AWAKE: A Proton-Driven Plasma Wakefield Experiment at CERN

presented by:

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for the AWAKE collaboration

MAX-PLANCK-GESELLSCHAFT

AWAKE

Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating e^- on the wake of a p^+ bunch

OUTLINE

- Brief intro to PWFA
- Why p^+-bunch-driven PWFA?
- Short p^+-bunch-driven PWFA
- Self-modulation instability (SMI) of long particle bunches in dense plasmas
- AWAKE with SMI of SPS p^+-bunches
- Description of the experiment
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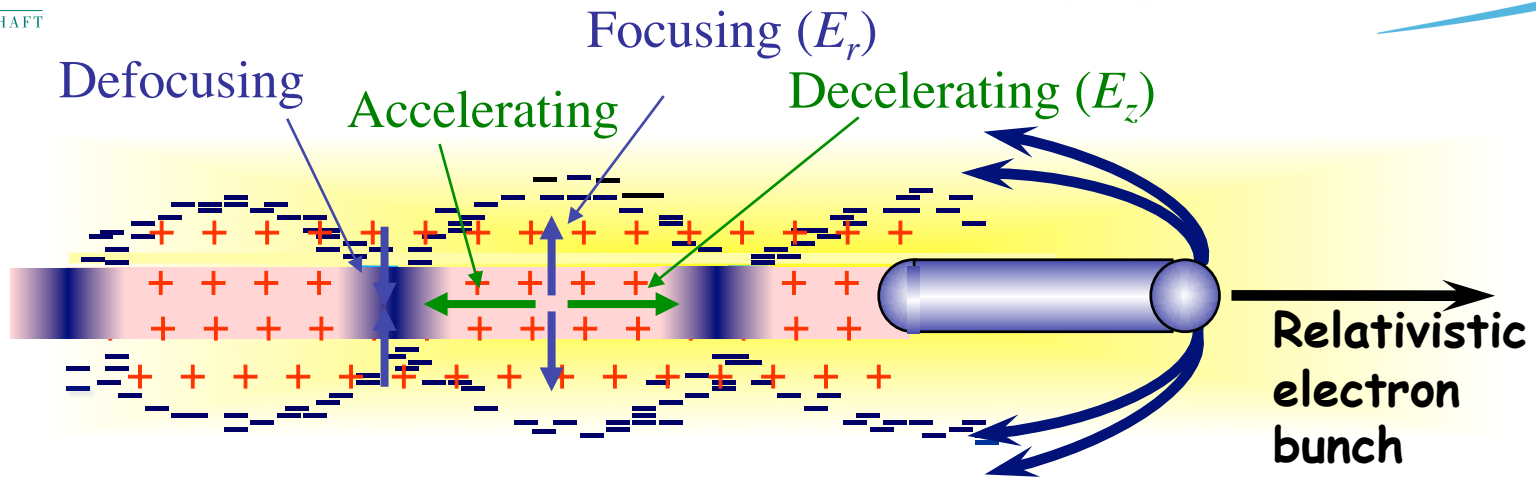
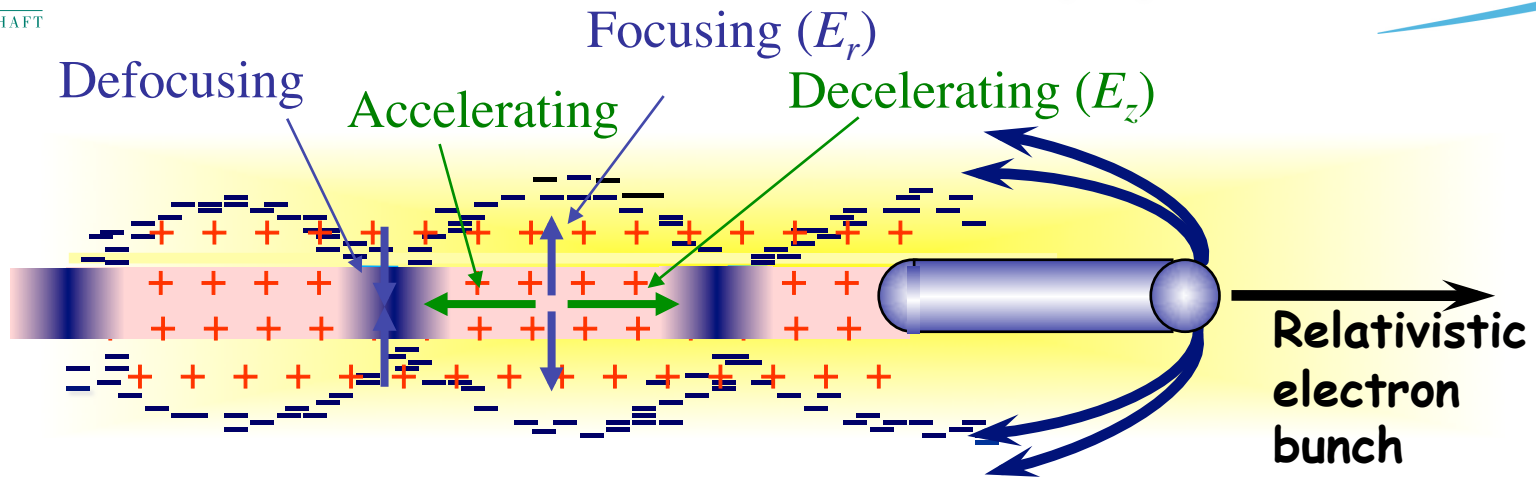
PLASMA WAKEFIELDS (e^-)



- 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 lengths”
  (beta function $\beta^*=\sigma^2/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

PLASMA WAKEFIELDS (e^-)



➡ Plasma wave/wake excited by a relativistic particle bunch

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

by space charge force => deceleration + focusing (MT/m)

k on axis => acceleration, GV/m

ver => ultra-relativistic wake

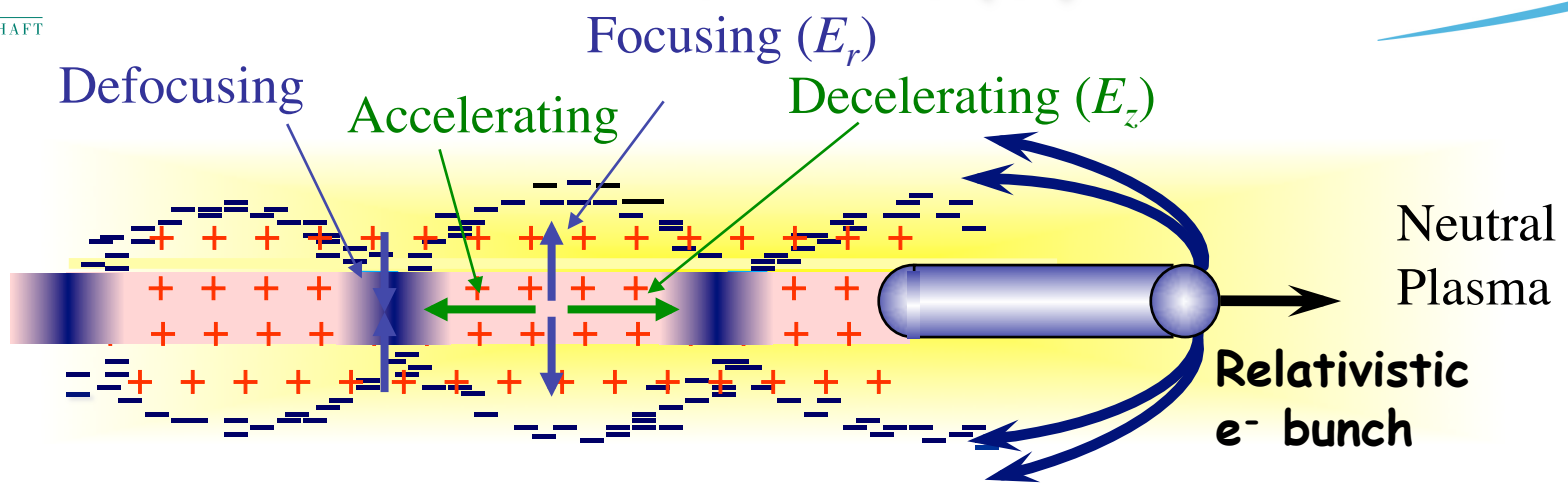
=> no dephasing (…)

ave long "Rayleigh lengths"

$^2/\varepsilon$~cm, m)

➡ Acceleration physics identical PWFA, LWFA

PWFA NUMBERS (e^-)



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

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

$$@\ k_{pe}\sigma_z \approx \sqrt{2}\ (with\ k_{pe}\sigma_r << 1)$$

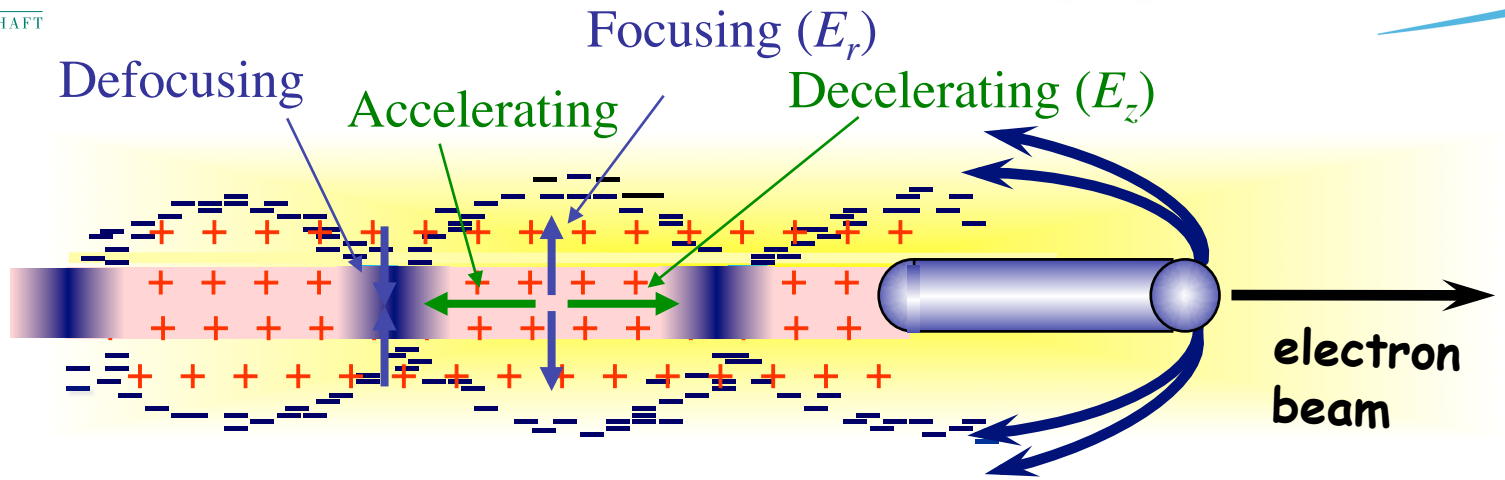
- Focusing strength:

$$\frac{B_\theta}{r} = \frac{1}{2}\frac{n_e e}{\varepsilon_0 c} = 3kT/m \times n_e(10^{14}\,cm^{-3}) \qquad (n_b > n_e)$$

- Scaling favor: -High charge: E_{acc}~N
  -Short bunch: E_{acc}~$1/\sigma_z^{\,2}$
  -High plasma density: n_e~$1/\sigma_z^{\,1/2}$

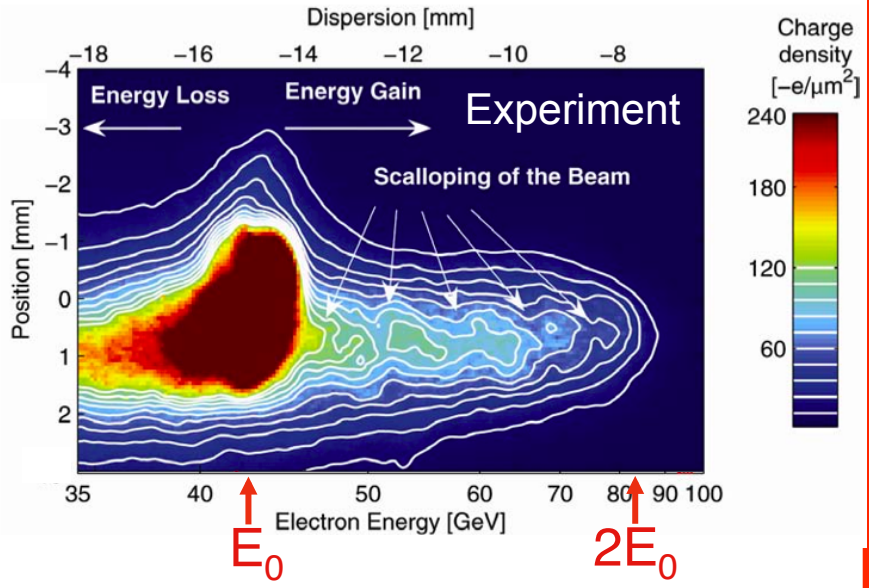
  for high gradient

PLASMA WAKEFIELDS (e^-)



- Plasma wave/wak… …h
- Plasma e^- expelle… …ation + focusing
- Plasma e^- rush ba… …tion
- Ultra-relativistic dr…
- Particle bunches h… …energy gain
  (beta function β^*=…
- Acceleration phys…

