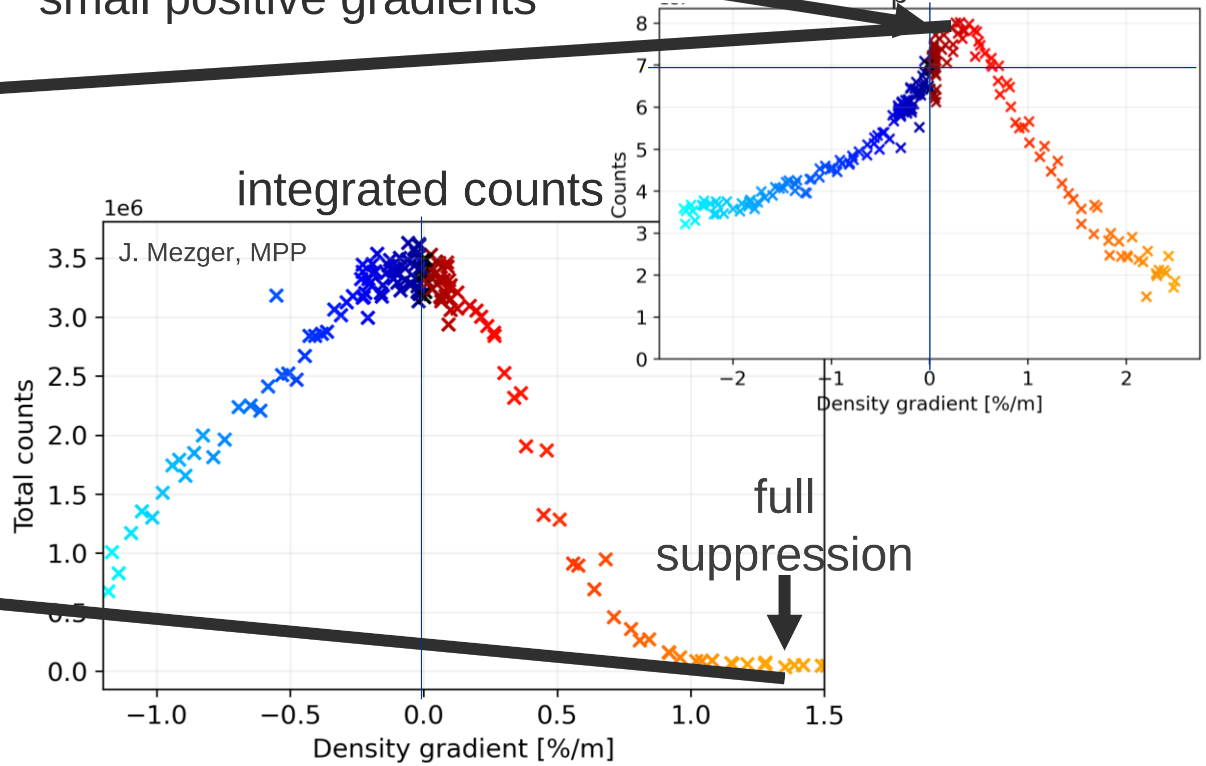


C. B. Schroeder, et al.,
Phys. Plasmas 19, 010703 (2012)

signal increase for
small positive gradients

$N_{p+} = 3 \times 10^{11}$

integrated counts



full
suppression

- less wakefield light for large positive and negative gradients
- consistent with theoretical prediction

