Proton Bunch Self-Modulation and Electron Acceleration in

AWAKE

Patric Muggli *for the AWAKE Collaboration*

Max Planck Institute for Physics

Munich

muggli@mpp.mpg.de

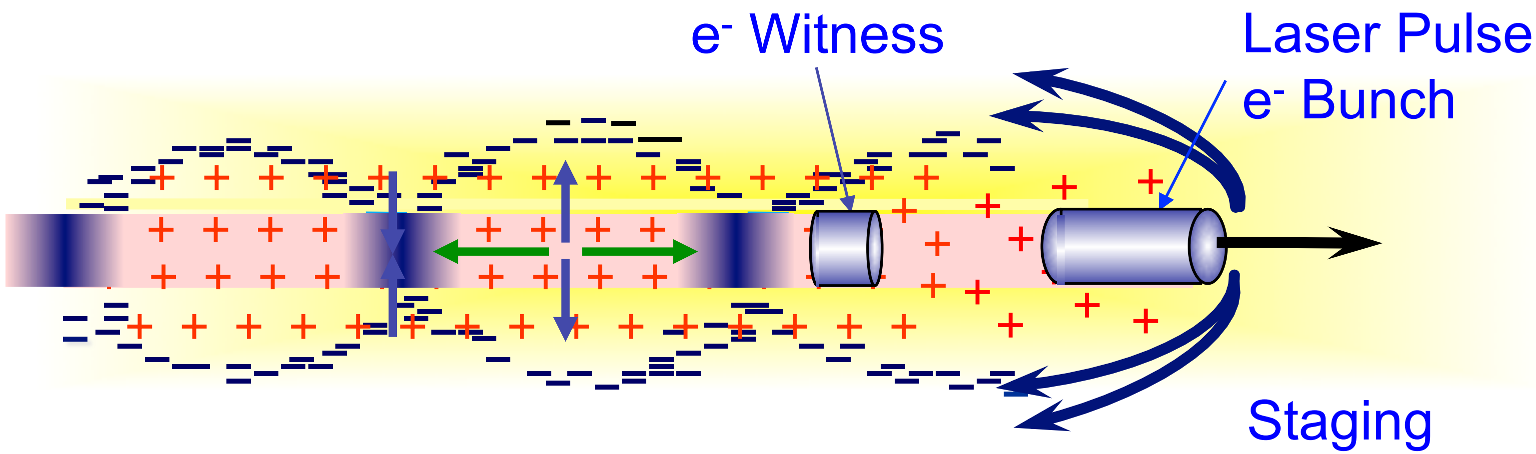
https://www.mpp.mpg.de/~muggli

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

MAX-PLANCK-GESELLSCHAFT

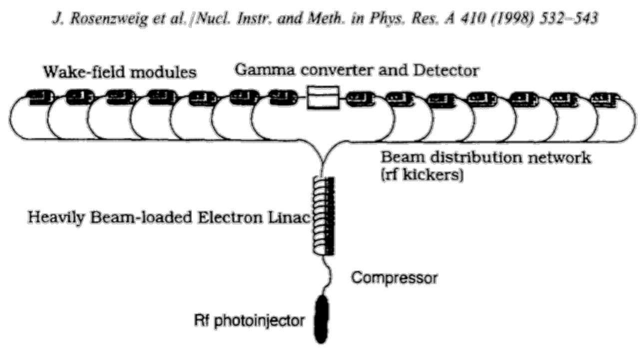
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

REACHING HIGH ENERGY



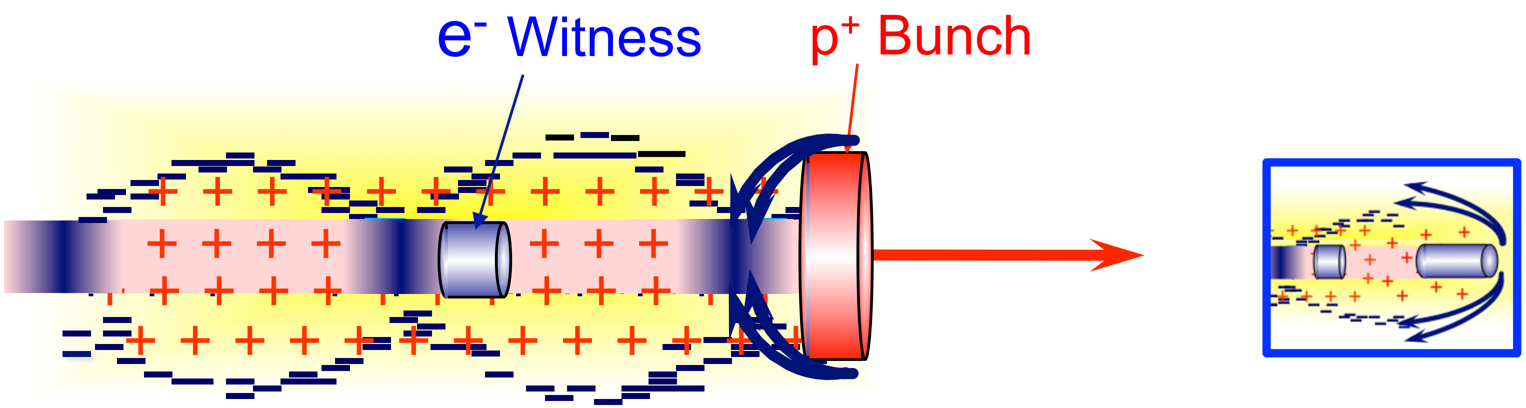
- High-energy bunch 1TeV, $1\times10^{10}e^-$ or e^+ 1.6 kJ
- Typical drivers:
  - PW laser pulse <100 J
  - e^- bunch ($2\times10^{10}e^-$, 10GeV/e^-) 32 J

Staging

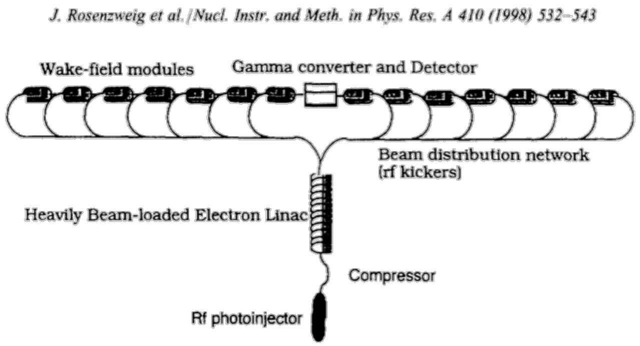


Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

REACHiNG HiGH ENERGY



Staging

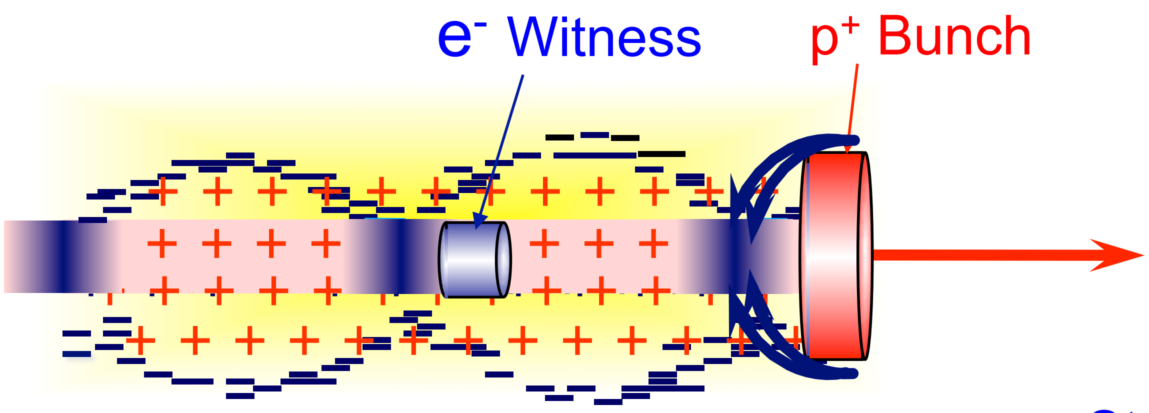


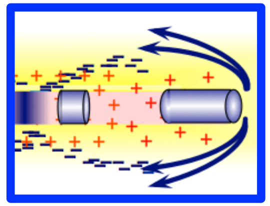
- ✧High-energy bunch 1TeV, $1\times10^{10}e^-$ or e^+ — 1.6 kJ
- ✧Typical drivers:
  - ✧PW laser pulse — <100 J
  - ✧e^- bunch ($2\times10^{10}e^-$, 10GeV/e^-) — 32 J
- ✧Proton bunch driver:
  - ✧SPS, 400GeV bunch with $10^{11}p^+$ — 6.4 kJ
  - ✧LHC, 7TeV bunch with $10^{11}p^+$ — 112 kJ

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

AWAKE

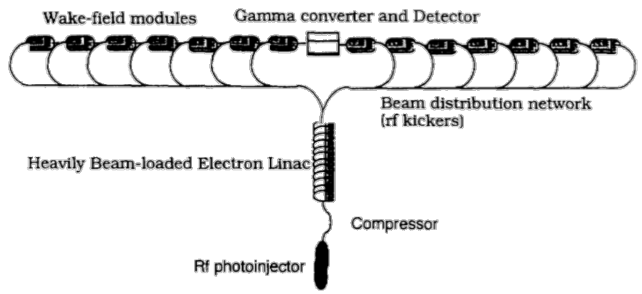
REACHiNG HiGH ENERGY



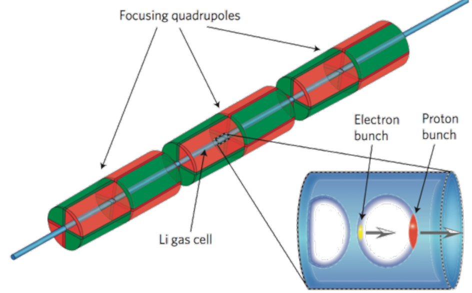


Staging

J. Rosenzweig et al. / Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543



Caldwell, Nat. Phys. 5, 363, (2009)



✧High-energy bunch 1TeV, $1\times10^{10}e^-$ or e^+ 1.6 kJ

✧Typical drivers:
- ✧PW laser pulse <100 J
- ✧e^- bunch ($2\times10^{10}e^-$, 10GeV/e^-) 32 J

✧Proton bunch driver:
- ✧SPS, 400GeV bunch with $10^{11}p^+$ 6.4 kJ
- ✧LHC, 7TeV bunch with $10^{11}p^+$ 112 kJ

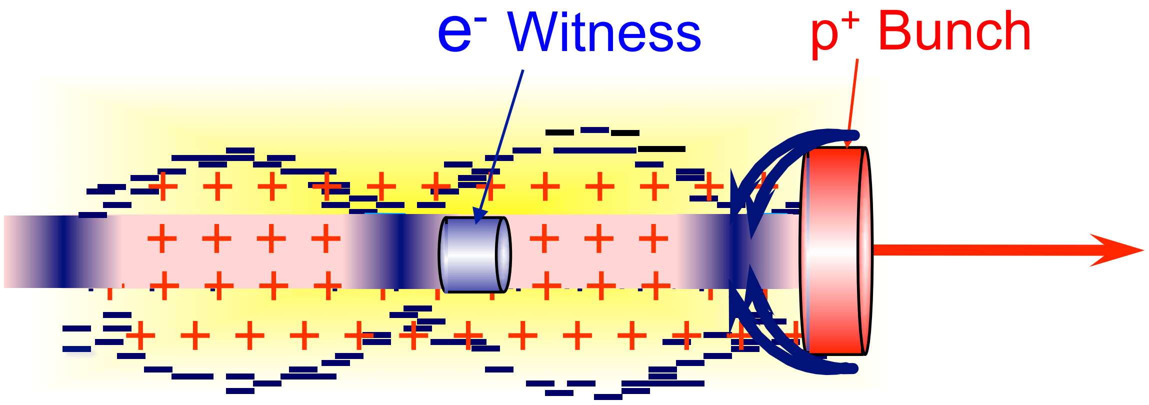
✧A single SPS or LHC bunch to produce a TEV e^-/e^+ bunch in a single PWFA stage!

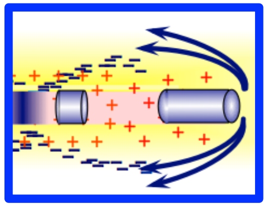
✧Large average gradient! (≥1GeV/m, 100's m)

✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)

MAX-PLANCK-GESELLSCHAFT

PWFA SCALiNGS - AWAKE





$$\sigma_z \cong \sqrt{2}\left(c/\omega_{pe}\right)$$

$$\sigma_r \leq c/\omega_{pe}$$

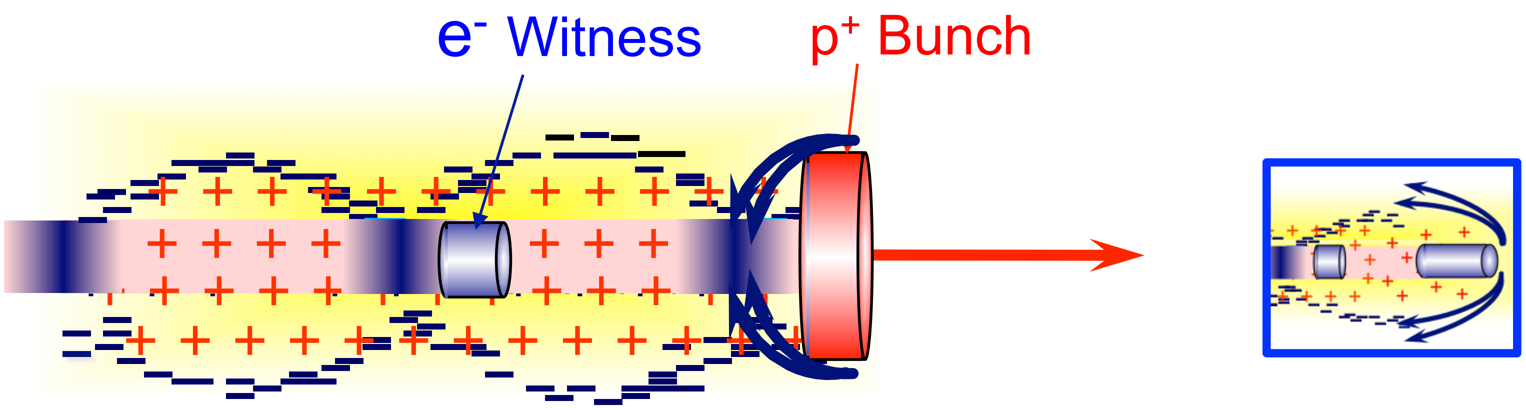
} To effectively drive wakefields …

$$E_{z,\max} \propto E_{WB} = \frac{m_e c \omega_{pe}}{e}$$

… and reach a significant fraction of the cold plasma wave breaking field amplitude

AWAKE: CERN SPS p^+ bunch, σ_z=6-12cm, σ_r=200μm (N=3x10^{11}p^+, 400GeV)

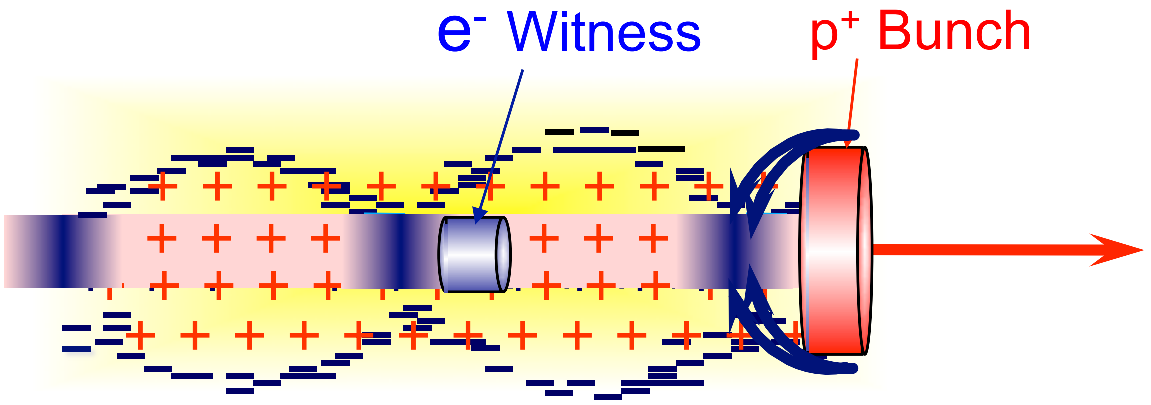
PWFA SCALiNGS - AWAKE

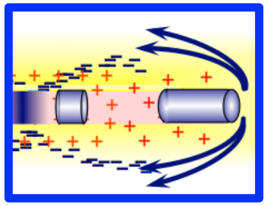


AWAKE:
CERN SPS bunch

	$\sigma_z = 6\,cm$	$\sigma_r = 200\ \mu m$
$\sigma_z \cong \sqrt{2}\left(c/\omega_{pe}\right)$		
$\sigma_r \leq c/\omega_{pe}$		
$E_{z,\max} \propto E_{WB} = \dfrac{m_e c \omega_{pe}}{e}$		

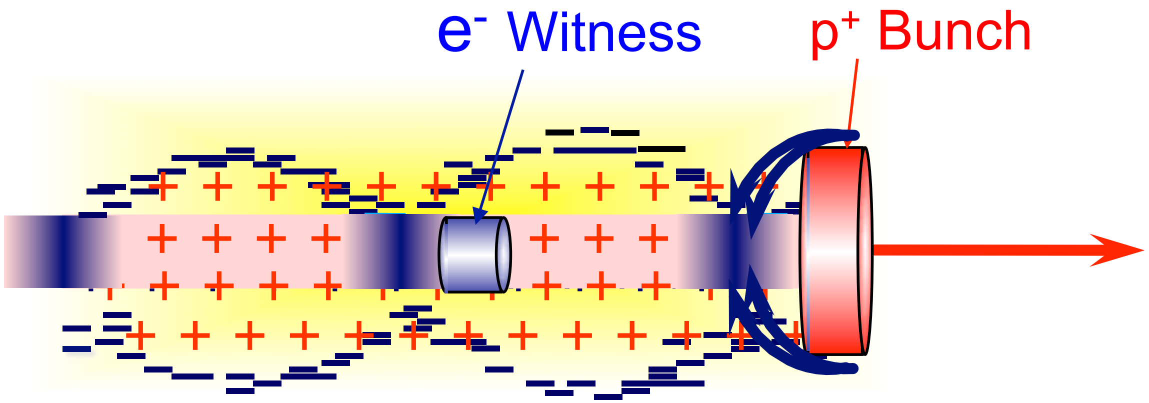
PWFA SCALINGS - AWAKE

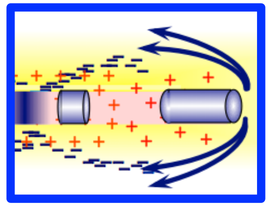




AWAKE: CERN SPS bunch	$\sigma_z = 6\ cm$	$\sigma_r = 200\ \mu m$
$\sigma_z \cong \sqrt{2}\left(c/\omega_{pe}\right)$	$n_{e0} \cong \frac{2\varepsilon_0 m_e c^2}{e^2}\frac{1}{\sigma_z^2} = 1.6\times 10^{10}\ cm^{-3}$	
$\sigma_r \leq c/\omega_{pe}$	$\sigma_r << c/\omega_{pe}$	
$E_{z,\max} \propto E_{WB} = \frac{m_e c\omega_{pe}}{e}$	$E_{z,\max} \cong \frac{m_e c^2}{e}\frac{\sqrt{2}}{\sigma_z} = 12\ MV/m$	

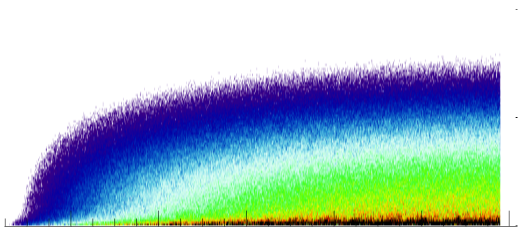
PWFA SCALINGS - AWAKE



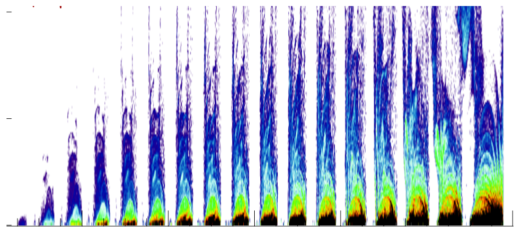


AWAKE: CERN SPS bunch	$\sigma_z = 6\ cm$	$\sigma_r = 200\ \mu m$
$\sigma_z \cong \sqrt{2}\left(c/\omega_{pe}\right)$	$n_{e0} \cong \frac{2\varepsilon_0 m_e c^2}{e^2}\frac{1}{\sigma_z^2} = 1.6\times10^{10}\ cm^{-3}$	$\sigma_z >> c/\omega_{pe}$
$\sigma_r \leq c/\omega_{pe}$	$\sigma_r << c/\omega_{pe}$	$n_{e0} \geq \frac{\varepsilon_0 m_e c^2}{e^2}\frac{1}{\sigma_r^2} = 7.1\times10^{14}\ cm^{-3}$
$E_{z,\max} \propto E_{WB} = \frac{m_e c\omega_{pe}}{e}$	$E_{z,\max} \cong \frac{m_e c^2}{e}\frac{\sqrt{2}}{\sigma_z} = 12\ MV/m$	$E_{z,\max} \geq \frac{m_e c^2}{e}\frac{1}{\sigma_r} = 2.5\ GV/m$

PWFA SCALiNGS - AWAKE



Self-Modulation →



AWAKE: CERN SPS bunch	$\sigma_z = 6\ cm$	$\sigma_r = 200\ \mu m$
$\sigma_z \cong \sqrt{2}\left(c/\omega_{pe}\right)$	$n_{e0} \cong \frac{2\varepsilon_0 m_e c^2}{e^2}\frac{1}{\sigma_z^2} = 1.6\times 10^{10}\ cm^{-3}$	$\sigma_z >> c/\omega_{pe}$
$\sigma_r \leq c/\omega_{pe}$	$\sigma_r << c/\omega_{pe}$	$n_{e0} \geq \frac{\varepsilon_0 m_e c^2}{e^2}\frac{1}{\sigma_r^2} = 7.1\times 10^{14}\ cm^{-3}$
$E_{z,\max} \propto E_{WB} = \frac{m_e c\omega_{pe}}{e}$	$E_{z,\max} \cong \frac{m_e c^2}{e}\frac{\sqrt{2}}{\sigma_z} = 12\ MV/m$	$E_{z,\max} \geq \frac{m_e c^2}{e}\frac{1}{\sigma_r} = 2.5\ GV/m$

