First Experimental Results of the AWAKE Experiment

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MAX-PLANCK-GESELLSCHAFT

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AWAKE?

AWAKE is*:

a p^+-driven, plasma wakefield acceleration experiment

aiming to

accelerate e^- to high energies (GeV-TeV)

for application to HEP (e^-/p^+)

1st step: p^+ bunch self-modulation

*AWAKE = Advanced WAKefield Experiment

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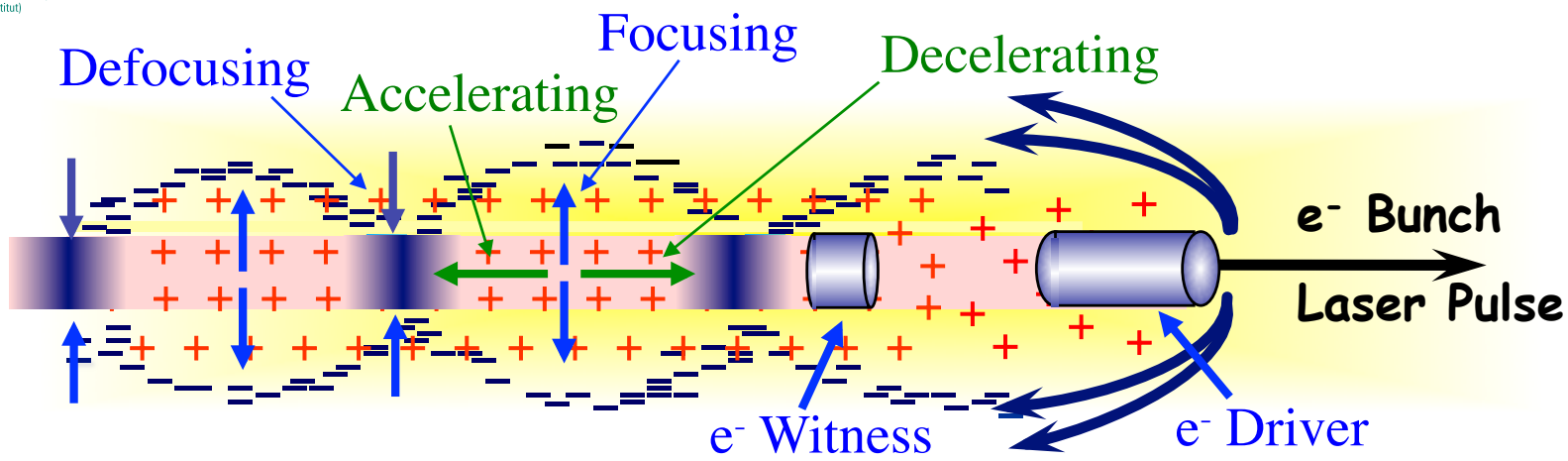
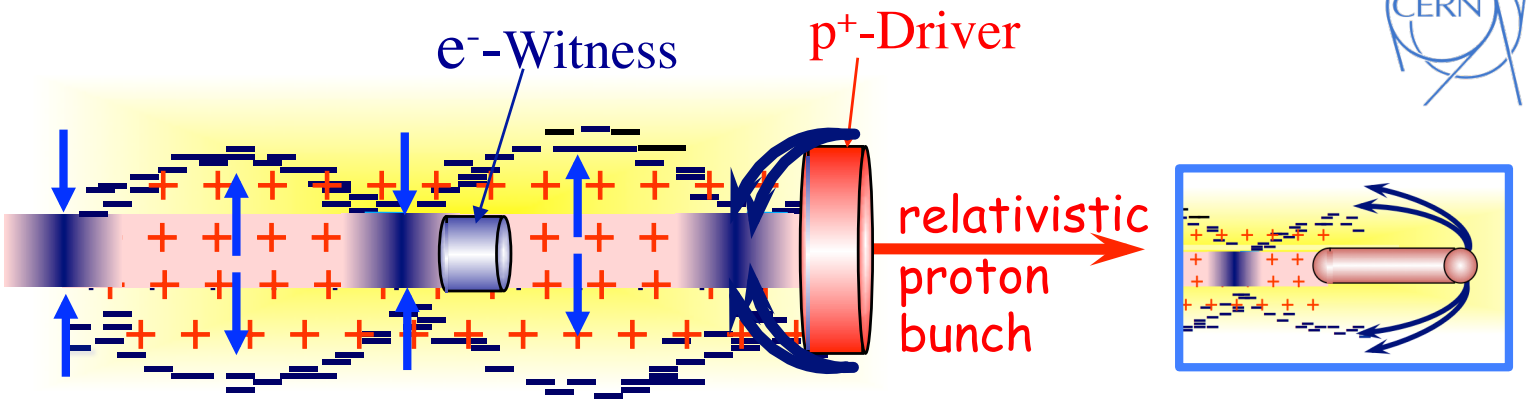
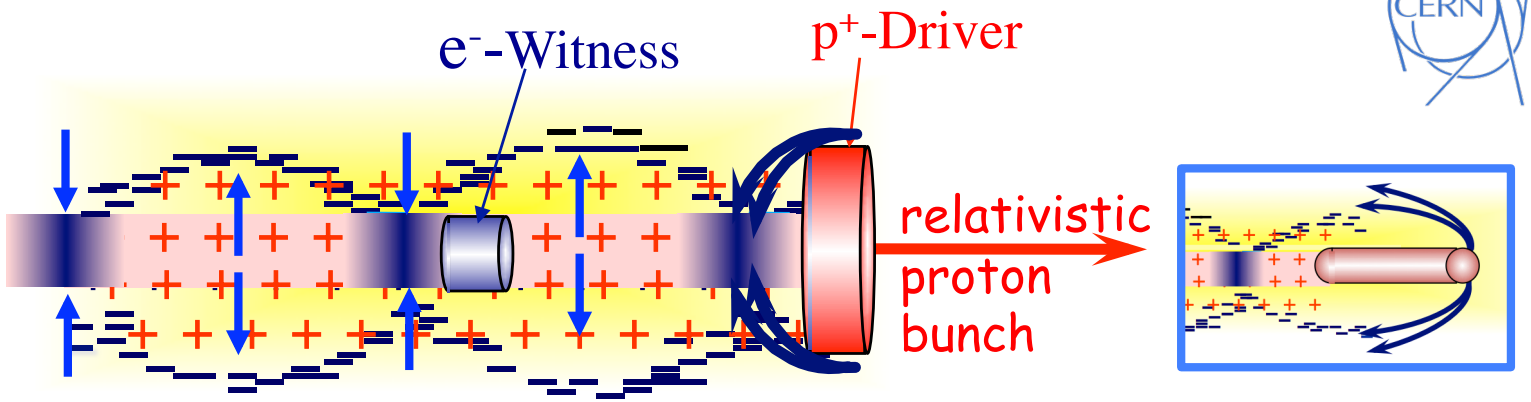
PLAMA WAKEFIELDS & ENERGY TRANSFER



p⁺-DRIVEN PWFA



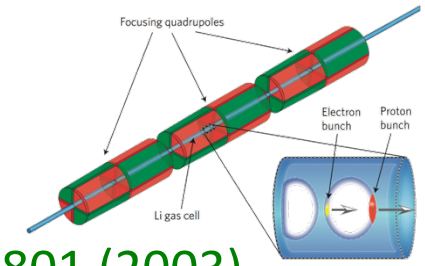
p^+-DRIVEN PWFA



- ILC-CLIC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- CERN-SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  CERN-LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- A single LHC bunch could produce an ILC bunch in a single PWFA stage!

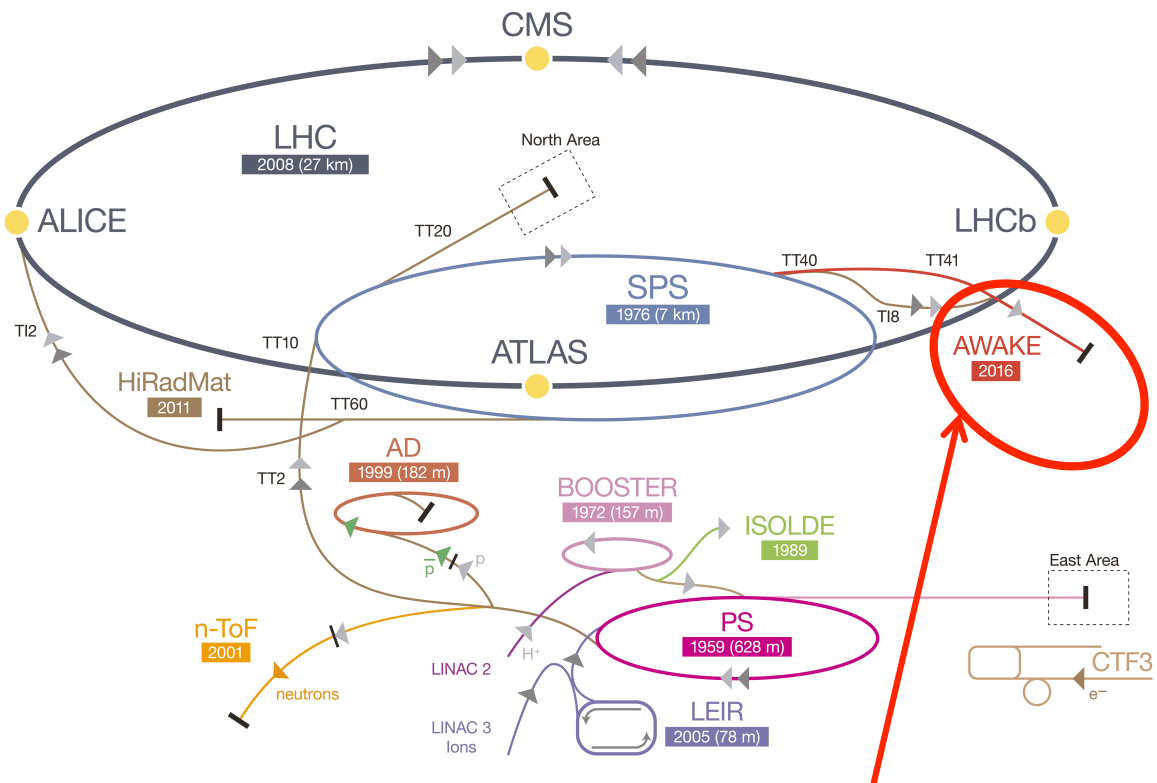
Caldwell, Nat. Phys. 5, 363, (2009)