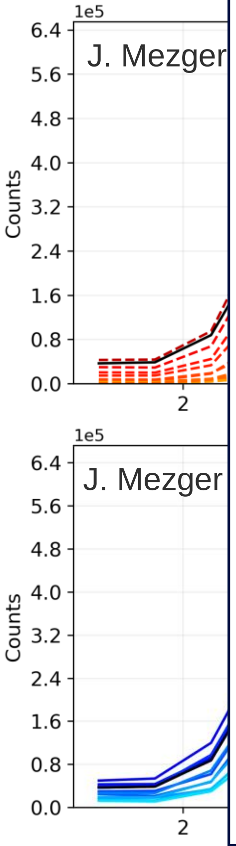
Self-modulation instability suppression

Prediction from … instability

C. B. Schroeder

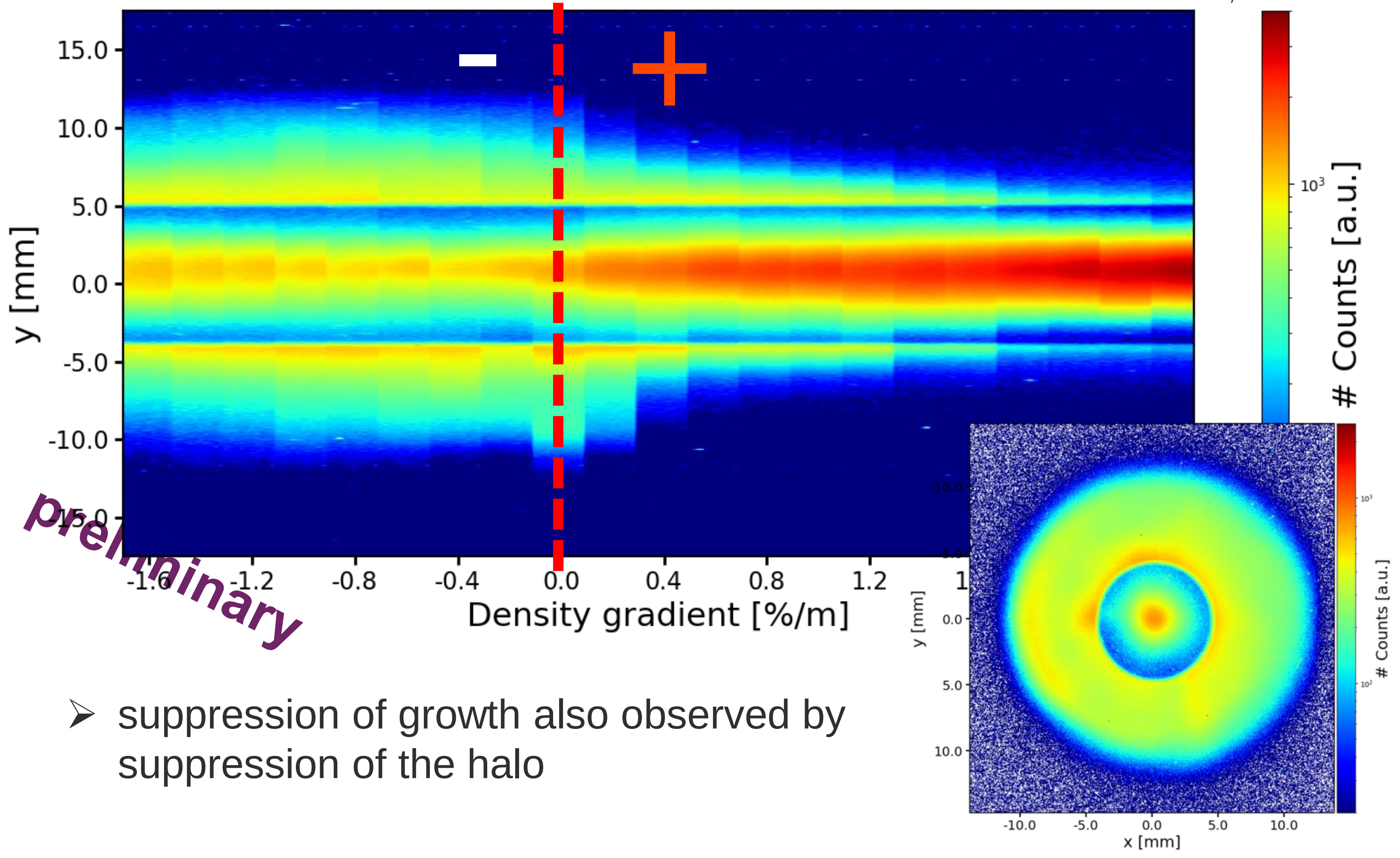
measurem…

al…



n_{pe} =3.8x10^{14} cm^3 N_{p+}=1.5x10^{11} per bunch , RIF=+220 ps

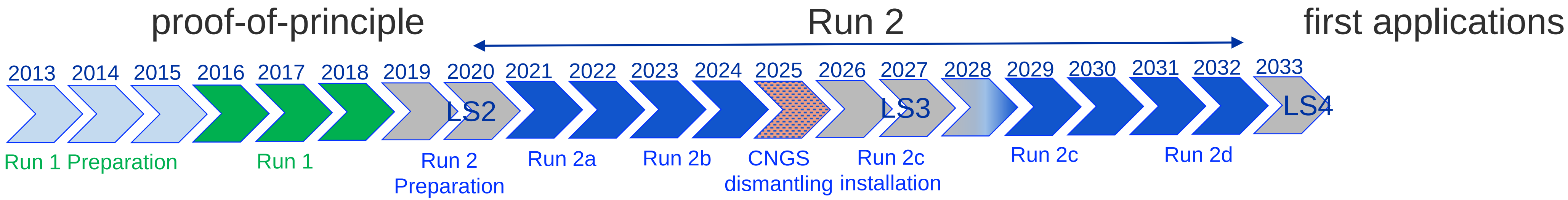
A. Clairembaud, MPP



- suppression of growth also observed by suppression of the halo

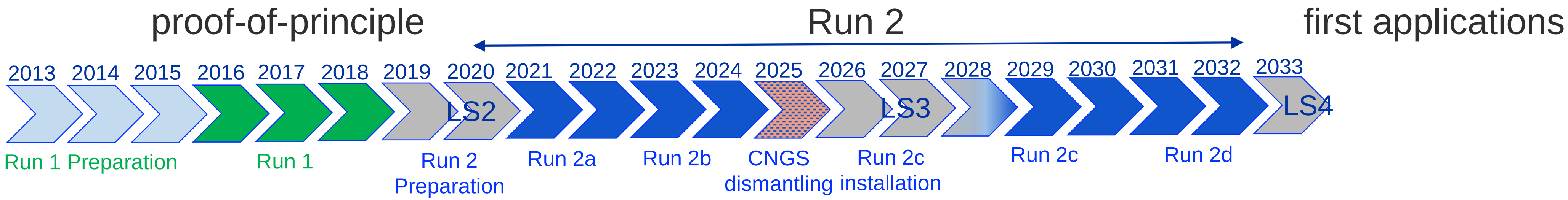
AWAKE progress toward particle physics applications

AWAKE has a clear time-line towards an accelerator



- milestones for AWAKE Run 2: → transition from proof-of-principle to applications

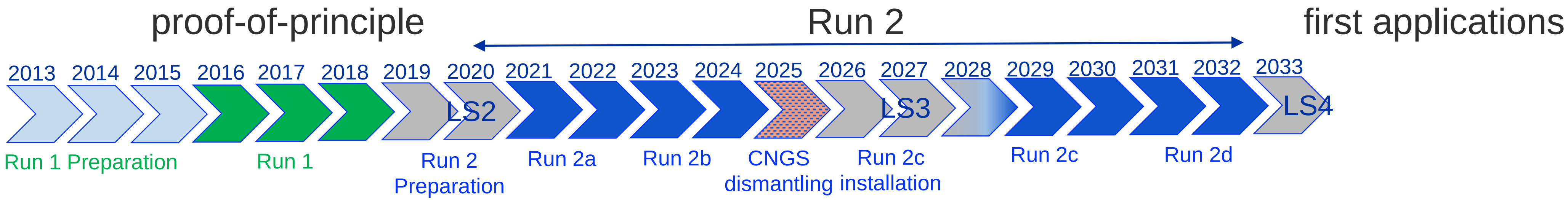
AWAKE has a clear time-line towards an accelerator



- milestones for AWAKE Run 2: → transition from proof-of-principle to applications

✓ - **Run 2a:** demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch

AWAKE has a clear time-line towards an accelerator



proof-of-principle

Run 2

first applications

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

LS2 LS3 LS4

Run 1 Preparation

Run 1

Run 2 Preparation

Run 2a

Run 2b

CNGS dismantling

Run 2c installation

Run 2c

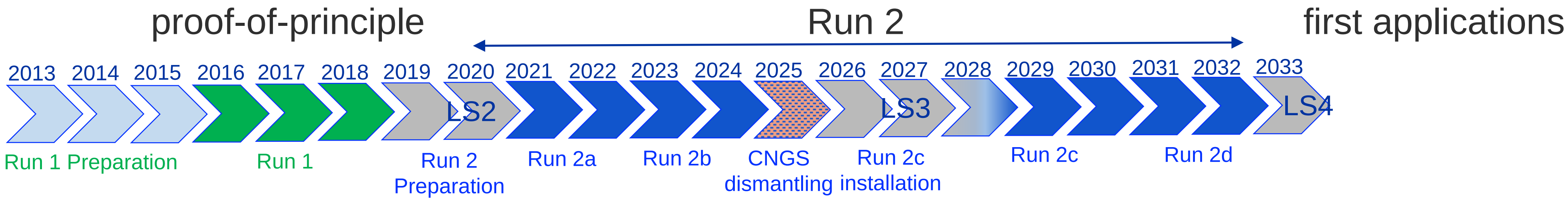
Run 2d

- milestones for AWAKE Run 2: → transition from proof-of-principle to applications

