A Proton-driven Plasma Wakefield Accelerator Experiment with CERN SPS Bunches

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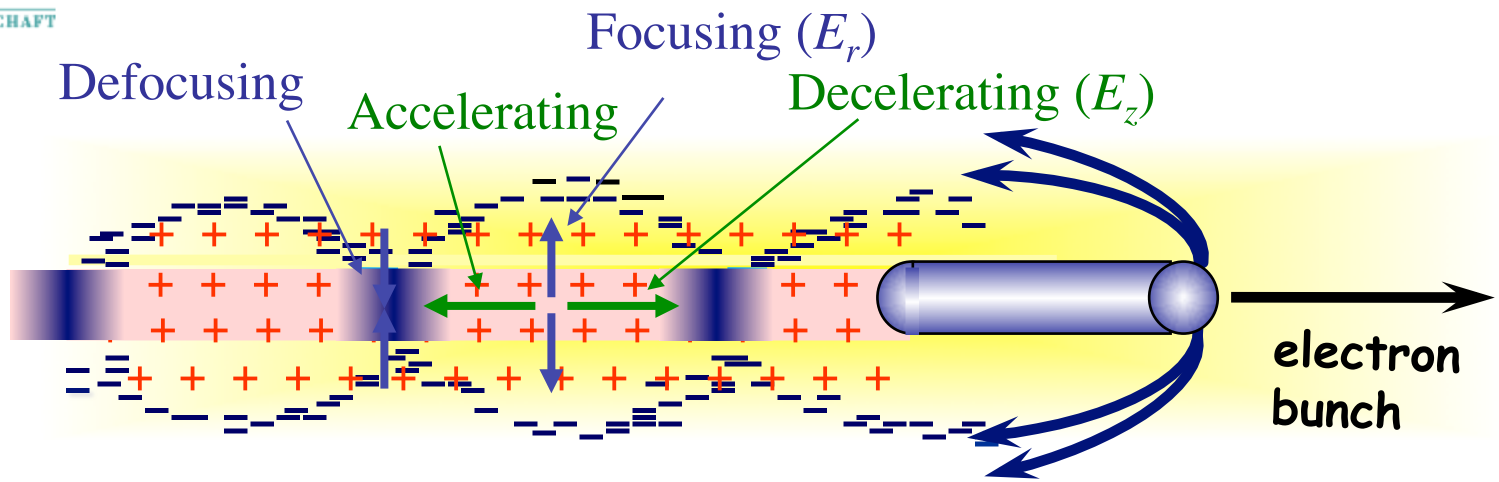
for the
Proton-driven Plasma Wakefield Acceleration Collaboration

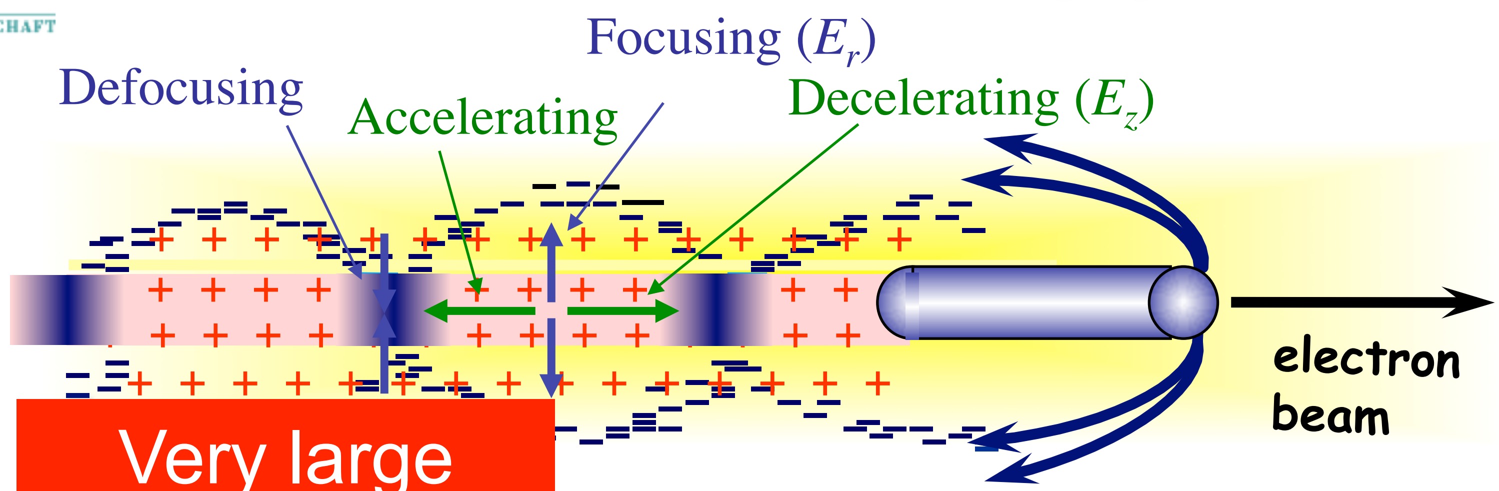
PLASMA WAKEFIELDS (e^-)



- 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 $\sim n_e^{1/2}$, $1/\sigma_z$, GV/m
- Ultra-relativistic driver => Ultra-relativistic wake
  => no dephasing (…)
- Particle bunches have long "Rayleigh lengths
  (beta function $\beta^*=\sigma^2/\varepsilon\sim$cm, m)
- Acceleration physics identical PWFA, LWFA

MAX-PLANCK-GESELLSCHAFT

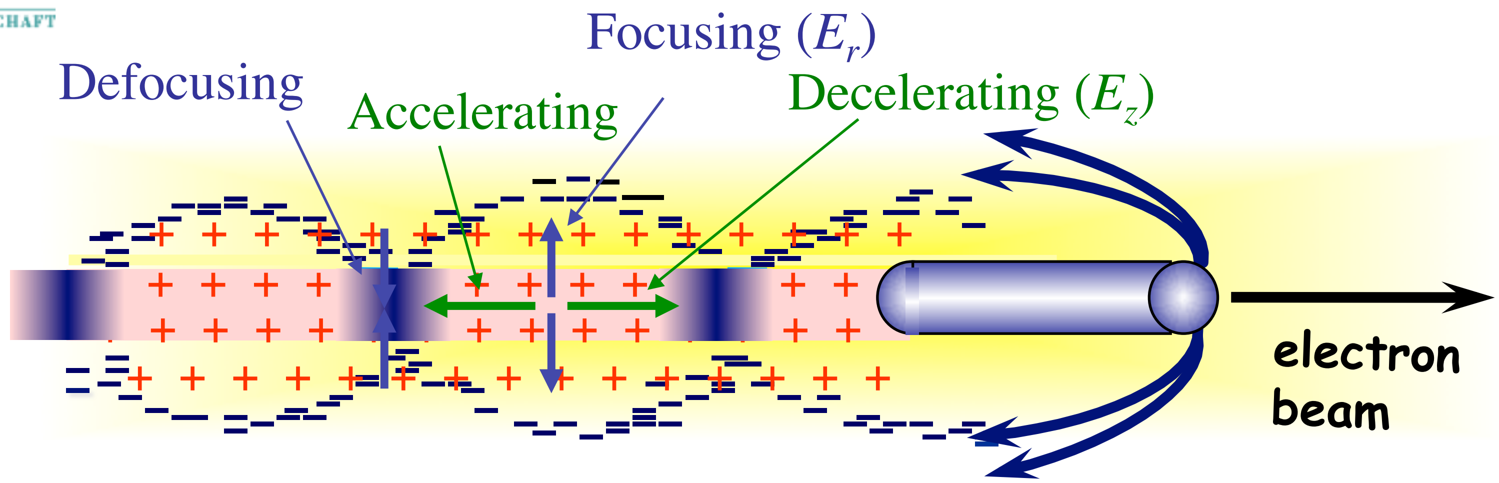
PLASMA WAKEFIELDS (e^-)