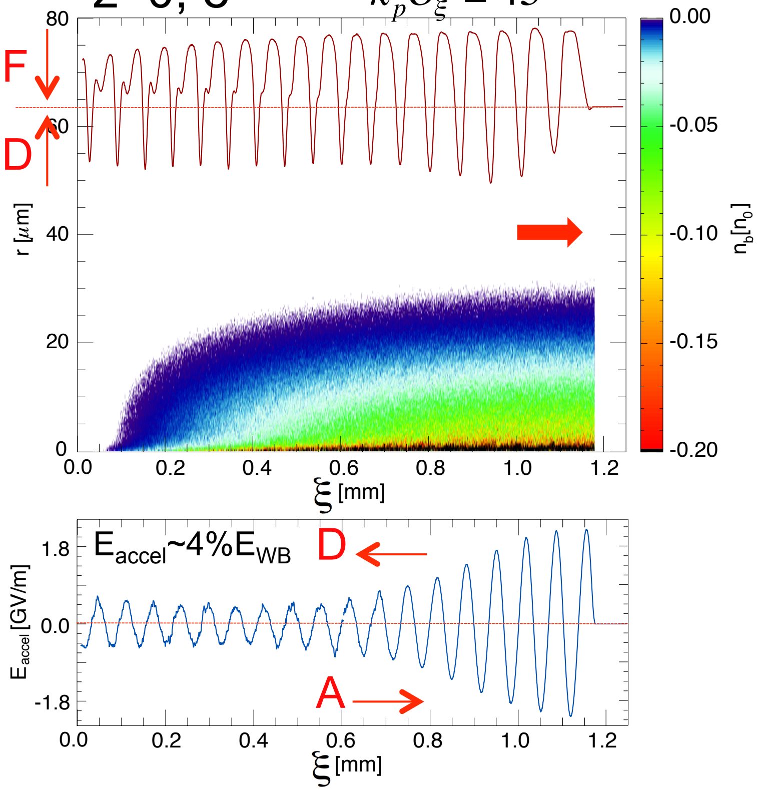
✧Scaling with σ_r => $\sigma_z >> c/\omega_{pe}$ => self-modulation process

✧GV/m accelerating fields with bunch train

SEEDED SELF-MODULATiON (SSM)

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

J. Vieira, IST



- ✧Long, thin bunch in a dense plasma: $\sigma_z >> c/\omega_{pe}$, $\sigma_r \sim c/\omega_{pe}$, $c/\omega_{pe} \sim n_e^{-1/2}$

$$W_\perp(\xi, r) = \frac{e n_{b0}}{\epsilon_0 k_{pe}} \int_{-\infty}^{\xi} n_{b_\parallel}(\xi') sin[k_{pe}(\xi - \xi')] d\xi' \cdot \frac{dR(r)}{dr},$$

$$R(r) = k_{pe}{}^2 K_0(k_{pe} r) \int_0^r r' dr' n_{b\perp}(r') I_0(k_{pe} r') + k_{pe}{}^2 I_0(k_{pe} r) \int_r^\infty r' dr' n_{b\perp}(r') K_0(k_{pe} r'),$$

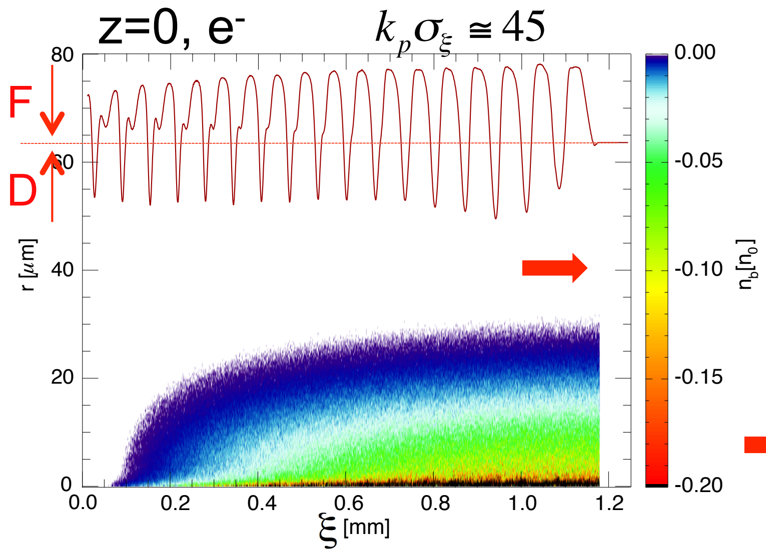
Focusing $W_\perp \rightarrow \sigma_r \downarrow \rightarrow n_b(\propto \sigma_r^{-2}) \uparrow \rightarrow W_\perp(n_b) \uparrow$

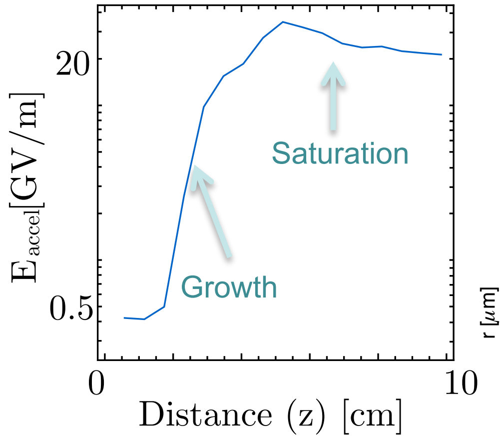
Feedback

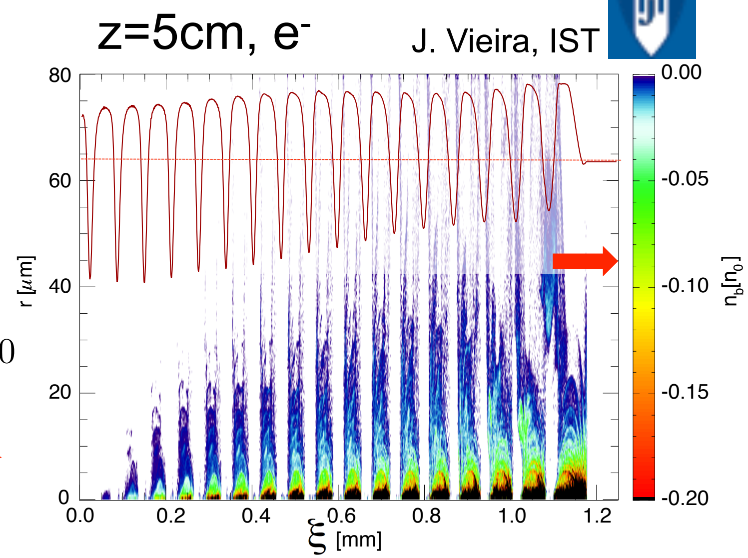
- ✧Seeding = Control
- ✧$W_z \sim W_{perp}$

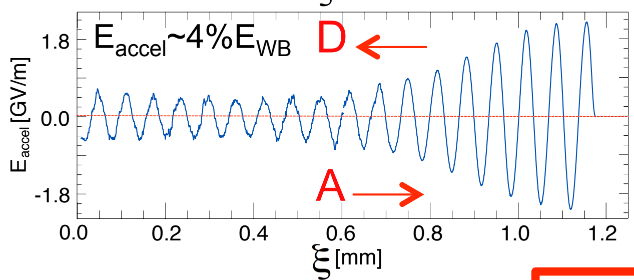
J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

SEEDED SELF-MODULATiON (SSM)

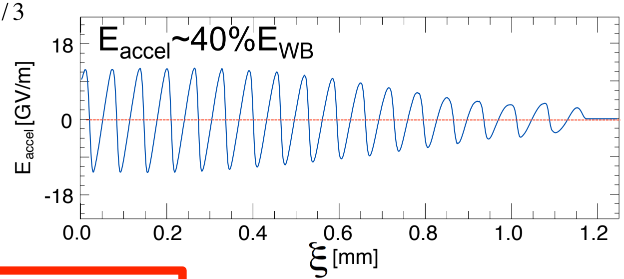








$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



Grows along the bunch & along the plasma

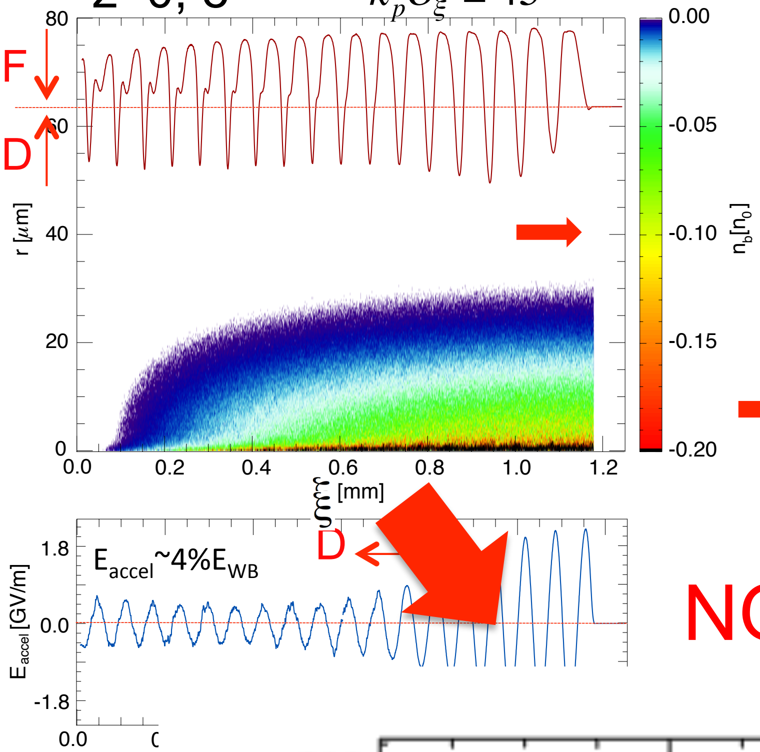
Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

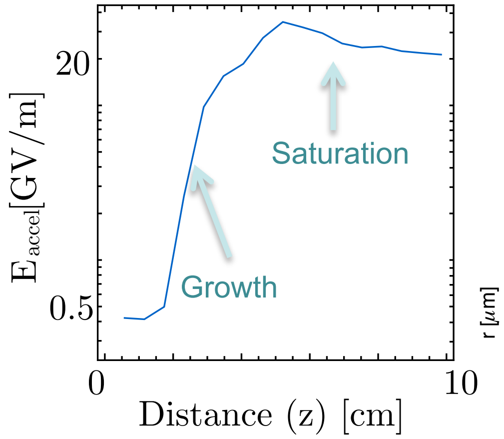
✧Initial small transverse wakefields modulate the bunch density with period $\sim\lambda_{pe} << \sigma_{z,\xi}$

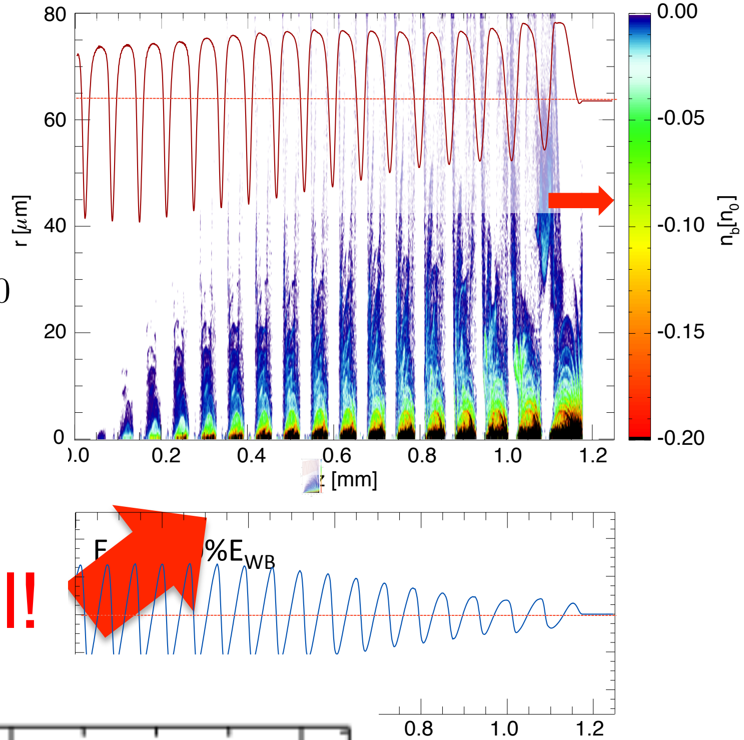
✧Associated longitudinal wakefields reach large amplitude through resonant excitation

J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

SEEDED SELF-MODULATION (SSM)

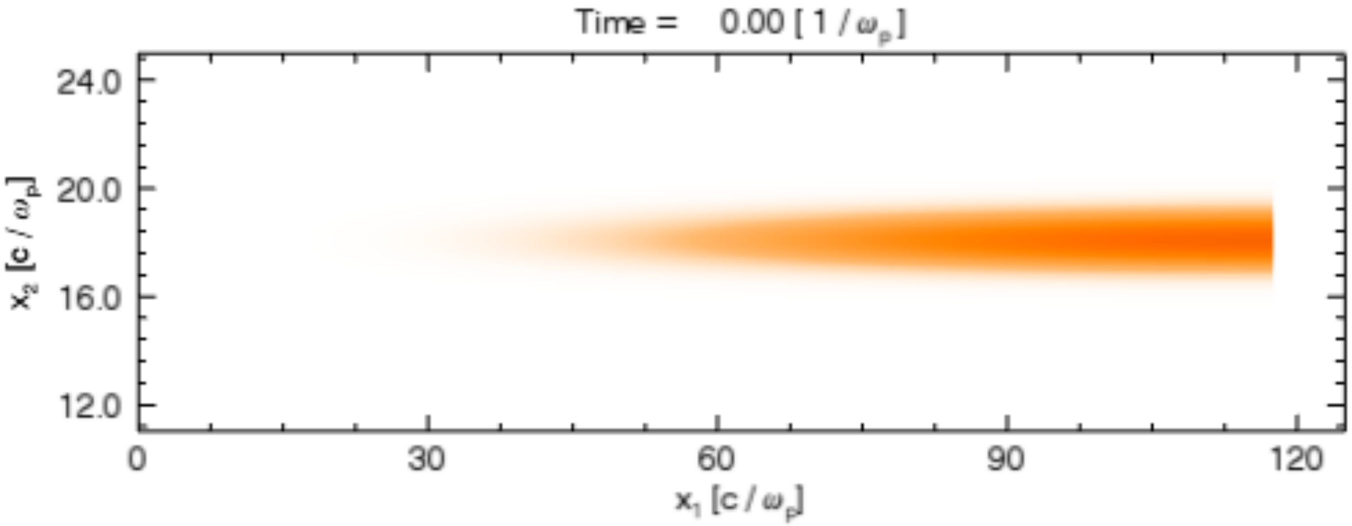




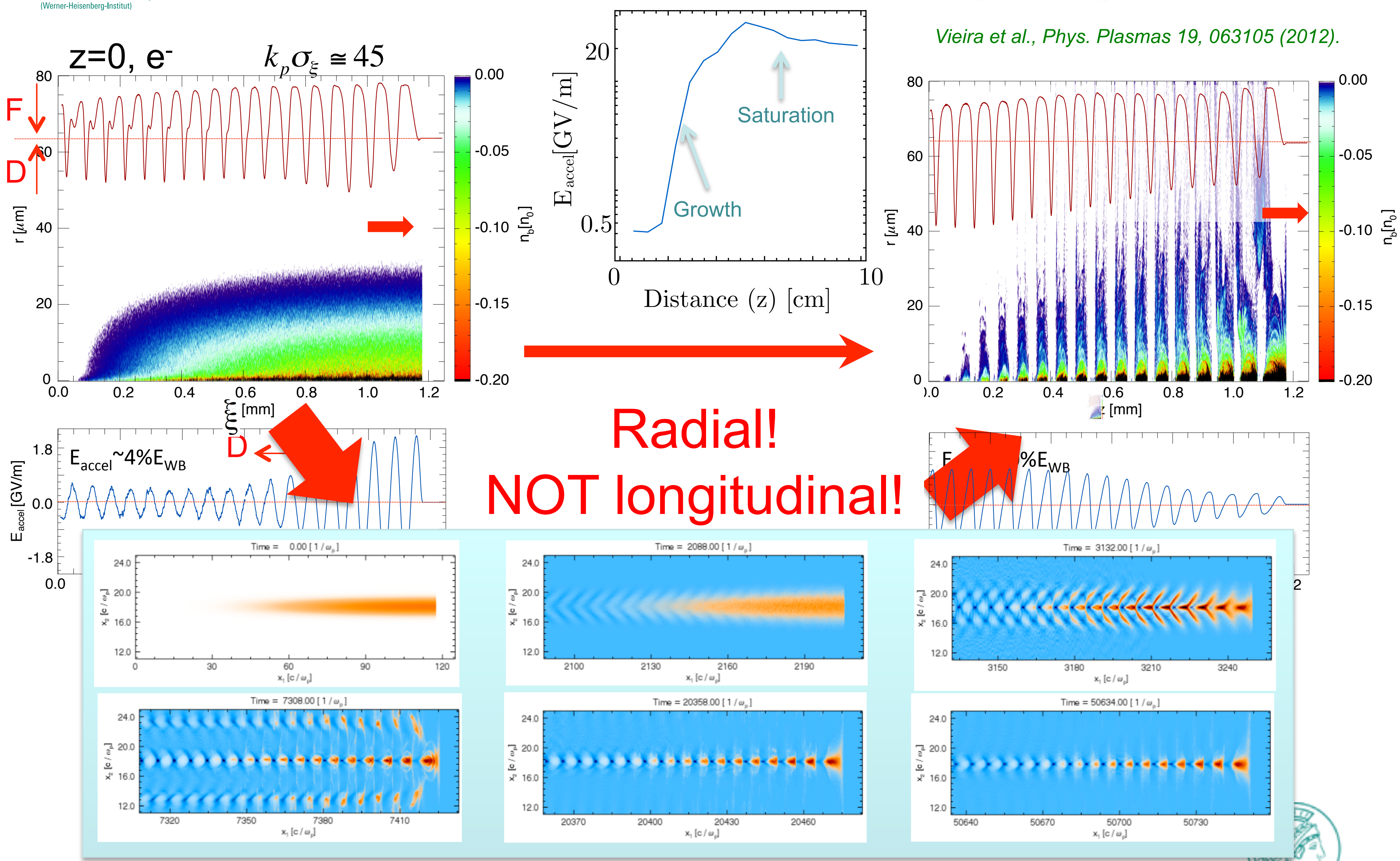


Radial!

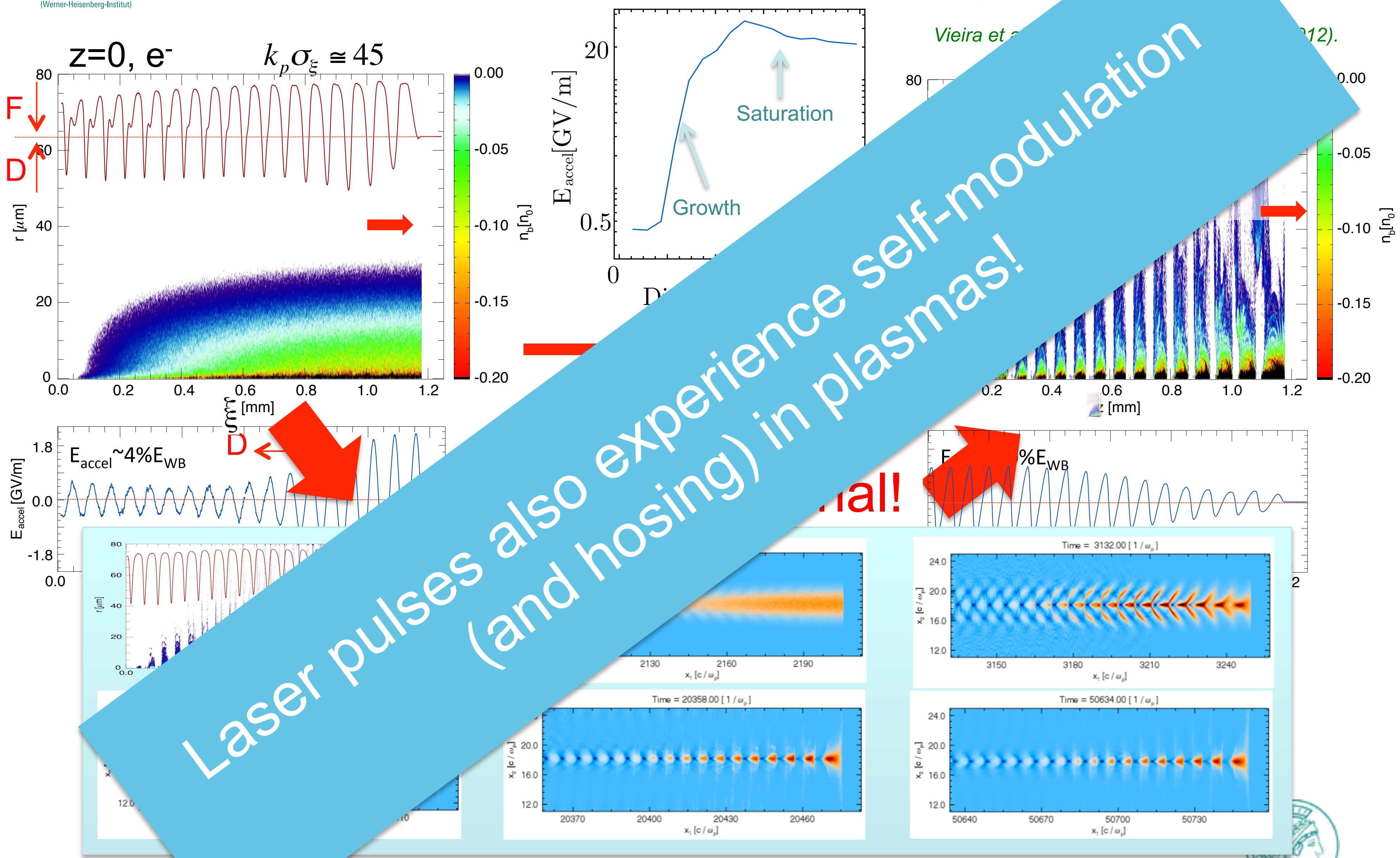
NOT longitudinal!