✓ - **Run 2a:** demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch

now - **Run 2b:** maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density

AWAKE has a clear time-line towards an accelerator



proof-of-principle

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first applications

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

LS2 LS3 LS4

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Run 2d

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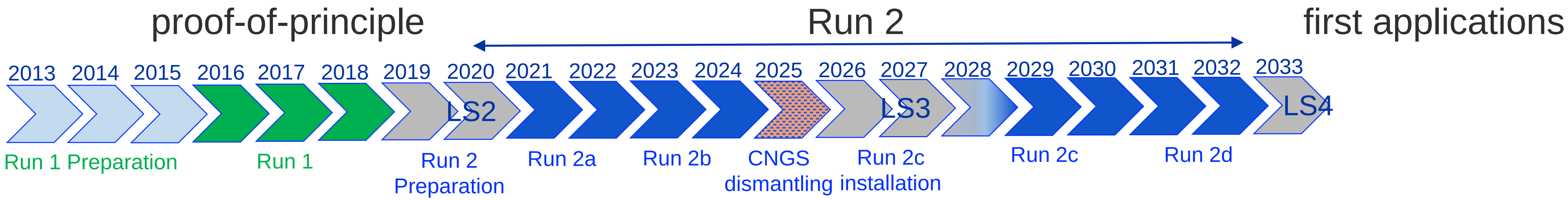
✓ - **Run 2a:** demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch

now - **Run 2b:** maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density
- **Run 2c:** demonstrate electron acceleration and emittance control of externally injected electrons.
- **Run 2d:** development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity.

Approved in June 2024!

AWAKE has a clear time-line towards an accelerator



proof-of-principle

Run 2

first applications

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

LS2 LS3 LS4

Run 1 Preparation

Run 1

Run 2 Preparation

Run 2a

Run 2b

CNGS dismantling

Run 2c installation

Run 2c

Run 2d

- ➢ milestones for AWAKE Run 2: → transition from proof-of-principle to applications

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➢ **Run 2c:** demonstrate electron acceleration and emittance control of externally injected electrons.

➢ **Run 2d:** development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity.

➢ propose **first applications** for particle physics experiments with 50-200 GeV electron bunches

New rubidium vapor source that also allows for density step (Run 2b)

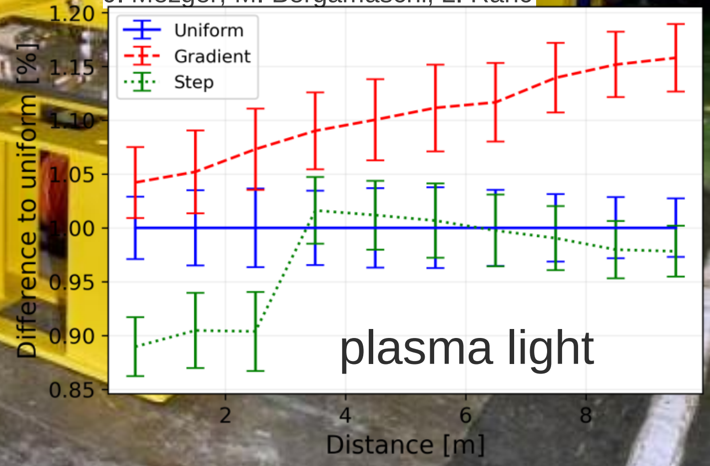
installed July 2023

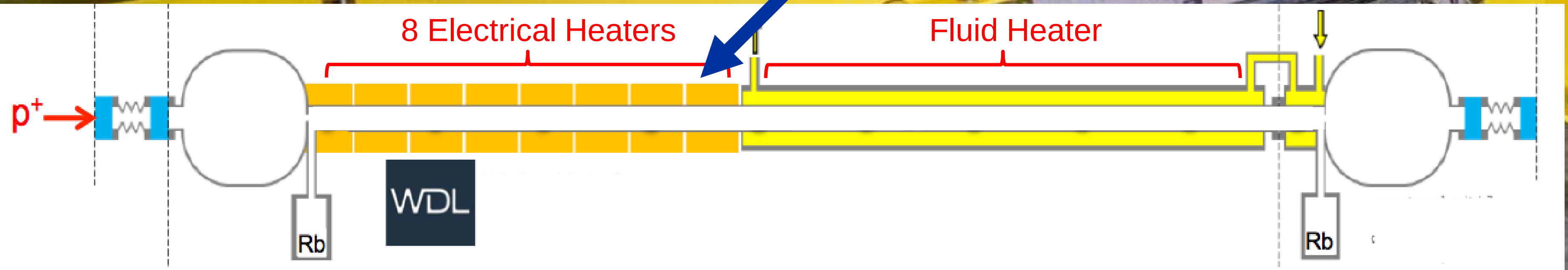
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MPP, WDL

individually controllable heating sections allow to impose a density step along z

J. Mezger, M. Bergamaschi, L. Ranc





Run 2b: first results

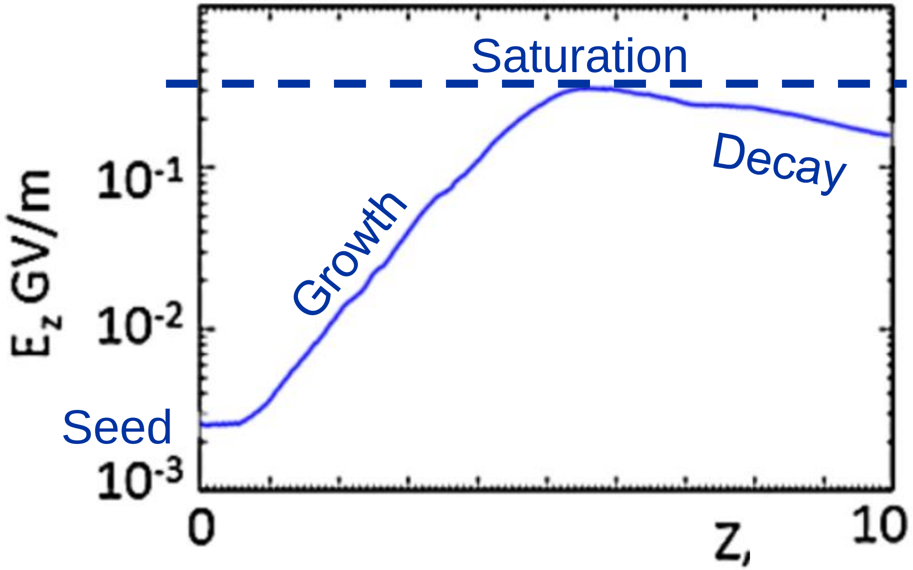
Effect of the density step

Clear effect!

prediction: optimum density step → stabilizes wakefield amplitude after saturation

Caldwell, POP 18, 103101 (2011)

Pukhov, PRL 107 145003 (2011)