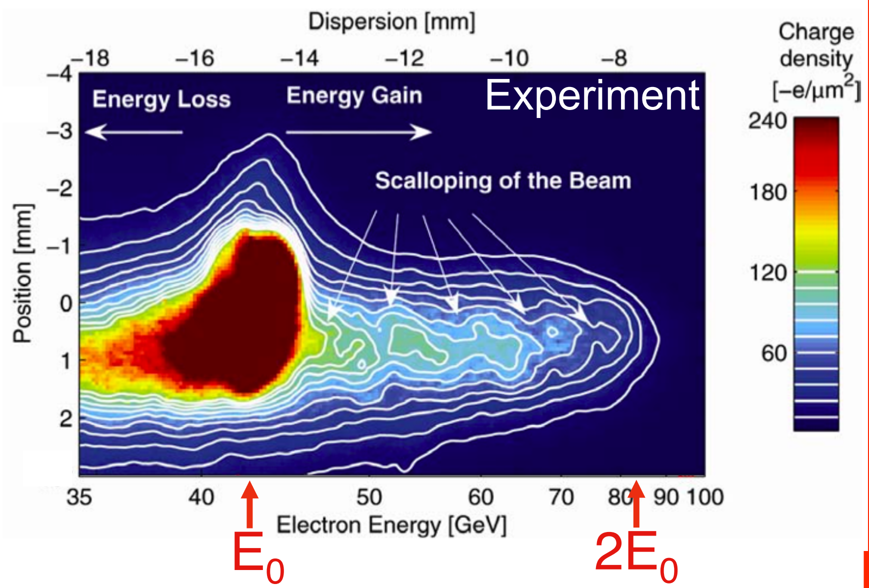
Very large energy gain possible with high-energy bunches!

- Plasma … a relativistic particle bunch
- Plasma … charge force => deceleration + focusing (MT/m)
- Plasma … => acceleration ~$n_e^{1/2}$, $1/\sigma_z$, 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^-)



Blumenfeld *et al.*, Nature 445, 2007



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

ivistic particle bunch

forces => deceleration + focusing

=> acceleration

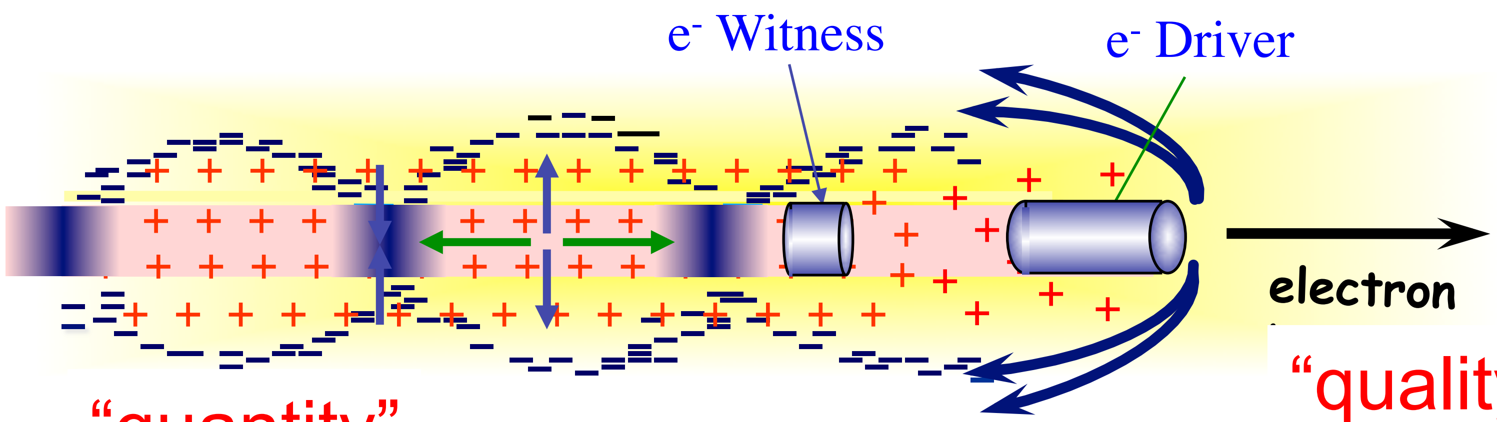
ivistic wake

sing (…)

lengths”

LWFA

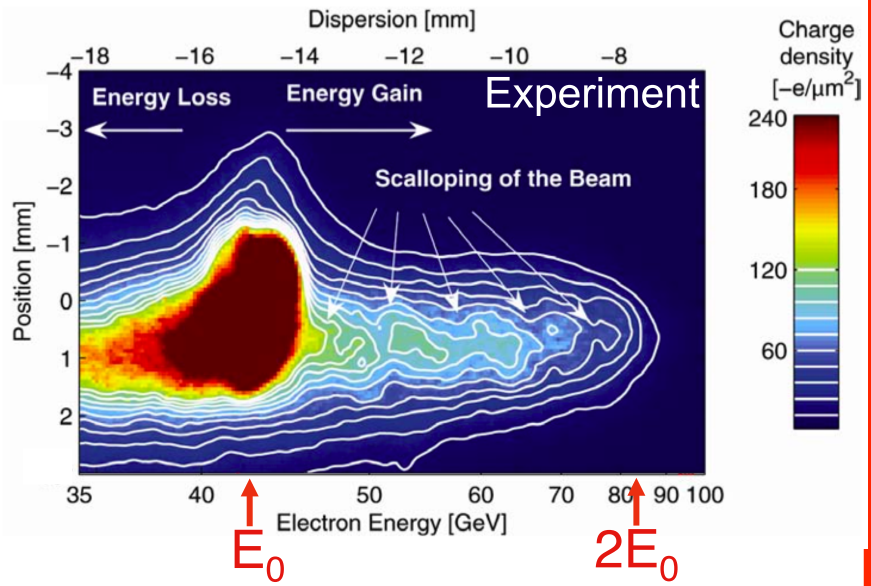
PLASMA WAKEFIELDS (e^-)



"quantity"

"quality"

