proton bunch self-modulation

and

electrons acceleration

in plasma

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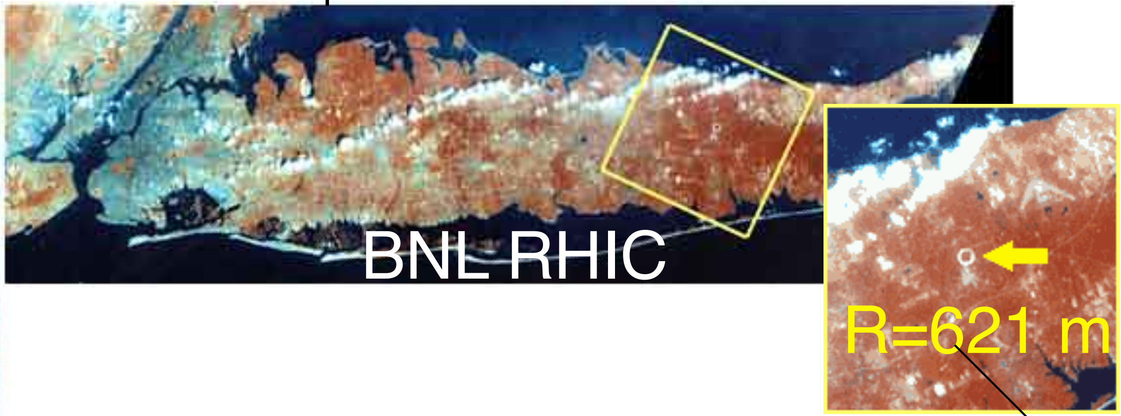
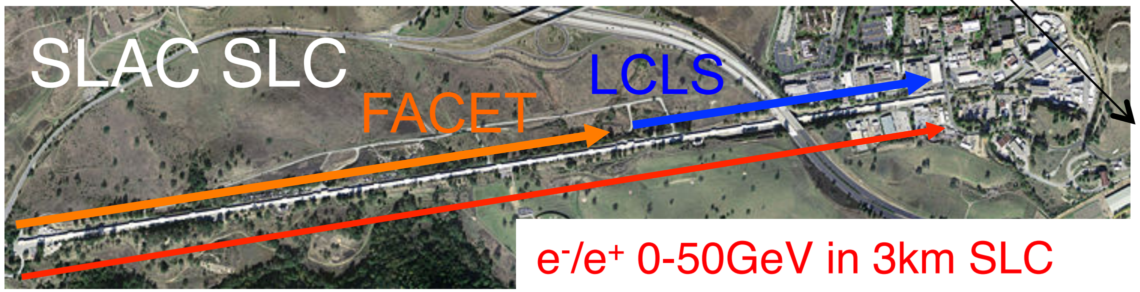
Particle Accelerators

"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
- Can we make them smaller (and cheaper) and with a higher energy?

Particle Accelerators

“The
to be

Hadron accelerators limited by magnetic field

$$r_{Larmor} = \frac{\gamma m c}{q B_0} = r_{accelerator}$$

B_0~8T for LHC (7TeV, r~4.3km)

B_0~20T for FCC (100TeV, r~16km)

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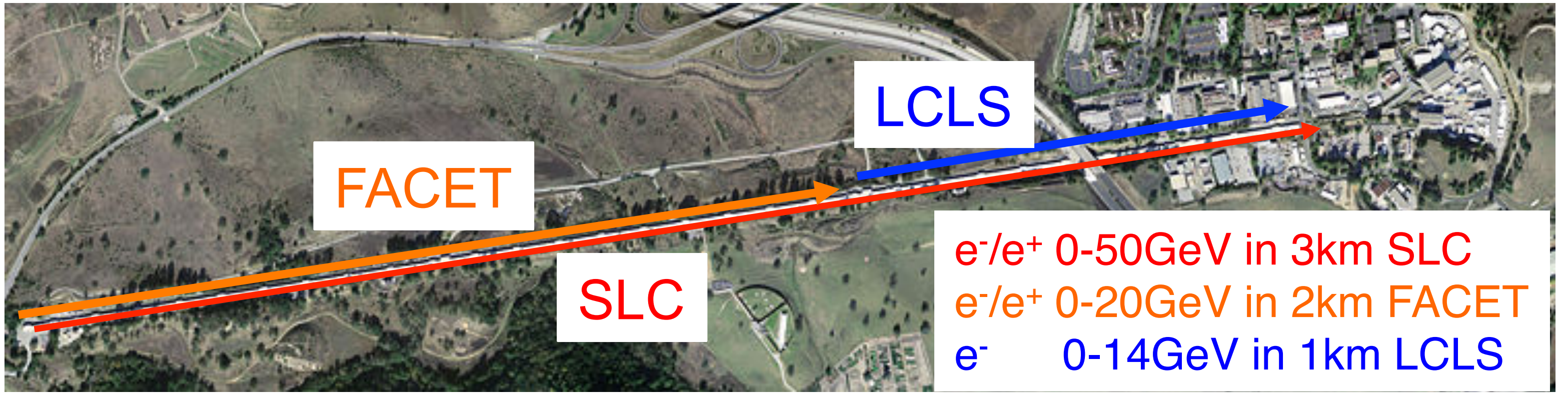
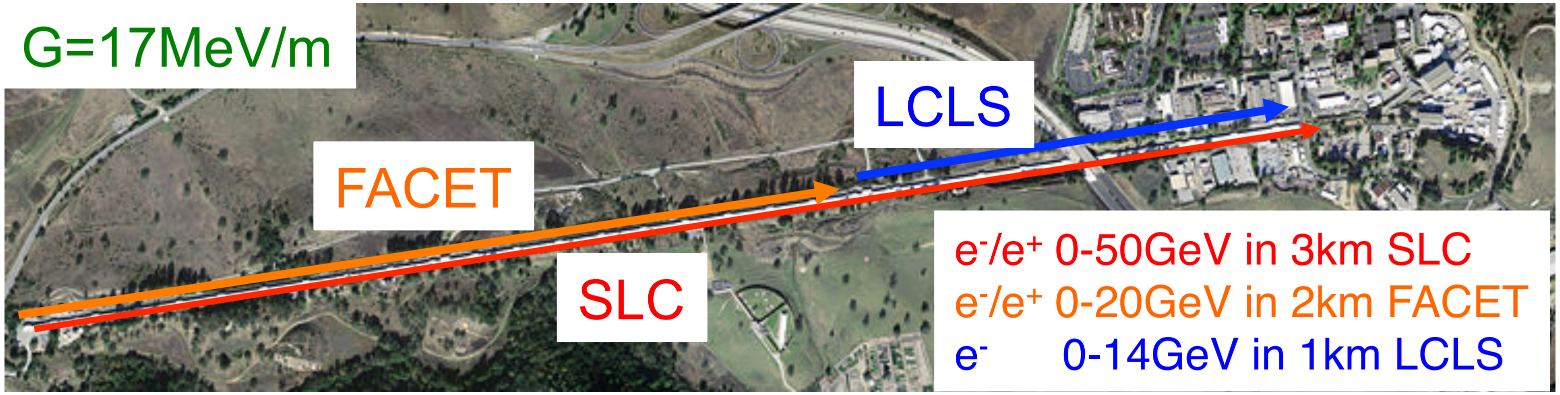
LiNEAR PARTiCLE ACCELERATORS (e^-/e^+)



➡ Particles' energy determined by particle physics need (HEP, FEL, …)

LINEAR PARTICLE ACCELERATORS (e^-/e^+)



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Accelerator length ~ $\frac{\text{Particles' final energy}}{\text{Accelerating gradient}}$

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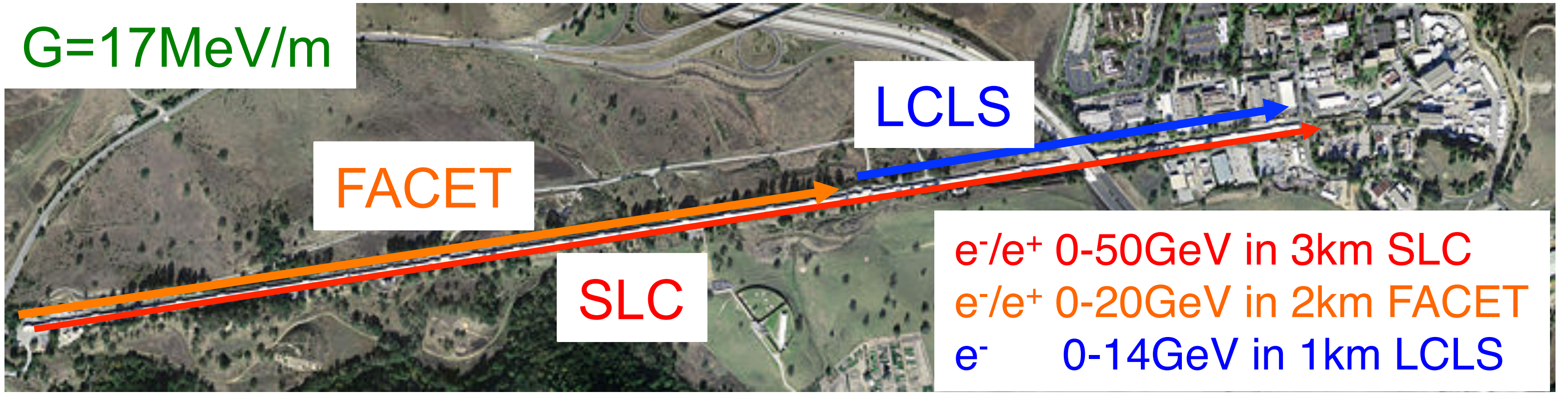
LINEAR PARTICLE ACCELERATORS (e^-/e^+)

G=17MeV/m



60 x E
6 x G
16 x L

G=60-100MeV/m

➡ Particles' energy determined by particle physics need (HEP, FEL, …)

$$\searrow \text{Accelerator length} \sim \frac{\text{Particles' final energy}}{\text{Accelerating gradient}} \nearrow$$

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ACCELERATiNG FiELD/GRADiENT LiMiTATiONS

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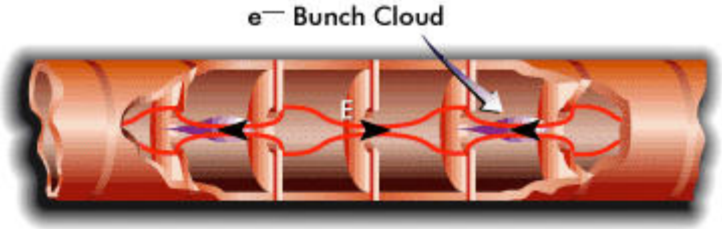
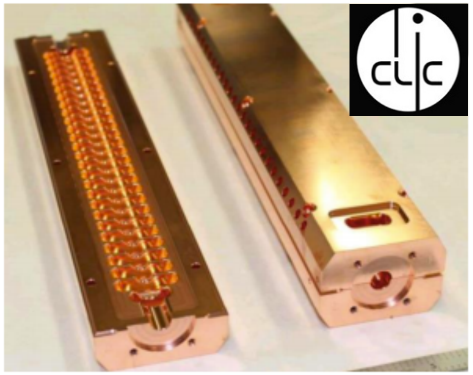
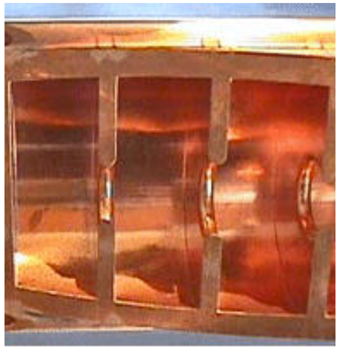
(Werner-Heisenberg-Institut)

- Gradient/field limit in (warm) RF structures: <200MV/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

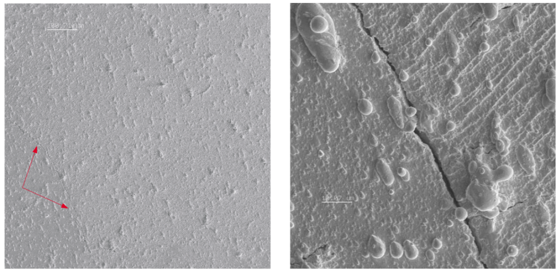


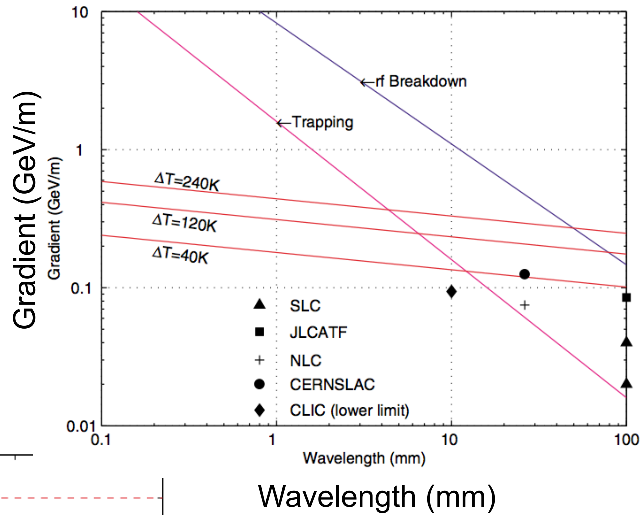


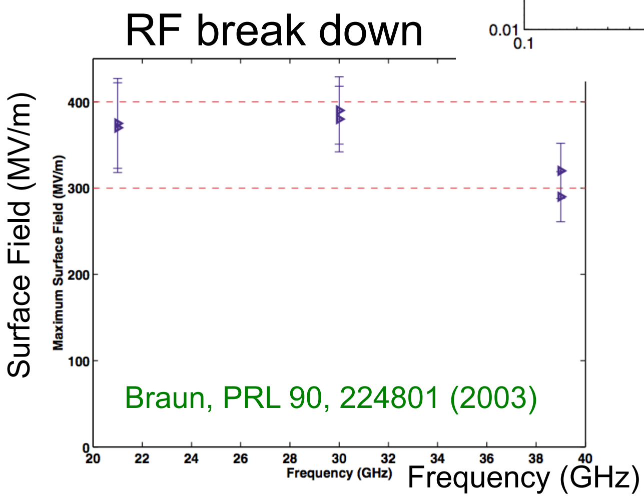


Pulsed heating fatigue

Pritzkau, PRSTAB 5, 112002 (2002)







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ACCELERATING FIELD/GRADIENT LIMITATIONS

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

AWAKE

- ✧Gradient/field limit in (warm) RF structures: <200MV/m
- ✧RF break down (plasma!!) and pulsed heating fatigue
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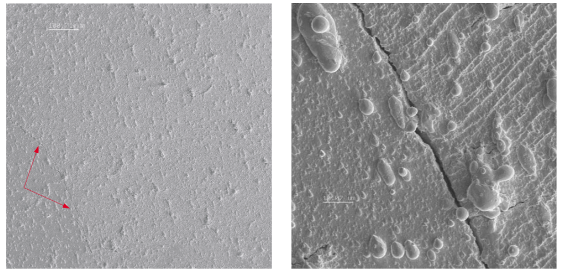
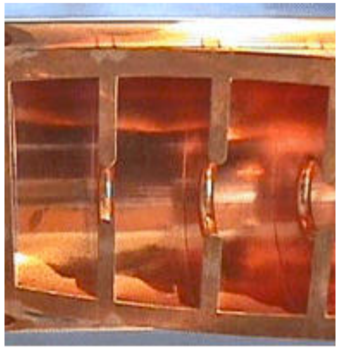
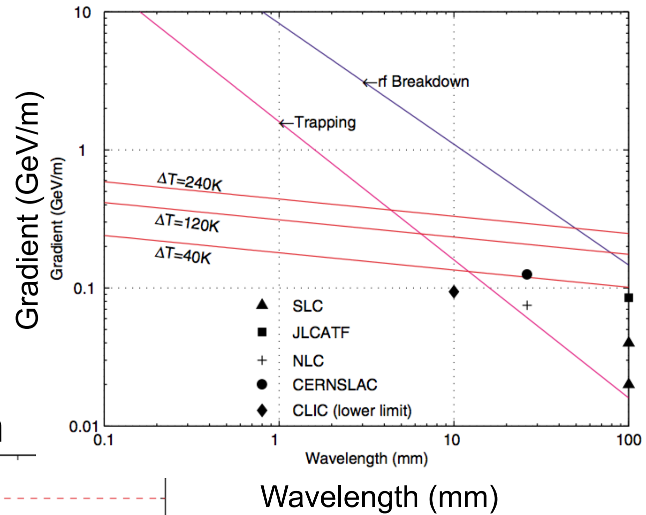
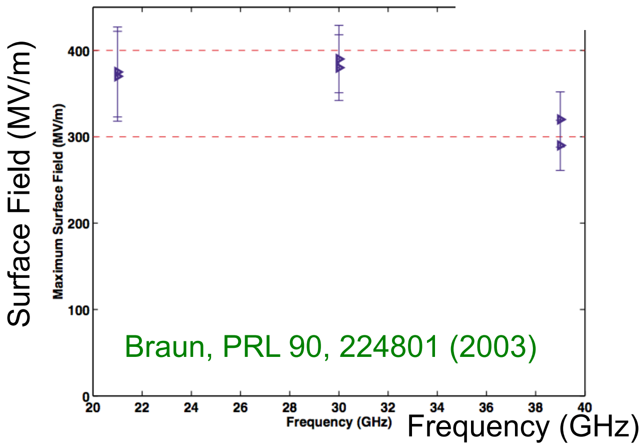






RF-accelerators:
Accelerating field limited to <100MVm
by metal damage:
-RF-breakdown
-pulsed heating
Practical limit …

RF break down



Braun, PRL 90, 224801 (2003)

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PARTICLE ACCELERATORS

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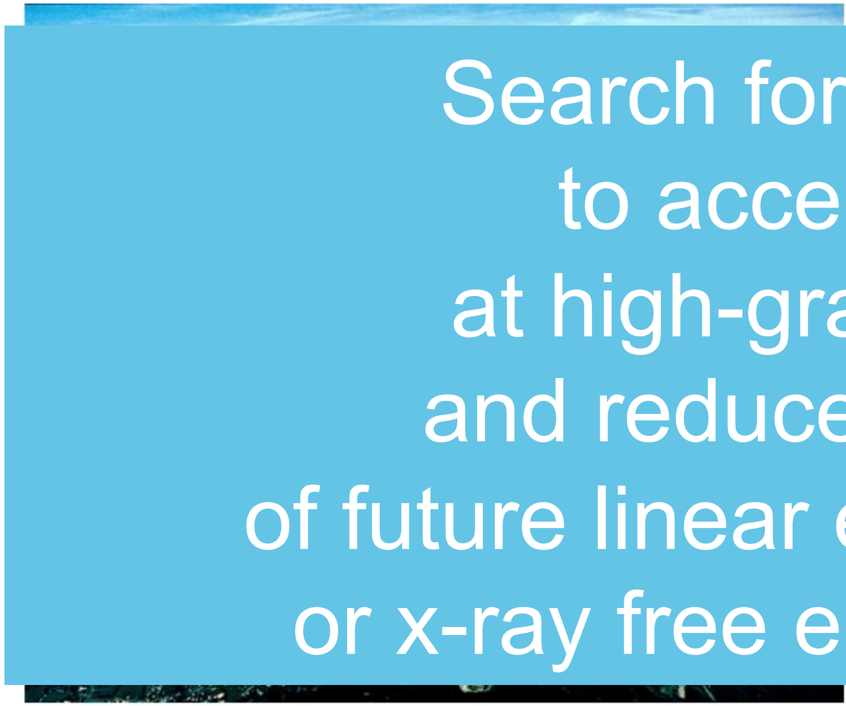

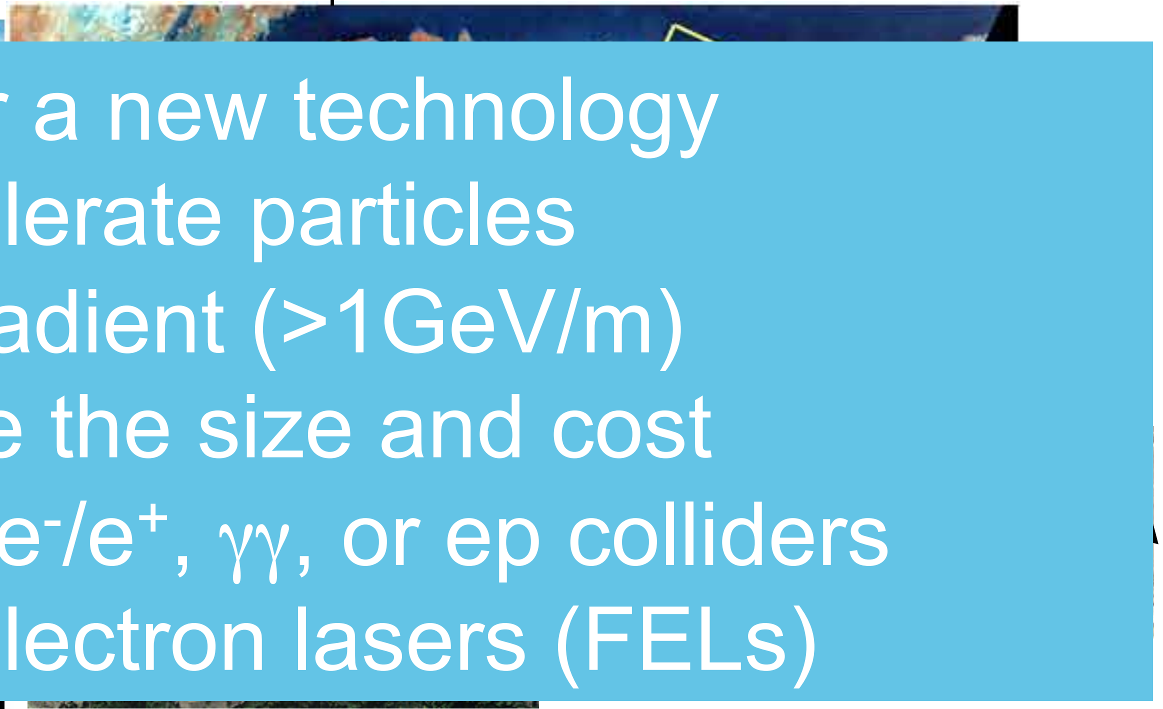

Search for a new technology to accelerate particles at high-gradient (>1GeV/m) and reduce the size and cost of future linear e^-/e^+, $\gamma\gamma$, or ep colliders or x-ray free electron lasers (FELs)

e^-/e^+ 0-20GeV in 2km FACET

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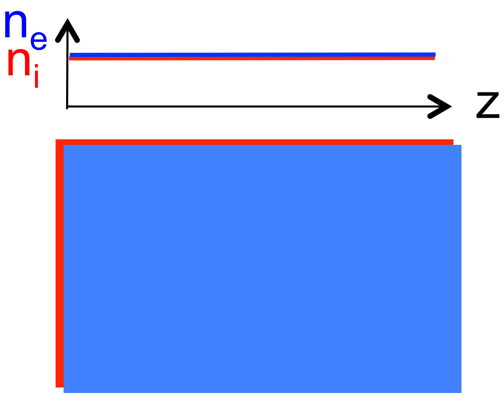
PLASMA

✧Relativistic Electron, Electrostatic Plasma Wave (E_z//k, B=0):



Initially neutral: n_e=n_i

Wikipedia Plasma: (from Greek πλάσμα, "anything formed"[1]) is one of the four fundamental states of matter, the others being solid, liquid, and gas. A plasma has properties unlike those of the other states.

Plasma: "Gas" of charged (ionized) particles (e^-, ions) that exhibits a collective behavior (screening, waves, etc.)

Acceleration of relativistic particles:

✧Wave

✧$\vec{E} // \vec{v}_p // \vec{k} \quad \Rightarrow$ Energy transfer

✧$v_\varphi \cong v_p \cong c \quad \Rightarrow$ Stay in phase

➤Relativistic, electro-static, plasma wave, wake

[1] a) the body, as fashioned by the Creator
b) of a story which is fictitious but possible
c) pretence

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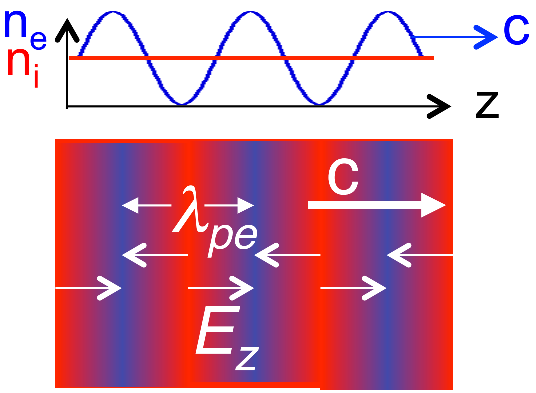
PLASMA

✧Relativistic Electron, Electrostatic Plasma Wave (E$_z$//k, B=0):



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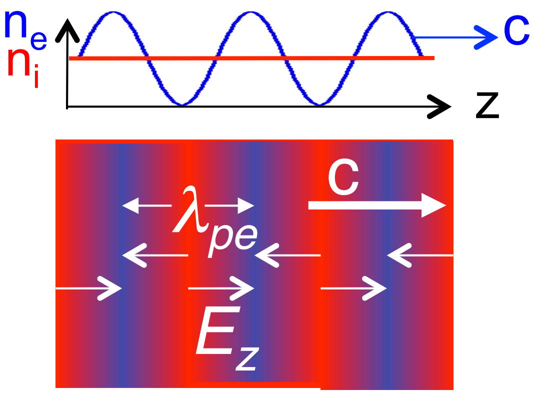

$$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\varepsilon_0}$$

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

$$k_{pe}E_z=\frac{\omega_{pe}}{c}E_z=\frac{n_e e}{\varepsilon_0}$$

$$E_{WB}=m_e c\omega_{pe}/e$$

Cold Plasma

"Wavebreaking" Field

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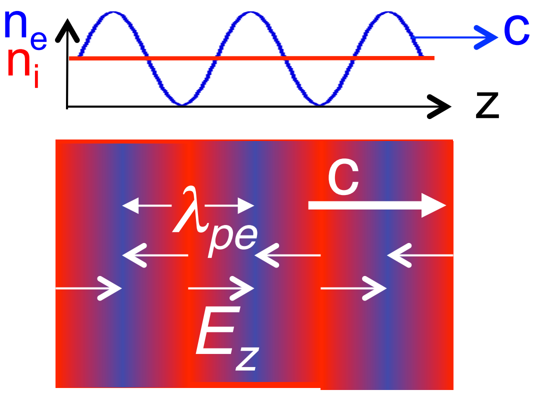

LARGE
Collective response!

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$$E_z=\left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2}\cong 100\sqrt{n_e\left(cm^{-3}\right)}=1\,GV/m$$

@n_e=10^{14} cm^{-3}

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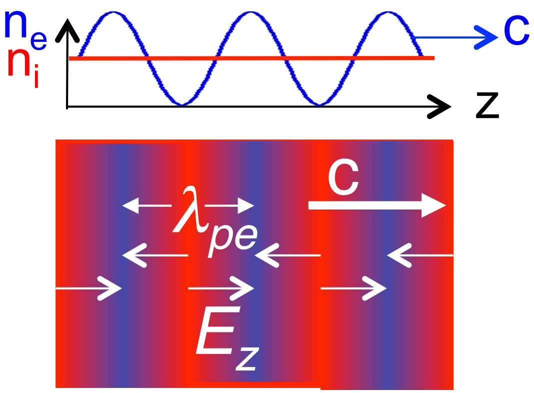

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@n_e=10^{14} cm^{-3}

AWAKE : 10^{14}-10^{15} cm^{-3}, E_{WB}~GV/m

PLASMA

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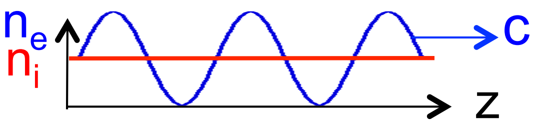

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0}$$

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

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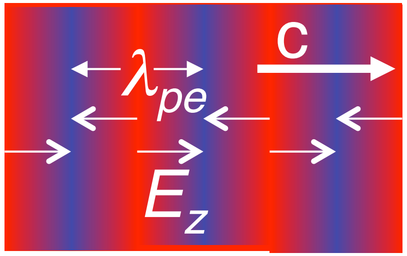

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@n_e=10^{14} cm^{-3}

✧Plasmas can sustain very large (collective) E_z-field, acceleration

✧Wave, wake phase velocity = driver velocity (~c when relativistic)

✧Plasma is already (partially) ionized, difficult to "break-down"

✧No fabrication, no damage

✧Plasma wave or wake can be driven by:

- ➢Intense laser pulse
- ➢Dense particle bunch

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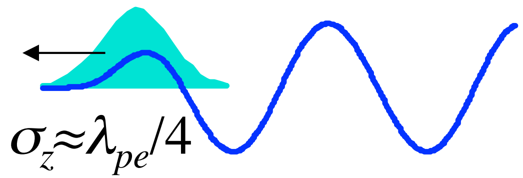
4 PLASMA-BASED ACCELERATORS*

- **Plasma Wakefield Accelerator (PWFA)**

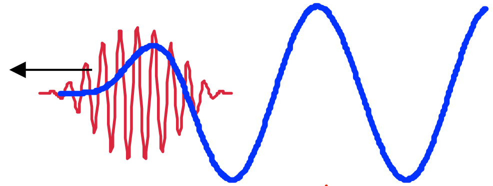
  A high energy particle bunch (e^-, e^+, ...)

  P. Chen et al., Phys. Rev. Lett. 54, 693 (1985)



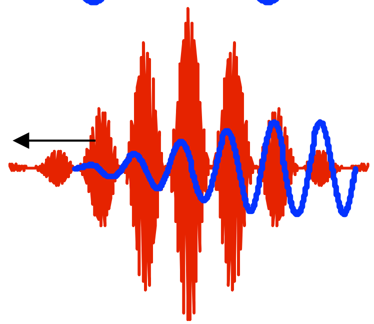
- **Laser Wakefield Accelerator (LWFA)** *

  A short laser pulse (photons, ponderomotive)



- **Plasma Beat Wave Accelerator (PBWA)** *

  Two frequencies laser pulse, i.e., a train of pulses



- **Self-Modulated Laser Wakefield Accelerator (SMLWFA)** *

  Raman forward scattering instability in a long pulse (LWFA of 20th century)

*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

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OUTLINE

- ✧ Introduction to plasma wakefield accelerator (PWFA)
- ✧ Seeded Self-Modulation (SSM)
- ✧ AWAKE experiment
- ✧ SSM experimental results
  - ✧ Demonstration
  - ✧ Physics
- ✧ e^- acceleration
- ✧ Future and Summary

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OUTLiNE

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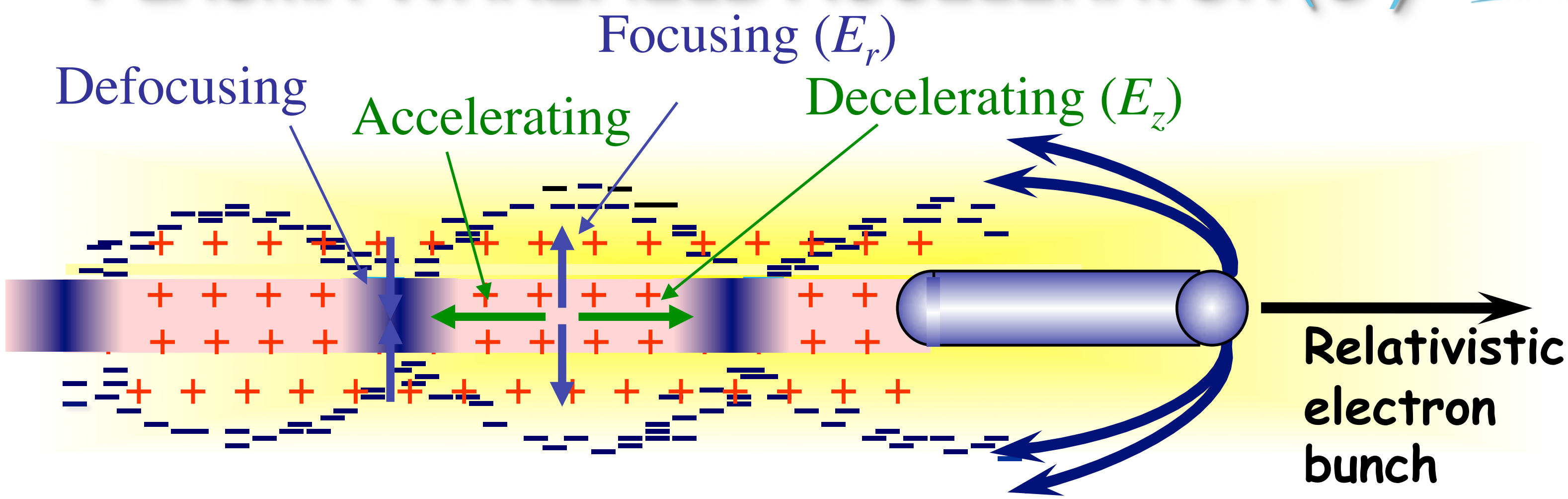
PLASMA WAKEFIELD ACCELERATOR (e^-)



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge force => deceleration + focusing (MT/m)
- Plasma e^- rush back on axis => acceleration, GV/m
- Ultra-relativistic driver => ultra-relativistic wake
  => no dephasing
- Particle bunches have long “Rayleigh length”
  (beta function $\beta^*=\sigma^{*2}/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

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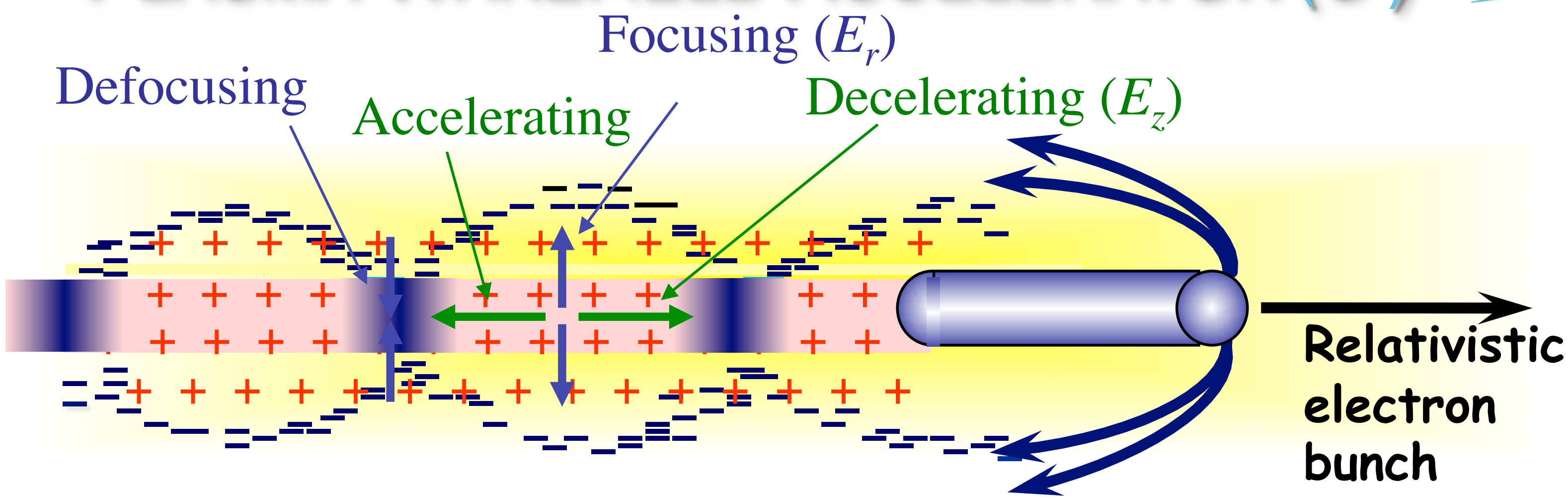
PLASMA WAKEFIELD ACCELERATOR (e^-)



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Very large energy gain possible with short, high-energy relativistic bunches!

