AWAKE

Plasma Wakefield Acceleration
and
Beam-Plasma Physics

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MAX-PLANCK-INSTITUT
FÜR PHYSIK

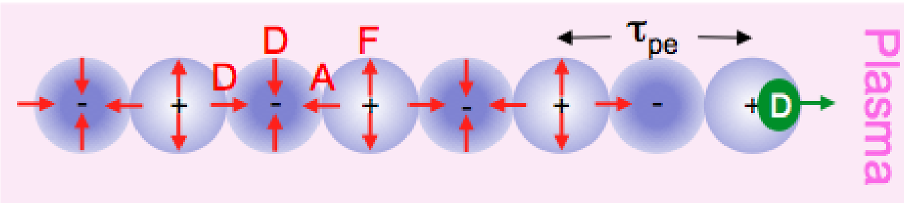
✧Advanced WAKefield Experiment

AWAKE collaboration: 22 institutes world-wide

- 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

Experiment @ CERN

RELATIVISTIC PARTICLE BUNCH MEETS PLASMA



D=driver
W=witness

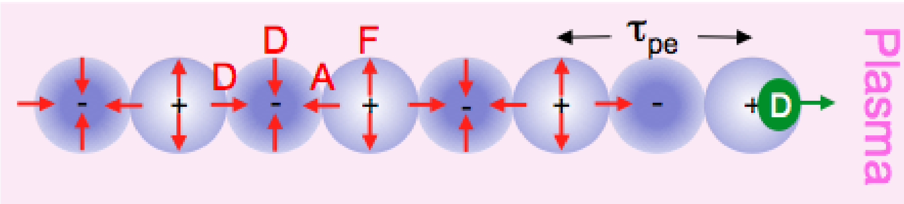
✧Relativistic Bunch ⬄ Radial Space Charge Field ⬄ Plasma Screening

⬄ Azimuthal Magnetic Field ⬄ Plasma Return Current

✧High Frequency Regime ⬄ Time ~$1/\omega_{pe}$ ⬄ Space ~$c/\omega_{pe}=1/k_{pe}$, $\lambda_{pe}=2\pi/k_{pe}$, v_b~c, $\gamma>>1$, (ω_{pi})

$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2} \gg \omega_{pi}$$

Relativistic Particle Bunch Meets Plasma



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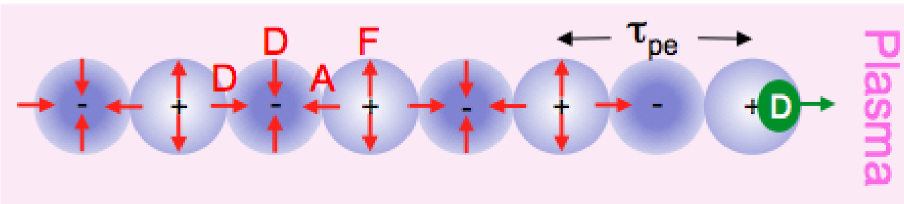
✧Screening ⬄ Plasma Wakefields (Langmuir Wave, E_z) ⬄ Self-Modulation and Hosing Instabilities ⬄ Accelerators

✧Return Current ⬄ Filamentation Instability (~Weibel Instability), Generation of Magnetic Fields ⬄ Astrophysics

Relativistic Particle Bunch Meets Plasma



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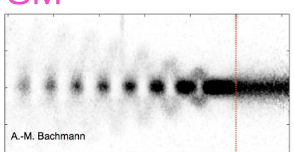
SM



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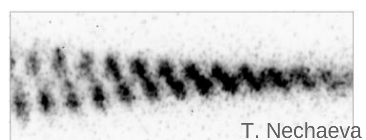

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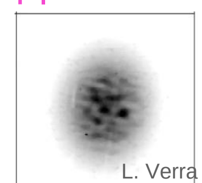
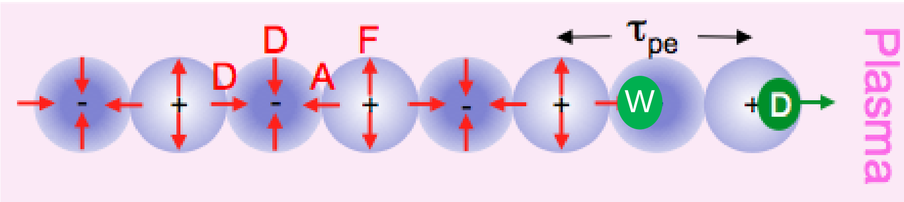


RELATIVISTIC PARTICLE BUNCH MEETS PLASMA



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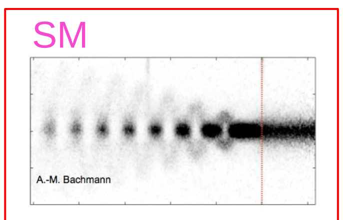

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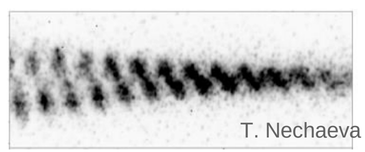

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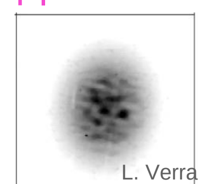

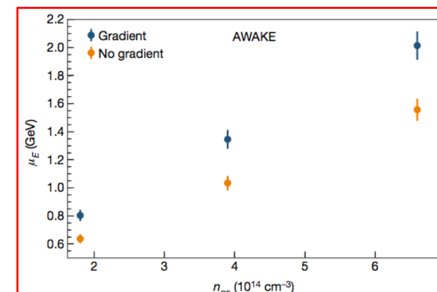

Main motivation:

✧Produce high-energy e^- bunches (200GeV, 5TeV), in a high-gradient (1GeV/m) plasma-based accelerator (PWFA) driven by a p^+ bunch, for particle physics applications (dark photon searches, very-high-energy ep collider)

✧Drive wakefields in plasma with a proton (p^+) bunch

✧Accelerate externally-injected electrons (e^-) to GeV (SPS) to TeV (LHC) energy scale

✧Relativistic proton (p^+) bunches with tens to hundreds of kJ <u>are available</u>

✧Driving wakefields in plasma with a proton (p^+) bunch

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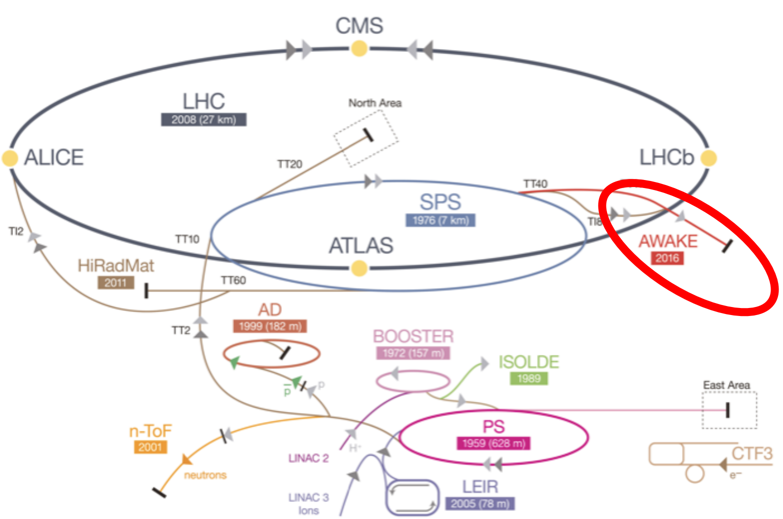

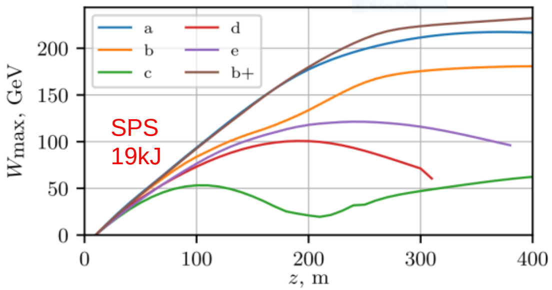

P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

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

2D numerical simulation results

AWAKE

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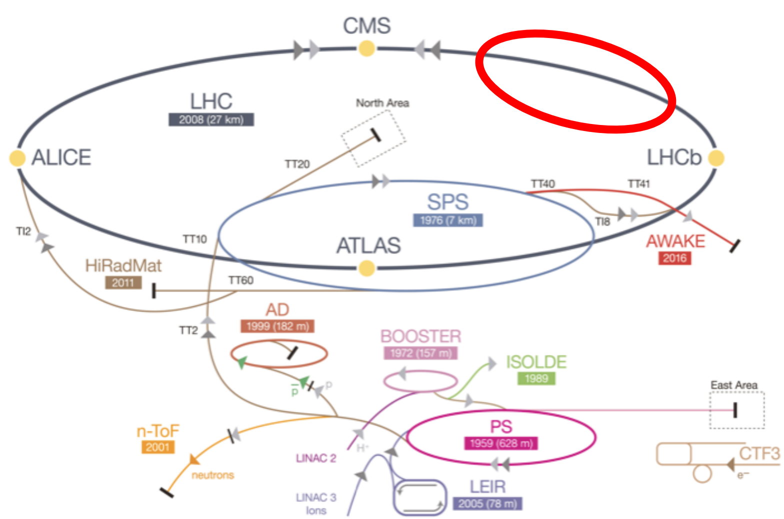

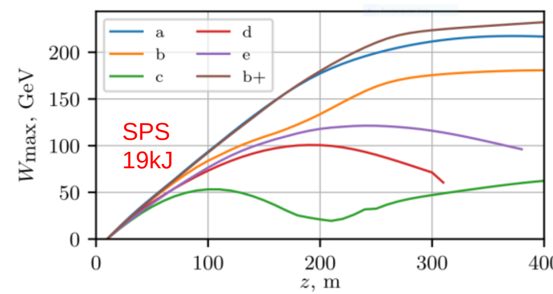

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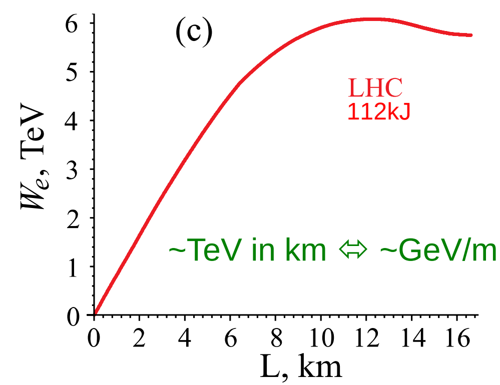


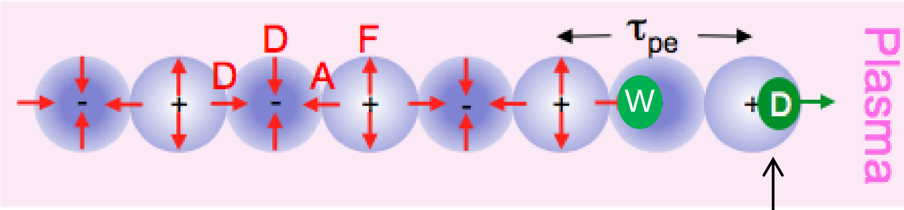
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

LHC driver (119kJ):
~5TeV in ~7km
~10^9 e^-

1GeV/m!

PLASMA WAKEFIELDS

Short driver (e^-), $\sigma_t \leq 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$, "resonant"



✧~Langmuir wave in 1D, on axis

Short and Narrow

$k_{pe}\sigma_z = \sqrt{2}$ $k_{pe}\sigma_r \sim 1$

n_{e0}, k_{pe}, c/ω_{pe}

Scaling:

$$\sigma_t, \tau \leq 1/\omega_{pe} \propto n_{e0}^{-1/2}$$

$$\sigma_r \leq c/\omega_{pe} \propto n_{e0}^{-1/2}$$

$$E_{WB} = \frac{m_e c}{e}\omega_{pe} \propto n_{e0}^{1/2}$$

fit within the "structure", "bubble"

$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$

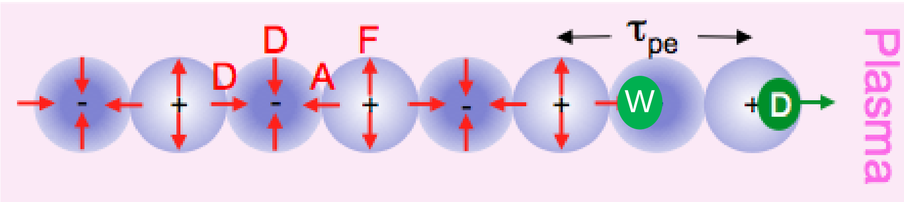
Plasma e^- angular frequency

$$c/\omega_{pe}$$

Plasma skin depth

PLASMA WAKEFIELDS

Short driver (e^-), $\sigma_t \leq 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$, "resonant"



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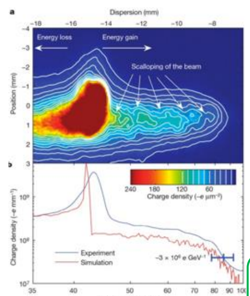
$$c/\omega_{pe}$$

PWFA, short e^- bunch



Blumenfeld, Nature 445, 741 (2007)

n_{e0}=2.7x10^{17}cm^{-3}

60fs e^- bunch

2x10^{10}e^-, 42GeV, ~50J

~42GeV energy gain

~52GeV/m, 85cm

SLAC

BERKELEY LAB

LWFA, short laser pulse

Gonsalves, PRL 122, 084801 (2019)

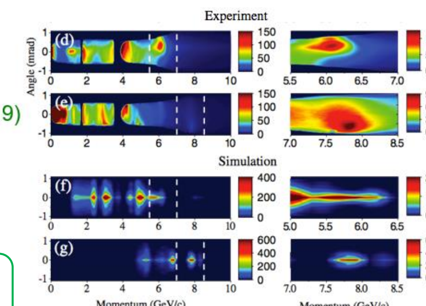
n_{e0}=3x10^{17}cm^{-3}

~40fs laser pulse

~40J, 1PW

~8GeV energy gain

~39GeV/m, 20cm

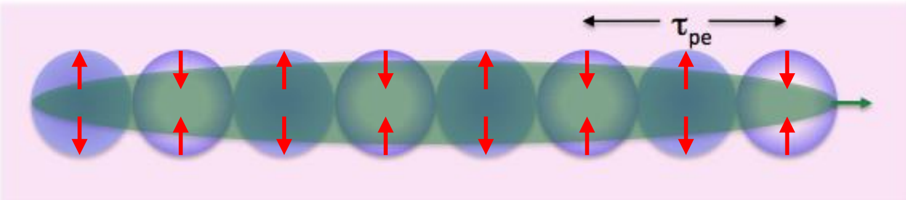


High energy gain & gradient!!

SELF-MODULATiON

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

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



Short and Narrow → Long and Narrow

$k_{pe}\sigma_z = \sqrt{2}$ $k_{pe}\sigma_r \sim 1$

$k_{pe}\sigma_z >> 1$ $k_{pe}\sigma_r \sim 1$

n_{e0}, k_{pe}, c/ω_{pe}

Blumenfeld, Nature 445, 741 (2007)

- $n_{e0}=2.7\times10^{17}cm^{-3}$
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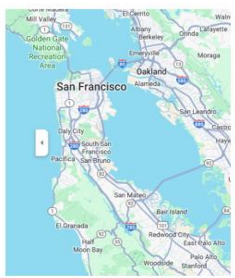


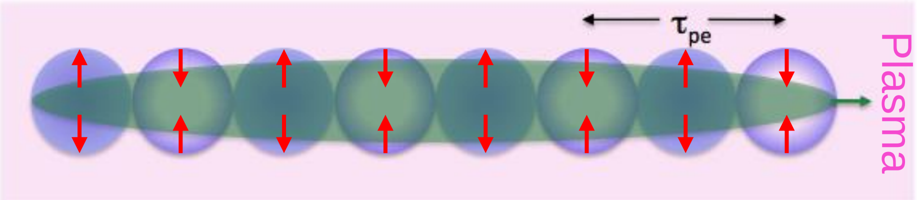
p^+ bunch, CERN:
SPS: 400GeV, 3×10^{11} → 19kJ
LHC: 7TeV, 1×10^{11} → 119kJ

~200ps

10-100J → 10-100kJ!

$$E_{WB} = \frac{m_e c}{e}\frac{\sqrt{2}}{\sigma_\tau} \propto n_{e0}^{1/2}$$

Long driver (p^+), σ_t>>1/ω_{pe}, σ_r~c/ω_{pe}, initially non-resonant



(1)

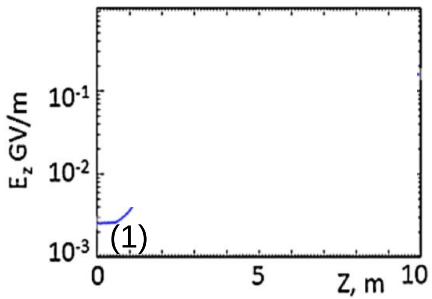
Initial (transverse) wakefields

Periodic focusing/defocusing (1)

$$\omega_{pe} = \left(\frac{n_{e0}e^2}{\epsilon_0 m_e}\right)^{1/2}$$

Plasma e^- angular frequency

Pukhov, PRL107 145003 (2011)

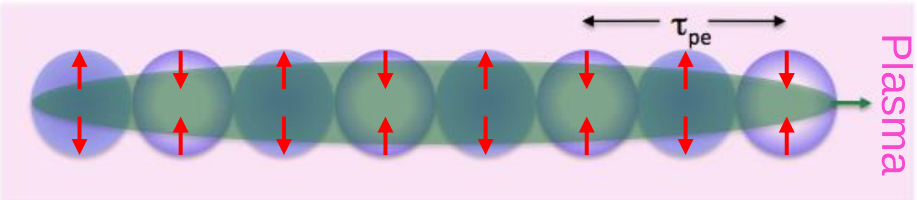


✧E_z-field along the plasma

Relativistic particles do not (appreciably) dephase!
SM ⇔ transverse effect!

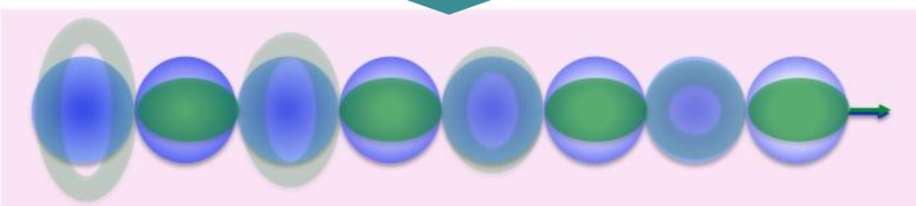
SELF-MODULATION

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



(1)

Self-modulation



(2)

<u>Growth mechanism:</u>

Initial (transverse) wakefields

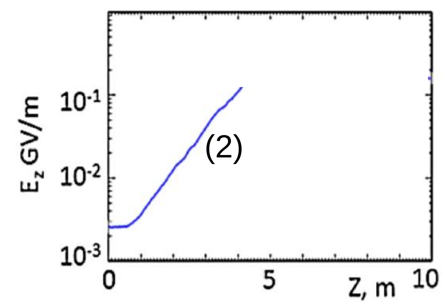
Periodic focusing/defocusing

Density modulation

Wakefields

(2)

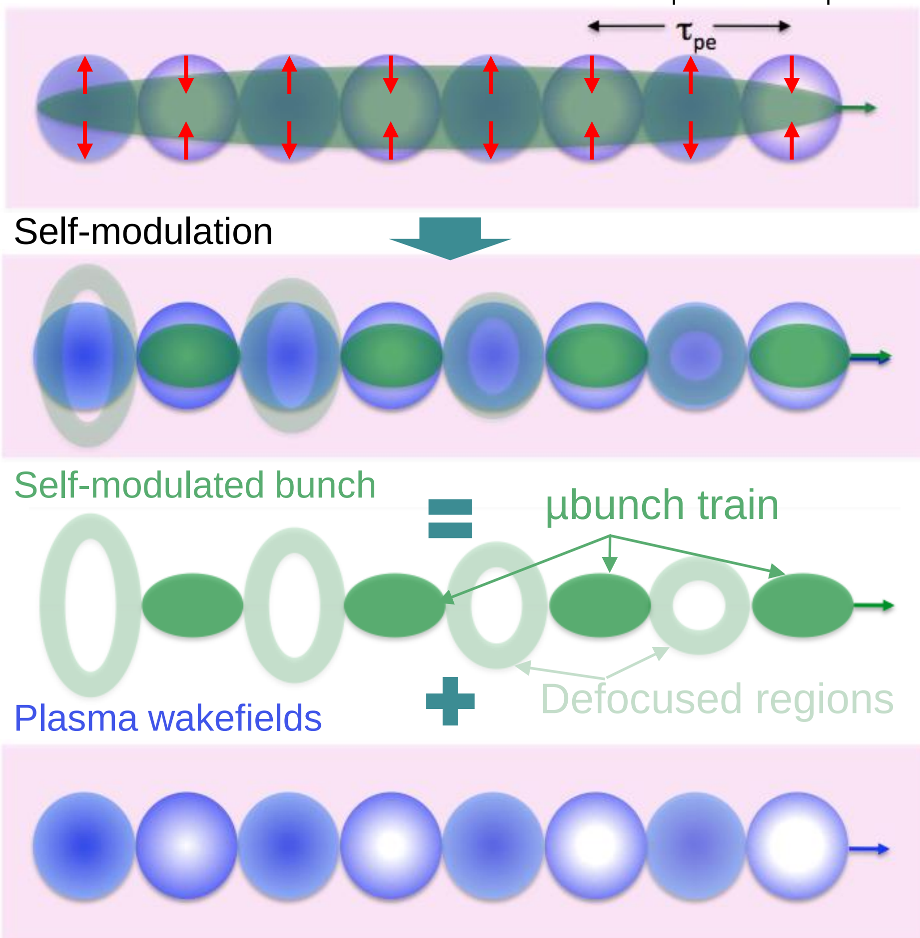
Pukhov, PRL107 145003 (2011)



Growth along the bunch and plasma!

SELF-MODULATION

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



Growth mechanism:

Initial (transverse) wakefields

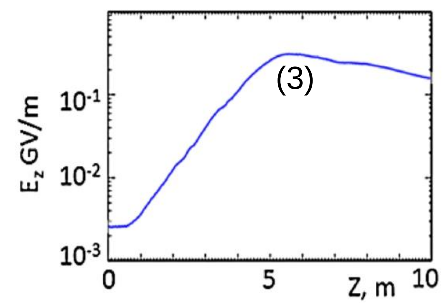
Periodic focusing/defocusing

Density modulation

Wakefields

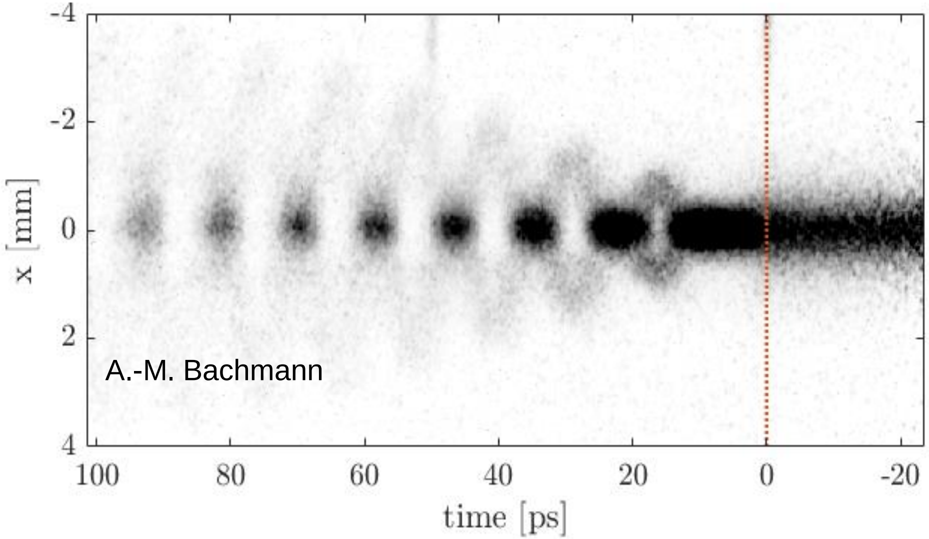
Full modulation - bunch train (3)

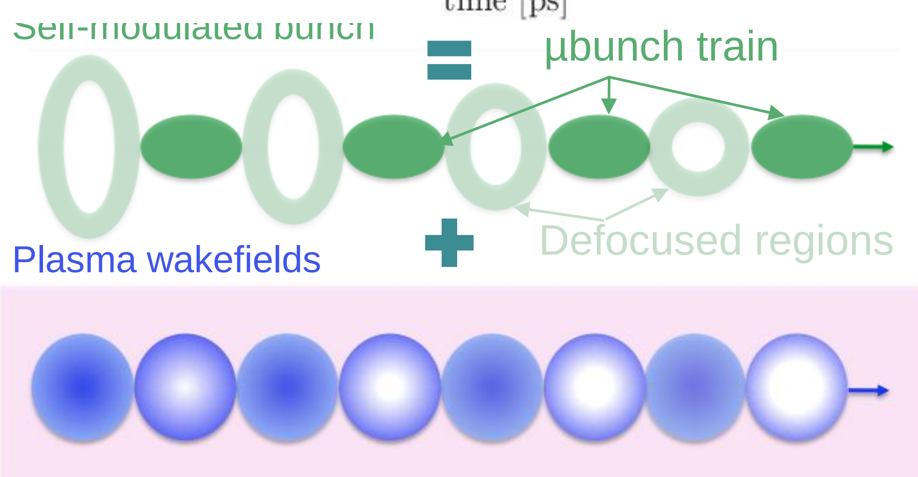
Pukhov, PRL107 145003 (2011)



(3)
- ✧Train period $\sim\tau_{pe}=2\pi/\omega_{pe}$
- ✧µbunch length < τ_{pe}
- ✧Resonantly drives wakefields to large amplitude
- ✧Self-modulation necessary to drive ~GV/m accelerating fields in $\sim10^{14}cm^{-3}$ density plasma