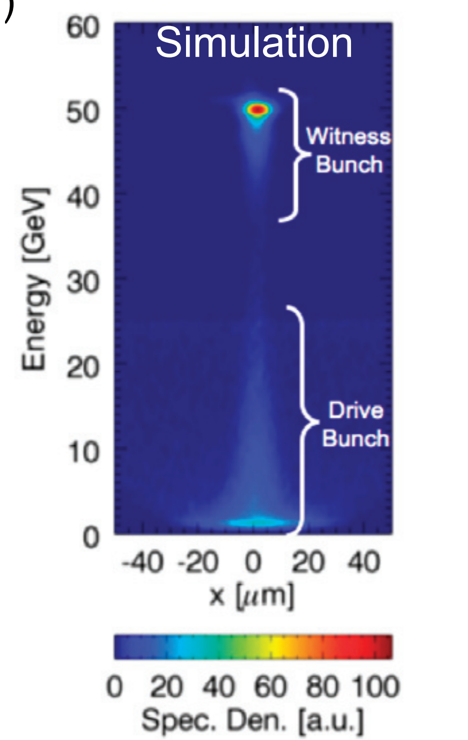
Blumenfeld, Nature 445, 2007



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

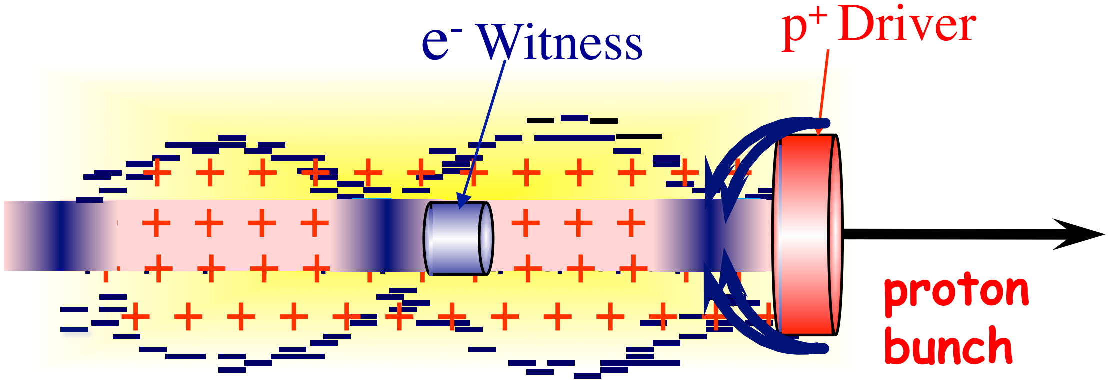
SLAC FACET

Hogan, NJP 12, 2010



LWFA

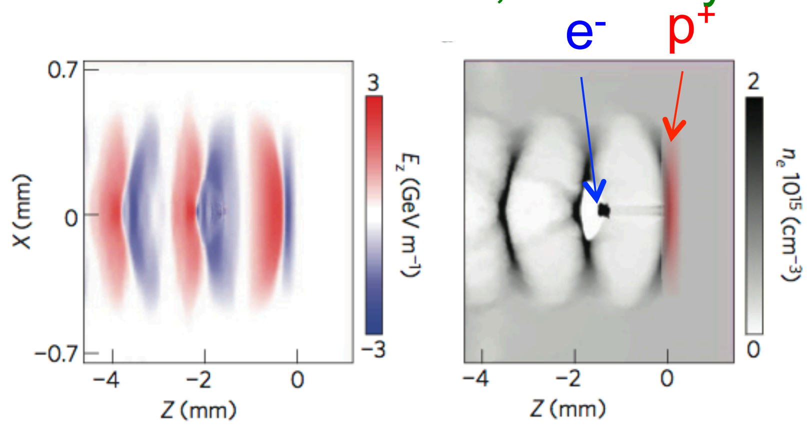
PROTON-DRIVEN PLASMA WAKEFIELDS (p^++e^-)

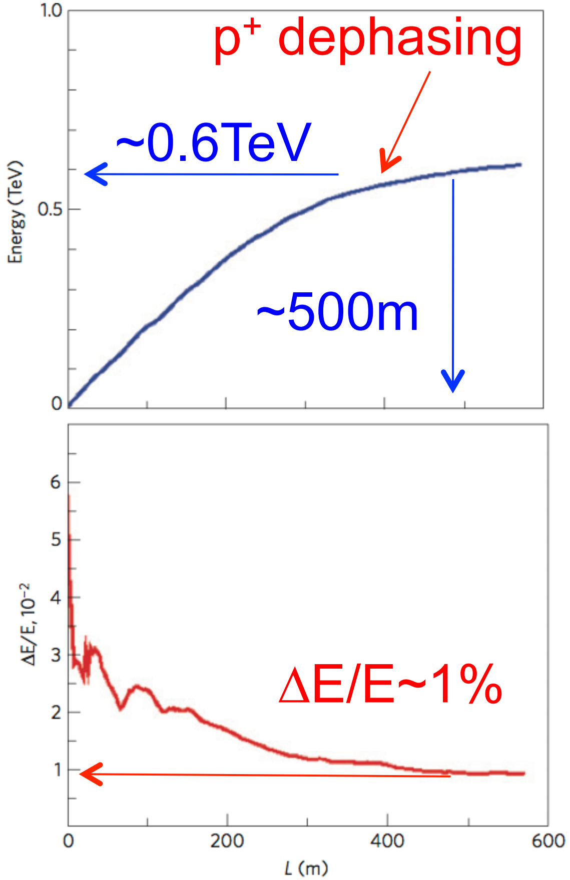


- SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J
  ILC, 0.5TeV bunch with $2x10^{10}e^-$ ~1.6kJ
- SLAC-like driver for staging (FACET= 1 stage, collider 50^+ stages)
- SPS, 450GeV bunch with $10^{11}p^+$ ~7.2kJ
  LHC, 7TeV bunch with $10^{11}p^+$ ~112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- Large <u>average</u> gradient! (~1GeV/m, 100's m)

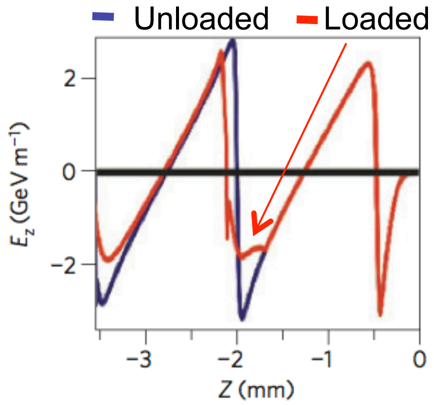
PROTON-DRIVEN PWFA

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





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



- Use "pancake" p^+ bunch to drive wakefields (cylinder for e^- driver)
- Loaded gradient ~1.5GV/m, efficiency ~ 10% (recycling?)
- ILC-like e^- bunch from a single p^+-driven PWFA
- σ_z≈100μm do not exist!

SELF-MODULATION INSTABILITY (SMI)

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

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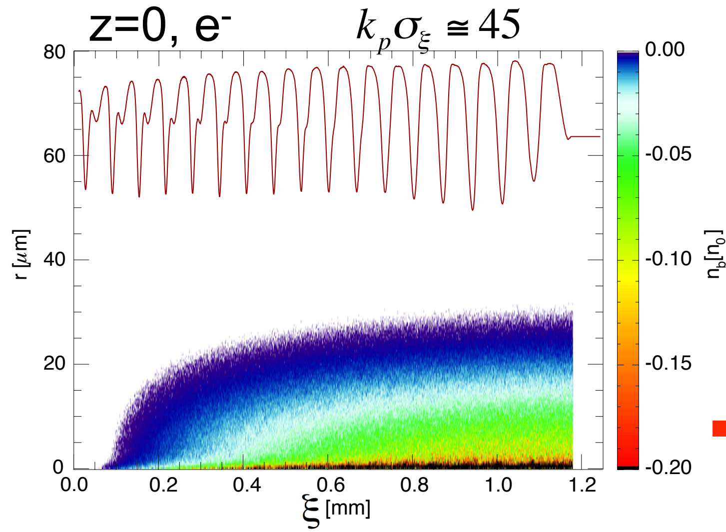
Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia
(Received 16 April 2010; published 25 June 2010)