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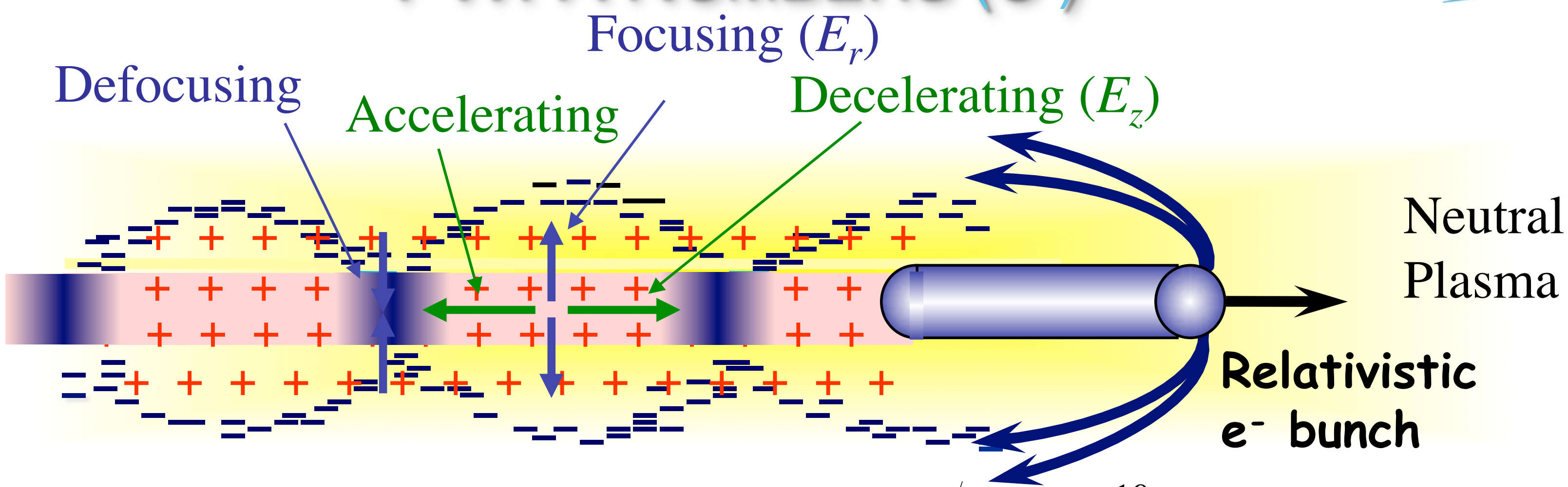
PWFA NUMBERS (e^-)



✧Linear theory ($n_b << n_e$) scaling:

$$E_{acc} \cong 110(MV/m)\frac{N/2\times10^{10}}{(\sigma_z/0.6mm)^2} \approx N/\sigma_z^2$$

$@\ k_{pe}\sigma_z \approx \sqrt{2}$ *(with $k_{pe}\sigma_r << 1$)* $\qquad k_{pe} = \omega_{pe}/c \propto n_e^{1/2}$

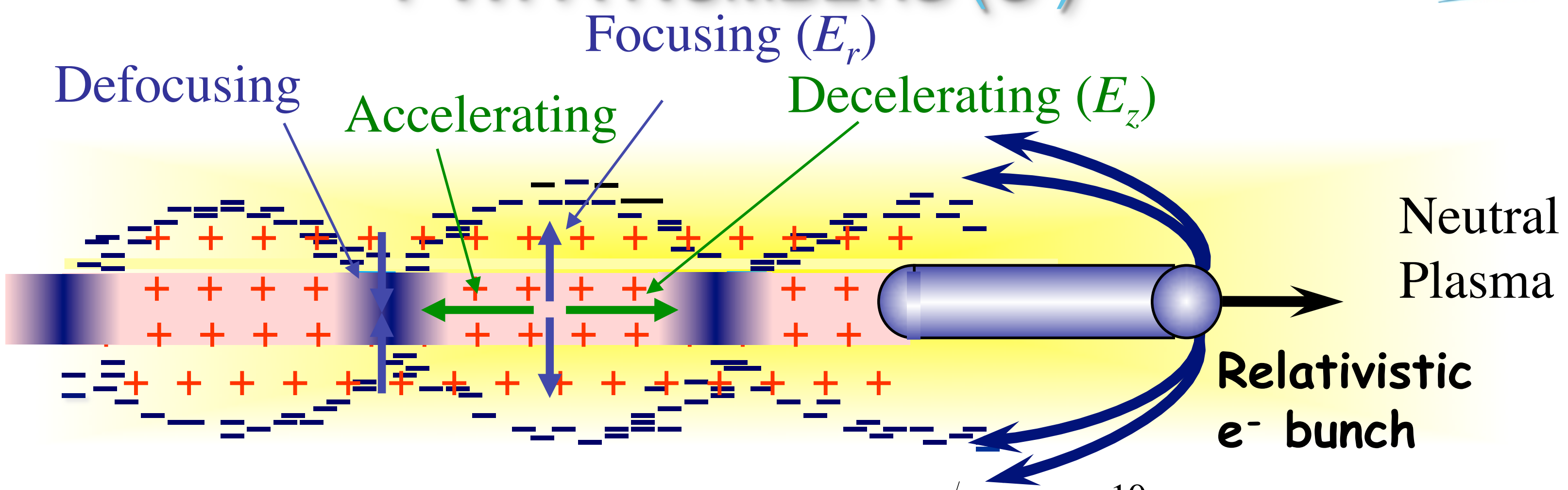
✧Focusing strength: $\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c}$ $\quad (n_b > n_e)$

✧N=2x10[10]: σ_z=600 μm, n_e=2x10[14] cm[-3], E_{acc}~100 MV/m, B_θ/r=6 kT/m
σ_z= 20 μm, n_e=2x10[17] cm[-3], E_{acc}~ 10 GV/m, B_θ/r=6 MT/m

✧Frequency: 100GHz to >1THz, "structure" size 1mm to 100μm

✧Conventional accelerators: MHz-GHz, E_{acc}<150 MV/m, B_θ/r<2 kT/m

PWFA NUMBERS (e^-)



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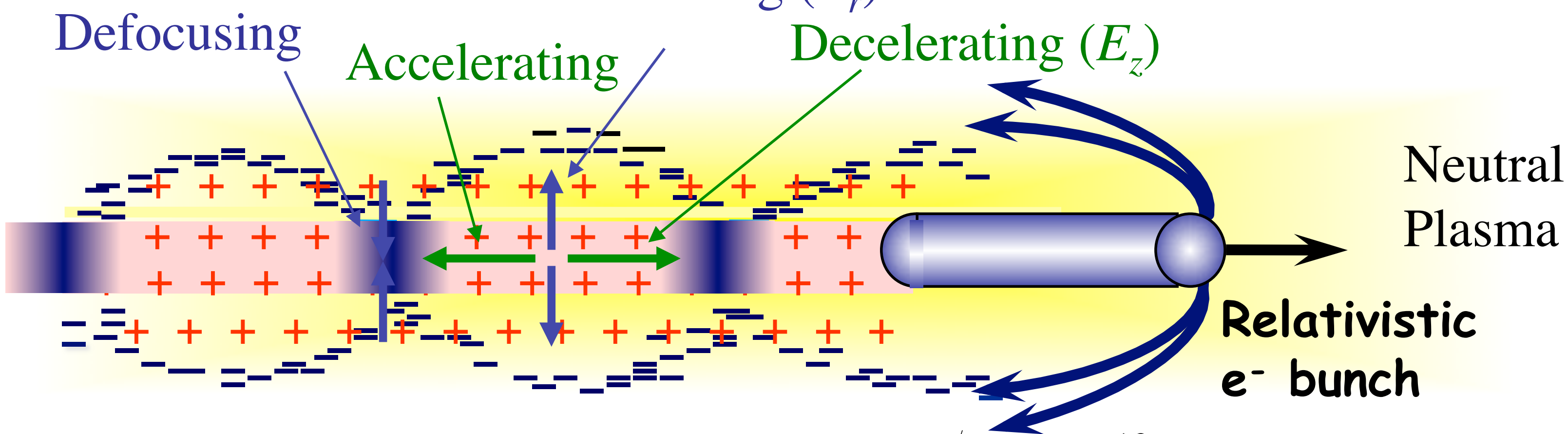
AWAKE

PWFA NUMBERS (e^-)



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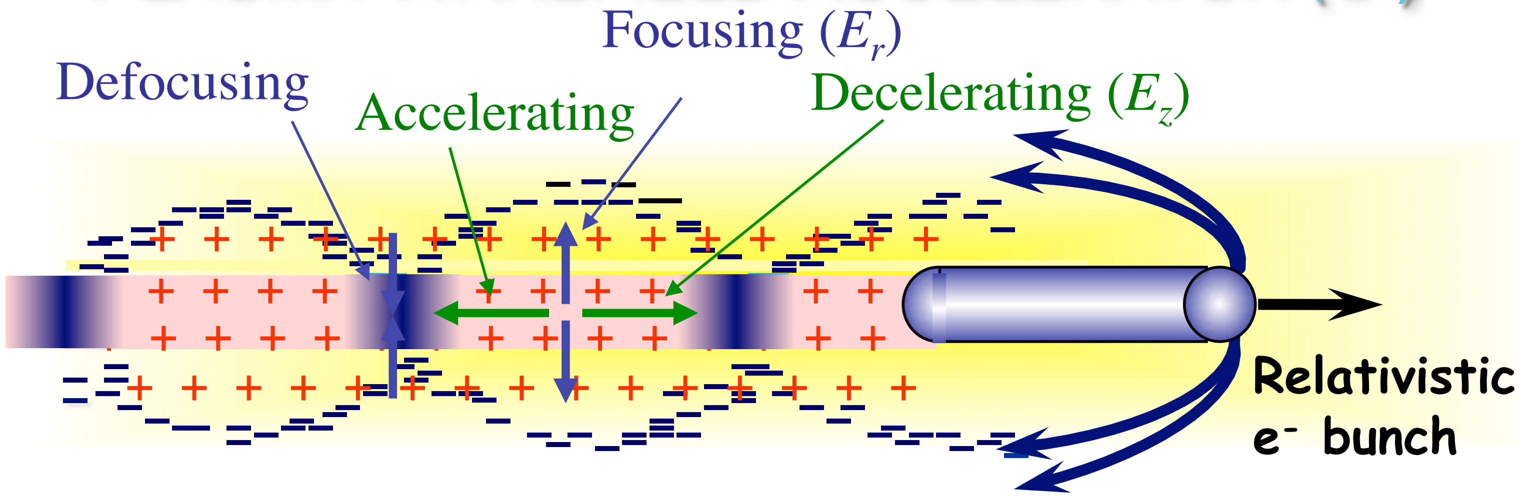
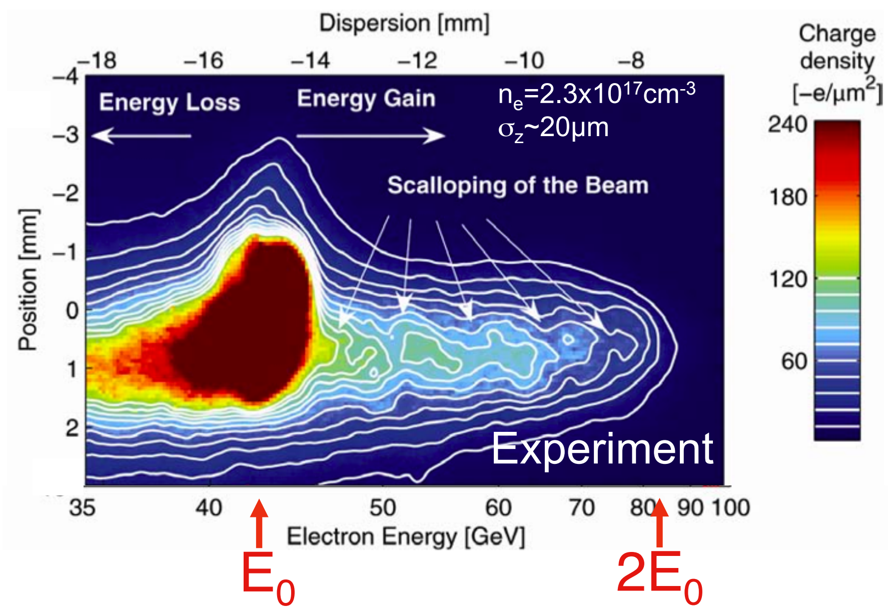
PLASMA WAKEFIELD ACCELERATOR (e^-)



Blumenfeld, Nature 445, 741 (2007)



42 => 84GeV in 85cm! 50GeV/m

Muggli, Phys. Rev. Lett. 93, 014802 (2004)
Hogan, Phys. Rev. Lett. 95, 054802 (2005)
Muggli, Hogan, Comptes Rendus Physique, 10 (2-3), 116 (2009)
Muggli, New J. Phys. 12, 045022 (2010)

n_e=2.3x10^{17}cm^{-3}
σ_z=20μm
σ_r=10μm
N=2x10^{10}

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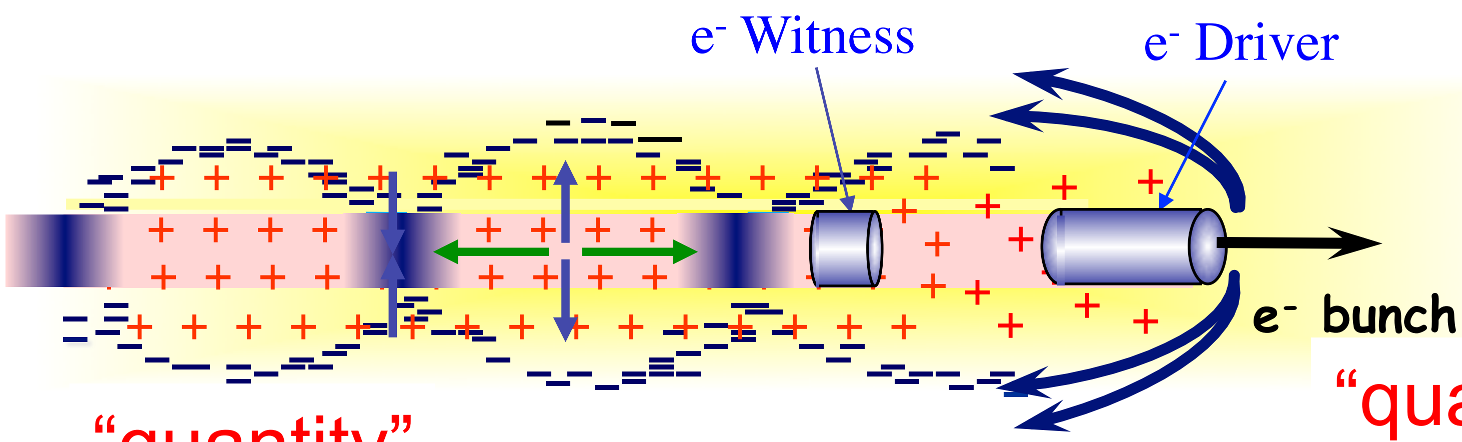
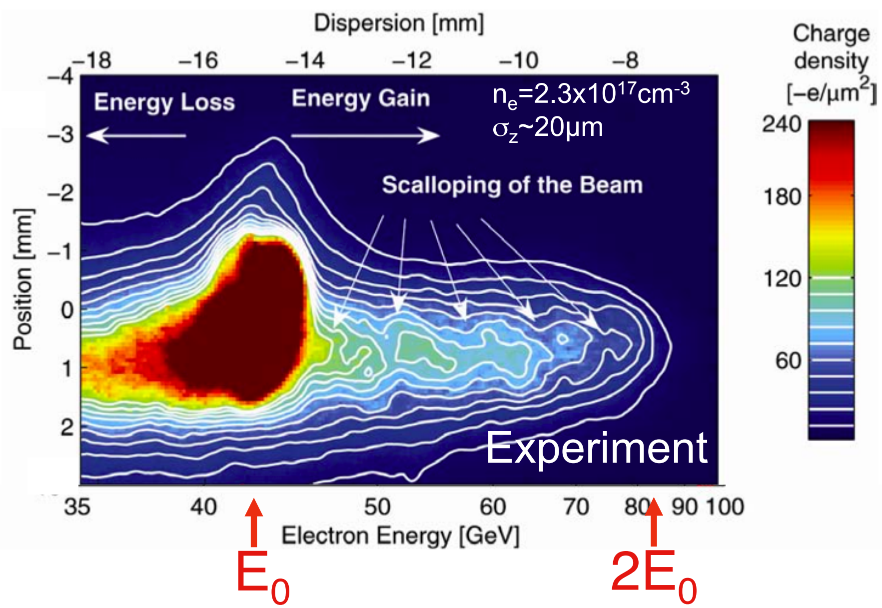
PLASMA WAKEFIELD ACCELERATOR (e⁻)



"quantity"

"quality"

Blumenfeld, Nature 445, 741 (2007)

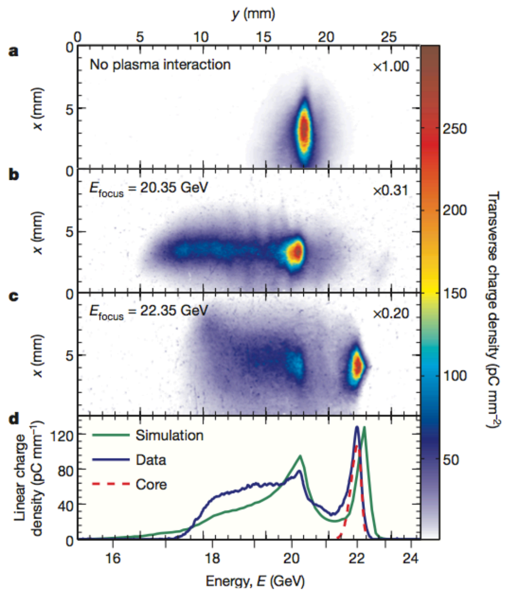


42 => 84GeV in 85cm! 50GeV/m

SLAC
FACET

E200

Litos,
Nature
515(6),92
(2014)



ΔE/E~%
η~30%

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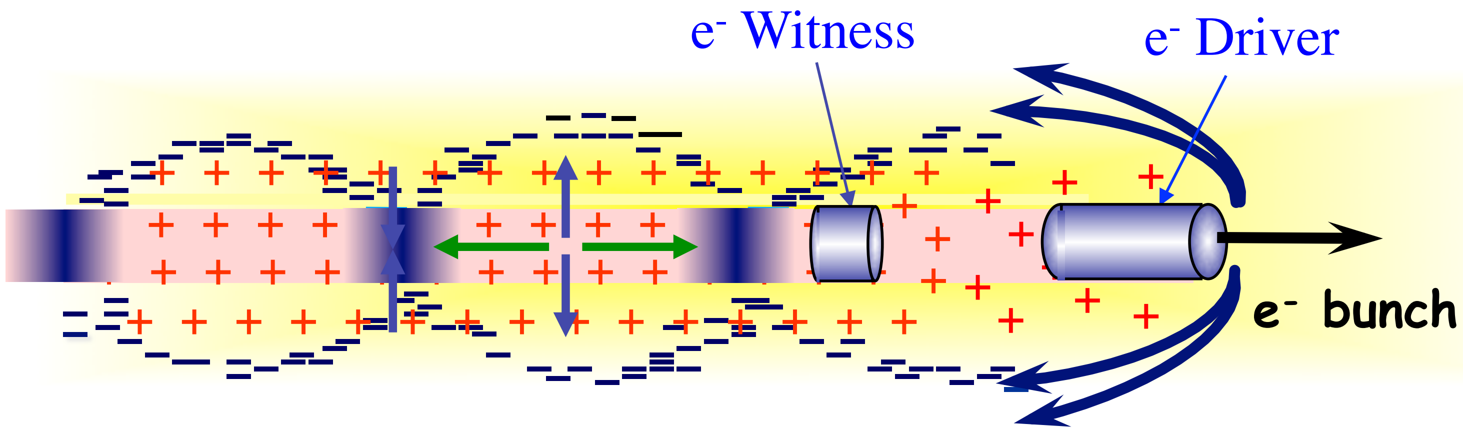
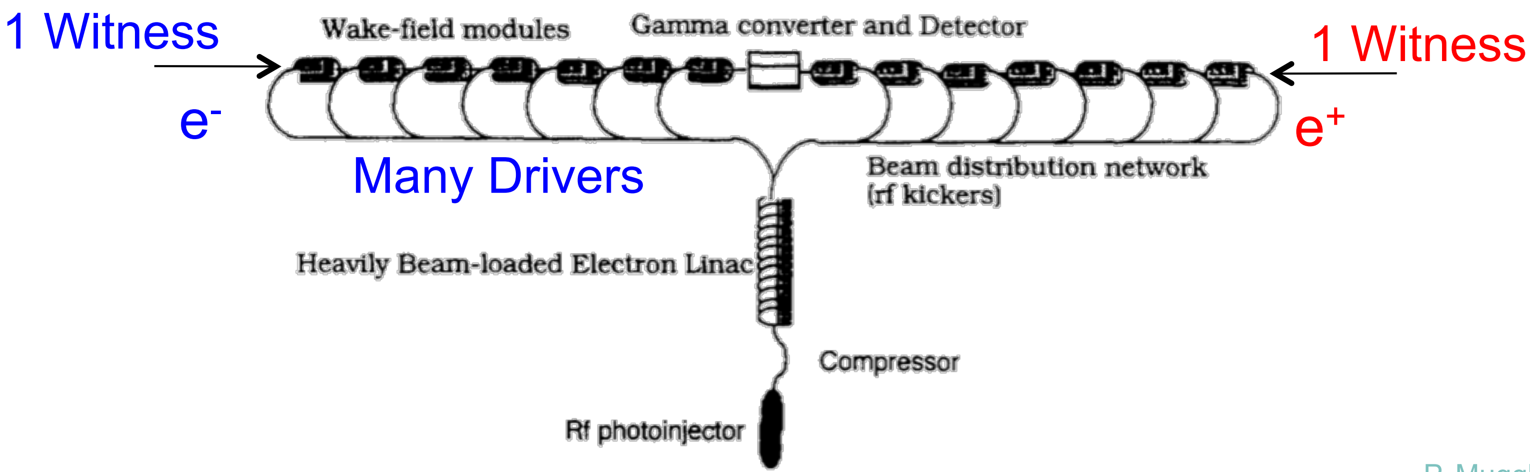
AWAKE

ENERGY CONSERVATION



- ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ
- SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J
- SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

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



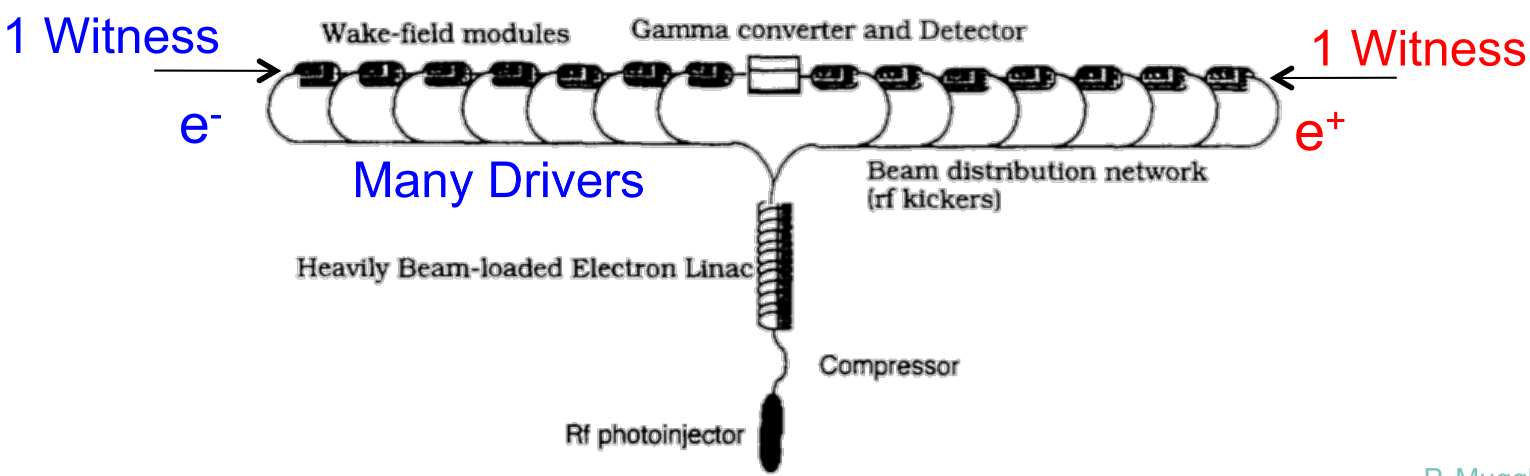
MAX-PLANCK-GESELLSCHAFT

ENERGY CONSERVATION

Same conclusion (staging) for LWFA:
PW laser pulses: 40J in 40fs

- ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ
- SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J
- SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)

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



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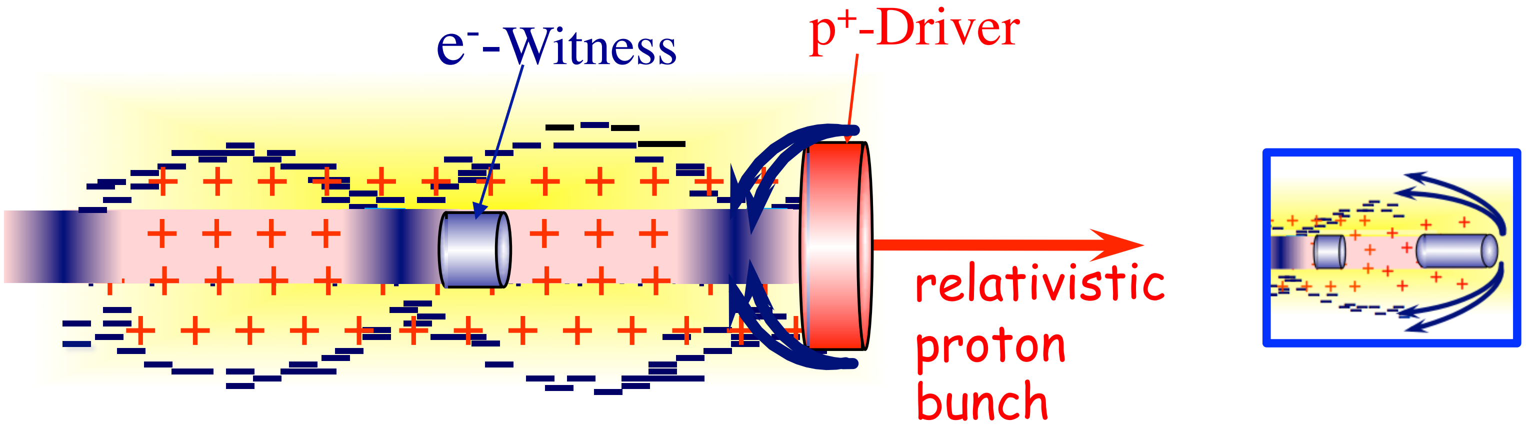
Energy Conservation



- ✧ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ
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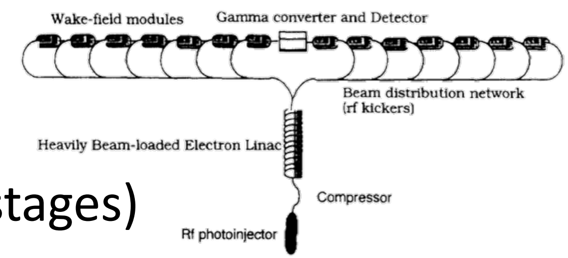
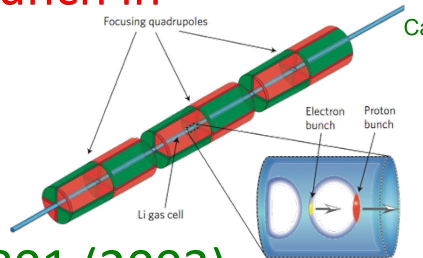
J. Rosenzweig et al. /Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543



- ✧SPS, 400GeV bunch with $10^{11}p^+$ ~6.4kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- ✧A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- ✧Large average gradient! (≥1GeV/m, 100's m)
- ✧Wakefields driven by e^+ bunch: Blue, PRL 90, 214801 (2003)



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

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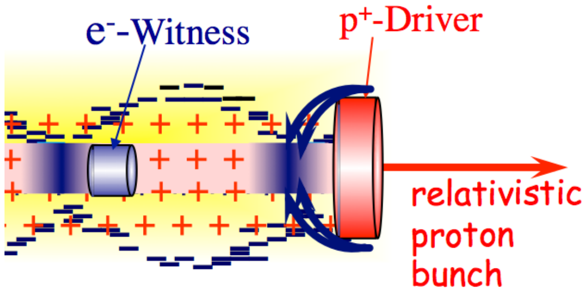
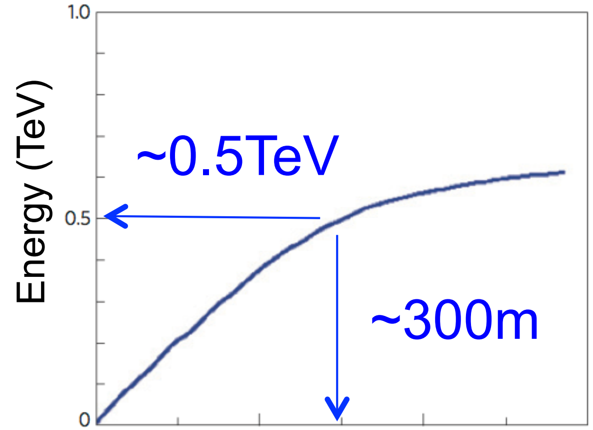
PROTON-DRIVEN PWFA

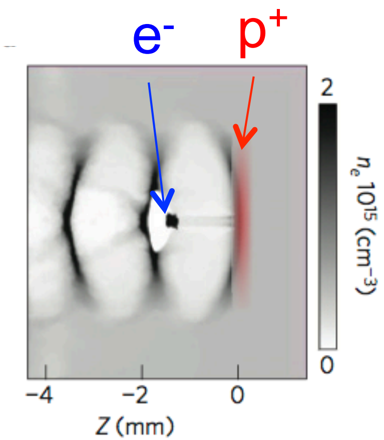
Caldwell, Nat. Phys. 5, 363, (2009)



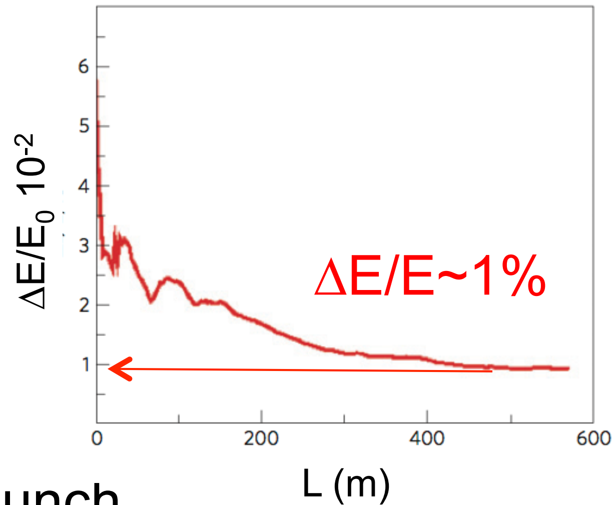
e⁻:	p⁺:
E_0=10GeV	E_0=1TeV
	σ_z=100µm
$N=10^{10}$	$N=10^{11}$
W_0=16J	W_0=16kJ
W_f=1kJ	

Single Stage





Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	T m^{-1}
Magnet length		0.7	m



✧Accelerate an e⁻ bunch on the wakefields of a p⁺ bunch

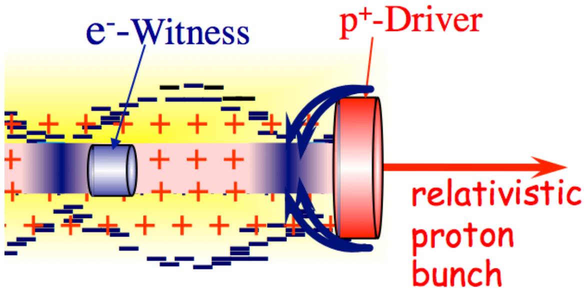
✧Single stage, no gradient dilution

✧Gradient ~1 GV/m over 100's m

✧Operate at lower n_e ($6\text{x}10^{14}$cm^{-3}), larger $(\lambda_{pe})^3$, easier life …

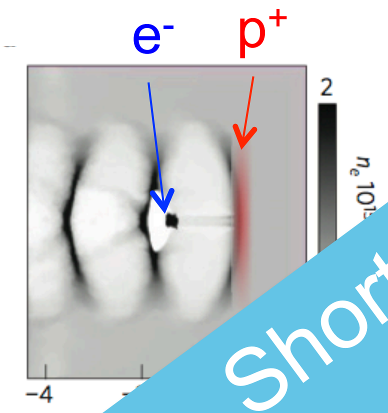
PROTON-DRIVEN PWFA

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

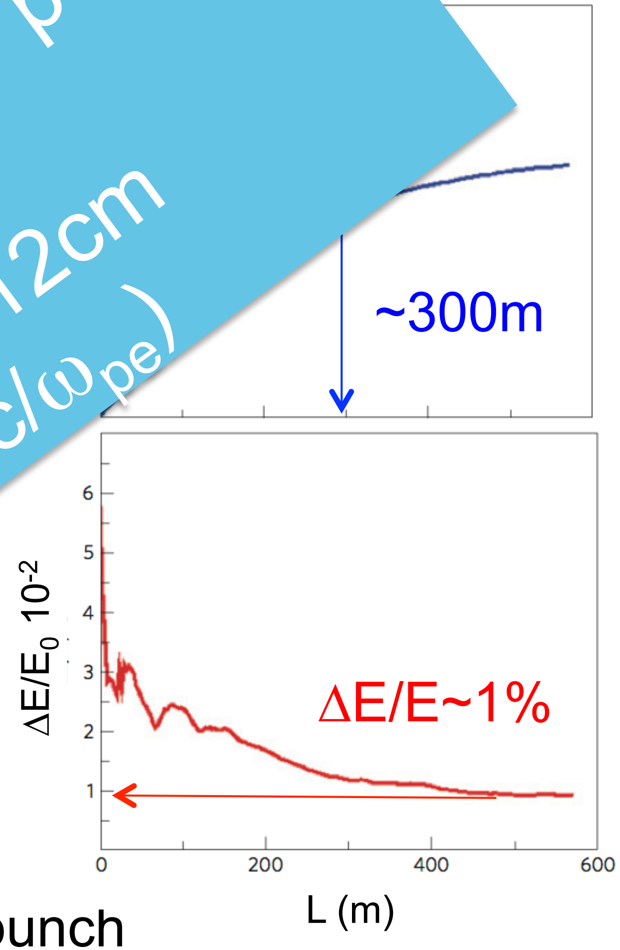


e⁻: p⁺:
E_0=10GeV
N

Single
Stag



		μm
		mrad
	0.43	mm
	1.5×10¹⁰	
	10	GeV
n_p	6×10¹⁴	cm⁻³
λ_p	1.35	mm
	1,000	T m⁻¹
	0.7	m



Short (100μm) bunches with 10^{11} p⁺ do not exist!!!

