

# Prospects and Limits of Plasma Wakefield Acceleration

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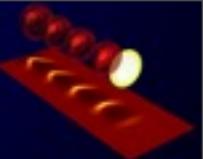
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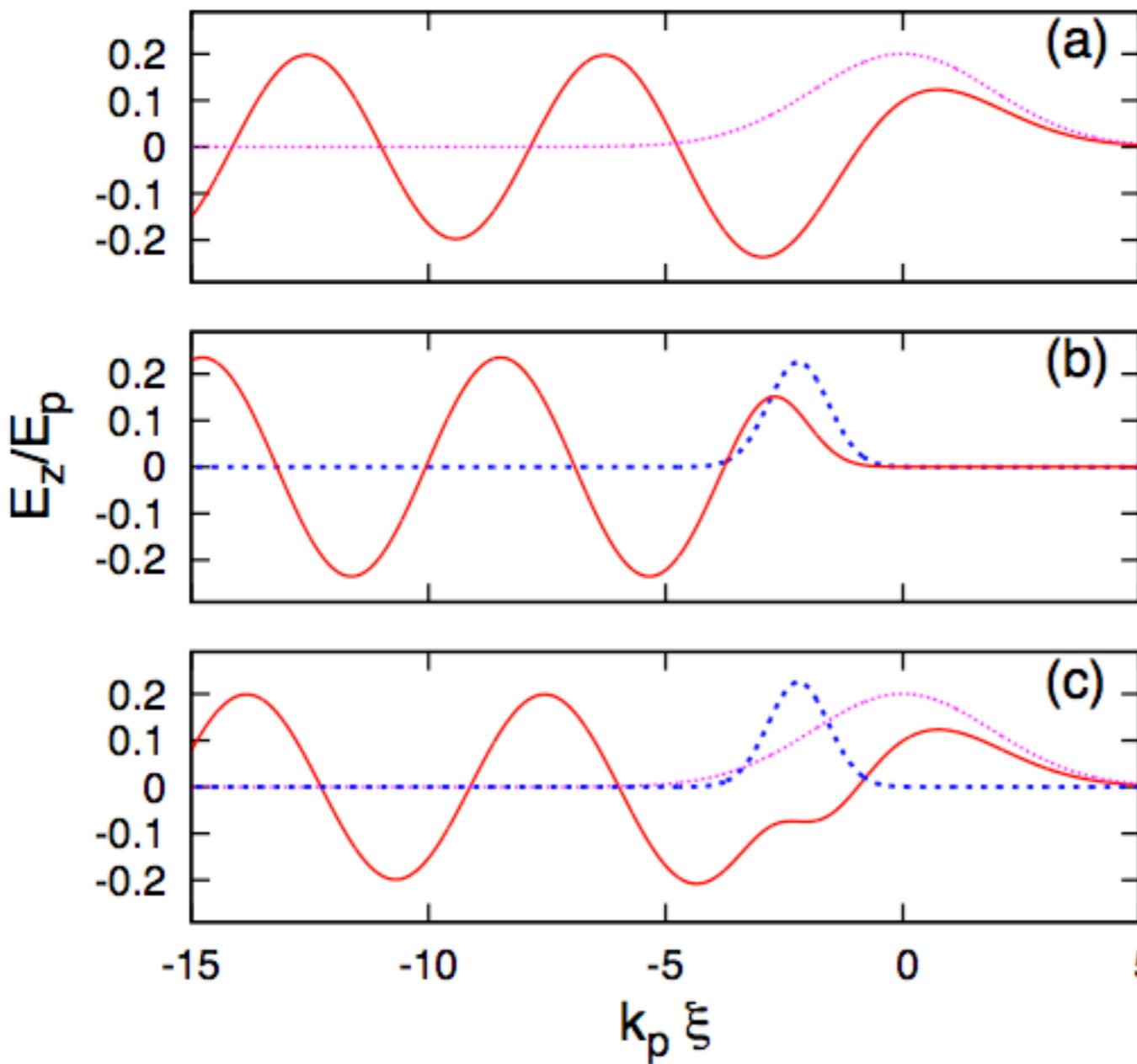
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# Laser and Particle Driven Wakefield



$$\left( \frac{\partial^2}{\partial t^2} + \omega_p^2 \right) \frac{\delta n}{n_0} = c^2 \nabla^2 \frac{a^2}{4} - \omega_p^2 \frac{n_b}{n_0}$$



Laser wakefield

$n_e = 7 \times 10^{18} \text{ cm}^{-3}$ ,  $\tau = 30 \text{ fs}$ ,  $a_0 = 0.5$

E-beam wakefield

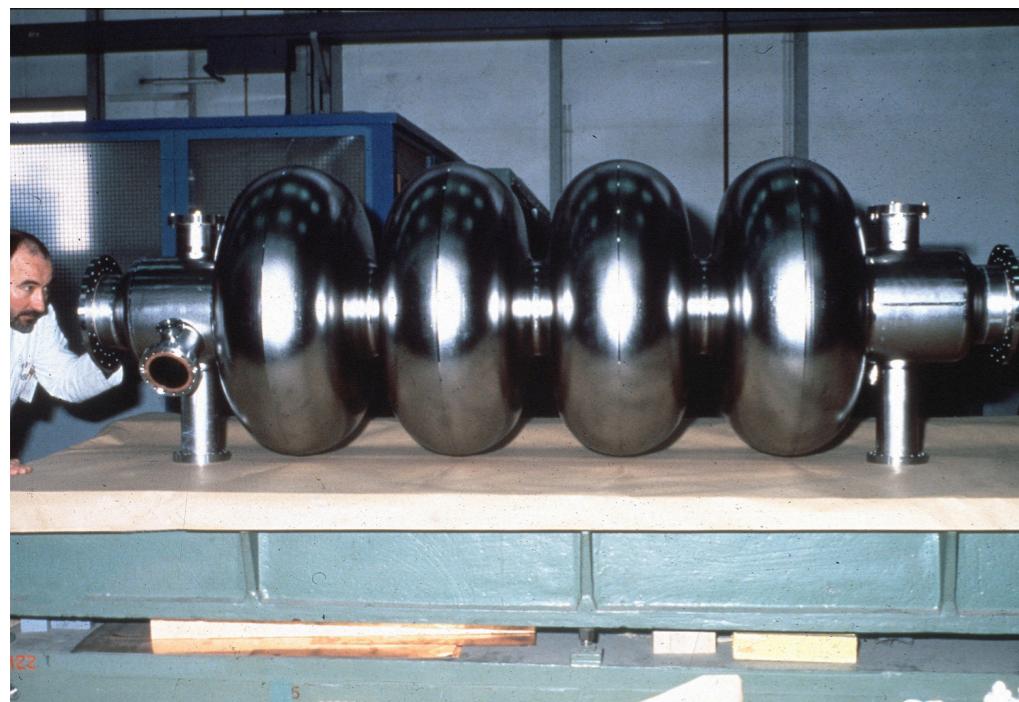
$n_b/n_e = 0.11$ ,  $\tau = 10 \text{ fs}$ ,  
 $d_{FWHM} = 4 \mu\text{m}$  ( $Q = 7 \text{ pC}$ )

The end of the bunch experiments a modified wakefield





## RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m



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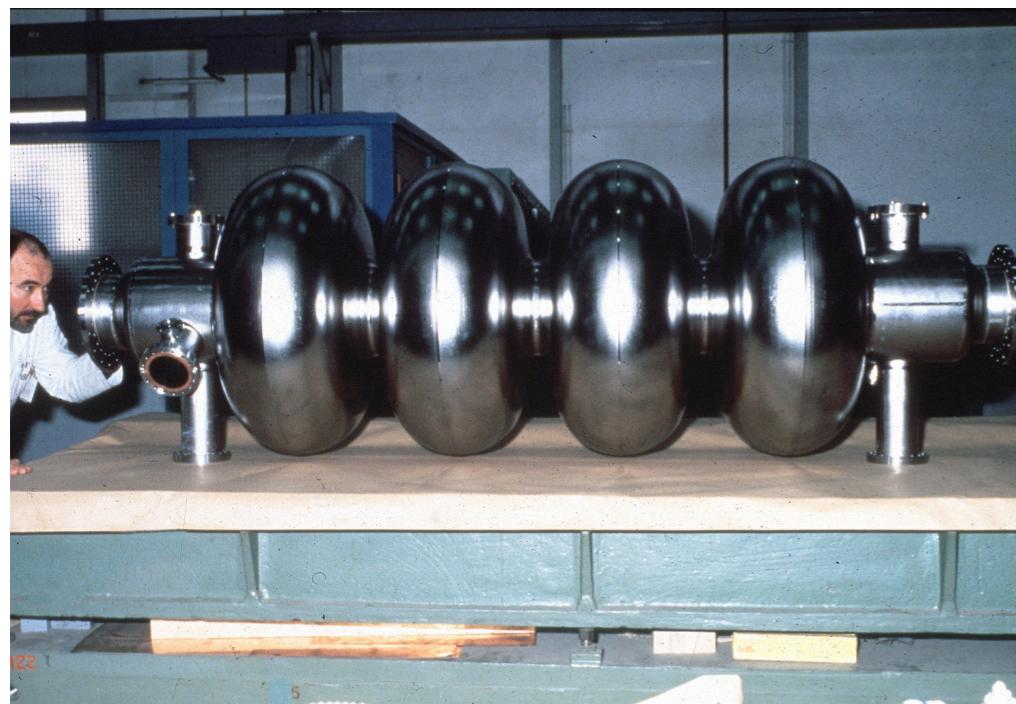
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# Compactness of Laser Plasma Accelerators



