Plasma Wakefield Acceleration and the AWAKE Project at CERN

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OUTLINE

- Introduction to Plasma Wakefield Accelerator (PWFA)
- Introduction to the self-modulation instability (SMI)
- SMI experiments at SLAC E209 with e^-/e^+
- SMI PWFA experiments at CERN with p^+ : AWAKE
- Summary

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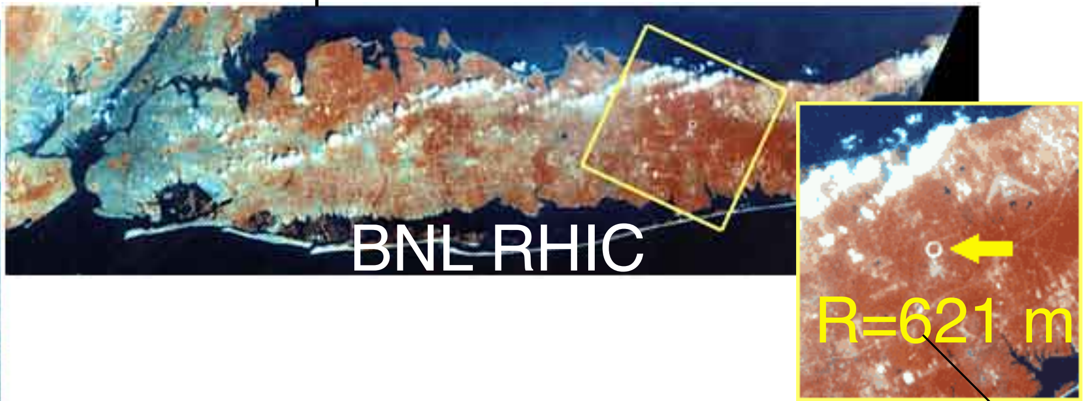
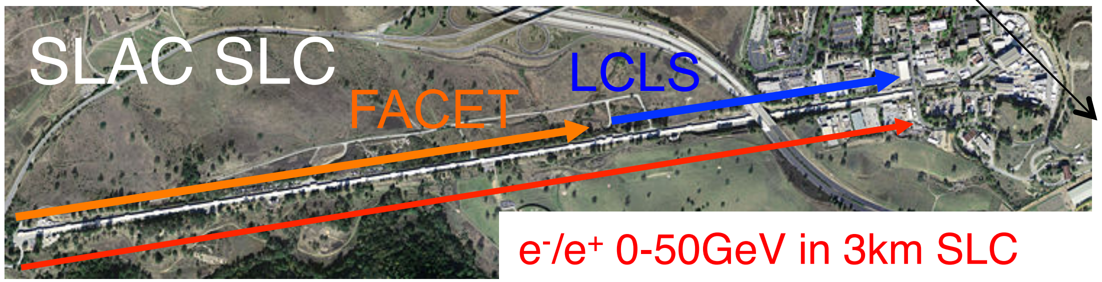
Particle Accelerators

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"



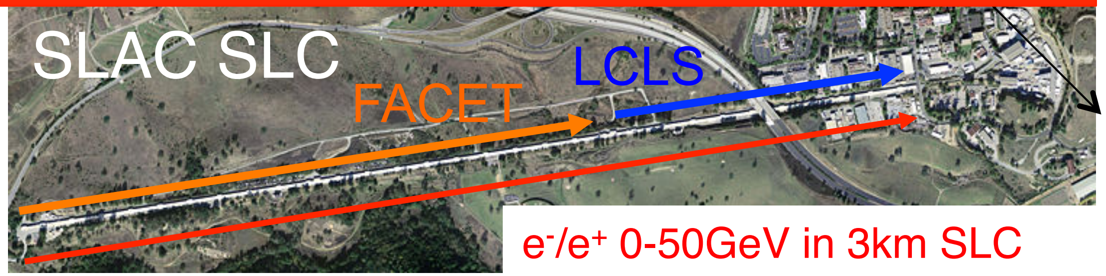


e^-/e^+ 0-50GeV in 3km SLC
e^-/e^+ 0-23GeV in 2km FACET
e^- 0-14GeV in 1km LCLS

- Some of the largest and most complex (and most expensive) scientific instruments ever built!
- All use rf technology to accelerate particles
- Can we make them smaller (and cheaper) and with a higher energy?

PARTICLE ACCELERATORS

Could plasmas be used to accelerate particles at high-gradient (>100MeV/m) and reduce the size and cost of a future linear e^-/e^+ collider or of an x-ray FEL?



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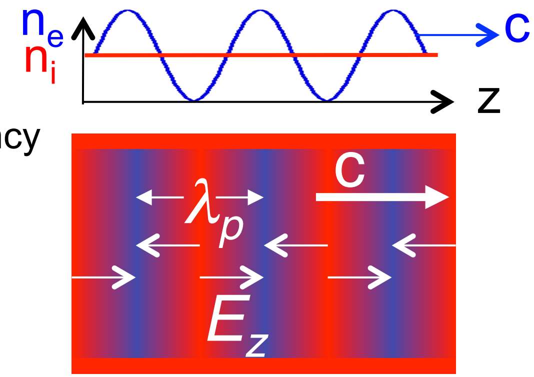
WHAT ABOUT PLASMAS?

- Relativistic Electron Electrostatic Plasma Wave (Electrostatic, E_z):

$$\vec{\nabla}\cdot\vec{E} = \frac{\rho}{\varepsilon_0} \qquad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0} \qquad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$$

Plasma Frequency



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

Cold Plasma "Wavebreaking" Field

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

LARGE

Collective response!

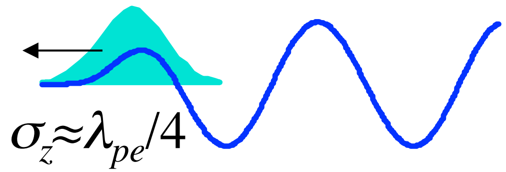
- Plasmas can sustain very large (collective) E_z-field, acceleration
- Wave, wake phase velocity = driver velocity (~c when relativistic)
- Plasma is already (partially) ionized, difficult to "break-down"
- Plasmas wave or wake can be driven by:
  - Intense laser pulses (LWFA)
  - Short particle bunch (PWFA)

4 PLASMA ACCELERATORS*

- Plasma Wakefield Accelerator (PWFA)

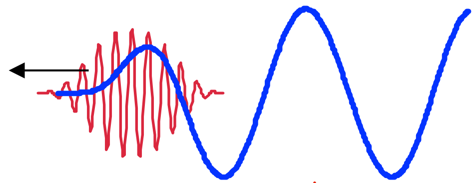
  A high energy particle bunch (e^-, e^+, ...)

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



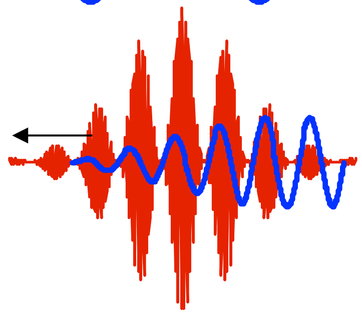
- Laser Wakefield Accelerator (LWFA)

  A short laser pulse (photons, ponderomotive)



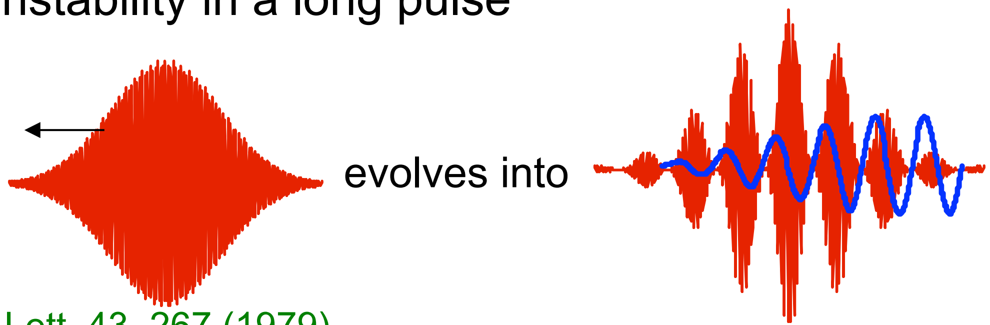
- Plasma Beat Wave Accelerator (PBWA)

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



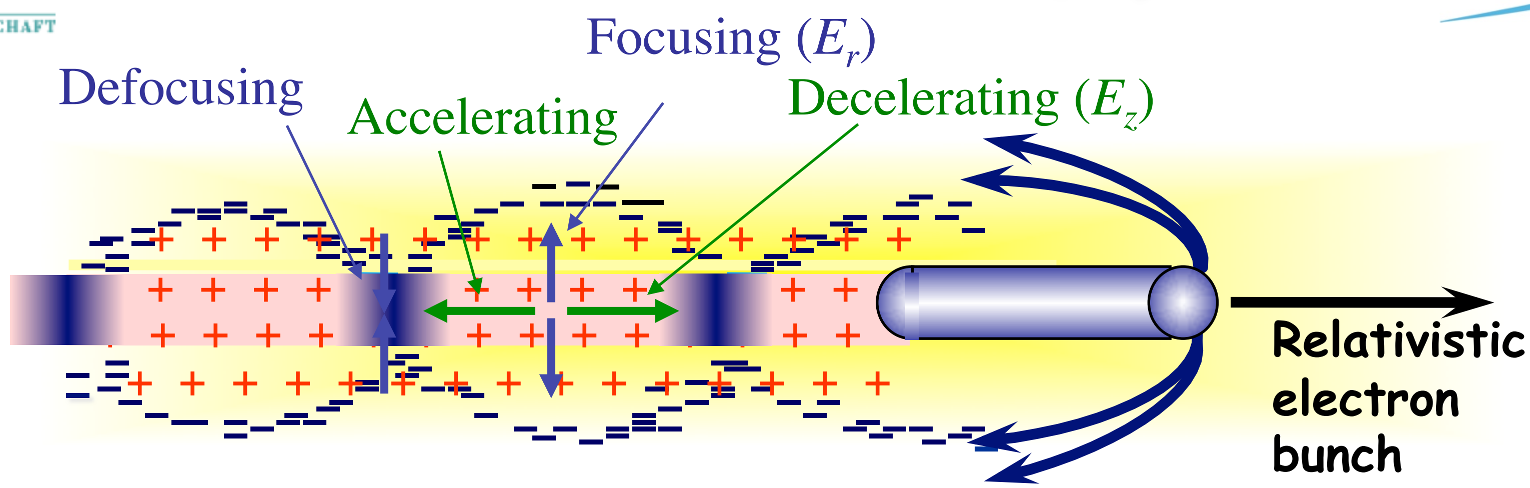
- Self-Modulated Laser Wakefield Accelerator (SMLWFA)

  Raman forward scattering instability in a long pulse



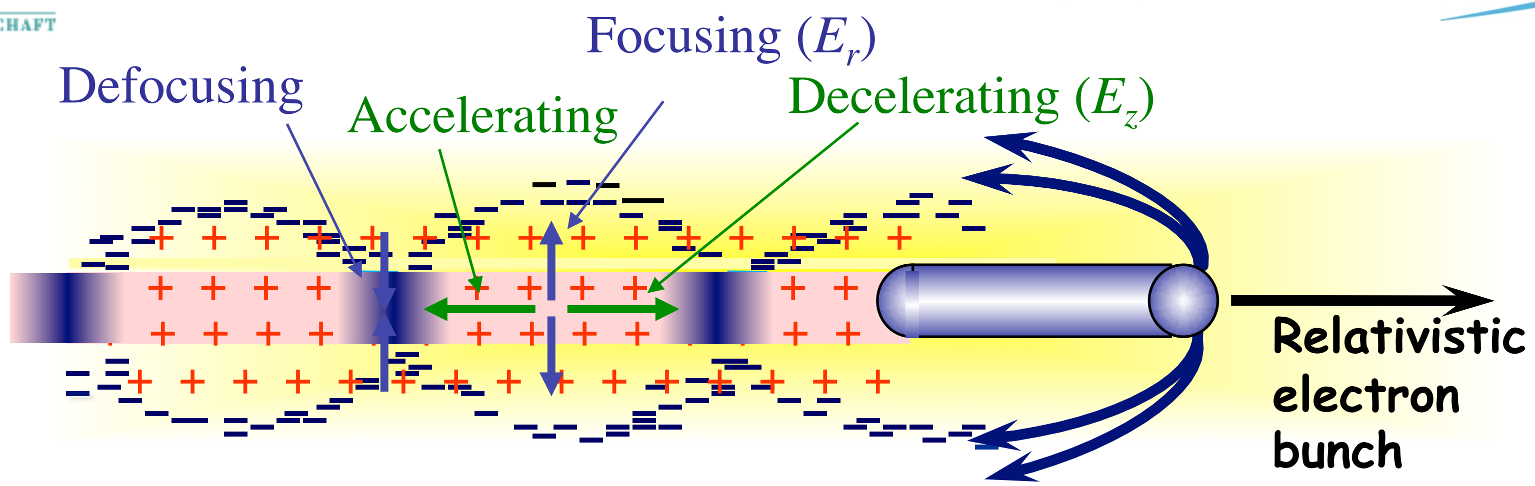
*Pioneered by J.M. Dawson, Phys. Rev. Lett. 43, 267 (1979)

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

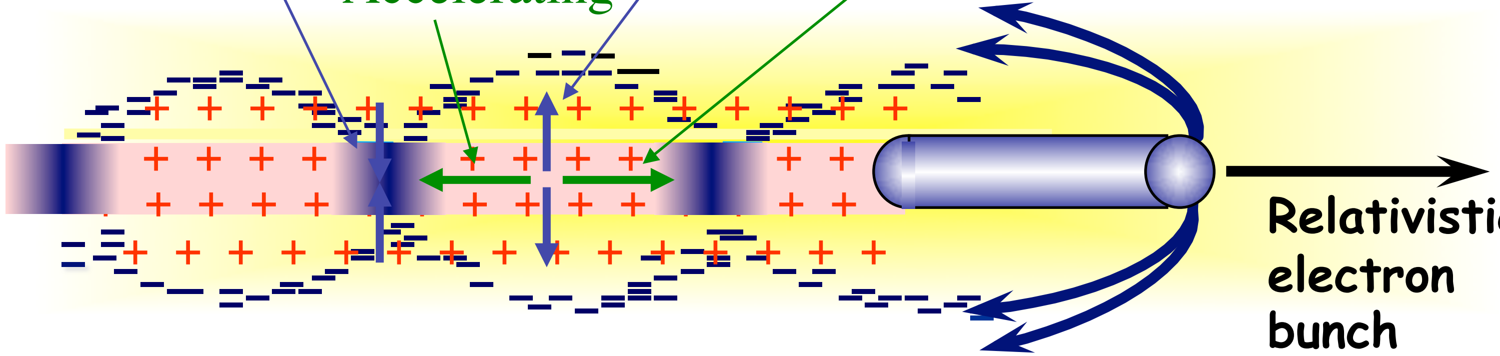
Plasma Wakefields (e^-)



- Plasma wave/wake excited by a relativistic particle bunch
- … by space charge force => deceleration + focusing (MT/m)
- …k on axis => acceleration ~$n_e^{1/2}$, GV/m
- …ver => ultra-relativistic wake
  => no dephasing (…)
- …ave long Rayleigh lengths"
  …$^2/\varepsilon$~cm, m)
- Acceleration physics identical PWFA, LWFA

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

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 $k_{pe}\sigma_r << 1$)