- No staging …
- Large average gradient! (≥1GeV/m, 100's m)
- Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)



PROTON BEAMS @ CERN

CERN's Accelerator Complex



AWAKE experimental area

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

σ_z=12cm!!

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

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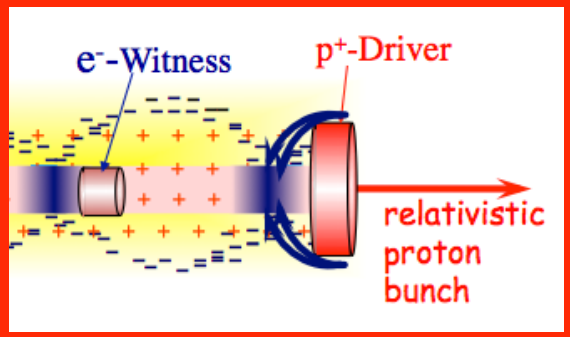
PROTON BEAMS @ CERN

CERN's Accelerator Complex

Parameter	PS	SPS	SPS Opt

Scaling

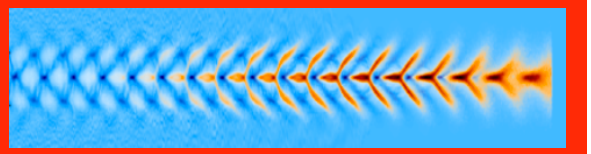


$\lambda_{pe} \sim \sigma_z$, $k_{pe}\sigma_z \sim 1$

$\lambda_{pe} = 2\pi c/\omega_{pe} = 2\pi c/(n_e e^2/\varepsilon_0 m_e)^{1/2}$

$\sigma_z = 12\text{cm} \sim \lambda_{pe} \rightarrow n_e \sim 8\times10^{10}\text{cm}^{-3}$

$\rightarrow E_{WB} = mc\omega_{pe}/e = 2\pi mc^2/e\lambda_{pe} \sim 27\text{MV/m}$



$\rightarrow \lambda_{pe} \sim \sigma_r = 200\mu\text{m}$, $k_{pe}\sigma_r \sim 1$, $n_e \sim 7\times10^{14}\text{cm}^{-3}$

$\rightarrow E_{WB} \sim 2.5\text{GV/m}$, $f_{pe} \sim 237\text{GHz}$

$\rightarrow \sigma_z \sim 12\text{cm}$ with period $\lambda_{pe} \sim 1.2\text{mm}$!!

$\rightarrow$ Use seeded self-modulation (SSM)

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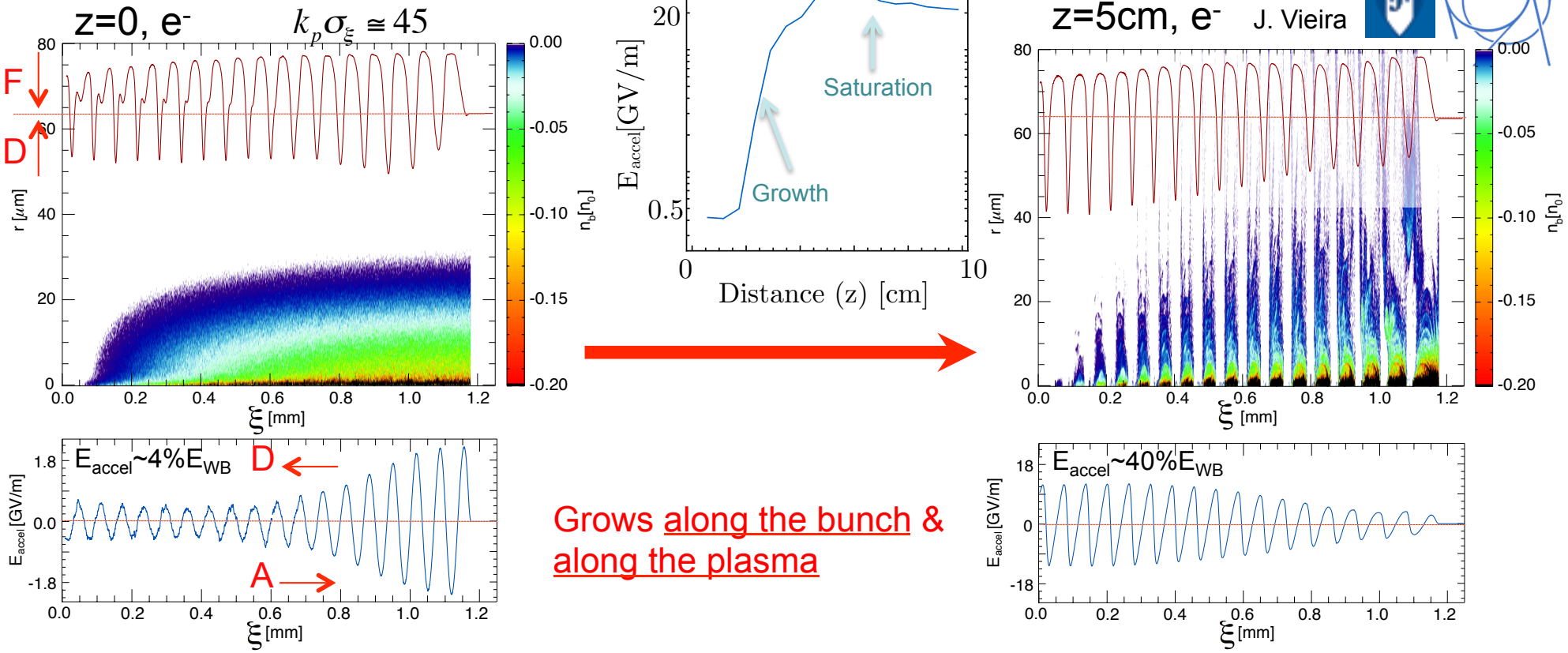
SEEDED SELF-MODULATION (SSM)



Grows along the bunch & along the plasma

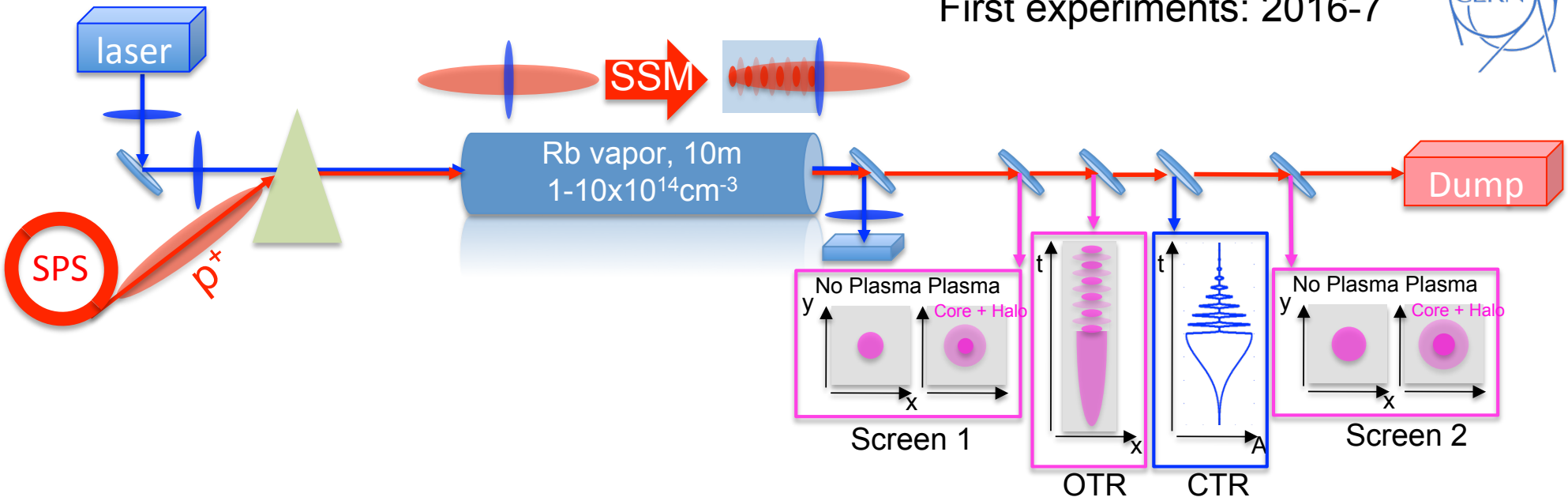
Kumar et al., PRL 104, 255003 (2010)
Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