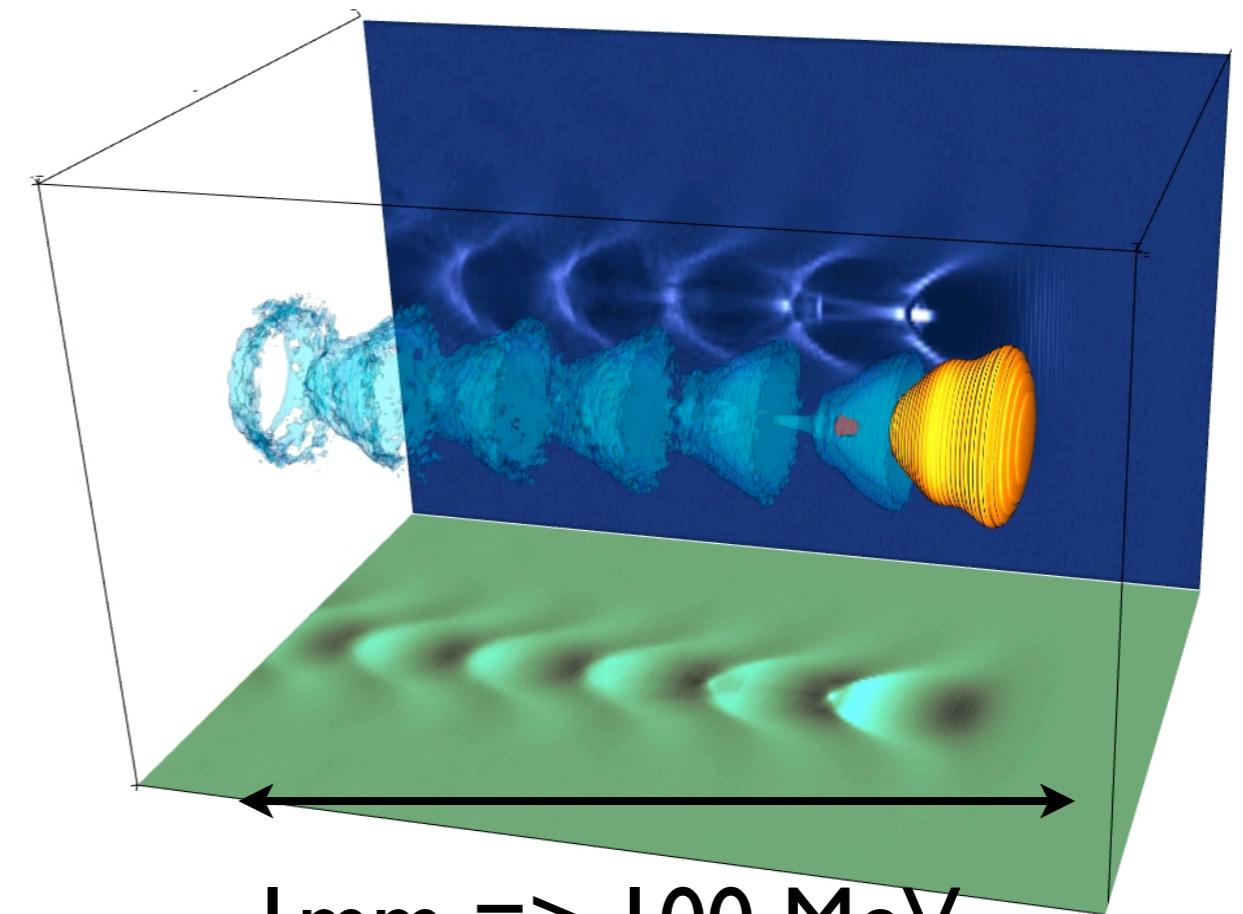
## RF Cavity



↔ 1 m => 100 MeV Gain

Electric field < 100 MV/m

## Plasma Cavity



↔ 1 mm => 100 MeV

Electric field > 100 GV/m

V. Malka et al., Science 298, 1596 (2002)



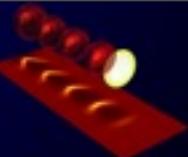
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- Very high gradient of hundreds of GV/m ✓
- Good beam quality & Monoenergetic dE/E down to 1 % ✓
- Beam is very stable ✓
- Energy is tunable: up to 400 MeV ✓
- Charge is tunable: 1 to tens of pC ✓
- Energy spread is tunable: 1 to 10 % ✓
- Ultra short e-bunch : 1,5 fs rms ✓
- Low divergence : 2 mrad ✓
- Low emittance<sup>1-3</sup> : <  $\pi \cdot \text{mm} \cdot \text{mrad}$  ✓
- With PW class laser : peak energy at 3 GeV ✓

**All these, in the Non Linear Regime !**



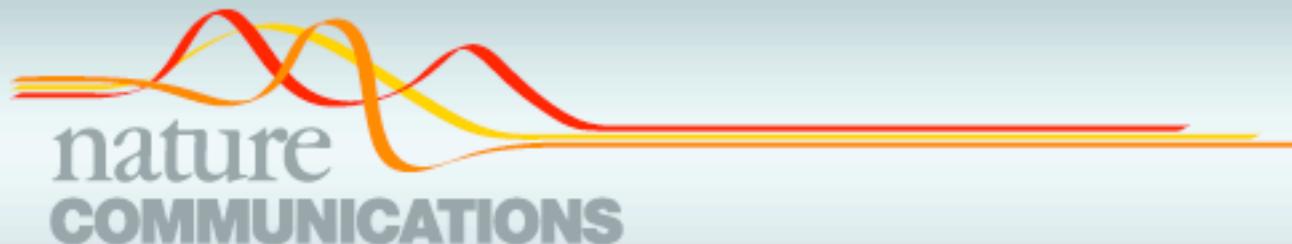
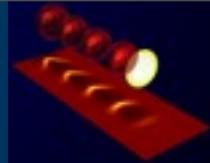
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## ARTICLE

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OPEN

## Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

Xiaoming Wang<sup>1</sup>, Rafal Zgadzaj<sup>1</sup>, Neil Fazel<sup>1</sup>, Zhengyan Li<sup>1</sup>, S. A. Yi<sup>1</sup>, Xi Zhang<sup>1</sup>, Watson Henderson<sup>1</sup>, Y.-Y. Chang<sup>1</sup>, R. Korzekwa<sup>1</sup>, H.-E. Tsai<sup>1</sup>, C.-H. Pai<sup>1</sup>, H. Quevedo<sup>1</sup>, G. Dyer<sup>1</sup>, E. Gaul<sup>1</sup>, M. Martinez<sup>1</sup>, A. C. Bernstein<sup>1</sup>, T. Borger<sup>1</sup>, M. Spinks<sup>1</sup>, M. Donovan<sup>1</sup>, V. Khudik<sup>1</sup>, G. Shvets<sup>1</sup>, T. Ditmire<sup>1</sup> & M. C. Downer<sup>1</sup>



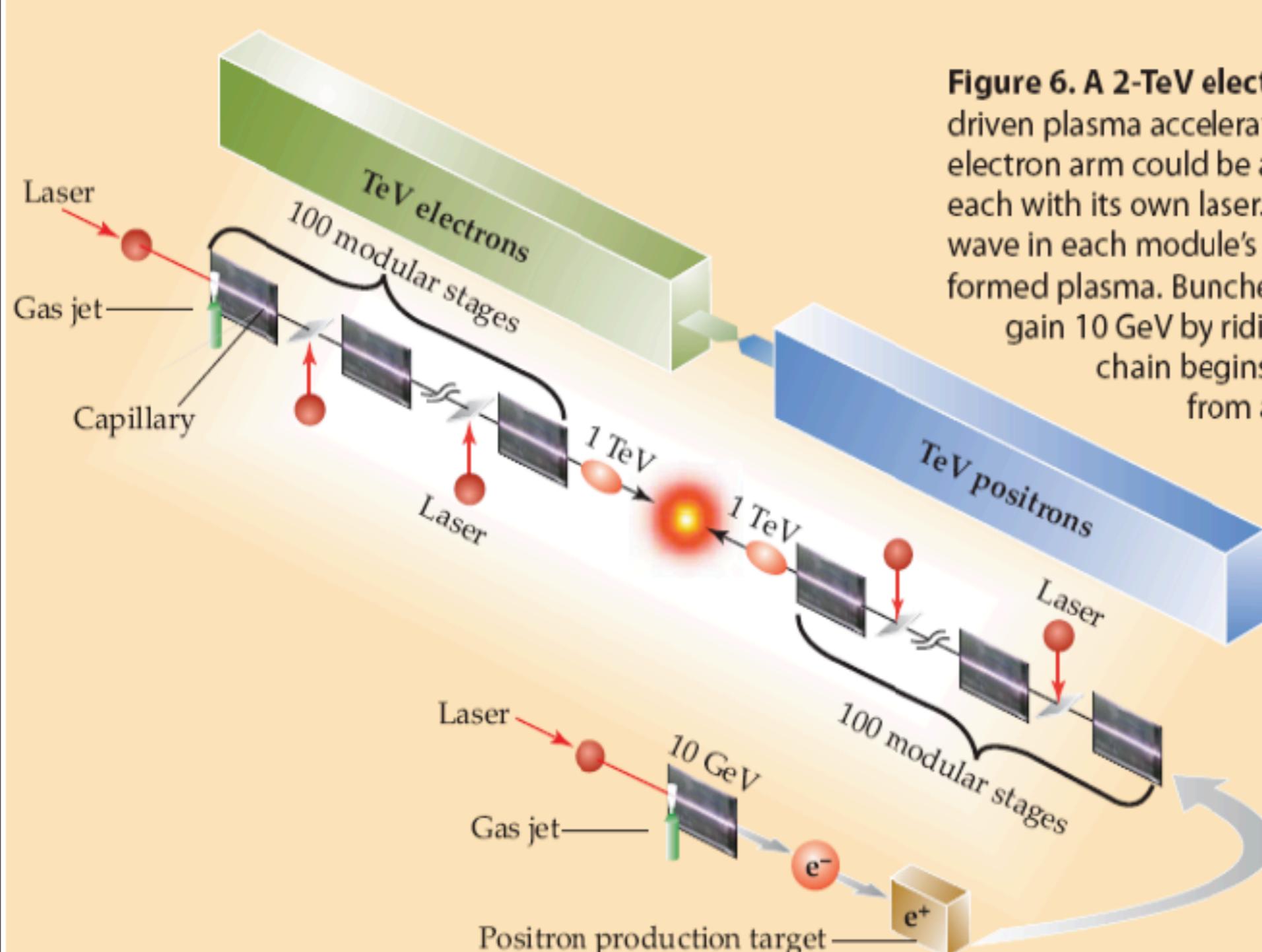
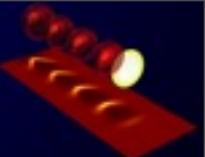
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# Concept of Laser-Driven Plasma Linac: «Artistic view»

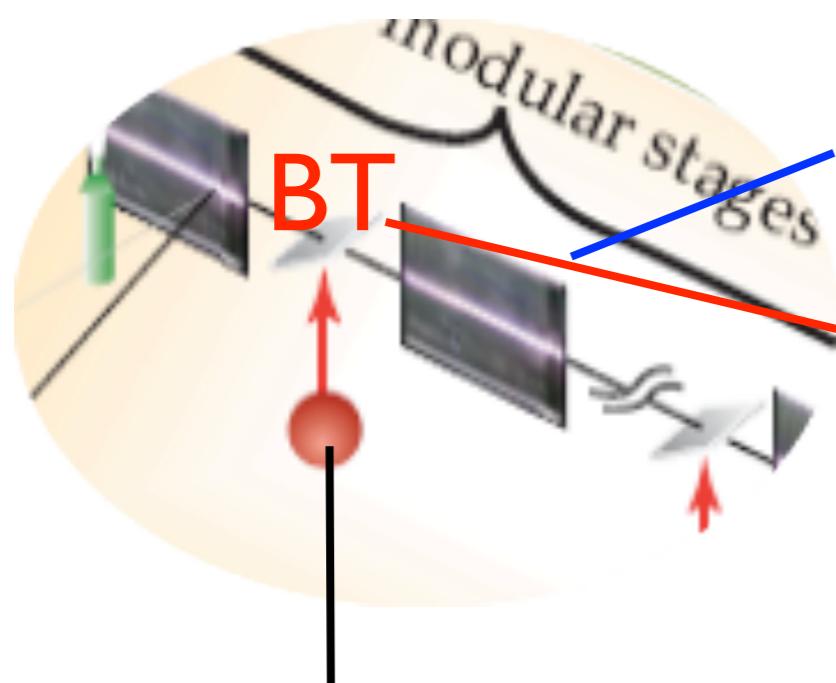
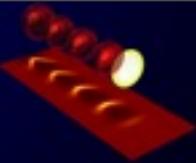


**Figure 6. A 2-TeV electron–positron collider** based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, et al.,

W. Leemans et al., Phys. Today, March 2009

# Concept of Laser-Driven Plasma Linac : Challenges



plasma accelerator  
stage 0.1 to 1m,  $\eta = 1\%$

Beam transport :  
1, 10 m to up to few  
km in the last stages

laser : 10x50 m + focal of 5-10 m,  $\eta = \text{few \%}$

$\eta = ? \%$

overall wall-plug efficiency:  $10^{-3}, 10^{-4}$ ,  
i.e. for a 1 MW e,  $e^+$  beam,  
required power of 1-10 GW

100 of kHz-PW Laser reliability,  
plasma discharge reliability,  
etc..

