Beam-Plasma Interaction Studies and Plasma Wakefield Acceleration for Application to Particle Physics

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✧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

- A number of interesting (important?) experimental results
  (many simulation results, but focus on …)
- Clear plan towards application to particle physics
- Opportunities to contribute

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

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

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

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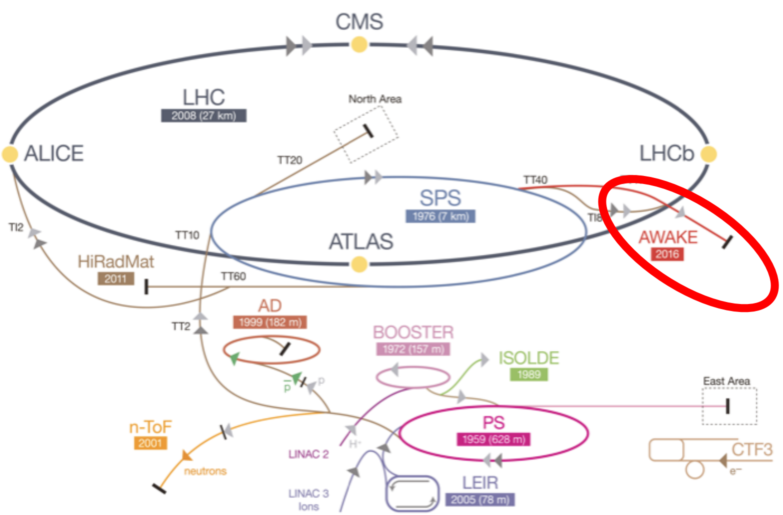

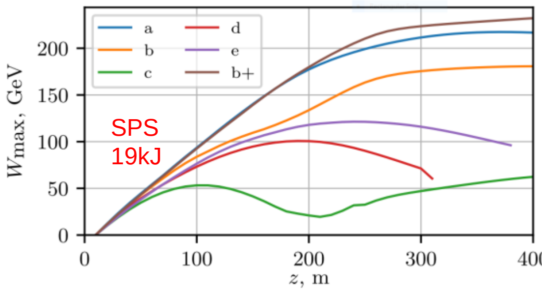

P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

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

2D numerical simulation results

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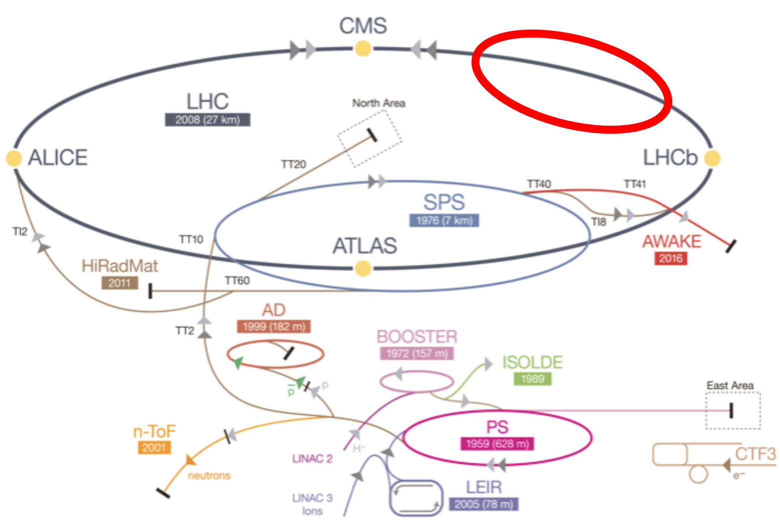

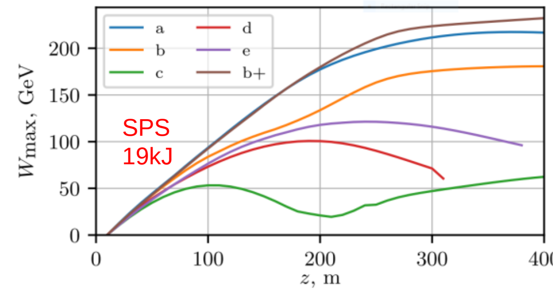

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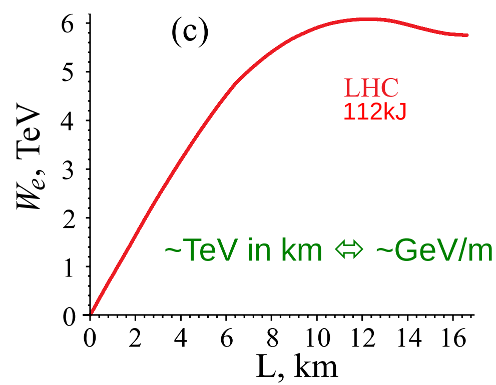
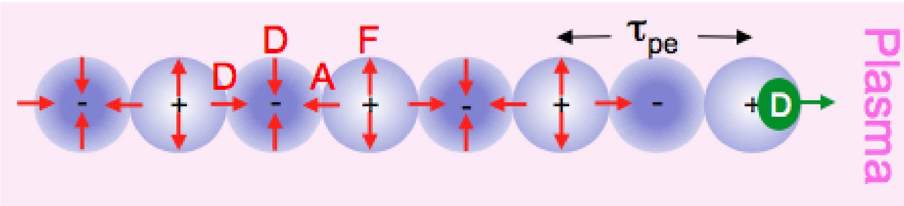


LHC driver (119kJ):
~5TeV in ~7km
~10^9 e^-

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

RELATIVISTIC PARTICLE BUNCH MEETS PLASMA



D=driver

✧Relativistic Bunch ⇔ Radial Space Charge Field ⇔ Plasma Screening

⇔ Azimuthal Magnetic Field ⇔ Plasma Return Current

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

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

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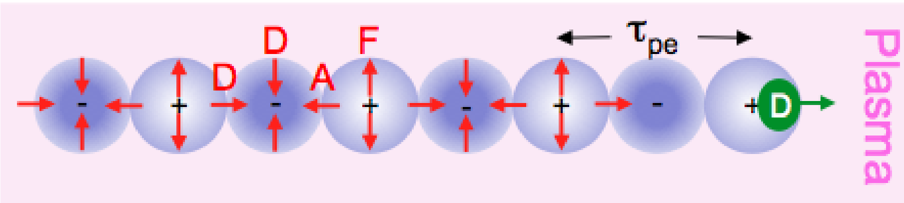

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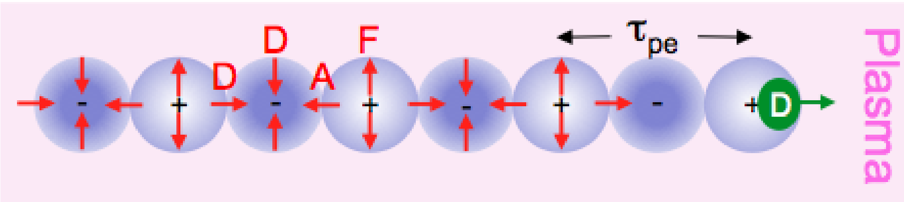
✧Screening ⬄ Plasma Wakefields (Langmuir Wave, E_z) ⬄ Self-Modulation and Hosing Instabilities ⬄ Accelerators

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

Relativistic Particle Bunch Meets Plasma



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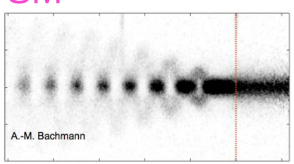

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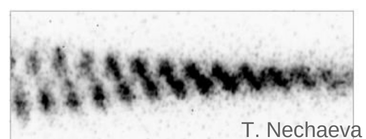

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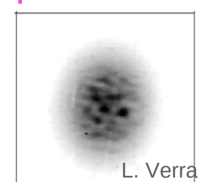

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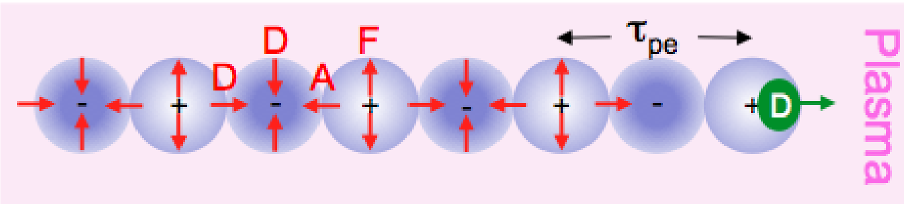

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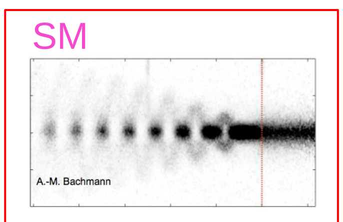

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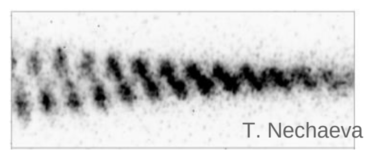

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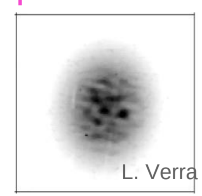
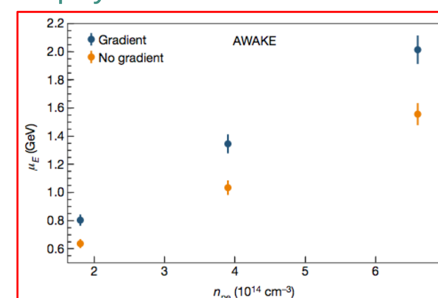


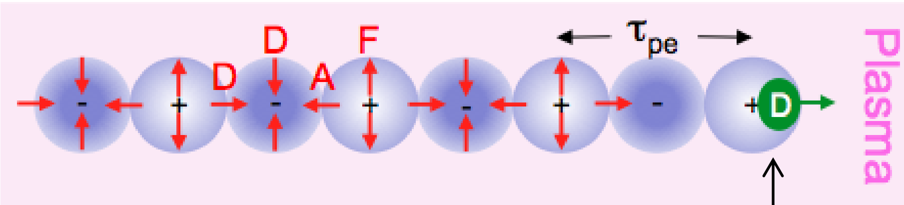


Main motivation:

✧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)

PASMA WAKEFIELDS

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



✧~Langmuir wave in 1D, on axis

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"

$$E_z \cong \frac{n_{b0}}{n_{e0}} E_{WB}$$

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

c/ω_{pe} Plasma skin depth

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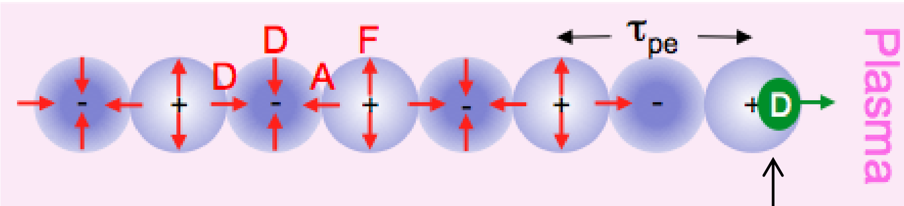

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Favors small[3] driver, high density $n_b \sim n_{e0}$

$E_{WB}(n_{e0}=3\text{x}10^{17}\text{cm}^{-3})$=53GV/m, c/ω_{pe}= 10µm

$E_{WB}(n_{e0}=7\text{x}10^{14}\text{cm}^{-3})$=2.5GV/m, c/ω_{pe}=200µm

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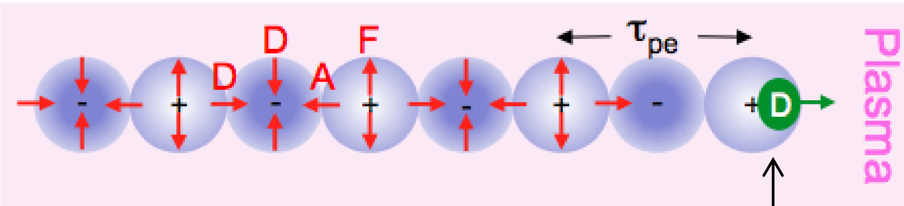

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Plasma e^- angular frequency

$$c/\omega_{pe}$$

Plasma skin depth

High-gradient acceleration
>1GeV/m

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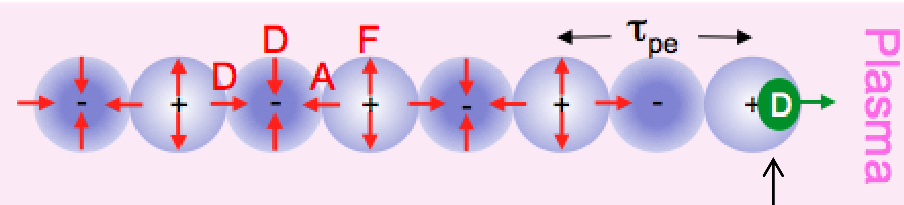

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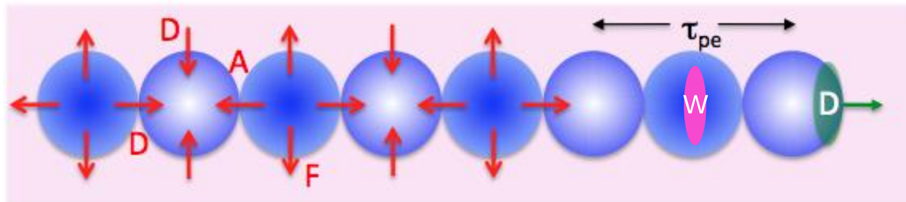
✧Driver: laser pulse, laser wakefield accelerator (LWFA)
particle bunch, plasma wakefield accelerator (PWFA)

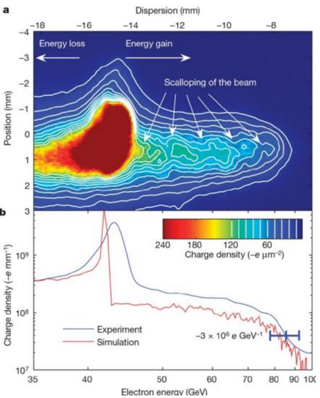
T. Tajima, J. Dawson, Phys. Rev. Lett. 43, 267 (1979)
P. Chen, et al., Phys. Rev. Lett. 54, 693 (1985)

PLASMA WAKEFIELDS

Short driver: electron bunch, laser pulse



PWFA, short e⁻ bunch



Blumenfeld, Nature 445, 741 (2007)

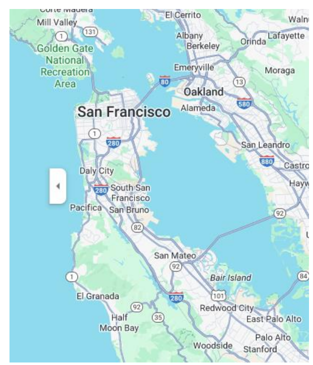
n_{e0}=2.7x10^{17}cm^{-3}

60fs e⁻ bunch

2x10^{10}e⁻, 42GeV, ~50J

~42GeV energy gain

~52GeV/m, 85cm



LWFA, short laser pulse

Gonsalves, PRL 122, 084801 (2019)

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~40J, 1PW

~8GeV energy gain

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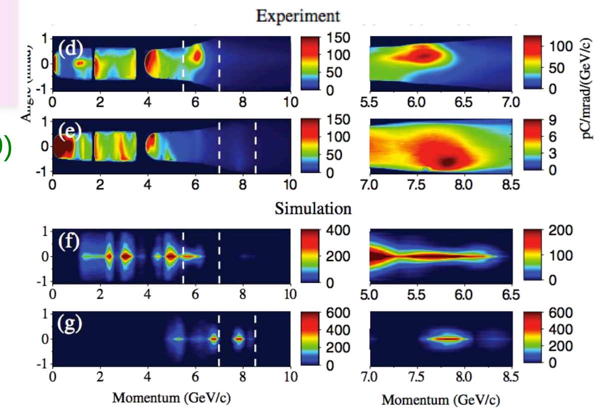

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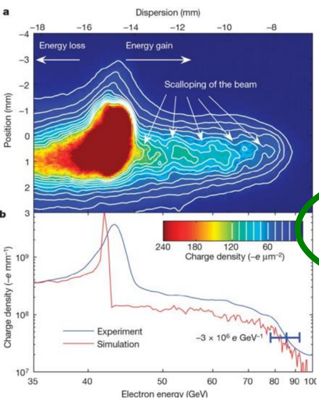

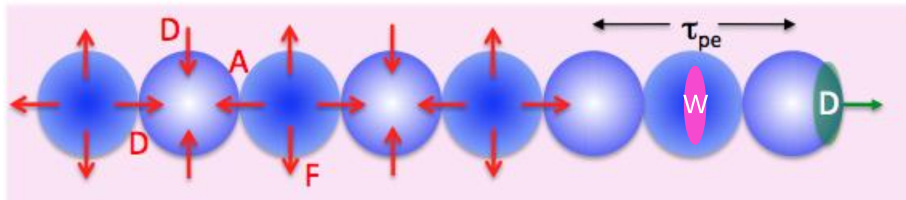

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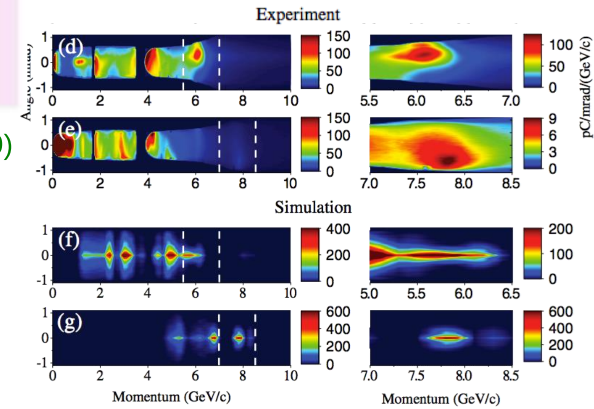

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Very similar parameters!

PLASMA WAKEFIELDS

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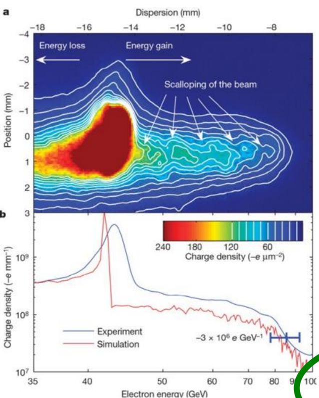

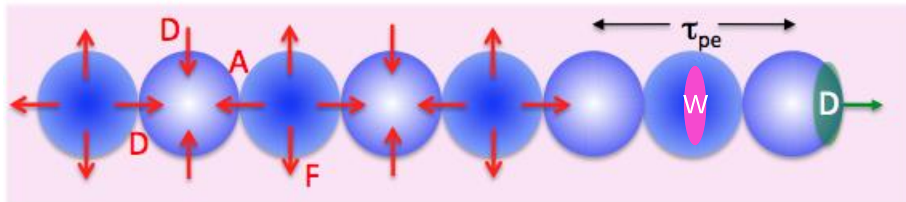

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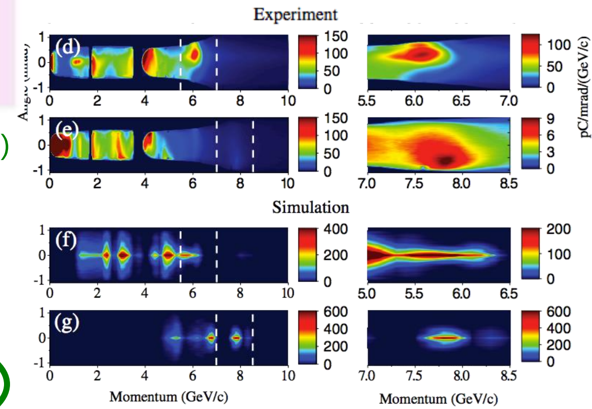

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Note: RF-based accelerators <100MeV/m!

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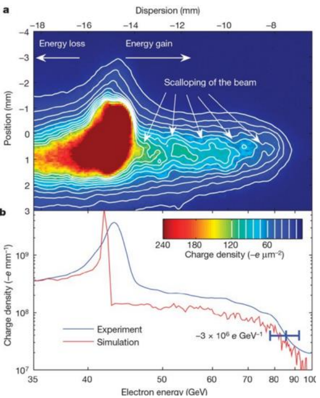

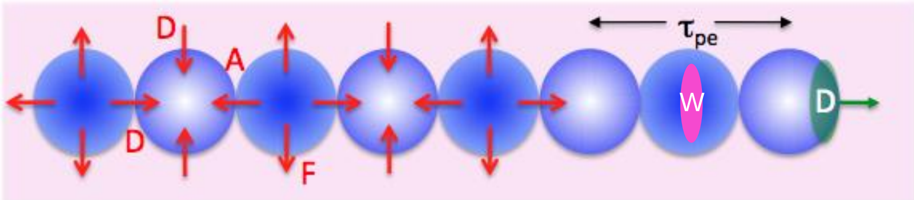

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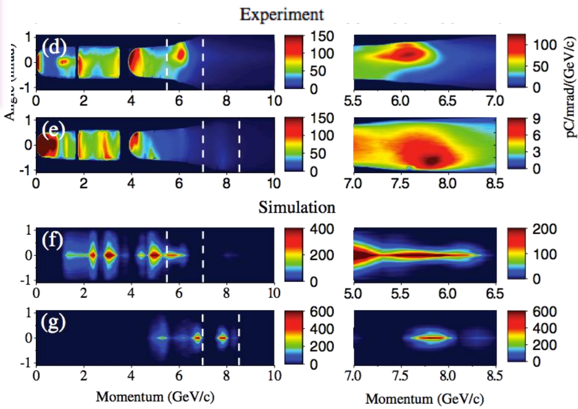

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Witness bunch energy gain (J) ≤ Drive bunch energy

PLASMA WAKEFIELDS

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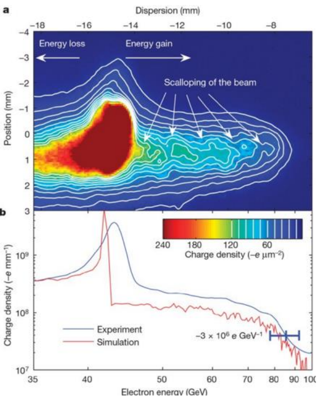
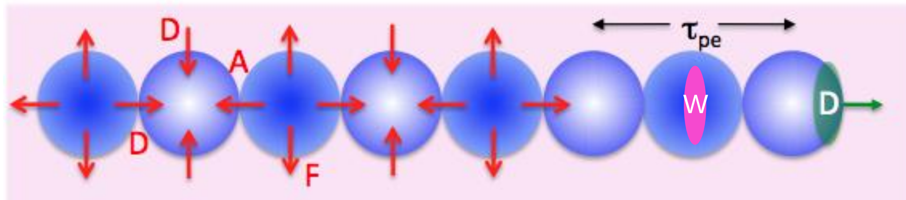
PWFA, short e^- bunch





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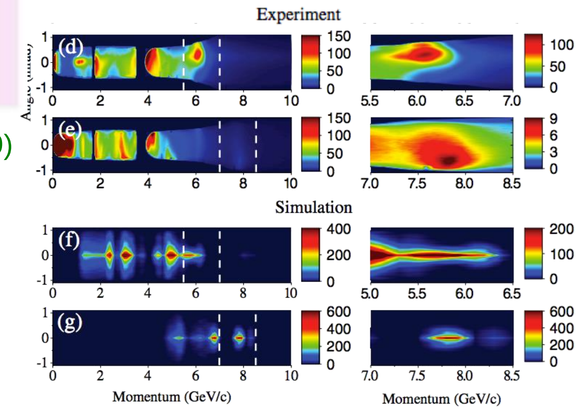

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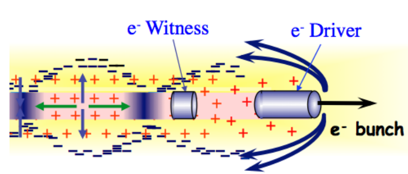
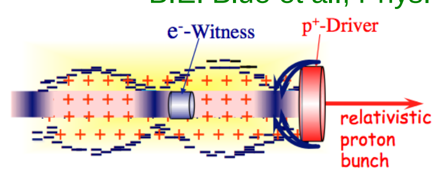
p^+ bunches: SPS ⇔ 3x10^{11}p^+ ⇔ 400 GeV ⇔ 19kJ

LHC ⇔ 1x10^{11}p^+ ⇔ 7 TeV ⇔112kJ

✧Very large energy gain in a single plasma

B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (2003).

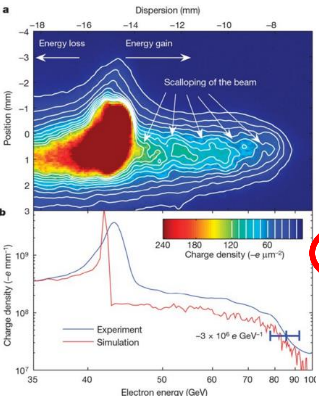


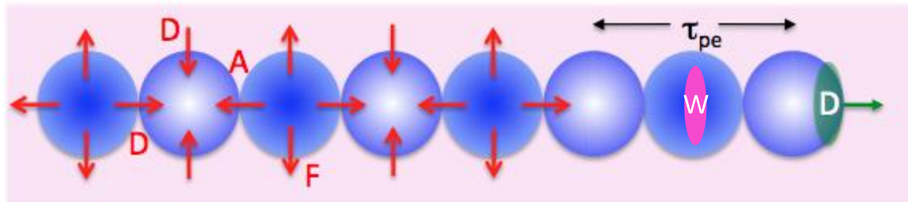


PLASMA WAKEFIELDS

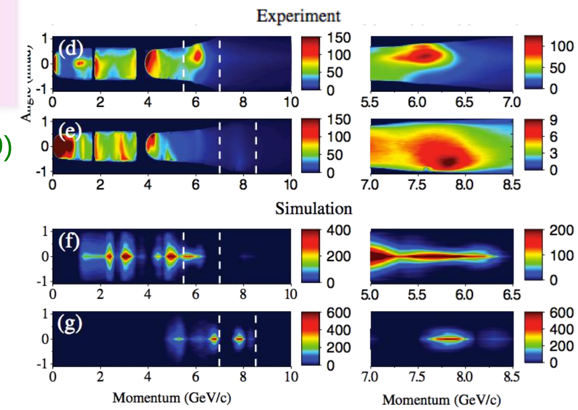
Short driver: electron bunch, laser pulse

PWFA, short e^- bunch





LWFA, short laser pulse



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

σ_t ~1/ω_{pe}

E_{WB}~50GV/m

Gonsalves, PRL 122, 084801 (2019)

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

~40fs laser pulse

~40J, 1PW

~8GeV energy gain

~39GeV/m, 20cm

Scaling:

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

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

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

p^+ bunches: SPS ⇔ 3x10^{11}p^+ ⇔ 400 GeV ⇔ 19kJ

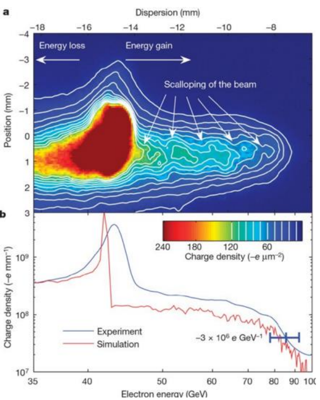
LHC ⇔ 1x10^{11}p^+ ⇔ 7 TeV ⇔112kJ

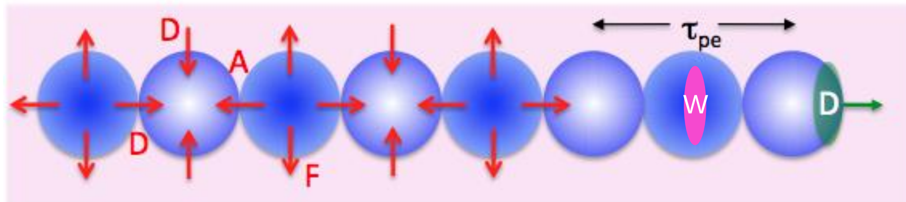
Scaling: τ= 300ps ⇔ n_{e0}=3.5x10^{9}cm^{-3} ⇔ E_{WB}=5.7MV/m!