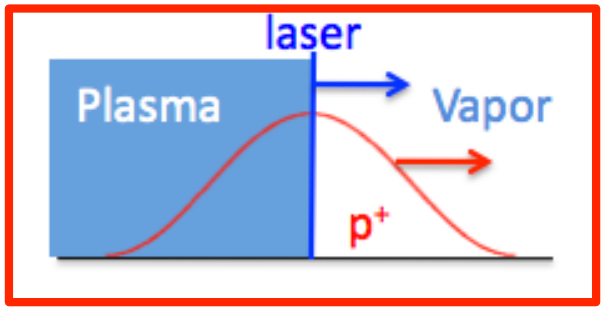
- Initial seed transverse wakefields modulate the bunch density with period $\sim\lambda_{pe} << \sigma_{z,\xi}$
- Longitudinal wakefields reach large amplitude through resonant excitation

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

AWAKE EXPERIMENT

First experiments: 2016-7





✧Ionization front seeding

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RUBIDIUM VAPOR SOURCE

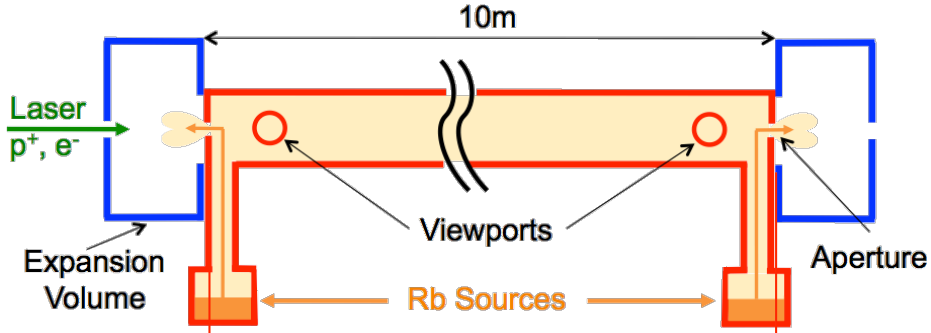
Source requirements:
- ✧$10^{14} \le n_e \le 10^{15} cm^{-3}$
- ✧$\Delta n_e/n_e < 0.2\%$
- ✧Few cm n_e ramp

$\xrightarrow[\text{Field-ionization}]{\text{Laser}}$

$n_e = n_{Rb}$

Same for n_{Rb}

$r_p > 1mm$

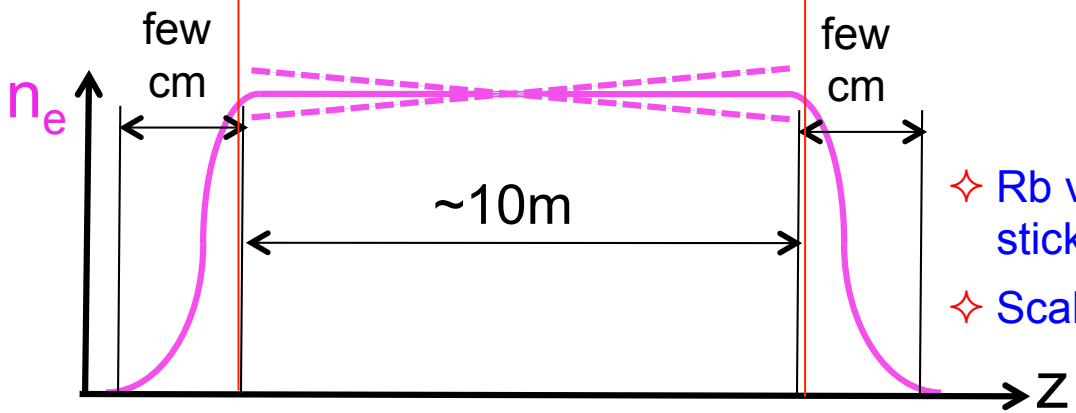


F. Batsch (MPP)
E. Oz (MPP)
R. Kersevan (CERN)
G. Plyushchev (CERN/MPP/EPFL)

✧Impose very uniform T: $\delta n_{Rb}/n_{Rb} = \delta T/T < 0.2\%$

✧$160 \le T \le 220°C$ for $10^{14} \le n_{Rb} \le 10^{15} cm^{-3}$

✧Control n_{Rb} gradient with Rb source T



✧ Rb vapor expands into vacuum and sticks to cold walls: short ramp

✧ Scale length ~ diameter aperture: 1cm

✧n_{Rb} measured at both end with <0.3% accuracy using white light interferometry

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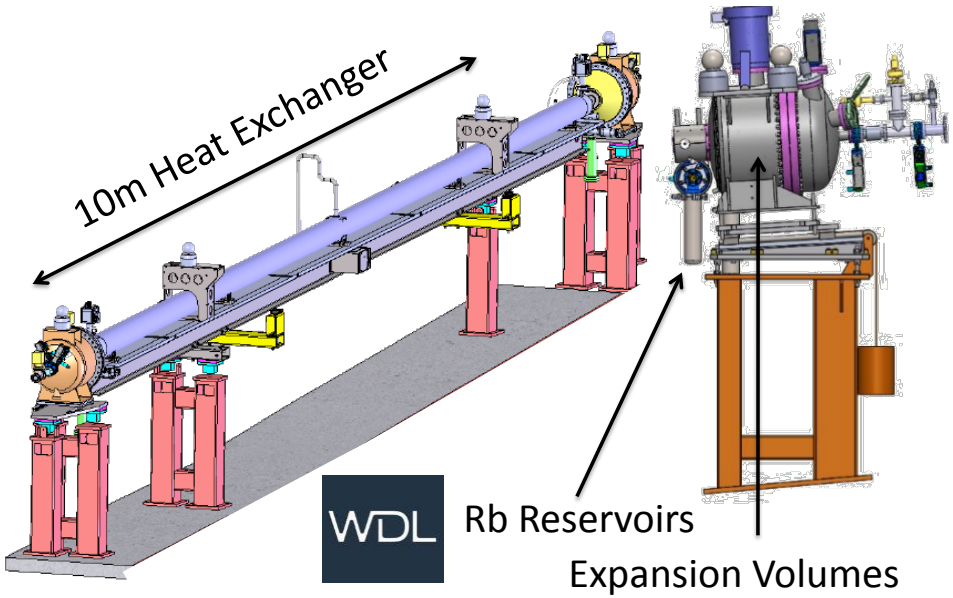
Rb VAPOR SOURCE (heat exchanger)

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

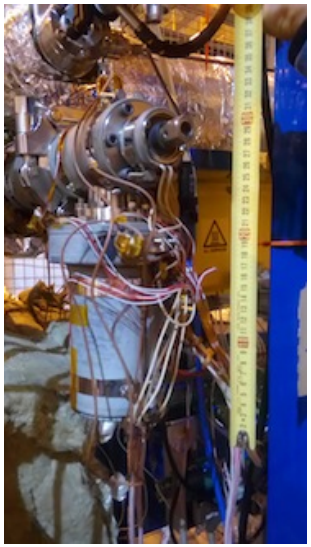
AWAKE

CERN

Development of the ends



Installed in AWAKE!



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Rb VAPOR SOURCE (heat exchanger)

Development of the ends

Installed in AWAKE!