V. Malka Phys. of Plasma 19, 055501 (2012)

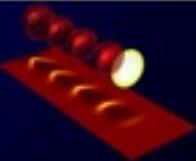


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I PW laser at high rep rate (>100Hz): today in the best 1 Hz

Plasma and vacuum chambers

Transport between stages

Thermal effects on the guiding structure wall

External guiding/self-guiding

Collimation and beam filtering

Accelerating plasma structure: linear (<1 GV/m) or non-linear (>few GV/m to 100s GV/m)

High efficiency laser driver : today in the best 1%

Courtesy of R. Assmann



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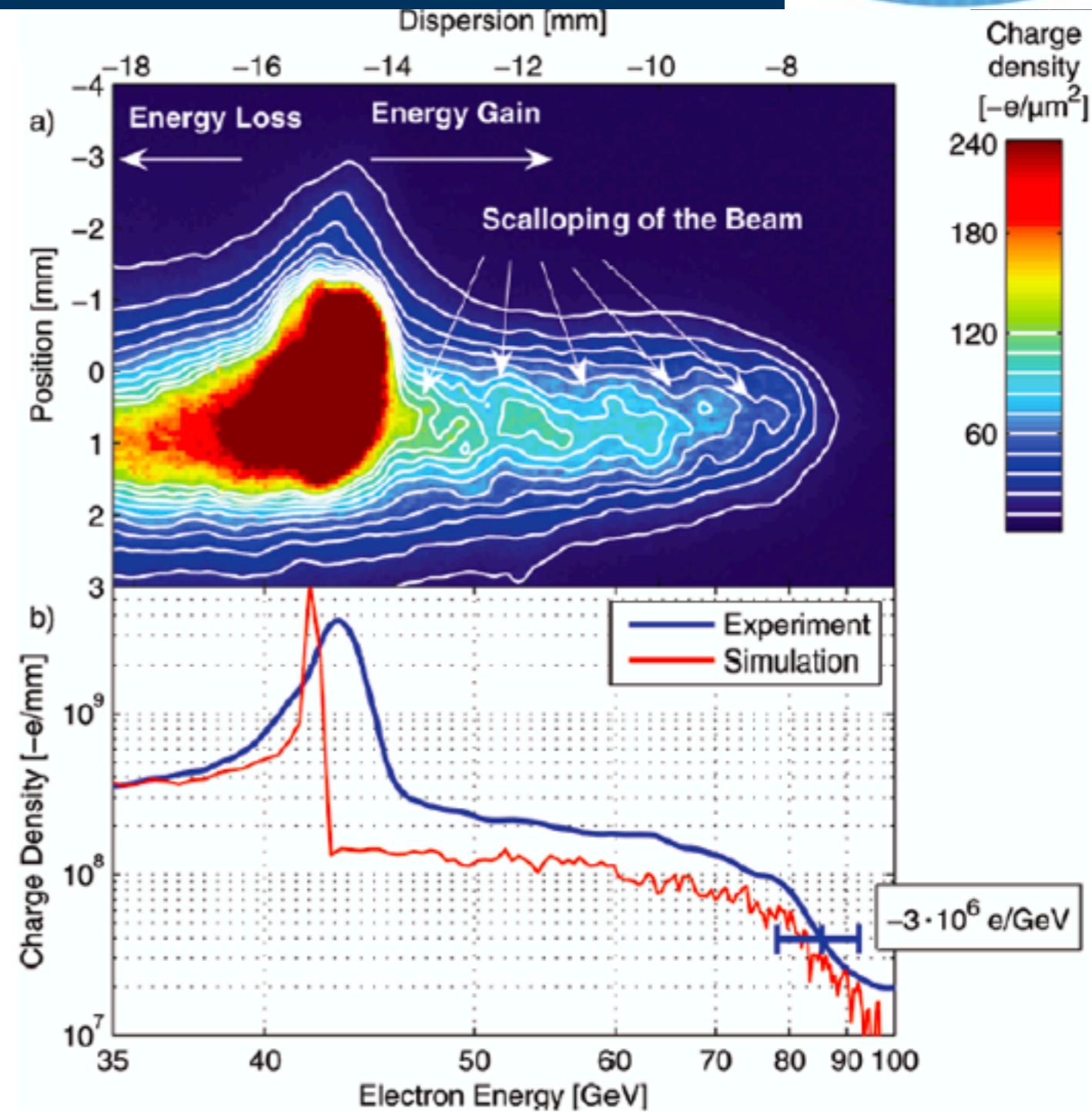
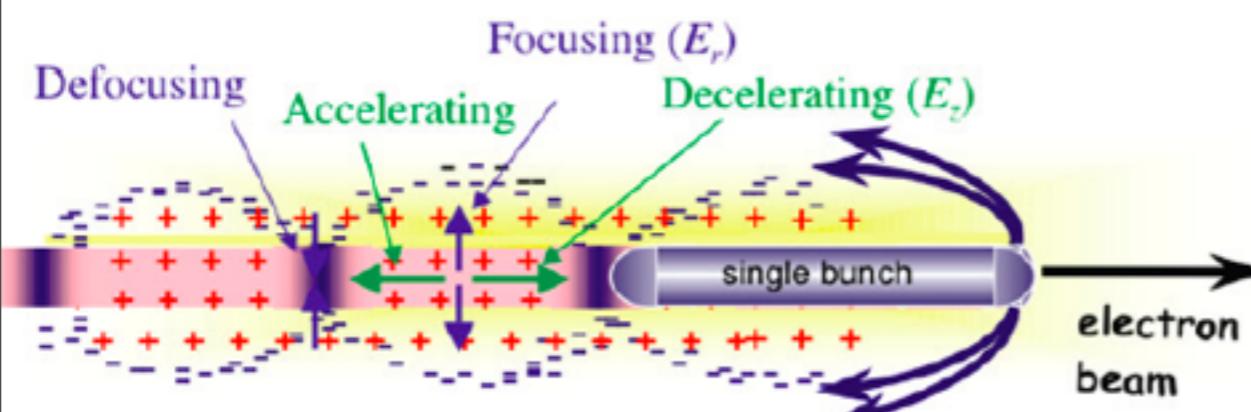
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# Single bunch PWFA at SLAC/FACET



Courtesy of P. Muggli

Blumenfeld et al., Nature 445 (2007), P. Muggli et al., Comptes Rendus de Physique 10 (2009)



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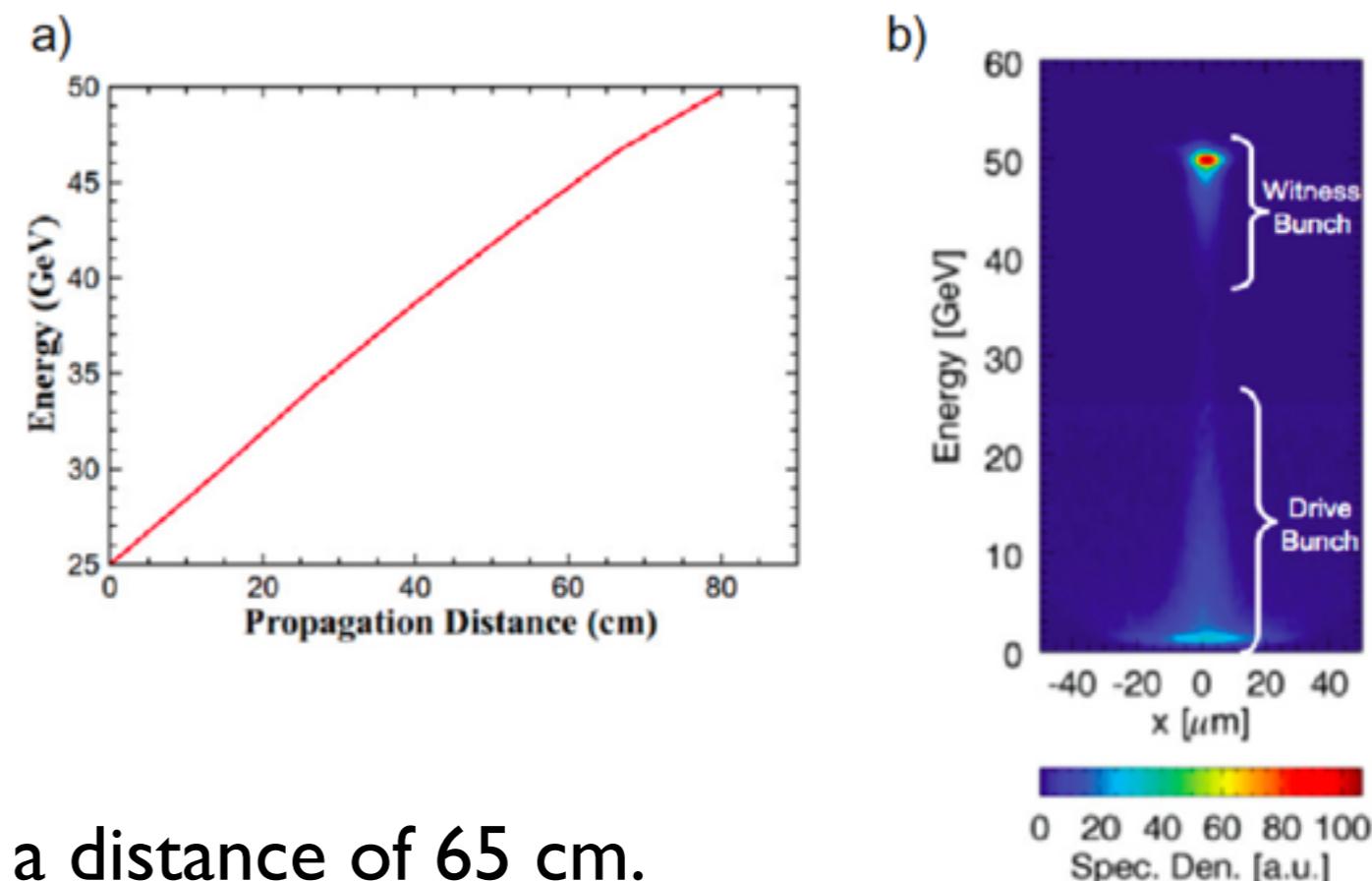
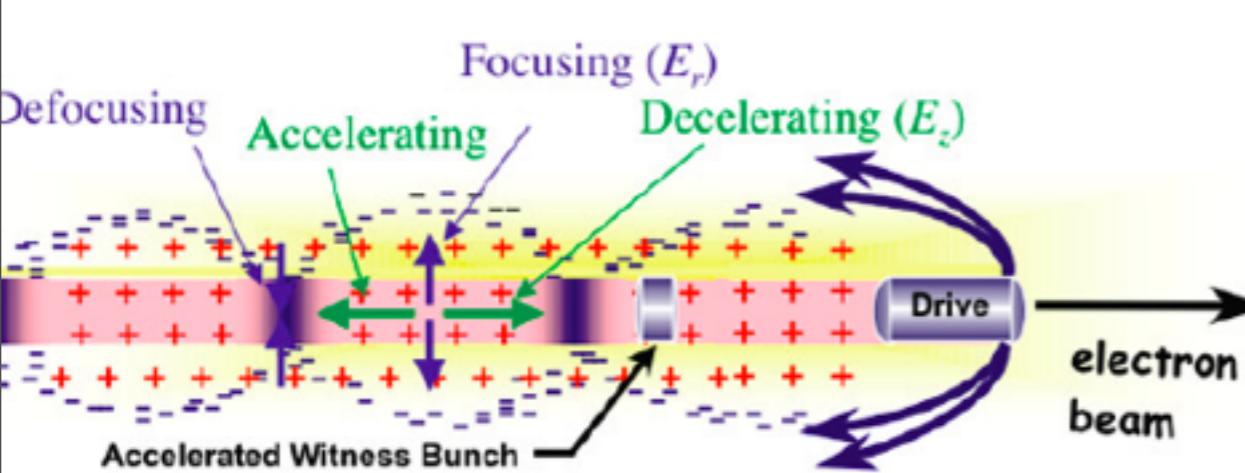
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*work in progress*