Plasma WakeFields

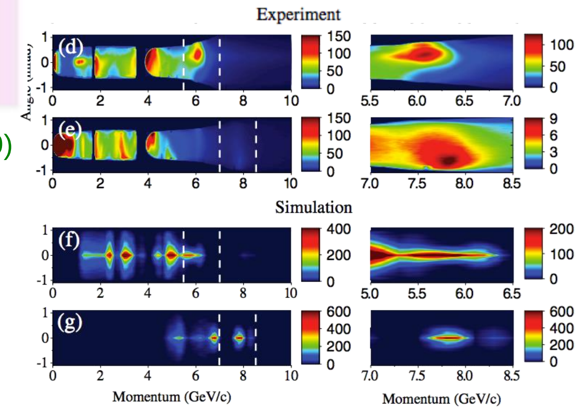
Short driver: electron bunch, laser pulse

PWFA, short e^- bunch





LWFA, short laser pulse



Blumenfeld, Nature 445, 741 (2007)

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Scaling: τ= 300ps ⇔ n_{e0}=3.5x10^9cm^{-3} ⇔ E_{WB}=5.7MV/m!

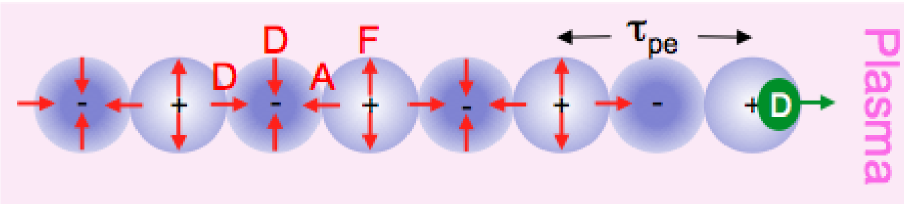
Self-Modulation!

✧Reach high energies (TeV) in a single, GV/m (accelerator) plasma driven by a high-energy (kJ) SM'ed p^+ bunch

Kumar et al., PRL 104, 255003 (2010)

SELF-MODULATiON

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



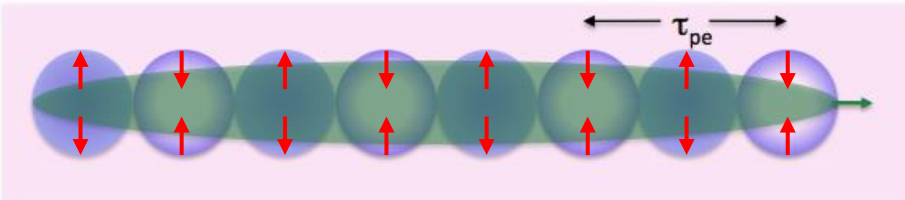
Short and Narrow => Long and Narrow

$k_{pe}\sigma_z<1$

$k_{pe}\sigma_r\sim1$

SELF-MODULATiON

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

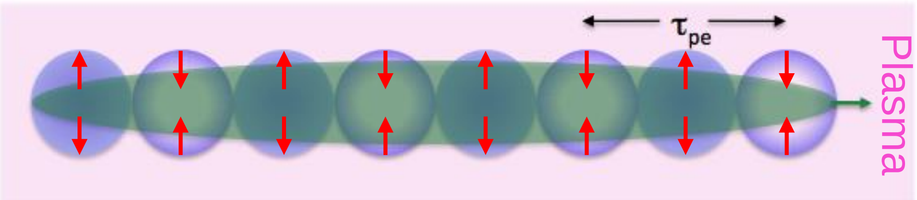


Short and Narrow => Long and Narrow

$k_{pe}\sigma_z<1$	$k_{pe}\sigma_z>>1$
$k_{pe}\sigma_r\sim 1$	$k_{pe}\sigma_r\sim 1$
	⬇
	n_{e0}, c/ω_{pe}

Self-Modulation

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



(1)

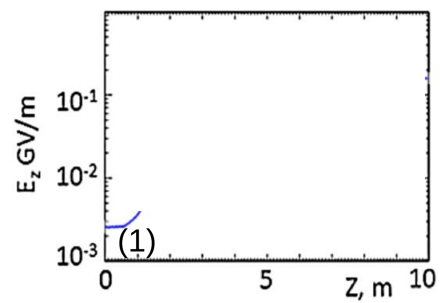
Initial (transverse) wakefields

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)

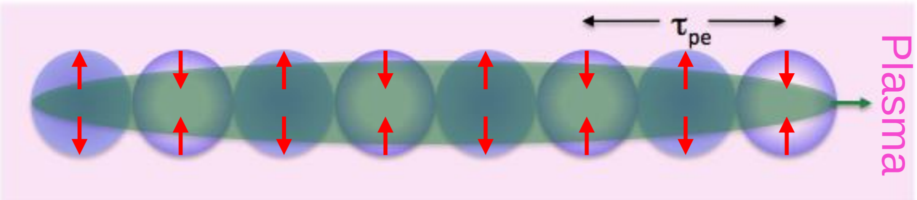


✧E_z-field along the plasma

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

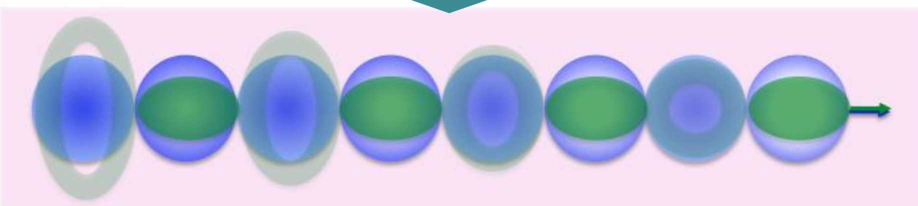
SELF-MODULATiON

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



(1)

Self-modulation



(2)

Growth mechanism:

Initial (transverse) wakefields

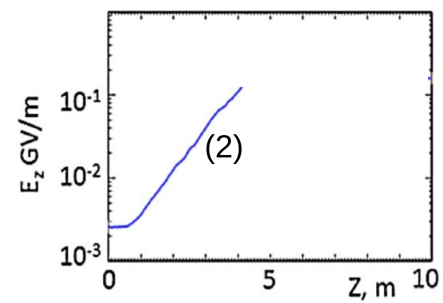
Periodic focusing/defocusing

Density modulation

Wakefields

(2)

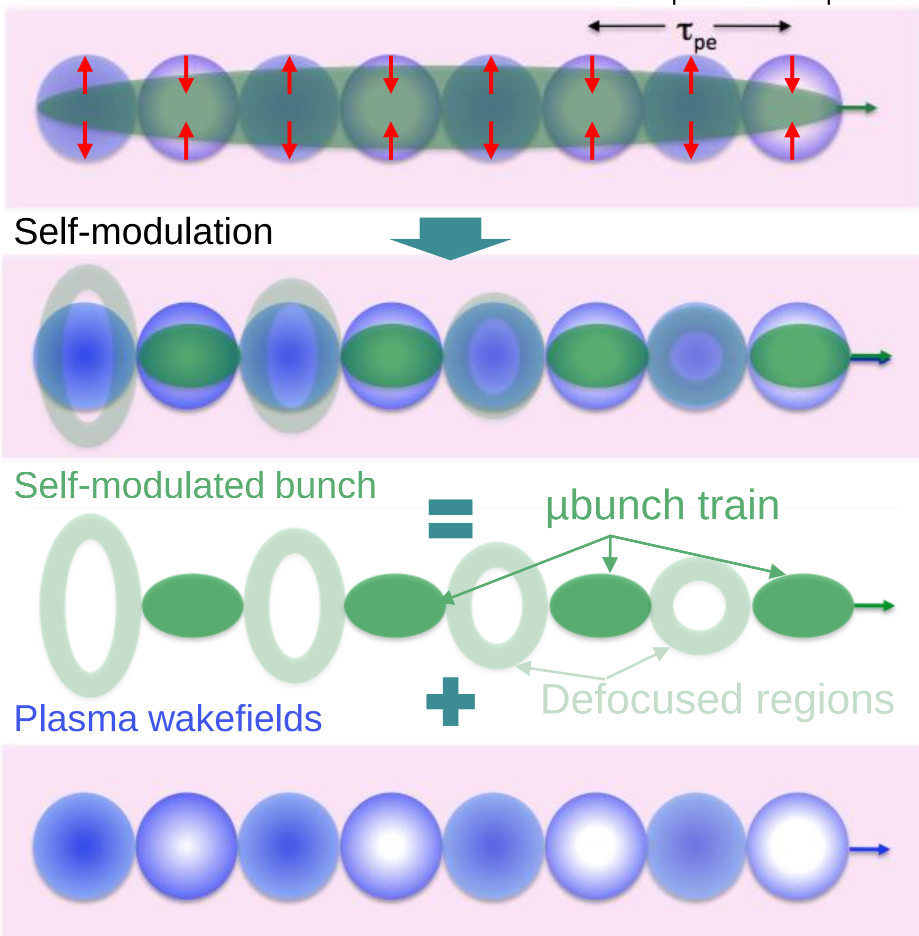
Pukhov, PRL107 145003 (2011)



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

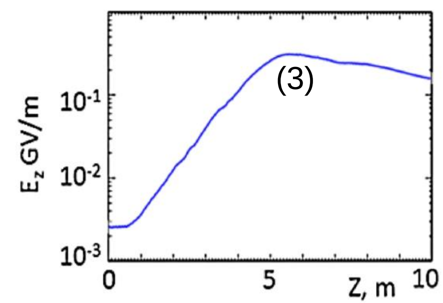
Periodic focusing/defocusing

Density modulation

Wakefields

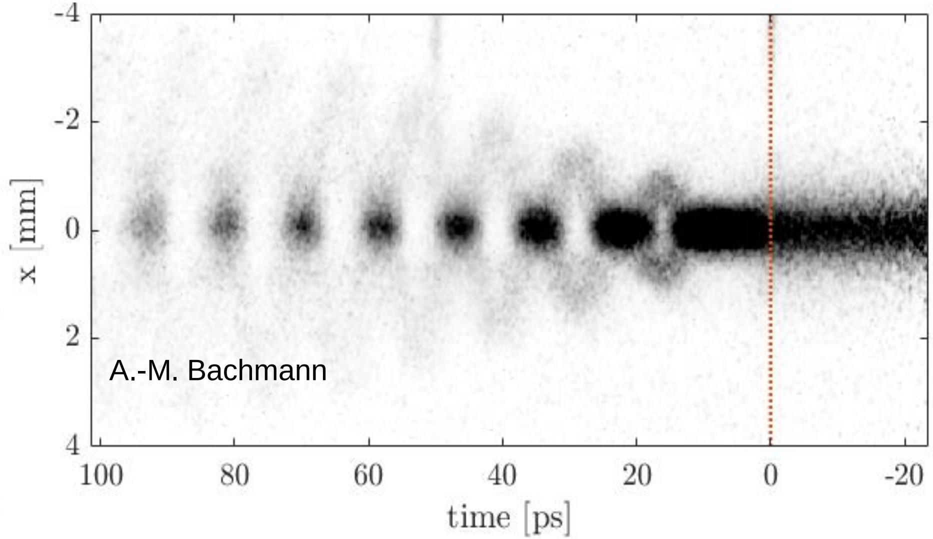
Full modulation - bunch train (3)

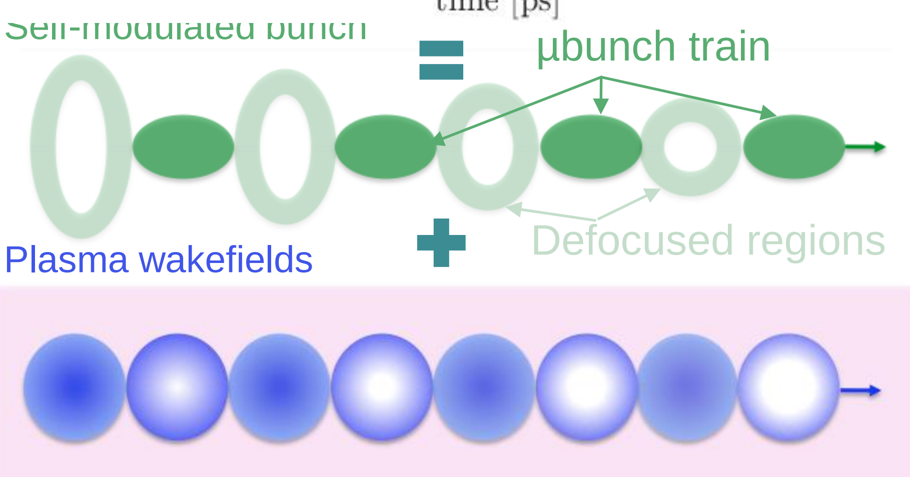
Pukhov, PRL107 145003 (2011)



(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





Growth mechanism:

Initial (transverse) wakefields

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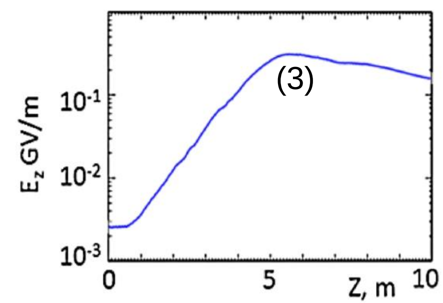
Wakefields

Full modulation - bunch train (3)

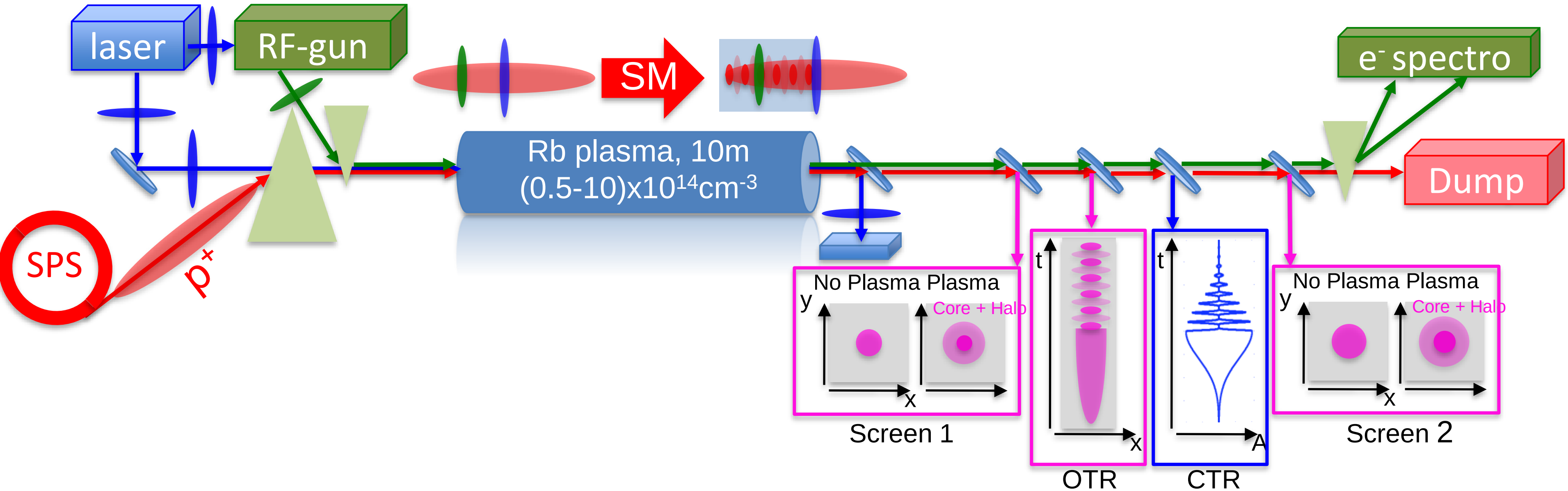
Pukhov, PRL107 145003 (2011)



(3)

- ✧Train period ~$\tau_{pe}=2\pi/\omega_{pe}$
- ✧μbunch length < τ_{pe}
- ✧Resonantly drives wakefields to large amplitude
- ✧Self-modulation necessary to drive ~GV/m accelerating fields in ~$10^{14}cm^{-3}$ density plasma

AWAKE EXPERiMENTAL SETUP

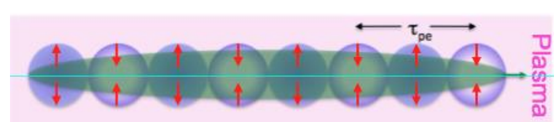


E=400GeV
σ_z=6cm!!
Long

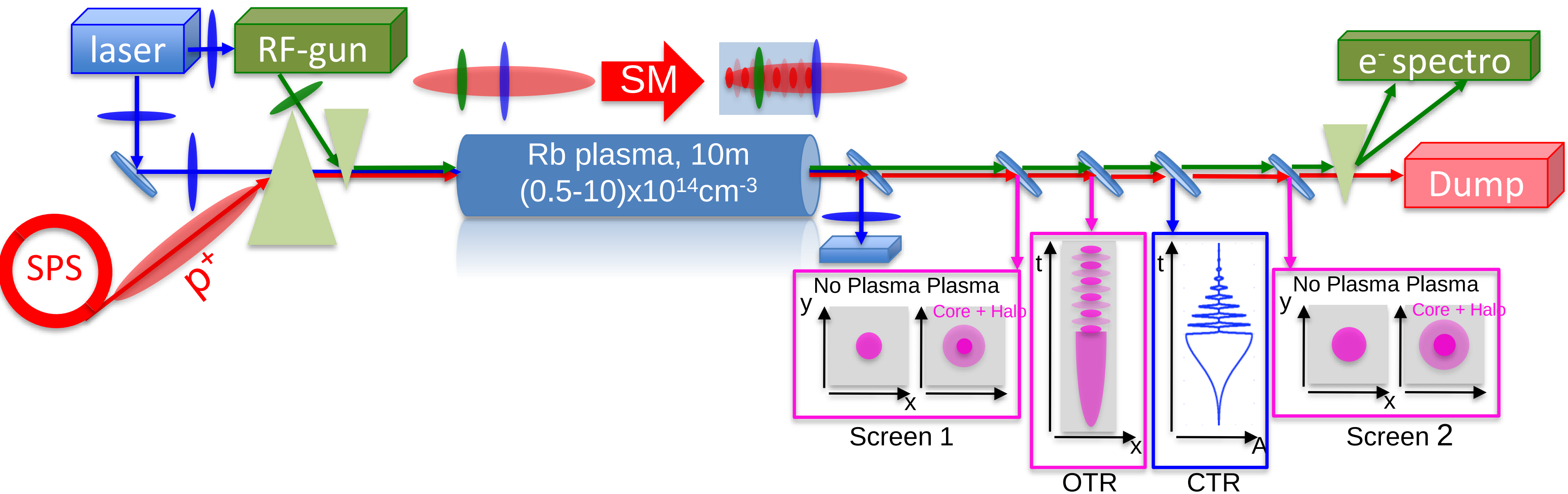
N=(1-3)x10^{11}p$^+$
σ_r=200µm
Narrow

✧Plasma density from σ_r

SM regime …



AWAKE EXPERiMENTAL SETUP



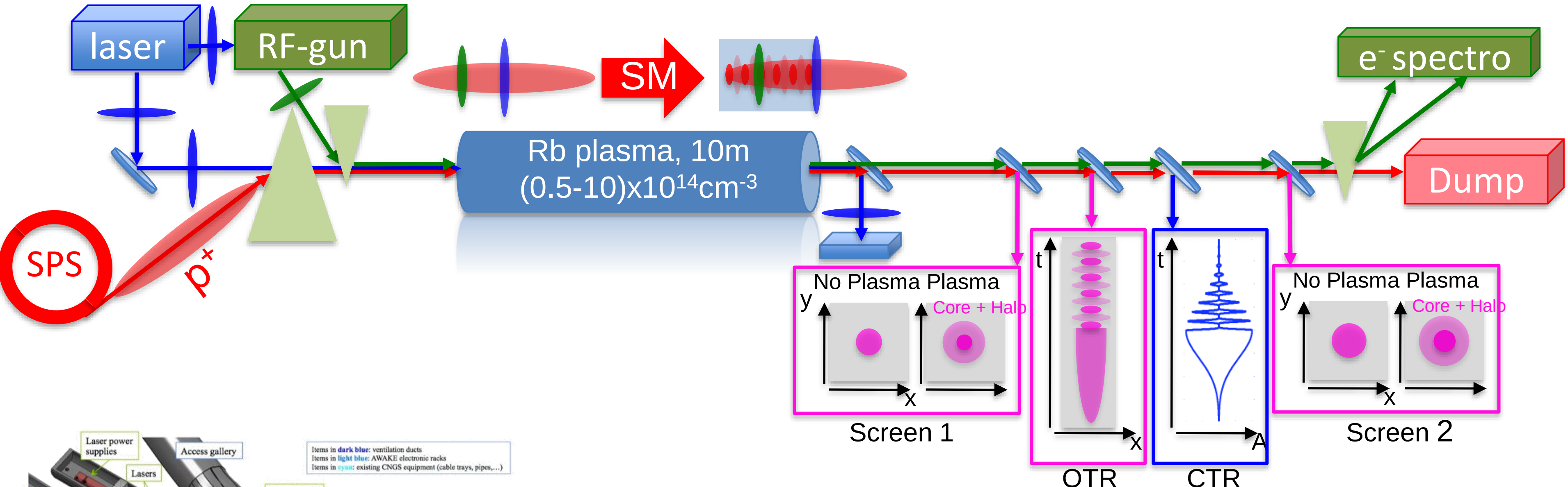
E=400GeV
σ_z=6cm!!
$c/\omega_{pe} \approx \sigma_r$ ⇔

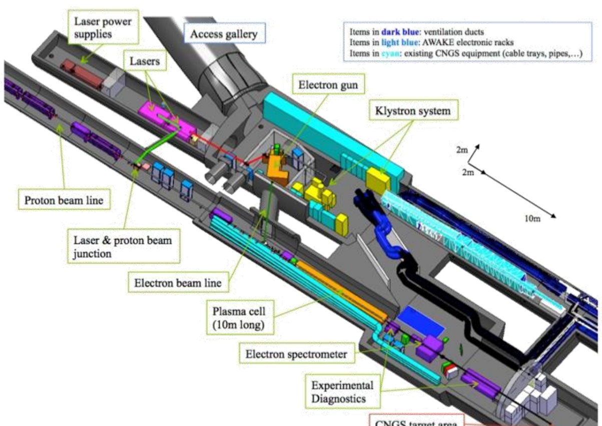
N=(1-3)x$10^{11}p^+$
σ_r=200µm
n_e ~7x10^{14} cm^{-3}
λ_{pe}~1.3mm<<σ_z
f_{pe} ~240GHz
E_{WB}~2.5GV/m
L_p ~10m~2β^*

✧Plasma density from σ_r

➡ SM ~ 1GeV/m

AWAKE EXPERIMENTAL SETUP





E=400GeV
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N=(1-3)x10^{11}p$^+$
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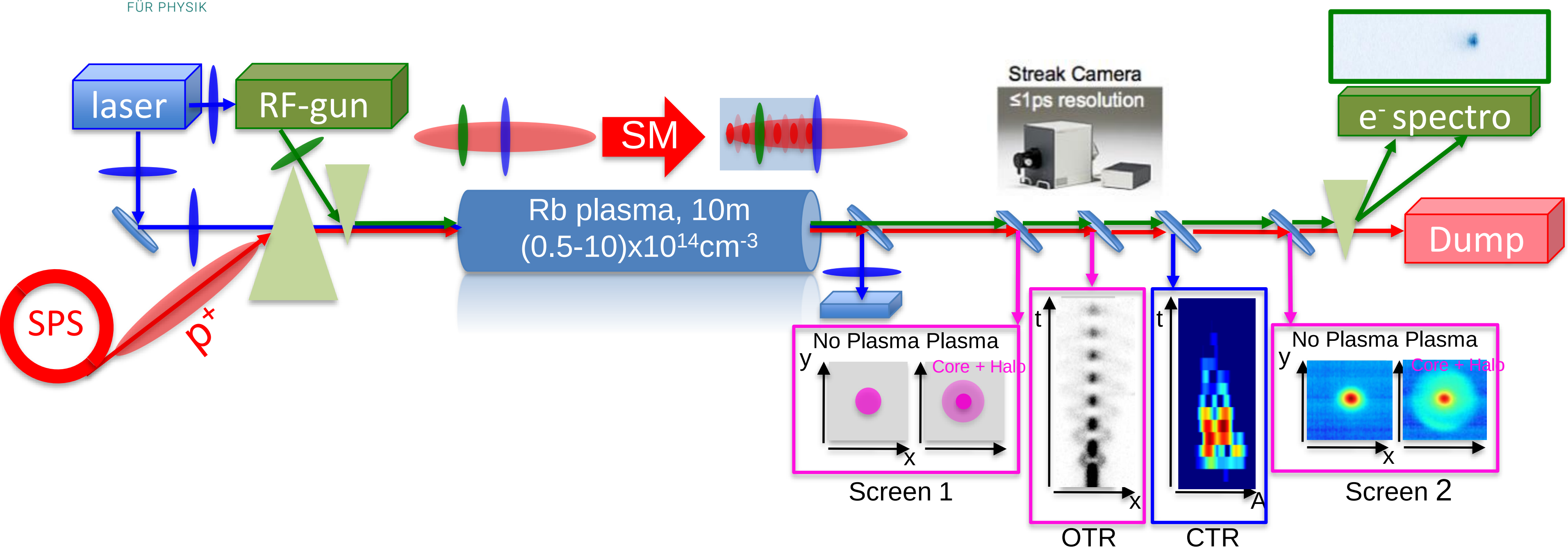
✧Plasma density from σ_r