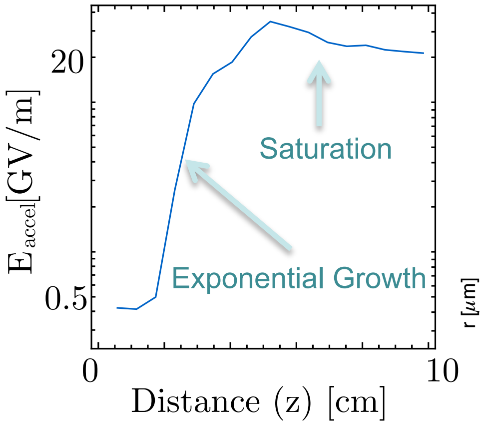
An analytical model for the self-modulation instability of a long relativistic proton bunch propagating in uniform plasmas is developed. The self-modulated proton bunch resonantly excites a large amplitude plasma wave (wakefield), which can be used for acceleration of plasma electrons. Analytical expressions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

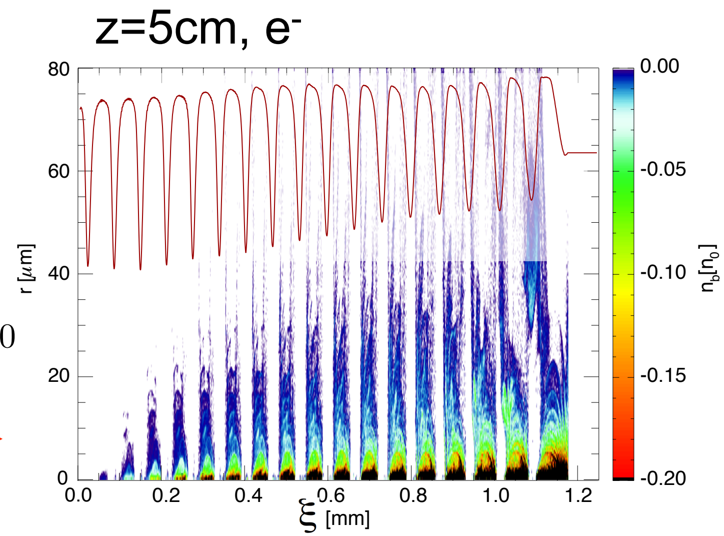
DOI: 10.1103/PhysRevLett.104.255003 PACS numbers: 52.35.−g, 52.40.Mj, 52.65.−y

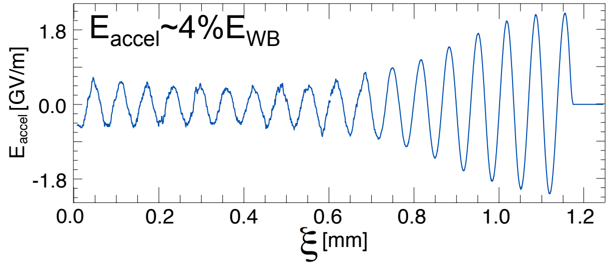
- Idea developed "thanks" to the non-availability of short p^+ bunches
- Very similar to Raman self-modulation of long laser pulses (LWFA of the 20^{th} century)

SELF-MODULATION INSTABILITY (SMI)

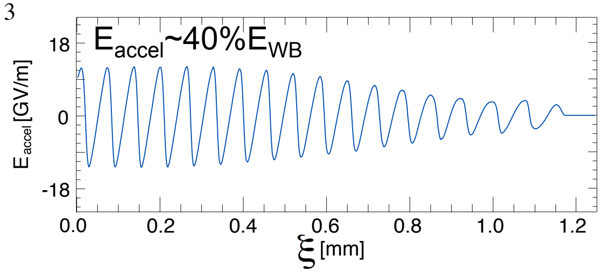








$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



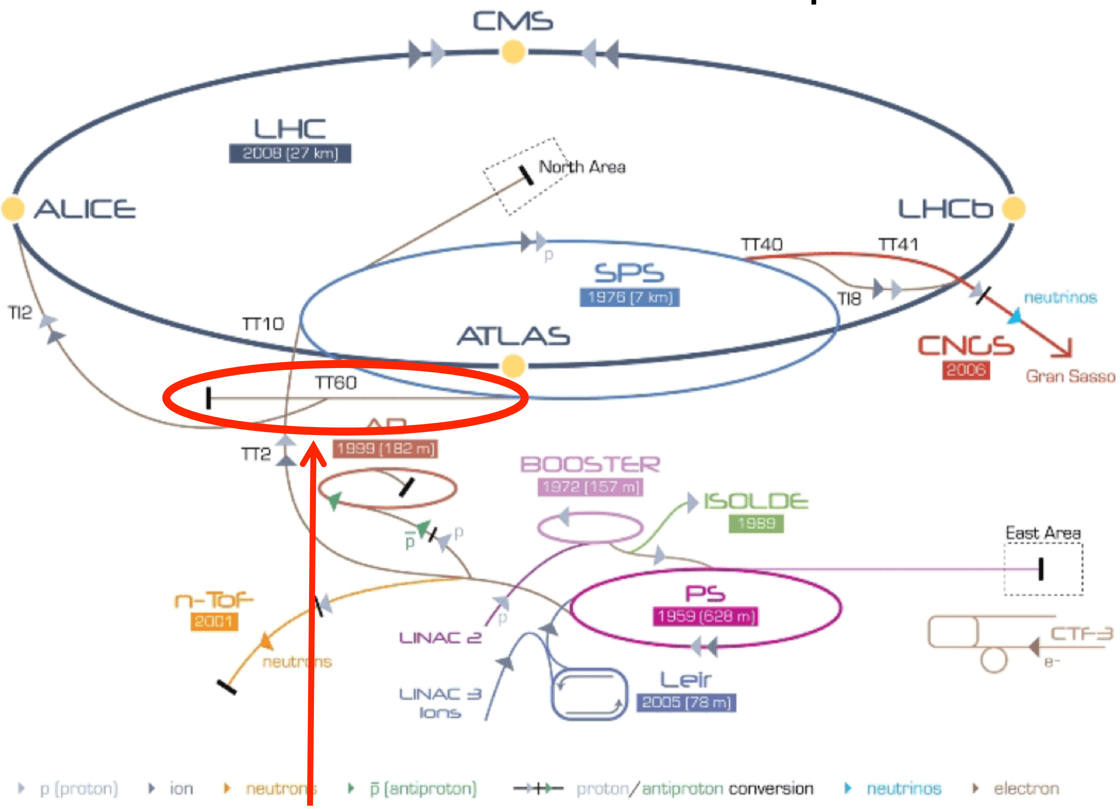
Grows along the bunch & along the plasma
Convective instability

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

- Initial small transverse wakefields modulate the bunch density
- Associated longitudinal wakefields reach large amplitude through resonant excitation: ~$E_{WB}=mc\omega_{pe}/e$~46GV/m @ $n_e=2.3\times10^{17}cm^{-3}$
- Acceleration of an injected witness bunch

