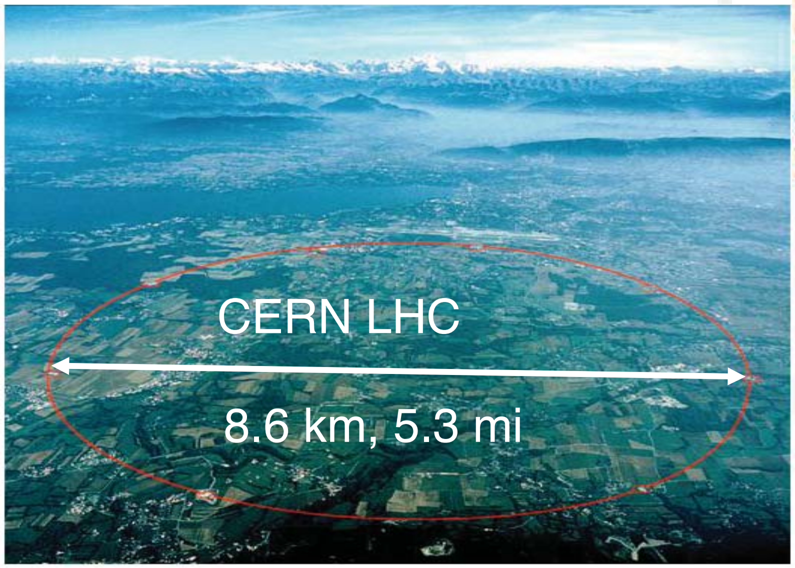
Beam-Plasma Interactions for Particle Acceleration and Basic Studies at AWAKE

Patric Muggli *AWAKE collaboration*
Max Planck Institute for Physics
Munich
muggli@mpp.mpg.de
https://www.mpp.mpg.de/~muggli

MAX-PLANCK-INSTITUT FÜR PHYSIK

PARTICLE ACCELERATORS



"The 2.4-mile circumference RHIC ring is large enough to be seen from space"

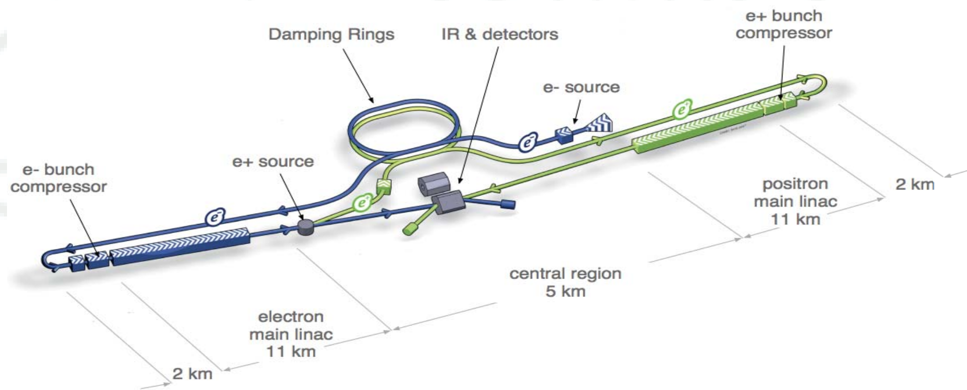
e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

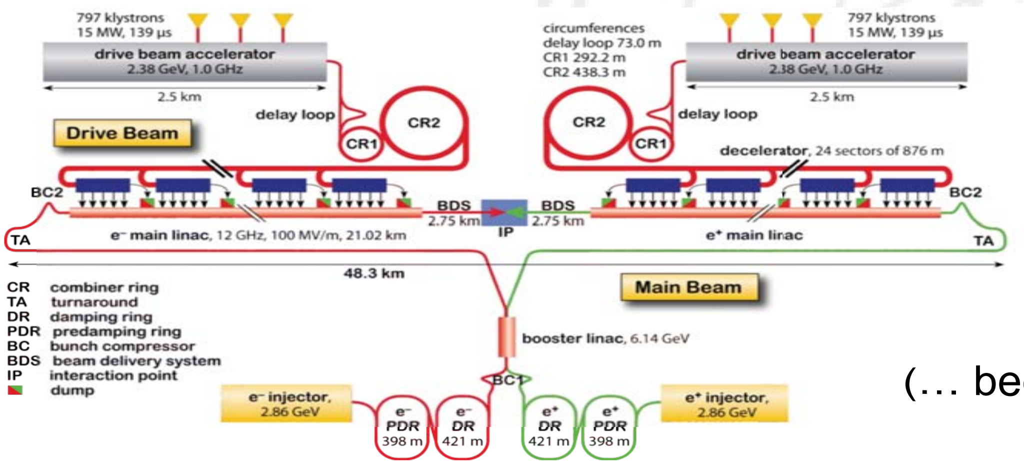
✧ Some of the largest and most complex (and most expensive) scientific instruments ever built!

✧ All use radio frequency (RF) technology to accelerate particles

PARTICLE ACCELERATORS

The future is …

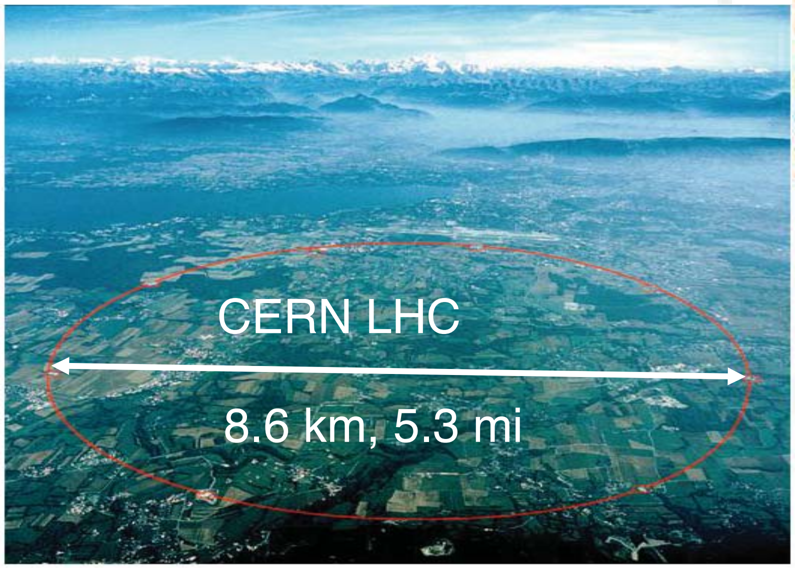




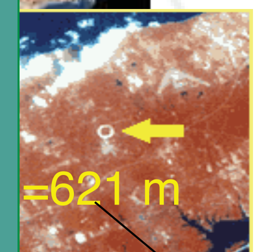
… large and larger…

(… because of higher and higher energies)

Particle Accelerators



"The 2.4-mile circumference RHIC ring is large enough to be seen from space"



Hadron accelerators
energy limited by magnetic field:

$$r_{Larmor} = \frac{\gamma mc}{qB_0} = r_{accelerator}$$

B_0~ 8T for LHC
(p^+, 7TeV, C=27km)

B_0~16T for FCC
(p^+, 50TeV, C=100km)

SLC
FACET
e^- 0-14GeV in 1km LCLS

- ✧ Some of the largest and most complex (and most expensive) scientific instruments ever built!
- ✧ All use radio frequency (RF) technology to accelerate particles

Particle Accelerators

Light particles (e^-/e^+) accelerator
Limited by synchrotron radiation

$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$

Linear for high energy!
Energy limited by the accelerating gradient:

$$\searrow L = \frac{E(eV)}{G(eV/m)} \nearrow$$

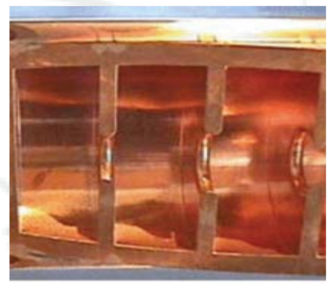
"The 2.4-mile circumference RHIC ring is large enough to be seen from space"

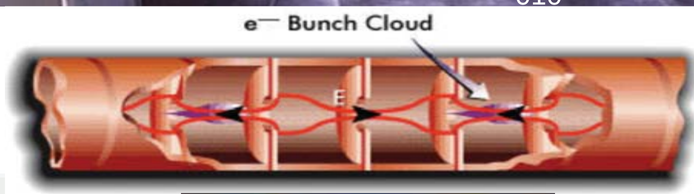
e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-20GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

- ✧ Some of the largest and most complex (and most expensive) scientific instruments ever built!
- ✧ All use radio frequency (RF) technology to accelerate particles

ACCELERATING FIELDS

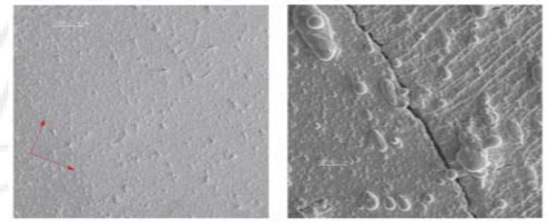
- ✧Gradient/field limit in (warm) RF structures: <1GV/m
- ✧RF break down (plasma!!) and pulsed heating fatigue
- ✧Accelerating field on axis, damage on the surface
- ✧Material limit, metals in the GHz freq. range (Cu, Mo, etc.)
- ✧Does not (seem to) increase with increasing frequency

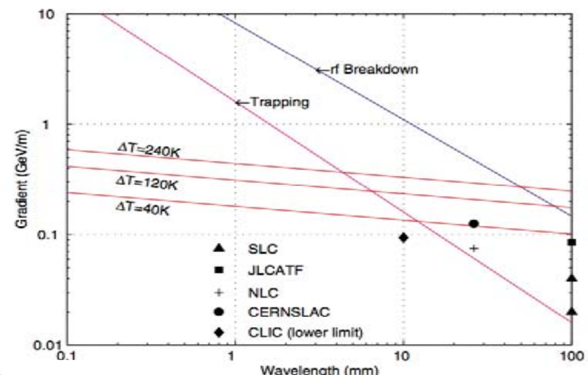




Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)





RF break down

Braun, PRL 90, 224801 (2003)

ACCELERATiNG FiELDS

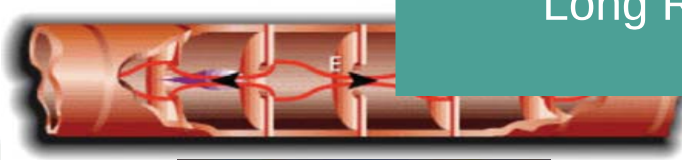
✧Gradient/field limit in (warm) RF structures: <1GV/m

✧RF break down (plasma!!) and pulsed heating fatigue

✧Accelerating field on

✧Material limit, metals

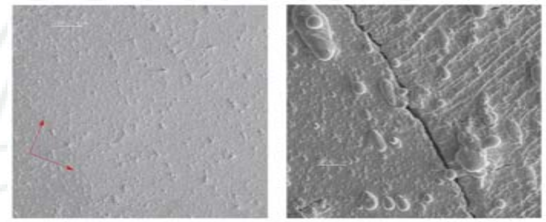
✧Does not (seem to) i

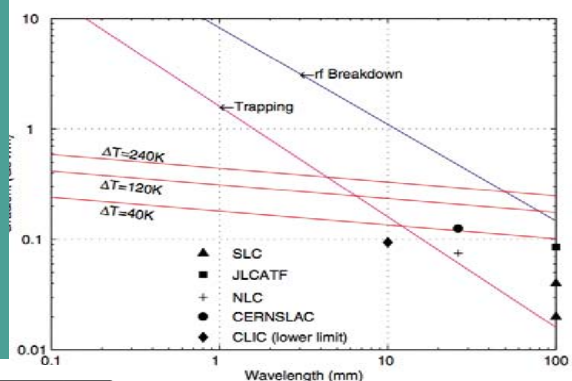


RF-accelerators:
Accelerating field limited to <1GV/m
(low break-down rate)
by metal damage:
-RF-breakdown
-pulsed heating
Copper: low damage threshold
Long RF pulses (high Q)

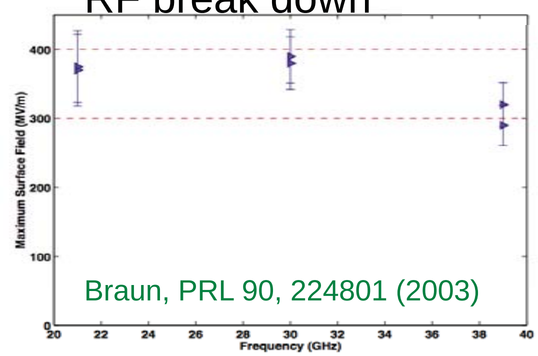
Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)





RF break down



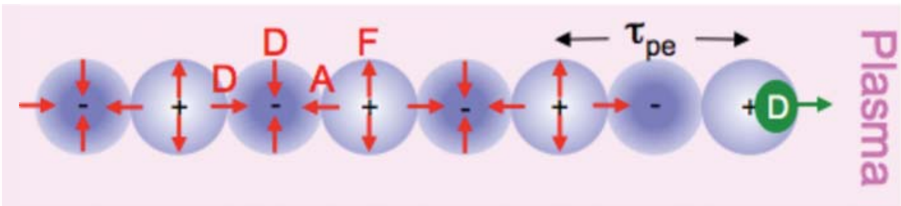
Braun, PRL 90, 224801 (2003)

PARTICLE ACCELERATORS

Search for a new technology
to accelerate particles
at high-gradient (>1GeV/m)
and reduce the size and cost
of a future linear e^-/e^+ collider
or of an x-ray FEL
… and (many) low energy applications

- ✧ Some of the largest and most complex (and most expensive) scientific instruments ever built!
- ✧ All use radio frequency (RF) technology to accelerate particles

Relativistic Particle Bunch Meets Plasma



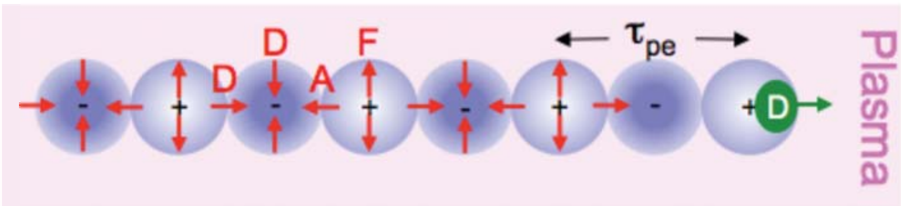
D=driver

✧Relativistic Bunch ⇔ Radial Space Charge Field ⇔ Plasma Screening

⇔ Azimuthal Magnetic Field ⇔ Plasma Return Current

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

RELATIVISTIC PARTICLE BUNCH MEETS PLASMA



D=driver

✧Relativistic Bunch ⇔ Radial Space Charge Field ⇔ Plasma Screening

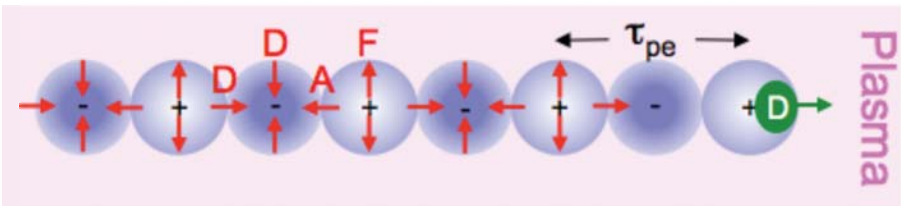
⇔ Azimuthal Magnetic Field ⇔ Plasma Return Current

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

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

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

RELATIVISTIC PARTICLE BUNCH MEETS PLASMA



D=driver

✧Relativistic Bunch ⇔ Radial Space Charge Field ⇔ Plasma Screening

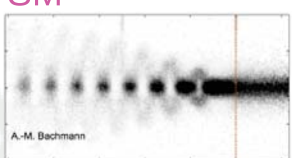
⇔ Azimuthal Magnetic Field ⇔ Plasma Return Current

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

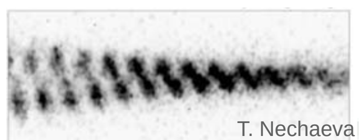
✧Screening ⇔ Plasma Wakefields (Langmuir Wave, E_z) ⇔ Self-Modulation and Hosing Instabilities ⇔ Accelerators

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

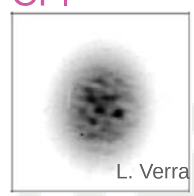
SM



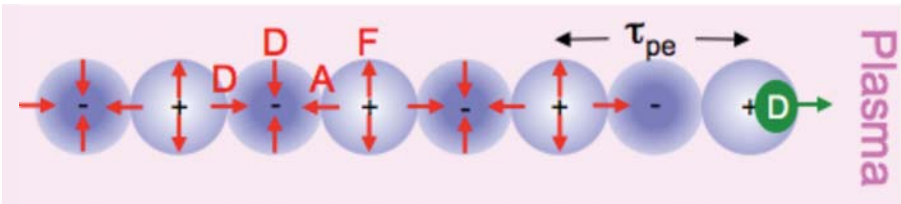
H



CFI



RELATIVISTIC PARTICLE BUNCH MEETS PLASMA



D=driver

✧Relativistic Bunch ⬄ Radial Space Charge Field ⬄ Plasma Screening

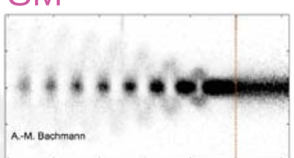
⬄ Azimuthal Magnetic Field ⬄ Plasma Return Current

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

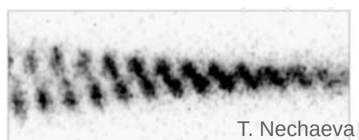
✧Screening ⬄ Plasma Wakefields (Langmuir Wave, E_z) ⬄ Self-Modulation and Hosing Instabilities ⬄ Accelerators

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

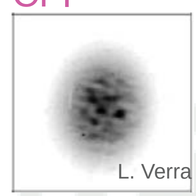
SM



H



CFI

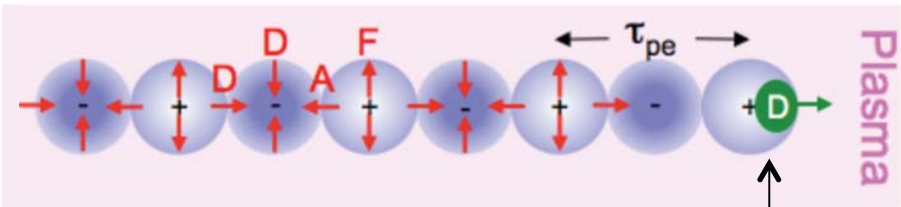


Main motivation:

✧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:

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

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

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

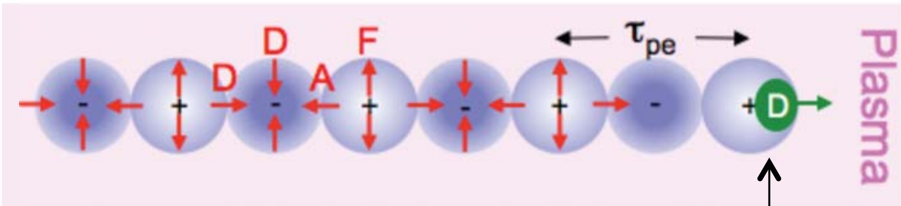
fit within the "structure", "bubble"

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

c/ω_{pe} Plasma skin depth

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"

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

c/ω_{pe} Plasma skin depth

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

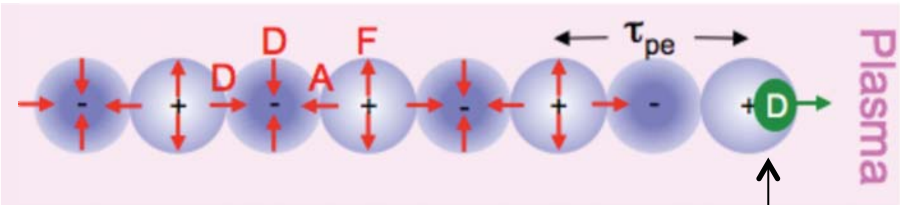
$E_{WB}(n_{e0}=3\text{x}10^{17}\text{cm}^{-3})$=53GV/m, c/ω_{pe}= 10µm

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

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

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"

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

c/ω_{pe} Plasma skin depth

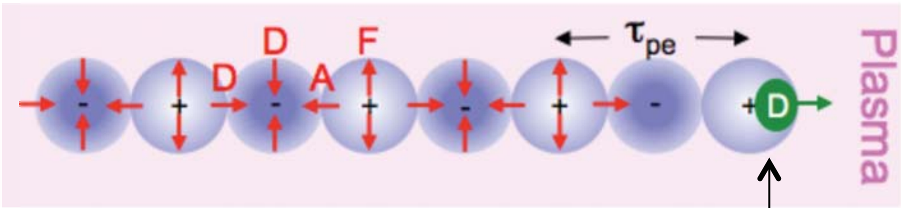
High-gradient acceleration
>1GeV/m
High frequency
>100GHz

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

$E_{WB}(n_{e0}=3\text{x}10^{17}\text{cm}^{-3})$=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
Favors small^3 driver, high density $n_b \sim n_{e0}$

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"

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

c/ω_{pe} Plasma skin depth

High-gradient acceleration
>1GeV/m
High frequency
>100GHz

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

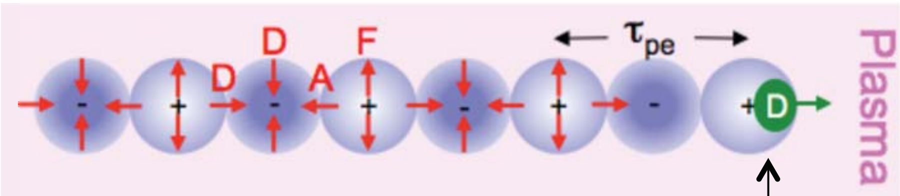
$E_{WB}(n_{e0}=3\text{x}10^{17}\text{cm}^{-3})$=53GV/m, c/ω_{pe}= 10µm
$E_{WB}(n_{e0}=7\text{x}10^{14}\text{cm}^{-3})$=2.5GV/m, c/ω_{pe}=200µm
Favors small^3 driver, high density $n_b \sim n_{e0}$

✧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)

PASMA WAKEFIELDS

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



Control Room

In 1D
Plasma Wakefield
=
Langmuir, Electro-Static Wave!