- ➢ density step rephases micro bunches in the wakefields

K. V. Lotov, Physics of Plasmas 22, 103110 (2015)

Run 2b: first results

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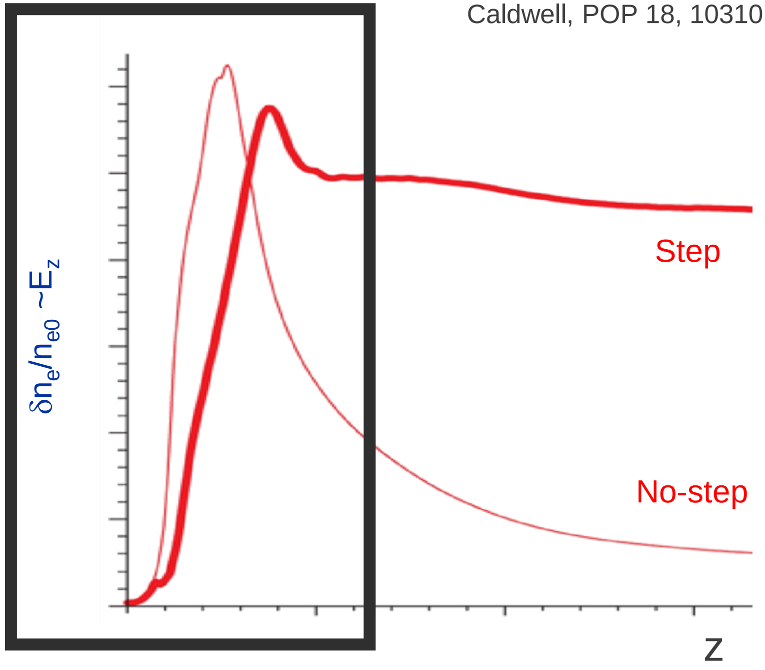
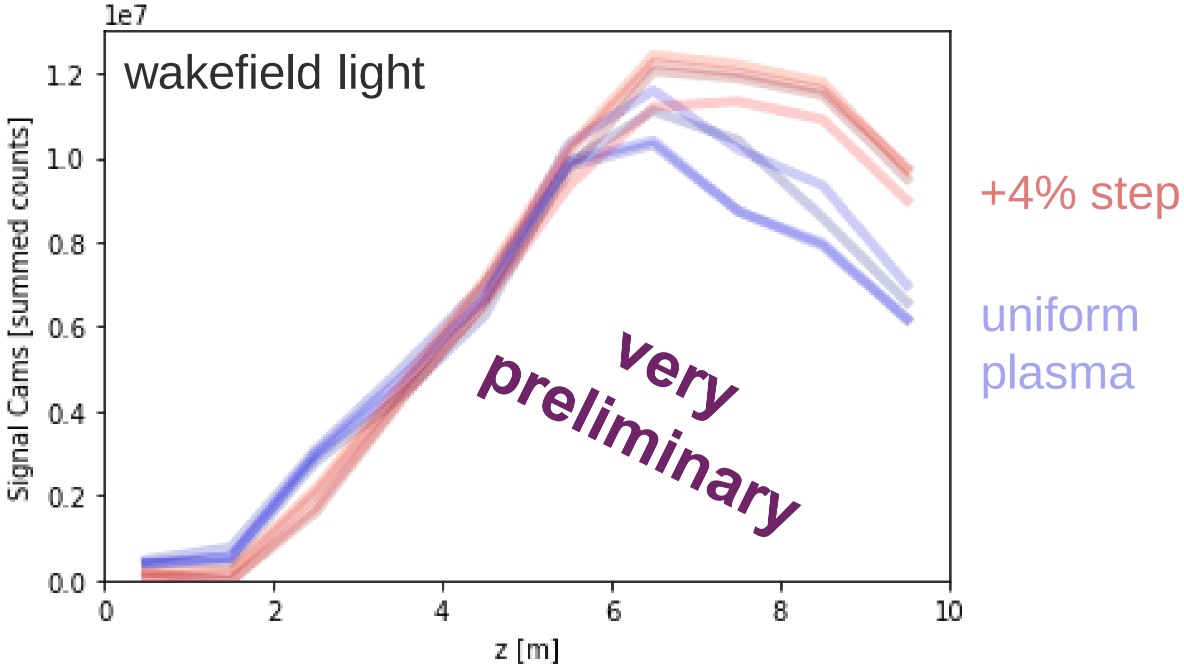


Caldwell, POP 18, 103101 (2011)

step at 1.75m, 2e14, 3e11, RIF: -200ps



- density step rephases micro bunches in the wakefields

K. V. Lotov, Physics of Plasmas 22, 103110 (2015)

- more wakefield light with density step after saturation

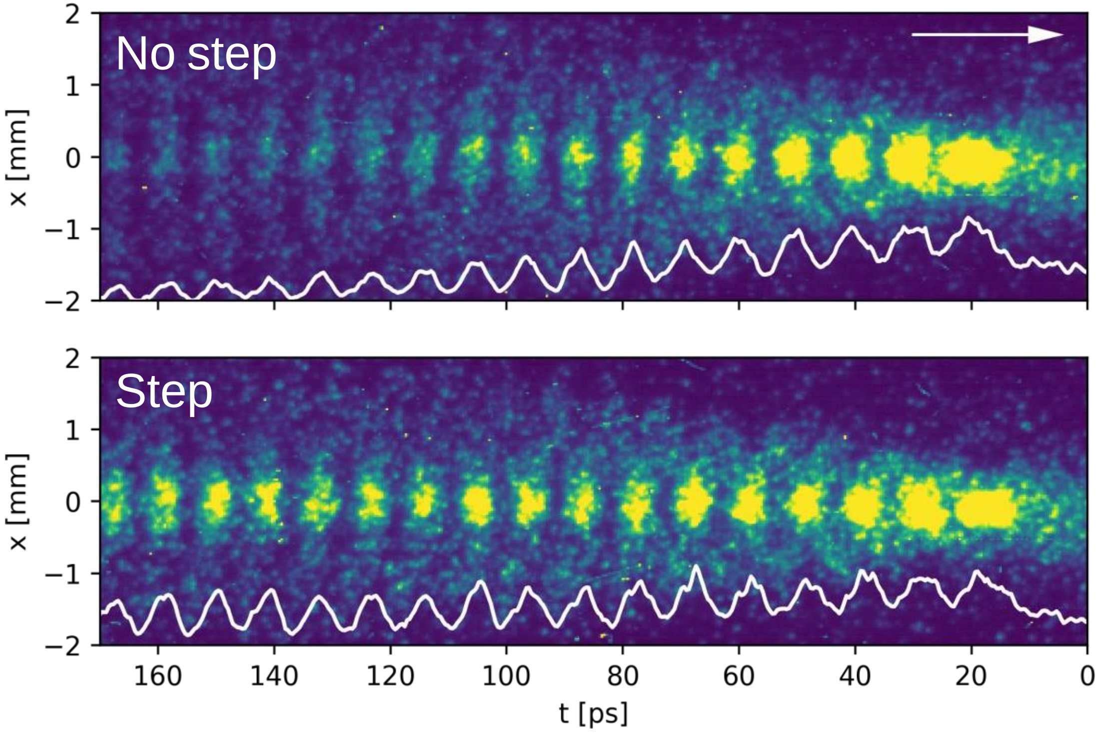
Run 2b: first results

Effect of the density step

Clear effect!