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

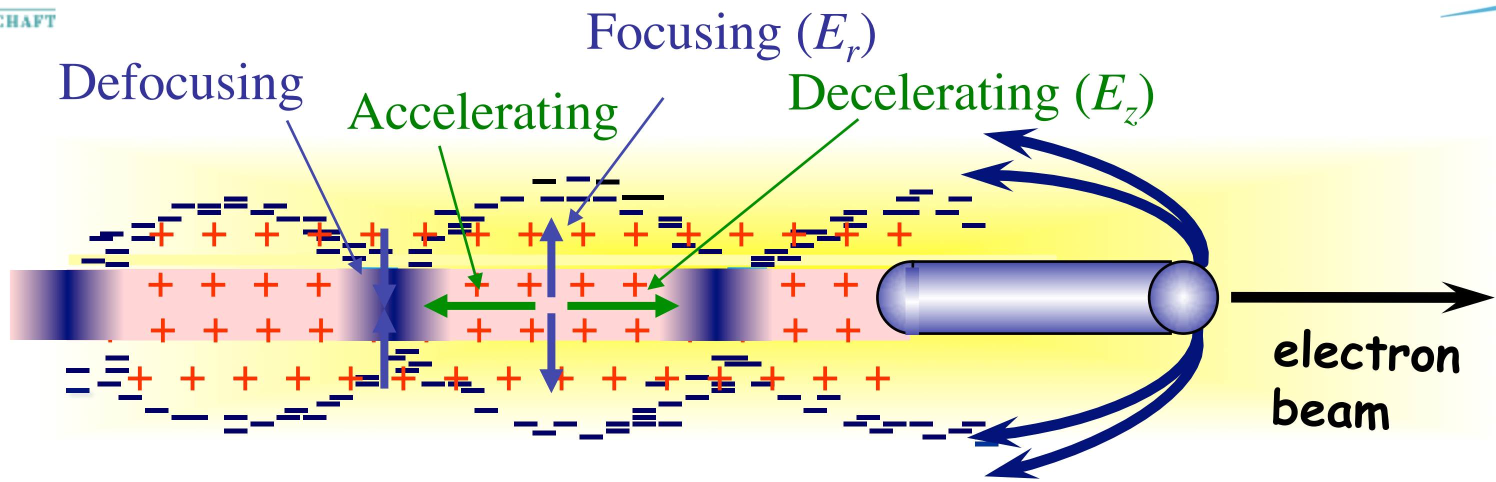
- $N=2\times10^{10}$: $\sigma_z=600\ \mu m$, $n_e=2\times10^{14}\ cm^{-3}$, $E_{acc}\sim100$ MV/m, $B_\theta/r=6$ kT/m

  $\sigma_z=20\ \mu m$, $n_e=2\times10^{17}\ cm^{-3}$, $E_{acc}\sim10$ GV/m, $B_\theta/r=6$ MT/m

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

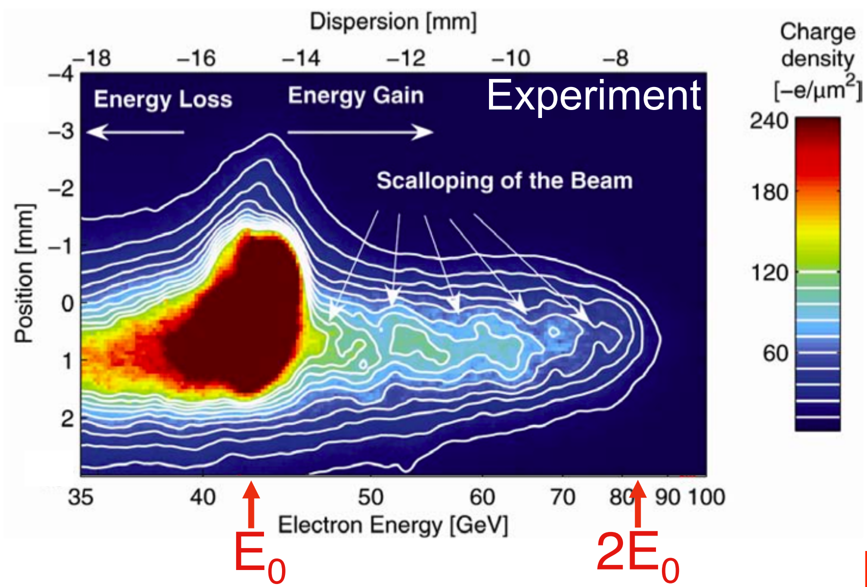
- Conventional accelerators: MHz-GHz, $E_{acc}<150$ MV/m, $B_\theta/r<2$ kT/m

PLASMA WAKEFIELDS (e⁻)



P. Muggli and M.J. Hogan, Comptes Rendus Physique, 10(2-3), 116 (2009).

Blumenfeld, Nature 445, 2007



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

ivistic particle bunch

forces => deceleration + focusing

=> acceleration

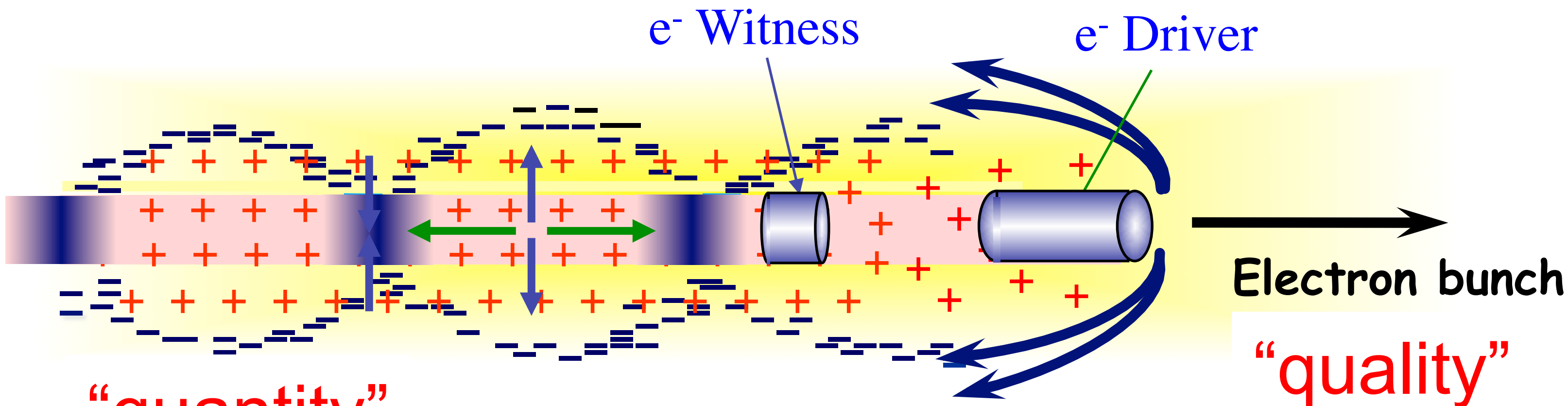
ivistic wake

sing (…)

lengths”

LWFA

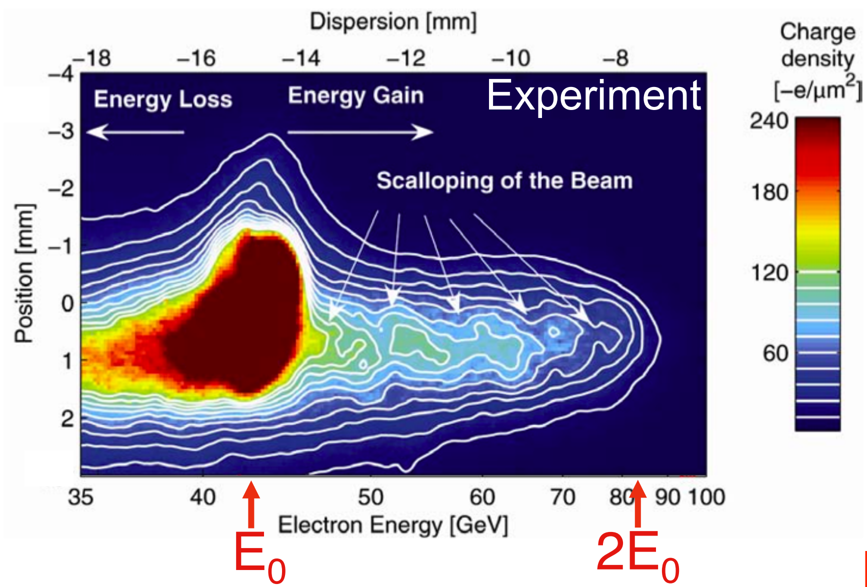
PLASMA WAKEFIELDS (e^-)



"quantity"

"quality"

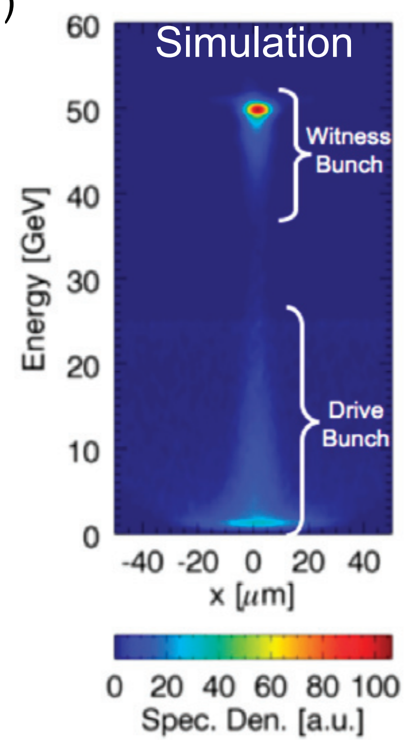
Blumenfeld, Nature 445, 2007



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

SLAC FACET

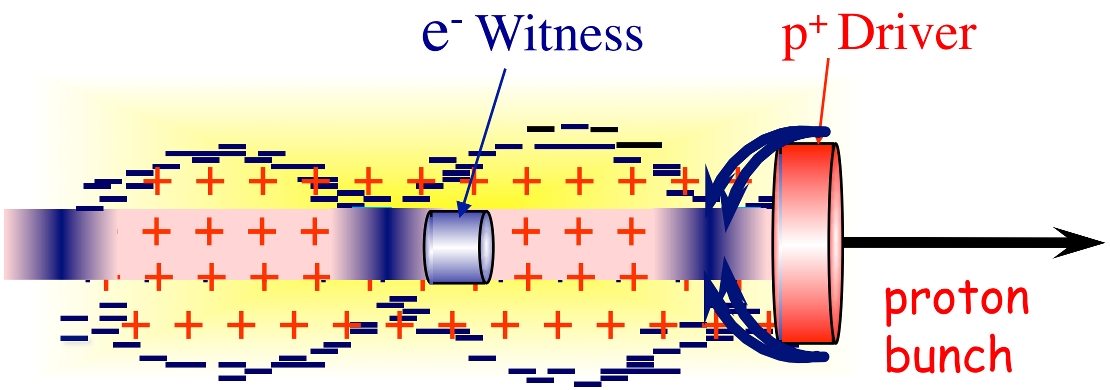
Hogan, NJP 12, 2010



LWFA

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

The "Driver Issue"

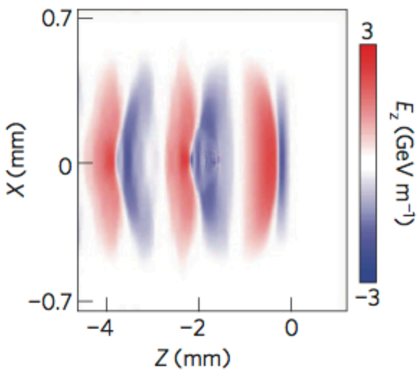


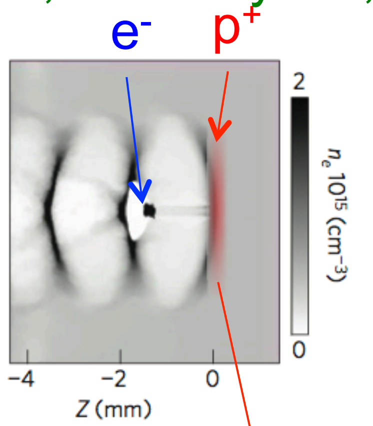
- SLAC, 20GeV bunch with $2\times10^{10}e^-$ ~60J Driver
  ILC, 0.5TeV bunch with $2\times10^{10}e^-$ ~1.6kJ Witness
- SLAC-like driver for staging (FACET= 1 stage, collider 10^+ stages)
- SPS, 450GeV bunch with $3\times10^{11}p^+$ ~22kJ Driver
  LHC, 7TeV bunch with $3\times10^{11}p^+$ ~336kJ Driver
- A single SPS or LHC p^+ bunch could produce an ILC bunch in a single (or a few) PWFA stage(s)!
- Large average gradient! (~GeV/m, 100's m)

PROTON-DRIVEN PWFA

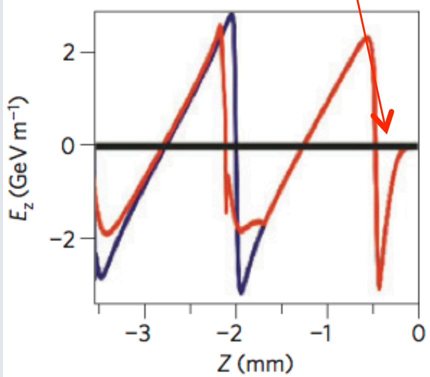
Caldwell, Nat. Phys. 5, 363, (2009)

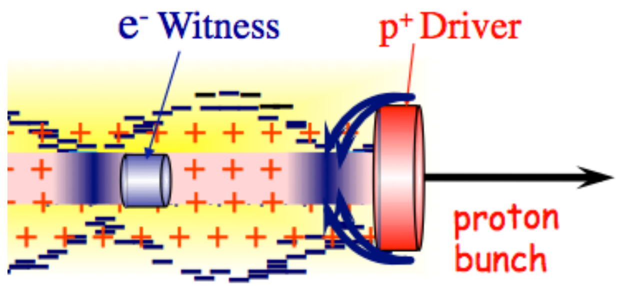
p+:
E_0=1TeV
σ_z=100µm
N=$10^{11}p^+$
e^-:
E_0=1GeV
N=$10^{11}e^-$



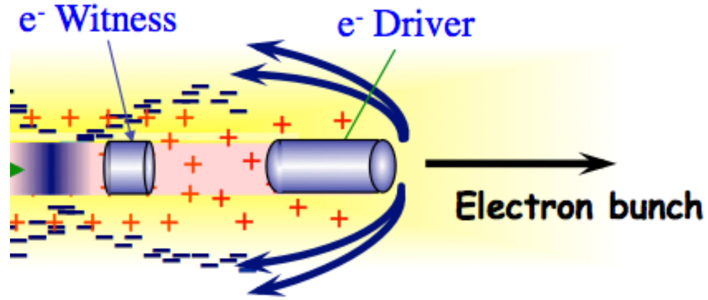


Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons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





Phase difference!

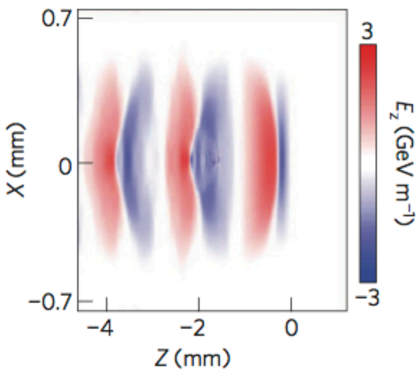


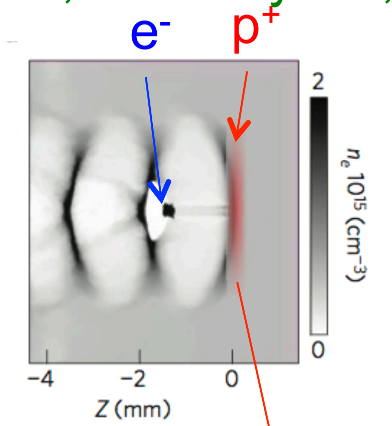
- Use "pancake" p^+ bunch to drive non-linear wake (cylinder for e^- driver)
- Gradient ~1.5GV/m (av.)