SEEDED SELF-MODULATION (SSM)



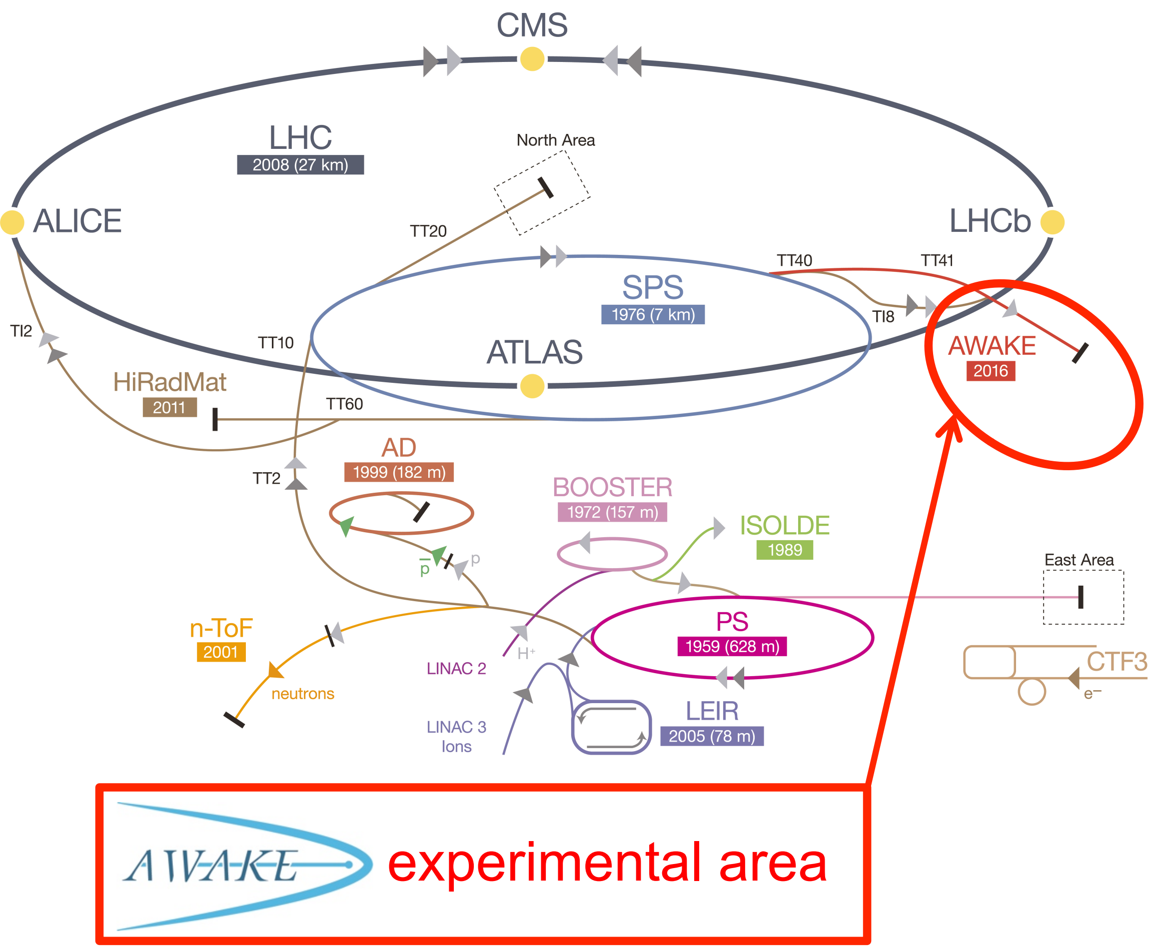
SEEDED SELF-MODULATiON (SSM)



Laser pulses also experience self-modulation (and hosing) in plasmas!

PROTON BEAMS @ CERN

CERN's Accelerator Complex



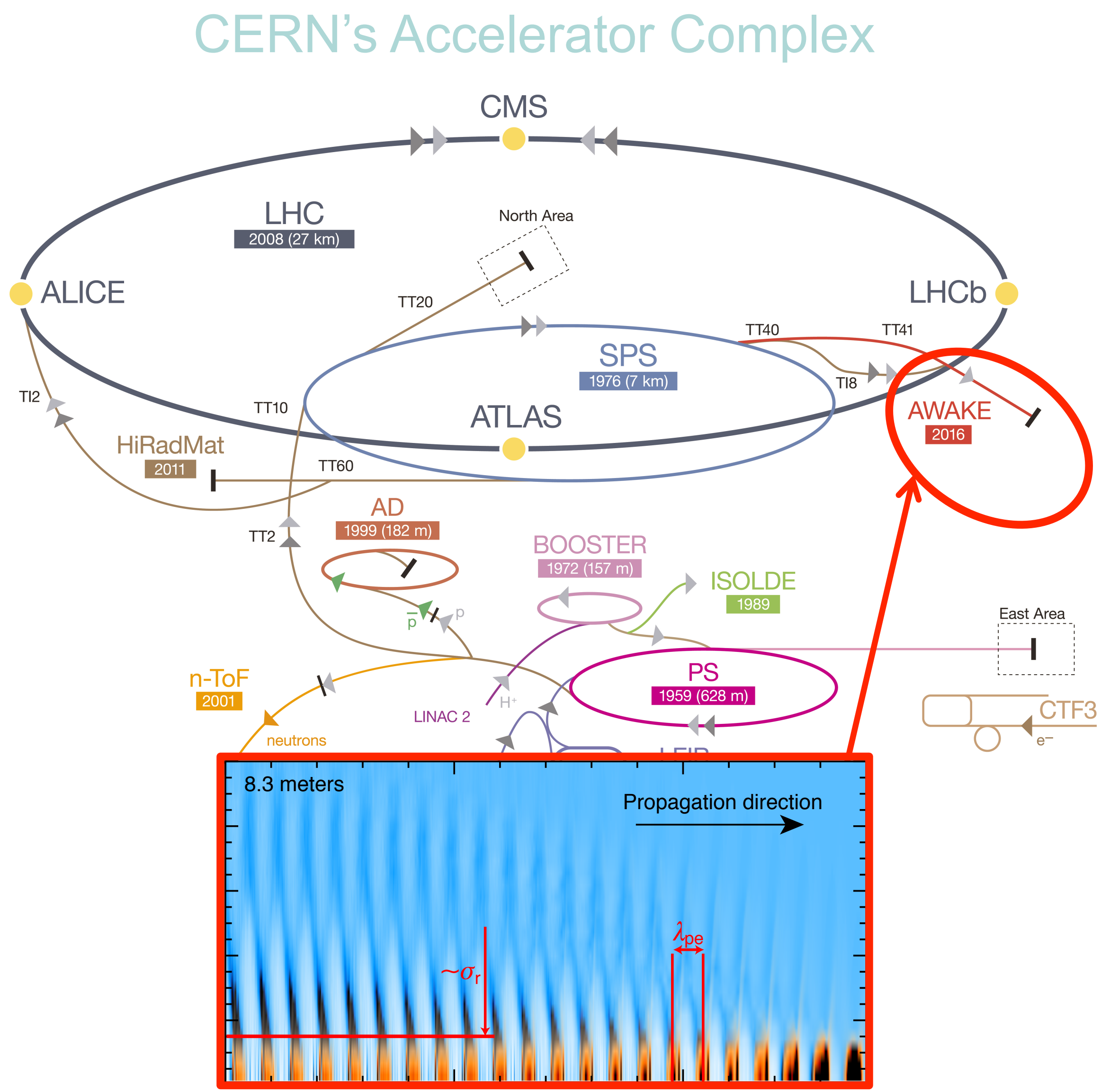
Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	400	400
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (μm)	400	200	200
β^* (m)	1.6	5	5

✧SPS beam: high energy, small σ_r^*, long β^*

PROTON BEAMS @ CERN

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

AWAKE



Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	400	400
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (µm)	400	200	200
β^* (m)	1.6	5	5

$c/\omega_{pe}\approx\sigma_r \Leftrightarrow$ n_e ~7×10^{14}cm^{-3}

λ_{pe}~1.3mm<<σ_z

f_{pe} ~240GHz

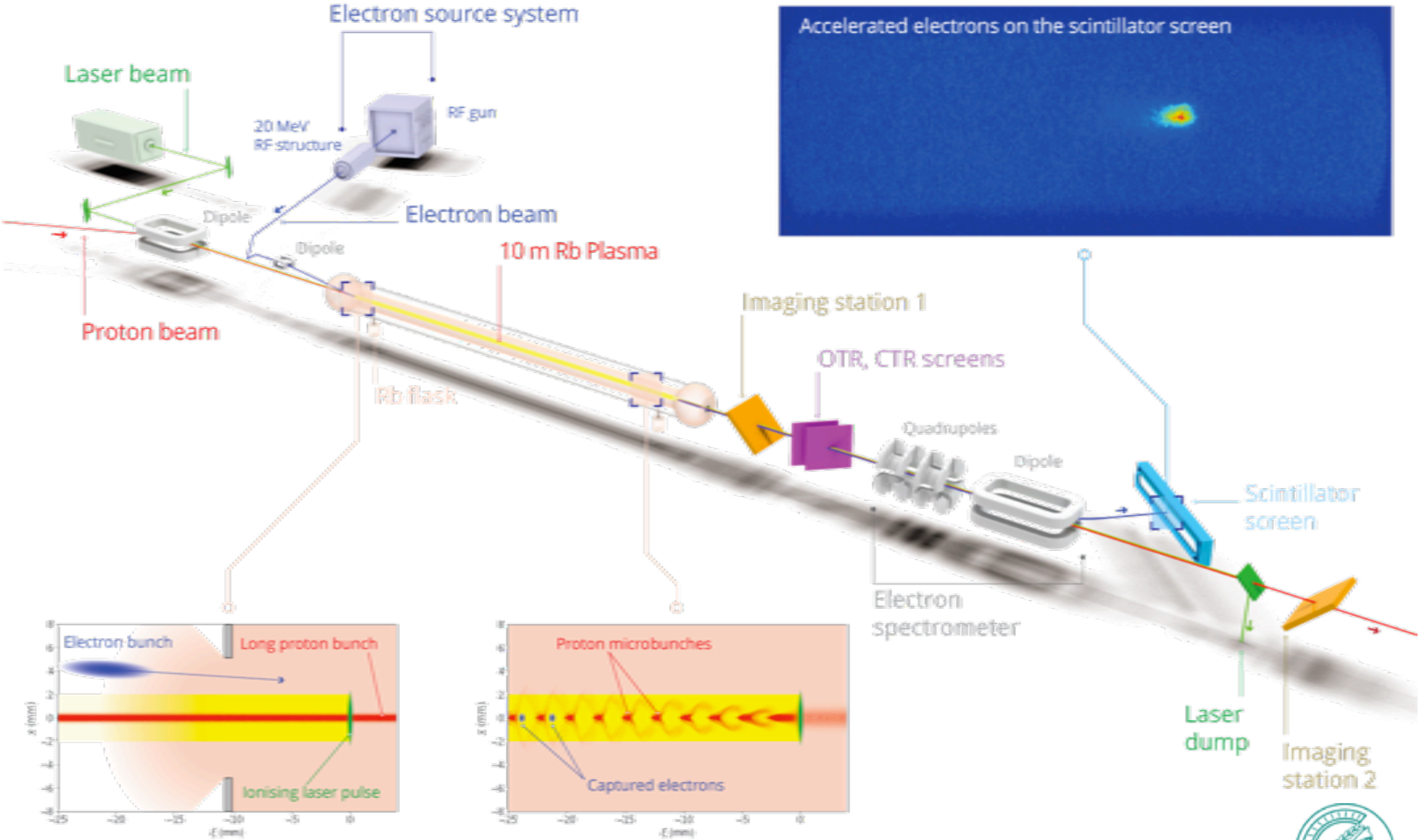
L_p ~10m~2β^*

E_{WB}~2.5GV/m

✧SPS beam: high energy, small σ_r^*, long β^*

MAX-PLANCK-GESELLSCHAFT

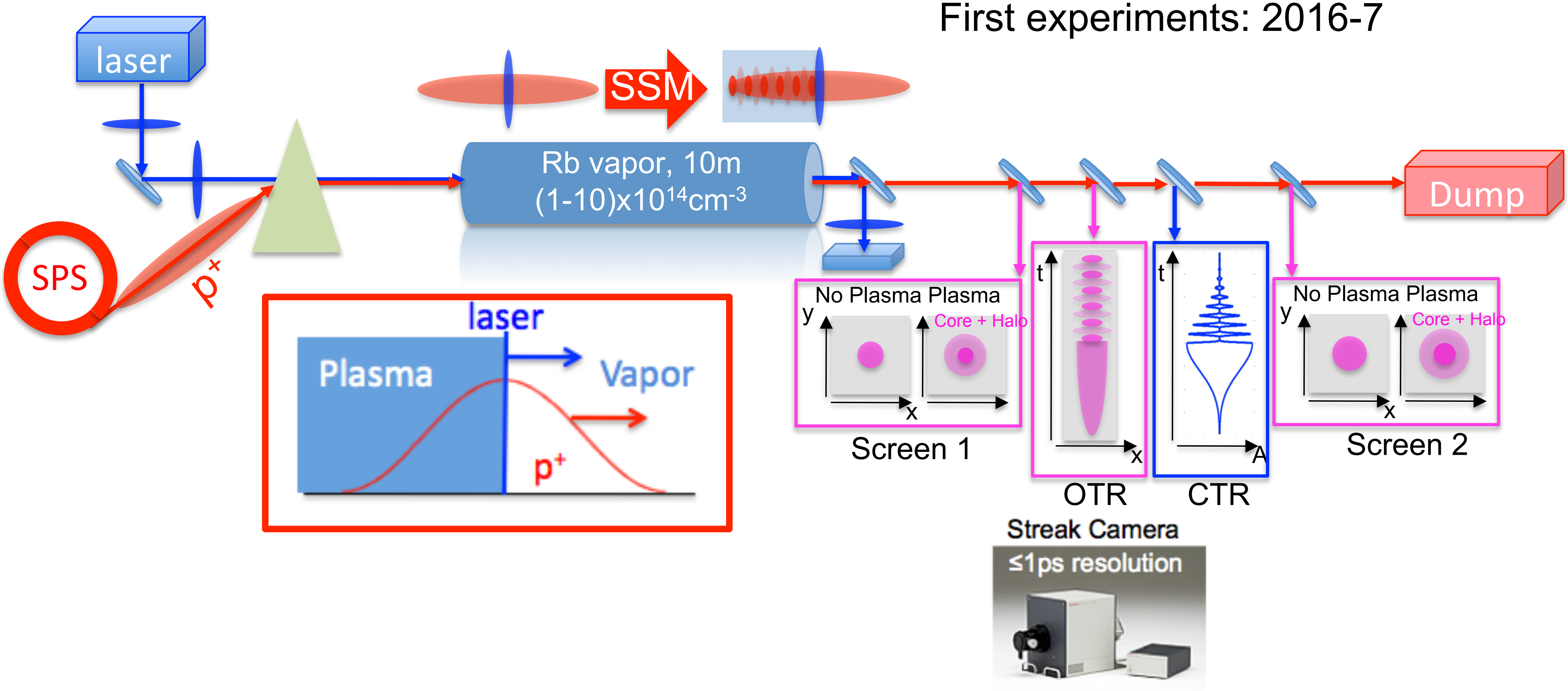
AWAKE EXPERiMENT



AWAKE, Nature 561, 363 (2018)