PROTON BEAMS @ CERN

CERN Industrial Beam Complex



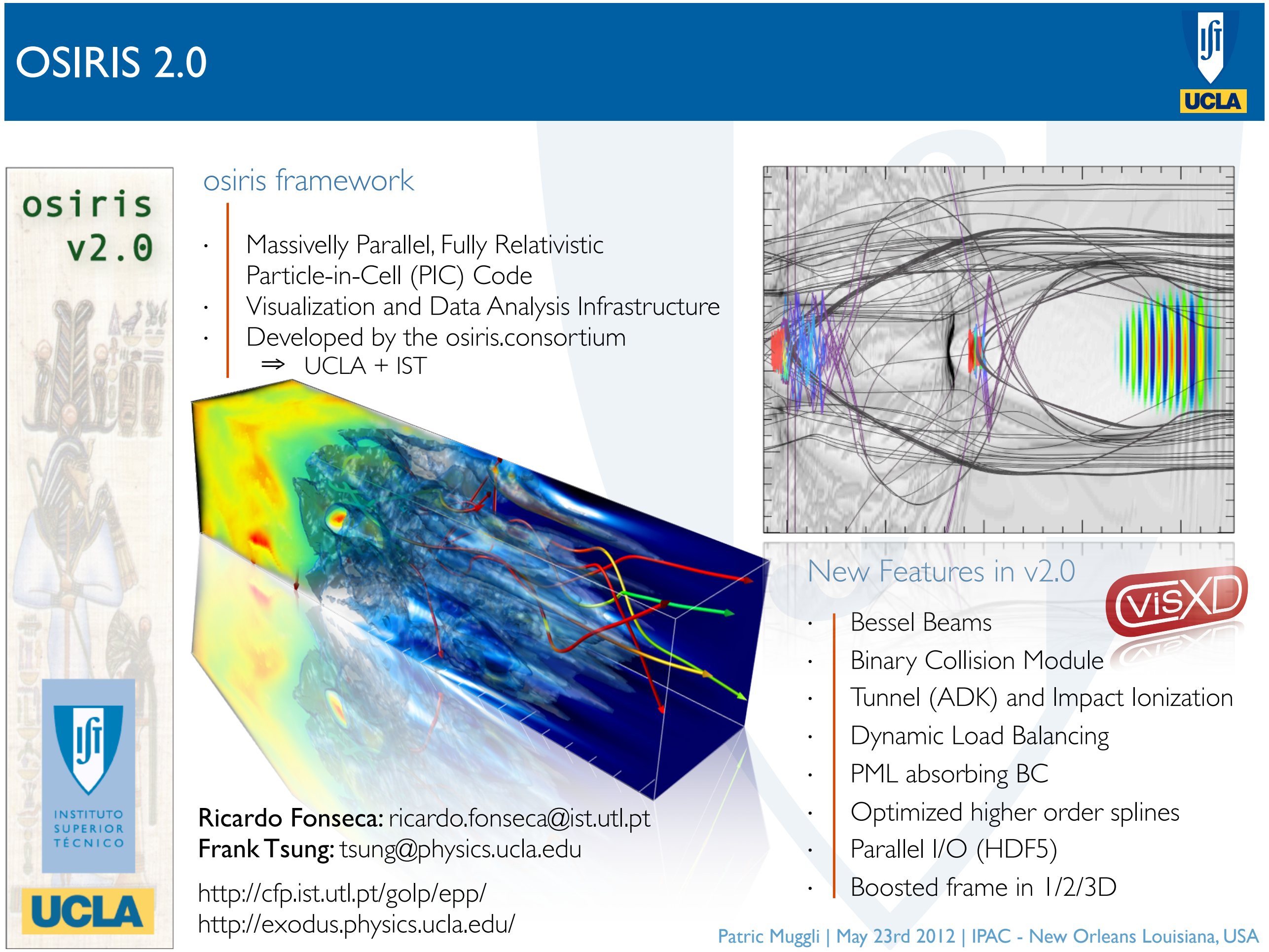
Parameter	PS	SPS	SPS Opt
E_0 (GeV)	24	450	450
N_p (10^{10})	13	10.5	30
$\Delta E/E_0$ (%)	0.05	0.03	0.03
σ_z (cm)	20	12	12
ε_N (mm-mrad)	2.4	3.6	3.6
σ_r^* (µm)	400	200	200
β^* (m)	1.6	5	5

L_p~5-10m
n_e~7×10^{14}cm^{-3} ($k_p\sigma_r\approx1$)
λ_{pe}~1.3mm<<σ_z
f_{pe}~240GHz

TT61, West area, ~600m tunnel + experimental area

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

Proton-driven PWFA Simulations



- VLPL A. Pukhov, J. Plasma Phys. 61, 425 (1999)
- LCODE, K. V. Lotov, Phys. Rev. ST Accel. Beams 6, 061301 (2003)

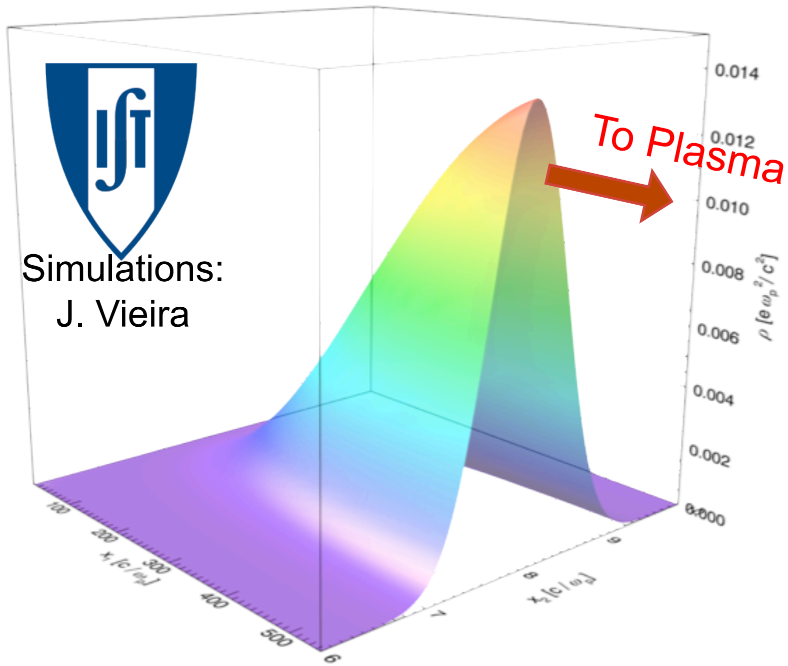
PROTON-DRIVEN PWFA @ CERN

- Self-modulation of long (~12cm~100λ_{pe}), 450GeV SPS bunch
- OSIRIS 2D simulations

Proton bunch	Electron bunch
$\sigma_{\|\|}$ = 12 cm $\sigma_{\perp}$= 200 μm N = 11.5x10^{10} (30.0x10^{10}) n_b/n_0 = 0.00217 (linear PWFA) γ = 479.6	$\sigma_{\|\|}$ = 100 mm (very long) $\sigma_{\perp}$= 200 μm n_b/n_0 = 1.32x10^{-7} γ = 20 (10 MeV)

Plasma	Box
n_0 = 7x10^{14} cm^{-3} λ_p= 1.2 mm ~ $\sigma_{\|\|}$ /100 Uniform density Immobile ions Length = up to15 meters	$n_{\perp}$ = 425 cells $n_{\|\|}$ = 18000 cells 4 particles per cell quadratic splines