➡ SM ~ 1GeV/m

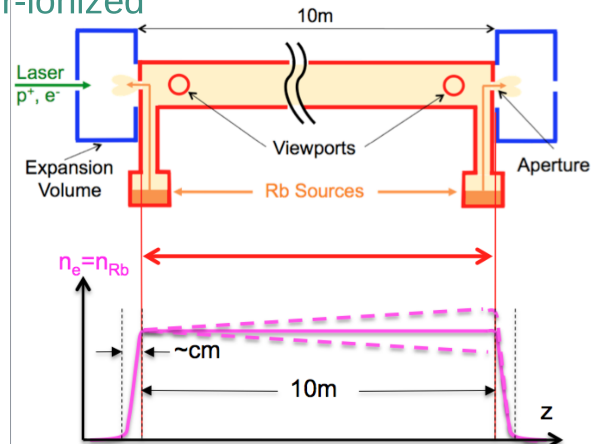
AWAKE EXPERIMENTAL SETUP



PLASMA SOURCES

MAX-PLANCK-INSTITUT FÜR PHYSIK

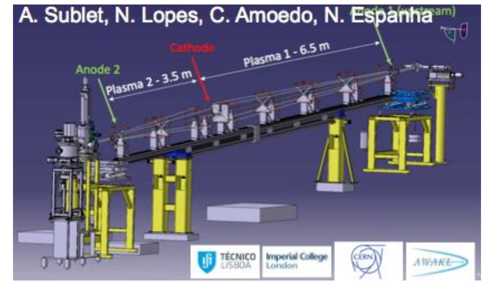
✧Rubidium vapor source $0.5<n_{e0}<10*10^{14}cm^{-3}$
✧Laser-ionized



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

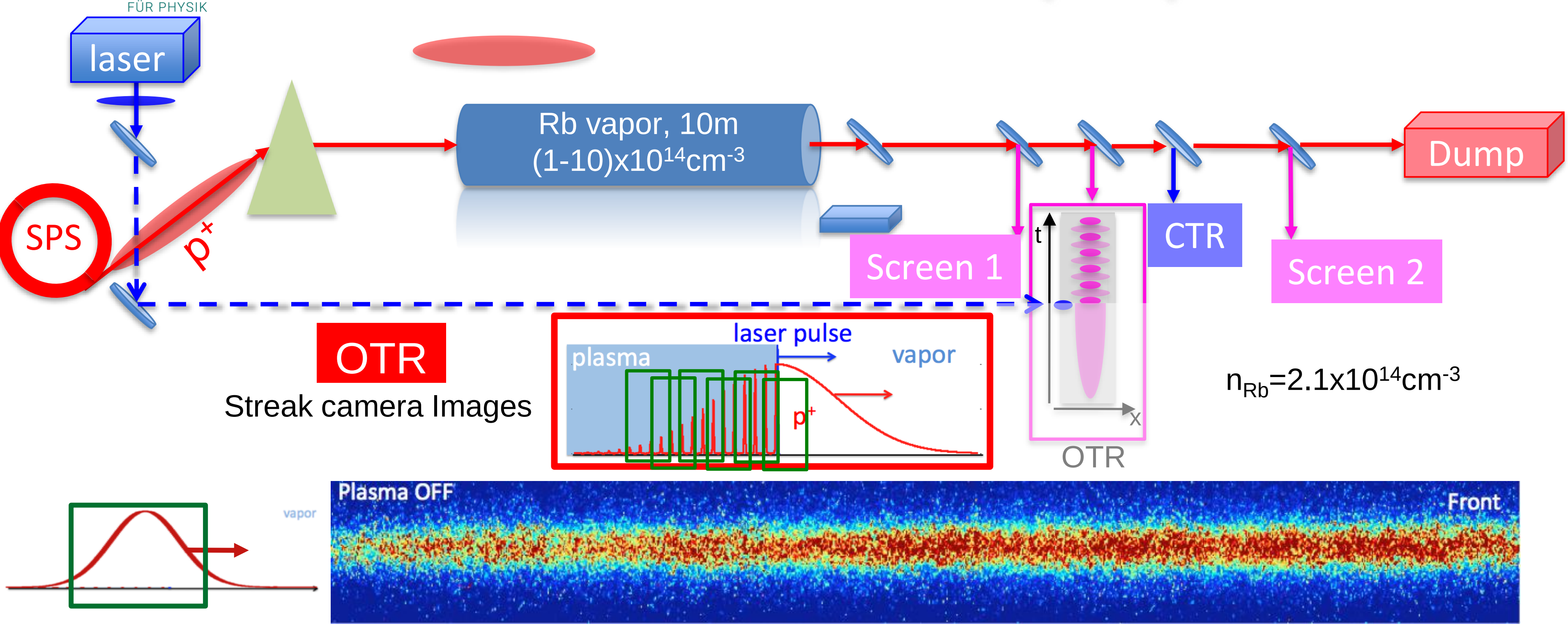
✧Very uniform density uniformity: $\Delta n_e/n_{e0}<0.5\%$

✧Discharge plasma source



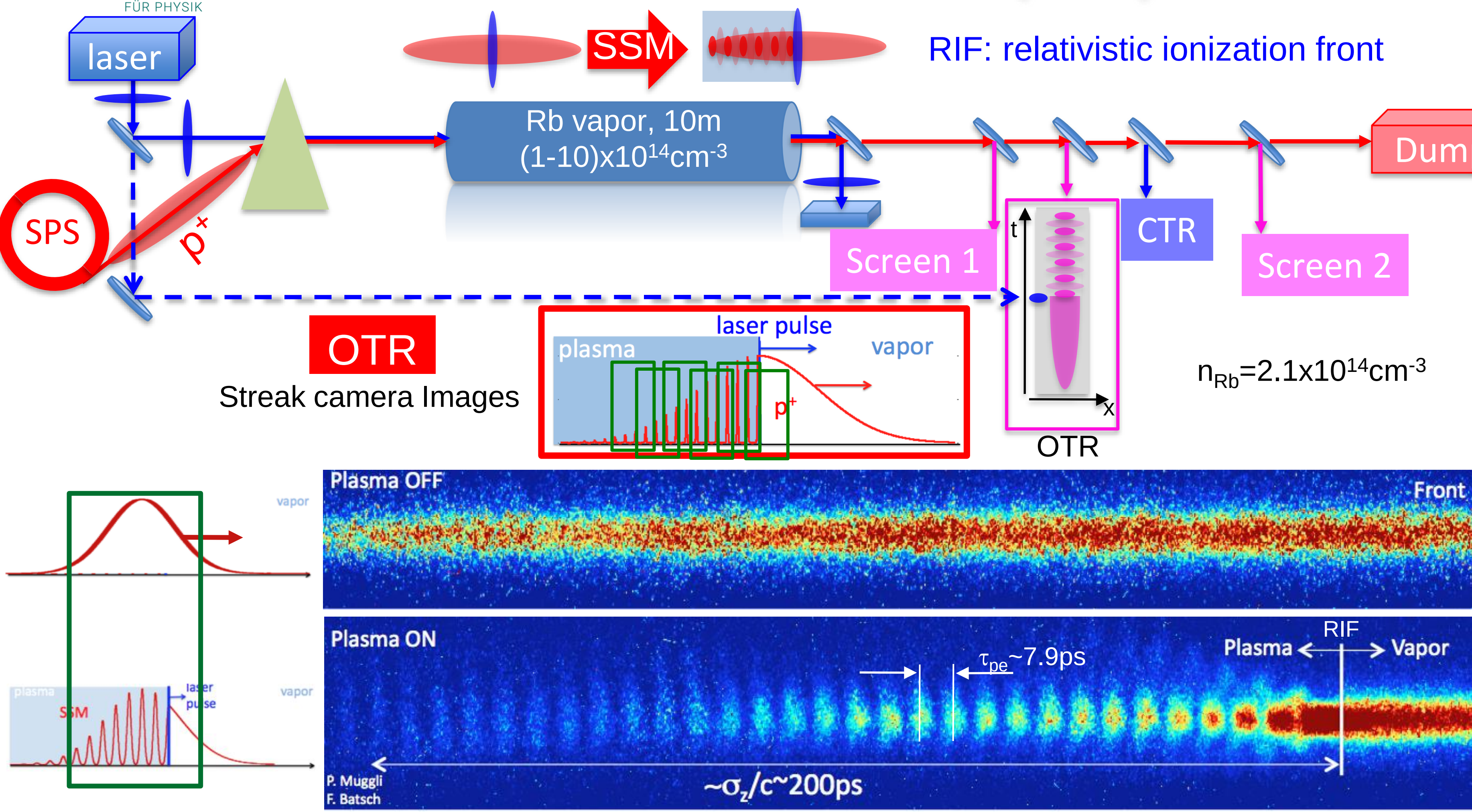
✧Flexibility:
- ✧ Plasma length: 3.5, 6.5, 10m
- ✧ Density $0.1\text{-}20x10^{14}cm^{-3}$
- ✧ Gas-ion mass: He, Ar, Xe (ω_{pi})
- ✧ Access to plasma light

SEEDED SELF-MODULATION (SSM)



✧No plasma
✧No density modulation
✧No centroid position oscillation

SEEDED SELF-MODULATiON (SSM)



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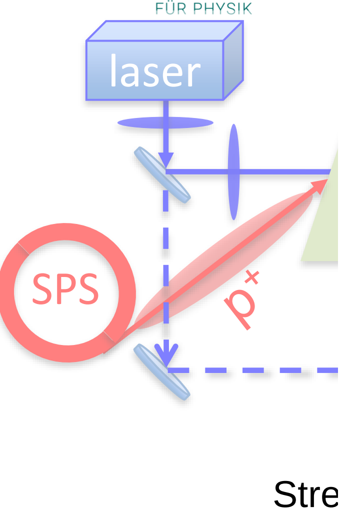
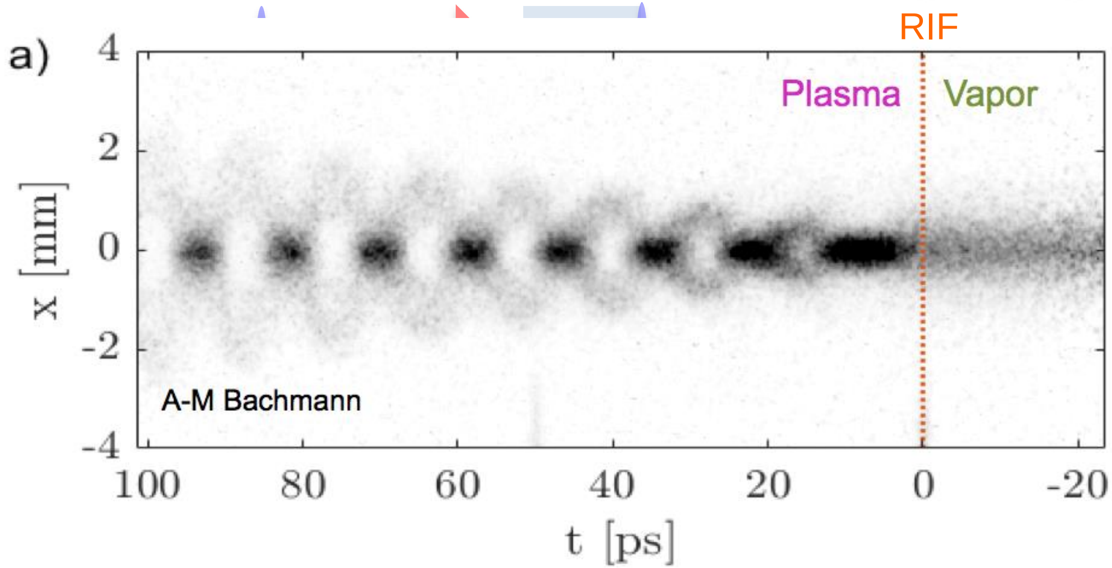
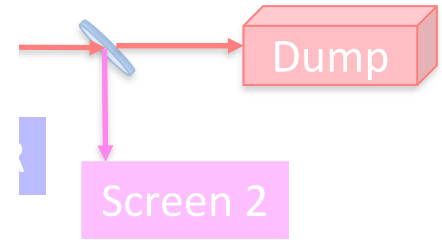
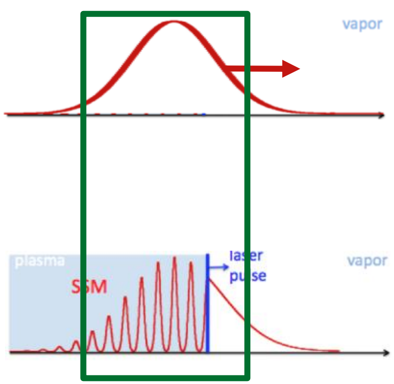
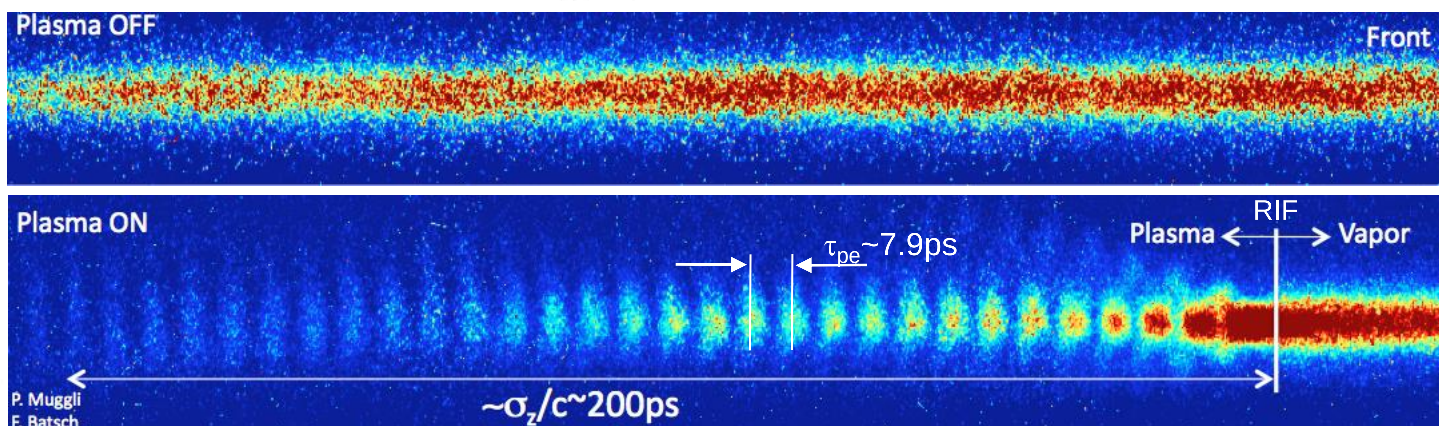




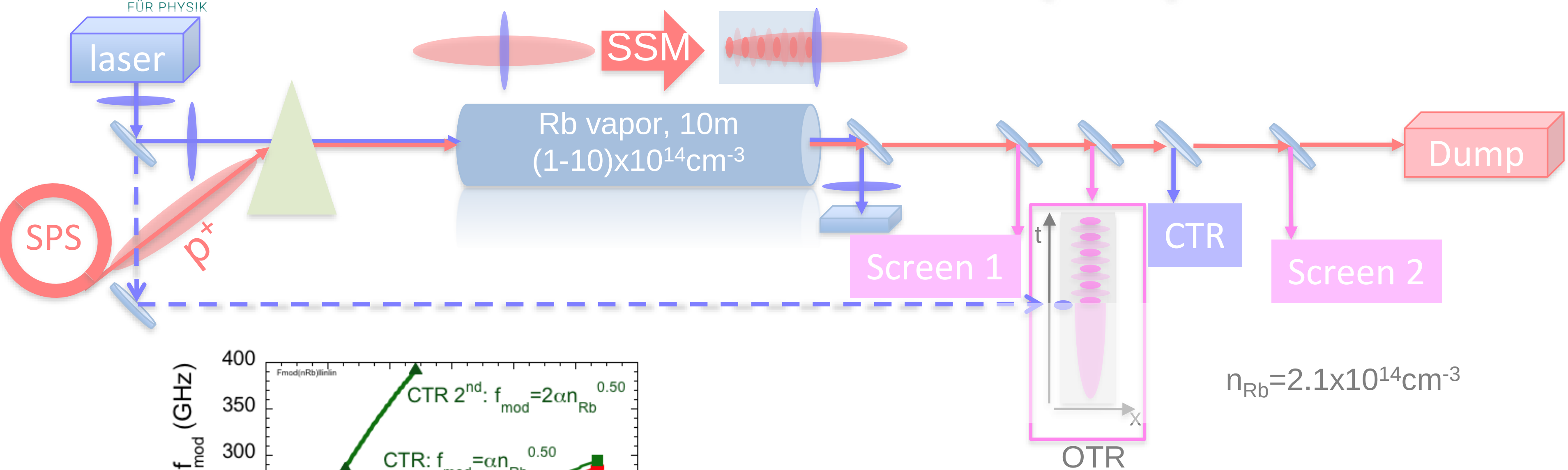


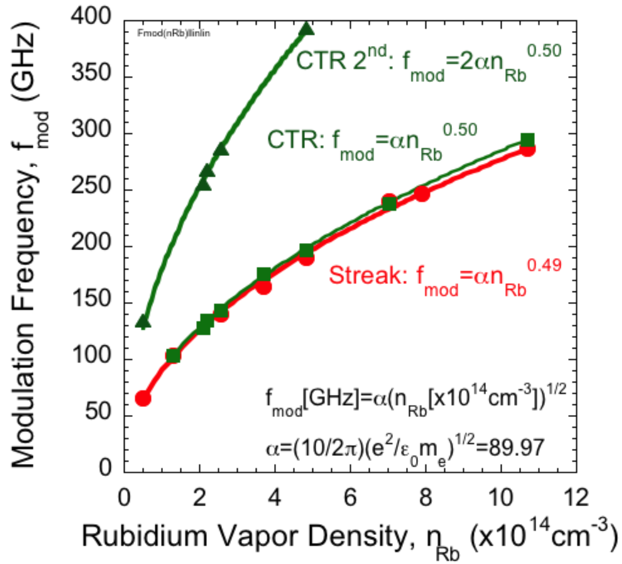
n_{Rb}=2.1x10^{14}cm^{-3}





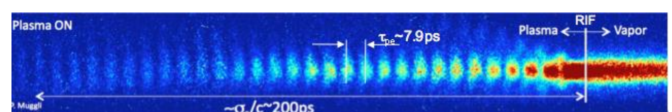
SEEDED SELF-MODULATiON (SSM)





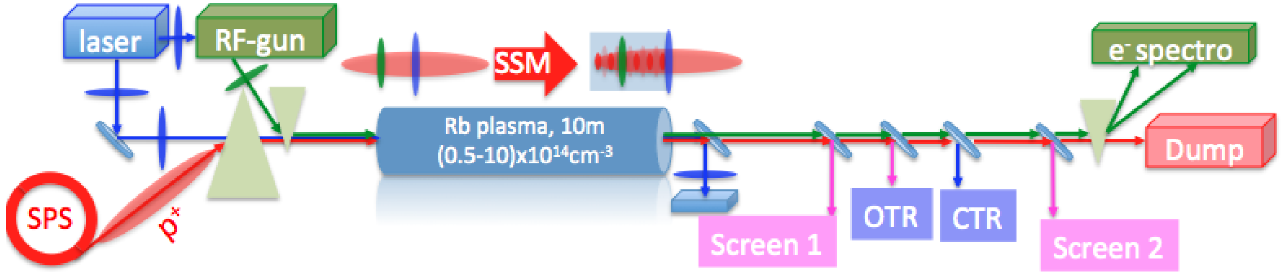
$n_{Rb}=2.1\times 10^{14}cm^{-3}$

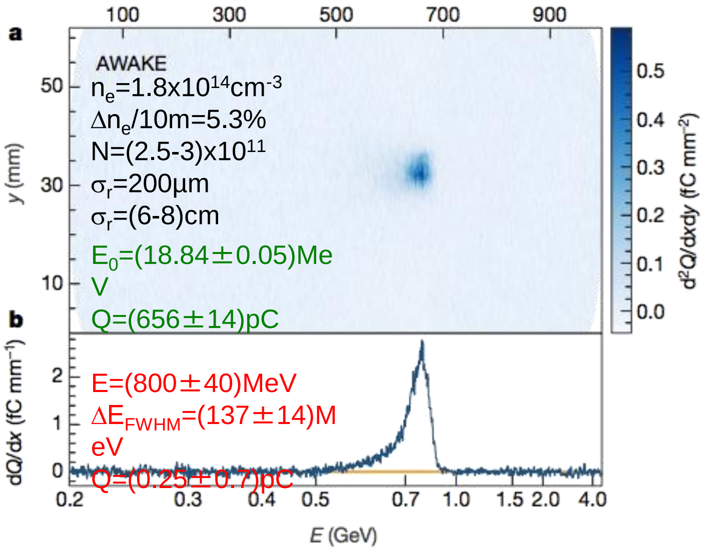
✧ Modulation frequency = f_{pe}

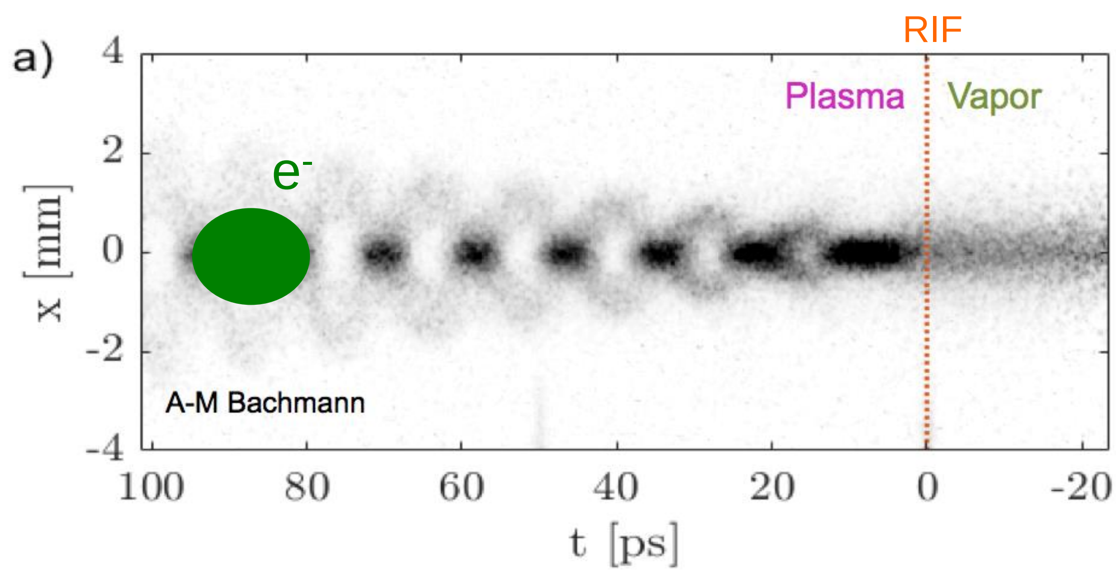


 AWAKE, Phys. Rev. Lett. 122, 054802 (2019) M. Turner et al., Phys. Rev. Lett. 122, 054801 (2019)

ACCELERATION EXTERNALY-INJECTED e^-



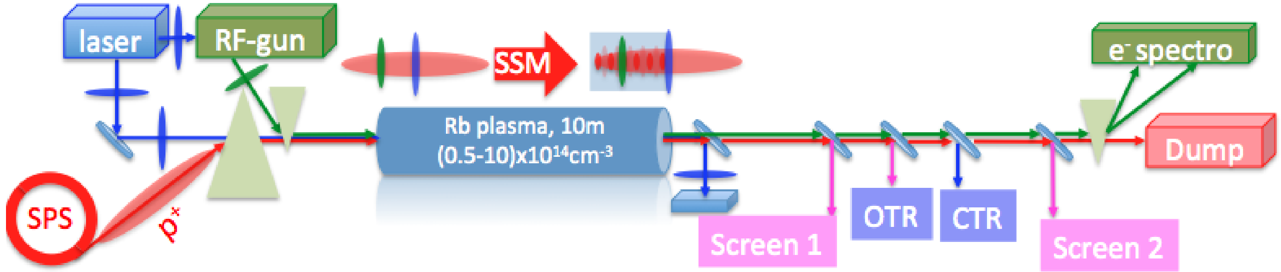


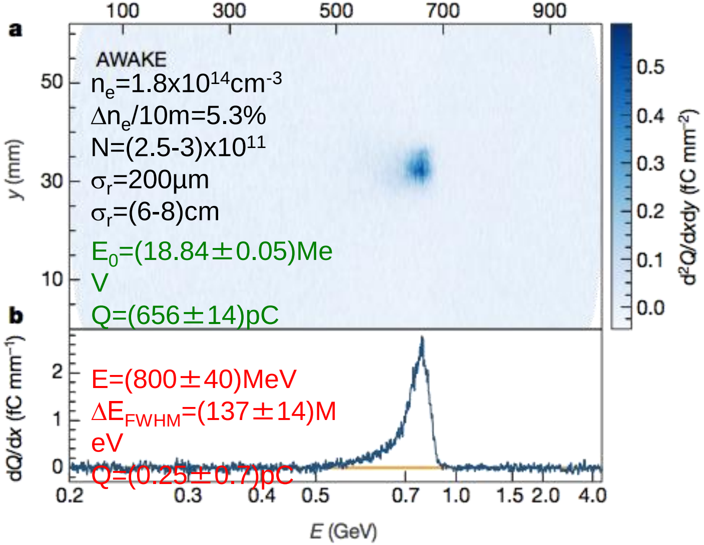


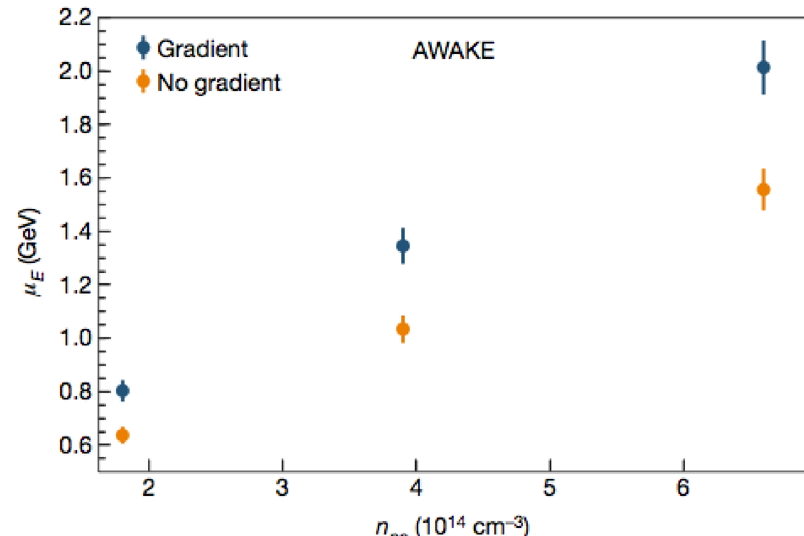
- ✧ Injection test e^- at an angle (~1-3mrad)
- ✧ Finite $\Delta E/E$

AWAKE, Nature 561, 363 (2018)