$E_{WB}(n_{e0}=3x10^{17}cm^{-3})=53GV/m$, $c/\omega_{pe}= 10µm$

$E_{WB}(n_{e0}=7x10^{14}cm^{-3})=2.5GV/m$, $c/\omega_{pe}=200µm$

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

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

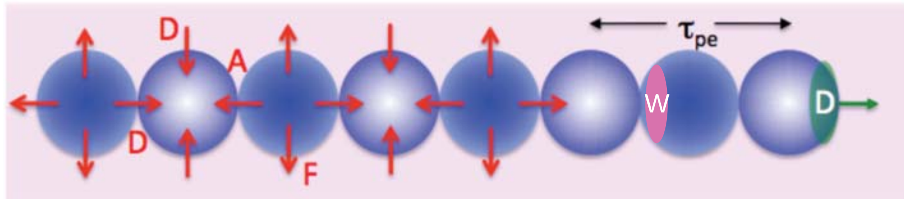
c/ω_{pe} Plasma skin depth

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

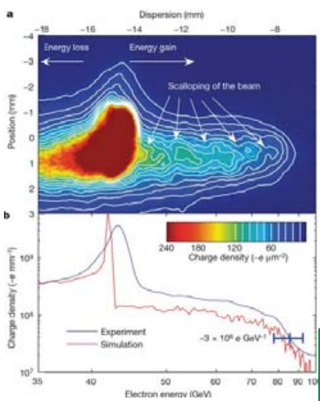
T. Tajima, J. Dawson, Phys. Rev. Lett. 43, 267 (1979)
P. Chen, et al., Phys. Rev. Lett. 54, 693 (1985)

PLASMA WAKEFIELDS

Short driver: electron bunch, laser pulse



PWFA, short e^- bunch



Blumenfeld, Nature 445, 741 (2007)

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

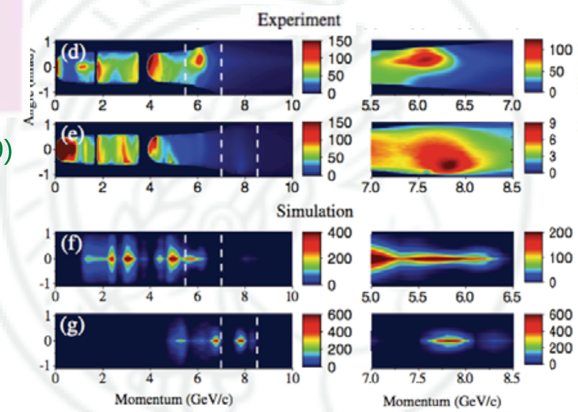
60fs e^- bunch

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

~42GeV energy gain

~52GeV/m, 85cm

LWFA, short laser pulse



Gonsalves, PRL 122, 084801 (2019)

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

~40fs laser pulse

~40J, 1PW

~8GeV energy gain

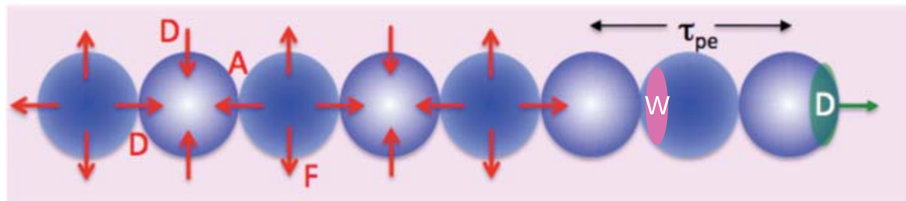
~39GeV/m, 20cm

Very large energy gain
Very large gradient!

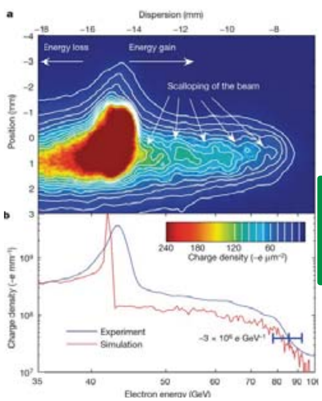
Note: RF-based accelerators <1GeV/m!

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

SLAC

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

~42GeV energy gain

~52GeV/m, 85cm

σ_t ~1/ω_{pe}

E_{WB}~50GV/m

LWFA, short laser pulse

Gonsalves, PRL 122, 084801 (2019)

BERKELEY LAB

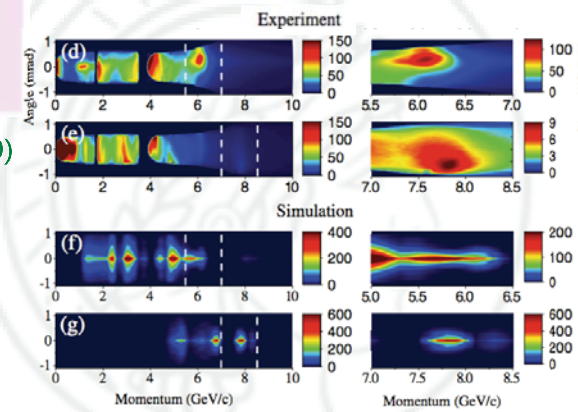
n_{e0}=3x10^{17}cm^{-3}

~40fs laser pulse

~40J, 1PW

~8GeV energy gain

~39GeV/m, 20cm



Scaling:

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

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

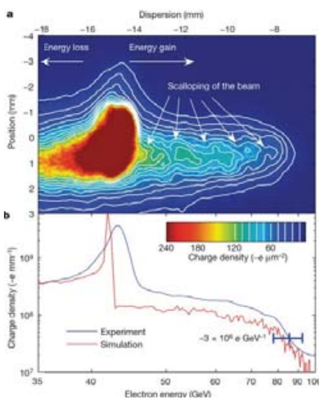
$$E_{WB} = \frac{m_e c}{e}\omega_{pe} \propto n_{e0}^{1/2}$$

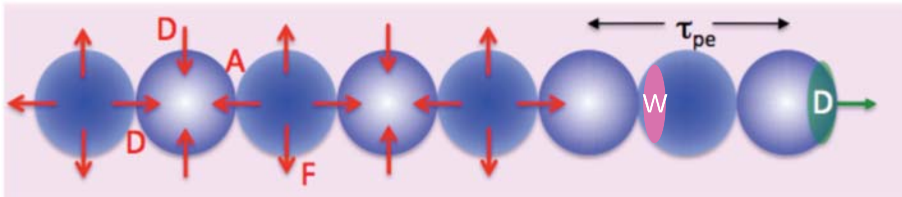
Very similar parameters!

PLASMA WAKEFIELDS

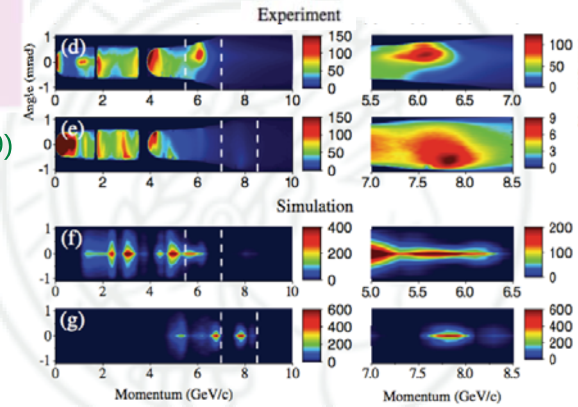
Short driver: electron bunch, laser pulse

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

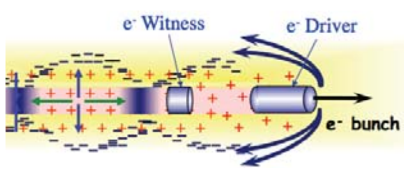
~8GeV energy gain

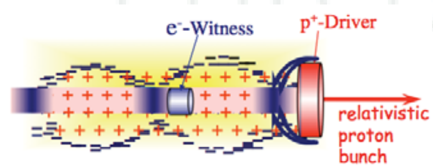
~39GeV/m, 20cm

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

LHC ⬄ 1x10^{11}p$^+$ ⬄ 7 TeV ⬄112kJ

✧Very large energy gain in a single plasma!

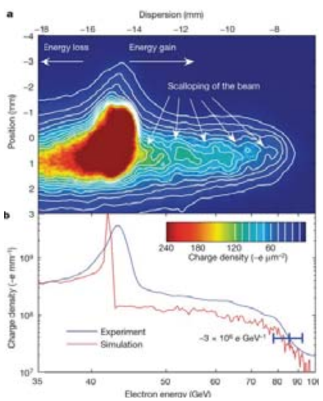


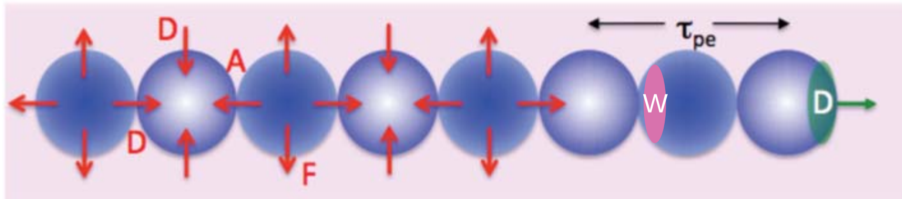


PLASMA WAKEFIELDS

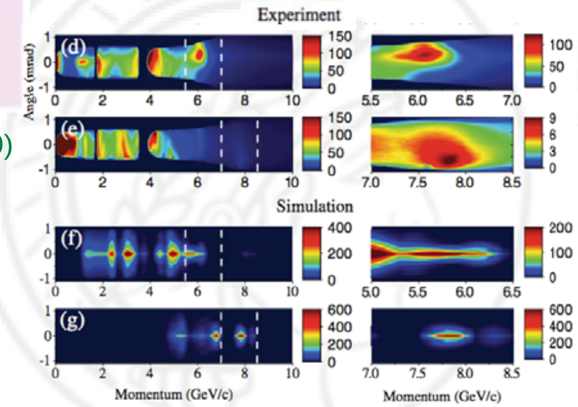
Short driver: electron bunch, laser pulse

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 ~$1/\omega_{pe}$

E_{WB}~50GV/m

Gonsalves, PRL 122, 084801 (2019)

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

~40fs laser pulse

~40J, 1PW

~8GeV energy gain

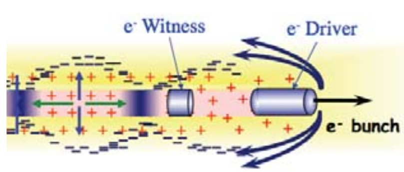
~39GeV/m, 20cm

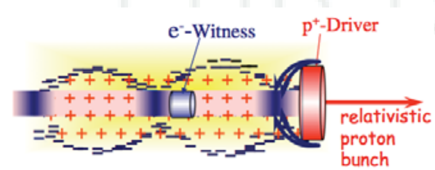
p^+ bunches: SPS ⇔ 3x10^{11}p^+ ⇔ 400 GeV ⇔ 19kJ

LHC ⇔ 1x10^{11}p^+ ⇔ 7 TeV ⇔112kJ

✧Very large energy gain in a single plasma!

✧Witness energy gain ≤ driver energy loss!

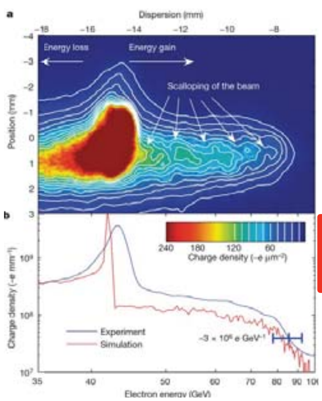


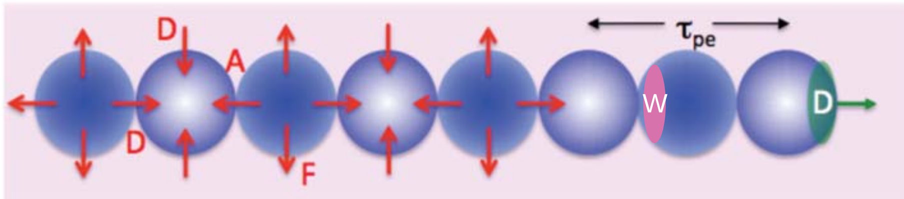


PLASMA WAKEFIELDS

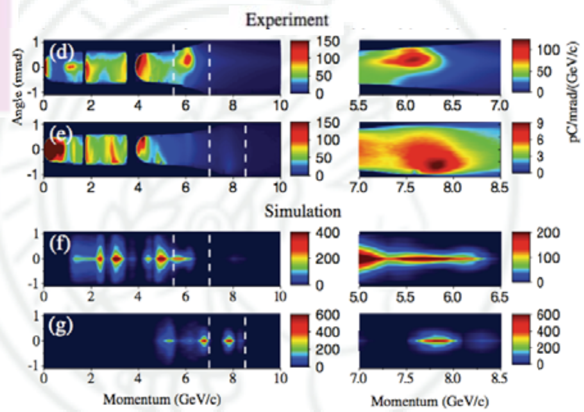
Short driver: electron bunch, laser pulse

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:

$$\sigma_t, \tau \leq 1/\omega_{pe} \propto n_{e0}^{-1/2}$$
$$\sigma_r \leq c/\omega_{pe} \propto n_{e0}^{-1/2}$$
$$E_{WB} = \frac{m_e c}{e}\omega_{pe} \propto n_{e0}^{1/2}$$

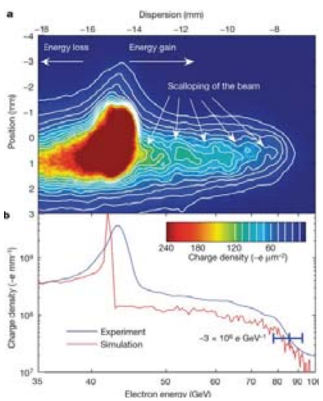
p^+ bunches: SPS ⇔ 3x10^{11}p^+ ⇔ 400 GeV ⇔ 19kJ
LHC ⇔ 1x10^{11}p^+ ⇔ 7 TeV ⇔112kJ

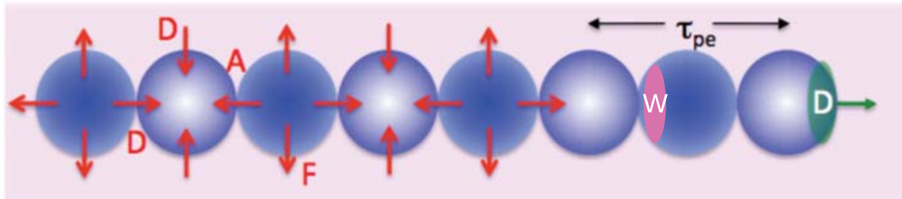
Scaling: τ= 300ps ⇔ n_{e0}=3.5x10^{9}cm^{-3} ⇔ E_{WB}=5.7MV/m!

PLASMA WAKEFIELDS

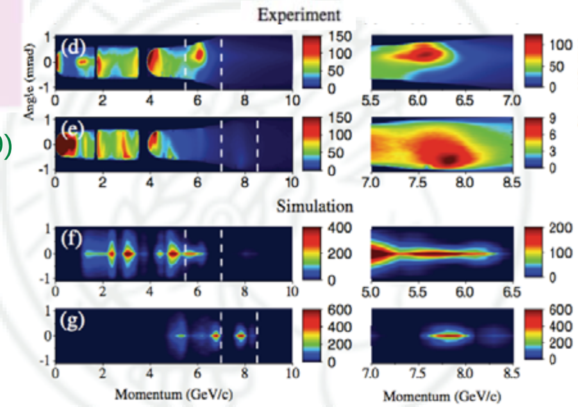
Short driver: electron bunch, laser pulse

PWFA, short e⁻ bunch





LWFA, short laser pulse



Blumenfeld, Nature 445, 741 (2007)

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

60fs e⁻ bunch

2x10^{10}e⁻, 42GeV, ~50J

~42GeV energy gain

~52GeV/m, 85cm

SLAC

σ_t ~$1/\omega_{pe}$

E_{WB}~50GV/m

BERKELEY LAB

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!

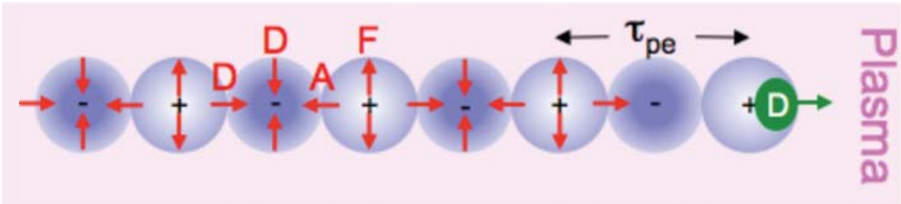
Self-Modulation!