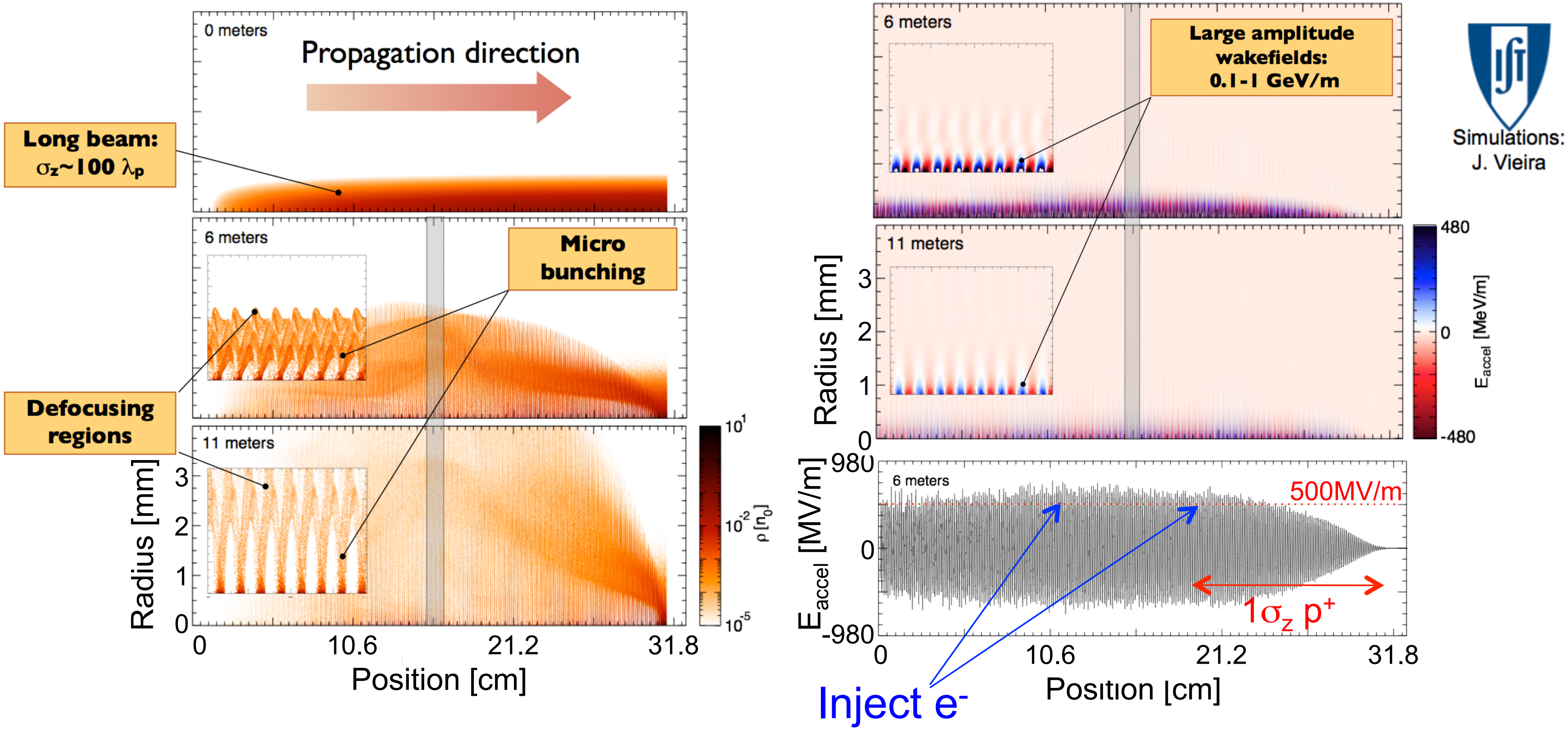
Simulations:
J. Vieira



- Simulations include seeding of the instability (cut p^+ bunch, short ionizing laser pulse)
- Long, test-particle e^- witness bunch

PROTON-DRIVEN PWFA @ CERN

❒ SMI of long (~12cm), 450GeV SPS bunch @ $\lambda_{pe}\approx$1.2mm



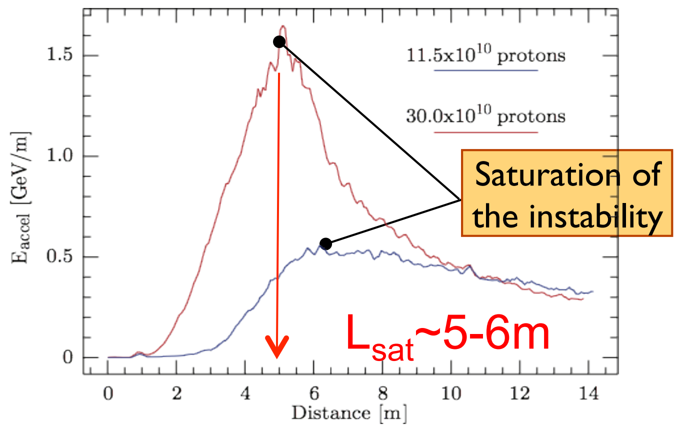
❒ Drives large amplitude (0.1-1GV/m) accelerating fields

❒ E_z (acceleration) sampled by injecting (~10MeV) e^- bunch

PROTON-DRIVEN PWFA @ CERN

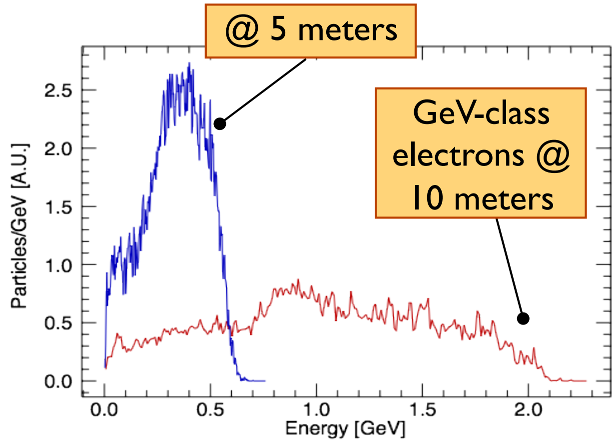
- SMI of long (~12cm), 450GeV SPS bunch @ λ_{pe}

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)

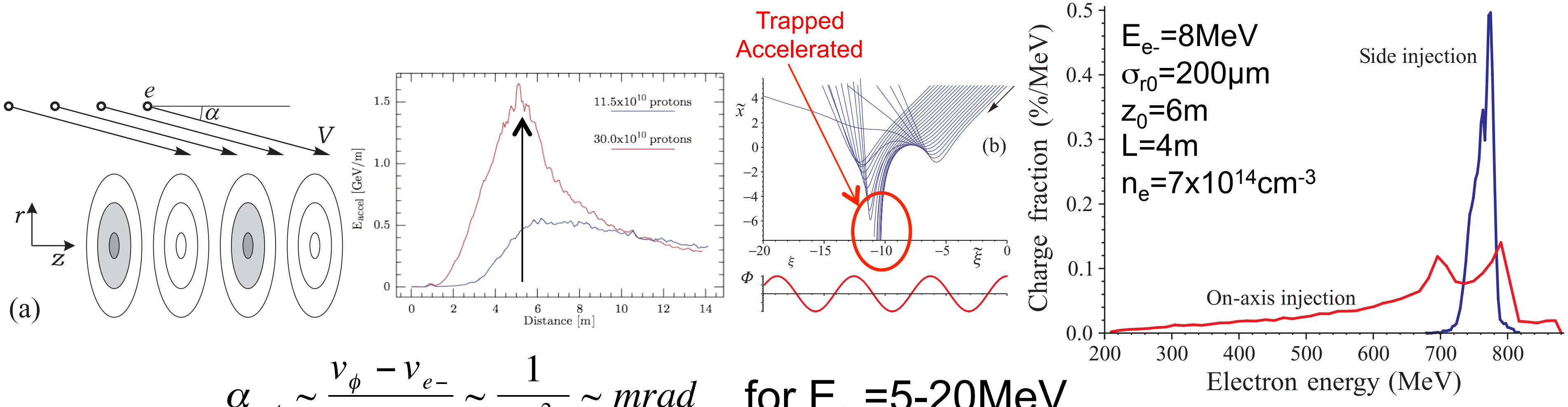
Test e^-s

- Growth of instability / p^+ density modulation / E_z
- Injected e^- gain ~1-2GeV in 5-7m plasma
- Injected of short e^- bunch would produce narrow $\Delta E/E$
- Preserve large E_z by changing n_e (K. Lotov)

e^- SIDE INJECTION

Lotov, J. Plasma Phys. (2012)