CERN PS-SPS-LHC σ_z~6-12cm

E_{WB}=12-6MV/m ($\sigma_z \sim \sqrt{2}c/\omega_{pe}$)

n the wakefields of a p⁺ bunch

✧ dient dilution

✧Gr n over 100's m

✧Ope ower n_e (6×10^{14}cm⁻³), larger $(\lambda_{pe})^3$, easier life …

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SELF-MODULATION INSTABILITY (SMI)

✧CERN p^+ bunches (PS, SPS, LHC) ~6-12cm long

✧$E_{WB} \sim \omega_{pe} \sim n_e^{1/2}$ and $\sigma_z \sim \lambda_{pe} \sim n_e^{-1/2}$ => $E_{WB} \sim 1/\sigma_z$

} $\lambda_{pe} << \sigma_{z,\xi}$

PRL 104, 255003 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Self-Modulation Instability of a Long Proton Bunch in Plasmas

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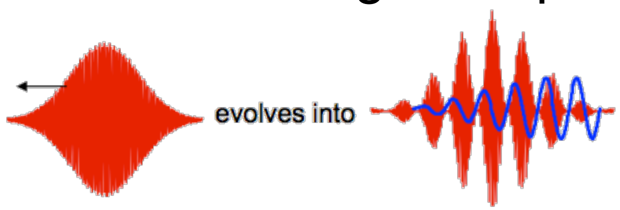
(Received 16 April 2010; published 25 June 2010)

An analytical model for the self-modulation instability of a long relativistic proton bunch propagating in uniform plasmas is developed. The self-modulated proton bunch resonantly excites a large amplitude plasma wave (wakefield), which can be used for acceleration of plasma electrons. Analytical expressions for the linear growth rates and the number of exponentiations are given. We use full three-dimensional particle-in-cell (PIC) simulations to study the beam self-modulation and transition to the nonlinear stage. It is shown that the self-modulation of the proton bunch competes with the hosing instability which tends to destroy the plasma wave. A method is proposed and studied through PIC simulations to circumvent this problem, which relies on the seeding of the self-modulation instability in the bunch.

DOI: 10.1103/PhysRevLett.104.255003 PACS numbers: 52.35.−g, 52.40.Mj, 52.65.−y

✧Idea developed "thanks" to the non-availability of short p^+ bunches

✧Very similar to Raman self-modulation of long laser pulses (LWFA of the 20th century)



OUTLiNE

- ✧ Introduction to plasma wakefield accelerator (PWFA)
- ✧ Seeded Self-Modulation (SSM)
- ✧ AWAKE experiment
- ✧ SSM experimental results
  - ✧ Demonstration
  - ✧ Physics
- ✧ e^- acceleration
- ✧ Future and Summary

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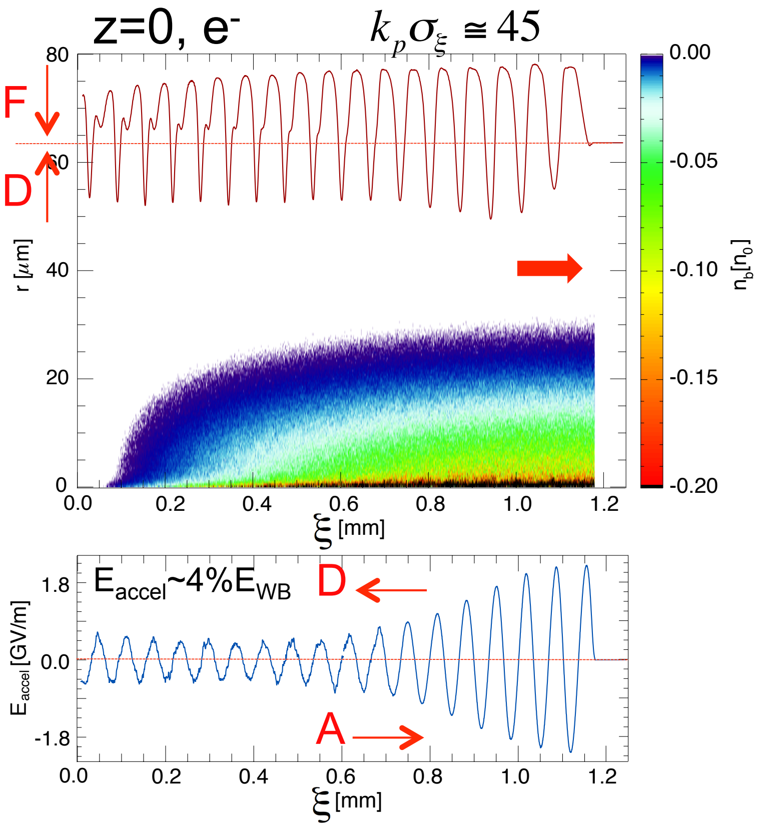
SEEDED SELF-MODULATiON (SSM)

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

J. Vieira, IST



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

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

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

Growth mechanism:

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

Feedback

✧ Seeding = Control
✧ Wakefields start @ seed
✧ $W_z \sim W_{perp}$

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

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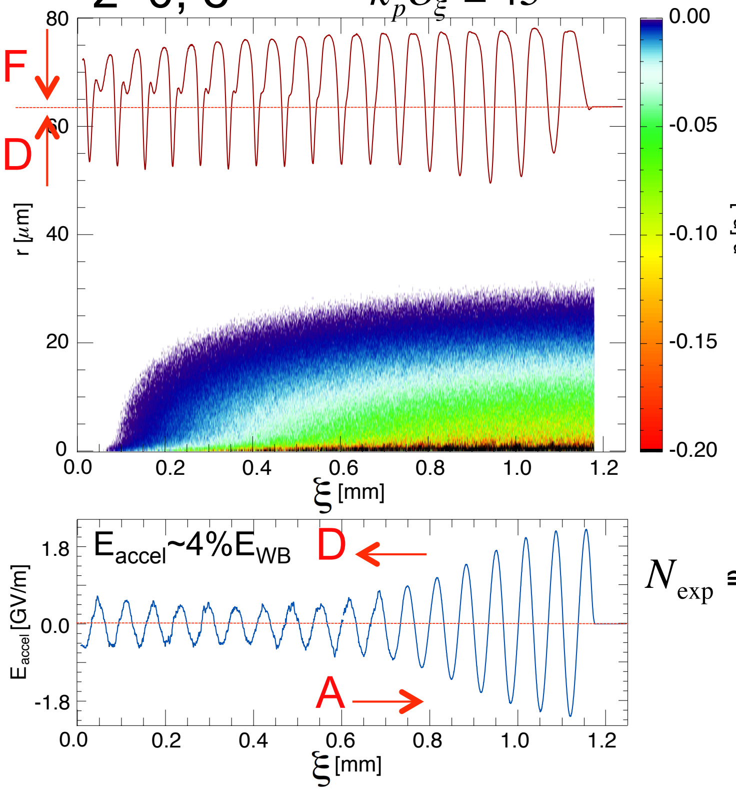
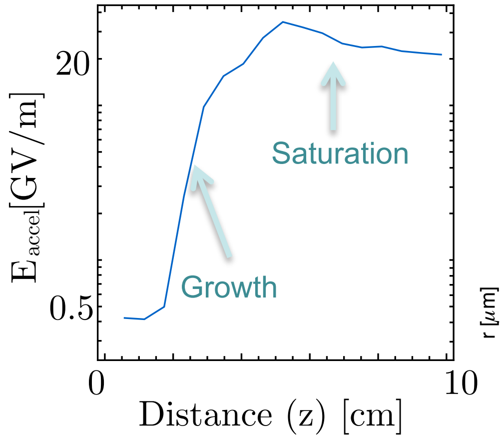
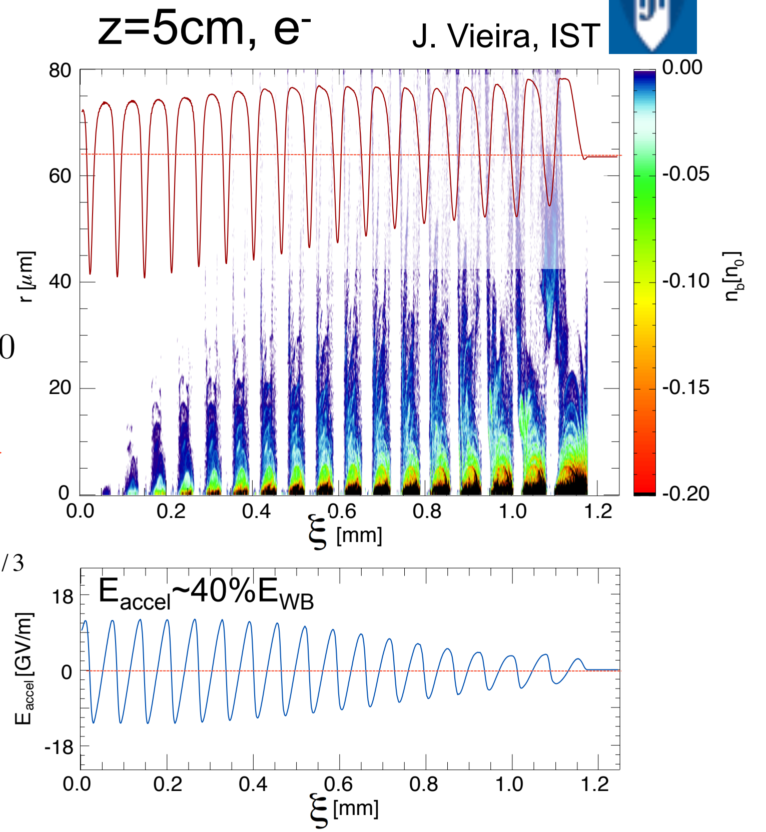
SELF-MODULATION INSTABILITY (SSM)







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

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)

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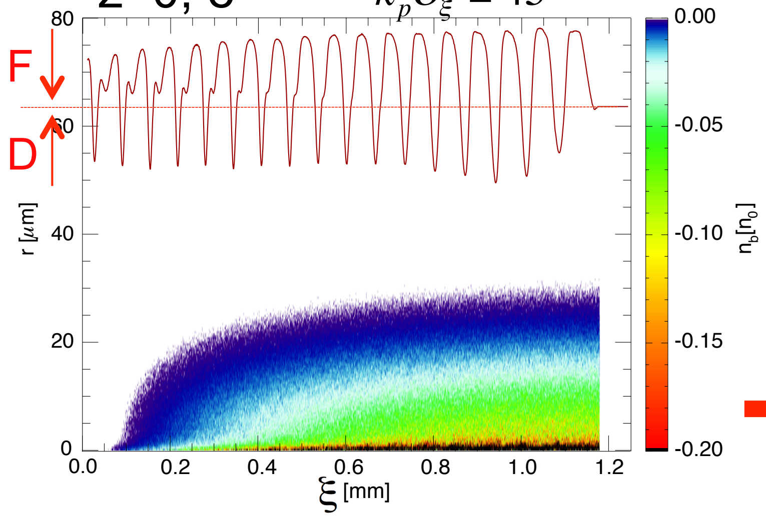
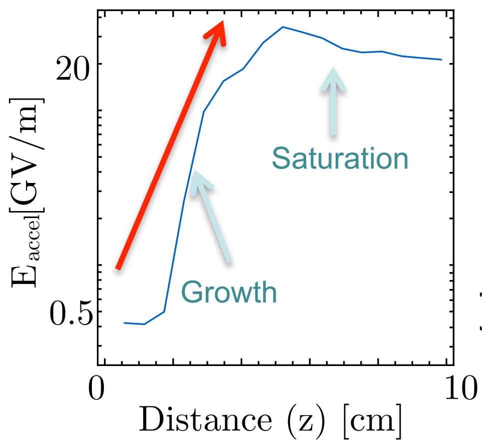
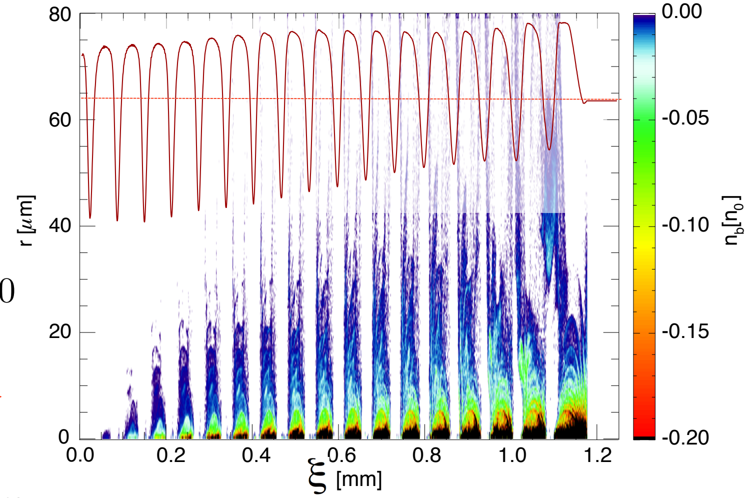
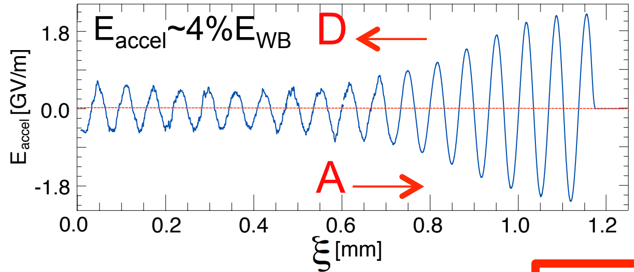
SELF-MODULATION INSTABILITY (SSM)









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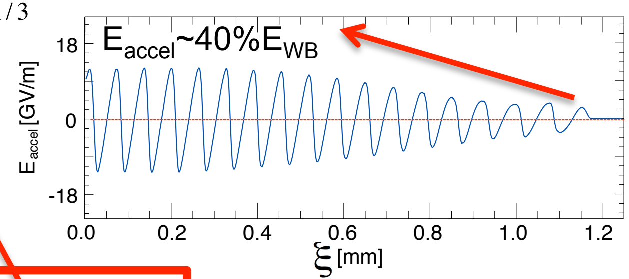

Grows along the bunch & along the plasma

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)

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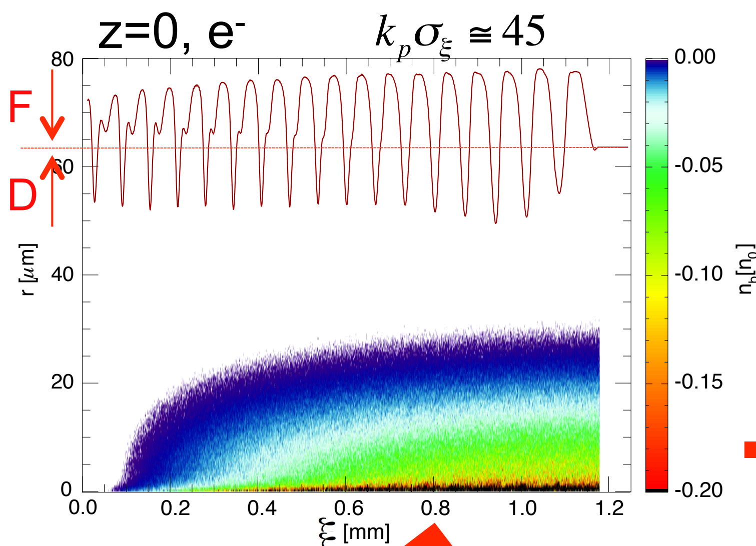
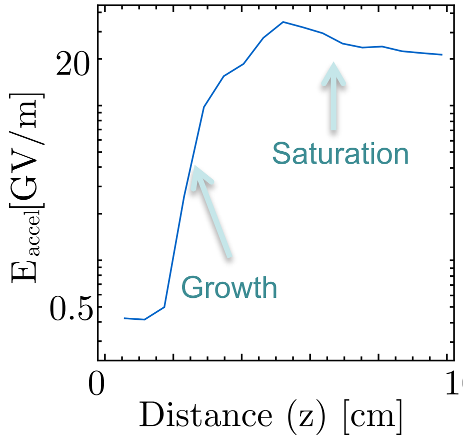
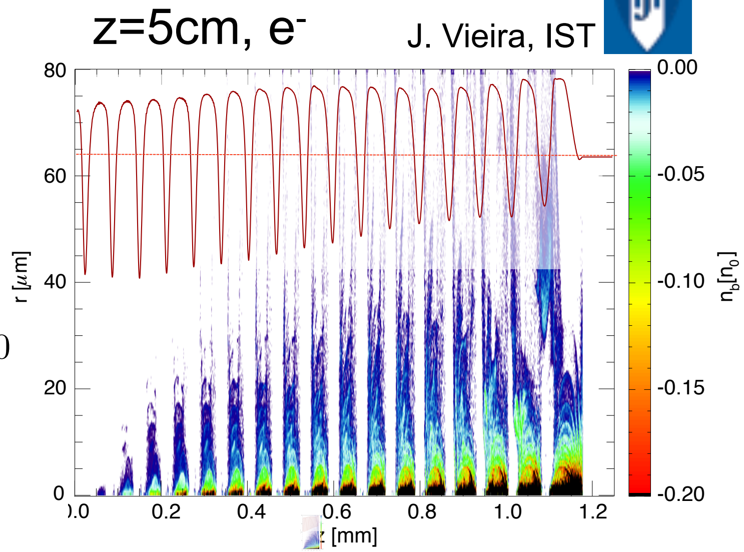
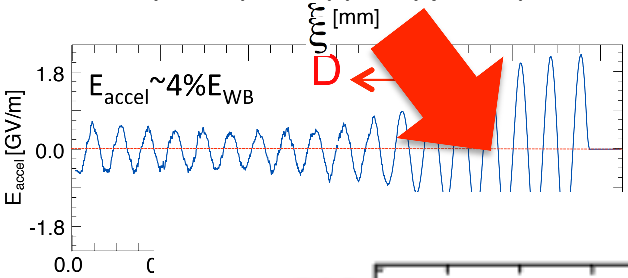
SELF-MODULATION INSTABILITY (SMI)





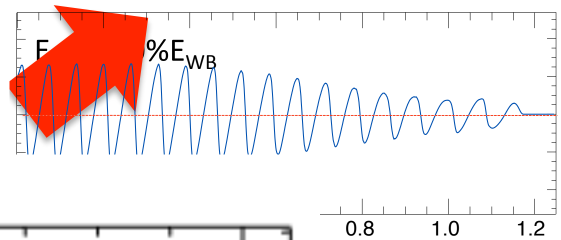
J. Vieira, IST

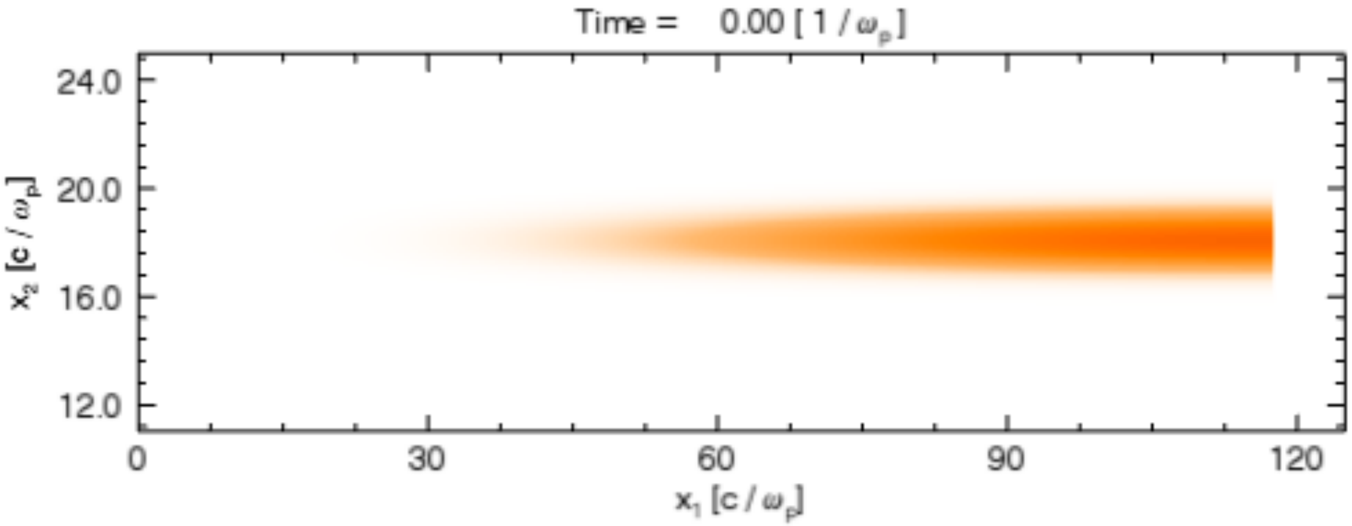




Radial!

NOT longitudinal!





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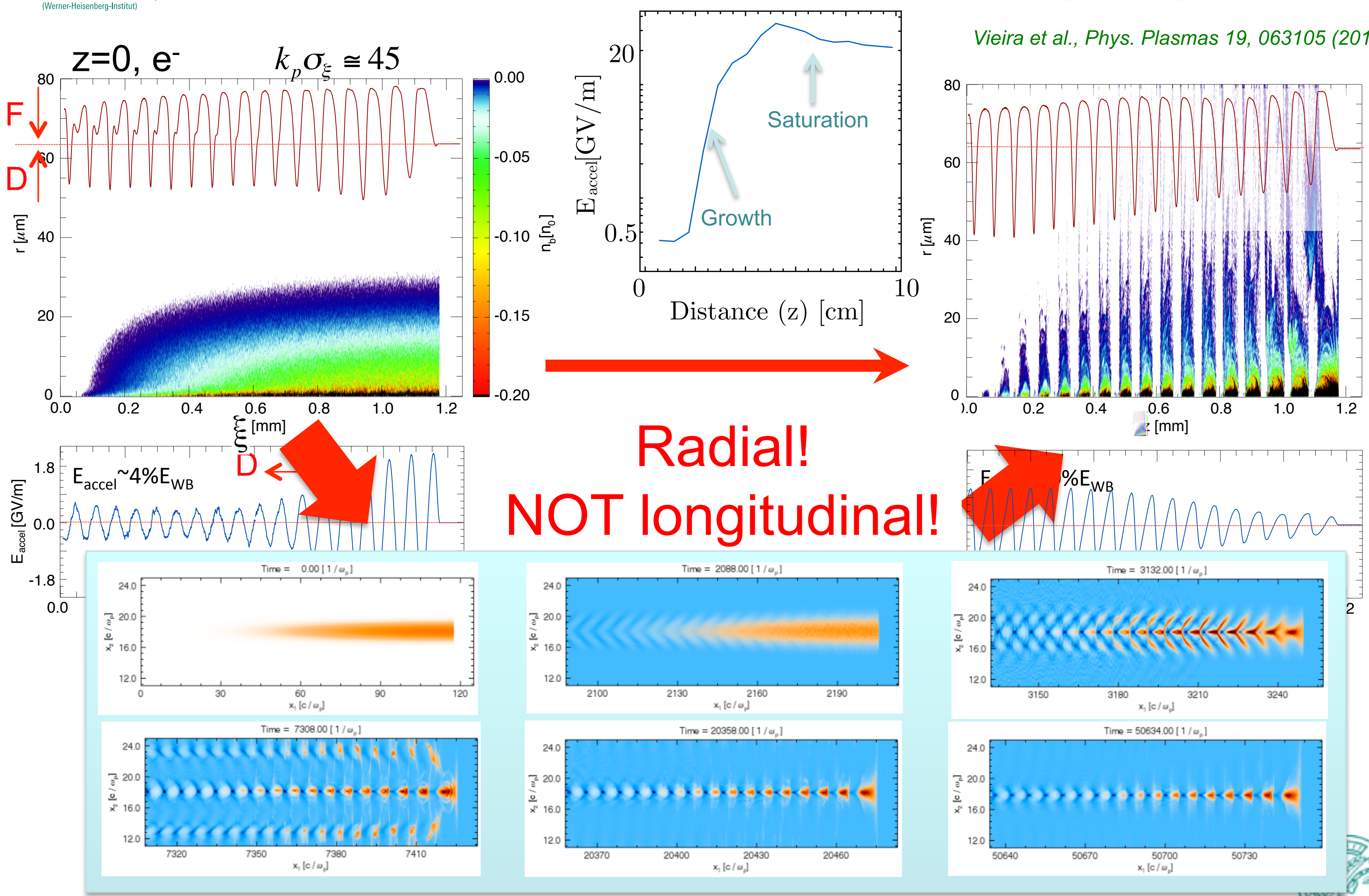
SELF-MODULATION INSTABILITY (SMI)

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



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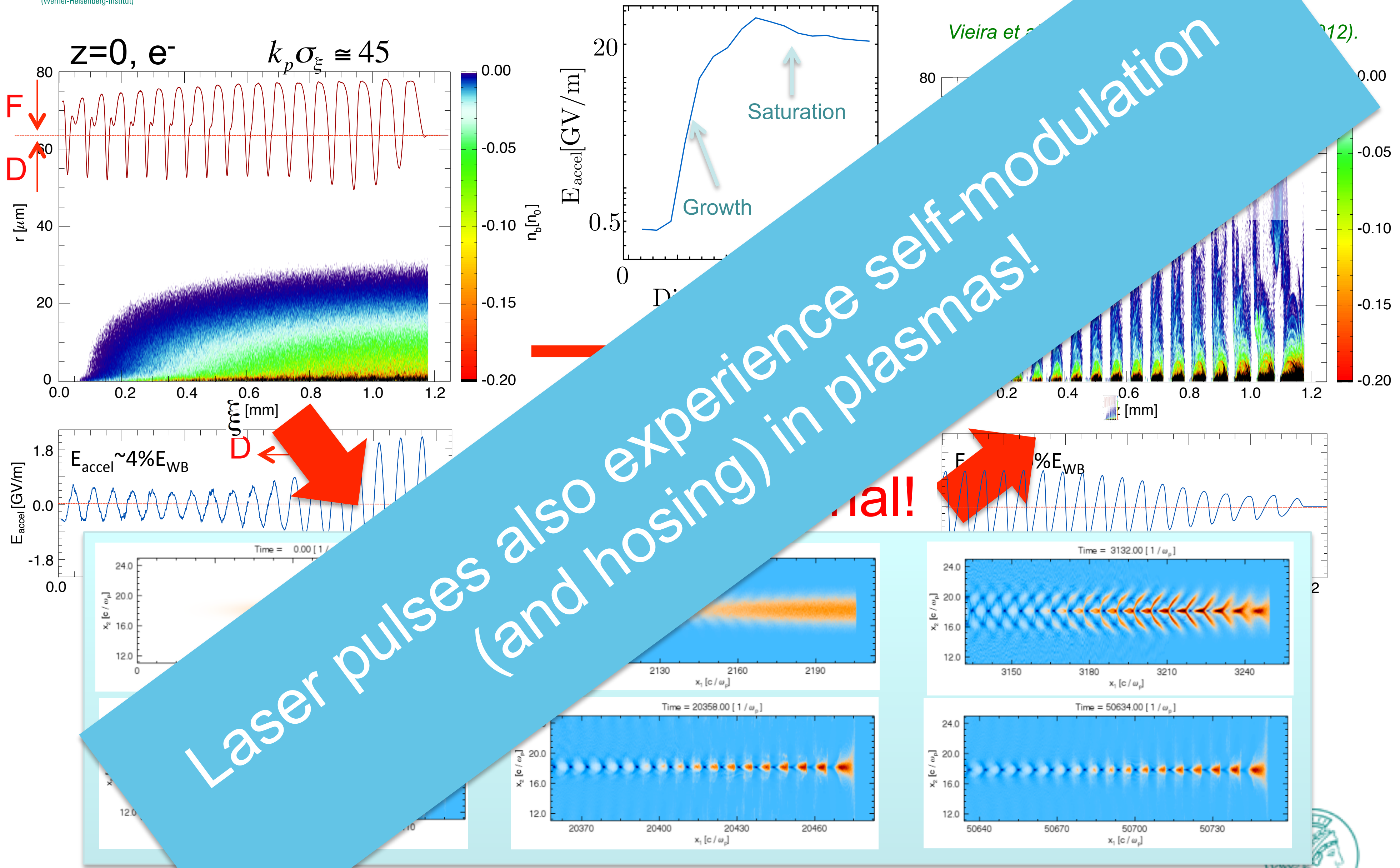
AWAKE

SELF-MODULATION INSTABILITY (SMI)



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

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OUTLiNE

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- SSM experimental results
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- e^- acceleration
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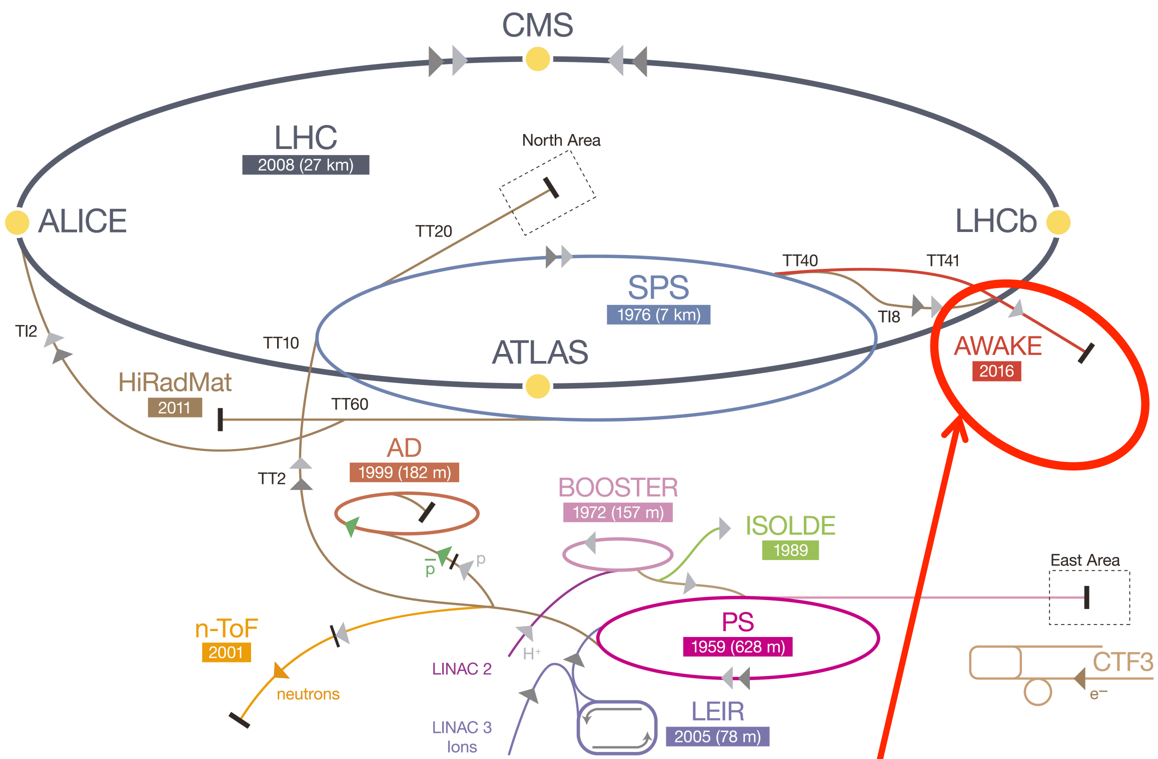
PROTON BEAMS @ CERN

CERN's Accelerator Complex



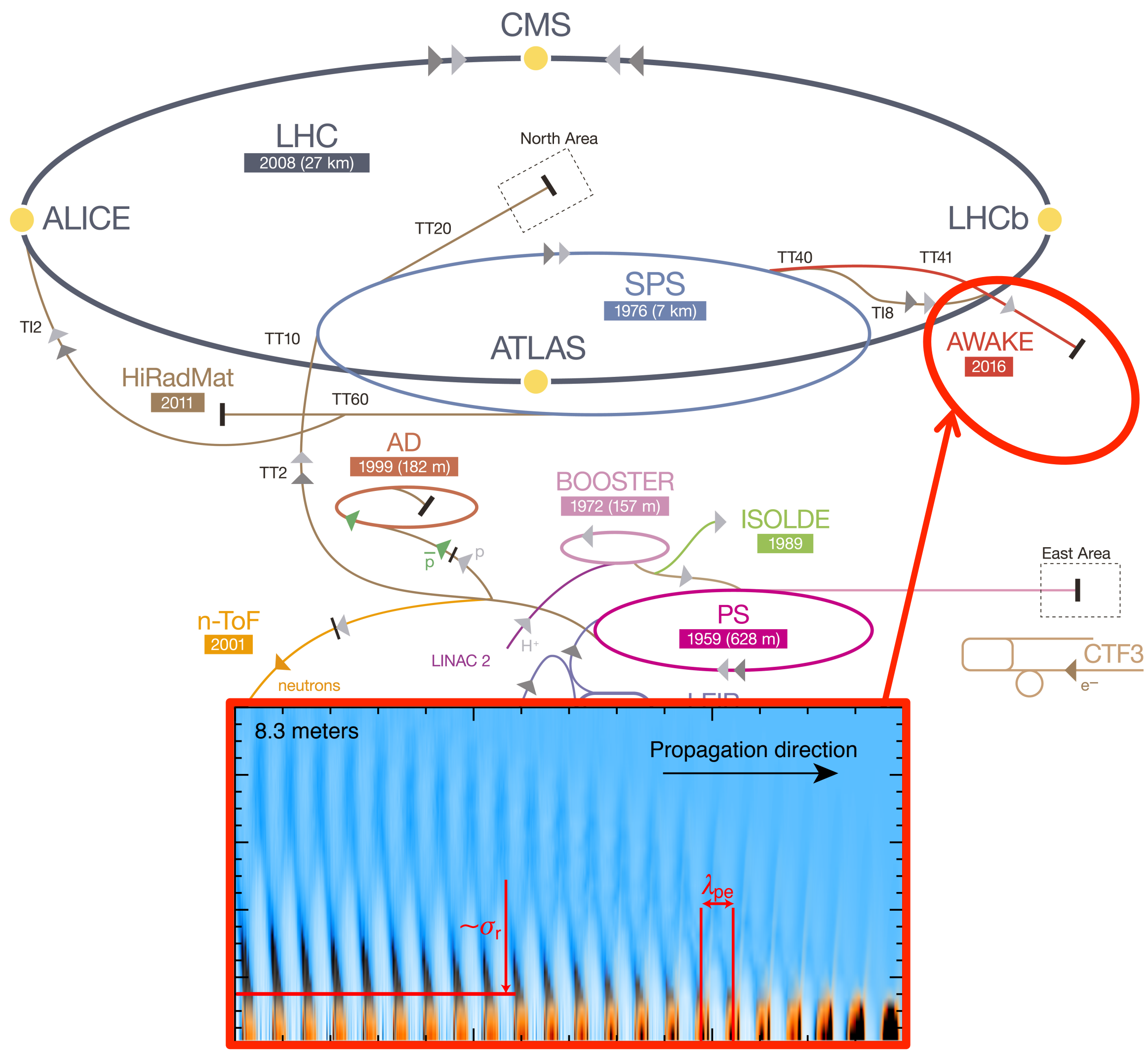
experimental area

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

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

PROTON BEAMS @ CERN

CERN's Accelerator Complex



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σ_r^* (µm)	400	200	200
β^* (m)	1.6	5	5

$c/\omega_{pe} \approx \sigma_r \Leftrightarrow$ $n_e \sim 7\text{x}10^{14}\text{cm}^{-3}$

$\lambda_{pe} \sim 1.3\text{mm} << \sigma_z$

$f_{pe} \sim 240\text{GHz}$

$L_p \sim 10\text{m} \sim 2\beta^*$

$E_{WB} \sim 2.5\text{GV/m}$

- ✧SPS beam: high energy, small σ_r^*, long β^*
- ✧$\sigma_r \sim c/\omega_{pe}$, $\sigma_z >> c/\omega_{pe}$