Blumenfeld, Nature 445, 2007



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

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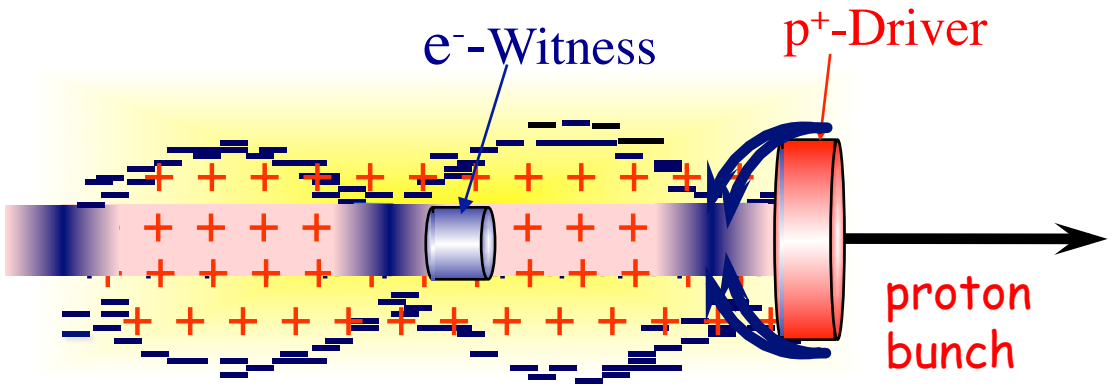
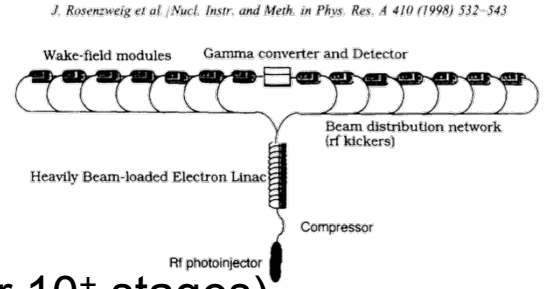
WHY p^+-DRIVEN PWFA?

- Because we can!
- They carry large amounts of energy (kJ)
- Sustain large <u>average</u> gradient (GeV/m) over long distances

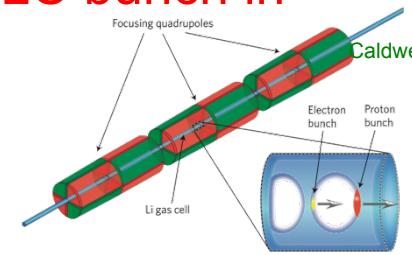
WHY p^+-DRIVEN PWFA?



- 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)
- 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)

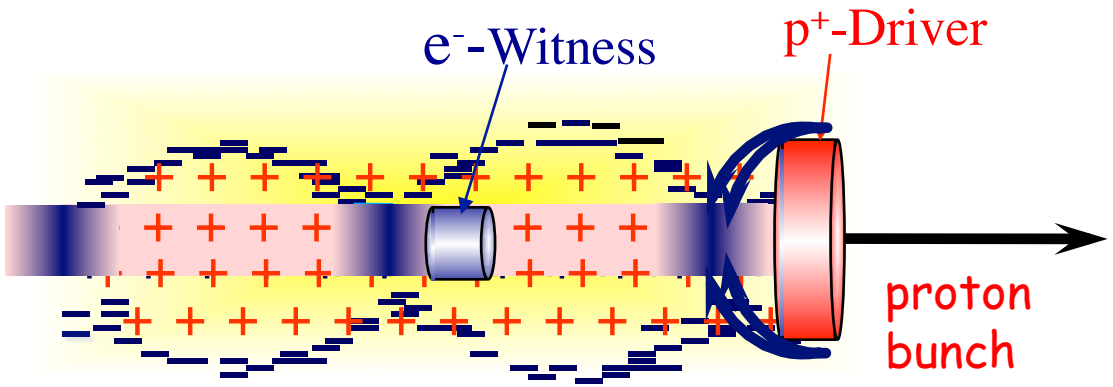


Caldwell, Nat. Phys. 5, 363, (2009)

P. Muggli, 06/04/2013, EAAC 2103

WHY p+-DRIVEN PWFA?

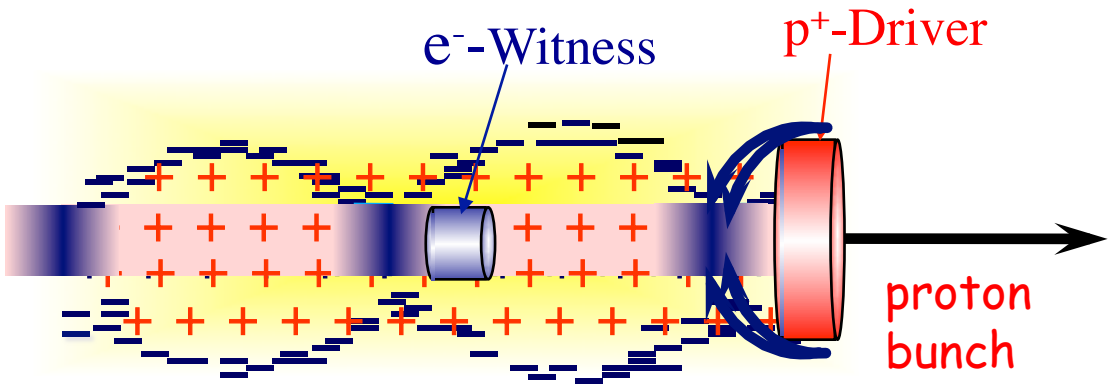
Pancake-like bunch: $\sigma_{x,y}>\sigma_z$



- large <u>average</u> gradient: n_e~10^{14}-10^{15}cm^{-3}, ~1GeV/m over 100's m
- large accelerating structure: ~λ_{pe}^3~$n_e^{-3/2}$~mm^3, easier injection
- large matched radius: $\sigma_{r,m} = \left(\frac{1}{2\pi r_e}\right)^{1/4}\left(\frac{\varepsilon_N^2}{\gamma n_e}\right)^{1/4}$
- Less betatron radiation: $P_\beta \propto \gamma^2 n_e^2 r^2 \propto n_e^2 \sigma_{r,m}^2 \propto n_e^{3/2}$

and: $E_\beta \propto P_\beta L_{acc} = P_\beta \frac{W_{fin}}{E_{acc}} = P_\beta \frac{W_{fin}}{E_{WB}} \propto n_e$

WHY p⁺-DRIVEN PWFA?



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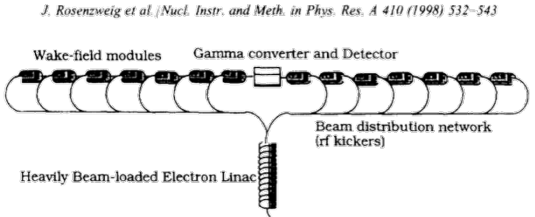
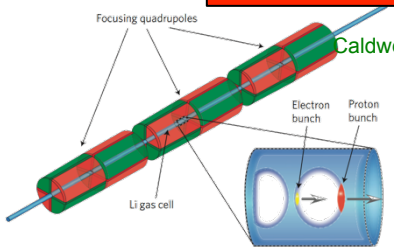


Interesting PWFA drivers at CERN

P. Muggli, 06/04/2013, EAAC 2103



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PROTON-DRIVEN PWFA

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

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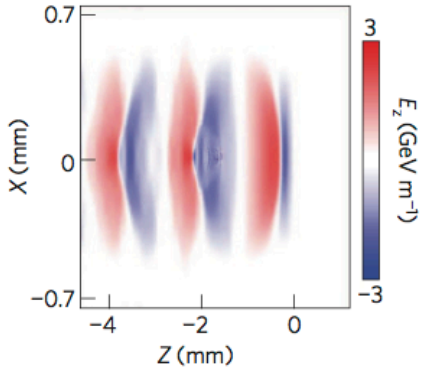
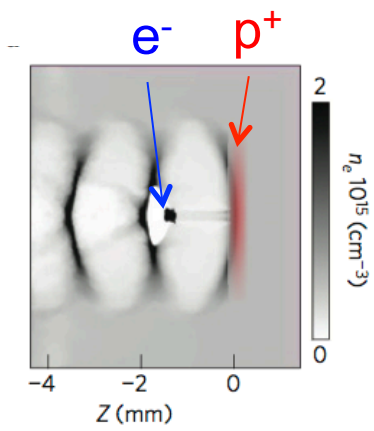
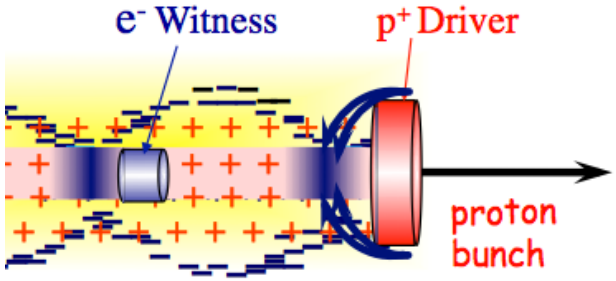
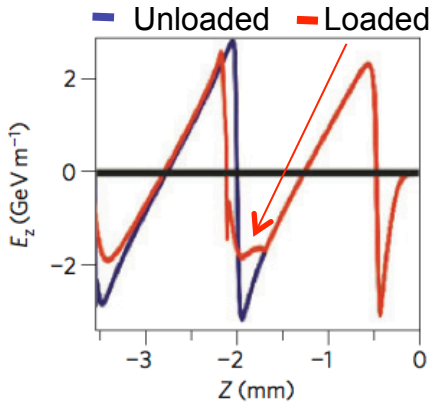
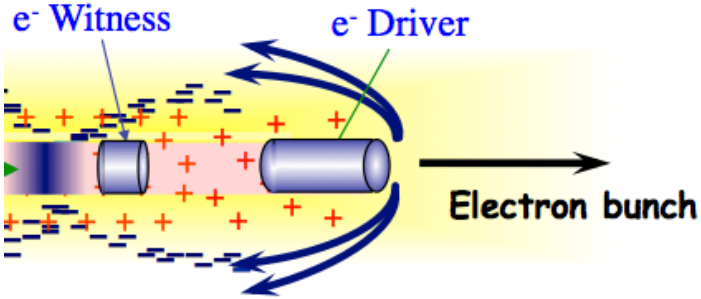






Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	μm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons 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





EAAC 2103

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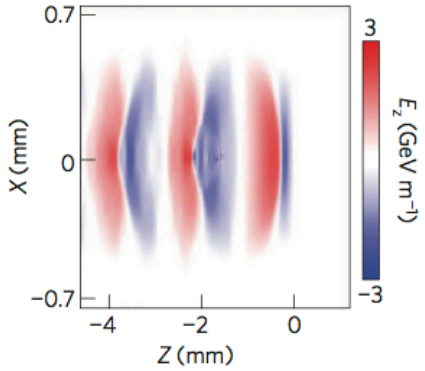

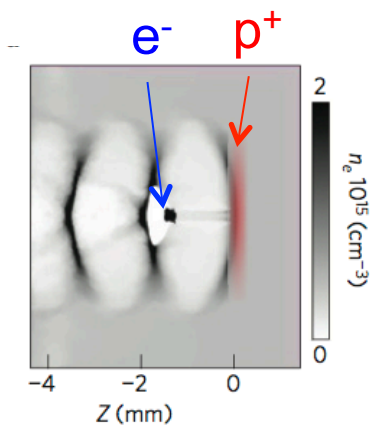

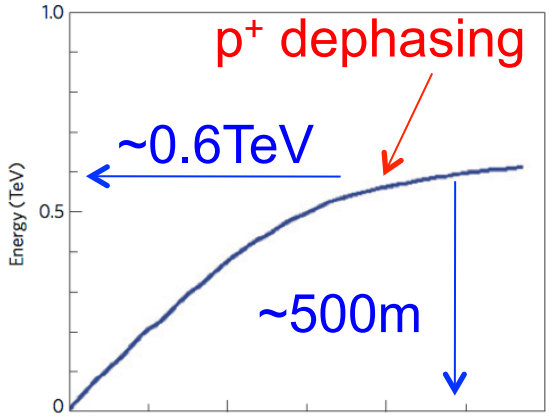

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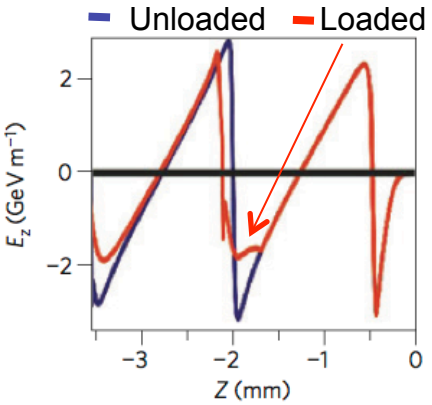