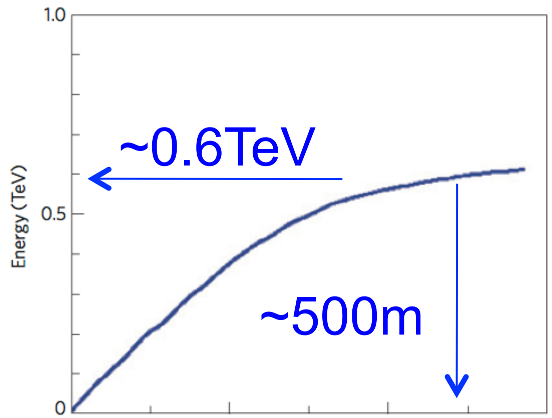
PROTON-DRIVEN PWFA

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

p+:
E_0=1TeV
σ_z=100µm
N=10^{11}
e⁻:
E_0=1GeV
N=10^{11}







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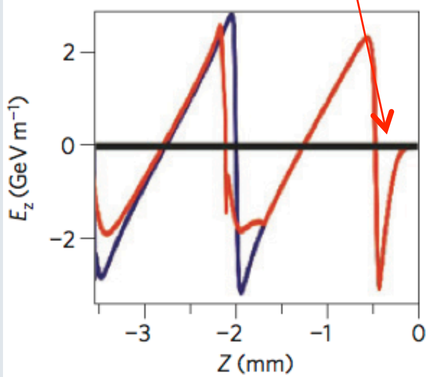
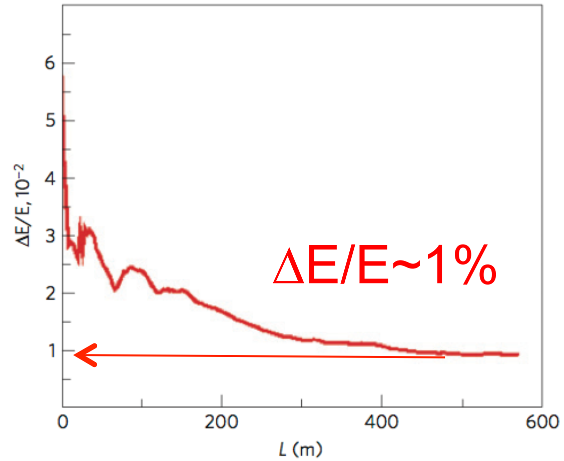
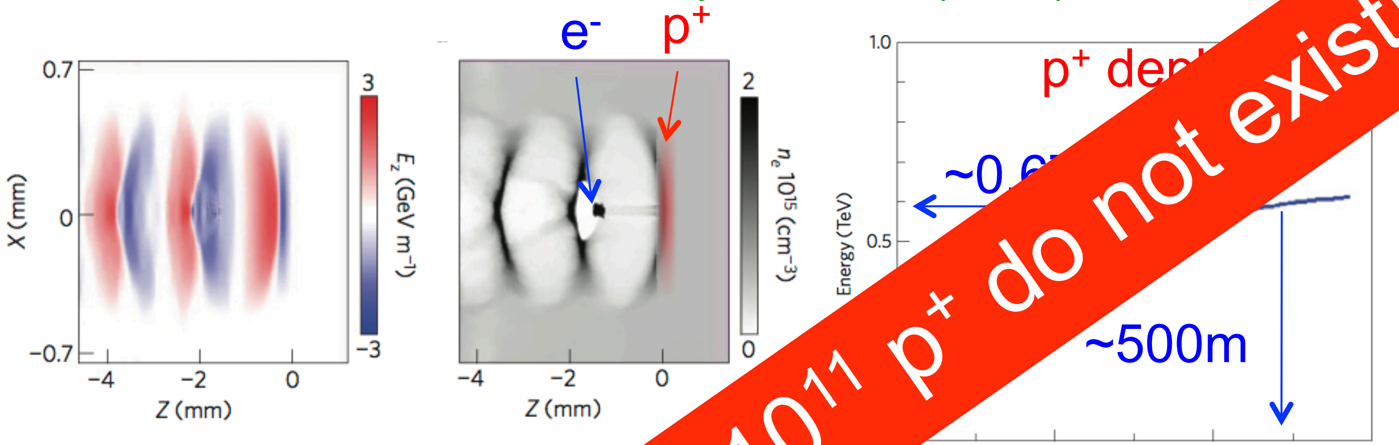




- Energy gain ~600GeV in ~500m plasma
- Reasonable energy spread
- Dephasing of (not so) relativistic p⁺

PROTON-DRIVEN PWFA

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



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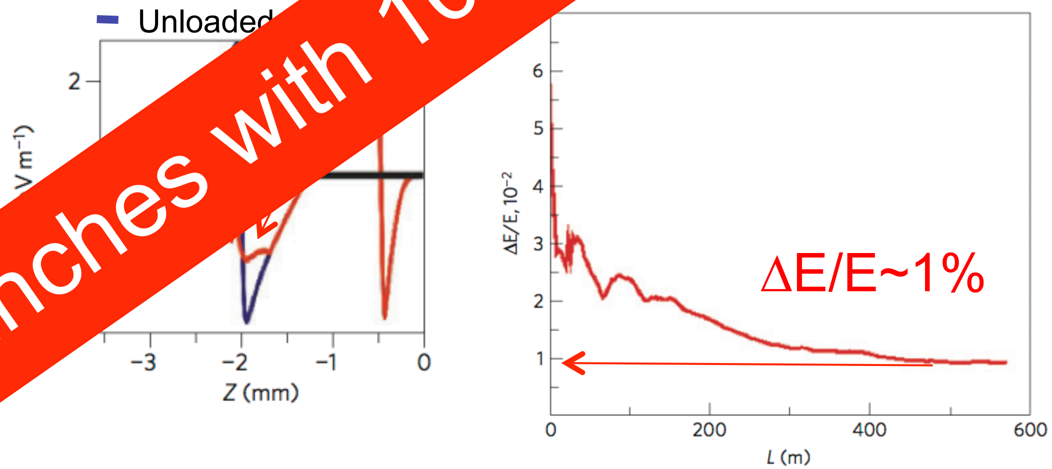
Plasma wavelength	λ_p		
Magnetic field gradient			
Magnet length			



σ_z≈100μm bunches with 10^{11} p+ do not exist!

- G... 1.5GV/m (av.), efficiency ~ 10%
- ...ke e- bunch from a single p+-driven PWFA
- Driver recycling?

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

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)

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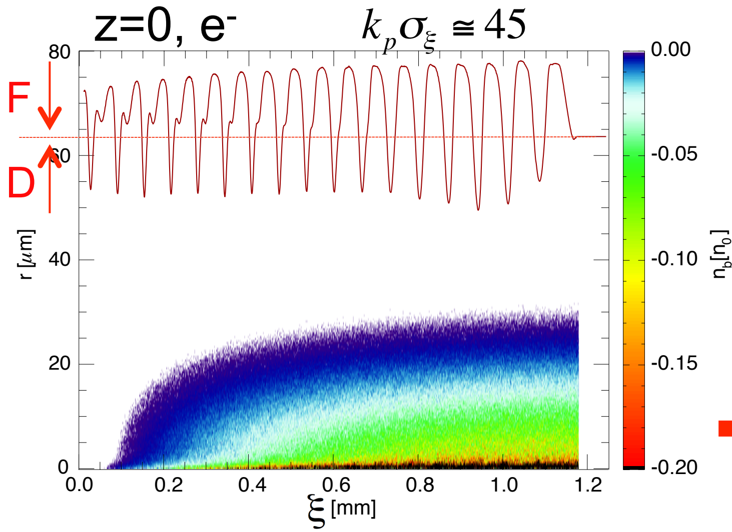
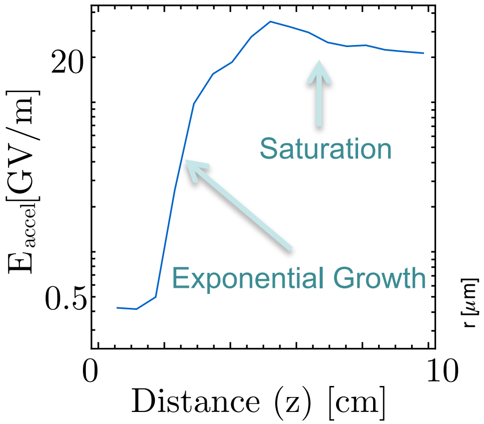
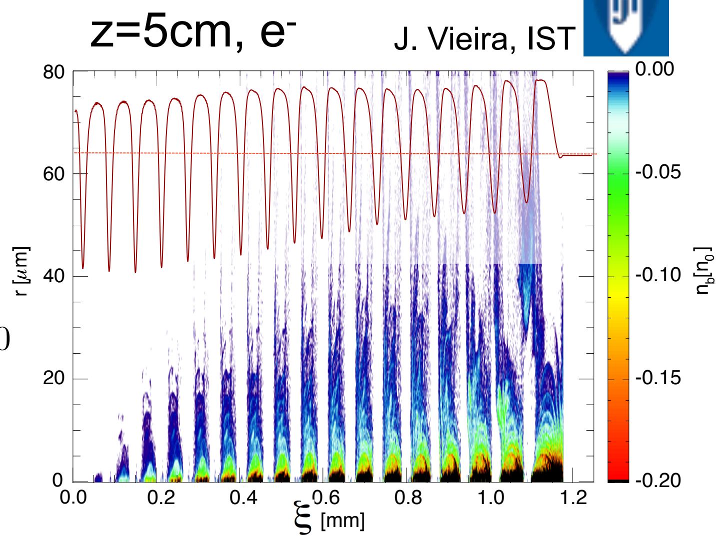
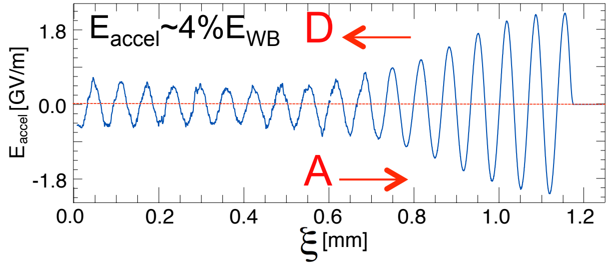
Self-Modulation Instability (SMI)

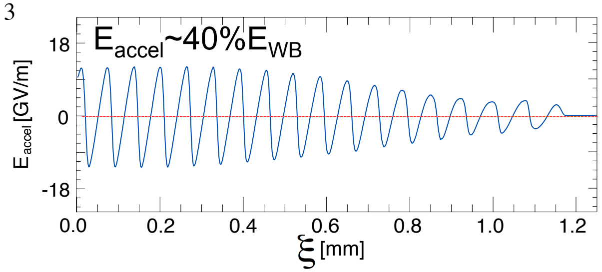








$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



Grows <u>along the bunch</u> & <u>along the plasma</u>
Convective instability

Pukhov 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}

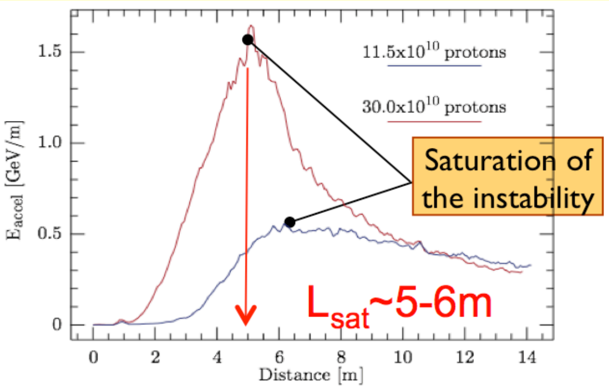
J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

SM-PWFA PARAMETERS

❒ Experimental parameters determined by beam parameters

❒ CERN AWAKE

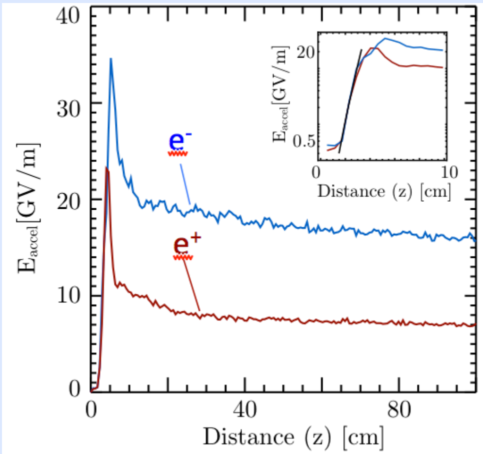
- p^+-driven
- SMI saturates in ~5m
- Study SMI or p^+-bunches
- Remain in ~linear PWFA regime
- ~GV/m over 10^+ m
- Externally inject e^-
- Accelerator experiments



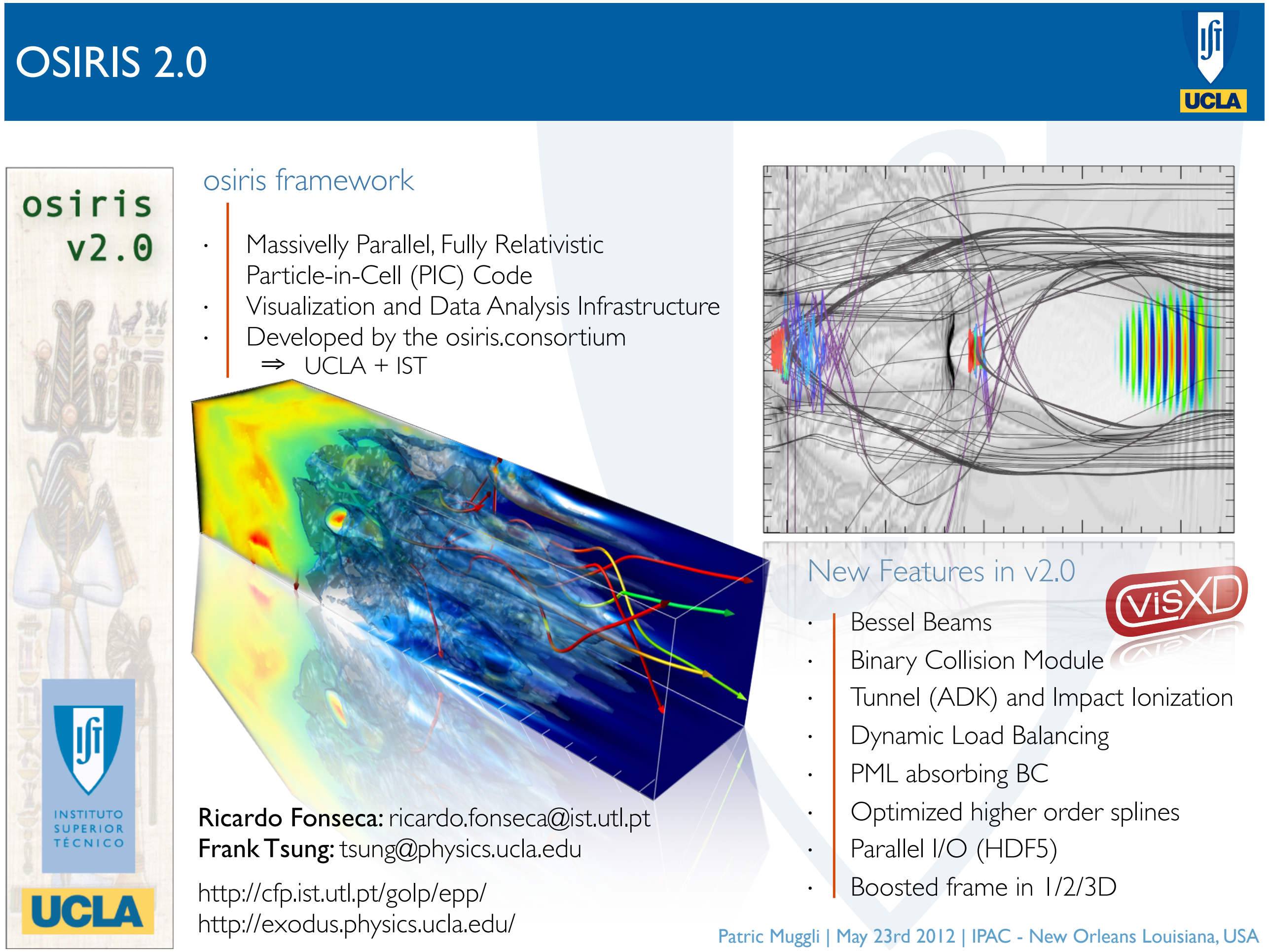
Parameter	PDPWFA	PWFA
$n_e[\mathrm{cm}^{-3}]$	6×10^{14}	2.3×10^{17}
$f_{pe}[\mathrm{GHz}]$	220	4'300
$\sigma_r[\mu\mathrm{m}]$	200	10
$\sigma_r[c/\omega_{pe}]$	0.9	0.9
$\sigma_\xi[\mathrm{cm}]$	12	5×10^{-2}
$\sigma_\xi[c/\omega_{pe}]$	553	45
σ_ξ/λ_{pe}	88	7
$E_0[\mathrm{GeV}]$	400	20.5
γ_0	426	40'000
N_{part}	30×10^{10}	2×10^{10}
n_b/n_0	2×10^{-2}	10^{-1}
$L^{\mathrm{plasma}}[\mathrm{m}]$	10	1
$L^{\mathrm{plasma}}[c/\omega_{pe}]$	46'056	90'173
$L^{\mathrm{plasma}}/\lambda_{pe}$	7'330	14'352
$\epsilon_N[\mathrm{mm}\cdot\mathrm{mrad}]$	3.83	50

❒ SLAC E209

- e^-/e^+-driven
- SMI saturates in ~5cm
- Compare SMI of e^-/e^+ bunches
- Reaches nonlinear PWFA regime
- >10GV/m
- Multi GeV energy gain (drive particles) in ~1m
- SMI diagnostic