Measured ΔT<0.5°C, 150-210°C

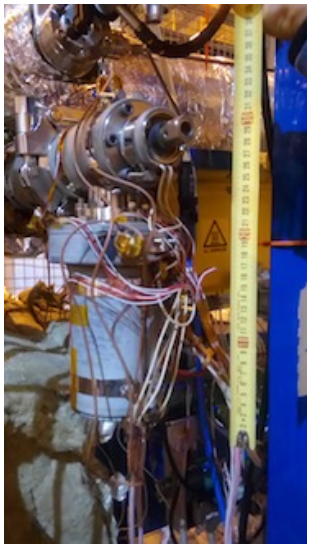
ΔT/T~0.1%

Source satisfies density uniformity requirements

WDL

Rb Reservoirs

Expansion Volumes



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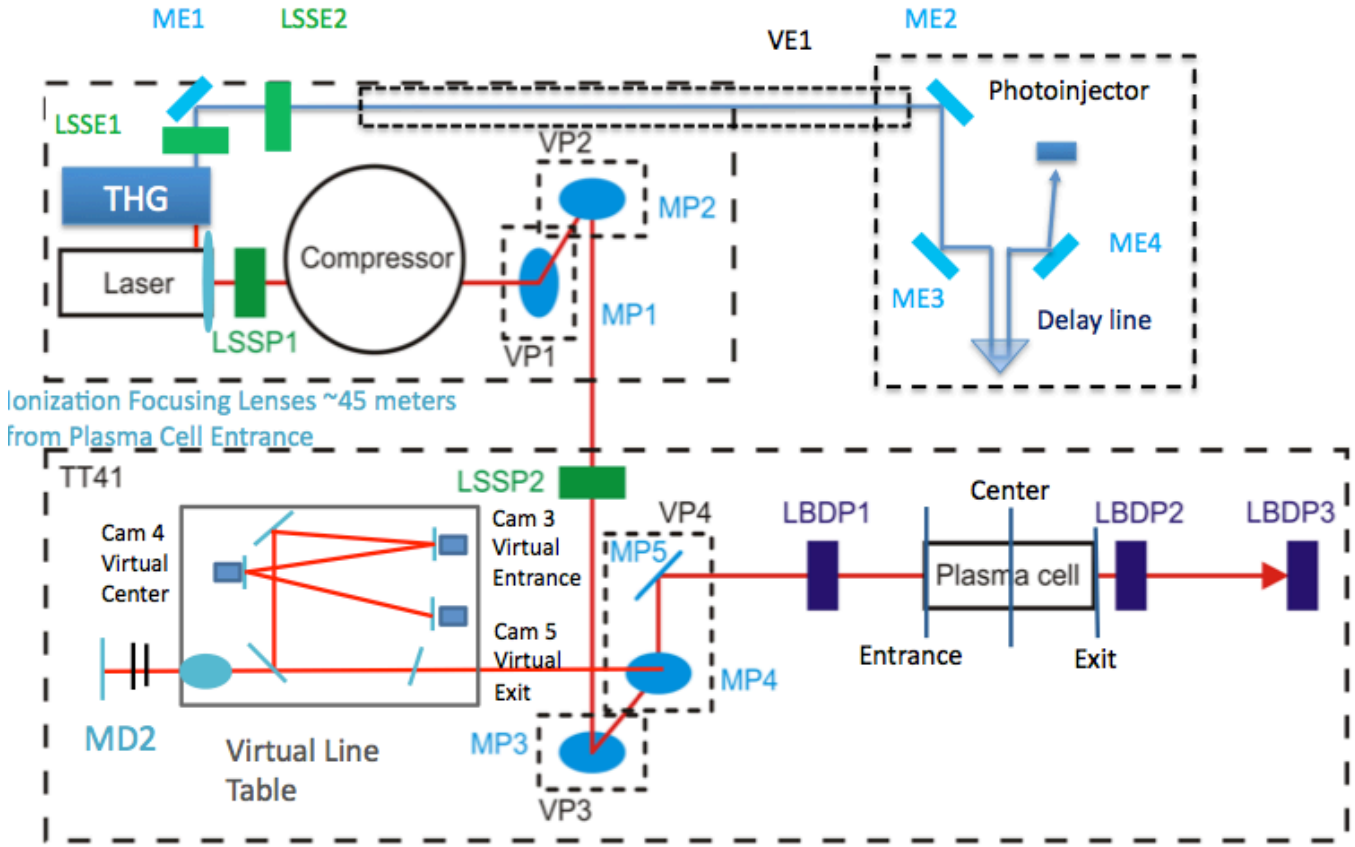
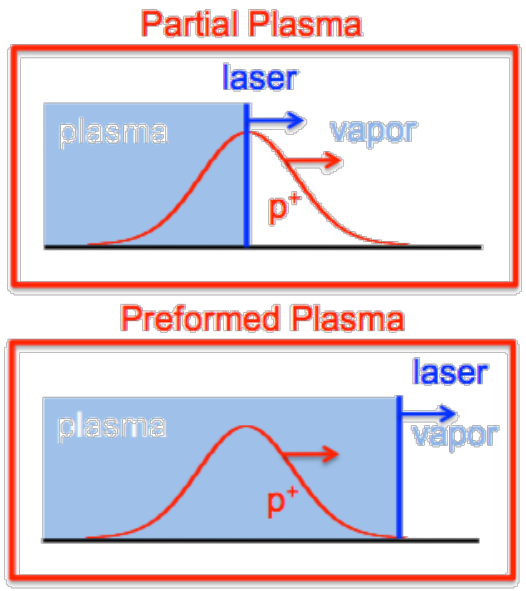
LASER & PLASMA





J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN

- ✧Fiber/Ti-Sapphire laser: ~100fs, E_{max}=450mJ
- ✧Rb: ϕ_{IP}=4.177eV, I_{app}~1.7x10^{12}Wcm^{-2},
- ✧r_0~1mm, Z_R~5m, I_{max}>10x10^{12}Wcm^{-2}
- ✧Field ionization => n_e=n_{Rb}, uniformity and ramps
- ✧Virtual plasma for alignment

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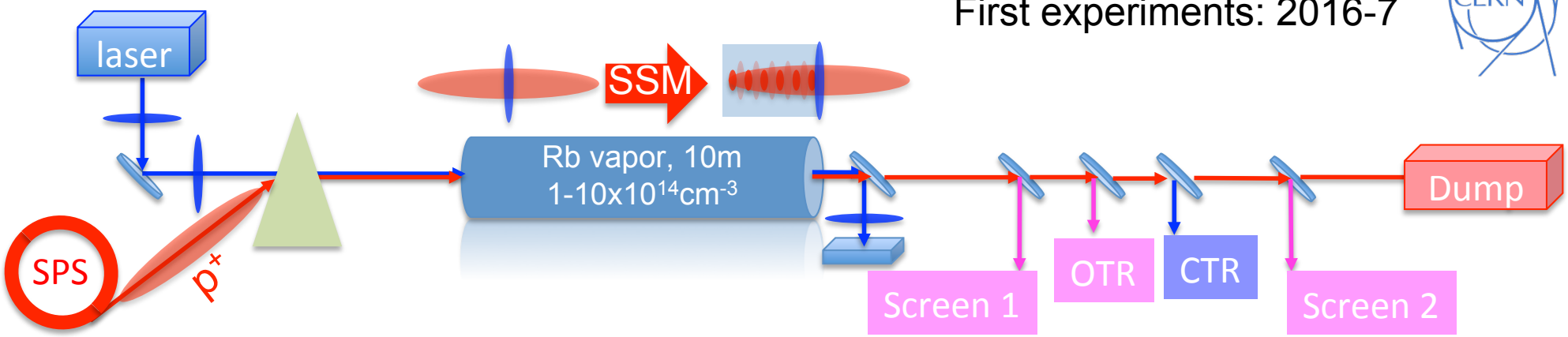
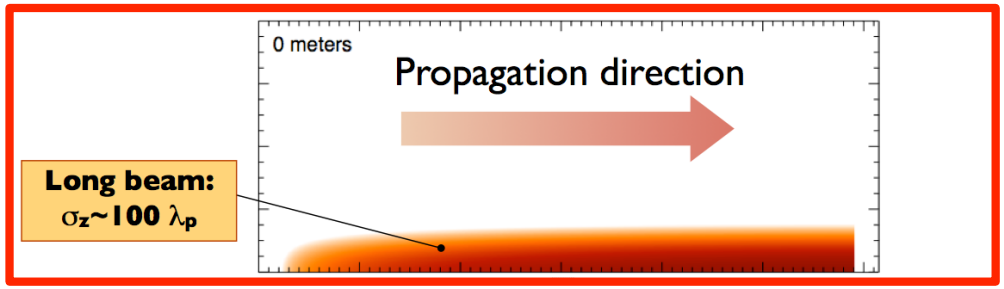
AWAKE EXPERIMENT @ CERN

First experiments: 2016-7





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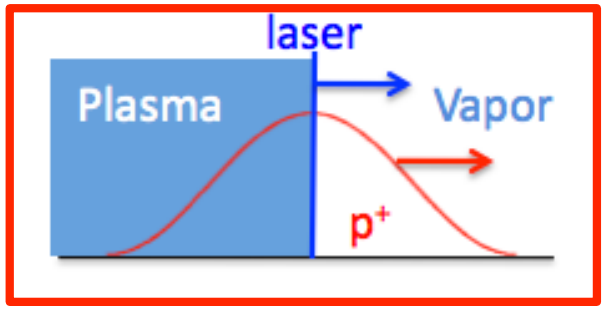

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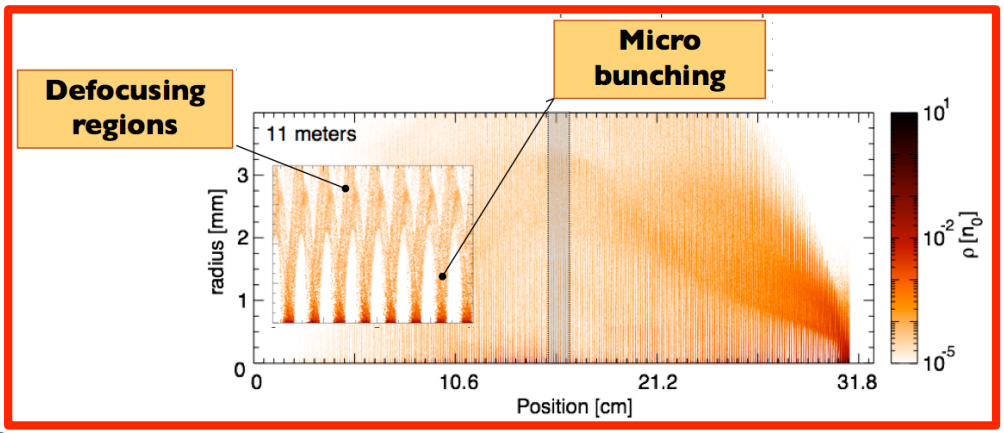