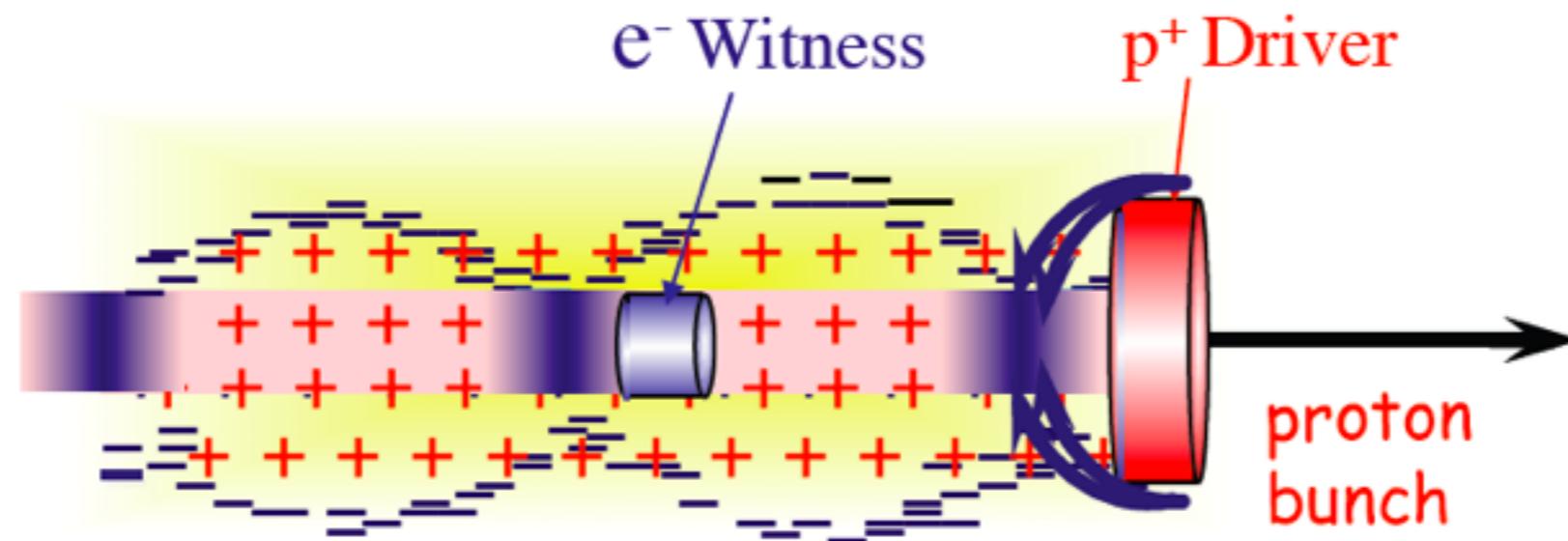
The energy gain is almost linear up to a distance of 65 cm.  
At 80 cm, the 25 GeV witness bunch has doubled in energy  
with an 3% energy spread.

The energy transfer efficiency from the wake to the witness bunch is almost 56%.  
The efficiency from the drive to the witness bunch is greater than 30%.

M. Hogan et al., NJP, 12 (2010)

Courtesy of P. Muggli

# Proton Driven PWFA at CERN :AWAKE project



- => SLAC, 20GeV bunch with  $2 \times 10^{10} e^-$  ~60J Driver
- => SLAC-like driver for staging (FACET= 1 stage, collider 10+ stages)
- => SPS, 450GeV bunch with  $3 \times 10^{11} p^+$  ~22kJ Driver  
LHC, 7TeV bunch with  $3 \times 10^{11} p^+$  ~336kJ Driver
- => A single SPS or LHC  $p^+$  bunch could produce an ILC bunch in a single PWFA stage!

**Large average gradient (~GeV/m, 100's m)**

Courtesy of P. Muggli



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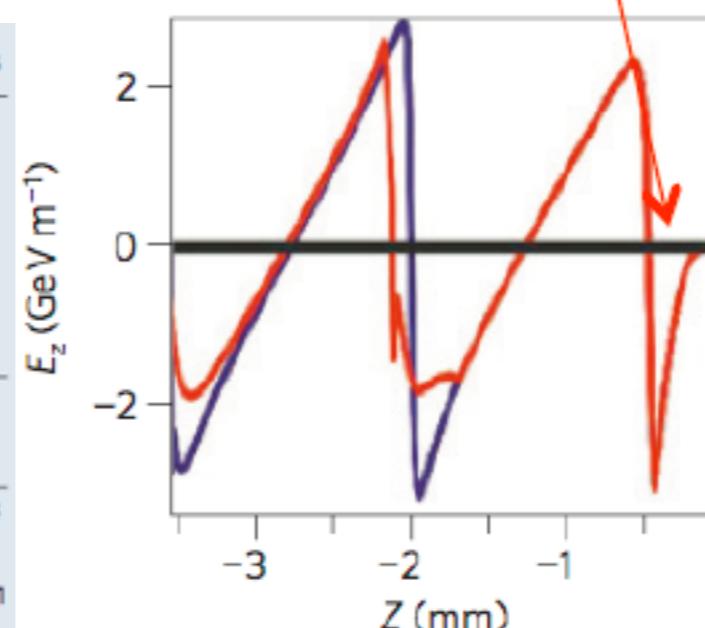
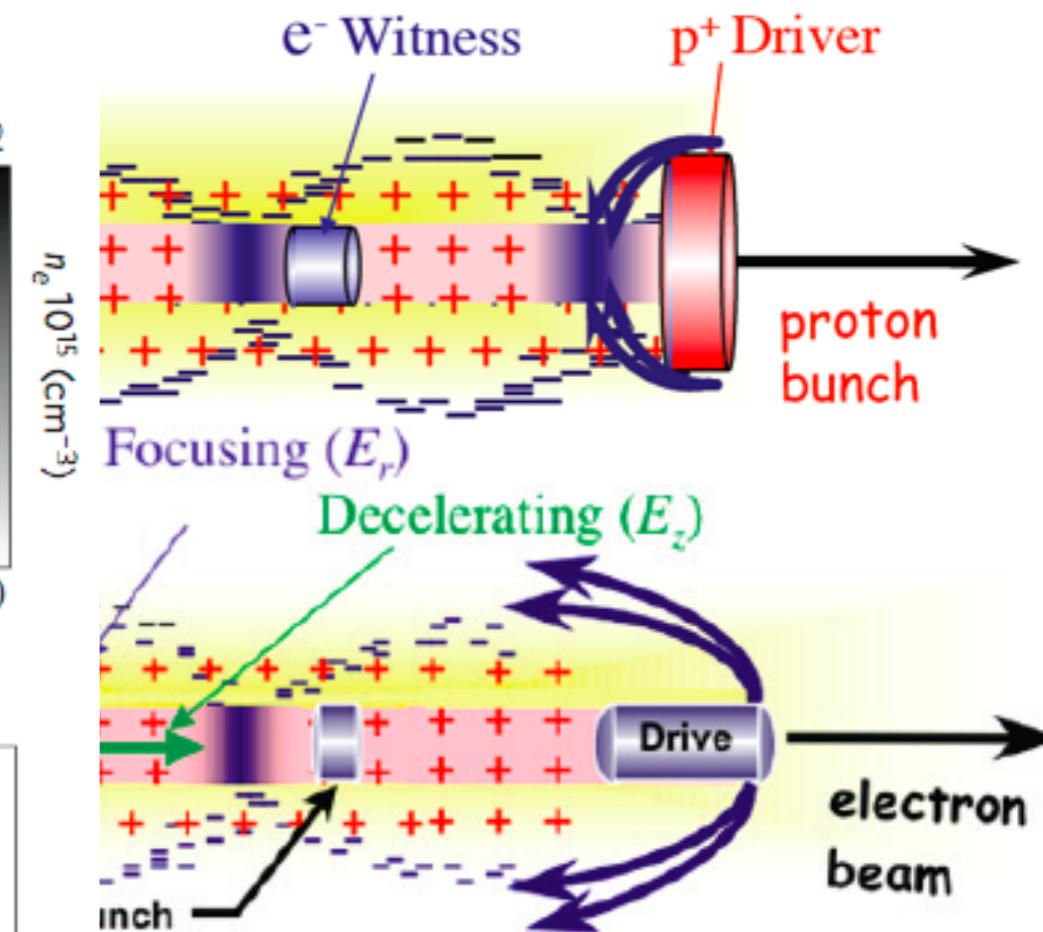
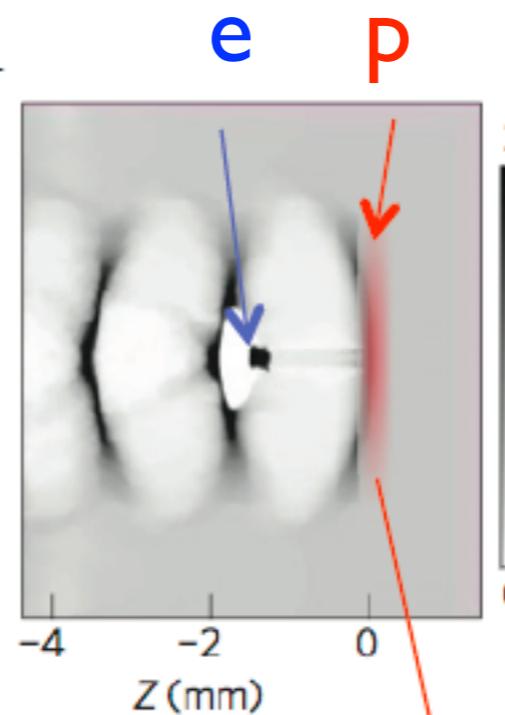
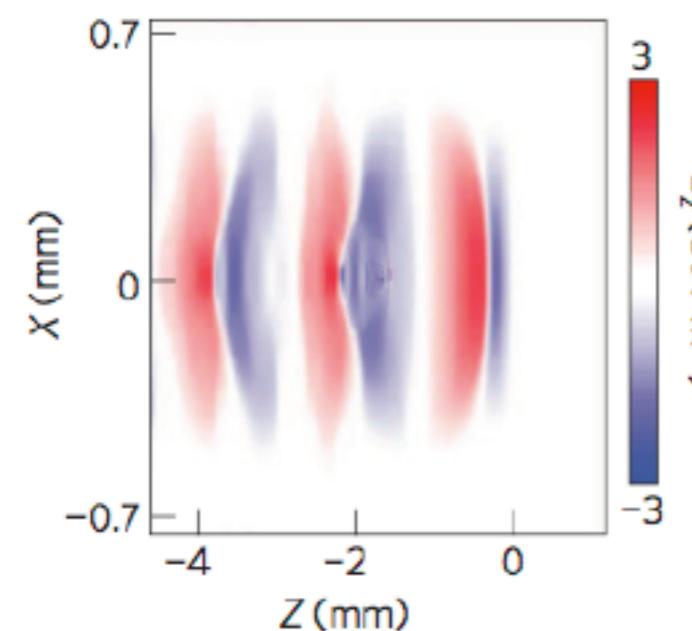
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# Proton Driven PWFA at CERN :AWAKE project