- Low energy test e- injected sideways are trapped and bunched



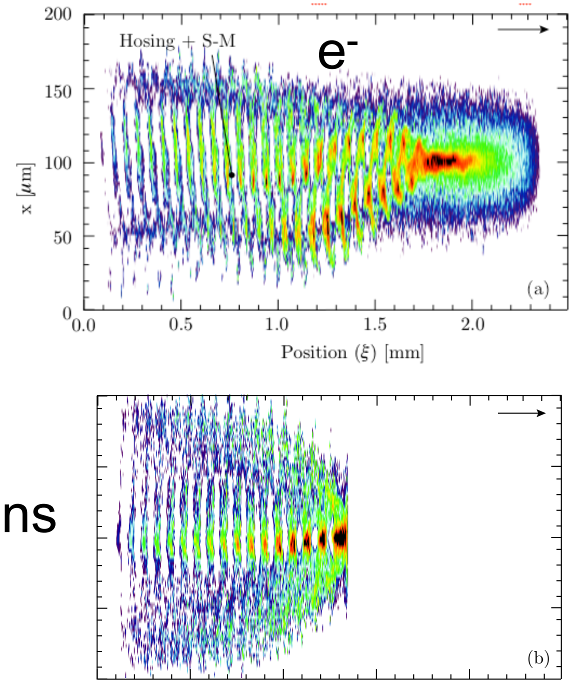
$$\alpha_{opt} \sim \frac{v_\phi - v_{e-}}{c} \sim \frac{1}{2\gamma_{e-}^2} \sim mrad$$

for E_{e-}=5-20MeV

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

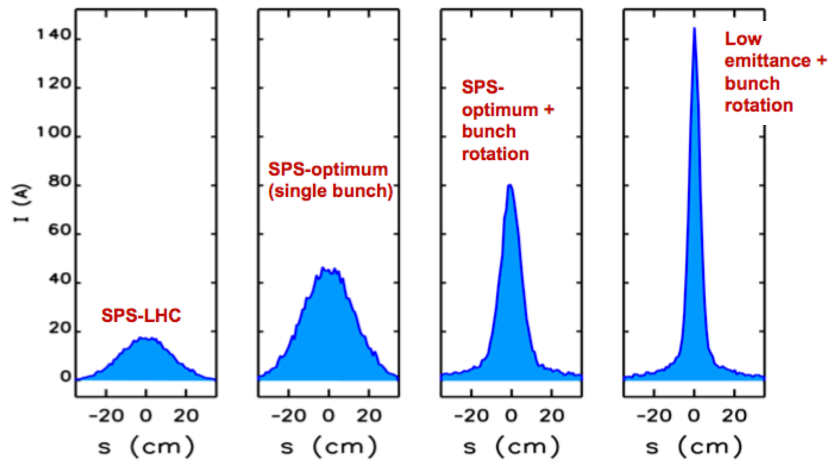
CHALLENGES WITH PROTON-DRIVEN PWFA

- Hosing instability ($\sigma_z >> \lambda_{pe}$):
  - Seeding favors SMI over hosing
  - Computational challenge, need 3D



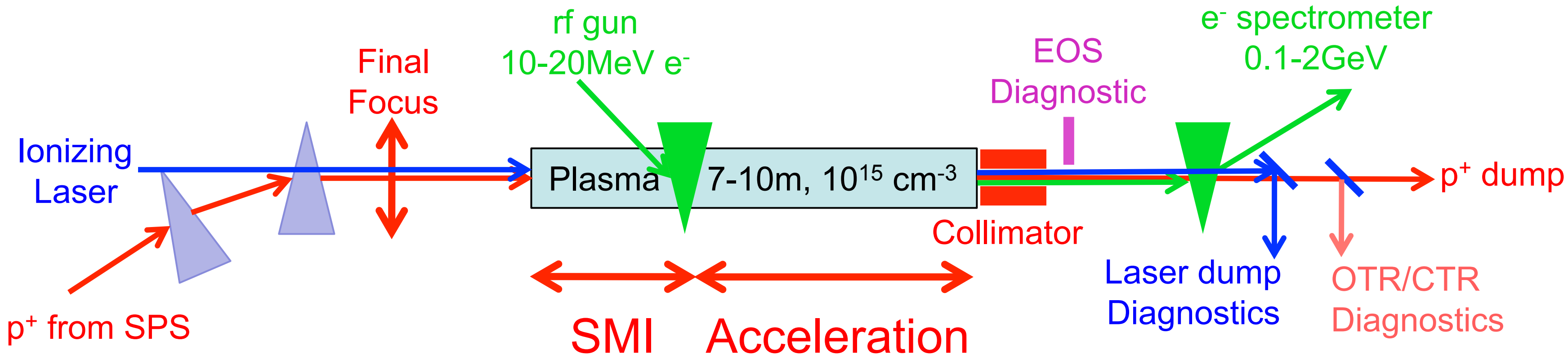
- Plasma density uniformity:
  - $\sigma_z >> \lambda_{pe}$ => resonant excitation, $\delta\omega \sim \omega_{pe}/N$
  - Dephasing of low energy side injected electrons
  - Require $\delta n_e/n_{e0} \sim 0.1\%$

- In-ring compression of p^+ bunch (x4, A. Petrenko)

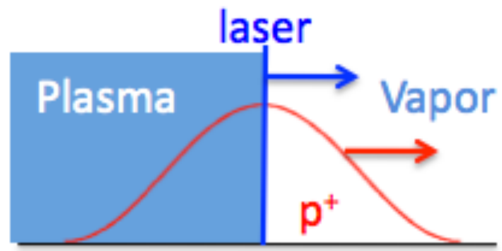


- Larger wakefield
- Reach nonlinear PWFA regime?