ACCELERATiON EXTERNALY-INJECTED e⁻



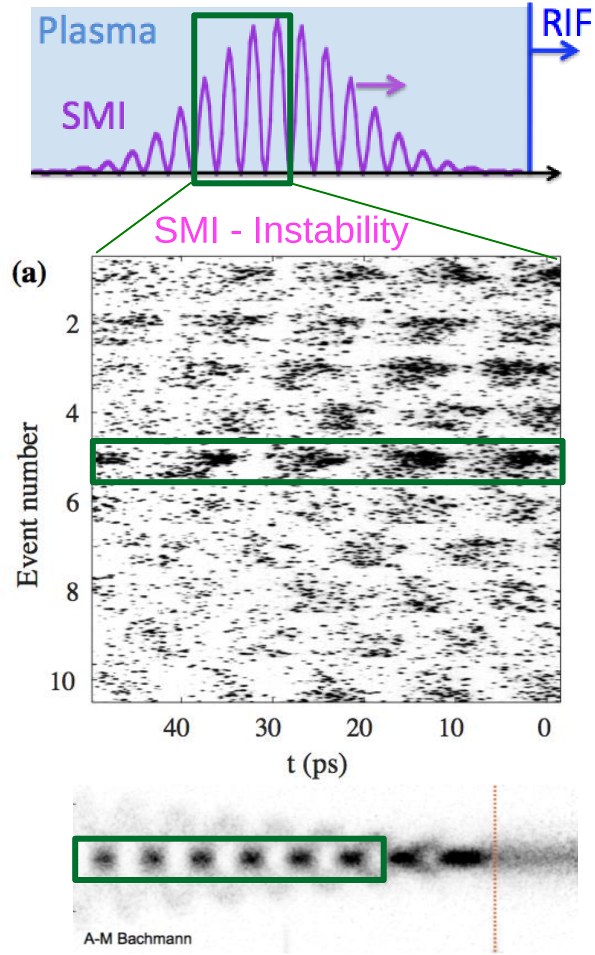




- ✧ Injection test e^- at an angle (~1-3mrad)
- ✧ Finite ΔE/E
- ✧ Up to 2GeV energy gain (from ~19MeV)
- ✧ Captured charge: ~pC

AWAKE, Nature 561, 363 (2018)

SEEDED SELF-MODULATiON (SSM)



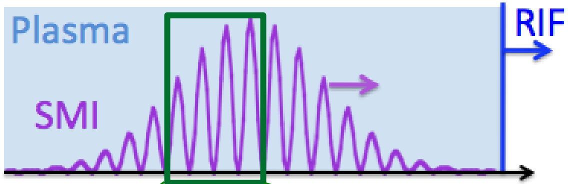
μ-bunches
@ varying times

10 events

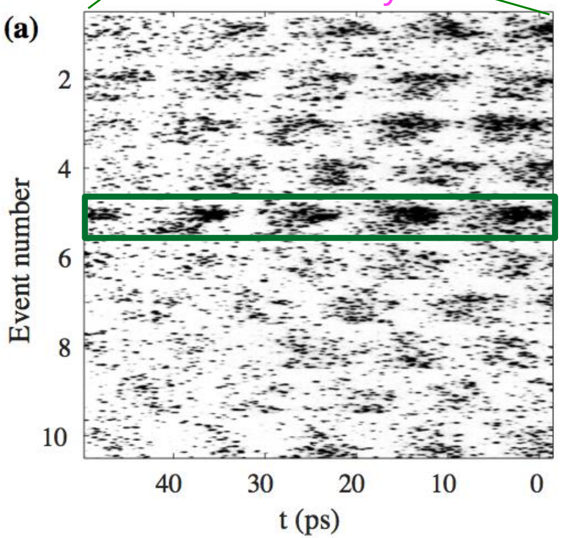
$n_{e0}=10^{14}cm^{-3}$
$N_{p+}=3x10^{11}$

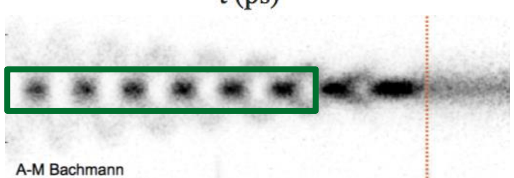
F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

SEEDED SELF-MODULATiON (SSM)



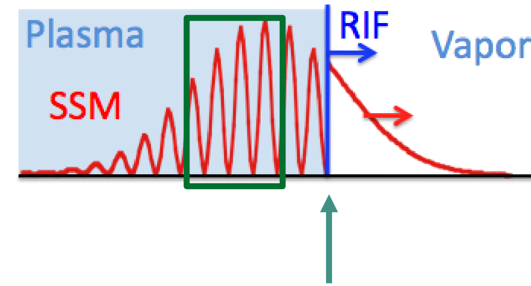
SMI - Instability





µ-bunches
@ varying times

10 events

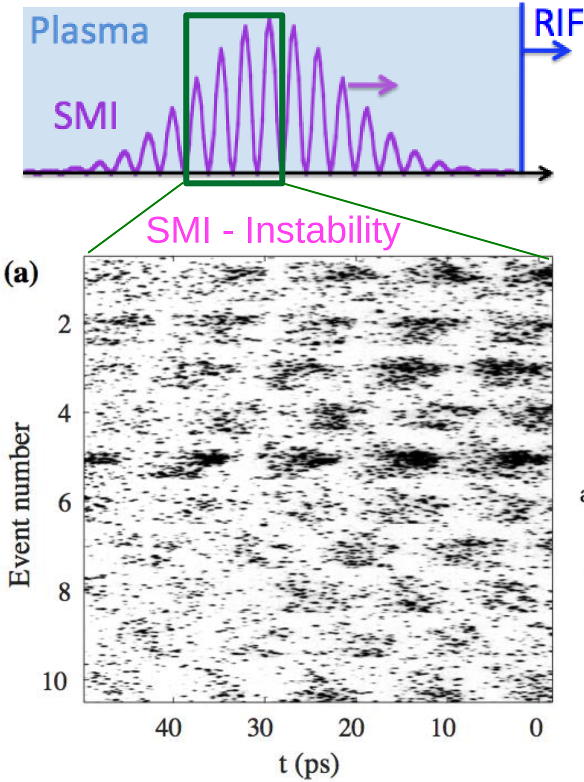


Wakefields
start
here!

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

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

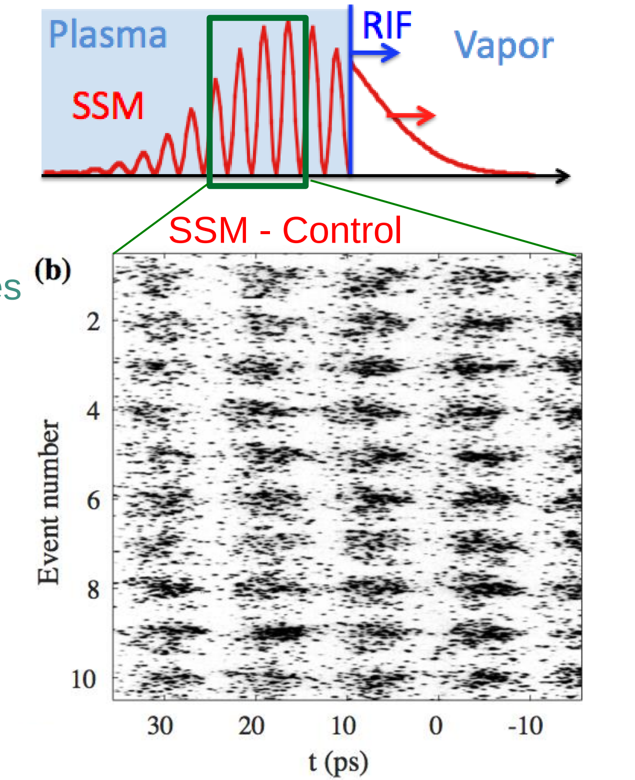
SEEDED SELF-MODULATiON (SSM)



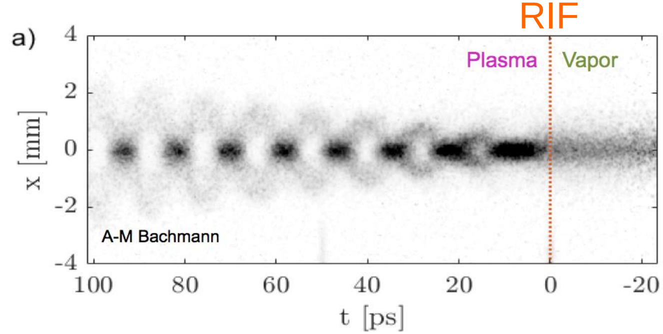
Relativistic Ionization Front
(RIF)
Seeding

μ-bunches
@ varying times

μ-bunches
@ fixed times



REPRODUCIBLE!

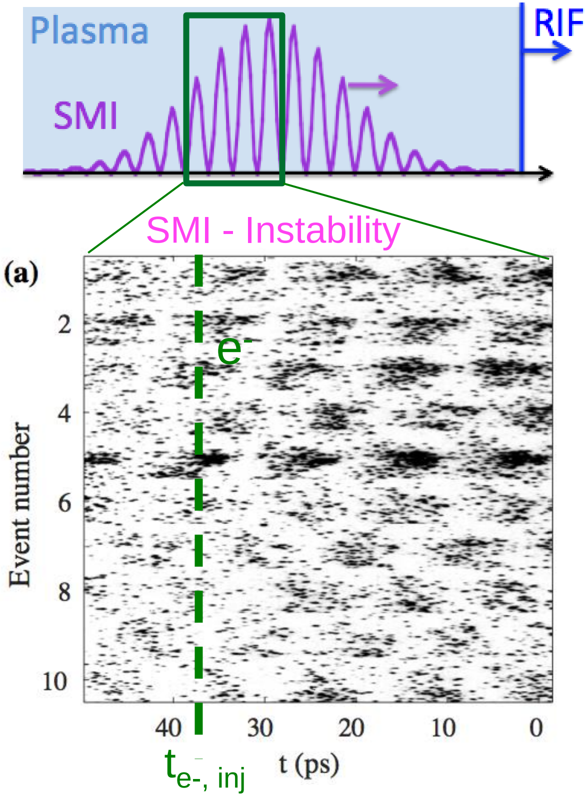


✧Summed image confirms reproducibility
✧Wakefields start at the RIF

✧Transition from SMI to SSM
✧SSM, RIF seeding: $\Delta\Phi/2\pi \leq 8\%$

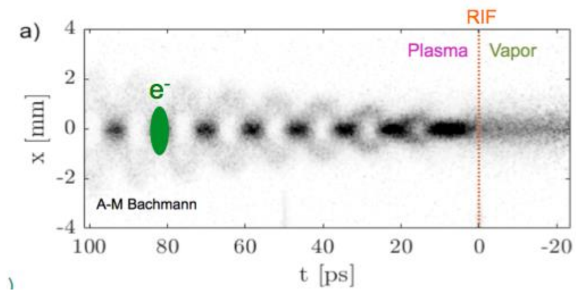
F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

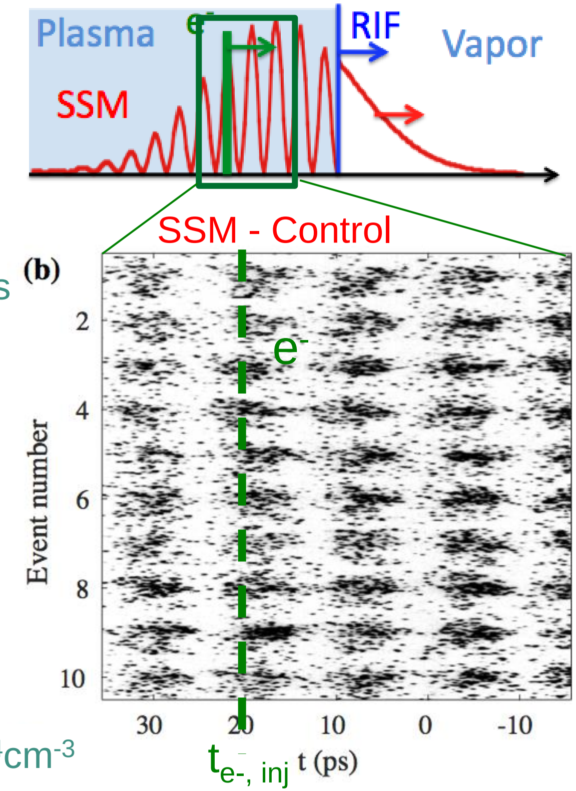
SEEDED SELF-MODULATiON (SSM)



Relativistic Ionization Front (RIF) Seeding

µ-bunches @ varying times → µ-bunches @ fixed times





SMI –SSM transition:

✧$t_{RIF} \sim 2\sigma_{p+}$

✧$2.8 MV/m \leq E_{z,seed} \leq 4 MV/m$ @ $n_e = 10^{14} cm^{-3}$

✧Transition from SMI to SSM

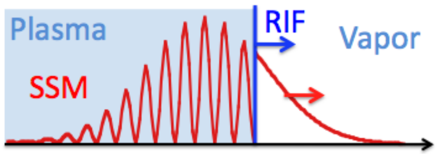
✧SSM, RIF seeding: $\Delta\Phi/2\pi \leq 8\%$

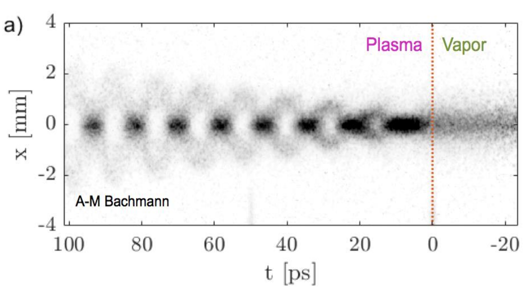
✧Essential for deterministic external injection of a e^- bunch in the *accelerating* and *focusing* phase of the wakefields

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

e-BUNCH SEEDING OF SM

✧RIF seeding of SM

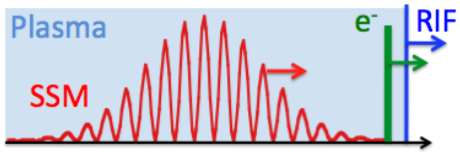




Abrupt start of the plasma ($<<1/\omega_{pe}$) to seeds wakefields

e-Bunch Seeding of SM

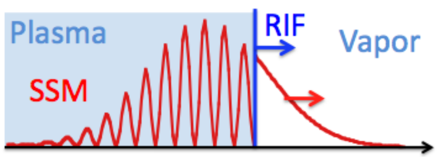
✧e-bunch seeding of SM

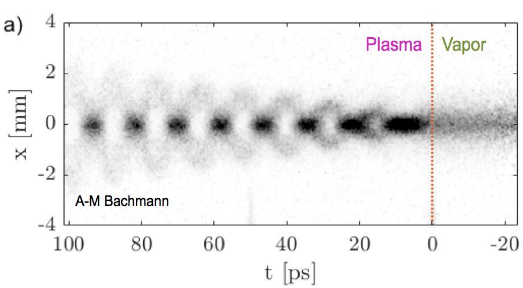


Wakefields start here!

e^- bunch wakefields to seed

✧RIF seeding of SM

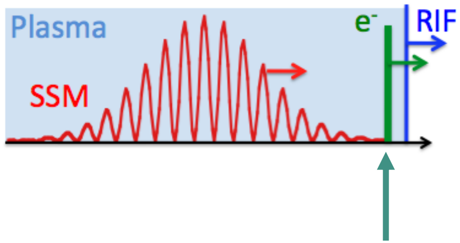




Abrupt start of the plasma ($<<1/\omega_{pe}$) to seeds wakefields

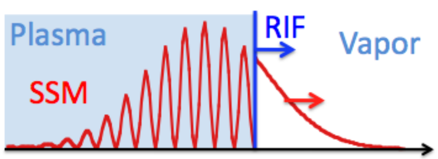
e-BUNCH SEEDING OF SM

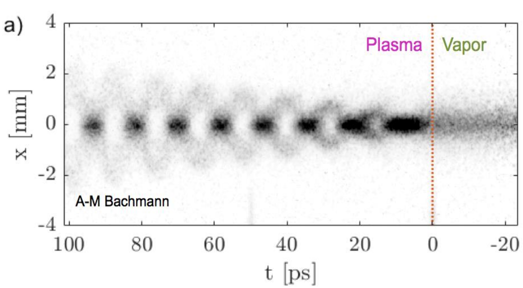
✧e-bunch seeding of SM

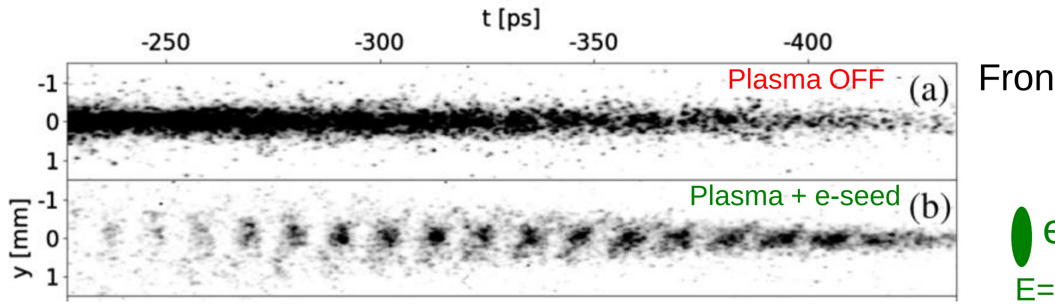


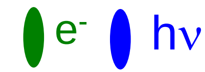
Wakefields start here!

✧RIF seeding of SM









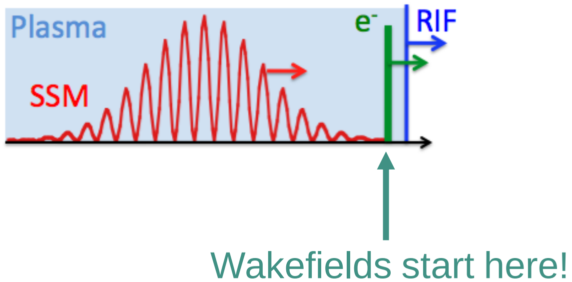
E=19MeV
Q=250pC
σ_r=200µm
σ_t=3-5ps
$n_{e0}=10^{14}cm^{-3}$

✧SM is reproducible (summed image)

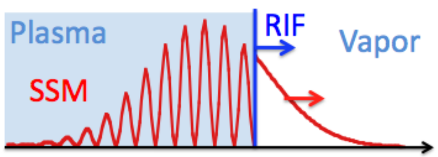
L. Verra, (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

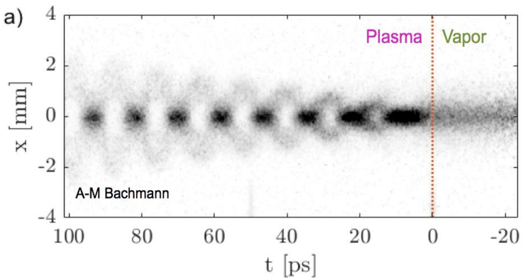
e-BUNCH SEEDING OF SM

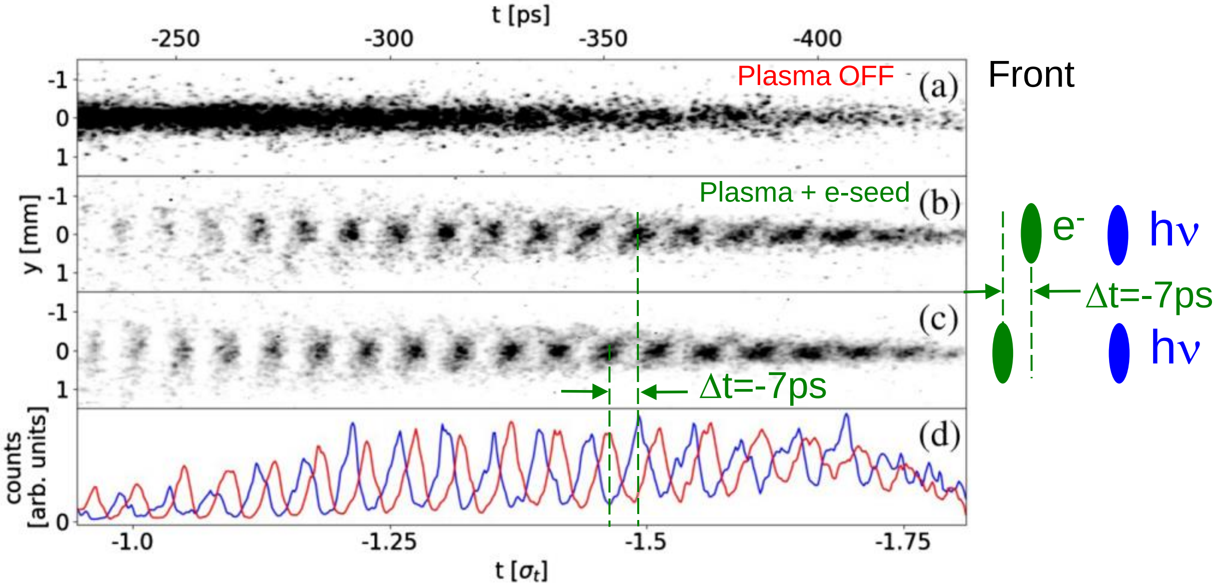
✧e-bunch seeding of SM



✧RIF seeding of SM







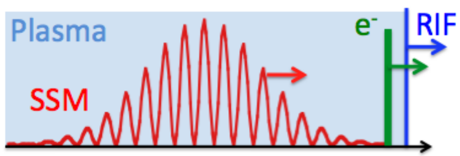
✧SM is reproducible (summed image)

✧SM is seeded by the (wakefields driven by the) e- bunch, e-SSM

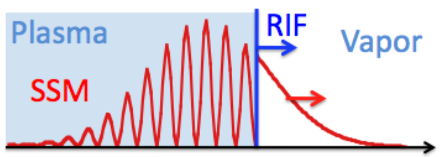
L. Verra, (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

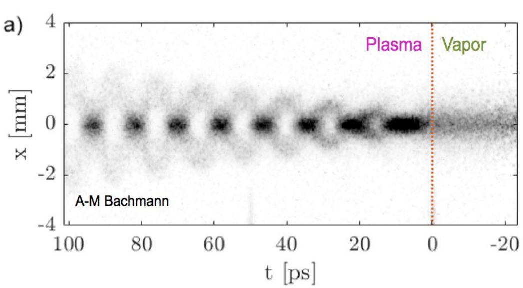
e-BUNCH SEEDING OF SM

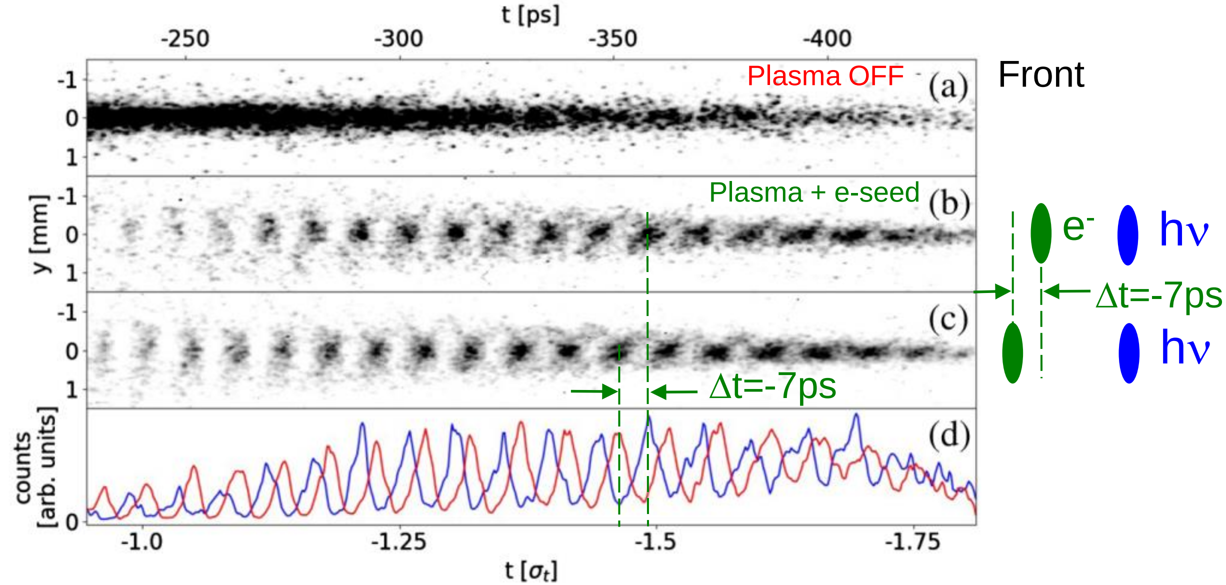
✧e-bunch seeding of SM



✧RIF seeding of SM







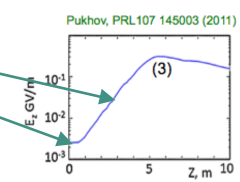
✧SM is reproducible (summed image)

✧SM is seeded by the (wakefields driven by the) e⁻ bunch, e-SSM

✧Control growth rate Γ with Q_{p+}

✧Control seed amplitude $W_{perp,0}$ with Q_e

✧Entire bunch self-modulates!