SELF-MODULATiON





<u>Growth mechanism:</u>

Initial (transverse) wakefields

↓

Periodic focusing/defocusing

↓

Density modulation

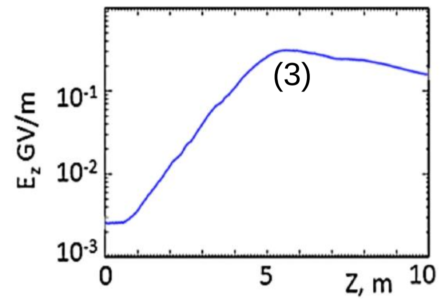
↓

Wakefields

↓

Full modulation - bunch train (3)

Pukhov, PRL107 145003 (2011)



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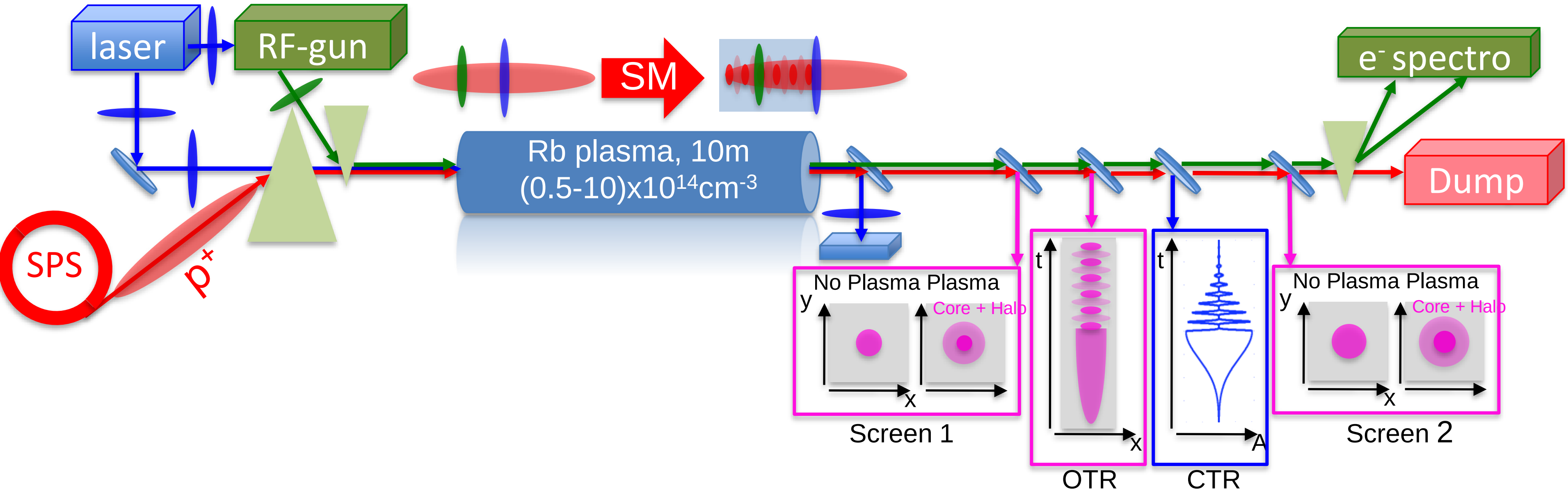
AWAKE EXPERIMENTAL SETUP

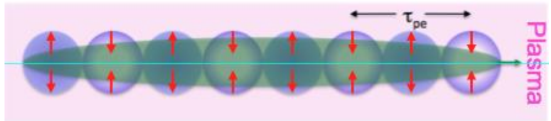


E=400GeV
σ_z=6cm!!
Long

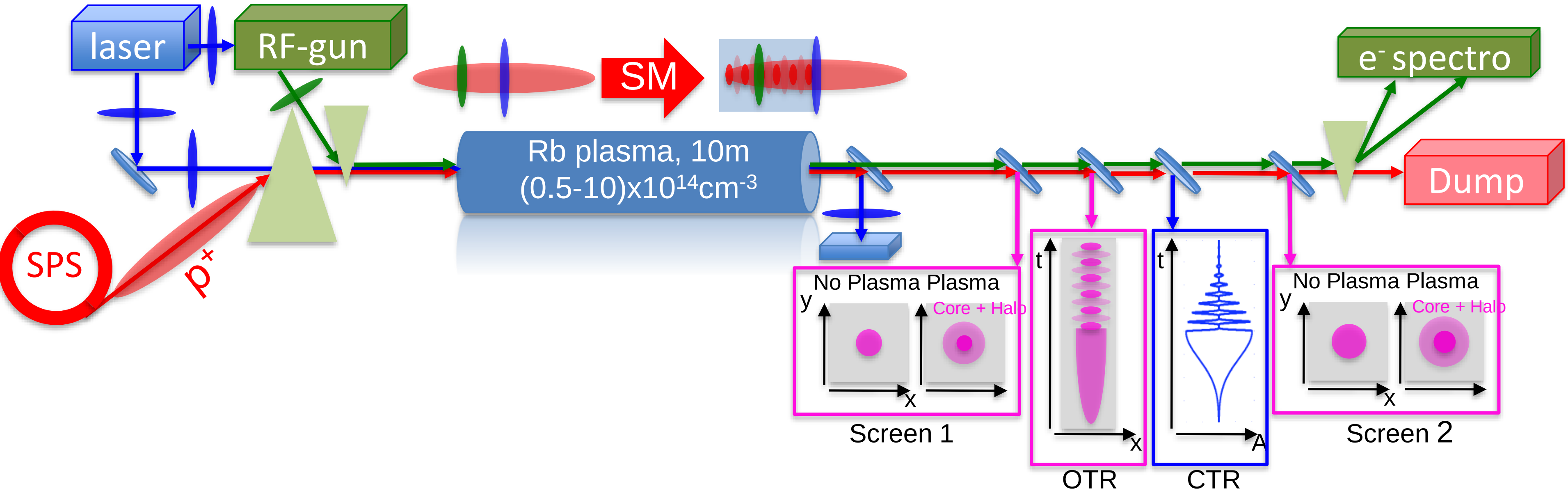
N=(1-3)x10^{11}p$^+$
σ_r=200µm
Narrow

✧Plasma density from σ_r

SM regime …



AWAKE EXPERIMENTAL SETUP

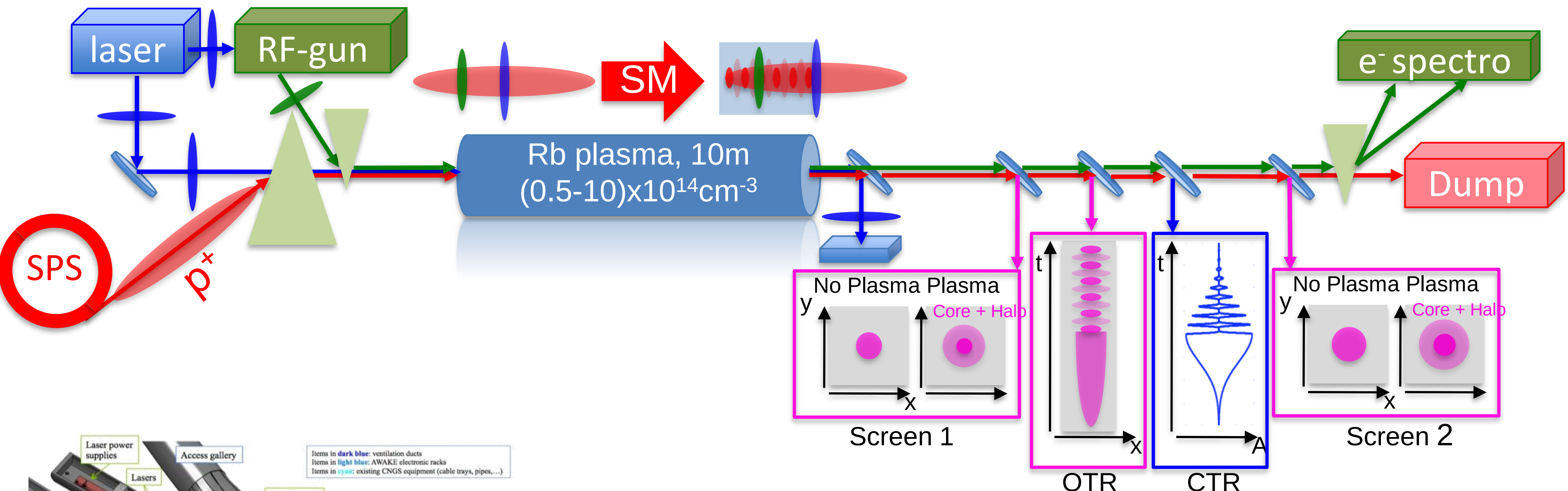


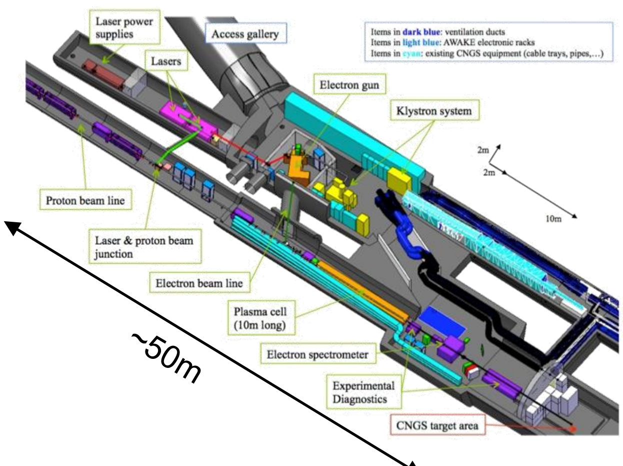
$E=400GeV$ $N=(1\text{-}3)\times10^{11}p^+$
$\sigma_z=6cm!!$ $\sigma_r=200\mu m$
$c/\omega_{pe}\approx\sigma_r$ ⇔ $n_e \sim 7\times10^{14}\ cm^{-3}$
$\lambda_{pe}\sim1.3mm<<\sigma_z$
$f_{pe}\sim240GHz$
$E_{WB}\sim2.5GV/m$
$L_p\sim10m\sim2\beta^*$

✧Plasma density from σ_r

SM ~ 1GeV/m

AWAKE EXPERiMENTAL SETUP





E=400GeV

σ_z=6cm!!

$c/\omega_{pe} \approx \sigma_r$ ⇔

N=(1-3)x$10^{11}$$p^+$

σ_r=200µm

n_e ~7x10^{14} cm^{-3}

λ_{pe}~1.3mm<<σ_z

f_{pe} ~240GHz

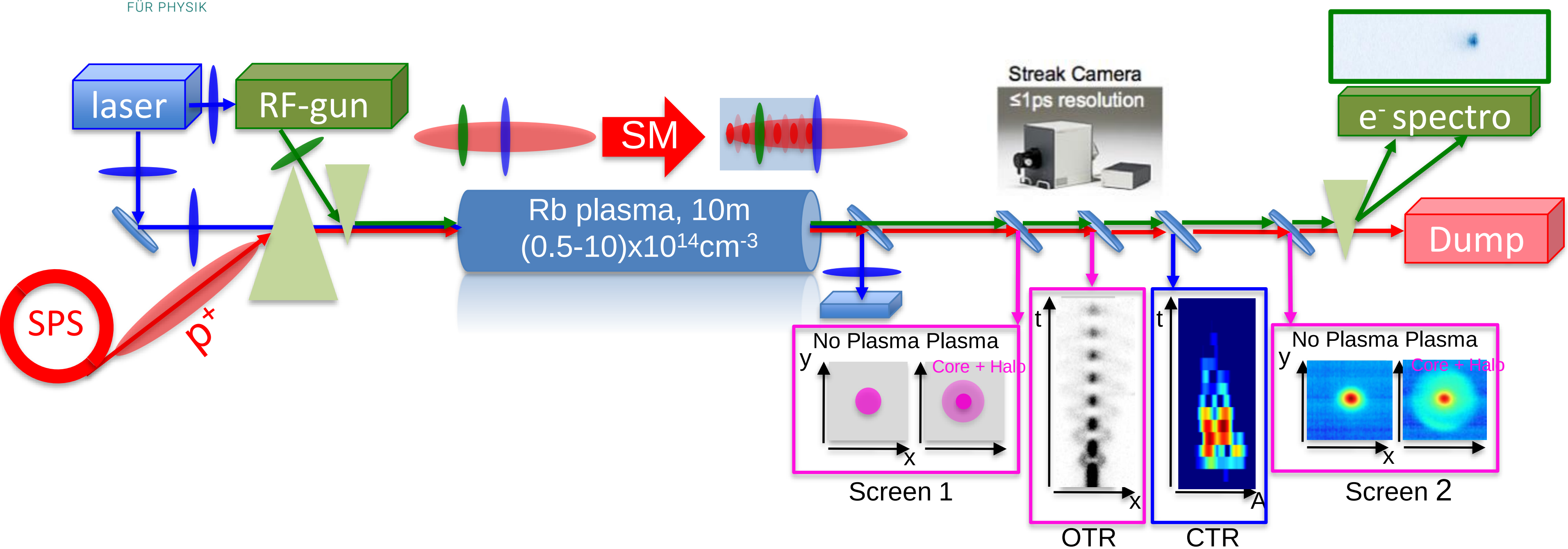
E_{WB}~2.5GV/m

L_p ~10m~2β*

✧Plasma density from σ_r

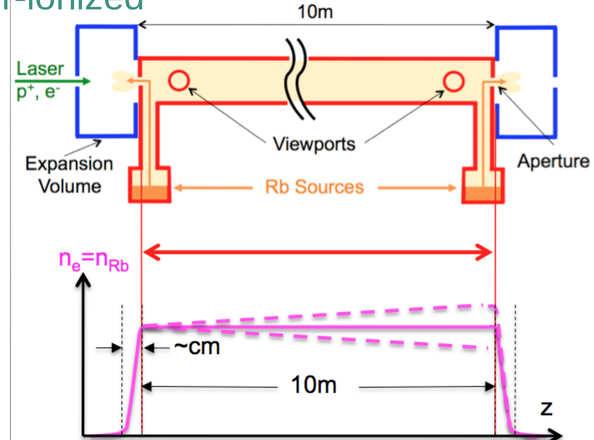
➡ SM ~ 1GeV/m

AWAKE EXPERiMENTAL SETUP

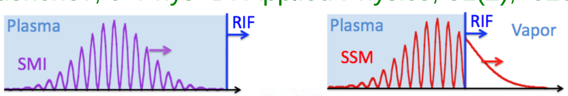


PLASMA SOURCES

✧Rubidium vapor source $0.5<n_{e0}<10*10^{14}cm^{-3}$
✧Laser-ionized

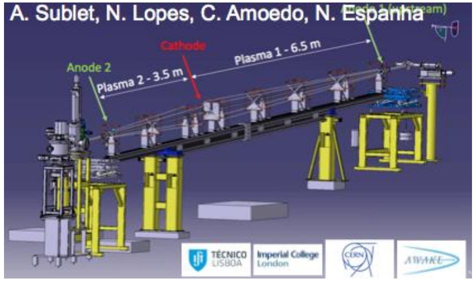


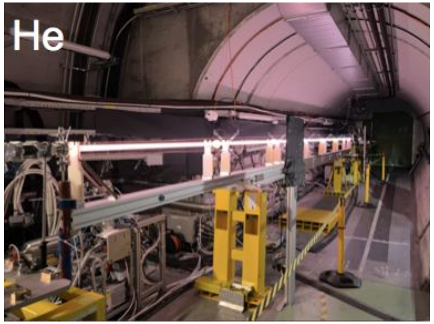
Oz, Nucl. Instr. Meth. Phys. Res. A 740(11), 197 (2014)
Plyushchev, J. Phys. D: Applied Physics, 51(2), 025203 (2017)

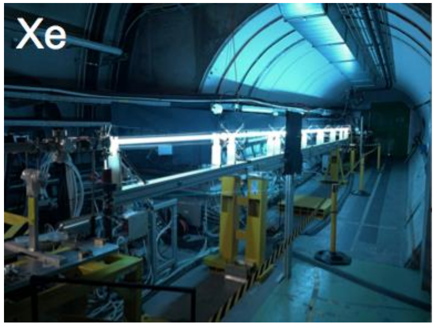


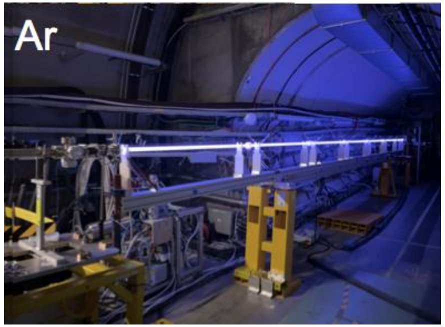
✧Very uniform density uniformity: $\Delta n_e/n_{e0}<0.5\%$

✧Discharge plasma source



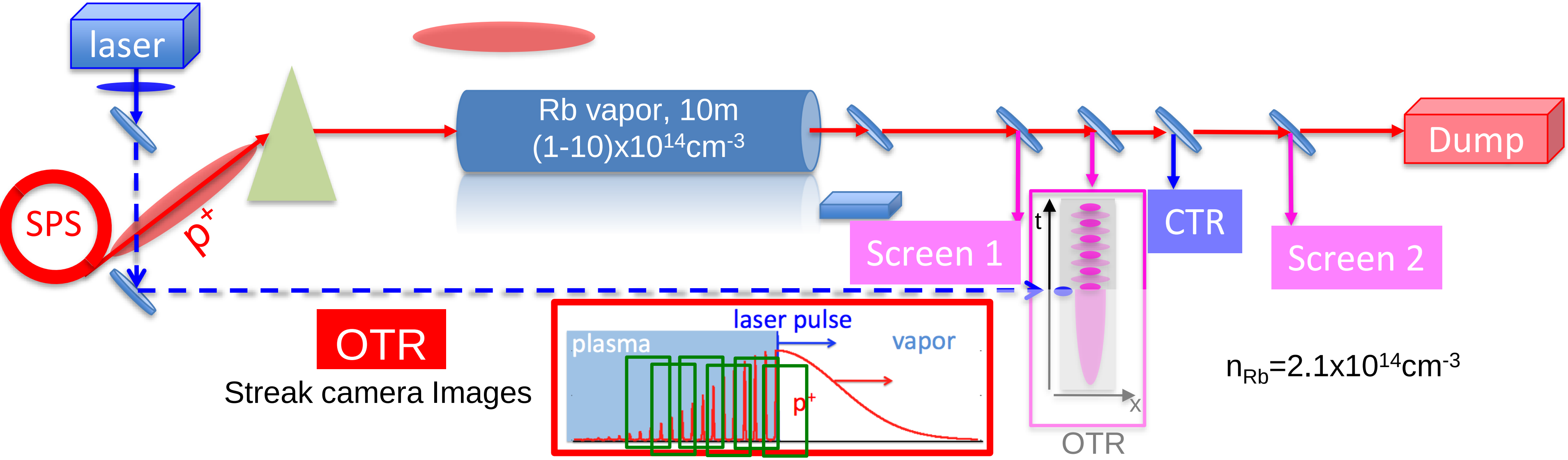


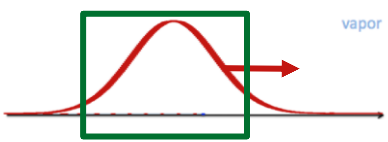


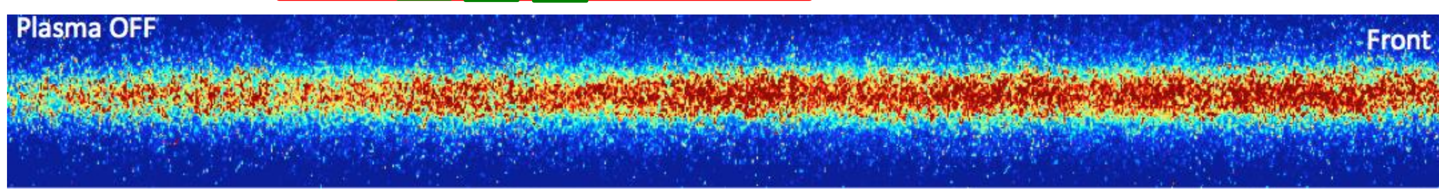


✧Flexibility:
- ✧ Plasma length: 3.5, 6.5, 10m
- ✧ Density $0.1\text{-}20x10^{14}cm^{-3}$
- ✧ Gas-ion mass: He, Ar, Xe (ω_{pi})
- ✧ Access to plasma light

SEEDED SELF-MODULATiON (SSM)





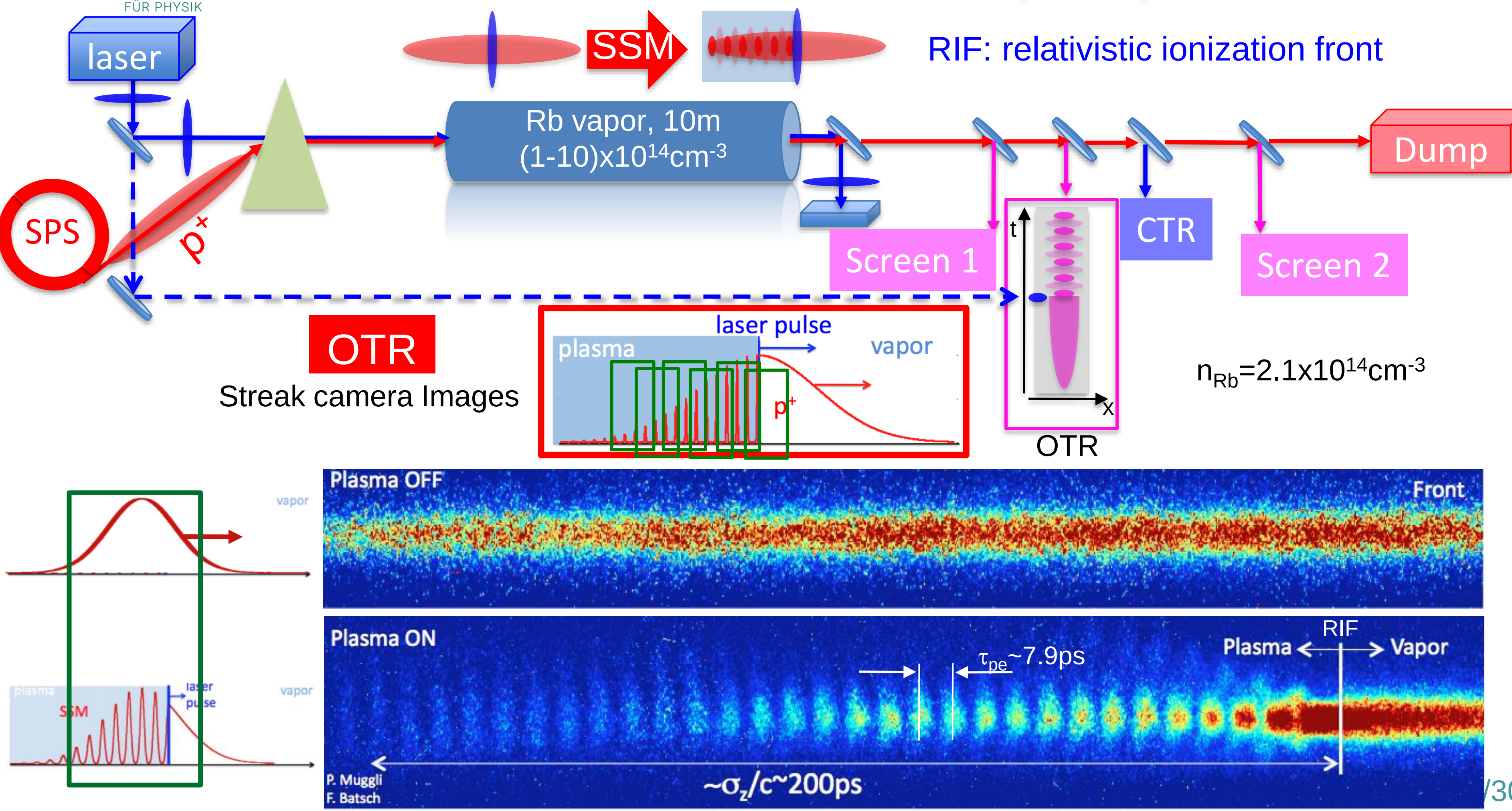


✧No plasma

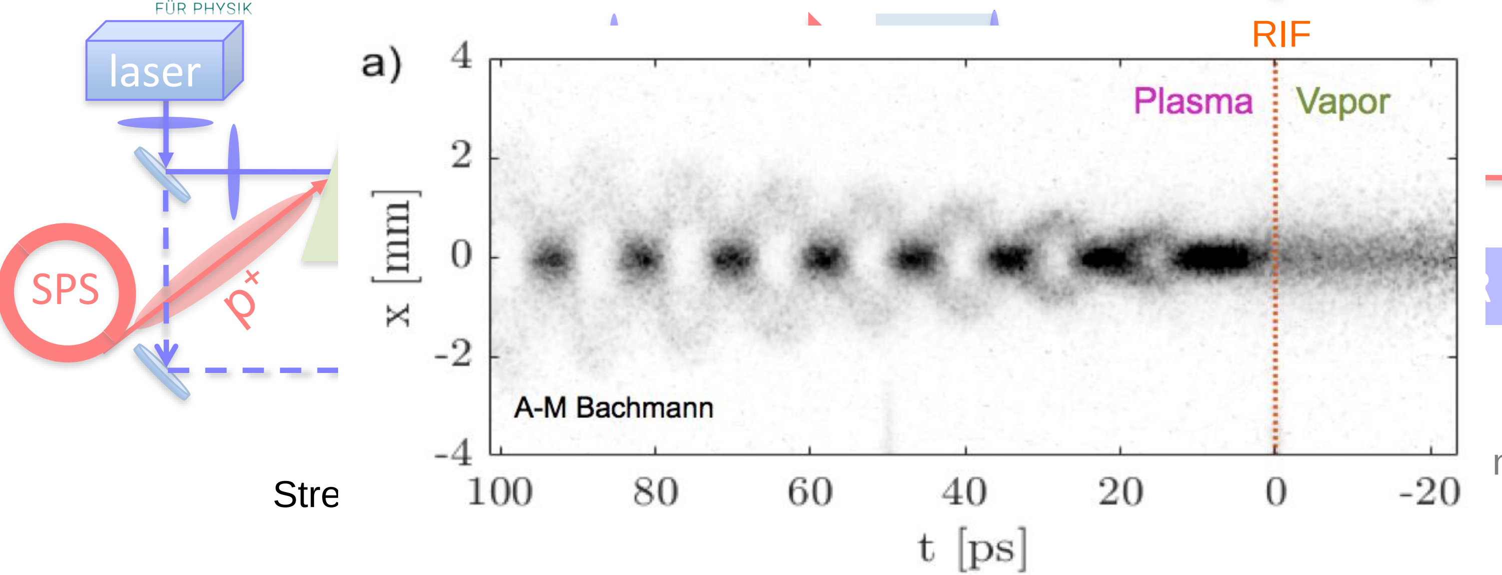
✧No density modulation

✧No centroid position oscillation

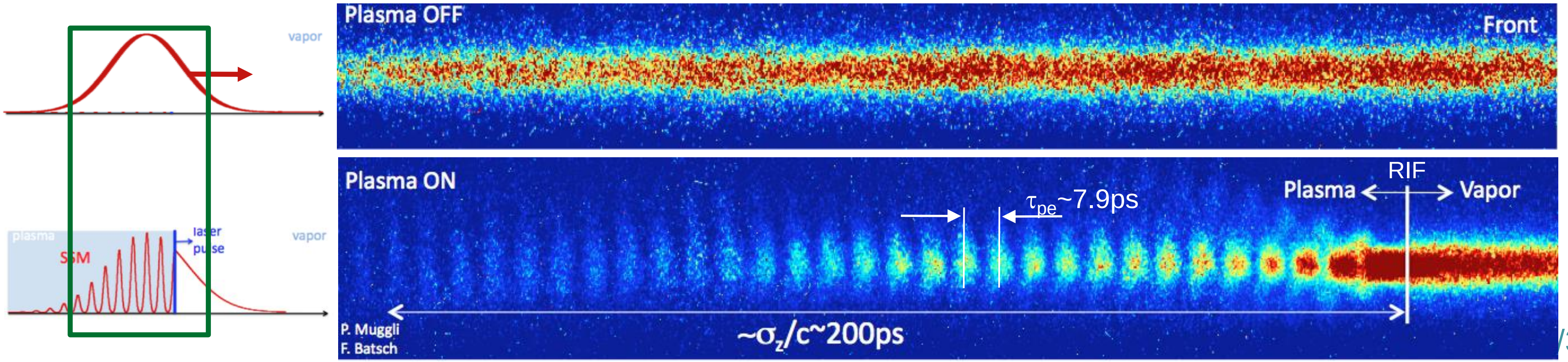
SEEDED SELF-MODULATION (SSM)