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

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

SELF-MODULATION

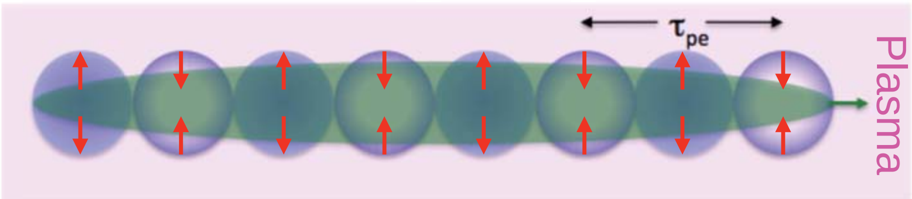
Short driver (e^-), $\sigma_t \leq 1/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$, "resonant"



Short and narrow => long and narrow

SELF-MODULATION

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



(1)

Initial (transverse) wakefields

Periodic focusing/defocusing

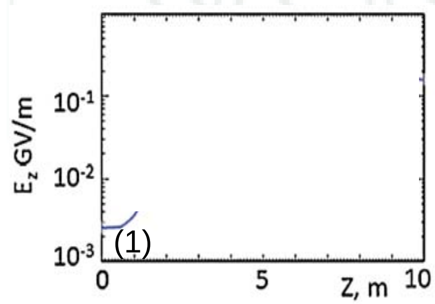
(1)

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

Plasma e^- angular frequency

✧E_z-field along the plasma

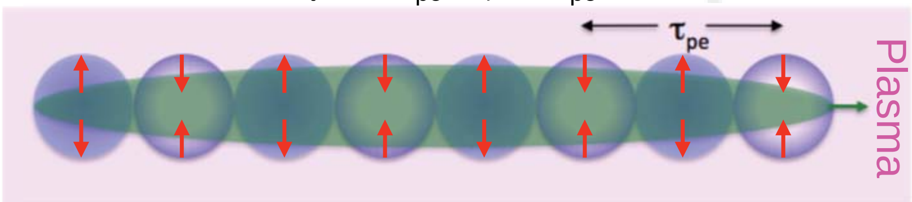
Pukhov, PRL107 145003 (2011)



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

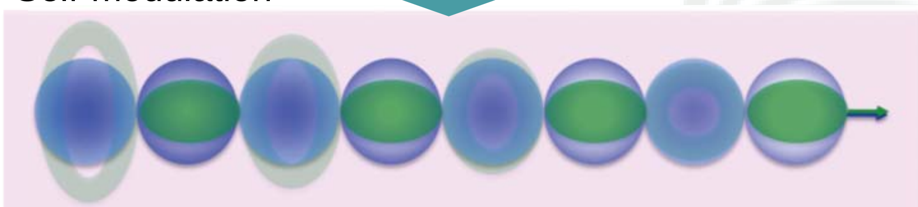
Self-Modulation

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



(1)

Self-modulation



(2)

Growth mechanism:

Initial (transverse) wakefields

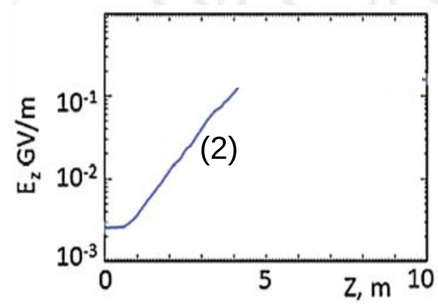
(1)

Periodic focusing/defocusing

(2)

Density modulation

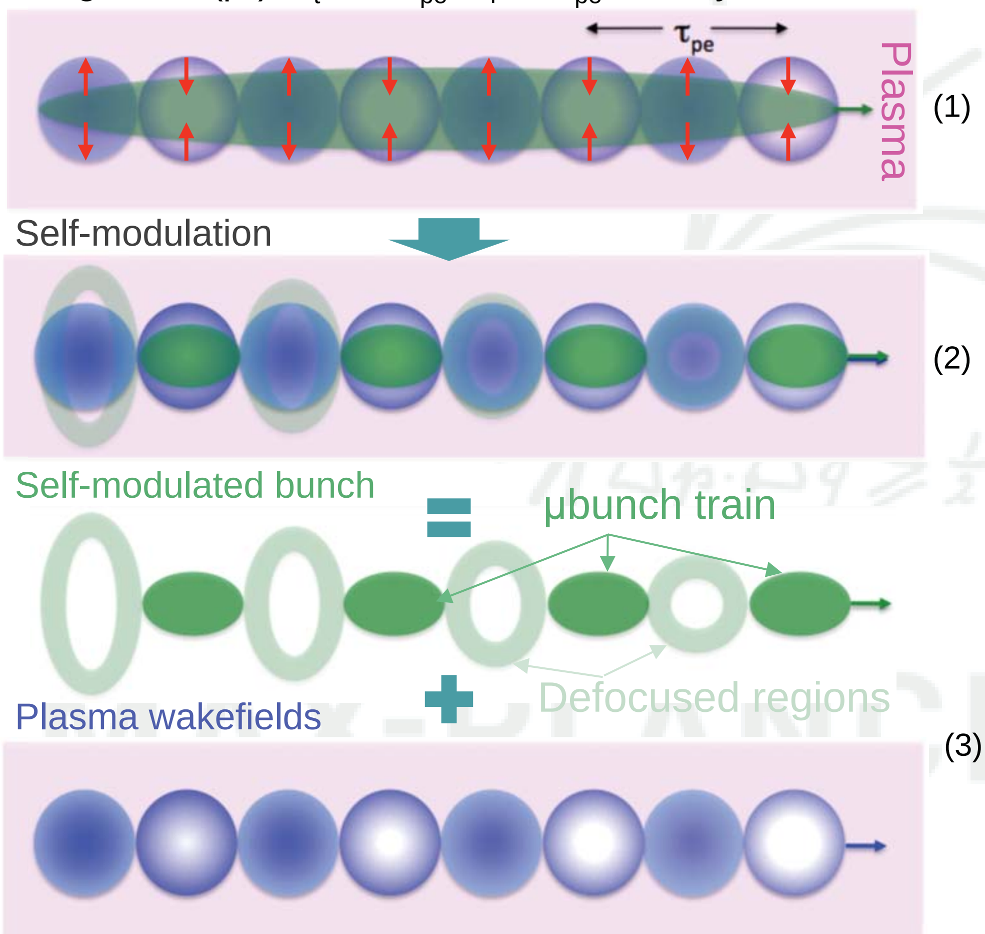
Pukhov, PRL107 145003 (2011)



Growth!

SELF-MODULATION

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



Growth mechanism:

Initial (transverse) wakefields

(1)

Periodic focusing/defocusing

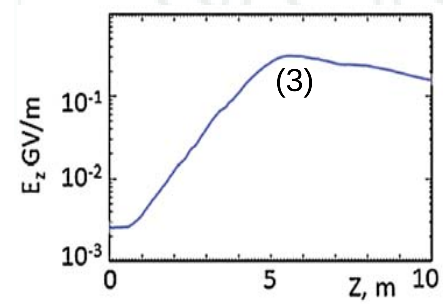
(2)

Density modulation

Full modulation - bunch train

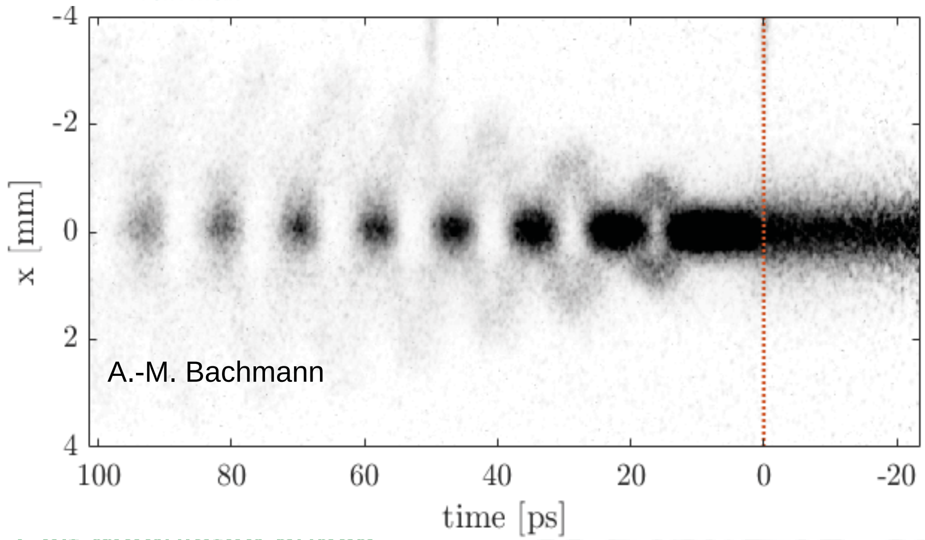
(3)

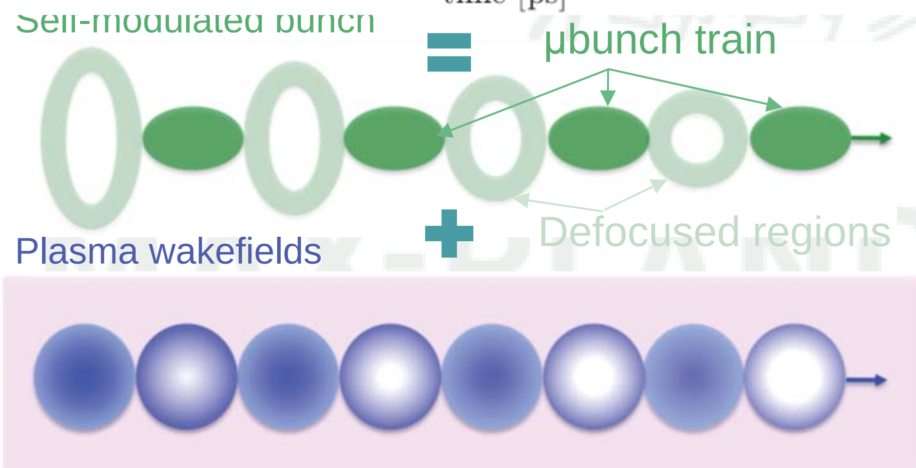
Pukhov, PRL107 145003 (2011)



- Train period $\sim\tau_{pe}=2\pi/\omega_{pe}$
- μbunch duration $< \tau_{pe}$
- 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:

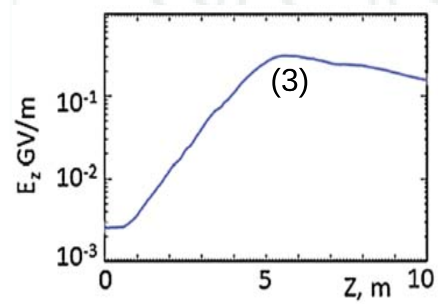
Initial (transverse) wakefields

Periodic focusing/defocusing

Density modulation

Full modulation - bunch train (3)

Pukhov, PRL107 145003 (2011)

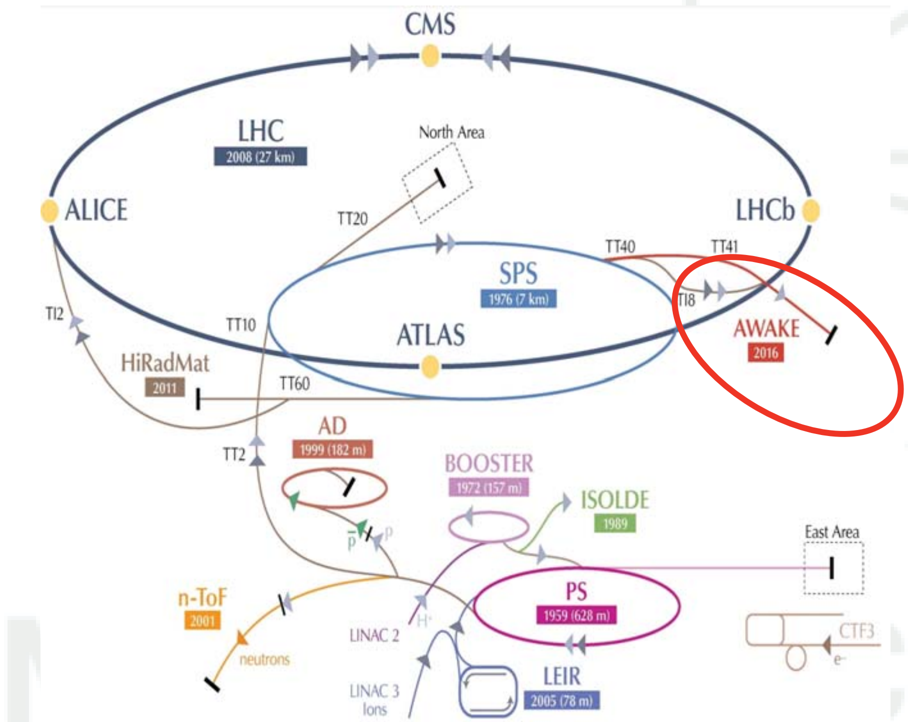


(3)

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

AWAKE @ CERN

CERN Accelerator Complex

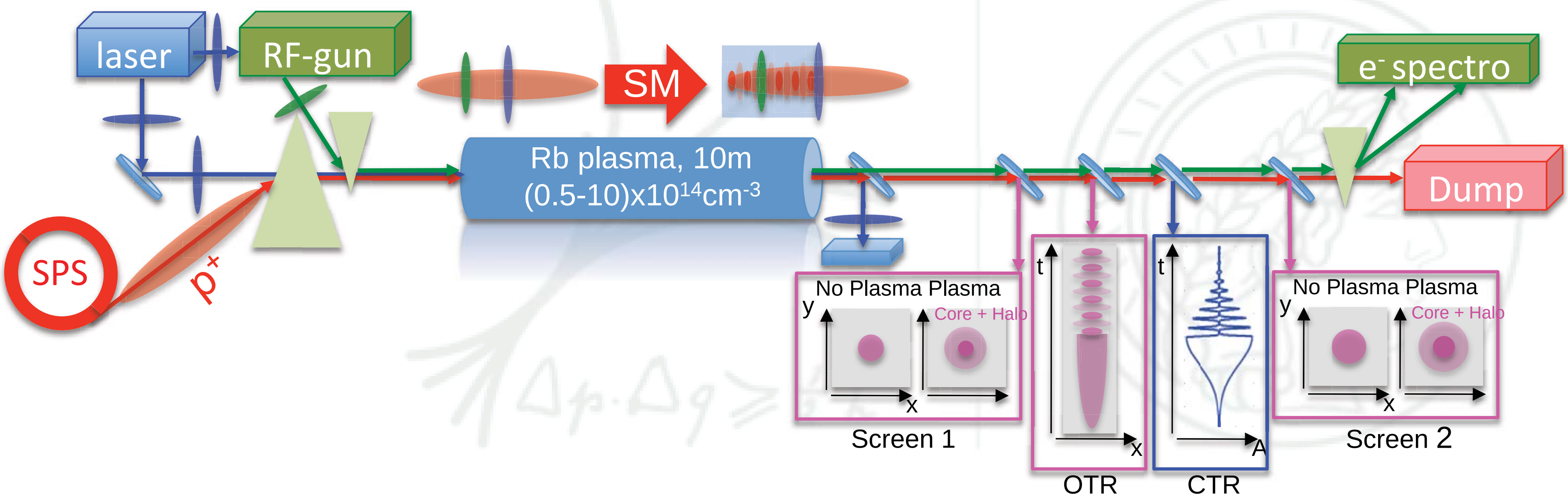


AWAKE Control Room
(-60m)

AWAKE Plasma
(-100m)