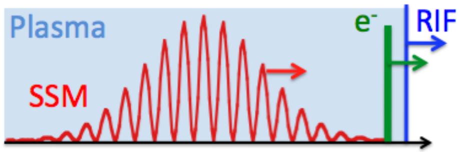


✧Demonstrated seeding of SM with e-bunch

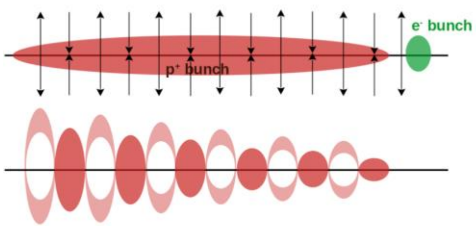
L. Verra, (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

HOSiNG

✧e-bunch seeding of SM



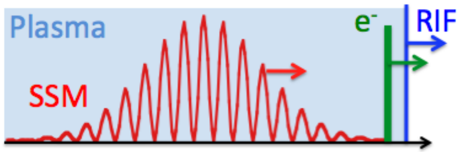
✧e^- and p^+ aligned …



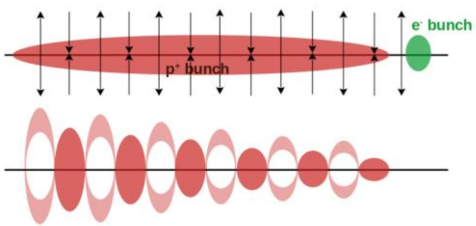
✧… axi-symmetric SM

HOSiNG

✧e-bunch seeding of SM

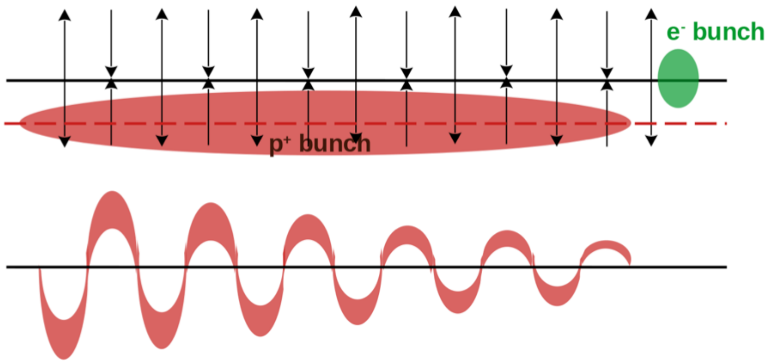


✧e⁻ and p⁺ aligned …



✧… axi-symmetric SM

✧e⁻ and p⁺ mis-aligned …

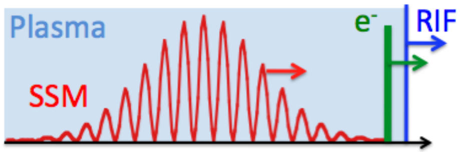


✧… non-axi-symmetric hosing (mis-alignment plane)

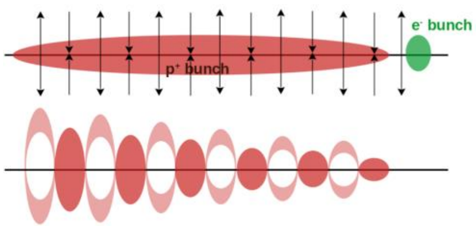
✧… and SM in the perpendicular plane ("no misalignment" plane)

HOSiNG

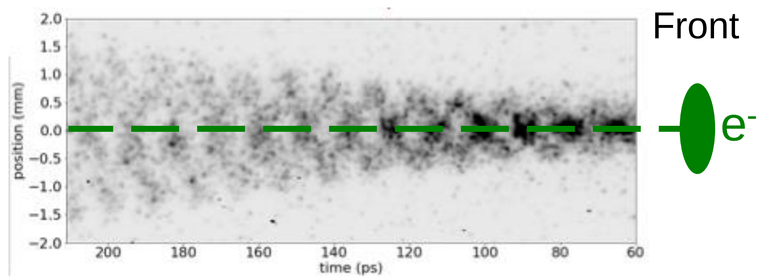
✧e-bunch seeding of SM



✧e⁻ and p⁺ aligned …



✧… axi-symmetric SM



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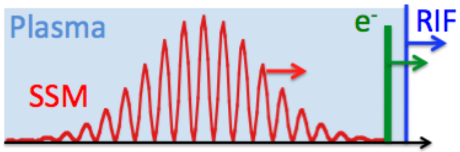
$n_{e0}=10^{14}cm^{-3}$
$N_{p+}=3x10^{11}$

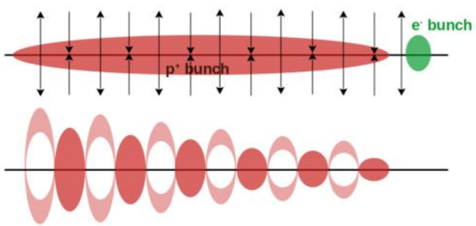
✧e^-/p^+ aligned
✧Self-modulation
✧Symmetric

HOSiNG

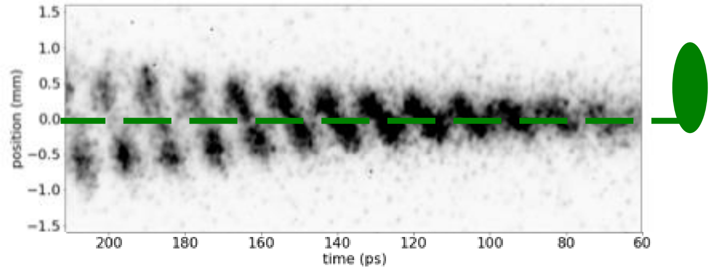
✧e-bunch seeding of SM



✧e^- and p^+ aligned …



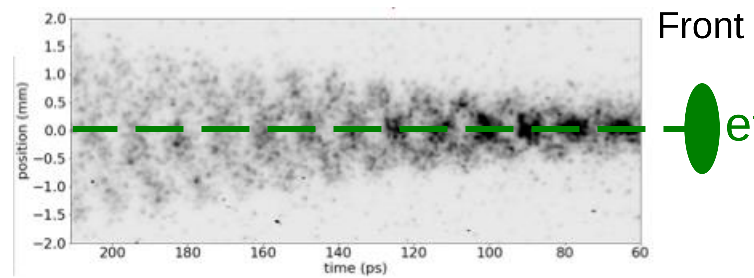
✧… axi-symmetric SM



✧e^-/p^+ mis-aligned

✧Hosing

✧Centroid oscillation



✧e^-/p^+ aligned

✧Self-modulation

✧Symmetric

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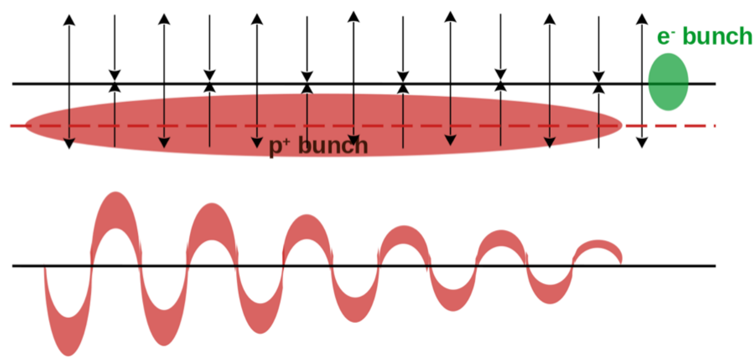


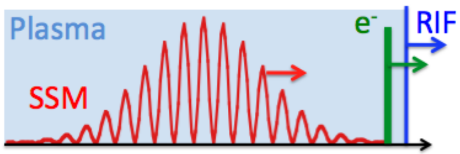
✧SM and HI together

✧f_{HI}~f_{SM}~f_{pe}

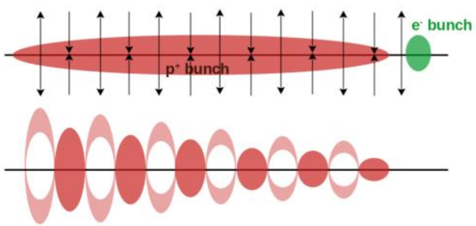
✧Induced by wakefields

HOSiNG

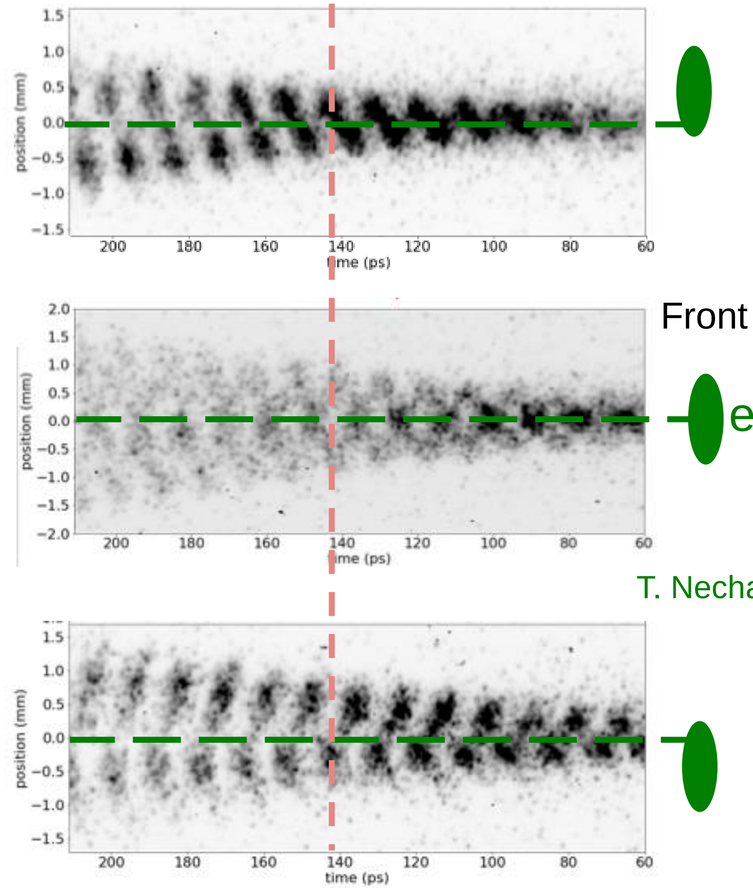
✧e-bunch seeding of SM



✧e⁻ and p⁺ aligned …



✧… axi-symmetric SM



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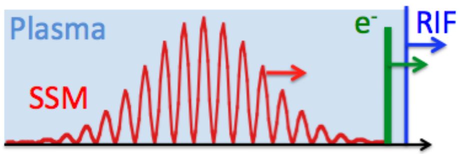
✧e⁻/p⁺ mis-aligned
✧Hosing
✧Centroid oscillation

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

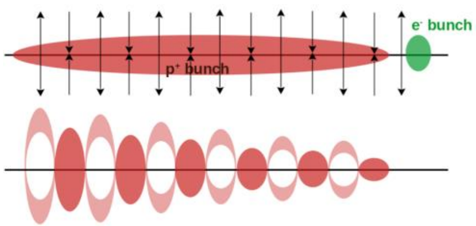
✧e⁻/p⁺ mis-aligned
✧Hosing
✧Reversed!

HOSiNG

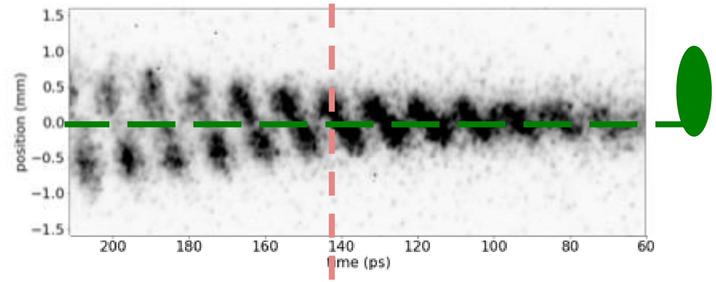
✧e-bunch seeding of SM



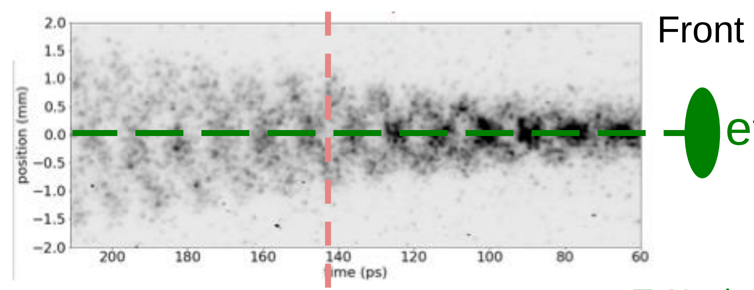
✧e- and p+ aligned …



✧… axi-symmetric SM



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



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

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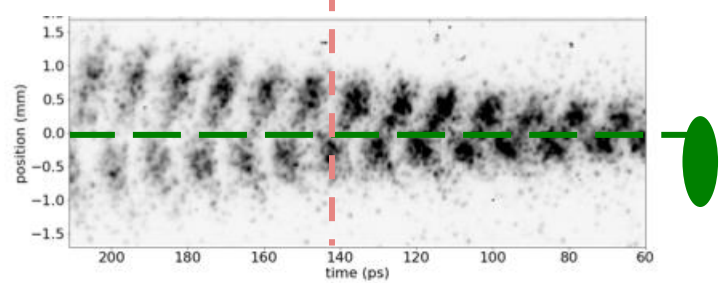
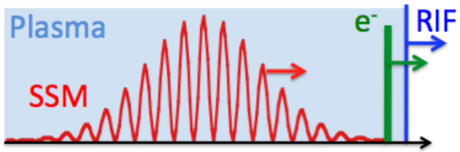


✧e-/p+ mis-aligned
✧Hosing
✧Reversed!

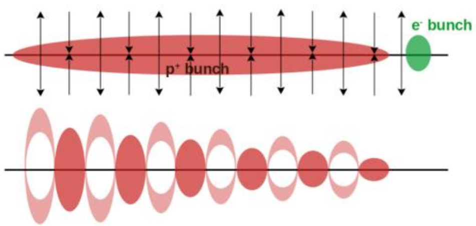
✧Hosing could deteriorate, limit the acceleration process…

HOSiNG

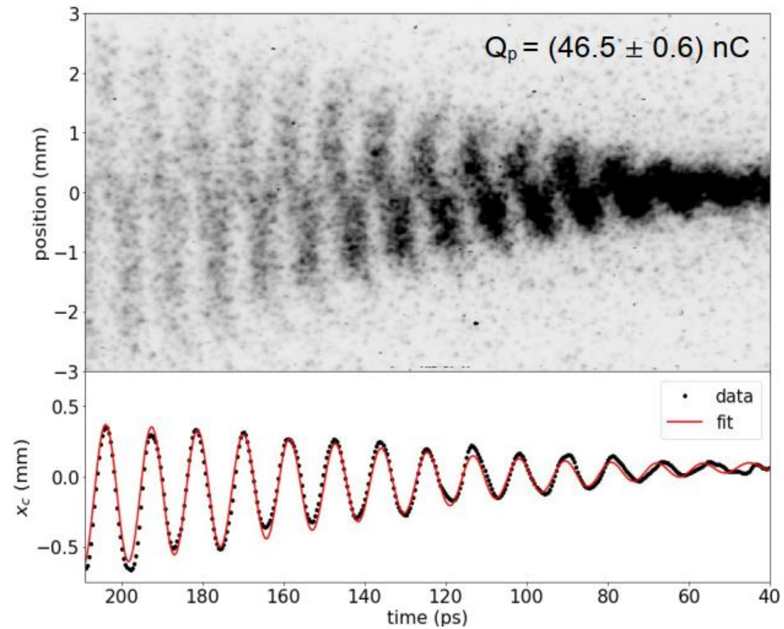
✧e-bunch seeding of SM



✧e- and p+ aligned …



✧… axi-symmetric SM



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$$x_c = \delta_c \frac{e^{N_h}}{N_h^{1/2}} \frac{3^{1/4}}{(8\pi)^{1/2}} \cos\left(\pi/12 - k_p \xi - N_h/\sqrt{3}\right)$$ *

δ_c = f(e- parameters) – initial amplitude

N_h = f(p+ parameters) – growth rate

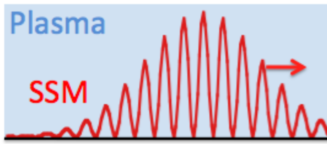
Fit (leastsq): $x_{c,coupled} = x_c\left[1+\epsilon \sin\left(k_p \xi\right)\right]$ *

C. Schroeder, Phys. rev. E 86, 026402 (2012)

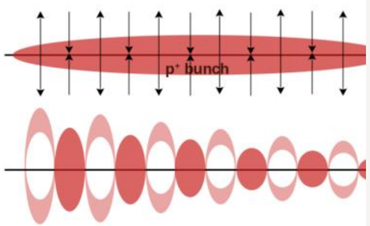
✧Observation “fits hosing model”….

HOSiNG

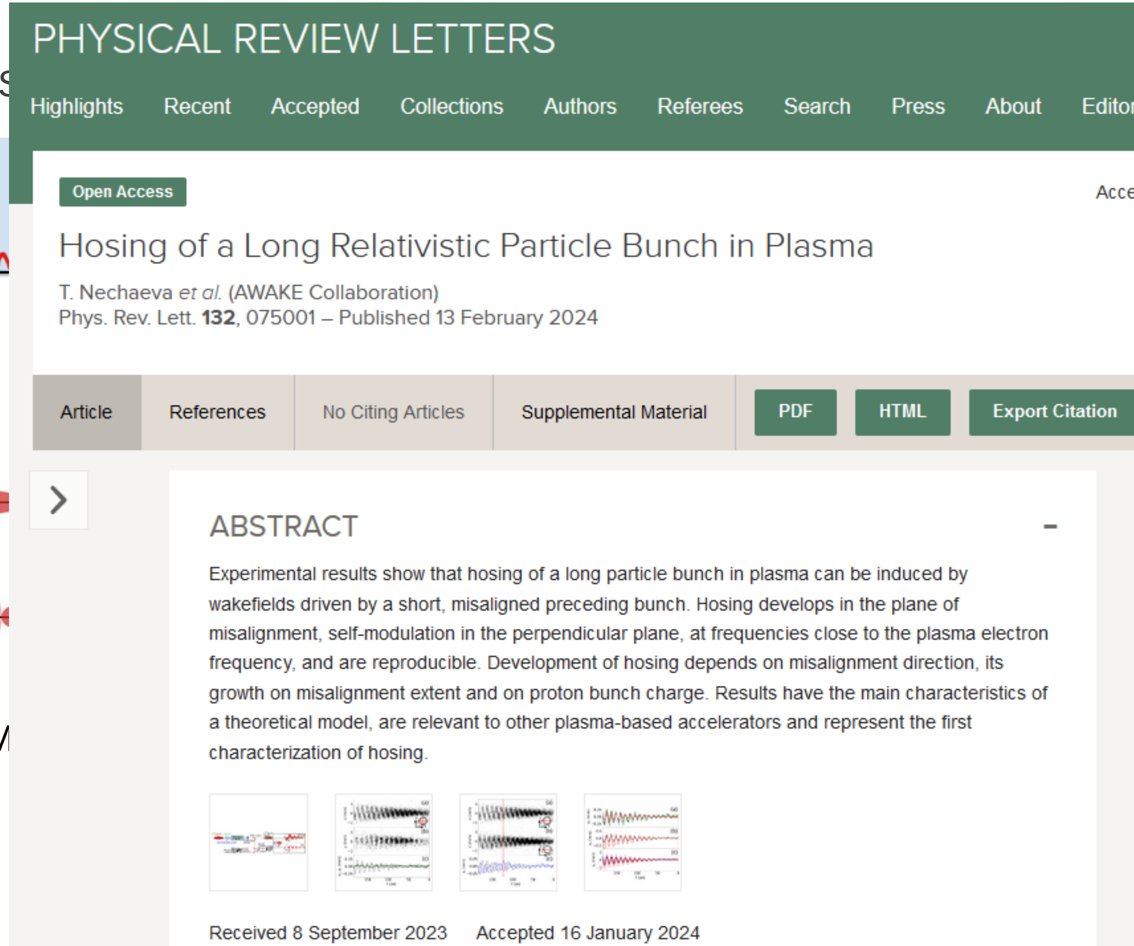
✧e-bunch seeding of S



✧e^- and p^+ aligned …



✧… axi-symmetric SM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Hosing of a Long Relativistic Particle Bunch in Plasma

T. Nechaeva *et al.* (AWAKE Collaboration)

Phys. Rev. Lett. **132**, 075001 – Published 13 February 2024

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ABSTRACT

Experimental results show that hosing of a long particle bunch in plasma can be induced by wakefields driven by a short, misaligned preceding bunch. Hosing develops in the plane of misalignment, self-modulation in the perpendicular plane, at frequencies close to the plasma electron frequency, and are reproducible. Development of hosing depends on misalignment direction, its growth on misalignment extent and on proton bunch charge. Results have the main characteristics of a theoretical model, are relevant to other plasma-based accelerators and represent the first characterization of hosing.

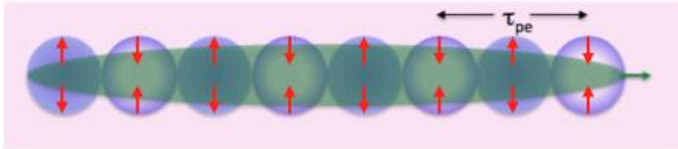
Received 8 September 2023 Accepted 16 January 2024

lechaeva

✧Observation "fits hosing model"….

FILAMENTATION INSTABILITY

✧ σ_{r0}<c/ω_{pe}: optimum for wakefield generation …

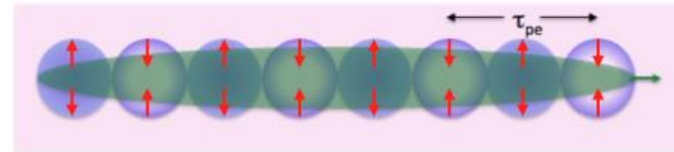


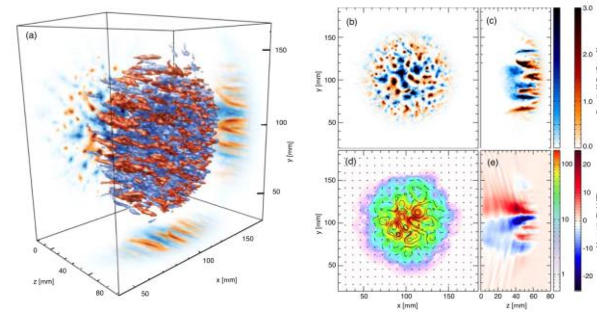
Return current outside the bunch
Only one mode, wakefields can develop

FiLAMENTATiON INSTABiLiTY

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

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



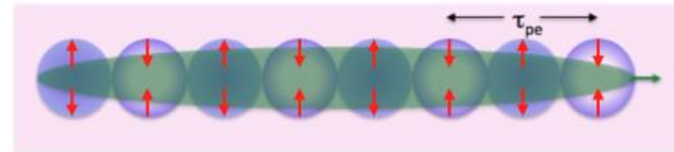


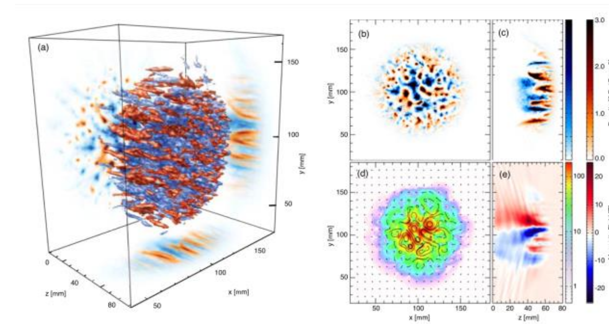
Shukla, J. Plasma Phys. 84(3) 905840302 (2018)
Allen, Phys. Rev. Lett. 109, 185007 (2012)

FiLAMENTATiON INSTABiLiTY

AWAKE

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





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

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)

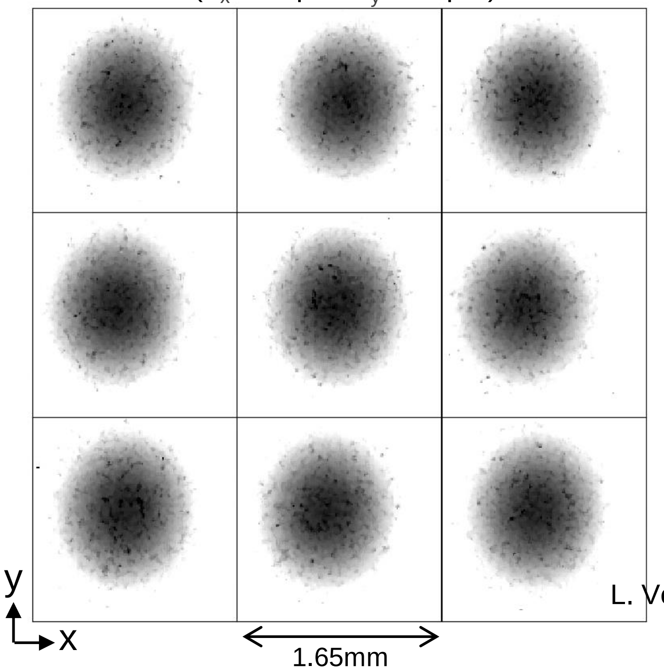
FILAMENTATION INSTABILITY

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

FiLAMENTATiON INSTABiLiTY

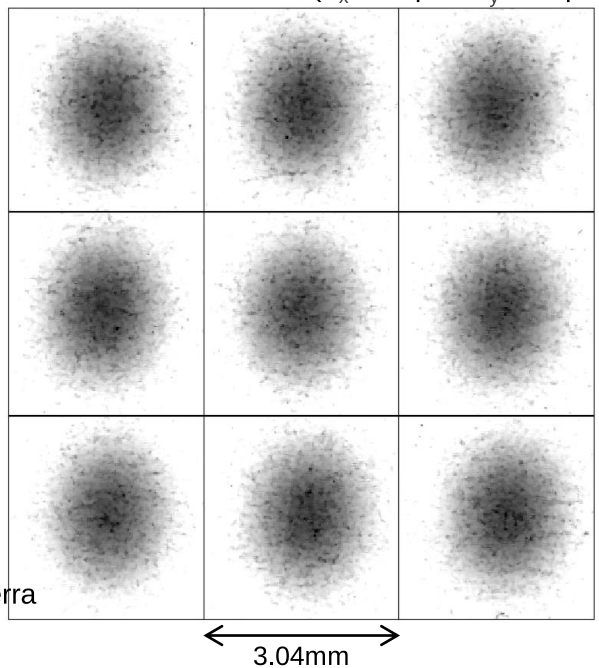
Transverse Filamentation: σ_{r0}~200 => 550µm>>c/ω_{pe} AND σ_z>>c/ω_{pe}

Entrance (σ_x=480µm, σ_y=520µm)

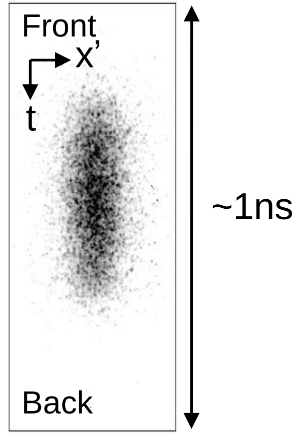


L. Verra

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



Plasma OFF



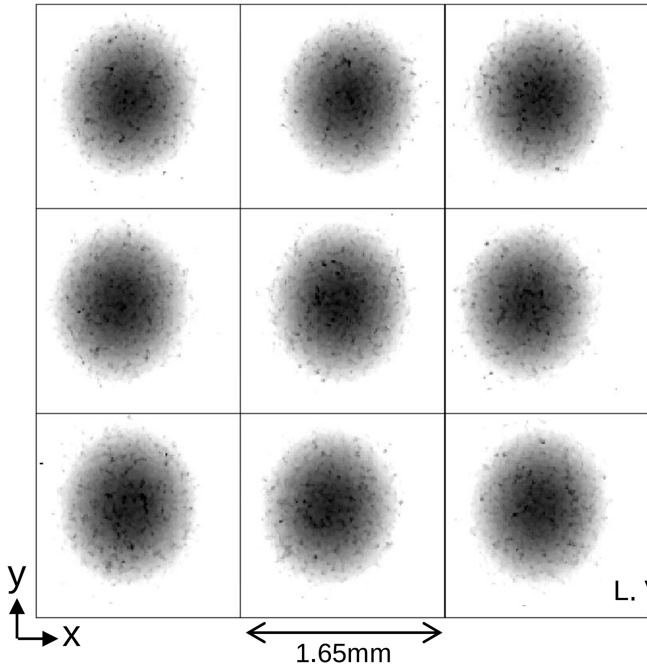
σ_{slit}=1.0mm
σ_t=170ps

✧Incoming bunch without transverse features (Gaussian)