SEEDED SELF-MODULATiON (SSM)

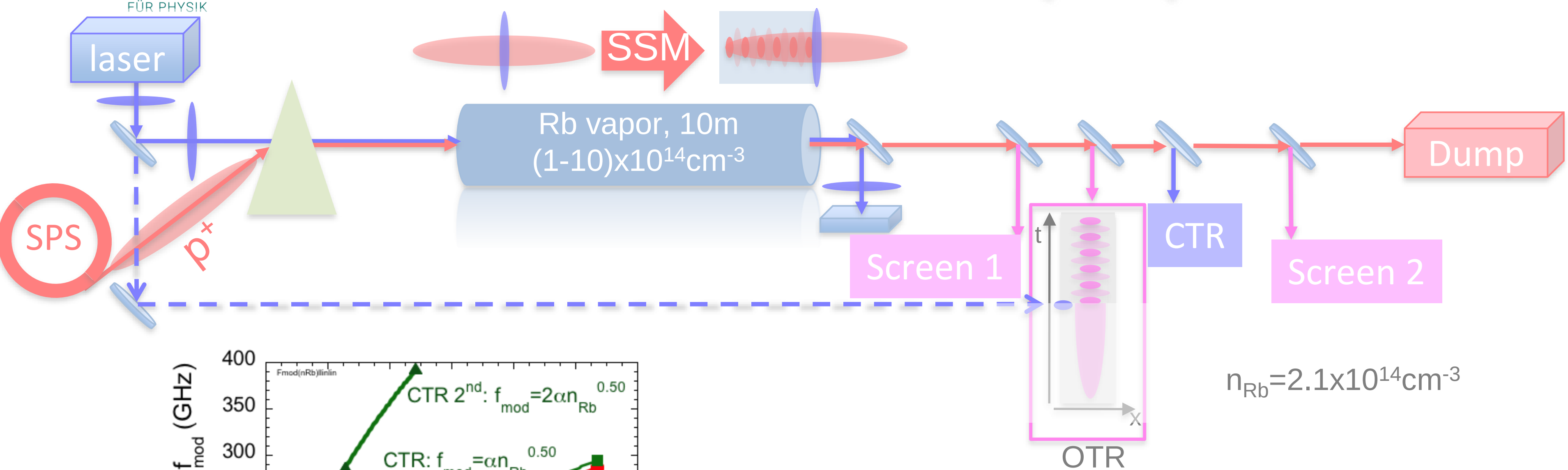


n_{Rb}=2.1x10^{14}cm^{-3}

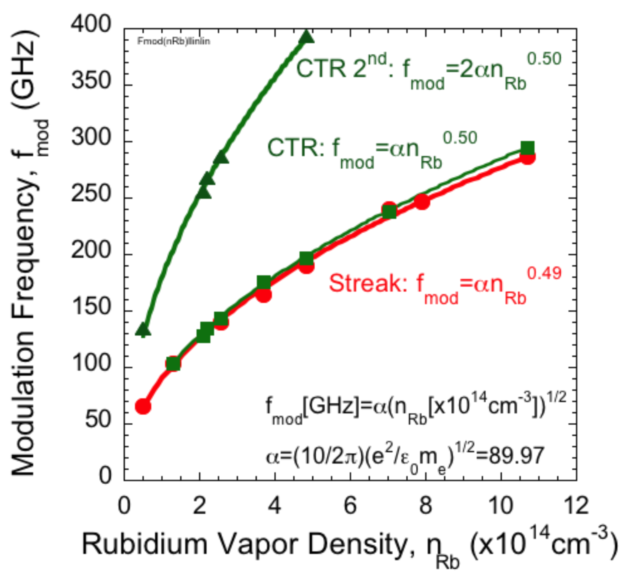


 AWAKE, Phys. Rev. Lett. 122, 054802 (2019) M. Turner et al., Phys. Rev. Lett. 122, 054801 (2019)

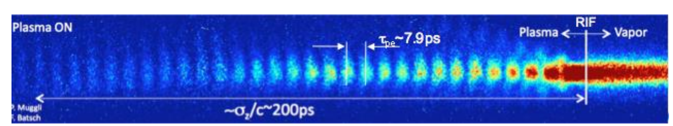
SEEDED SELF-MODULATiON (SSM)



n_{Rb}=2.1x10^{14}cm^{-3}

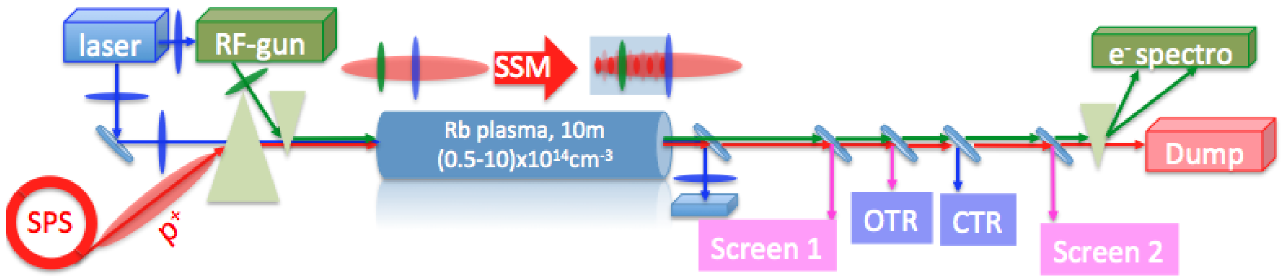


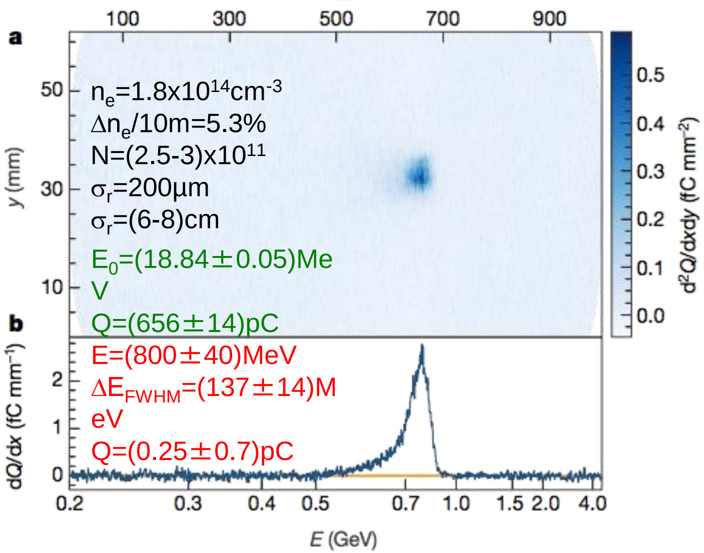
✧ Modulation frequency = f_{pe}

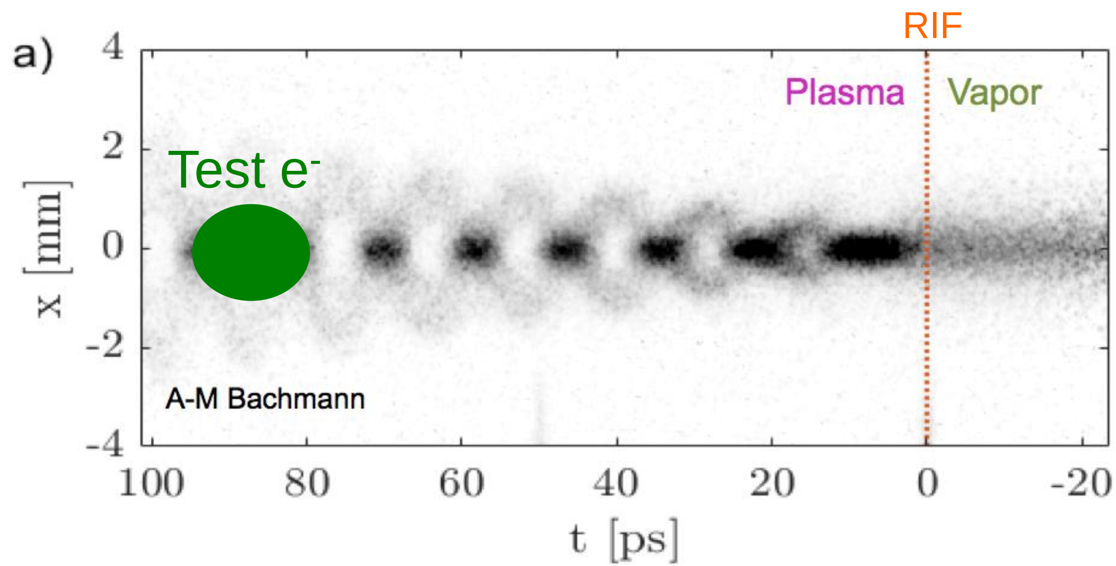


 AWAKE, Phys. Rev. Lett. 122, 054802 (2019) M. Turner et al., Phys. Rev. Lett. 122, 054801 (2019)

ACCELERATiON EXTERNALY-INJECTED e^-



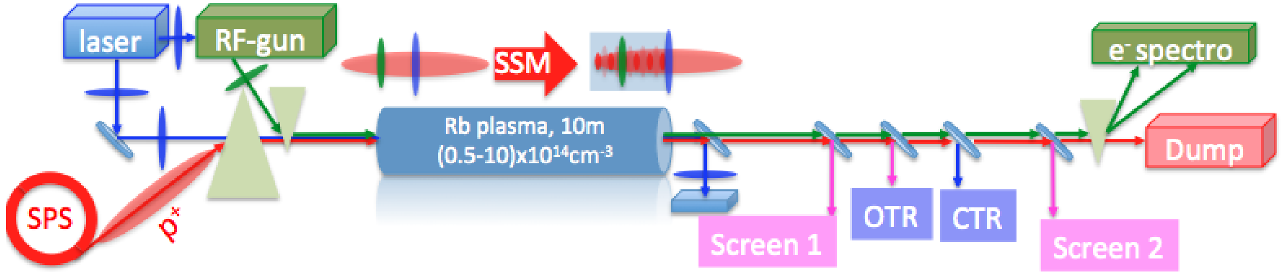


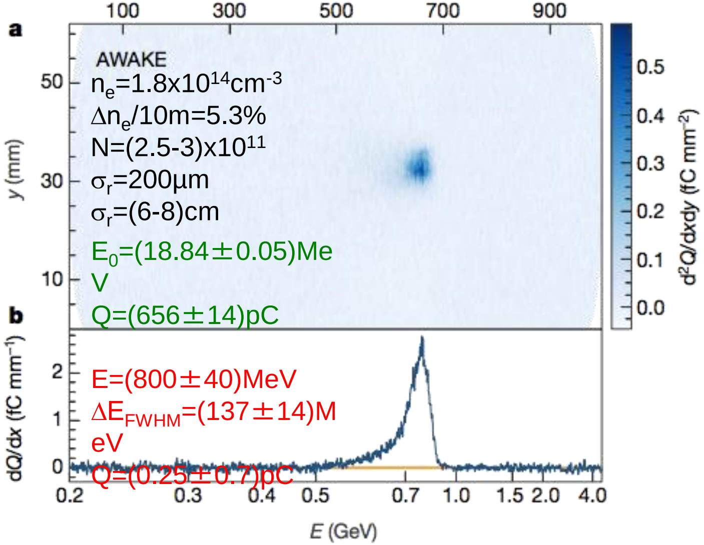


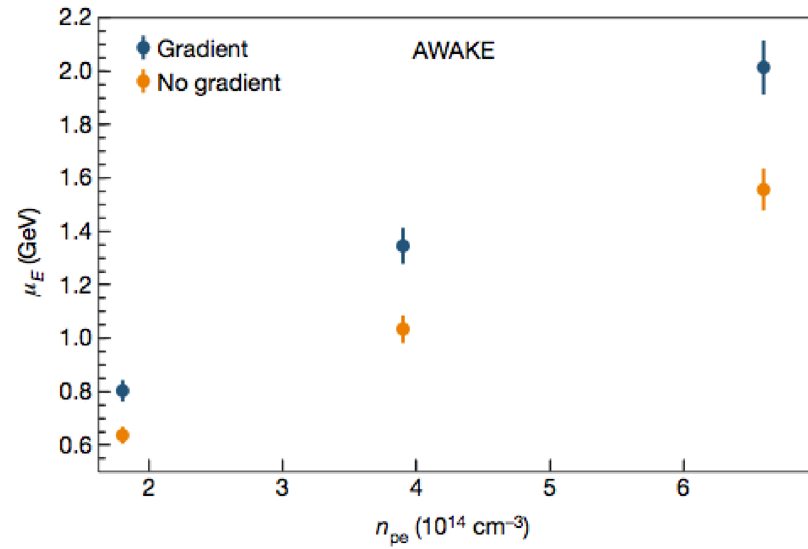
- ✧ Injection test e^- at an angle (~1-3mrad)
- ✧ Finite $\Delta E/E$

AWAKE, Nature 561, 363 (2018)

ACCELERATiON EXTERNALY-INJECTED e$^-$



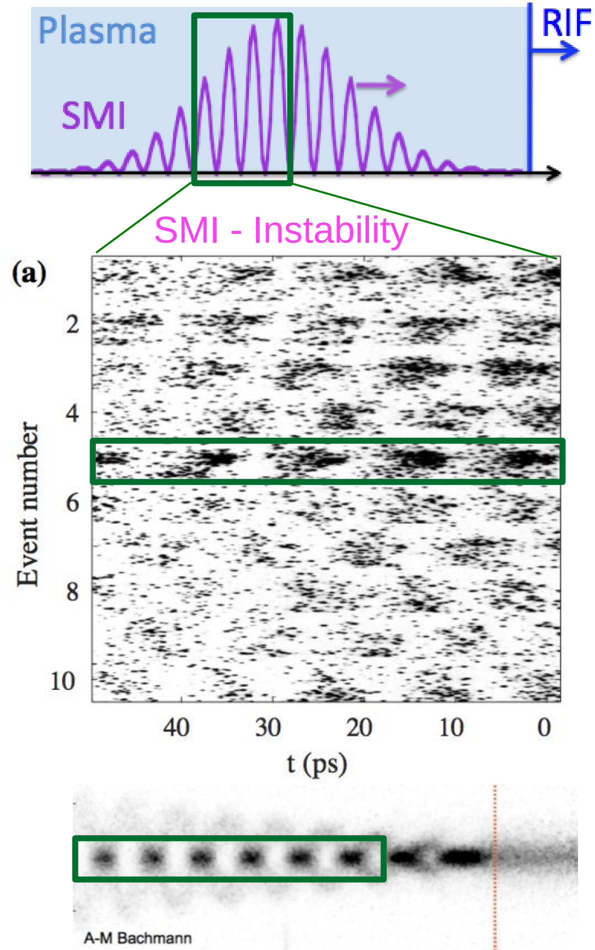




- ✧ Injection test e$^-$ at an angle (~1-3mrad)
- ✧ Finite $\Delta E/E$
- ✧ Up to 2GeV energy gain (from ~19MeV)
- ✧ Captured charge: ~pC

AWAKE, Nature 561, 363 (2018)

SEEDED SELF-MODULATiON (SSM)



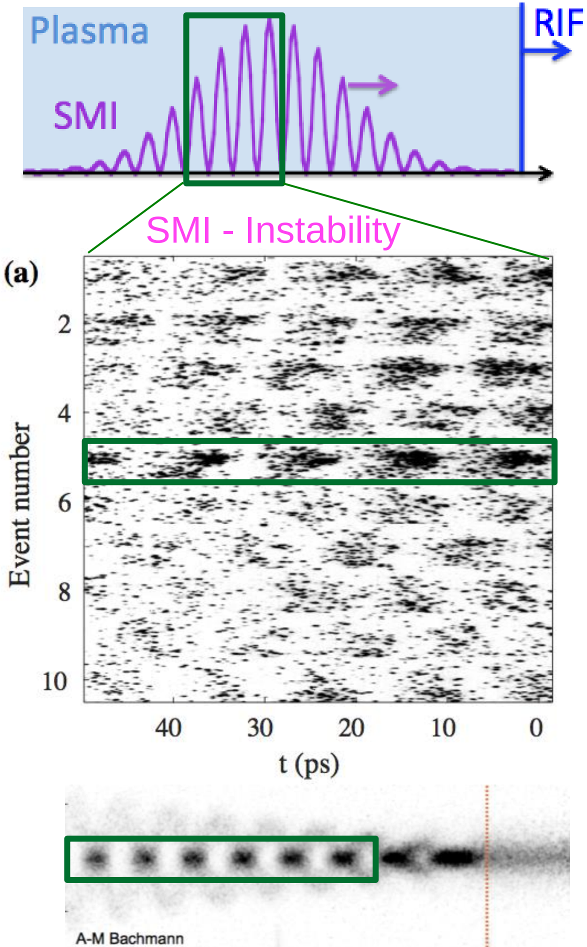
µ-bunches
@ varying times

10 events

$n_{e0}=10^{14}cm^{-3}$
$N_{p+}=3x10^{11}$

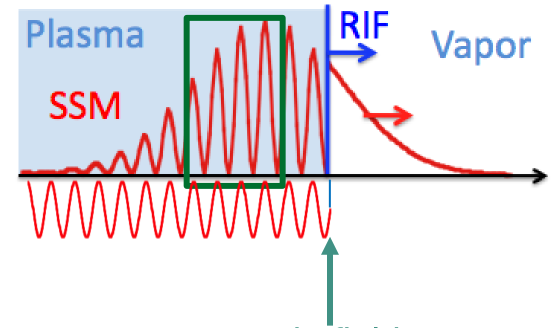
F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

SEEDED SELF-MODULATiON (SSM)



μ-bunches
@ varying times

10 events

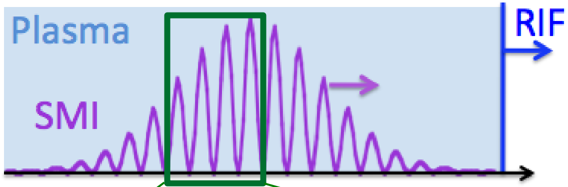


Wakefields
start
here!

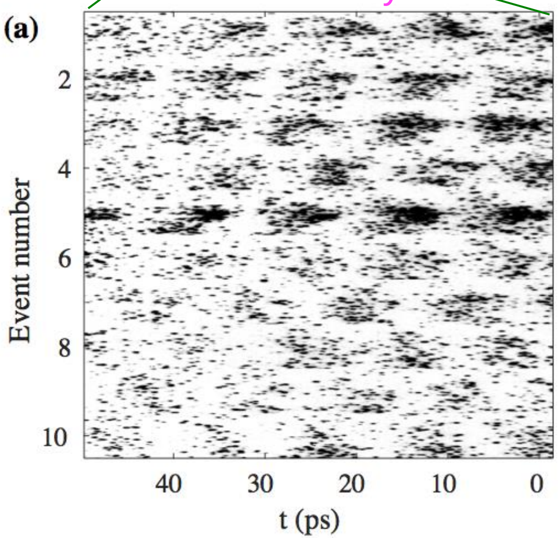
✧Relativistic ionization front (RIF)
✧Abrupt (<<$1/\omega_{pe}$) start beam/plasma interaction
✧Seed wakefields

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

SEEDED SELF-MODULATiON (SSM)



SMI - Instability

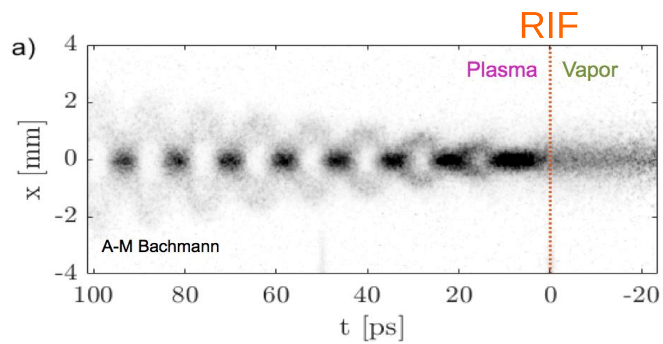


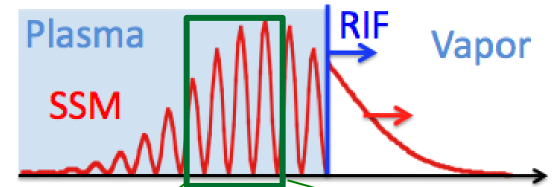
Relativistic Ionization Front
(RIF)
Seeding

µ-bunches
@ varying times

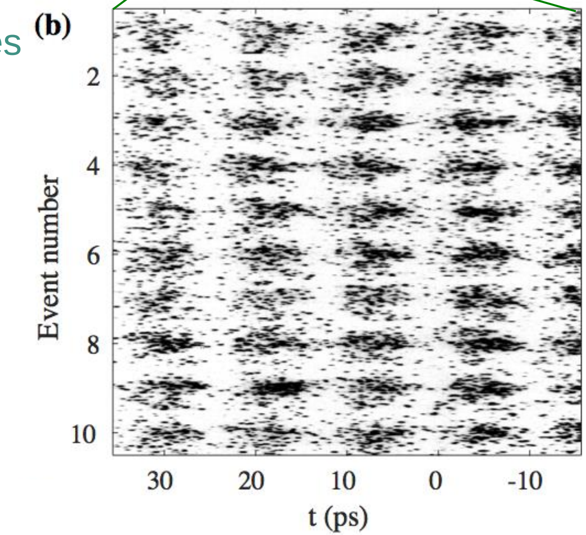
µ-bunches
@ fixed times

REPRODUCIBLE!