BASE-LINE EXPERIMENTAL SETUP

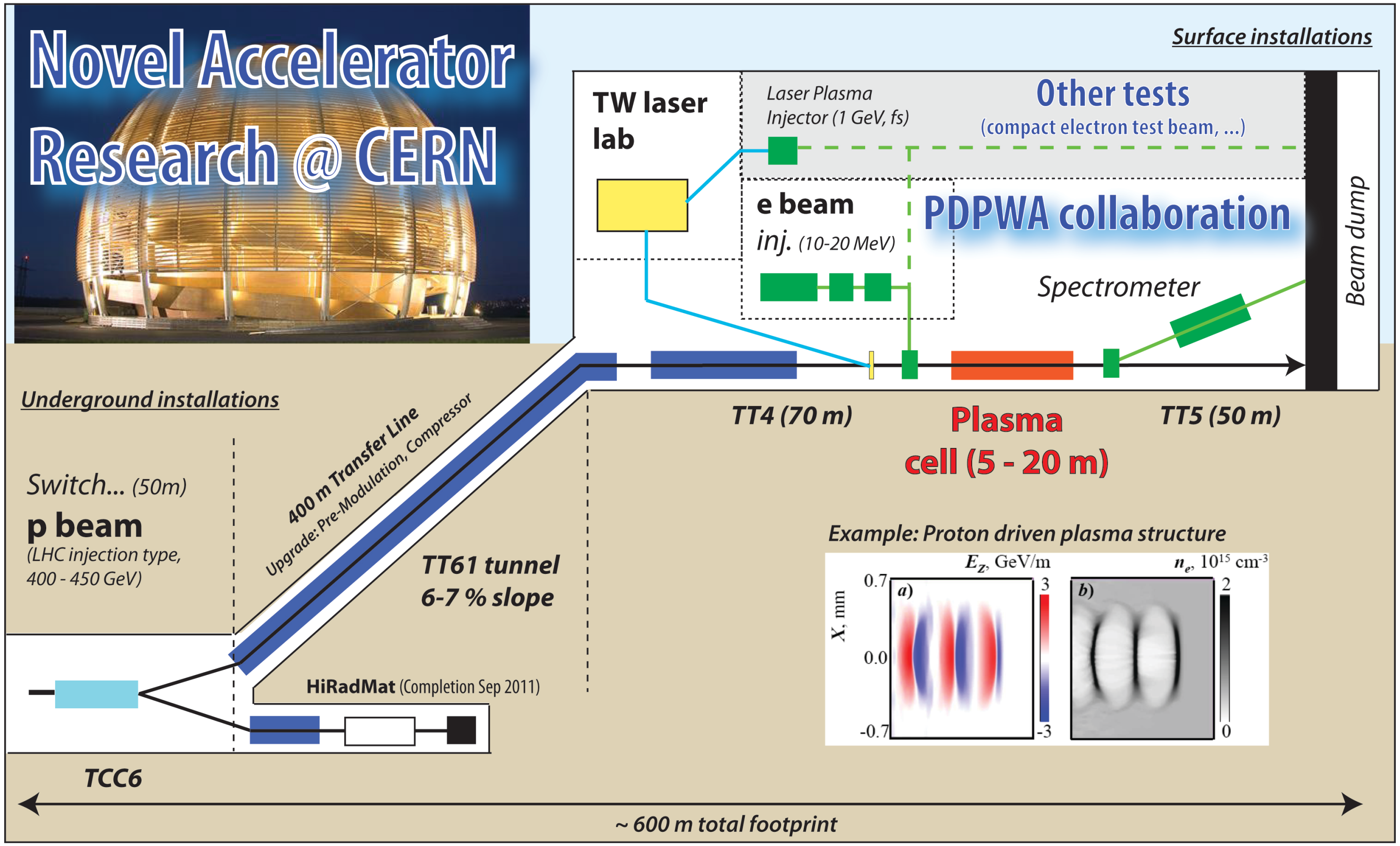


- Laser ionization of a metal vapor (Li, Rb, etc.), 7-10m plasma, $n_e=10^{14}-10^{15}cm^{-3}$



- Injection of 10-20MeV test e- at the 3m point (SMI saturated, $v_\phi=v_{p+}$)
- ISM-acceleration separated
- 0.1-2GeV electron spectrometer
- OTR + streak camera, electro-optic sampling for p^+-bunch modulation diag.
- Additional optical diagnostics

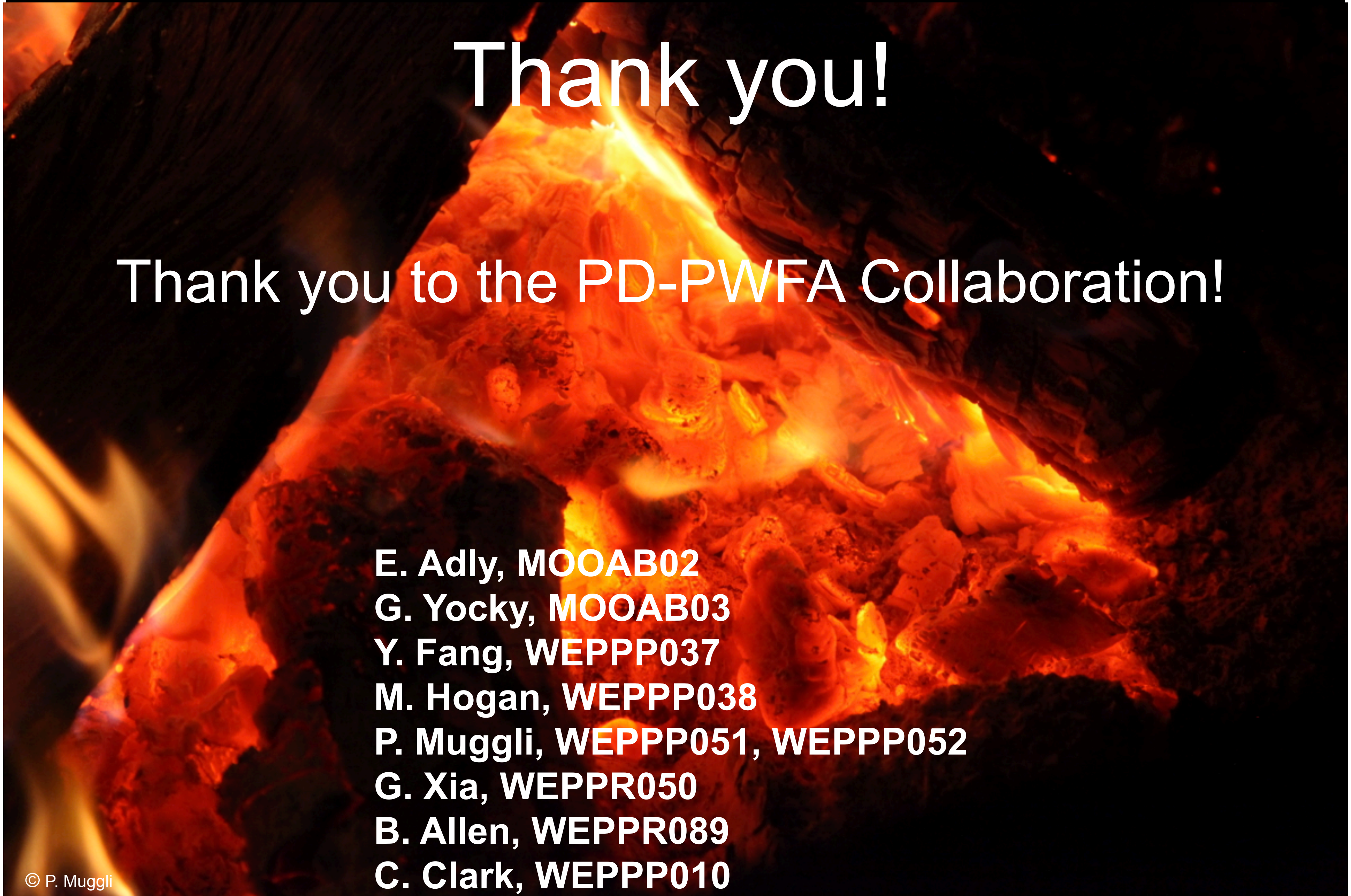
PROTON-DRIVEN PWFA @ CERN



- Conceptual design report due end of 2012
- Experiments 2015-… for ~GeV energy gain in SMI regime
- Program for TeV class e- from p^{+}-driven PWFA, driven by MPP
- International collaboration: CERN, Germany, UK, Russia, Portugal, USA, …

SUMMARY

- High-energy (eV, J) p^+ interesting as PWFA drivers (for e^- acceleration)
- New approach: few stages (1?), driver recycling, …
- Maintain large average gradient (~1GV/m), operate at low n_e, …
- Very large energy gains possible in simulations (Caldwell, Phys. Plasma, 2011)
- Require 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
- SMI in linear PWFA regime, good for e^+ acceleration …
- Experiments in 2015, forming collaboration, defining setup, …
- CERN building a facility for p^+-driven PWFA and more …



Thank you!

Thank you to the PD-PWFA Collaboration!

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G. Xia, WEPPR050
B. Allen, WEPPR089
C. Clark, WEPPP010
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