$P^+$   
 $E_0 = 1 \text{ TeV}$   
 $\sigma_z = 100 \mu\text{m}$   
 $N = 10^{11} P^+$   
  
 $e^-$   
 $E_0 = 1 \text{ GeV}$   
 $N = 10^{11} e^-$



Parameter	Symbol	Value	Units
Protons in drive bunch	$N_p$	$10^{11}$	
Proton energy	$E_p$	1	TeV
Initial proton momentum spread	$\sigma_p/p$	0.1	
Initial proton bunch longitudinal size	$\sigma_z$	100	$\mu\text{m}$
Initial proton bunch angular spread	$\sigma_\theta$	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	$N_e$	$1.5 \times 10^{10}$	
Energy of electrons in witness bunch	$E_e$	10	GeV
Free electron density	$n_e$	$6 \times 10^{14}$	$\text{cm}^{-3}$
Plasma wavelength	$\lambda_p$	1.35	mm
Magnetic field gradient		1,000	$\text{T m}^{-1}$
Magnet length		0.7	m

Caldwell et al., Nature Physics, 5, 363 (2009)

Courtesy of P. Muggli

Gradient  $\sim 1.5 \text{ GV/m}$  (av.): Gain of 0.6 TeV in 500 meter  
 Reasonable energy spread of less than 1%

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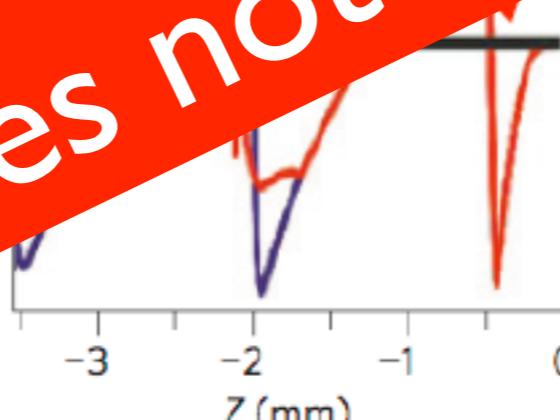
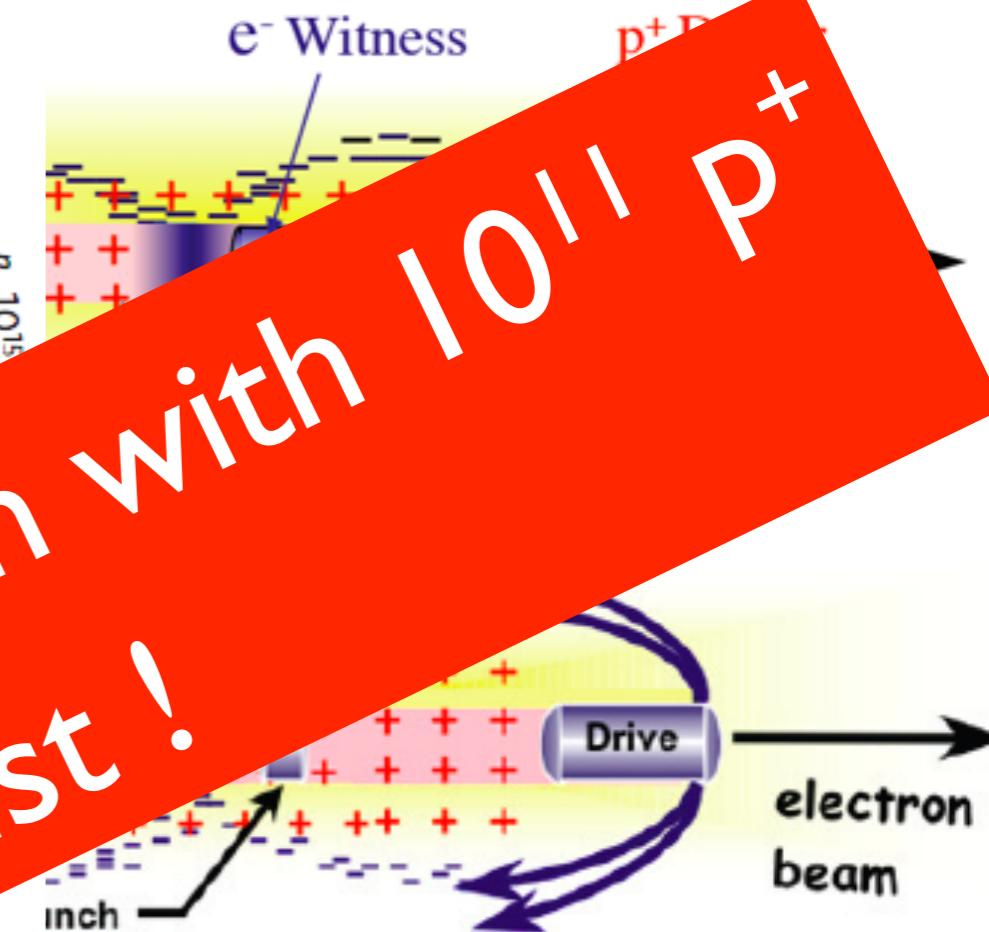
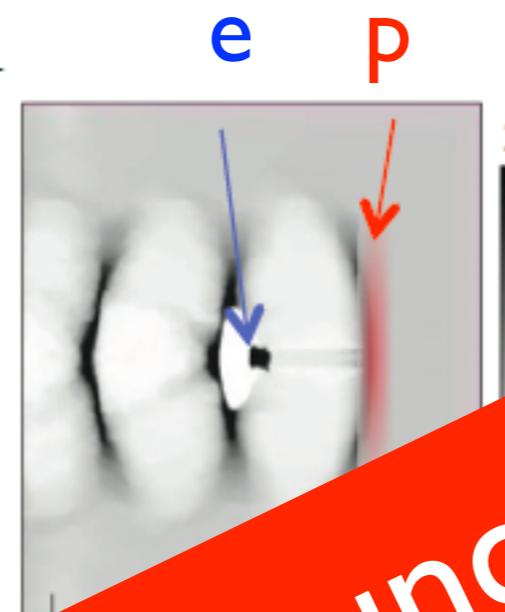
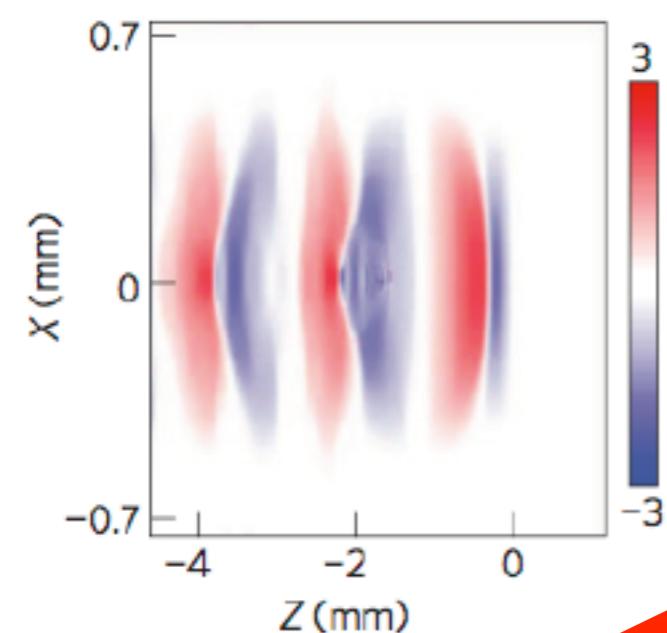
# Proton Driven PWFA at CERN :AWAKE project



$P^+$   
 $E_0 = 1 \text{ TeV}$   
 $\sigma_z = 100 \mu\text{m}$   
 $N = 10^{11} P^+$

$e^-$   
 $E_0 = 1 \text{ GeV}$   
 $N = 10^{11} e^-$

Parameter	Symbol	Value
Protons in drive bunch	$N_p$	10 <sup>11</sup>
Proton energy	$E_p$	1 TeV
Initial proton momentum spread		
Initial proton bunch longitudinal		
Initial proton bunch angular		
Initial proton bunch		
Electron beam energy	$E_e$	1 GeV
Electron beam current	$I_e$	10 <sup>11</sup> A
Plasma density	$n_p$	10 <sup>15</sup> m <sup>-3</sup>
Magnetic field	$B$	1 T
Magnetic gradient	$dB/dz$	1.5 Gv/m



Caldwell et al., Nature Physics, 5, 363 (2009)