SSM - Control

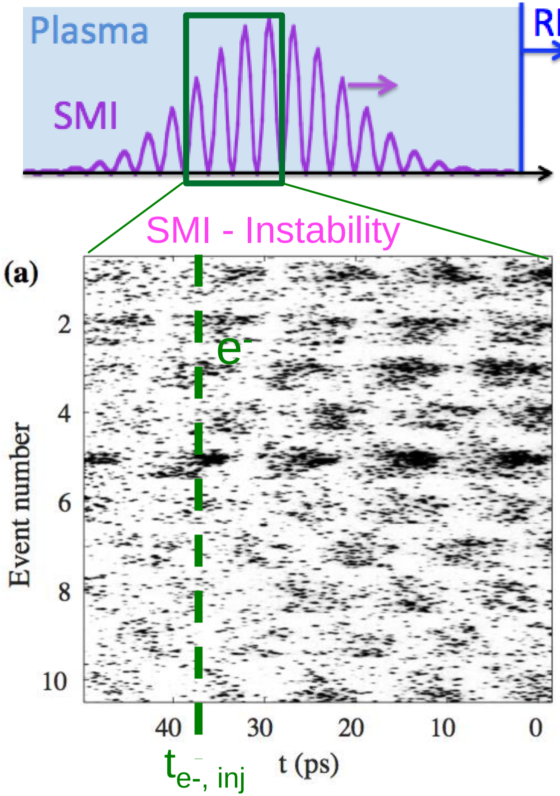


✧Transition from SMI to SSM
✧SSM, RIF seeding: $\Delta\Phi/2\pi \leq 8\%$
✧SMI –SSM transition:
  ✧$t_{RIF} \sim 2\sigma_{p+}$
  ✧$2.8\text{MV/m} \leq E_{z,seed} \leq 4\text{MV/m}$ @ $n_e=10^{14}\text{cm}^{-3}$

✧Summed image confirms reproducibility
✧Wakefields start at the RIF

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

SEEDED SELF-MODULATiON (SSM)

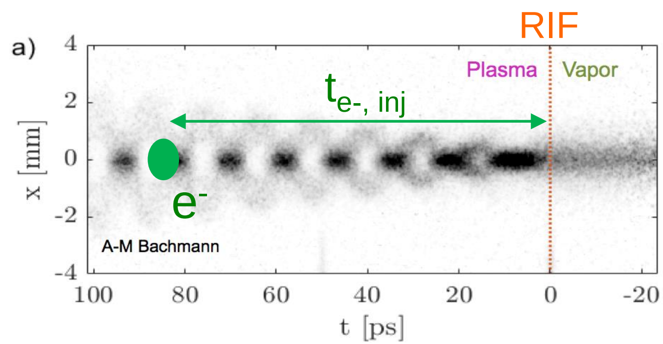


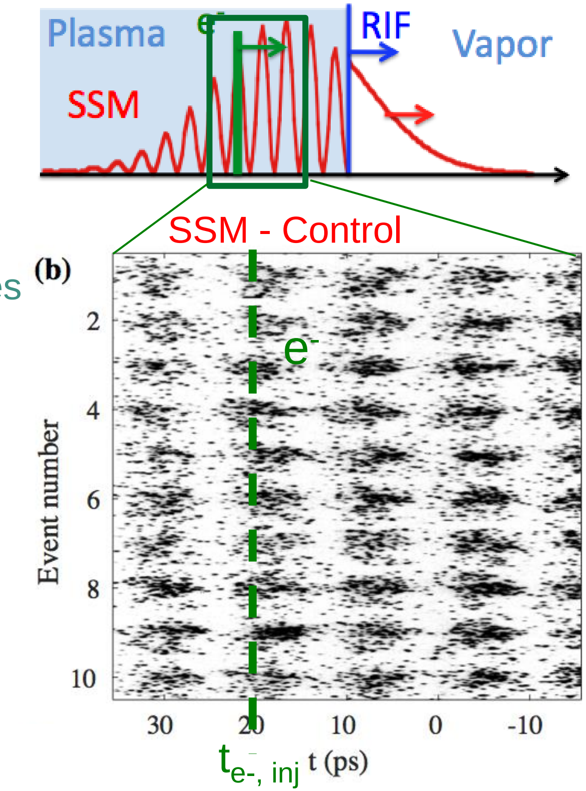
Relativistic Ionization Front
(RIF)
Seeding

μ-bunches
@ varying times

μ-bunches
@ fixed times

REPRODUCIBLE!

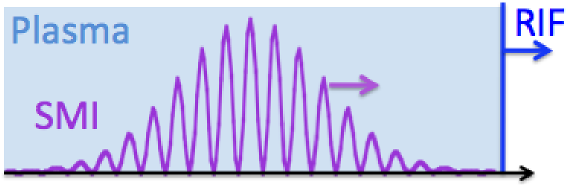




✧Reproducibility essential for deterministic injection/acceleration
✧$t_{e-, inj}$ fixed!

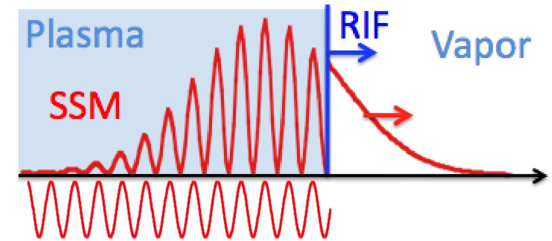
F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

SEEDED SELF-MODULATiON (SSM)



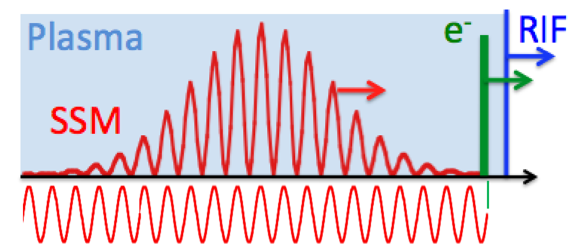
SMI - Instability

Relativistic Ionization Front (RIF) Seeding



SSM - Control

e-bunch Seeding



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

PHYSICAL REVIEW LETTERS

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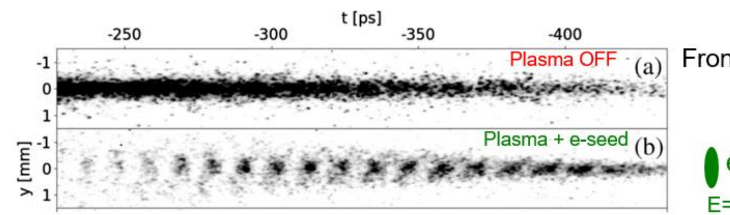
Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma

L. Verra *et al.* (AWAKE Collaboration)
Phys. Rev. Lett. **129**, 024802 – Published 6 July 2022

Physics See synopsis: Controlling Instabilities in a Plasma Particle Accelerator



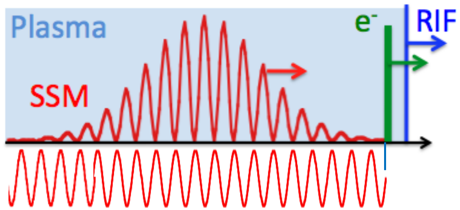
e⁻ hν

E=19MeV
Q=250pC
σ_r=200µm
σ_t=3-5ps
$n_{e0}=10^{14}cm^{-3}$

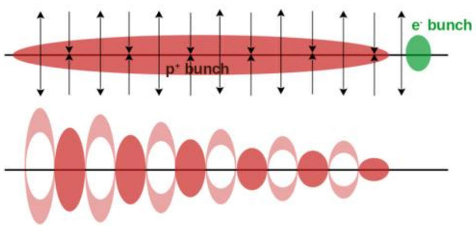
- ✧SSM seeded by wakefields of e-bunch
- ✧Same reproducibility as RIF-seeding
- ✧SSM of entire bunch
- ✧Independent control of seed (e^-) and growth (p^+, n_{e0}) parameters

HOSiNG

✧e-bunch seeding of SM



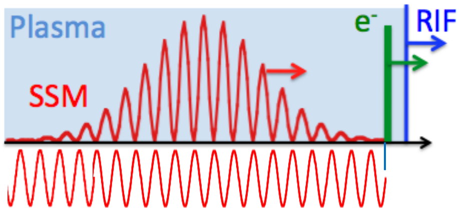
✧e$^-$ and p$^+$ aligned …



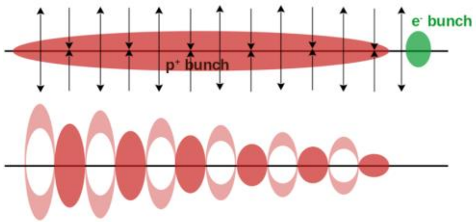
✧… axi-symmetric SM

HOSING

✧e-bunch seeding of SM

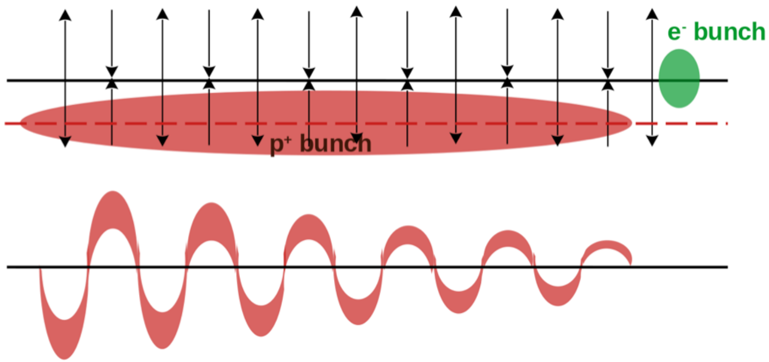


✧e^- and p^+ aligned …



✧… axi-symmetric SM

✧e^- and p^+ mis-aligned …



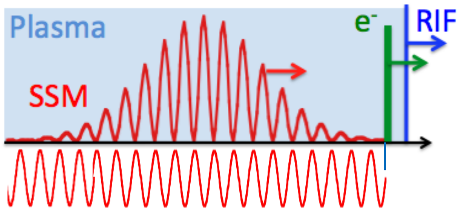
✧… non-axi-symmetric hosing (mis-alignment plane)

✧… and SM in the perpendicular plane (“no misalignment” plane)

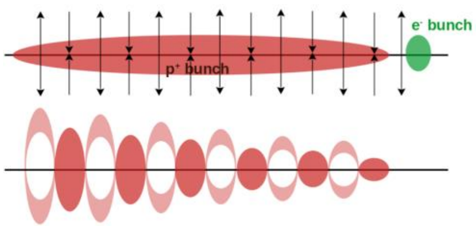
T. Nechaeva et al., AWAKE Collaboration, Phys. Rev. Lett. 132, 075001 (2024)

HOSiNG

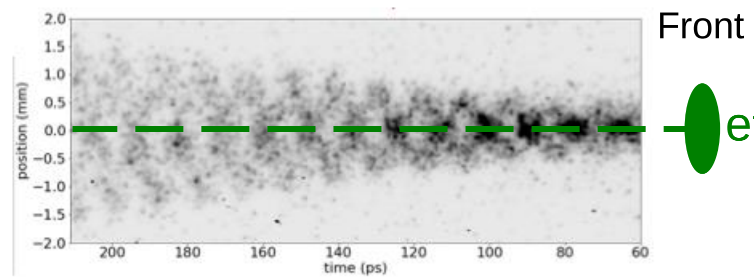
- e-bunch seeding of SM



- e^- and p^+ aligned …



- … axi-symmetric SM



- e^-/p^+ aligned
- Self-modulation
- Symmetric

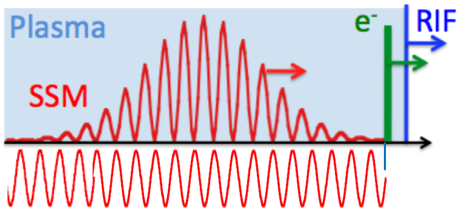
T. Nechaeva

$n_{e0}=10^{14}cm^{-3}$
$N_{p+}=3x10^{11}$

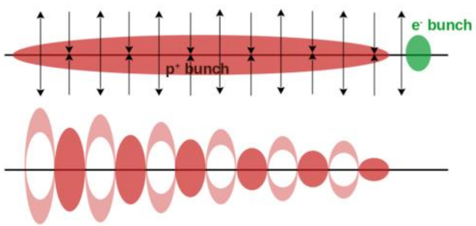
T. Nechaeva et al., AWAKE Collaboration, Phys. Rev. Lett. 132, 075001 (2024)

HOSiNG

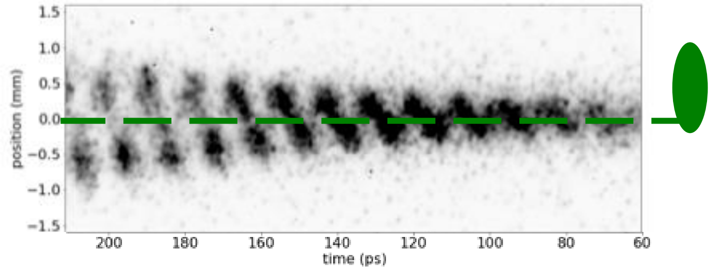
✧e-bunch seeding of SM



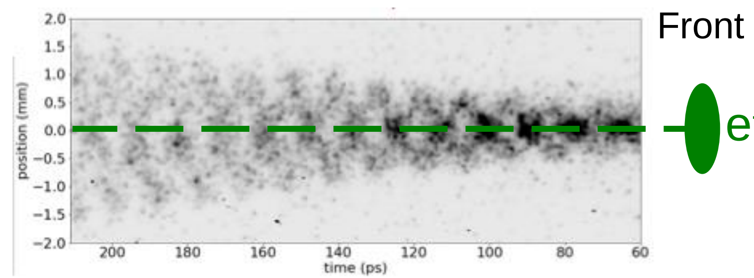
✧e- and p+ aligned …



✧… axi-symmetric SM

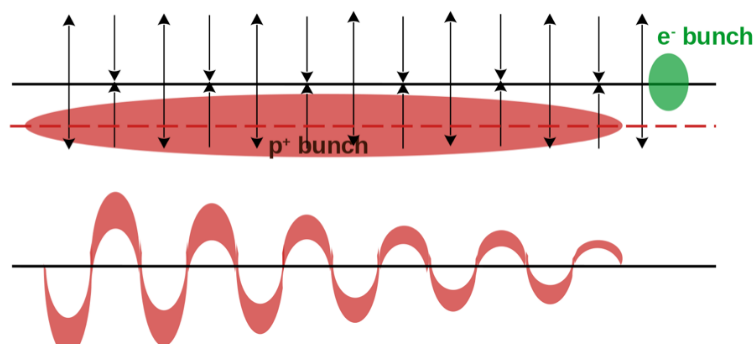


✧e^-/p^+ mis-aligned
✧Hosing
✧Centroid oscillation



✧e^-/p^+ aligned
✧Self-modulation
✧Symmetric

T. Nechaeva

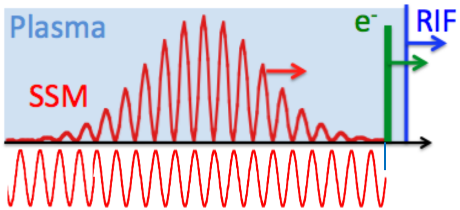


✧SM and HI together
✧$f_{HI} \sim f_{SM} \sim f_{pe}$
✧Induced by wakefields

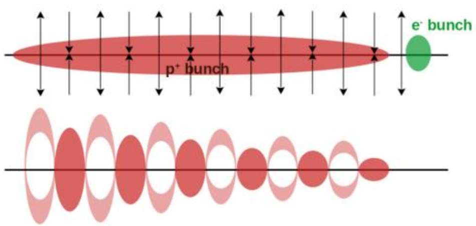
T. Nechaeva et al., AWAKE Collaboration, Phys. Rev. Lett. 132, 075001 (2024)

HOSiNG

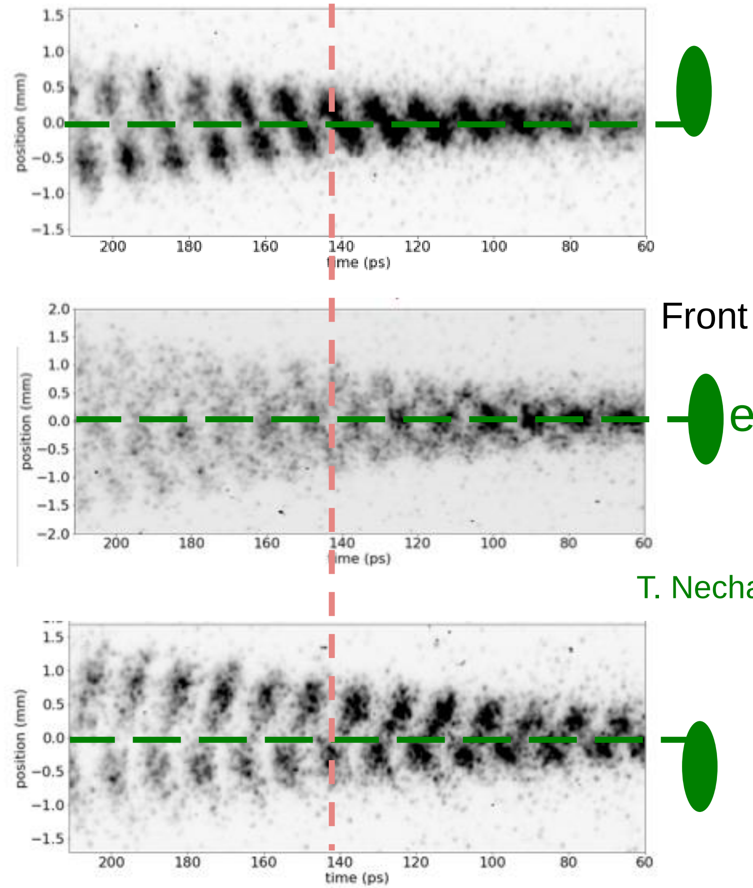
✧e-bunch seeding of SM



✧e^- and p^+ aligned …



✧… axi-symmetric SM



✧e^-/p^+ mis-aligned
✧Hosing
✧Centroid oscillation

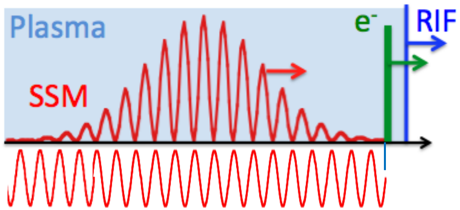
✧e^-/p^+ aligned
✧Self-modulation
✧Symmetric

✧e^-/p^+ mis-aligned
✧Hosing
✧Reversed!

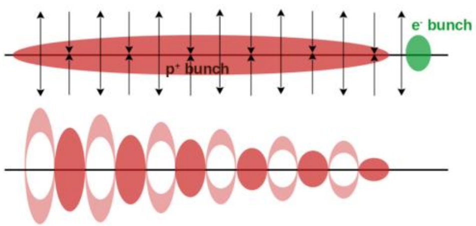
T. Nechaeva et al., AWAKE Collaboration, Phys. Rev. Lett. 132, 075001 (2024)

HOSiNG

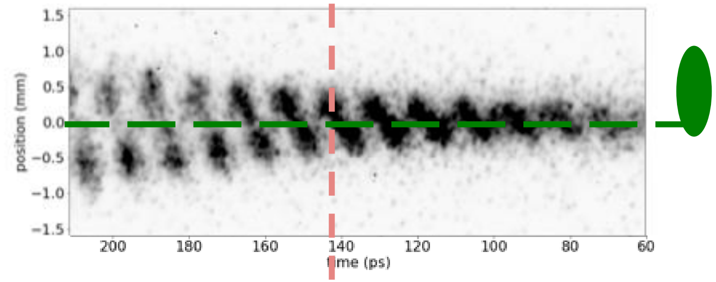
✧e-bunch seeding of SM



✧e$^-$ and p$^+$ aligned …

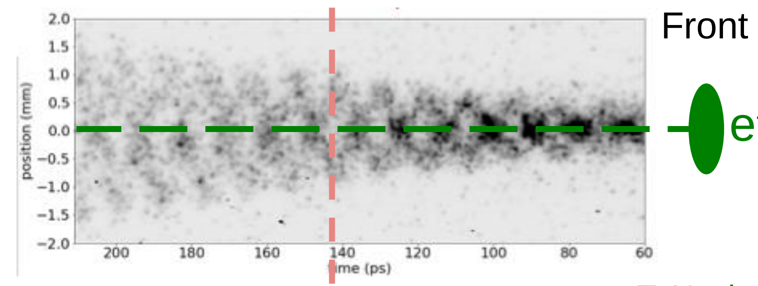


✧… axi-symmetric SM



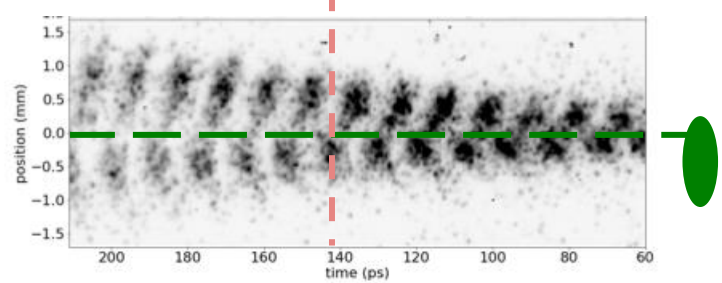
✧e$^-$/p$^+$ mis-aligned
✧Hosing
✧Centroid oscillation

Front



✧e$^-$/p$^+$ aligned
✧Self-modulation
✧Symmetric

T. Nechaeva



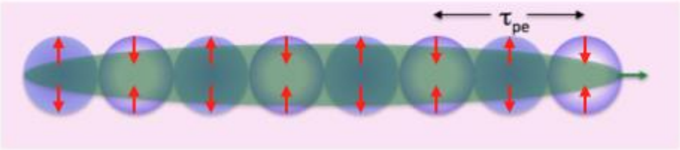
✧e$^-$/p$^+$ mis-aligned
✧Hosing
✧Reversed!

T. Nechaeva et al., AWAKE Collaboration, Phys. Rev. Lett. 132, 075001 (2024)

✧Hosing could deteriorate, limit the acceleration process…

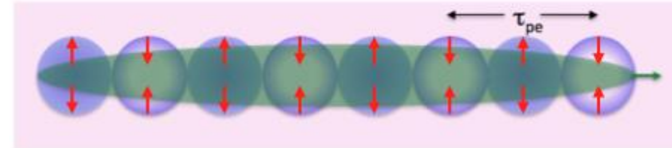
FILAMENTATION INSTABILITY

✧ σ_{r0}<c/ω_{pe}: ($k_{pe}\sigma_{r0}$ <1) optimum for wakefield generation …



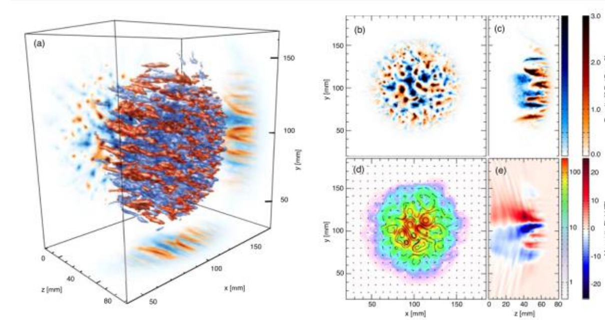
Return current outside the bunch
Wakefields can develop

FiLAMENTATiON INSTABiLiTY



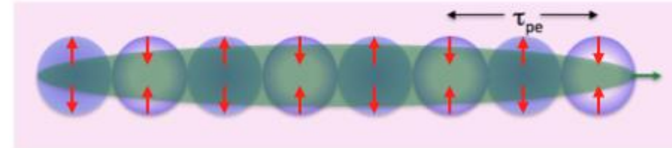
- ✧σ_{r0}<c/ω_{pe}: ($k_{pe}\sigma_{r0}$ <1) optimum for wakefield generation …
- ✧σ_{r0}>>c/ω_{pe}: ($k_{pe}\sigma_{r0}$ >>1) filamentation instabilities can develop …
  - ✧Equal streams: current filamentation instability (CFI)
  - ✧Unequal streams: oblique modes, wakefields, …

$n_b << n_{e0}$
$v_{p+} >> v_e$ → $\vec{k} = \vec{k}_\perp + \vec{k}_{||}$



Shukla, J. Plasma Phys. 84(3) 905840302 (2018)
Allen, Phys. Rev. Lett. 109, 185007 (2012)

FiLAMENTATiON INSTABiLiTY

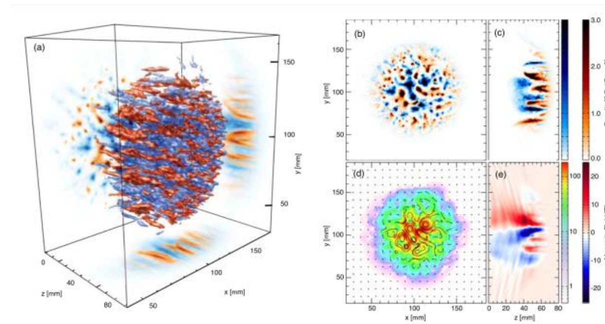


✧ $\sigma_{r0}<c/\omega_{pe}$: ($k_{pe}\sigma_{r0}$ <1) optimum for wakefield generation …

✧ $\sigma_{r0}>>c/\omega_{pe}$: ($k_{pe}\sigma_{r0}$ >>1) filamentation instabilities can develop …

- ✧ Equal streams: current filamentation instability (CFI)
- ✧ Unequal streams: oblique modes, wakefields, …

$n_b<< n_{e0}$
$v_{p+}>> v_e$ → $\vec{k}=\vec{k}_{\perp}+\vec{k}_{||}$



✧ Astrophysics: generation of magnetic fields in the universe?