✧AWAKE: 400GeV p$^+$ bunch for the SPS, injector for LHC

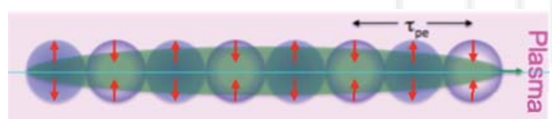
AWAKE EXPERIMENTAL SETUP



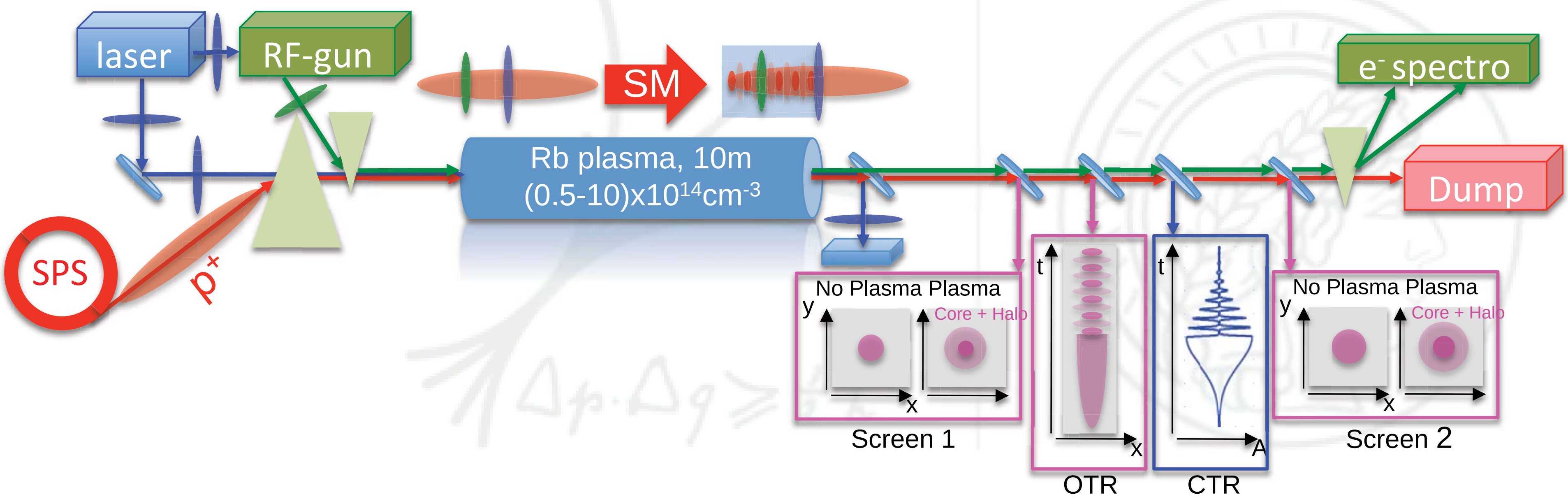
E=400GeV σ_z=6cm!! → Long

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

✧Plasma density from σ_r



AWAKE EXPERIMENTAL SETUP



$E=400GeV$ $N=(1\text{-}3)x10^{11}p^+$

$\sigma_z=6cm!!$ $\sigma_r=200\mu m$

$c/\omega_{pe}\approx\sigma_r$ ⇔ n_e ~$7x10^{14}$ cm^{-3}

λ_{pe}~$1.3mm<<\sigma_z$

f_{pe} ~240GHz

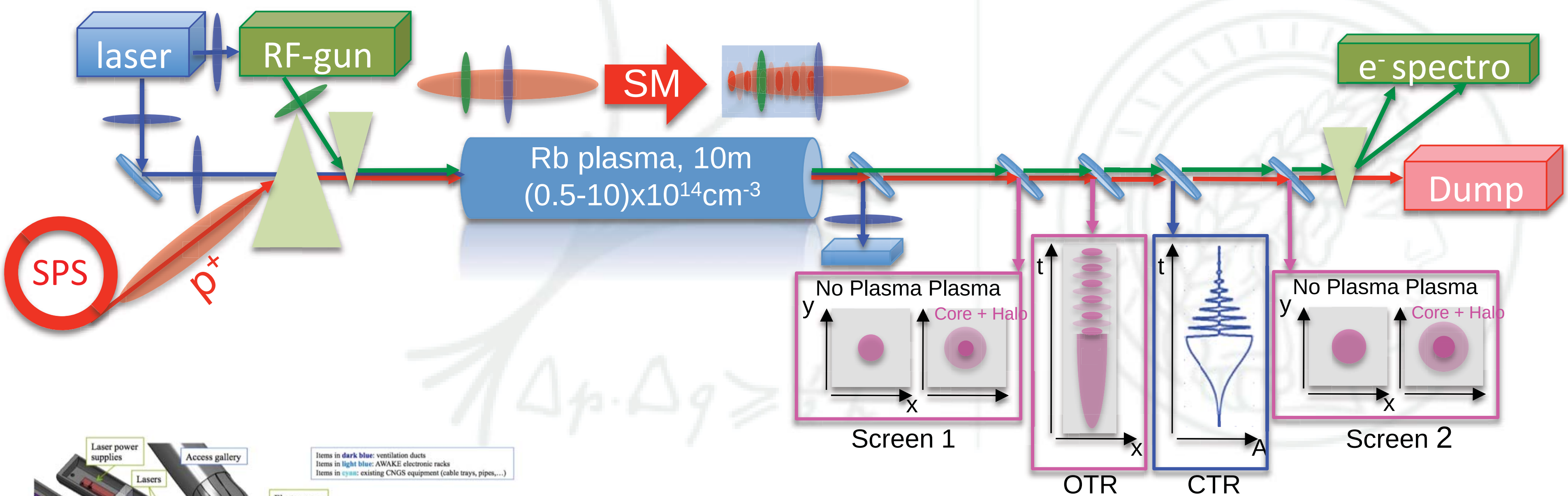
E_{WB}~2.5GV/m

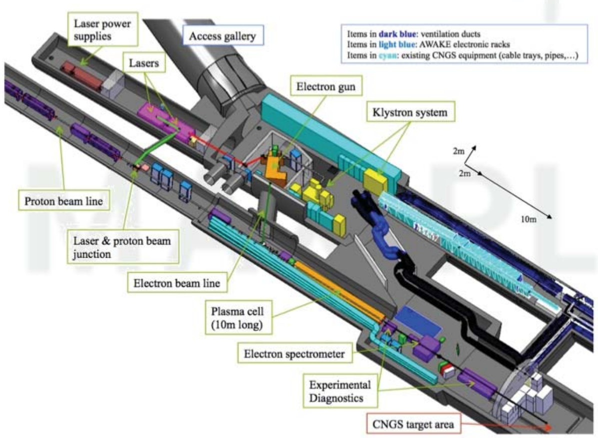
L_p ~10m~2β*

✧Plasma density from σ_r

SM ~ 1GeV/m

AWAKE EXPERIMENTAL SETUP





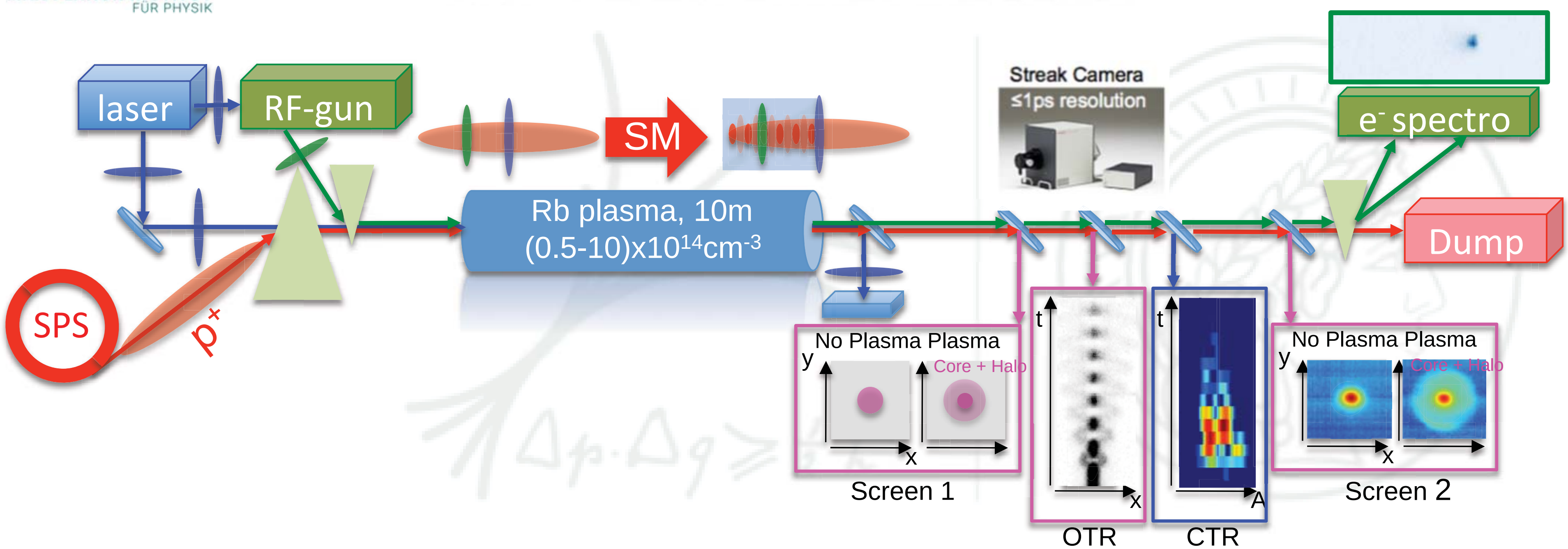
E=400GeV
σ_z=6cm!!
$c/\omega_{pe} \approx \sigma_r$ ⇔

N=(1-3)x10^{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

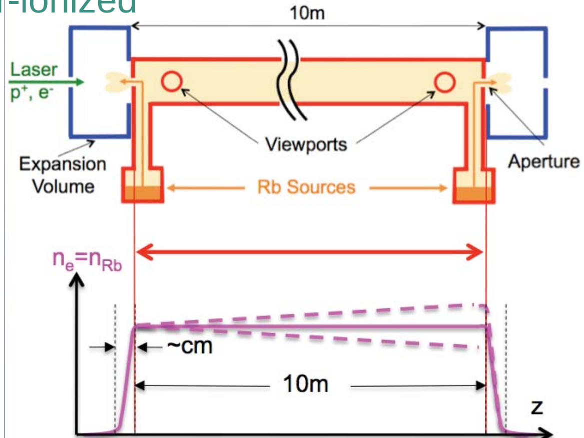
AWAKE EXPERIMENTAL SETUP



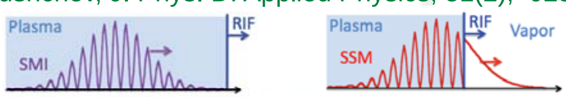
Plasma Sources

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

✧Laser-ionized

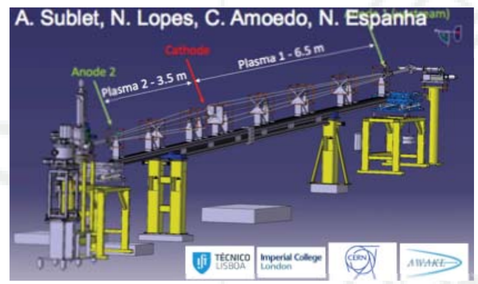


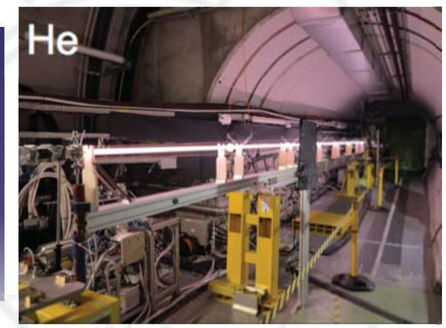
Oz, Nucl. Instr. Meth. Phys. Res. A 740(11), 197 (2014)
Plyushchev, J. Phys. D: Applied Physics, 51(2), 025203 (2017)

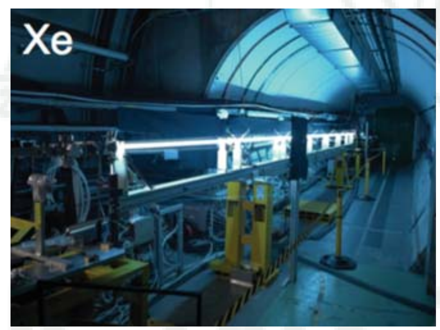


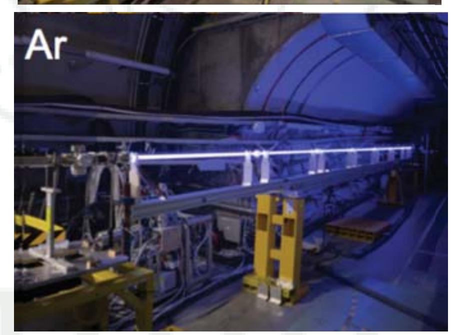
✧Very uniform density uniformity: $\Delta n_e/n_{e0}<0.5\%$

✧Discharge plasma source





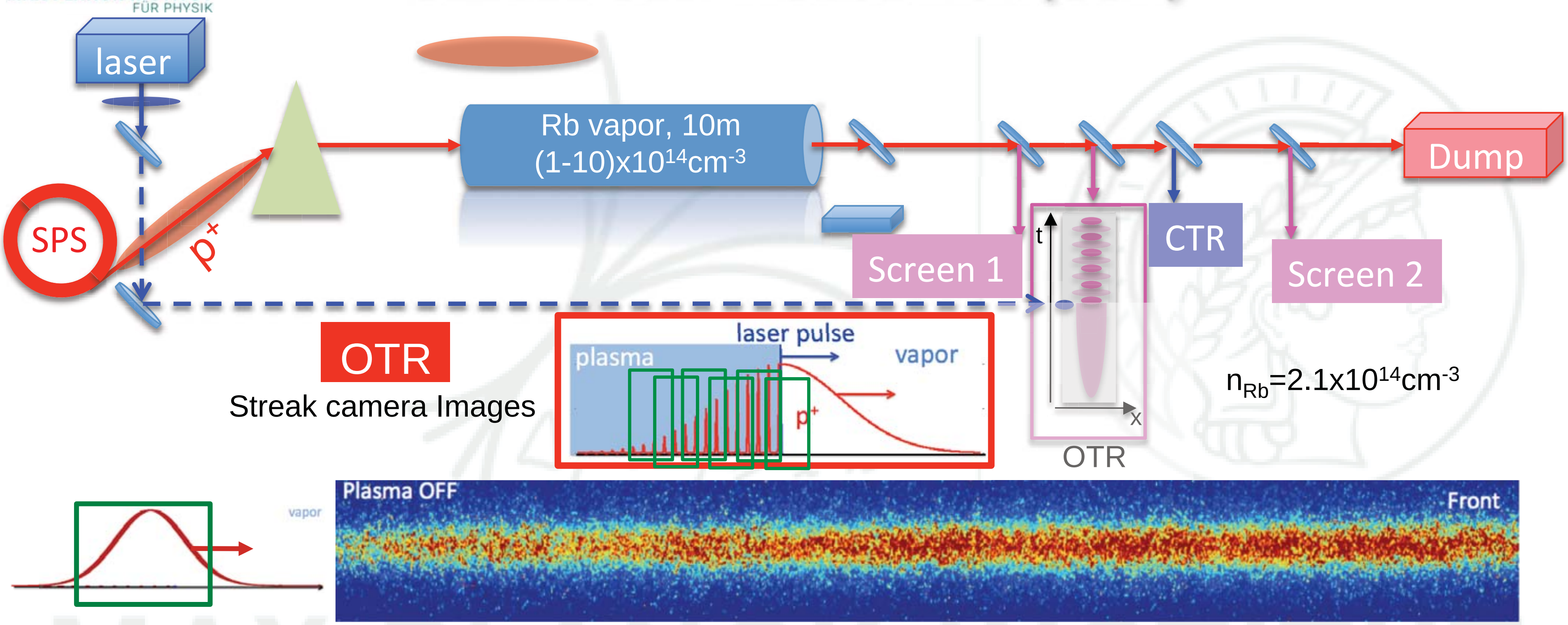




✧Flexibility:

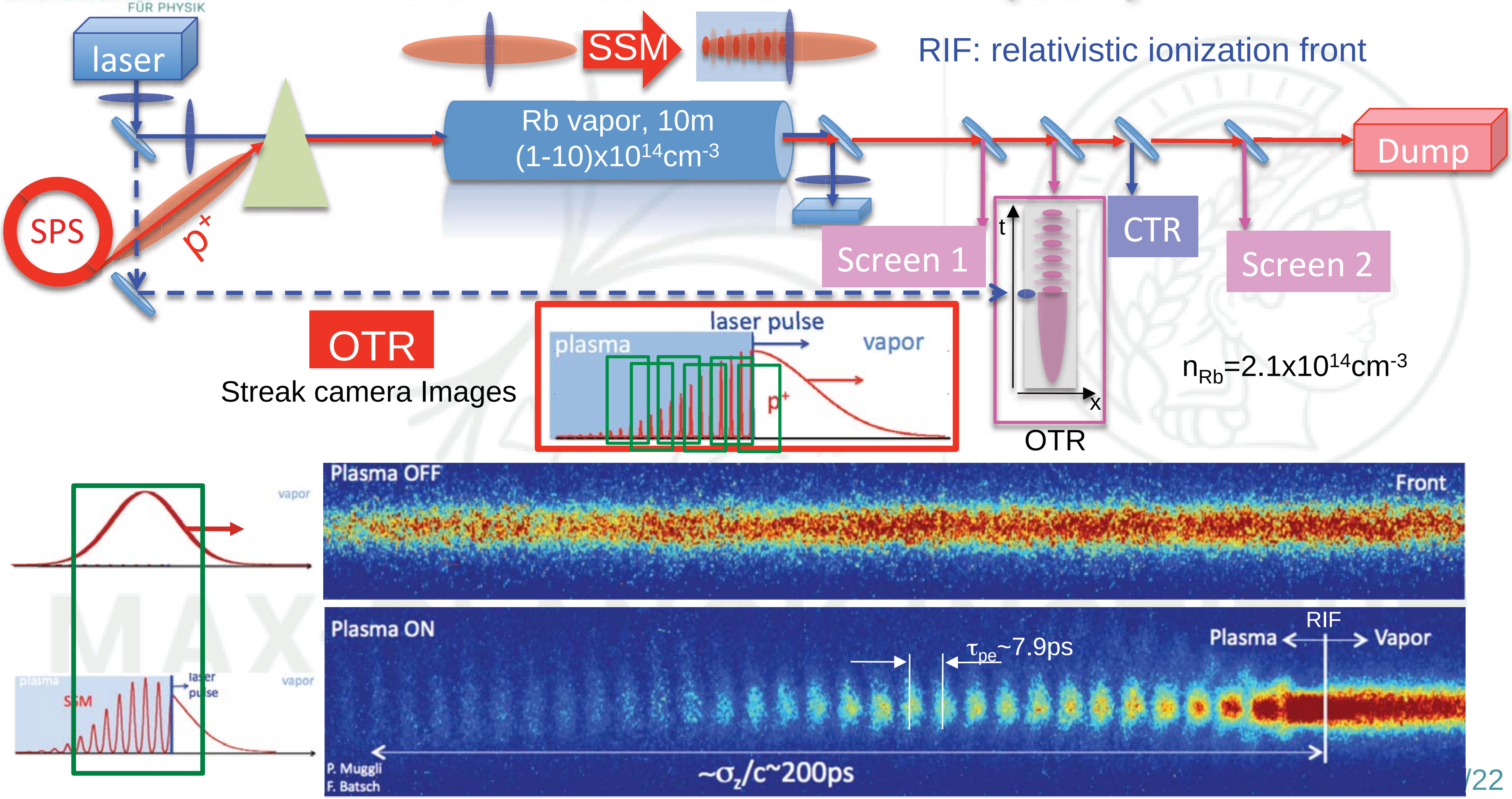
- ✧ Plasma length: 3.5, 6.5, 10m
- ✧ Density $0.1\text{-}20\times10^{14}cm^{-3}$
- ✧ Gas-ion mass: He, Ar, Xe (ω_{pi})
- ✧ Access to plasma light

SEEDED SELF-MODULATION (SSM)

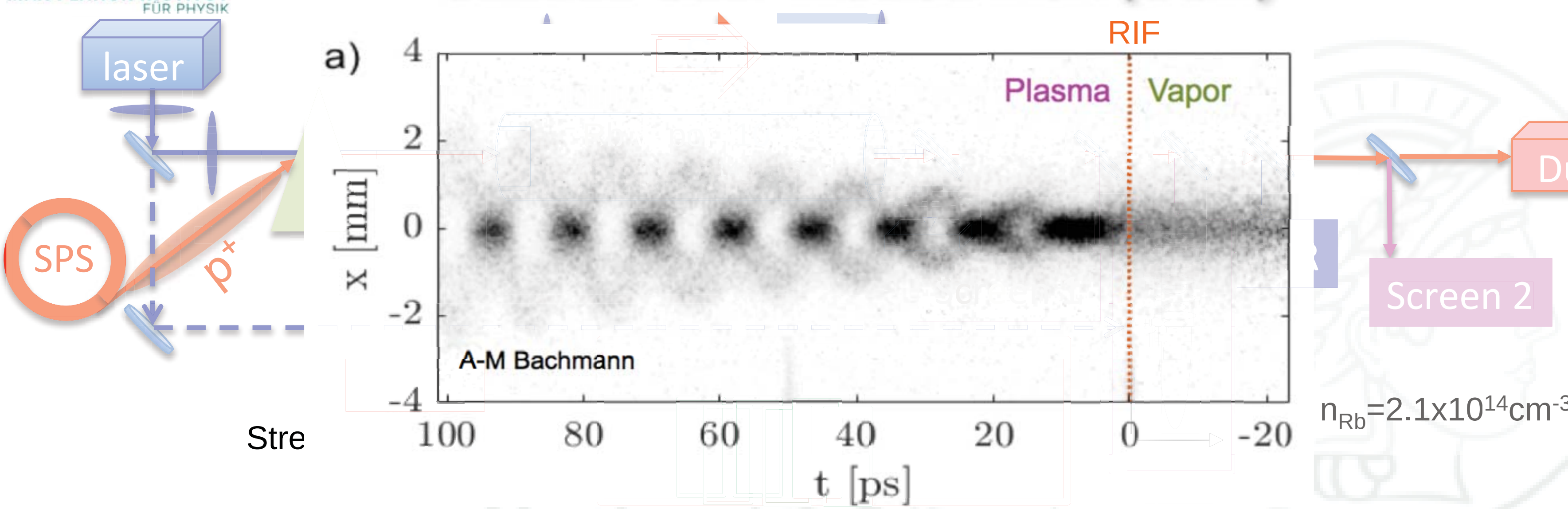


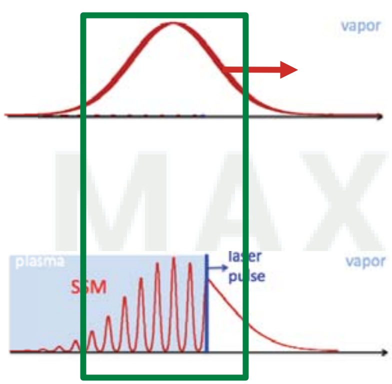
✧No plasma
✧No density modulation
✧No centroid position oscillation