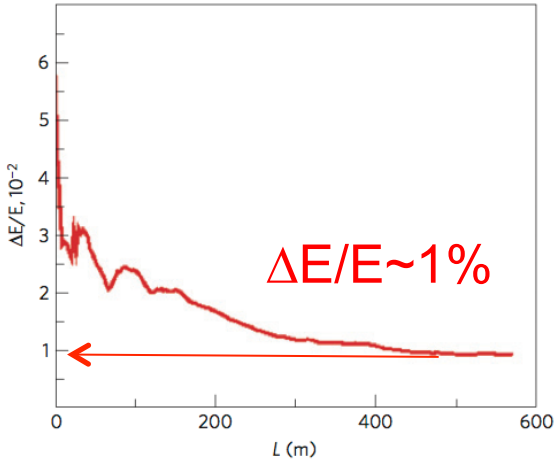

P. Muggli, 06/04/2013, EAAC 2103

- Use “pancake” p^+ bunch ($\sigma_r>\sigma_z$) to drive wakefields (cylinder for e^- driver)
- Loaded gradient ~1.5GV/m
- ILC-like e^- bunch from a single p^+-driven PWFA

PROTON-DRIVEN PWFA

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

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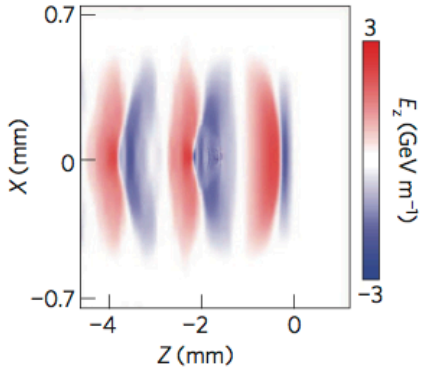

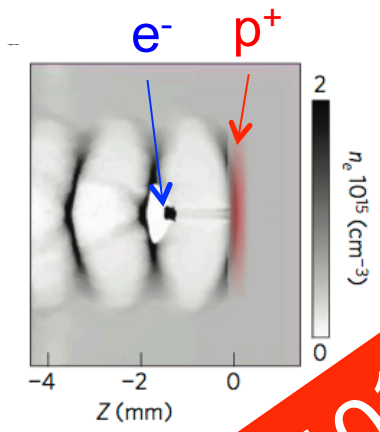

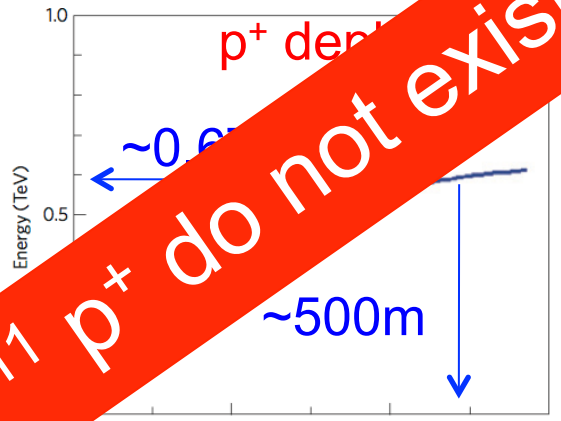

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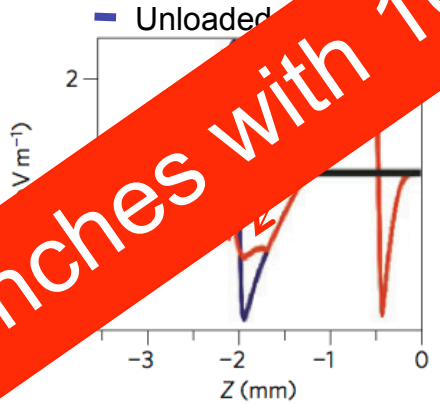

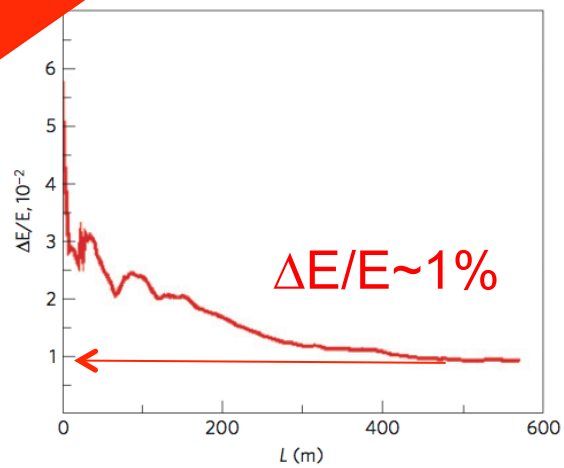

$\sigma_z \approx 100\mu m$ bunches with 10^{11} p^+ do not exist!

- Use "[illegible] p^+ bunch to drive wakefields (cylinder for e^- driver)
- [illegible]adient ~1.5GV/m, efficiency ~ 10% (recycling?)
- I[illegible]ike e^- bunch from a single p^+-driven PWFA

P. Muggli, 06/04/2013, EAAC 2103

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SELF-MODULATION INSTABILITY (SMI)

- CERN p^+ bunches (PS, SPS, LHC) ~12cm long
- $n_e \sim 10^{14} cm^{-3}$, $E_{WB} \sim 1 GeV$, $\lambda_{pe} \sim mm$

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

Self-Modulation Instability of a Long Proton Bunch in Plasmas

Naveen Kumar* and Alexander Pukhov
Institut für Theoretische Physik I, Heinrich-Heine-Universität, Düsseldorf D-40225 Germany

Konstantin Lotov
Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia
(Received 16 April 2010; published 25 June 2010)

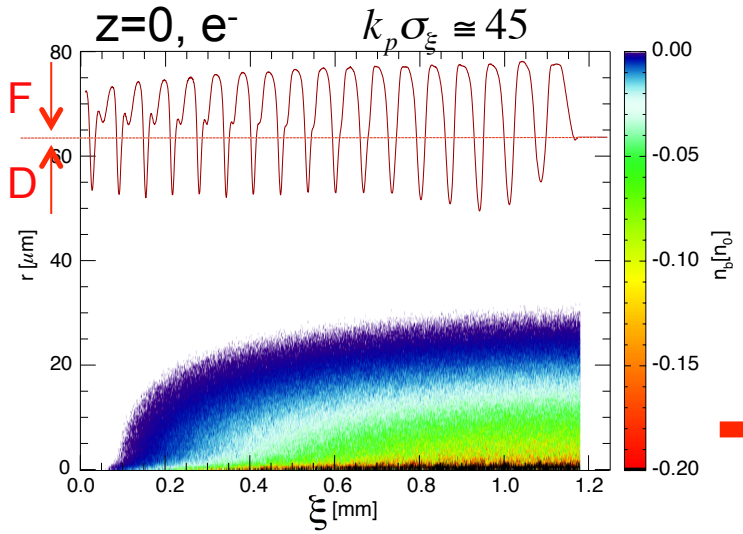
An analytical model for the self-modulation instability of a long relativistic proton bunch propagating in uniform plasmas is developed. The self-modulated proton bunch resonantly excites a large amplitude plasma wave (wakefield), which can be used for acceleration of plasma electrons. Analytical expressions 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.

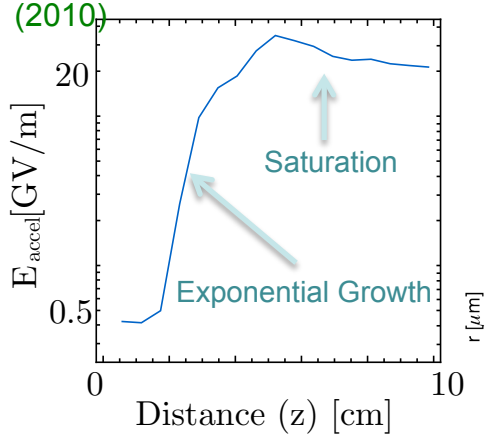
DOI: 10.1103/PhysRevLett.104.255003 PACS numbers: 52.35.−g, 52.40.Mj, 52.65.−y

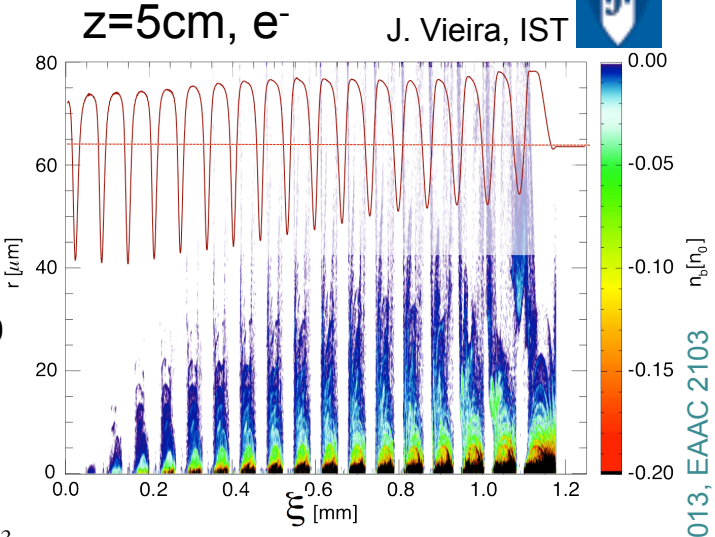
- Idea developed “thanks” to the non-availability of short p^+ bunches
- Very similar to Raman self-modulation of long laser pulses (LWFA of the 20th century)

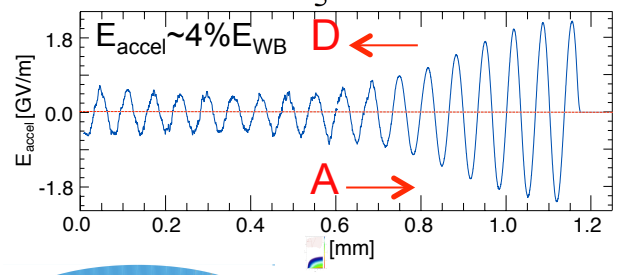
SELF-MODULATION INSTABILITY (SMI)

Kumar, PRL 104, 255003 (2010)

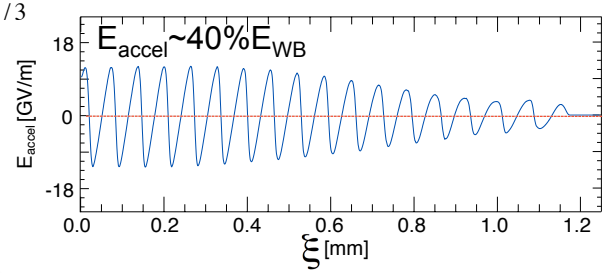








$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



P. Muggli, 06/04/2013, EAAC 2103

E209

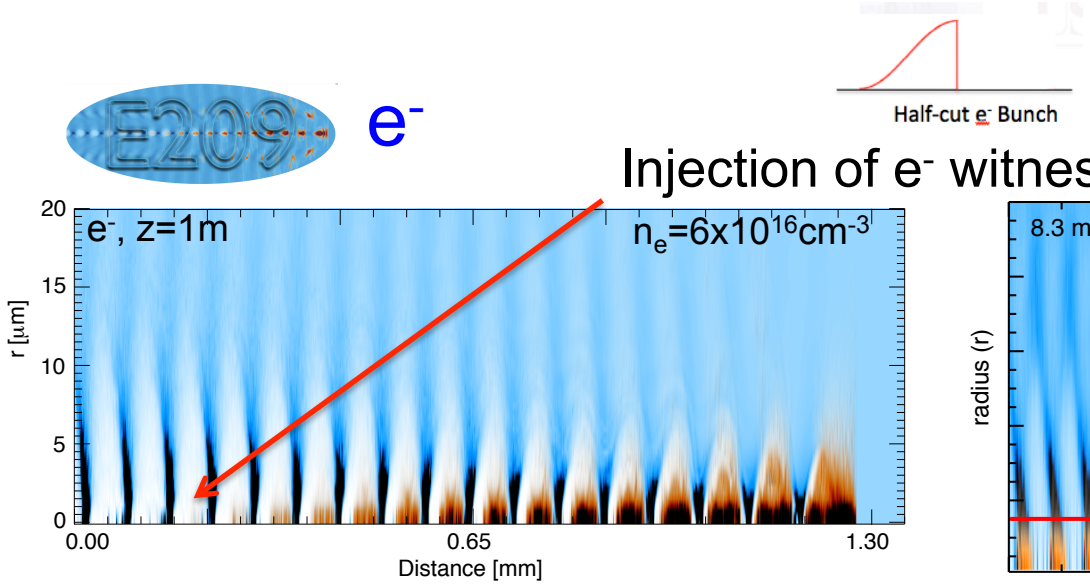
Grows along the bunch & along the plasma
Convective instability

Pukhov, PRL 107, 145003 (2011)
Schroeder, PRL 107, 145002 (2011)