FILAMENTATION INSTABILITY

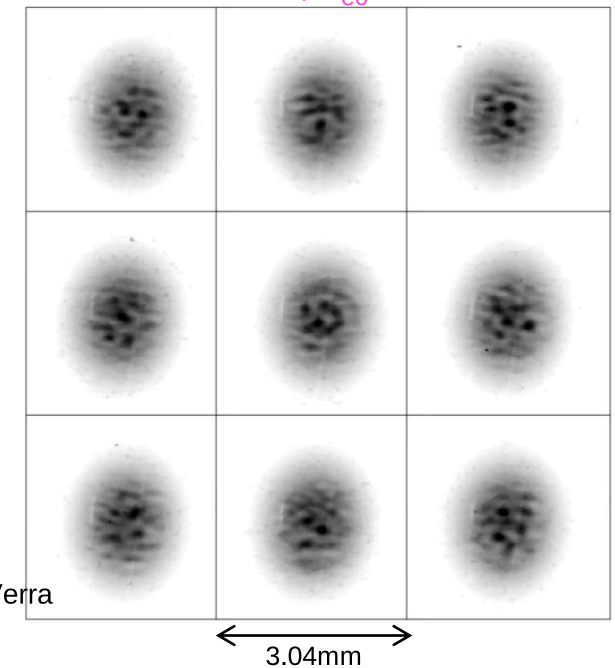
Transverse Filamentation: σ_{r0}~550µm~3.2c/ω_{pe} AND σ_z>>c/ω_{pe}

Entrance

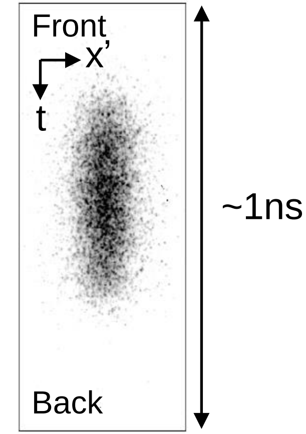


L. Verra

Exit: Plasma ON, $n_{e0}=9\times10^{14}cm^{-3}$



Plasma OFF



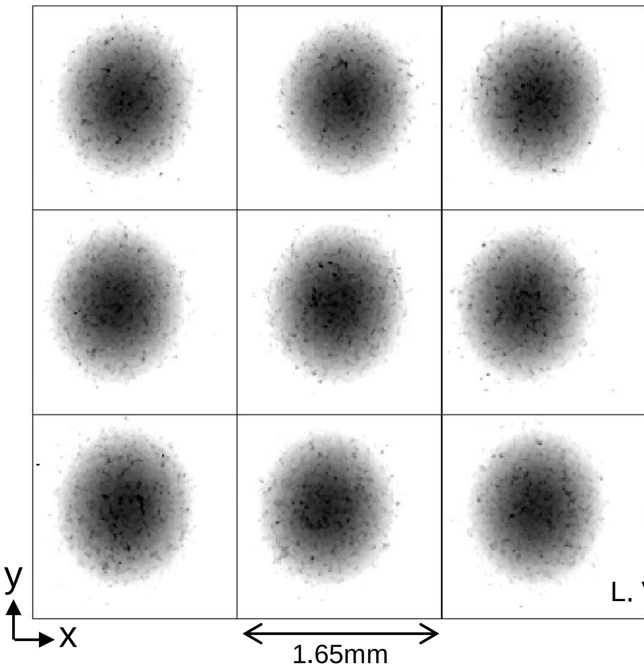
✧Incoming bunch without transverse features (Gaussian)

✧Filaments with plasma

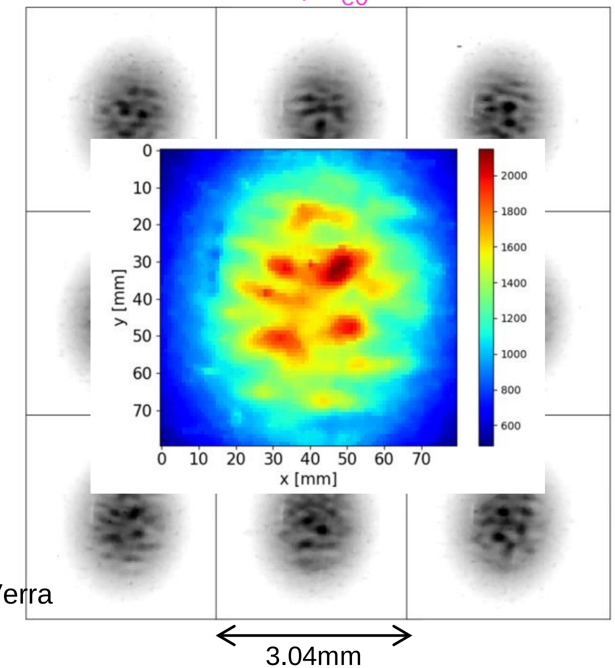
FiLAMENTATiON INSTABiLiTY

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

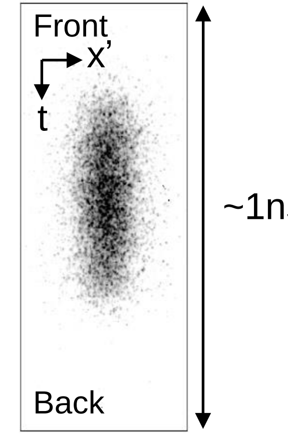
Entrance



Exit: Plasma ON, $n_{e0}=9\times10^{14}cm^{-3}$



Plasma OFF

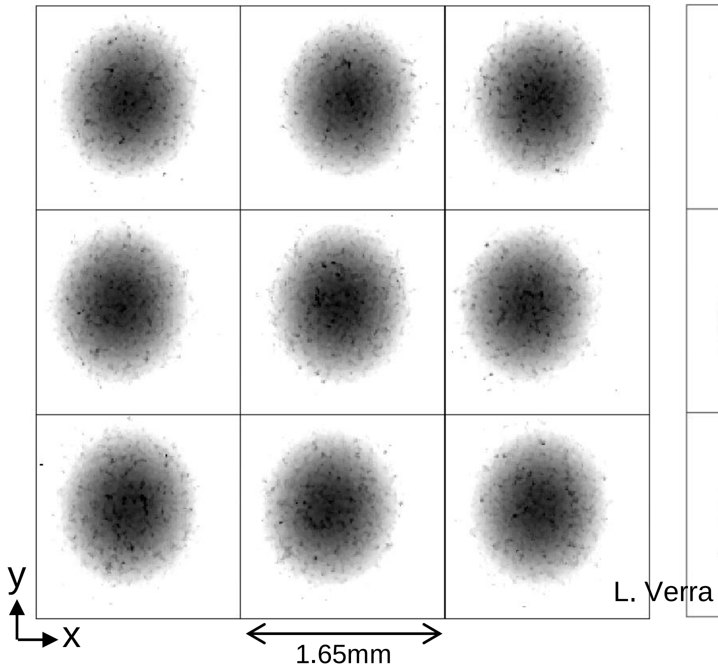


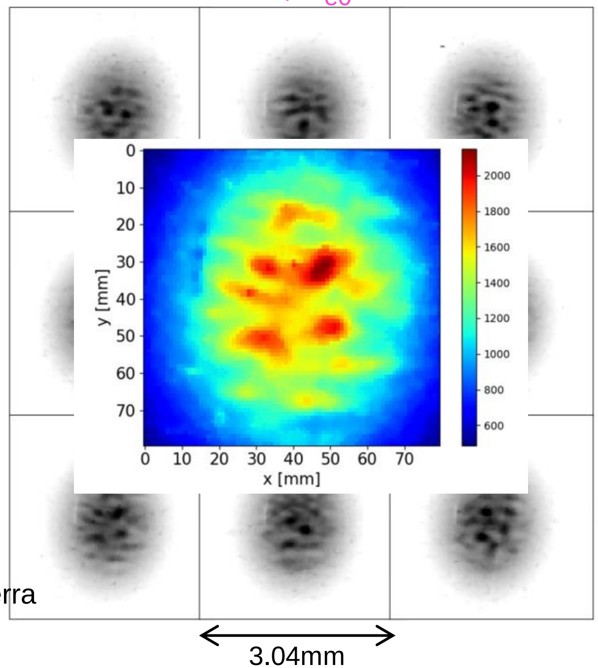
✧Incoming bunch without transverse features

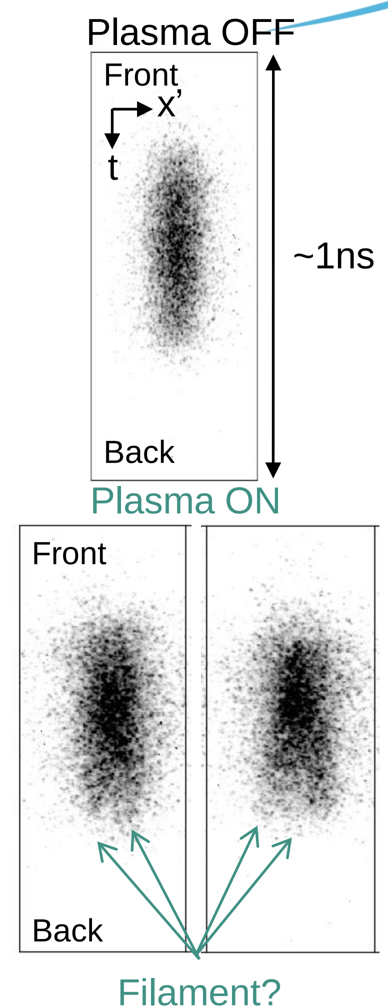
✧Filaments with plasma

FiLAMENTATiON INSTABiLiTY

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







✧Incoming bunch without transverse features

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

Shukla, J. Plasma Phys. 84(3) 905840302 (2018)
P. San Miguel Claveria, Phys. rev. Res. 4, 023085 (2022)

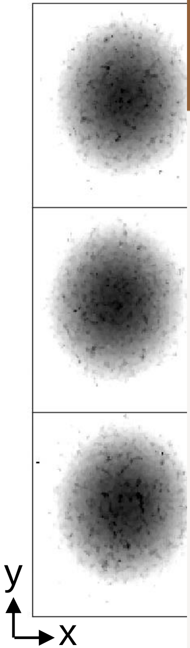
FiLAMENTATiON INSTABiLiTY

MAX-PLANCK-INSTITUT FÜR PHYSIK

AWAKE

Transverse P

Entrance



PHYSICAL REVIEW E
covering statistical, nonlinear, biological, and soft matter physics

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Accepted Paper

Filamentation of a relativistic proton bunch in plasma

Phys. Rev. E

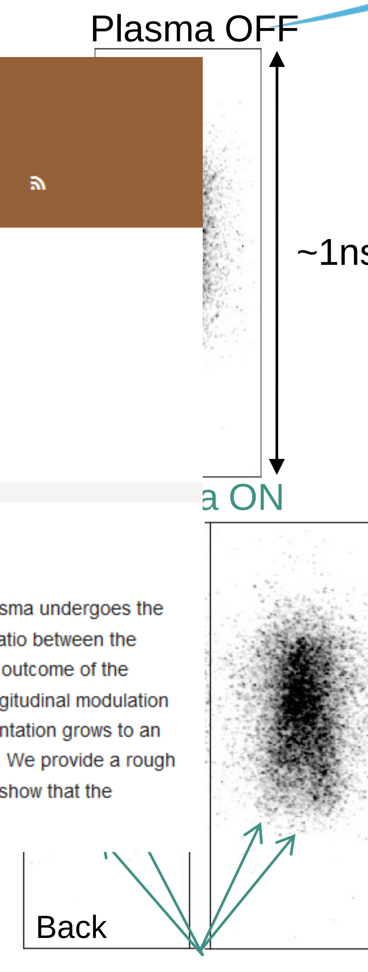
L. Verra et al.

Accepted 25 March 2024

ABSTRACT

ABSTRACT

We show in experiments that a long, underdense, relativistic proton bunch propagating in plasma undergoes the oblique instability, that we observe as filamentation. We determine a threshold value for the ratio between the bunch transverse size and plasma skin depth for the instability to occur. At the threshold, the outcome of the experiment alternates between filamentation and self-modulation instability (evidenced by longitudinal modulation into microbunches). Time-resolved images of the bunch density distribution reveal that filamentation grows to an observable level late along the bunch, confirming the spatio-temporal nature of the instability. We provide a rough estimate of the amplitude of the magnetic field generated in the plasma by the instability and show that the associated magnetic energy increases with plasma density.

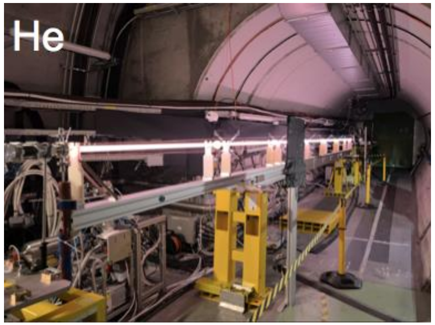


✧Incoming bunch without transverse features

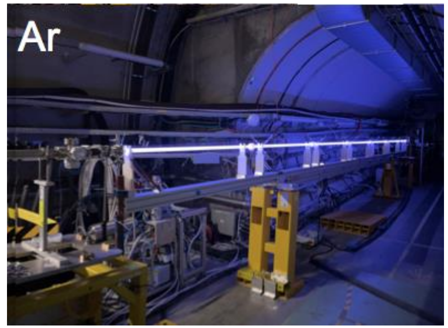
✧Filaments with plasma, late along the bunch, early stage?

Shukla, J. Plasma Phys. 84(3) 905840302 (2018)
P. San Miguel Claveria, Phys. rev. Res. 4, 023085 (2022)

DISCHARGE PLASMA SOURCE

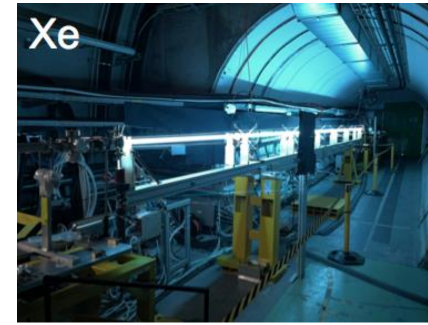


✧A_{He}=4



✧A_{Ar}=40

✧A_{Rb}=85



✧A_{xe}=131

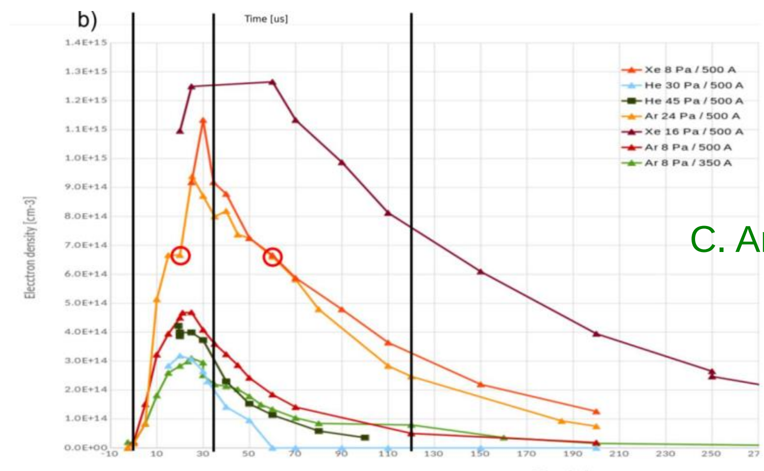
Discharge plasma source (DPS):

✧Quick change of density

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

✧**Change ion species: He, Ar, Xe**

✧No alignment (r_p~10mm)



C. Amoedo et. al

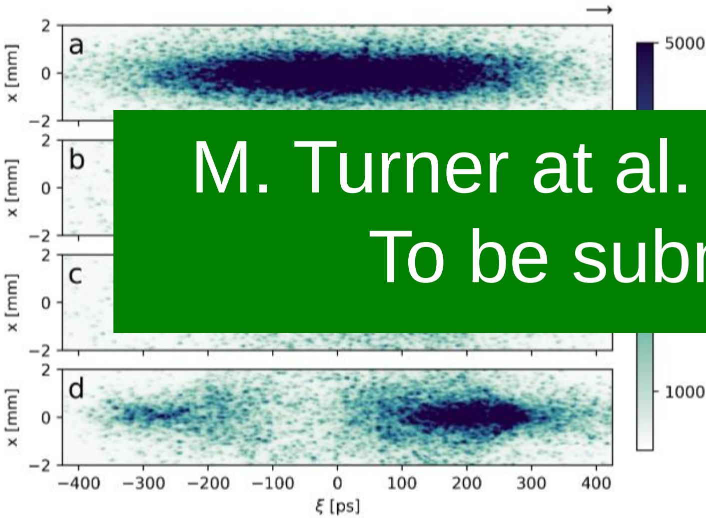
ION MOTION

Effect of ion motion on:

✧Accelerated bunch quality

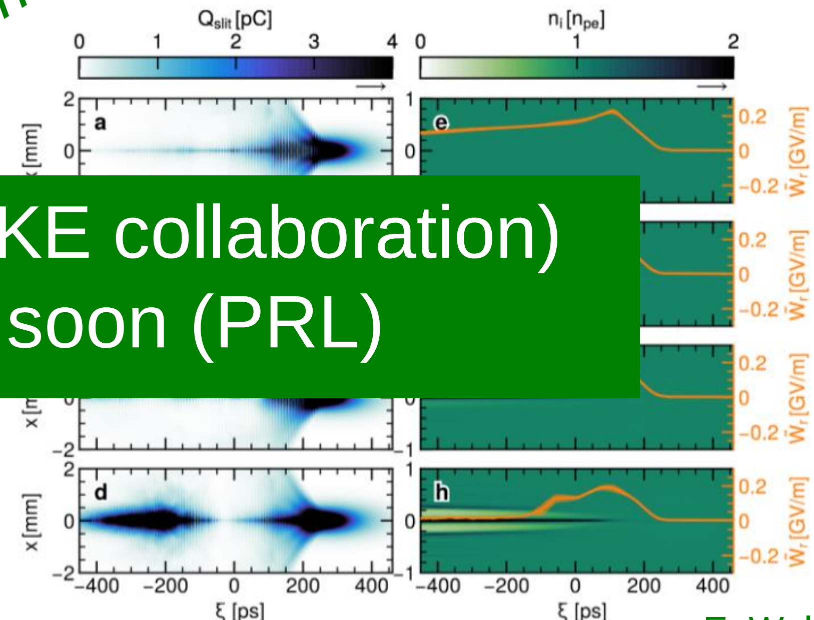
✧Acceleration process

Preliminary



M. Turner at al. (AWAKE collaboration)
To be submitted soon (PRL)

M. Turner



E. Walter

Long, low density bunch:

✧Typical SMI (Xe, Ar)

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

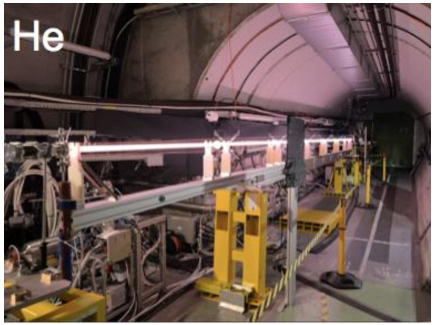
✧More “tail” with lighter ion (He), larger wakefield amplitude (N_{p+}, n_{e0}) (Ar)

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

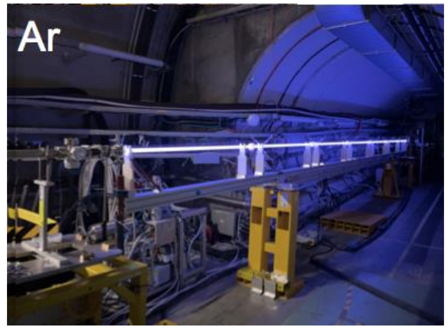
$$\boldsymbol{F}_p \cong -\frac{e^2}{4m_e\omega_{pe}^2}\boldsymbol{\nabla}W_r^2$$

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

DISCHARGE PLASMA SOURCE

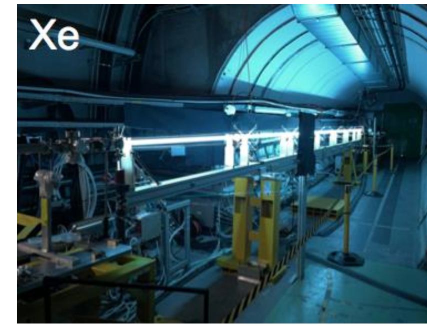


✧A_{He}=4



✧A_{Ar}=40

✧A_{Rb}=85



✧A_{xe}=131

Discharge plasma source (DPS):

✧Quick ch

✧Reach h

✧**Change ion species: He, Ar, Xe**

✧No alignment (r_p~10mm)

Ion motion not an issue with Rb!!

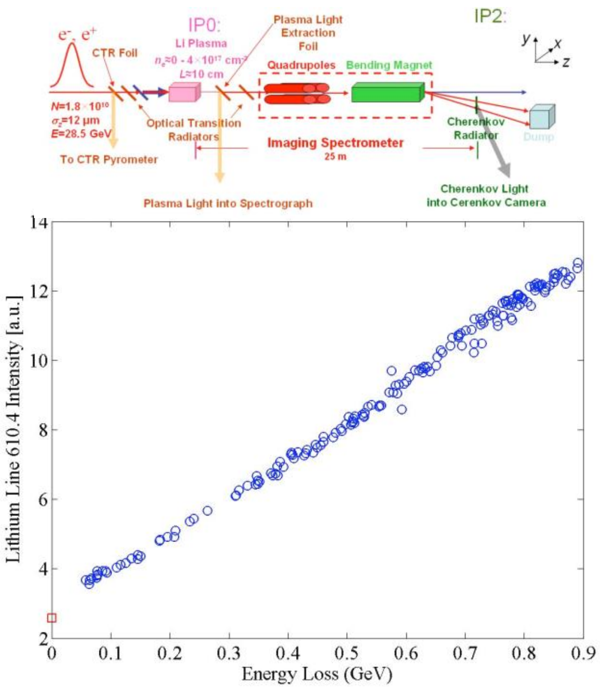
C. Amoedo et. al

WAKEFiELD LiGHT

✧Wakefields ⇔ energy deposited into plasma e^-

✧Energy must dissipate

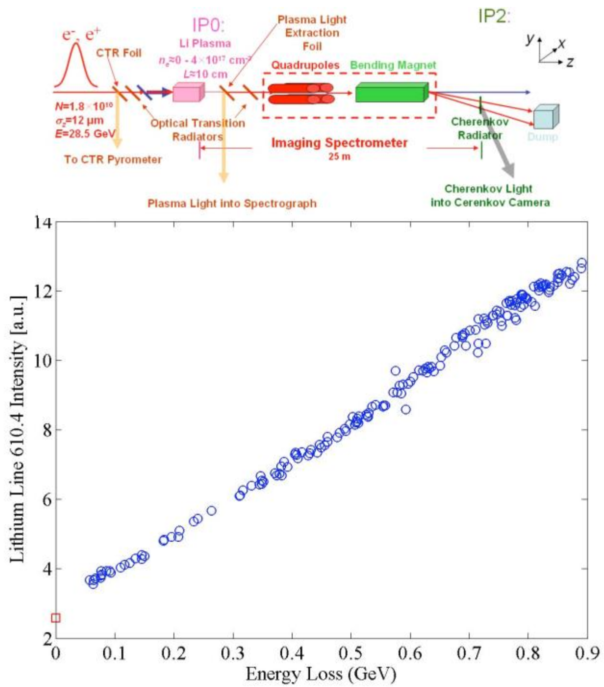
✧Dissipation of wakefields produces “wakefield light” (atomic line radiation)



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

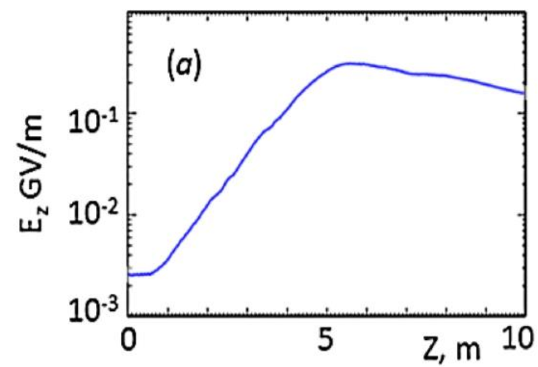
WAKEFiELD LiGHT

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



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

Pukhov, PRL107 145003 (2011)

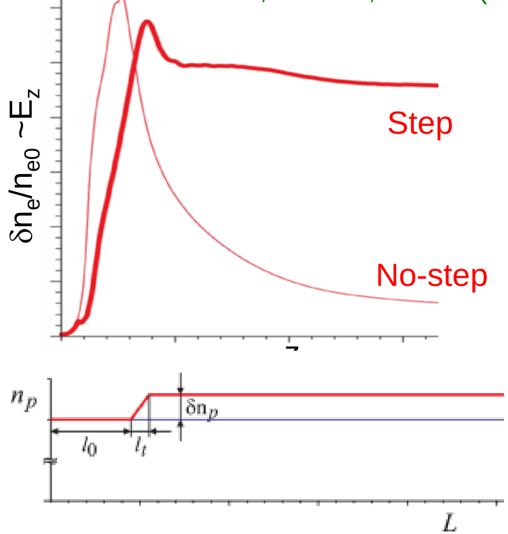


- ✧SM grows along the plasma
- ✧Can the growth be observed?