very preliminary

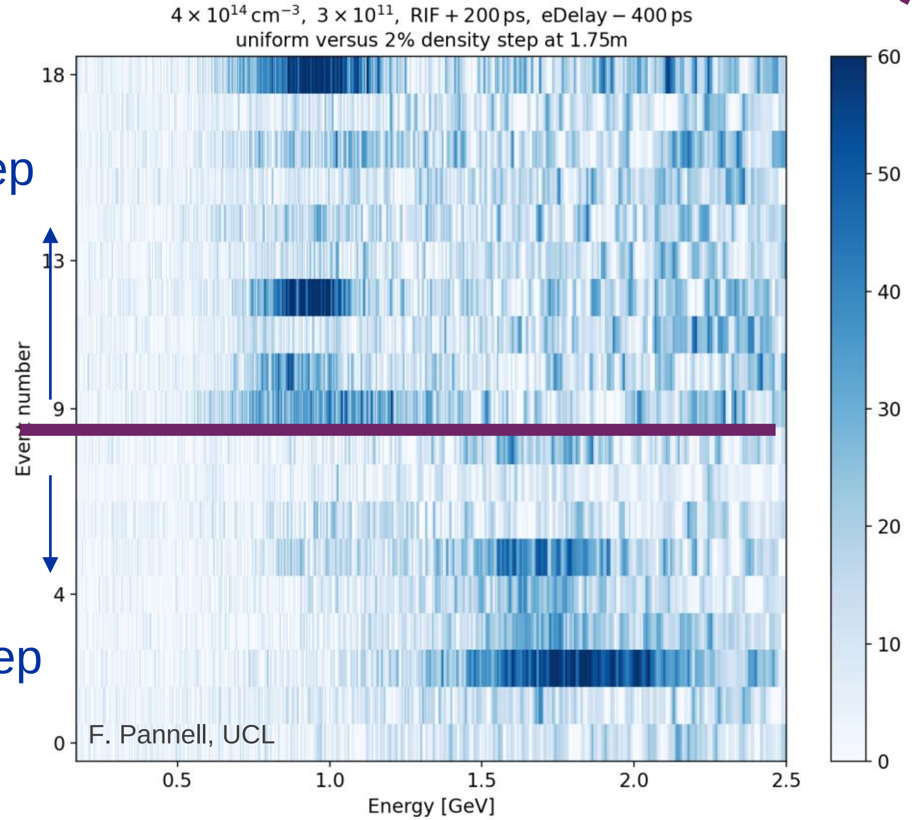
- ➢ longer bunch trains on the time resolved images of the proton bunch



5% step at 1.75m, n_{pe}~$2x10^{14}$ cm^{-3}, n_{p+}=1.5e11 p+/bunch

no step

2% step

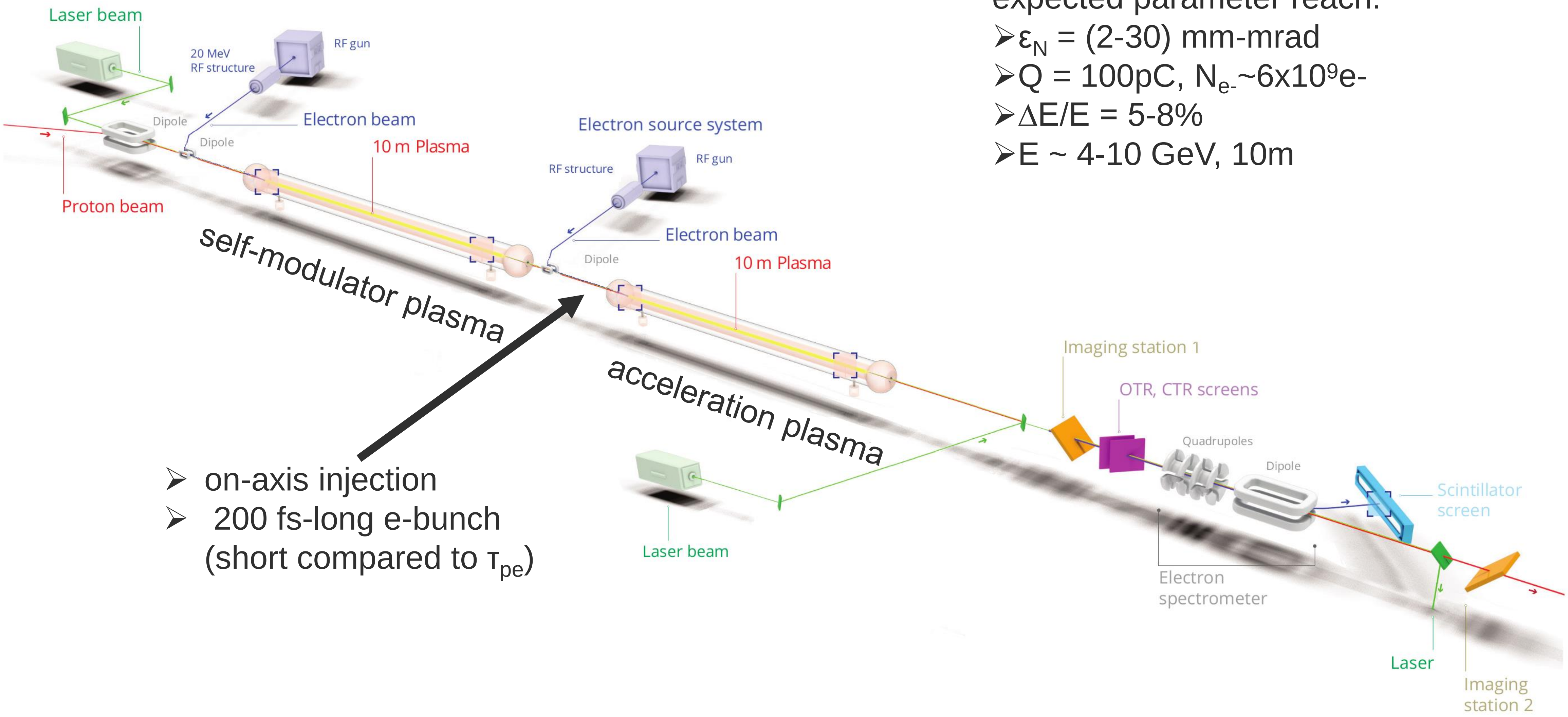


- ➢ higher energy gain by externally injected 20 MeV electrons with step

AWAKE Run 2c: quality acceleration

expected parameter reach:

- ➢ε_N = (2-30) mm-mrad
- ➢Q = 100pC, N_{e-}~6x10^9e-
- ➢$\Delta E/E$ = 5-8%
- ➢E ~ 4-10 GeV, 10m