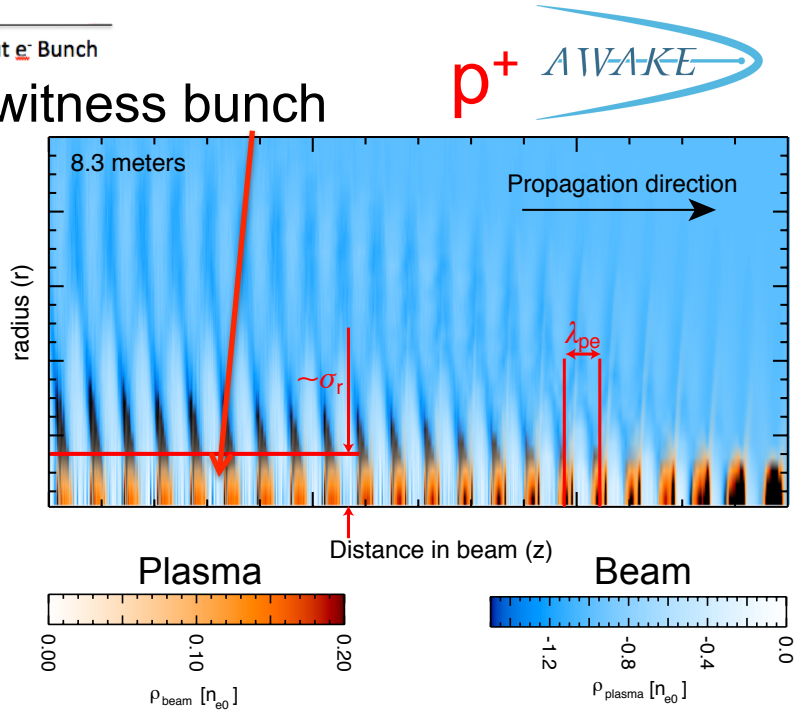
- Initial small transverse wakefields modulate the bunch density
- Associated longitudinal wakefields reach large amplitude through resonant excitation
- Acceleration of an injected witness bunch

Vieira, Phys. Plasmas 19, 063105 (2012)

COMPARISON e^-/p^+



Muggli, Proc. IPAC 2012



Muggli, Proc. IPAC 2013

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- Drive particles (e^-, p^+) sit in opposite wakefield phases
- p^+ in much narrower, less uniform regions of the wakefields than e^-

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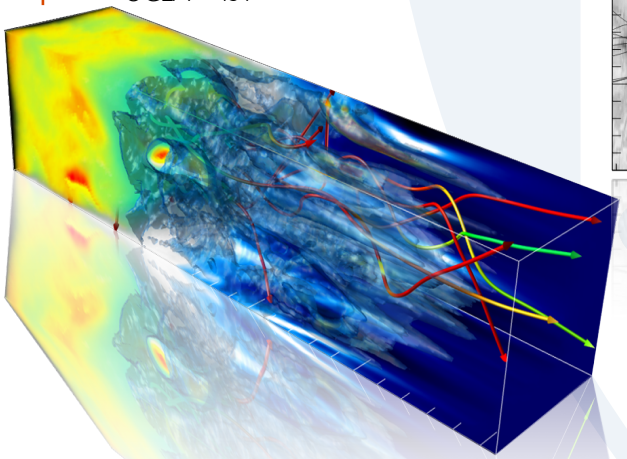
PROTON-DRIVEN PWFA SIMULATIONS

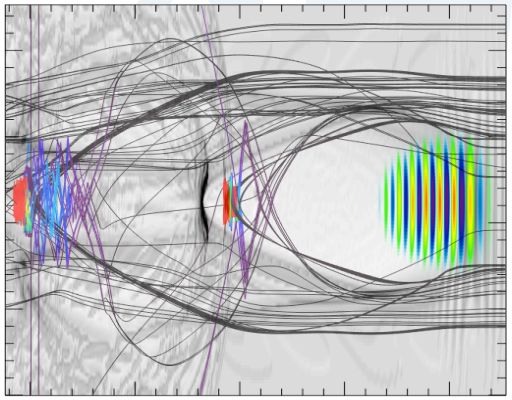
OSIRIS 2.0

osiris v2.0

osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST





New Features in v2.0

- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

Ricardo Fonseca: ricardo.fonseca@ist.utl.pt
Frank Tsung: tsung@physics.ucla.edu

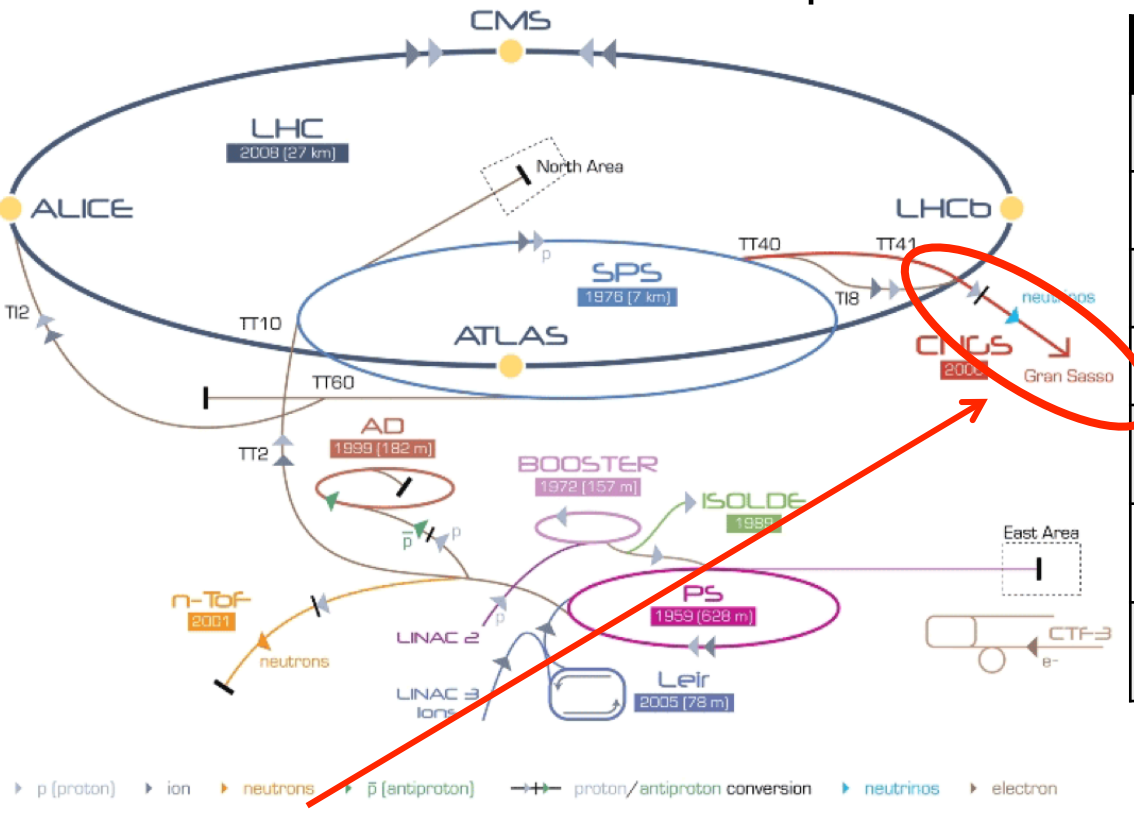
http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

Patric Muggli | May 23rd 2012 | IPAC - New Orleans Louisiana, USA

- VLPL, A. Pukhov, J. Plasma Phys. 61, 425 (1999)
- LCODE, K. V. Lotov, Phys. Rev. ST Accel. Beams 6, 061301 (2003)
- Challenging simulations: σ_z, $L_{plasma} >> c/\omega_{pe}$

PROTON BEAMS @ CERN

CERN Industrial Beam Complex



CNGS experimental area

Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	450	450
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

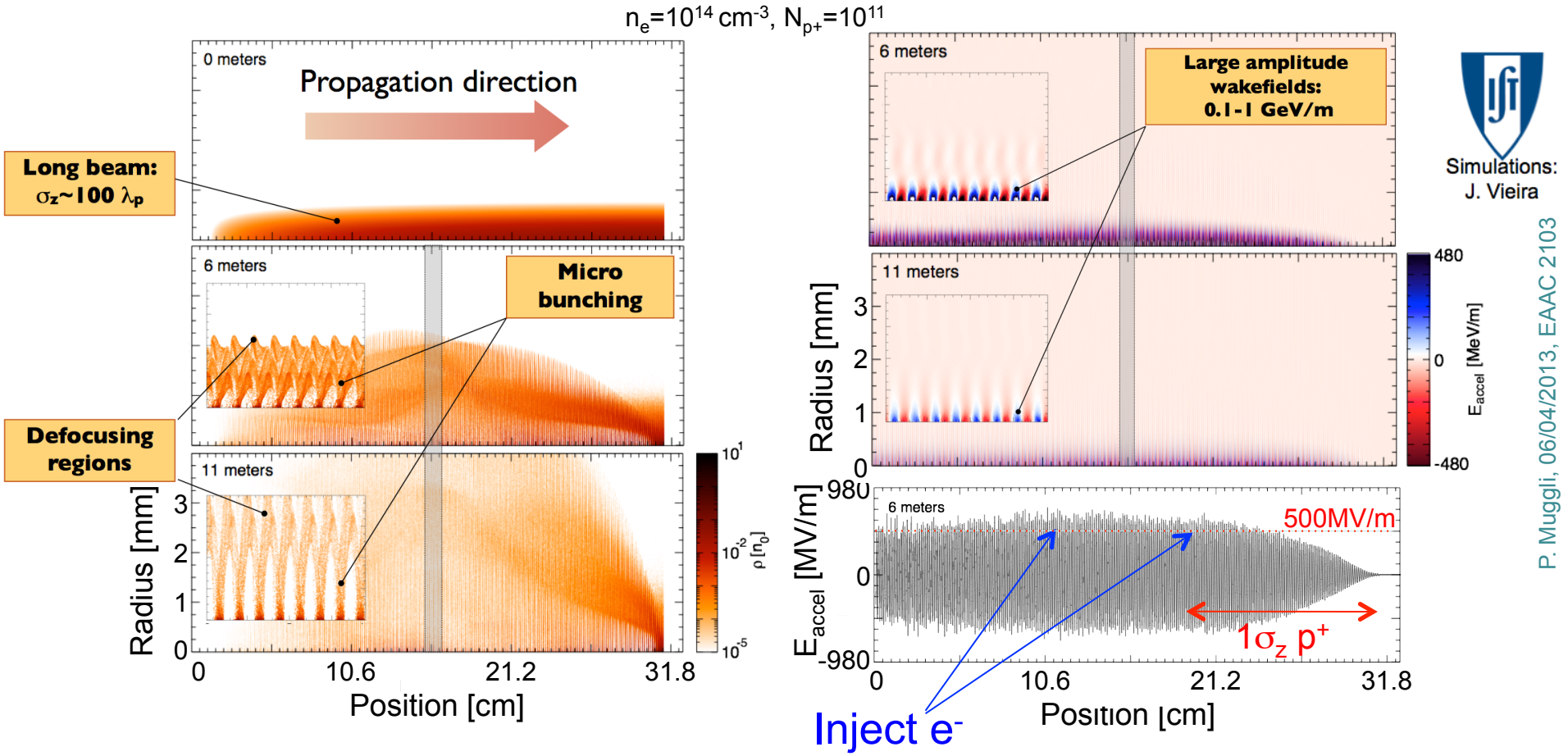
P. Muggli, 06/04/2013, EAAC 2103

$n_e \sim 7 \times 10^{14} cm^{-3}$ ($k_p \sigma_r \approx 1$)
$\lambda_{pe} \sim 1.3mm << \sigma_z$
$f_{pe} \sim 240GHz$
$L_p \sim 5\text{-}10m$

- SPS beam: high energy, low σ_r^*, long β^*
- Initial goal: ~GeV gain by externally injected e^-, in 5-10m of plasma in self-modulated p^+ driven PWFA

p⁺-DRIVEN PWFA @ CERN

✧SMI of long (~12cm), 450GeV SPS bunch @ λ_{pe}≈1-3mm



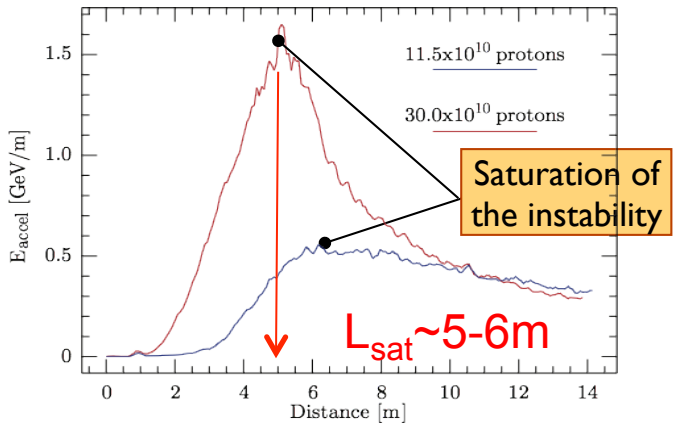
✧Drives large amplitude (0.1-1GV/m) accelerating fields

✧E_z (acceleration) sampled by injecting (~10MeV) e⁻ bunch

p⁺-DRIVEN PWFA @ CERN

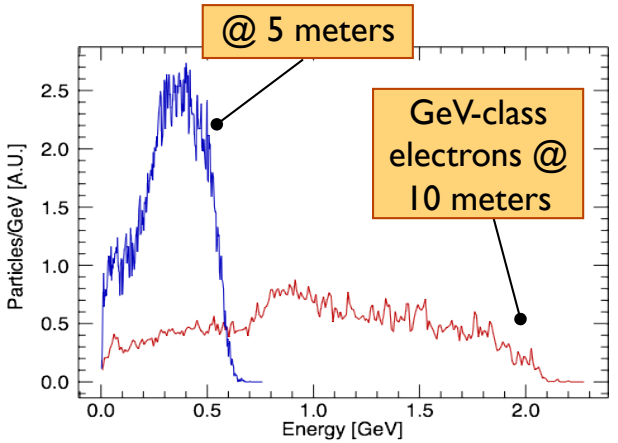
✧SMI of long (~12cm), 450GeV SPS bunch @ λ_{pe}