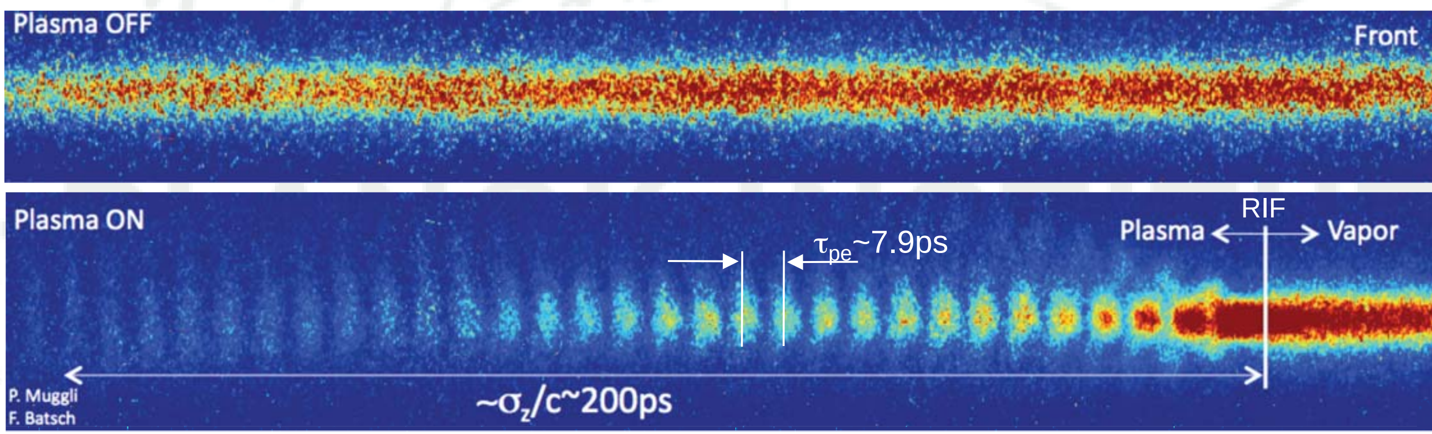
SEEDED SELF-MODULATION (SSM)



SEEDED SELF-MODULATiON (SSM)

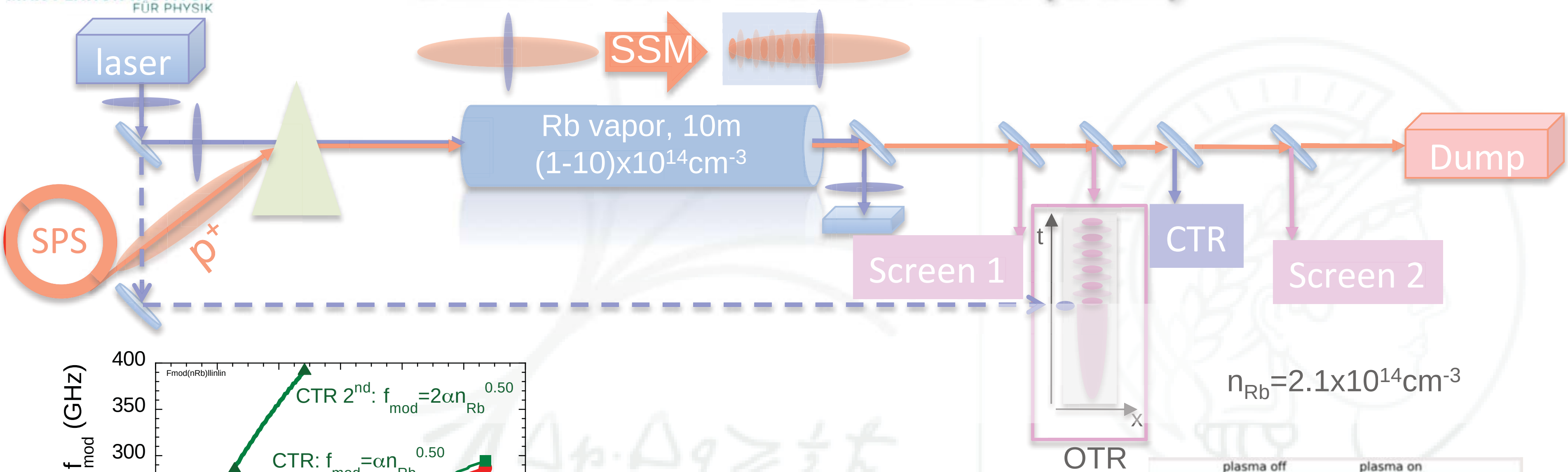




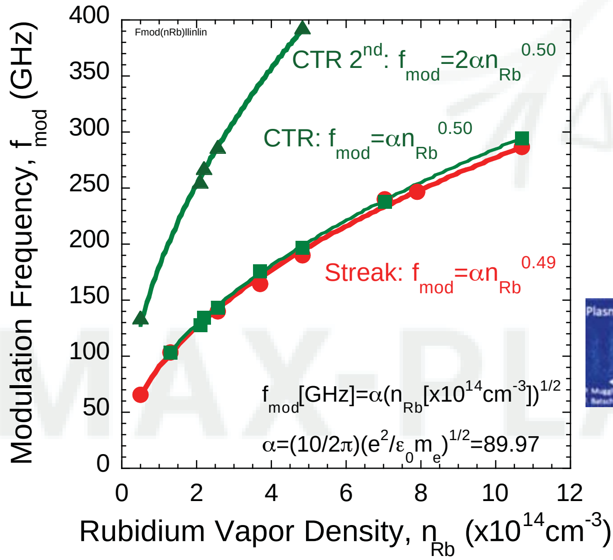


AWAKE, Phys. Rev. Lett. 122, 054802 (2019) M. Turner et al., Phys. Rev. Lett. 122, 054801 (2019)

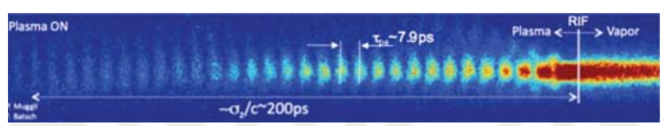
SEEDED SELF-MODULATiON (SSM)

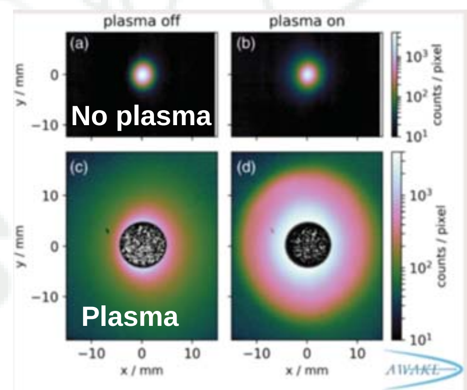


n_{Rb}=2.1x10^{14}cm^{-3}



✧ Modulation frequency = f_{pe}

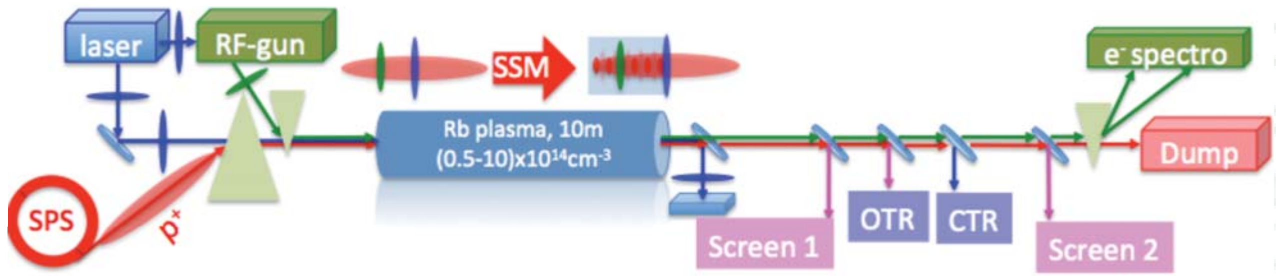


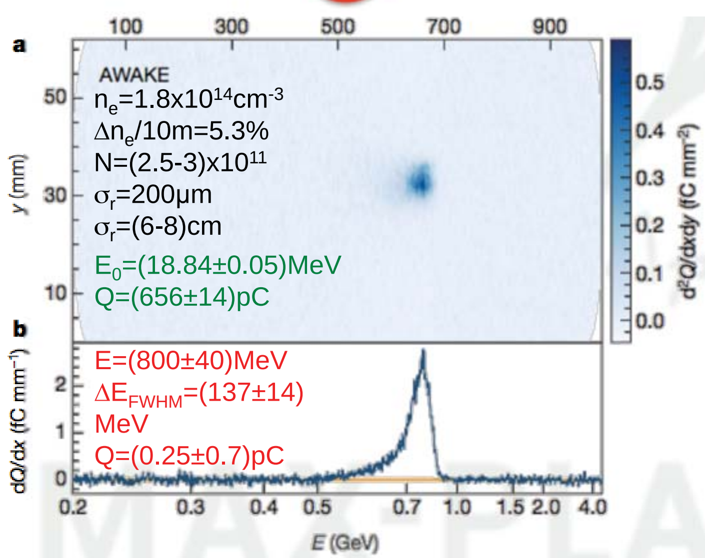


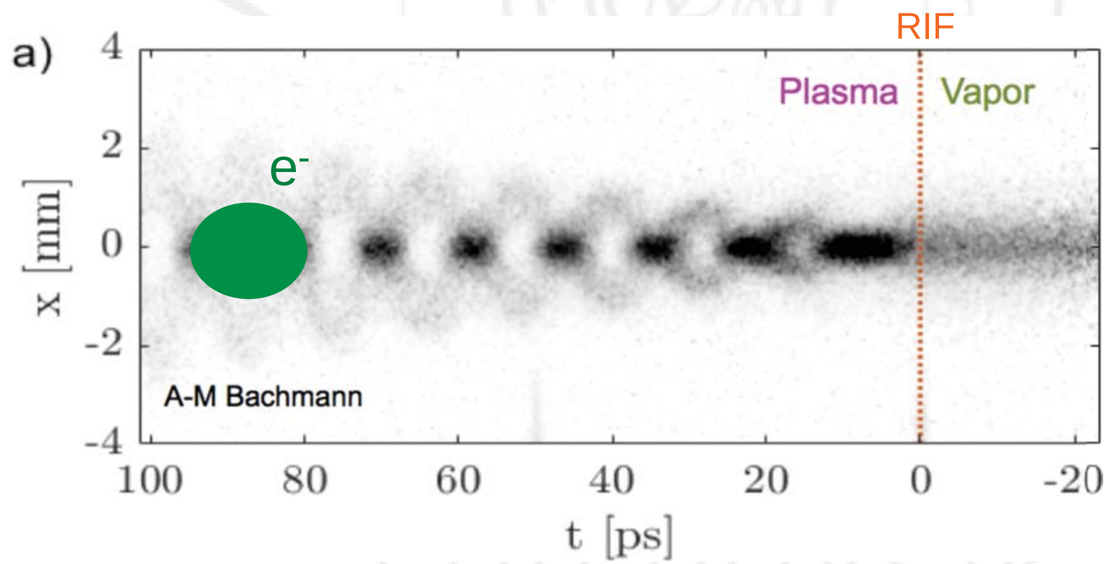
✧ SSM ⇔ halo

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

ACCELERATiON EXTERNALY-INJECTED e⁻



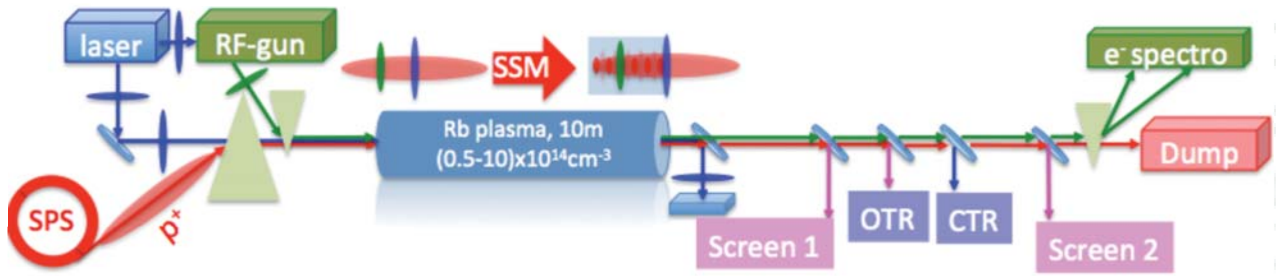


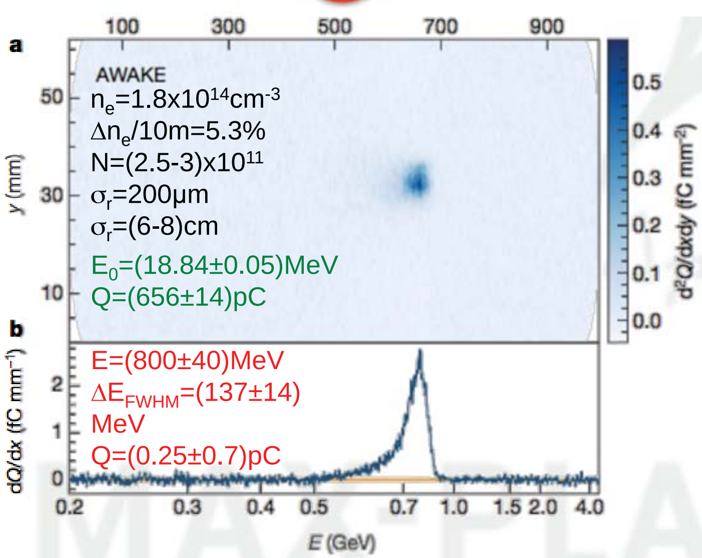


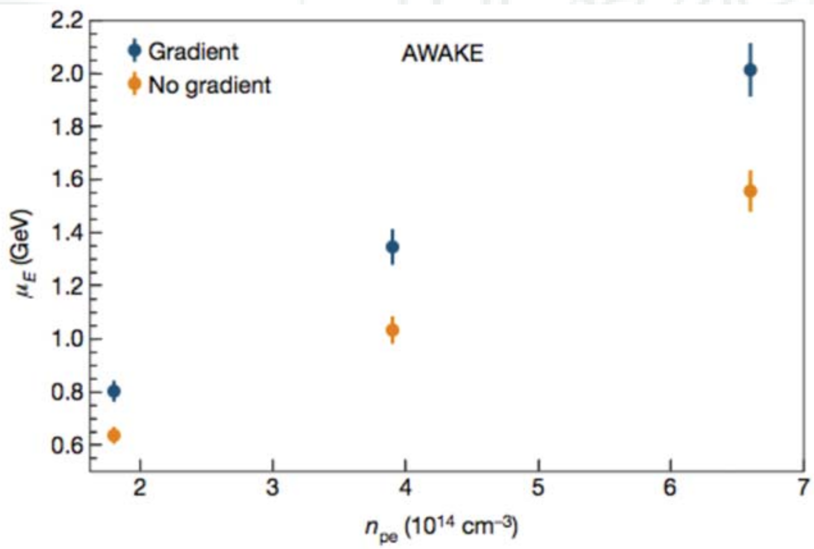
✧ Injection test e⁻ at an angle (~1-3mrad)
✧ Finite ΔE/E

AWAKE, Nature 561, 363 (2018)

ACCELERATiON EXTERNALY-INJECTED e^-



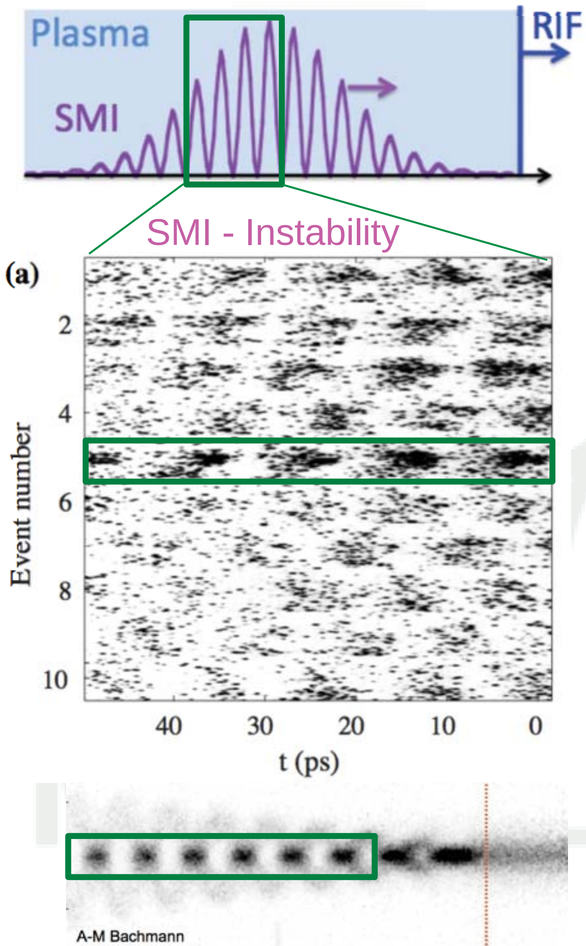




- ✧ Injection test e^- at an angle (~1-3mrad)
- ✧ Finite $\Delta E/E$
- ✧ Up to 2GeV energy gain (from ~19MeV)
- ✧ Captured charge: ~pC

AWAKE, Nature 561, 363 (2018)

SEEDED SELF-MODULATiON (SSM)



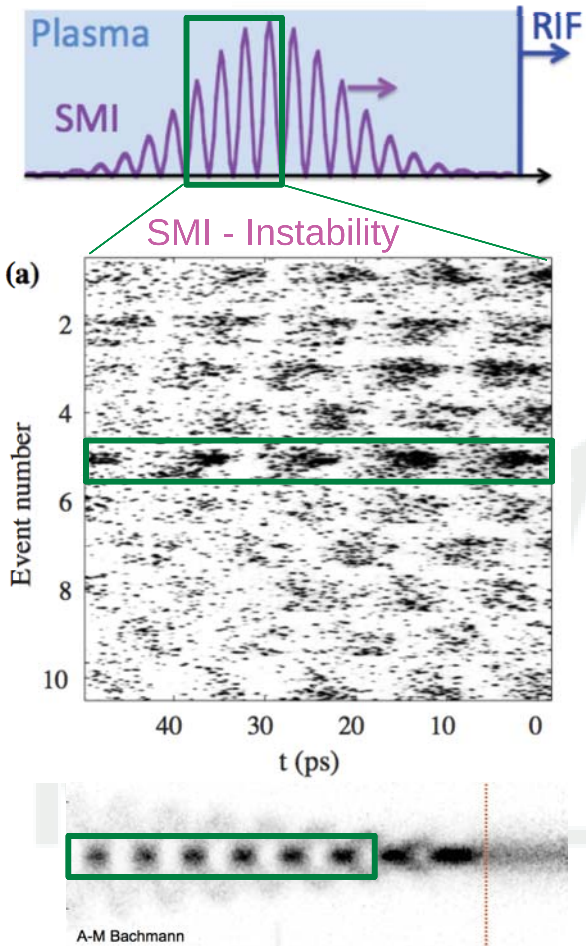
μ-bunches
@ varying times

10 events

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

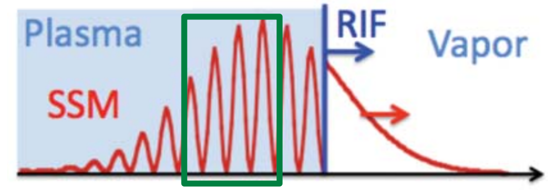
F. Batsch et al., Phys. Rev. Lett. 126, 164802 (2021)

SEEDED SELF-MODULATION (SSM)



µ-bunches
@ varying times

10 events

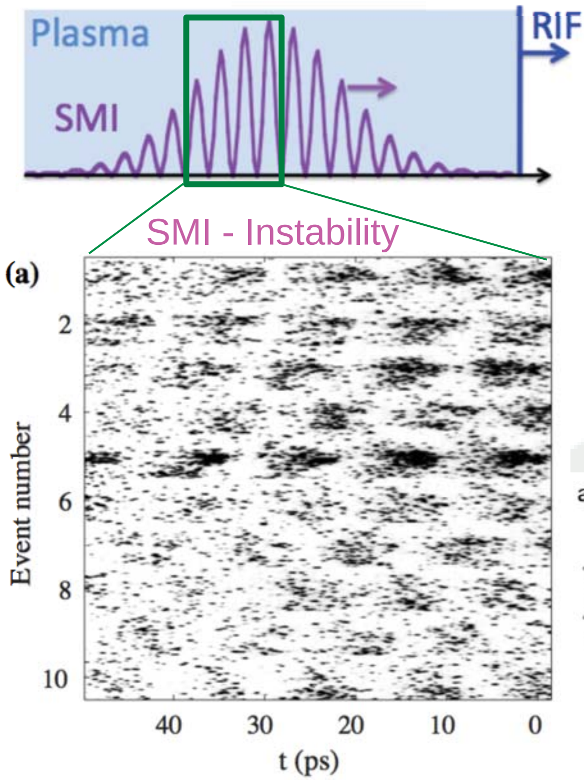


Wakefields start here!