Courtesy of P. Muggli

Gradient  $\sim 1.5 \text{ GV/m}$  (av.): Gain of 0.6 TeV in 500 meter

Reasonable energy spread of less than 1%

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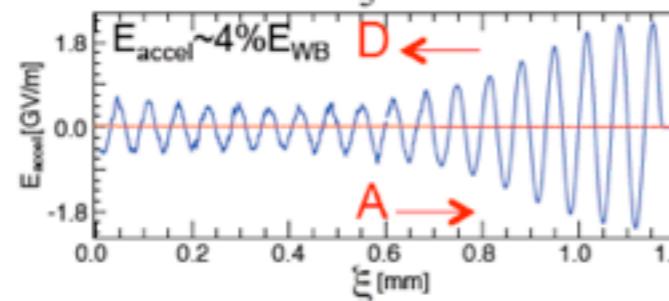
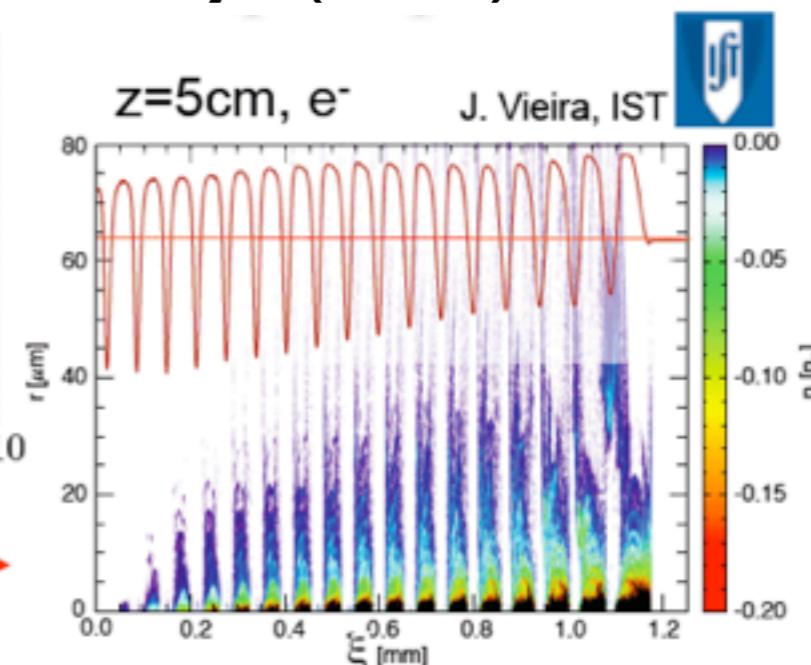
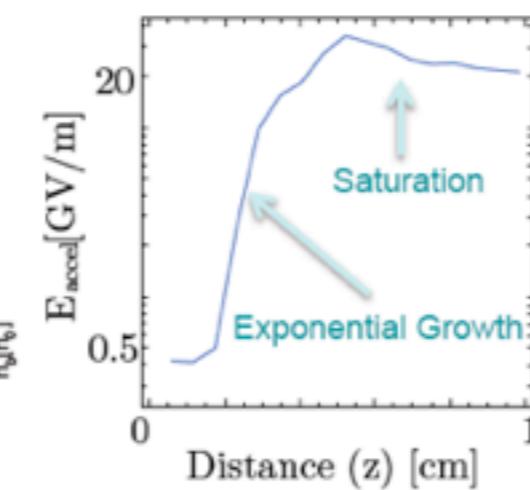
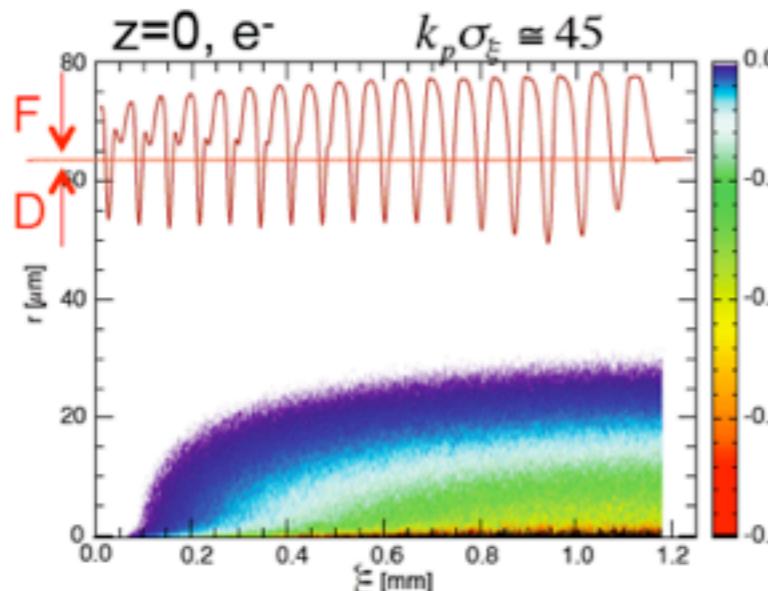
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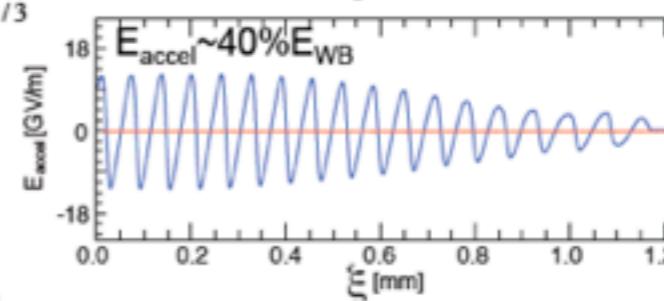


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## Self-Modulation Instability (SMI)



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



Grows along the bunch & along the plasma  
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:  $\sim E_{\text{WB}} = mc\omega_{pe}/e \sim 46 \text{ GV/m}$  @  $n_e = 2.3 \times 10^{17} \text{ cm}^{-3}$

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

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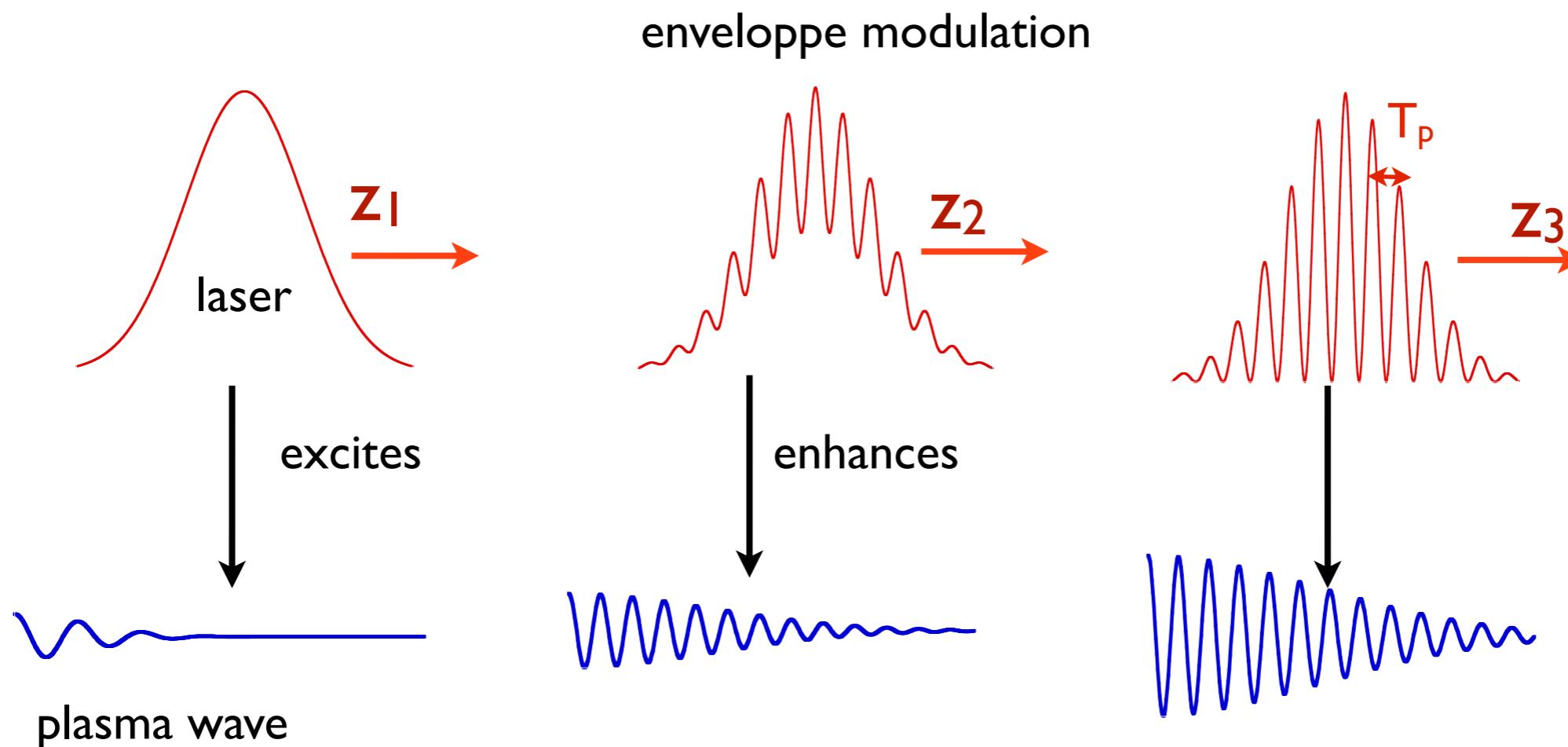
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## Self modulated laser wakefield scheme : $cT_{\text{laser}} \gg T_p$