Maximum accelerating gradients



- Maximum fields achieved at 5 m of propagation
- GeV/m wakefields can be excited
- Wake phase velocity on the order of driver velocity (large dephasing lengths)

Test electron beam spectra using $3x10^{11}$ p^+



- Acceleration of external electrons to high energies
- High energies can be achieved (once the instability saturates lengths)

Simulations: J. Vieira

Electron bunch

- $\sigma_{||}$ = 100 mm
- $\sigma_{\perp}$ = 200 μm
- $n_b/n_0 = 1.32x10^{-7}$
- γ = 20 (10 MeV)

Test e⁻

✧Growth of instability => p^+ density modulation => large E_z

✧Injected e^- gain ~1-2GeV in 10m plasma

✧Injected of short e^- bunch could produce small ΔE/E

Phase velocity of the wake

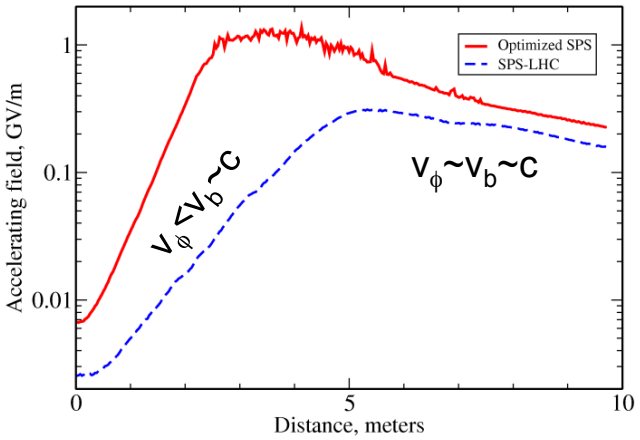
HQ-VLPL3D simulation

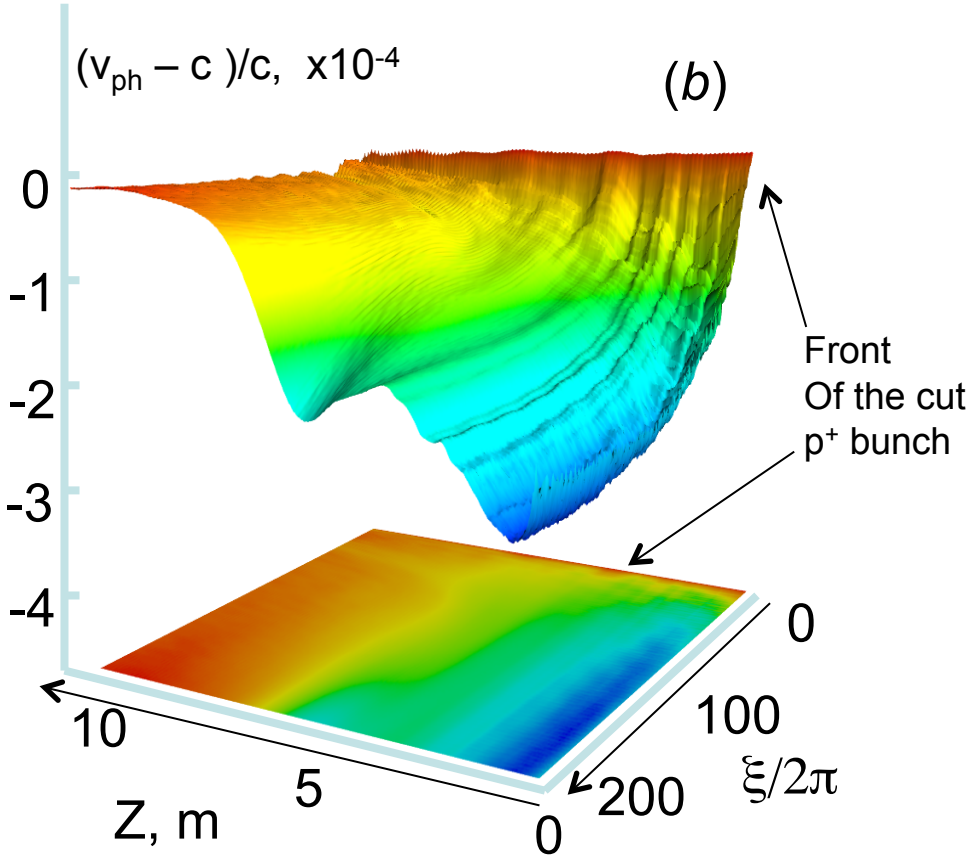
Pukhov et al., Phys Rev Lett (2011)
Schroeder, Phys. Rev. Lett. (2011)

The wake is slowed down. Its minimum gamma-factor is

$\gamma_{min} \sim 40 \quad << \quad \gamma_{p+} \sim 460$

This is order of magnitude below that of the beam





P. Muggli, 06/04/2013, EAAC 2103

pukhov@tp1.uni-duesseldorf.de

- Phase velocity of wakefield $<v_p \approx c$ in the growth phase
- External injection <u>after</u> saturation of SMI

Phase velocity of the wake

HQ-VLPL3D simulation

Pukhov et al., Phys Rev Lett (2011)
Schroeder, Phys. Rev. Lett. (2011)

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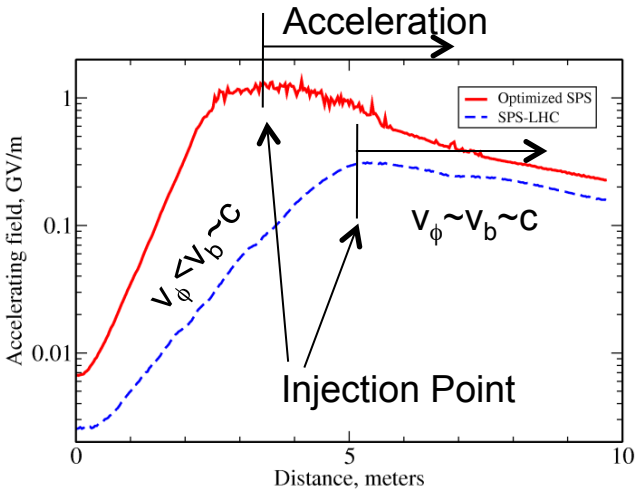
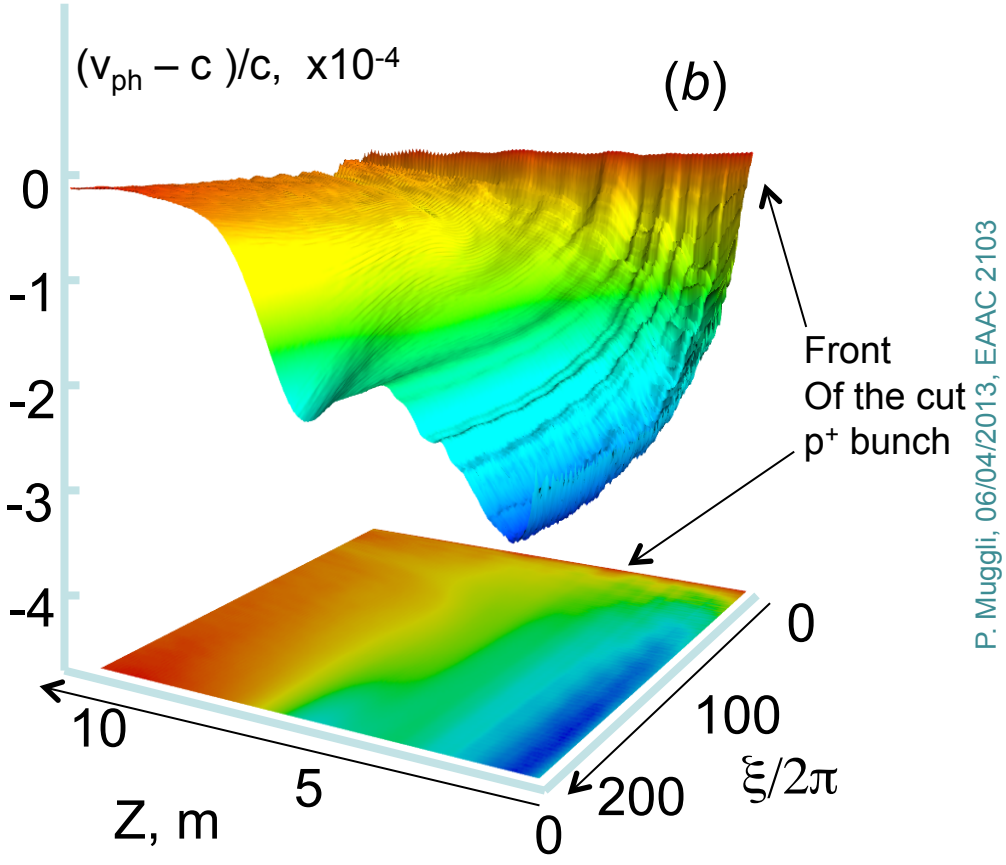




P. Muggli, 06/04/2013, EAAC 2103

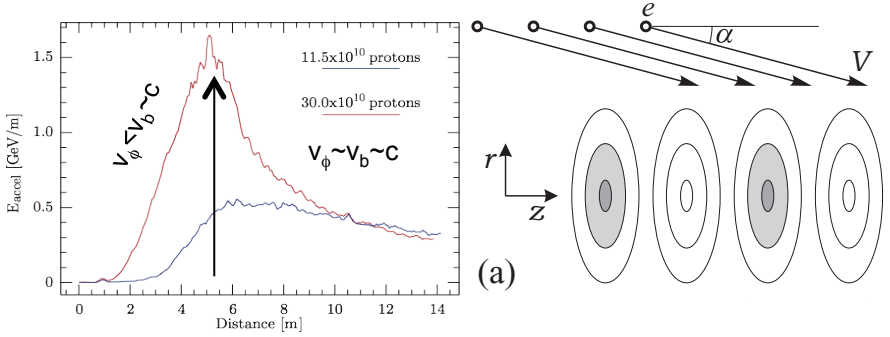
pukhov@tp1.uni-duesseldorf.de

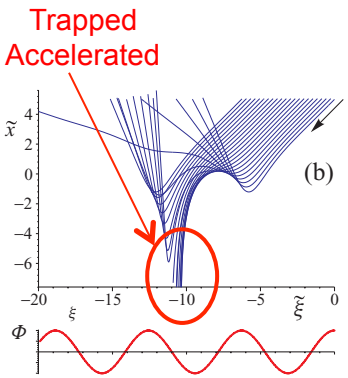
- Phase velocity of wakefield $<v_p \approx c$ in the growth phase
- External injection after saturation of SMI

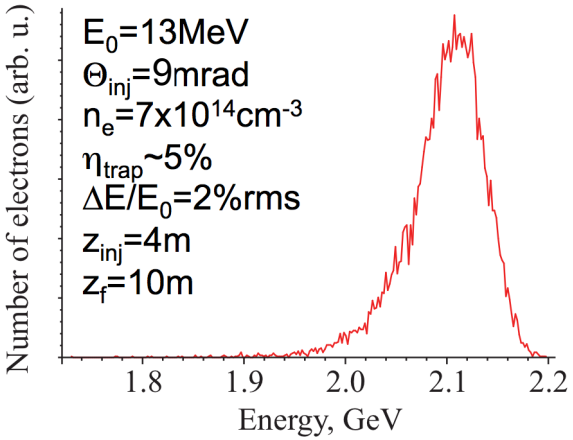
e⁻ SIDE INJECTION

Lotov, J. Plasma Phys. (2012)

- Single, long plasma
- Low energy test e⁻ injected sideways are trapped and bunched in a few wake buckets