✧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)

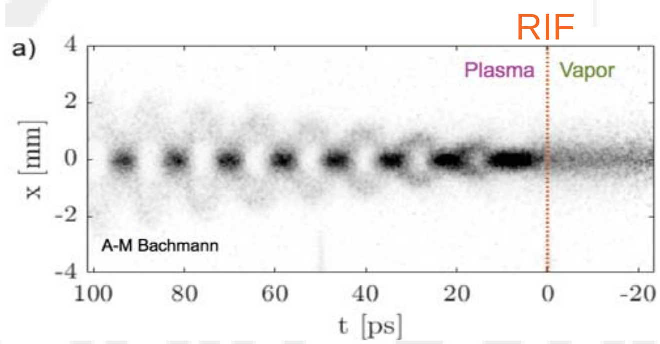


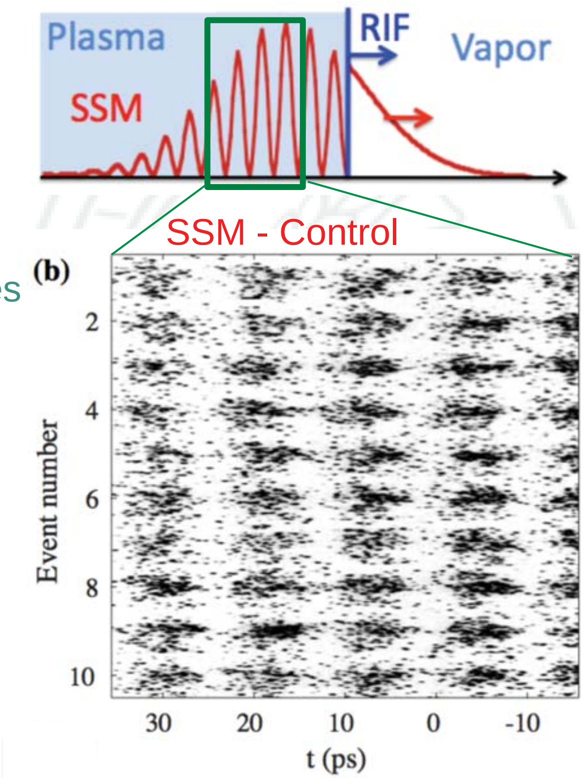
Relativistic Ionization Front
(RIF)
Seeding

μ-bunches
@ varying times

μ-bunches
@ fixed times

REPRODUCIBLE!



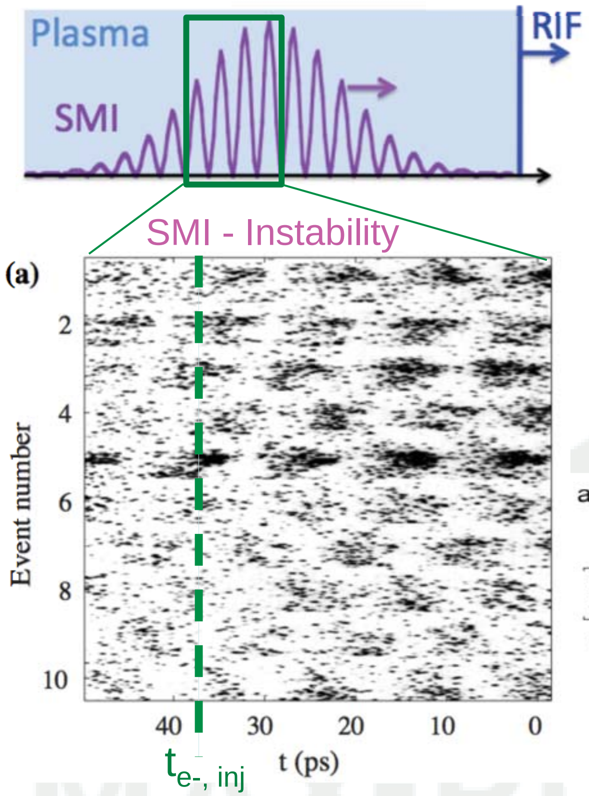


✧Summed image confirms reproducibility
✧Wakefields start at the RIF

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

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

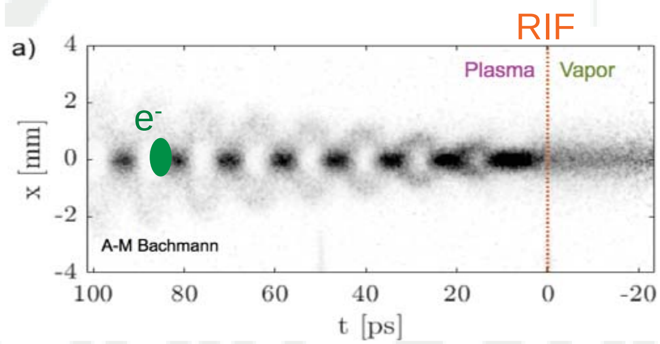
SEEDED SELF-MODULATiON (SSM)

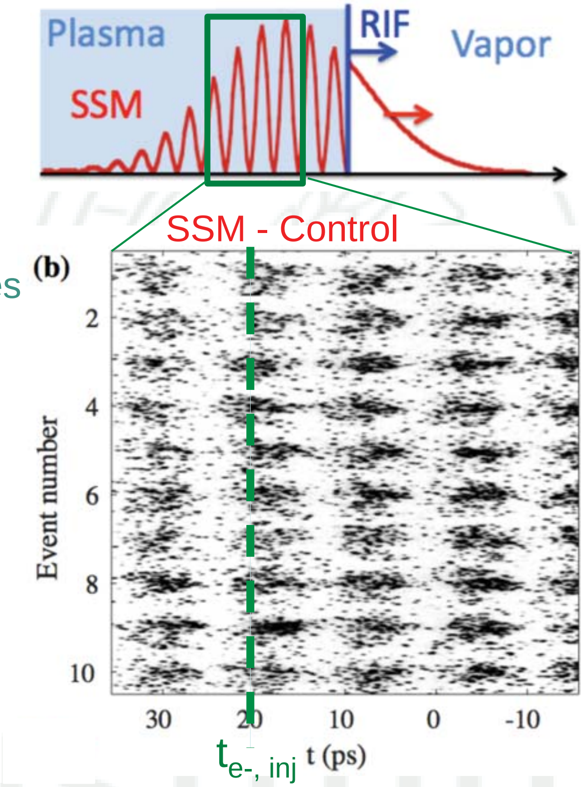


Relativistic Ionization Front (RIF) Seeding

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

REPRODUCIBLE!





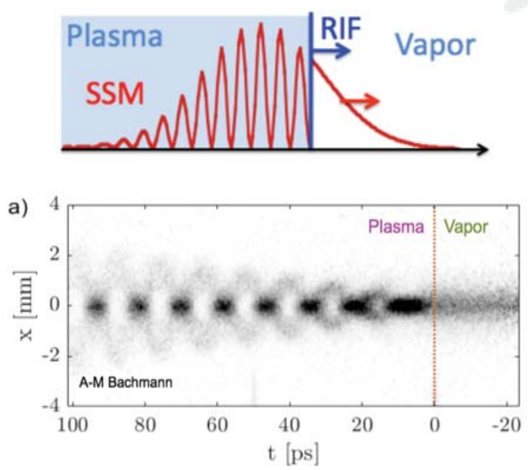
✧Summed image confirms reproducibility
✧Wakefields start at the RIF

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

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

e-BUNCH SEEDING OF SM

✧RIF seeding of SM



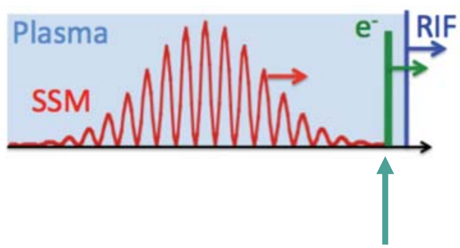
Abrupt start of the plasma (<<1/ω_{pe}) to seeds wakefields

e-BUNCH SEEDING OF SM

MAX-PLANCK-INSTITUT FÜR PHYSIK

AWAKE

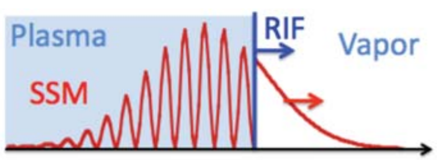
✧e-bunch seeding of SM

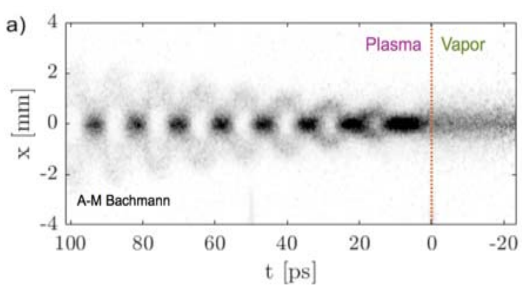


Wakefields start here!

e- bunch wakefields to seed

✧RIF seeding of SM

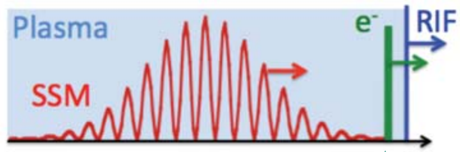




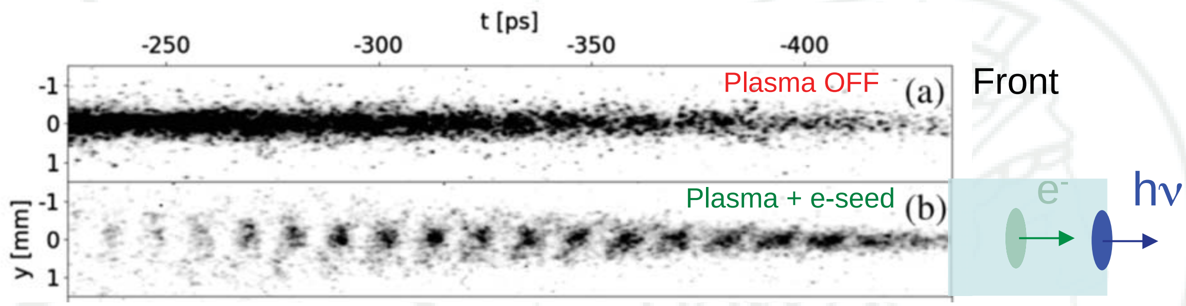
Abrupt start of the plasma ($<<1/\omega_{pe}$) to seeds wakefields

e-Bunch Seeding of SM

✧e-bunch seeding of SM

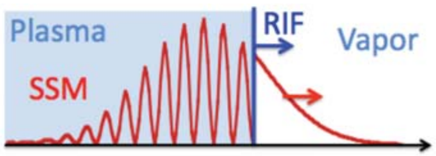


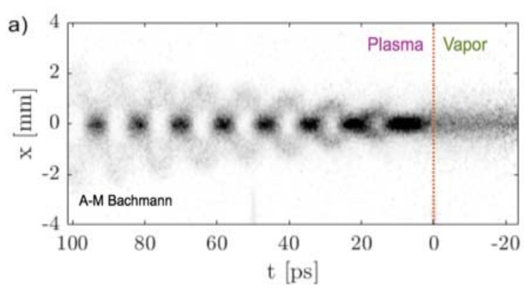
Wakefields start here!



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

✧RIF seeding of SM



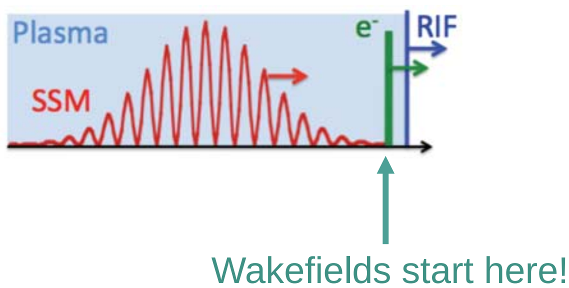


✧SM is reproducible (summed image)

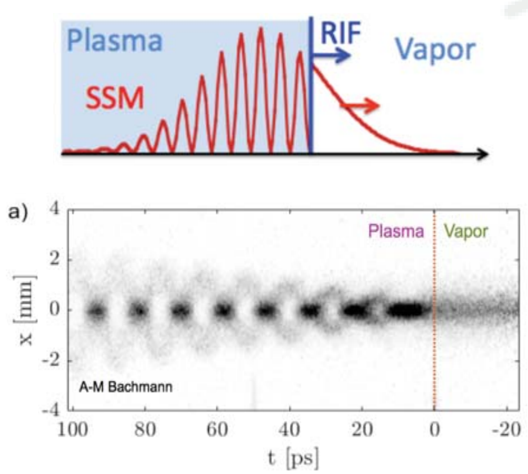
L. Verra, (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

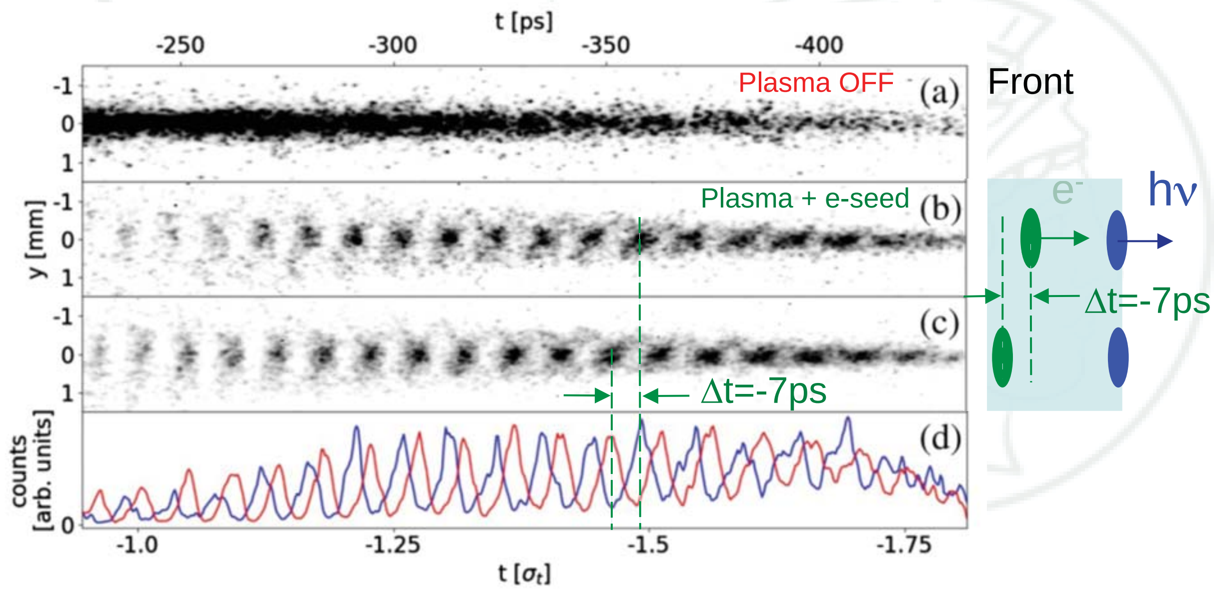
e-BUNCH SEEDING OF SM

✧e-bunch seeding of SM



✧RIF seeding of SM





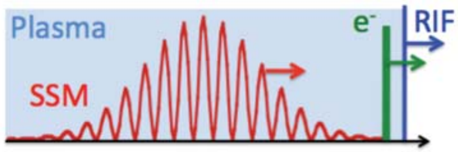
✧SM is reproducible (summed image)

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

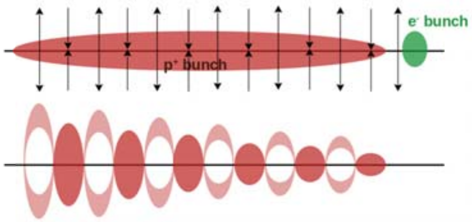
L. Verra, (AWAKE Coll.), Phys. Rev. Lett. 129, 024802 (2022)

HOSiNG

✧e-bunch seeding of SM



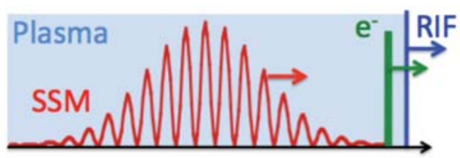
✧e^- and p^+ aligned …



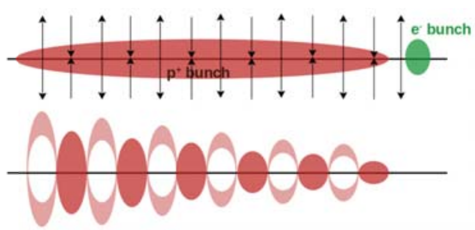
✧… axi-symmetric SM

HOSiNG

✧e-bunch seeding of SM

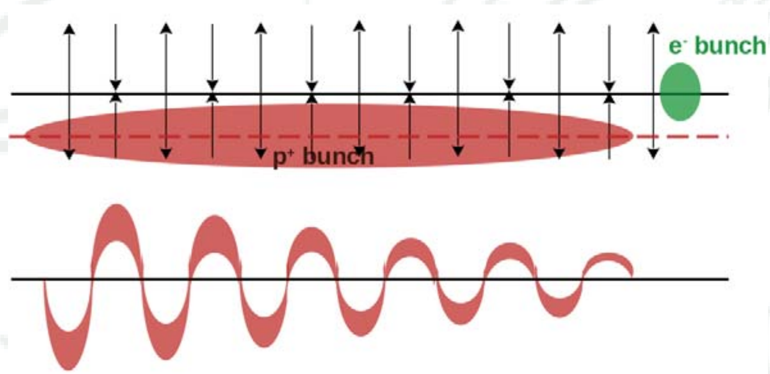


✧e- and p+ aligned …



✧… axi-symmetric SM

✧e- and p+ mis-aligned …

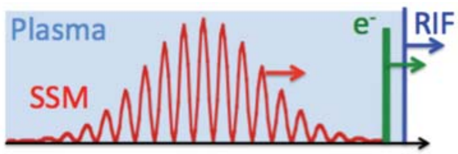


✧… non-axi-symmetric hosing (mis-alignment plane)