- ✧ Collision: neutral, expanding supernova plasma – interstellar plasma

Core-collapse, or type II supernovas, are caused by the implosion of massive stars like red supergiants. (Supplied: ESA/Hubble/L. Calcada)

✧ CFI :

- ✧ Generates magnetic fields
- ✧ Converts kinetic energy of the expanding plasma into B-field energy and plasma kinetic energy
- ✧ Evolution: filaments -> coalescence -> shock formation

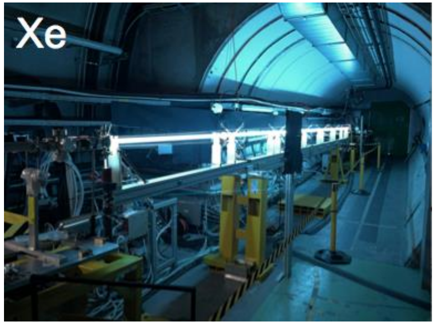
✧ Study FI with relativistic particle bunch (p^+) or “fireball” (e^- e^+) beam

✧ “Astrophysics in the lab”

Shukla, J. Plasma Phys. 84(3) 905840302 (2018)
C.D. Arrowsmith, Nat. Comm. 15, 5029 (2024)

Filamentation Instability

Transverse Filamentation: σ_{r0}~200 => 550μm>>c/ω_{pe} AND σ_z>>c/ω_{pe}

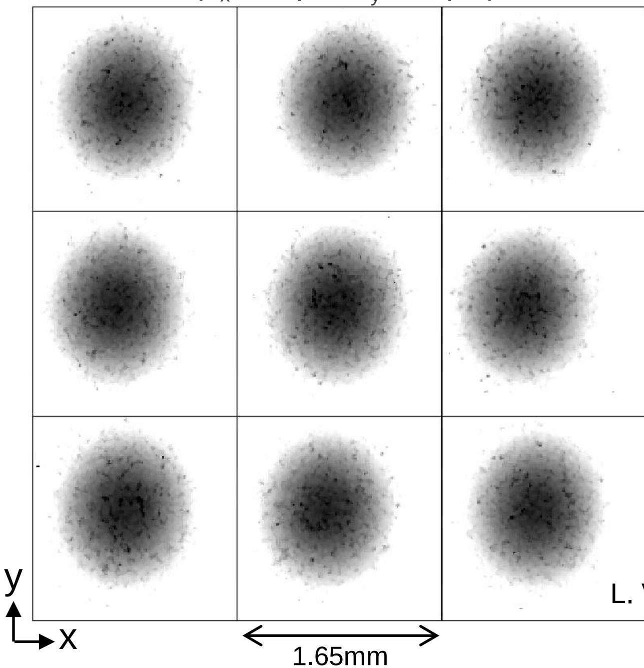


L. Verra et al., AWAKE Collaboration, Phys. Rev. E 109, 055203 (2024)

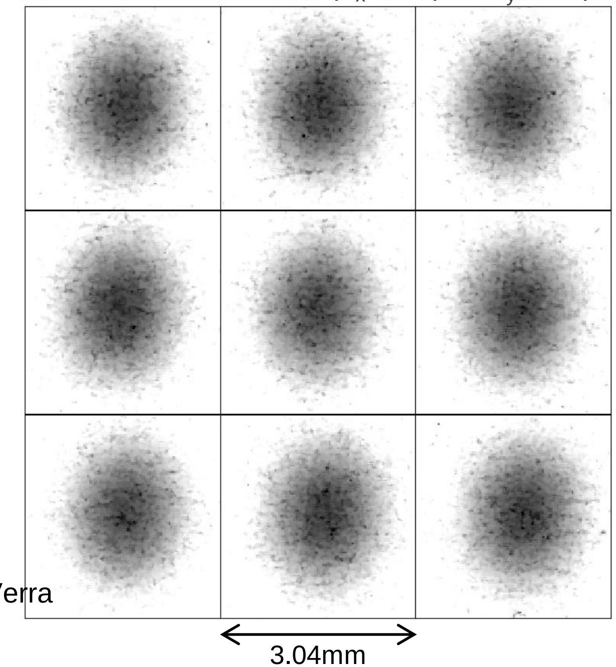
FiLAMENTATiON INSTABiLiTY

Transverse Filamentation: σ_{r0}~200 => 550µm>>c/ω_{pe} AND σ_z>>c/ω_{pe}

Entrance (σ_x=480µm, σ_y=520µm)

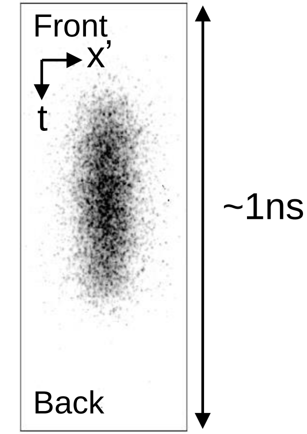


Exit: Plasma OFF (σ_x=810µm, σ_y=870µm)

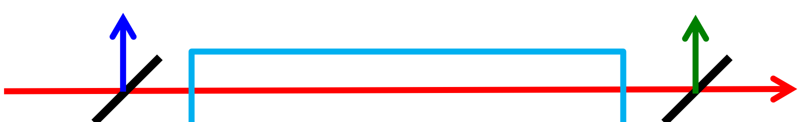


L. Verra

Plasma OFF



σ_{slit}=1.0mm
σ_t=170ps

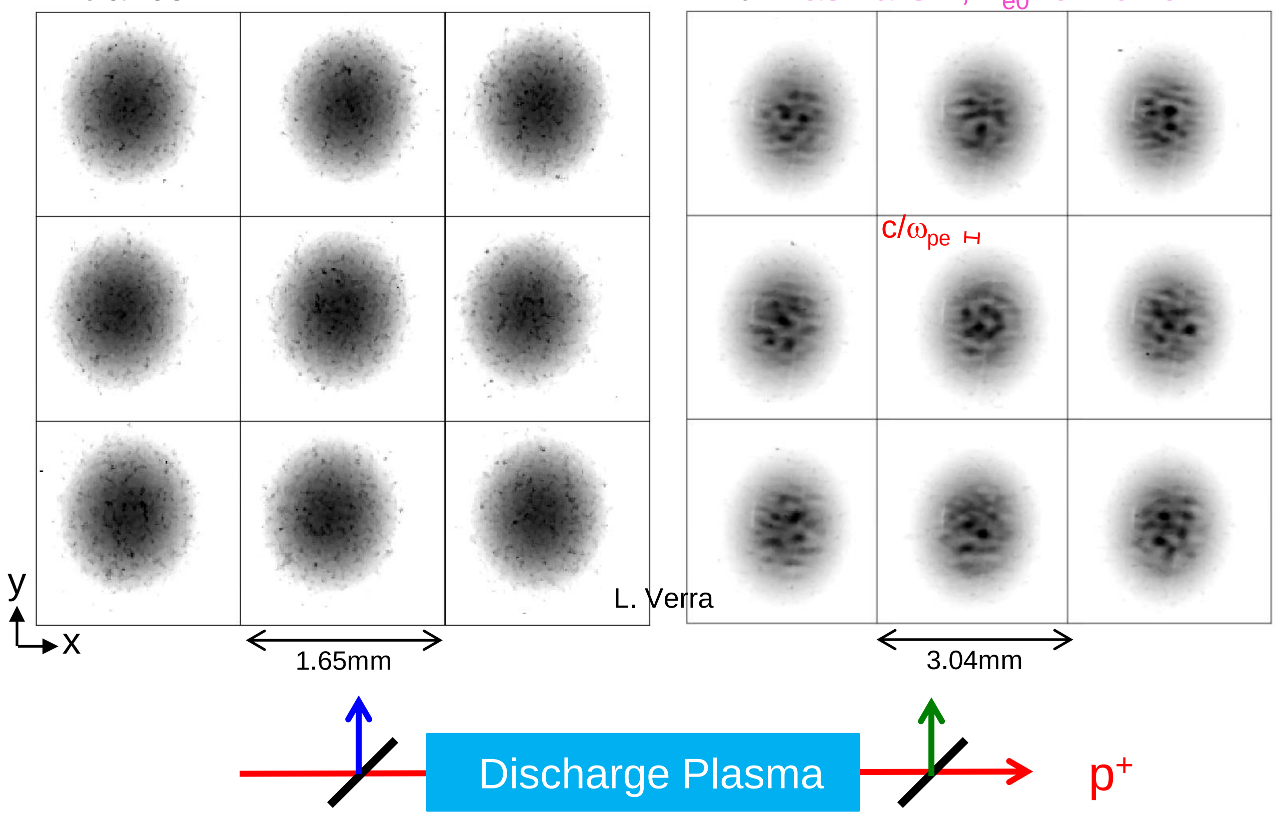


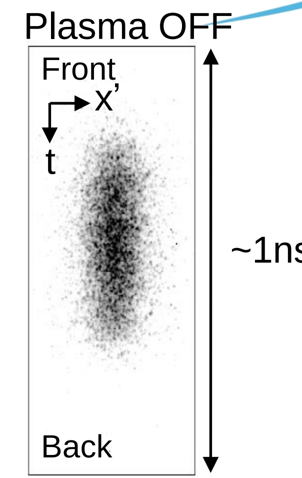
✧Incoming bunch without transverse features (Gaussian)

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

FiLAMENTATiON INSTABiLiTY

Transverse Filamentation: σ_{r0}~550µm~3.2c/ω_{pe} AND σ_z>>c/ω_{pe}





✧Incoming bunch without transverse features (Gaussian)

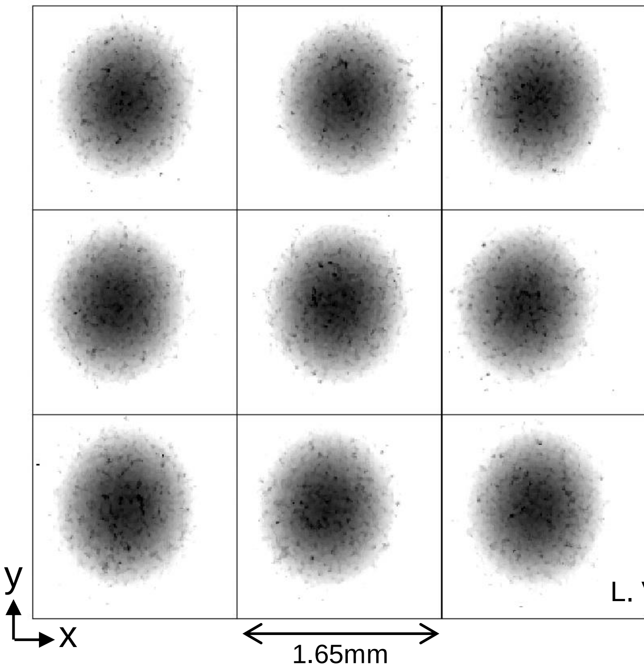
✧Filaments with plasma

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

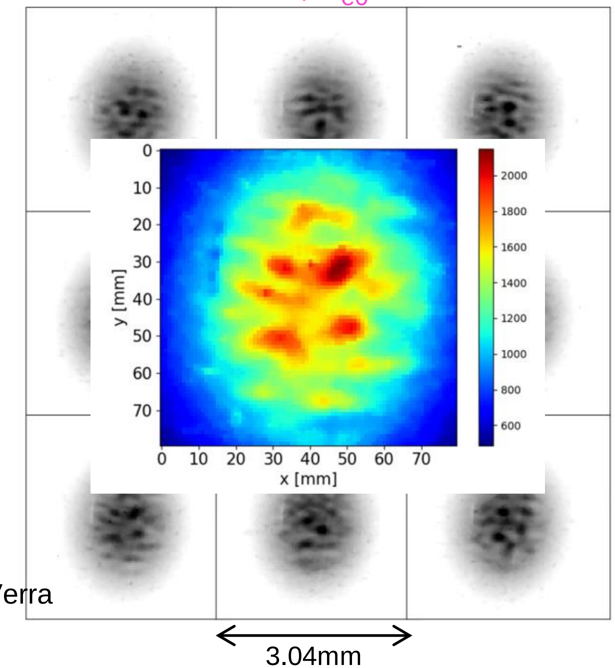
FILAMENTATION INSTABILITY

Transverse Filamentation: σ_{r0}~550µm~3.2c/ω_{pe} AND σ_z>>c/ω_{pe}

Entrance

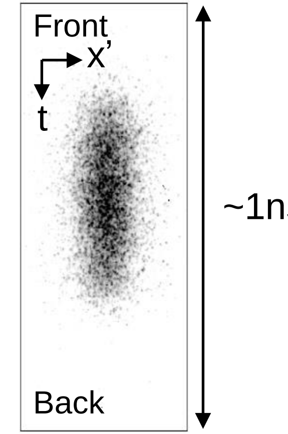


Exit: Plasma ON, n_{e0}=9x10^{14}cm^{-3}



L. Verra

Plasma OFF



✧Incoming bunch without transverse features (Gaussian)

✧Filaments with plasma

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

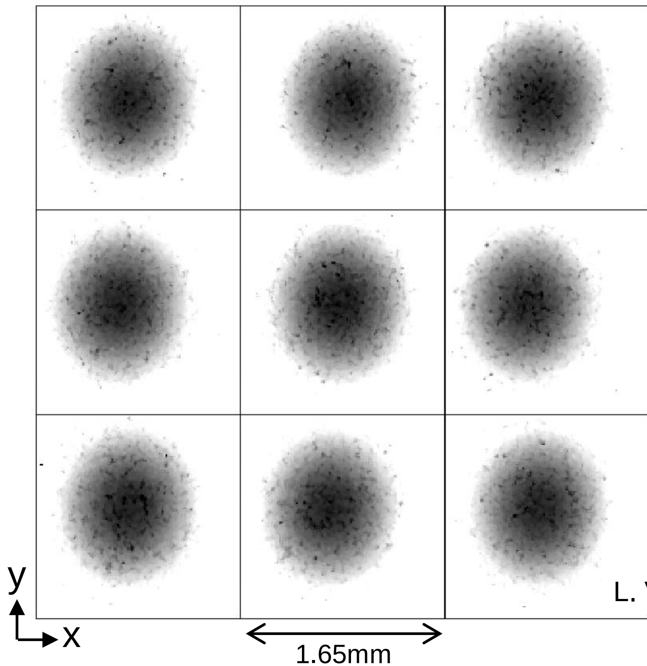
MAX-PLANCK-INSTITUT FÜR PHYSIK

FiLAMENTATiON INSTABiLiTY

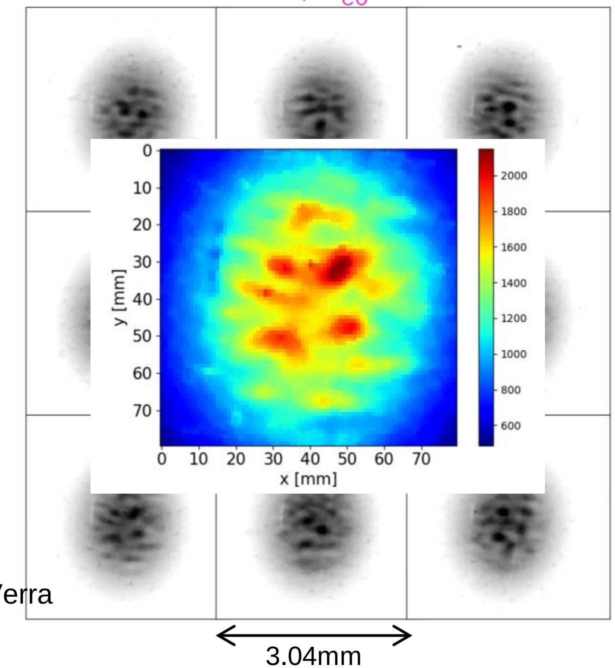
AWAKE

Transverse Filamentation: σ_{r0}~550µm~3.2c/ω_{pe} AND σ_z>>c/ω_{pe}

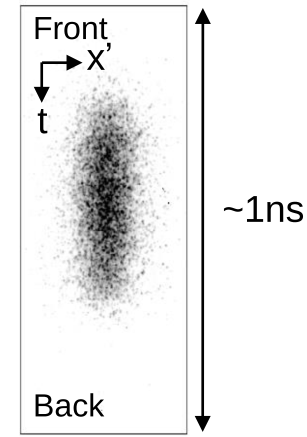
Entrance



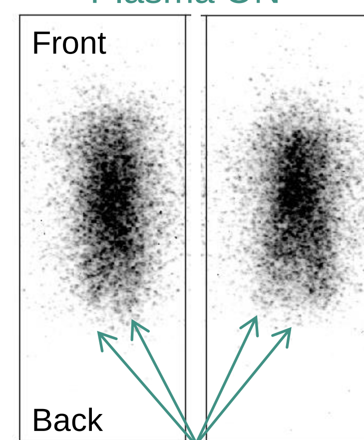
Exit: Plasma ON, n_{e0}=9x10^{14}cm^{-3}



Plasma OFF



Plasma ON



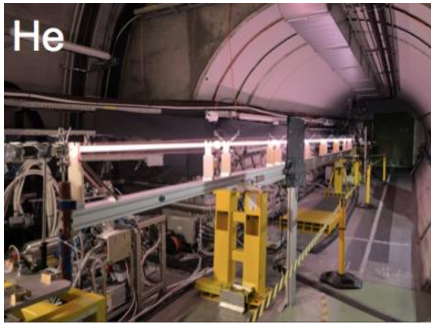
Filament?

✧Incoming bunch without transverse features (Gaussian)

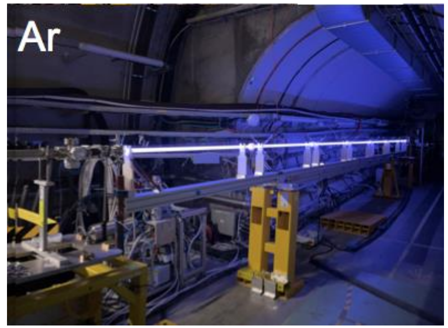
✧Filaments with plasma, late along the bunch, early stage?

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

DISCHARGE PLASMA SOURCE

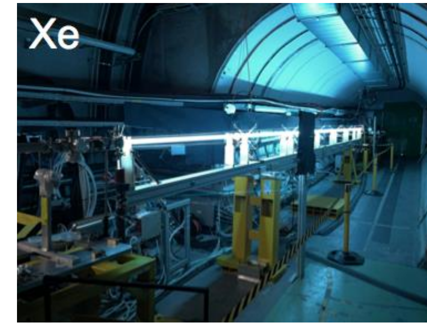


✧A_{He}=4



✧A_{Ar}=40

✧A_{Rb}=85



✧A_{xe}=131

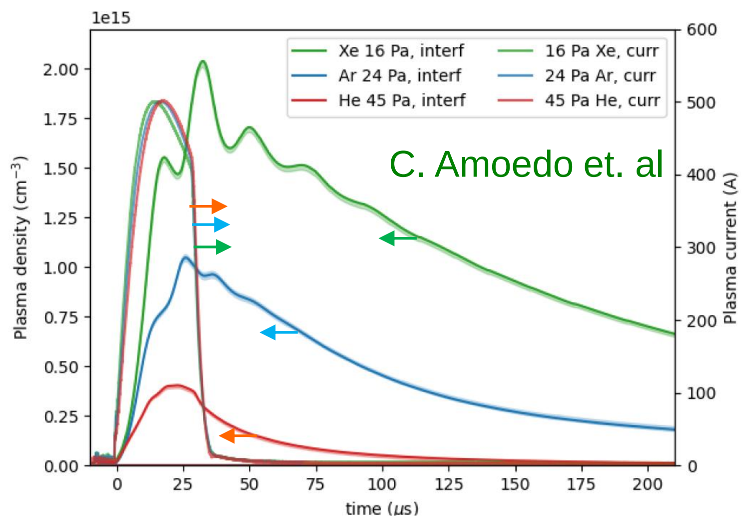
Discharge plasma source (DPS):

✧Quick change of density

✧Reach high plasma densities >10^{15}cm^{-3}

✧**Change ion species: He, Ar, Xe**

✧No alignment (r_p~10mm)

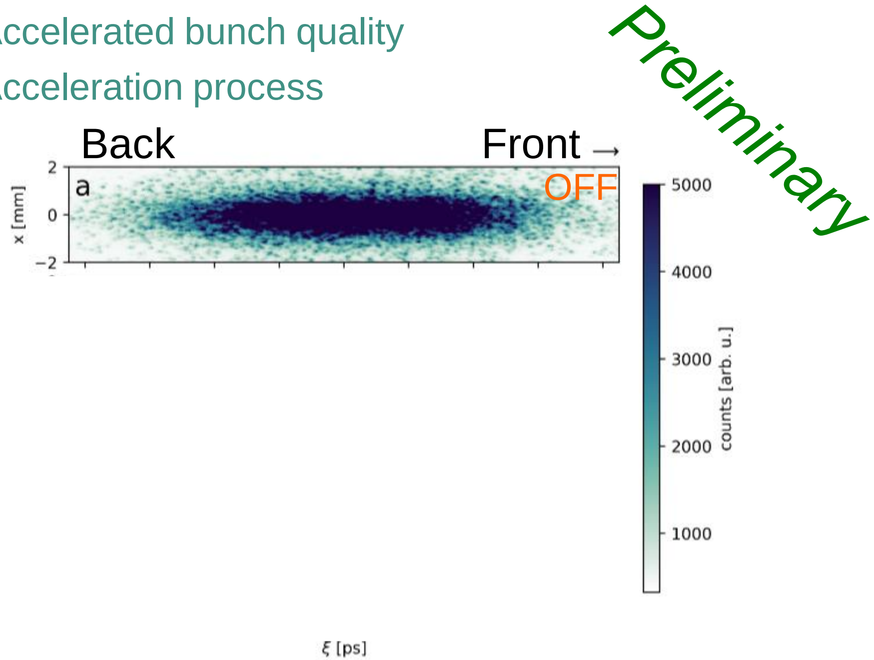


Ion Motion?

Effect of ion motion on:

✧Accelerated bunch quality

✧Acceleration process



M. Turner

Long, low density bunch:

Plasma:

✧Light, mobile electrons

✧Heavy ($m_i \geq 1832 m_e$) immobile ions

✧ $\omega_{pe} >> \omega_{pi}$

✧ps ⬄ ns

✧Large force, ions move at ω_{pe} scale?

✧Not seeded: SMI

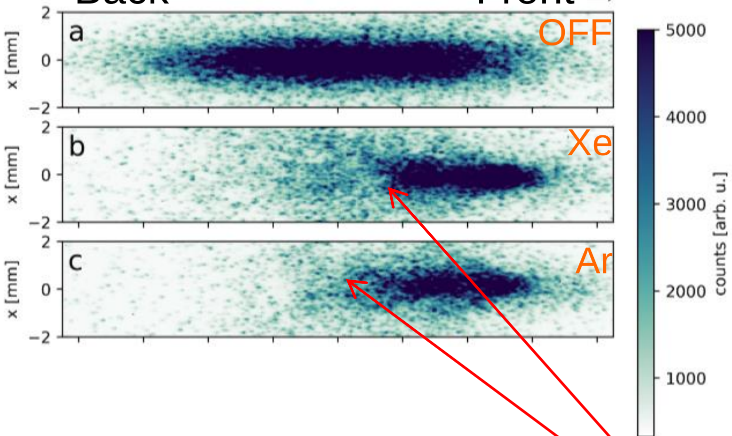
ION MOTION?

Effect of ion motion on:

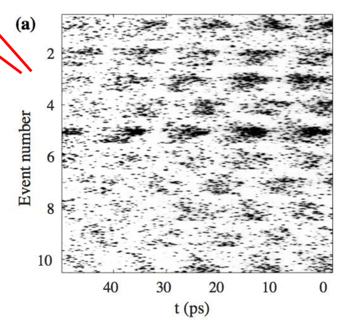
✧Accelerated bunch quality

✧Acceleration process

Preliminary



No!



M. Turner

Long, low density bunch:

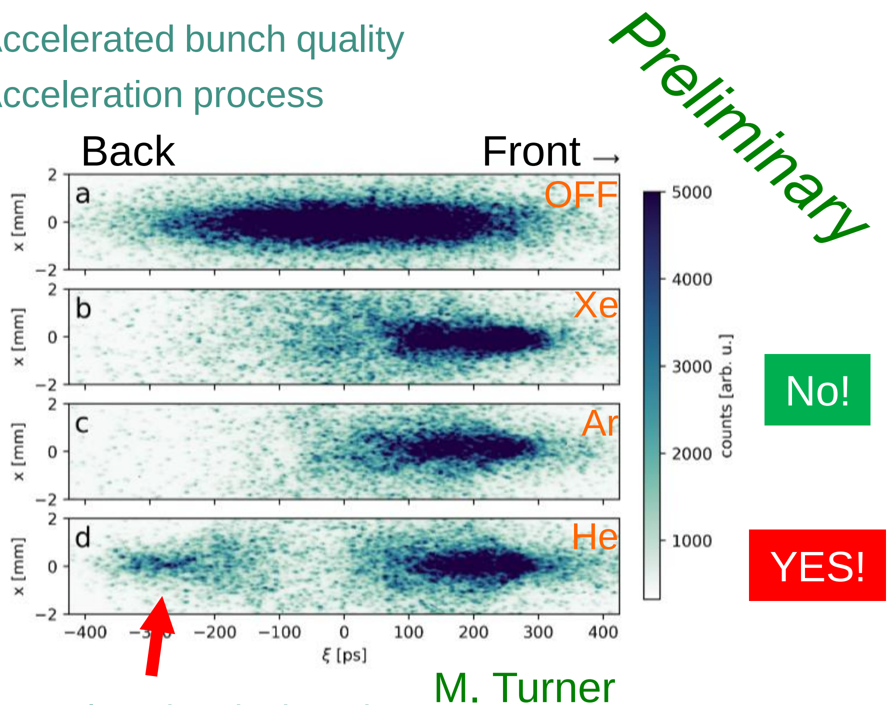
✧Typical SMI (Xe, Ar)

ION MOTION?