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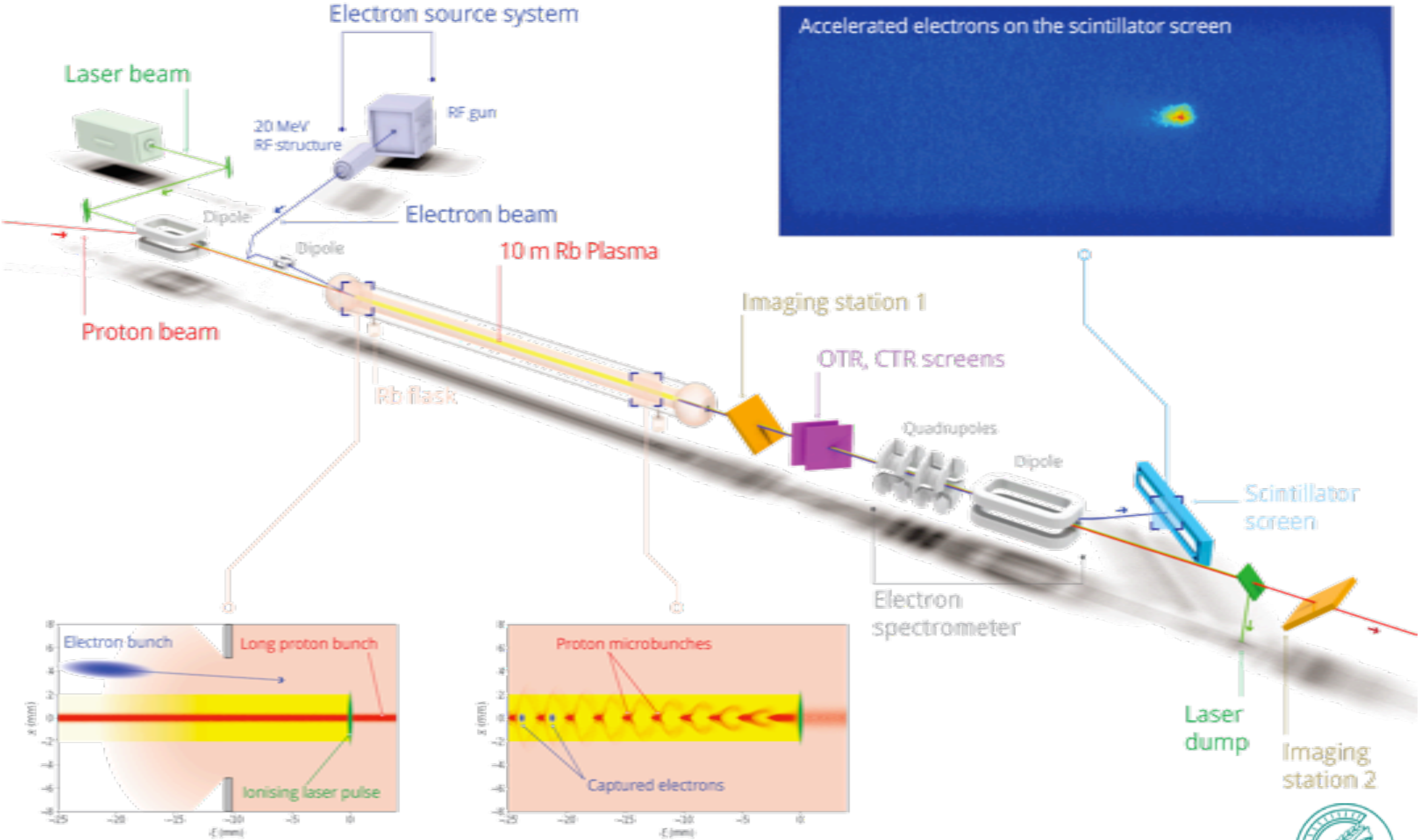
AWAKE EXPERiMENT



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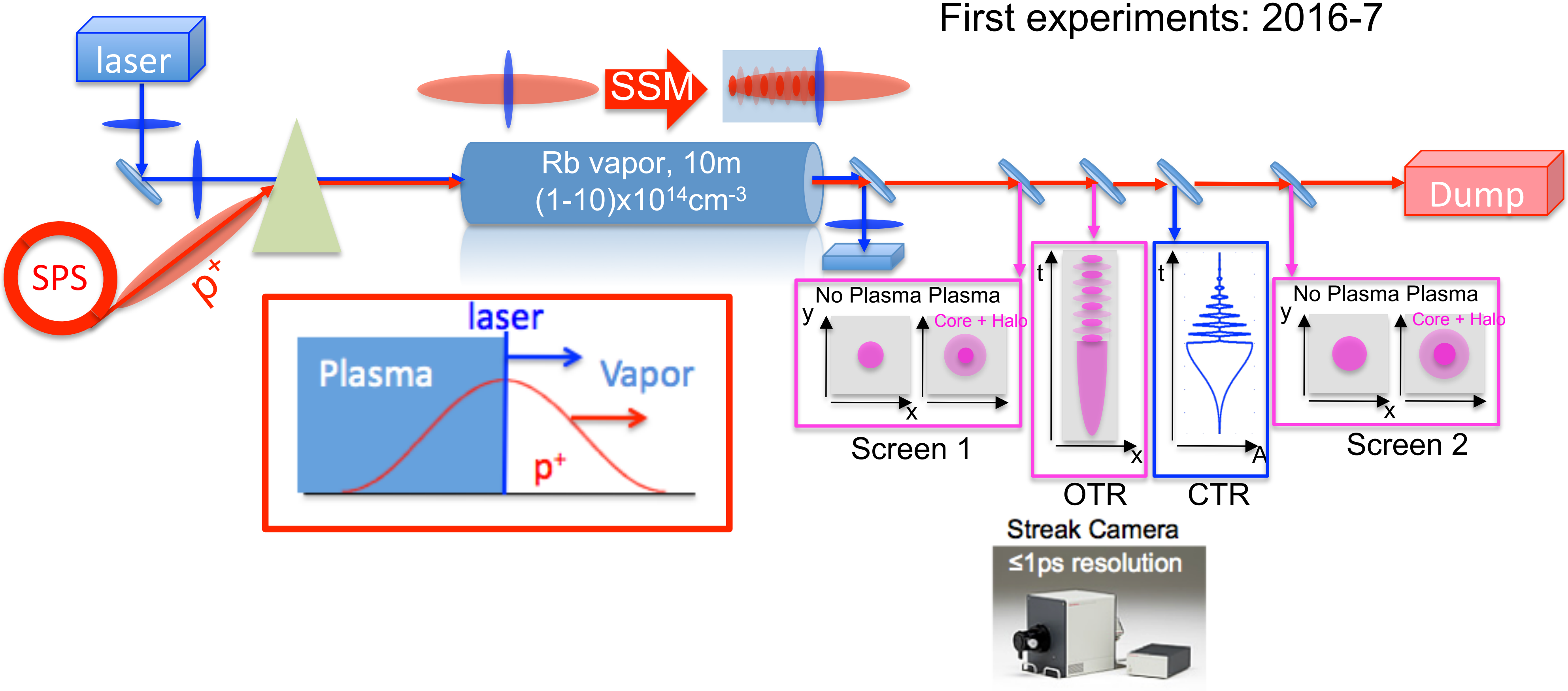
AWAKE, Nature 561, 363 (2018)

AWAKE EXPERIMENT

First experiments: 2016-7



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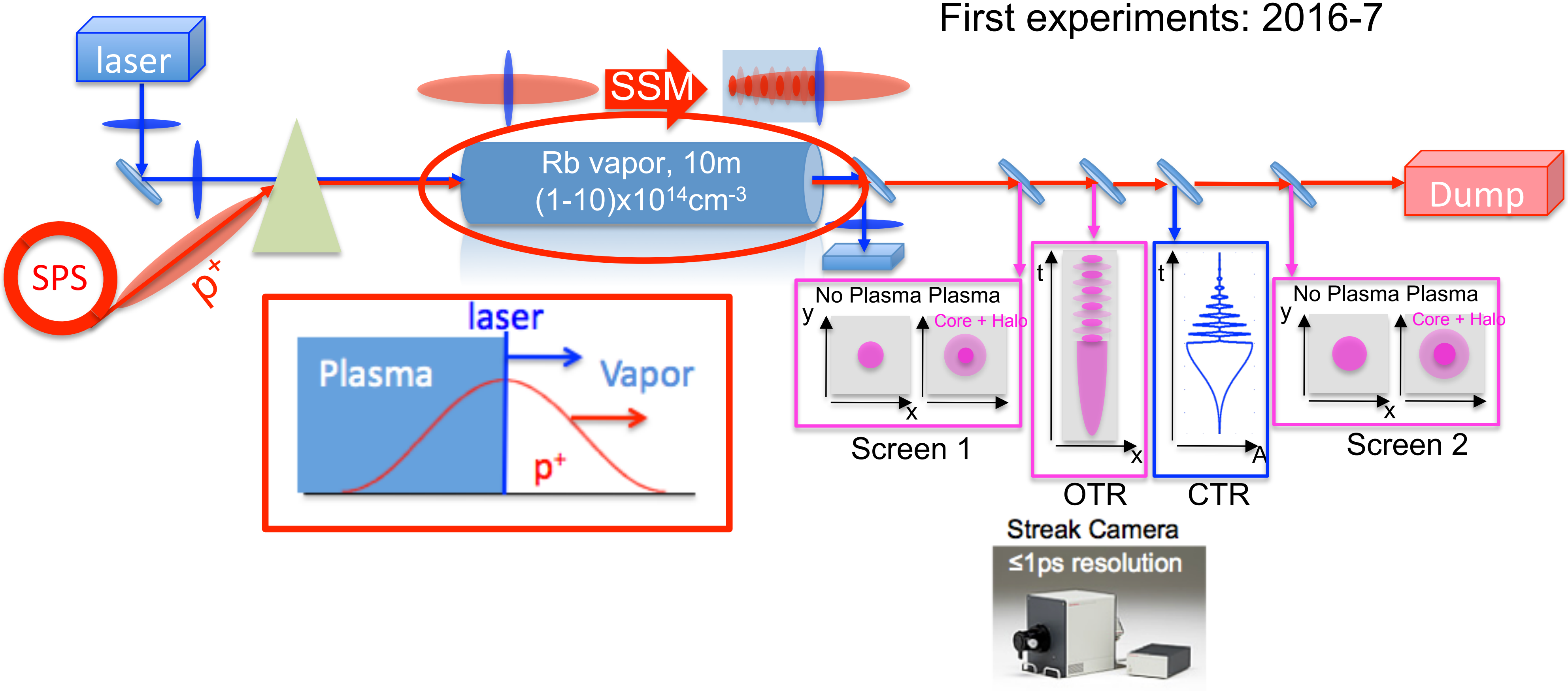
AWAKE EXPERIMENT

First experiments: 2016-7



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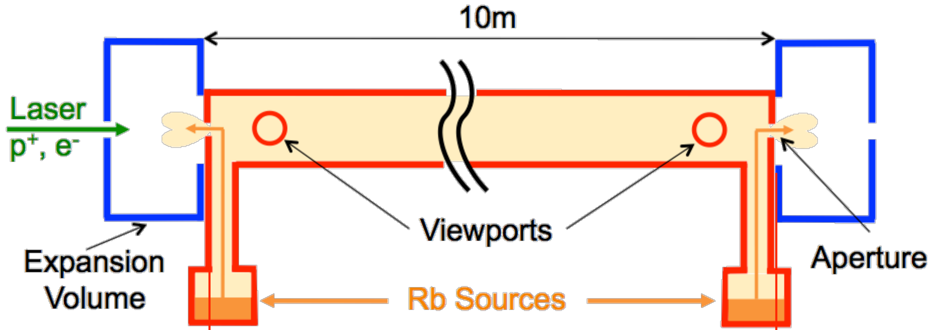
RUBIDIUM VAPOR SOURCE

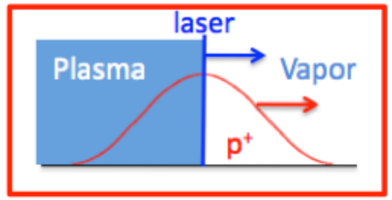
Source requirements:
- ✧ $10^{14} \leq n_e \leq 10 \times 10^{14}$ cm^{-3}
- ✧ $\Delta n_e/n_e < 0.2\%$
- ✧ Few cm n_e ramp

Laser Field-ionization →

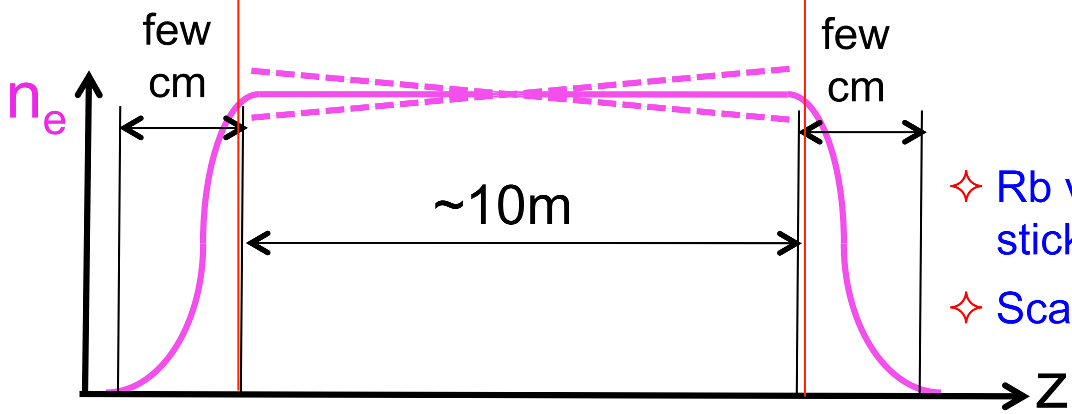
$n_e = n_{Rb}$
Same for n_{Rb}
$r_p > 1$mm



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



- ✧ Impose very uniform T: $\delta n_{Rb}/n_{Rb} = \delta T/T < 0.2\%$
- ✧ $160 \leq T \leq 220$°C for $10^{14} \leq n_{Rb} \leq 10^{15}$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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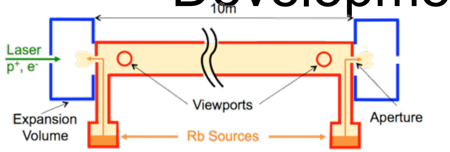
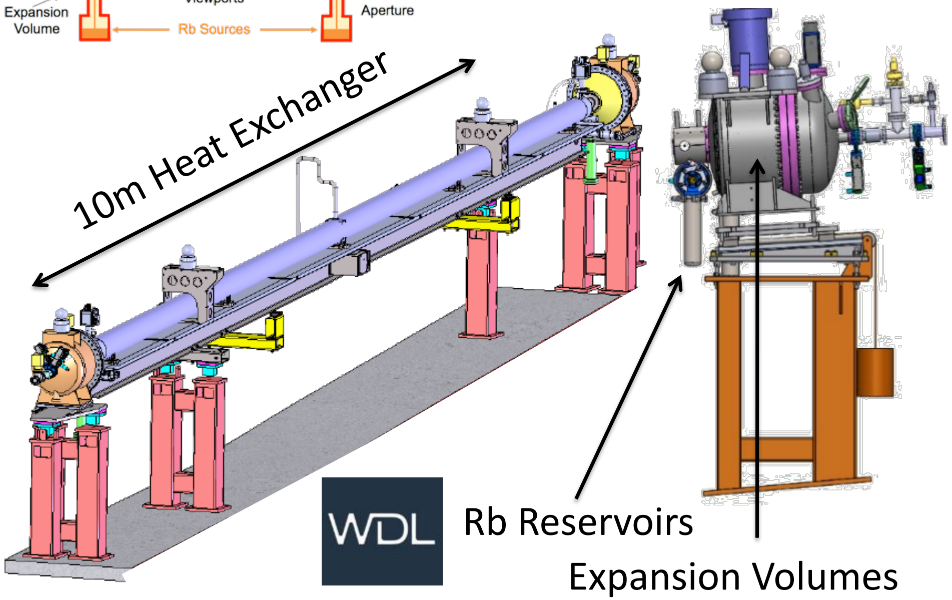
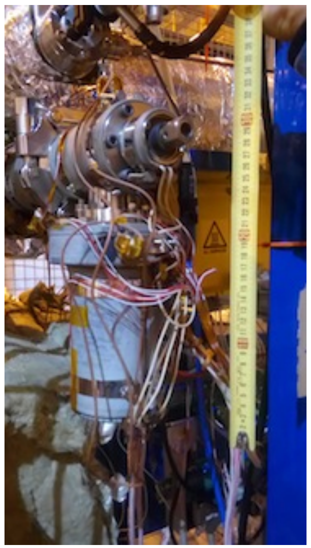
Rb VAPOR SOURCE (heat exchanger)

Development of the ends





Installed in AWAKE!



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Rb VAPOR SOURCE (heat exchanger)

Development of the ends

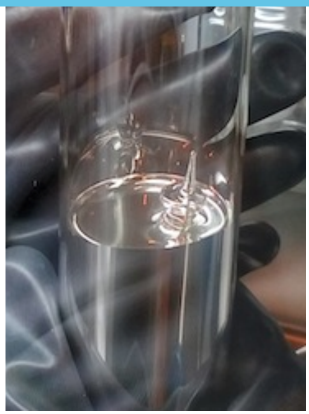
Installed in AWAKE!

Measured $\Delta T<0.5^oC$, 150-210^oC
$\Delta T/T \sim 0.1\%$

Source satisfies density uniformity requirements

E. Oz et al., Nucl. Instr. Meth. Phys. Res. A 740(11), 197 (2014)
G. Plyushchev et al., Journal of Physics D: Applied Physics, 51(2), 025203 (2017)
F. Batsch et al., Nucl. Instr. and Meth. in Phys. Res. A, 909, 359 (2018)

Measurement of n_{Rb} with <0.3% accuracy



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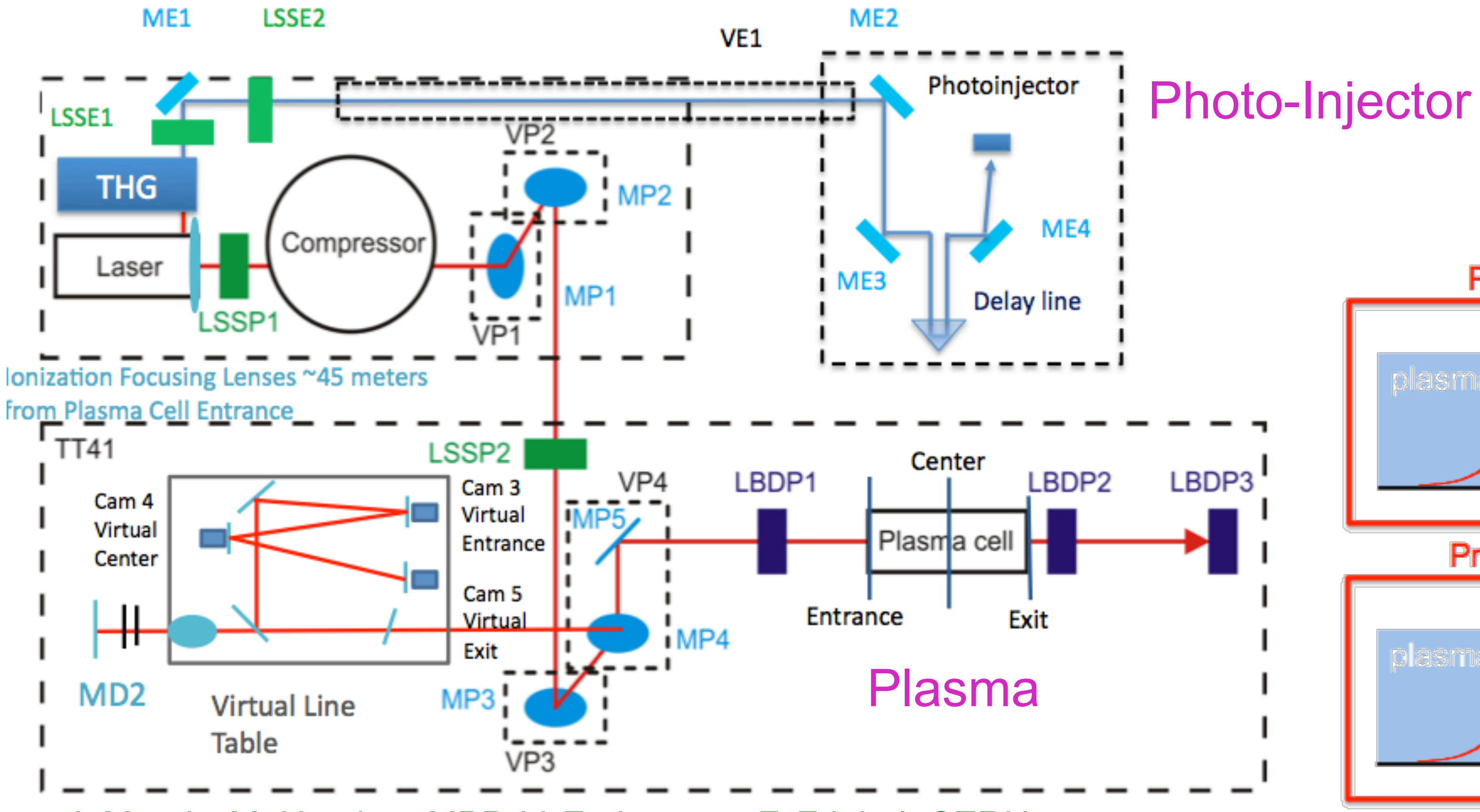
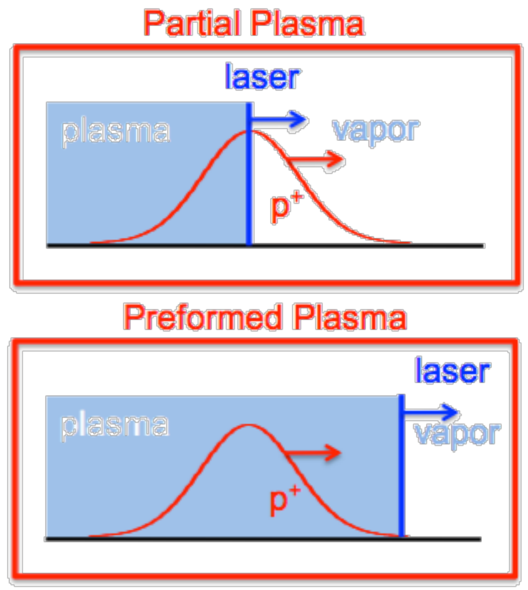
Max-Planck-Institut für Physik

LASER & PLASMA



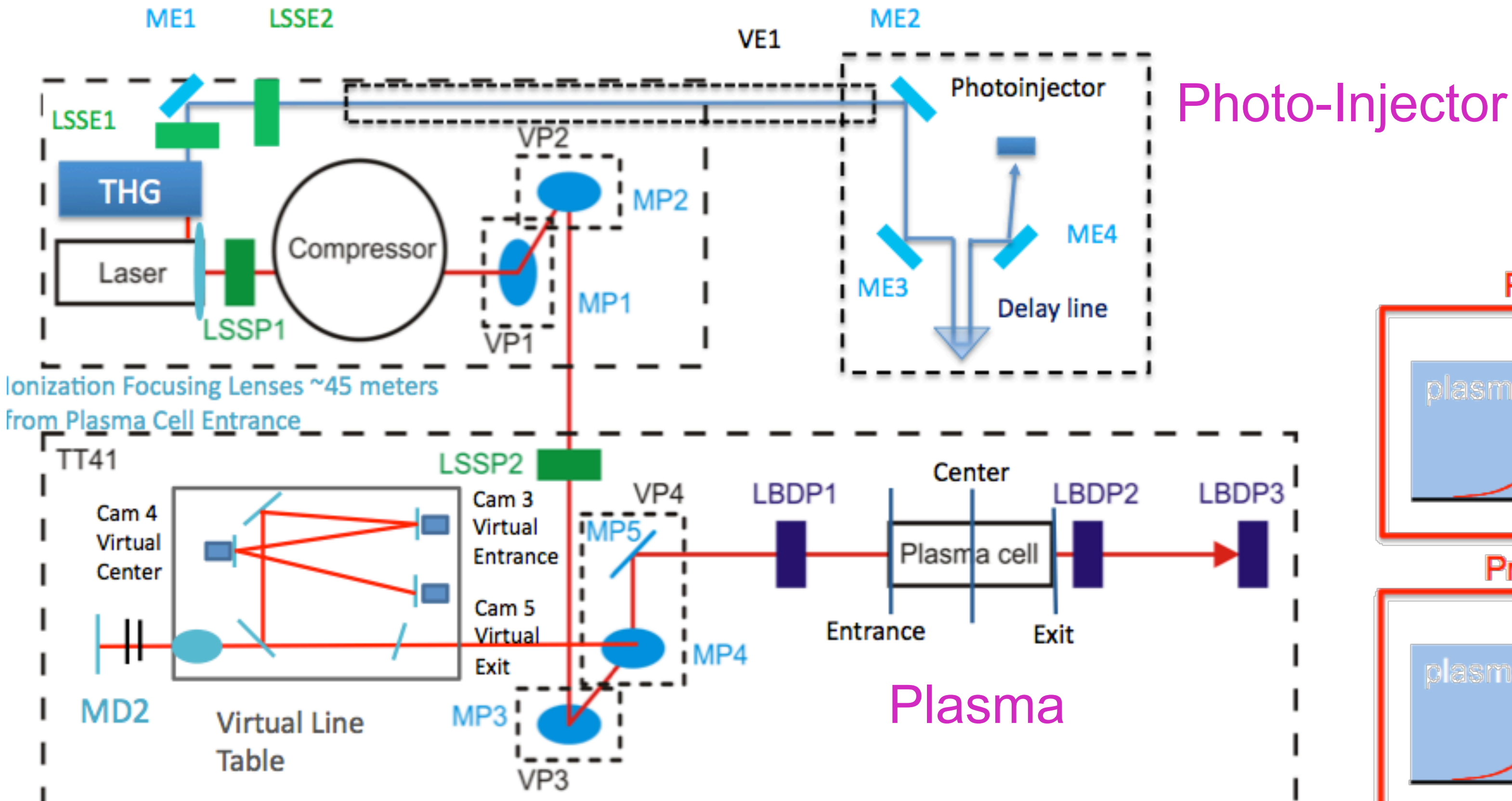


J. Moody, M. Huether, MPP, V. Fedosseev, F. Friebel, CERN

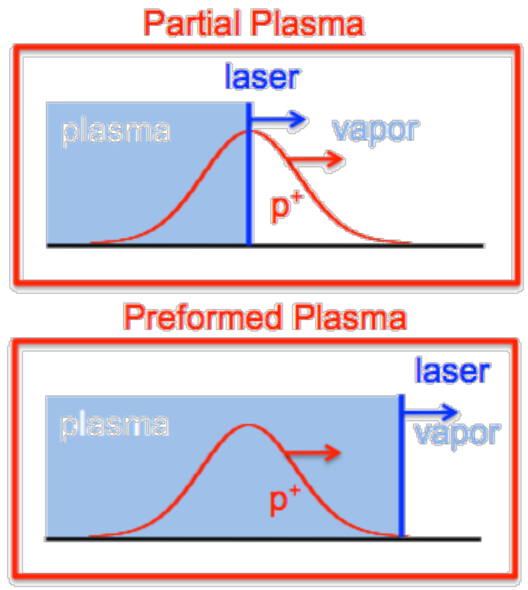
- ✧Fiber/Ti-Sapphire laser: E_{max}=450mJ, ~120fs<<$2\pi/\omega_{pe}$~ps
- ✧Rb: ϕ_{IP}=4.177eV, I_{app}~1.7×10^{12}Wcm^{-2}
- ✧r_0~1mm, Z_R~5m, I_{max}>10×10^{12}Wcm^{-2}>I_{app}
- ✧Field ionization => $n_e=n_{Rb}$, uniformity and ramps
- ✧Virtual plasma for alignment

© P. Muggli

LASER & PLASMA



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



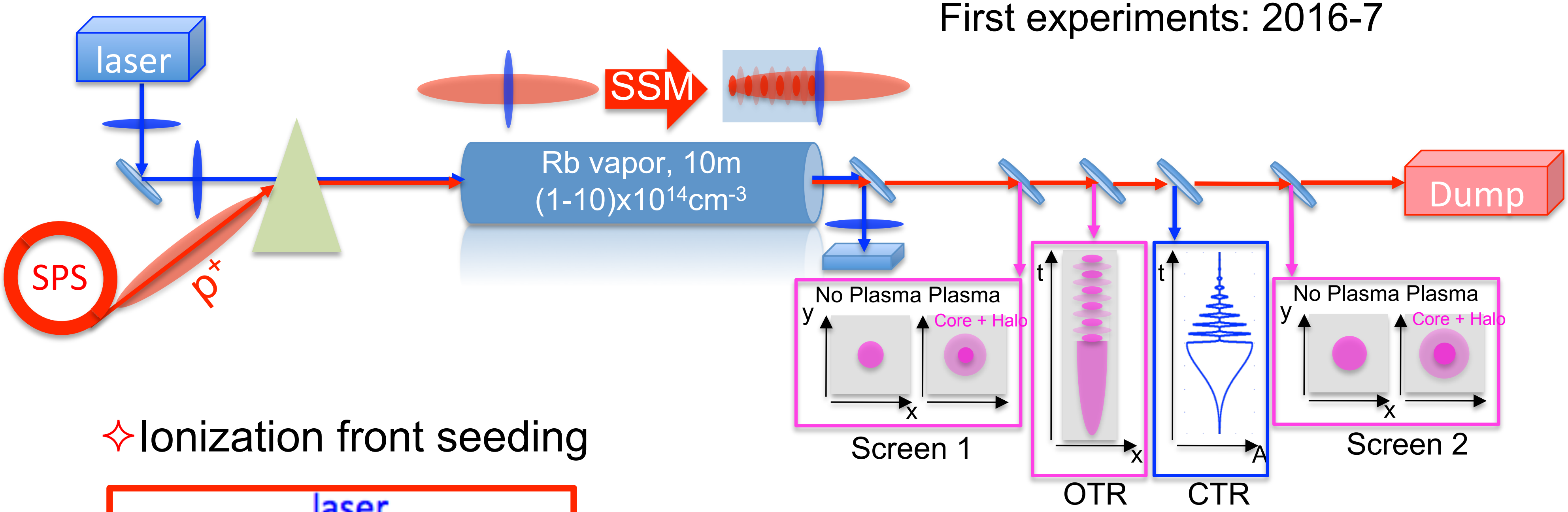
✧Laser-ionization allows for seeding <u>and</u> pre-formed plasma

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

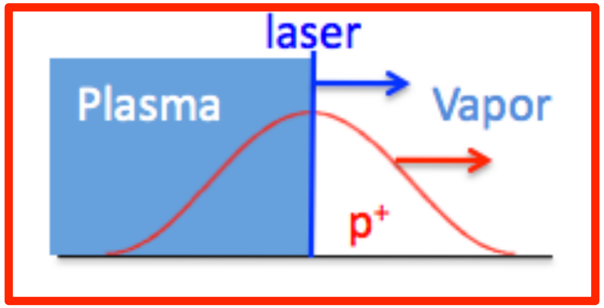
✧Field-ionization (1^{st} e^-): $n_e=n_{Rb}$

AWAKE SEEDiNG

First experiments: 2016-7



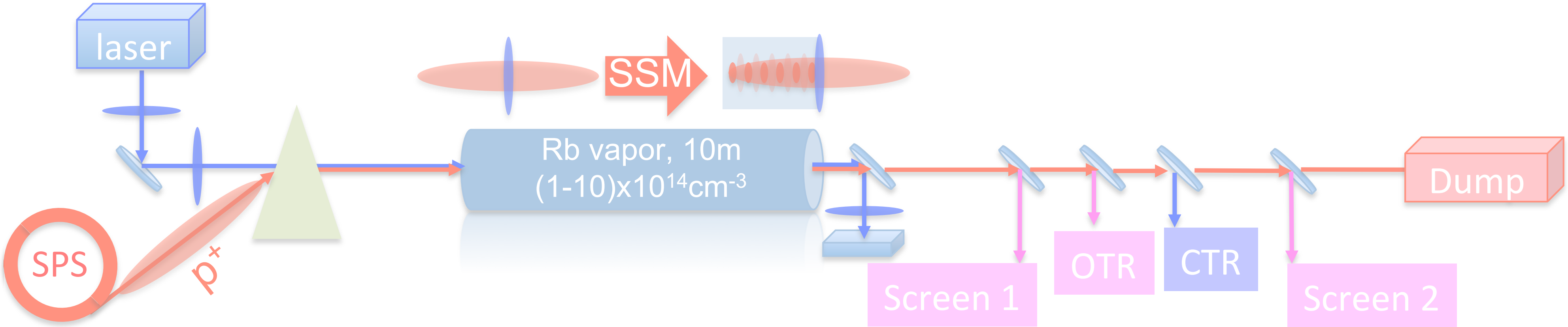
✧Ionization front seeding

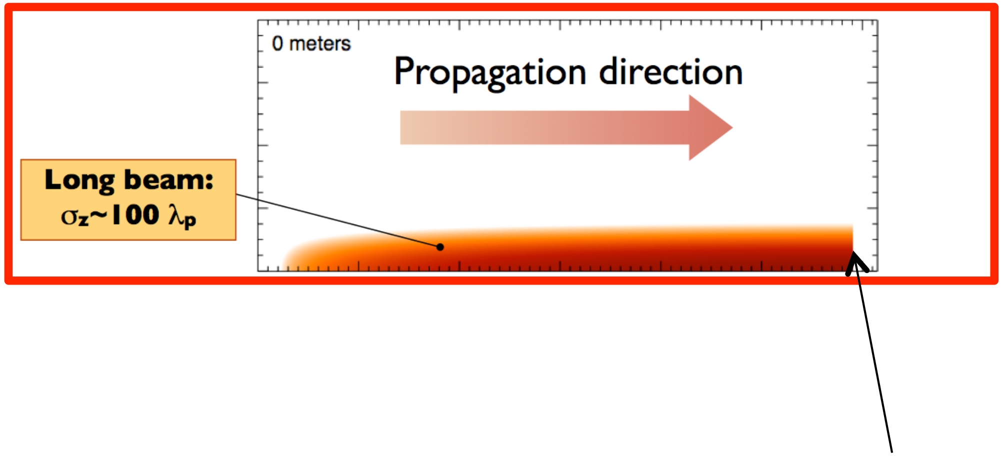


✧Sharp (<<λ_{pe}, $1/\omega_{pe}$), relativistic vapor/plasma boundary propagating within the p^+ bunch => relativistic ionization front seeding