PLASMA DENSITY STEP

✧Constant plasma density: wakefields decrease after saturation

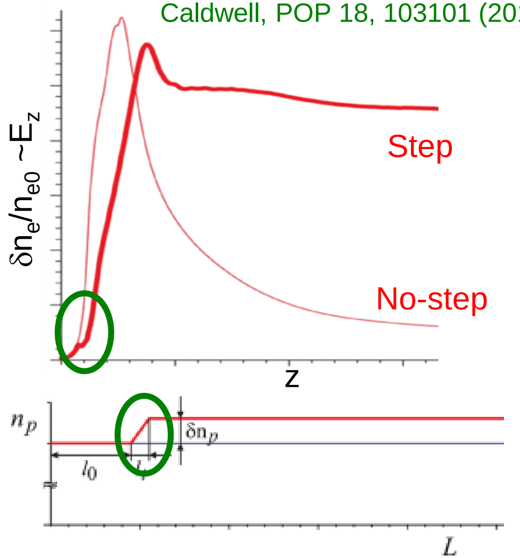
Caldwell, POP 18, 103101 (2011)



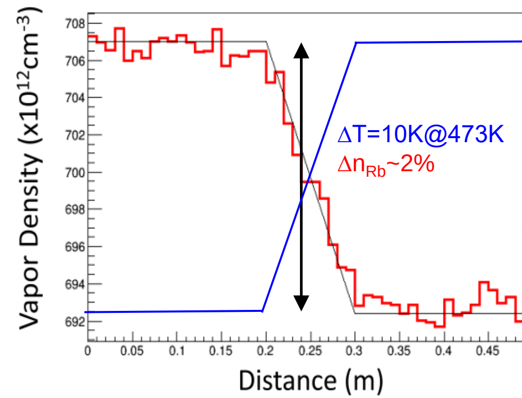
PLASMA DENSITY STEP

✧Constant plasma density: wakefields decrease after saturation

Caldwell, POP 18, 103101 (2011)



G. Plyuschev , J. Phys. D: 51(2), 025203 (2017)

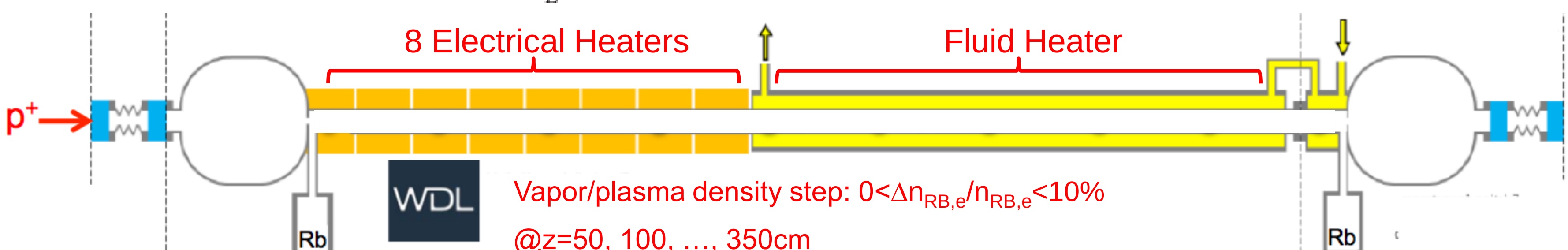


DSMC simulations:

Temperature step

Vapor density step

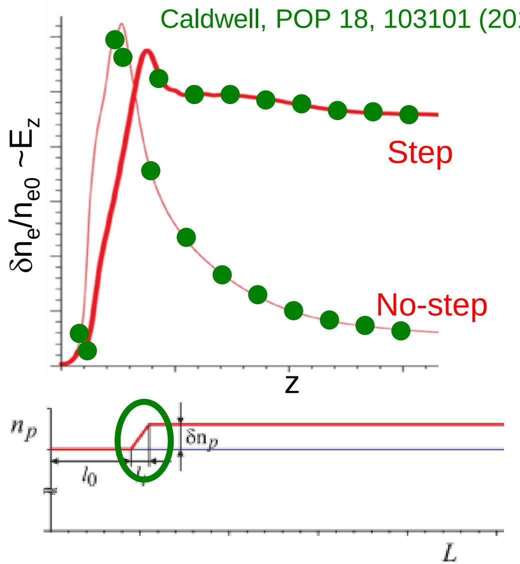
Plasma density step

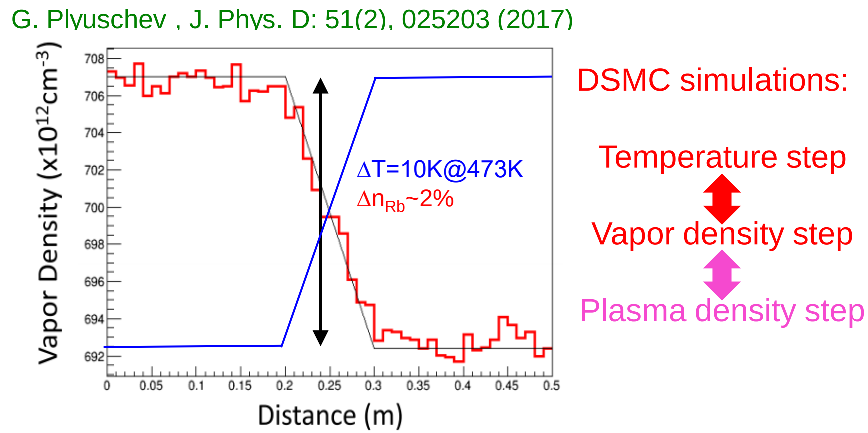


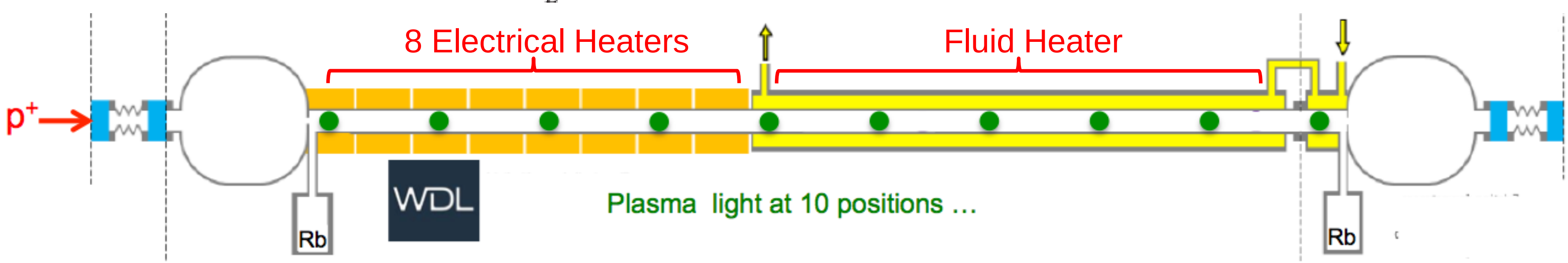
✧Vapor source allows for temperature / rubidium density / plasma density (ionization) step

PLASMA DENSITY STEP

✧Constant plasma density: wakefields decrease after saturation







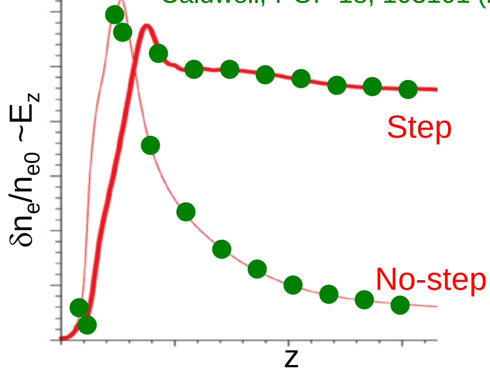
✧Vapor source allows for temperature / rubidium density / plasma density (ionization) step

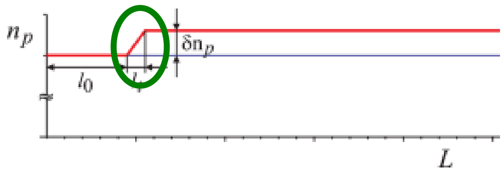
✧Plasma light allows for mapping of the amplitude of wakefields

PLASMA DENSITY STEP

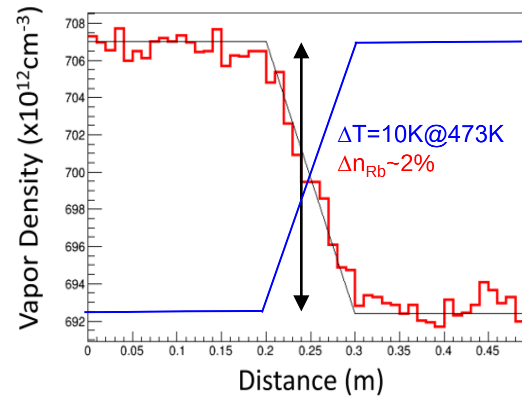
✧Constant plasma density: wakefields decrease after saturation

Caldwell, POP 18, 103101 (2011)





G. Plyuschev , J. Phys. D: 51(2), 025203 (2017)

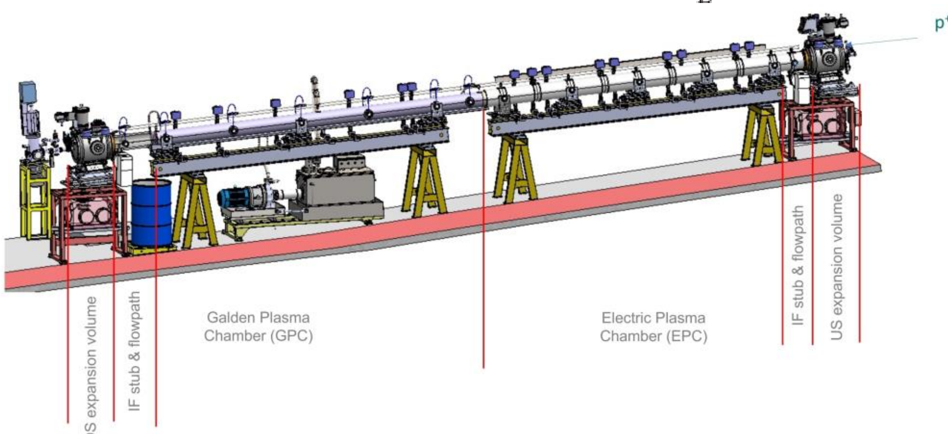


DSMC simulations:

Temperature step

Vapor density step

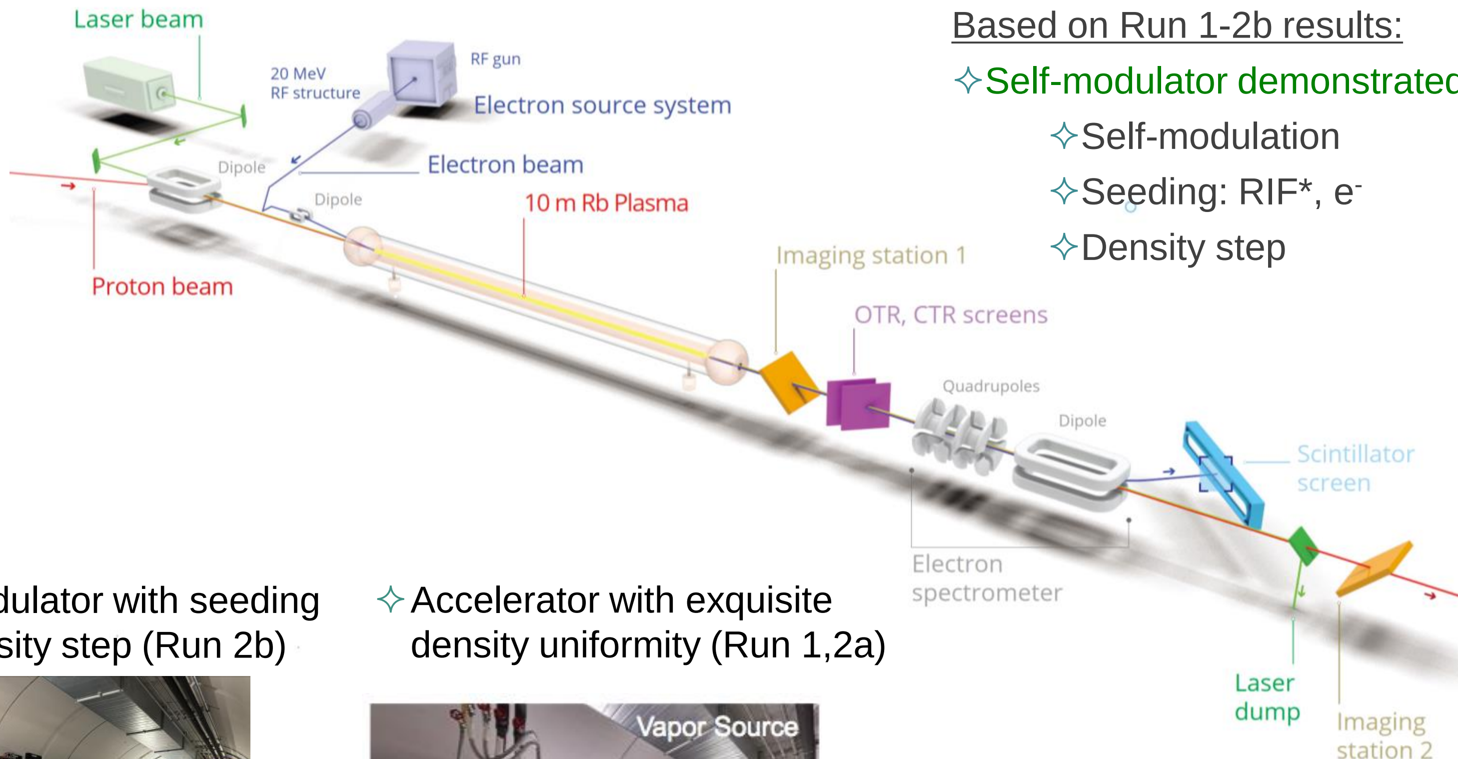
Plasma density step



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

Based on Run 1-2b results:

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



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

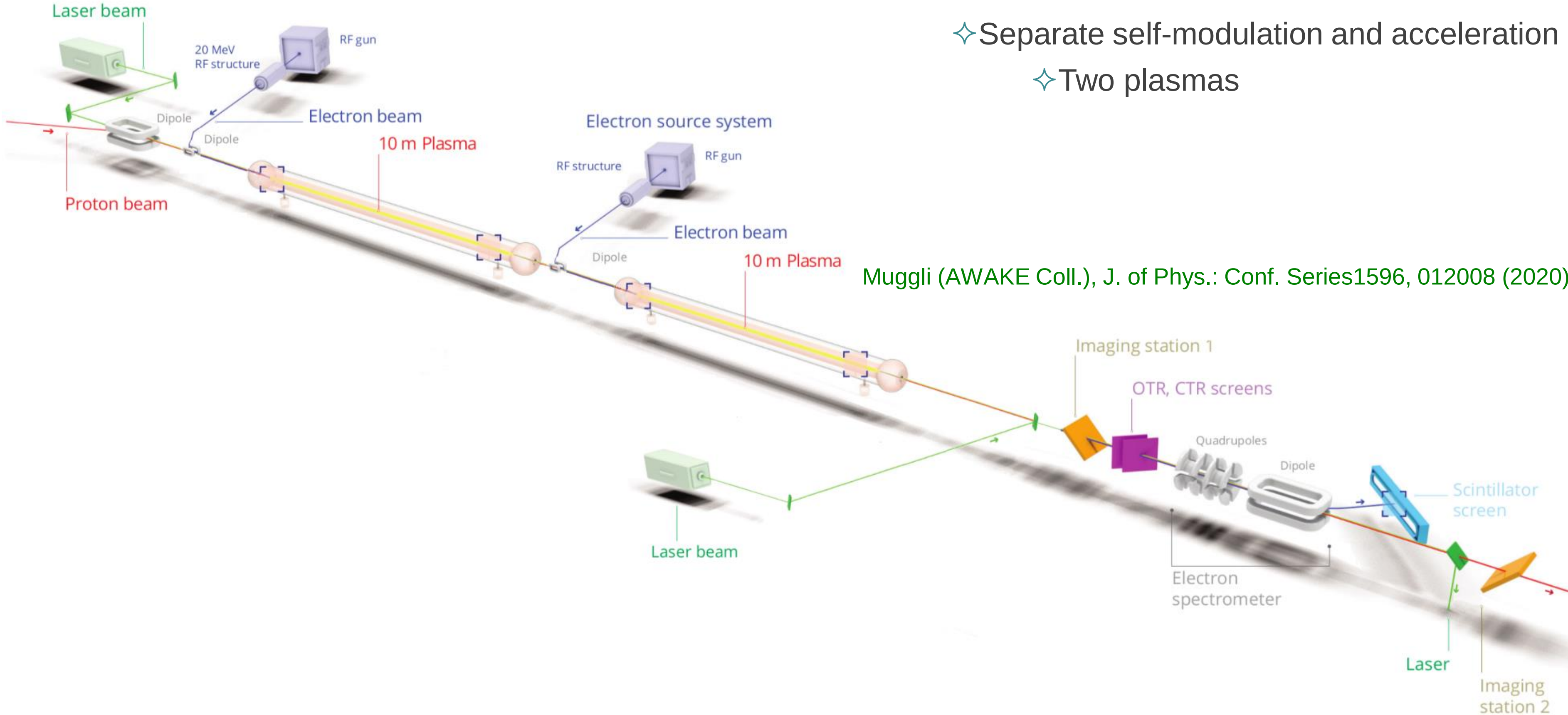
- ✧Accelerator with exquisite density uniformity (Run 1,2a)

*RIF: Relativistic Ionization Front

Run 2c,d: Accelerate e⁻ Bunch, Quality

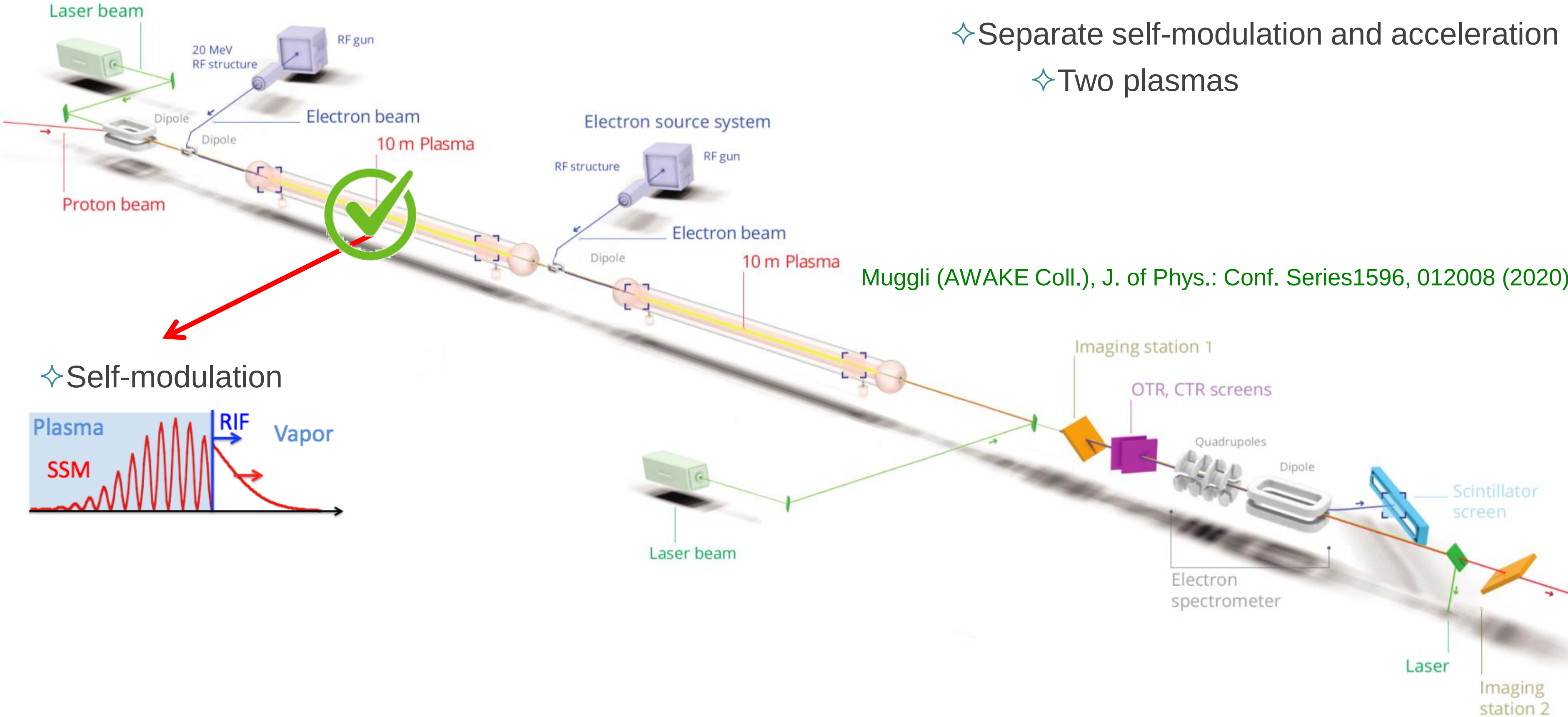
✧Separate self-modulation and acceleration

✧Two plasmas



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

Run 2c,d: Accelerate e⁻ Bunch, Quality



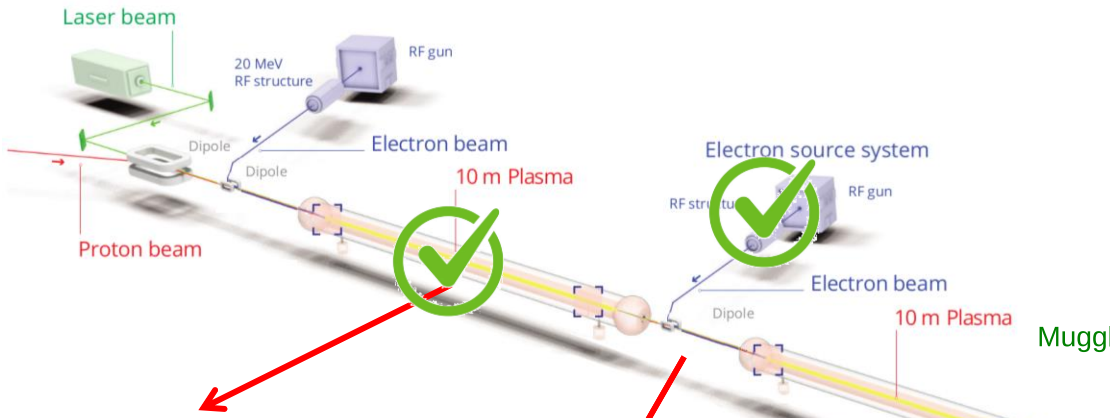
✧Separate self-modulation and acceleration

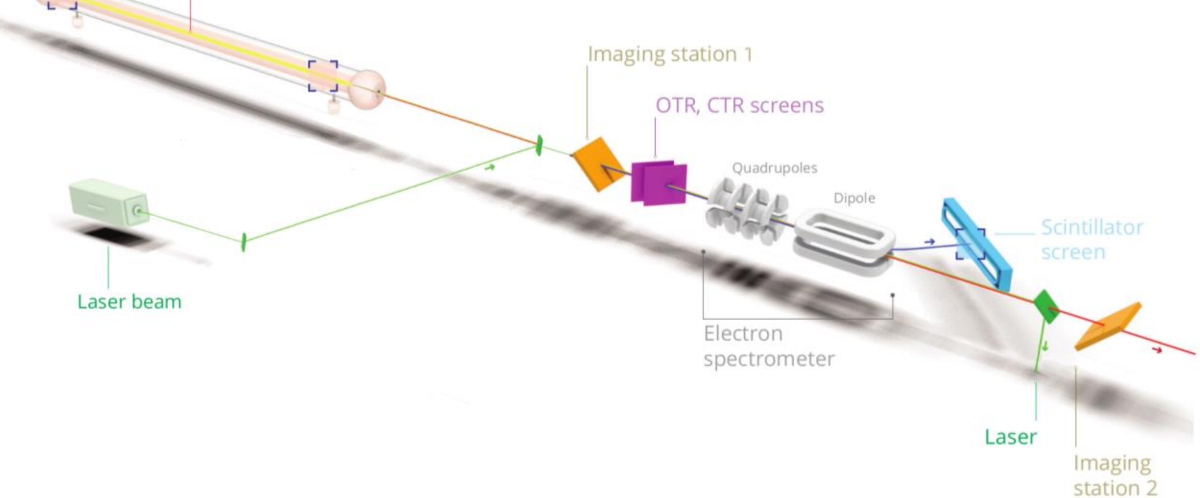
✧Two plasmas

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

✧Self-modulation

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

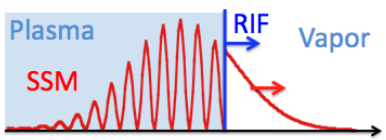




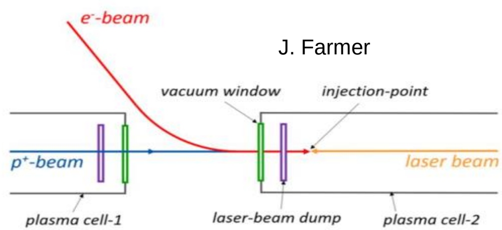
- ✧Separate self-modulation and acceleration
  - ✧Two plasmas
- ✧External injection of e$^-$ (on axis)

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

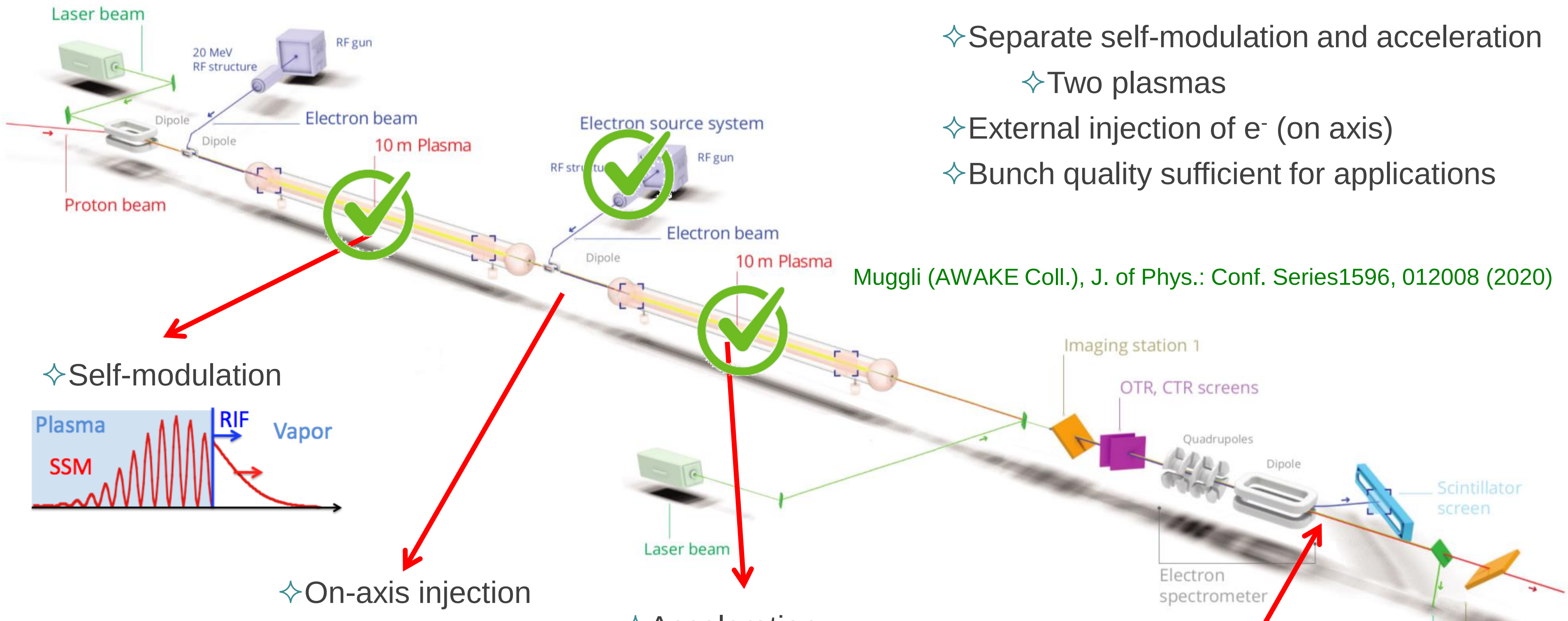
- ✧Self-modulation



- ✧On-axis injection



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

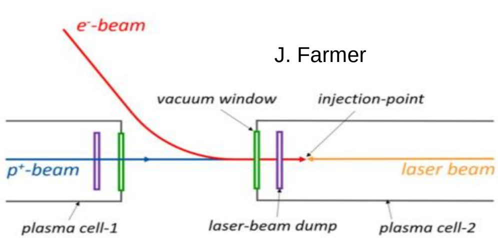


- ✧Separate self-modulation and acceleration
  - ✧Two plasmas
- ✧External injection of e^- (on axis)
- ✧Bunch quality sufficient for applications