SMI-PWFA SIMULATIONS



Benchmarking with (for AWAKE only!):

- OSIRIS: R. A. Fonseca et al., Lect. Notes Comput. Sci. 2331, 342 (2002).
- VLPL A: Pukhov, J. Plasma Phys. 61, 425 (1999)
- LCODE: K. V. Lotov, Phys. Rev. ST Accel. Beams 6, 061301 (2003)

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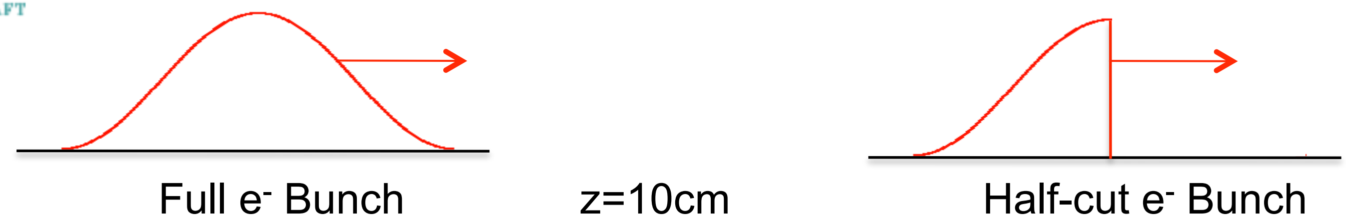
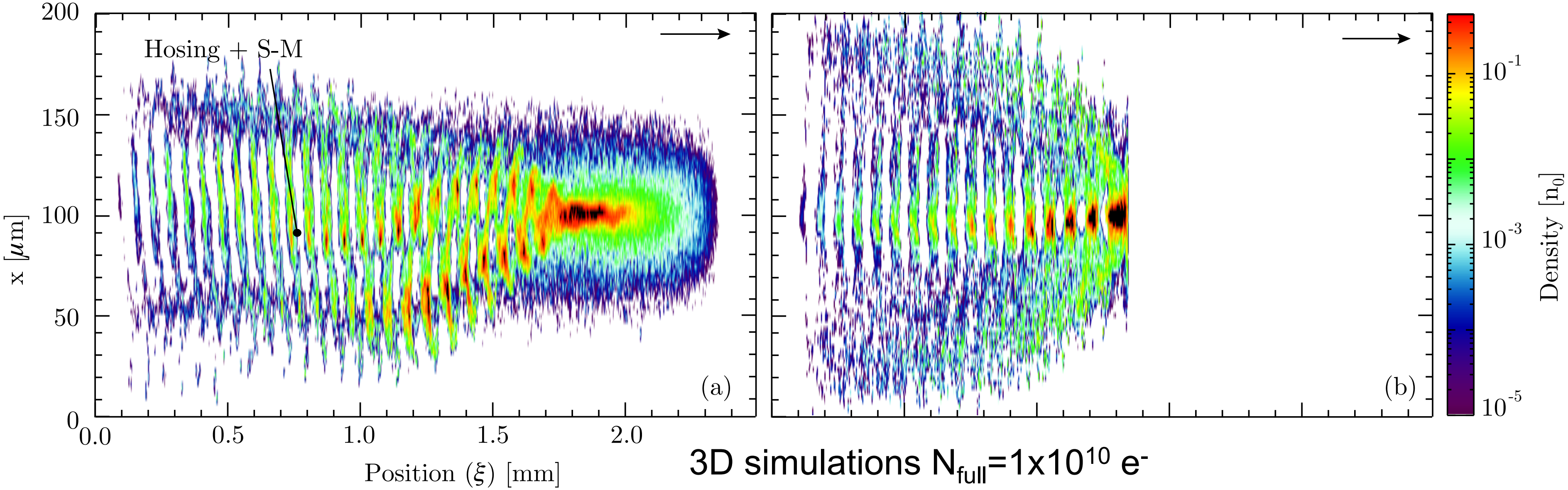
- ❒ Summary

SEEDING OF SMI

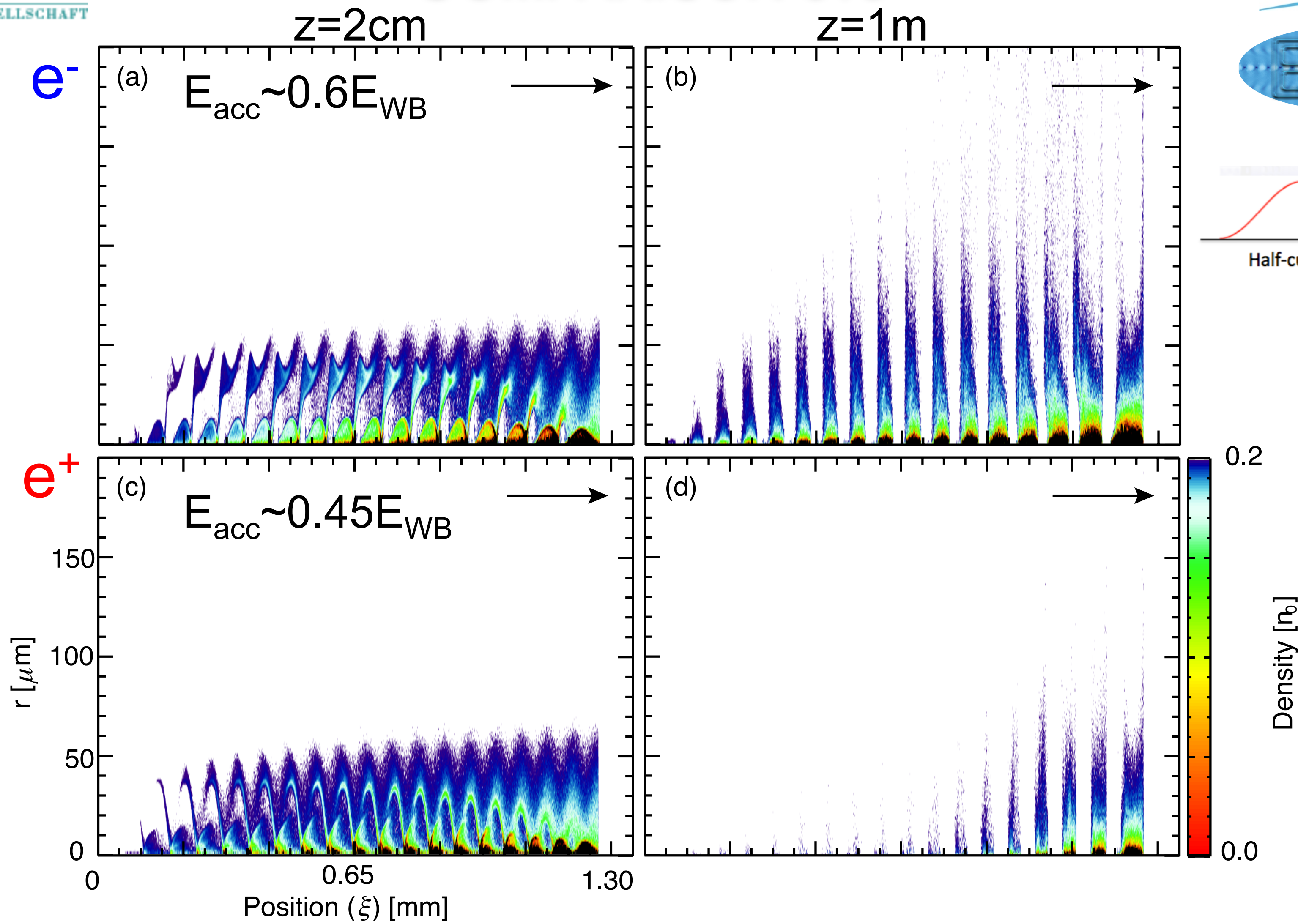


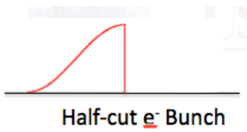


3D simulations $N_{full}=1\times10^{10}$ e^-

- Long bunches in plasmas are subject a two-stream instability or hosing-like instability Witthum, Phys. Fluids B 4, 730 (1992).
- Seeding SM with shaped bunch decreases hosing (preformed plasma)
- Use 2D simulations with shaped bunches <=> no hosing

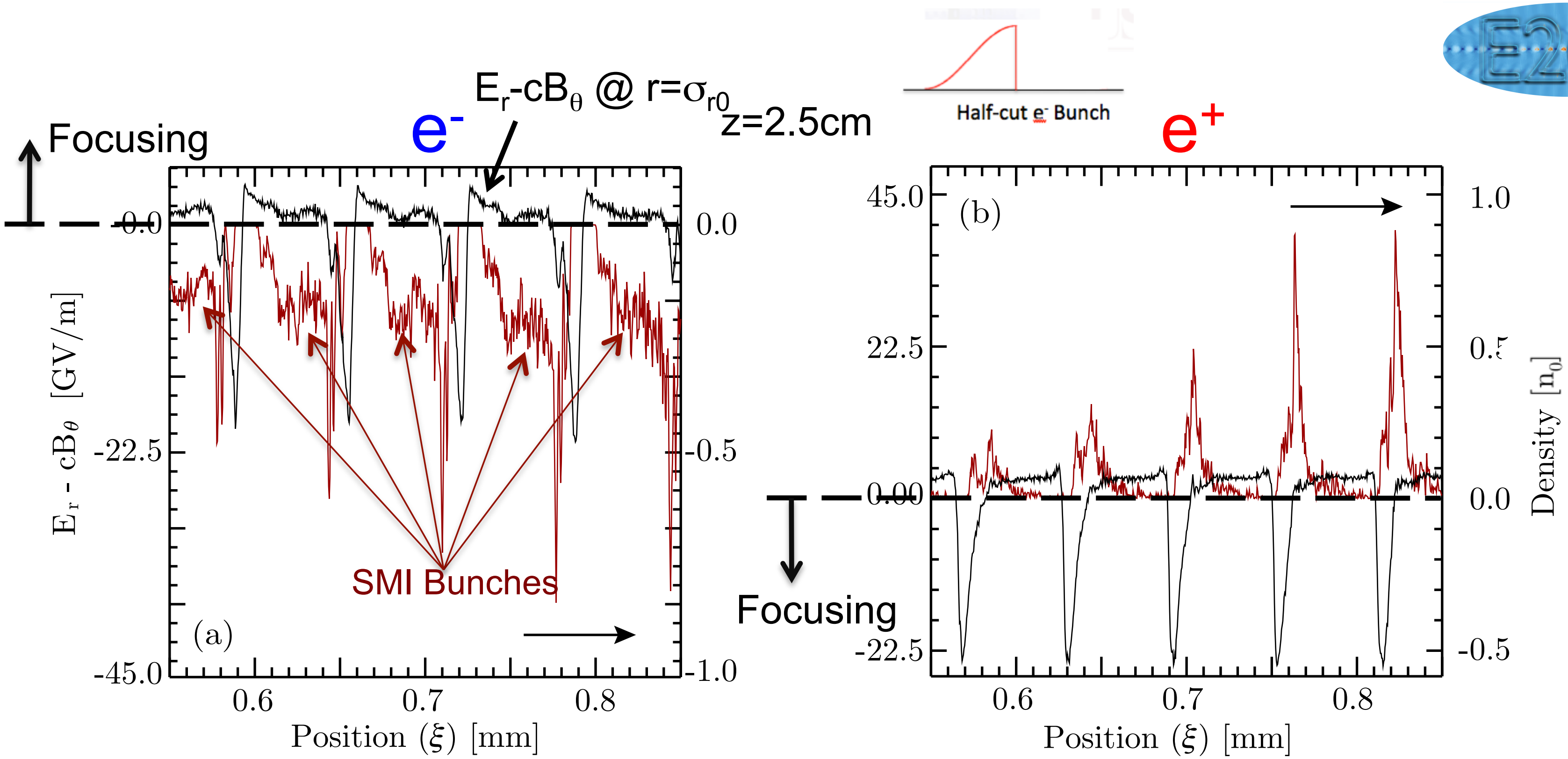
COMPARISON e^-/e^+





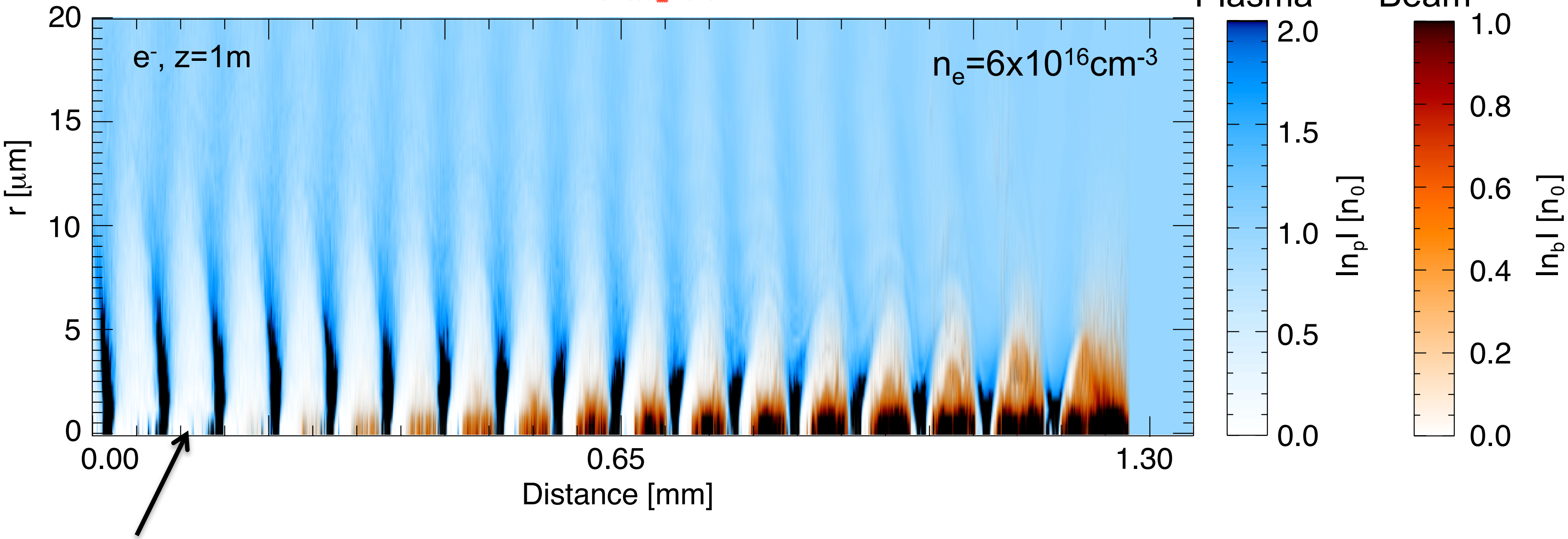
- SMI of e^- and e^+ identical only in linear regime (E_{acc}<<E_{WB})
- SMI leads to the resonant excitation of wakefields
- Less e^+ remain to drive wakefields in the non-linear regime

FOCUSING NONLINEAR REGIME



- Focusing structure in the nonlinear, blowout regime more favorable for e^- than for e^+
- More e^- to drive wakefields to larger amplitudes
- Focusing and bunch profiles evolve along z