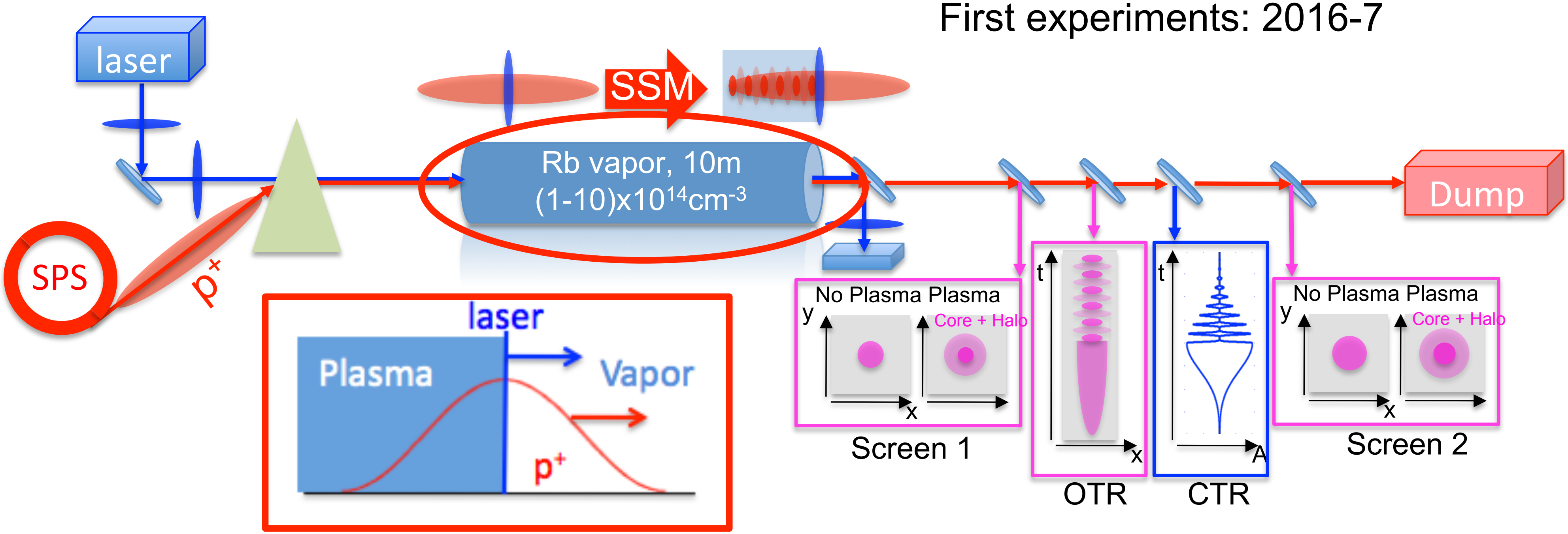
AWAKE EXPERIMENT

First experiments: 2016-7

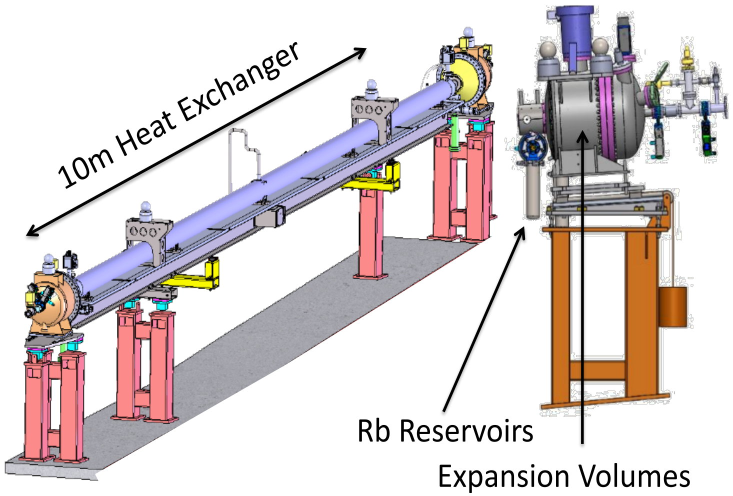


Rubidium Vapor Source

First experiments: 2016-7



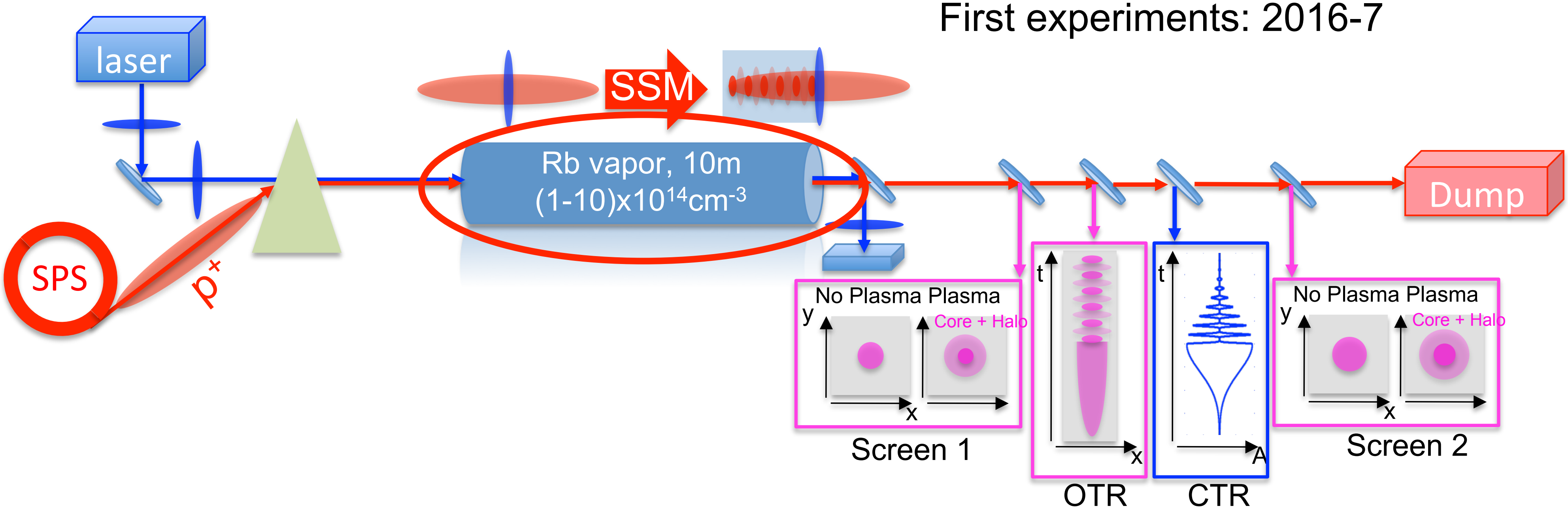
No windows, no differential pumping



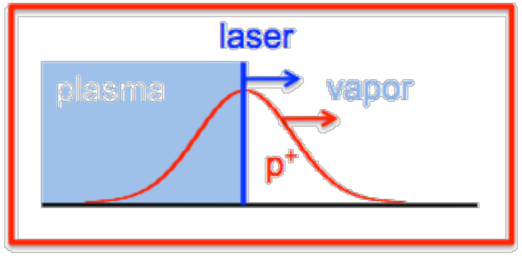
Rubidium

IONIZATION-SEEDING

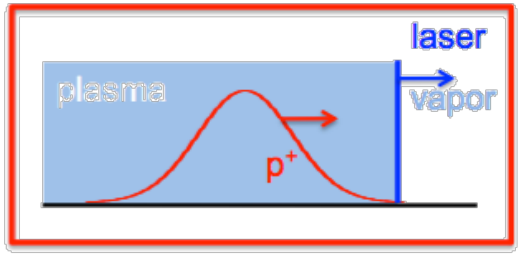
First experiments: 2016-7



Ionization Front Seeding



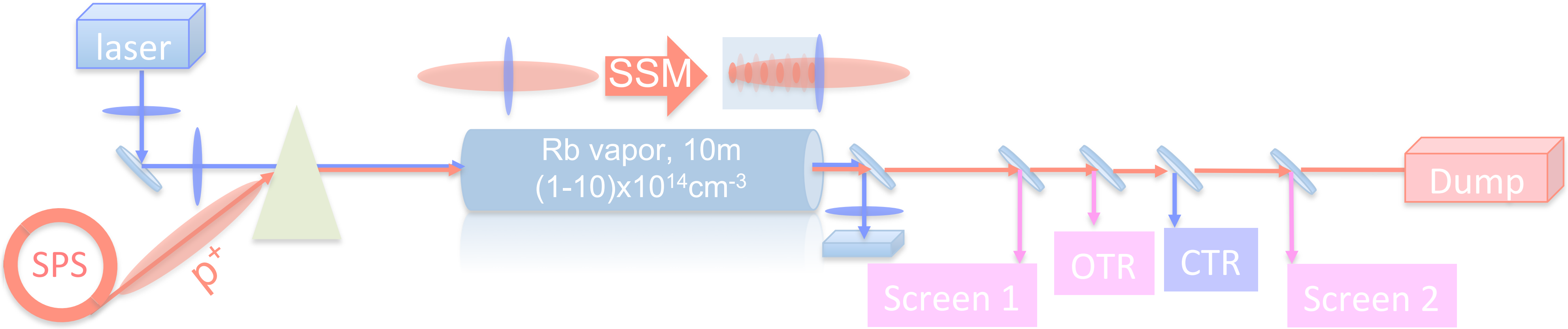
Preformed Plasma

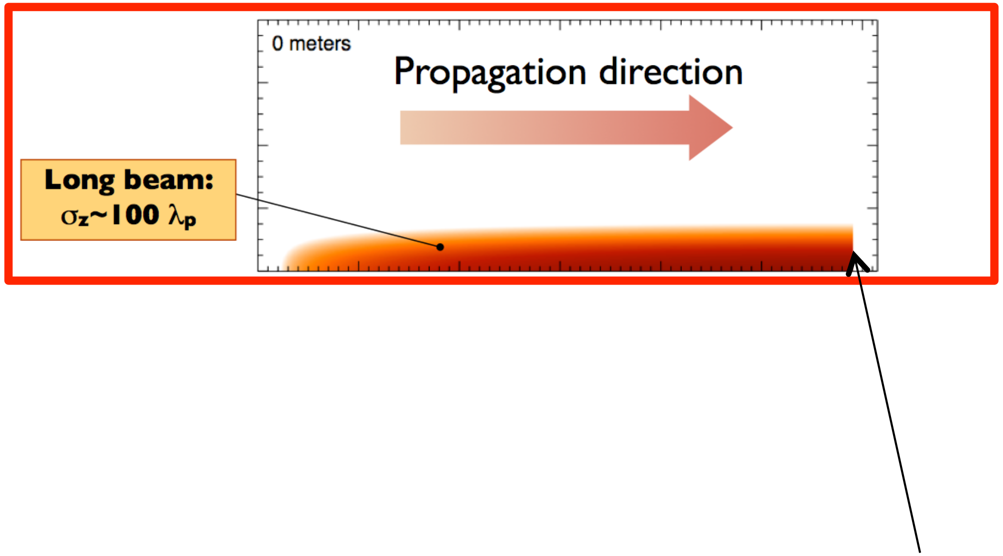


✧Laser-ionization allows for ionization-front seeding and pre-formed plasma

✧Laser pulse produces synchronized e^- for injection/acceleration

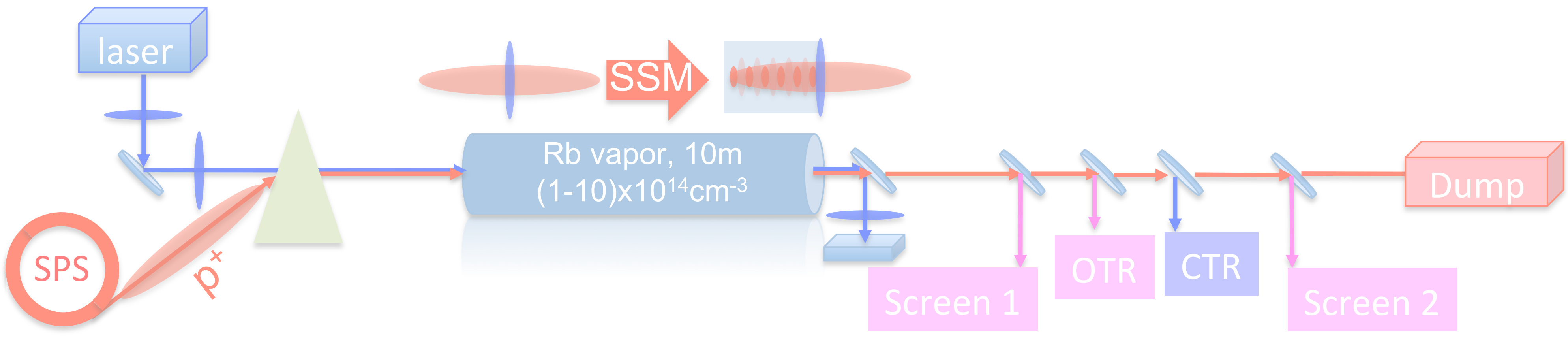
AWAKE EXPERiMENT

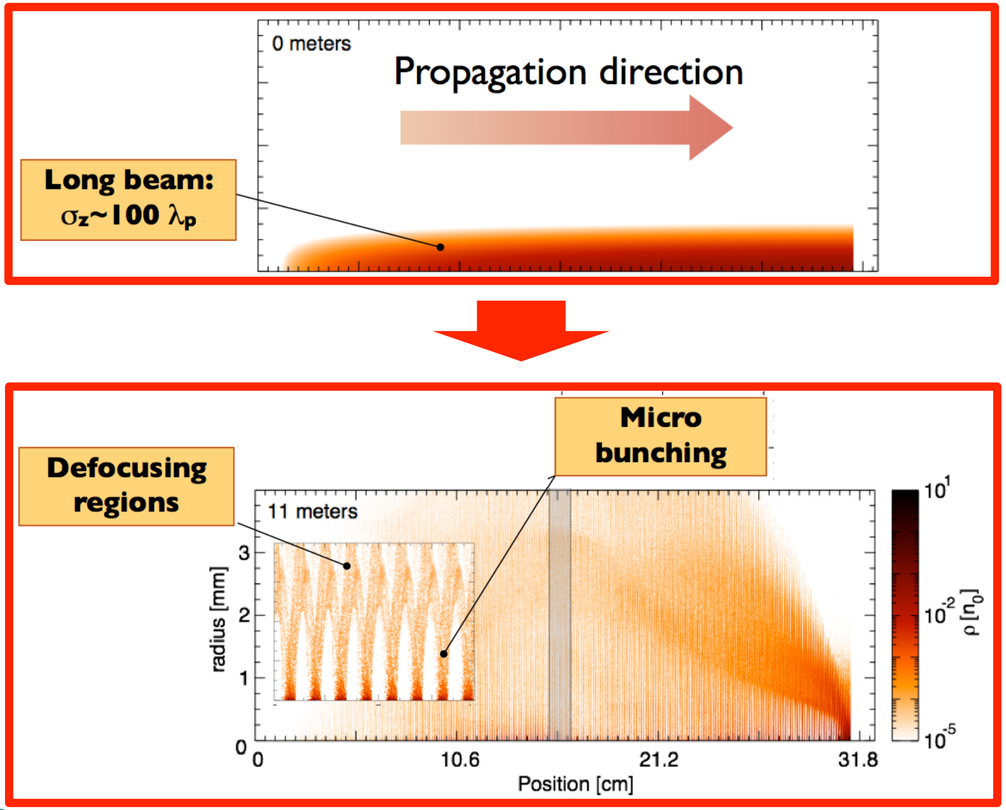




"Sharp" ($\tau_{ioniz}<\tau_{laser}$=210fs<$1/f_{pe}$) start of the beam/plasma interaction for SSM seeding
Experiment: ionization front seeding

AWAKE EXPERiMENT





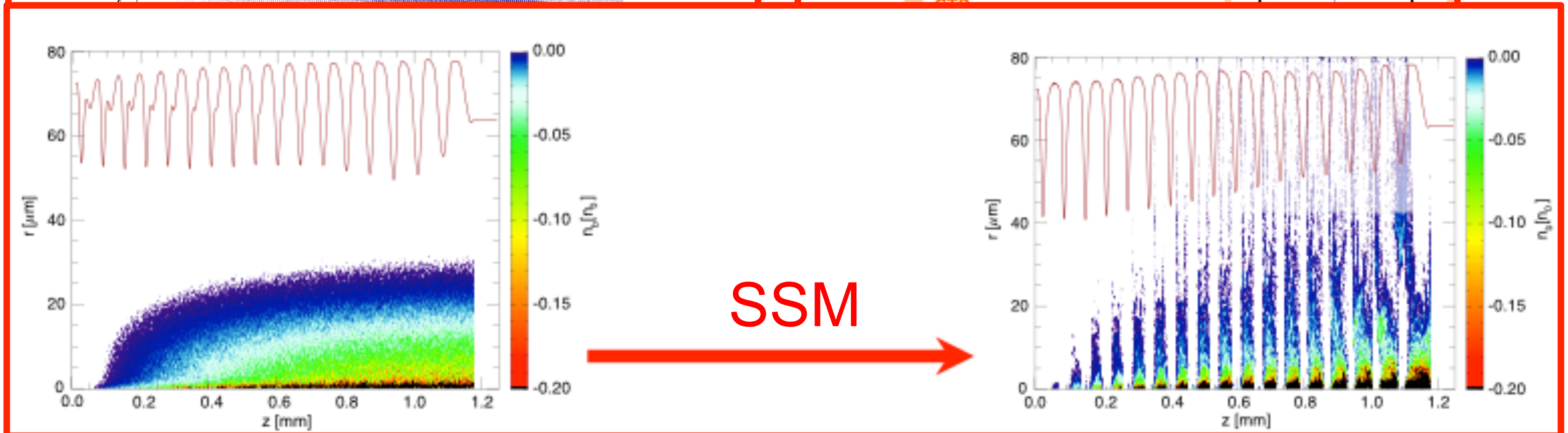
- ✧ The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~$7x10^{14}cm^{-3}$)
- ✧ ~$100\lambda_{pe}$ per σ_z

AWAKE EXPERIMENT

First experiments: 2016-7

1st goal of AWAKE (2016-17):
demonstrate and study
the seeded self-modulation (SSM)
of a long p^+ bunch in a dense plasma

$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$



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

AWAKE EXPERiMENT

First experiments: 2016-7

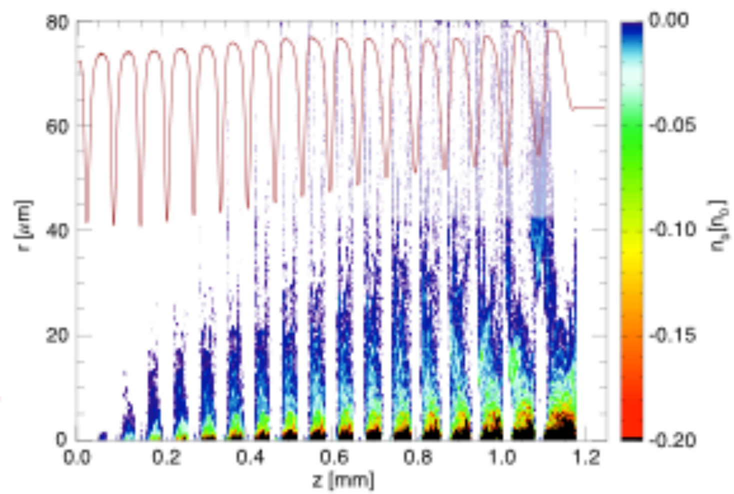
1^{st} goal of AWAKE (2016-17): demonstrate and study the seeded self-modulation (SSM) of a long p^+ bunch in a dense plasma

$$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$$

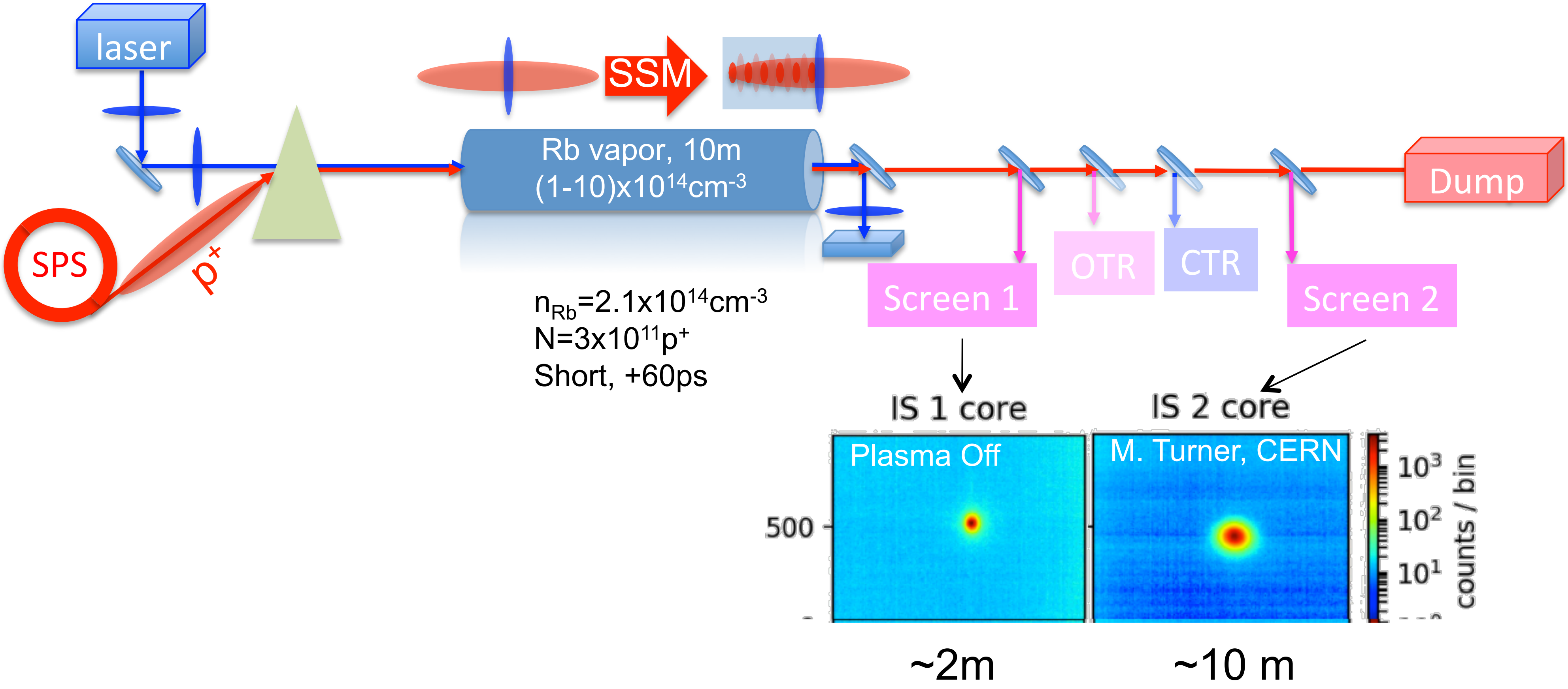
Three p^+ bunch observables

- Defocused p^+
- p^+ bunch modulation at f_{pe}
- Emission of coherent transition radiation at f_{pe}

SSM →



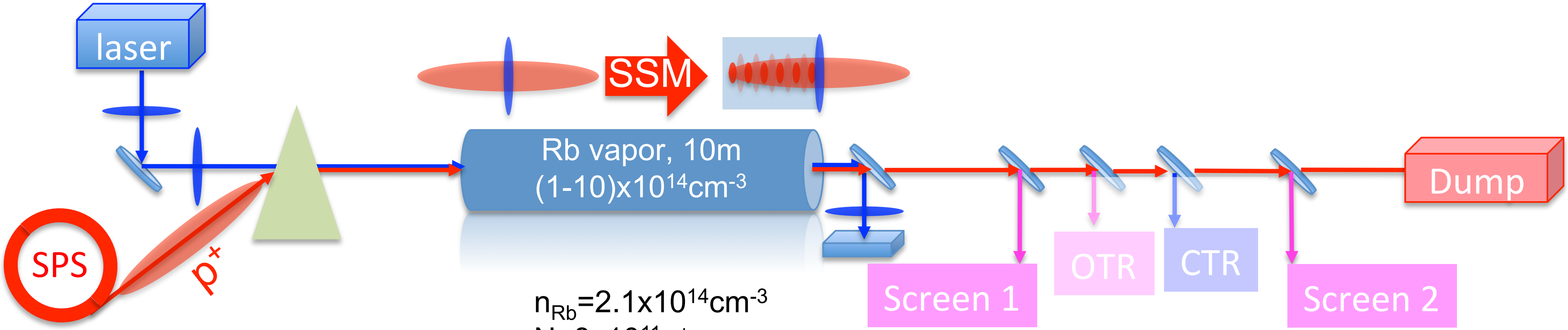
TWO-SCREEN SSM



$n_{Rb}=2.1\times10^{14}cm^{-3}$
$N=3\times10^{11}p^{+}$
Short, +60ps

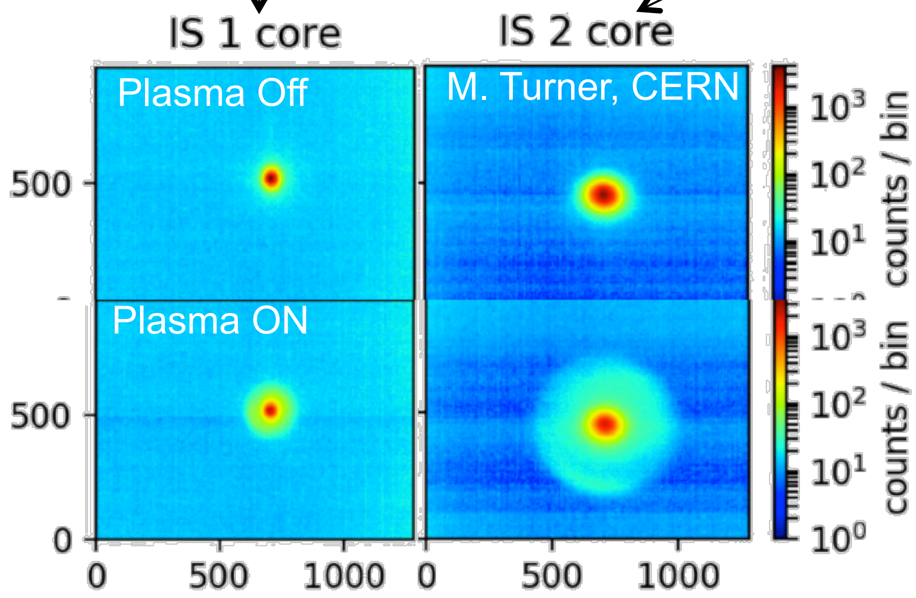
M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

TWO-SCREEN SSM



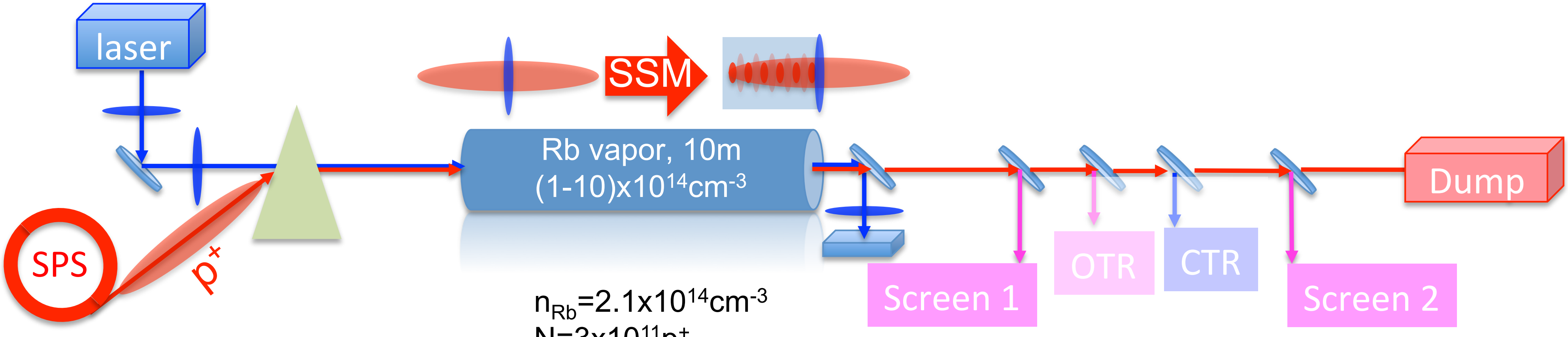
n_{Rb}=2.1x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Short, +60ps

✧ p$^+$ defocused by the transverse wakefield (SSM) form a halo



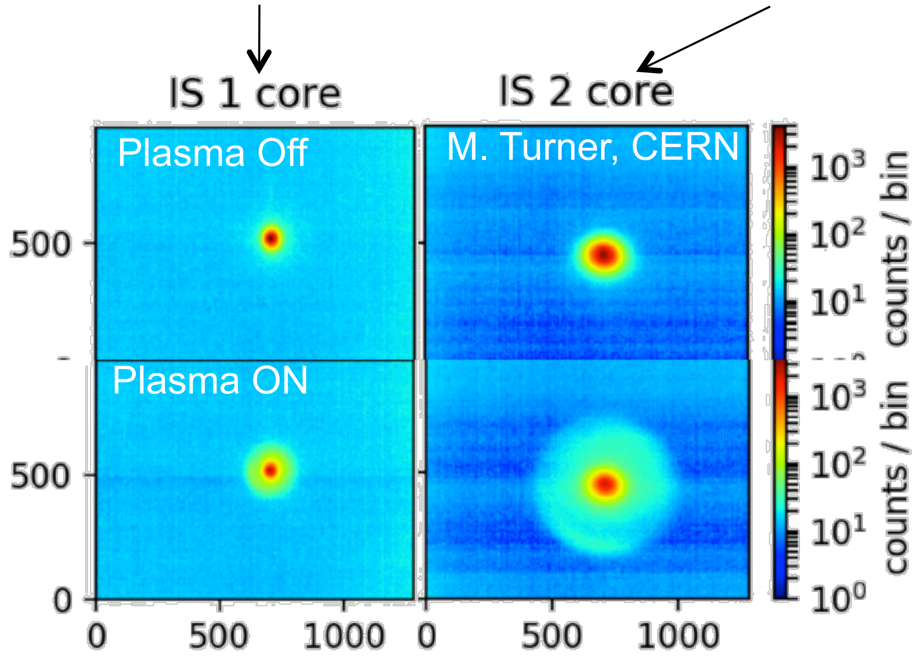
M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