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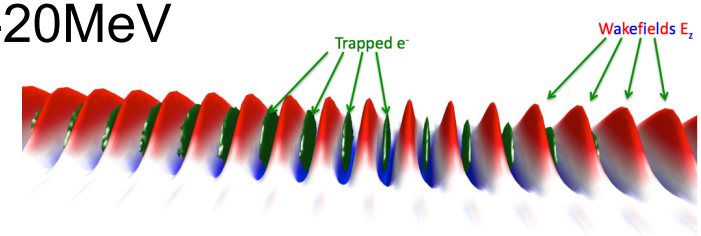
$$\alpha_{opt} \sim \frac{v_\phi - v_{e-}}{c} \sim \frac{1}{2\gamma_{e-}^2} \sim mrad$$

for E_{e-}=5-20MeV



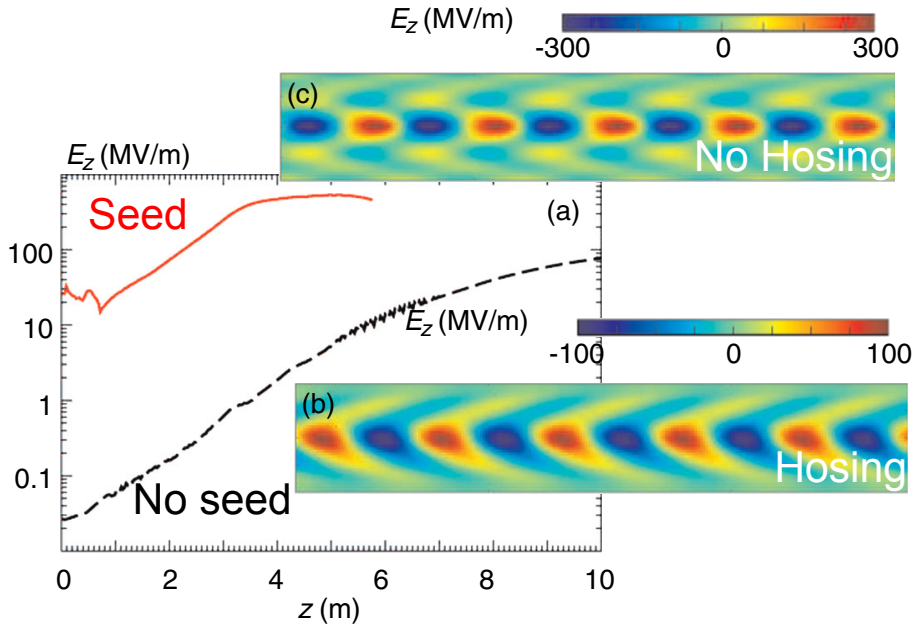
Simulation by A. Pukhov

- Inject in saturated SMI, $v_\phi = v_b \approx c$
- Generates narrow final energy spectrum
- Trapping efficiency <60%, test particles

SMI SEEDING

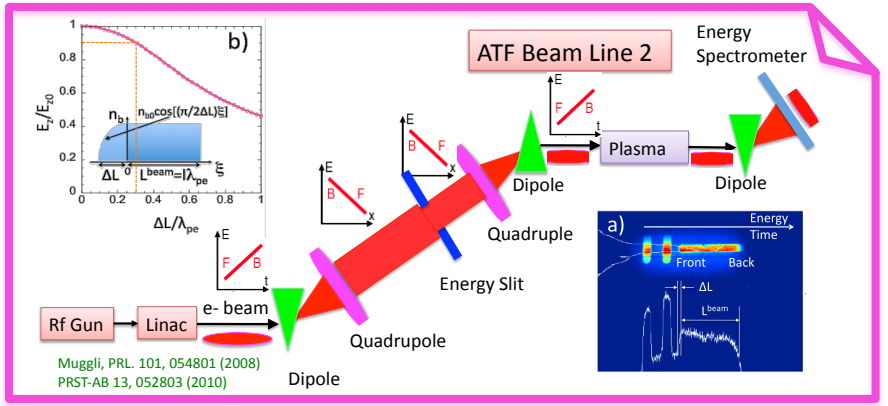
- SM Instability, grows from noise, “random”
- Instabilities can be seeded by a larger-than-noise signal

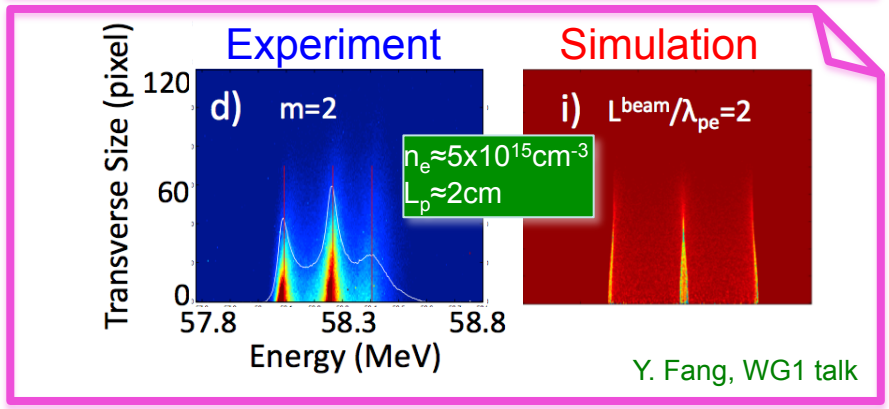
Preceding e⁻-bunch



Lotov, PRST-AB 16, 041301 (2013)

“Cut” bunch or plasma





Fang, to be published

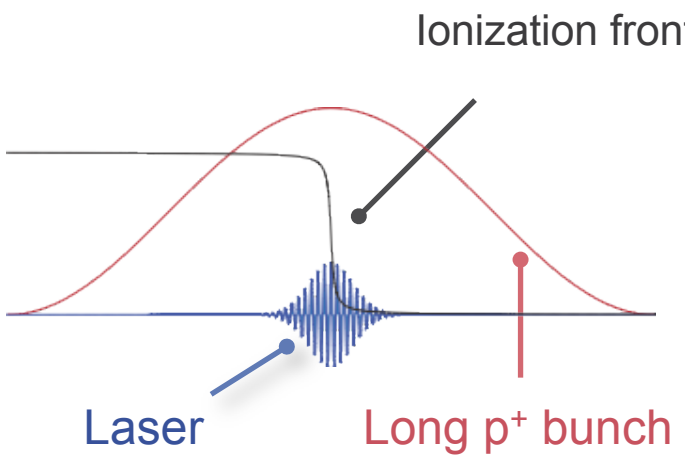
P. Muggli, 06/04/2013, EAAC 2103

- Shortens length to saturation
- Suppresses hosing

- Generates periodic wakefield

Creating plasma and cut proton bunch simultaneously
Ionizing laser pulse

Laser pulse on top of proton bunch



- Laser pulse creates ionization front
- Ionization front acts as if long proton bunch is sharply cut
- Laser pulse excites wakes to directly seed the instability

D. Gordon et al, PRE, **64** 046404 (2001).

PIC simulations are demanding

- ω_0/ω_{pe} ~ 1000 - 4000
- 1000-4000x smaller $\Delta x_{||}$
- 1000-4000x more CPUh
- **~10 million CPUhours using standard full-PIC for 5 m**

Equation for the laser envelope
Ponderomotive guiding center

Equation for laser pulse envelope:

$$\partial_\tau a = \frac{1}{2i\omega_0}\left[\left(1+\frac{1}{i\omega_0}\frac{\partial}{\partial\xi}+\nabla_\perp^2\right)\right]a$$

$\partial_\tau a$: t=τ; $\frac{1}{2i\omega_0}$: laser frequency; $\frac{1}{i\omega_0}\frac{\partial}{\partial\xi}$: ξ=x-ct; $\nabla_\perp^2$: laser envelope

D. Gordon, et al., IEEE-TPS, **28** 1135-1143 (2000).

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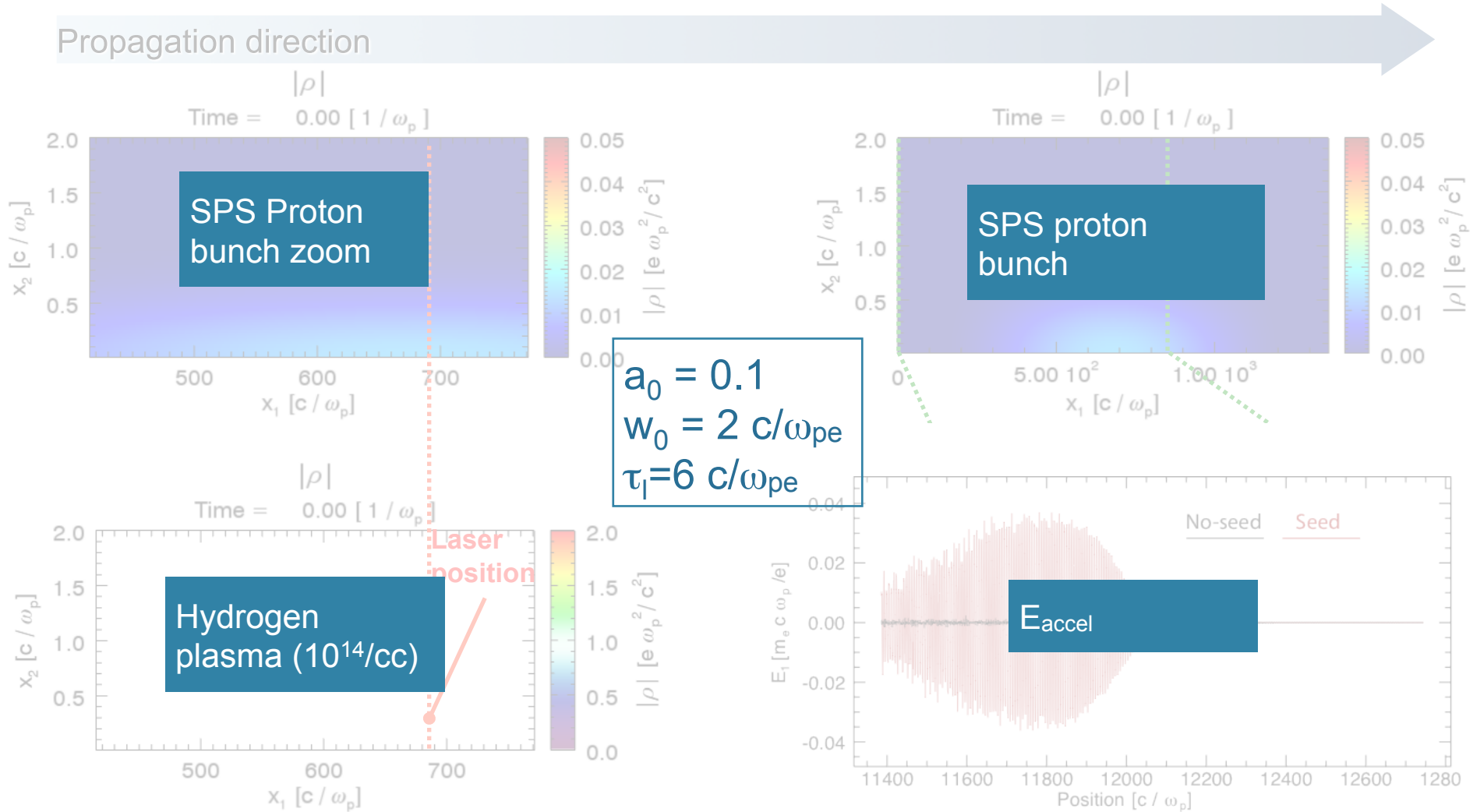
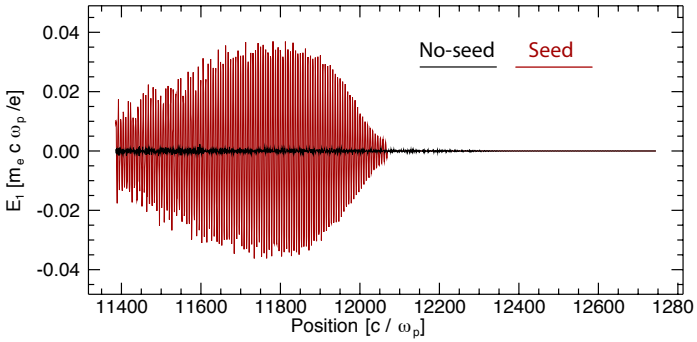
Creating plasma and cut proton bunch simultaneously
Ionizing laser pulse



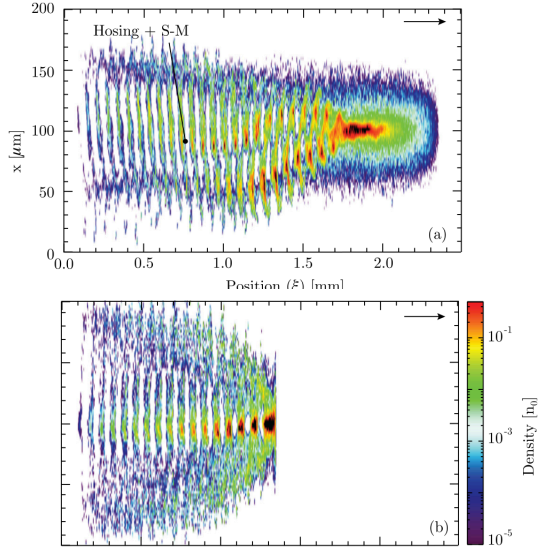
Immobile ions are considered to avoid plasma ion motion
J. Vieira et al, Phys. Rev. Lett. **109** 145005 (2012)

SMI SEEDING IS NECESSARY

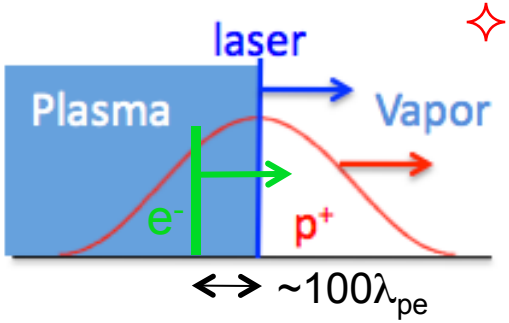


✧No seed, no SMI (over 10m)

SLAC e⁻ beam case, Vieira et al., PoP (2012)