- The long (σ_z~12cm) p$^+$ bunch self-modulates with period λ_{pe}~1.2mm (n_e~7x10^{14}cm^{-3})
- ~100λ_{pe} per σ_z

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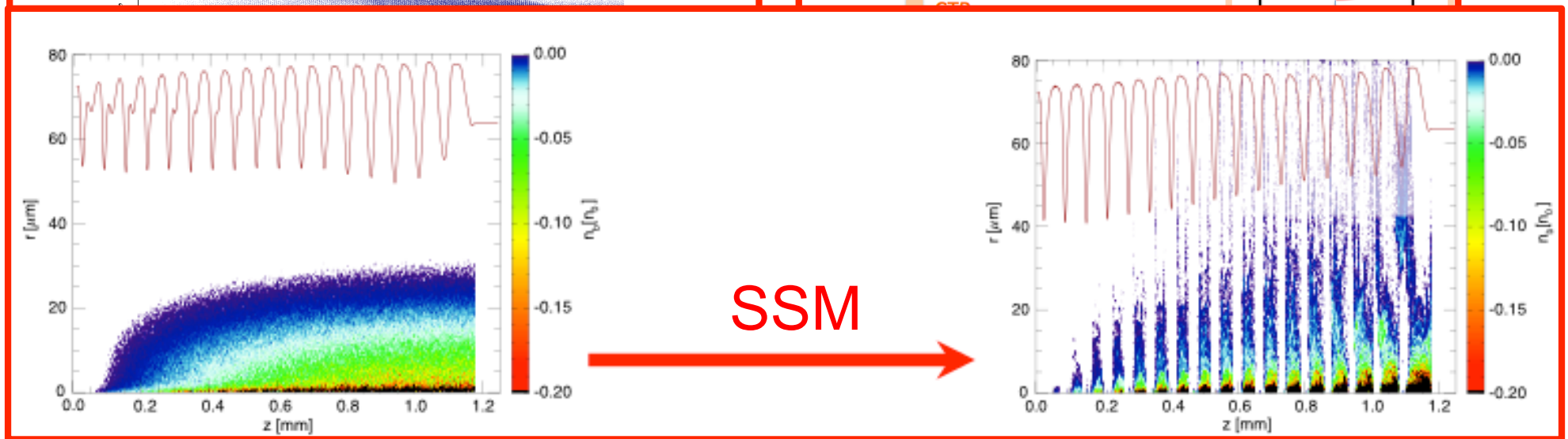
AWAKE EXPERIMENT @ CERN

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



AWAKE EXPERIMENT @ CERN

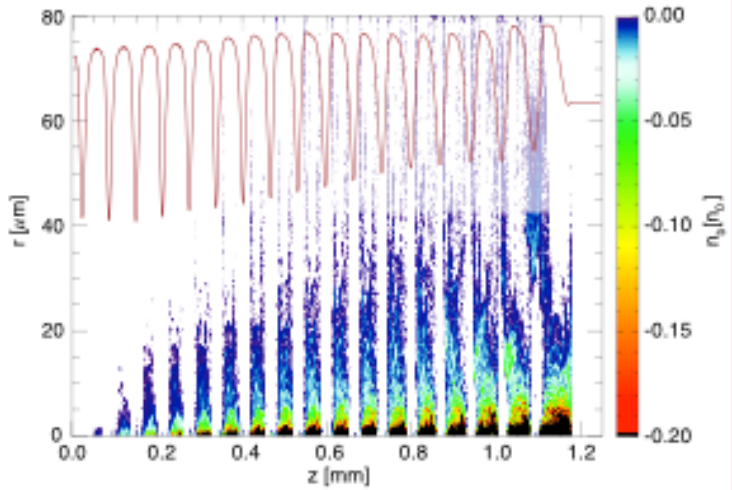
First experiments: 2016-7

1st goal of AWAKE (2016-17):
demonstrate and study
the seeded self-modulation (SSM)
of a long p^+ bunch in a dense plasma
$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$

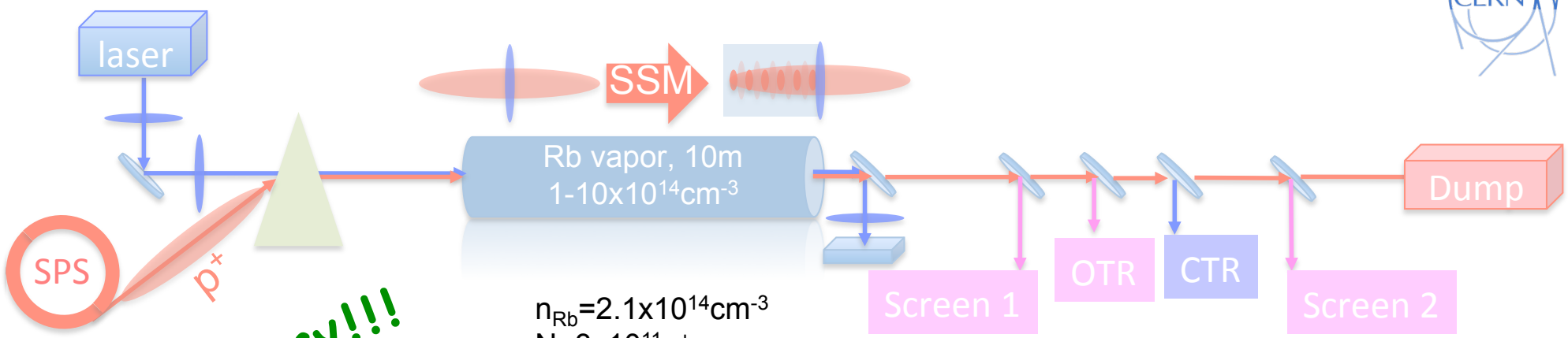
Three p^+ bunch observables

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

SSM

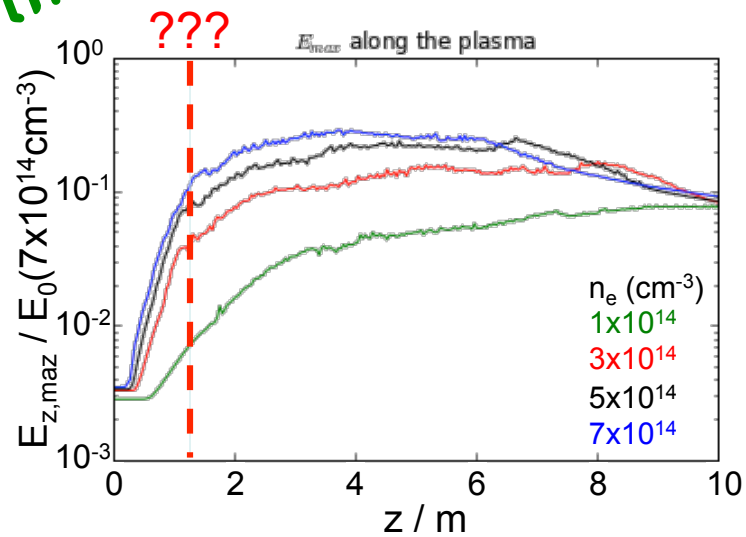


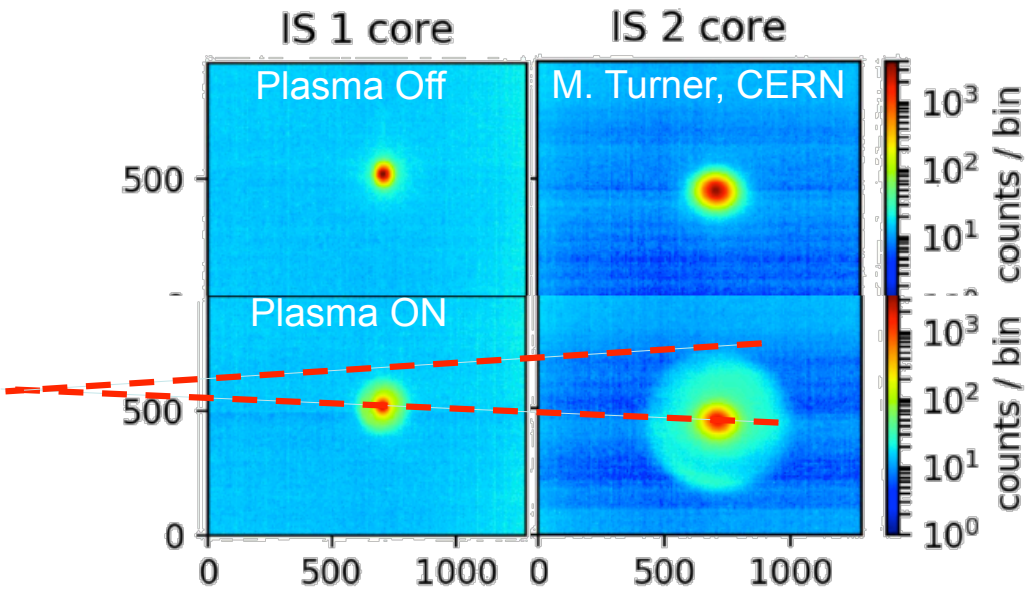
TWO-SCREEN SSM



Preliminary!!!