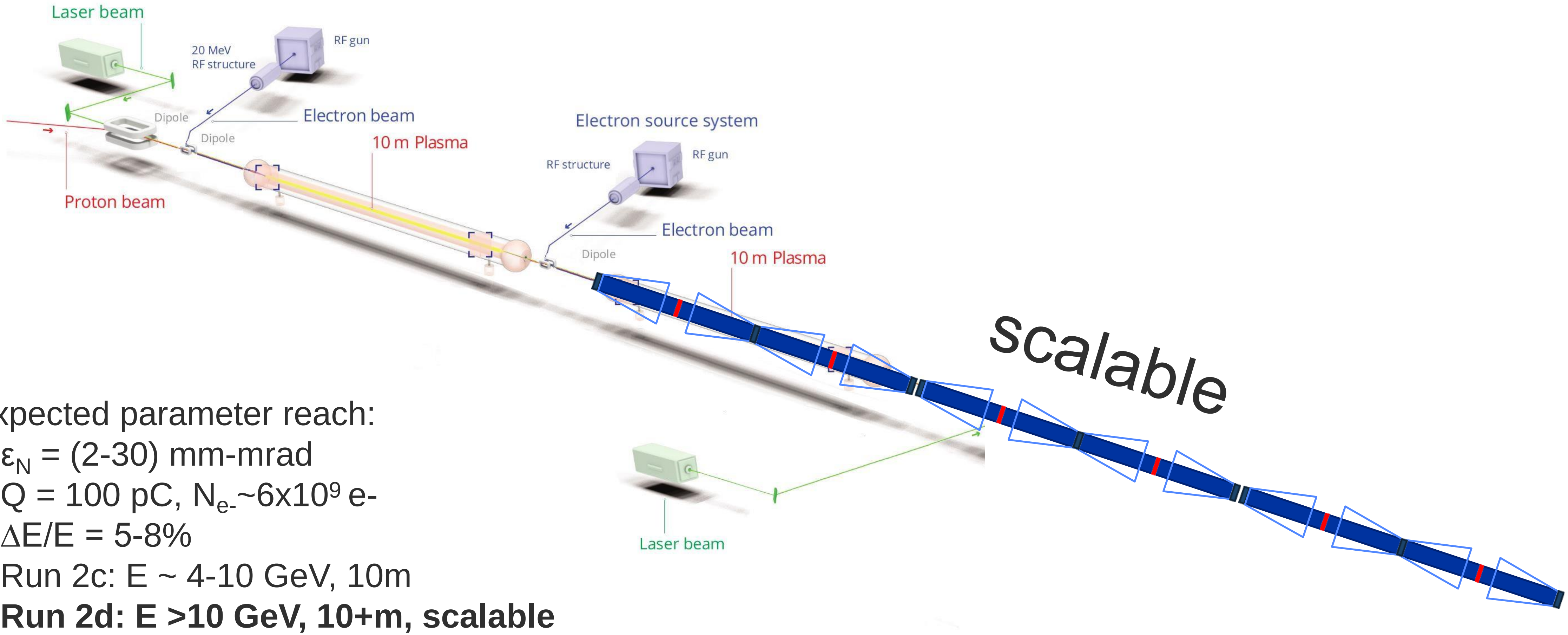
self-modulator plasma

acceleration plasma

- ➢ on-axis injection
- ➢ 200 fs-long e-bunch (short compared to τ_{pe})

Run 2d: demonstration of scalability

scalable plasma source for acceleration



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- ➢Q = 100 pC, N_{e-}~$6x10^9$ e-
- ➢$\Delta E/E$ = 5-8%
- ➢Run 2c: E ~ 4-10 GeV, 10m
- ➢**Run 2d: E >10 GeV, 10+m, scalable**

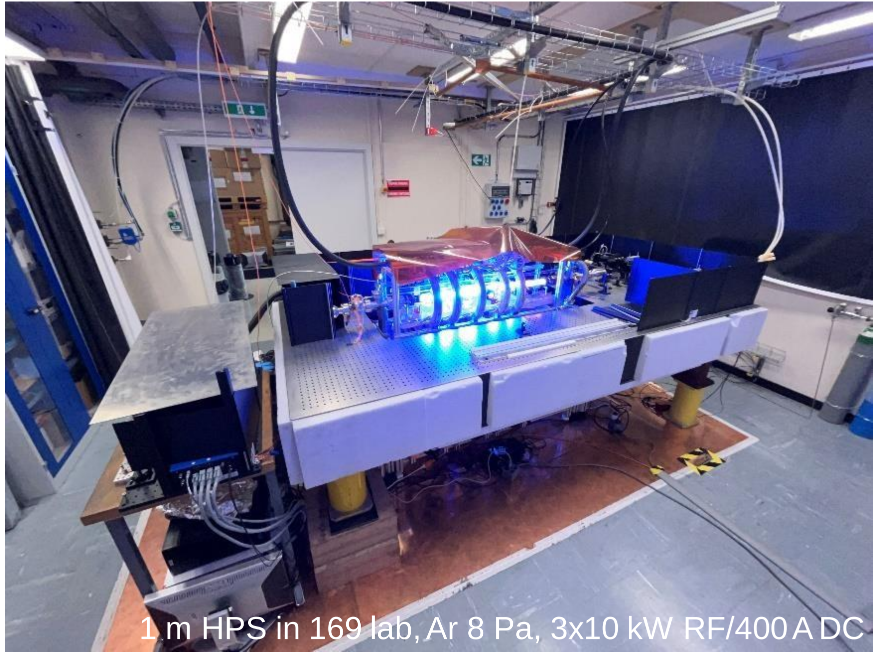
AWAKE is developing plasma source technologies

A. Sublet (CERN)

- AWAKE dedicated plasma sources R&D program launched in 2018
- well defined plan with 5 institutes + CERN as host, 6 PhD works
- **two dedicated labs at CERN**, capable to house up to 20 m long source and diagnostics

talk + poster by
C. Amoedo, WG3

HPS lab (launched in 2019)


1 m HPS in 169 lab, Ar 8 Pa, 3x10 kW RF/400 A DC

CERN
Max-Planck-Institut für Plasmaphysik
EPFL
College of Engineering UNIVERSITY OF WISCONSIN-MADISON

already demonstrated:
→ Density ~10^{15} cm^{-3}

DPS lab (launched in 2021)