© P. Muggli

AWAKE EXPERIMENT @ CERN





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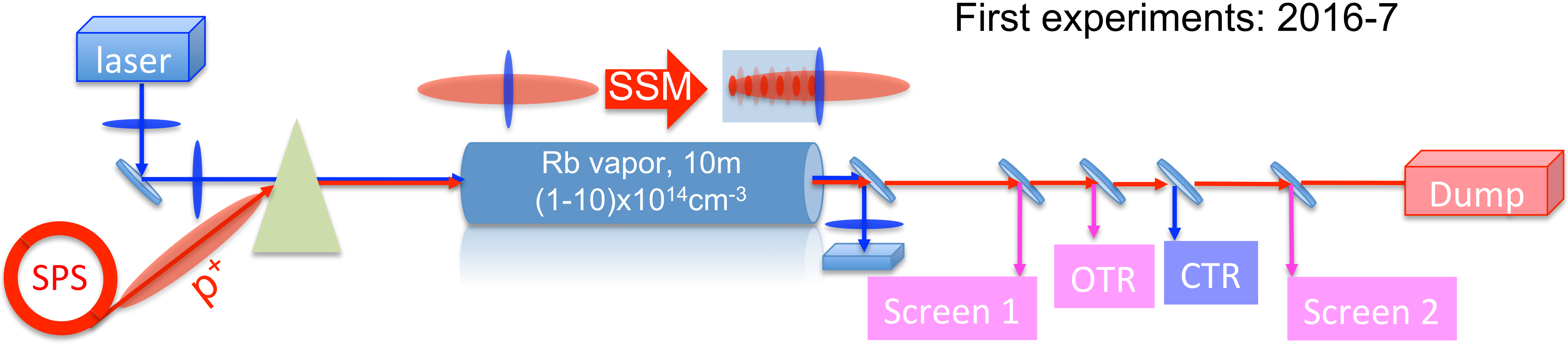
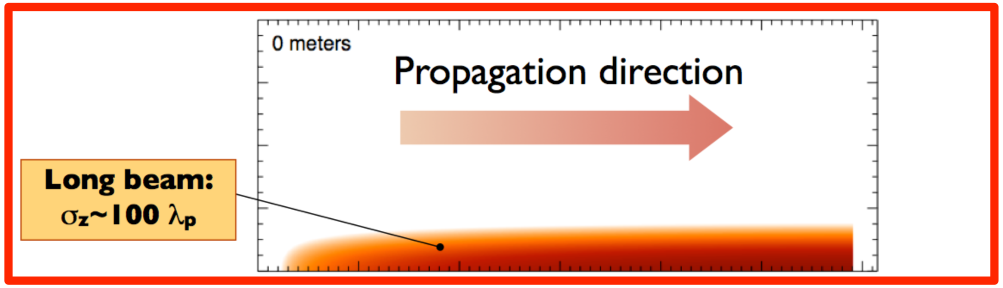
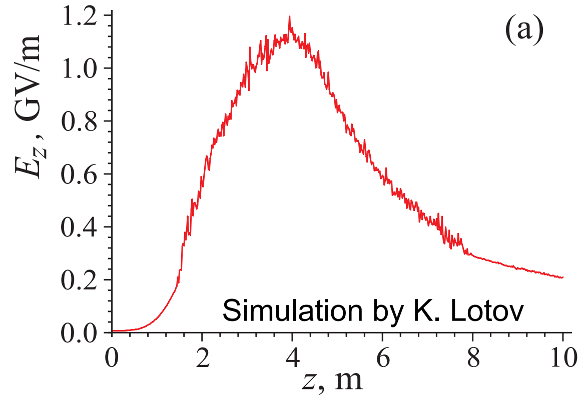
AWAKE EXPERiMENT @ CERN

First experiments: 2016-7







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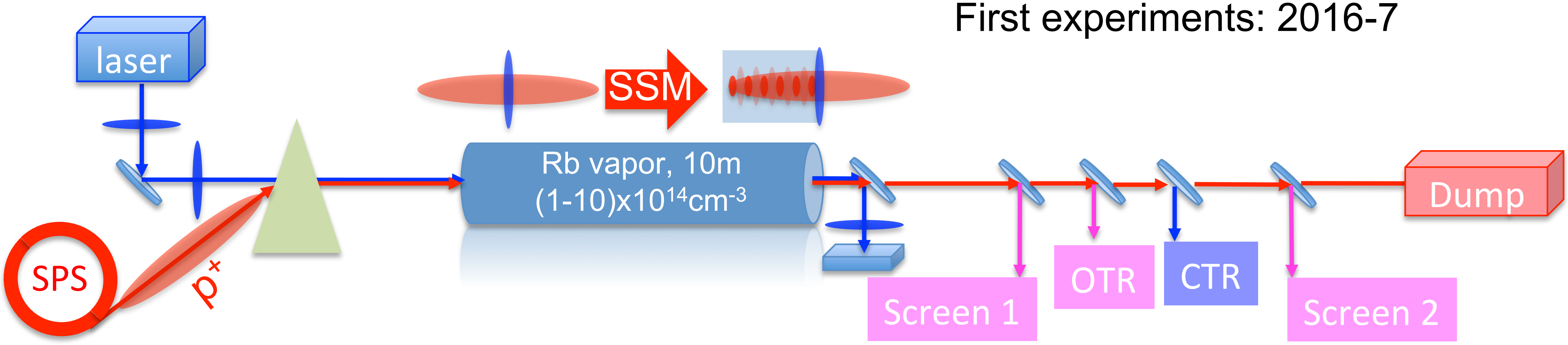
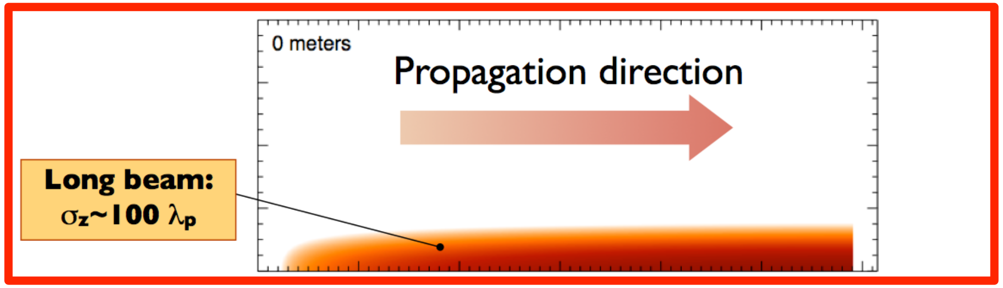
AWAKE EXPERIMENT @ CERN

First experiments: 2016-7





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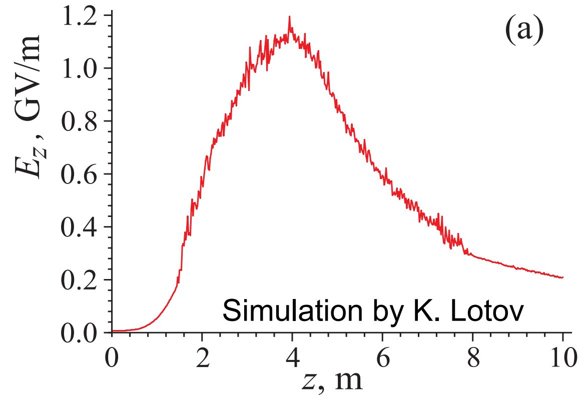

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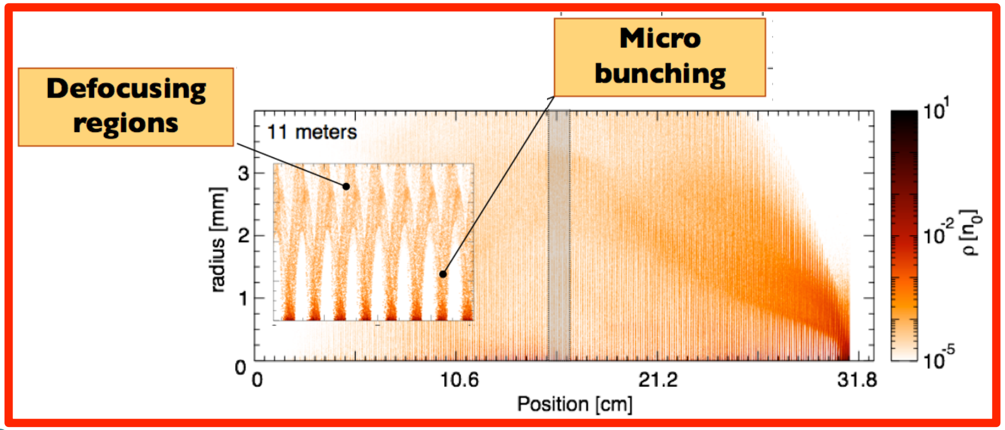

- The long (σ_z~12cm) p^+ bunch self-modulates with period λ_{pe}~1.2mm (n_e~$7x10^{14}cm^{-3}$)
- ~$100\lambda_{pe}$ per σ_z

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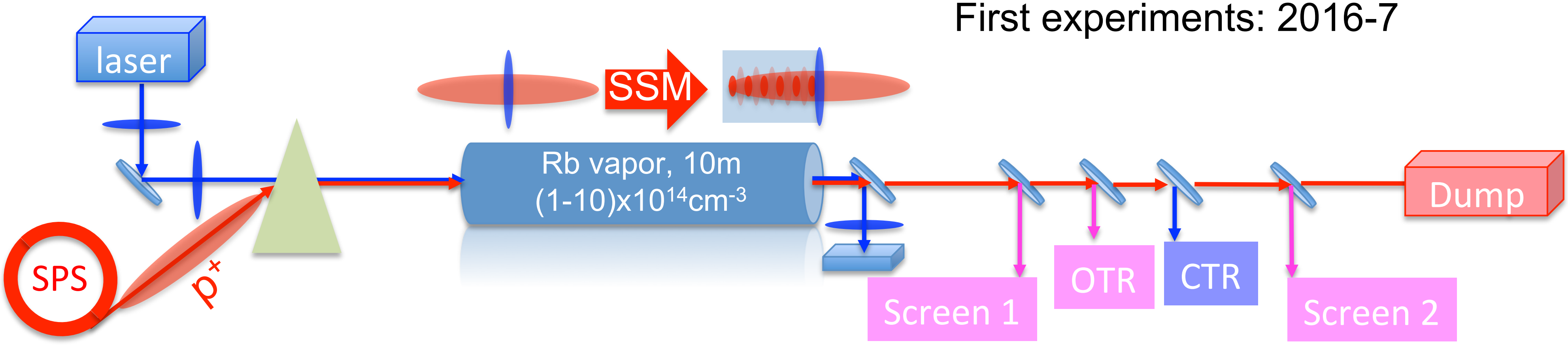
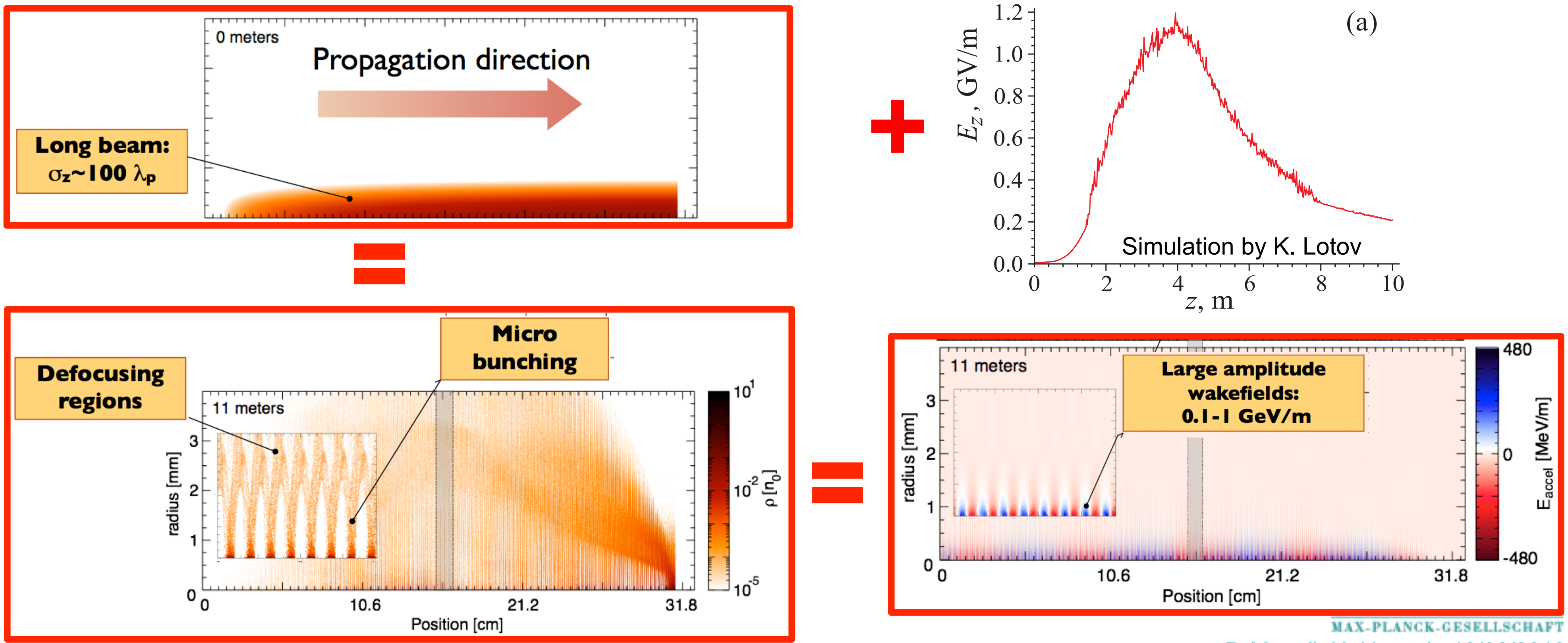
AWAKE EXPERiMENT @ CERN

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

First experiments: 2016-7





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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

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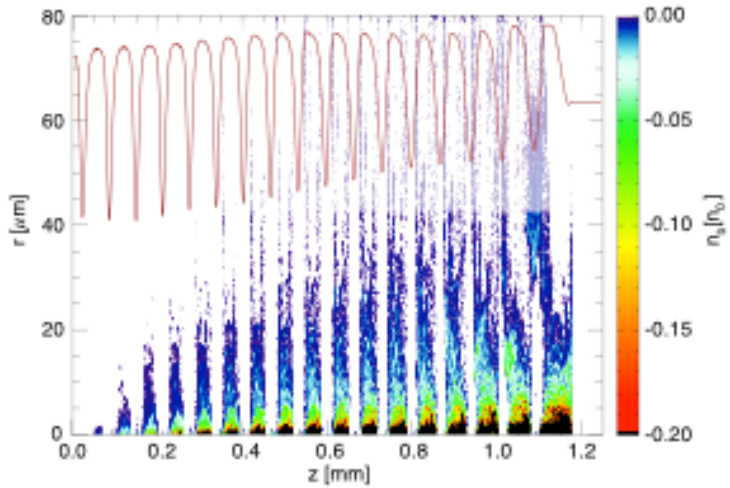
of a long p^+ bunch in a dense plasma
$\sigma_z >> \lambda_{pe} \sim n_e^{-1/2}$

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



OUTLINE

- Introduction to plasma wakefield accelerator (PWFA)
- Seeded Self-Modulation (SSM)
- AWAKE experiment
- SSM experimental results
  - Demonstration
  - Physics
- e⁻ acceleration
- Future and Summary

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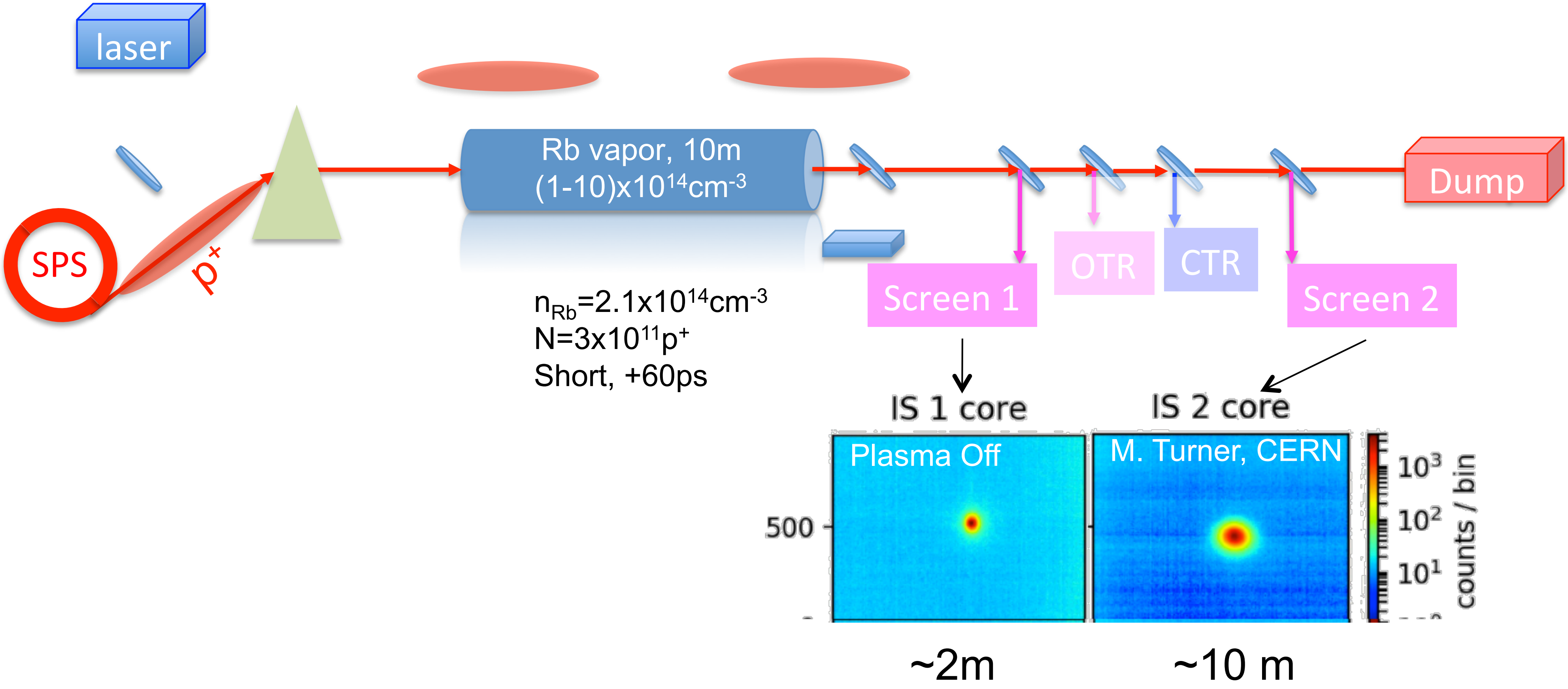
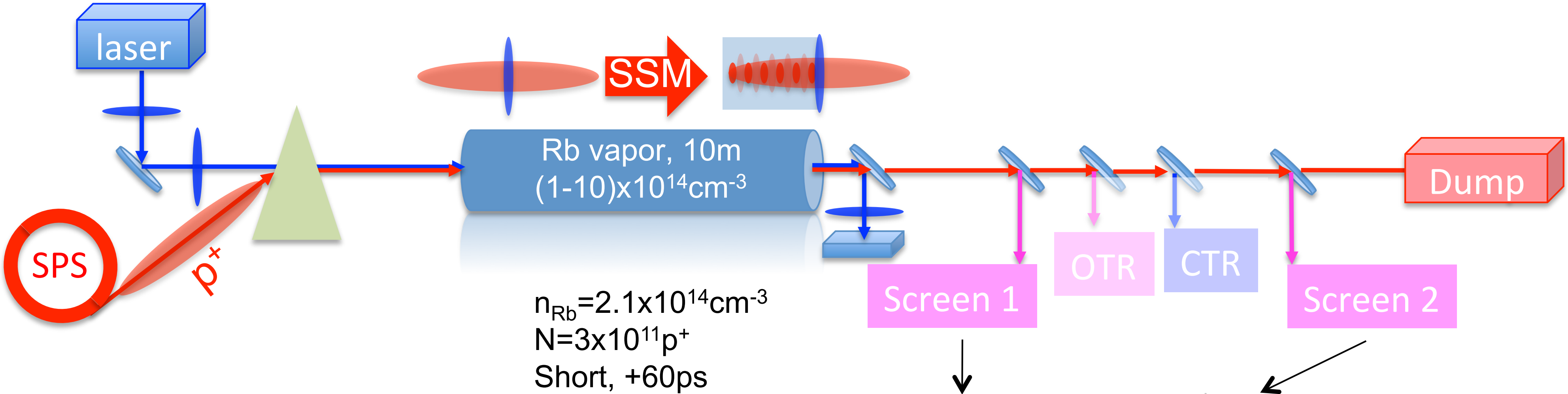
TWO-SCREEN SSM

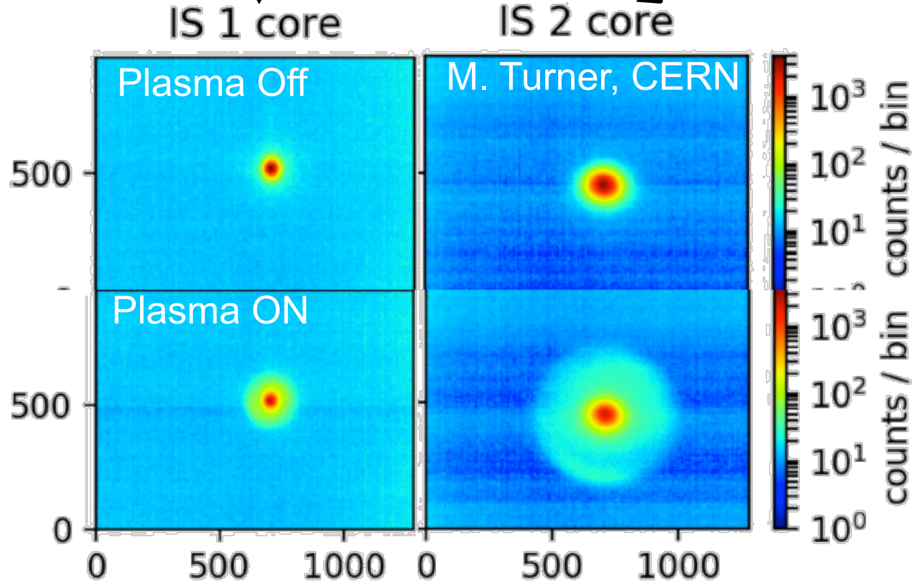


M. Turner, Phys. Rev. Lett. 122, 054801 (2019)

TWO-SCREEN SSM



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



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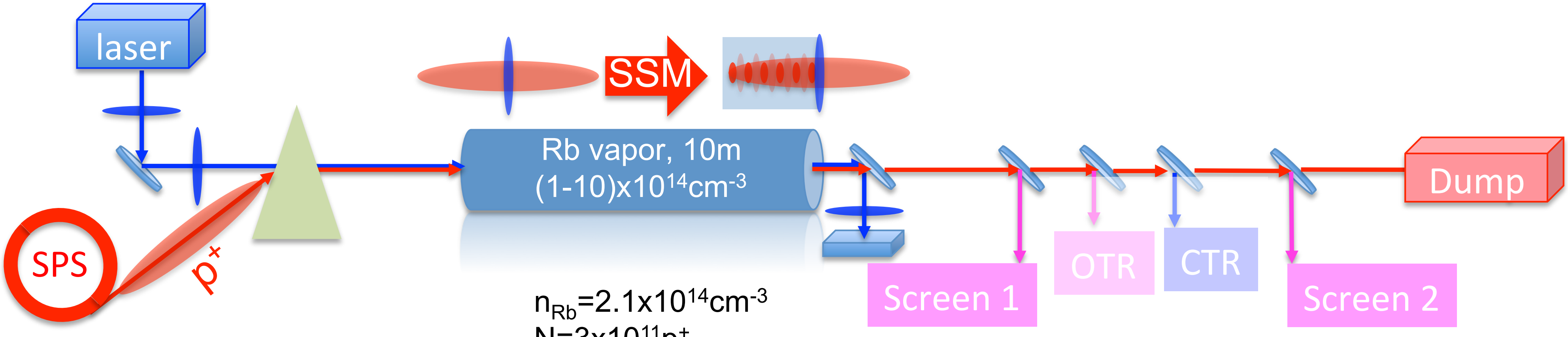
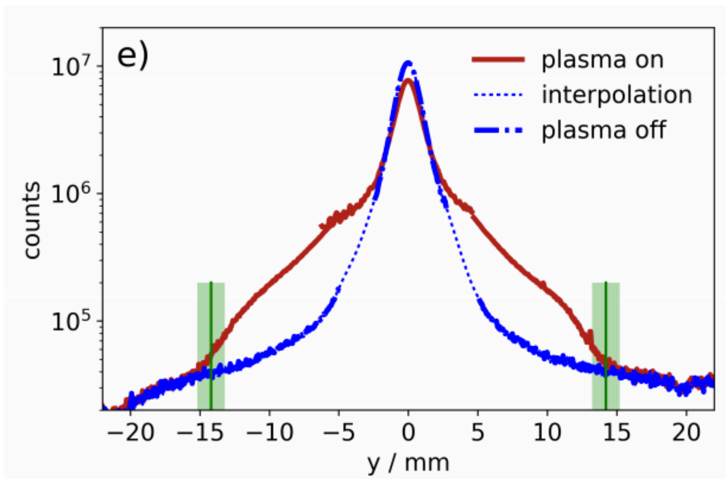
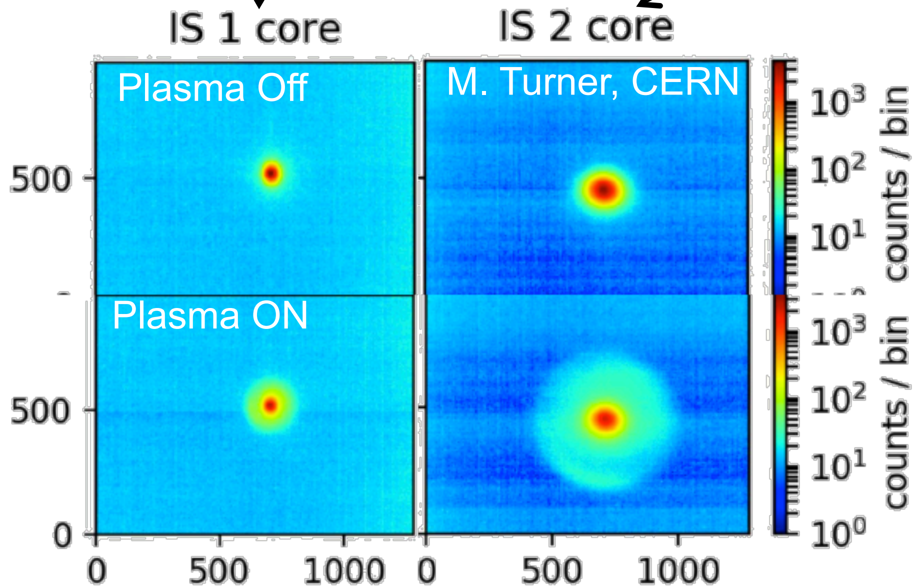


n_{Rb}=2.1x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Short, +60ps

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





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

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Two-Screen SSM

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

AWAKE

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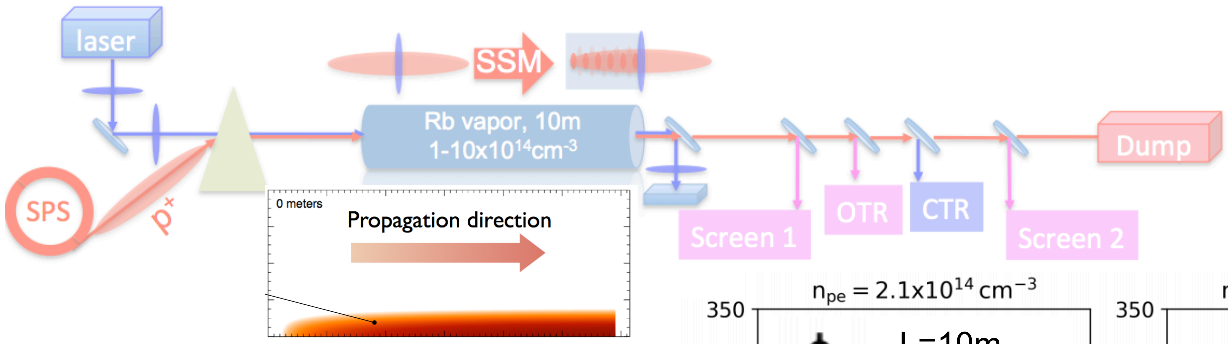
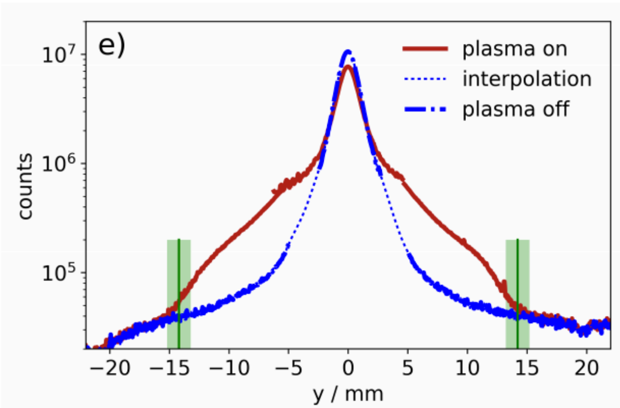
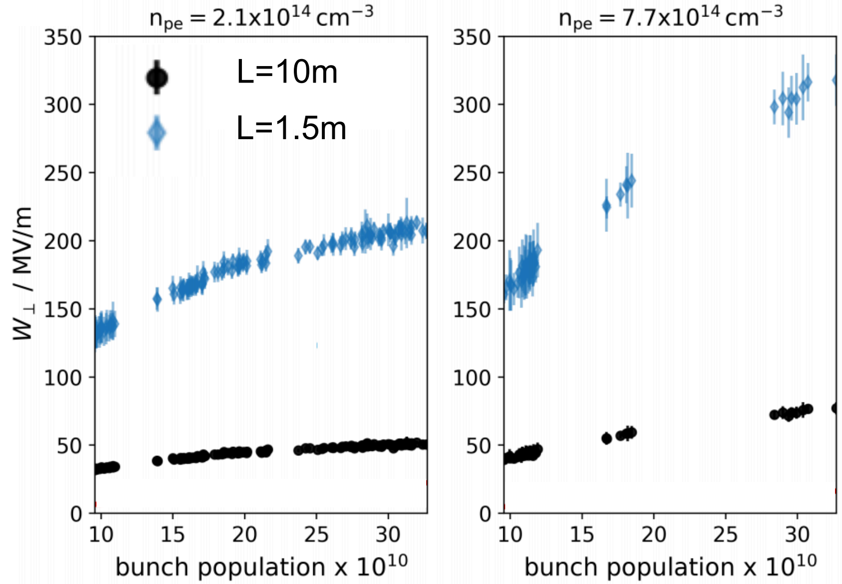
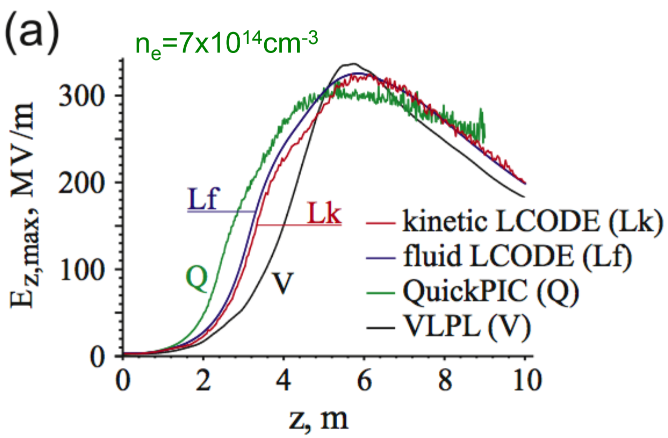




Angle

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





Caldwell, NIMA 829, 3 (2016)

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

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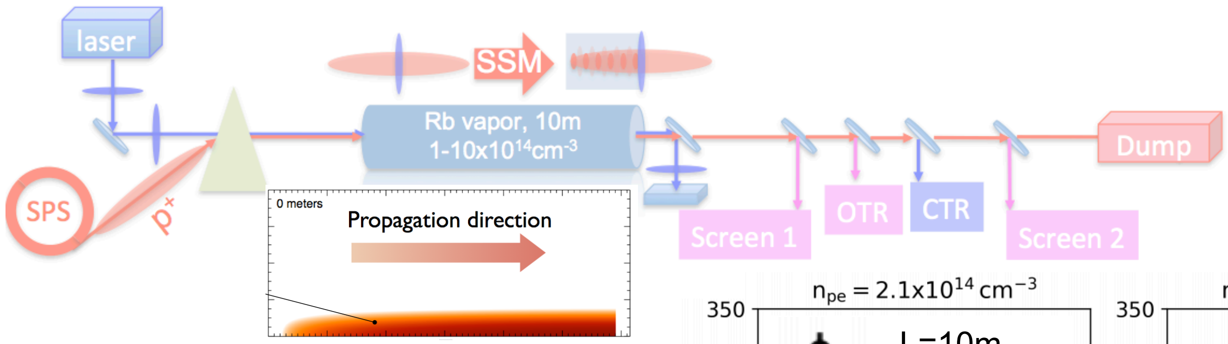
TWO-SCREEN SSM



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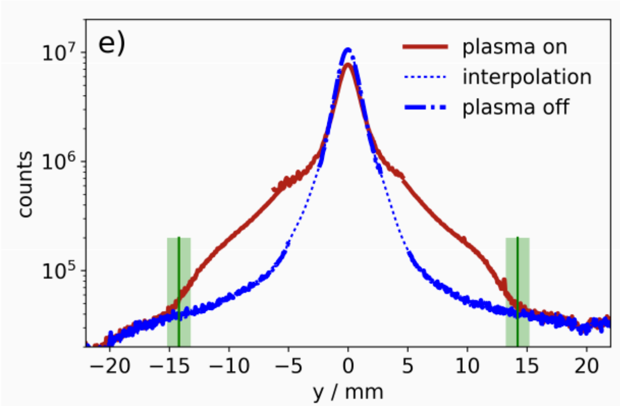
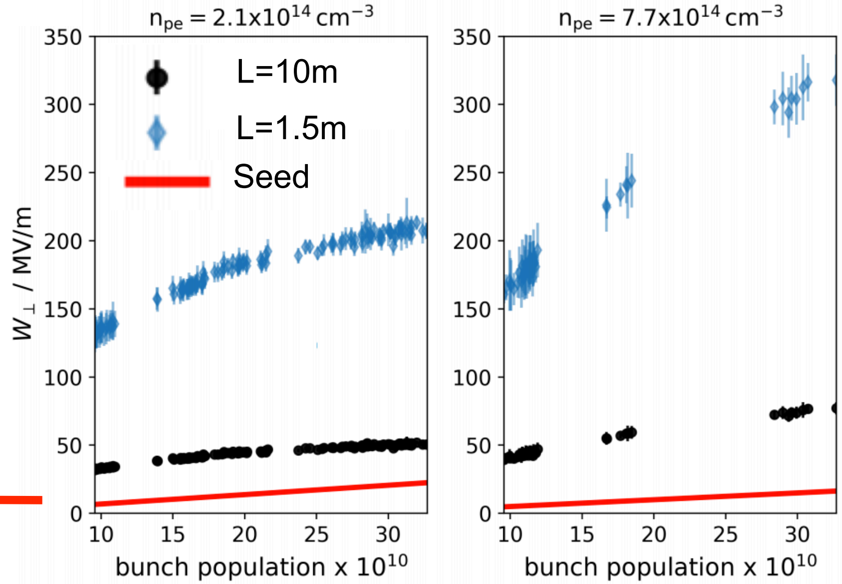


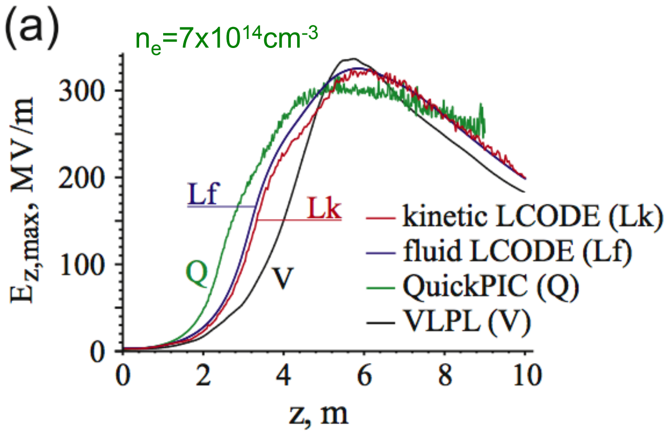
Angle

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

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

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)