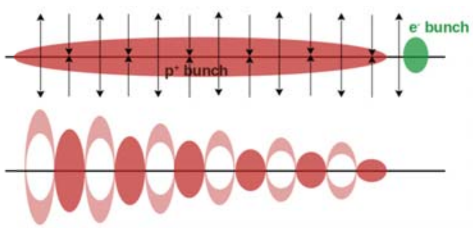
✧… and SM in the perpendicular plane ("no misalignment" plane)

HOSiNG

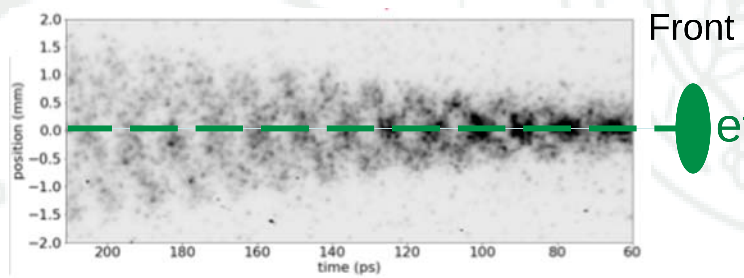
✧e-bunch seeding of SM



✧e^- and p^+ aligned …



✧… axi-symmetric SM



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

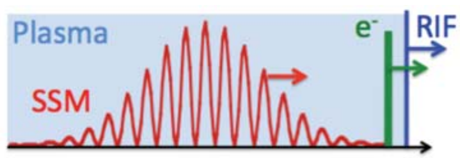
T. Nechaeva

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

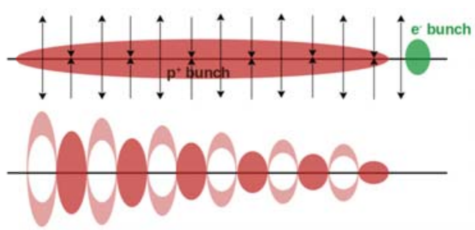
Preliminary

HOSiNG

✧e-bunch seeding of SM

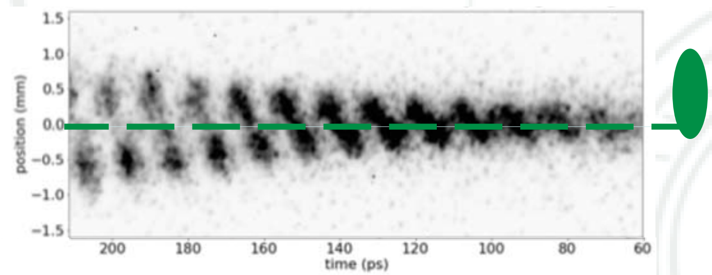


✧e- and p+ aligned …



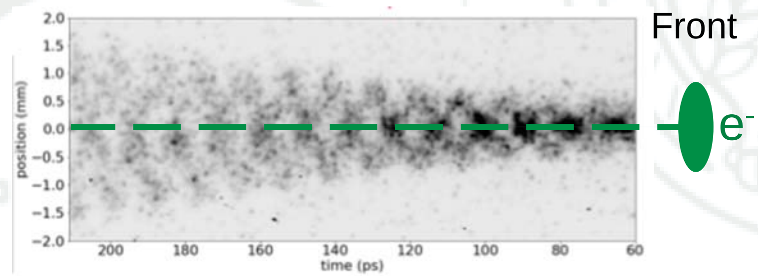
✧… axi-symmetric SM

Preliminary



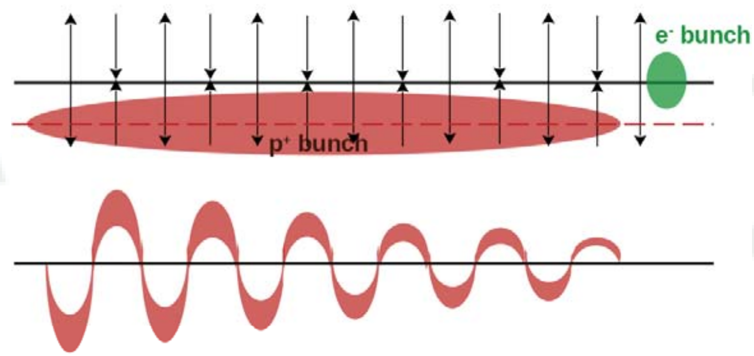
✧e-/p+ mis-aligned
✧Hosing
✧Centroid oscillation

Front



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

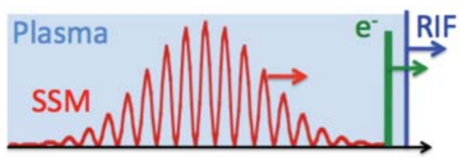
T. Nechaeva



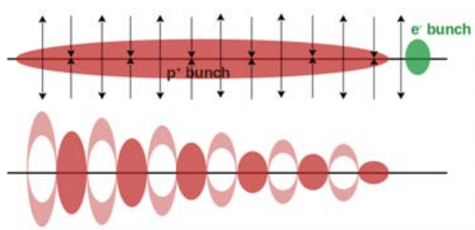
✧SM and HI together
✧$f_{HI} \sim f_{SM} \sim f_{pe}$
✧Induced by wakefields

HOSiNG

✧e-bunch seeding of SM

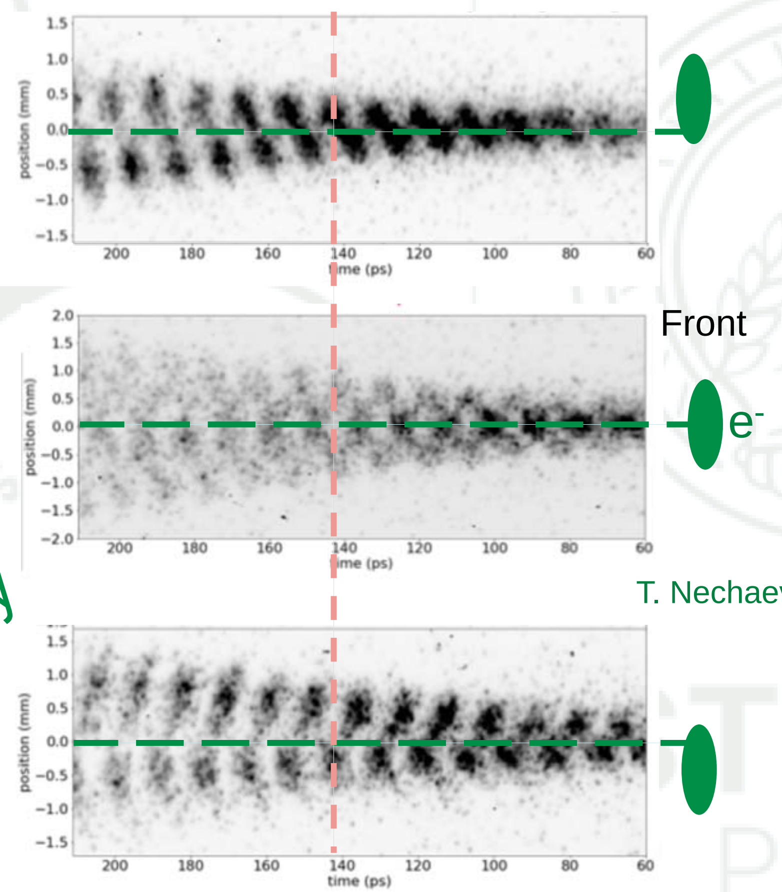


✧e- and p+ aligned …



✧… axi-symmetric SM

Preliminary



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

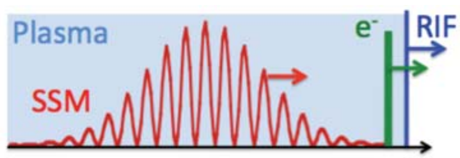
✧e^-/p^+ aligned
✧Self modulation
✧Symmetric

T. Nechaeva

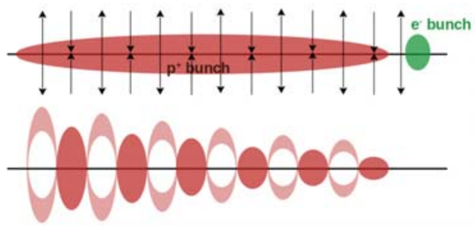
✧e^-/p^+ mis-aligned
✧Hosing
✧Reversed!

HOSiNG

✧e-bunch seeding of SM

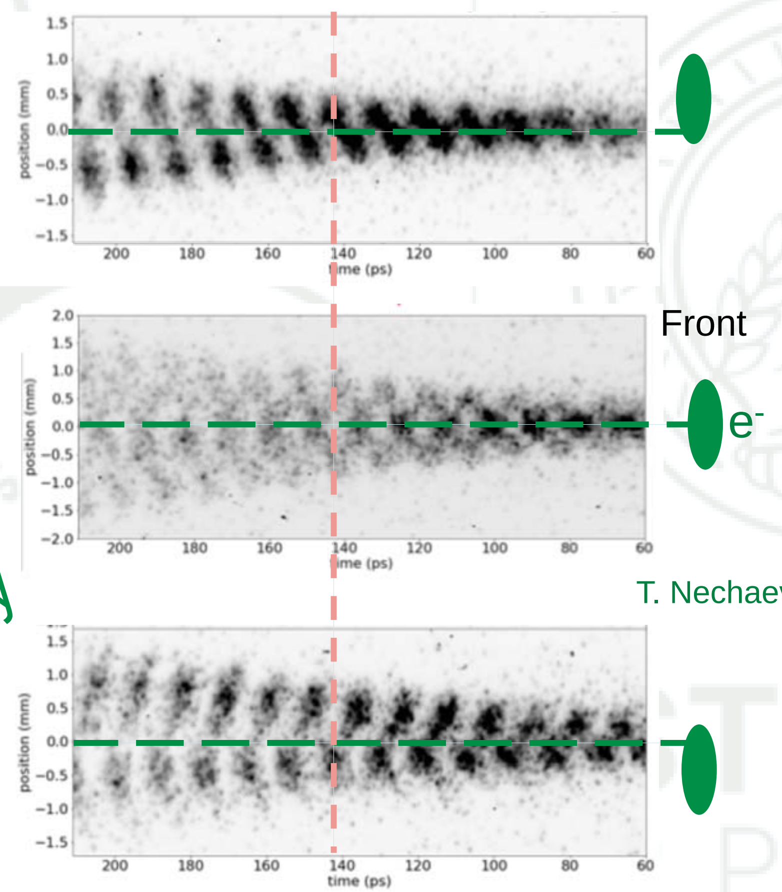


✧e^- and p^+ aligned …



✧… axi-symmetric SM

Preliminary



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

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

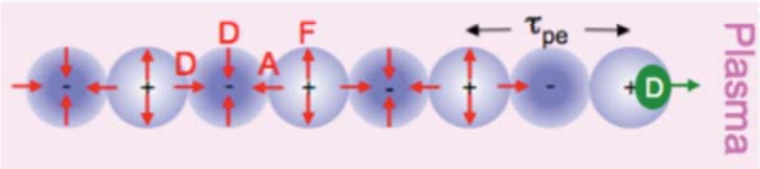
T. Nechaeva

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

✧Hosing could deteriorate, limit the acceleration process…

CURRENT FILAMENTATION INSTABILITY

✧Wakefields: $\sigma_{r0}<c/\omega_{pe}$



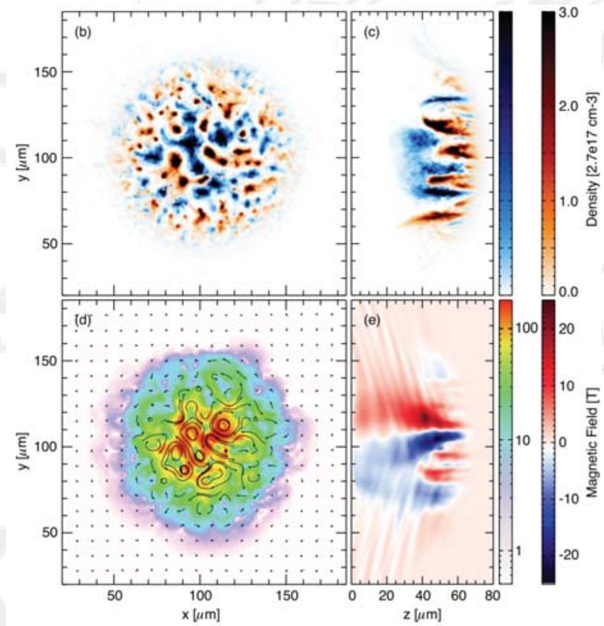
Return current flows <u>outside</u> the bunch ($k_{pe}\sigma_r<1$)

Current Filamentation Instability

- ✧Wakefields: $\sigma_{r0}<c/\omega_{pe}$
- ✧Beam Transverse Current Filamentation Instability (CFI): $\sigma_{r0}>>c/\omega_{pe}$
  - ✧Return current inside the bunch

    - ✧Non-uniformities in return currents
    - ✧Opposite currents repel each other
    - ✧Beam filamentation at the c/ω_{pe} scale
    - ✧Growth rate:

$$\Gamma = \sqrt{\frac{n_{b0}/n_{e0}}{\gamma}}\omega_{pe}$$



P. Muggli et al. arXiv:1306.4380 [physics.plasm-ph]

Current Filamentation Instability

- Wakefields: $\sigma_{r0} < c/\omega_{pe}$
- Beam Transverse Current Filamentation Instability (CFI): $\sigma_{r0} >> c/\omega_{pe}$
  - Return current inside the bunch
    - Non-uniformities in return currents
    - Opposite currents repel each other
    - Beam filamentation at the c/ω_{pe} scale
    - Growth rate:

$$\Gamma = \sqrt{\frac{n_{b0}/n_{e0}}{\gamma}}\omega_{pe}$$

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

- 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

CURRENT FILAMENTATION INSTABILITY

✧Wakefields: $\sigma_{r0}<c/\omega_{pe}$

✧Beam Transverse Current Filamentation Instability (CFI): $\sigma_{r0}>>c/\omega_{pe}$

- ✧Return current inside the bunch
  - ✧Non-uniformities in return currents
  - ✧Opposite currents repel each other
  - ✧Beam filamentation at the c/ω_{pe} scale
  - ✧Growth rate:

$$\Gamma = \sqrt{\frac{n_{b0}/n_{e0}}{\gamma}}\omega_{pe}$$

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

✧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 CFI with relativistic particle bunch (p^+)

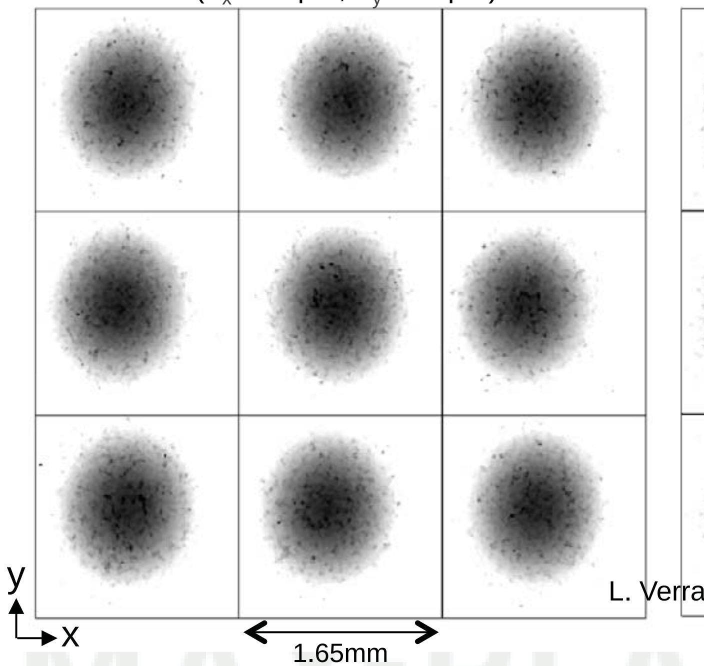
✧"Astrophysics in the lab"

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

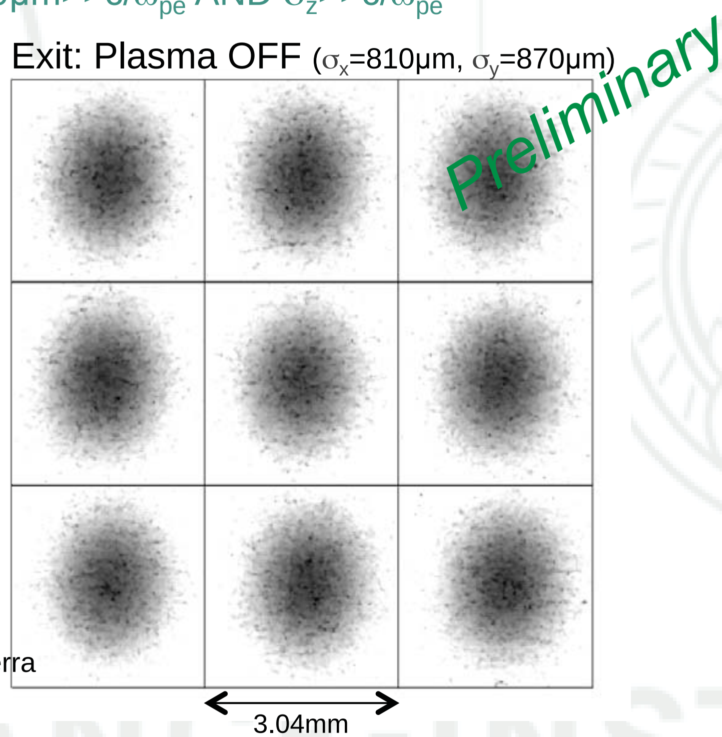
CURRENT FILAMENTATION INSTABILITY

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

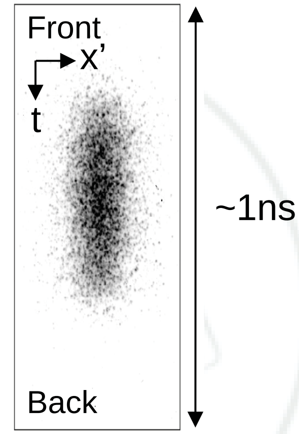
Entrance (σ_x=480µm, σ_y=520µm)