n_{Rb}=2.1x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Short, 1/2





- ✧p$^+$ defocused by the transverse wakefield (SSM) form a halo
- ✧p$^+$ focused form a tighter core
- ✧Information about saturation length?
- ✧Estimate of the transverse wakefields amplitude ($\int W_{per} dr$)

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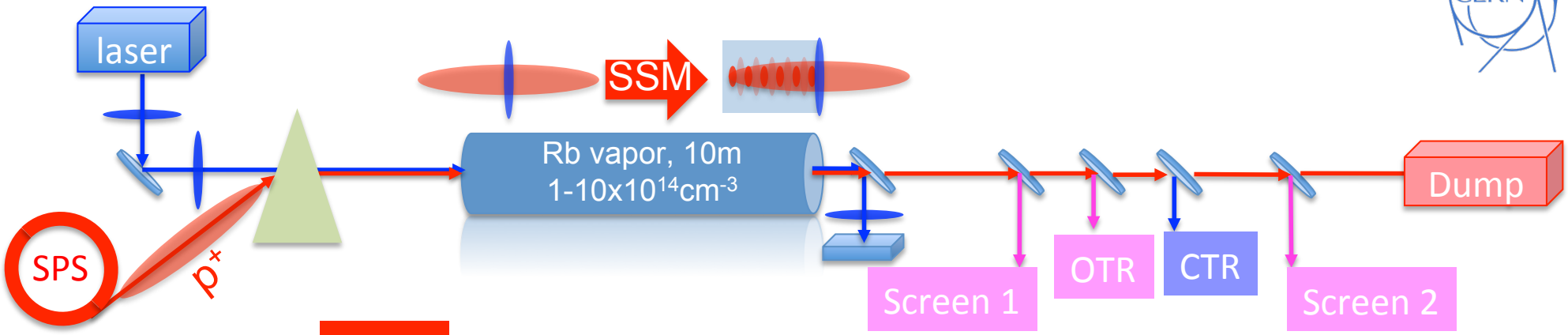
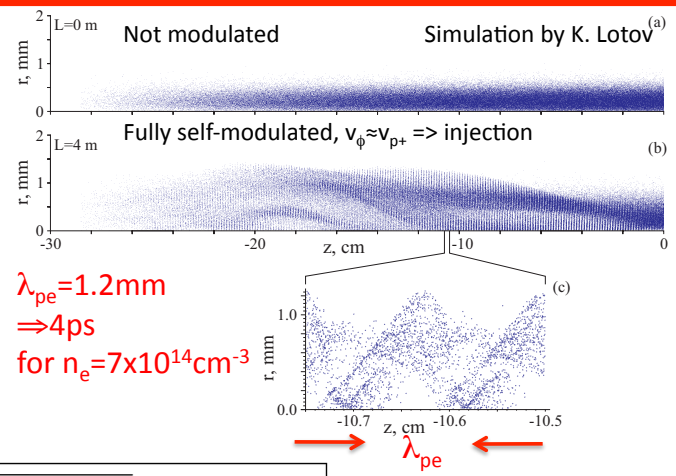
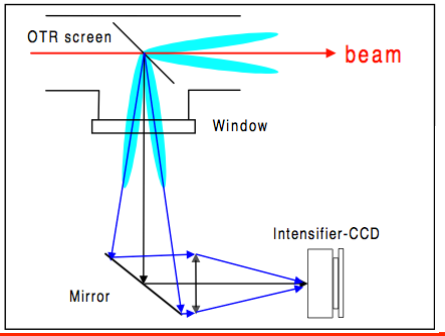
SSM DiAGNOSTiCS



OTR



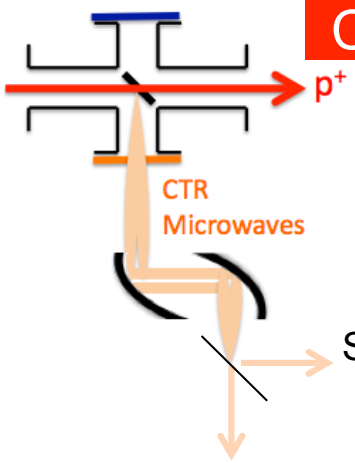
λ_{pe}=1.2mm
⇒4ps
for n_e=7x10^{14}cm^{-3}



Streak Camera

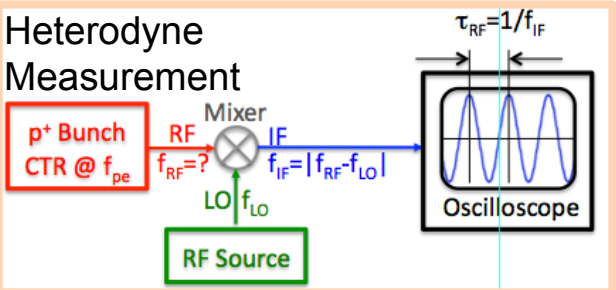
≤1ps resolution

CTR



$1 \le n_e \le 10\times10^{14}$cm^{-3}
$90 \le f_{pe} \le 280$GHz

Heterodyne Measurement



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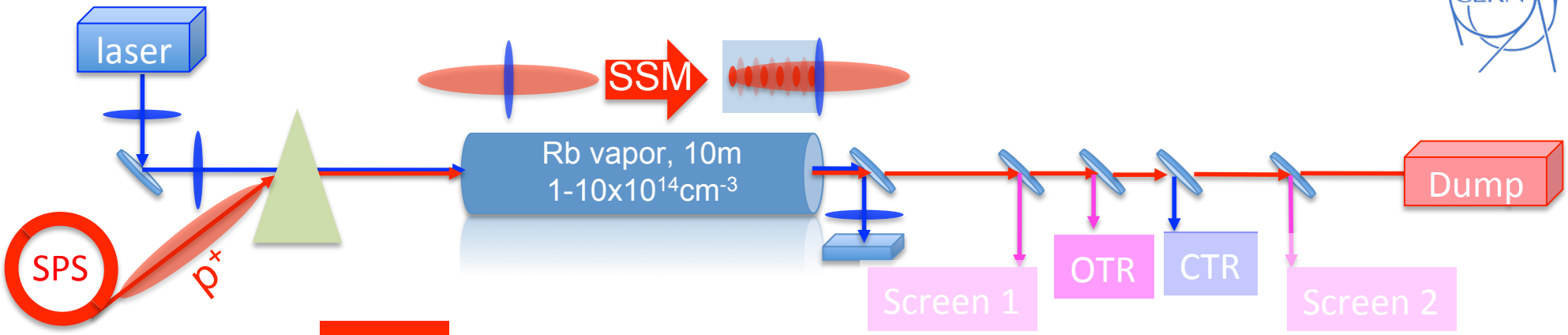
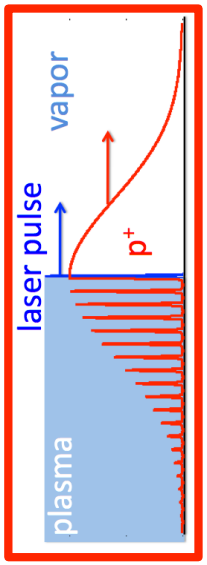
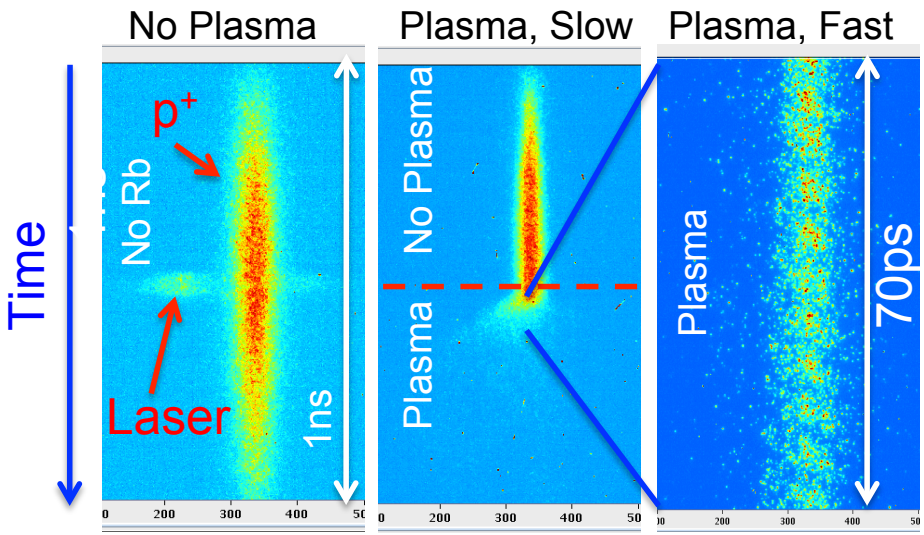
SEEDED SM



OTR



Streak camera Images



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

Preliminary!!!