Effect of ion motion on:

✧Accelerated bunch quality

✧Acceleration process



Long, low density bunch:

✧Typical SMI (Xe, Ar)

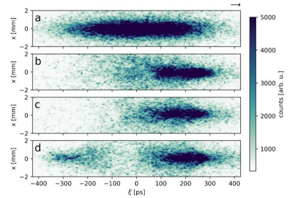
✧"Tail" appear in the back of the bunch (He)

ION MOTION

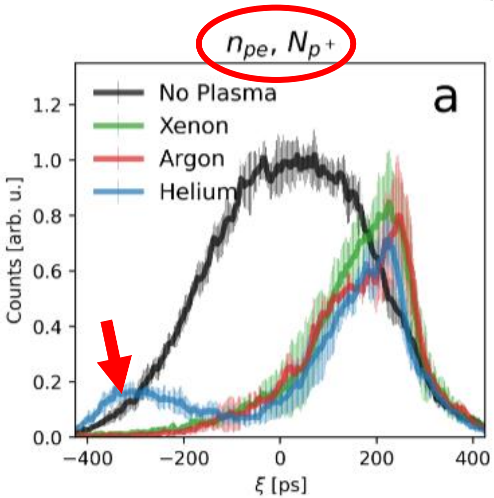
Effect of ion motion on:

✧Accelerated bunch quality

✧Acceleration process



M. Turner



✧ “Tail” with He, not with Ar, Xe

Long, low density bunch:

✧Typical SMI (Xe, Ar)

✧“Tail” appear in the back of the bunch (He)

Preliminary

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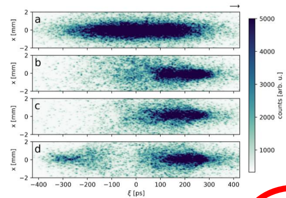
ION MOTION

AWAKE

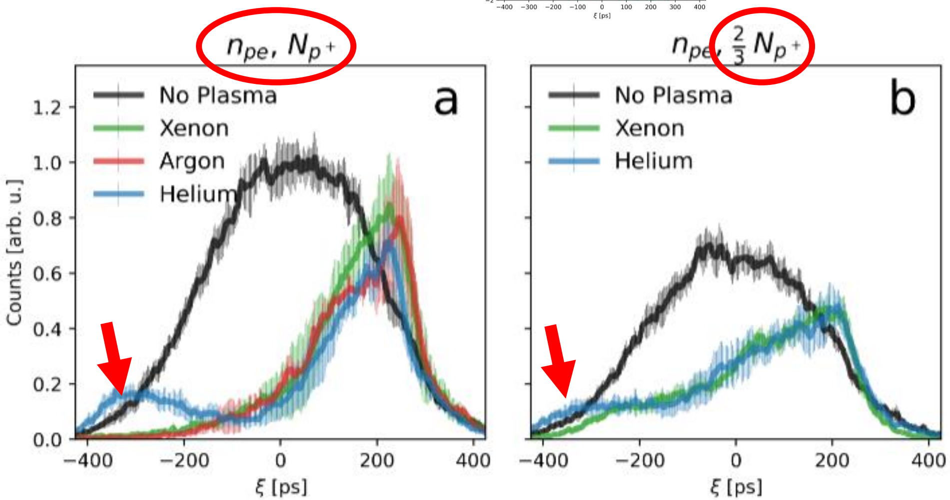
Effect of ion motion on:

✧Accelerated bunch quality

✧Acceleration process



M. Turner



✧ "Tail" with He, not with Ar, Xe

✧Lower wakefield amplitude, less tail

Long, low density bunch:

✧Typical SMI (Xe, Ar)

✧"Tail" appear in the back of the bunch (He)

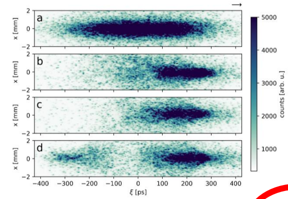
Preliminary

Ion Motion

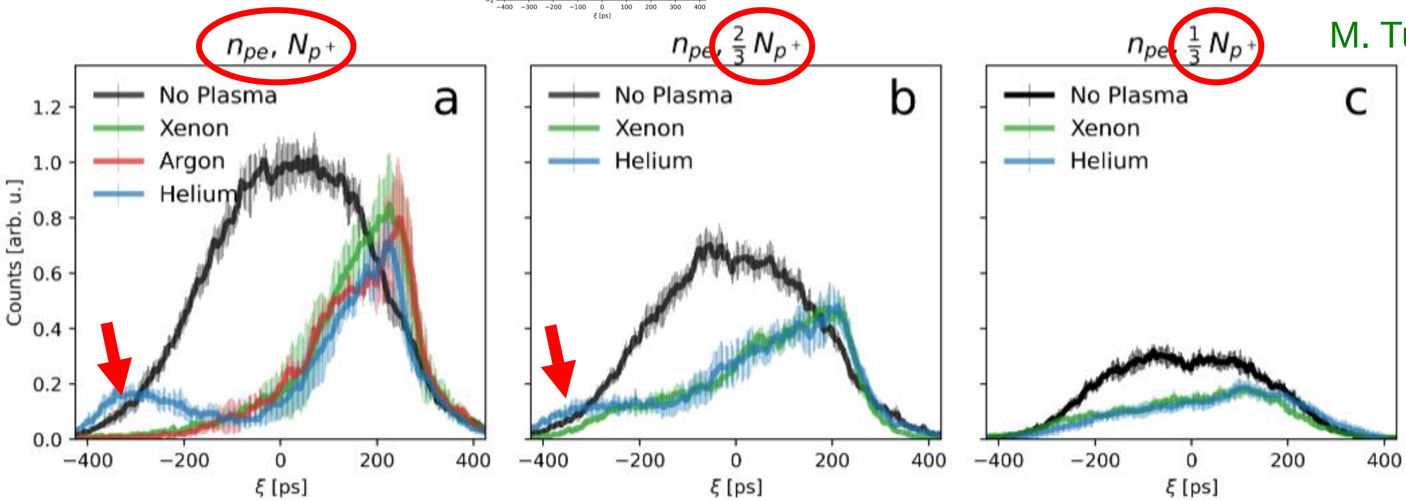
Effect of ion motion on:

✧Accelerated bunch quality

✧Acceleration process



M. Turner



✧ "Tail" with He, not with Ar, Xe

✧Lower wakefield amplitude, less tail

✧Even less

Long, low density bunch:

✧Typical SMI (Xe, Ar)

✧"Tail" appear in the back of the bunch (He)

Preliminary

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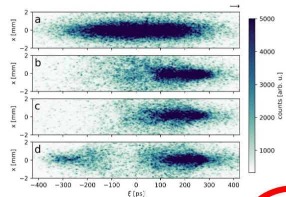
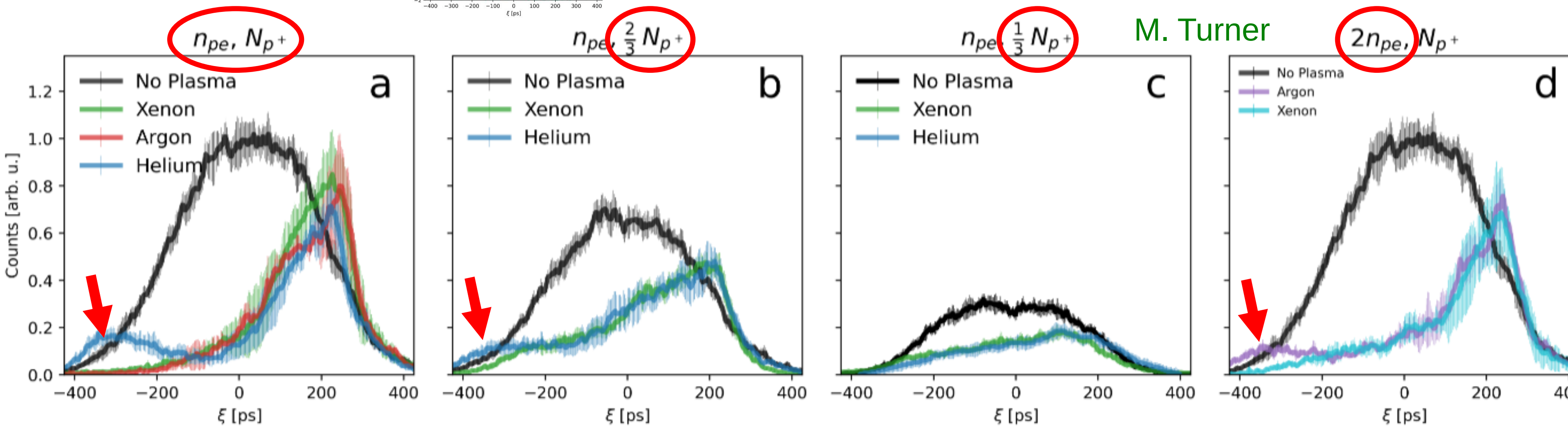
ION MOTION

Effect of ion motion on:

✧Accelerated bunch quality

✧Acceleration process





✧ "Tail" with He, not with Ar, Xe

✧Lower wakefield amplitude, less tail

✧Even less

✧Higher wakefield amplitude, tail with Ar, but not with Xe

Long, low density bunch:

✧Typical SMI (Xe, Ar)

✧"Tail" appear in the back of the bunch (He)

✧More "tail" with lighter ion (He), larger wakefield amplitude (N_{p+}, n_{e0}) (Ar)

Preliminary

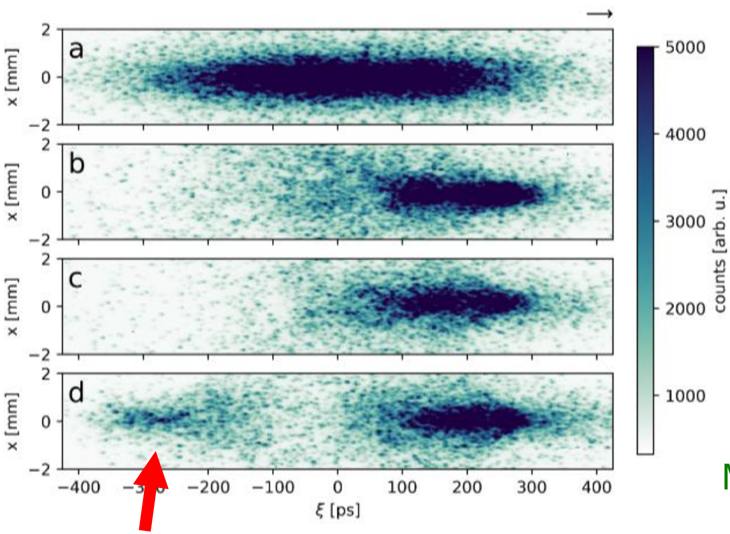
Ion Motion

Effect of ion motion on:

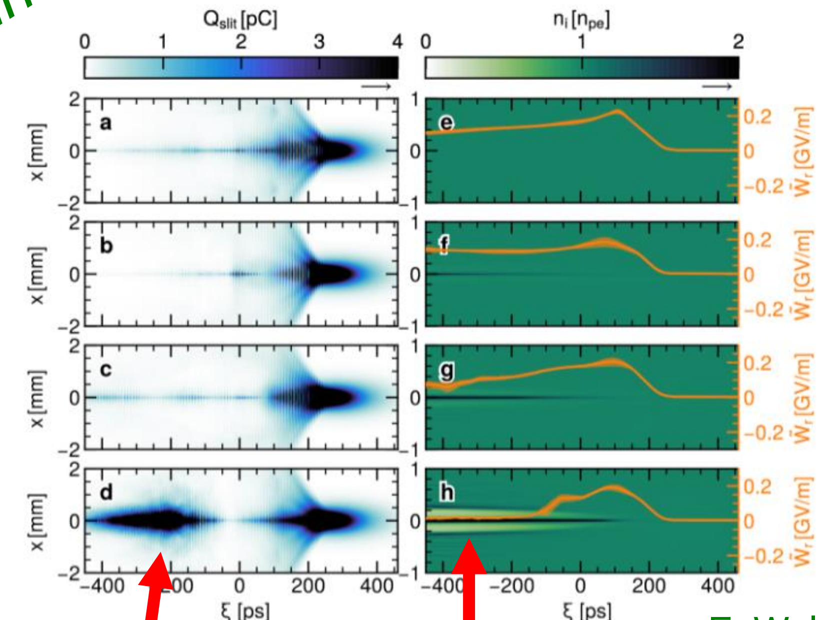
✧Accelerated bunch quality

✧Acceleration process

Preliminary



M. Turner



E. Walter

Long, low density bunch:

✧Typical SMI (Xe, Ar)

✧"Tail" appear in the back of the bunch (He)

✧More "tail" with lighter ion (He), larger wakefield amplitude (N_{p+}, n_{e0}) (Ar)

✧Numerical simulations confirm: ion motion because of ponderomotive force of the wakefields

$$\boldsymbol{F}_p \cong -\frac{e^2}{4m_e\omega_{pe}^2}\boldsymbol{\nabla}W_r^2$$

J. Vieira, Phys. Rev. Lett. 109, 145005 (2012)

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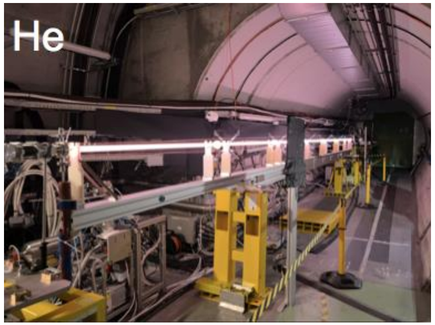
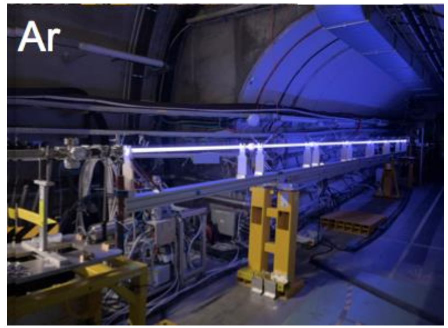
DISCHARGE PLASMA SOURCE

AWAKE

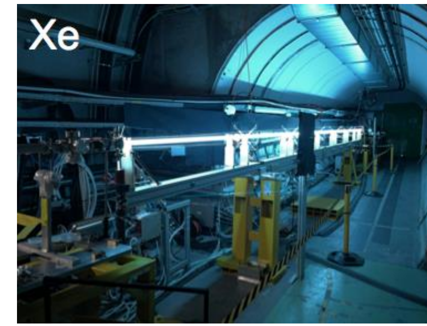


✧A_{He}=4



✧A_{Ar}=40

✧A_{Rb}=85



✧A_{xe}=131

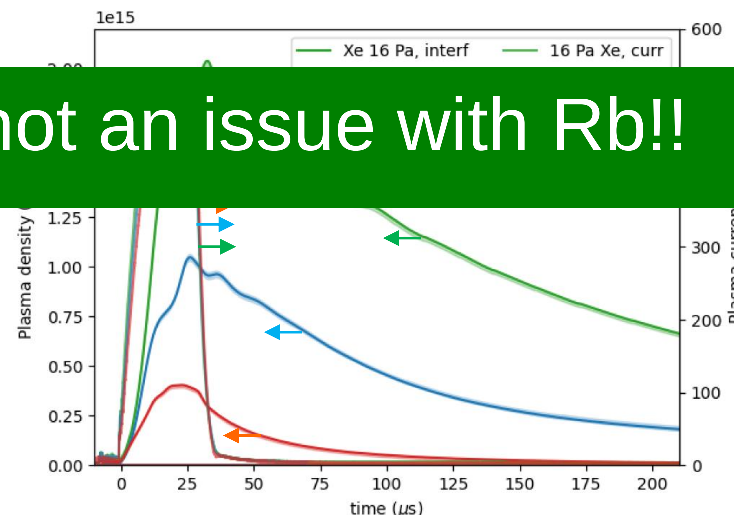
Discharge plasma source (DPS):

✧Quick ch

✧Reach h

✧**Change**

✧No alignment (r_p~10mm)



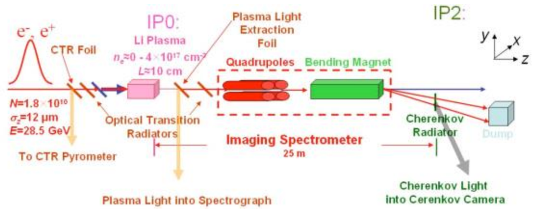
Ion motion not an issue with Rb!!

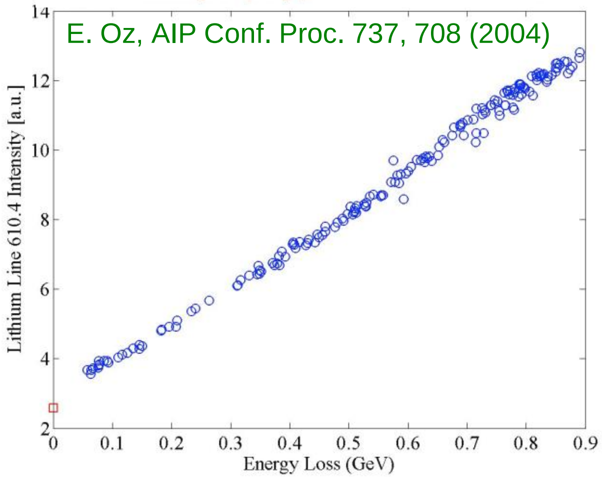
WAKEFiELD LiGHT

✧Wakefields ⬄ energy deposited into plasma e^-

✧Energy must dissipate

✧Dissipation of wakefields produces “wakefield light” (atomic line radiation)





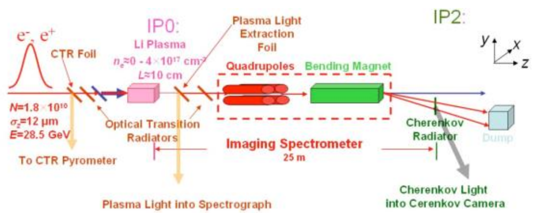
✧Light from wakefields proportional to energy deposited

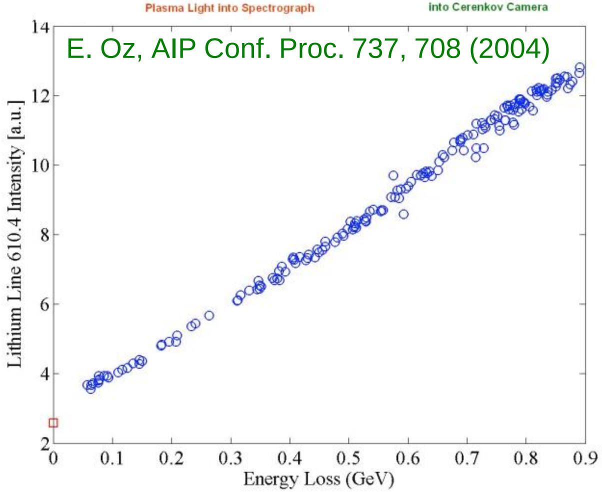
WAKEFIELD LIGHT

✧Wakefields ⬄ energy deposited into plasma e^-

✧Energy must dissipate

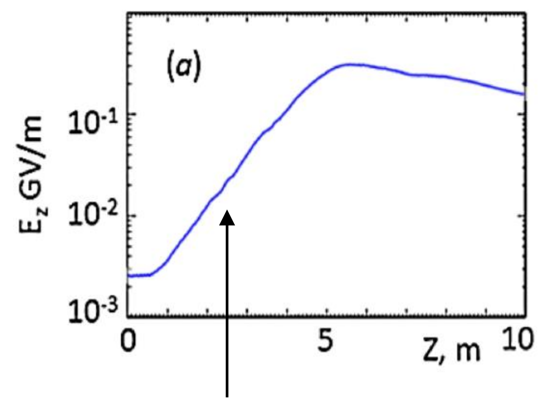
✧Dissipation of wakefields produces “wakefield light” (atomic line radiation)





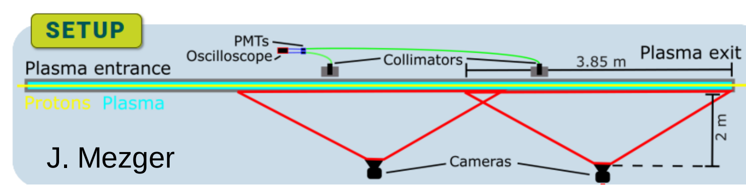
✧Light from wakefields proportional to energy deposited

Pukhov, PRL107 145003 (2011)



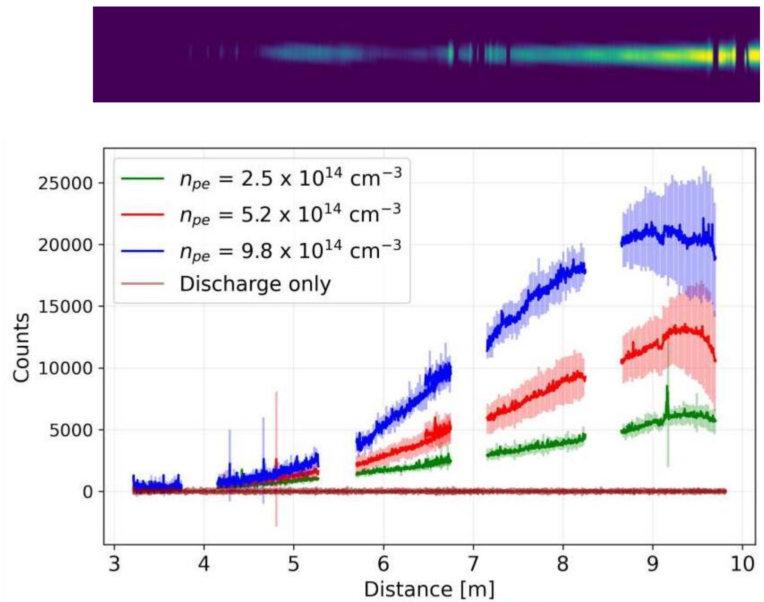
✧SM grows along the plasma

✧Can the growth be observed?



WAKEFIELD LIGHT

- ✧Wakefields ⇔ energy deposited into plasma e^-
- ✧Energy must dissipate
- ✧Dissipation of wakefields produces "wakefield light" (atomic line radiation)

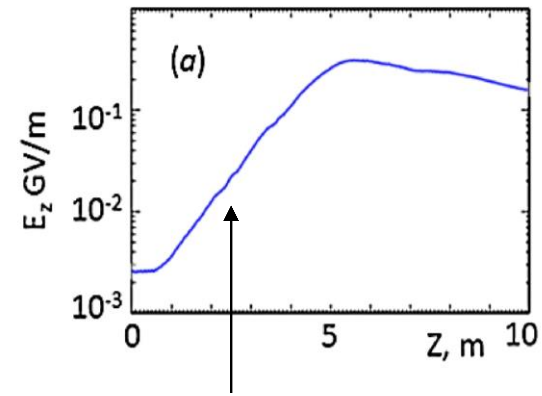


- ✧Growth of SM along the plasma visible

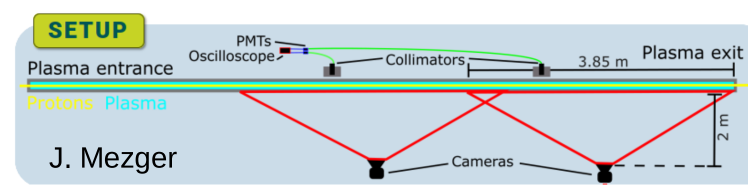
J. Mezger

- ✧Measurement for growth rate?

Pukhov, PRL107 145003 (2011)



- ✧SM grows along the plasma
- ✧Can the growth be observed?



WAKEFIELD LIGHT

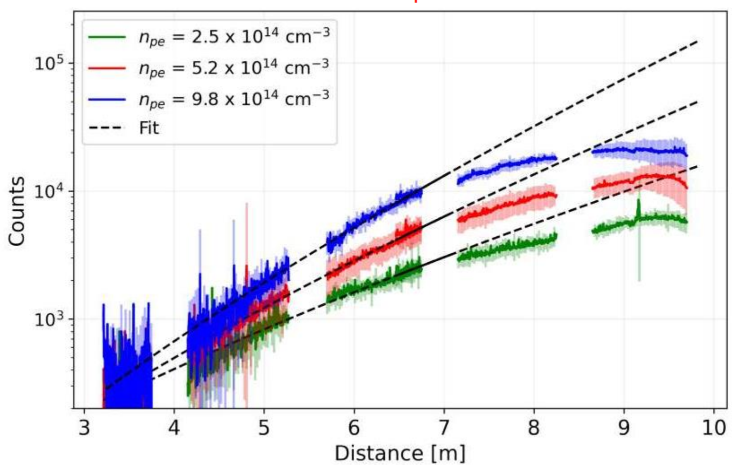
✧Wakefields ⇔ energy deposited into plasma e^-

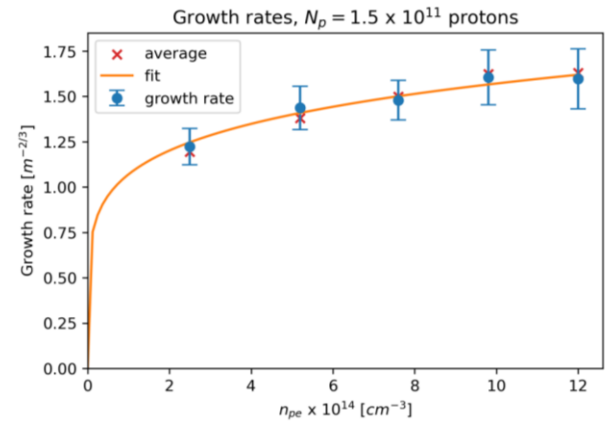
✧Energy must dissipate

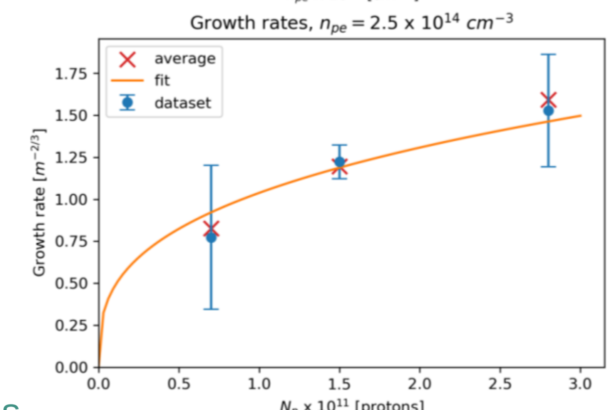
✧Dissipation of wakefields produces "wakefield light" (atomic line radiation)

$$E = E_0 e^{z^{2/3}\Gamma} \qquad \Gamma = \frac{3^{3/2}}{4}\left(\frac{m_e k_{pe}^3}{n_e m_p \gamma}\nu n_b(\zeta, r=0)\zeta\right)^{1/3}$$

$\Gamma \sim n_b^{1/3}$ // $n_{pe}^{1/6}$







✧Growth of SM along the plasma visible J. Mezger

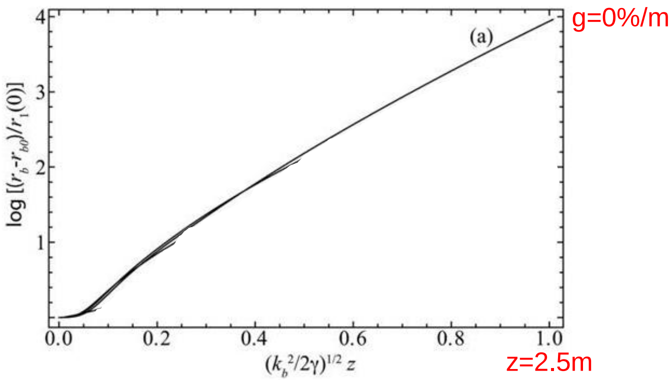
✧Measurement for growth rate?