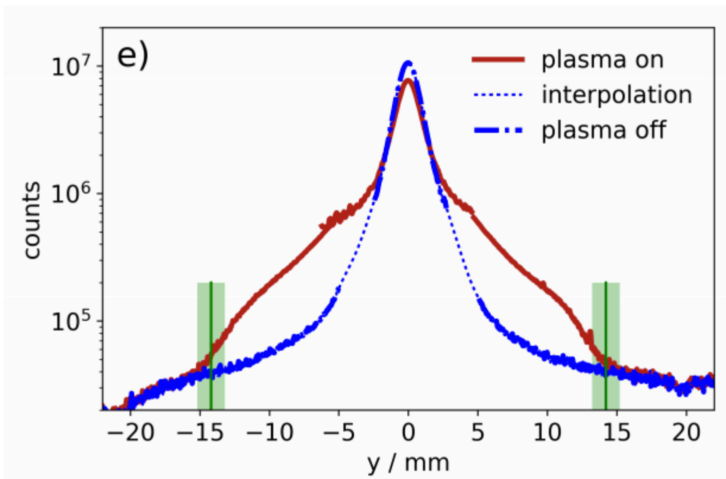
TWO-SCREEN SSM



n_{Rb}=2.1x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Short, +60ps

✧ p$^+$ defocused by the transverse wakefield (SSM) form a halo





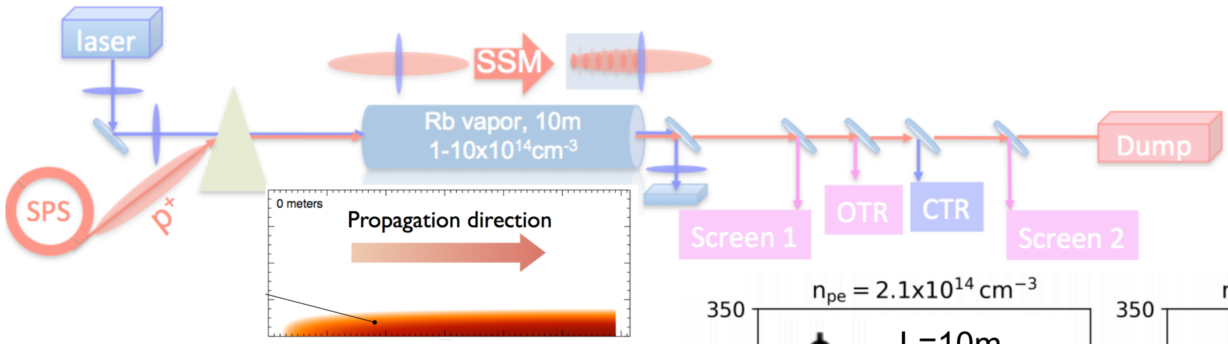
M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

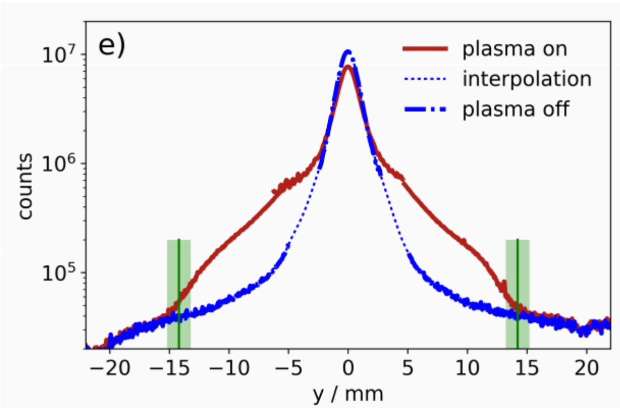
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

AWAKE

TWO-SCREEN SSM

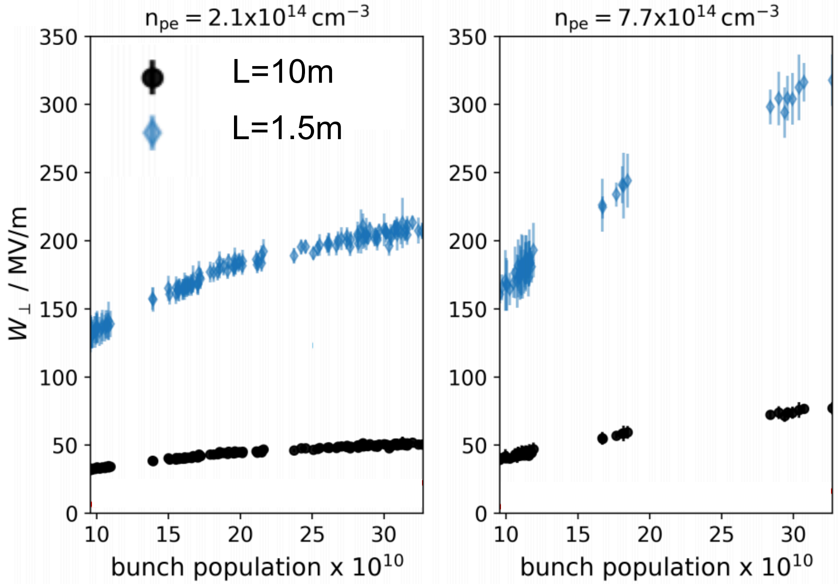
$n_{Rb}=2.1\times10^{14}cm^{-3}$
$N=3\times10^{11}p^{+}$
Short, +60ps

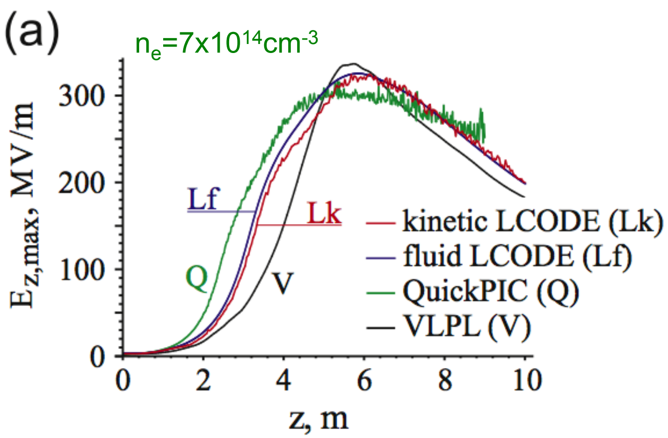




Angle

$$W_{\perp,av}=\frac{\theta\cdot p_{\parallel}c}{q\cdot L}$$





Caldwell, NIMA 829, 3 (2016)

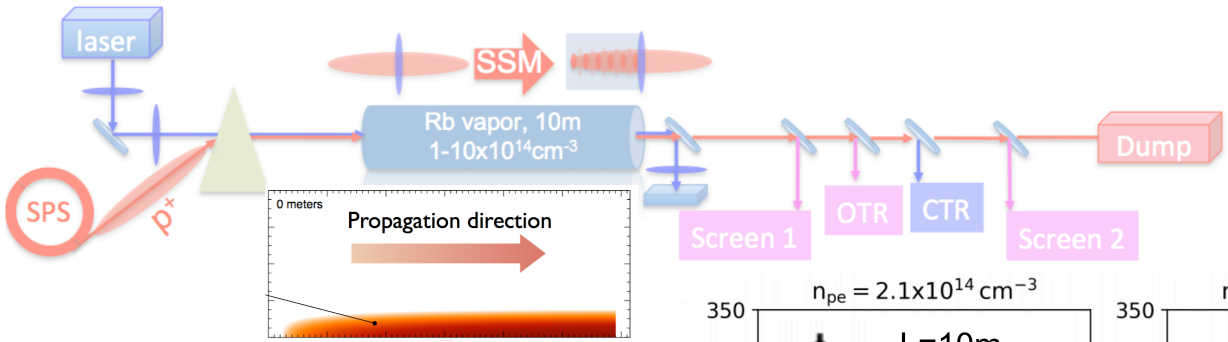
M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

MAX-PLANCK-GESELLSCHAFT

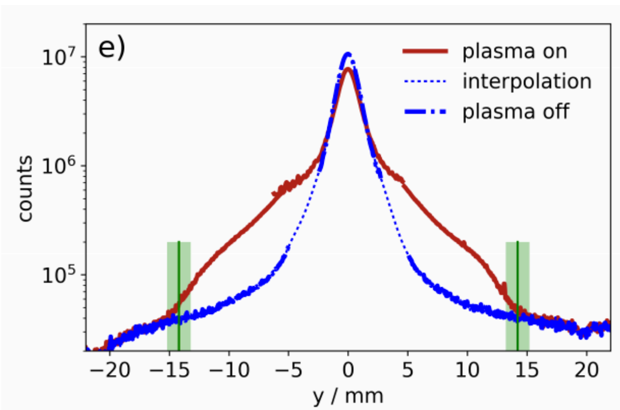
TWO-SCREEN SSM

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

AWAKE



$n_{Rb}=2.1\times10^{14}cm^{-3}$
$N=3\times10^{11}p^{+}$
Short, +60ps

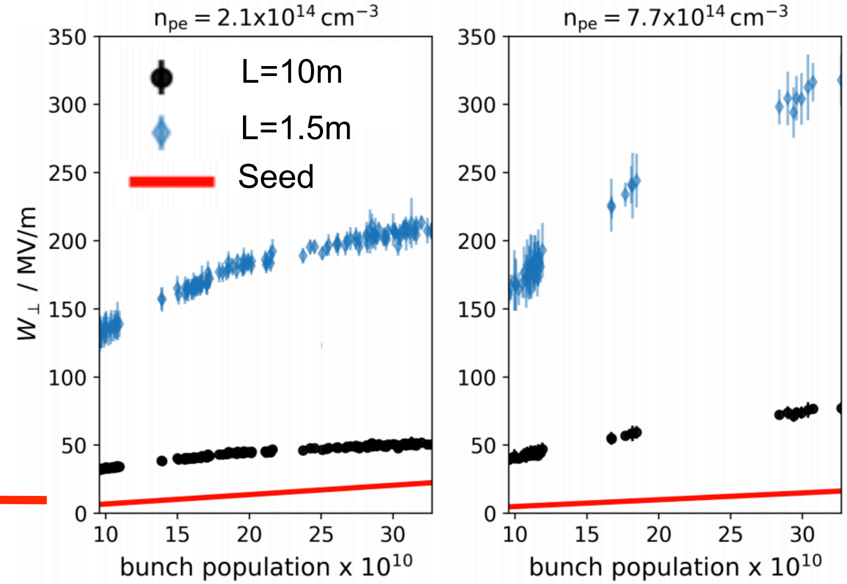


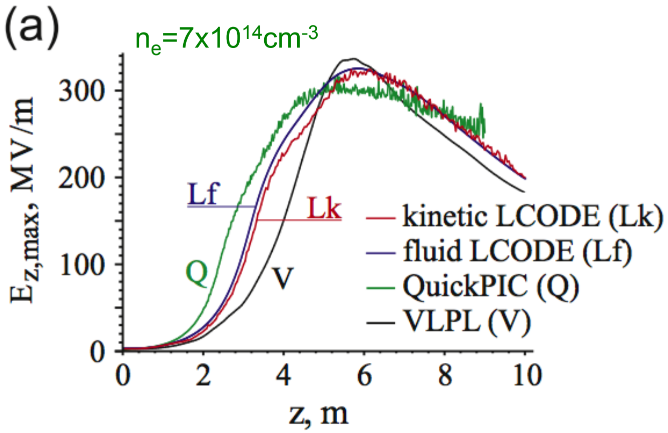
Angle

$$W_{\perp,av}=\frac{\theta\cdot p_{\parallel}c}{q\cdot L}$$

$$W_{\perp}\cong\frac{m_e c^2}{e}\frac{n_{b\parallel}}{n_e}\frac{1}{\sigma_r}$$

Seeding



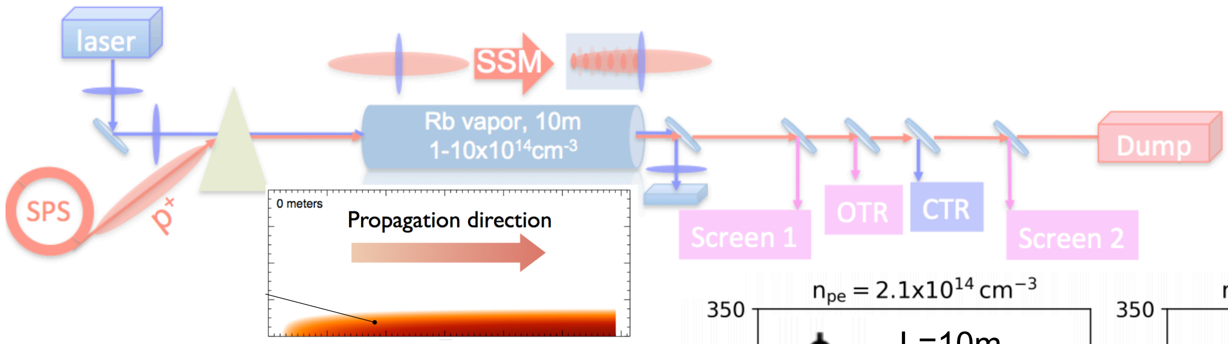


Caldwell, NIMA 829, 3 (2016)

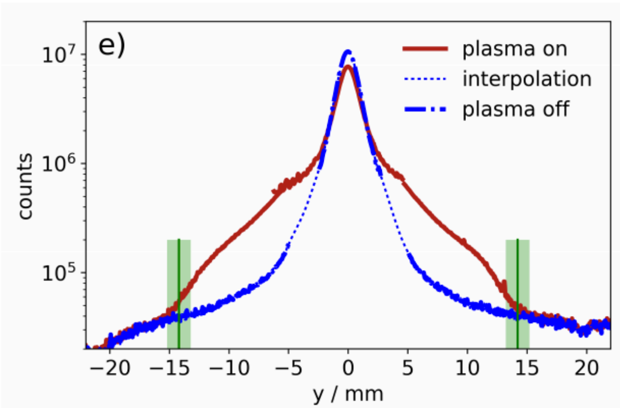
- ✧ Deflection angle larger than expected from seed fields
- ✧ For $\sigma_r \sim c/\omega_{pe}$, $W_z \sim W_{perp}$

M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

TWO-SCREEN SSM



$n_{Rb}=2.1\times10^{14}cm^{-3}$
$N=3\times10^{11}p^{+}$
Short, +60ps

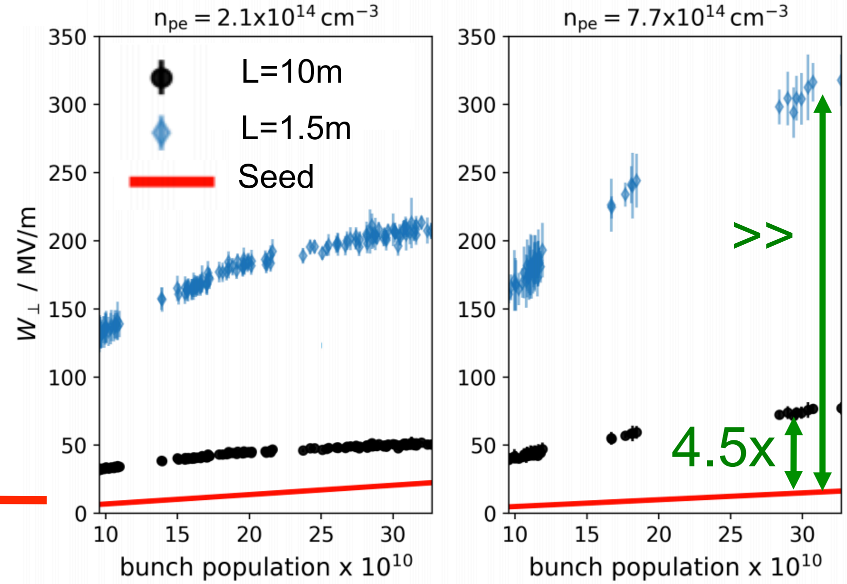


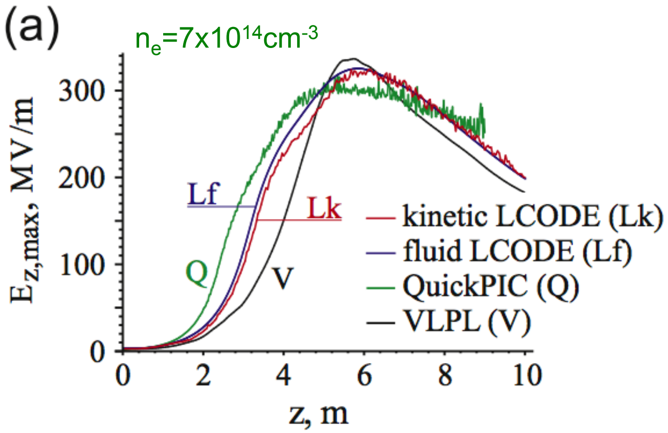
Angle

$$W_{\perp,av} = \frac{\theta \cdot p_{\|} c}{q \cdot L}$$

$$W_{\perp} \cong \frac{m_e c^2}{e} \frac{n_{b\|}}{n_e} \frac{1}{\sigma_r}$$

Seeding





Caldwell, NIMA 829, 3 (2016)

✧ Deflection angle larger than expected from seed fields

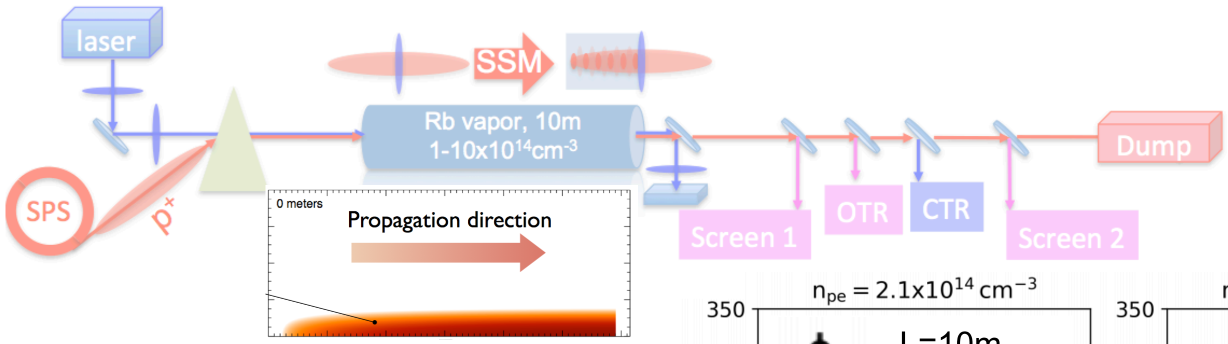
✧ For $\sigma_r \sim c/\omega_{pe}$, $W_z \sim W_{perp}$