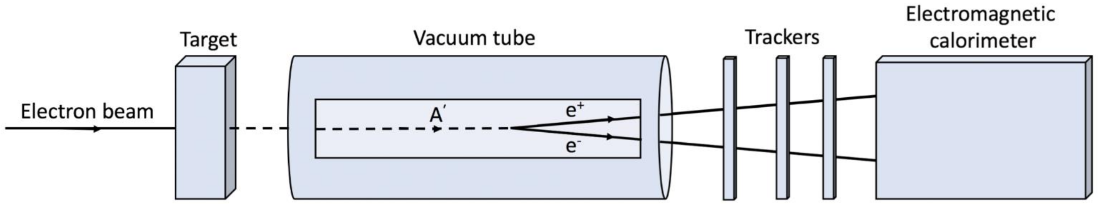
CERN
TÉCNICO LISBOA
Imperial College London

to be demonstrated:
→ uniformity (+measurement)
→ tunability

Possible applications to particle physics

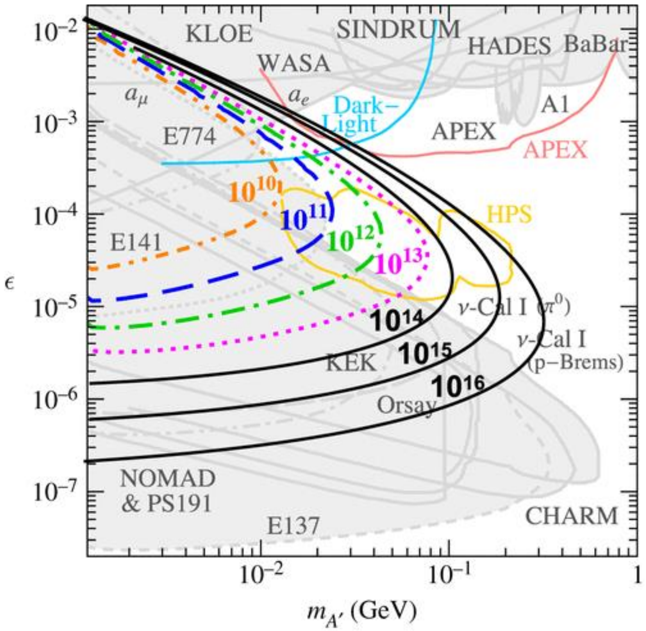
Once Run 2 is completed, AWAKE is in a position to start with first particle physics applications

- 50-200 GeV e-, using SPS p^+ bunch as driver:
  - fixed target, beam-dump experiments: search for dark photons
  - nonlinear QED: e^-/photon collisions
  - ep or eA collisions, QCD, structure of matter
  - …



A. Caldwell and M. Wing,
The European Physical Journal C76, (2016)

M. Wing, Phil. Trans. Royal Soc 377,20180185 (2019)
AWAKE collaboration, Symmetry 2022, 14(8), 1680



- TeV e-, using LHC p^+ bunch as driver:
  - High energy ep or eA collider

- luminosity of collider applications limited by single use of low rep-rate p^+ bunch production

AWAKE Collaboration: 23 Institutes World-Wide

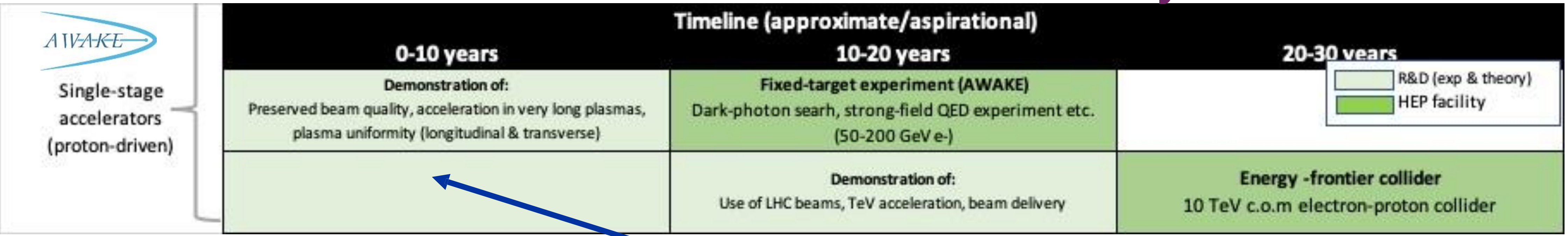
- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-Universität of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE – Instituto Universitéario de Lisboa, Lisbon, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk Russia
- GoLP/Institutode Plasmas e Fusao Nuclear, Instituto Superior Téchnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Uppsala, Sweden
- Wigner Institute, Budapest, Hungary
- Swiss Plasma Center group of EPFL, Lausanne Switzerland

R. Pattathil,
presented at EAAC 2023

ESPP roadmap

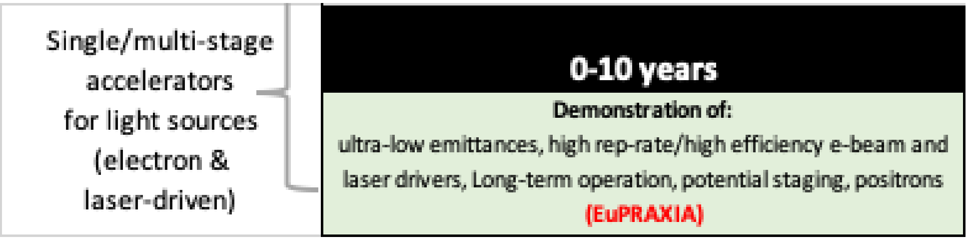
Advanced accelerator community

Talk by S. Hooker
Monday, Plenary

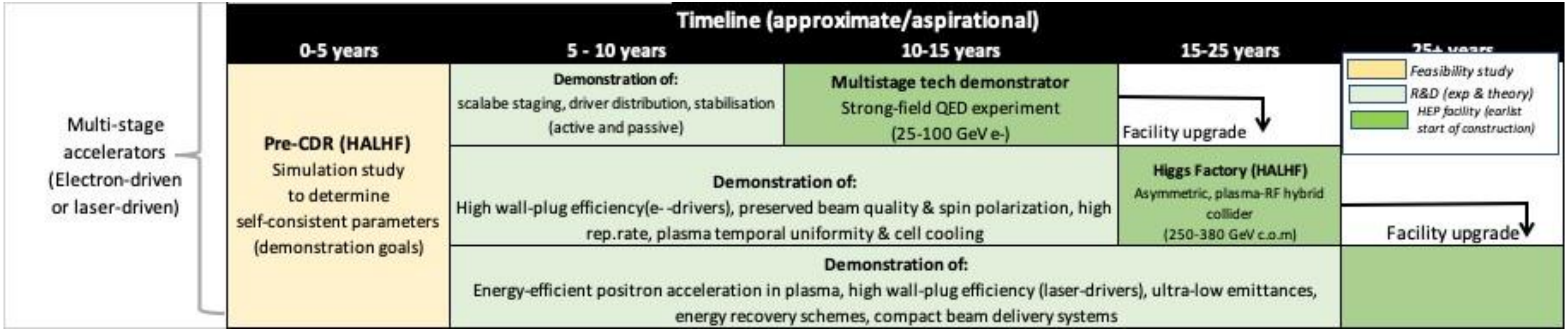


	Timeline (approximate/aspirational)		
	0-10 years	10-20 years	20-30 years
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-)	▨ R&D (exp & theory) 🟩 HEP facility
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

AWAKE aims for particle physics applications and is therefore part of the ESPP process