✧Measured growth rate consistent with n_{e0} and N_{p+} dependencies

SSM SUPPRESSiON

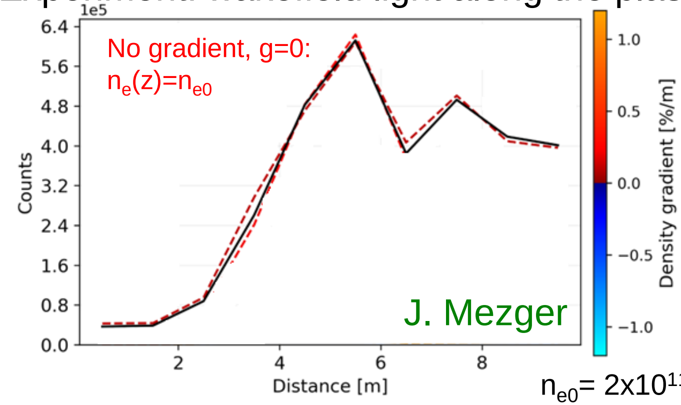
✧Theory prediction: plasma density gradient suppressed SM

Theory: bunch radial modulation



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

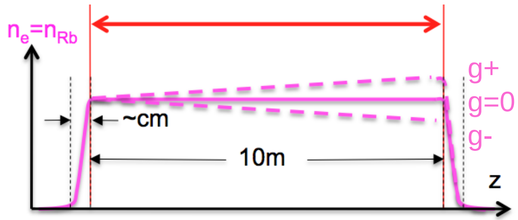
Experiment: wakefield light along the plasma



n_{e0}= 2x10^{11}cm^{-3}
N_{p+}= 0.5x10^{11}

Preliminary

Gradient: g[%/m]=100(n_e(L=10m)-n_{e0})/n_{e0}

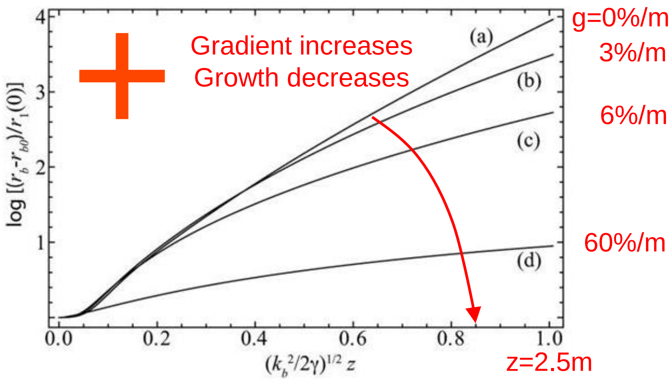


✧Can apply positive/negative, linear plasma density gradients

SSM SUPPRESSiON

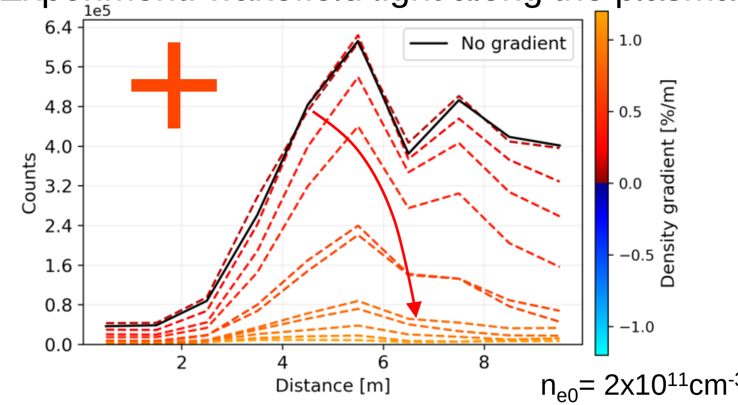
✧Theory prediction: plasma density gradient suppressed SM

Theory: bunch radial modulation

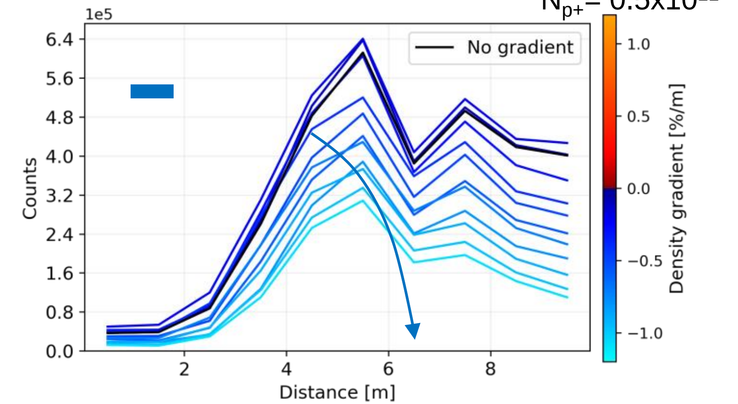


C. B. Schroeder, et al., *Phys. Plasmas* 19, 010703 (2012)

Experiment: wakefield light along the plasma



n_{e0}= 2x10^{11}cm^{-3}
N_{p+}= 0.5x10^{11}



Preliminary

✧Positive and negative gradient suppression of SM

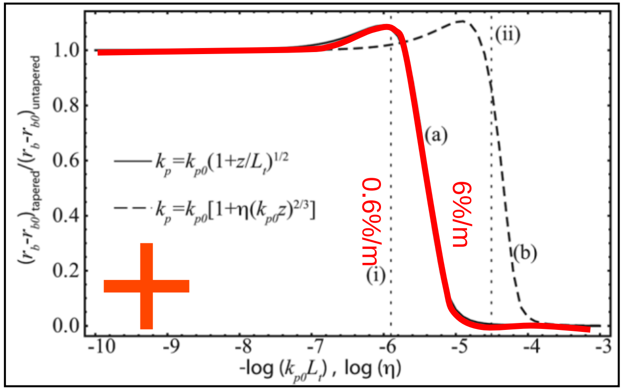
✧Consistent with predictions …

✧Observe also for negative gradients …

SSM SUPPRESSiON

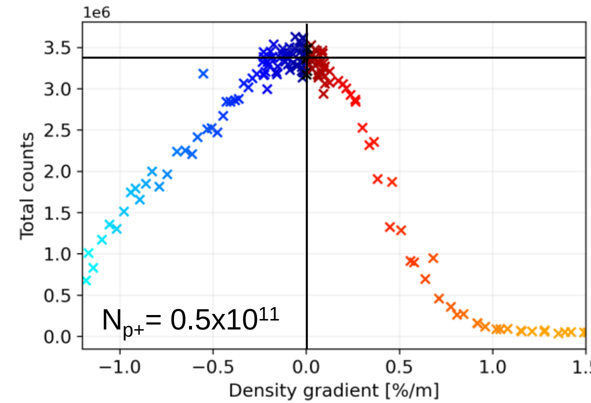
✧Theory prediction: more modulation of small positive gradient

Theory: bunch radial modulation



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

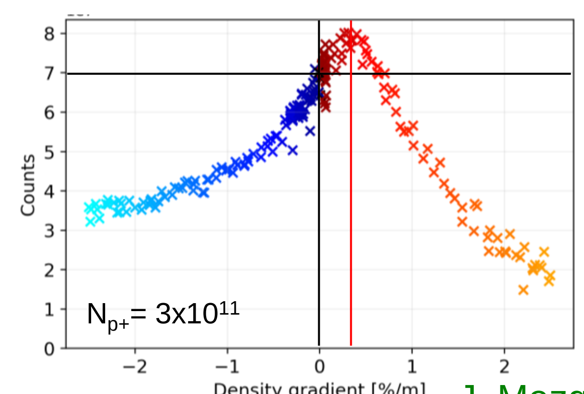
Experiment: sum of wakefield light



n_{e0}= 2x10^{11}cm^{-3}

Preliminary

✧In general: less light → "less wakefields"

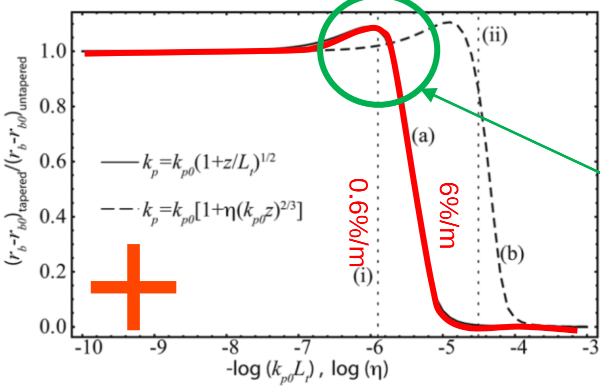


J. Mezger

SSM SUPPRESSiON

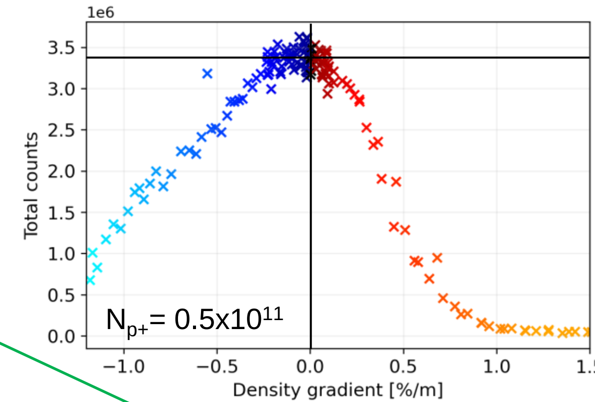
✧Theory prediction: more modulation of small positive gradient

Theory: bunch radial modulation

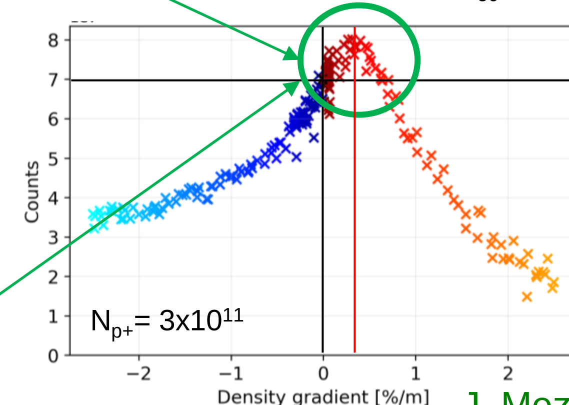


C. B. Schroeder, et al., *Phys. Plasmas* 19, 010703 (2012)

Experiment: sum of wakefield light



n_{e0}= 2x10^{11}cm^{-3}

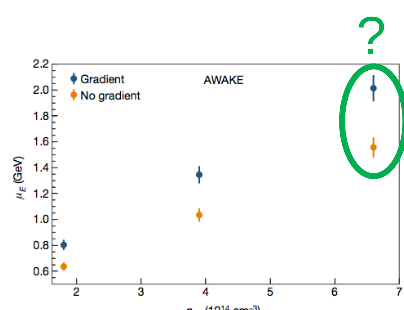


J. Mezger

✧In general: less light → “less wakefields”

✧“More wakefields” with small gradient (g~0.5%/m)!

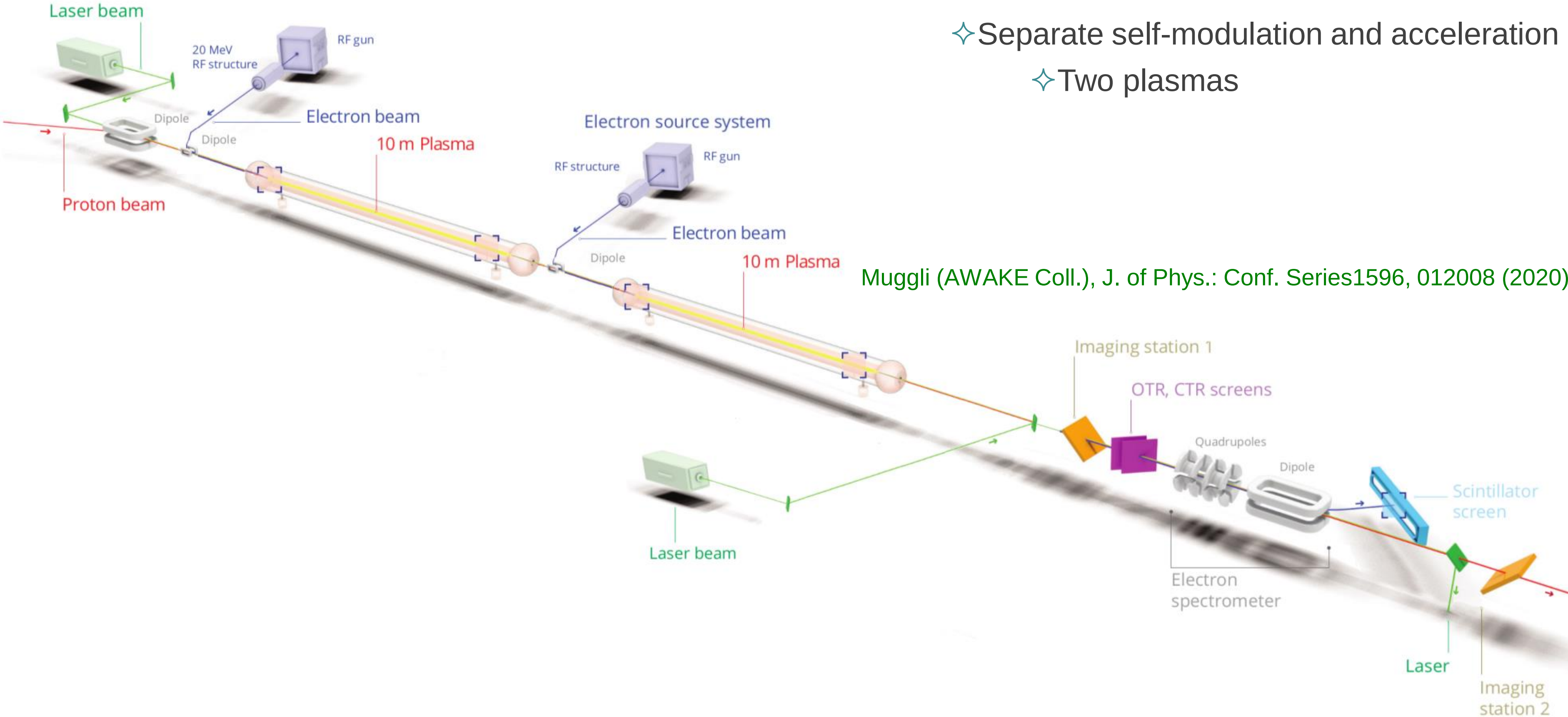
✧Consistent with predictions …



RUN 2c,d: ACCELERATE e⁻ BUNCH, QUALITY

✧Separate self-modulation and acceleration

✧Two plasmas

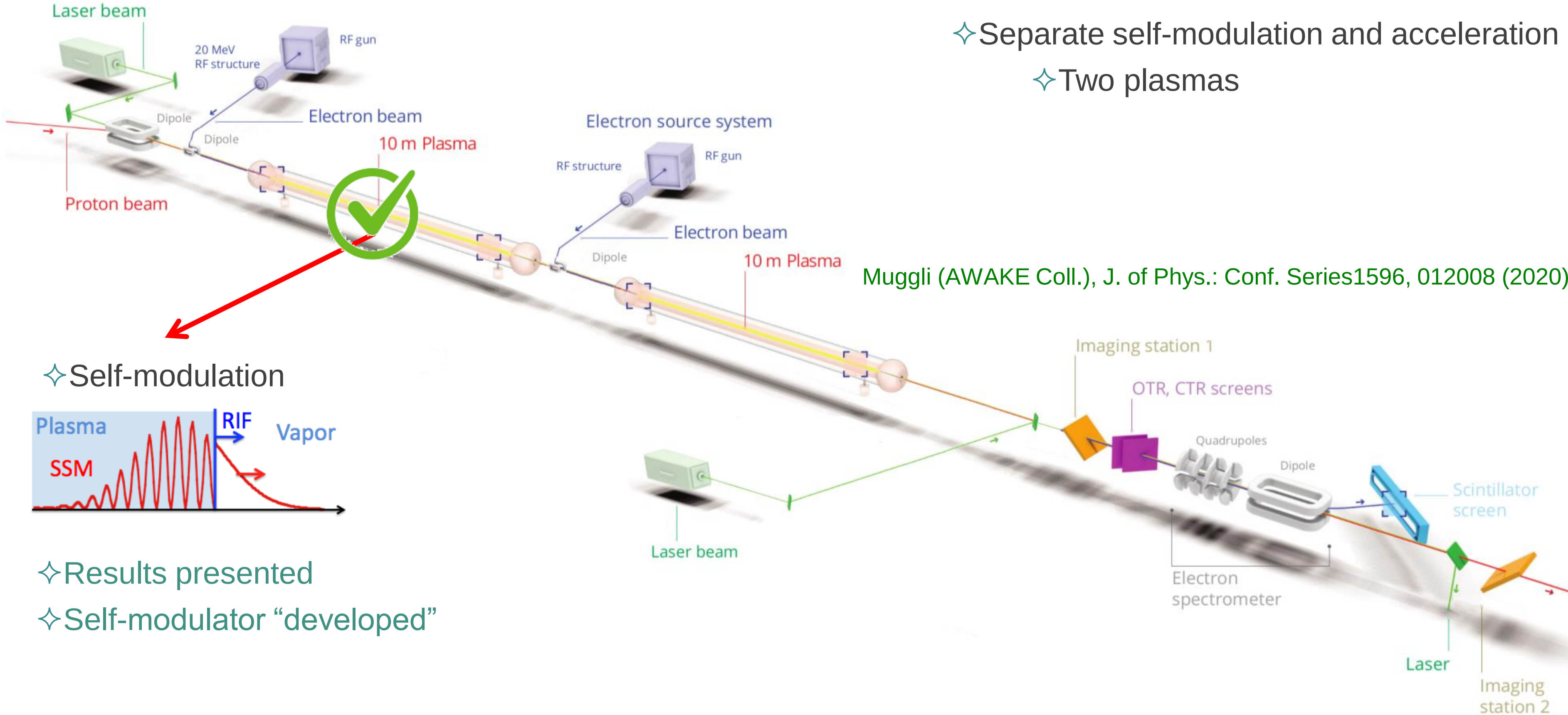


Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

RUN 2c,d: ACCELERATE e⁻ BUNCH, QUALITY

✧Separate self-modulation and acceleration

✧Two plasmas



Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

✧Self-modulation

✧Results presented

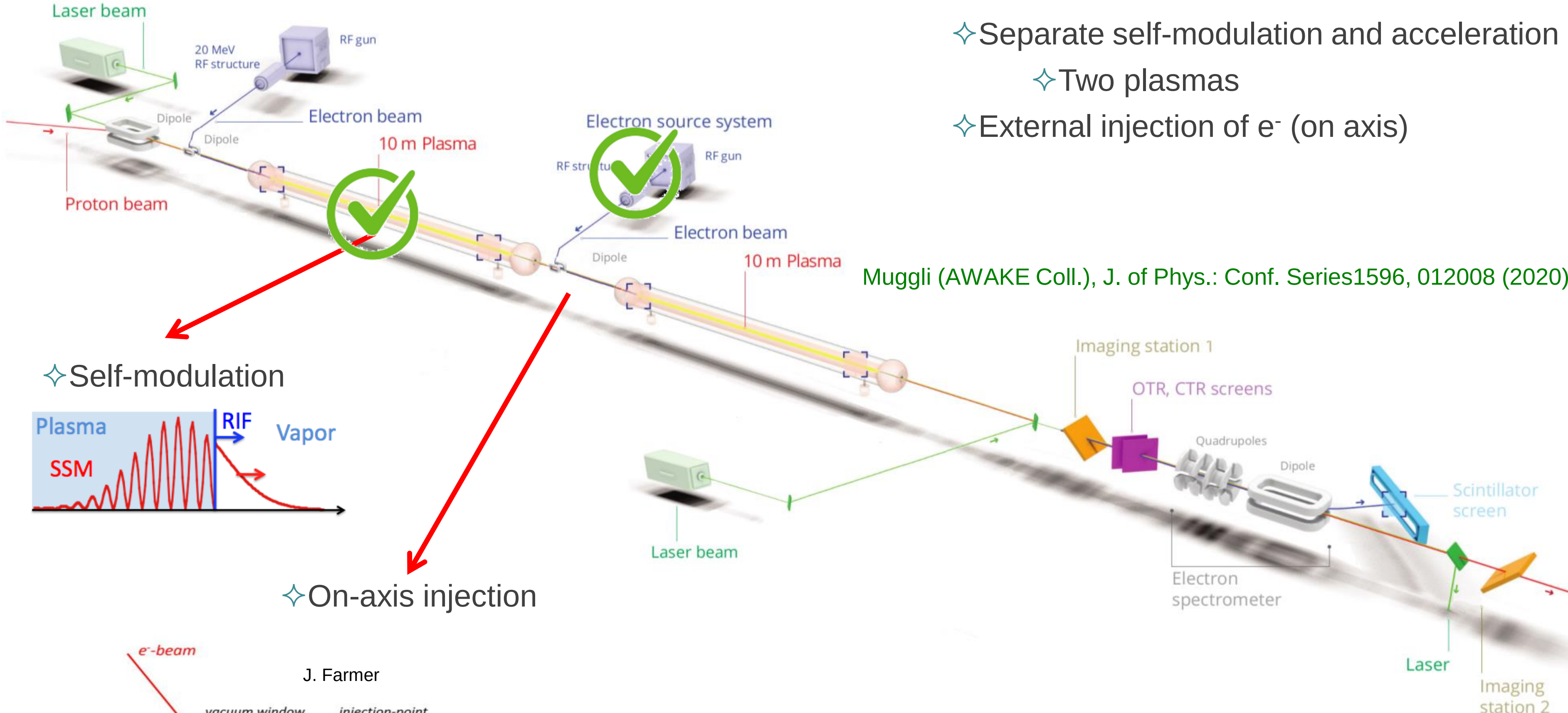
✧Self-modulator "developed"

RUN 2c,d: ACCELERATE e⁻ BUNCH, QUALITY

✧Separate self-modulation and acceleration

✧Two plasmas

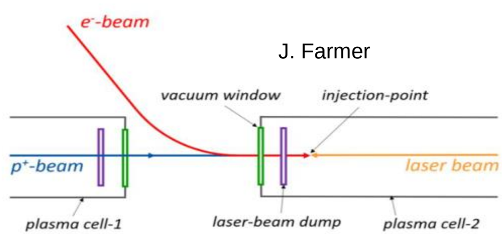
✧External injection of e⁻ (on axis)



Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

✧Self-modulation

✧On-axis injection

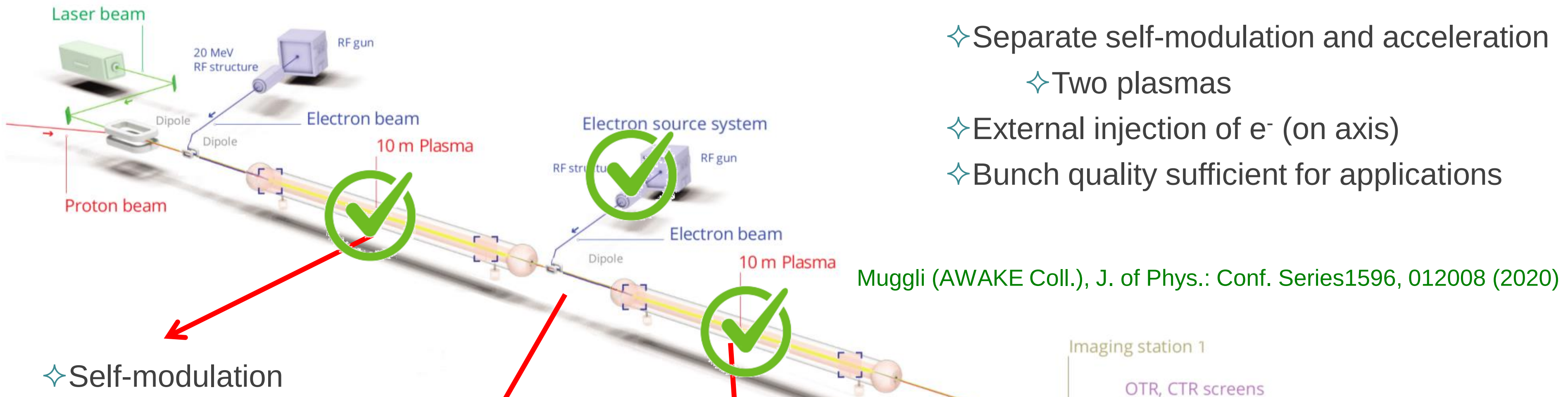


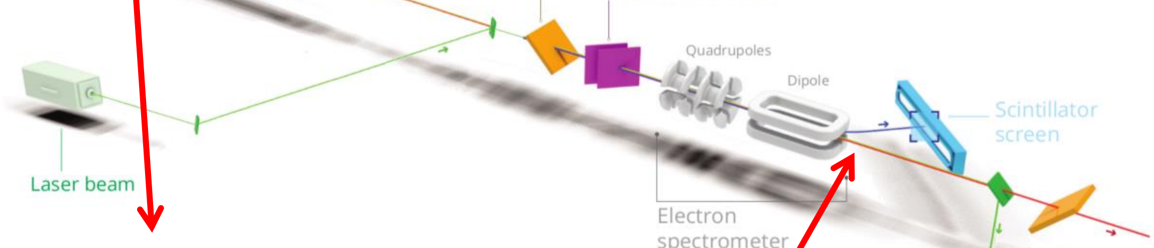
J. Farmer

RUN 2c,d: ACCELERATE e⁻ BUNCH, QUALITY

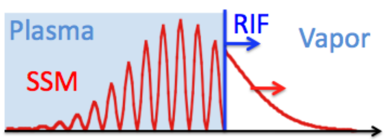
✧Separate self-modulation and acceleration
  ✧Two plasmas
✧External injection of e⁻ (on axis)
✧Bunch quality sufficient for applications

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

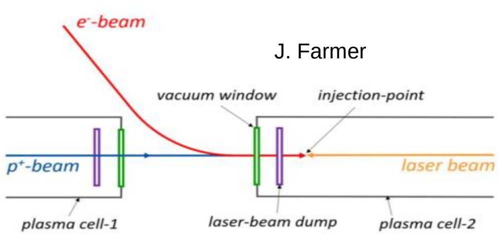




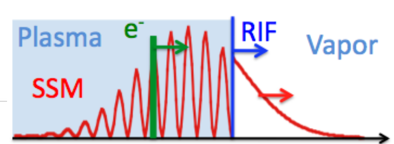
✧Self-modulation



✧On-axis injection



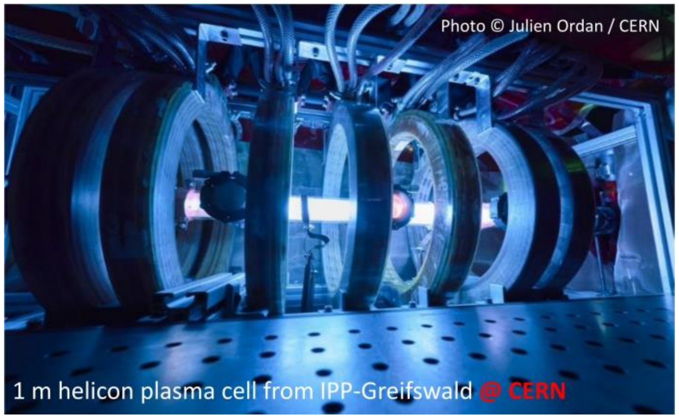
✧Acceleration

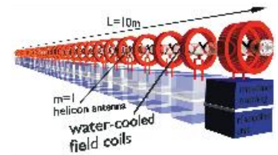


✧Quality
✧Particle Physics!