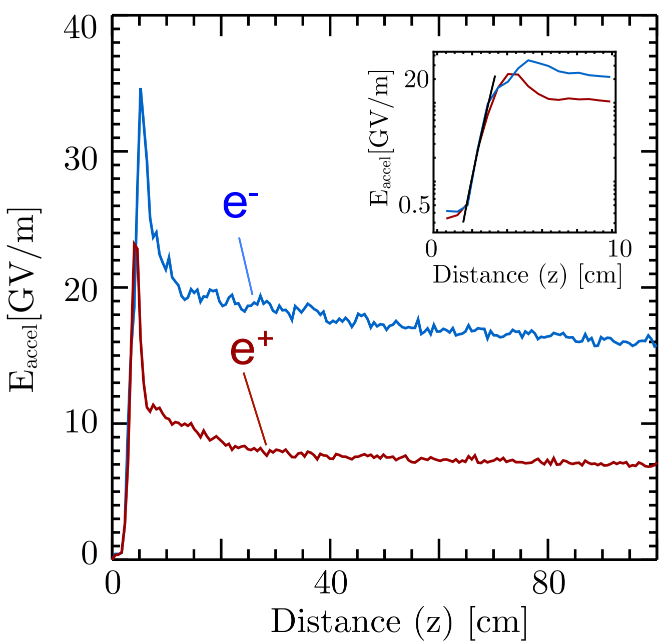
WEAKLY NONLINEAR REGIME

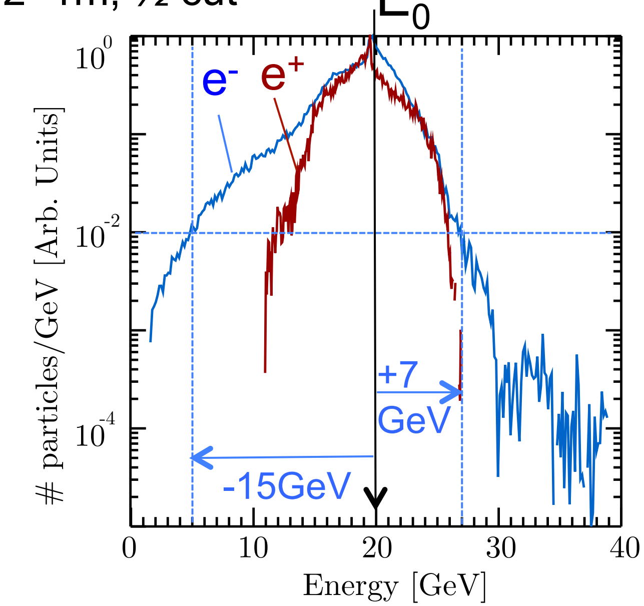


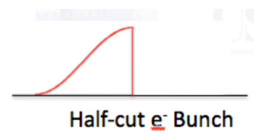
Injection of a witness bunch

- Evolves into $n_b > n_e$, fields add, reach weakly non-linear regime
- "Bubbles", pure ion column generated, but fields add $r_{Bubble} \approx r_{beam}$

WAKEFIELDS & ENERGY CHANGE
(by drive particles)



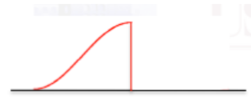


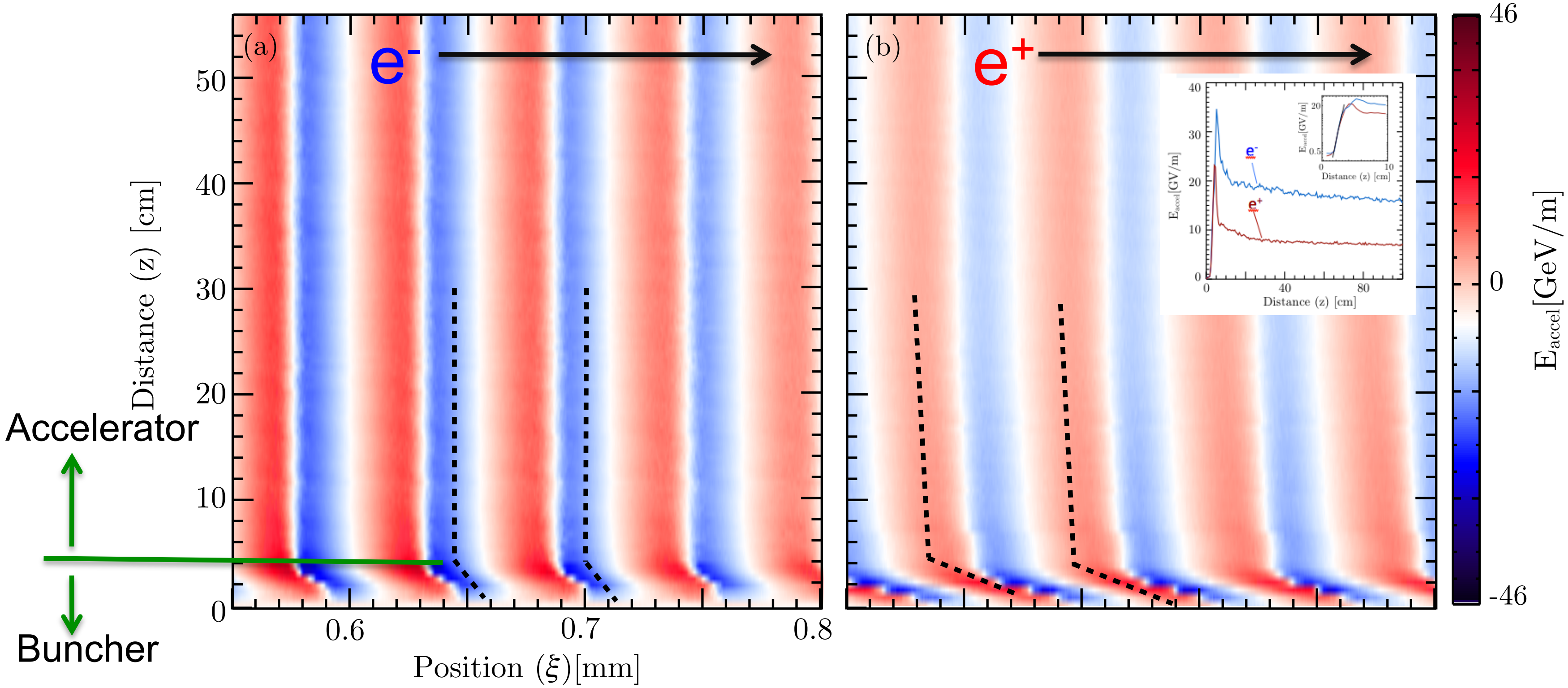


- Peak SMI wakefield (~35GV/m) ~ single bunch peak field (~50GV/m)
  E_{WB}=46GV/m @ n_e=2.3x10^{17}cm^{-3}
- Large energy loss >10GeV (e⁻ @1%/GeV level)
- Energy gain >5GeV (e⁻, e⁺ @1%/GeV level)
- No externally injected particles

SMI Phase Velocity

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





- Wakefield slips "backwards" for z<5cm => buncher
  Wakefield ~v_b~c for z>5cm => accelerator
- Better structure with e^- than with e^+
- Observable effect? Not so important since no external injection

E209 @ SLAC

- SMI physics with e^- and e^+
- Seeding SMI with shaped bunch in pre-formed plasma
- SMI – hosing instability competition
- No externally injected e^-
- Multi-GeV energy gain/loss in m plasma

OUTLINE

❒ Introduction to Plasma Wakefield Accelerator (PWFA)

❒ Introduction to the self-modulation instability (SMI)

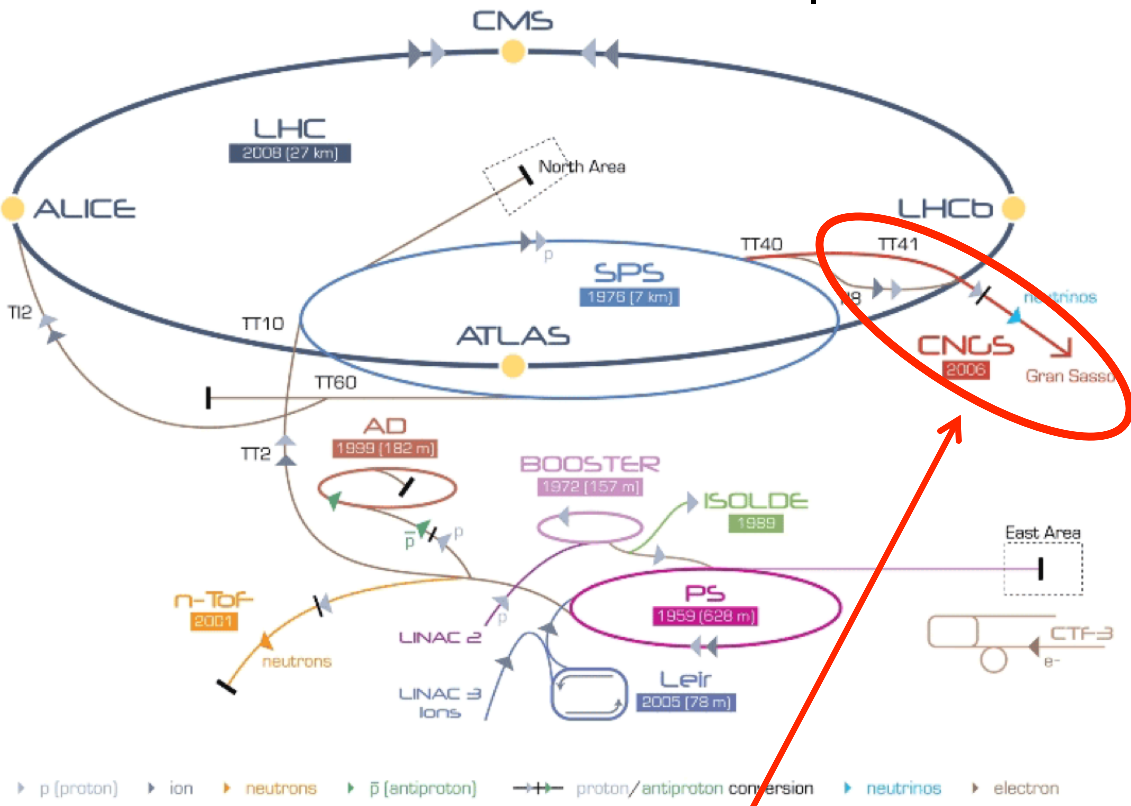
❒ SMI experiments at SLAC E209 with e^-/e^+

❒ SMI PWFA experiments at CERN with p^+ : AWAKE

❒ Summary

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

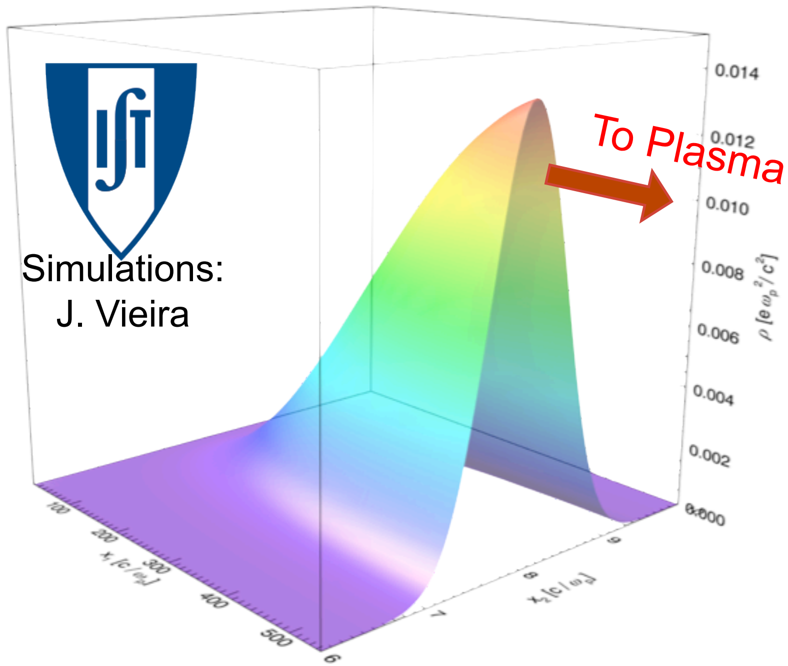
L_p~5-10m
n_e~$7\times10^{14}cm^{-3}$ ($k_p\sigma_r\approx1$)
λ_{pe}~$1.3mm<<\sigma_z=12cm$
f_{pe}~240GHz

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

PROTON-DRIVEN PWFA @ CERN

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

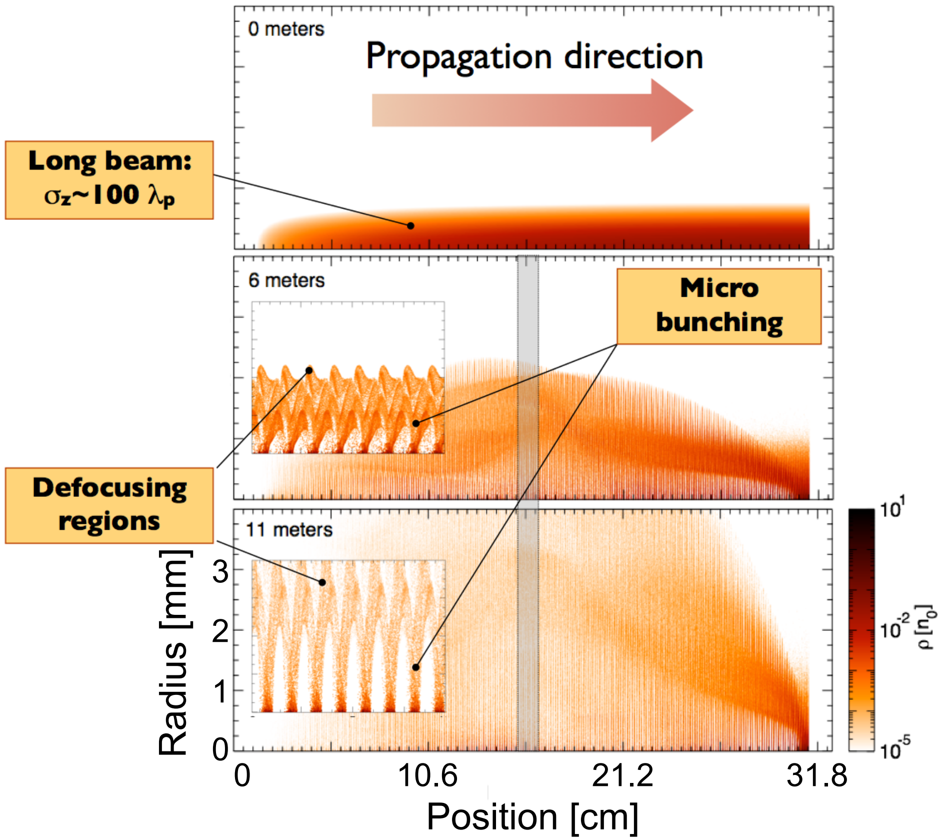
Proton bunch	Electron bunch
$\sigma_{\|\|}$ = 12 cm $\sigma_{\perp}$= 200 μm N = 11.5x10^{10} (30.0x10^{10}) n_b/n_0 = 0.00217 (linear PWFA) γ = 479.6	$\sigma_{\|\|}$ = 10 cm (very long) $\sigma_{\perp}$= 200 μm n_b/n_0 = 1.32x10^{-7} γ = 20 (10 MeV)
Plasma	**Box**
n_0 = 7x10^{14} cm^{-3} λ_p= 1.2 mm ~ $\sigma_{\|\|}$ /100 Uniform density Immobile ions Length = up to15 meters	$n_{\perp}$ = 425 cells $n_{\|\|}$ = 18000 cells 4 particles per cell quadratic splines

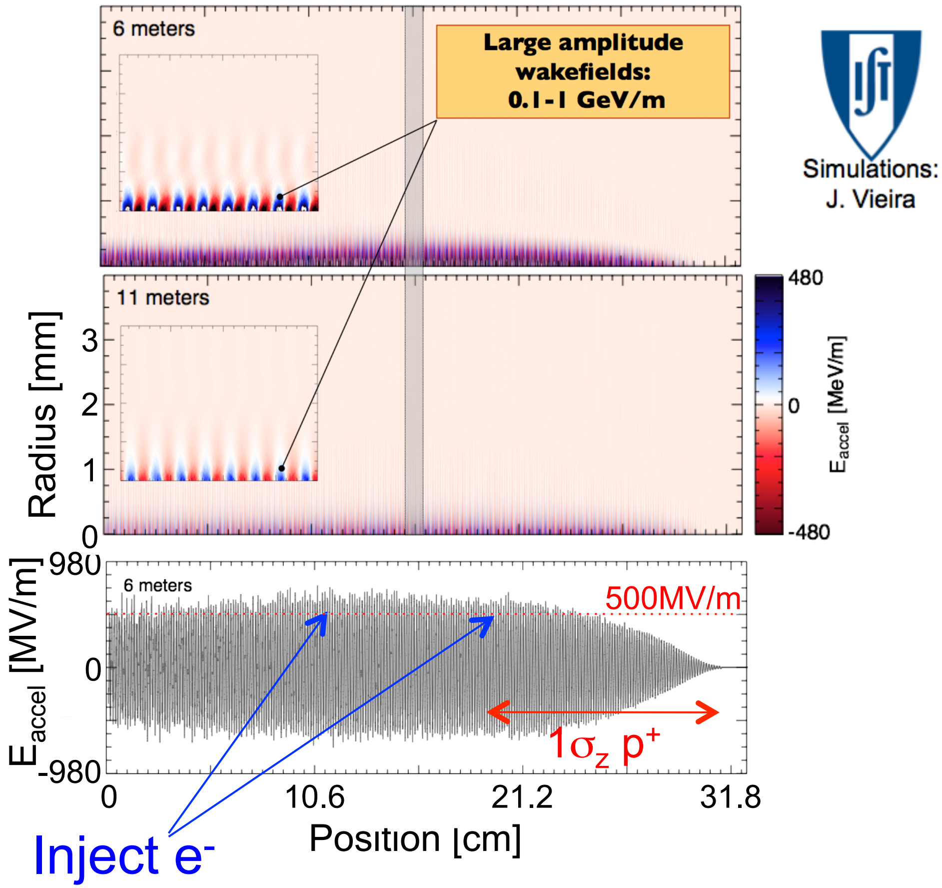


- Simulations include seeding of the instability (cut p^+ bunch, short ionizing laser pulse)
- Long, test-particle e^- witness bunch