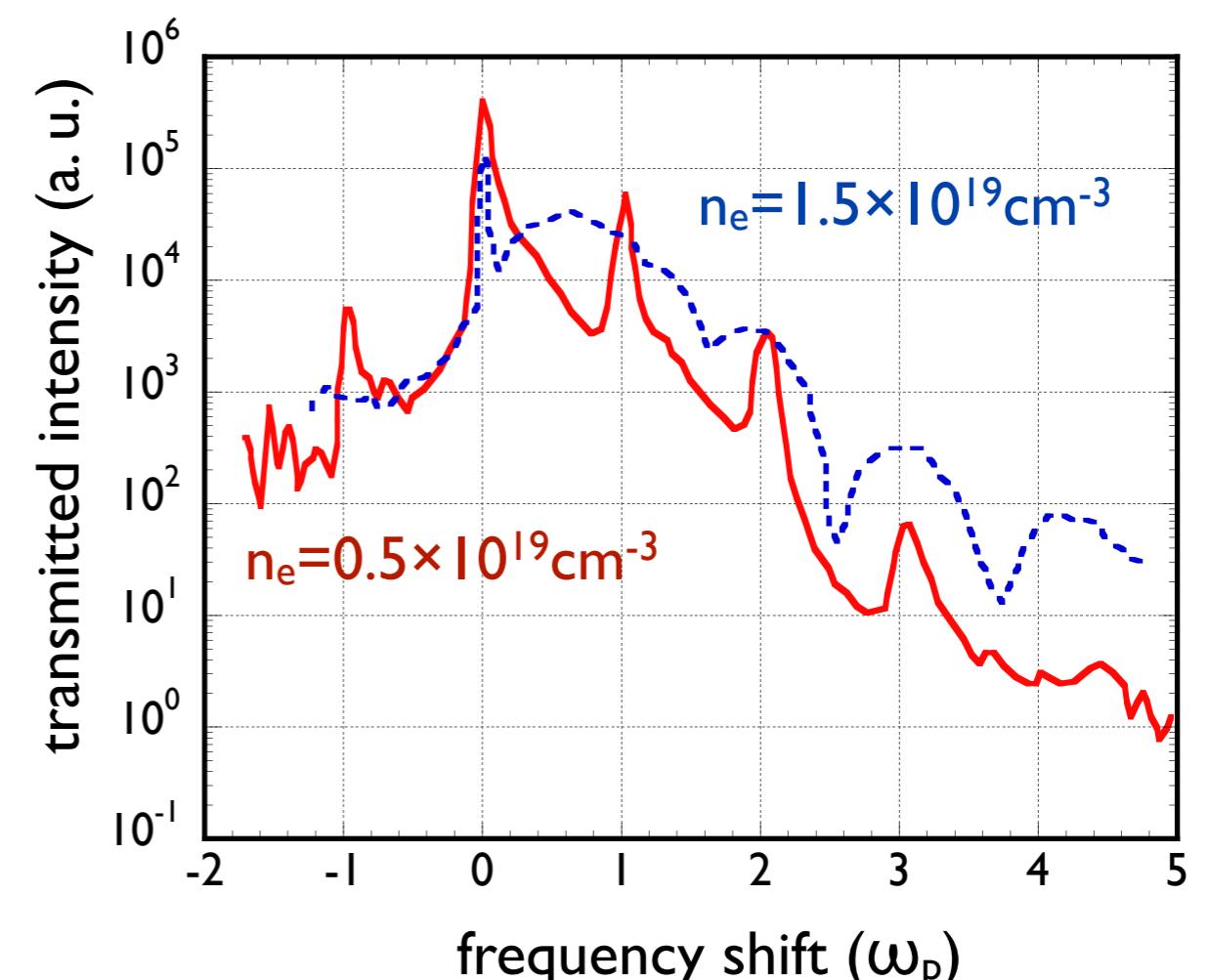
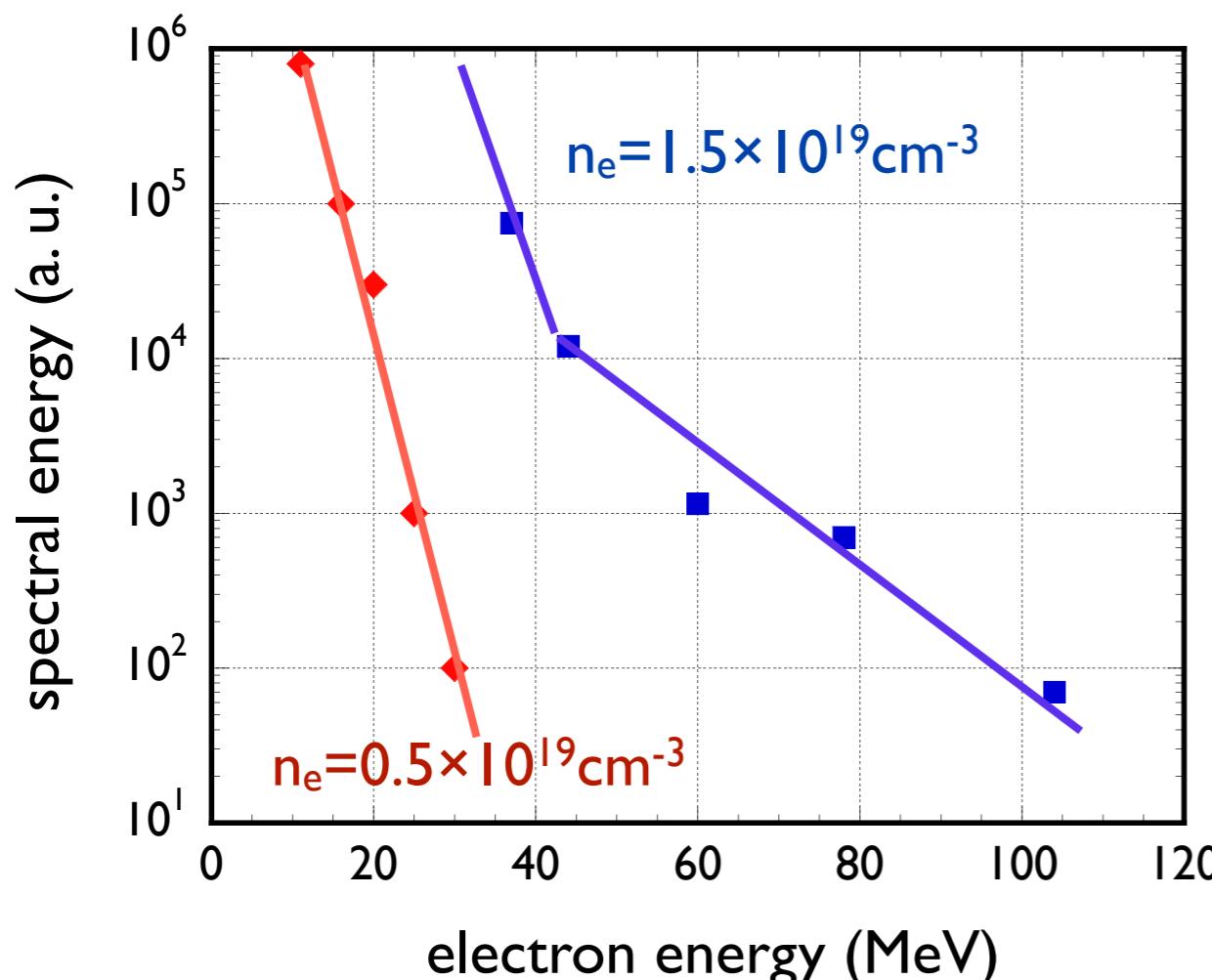
(Andreev et al., Antonsen et al., Sprangle et al. 1992)



$P_L > P_c(\text{GW}) = 17 n_c/n_e$  then wavebreaking can occurred

A. Modena et al., Nature (1995)

# Relativistic wave breaking (RAL/IC/UCLA/LULI)



Multiple satellites : high amplitude plasma waves  
Broadening at higher densities  
Loss of coherence of the relativistic plasma waves

A. Modena *et al.*, Nature (2005)

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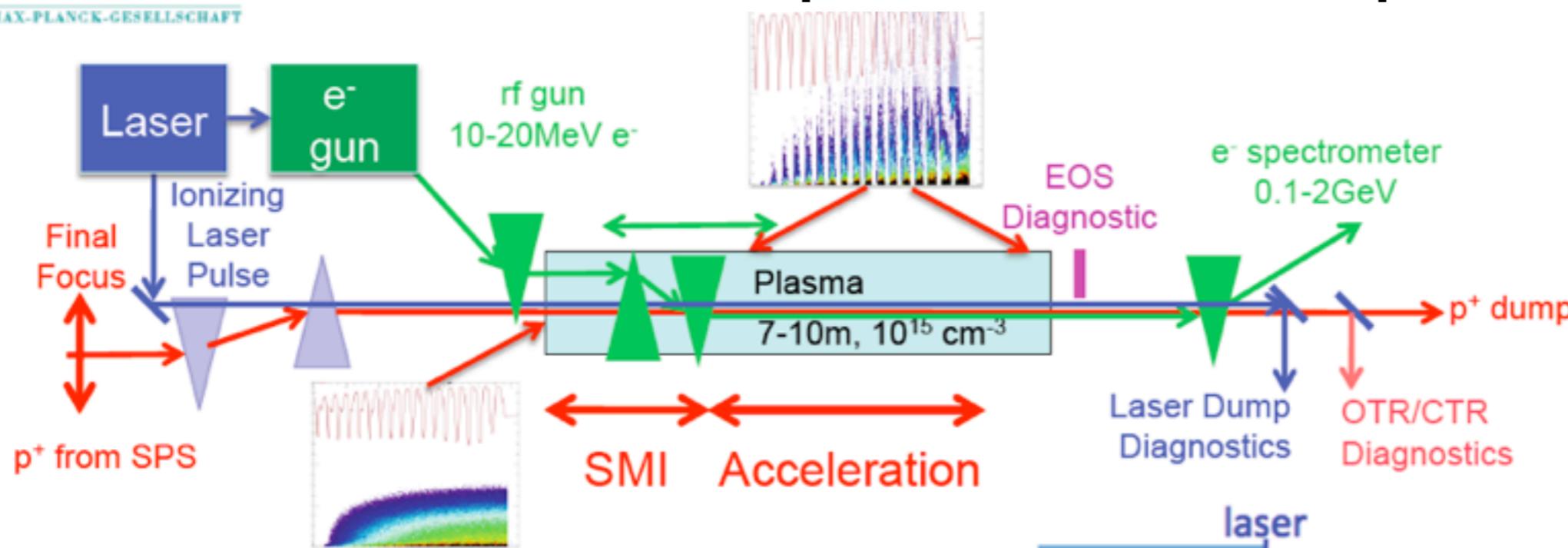
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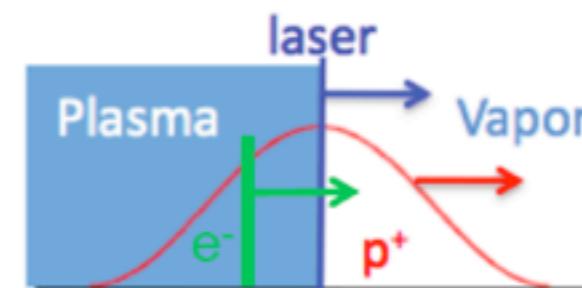
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## Based-Line Experimental Set-up



- Laser ionization of a Rb metal vapor, 7-10m plasma,  $n_e = 10^{14}-10^{15} \text{ cm}^{-3}$
- 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