Scalable Plasma Source

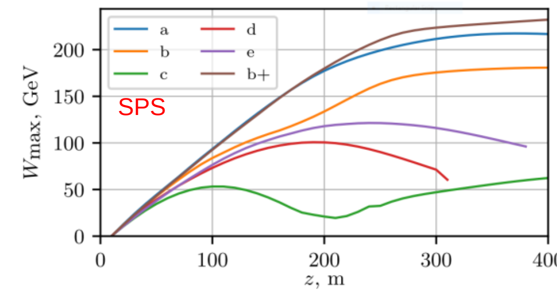
- ✧Laser ionization does not scale to long plasma lengths (100m-1km): laser pulse energy depletion!
- ✧Plasma source development laboratory at CERN
- ✧Helicon source: magnetized RF discharge   Buttenschön, PPFC 60(7), 075005 (2018)



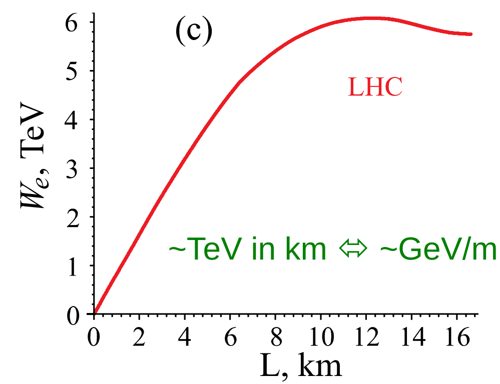


Max-Planck-Institut für Plasmaphysik

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

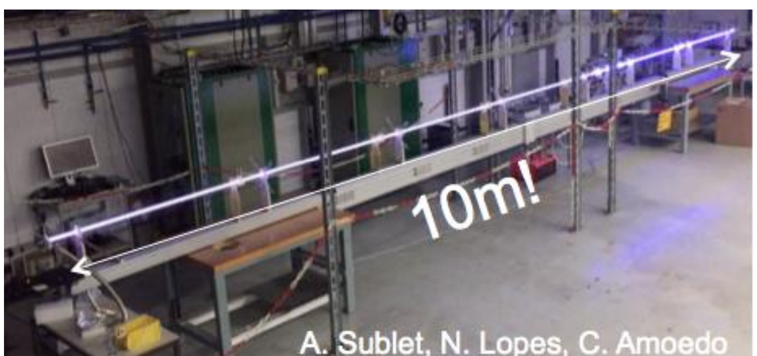


P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)



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

- ✧Pulsed discharge   Torrado, IEEE-TPS 51(12) (2023)



TÉCNICO LISBOA

Imperial College London

CERN

- ✧ Challenge: plasma density uniformity!

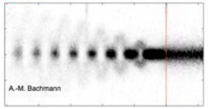
$\Delta n_e/n_{e0} << 1/N_{\mu b}$, $N_{\mu b\neq}$~100 => $\Delta n_e/n_{e0} < 0.2\%$

SUMMARY

✧AWAKE:

✧Observed three instabilities, etc., etc.

SM



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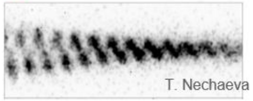
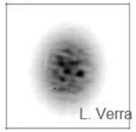


FI

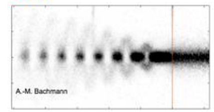


SUMMARY

✧AWAKE:

✧Observed three instabilities, etc., etc.

SM



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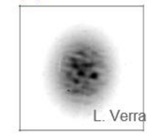
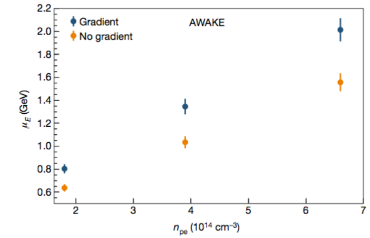
FI

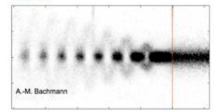


✧Seeded/controlled SM to accelerate e^- to GeV energy level



SUMMARY

✧AWAKE:

SM


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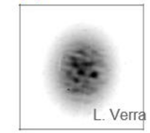
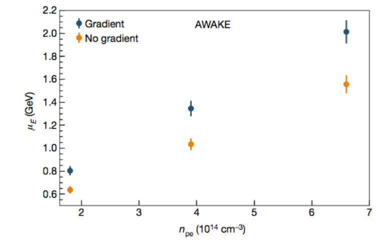
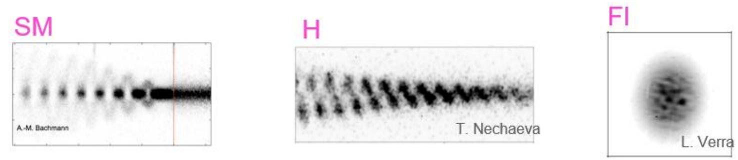
FI




- ✧Observed three instabilities, etc., etc.
- ✧Seeded/controlled SM to accelerate e^- to GeV energy level
- ✧Developing a self-modulator for a long p^+ bunch

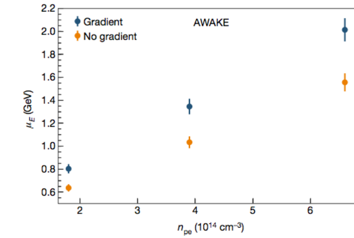
SUMMARY

✧AWAKE:



✧Observed three instabilities, etc., etc.

✧Seeded/controlled SM to accelerate e^- to GeV energy level

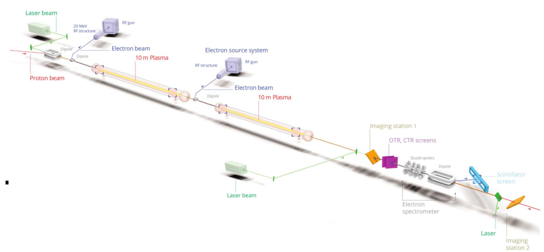


✧Developing a self-modulator for a long p^+ bunch

✧Clear plans for an accelerator: self-modulation, injection, acceleration

✧Large energy gain

✧Scalability to very large ..

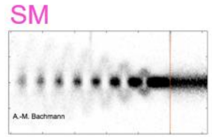


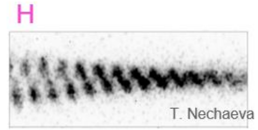
Muggli (AWAKE Coll.)
J. of Phys.: Conf. Series1596, 012008 (2020).

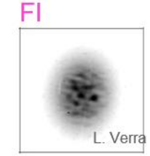
SUMMARY

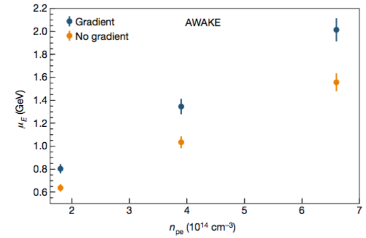
✧AWAKE:

✧Observed three instabilities, etc., etc.









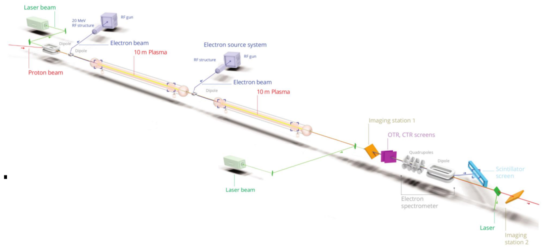
✧Seeded/controlled SM to accelerate e⁻ to GeV energy level

✧Developing a self-modulator for a long p⁺ bunch

✧Clear plans for an accelerator: self-modulation, injection, acceleration

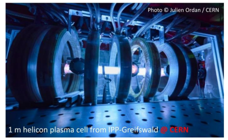
✧Large energy gain

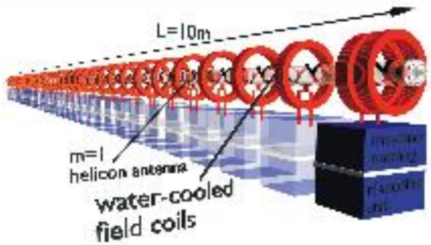
✧Scalability to very large ..

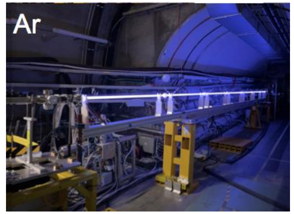


Muggli (AWAKE Coll.)
J. of Phys.: Conf. Series1596, 012008 (2020).

✧Development of scalable plasma sources





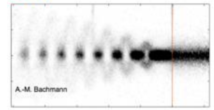


SUMMARY

✧AWAKE:

✧Observed three instabilities, etc., etc.

SM



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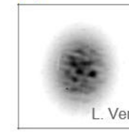
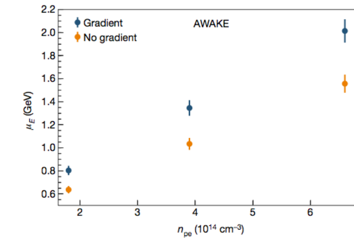




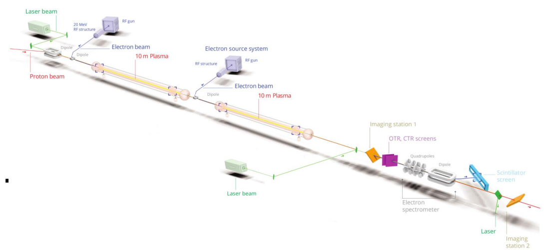
✧Seeded/controlled SM to accelerate e^- to GeV energy level

✧Developing a self-modulator for a long p^+ bunch

✧Clear plans for an accelerator: self-modulation, injection, acceleration

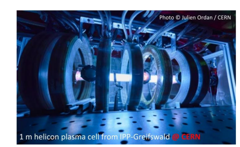
✧Large energy gain

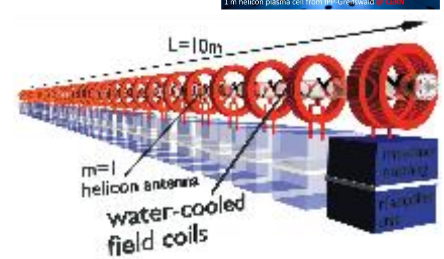
✧Scalability to very large ..



Muggli (AWAKE Coll.)
J. of Phys.: Conf. Series1596, 012008 (2020).

✧Development of scalable plasma sources





✧Propose particle physics experiments in the 2030's

✧Dark photon search

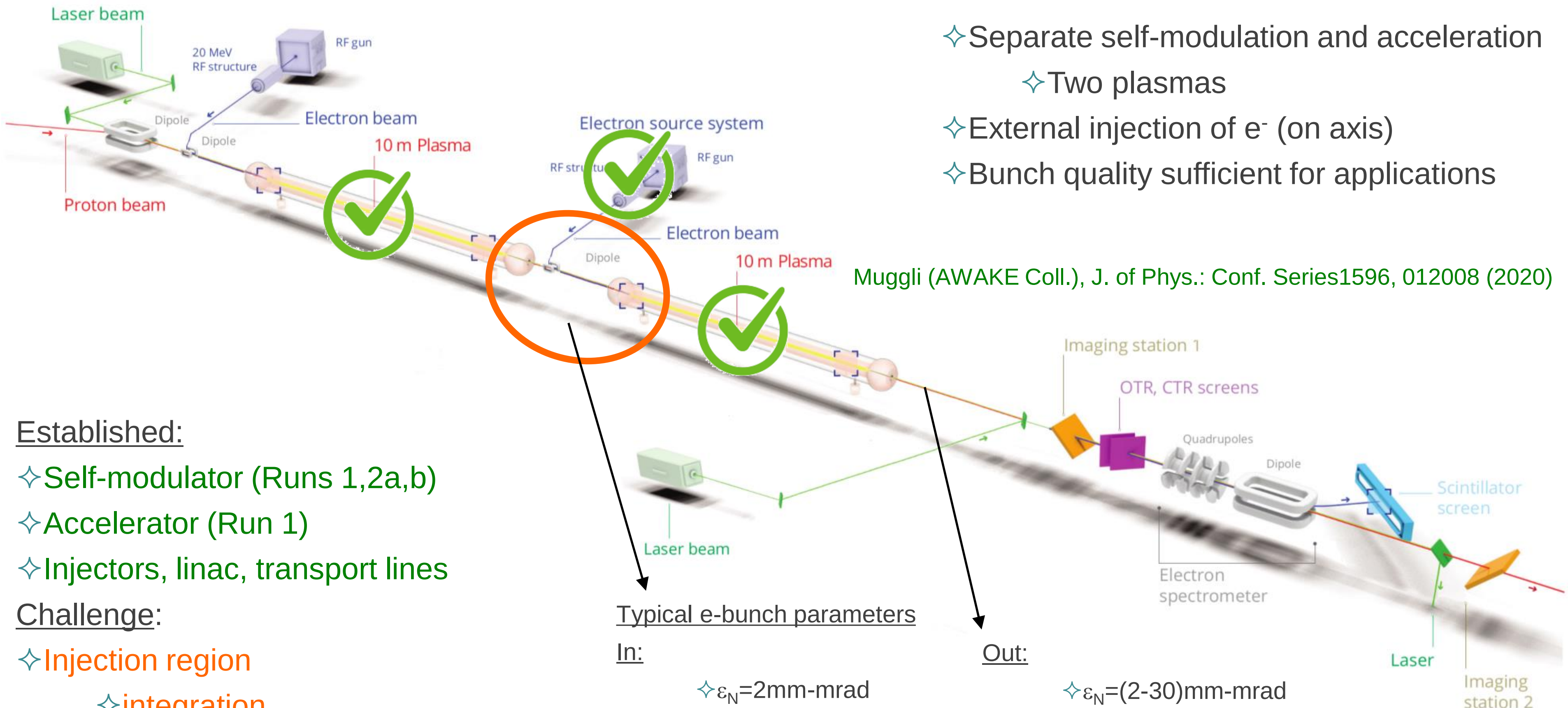
Thank you to my collaborators

Thank you!

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

muggli@mpp.mpg.de

RUN 2c: e⁻-EXTERNAL INJECTION EXPERIMENT



- ✧Separate self-modulation and acceleration
  - ✧Two plasmas
- ✧External injection of e^- (on axis)
- ✧Bunch quality sufficient for applications

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

Established:

- ✧Self-modulator (Runs 1,2a,b)
- ✧Accelerator (Run 1)
- ✧Injectors, linac, transport lines

Challenge:

- ✧Injection region
  - ✧integration
  - ✧alignment, p^+ and e^- beams
  - ✧diagnostics

Typical e-bunch parameters

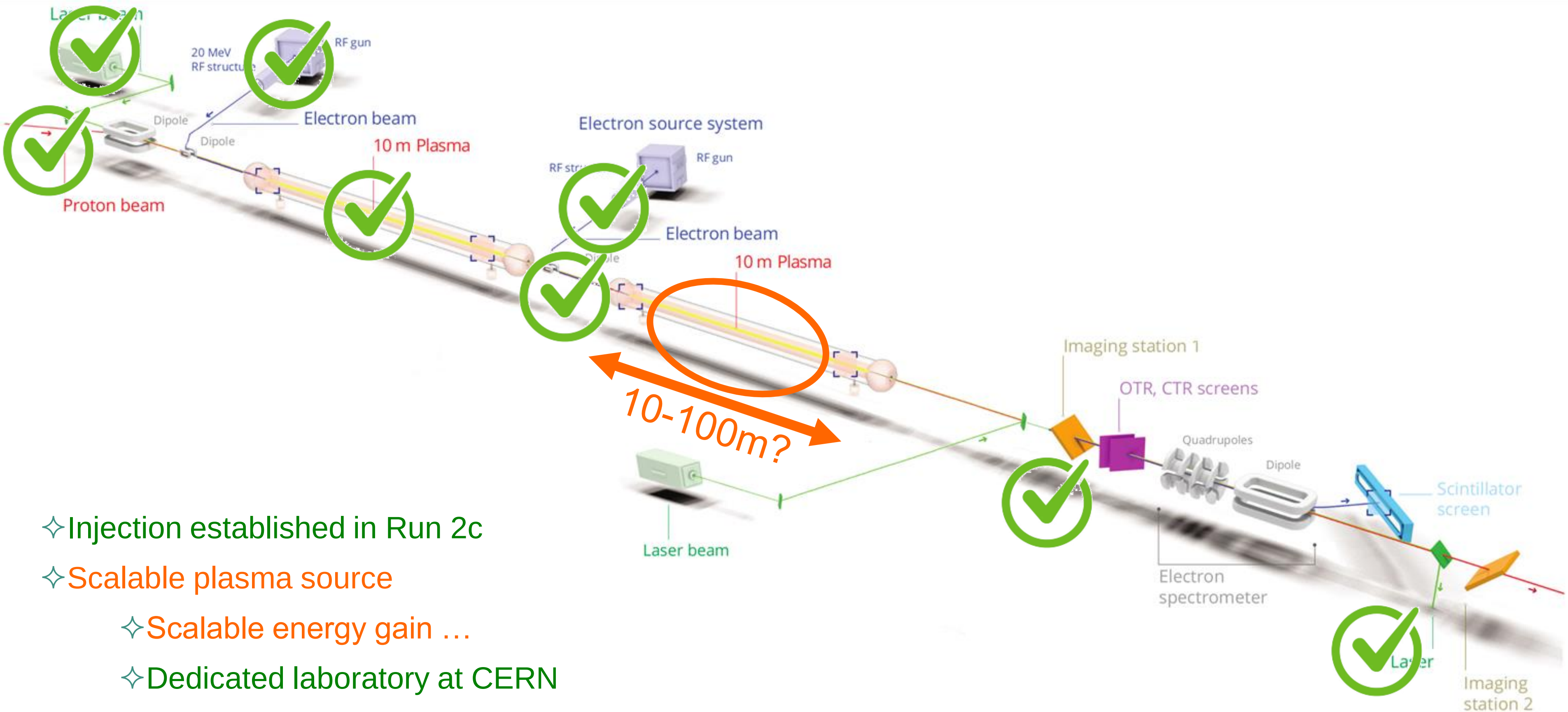
In:

- ✧ε_N=2mm-mrad
- ✧Q=100pC, N_{e-}~$6\times10^9 e^-$
- ✧150MeV
- ✧σ_t=200fs
- ✧Jitter<100fs

Out:

- ✧ε_N=(2-30)mm-mrad
- ✧Q=100pC, N_{e-}~$6\times10^9 e^-$
- ✧ΔE/E=5-8%
- ✧E~4-10⁺GeV

RUN 2d: CHALLENGE



✧Injection established in Run 2c

✧Scalable plasma source

✧Scalable energy gain …

✧Dedicated laboratory at CERN

Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

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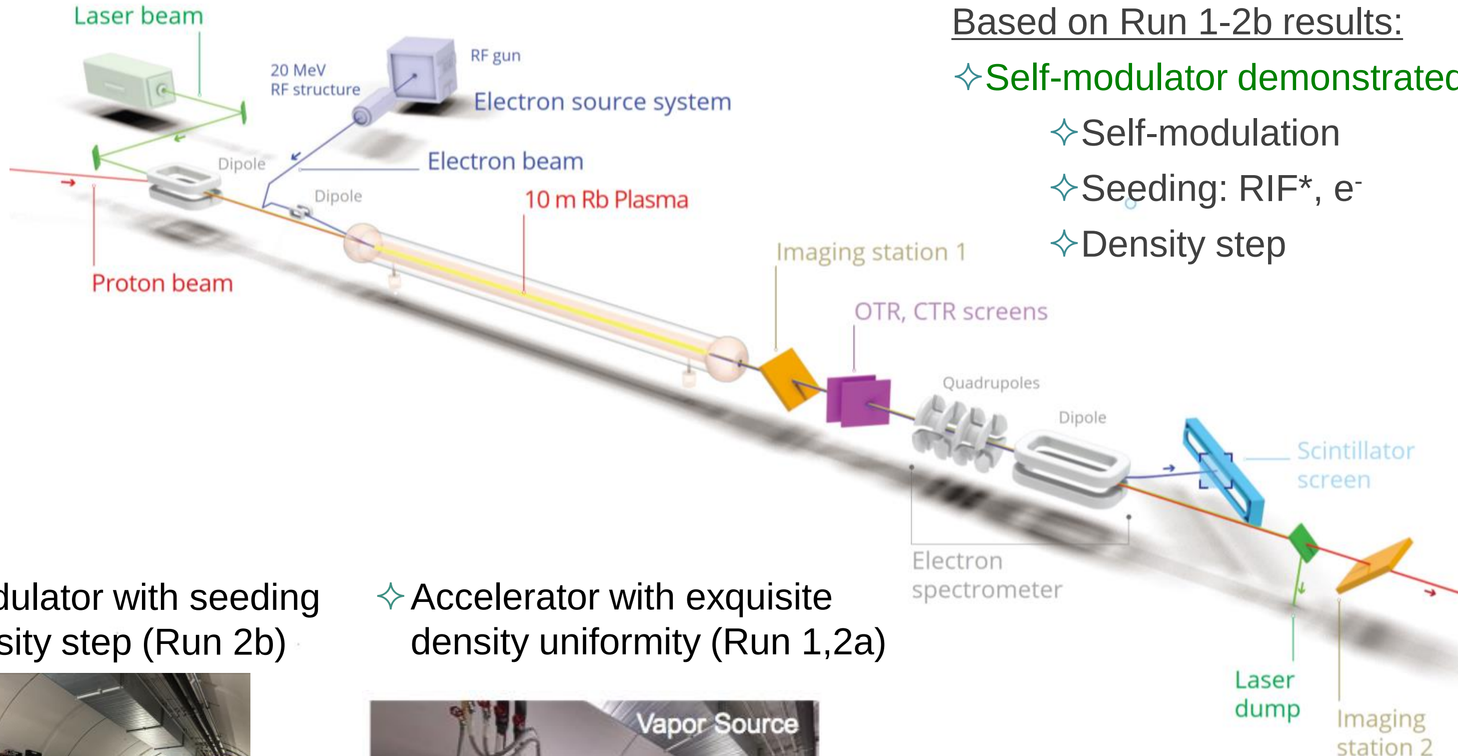
RUN 1,2a,b: SELF-MODULATOR FOR RUN 2c,d



<u>Based on Run 1-2b results:</u>

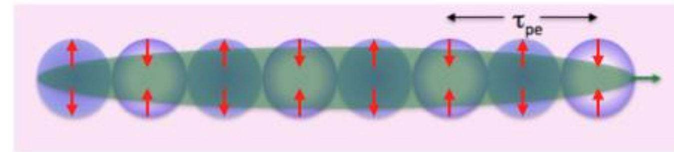
- ✧Self-modulator demonstrated
  - ✧Self-modulation
  - ✧Seeding: RIF*, e^-
  - ✧Density step

- ✧Self-modulator with seeding and density step (Run 2b)

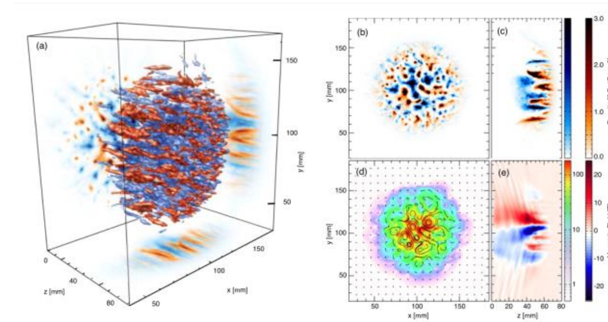
- ✧Accelerator with exquisite density uniformity (Run 1,2a)

*RIF: Relativistic Ionization Front

FiLAMENTATiON INSTABiLiTY



- ✧σ_{r0}<c/ω_{pe}: optimum for wakefield generation …
- ✧σ_{r0}>>c/ω_{pe}: filamentation instabilities can develop …
  - ✧Equal streams: current filamentation instability (CFI)
  - ✧Unequal streams: oblique modes, wakefields, …



$$\Gamma = \frac{\sqrt{3}}{2^{4/3}}\left(\frac{n_{b0}m_e}{n_{pe}m_p\gamma_p}\right)^{1/3}\omega_{pe} = \Gamma_e\left(\frac{m_e}{m_p}\right)^{1/3} \qquad \vec{k} = \vec{k}_\perp + \vec{k}_\parallel$$

Core-collapse, or type II supernovas, are caused by the implosion of massive stars like red supergiants. (Supplied: ESA/Hubble/L Calçada)

- ✧Astrophysics: generation of magnetic fields in the universe?
- ✧Collision: neutral, expanding supernova plasma – interstellar plasma
- ✧CFI :
  - ✧Generates magnetic fields
  - ✧Converts kinetic energy of the expanding plasma into B-field energy and plasma kinetic energy
  - ✧Evolution: filaments -> coalescence -> shock formation
- ✧Study FI with relativistic particle bunch (p^+)
- ✧"Astrophysics in the lab"

Shukla, J. Plasma Phys. 84(3) 905840302 (2018)
Allen, Phys. Rev. Lett. 109, 185007 (2012)