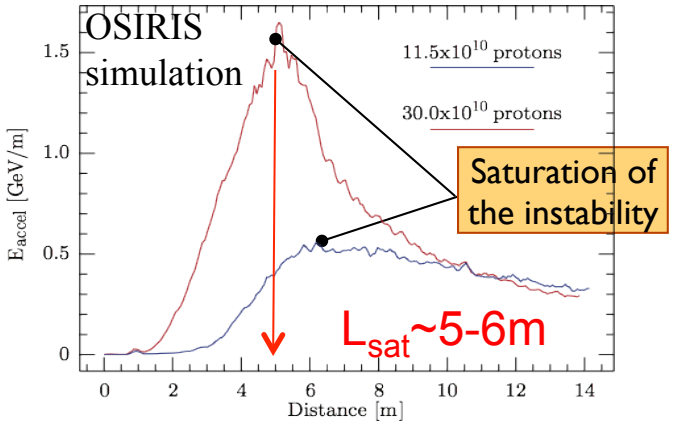
✧Hosing mitigation

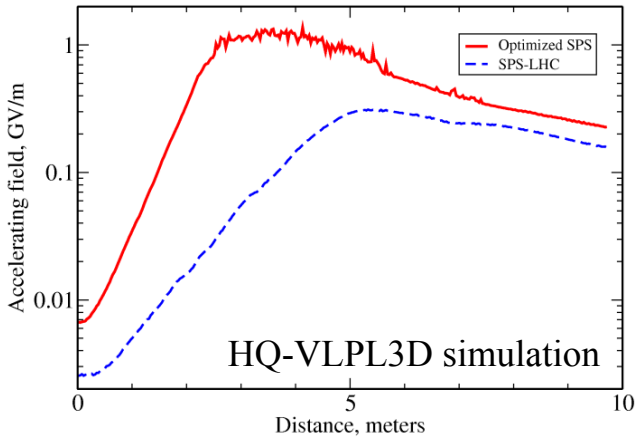


✧Deterministic e⁻ injection
Laser pulse determines phase of wakefields

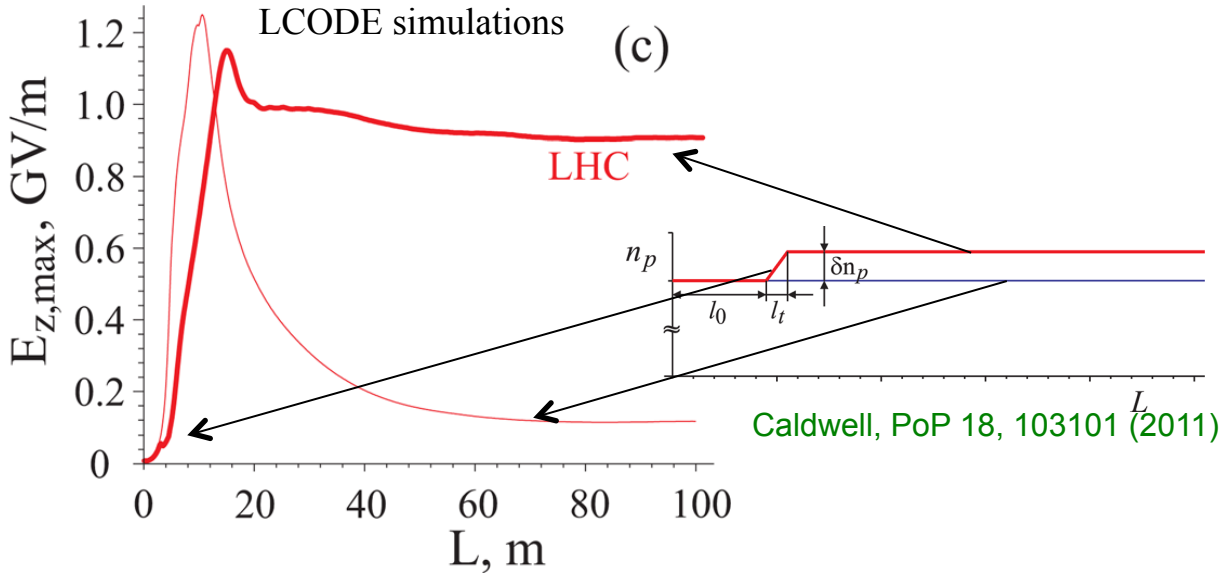
MAINTAINING HIGH GRADIENT

- Gradient decrease, continuous evolution of beam and wakefields





Parameter	LHC
δn_p (%)	1.6
l_0 (m)	3
l_t (m)	1.5
N_{mb}	125
L_{diffr} (m)	2500
$E_{z,max}$ (MV/m)	900
L_{depl} (km)	7.8
W'	0.6
L_{dec} (m)	9500
W_{dec} (GeV)	7700
W_E (GeV)	10
L_{deph} (m)	30 000
W_{deph} (GeV)	17 000



Caldwell, PoP 18, 103101 (2011)

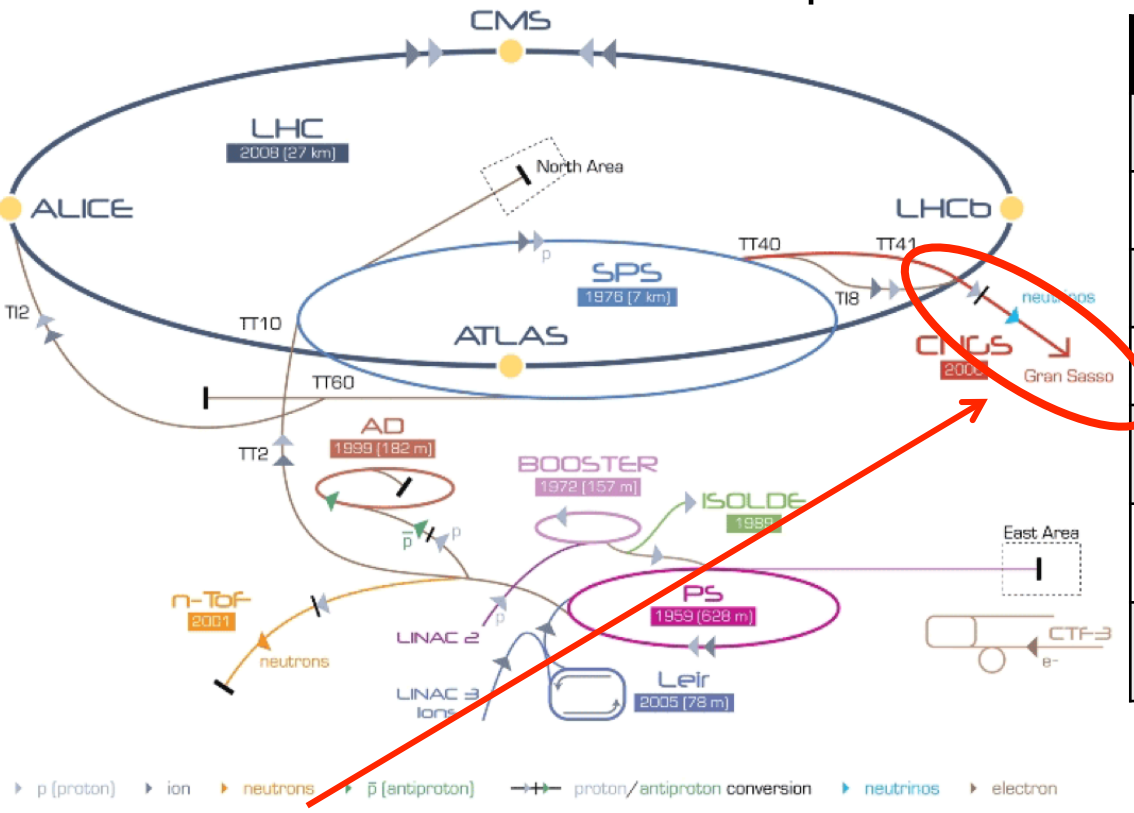
- Step in n_e at %-level can maintain close to saturated gradient value

OUTLINE

- Brief intro to PWFA
- Why p^+-bunch-driven PWFA?
- Short p^+-bunch-driven PWFA
- Self modulation instability (SMI) of long particle bunches in dense plasmas
- AWAKE with SMI of SPS p^+-bunches
- Description of the experiment
- Summary

PROTON BEAMS @ CERN

CERN Industrial Beam Complex



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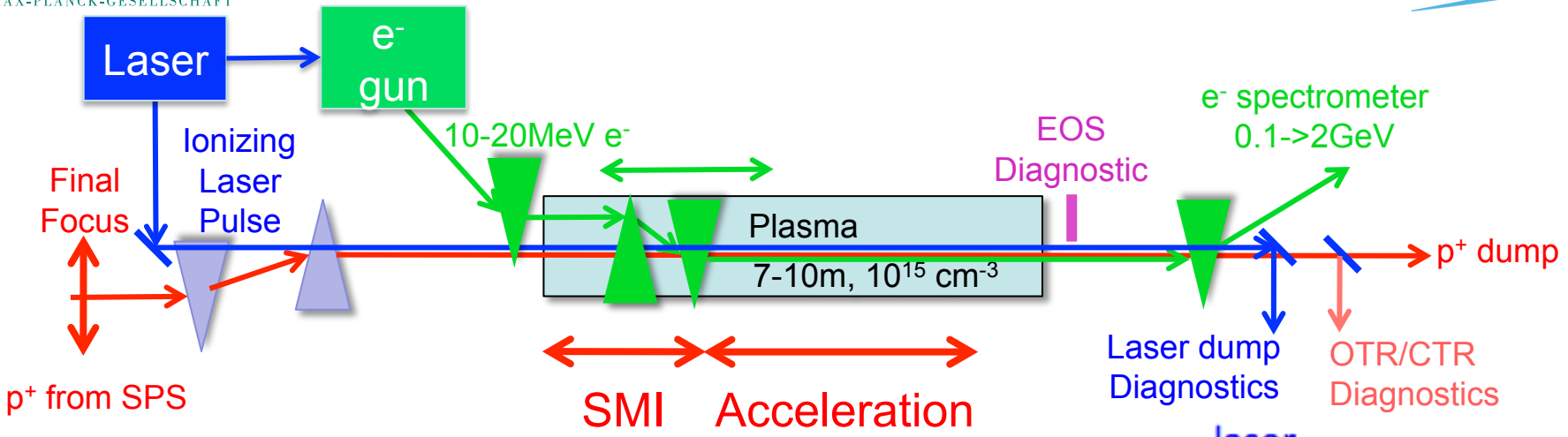
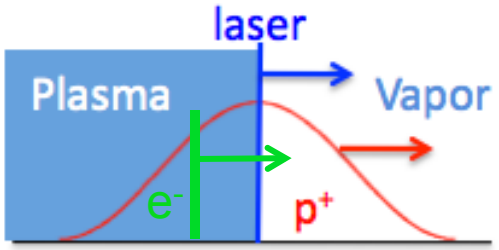
$n_e \sim 7 \times 10^{14} cm^{-3}$ ($k_p \sigma_r \approx 1$)
$\lambda_{pe} \sim 1.3mm << \sigma_z$
$f_{pe} \sim 240GHz$
$L_p \sim 5\text{-}10m$

- SPS beam: higher energy, lower σ_r^*, longer β^*
- Initial goal: ~GeV gain by externally injected e^-, in 5-10m of plasma in self-modulated p^+ driven PWFA

BASE-LINE EXPERIMENTAL SETUP





- Laser ionization of a metal vapor (Rb), 7-10m plasma, $n_e=10^{14}$-10^{15}cm^{-3} (E. Oz poster)
- Injection of 10-20MeV test e- at the 3-5m point (SMI saturated, $v_\phi=v_{p+}\sim c$)
- SMI-acceleration separated
- 0.1-5GeV electron spectrometer
- OTR + streak camera, electro-optic sampling for p$^+$-bunch modulation diag. (R. Tarkeshian, WG5 18:00)
- Additional optical diagnostics