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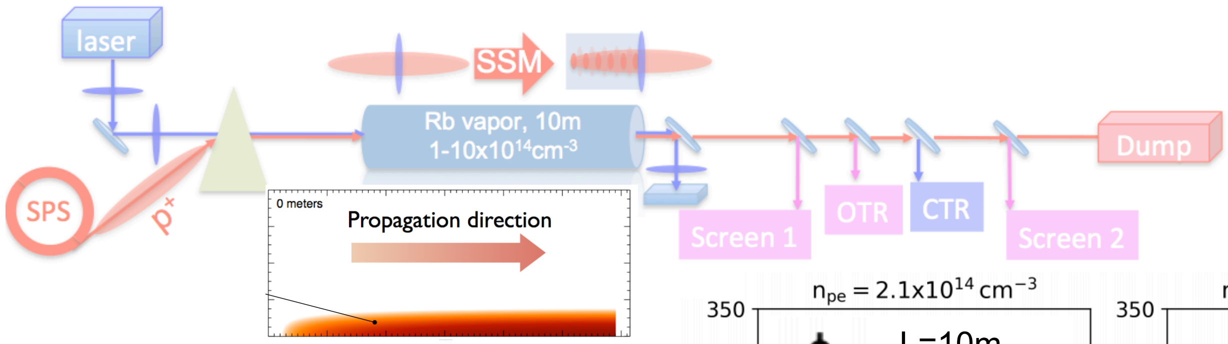
TWO-SCREEN SSM

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

AWAKE



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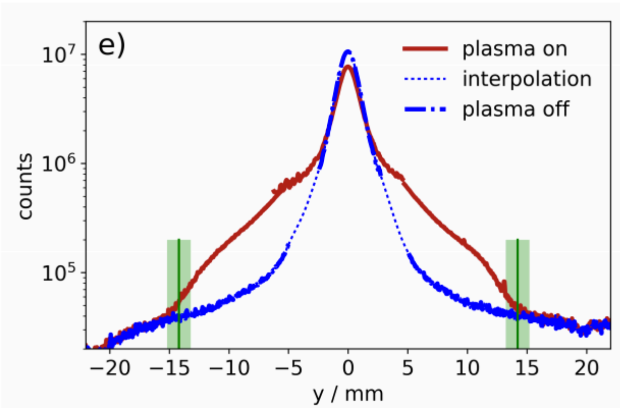

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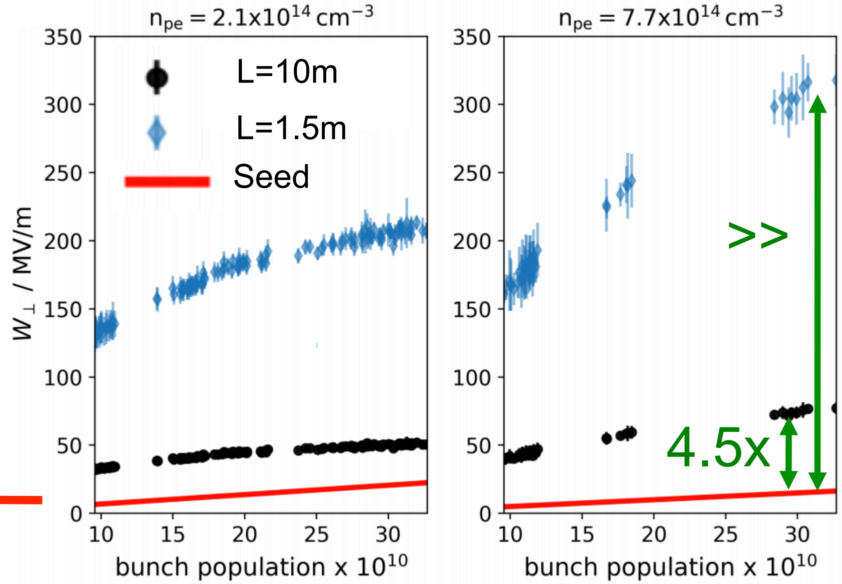
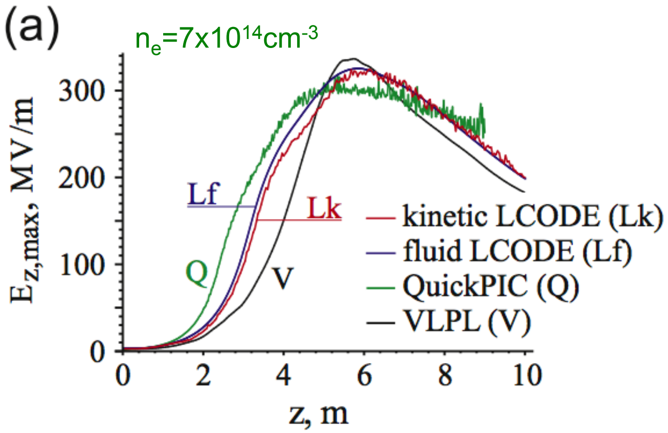
$$W_{\perp}\cong\frac{m_ec^2}{e}\frac{n_{b\parallel}}{n_e}\frac{1}{\sigma_r}$$

Seeding





Caldwell, NIMA 829, 3 (2016)

✧ Deflection angle larger than expected from seed fields

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

✧ Wakefields grew along the bunch

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

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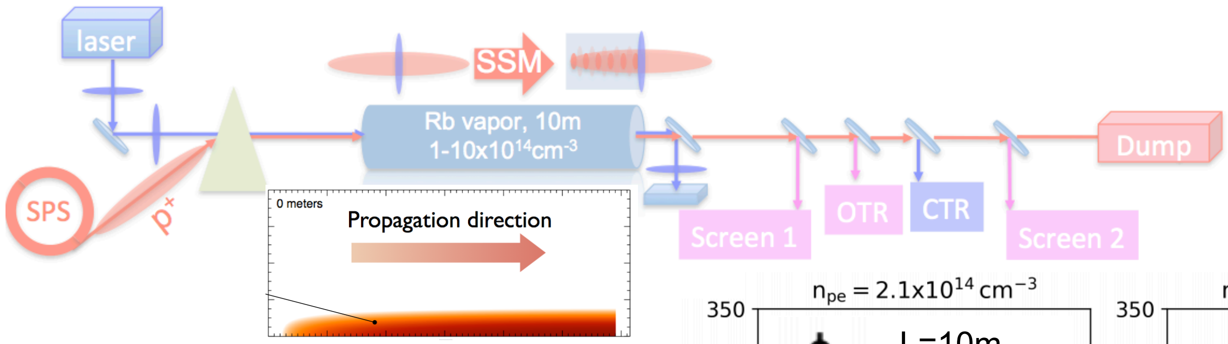
MAX-PLANCK-GESELLSCHAFT

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

AWAKE

TWO-SCREEN SSM



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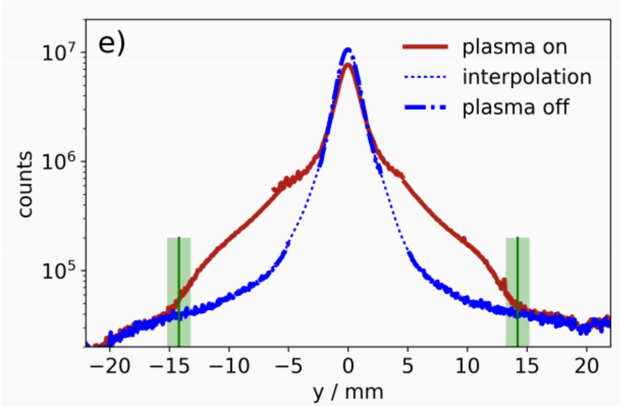

Angle

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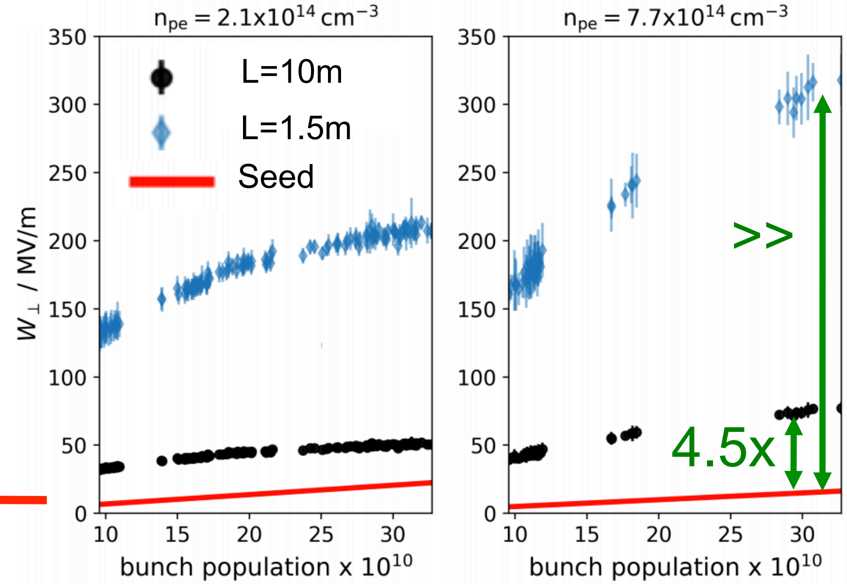
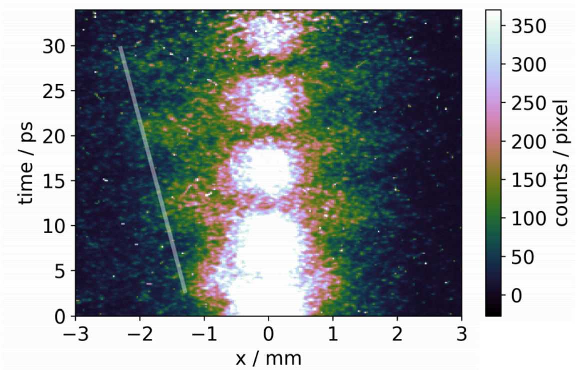
Seeding





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

✧ Wakefields grow … along the bunch and along the plasma

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

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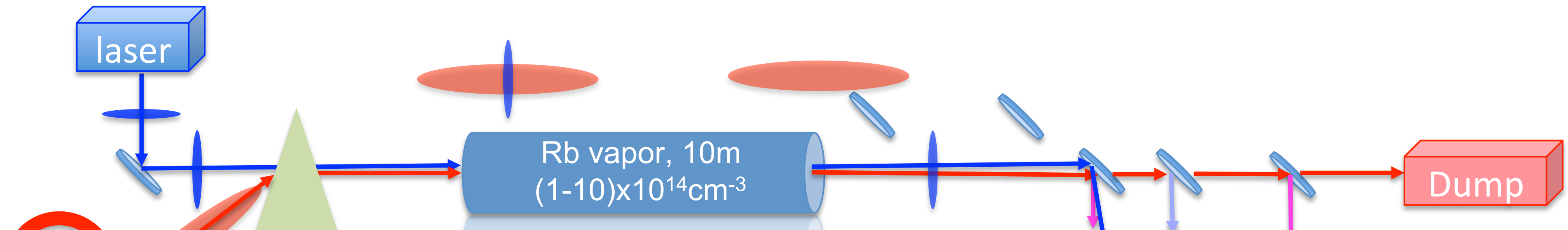
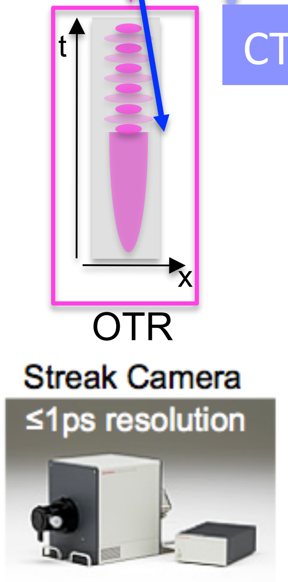
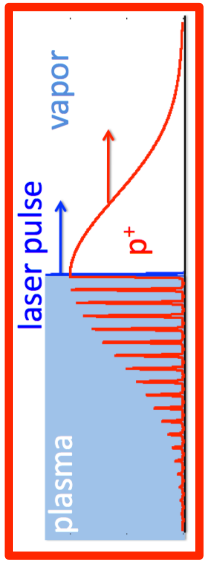
SEEDED SM

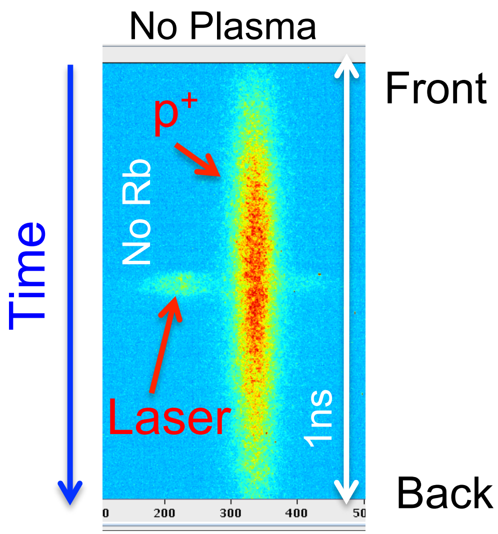






OTR

Streak camera Images



✧Timing at the ps scale

K. Rieger, MPP

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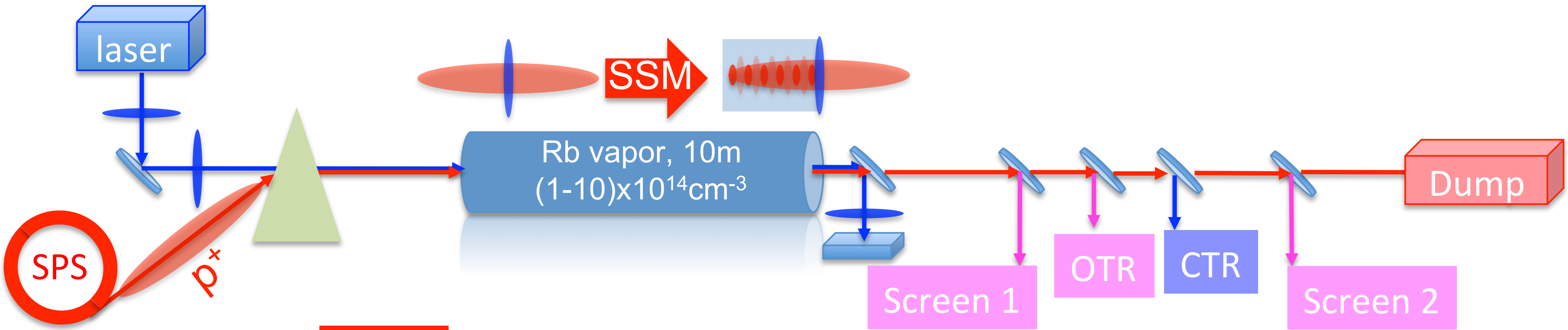
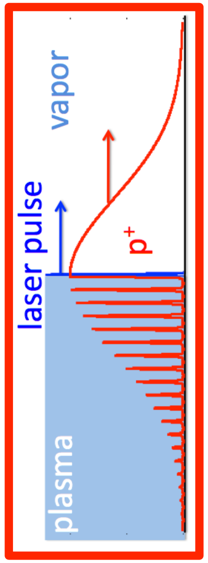
AWAKE, Phys. Rev. Lett. 122, 054802 (2019)

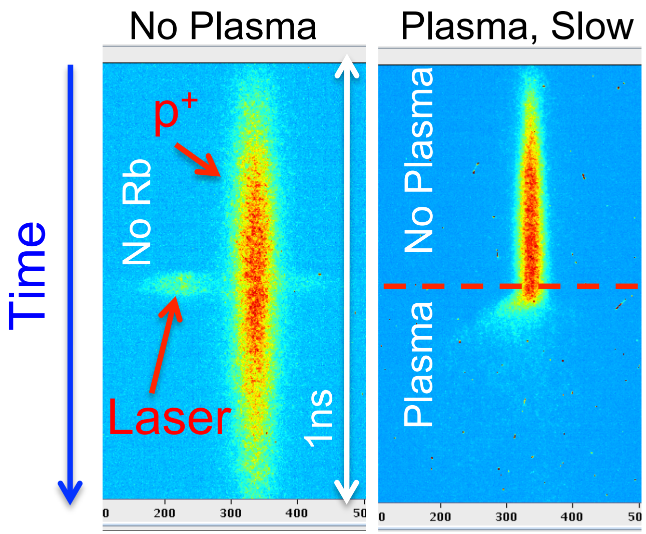
SEEDED SM





OTR

Streak camera Images



n_{Rb}=3.7x10^{14}cm^{-3}
N=3x10^{11}p$^+$
Long

K. Rieger, MPP

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

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

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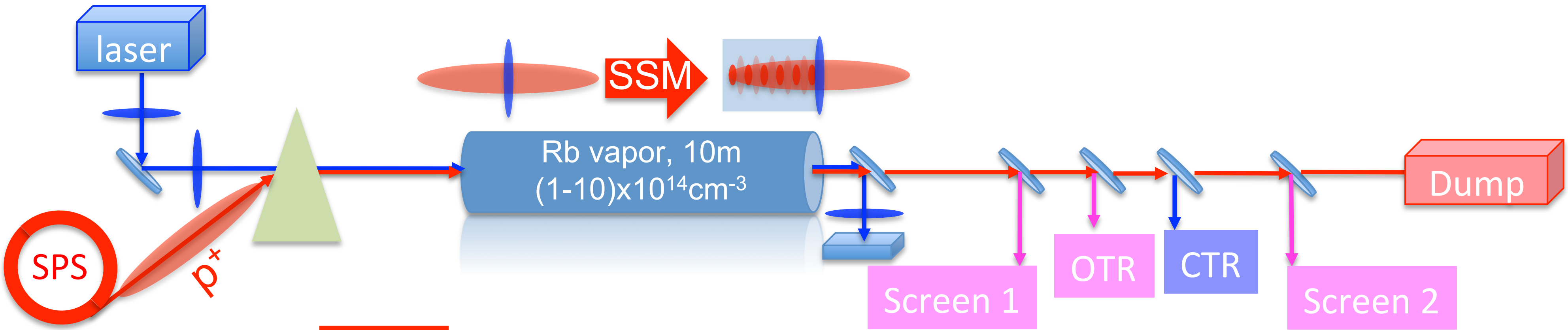
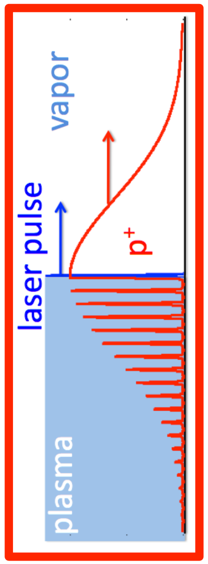
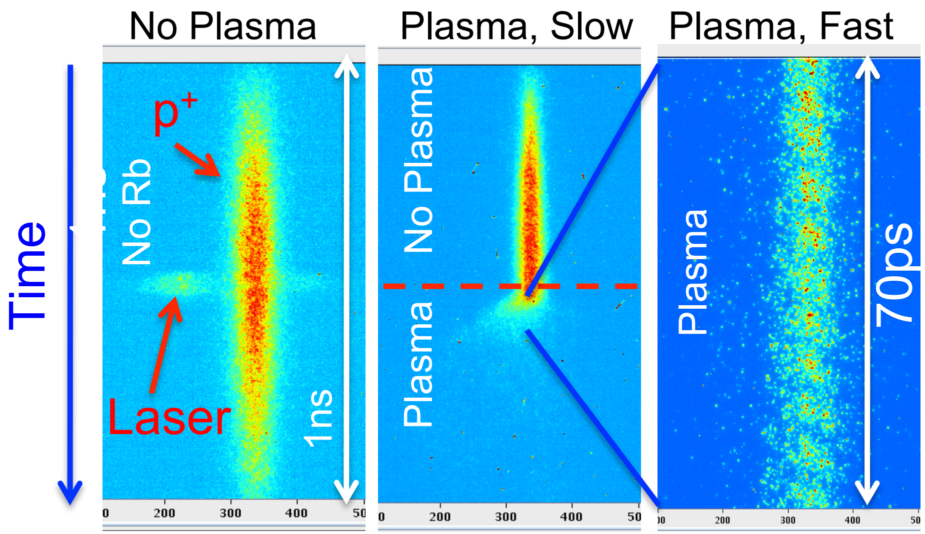
SEEDED SM



OTR

Streak camera Images





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

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)

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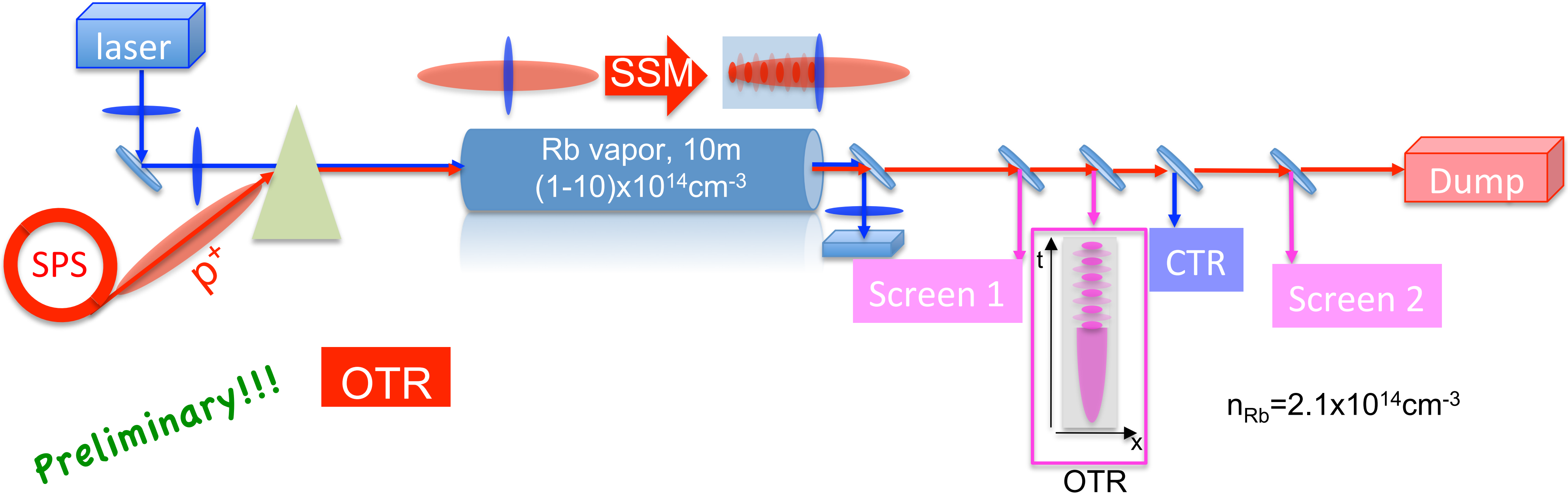
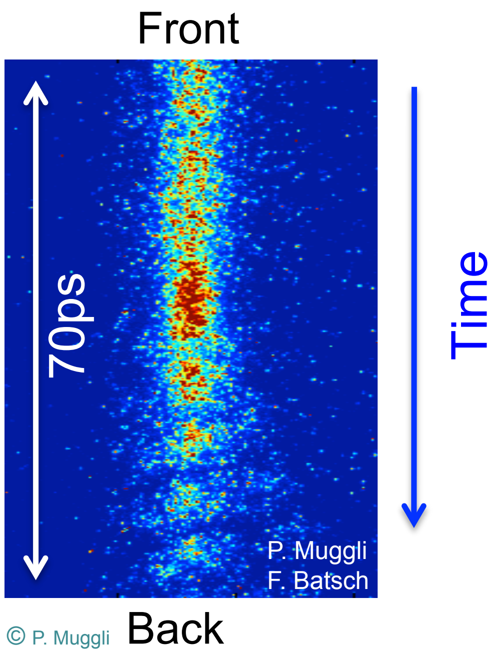
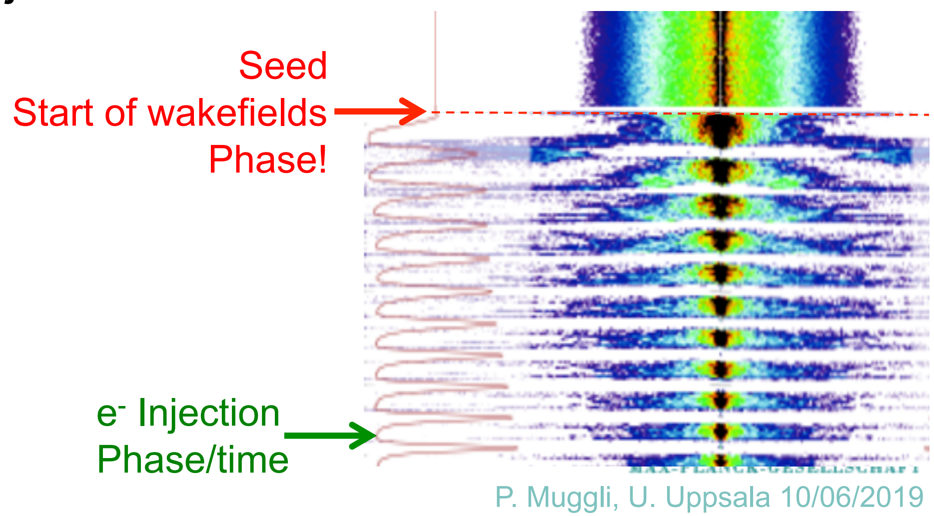
μ-BUNCH TRAIN



✧Is the μ-bunches timing "repeatable"?

✧Streak camera trigger jitter (~20ps rms)





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μ-BUNCH TRAIN

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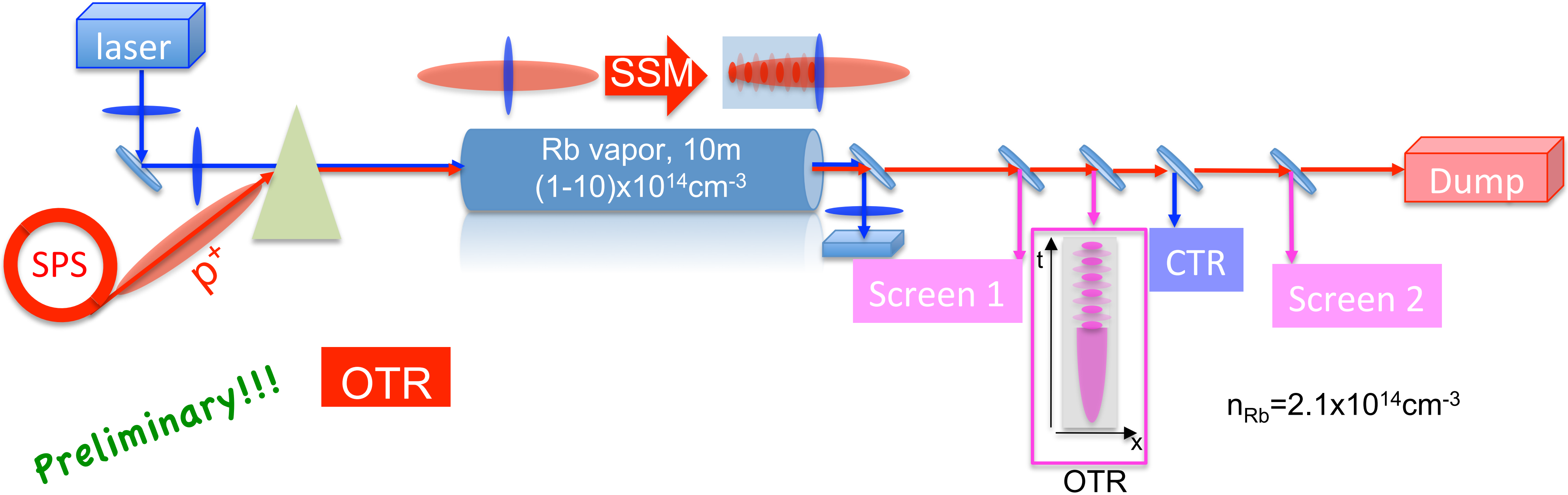
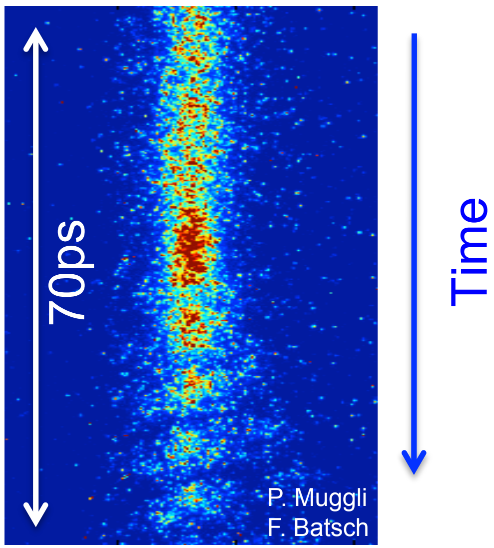
(Werner-Heisenberg-Institut)



Preliminary!!!

OTR

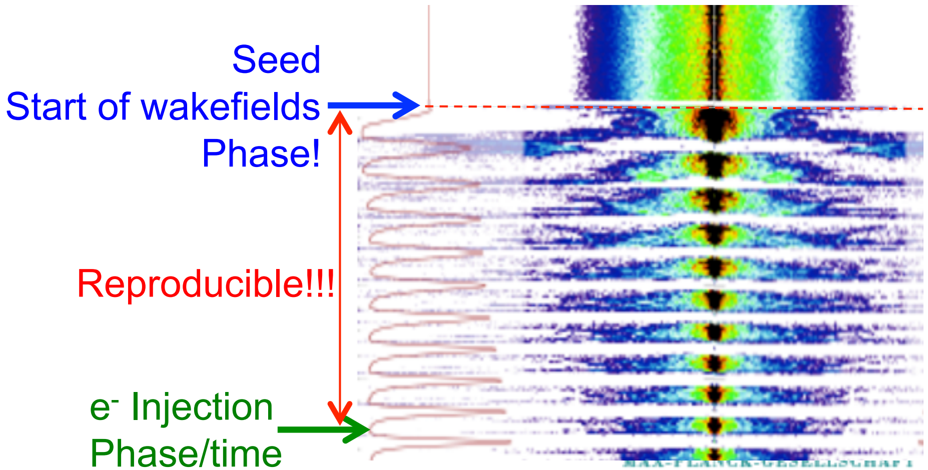
Front



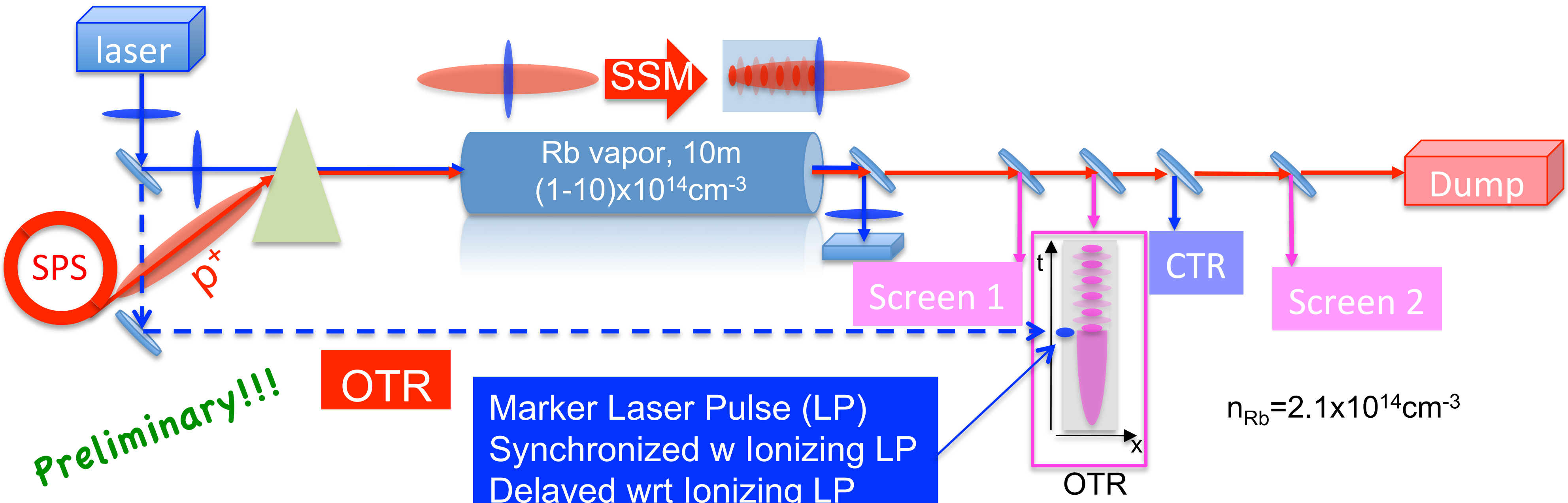
© P. Muggli Back

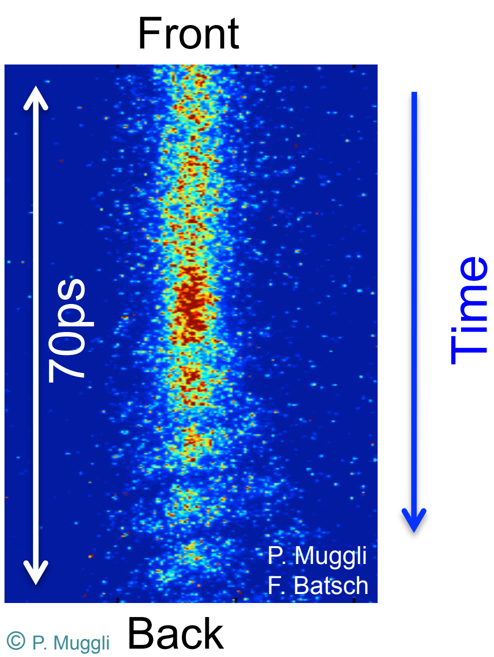
✧Is the μ-bunches timing "repeatable"?

✧Streak camera trigger jitter (~20ps rms)



μ-BUNCH TRAIN





✧Is the μ-bunches timing "repeatable"?