M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

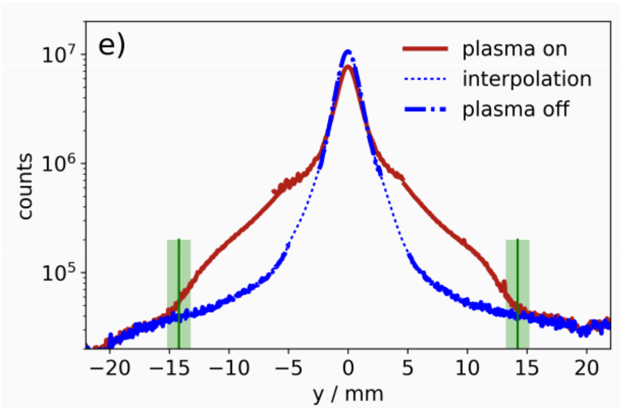
TWO-SCREEN SSM

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

AWAKE



$n_{Rb}=2.1\times10^{14}cm^{-3}$
$N=3\times10^{11}p^{+}$
Short, +60ps

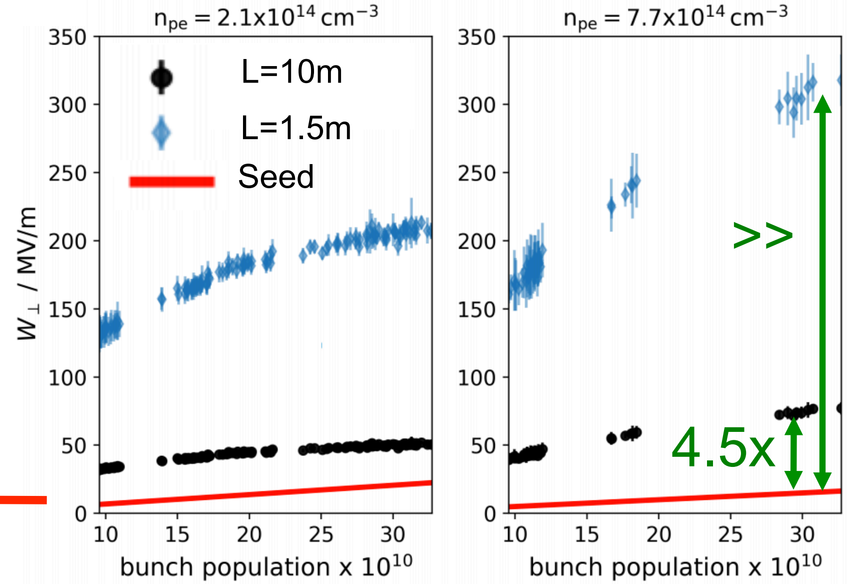


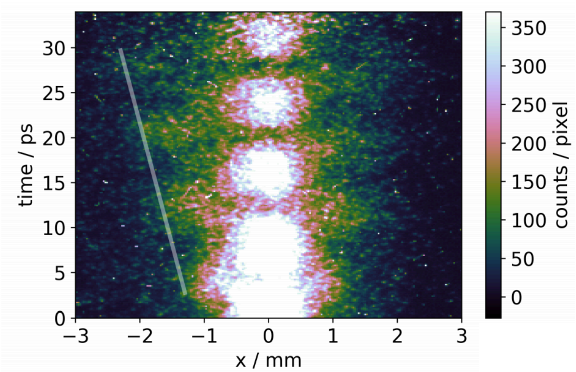
Angle

$$W_{\perp,av}=\frac{\theta\cdot p_{\parallel}c}{q\cdot L}$$

$$W_{\perp}\cong\frac{m_ec^2}{e}\frac{n_{b\parallel}}{n_e}\frac{1}{\sigma_r}$$

Seeding





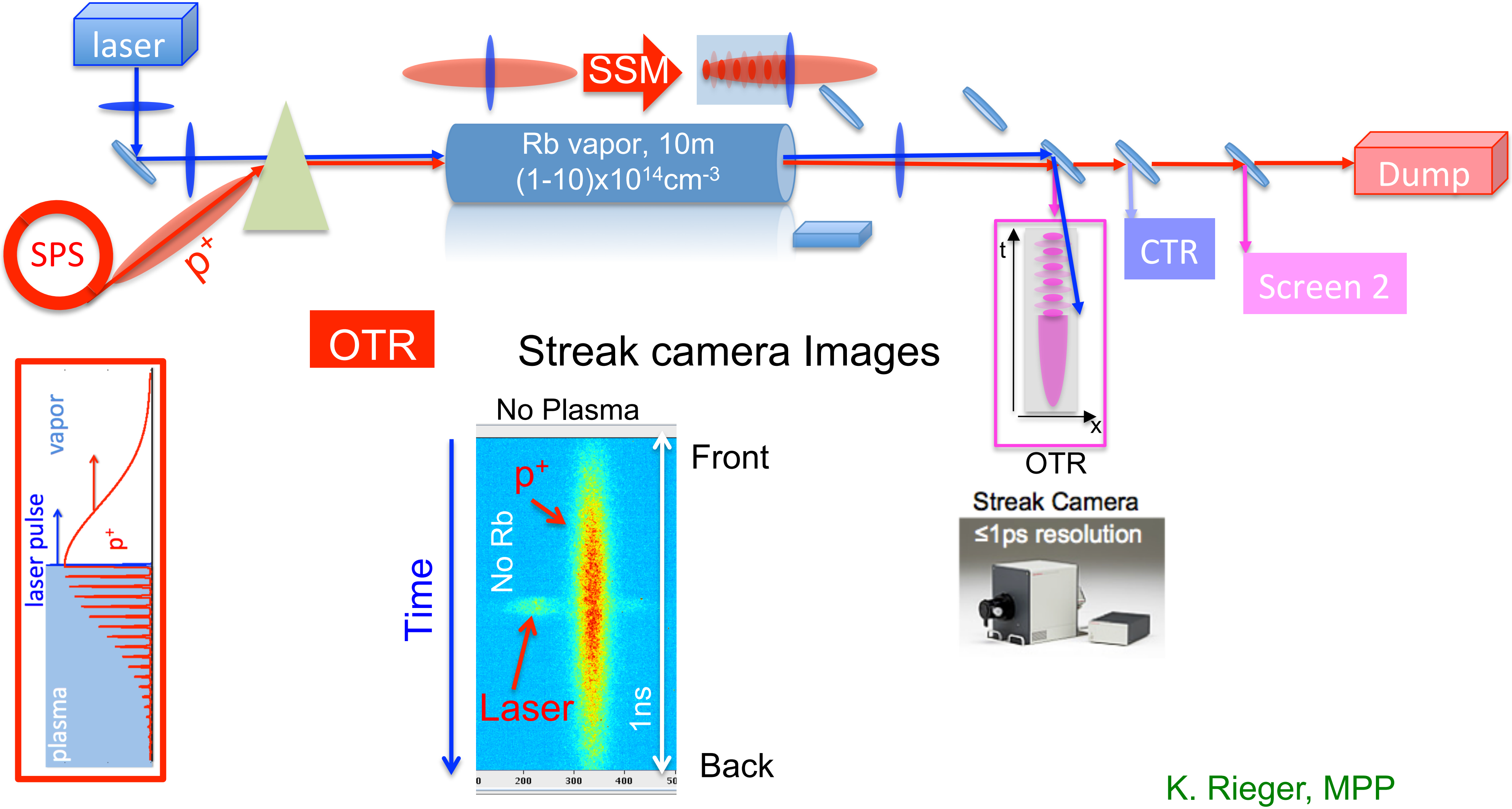
- ✧ Deflection angle larger than expected from seed fields
- ✧ For σ_r~c/ω_{pe}, W_z~W_{perp}
- ✧ "Radius" of deflected p^+ increases along the bunch

✧ Wakefields grow … along the bunch <u>and</u> along the plasma

M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

MAX-PLANCK-GESELLSCHAFT

SEEDED SM

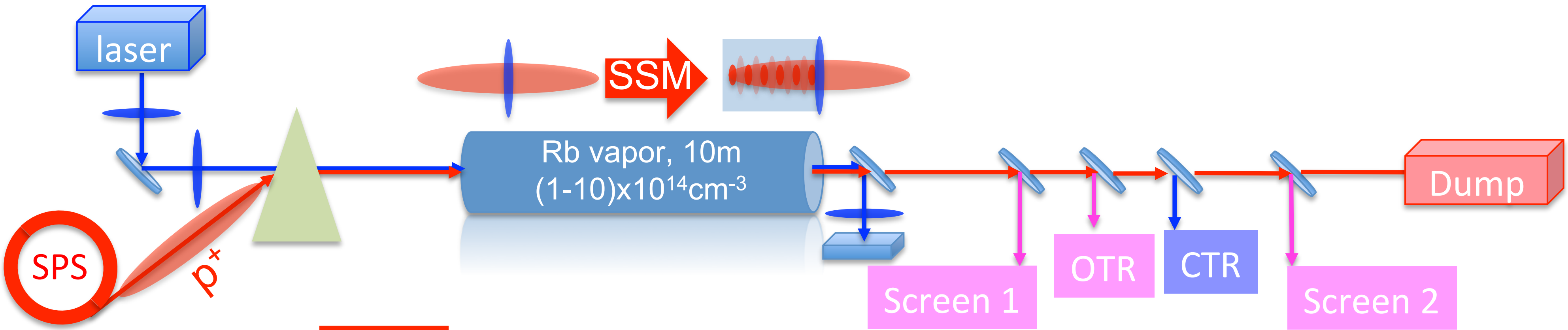


K. Rieger, MPP

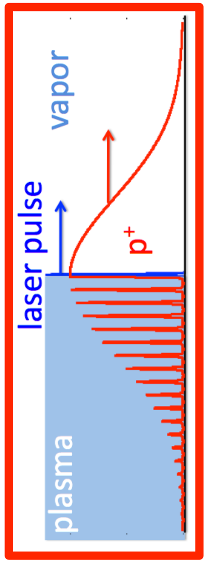
✧Timing at the ps scale

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

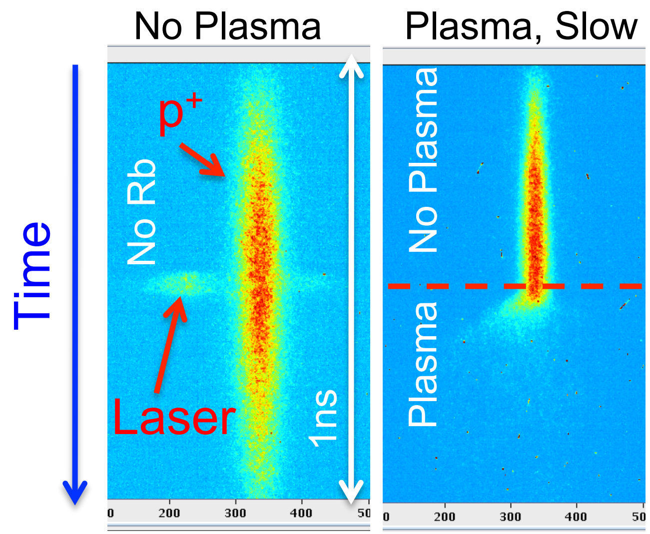
SEEDED SM



OTR



Streak camera Images



n_{Rb}=3.7x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Long
f_{mod}~164GHz

K. Rieger, MPP

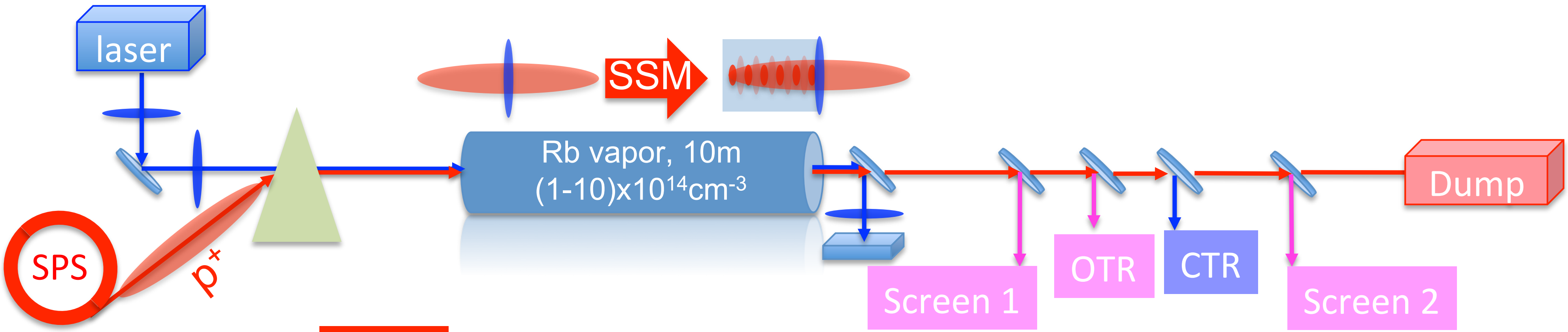
✧Timing at the ps scale
✧Effect starts at laser pulse timing → SM seeding

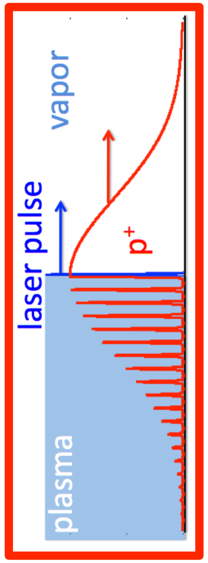
AWAKE, Phys. Rev. Lett. 122, 054802 (2019)

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

SEEDED SM

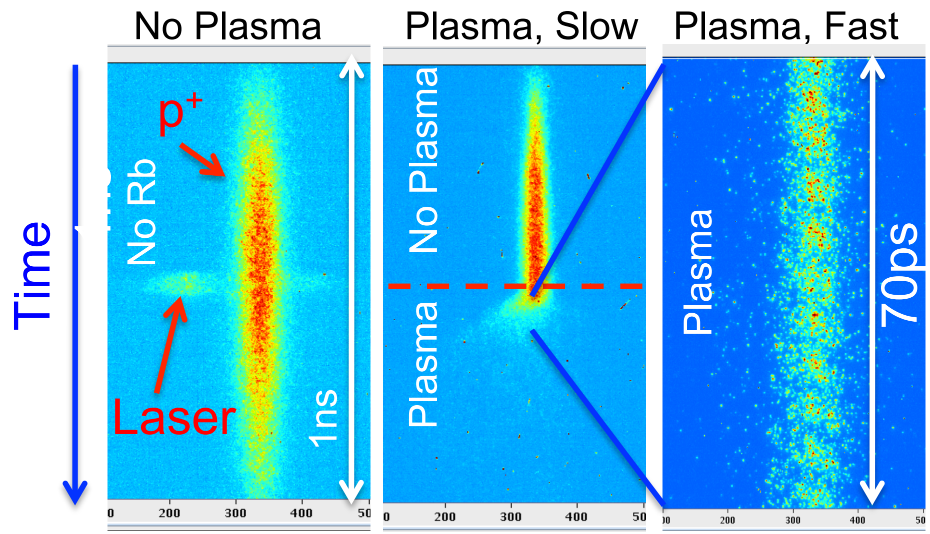
AWAKE





OTR

Streak camera Images



n_{Rb}=3.7x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Long
f_{mod}~164GHz

K. Rieger, MPP

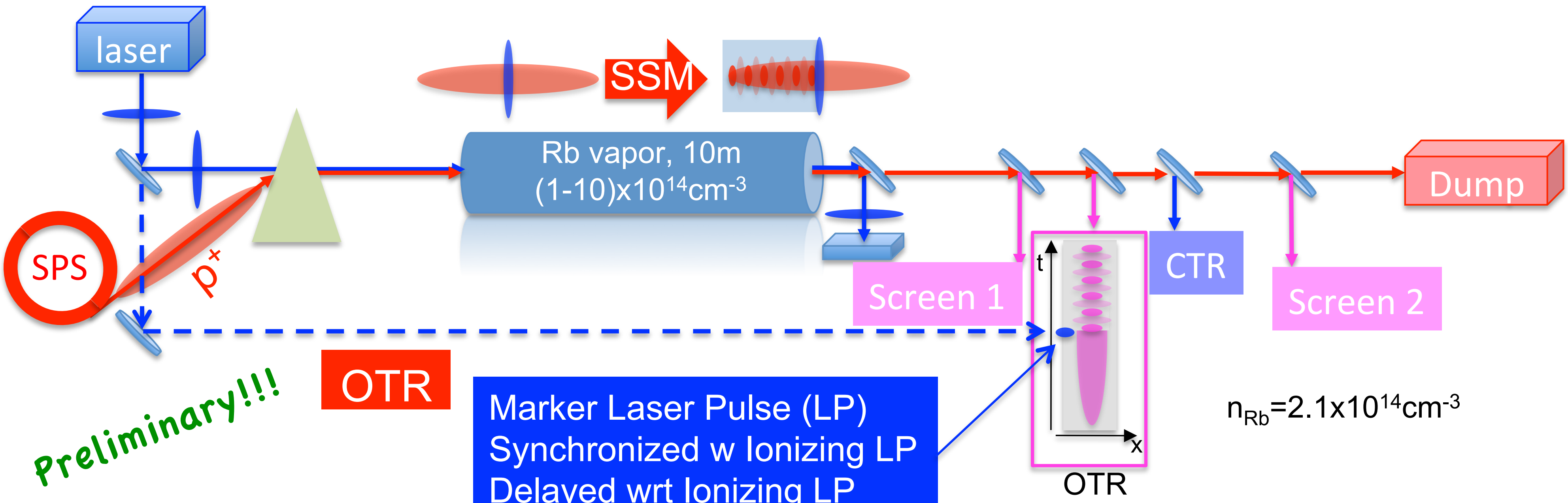
- ✧Timing at the ps scale
- ✧Effect starts at laser pulse timing → SM seeding
- ✧Density modulation at the ps-scale visible

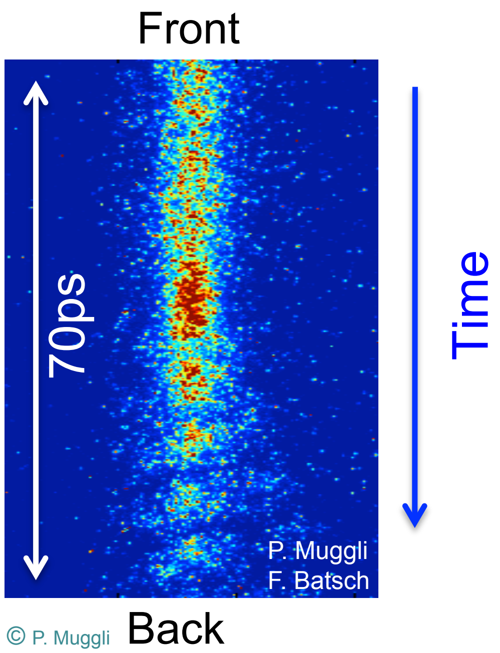
AWAKE, Phys. Rev. Lett. 122, 054802 (2019)

MAX-PLANCK-GESELLSCHAFT

μ-BUNCH TRAIN

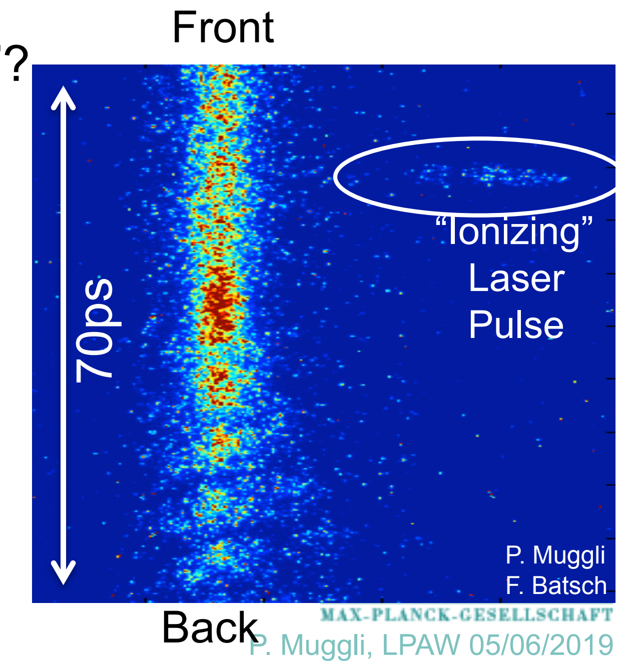
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



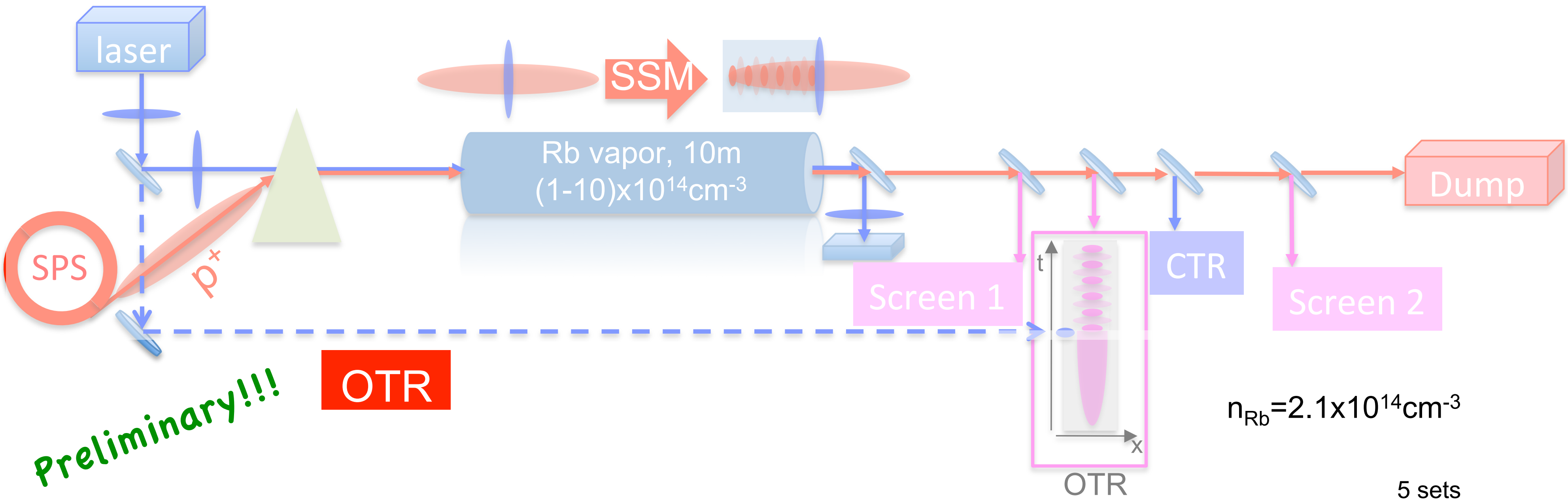


✧Is the μ-bunches timing "repeatable"?
✧Streak camera trigger jitter (~20ps rms)

✧Marker laser pulse synchronized with ionization laser pulse at the sub-ps time scale



μ-BUNCH TRAIN

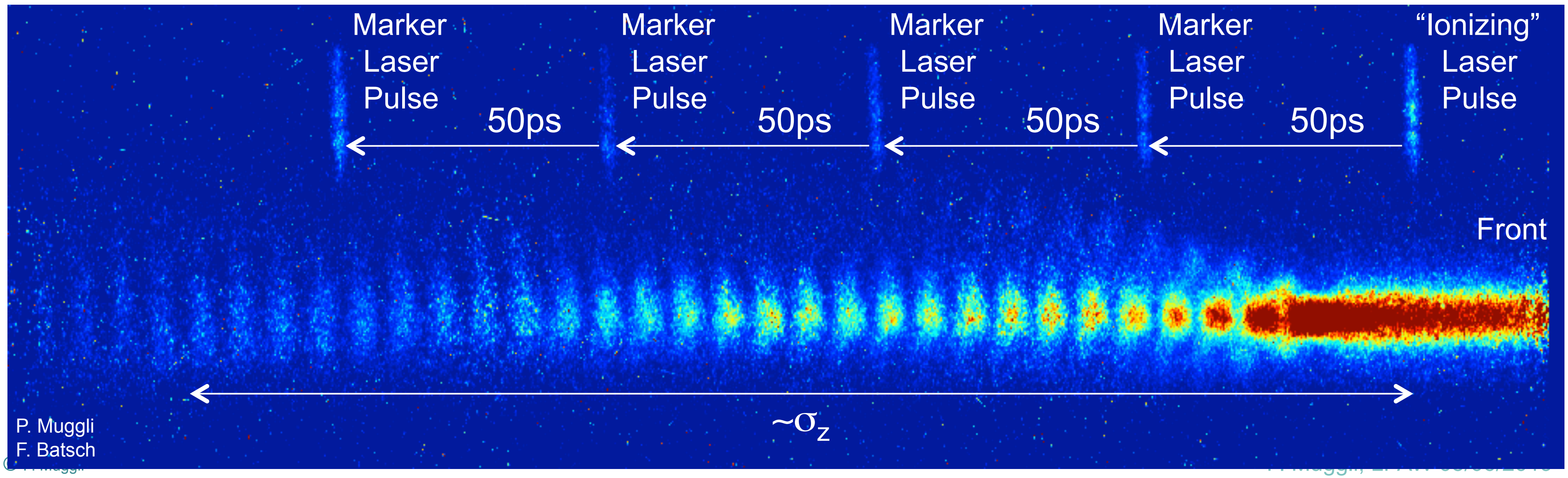


Preliminary!!!