PROTON-DRIVEN PWFA @ CERN

- SMI of long (~12cm), 450GeV SPS bunch @ λ_{pe}≈1.2mm



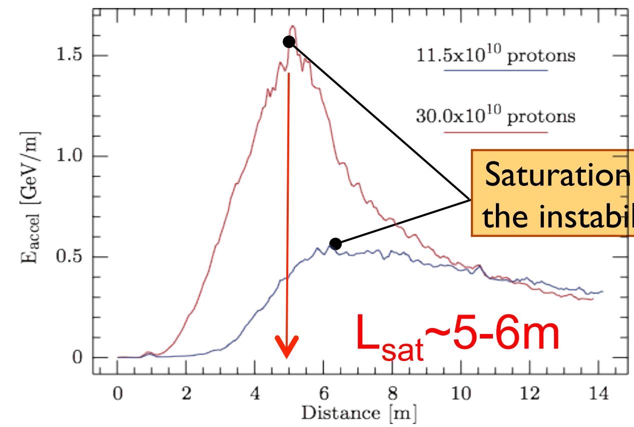


- Drives large amplitude (0.1-1GV/m) accelerating fields
- E_z (acceleration) sampled by injecting (~10MeV) e^- bunch

PROTON-DRIVEN PWFA @ CERN

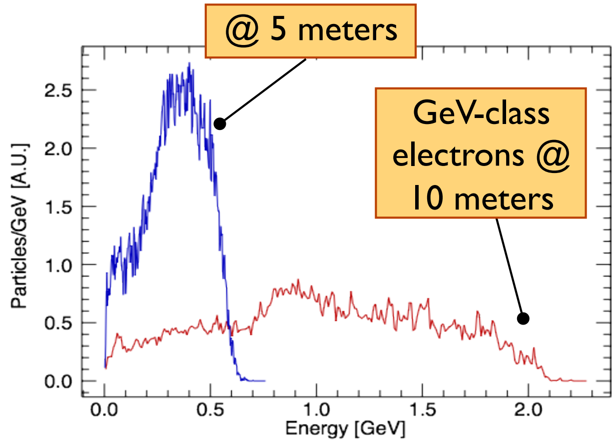
- SMI of long (~12cm), 450GeV SPS bunch @ λ_{pe}

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 3×10^{11} p^+



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

Simulations: J. Vieira

σ_l = 10 cm (very long)
$\sigma_\perp$ = 200 µm
$n_b/n_0 = 1.32\times10^{-7}$
γ = 20 (10 MeV)

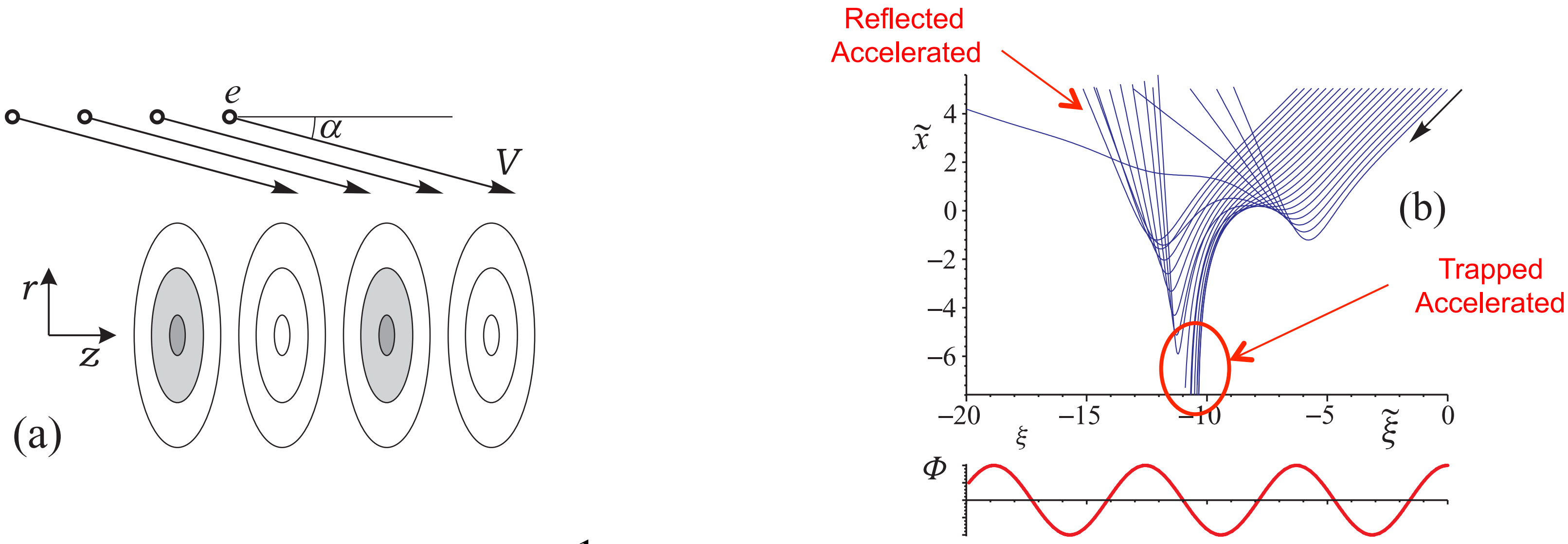
Test e^-

- 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

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

Phase velocity of the wake

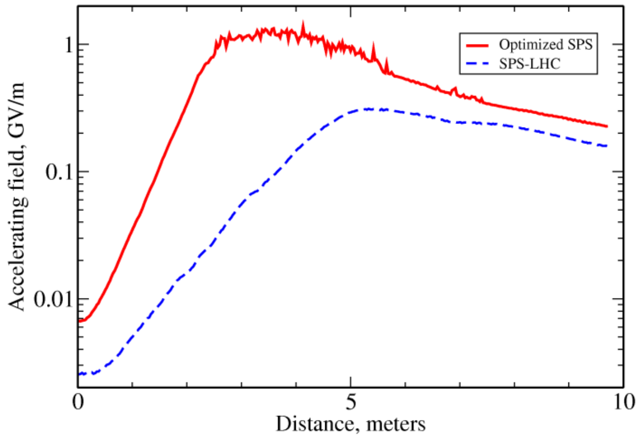
HQ-VLPL3D simulation

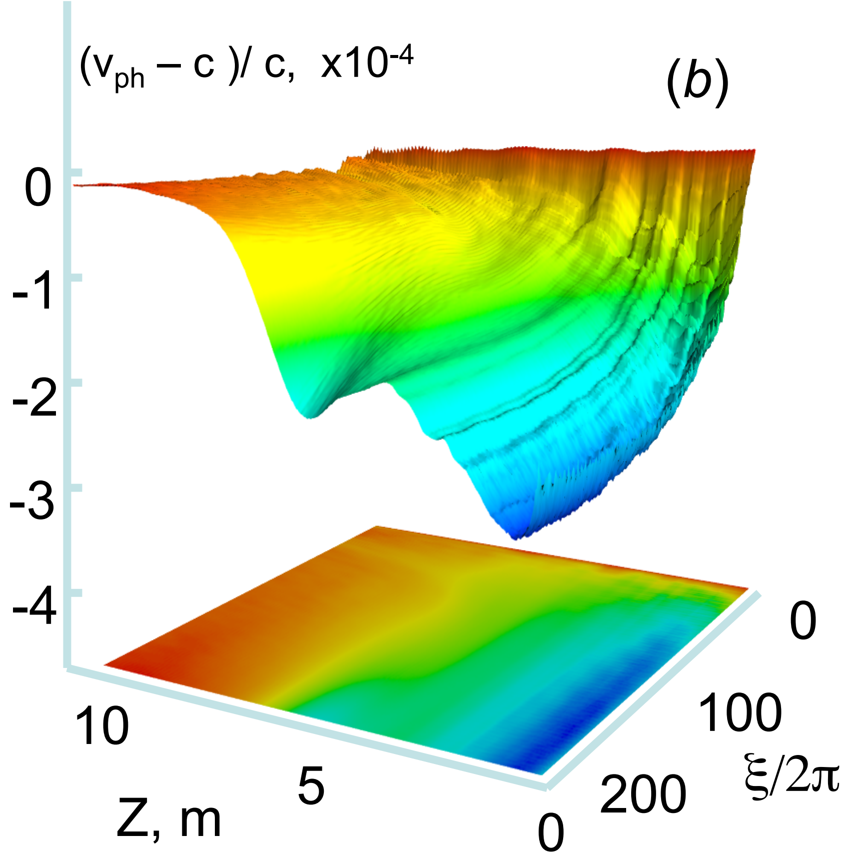
Pukhov et al., Phys Rev Lett (2011)

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

$\gamma_{min} \sim 40$

This is order of magnitude below that of the beam



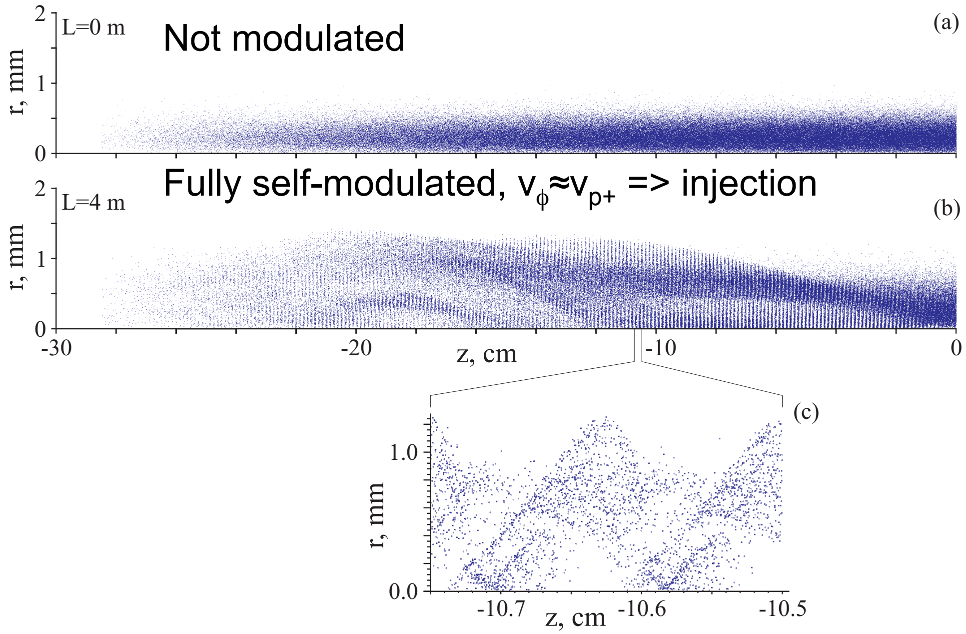


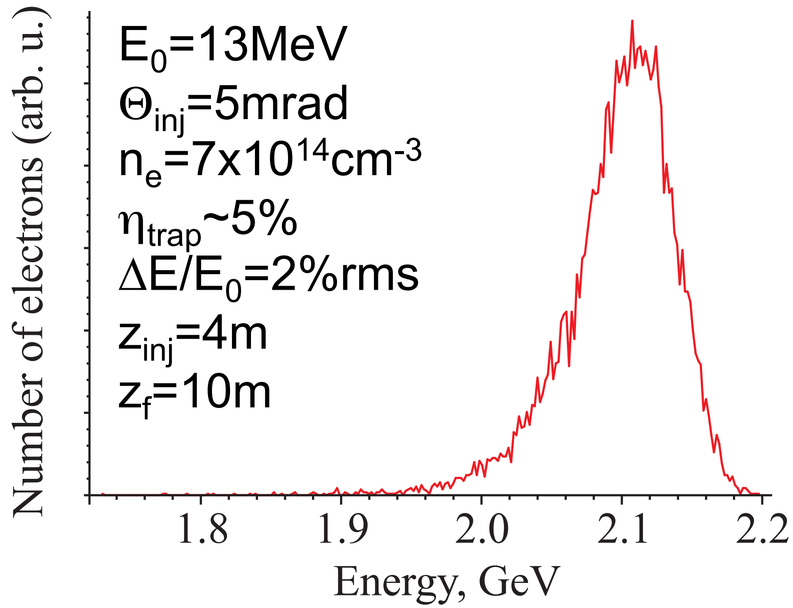
pukhov@tp1.uni-duesseldorf.de

SIDE INJECTION SIMULATION RESULTS

Table 1: *Proton beam parameter at upstream entrance of the plasma cell.*

Parameter	Nominal Value
Energy	400GeV
Bunch Intensity	3×10^{11} p^+
Energy per Bunch	19.2kJ
Repetition Rate	0.03Hz
Energy Spread	0.34% (rms)
Transverse Normalized Emittance	ε_N= 3.5mm-mrad
Focused Transverse Size (at β*=5m)	σ_r*= 0.2mm
Bunch Length	σ_z= 12cm
Angle Accuracy	<0.05mrad
Pointing Accuracy	<0.5mm
Focal Position	Plasma Cell Entrance
Number of Run Periods/Year	4
Length of Run Period	2 weeks
Total Number of Protons/Year	4.86×10^{16}

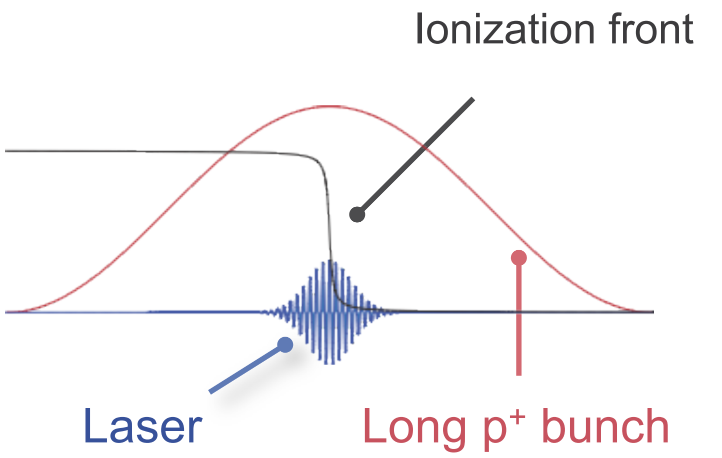




- Results from LCODE, K. Lotov

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 Δx_{II}
- 1000-4000x more CPUh
- **~10 million CPUhours using standard full-PIC for 5 m**