✧Streak camera trigger jitter (~20ps rms)

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μ-Bunch Train

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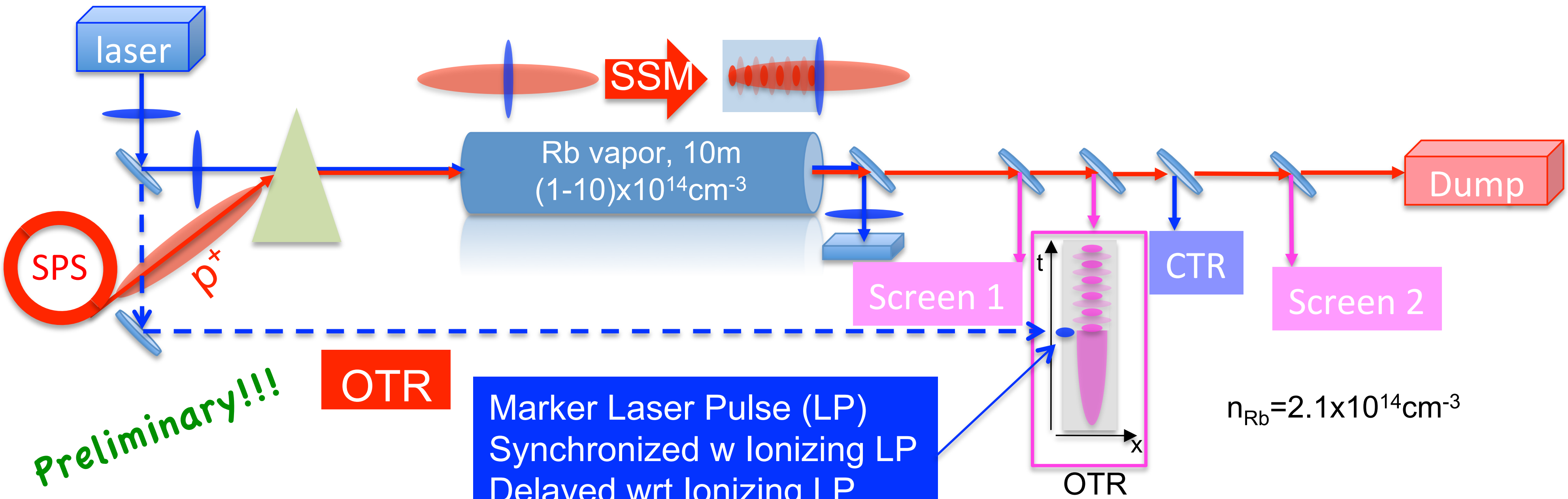
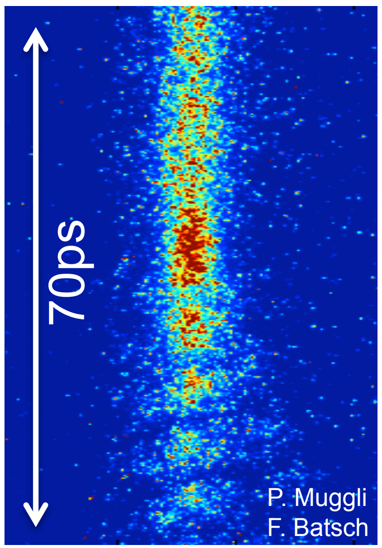


Preliminary!!!

Front



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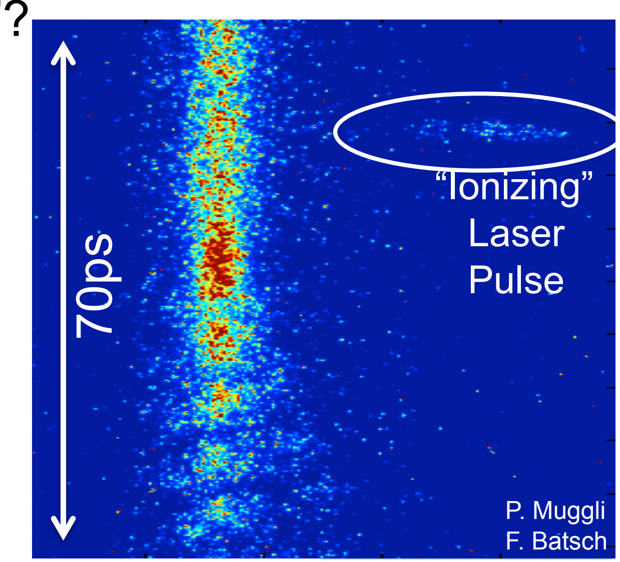
Time

- ✧ 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

Front



Back

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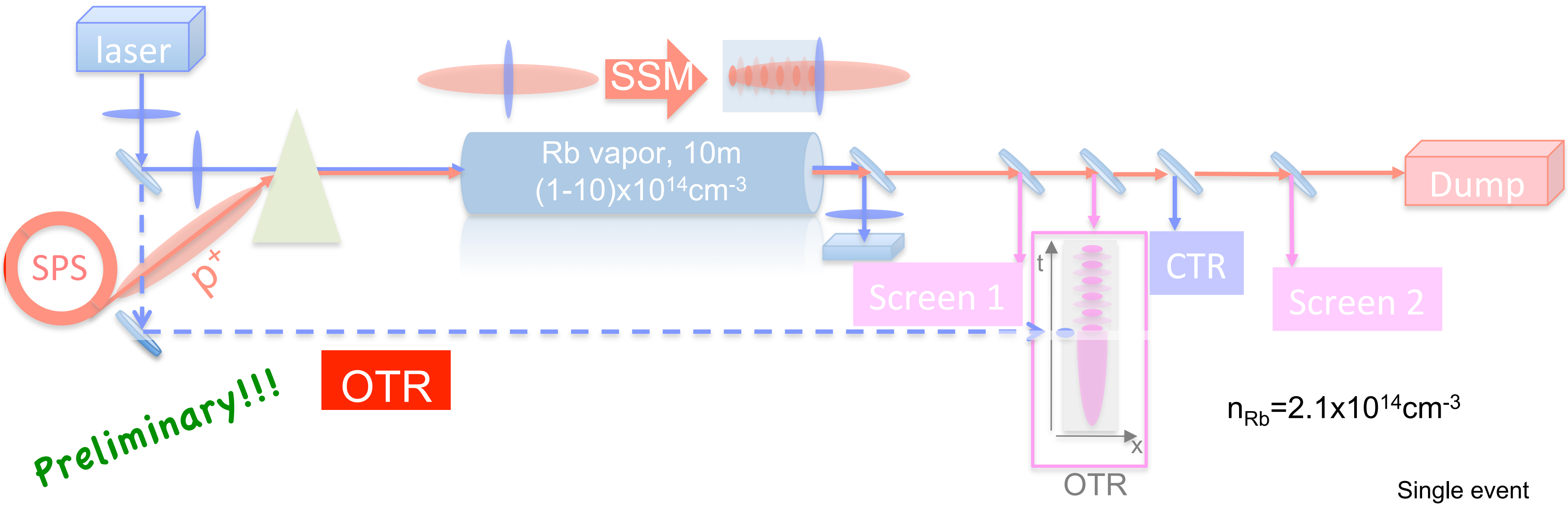
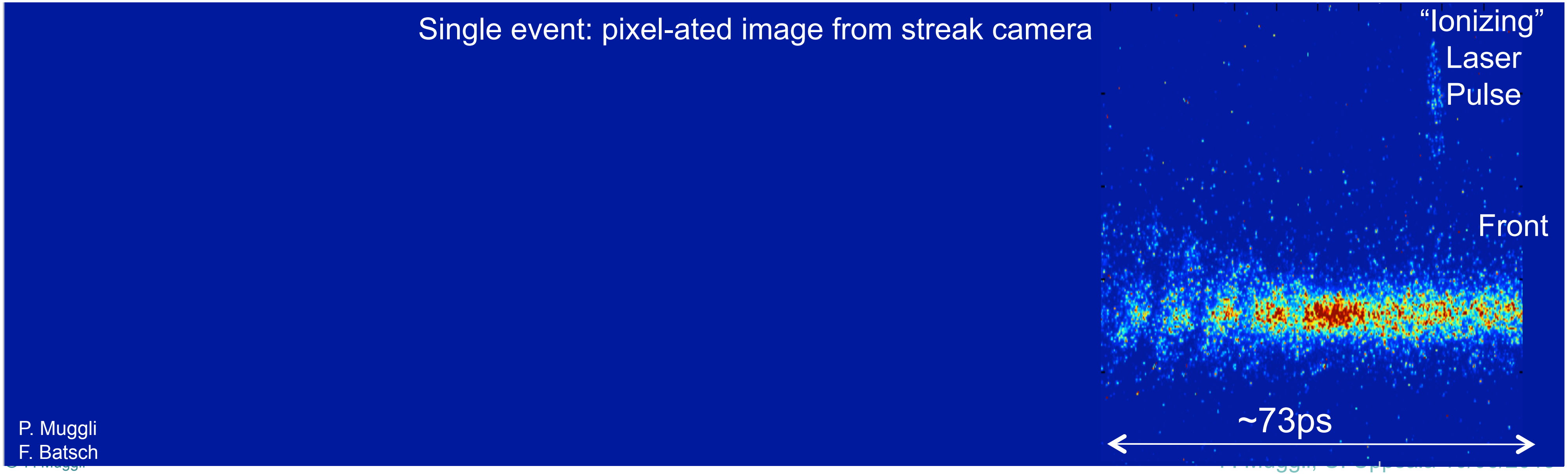
μ-BUNCH TRAIN



Streak camera Images



μ-Bunch Train

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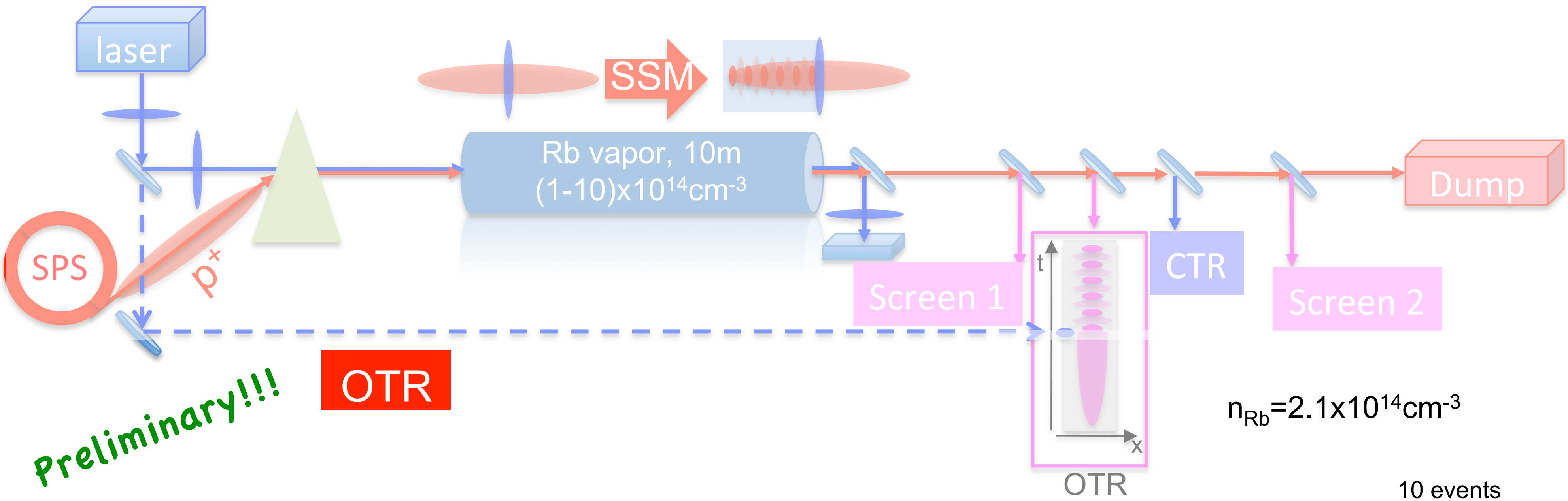


Preliminary!!!

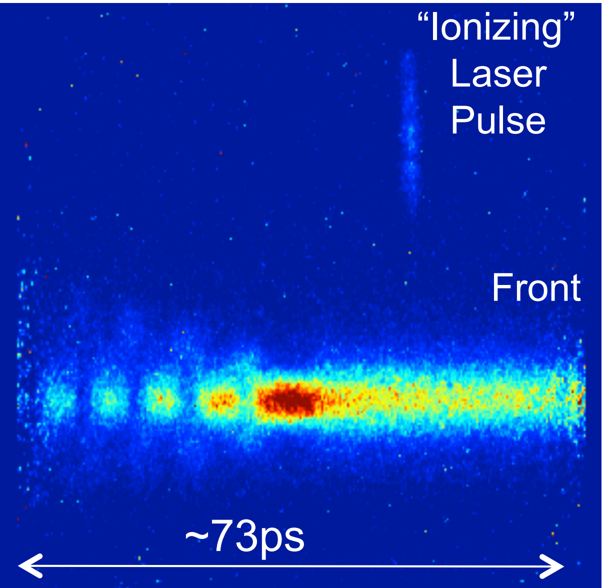
OTR

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

10 events

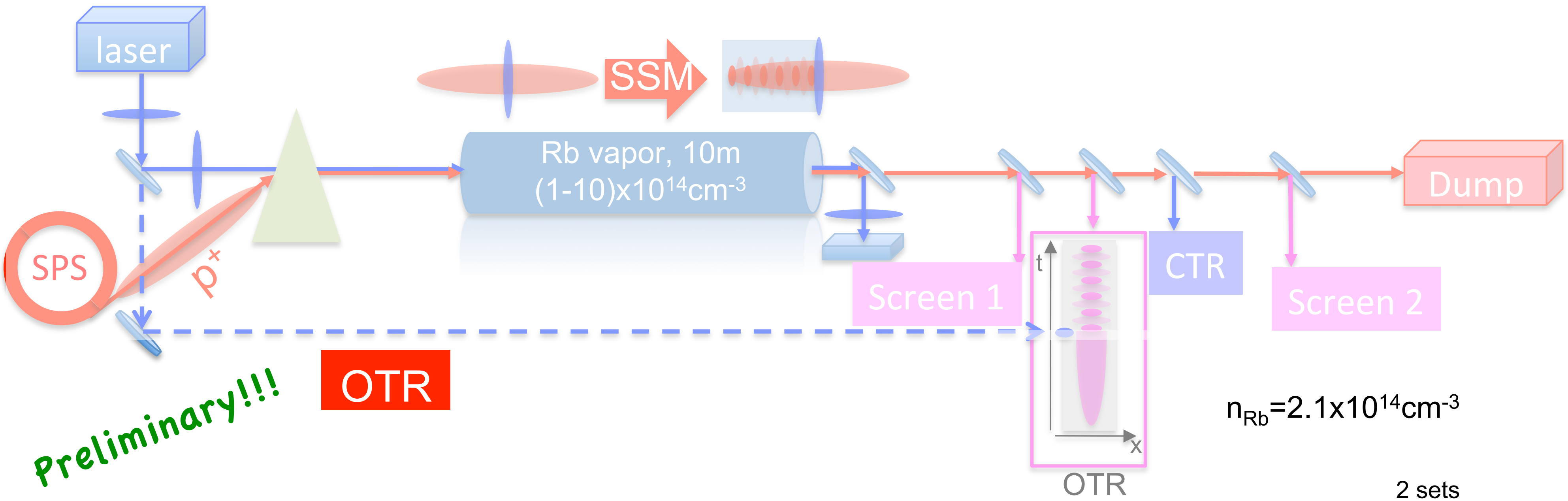
Streak camera Images

10 consecutive events aligned to marker laser pulse
Bunches add => modulation fixed wrt ionizing laser pulse
=> modulation fixed wrt to seed!!



P. Muggli
F. Batsch

μ-BUNCH TRAIN



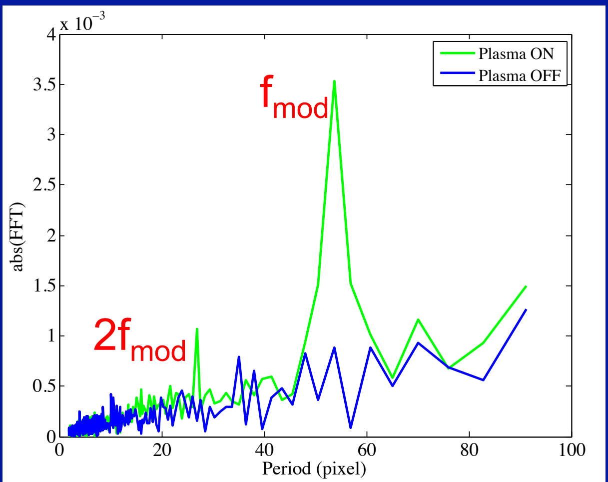
Preliminary!!!

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

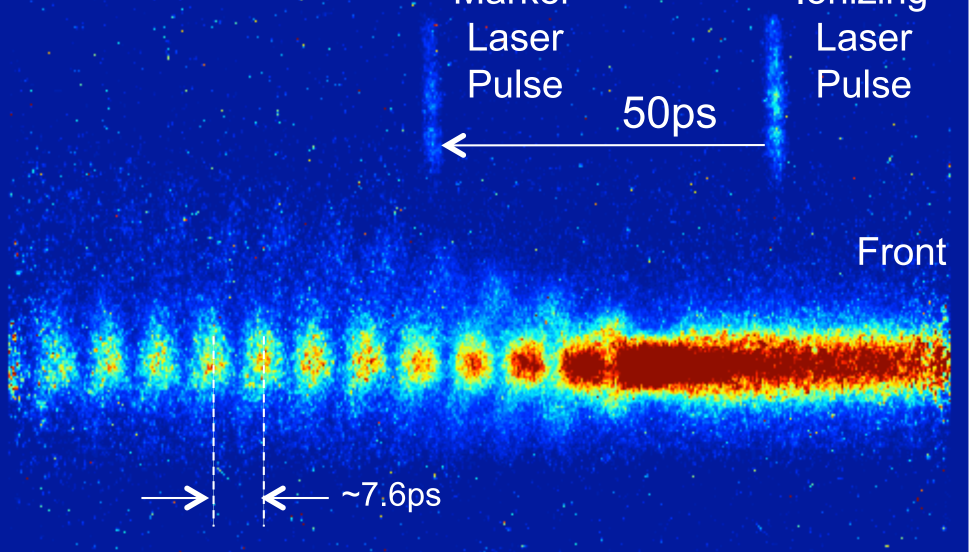
Streak camera Images

2 sets
10 events each

$f_{mod}=131.0GHz \Leftrightarrow f_{Rb}=130.9GHz$



Changed
Color
Scale!



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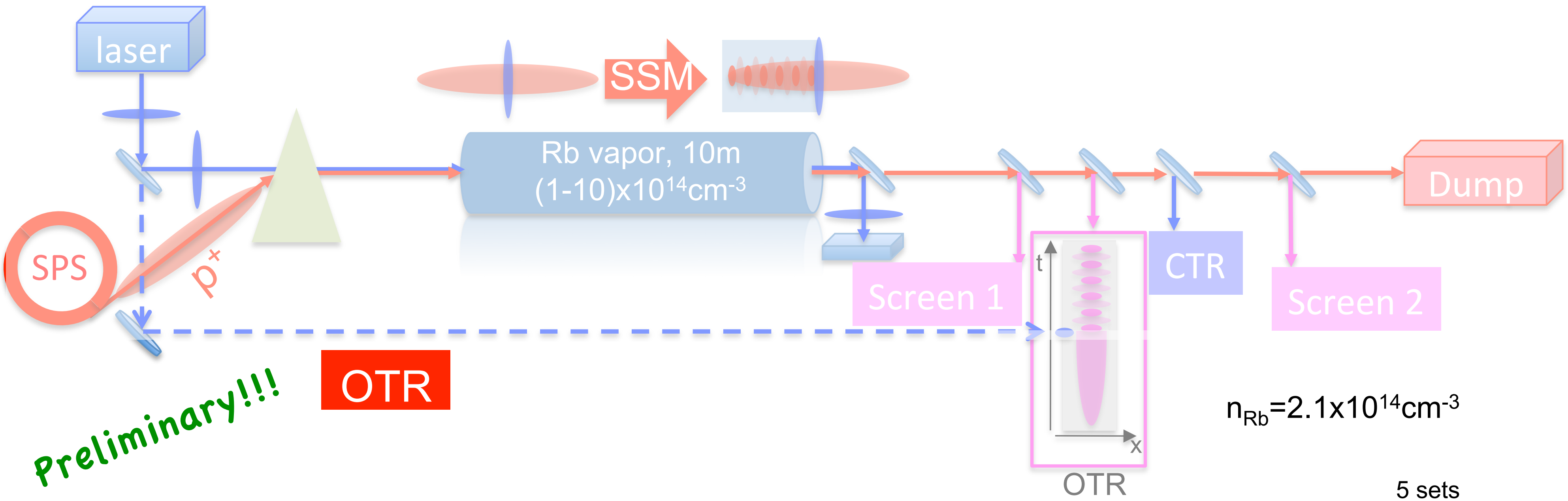
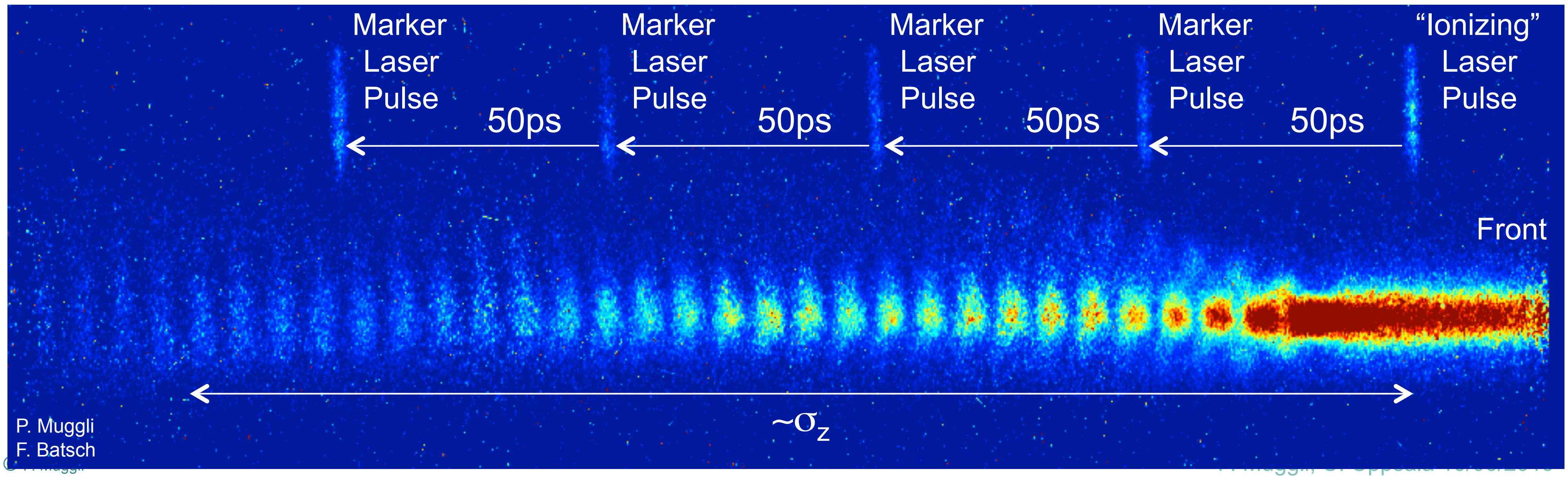
F. Batsch

μ-BUNCH TRAIN

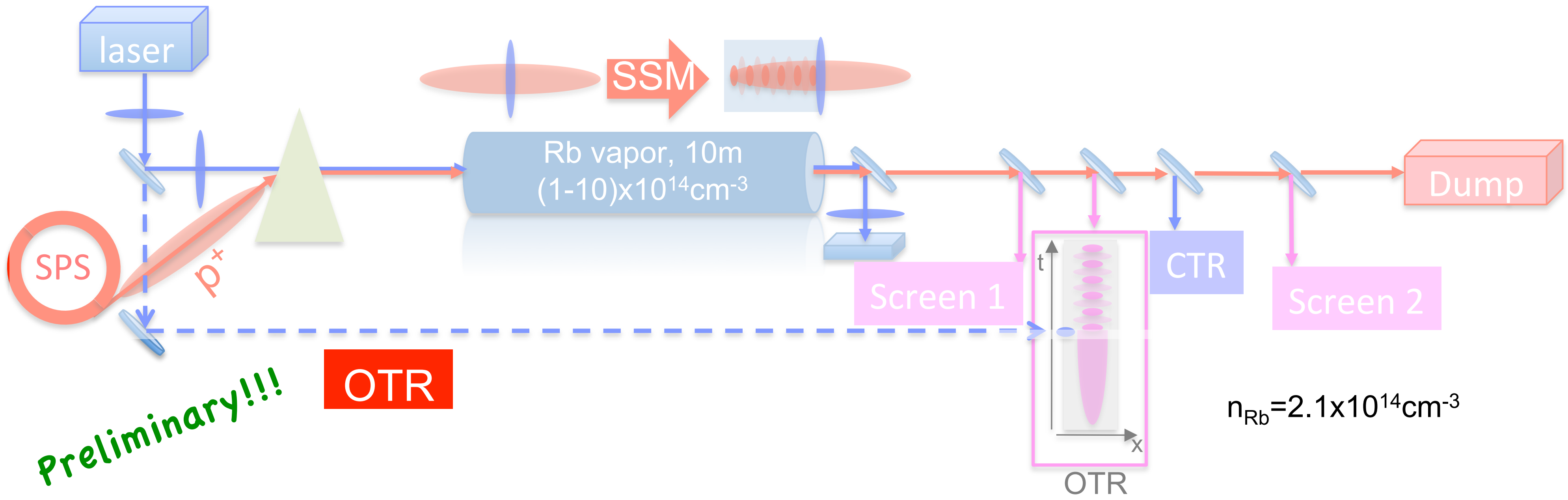


5 sets
10 events each

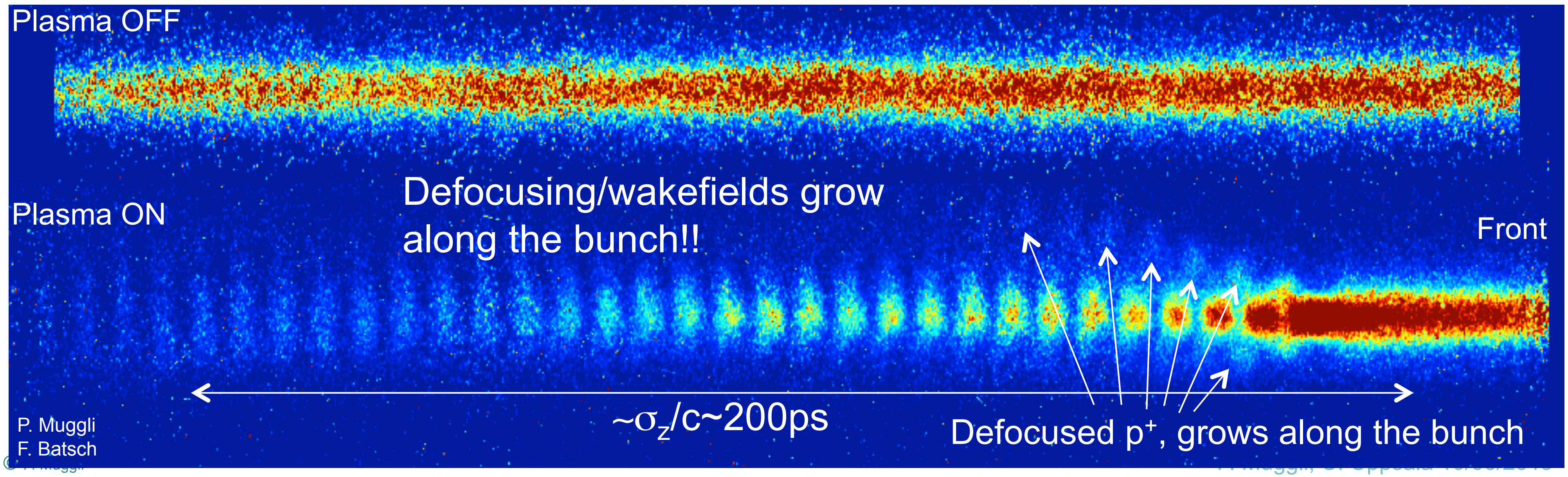
Streak camera Images



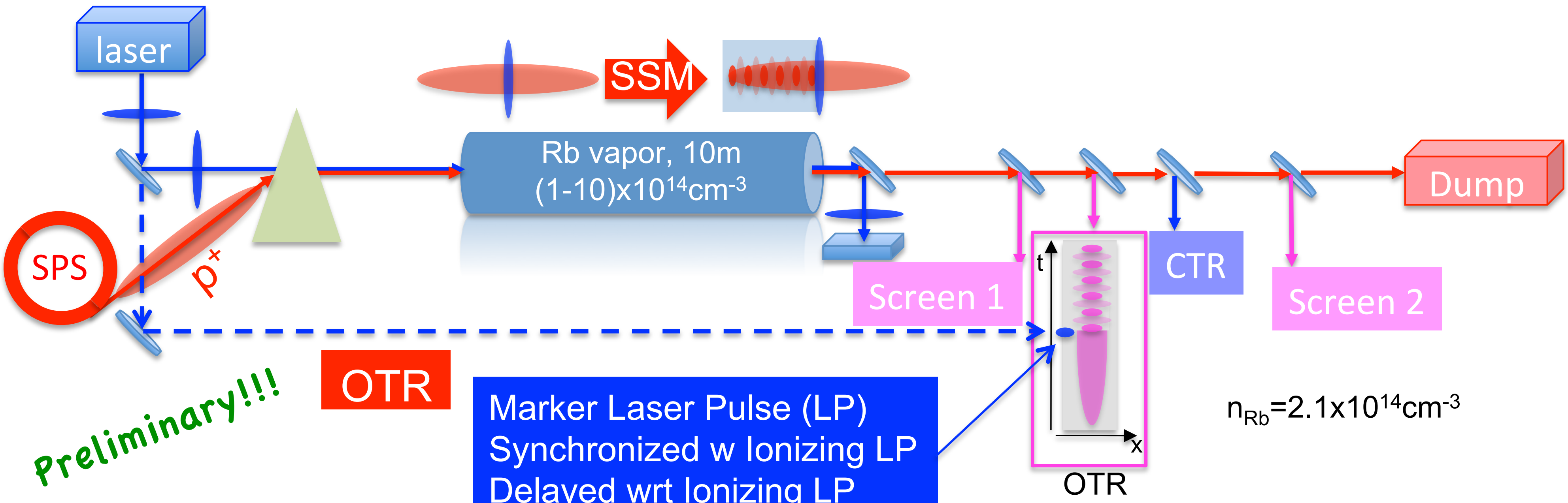
μ-BUNCH TRAIN

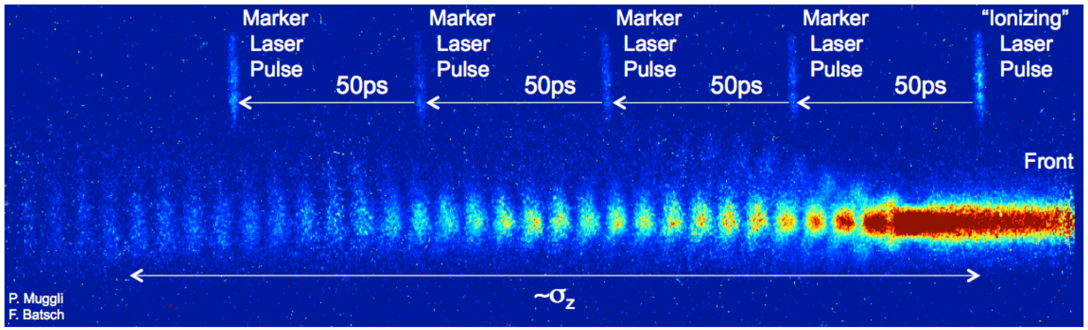


Streak camera Images



μ-BUNCH TRAiN





- ✧ Micro-bunches present over long time scale $\sim\sigma_z/c$ 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"

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SSM PHASE

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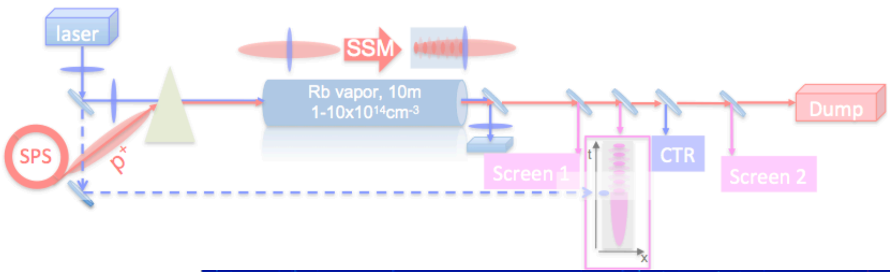
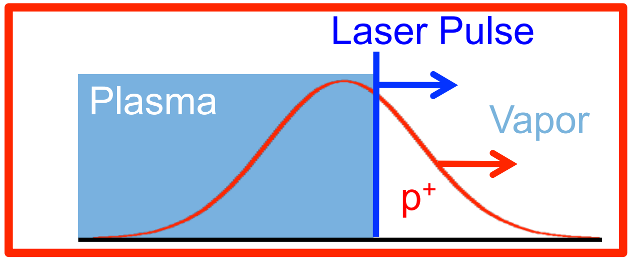
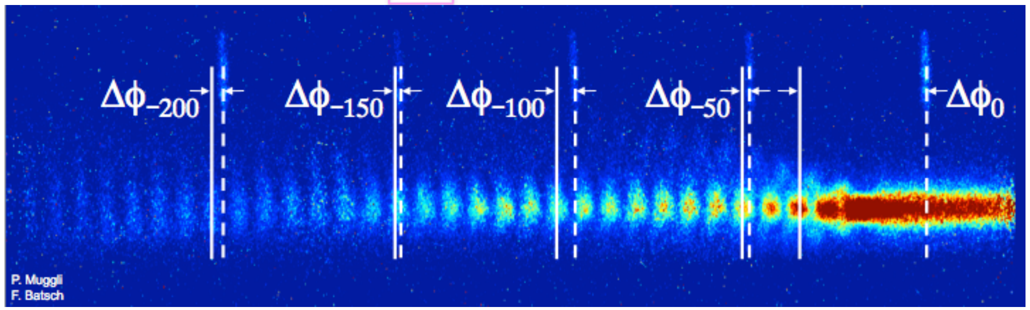
Preliminary!!!