$n_{Rb}=2.1\times10^{14}cm^{-3}$

5 sets
10 events each

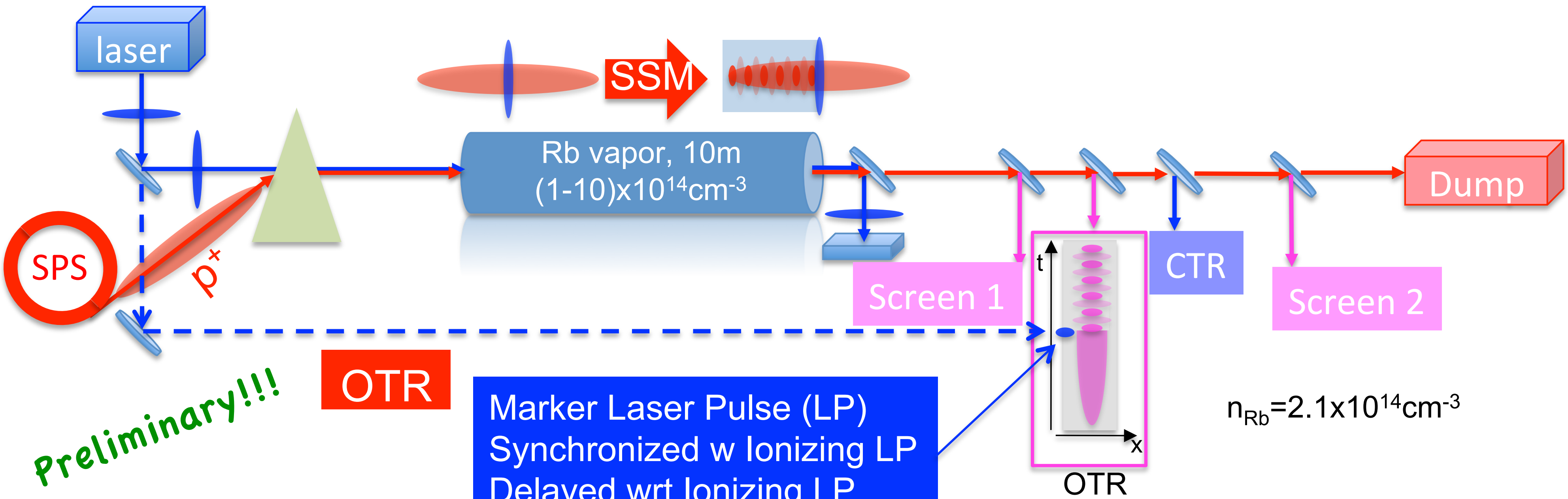
Streak camera Images



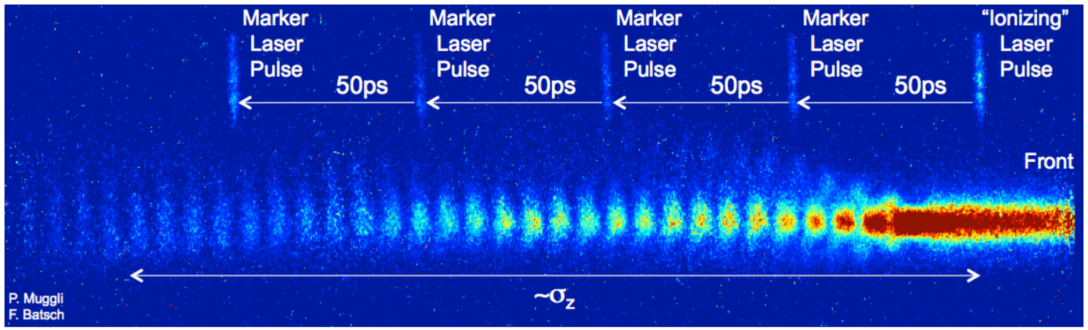
μ-BUNCH TRAIN

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

AWAKE



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

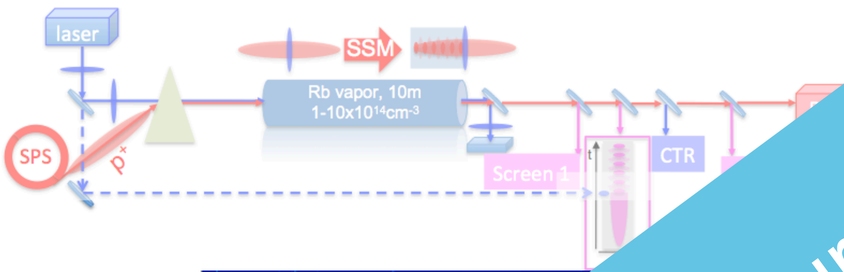


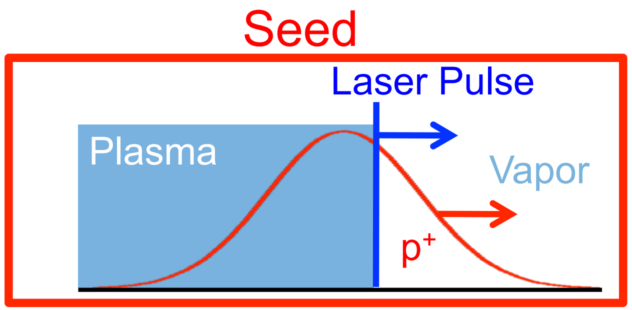
- Micro-bunches present over long time scale ~σ_z/c from seed point
- "Stitching" demonstrates reproducibility of the μ-bunch process against bunch parameters variations (N=2.5x10^{11}±10%, σ_{zt}=220±10ps, σ_r)
- Phase stability essential for e^- external injection: SSM not SMI!!! Wakefields "amplifier"

MAX-PLANCK-GESELLSCHAFT

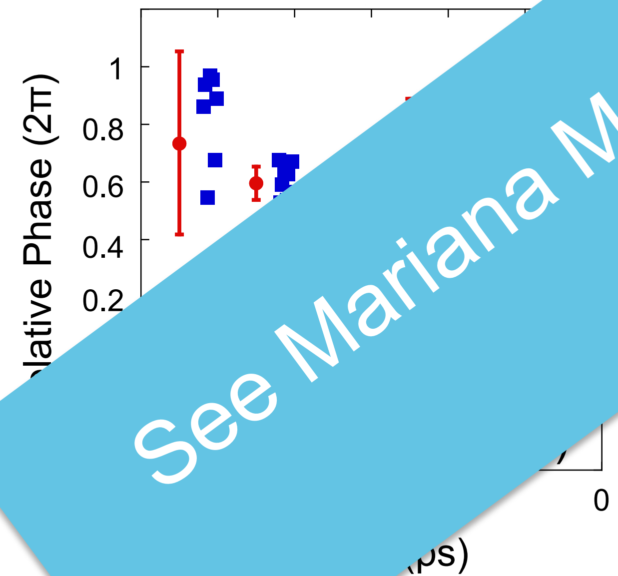
SSM PHASE

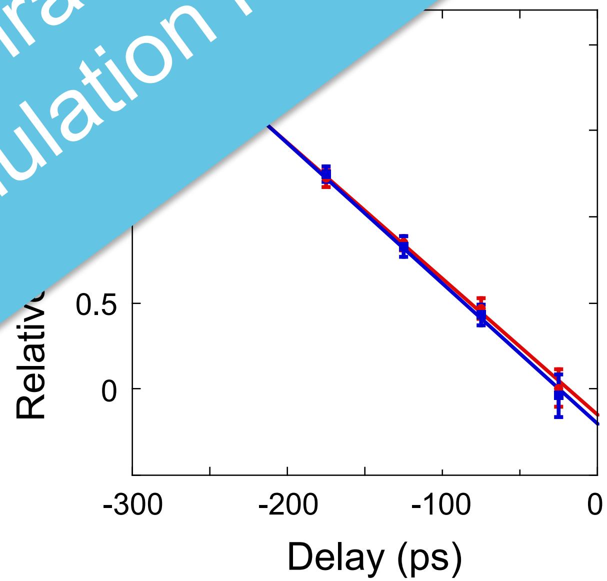
Preliminary!!!





See Mariana Moreira's talk on Thursday for simulation results





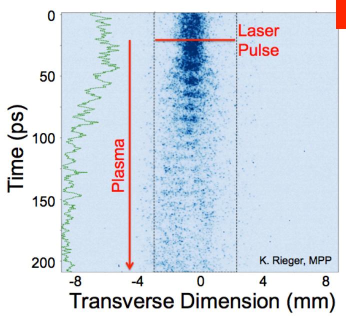
- ✧ Va… …unch parameters (σ_z, σ_r, N, …) => phase variation?
- ✧ Rela… phase varies by ≤$0.2\lambda_{pe}$

SSM FREQUENCY

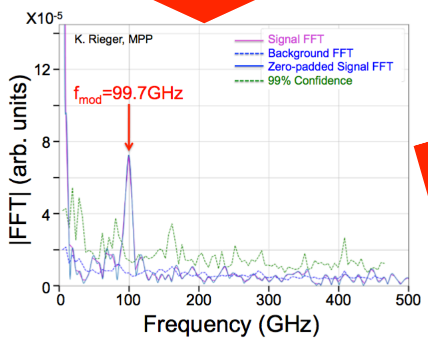
AWAKE, Phys. Rev. Lett. 122, 054802 (2019)

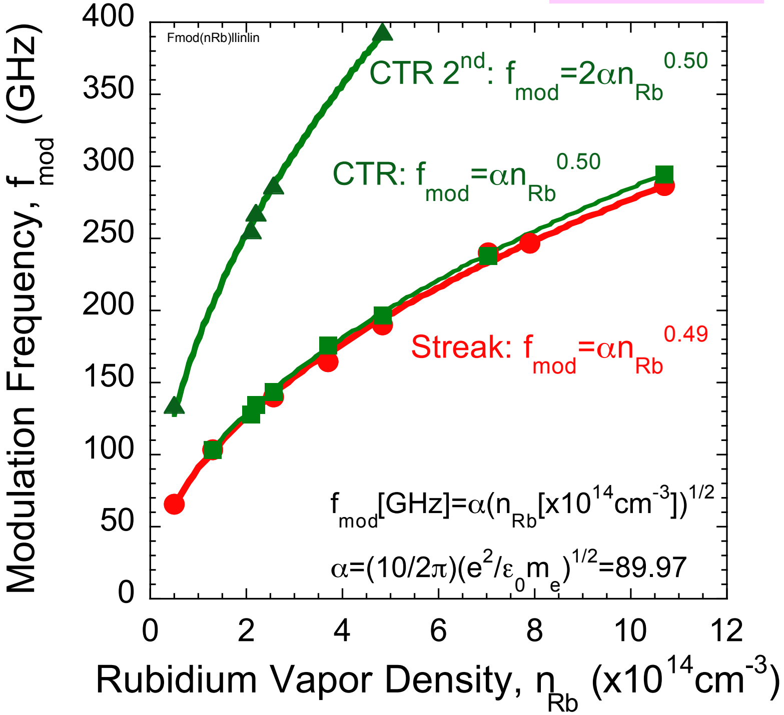
Preliminary!!!

OTR



FFT





CTR

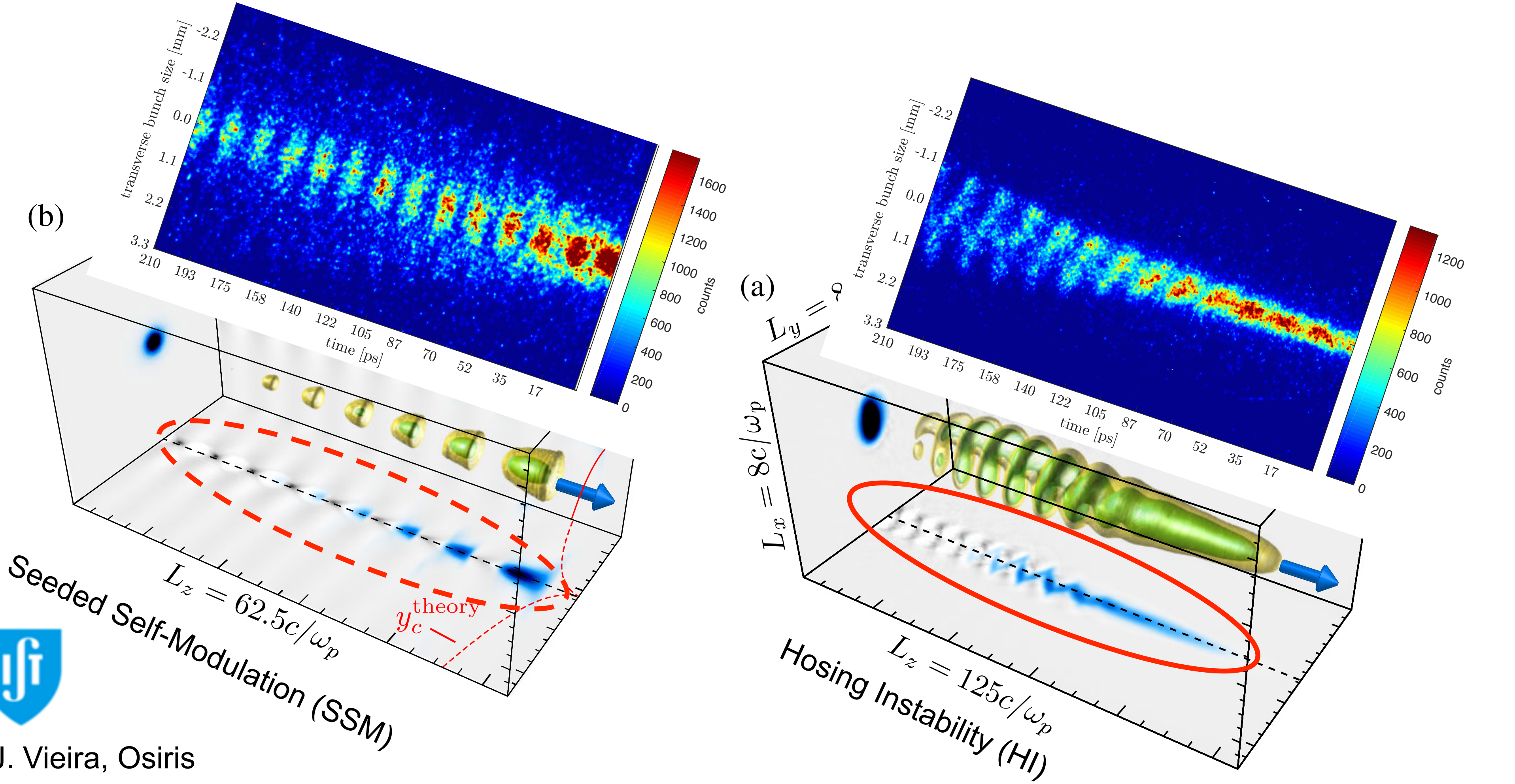
K. Rieger,
M. Martyanov,
F. Braunmueller, MPP

$$\omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$$ Plasma Frequency

- ✧ $f_{mod} \sim n_{Rb} \rightarrow n_e = n_{Rb}$ ionization and $f_{mod} \sim f_{pe}$
- ✧ CTR signal detected at harmonics (not calibrated)
- ✧ Modulation is nonlinear

HOSiNG INSTABiLiTY

✧Self-modulation (SMI, SSM) cylindrically symmetric (2D)



J. Vieira, Osiris

✧Hosing instability within frequency ω_{pe}

✧Observed only with low n_{e0}

M. Huether

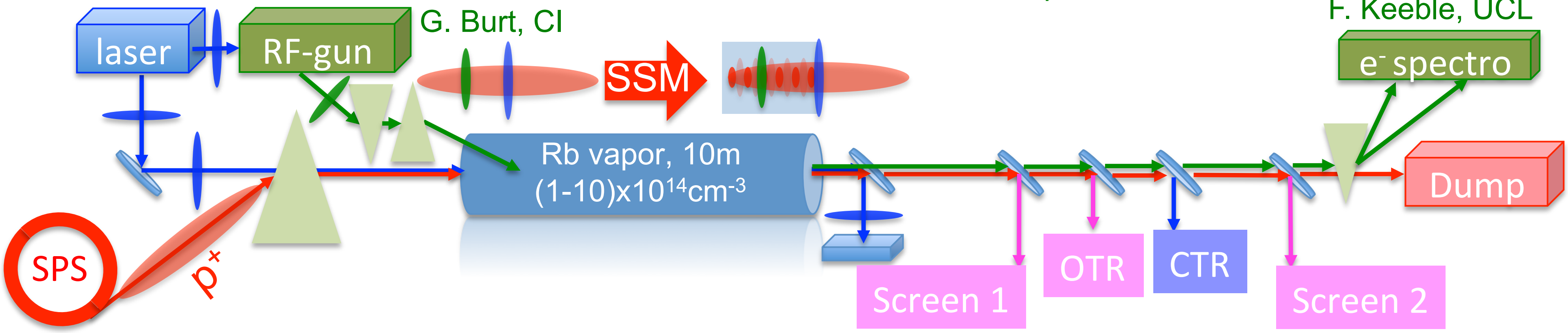
Work in progress!!

J. Vieira et al., Phys. Rev. Lett. 112, 205001 (2014).

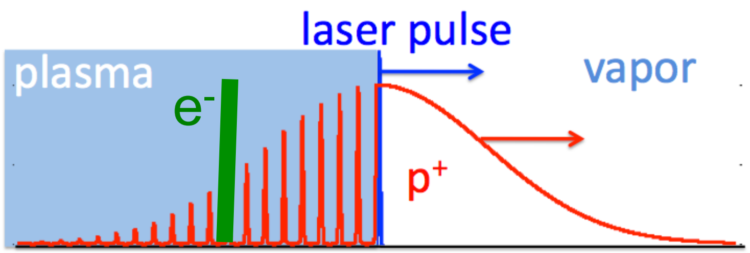
WAKEFIELDS SAMPLING / ACCELERATION

S. Doebert, C. Bracco, F. Velotti, CERN, K. Pepitone, CERN, G. Burt, CI

F. Keeble, UCL



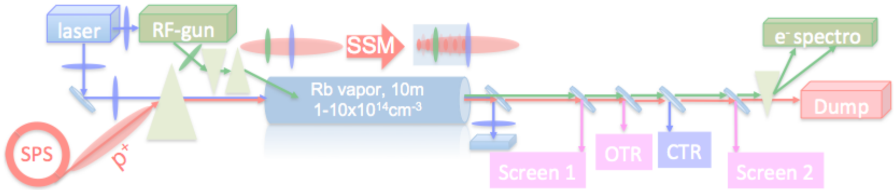
- SSM ⇔ transverse wakefields
- Acceleration to sample longitudinal wakefields
- "long" e^- bunch: $\tau_{z,e-} \sim 1/f_{pe}$

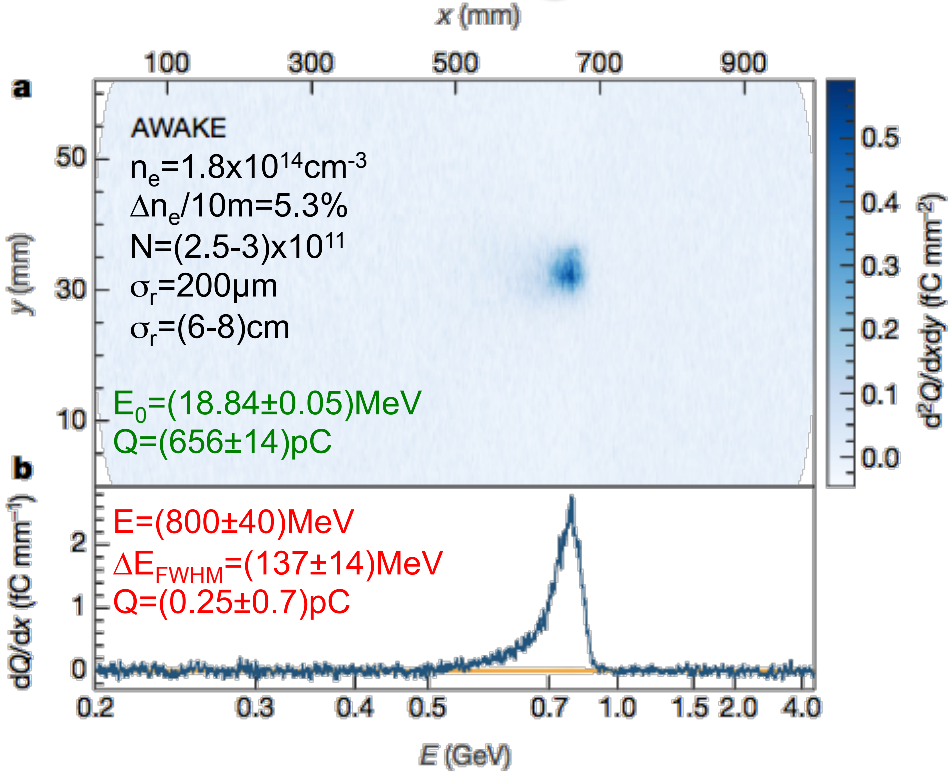


Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

WAKEFIELDS SAMPLING / ACCELERATION

AWAKE

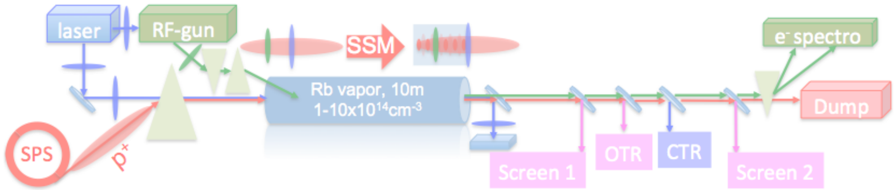


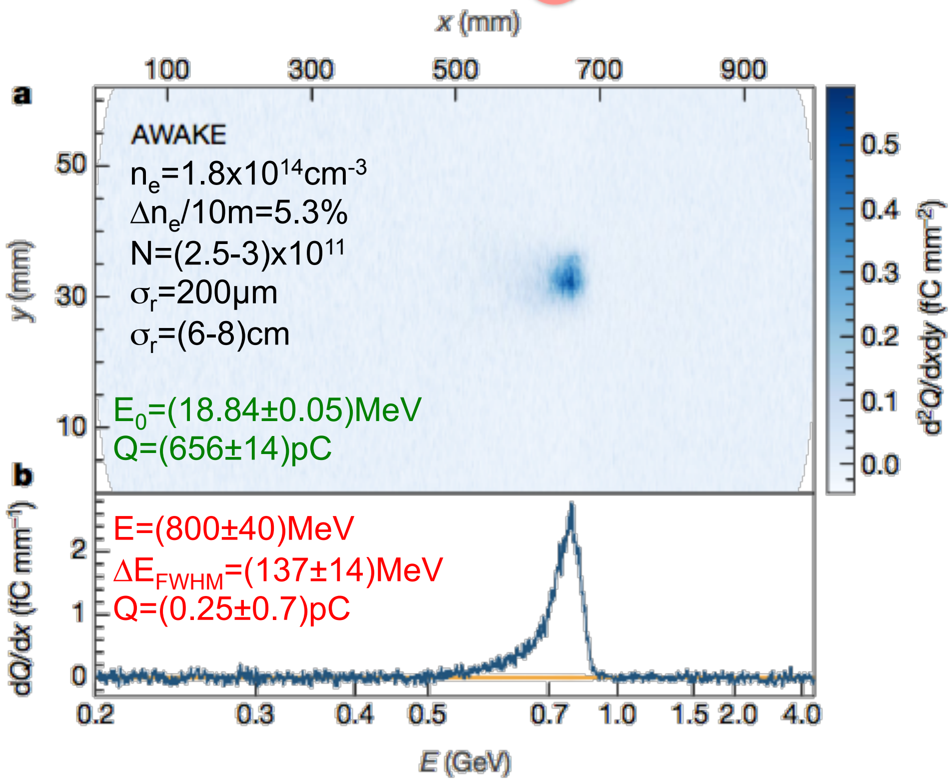


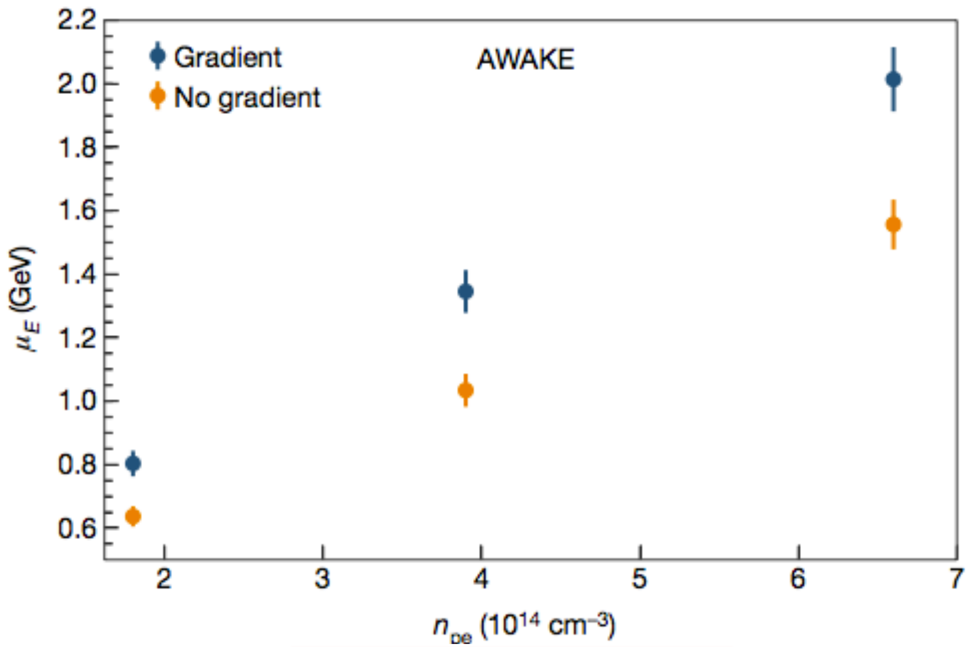
- ✧ Injection at an angle (~1-3mrad)
- ✧ Finite $\Delta E/E$