K. Rieger, MPP

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

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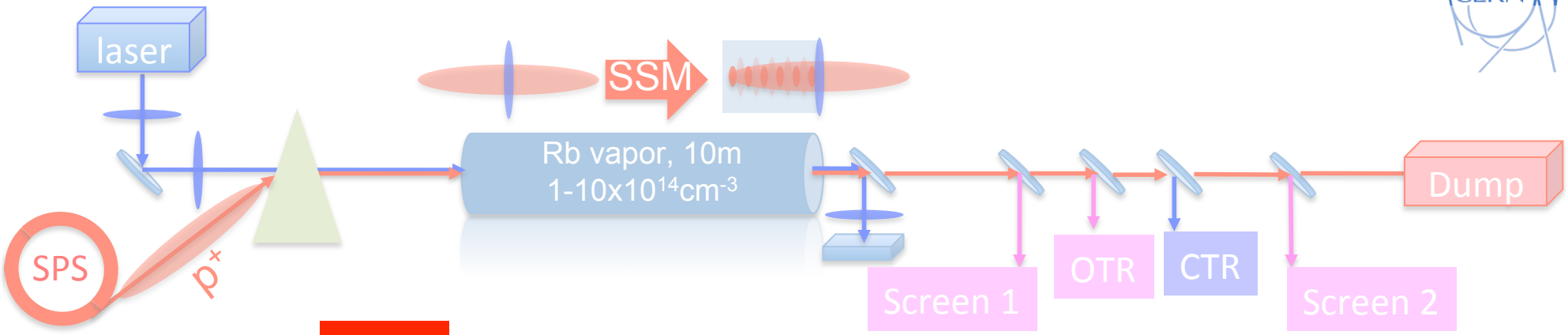
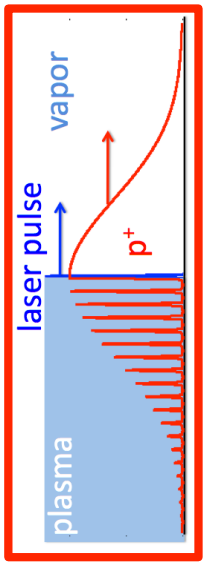
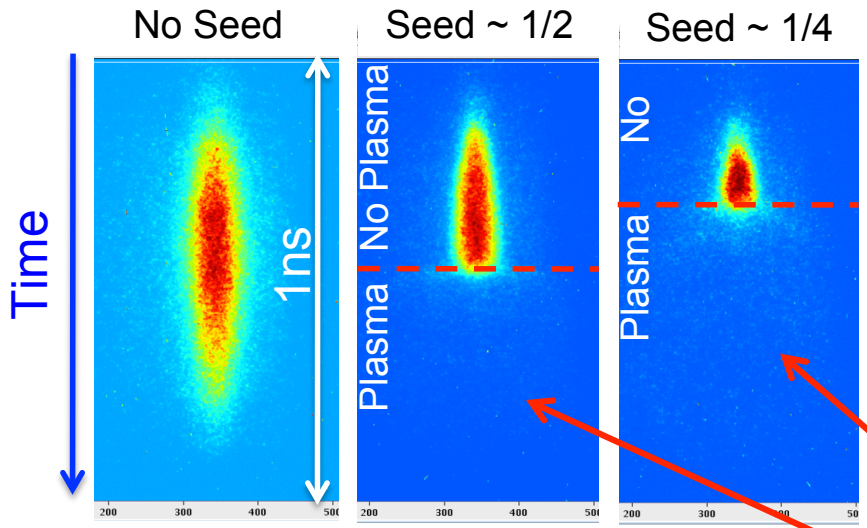
SEEDED SM



OTR



Streak camera Images



n_{Rb}=2.2x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Short

Preliminary!!!

p$^+$ defocused by SSM

- ✧Various seeding position/times
- ✧Effect starts at laser timing → SM seeding
- ✧Stronger effects with seed at ¼ than ½

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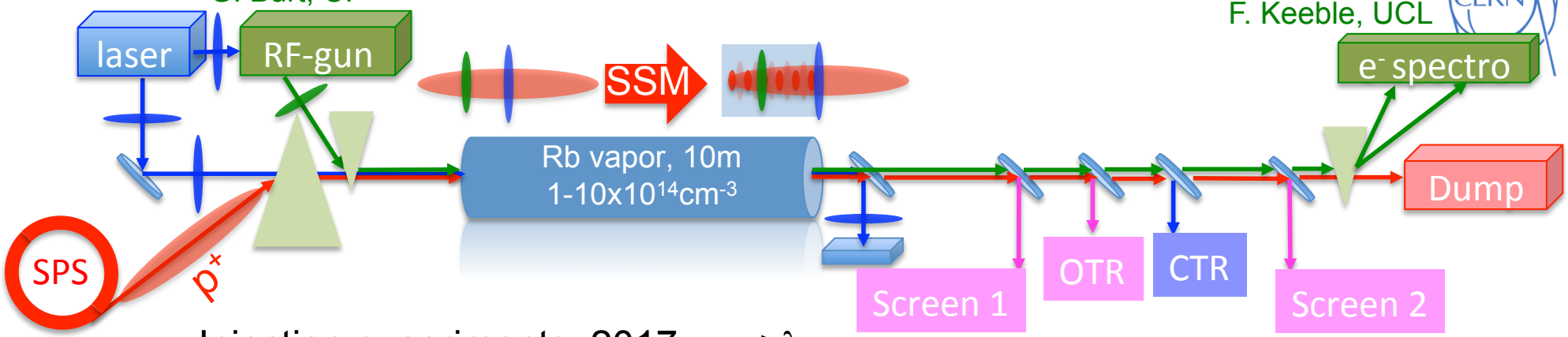
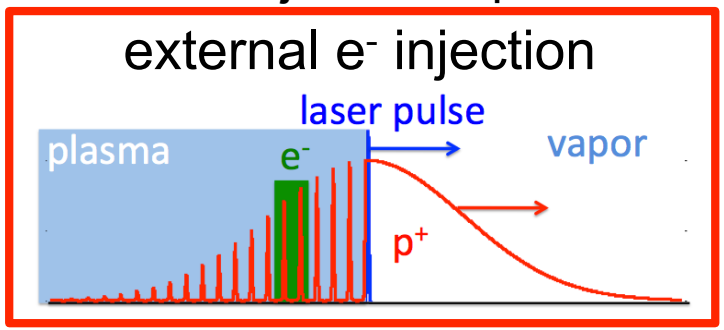
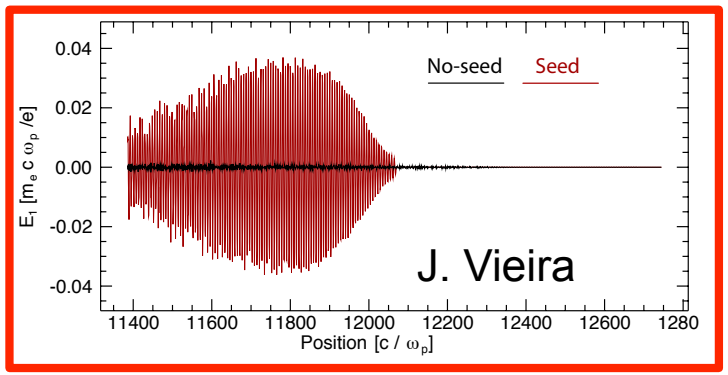
WAKEFIELDS SAMPLING / ACCELERATION

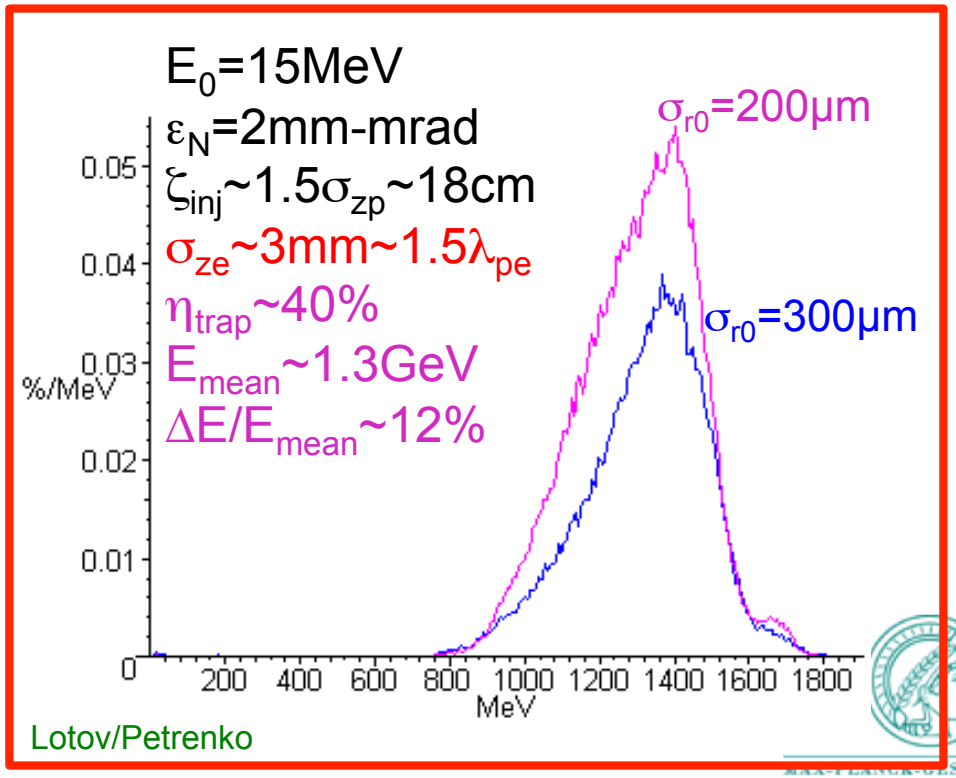
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
S. Doebert, , K. Pepitone, CERN
G. Burt, CI
F. Keeble, UCL