Equation for the laser envelope
Ponderomotive guiding center

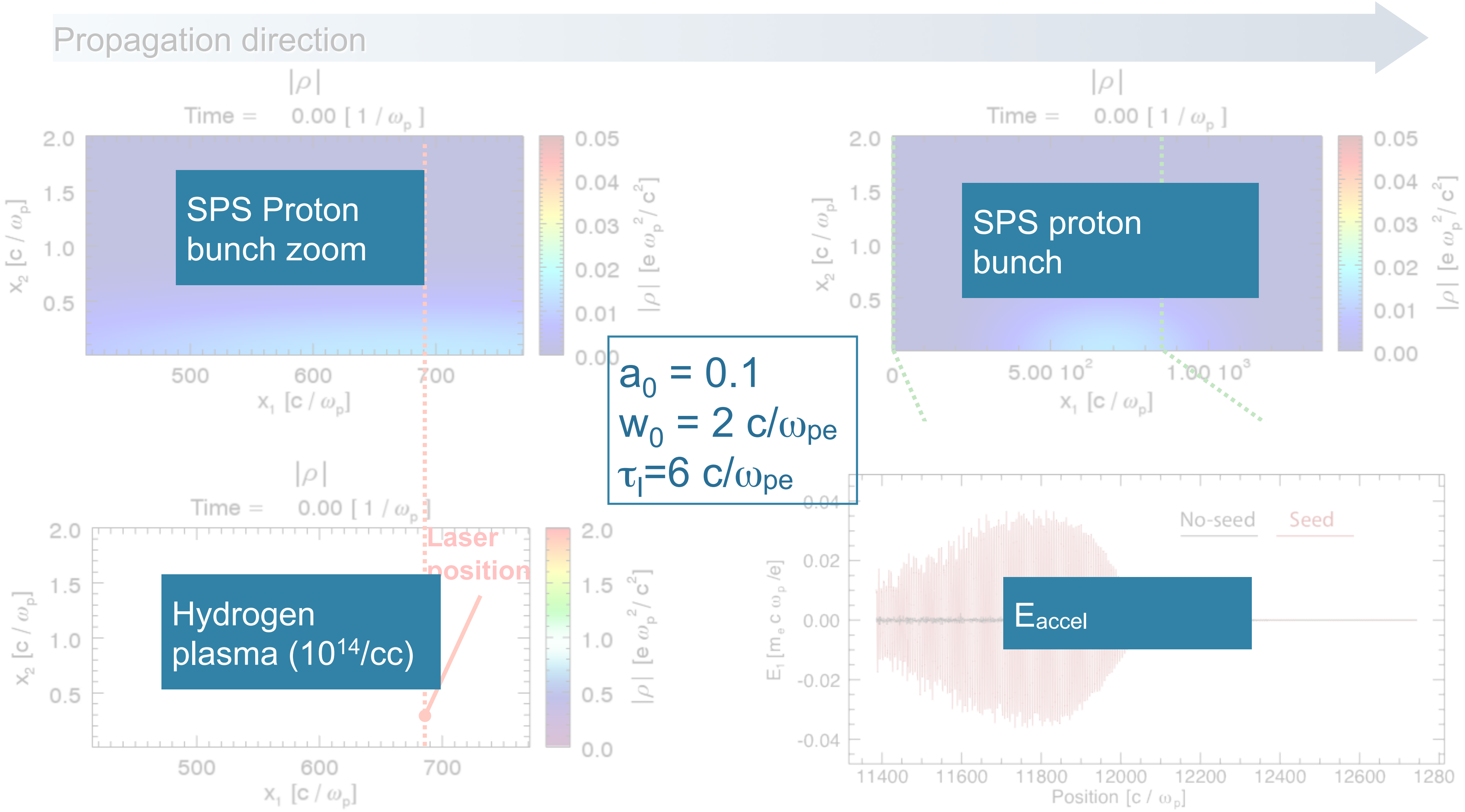
Equation for laser pulse envelope:

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

t=τ; laser frequency; ξ=x-ct; laser envelope

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

Creating plasma and cut proton bunch simultaneously
Ionizing laser pulse

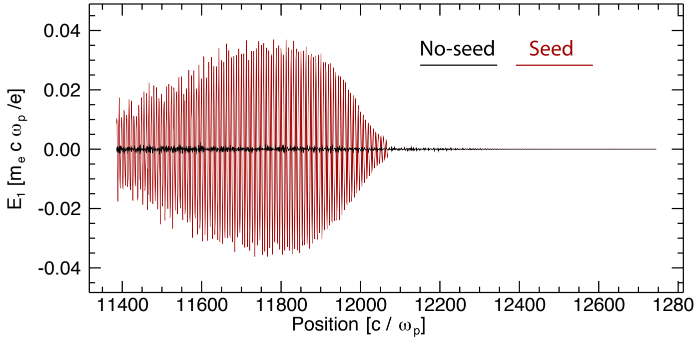


$a_0 = 0.1$
$w_0 = 2\ c/\omega_{pe}$
$\tau_l = 6\ c/\omega_{pe}$

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

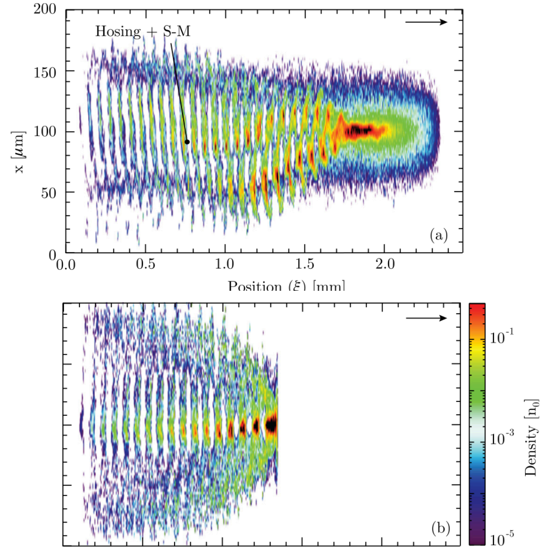
SMI SEEDING

- Seeding of SMI is NECESSARY

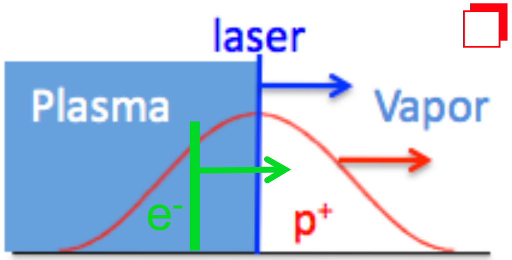


- No seed no SMI (over 10m)

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



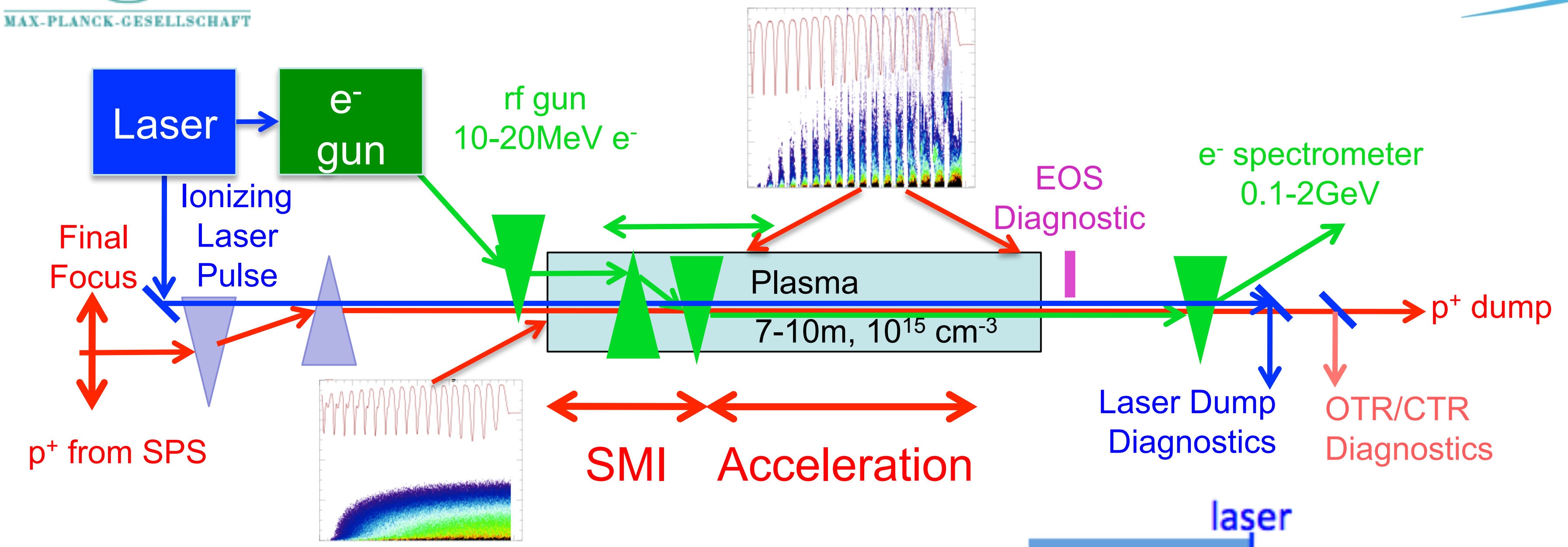
- Hosing mitigation

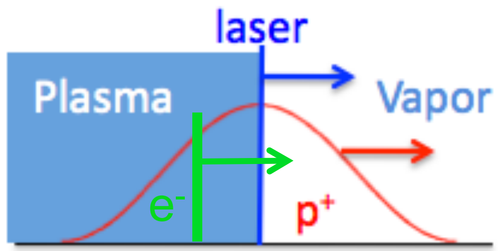


- Deterministic e- injection

- Need to keep laser-ionized source for seeding

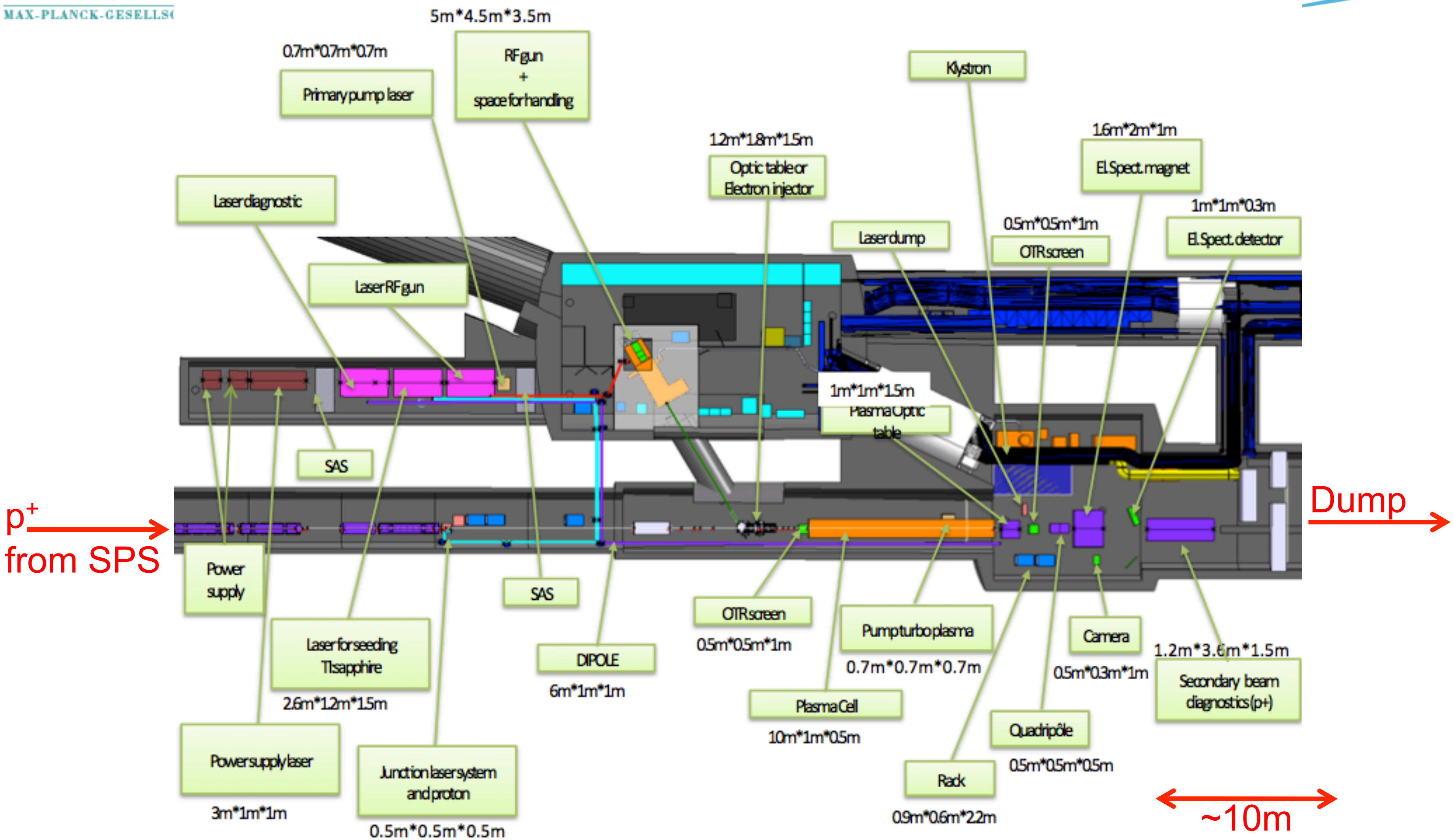
BASE-LINE EXPERIMENTAL SETUP





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

CNGS EXPERIMENTAL AREA

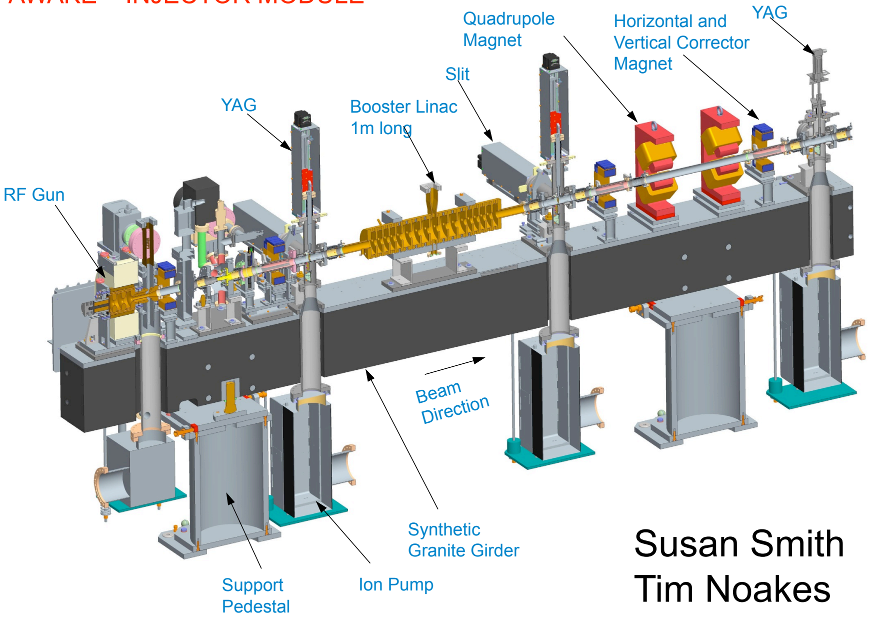


Edda Gschwendtner CERN Project Manager
Chiara Braco, Ans Pardon, …

e⁻ GUN PHOTO INECTOR

- Two possible options:
  - New gun from ASTeC Daresbury Laboratory

AWAKE – INJECTOR MODULE



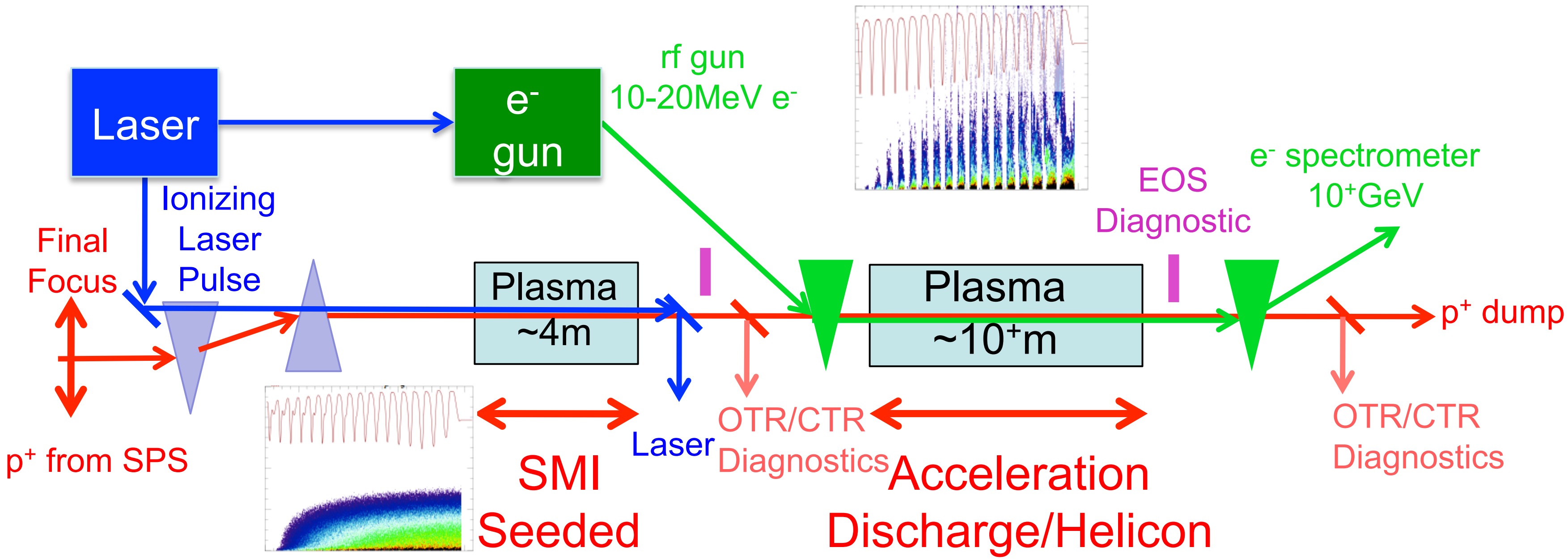
Susan Smith
Tim Noakes

Table 3: *Design parameters for the electron bunch to be injected in the plasma wakefields.*

Parameter	Nominal Value
Beam Energy	5-20MeV
Energy Spread (rms)	<1%
Bunch Length	0.3-5ps
Laser/RF Synchronization	0.1ps
Synchronization to Experiment	0.1ps
Repetition Rate	10Hz
Focused Transverse Size	<250µm
Angular Divergence	<3 mrad
Normalized Emittance	0.5 mm-mrad
Charge	1-100pC

  - PHIN gun from CERN-CLIC
  - Must provide long (side injection, 1 plasma) and short (on axis, 2-plasma) bunches
  - Ionization laser will also be used for the pho-injector (synchronization!)