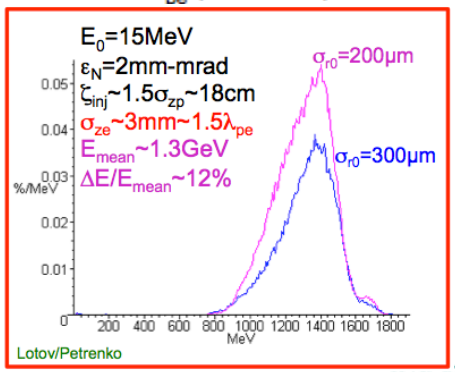
AWAKE, Nature 561, 363 (2018)

WAKEFIELDS SAMPLING / ACCELERATION





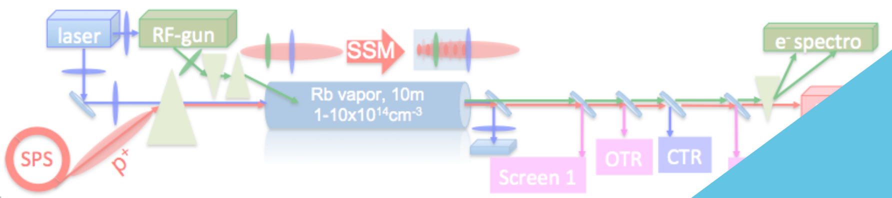


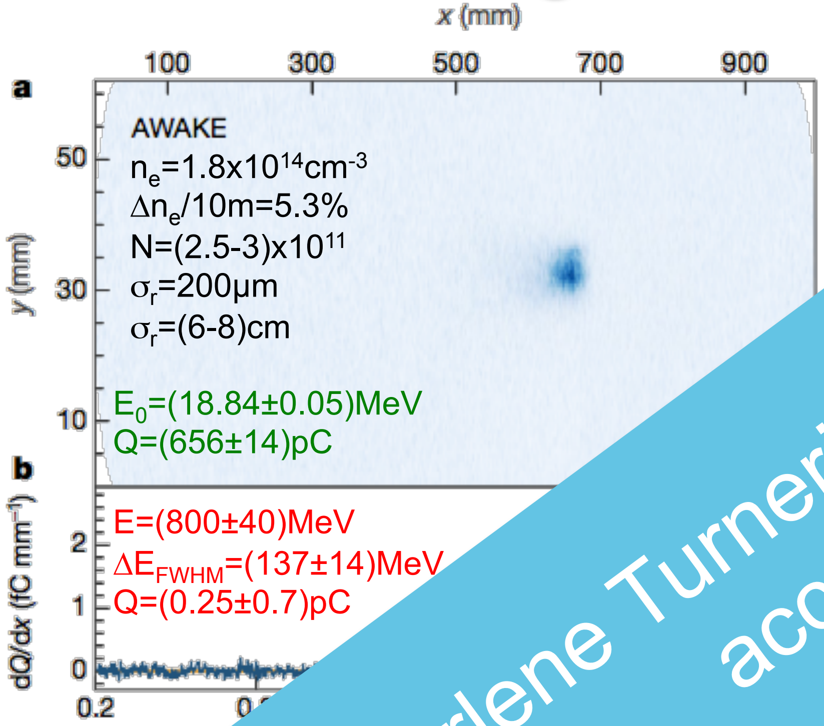


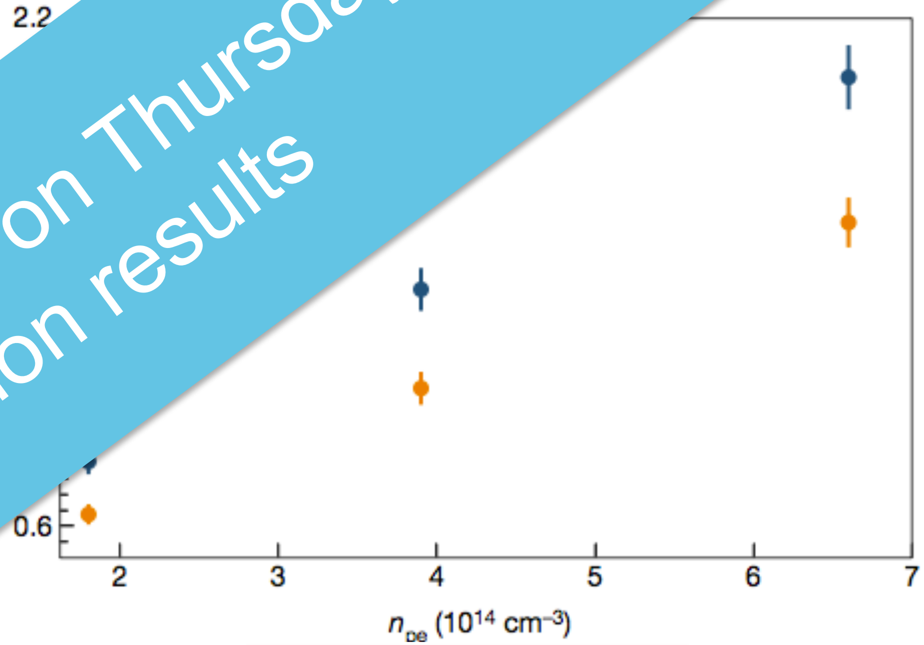
- ✧ Injection at an angle (~1-3mrad)
- ✧ Finite ΔE/E
- ✧ Up to 2GeV energy gain
- ✧ Captured charge: ~pC

AWAKE, Nature 561, 363 (2018)

WAKEFIELDS SAMPLING / ACCELERATIO







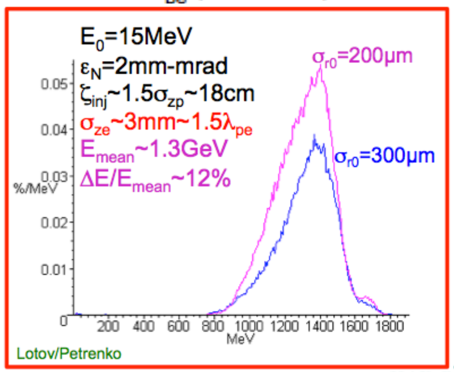
See Marlene Turner's talk on Thursday for more acceleration results

✧ ... rad)

✧ Fi...

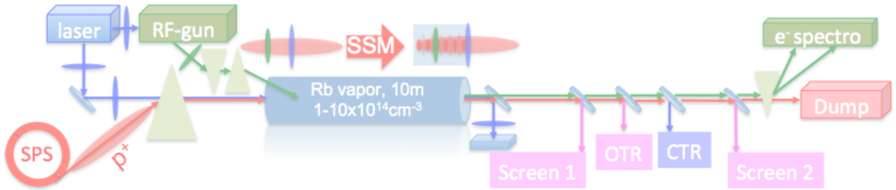
✧ Up ... gain

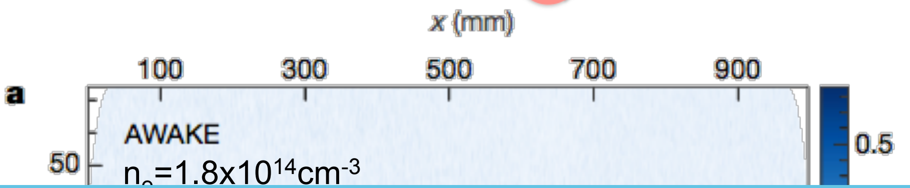
✧ Captu... ~pC

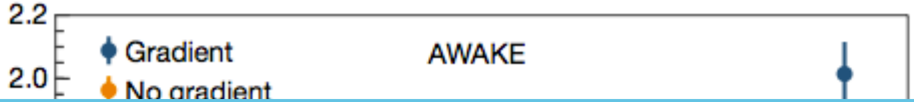


AWAKE, Nature 561, 363 (2018)

WAKEFiELDS SAMPLiNG / ACCELERATiON



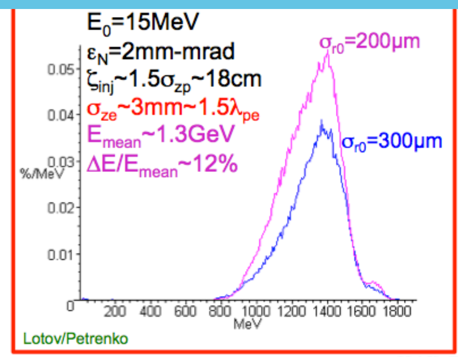




2nd goal of AWAKE (2018):
Externally inject (~15MeV) electrons
into the wakefields
and
reach ~GeV energy gain with finite $\Delta E/E$

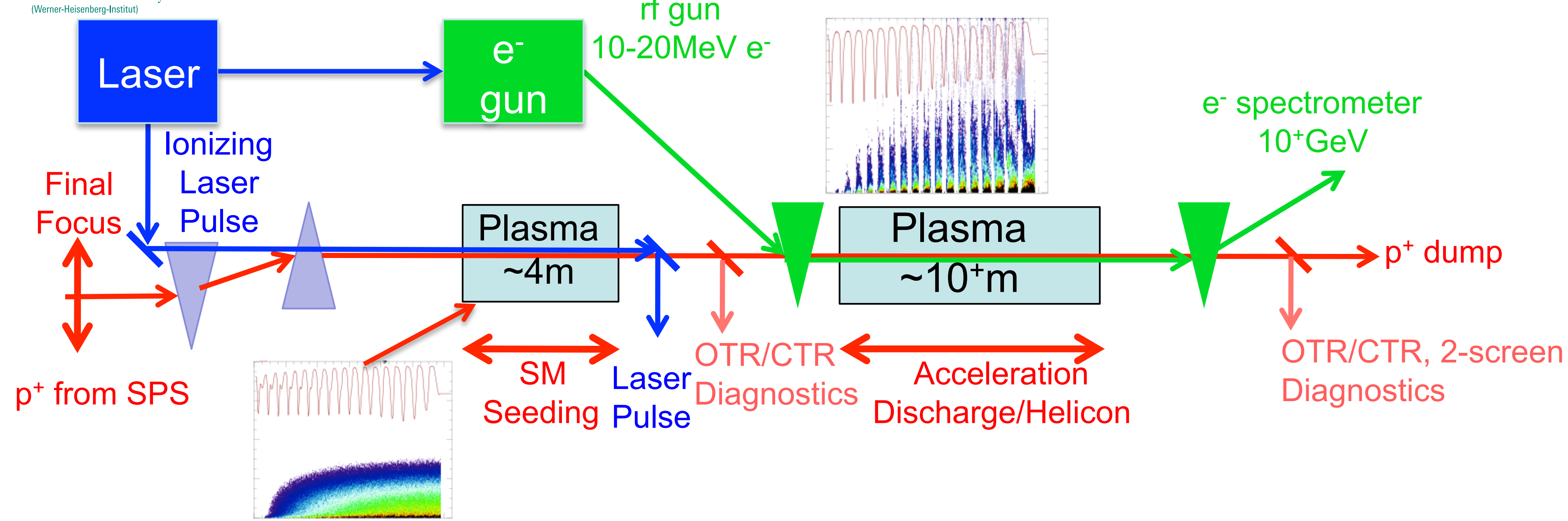
E (GeV)

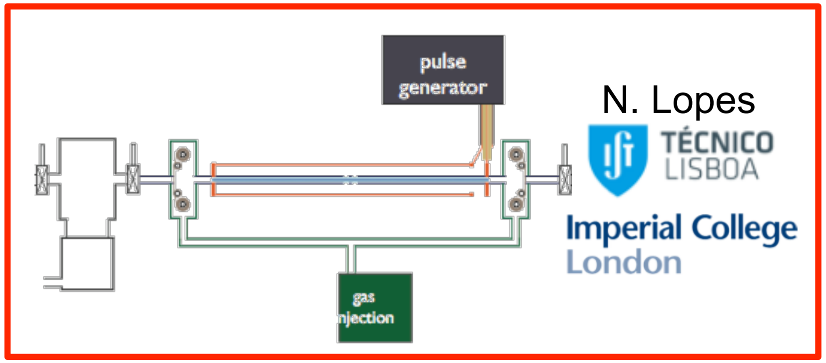
- ✧ Injection at an angle (~1-3mrad)
- ✧ Finite $\Delta E/E$
- ✧ Up to 2GeV energy gain
- ✧ Captured charge: ~0.25pC

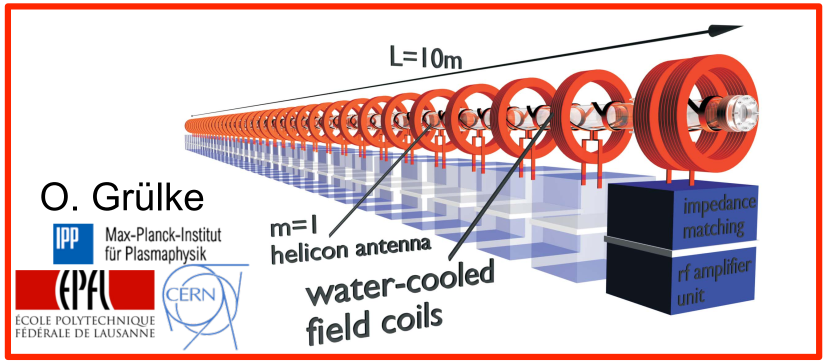


AWAKE, Nature 561, 363 (2018)

EXPERIMENTAL SETUP RUN II







✧ Laser ionization of a metal vapor (Rb), 3-4m plasma for p+ SSM only, SEEDING NECESSARY!

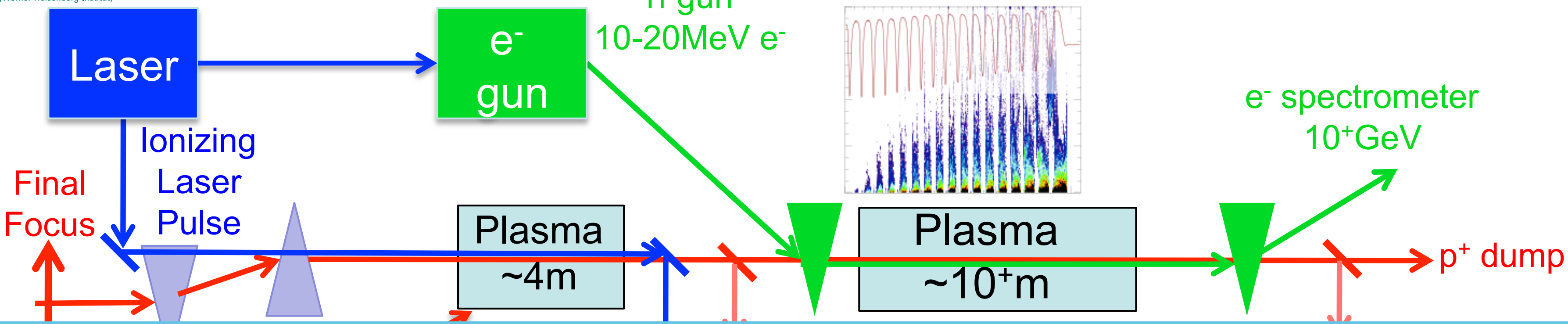
✧~10m discharge or helicon source for acceleration only (scales to 100's m)

✧Inject short e- bunch (σ_z<<λ_{pe}), quality of the bunch: $\Delta E/E$, ε => beam loading and blow-out

✧Bunch rather than particle acceleration ….

✧2021-LS3, **RUN II**

EXPERiMENTAL SETUP RUN II



AWAKE Run 2:

-demonstrate acceleration of an e^- bunch

(blow-out, beam loading, matching, $\tau_{z,e-}$~$1/f_{pe}$ => $\Delta E/E$, ε)

-Scalability of plasma source and acceleration

"From Acceleration to Accelerator"

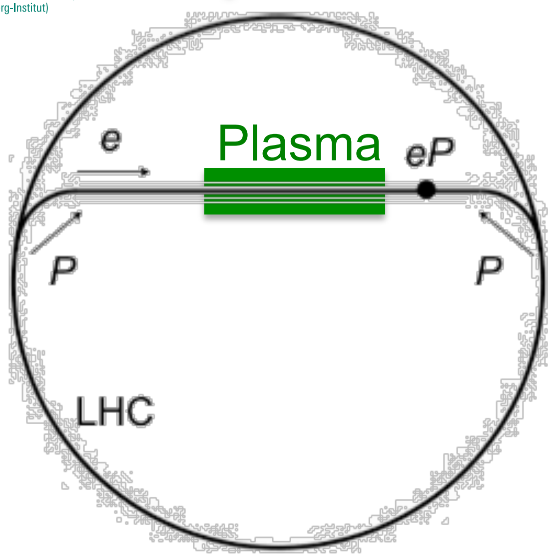
✧~10m discharge or helicon source for acceleration only (scales to 100's m)

✧Inject short e^- bunch ($\sigma_z \ll \lambda_{pe}$), quality of the bunch: $\Delta E/E$, ε => beam loading and blow-out

✧Bunch rather than particle acceleration ….

✧2021-LS3, **RUN II**

p^+-DRIVEN PWFA FOR e^-/p^+ COLLIDER

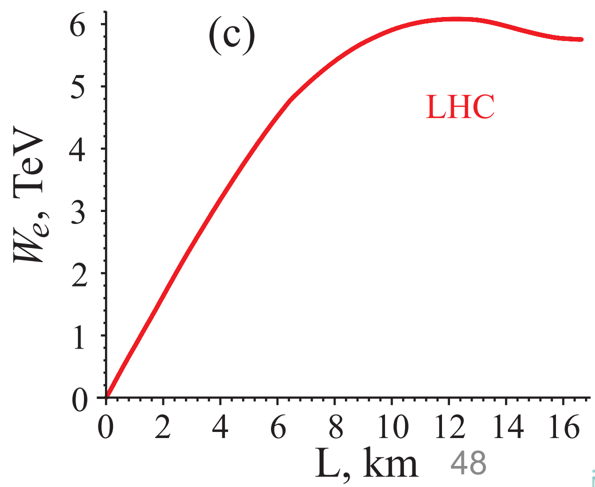


- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
  - ~*3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4\ \mu m$

$$\mathcal{L} = f\frac{N_e \cdot N_p}{4\pi\sigma_x \cdot \sigma_y}$$
$$\approx 5 \cdot 10^{28}\text{cm}^{-2}\text{s}^{-1}$$

simulation of existing LHC bunch in plasma with trailing electrons …

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



+ fixed target or beam dump experiments …

A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463.

SUMMARY

- AWAKE aims at ~1GeV/m gradient using the seeded self-modulation (SSM) of a long p^+ bunches in a plasma ($\sigma_z >> \lambda_{pe}$) => e^- acceleration
- Important/interesting SSM results:
  - SSM seeding
  - Modulation phase stability against p^+ bunch variations: key for e^- injection and acceleration, NO instability
- Acceleration of externally injected e^- possible
  - 18MeV => ~2GeV, $\Delta E/E << 1$
- Interesting beam-plasma interaction physics results
  - SSM growth
  - Observe and control SSM-SMI-HI, Hi @ ω_{pe}
  - $f_{SSM,SMI\text{-}HI} = f_{Rb} = f_{pe}$
  - Ionization front and e^- bunch seeding
- Run II: (2021-): two plasmas, SSM, quality of the accelerated e^- bunch: $\Delta E/E$, ε, …
- Application of p^+-driven-PWFA: e^-/p^+ collisions

E. Gschwendtner et al., Nucl. Instr. and Meth. in Phys. Res. A 829, 76 (2016)
E. Öz et al., Nucl. Instr. and Meth. in Phys. Res. A 829, 321 (2016)
E. Öz et al., Nucl. Instr. Meth. Phys. Res. A 740(11), 197 (2014)
A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463
A. Caldwell et al., Nucl. Instrum. A 829 (2016) 3
P. Muggli et al., Plasma Physics and Controlled Fusion, 60(1) 014046 (2017)

Thank you to my collaborators!

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