Injection experiments: 2017: $\sigma_{ze-}>\lambda_{pe}$







✧ Accelerate e$^-$ to GeV energy with ~GeV/m gradient and finite $\Delta E/E$

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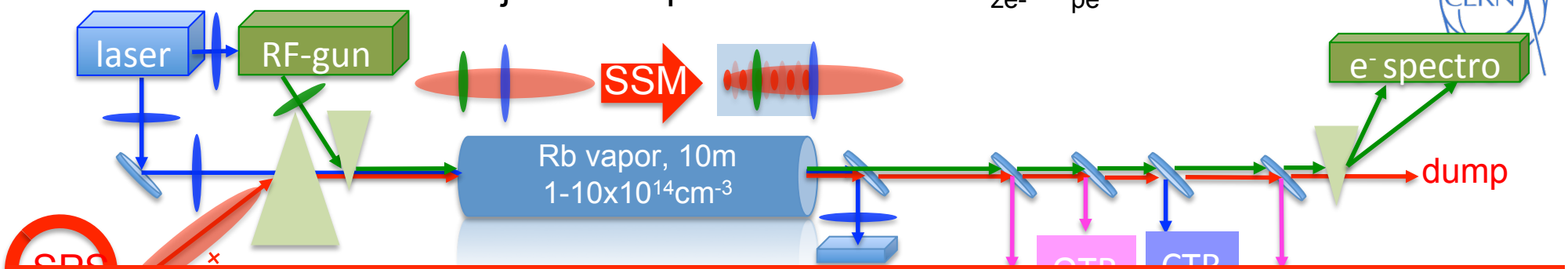
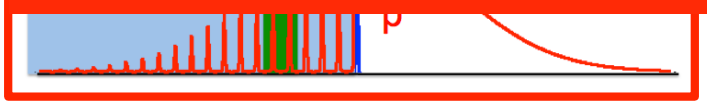
WAKEFIELDS SAMPLING / ACCELERATION

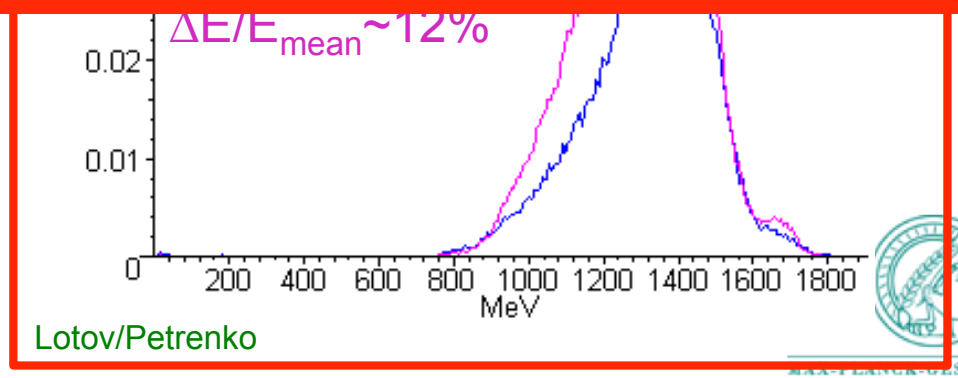
Injection experiments: 2017: $\sigma_{ze-} > \lambda_{pe}$



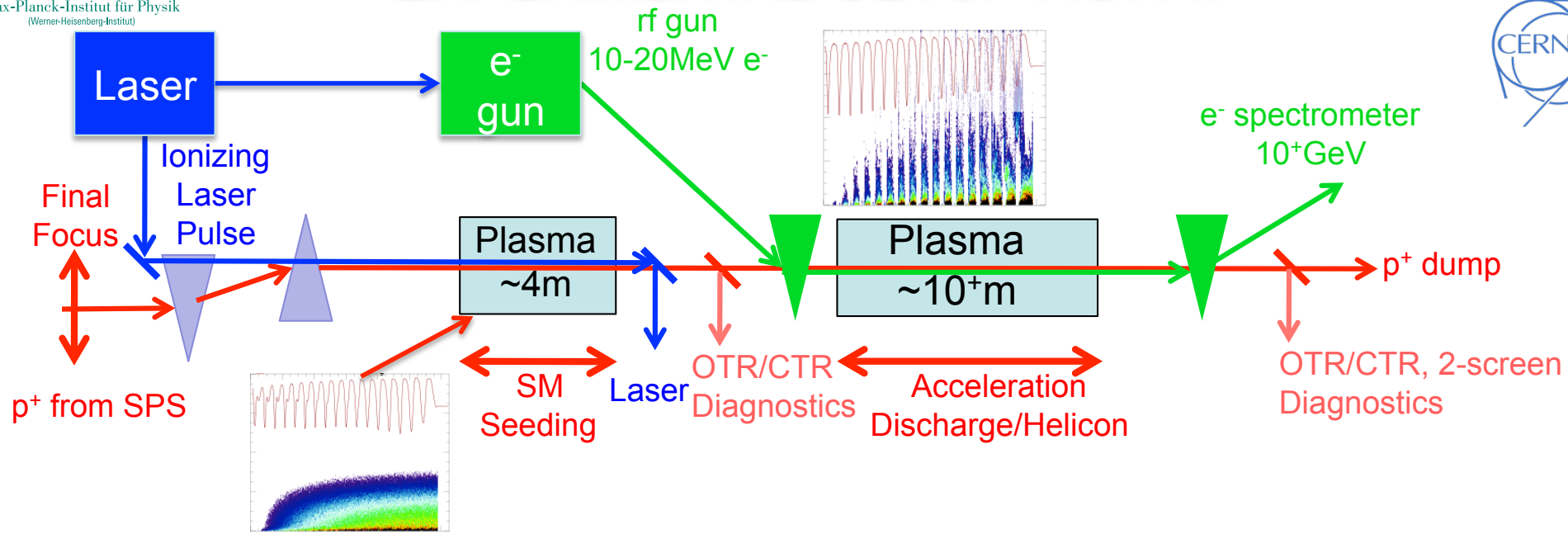
2nd goal of AWAKE (2018):
Externally inject (~15MeV) electrons into the wakefields
and
reach ~GeV energy gain with finite ΔE/E

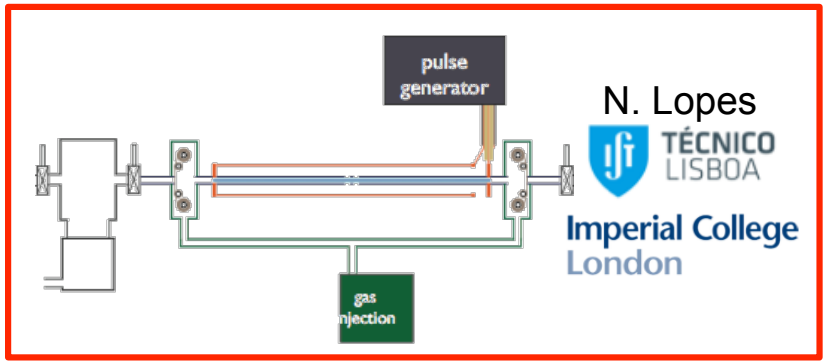


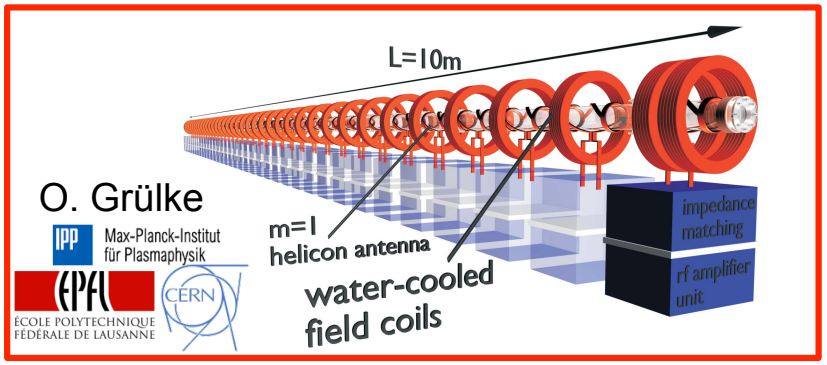
- Accelerate e$^-$ to GeV energy with ~GeV/m gradient and finite ΔE/E



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 ($\sigma_z \ll \lambda_{pe}$), quality of the bunch: $\Delta E/E$, ε => beam loading and blow-out
- ✧Density step to maintain accelerating gradient

✧2021-LS3, **RUN II**

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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:
  - Observe SSM (defocusing, μ-bunches)
  - Demonstrate seeding: SSM
  - μ-bunch structure (very) stable against p^+ variations: key for e^- injection and acceleration, NO instability
  - No seeding => SMI or hose instability
  - $f_{mod} \sim f_{Rb} \sim f_{pe}$
- Many results not presented, see WG talks and posters!!!!
- SSM and e^- acceleration demo experiments in 2017-18
- Run II: (2021-): two plasmas, quality of the accelerated e^- bunch: $\Delta E/E$, ε
- Application of p^+-driven-PWFA: e^-/p^+ collisions

Preliminary!!!
Analysis to come!

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