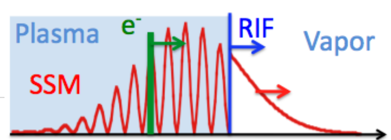
Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

✧Self-modulation

✧On-axis injection

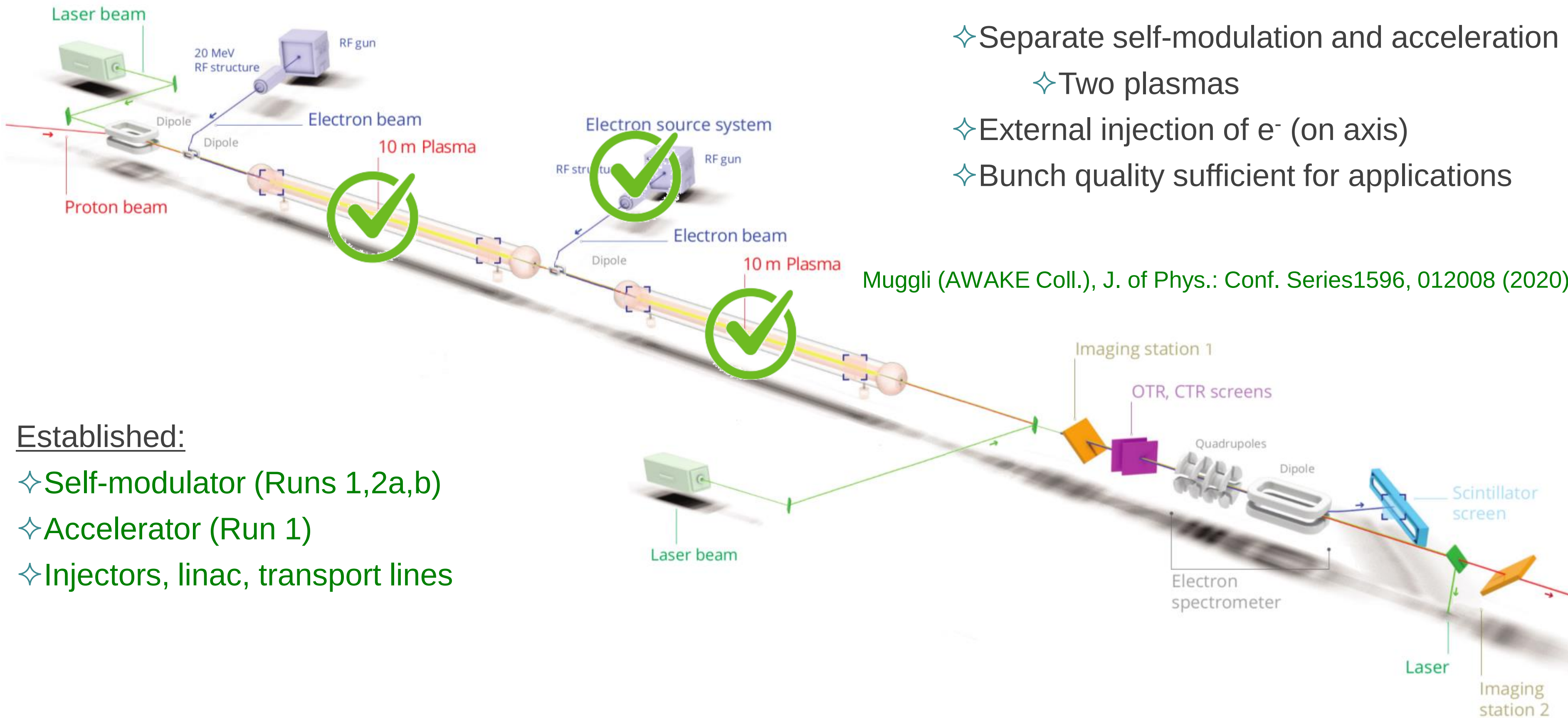


✧Acceleration



✧Quality

RUN 2c: e⁻-EXTERNAL INJECTiON EXPERiMENT



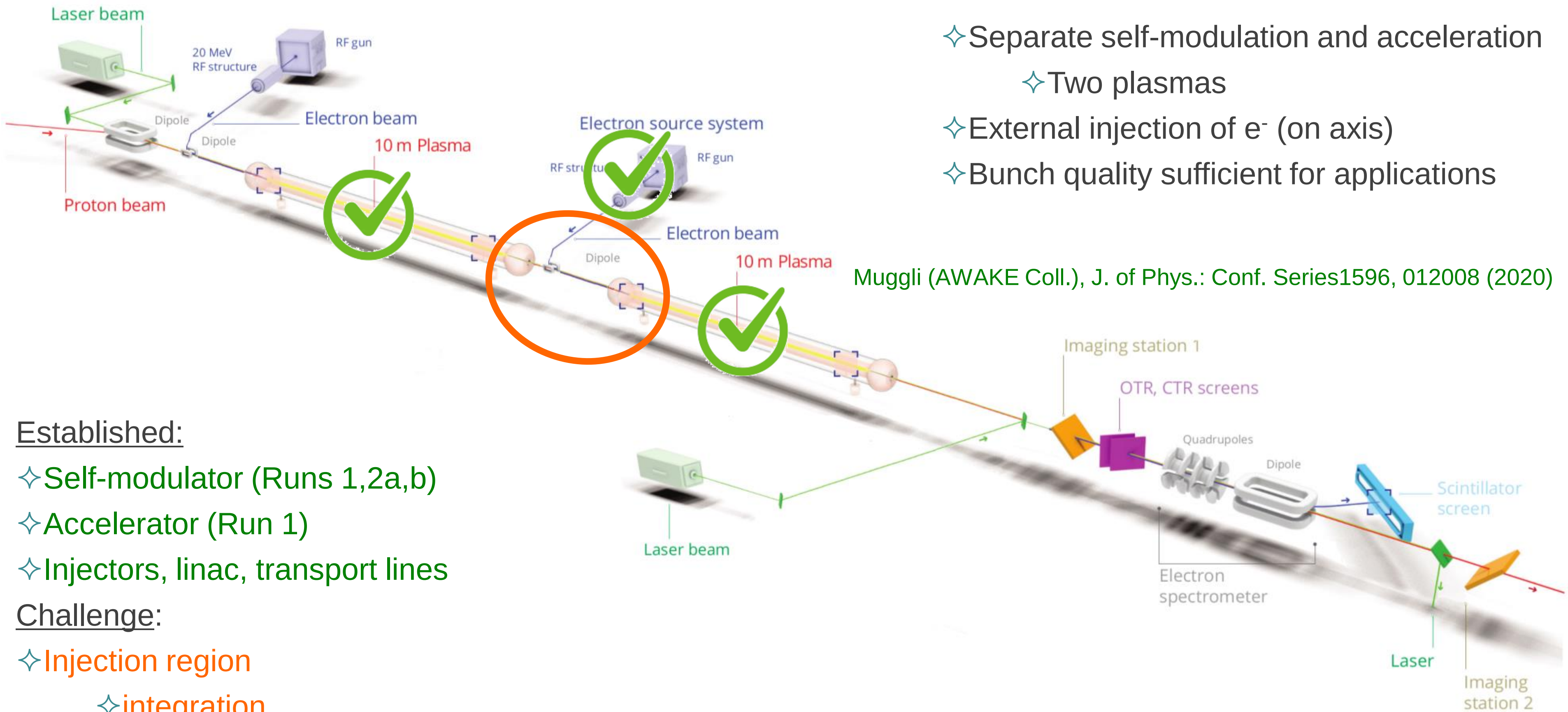
- ✧Separate self-modulation and acceleration
  - ✧Two plasmas
- ✧External injection of e⁻ (on axis)
- ✧Bunch quality sufficient for applications

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

Established:

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

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)

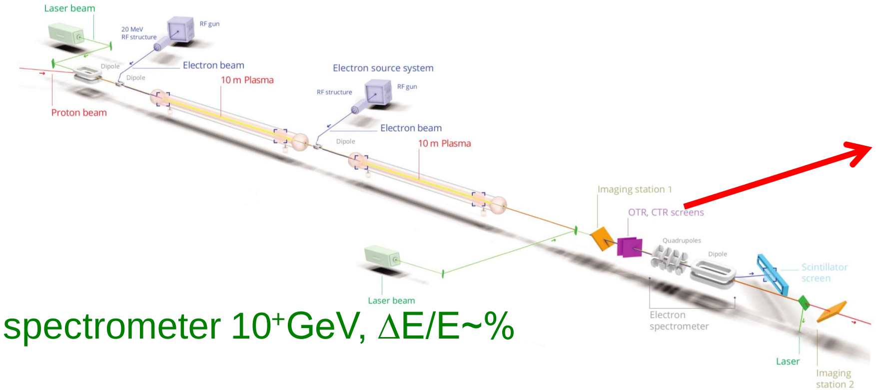
Established:

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

Challenge:

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

DIAGNOSTICS: e^- BUNCH



Typical e-bunch parameters

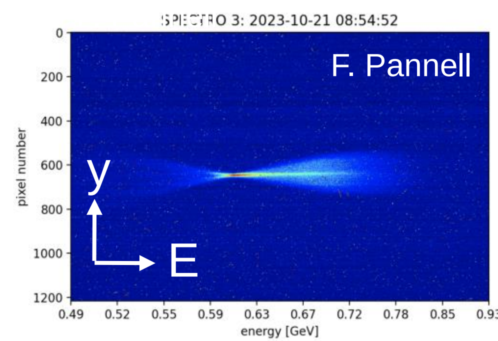
In:

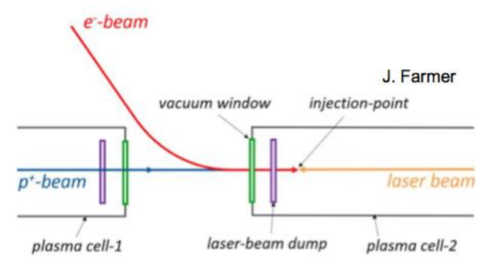
- ✧ ε_N=2mm-mrad
- ✧ Q=100pC, N_{e-}~6x$10^9$$e^-$
- ✧ 150MeV
- ✧ σ_t=200fs
- ✧ Jitter<100fs

Out:

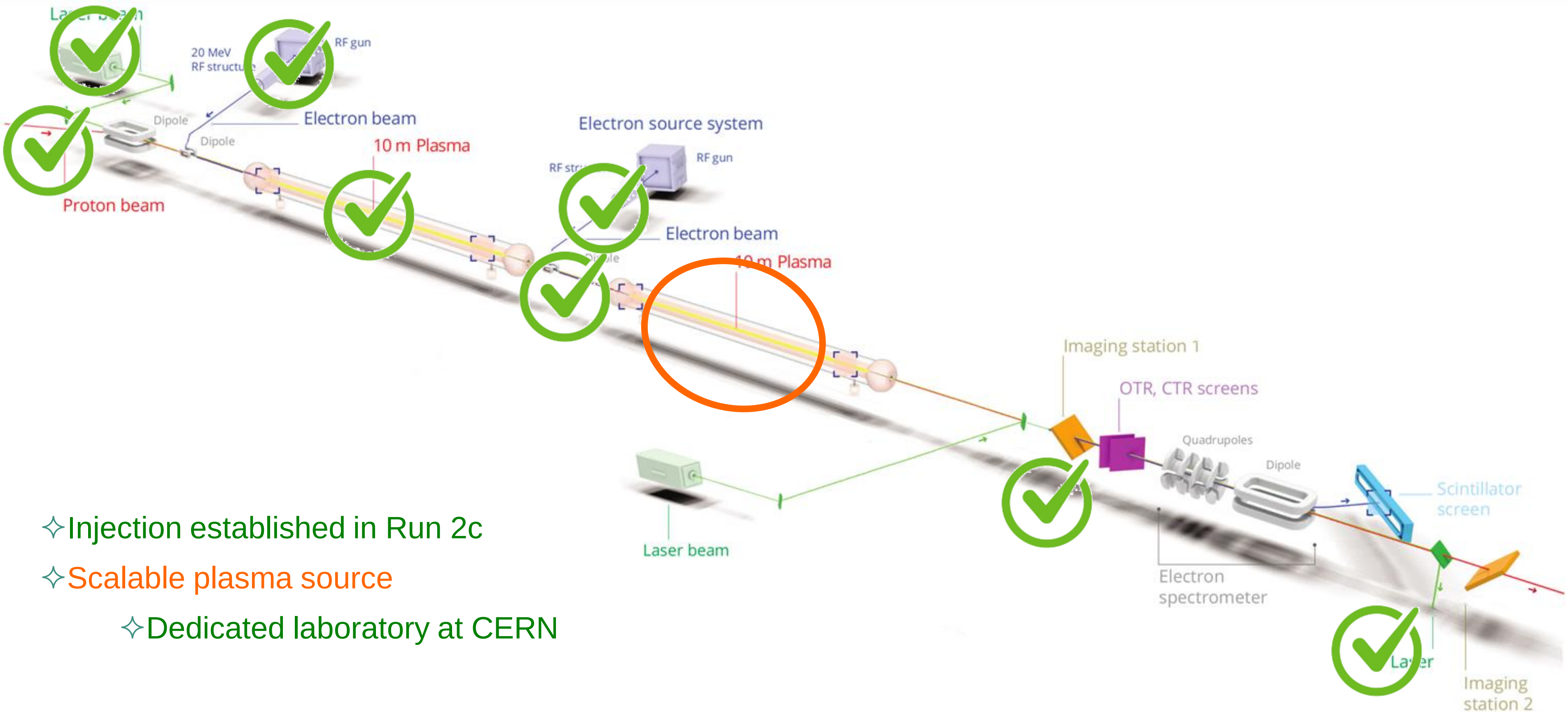
- ✧ ε_N=(2-30)mm-mrad
- ✧ Q=100pC, N_{e-}~6x$10^9$$e^-$
- ✧ ΔE/E=5-8%%
- ✧ E~4-10^+GeV

- ✧ Energy:
  - ✧ Imaging magnetic spectrometer 10^+GeV, ΔE/E~%
- ✧ Emittance (ε_N=2-30µm)
  - ✧ butterfly method
  - ✧ micro-lens array (optical pepper-pot)
- ✧ Bunch length (σ_z=60µm)
  - ✧ OTR + streak camera (200fs)
  - ✧ electro-optical sampling (EOS)
  - ✧ time-deflecting cavity (TDC)
  - ✧ coherent emission (relative)
- ✧ Focal size, alignment, position&pointing
  - ✧ Imaging, YAG screen
  - ✧ synchrotron radiation (relative)





RUN 2d: CHALLENGE



✧Injection established in Run 2c

✧Scalable plasma source

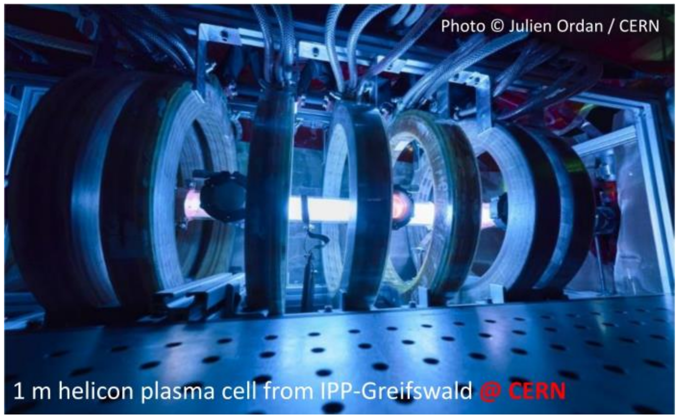
✧Dedicated laboratory at CERN

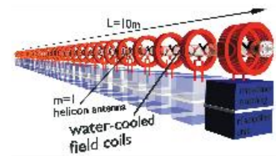
Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020)

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

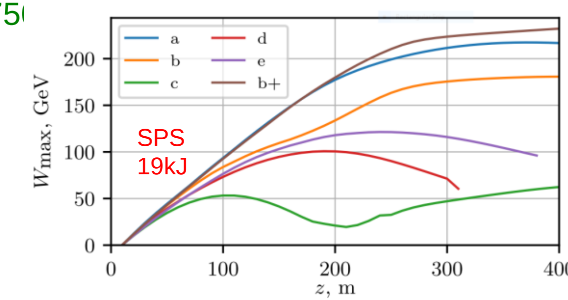
Buttenschön, PPFC 60(7), 075





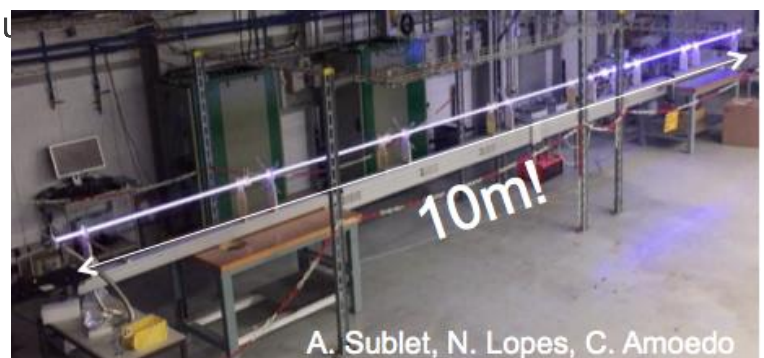
Max-Planck-Institut für Plasmaphysik

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



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

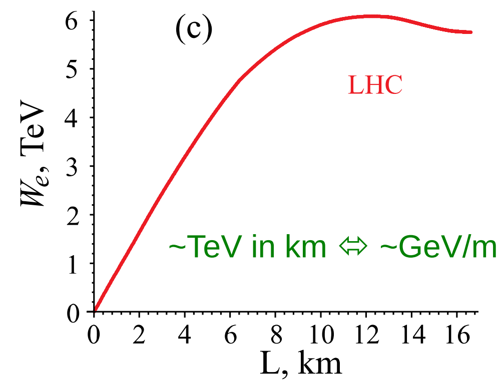
- ✧Pu



TÉCNICO LISBOA

Imperial College London

CERN



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

- ✧Challenge: plasma density uniformity!

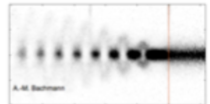
$\Delta n_e/n_{e0} << 1/N_{\mu b}$, $N_{\mu b\neq} \sim 100 \Rightarrow \Delta n_e/n_{e0} < 0.2\%$

SUMMARY

✧AWAKE:

✧Observed three instabilities

SM



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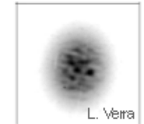

SUMMARY

✧AWAKE:

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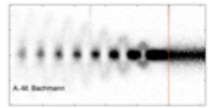
SM



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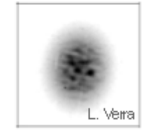
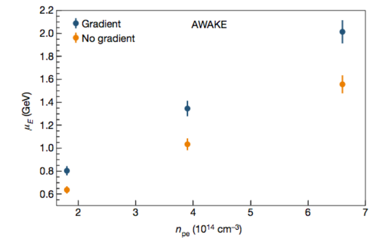


✧Seeded/controlled SM to accelerate e⁻ to GeV energy level

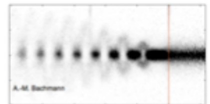


SUMMARY

✧AWAKE:

✧Observed three instabilities

SM



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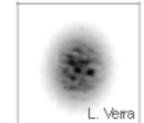
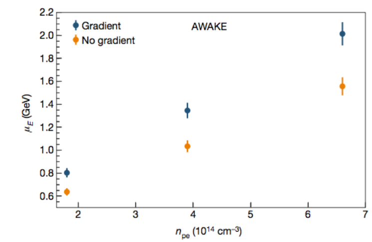


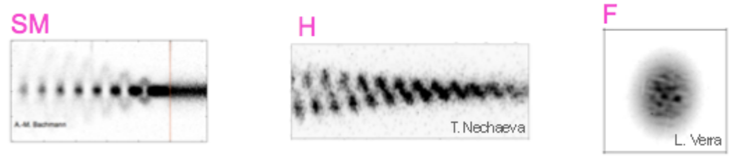


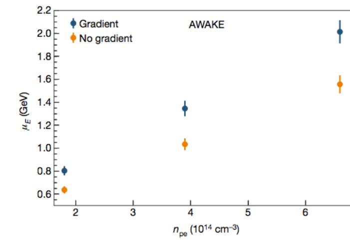
✧Seeded/controlled SM to accelerate e^- to GeV energy level

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

SUMMARY

✧AWAKE:





✧Observed three instabilities

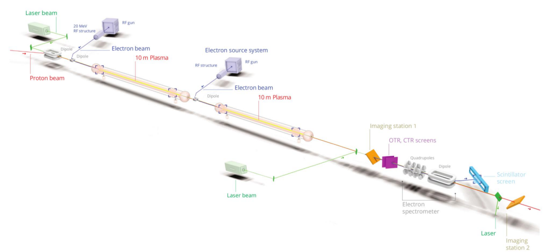
✧Seeded/controlled SM to accelerate e^- to GeV energy level

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

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

✧Large energy gain

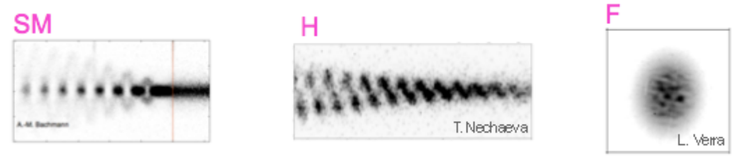
✧Scalability to very large …



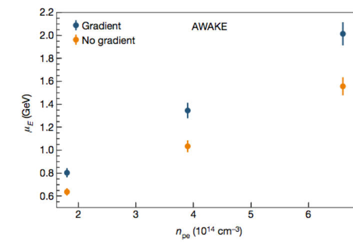
Muggli (AWAKE Coll.)
J. of Phys.: Conf. Series1596, 012008 (2020).

SUMMARY

✧AWAKE:



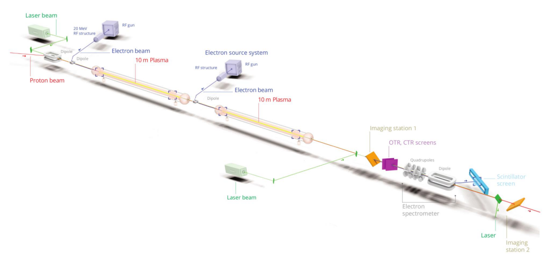
✧Observed three instabilities



✧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

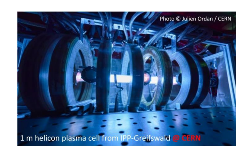


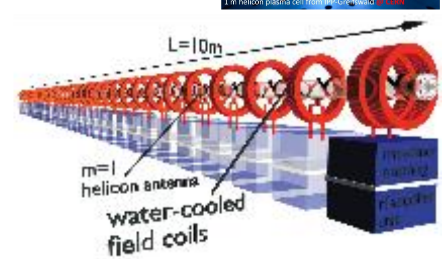
✧Large energy gain

✧Scalability to very large …

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

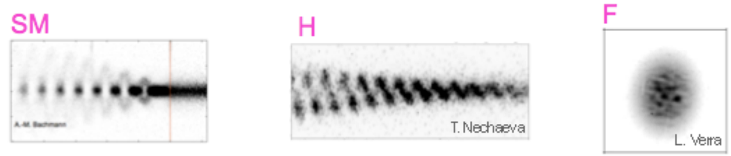
✧Development of scalable plasma sources

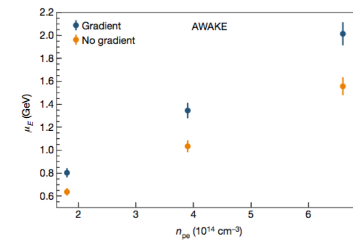




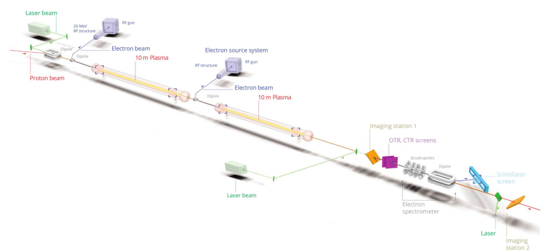
SUMMARY

✧AWAKE:

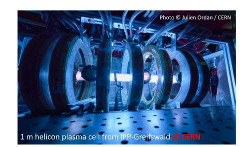


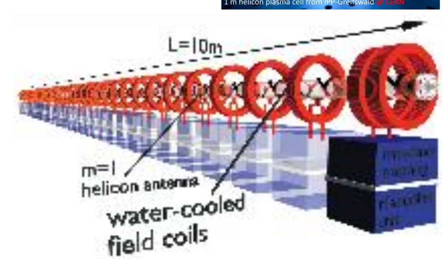


- ✧Observed three instabilities
- ✧Seeded/controlled SM to accelerate e^- to GeV energy level
- ✧Developing a self-modulator for a long p^+ bunch
- ✧Clear plans for an accelerator: self-modulation, injection, acceleration
- ✧Large energy gain
- ✧Scalability to very large …
- ✧Development of scalable plasma sources
- ✧Propose particle physics experiments in the 2030's
- ✧Dark photon search



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





SUMMARY

✧AWAKE:

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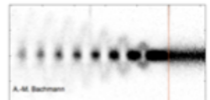
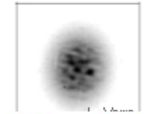
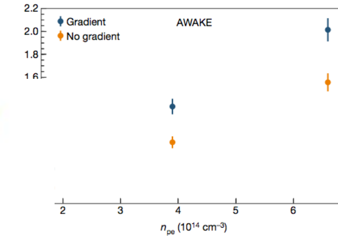






AWAKE collaboration: 22 institutes world-wide

✧Seeded/cont

✧Developing a

✧Clear plans f

✧Large energy

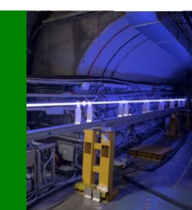
✧Scalability to

- 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

oll.)

Series1596, 012008 (2020).

✧Development of scalable plasma sources



✧Prop

✧Dark

AWAKE is a collaboration
Opportunities for contributions!

AWAKE – EUROPEAN CONTEXT

✧ AWAKE is a major component of roadmap implemented by the laboratory directors group (LDG) as an outcome of the European Strategy for Particle Physics

	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-)	Legend: 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

	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)

R&D on plasma-based light sources will de-risk HALHF and other plasma-based collider concepts considerably

	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	Legend: 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			

✧A number of interesting (important?) experimental results
(many simulation results, but focus on …)

✧Clear plan towards application to particle physics

✧Opportunities to contribute

Thank you to my collaborators

Thank you!

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