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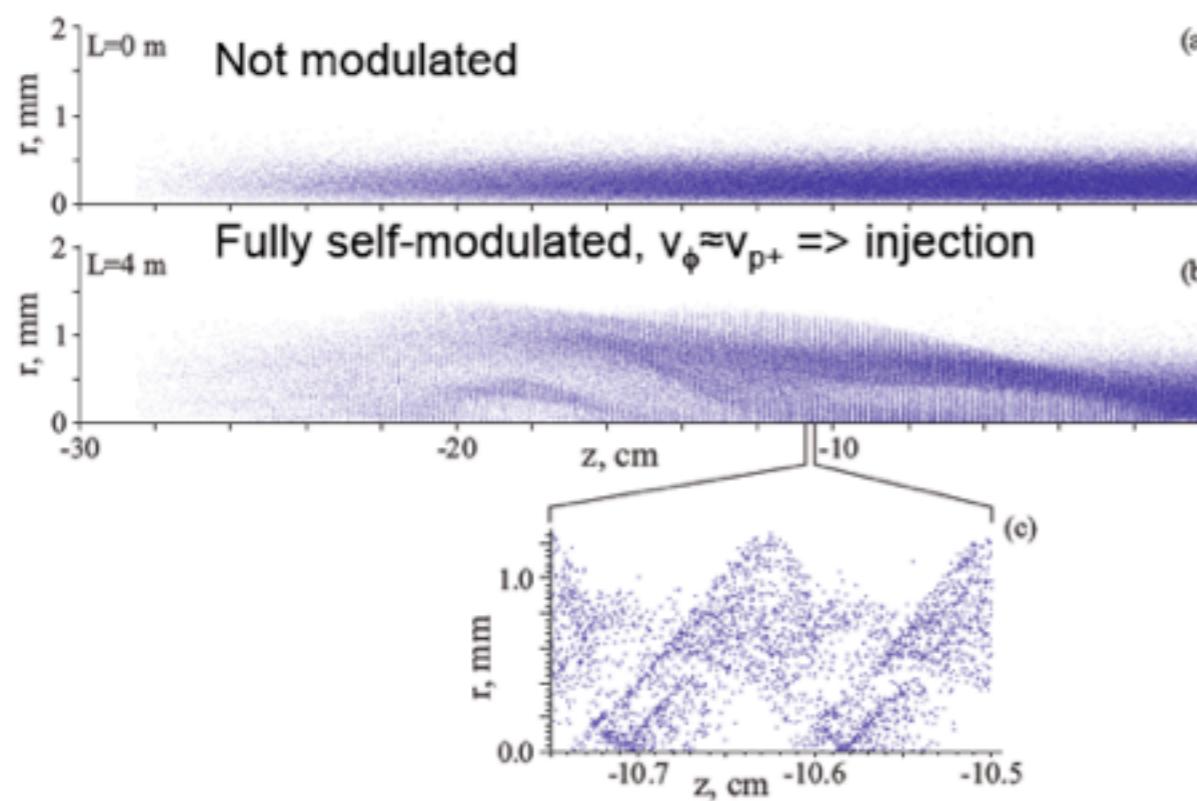
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## Side Injection Simulation Results

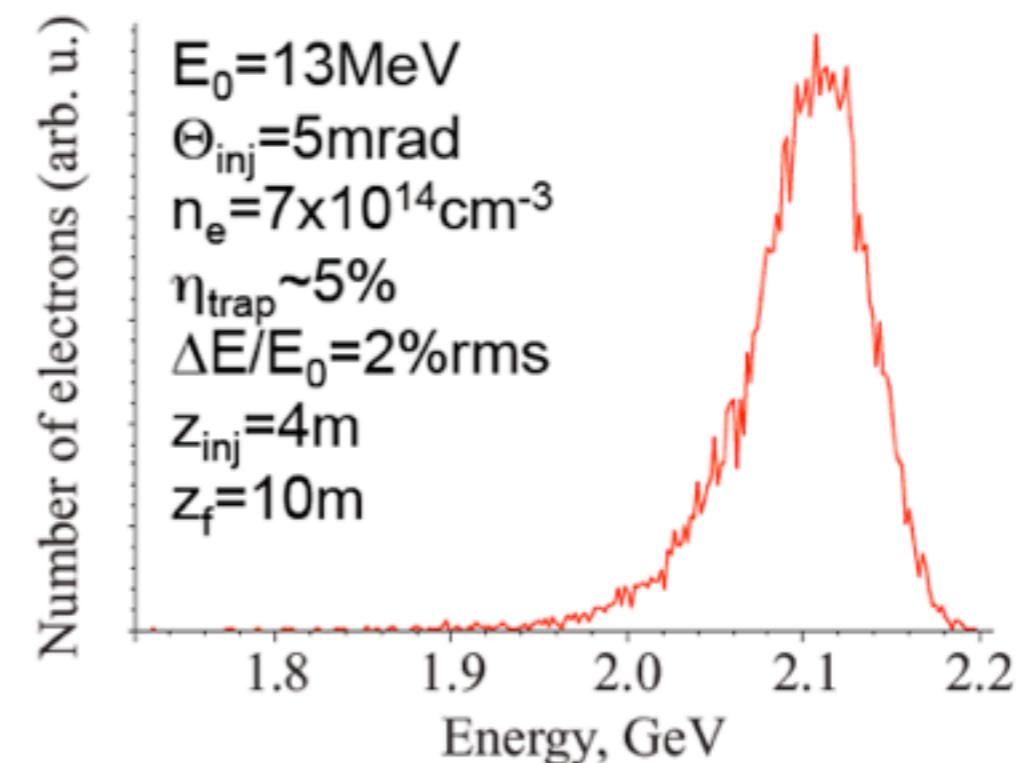


**Table 1:** Proton beam parameter at upstream entrance of the plasma cell.

Parameter	Nominal Value
Energy	400GeV
Bunch Intensity	$3 \times 10^{11} p^+$
Energy per Bunch	19.2kJ
Repetition Rate	0.03Hz
Energy Spread	0.34% (rms)
Transverse Normalized Emittance	$\epsilon_N = 3.5 \text{ mm-mrad}$
Focused Transverse Size (at $\beta^*=5\text{m}$ )	$\sigma_t^* = 0.2\text{mm}$
Bunch Length	$\sigma_z = 12\text{cm}$
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	$4.86 \times 10^{15}$



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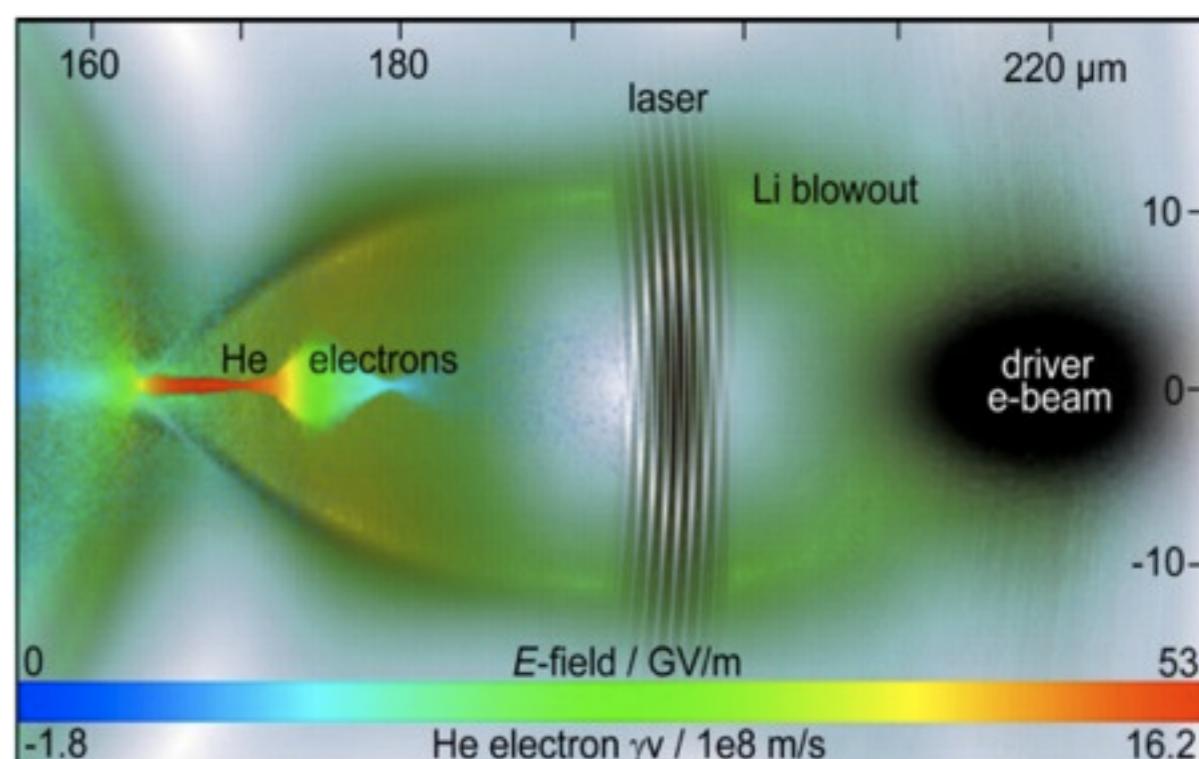


□ Results from LCODE, K. Lotov



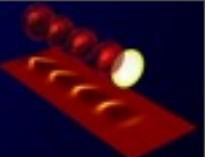
## Ultra-Bright Electron Beams with PWFA and Laser

- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Ultra-high brightness beams for BES applications:
  - Unprecedented emittance (down to  $10^{-9}$  m rad)
  - Sub- $\mu\text{m}$  spot size
  - fs pulses
- Ingredients: electron & laser pulse (synchronized to fs level), plasma source with mixed ionization threshold
- Release laser pulse is strongly focused, needs  $100 \mu\text{J}$ , only, to ionize medium locally in focus at  $10^{15} \text{W/cm}^2$



Courtesy of M. Hogan

**Leverages efficiency and rep rate of conventional accelerators to produce beams with very high brightness for XFEL applications**



## Short term perspective (< 10 years):

Relevant applications in medicine, radiobiology, material science

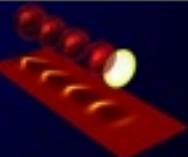
Compact FEL with moderate average power (10 Hz system)

Compact X ray source (Thomson, Compton, Betatron, or FEL)

## Long term possible applications (>40-50 years):

High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, acceleration of positron, etc...)

V. Malka et al., Nature Physics **4** (2008), V. Malka Phys. of Plasma **19**, 055501 (2012)  
E. Esarey et al., Rev. Mod. Phys. **81** (2009), S. Corde et al., Rev. Mod. Phys. **85** (2013)



Proton beam seems today the best driver

Proton beam will be benefit of shortness

2 GeV high quality e- beam (4 m & GV/m)

Doubling 42 GeV electron energy in less than 1 m

Positron acceleration is demonstrated

Increasing activities (FACET, CLARA, INFN, DESY)

Many challenges/open questions :

Producing stable, reliable and long plasma devices

Synchronization/jitter issues

Beam loading effects

Emittance and energy spread measurements are requested



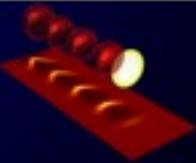
<http://loa.ensta.fr/>

European Coordination for Accelerator Research & Development EUCARD2, CERN, June 10-14 (2013)



UMR 7639





Laser-PWAs allow today to explore several applications with the hope of compactness and cost reduction. They allow to produce secondary sources for many applications (particularly for pump-probe experiments, bright X-rays beam, electron diffraction, radiotherapy, non destructive material inspection, compact FEL, etc...)

Particle-PWAs appear today as the best candidates for future accelerators of interest for HEP

Proton beam driver exist and allow a single stage efficient accelerator

The involvement of accelerators community will be a key element of success of this wonderful and exciting research



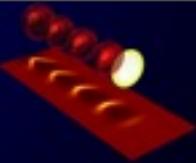
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Laser-PWAs allow today to explore several applications with the hope of compactness and cost reduction. They allow to produce secondary sources for many applications (particularly for pump-probe experiments, bright X-rays beam, electron diffraction,

It is a very exciting time for plasma accelerators !

Proton beam driver exist and allow a single stage efficient accelerator

The involvement of accelerators community will be a key element of success of this wonderful and exciting research



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