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



Plasma OFF



σ_{slit}=1.0mm
σ_t=170ps

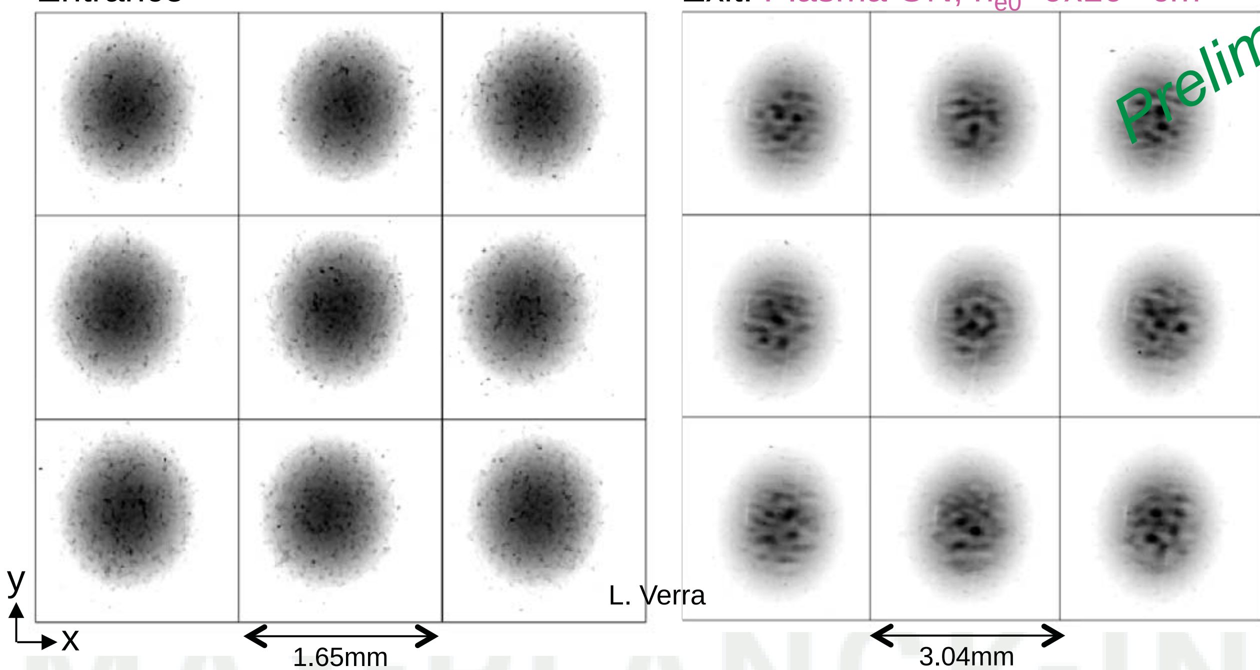
✧Incoming bunch without transverse features (Gaussian)

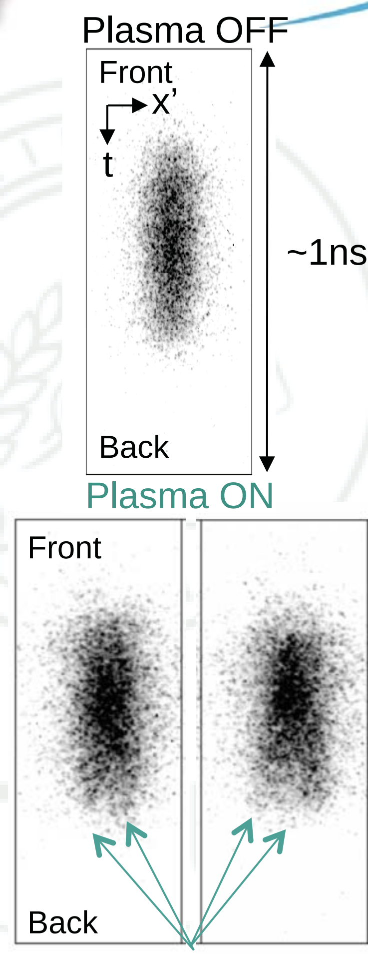
Current Filamentation Instability

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

Entrance

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





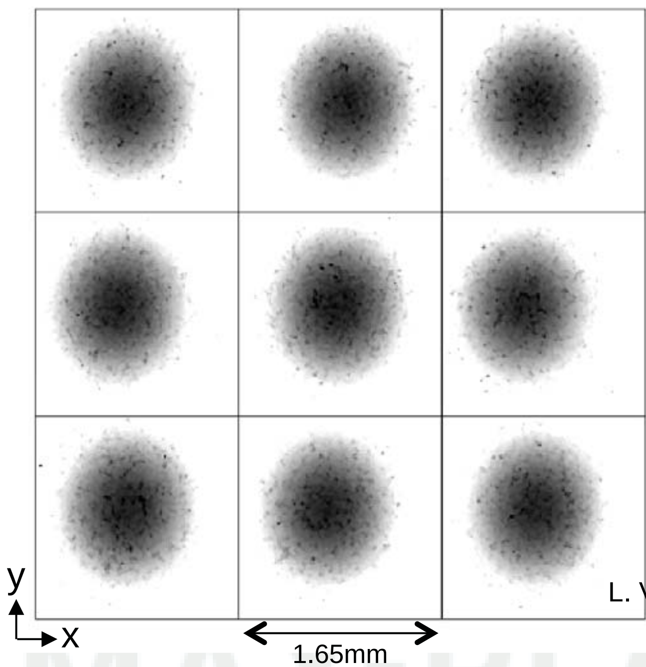
✧Incoming bunch without transverse features

✧Bunch after the plasma shows filaments

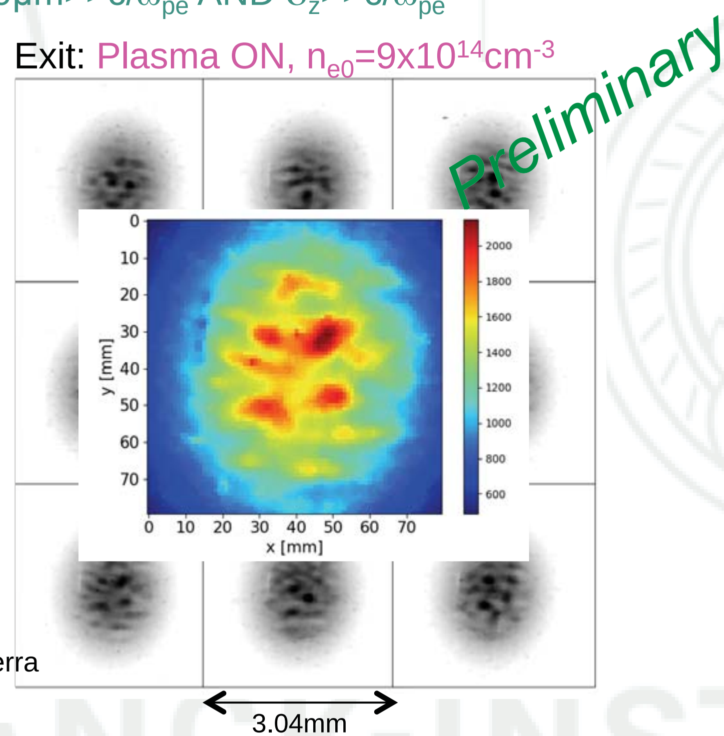
Current Filamentation Instability

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

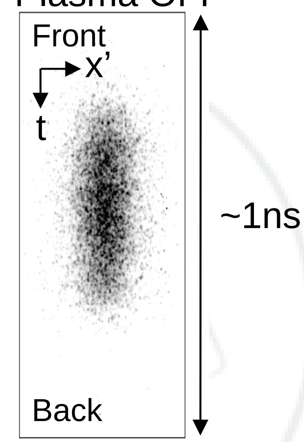
Entrance



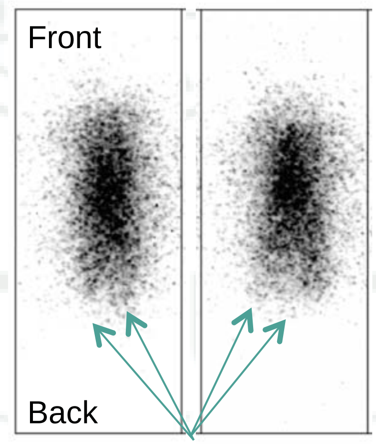
Exit: Plasma ON, $n_{e0}=9\times10^{14}cm^{-3}$



Plasma OFF



Plasma ON

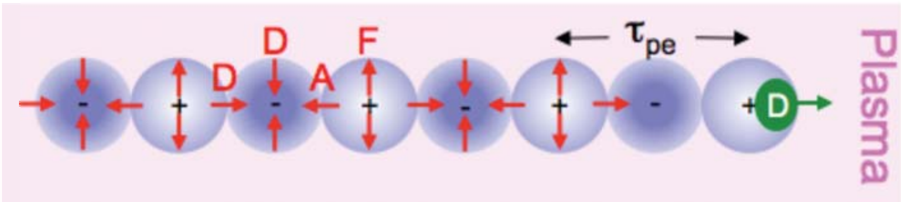


✧Incoming bunch without transverse features

✧Bunch after the plasma shows filaments

Relativistic Particle Bunch Meets Plasma

MAX-PLANCK-INSTITUT FÜR PHYSIK



D=driver

✧Relativistic Bunch ⬄ Radial Space Charge Field ⬄ Plasma Screening

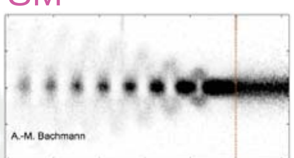
⬄ Azimuthal Magnetic Field ⬄ Plasma Return Current

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

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

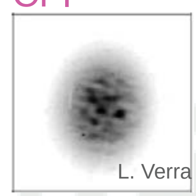
✧Return Current ⬄ Current Filamentation Instability (~Weibel Instability), Generation of Magnetic Fields ⬄ Astrophysics

SM



H

CFI



Main motivation:

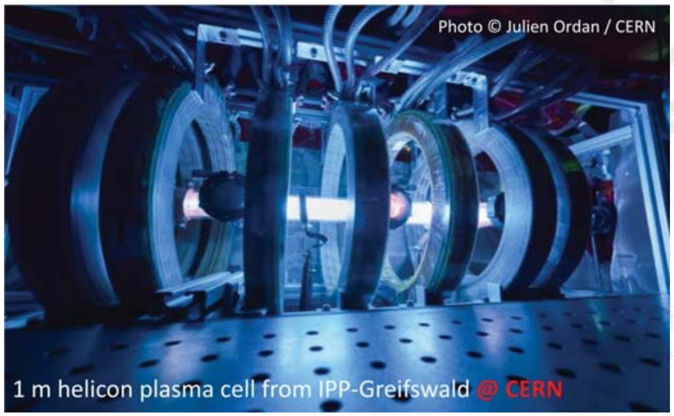
✧Produce high-energy e^- bunches (200GeV, 5TeV), in a high-gradient (1GeV/m) plasma-based accelerator (PWFA) driven by a p^+ bunch, for particle physics applications (dark photon searches, very-high-energy ep collider)

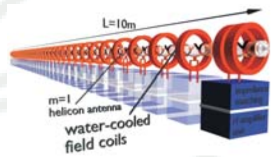
Scalable Plasma Source

✧Laser ionization does not scale to long plasma lengths (100m-1km): laser pulse energy depletion!

✧Plasma source development laboratory at CERN

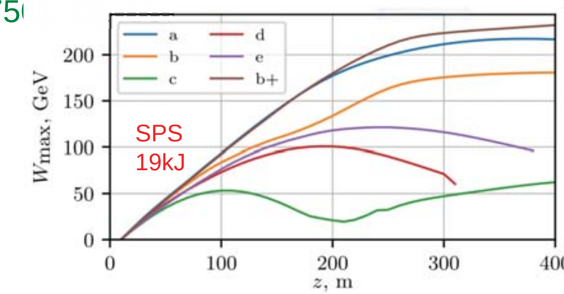
✧Helicon source: magnetized RF discharge Buttenschön, PPFC 60(7), 075





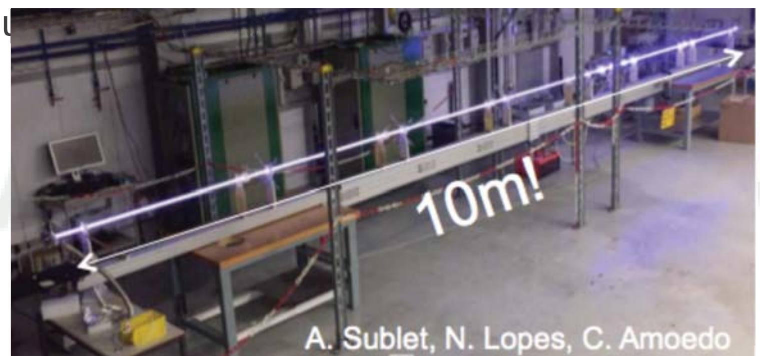
IPP Max-Planck-Institut für Plasmaphysik

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



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

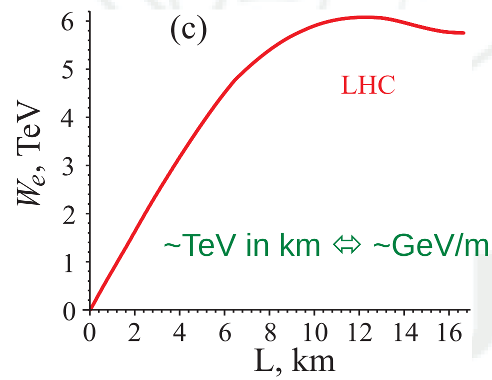
✧Pu



TÉCNICO LISBOA

Imperial College London

CERN



~TeV in km ⇔ ~GeV/m

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

✧Challenge: plasma density uniformity!

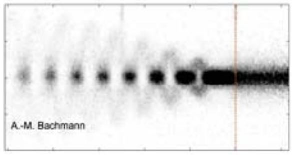
$\Delta n_e/n_{e0} << 1/N_{\mu b}$, $N_{\mu b \neq} \sim 100 \Rightarrow \Delta n_e/n_{e0} < 0.2\%$

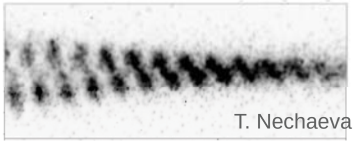
Summary

✧Beam-plasma interaction

✧AWAKE:

- ✧Plasma wakefield acceleration of e^- bunch for application to particle physics (200GeV, 5TeV)
- ✧Requires self-modulation (SM) of the p^+ bunch to reach high gradient, ~1GeV/m
- ✧Requires seeding/control of SM process: RIF, e^- bunch
- ✧Avoid hosing instability (HI), study HI
- ✧Avoid current filamentation instability (CFI): $\sigma_r < c/\omega_{pe}$

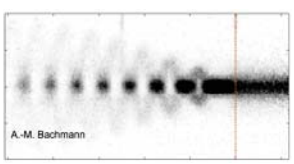


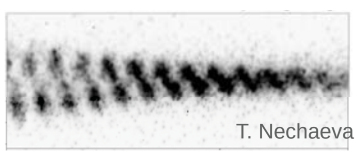


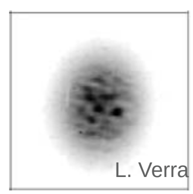
SUMMARY

- ✧Beam-plasma interaction
- ✧AWAKE:
  - ✧Plasma wakefield acceleration of e^- bunch for application to particle physics (200GeV, 5TeV)
  - ✧Requires self-modulation (SM) of the p^+ bunch to reach high gradient, ~1GeV/m
  - ✧Requires seeding/control of SM process: RIF, e^- bunch
  - ✧Avoid hosing instability (HI), study HI
  - ✧Avoid current filamentation instability (CFI): $\sigma_r<c/\omega_{pe}$

- ✧Study astrophysics in the laboratory, generation of magnetic fields
  - ✧Study CFI: $\sigma_r>c/\omega_{pe}$
  - ✧Alternate SM/CFI with $\sigma_{r=}$~$1.6c/\omega_{pe}$



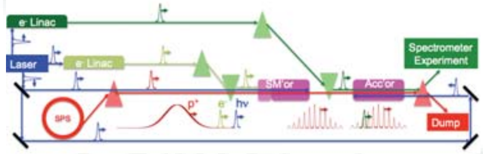




SUMMARY

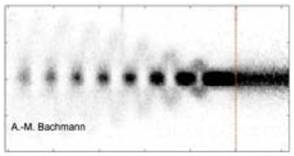
- ✧Beam-plasma interaction
- ✧AWAKE:
  - ✧Plasma wakefield acceleration of e^- bunch for application to particle physics (200GeV, 5TeV)
  - ✧Requires self-modulation (SM) of the p^+ bunch to reach high gradient, ~1GeV/m
  - ✧Requires seeding/control of SM process: RIF, e^- bunch
  - ✧Avoid hosing instability (HI), study HI
  - ✧Avoid current filamentation instability (CFI): $\sigma_r<c/\omega_{pe}$

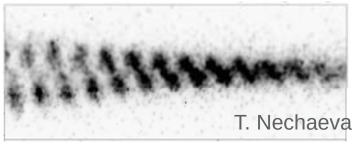
Muggli (AWAKE Coll.), J. of Phys.: Conf. Series1596, 012008 (2020).

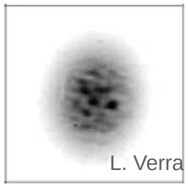


- ✧Study astrophysics in the laboratory, generation of magnetic fields
  - ✧Study CFI: $\sigma_r>c/\omega_{pe}$
  - ✧Alternate SM/CFI with $\sigma_{r=}$~$1.6c/\omega_{pe}$

- ✧Clear plan towards reaching high-energy gain
  - ✧Possible particle physics experiments in early 2030's



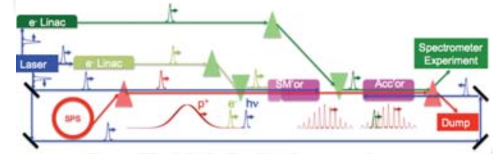




SUMMARY

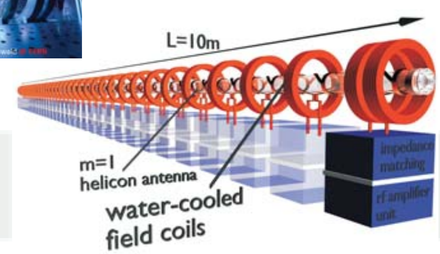
- Beam-plasma interaction
- AWAKE:
  - Plasma wakefield acceleration of e^- bunch for application to particle physics (200GeV, 5TeV)
  - Requires self-modulation (SM) of the p^+ bunch to reach high gradient, ~1GeV/m
  - Requires seeding/control of SM process: RIF, e^- bunch
  - Avoid hosing instability (HI), study HI
  - Avoid current filamentation instability (CFI): $\sigma_r < c/\omega_{pe}$

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

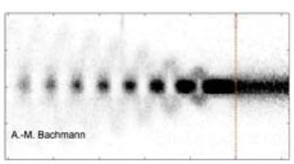


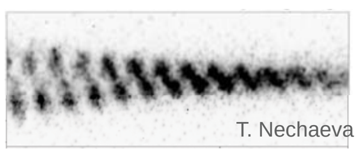
- Study astrophysics in the laboratory, generation of magnetic fields
  - Study CFI: $\sigma_r > c/\omega_{pe}$
  - Alternate SM/CFI with $\sigma_{r=} \sim 1.6c/\omega_{pe}$

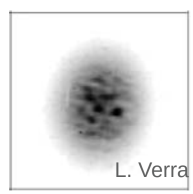
- Clear plan towards reaching high-energy gain
  - Possible particle physics experiments in early 2030's



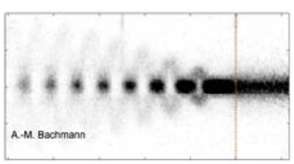
- Develop long plasma sources: L>100m, $n_{e0}=10^{14}$-10^{15}cm^{-3}
  - Discharge, helicon plasma source

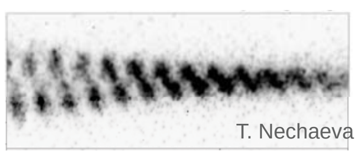


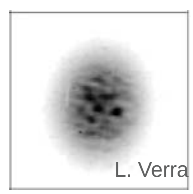




SUMMARY







“Three pictures are worth …”

Thank you to my collaborators

Thank you!

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