	0-10 years
Single/multi-stage accelerators for light sources (electron & laser-driven)	**Demonstration of:** ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons **(EuPRAXIA)**



	Timeline (approximate/aspirational)				
	0-5 years	5 - 10 years	10-15 years	15-25 years	25+ years
Multi-stage accelerators (Electron-driven or laser-driven)	**Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** scalabe staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25-100 GeV e-)	Facility upgrade	🟨 *Feasibility study* ▨ *R&D (exp & theory)* 🟩 *HEP facility (earlist start of construction)*
		Demonstration of: High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling		**Higgs Factory (HALHF)** Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m)	Facility upgrade
		Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser-drivers), ultra-low emittances, energy recovery schemes, compact beam delivery systems			🟩

Summary and conclusions

- AWAKE is a **proton-driven** plasma wakefield acceleration experiment
  - wakefields are driven resonantly by a micro bunch train formed by self-modulation
  - very large single stage energy gain possible (~100GeV- few TeV)

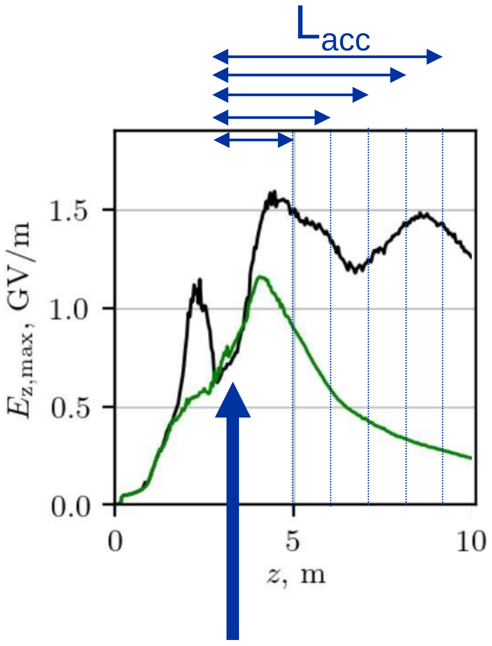
- New **physics results**, relevant to understanding and controlling self-modulation
  - wakefield growth, ion motion, filamentation instability, amplitude stability, instability suppression

- the goal is to build an accelerator for particle physics applications
  - requires:
    - **control** of self-modulation
    - **quality** acceleration (external injection…)
    - **scalable** plasma sources
  - these are also relevant for other plasma-based accelerators

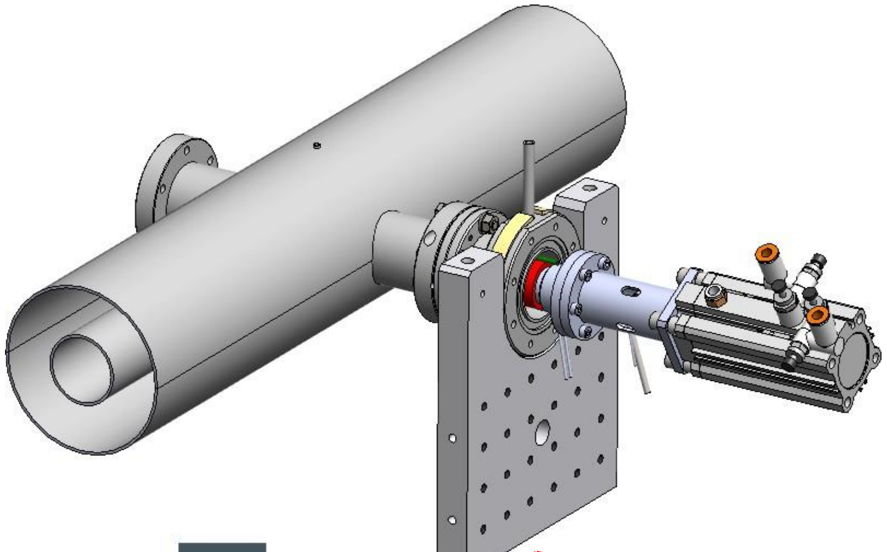
- **goal:** propose particle physics applications in the early 2030’s based on the AWAKE concept

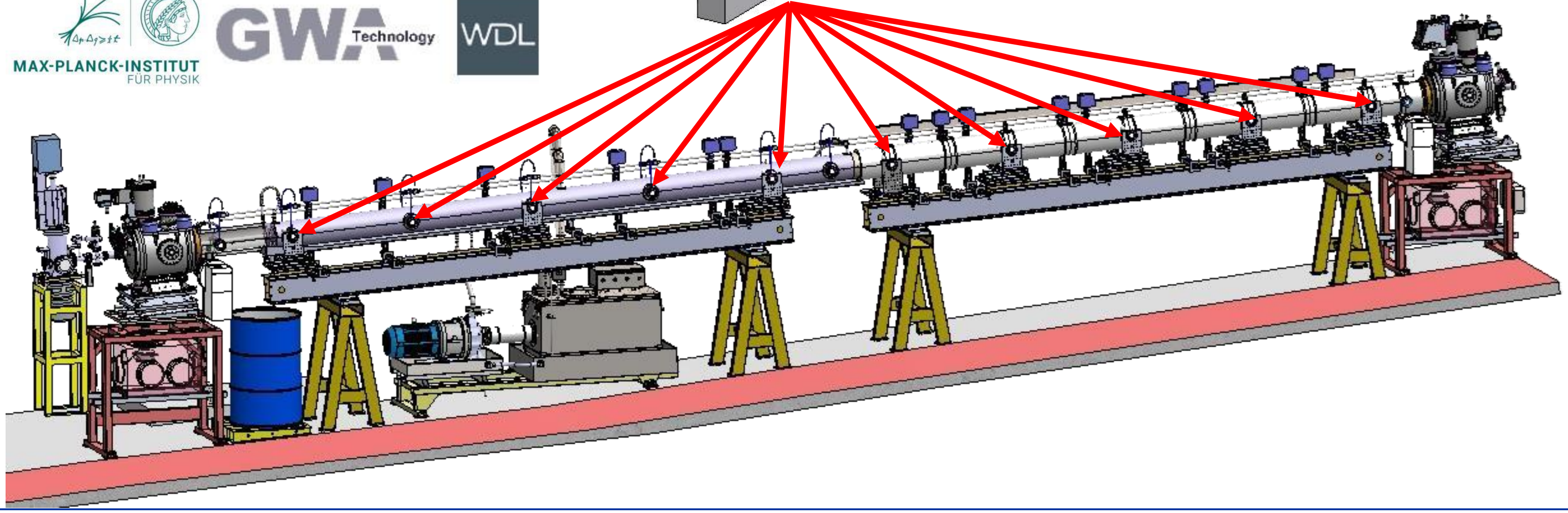
Changing plasma length to measure gradients

Vary plasma length by stopping the ionizing laser



injection





thin beam dumps for changing plasma length