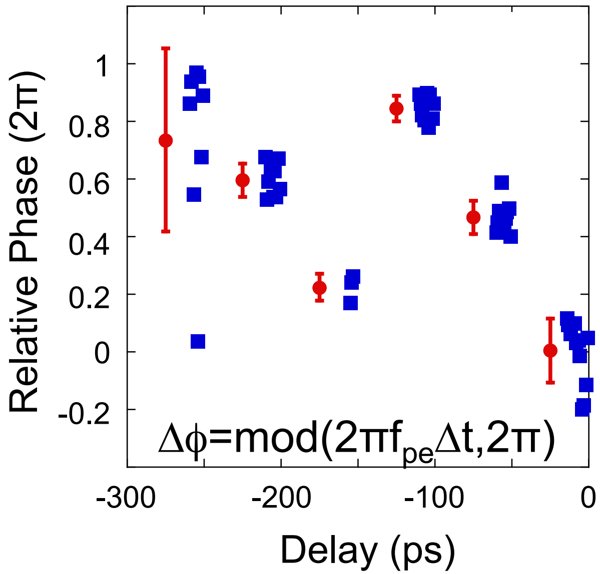


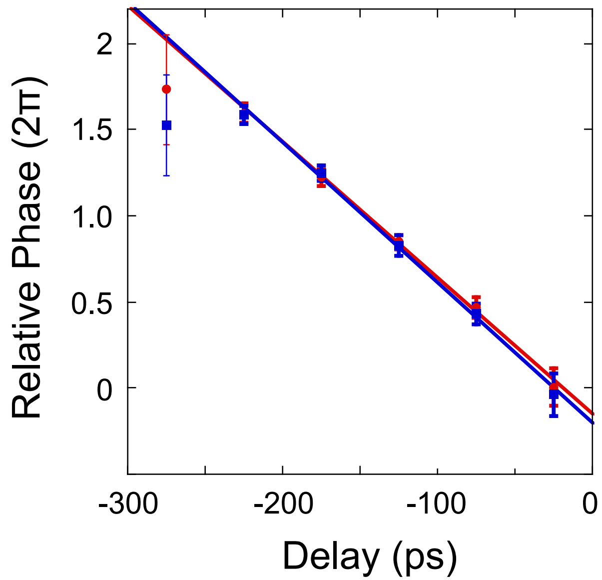
n_{Rb}=2.1x10^{14}cm^{-3}

Seed









- ✧ Variation in bunch parameters (σ_z, σ_r, N, …) => phase variation?
- ✧ Relative phase varies by ≤0.2λ_{pe}

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SSM FREQUENCY

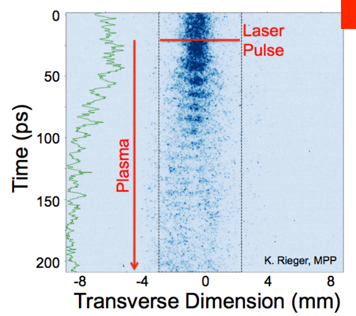
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

AWAKE

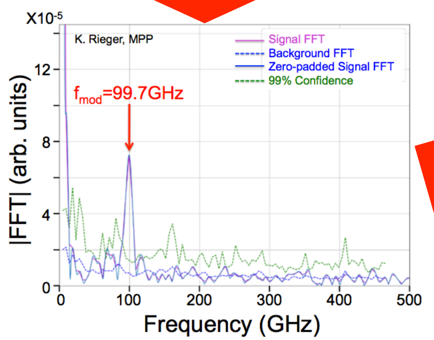
AWAKE, Phys. Rev. Lett. 122, 054802 (2019)

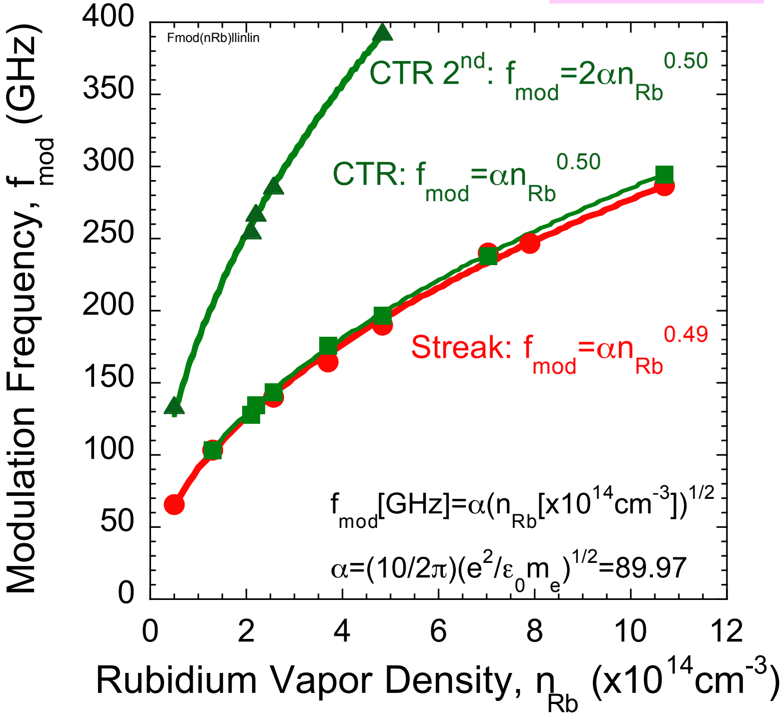
Preliminary!!!

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

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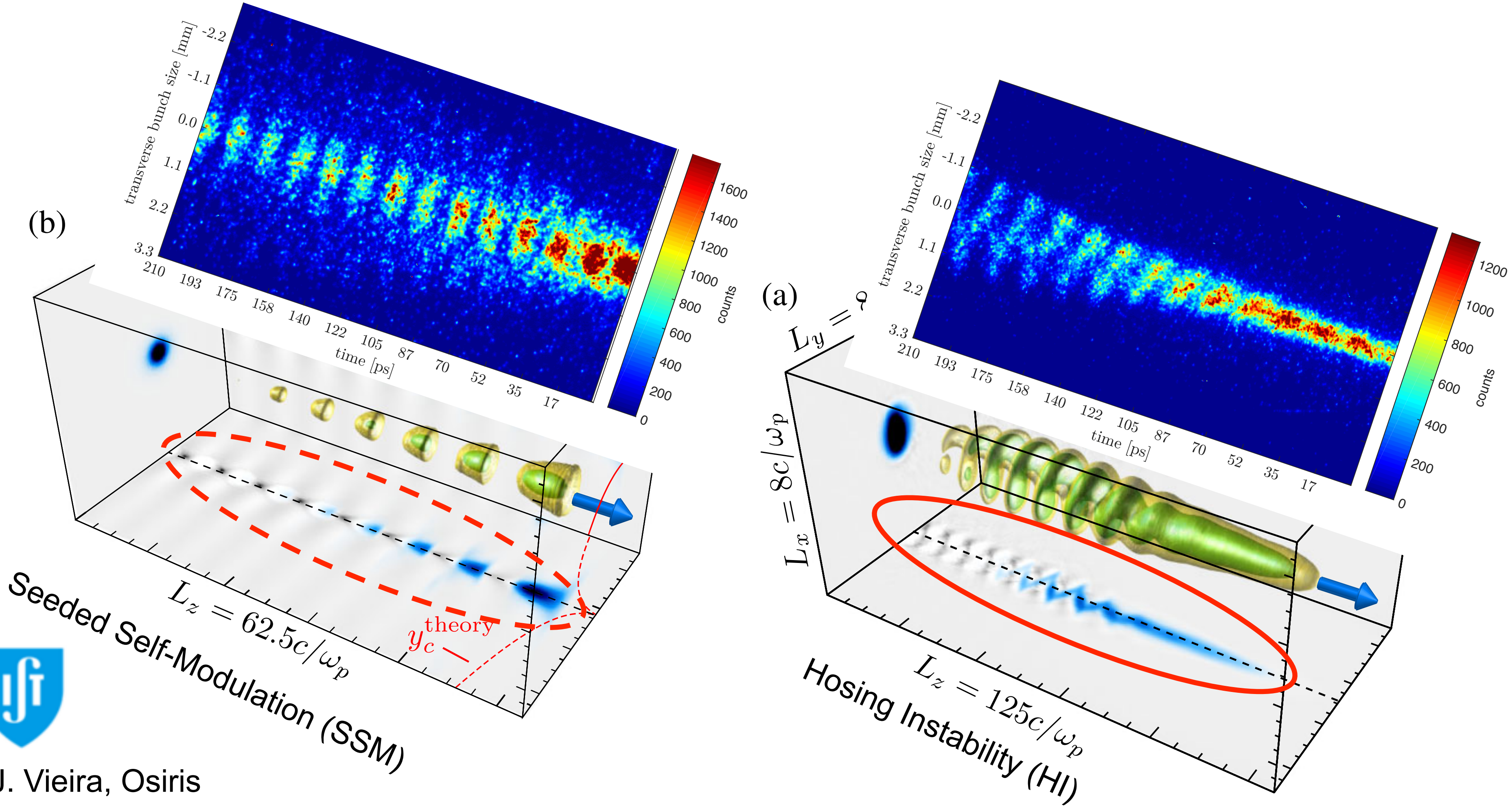
HOSiNG INSTABiLiTY

✧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!!

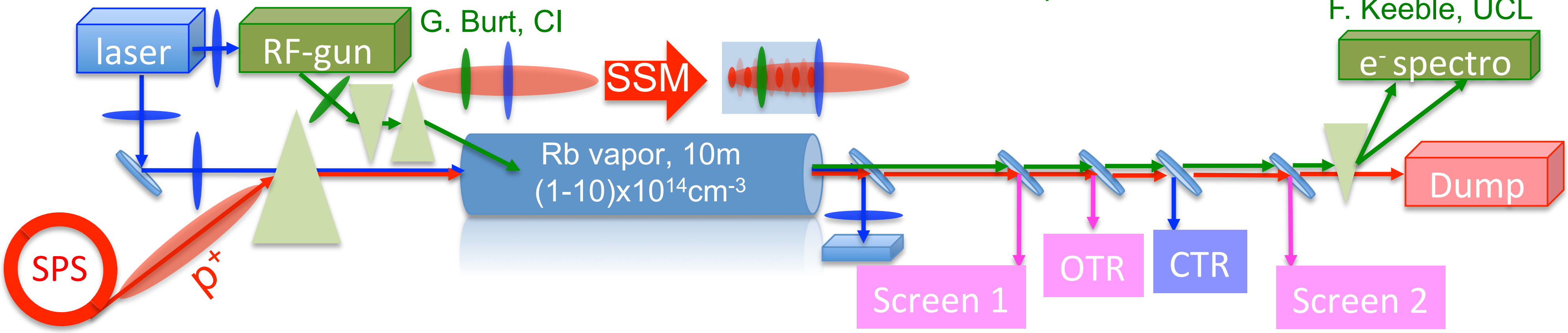
J. Vieira et al., Phys. Rev. Lett. 112, 205001 (2014)

OUTLINE

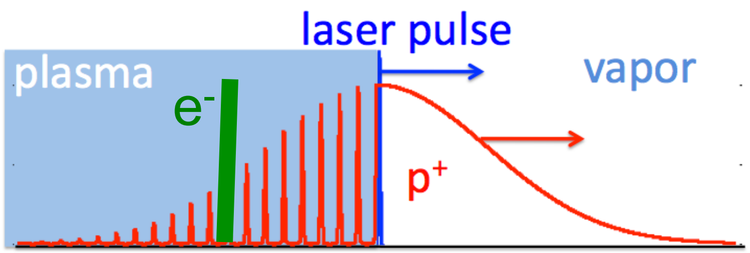
- Introduction to plasma wakefield accelerator (PWFA)
- Seeded Self-Modulation (SSM)
- AWAKE experiment
- SSM experimental results
  - Demonstration
  - Physics
- e^- acceleration
- Future and Summary

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: $\tau_{z,e-}$~$1/f_{pe}$ => reduced timing requirements
- ✧Inject at all phases, wakefields capture a fraction …



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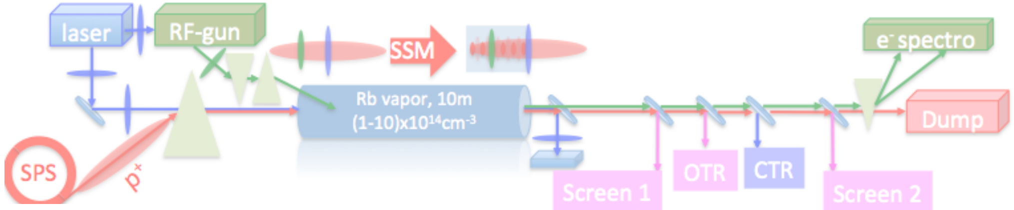
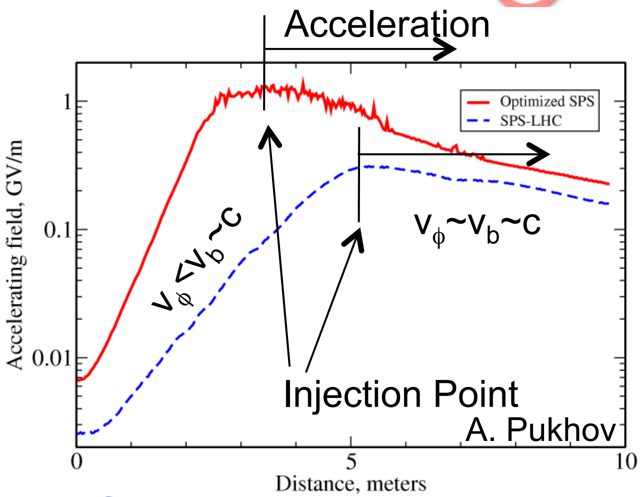
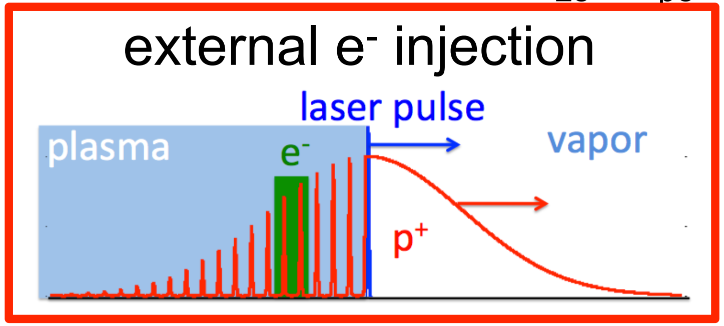
WAKEFIELDS SAMPLING / ACCELERATION

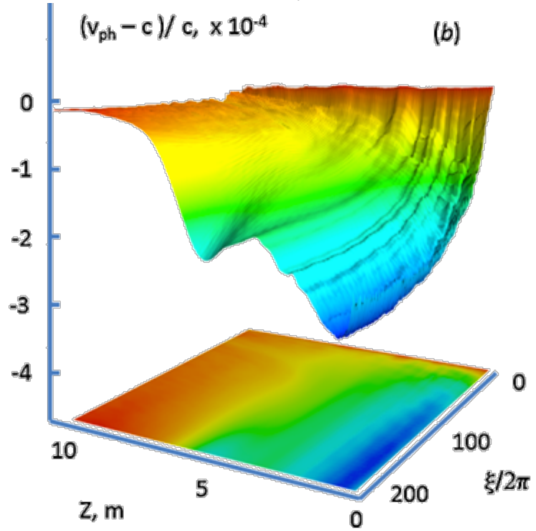


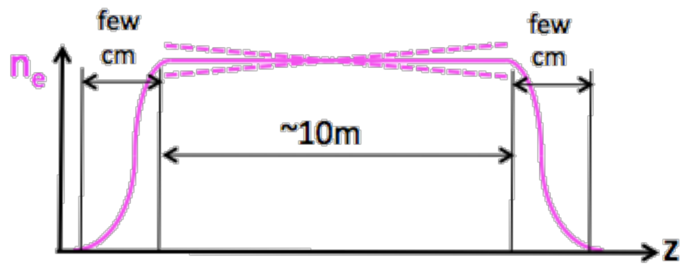


Pukhov, PRL107 145003 (2011)

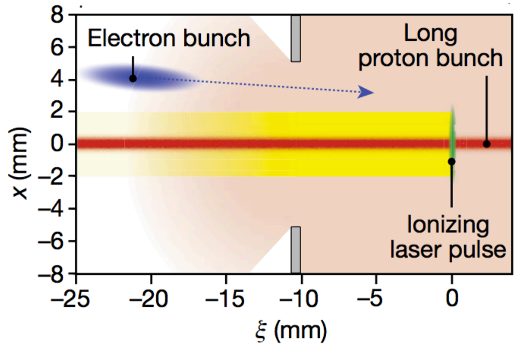
Injection experiments: $\sigma_{ze-} > \lambda_{pe}$







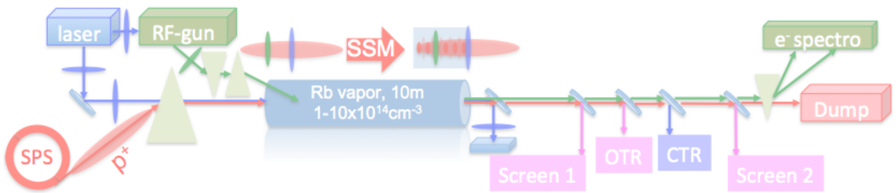
Plasma Density Ramp

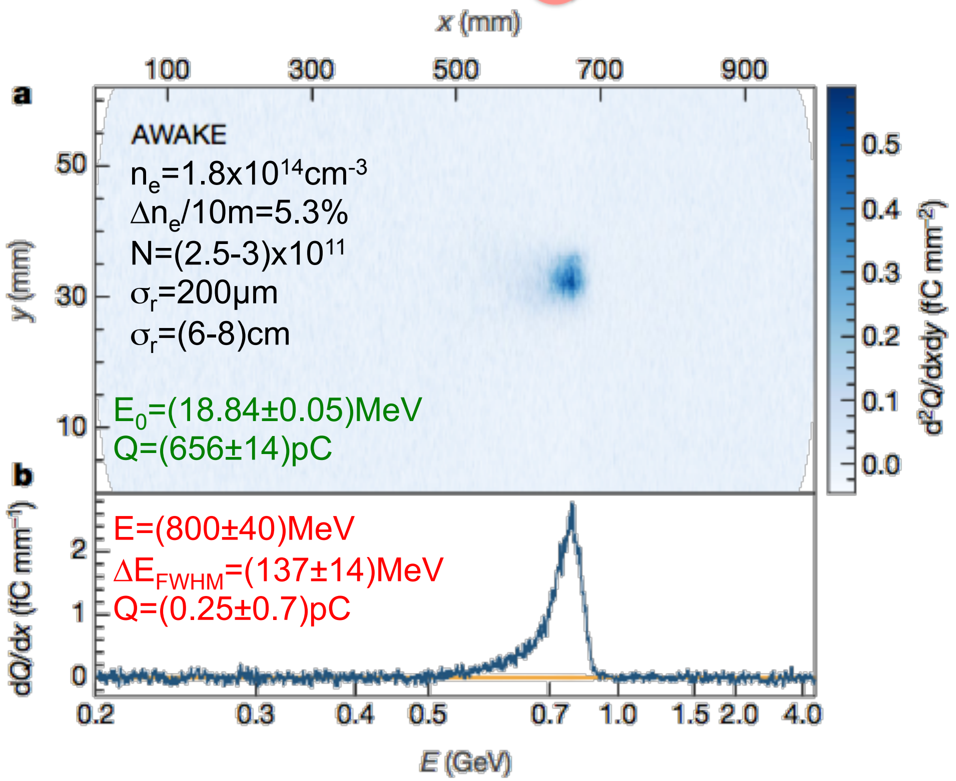


✧ Side injection of "long" e- bunch

© P. Muggli

WAKEFIELDS SAMPLING / ACCELERATION





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

AWAKE, Nature 561, 363 (2018)

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WAKEFIELDS SAMPLING / ACCELERATION

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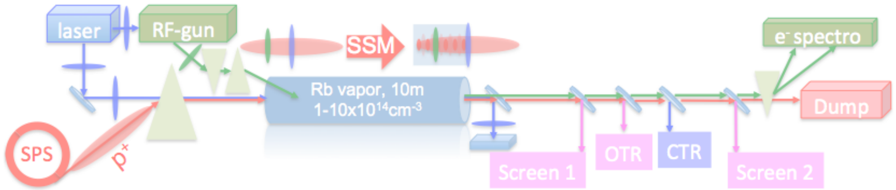
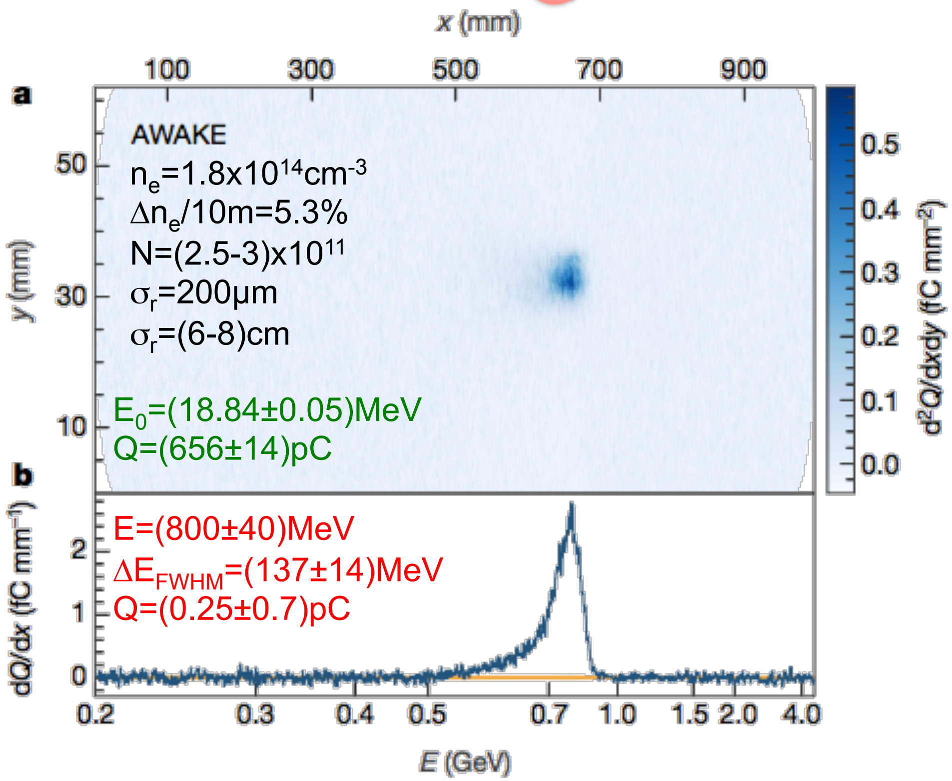
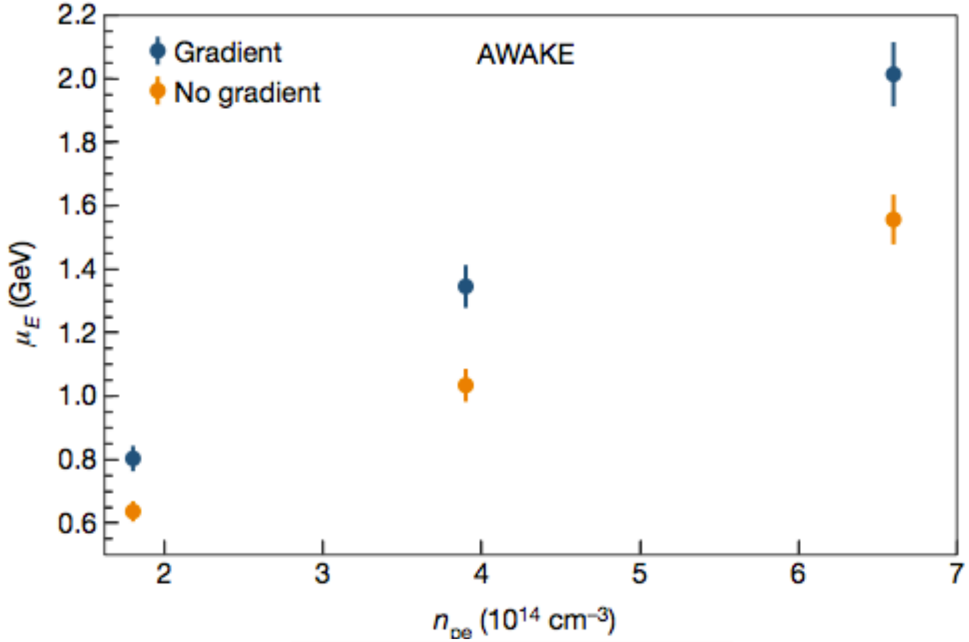
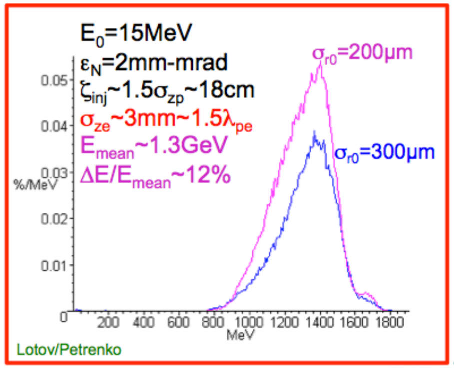
(Werner-Heisenberg-Institut)









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

AWAKE, Nature 561, 363 (2018)

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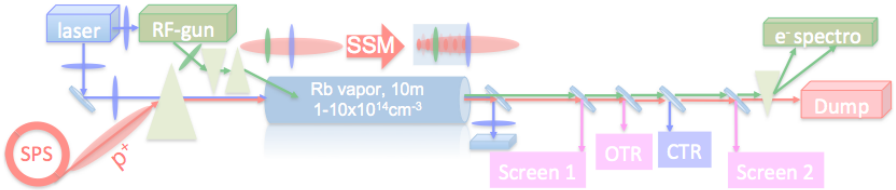
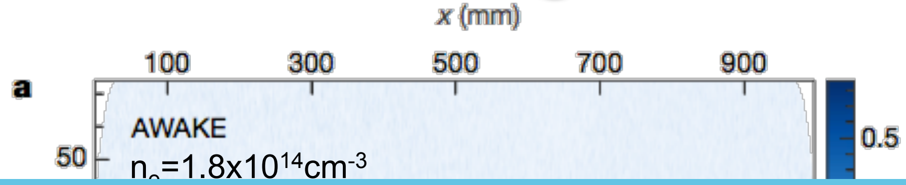
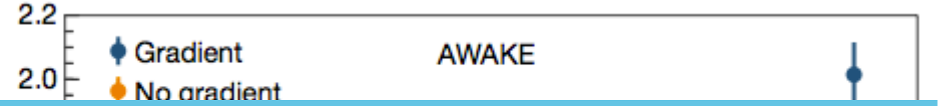
WAKEFIELDS SAMPLING / ACCELERATION

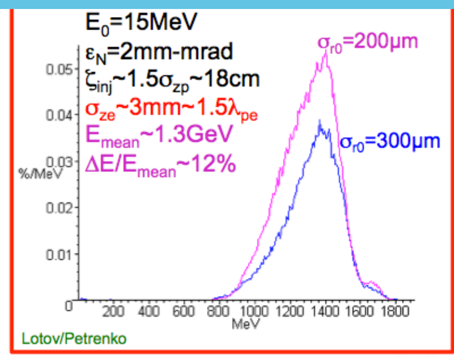






2[nd] goal of AWAKE (2018):
Externally inject (~15MeV) electrons into the wakefields and reach ~GeV energy gain with finite ΔE/E

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



AWAKE, Nature 561, 363 (2018)

OUTLiNE

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- Seeded Self-Modulation (SSM)
- AWAKE experiment
- SSM experimental results
  - Demonstration
  - Physics
- e^- acceleration
- Future and Summary

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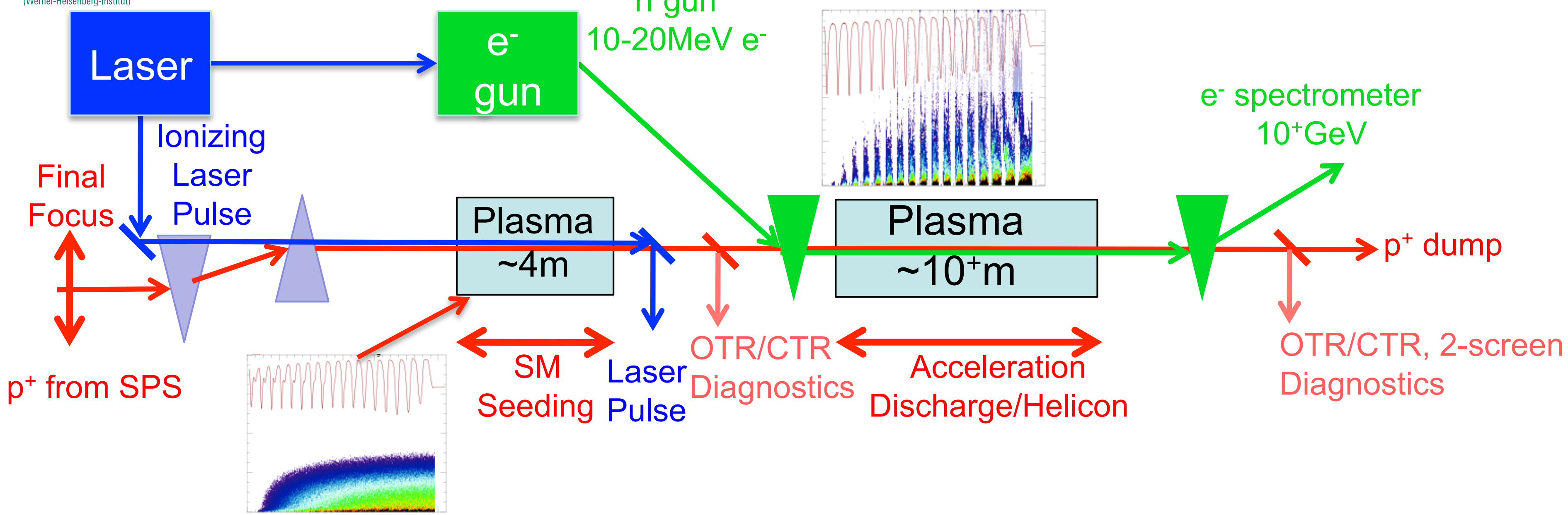
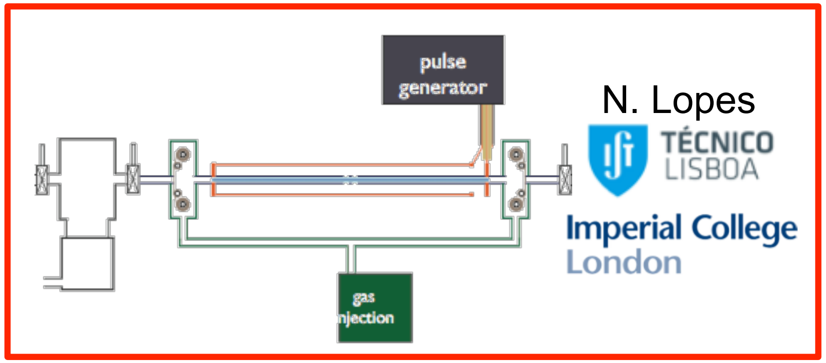
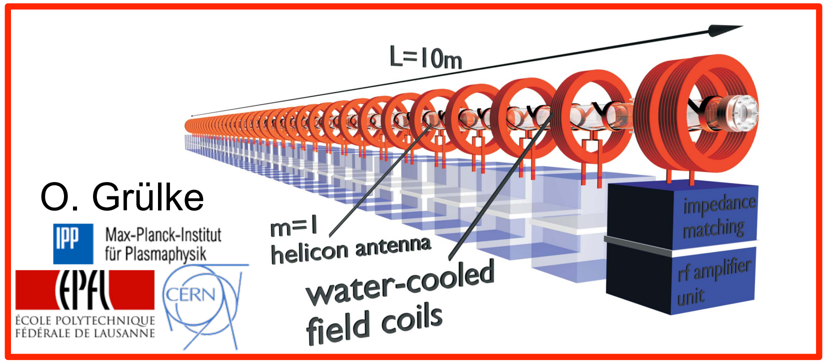
EXPERIMENTAL SETUP RUN II







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

✧Bunch rather than particle acceleration ….

✧2021-LS3, **RUN II**

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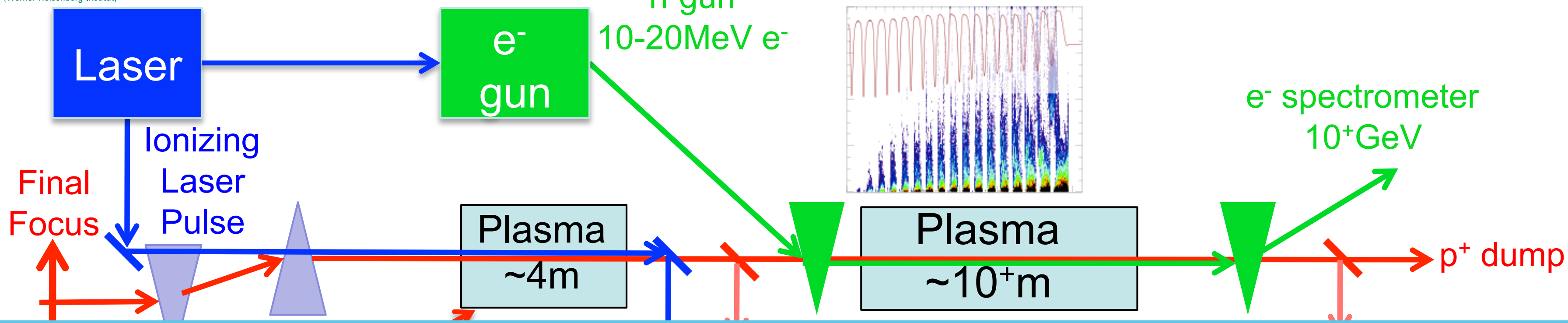
EXPERIMENTAL SETUP RUN II



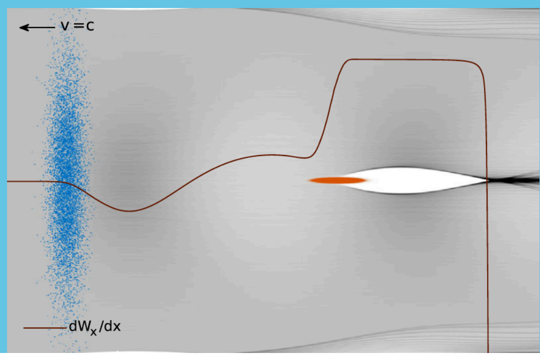
AWAKE Run 2:

-demonstrate acceleration of an e$^-$ bunch

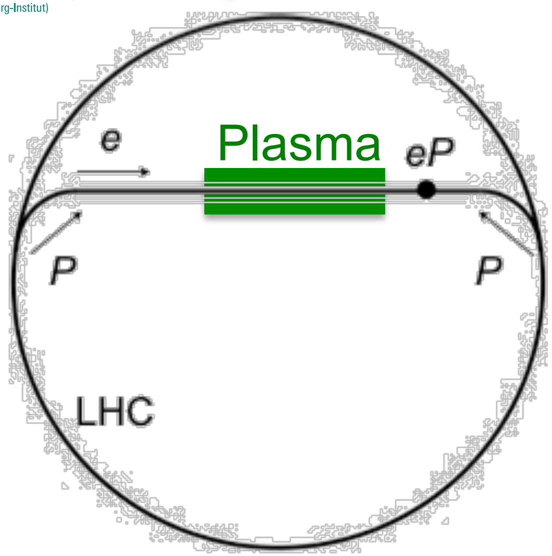
(blow-out, beam loading, matching, $\tau_{z,e-}$~$1/f_{pe}$ => $\Delta E/E$, ε)

-Scalability of plasma source and acceleration

“From Acceleration to Accelerator”



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

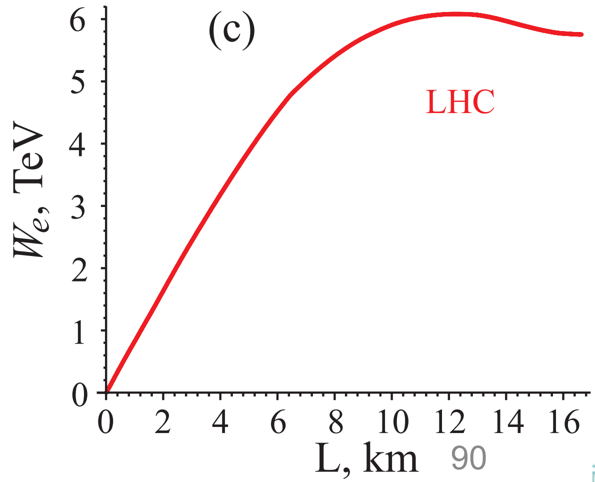


- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity ?
- Assume
    - ~*3000* bunches every *30 mins*, gives *f ~ 2 Hz*.
    - $N_p \sim 4\times10^{11}$, $N_e \sim 1\times10^{11}$
    - $\sigma \sim 4\ \mu m$

$$\mathcal{L} = f\frac{N_e\cdot N_p}{4\pi\sigma_x\cdot\sigma_y}$$
$$\approx 5\cdot10^{28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

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.

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SUMMARY

AWAKE

- 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, $\Delta E/E << 1$

Accelerator Physics

- Interesting beam-plasma interaction physics results
  - SSM growth
  - Observe and control SSM-SMI-HI, Hi @ ω_{pe}
  - $f_{SSM,SMI-HI} = f_{Rb} = f_{pe}$
  - Ionization front and e^- bunch seeding

Beam/Plasma Physics

HEP?

- Run II: (2021-): two plasmas, SSM, quality of the accelerated e^- bunch: $\Delta E/E$, ε, …
- Application of p^+-driven-PWFA: beam dump experiments, 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)

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Thank you to my collaborators!

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