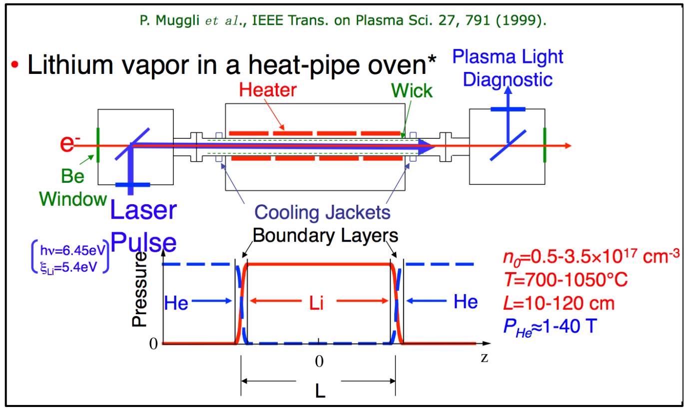
p^+-PWFA ACCELERATOR PHYSICS



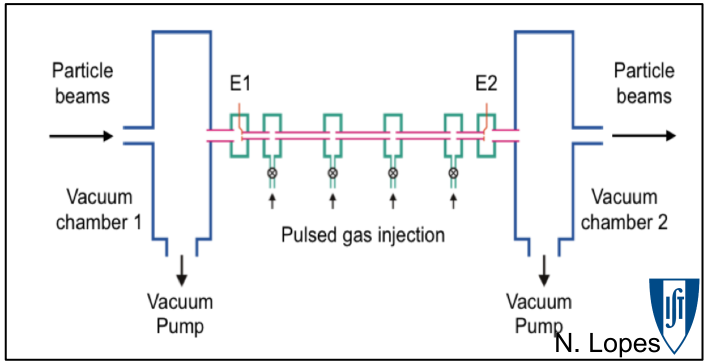
- Laser ionization of a metal vapor (Rb),
  3-4m plasma for p^+ self-modulation only, SEEDING NECESSARY!
- ~10m discharge or helicon source for acceleration only
- Helicon plasma source scales well to very long plasmas (>100m)
- Maybe able to tune plasma densities to maintain accelerating gradient

PLASMA SOURCE FOR PWFA @ CERN

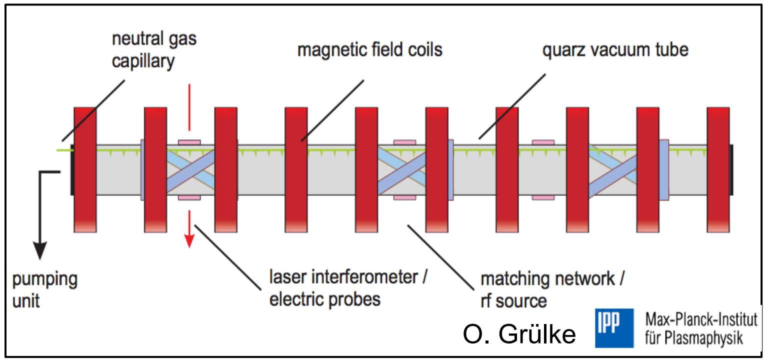
- Metal vapor source (Li, Cs) ~ SLAC experiments
    - Very uniform, very well known
    - Ionization? Scaling to long length?



- Long gas discharge
    - Simple, scalable
    - Density?



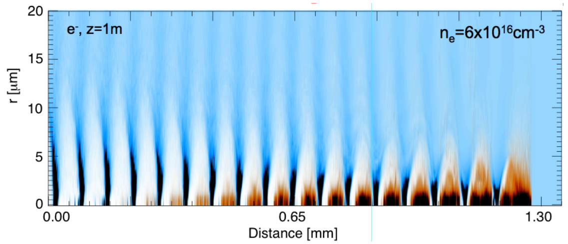
- Helicon source
    - Scalable
    - Density? Uniformity?



- Others?
- Choice to be made

PLASMA DENSITY REQUIREMENTS

- SMI-PWFA: instability + resonantly driven

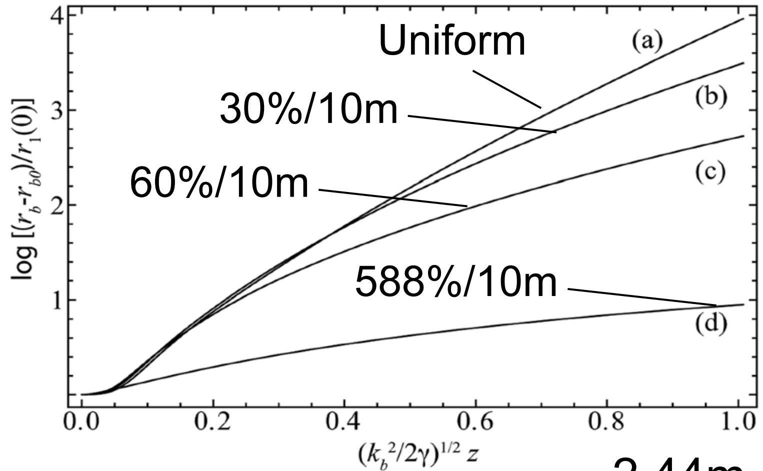


- Requirements for SMI growth rate

For a linear gradient: $$\frac{n_e(z)}{n_{e0}} = 1 + \frac{z}{L}$$

Instability suppressed if: $$L < \left(\frac{2\gamma n_{e0} m_p}{n_{b0} m_e}\right)^{1/3} \sigma_z^{2/3} L_p^{1/3}$$

Schroeder, Phys. Plasmas 19, 010703 (2012)



2.44m

- Requirements witness bunch acceleration

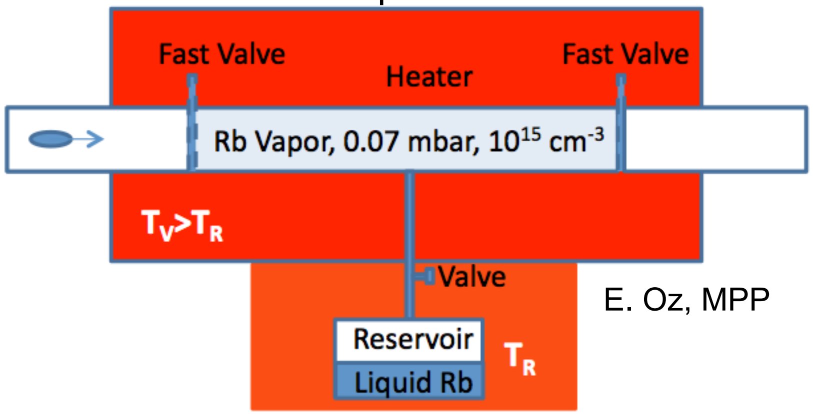
If λ_{pe} changes locally injected electron will be defocused

$$\Delta\phi = \frac{2\pi\xi}{\lambda_{pe0}} \frac{1}{2} \frac{\delta n_e}{n_{e0}} < \frac{\pi}{2} \quad \Rightarrow \quad \frac{\delta n_e}{n_{e0}} < \frac{\lambda_{pe0}}{4\xi} \cong \frac{\lambda_{pe0}}{4\sigma_z} \cong 0.25\%$$

- Tight requirement!

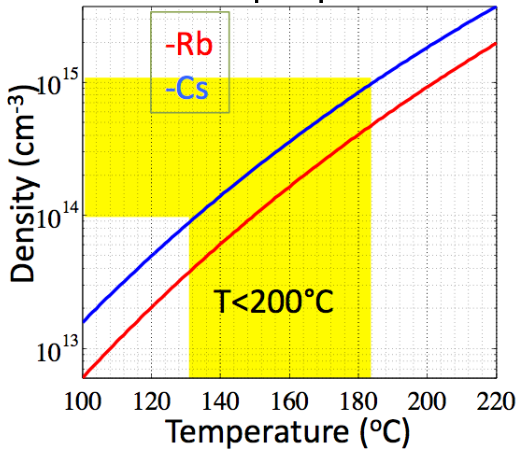
PLASMA DENSITY REQUIREMENTS

Rubidium vapor source sketch



E. Oz, MPP

Rubidium vapor pressure curve



- Statistical temperature variations in a gas: $\left\langle (\Delta T)^2 \right\rangle = \frac{k_B T}{C_V} \Rightarrow \frac{\sqrt{\left\langle (\Delta T)^2 \right\rangle}}{T} = \sqrt{\frac{k_B}{C_V T}} = \left|\frac{\delta n}{n}\right| \propto 10^{-14}$

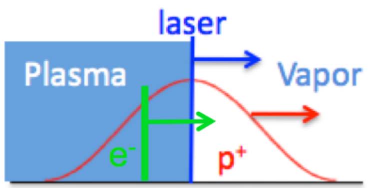
  Typically: C_V=1000J/kgK

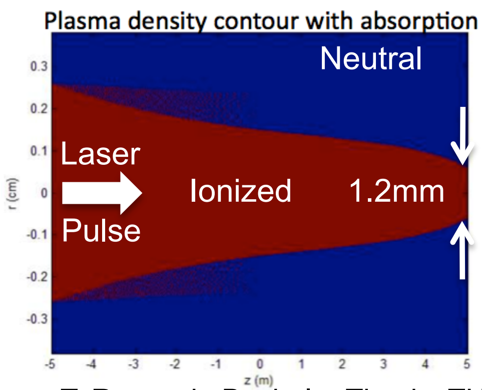
- Tunnel Ionization, threshold process:

$I_{Rb} \approx (\phi_{Rb}/\phi_{He})^4 I_{He} \approx 1.7 \times 10^{12}$Wcm^{-2}

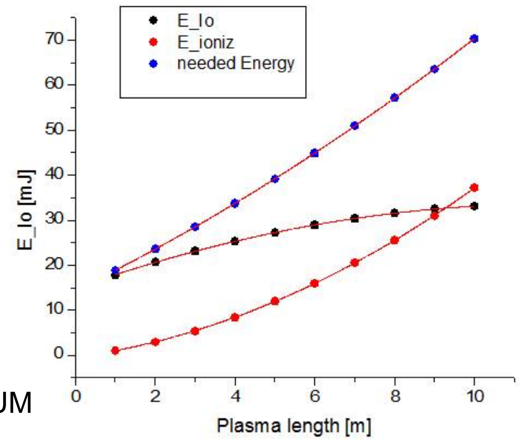
$I_{He} \approx 1.54 \times 10^{14}$Wcm^{-2}, ϕ_{Rb}=4.2eV, ϕ_{He}=24.6eV

S. Augst et al., Phys. Rev. Lett. 63, 2212 (1989)





T. Rusnack, Bachelor Thesis, TUM



- Uniform neutral density (T) + threshold ionization + co-propagation

OUTLINE

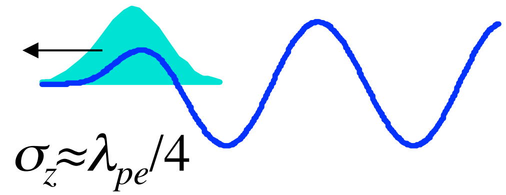
- Introduction to Plasma Wakefield Accelerator (PWFA)
- Introduction to the self-modulation instability (SMI)
- SMI experiments at SLAC E209 with e^-/e^+
- SMI PWFA experiments at CERN with p^+: AWAKE
- Summary

5 ~~4~~ PLASMA ACCELERATORS*

- **Plasma Wakefield Accelerator (PWFA)**

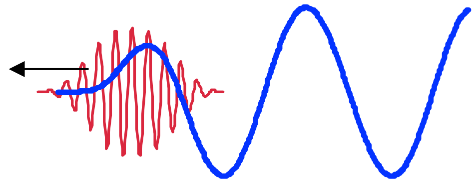
  A high energy particle bunch (e^-, e^+, ...)

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



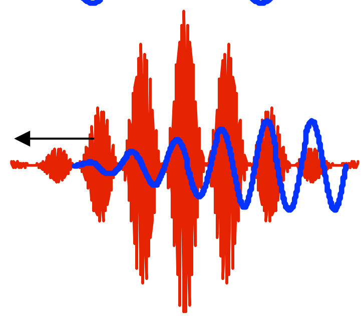
- **Laser Wakefield Accelerator (LWFA)**

  A short laser pulse (photons)



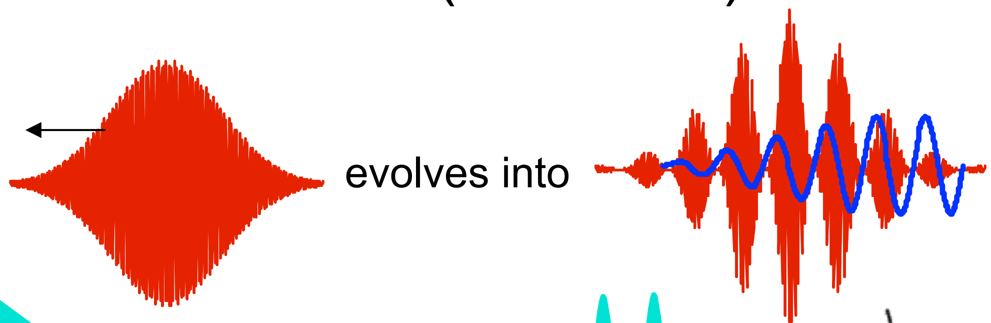
- **Plasma Beat Wave Accelerator (PBWA)**

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

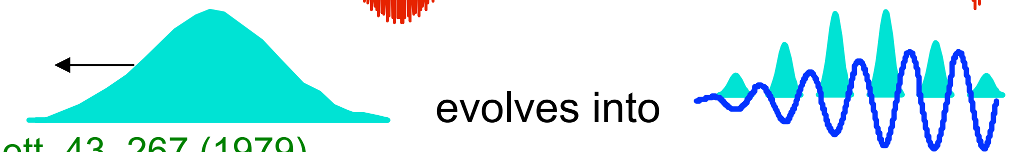


- **Self-Modulated Laser Wakefield Accelerator (SMLWFA)**

  Raman forward scattering instability
  in a long laser pulse



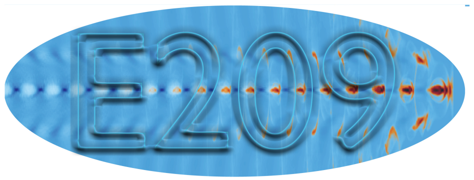
- **Self-Modulated PWFA (SMPPWFA)**



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

SUMMARY

- p+ bunches are the only drivers with enough energy for PWFA to the energy frontier
- Observe self-modulation instability (SMI) of long particle bunches in plasma
- Signs of SMI seeding in ATF experiments
- SLAC E209 SMI physics experiment with e^-/e^+ (2013)
  - Transverse modulation
  - Large wakefields (~10GV/m)
  - Seeding (cut bunch)
  - SMI/hosing competition
  - e^-/e^+ differences
  - …



- SMI PWFA experiments at CERN with p^+ (2015)
  - PWFA driven by p^+ bunch
  - SMI of p^+ bunch
  - Seeding (laser ionization)
  - ~GV/m over 10m
  - External injection of electrons
  - …
  - Beginning of a long term program at CERN for p^+-driven PWFA
- Other SMI experiments (DESY, UK, …)