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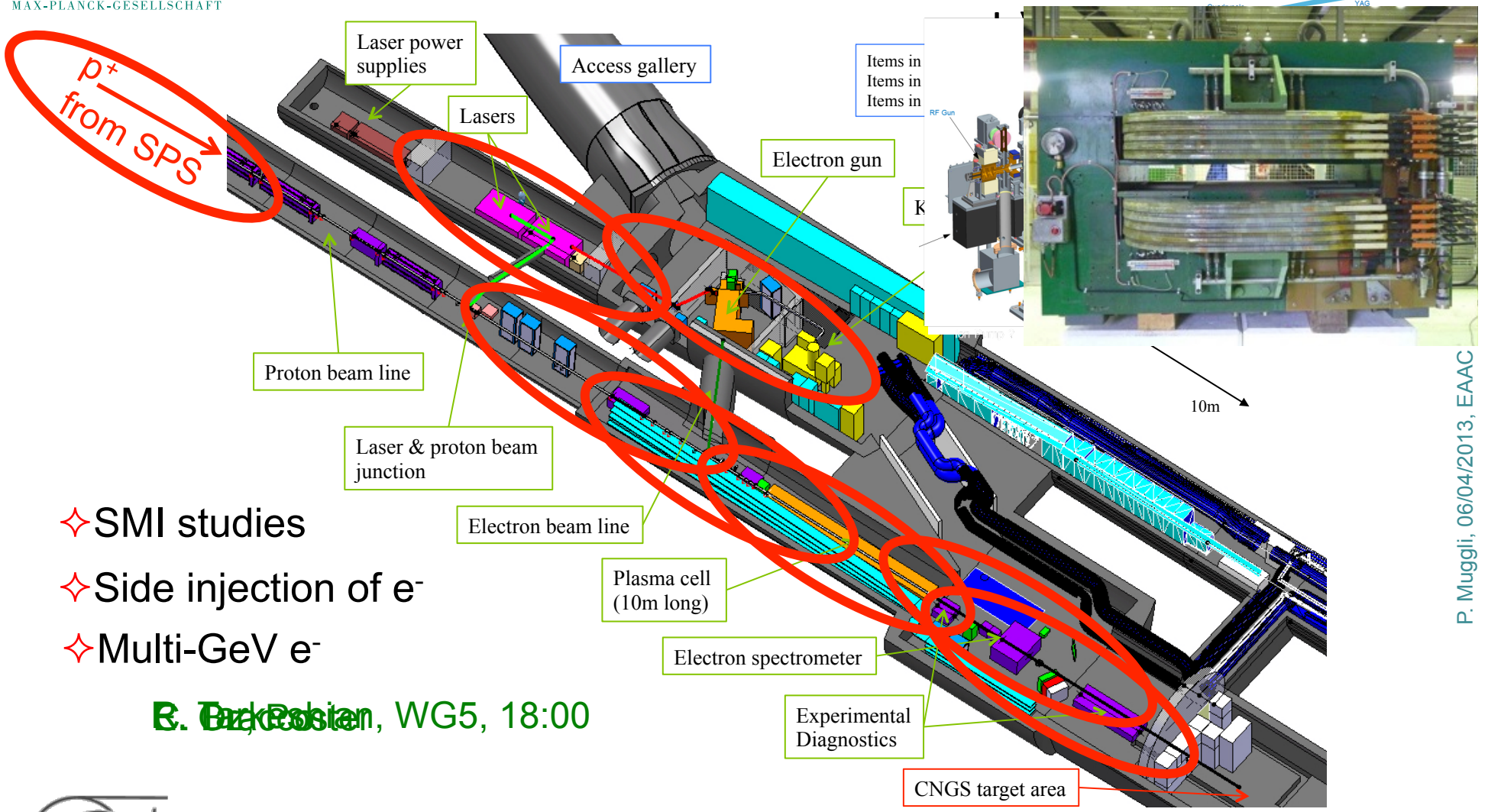
CNGS Experimental Area



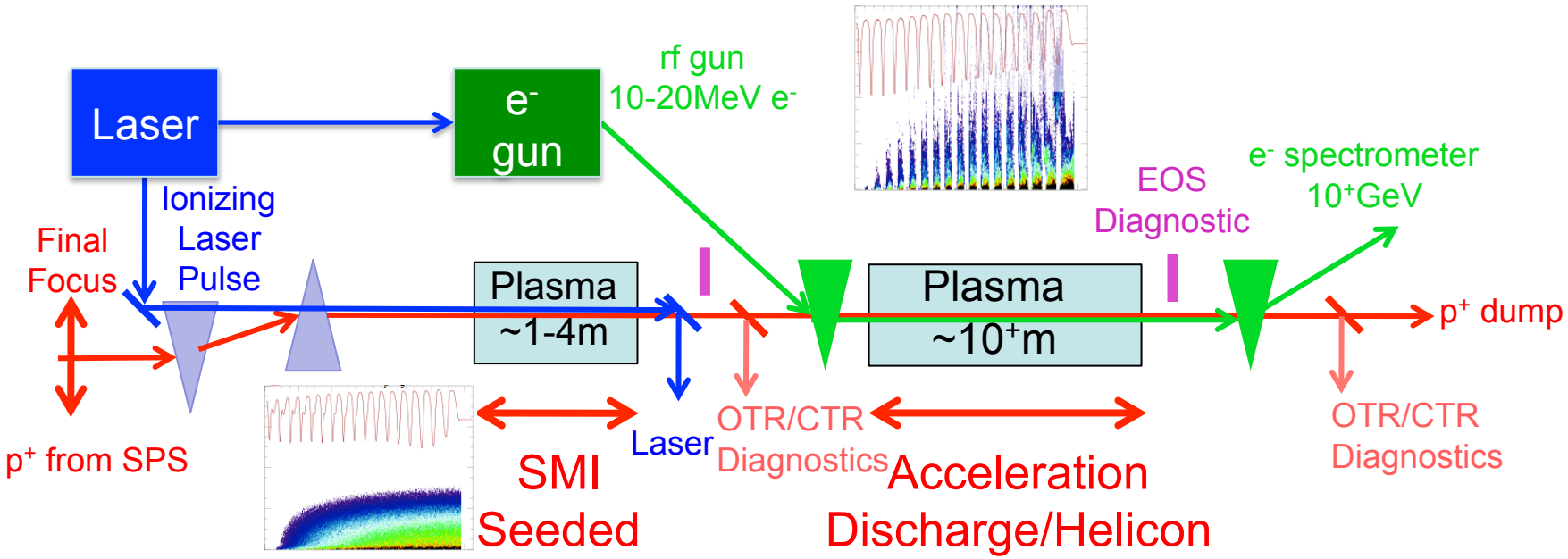
- SMI studies
- Side injection of e^-
- Multi-GeV e^-

R. Tarkeshian, WG5, 18:00

Edda Gschwendtner CERN Project Leader
Chiara Bracco, Ans Pardons, …

P. Muggli, 06/04/2013, EAAC

p⁺-PWFA Accelerator Physics



P. Muggli, 06/04/2013, EAAC 2103

- Laser ionization of a metal vapor (Rb),
  1-4m plasma for p⁺ self-modulation only, SEEDING NECESSARY!
- ~10m discharge or helicon source for acceleration only
- Beam loading, optimal injection, etc.
- Tune plasma densities to maintain accelerating gradient

GOALS OF AWAKE EXPERIMENT

- study the physics of p^+ bunch SMI (radial modulation, seeding, …)
- probe the longitudinal (accelerating) wakefields with externally injected e^-
- study injection dynamics (side or on-axis injection) of e^-
- produce multi-GeV e^- with ~GeV/m gradient maintained over m-distances
- develop long, scalable and uniform plasma cells
- develop schemes for the production and acceleration of short p^+ bunches
- Comprehensive program in advanced plasma-based accelerators

- "Feasibility Study of the AWAKE Facility at CERN", E. Gschwendtner
- "Primary Beam Lines for the AWAKE project at CERN", C. Bracco
- "a novel plasma source for beam driven wakefield acceleration", E. Oz
- "Electron injection into proton driven plasma wake-field for the AWAKE experiment at CERN", A. Petrenko
- "Proton bunch compression studies for the AWAKE experiment in the CERN SPS", H. Timko
- "THz diagnostics for the plasma density and charged particle self-modulation measurement in AWAKE experiments ", R. Tarkeshian
- "Challenges in Modeling Beam Driven Plasma Accelerators", J. Vieira
- "Collider design issues based on proton-driven plasma wakefield acceleration", G. Xia

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MAX-PLANCK-GESELLSCHAFT

AWAKE

Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating e^- on the wake of a p^+ bunch

SUMMARY

- High-energy (eV, J) p^+ bunches interesting as PWFA drivers (for e^- accel.)
- New approach: few stages (1?), driver recycling, large average gradient (~1GV/m?), operate at low n_e, relaxed parameters, …
- Very large energy gains possible in simulations (Caldwell, Nat. Phys. 5, 363, (2009), Caldwell, Phys. Plasma, 2011)
- Requires short p^+ bunches, very long plasmas
- Propose p-o-p experiments with long CERN-SPS bunches
- Operate in self-modulated regime to accelerate e^- to ~GeV in 5-10m
- Experiments in 2015, forming collaboration, defining setup, …
- CERN building a facility for p^+-driven PWFA and more …
- Long term program towards single p^+-bunch driver PWFA

ΞAAC 2103

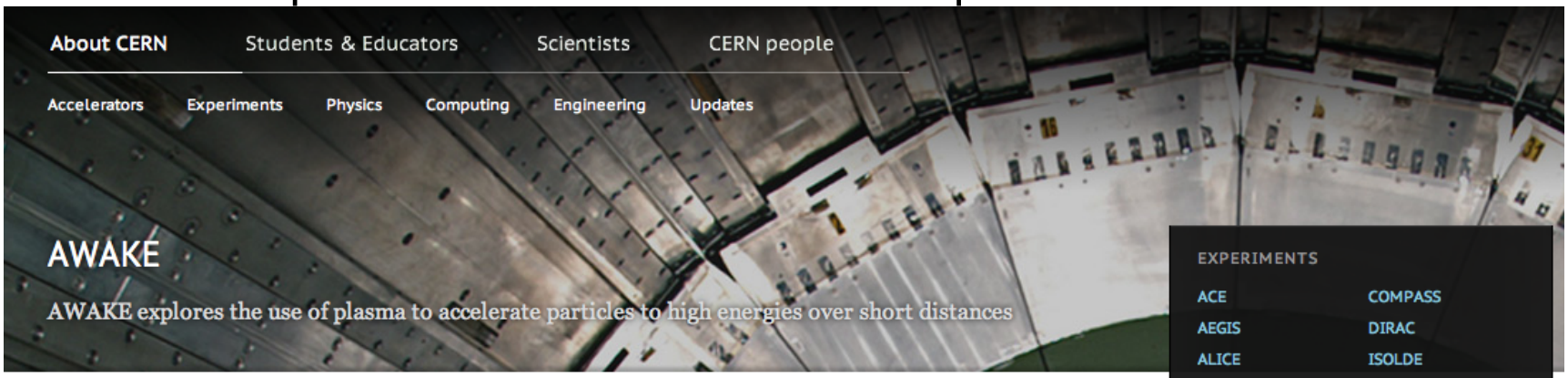
P. Muggli

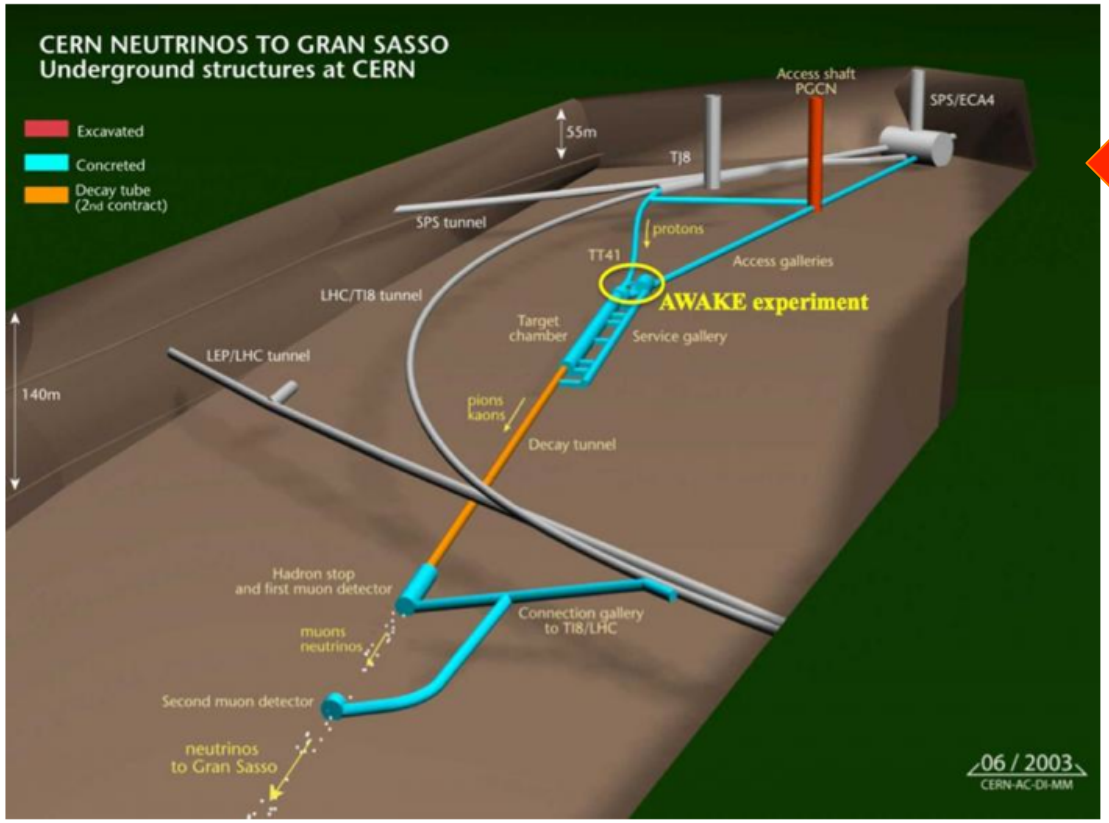
Thank you!

Thank you to the AWAKE Collaboration!

IF IT IS ON THE WEB …

http://home.web.cern.ch/about/experiments/awake





EXPERIMENTS

ACE	COMPASS
AEGIS	DIRAC
ALICE	ISOLDE
ALPHA	LHCb
AMS	LHCf
ASACUSA	MOEDAL
ATLAS	NA61/SHINE
ATRAP	NA62
AWAKE	nTOF
CAST	OSQAR
CLOUD	TOTEM
CMS	

PAST EXPERIMENTS

ALEPH	OPAL
DELPHI	UA1
L3	UA2

ABOUT CERN

About CERN
Computing
Engineering
Experiments
How a detector works
more →